Highlights of Heavy Flavor Physics from PHENIX

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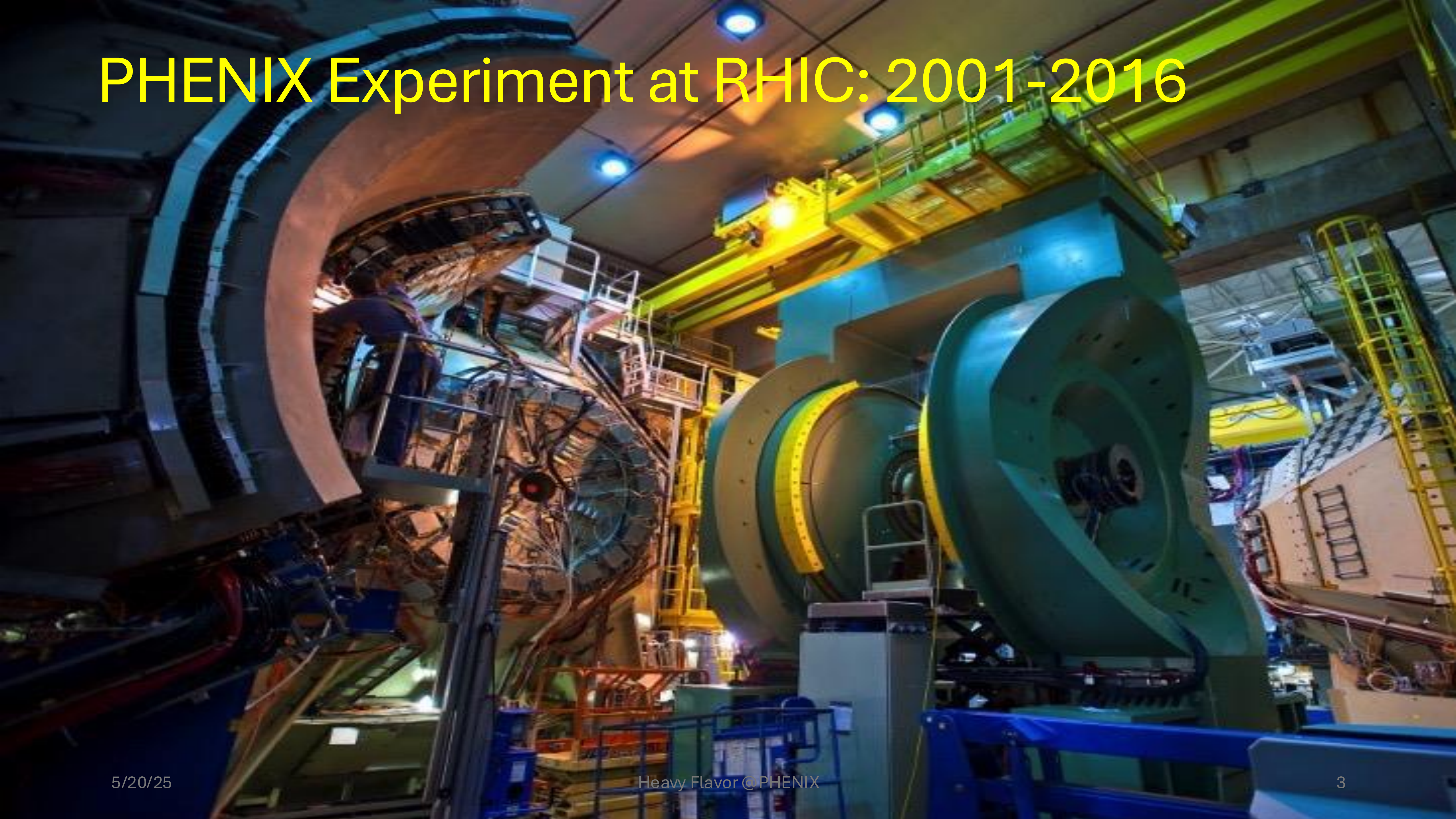
For the PHENIX Collaboration

RHIC/AGS Annual Users Meeting
05/20/2025

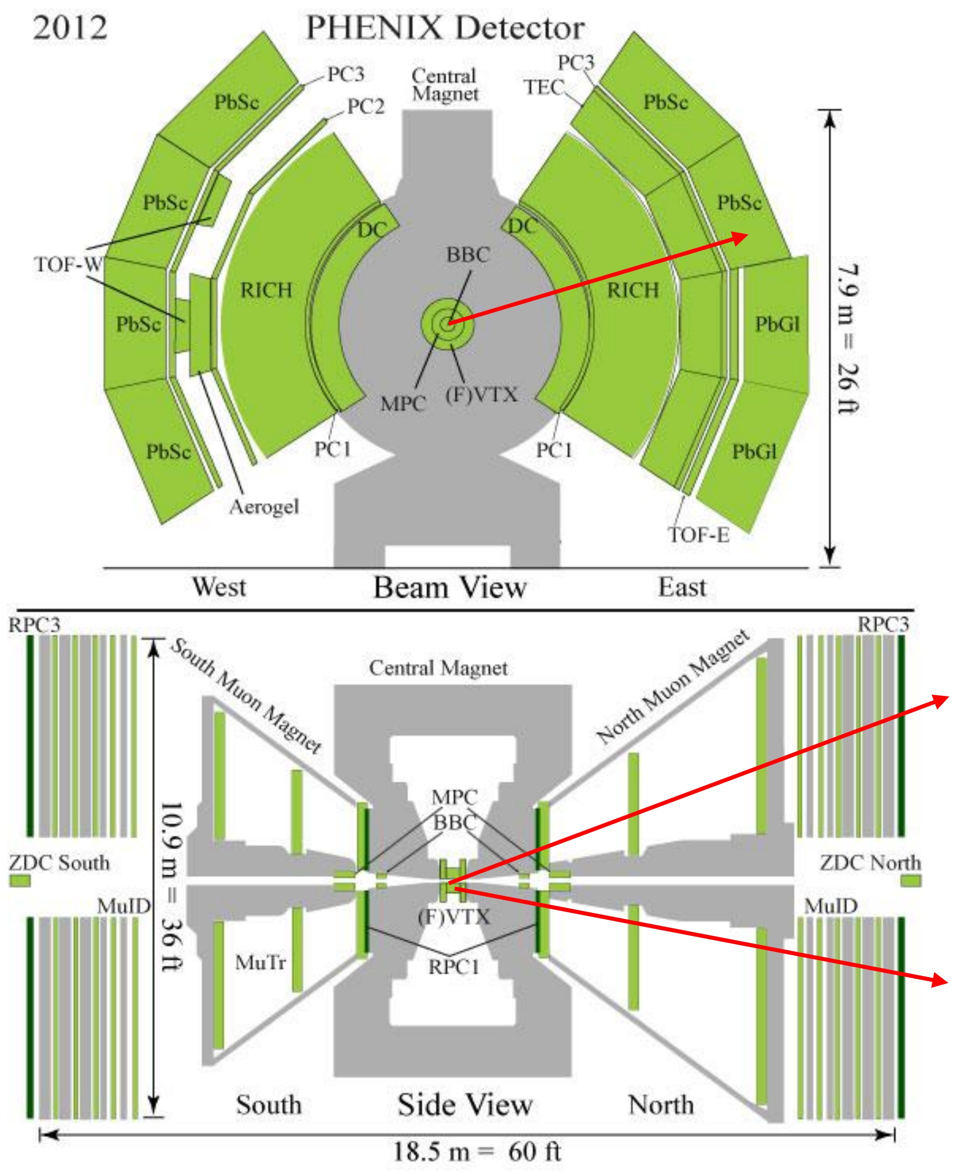
Outline

- Motivation & Introduction
- PHENIX Detector & Measurements
- Heavy Flavor in Heavy Ion
    - ➢QGP
    - ➢CNM
- Spin Physics with Heavy Flavor
    - ➢Gluon TMD
- Summary and Outlook

PHENIX Experiment at RHIC: 2001-2016



PHENIX Detector & Measurements



Central Arms | η | < 0.35
- Identified charged hadrons
- Neutral Pions/Etas
- Direct Photon
- J/ψ (e+e-)
- Heavy Flavor (VTX), e+/e-

Muon Arms 1.2 < | η | < 2.4
- J/ψ
- Unidentified charged hadrons
- Heavy Flavor (FVTX)

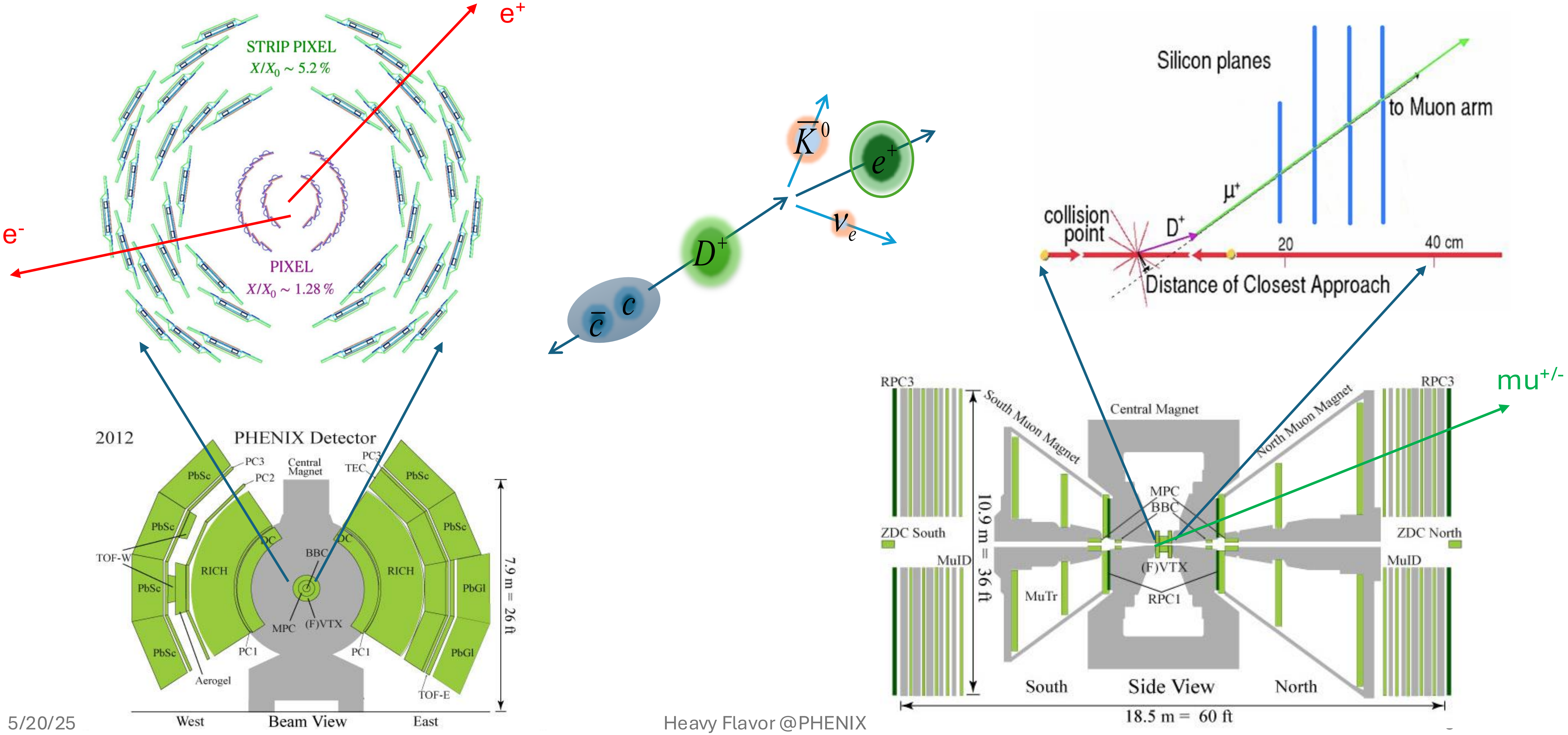
BBC/MPC 3.1 < | η | < 3.9
- Neutral Pion's, Eta's
- Charged particles

ZDC |η| ~ 5.9
- Neutrons

Electron ID:
- VTX
- Tracking
- RICH
- EMCal

Muon ID:
- FVTX
- MuTraker
- MuID

Silicon Detectors: SVT and FVTX



Broad Physics Topics being explored: HI, Spin to BSM

- continue producing high impact physics beyond 2016

Disentangling centrality bias and final-state effects in the production of high-p_T neutral pions using direct photons in $d+$Au collisions at $\sqrt{s_{NN}} = 200$ GeV Phys. Rev. Lett. 134, 022302 (2025)

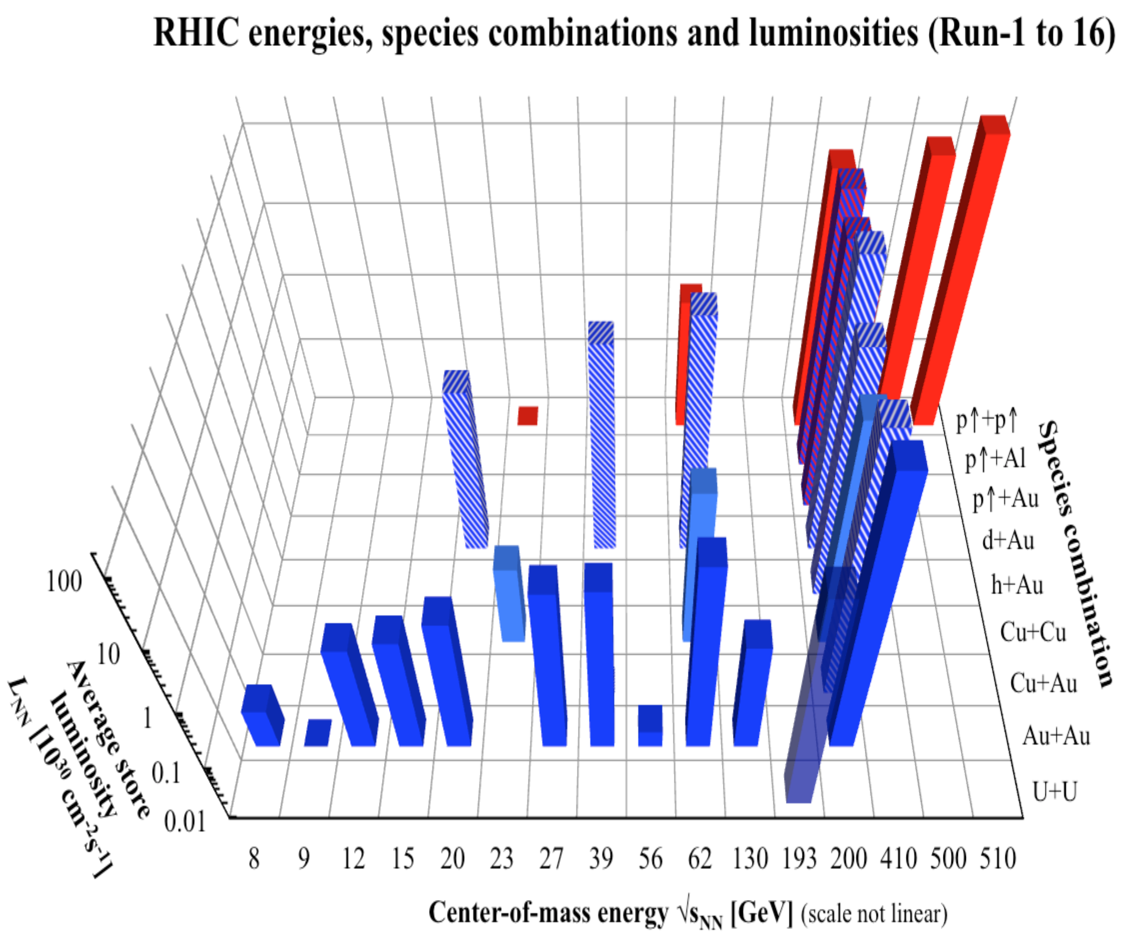
Charm- and bottom-quark production in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV Phys. Rev. C 109, 044907 (2024)

Measurements at forward rapidity of elliptic flow of charged hadrons and open-heavy flavor muons in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV arXiv:2409.12715

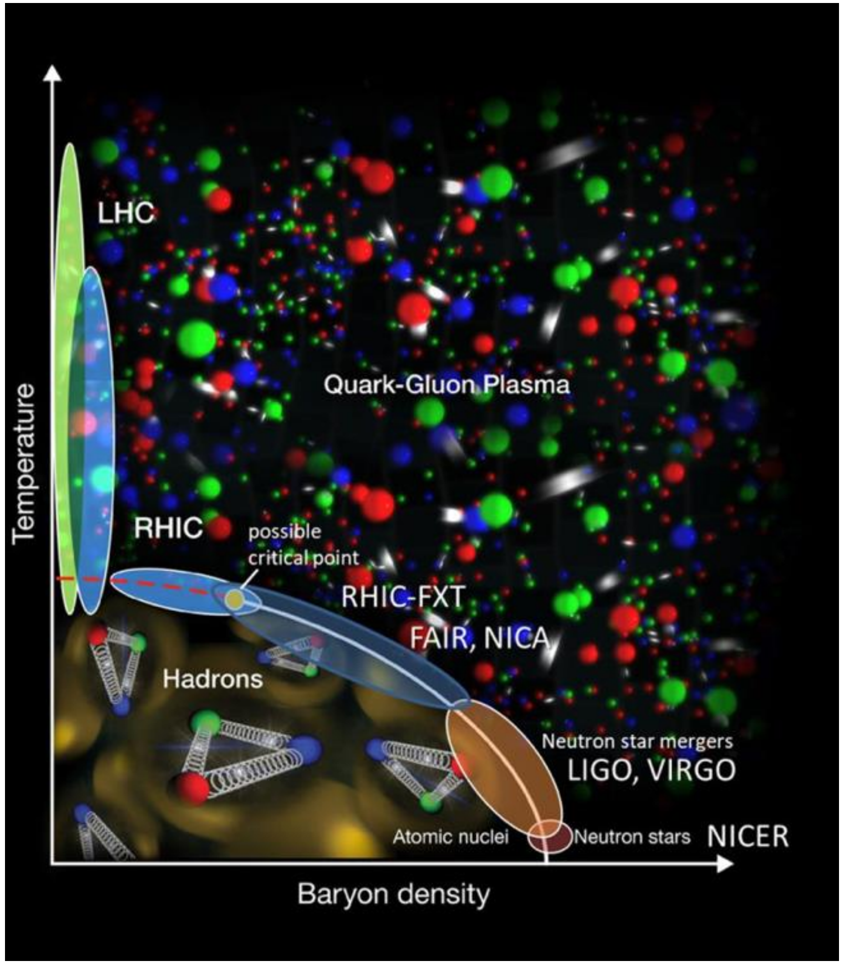
Measurement of elliptic flow J/ψ in $\sqrt{s_{NN}} = 200$ GeV Au+Au collisions at forward rapidity arXiv:2409.12756

Multiplicity dependent J/ψ and ψ(2S) production at forward and backward rapidity in in $p+p$ collisions at $\sqrt{s} = 200$ GeV arXiv:2409.03728

HF Physics



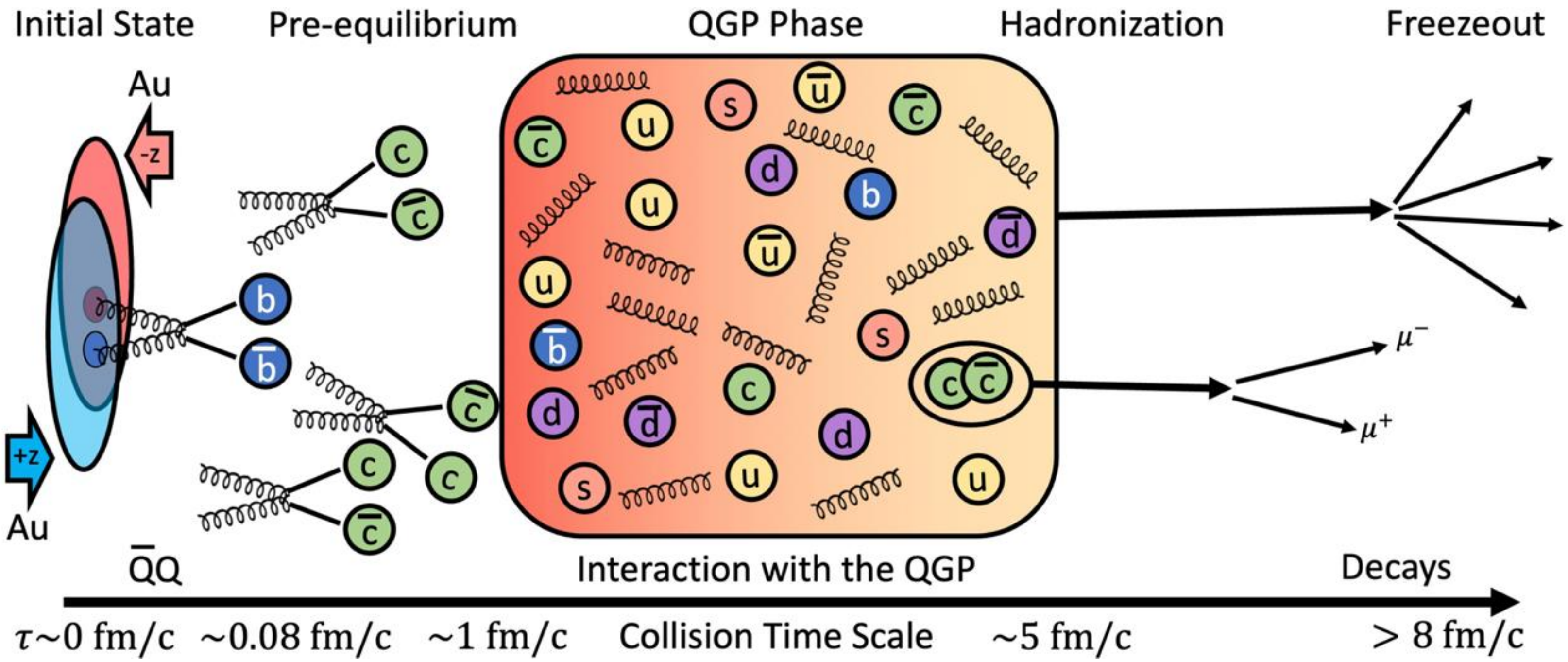
Heavy Flavor in Heavy Ion



Key questions:

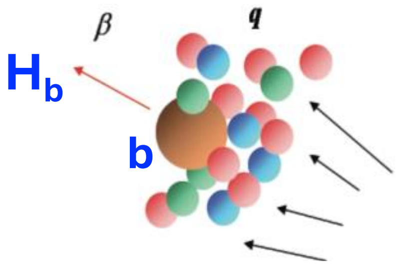
1. QGP properties and dynamics
   - Density, temperature viscosity, energy loss
   - Color screening
2. QGP evolution and hadronization
3. CNM contributions

Velkovska, HP2024

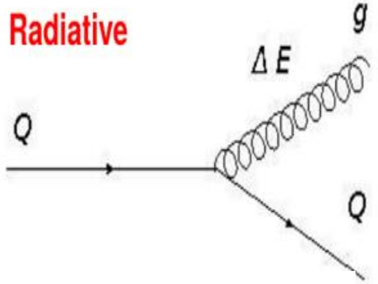


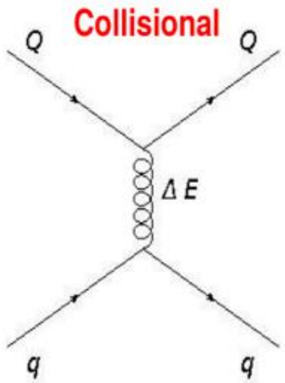
Nuclear Modification Factor R_{AA}

- Mass dependence of dE/dx

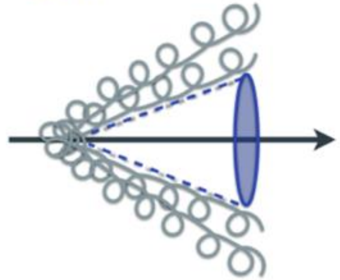


$$R_{AA}(pt) = \frac{\frac{dN_{AA}}{dp_T}}{\langle N_{coll}\rangle \frac{dN_{pp}}{dp_T}}$$





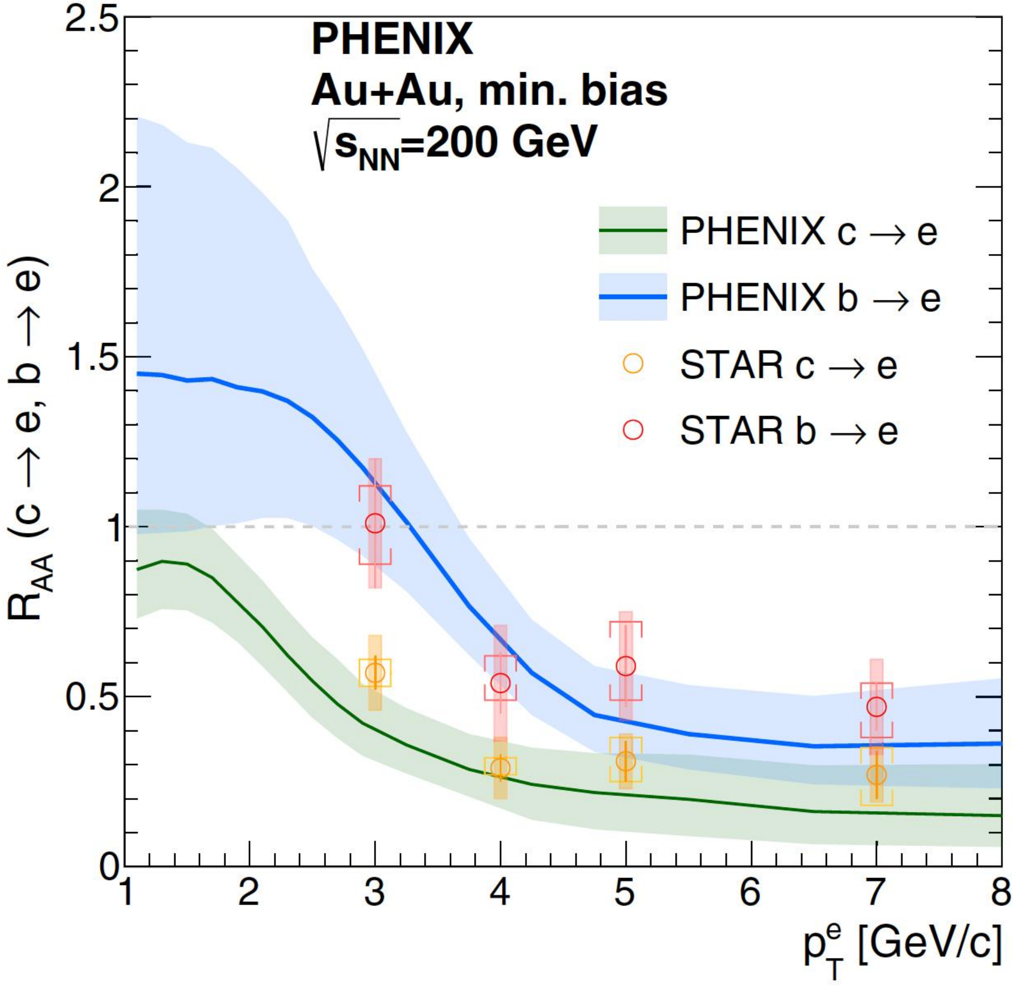
large parton mass



Less dE/dx for heavy quarks

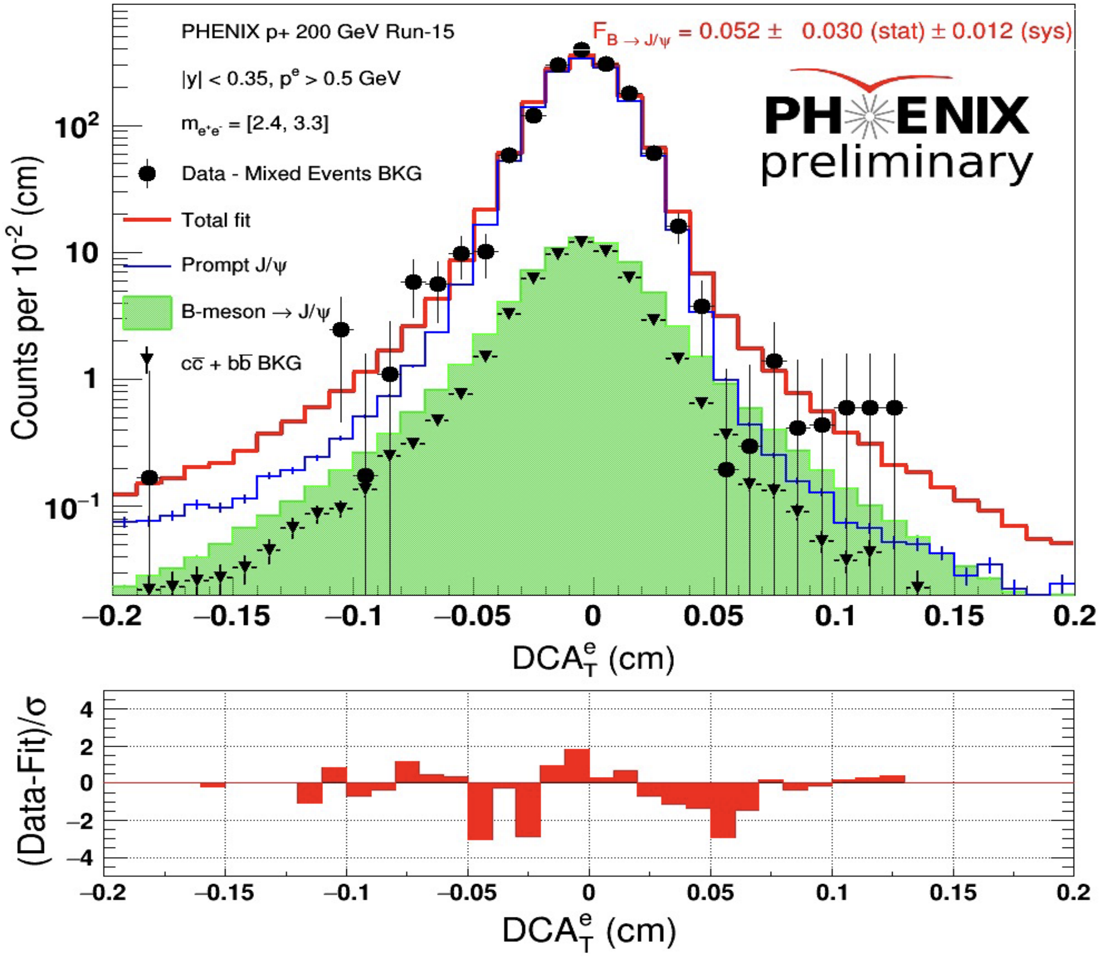
$$\theta_{\mathrm{dead}} \approx m_Q/E$$

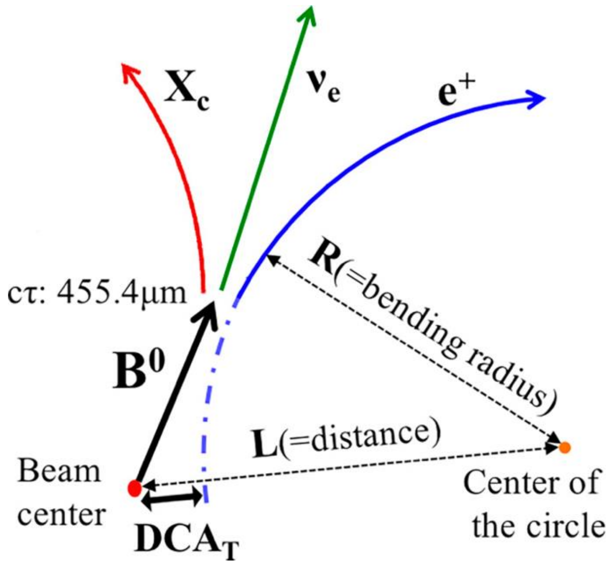
PRC 109, 044907 (2024)

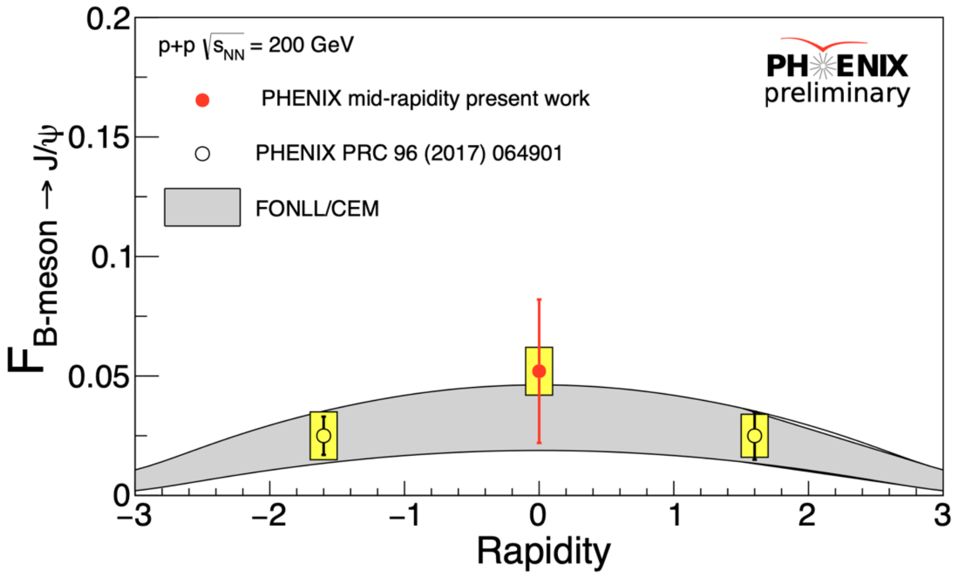


$B \rightarrow J/\psi \rightarrow e^+e^-$: prompt vs displaced

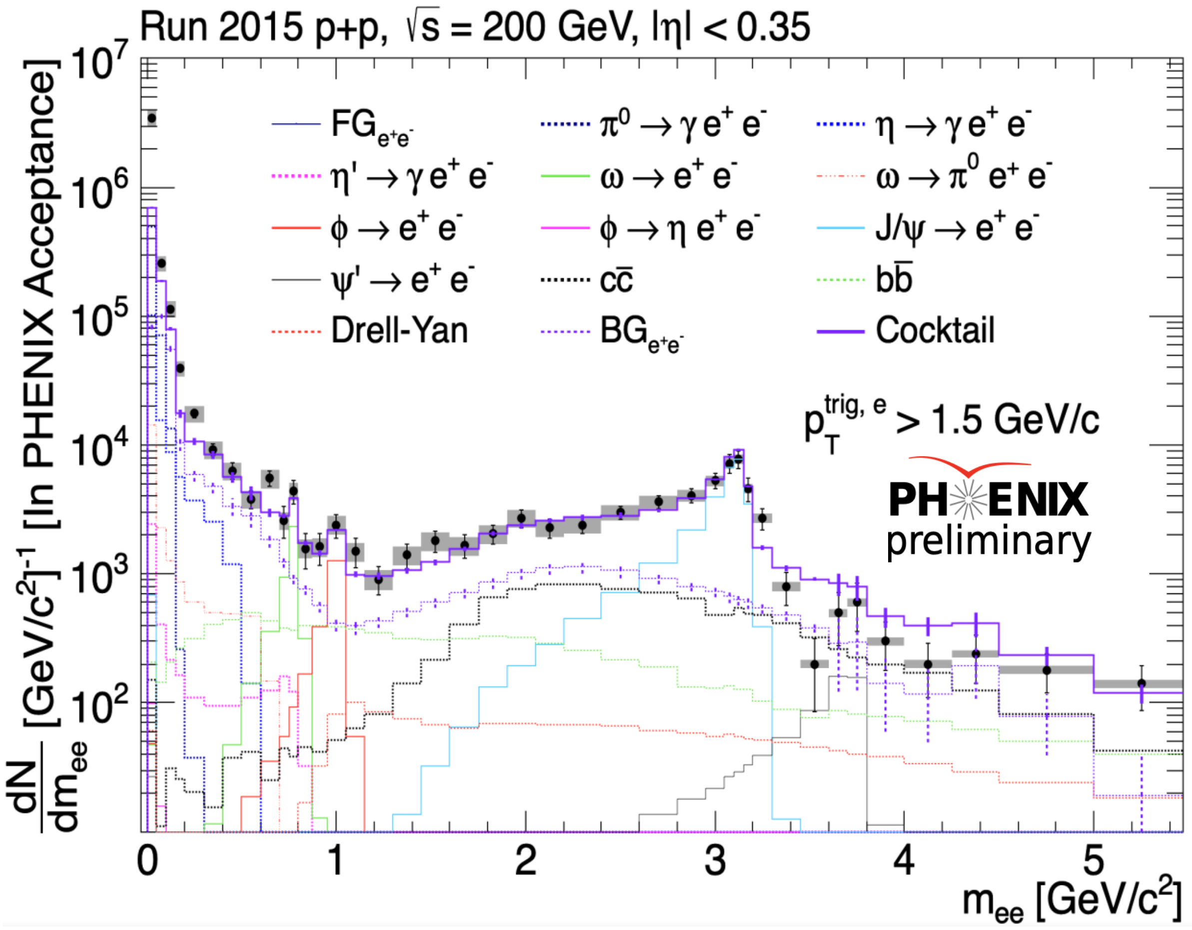
$F_{B\rightarrow J/\psi} = 0.052 \pm 0.030\ (\text{stat}) \pm 0.012\ (\text{sys})$



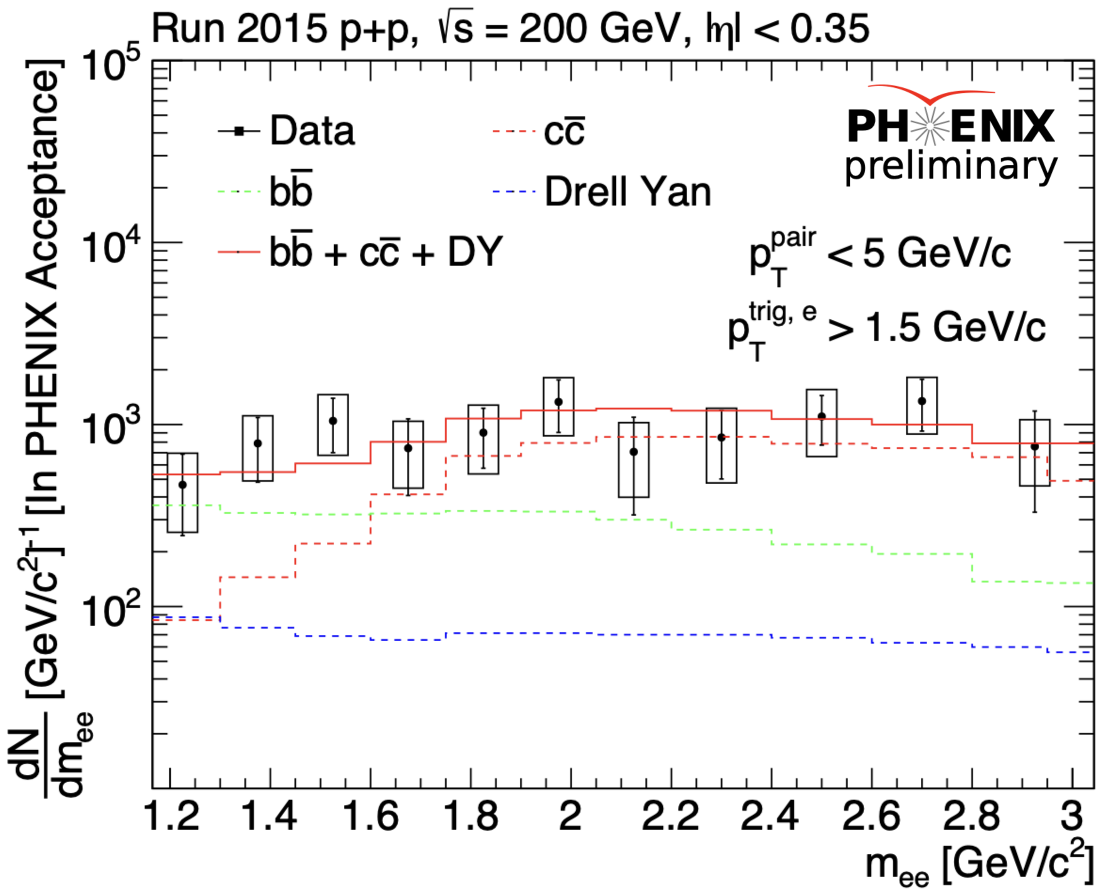




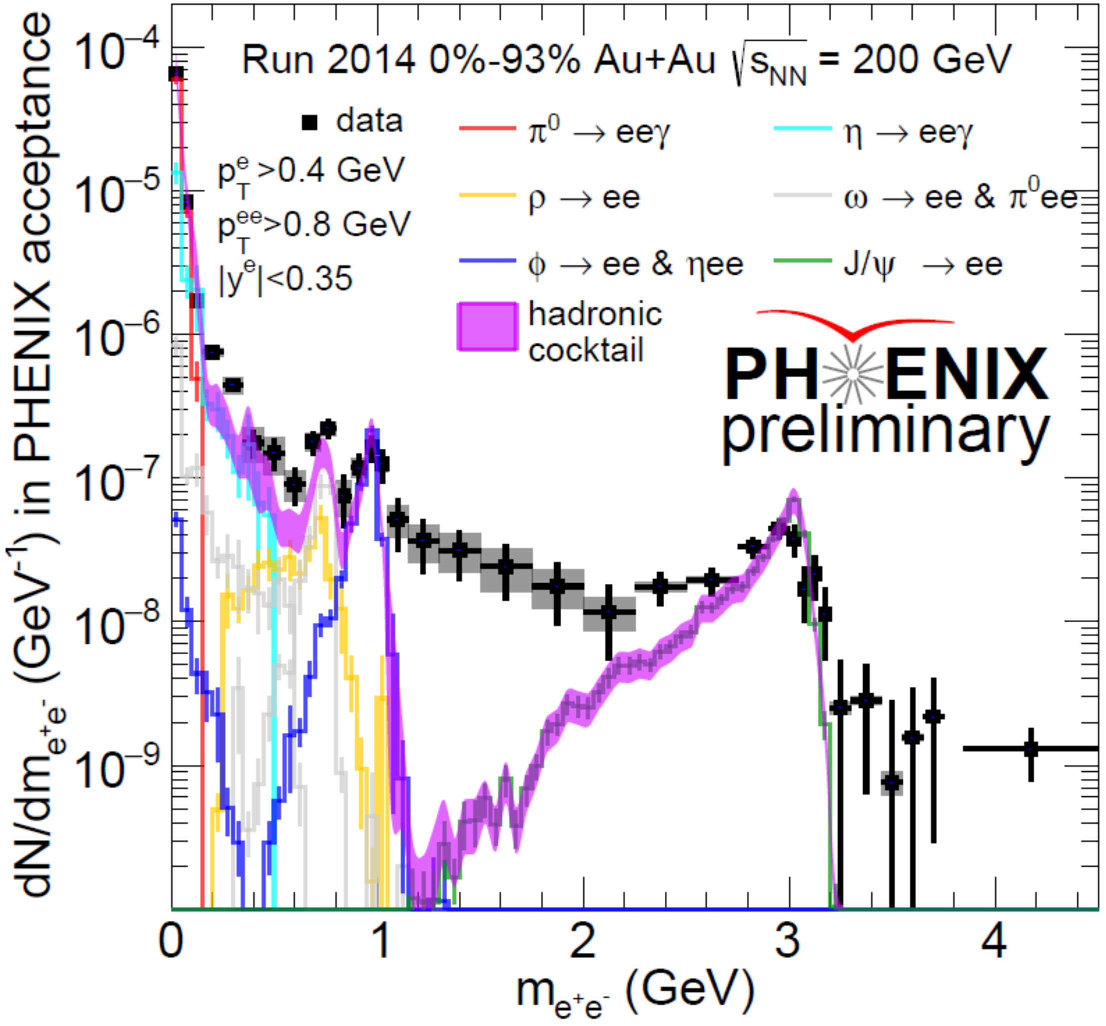
HF and Drell-Yan in p+p: e^+e^- Cocktail



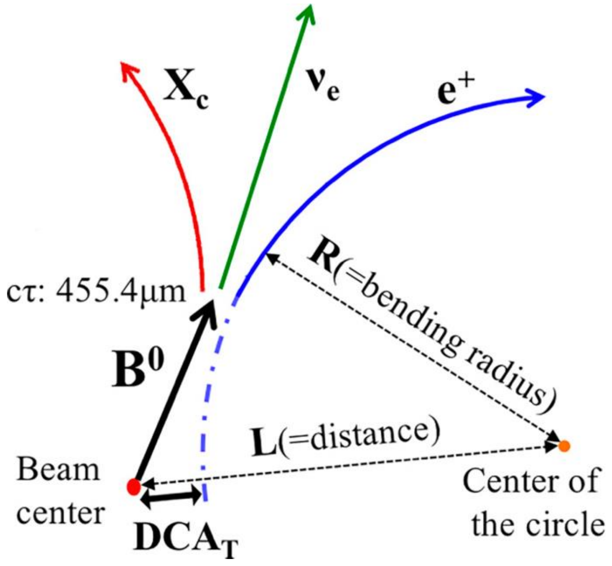
Open HF Signals from di-electrons

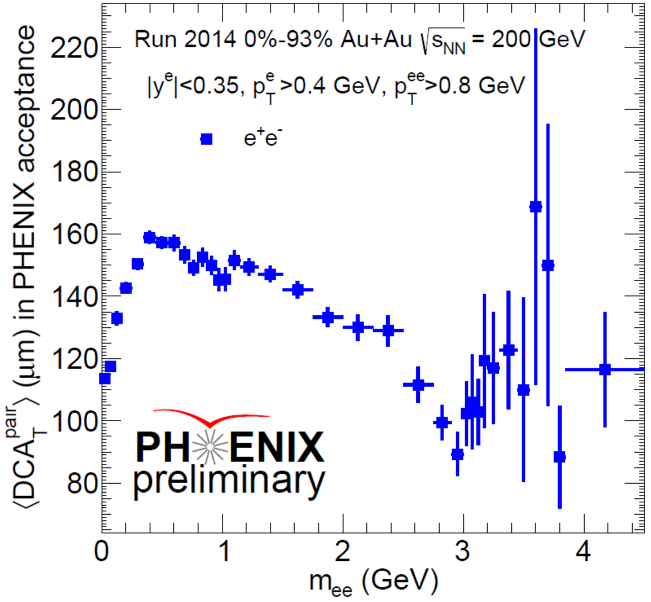


HF and Thermal in Au+Au: e^+e^- Cocktail

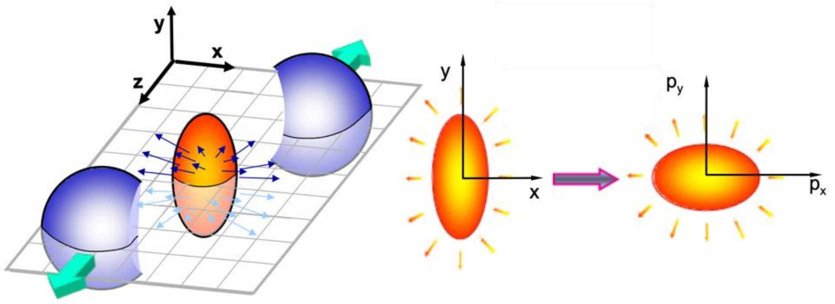


The additional contributions may include pairs from heavy flavor decays and thermal radiations
-> First attempt to directly measure HF and thermal contributions with DCA at RHIC





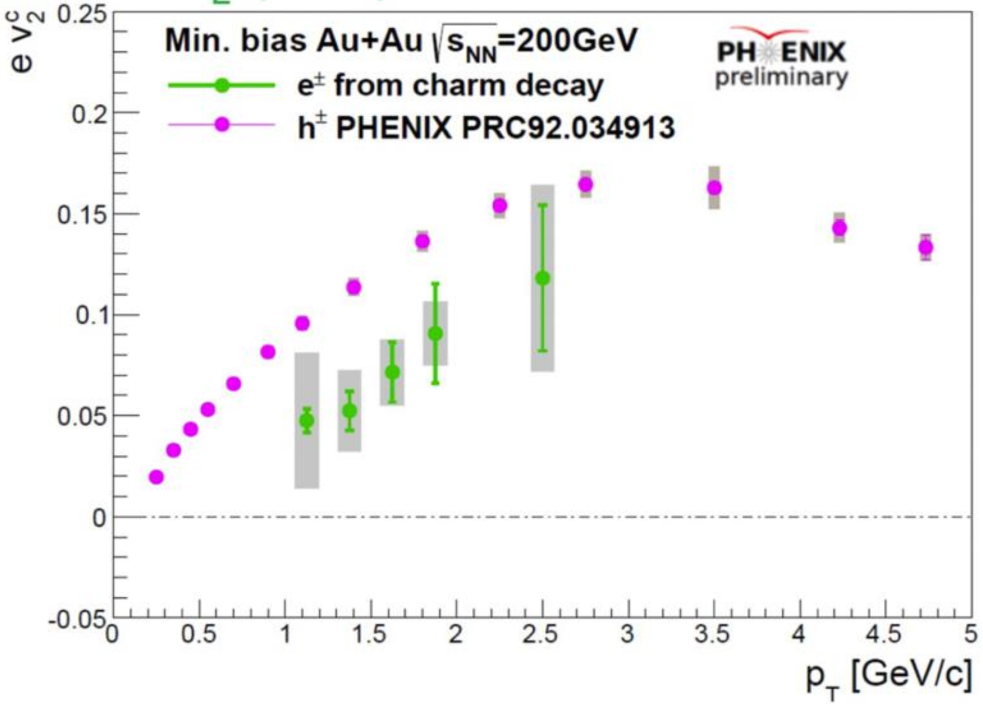
Charm and Beauty "Flow" v_2



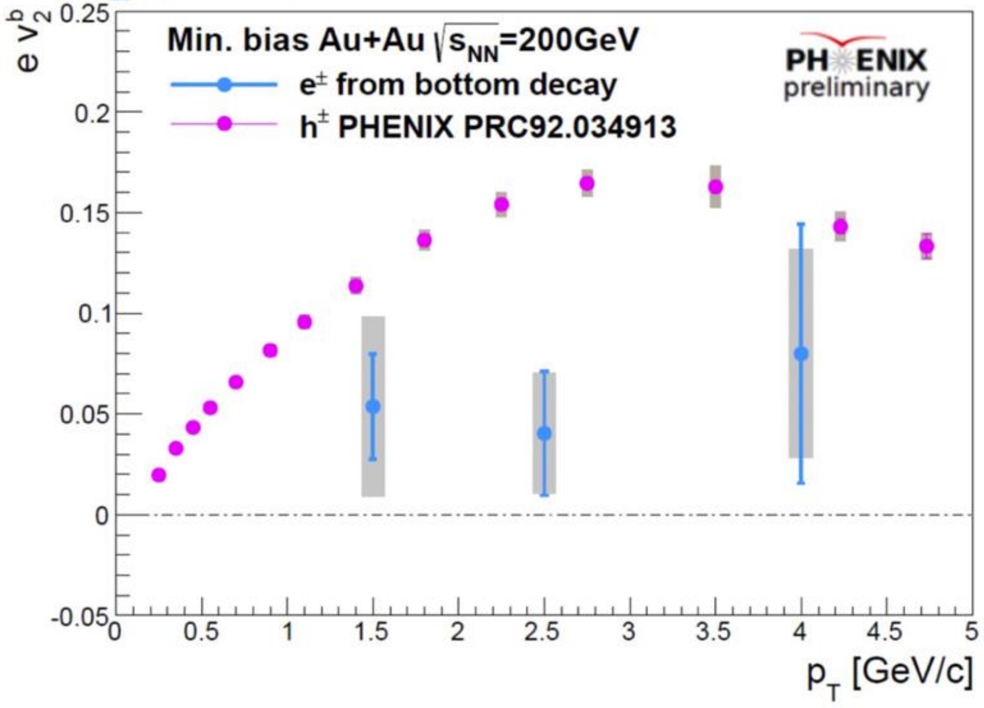
$$E\frac{d^3N}{dp_T} = \frac{1}{2\pi}\frac{d^2N}{p_T dp_T dy}\left\{1 + \sum_{i=1}^{\infty} v_n cos[n(\varphi - \Psi_n)]\right\}$$

$$v_2 = \langle cos[2(\varphi - \Psi_2)]\rangle$$

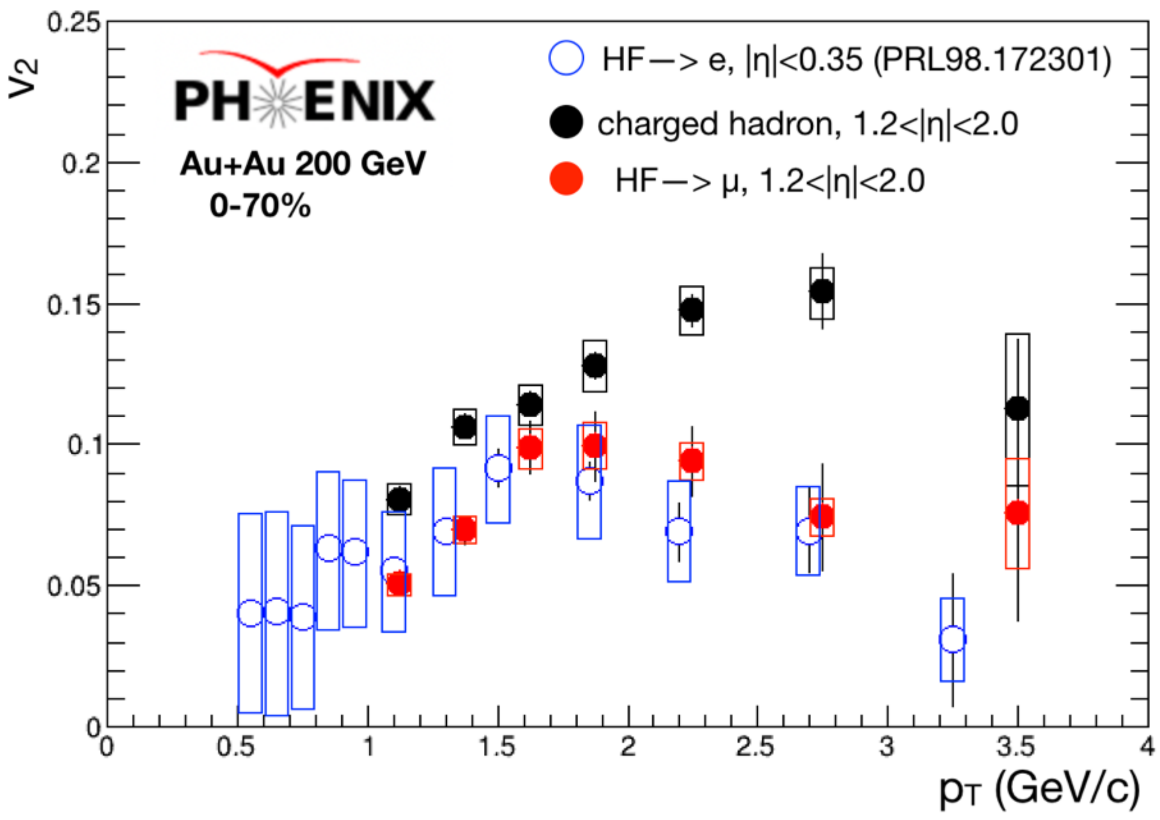
$v_2^c(c\to e)$



$v_2^b(b\to e)$



Open HF v_2 Observed at the Froward Rapidity

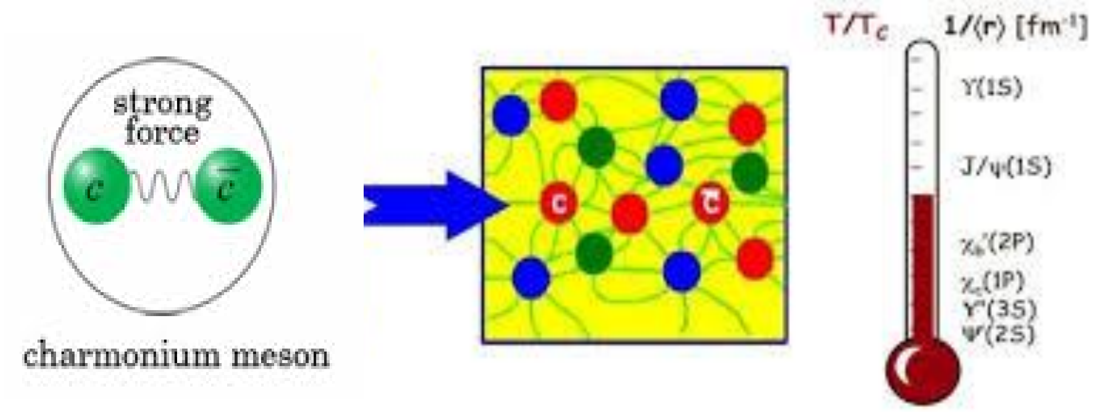


PHENIX, arXiv:2409.12715

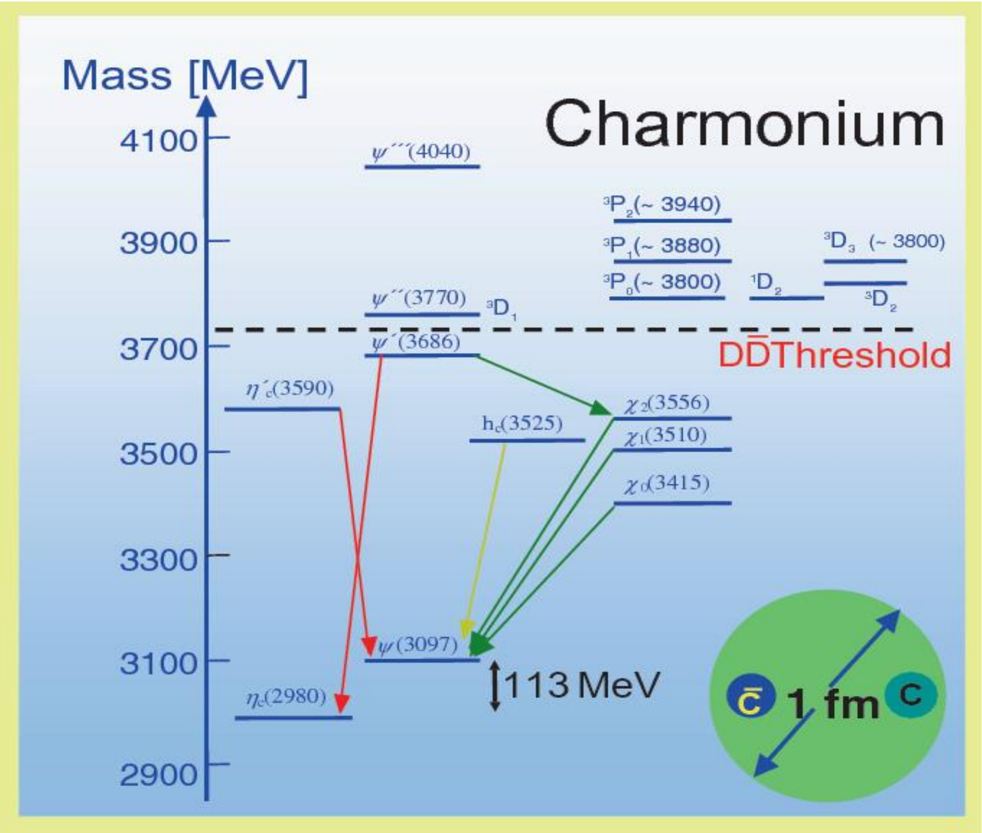
- First observation of none-zero open heavy flavor v2 at the forward rapidity
  - Consistent with mid-rapidity HF results
  - Smaller than light hadron v2
  - **Similar magnitude in central and forward rapidity!**

Quarkonium in Heavy Ion
- color screening?

Matsui & Satz, Phys. Lett. B178 (1986)
- first quantitative predictions



https://link.springer.com/chapter/10.1007/978-3-030-79489-7_2/figures/1



Binding energy ~ O(10^2) MeV ~ QGP Temperatures

Quarkonium dissociation by string breaking

S. Digal et al. / Physics Letters B 514 (2001) 57–62

State	J/ψ	χ_c	ψ'	Υ	χ_b	Υ'	χ_b'	Υ''
E_s^i (GeV)	0.64	0.20	0.05	1.10	0.67	0.54	0.31	0.20
T_d/T_c	–	0.74	0.1–0.2	–	–	$\gtrsim 0.93$	0.83	0.74

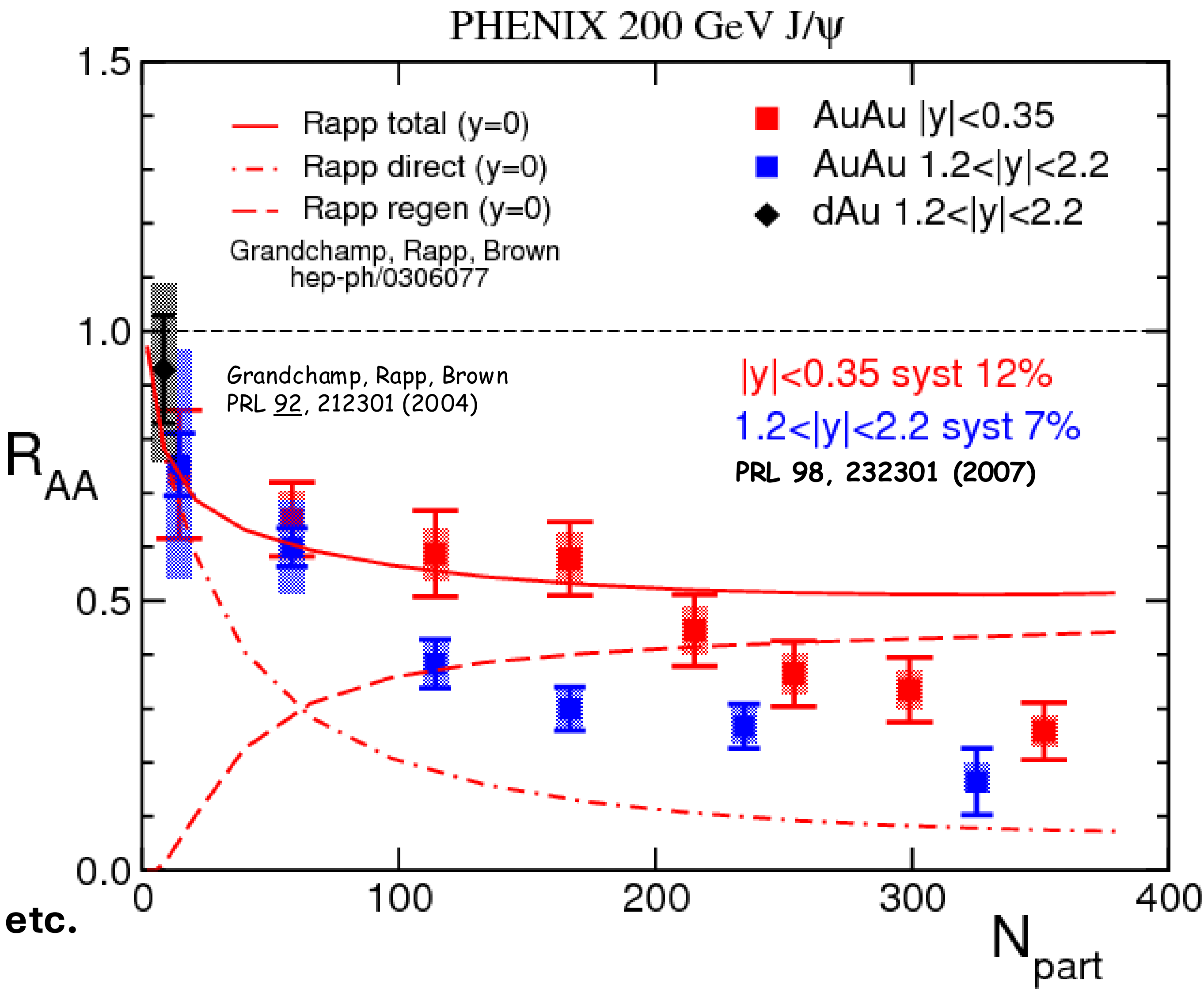
Suprises from the first J/Psi Measurements in Au+Au (2007)

- New phenomena, regeneration compensating for screening!

- Larger gluon density at RHIC expected to give stronger suppression than SPS
  - ➢ Larger charm production at RHIC gives higher probability of regeneration, <c-cbar> ~20 in central Au+Au at top energy
- Forward rapidity lower than mid due to smaller open-charm density there for recombination

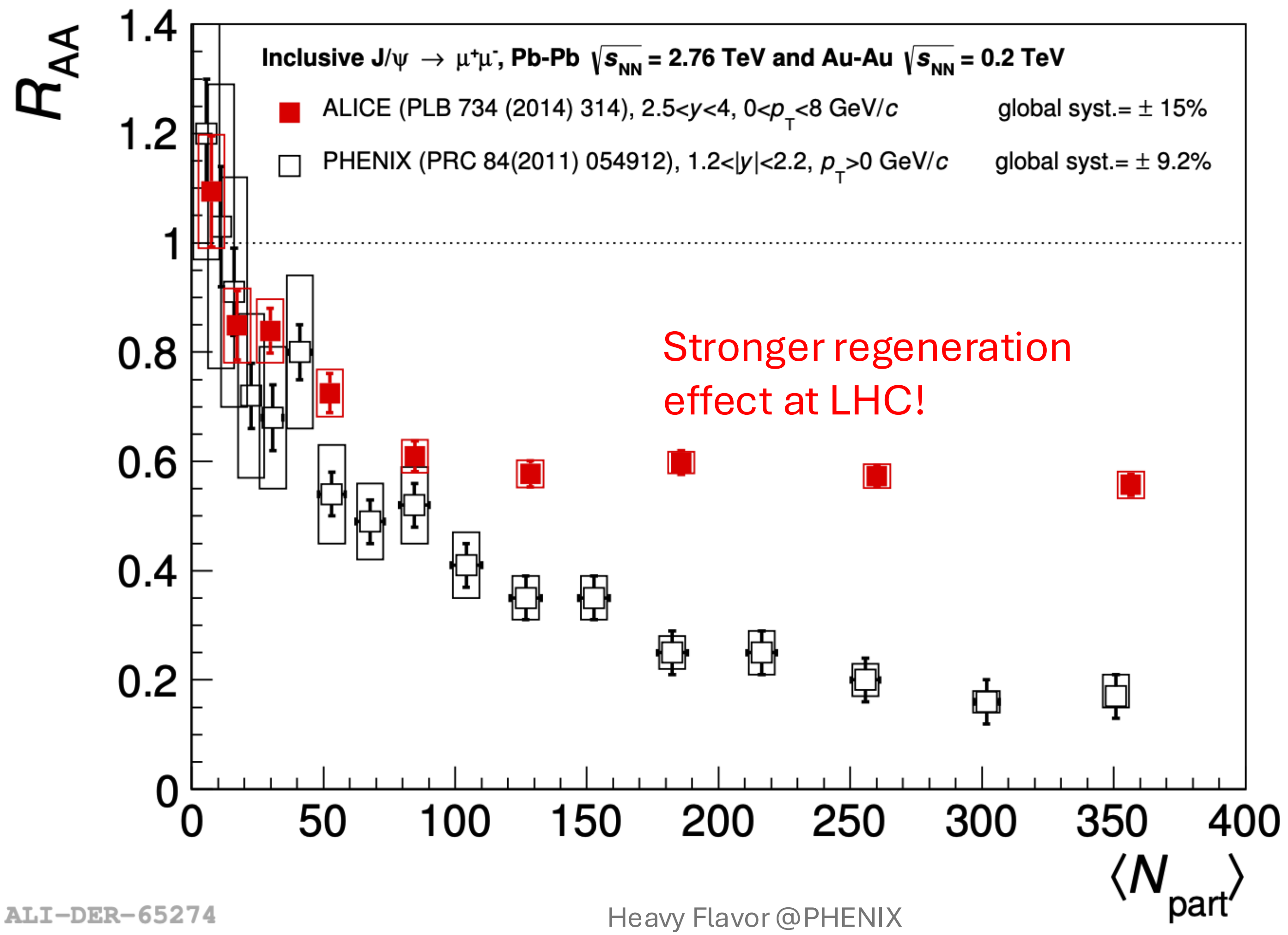
- Sensitive to open-charm production
  - ➢ Expect inherited flow from open charm;
  - ➢ Expect regeneration would be HUGE at the LHC! Confirmed many years later!

Need to go beyond a simple "color screening" model,
- check other observables/effects: flow, particle ratios etc.

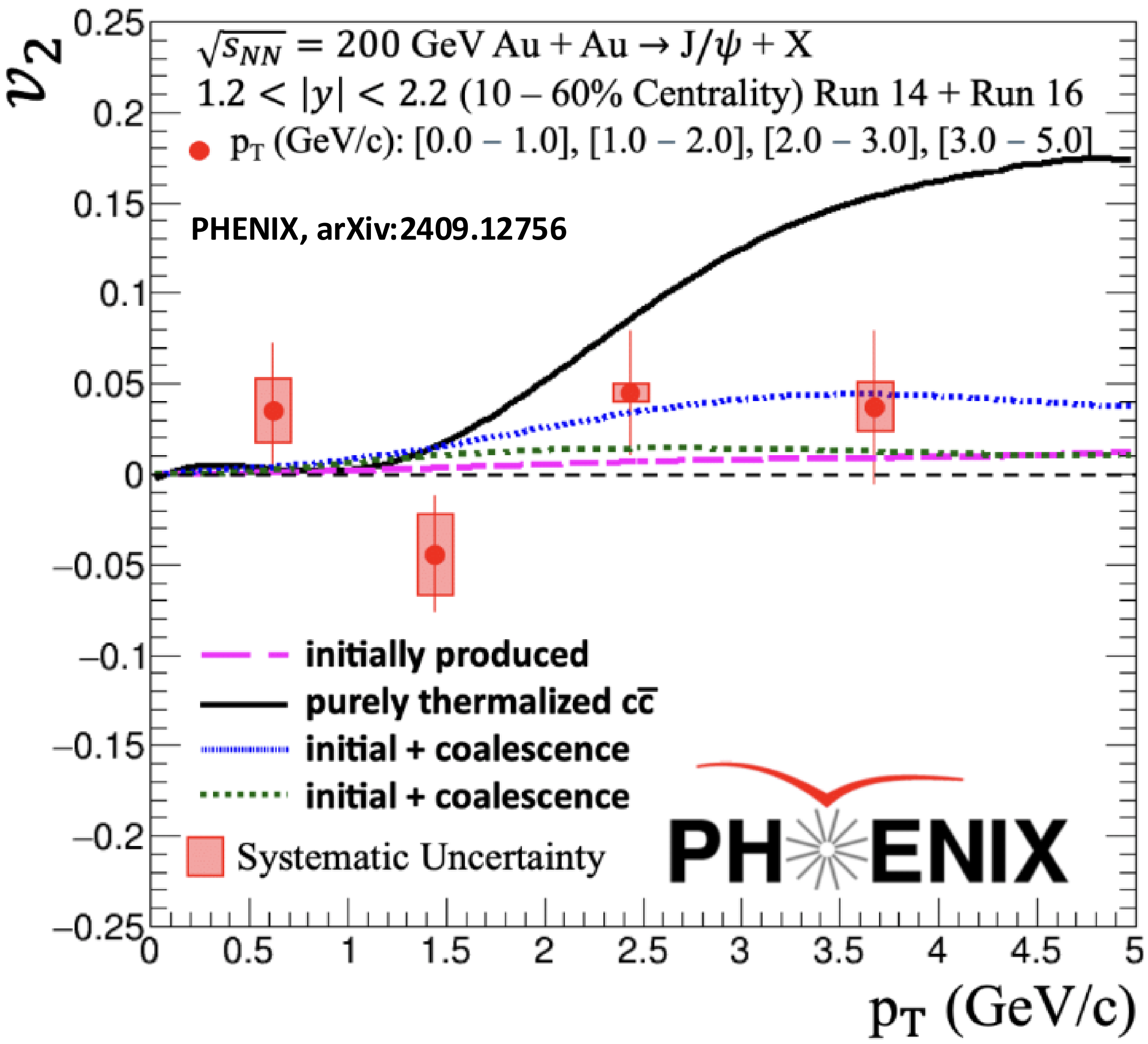


J/ψ Nuclear Modification: RHIC vs LHC

Further confirmed the coalescence of charm and anticharm quarks leads to J/ψ regeneration at LHC



First J/ψ "Flow" v_2 in the Forward Rapidity



- PHENIX v2 in the forward rapidity, consistent with zero
  - ➢ Open charm, none-zero v2!
    - Light quark contributions?
  - ➢ J/Psi formation
    - weak "recombination" in the forward rapidity?

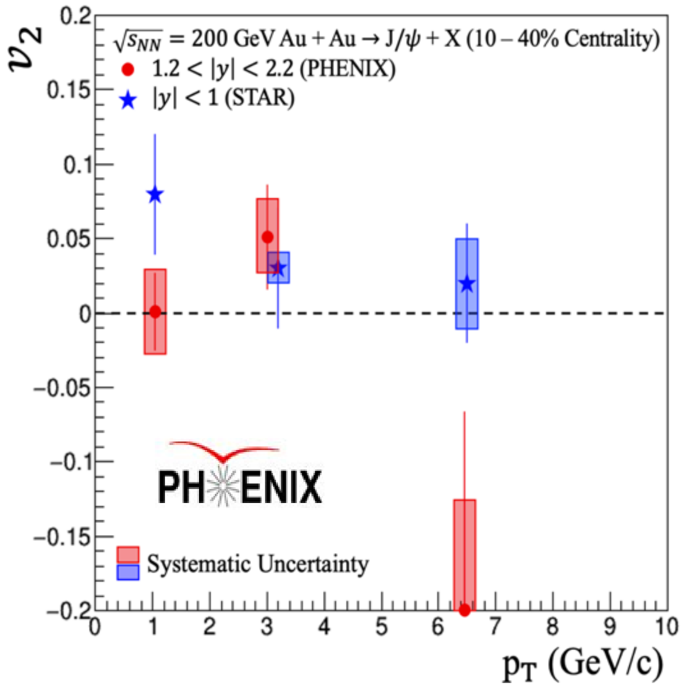
- Run2016 Au+Au, in progress
  - 4x more stat!

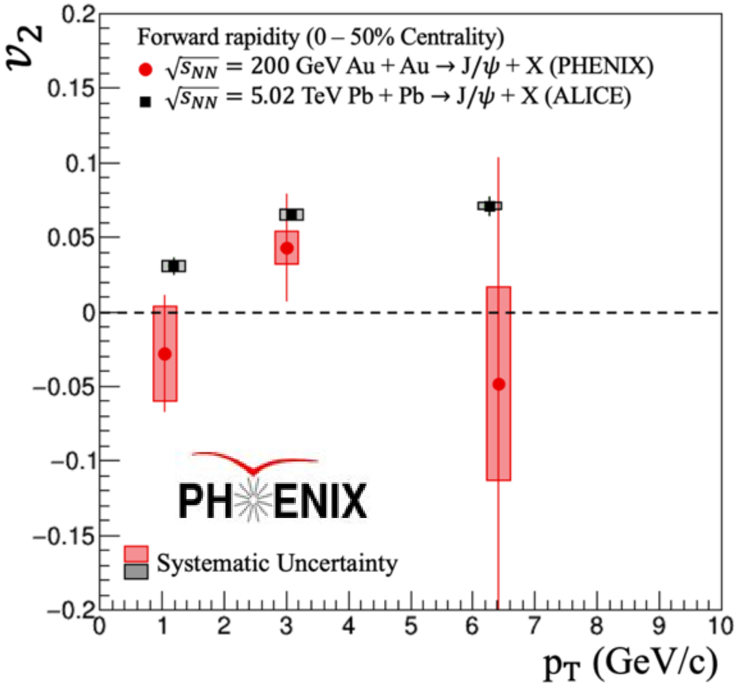
J/Psi v2: energy, rapidity and centrality dependence, RHIC and LHC

Forward J/ψ v_2 at RHIC is consistent with zero, but non-zero at LHC

- Consistent to the cc regeneration scenario at LHC

PHENIX, arXiv:2409.12756





- None zero v2
  - STAR (central)
  - ALICE (forward)

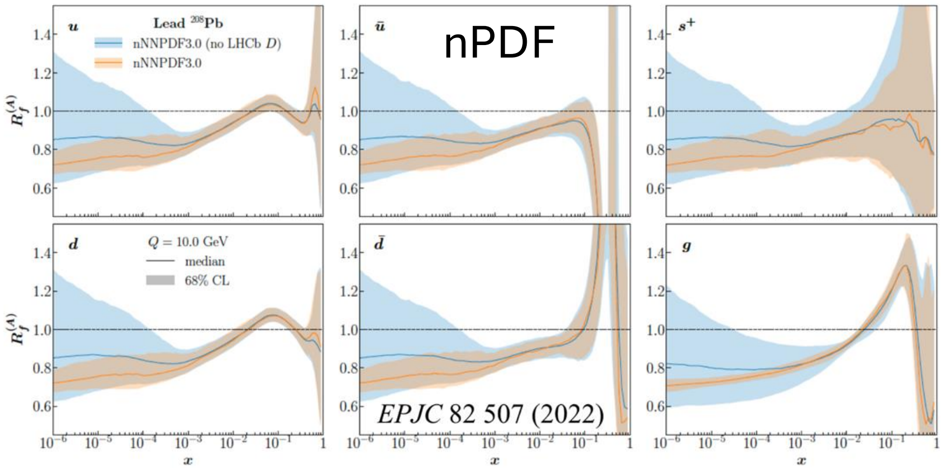
- PHENIX v2 in the forward rapidity, consistent with zero
  - Open charm, none-zero v2!
  - J/Psi formation

Study CNM with HF in pA

- Initial state, nPDF
- Final state, hadronization
- Multi-parton interactions

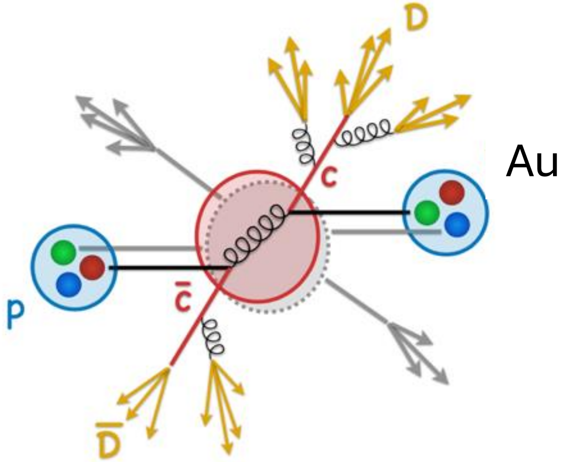
(None)universality of PDF and FF and QCD factorization

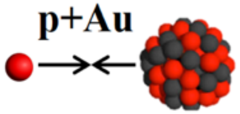
nPDF



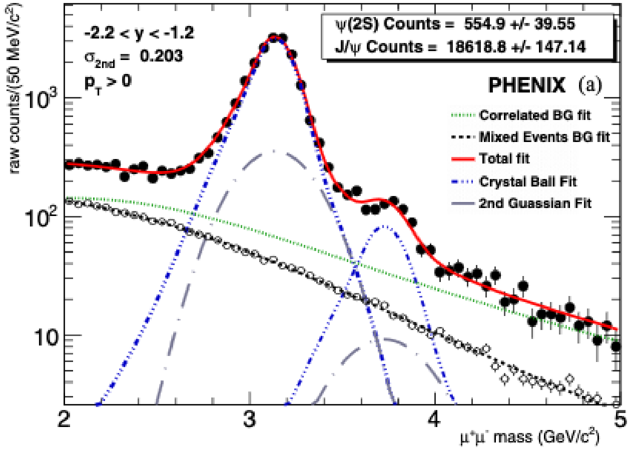
Hard process

$Q^2 \to \infty$

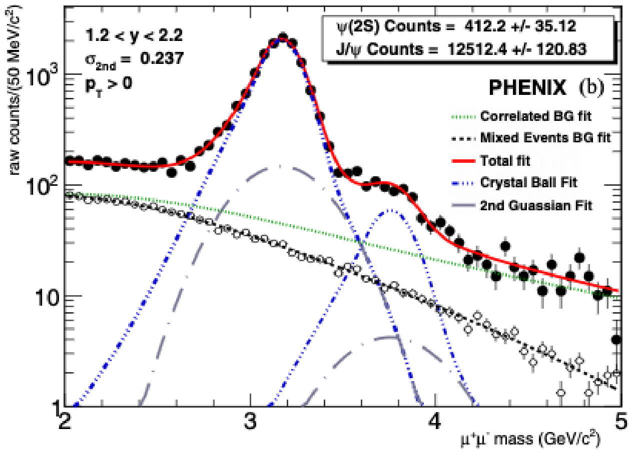




backward



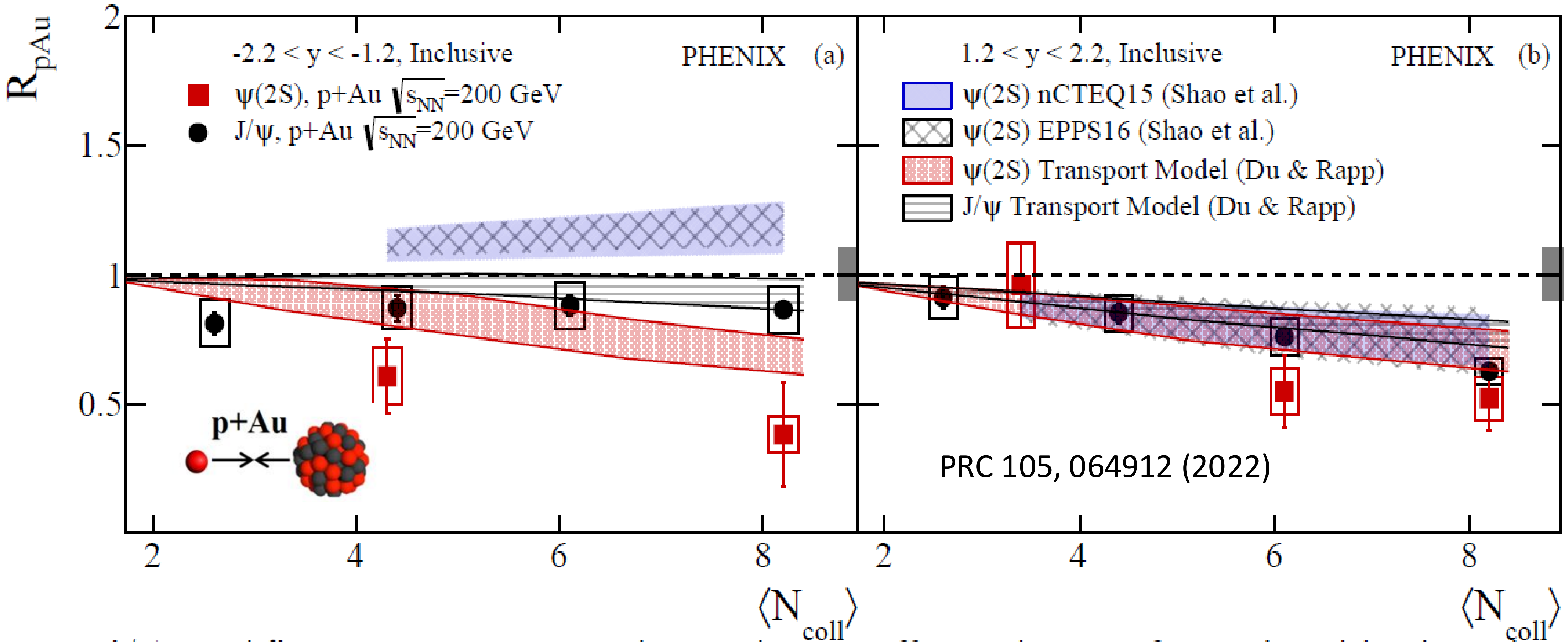
forward



$$\sigma_{hh\to Hh} = \mathrm{PDF}(x_a, Q^2)\ \mathrm{PDF}(x_b, Q^2) \otimes \sigma_{ab\to q\bar{q}} \otimes D_{q\to h}(z_q, Q^2)$$

Parton distribution functions	Partonic cross section	Fragmentation functions
(non perturbative)	(perturbative)	(non perturbative)

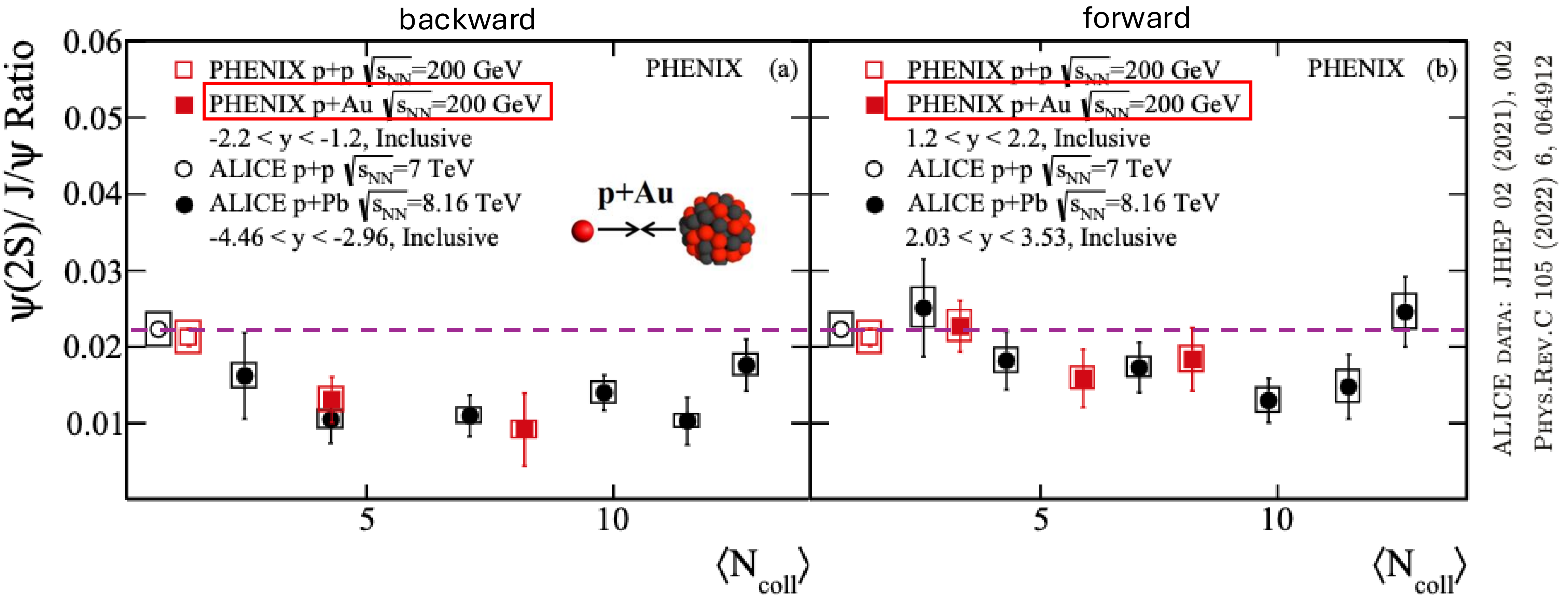
J/ψ and ψ(2S) in Small Systems: p+Au



1. J/ψmodification consistent with INITIAL state effects at FW and BW rapidity
2. ψ(2S) modification indicates presence of FINAL state effects at BW rapidity

ψ(2S) to J/ψ Ratios in p+A at RHIC and LHC

- sensitive to FSI



- Similar suppression pattern, weak energy dependence
- Final stat effect is significant, and larger in the backward rapidity where multiplicity is higher

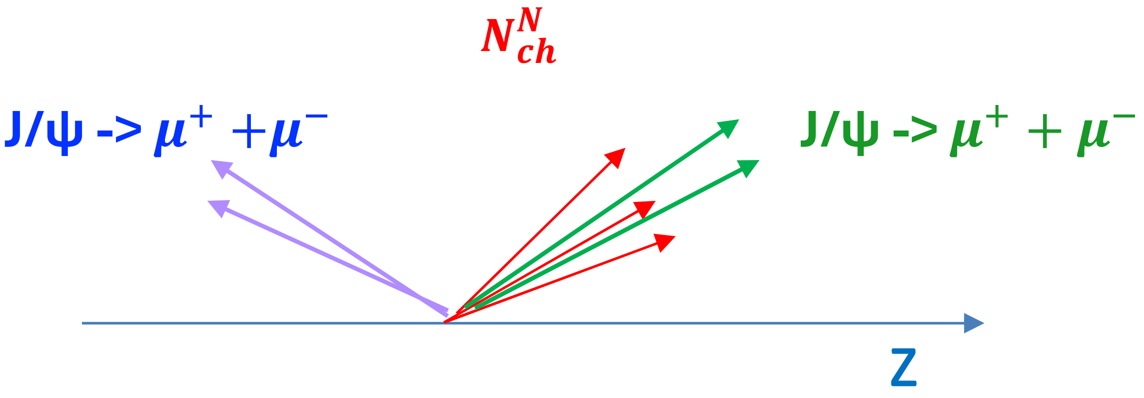
J/ψ Yields vs Event Multiplicity in pp

- sensitive to underlying event activities, MPI

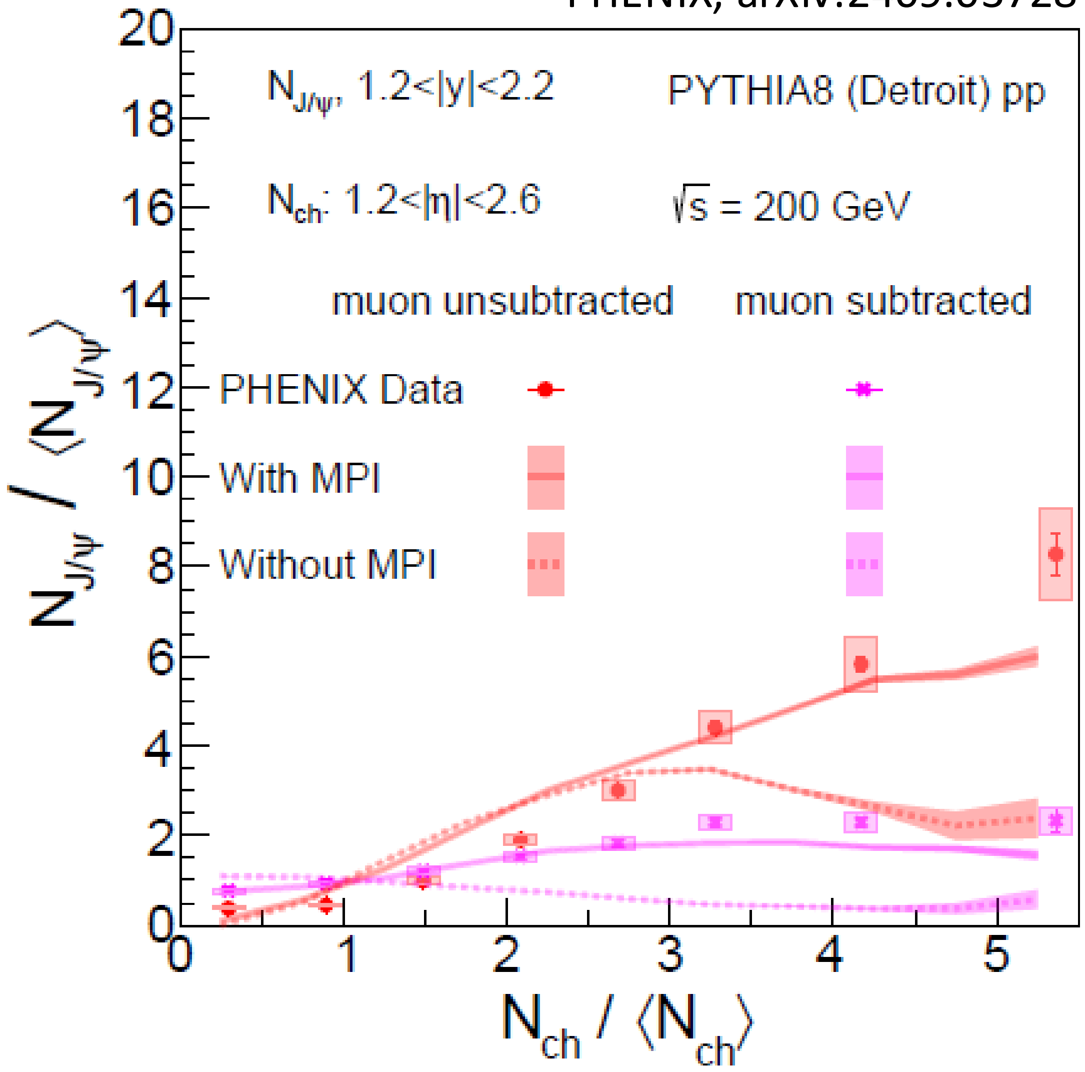
RED = Tracklets N_{ch}^{N} (1.2 < η < 2.4)

Green = J/ψ (1.2 < y < 2.2)

Blue = J/ψ (-2.2 < y < -1.2)

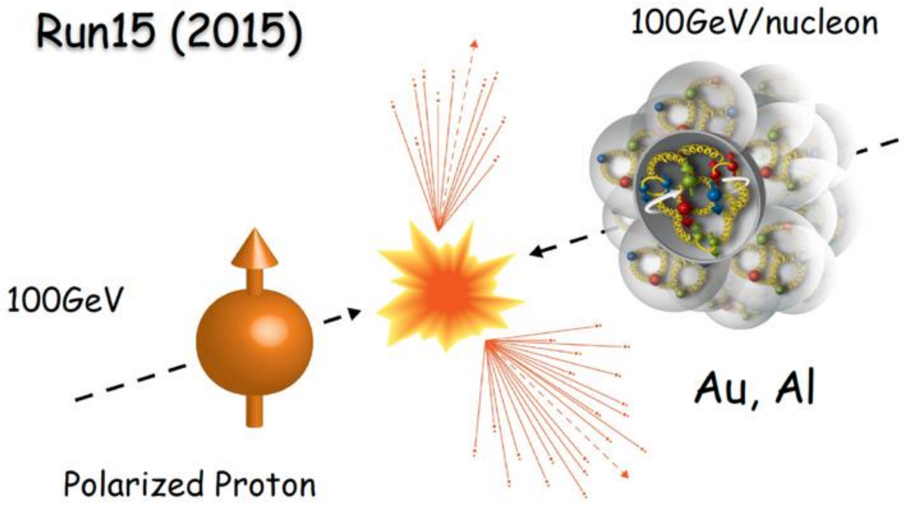


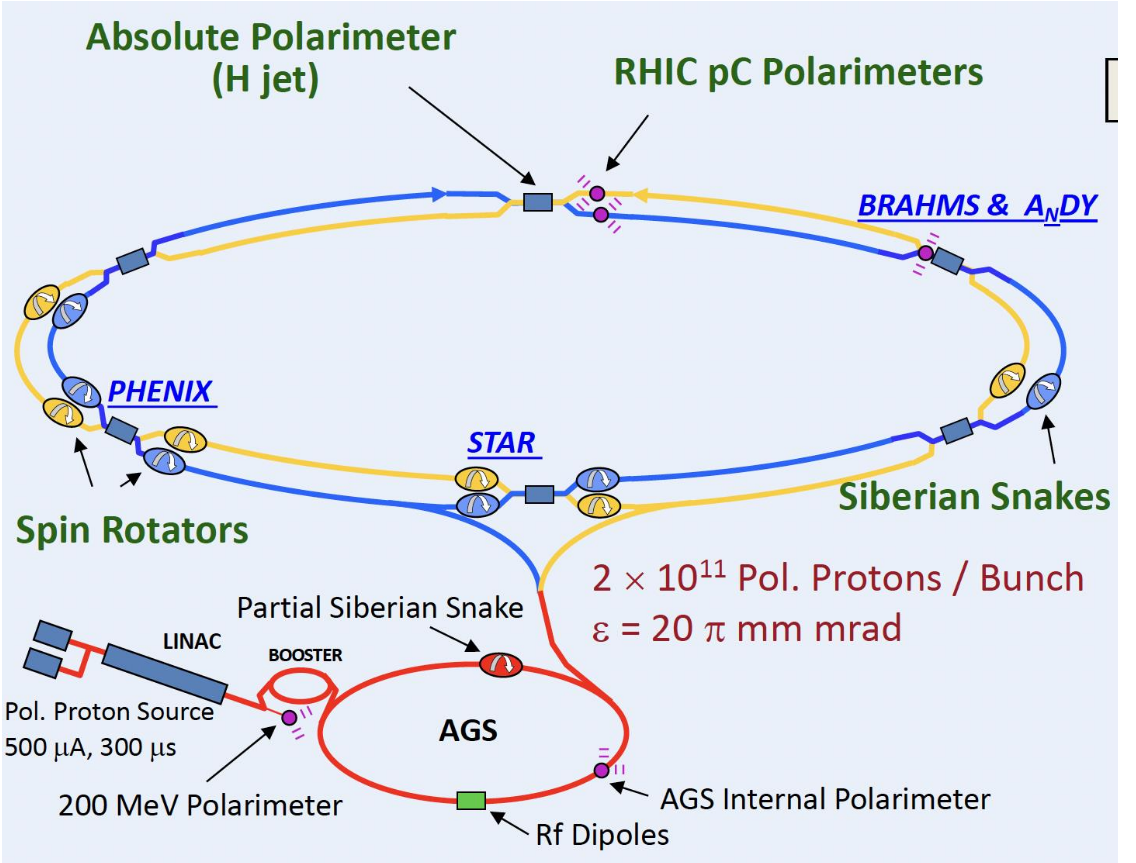
PHENIX, arXiv:2409.03728



Spin Physics with HF Probes in Polarized pp

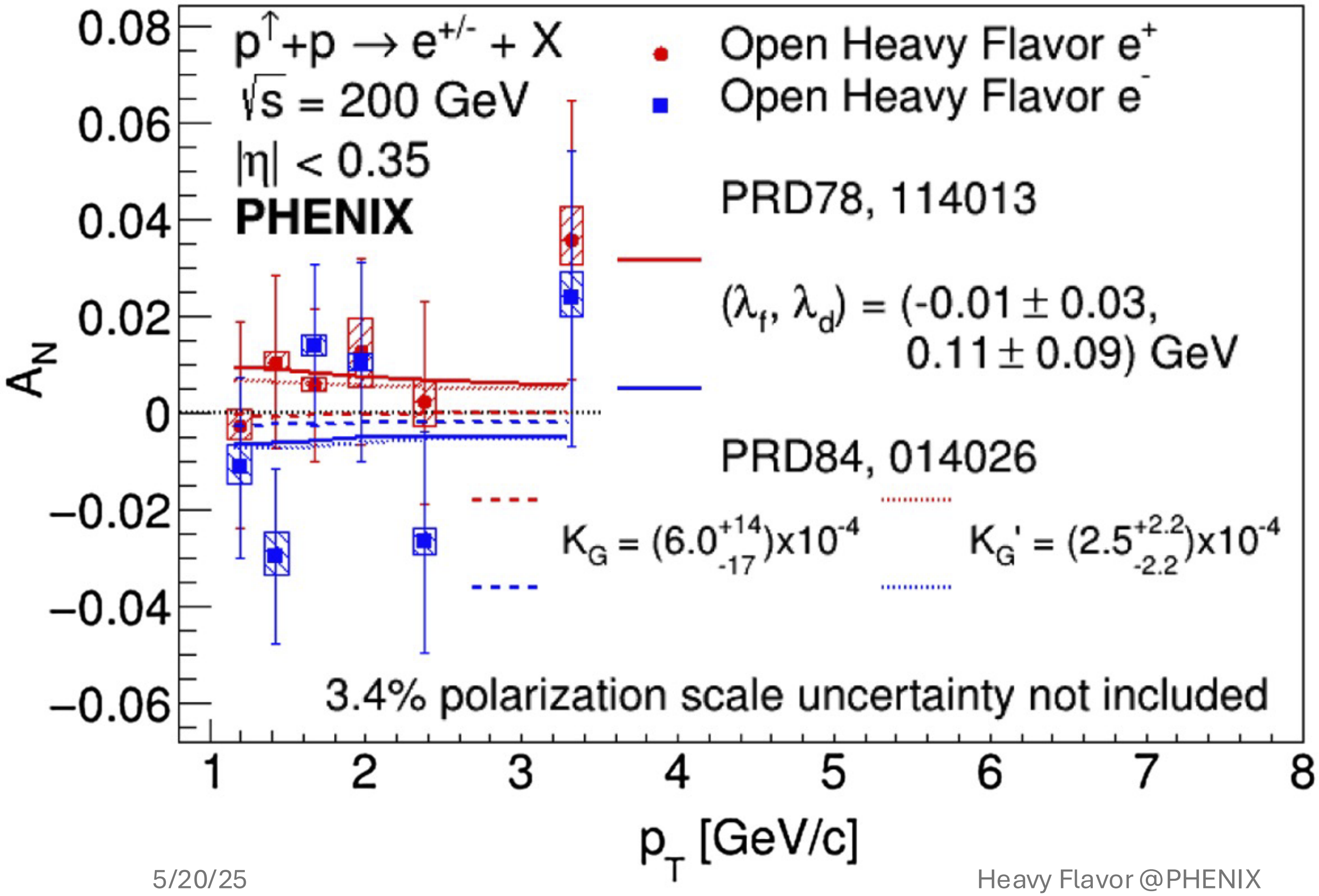
- Probe gluon distributions
  - ➢Gluon polarization
  - ➢Gluon TMD
  - ➢Spin in pA!

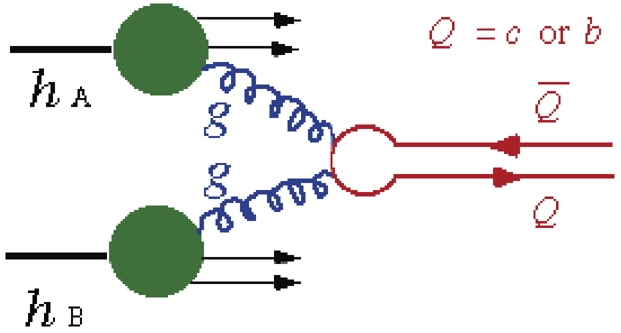




Probe Gluon TMD with HF A_N: central rapidity

PRD107, 052012 (2023)





Dominated by gluon-gluon fusion

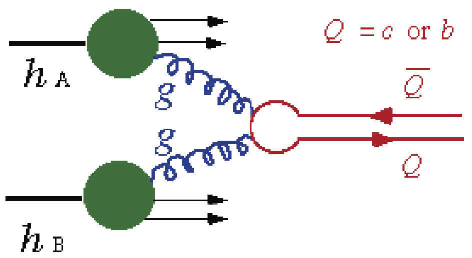
Constrain tri-gluon correlation functions in the Twist-3 collinear framework

- *Z.Kang, J.Qiu, W.Vogelsang, F.Yuan, PRD78,114013*
- *Y.Koike, S.Yoshida, PRD84,014026*

Probe Gluon TMD with HF A_N: forward rapidity

J/ψ production sensitive to gluon distribution
_A_N sensitive to J/ψ production mechanism_

F.Yuan, PRD78, 014024:
For non-zero gluon Sivers, A_N vanishes in color octet model, but survives in color singlet model



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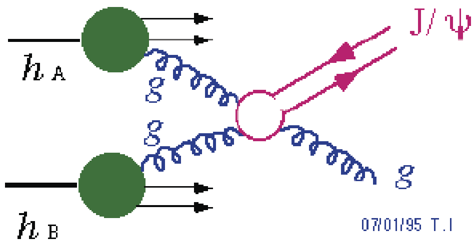
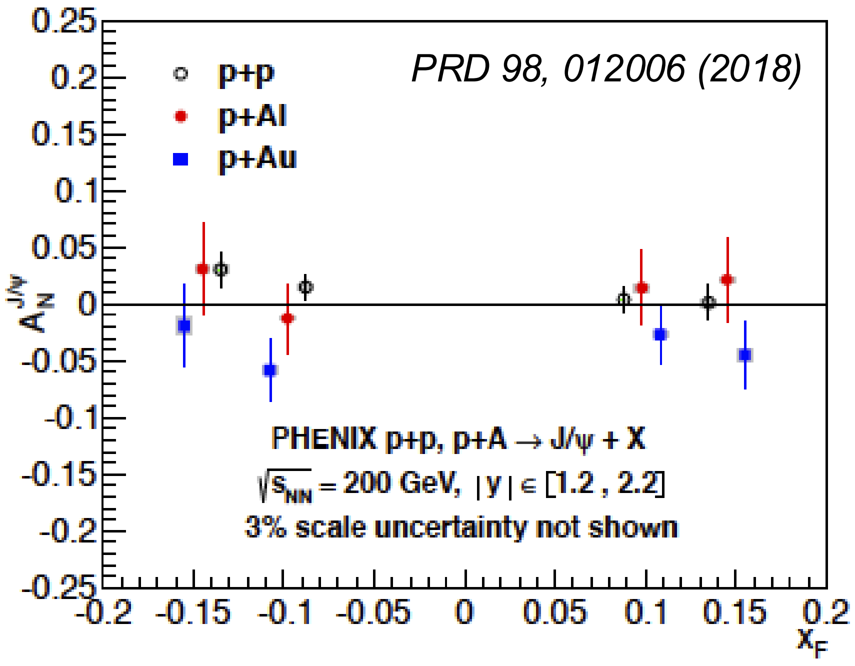
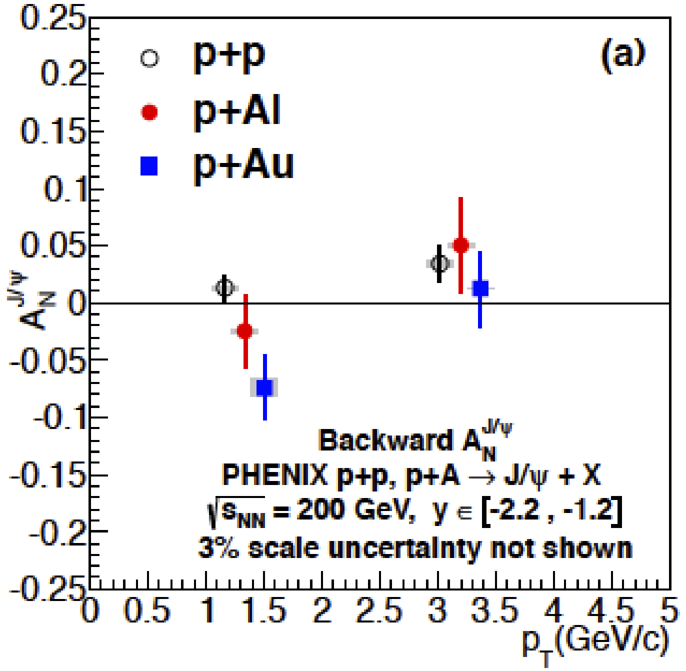
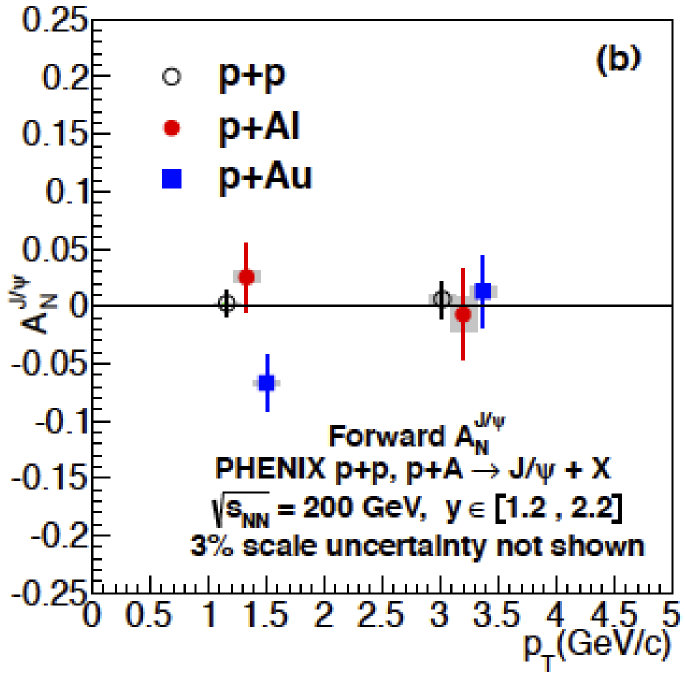


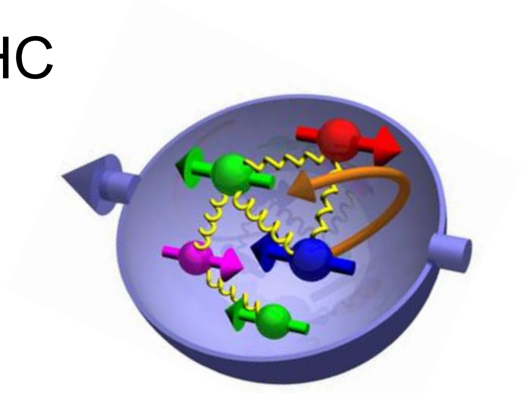


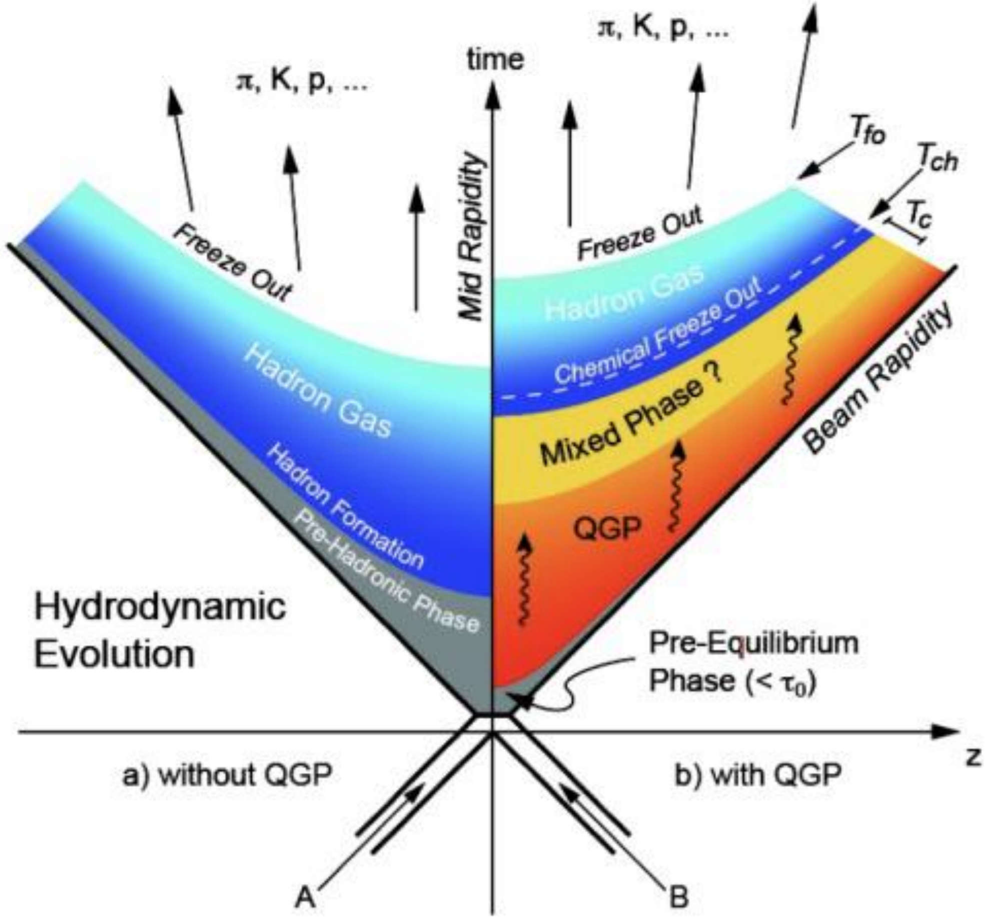




Summary and Outlook

- Good progress toward understanding QGP formation and evolution
- Aim for a precision quantitative QCD description of the QGP
- Future precision measurements & multi-scale probes
  - ➢Jets, HF, photons etc.
  - ➢sPHENIX & STAR at RHIC, LHC
- EIC and beyond
  - CNM
  - Nucleon structure and more

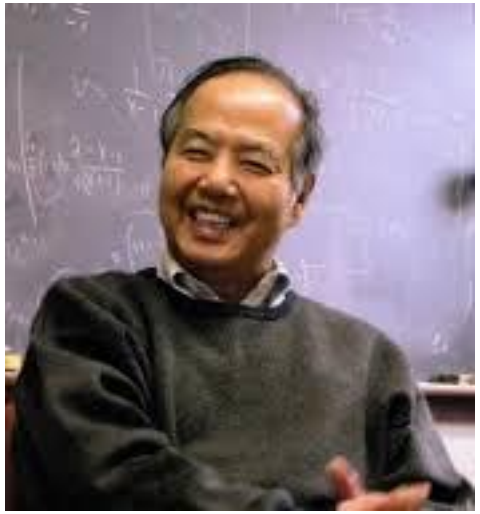




Spin & QCD **CNM** **QGP**

PHENIX

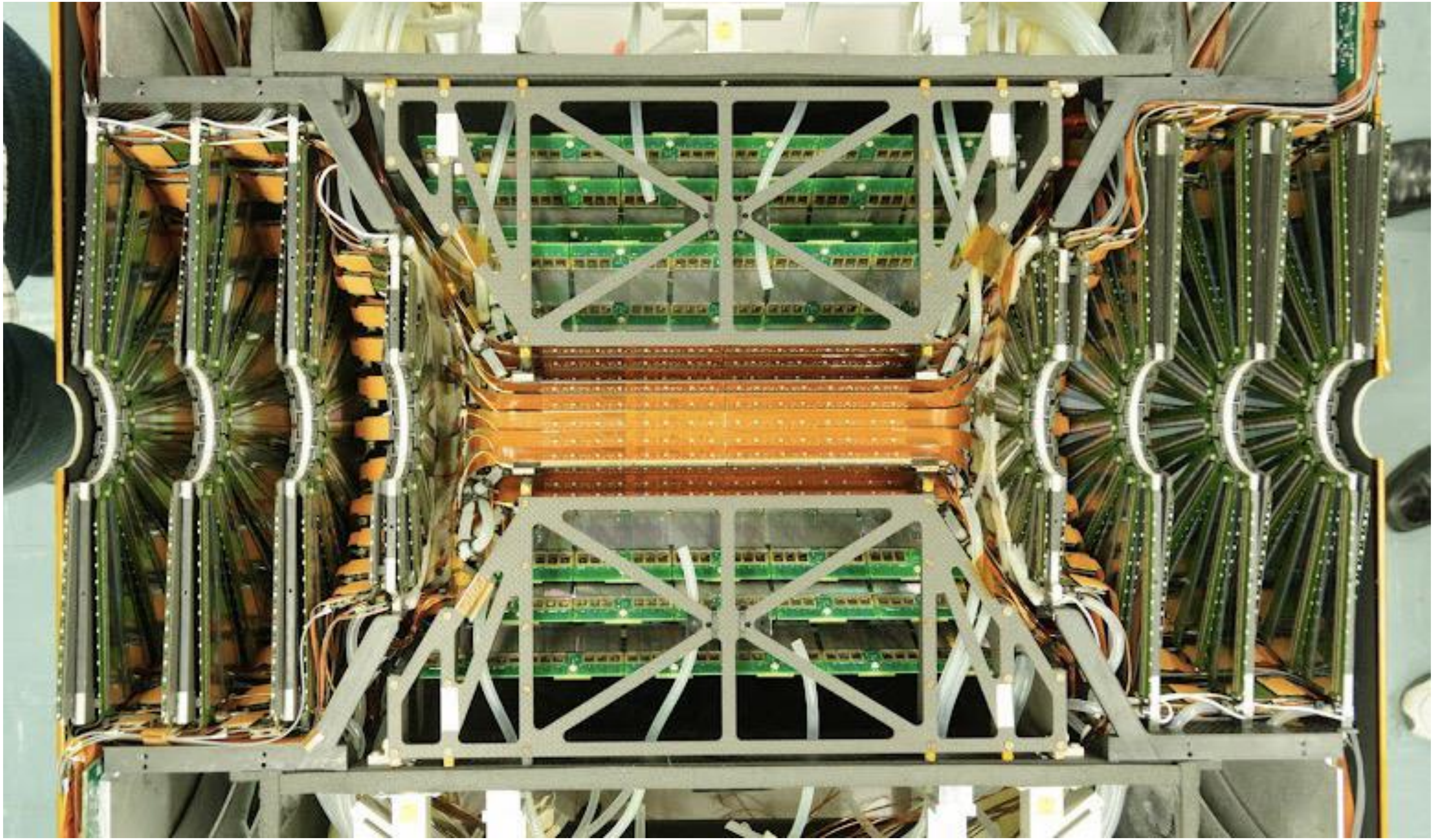
Birth of Relativistic Heavy Ion Collider (RHIC) at BNL, 1983

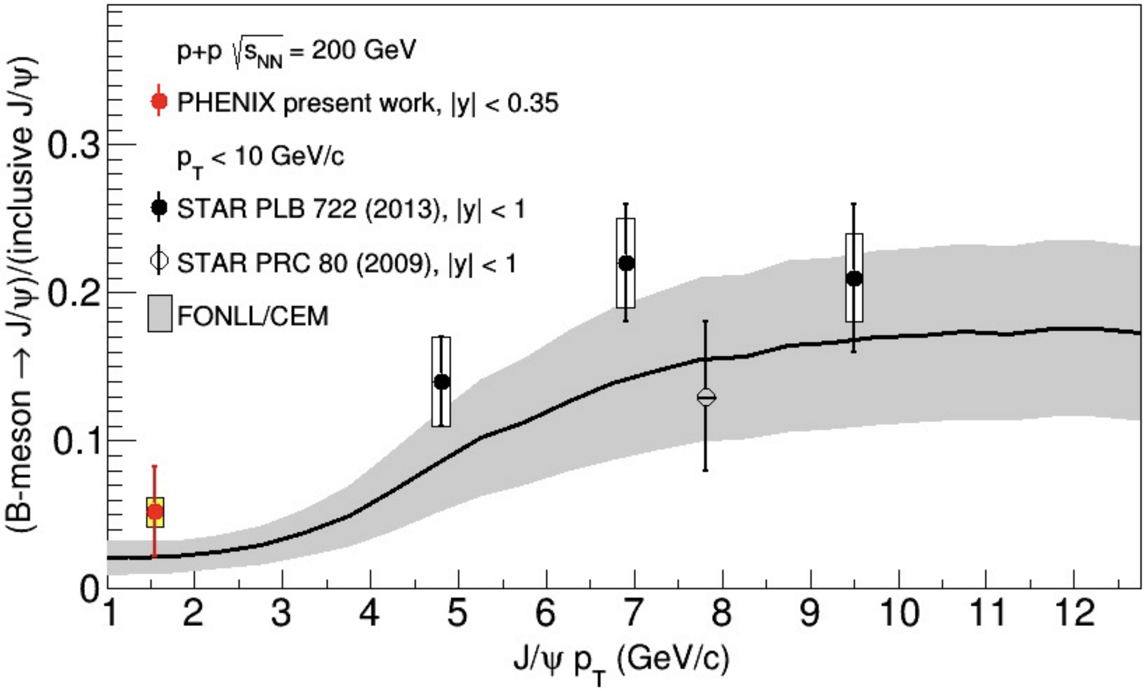


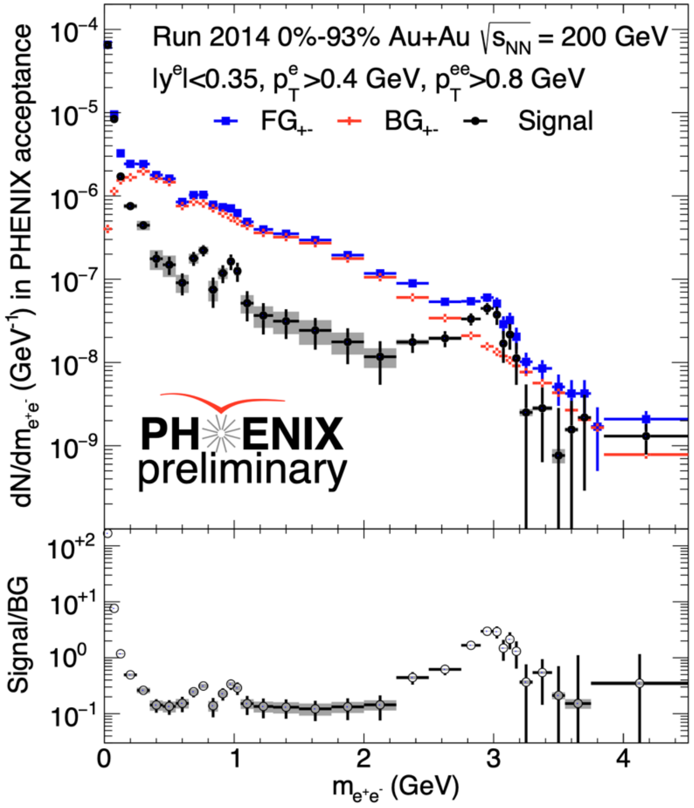
T. D. Lee
Nobel Prize, 1957

RHIC has proven to be an exceptional ‘playground’ for advancing our understanding of QCD and Nuclear Matter

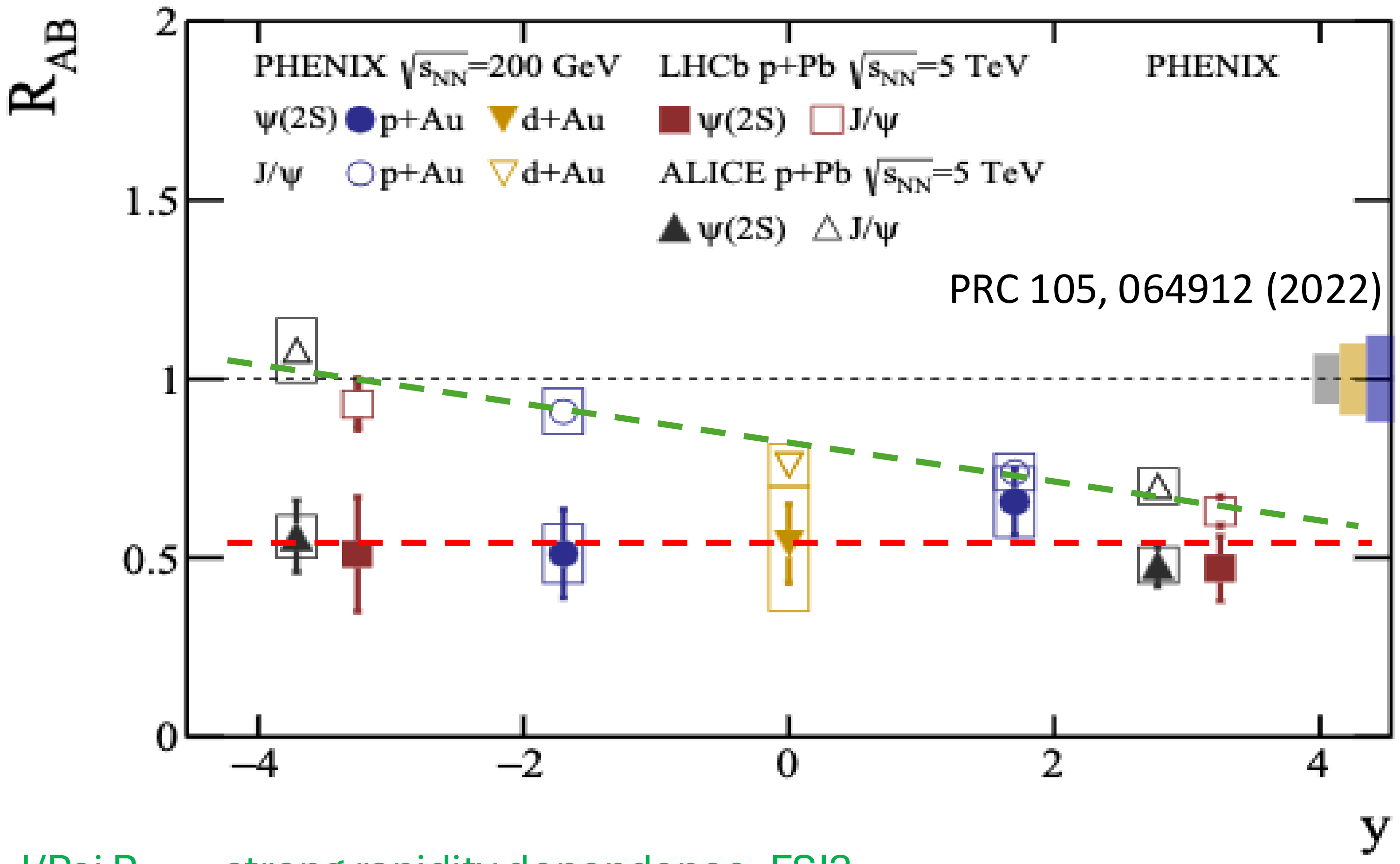
Backup slides




p+p $\sqrt{s_{NN}}$ = 200 GeV
PHENIX present work, |y| < 0.35
p_T < 10 GeV/c
STAR PLB 722 (2013), |y| < 1
STAR PRC 80 (2009), |y| < 1
FONLL/CEM
(B-meson → J/ψ)/(inclusive J/ψ)
J/ψ p_T (GeV/c)

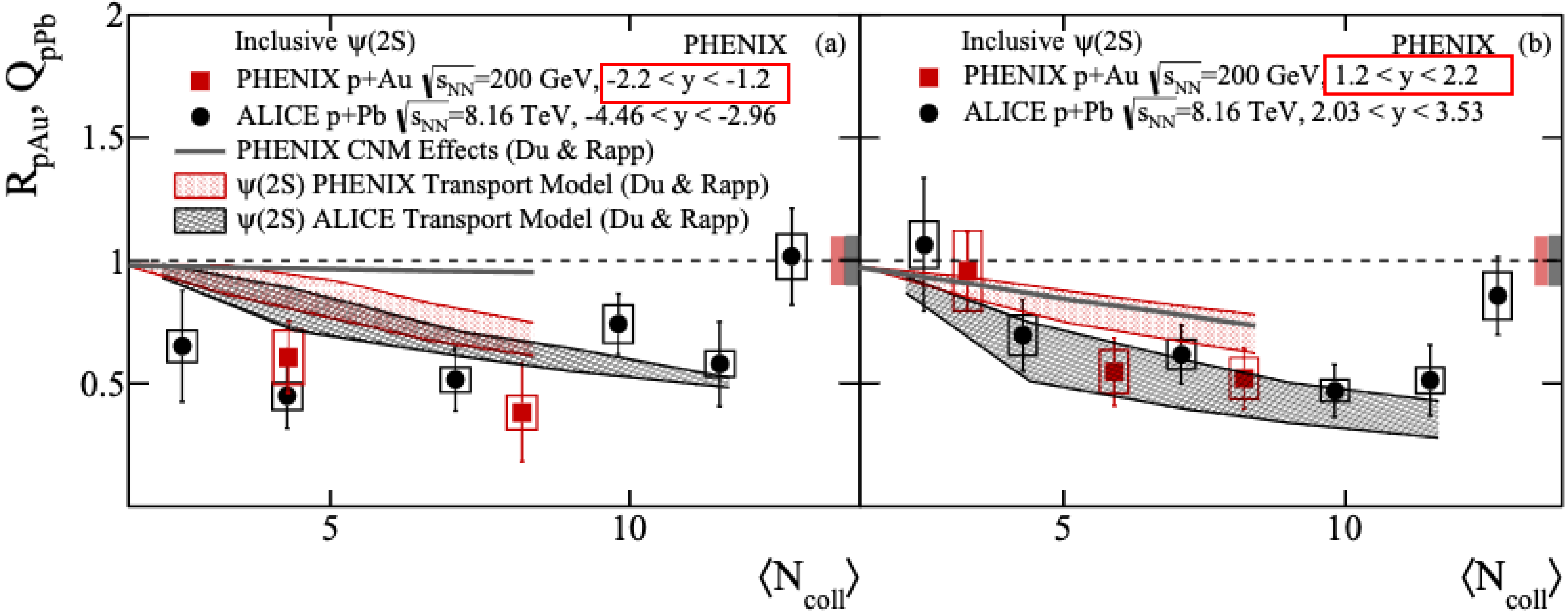

Run 2014 0%-93% Au+Au $\sqrt{s_{NN}}$ = 200 GeV
$|y^e|<0.35$, $p_T^e>0.4$ GeV, $p_T^{ee}>0.8$ GeV
FG_{+-}
BG_{+-}
Signal
PHENIX preliminary
$dN/dm_{e^+e^-}$ (GeV^{-1}) in PHENIX acceptance
Signal/BG
$m_{e^+e^-}$ (GeV)

RHIC vs LHC R_{AB} : Put them all together



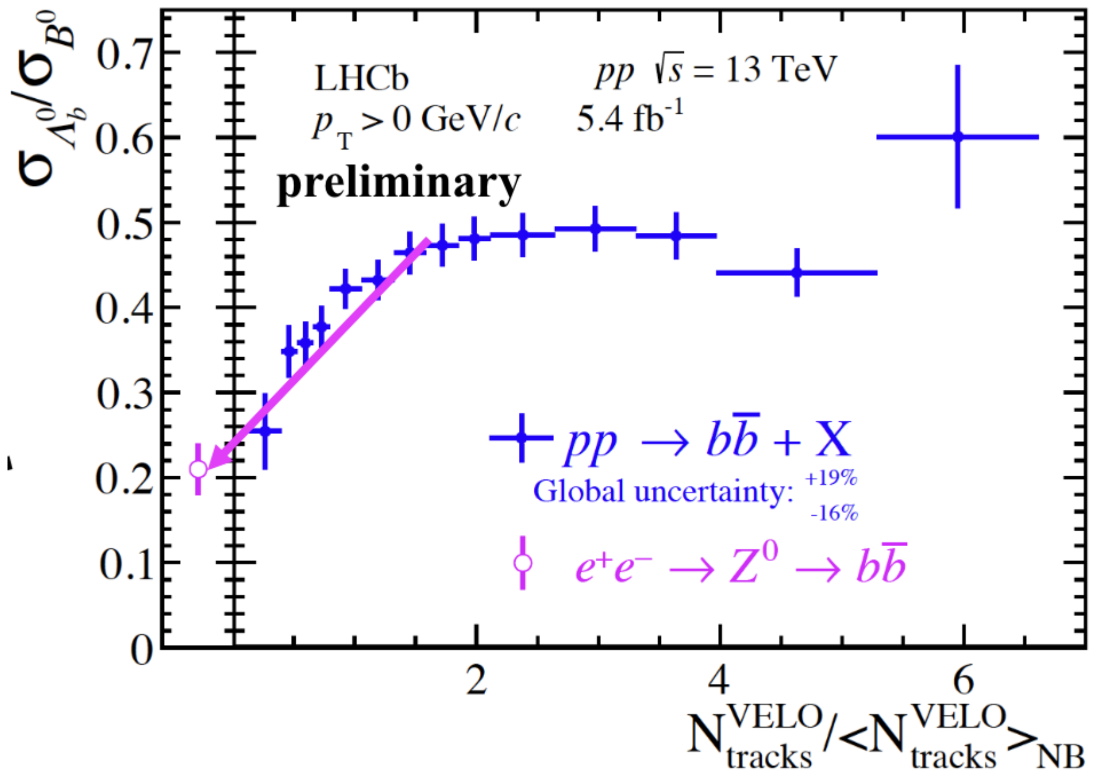
- J/Psi R_{AB} ~ strong rapidity dependence, FSI?
- Psi(2S) R_{AB} remain ~flat vs rapidity, also independent of collision energy, suppression already saturated?

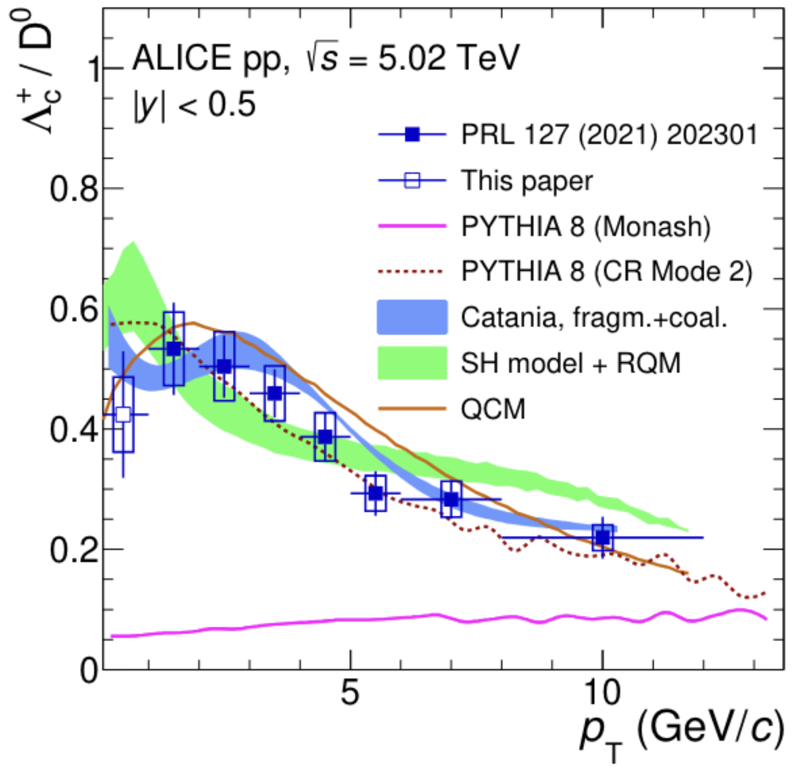
Compared with Models: RHIC and LHC



- stronger suppression in the backward rapidity, more final state effects not accounted for?

HF Hadronization & Event Multiplicity





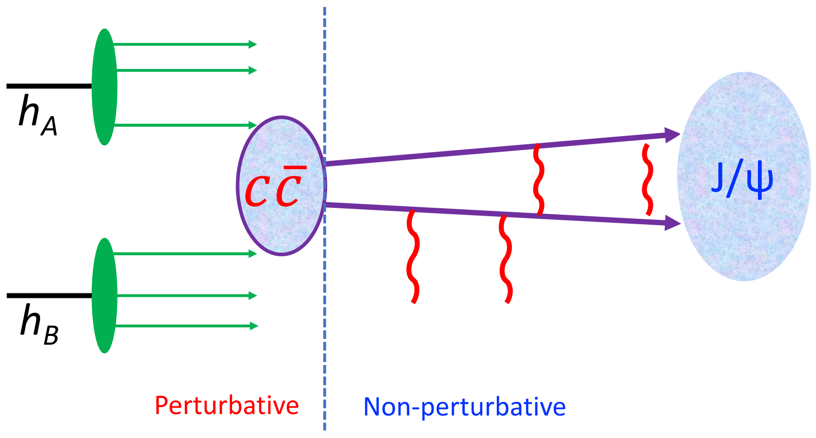
J/ψ Production

Perturbative + **Non-perturbative**

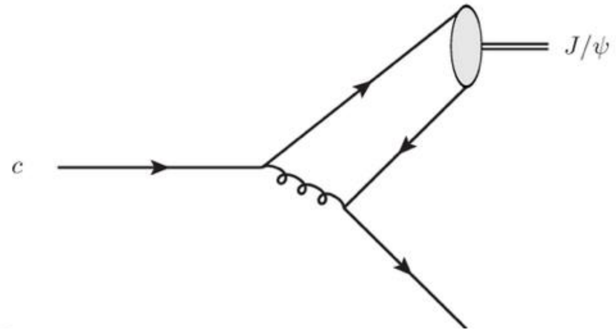
- J/ψ ($c\bar{c}$), a simplest QCD system

- "$c\bar{c}$" pair from hard processes
  - Low pT:
    - Traditional "single" hard scattering process in "p+p"
    - Multiple semi-hard parton interactions (MPI), important at high energy
  - High pT:
    - Jet fragmentation and parton shower, important at high pT

- "$c\bar{c}$" hadronization to J/ψ
  - Color neutralization
    - NRQCD
    - Color evaporation
  - Interactions with QCD medium in HI
  - Recombination if multiple < $c\bar{c}$ > pairs created in HI



I. Belyaev et al, Mod. Phy. Lett. A, (2017)



Charm jet parton shower..