The sPHENIX Experiment at RHIC

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(for the sPHENIX Collaboration)

XLIX
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on Multiparticle Dynamics

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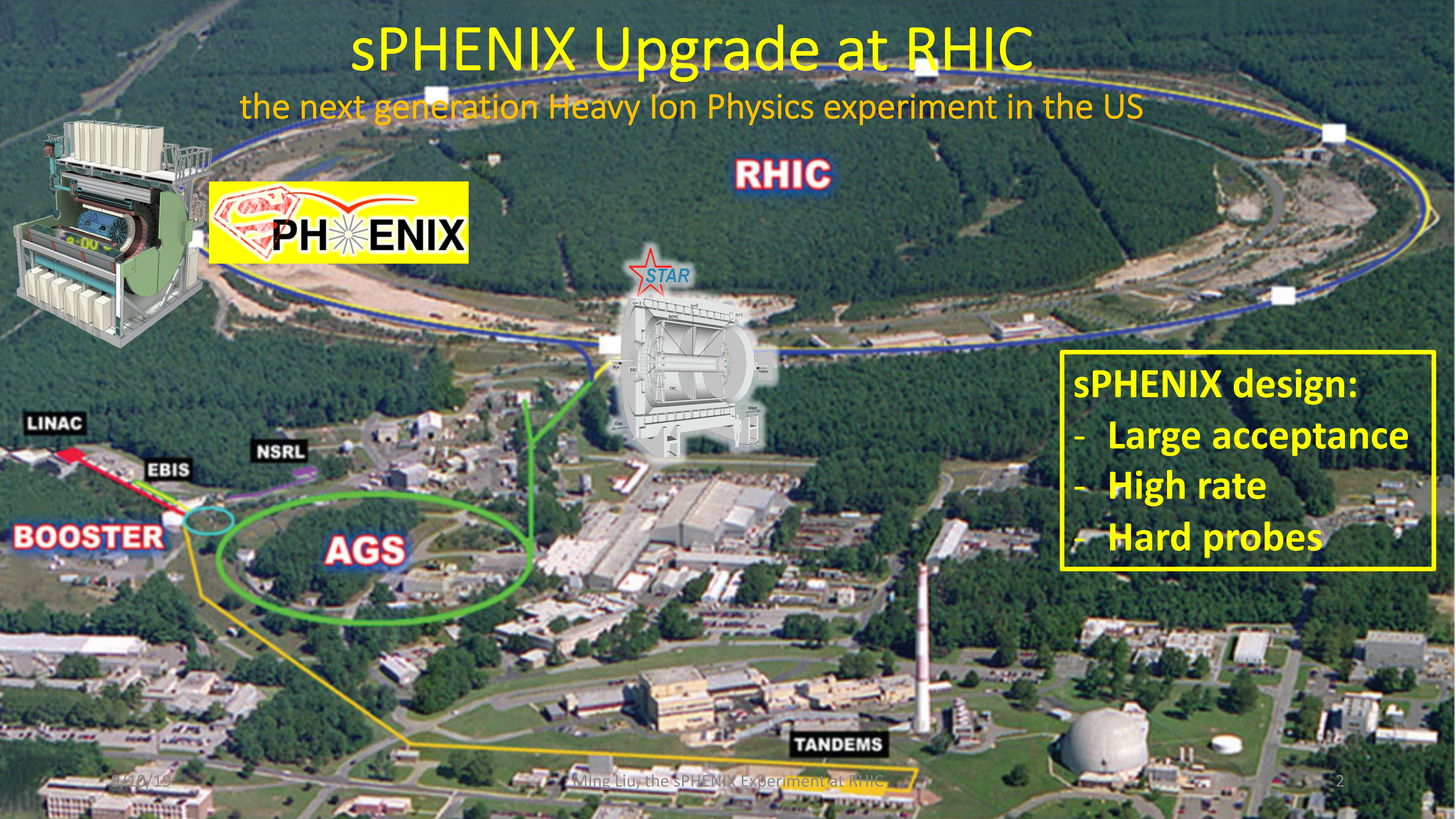
sPHENIX Upgrade at RHIC

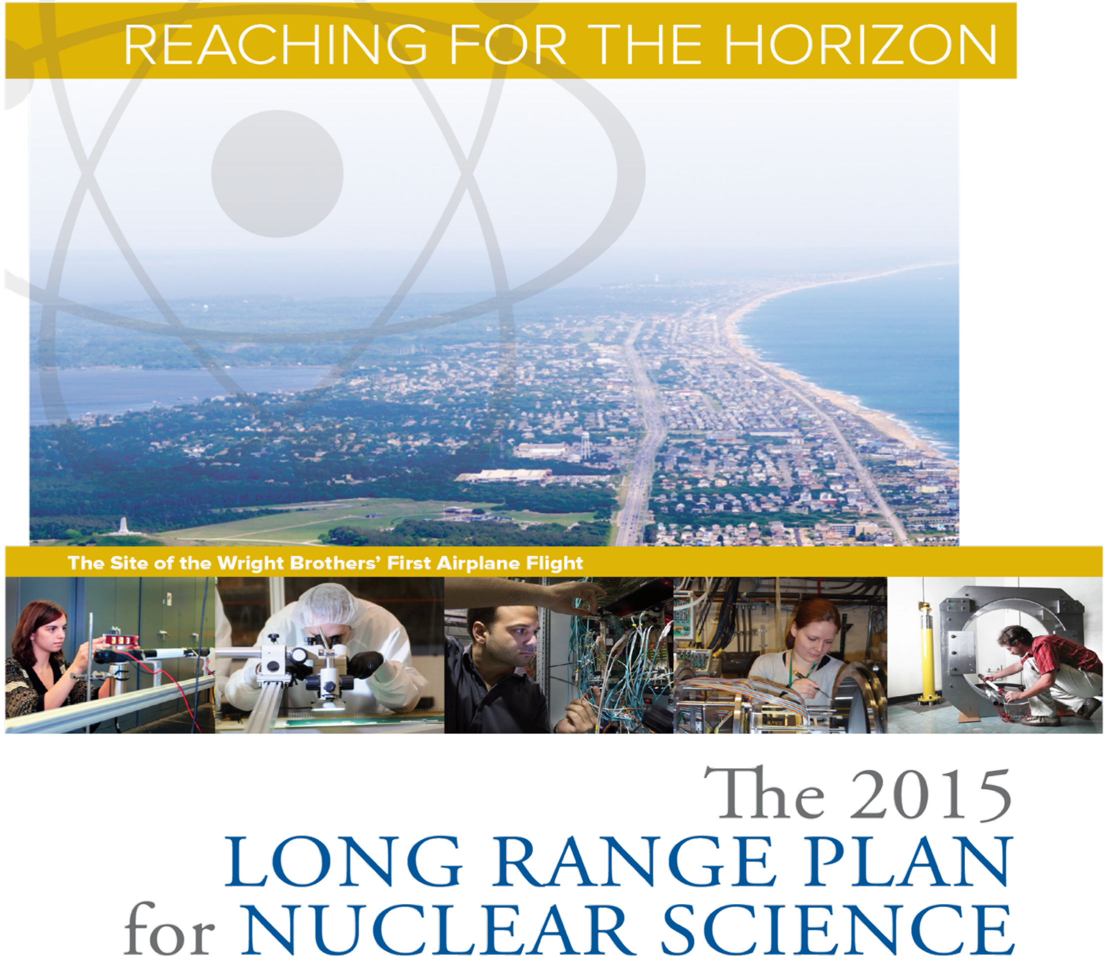
the next generation Heavy Ion Physics experiment in the US



sPHENIX design:
- Large acceptance
- High rate
- Hard probes

US Nuclear Physics Long Range Plan (2015)

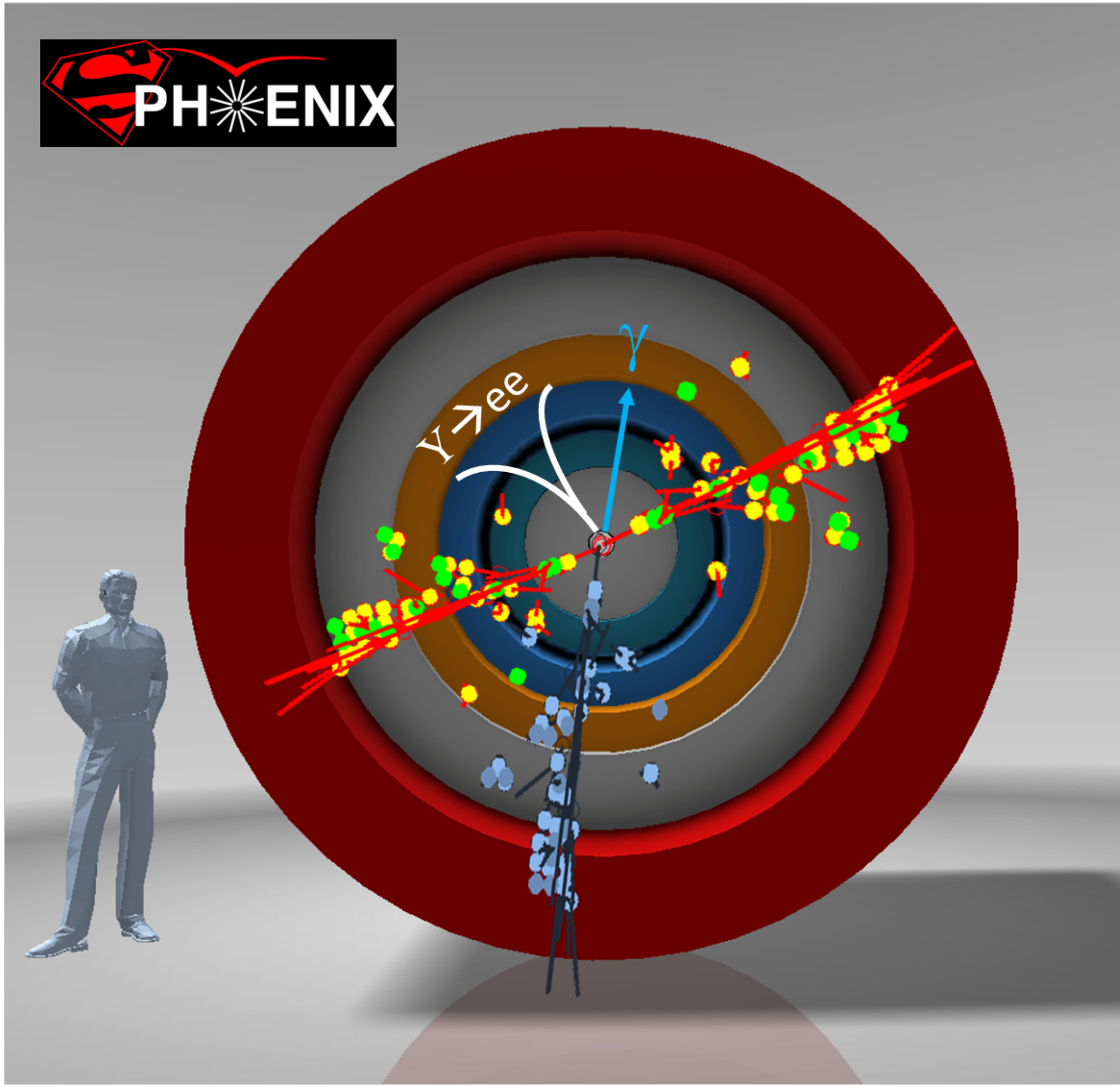
sPHENIX – to understand "Inner Workings of QGP"



"To understand the workings of the QGP, there is no substitute for microscopy. We know that if we had a sufficiently powerful microscope that could resolve the structure of QGP on length scales, say a thousand times smaller than the size of a proton, what we would see are quarks and gluons interacting only weakly with each other. **The grand challenge for this field in the decade to come is to understand how these quarks and gluons conspire to form a nearly perfect liquid."**

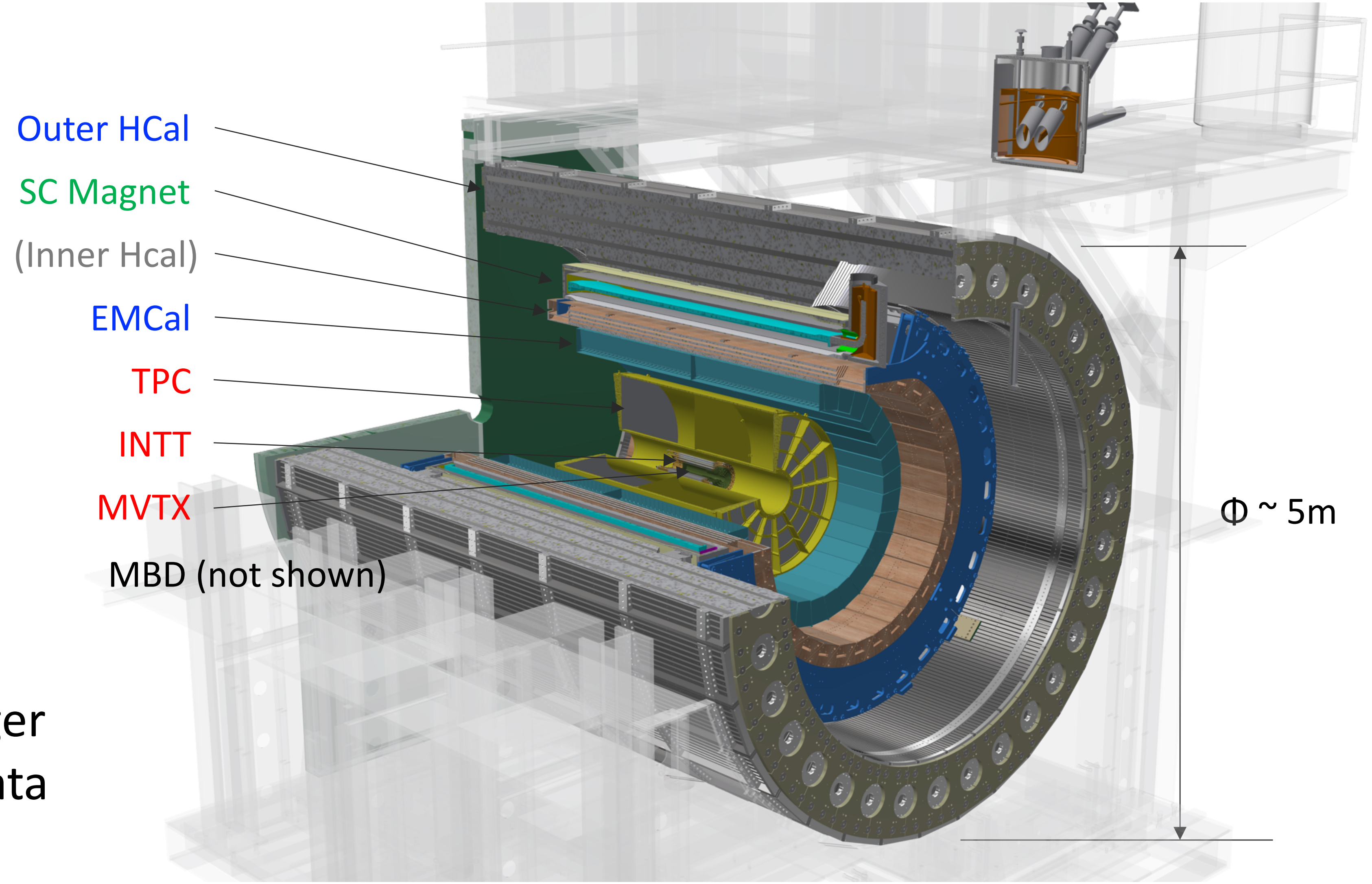
Outline

- sPHENIX detector and HI physics
  - Jets and photons
  - Upsilons
  - Open heavy flavors
- Cold-QCD physics opportunity
  - Spin, TMD, nPDF
  - Forward upgrade
- Outlook



The sPHENIX Detector

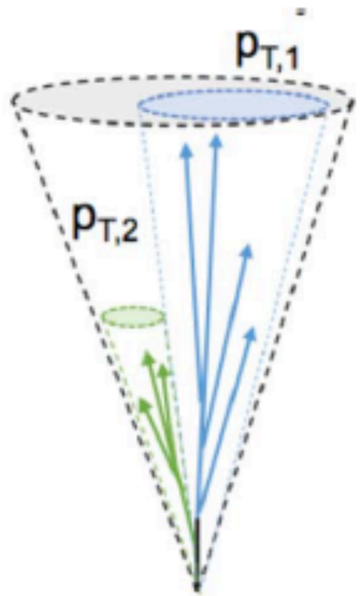
A high rate and large acceptance detector for heavy ion physics at RHIC



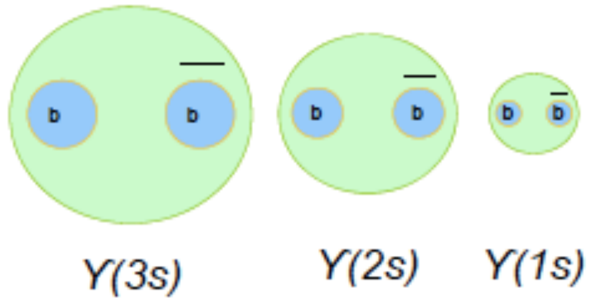
- |eta| < 1.1
- B: 1.4 T
- 15 kHz trigger
- >10 GB/s data

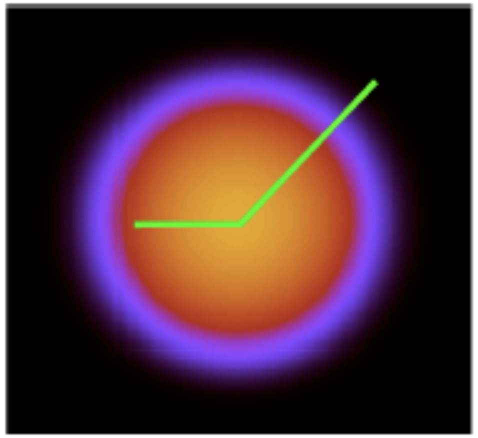
Probing the Inner Workings of QGP in sPHENIX
- Key Capabilities

Jet structure
vary momentum/angular scale of probe

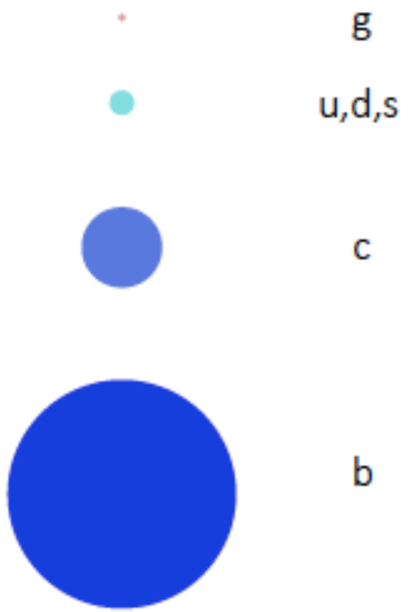


Quarkonium spectroscopy
vary size of probe

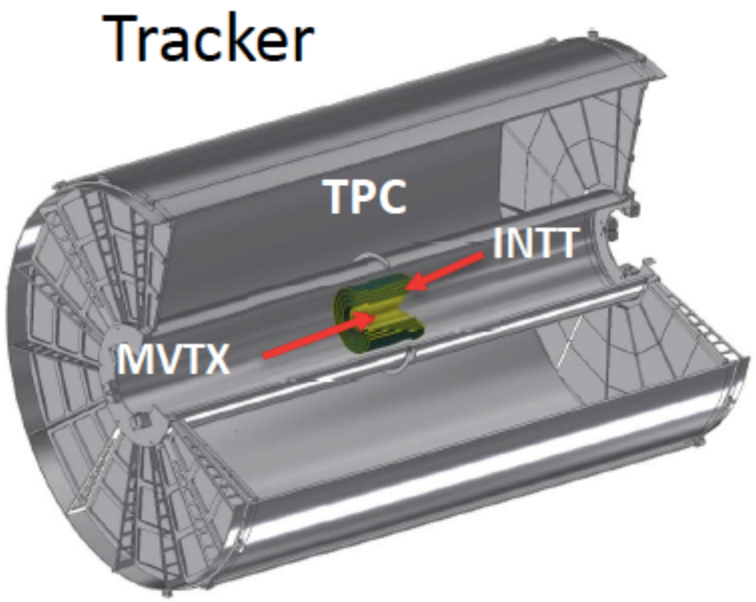


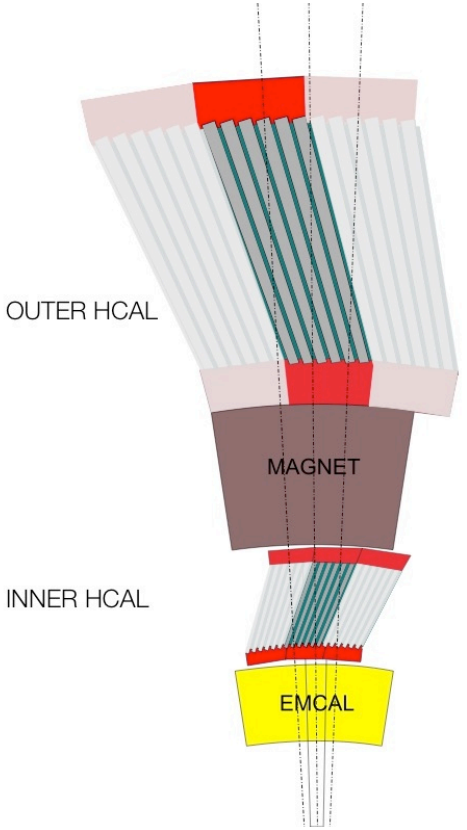


Parton energy loss
vary mass/momentum of probe



sPHENIX Detector Sub-Systems





- Outer HCAL ≈3.5λ_I
- Magnet ≈1.4X_0
- Inner HCAL ≈1λ_I
- EMCAL ≈18X_0 (≈1λ_I)

MVTX (based on ALICE ITS/IB):
- 3-layer MAPS vertex tracker, R = 2.5 – 4.0cm
- Excellent DCA resolution, $DCA_{r\phi}$< 50 µm @ p_T > 1 GeV/c

INTT:
- 2-layer Si strip, R = 7 – 10cm

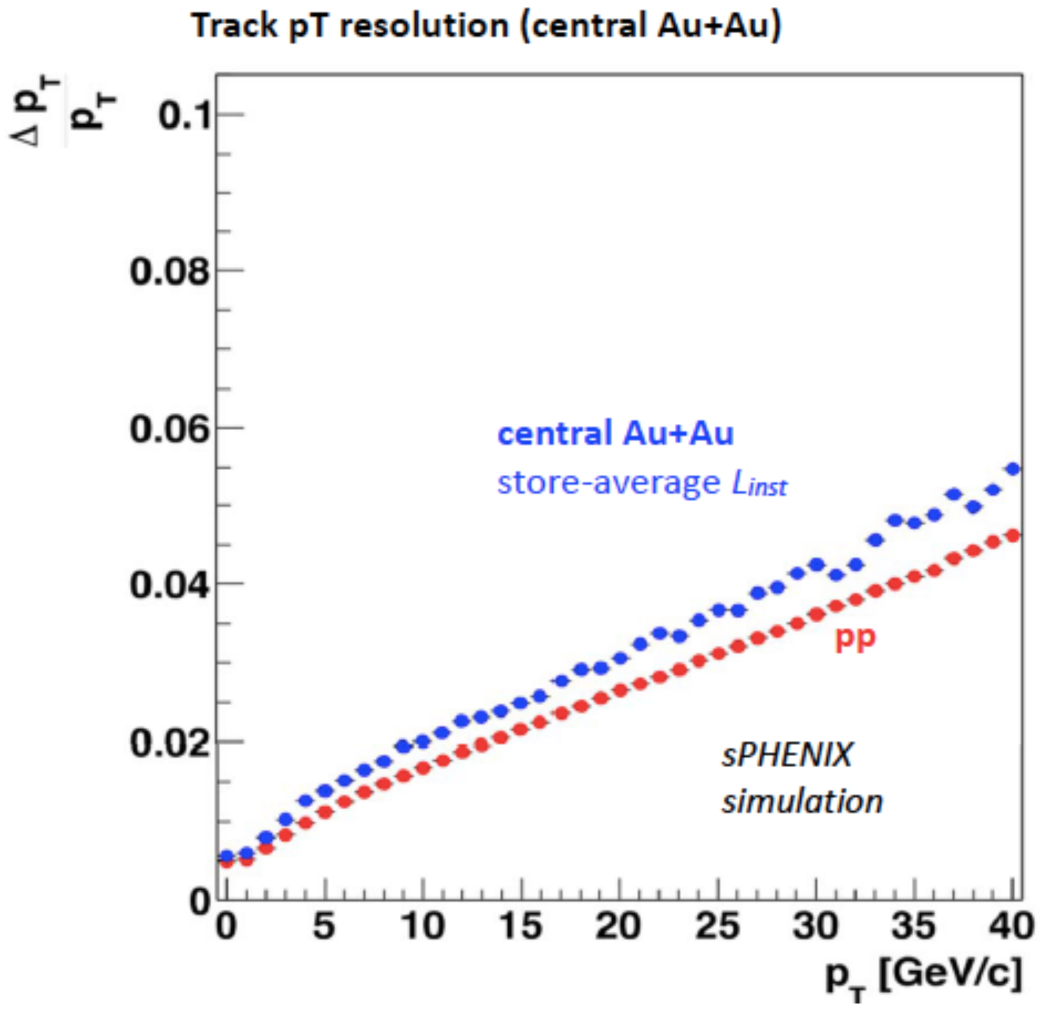
TPC:
- 48 layer, continuous readout, R = 20 - 78 cm
- Excellent momentum resolution p_T = 0.2 - 40 GeV/c

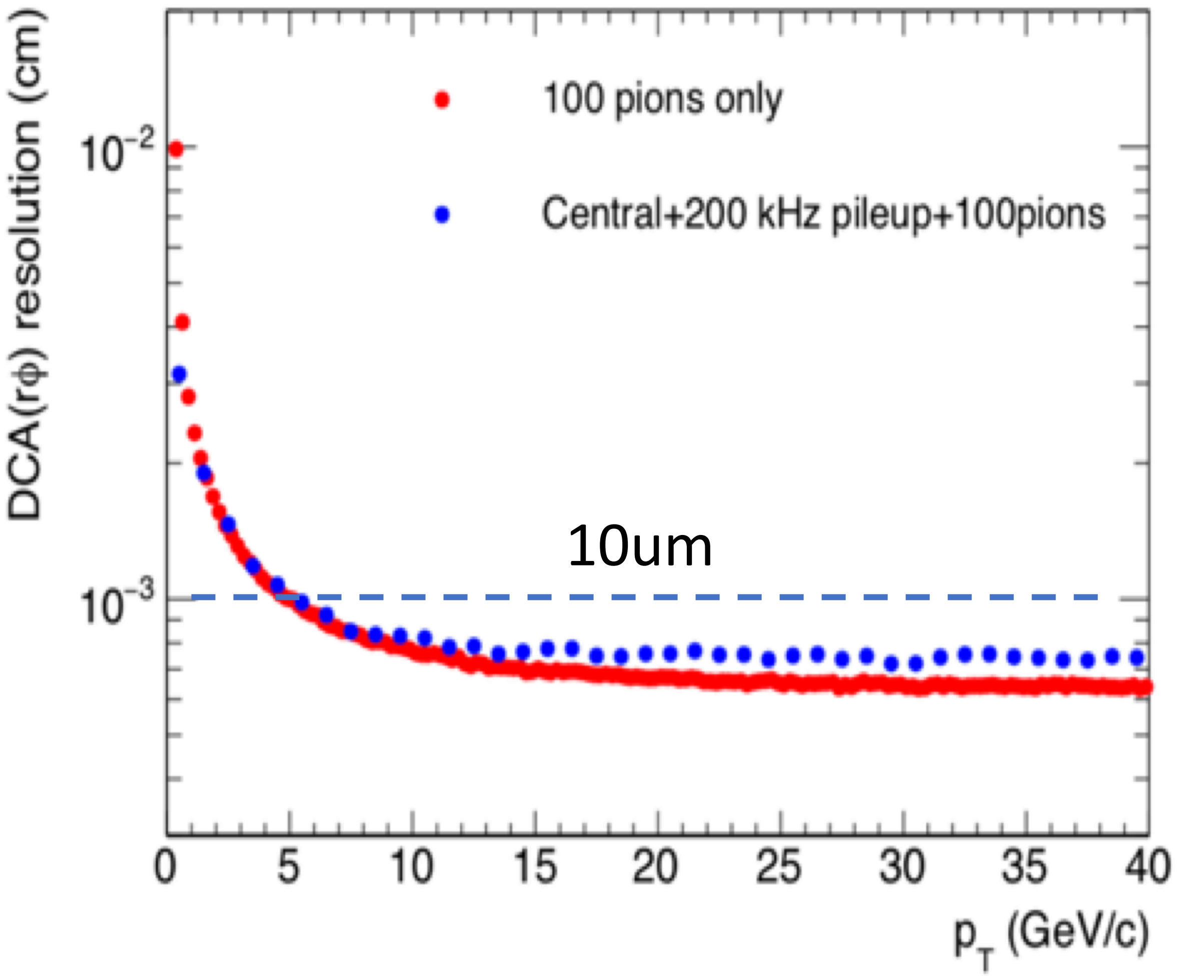
EMCal: Scintillating fibers embedded in W powder
- $\Delta\eta\times\Delta\phi$ = 0.024×0.024
- σ_E/E = 16%/√E $\oplus$ 5%

HCal: Plastic scintillating tiles + tilted Steel/Al plates
- $\Delta\eta\times\Delta\phi$ = 0.1×0.1
- σ_E/E = 100%/√E

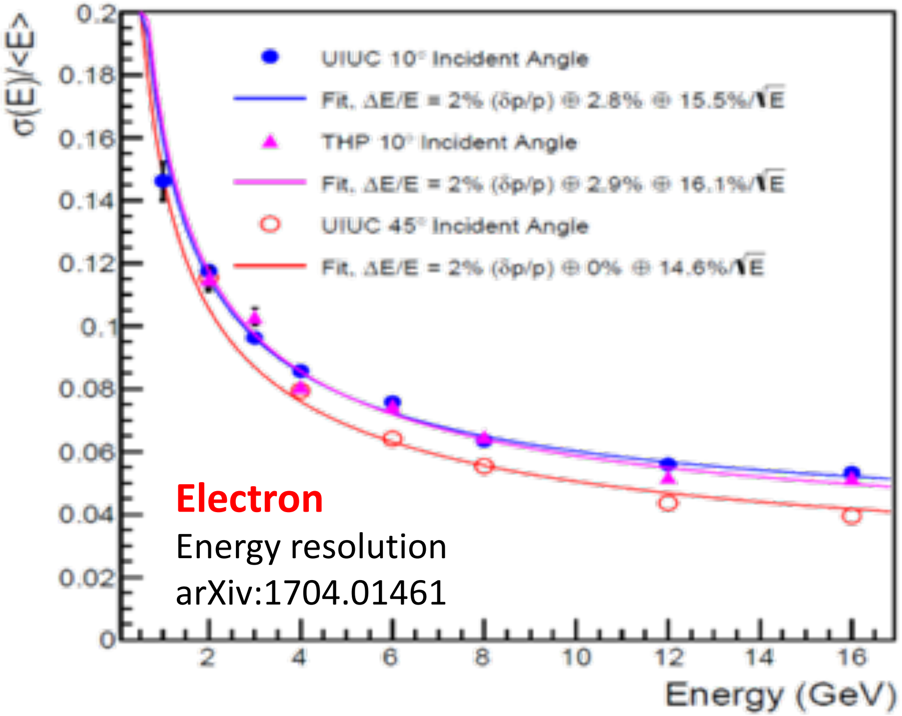
Detector Performance: Tracking

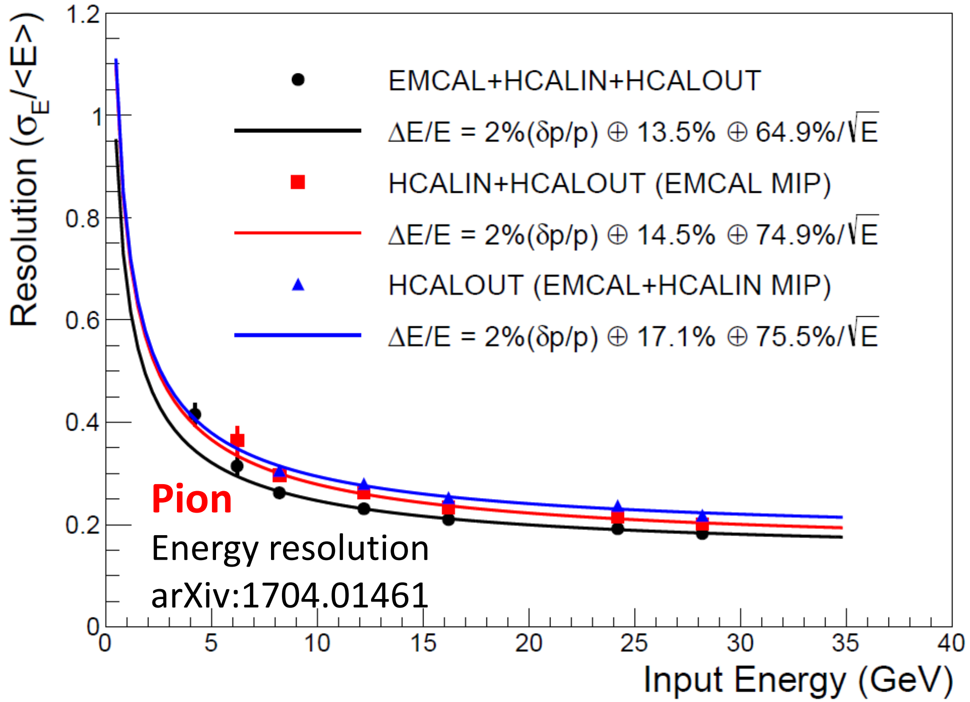
GEANT simulations verified with test beam data

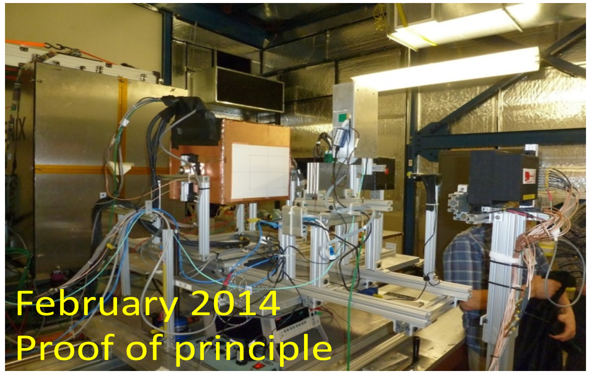




Test Beam Data: EMCal & HCal



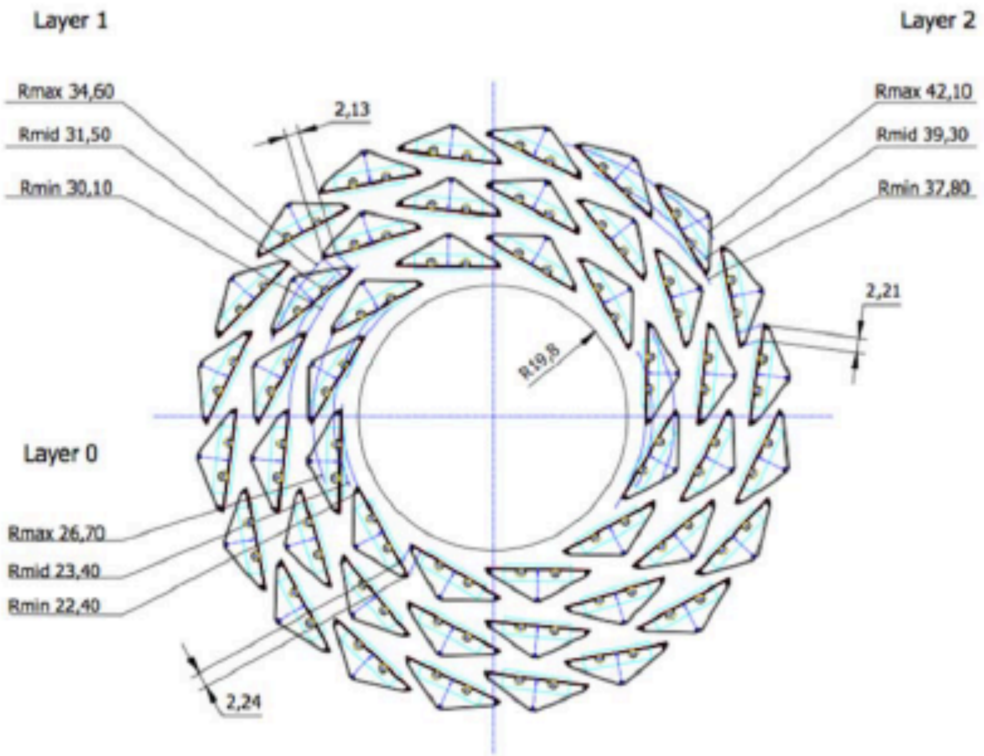




Monolithic-Active-Pixel-Sensor (MAPS) based VerTeX detector
-- for Open Heavy Quark Measurements

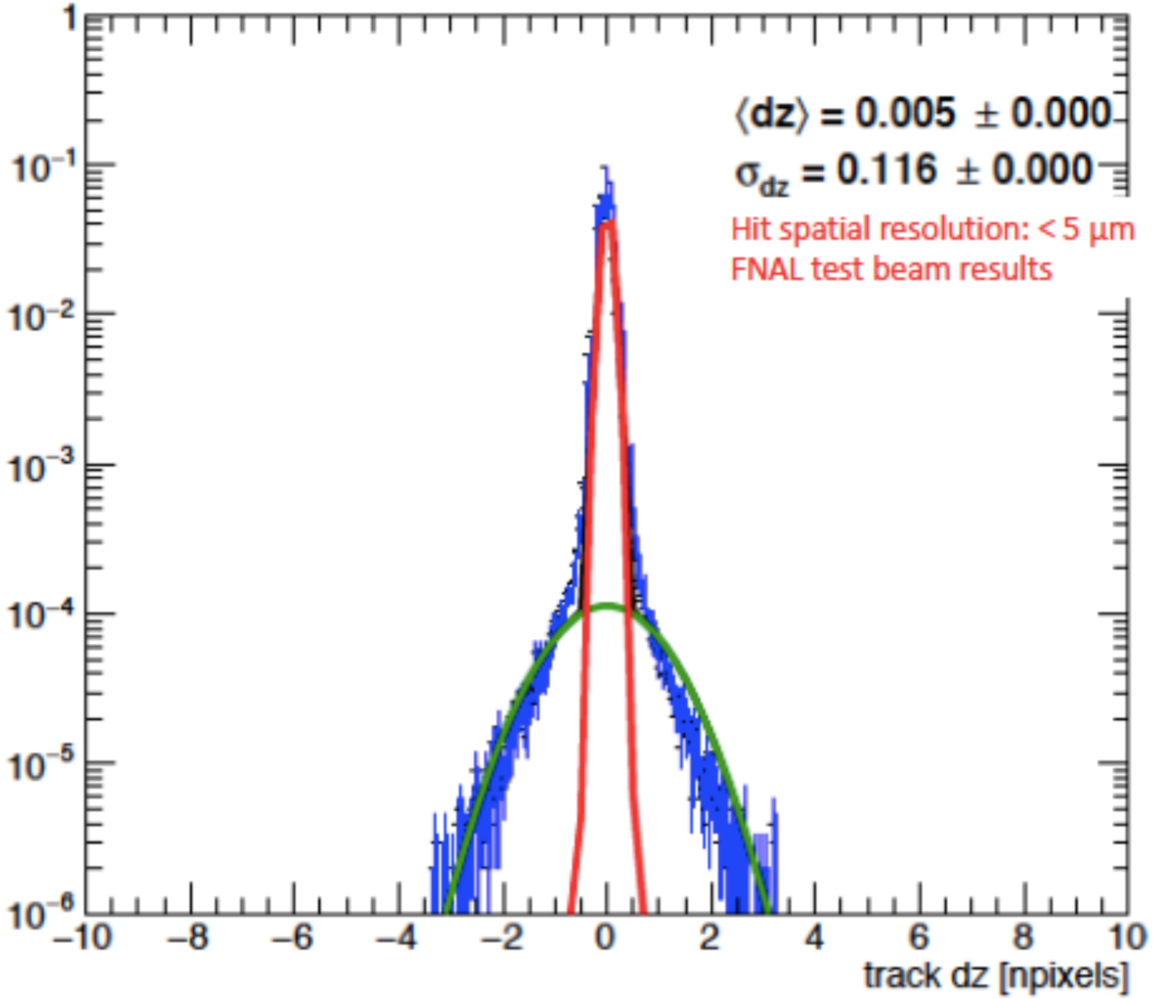
sPHENIX

Stave layout beam view



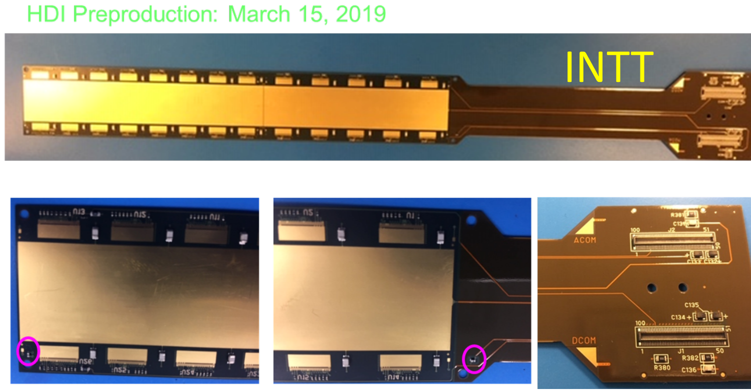
MVTX based on copy of ALICE staves with support structure modified for sPHENIX

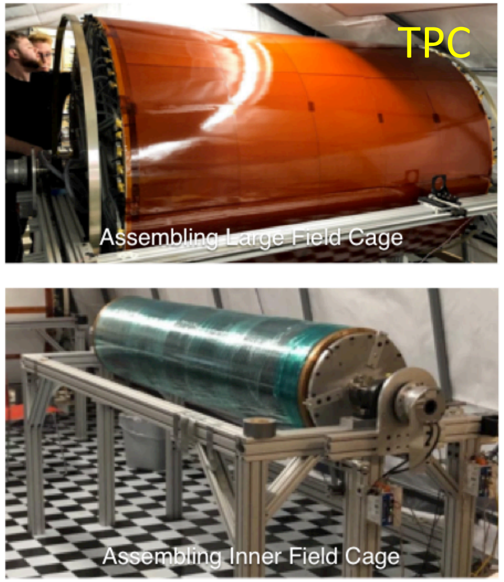
MVTX spatial resolution

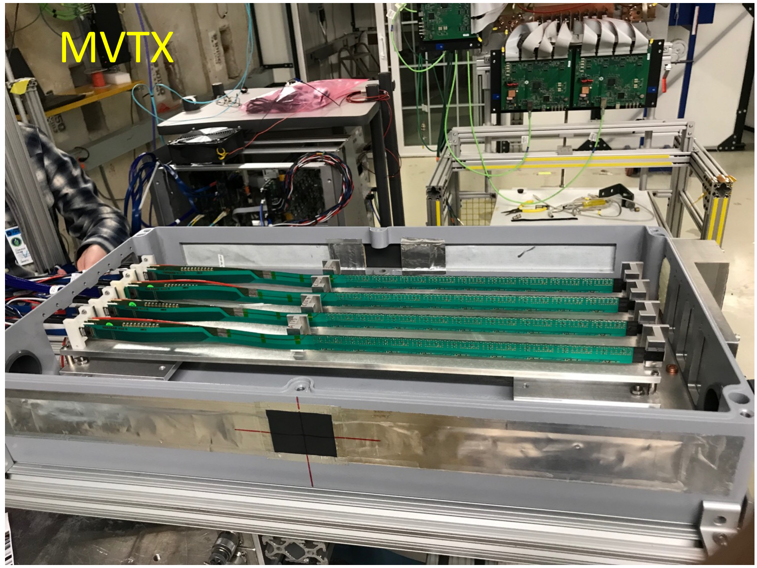


Detector Status and Highlights

- All 32 oHCAL sectors received at BNL
- EMCAL sector 0 assembled at BNL
- TPC GEM pre-production started
- MVTX staves and Readout Units production in progress
- Successful MVTX, INTT, TPC beam tests at FNAL







Evolving sPHENIX Run Plan

Year	Species	Energy [GeV]	Phys. Wks	Rec. Lum.	Samp. Lum.	Samp. Lum. All-Z
Year-1	Au+Au	200	16.0	7 nb^{-1}	8.7 nb^{-1}	34 nb^{-1}
Year-2	p+p	200	11.5	—	48 pb^{-1}	267 pb^{-1}
Year-2	p+Au	200	11.5	—	0.33 pb^{-1}	1.46 pb^{-1}
Year-3	Au+Au	200	23.5	14 nb^{-1}	26 nb^{-1}	88 nb^{-1}
Year-4	p+p	200	23.5	—	149 pb^{-1}	783 pb^{-1}
Year-5	Au+Au	200	23.5	14 nb^{-1}	48 nb^{-1}	92 nb^{-1}

1^{st} campaign

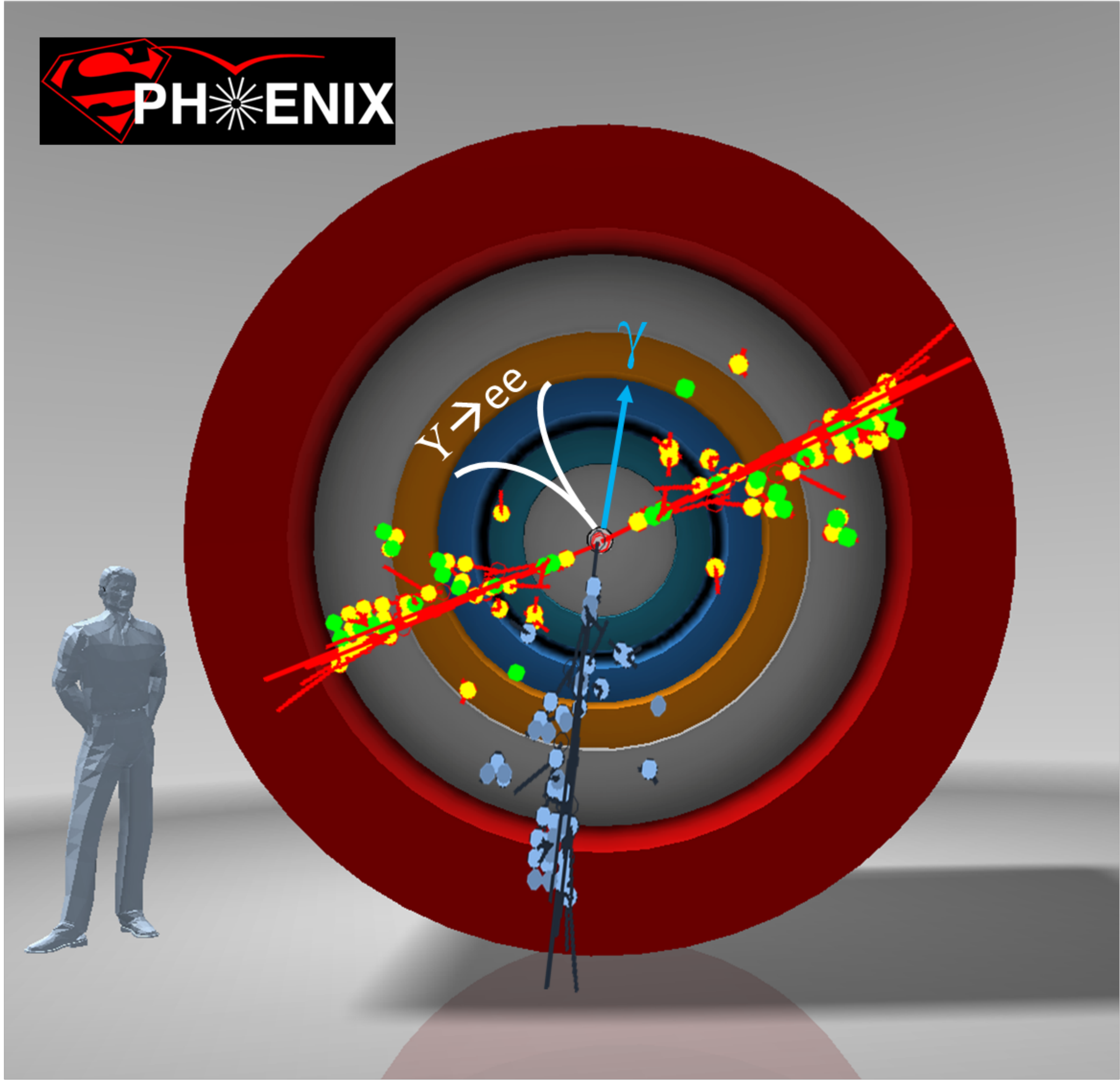
2^{nd} campaign

- Guidance from ALD to think in terms of a multi-year run plan
- Consistent with language in DOE CD-0 "mission need" document
- Incorporates BNL C-AD guidance on luminosity evolution
- Incorporates commissioning time in first year

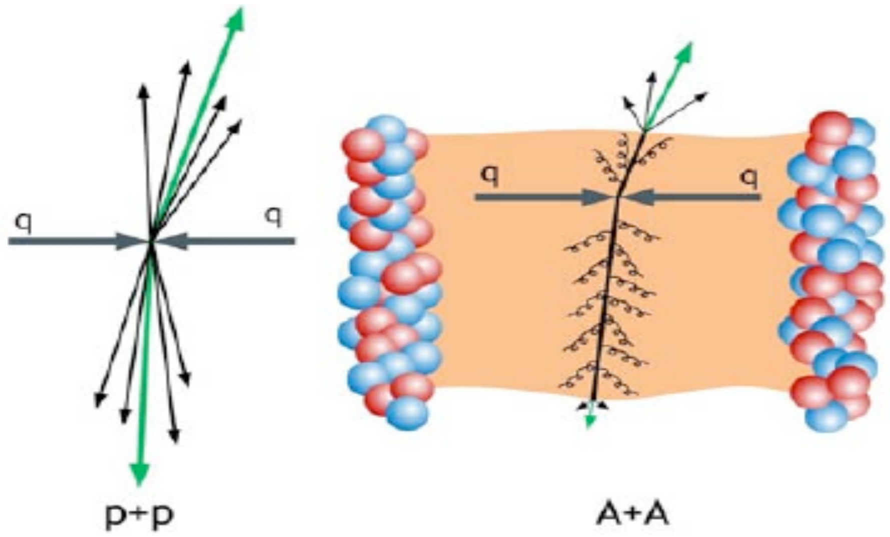
Minimum bias Au+Au at 15 kHz for |z| < 10 cm:
47 billion (Year-1) + **96 billion** (Year-3) + **96 billion** (Year-5) = Total **239 billion events**

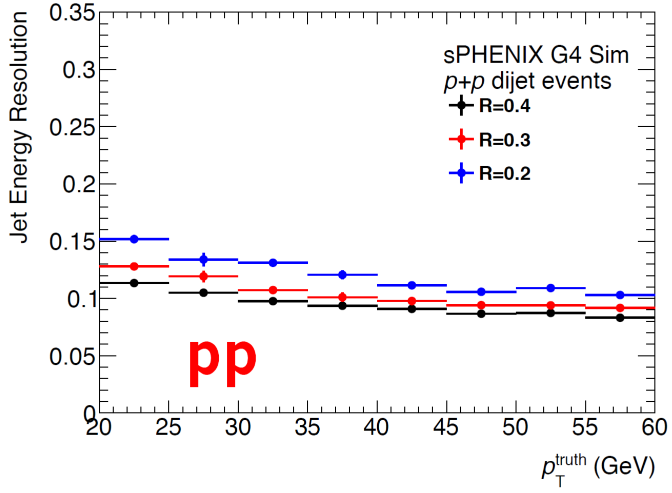
sPHENIX 3 Physics Pillars

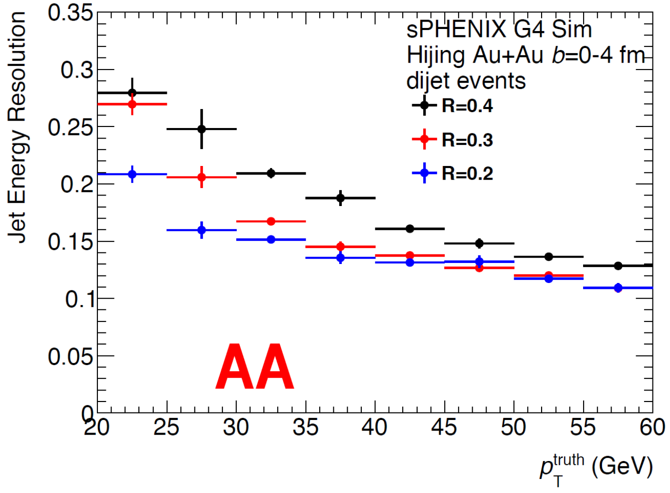
1. Jets and photons
2. Upsilons
3. Open Heavy Quarks

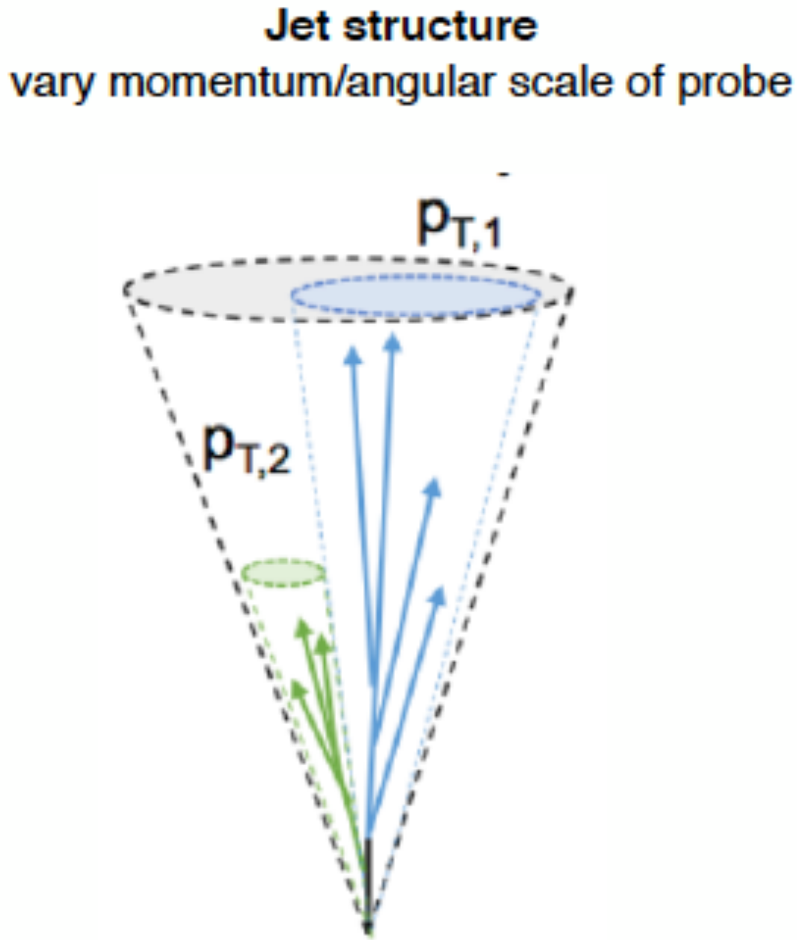


(I): Precision Calorimetry + Tracking for Jets and Photons









Calorimeter jets + **precision tracking** for jet reconstruction and jet structure - New era in RHIC HI jet physics!

Key Observable: Direct Photon Tagged Jets

γ+Jet momentum balance

$$X_{\mathrm{jet},\gamma} = \frac{p_T^{jet}}{p_T^{\gamma}}$$

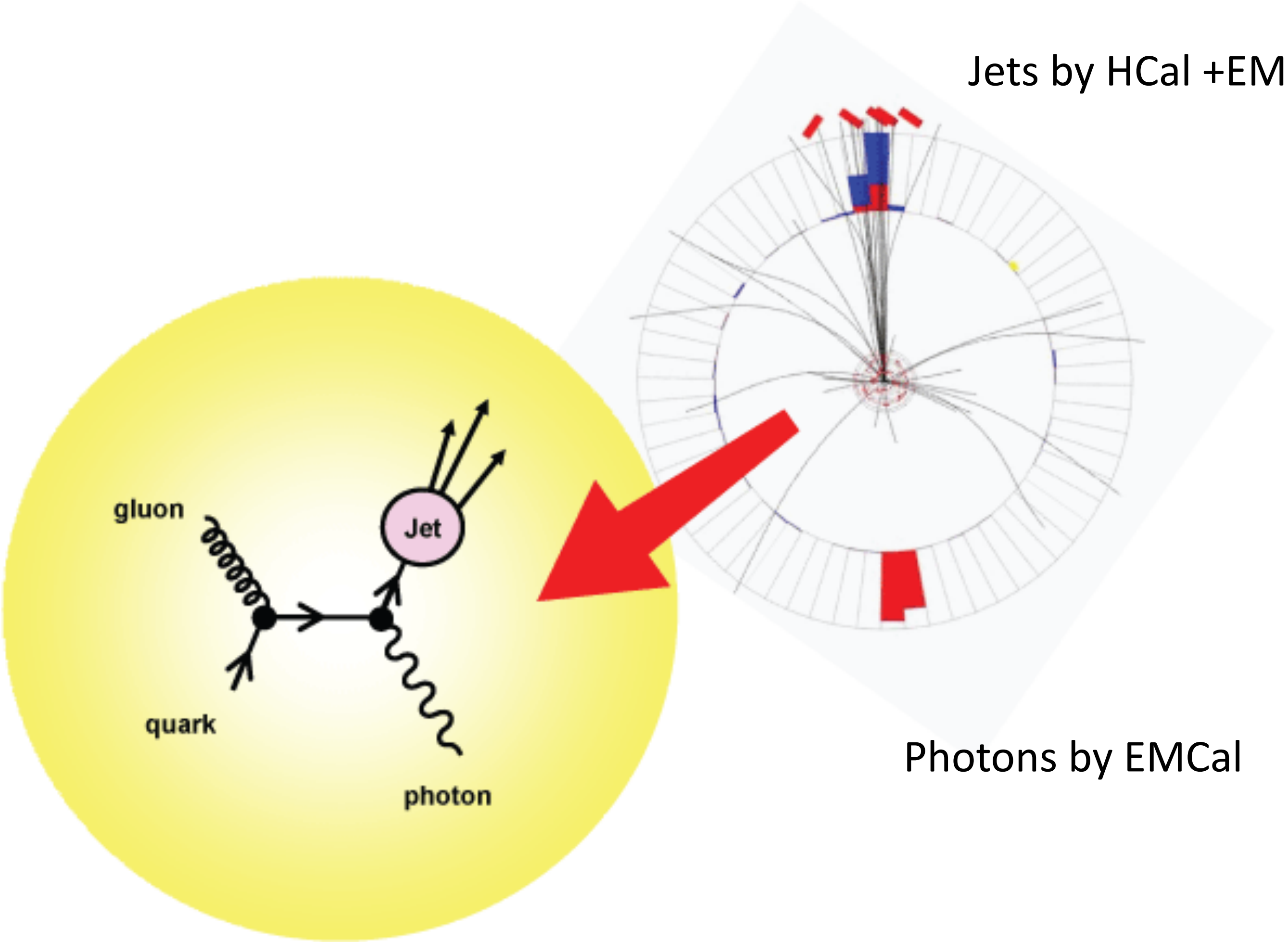
Parton energy loss in QGP

Jet fragmentation in QGP

Jet shape modification

Mostly quark jets: ~80%

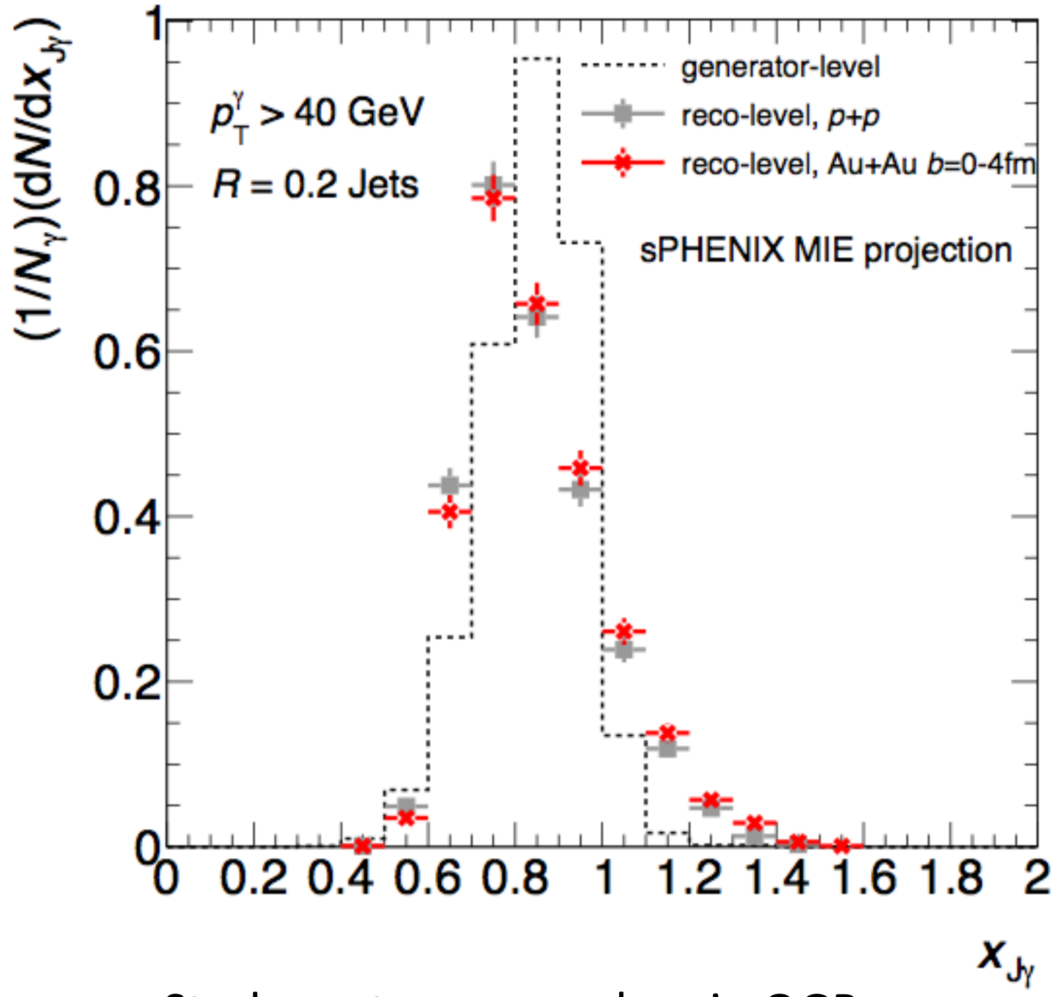
Jets by HCal +EMCal



Photons by EMCal

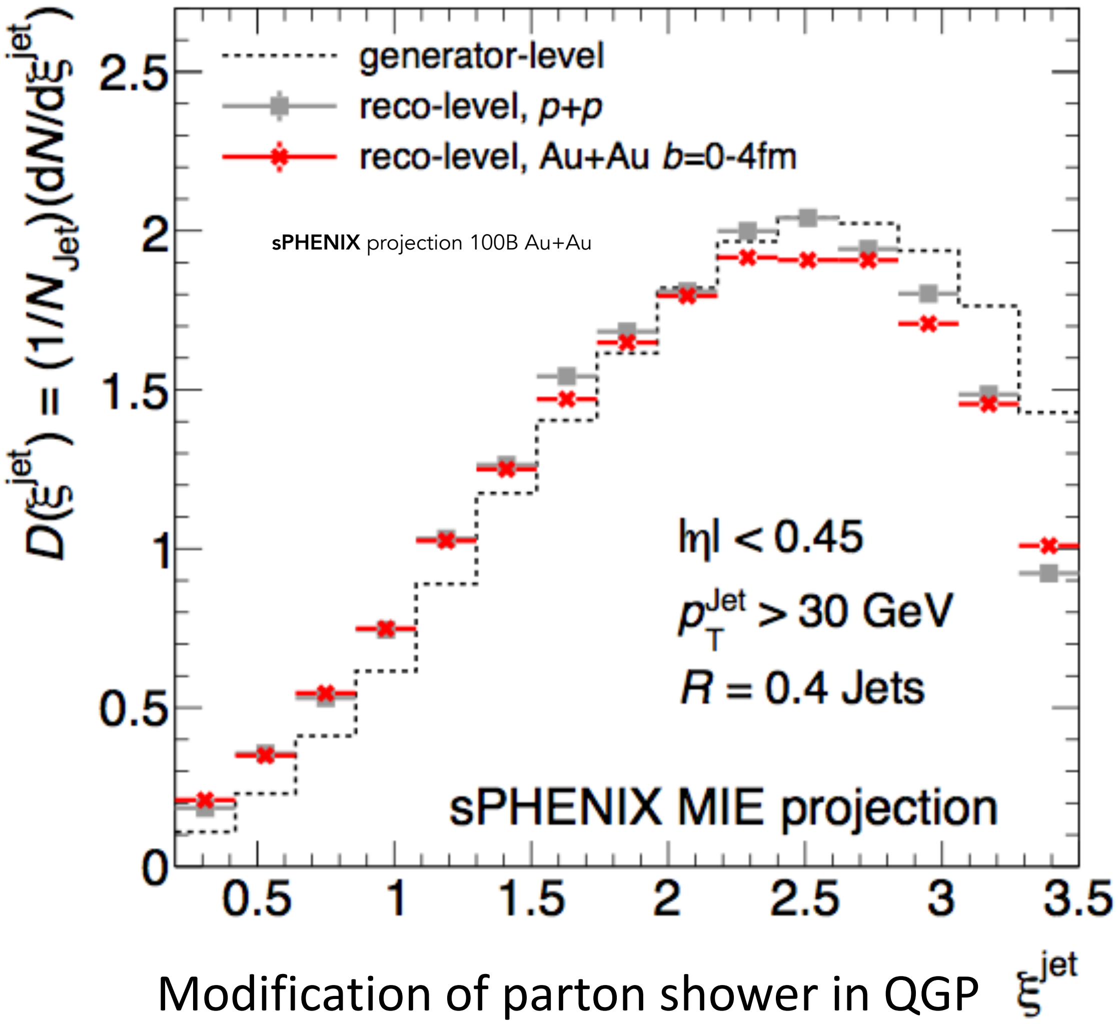
Modification of Photon-tagged Jets

γ+Jet momentum balance



Study parton energy loss in QGP

γ+Jet fragmentation function

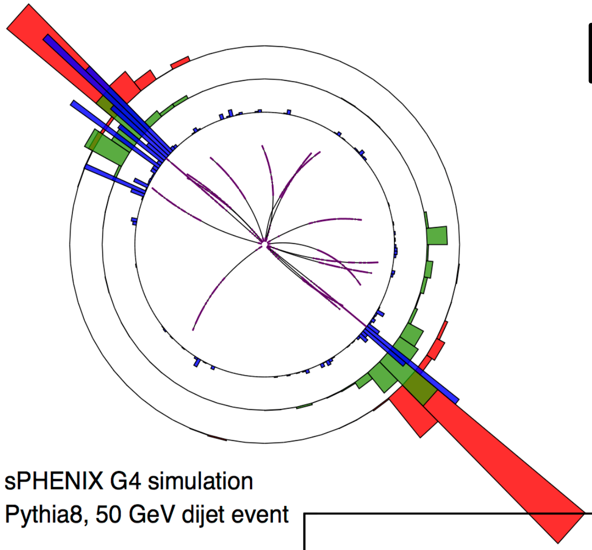


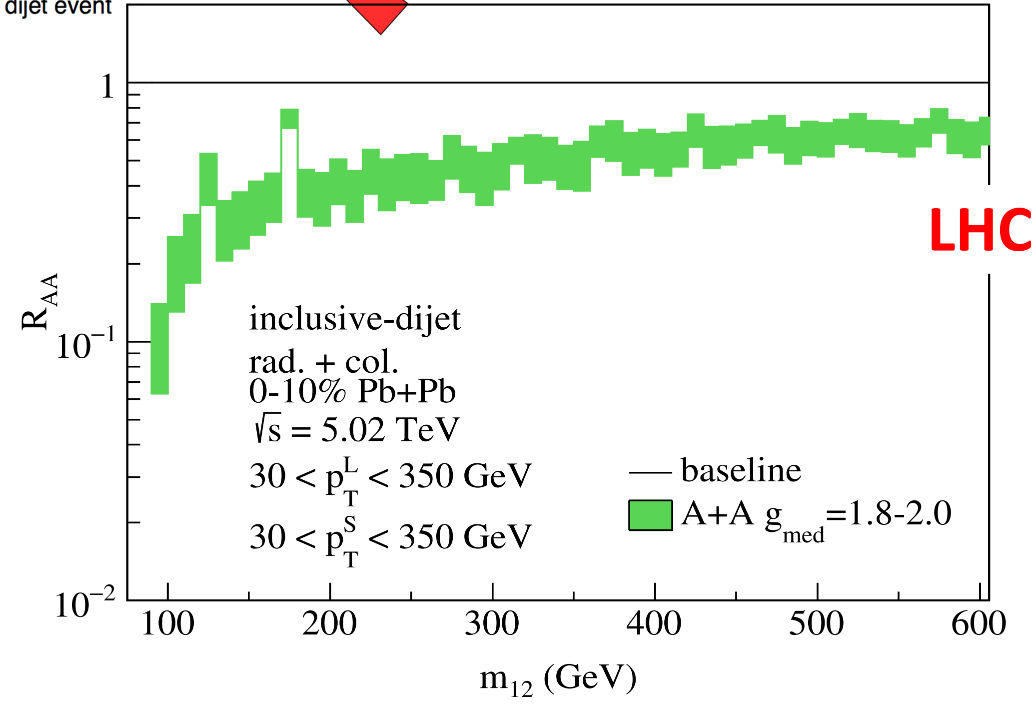
Modification of parton shower in QGP

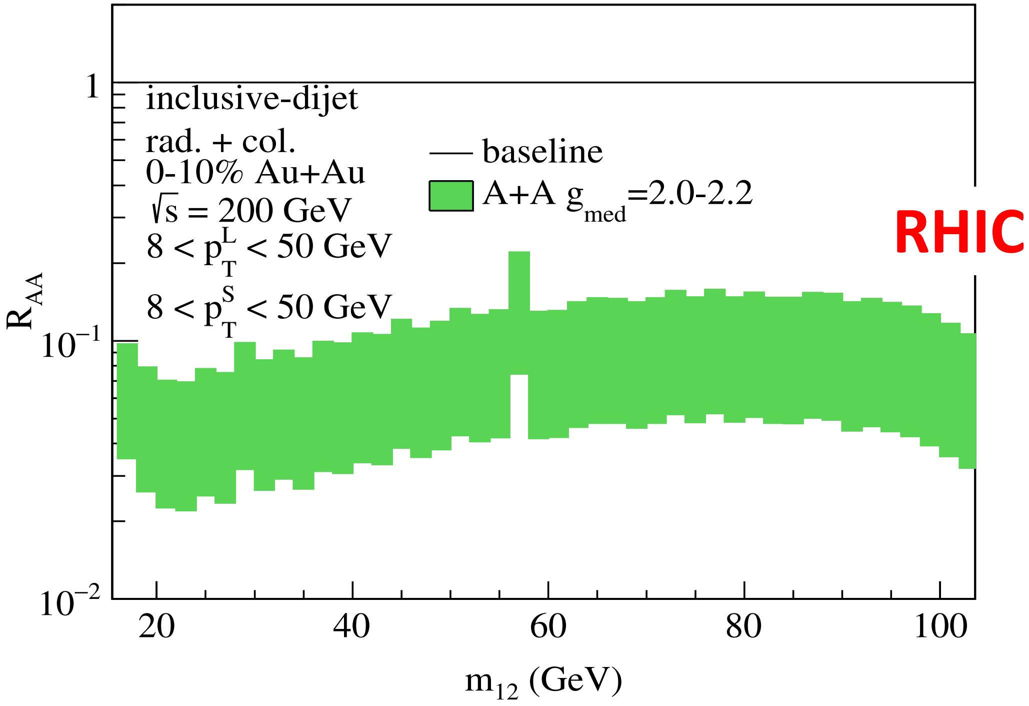
Di-Jets Modification: LHC vs RHIC

Increased coupling at low energy to the medium near T_c

→ stronger di-jet suppression expected at RHIC







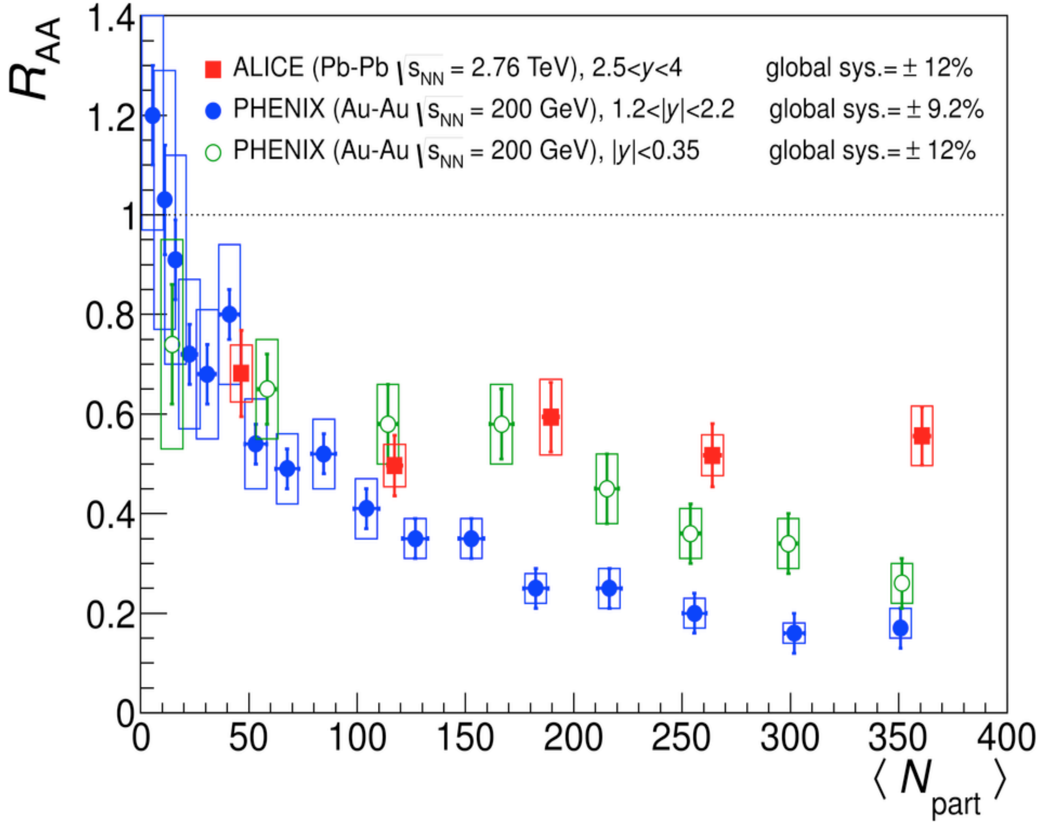
Z-B Kang, J Reiten, I Vitev, B Yoon, "Light and heavy flavor dijet production and dijet mass modification in heavy ion collisions", Phys. Rev. D99 034006 (2019)

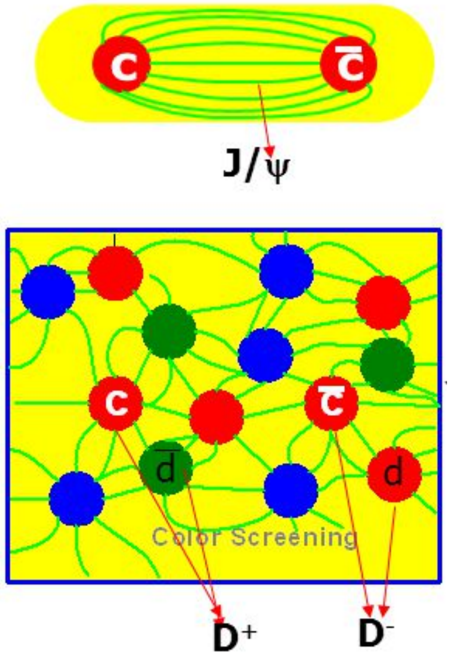
(II) J/Psi Suppression Observed, w/ Surprises, @RHIC and LHC

1. QGP Suppression
   - Color screening
   - Breakup w/ "co-movers"
2. Regeneration
   - Coalescence of many c-cbar pairs produced in A+A

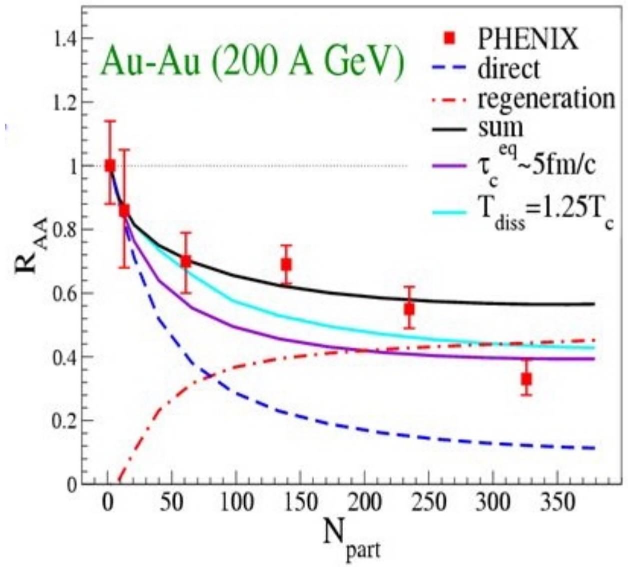
Upsilons! – focus of sPHENIX

- No regeneration





Zhuang et al.

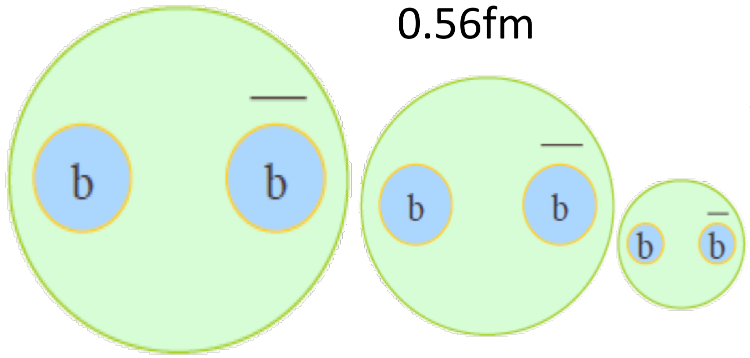


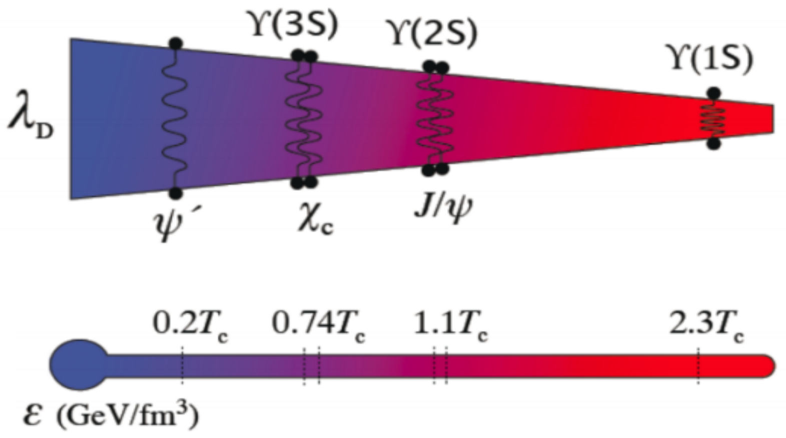
Upsilon Spectroscopy at RHIC

Υ(3s)- 0.78fm

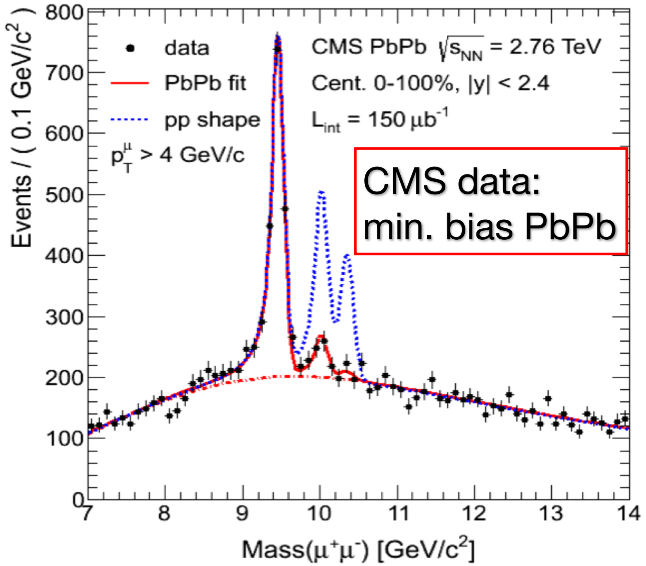
Υ(2s) – 0.56fm

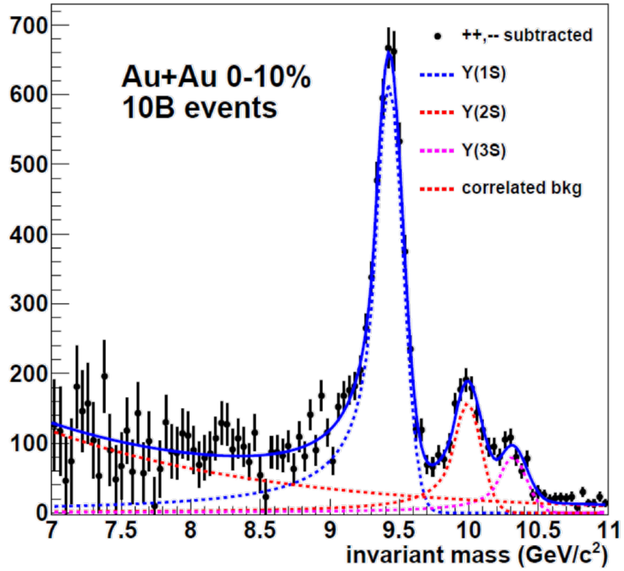
Υ(1s) – 0.28fm

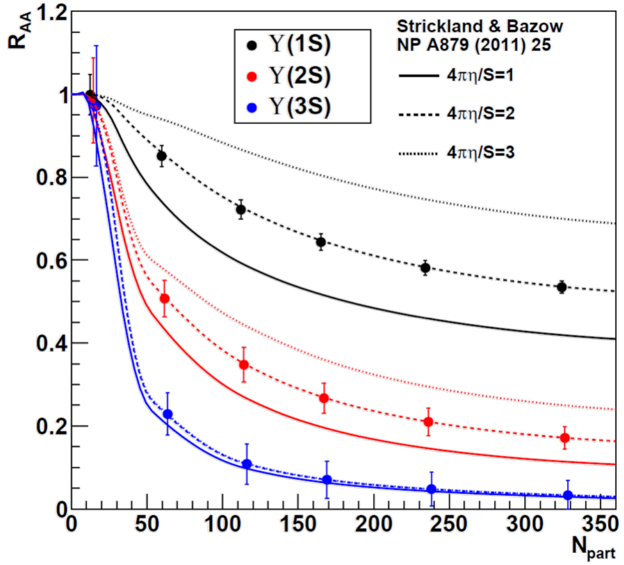




sPHENIX: Thermometer of QGP via clean separation of three Upsilon states

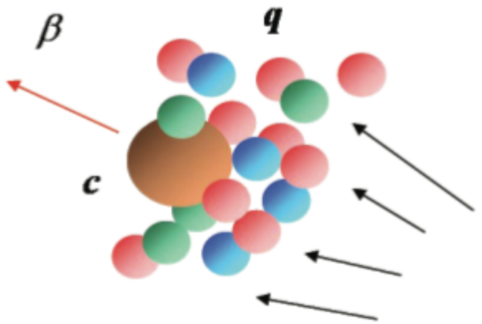




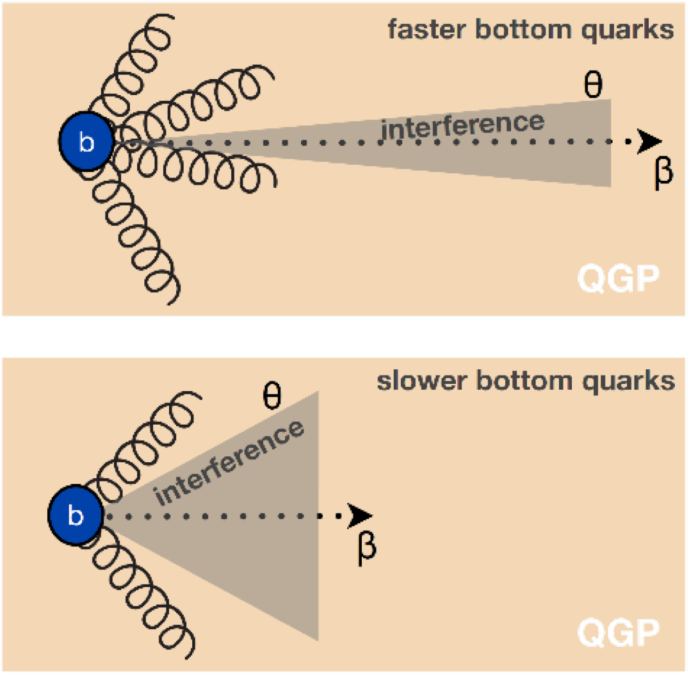


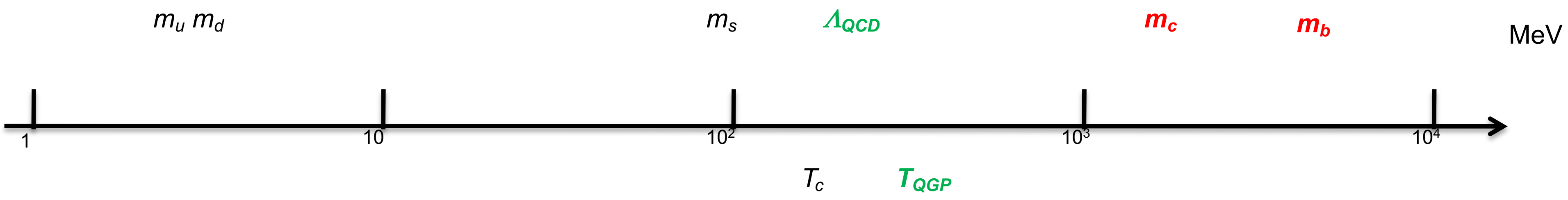
(III): Heavy Quarks - Unique Probe of QGP

- Study mass dependence
  - Jet quenching
  - “Flow” – interaction with medium
- Access QGP properties



Mass dependent radiation dE/dx

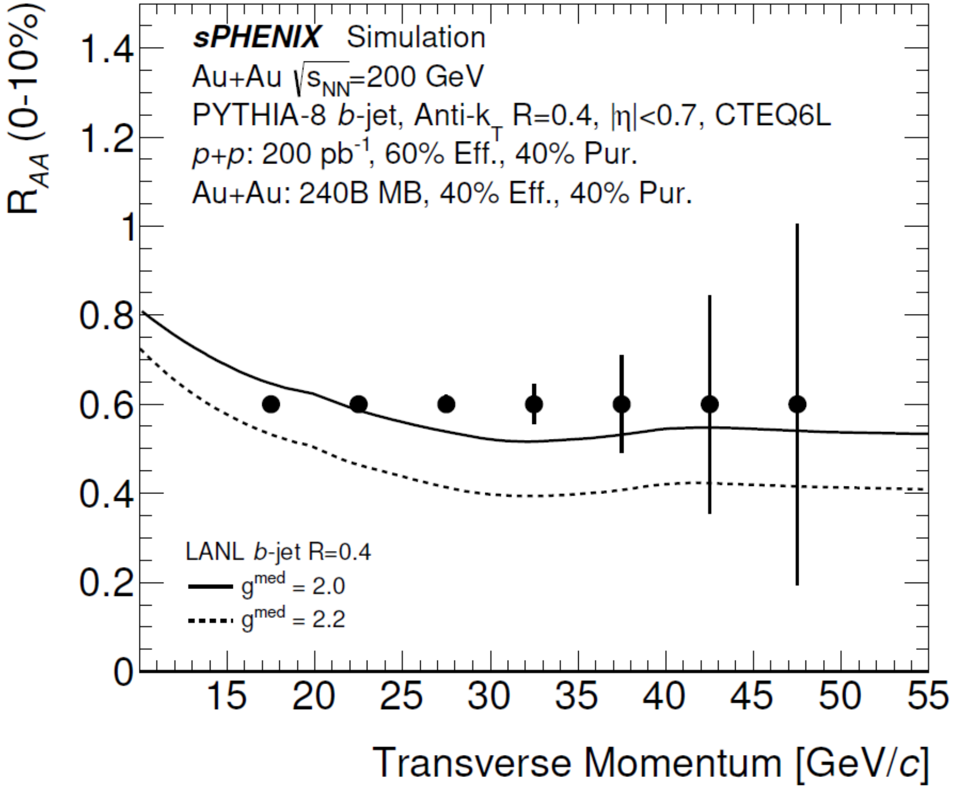




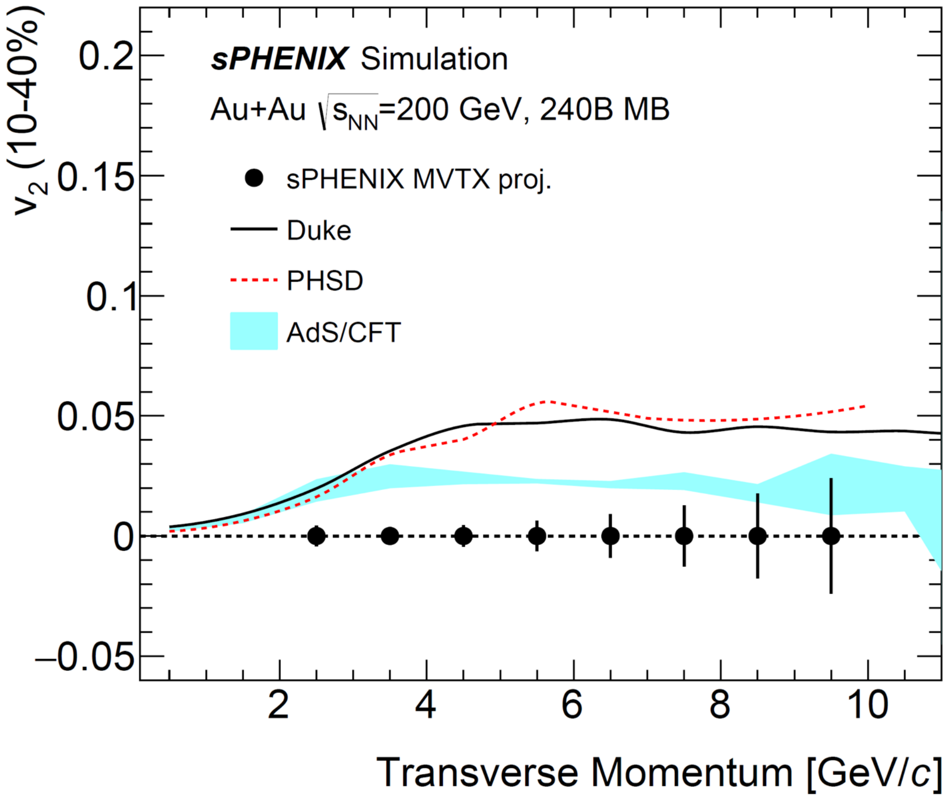
B-Hadron and b-jet Projections

- Inclusive B-hadron/b-jet suppression and v_2 at RHIC
- Strong constraints on energy loss model of high energy probe in QGP
- Bottom quark collectivity → clean access to D_{HQ} at RHIC energy

Inclusive b-jet R_{AA}

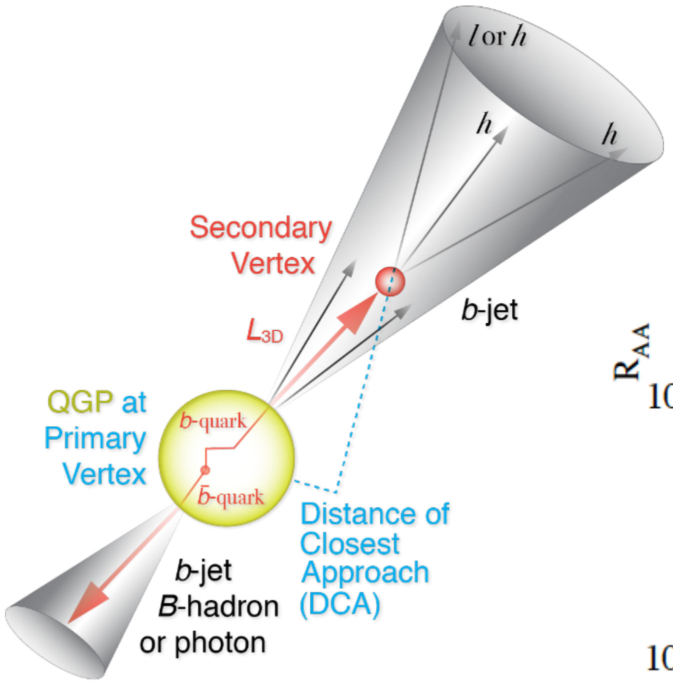


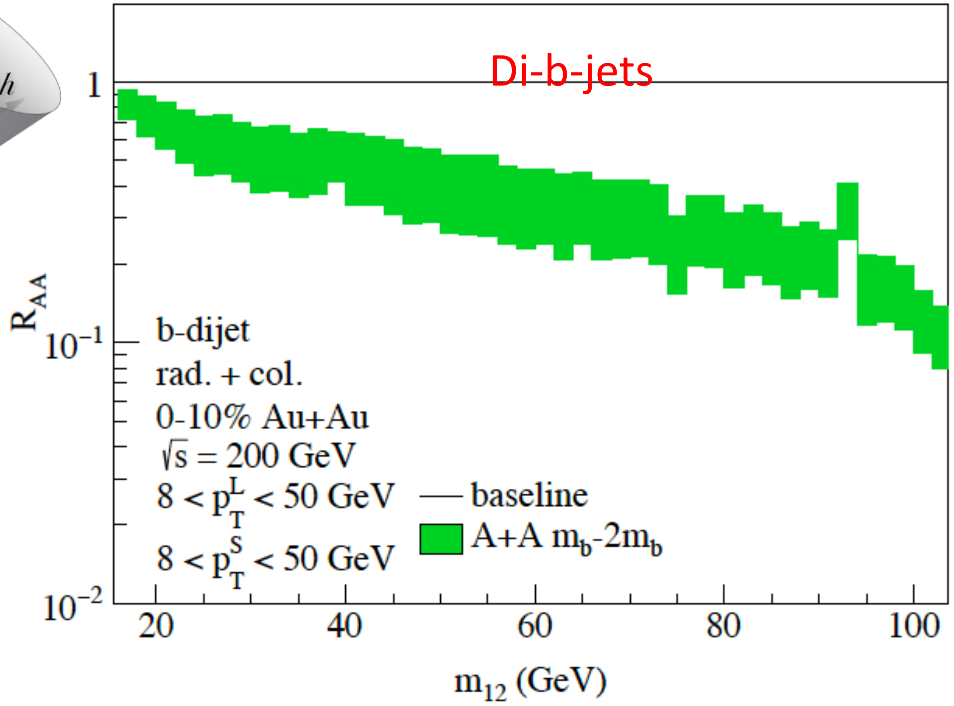
non-prompt *D*-meson and predictions for sPHENIX

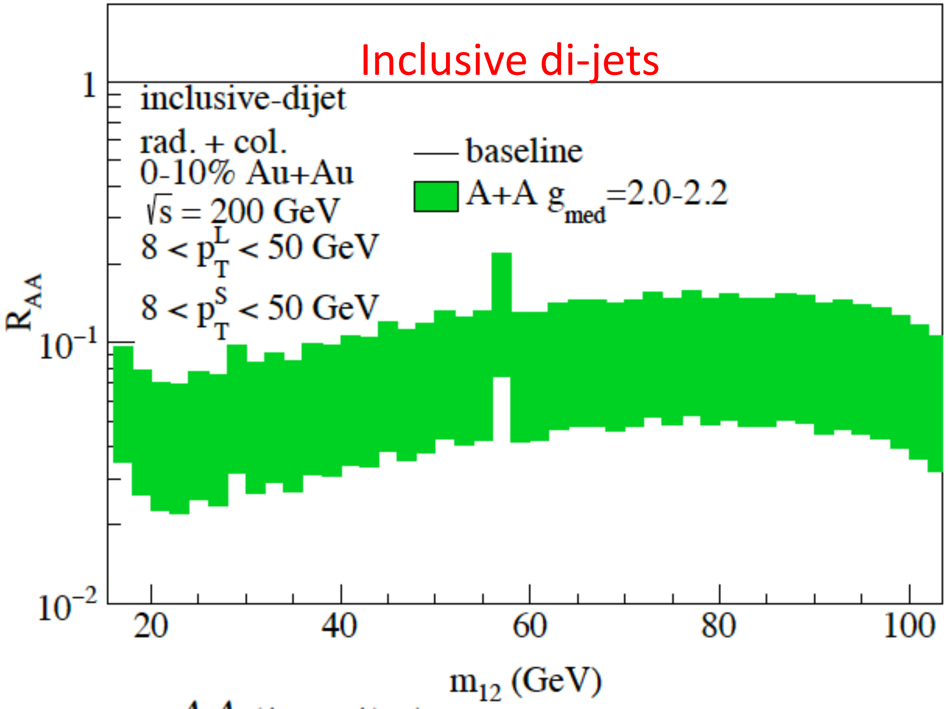


Di-b-Jet Modifications

Jared's talk: Monday



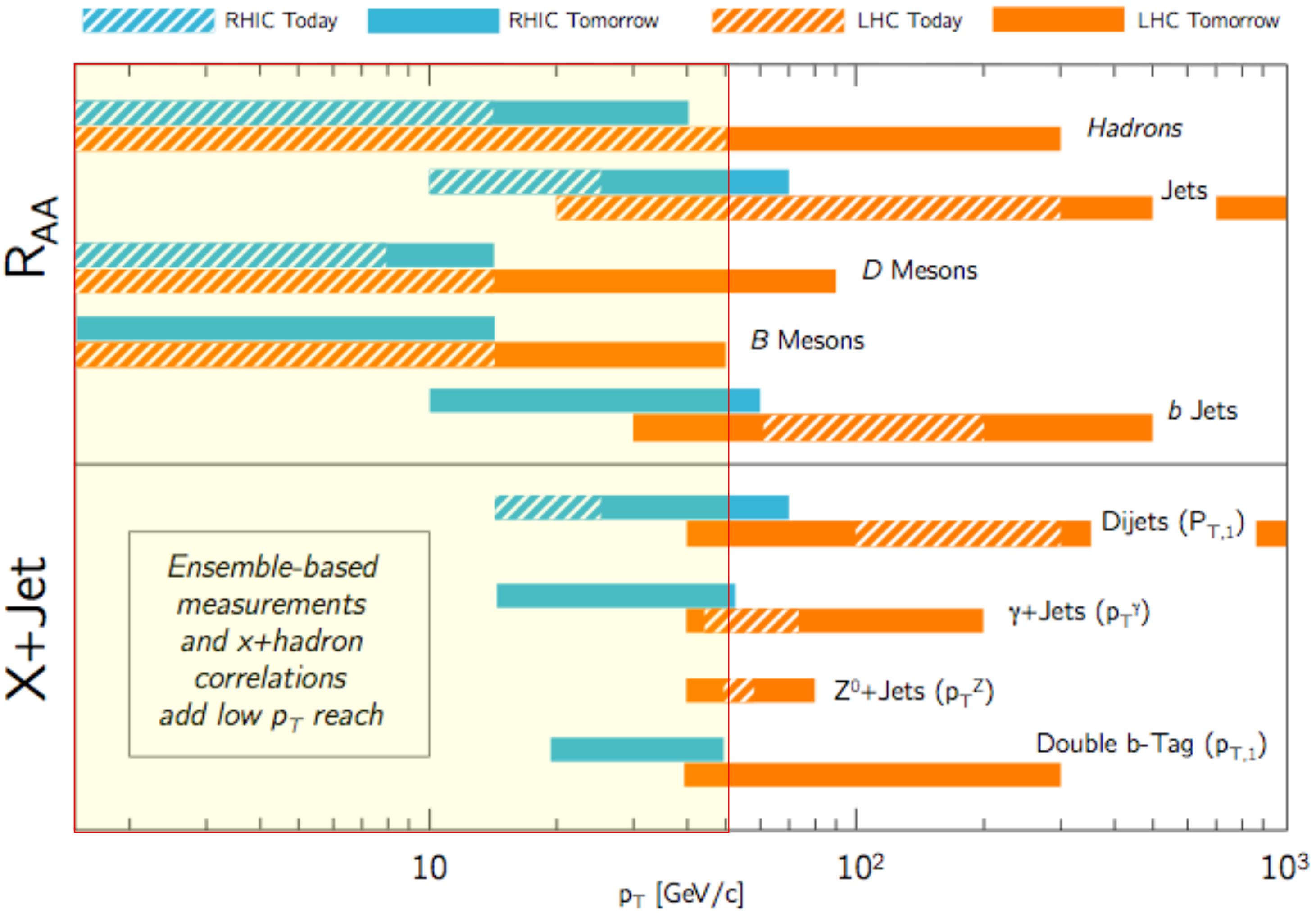




$$R_{AA}(m_{12}, |\mathbf{b}_\perp|) = \frac{1}{\langle N_{\rm bin}\rangle} \frac{d\sigma^{AA}(|\mathbf{b}_\perp|)/dm_{12}}{d\sigma^{pp}/dm_{12}}$$

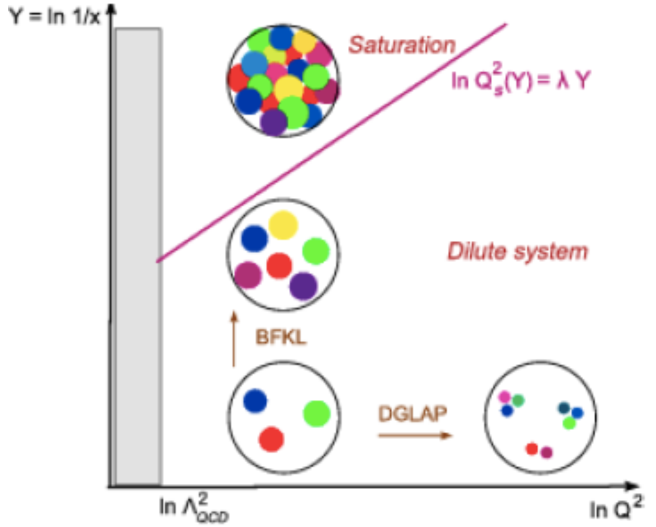
sPHENIX Complements LHC Measurements

- Excellent coverage at low-medium pT
- Precision measurements with high statistics
- Larger QGP effects at RHIC for many observables at low pT
- Same probes at RHIC and LHC

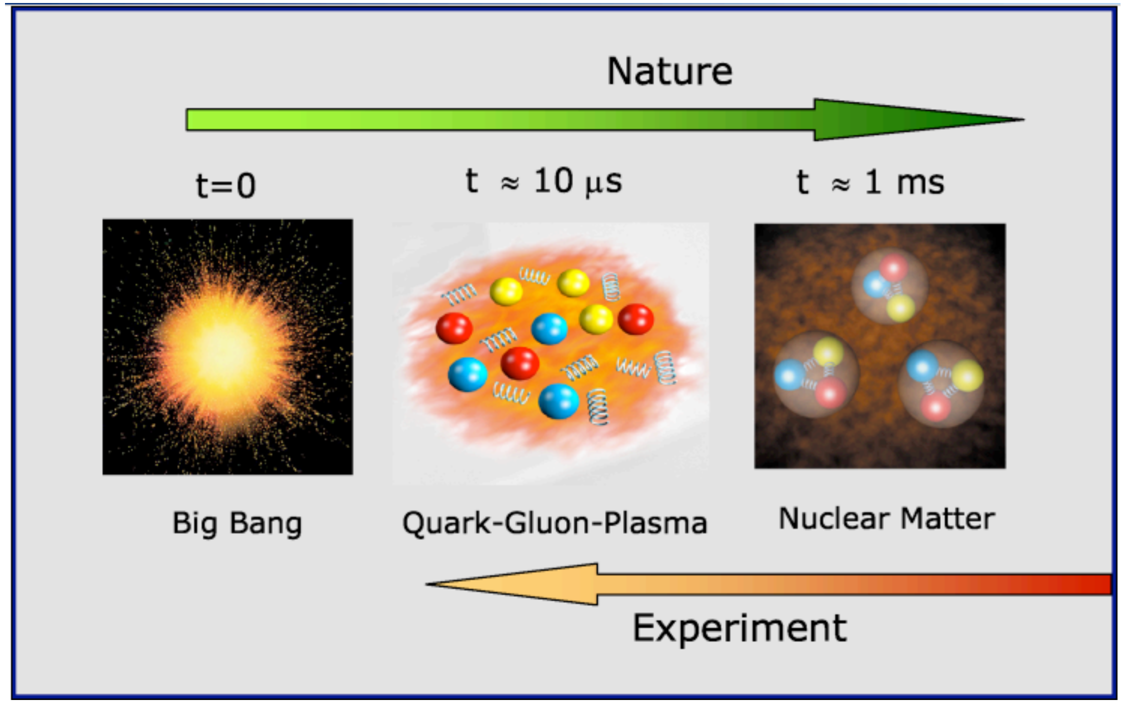


A Broad Physics Program with sPHENIX

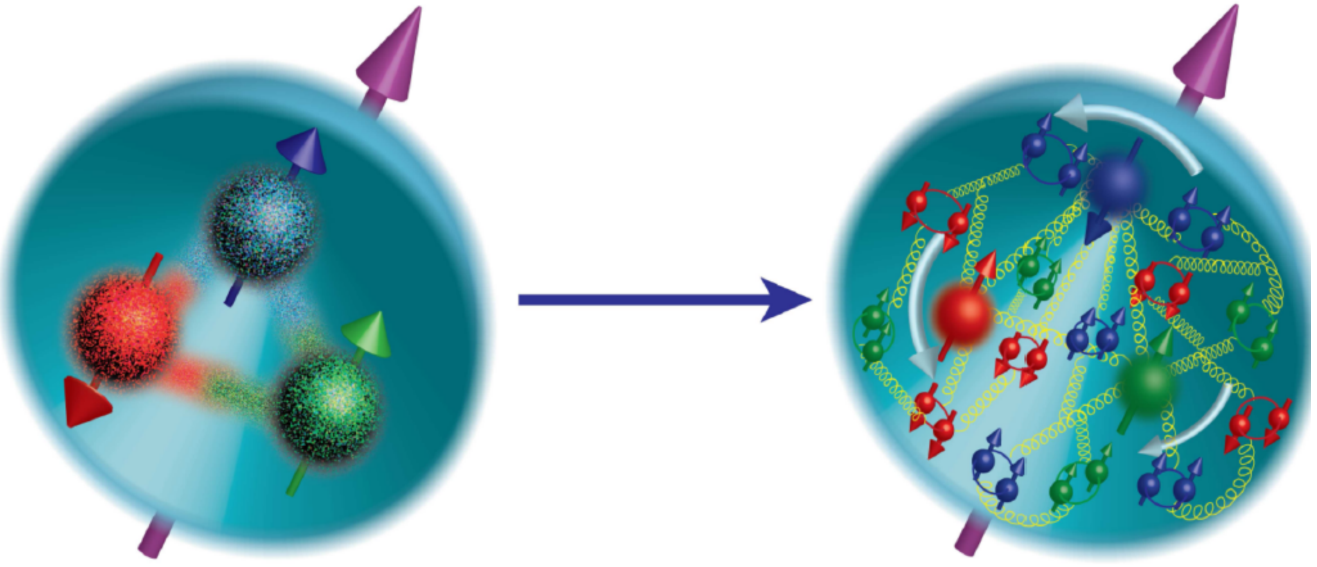
- Nuclear matter under extreme condition, "QGP"
- Nucleon and nuclear structures, novel QCD dynamics, "Cold QCD"



"Hot" QGP physics

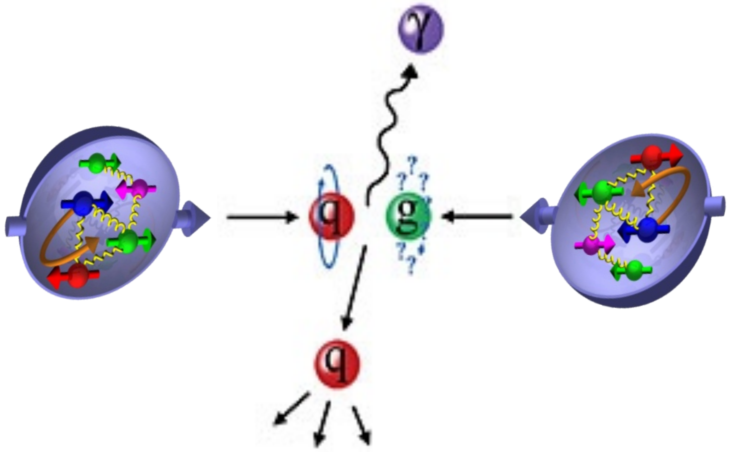


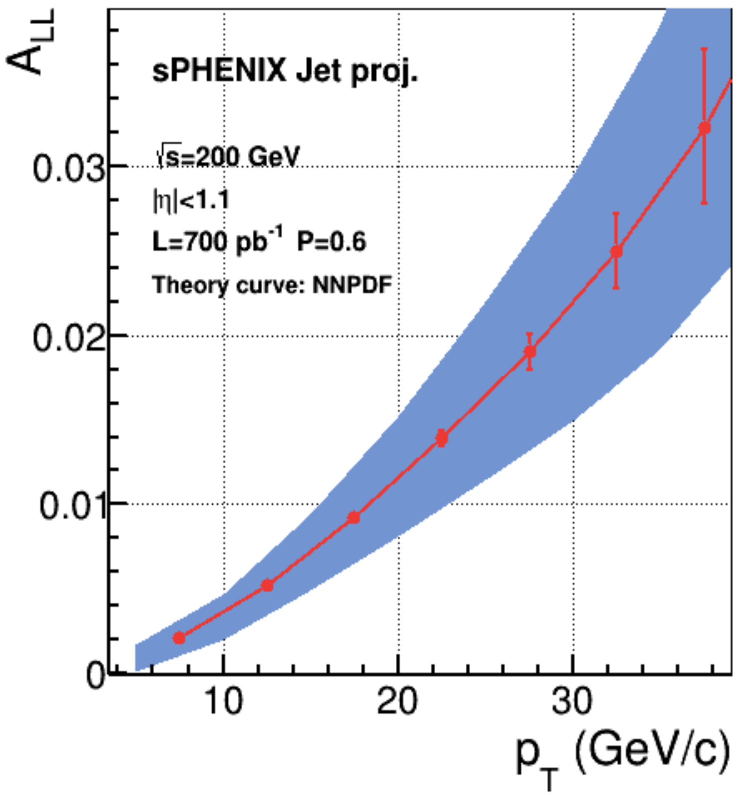
"Cold" QCD physics

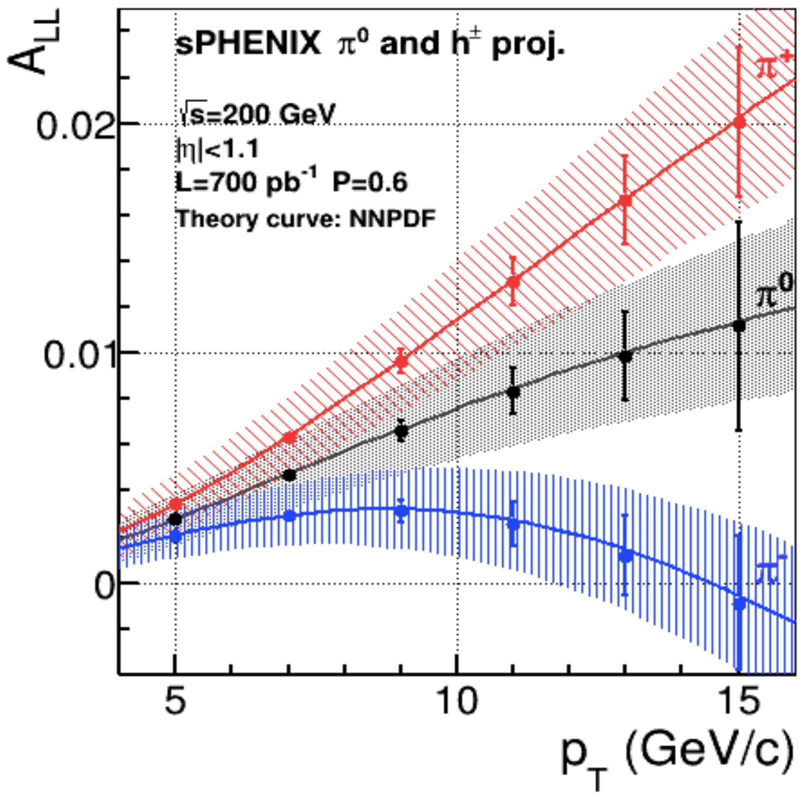


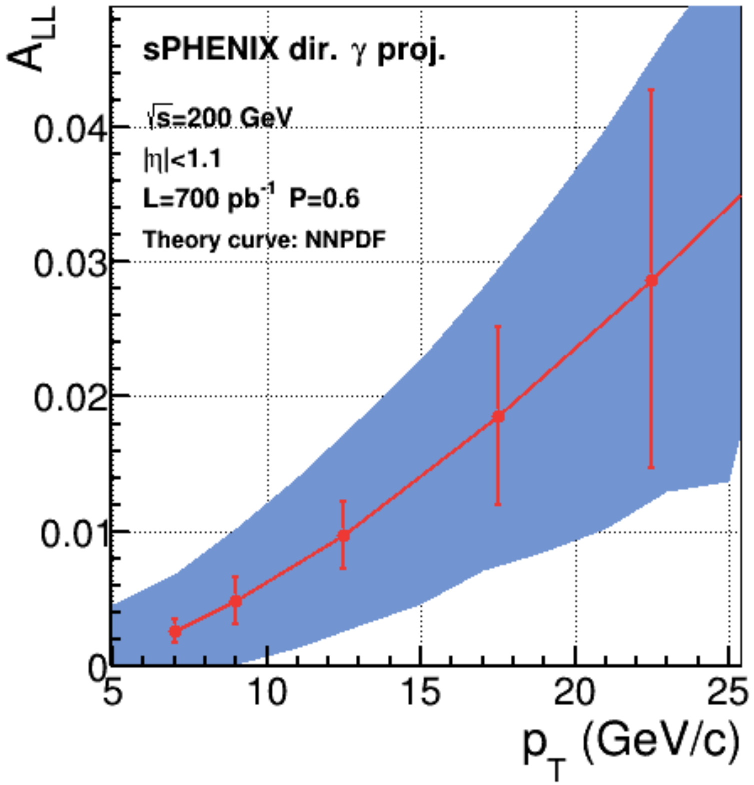
Study Gluon Polarization

- Jets, hadrons, direct photons and more

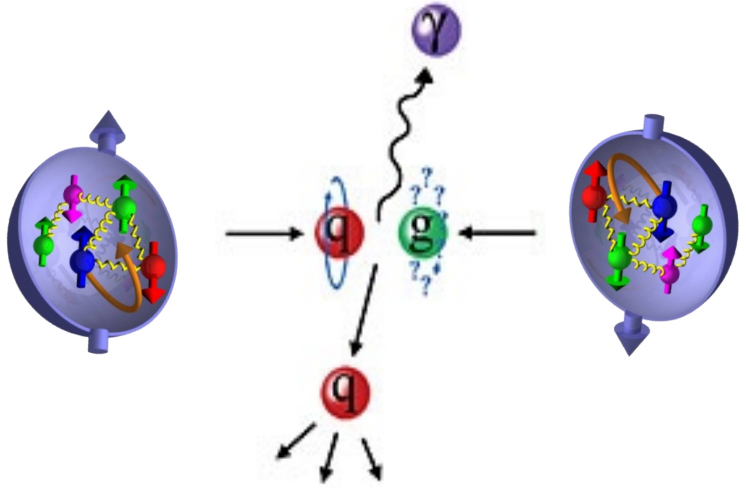


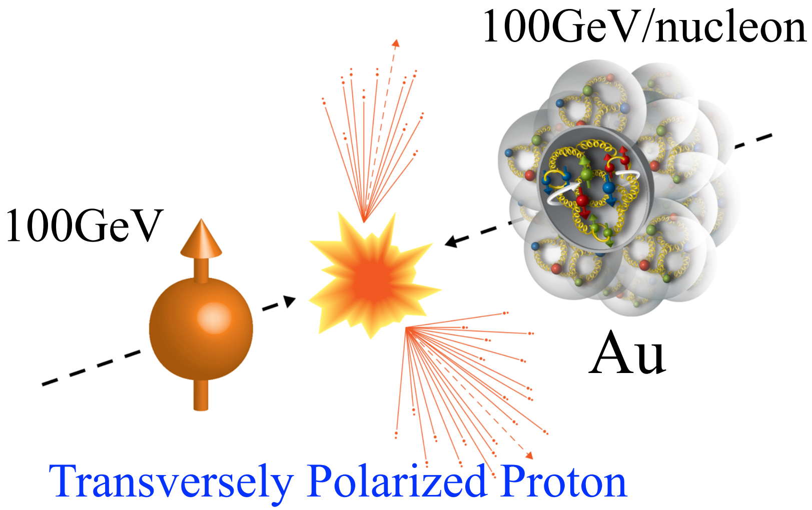


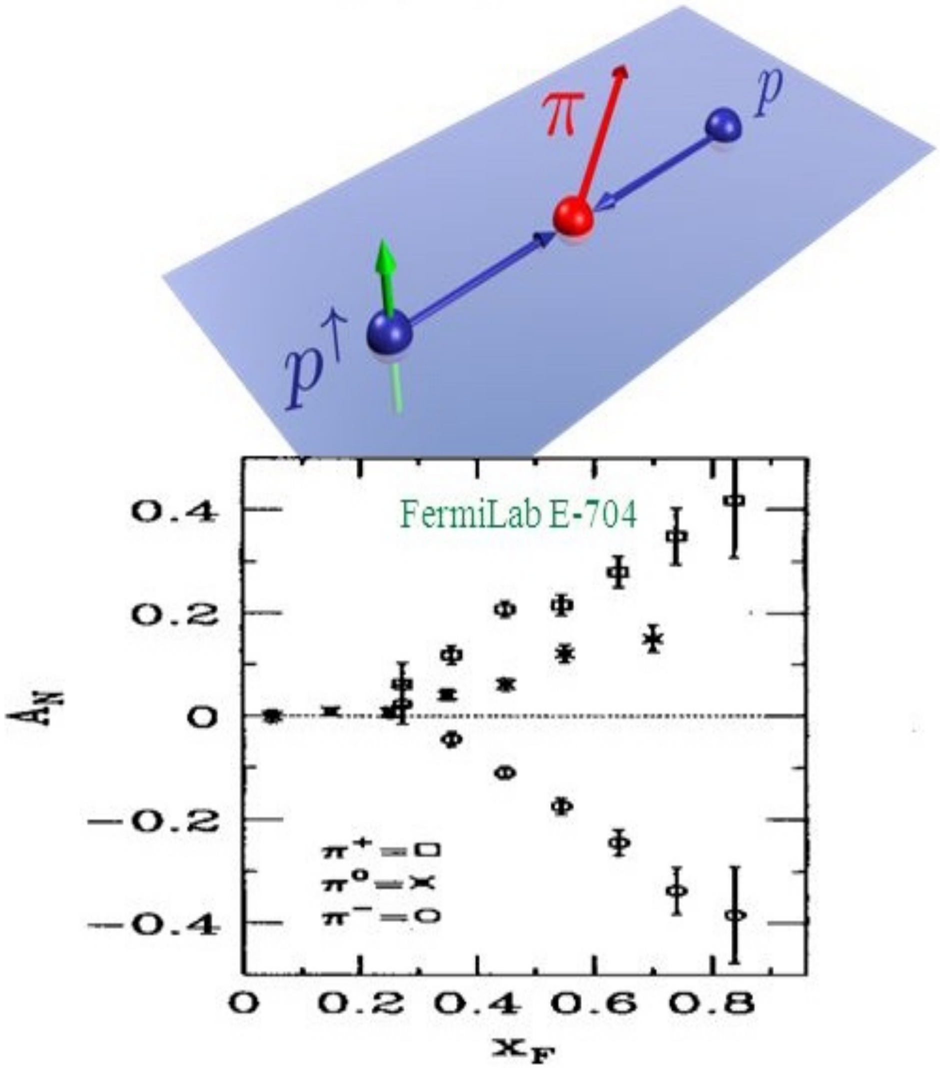




Physics with Transversely Polarized p+p/A Collisions at RHIC







Probe the Underlying Physics via Hard Scatterings TMD, Collinear Twist-3 Factorizations

sPHENIX

(i) Sivers mechanism:

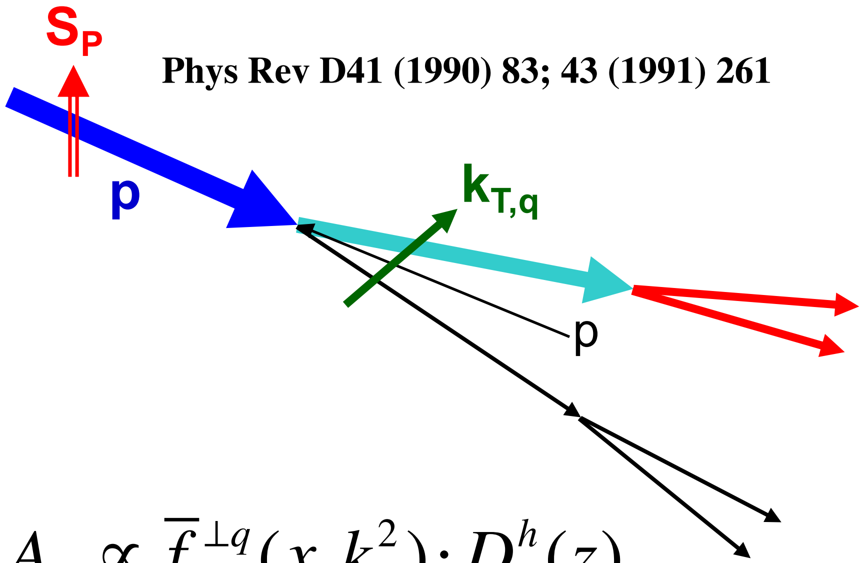
correlation proton spin & parton k_T

(ii) Collins mechanism:

Transversity × spin-dep fragmentation

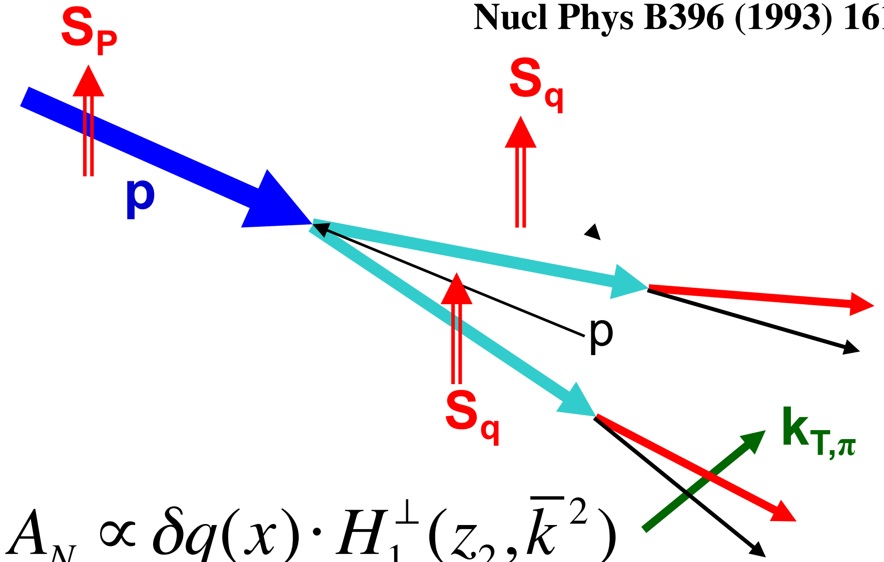
SIDIS:

Phys Rev D41 (1990) 83; 43 (1991) 261



$$A_N \propto \overline{f}_{1T}^{\perp q}(x, k_\perp^2) \cdot D_q^h(z)$$

Nucl Phys B396 (1993) 161

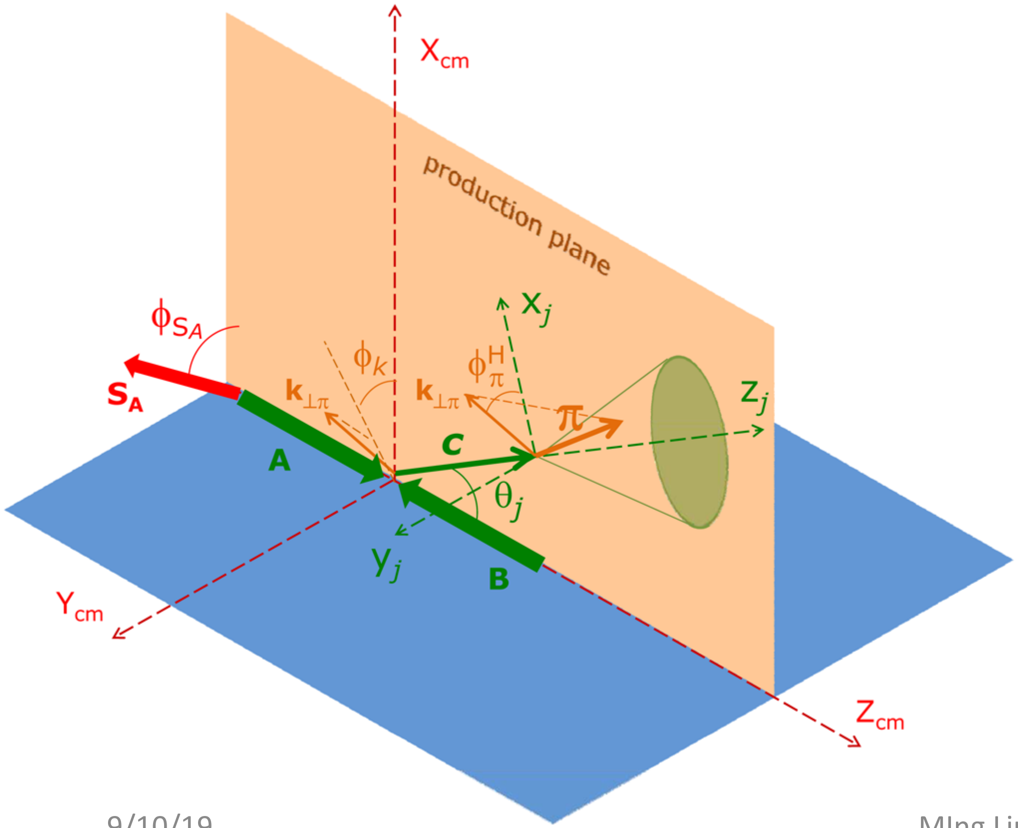


$$A_N \propto \delta q(x) \cdot H_1^\perp(z_2, \overline{k}_\perp^2)$$

p+p/A: **Collinear Twist-3 (RHIC):** quark-gluon/gluon-gluon correlations

Access Sivers and Collins with Jet and Hadron Azimuthal Distributions in Transversely Polarized p+p/A Collisions

Feng Yuan, PRL 100, 032003 (2008)
Umberto D'Alesio et al PRD 83 034021 (2011)



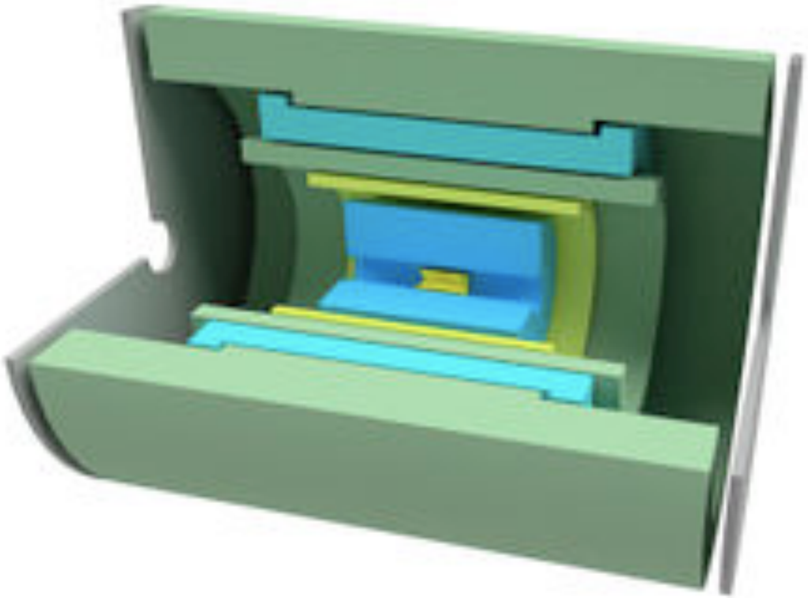
$$\frac{E_j d\sigma^{A(S_A)B\to \text{jet}+\pi+X}}{d^3\boldsymbol{p}_j dz d^2\boldsymbol{k}_{\perp\pi}} = \sum_{a,b,c,d,\{\lambda\}} \int \frac{dx_a dx_b}{16\pi^2 x_a x_b s} d^2\boldsymbol{k}_{\perp a}$$
$$\times d^2\boldsymbol{k}_{\perp b} \rho^{a/A,S_A}_{\lambda_a \lambda'_a} \hat{f}_{a/A,S_A}(x_a, \boldsymbol{k}_{\perp a}) \rho^{b/B}_{\lambda_b \lambda'_b} \hat{f}_{b/B}(x_b, \boldsymbol{k}_{\perp b})$$
$$\times \hat{M}_{\lambda_c,\lambda_d;\lambda_a,\lambda_b} \hat{M}^*_{\lambda'_c,\lambda_d;\lambda'_a,\lambda'_b} \delta(\hat{s}+\hat{t}+\hat{u}) \hat{D}^{\pi}_{\lambda_c,\lambda'_c}(z, \boldsymbol{k}_{\perp\pi}).$$

$A_N^{\sin\phi_{S_A}}$ → "Sivers-like" (Jet)

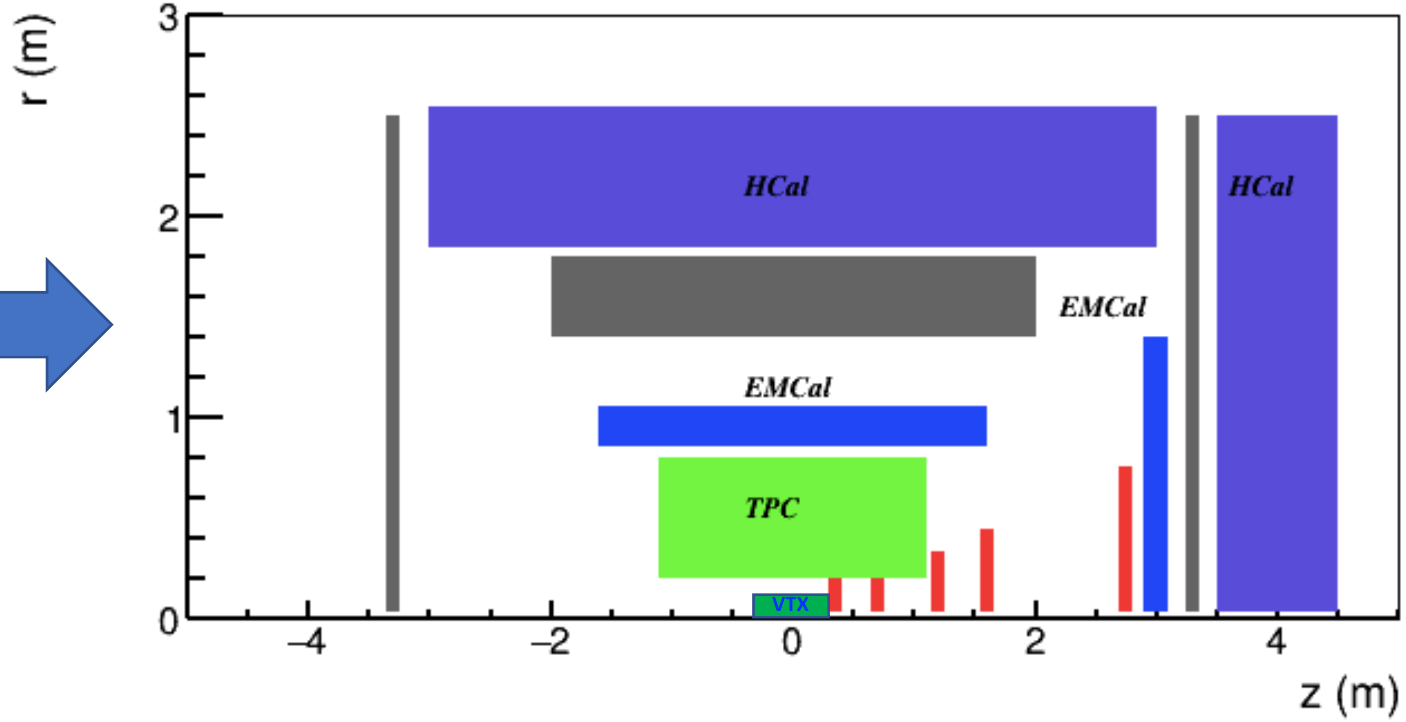
$A_N^{\sin(\phi_{S_A} \mp \phi_\pi^H)}$ → "Collins-like" (hadron)

Forward Upgrade Proposal

Forward upgrade will bring in new physics capability – TMD, small-x physics, QGP over broader kinematics etc.

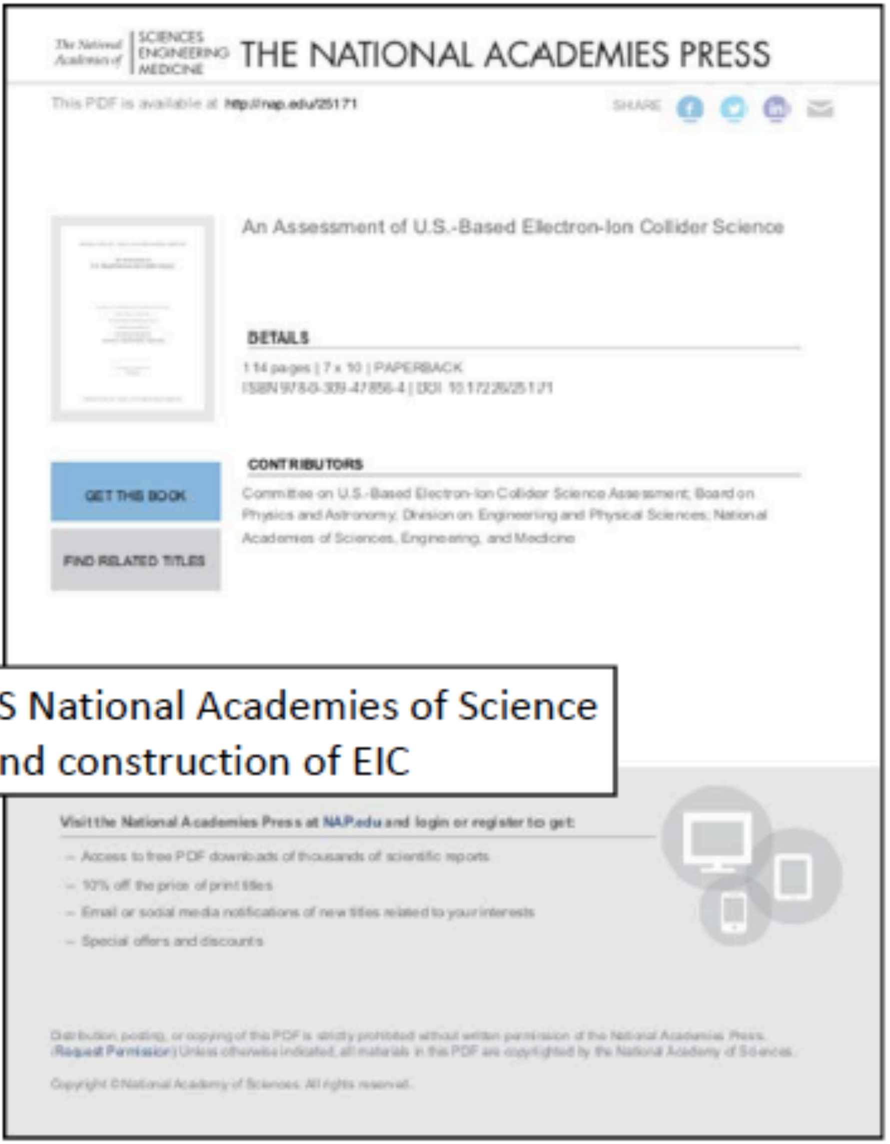


sPHENIX Barrel Detectors:
- MVTX, INTT, TPC
- EMCal, HCal



sPHENIX Forward Upgrade
- EMCal, Hcal, Tracking

sPHENIX at Electron Ion Collider (EIC)



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This PDF is available at http://nap.edu/25171

An Assessment of U.S.-Based Electron-Ion Collider Science

DETAILS

114 pages | 7 x 10 | PAPERBACK
ISBN 978-0-309-47856-4 | DOI 10.17226/25171

CONTRIBUTORS

Committee on U.S.-Based Electron-Ion Collider Science Assessment; Board on Physics and Astronomy; Division on Engineering and Physical Sciences; National Academies of Sciences, Engineering, and Medicine

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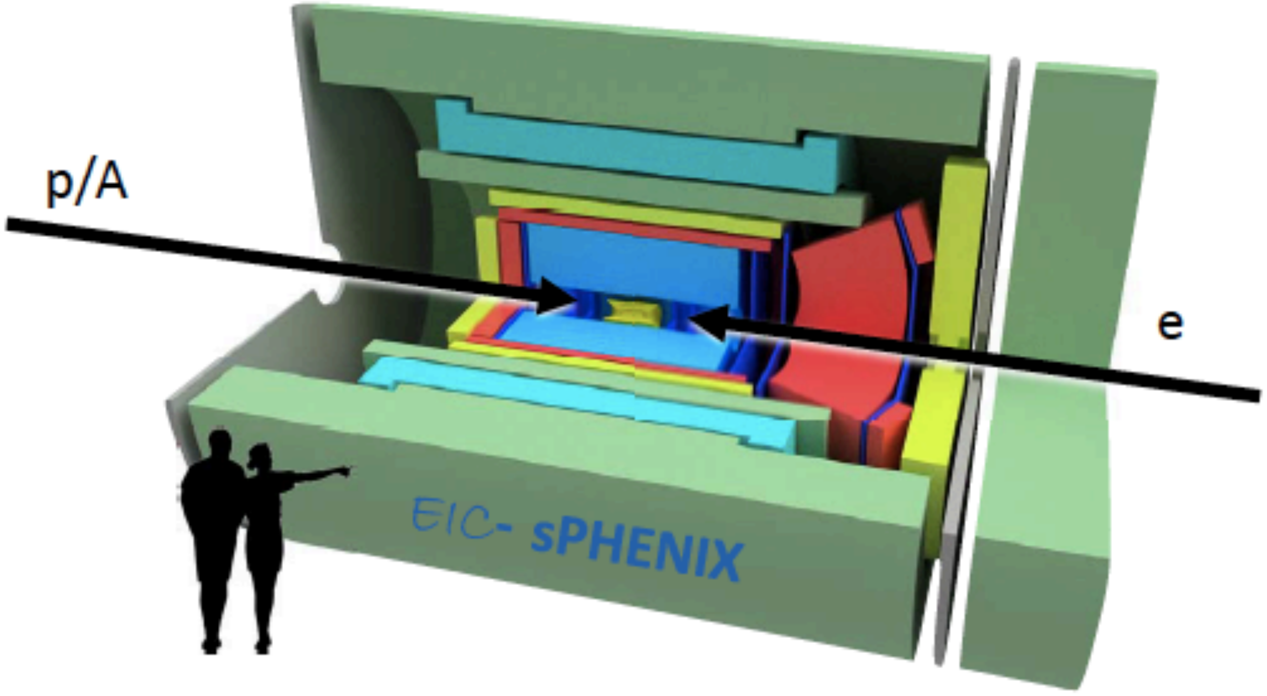
Timely: US National Academies of Science recommend construction of EIC

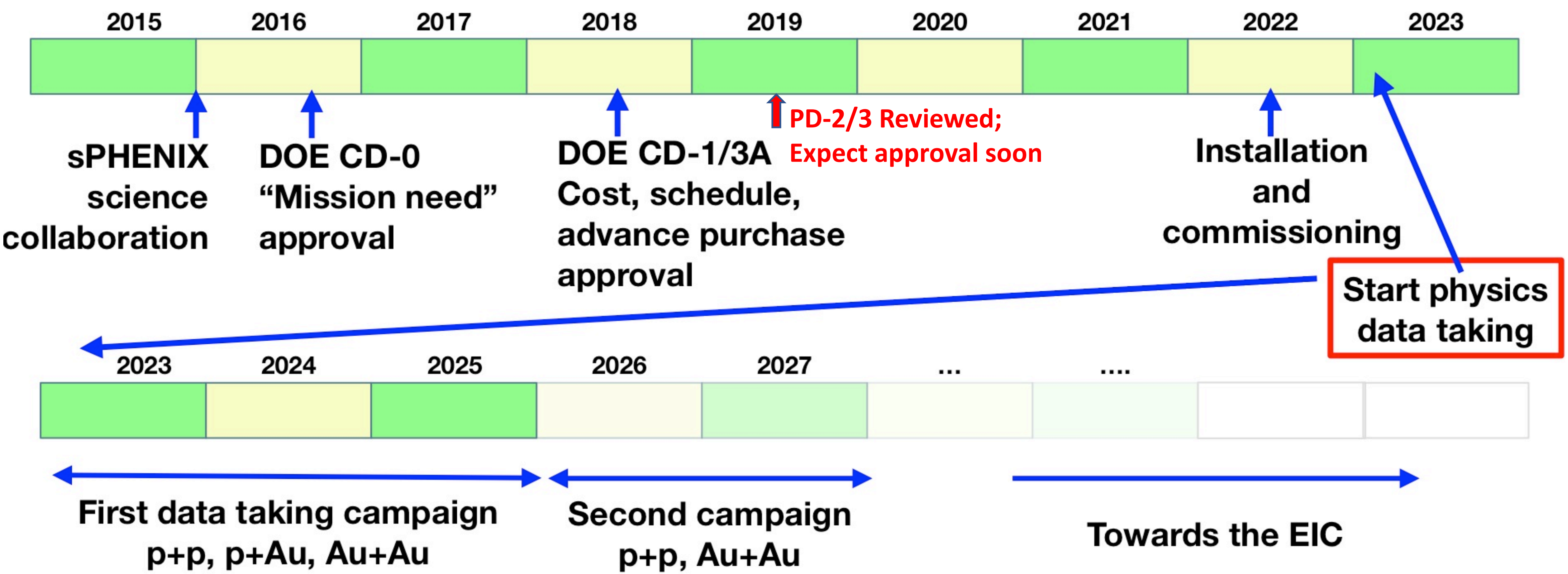
Study group (incl. non-sPHENIX members) working on EIC detector design based on sPHENIX



Solenoid
Flux return
Central tracking
Electromagnetic calorimeter
Forward/backward tracking
Hadron calorimeter
Particle ID

A Day-1 EIC Detector based on sPHENIX

sPHENIX Timeline



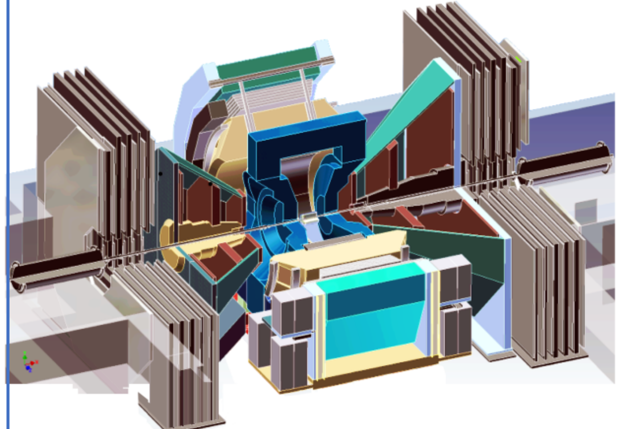
record 240B minimum bias Au+Au events

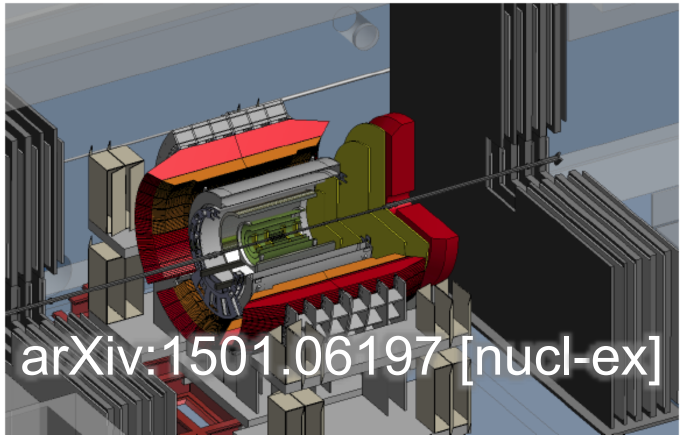
record 35/nb, sample 83/nb

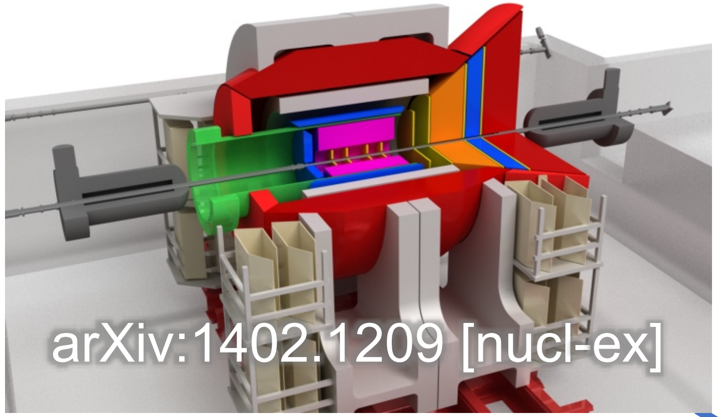
Summary and Outlook

sPHENIX

PHENIX experiment	PHENIX	An EIC detector
• 16y+ operation • Broad spectrum of physics (QGP, Hadron Physics, Dark Matter) • 170+ physics papers with 24k citations • Last run in this form 2016	• Comprehensive central upgrade base on BaBar magnet • Jet, heavy flavor and beauty quarkonia physics program → nature of QGP • Possible forward tracking and calorimeter upgrade → Spin,TMD	• Path of PHENIX upgrade leads to a capable EIC detector • Large coverage of tracking, calorimetry and PID • Open for new collaboration/new ideas







2000-2016 | 2017→2022; Physics: 2023+ | >2025+ | Time

RHIC: A+A, spin-polarized p+p, spin-polarized p+A

EIC: e+p, e+A

The *Growing* sPHENIX Collaboration

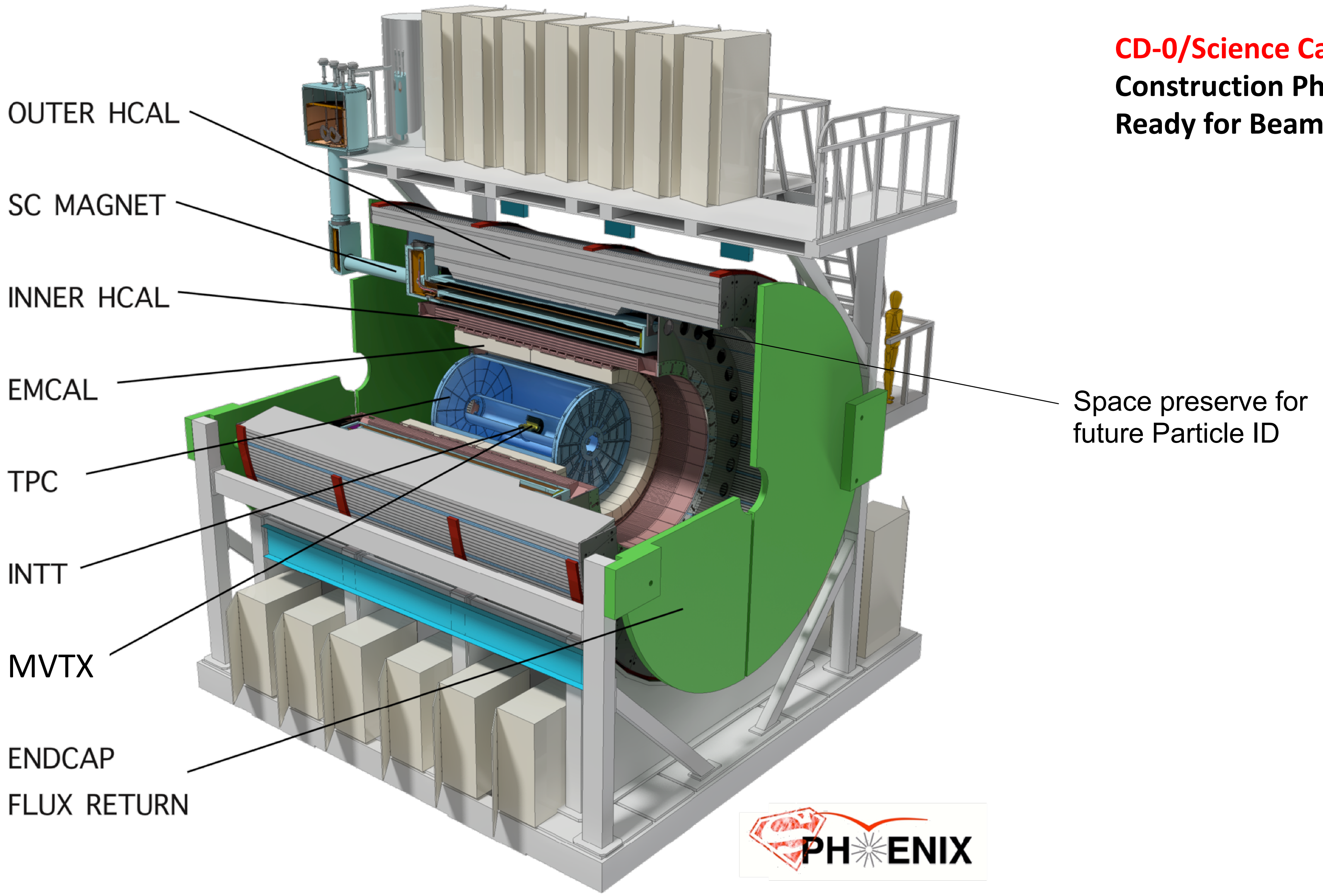
77 institutions – 17 since formation of collaboration in December 2015

Augustana University
Banaras Hindu University
Baruch College, CUNY
Brookhaven National Laboratory
China Institute for Atomic Energy
CEA Saclay
Central China Normal University
Chonbuk National University
Columbia University
Eötvös University
Florida State University
Fudan University
Georgia State University
Howard University
Hungarian sPHENIX Consortium
Insititut de physique nucléaire d'Orsay
Institute for High Energy Physics, Protvino
Institute of Nuclear Research, Russian Academy of Sciences, Moscow
Institute of Physics, University of Tsukuba
Institute of Modern Physics, China
Iowa State University
Japan Atomic Energy Agency
Charles University (CUNI), Prague
Czech Technical University in Prague (CTU)
Korea University
Lawrence Berkeley National Laboratory
Lawrence Livermore National Laboratory
Lehigh University
Los Alamos National Laboratory
Massachusetts Institute of Technology
Muhlenberg College
Nara Women's University
National Central University
National Research Centre "Kurchatov Institute"
National Research Nuclear University "MEPhI"
New Mexico State University
Oak Ridge National Laboratory
Ohio University
Peking University
Petersburg Nuclear Physics Institute
Purdue University
Rice University
RIKEN
RIKEN BNL Research Center
Rikkyo University
Rutgers University
Saint-Petersburg Polytechnic University
Sejong University
Shanghai Institute for Applied Physics
Stony Brook University
Sun Yat Sen University
Temple University
Tokyo Institute of Technology
Tsinghua University
Universidad Técnica Federico Santa María
University of California, Berkeley
University of California, Los Angeles
University of California, Riverside
University of Colorado, Boulder
University of Debrecen
University of Houston
University of Illinois, Urbana-Champaign
University of Jammu
University of Maryland
University of Michigan
University of New Mexico
University of North Carolina at Greensboro
University of Sao Paolo
University of Tennessee, Knoxville
University of Texas, Austin
University of Tokyo
University of Science and Technology, China
Vanderbilt University
Wayne State University
Weizmann Institute
Yale University
Yonsei University

Backup slides

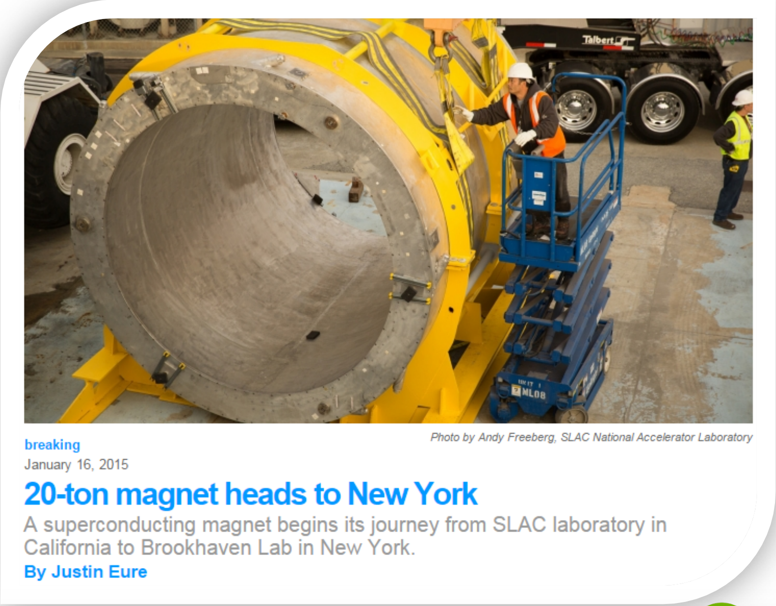
sPHENIX: a State of the Art Detector for Heavy Ion Physics at RHIC

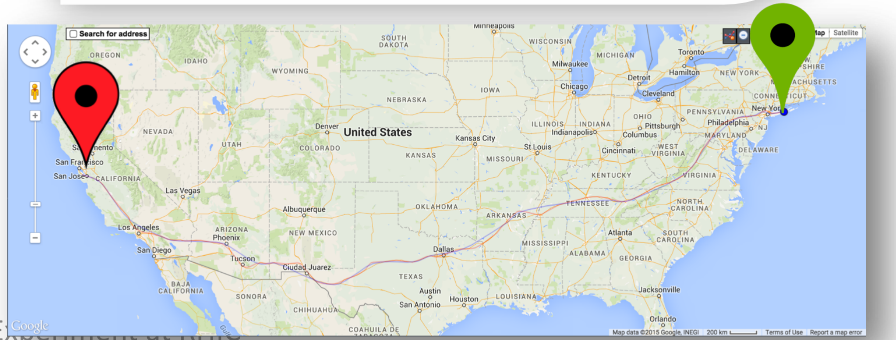
CD-0/Science Case	Sept 2016
Construction Phase	Jul 2018 -22
Ready for Beam	Jan 2023



Super conducting magnet

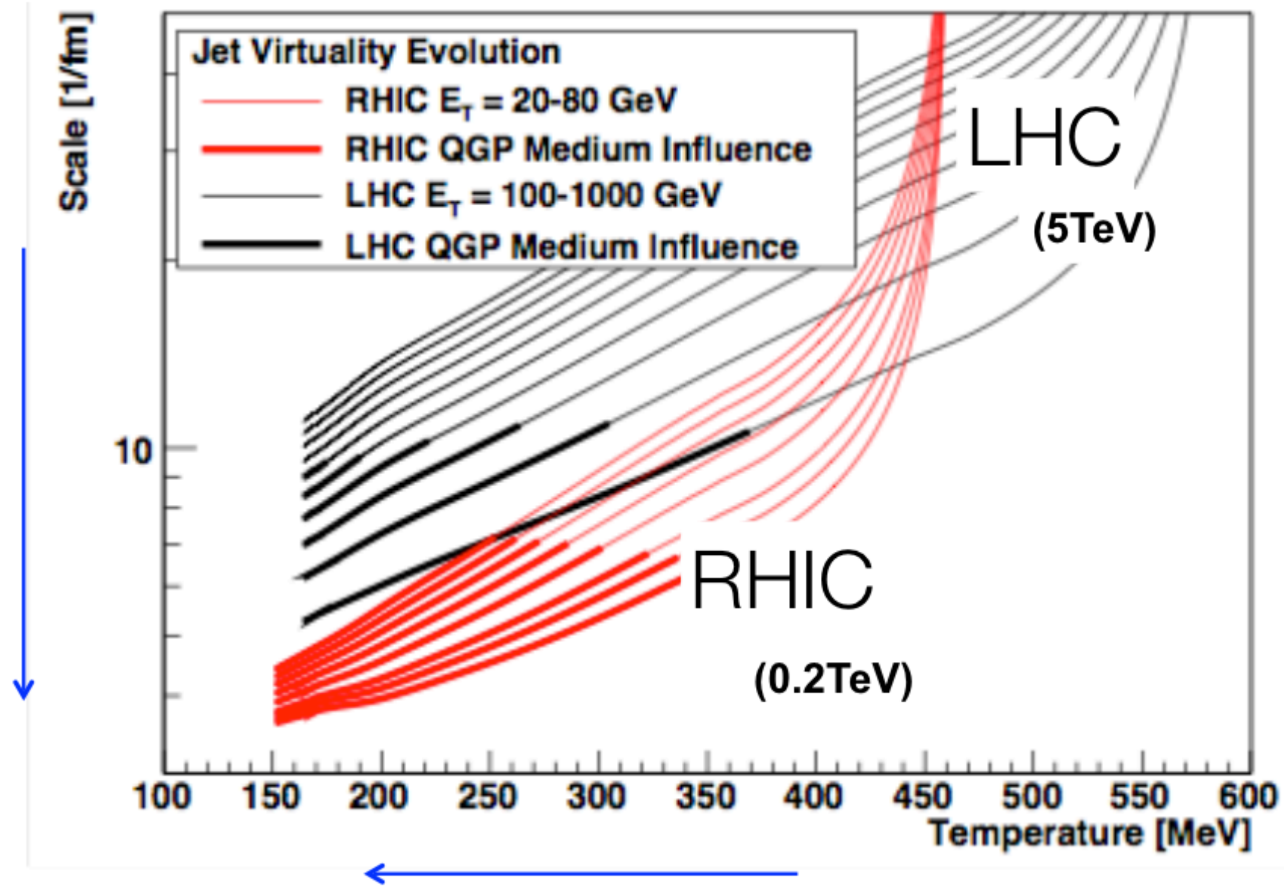
- 1.4 Tesla magnet, Φ = 2.8 m, L = 3.8 m Previously used in BaBar @ SLAC
- Moved to BNL in Feb 2015
- Successful cold low field test in 2016
- Full field test in 2018





Jet Evolution @ RHIC

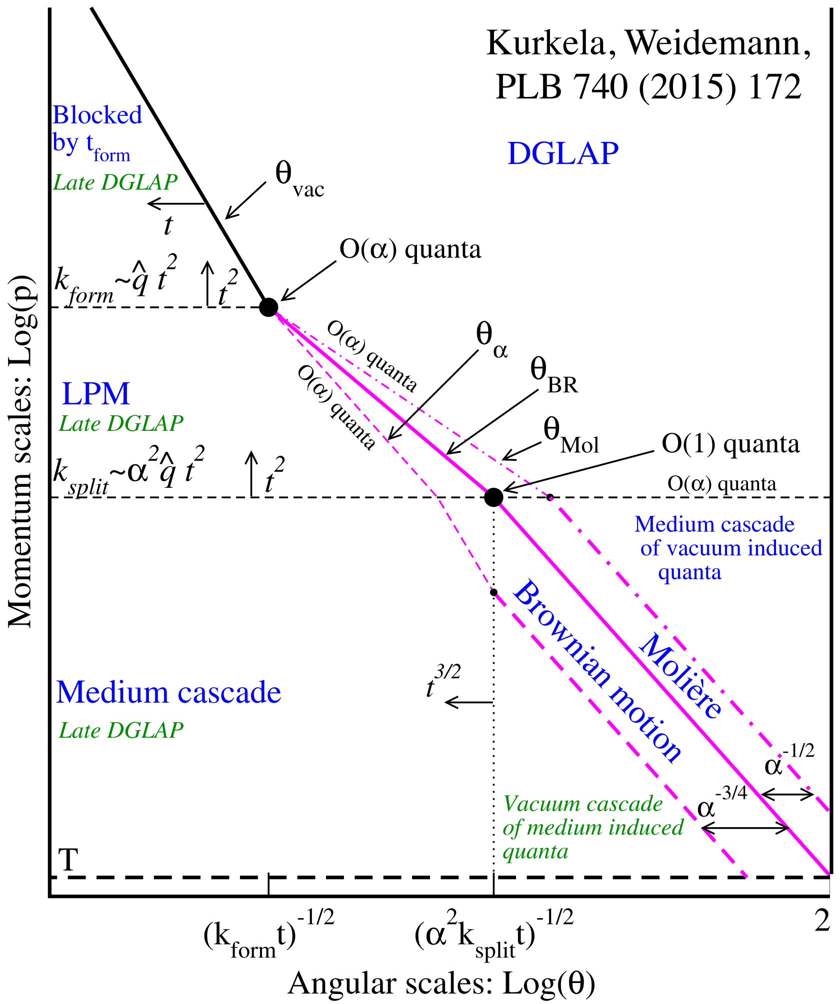
M. Habich, J. Nagle, and P. Romatschke, EPJC, 75:15 (2015)



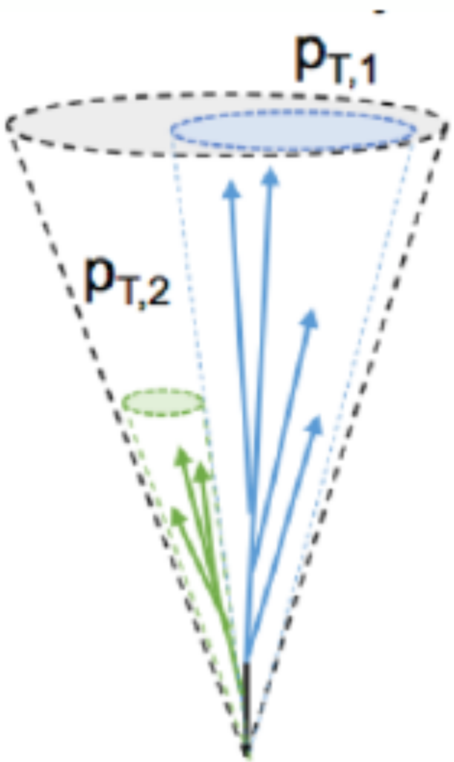
QGP@RHIC → Closer to transition temperature

- Better access to strong coupling regime
- Larger fraction of jet evolution dominated by QGP medium @RHIC

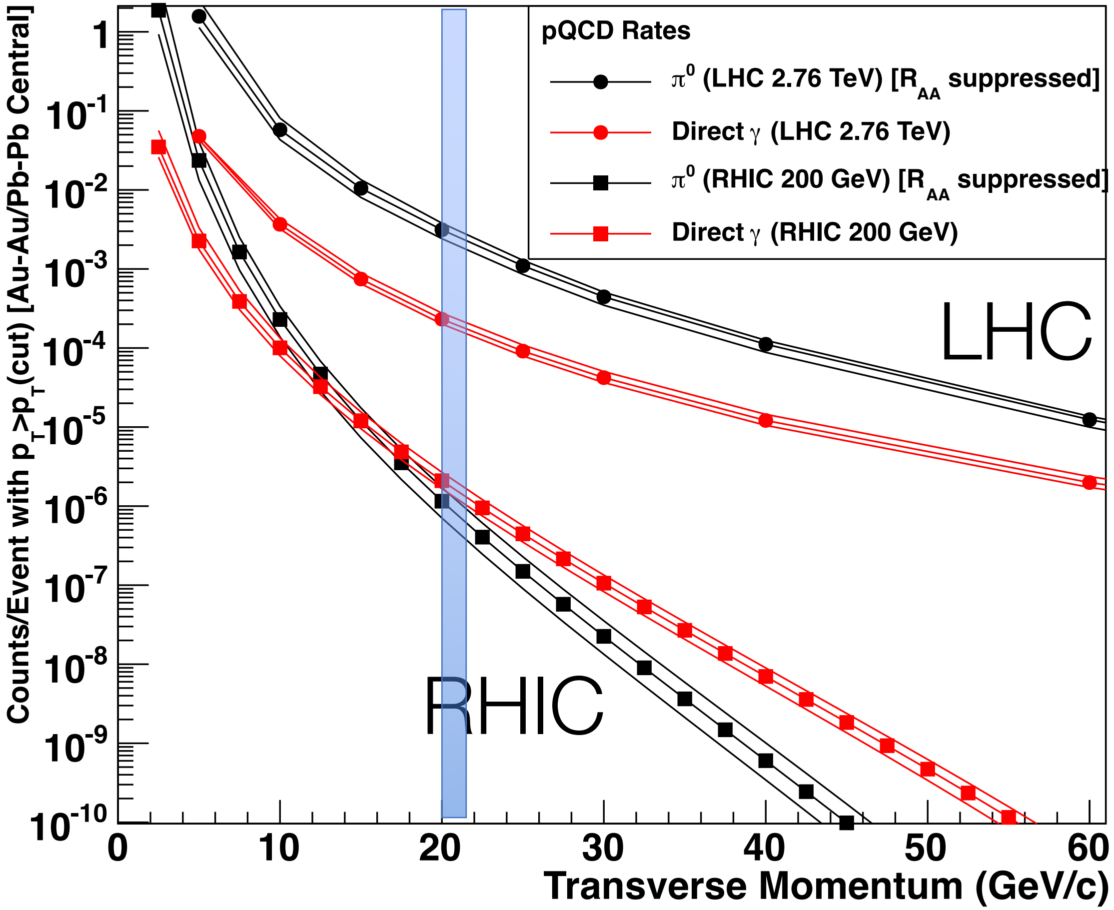
Core sPHENIX Science Program



Jet structure
vary momentum/angular scale of probe



γ – Jet Correlations

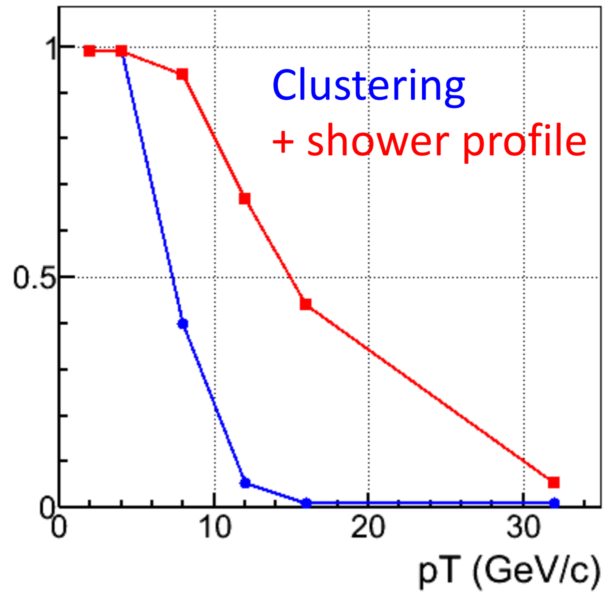


Allows for γ/π^0 discrimination up to ~20 GeV/c

For 20 GeV γ

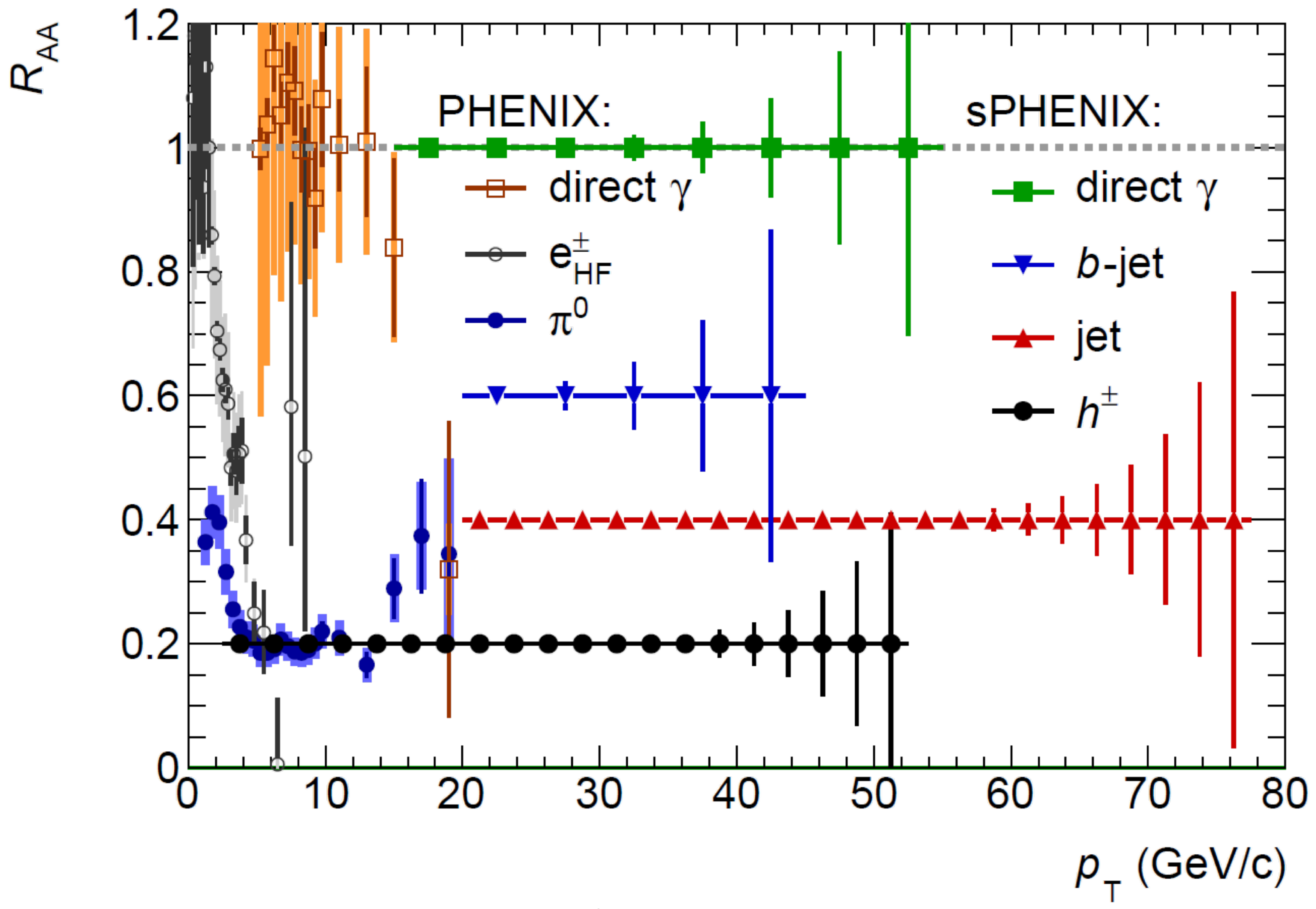
- S/B is 20x larger at RHIC than LHC
- UE 2.5x smaller

π^0 eff vs p_T



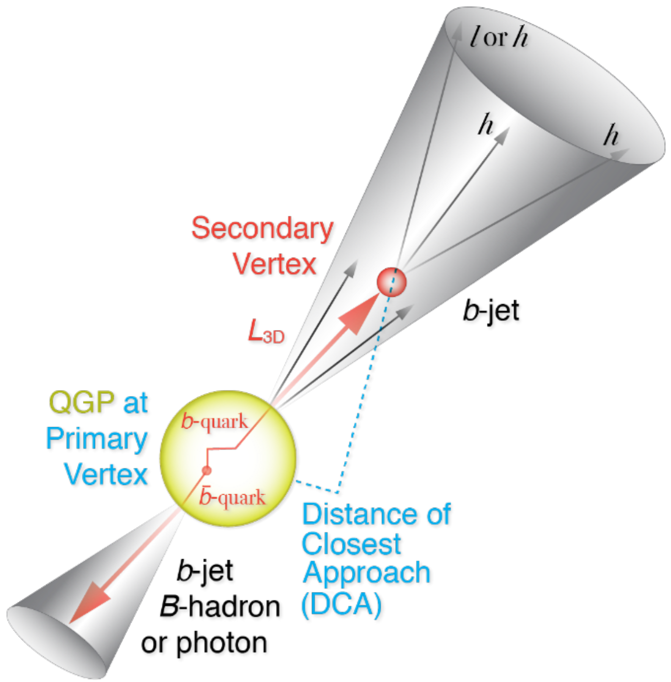
A Broad Physics Program with Jets @sPHENIX

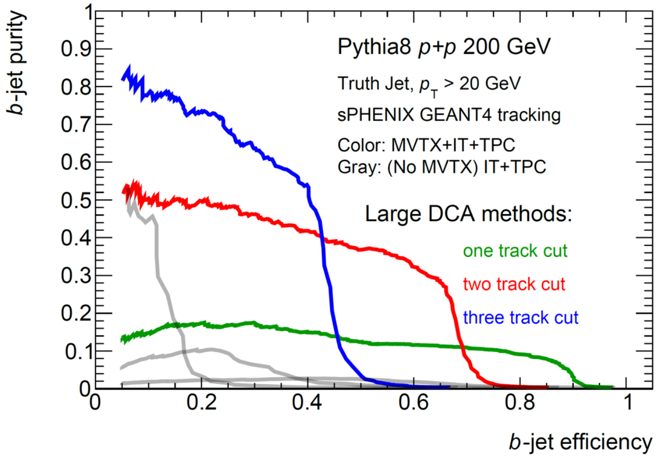
Parton Mass and Flavor Dependence of Jet Suppression and more

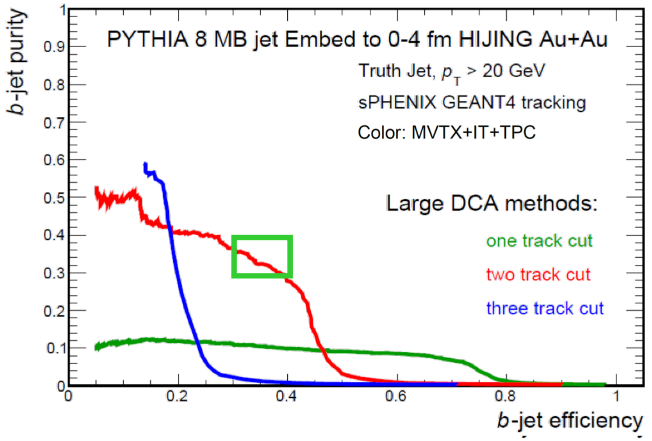


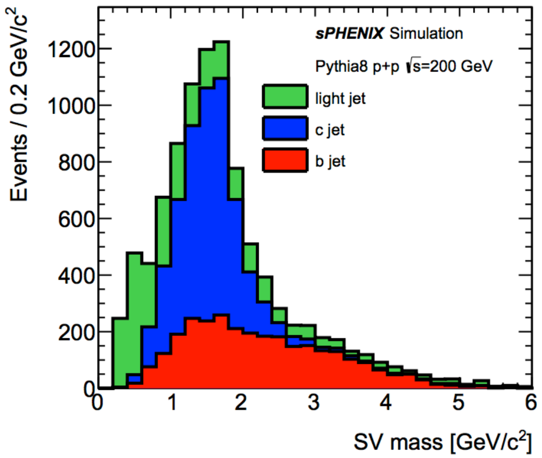
B-jet tagging

- Multi-tracks w/ large DCA
- 2nd vertex mass reco'd





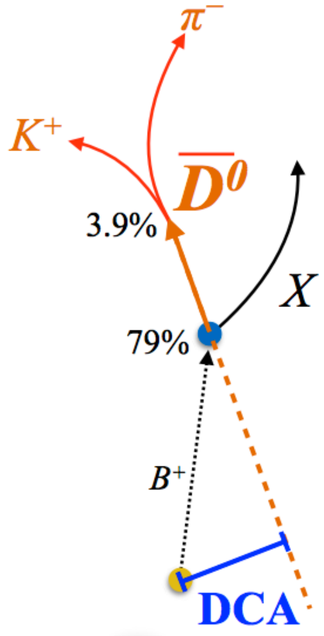


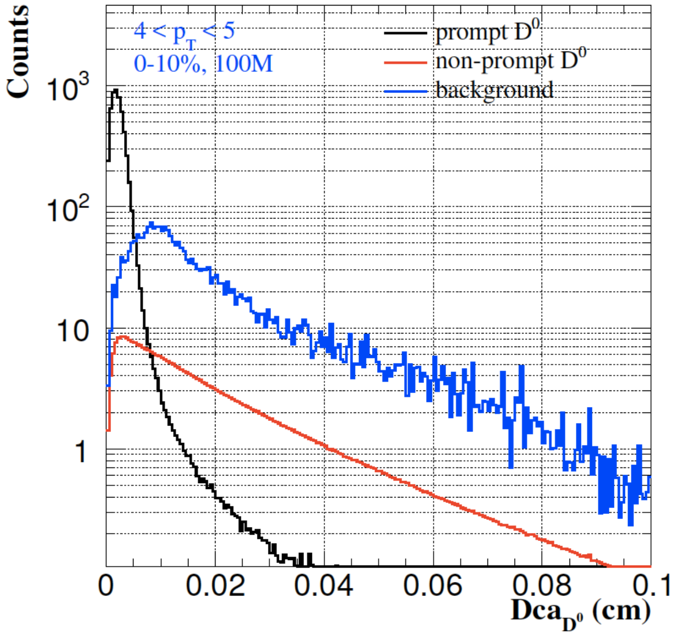


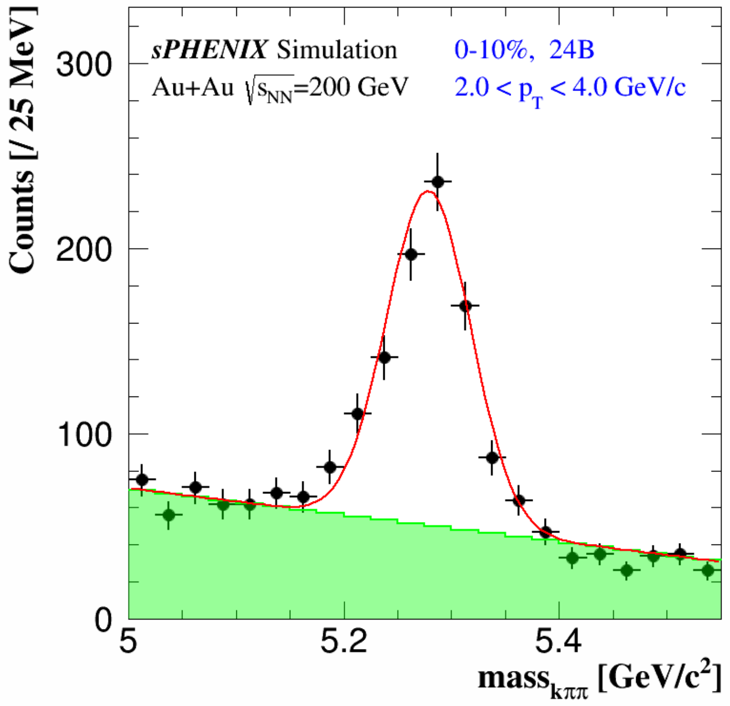
CMS work-point, Phys. Rev. Lett. 113, 132301 (2014)

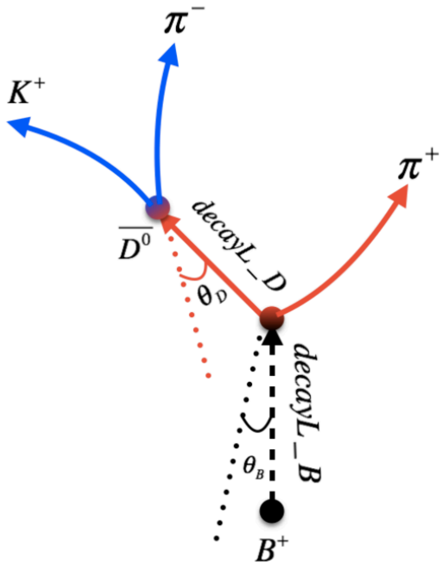
B-hadron Tagging

- Impact parameter (DCA) method to tag non-prompt D^0 from B-meson decays
- Inclusive and exclusive channels possible









Charm Chemistry - Introduction

Charm baryon vs meson

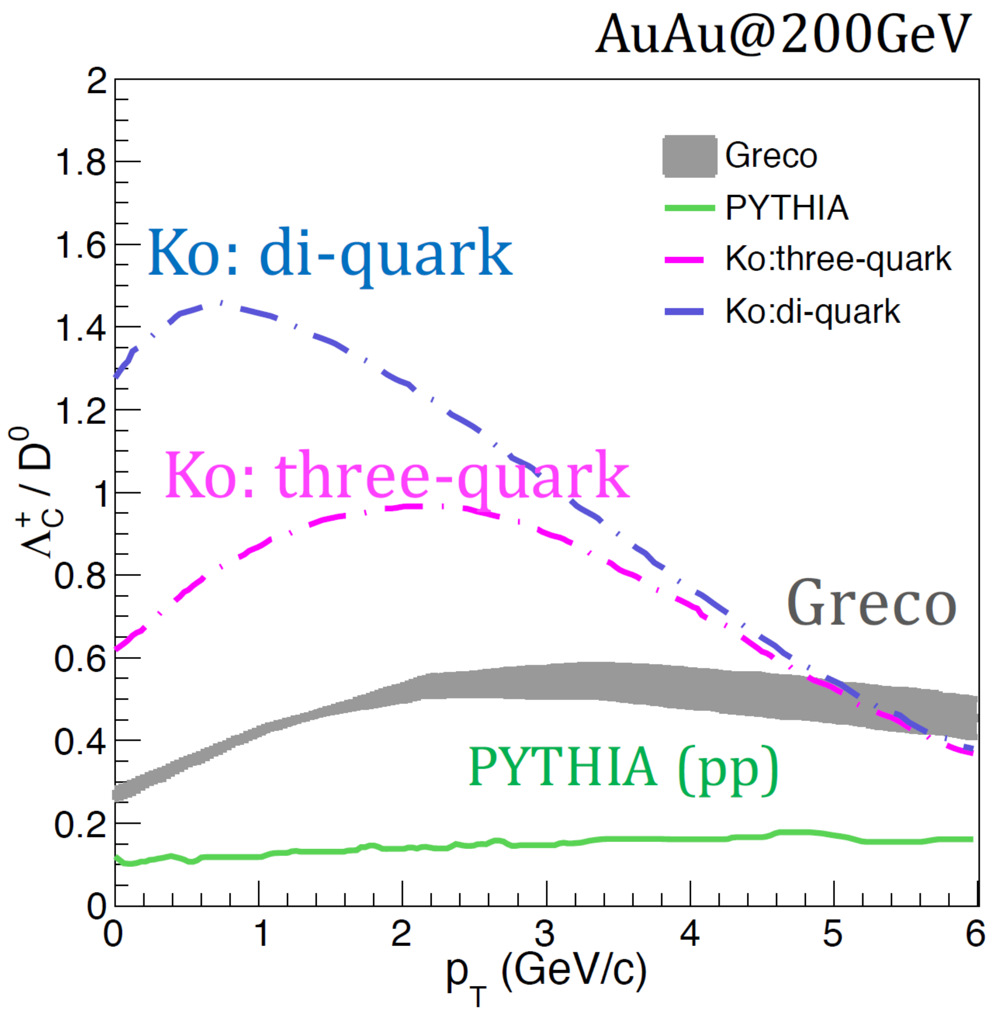
- Heavy quarks transport in

QGP and hadronic phase of the medium

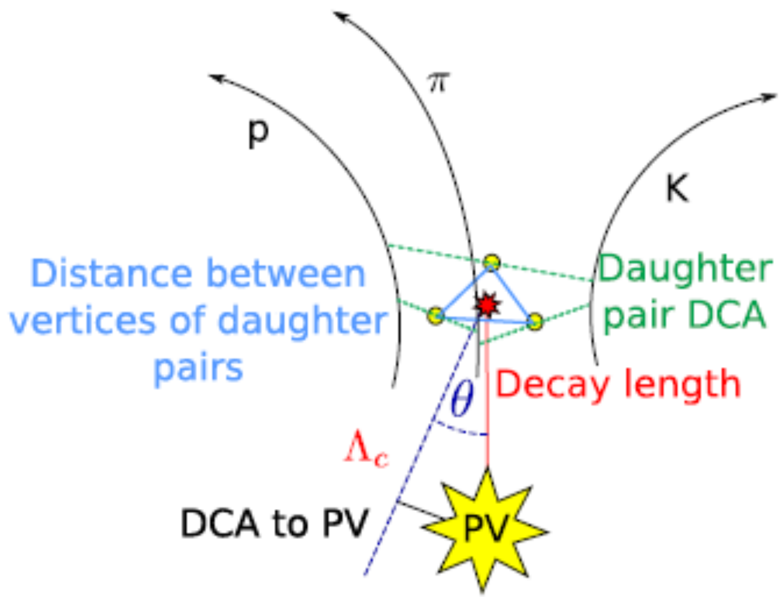
- Charm quark hadronization via coalescence

Lambda baryons

Particle name	Symbol	Quark content	Rest mass (MeV/c^2)	I	J^P	Q (e)	S	C	B'	T	Mean lifetime (s)	Commonly decays to
Lambda[6]	Λ^0	uds	1 115.683 ±0.006	0	$\frac{1}{2}^+$	0	−1	0	0	0	$(2.631 \pm 0.020) \times 10^{-10}$	$p^+ + \pi^-$ or $n^0 + \pi^0$
charmed Lambda[15]	Λ_c^+	udc	2 286.46 ±0.14	0	$\frac{1}{2}^+$	+1	0	+1	0	0	$(2.00 \pm 0.06) \times 10^{-13}$	See Λ_c^+ decay modes
bottom Lambda[16]	Λ_b^0	udb	5 620.2 ±1.6	0	$\frac{1}{2}^+$	0	0	0	−1	0	$1.409^{+0.055}_{-0.054} \times 10^{-12}$	See Λ_b^0 decay modes
top Lambda†	Λ_t^+	udt	—	0	$\frac{1}{2}^+$	+1	0	0	0	+1	—	—

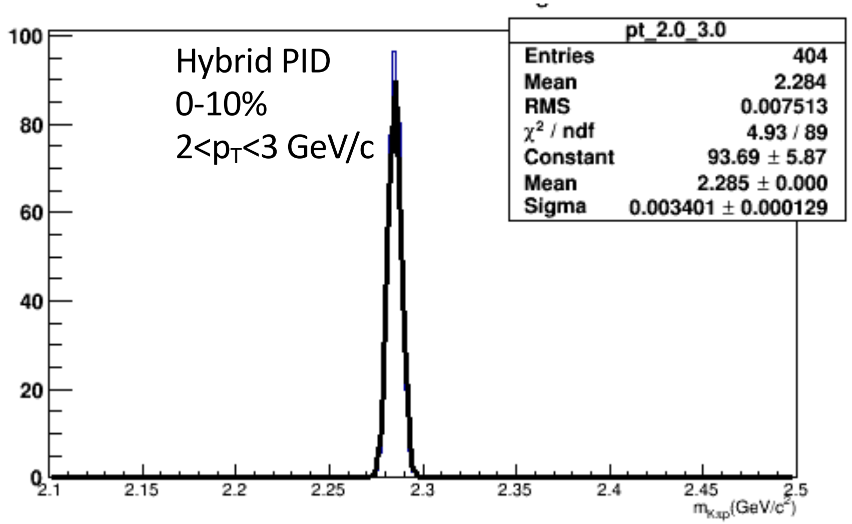


Reconstruction of Λ_c



$\Lambda_c \rightarrow K^- p \pi^+$

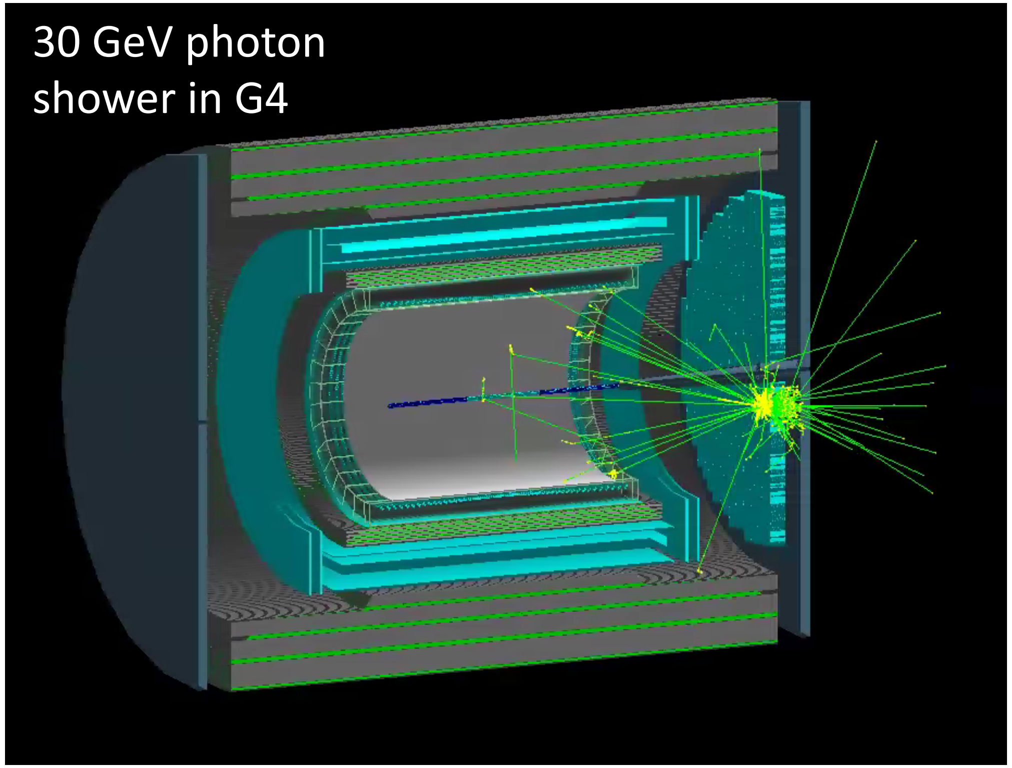
Daughters p_T > 0.6GeV
Daughters DCA < 50 μm
p DCA > 75 μm,
K DCA > 96 μm,
π DCA > 65 μm
Decay length Lc > 200 μm
DCA Lc < 100 μm



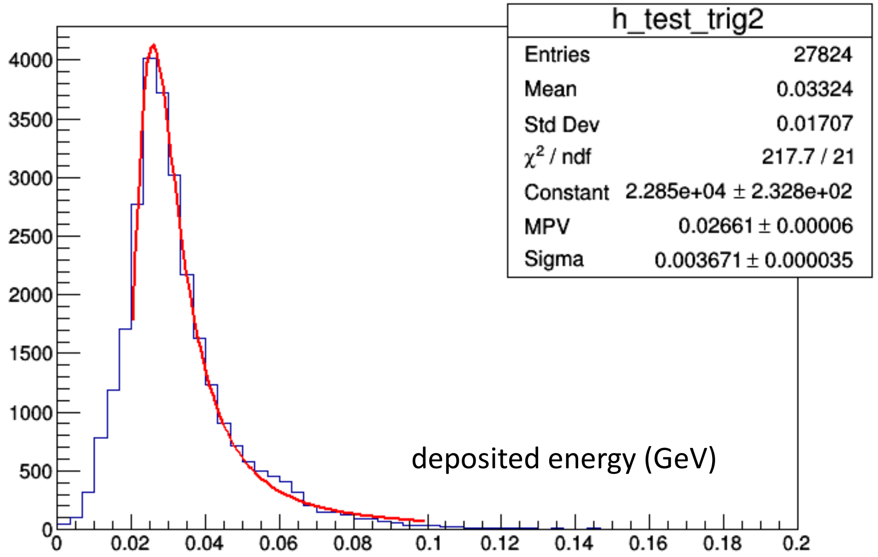
Centrality	Running events		Scaled events
	signal	Background	
0-10%	5B	2B	24B
10-20%	3B	1B	24B
20-40%	3B	1B	48B
40-60%	3B	1B	48B
60-80%	5B	8B	48B

Forward EMCal Simulations and Calibration

Full simulation setup exists in G4:



Cosmics energy response determined with vertical muons down into fEMC stack in standard G4 setup (3% sampling):



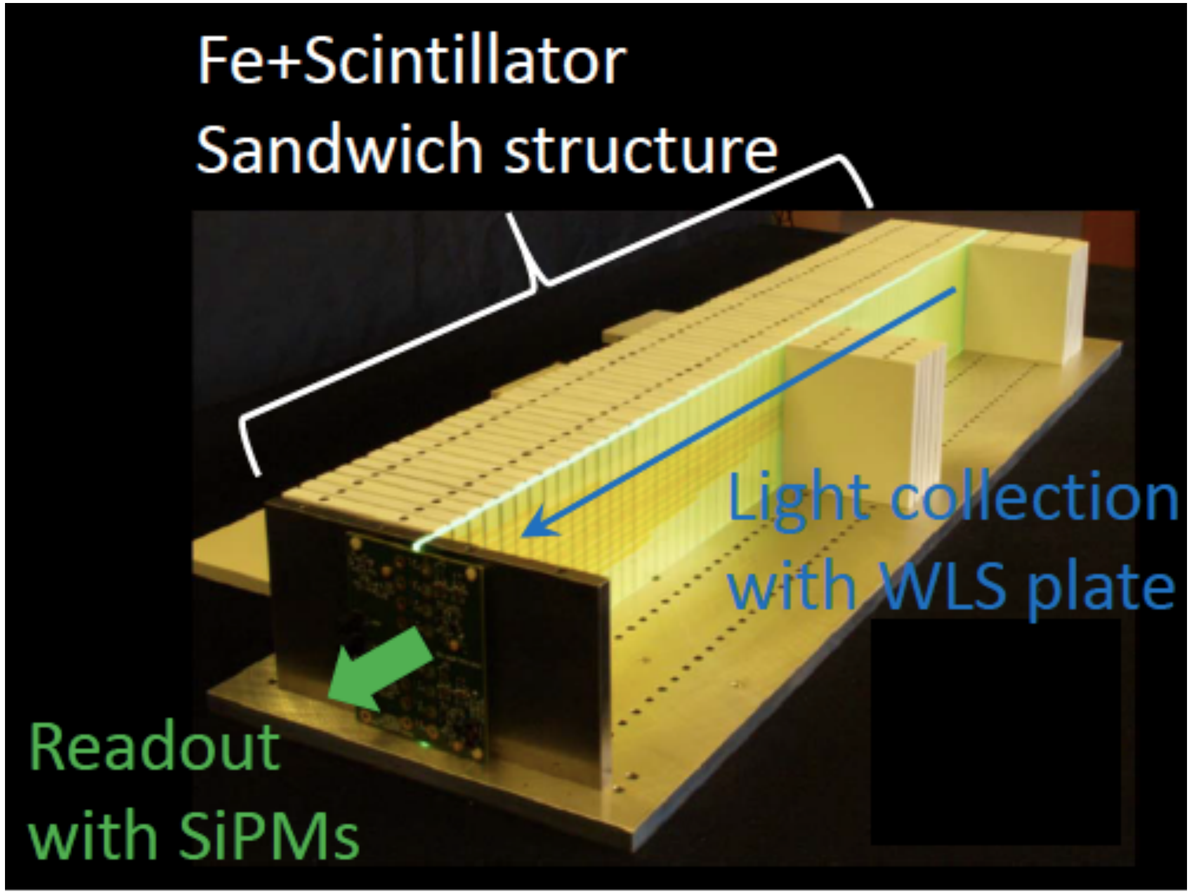
MPV is 26.6 MeV

~3 pixels/0.0266 GeV = 113 SiPM pixels/GeV

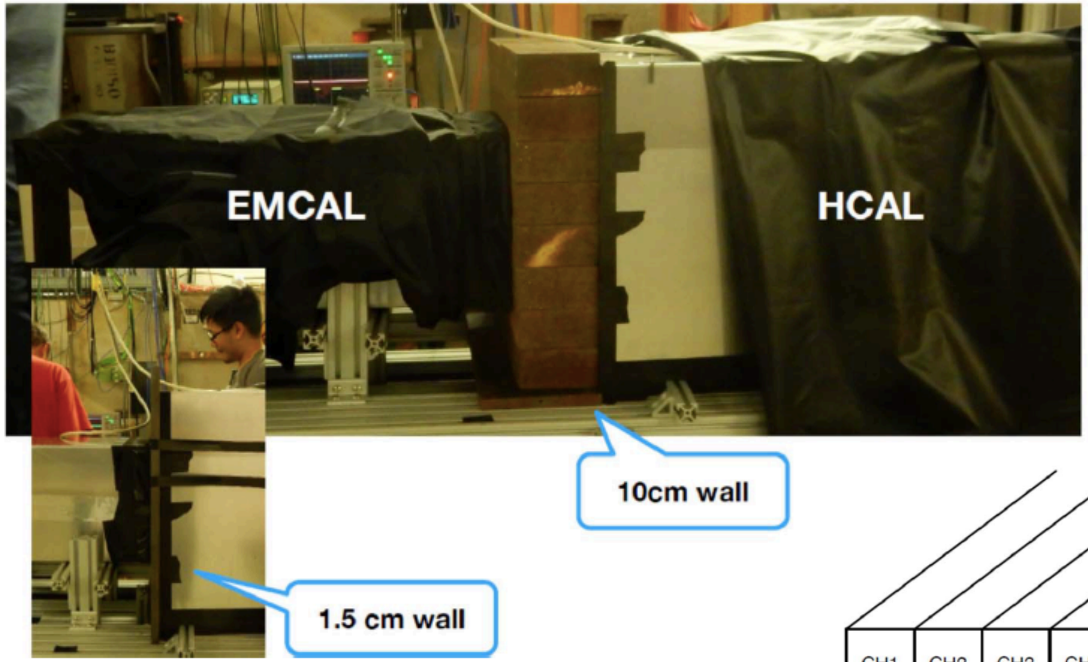
NIM A 406 (1998) 227-258:
- 136 +/- 5 p.e. /GeV (BCF-10, cosmics)
- 217 +/- 68 p.e. /GeV (BCF-12, laser)

Forward Hadronic Calorimeter R&D

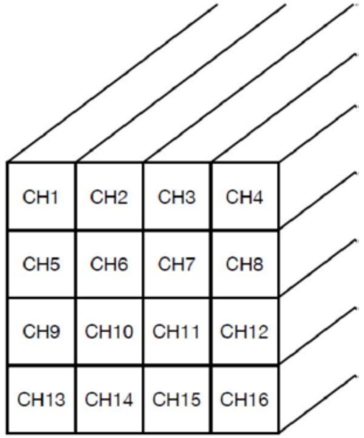
- Essential for forward jet reconstruction, hadron energy measurement, and triggering
- Collaboration with UCLA group for STAR upgrade and EIC detector R&D



HCal Prototype Test Beam Results



$$\sigma_E/E = 70\%/\sqrt{E}\ (\text{GeV})$$



Calorimeters consist of 4×4 towers.