BROOKHAVEN NATIONAL LABORATORY

Strangeness in Quark Matter 2016

from 27 June 2016 to 1 July 2016
UC Berkeley

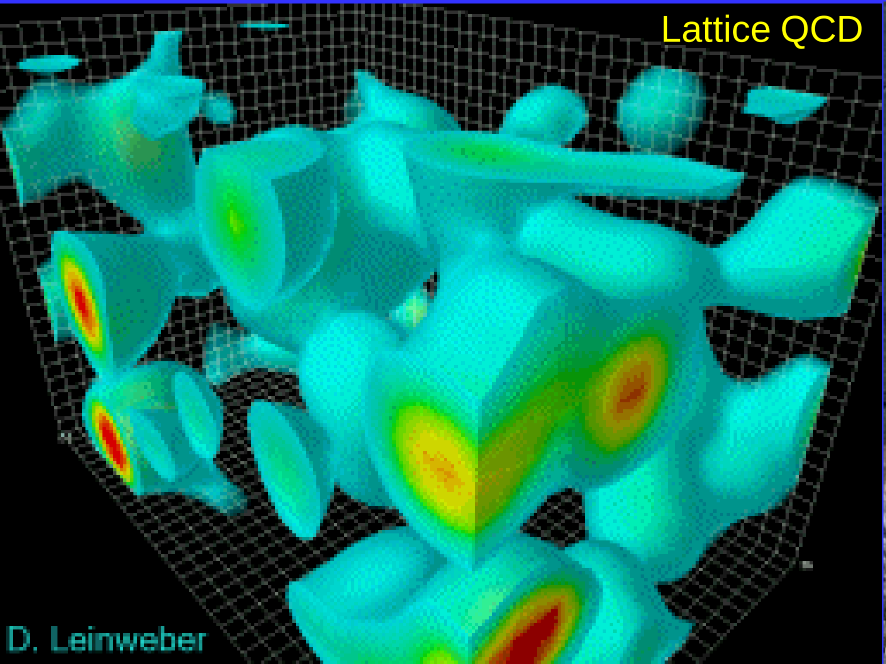
Latest Results

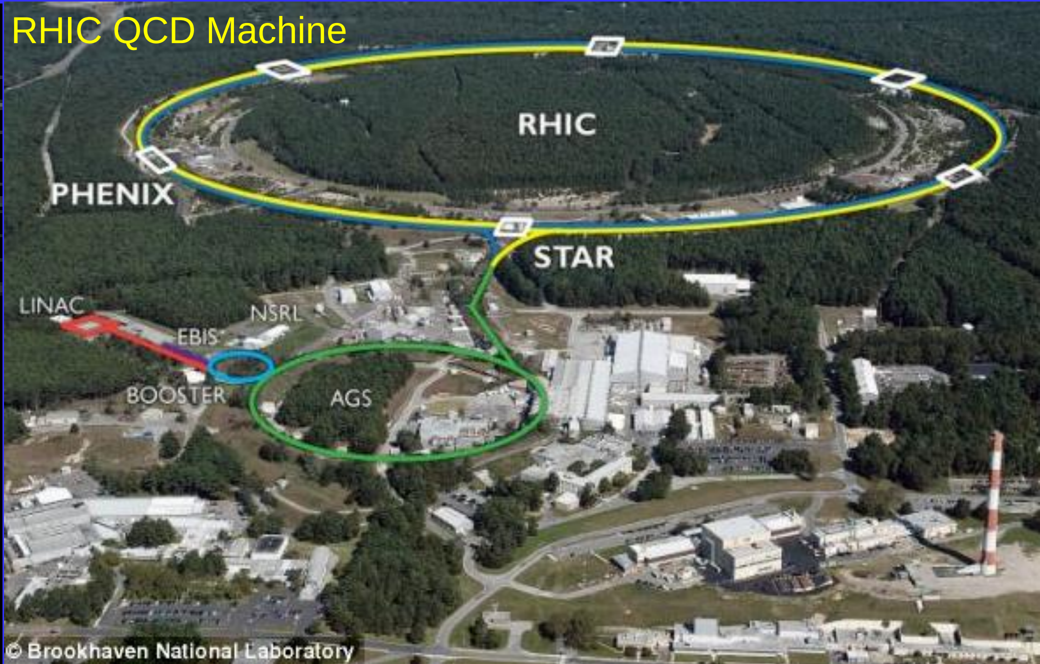
Open Heavy Flavor and Quarkonia

PHENIX Experiment at RHIC

Rachid Nouicer

for the PHENIX collaboration



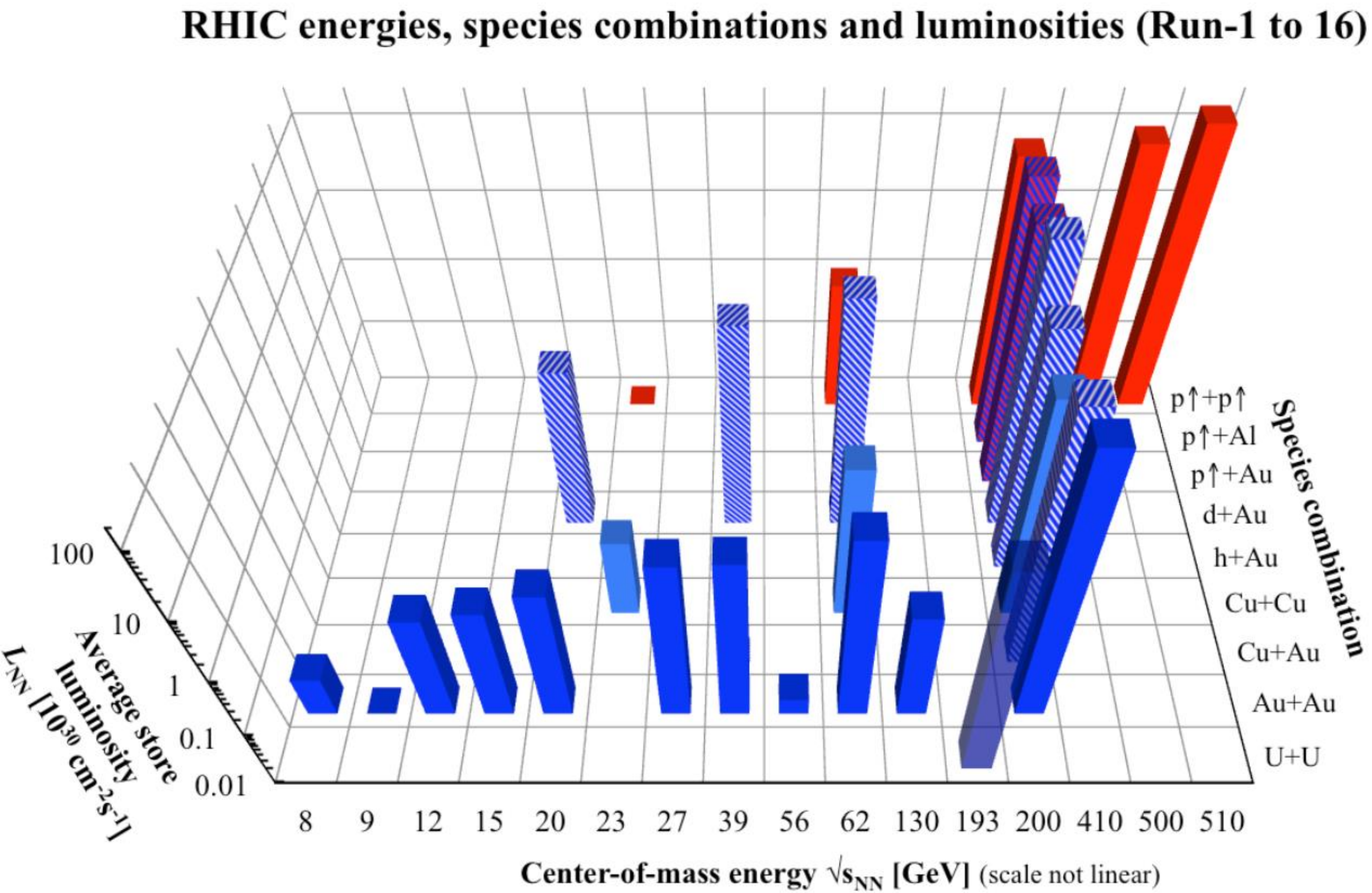


RHIC Amazing QCD Machine: Many Species and Many Energies!

Run	Species	Total particle energy [GeV/nucleon]	total delivered Luminosity [μb^{-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 [μb^{-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 Au+Au	200 200 62.4 19.6 39 200	$46.1x10^{-3}$ $46.1x10^{-3}$ $44.0x10^{-3}$ $7.2x10^{-3}$ --- in progress

RHIC Amazing QCD Machine: Many Species and Many Energies!



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?

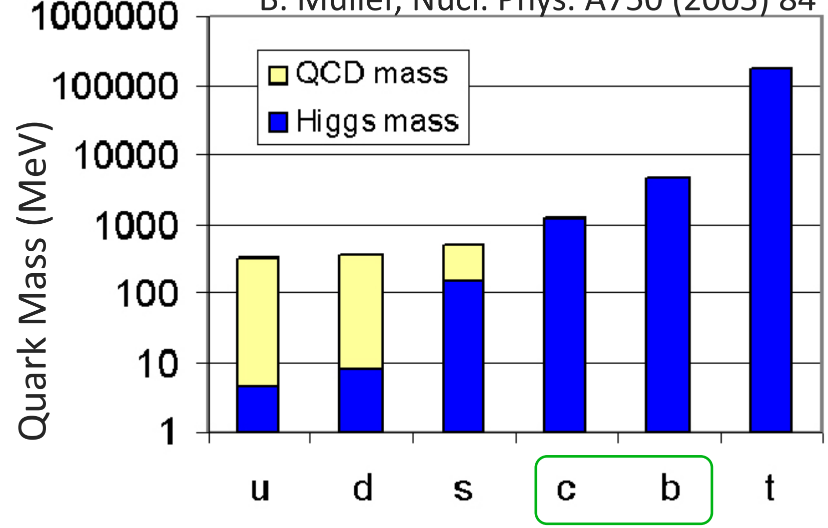
Each parameter probes different admixtures of nuclear modification

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**

B. Muller, Nucl. Phys. A750 (2005) 84



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

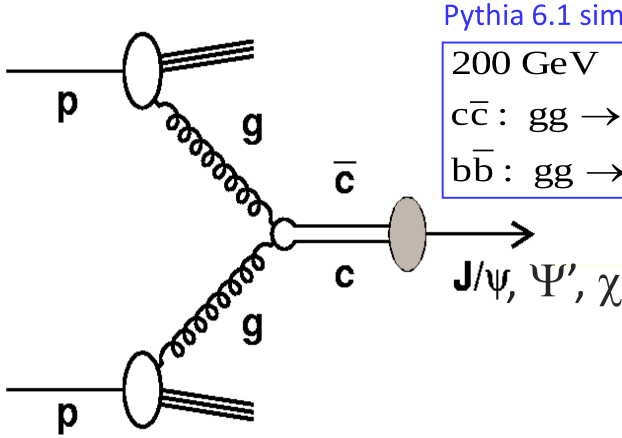
State	J/ψ	χ_c	ψ'	Υ	χ_b	Υ'	χ_b'	Υ''
Mass (GeV)	3.10	3.53	3.68	9.46	9.99	10.02	10.36	10.36
ΔE (GeV)	0.64	0.20	0.05	1.10	0.67	0.54	0.31	0.20
Radius (fm)	0.25	0.36	0.45	0.14	0.22	0.28	0.34	0.39

- 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)

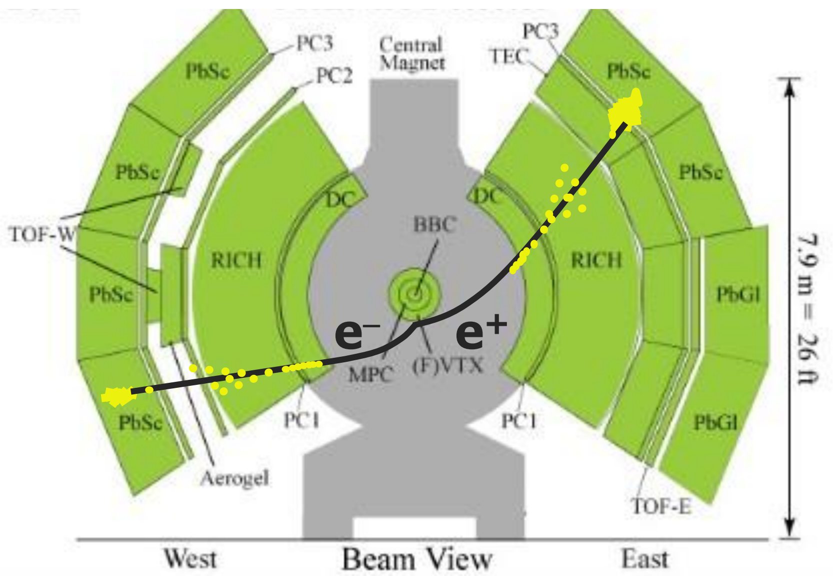
200 GeV
$c\bar{c}$: $gg \rightarrow c\bar{c}$ 95%
$b\bar{b}$: $gg \rightarrow b\bar{b}$ 85%

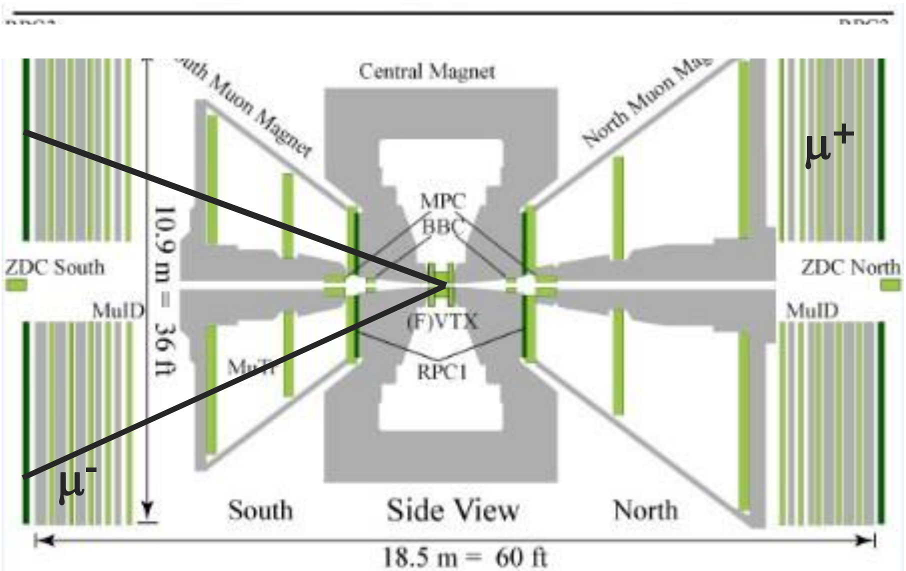


Measuring Heavy Flavor in PHENIX

PHENIX: optimized to measure leptons:

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





Mid-rapidity: J/ψ, ϒ → $e^+ e^-$

- $|\eta| < 0.35$, $\Delta\phi = 2 \times \pi/2$, $p > 0.2$ GeV
- Drift and pad chamber for tracking
- Cerenkov detector (RICH) and calorimeter (EMCAL) electron ID
- Silicon Vertex Tracker (VTX)

Forward rapidity: J/ψ, ϒ → $\mu^+ \mu^-$

- $1.2 < |\eta| < 2.2$, $\Delta\phi = 2\pi$, $p > 2$ GeV
- Muon Tracker reconstructs trajectories and determines momentum
- Muon magnets and Muon Identifier steel absorb hadrons, pion rejection
- Forward Silicon Vertex Tracker (FVTX)

What have we learned from Open Heavy Flavor?

The variety and precision of results keep expanding, revealing interesting features

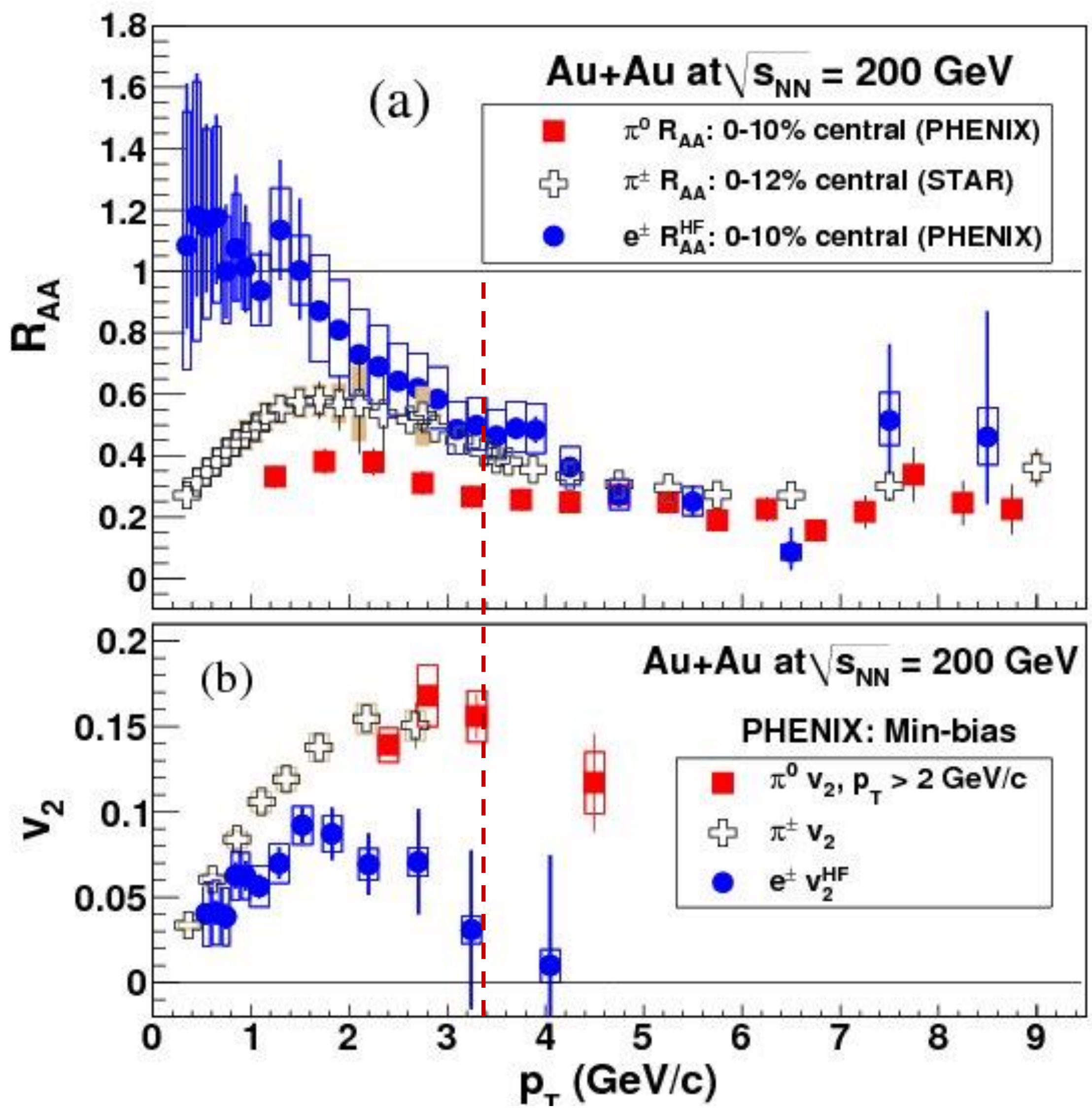
Heavy Flavor Electrons

High-p_T

- Significant suppression
- Similar suppression of light hadrons and EHF (c+b): what about c→e and b→e?

Low-p_T

- Little suppression
- EHF less suppressed than light hadrons.
- Significant v_2, but less than light hadrons.



What have we learned from Open Heavy Flavor?

EHF : Au + Au vs. d+Au at 200 GeV

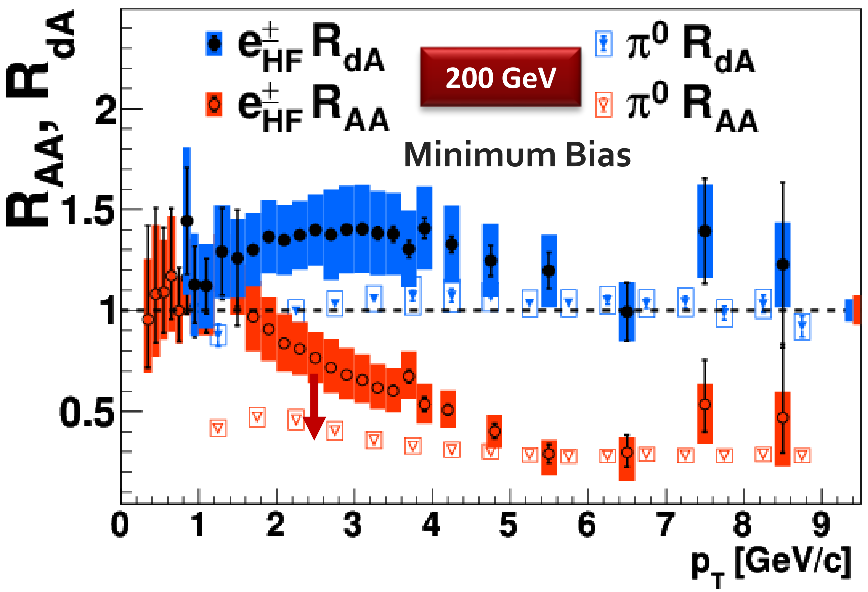
d+Au: no suppression observed over p_T

Baseline is no longer R_{AA}=1

Implies R_{AA} is more strongly suppressed for p_T < 4!

Need detailed calculations to propagate effects to Au+Au collisions!

PHENIX: PRL 109 242301

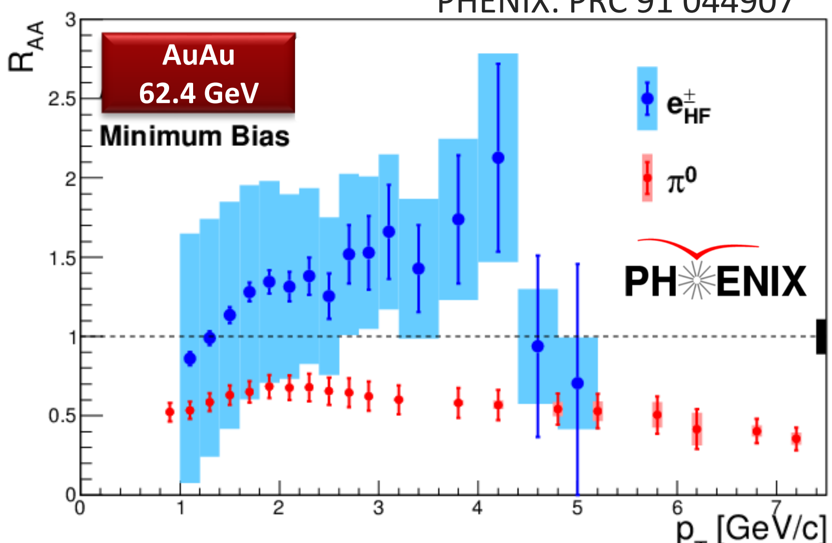


Au + Au at 62.4 GeV

- In contrast to 200 GeV AuAu, the 62.4 GeV R_{AuAu} show clear enhancement
- Due to less energy loss? larger Cronin effects? or combination of those factors and other effects?

But: p + p comes from ISR. We need more p + p data at 62 GeV!

PHENIX: PRC 91 044907

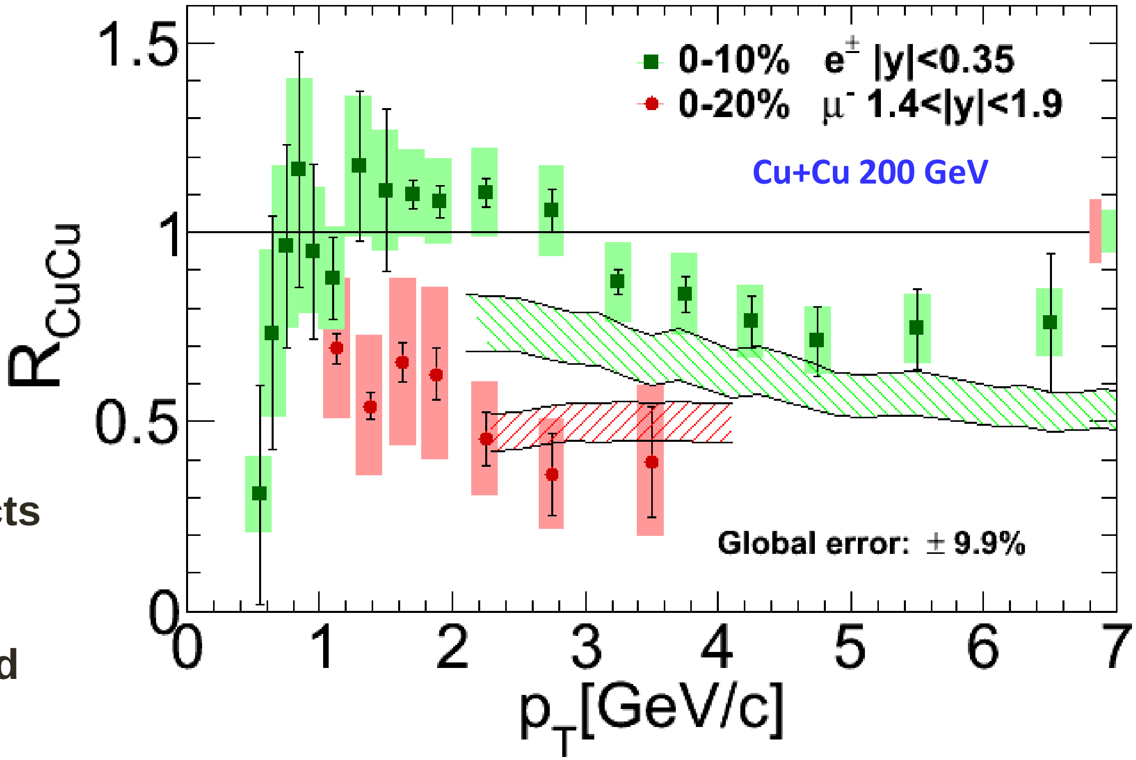


What have we learned from Open Heavy Flavor?

Single electrons e^{HF} vs single muons μ^{HF}
Mid-rapidity vs forward rapidity

Suppression is stronger at forward rapidity than mid-rapidity- why ?

PHENIX: PRC 90 034903



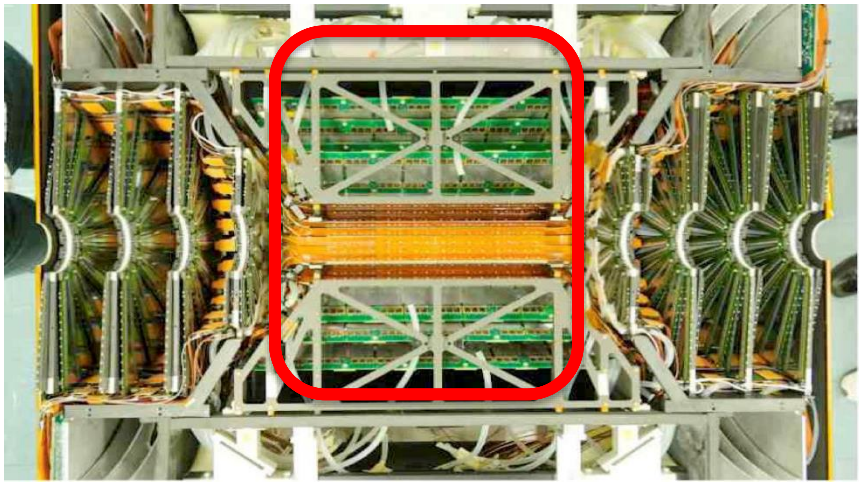
✧ Data in agreement with I. Vitev's prediction that accounts for:

(1) for final state energy loss effects with his dissociation model
(2) cold nuclear matter effects, such as nuclear shadowing and parton multiple scattering

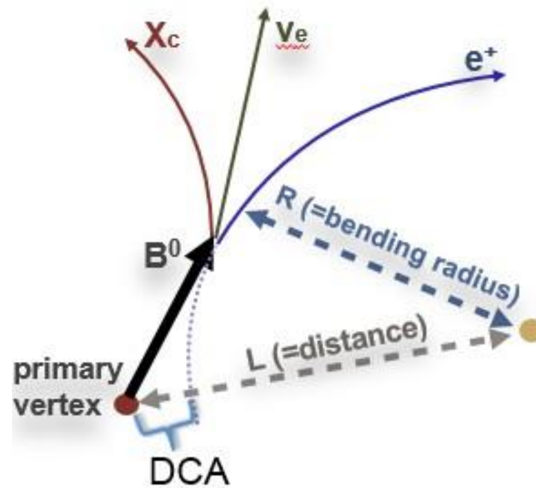
Indication of Cold Nuclear Matter (CMN) effects at forward rapidity in Cu+Cu system at 200 GeV

What NEW on Open Heavy Flavor?

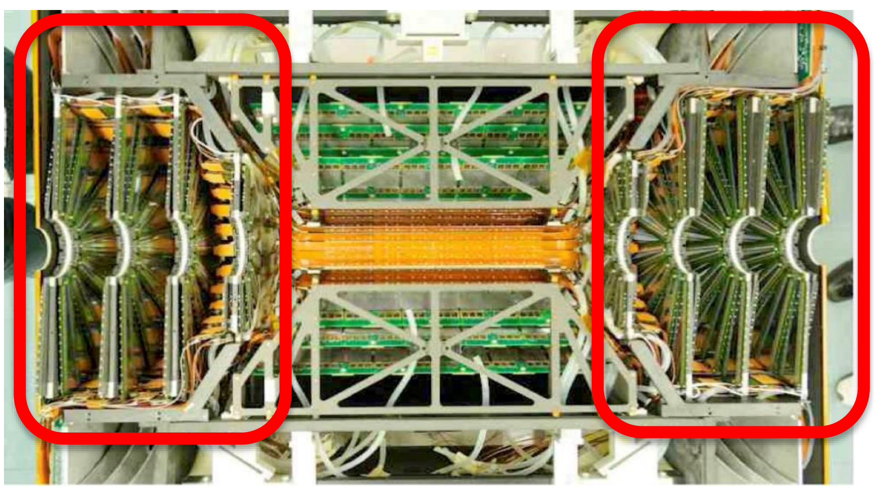
c/b separation by secondary vertex



VTX detector

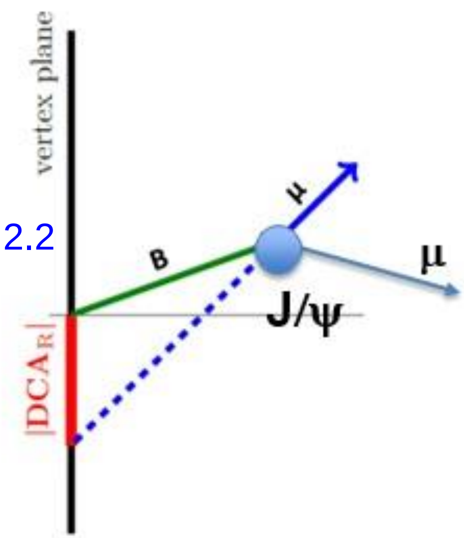


- VTX (2011):
  - Midrapidity: |η | <1.2
    - AuAu 200 GeV:
      - ~ 60 μm DCAT resolution



FVTX detector

- FVTX (2012):
- Forward rapidity - 1.2 < |η| < 2.2
- Improved muon momentum resolution & precise tracking



What NEW on Open Heavy Flavor?

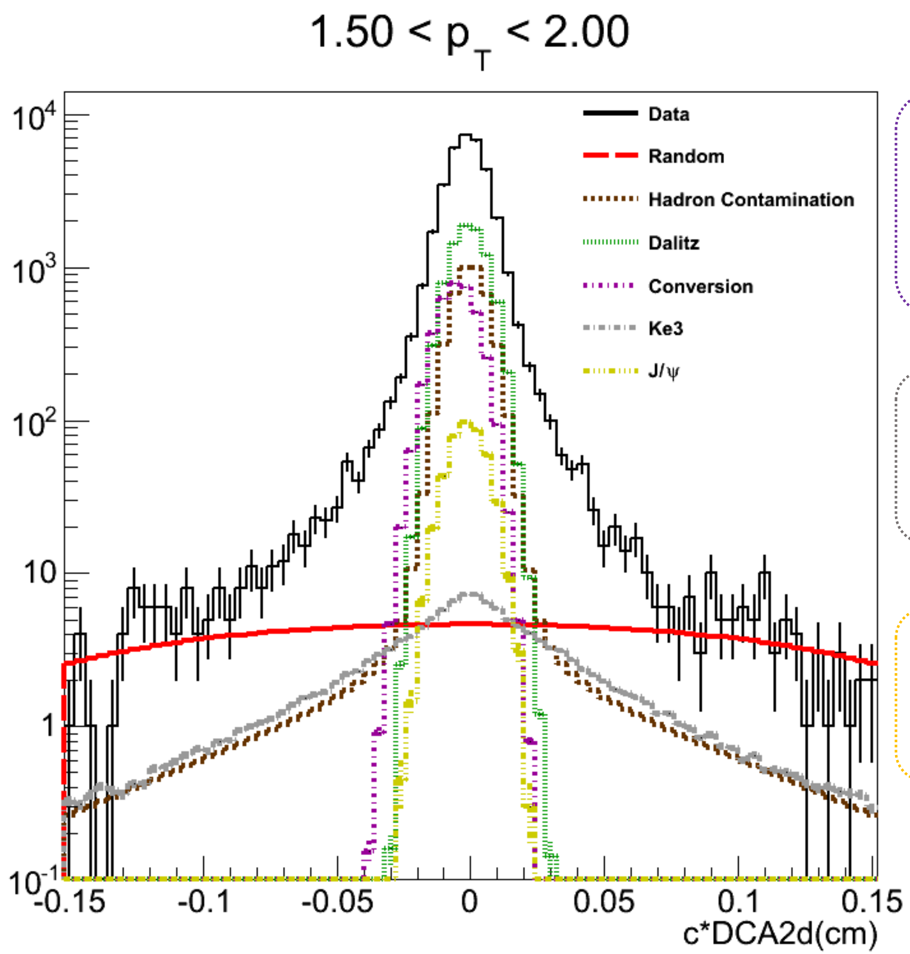
First Results from PHENIX VTX: b/c separation

DCA_T Distributions: Backgrounds

High-Multiplicity Bkg.
Data driven shape
Tracks with large DCA_L

Mis-identified hadrons:
Data driven shape
RICH Swap Method

Dalitz:
Monte Carlo shape
With measured yield



PHENIC: PRC **93**, 034904 (2016)

Conversions:
Monte Carlo shape
With Measured Pi0 yield
~75% rejected

Ke3:
Monte Carlo shape
With measured yield

$J/\psi \to e^+e^-$:
Monte Carlo shape
With measured yield

What NEW on Open Heavy Flavor?

First Results from PHENIX VTX: b/c separation

DCA_T Distributions: b/c separation

b → e

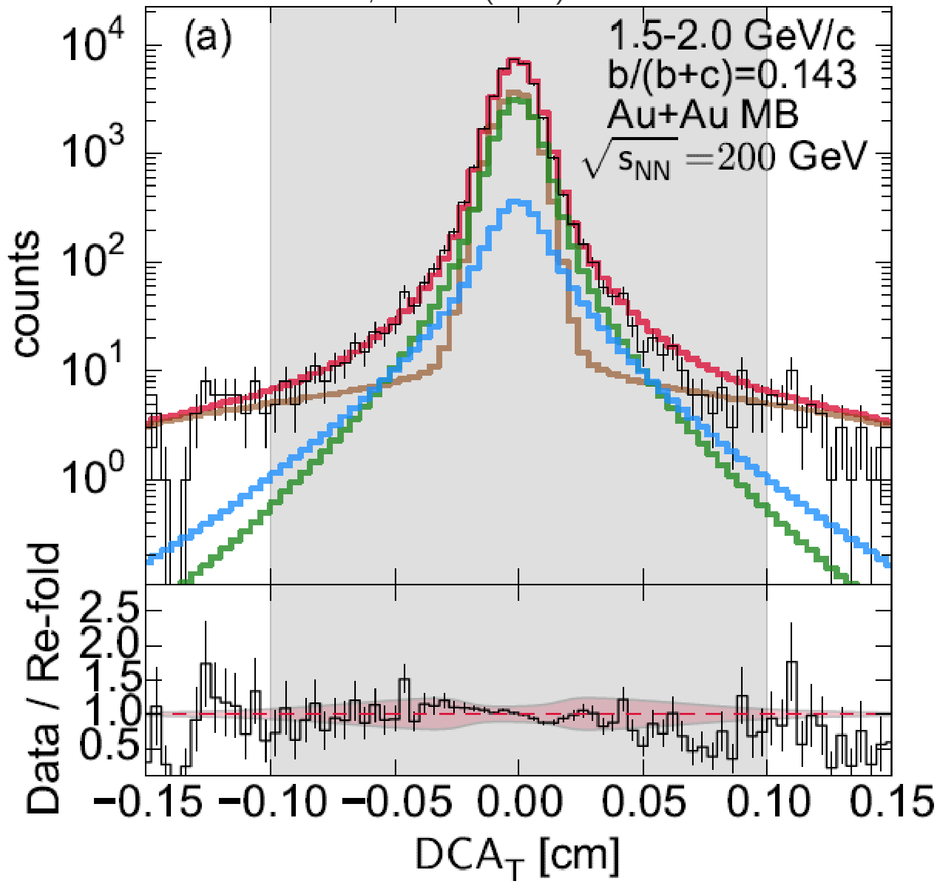
c → e

Total

Data

Backgrounds

PHENIC: PRC **93**, 034904 (2016)



c->e:
Monte Carlo shape
Normalization
from unfolding

b->e:
Monte Carlo shape
Normalization from
unfolding

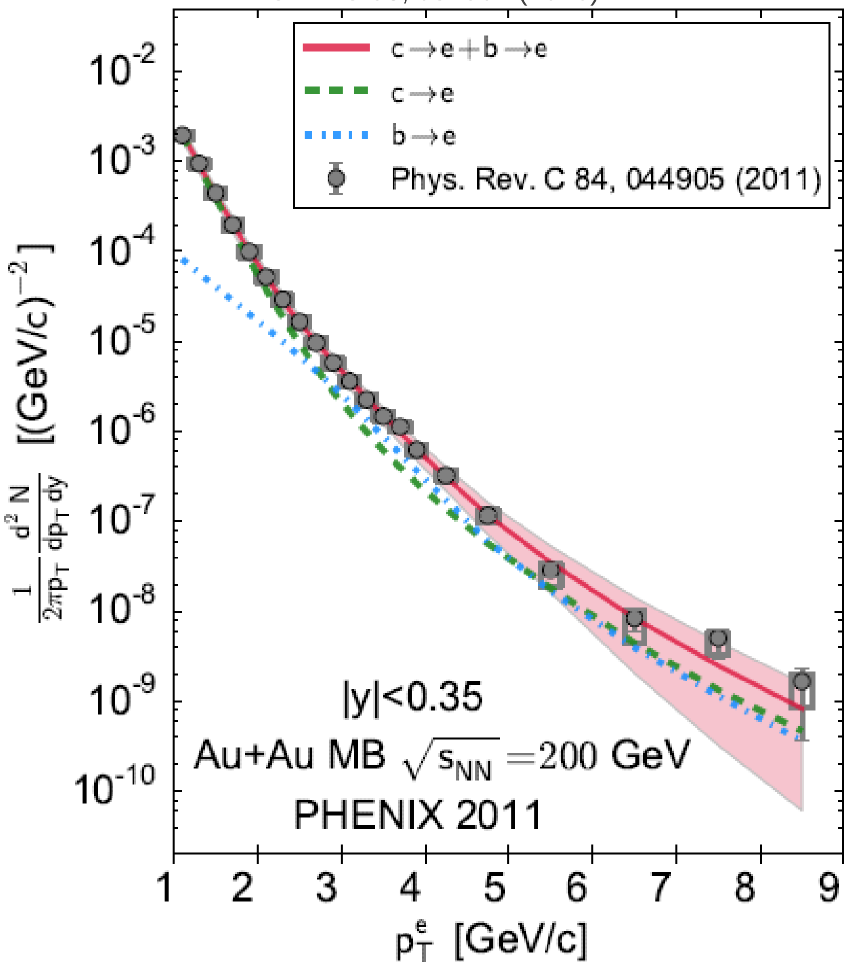
The charm and bottom yield predicted by the unfolding is consistent with electron measured DCA_T distributions.

What NEW on Open Heavy Flavor?

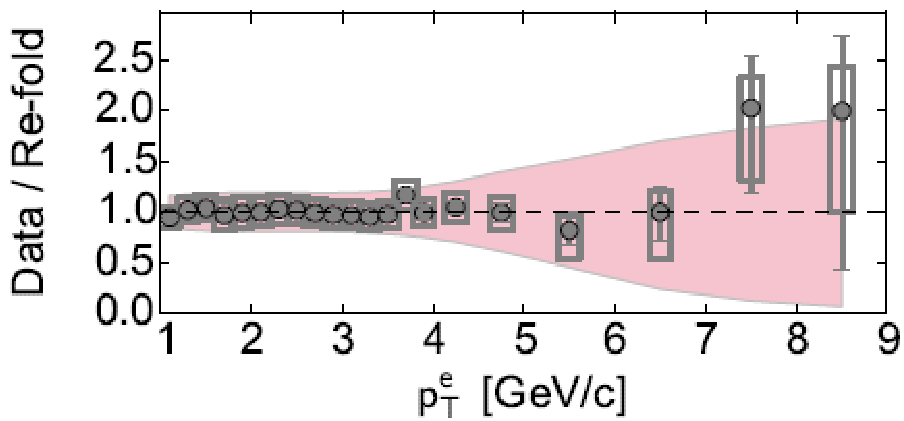
First Results from PHENIX VTX: b/c separation

Invariant yield compared to previous published results

PHENIC: PRC **93**, 034904 (2016)



The unfolding results are consistent with the previous published inclusive heavy flavor electron invariant yields.

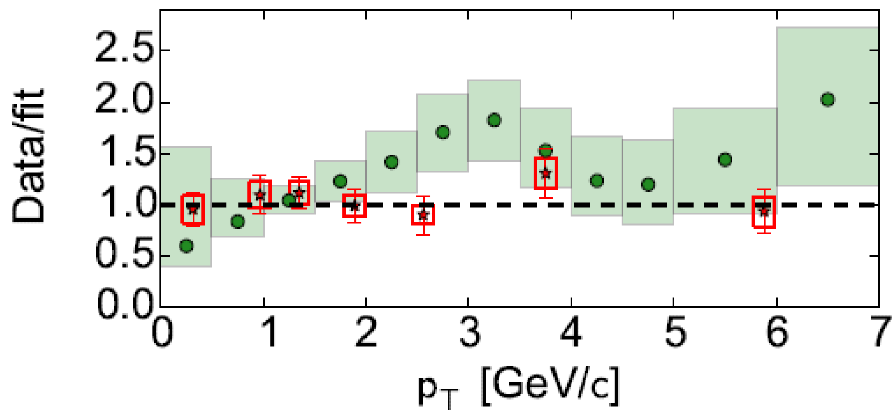


What NEW on Open Heavy Flavor?

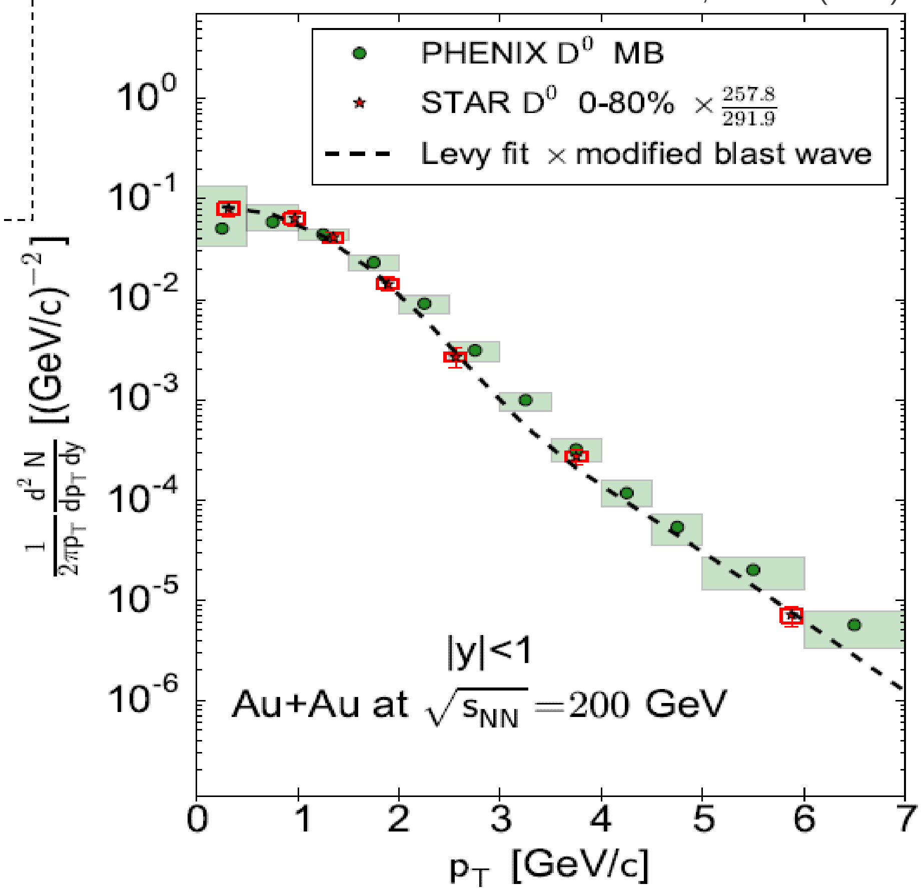
First Results from PHENIX VTX: b/c separation

Invariant yield:

PHENIX unfolded D^0 p_T spectra agrees within uncertainties with measurements from STAR.



PHENIC: PRC **93**, 034904 (2016)

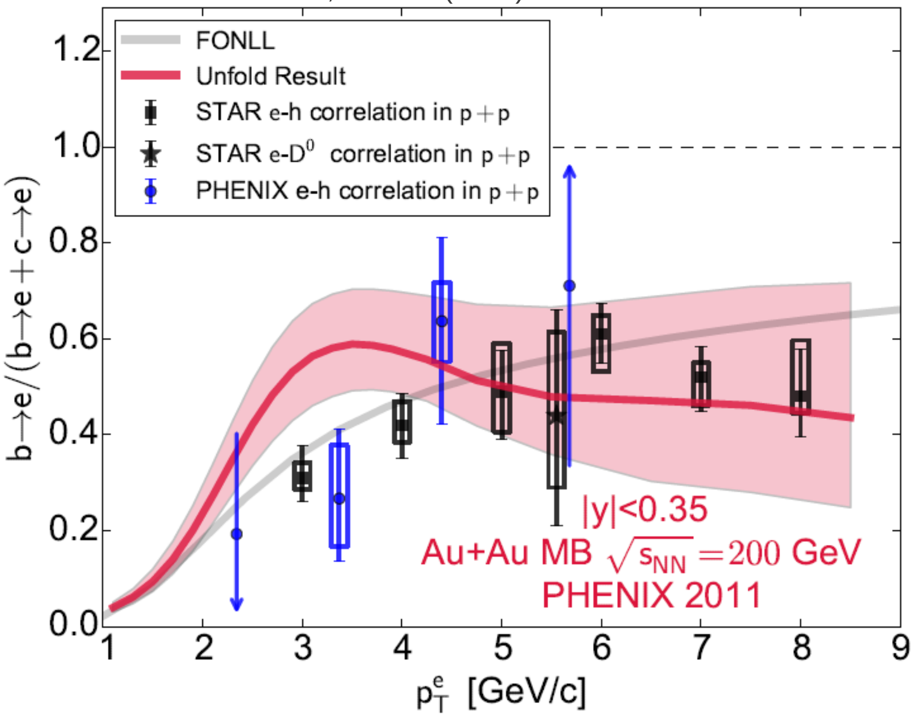


What NEW on Open Heavy Flavor?

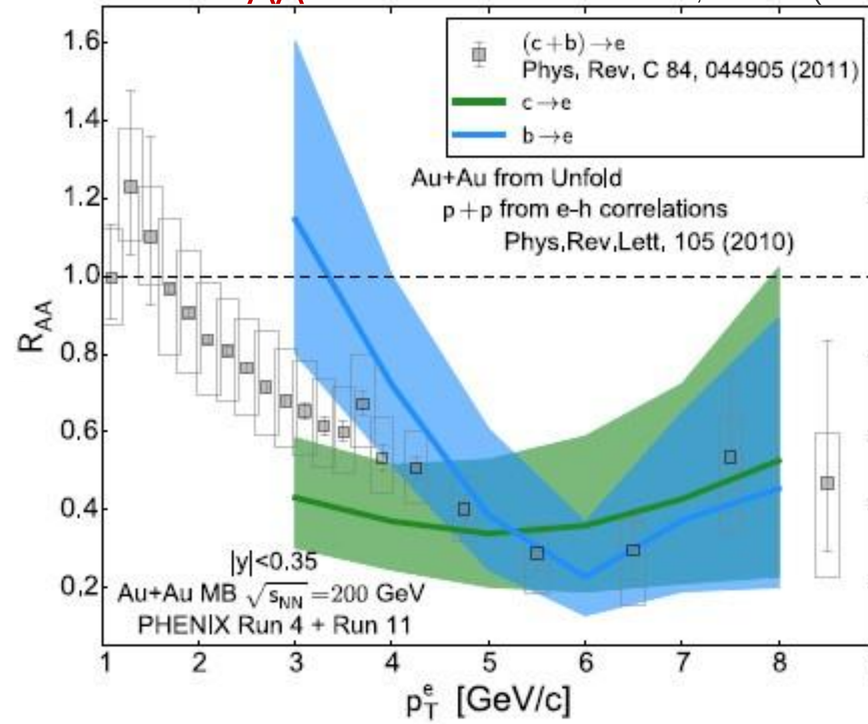
First Results from PHENIX VTX: b/c separation

Bottom and Charm R_{AA}

PHENIC: PRC **93**, 034904 (2016)



PHENIC: PRC **93**, 034904 (2016)



$$R_{AA}^{c\to e} = \frac{(1-F_{\rm AuAu})}{(1-F_{pp})} R_{AA}^{\rm HF}$$

$$R_{AA}^{b\to e} = \frac{F_{\rm AuAu}}{F_{pp}} R_{AA}^{\rm HF},$$

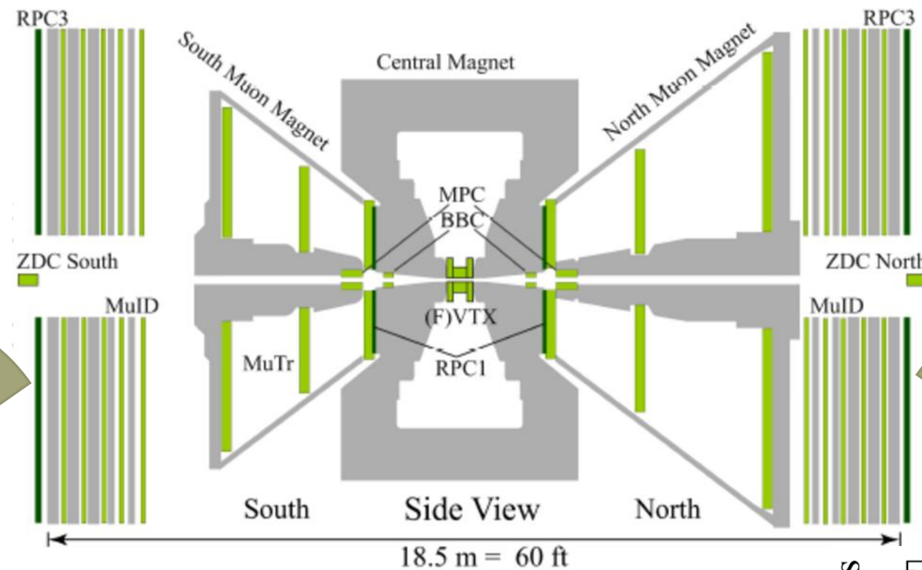
We see that around $p_T < 4$ GeV the electrons from bottom experience much less suppression than electrons from charm.

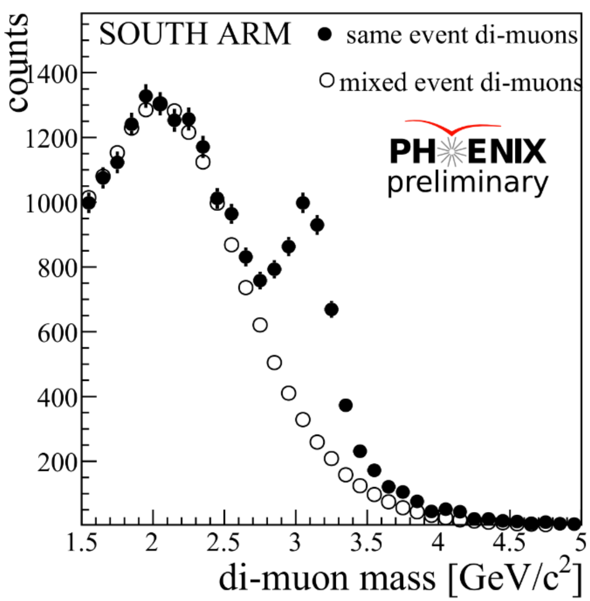
Stay Tuned:

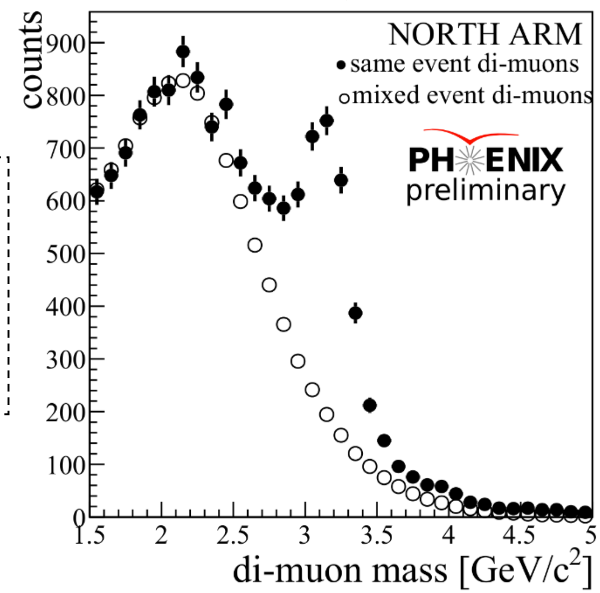
- 2014 data set x10 better statistics than 2011
  - Decrease uncertainties
  - Increase p_T reach
  - Centrality separation
- Good 2015 p+p and p+Au data sets

What NEW on Open Heavy Flavor?

First Results from the PHENIX FVTX: B → J/ψ







Using muon pairs in the J/ψ mass region an analysis was performed to determine the fraction from B → J/ψ decays

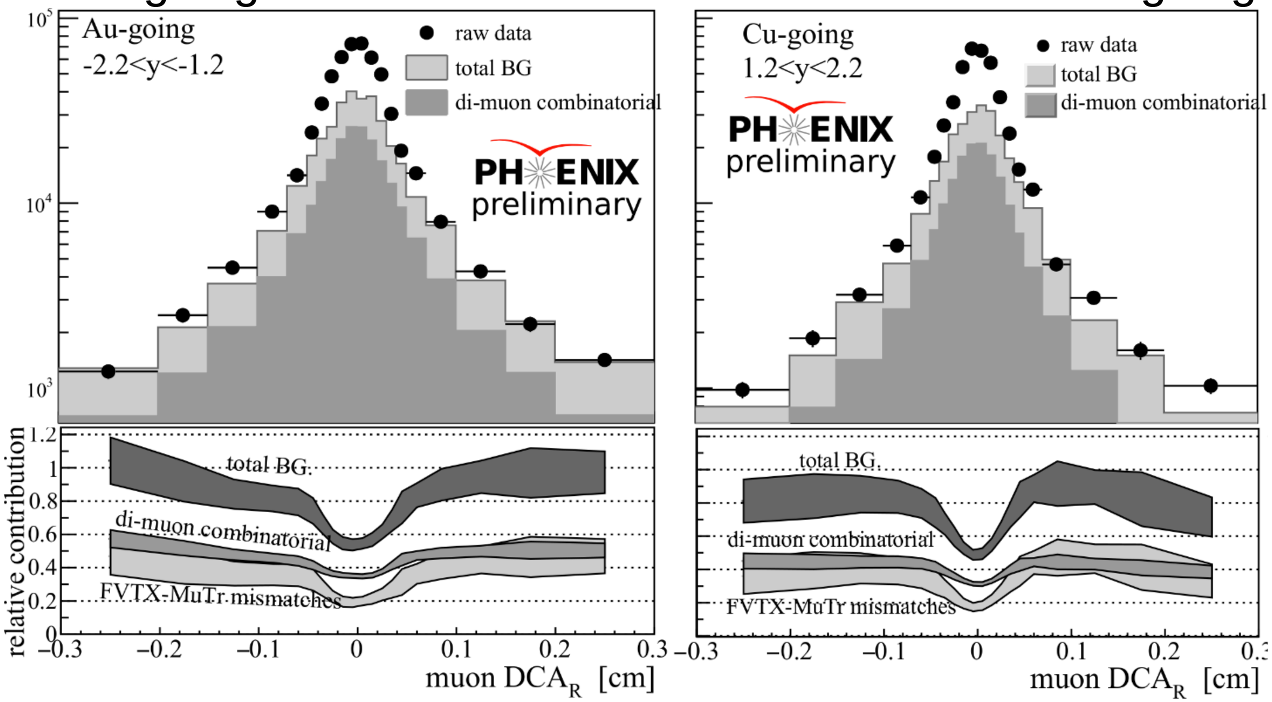
Xuan Li talk on Thursday 30/6 at 9:40 AM

What NEW on Open Heavy Flavor?

NEW!

First Results from the PHENIX FVTX: $B \rightarrow J/\psi$

Background components



Two sources of background:

- Di-muon combinatorial
- FVTX-MuTr mismatches: Coming from incorrectly matching a MuTr track to the FVTX stand alone track.

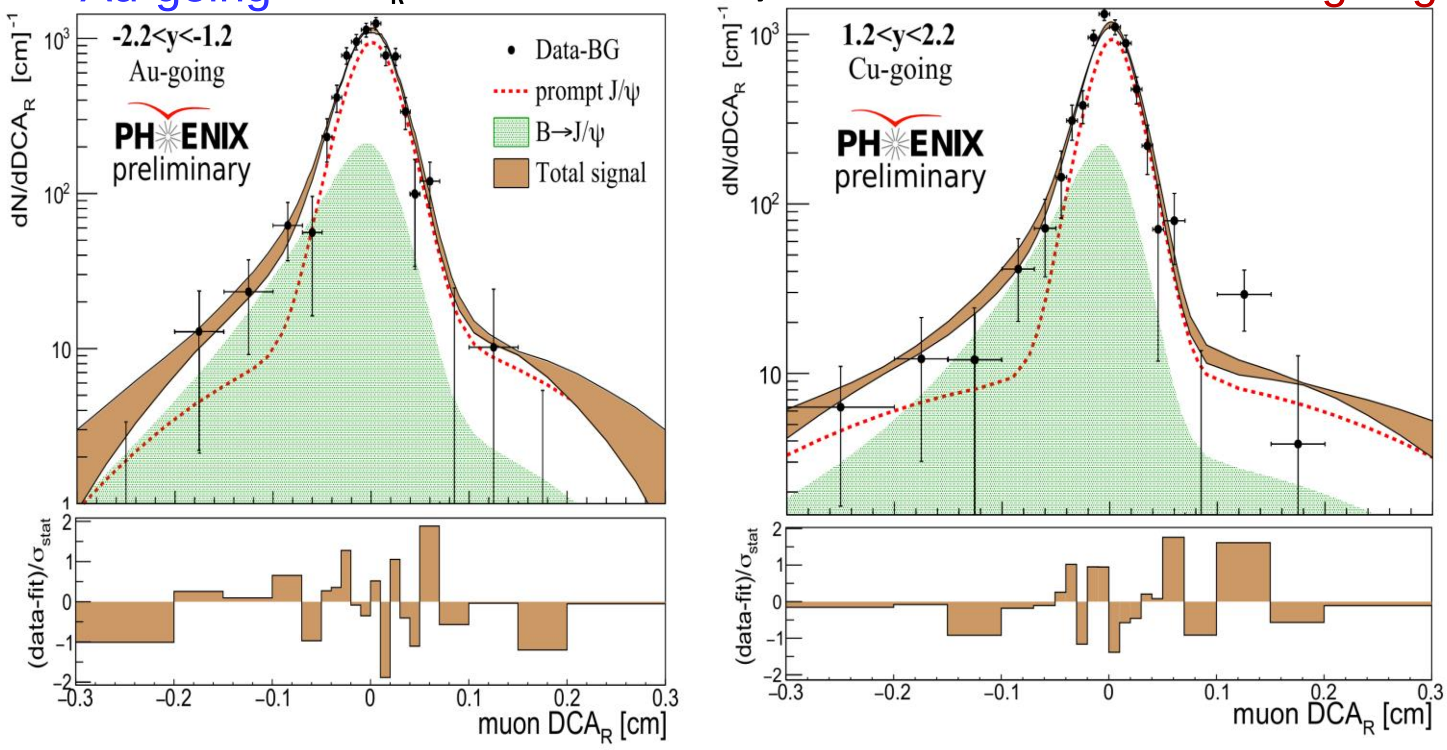
Signal templates and backgrounds are fitted together to extract the $B \rightarrow J/\psi$ fraction.

What NEW on Open Heavy Flavor?

First Results from the PHENIX FVTX: B → J/ψ

B→ J/ψ prompt J/ψ separation through DCA_R

Au-going DCA_R Distributions for clarity are shown BG subtracted Cu-going



- Prompt J/ψ and B-> J/ψ DCA_R template shapes, determined using MC simulations, were used in the fit.

- The sum of the DCA_R contributions agrees well with the data as shown in the bottom panel.

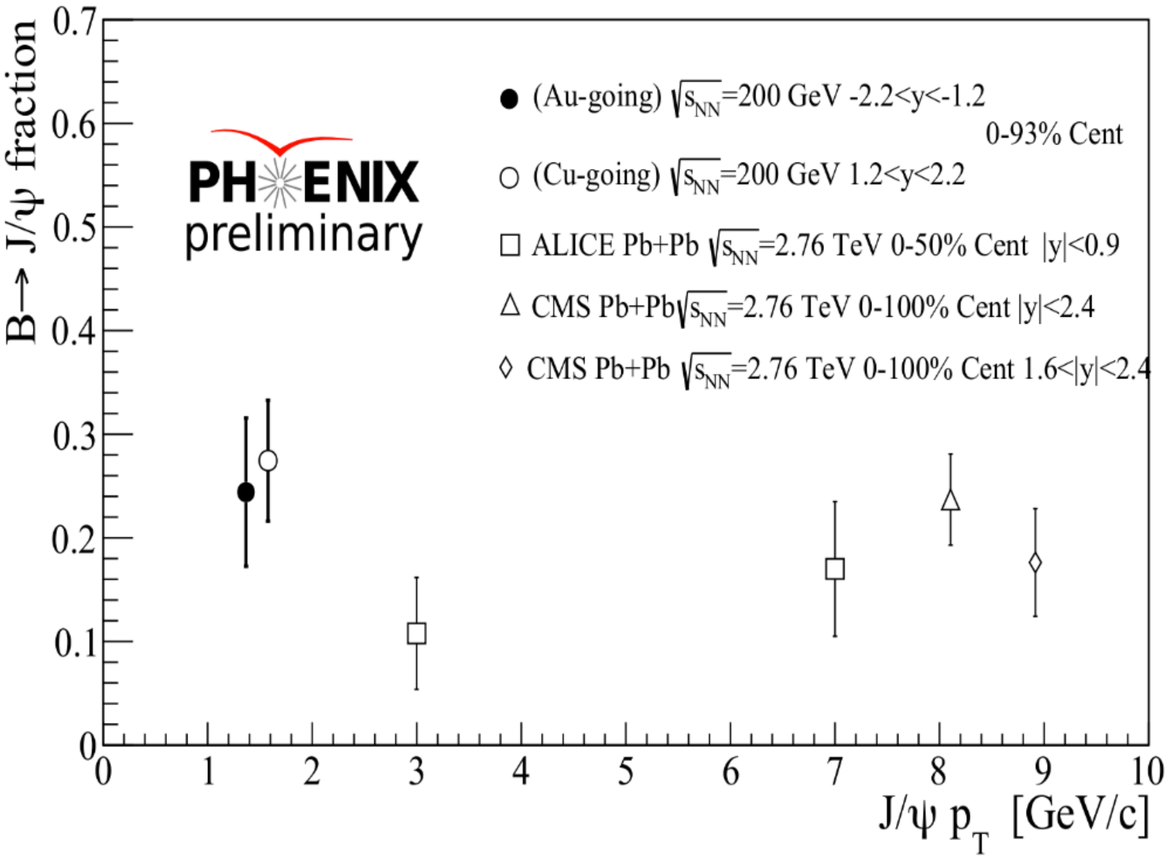
What NEW on Open Heavy Flavor?

First Results from the PHENIX FVTX: $B \rightarrow J/\psi$

B->J/ψ fraction

- $F_{B \rightarrow J/\psi}$ was determined for both the gold and copper going directions.

- Difference is attributed to a smaller suppression of B mesons relative to inclusive J/ψ at RHIC energies



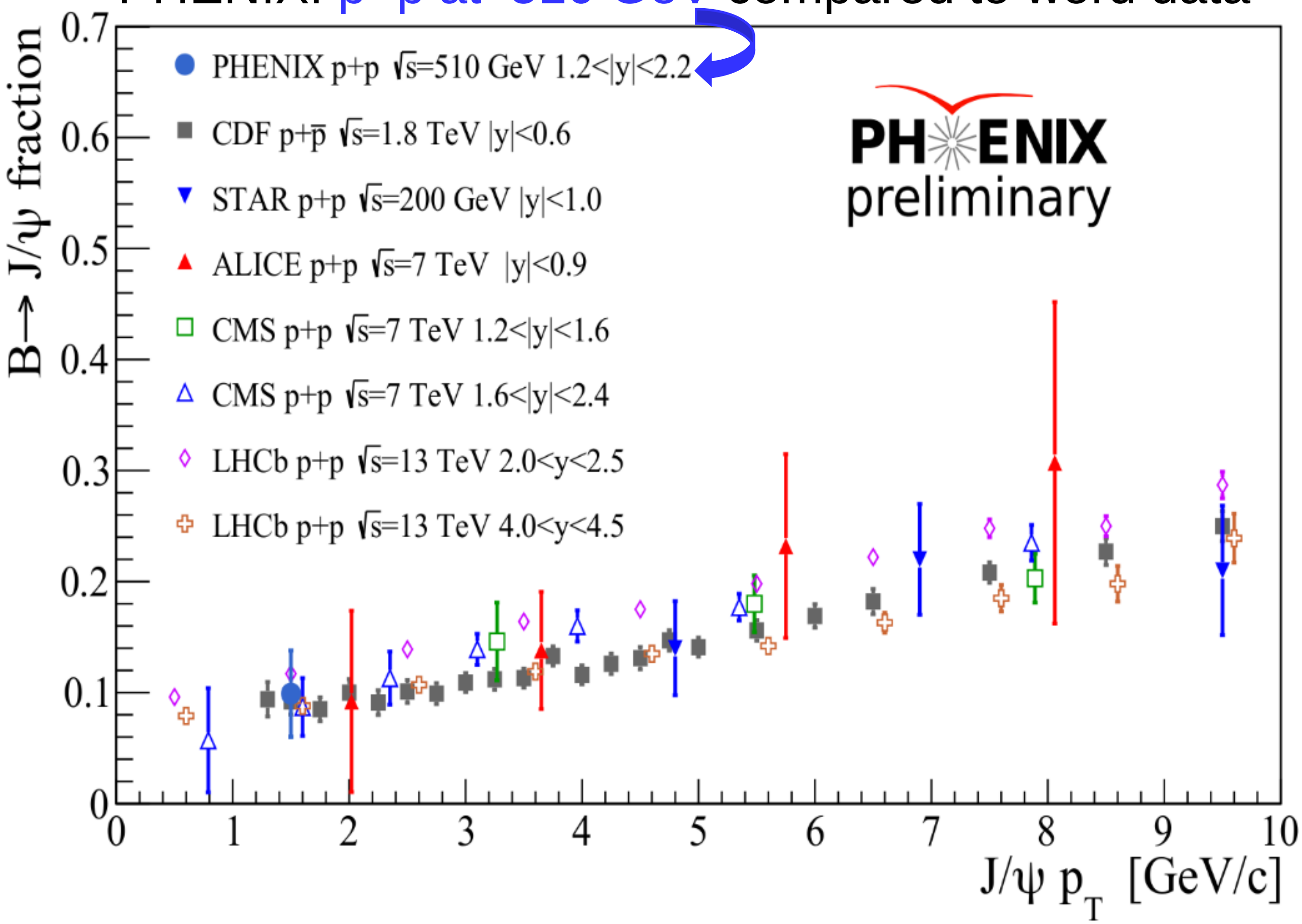
What NEW on Open Heavy Flavor?

First Results from the PHENIX FVTX: B → J/ψ

B->J/ψ fraction

PHENIX: p+p at 510 GeV compared to word data

Excellent agreement with world data



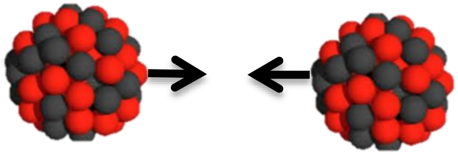
The B →J/ψ fraction does not have the energy dependence for J/ψ $p_T < 5$ GeV/c region.

What NEW on Quarkonia?

Quarkonia Results

What have we learned from

Colliding symmetric systems?

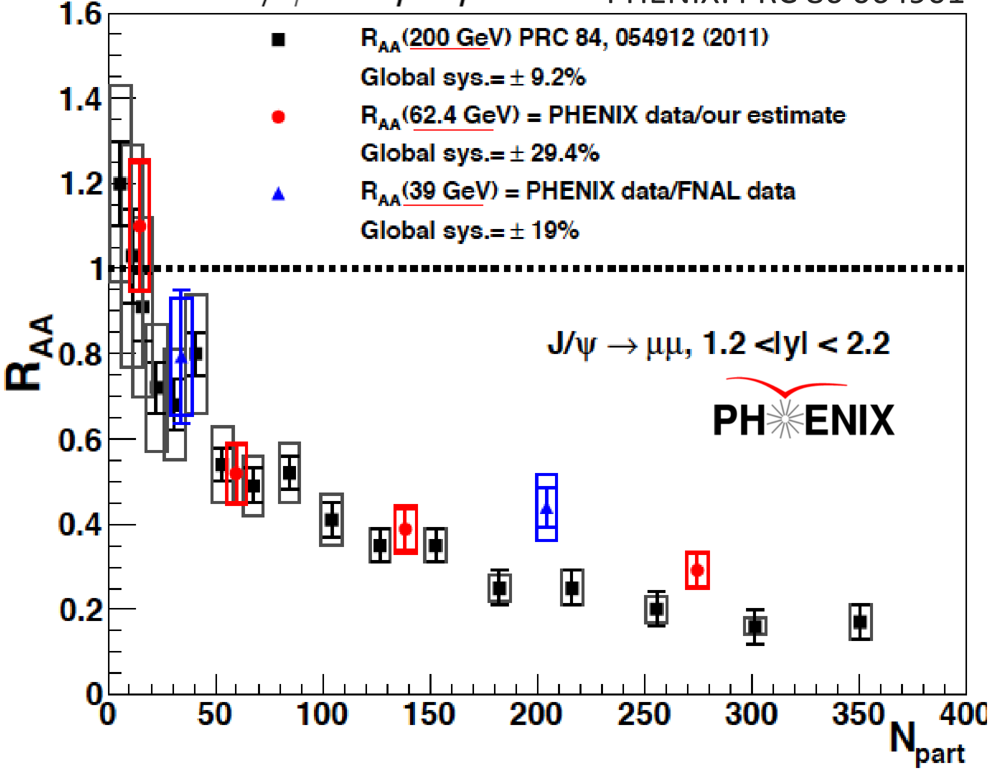


System and Energy Dependence

Bound Heavy Flavor: J/ψ R_{AA}

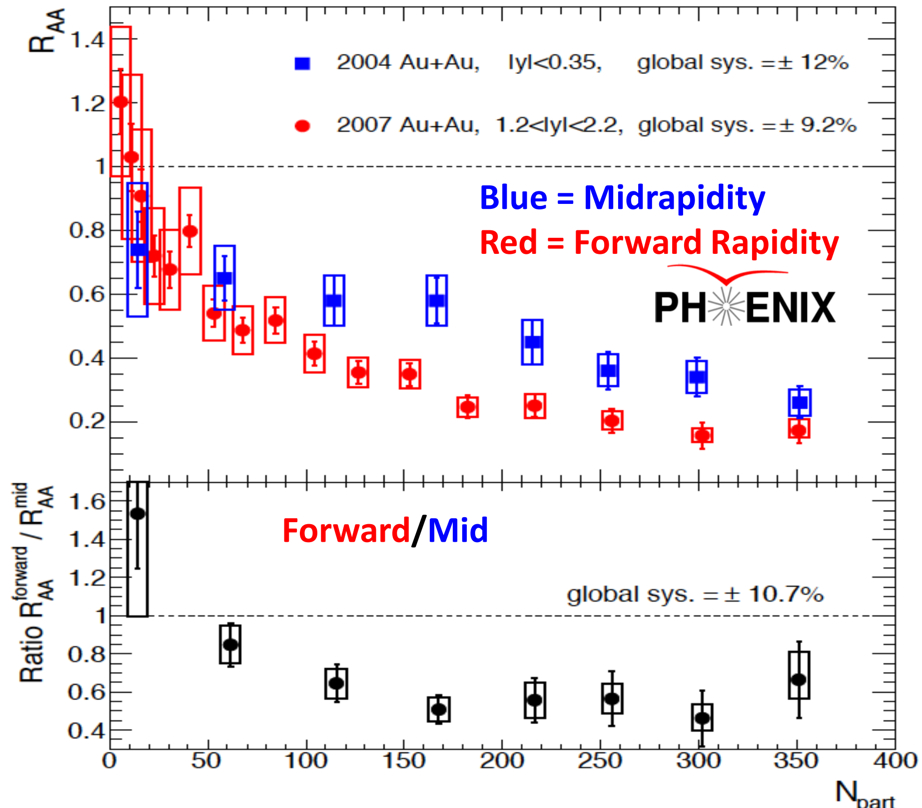
Au+Au at different energies

$J/\psi \rightarrow \mu^+\mu^-$ PHENIX: PRC 86 064901



Au+Au at 200 GeV mid- vs. forward rapidities

PHENIX: PRC 84 054912



In Au+Au and at forward rapidity:
R_{AA} show similar suppression at different collision energies:
200, 62.4 and 39 GeV

Significant J/ψ suppression at mid- and forward rapditiy regions is observed in central Au + Au collisions
R_{AA} decreases with increasing N_{part}

Quarkonia: What have we learned from colliding symmetric systems?

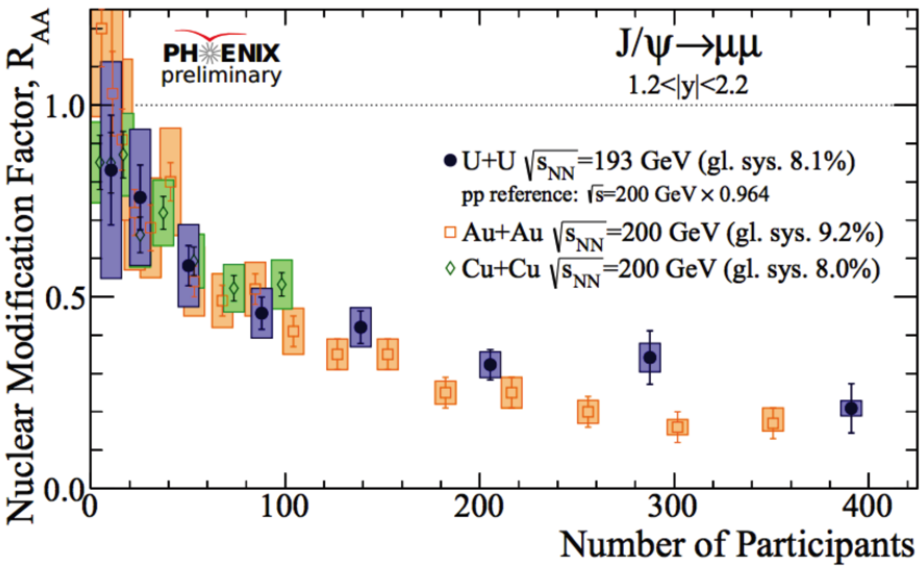
Bound Heavy Flavor: J/ψ R_{AA}

System Size study:

Cu+Cu, Au+Au and U +U ≈ 200 GeV

J/ψ → $\mu^+ \mu^-$ at forward rapidity

$1.2 < |y| < 2.2$

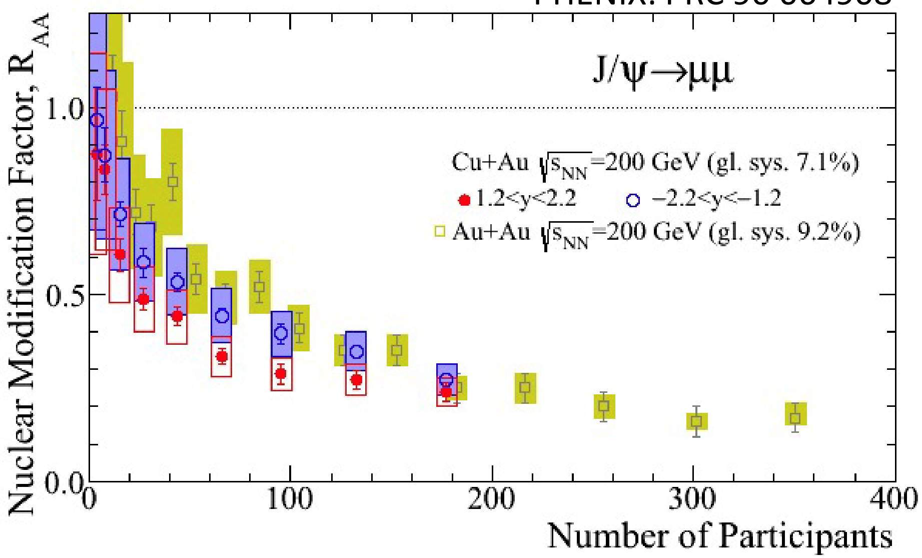


System Size study:

Cu+Au vs Au+Au at 200 GeV

J/ψ → $\mu^+ \mu^-$

PHENIX: PRC 90 064908

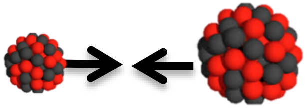


Not much net effect on R_{AA} at forward rapidity from increasing system size of colliding nuclei!

Is this what we expected?

- Similar suppression in Cu+Au compared to Au+Au
- Forward (Cu-going) more suppressed than Backward → CNM effects?

Quarkonia production in small systems

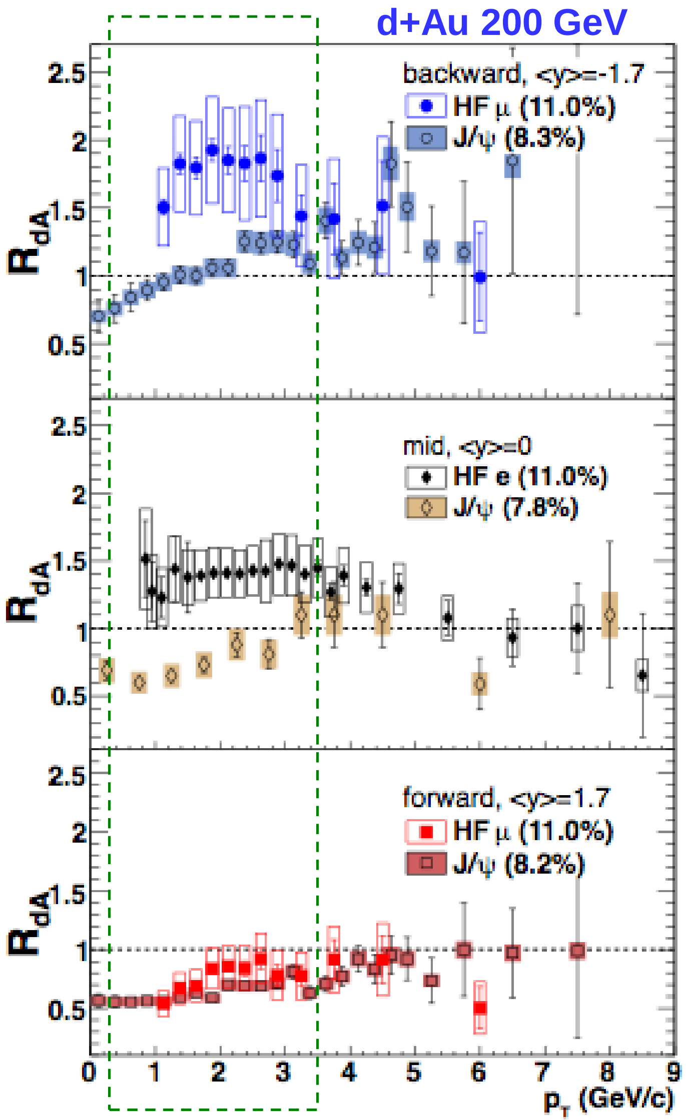


Explore the CNM effect via Charmonia

What NEW on Quarkonia?

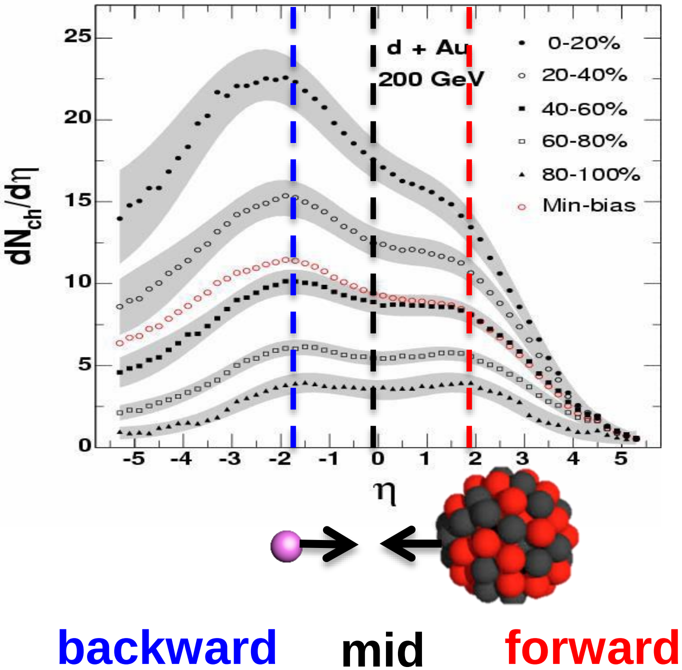
PEHNIX: PRC 87 034904
PHENIX: PRL 112 252301

Comparison between open and closed heavy flavor



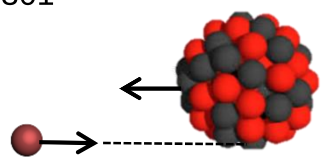
- **In the most central collision:**
  1) R_{dA} of HF muon and J/ψ are still consistent at forward rapidity
  2) however, clearly different at backward rapidity
  3) charm production is enhanced but J/ψ production is significantly suppressed due to nuclear breakup inside dense co-movers at backward rapidity

PHOBOS: PRC 72 031901



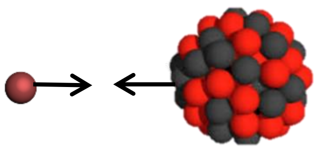
Quarkonia: Suppression of ψ’ in central d+Au collisions

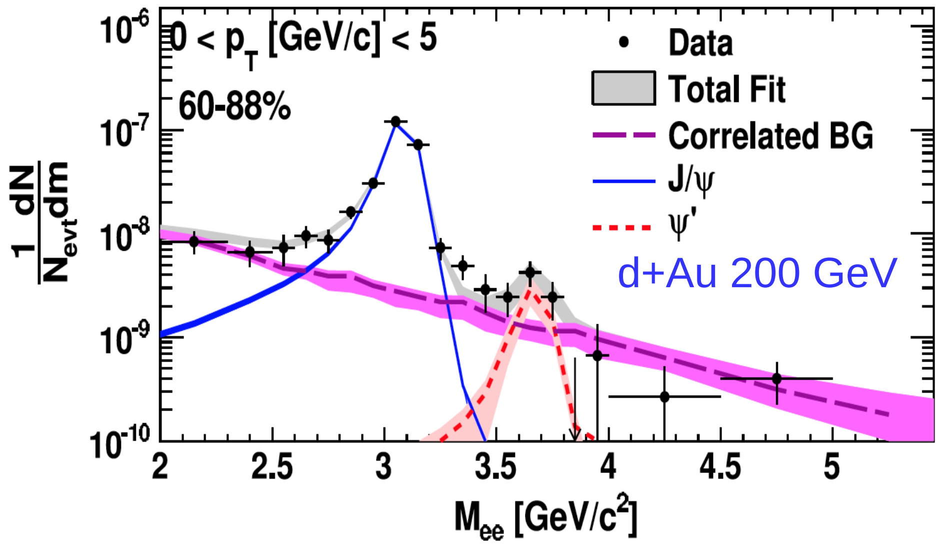
PHEN IX: PRL 111, 202301

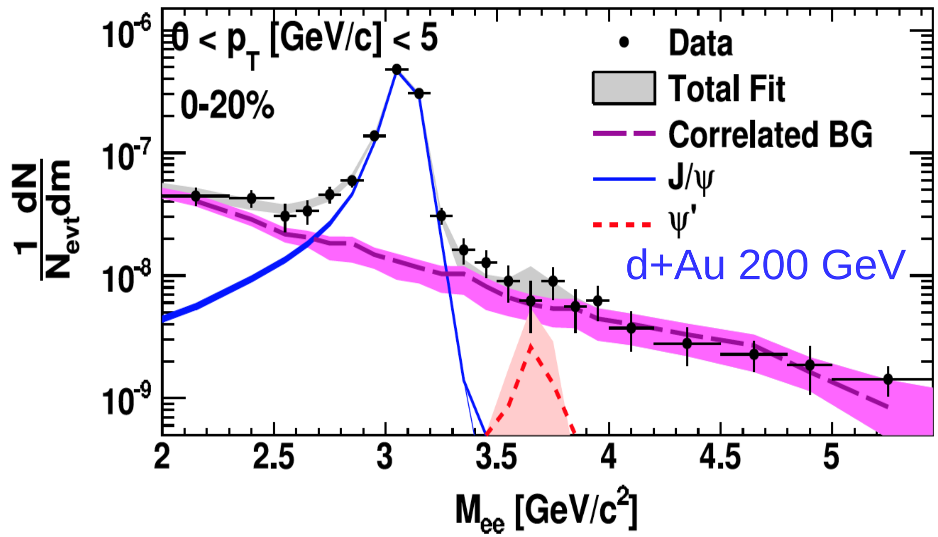


peripheral
60—88%
N_{coll} ~ 3

central
0—20%
N_{coll} ~ 15



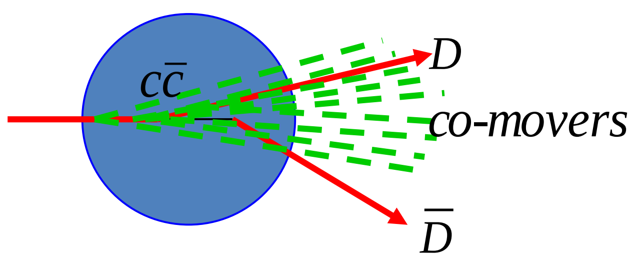


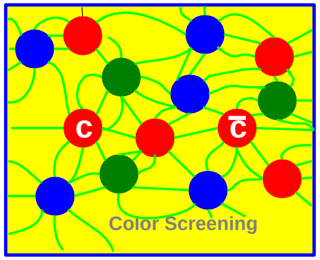


Breakup of quarkonia due to interaction with nuclear matters

1) Large suppression of the weakly bounded state ψ’

2) Interaction with nucleus? co-movers? or medium?

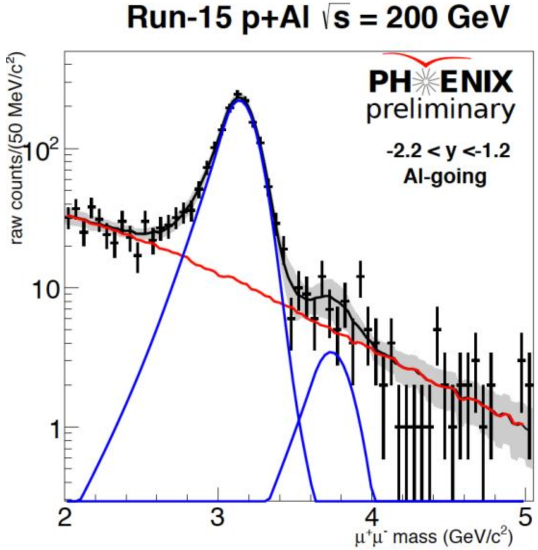


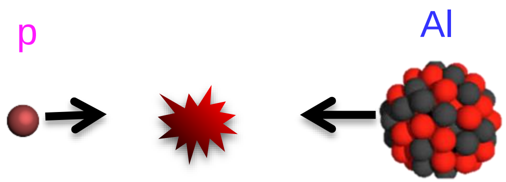


Quarkonia: ψ’ at forward/backward in central collision

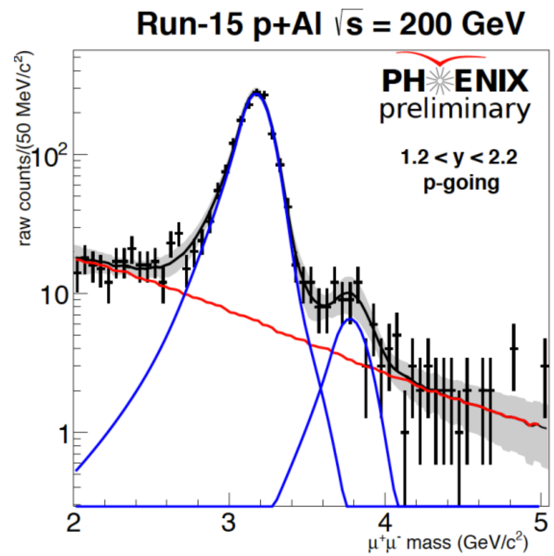
NEW!

Backward: Al-going direction

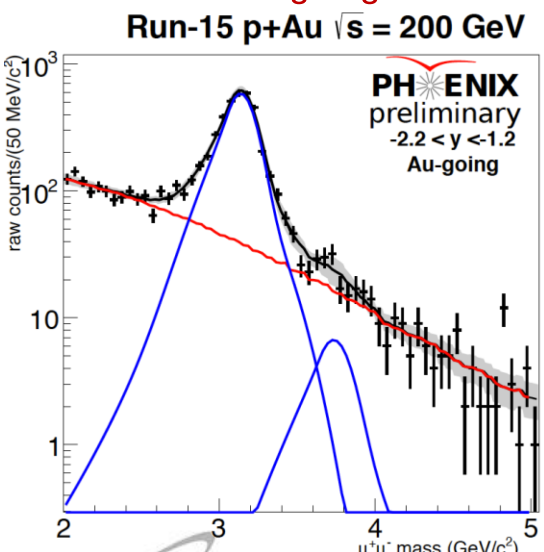


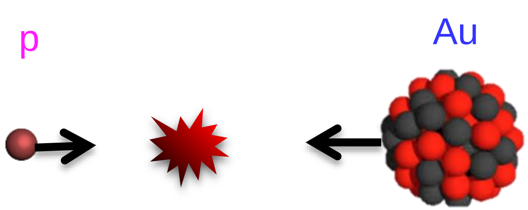


Forward: p-going direction

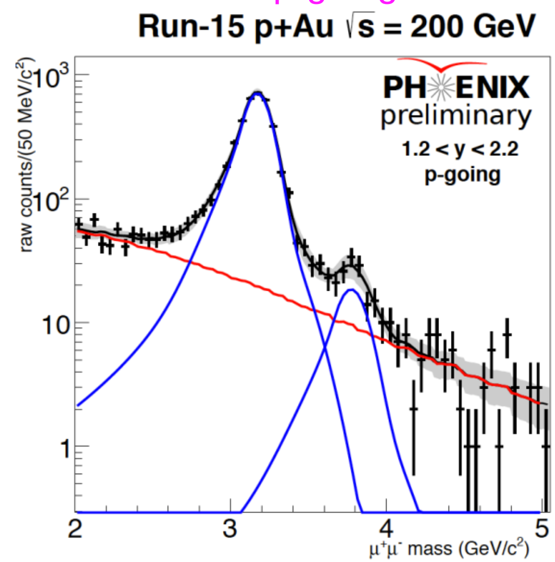


Backward: Au-going direction





Forward: p-going direction

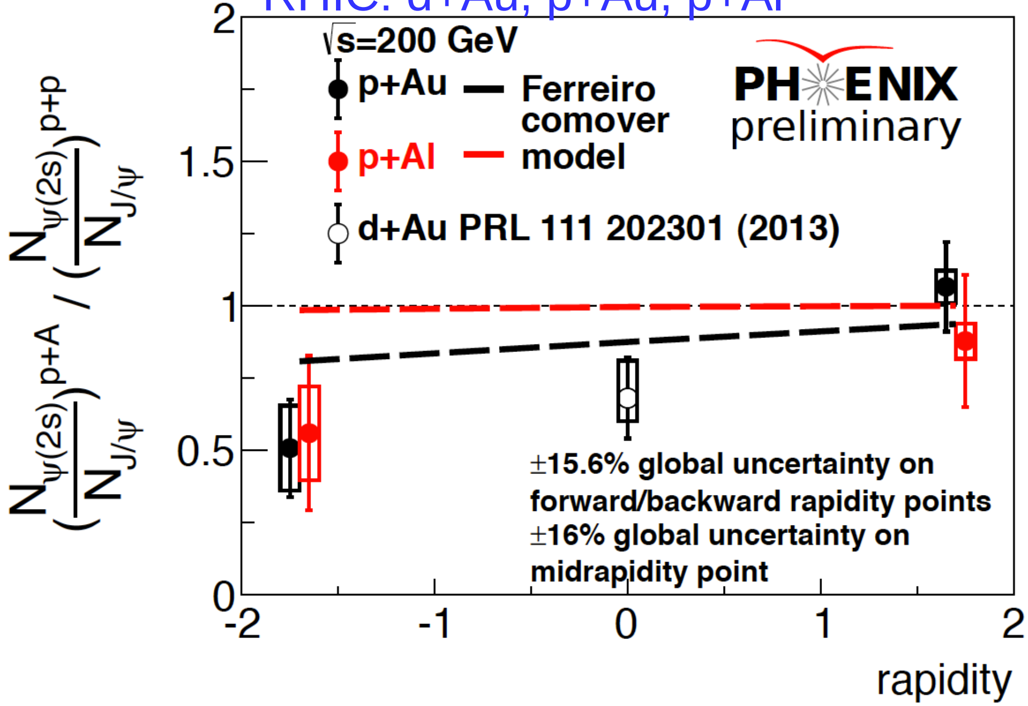


Quarkonia: ψ’ at forward/backward in central collision

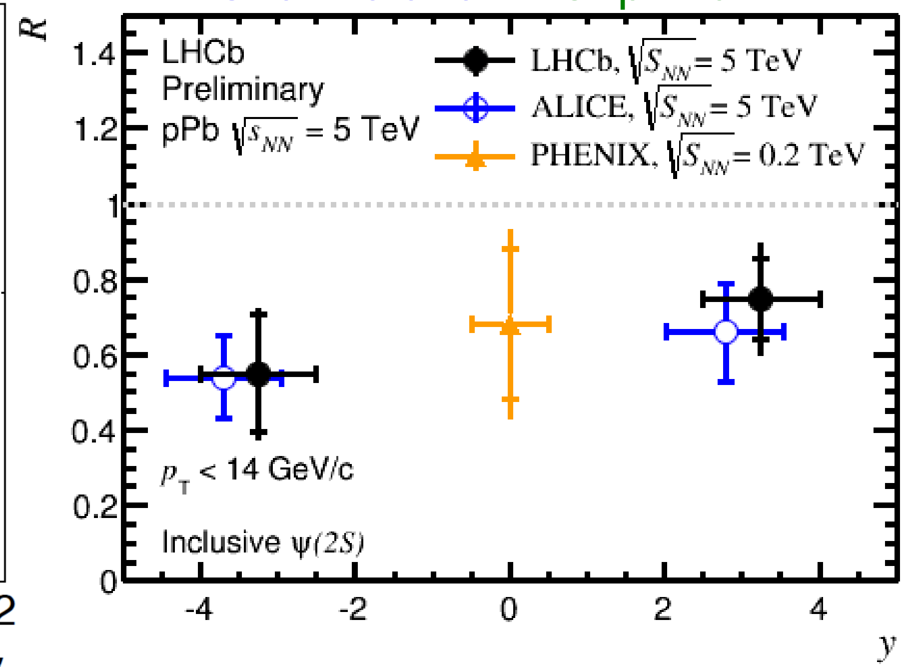
NEW!

ψ’ broken up

RHIC: d+Au, p+Au, p+Al



RHIC: d+Au and LHC: p+Pb



- Qualitatively agrees with the co-mover dissociation model.
- Comparison with the QGP model work in progress.

- Similar relative suppression of ψ’ at backward rapidity, but larger relative suppression of ψ’ at forward rapidity at LHC

Summary

- **Without Doubt RHIC is Amazing QCD Machine**
  - Many Species Many Energies, and High Luminosity and Stability

- **Open Heavy Flavor**
  - **Au+Au at 200 GeV:** electrons from bottom similarly suppressed to those from charm for p_T > 4 GeV/c, but less suppressed than charm for p_T < 4 GeV/c
  - **Cu+Au at 200 GeV**: B-mesons → J/ψ at forward-rapidity are less suppressed than prompt J/ψ
  - **p+p at 510 GeV:** no center of mass energy dependence for low p_T (< 5 GeV/c) B-meson decayed J/ψ and excellent agreement with word data

- **Quarkonia Measurements at Small System**
  - ψ' larger suppression than J/ψ at mid and backward rapidity
    - Qualitatively agrees with the co-mover dissociation model
  - Similar relative suppression of ψ' at backward rapidity, but larger relative suppression of ψ' at forward rapidity at LHC

- **Stay Tuned …!**
  - **More statistic:** decrease uncertainties, increase p_T reach, centrality separation → more surprises…

Thank you