sPHENIX @RHIC

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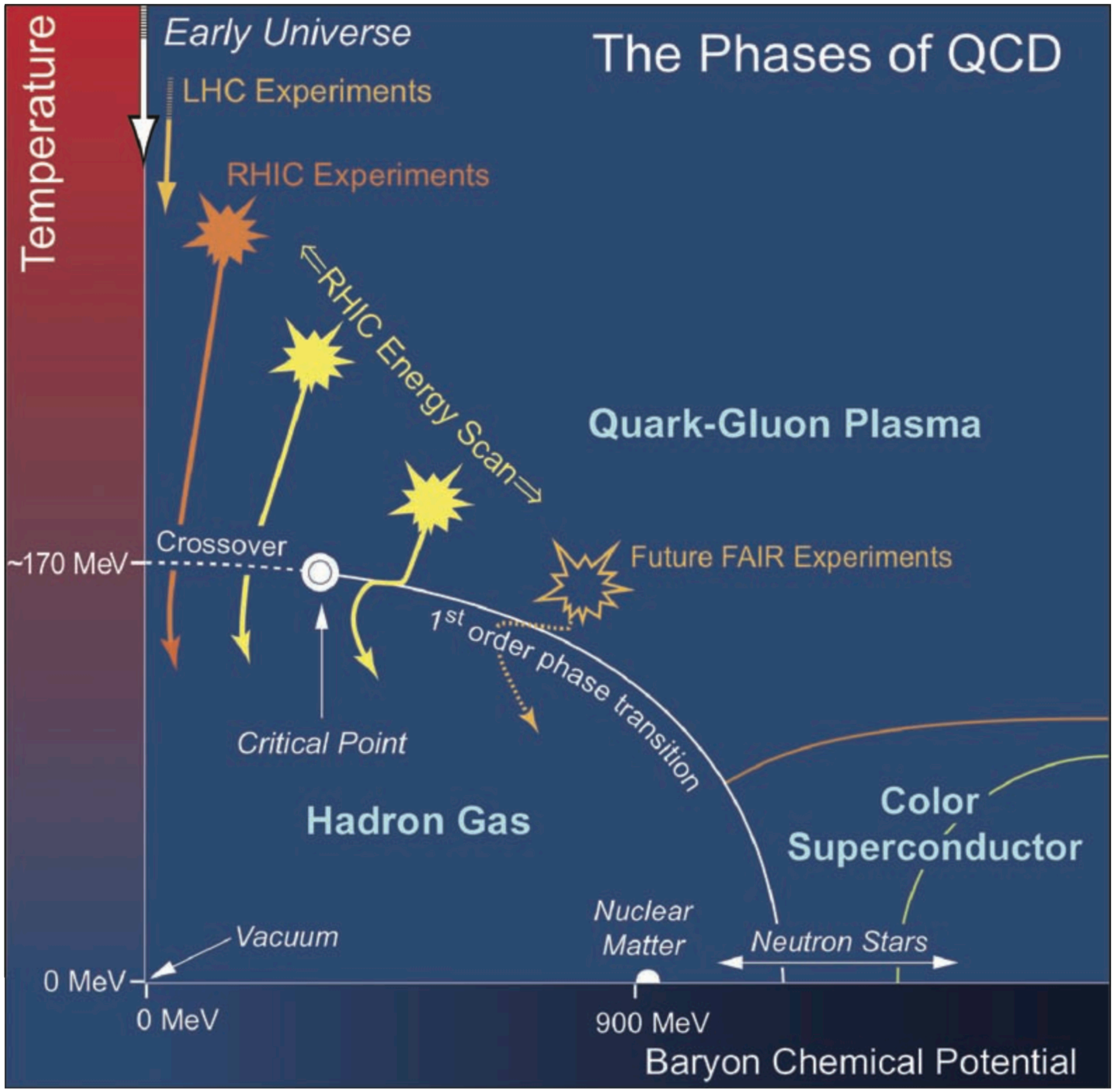
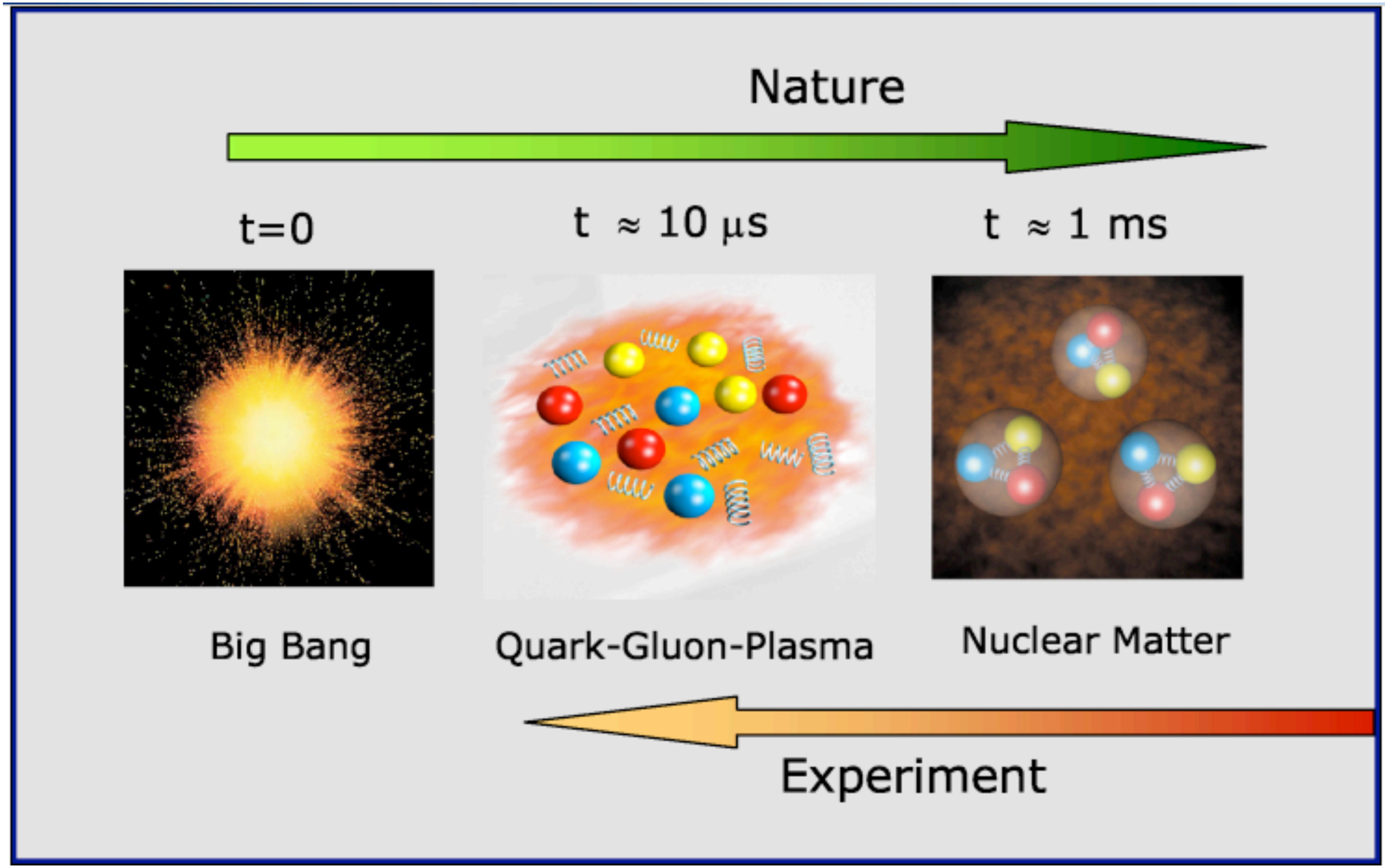
Outline

- Discovery of QGP at RHIC
  - Jet quenching in QGP
  - J/Psi suppression in QGP
- The next step – sPHENIX
  - Physics
  - Detectors
- Heavy Flavor Physics with MVTX upgrade
- Outlook

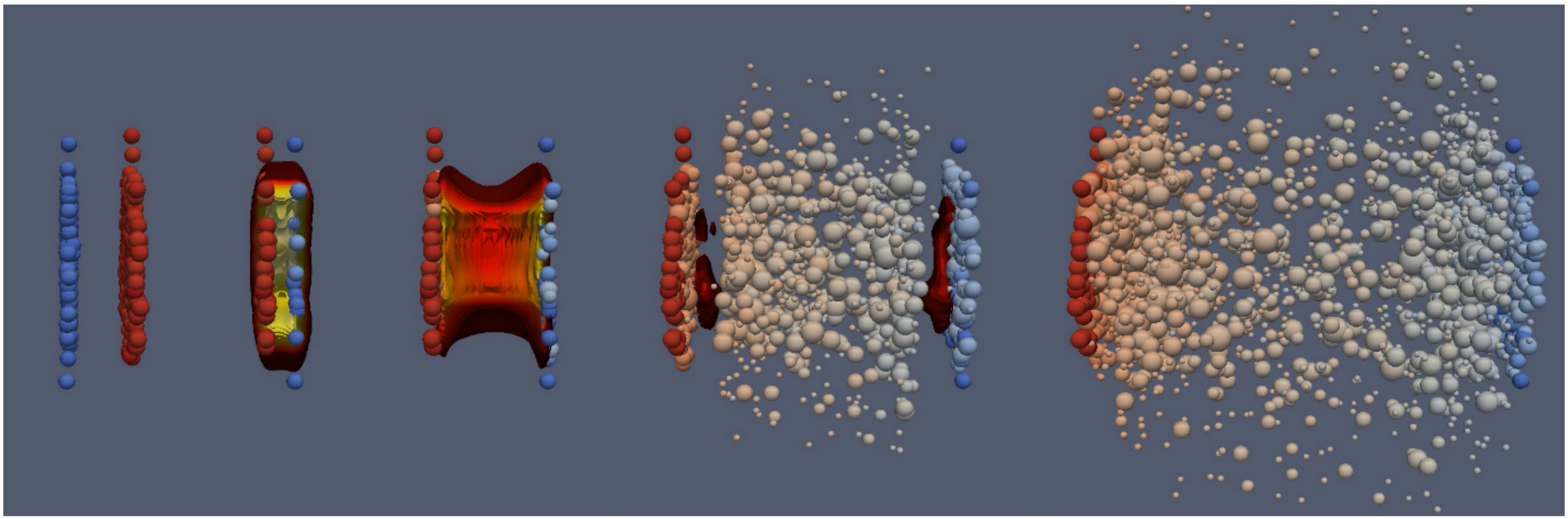
Early Universe and QCD Phase



Recreate a State of the Early Universe?



Create QGP in Heavy Ion Collisions?!



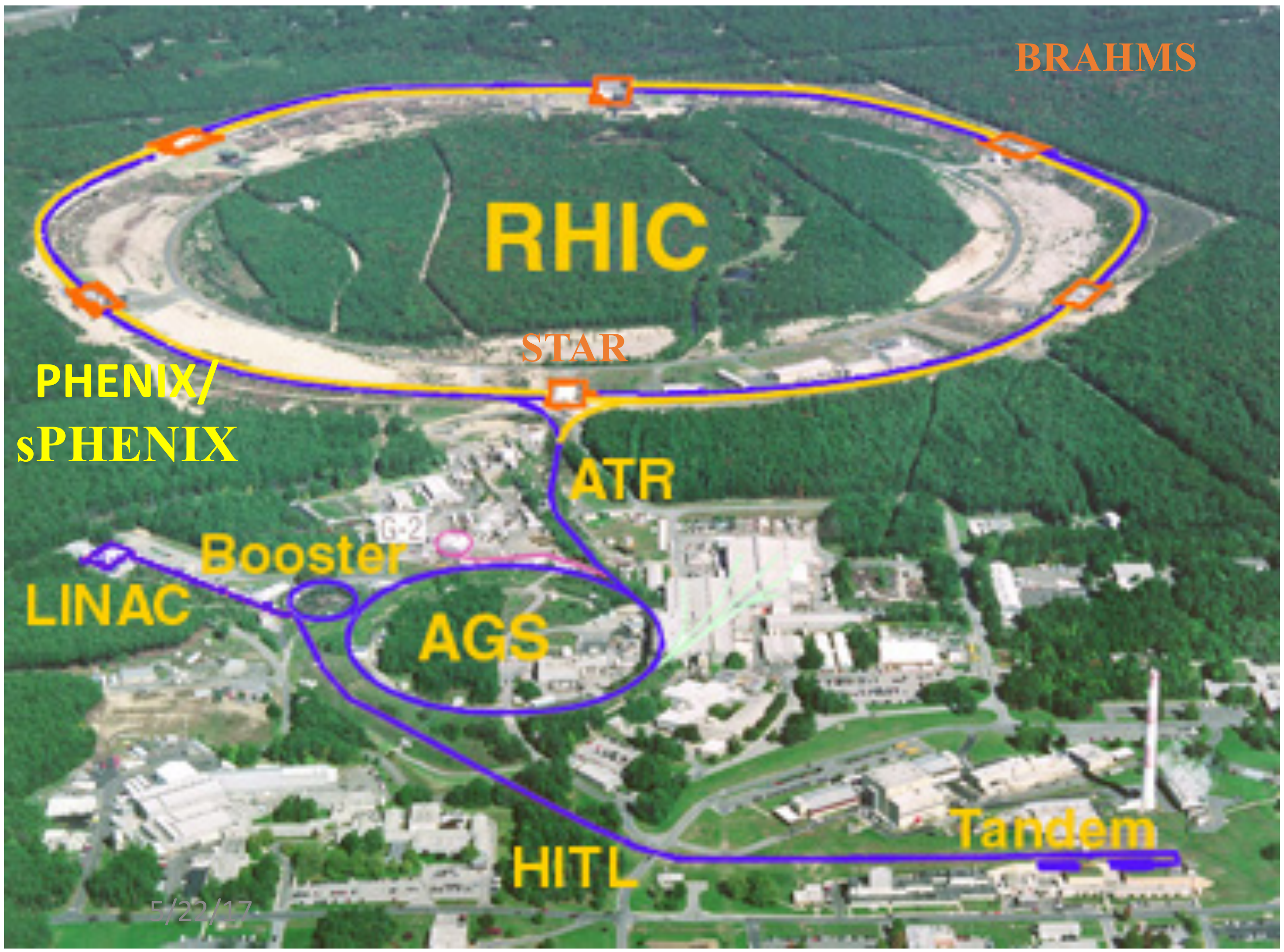
Au + Au collision

QGP

Hadrons

The **R**elativistic **H**eavy **I**on **C**ollider
at Brookhaven National Laboratory

RHIC's First Decades: A discovery Machine



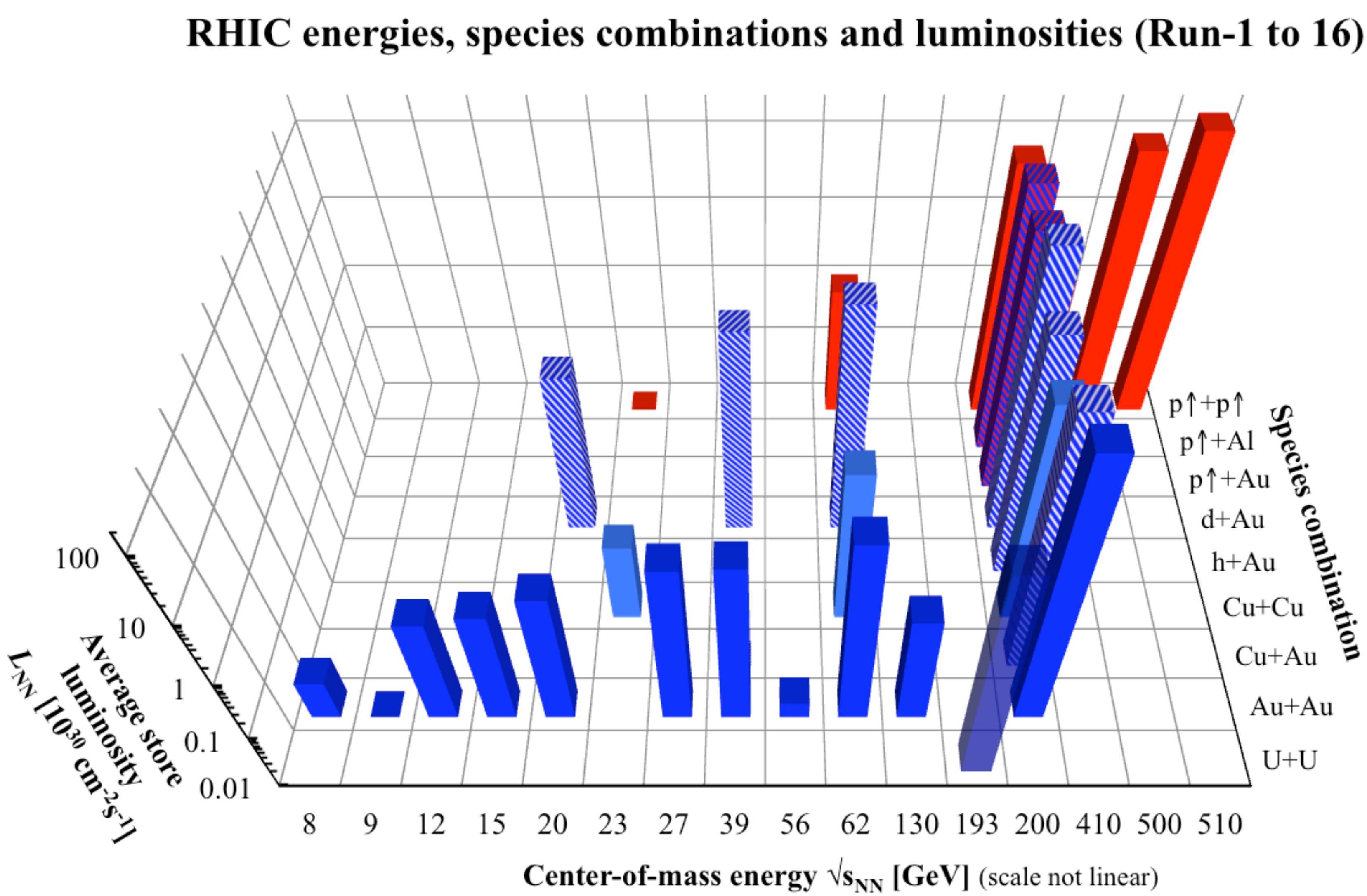
HI
New state of matter
QGP
De-confinement
…

polarized proton
Nucleon Spin Structure
Spin Fragmentation
pQCD
…

RHIC is a QCD Lab:

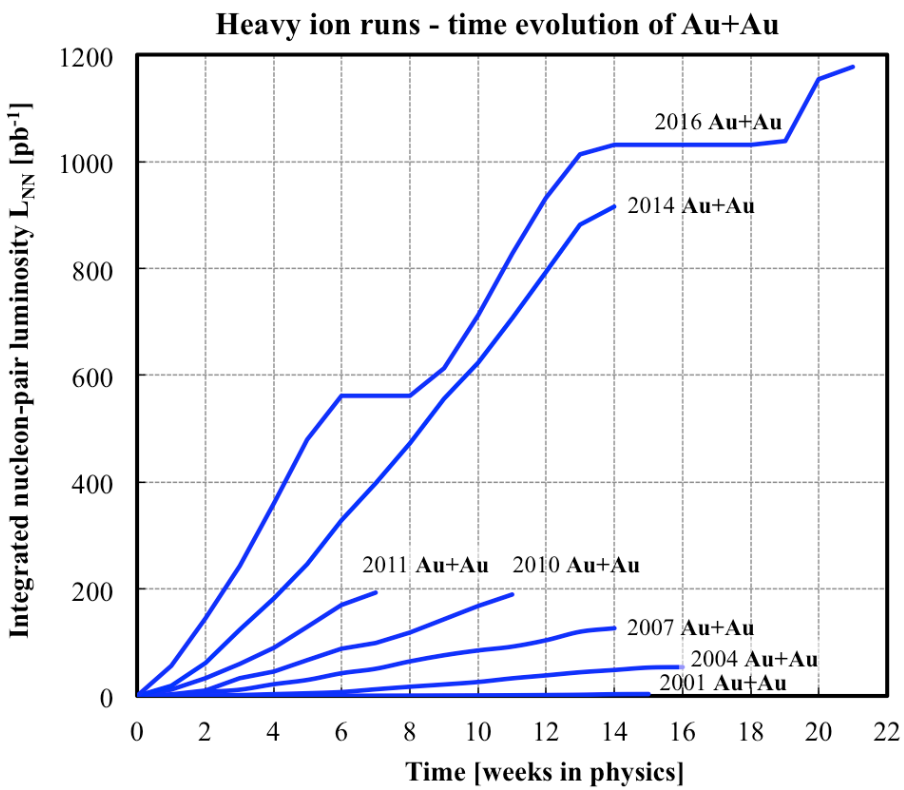
PHENIX -> sPHENIX -> EIC

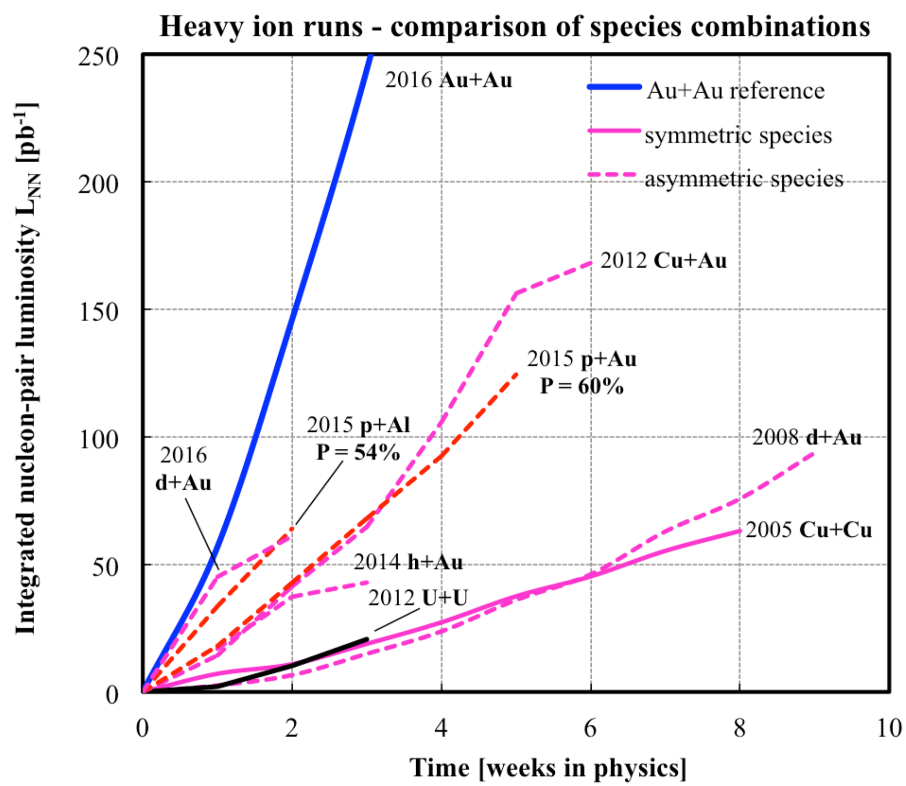
RHIC – a very flexible machine



RHIC Runs: 2001 – 2016+

- PHENIX completed data taking in 2016, in transition into sPHENIX upgrade
- STAR continues to ~2020, BES-II etc.

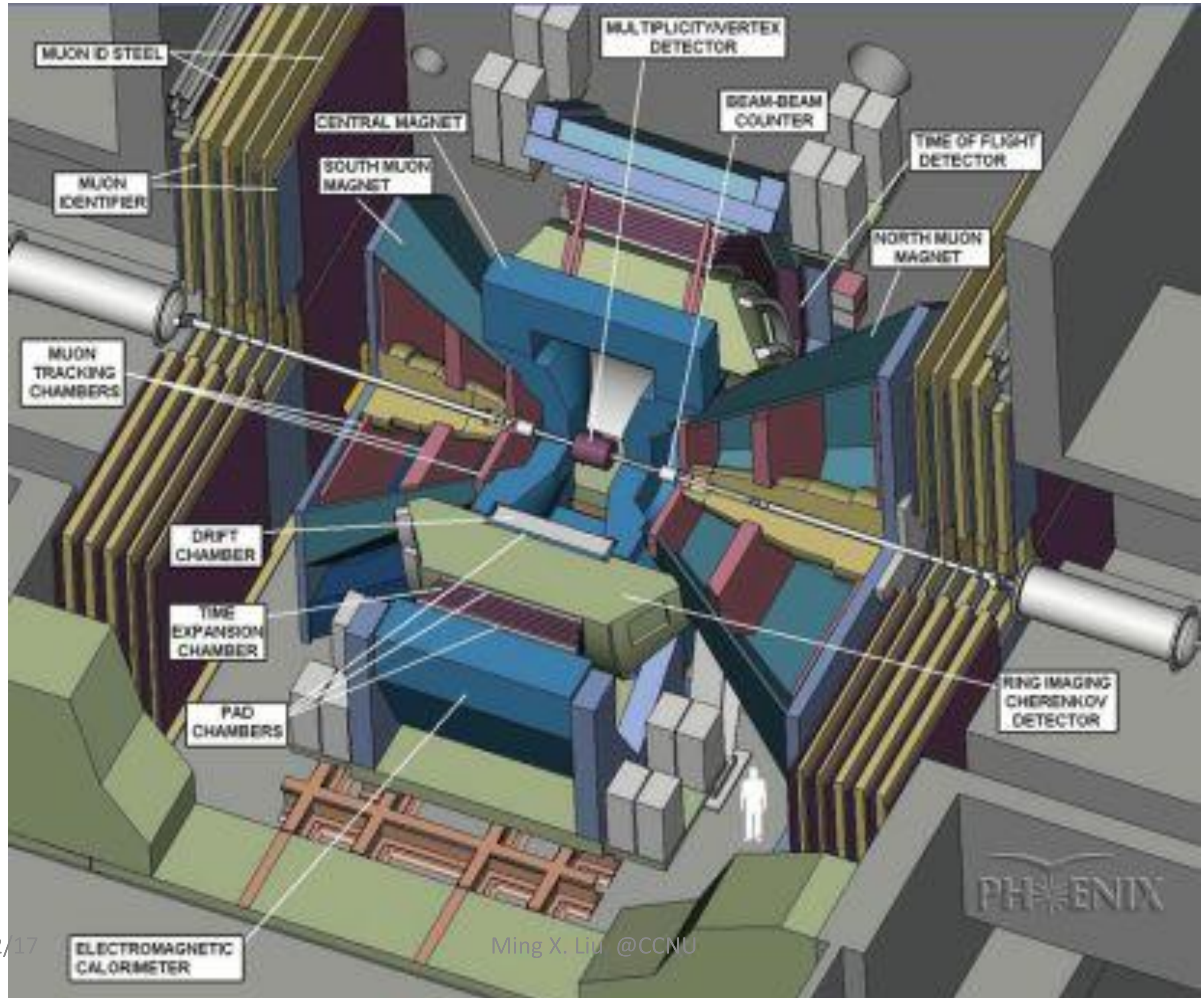




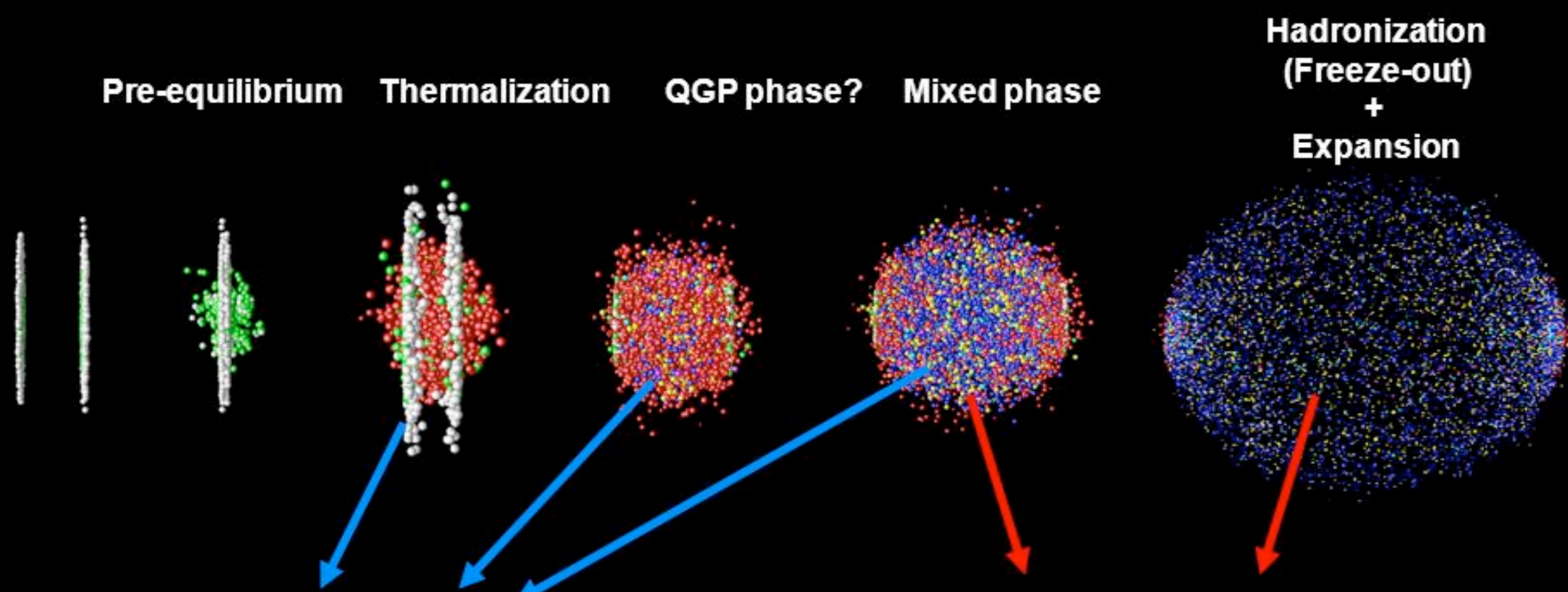
PHENIX Detectors at RHIC: 2001-2016

A large international collaboration, ~500 scientists from 13 countries

PHENIX Detectors



History of Heavy Ion Collisions



$\gamma, \gamma^* \rightarrow e^+e^-, \mu^+\mu^-$

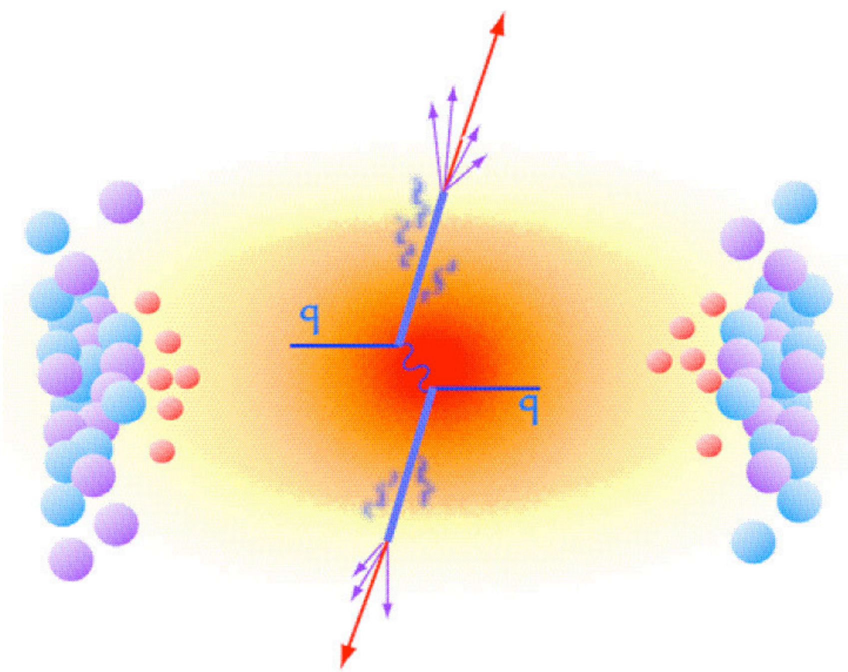
π, K, p, n, ϕ, Λ, Δ, Ξ, Ω, d,…

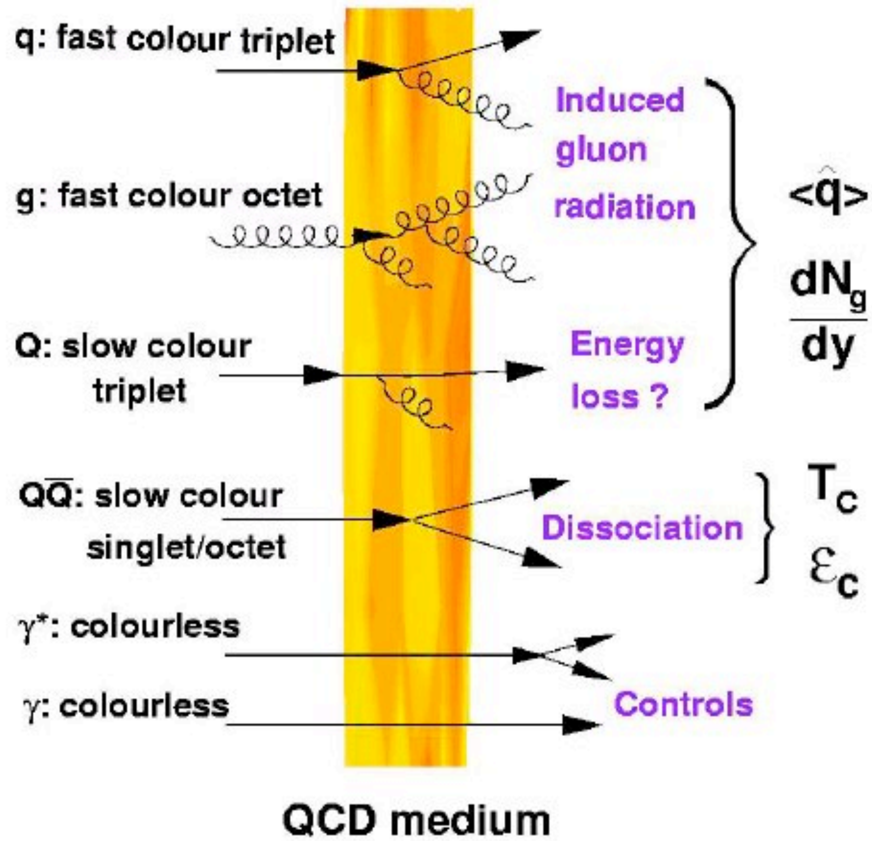
Real and virtual photons from q scattering sensitive to the early stages (penetrative probes).

Hadrons reflect medium properties when inelastic collisions stop (chemical freeze-out).

QGP and Jet Quenching

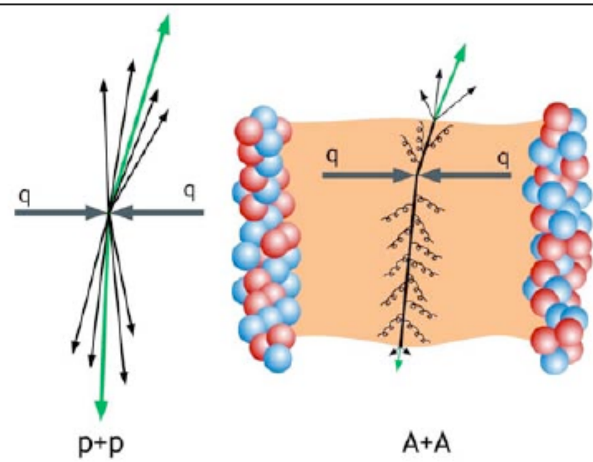
High density QGP medium suppresses high energy particle productions

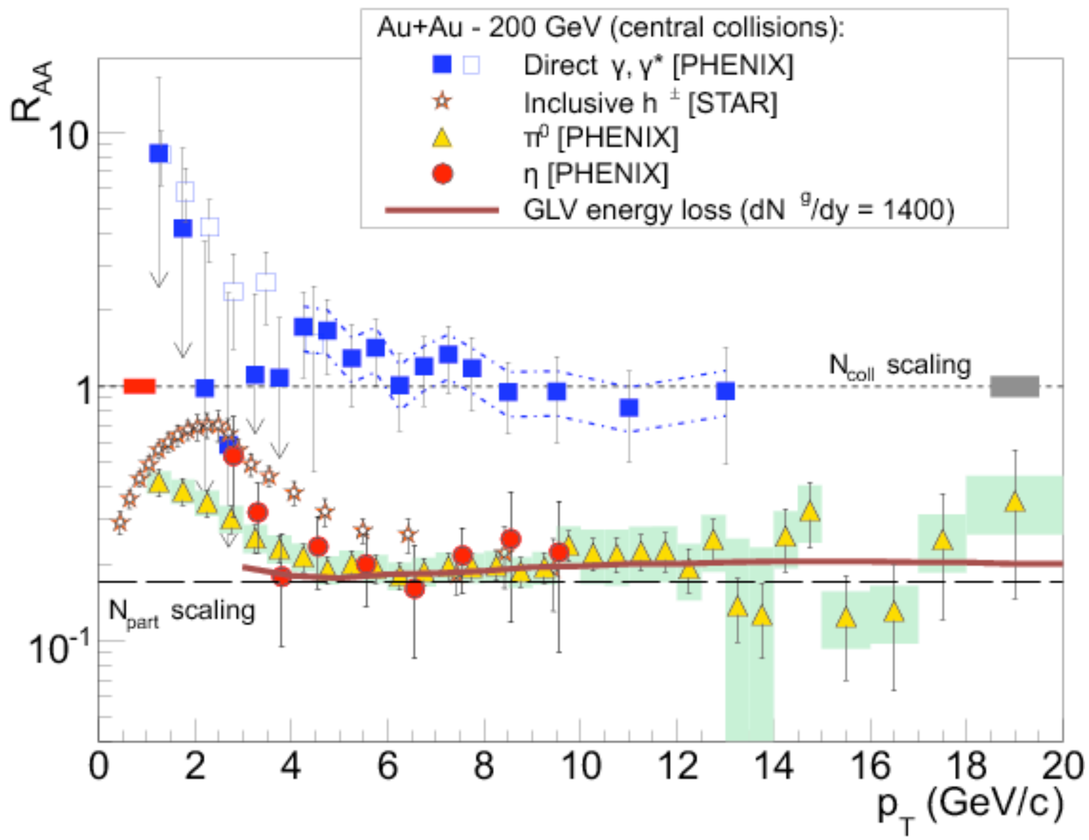




Large Jet Quenching Observed @RHIC

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

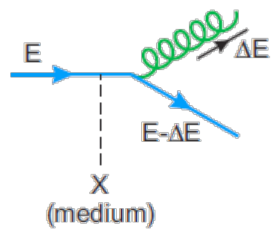




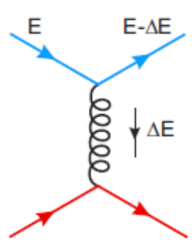
QGP density > 10x normal nucleus

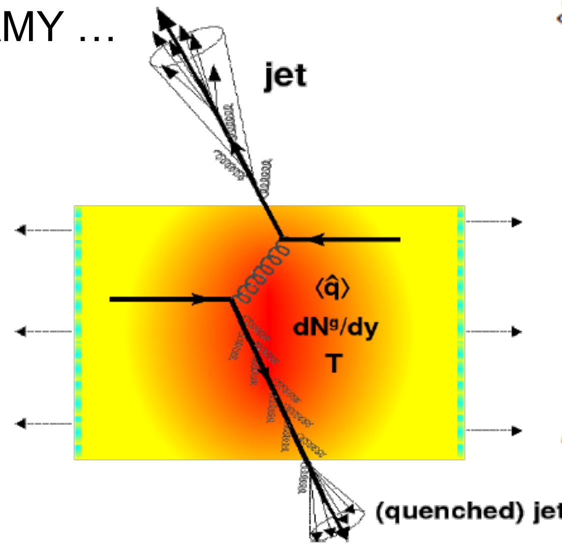
QGP and Jet Quenching

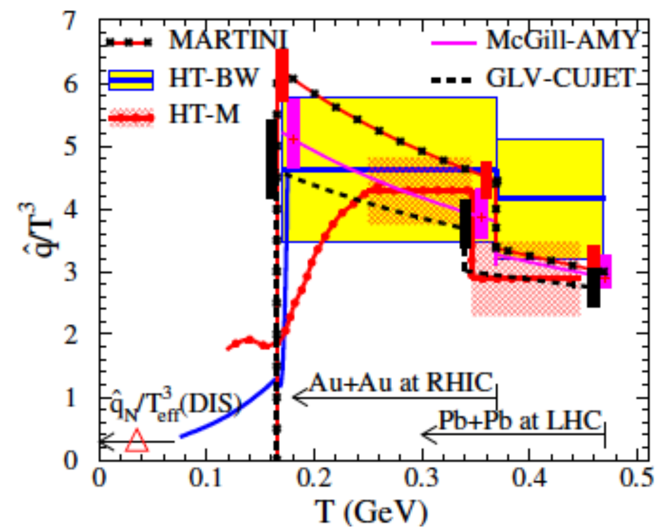
- Various parton energy loss mechanisms
  - Radiative energy loss
    - e.g. DGLV, BDMPS, AMY …



  - Collisional energy loss







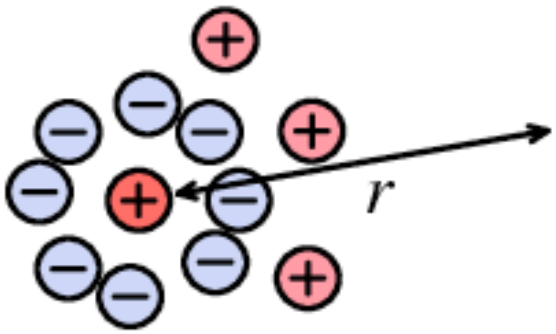
$$R_{AA} = \frac{1}{\langle n_{coll} \rangle} \frac{\pi^0 \text{ in AuAu collisions}}{\pi^0 \text{ in pp collisions}}$$

Theoretical quenching factor
- much model dependent!

$$R_{AA} \sim \int \rho_{QGP}(x) \cdot [\frac{dE}{dx}(\hat{q})] \cdot dx$$

$$<\hat{q}> = \frac{\langle k_T^2 \rangle}{L} \approx \frac{\mu^2}{\lambda} = \quad 2 \sim 20\, GeV^2/fm$$

QGP Color Screening and J/Psi Suppression

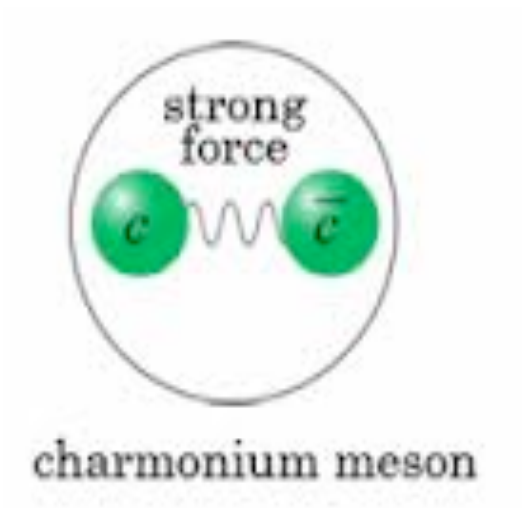


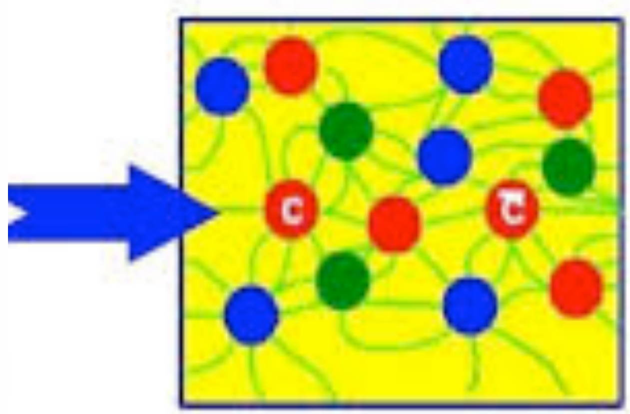
$$V(r) = V_0 \frac{e^{-r/\lambda_D}}{r}$$

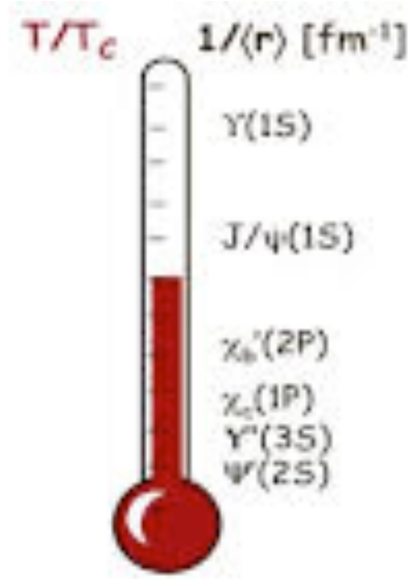
$$\lambda_D = C \times \sqrt{\frac{T}{n}}$$

Plasma Debye Length:

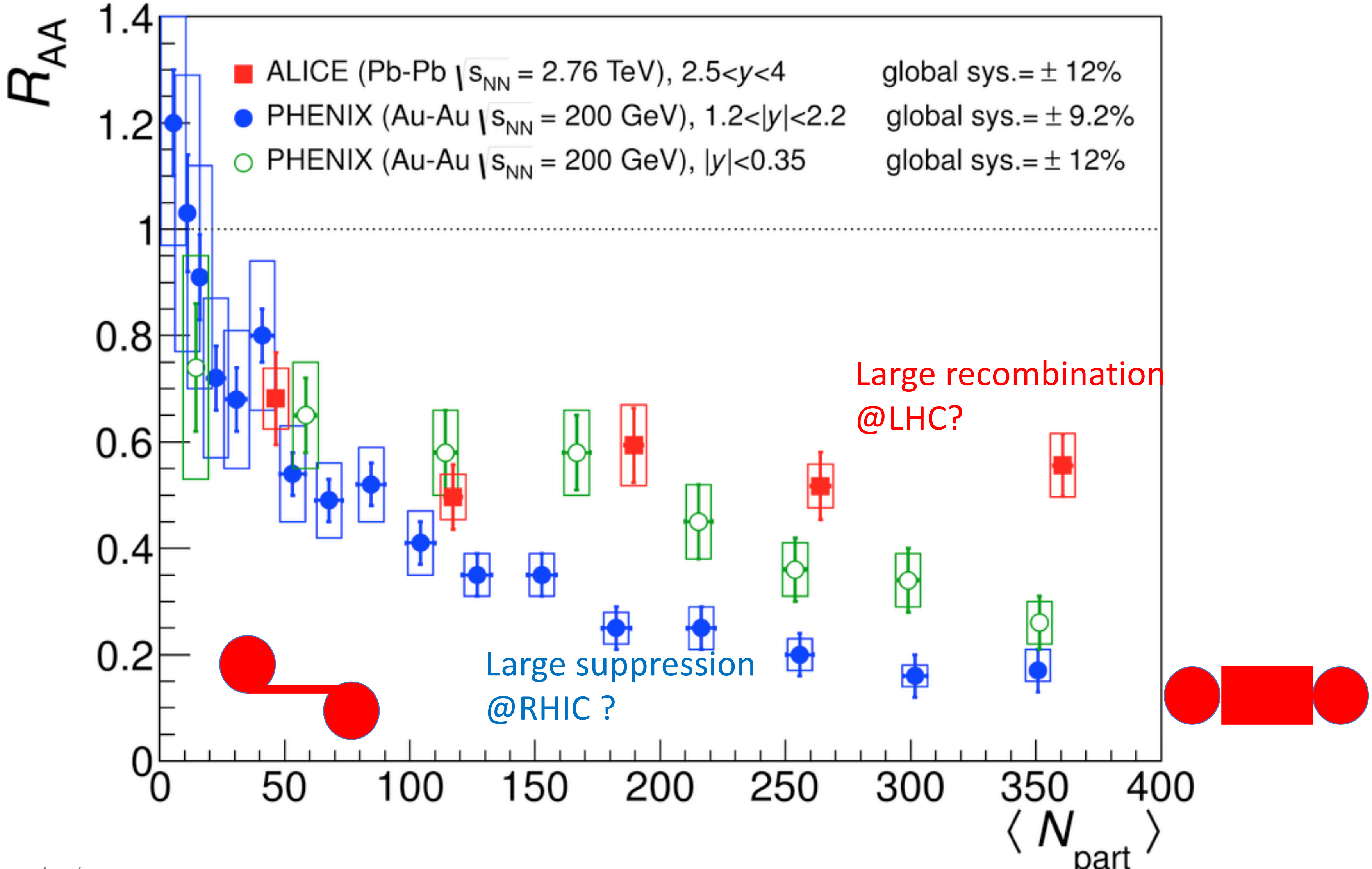
The shorter the r_D, the stronger the screening effects







J/Psi Suppression at RHIC and LHC
a surprise?

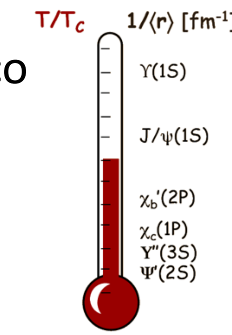


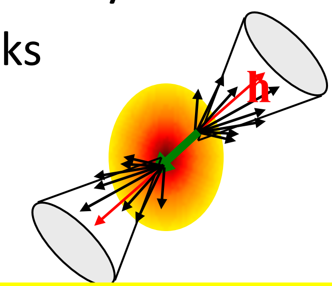
Compare RHIC vs LHC Results

LHC ~ RHIC! @high pT

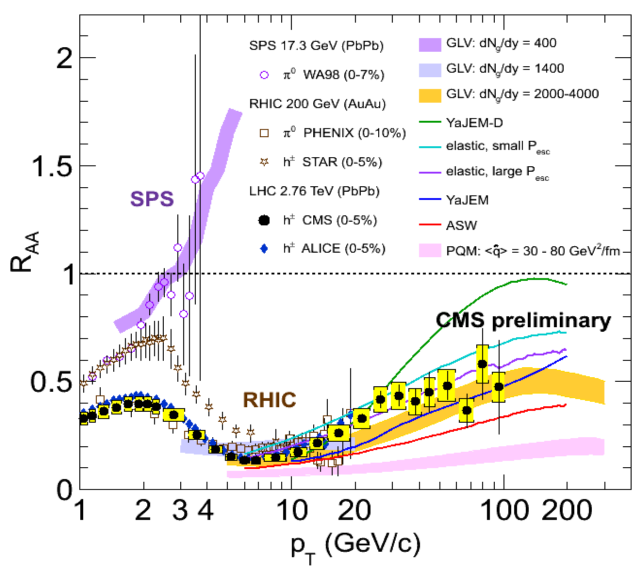
- Parton dE/dx & QGP properties
  - Radiation & collisional dE/dX
    - Light vs heavy quarks
  - CNM effects

- QGP color screening & heavy quarkonia "melting"
  - Color screening & reco
  - CNM effects

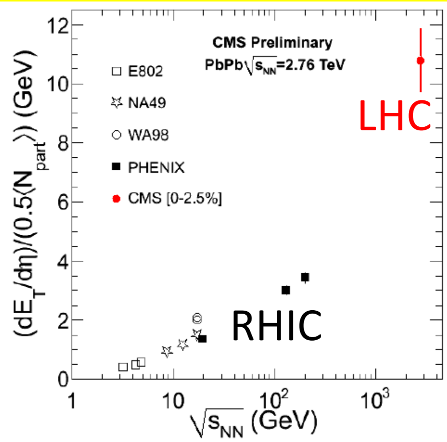




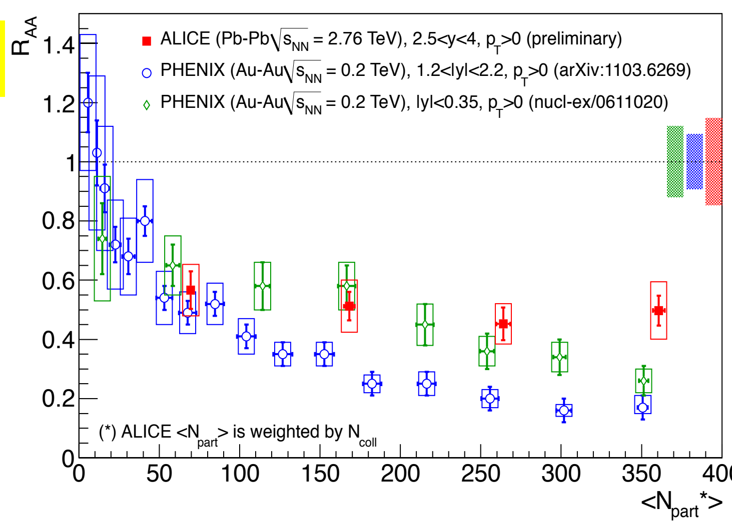
Jet suppression



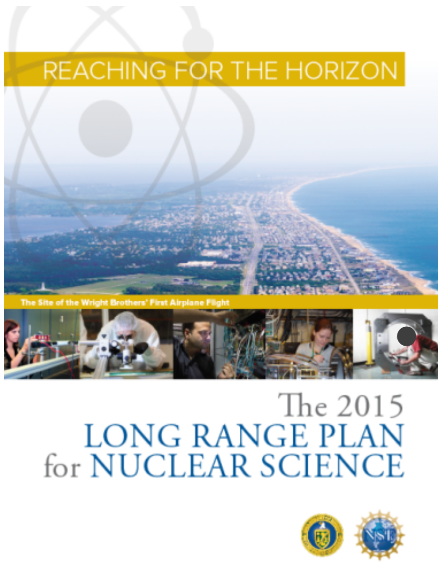
Achieved QGP Densities



J/Psi suppression



Why sPHENIX @RHIC?

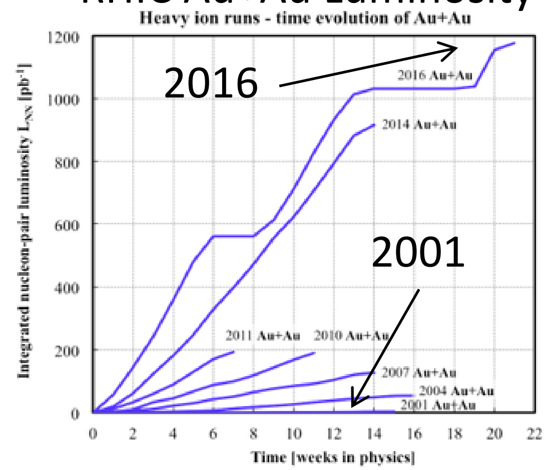


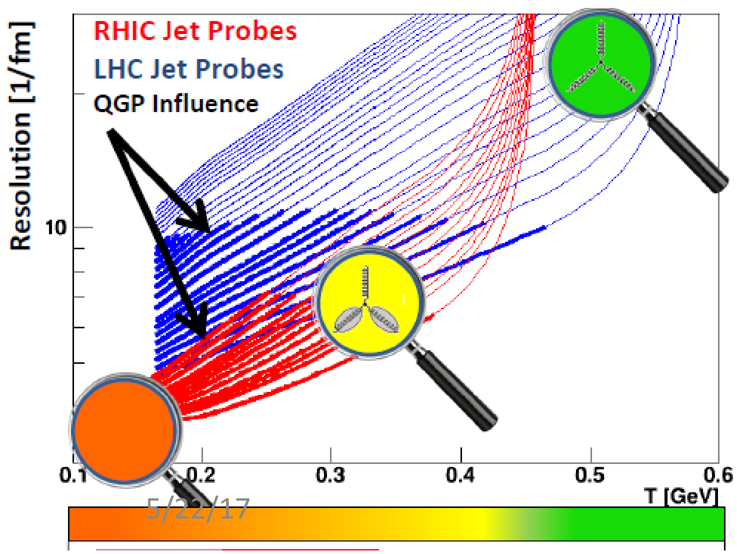
RECOMMENDATION I

The progress achieved under the guidance of the 2007 Long Range Plan has reinforced U.S. world leadership in nuclear science. 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.

RHIC Au+Au Luminosity

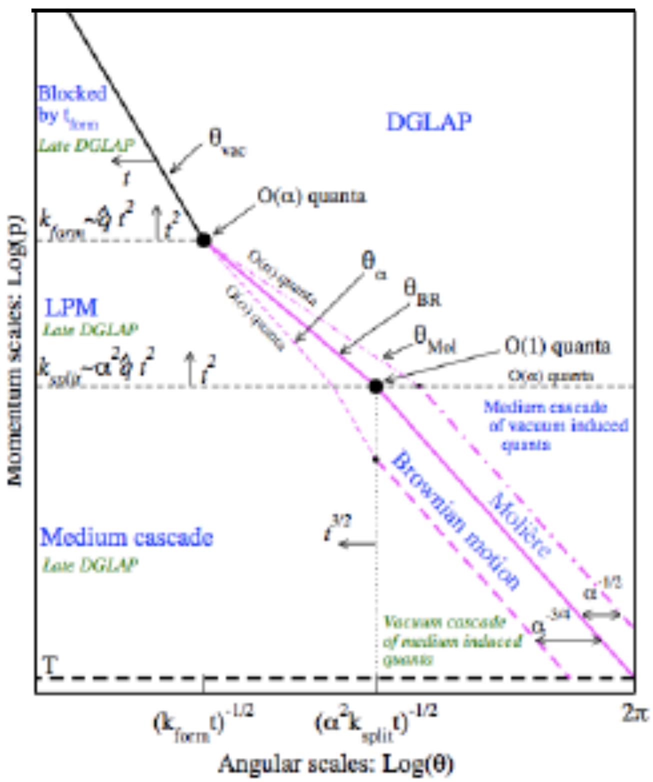




There are two central goals of measurements planned at RHIC, as it completes its scientific mission, and at the LHC: **(1) Probe the inner workings of QGP by resolving its properties at shorter and shorter length scales. The complementarity of the two facilities is essential to this goal, as is a state-of-the-art jet detector at RHIC, called sPHENIX. (2) Map the phase diagram of QCD with experiments planned at RHIC.**

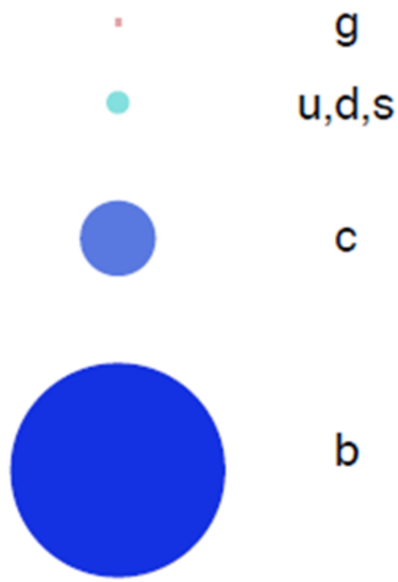
Probe QGP at multiple scales

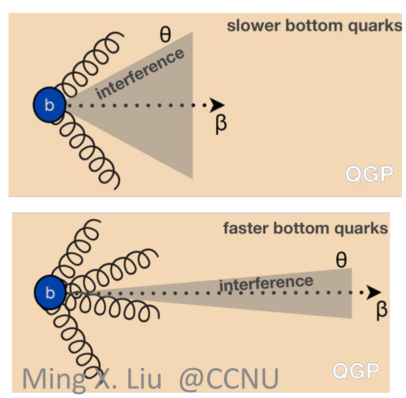
Jet evolution and structure



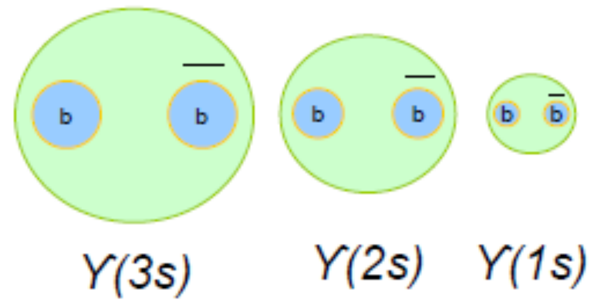
Phys. Lett. B 740 172 (2015)

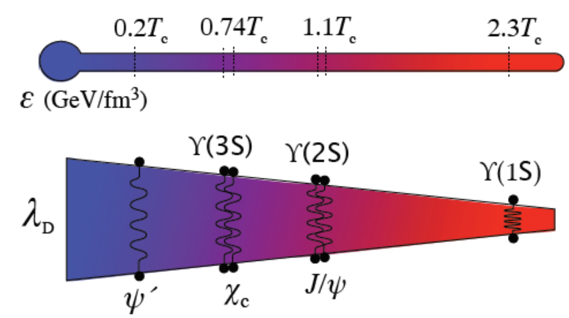
Parton Mass/Flavor



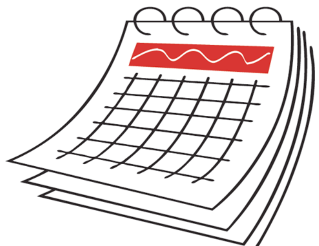


Upsilon spectroscopy

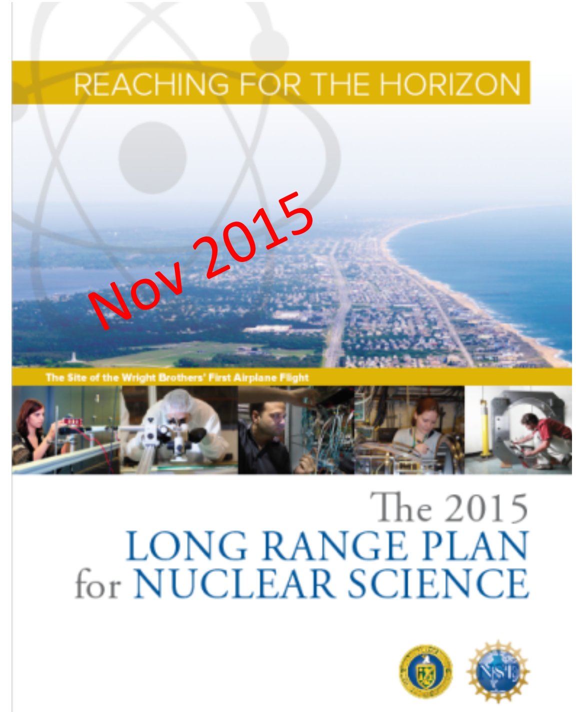




sPHENIX Status



- ✓Collaboration formed (Dec 2015)
- ✓Successful magnet tests
- ✓Successful Test Beam of calorimeter system
- ✓Tracking system defined:
  - ✓TPC and Silicon tracking
- ✓Improved simulations
- ✓CD-0! Approve Mission Need
  - DOE project phase: **Initiation**
- **CD-1 review Nov. 2017**



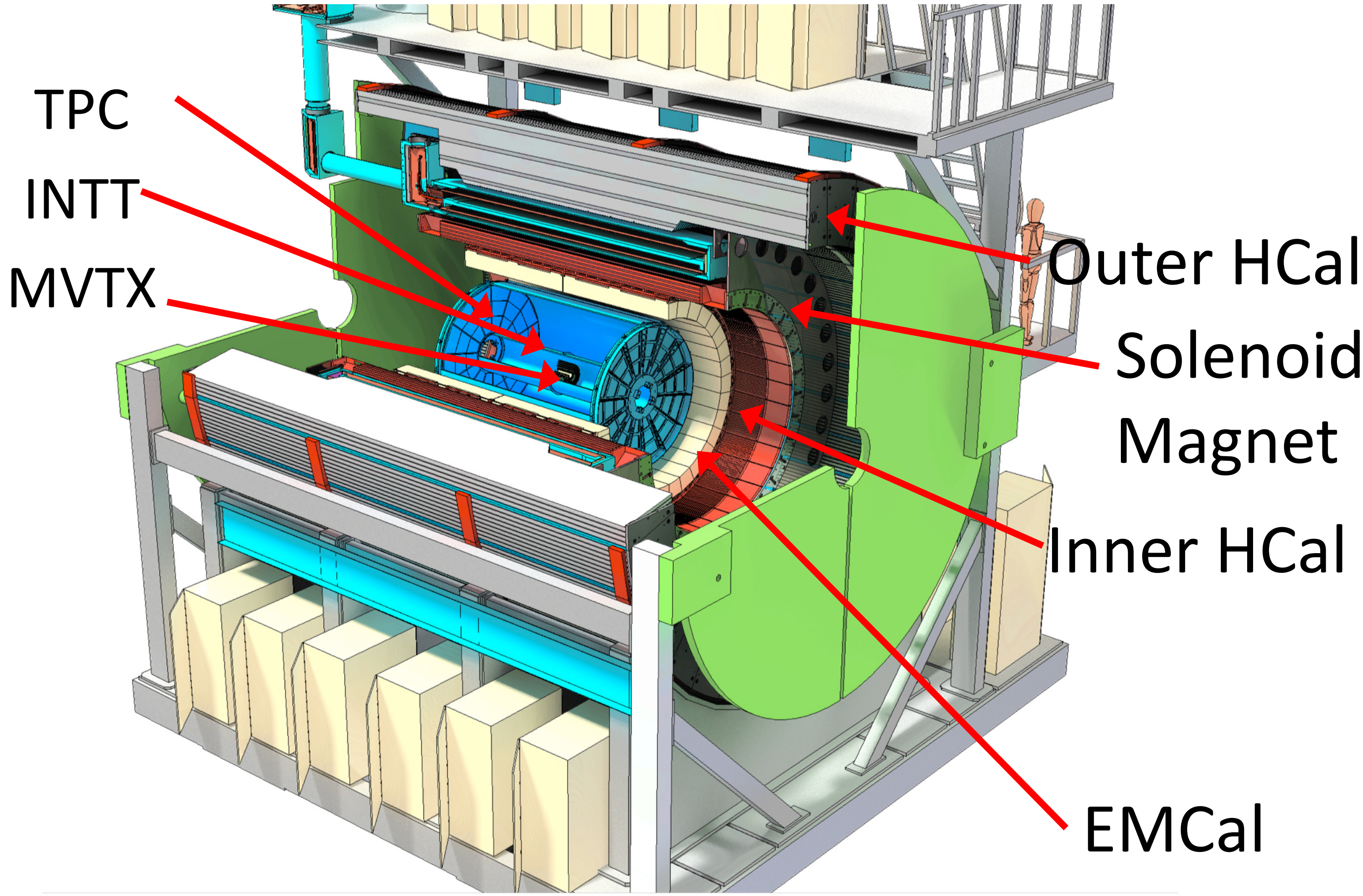
sPHENIX Gets CD0 for Upgrade to Experiment Tracking the Building Blocks of Matter

First step on a path toward a detector with unprecedented capabilities for deciphering how the properties of the hottest matter in the universe emerge from the interactions of its fundamental particles

Oct 2016

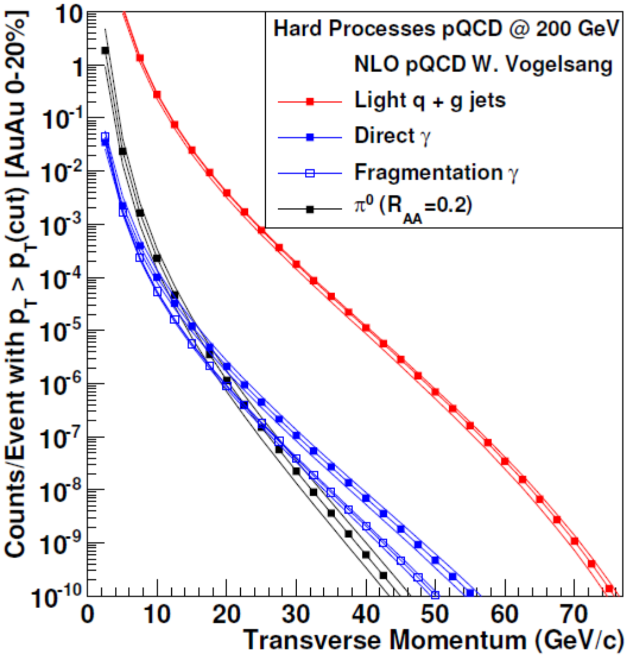
January 13, 2017

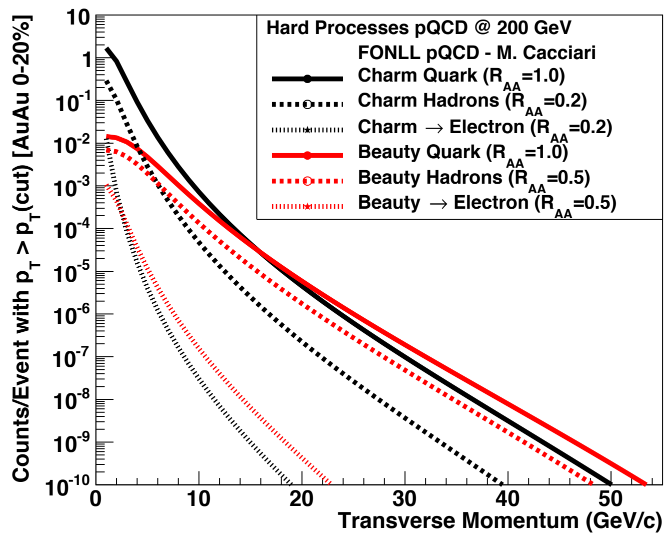
Detector Designed for Measurements



Measurements of sPHENIX

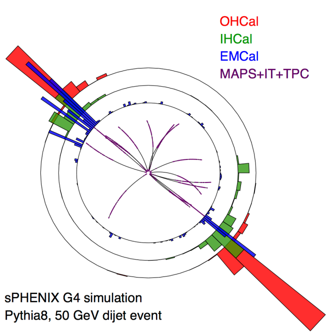
22 weeks of Au+Au at RHIC
→ 100B MB events
→ 20B 0-20% events

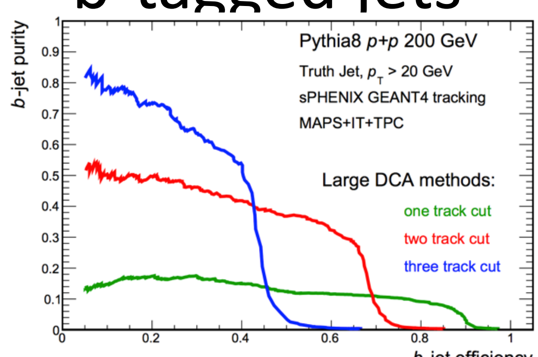


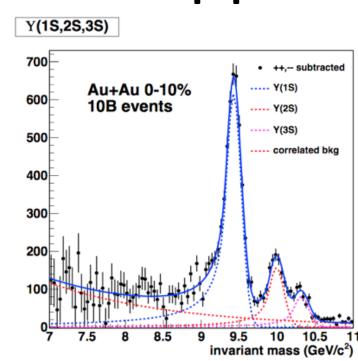


Central Yields	p_T Range
10^7 jets	> 20 GeV/c
10^6 jets	> 30 GeV/c
10^4 γ_{dir}	> 20 GeV/c
10^4 b-jets	> 20 GeV/c

- Jet Structure
- b-tagged jets
- 3 state ϒ suppression

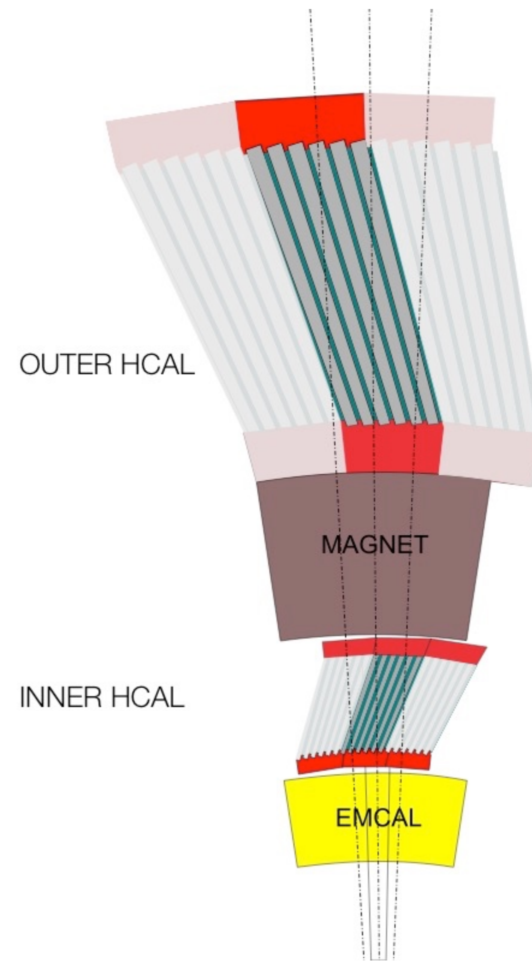




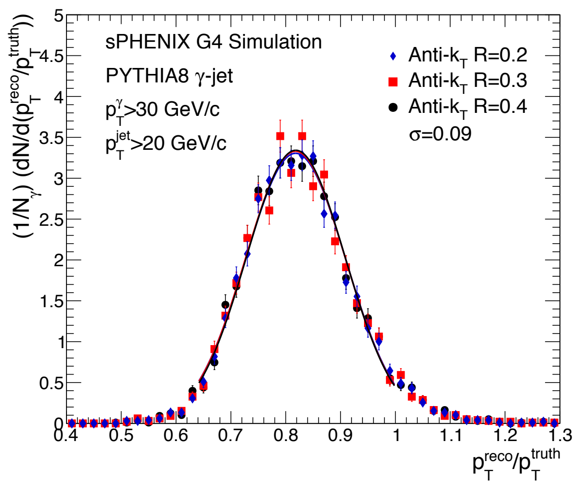


Calorimetry for Jet Physics

Physics Goal	Detector Requirement
Jets/Fragmentation Functions/jet substructure	Single particle Resolution: $\sigma/E < 100\%/\sqrt{E}$
Distinguish Upsilon States	Good e/π separation
HF jet tagging	Electron ID

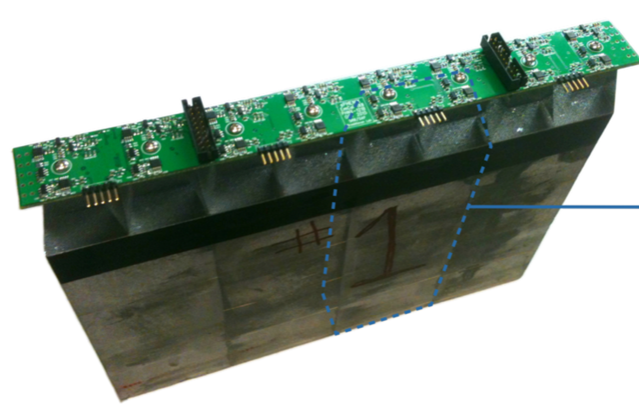


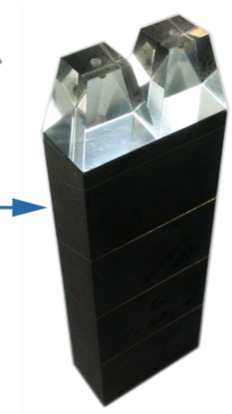
- Designed to Measure Jet energy



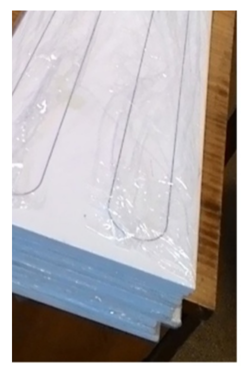
The Calorimeters

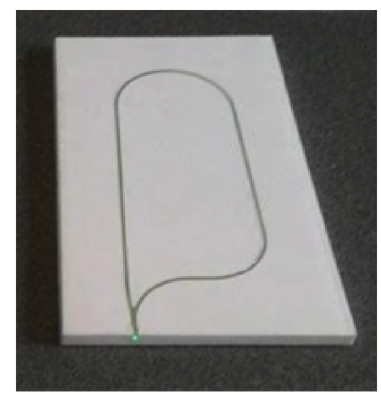
- EMCal Towers: fibers embedded in Tungsten-epoxy





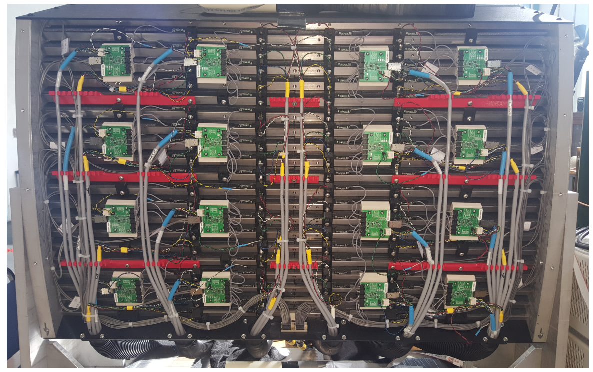
- HCal: Plastic scintillator tiles with embedded fiber between tilted steel plates

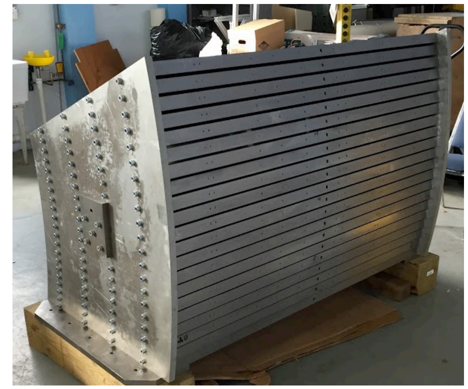




- All read-out with SiPMs

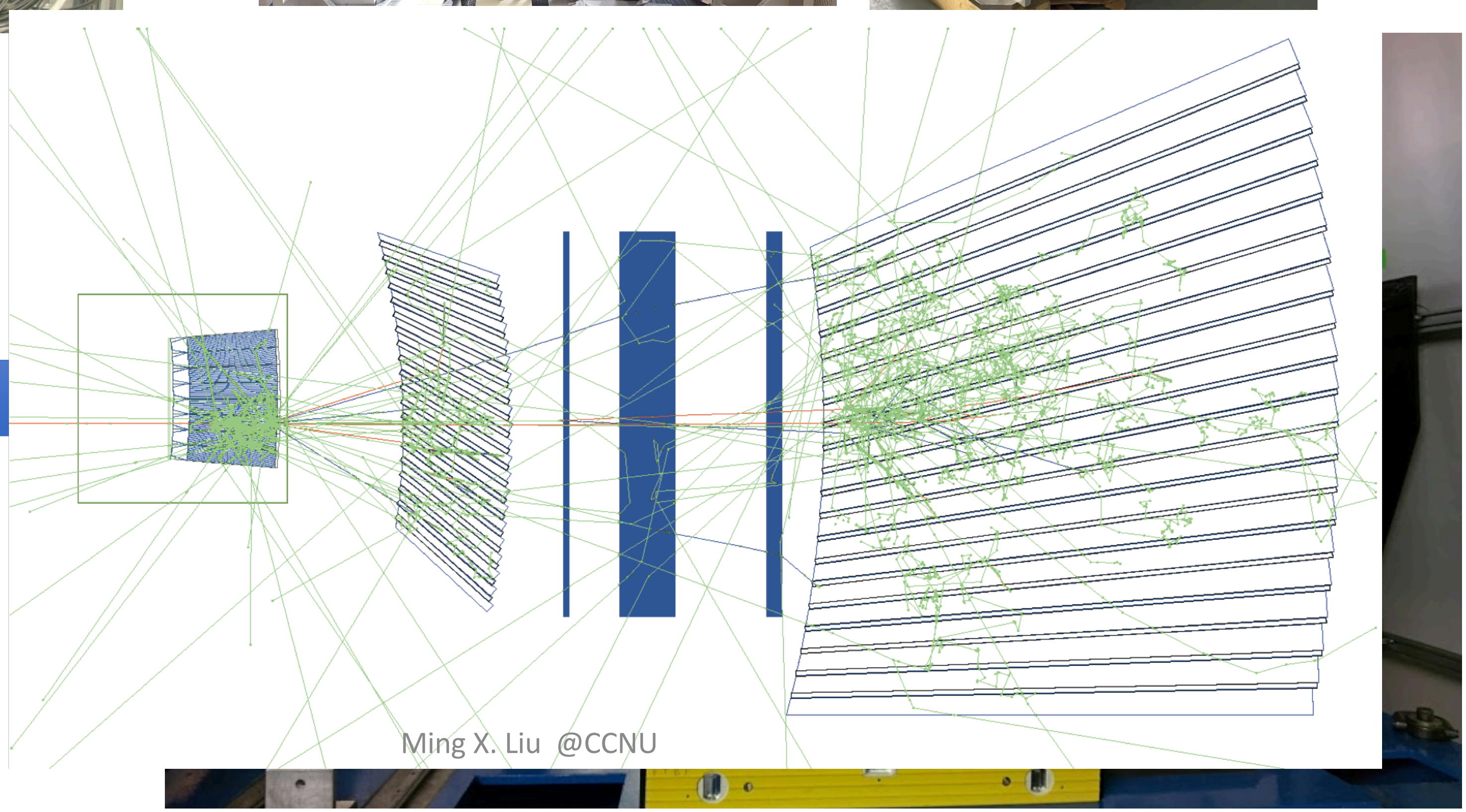
Test Beam 2016



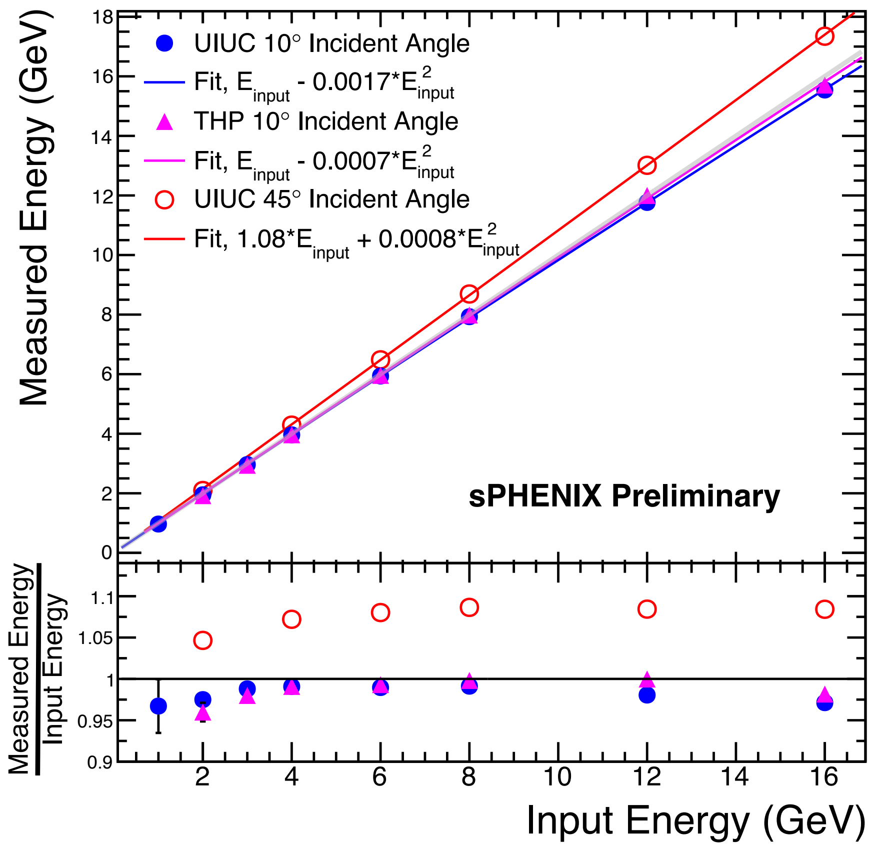


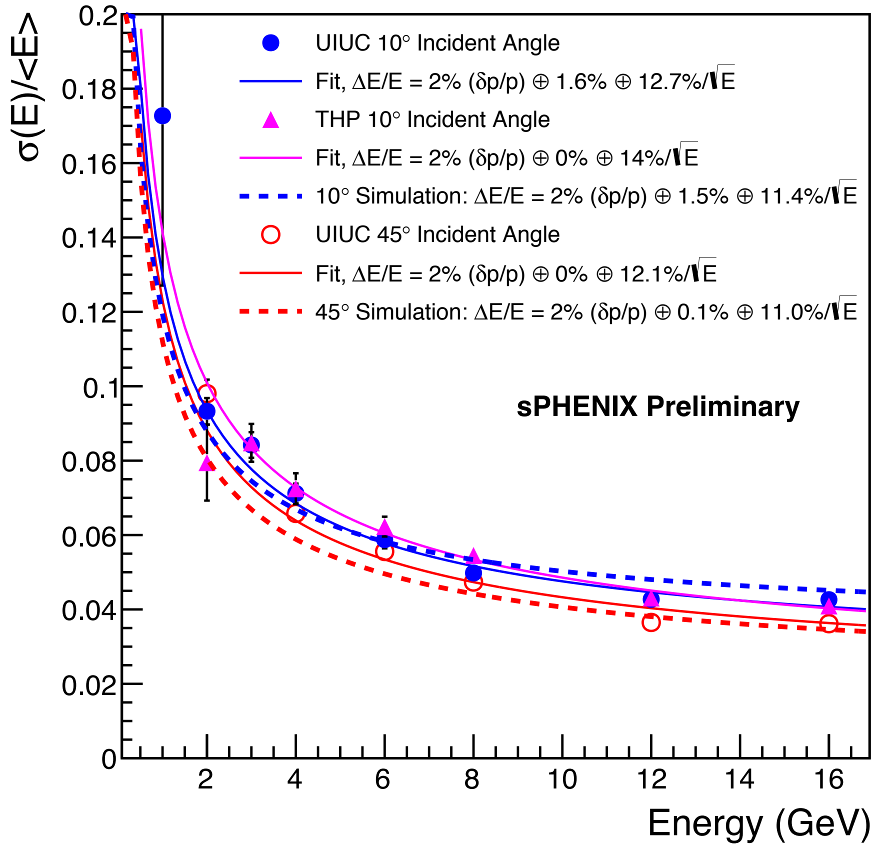
How well does simulation reproduce the data?

Beam



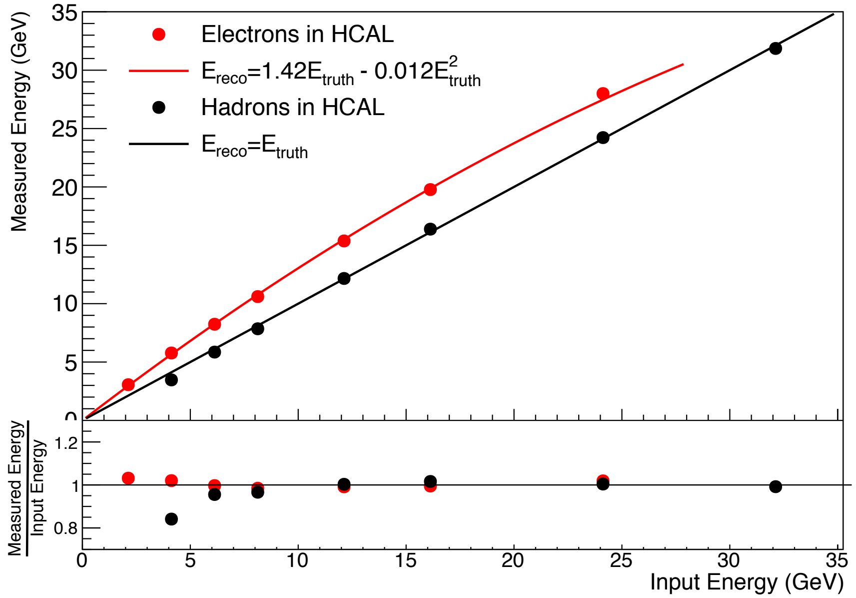
Test Beam 2016 – EMCal Results

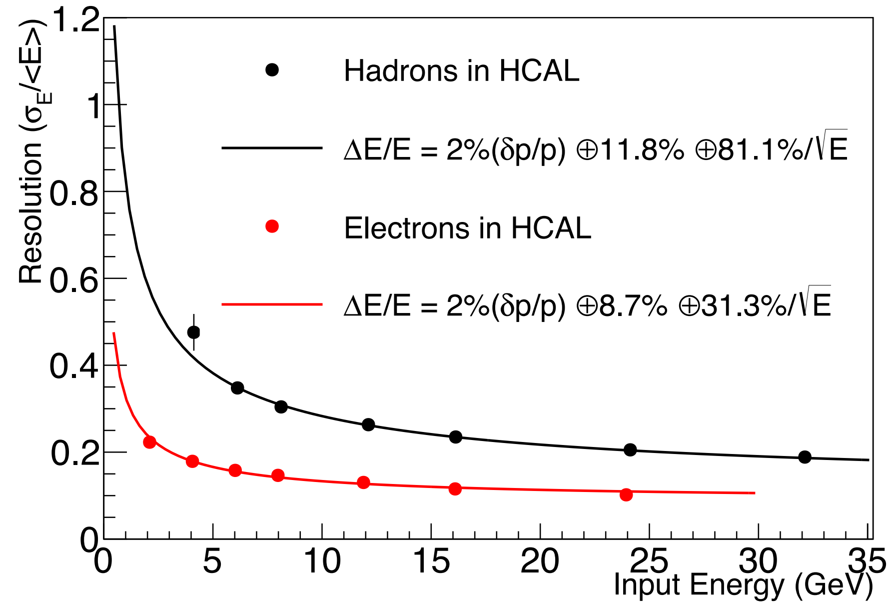


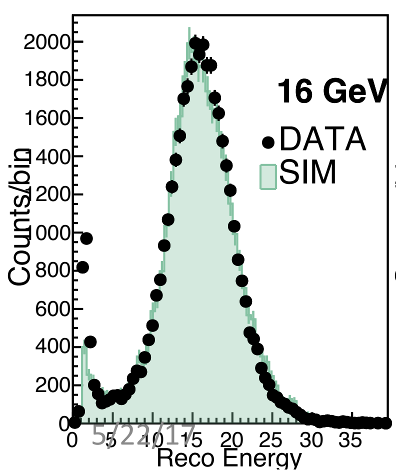


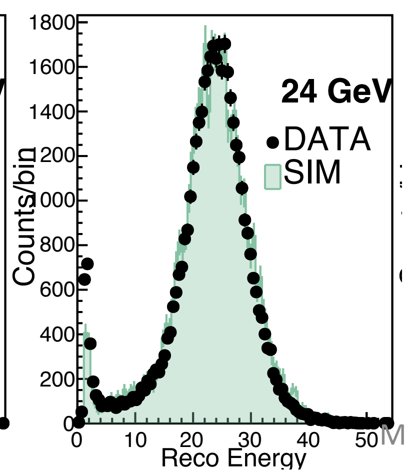
- Resolution meets sPHENIX requirements
- Excellent data-simulation agreement

Test Beam 2016 – HCal Results





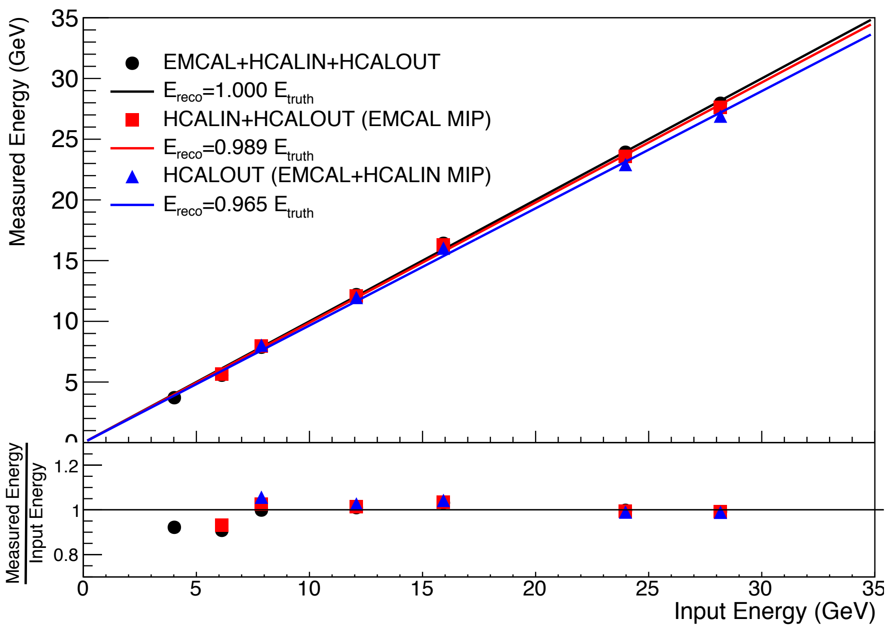


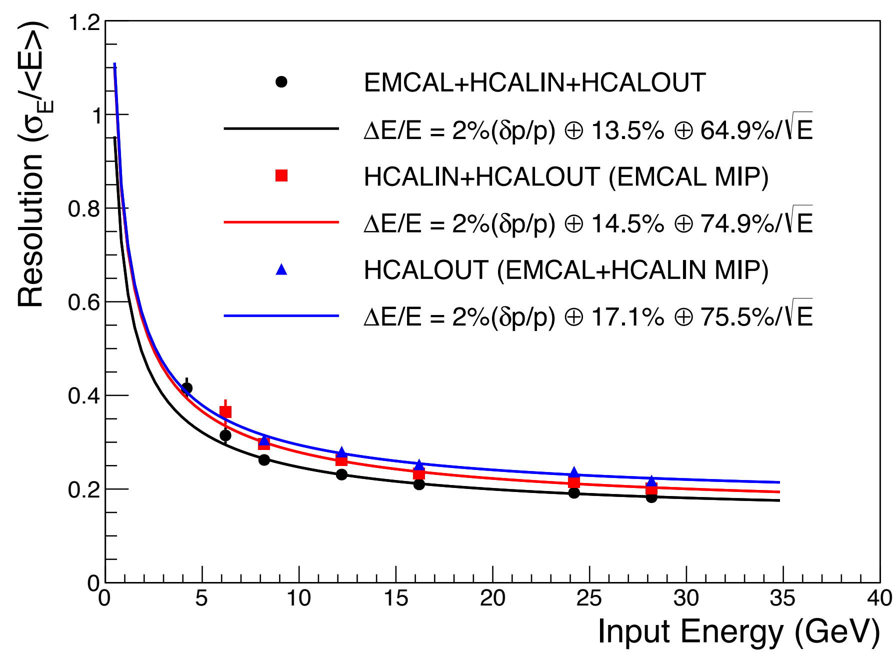


- Resolution within sPHENIX expectations
- Excellent data-simulation agreement

Test Beam 2016 – Hadrons

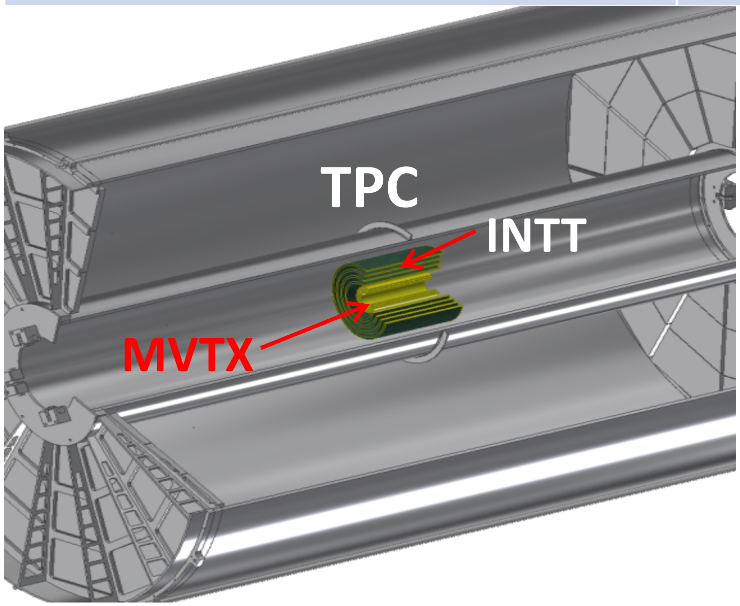
- Combined system takes into account where the particles shower develops
- Satisfies the single particle energy resolution needed for sPHENIX program

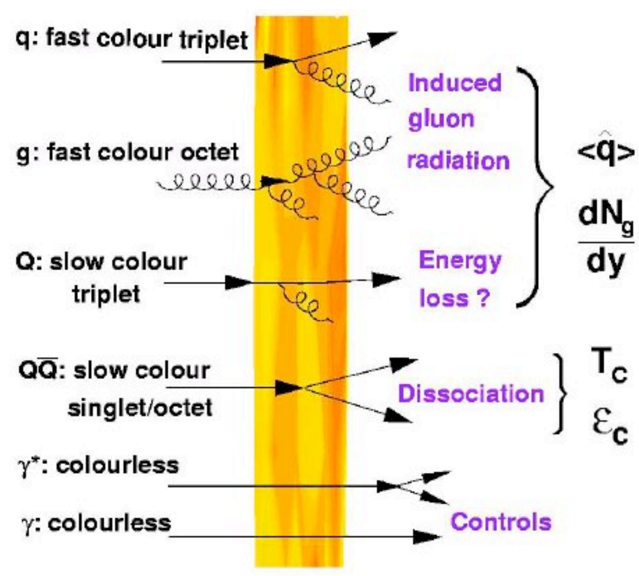




Importance of Tracking for QGP Physics

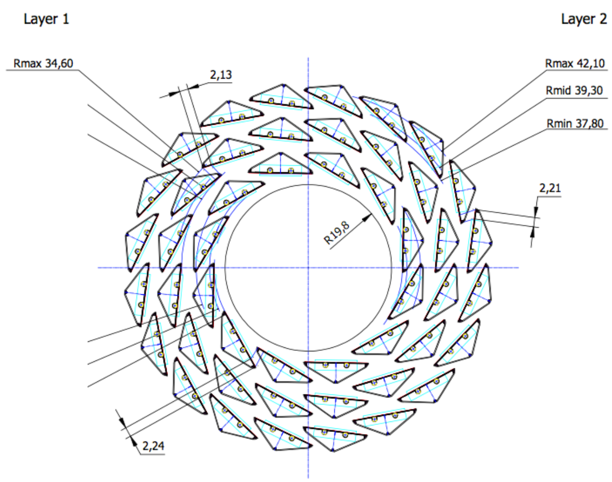
Physics Goal	Detector Requirement
Fragmentation Functions	Excellent Momentum Resolution: dp/p ~ 0.2%p to > 40 GeV/c
Jet Substructure	Excellent track pattern recognition
Distinguish Upsilon States	Mass resolution: $\sigma_M < 100$ MeV/c^2
HF jet tagging	Precise DCA resolution $\sigma_{DCA} < 100$ µm
High Statistics Au+Au 200 GeV	Handle multiplicity and full RHIC luminosity



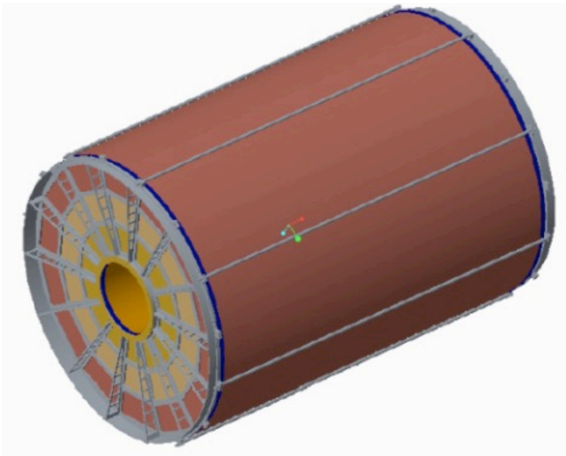


Tracking for Jets and Upsilons

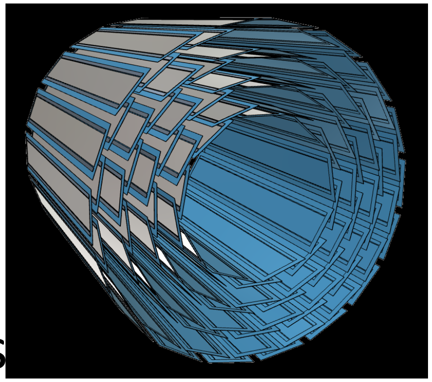
MVTX



- 3 layers Si pixel
- Based on ALICE ITS upgrade
- $DCA_{xy} < 70\ \mu m$
- $|z_{vtx}| < 10$ cm



INTT

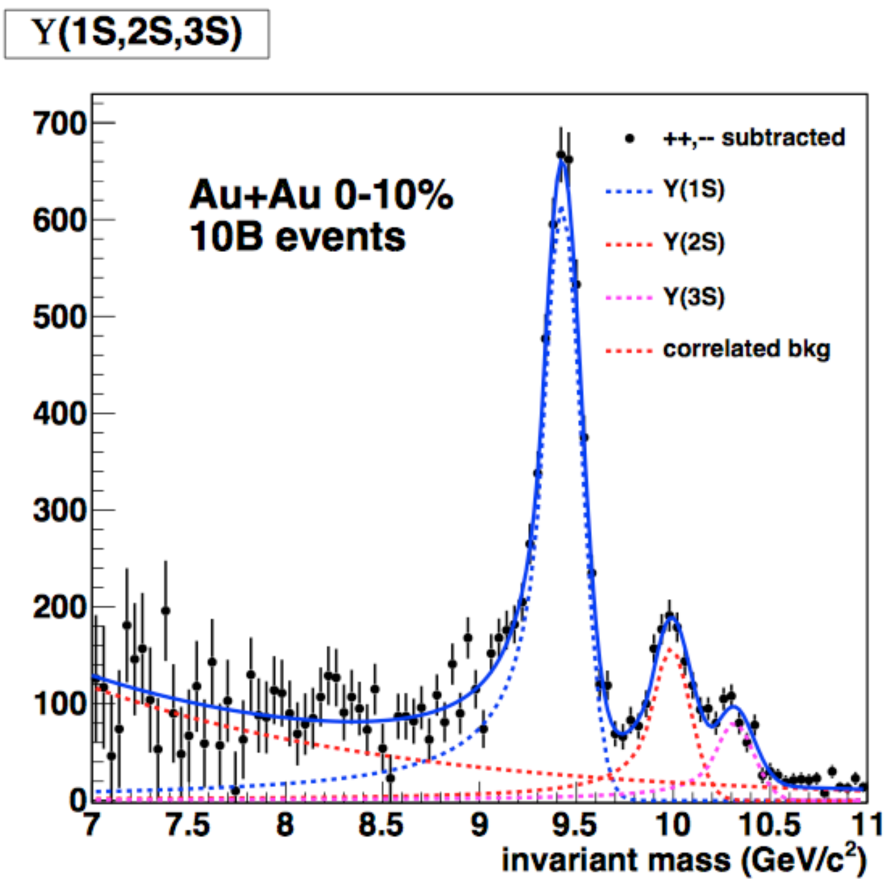


- 4 layers Si strips
- Use PHENIX FVTX electronics
- Pattern recognition, DCA, connect tracking systems, reject pile-up

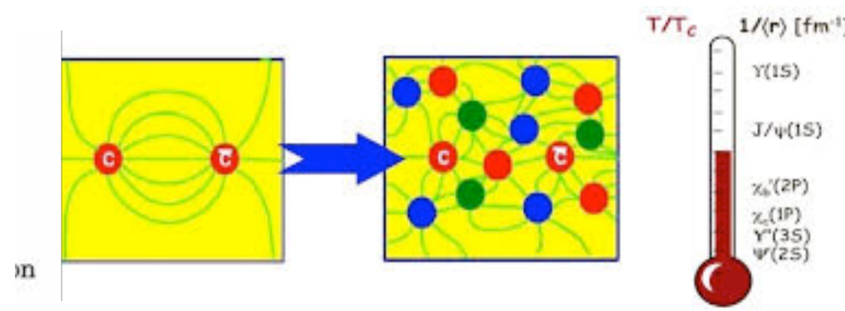
TPC

- Radius 20–78 cm
- ~250 µm effective hit resolution
- Continuous (non-gated) readout
- Pattern recognition, momentum resolution, p_T 0.2-40 GeV/c

Designed to Measure Upsilons

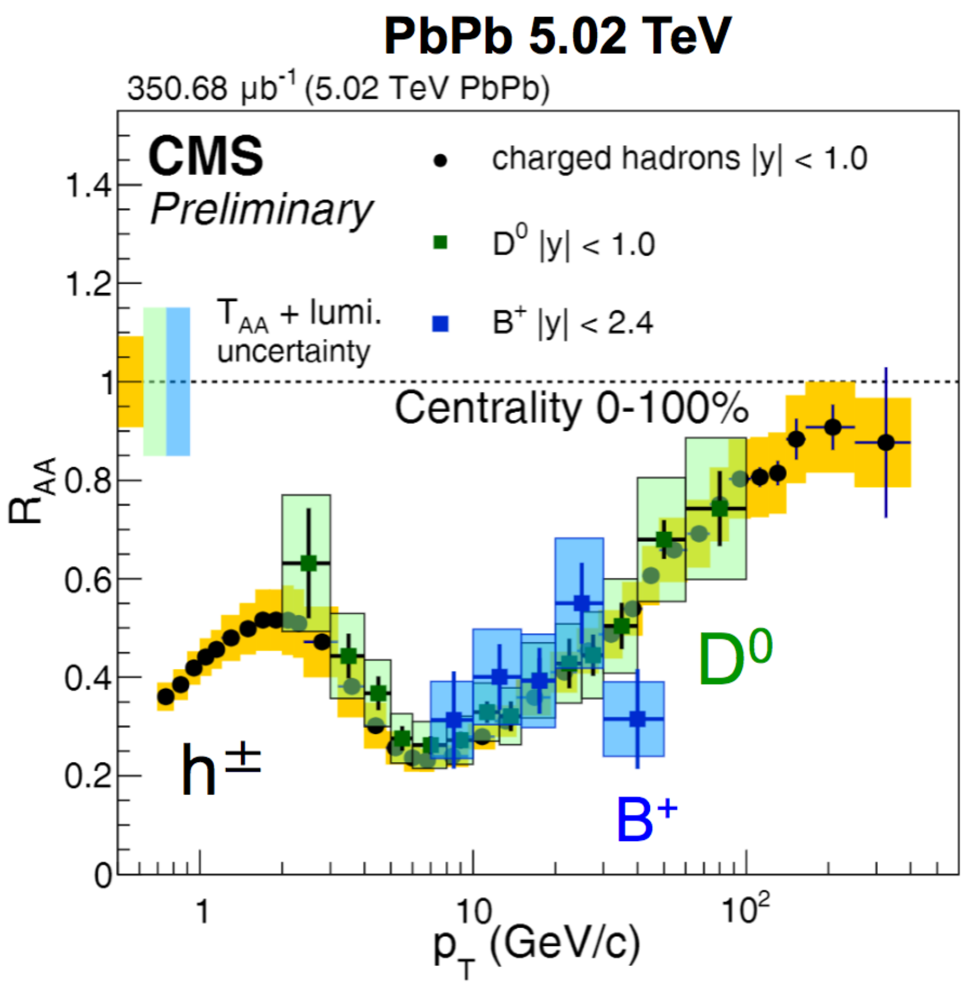


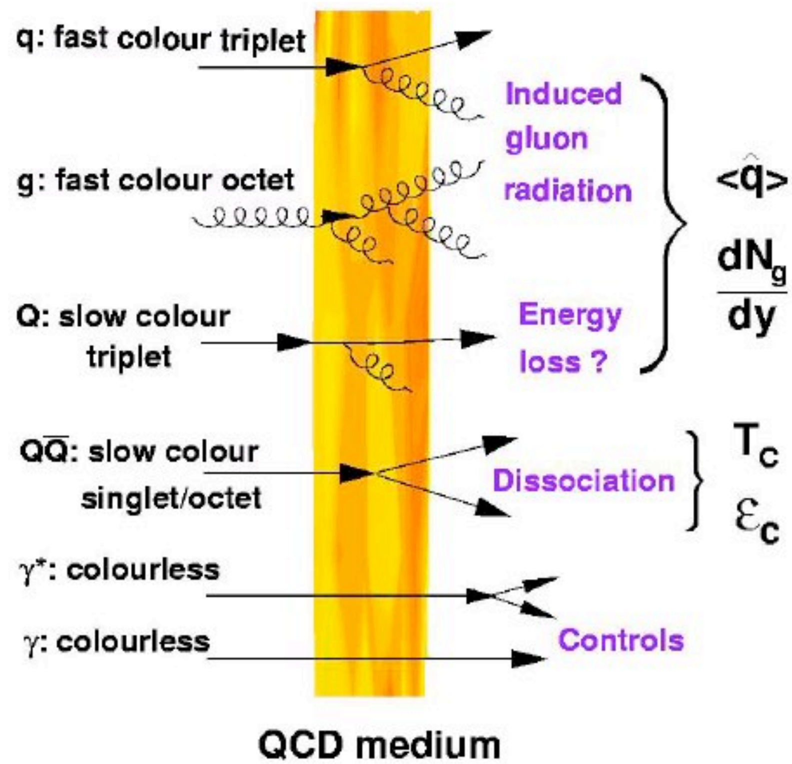
- Modeled as uniform cylindrical tracking layers
- Single track efficiency 90% by 5 GeV/c in p+p
- Momentum resolution ~0.06 at 30 GeV/c



Surprises in Jet Quenching

Important to study heavy flavor at low pT ~ M

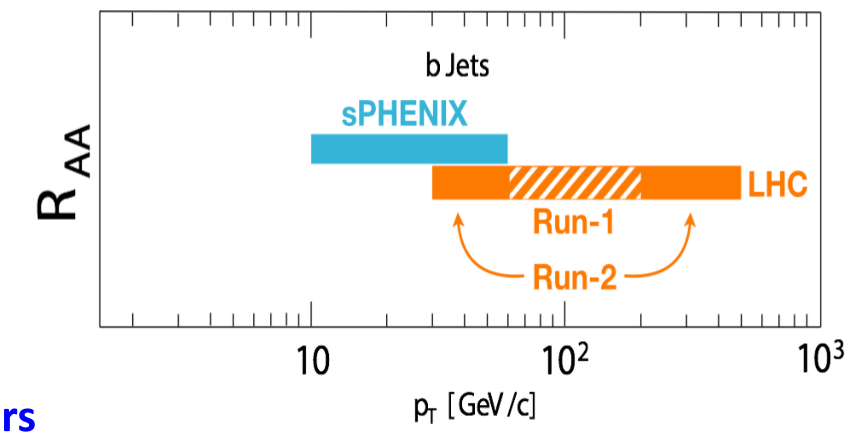




Open Heavy Flavor Physics: the 3rd Pillar

- sPHENIX is the next flagship heavy ion physics experiment in US
  - Jets
  - Upsilons
  - B-jets & B-hadrons
- MVTX will complete b-jet physics

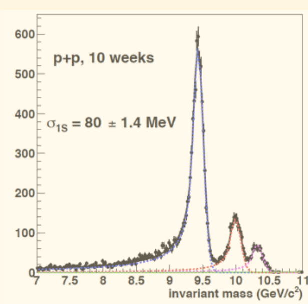
Cannot be done at the LHC for lack of low pT reach and huge backgrounds



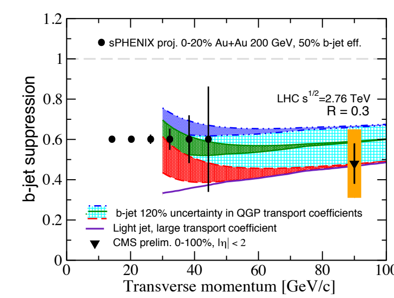
sPHENIX Three Physics Pillars

Jets

Upsilons

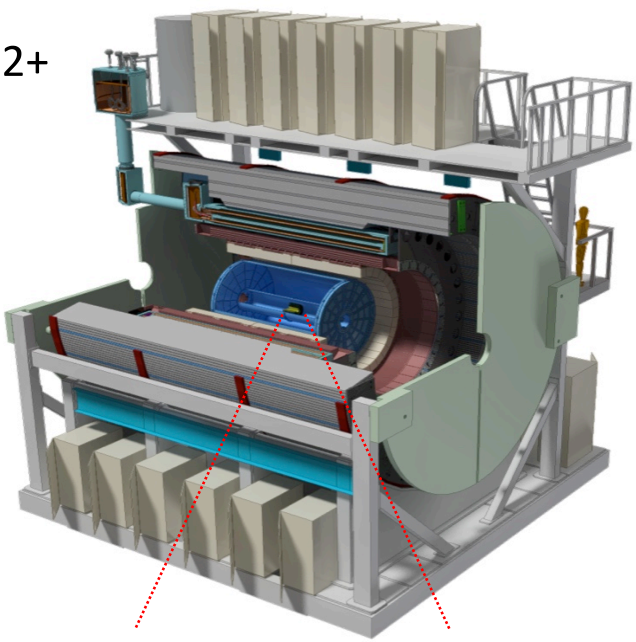


B-Jets Physics

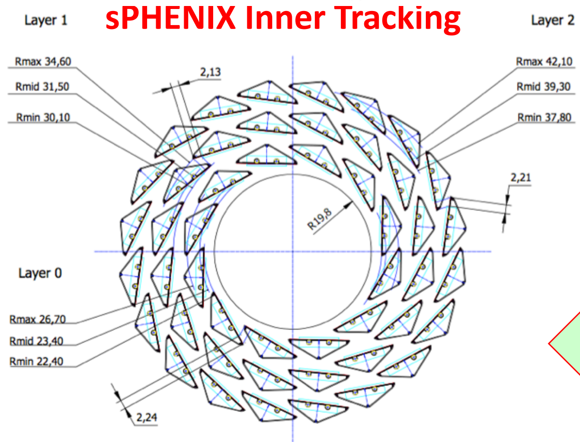


MAPS-based Vertex Detector (MVTX) Upgrade

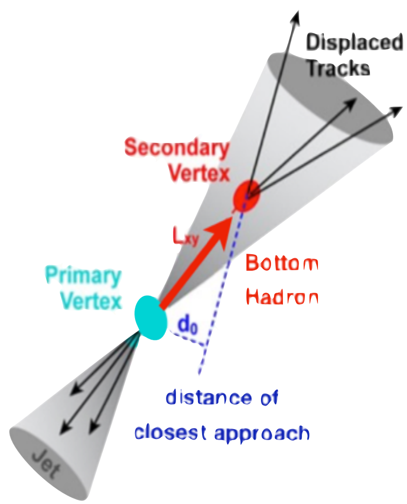
2022+



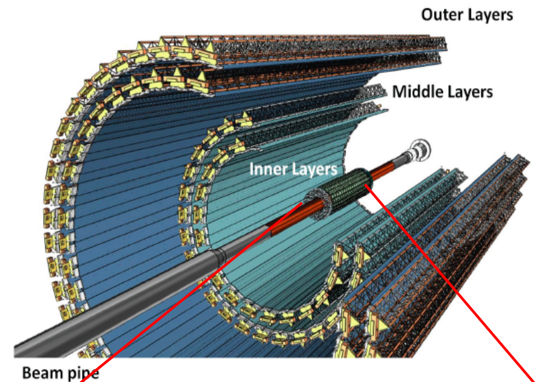
sPHENIX Inner Tracking

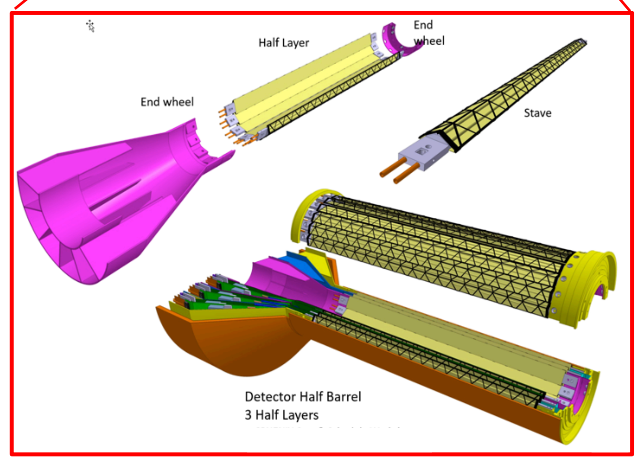


Key issues:
- Readout
- Mechanics



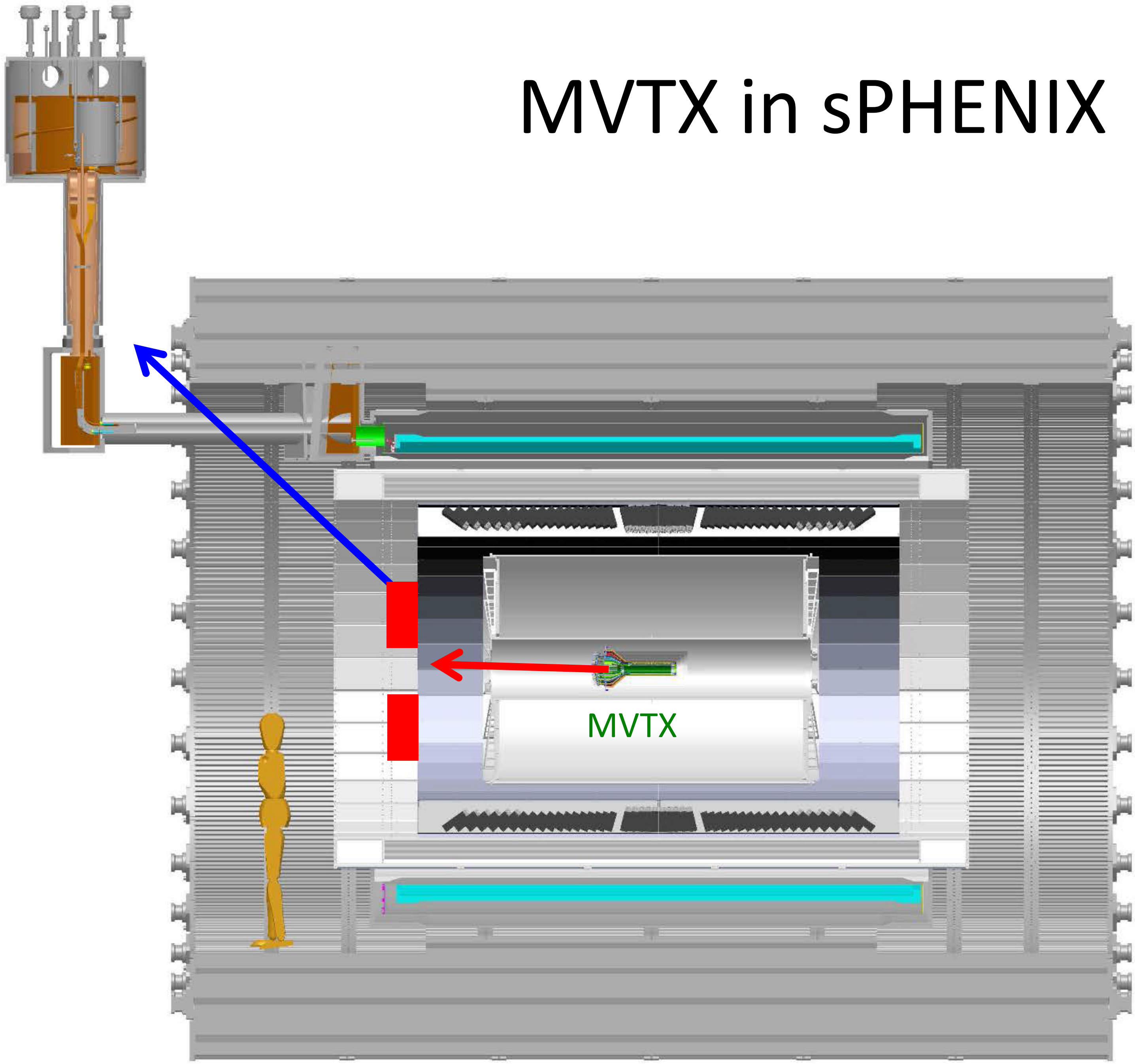
ALICE ITS Upgrade (2021+);
Inner Tracker System





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

MVTX in sPHENIX



Project Tasks and Timeline

FY2016 FY2017 FY2018 FY2019 FY2020 FY2021

sPHENIX baseline

CD-0 9/2016

CD-1

CD-2/3 8/1

Ready for Beam 6/1

ALICE ITS/IB Prod. ends

Key R&D

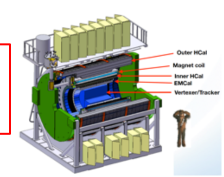
Readout R&D
Mech. design
@LANL/ALICE

Mech. Integr.
& Prototype
@MIT/LBNL

A schedule driven project!

Production

MAPS Prod. & QA @ALICE → Stave prod.&test @CERN; RU prod @CERN CRU Prod. @US → Detector Assembly & Test @LBNL → Det. Install. @BNL

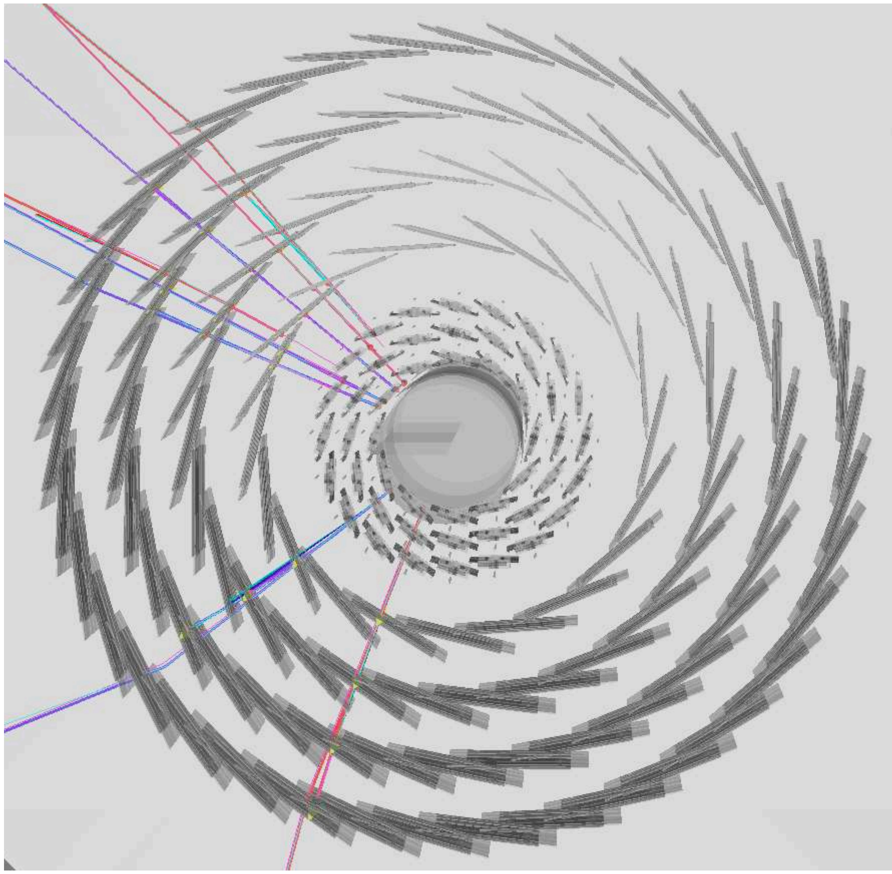


+2% +50%

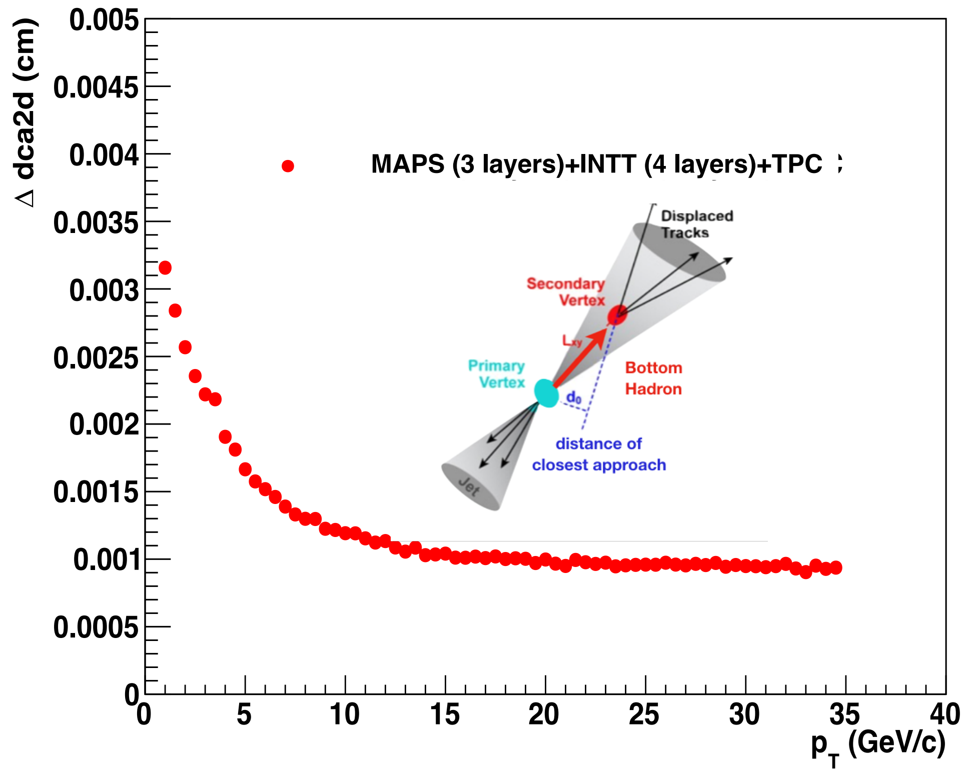
"MoU" w/ ALICE/ITS: 11/2016

- Produce MAPS chips and Stave Space frames for sPHENIX as part of ALICE production!
- Full staves and RU & CRU production cost & schedule → **MVTX MIE**

MVTX Designed to Measure b-jets



- Outstanding DCA resolution
  - 25 μm for p_T 1-2 GeV/c



- Simulation Improvements:
  - Realistic ladder geometry

TAMU Model

heavy quark diffusion and hadronization/recombination

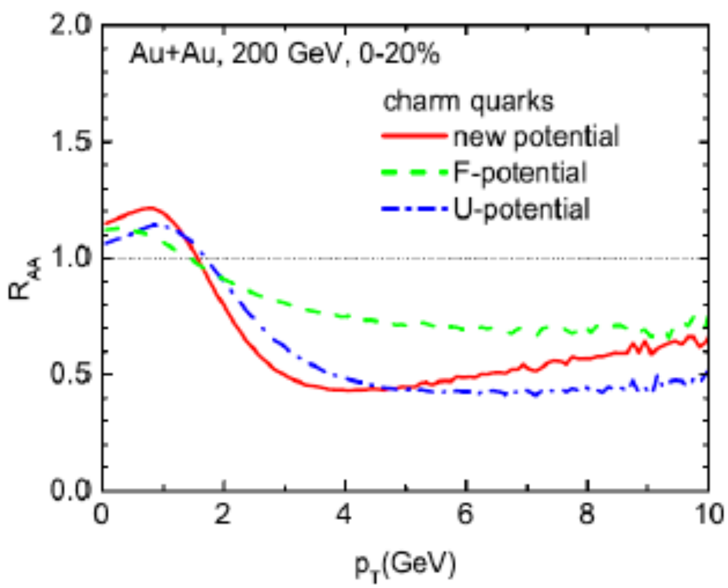
Langevin Simulation and Charm-Quark Spectra

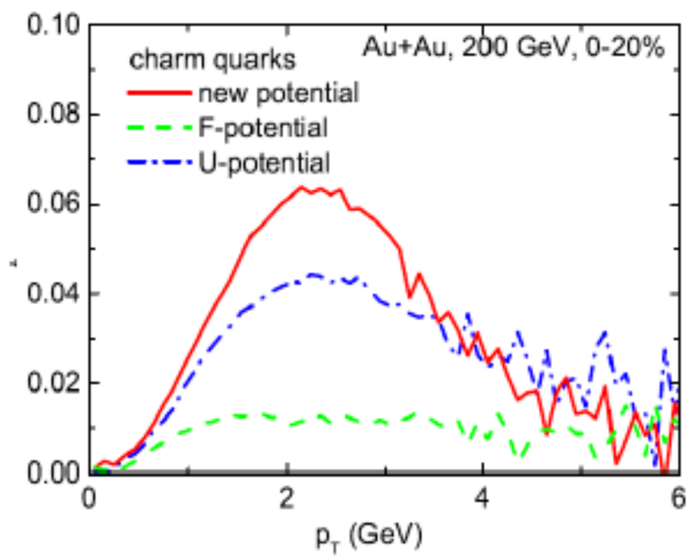
Transport Coefficient for Heavy Quark

$$\Gamma = A(p) + O\left(\frac{T}{M_Q}\right); \;\; D(p) = \Gamma(p)E(p)T$$

Langevin Equation

$$d\mathbf{x} = \mathbf{p}dt$$
$$d\mathbf{p} = -\Gamma\mathbf{p}\,dt + \sqrt{D(p+dp)dt}\rho$$

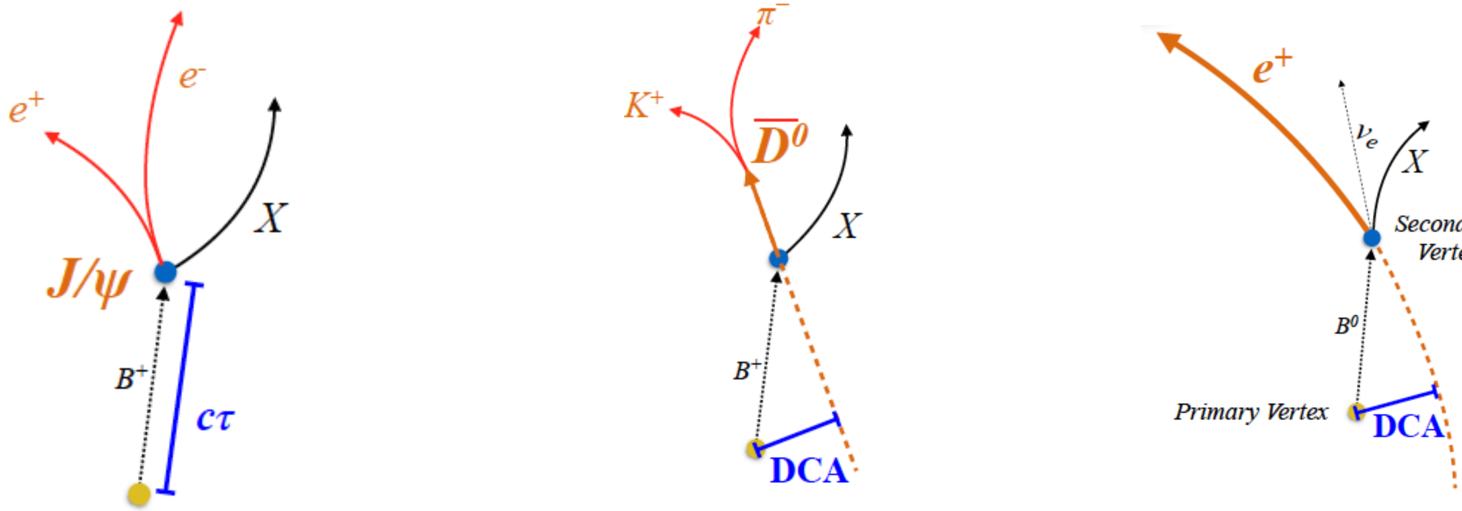


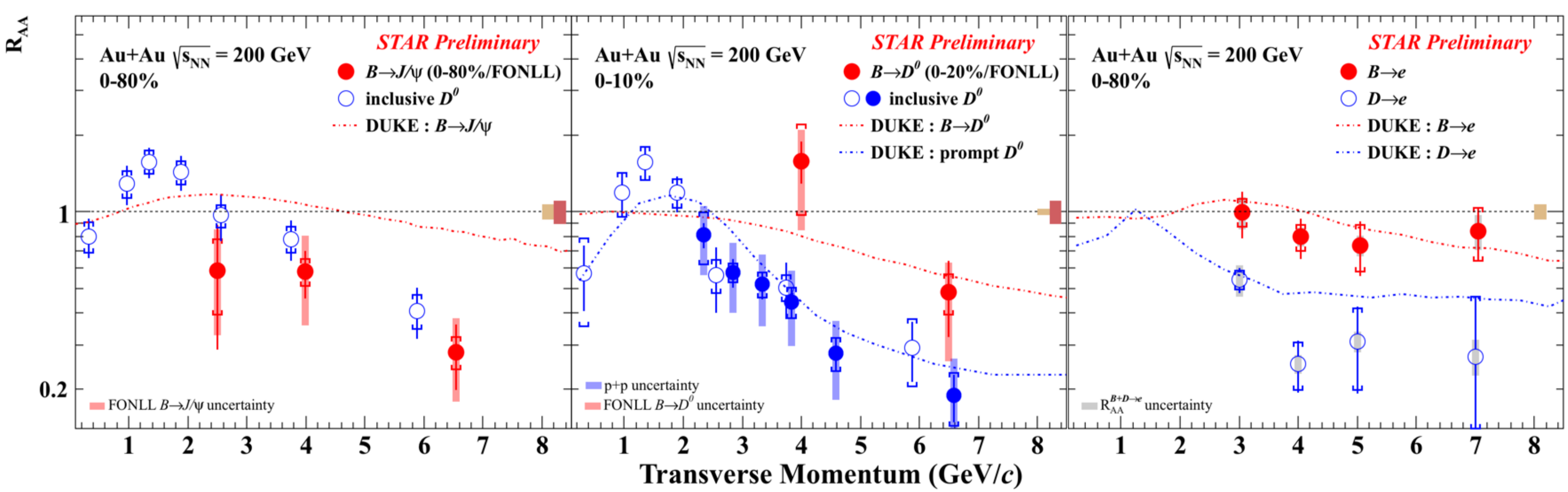


M He+S.YF Liu+Ralf Rapp inprep

B Production @RHIC

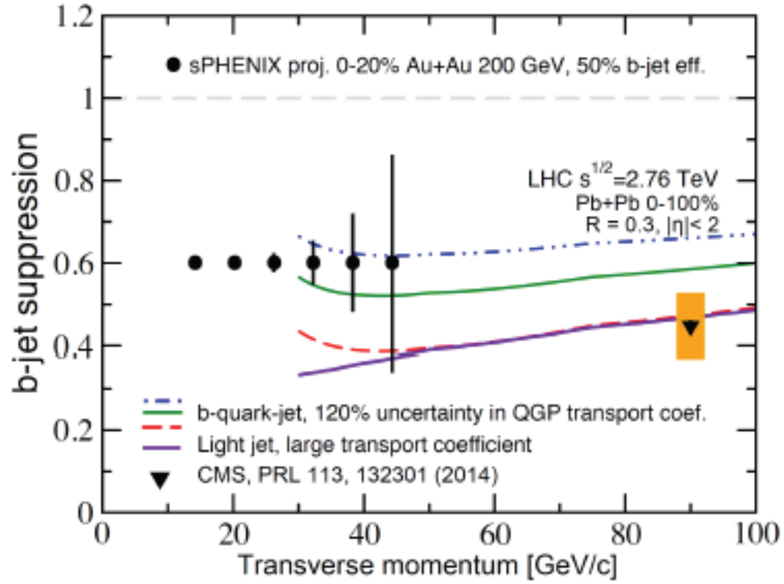
STAR: QM17





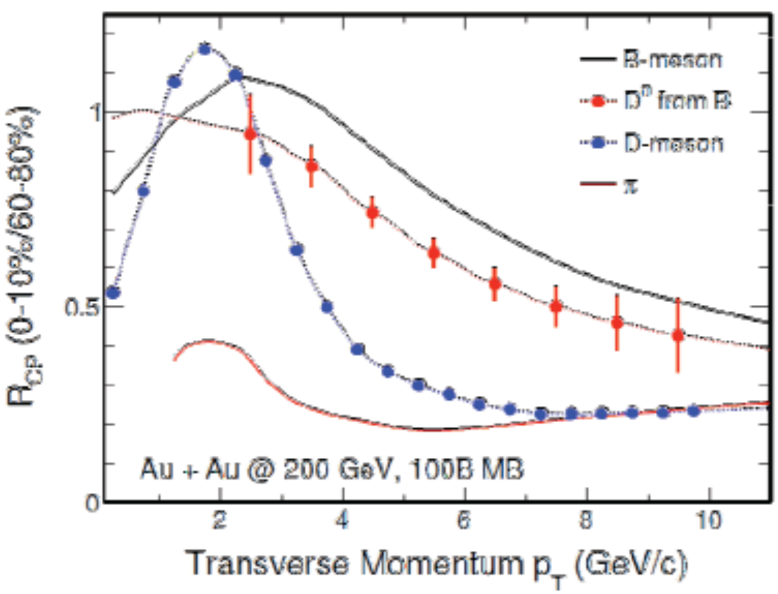
Money Plots for MVTX

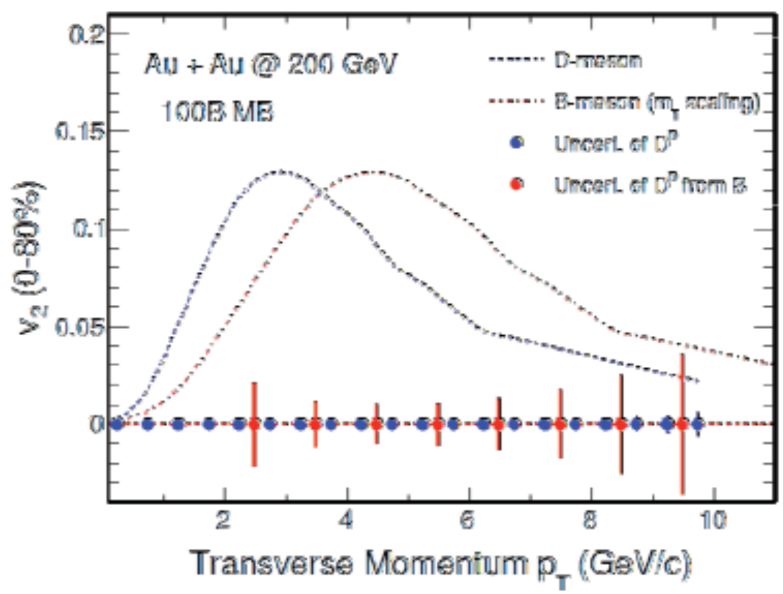
X. Dong



Open bottom production at midrapidity over a broad momentum region
- B-meson <15 GeV/c
- b-jet >15 GeV/c

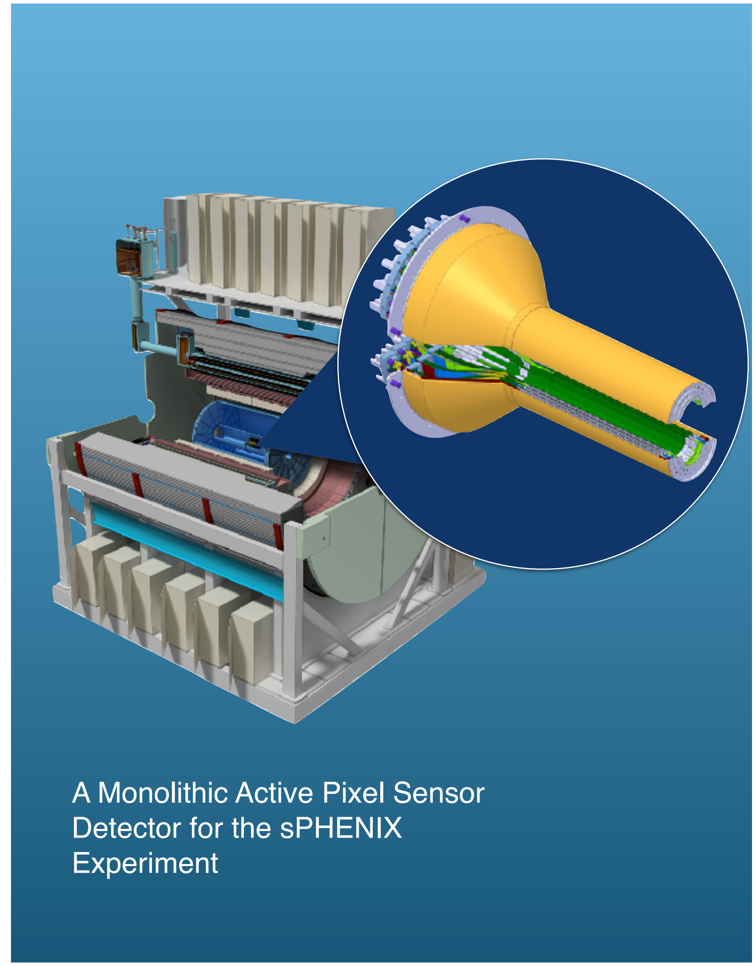
vs. LHC
- Complementarity - different QGP media
- Uniqueness - less gluon splitting



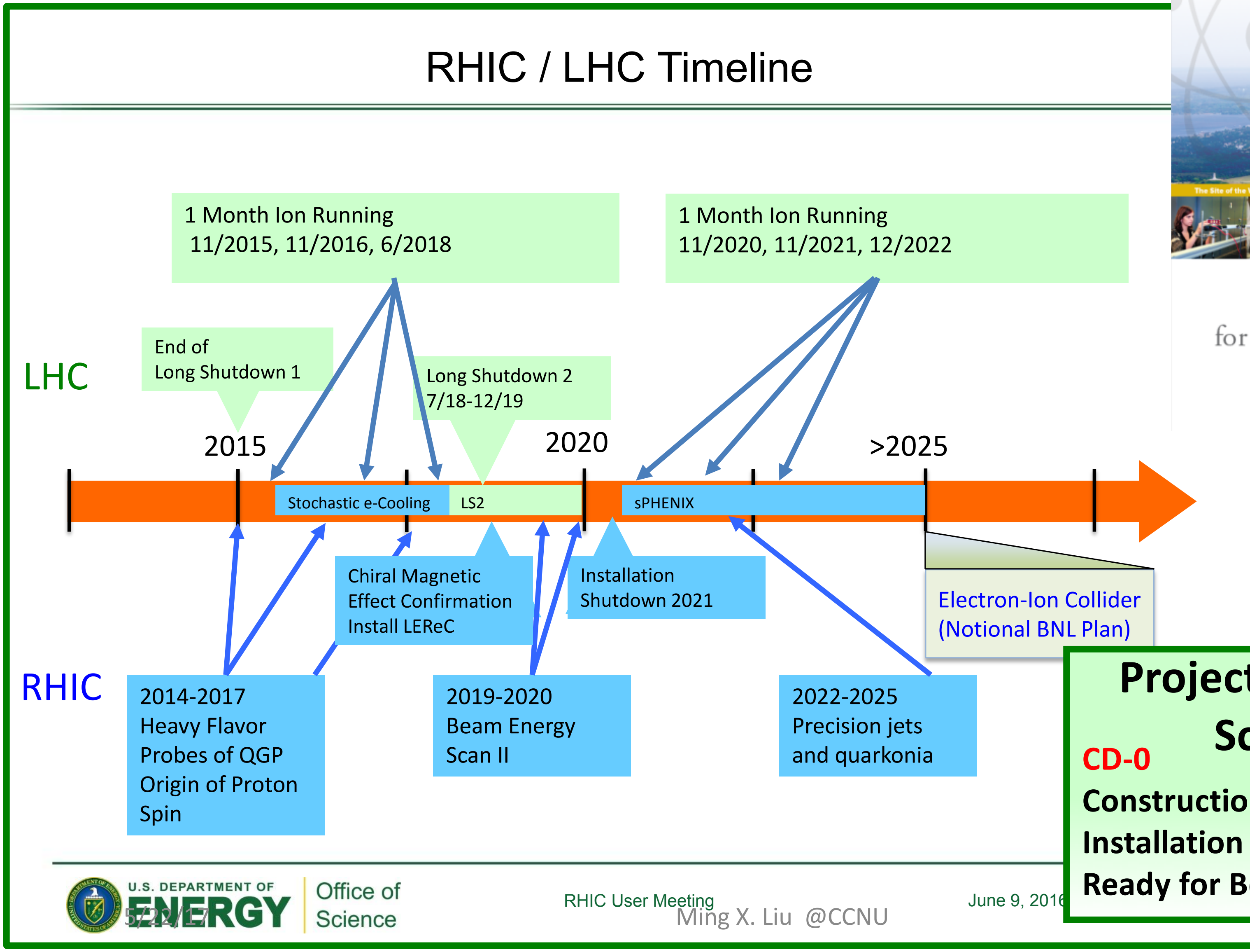


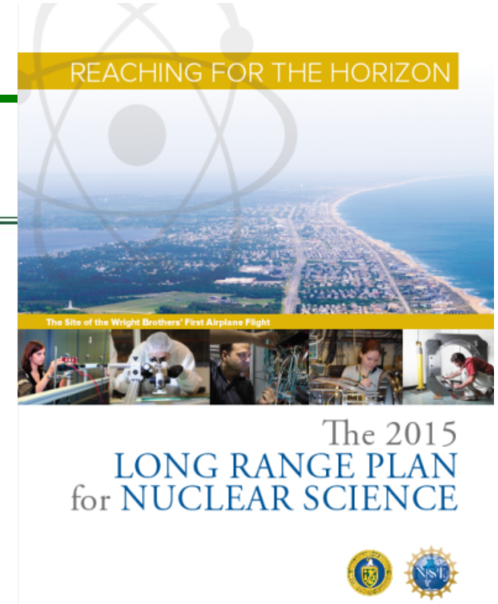
MVTX Project Status and Plan

- Pre-proposal submitted to DOE, 2/2017
  - Follow-up discussions with DOE and BNL managers
- Plan to update proposal to DOE, late 2017
  - Expanded science "CD0" + Cost & Schedule "CD1"
  - Funding in FY18, stave production @CERN in Aug. 2018+, ~6 months;
  - Other options being explored for stave production @CERN/CCNU for delayed ALICE/ITS or funding
- BNL Director's Review July 10-11, 2017
  - Expanded science "CD0" + Cost & Schedule "CD1"
- System integration R&D
  - Readout
  - Mechanical support



Outlook





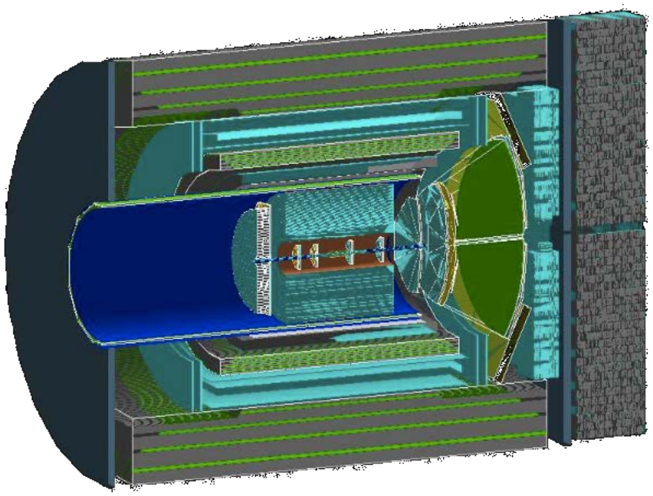
Projected sPHENIX Schedule

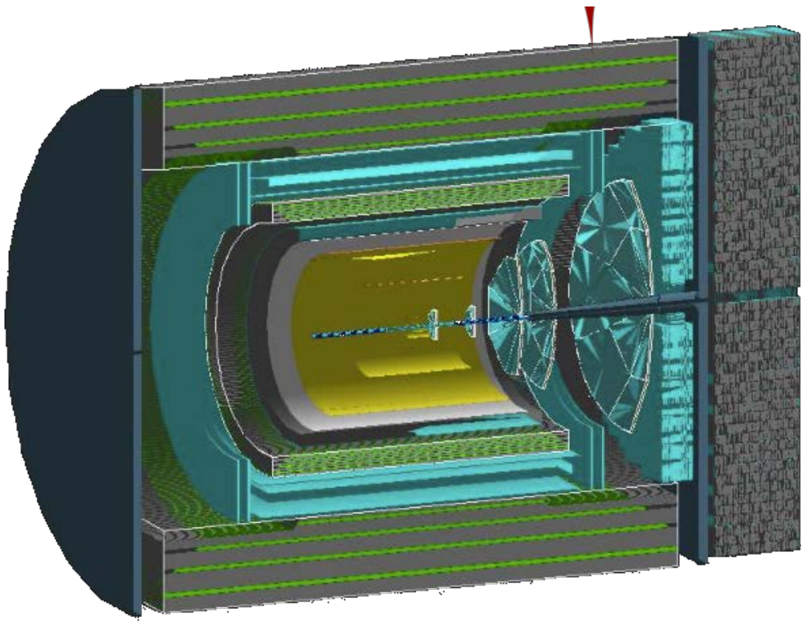
CD-0	9/2016
Construction Phase	Jul 2018
Installation complete	Apr 2021
Ready for Beam	Jan 2022

Forward s/ePHENIX

- **Partonic structure of the proton**
- **Low-x and Saturation**
- **Spin-momentum correlations**
- **Diffraction**
- **Hadronization in e+A**

Cold QCD at EIC





sPHENIX era Cold QCD

- Transverse spin phenomena
- Collective behavior in small systems
- Pre-equilibrium QGP
- CNM physics in p+A

Summary

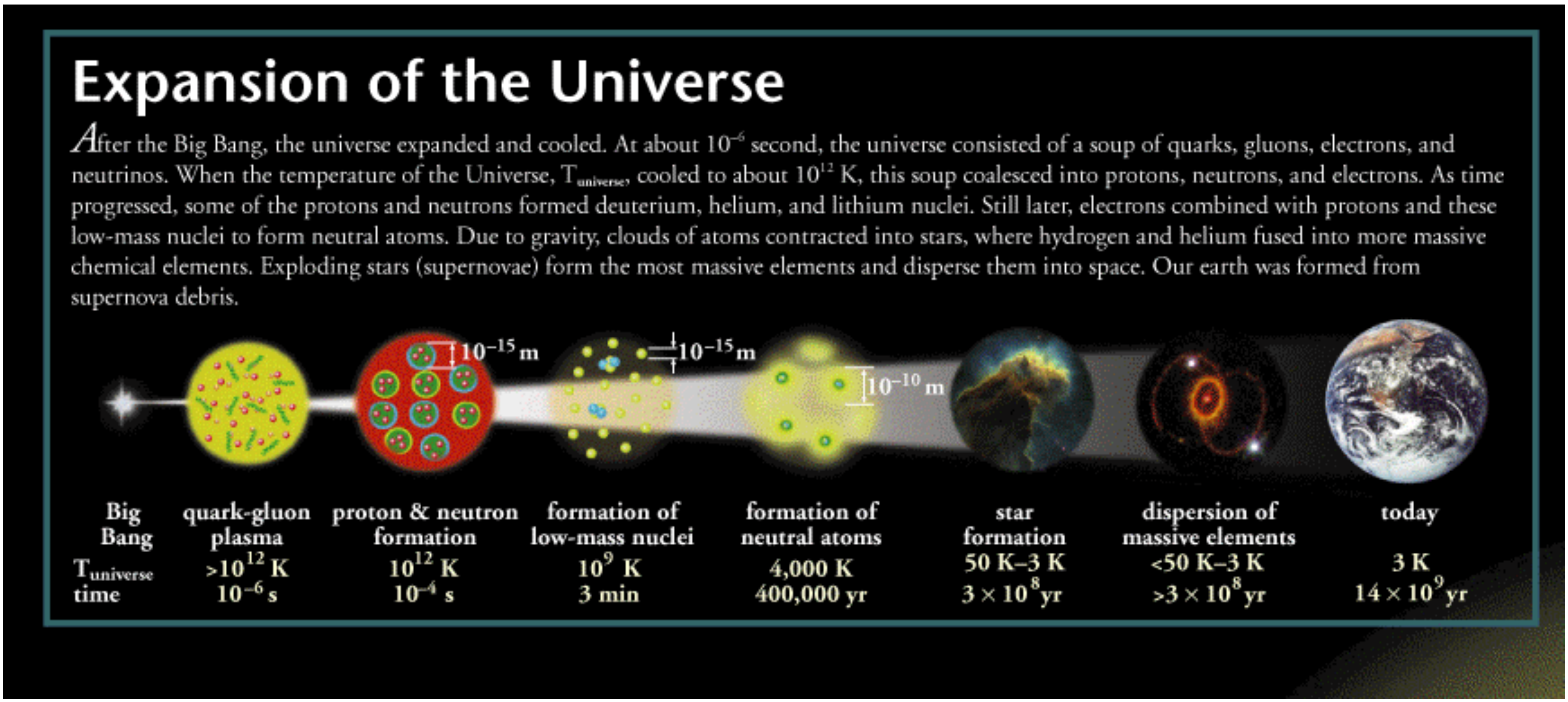
- sPHENIX obtained CD-0 and working toward next stage
  - Topical groups studying the physics goals
    - Jet structure
    - HF jets
    - Heavy quarkonia
    - Cold QCD, spin, saturation
- Tracking defined:
  - MVTX, INTT, TPC
- Beam tests of calorimeter system
  - Calorimeter performance within sPHENIX requirements
  - Simulation reproduces the data very well
- Active collaboration with lots to do:
  - https://www.facebook.com/sPHENIX.Experiment/
  - Looking forward to data in 2022

- 62 institutions, 235 collaborators & growing
- 3rd Collaboration Meeting @ GSU Dec 2016

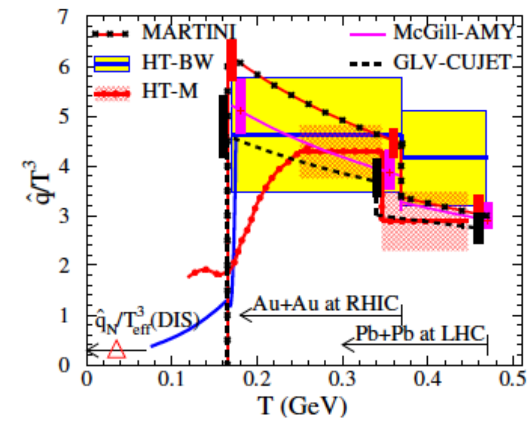
Please join us for the exciting journey!

Backup slides

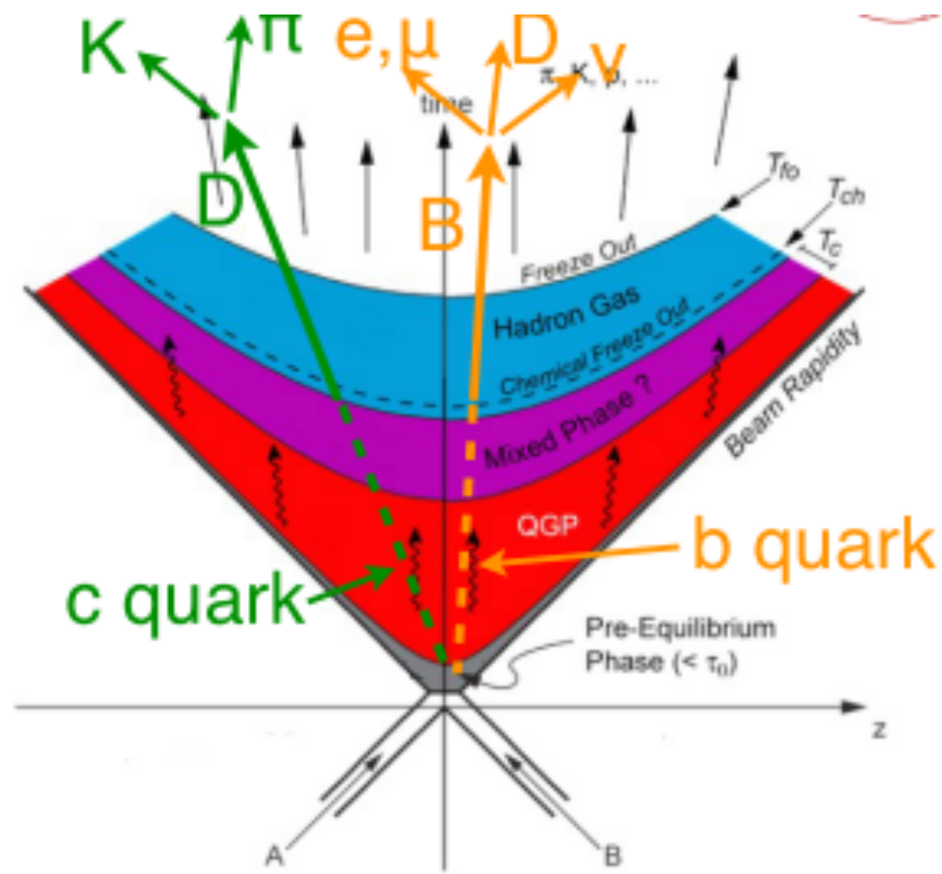
Big Bang and Early Universe



B Physics @sPHENIX

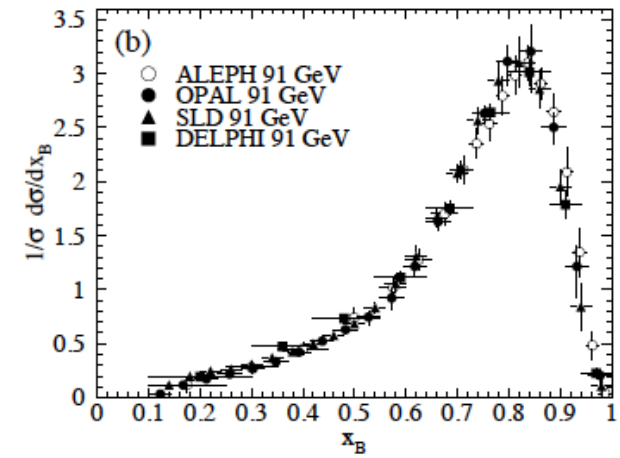


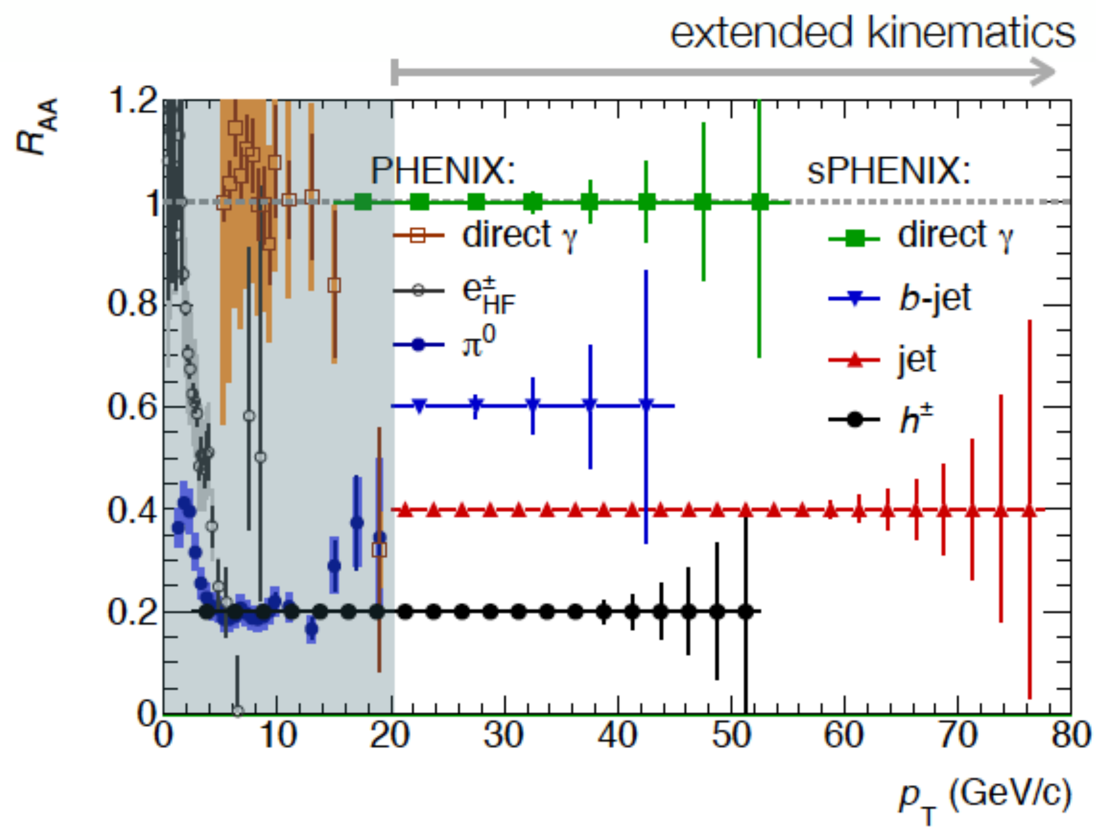
- RHIC physics reach
  - PHENIX
  - STAR
- D physics well covered by RHIC and LHC/ALICE
  - What we learned
  - Desires B measurements at low pT
- sPHENIX opportunity
  - Precision B and b-jet measurements
  - Upsilons



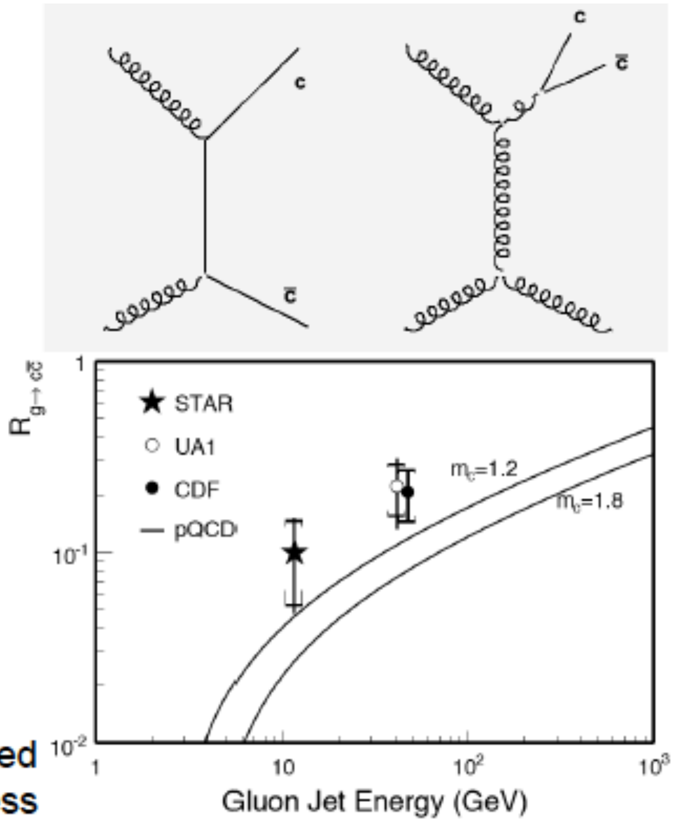
sPHENIX Coverage

- Low pT B mesons?
  - 0<pT<20GeV
  - Currently limited at both RHIC/LHC to
    - B->J/Psi + X
    - B->leptons + X
- Inclusive B measurements
  - R_{AA}
  - V_2
  - Correlations
- B-Jet in A+A
  - <Z> ~ 0.8 in p+p
  - pT_Jet >~20GeV





Theory Predictions



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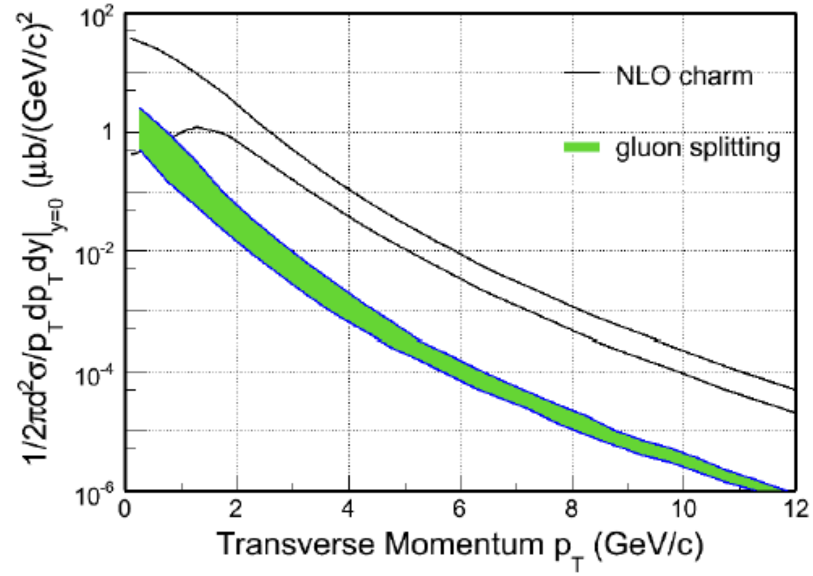
STAR PRD79 (2009) 112006



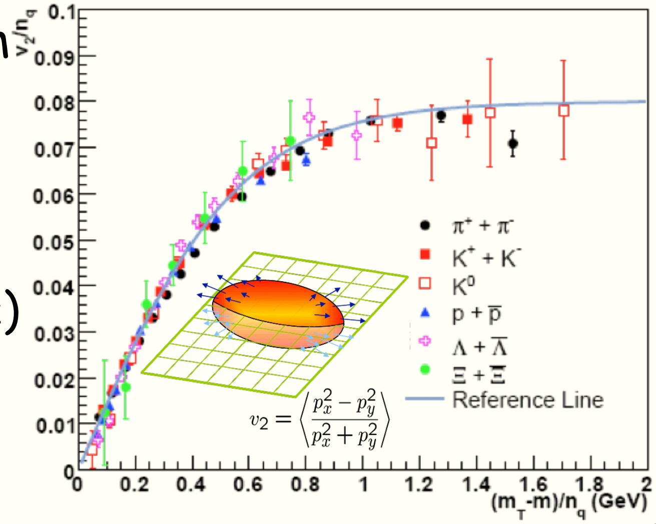
Charm production in jets at p_T ~ 2-10 GeV/c has a small contribution from gluon splitting and is dominated by jets initiated by charm quarks

What we observed so far:sQGP

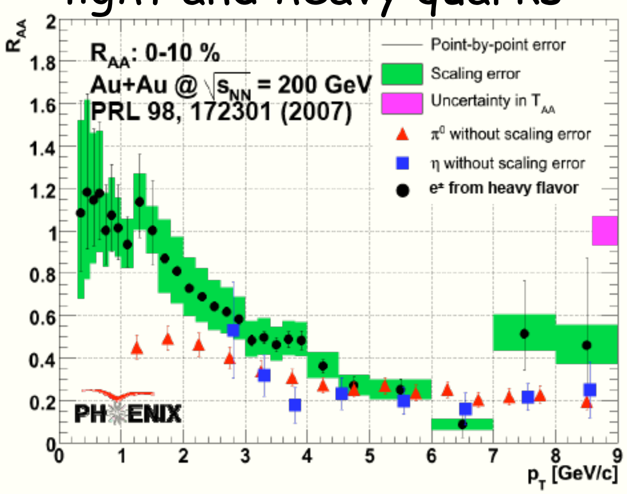
partonic degrees of freedom

Hydro calculations which reproduce v2 of hadrons indicate:

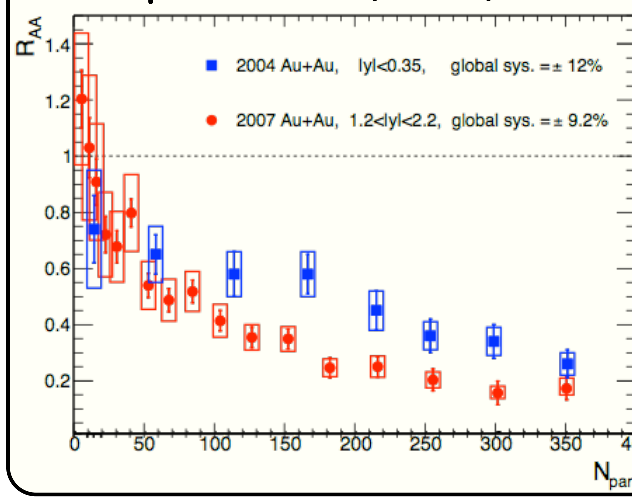
- rapid thermalization (<1fm/c)
- formation of a strongly interacting medium



strong energy loss of light and heavy quarks



suppression of heavy quarkonia (J/ψ)

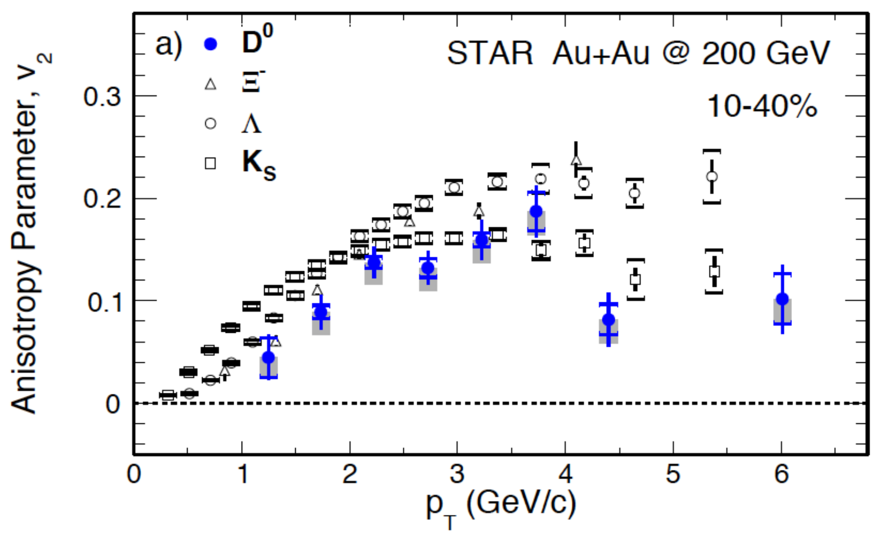


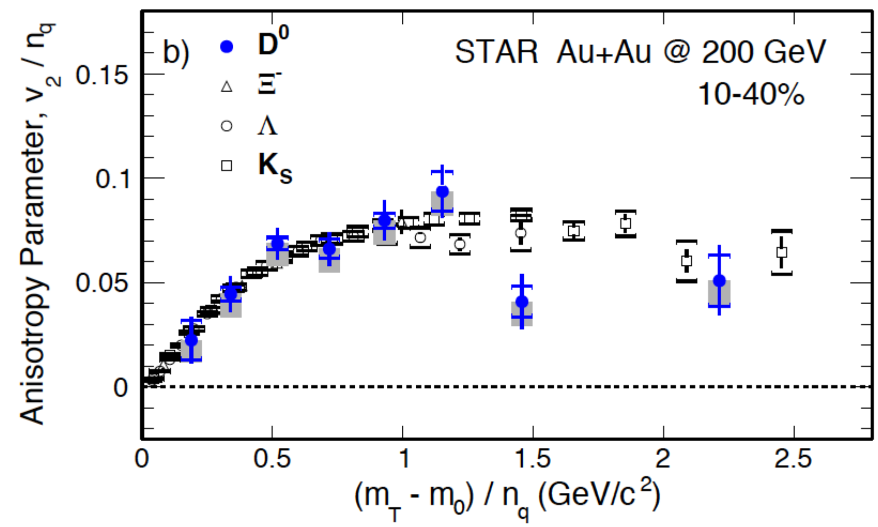
Elliptic Flow of D^0 in 10-40%

STAR

Liang He, Tue 17:10

Mass ordering **NCQ scaling**





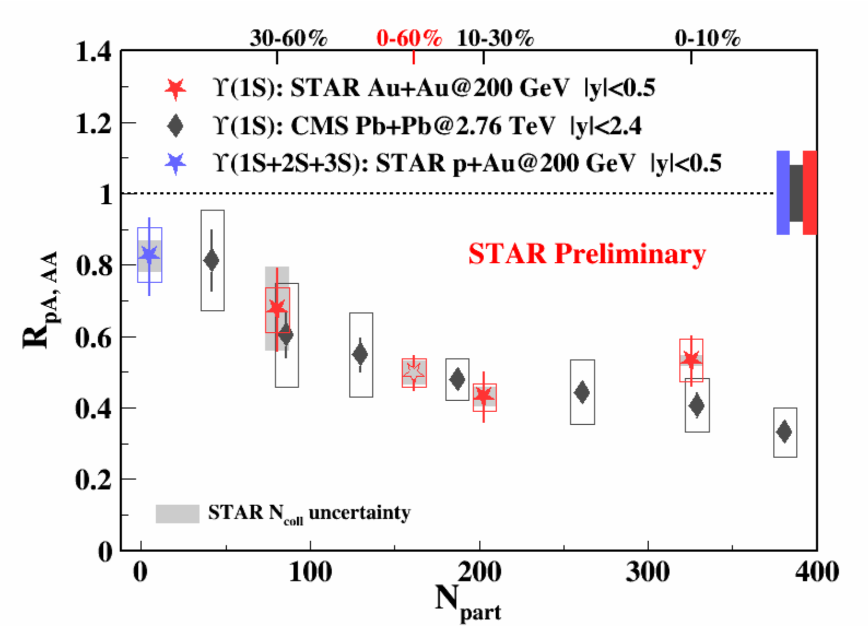
- D^0 v_2 for 10-40% follows mass ordering and NCQ scaling of other hadrons
  → Evidence for thermalization of charmed mesons

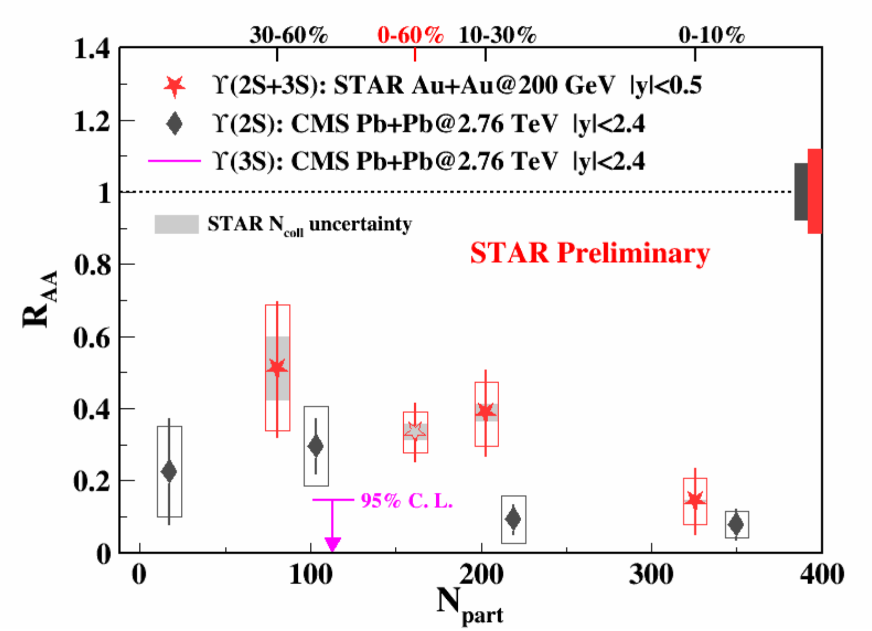
Submitted
arXiv:1701.06060

* Whole 2014 HFT data from second pass of production

Upsilon Production

QM17, Zaochen Ye



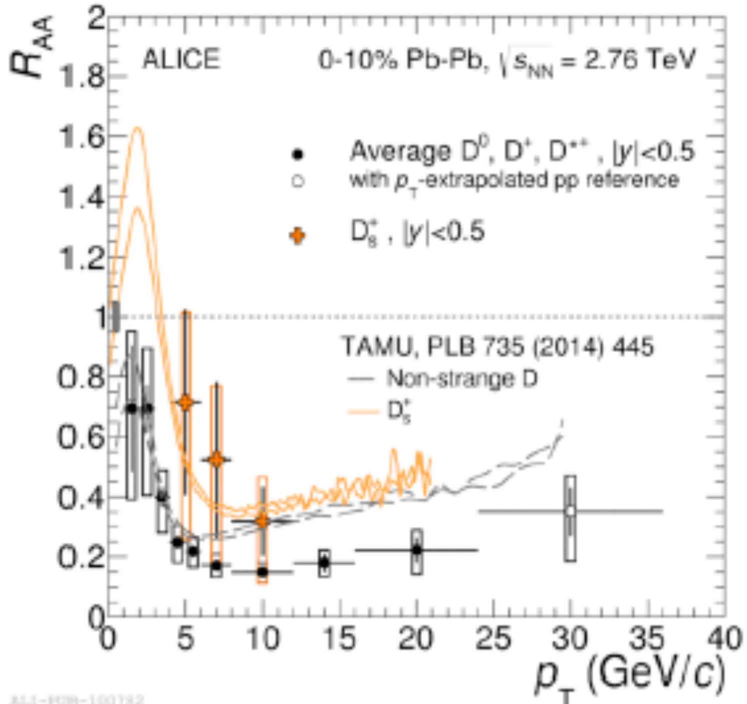


- Indication for more suppression towards more central collisions
- In central collisions ϒ(2S+3S) is more suppressed than ϒ(1S)
  → sequential melting
- Indication for less suppression than at LHC for ϒ(2S+3S)

ALICE

D-meson R_{AA}

$$R_{AA}^{D}(p_T) = \frac{dN_{AA}^{D}/dp_T}{\langle T_{AA}\rangle \times d\sigma_{pp}^{D}/dp_T}$$



ALICE:
arXiv:1509.06888
arXiv:1509.07287

Large suppression in a wide p_T range:

- factor of 4-5 in 5<p_T<15 GeV/*c*

D_s in Pb-Pb collisions:

- suppression by a factor 3-5 in 8-12 GeV/*c*
- low-p_T R_{AA} described by TAMU model based on on heavy-quark diffusion and hadronization via recombination

TAMU, Phys. Lett. B 735 (2014) 445

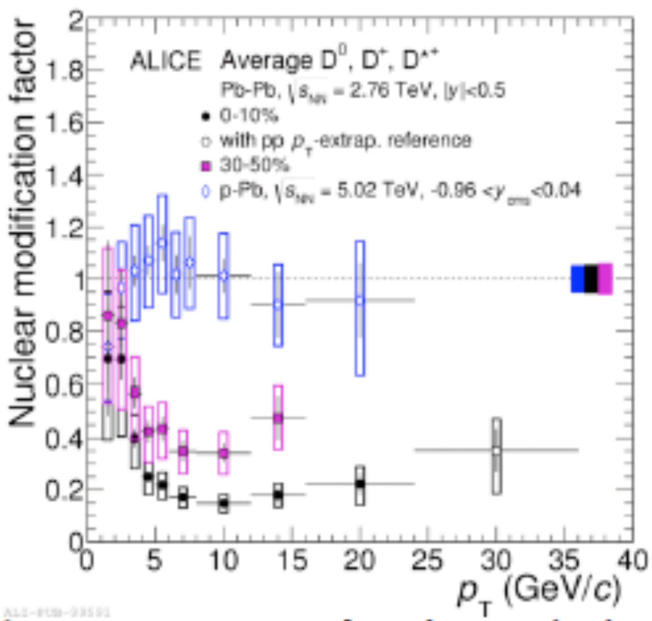
- more statistics needed to conclude on possible enhancement at low p_T due to c-quark recombination with strange quarks

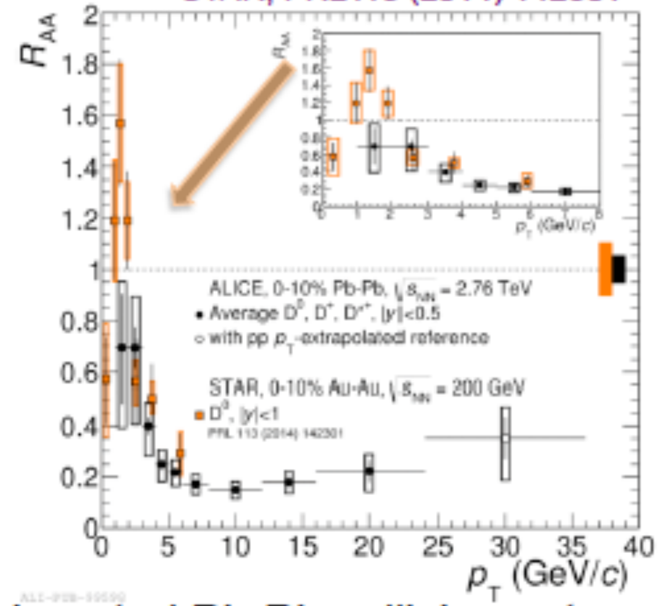
Kuznetsova, Rafelski, EPJ C51(2007)113
He et al., arXiv:1204.4442;
Andronic et al., arXiv:0708.1488

Strong charm energy loss in the medium

D-meson R_{AA}

ALICE:
arXiv:1509.06888
arXiv:1509.07287
STAR, PRL113 (2014) 142301





Strong suppression in central and semi-central Pb-Pb collisions at intermediate-high p_T **due to final-state effects** (R_{pPb}~1)

D mesons at RHIC vs LHC: different R_{AA} trend for p_T<2 GeV/c?

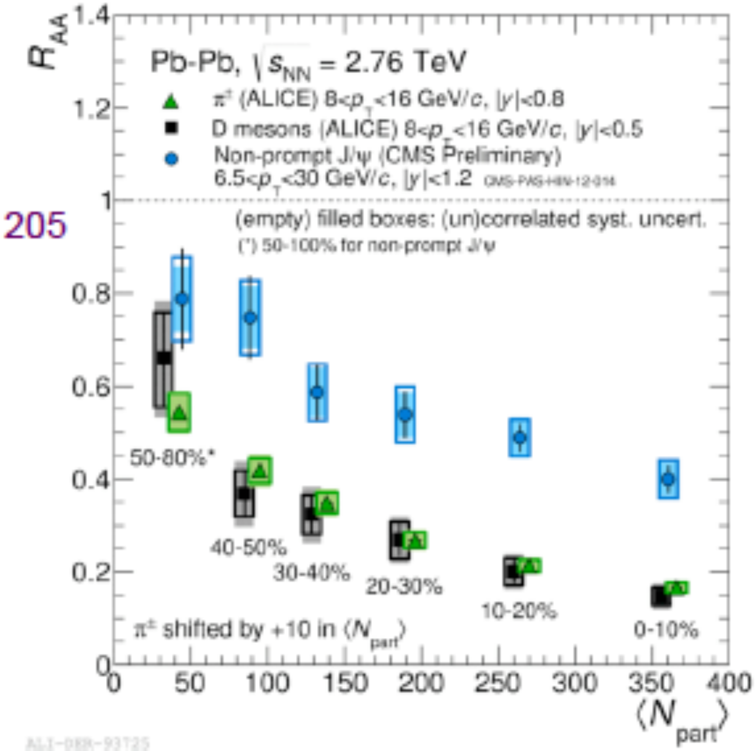
Stronger shadowing, less steep pp spectrum at LHC, different effect of radial flow and coalescence. Some models (TAMU, Phys. Lett. B 735 (2014) 445) can describe both results.

Low-p_T measurements crucial to test binary scaling in charm production

R_{AA}: D mesons and non-prompt J/ψ

Mass dependence of energy loss?

ALICE, JHEP 1511 (2015) 205
CMS, PAS-HIN-12-014

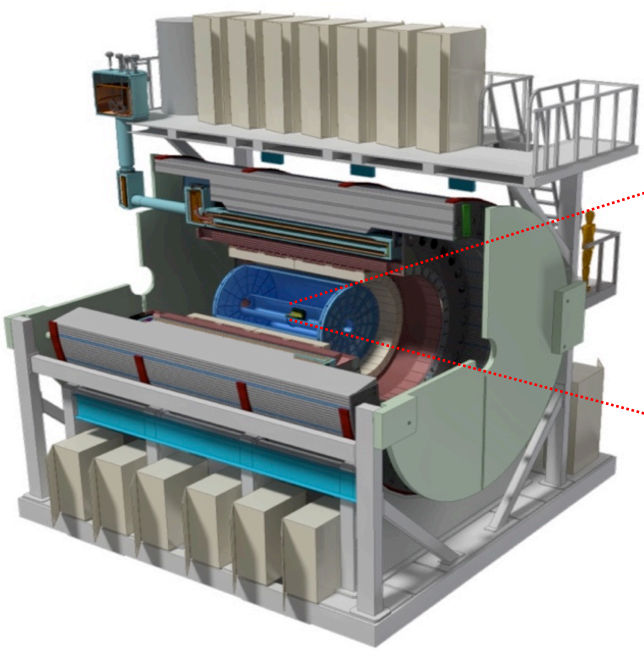


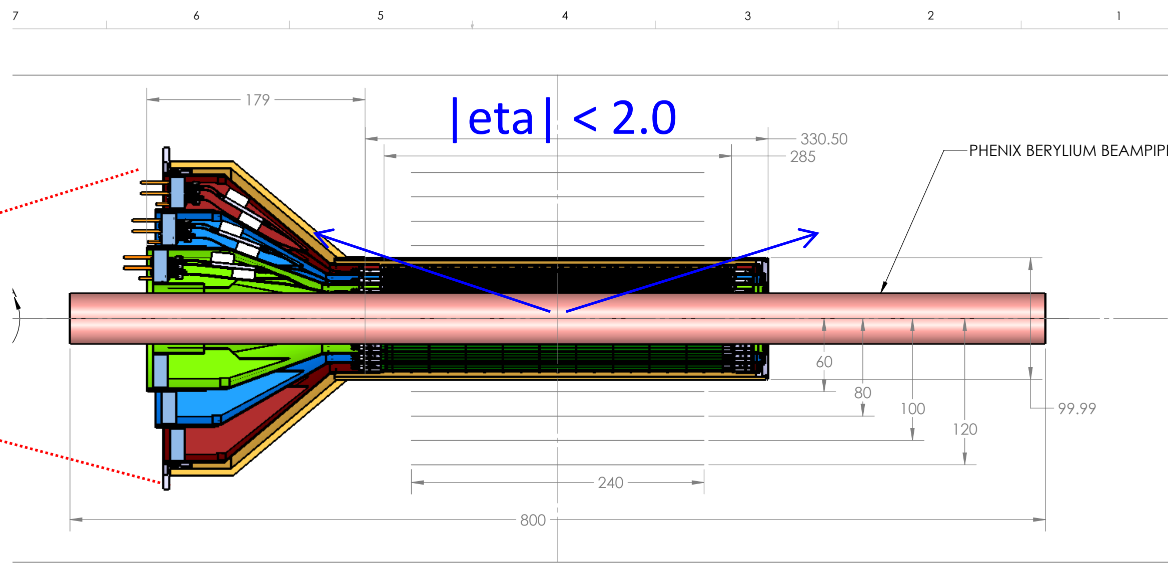
D: pT > 8GeV
B->J/Psi: pT > 6.5GeV

similar kinematics for D and B mesons (**<p_T>~10 GeV/c**)
different y ranges for D and non-prompt J/ψ

Indication of a difference between charm and beauty suppression in central collisions

MAPS-based Vertex Detector (MVTX)





R = 2.4; 3.2; 3.9cm;
L = 27.1cm

- "Adopt" ALICE ITS Upgrade Inner Barrel 3-layer MAPS detector
  - Mini. risk, Max. Physics
- Precision vertexing for b-jet/B-hadron tagging with high efficiency and high purity
- B-jet modification in QGP at low-medium pT to determine QGP properties, study mass-dependence on collisional vs radiative energy loss, flow etc.
- A separate DOE MIE to build the full detector, WBS 1.12, ~$5M for construction;
- Early R&D by LANL/LDRD, $5M, FY17-19, readout and mechanical integration;

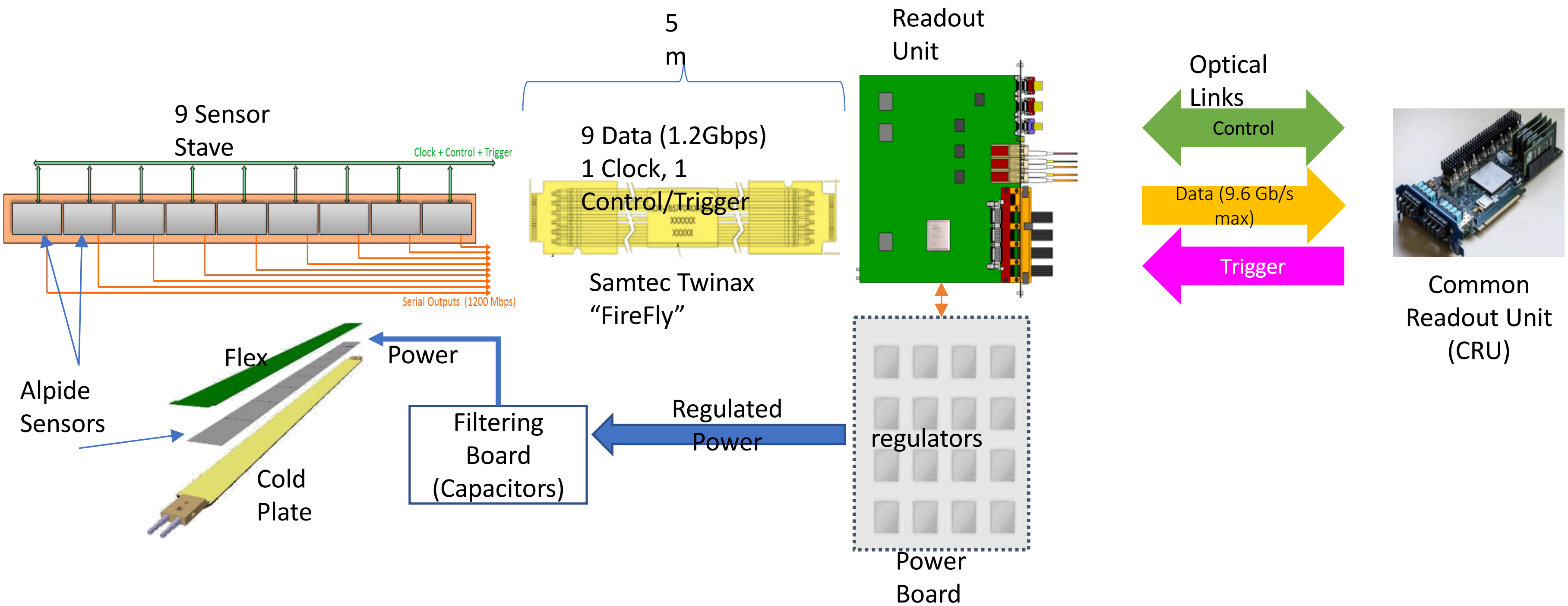
Scope of the MVTX Project

- MAPS staves & Electronics
  - MAPS Detectors
    - “MoU” to build 68 ITS MAPS staves
    - No modification
  - Readout Electronics
    - Use ALICE/ITS, RU + CRU
    - Modify/reprogram CRU for sPHENIX
      - Plan-B: build a custom board to convert ALICE/ITS into sPHENIX DAQ format; BNL FILEX etc.
    - R&D by LANL LDRD
  - Production
    - Extend ALICE/ITS MAPS stave production
    - sPHENIX personnel help assembly and testing staves at CERN
    - Reproduce additional ALICE RU+CRU for sPHENIX
    - Final assembly and test in US/LBNL
  - Ancillary systems, copy ALICE
    - LV, cables, crates, racks etc.
    - Slow control, safety and monitoring

- Mechanics & Cooling
  - No/(some) changes to ALICE/ITS inner tracker mechanical structures
    - End Wheels
    - Cylindrical structure shells
    - Detector half barrels
    - Service half barrels
    - Detector and Service half barrels
    - Half support structures
  - Mechanical Integration
    - Conceptual design by LANL LDRD
    - Prototype by sPHENIX R&D
    - Design integration frames
    - Carbon frames etc.
    - Installation tooling etc.
  - Copy ALICE cooling plant design
    - Minor modification to fit sPHENIX
    - Smaller heat load than ALICE ITS
  - Metrology and Survey

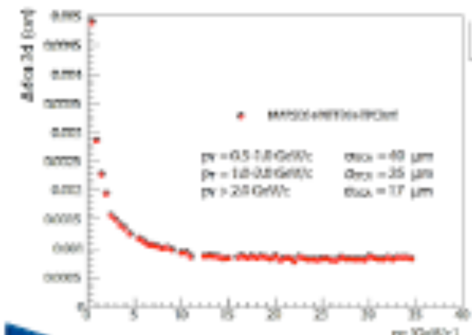
WBS 1.12: a new MIE fund the full MAPS Vertex Detector, ~$5M

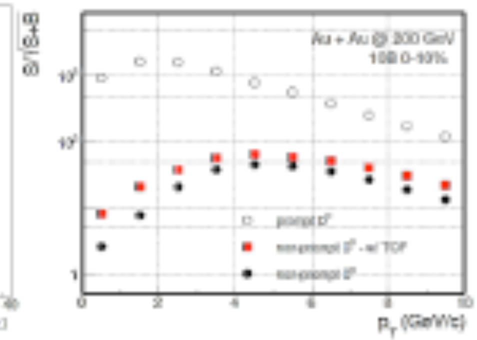
ITS Readout and Control System

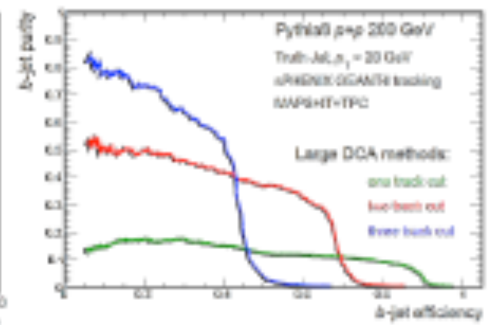


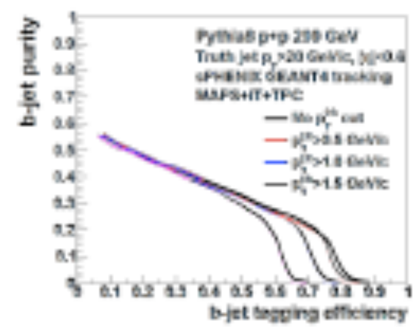
MVTX proposal TODO
Technical performances:

- Realistic implementation in Geant4
  - Completed: implement ladder structure in simulation – Tony F., Gaku M.
  - Completed : digitization of MAPS detector - Tony F.
  - By end Apr: Update tracking performance plots for MAPS, DCA and dp/p resolutiosn - Tony F.
  - By summer (?): complete the pile-up simulation framework – Mike M., Yorito Y.
- *b*-jet tagging algorithm
  - By summer, help needed : Investigating full-detector fast simulation for b-jet simulation. Look into general packages e.g. DELPHES.
  - By summer: Full calorimetry simulation with secondary vertexing tagger – Sanghoon L.
  - By summer: Full calorimetry simulation with high-DCA track counting – Haiwang Y.
  - It will be very useful to use new in-development pattern recognition software to bring back hit collection efficiency.









7 Organization and Collaboration

Here we discuss the current collaborating institutions and their focus areas. Based on their technical expertise and available resources, LANL, LBNL and MIT/Bates groups are leading the three major technical tasks of the project: 1) readout electronics integration; 2)carbon mechanical support frames production and 3) cooling and mechanical system integration, respectively.

Los Alamos National Lab (LANL) : Readout electronics and mechanics integration.

Lawrence Berkeley National Lab (LBNL) : Carbon structure, production, LV and HV power system, full detector assembly and test.

Brookhaven National Lab (BNL) : System integration and services, safety and monitoring.

Massachusetts Institute of Technology (MIT/Bates) : Mechanical system integration and cooling.

Massachusetts Institute of Technology (MIT) : Stave assembly and testing at CERN.

University of Texas at Austin (UT Austin) : MVTX readout electronics integration and testing.

University of Colorado : *b*-jet simulations and future hardware.

Iowa State University (ISU) : Detector assembly and testing, simulations.

Florida State University (FSU) : Offline and simulations.

University of New Mexico (UNM) : LV cabling & connectors.

New Mexico State University (NMSU) : Tracking algorithm and physics simulations.

Georgia State University (GSU) : Online software and trigger development.

University of California at Los Angeles (UCLA) : Simulation and readout testing.

University of California at Riverside (UCR) : Detector assembly and testing, simulations.

Yonsei University (Korea) : MAPS chips QA and readout, simulations

RIKEN/RBRC (Japan) : Mechanical integration, cooling, cabling, simulation, patter recognition.

Purdue: Detector assembly and testing, analysis. Silicon lab available.

Central China Normal University (CCNU/China): MAPS chip and stave test at CERN and/or CCNU.

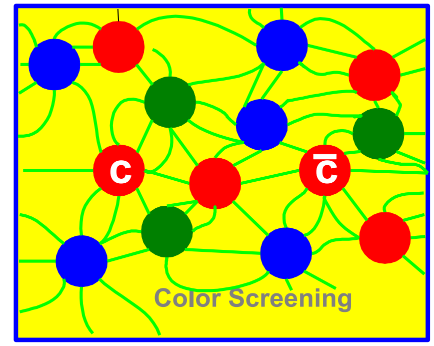
Univ. of Science and Technology of China (USTC/China): MAPS chip and stave test, simulations.

Potential new groups:

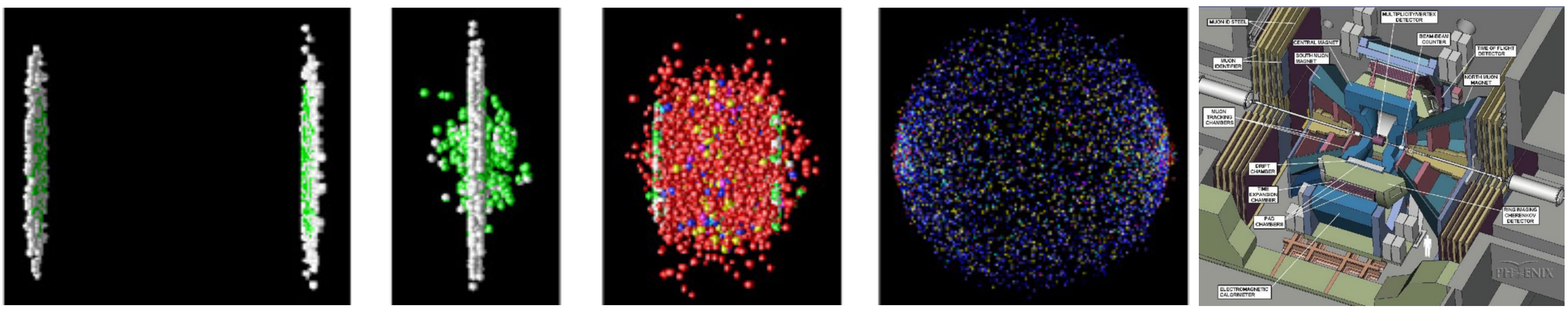
- Czech groups
- Peking Univ.
- CCNU – lab
- USTC

The Goals of Little Bang: QGP Physics

- Understand the Properties of QGP
- Explore the QCD phase diagram

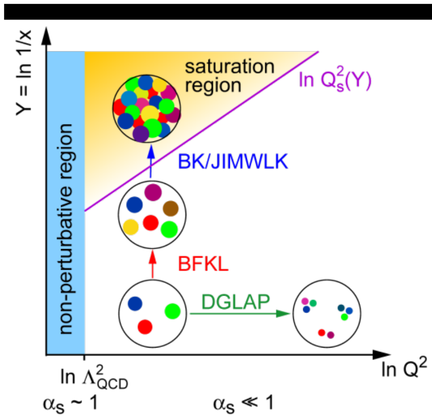


- Before collision
- Initial state CNM effects
- QGP
- Hadron gas
- Hadrons detected



Heavy Ion Collision – Time Evolution

Time (fm/c)



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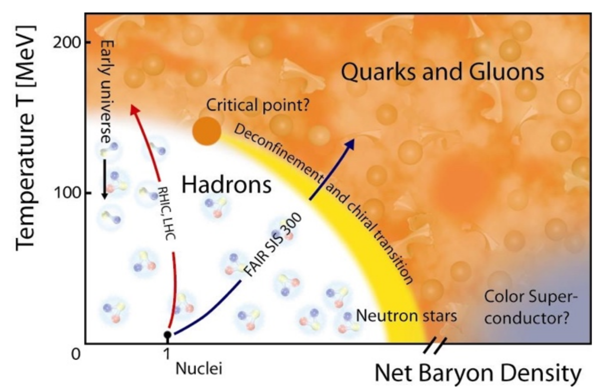
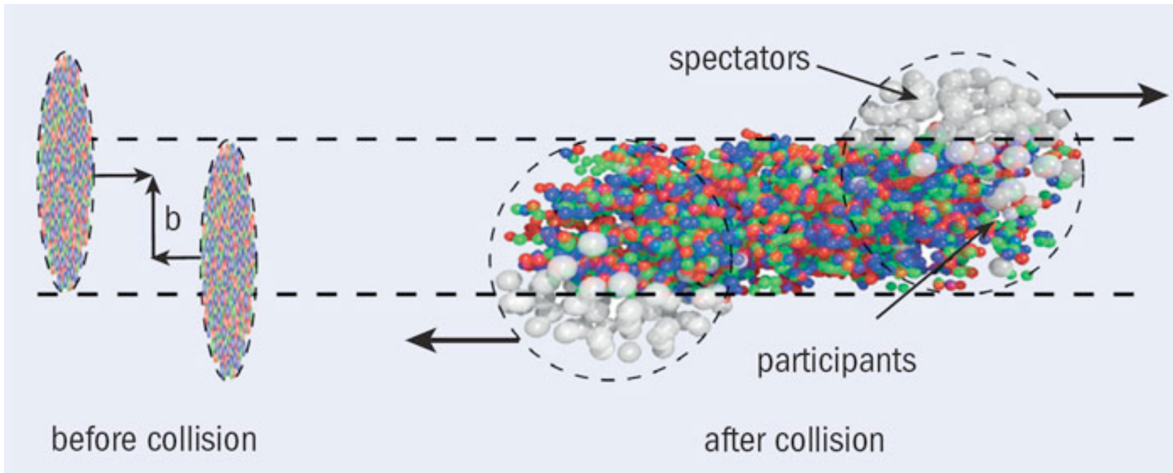
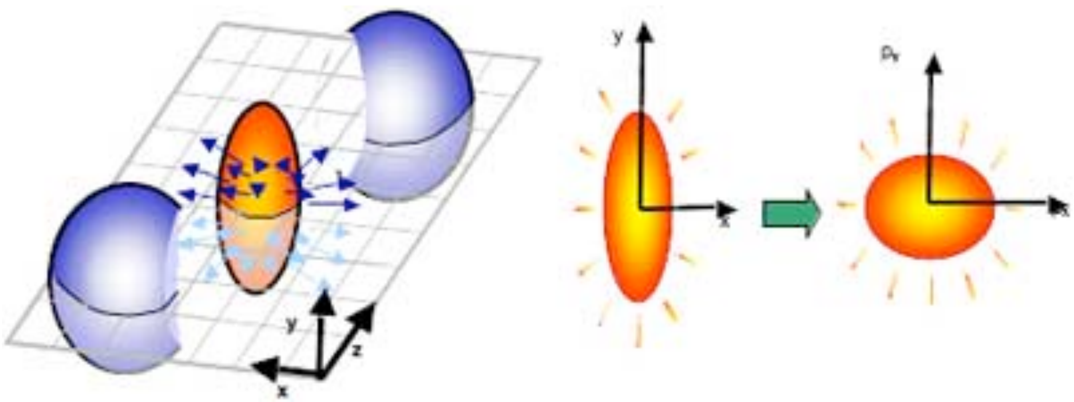
- Gluon saturation
- Parton shadowing
- CNM Parton energy loss

Ming X. Liu @CCNU



QGP Medium Behavior



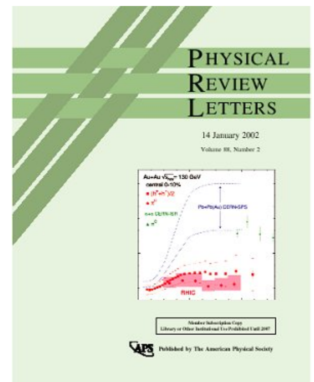


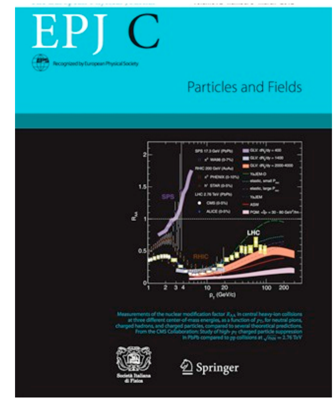
Anisotropic flow

$$\varepsilon = \frac{\langle y^2 - x^2 \rangle}{\langle y^2 + x^2 \rangle} \qquad v_2 = \langle \cos 2\varphi \rangle, \;\; \varphi = \tan^{-1}\left(\frac{p_y}{p_x}\right)$$

QGP Discovery @RHIC: 2004

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





- Unambiguous evidence for phase transition from ordinary nuclear matter to QGP (T~175 MeV, ~10^{12} degrees)
- Exhibits strong collective behavior, has huge stopping power for color-charged particles (quarks, gluons – the fundamental constituents)

Fundamental discovery:

QGP is not a weakly interacting gas of quarks and gluons, but rather a strongly coupled **near-perfect liquid!**