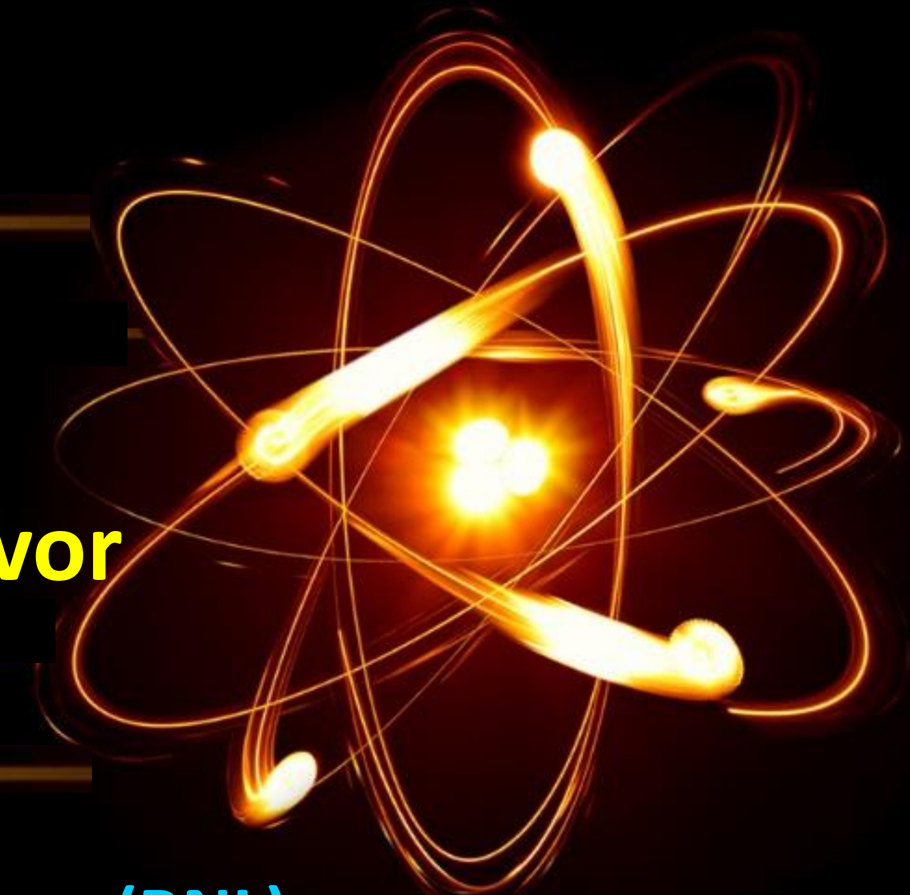
# Probing Properties of Hot and Dense QCD Matter with Heavy Flavor at PHENIX



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3rd International Conference on New Frontiers in Physics
August 2nd, 2014

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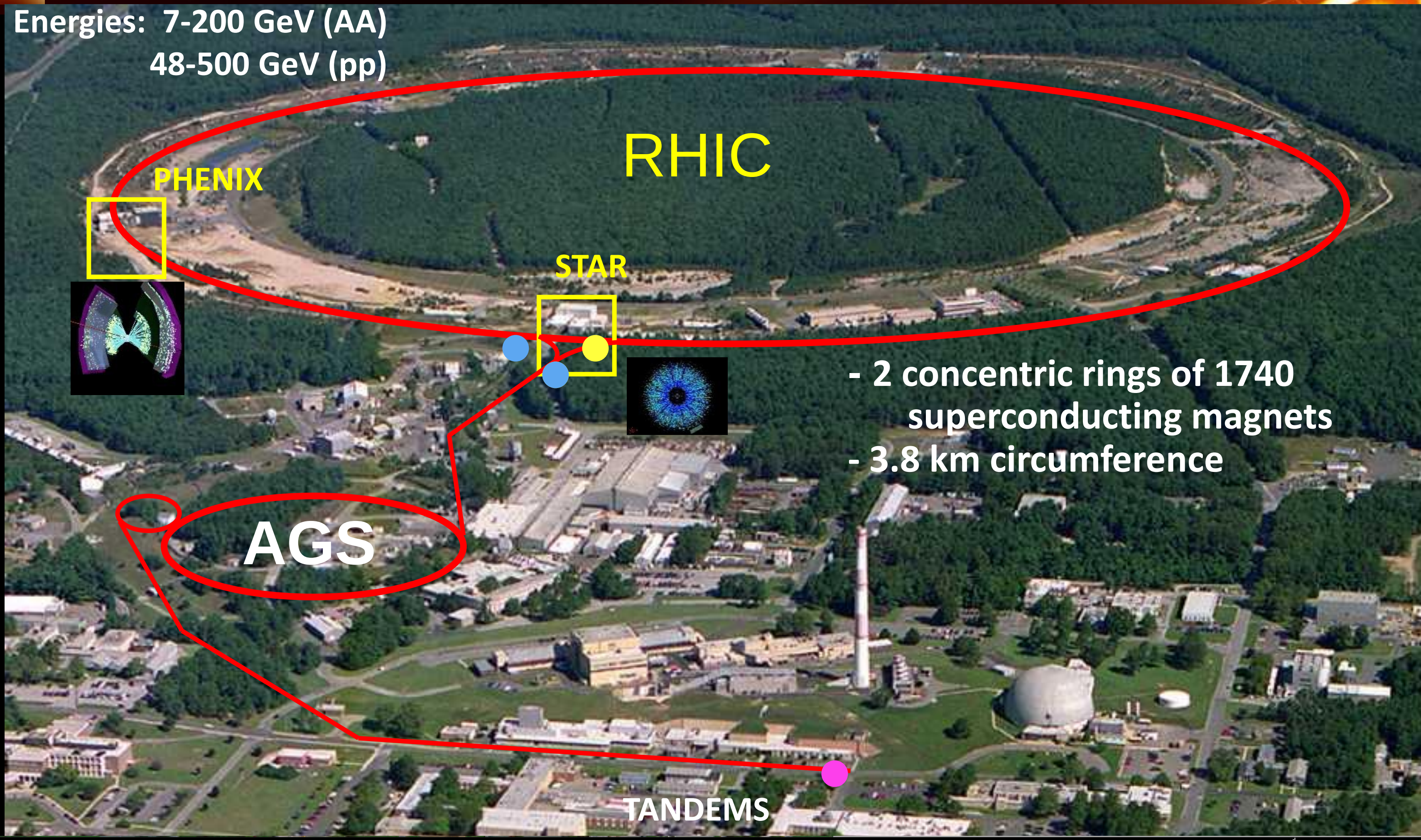
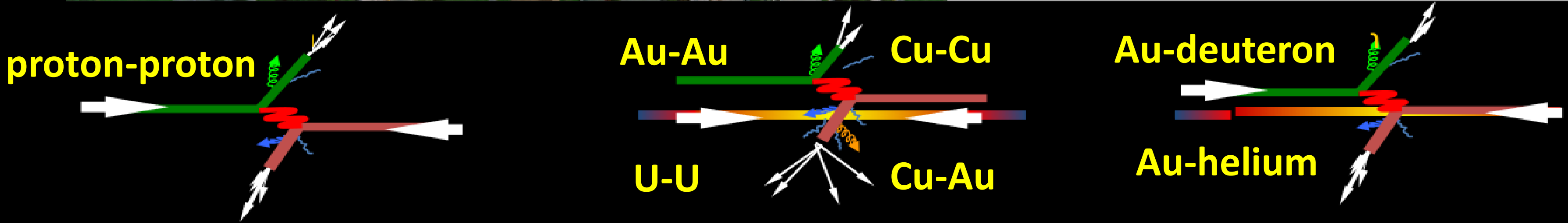
# Relativistic Heavy Ion Collider (RHIC)



# RHIC Produces Extensive Data



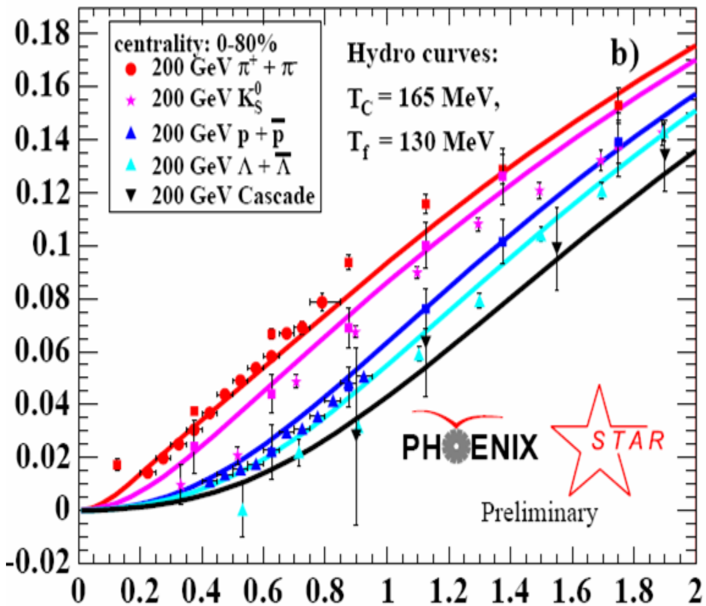

| RHIC Run | Year | Species | Energy | Ldt |
|---|---|---|---|---|
| Run-1 | 2000 | Au+Au | 130 GeV | 1 μb-1 |
| Run-2 | 2001-2 | Au+Au | 200 GeV | 24 μb-1 |
| Run-2 | | Au+Au | 19 GeV | 0.4 μb-1 |
| | | p+p | 200 Gev | 150 nb-1 |
| Run-3 | 2002/3 | d+Au | 200 GeV | 2.74 nb-1 |
| | | p+p | 200 GeV | 0.35 nb-1 |
| Run-4 | 2003/4 | Au+Au | 200 GeV | 241 μb-1 |
| | | Au+Au | 62.4 GeV | 9 μb-1 |
| Run-5 | 2005 | Cu+Cu | 200 GeV | 3 nb-1 |
| | | Cu+Cu | 62.4 GeV | 0.19 nb-1 |
| | | Cu+Cu | 22.4 GeV | 2.7 μb-1 |
| Run-6 | 2006 | p+p | 200 GeV | 10.7 pb-1 |
| | | p+p | 62.4 GeV | 100 nb-1 |
| Run-7 | 2007 | Au+Au | 200 GeV | 813 μb-1 |
| Run-8 | 2007/2008 | d+Au | 200 GeV | 80 nb-1 |
| | | p+p | 200 GeV | 5.2 pb-1 |
| | | Au+Au | 9.2 GeV | |
| Run-9 | 2009 | p+p | 200 GeV | 16 pb-1 |
| | | p+p | 500 GeV | 14 pb-1 |
| Run-10 | 2010 | Au+Au | 200 GeV | 1.3 nb-1 |
| | | Au+Au | 62.4 GeV | 100 μb-1 |
| | | Au+Au | 39 GeV | 40 μb-1 |
| | | Au+Au | 7.7 GeV | 260 mb-1 |
| Run-11 | 2011 | p+p | 500 GeV | 27 pb-1 |
| | | Au+Au | 200 GeV | 915 μb-1 |
| | | Au+Au | 27 GeV | 5.2 μb-1 |
| | | Au+Au | 19.6 GeV | 13.7 M event |
| Run-12 | 2012 | p+p | 200 GeV | 9.2 pb-1 |
| | | p+p | 510 GeV | 30 pb-1 |
| | | U+U | 193 GeV | 171 μb-1 |
| | | Cu+Au | 200 GeV | 4.96 nb-1 |
| Run-13 | 2013 | p+p | 510 GeV | 156 pb-1 |
| Run-14 | 2014 | Au+Au | 15 GeV | 44.2 μb-1 |
| | | Au+Au | 200 GeV | 45.1 nb-1 |
| | | He+Au | 200 GeV | 134 nb-1 |

# RHIC Experiments: Discoveries

*RHIC experiments take advantage of RHIC data and make major discoveries:*

*creation of strongly-coupled QCD matter at high temperature and energy density*

$v_2(p_T,m)$

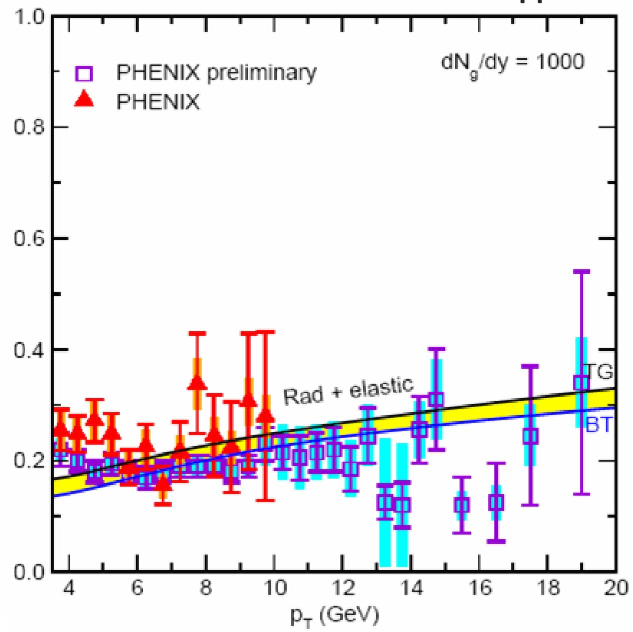



**Collective Expansion:**

ideal hydrodynamics

(QGP equation-of-state)

$R_{AA}(p_T)=(spec)_{AA}/(spec)_{pp}$

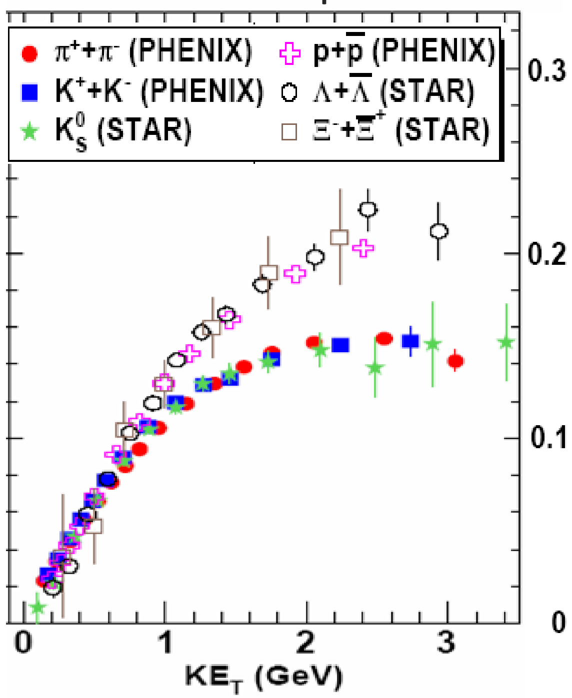



**Quark Energy-Loss:**

perturbative QCD

(gluon radiation)

$v_2(KE_T,n_q)$




**Hadronization:**

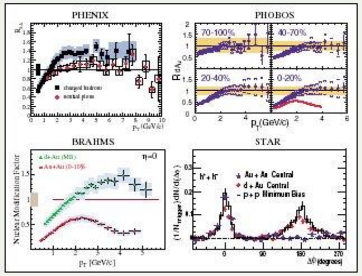
quark coalescence

**rapid thermalization, "perfect liquid" ⇒ strongly-interacting QGP**

# RHIC Discoveries in the Press

**Physical Review Letters**

Articles published week ending
15 August 2003
Volume 91, Number 7

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**The Collaboration of the four experiments: PHENIX, BRAHMS, PHOBOS and STAR at RHIC**

**CONCLUDED**

**that strongly-interacting matter**

**has been created in**

**most central Au+Au collisions**

**at 200 GeV**

RHIC Scientists Serve Up "Perfect" Liquid

New state of matter more remarkable than predicted -- raising many new questions

Monday, April 18, 2005

TAMPA, FL -- The four detector groups conducting research at the Relativistic Heavy Ion Collider (RHIC) -- a giant atom "smasher" located at the U.S. Department of Energy's Brookhaven National Laboratory -- say they've created a new state of hot, dense matter out of the quarks and gluons that are the basic particles of atomic nuclei, but it is a state quite different and even more remarkable than had been predicted. In peer-reviewed papers summarizing the first three years of RHIC findings, the scientists say that instead of behaving like a gas of free quarks and gluons, as was expected, the matter created in RHIC's heavy ion collisions appears to be more like a *liquid*.

"Once again, the physics research sponsored by the Department of Energy is producing historic results," said Secretary of Energy Samuel Bodman, a trained chemical engineer. "The DOE is the principal federal funder of basic research in the physical sciences, including nuclear and high-energy physics. With today's announcement we see that investment paying off."

"The truly stunning finding at RHIC that the new state of matter created in the collisions of gold ions is more like a liquid than a gas gives us a profound insight into the earliest moments of the universe," said Dr. Raymond L. Orbach, Director of the DOE Office of Science.

Also of great interest to many following progress at RHIC is the emerging connection between the collider's results and calculations using the methods of string theory, an approach that attempts to explain fundamental properties of the universe using 10 dimensions instead of the usual three spatial dimensions plus time.

Secretary of Energy Samuel Bodman

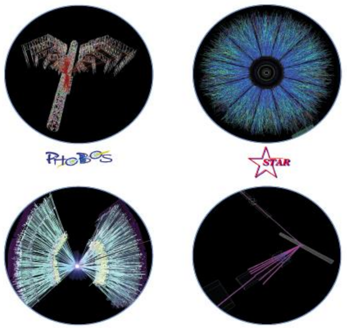
BNL -73847-2005
Formal Report

Hunting the Quark Gluon Plasma

Results from the first 3 years at RHIC

Assessments by the experimental collaborations

April 18, 2005




Relativistic Heavy Ion Collider (RHIC) • Brookhaven National Laboratory, Upton, NY 11974-5000

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**RHIC Scientists Serve Up 'Perfect' Liquid: New State Remarkable Than Predicted**

*Apr. 25, 2005* — TAMPA, FL -- The four detector groups conducting research at the Relativistic Heavy Ion Collider (RHIC) -- a giant atom "smasher" located at the U.S. Department of Energy's Brookhaven National Laboratory -- say they've created a new state of hot, dense matter out of the quarks and gluons that are the basic particles of atomic nuclei, but it is a state quite different and even more remarkable than had


*These images co and collective mo the predicted gas (Figure A, see mp that has been obs RHIC (Figure B, s "force lines" and animated version degree of interact what is now being liquid. (Courtesy Laboratory)*

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**CERN COURIER**

May 6, 2005

**RHIC groups serve up 'perfect' liquid**

The four detector groups conducting research at the Relativistic Heavy Ion Collider (RHIC) at the Brookhaven National Laboratory have announced results indicating that they have observed a state of hot, dense matter that is more remarkable than had been predicted. In papers summarizing the first three years of RHIC findings, to be published simultaneously by the journal *Nuclear Physics A*, the four collaborations (BRAHMS, PHENIX, PHOBOS and STAR) say that instead of behaving like a gas of free quarks and gluons, as was expected, the matter

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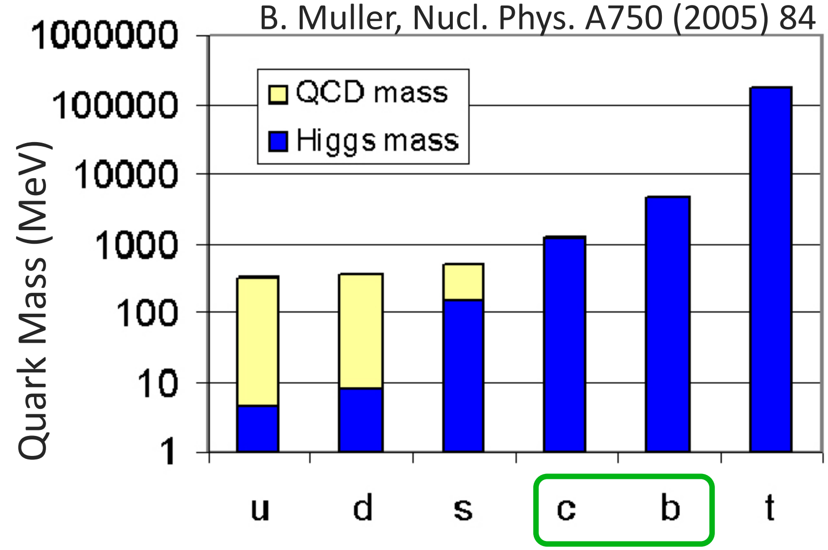
# Heavy Flavors: Ideal Probes of Nuclear Matter

- 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



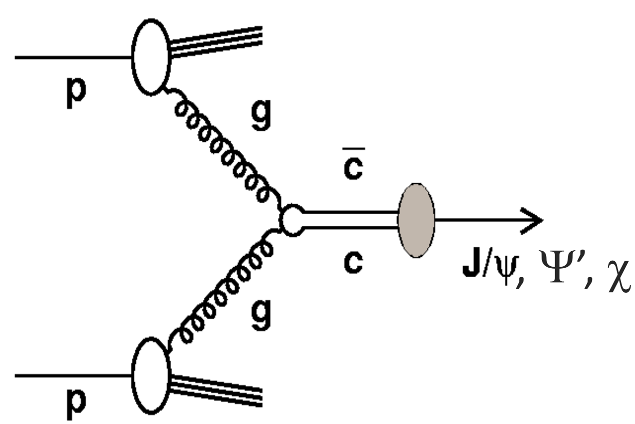

- Heavy quarks ($c\bar{c}$, $b\bar{b}$)
  - Bound states (J/ψ, ϒ)

| State | $J/\psi$ | $\chi_c$ | $\psi'$ | $\Upsilon$ | $\chi_b$ | $\Upsilon'$ | $\chi_b'$ | $\Upsilon''$ |
|---|---|---|---|---|---|---|---|---|
| Mass (GeV) | 3.10 | 3.53 | 3.68 | 9.46 | 9.99 | 10.02 | 10.36 | 10.36 |
| $\Delta E$ (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 ($m_Q \gg T_{cri}$ , $\Lambda_{QCD}$ )
  **→ higher penetrating power**

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

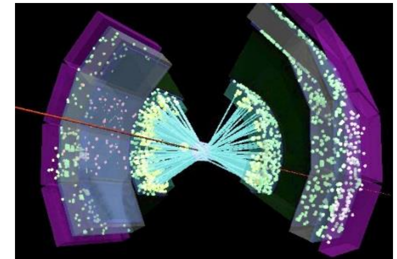
M. Gyulassy and Z. Lin, Phys. Rev. C51 (1995) 2177



# Heavy Flavors Energy Loss

**Thermalization of QGP**

**Hadronisation: QGP lifetime?**



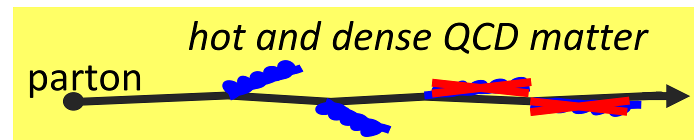
**Hard Scattering**

**Quarkonia melts and flow develops**

~0.1 ~1 ~10 $10^{15}$ *time scale* (fm/c)

Charm production $\tau \sim \hbar/2m_Q$

**Parton energy loss**




(1) **Radiative parton energy loss** is color charge dependent (Casimir coupling factor $C_R$)

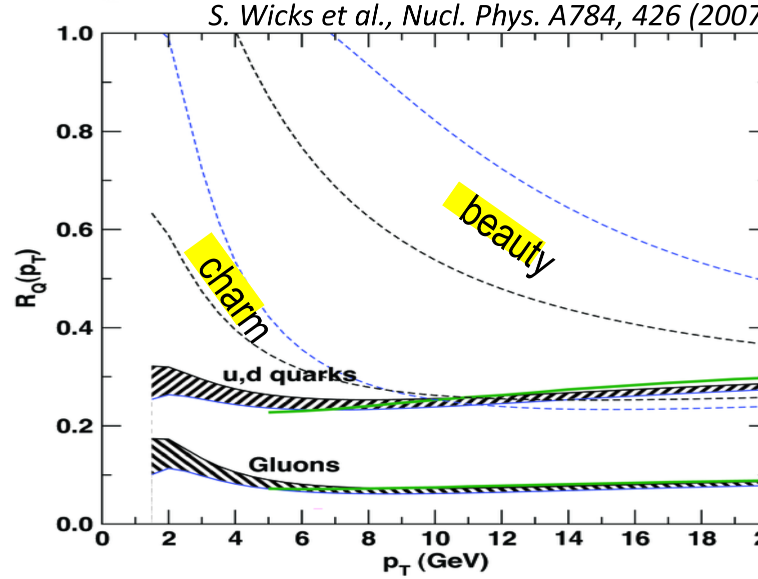
*R.Baier et al., Nucl. Phys. B483, 291 (1997) ("BDMPS")*

$$\langle E_{medium} \rangle \propto \alpha_S C_R \hat{q} L^2$$

(2) **Dead-cone effect:** gluon radiation suppressed at small angles ($\theta < m_Q/E_Q$)

*Y. Dokshitzer et al. PLB 519, 199 (2001)*

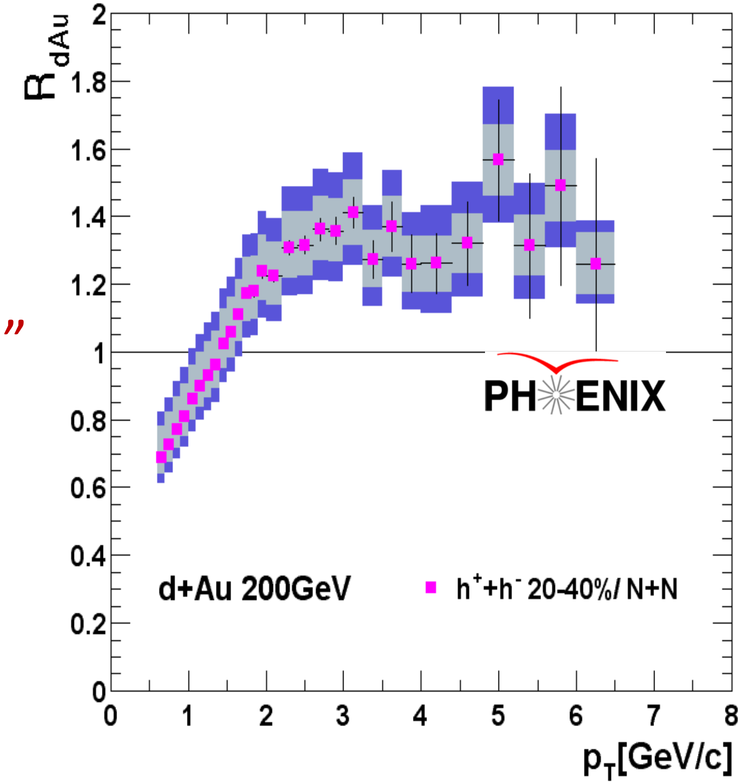
*S. Wicks et al., Nucl. Phys. A784, 426 (2007)*




$\Delta E_g > \Delta E_{u,d,s} > \Delta E_c > \Delta E_b \rightarrow R_{AA}(\pi) < R_{AA}(D) < R_{AA}(B)$

# Challenge: Medium Effects "Hot versus Cold Nuclear matters"

- p+p data:
  - → baseline of heavy ion measurements
  - → test of pQCD calculation:
  - $m_c$ ~ 1.3 GeV, $m_b$ ~ 4.8 GeV >> $T_c$ , $\Lambda_{QCD}$
  - → less affected than light quarks




- Heavy ion data: "Hot nuclear matter i.e. Au+Au"
  - HF they travel through the created medium interacting with its constituents

  Studying energy loss of heavy flavors

  → independent way to extract properties of the medium.

Nuclear modification factor
$$R_{AA} = \frac{1}{N_{coll}} \frac{dN_{AA}}{dN_{pp}}$$

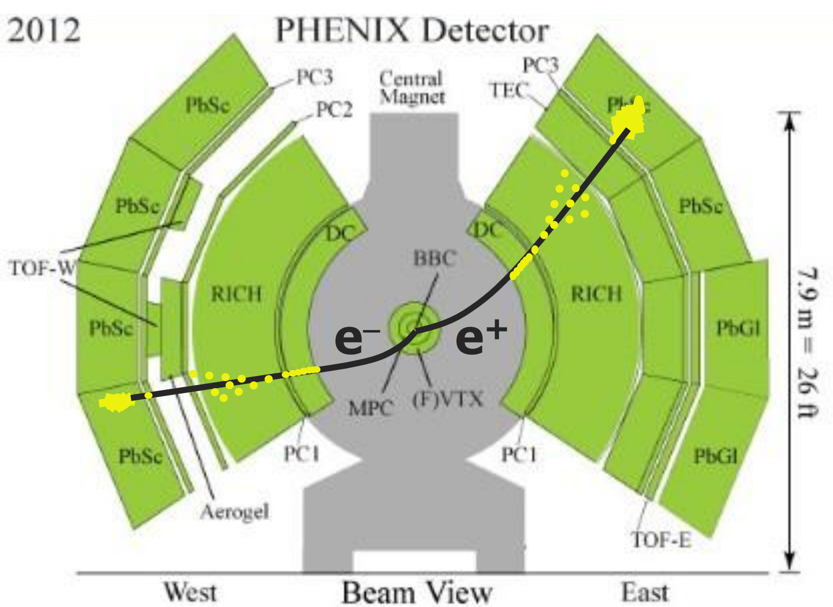
- d+Au data: assess cold matter effects

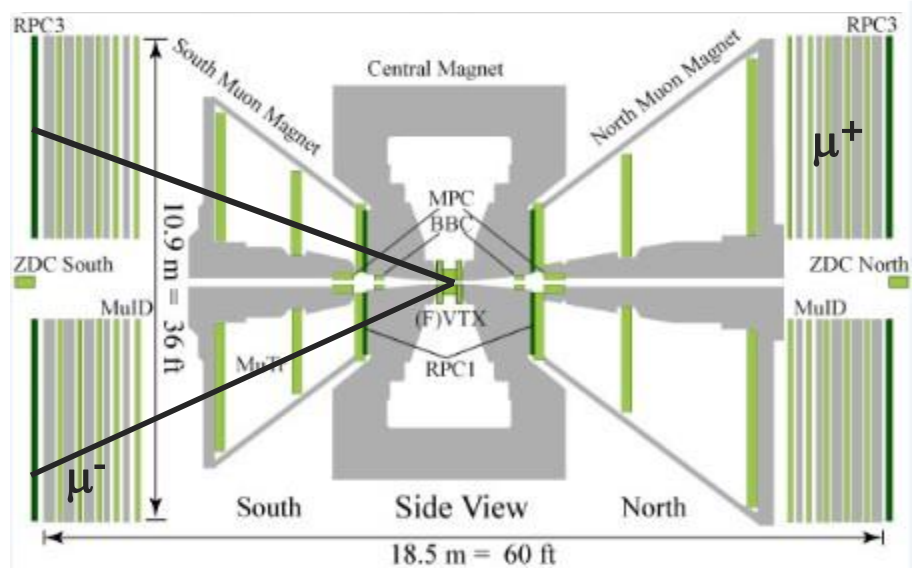
- **Nuclear Shadowing — initial-state effect on the parton distributions affecting total rate,** important as a function of $y/x_F$
- **Energy Loss — initial-state effect,** elastic scatterings of projectile parton before hard scattering creating quarkonium state, need to study Drell-Yan production to get a handle on the strength when shadowing included
- **Intrinsic Charm — initial-state effect,** if light-cone models correct, should only contribute to forward production, assumed to have different A dependence than normal J/ψ production
- **Absorption — final-state effect,** after cc that forms the J/ψ has been produced, pair breaks up in matter due to interactions with nucleons

# 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 → $e^+ e^-$**

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

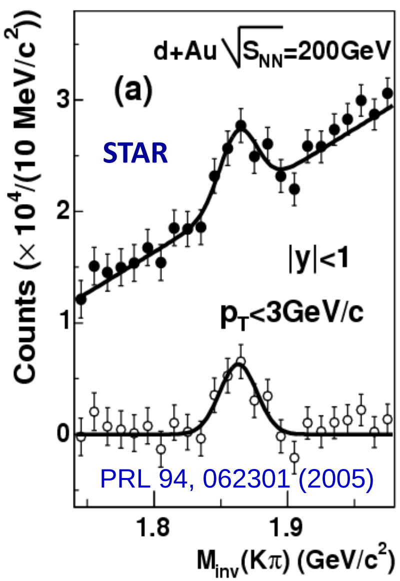
**Forward rapidity: J/ψ, ϒ → $\mu^+ \mu^-$**

- $1.2 < |\eta| < 2.2$, $\Delta\phi = 2\pi$, $p > 2$ GeV
- Cathode strip chamber tracking
- Muon ID: layered absorbers and Iarocci tubes
- Forward Silicon Vertex Tracker (FVTX)

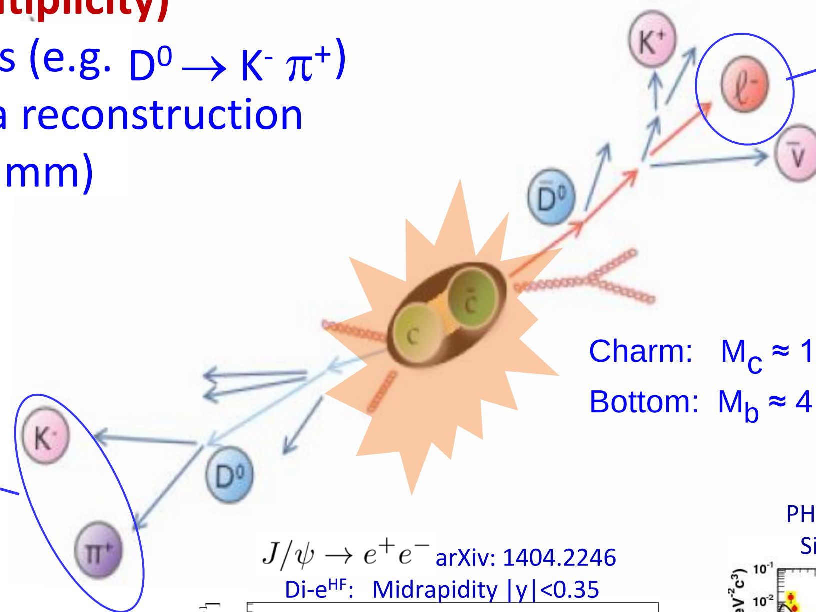
# How to Measure Heavy Flavors

**Direct (ideal but difficult at high multiplicity)**

- complete reconstruction of decays (e.g. $D^0 \rightarrow K^- \pi^+$)
- significant improvement in S/B via reconstruction of secondary decay vertex (~100 mm)




**Direct measurement**

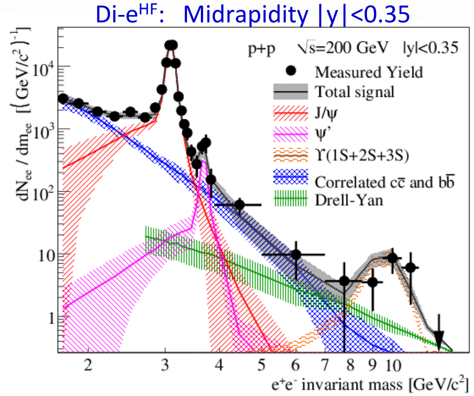



**Indirect measurement**

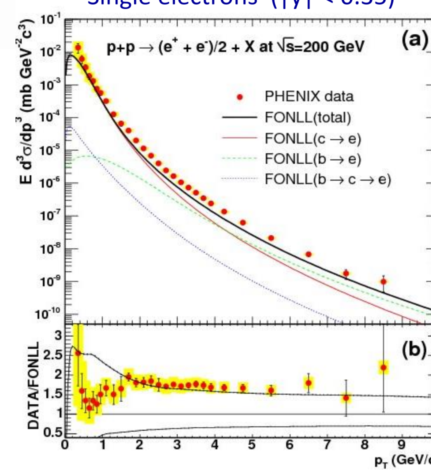
Charm: $M_c \approx 1.5$ GeV
Bottom: $M_b \approx 4.7$ GeV

| Meson | $D^\pm$ ($D^0$) |
|---|---|
| Mass | 1.87 (1.87) GeV |
| BR $D^0$ --> $K\pi$ | (3.85 ± 0.10) % |
| BR D --> e +X | 17.2 (6.7) % |
| BR D --> $\mu$ +X | 17.2 (6.6) % |

$J/\psi \rightarrow e^+e^-$ arXiv: 1404.2246
Di-$e^{HF}$: Midrapidity |y|<0.35




PHENIX: PRL 97, 252002 (2006)
Single electrons (|y| < 0.35)




**Indirect alternative**

- contribution of semi-leptonic heavy-flavor hadron decays to single (pair) lepton spectra

# Open Heavy Flavor (single $e^{HF}$): D- and B-mesons Decays

**1) Au + Au at 200 GeV**

$1.5 < p_T < 5$ GeV/c : $R_{AA}(e^{HF}) < R_{AA}(\pi^0)$

$p_T > 5$ GeV/c : $R_{AA}(e^{HF}) \sim R_{AA}(\pi^0)$

→ at 200 GeV Au+Au collisions :
heavy quark ($e^{HF}$) suppression is similar to that of light quarks ($\pi^0$) in the medium

**2) d + Au at 200 GeV**

no suppression observed over $p_T$

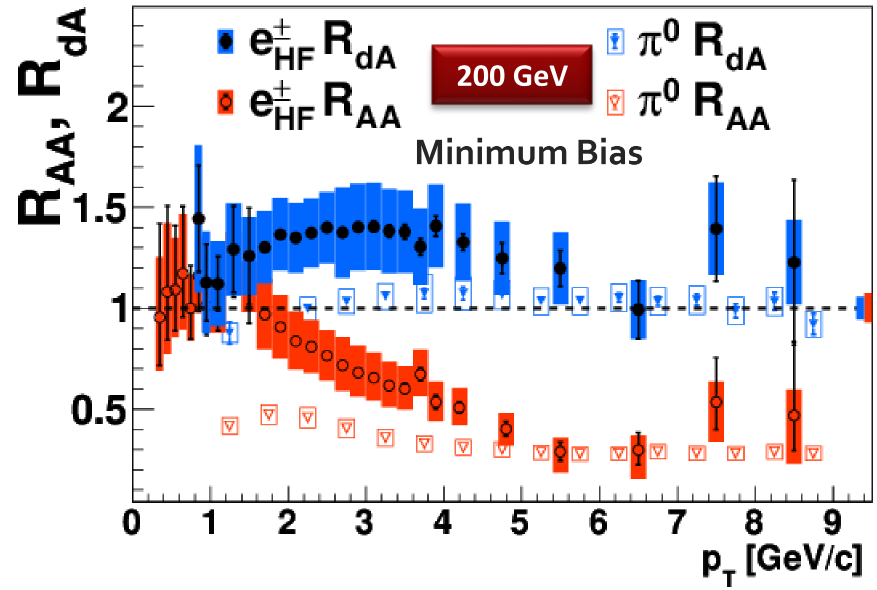
→ $e^{HF}$, $\pi^0$ are quenched due to the hot nuclear medium created in Au+Au at 200 GeV
→ final state effect

**3) Au + Au at 62.4 GeV**

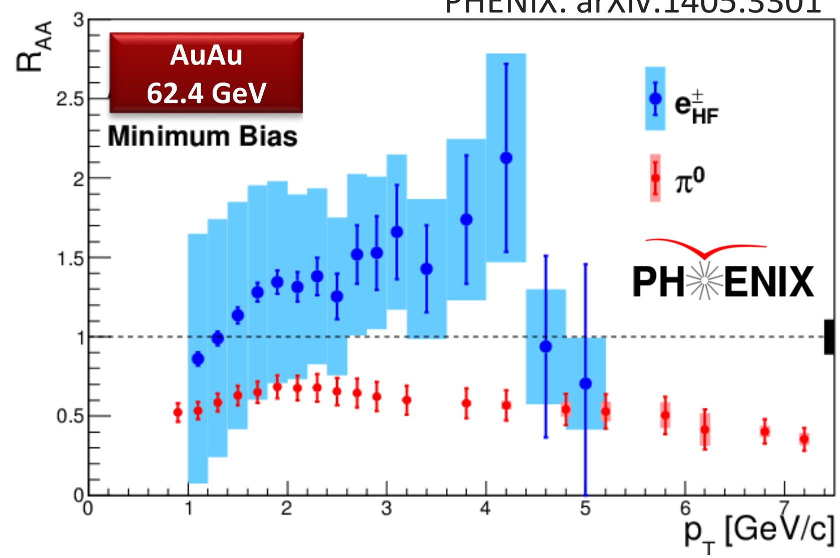
- In contrast to 200 GeV AuAu, the 62.4 GeV $R_{AuAu}$ show clear enhancement
- Due to less energy loss? larger Cronin effects? or combination of those factors and other effects?

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

PHENIX: PRL 109 242301




PHENIX: arXiv:1405.3301



# Open Heavy Flavor (single $e^{HF}$) in Cu+Cu at 200 GeV

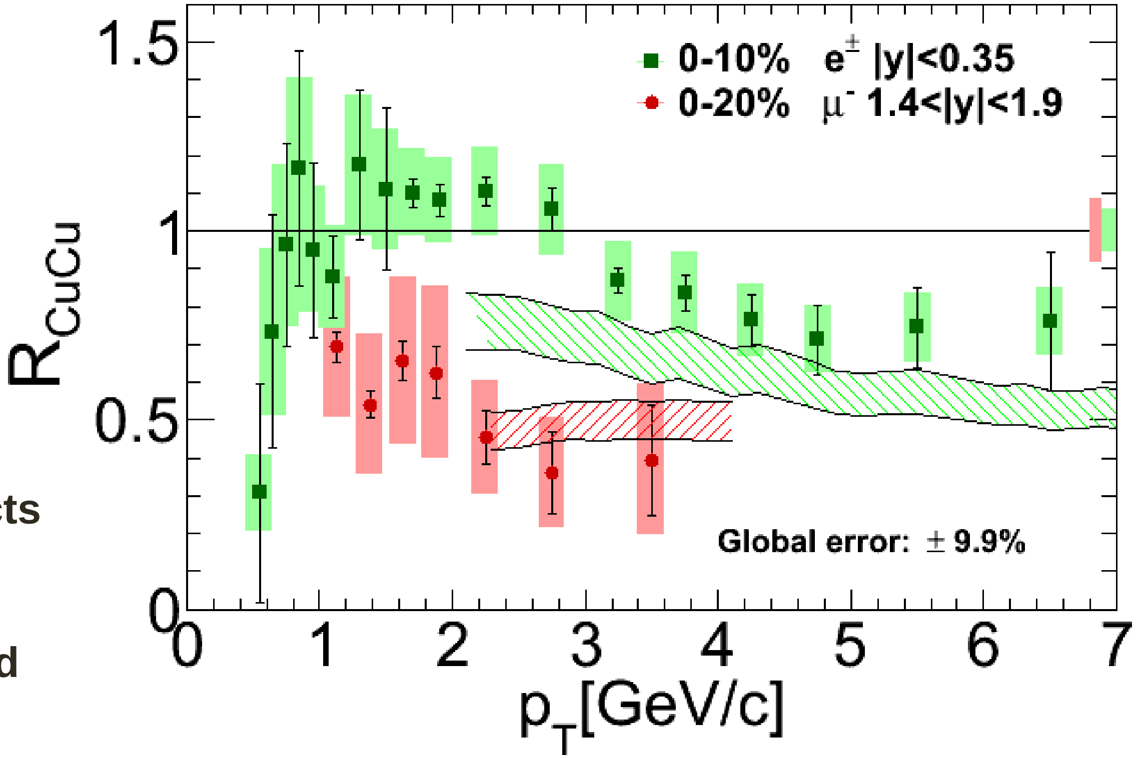
## Single electrons $e^{HF}$ vs single muons $\mu^{HF}$
## Mid-rapidity vs forward rapidity

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

✧ 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**

PHENIX: arXiv:1310.8286



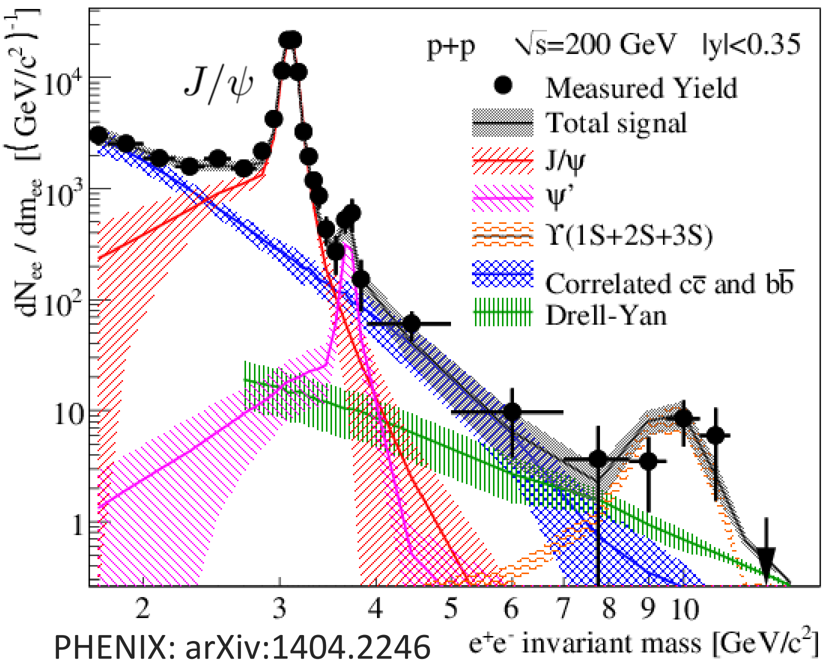

Indication of Cold Nuclear Matter (CMN) effects at forward rapidity in Cu+Cu system at 200 GeV

# Bound Heavy Flavor: Di-leptons $e^+e^-$ or $\mu^+\mu^-$

**p+p at 200 GeV**

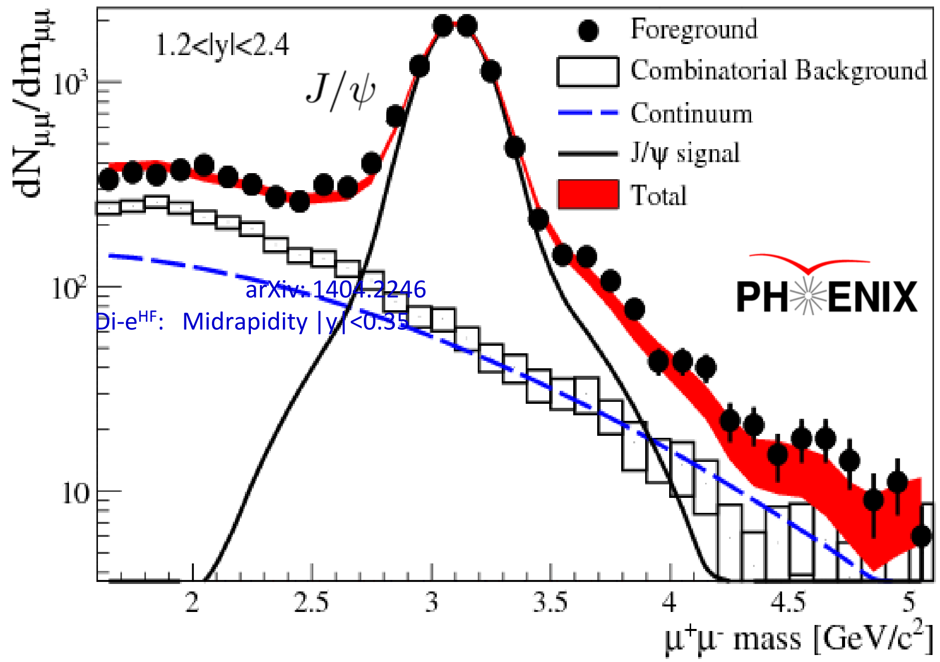
$$J/\psi \rightarrow e^+e^- \qquad\qquad J/\psi \rightarrow \mu^+\mu^-$$

Di-$e^{HF}$: Mid-Rapidity $|y|<0.35$




PHENIX: arXiv:1404.2246

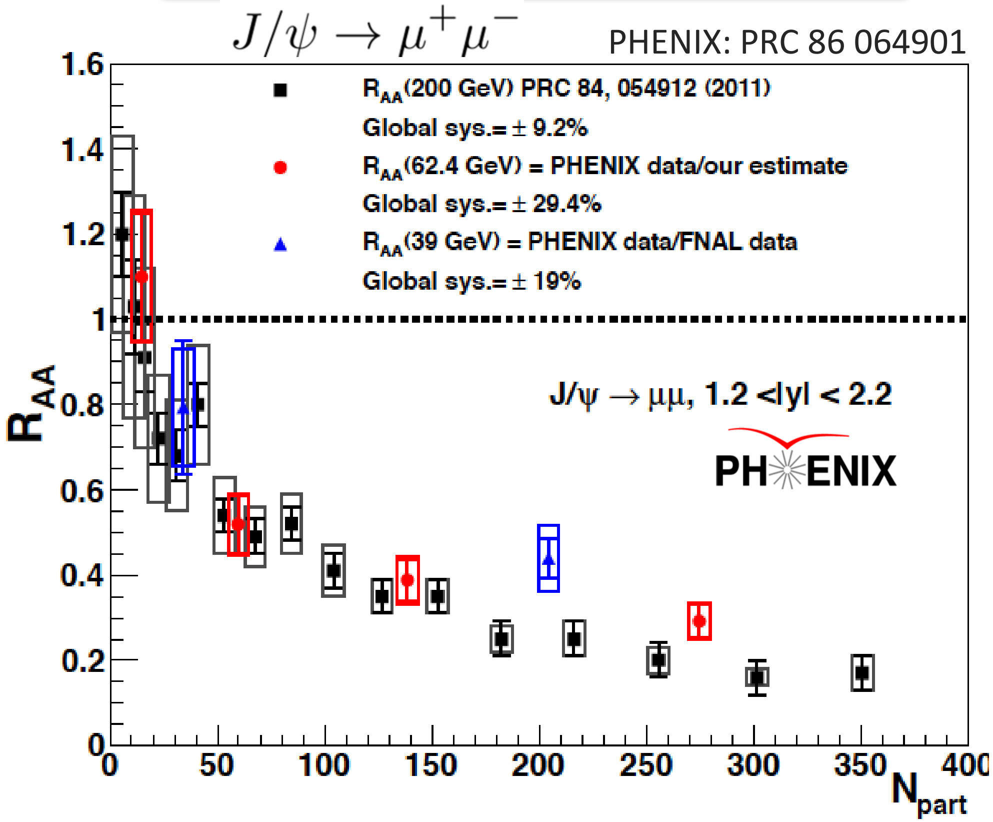
Di- $\mu^{HF}$: Forward Rapidity $1.2 < |y| < 2.2$




PHENIX has excellent capabilities of measuring different quarkonia states in di-electron and di-muon channels.

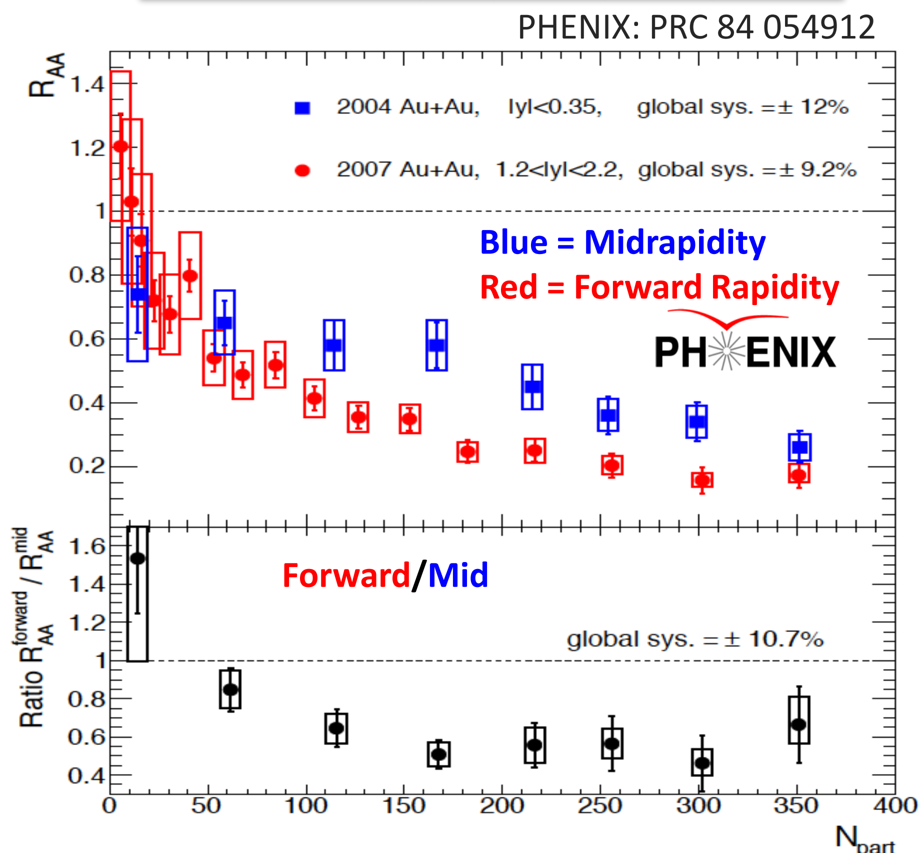
# Bound Heavy Flavor: J/ψ $R_{AA}$

## Au+Au at different energies




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

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

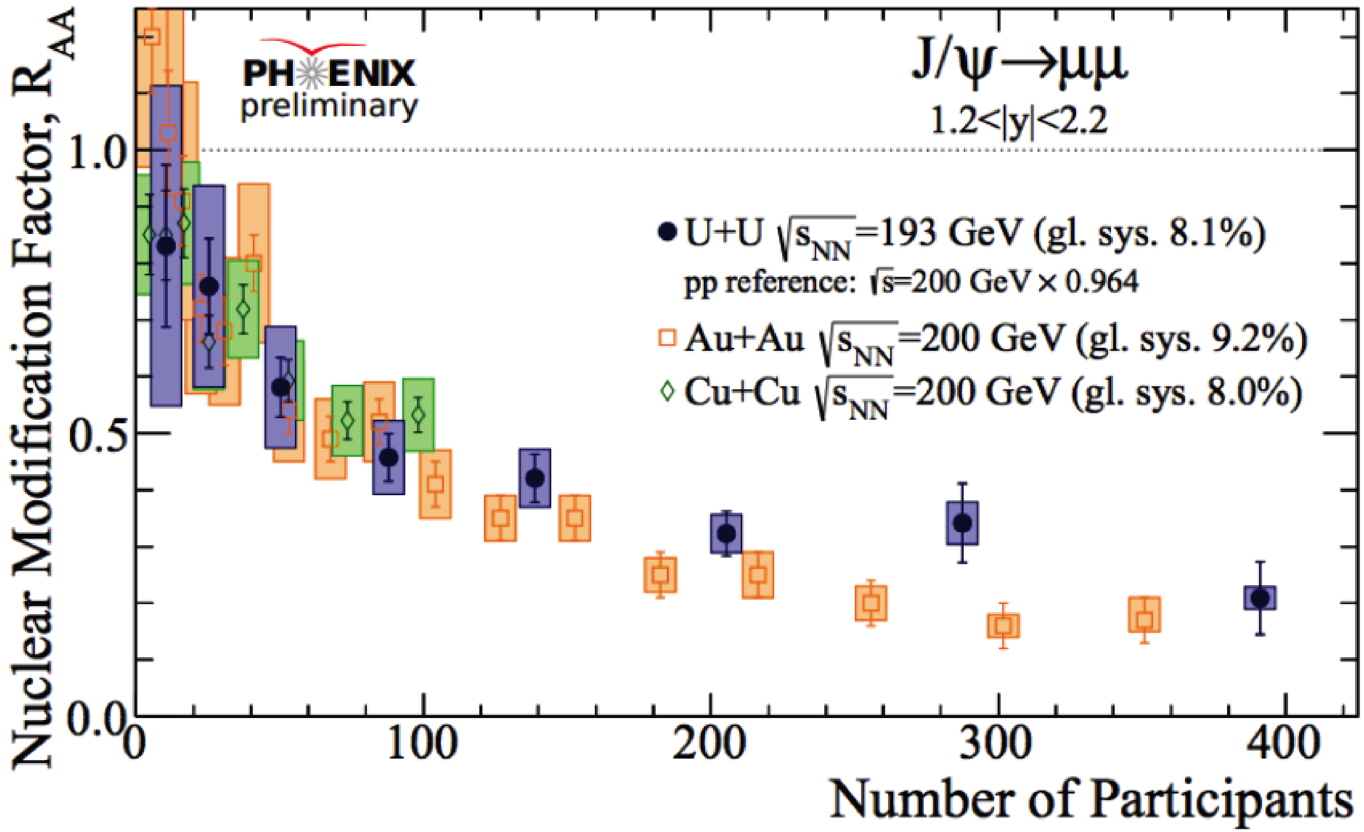



**Significant J/ψ suppression** at mid- and forward rapditiy regions is observed in central Au + Au collisions
$R_{AA}$ decreases with increasing $N_{part}$

# 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 $1.2 < |y| < 2.2$



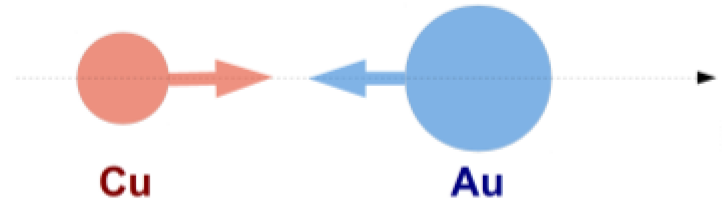

**Not much net effect on $R_{AA}$ at forward rapidity from increasing system size of colliding nuclei!**

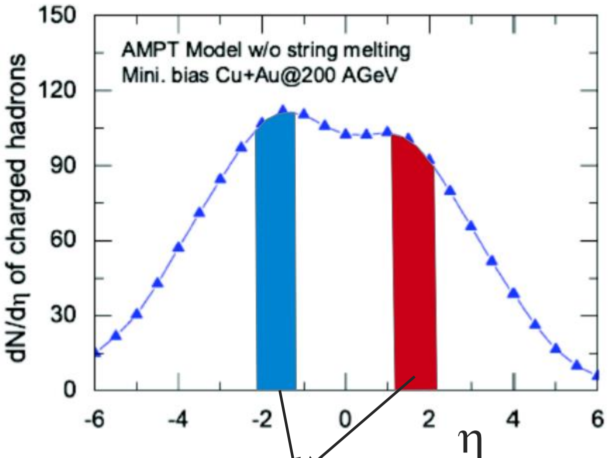
**Is this what we expected?**

# Bound Heavy Flavor: J/ψ $R_{AA}$

System Size study of : Cu+Au vs Au+Au at 200 GeV

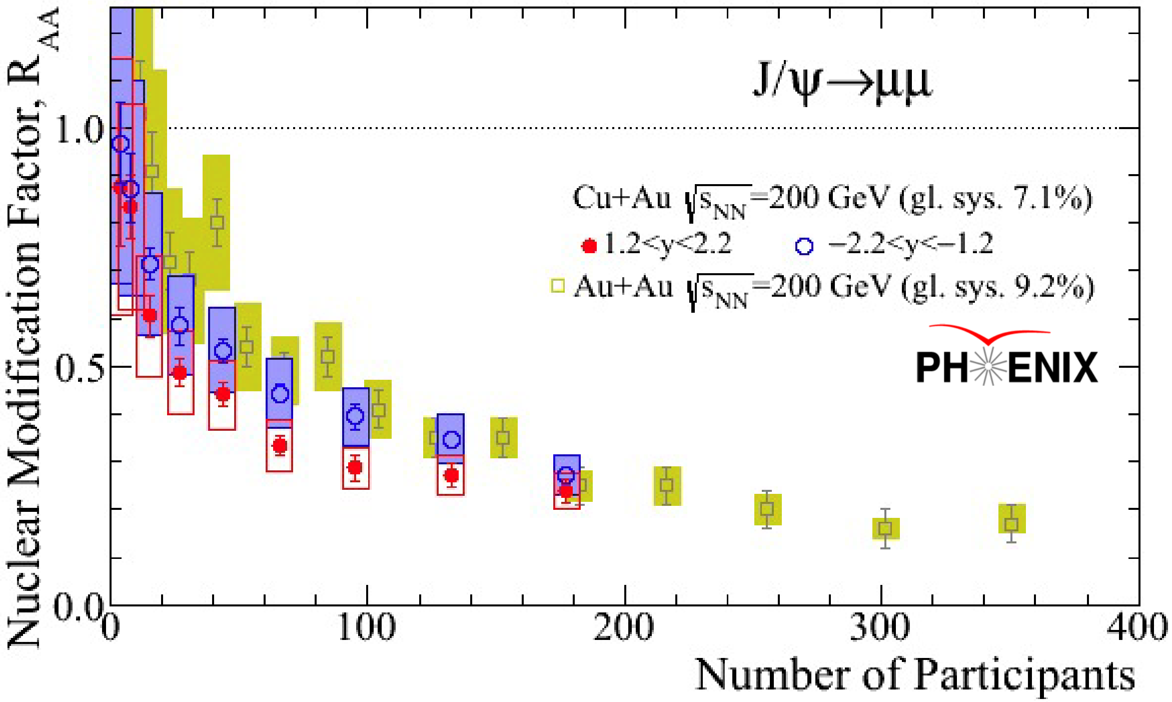
$J/\psi \rightarrow \mu^+ \mu^-$




1.2 < |η| < 2.2

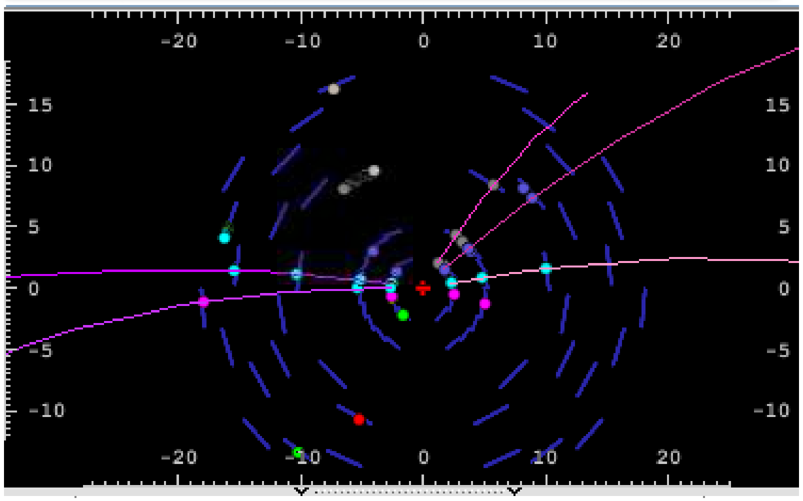
PHENIX: arXiv:1404.1873



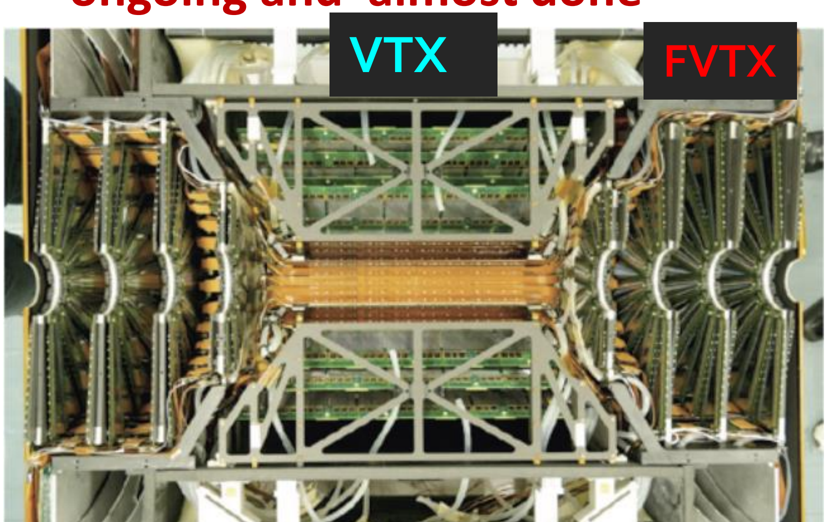

- Similar suppression in Cu+Au compared to Au+Au
- Forward (Cu-going) more suppressed than Backward → CNM effects?

# Charm/Bottom Separation with VTX/FVTX: Coming Soon

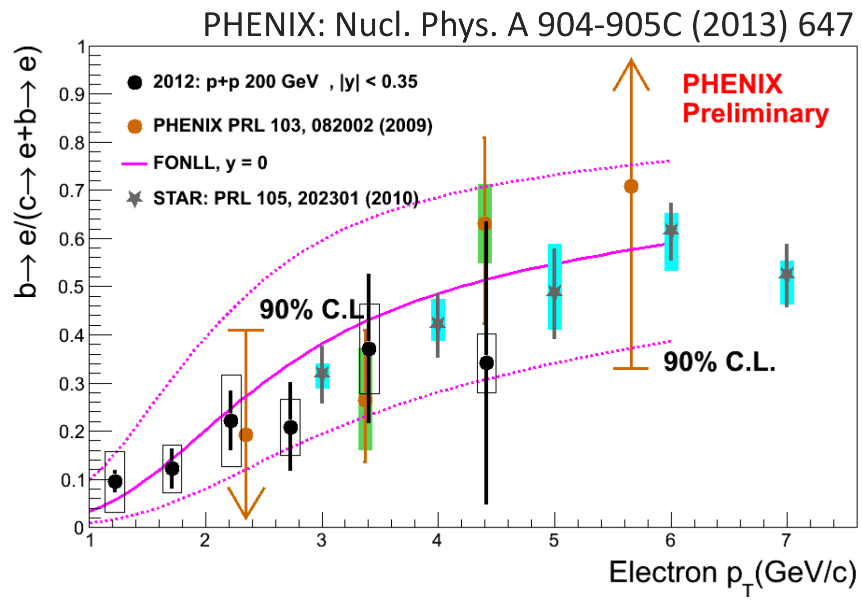
## VTX in Run 2012: p+p at 200 GeV

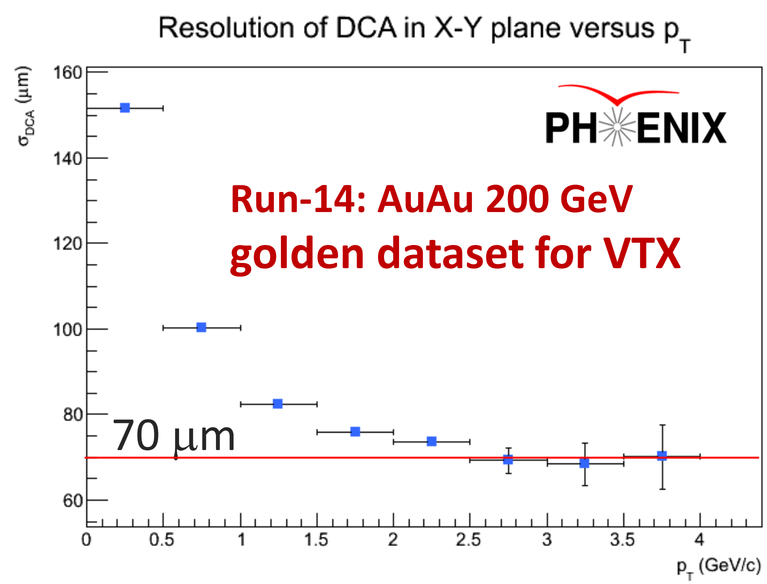


- **Alignment of VTX for Run-14 is ongoing and almost done**




**STAR indirect measurement consistent with our results**



# Summary

- In p+p collisions, $e^{HF}$ yields have been measured and agree with pQCD calculations (FONLL)
- Open Heavy Flavor, $e^{HF}$ , shows medium effects similar to those light hadrons ($\pi^0$) in central Au+Au collisions
- Initial states effects (d+Au) do not appear to explain $e^{HF}$ suppression in Au+Au: consistent with creation of a very dense and strongly interacting deconfined medium
- In Au+Au and at forward rapidity: $R_{AA}$ ($J/\psi$ ) show similar suppression at different collision energies: 200, 62.4 and 39 GeV
- Varying system size does not appear to have much effect on $R_{AA}$ ($J/\psi$) : Cu+Cu, Au+Au, U+U, Cu+Au
- VTX/FVTX will provide nuclear modification and collective flow of charm and bottom separately using DCA:
  - Data analysis is ongoing
  - Run-14 data are the golden dataset for VTX/FVTX