# Plan for Today

### 02/01/2018



1.	LDRD office introduction & review charge (5')	8:00-8:05	Bill Priedhorsky
2.	LDRD overview and goals (35')	8:05-8:40	Ming Liu
	<ul> <li>High-level summary of Experiment and Theory</li> </ul>		

Cost & schedule of LDRD

3. Progress and Plan (I)

a. Theory – Introduction and perturbative QCD (20') 8:40 – 9:00 Ivan Vitev

 Soft Collinear Effective Theory for b-jet substructure (15')

9:00 - 9:15 Chris Lee

c. Molecular Dynamics simulations (15')

9:15 - 9:30 Jerome Daligault

d. Hydro and numerical computations (15') 9:30 - 9:45 Boram Yoon

### Coffee break - 15'

9:45-10:00

4. Progress and Plan (II)

a.	Physics & detector simulations (15')	10:00-10:15 Darren McGlinchey
b.	ALPIDE introduction & test stand (15')	10:15-10:30, Xuan Li
c.	MVTX readout integration (15')	10:30-10:45 Alex Tkatchev
d.	Telescope & tracking test (15')	10:45-11:00 Sho Uemura
e.	MVTX mechanical conceptual design (15')	11:00-11:15 Walt Sondheim

Summary and transition plan MVTX proposal (25')
 11:15-11:40 Cesar da Silva

Cost & schedule of MVTX/sPHENIX

### End of presentations, short break - 10'

6.	Executive closed session/Lunch (60')	11:50-12:50 Committee
7.	Panel meet with PI/co-PI (10')	12:50-13:00 Committee





# Probing Quark-Gluon Plasma with Bottom Quark Jets at sPHENIX

Ming Liu (PI) P-25 02/01/2018

Thanks for the strong support from LDRD Office and LANL Program Management



# The LDRD Team



- Experimental group
  - P-25, AOT
  - Detector readout and mechanical support R&D
  - Detector modeling and simulations
  - Physics simulations
- Theoretical group
  - T-2, T-5, CCS-7
  - Physics modeling & simulations
- Budget: 1.6M/Year, FY17-19
  - 1/3 on experimental T&E
  - 1/3 on theoretical T&E
  - 1/3 on Hardware & M&S



















































# **Outline**



LDRD scientific goals

Project scope, status and plan

Mission impacts

Transition Plan



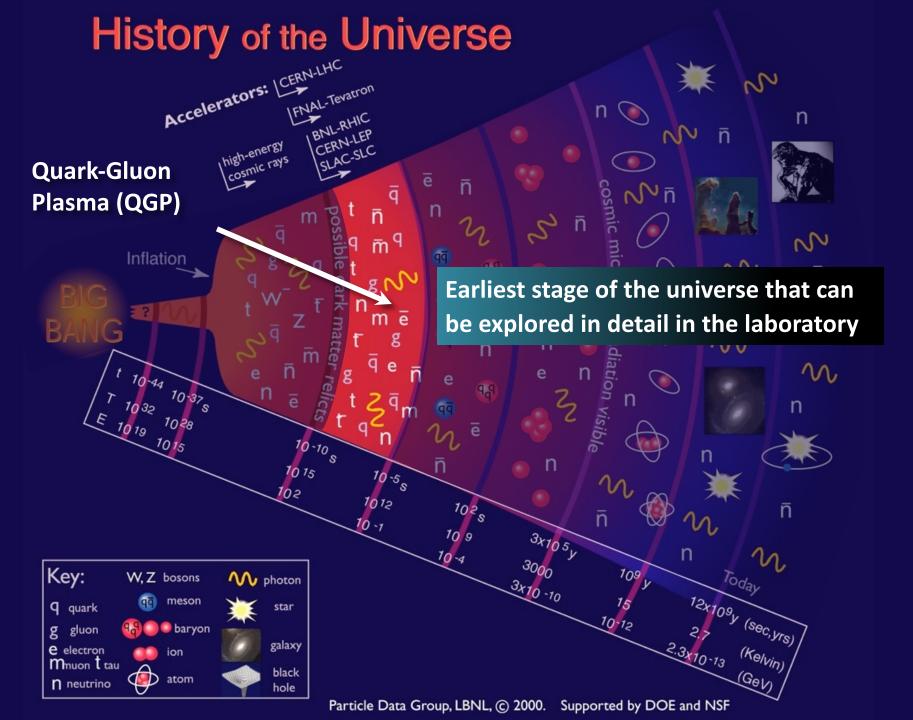


LONG RANGE PLAN for NUCLEAR SCIENCE









# **QGP** Discovery



# nature Interna

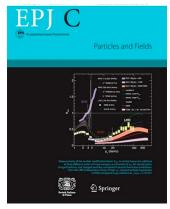
The New York Times

QGP discovery announced in 2004 by RHIC experiments, confirmed later at LHC

PHENIX mission completed in 2016 Upgrade path – sPHENIX @RHIC







- Unambiguous evidence for phase transition from ordinary nuclear matter to QGP  $(T_{QGP}^{-175} MeV, ^{-10^{12}} degrees)$
- Fundamental discovery: QGP is not a weakly interacting gas of quarks and gluons, but rather a strongly coupled near-perfect liquid!
- Exhibits strong collective behavior, has huge stopping power for color-charged particles (quarks, gluons – the fundamental constituents)

Big Question for Science: From what microscopic structure do these properties emerge? 

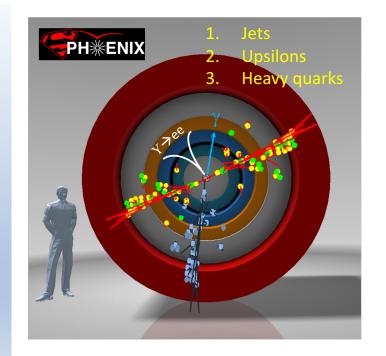
Requires new observables!



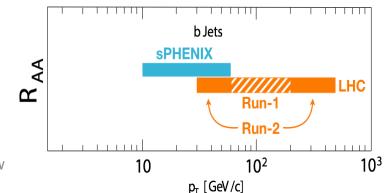
# **Bring Big Science to LANL**



- sPHENIX the next US NP flagship heavy ion physics program, to study the inner workings of QGP
  - Granted CD0 9/2016; CD1 scheduled 5/2018
  - Constr. 2019 2022; Physics run: 5+ years
- This LDRD will allows LANL to take a leadership role in sPHENIX and be a key player in the Heavy Ion physics frontier
  - Innovation: develop a new open heavy flavor physics program, identified as the 3<sup>rd</sup> Science Pillar of the sPHENIX experiment
  - Bring new state of the art technical capability to LANL applied program, also future EIC program



### Complement & extend current and future RHIC and LHC QGP programs



### Evolving sPHENIX multi-year run plan (2016 BNL Proj.)

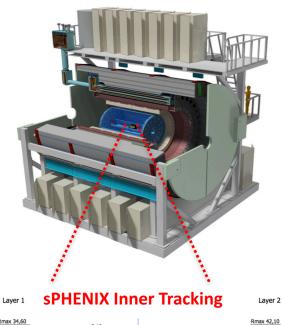
Year	Species	Energy [GeV]	Phys. Wks	Rec. Lum.	Samp. Lum.	Samp. Lum. All-Z
2022	Au+Au	200	16.0	$7~{ m nb^{-1}}$	$8.7 \; { m nb^{-1}}$	$34 \; {\rm nb^{-1}}$
2023	p+p	200	11.5	_	$48 \text{ pb}^{-1}$	$267 \text{ pb}^{-1}$
2023	p+Au	200	11.5	—	$0.33 \text{ pb}^{-1}$	$1.46 \; \mathrm{pb^{-1}}$
2024	Au+Au	200	23.5	$14 \; {\rm nb^{-1}}$	$26 \; {\rm nb^{-1}}$	$88 \text{ nb}^{-1}$
2025	p+p	200	23.5	_	$149 \; \mathrm{pb^{-1}}$	$783 \; \mathrm{pb^{-1}}$
2026	Au+Au	200	23.5	$14 \; {\rm nb^{-1}}$	$48 \; {\rm nb^{-1}}$	$92 \text{ nb}^{-1}$

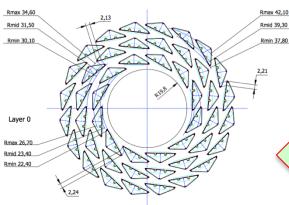


## LANL Proposed Monolithic-Active-Pixel-Sensor-based Vertex Detector (MVTX)



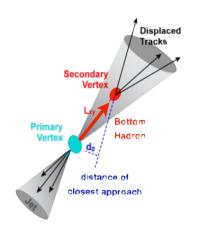
### sPHENIX upgrade @RHIC





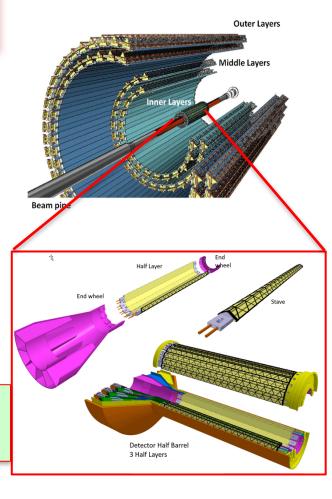
### Key integration tasks:

- Readout
- Mechanics



"Adopt" ALICE/ITS
Mini. risk,
Max. physics

### ALICE ITS Upgrade @CERN; Inner Tracker System (2021+)



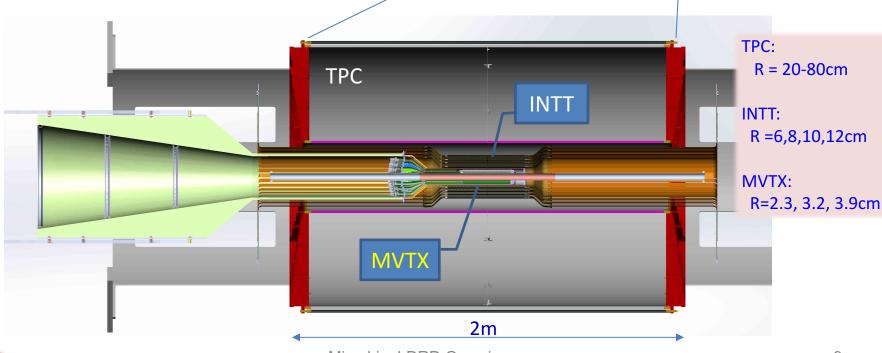


# **SPHENIX Tracking System with MVTX**



 Side view of the sPHENIX Tracking system with a conceptual design of MVTX mechanical system

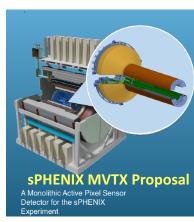




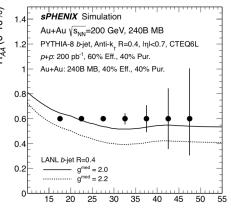
# **LDRD Scientific Goals**



- Develop a next generation QGP physics program with heavy quark jets at RHIC with full detector and physics simulation and modeling
- Carry out key detector R&D to demonstrate the open heavy flavor physics capability in the sPHENIX with MVTX
- Develop a proposal to DOE to build a state-ofthe-art MAPS-based Vertex Detector for the sPHENIX
- New theoretical study of QGP tomography with b-jets

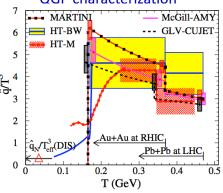


### B-jet suppression in QGP



Transverse Momentum [GeV/c]

### **OGP** characterization



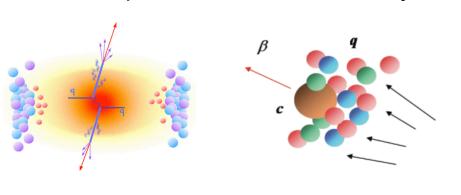


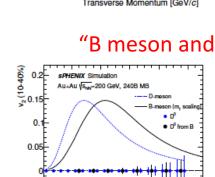
# **New Physics Reach with MVTX**



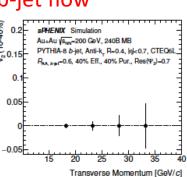
### Ivan and Darren's talks

- Heavy quarks unique probe of QGP w/ new scales, m<sub>c</sub>, m<sub>b</sub>
  - Study mass dependence
    - Jet quenching & energy loss
    - Flow interaction with medium
  - Access QGP properties
    - · Temperature, density, coupling, transport coefficients, viscosity etc.





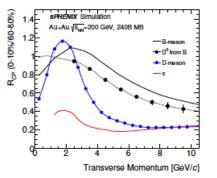
Transverse Momentum [GeV/c]

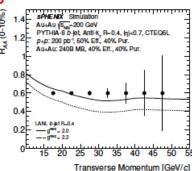


### $m_{ii} m_{d}$ $m_s$ $\Lambda_{\sf OCD}$ $m_c$ $m_{h}$ MeV 10 102 103

"Money plots" from MVTX proposal

### "B meson and b-jet modification"





### "B meson and b-jet flow"



# LDRD Project Scope



Established at the beginning of this project feasibility review 1/2017

### Minimal scope

- Develop a MVTX prototype telescope with 4 ALPIDE sensors/staves with ALICE readout units, complete sPHENIX DAQ integration
- Complete R&D on mechanical conceptual design, sPHENIX system integration
- Develop b-jet tagging algorithms for p+p and Au+Au
- DOE MIE proposal submitted to fund the full detector construction
- Complete b-jet theory for precision tomography of QGP with sPHENIX

### Desired scope

- Develop a full 4-production-staves MAPS telescope, test beam run with integrated sPHENIX DAQ
- → DOE MIE proposal approved for the full detector construction



# DRD Timeline: Experiment Los Alamos NATIONAL LABORATORY EST. 1943

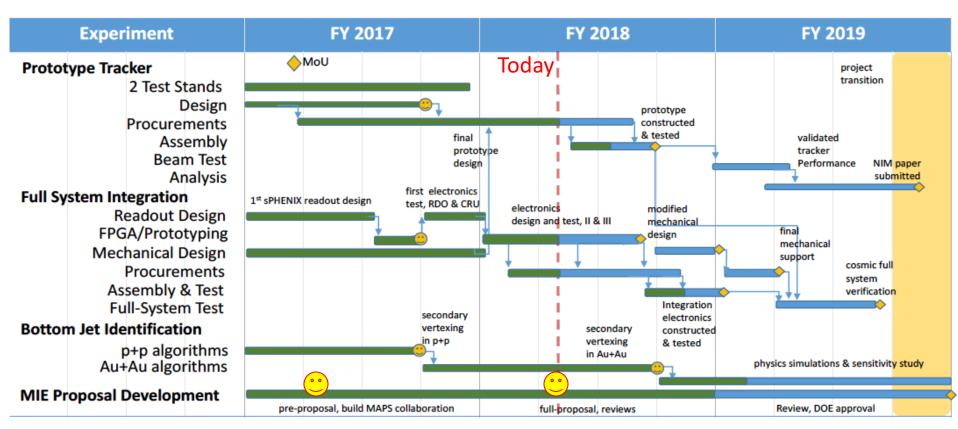


### Milestones achieved

- **MOU** with ALICE
- B-tagging in p+p and Au+Au
- BNL Director's Review, recom'ed to proceed w/ full proposal
- Full readout chain demonstrated
- Mechanical conceptual design
  - Collaboration formed and full **MVTX** proposal completed

Talks by Darren, Xuan, Alex, Sho, Walt, Cesar

On track to succeed!





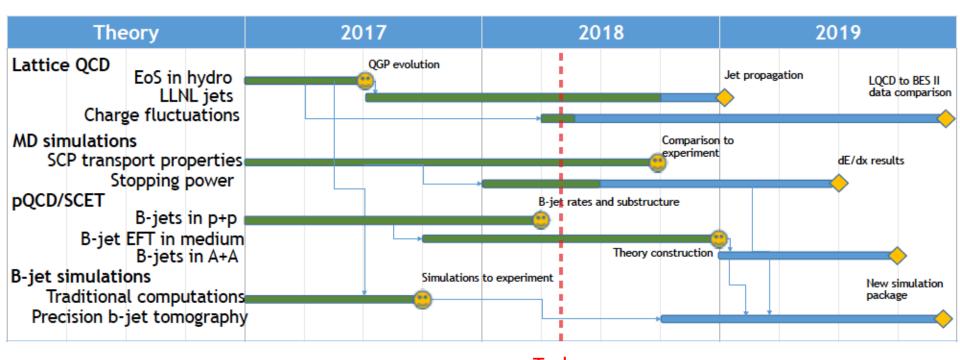
# LDRD Scope: Theory



### Significant progress

Ivan's talk

- New calculations and new observables
- Met milestones, some ahead of time







# **ALICE Pixel Detector (ALPIDE)**

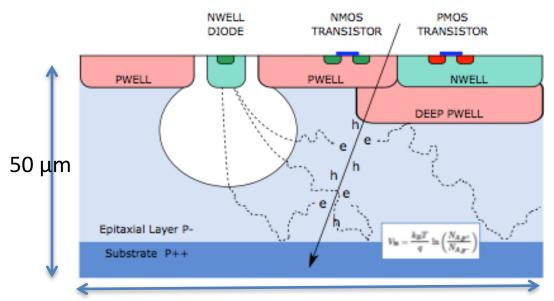


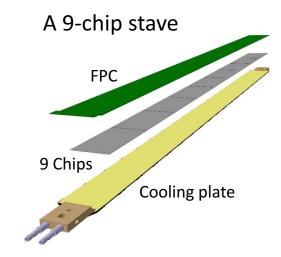
### The 2<sup>nd</sup> generation state of the art MAPS technology

### ALPIDE highlights:

- Very fine pitch (28x28 μm)
- High hit efficiency (>99%) and low noise (<10<sup>-6</sup>)
- − Fast response, ~5µS
- Ultra-thin/low mass,  $50\mu m$  (~0.3%  $X_0$ )
- On-pixel digitization, low power dissipation
- Sensor chip: 1.5cm x 3.0cm, 0.5M pixels (512x1024)

### An ideal detector for QGP b-jet physics!





### Tower Jazz 0.18 μm CMOS

feature size 180 nm

metal layers 6

gate oxide 3nm

substrate:  $N_A \sim 10^{18}$ epitaxial layer:  $N_A \sim 10^{13}$ deep p-well:  $N_A \sim 10^{16}$ 



Ming Liu, LDRD Overview

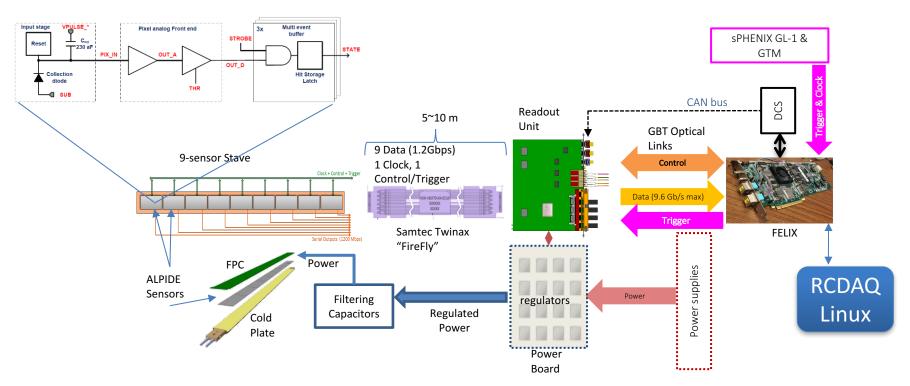
# LDRD Highlights (I)

### **MVTX** Sensors, Readout and Control System Developed



### Alex and Xuan's talks

### **ALPIDE** pixel circuit



- 1) Demonstrated full high-speed readout chain,
  - 1 Stave + RU + FELIX + RCDAQ/sPHENIX
  - Eliminated the highest technical risk "readout integration"
- 2) ALPIDE and Power Unit control and monitor being evaluated

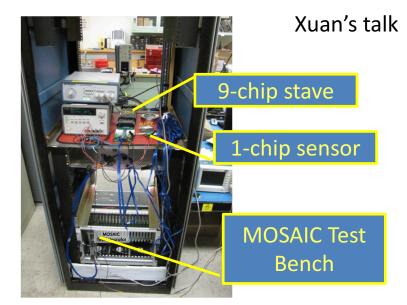


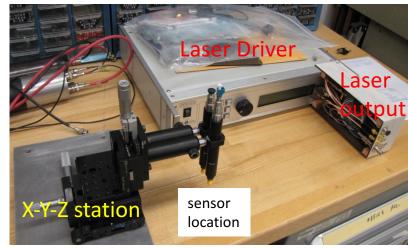
# LDRD Highlights (II)

Los Alamos NATIONAL LABORATORY EST. 1943

**ALPIDE Characterization & Optimization in Progress** 

- MOSAIC test bench in operation
  - Allows high-speed readout of ALPIDE chip, 1.2Gbps
  - Scanned sensor response parameters – optimization of operating point in progress
- Laser testing system setup in preparation
  - Laser pulses to inject MIP-level signal to each pixel
  - Scan full parameter space to optimize the operation point for sPHENIX







### MVTX Prototype Telescope Development



### Sho and Darren's talks

### Goal: A 4-stave telescope

- Sensor response and cluster size, MC tuning
- Hit spatial resolution
- Tracking and offline reconstruction
- Full readout chain
- Cooling and mechanical stability

### 1st beam test at Fermilab, 3/2018

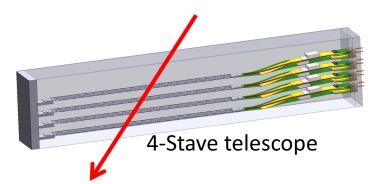
- Multi-layer ALPIDE chips telescope being assembled at LANL
- Readout system developed
- MC and offline analysis code developed

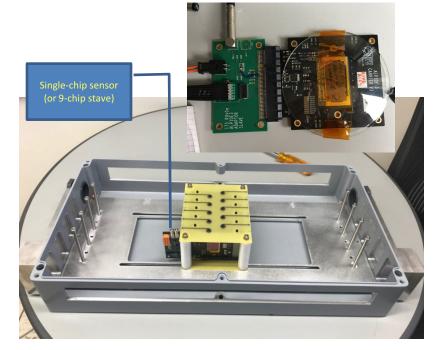
### Cosmic test later 2018

- Tracking and offline reconstruction
- Benchmark MC response

### In process

- Staves & readout electronics procurement
- Negative pressure system design







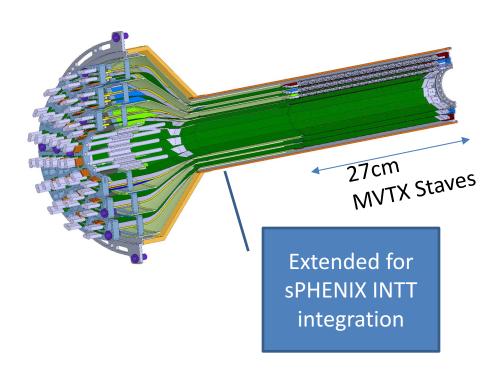
# LDRD Highlights (III)

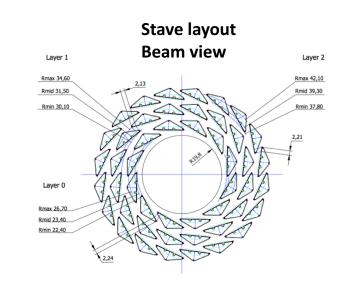


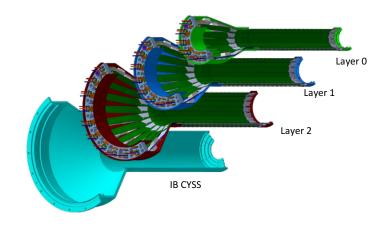


### Walt's talk

 View of MVTX half detector assembly with extended central barrel





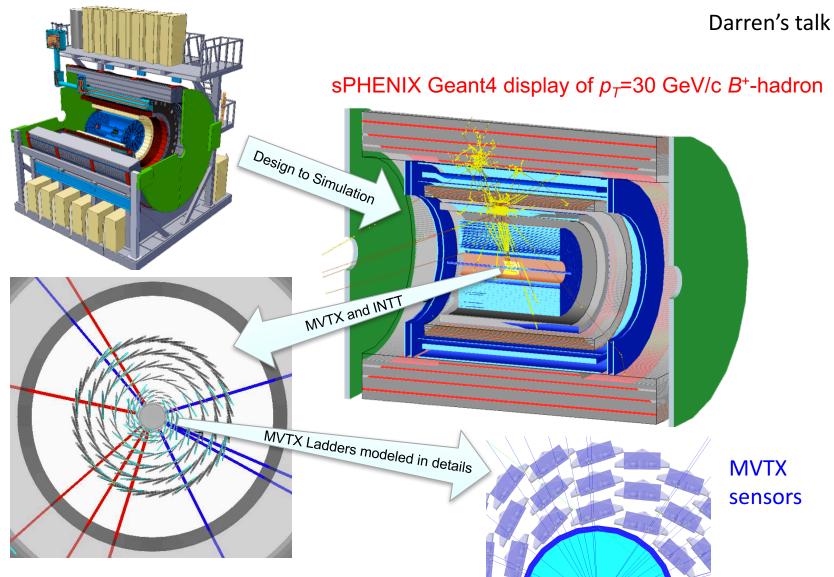




# LDRD Highlights (IV)



Simulation for b-jet and B-meson tagging





# **Procurements in FY17-18**

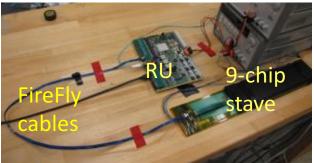


### ALPIDE Sensors

- 1 single chip with slow readout DAQ boards
- 5 single chip sensors with high-speed readout adaptor
  - 10 more to be produced locally
- 1 9-chip stave module
  - 5 more ordered for FY18
- Readout Units
  - 1 RU v1.0
    - 5 RU v1.x ordered FY18
- FELIX back end
  - 1 FELIX v1.5
    - 2 FELIX v2.0 available soon
- Linux DAQ server
  - 1 Linux in operation
- Power system
  - 1 32-chan power distribution boards
  - CEAN rad-hard power modules and server
    - CEAN rad-hard bulk power supply available later in FY18
- Telescope mechanical support
  - 1 box made
- Cooling system
  - Chiller purchased and tested
  - Negative-pressure system design in progress















# **FY18 Milestones**



### Achieved:

- Developed full high-speed readout chain with ALPIDE sensors and stave and near final readout electronics RU and FELIX, and integrated the readout chain with sPHENIX RCDAQ
  - Removed the highest risk item in the project the readout system integration
- Completed initial sPHENIX MVTX mechanical system integration and layout
- Completed and benchmarked b-jet tagging for pp and AuAu with full detector GEANT simulations
- Completed the MVTX full proposal, to be submitted to BNL ALD

### In progress:

- To construct a 4-stave/chip MVTX prototype telescope and take cosmic ray data
  - Mechanical enclosure completed
  - More Staves and RUs ordered
  - · Cooling system under development
- To complete readout and control integration with the final electronics (RUv.1x and FELIXv2.0) for full system integration



# Major Tasks to Complete the Project



- ALPIDE sensor characterization and optimization
  - Readout and trigger optimization for sPHENIX
  - Laser system in preparation

2018







- Full readout and control integration in sPHENIX
  - Full readout with RHIC clock and trigger
    - RUv1.x, FELIXv2.0 and firmware & controls
    - Electronics production/procurements in process
    - sPHENIX DAQ system development in progress

2019







- MVTX mechanical system integration in sPHENIX
  - Barrel section extension R&D
    - Signal extension and long SamTec cables
  - Mechanical system integration
    - MVTX & INTT









- MVTX prototype telescope final beam test at Fermilab
  - Demonstrate tracking capability, spatial resolution
  - High trigger rate (15kHz) at high event multiplicity









# Major Technical Challenges and Risks from Previous Feasibility Review Mitigated/Addressed



- Project Risks with timely procurements of R&D items from CERN
  - ALPIDE Sensors:
    - a "Plan-B" was developed to us ~4 single chip ALPIDE sensors.
  - Readout electronics and custom design
    - A prototype Readout Unit (RU) with Xilinx evaluation board KC705 was developed before the arrival of RUv1.0
    - An alternative path was successfully developed with ATLAS FELIX board to replace ALICE CRU
  - Risks mitigated, full readout chain electronics integration designed and tested.
- Needs of the test beam for the full proposal
  - With the successful R&D of the full readout chain and sensors, we have determined that a test beam is not required for the full proposal submission.
  - 1<sup>st</sup> teat beam in preparation, ahead of schedule, to study sensor response and readout characterization.
  - Full proposal completed and to be submitted next week
- Add more milestones to MIE proposal development
  - Implicit milestones in the LDRD project:
    - 1. To build a collaboration and submit a pre-proposal by the end of the first year FY17;
    - 2. To have science and technical reviews in the 2<sup>nd</sup> year and complete a full proposal by the end of FY18;
    - 3. To have the full proposal reviewed and approved by DOE by the end of FY19.
  - Achieved:
    - 1. The 1<sup>st</sup> milestone in Feb 2017, ahead of plan; the MVTX detector collaboration is formed and growing, with 22 institutions from the world
    - 2. The 2<sup>nd</sup> milestone in Jan 2018, ahead of plan. Successful MVTX BNL Directors review in July 2017.
    - 3. LANL LDRD team is working closely with sPHENIX and BNL management to realize the full program.
  - Full proposal completed and to be submitted next week
- Setup simulation milestones for the MIE proposal
  - A full sPHENIX tracking simulation package has been developed, milestones achieved and used for realistic b-jet tagging study for the full MVTX proposal.
  - Full proposal completed and to be submitted next week



# Mission Impact



This LDRD directly contributes to the LANL NPAC (Nuclear, Particle, Astrophysics and Cosmology) and DOE Nuclear Physics program, expand the leadership of LANL at national & international level:

- High impact on big science
  - New physics programs at RHIC and EIC
- Define the directions for LANL basic and applied programs
  - Long-term DOE NP Program
  - New hiring Xuan, Sho(P-25), Darren(XTD/P-25)
  - Promotions Mike(XCP), Cesar
  - Applications to LANL applied program
- New ideas/proposals developed based on R&D from this LDRD project
  - New x-ray imaging with MAPS
  - New neutron detector with MAPS
  - High-speed MAPS readout R&D for MARIE & EIC programs

### **NSAC Long Range Plan 2015**

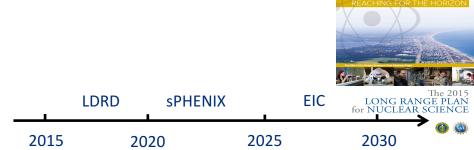
### Recommendation #1 (RHIC):

The highest priority in this 2015 Plan is to capitalize on the investments made.

 The upgraded RHIC facility provides unique capabilities that must be utilized to explore the properties and phases of quark and gluon matter in the high temperatures of the early universe and to explore the spin structure of the proton.

### Recommendation #3 (EIC):

We recommend a high-energy high-luminosity polarized EIC as the highest priority for new facility construction following the completion of FRIB.





# MVTX Full Proposal Development



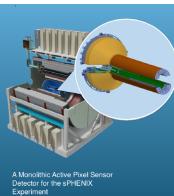
- MVTX detector collaboration formed, 1/2017
  - International collaboration of 22 institutions, and counting
  - Bi-weekly detector R&D and physics simulation meetings
  - Weekly project development meetings, project leaders from LANL, BNL, MIT and LBNL
- A pre-proposal completed and submitted through BNL ALD to DOE in Feb. 2017
  - Initial feedback from DOE, positive, compelling science
- Successful MVTX BNL Directors review, July 2017
  - Recommended to proceed with a full proposal
- Organized workshops for detector R&D and physics program development
  - MVTX physics and detector design, 1/2017, LBNL
  - Readout electronics R&D, 4/2017, UT-Austin
  - Cost & schedule workfest, 6/2017, BNL
  - MVTX and Heavy Flavor physics, 12/2017, Santa Fe

submitted

A full MVTX proposal completed and to be submitted to BNL ALD 2/2018











Full proposal completed

~1 year ahead of plan

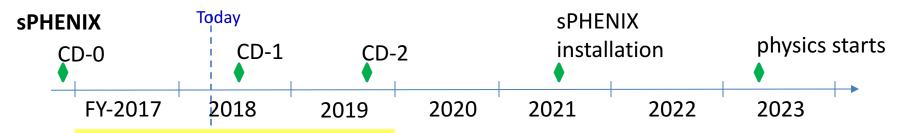
# Transition Plan



- The transition plan details are still being worked out and evolving
  - Develop a long term DOE NP program

Cesar's talk

- MVTX funding news (received by MVTX group on 1/19/2018)
  - From email by BNL Associate Laboratory Director (ALD) Dr. Berndt Mueller:
    - DOE "appreciate the compelling science this instrument could enable ..." "but unfortunately in our present outlook, we do not foresee at this time that we would be able to identify new DOE funding for the purpose of implementing the MVTX" and "encourage efforts to secure such [external] contributions..."
  - ALD commented that even if no additional funds expected from DOE at this time, DOE would allow us to proceed with the construction of the MVTX if financially feasible as the scientific case is compelling (fundings from RHIC + foreign contributions).
- LDRD team is working closely with sPHENIX collaboration and BNL management to seek alternative path to fund the full MVTX detector.
  - Several options being explored within the sPHENIX collaboration
  - Possible direct and indirect foreign contributions



LDRD:

Readout & mechanics R&D Secure funding for MVTX

Transition to MVTX/sPHENIX program



# Summary



- Achieved all LDRD milestones, some ahead of time, risks mitigated
  - Designed and tested full readout system
  - Developed mechanical conceptual design
  - Completed b-jet tagging and preliminary physics study with full simulations
- A MVTX prototype telescope being constructed
  - In preparation for the 1<sup>st</sup> beam test at Fermilab w/ sPHENIX
- New theoretical development
  - High impact papers published
- Developed a new heavy quark physics program for sPHENIX
  - Completed the full MVTX proposal, to be submitted to BNL ALD next week
  - DOE "appreciate the compelling science", but new funding is challenging at this time
- Broad impact on LANL NP and other applied programs
  - New hires and promotions, new ideas and proposals

On track to meet LDRD goals for FY18 and FY19









# Theory: Introduction and perturbative QCD

Ivan Vitev (co-PI) T-2



# The Quark-Gluon Plasma and Bottom Quark Jets



**pQCD:** b-jets and heavy flavor, energy loss and b-jet substructure in the QGP

**SCET:** b-jets in p+p, energy correlators, resummation

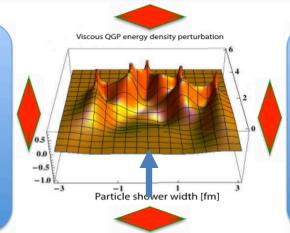
**MD:** Transport properties of SCPs. Stopping power for heavy fermions

LQCD: EOS in fluctuating hydro, simulations of jet propagation

### **Integrated effort:**

**Perturbative QCD/SCET and jet simulations**: most precise bjet theory in proton collisions, new theory for heavy ion collisions, b-jet substructure, b-jet tomography of the QGP





Lattice QCD:
EoS, input for hydro, charge number fluctuations near the phase transition

**Experiment:** Tracker design, prototype construction, jet finder development, ongoing and improved PHENIX and STAR BES II analyses

T-2, T-5 and CCS-7 groups in close collaboration with experiment

Staff: J. Daligault, R. Gupta, Z. Kang, C. Lee, I. Vitev, B. Yoon

PD: H. Li, F. Ringer, M. Sievert, V. Vaidya

Students: S. Aronson, D Bernstein, B. Odegard, J. Reiten, P. Shrivastava

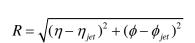


Theory deliverable: package for precision b-jet tomography at sPHENIX and predictions for experiment

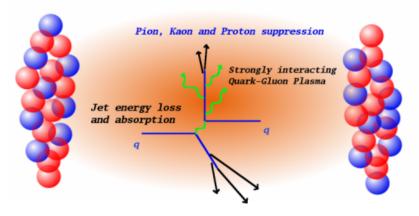
# Traditional Energy Loss and B-jet Suppression Simulations for sPHENIX

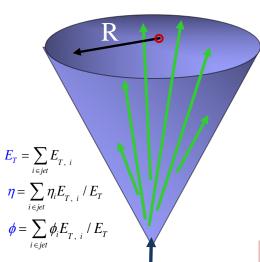


# Provide b-jet suppression magnitude input: assess exp. sensitivity to QGP properties



# Jets present unique challenges





$$\frac{\sigma^{AA}(R,\omega^{\min})}{d^2 E_T dy} = \int_{\epsilon=0}^1 d\epsilon \sum_{q,q} P_{q,g}(\epsilon) \frac{1}{(1 - (1 - f_{q,g}) \cdot \epsilon)^2} \frac{\sigma_{q,g}^{NN}(R,\omega^{\min})}{d^2 E_T' dy}$$

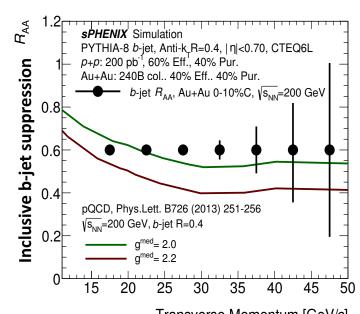
$$R_{AA} = \frac{Observable\ in\ A + A}{Norm*Observable in\ p + p}$$

Theory uncertainties cancel in the ratio

I. Vitev et al. (2018)

### Provided results to sPHENIX for the full DOE proposal.

Constraints on the coupling "g" between the jet and the medium better than 10%, transport coefficients ~ 30%



# Evaluating the In-medium Jet Function and Heavy Ion Phenomenology



# **Beyond traditional energy loss:** incorporate the technology of higher order calculations and resummation from HEP

 Inclusive jet cross sections can be formulated in terms of semi-inclusive jet functions J(z,ωR,μ)

$$\frac{d\sigma^{pp\to jetX}}{dp_T d\eta} = \sum_{a,b,c} f_a \otimes f_b \otimes H^c_{ab} \otimes J_c$$

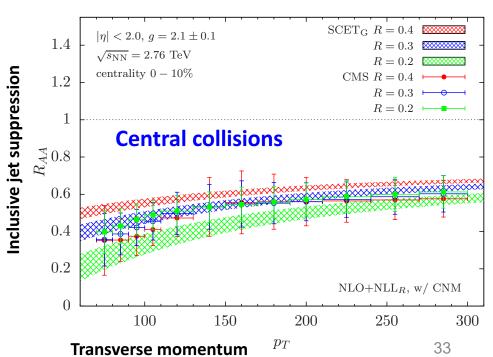
 Demonstrated that J(z,ωR,μ) is related to the Altarelli-Parisi splitting functions (parton showers)

$$\begin{split} J_q^{\mathrm{med},(1)}(z,\omega R,\mu) &= \left[ \int_{z(1-z)\omega\,\tan(R/2)}^{\mu} dq_{\perp} P_{qq}(z,q_{\perp}) \right]_{+} \\ &+ \int_{z(1-z)\omega\,\tan(R/2)}^{\mu} dq_{\perp} P_{gq}(z,q_{\perp}) \,. \end{split}$$

Z. Kang et al . PLB (2017)

$$d\sigma_{\text{PbPb}}^{\text{jet}} = d\sigma_{pp}^{\text{jet,vac}} + d\sigma_{\text{PbPb}}^{\text{jet,med}}$$

$$d\sigma_{\mathrm{PbPb}}^{\mathrm{jet,med}} = \sum_{i=q,\bar{q},g} \sigma_i^{(0)} \otimes J_i^{\mathrm{med}}$$





### **Effective Theory of Heavy Quark Propagation in Nuclear Matter**



### Formulated a new effective theory SCET<sub>M.G</sub> – for massive quarks & Glauber gluon interactions

$$\mathcal{L}_{\text{QCD}} = \bar{\psi}(i\cancel{D} + \cancel{m})\psi$$

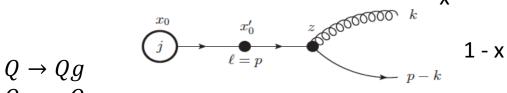
$$iD^{\mu} = \partial^{\mu} + gA^{\mu}$$

$$iD^{\mu} = \partial^{\mu} + gA^{\mu} \qquad A^{\mu} = A_c^{\mu} + A_s^{\mu} + A_G^{\mu}$$

With the field scaling in the covariant gauge for the Glauber field there is no room for interplay with mass in the LO Lagrangian

Result:  $SCET_{M,G} = SCET_{M} \times SCET_{G}$ 

**Splitting functions** 

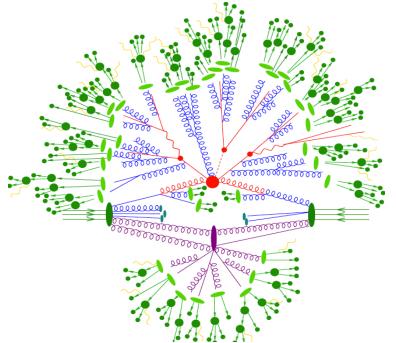


 $Q \rightarrow gQ$  $g \to Q\bar{Q}$  $g \rightarrow gg$ 

**Precise understanding of the** mass dependence.

$$\left(\frac{dN}{dxd^2k_{\perp}}\right)_{g\to Q\bar{Q}} = T_R \frac{\alpha_s}{2\pi^2} \frac{1}{k_{\perp}^2 + m^2} \left[ x^2 + (1-x)^2 + \frac{2x(1-x)m^2}{k_{\perp}^2 + m^2} \right]$$

$$\left(\frac{dN}{dxd^2k_{\perp}}\right)_{Q\to Qg} = C_F \frac{\alpha_s}{\pi^2} \frac{1}{k_{\perp}^2 + x^2m^2} \left[ \frac{1 - x + x^2/2}{x} - \frac{x(1-x)m^2}{k_{\perp}^2 + x^2m^2} \right]$$



Z. Kang *et al* . JHEP (2017)



### QCD In-medium Splitting Functions



### **Full in-medium splitting functions**

$$\left( \frac{dN^{\text{med}}}{dxd^{2}k_{\perp}} \right)_{Q \to Qg} = \frac{\alpha_{s}}{2\pi^{2}} C_{F} \int \frac{d\Delta z}{\lambda_{g}(z)} \int d^{2}q_{\perp} \frac{1}{\sigma_{el}} \frac{d\sigma_{el}^{\text{med}}}{d^{2}q_{\perp}} \left\{ \left( \frac{1 + (1 - x)^{2}}{x} \right) \left[ \frac{B_{\perp}}{B_{\perp}^{2} + \nu^{2}} \right] \times \left( \frac{B_{\perp}}{B_{\perp}^{2} + \nu^{2}} - \frac{C_{\perp}}{C_{\perp}^{2} + \nu^{2}} \right) \left( 1 - \cos[(\Omega_{1} - \Omega_{2})\Delta z] \right) + \frac{C_{\perp}}{C_{\perp}^{2} + \nu^{2}} \cdot \left( 2 \frac{C_{\perp}}{C_{\perp}^{2} + \nu^{2}} - \frac{A_{\perp}}{A_{\perp}^{2} + \nu^{2}} \right) - \frac{B_{\perp}}{B_{\perp}^{2} + \nu^{2}} \right) \left( 1 - \cos[(\Omega_{1} - \Omega_{3})\Delta z] \right) + \frac{B_{\perp}}{B_{\perp}^{2} + \nu^{2}} \cdot \frac{C_{\perp}}{C_{\perp}^{2} + \nu^{2}} \left( 1 - \cos[(\Omega_{2} - \Omega_{3})\Delta z] \right) + \frac{A_{\perp}}{A_{\perp}^{2} + \nu^{2}} \cdot \left( \frac{D_{\perp}}{D_{\perp}^{2} + \nu^{2}} - \frac{A_{\perp}}{A_{\perp}^{2} + \nu^{2}} \right) \left( 1 - \cos[\Omega_{4}\Delta z] \right) - \frac{A_{\perp}}{A_{\perp}^{2} + \nu^{2}} \cdot \frac{D_{\perp}}{D_{\perp}^{2} + \nu^{2}} \left( 1 - \cos[\Omega_{5}\Delta z] \right) + \frac{1}{N_{c}^{2}} \frac{B_{\perp}}{B_{\perp}^{2} + \nu^{2}} \cdot \left( \frac{A_{\perp}}{A_{\perp}^{2} + \nu^{2}} - \frac{B_{\perp}}{B_{\perp}^{2} + \nu^{2}} \right) \left( 1 - \cos[(\Omega_{1} - \Omega_{2})\Delta z] \right)$$

### Kinematic variables

$$egin{aligned} A_{\perp} &= k_{\perp}, \; B_{\perp} = k_{\perp} + x q_{\perp}, \; C_{\perp} = k_{\perp} - (1-x) q_{\perp}, \; D_{\perp} = k_{\perp} - q_{\perp}, \ &\Omega_1 - \Omega_2 = rac{B_{\perp}^2 + 
u^2}{p_0^+ x (1-x)}, \; \Omega_1 - \Omega_3 = rac{C_{\perp}^2 + 
u^2}{p_0^+ x (1-x)}, \; \Omega_4 = rac{A_{\perp}^2 + 
u^2}{p_0^+ x (1-x)}, \end{aligned}$$

See talk by B. Yoon on the evaluation of the splitting functions

$$\nu = m \qquad (g \rightarrow Q\bar{Q}),$$

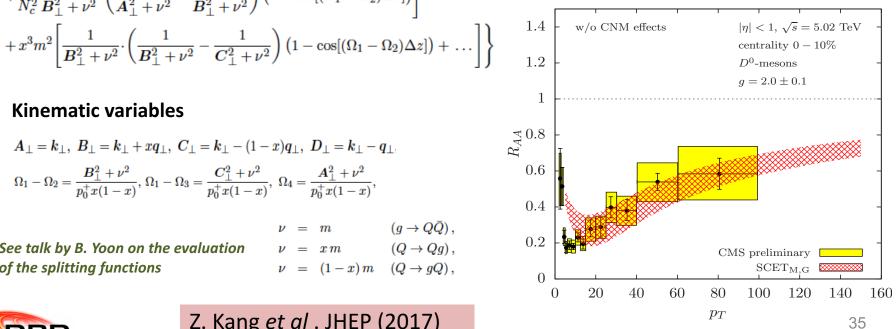
$$\nu \ = \ x \, m \qquad \qquad (Q \to Qg) \, ,$$

$$\nu \ = \ (1-x)\,m \quad (Q\to gQ)\,,$$

### Performed the First NLO heavy flavor calculation in HIC

$$d\sigma_{\text{PbPb}}^{H} = d\sigma_{pp}^{H,\text{NLO}} + d\sigma_{\text{PbPb}}^{H,\text{med}}$$

Gives an improved description of open heavy flavor suppression from radiative processed down to lower p<sub>T</sub>



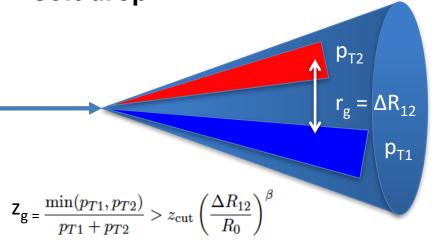


# **Groomed Soft Dropped Jet Distributions** in SCET<sub>G</sub>



Substructure of jets: the longitudinal and transverse momentum distribution of particles within jets, jets within jets

Groomed jet distribution using "soft drop"



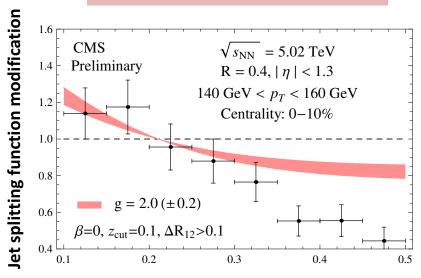
They are calculable from first principles and directly related to the splitting functions

$$p_i(z_g) = \frac{\int_{k_{\Delta}}^{k_R} dk_{\perp} \overline{\mathcal{P}}_i(z_g, k_{\perp})}{\int_{z_{cut}}^{1/2} dx \int_{k_{\Delta}}^{k_R} dk_{\perp} \overline{\mathcal{P}}_i(x, k_{\perp})}$$

# Demonstrated the great utility of these new distributions:

 Probe the early time dynamics / splitting when the jet forms in the QGP

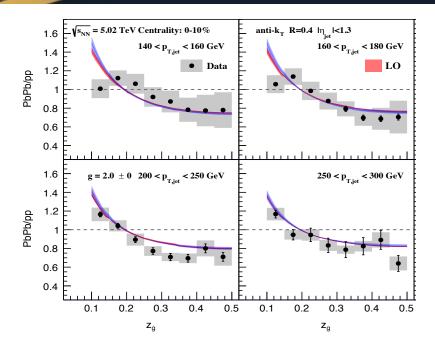
Y. T. Chien et al. PRL (2017)



Subjet momentum fraction z<sub>g</sub>

# Inverting the Mass Hierarchy of Jet Quenching Effects





### Sudakov resummation:

accounts for multiple branchings

$$\frac{dN_{j}^{\text{vac,MLL}}}{dz_{g}d\theta_{g}} = \sum_{i} \left(\frac{dN^{\text{vac}}}{dz_{g}d\theta_{g}}\right)_{j \to i\bar{i}}$$

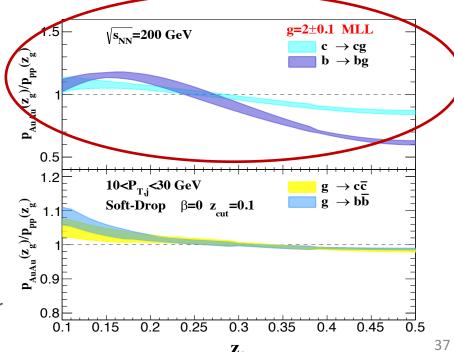
$$\exp\left[-\int_{\theta_{g}}^{1} d\theta \int_{z_{\text{cut}}}^{1/2} dz \sum_{i} \left(\frac{dN^{\text{vac}}}{dzd\theta}\right)_{j \to i\bar{i}}\right]$$
Sudakov Factor

H. Li et al. (2018)

See talk by C. Lee on other substructure observables

## B-jet substructure in heavy ion collisions:

- Discovered a new way to constrain mass effects in parton showers
- At RHIC jet energies, we predict a unique reversal of the mass hierarchy effects on jet splitting





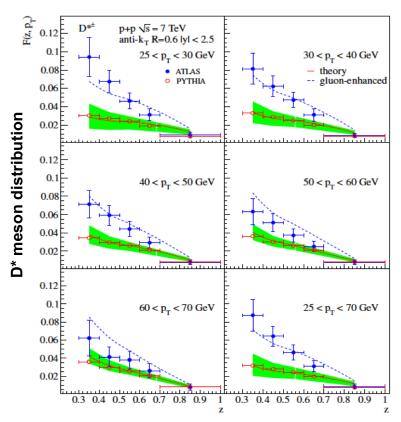
# New Constraints on Gluon Fragmentation in Heavy Mesons



#### Milestones met: achievements beyond the original research scope

 Clearly the gluon contribution to heavy flavor is very important for reactions with nuclei

	data		#data	
	$_{ m type}$	$\mathcal{N}_i$	in fit	$\chi^2$
	incl.	0.991	17	31.0
	incl.	1.000	9	6.5
	c   ag	1.002	9	8.6
	$b   \mathrm{tag}$	1.002	9	5.6
	$D^{*\pm}$	1	5	13.8
$\sqrt{S} = 7 \text{ TeV}$	$D^{*+}$	1.011	3	2.4
$\sqrt{S} = 2.76 \text{ TeV}$	$D^{*+}$	1.000	1	0.3
	$D^{*+}$	1.017	2	1.1
$2 \le \eta \le 2.5$	$D^{*\pm}$	1	5	8.2
$2.5 \le \eta \le 3$	$D^{*\pm}$	1	5	1.6
$3 \le \eta \le 3.5$	$D^{*\pm}$	1	5	6.5
$3.5 \leq \eta \leq 4$	$D^{*\pm}$	1	1	2.8
$25 \le \frac{p_T^{ m jet}}{{ m GeV}} \le 30$	$(\mathrm{jet}D^{*\pm})$	1	5	5.5
$30 \leq \frac{p_T^{\rm jet}}{{\rm GeV}} \leq 40$	$(\mathrm{jet}D^{*\pm})$	1	5	4.1
$40 \leq \frac{p_T^{\rm jet}}{{\rm GeV}} \leq 50$	$(\mathrm{jet}D^{*\pm})$	1	5	2.4
$50 \le \frac{p_T^{ m jet}}{{ m GeV}} \le 60$	$(\mathrm{jet}D^{*\pm})$	1	5	0.9
$60 \le \frac{p_T^{ m jet}}{{ m GeV}} \le 70$	$(\mathrm{jet}D^{*\pm})$	1	5	1.6
			96	102.9
	$\sqrt{S} = 2.76 \text{ TeV}$ $2 \le \eta \le 2.5$ $2.5 \le \eta \le 3$ $3 \le \eta \le 3.5$ $3.5 \le \eta \le 4$ $25 \le \frac{p_T^{\text{jet}}}{\text{GeV}} \le 30$ $30 \le \frac{p_T^{\text{jet}}}{\text{GeV}} \le 40$ $40 \le \frac{p_T^{\text{jet}}}{\text{GeV}} \le 50$ $50 \le \frac{p_T^{\text{jet}}}{\text{GeV}} \le 60$	$\begin{array}{c} \text{type} \\ \text{incl.} \\ c \text{ tag} \\ b \text{ tag} \\ \hline \\ \sqrt{S} = 7 \text{ TeV} \\ \sqrt{S} = 2.76 \text{ TeV} \\ D^{*+} \\ D^{*+} \\ D^{*+} \\ 2 \leq \eta \leq 2.5 \\ 2.5 \leq \eta \leq 3 \\ 3 \leq \eta \leq 3.5 \\ D^{*\pm} \\ \end{array}$	$\begin{array}{c ccccccccccccccccccccccccccccccccccc$	$\begin{array}{c ccccccccccccccccccccccccccccccccccc$



Momentum fraction

Performed global refit of fragmentation functions to world's data including semi-inclusive annihilation, inclusive hadron production and hadrons in jets

Excellent x²/DOF ~ 1 38



#### Final Results for D\* Fragmentation Functions

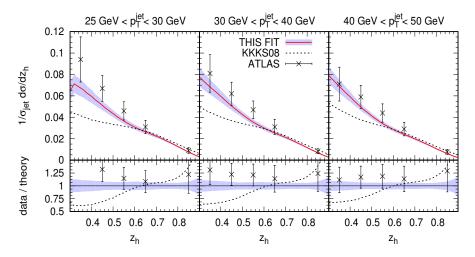


#### Fit at NLO in Mellin space

$$\frac{d\sigma^{pp\to(\text{jet }h)X}}{dp_T^{\text{jet}}d\eta^{\text{jet}}dz_h} = \frac{2p_T^{\text{jet}}}{S} \sum_{a,b,c} \int_{x_a^{\text{min}}}^1 \frac{dx_a}{x_a} f_a(x_a,\mu)$$

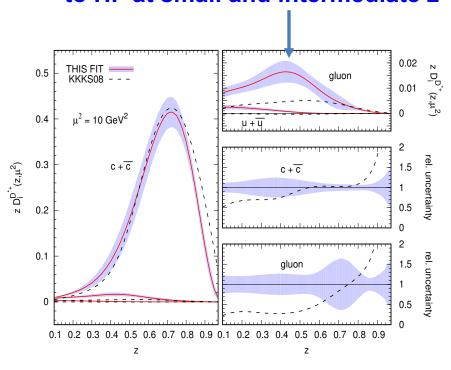
$$\times \int_{x_b^{\min}}^1 \frac{dx_b}{x_b} f_b(x_b, \mu) \int_{z_c^{\min}}^1 \frac{dz_c}{z_c^2} \frac{d\hat{\sigma}_{ab}^c(\hat{s}, \hat{p}_T, \hat{\eta}, \mu)}{v dv dw}$$

$$\times \mathcal{G}_c^h(z_c, z_h, \mu, R)$$
,



## Obtained much improved description of D\* in jets

Significant enhancement of the gluon fragmentation component to HF at small and intermediate z

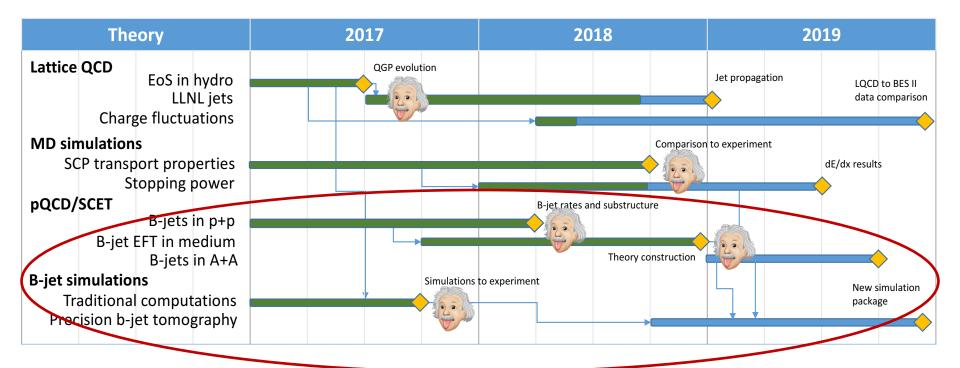


Important implications for heavy flavor suppression in the QGP: larger color charge = larger suppression



#### Theory Timetable and Future pQCD Work





#### **Future work:**

- Main focus: the new simulation package milestone, combining all theory advances
- Specific tasks: b-jet quenching from semi-inclusive jet functions, incorporation of HF splitting functions in a hydrodynamic background, collisional E-loss; extend several calculations down to RHIC energies
- New opportunities: di b-jet correlations, c-jets, soft-Glauber interactions



#### **Summary of pQCD Accomplishments**



- Publications 9 refereed publications in the leading journals in the field (including 3 letters), 1 more near completion. 4 refereed conference proceedings
  - Y. Chien, I. Vitev, Physical Review Letters 119: 112301 (2017)
  - Z. Kang, F. Ringer, and I. Vitev, Journal of High Energy Physics. **1703**: 146 (2017)
  - Z. Kang, F. Ringer, and I. Vitev, Physics Letters
     B. 769: 242-248 (2017)
  - D. Anderle, T. Kaufmann, M. Strattman,
     F. Ringer, I. Vitev, Physical Review D 96 034028 (2017) ...



- Talks given 16 talks and seminars, many invited, including plenary
  - I. Vitev, "Jets in SCET", Precision spectroscopy of the QGP with jets and heavy flavor, INT, Seattle, WA, 2017
  - F. Ringer, "Inclusive jets and their substructure in SCET", Jets@LHC, Bangalore, India, 2017
  - H. Li, "Inverting the mass hierarchy of jet quenching effects with b-jet substructure sPHENIX Collaboration Workshop, Santa Fe, NM 2017 ...
- Summary Work is well on track, we have met all milestones (some considerably ahead of time). This allowed us to seize the opportunity to expand the originally proposed scope and impact, better understand heavy flavor fragmentation and work on collisional energy loss / b-jet correlations



#### The Broader Impact of pQCD/SCET Theory

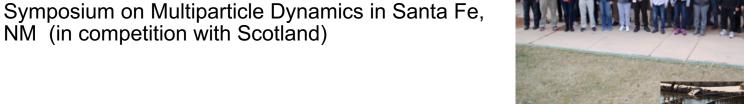


#### Follow on projects / grants:

NSF three year award \$60K/y, "Perturbative QCD Study for Jet and Heavy Flavor Production". August 2017 – August 2020

#### Conferences:

Co-organized conferences related to jet and heavy flavor physics—Santa Fe Jets and Heavy Flavor workshop, 2017, 2018. UCLA jet physics workshop 2017. Selected to host 2019 International Symposium on Multiparticle Dynamics in Santa Fe, NM (in competition with Scotland)



#### Personnel

F. Ringer to LBNL, now on UIUC shortlist; H. Xing to ANL/Northwestern, standing Assistant Professorship offer from Southern China Normal U.; D. Kang to Fudan U., professor; M. Sievert was a finalist at NMSU, to Rutgers U.; H. Li joined us from Monash U. Australia; Consult with D. Neill, Feynman to staff.









# Effective field theories for precision b-jet substructure

Christopher Lee T-2



#### **T-2 Effort and Affiliated Scientists**



#### **Co-I Christopher Lee**

Leading effective field theory (EFT) effort on *b*-jets in *pp* collisions

#### Postdoc Varun Vaidya







Constructing effective field theory and performing analytic calculations for *b*-jet substructure.

#### PhD student Prashant Shrivastava (CMU)

Monte Carlo simulations and EFT calculations to explore and test best variables to probe *b*-jet substructure. DR supported Summer 2017 visit to LANL, ongoing collaboration.

### Affiliated LANL scientists: Duff Neill (Feynman Fellow),

**Yiannis Makris (postdoc)** 

Improved observables and EFT calculation for transverse-momentum-dependent jet phenomenology.

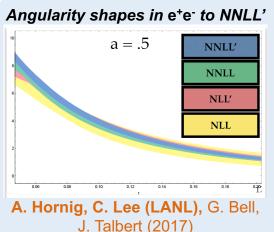


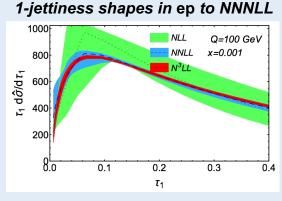


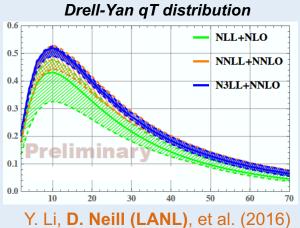
#### **SCET** and precision jet structure



Powerful EFT methods (Soft Collinear Effective Theory = SCET) developed in 2000s leading to vast improvements in accuracy of jet cross sections in e+e-, ep, and pp collisions:





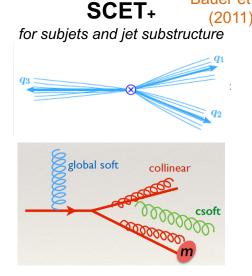


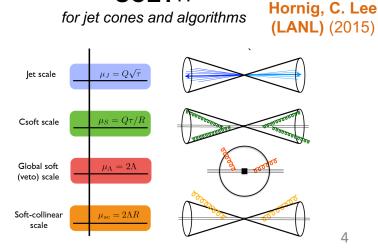
D. Kang, C. Lee (LANL), I. Stewart (2016)

Bauer et al.

Y.-T. Chien, A. SCET++

New versions of SCET introduced in 2010s applicable to more differential probes of jet substructure:







#### New observables to probe jet substructure



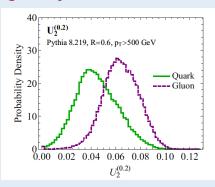
C. Lee, P. Shrivastava, V. Vaidya formed collaboration to apply two recent theoretical ideas in jet physics to precision b-jet substructure:

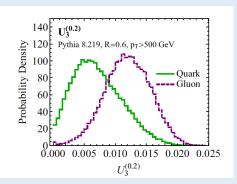
#### **Energy correlation functions:**

$$U_1^{lpha} = \sum_{1 \leq i < j < n_J} z_i z_j heta_{ij}^{lpha}$$
 Moult, Necib, Thaler (2016)

$$U_2^{\alpha} = \sum_{1 \leq < j < k < n_J} z_i z_j z_k \min\{\theta_{ij}^{\alpha}, \theta_{ik}^{\alpha}, \theta_{jk}^{\alpha}\}$$

#### shown to be excellent light quark jet vs. gluon jet discriminants:

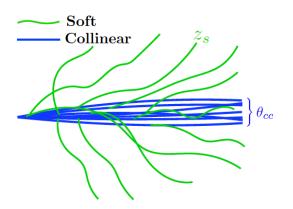




and designed to be well suited for analytic calculation using factorization and resummation in SCET

#### **Jet Grooming:**

"Soft Drop" algorithm: Larkoski, Marzani, Soyez, Thaler (2014)



Step through branching history of reclustered

Remove branches failing soft drop condition:

$$\frac{\min[p_{Ti}, p_{Tj}]}{p_{Ti} + p_{Tj}} > z_{\text{cut}}$$

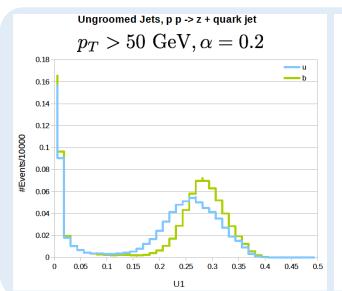


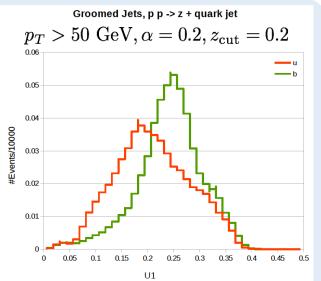
#### Performance on b-jets in Monte Carlo



Combining jet grooming with energy correlators provides cleaner distributions for light jets and b jets:

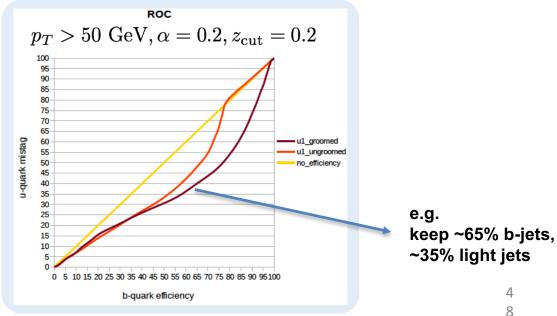
$$U_1^{\alpha} = \sum_{1 \le i < j < n_J} z_i z_j \theta_{ij}^{\alpha}$$





Performance in distinguishing light and heavy quark jets:

Better performance for groomed variable than ungroomed

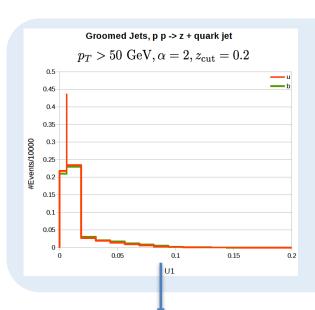


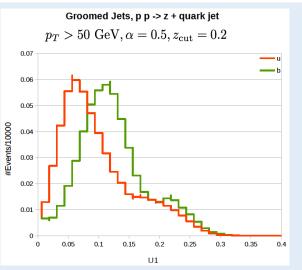


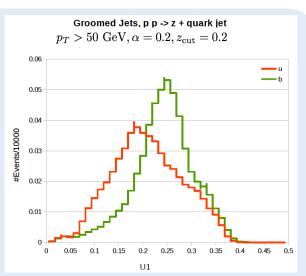
#### **Performance on b-jets in Monte Carlo**



Varying angular exponent in energy correlator can enhance discriminating power:  $U_1^{\alpha} = \sum_{1 \leq i < j < \leq n_J} z_i z_j$ 







Little to no discriminating power



improved discriminating power

**Motivates theoretical calculations:** 

predict groomed U<sub>1</sub> distributions using EFT

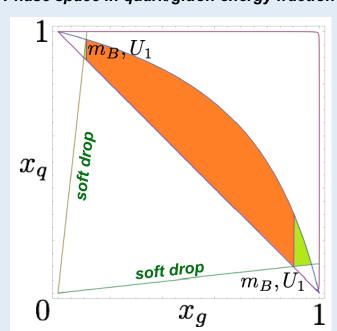


#### **Progress on analytic EFT predictions**

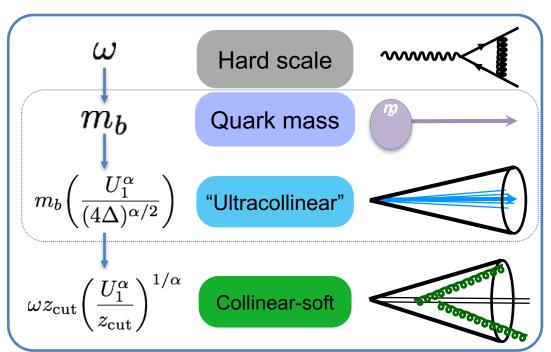


#### Performed one-loop (one-gluon emission) EFT calculation for massive quark $U_1^{lpha}$

Phase space in quark/gluon energy fraction



Hierarchy of scales defining EFT: SCET+ + HQET



E.g. ordinary SCET jet functions, factors into separate "ultracollinear" and HQET matching functions:

$$J = \frac{\alpha_s C_F}{\pi} \left( \frac{1}{\alpha - 1} L_C^2 + L_V^2 + L_C + \frac{1}{2} L_V \right) \qquad L_C = \ln \left( \frac{\mu}{\omega U_1^{\alpha}} \right) \Delta^{\frac{\alpha - 1}{2}} \qquad \Delta = \frac{m^2}{\omega^2}$$

$$L_C = \ln\!\left(rac{\mu}{\omega U_1^lpha}
ight)\!\Delta^{rac{lpha-1}{2}} \qquad \Delta = rac{m^2}{\omega^2} 
onumber \ L_V = \lnrac{\mu}{m}$$



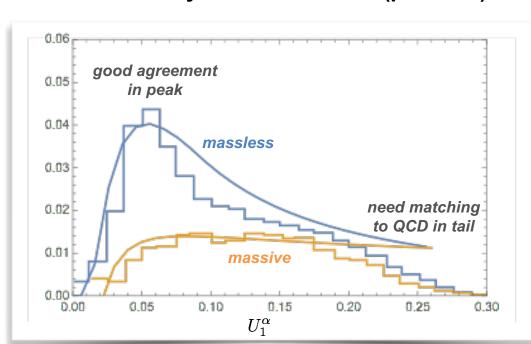
#### **Progress on analytic EFT predictions**



## Computed all needed anomalous dimensions to one-loop accuracy, enough for NLL accuracy of resummed cross section:

$$\frac{1}{\sigma_0} \frac{d\sigma}{dU_1^{\alpha}} = \frac{1}{e_2^{(\alpha)}} Exp\left(K_{H_+}(\omega, \mu_0^{H_+}) + K_{CS}(\omega, \mu_0^{CS}) + K_{B_+}(\omega, \mu_0^{B_+})\right) \left[\Gamma\left(-\frac{2}{\alpha}\omega_{CS}(\omega, \mu_0^{CS}) - 2\omega_{B_+}(\omega, \mu_0^{B_+})\right)\right]^{-1}$$

## shape of massless and massive quark jet distributions vs. Pythia Monte Carlo (partonic):



#### Timeline:

FY17: Monte Carlo tests of jet observables and grooming



early FY18: NLL perturbative calculations of groomed jet observables



#### **Spring/Summer FY18:**

matching to fixed-order QCD in tail region

model of nonperturbative effects, universality in endpoint region

publication on EFT predictions of groomed heavy quark jet substructure

#### **FY19**:

effects of modification in QGP

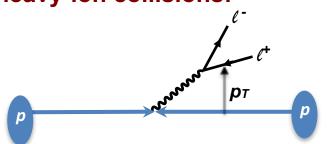


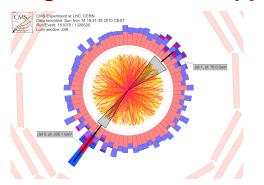
## Related publications advancing TMD phenomenology

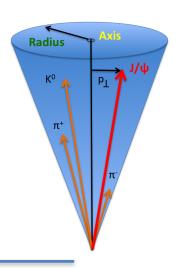


Transverse-momentum distributions of radiation within events and within jets play important role in probing QCD effects in pp

and heavy-ion collisions:





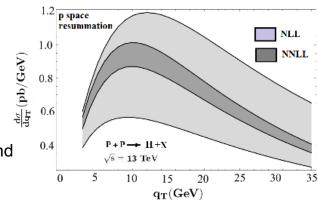


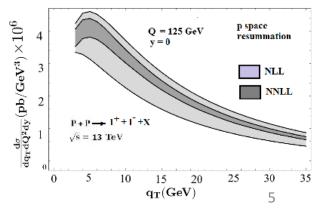
## New EFT method for *analytic* resummation of transverse-momentum-dependent (TMD) cross sections:

**D. Kang, C. Lee, V. Vaidya**, "A fast and accurate method for perturbative resummation of transverse momentum-dependent observables," under review by JHEP, LA-UR-17-27820 [arXiv:1710.00078]

Results shown for Drell-Yan processes; general method applicable to any TMD factorized observable

Invited talks at APS (VV 2/17), SF Jets (DK 2/17), SCET (VV 3/17), and UCLA (CL, 5/17)





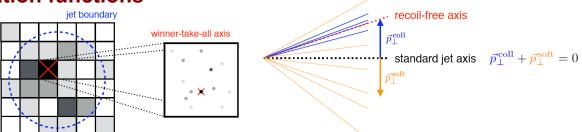


## Related publications advancing TMD phenomenology



Improved definition of jet axes leading to more robust theoretical predictions and new *universal* TMD fragmentation functions

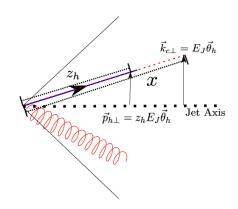
**D. Neill**, I. Scimemi, W. Waalewijn, "Jet axes and universal transversemomentum-dependent fragmentation," JHEP 1704 (2017) 020 [arXiv:1612.04817]



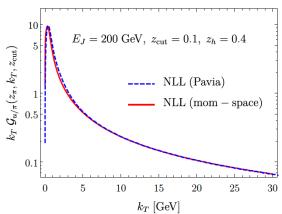
Jet axis insensitive to recoil of soft radiation

### TMD Evolution of Groomed Jets providing sensitive probe of nonperturbative models of TMD hadron structure

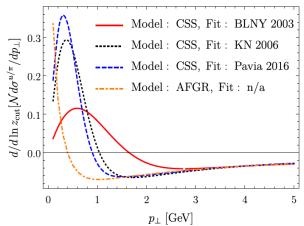
Y. Makris, D. Neill, V. Vaidya, "Probing transverse-momentum dependent evolution with groomed jets," under review by JHEP, LA-UR-17-31338 [arXiv:1712.07653] + Invited talk at SF Jets (YM 1/18)



Hadron identified inside a jet



Perturbative TMD cross section vs. Monte Carlo



Distinguishing nonperturbative model predictions at low pt

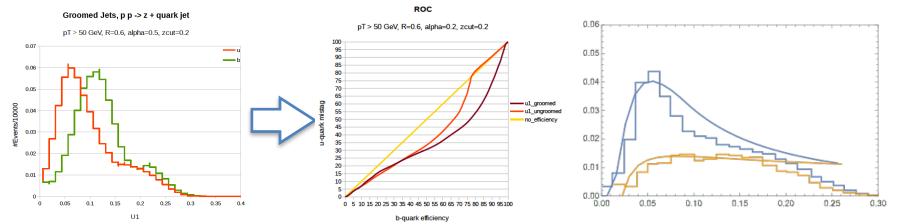


#### **Summary of EFT Efforts**



# Advances on several fronts in applying EFT to precision jet phenomenology in hadron collisions

One paper on groomed *b*-jet substructure in preparation, one talk (VV) in preparation for SCET 2018.



Three papers submitted/published and five invited talks on TMD phenomenology in hadron coll

Progress in FY18-19 will lead to more robust predictions for *b*-jet substructure in *pp* and heavy-ion collisions









# Molecular Dynamics Simulations

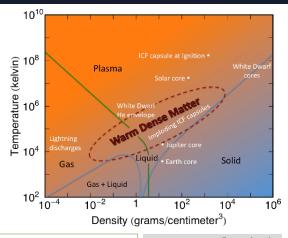
Jérôme Daligault Applied Math. and Plasma Theory, T-5



#### **Objectives**



Explore the potentially fruitful analogies between Quark-Gluon Plasmas and Warm Dense Matter to provide physical insights and theoretical guidance on the effects of strong coupling on b-jet stopping power phenomenology

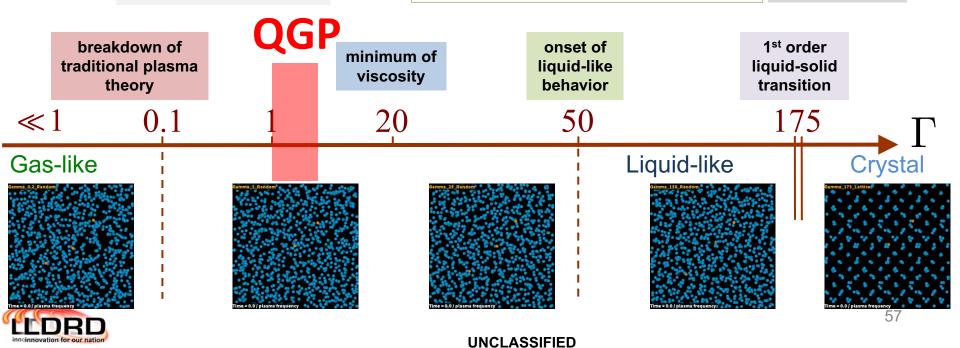


#### **Coulomb coupling strength**

$$\Gamma = \frac{E_{pot}}{E_{kin}} = \frac{q^2 / a}{k_B T}$$

How does strong coupling affect the stopping power of plasmas ?

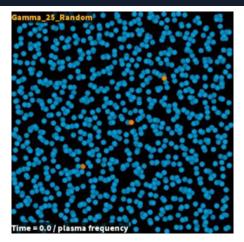
$$S = -\frac{dE(V)}{dx}$$

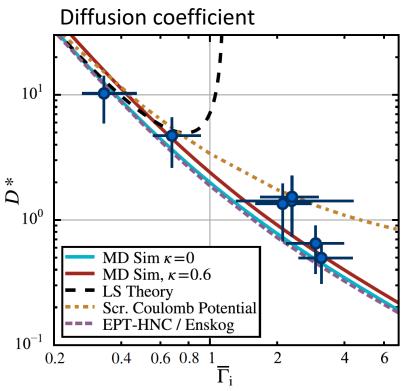


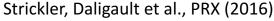
#### **Methods: molecular dynamics**

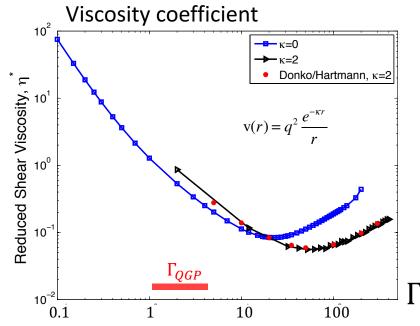


## Classical Molecular Dynamics













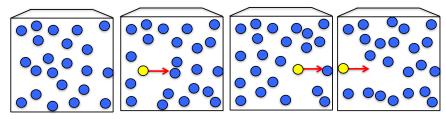
#### Methods: molecular dynamics of dE/dx Los Ala



#### Classical **Molecular Dynamics**

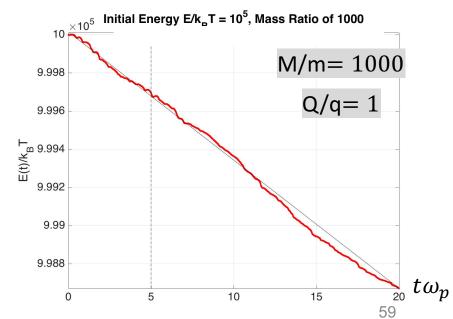
S: molecular dynamics of dE/dx 
$$\frac{\mathbf{LosAlamos}}{\mathbf{LosAlamos}}$$

$$\begin{bmatrix}
m \frac{d^2 \mathbf{r}_i}{dt^2} = -\nabla_{\mathbf{r}_i} \left[ \sum_{i \neq j} \frac{q^2}{|\mathbf{r}_i - \mathbf{r}_j|} \right] - \nabla_{\mathbf{r}_i} \left[ \sum_{i} \frac{Qq}{|\mathbf{R} - \mathbf{r}_i|} \right] \\
M \frac{d^2 \mathbf{R}}{dt^2} = -\nabla_{\mathbf{R}} \left[ \sum_{i} \frac{Qq}{|\mathbf{R} - \mathbf{r}_i|} \right] \\
+ \text{PBC}
\end{bmatrix}$$
(1 \leq i \leq N)



- We developed an MD code to perform dE/dx
- We determined viscosity coefficient and location of viscosity minimum
- We are performing extensive parameter study of dE/dx

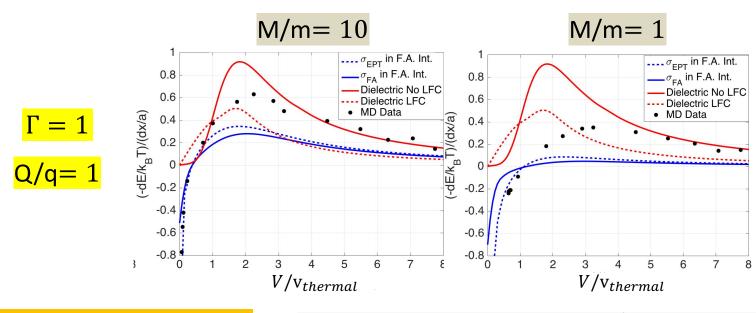
M/m, Q/q,  $\Gamma$ 





#### Effect of strong coupling on dE/dx





#### Classic plasma theory

mean field theory :  $\Gamma \ll 1$  m/M  $\ll 1$ 

$$-\frac{dE(V)}{dx} = -\frac{Q^2}{\pi V^2} \int \frac{dk}{k} \int_{-kv}^{kv} d\omega \omega \operatorname{Im} \frac{1}{\epsilon(k,\omega)}$$

$$-\frac{dE(V)}{dx} = \frac{mM}{4(m+M)V^2} \int d\vec{v} \, \frac{F_{MB}(v)}{v} \int_{|v-V|}^{v+V} dv_r v_r^4 \sigma_{tr}(v_r) \left( \frac{M-m}{M+m} + \frac{V^2 - v^2}{v_r^2} \right)$$

binary collisions including strong coupling effects dynamical dielectric effects neglected

renormalized binary scattering cross section



#### Strong coupling vs non-linear effects



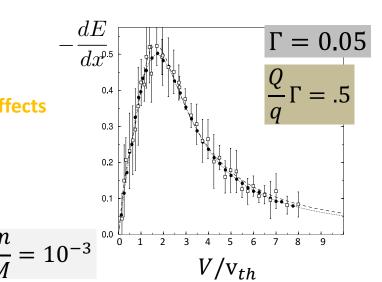
# Weak coupling theory breaks down for $\Gamma>0.1$ but strong coupling effects arise together with non-linear effects

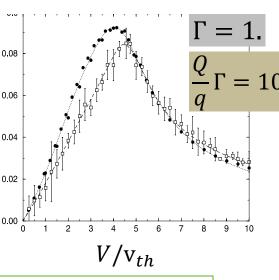
## Dimensionless Hamiltonian

$$r \propto n^{-1/3}$$
$$v \propto v_{th}$$

$$\frac{H}{k_BT} = \underbrace{\frac{M}{m}\tilde{V}^2}_{i} + \underbrace{\frac{Q}{q}}_{i} \sum_{i} \frac{1}{|\tilde{r}_i - \tilde{R}|} + \left(\sum_{i} \frac{\tilde{v}_i^2}{2} + \sum_{i \neq j} \frac{1}{|\tilde{r}_i - \tilde{r}_j|}\right)$$
 projectile projectile - plasma plasma

- MD simulationsnon-linearity + coupling effects
- OOO PIC simulations
  non-linearity only





2<sup>nd</sup> milestone well underway



#### **Summary**



- Performed simulations to understand how strong coupling effects affect transport properties and stopping power of plasmas
   1st milestone met, 2nd well underway
- We will now work with DR team members (I. Vitev) to figure out what these findings tell us about QGP's
- Work done in collaboration with 2017 summer student David Bernstein, Univ. of Iowa. David has started a PhD on this topic
- Publications: Phys. Rev. E 96, 043202 (2017) 95, 013206 (2017)
- Manuscript on dE/dx in preparation
- Talks: 2017 APS-DPP (contr.) 2017 White Dwarfs Physics Wkp (invited) Charged Particle Transport Wkp (invited)









# Hydrodynamic Simulation and Splitting Function Calculation

Boram Yoon CCS-7



#### **Hydrodynamic Simulation**



#### Relativistic viscous hydrodynamics for b-jets

 Reliable description of the QGP required to understand b-jet production in heavy-ion collisions

Hydrodynamic medium

→ b-jet splitting functions and propagation



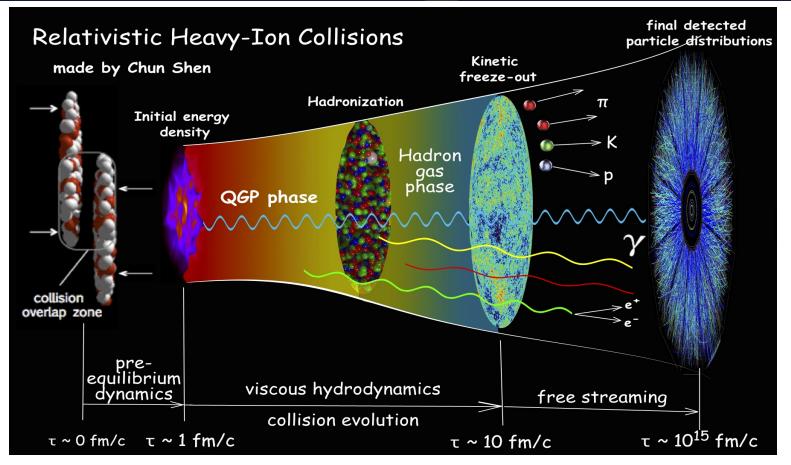
- Relativistic viscous hydrodynamics describes soft particle production in RHIC & LHC
- State-of-the-art hydrodynamics including viscosity and density fluctuations

$$d_{\mu}T^{\mu\nu} = 0, \ T^{\mu\nu} = eu^{\mu}u^{\nu} - (p+\Pi)\Delta^{\mu\nu} + \pi^{\mu\nu}$$

Inputs: Initial condition & Equation of State (EOS)





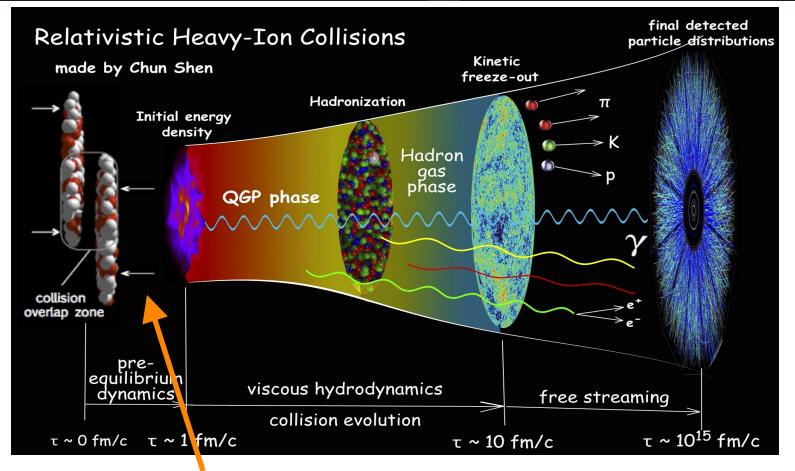


#### iEBE-VISHNU package

- Hydro + hadron cascade simulator for relativistic heavy-ion collisions
- Developed by Chun Shen (2016)







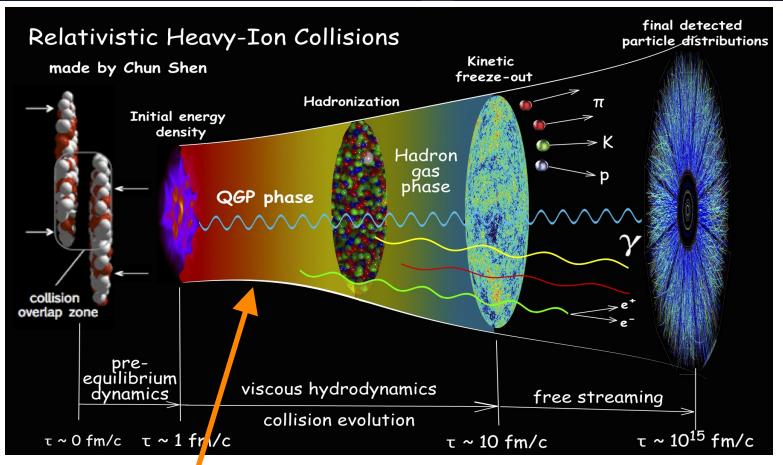
#### Initial Condition Generation

- MC-Glauber model using SuperMC
- includes fluctuation

$$S \propto \frac{1-\alpha}{2}N_{\rm part} + \alpha N_{\rm coll}$$







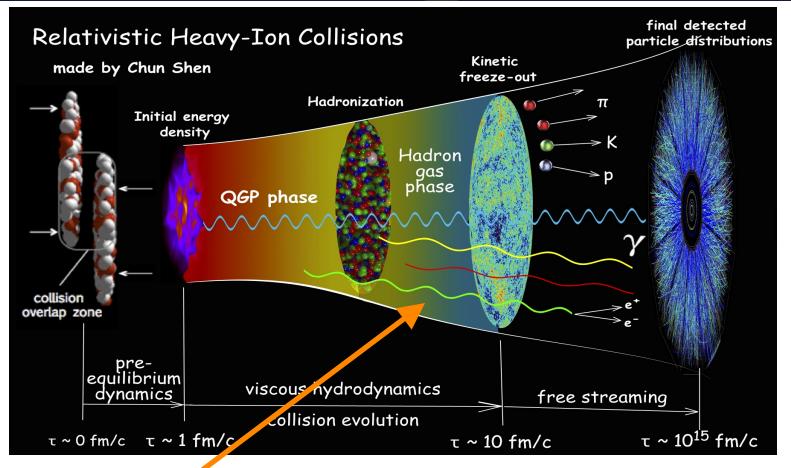
#### Hydrodynamic Simulation

Solving second-order Israel-Stewart equation in (2+1)-dimension

$$d_{\mu}T^{\mu\nu} = 0, \ T^{\mu\nu} = eu^{\mu}u^{\nu} - (p+\Pi)\Delta^{\mu\nu} + \pi^{\mu\nu}$$







- Freeze-out and Particle Sampling
  - Fast Cooper-Frye using iS & iSS, hadron cascade using UrQMD

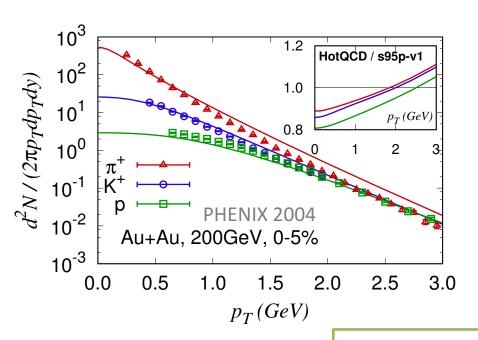


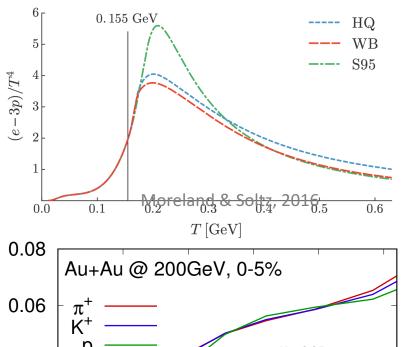
#### **EOS from HotQCD Collaboration**

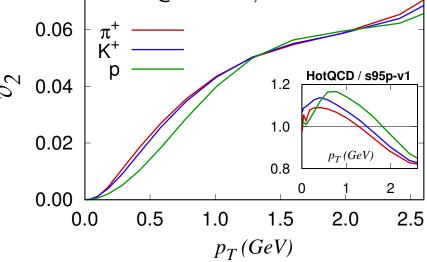


#### Inclusion of HotQCD EOS in simulation

- Replaced older s95p-v1 (2010) parameterization by newer HotQCD (2014) collaboration results
- 20% difference found in spectra and flow coefficients (s95p-v1 vs HotQCD)







Milestone met: Hydrodynamic simulation with HotQCD EOS



#### **Splitting Function Calculation**



#### Heavy-quark splitting functions are evaluated in the hydrodynamic medium

#### Geometry of heavy-ion collision

#### Jets from binary collision

$$T_{AA} = \int d^2r \, T(r - b/2) \, T(r + b/2)$$

T(r): thickness  $\leftarrow$  Woods-Saxon nuclear density

$$N_{\rm coll} = T_{\rm AA}(b)\sigma_{\rm in}$$
 ( $\sigma_{\rm in}$ =42mb @ 200GeV)

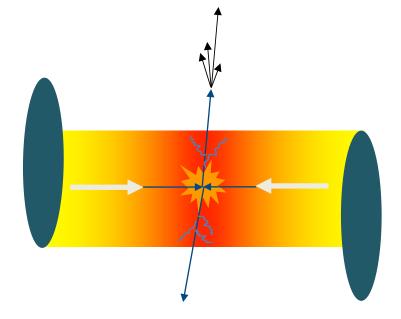
#### Medium from participants

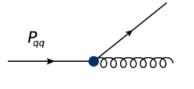
$$\frac{d^2 N_{\text{part}}}{d^2 r} = T_a \left( r + \frac{b}{2} \right) \left\{ 1 - \exp \left[ -\sigma_{\text{in}} T_b \left( r - \frac{b}{2} \right) \right] \right\}$$

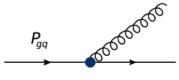
$$+ T_b \left( r - \frac{b}{2} \right) \left\{ 1 - \exp \left[ -\sigma_{\text{in}} T_b \left( r + \frac{b}{2} \right) \right] \right\}$$

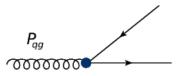
#### Parton splitting

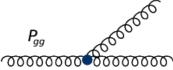
- Jets propagating medium may split  $q \rightarrow qg$ ,  $q \rightarrow gq$ ,  $g \rightarrow gg$ ,  $g \rightarrow q\overline{q}$ 













#### **Splitting Function Calculation**



 Medium-induced parton splitting kernels are calculated (JHEP 2017) and coded up by Ivan Vitev

$$\begin{split} \left(\frac{dN}{dxd^{2}\boldsymbol{k}_{\perp}}\right)_{\left\{g\to gg\atop g\to q\bar{q}\right\}} &= \left\{\frac{\frac{\alpha_{s}}{2\pi^{2}}2C_{A}(\frac{x}{1-x}+\frac{1-x}{x}+x(1-x))}{\frac{\alpha_{s}}{2\pi^{2}}T_{R}(x^{2}+(1-x)^{2})}\right\} \int d\Delta z \left\{\frac{1}{\lambda_{g}(z)}\right\} \int d^{2}\boldsymbol{q}_{\perp} \frac{1}{\sigma_{el}} \frac{d\sigma_{el}^{medium}}{d^{2}\boldsymbol{q}_{\perp}} \\ &\times \left[2\frac{\boldsymbol{B}_{\perp}}{\boldsymbol{B}_{\perp}^{2}} \cdot \left(\frac{\boldsymbol{B}_{\perp}}{\boldsymbol{B}_{\perp}^{2}} - \frac{\boldsymbol{A}_{\perp}}{\boldsymbol{A}_{\perp}^{2}}\right) \left(1-\cos\left[(\Omega_{1}-\Omega_{2})\Delta z\right]\right) + 2\frac{\boldsymbol{C}_{\perp}}{\boldsymbol{C}_{\perp}^{2}} \cdot \left(\frac{\boldsymbol{C}_{\perp}}{\boldsymbol{C}_{\perp}^{2}} - \frac{\boldsymbol{A}_{\perp}}{\boldsymbol{A}_{\perp}^{2}}\right) \left(1-\cos\left[(\Omega_{1}-\Omega_{2})\Delta z\right]\right) \\ &+ \left\{\frac{-\frac{1}{2}}{N_{c}^{2}-1}\right\} \left(2\frac{\boldsymbol{B}_{\perp}}{\boldsymbol{B}_{\perp}^{2}} \cdot \left(\frac{\boldsymbol{C}_{\perp}}{\boldsymbol{C}_{\perp}^{2}} - \frac{\boldsymbol{A}_{\perp}}{\boldsymbol{A}_{\perp}^{2}}\right) \left(1-\cos\left[(\Omega_{1}-\Omega_{2})\Delta z\right]\right) \\ &+ 2\frac{\boldsymbol{C}_{\perp}}{\boldsymbol{C}_{\perp}^{2}} \cdot \left(\frac{\boldsymbol{B}_{\perp}}{\boldsymbol{B}_{\perp}^{2}} - \frac{\boldsymbol{A}_{\perp}}{\boldsymbol{A}_{\perp}^{2}}\right) \left(1-\cos\left[(\Omega_{1}-\Omega_{3})\Delta z\right]\right) - 2\frac{\boldsymbol{C}_{\perp}}{\boldsymbol{C}_{\perp}^{2}} \cdot \frac{\boldsymbol{B}_{\perp}}{\boldsymbol{B}_{\perp}^{2}} \left(1-\cos\left[(\Omega_{2}-\Omega_{3})\Delta z\right]\right) \\ &+ 2\frac{\boldsymbol{A}_{\perp}}{\boldsymbol{A}_{\perp}^{2}} \cdot \left(\frac{\boldsymbol{A}_{\perp}}{\boldsymbol{A}_{\perp}^{2}} - \frac{\boldsymbol{D}_{\perp}}{\boldsymbol{D}_{\perp}^{2}}\right) \left(1-\cos\left[\Omega_{4}\Delta z\right]\right) + 2\frac{\boldsymbol{A}_{\perp}}{\boldsymbol{A}_{\perp}^{2}} \cdot \frac{\boldsymbol{D}_{\perp}}{\boldsymbol{D}_{\perp}^{2}} \left(1-\cos\left[\Omega_{5}\Delta z\right]\right)\right) \right], \end{split}$$

- Use a simple model for QGP medium background
- Take 3 days on a 32 Core Xeon node for a parameter set
  - Need to be repeated for various couplings, energies, centralities, ...



# Splitting Function Calculation with realistic QGP medium

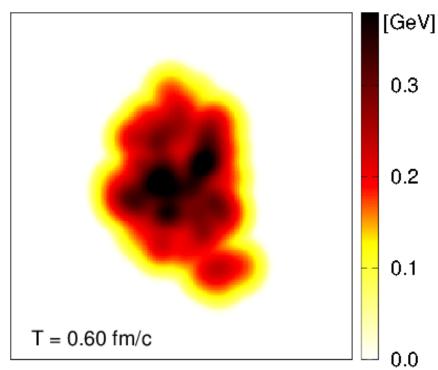


### Major accomplishment in lattice QCD and simulation part

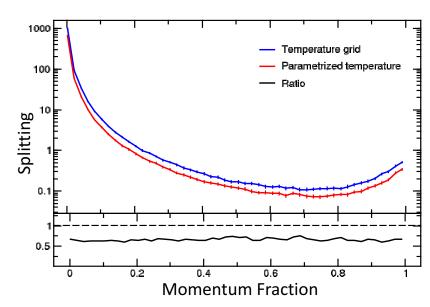
Improved QGP medium

Simple Bjorken model → hydrodynamic simulation w/ full transverse expansion

E = 100 GeV, b = 3.1 fm (0-10% Centrality)



Evolution of medium temperature in Au+Au



- Large difference found in the splitting functions on model vs hydro simulation QGP medium
- Code takes 6 times more time



# **Splitting Function Code Optimization**



## Refactoring

- Original code has complicated structure that restricts extensions, and many redundant replications
- Only GNU compiler can compile it due to the nested functions
- Code is restructured (in C++) and shortened (24K → 8K lines)

- Arithmetic calculations are optimized to be more efficient
- 20x speed improvement accomplished

# Effective incorporation of simulated QGP medium

- Reduced overhead for calling QGP medium grid function
- 2x speed improvement accomplished

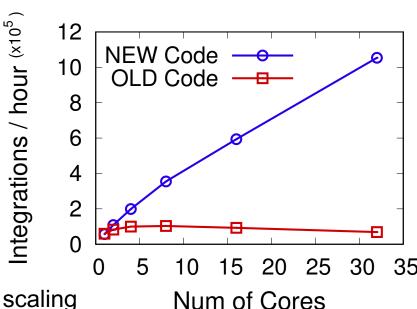


# **Splitting Function Code Optimization**



#### Efficient on-node parallelization

- Original code uses parallelization supported by Cuba numerical integration library (pthread)
- Scales terribly
- Problem can be embarrassingly parallelizable by distributing integrations for different energy/momenta for different cores
- New parallelization shows much better scaling
- 10x speed improvement accomplished



#### Overall improvement: 18 days → 1 hour

- Precise splitting probability on variety of simulation parameters
- Easy to read, and easy to extend code base

Preparing for a paper for di-b-jet in LHC and RHIC (2018)

Milestone met: Jet propagation into fluctuating hydro medium



## Summary



# Hydrodynamic simulation

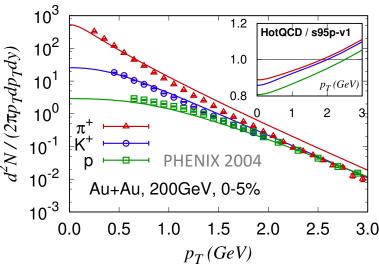
Improved Equation of State (EOS)

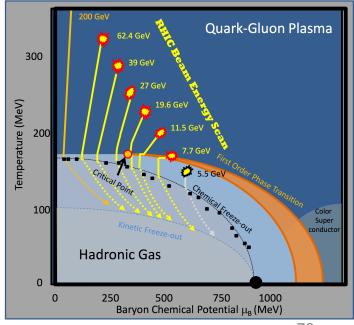
# Heavy quark splitting function calculation

- Realistic QGP background generated by the hydrodynamic simulation
- Optimized code for practical evaluation on various simulation parameters
- Paper in preparation

## FY18-19 plan

- Complete splitting function calculations
- Beam energy scan to address jet quenching at low center of mass energies















# sPHENIX LDRD Review:

# Physics & Detector Simulations

Darren McGlinchey XTD-PRI / P-25





## **Physics Reminder**



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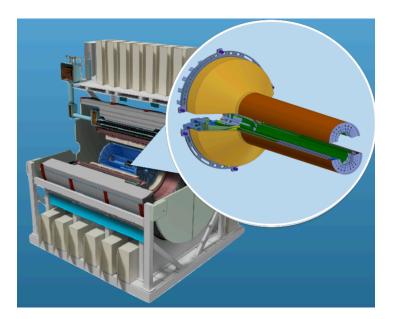
#### **Physics Goal:**

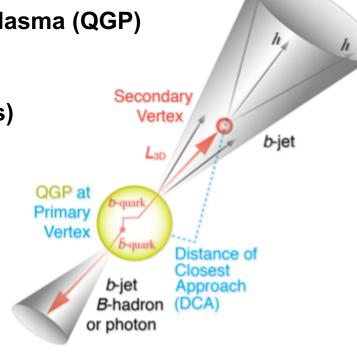
Study the properties of the Quark Gluon Plasma (QGP)

#### **Experimental Observable:**

Jets originating from bottom quarks (b-jets)

- Bottom quarks are heavy (4.2 GeV)
- Produced in initial collision, not QGP
- Well controlled in pQCD
- Provide access to fundamental transport properties





- Detected using the long lifetime of bottom quark hadrons
- Need excellent jet detection capabilities sPHENIX!
- Need high precision tracking and vertex determination MVTX!

... B-mesons are another important observable, but won't be discussed here



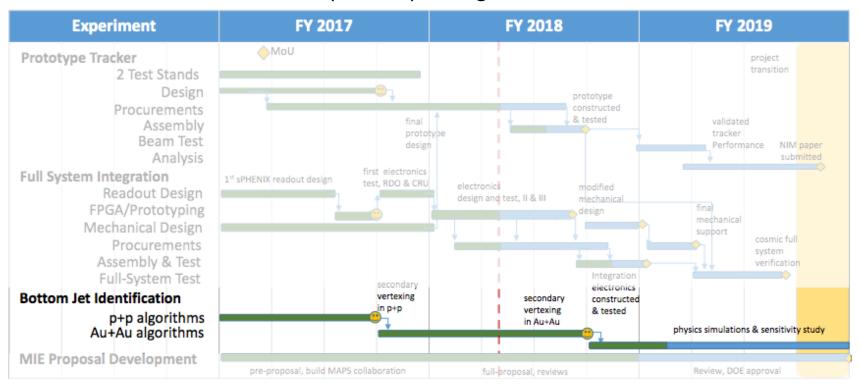


#### **Overview**



#### **LDRD Deliverable:**

Develop the software framework necessary for validation of the sPHENIX MAPS-based Vertex Detector (MVTX) design.



#### Manpower:

Sanghoon Lim (postdoc), Darren McGlinchey (postdoc), Xuan Li (staff)





# **sPHENIX Tracking Overview**



#### 3 layer MAPS Vertex Detector (MVTX):

- R = 2.3, 3.2, 3.9 cm
- Thickness: 50 μm (0.3% X<sub>0</sub>) per layer
- Cell dimension: 28 μm x 28 μm
- Using realistic detector geometry

# 4 layer Intermediate Silicon Strip Tracker (INTT):

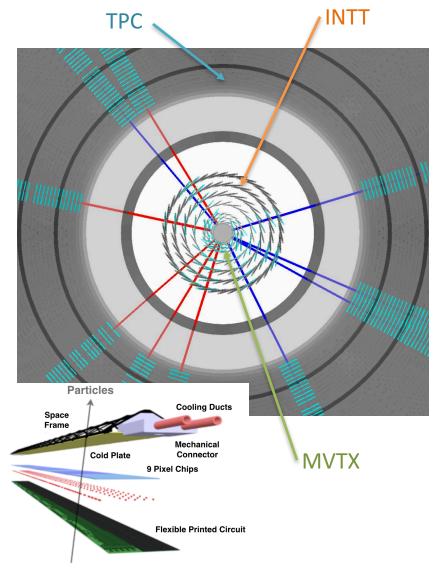
- R = 6, 8, 10, 12 cm
- Using realistic detector geometry

#### 40 layer Time Projection Chamber (TPC):

• R = 20 (40) - 80 cm

#### **Progress highlight:**

 Detailed stave geometry imported and used in all tracking studies

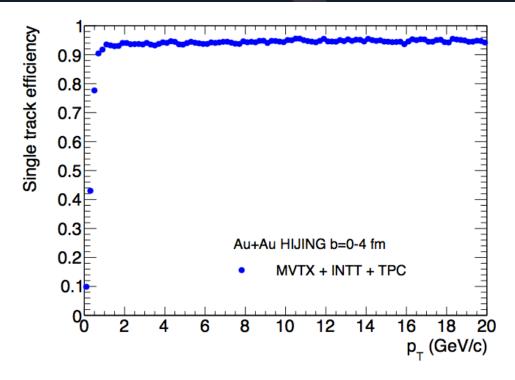






# **sPHENIX Tracking Performance (I)**





#### **Tracking performance:**

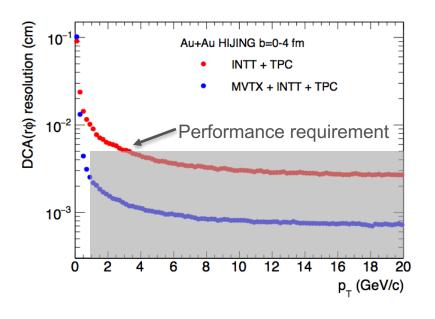
- Simulations of pions embedded in central Au+Au collisions (HIJING)
  - 100% detector efficiency, no event pile-up
- Hough transform for pattern recognition
- Kalman-filter (GenFit) for track propagation and fitting
- Single track efficiency ~95%

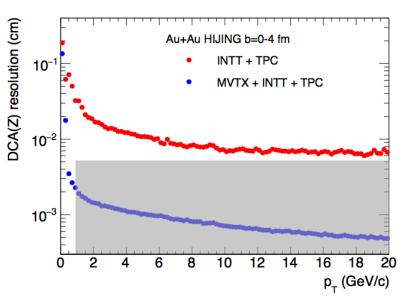




# **sPHENIX Tracking Performance (II)**







#### Tracking performance:

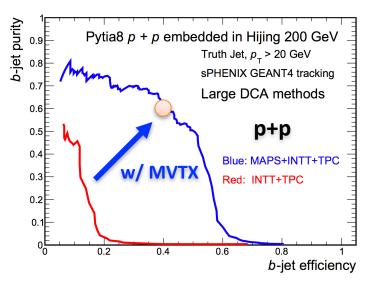
- Simulations of pions embedded in central Au+Au collisions (HIJING)
  - 100% detector efficiency, no event pile-up
- Significant improvement in **Distance of Closest Approach (DCA)** resolution with MVTX
- DCA(r $\phi$ ) resolution < 20  $\mu$ m for p<sub>T</sub> > 1 GeV (target of < 50  $\mu$ m for p<sub>T</sub> > 1 GeV)
- DCA(z) resolution < 20  $\mu$ m for p<sub>T</sub> > 1 GeV (target of < 50  $\mu$ m for p<sub>T</sub> > 1 GeV)

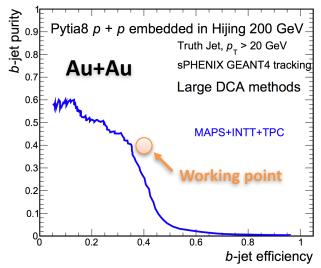


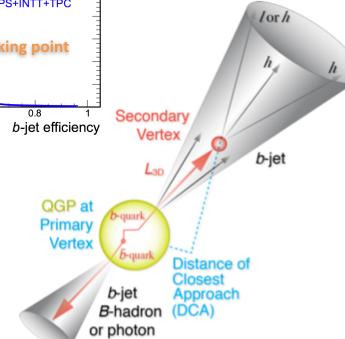


# b-jet Tagging: Algorithm I









#### **Algorithm I:**

- Utilize Distance of Closest Approach (DCA)
- Count the number of tracks in the jet with DCA larger than your cut
- Full Geant-4 simulation of p+p (pythia 8) and central Au+Au (Hijing) + reconstruction & tracking software
- No pile-up included (under development)

#### **Progress highlight:**

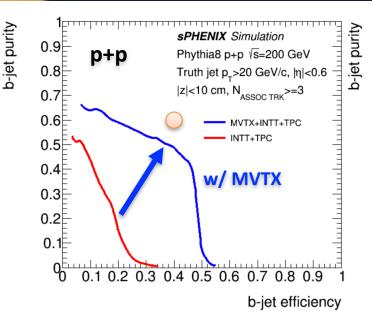
Algorithm successfully tested in p+p and Au+Au collisions!

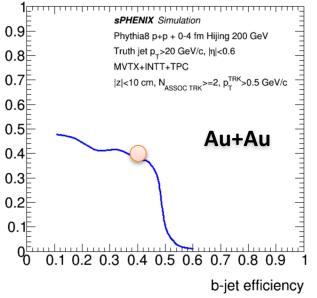




# b-jet Tagging: Algorithm II







# Secondary Vertex b-jet efficiency OGP at Primary Vertex Distance of

b-jet

or photon

B-hadron

Closest

(DCA)

Approach

#### **Algorithm II:**

- Utilize Secondary Vertex reconstruction
- Reconstruct secondary vertex & require ≥ 2 tracks associated with it
- Full Geant-4 simulation of p+p (pythia 8) and Au+Au (Hijing) + reconstruction & tracking software
- No pile-up included (under development)

#### **Progress highlight:**

Algorithm successfully tested in p+p and Au+Au collisions!

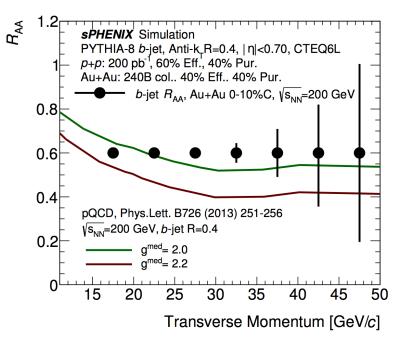




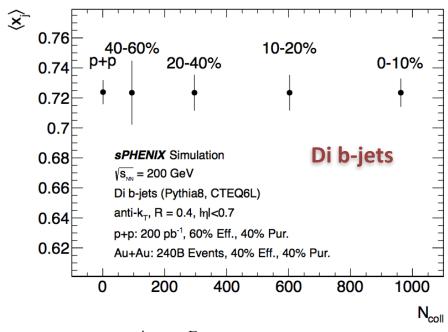
# **b-jet: Physics Projections**



#### Performance projections included in MVTX proposal submitted to DOE



$$R_{AA} = \frac{\text{Yield in Au + Au}}{N_{Coll} \times \text{Yield in p + p}}$$



$$x_j = \frac{p_T^A - p_T^B}{p_T^A + p_T^B} = (\text{Momentum imbalance})$$

#### **Progress highlight:**

Full physics projections included in proposal!





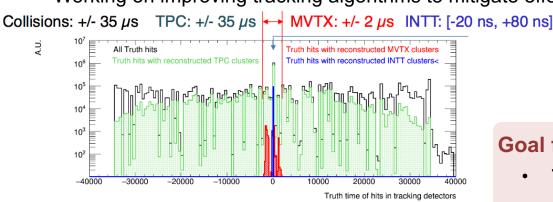
# Improving Realism: Event pile-up

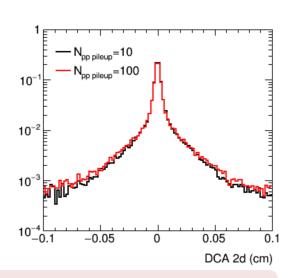


MVTX	[-5.0, +5.0]	130 (<<1% occ)	2 (<<1% occ)
INTT	[-0.02,+0.08]	1	1
TPC	[-35, +35]	910	14 (~35% occ)

#### **Event pile-up:**

- With high luminosity, expect multiple collisions per trigger due to integration times
- Largest effect in the Time Projection Chamber (TPC)
- Now have a full framework to test this in simulations (as of ~Nov 2017)
- Working on improving tracking algorithms to mitigate effect





#### **Goal for 2018:**

Test pile-up effect on b-jet performance

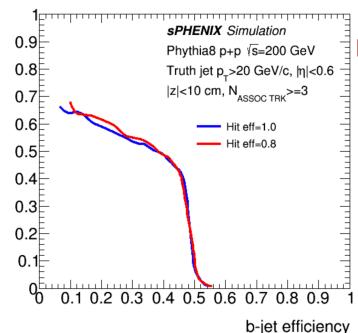




b-jet purity

# Improving Realism: Detector efficiency & alignment





#### **Detector efficiency:**

- Current efficiency studies test effect of random hit inefficiency
- 80% hit (channel) efficiency → little degradation in b-jet tagging efficiency & purity
- Need to test effect of dead chips & ladders on bjet performance

#### **Goal for 2018:**

Provide framework for detailed eff studies

#### **Detector alignment:**

- Currently assume perfect detector alignment
- Detector misalignment can worsen DCA resolution
- Add ability to mis-align detector between simulation & reconstruction stages
- Develop method for aligning the detector in real data
- The group has significant experience from PHENIX silicon detectors

#### **Goal for 2019:**

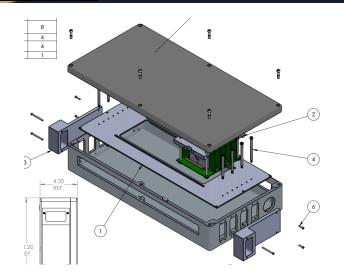
Provide sPHENIX MVTX alignment procedure





## **MVTX Prototype**





#### **MVTX** Prototype:

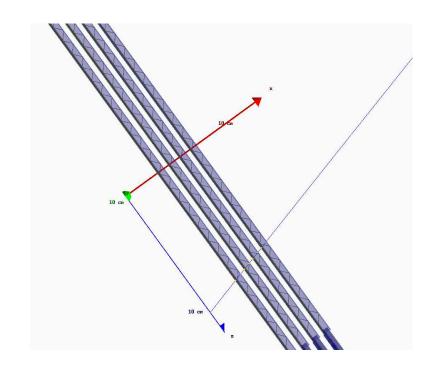
- Key deliverable of LDRD is 4 stave (or chip) telescope for cosmic ray & beam test studies
- Discussed in detail later by Sho Uemura

#### **Software & simulation goals:**

- Use the same software for simulation & data reconstruction
- Validate charge sharing in simulations
- Test alignment procedure

#### **Goal for 2018:**

 Validate charge sharing in simulations using real data







#### **Summary**



#### **Deliverable:**

Develop the software framework necessary for validation of the MVTX design.

#### **Progress:**

- Simulations now include realistic detector geometry
- B-jet tagging performance studied in both p+p and Au+Au using two methods
  - p+p: 60% efficiency, 40% purity
  - Au+Au: 40% efficiency, 40% purity
  - (assumes 100% detector efficiency and no event pile-up)
- Provided physics projections for b-jet R<sub>AA</sub> in MVTX proposal
  - We also have physics projections for other observables, b-jets highlighted here.

#### Goals for 2018-2019:

- [2018] Test pile-up effect on b-jet performance
- [2018] Make detailed efficiency studies
- [2018] Validate charge sharing in simulations using MVTX prototype data
- [2019] Provide sPHENIX MVTX alignment software and procedure (tested on MVTX prototype data)



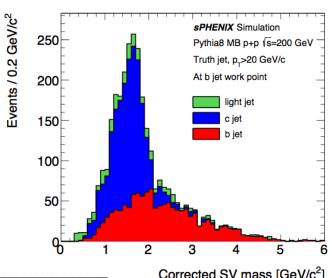


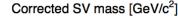
# **Backup: SV Mass**

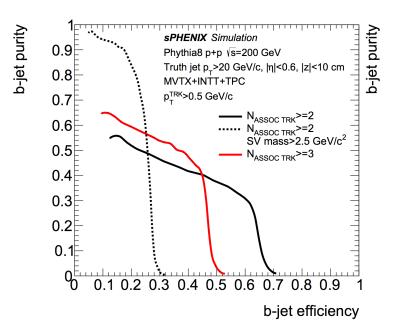


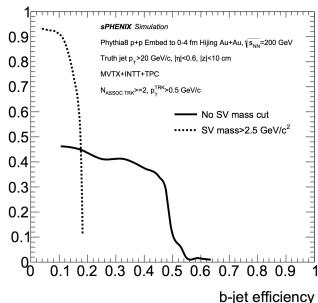
#### Using the secondary vertex mass:

- The corrected secondary vertex mass can help distinguish between light-, c-, and b-jets
- Adding a cut on the SV mass can drastically increase b-jet purity at the expense of efficiency







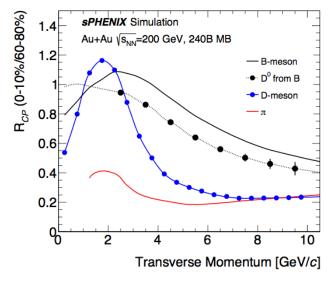


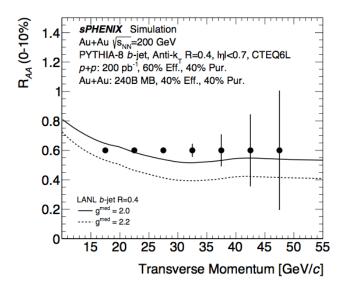


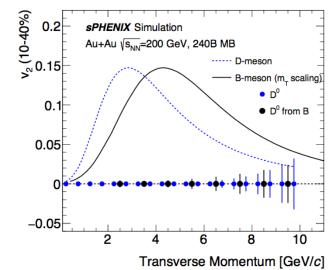


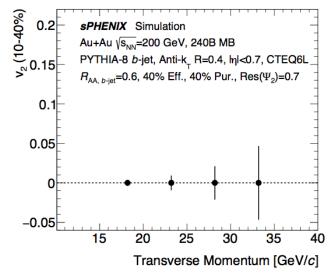
## **Backup: MVTX Projections**



















# sPHENIX LDRD Review

# **ALPIDE Introduction and Test Stand**

Xuan Li

P-25

## Outline

- ALPIDE chip introduction
- LDRD test bench setup
- LDRD test bench achievements
- Summary and Plans

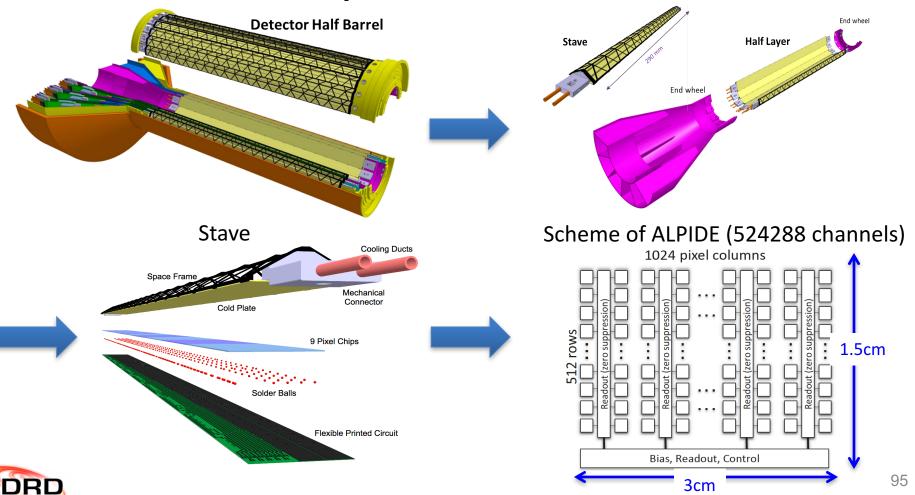


# The MVTX Basic Unit: ALPIDE sensor Los



# **ALPIDE** chip Introduction:

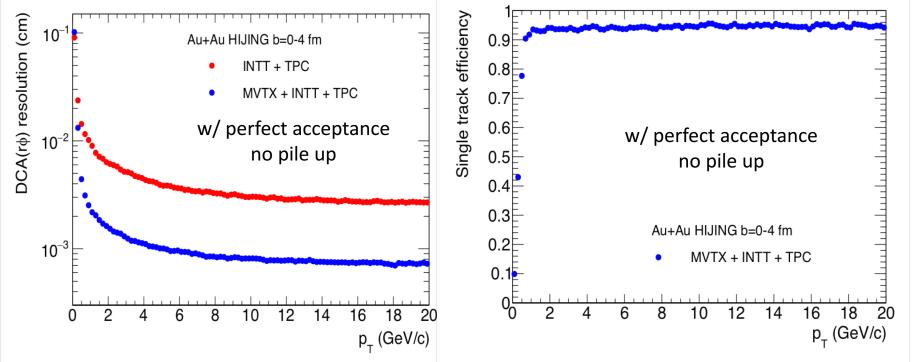
The 3-layer MVTX consists of 48 staves and each stave contains 9 ALPIDE chips.



# **MVTX Performance Requirements**



 The heavy flavor program at sPHENIX led by the MVTX requires good vertex resolution and high efficiency.

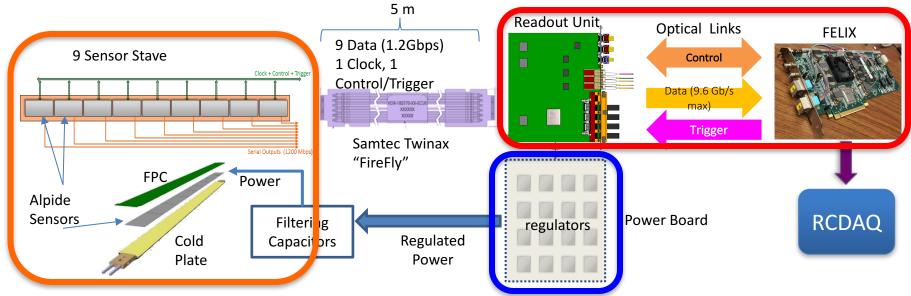


- Can MVTX meet these requirements in real data?
  - Small dead channel fraction → High efficiency.
  - High signal/noise ratio → Low background.



# **LDRD Test Bench Components**

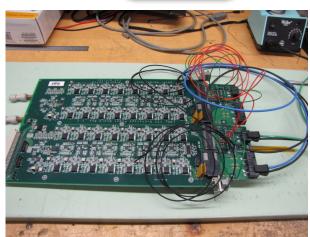








Purchased one stave and 5 individual ALPIDE chips.



**Purchased 1 Power Board** 

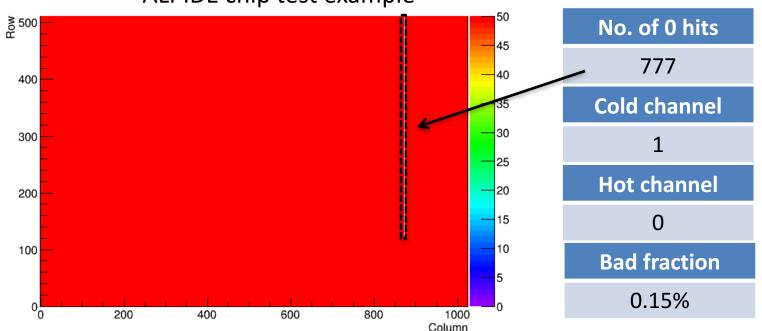


Test bench readout module: MOSAIC

# **ALPIDE Characterization: Good Active Area**



- Measure the dead areas for efficiency evaluation.
- Test with internal pulse generator:
  - Scanned available chips and stave at LANL through digital scan to verify the good channel fraction: the active pixel fraction is >>99%.
  - Similar results with different readout speed.
     ALPIDE chip test example



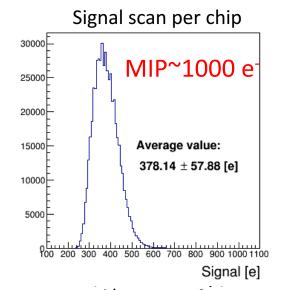


# ALPIDE Characterization: Low Noise (I)



- Charge injection with internal pulse generator:
  - Scanned available chips and stave at LANL through threshold scan: signal/noise based on charge injection study is > 60.
     Comparable with CERN test (~60).
- Proves the background contribution is low!

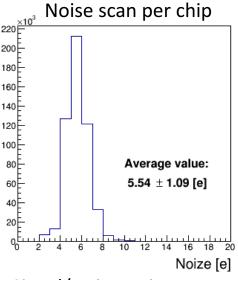
#### Chip test with internal trigger



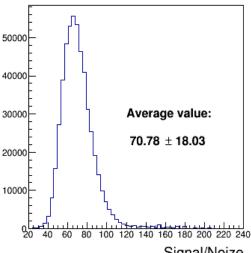
Signal/Noise uniformity

500
400
400
300
200
400
600
800
1000

Column



Signal/Noise scan per chip

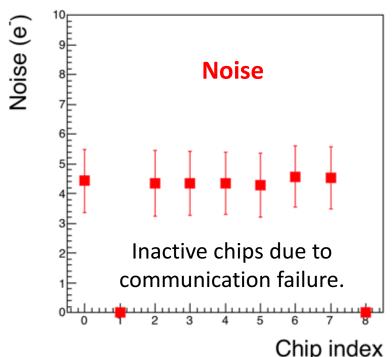


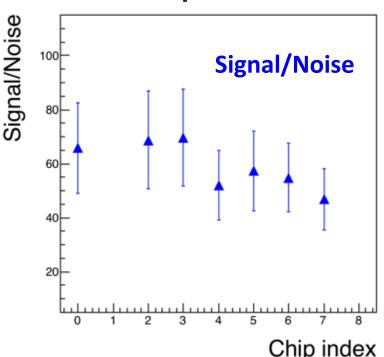
# ALPIDE Characterization: Low Noise (II)



- Charge injection with internal pulse generator:
  - Scanned available chips and stave at LANL through threshold scan: signal/noise based on charge injection study is around 60. Comparable with CERN test (~60).

Stave test with internal trigger: Simultaneous readout of all chips.

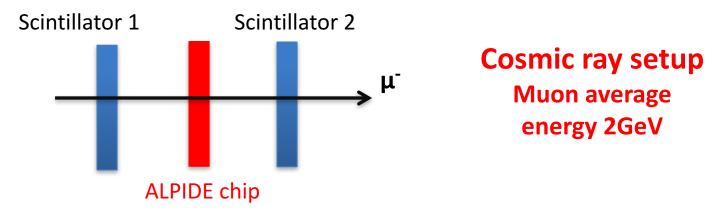




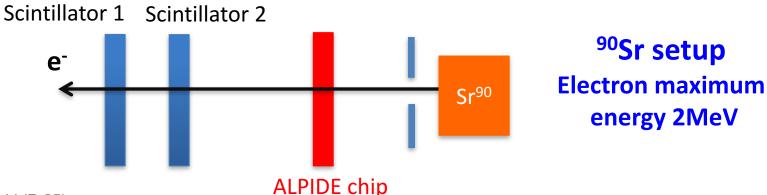
# **ALIPIDE Performance Evaluation Configuration**



- Study the ALPIDE performance with real particles.
- Tests in triggered mode with default delay at 2µs:
  - External trigger with cosmic ray muons (rate: ~0.1HZ).



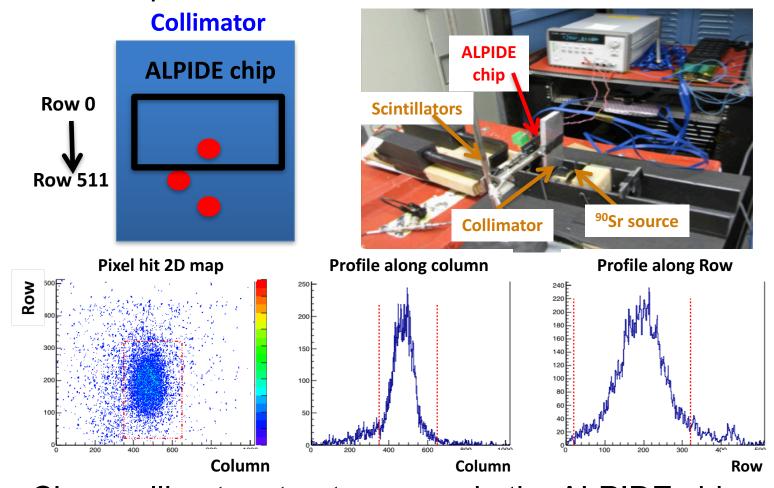
External trigger with <sup>90</sup>Sr beta decay electrons (rate: ~1Hz).



# Test Achievements: verify trigger timing and signal detection



- Time in trigger and observe physical signal.
- For example: <sup>90</sup>Sr source test.

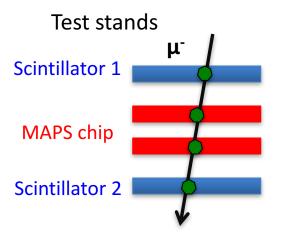


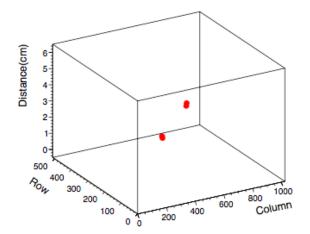
Clear collimator structure seen in the ALPIDE chip.

# Test Achievements: good hit resolution



Initial look at tracking with two layers of ALPIDE chips.



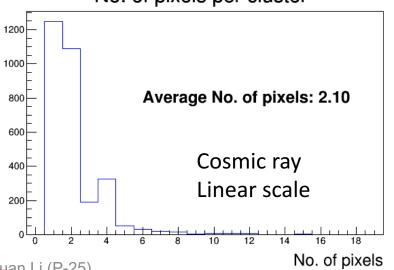


#### **Event Display**

Found clusters that belong to a cosmic ray muon track.

Characterize the cluster size: related to the hit resolution.





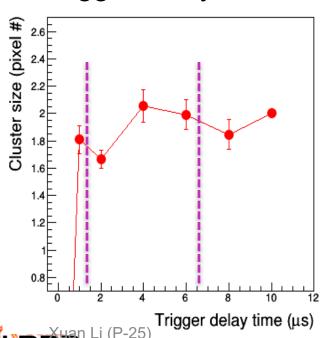
- Comparable with <sup>90</sup>Sr source test results and DESY beam test (cluster size < 3 pixels).</li>
- Average cluster size (2 pixels) indicate the hit resolution <</li>
   10µm → Meets requirements.

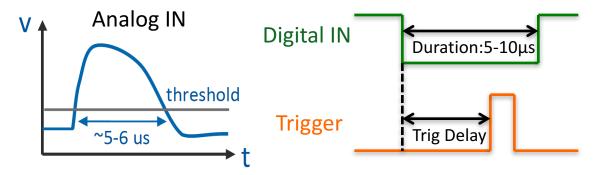


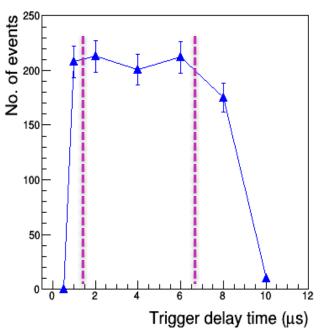
# **Under study: Trigger delay latency**



- Can the MVTX adapt to the sPHENIX trigger scheme with default trigger delay at 4-5 µs?
- The default ALPIDE trigger delay is 2µs.
- Need to tune the pulse shaping and trigger delay.





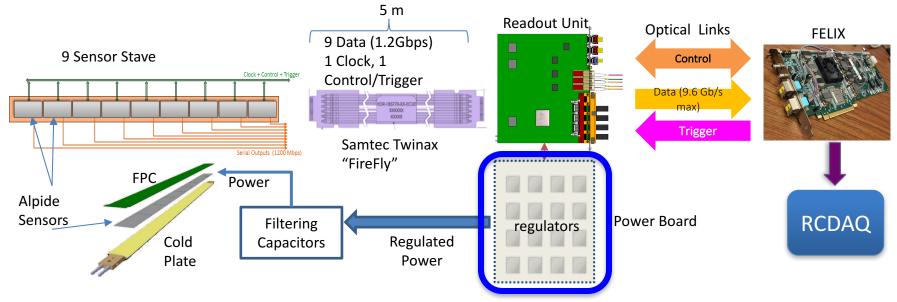


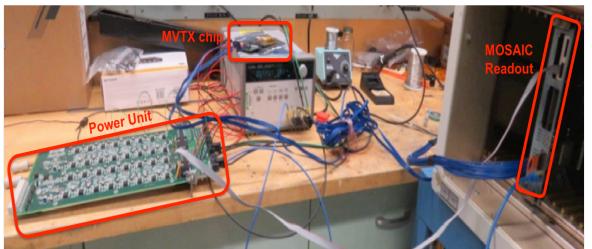
After lowering the threshold to optimize the pulse shaping time:

No significant performance differences with trigger delay from 2μs to 6μs.

# **Integration: Power Board Test**









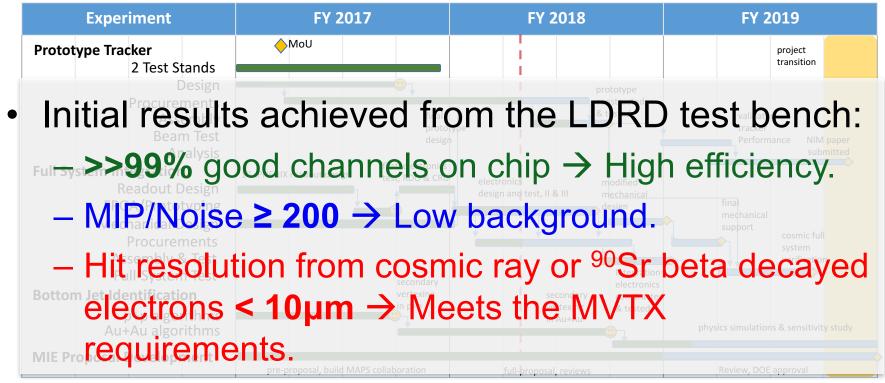


Successfully operating the ALPIDE using the Power Board prototype!



# Summary



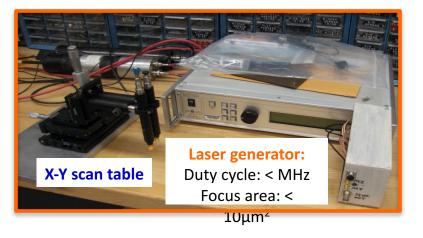


- Proof of principle study proves the feasibility to adapt the MVTX to the sPHENIX trigger scheme.
- Successful test of the Power Board prototype as part of the MVTX electronics.

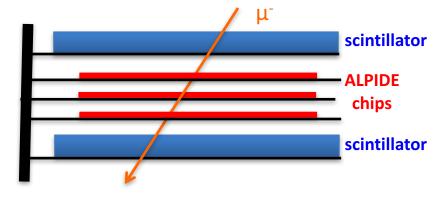
## **Plans**



- Set up the laser test bench to study the efficiency, noise rate, trigger delay time, threshold, pulse shaping, etc.
- Set up the telescope containing multiple layers of ALPIDE chips (staves) to study the track resolution, efficiency, etc, from cosmic ray and source tests.



#### Telescope for cosmic/source test

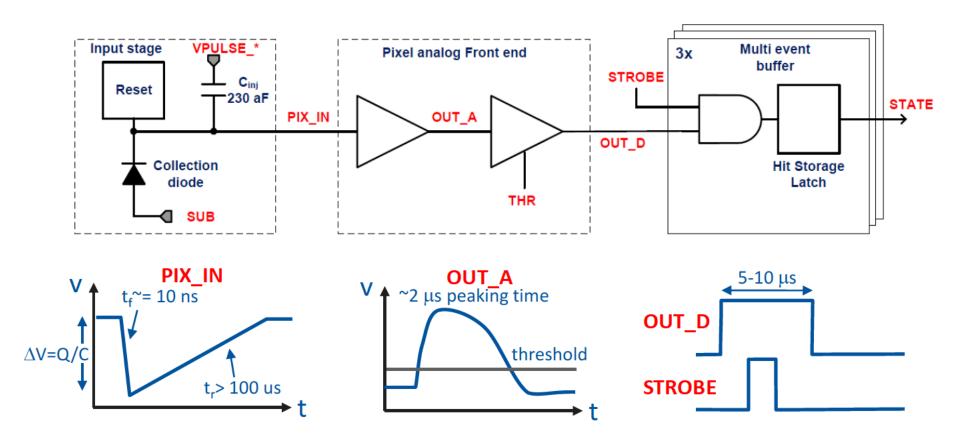


 Complete optimizing the ALPIDE performance with the RU+FELIX+PB full readout chain this summer.

# **Backup**



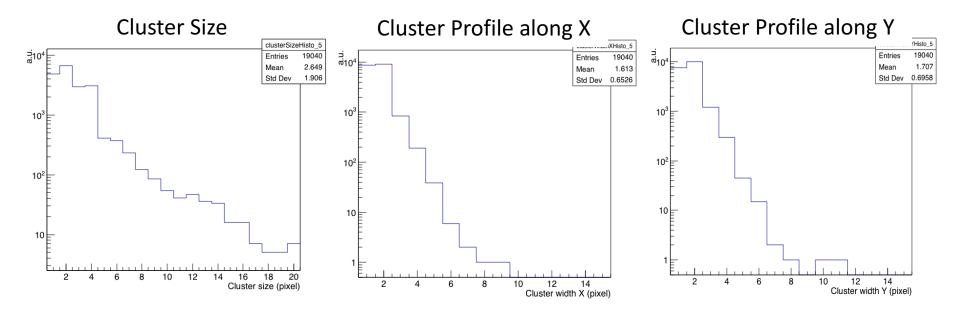
ALPIDE pixel block diagram.



## **Backup**



 Cluster evaluation by the CERN team from 450 MeV e- beam test.



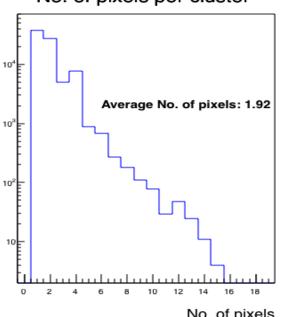
 Even particle energies are different, similar results are achieved between the test bench studies with cosmic ray or <sup>90</sup>Sr beta decayed electrons.

#### **Achievements: cluster determination**



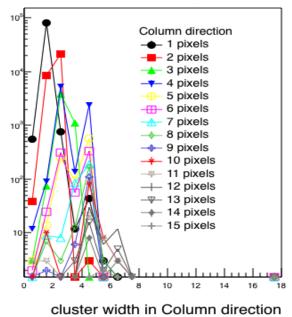
- Cluster size determined from 90Sr beta decayed electrons.
- The average cluster size determined from 90Sr source is comparable with cosmic ray test.

#### No. of pixels per cluster

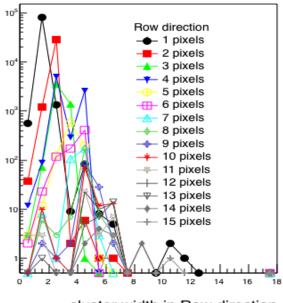


No. of pixels

#### cluster width in pixels



cluster width in pixels



cluster width in Row direction







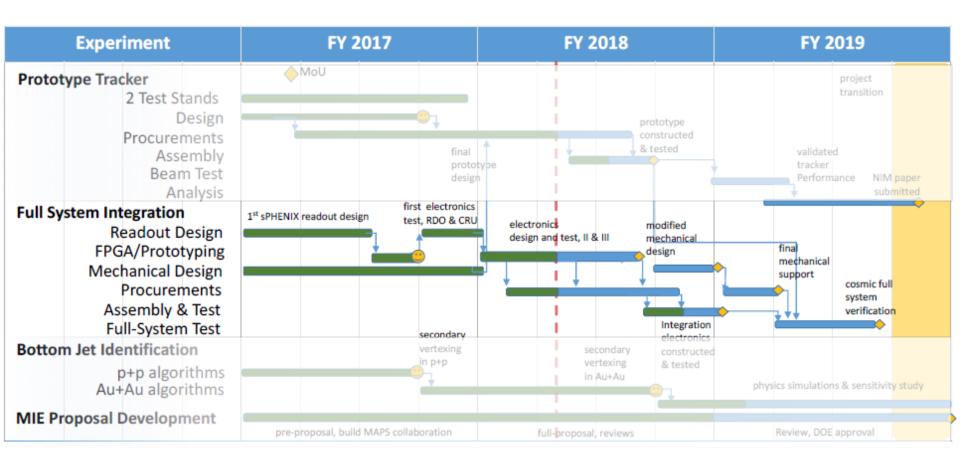
# sPHENIX LDRD Readout System Review

Alex Tkatchev P-25



# Schedule

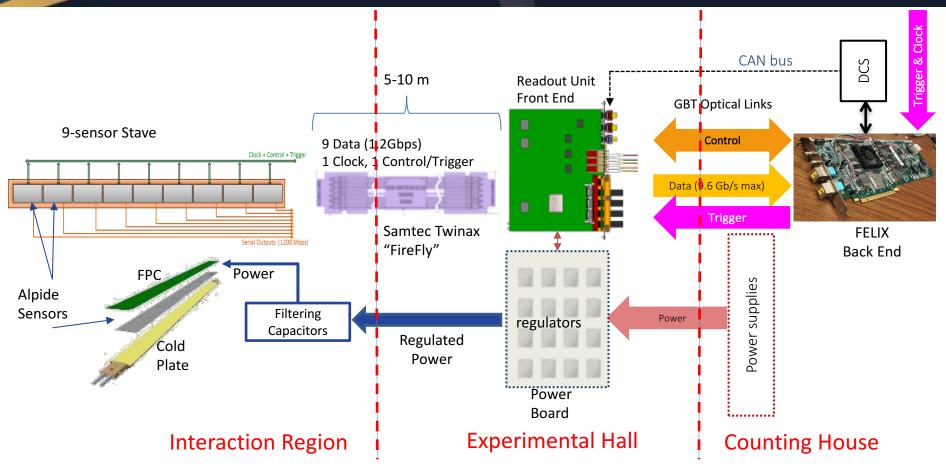






## **MVTX Electronics Overview**





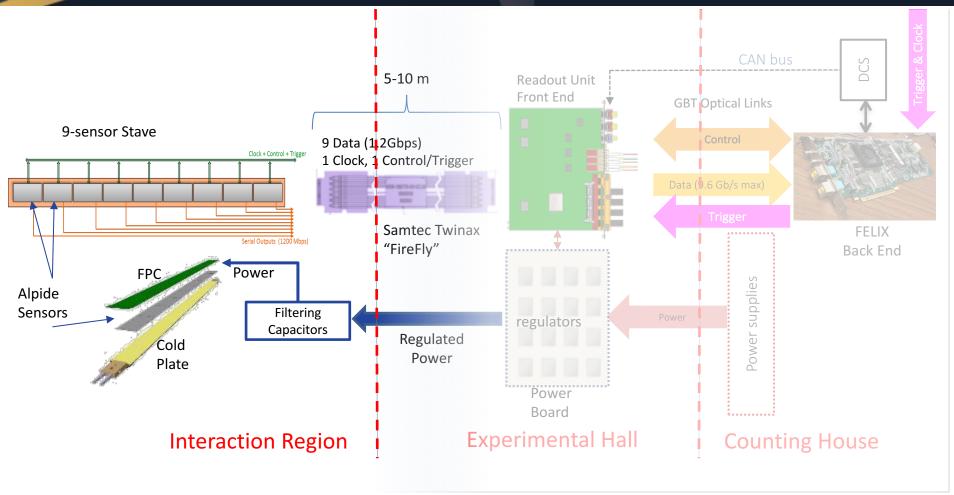
MVTX Detector Electronics consists of three parts

Sensor-Stave (9 ALPIDE chips) | Front End-Readout Unit | Back End-FELIX



## Sensor





MVTX Detector Electronics consists of three parts

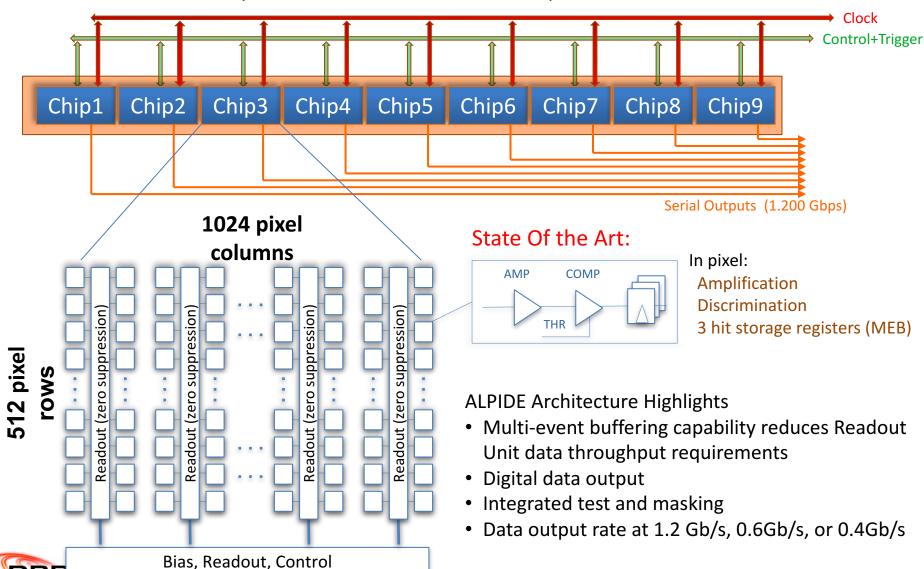
Sensor-Stave (9 ALPIDE chips) | Front End-Readout Unit | Back End-FELIX



## Stave

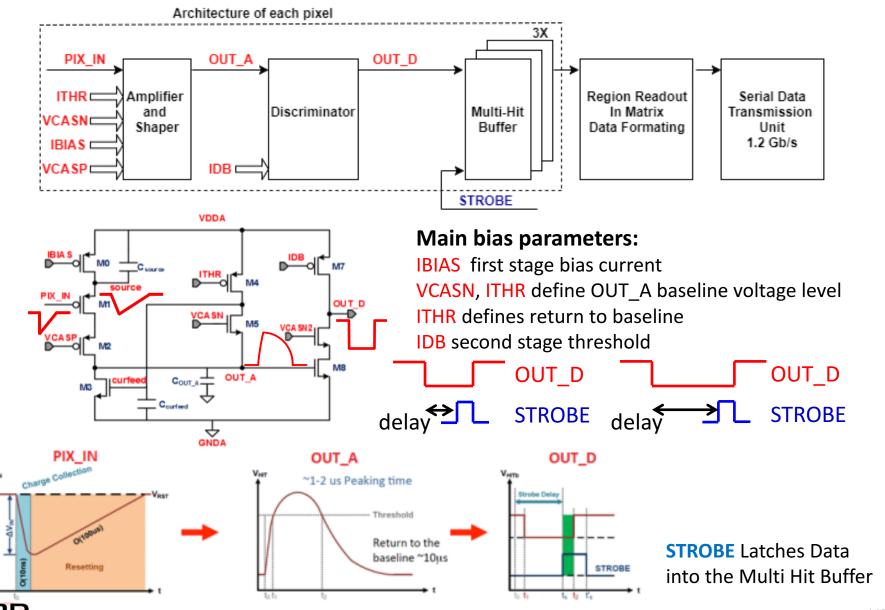


**Stave**– 9 chips, common clock and control, independent data lines



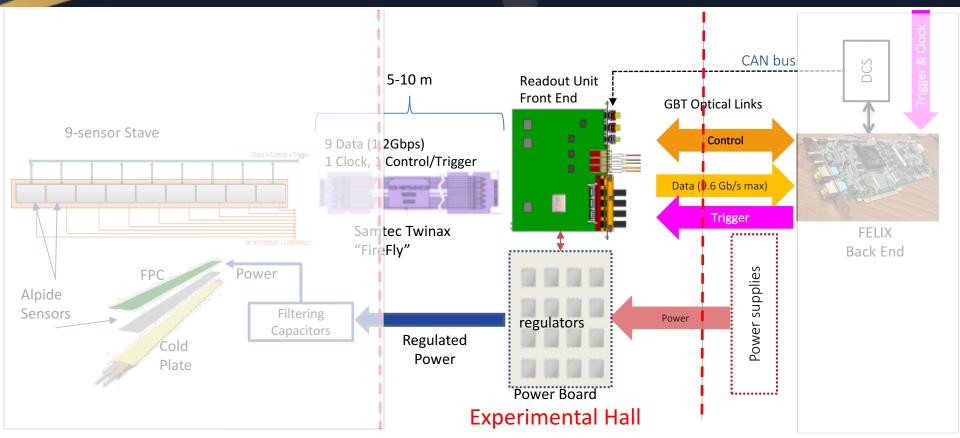
## **ALPIDE Characterization**





## MVTX Overview Readout Unit LOS Alar NATIONAL LABO





#### Front End-Readout Unit

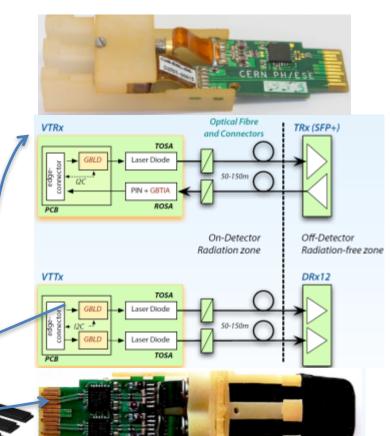
- Data **readout** from **Stave**
- Stave **status** and **power control**
- **Control** and **monitoring** to/from the **sensors**
- **Trigger & busy** management
- Data building and transmission through the rad-hard Giga Bit Transceivers 18

## Readout Unit



#### State Of the Art:

- Xilinx Kintex Ultrascale FPGA
- ProAsic FPGA (Manage Radiation Upsets)
- GBT ASIC (Rad. Tolerant Giga Bit Transceiver)
  - VTRx: Transciver up & down link
  - VTTx: Double Transmitter 2 \* up link:
- Samtec firefly copper twinax cable interface
  - 9 independent 1.2Gb/s data streams
  - 1 40MHz Clock
  - 1 Control Line Transition Board
     Samtec Firefly cable



VTRx sm —

Power Boards link

CAN bus

Diagnostic / busy IO

2 uplink (data) to FELIX

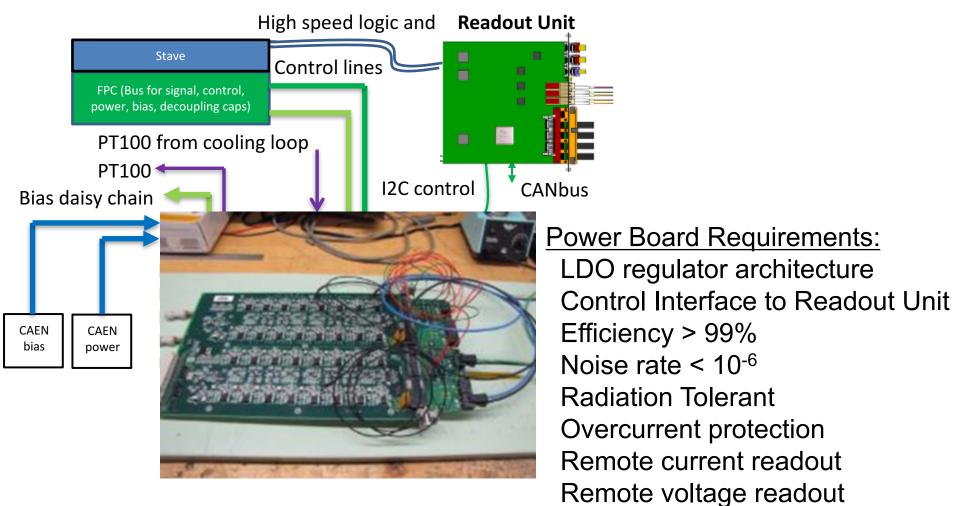
1 uplinks (data/CTRL) to FELIX

1 downlink (CTRL) from FELIX

1 trigger downlink directly to ensure low latency

## System Power Overview



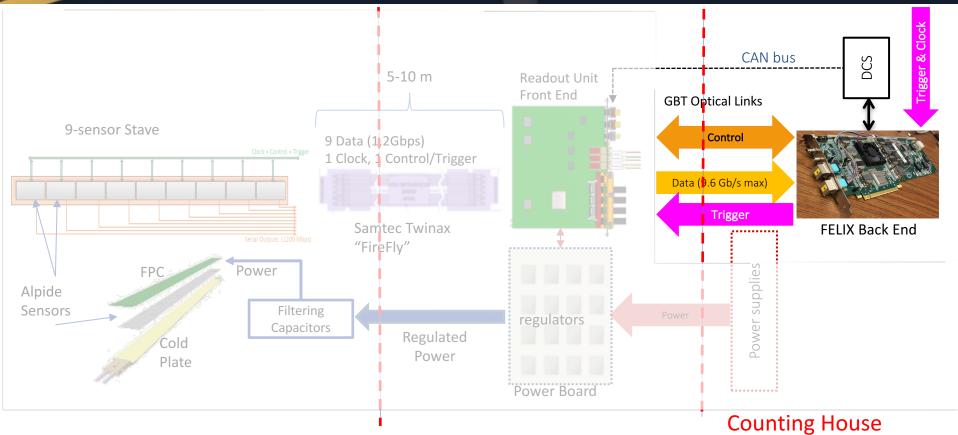




Remote voltage setting

## **MVTX Overview FELIX**





#### **Back End-FELIX:**

- Data readout from 8 Readout Units
- Slow Control and Monitoring to/from sensors
- Trigger and Timing systems interface
- Data aggregation and sub-event packaging
- Data transmission through the PCle to Server CPU

## **FELIX**



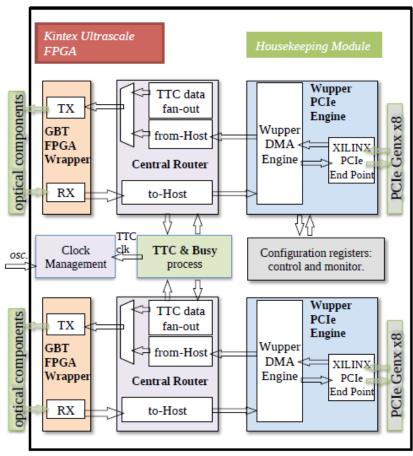


#### State Of the Art:

- Xilinx Kintex Ultrascale FPGA
- 48 bi-directional GBT links
- 16 lane Gen3 PCle

#### Performance Summary:

- PCle Tx > 100 Gb/s
- FEE Rx < 80 Gb/s</li>





## Data Rate Requirements



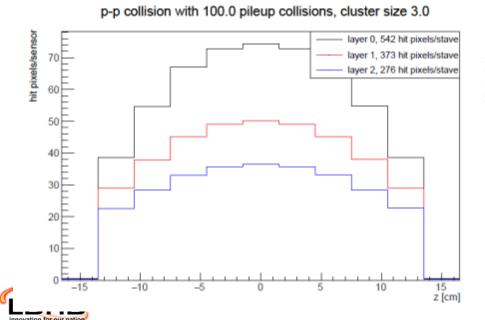
	10 <sup>-4</sup> noise	Hit occupancy only		Hit + noise occupancy	
	occupancy	p+p [MB/s]	Au+Au [MB/s]	p+p [MB/s]	Au+Au [MB/s]
L0 FEM	26	29	107	55	133
DAM	219	173	630	392	848
MVTX	1305	1041	3781	2346	5089

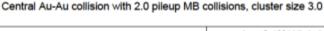
Readout Units 3 GBTX @ 0.4 GB/s = 1.2 GB/s >133MB/s

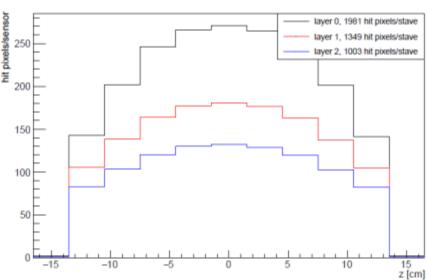
GBTx: 3.2-4.48Gb/s, 0.4 GB/s

FELIX (48 input on FELIX, twice the number needed to support 8 RUs (3 links))

2x 8-lane PCIe Gen 3 @ 7880 MB/s = 15760 MB/s > 848 MB/s







## **MVTX Readout Electronics**



#### Hardware

- 48 ALPIDE Staves (~200M Channels)
- 48 Front End Electronics (RUv1)
- 6 Back End Electronics (FELIX v2.x)



- 6 EBDC server
- 3 Power Boards+ Supplies



– 48 Stave to RU cables



144 Fiber optic cables (3 fibers x 48 FEE)

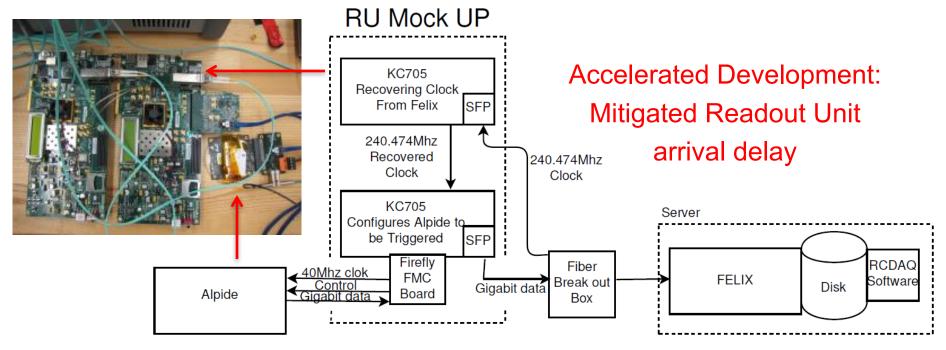


Spares at ~20%



# **R&D** Accomplishments





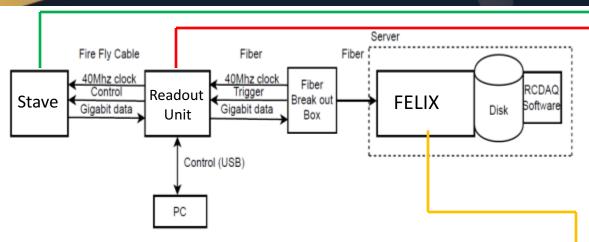
While RU (Readout Unit) was not available:

- Designed system to emulate RU on Xilinx Development Kits
  - ALPIDE triggered and read out at 15kHz, 448 hits
  - Developed prototype RCDAQ plugin
  - FELIX packs and places ALPIDE data on disk



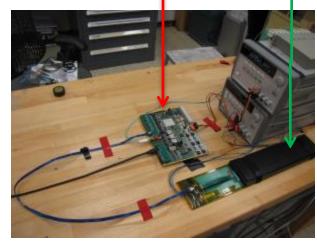
## **MVTX Full Chain**







- Once the Readout Unit arrived, successfully configured, triggered and readout Stave:
  - Readout Unit configures Stave using USB interface
  - FELIX distributes clock to Readout Unit
  - Readout Unit distributes clock to the Stave
  - Stave is triggered, sends data at 1.2Gb/s
  - Configured GBT link to recover clock from FELIX
  - Readout Unit receives the data and sends the data to FELIX over fiber using GBT link
  - FELIX packs data, stores it on disk using RCDAQ



Readout Unit + Stave



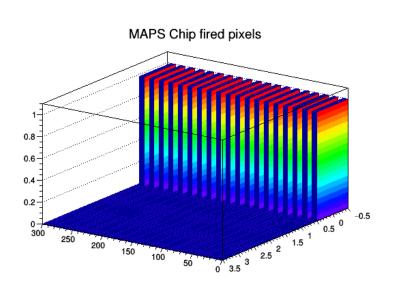
Server + FELIX

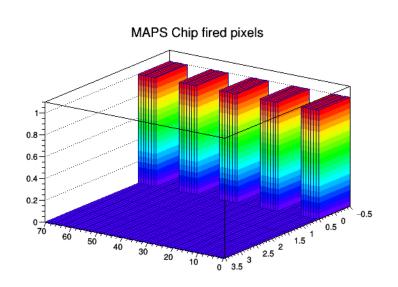


## **RCDAQ**



- RCDAQ = sPHENIX DAQ
  - Our accomplishments of integrating FELIX with RCDAQ prove that MVTX should tie into sPHENIX day one.
  - Plots generated by RCDAQ show pulsed Pixels readout by Readout Unit and FELIX





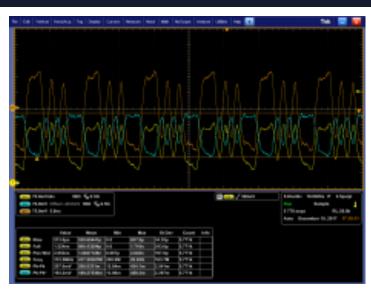
Full MVTX Readout Chain integrated with sPHENIX DAQ



## **MVTX Stave-RU Extension**







5 Meter

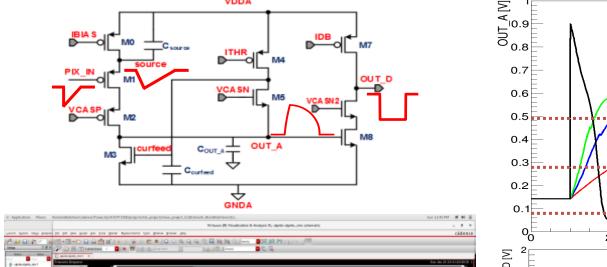
7 Meter

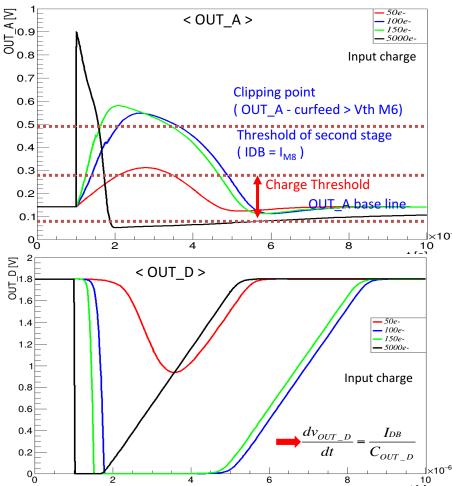
- Flex Cable Manufacturer Identified
- Signal Integrity of the longer Stave-RU interconnect cable for the MVTX mechanical configuration including overall length and necessary data output rate is under evaluation
  - Confirmed Default ALPIDE Data Transmission Settings are not suitable for cable lengths over 5m
  - 2 electronics options
    - Increase ALPIDE Drive Strength
    - Increase ALPIDE Preemphasis

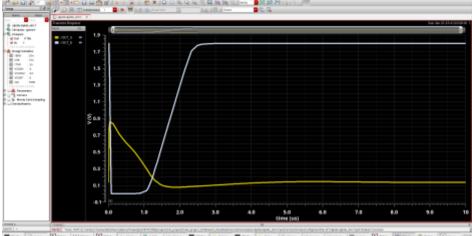


## **ALPIDE Simulations**









#### Need to Adapt ALPIDE Bias Parameters for use in MVTX

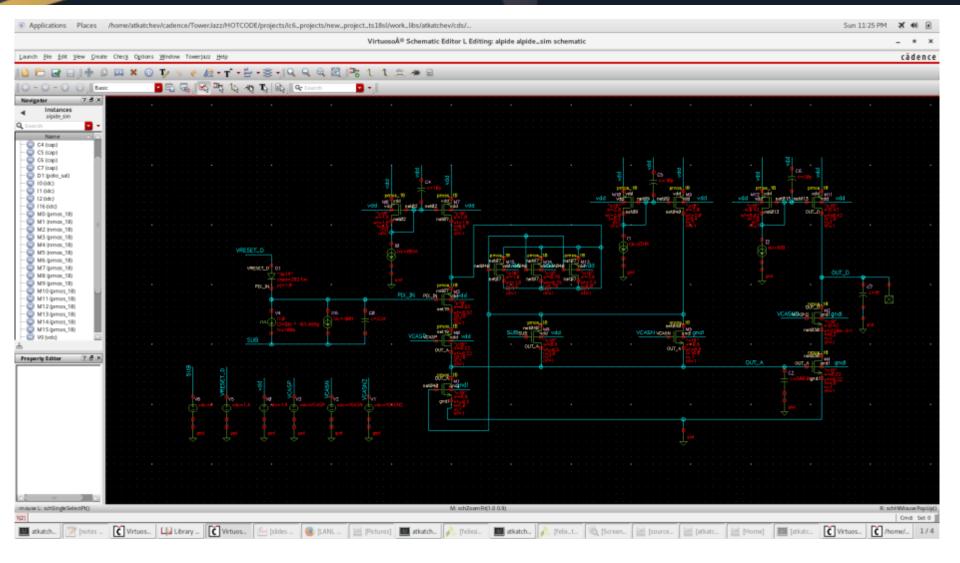
- Obtained evaluation license for Mentor Graphics Virtuoso
- Obtained technology files from Tower Jazz



Understood the effects of each Bias and Threshold Parameter on the output 129

# **ALPIDE Sim. Schematic**

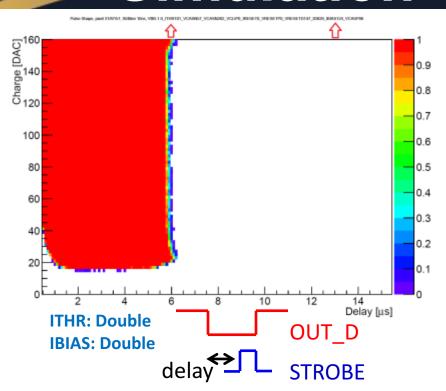


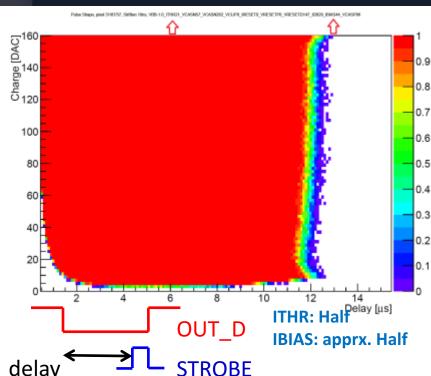




# Simulation Confirmation







- Pulse Shape Measurement with Charge Injection
  - Pulse Shape is measured by moving the timing of the (small) trigger window with respect to the injection time ("strobe delay")
  - Values extracted from 2D-measurement vs charge and trigger timing:
    - Time over threshold, maximum pulse length, time walk
- Creates a baseline for laser test stand efforts



# Risk Mitigation



#### Risks:

#### Previous LDRD Review

- Custom Electronics concerns
- CRU FELIX finalization

#### **BNL Directors Review**

 MVTX readout scheme integration into sPHENIX DAQ



#### **Achievements**

- Successfully demonstrated full readout chain:
  - STAVE->Readout Unit->FELIX
- Successfully integrated readout chain with RCDAQ (sPHENIX DAQ)
- Validated FELIX and Readout Unit performance for MVTX
  - System triggered at 15Khz
  - emulating 8 RU's on FELIX
- Power System at LANL





# **Future Deliverables**



- ALPIDE Characterization & Cluster Size Finalization
- ALPIDE Triggered & Continuous Modes
- Remote Readout Unit programming (over fiber)
- Readout Unit Radiation Upset (Scrubbing) Firmware
- FELIX programming (over PCIe)
- FELIX firmware revisions to adapt MVTX detector specs.
- RCDAQ (sPHENIX DAQ) finalization
- Signal Integrity evaluation of the longer Stave-RU interconnect for MVTX
- System Optimization & Documentation

Most tasks are well underway









# MVTX prototype and tracking tests

Sho Uemura P-25



## Goals for the MVTX prototype

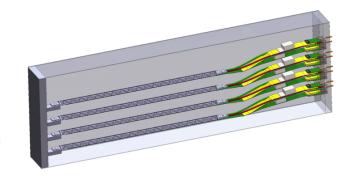


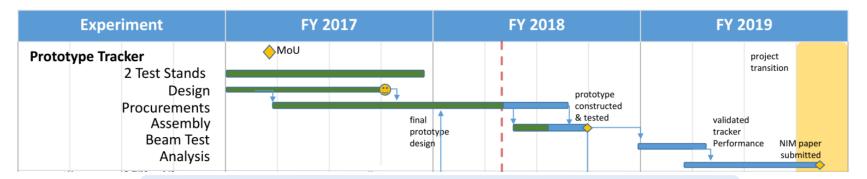
#### Prove the MVTX design meets physics requirements:

- Measure position resolution and hit efficiency
- Validate simulations of multiple scattering and cluster size
- Validate clustering, tracking, and alignment algorithms on real data
- Verify the full MVTX readout chain

#### **Deliverables:**

- MVTX prototype (the "telescope") with single sensors or staves, and full readout chain
- Beam test measurements validating the MVTX design





We have the hardware and readout: now we are ready to meet these goals in the next months

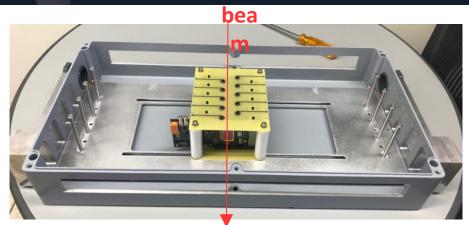


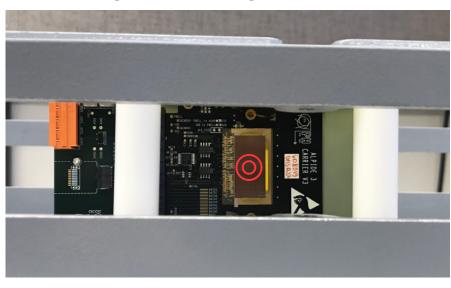
## **MVTX** prototype box

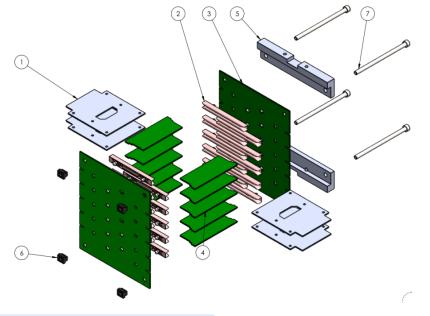


# One versatile box for different configurations

- Mounting hardware holds ALPIDE sensors or staves
  - O We will run with three ALPIDEs and one HIC (unmounted stave)
- Windows for beam test, cable feedthroughs, air cooling vents









### **Testing program**

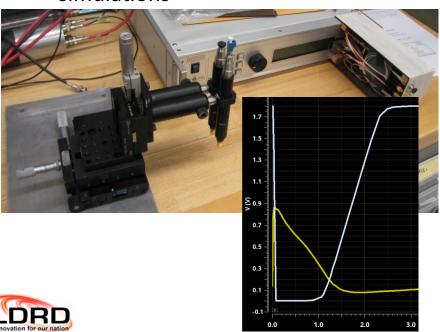


#### **Cosmic rays**

- Efficiency and resolution
- Preliminary alignment

#### Laser pulser

- **Optimize ALPIDE** parameters
- Validate ALPIDE simulations





#### **Beam tests**

- Large samples of clean tracks: precision alignment
- Momentum dependence
- High rate/high occupancy
- Integration with other sPHENIX subsystems



Beam tests are not essential, but very useful



#### 2018 beam test



#### **Fermilab Test Beam Facility**

- 120 GeV primary proton beam, 1-60 GeV secondary particles
- Great infrastructure: motion tables, cabling, trigger detectors

#### sPHENIX beam test

- Primary sPHENIX goal: test performance of the EMCal and HCal (month-long test program)
- ●The sPHENIX silicon detectors (MVTX and INTT) are opportunistic users: calorimeters are off March 6-9, INTT and MVTX will get beam



Ahead of schedule thanks to rapid progress on readout and prototype, and our good relations with sPHENIX

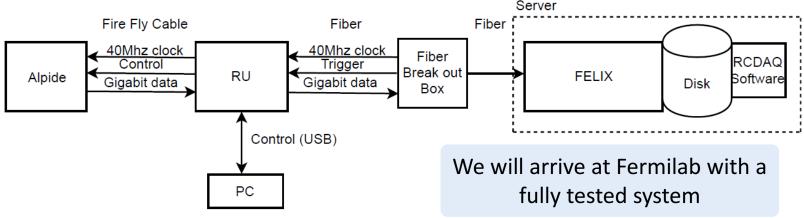


## 2018 beam test: preparations



#### Same proven readout chain

- Single Readout Unit for whole MVTX prototype
- Control PC in beam enclosure: control power supplies, program and control Readout Unit
- DAQ server in control room: fiber link to the RU, network gateway to the outside
- Bench test: run full readout chain using 53 MHz clock and scintillator trigger, exercise the monitoring – just like at Fermilab



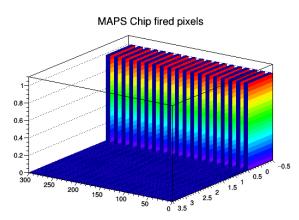


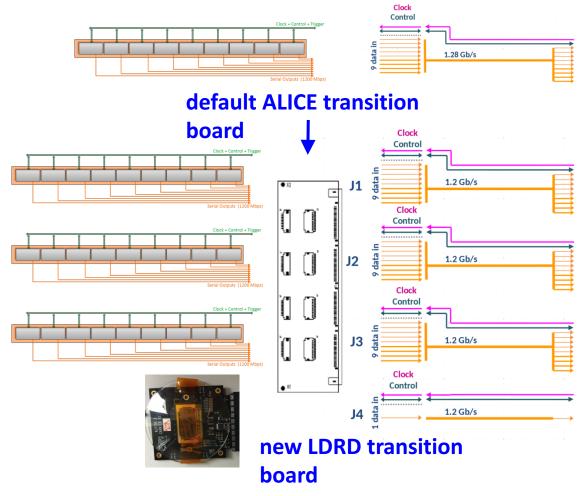
## 2018 beam test: preparations



# Development for the beam test

- New transition board supports four layers instead of one
- Clock and trigger: ready for test with 53 MHz clock and scintillator trigger
- Online decoding and monitoring using sPHENIX framework





Moving from development system to production



## 2018 beam test: schedule and run plan Los



#### Schedule

- Pack and ship week of Feb. 12
- Arrive Feb. 19, install Feb. 21, safety walkthrough Feb. 22
- Return March 3, ready for beam
- Expect INTT/MVTX joint beam time March 6-9 (nights)
- Uninstall and ship, return March 13

#### **Goals and stretch goals**

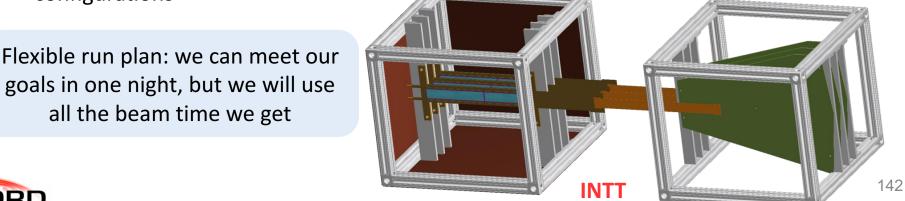
INTT is the primary user during our beam time: they are upstream of us and they request the beam: secondaries at 2 and 8 GeV, protons at 120 GeV

Main goal: 1-hour runs for each beam type (100k-1M tracks)

If possible: high occupancy run, latency scan, off-normal incidence, different ALPIDE

configurations

goals in one night, but we will use all the beam time we get



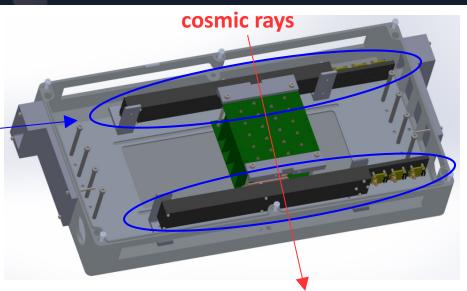


## Future studies and beam tests



#### **Cosmic ray telescope**

- After the Fermilab beam test, use the prototype with cosmic ray muons and SiPM-based trigger boxes
- Switch to staves when available, test cooling and power
  - "Full goal" of a 1/10 slice of MVTX including support systems



#### Goals for a second beam test

- We will join 2019 sPHENIX beam test, or schedule dedicated MVTX beam time
- We will have staves, not single chips
- sPHENIX trigger will be better defined, allowing DAQ integration between subsystems
- MVTX readout will be feature-complete, ready for readout stress tests



Prove a full system with complete software, firmware, and hardware - ready for the transition to MVTX

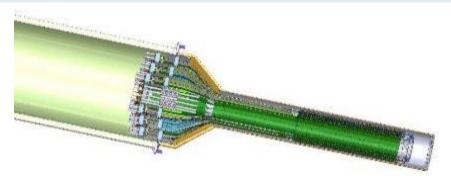






# sPHENIX LDRD Review MVTX mechanical conceptual design

Walter Sondheim P-25





#### **sPHENIX** experiment - MVTX Detector:



#### **MVTX** mechanical conceptual design:

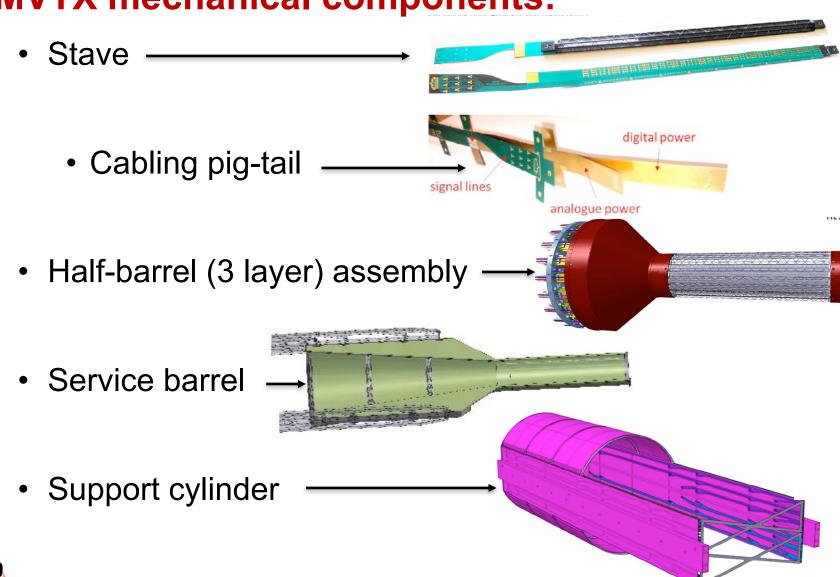
- Personnel involved:
- Walter Sondheim, P-25,
  - mechanical and integration engineering
- Christopher O'Shaughnessy, P-25,
  - mechanical engineer, physicist,
    - Focusing on MVTX telescope and cooling
- Hubert Van Hecke, P-25,
  - Physicist,
    - Prototype construction
- David Lee, P-25,
  - Physicist,
    - "Project" file management



#### **Outline:**

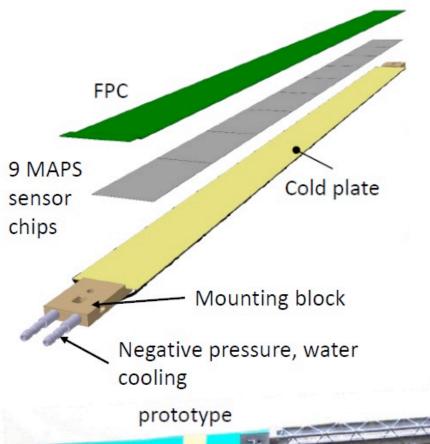


MVTX mechanical components:



#### **MVTX** tracker stave:





#### Stave assembly consists of:

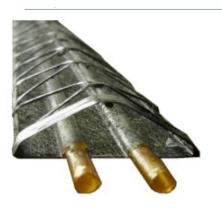
- One layer with 9 MAPS chips
- One thermally conductive carbon cold plate – space frame
- One carbon filament truss structure
- One flexible printed circuit (FPC) that is wire-bonded to the MAPS chips
- Bonded assembly





#### **MVTX** stave cooling:





Coolant: negative pressure single phase H<sub>2</sub>O
Pixel chip operational temperature < 30°C
Pixel chip max temperature non-uniformity < 5°C
Pixel chip (Alpide) power dissipation < 41 mW/cm<sup>2</sup>

Space Frame

Total power dissipation: 184.5 mW/chip X 9 chips per stave X 48 staves in the MVTX assembly = 79.7 Watts



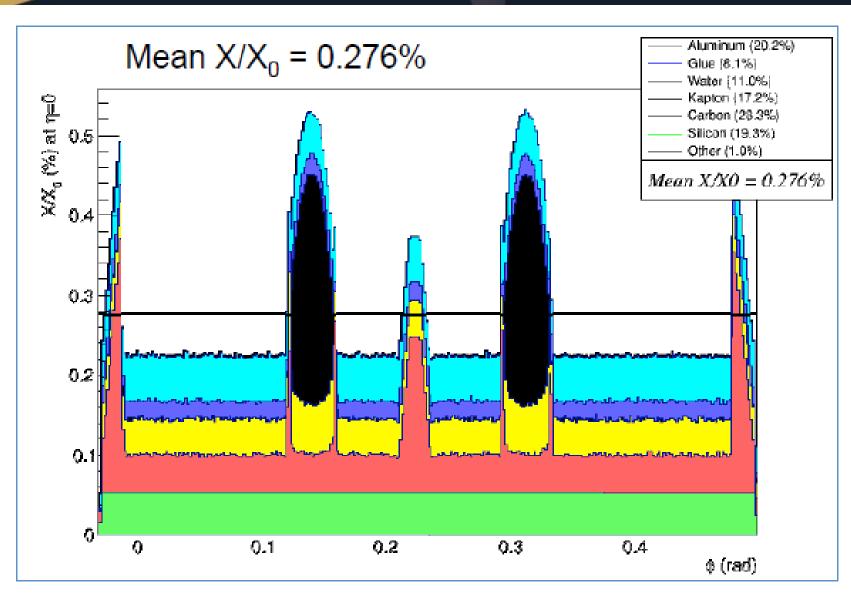
Full length cold plate assembly 290 mm, mass 1.7 gms. Full stave assembly, chips, FPC, cold plate mass 15.1 gms.

MXTX inner tracker stave cooling and support plate:



#### **MVTX** stave radiation length:



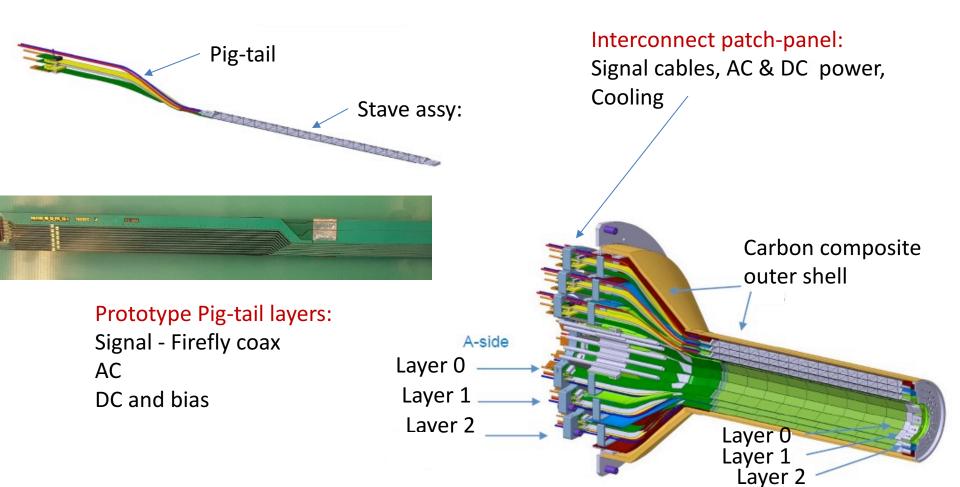




#### **Half Barrel Service Interconnect:**



#### **MVTX Services and Cabling and Cooling lines:**





Cooling: negative pressure water, plus dry air (nitrogen) flow

#### Composite technology demonstrated:



#### **Carbon composite production pieces:**





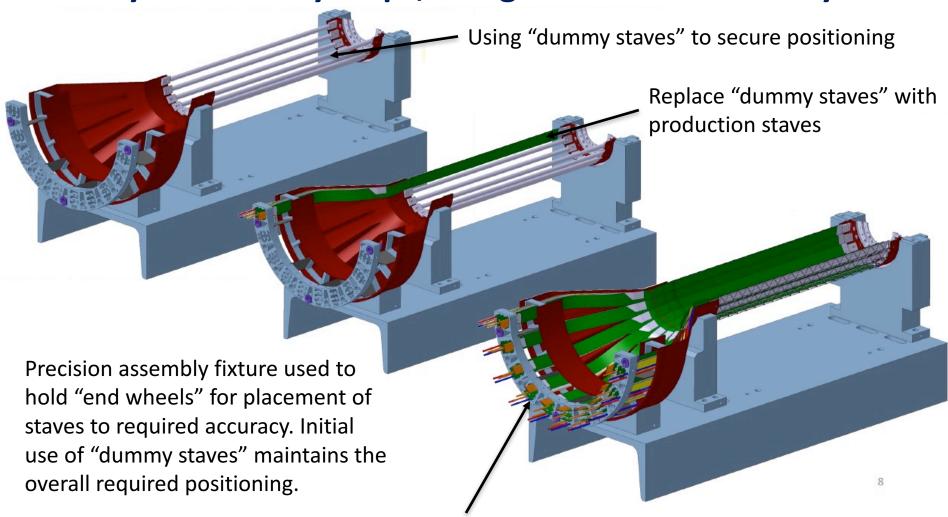
These composite prototype parts made at CERN, similar to ones needed for MVTX detector:



#### **MVTX** layer assembly steps:



#### MVTX layer assembly steps, using fixtures and dummy staves:



Stave "pig-tails" mounted in patch panel



#### **sPHENIX MVTX Detector:**



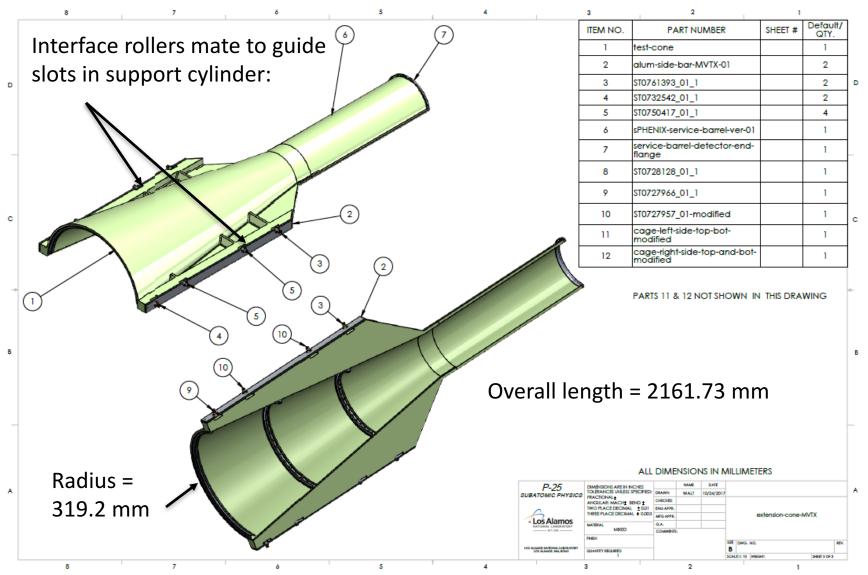
#### **MVTX** cabling configuration:

- Quantity (approximate): 48 staves x 5m = 240m
- Configuration:
  - 2x twisted pair sense wires (one each for analogue and digital)
  - 2x 0.283mm<sup>2</sup>, low inductance analogue supply (alternative: 0.155mm<sup>2</sup>)
  - 2x 1.500mm², low inductance digital supply (alternative: 0.750mm²)
  - 1x Coax RG178 analogue bias voltage (similar to Article No 30000-178-1) (OD= 1.8 ±0.1mm)
- Connection split into two layers for digital and analogue conductors



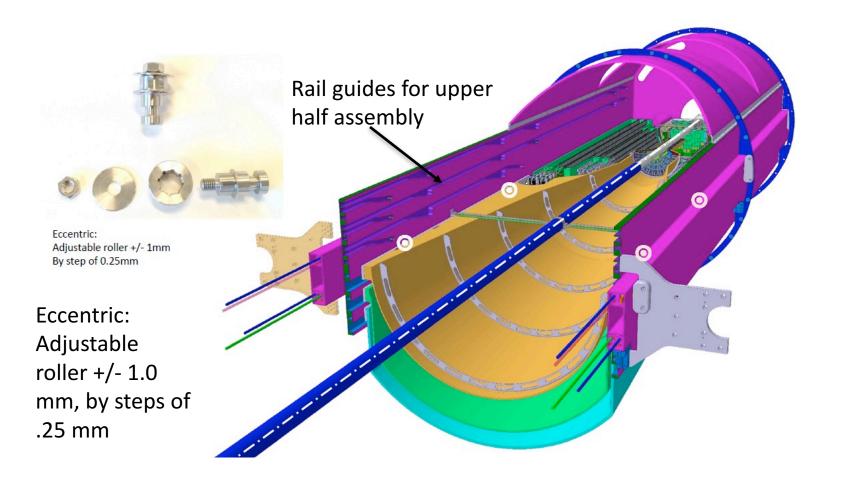
#### MVTX composite service barrel:





#### Possible MVTX installation cylinder:



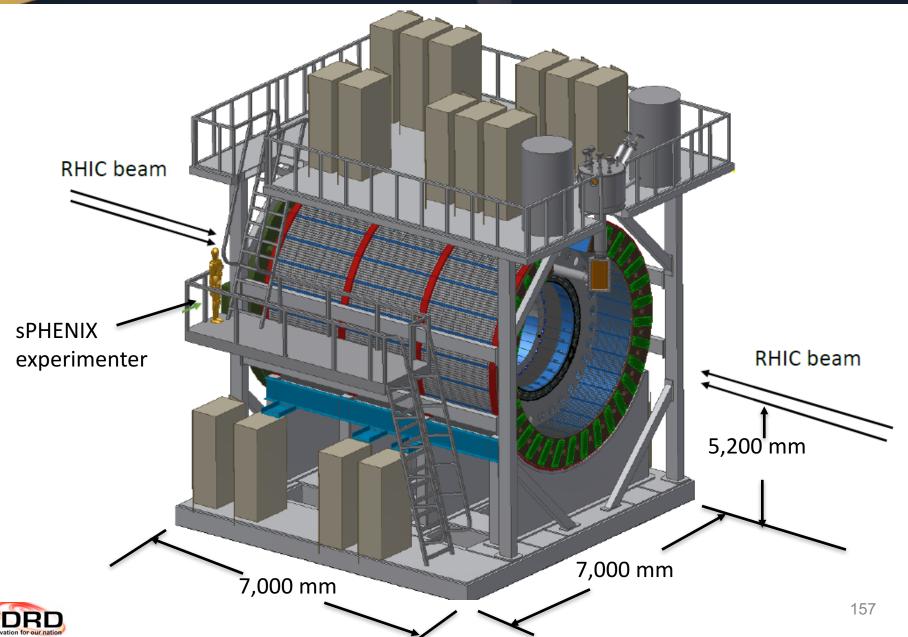


In sPHENIX we will not use a "service cone, rail system" anywhere near the size of that planned for the ALICE detector (shown here), but we will integrate their concept.



#### sPHENIX experiment CAD model:

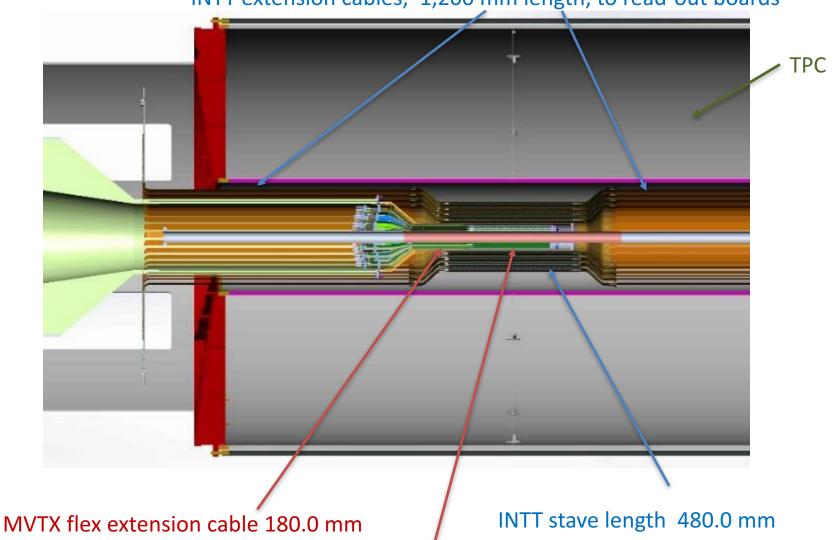




### MILESTONE: MVTX mechanical system conceptual design completed:



INTT extension cables, 1,200 mm length, to read-out boards



MVTX stave length 280.0 mm



#### **Milestones** & integration issues:



- Milestones continued:
  - Modified model to be compatible with sPHENIX tracking detectors and beam-pipe, installation plan
- The current design for the INTT detector does not have a support structure or additional services, power & cooling.
- There is interference between the INTT extension cables and the conical region of the MVTX ("Z" locations)
- Because of the different radial dimensions between the beam-pipe in ALICE and the beam-pipe in sPHENIX, each of the three MVTX layers needs to be moved outward in radius by .75 mm.
  - This translation will *still* allow each layer to be hermetic
- Continuation of integration issues will be taking place with all of the sPHENIX tracking detector systems: TPC, INTT & MVTX by the formation of a sPHENIX tracking integration task force.

**UNCLASSIFIED** 





#### Back-up:





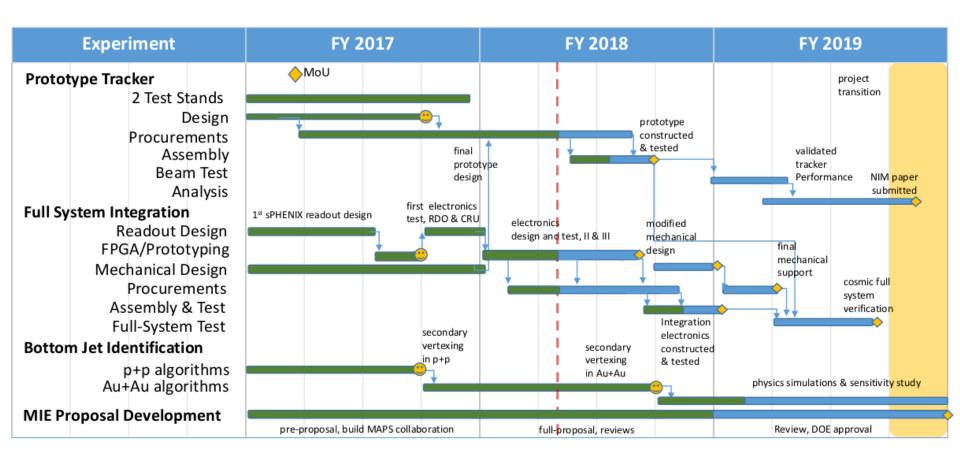
# Summary and Transition Plan

Cesar Luiz da Silva P-25



#### **Transition Plan**



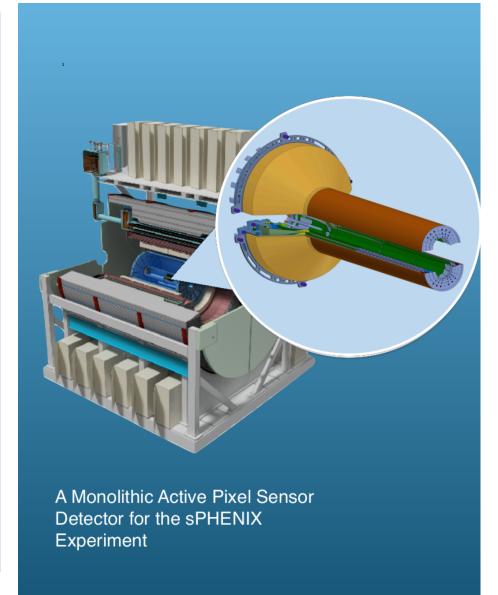




#### **Proposals to DOE**



- Pre-proposal submitted to DOE in February 2017
  - Physics goals
  - Detector concept
  - Estimated cost and schedule
- Wrote a full proposal, submitted to BNL ALD in January 2018, including
  - Detail cost, schedule, contingencies
  - More detailed detector concept
  - Expected performance
  - Simulations
  - Expansion of the physics program

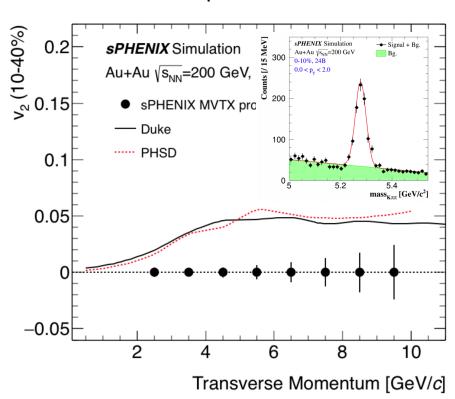




## Two Main Physics Topics added do sPHENIX Program

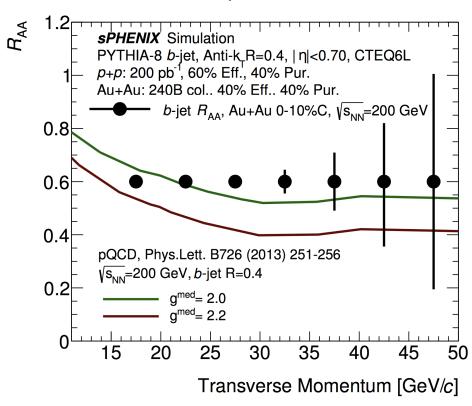


#### Low p<sub>T</sub> B-Meson



Probe QGP coupling, HF diffusion with Bhadrons.

#### High p<sub>⊤</sub> b-jets

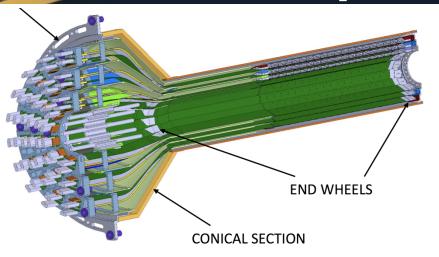


Probe the QGP microscopic structure with b-quarks.



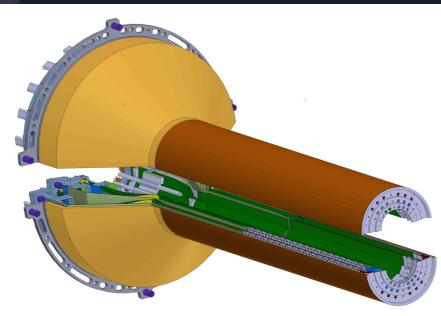
#### The Proposed MVTX Detector





	Layer 0	Layer 1	Layer 2
Radial position (min.) (mm)	23.7	31.4	39.1
Radial position (max.) (mm)	28.0	35.9	43.4
Length (sensitive area) (mm)	271	271	271
Active area (cm <sup>2</sup> )	421	562	702
Number of pixel chips	108	144	180
Number of staves	12	16	20





Key element	Deliverable
1	MVTX mechanical support interface to sPHENIX global rail frame
2	3-layer MVTX detector: R coverage 23 - 40 mm, 270mm in Z
	48 staves total, with each stave contains 9 ALPIDE sensor chips
	layer-0: 12 staves
	layer-1: 16 staves
	layer-2: 20 staves
	one RU per stave, total 48 RUs; 10 spare RUs
3	6 backend PC, hosting 6 FELIX boards; 2 spare FELIX boards
4	Two clam shells, with 3 MVTX layers integrated and aligned on each clam shell
5	36 tested staves to serve as spares and replacement components to allow for
	any needed repairs to the existing sectors of the MVTX detector,
	including complete replacement of the two inner most layers (28 staves)
6	Low voltage, Bias Voltage, Cabling and Cooling
7	A PC-based control and monitoring system

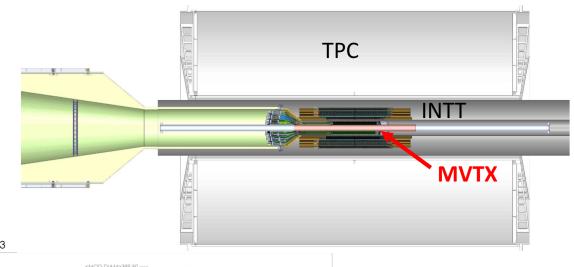


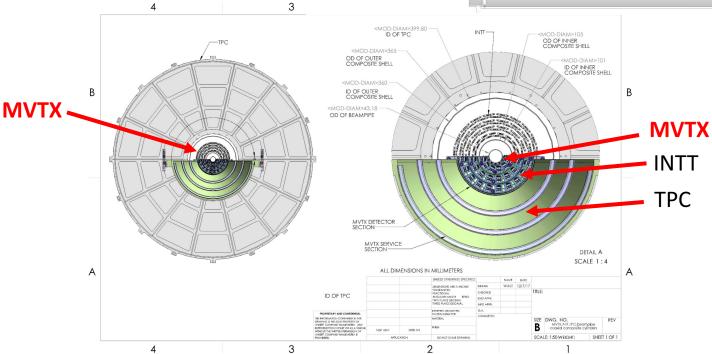
#### Integration with sPHENIX tracking

Los Alamos NATIONAL LABORATORY EST. 1943

Mechanical conceptual design stage.

Regular discussion with MIT and BNL on the integration with sPHENIX baseline tracking system: INTT and TPC.

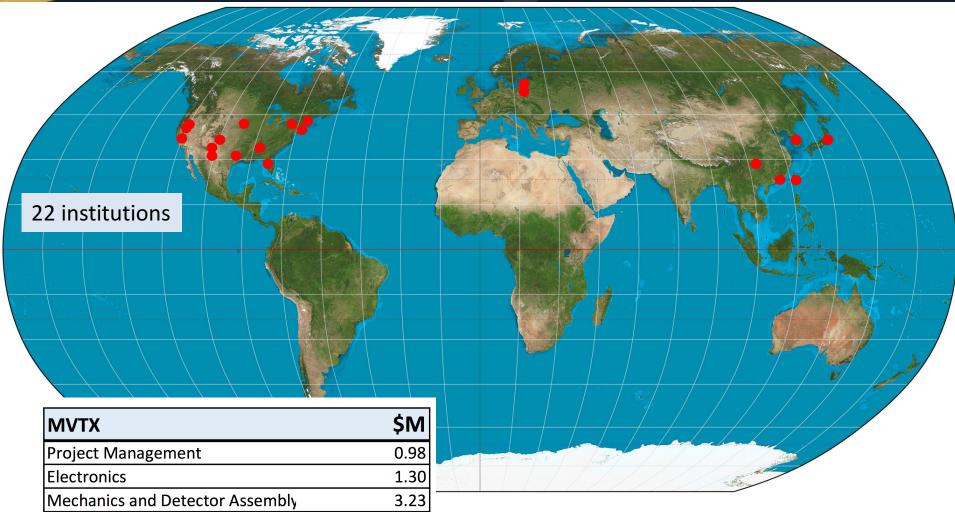






#### **MVTX Collaborators and Cost**





35% contingency



Integration and Infrastructures



TOTAL

Stave production at CERN starting immediately

after the end of the ALICE production.

1.02

6.54

#### **DOE Response to the MVTX Pre-Proposal**



From email by BNL Associated Lab Director on the response of DOE Nuclear Science on the MVTX pre-proposal sent on December 19th:

"Tim Hallman assured me that [DOE] appreciate the **compelling science this instrument could enable** and why it is considered very important to the sPHENIX experiment by the collaboration."

[Hallman] "informed me given their present budget outlook, whatever is accomplished for sPHENIX will have to be achieved in the context of flat base funding for RHIC and/or with foreign contributions."

DOE "very much appreciate and encourage efforts to secure such contributions, but unfortunately in our present outlook, we do not foresee at this time that we would be able to identify new DOE funding for the purpose of implementing the MVTX"

ALD commented that guidance is informed by **flat-flat budget** outlook for the rest of the decade.



#### **Funding Options**



#### At least two options for funding:

- sPHENIX baseline funding
  - The original idea to incorporate the cost of MVTX in the RHIC operation savings
  - Despite the tight budget for sPHENIX, it is expected a significant reduction of contingencies once purchases start to be executed.
     One example: sPHENIX management is now actively working on the purchase
    - of steel for the Hadronic Calorimeter in order to eliminate its large contingences to be used for MVTX.
  - Foreign collaborators demonstrated interest in funding parts of sPHENIX
- Better scenario for DOE/OS budget
  - Current expectation of flat-flat budget for the next two FYs is not confirmed yet
  - A scenario with DOE funding starting in FY20-21, once this LDRD is concluded and many of current contingences are reduced, is also possible

This situation is familiar to the team, same happened to the successiful PHENIX Muon arms and FVTX projects.

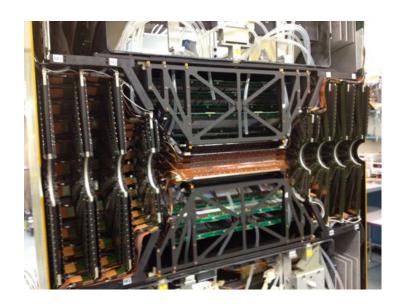


#### **A Little Bit of History**



This situation is familiar to the team, same happened to the successful PHENIX Muon arms and FVTX projects.





Regardless the funding option, this LDRD is essential to guarantee the MVTX design will be ready to bring this new exciting physics to sPHENIX.



#### **Stave Production at CERN**



- There will be enough ALPIDE chips for MVTX after ALICE ITS conclusion
- After conclusion of ALICE ITS, CERN will start to produce staves for a copy of the ALICE ITS for NICA experiment (Russia)
- Stave production facility and specialized personal will be available at CERN until at least 2020 for NICA production and other possibilities (MVTX)
- Meanwhile, we plan to send LANL postdocs and staff to the stave assembly facilities at CERN to obtain experience on this novel technology
- CERN is still in the first steps for totally automated stave production, a future production for MVTX will leverage this expertise



#### Conclusions



- The members of this LDRD lead the writing of a pre-proposal, submitted to DOE, and a full proposal, to be sent to BNL ALD, for the final MVTX detector for sPHENIX
- In the current status of the R&D, MVTX still has fairly large contingencies in some of the items, specially in the mechanical assembly and integration which is under discussion with LBNL, MIT and BNL
- DOE appreciated the compelling Physics that the MVTX can bring to the sPHENIX program, but cannot promise fundings until the budget forecast for DOE/OS improves
- Funding alternatives have started to be discussed, the most promising coming from the reduction of the sPHENIX baseline contingencies



#### **Conclusions**



- Stave assembly will continue and improve the automatization at CERN during the course of this LDRD, giving us time to find the funding for the final detector and still in the timeline of sPHENIX installation
- The recognition from DOE and BNL that MVTX can deliver the b-quark physics program to sPHENIX is an accomplishment of this LDRD. It is essential that this effort continue as scheduled

Thank You for Your Attendance!

