SQM2022

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on Strangeness in Quark Matter
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Brookhaven™
National Laboratory

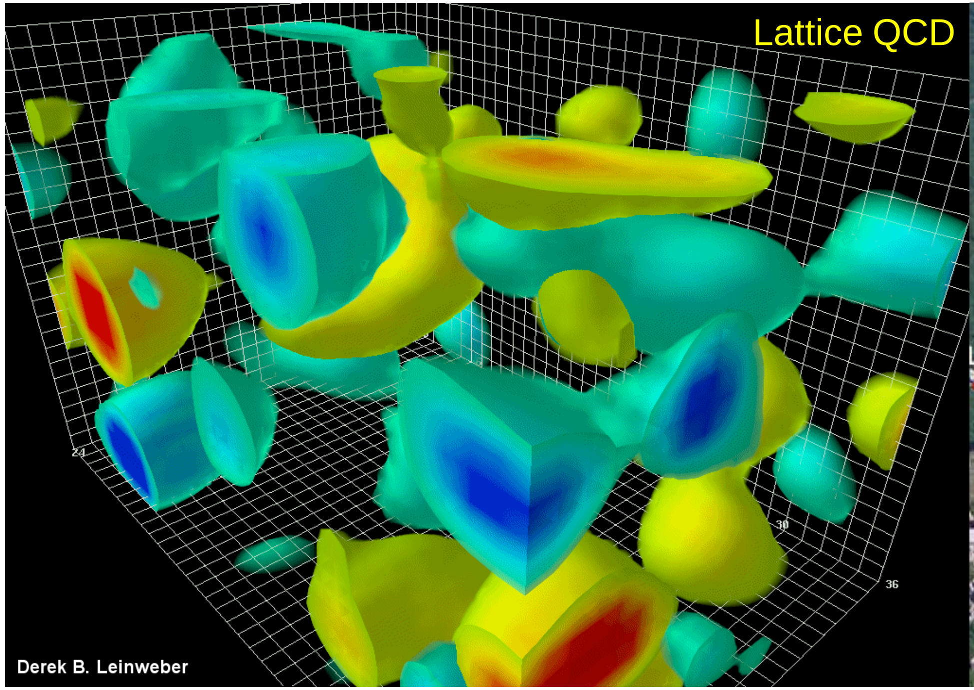
U.S. DEPARTMENT OF
ENERGY

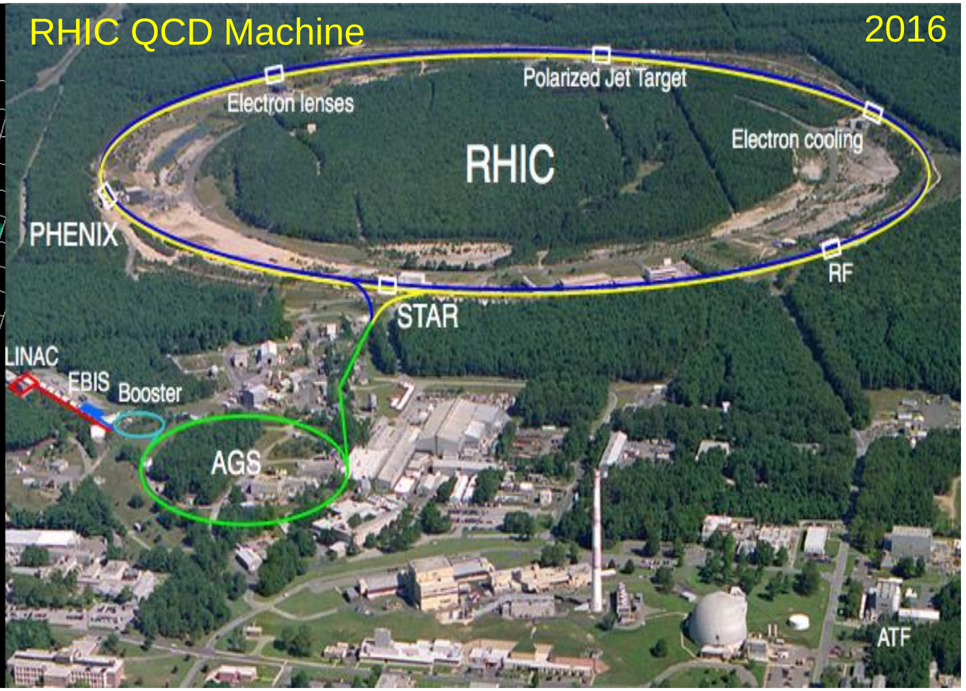
PHENIX Probing QCD Matter Through Heavy Flavor and Quarkonium at RHIC

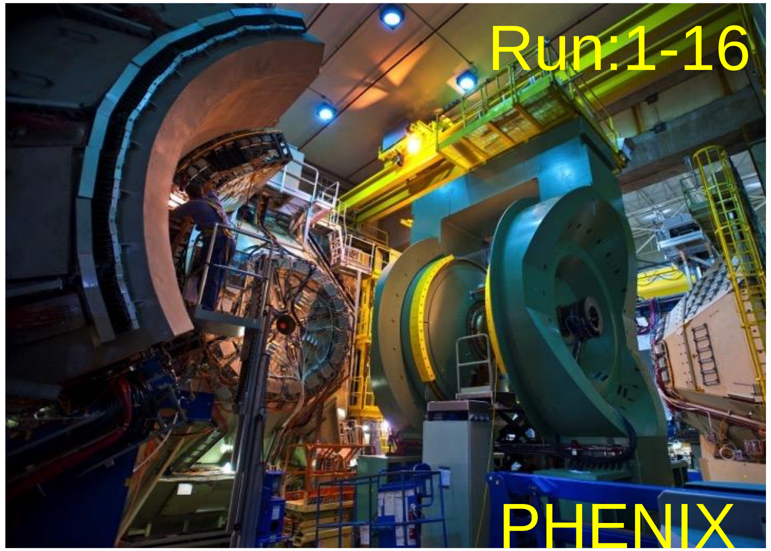
Rachid Nouicer, for the PHENIX Collaboration

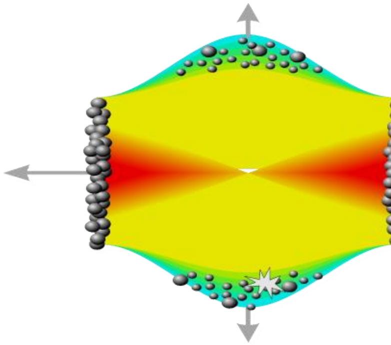
- PHENIX has several recent findings. Few (relevant) selected results:
  1. Open Heavy Flavor
  2. Quarkonium in “Small Systems”
  3. Summary

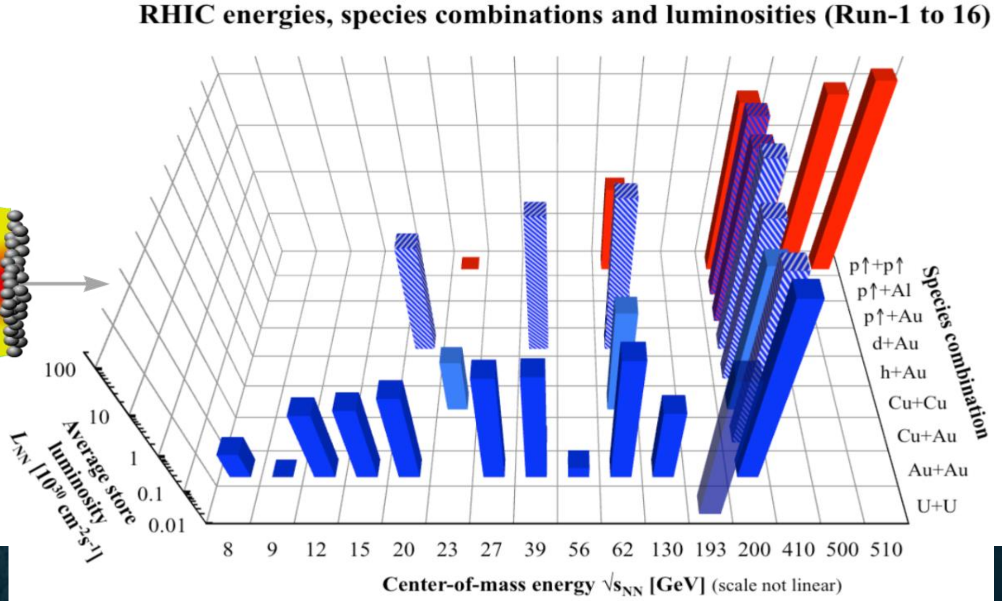
RHIC Amazing QCD Machine: Many Species and Energies











RHIC energies, species combinations and luminosities (Run-1 to 16)

PHENIX Collected and Enjoying Every Bit of RHIC Data

Run	Species	Total particle energy [GeV/nucleon]	total delivered Luminosity $[\mu b^{-1}]$
I (2000)	Au+Au Au+Au	56 130	< 0.001 20
II (2001/2002)	Au+Au Au+Au p+p	200 19.6 200	25.8 0.4 $1.4x10^{-6}$
III (2003)	d+Au p+p	200 200	$73x10^{-3}$ $5.5x10^{-6}$
IV(2004)	Au+Au Au+Au p+p	200 62.4 200	$3.53x10^{-3}$ 67 $7.1x10^{-6}$
V (2005)	Cu+Cu Cu+Cu Cu+Cu p+p p+p	200 62.4 22.4 200 410	$42.1x10^{-3}$ $1.5x10^{-3}$ $0.02x10^{-3}$ $29.5x10^{-6}$ $0.1x10^{-6}$
VI (2006)	p+p p+p	200 62.4	$88.6x10^{-6}$ $1.05x10^{-6}$
VII (2007)	Au+Au Au+Au	200 9.2	$7.25x10^{-3}$ Small
VIII (2008)	d+Au p+p Au+Au	200 200 9.6	$437x10^{-3}$ $38.4x10^{-6}$ Small

Run	Species	Total particle energy [GeV/nucleon]	Total delivered luminosity $[\mu b^{-1}]$
IX (2009)	p+p +p	500 200	$110x10^{-6}$ $114x10^{-6}$
X (2010)	Au+Au Au+Au Au+Au Au+Au Au+Au	200 62.4 39 7.7 11.5	$10.3x10^{-3}$ 544 206 4.23 7.8
XI (2011)	p+p Au+Au Au+Au Au+Au	500 19.6 200 27	$166x10^{-6}$ 33.2 $9.79x10^{-3}$ 63.1
XII (2012)	p+p p+p U+U Cu+Au	200 510 193 200	$74x10^{-6}$ $283x10^{-6}$ 736 $27x10^{-3}$
XIII (2013)	p+p	510	$1.04x10^{-9}$
XIV (2014)	Au+Au Au+Au ^{3}He+Au	14.6 200 200	44.2 $43.9x10^{-3}$ $134x10^{-3}$
XV (2015)	p+p p+Au p+Al	200 200 200	$282x10^{-6}$ $1.27x10^{-6}$ $3.97x10^{-6}$
XVI (2016)	Au+Au d+Au d+Au d+Au d+Au	200 200 62.4 19.6 39	$52.2x10^{-3}$ $46.1x10^{-3}$ $44.0x10^{-3}$ $7.2x10^{-3}$ $19.5x10^{-3}$

Heavy Flavor Approach to Study QCDM

We study QCD matter (Hot vs Cold) through heavy flavor production:

1) Open Heavy Flavor **2) Quarkonia**

Recipe on how to study hot and cold QCDM

System Size/ Collision Asymmetry

Change the relative contributions
of **Cold** and **Hot** nuclear matter effects

Centrality

Suppression vs path length

Collision Energy

Change system energy density

Momentum

Hard collision dynamics

Rapidity

Probes different gluon
(anti)shadowing

Heavy/Light

Mass ordering of suppression

Particle Species

Break-up, Temperature?

PHENIX Detector

- PHENIX: optimized to measure leptons: rapidity coverage: $1.2<|y|<2.2$ and $|y|<0.35$

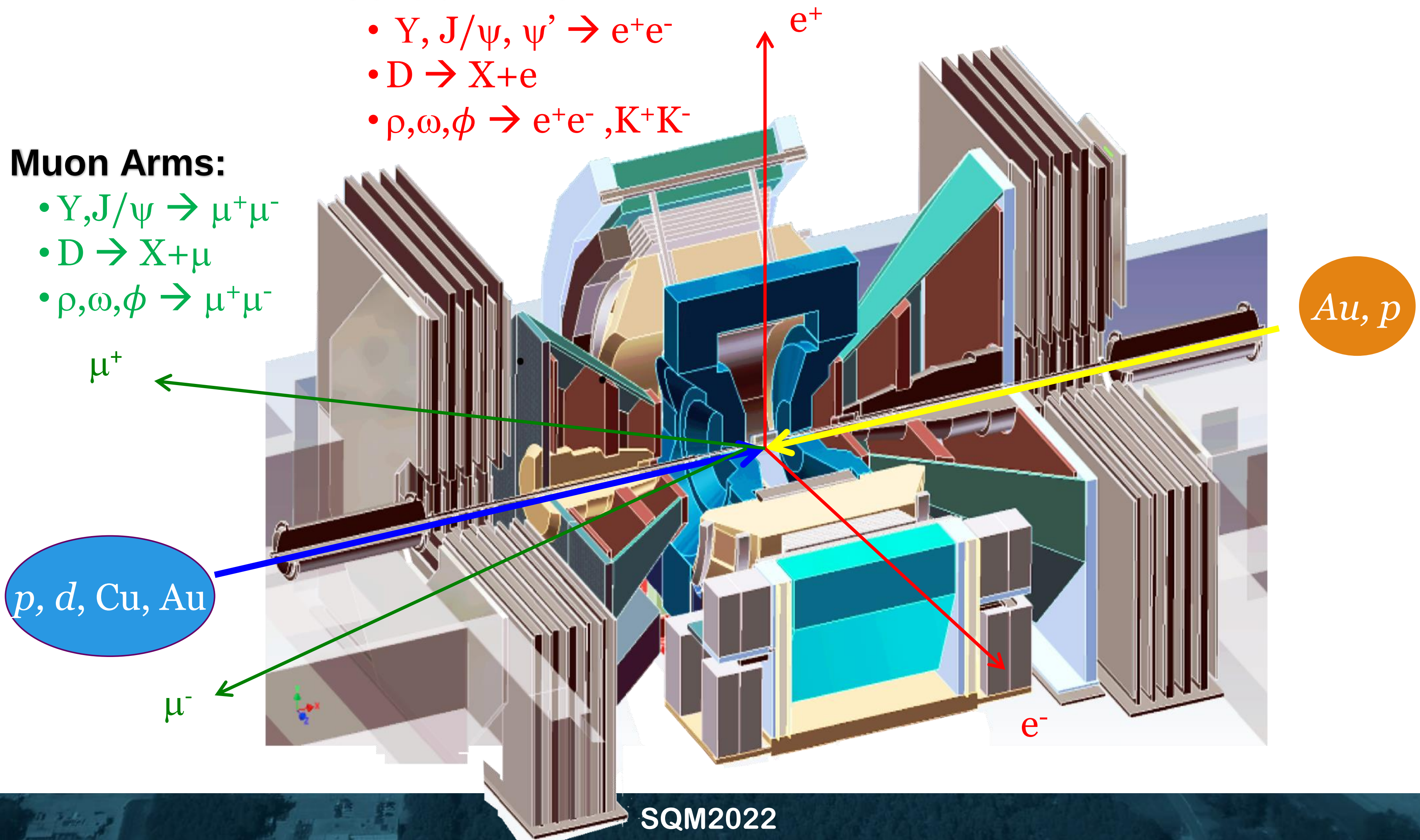
1) high rate capability 2) emphasis on mass resolution & particle ID 3) first level e&μ triggers

Central Arms:

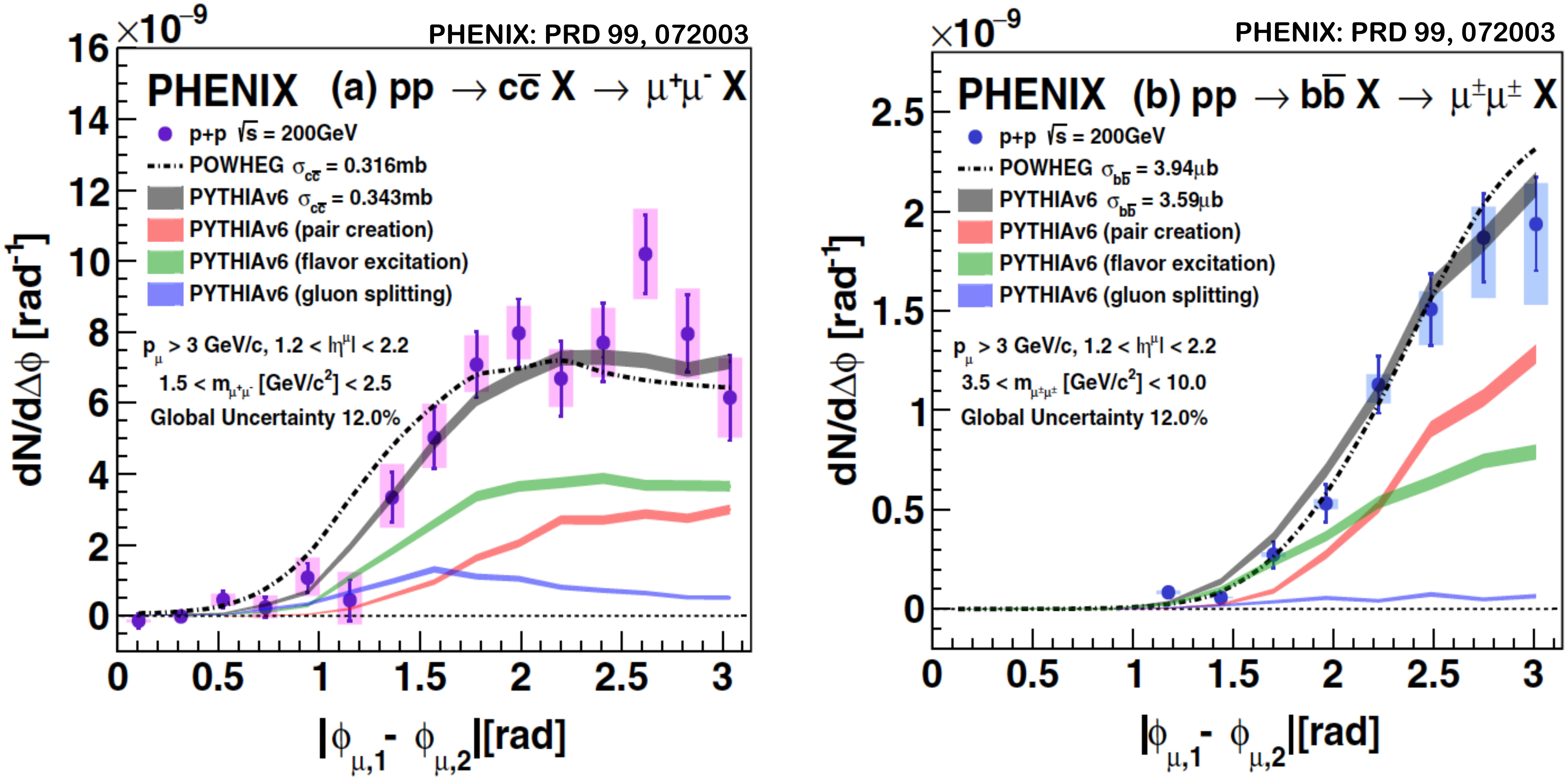
- Y, J/ψ, ψ' → e^+e^-
- D → X+e
- ρ,ω,ϕ → e^+e^- ,K^+K^-

Muon Arms:

- Y,J/ψ → $\mu^+\mu^-$
- D → X+μ
- ρ,ω,ϕ → $\mu^+\mu^-$



Heavy Flavor Production at RHIC

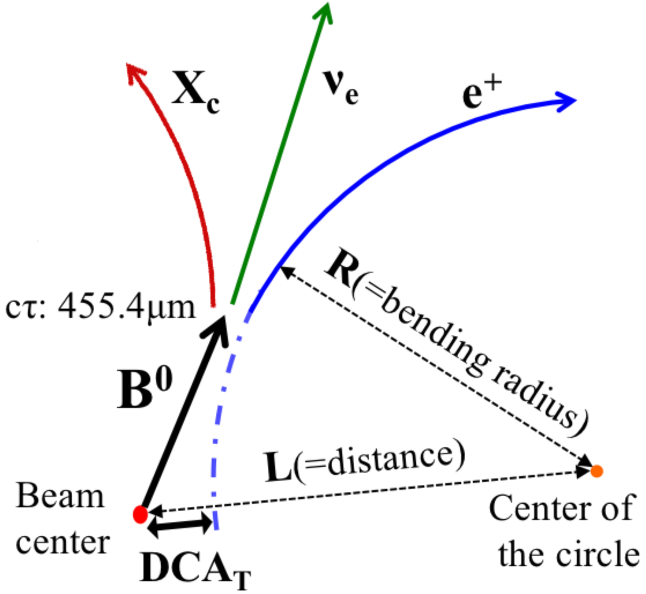


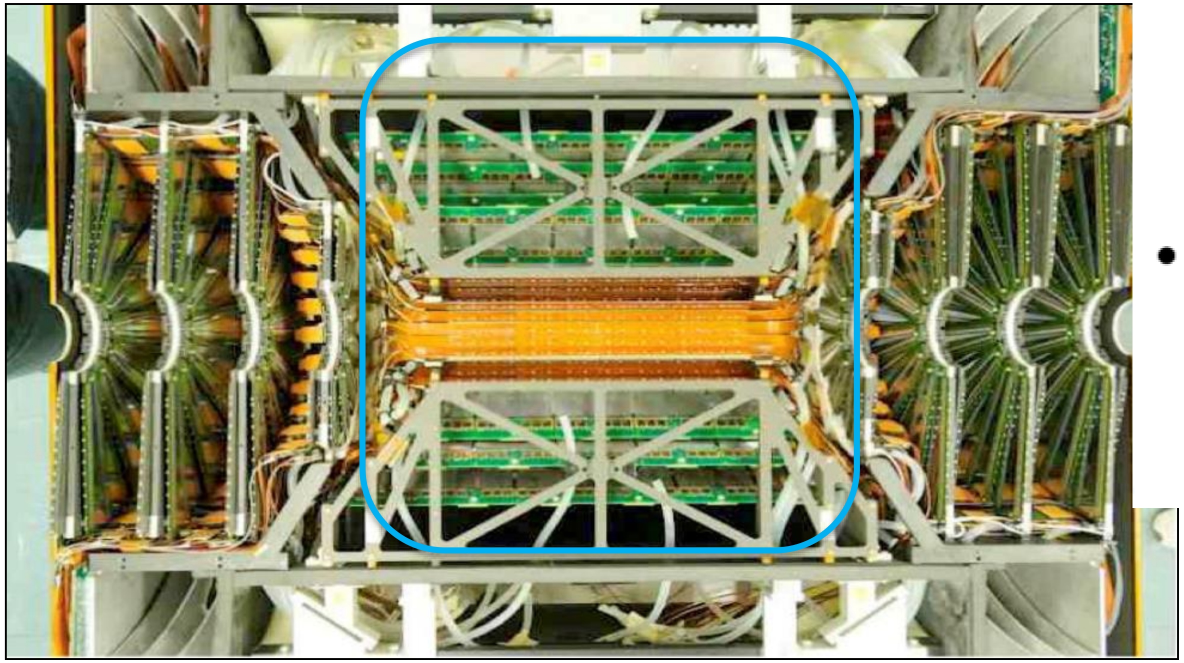
- Heavy flavors (charm & bottom) are predominantly produced in hard scattering
  - Dominant production mechanism at RHIC: pair creation and flavor excitation.

PHENIX Heavy Flavor Measurements: Bottom and Charm Separation

VTX Silicon detector:
4 barrels of silicon

- **VTX: |η | <1.2**





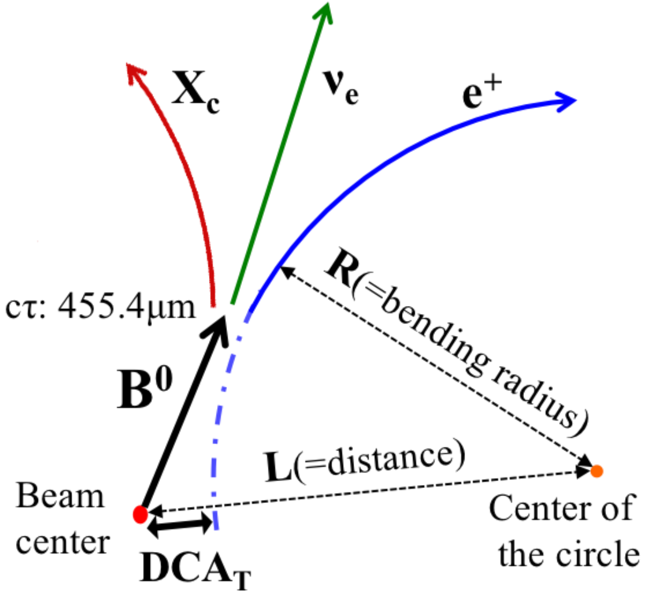
Bottom and Charm separation

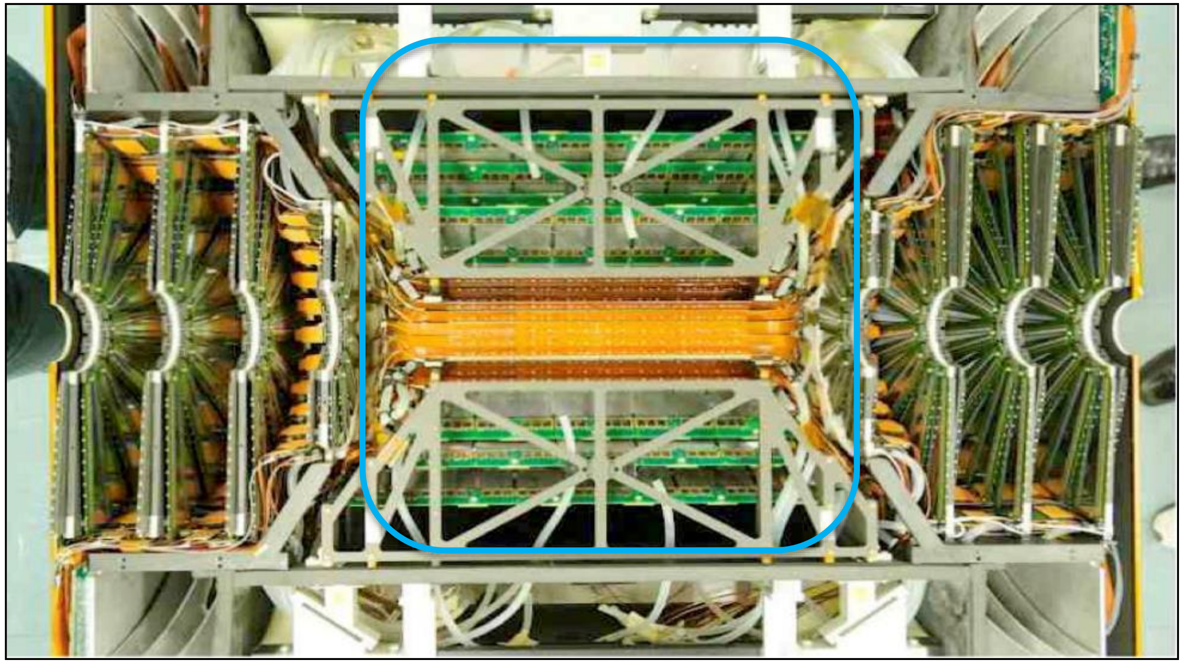
- Electrons from charm and bottom hadron decays
- Charm and bottom separation using the distance-of-closest-approach (DCA) and p_T distribution
- Bayesian unfolding method:
  - Separates charm and bottom contribution in electrons
  - Extract charm and bottom hadron yields

Heavy Flavor: Bottom and Charm Separation

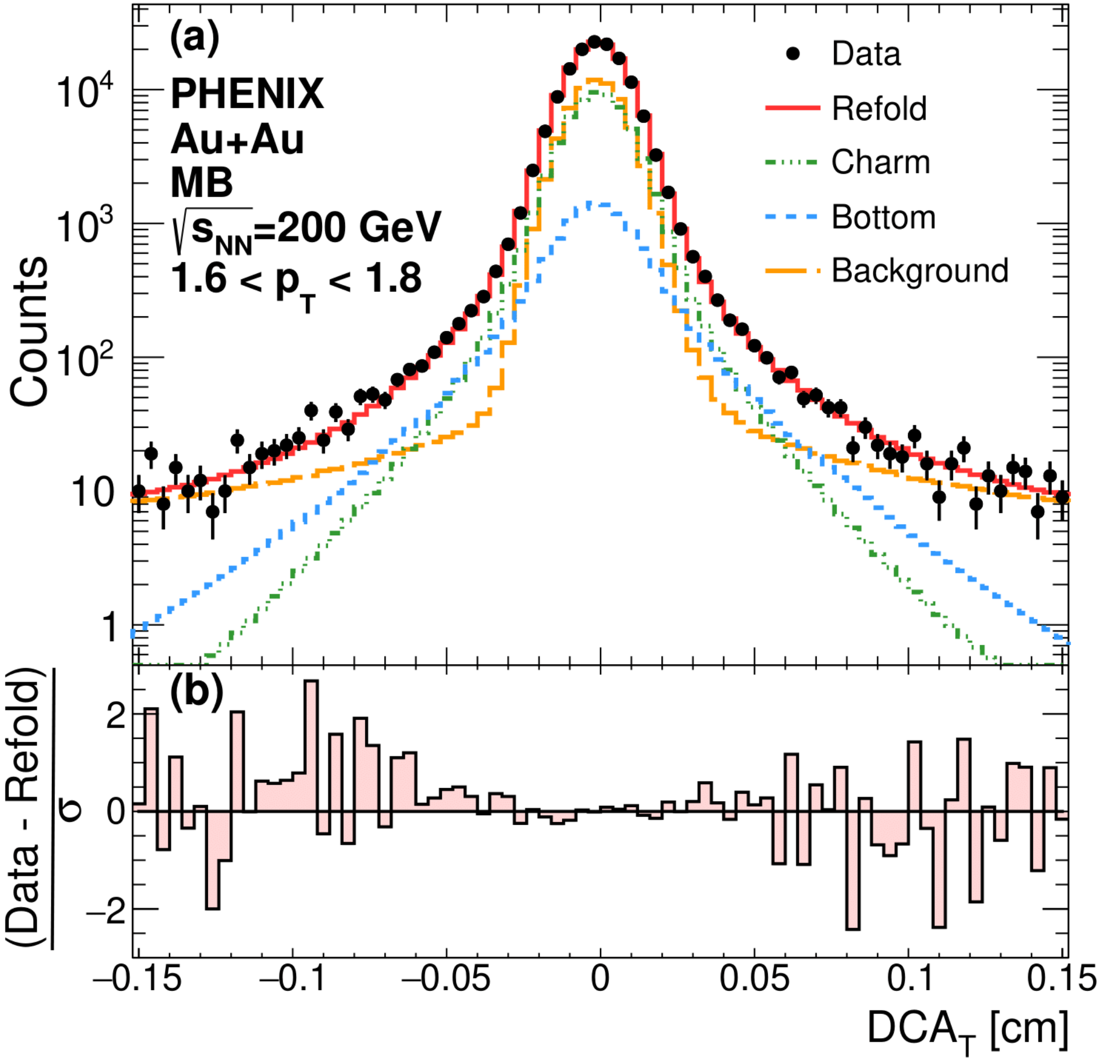
VTX Silicon detector:
4 barrels of silicon

- **VTX: |η | <1.2**



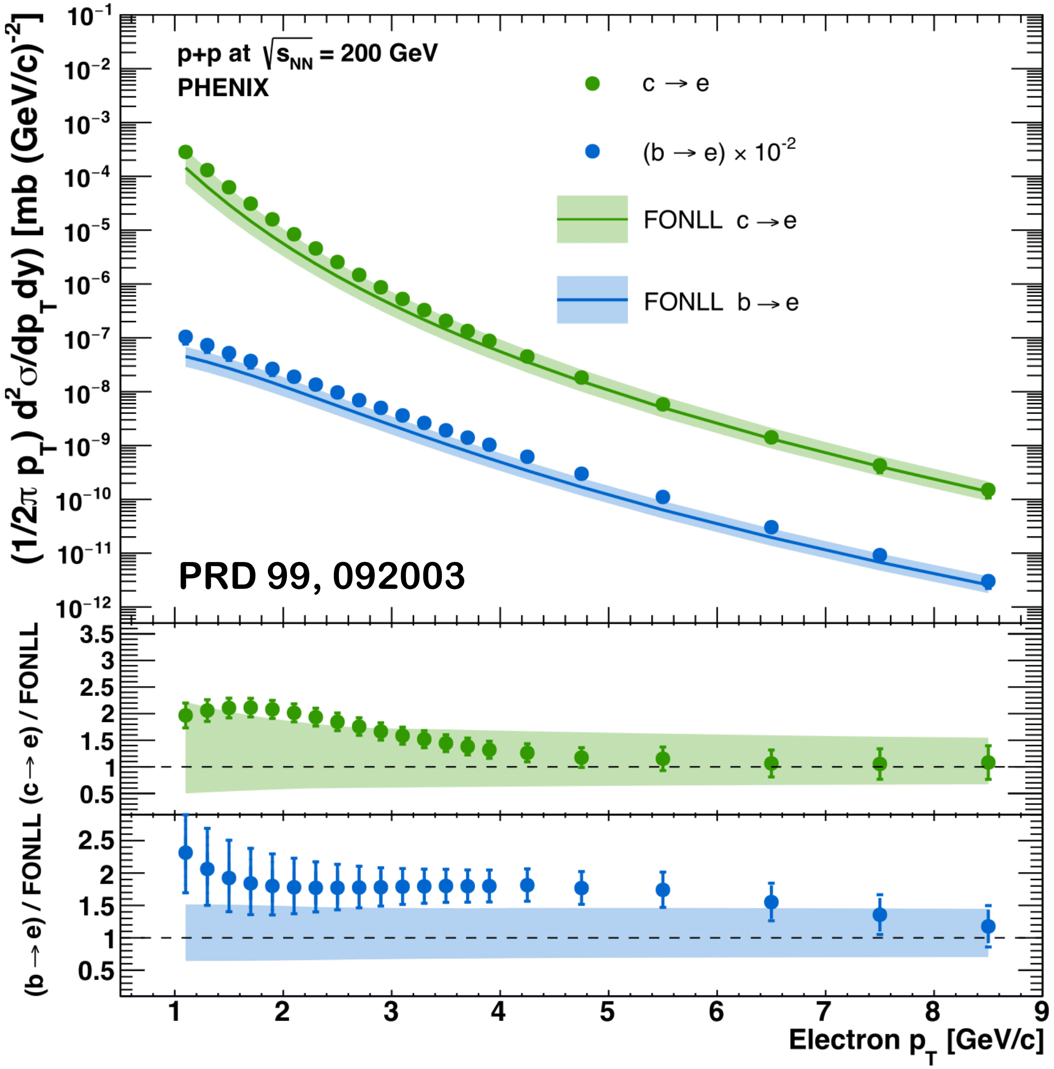


Bottom and Charm separation

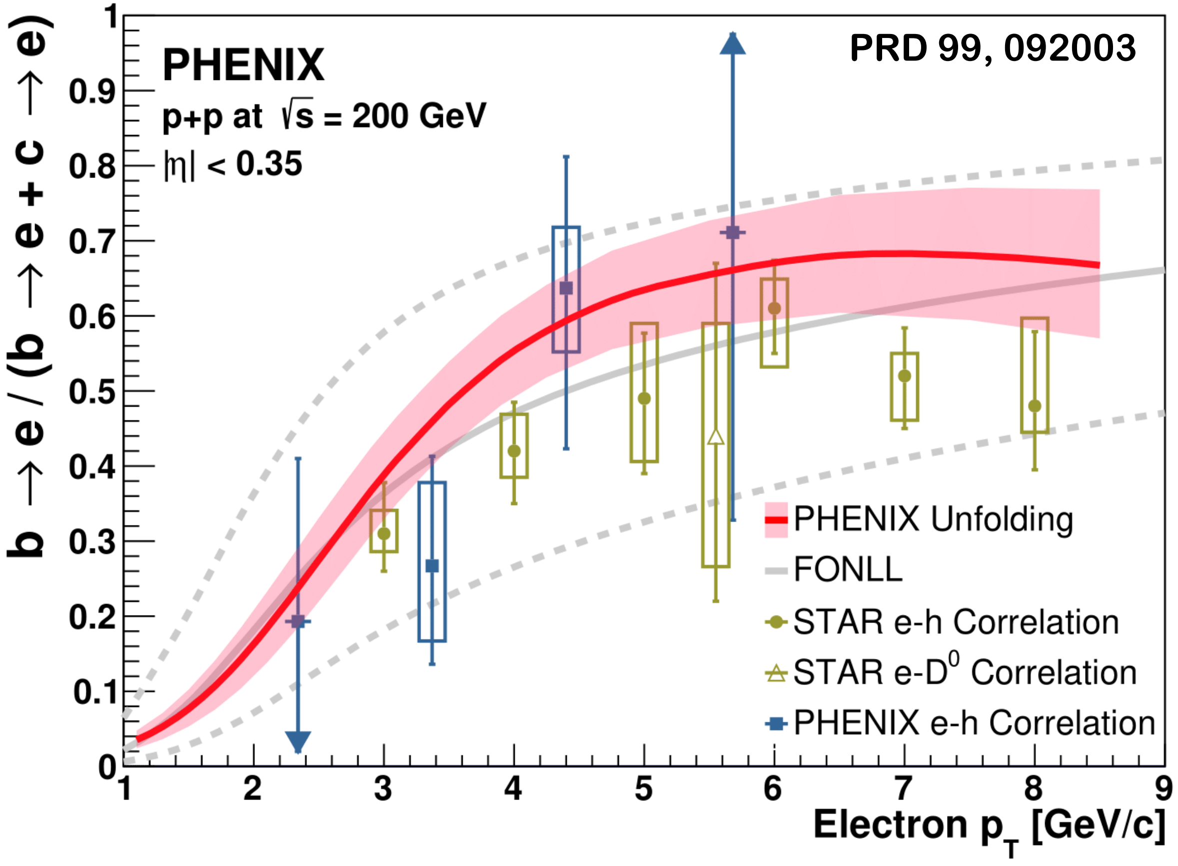


p + p Baseline: Bottom Electron Fraction

Spectra of Electrons from Charm and Bottom



Bottom Fraction vs p_T



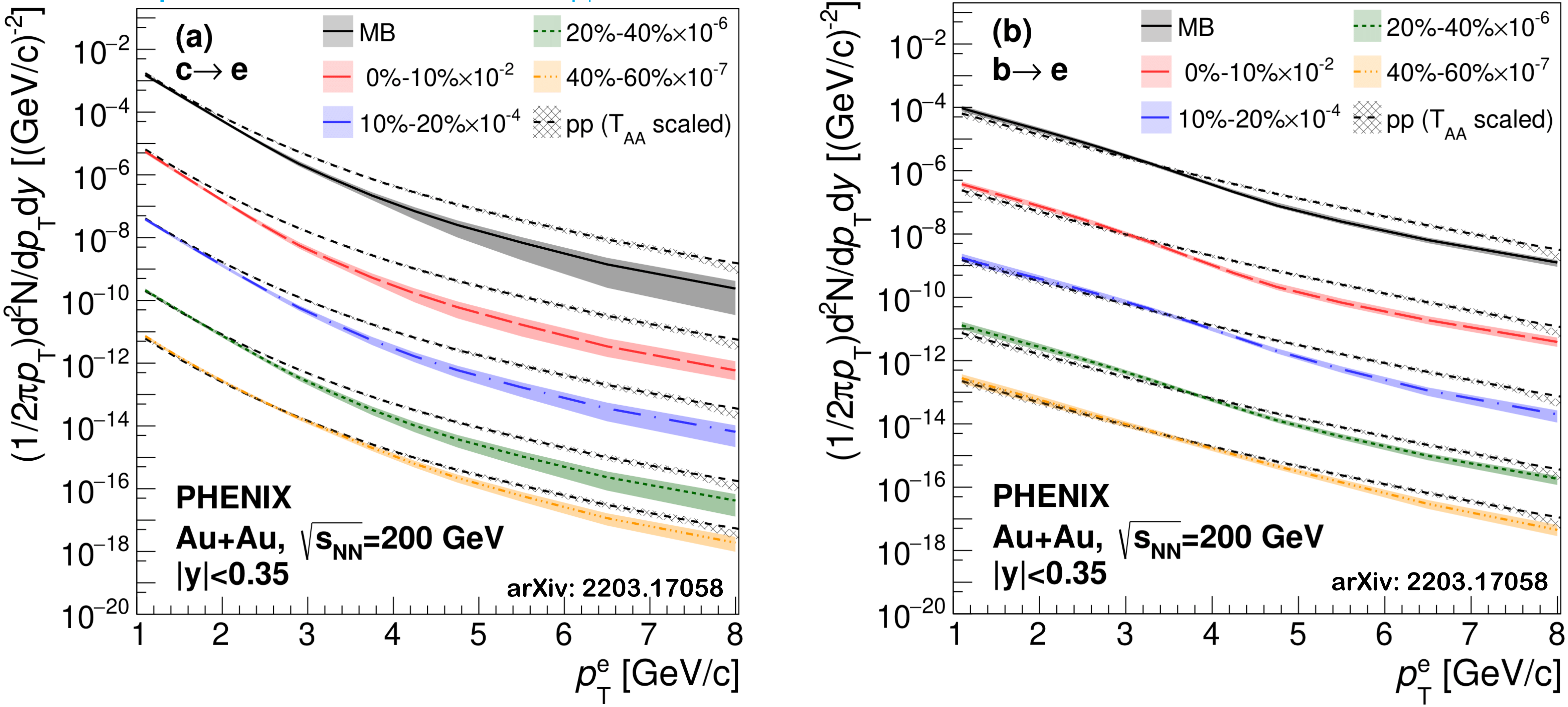
p+p baseline of charms and bottoms obtained w/ p_T = 1 ~ 8 GeV/c

Charm and Bottom Electron Yields in Au+Au at 200 GeV

Centrality Dependence of Spectra of Electrons from Charms and Bottoms obtained in Au+Au Collisions at 200 GeV

Spectra of Electrons from **Charm** vs p_T

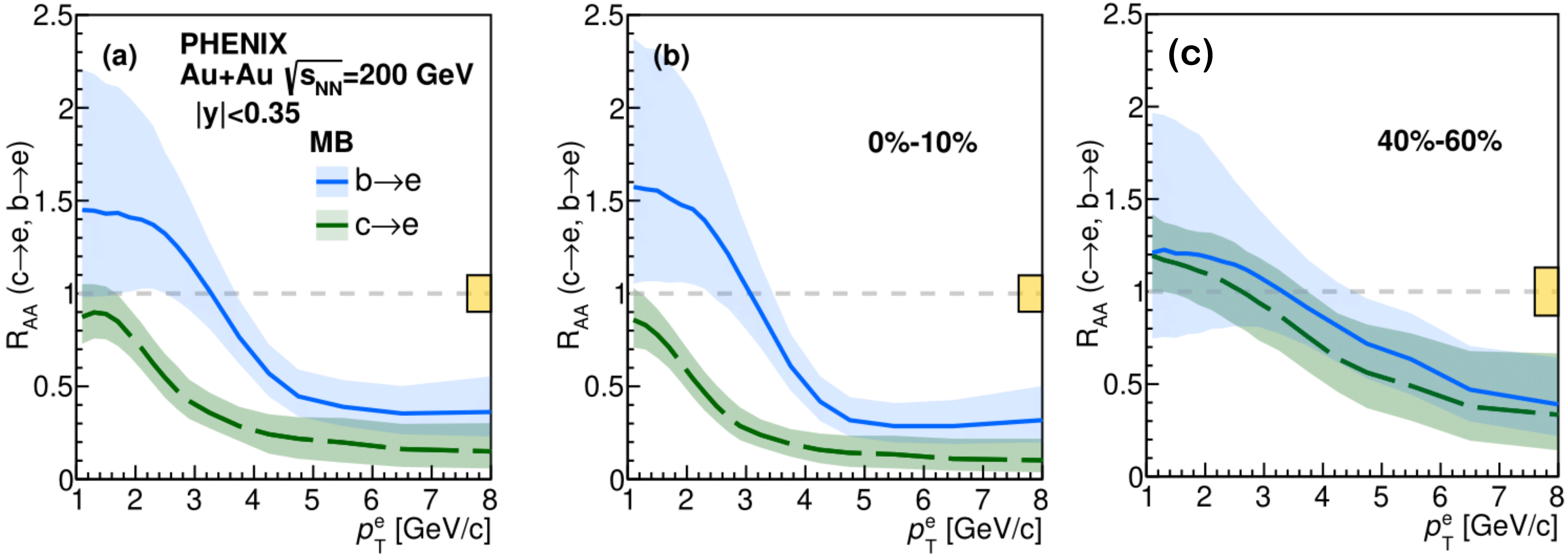
Spectra of Electrons from **Bottom** vs p_T



Centrality Dependence of R_{AA} (b→e) and R_{AA}(c→e)

PHENIX: Au+Au at 200 GeV

arXiv: 2203.17058



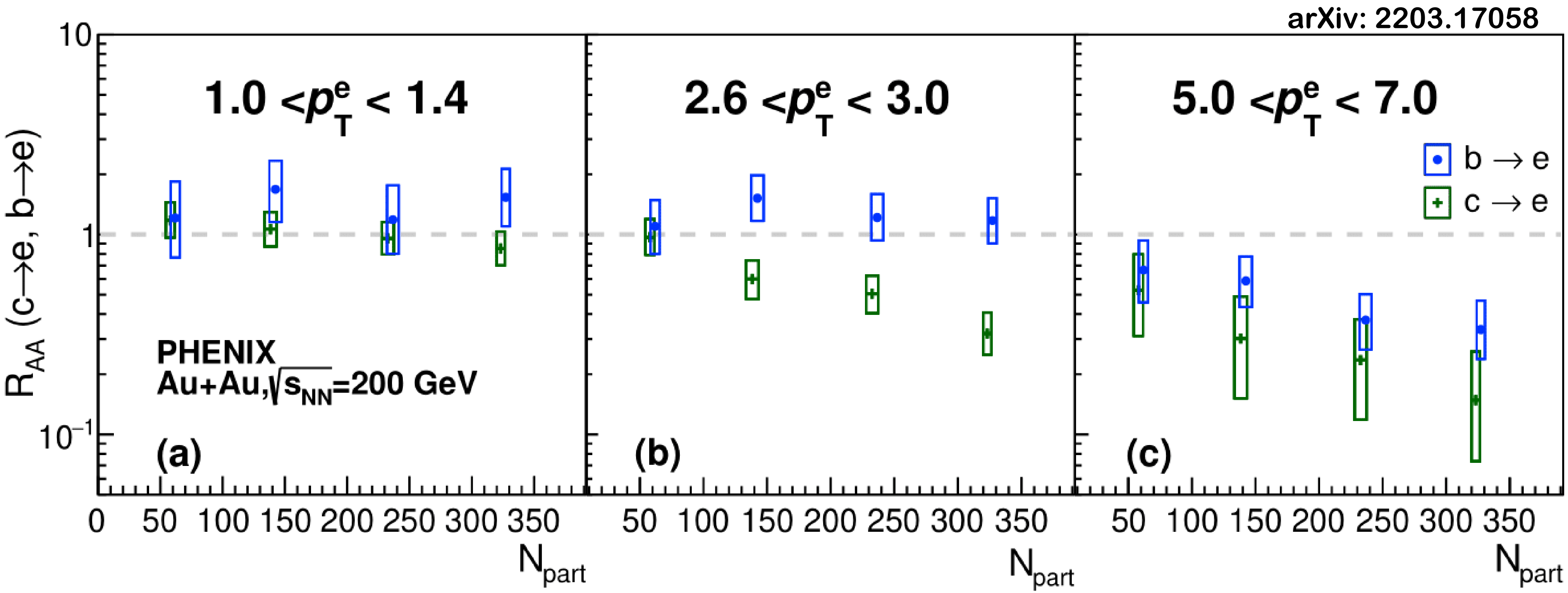
- Centralities: MB and 0-10%: bottom suppression is different from charm

  →Clear p_T Dependence

  → Mid-p_T: R_{AA} (b→e) > R_{AA} (c→e)
- Centrality: 40-60%: bottom and charm are similar and less suppressed

Centrality Dependence of R_{AA} (b→e) and R_{AA}(c→e)

PHENIX: Au+Au at 200 GeV



- R_{AA}(b→e) ~ R_{AA}(c-> e) ~ 1

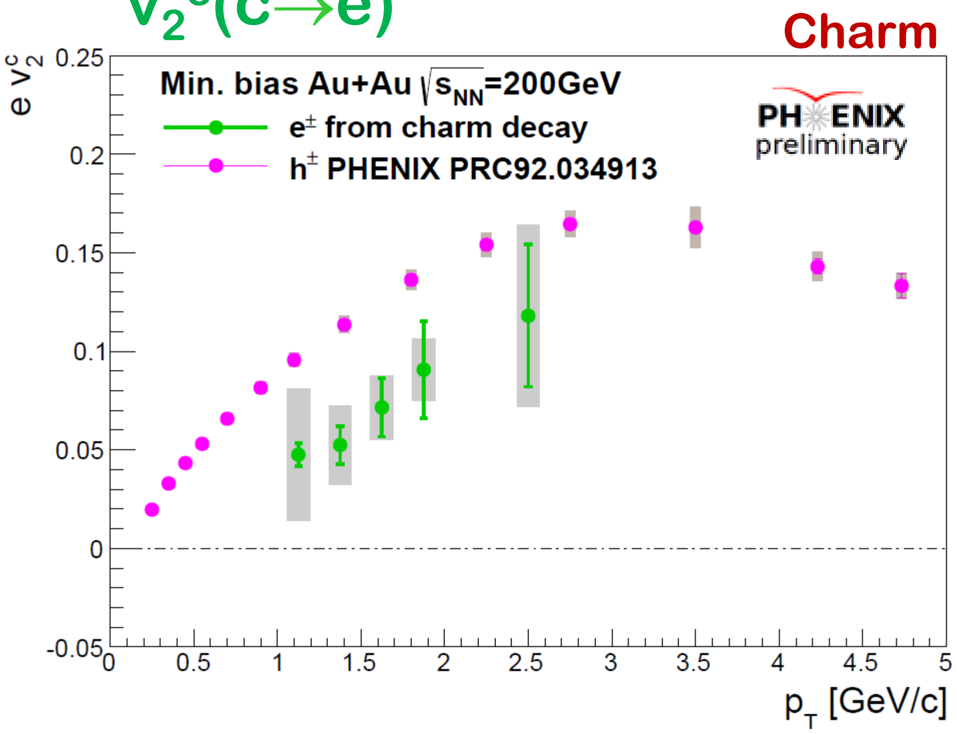
- R_{AA}(c→e) < R_{AA}(b-> e)
- R_{AA}(b → e) ~ 1

- R_{AA}(b→e) ~ R_{AA}(c-> e) < 1

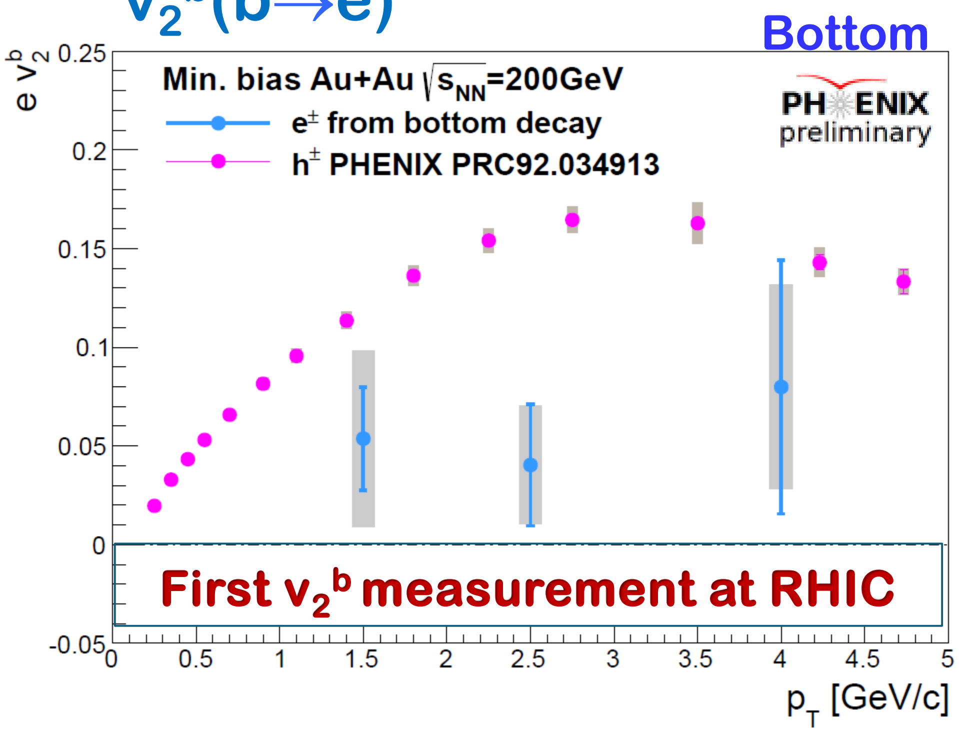
Clear Centrality and p_T Dependence Observed

Preliminary Results: Elliptic Flow of Charm and Bottom in Au+Au

$v_2^c(c \rightarrow e)$



$v_2^b(b \rightarrow e)$



- $v_2(c \rightarrow e)$ is positive and smaller than charged hadron v_2
- First $v_2(b \rightarrow e)$ measurement at RHIC
  - A hint of a positive v_2
  - Likely smaller than $v_2(c \rightarrow e)$

Quarkonia in “Small Systems”

- Do we see evidence of final state effects in light systems?
- How well do we understand quarkonia modification in light systems?

p+Au at 200 GeV

d+Au at 200 GeV

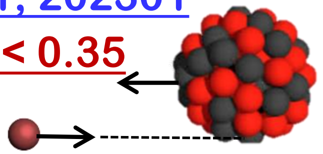
^{3}He+Au at 200 GeV

p+Al at 200 GeV

Intriguing Results Observed at Midrapidity in d+Au at 200 GeV at RHIC

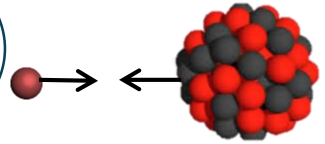
PHENIX: PRL 111, 202301

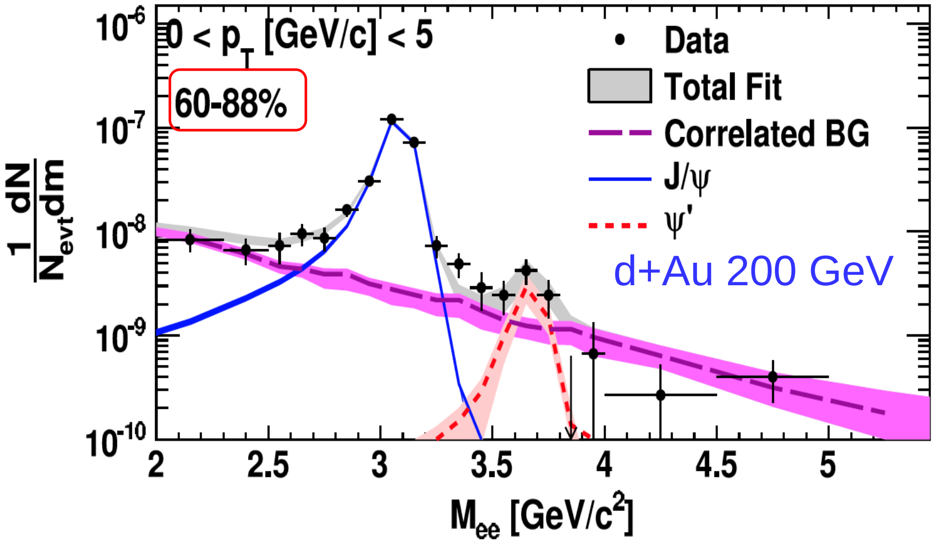
Mid- Rapidity |η| < 0.35

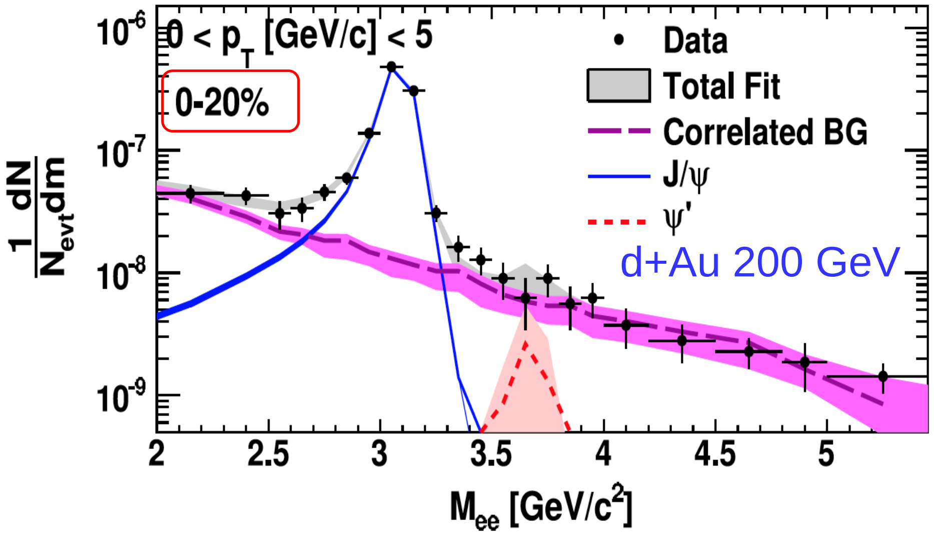


peripheral
60—88%
N_{coll} ~ 3

central
0—20%
N_{coll} ~ 15



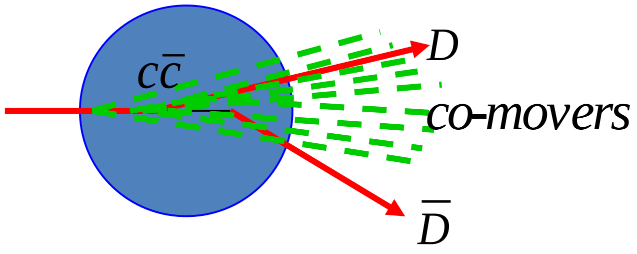


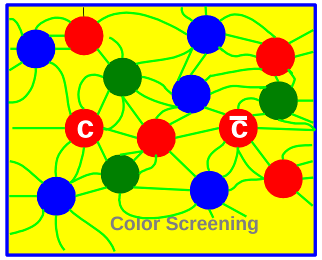


Breakup of quarkonia due to interaction with nuclear matters

1) Large suppression of the weakly bounded state ψ'

2) Interaction with nucleus? comovers? or medium?

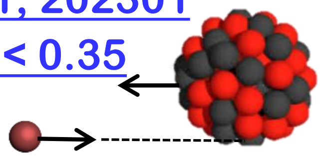




Intriguing Results Observed at Midrapidity in d+Au at 200 GeV at RHIC

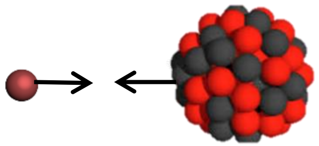
PHENIX: PRL 111, 202301

Mid- Rapidity |η| < 0.35

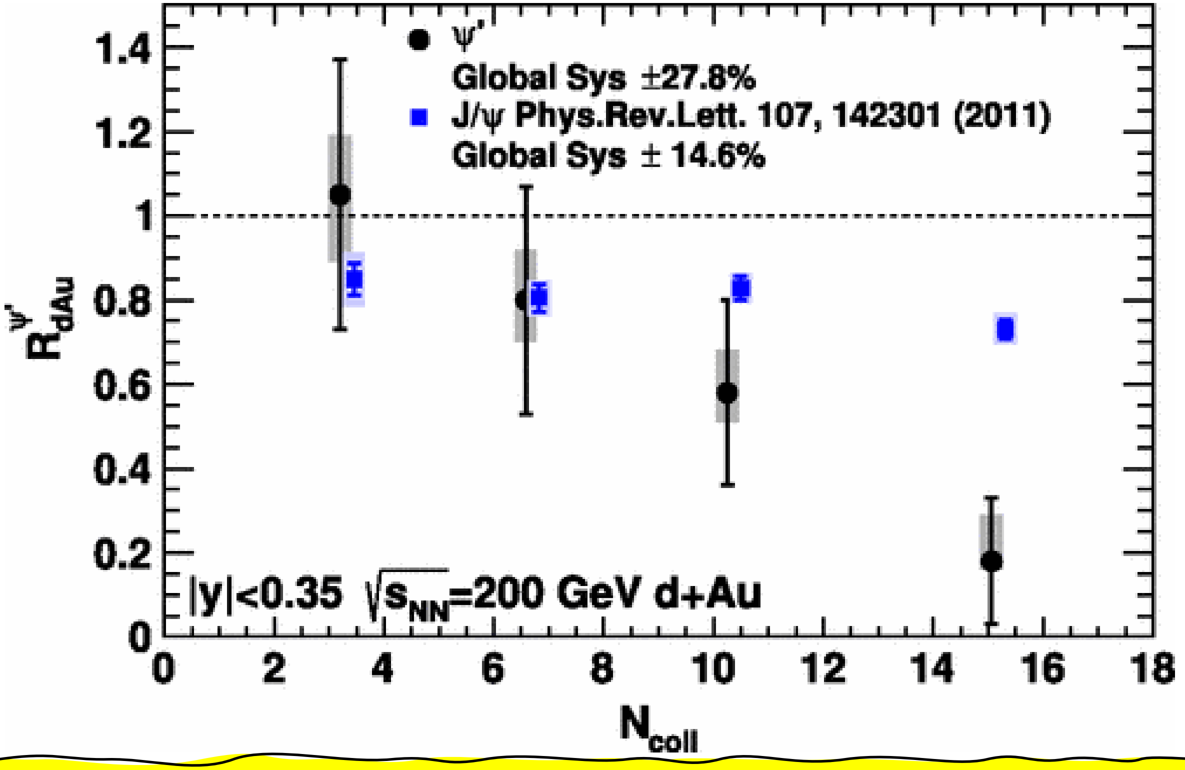


peripheral
60—88%
N_{coll} ~ 3

central
0—20%
N_{coll} ~ 15



Nuclear Modification Factor

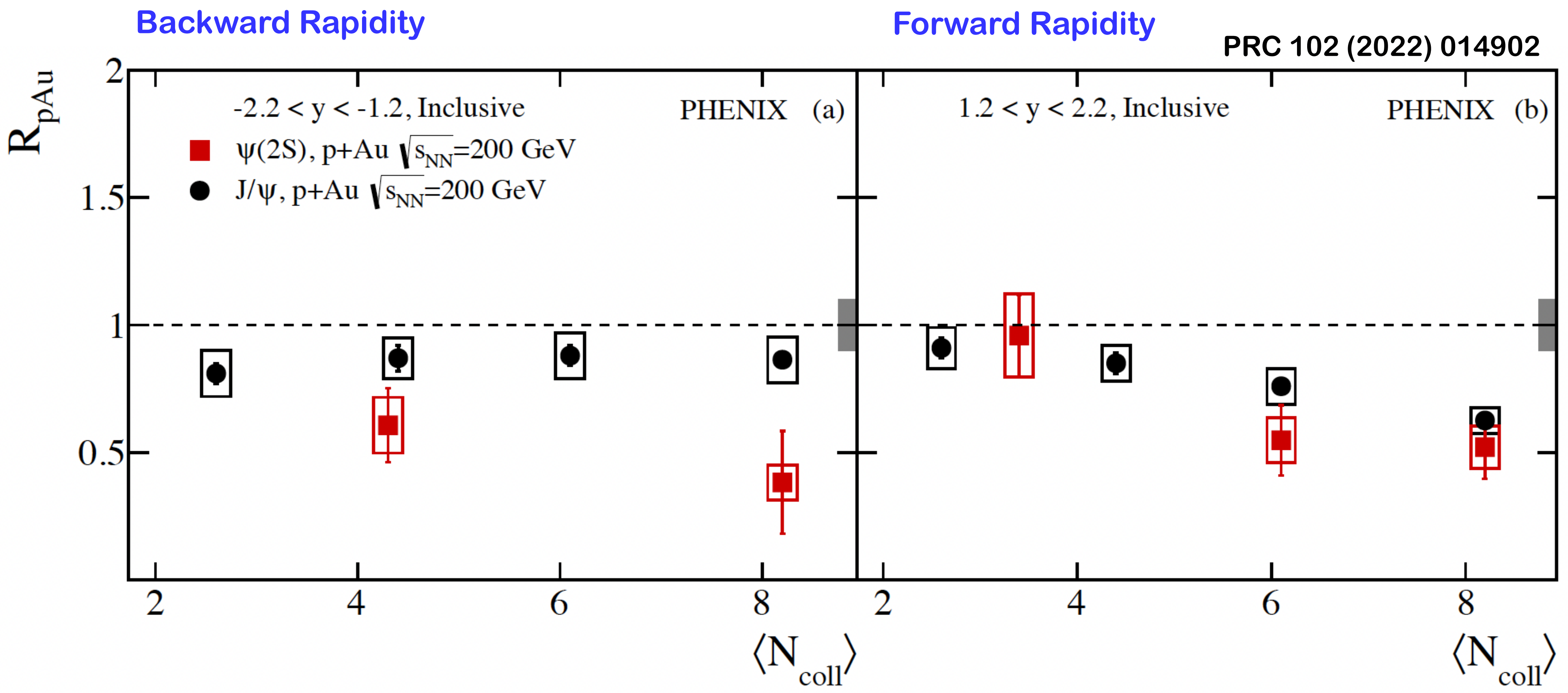


At mid-rapidity: ψ (2S) is more suppress than ψ(1S) in central d+Au collisions

→ What about forward/backward rapidity?

→ What about smaller systems?

Charmonia Nuclear Modification in p +Au Collisions at 200 GeV (RHIC)

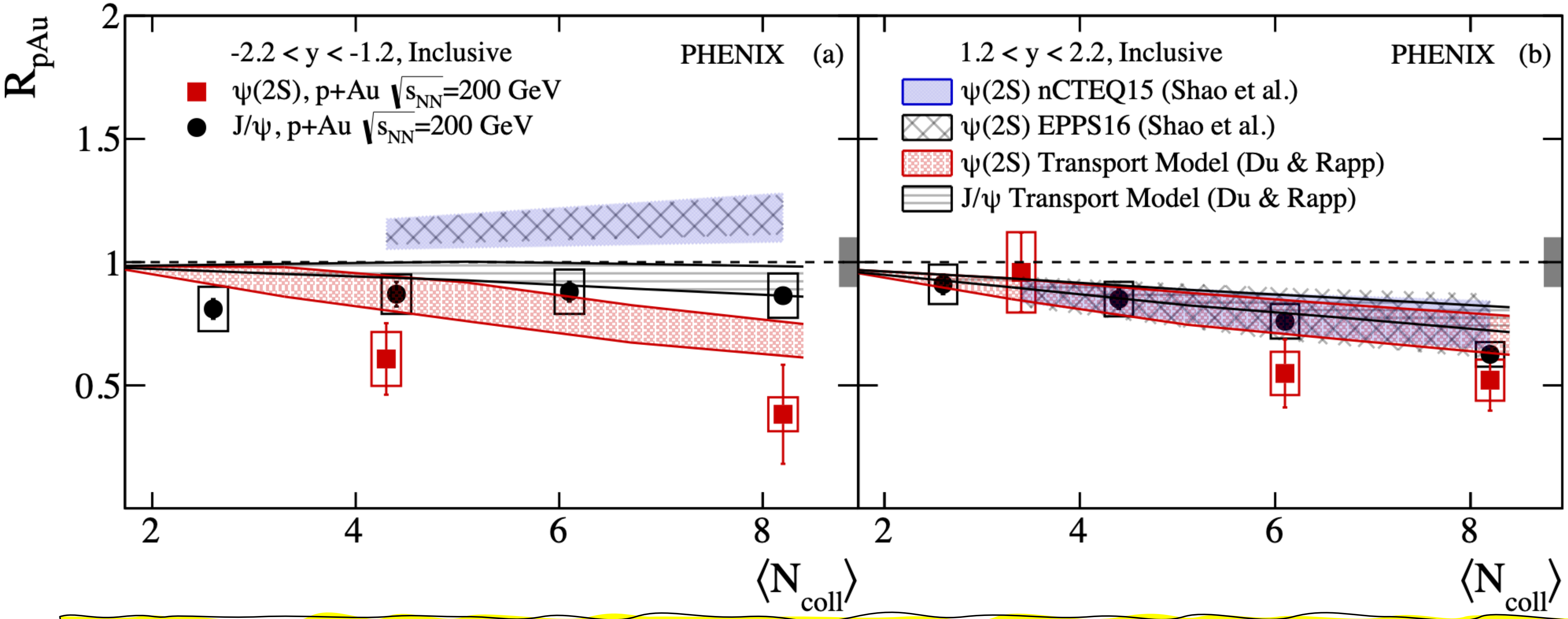


- At forward rapidity, J/ψ and $\psi(2S)$ modification follow similar trend
  - → Hints for a cold nuclear matter effects dominate
- At backward rapidity, clear difference in $\psi(2S)$ modification in most central collisions

Charmonia Nuclear Modification in p +Au Collisions at 200 GeV (RHIC)

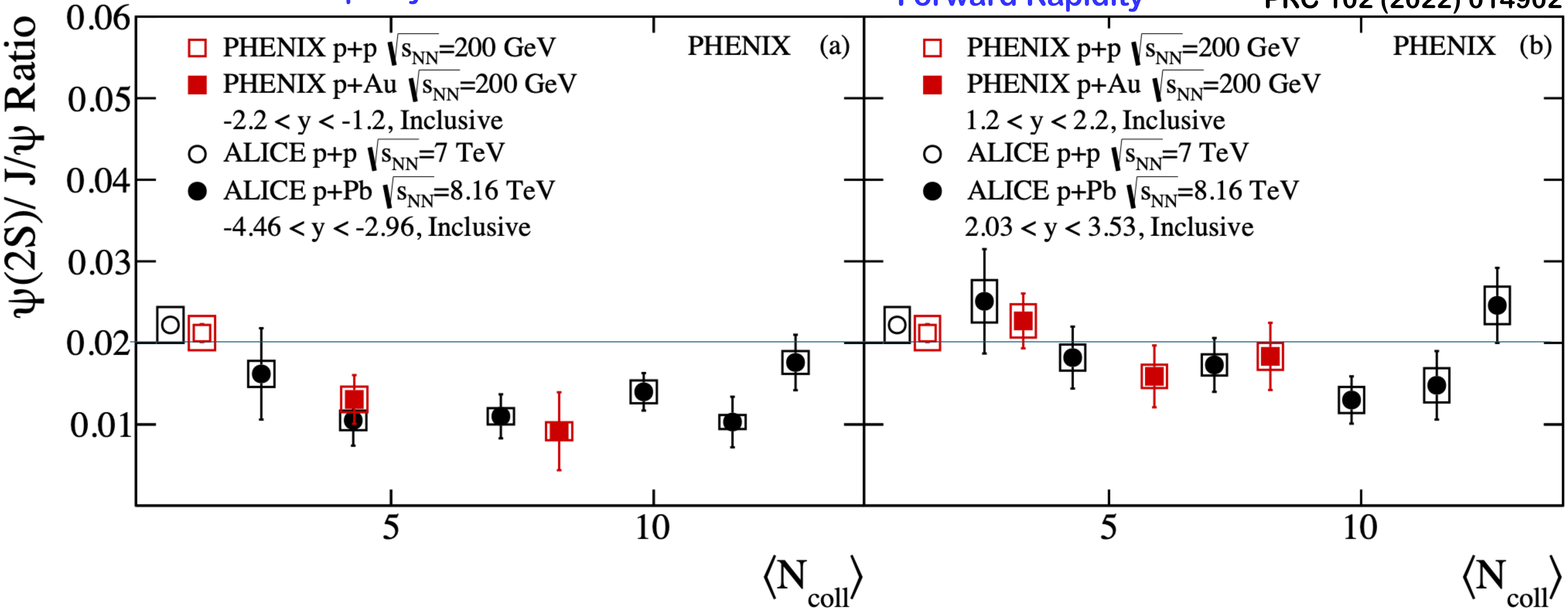
Let focus on ψ(2S) R_{pAu} centrality dependence compared with shadowing alone

Gluon shadowing - parton distributions are modified in a nucleus



- **Forward rapidity:**
  - **- Modification consistent with shadowing alone.**
- **Backward rapidity:**
  - **- Require addition of strong absorption + differential ψ(2S) suppression.**

ψ(2S)/J/ψ Ratio vs N_{coll} – RHIC(PHENIX)/LHC(ALICE) Energies



Backward Rapidity

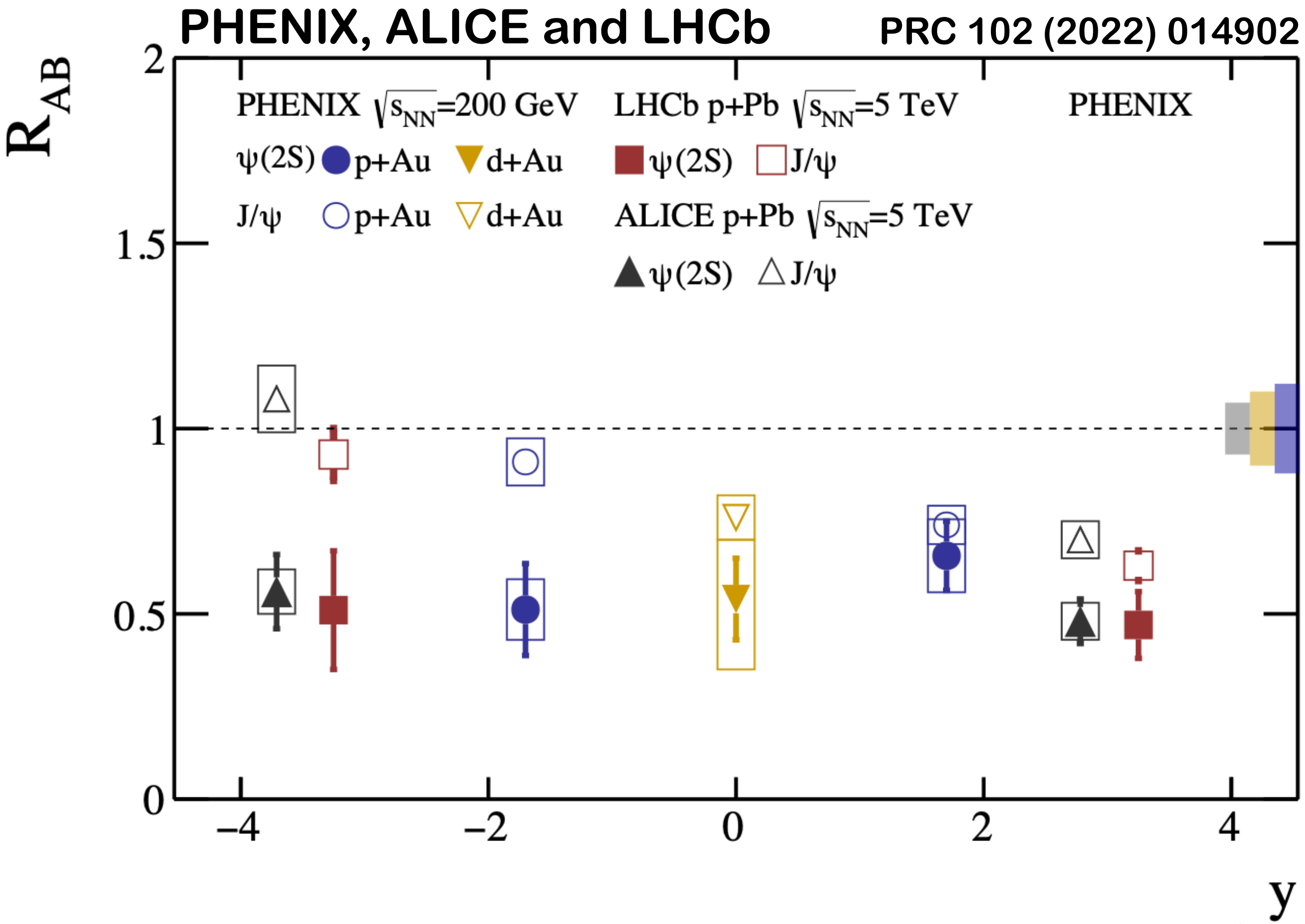
Forward Rapidity

PRC 102 (2022) 014902

PHENIX and ALICE ψ(2S) to J/ψ ratio vs N_{coll}:

- **Behavior is very similar at the two energies.**
- **The ratio is considerably smaller at backward rapidity.**

PHENIX, ALICE and LHCb Nuclear Modification Factors for J/ψ and ψ(2S) vs Rapidity



- J/ψ and ψ(2S) modification similar at forward rapidity:
  → Hint initial state effects dominate charmonium production
- PHENIX, LHCb, and ALICE at backward rapidity:
  - ψ(2S) is more suppressed than J/ψ: $R_{AB}(J/\psi) > R_{AB}(\psi(2S))$.

Summary

- **Heavy Flavor**
  - R_{AA} of electrons from charm and bottom have been measured separately in Au+Au at 200 GeV
    - Clear p_T and centrality dependence
    - In most central collisions 0-10%: bottom suppression is different than charm

      → consistent with the expected mass ordering: $\Delta E_b < \Delta E_c$ at mid-p_T
  - Elliptic flow $v_2(e^{HF})$, charm $v_2(c \rightarrow e)$ and bottom $v_2(b \rightarrow e)$ in MB Au+Au 200 GeV
    - $v_2^c(c \rightarrow e)$ increase smoothly with p_T
    - $v_2^b(b \rightarrow e)$ smaller than $v_2^c(c \rightarrow e)$
- **Quarkonia**
  - PHENIX has detailed measurements of $\psi(1S)$ and $\psi(2S)$ at both forward and backward rapidities in small systems.
  - $\psi(2S)$ modification in p+Au:
    - At forward rapidity:
      - Described reasonably well by shadowing alone
    - At backward rapidity:
      - Requires substantial additional suppression from final state effects