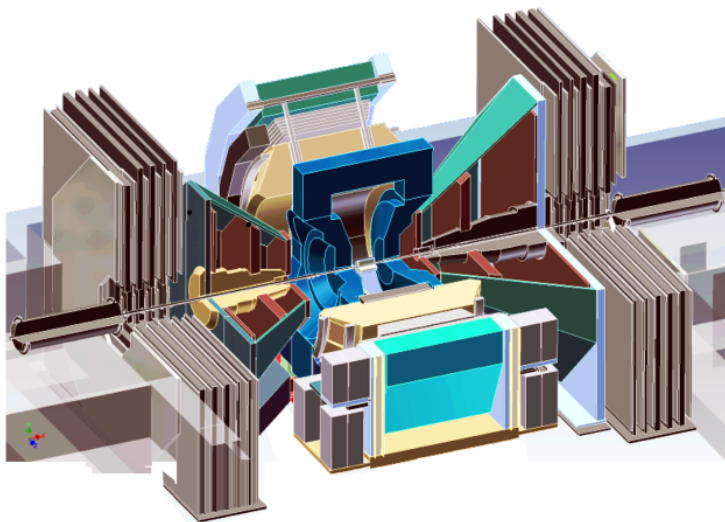


LANL Heavy Ion Physics Program at RHIC

With a long history of leading heavy flavor physics

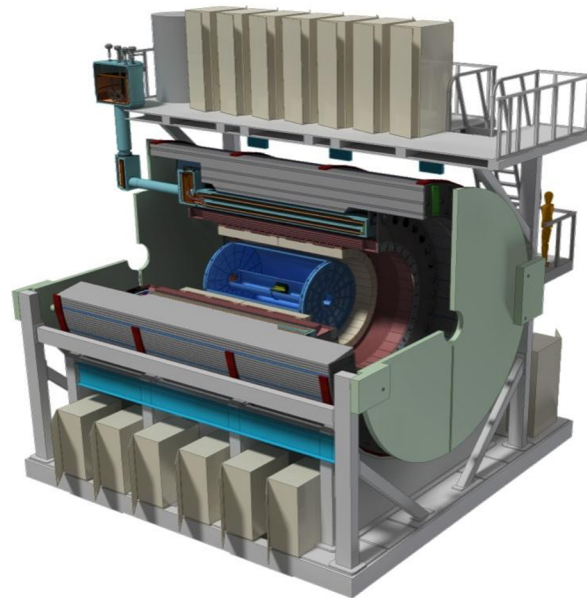
PHENIX physics: 2000->2016+

- Lead physics w/ muons
- MuTr completed: 2002
- FVTX completed: 2010



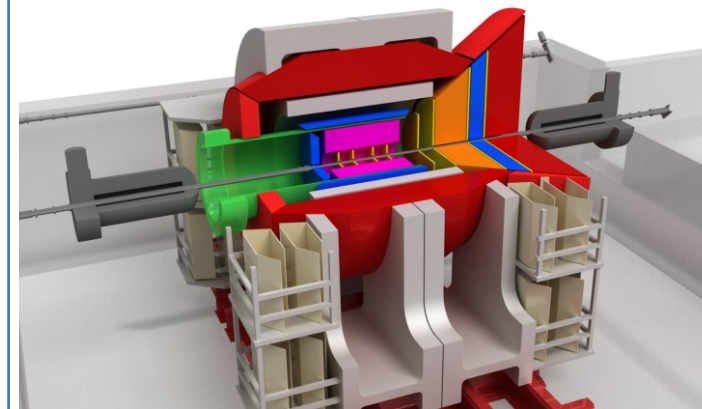
sPHENIX physics: 2023->2025+

- Lead HF Physics w/MVTX
- QGP, cold-QCD



EIC physics: ~2030

- Lead HF Physics
- Spin, gluon CGC/TMD



~2000

2016

~2025

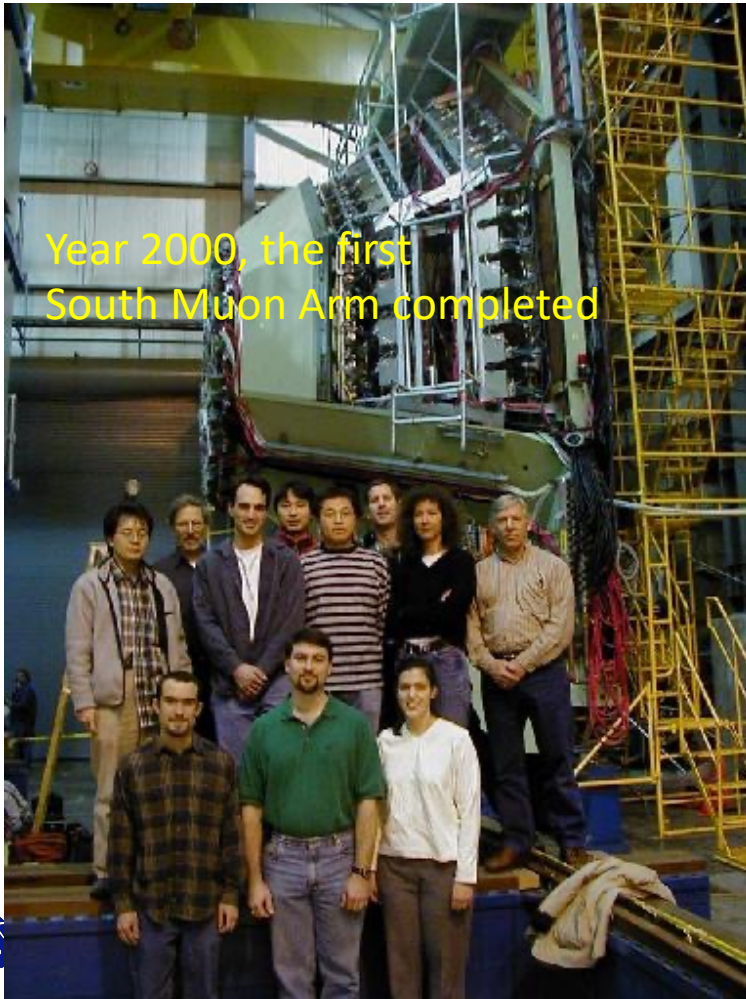


LANL-Led PHENIX Muon Trackers (20+ years, \$20M)

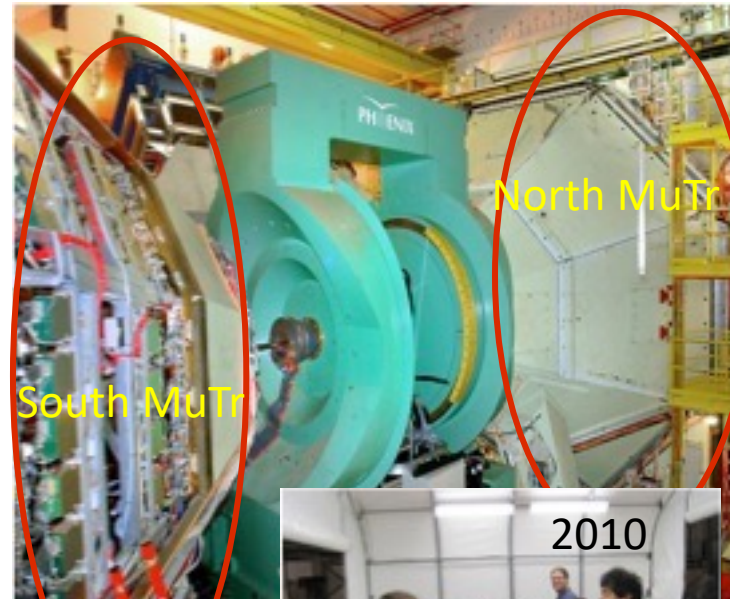
Muon Tracker Contributions - Designed, built, installed, commissioned two muon tracker systems

Responsibilities - DC Member, coordinate and perform maintenance and improvement

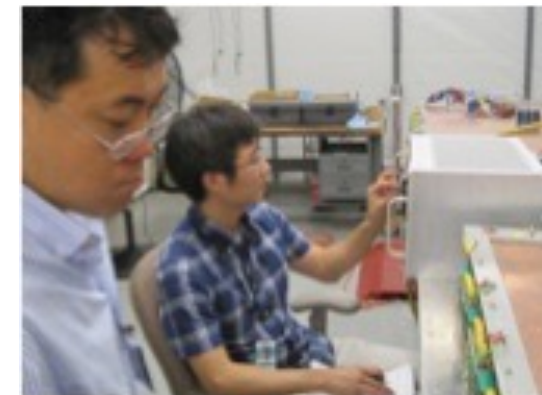
Muon Tracker Analyses - Have provided much of the simulation and reconstruction software, as well as online QA software for the Muon Trackers. **Lead roles in most muon physics analyses (QGP, CNM & Spin)**



Close collaboration with US, RIKEN/Japan and French Institutions



Ming Liu, Meeting with DOE



LANL-Led PHENIX FVTX Upgrade (10+ years,\$10M)

Started with LANL LDRD

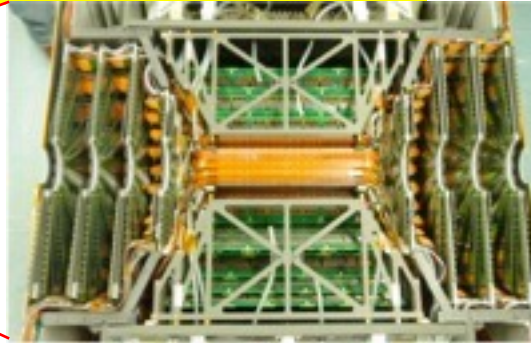
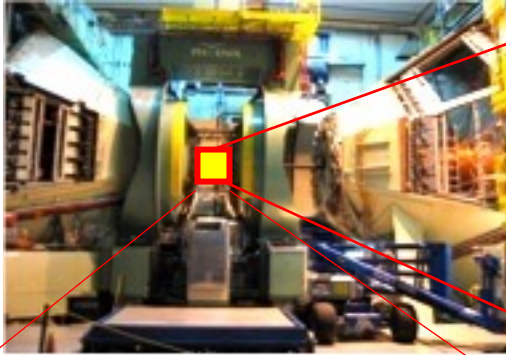
Commissioned and Took First Data in 2012 Run

Heavy Ion Physics - Heavy quark energy loss; QGP color screening; CNM effects

Spin Physics - Sea-quark and gluon polarizations; Transverse spin physics

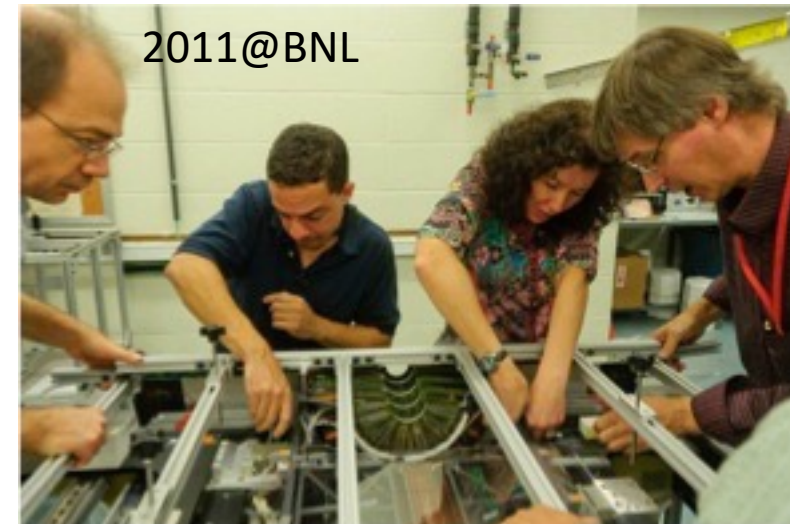
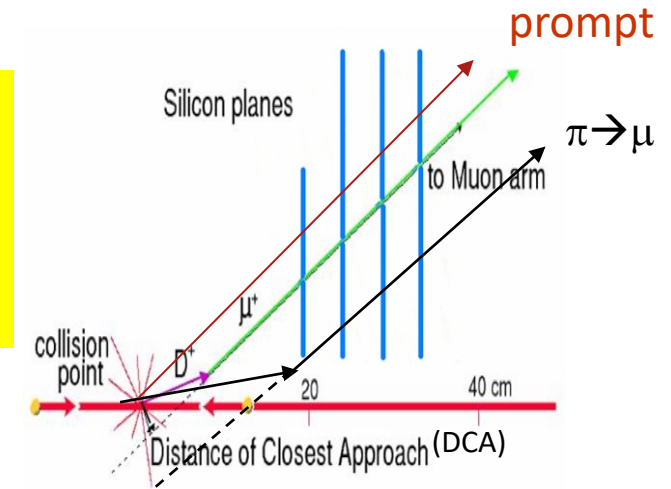
Produced many key physics measurements

Forward VerTeX Detector (FVTX)



New Tools:

- Open D, B
- J/psi and Psi'
- Drell-Yan
- W[±]



4/27/21

Ming Liu, Meeting with DOE

PHENIX Recent Highlights - I

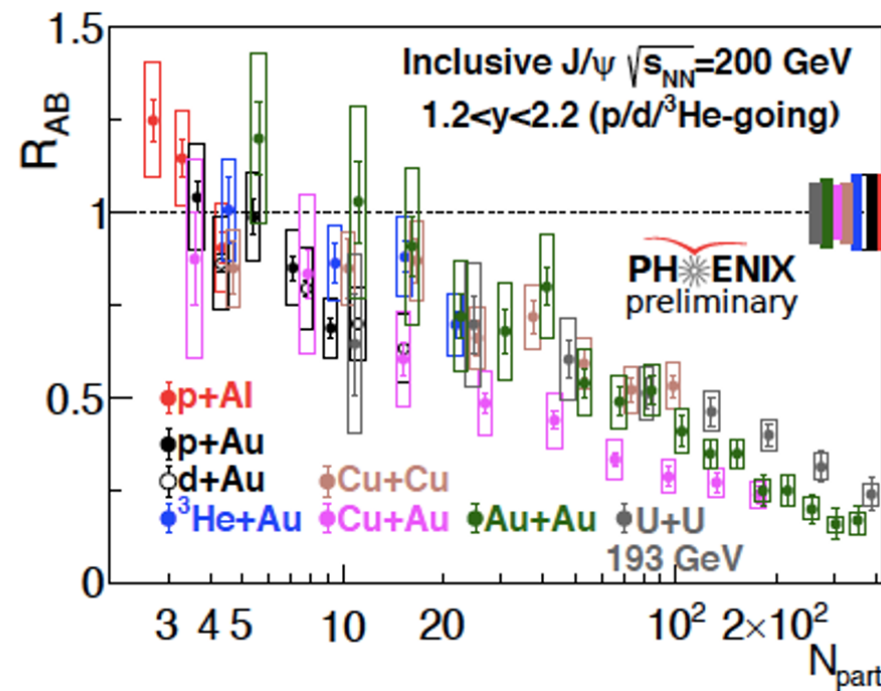
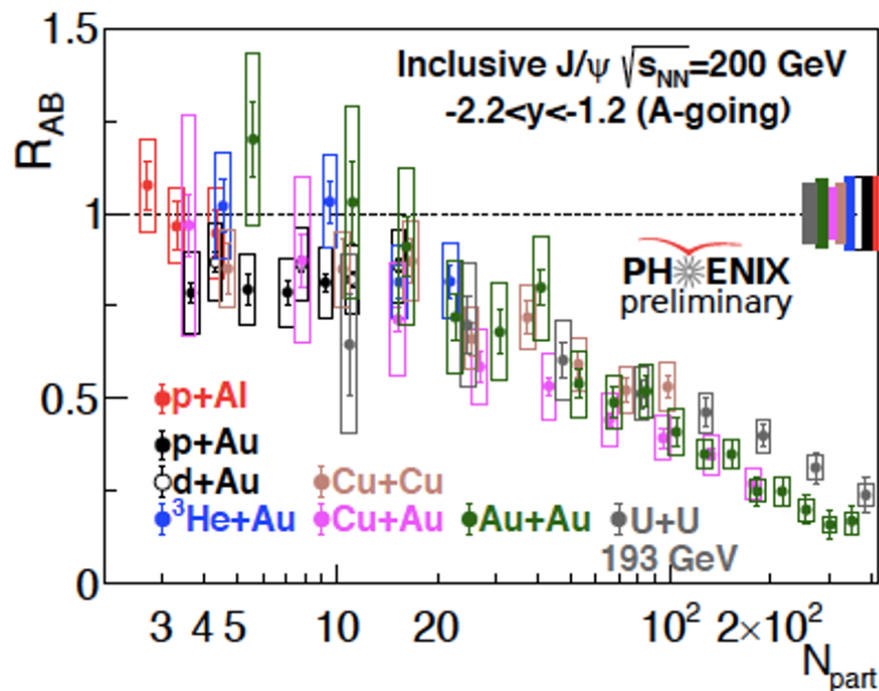
- PHENIX completed data taking in 2016, but physics analysis continues

News: 2 students coming to LANL to do analysis
FSU and Vanderbilt (DOE awarded)

Latest J/Psi nuclear-modification-factor R_{AB}

- From small p+p to large U+U collisions
- Forward and backward rapidity

Observed strong nuclear dependence in R_{AB}



Recent publications from muon analyses (LANL played major roles)

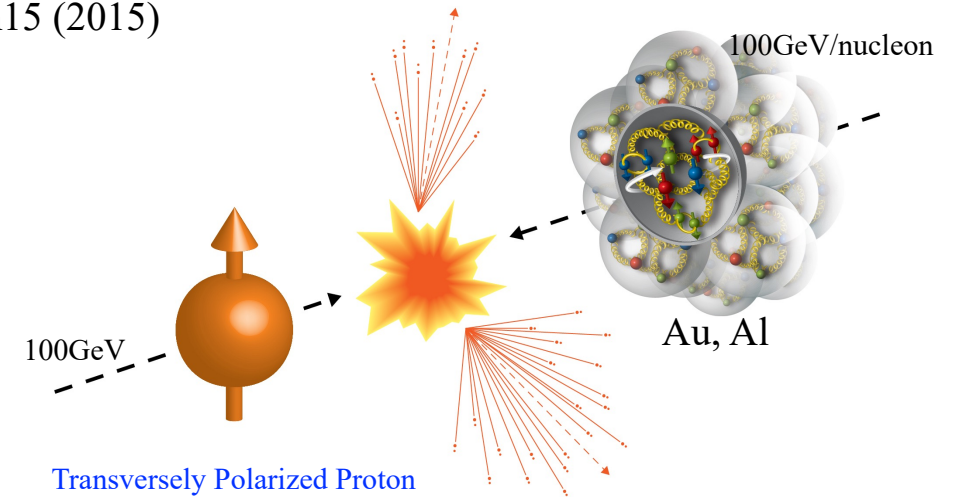
1. "Measurement of J/ ψ at forward and backward rapidity in p+p, p+Al, p+Au, and 3He+Au collisions at $\sqrt{s_{NN}}=200$ GeV", PRC (2020)
2. "Nuclear modification factor of charged hadrons at forward and backward rapidity in p+Au and p+Al collisions at $\sqrt{s_{NN}}=200$ GeV", PRC (2019)
3. "J/ ψ production at forward rapidity in pp collisions at $\sqrt{s}=510$ GeV", PRD (2019)
4. "Nuclear dependence of transverse single-spin asymmetry of charged hadrons at forward and backward rapidity in polarized p+p and p+Au collisions at $\sqrt{s_{NN}}=200$ GeV", PRL (2019)
5. "Measurements of muon pairs from open heavy flavor and Drell-Yan in pp collisions at $\sqrt{s}=200$ GeV", PRD (2019)
6. "Transverse Single-Spin Asymmetry in J/ ψ Production in Polarized p+p, p+Al, and p+Au Collisions at $\sqrt{s}=200$ GeV in PHENIX", PRC (2018)
7. "B-meson production at forward and backward rapidity in p+p and Cu+Au collisions at $\sqrt{s_{NN}}=200$ GeV", PRC (2017)
8. "Cross section and transverse single-spin asymmetry of single muons from open heavy flavor decays in polarized p+p collisions at $\sqrt{s}=200$ GeV", PRD (2017)
9. "Fraction of B-meson decayed J/ ψ measured in p+p collisions at $\sqrt{s_{NN}}=510$ GeV", PRD (2017)
10. "J/ ψ longitudinal double spin asymmetry measurement at forward rapidity in p+p collisions at $\sqrt{s}=510$ GeV" (2016)



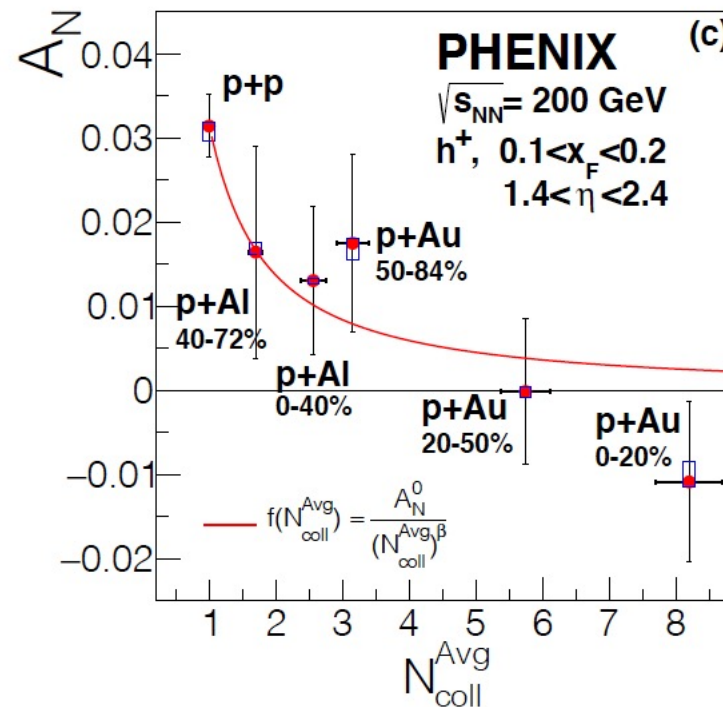
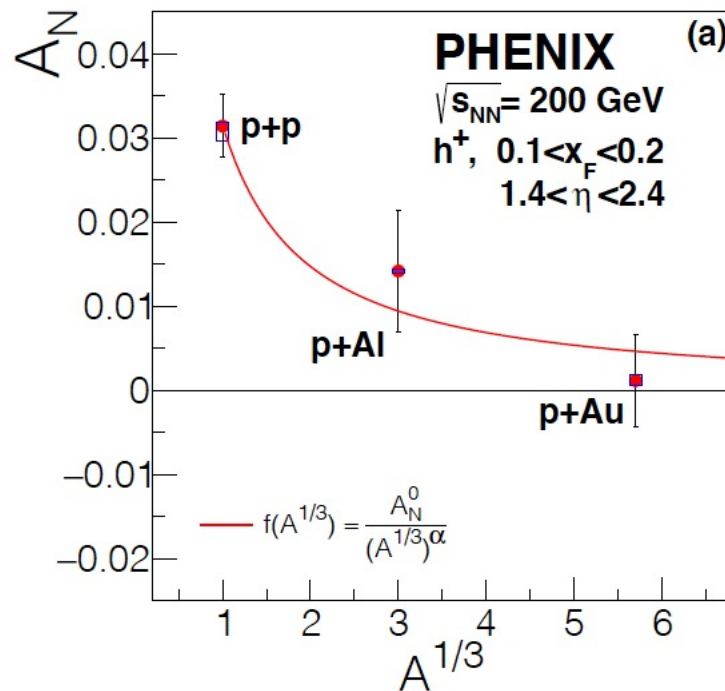
PHENIX Recent Highlights - II

Run15 (2015)

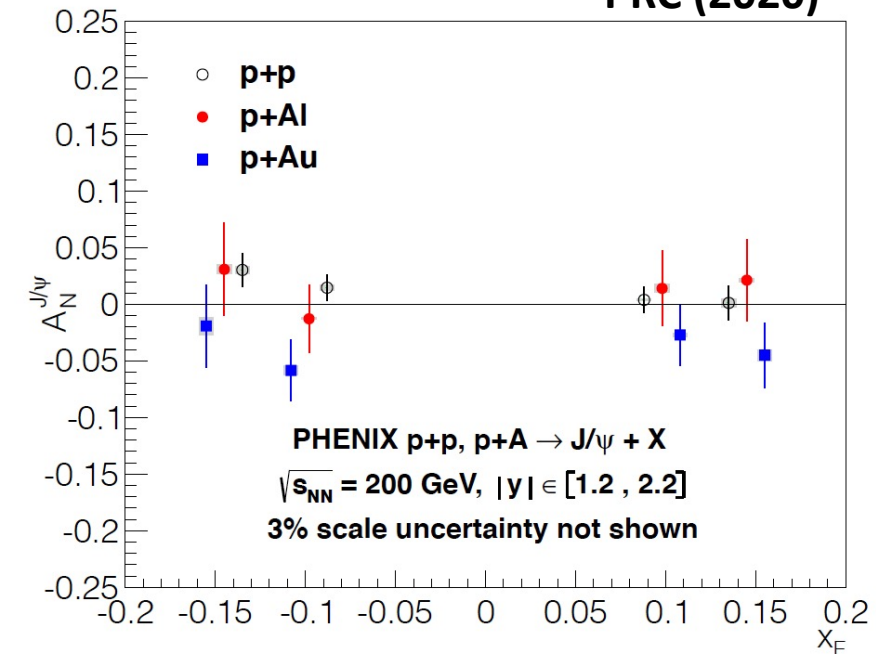
- Transvers spin to probe CNM in p+A
 - Forward hadrons with muon spectrometers
 - Forward and backward J/Psi
- Observed strong nuclear dependence in A_N



PRL 123, 122001 (2019)

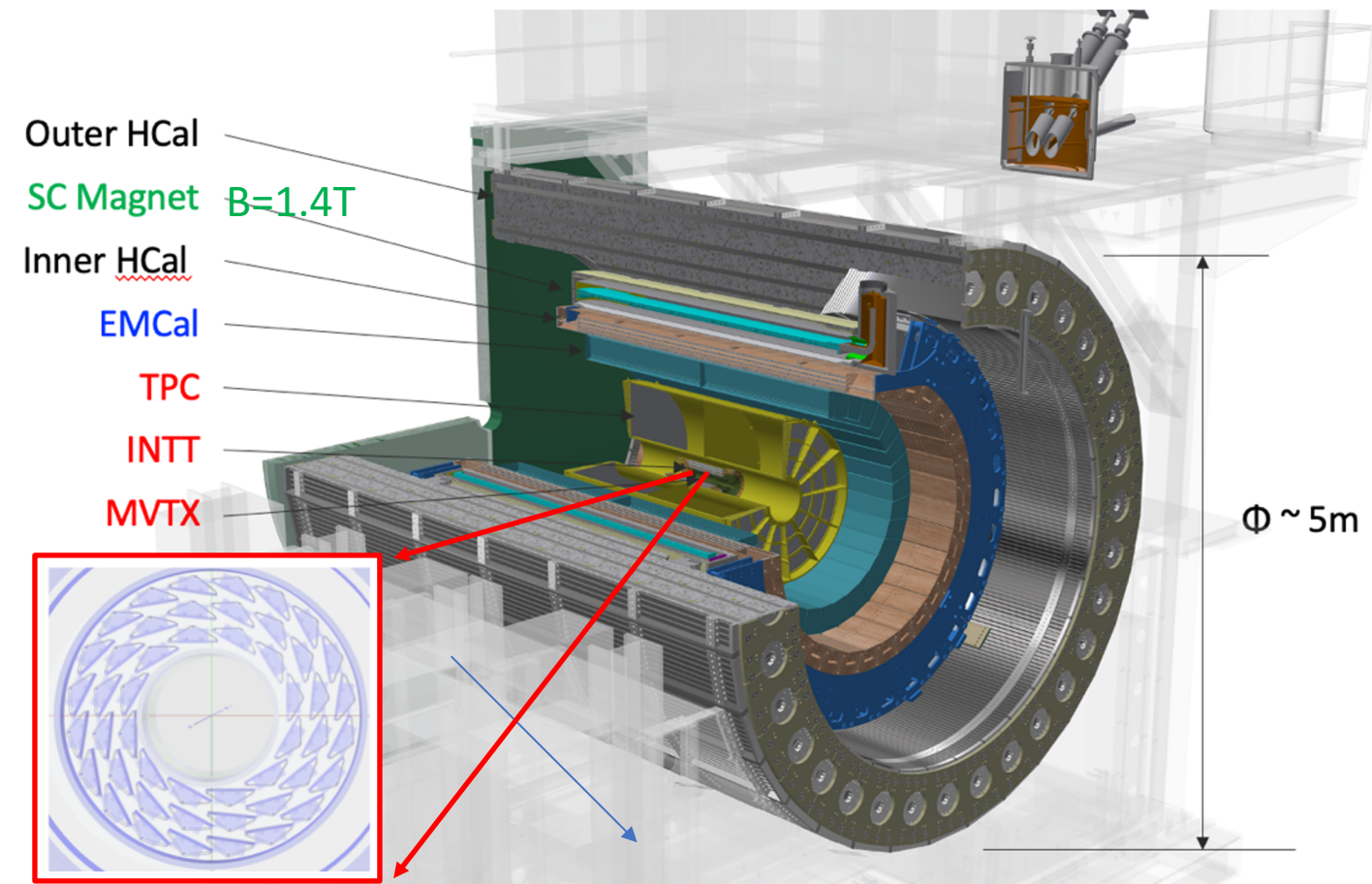


PRC (2020)



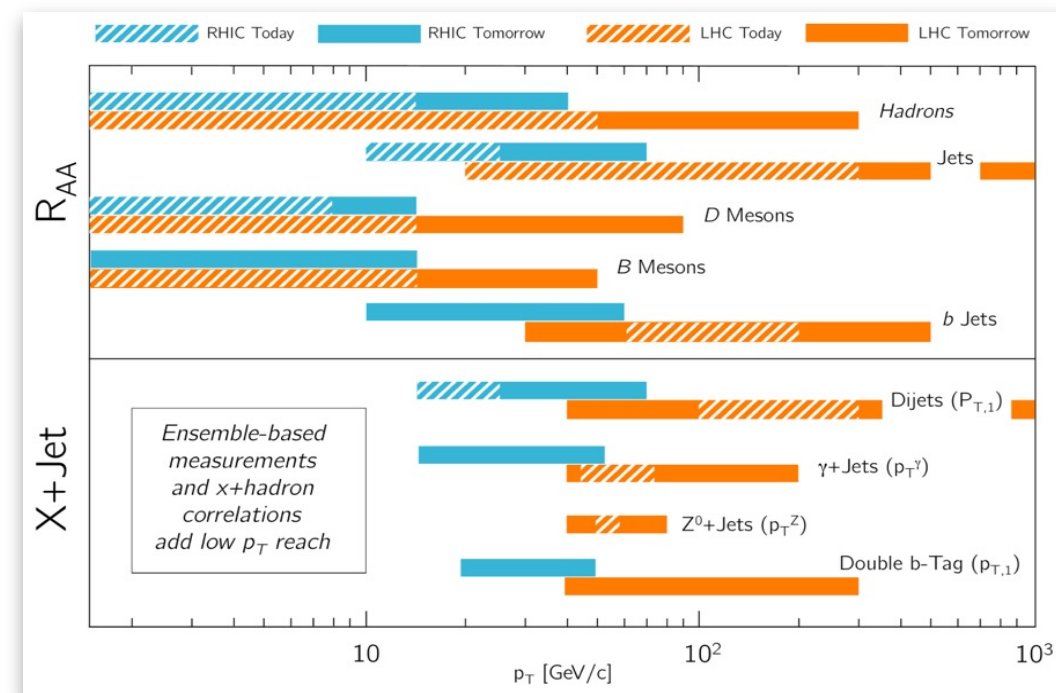
The sPHENIX Experiment: 2016 – 2025+

LANL's focus: Heavy Flavor physics with Monolithic-active-pixel-sensor-based VerTex detector (MVTX) upgrade



sPHENIX projections:

Complementary: RHIC vs LHC



Under construction, ready for day-1 physics 2023



4/26/21

Ming Liu, Meeting with DOE

6

LANL Led MVTX Detector Upgrade

Initiated by LANL LDRD (\$5M, 2016-2019)

- Technology selection & conceptual design
- Key R&D on readout and integration
- Physics program development

DOE/BNL project funding (\$6.4M, 2019 – 2023)

- Detector construction
- Sensor and readout electronics
- Integration & operation

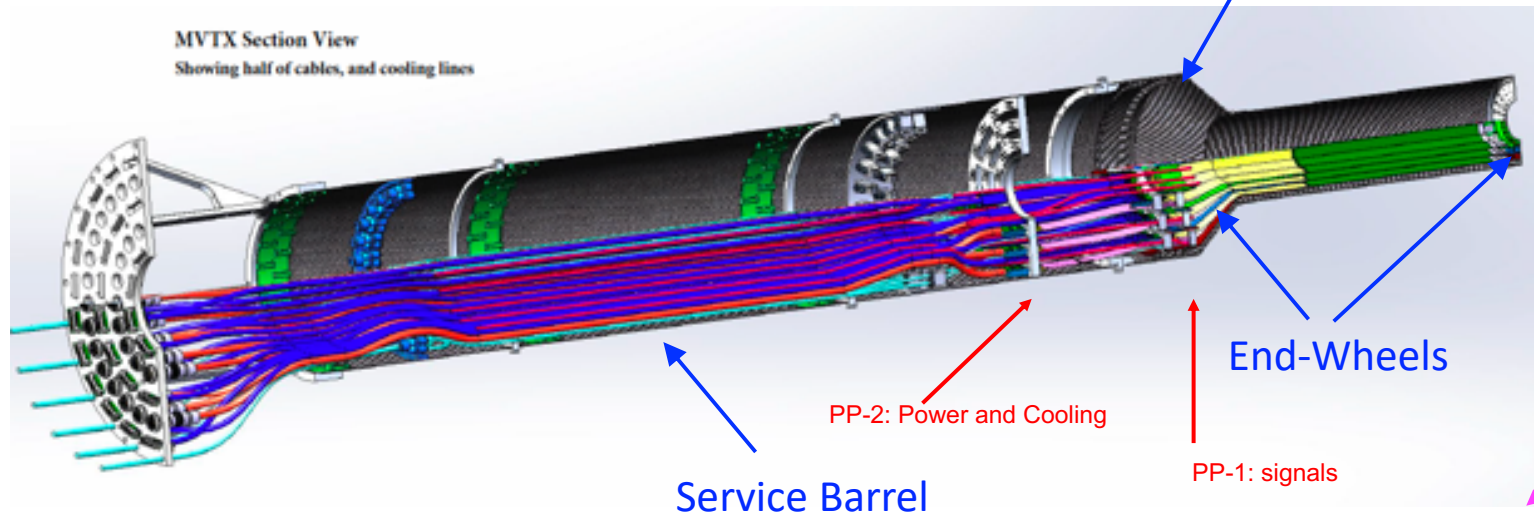
Excellent track DCA resolutions in pp, pAu and AuAu

3-layer sensor barrel:

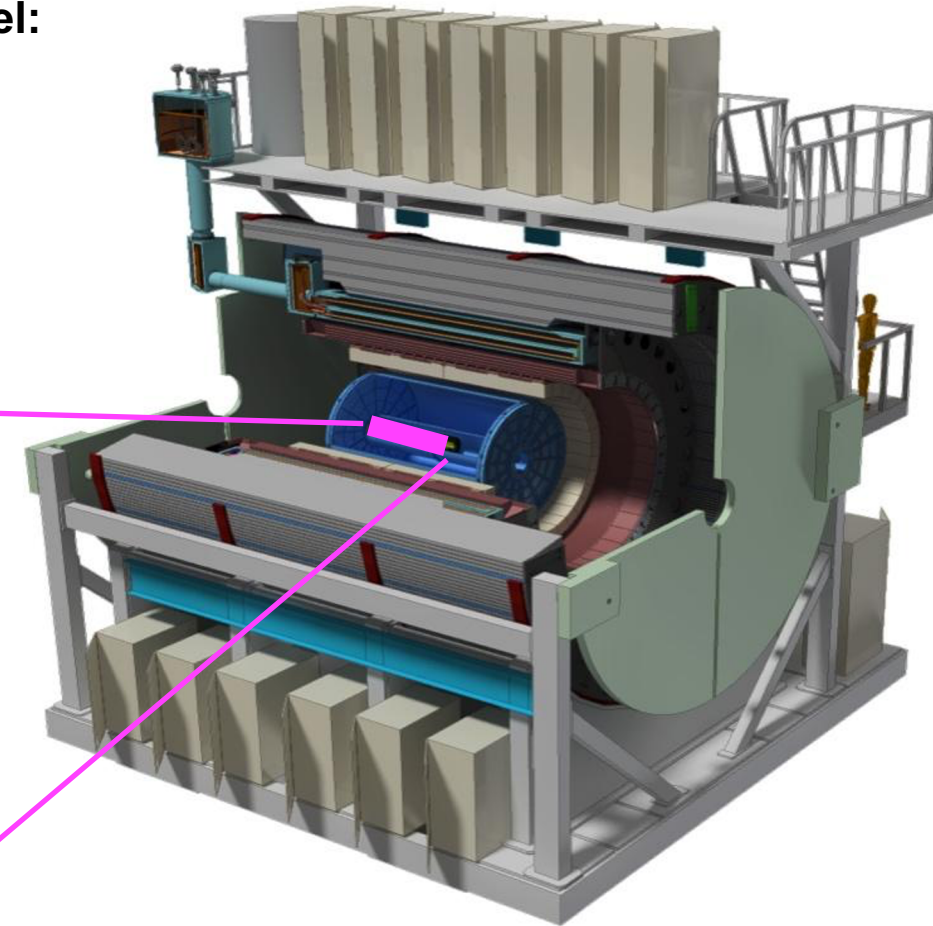
- pixel size: 27 x 29 μm
- stave thickness: 0.35% X_0
- Timing resolution: 5us
- 48 staves, 27.1cm long

To be installed in 2022, Day-1 physics 2023

MVTX Section View
Showing half of cables, and cooling lines



PP-3: External world



4/26/21

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LANL LDRD R&D Highlights (2016-2019)

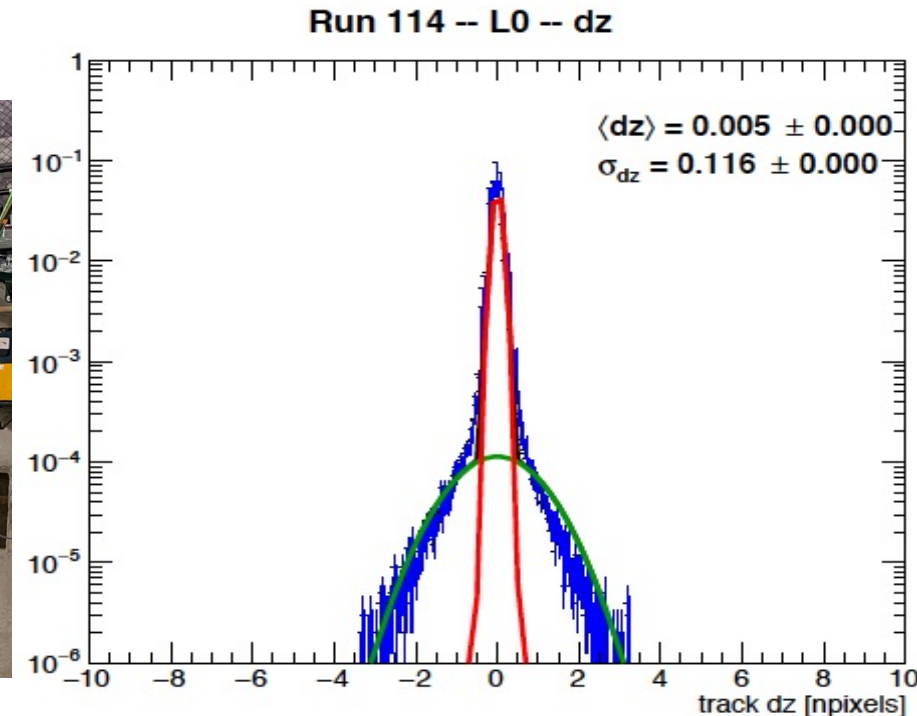
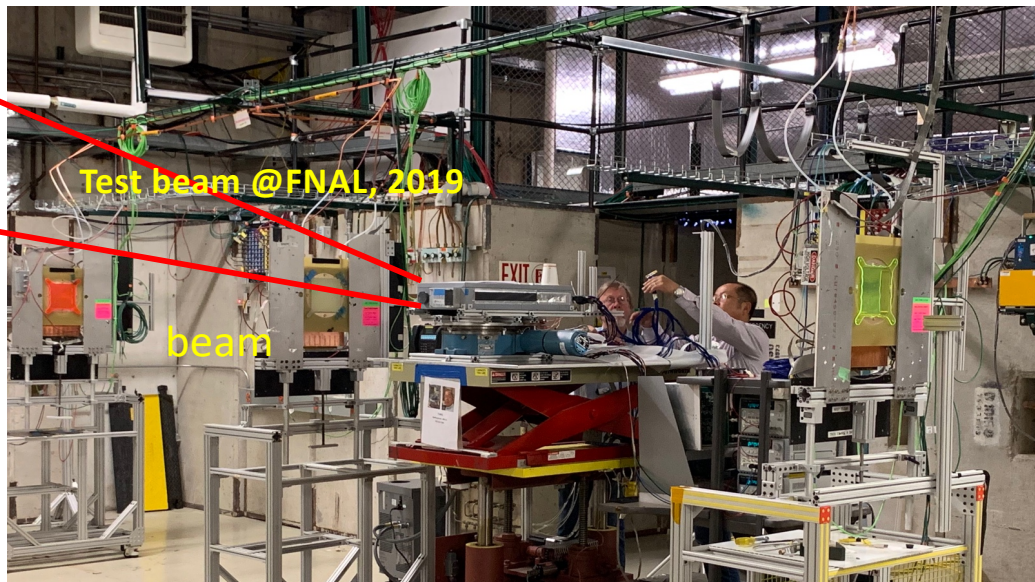
LDRD major achievements:

- ALPIDE sensor evaluation (collaboration with CERN)
- Prototype telescopes to demonstrate performance @Fermilab
- MVTX conceptual design - from readout to mechanical system
- Physics and detector simulations
- Theoretical model development
- **Developed the MVTX proposal, and secured funding DOE/BNL**
Significantly reduced the MVTX project technical and schedule risks



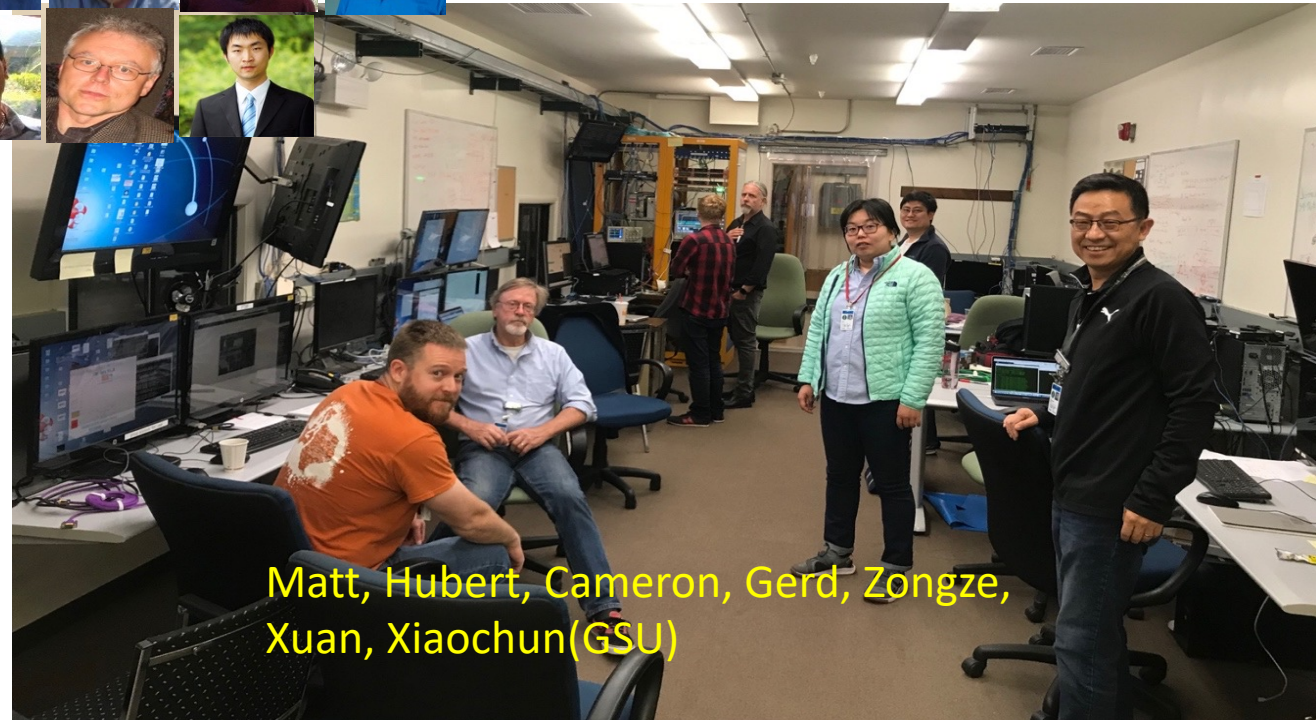
Fermilab Test Beam Results:

- Excellent spatial resolution: $<5 \text{ um}$;
- Track hit efficiency $> 99\%$



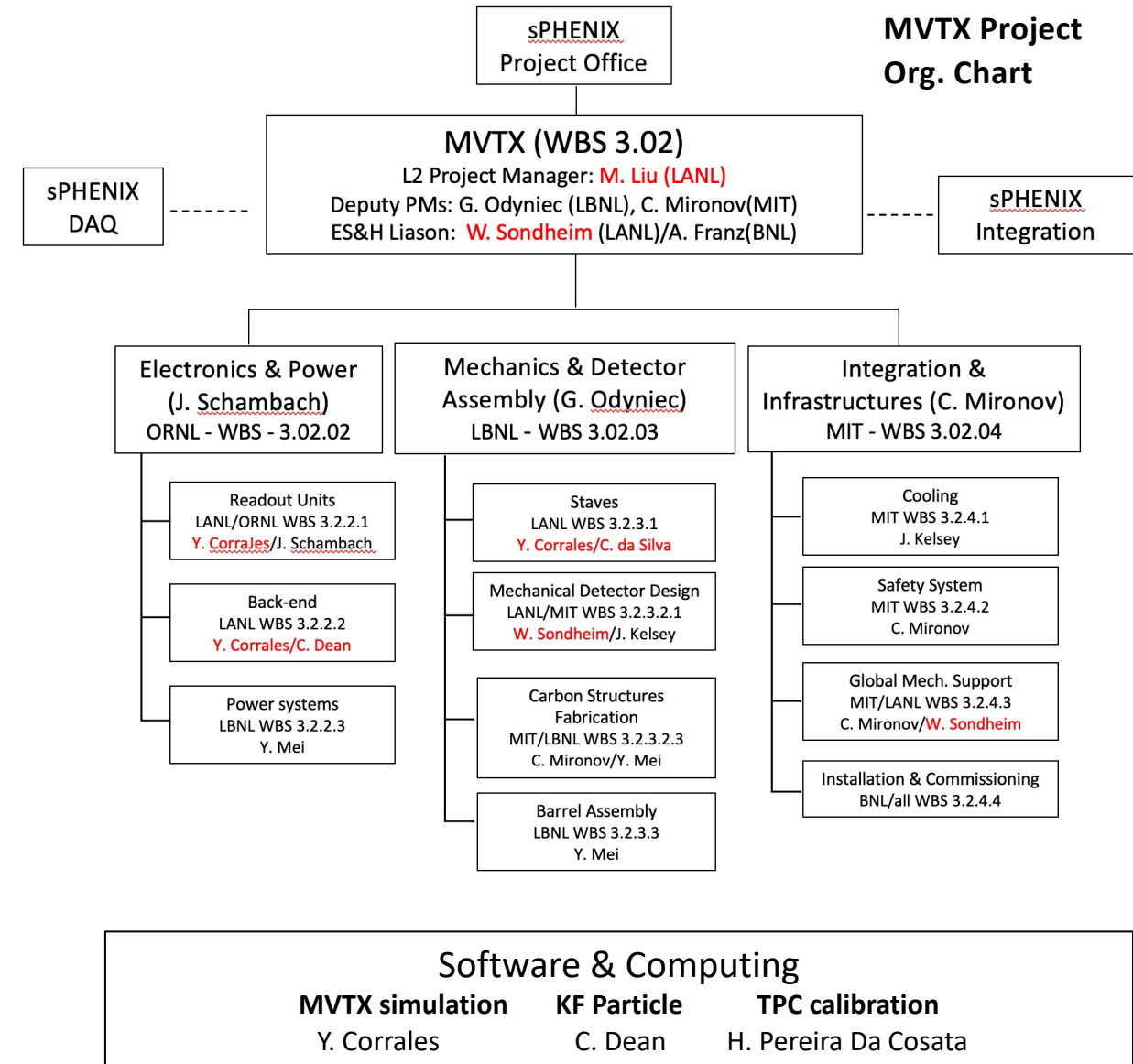
LANL LDRD's Success -> MVTX Project Approval

- MVTX Fermilab Test Beam in May-June 2019



sPHENIX MVTX Project

- **MVTX detector upgrade for HF physics**
 - Tag heavy hadrons through displaced decay vertices
 - Funded by DOE/BNL, under construction, 2019 – 2023
 - Ready for the full sPHENIX physics, 2023-2025+
 - **In collaboration with LBNL, MIT, BNL *et al.*, 20+ institution**
- **LANL plays major roles**
 - MVTX project management and oversee stave production at CERN
 - Mechanical system design and readout integration
 - MVTX detector geometry and response simulation
 - B-hadron and b-jet physics study
- **LANL LDRD/DR (FY2016-2019) for the initial R&D**
 - Physics and detector R&D
 - Pre-conceptual design

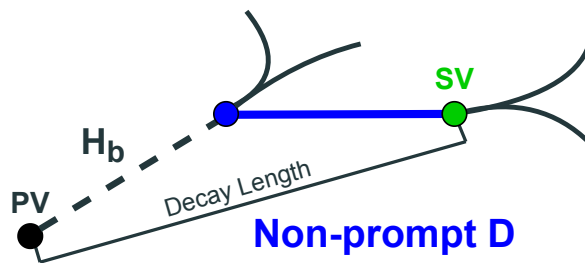
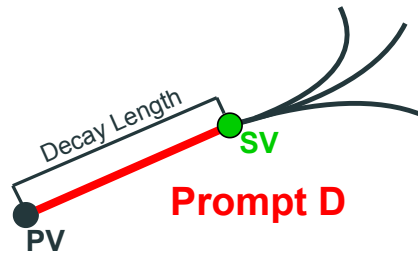


Getting Ready for Day-1 Physics - Monte Carlo Data Challenge



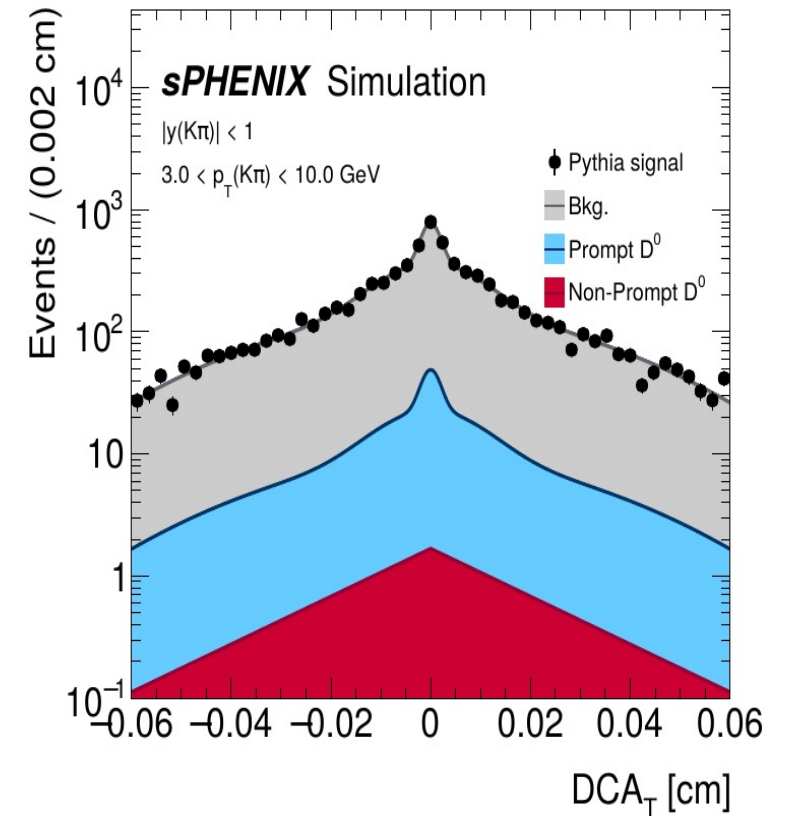
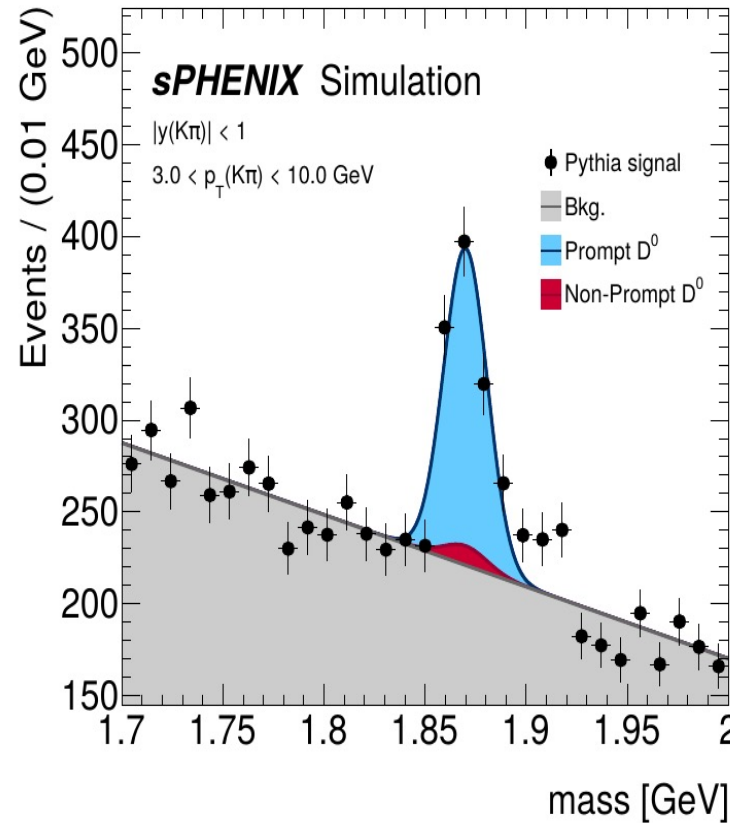
**PYTHIA 8 p+p with full
detector GEANT sim + reco**

$$p + p \rightarrow D^0 + X \rightarrow (K^- \pi^+) + X$$



$$p + p \rightarrow H_b + X \rightarrow (D^0 + X') + X$$

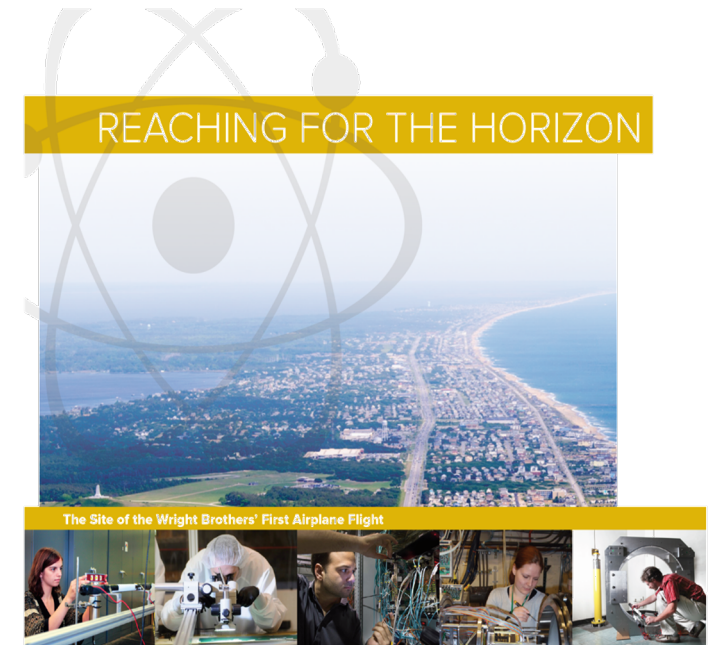
KFParticle package implemented for exclusive HF hadron reconstruction



Summary: LANL's Physics Programs at RHIC

- **Continue producing unique physics from PHENIX**
 - CNM, QGP
 - Spin physics
- **Leading MVTX upgrade for sPHENIX (– 2023)**
 - LANL LDRD developed the program (FY17-19)
 - R&D and construction, installation in fall 2022
 - Heavy quark physics program development
- **sPHENIX Heavy Quark Physics (2023-2025+)**
 - Probe the inner workings of QGP with heavy quarks
 - Study cold QCD matter, spin structure of nucleon, complimentary to EIC
- **Transition from sPHENIX to EIC (~2025+)**
 - EIC Physics and detector development - ECCE, EIC@IP6 proposals
 - Ready for EIC physics ~2030

LANL has a good combination of physics leadership and technical capabilities to carry out major scientific exploration at national and international level



The 2015
LONG RANGE PLAN
for **NUCLEAR SCIENCE**





PHENIX Experiment: Last Data Taking 2016

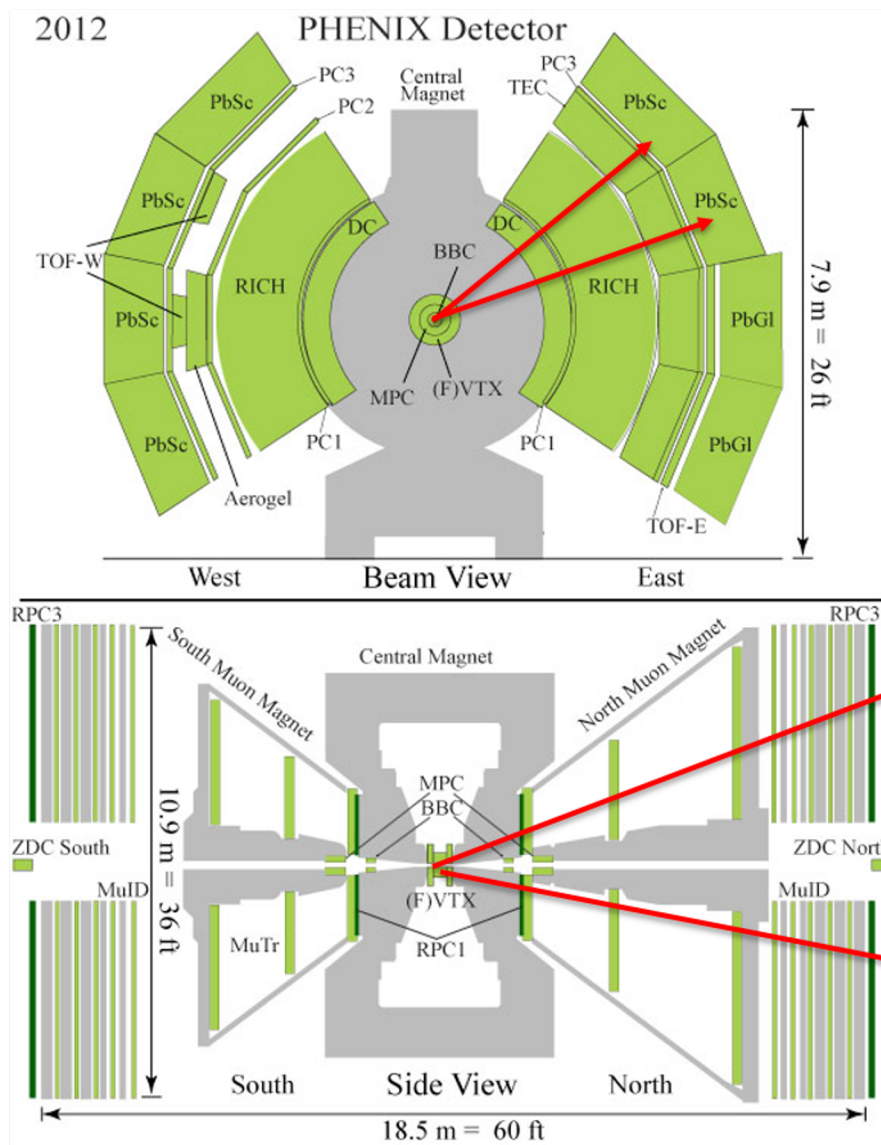
LANL focus:

Finish unique physics with muon measurements

- J/Psi, dimuons
- HF, singly muons
- FVTX capability
 - DCA
 - Evt_Multiplicity

Run15 p+p, p+Au, p+Al

Run14: Au+Au



Central Arms $|\eta| < 0.35$

- Identified charged hadrons
- **Neutral Pions**
- Direct Photon
- J/Psi
- Heavy Flavor

Muon Arms $1.2 < |\eta| < 2.4$

- **J/Psi**
- Unidentified charged hadrons
- **Heavy Flavor**

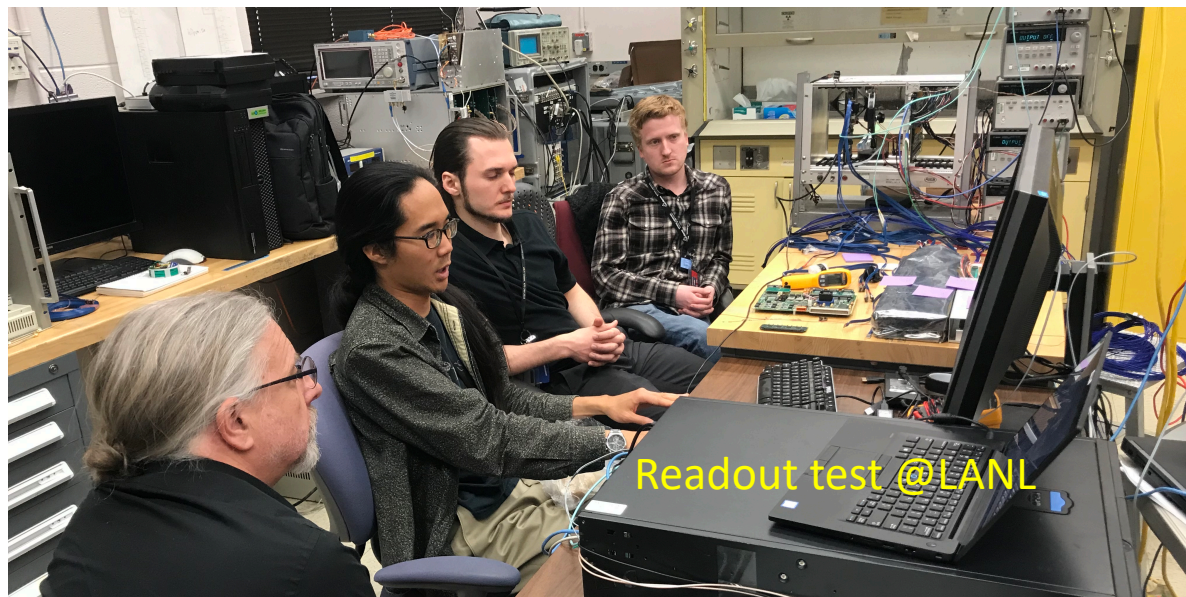
MPC $3.1 < |\eta| < 3.9$

- **Neutral Pion's**
- **Eta's** BBC ~ MPC: 3.1-3.9

ZDC $|\eta| \sim 5.9$

- **Neutrons**

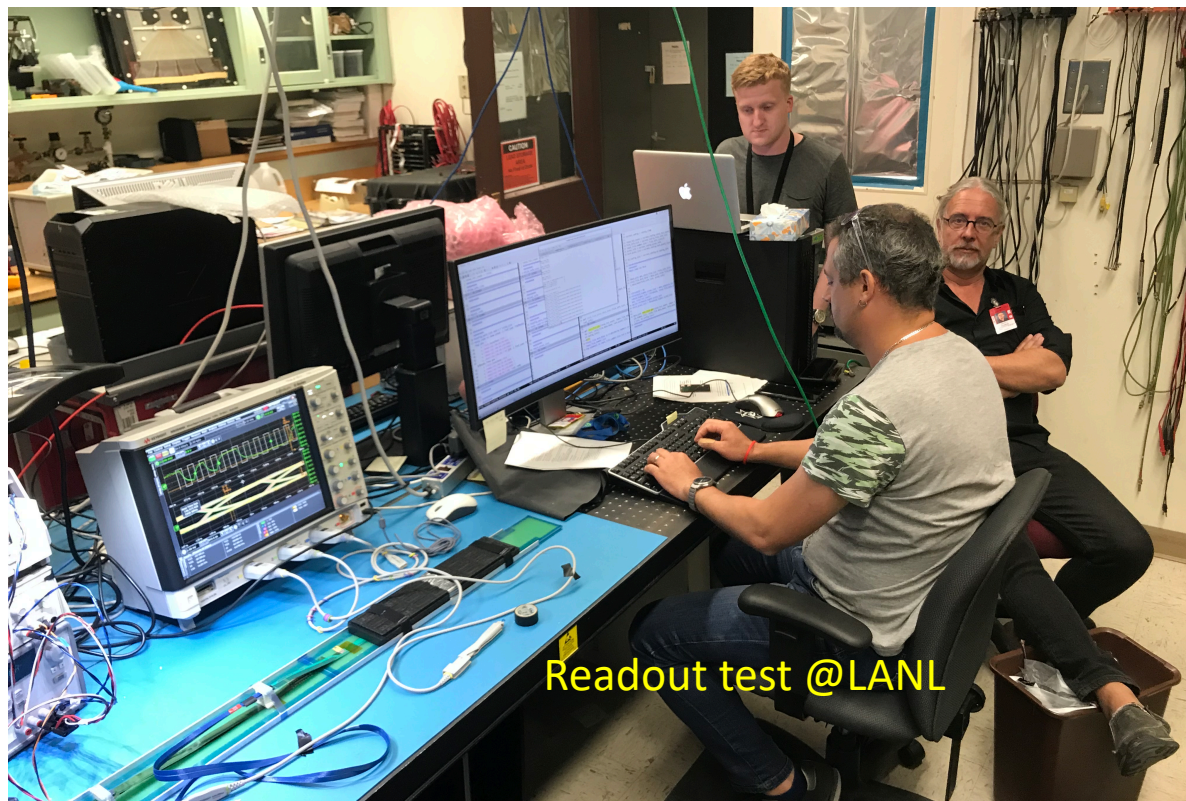




Readout test @LANL



Setup telescope @Fermilab



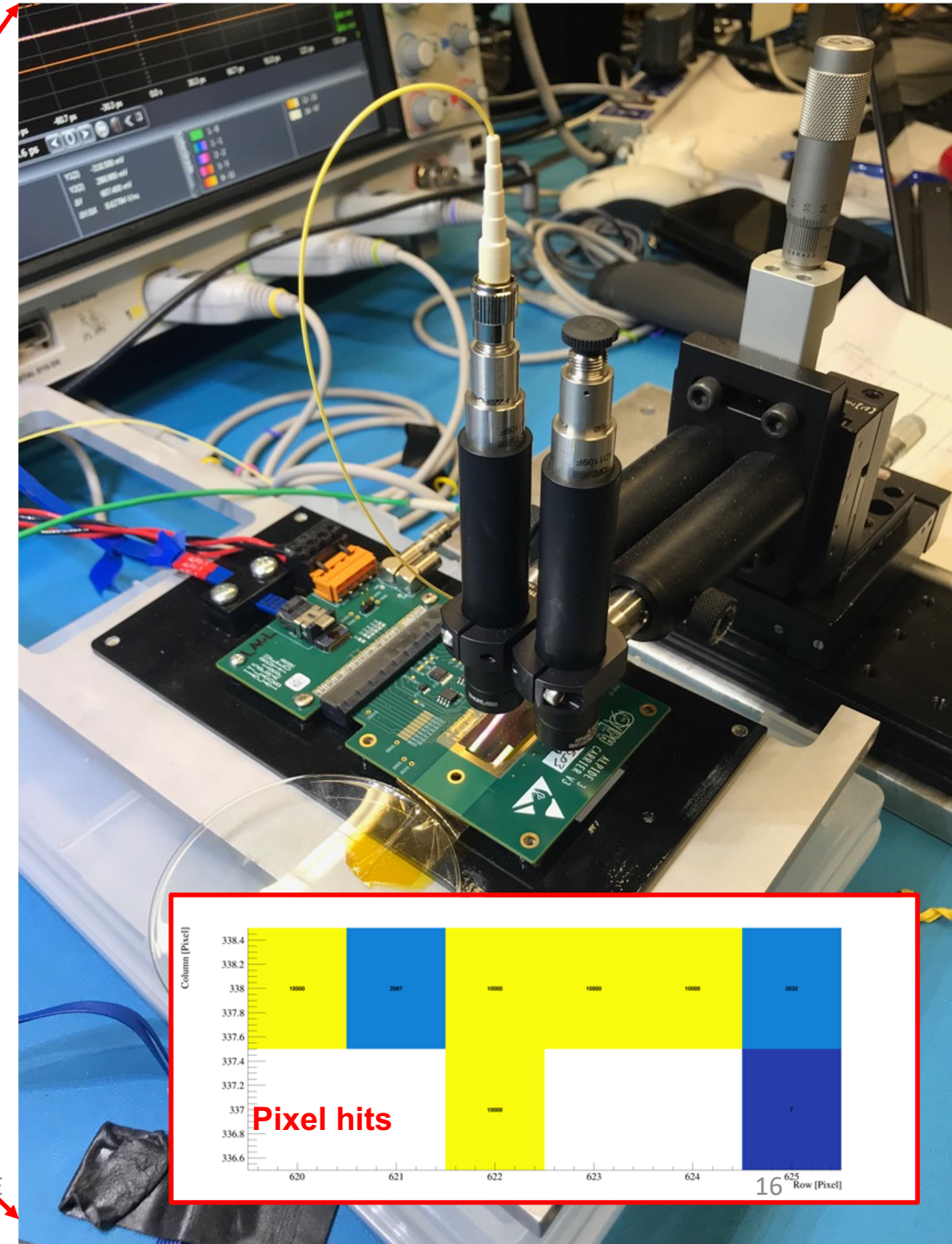
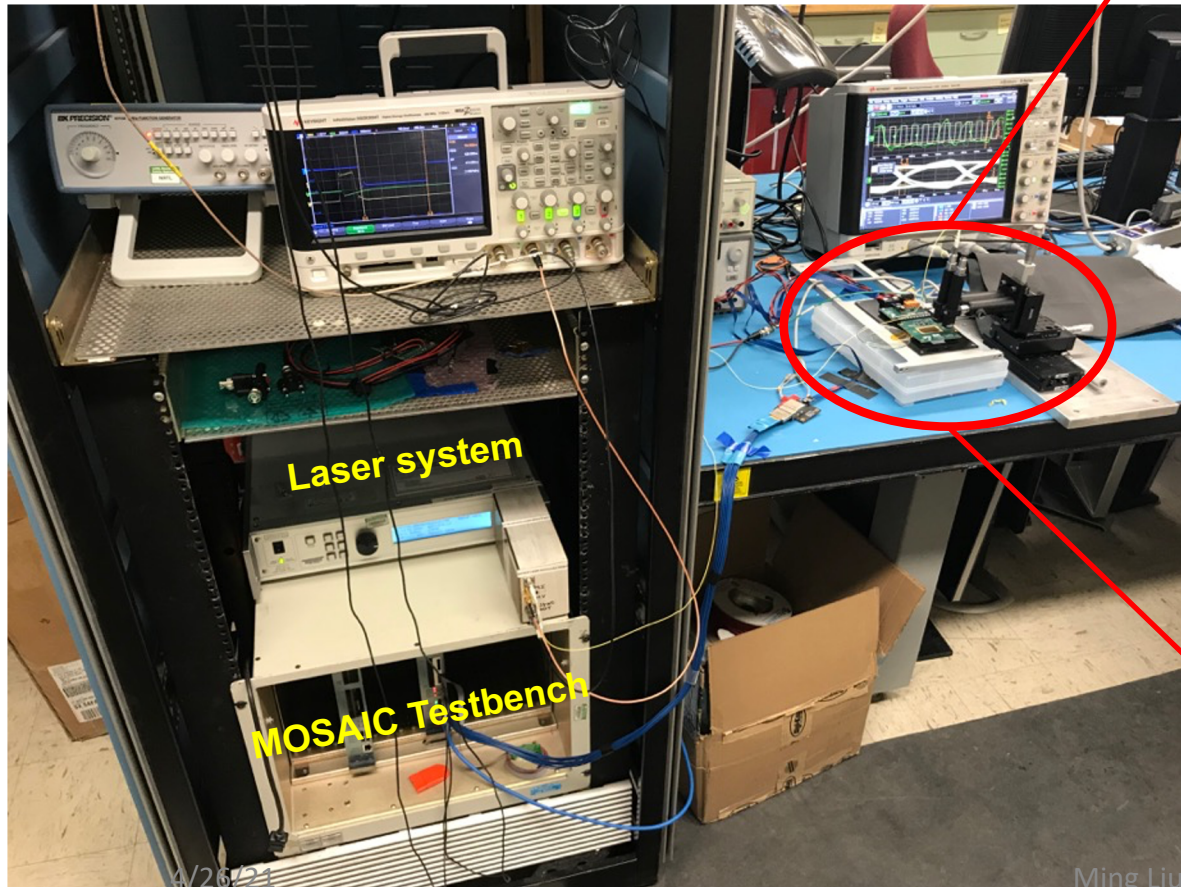
Readout test @LANL



MVX 3D Mockup @LANL

Study MAPS Performance with Pulsed Laser @LANL

- Inject “MIP” signal, focused laser beam
 - 850 nm laser, 4ns wide pulse, ~1 MIP
 - 50kHz trigger
 - **Find optimal MAPS operating parameters**



The Growing sPHENIX Collaboration

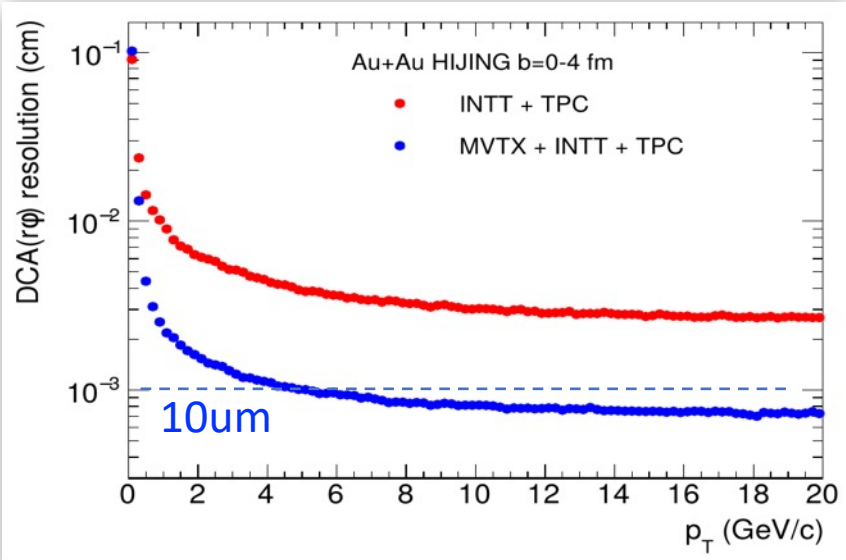
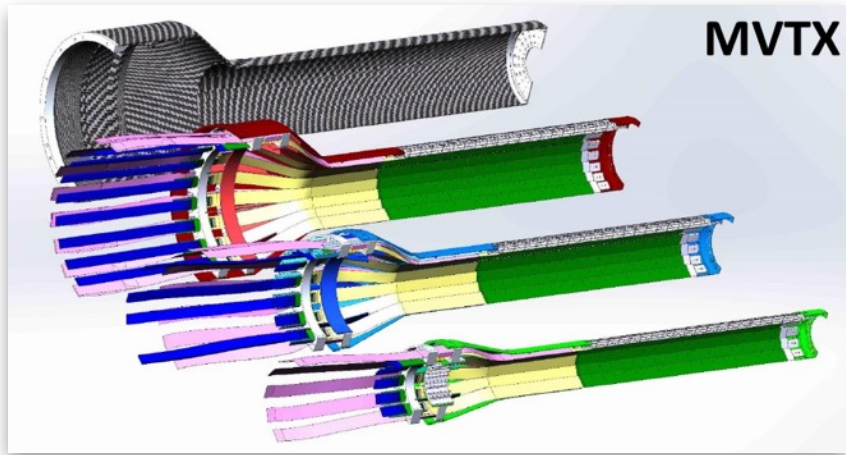
- sPHENIX is a large international collaboration
- 1st collaboration meeting, 12/2015
- 80 institutions total (as of 3/2020), and growing
- 25% non-US institutions
- MVTX upgrade group

LANL+LBNL+MIT+BNL+UT-Austin..., 20+ institutions



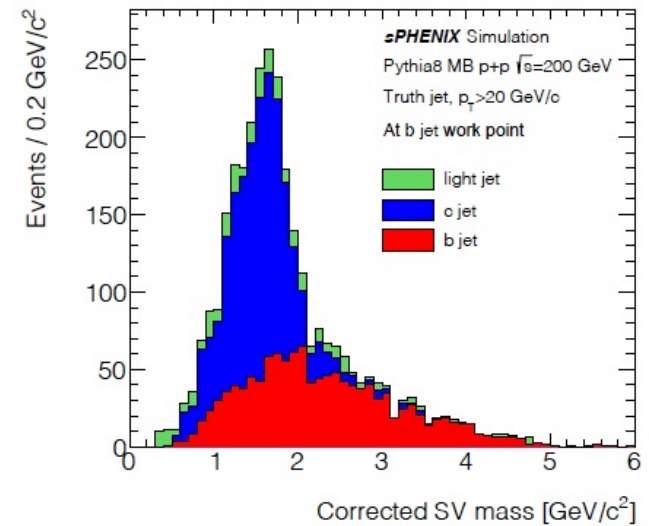
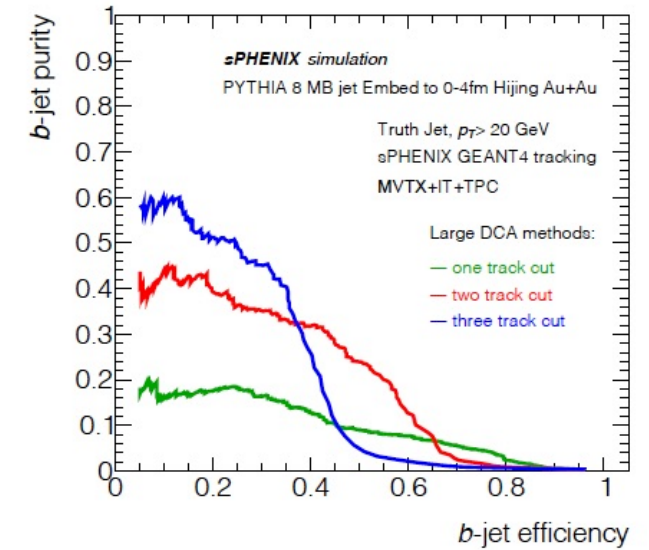
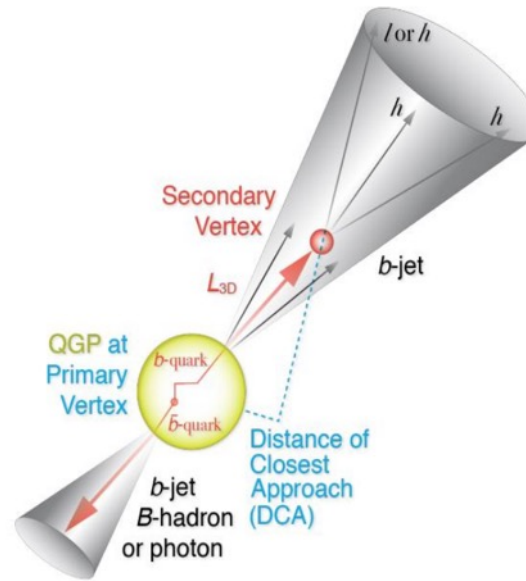
Open HF Tagging with MVTX Upgrade

- Monolithic-active-pixel-sensor based VerTeX detector



MVTX key parameters: (ALPIDE)

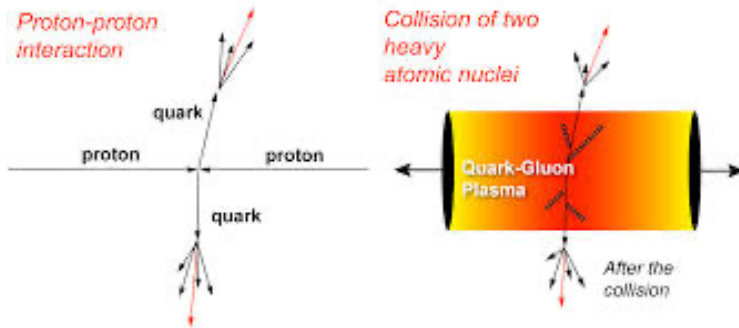
- pixel size: **27μm x 29 μm**
- ultra-thin stave: **0.35% X_0**
- Integration time: **~5μs**
- Multi-tracks w/ large DCA
- 2nd vertex mass
- Exclusive hadron reconstruction



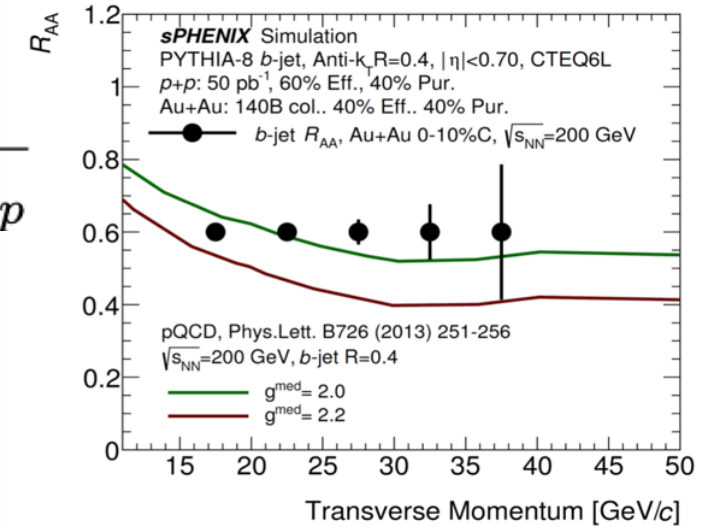
Open Heavy Flavor Physics Program – Key Observables

Nuclear modification of b-jets:

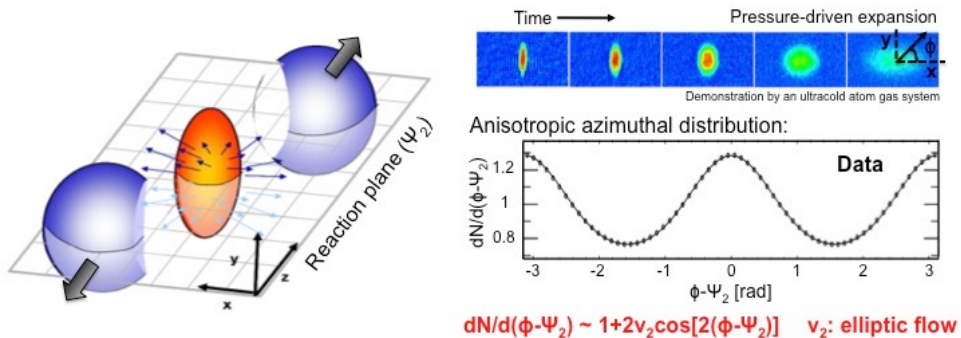
- Radiative energy loss
- Collisional energy loss



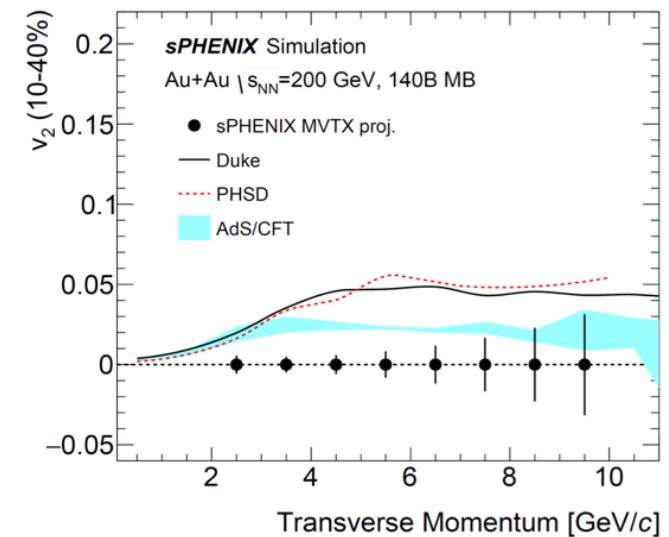
$$R_{AA} = \frac{\sigma_{AA}}{N_{bin} \times \sigma_{pp}}$$



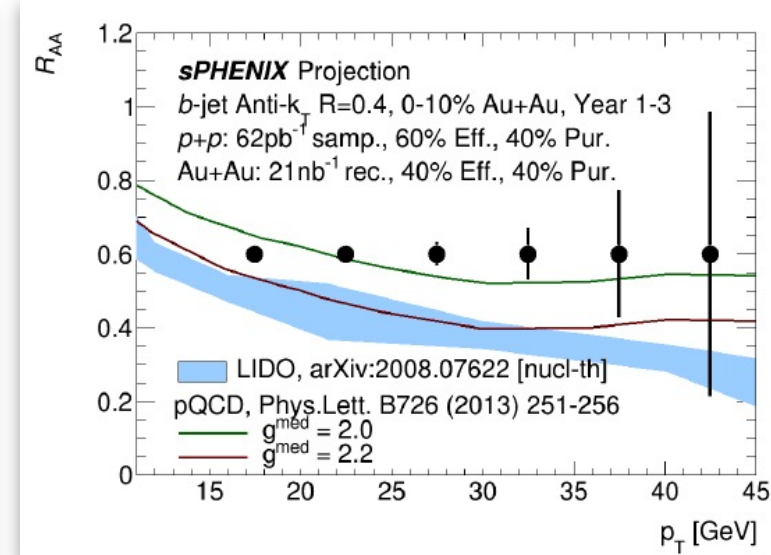
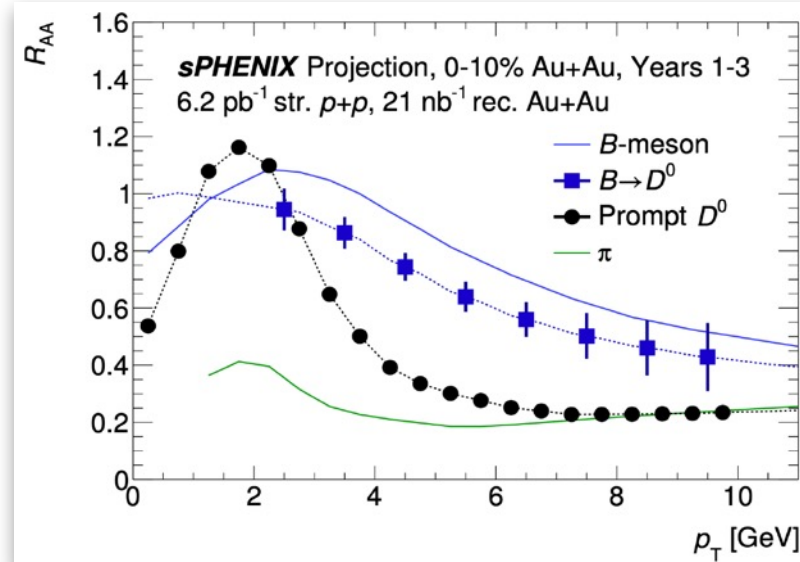
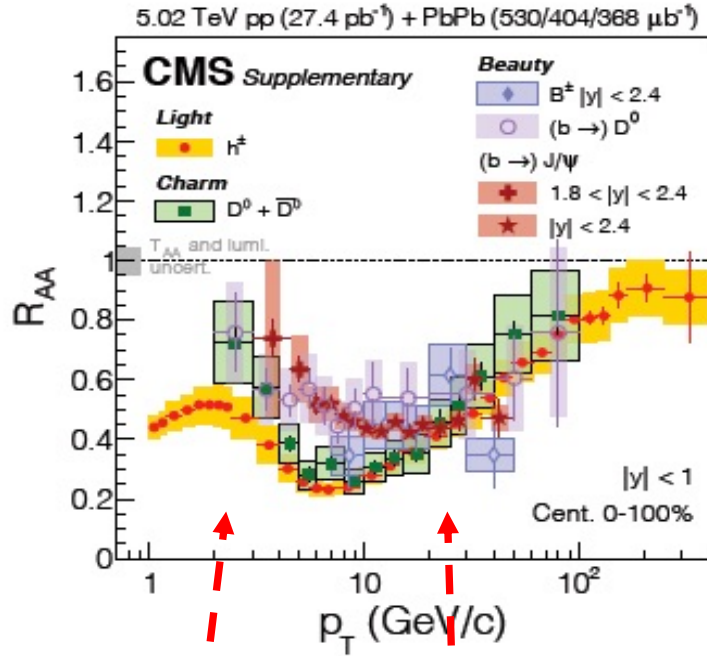
B-hadron azimuthal asymmetry - “Elliptic Flow” v₂



Sensitive to b-QGP coupling:
 - if no-interaction, v₂=0



Precision HF Hadron and b-Jet R_{AA}



Many factors affect the HF hadron production:

- Heavy quark energy loss in QGP: mass, p_T dependence
- Heavy quark diffusion in QGP
- Heavy quark hadronization in QGP

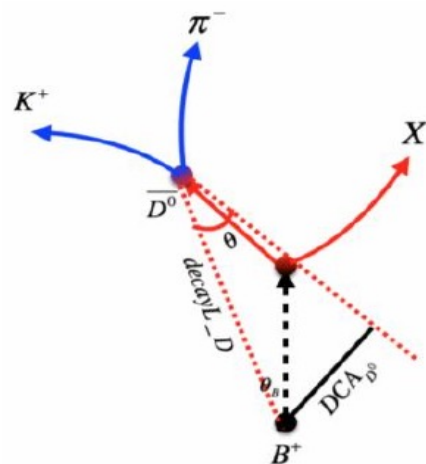
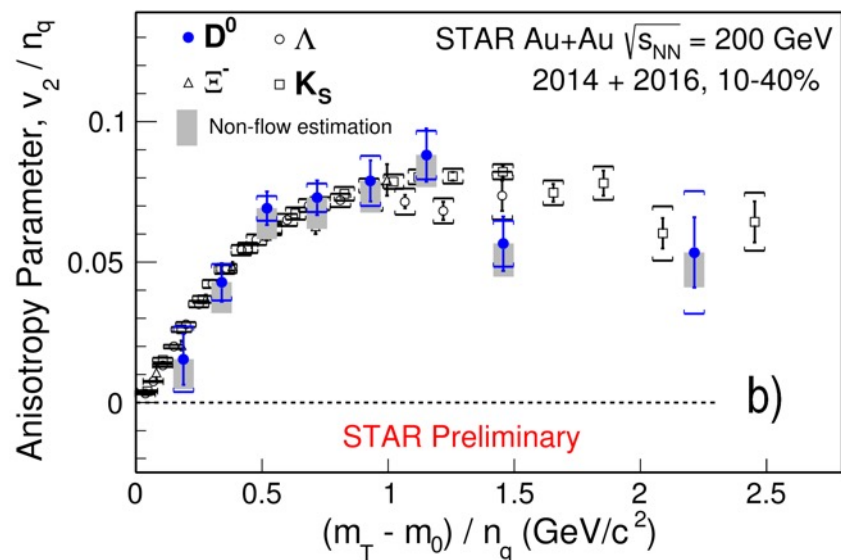
Also other observables:

- di-b-jet, modification of HF jet structures etc.

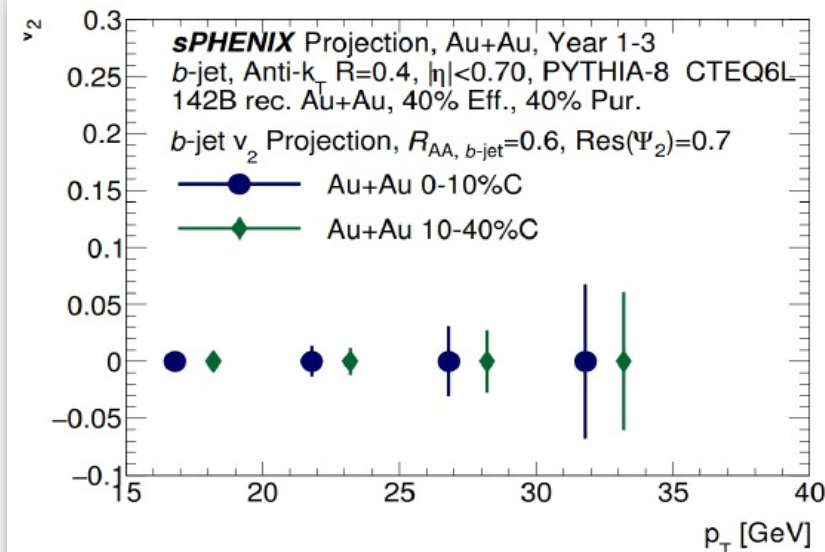
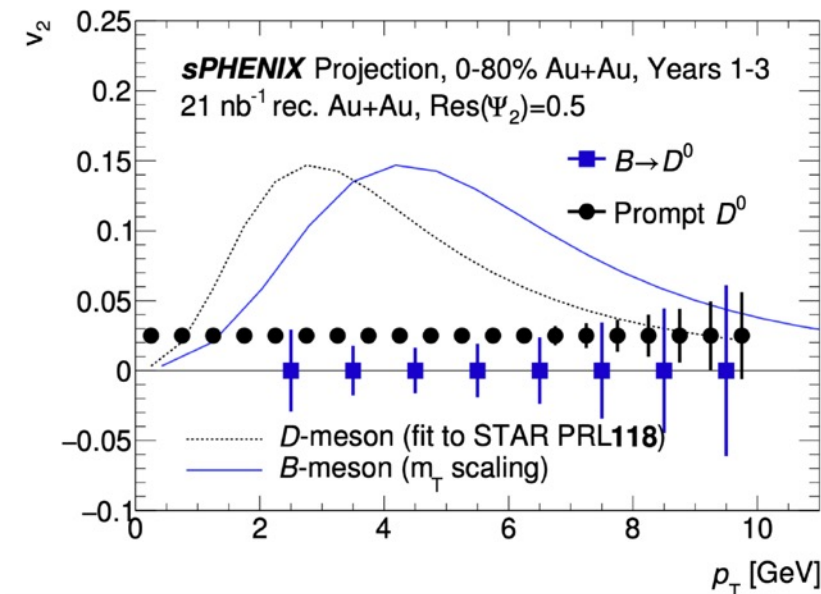


Precision “Flow” Measurements of B-hadron and b-Jets

STAR: D^0 v_2 m_T scaling observed



$B \rightarrow \bar{D}^0 + X$ (B.R. 60%)



Many factors affect the HF hadron production:

- Heavy quark energy loss in QGP
- Heavy b -quark diffusion in QGP
- Heavy quark hadronization in QGP

b -jet flow, pQCD:
- Energy loss induced v_2 ?

