Study QGP with sPHENIX Upgrade at the Relativistic Heavy Ion Collider

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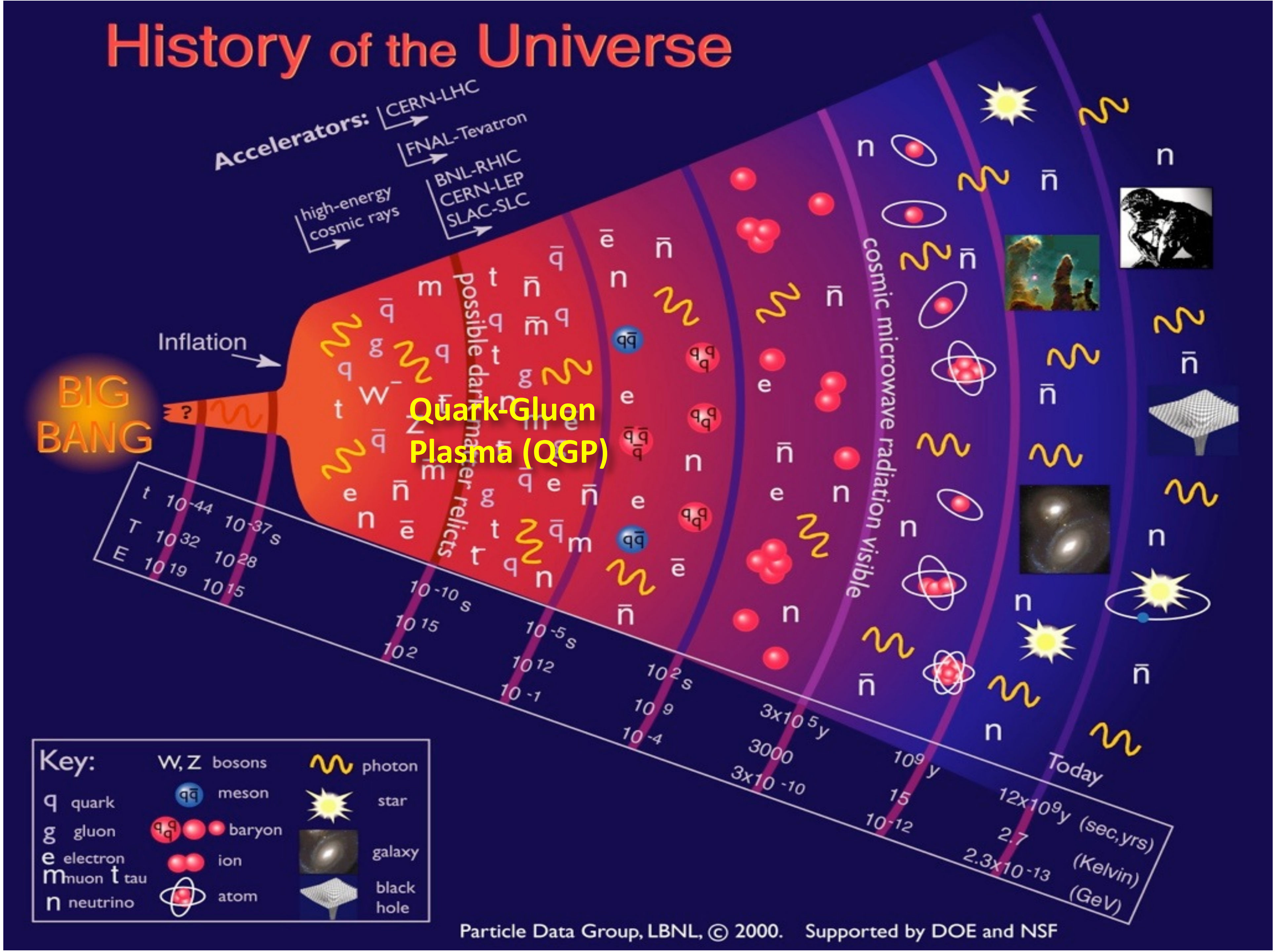
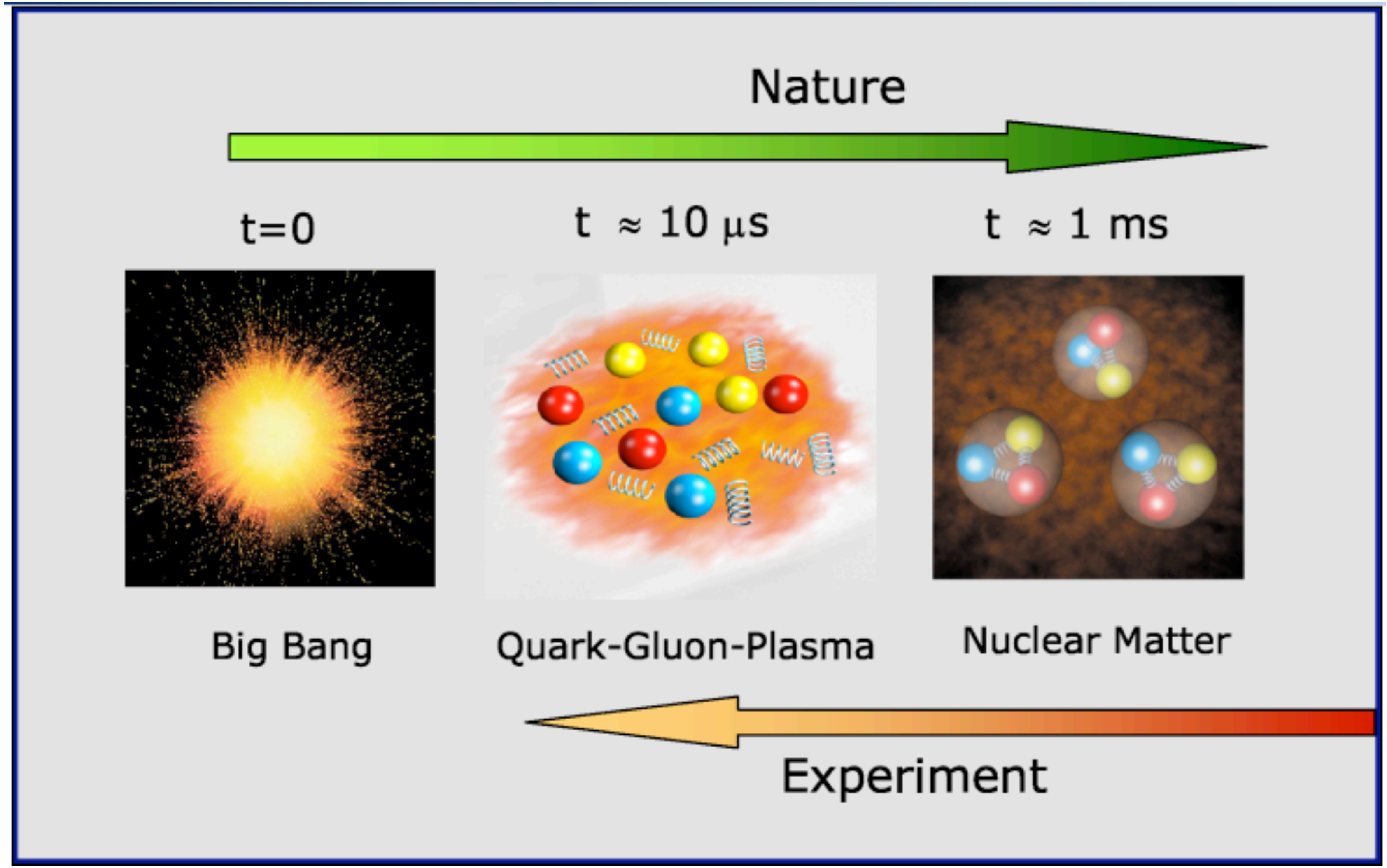
01/08/2018

Outline

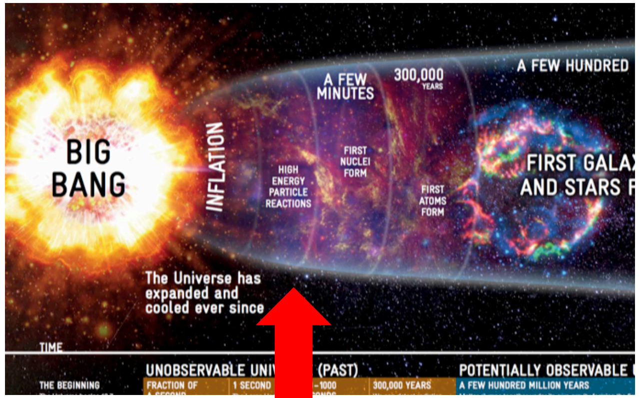
- Physics motivation
- sPHENIX proposal
- Heavy Flavor physics and MVTX upgrade
- Outlook


History of the Universe
Accelerators:
CERN-LHC
FNAL-Tevatron
BNL-RHIC
CERN-LEP
SLAC-SLC
high-energy cosmic rays
Inflation
BIG BANG
Quark-Gluon Plasma (QGP)
possible dark matter relicts
cosmic microwave radiation visible
t 10^-44 10^-37 s
T 10^32 10^28
E 10^19 10^15
10^-10 s
10^15
10^2
10^-5 s
10^12
10^-1
10^2 s
10^9
10^-4
3x10^5 y
3000
3x10^-10
10^9 y
15
10^-12
Today
12x10^9 y (sec,yrs)
2.7 (Kelvin)
2.3x10^-13 (GeV)
Key:
q quark
g gluon
e electron
m muon t tau
n neutrino
W, Z bosons
meson
baryon
ion
atom
photon
star
galaxy
black hole
Particle Data Group, LBNL, © 2000. Supported by DOE and NSF

Quark Gluon Plasma and Heavy Ion Collisions

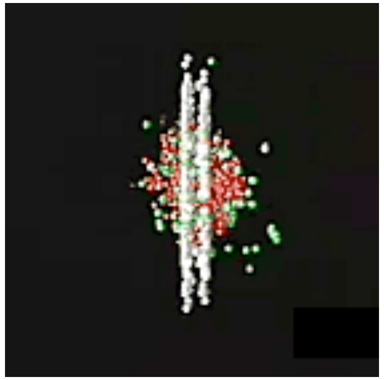


Heavy Ion Collisions
- Artists’ View

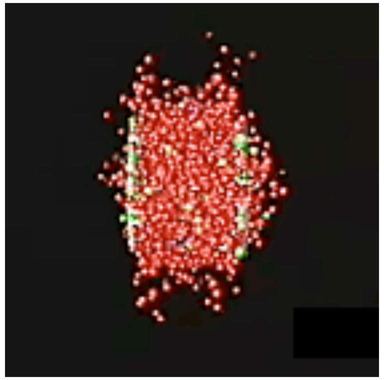


^{197}Au → ← ^{197}Au

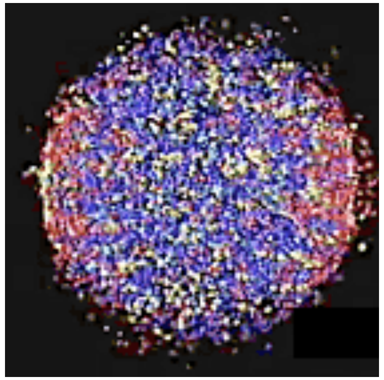
About to collide



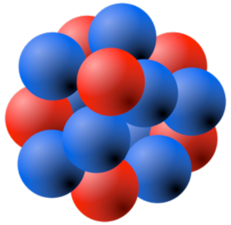
Ion collision



Quarks and gluons freed



QGP formed



→ ^{197}Au

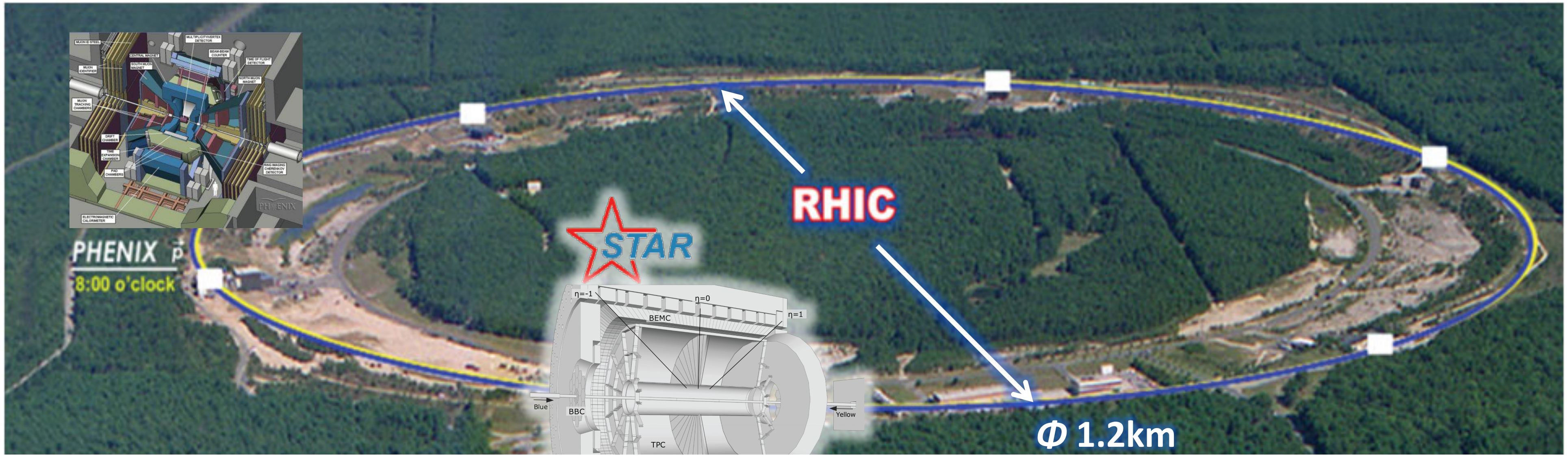
Relativistic Lorentz Contraction:

$$L = \frac{L_0}{\gamma(v)} = L_0\sqrt{1 - v^2/c^2}$$

At RHIC (LHC):

$$\gamma(v) \sim 100(2, 500)$$

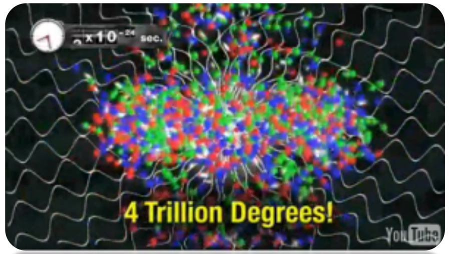
RHIC: Relativistic Heavy Ion Collider @BNL



Mar, (2010)

APS NEWS

RHIC Sets Temperature Record



PHENIX, Phys. Rev. Lett. 104, 132301

More

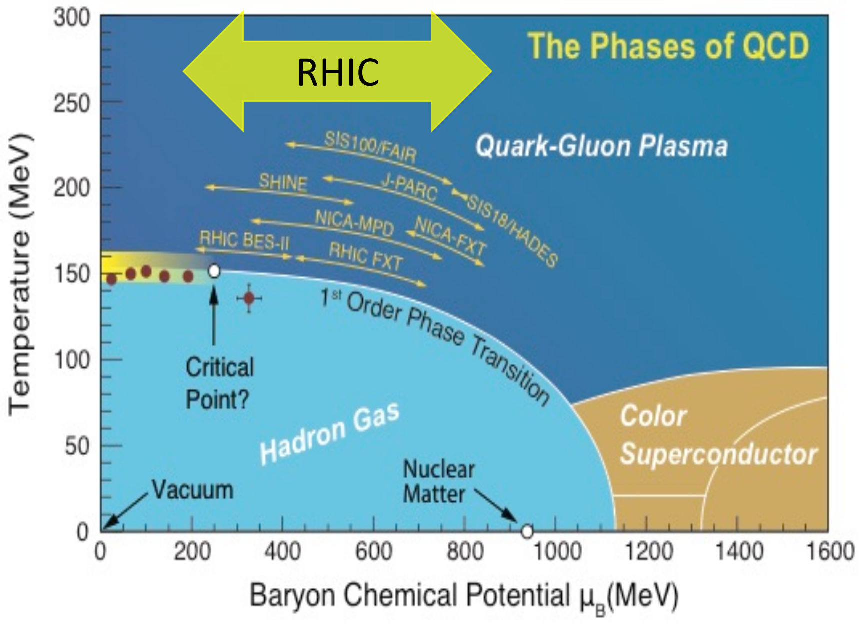
At the “April” meeting, physicists from Brookhaven National Lab announced that they measured the hottest temperature ever recorded, thus recreating an exotic form of matter that hasn’t existed since microseconds after the Big Bang. This is the first time that physicists were able to positively confirm the creation of the much sought after quark-gluon plasma.

“The RHIC at Brookhaven created matter that seems to be at a temperature of 4 trillion degrees Celsius. This is the hottest matter ever created in a laboratory,” said Steven Vigdor, Associate Laboratory Director for Nuclear Particle Physics at the Lab, “We’re talking about the highest temperature in the known universe,”

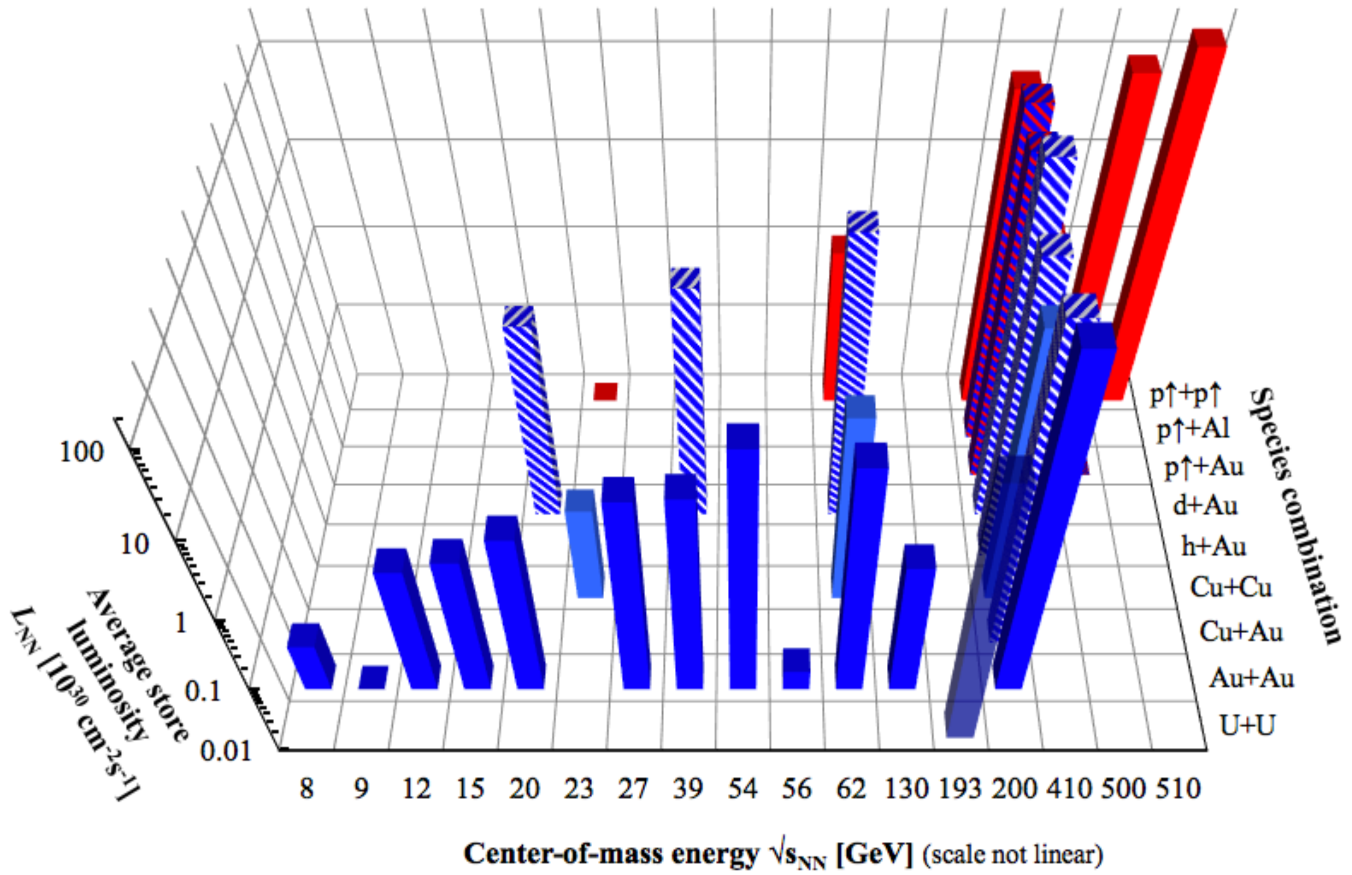
RHIC Delivers Whatever it Takes

The world's most versatile facility for the exploration of the phases of QCD matter from high temperature to high baryon density.

- **Discovery of "perfect liquid" QGP**
- **Discovery of jet quenching in QGP**
- **Proton spin decomposition, quark & gluon**

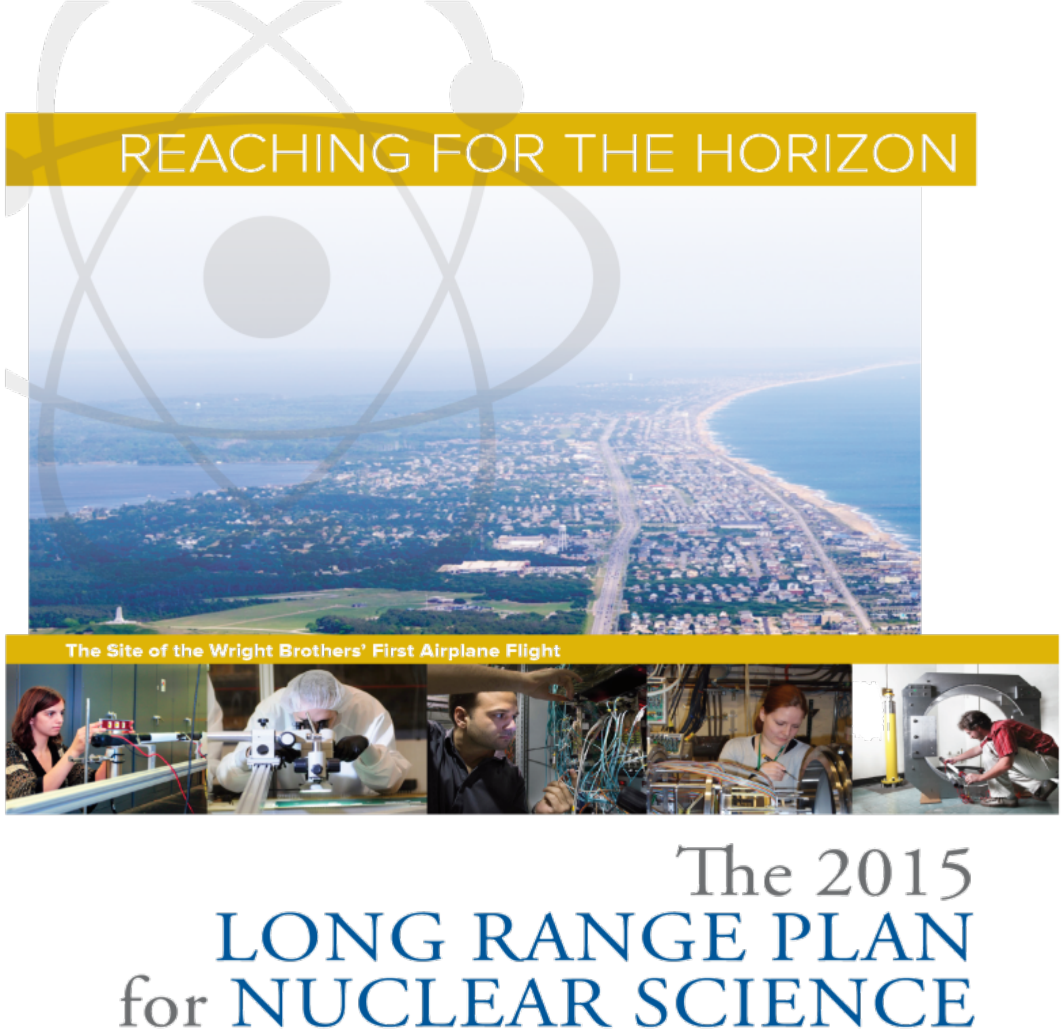


RHIC energies, species combinations and luminosities (Run-1 to 17)



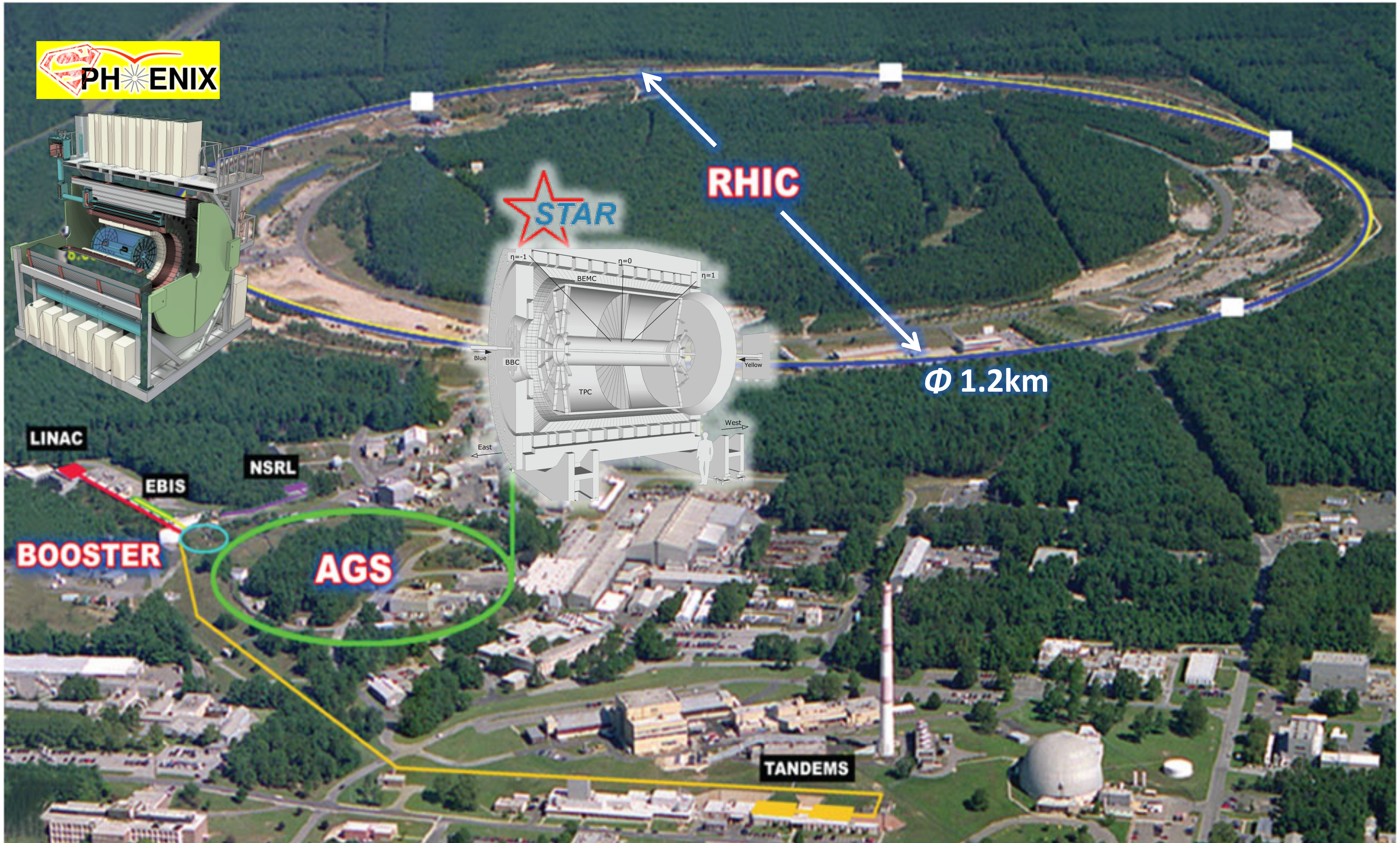
Run18 in preparation: ($^{96}Zr^{40+}$ + $^{96}Zr^{40+}$) and ($^{96}Ru^{44+}$ + $^{96}Ru^{44+}$)

Next Step: 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."**

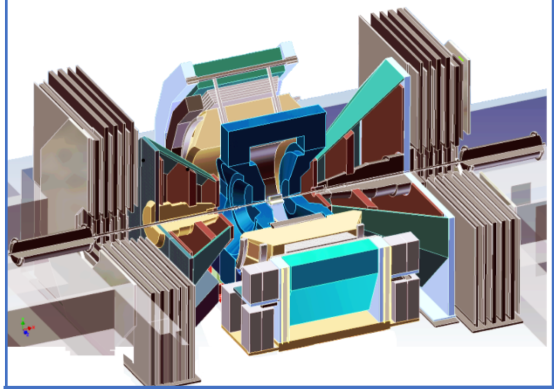
sPHENIX Upgrade
the next Generation HI experiment at RHIC



Evolution of the PHENIX Interaction Region

PHENIX experiment

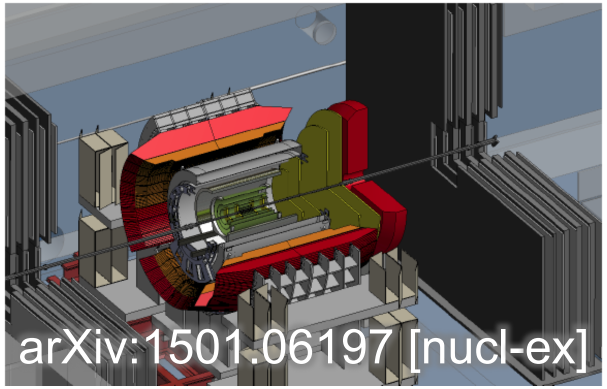
- 16y+ operation
- Broad spectrum of physics (QGP, Hadron Physics, Dark Matter)
- 170+ physics papers with 24k citations
- Last run in this form 2016



2000-2016

sPHENIX

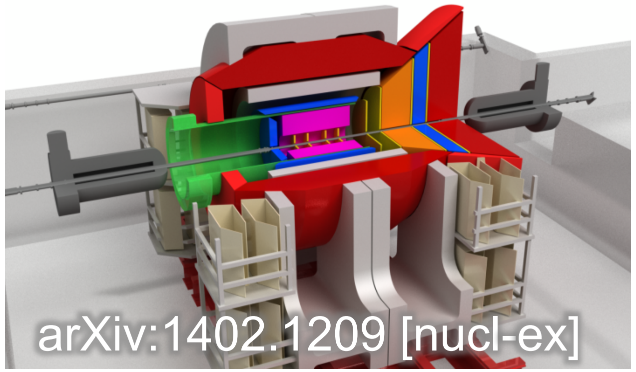
- Comprehensive central upgrade base on BaBar magnet
- Rich jet and beauty quarkonia physics program → nature of QGP
- Possible forward tracking, and calorimeter → Spin, CNM



2017→2022, CD-0@ 2016

An EIC detector

- Path of PHENIX upgrade leads to a capable EIC detector
- Large coverage of tracking, calorimetry and PID
- Open for new collaboration/new ideas

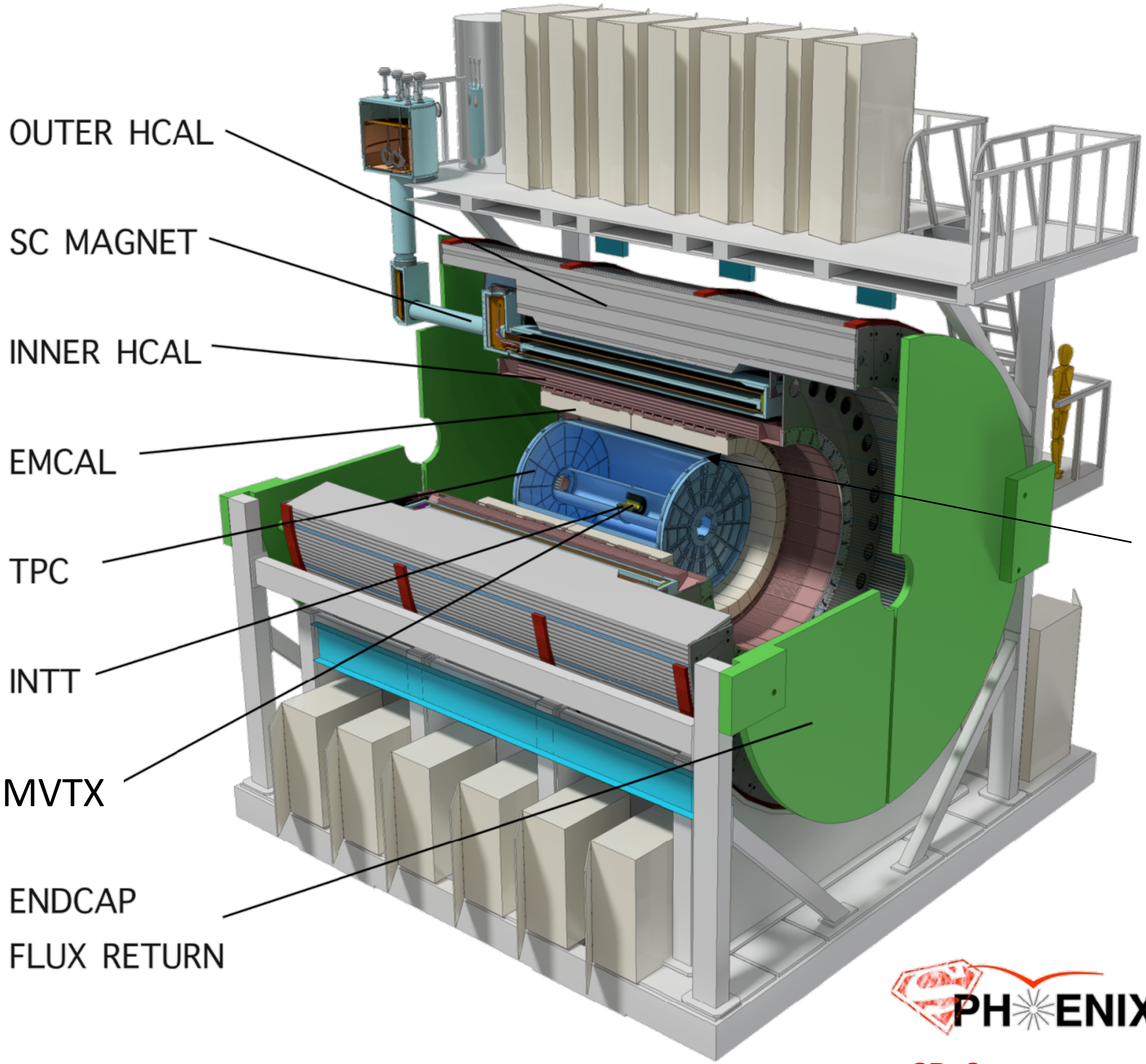


>2025

Time

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

EIC: e+p, e+A



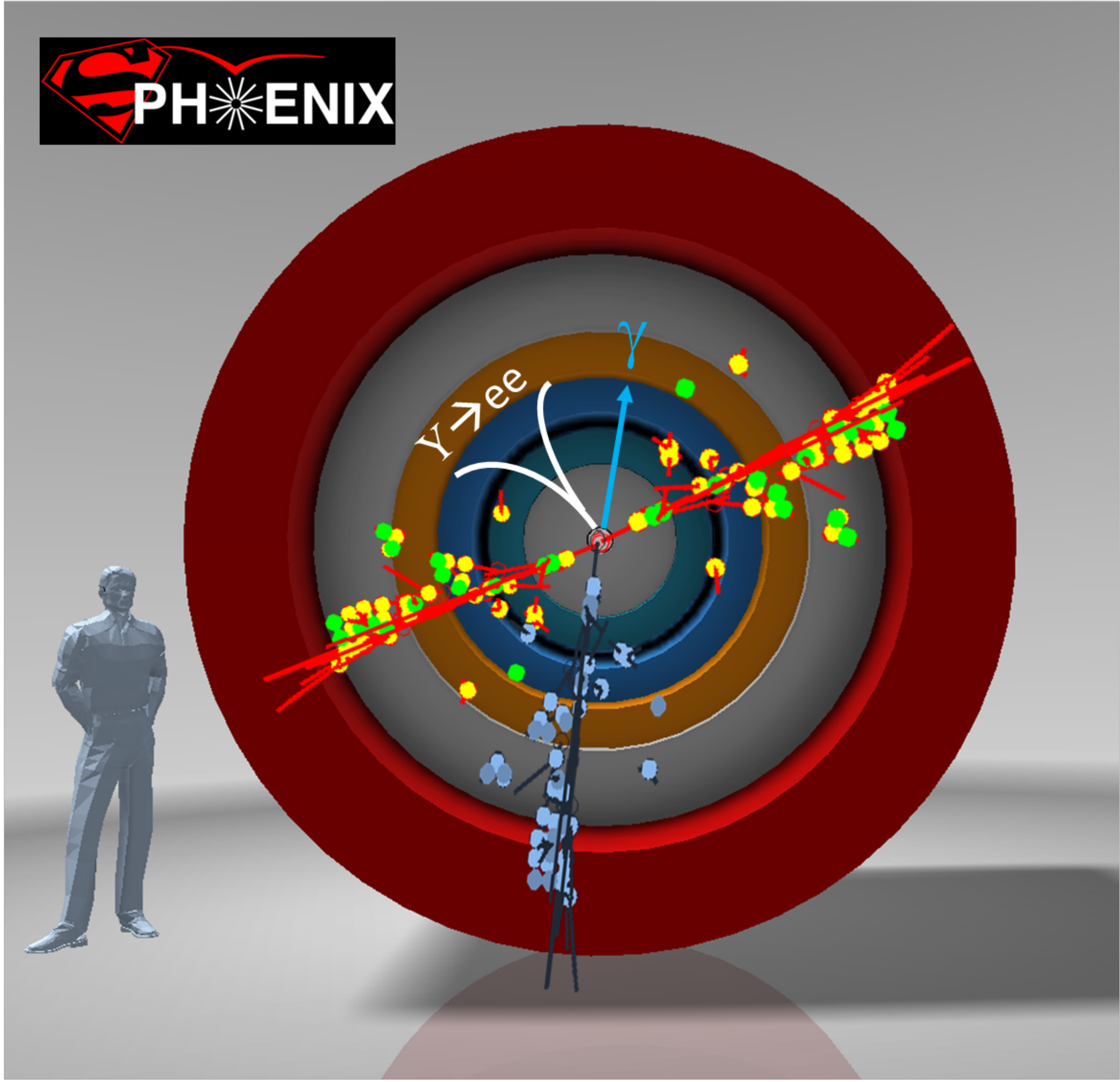
- High speed, 15 kHz trigger
- Large acceptance, |eta| < 1

PHENIX Detector

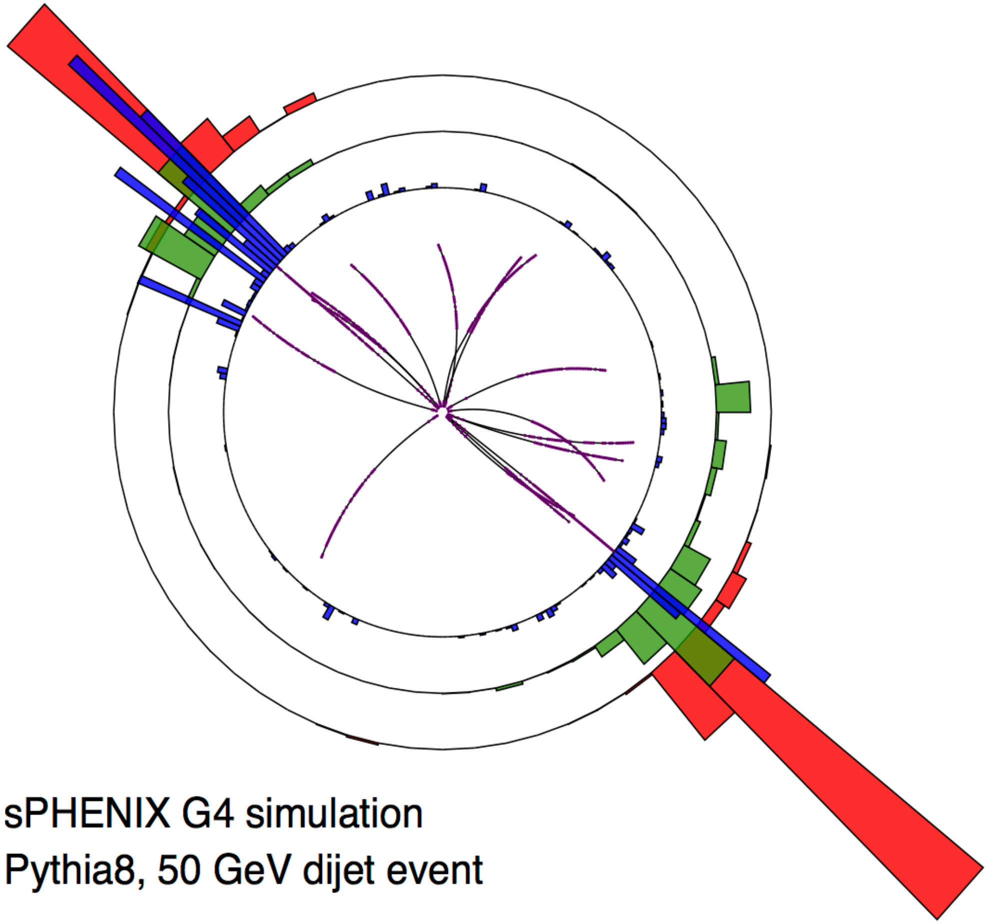
CD-0	**Sept 2016**
Construction Phase	**Jul 2018**
Ready for Beam	**Jan 2022**

sPHENIX 3 Physics Pillars

1. Jets
2. Heavy Quarks
3. Upsilons

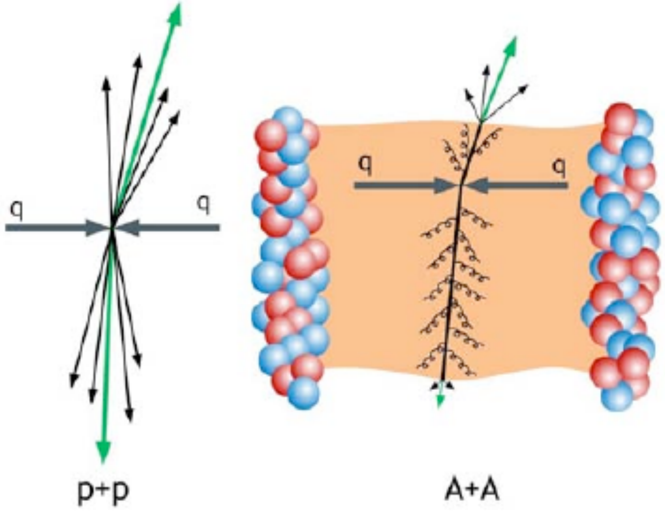


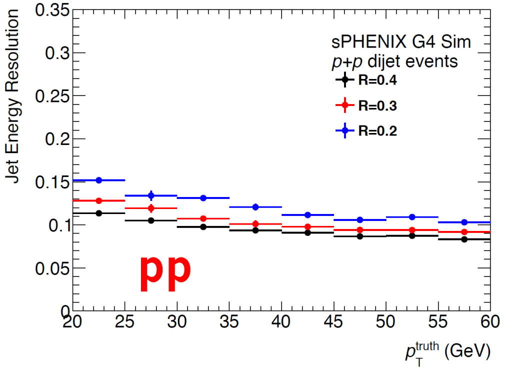
(I) Precision Calorimetry for Jets and Photons

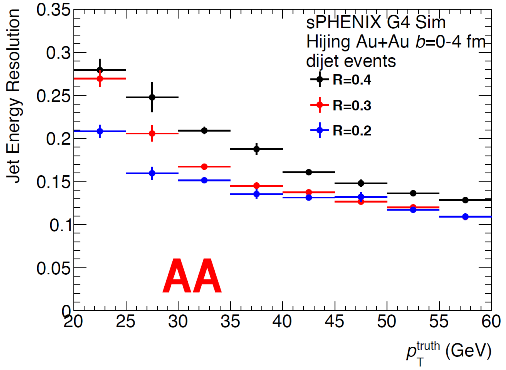


sPHENIX G4 simulation
Pythia8, 50 GeV dijet event

Jet production in p+p and Au+Au



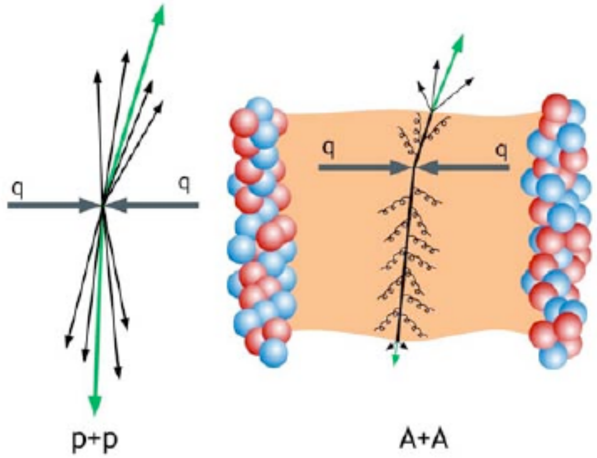


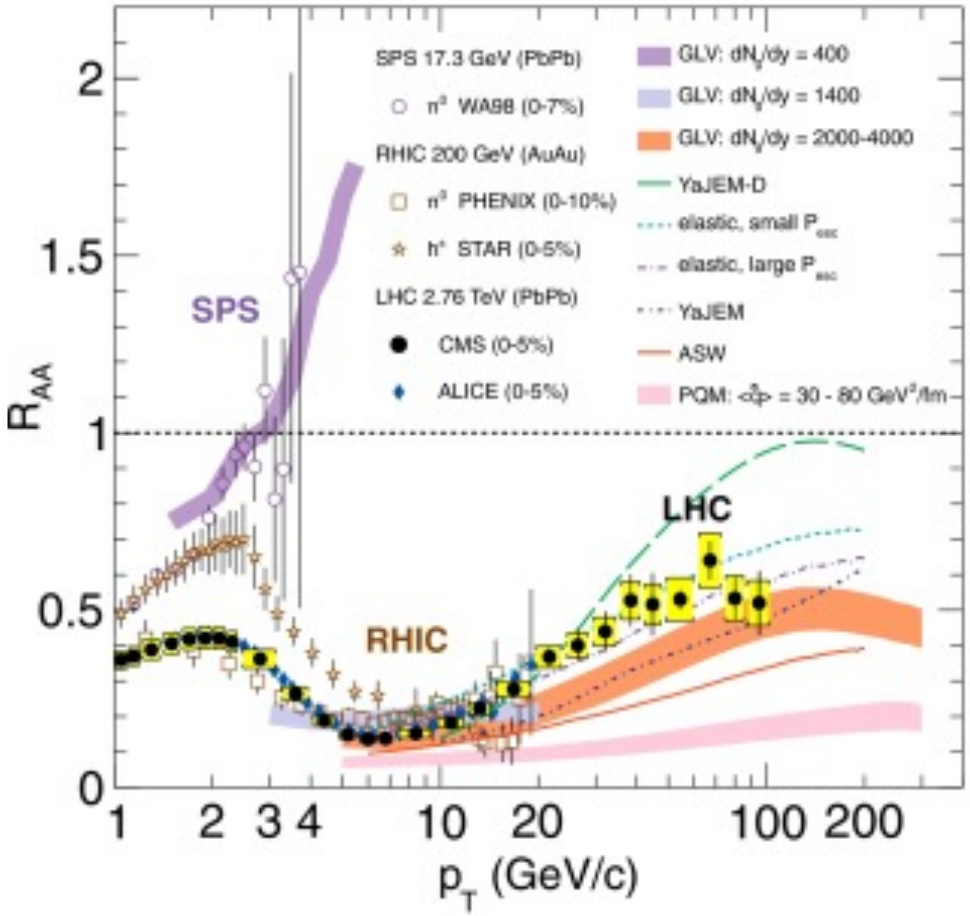


Excellent jet resolution in both p+p and A+A

Jet Quenching Observed @RHIC and LHC

$$R_{AA} = \frac{1}{N_{coll.}^{AA}} \frac{\sigma_{AA}}{\sigma_{pp}}$$





- Great progress in the last decade, but significant model dependence remains in the understanding of the physics of jet suppression and QGP properties at RHIC and LHC

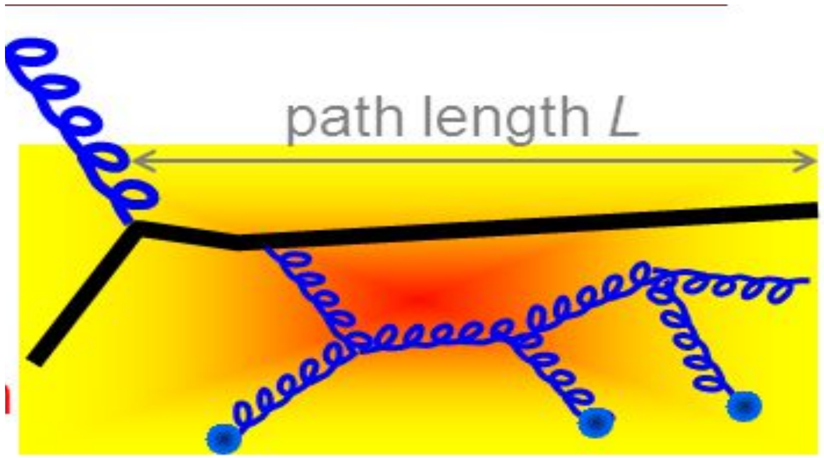
- sPHENIX goals - understand the inner workings of QGP

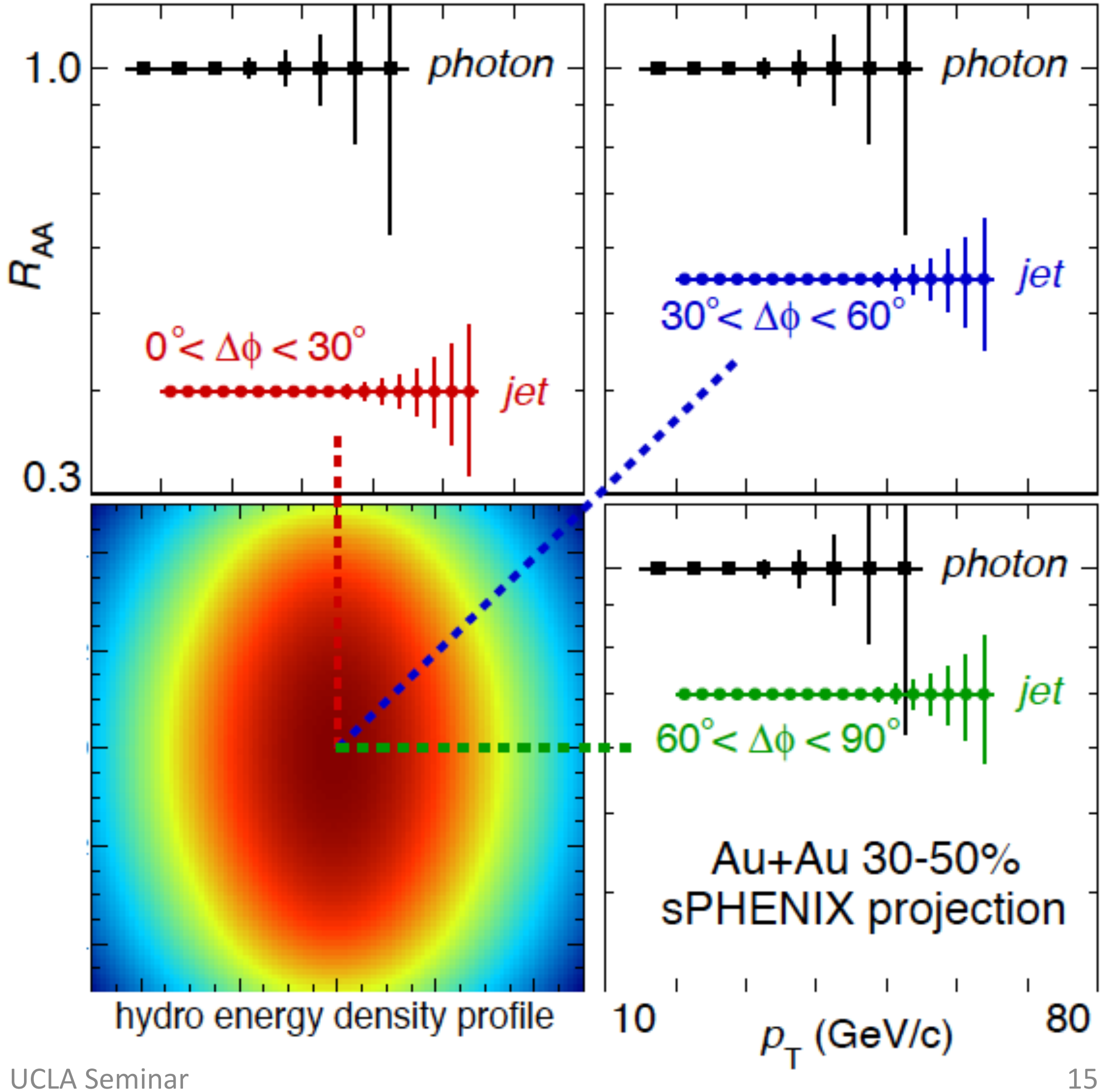
sPHENIX: Detail Study of the Path-length Dependence of Jet Suppression

Medium induced gluon radiation:

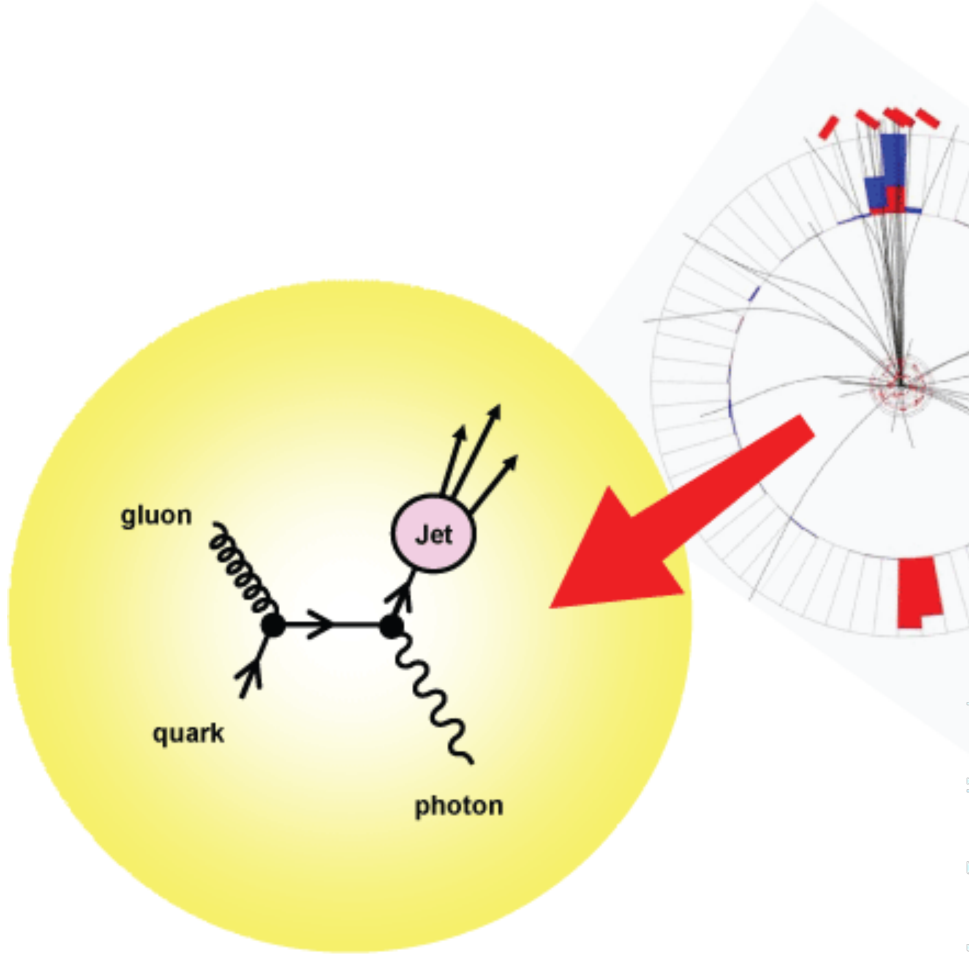
- BDMPS, GLV etc.

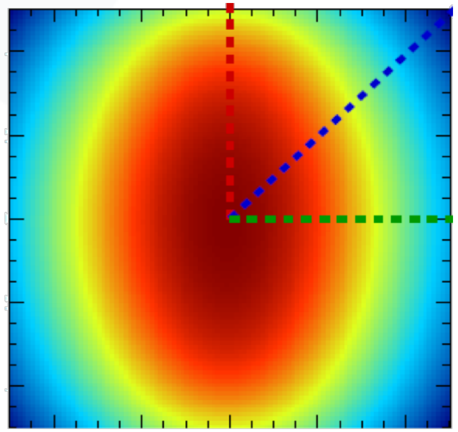
$$< \Delta E > \sim \alpha_s \times C_R \times \hat{q} \times L^2$$





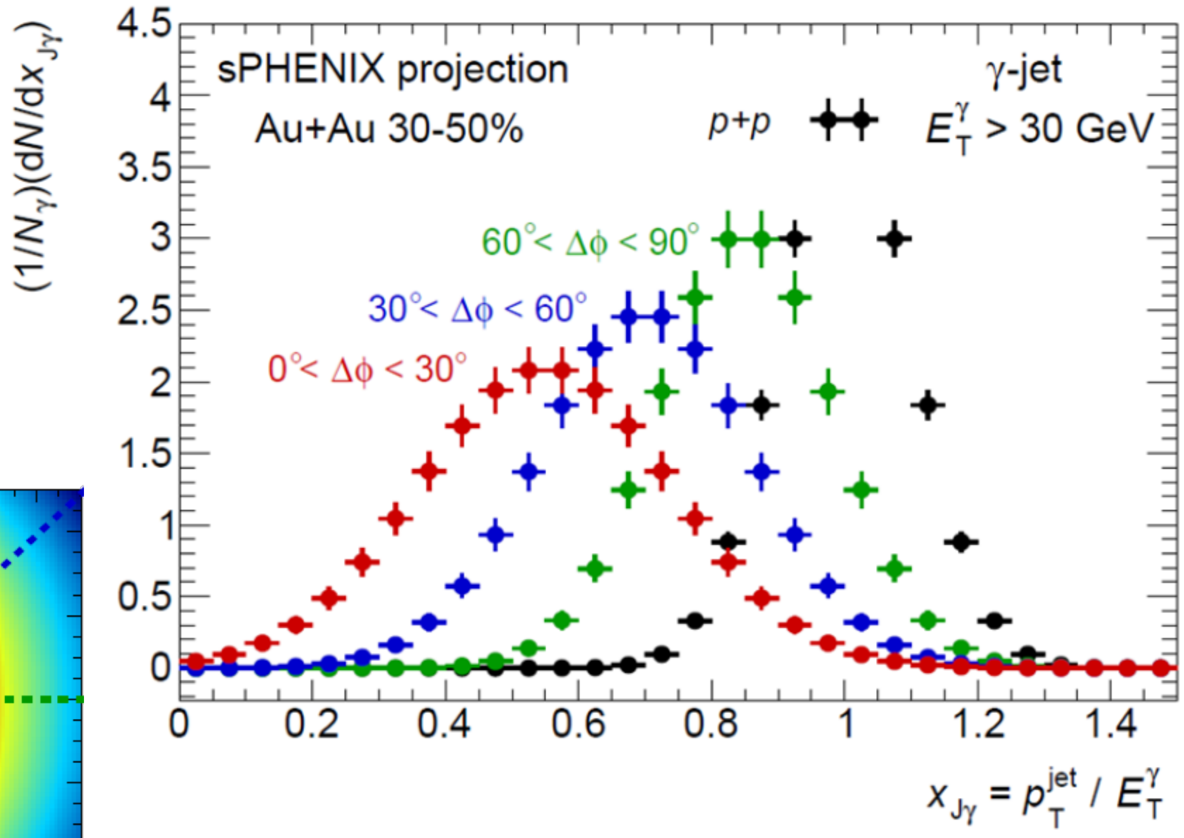
Direct Photon + Jet in Au+Au: Simulations





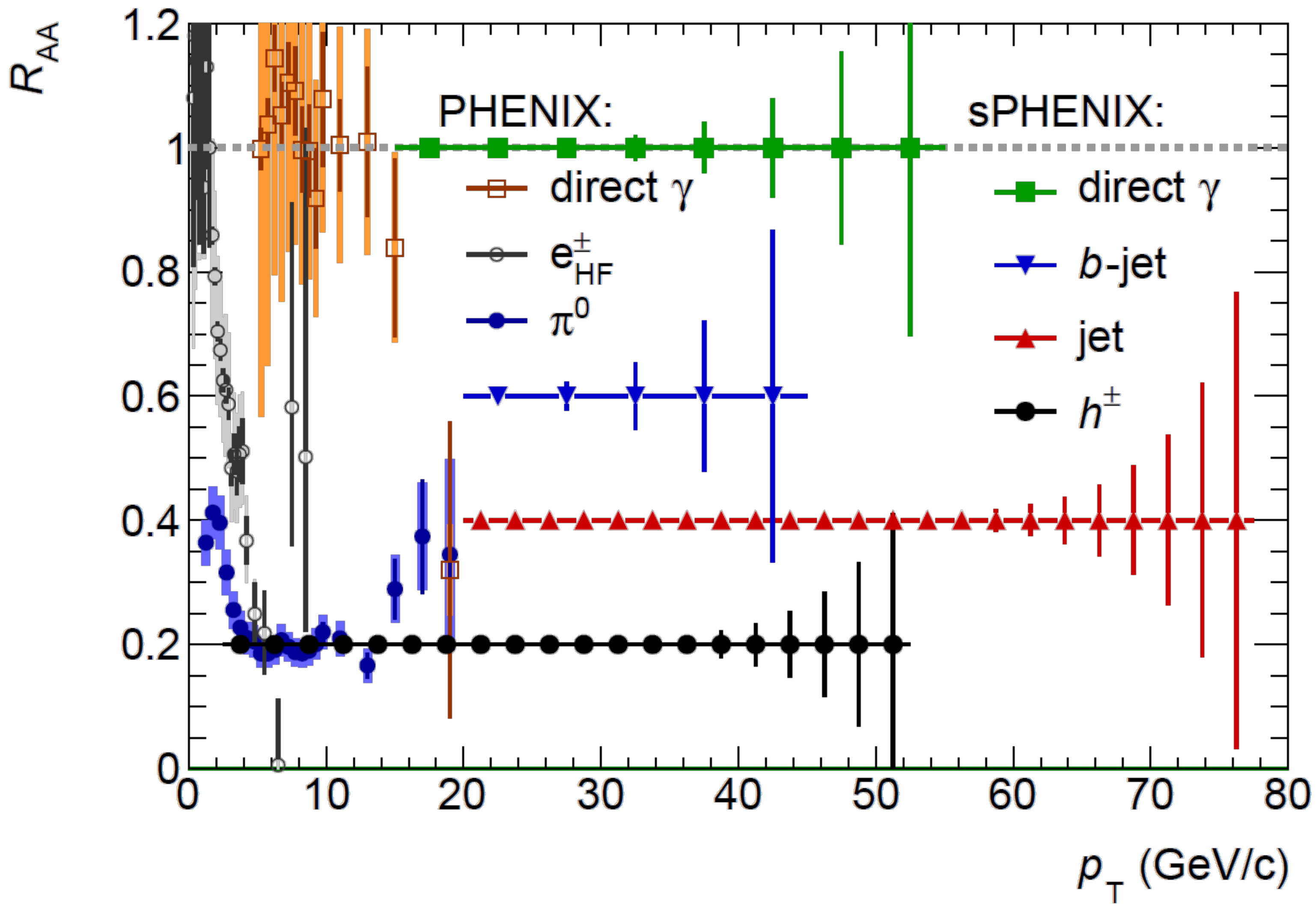
hydro energy density profile

Jet - direct photon momentum imbalance



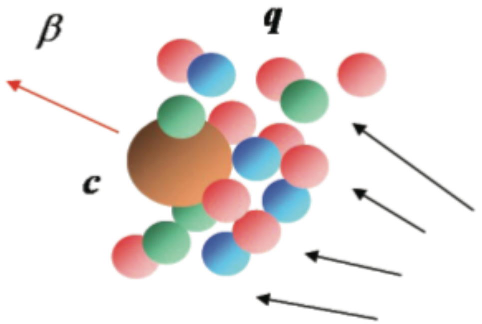
A Broad Physics Program with Jets @sPHENIX

Parton Mass and Flavor Dependence of Jet Suppression and more

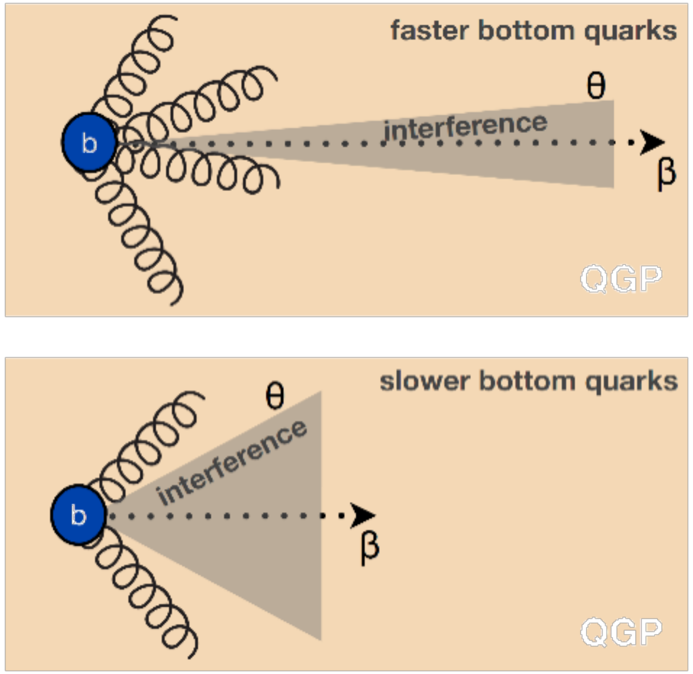


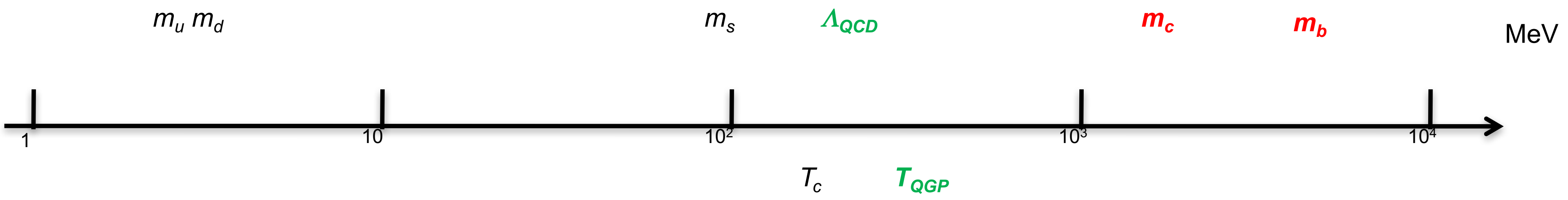
(II) Heavy Quarks - Unique Probe of QGP

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

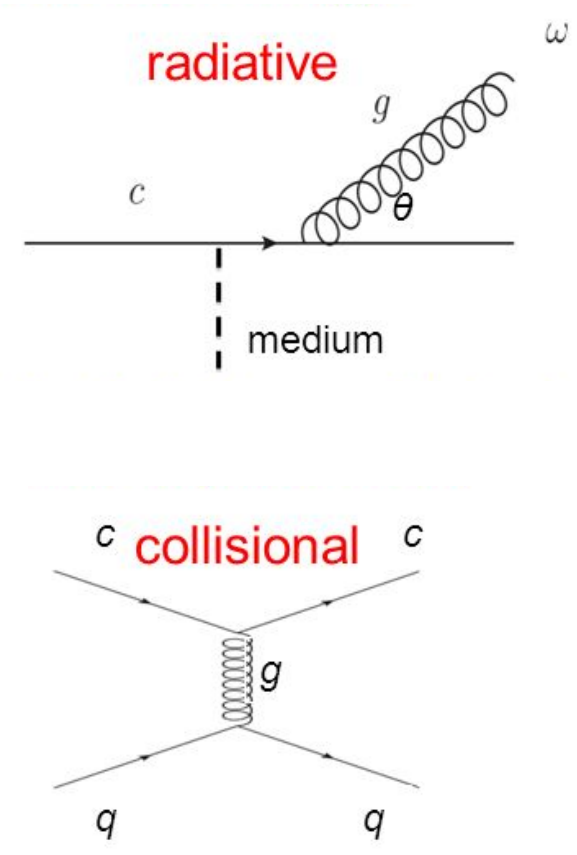


Mass dep.
radiation dE/dx



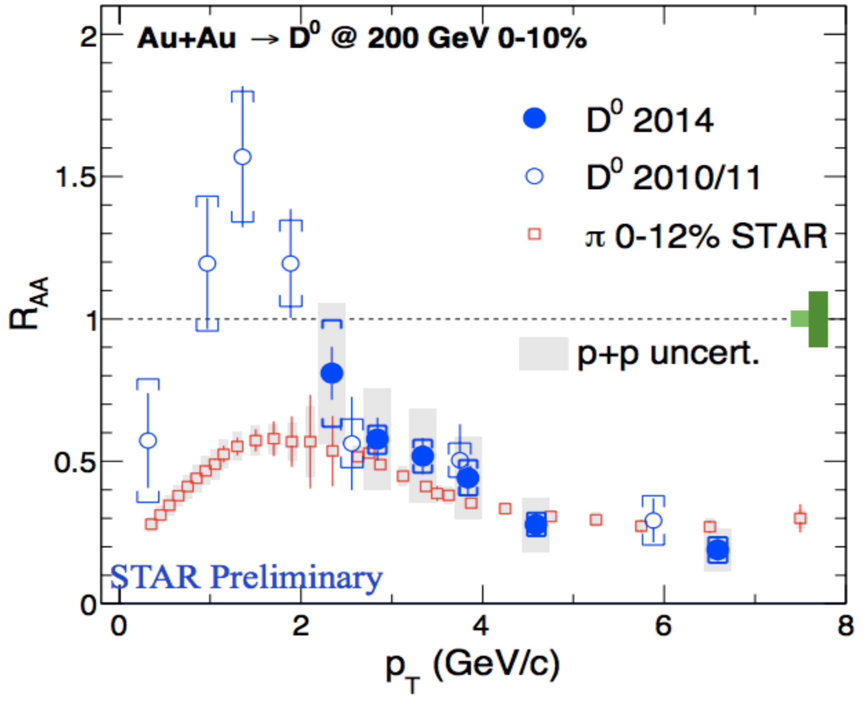


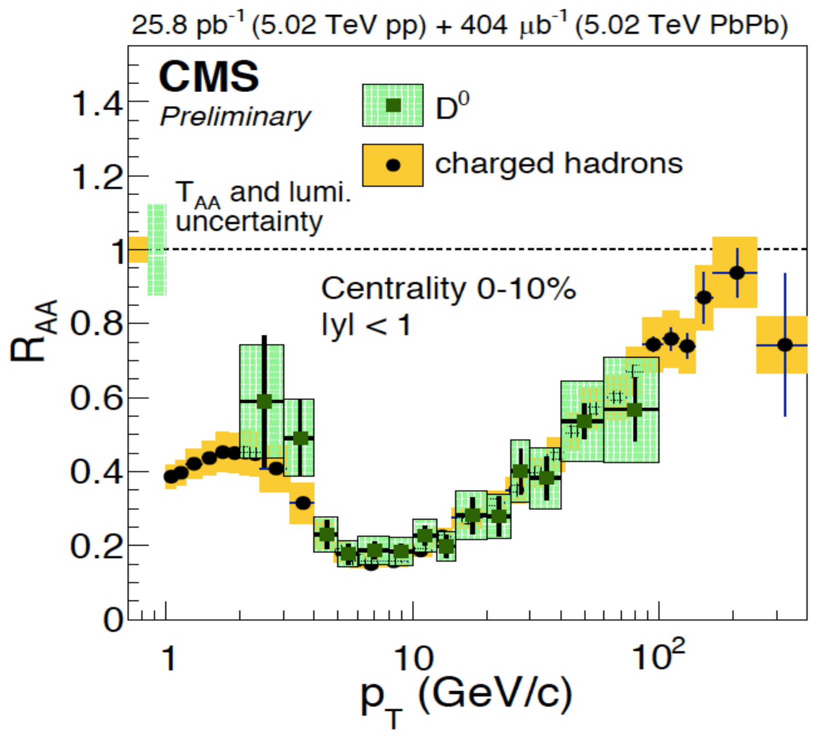
Recent Highlight I: Charm R_{AA} @RHIC and LHC



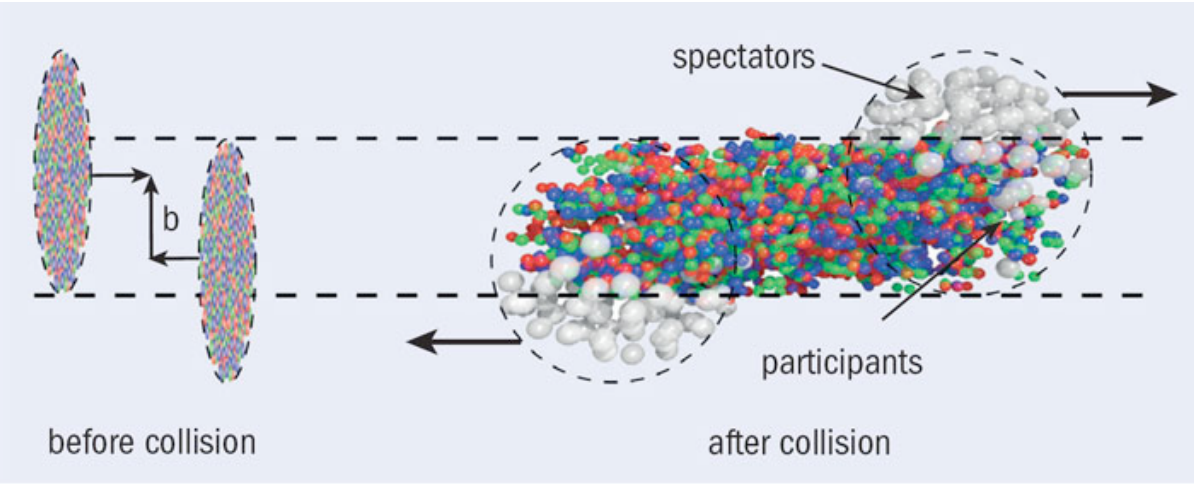
R_{AA} (D-meson) ~ R_{AA} (h) at high p_T ~> 4 GeV/c

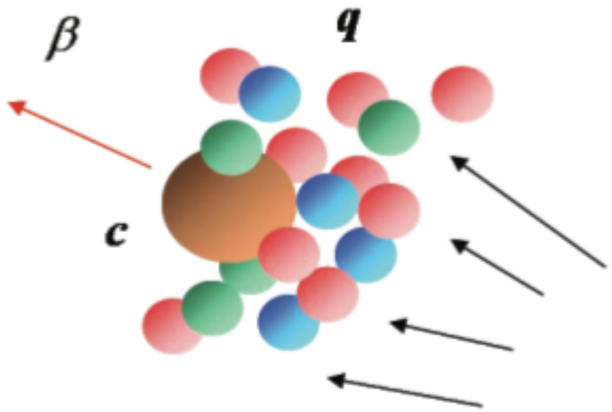
- significant suppression of charmed hadron R_{AA} in central A+A collisions
- strong charm-medium interactions
- mass effects?: expected important at low pT, dead-cone, collisional effects etc.

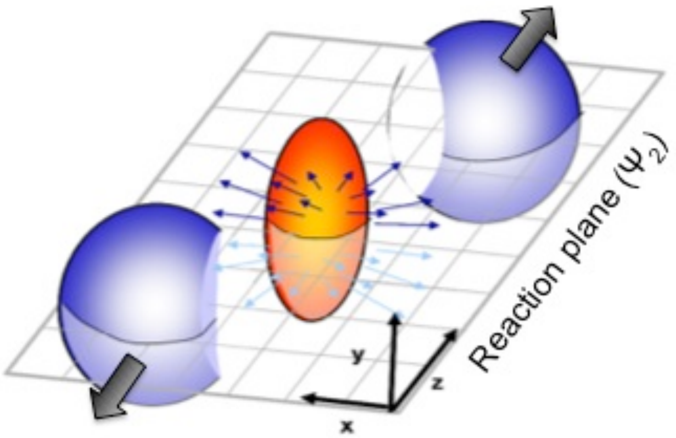


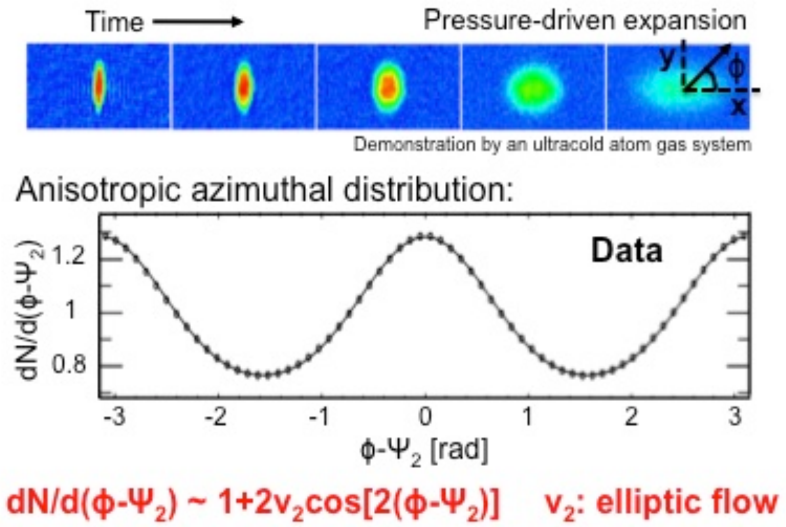


Particle "Flow" and QGP Medium Response



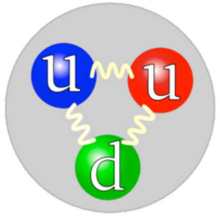






Anisotropic flow:
due to interactions w/ medium

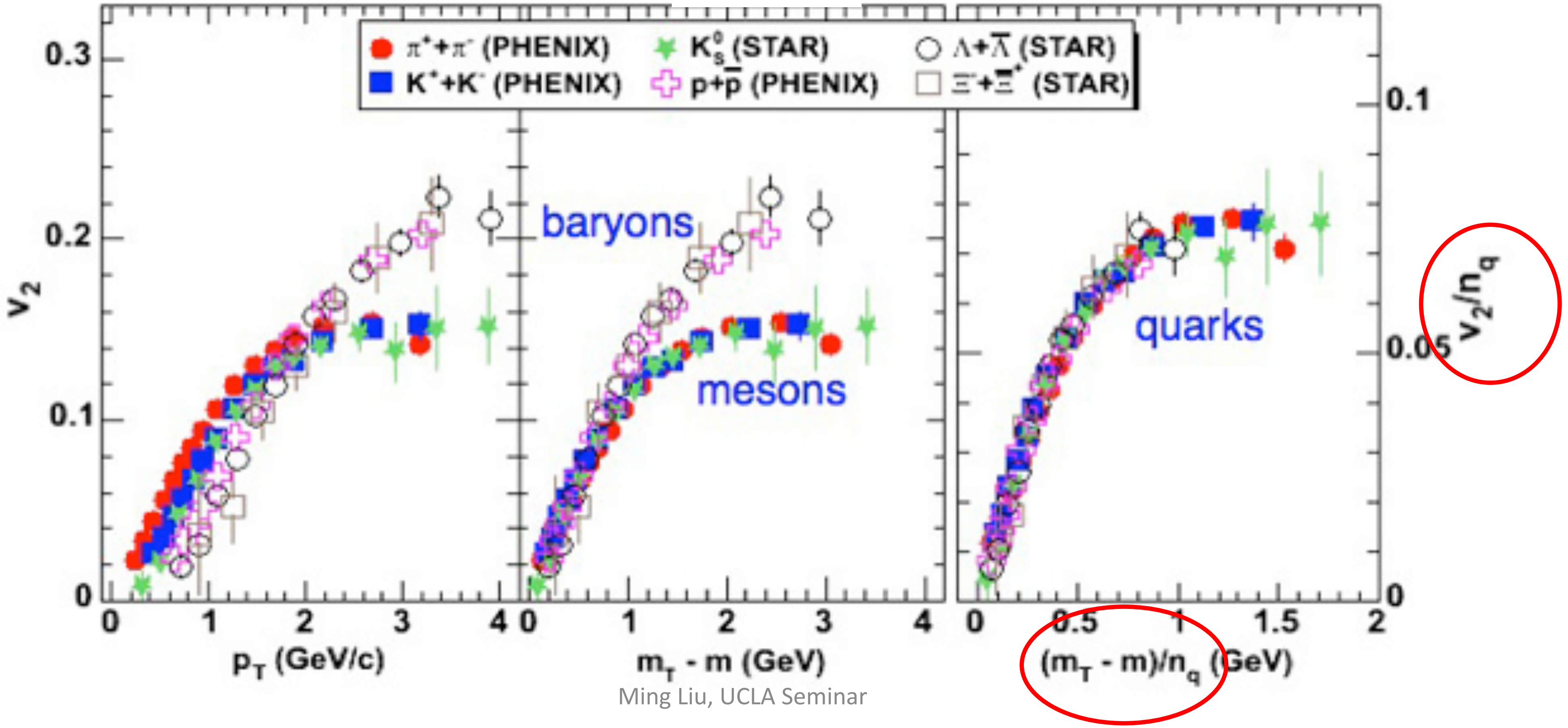
Universal Scaling of V_2 - Perfect QGP Liquid!?



Baryons: n_q=3

Mesons: n_q=2

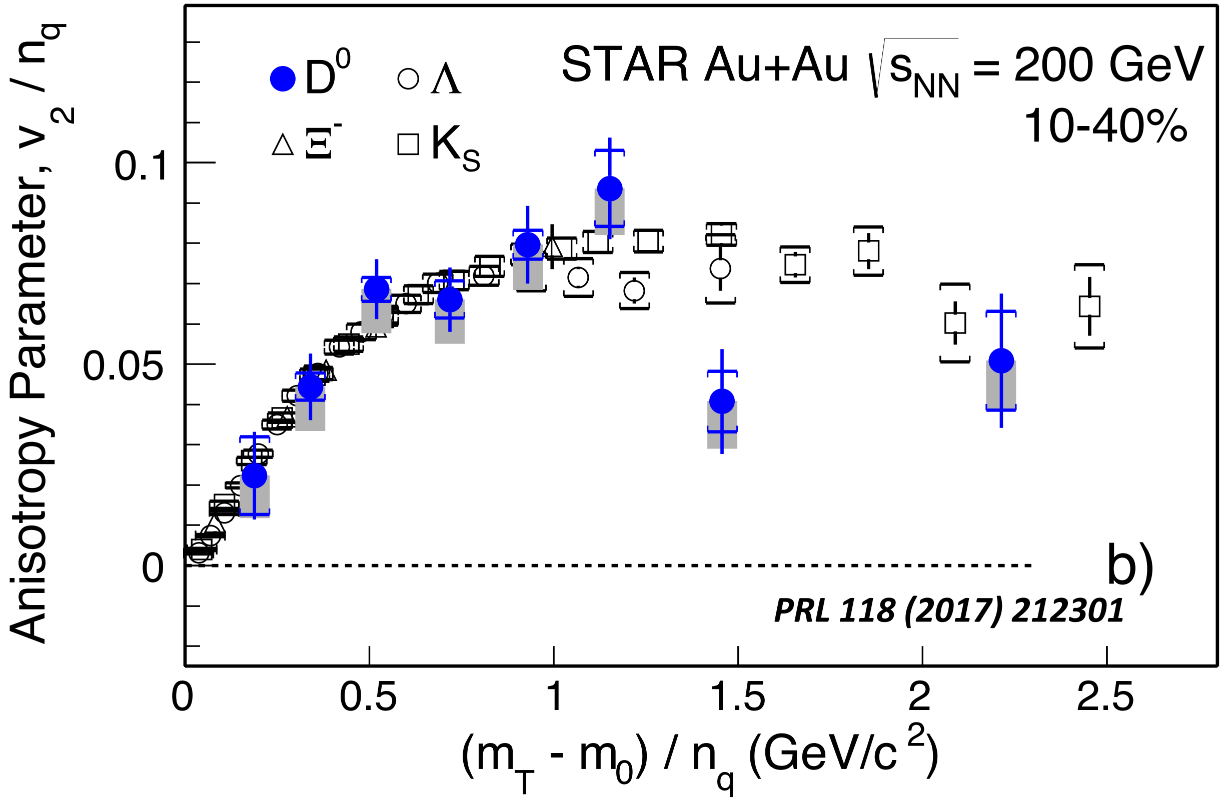
$$m_T = \sqrt{m^2 + p_T^2}$$

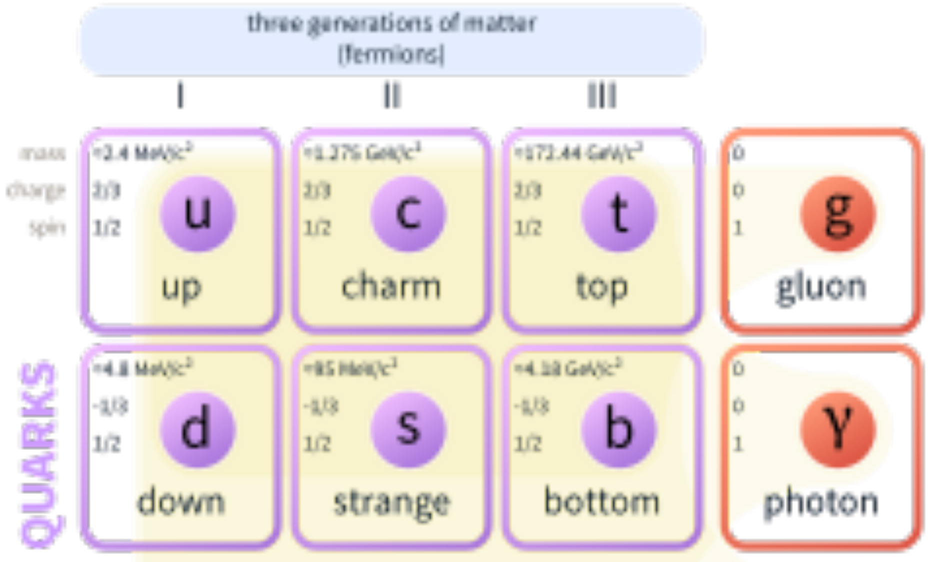


A Surprise from RHIC!

Charm quarks flow just as well as lighter quarks – “Perfect liquid”

Elliptic flow of D0 mesons (charm quarks)



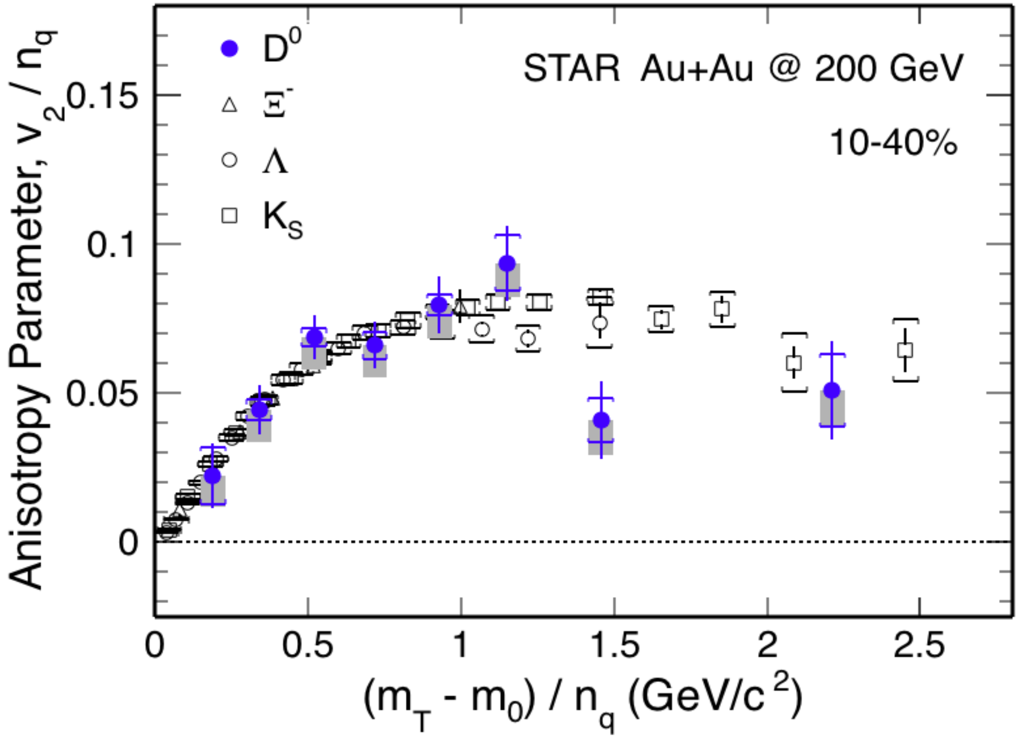


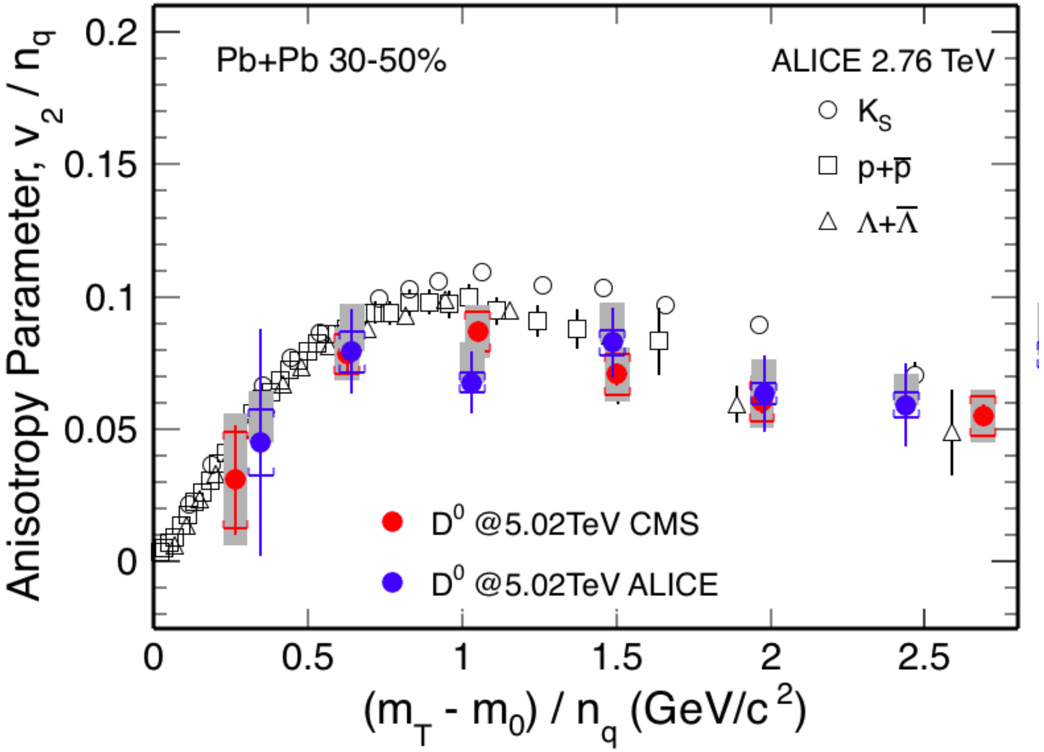
m(u,d) = 2~5 MeV
M(s) = 100 MeV

M(c) = 1,300 MeV
M(b) = 4,200 MeV
M(t) = 175,000 MeV
- PDG 2017

Recent Highlights II: Charm V_2 @RHIC and LHC

- v_2 of D^0 follows the same trend as light hadrons
  - Charm quarks flow the same as light quarks
- Strong coupling to medium at low pT?



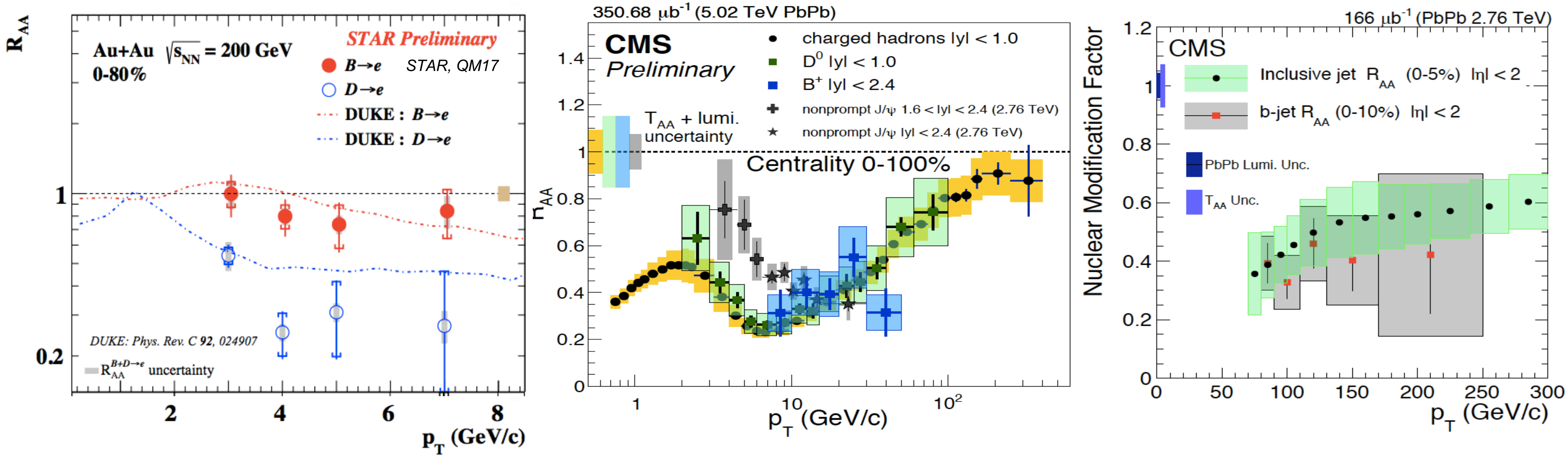


How about the much heavier Beauty?

$$M_b >> \Lambda_{QCD}, T_{QGP}$$

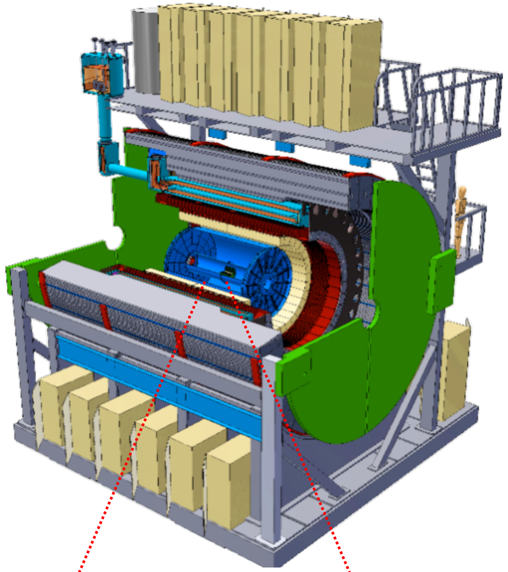
- R_{AA} (B->e) > R_{AA} (D->e, h) @low pT
- B^+ & b-jet ~ light hadrons & charm @high pT

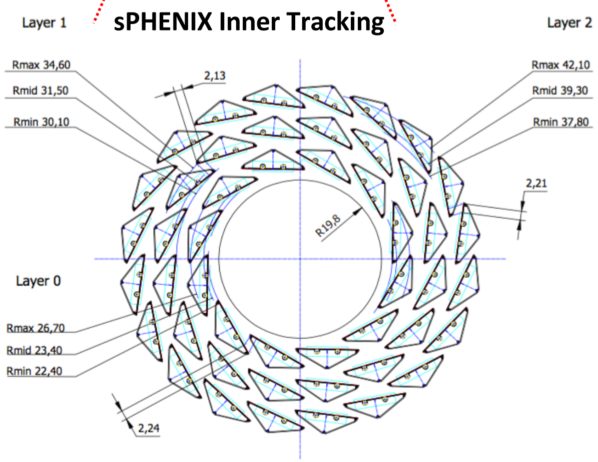
Highly desired:
precision measurements of
B @low-intermediate pT ~< 50GeV



MAPS-based VerTex detector: MVTX Upgrade

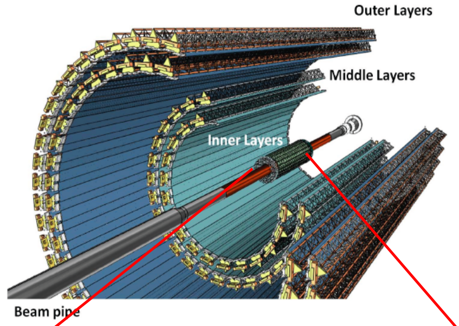
To enable B-hadron and b-jet physics in sPHENIX

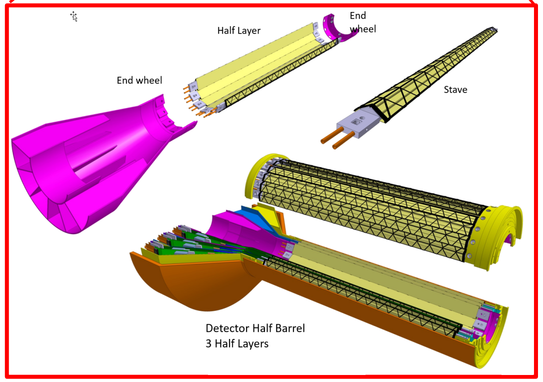




Adapt ITS/IB
- Min. Risks
- Max. Phys.

ALICE ITS Upgrade:
Inner Barrel Tracker

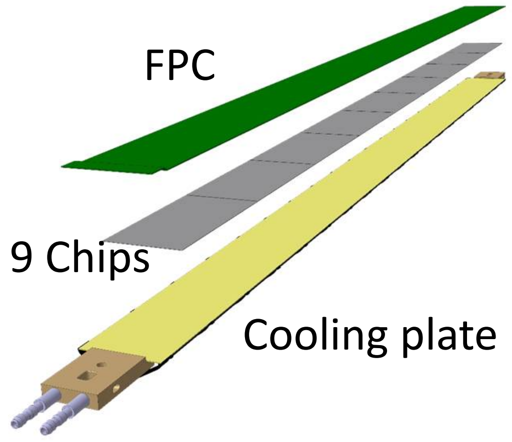




Monolithic-Active-Pixel-Sensors (MAPS)

The next Generation State of the Art Pixel Tracker

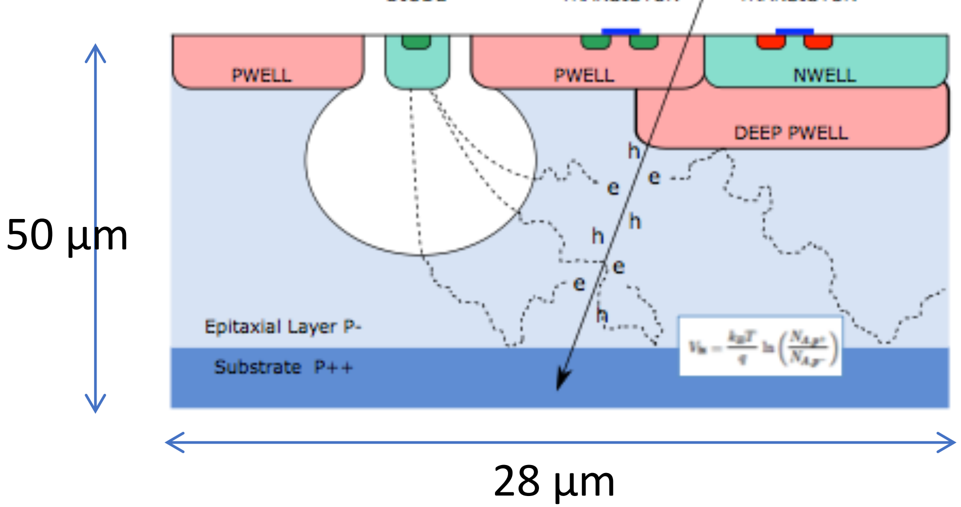
- **Advantages of ALICE MAPS/ALPIDE:**
  - Very fine pitch (28x28 µm)
  - High efficiency (>99%) and low noise ($<10^{-6}$)
  - Time resolution, as high as ~5 µs
  - Ultra-thin/low mass, 50µm (~0.3% X_0)
  - On-pixel digitization, low power dissipation



A 9-chip MAPS stave, 1.5 x 27cm^2

An ideal detector for QGP physics!

ALPIDE design



Tower Jazz 0.18 µm CMOS

- feature size 180 nm
- metal layers 6
- gate oxide 3nm

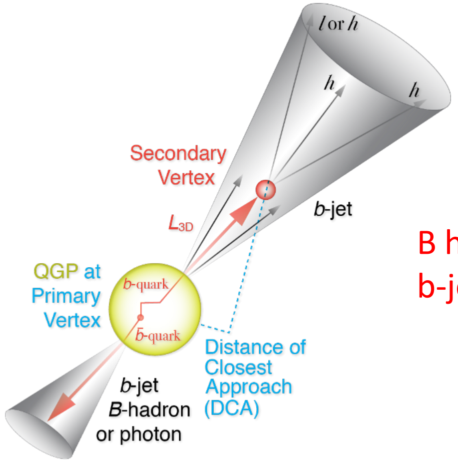
substrate: $N_A \sim 10^{18}$
epitaxial layer: $N_A \sim 10^{13}$
deep p-well: $N_A \sim 10^{16}$

RHIC Multi-Year Plan: sPHENIX 2022-2026+

Evolving

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

- Precision B-tagging w/ MVTX:
  - Tracking resolution better than 50um @pT=1GeV
  - High multiplicity HI collisions
  - Low multiplicity but high rate p+p collisions
  - High efficiency and high purity



B hadrons/pT<15GeV: *O*(1M)
b-jets/pT>15GeV: *O*(100K)

Physics Channels: Open Charm and Beauty

Hadron	Abundance	cτ (μm)
D^0	61%	123
D^+	24%	312
D_s	8%	150
Λ_c	6%	60
B^+	40%	491
B^0	40%	455
B_s	10%	453
Λ_b	10%	435

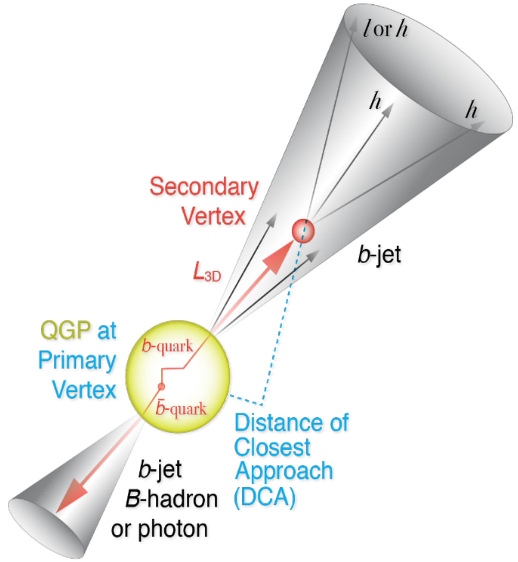
b-tagged jet and cor.	p_T>15 GeV

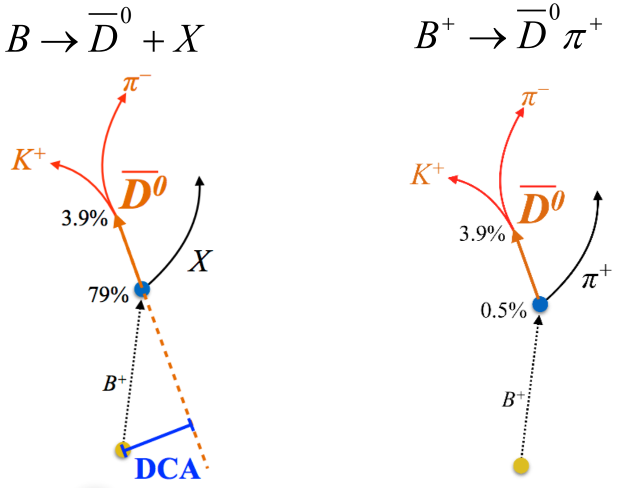
$B \rightarrow \overline{D}^0 + X$ 60%

$B^+ \rightarrow \overline{D}^0 \pi^+$ 0.5%

p_T<15 GeV

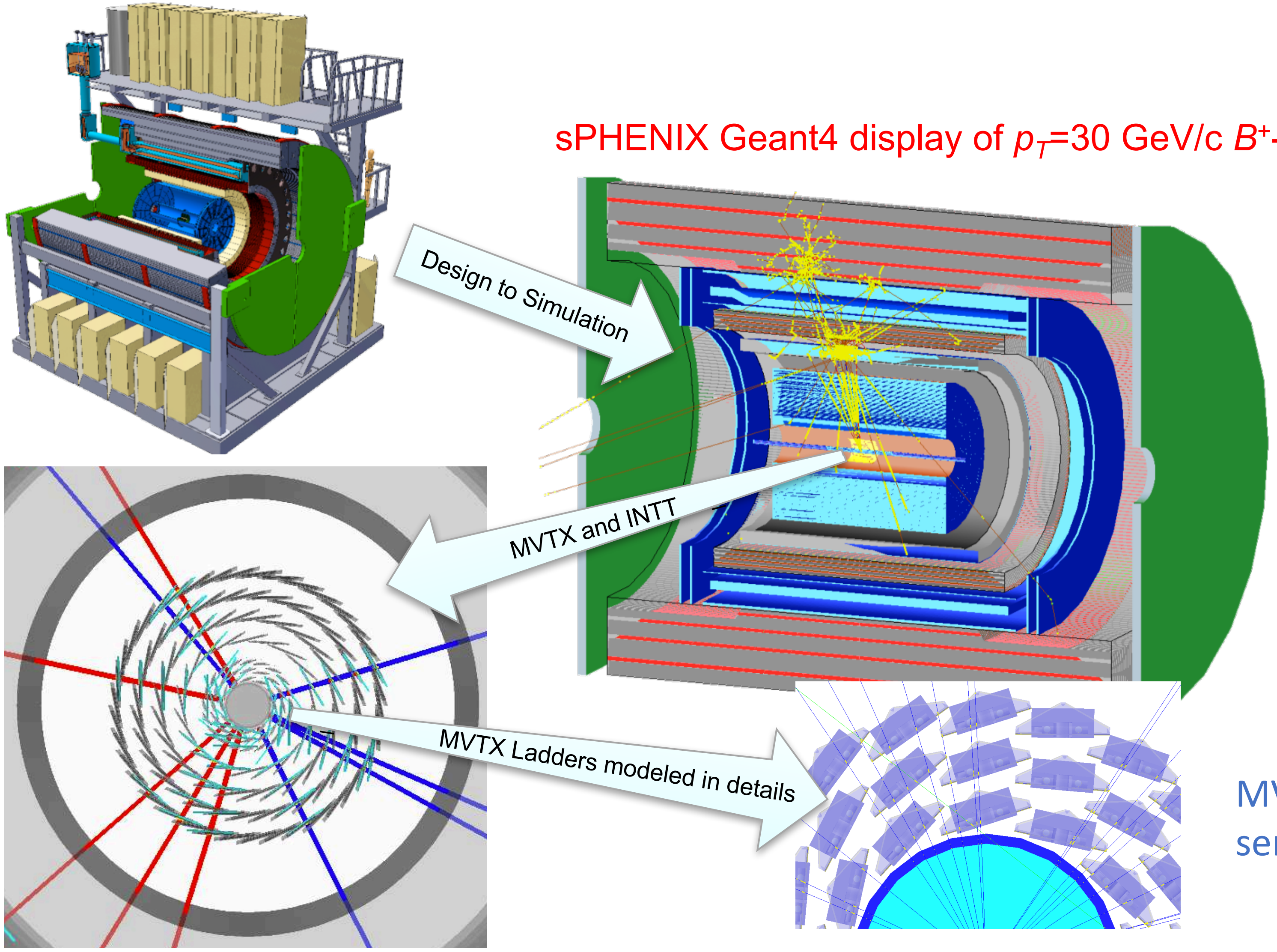
Exploring $B \rightarrow J/\psi + X$ and more





Simulation: *b*-jet and *B*-meson Tagging

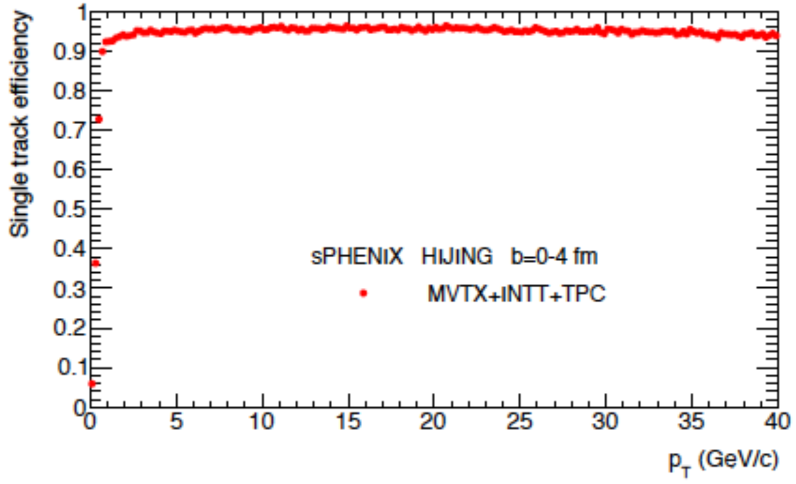
sPHENIX Geant4 display of p_T=30 GeV/c B^{+}-hadron



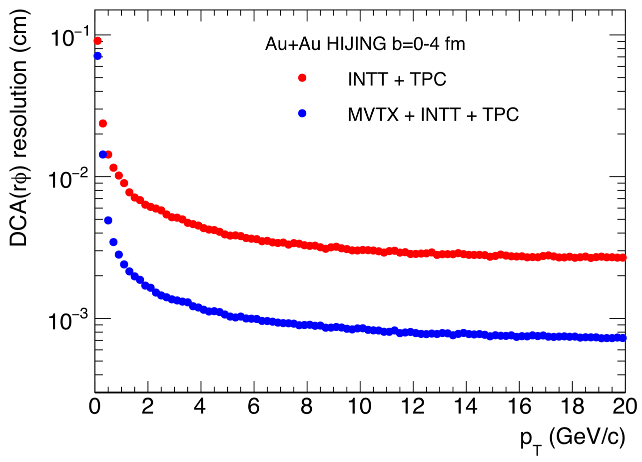
MVTX sensors

Tracking Performance with Full GEANT

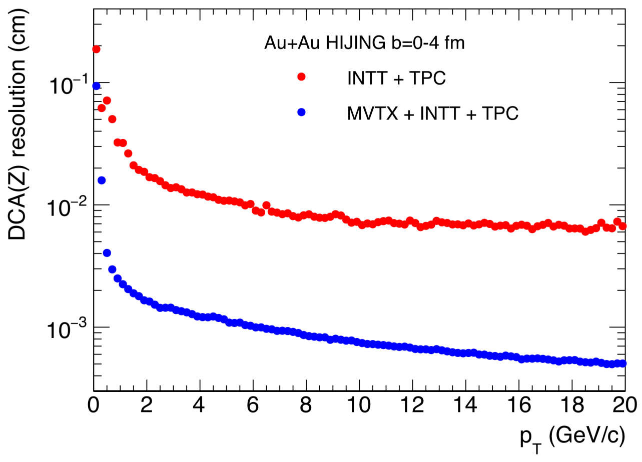
- MVTX geometry modeled and digitized according to ALICE ITS/IB
- Cluster resolution: ~5 μm
- DCA_{2D}, DCA_z<30 μm down to 1 GeV/c



DCA_rϕ

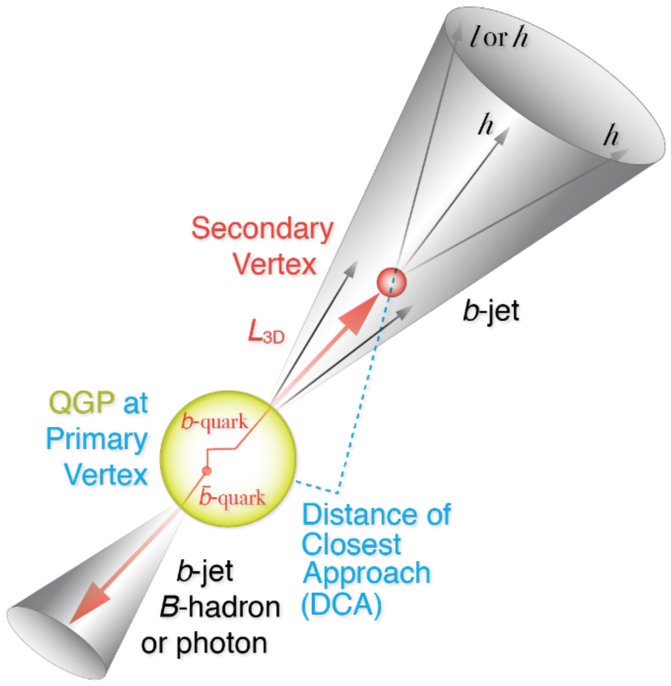


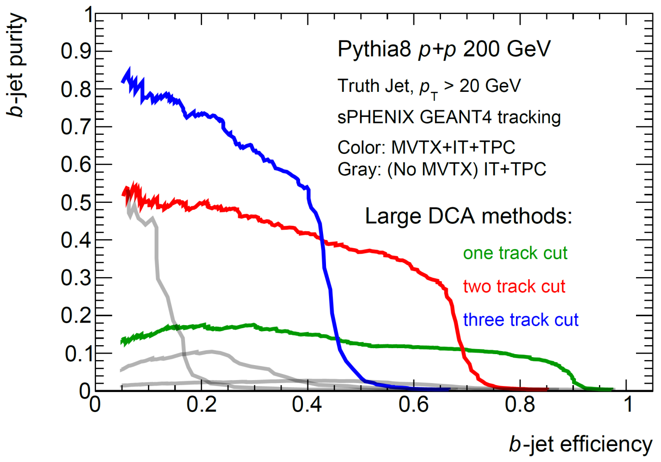
DCA_z

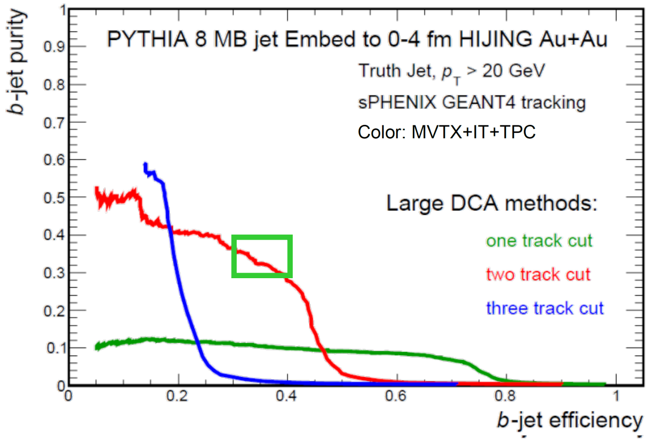


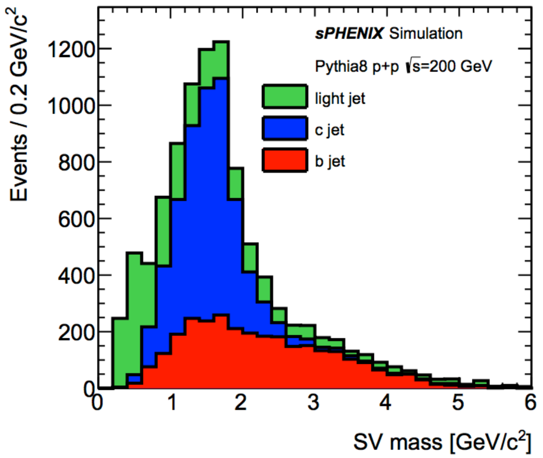
B-jet tagging

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





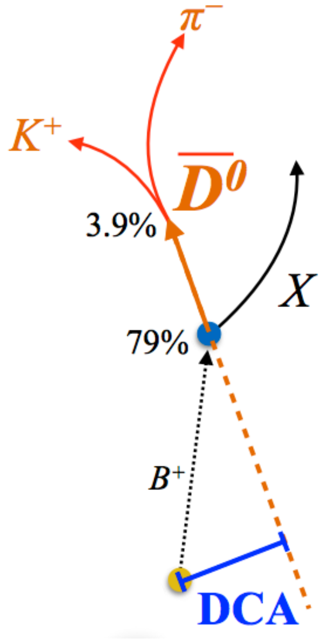


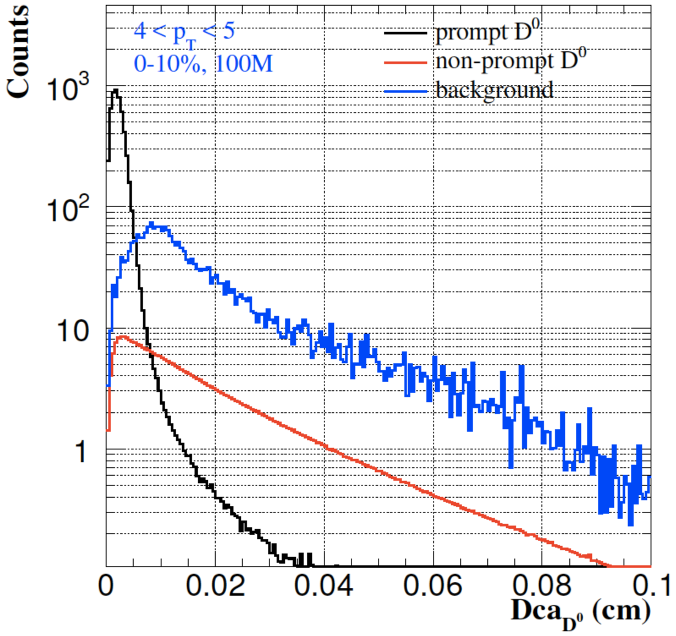


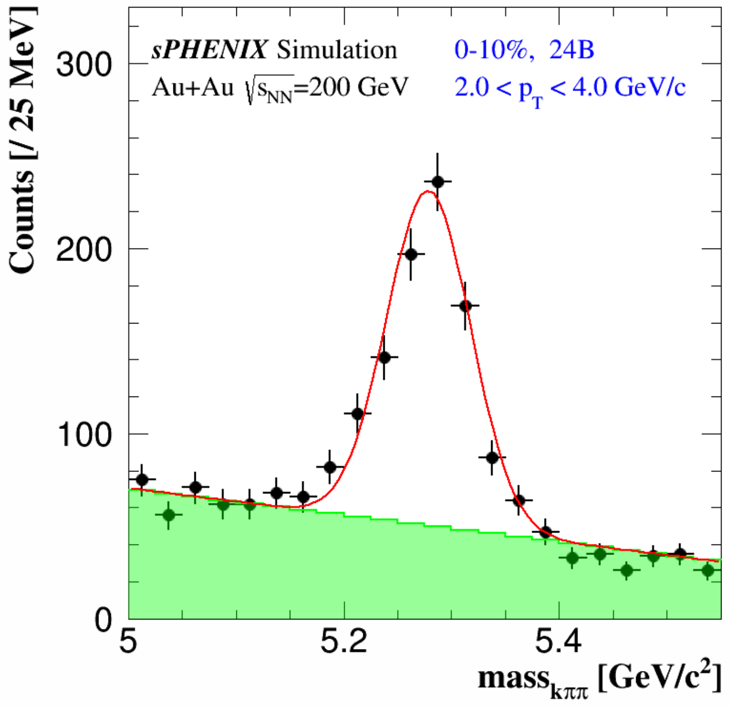
CMS work-point, Phys. Rev. Lett. 113, 132301 (2014)

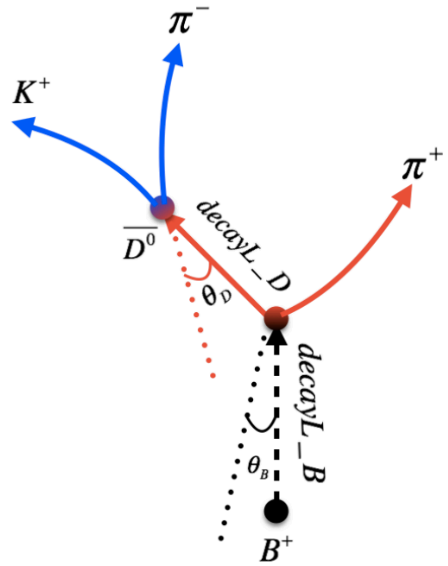
B-hadron Tagging

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





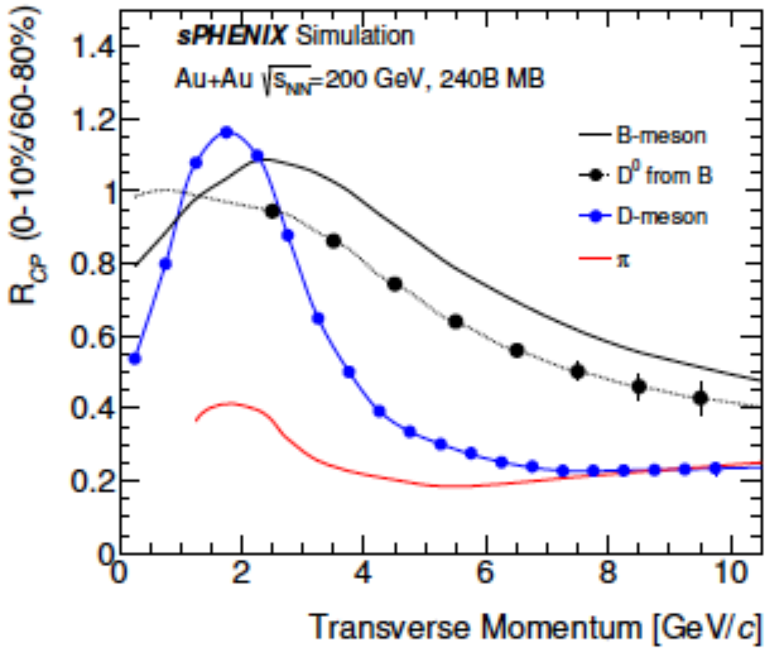


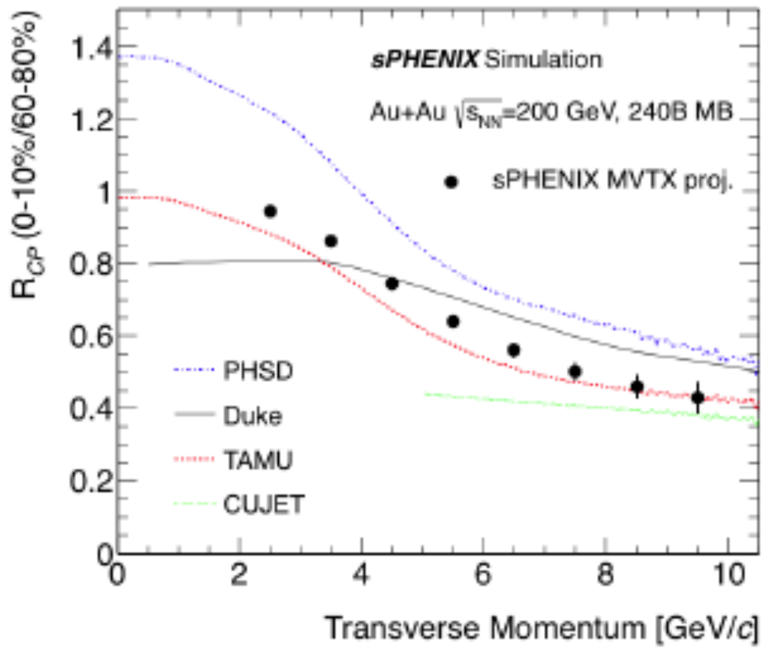


sPHENIX Projected R_{AA} Sensitivity

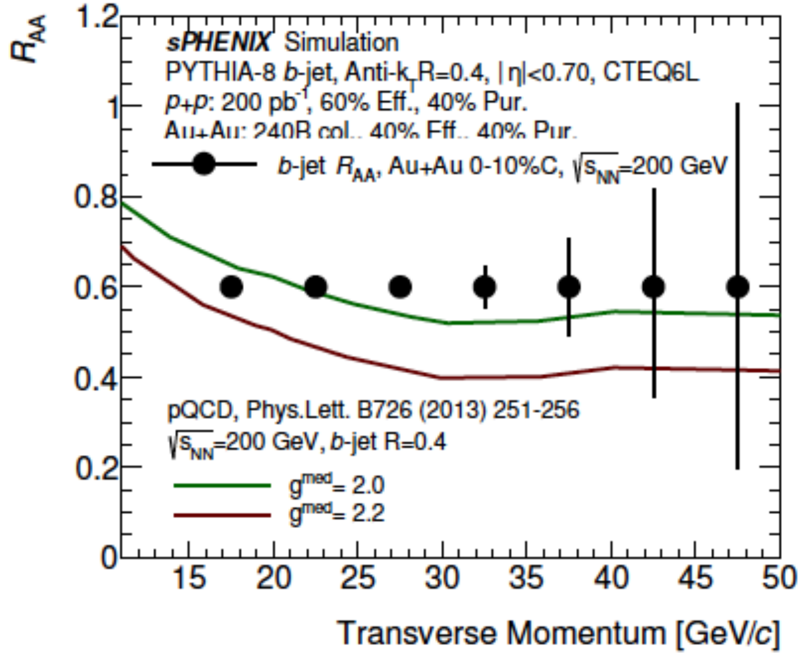
Open questions to be answered: energy loss mechanisms and QGP medium properties

B-Mesons





B-jets

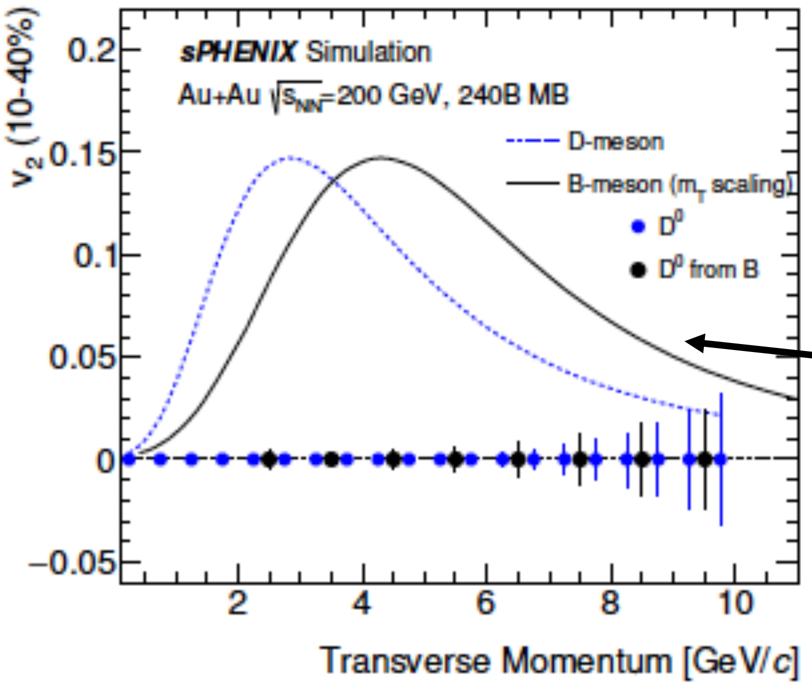


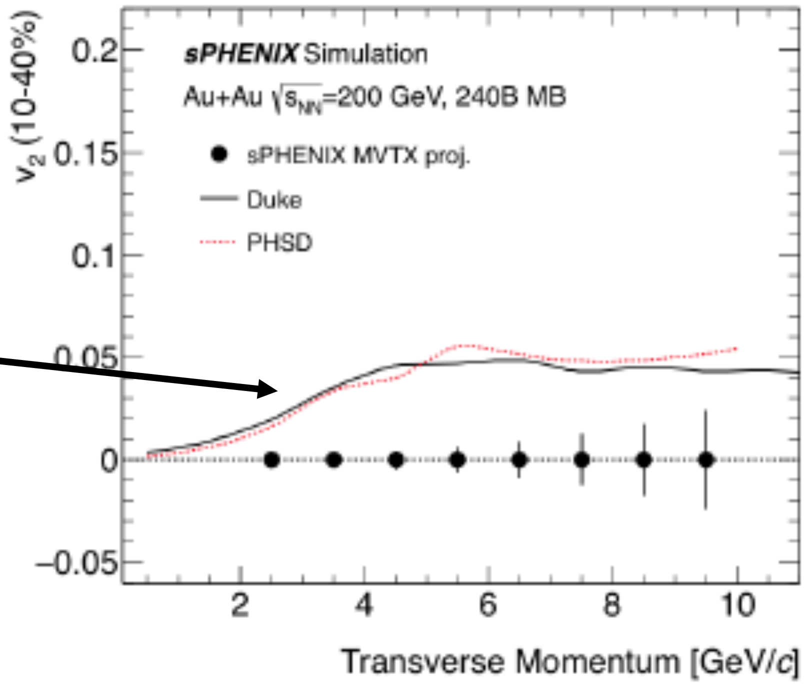
sPHENIX Project Elliptical Flow v_2

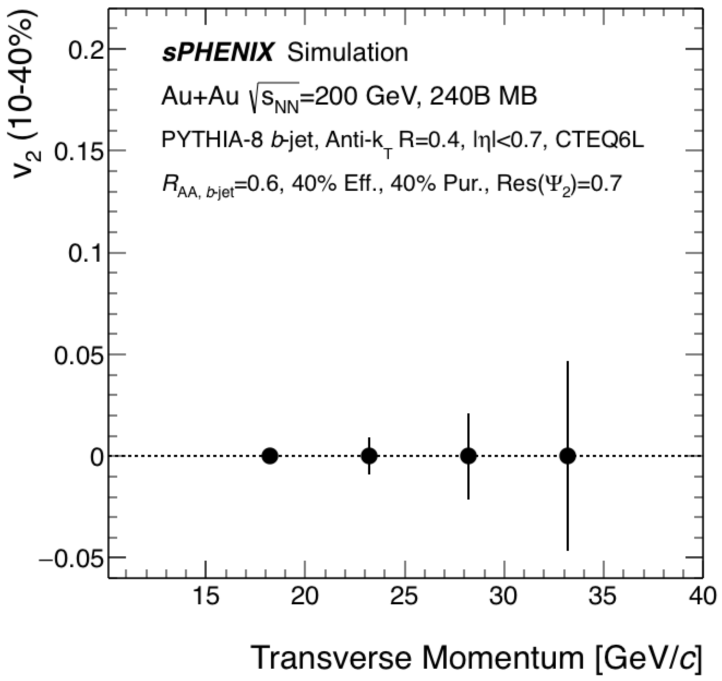
Open questions to be answered: nature of quasi-particles, medium interactions and transportation

B-Mesons

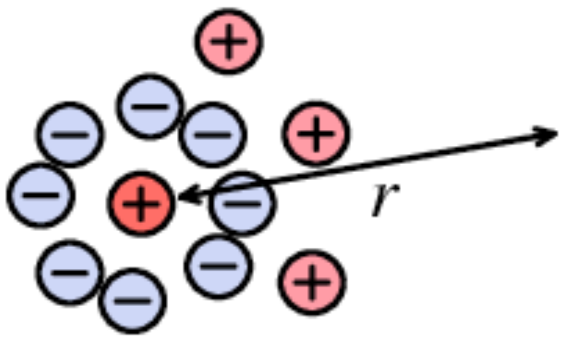
B-jets







(III) Heavy Quarkonia and QGP Color Screening

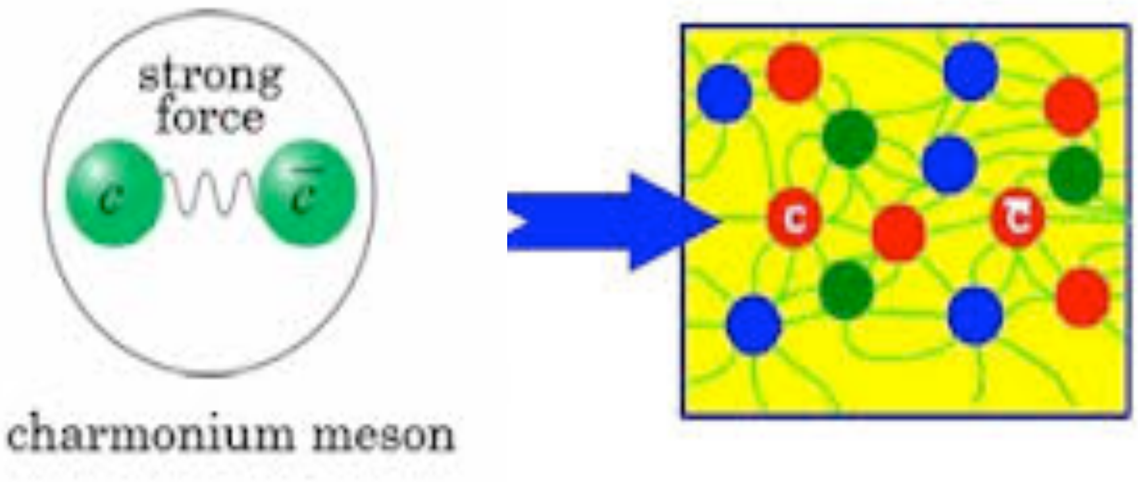


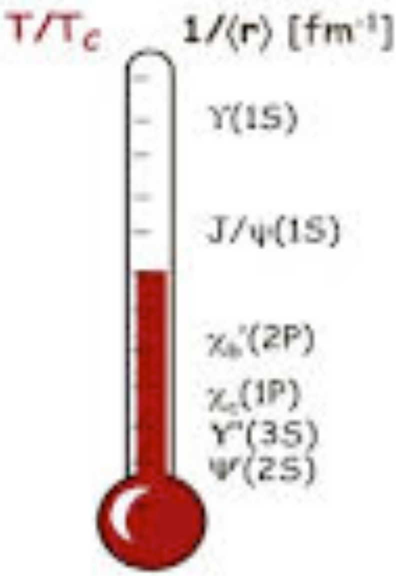
$$V(r) = V_0 \frac{e^{-r/\lambda_D}}{r}$$

$$\lambda_D = C \times \sqrt{\frac{T}{n}}$$

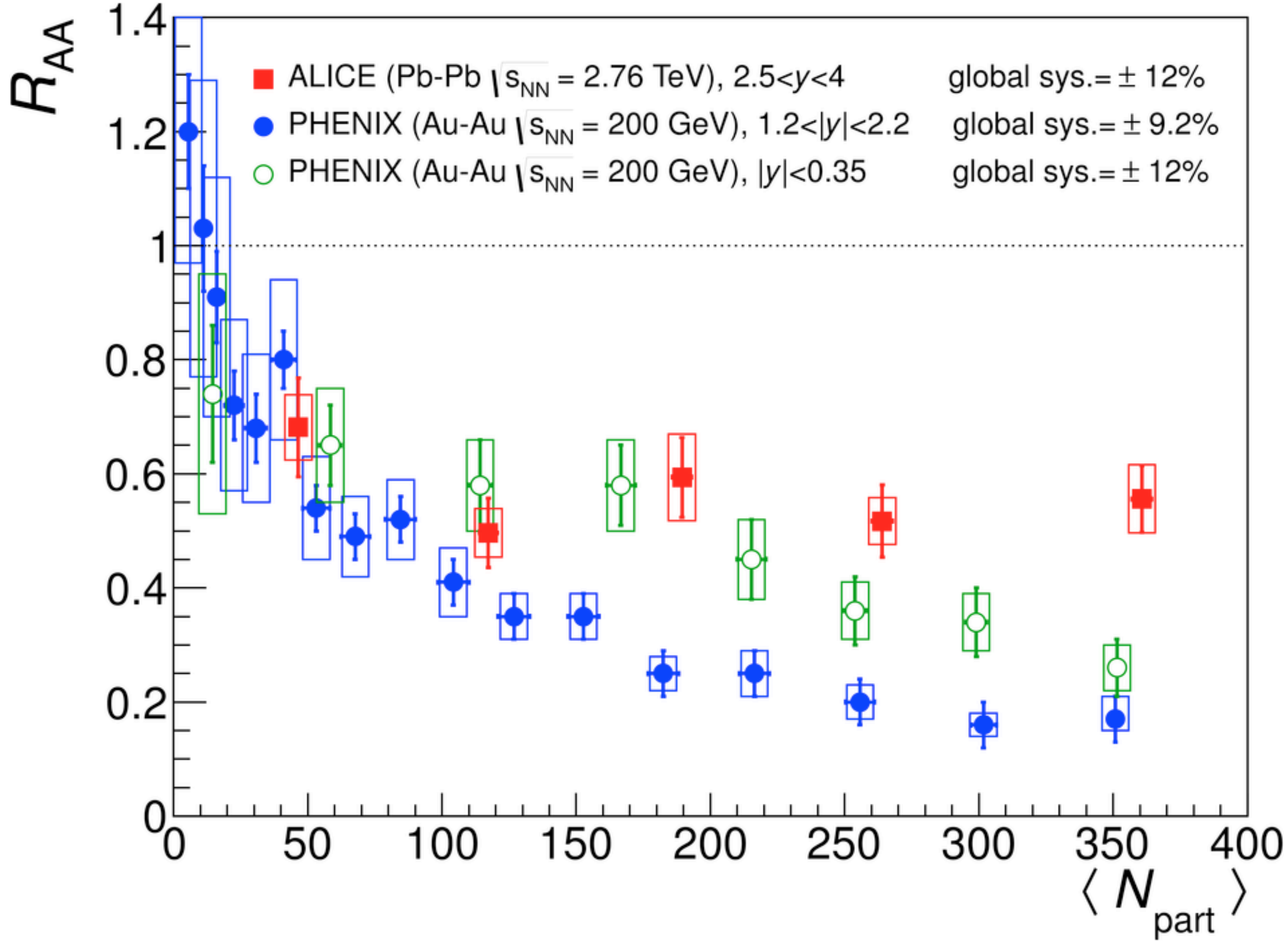
Plasma Debye Length:

The shorter the r_D, the stronger the screening effects





J/Psi Suppression Observed, w/ Surprises

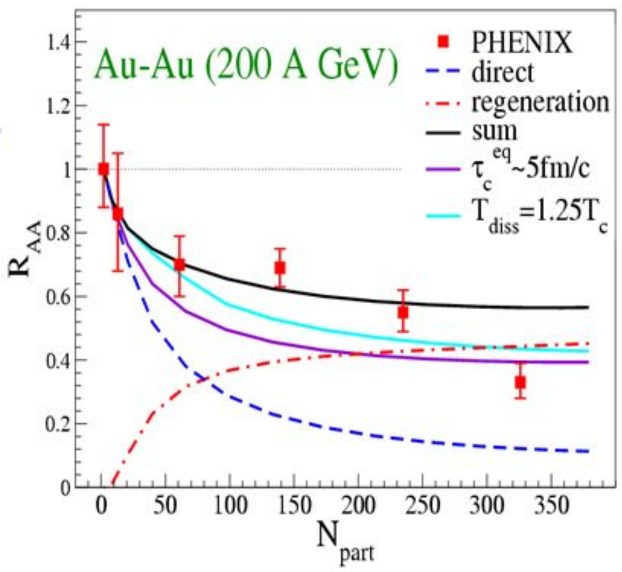


1. QGP Suppression
   - Color screening
   - Breakup w/ “co-movers”
2. Regeneration
   - Coalescence of many c-cbar pairs produced in A+A

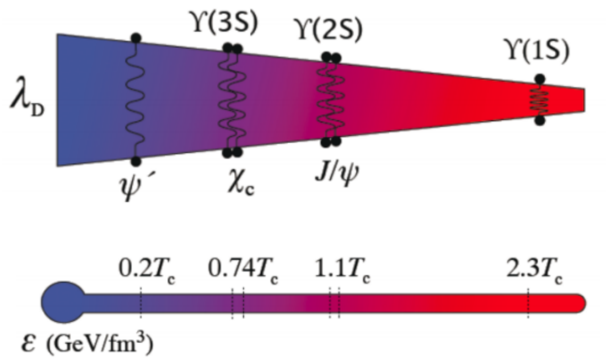
Upsilons! – focus of sPHENIX

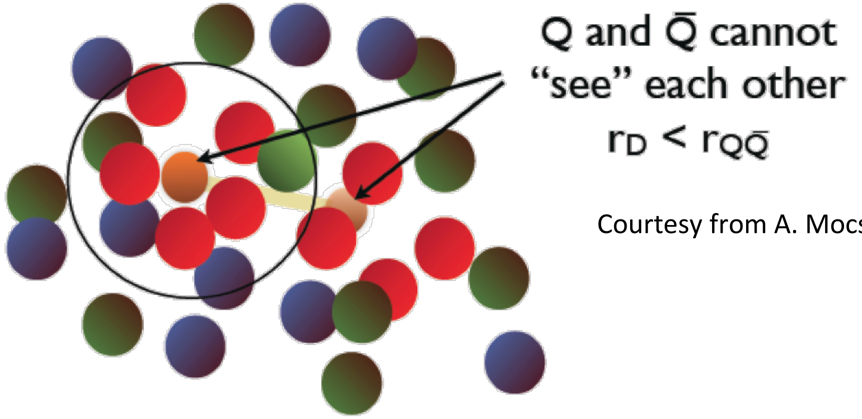
- Color screening
- Breakup w/ “co-movers”
- No regeneration

Zhuang et al.



Upsilon Spectroscopy



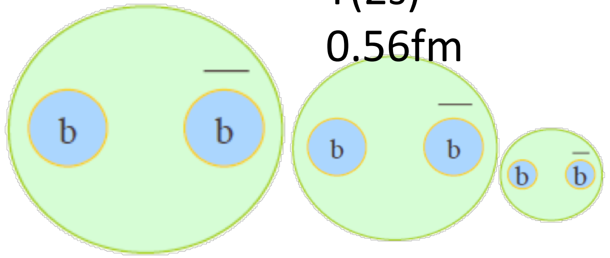


Courtesy from A. Mocsy

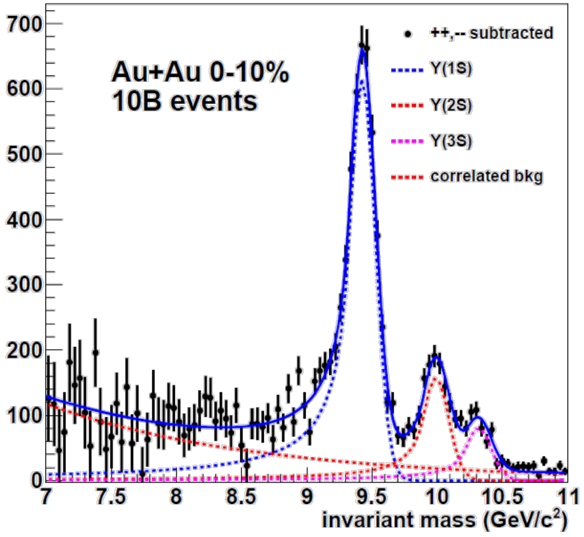
Υ(3s)- 0.78fm

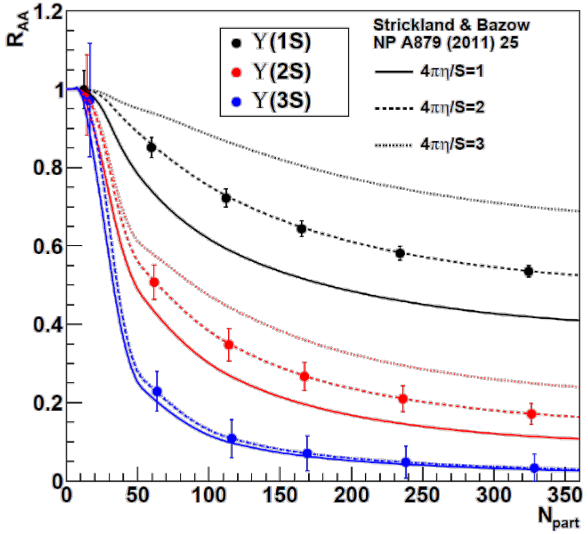
Υ(2s) – 0.56fm

Υ(1s) – 0.28fm

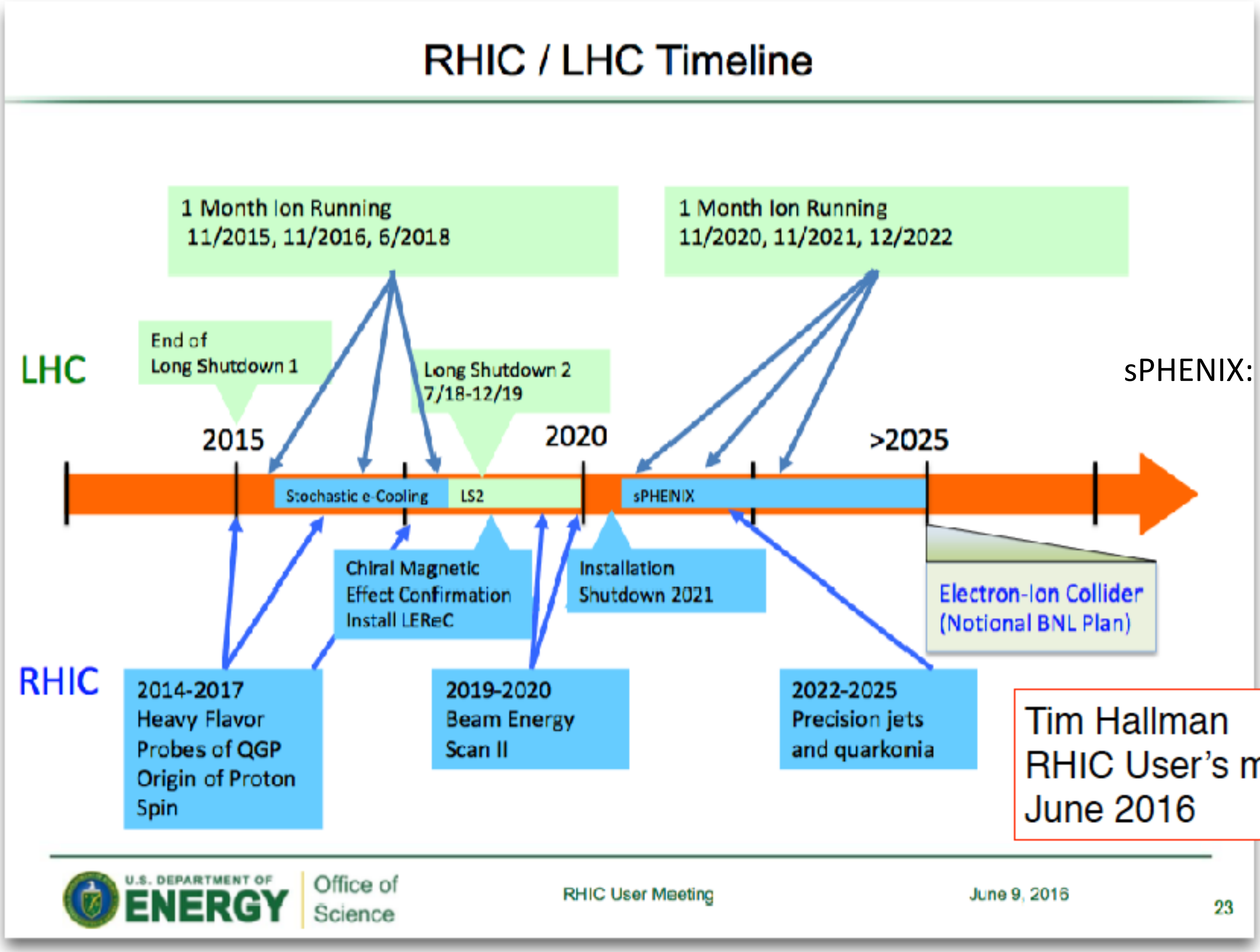


Thermometer of QGP via clean separation of three Upsilon states (M_{ee} < 100 MeV/c²)





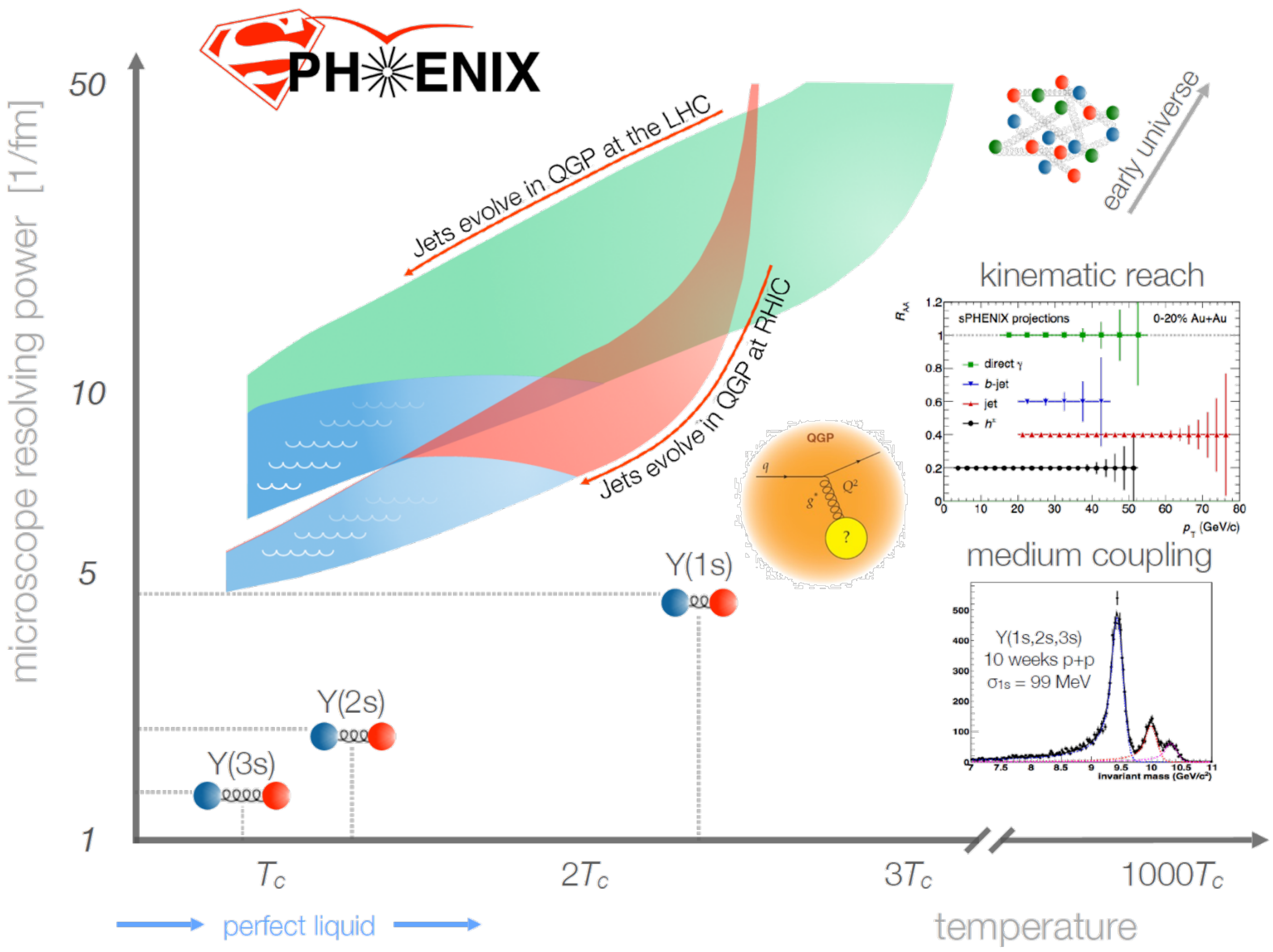
Potential timeline for sPHENIX, RHIC, LHC

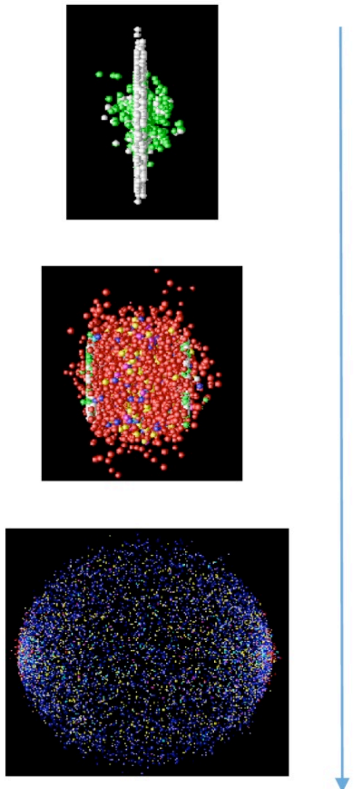


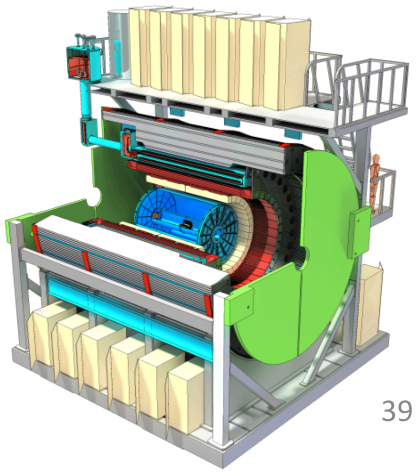
sPHENIX: 2023 - 2026+

Tim Hallman
RHIC User's meeting
June 2016

Summary and Outlook







- sPHENIX CD-0 granted Sept 2016; In preparation for CD-1, May 2018
- 1st data taking: Early 2023

Evolving sPHENIX Collaboration

Rutgers, 12/15

BNL, 6/16

Georgia State, 12/16

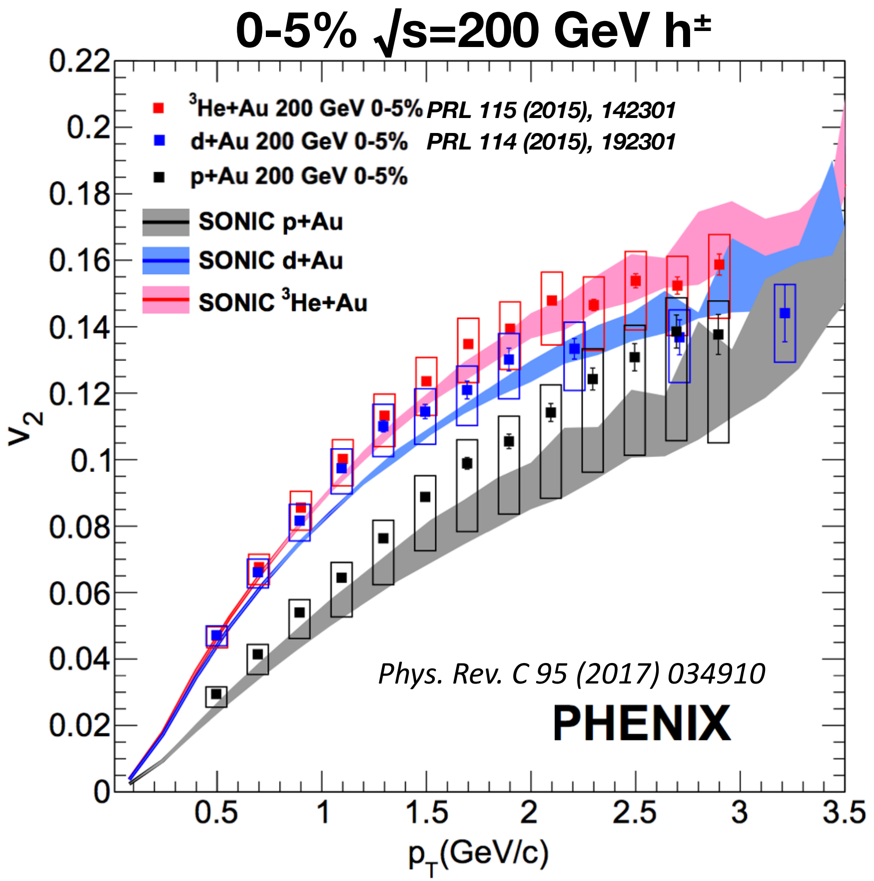
BNL, 5/17

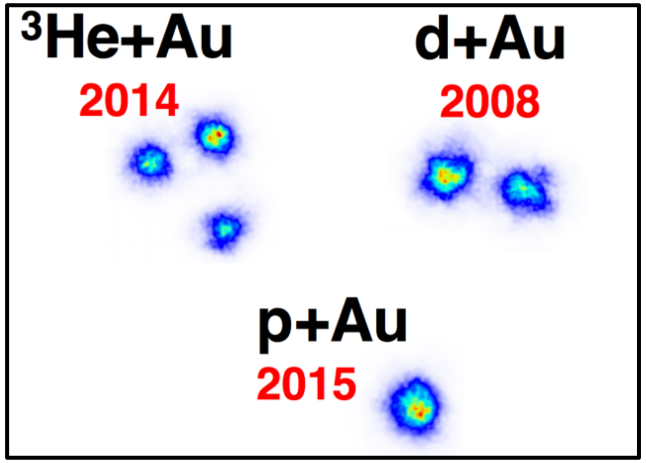
~70 institutions from world wide & growing!

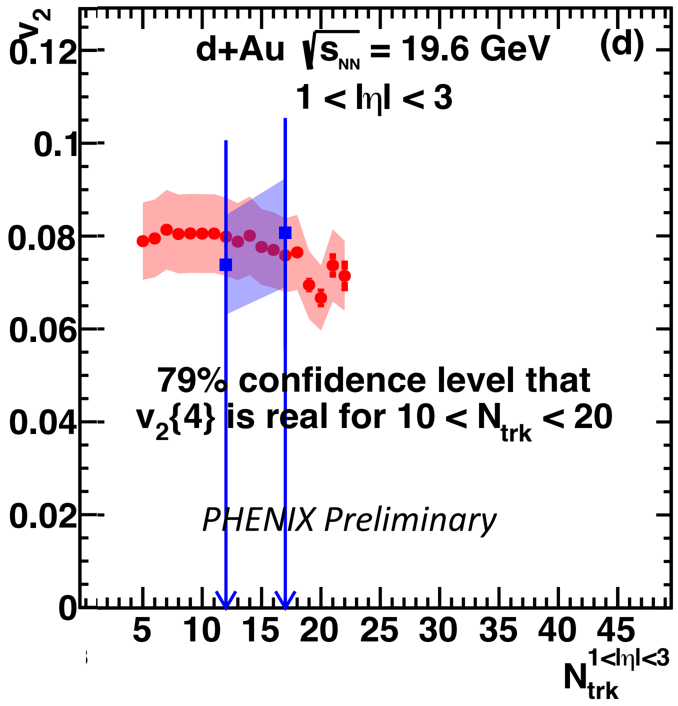
A new Chinese consortium joined sPHENIX, led by Prof. H. Huang!

backup

RHIC Highlight (2): Flow



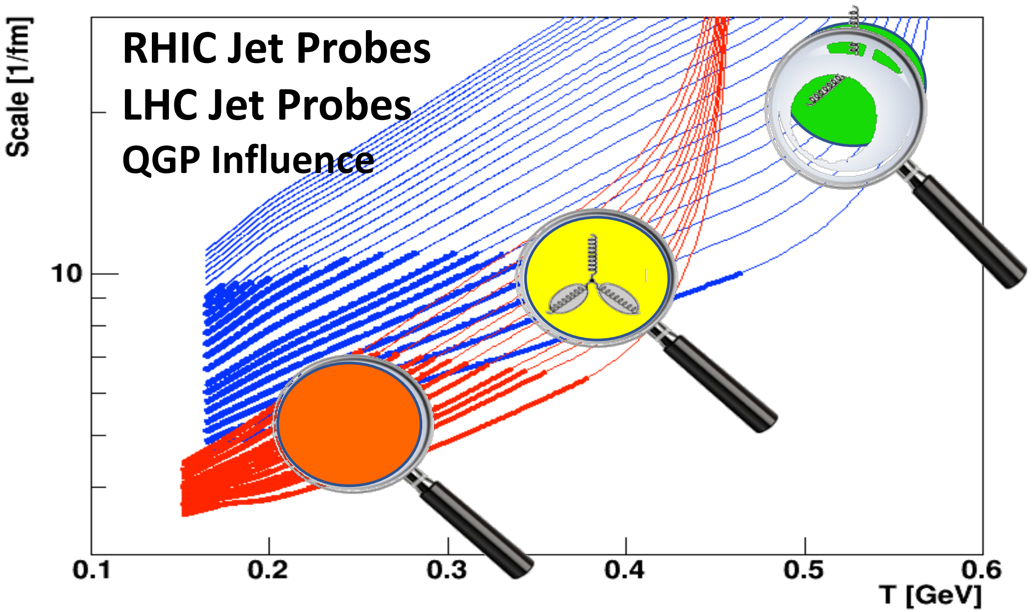


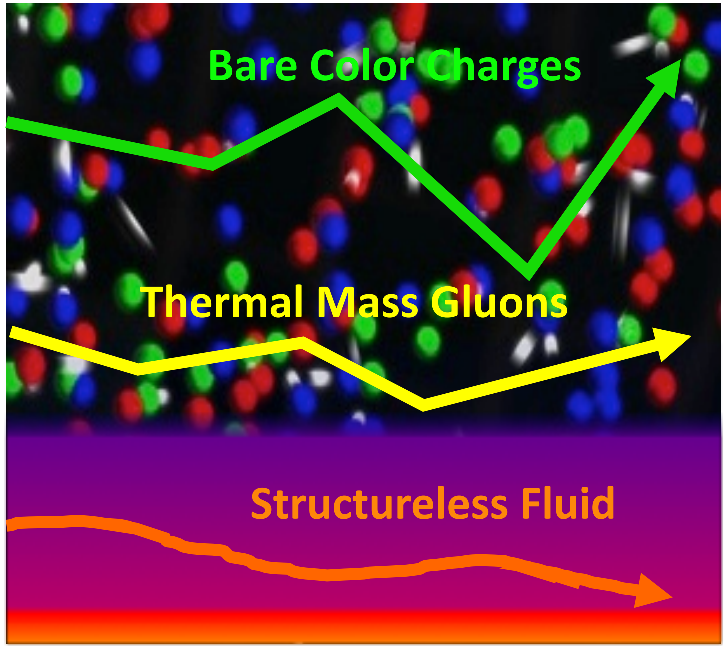


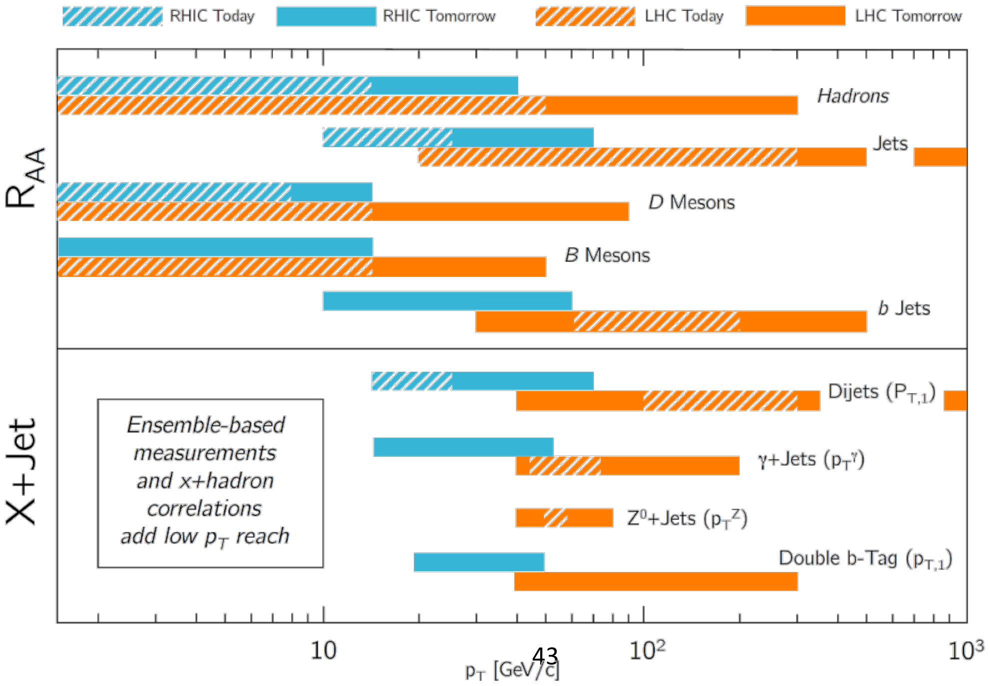
Signatures of collective flow exist even in the smallest systems and at the lowest RHIC energies

Jet Probes of QCD Structure

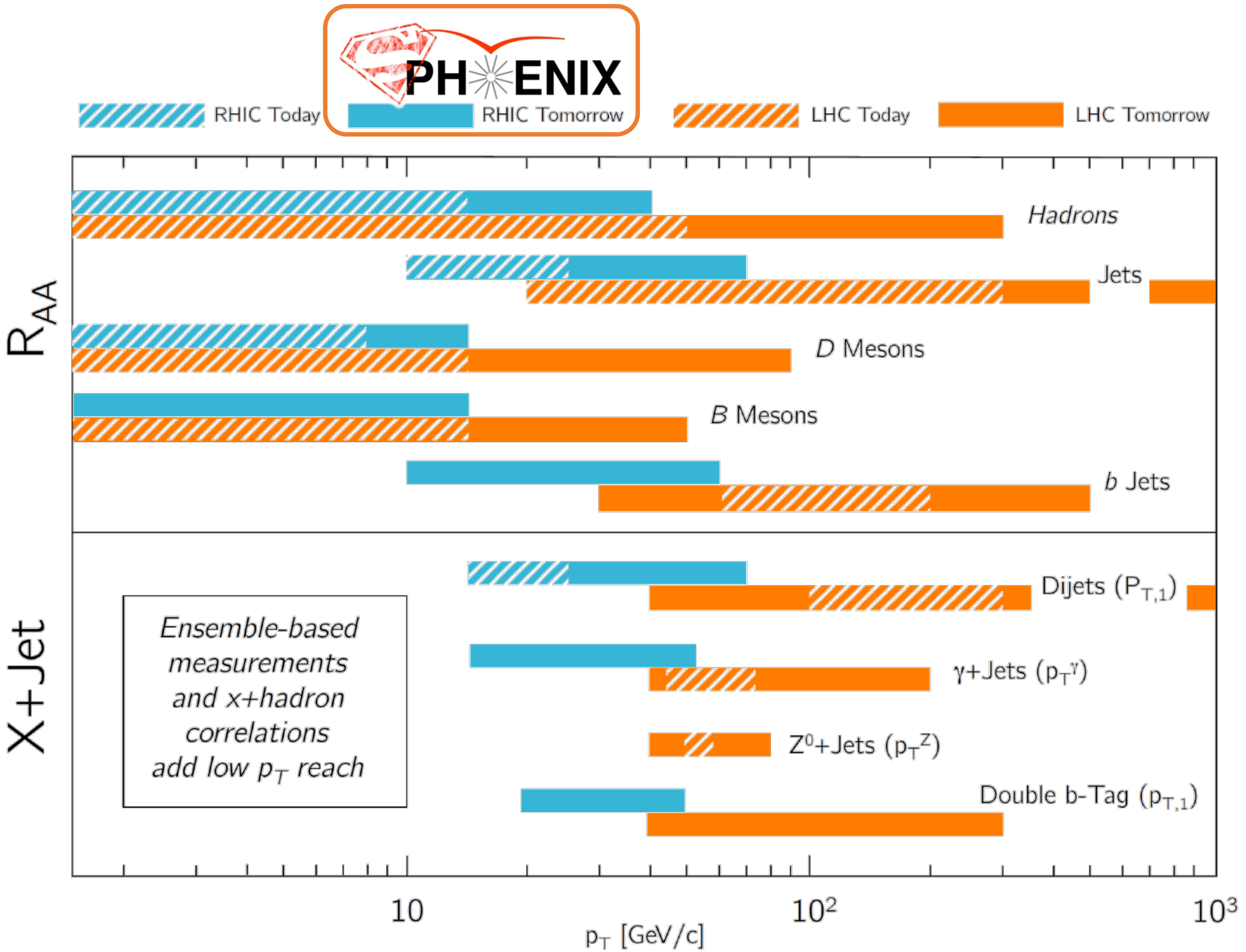
Parton virtuality evolves quickly and is sensitive to the medium at the <u>scale it probes</u>







- Unique critical microscope resolution range at RHIC
- Kinematic overlap between RHIC and LHC provides complementarity

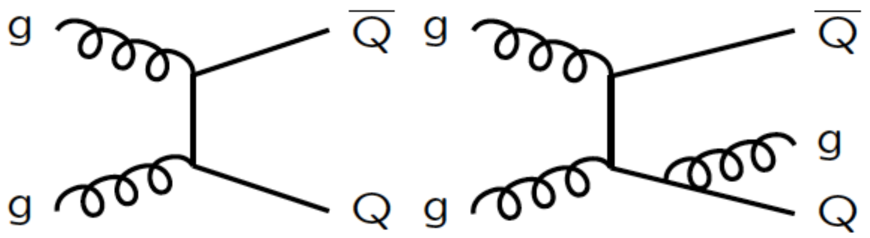

PHENIX
RHIC Today
RHIC Tomorrow
LHC Today
LHC Tomorrow
R_AA
Hadrons
Jets
D Mesons
B Mesons
b Jets
X+Jet
Dijets ($P_{T,1}$)
γ+Jets (p_T^{γ})
Z^0+Jets (p_T^Z)
Double b-Tag ($p_{T,1}$)
Ensemble-based measurements and x+hadron correlations add low p_T reach
10
10^2
10^3
p_T [GeV/c]

Heavy Quark Probes at RHIC

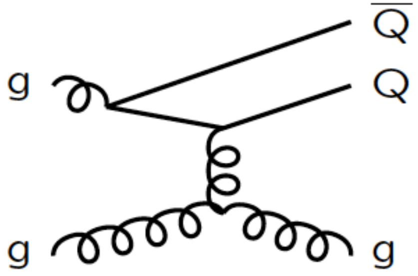
Uniqueness at RHIC

- dominated by pair creation, clean interpretation for experimental results

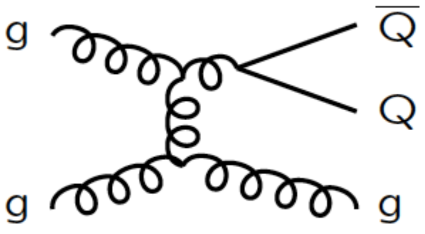
Pair Creation



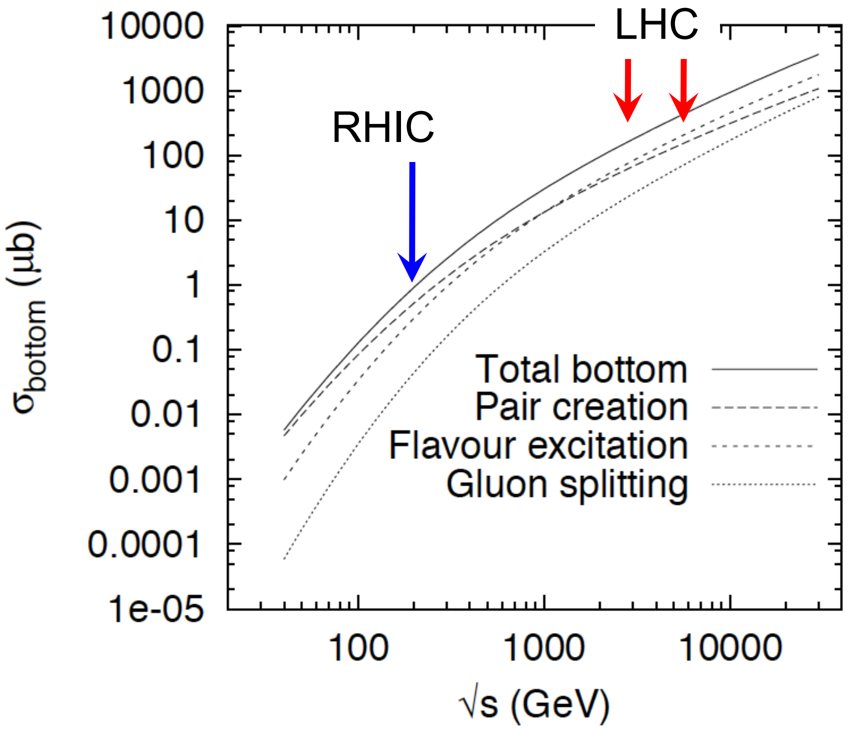
Flavor Excitation



Gluon Splitting



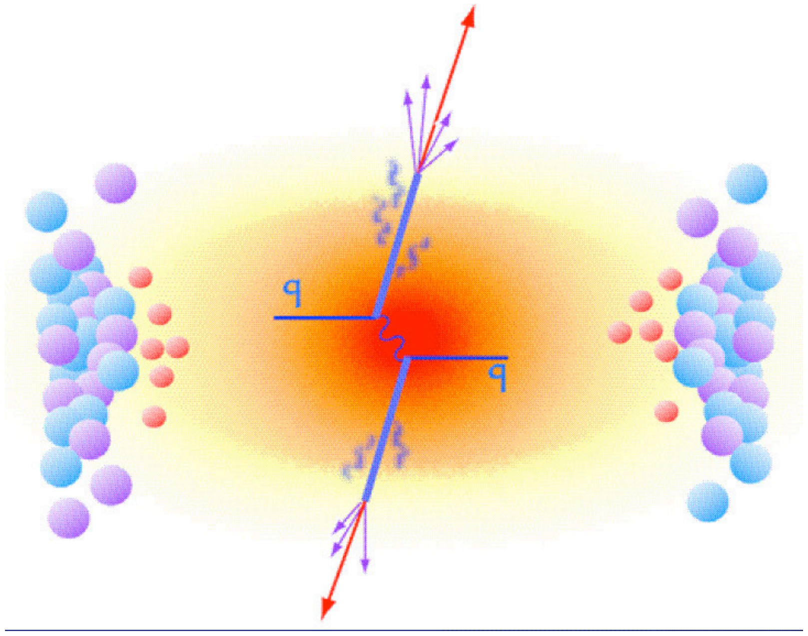
PYTHIA6

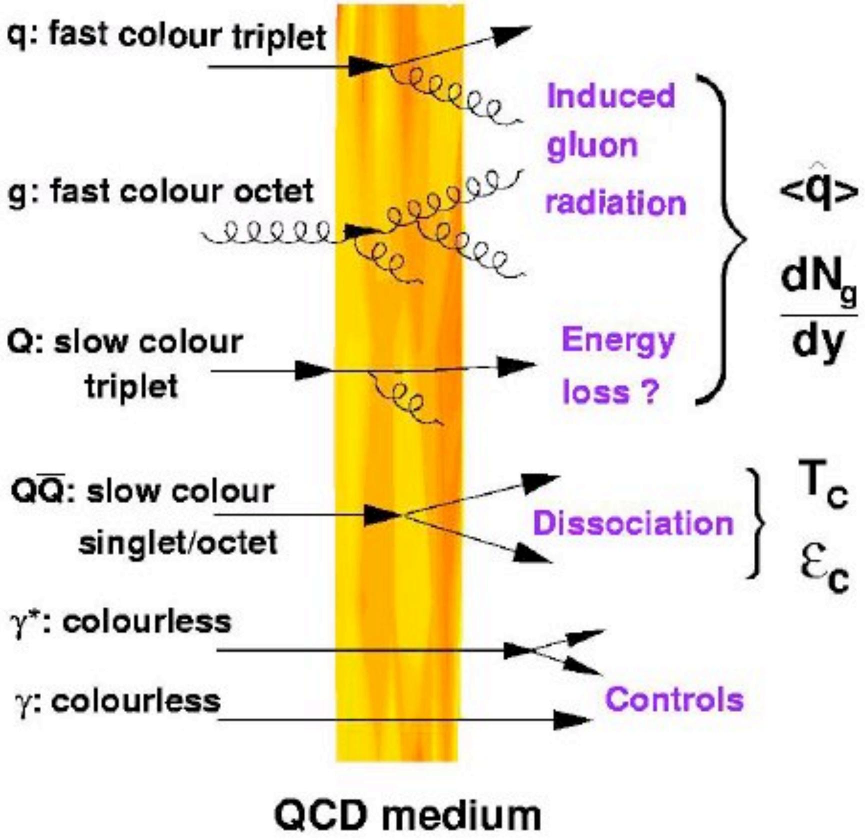


T. Sjostrand, EPJC17 (2000) 137

Topic-1: Probe the Density
QGP and Jet Quenching

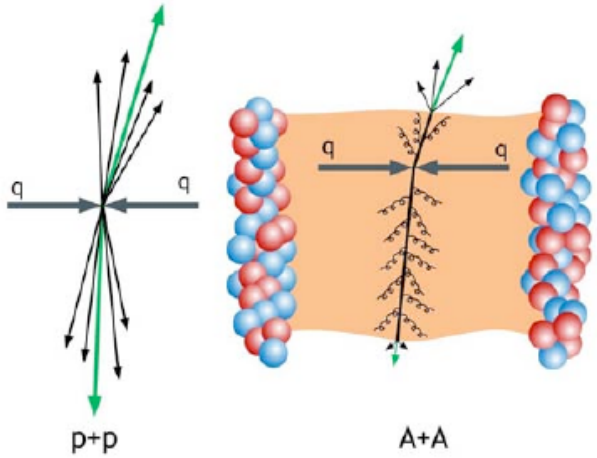
High density QGP medium created in
Heavy ion collisions:
~20x of normal nucleus

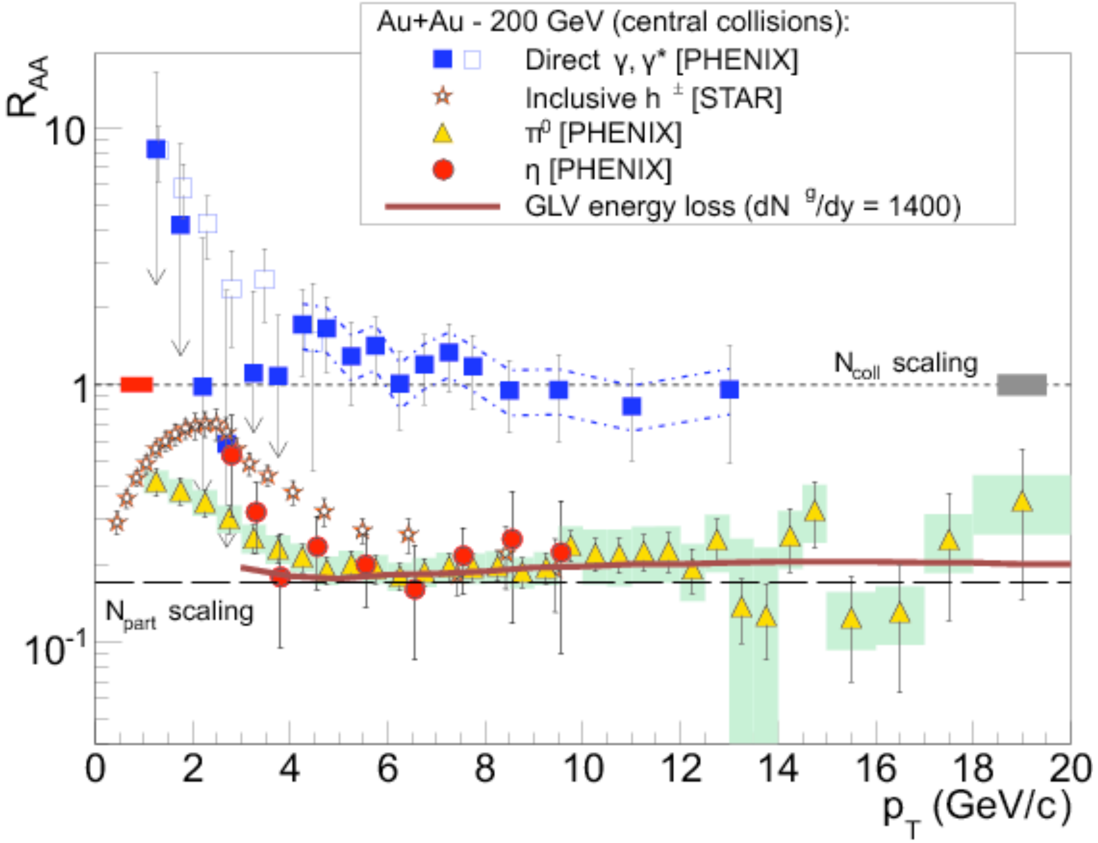




Jet Quenching Observed

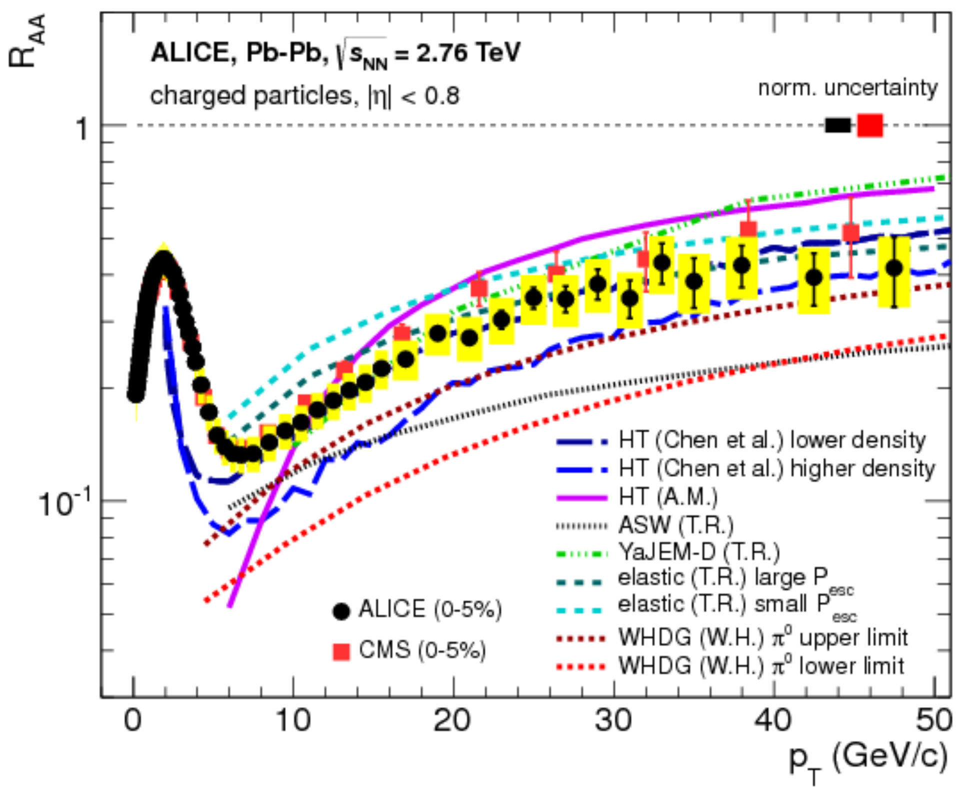
$$R_{AA} = \frac{1}{N_{coll.}^{AA}} \frac{\sigma_{AA}}{\sigma_{pp}}$$

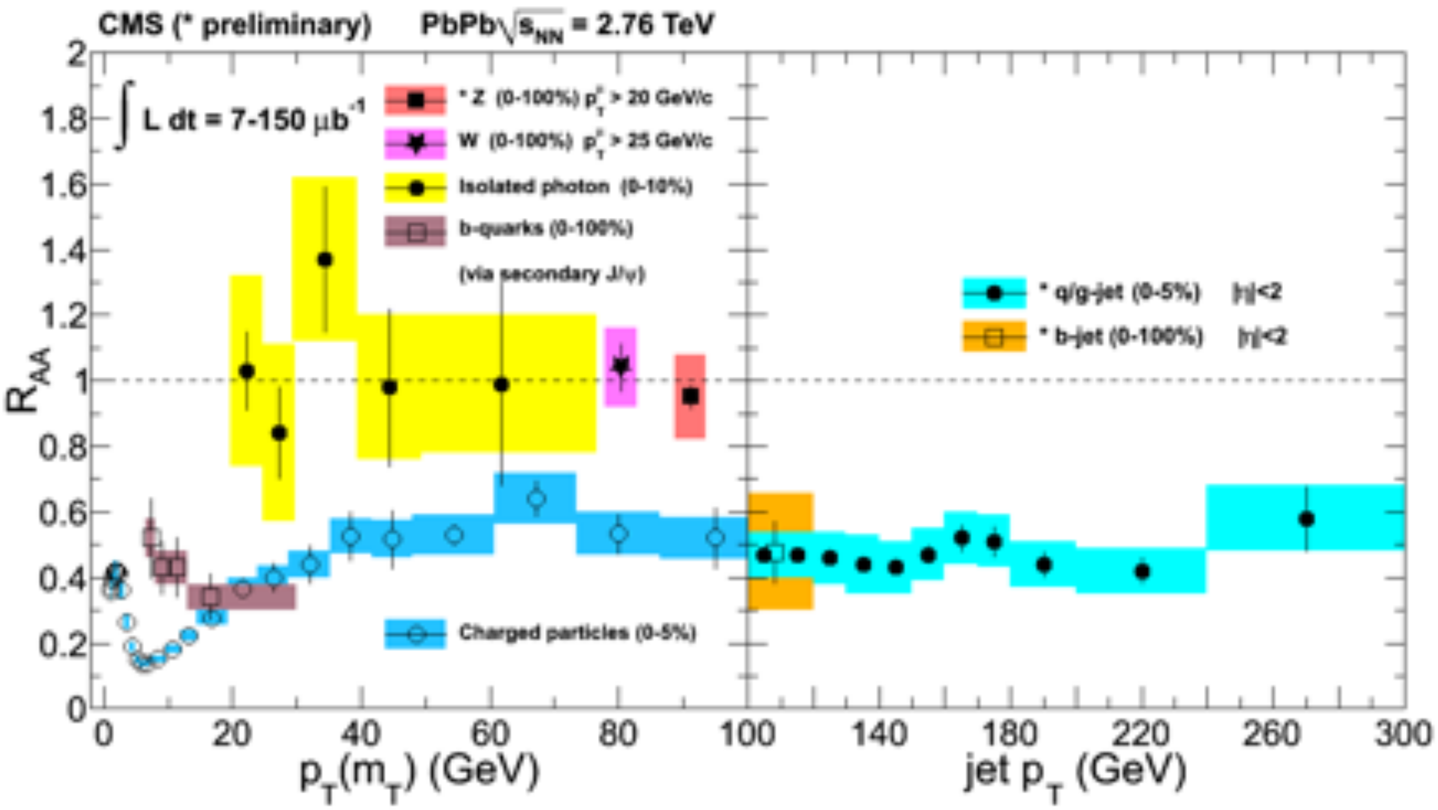




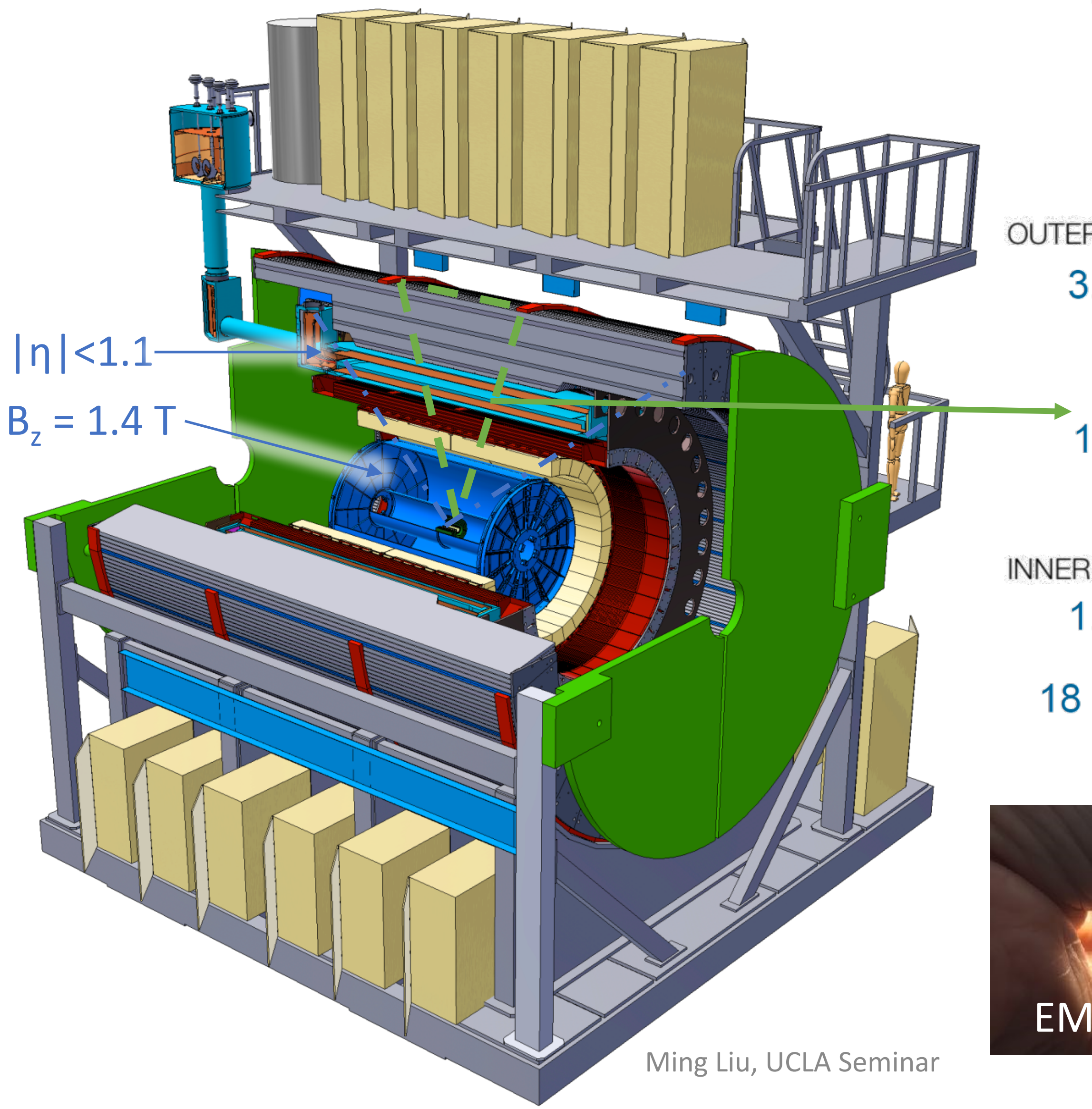
QGP density > 10x normal nucleus

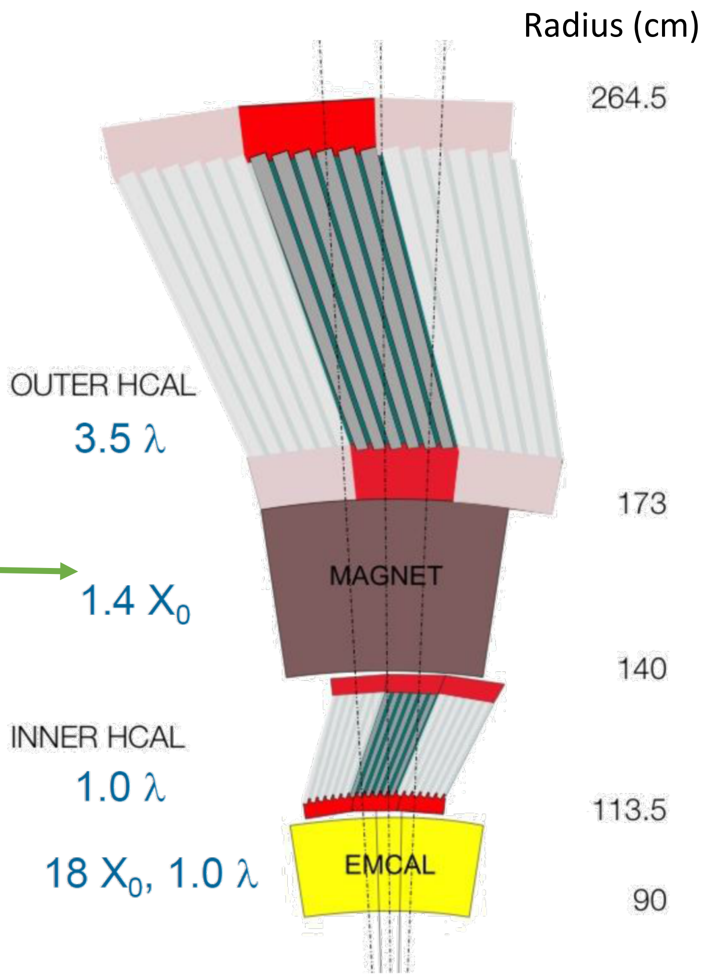
Jet Quenching @RHIC and LHC





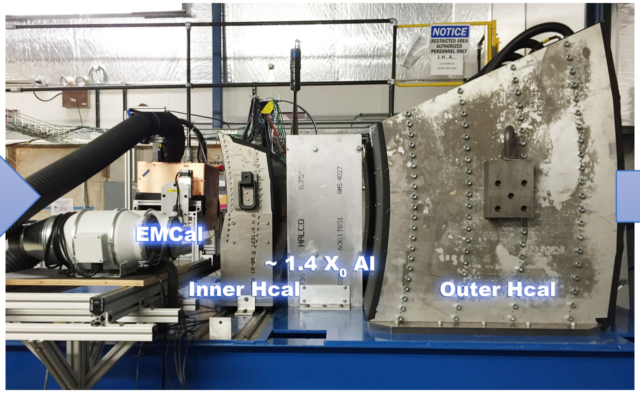
Detector highlights



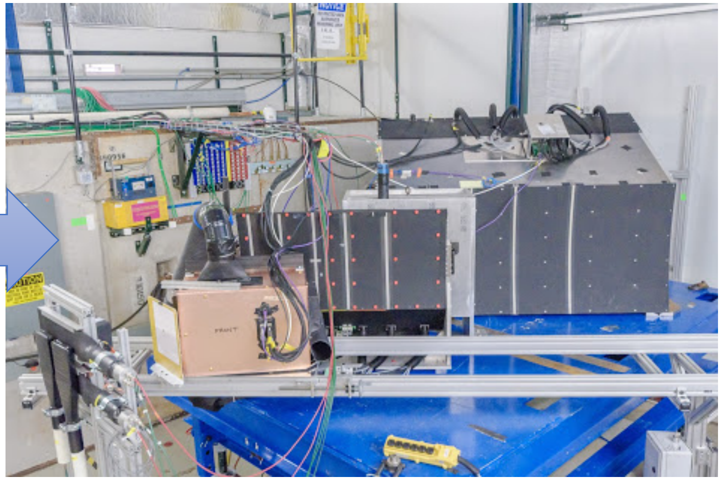


Calorimeters beam tests

February 2014
Proof of principle

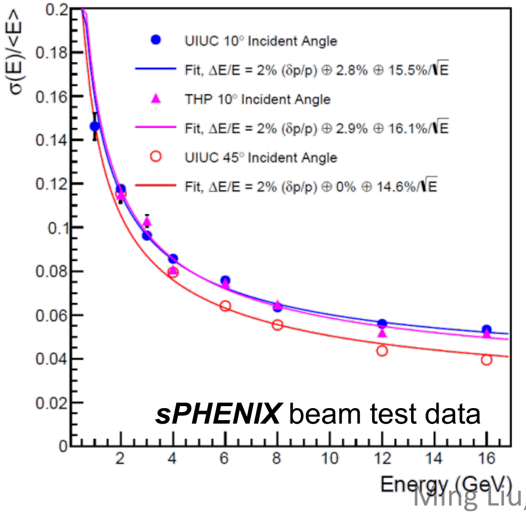


February 2016: η~0 prototype

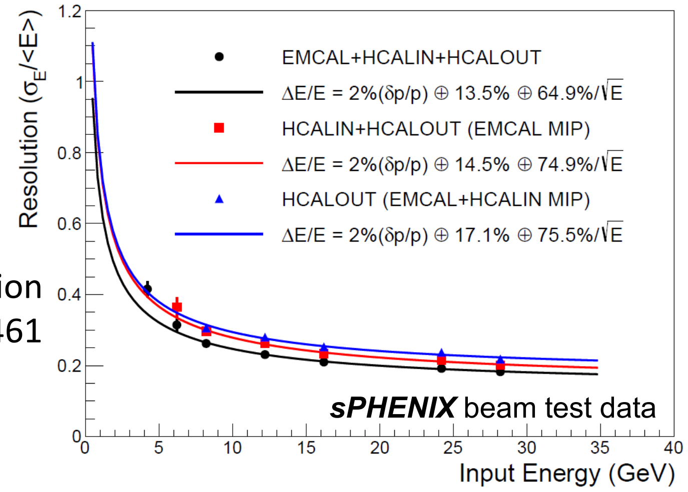


February 2017: η~0.9 prototype

Electron
Energy resolution
arXiv:1704.01461



Pion
Energy resolution
arXiv:1704.01461



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
- On-going full field test

Photo by Andy Freeberg, SLAC National Accelerator Laboratory

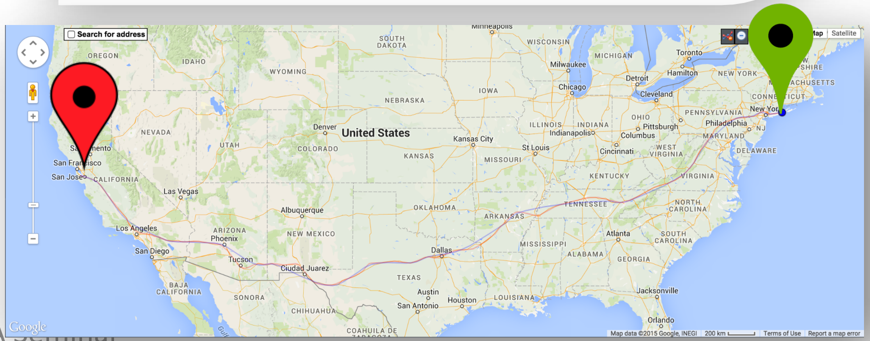
breaking

January 16, 2015

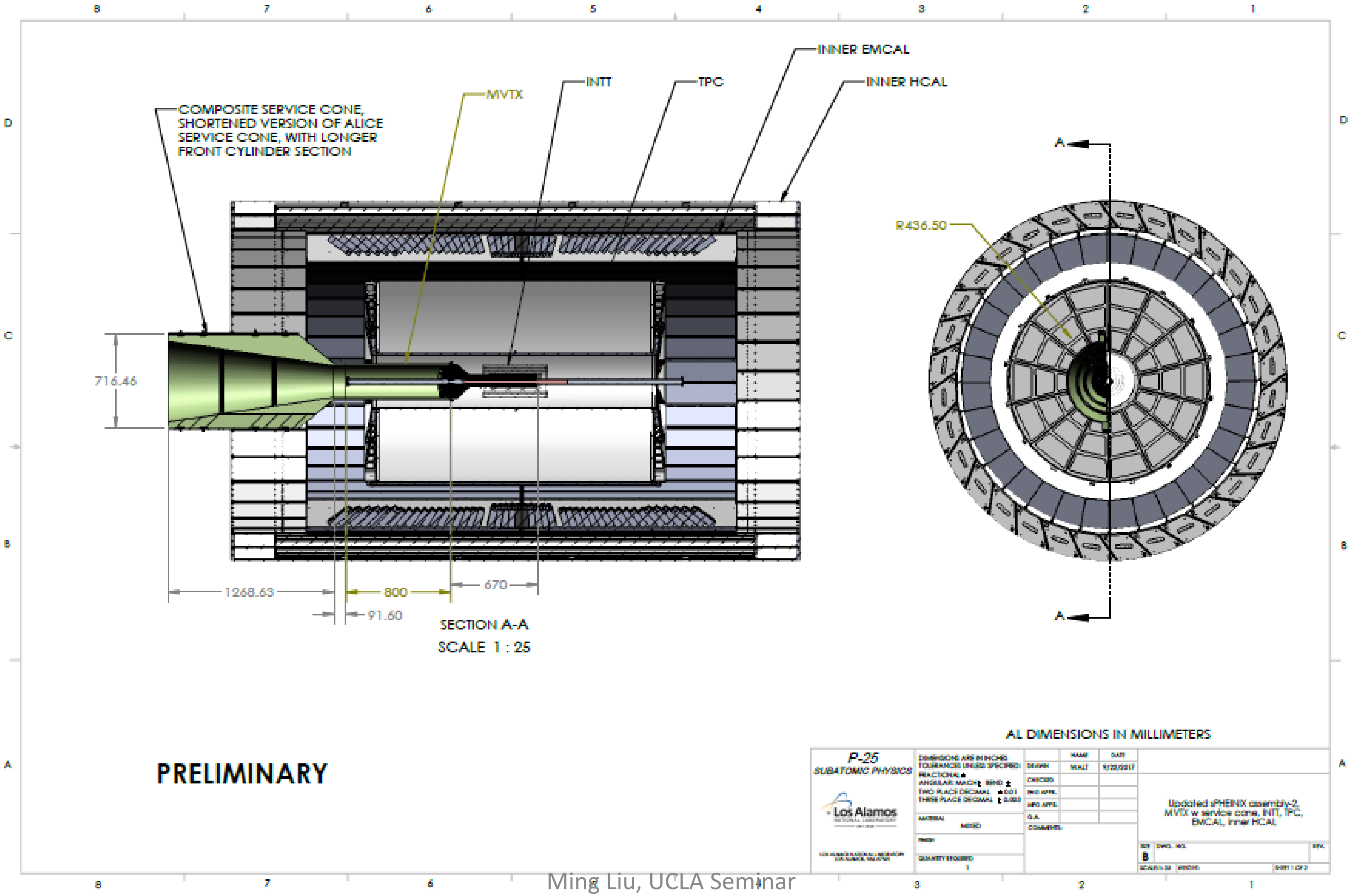
20-ton magnet heads to New York

A superconducting magnet begins its journey from SLAC laboratory in California to Brookhaven Lab in New York.

By Justin Eure



Sheet 1, section view of sPHENIX inner detector assembly (inside the superconducting solenoid magnet), the ALICE service barrel has been modified – shortened, see later sheets for detail



sPHERNIX cross-section view, including envelope for services; TPC and INTT, the following 2 slides detail views -