Overview of Recent Heavy Flavor Results from PHENIX at RHIC

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- PHENIX has several recent findings. Few (relevant) selected results:

  1. Open Heavy Flavor
  2. Quarkonia in “Small Systems”
  3. Summary

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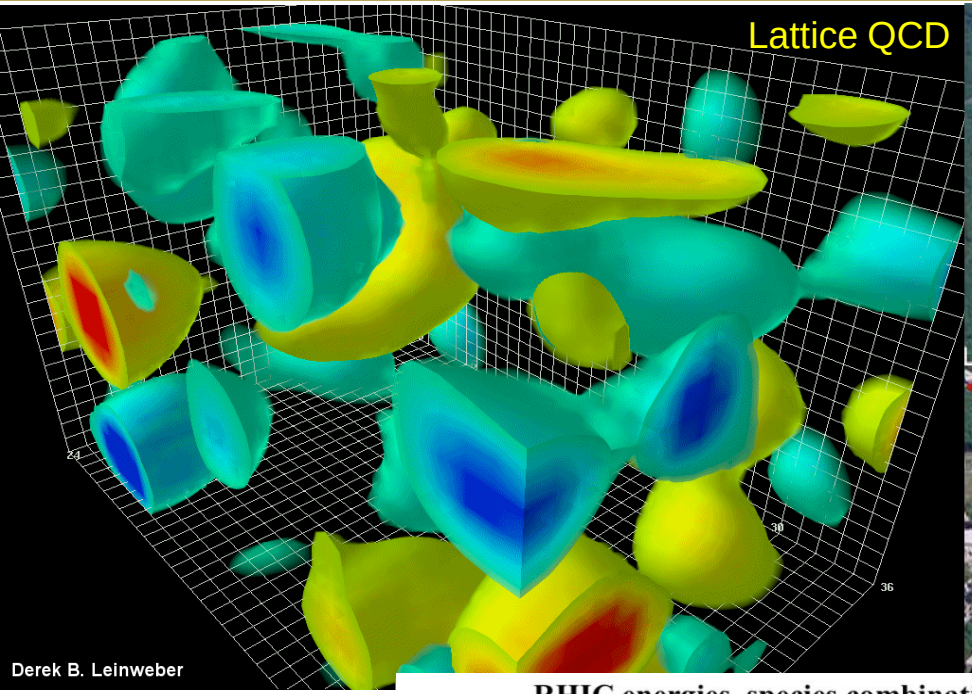
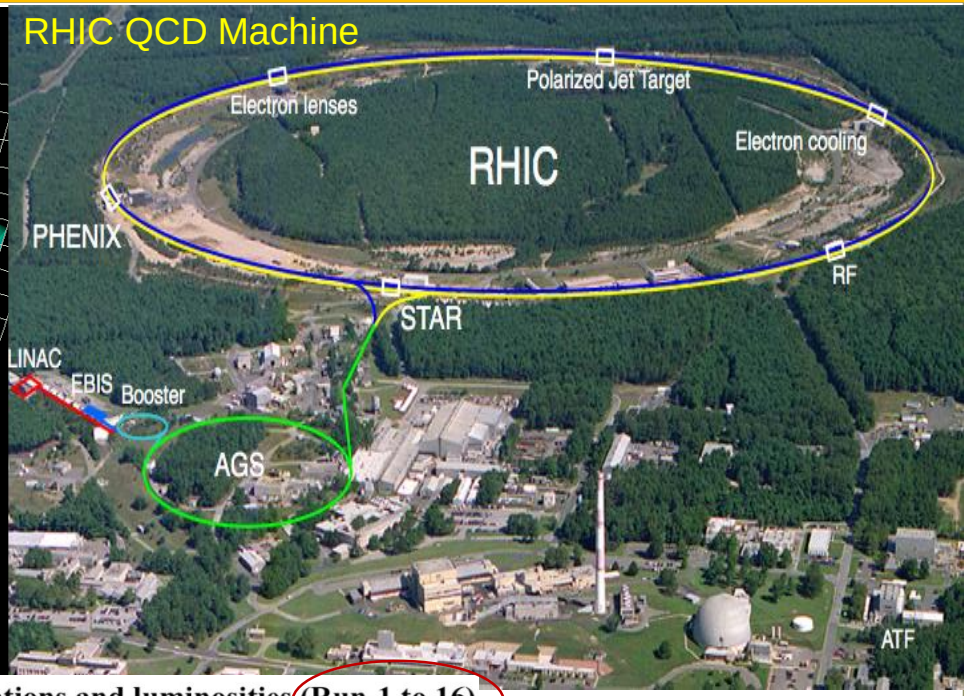
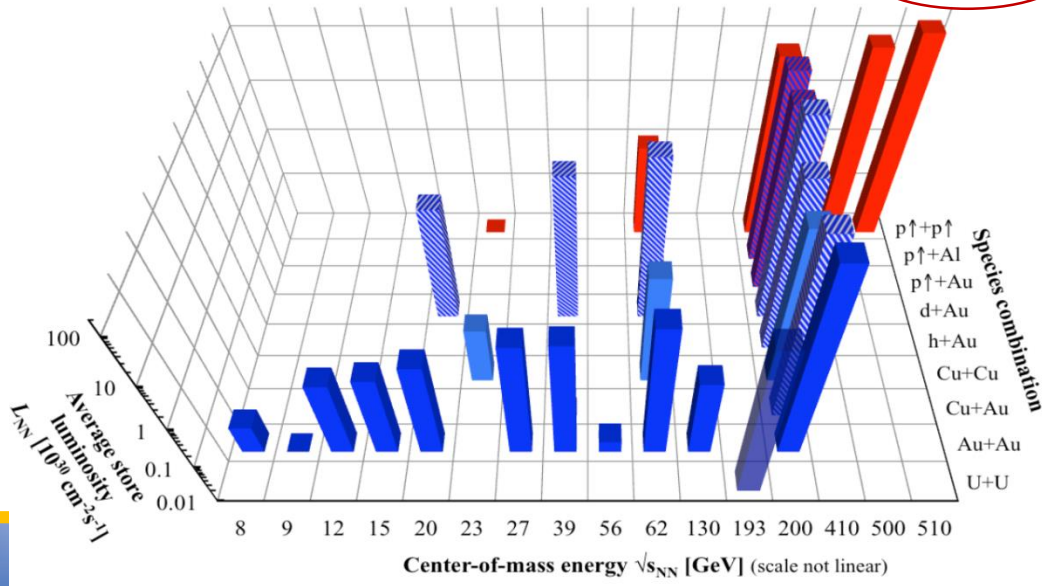
5th International Conference on Particle Physics and Astrophysics, 5-9 October 2020

RHIC Amazing QCD Machine: Many Species and Many 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 [μb^{-1}]
I (2000)	Au+Au	56	< 0.001
	Au+Au	130	20
II (2001/2002)	Au+Au	200	25.8
	Au+Au	19.6	0.4
	p+p	200	1.4×10^{-6}
III (2003)	d+Au	200	73×10^{-3}
	p+p	200	5.5×10^{-6}
IV(2004)	Au+Au	200	3.53×10^{-3}
	Au+Au	62.4	67
	p+p	200	7.1×10^{-6}
V (2005)	Cu+Cu	200	42.1×10^{-3}
	Cu+Cu	62.4	1.5×10^{-3}
	Cu+Cu	22.4	0.02×10^{-3}
	p+p	200	29.5×10^{-6}
	p+p	410	0.1×10^{-6}
VI (2006)	p+p	200	88.6×10^{-6}
	p+p	62.4	1.05×10^{-6}
VII (2007)	Au+Au	200	7.25×10^{-3}
	Au+Au	9.2	Small
VIII (2008)	d+Au	200	437×10^{-3}
	p+p	200	38.4×10^{-6}
	Au+Au	9.6	Small

Run	Species	Total particle energy [GeV/nucleon]	Total delivered luminosity [μb^{-1}]
IX (2009)	p+p	500	110×10^{-6}
	+p	200	114×10^{-6}
X (2010)	Au+Au	200	10.3×10^{-3}
	Au+Au	62.4	544
	Au+Au	39	206
	Au+Au	7.7	4.23
	Au+Au	11.5	7.8
XI (2011)	p+p	500	166×10^{-6}
	Au+Au	19.6	33.2
	Au+Au	200	9.79×10^{-3}
	Au+Au	27	63.1
XII (2012)	p+p	200	74×10^{-6}
	p+p	510	283×10^{-6}
	U+U	193	736
	Cu+Au	200	27×10^{-3}
XIII (2013)	p+p	510	1.04×10^{-9}
XIV (2014)	Au+Au	14.6	44.2
	Au+Au	200	43.9×10^{-3}
	^{3}He+Au	200	134×10^{-3}
XV (2015)	p+p	200	282×10^{-6}
	p+Au	200	1.27×10^{-6}
	p+Al	200	3.97×10^{-6}
XVI (2016)	Au+Au	200	52.2×10^{-3}
	d+Au	200	46.1×10^{-3}
	d+Au	62.4	44.0×10^{-3}
	d+Au	19.6	7.2×10^{-3}
	d+Au	39	19.5×10^{-3}

Heavy Flavor: Ideal Probe of QCD Matter

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

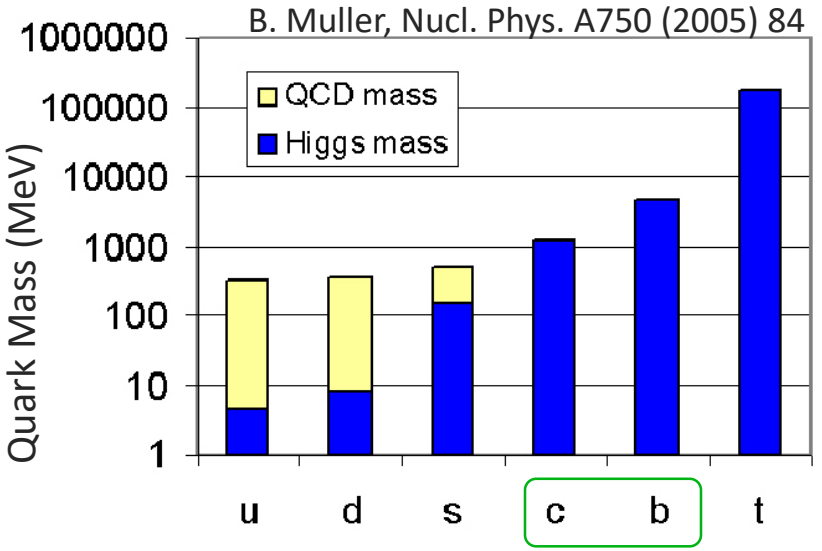
Break-up, Temperature?

Each parameter probes different admixtures of nuclear modification

Heavy Flavor: Ideal Probe of QCD Matter

Theoretical motivation

- Symmetry breaking
  - **Higgs mass:** electroweak symmetry breaking
    → **current quark mass**
  - **QCD mass:** chiral symmetry breaking
    → **constituent quark mass**
- Charm and beauty quark masses are not affected by QCD vacuum
  → **ideal probes to study QGP**



- Heavy quarks ($c\bar{c}$, $b\bar{b}$)
  - Bound states (J/ψ, Υ)

State	J/ψ	χ_c	ψ'	Υ	χ_b	Υ'	χ_b'	Υ''
Mass (GeV)	3.10	3.53	3.68	9.46	9.99	10.02	10.36	10.36
ΔE (GeV)	0.64	0.20	0.05	1.10	0.67	0.54	0.31	0.20
Radius (fm)	0.25	0.36	0.45	0.14	0.22	0.28	0.34	0.39

- Due to their mass ($m_Q >> T_{cri}$, Λ_{QCD})
  → **higher penetrating power**

- Gluon fusion dominates
  → **sensitive to initial state gluon distribution**

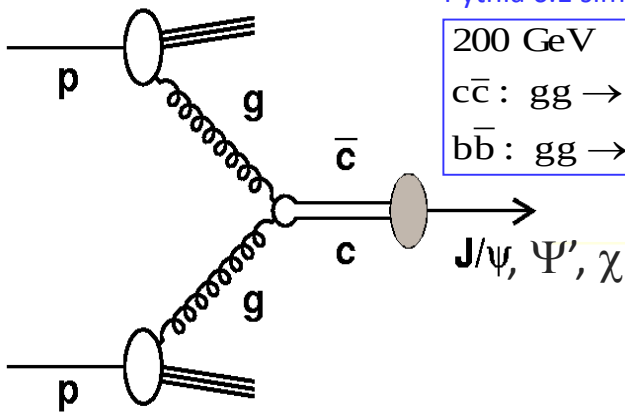
M. Gyulassy and Z. Lin, Phys. Rev. C51 (1995) 2177

Pythia 6.1 simulation (LO)

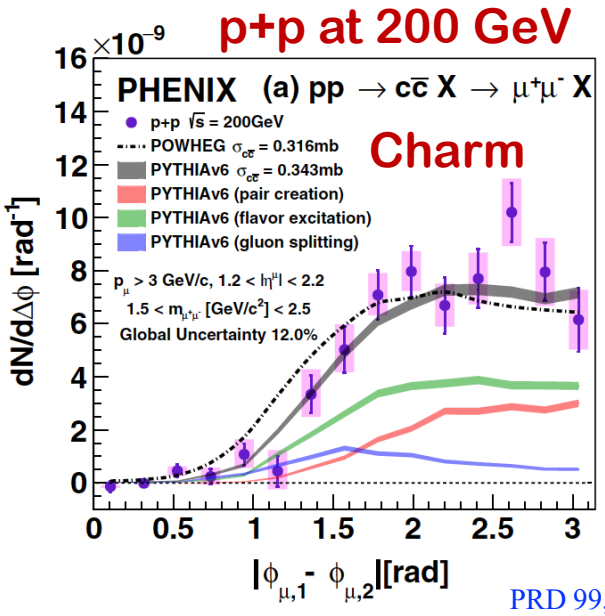
200 GeV

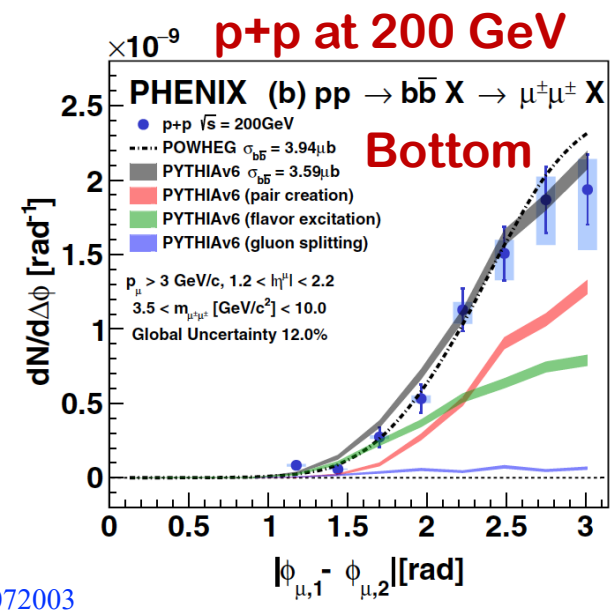
$c\bar{c}$: $gg \rightarrow c\bar{c}$ 95%

$b\bar{b}$: $gg \rightarrow b\bar{b}$ 85%

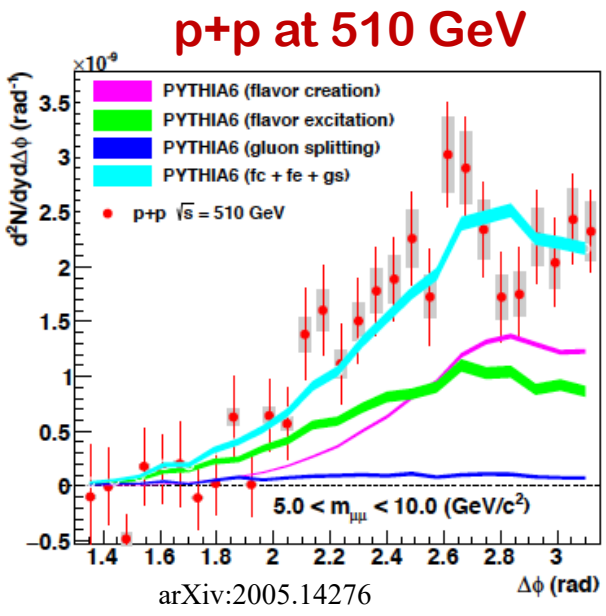


Heavy Flavor Production at RHIC





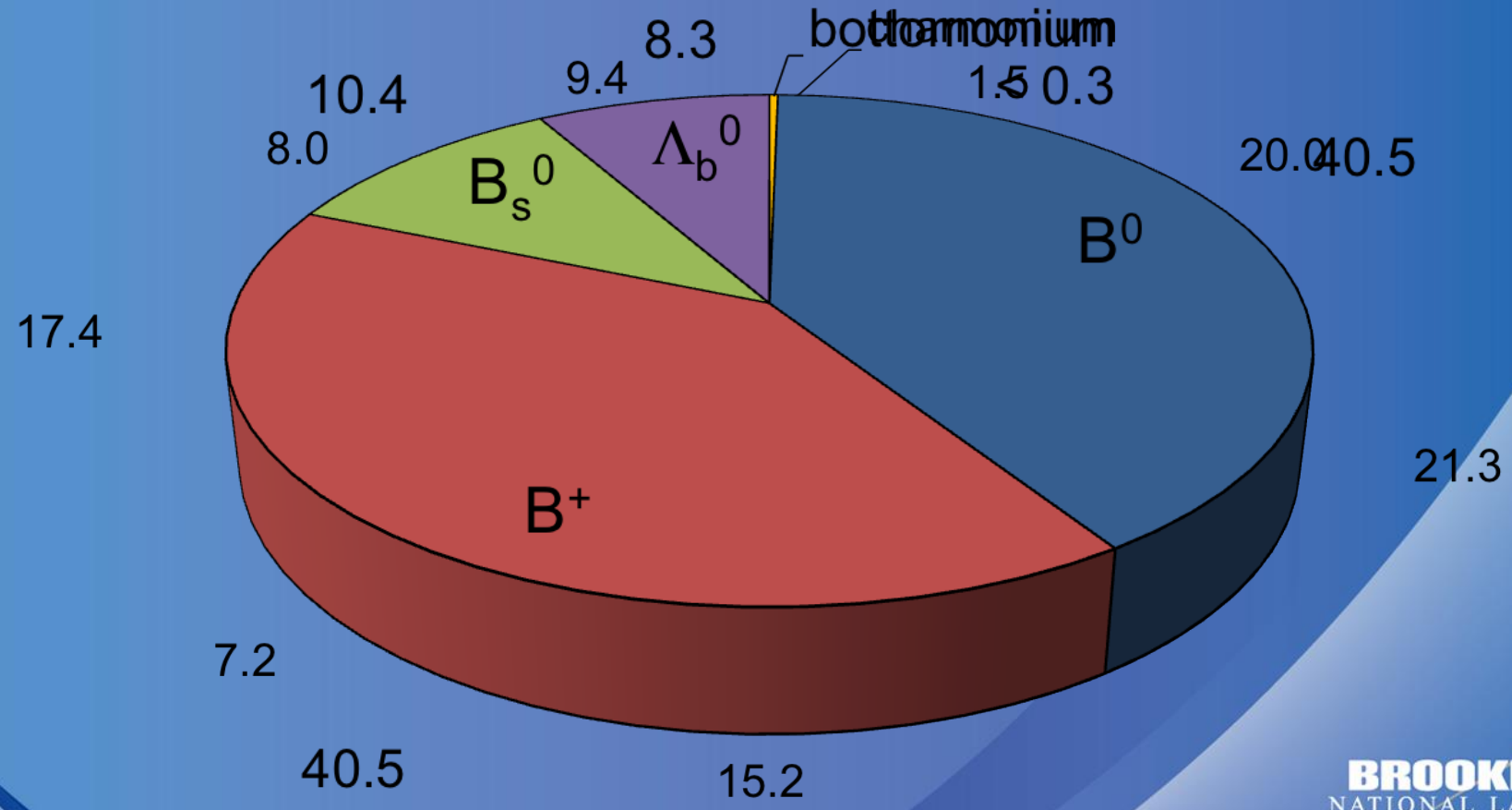
PRD 99, 072003



arXiv:2005.14276

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

Where does all the heavy flavor go?



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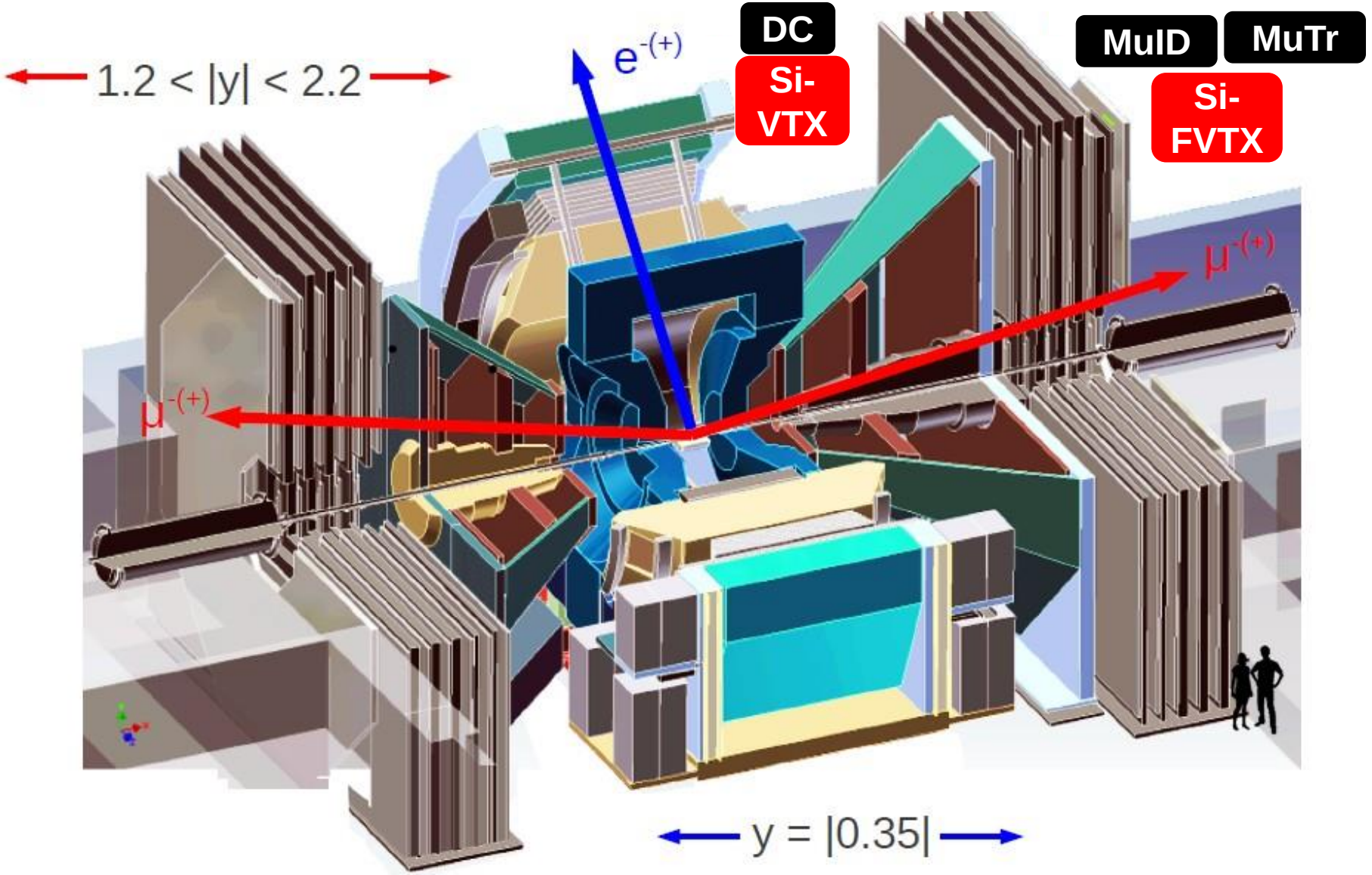
Open Heavy Flavor

Measuring Heavy Flavor in PHENIX

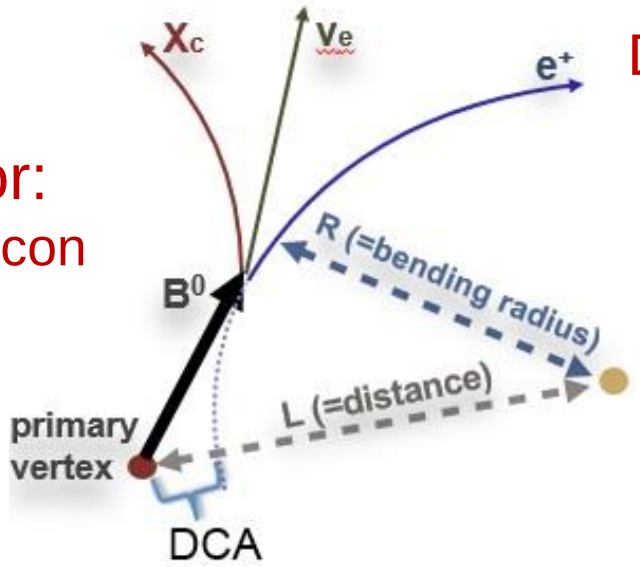
Mid-rapidity $J/\psi, \Upsilon \rightarrow e^+ e^-$ **RICH** **EMCal** **PC** **DC** **Si-VTX**

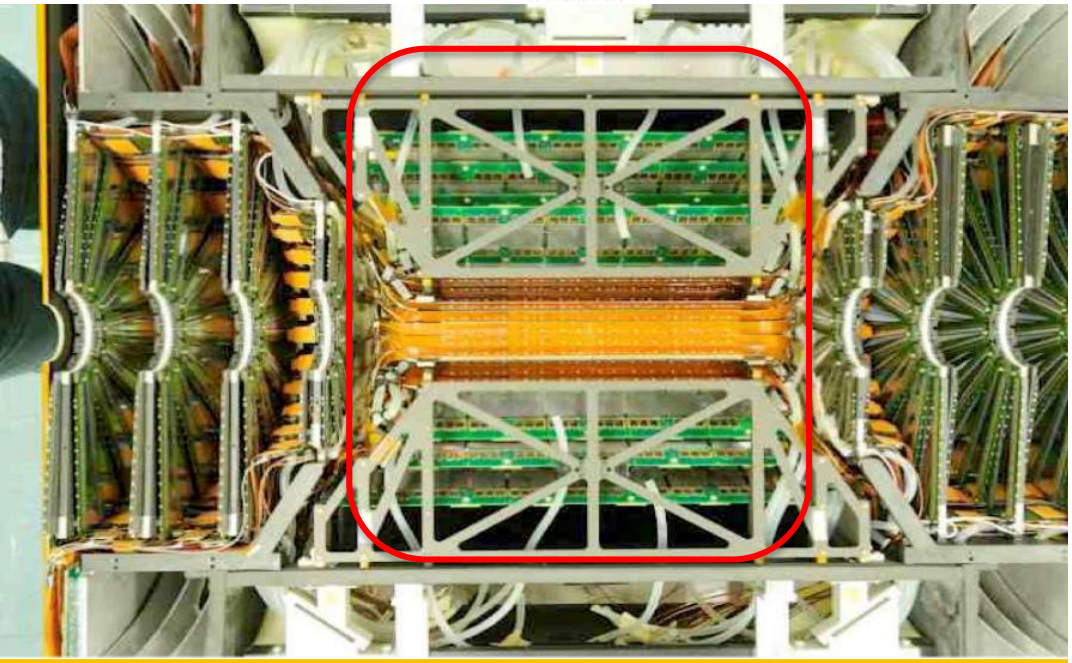
Forward rapidity: $J/\psi, \Upsilon \rightarrow \mu^+ \mu^-$ **MuID** **MuTr** **Si-FVTX**



PHENIX Central Heavy Flavor Tracker (VTX)

VTX detector:
4 barrels of silicon





DCA_T Distributions: b/c separation

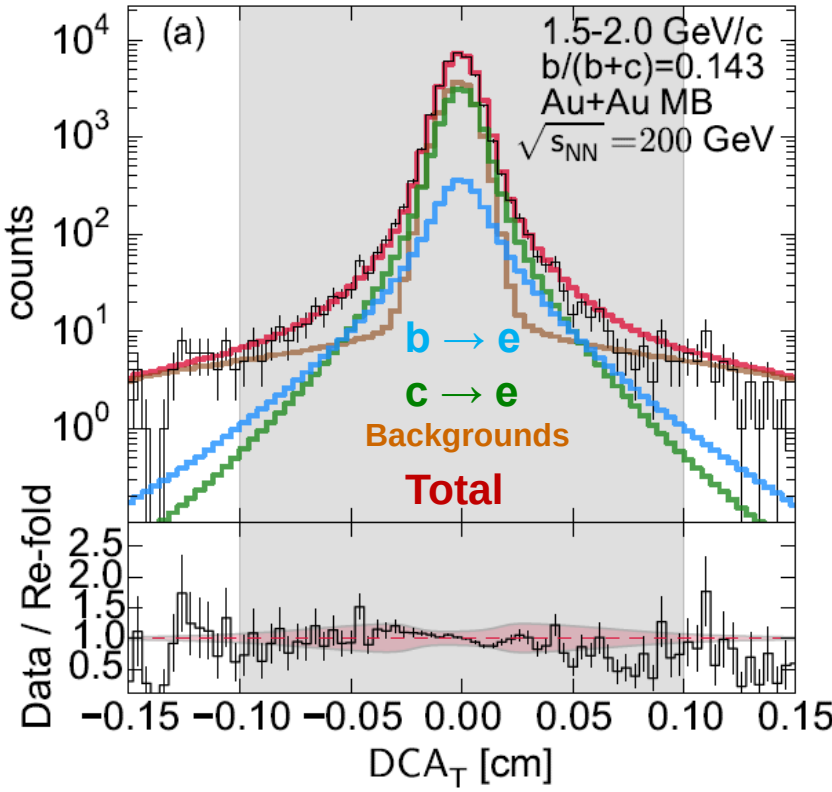
- VTX: $|\eta| < 1.2$
  - Au+Au 200 GeV: DCA_T resolution ~ 60 μm

Life time ($c\tau$)

D^0 : 123 μm

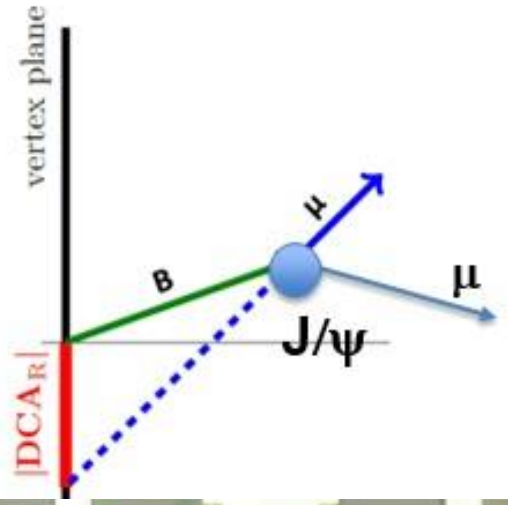
B^0 : 464 μm

PHENIX: PRC 93, 034904 (2016)



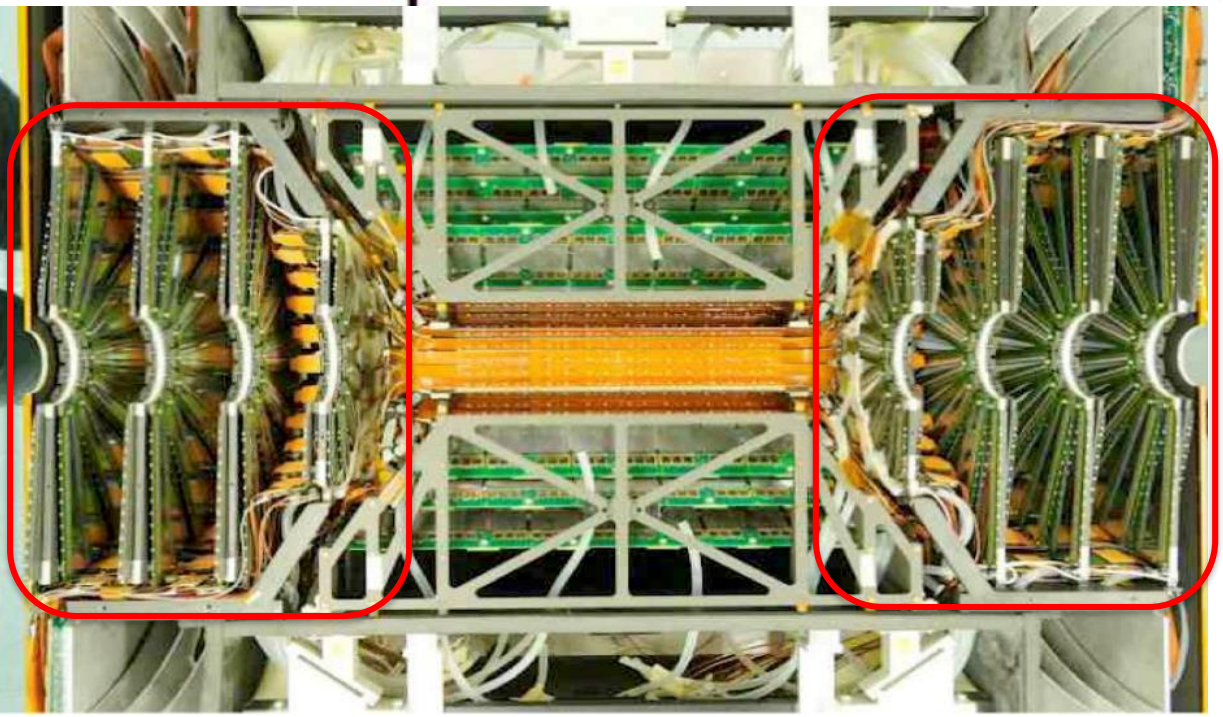
PHENIX Forward Heavy Flavor Tracker (FVTX)

FVTX detector:

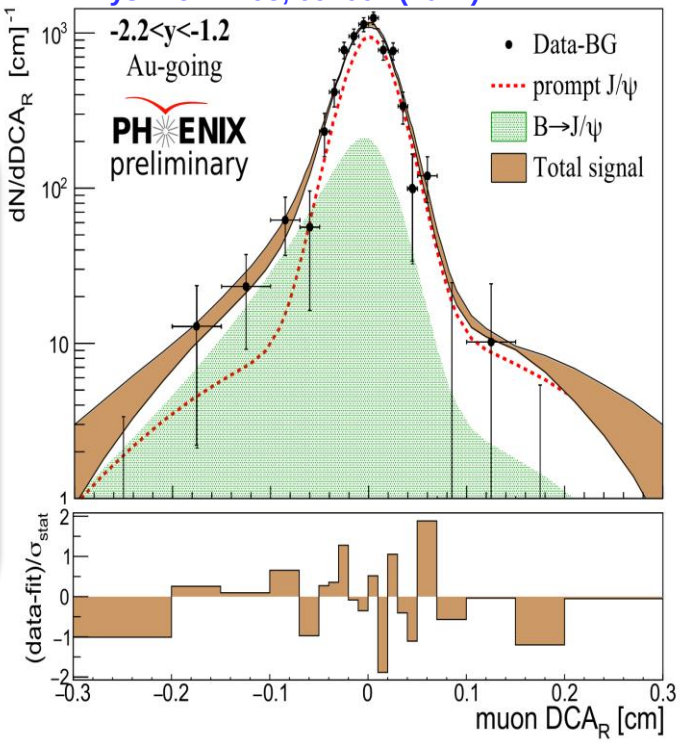


DCA_R Distributions: b/c separation

- FVTX:
  - Forward rapidity - $1.2 < |\eta| < 2.2$
  - Improved muon momentum resolution & precise tracking



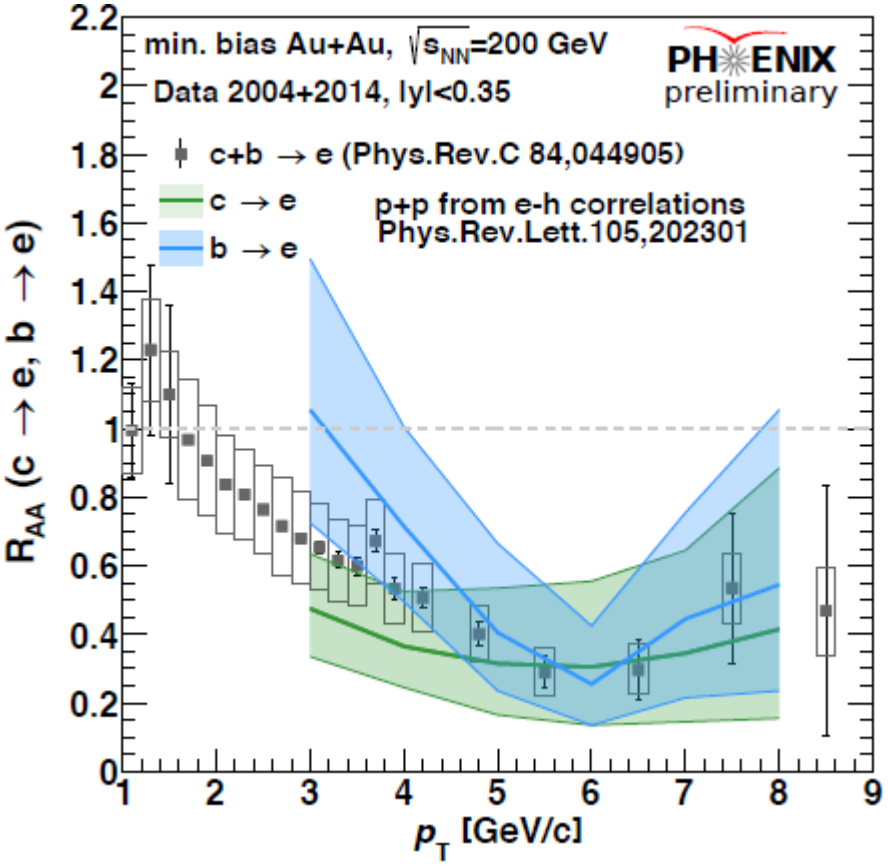
Phys. Rev. D 95, 092002 (2017)



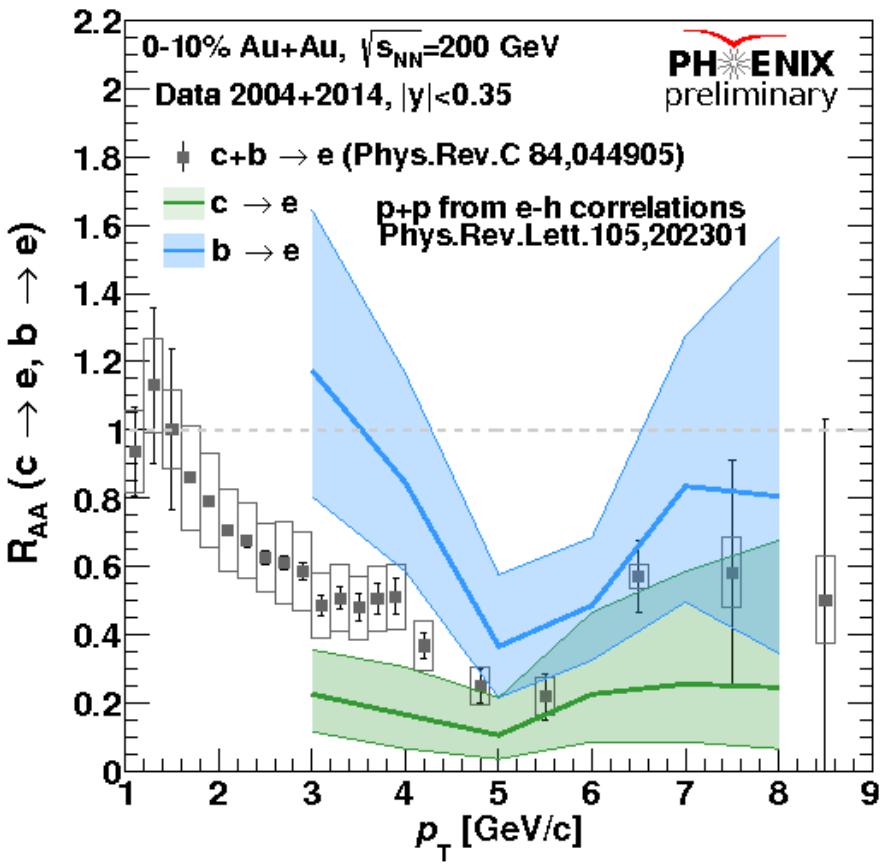
Part I
Open Heavy Flavor

$R_{AA}(b \rightarrow e)$ & $R_{AA}(c \rightarrow e)$ in Au+Au 200 GeV

Min. Bias in Run2014



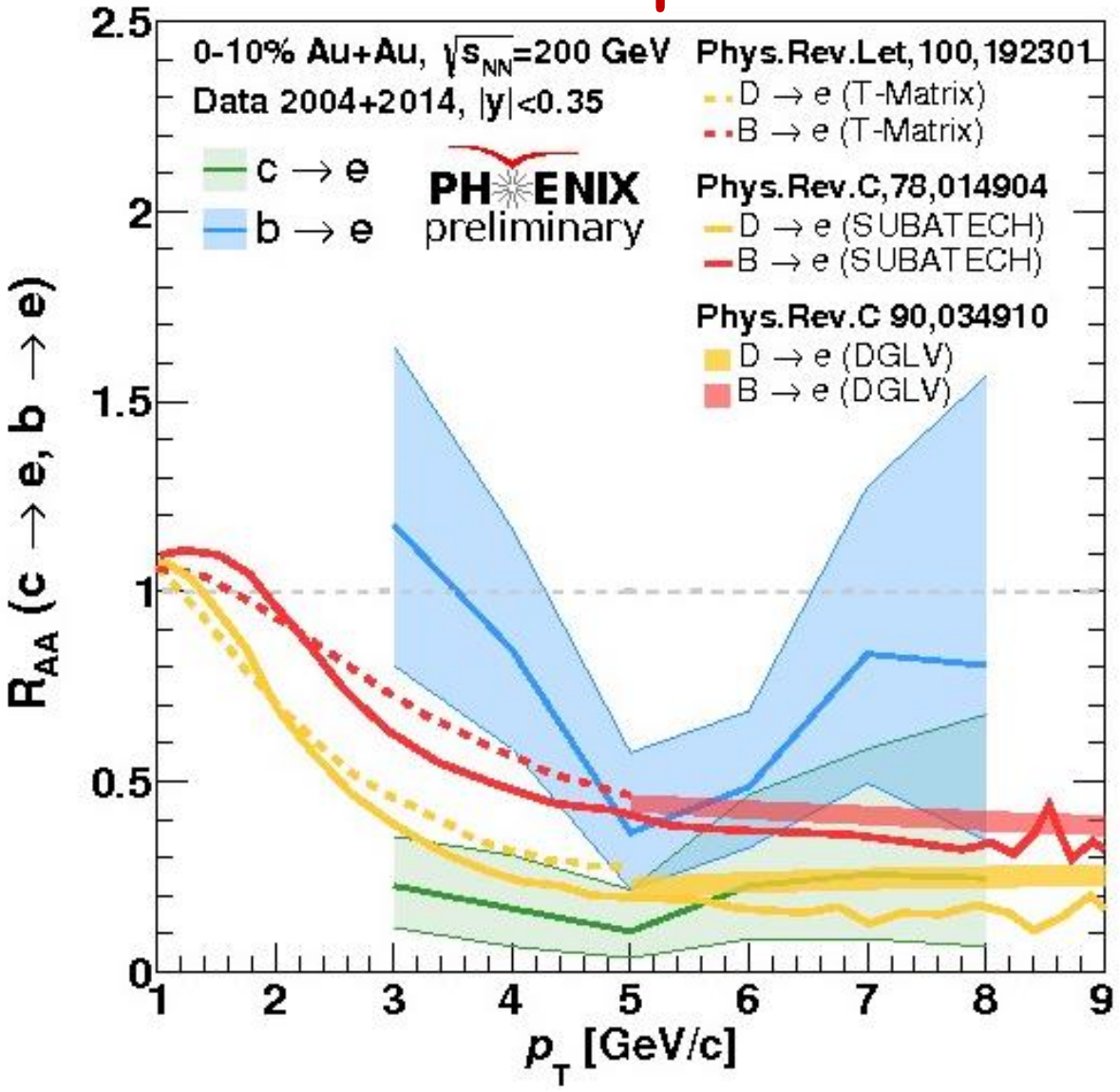
0-10% in Run2014



- In 0-10%, bottom and charm are more clearly separated for $p_T < 4.5$ GeV/c
- Charm is more suppressed in 0-10% than MB for $p_T < 4.5$ GeV/c region

R_{AA}(b→e) & R_{AA}(c→e) in Au+Au 200 GeV

Model Comparison



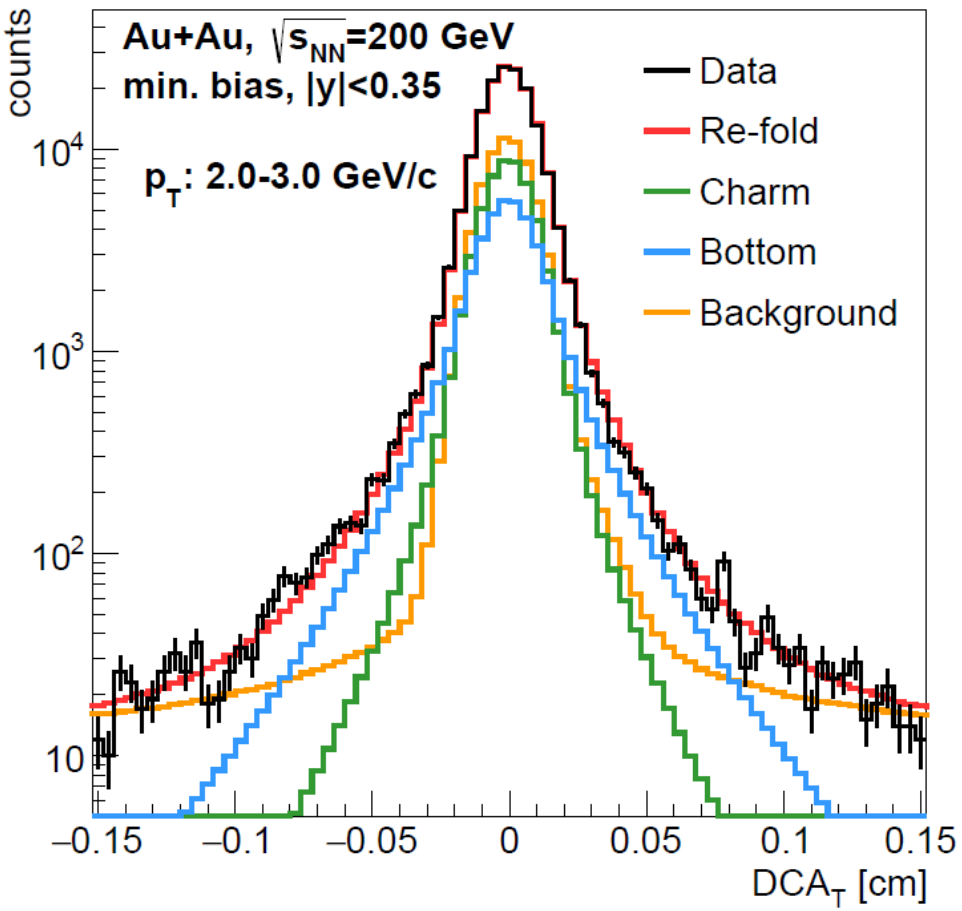
T-Matrix: (T-Matrix + small diffusion const ($2\pi TD = 4$). Strong QGP coupling.

- SUBATECH: Boltzmann equation + running coupling + realistic hard thermal loop calculations.

- GLV: Energy loss + plasma w/ static potentials.

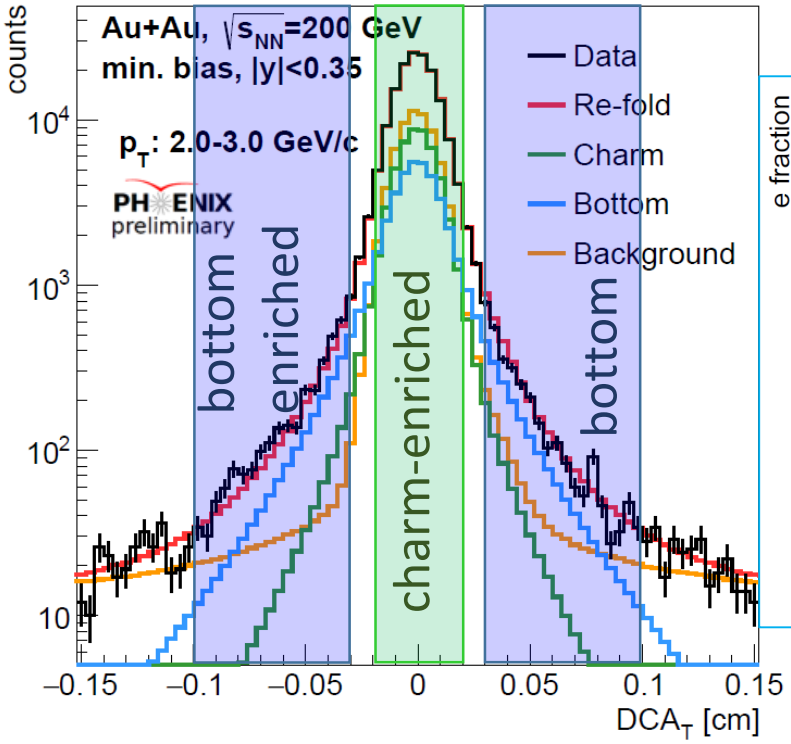
- More precise measurement needed to distinguish between different models.

Bottom and Charm with Large Statistics

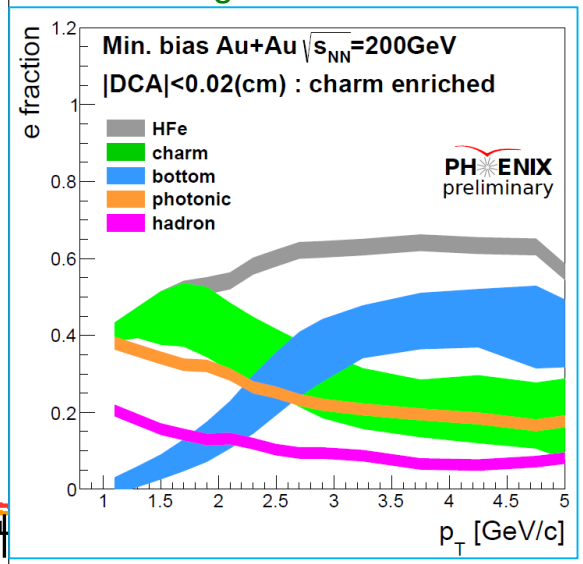


- Recorded large statistics of Au+Au 200 GeV in 2014
  - 17 B events = 4 times larger
- The dataset is available for the analysis.
- Charm and bottom separation using the DCA decomposition in progress
- Dataset enables heavy flavor elliptic flow measurements v_2^{HF}, $v_2^c\,(c \to e)$, $v_2^b\,(b \to e)$ preliminary (see next slides)

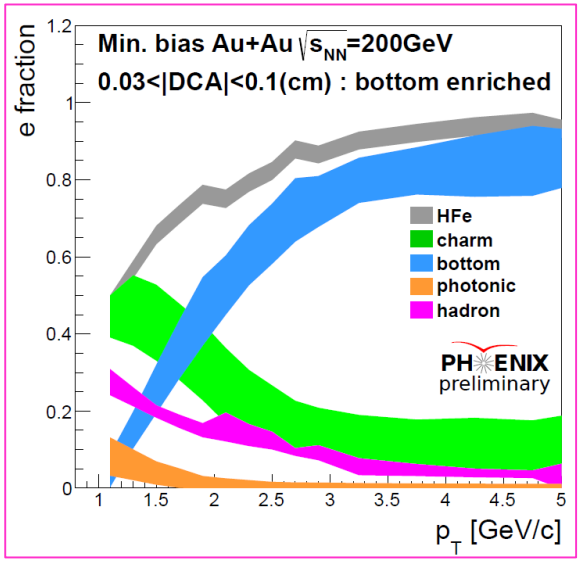
v_2 for c- and b- Enriched DCA Range



Peak region : Charm enriched



Tail region : Bottom enriched



DCA ranges:

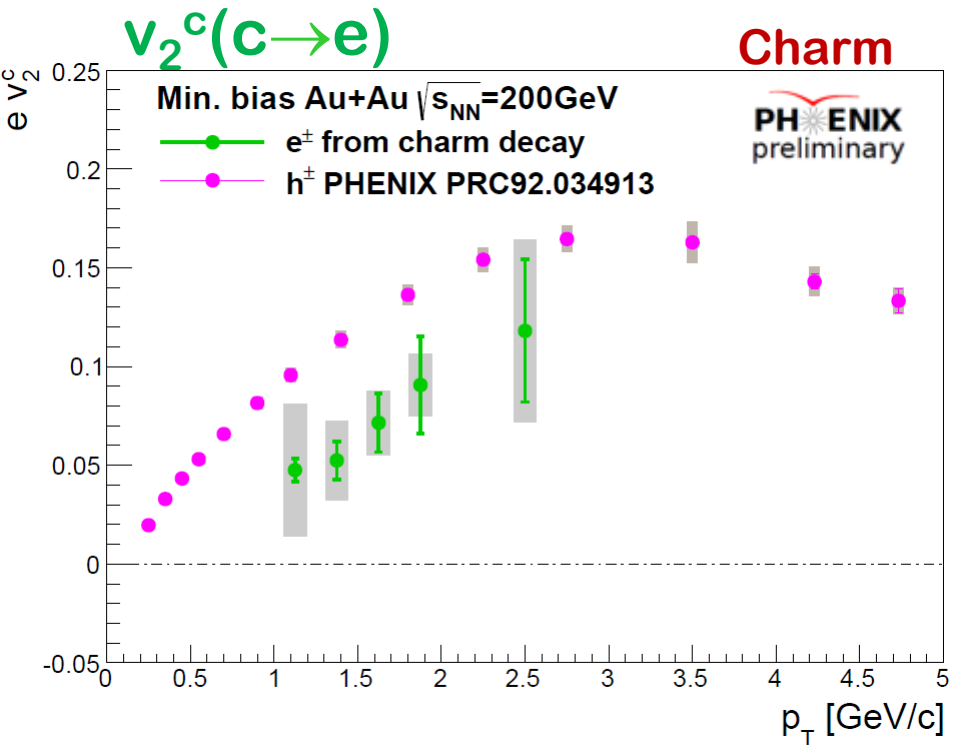
Peak : c-enriched : |DCA|<200 um

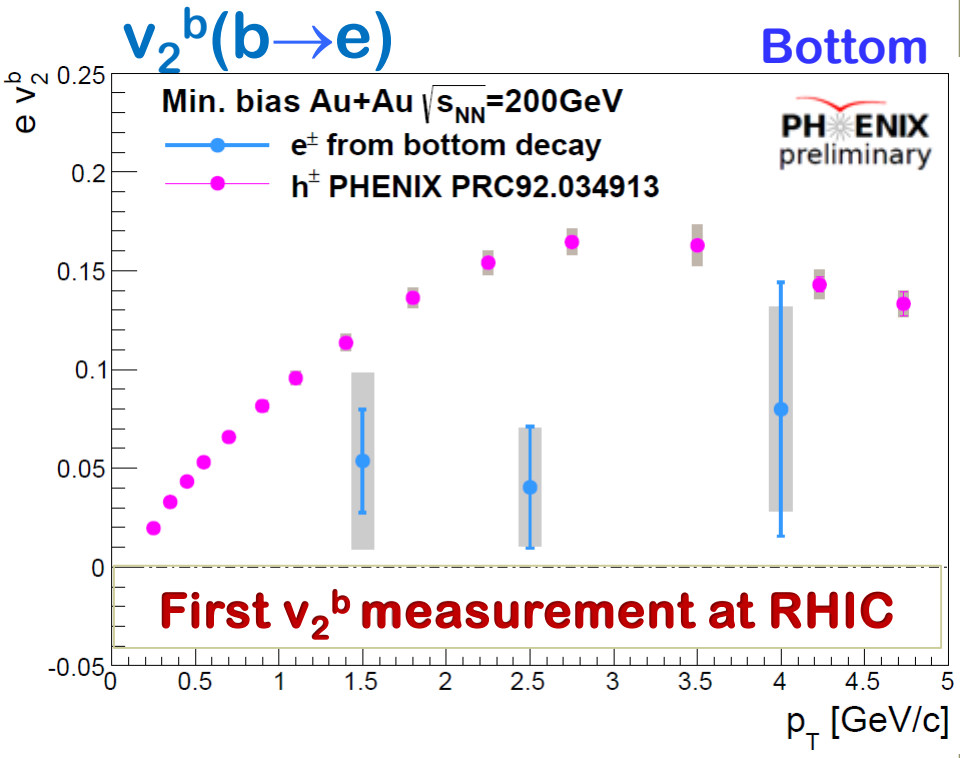
Tail : b-enriched : 300 < |DCA|<1000 um

$$v_2^{inc} = \underbrace{b \cdot v_2^b(b \to e) + c \cdot v_2^c(c \to e)}_{\mathrm{HFe} \cdot v_2^{HF}} + bg_0 \cdot v_2^{bg}$$

- **Look at v_2 from these DCA range**
  - **If v_2^b is small, v_2(b-enriched) < v_2(c-enriched)**

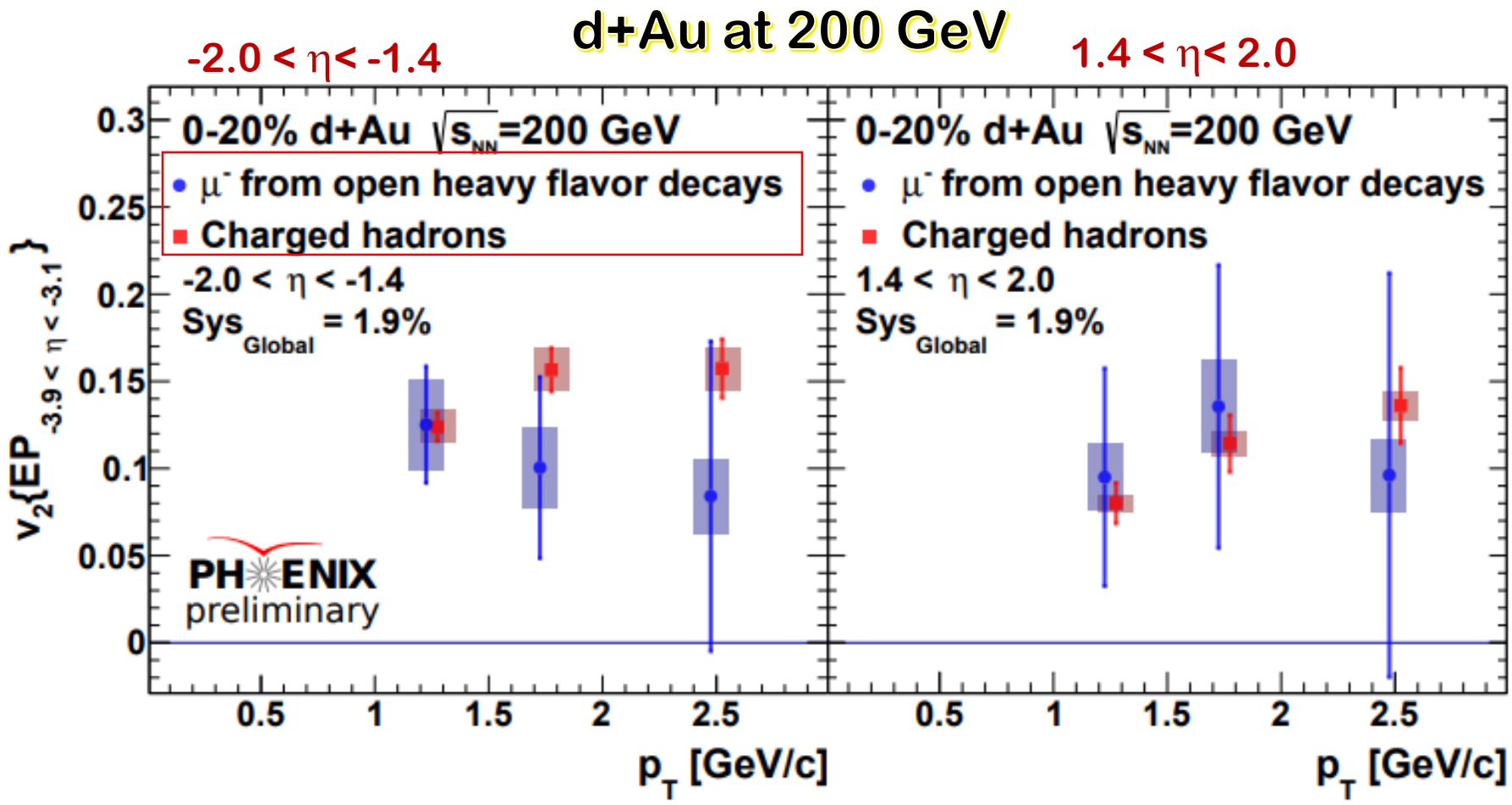
$v_2^c(c \rightarrow e)$ and $v_2^b(b \rightarrow e)$ in Au+Au 200GeV





- $v_2(c \rightarrow e)$ is positive and smaller than charged hadron v_2
- First $v_2(b \rightarrow e)$ measurement at RHIC
  - Consistent with zero within large uncertainty
  - Likely smaller than $v_2(c \rightarrow e)$

Backward/Forward Heavy Flavor Muon v_2^{HF}



- First measurement at RHIC
- Significant non-zero v_2 in d+Au collisions !!
  - 99.93% (98.61%) confidence level at backward (forward)

Part II

Quarkonia in "Small Systems"

p+Au at 200 GeV

d+Au at 200 GeV

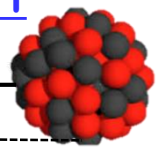
^{3}He+Au at 200 GeV

p+Al at 200 GeV

Suppression of ψ' in Central d+Au Collisions

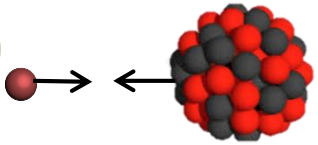
PHENIX: PRL 111, 202301

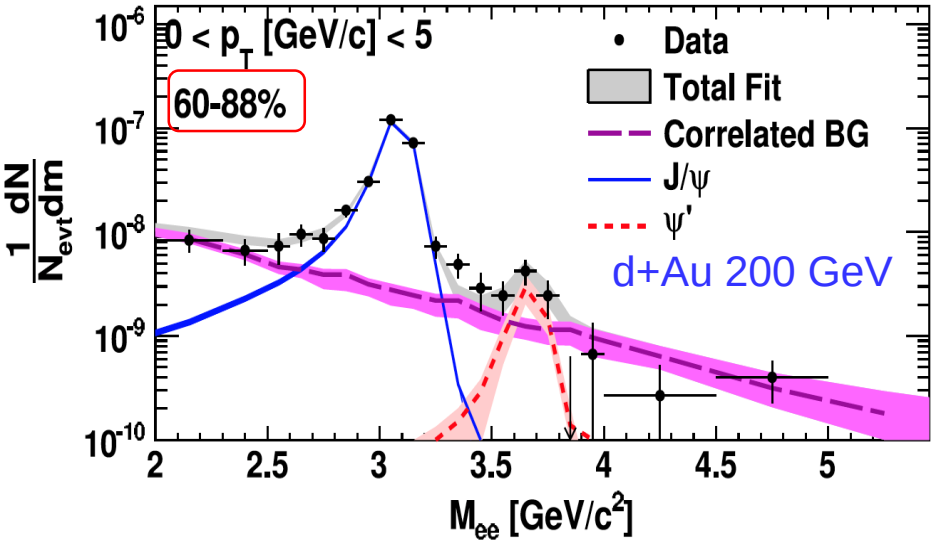
Mid- Rapidity |η| < 0.35

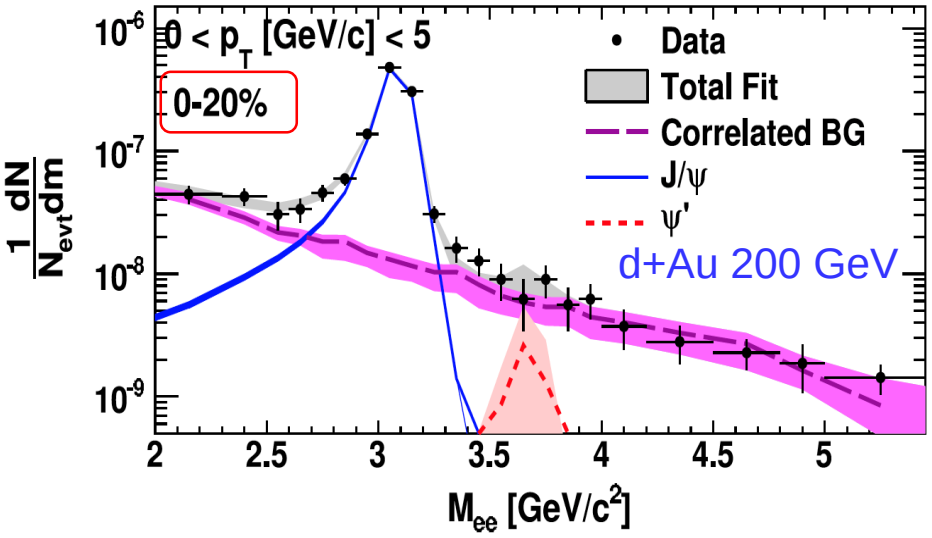


peripheral
60—88%
N_{coll} ~ 3

central
0—20%
N_{coll} ~ 15



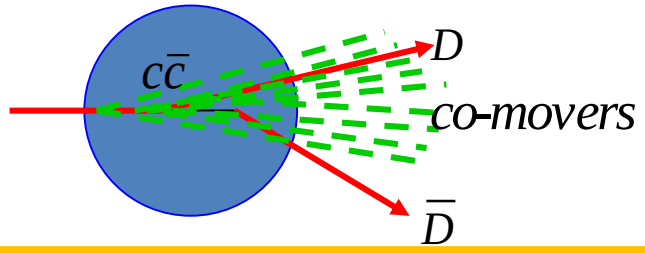


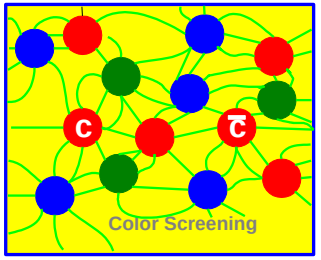


Breakup of quarkonia due to interaction with nuclear matters

1) Large suppression of the weakly bounded state ψ'

2) Interaction with nucleus? comovers? or medium?

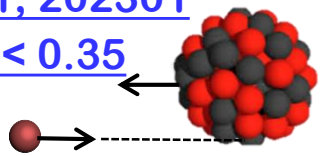




PHENIX Suppression of ψ' in Central d+Au Collisions

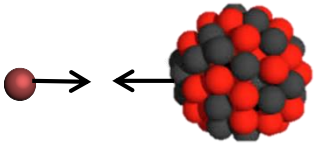
PHENIX: PRL 111, 202301

Mid- Rapidity |η| < 0.35

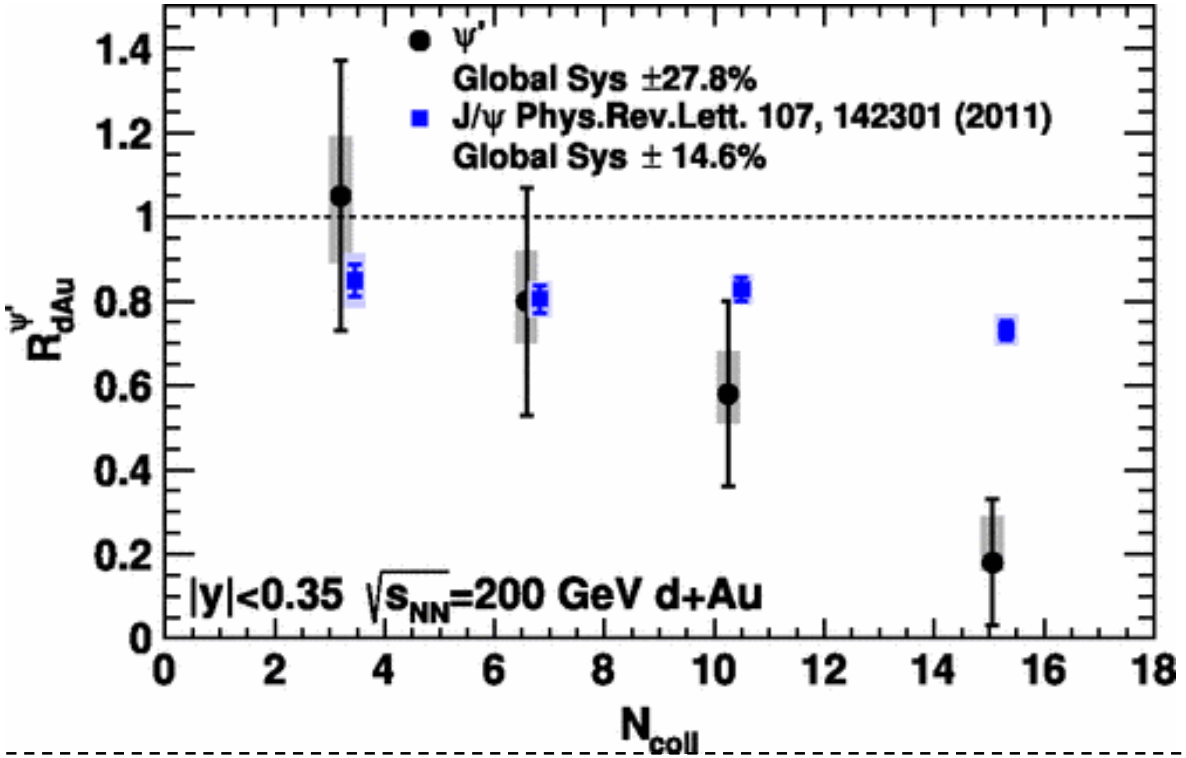


peripheral
60—88%
N_{coll} ~ 3

central
0—20%
N_{coll} ~ 15



Nuclear Modification Factor



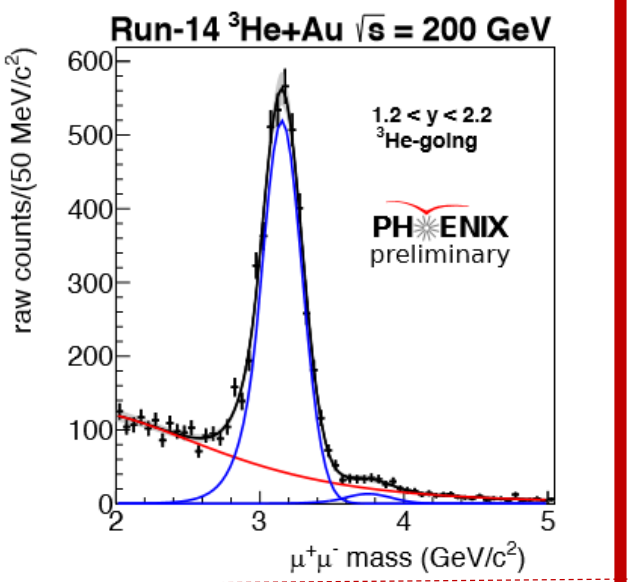
At mid-rapidity: ψ (2S) is more suppress than ψ(1S) in central d+Au collisions

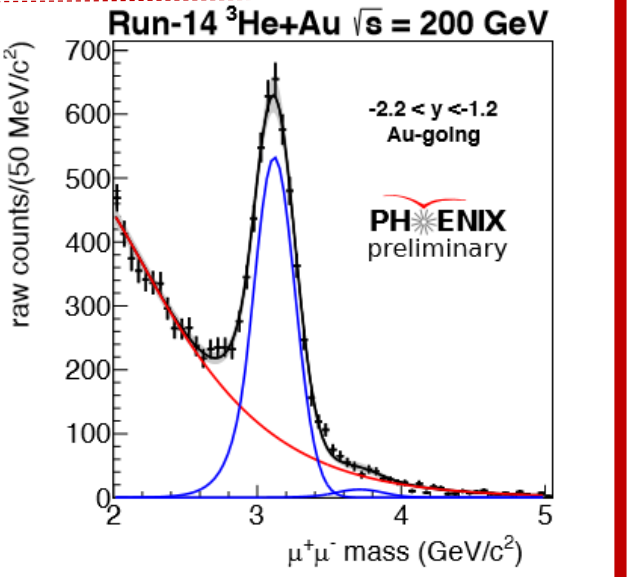
→ What about forward/backward rapidity?

→ What about smaller systems?

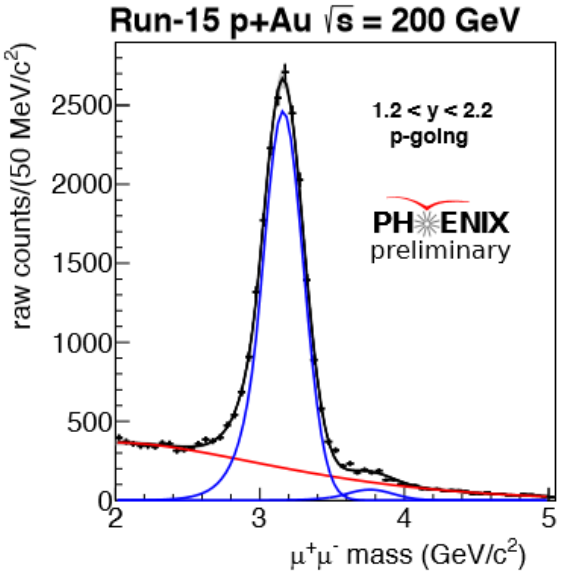
Forward/backward Rapidity ψ(1S) and ψ(2S)

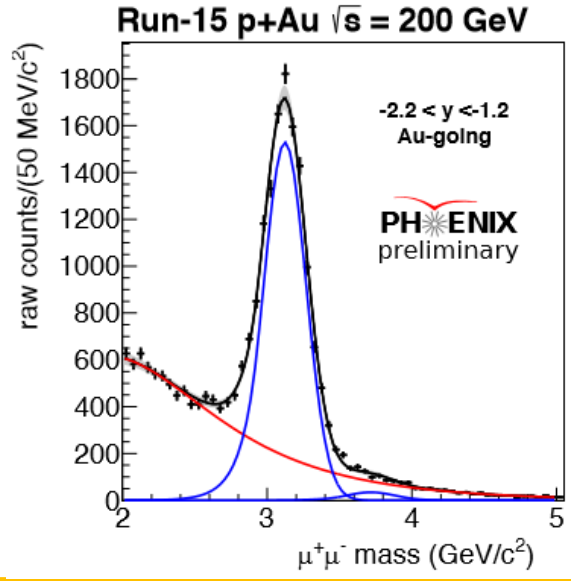
^{3}He + Au



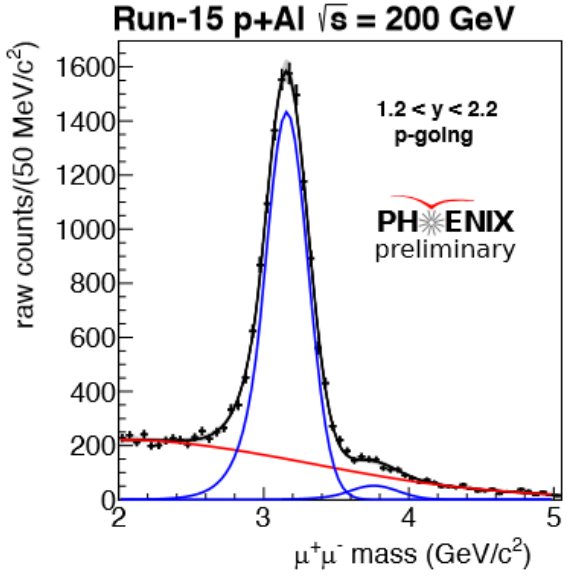


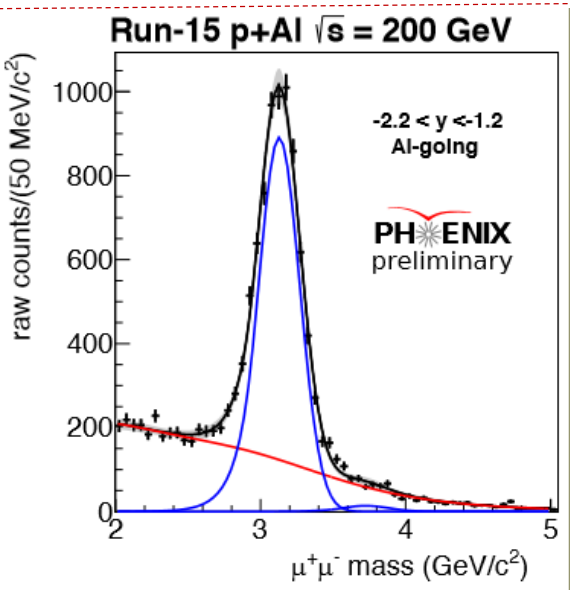
p + Au



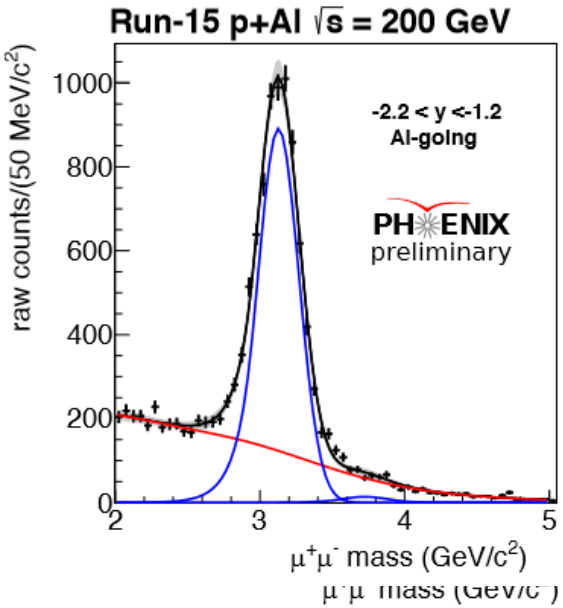


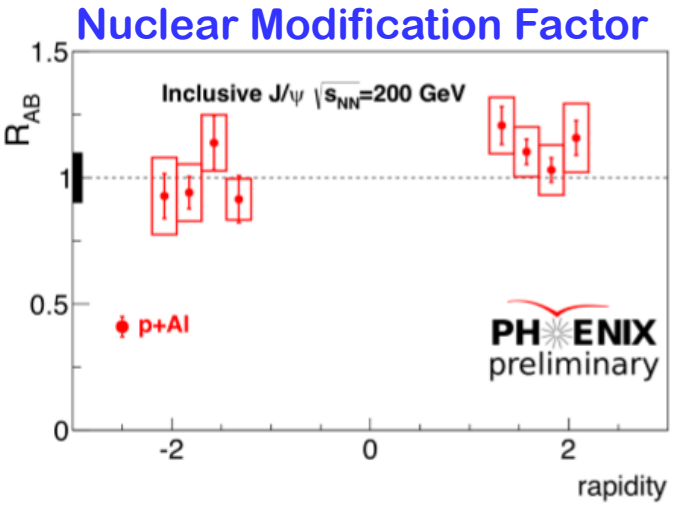
p + Al

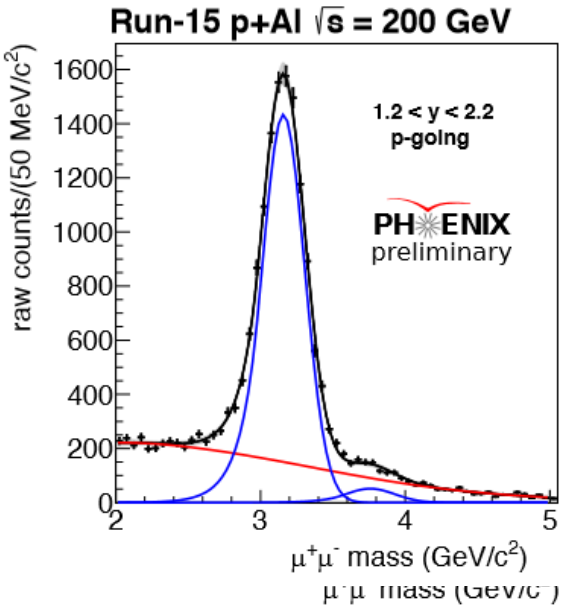




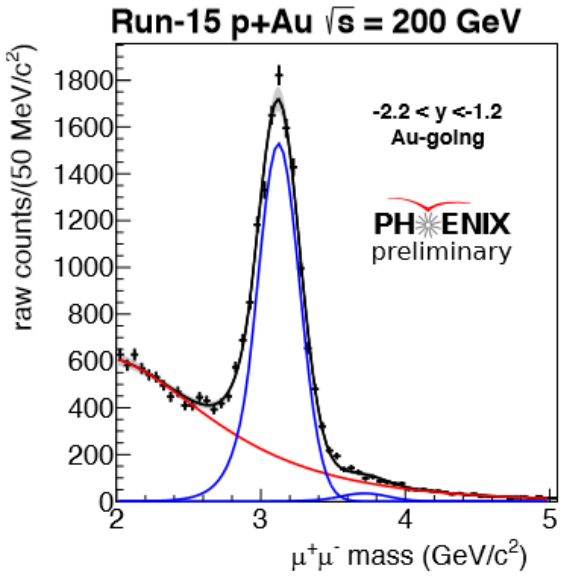
Quarkonia in p+Al at 200 GeV – Run 15

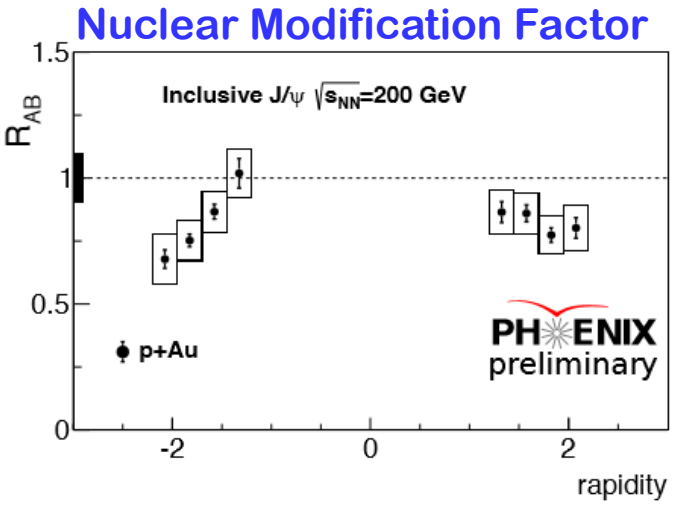


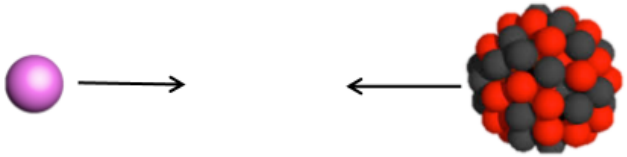


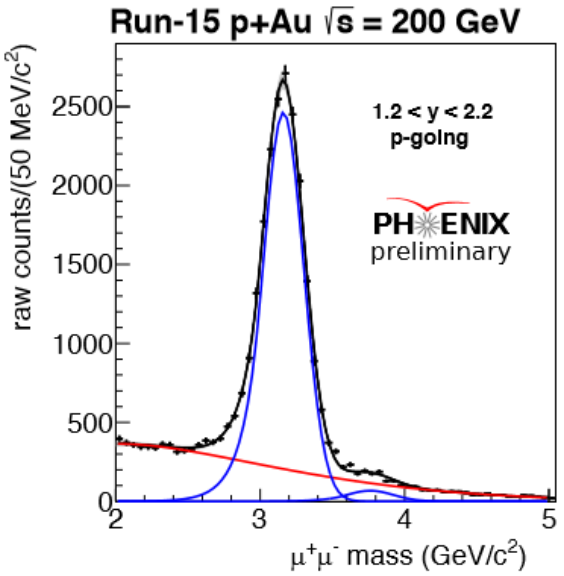


Quarkonia in p+Au at 200 GeV – Run 15

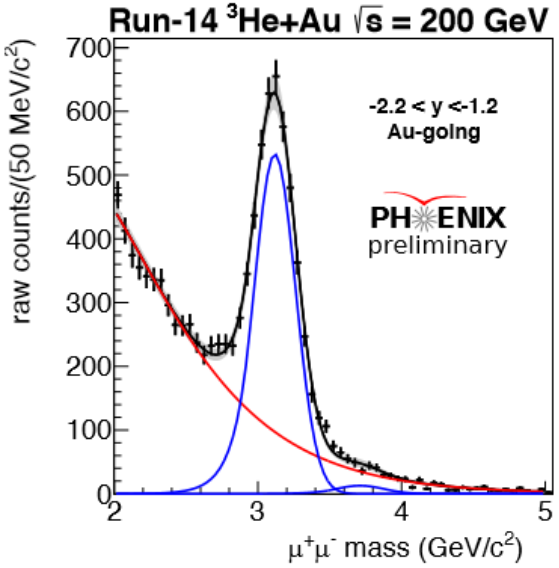


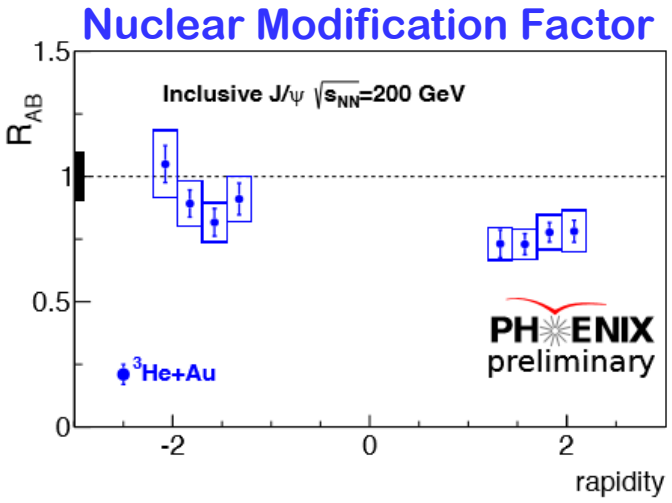


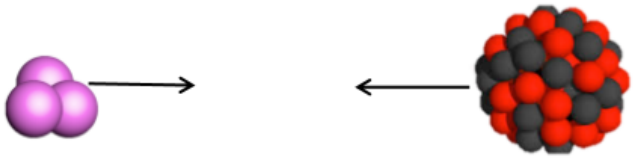


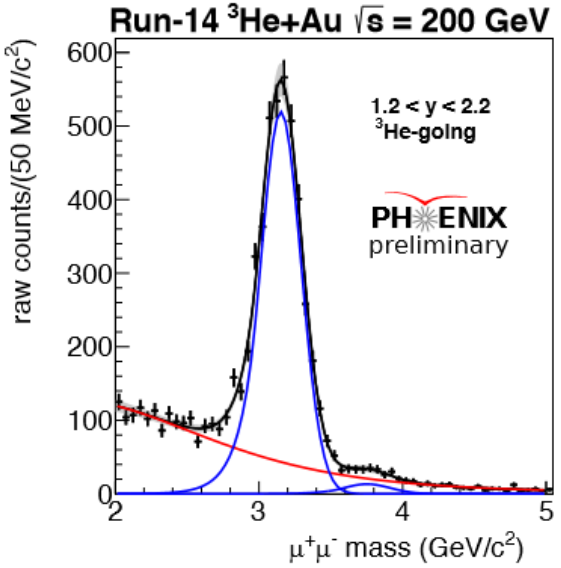


Quarkonia in ^{3}He+Au at 200 GeV – Run 14









Quarkonia in Small Systems: J/ψ

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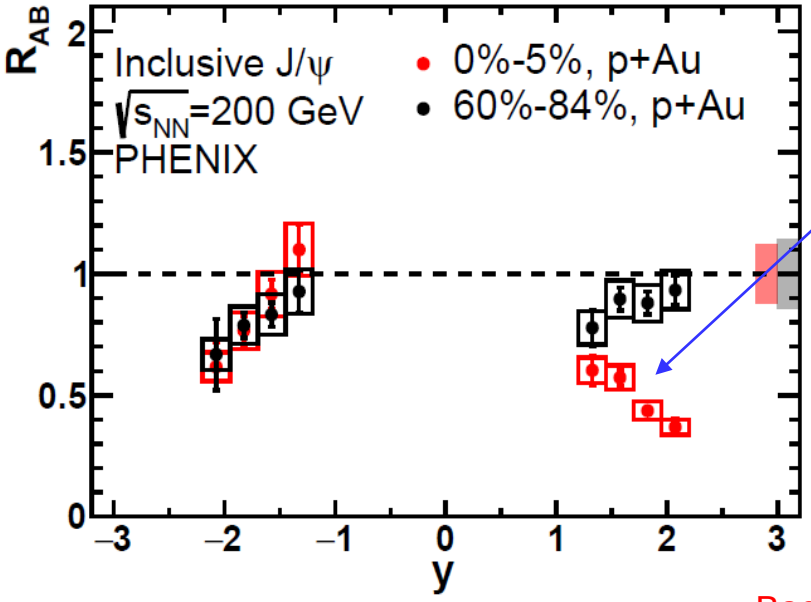
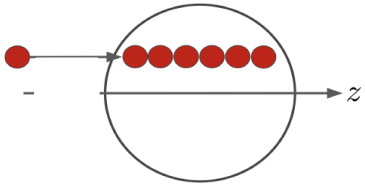


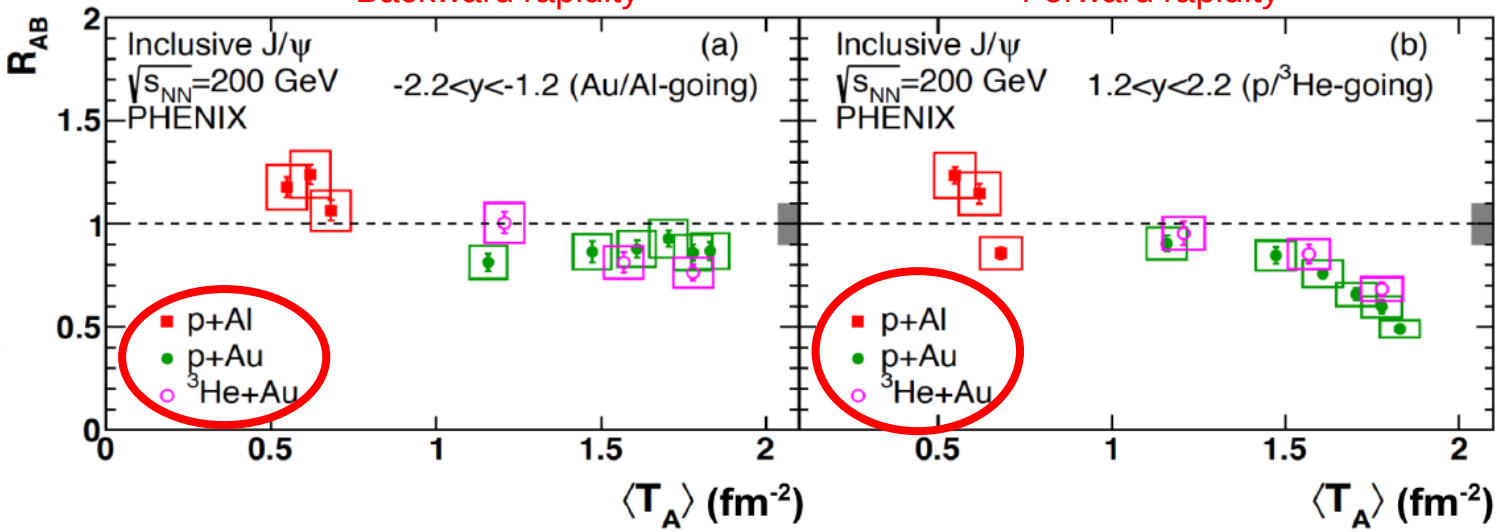
- p+Au: Very strong suppression at forward rapidity in 0-5% central bin
- Nuclear absorption effects at backward rapidity

- No projectile dependence at forward rapidity



Backward rapidity

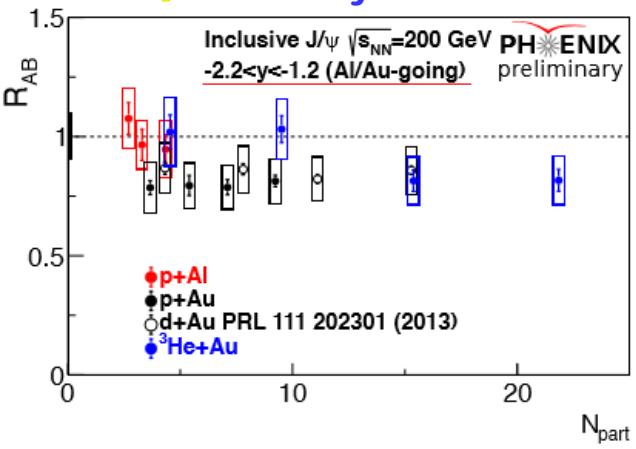
Forward rapidity

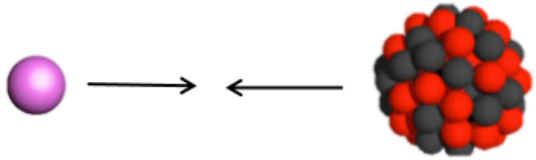


Quarkonia in Small Systems: J/ψ

Nuclear Modification Factor R_{AB} vs N_{part}

J/ψ -2.2 < y < 1.2



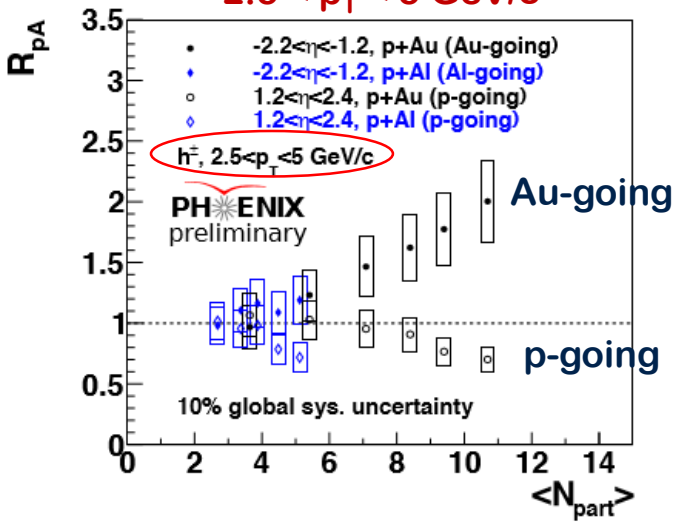


Charged Hadrons

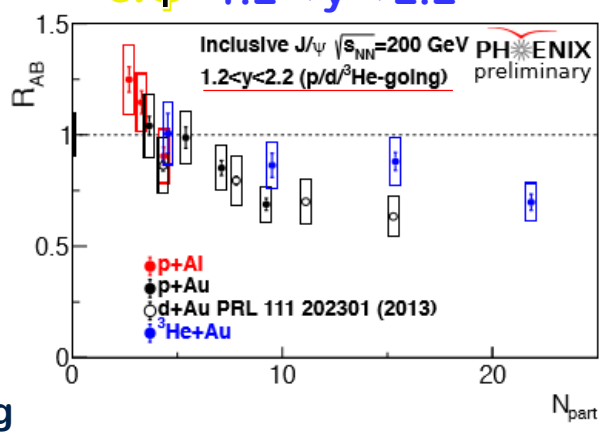
p+Au 200 GeV

p+Al at 200 GeV

2.5 < p_T < 5 GeV/c

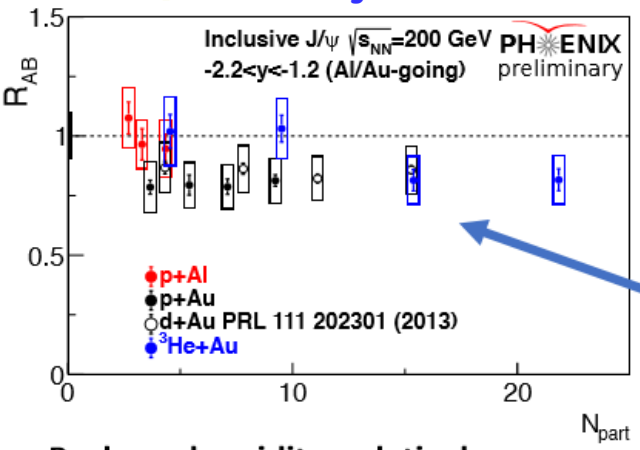


J/ψ 1.2 < y < 2.2

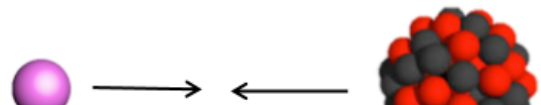


Quarkonia in Small Systems: J/ψ

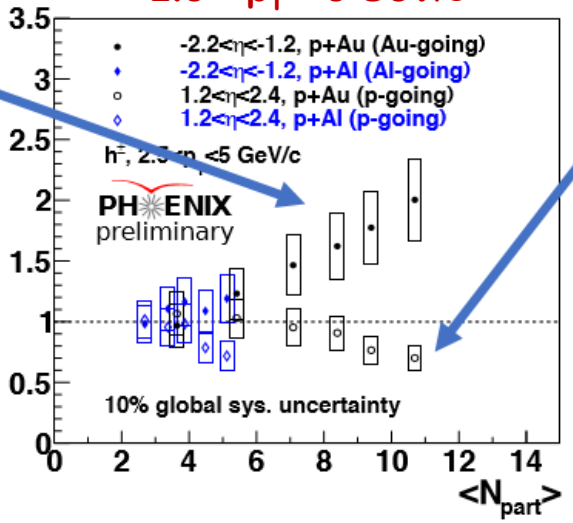
Nuclear Modification Factor R_{AB} vs N_{part}

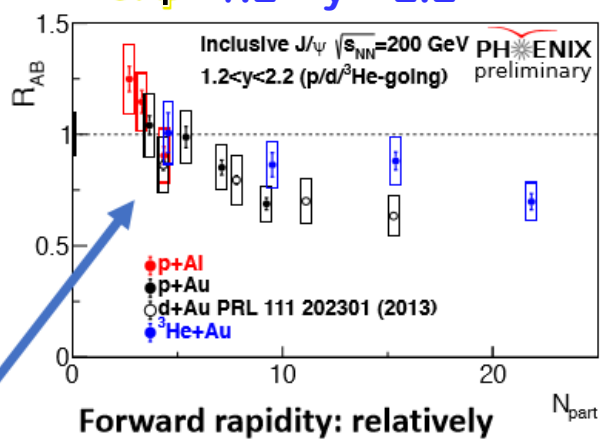


Backward rapidity: relatively high hadron density



Charged Hadrons
p+Au 200 GeV
p+Al at 200 GeV
2.5 < p_T < 5 GeV/c





Forward rapidity: relatively low hadron density

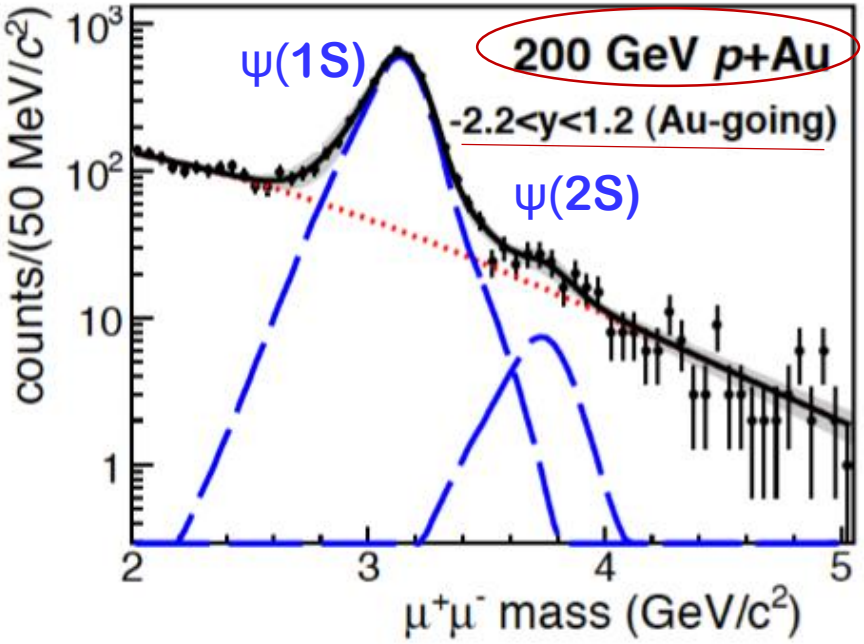
Charged hadrons enhanced
J/ψ suppressed
Suggests *"breakup"* may be dominant effect here

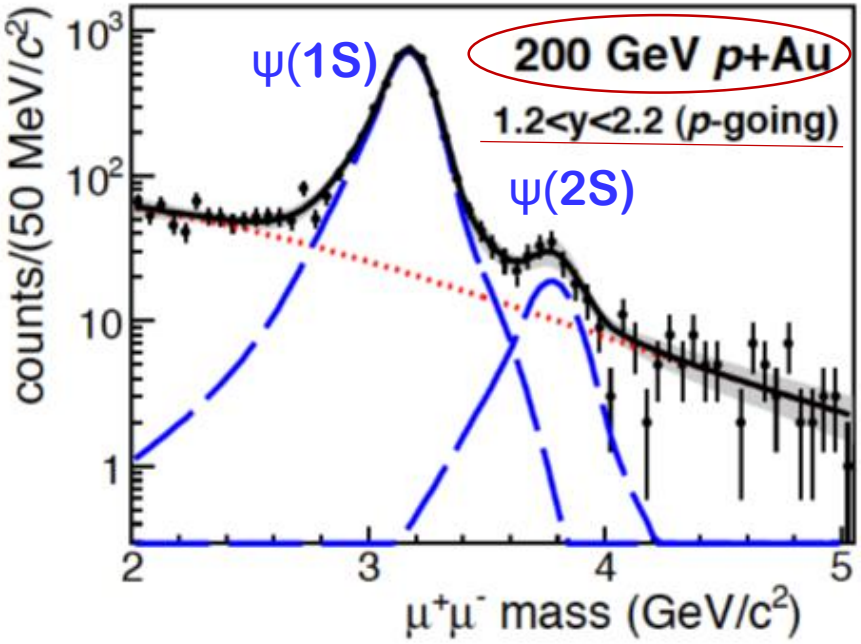
Charged hadrons suppressed
J/ψ suppressed
Suggests *shadowing* may be dominant effect here

Theoretical Models are needed

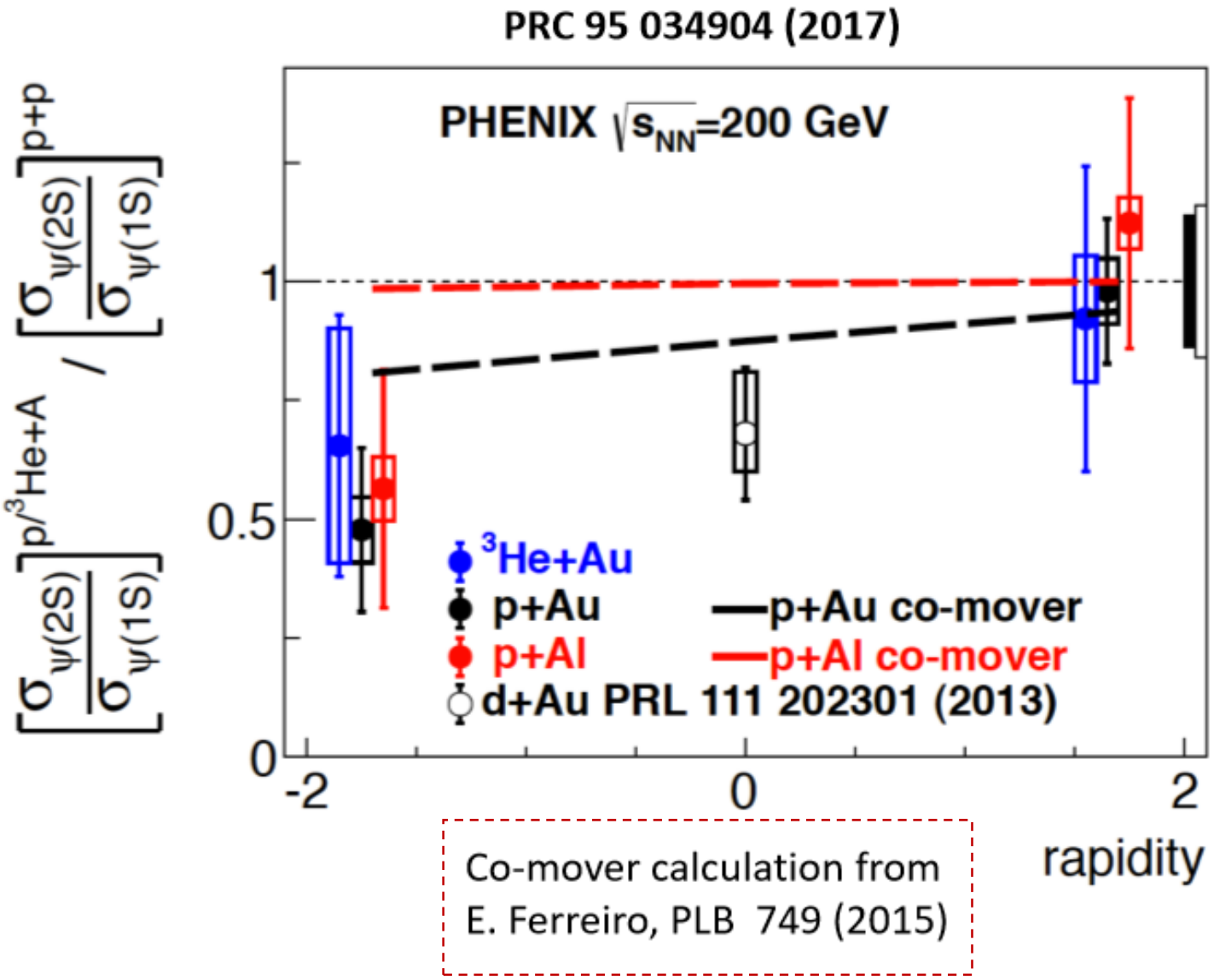
Forward/Backward Rapidity ψ: 1S vs 2S

What about the ψ(2S) in forward/backward rapidity and small systems?

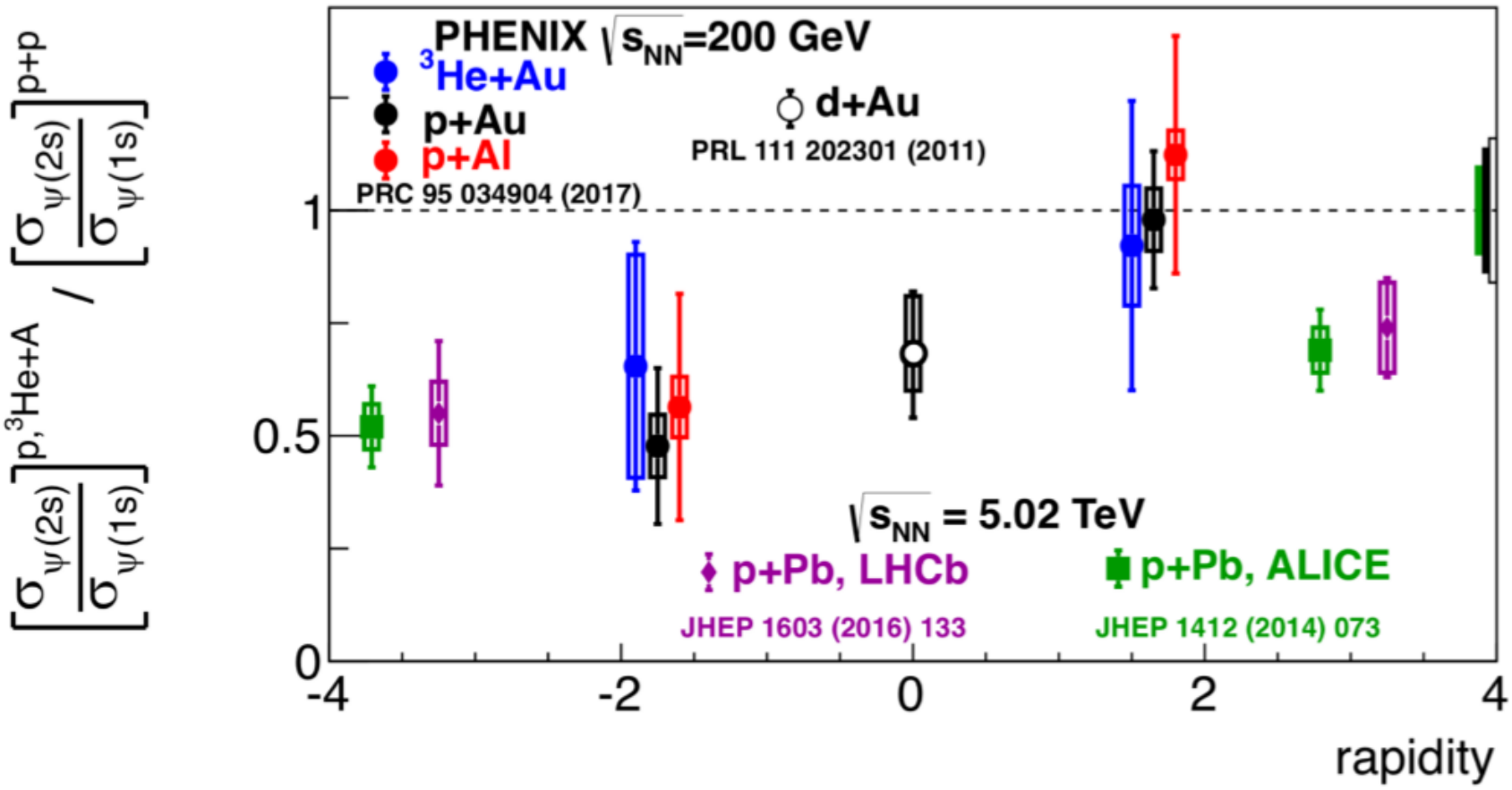




Quarkonia in Small Systems: ψ: 1S vs 2S



Quarkonia in Small Systems: ψ: 1S vs 2S



Little difference observed between forward/backward rapidity at LHC

Summary

- **Without Doubt RHIC is Amazing QCD Machine**
  - Many Species, Many Energies, and High Luminosity and Stability
- **Open Heavy Flavor**
  - PHENIX measures 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
  - Separated charm and bottom electron v_2
    - $v_2^c(c\rightarrow e)$ increase smoothly with p_T
    - $v_2^b(b\rightarrow e)$ is consistent with zero within statistical and systematic uncertainty
    - $v_2^b\,(b\rightarrow e)$ 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. Different effects become dominant as we move from small to large systems and in distinct kinematic regimes. Without doubt, these results became a challenge to many models and final physics interpretation still work in progress.
- **Stay Tuned …!**
  - **More statistic:** decrease uncertainties, increase p_T reach, centrality separation

    → more surprises: new bottom and charm results as a function are coming soon