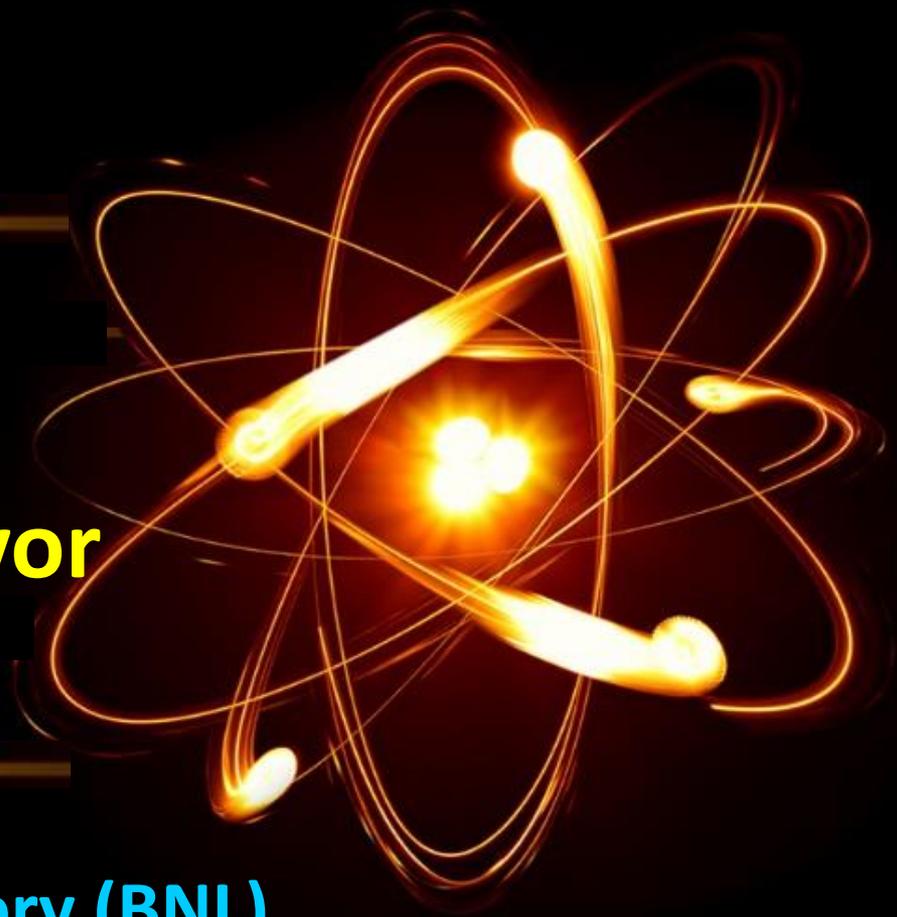

Probing Properties of Hot and Dense QCD Matter with Heavy Flavor at PHENIX



Rachid Nouicer
Brookhaven National Laboratory (BNL)

for the PHENIX collaboration

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



Relativistic Heavy Ion Collider (RHIC)



Energies: 7-200 GeV (AA)
48-500 GeV (pp)

RHIC

PHENIX



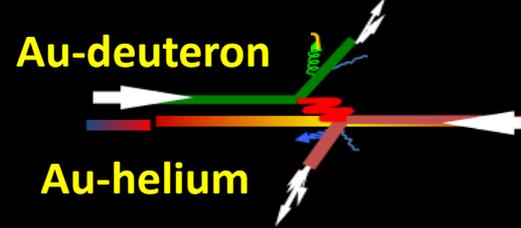
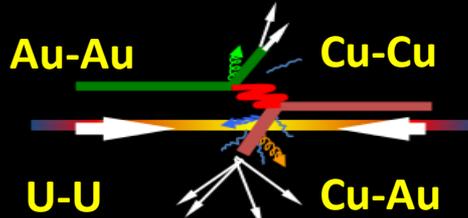
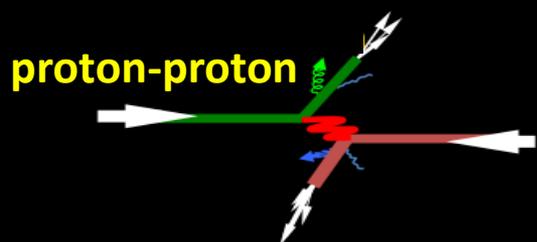
STAR



- 2 concentric rings of 1740 superconducting magnets
- 3.8 km circumference

AGS

TANDEM



RHIC Produces Extensive Data

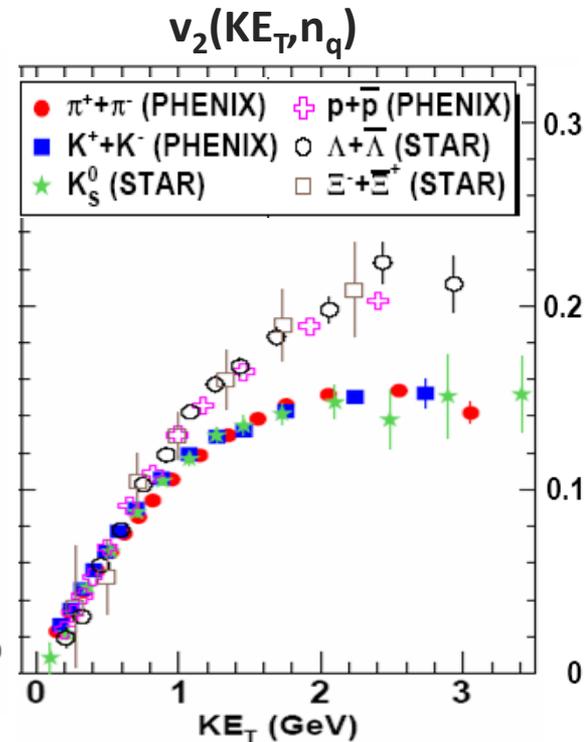
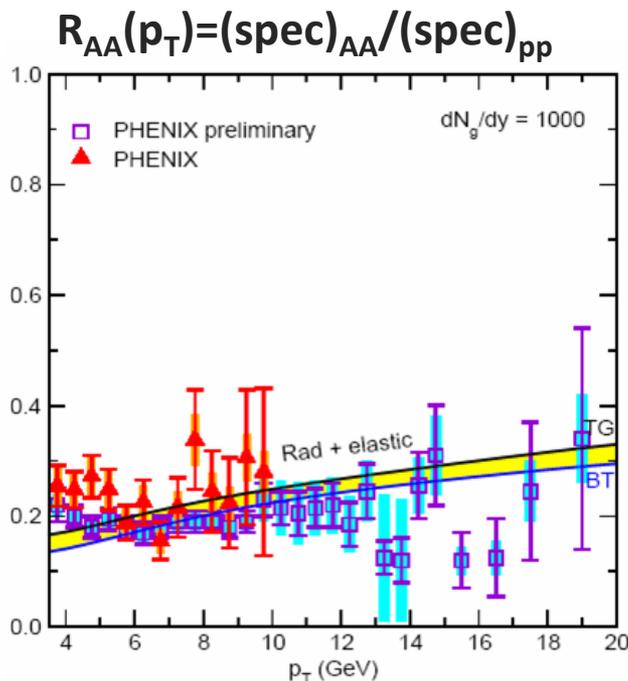
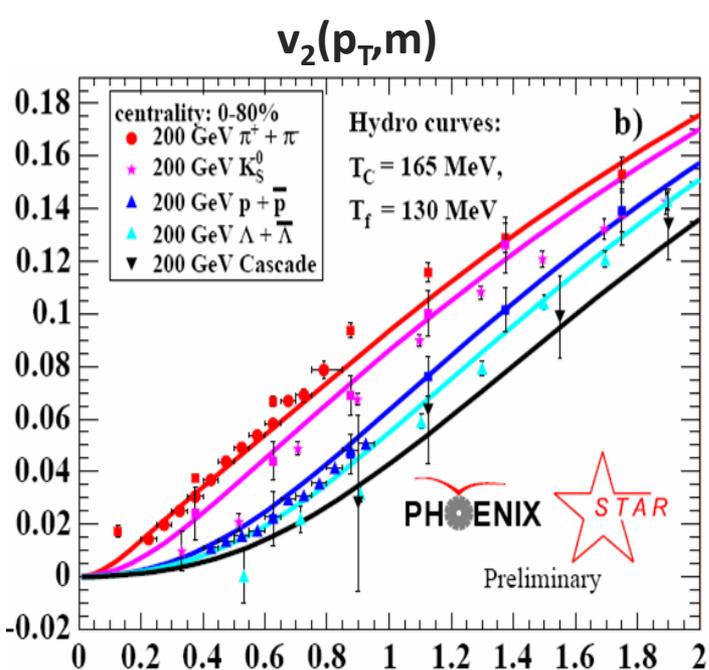


RHIC Run	Year	Species	Energy	Ldt
Run-1	2000	Au+Au	130 GeV	1 μb^{-1}
Run-2	2001-2	Au+Au	200 GeV	24 μb^{-1}
		Au+Au	19 GeV	0.4 μb^{-1}
		p+p	200 GeV	150 nb $^{-1}$
Run-3	2002/3	d+Au	200 GeV	2.74 nb $^{-1}$
		p+p	200 GeV	0.35 nb $^{-1}$
Run-4	2003/4	Au+Au	200 GeV	241 μb^{-1}
		Au+Au	62.4 GeV	9 μb^{-1}
Run-5	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*



Collective Expansion:

ideal hydrodynamics
 (QGP equation-of-state)

Quark Energy-Loss:

perturbative QCD
 (gluon radiation)

Hadronization:

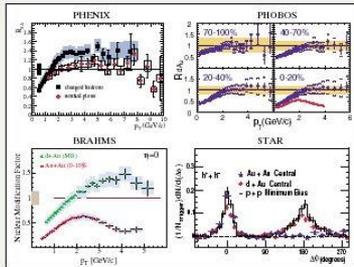
quark coalescence

rapid thermalization, “perfect liquid” \Rightarrow 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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APS Published by The American Physical Society

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

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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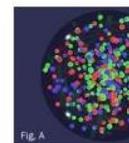
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Science News

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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 combine and collective more than the predicted gas (Figure A, see mp that has been observed at RHIC (Figure B, see "force lines" and an animated version degree of interaction what is now being liquid. (Courtesy of Laboratory)

International Journal of High-Energy Physics

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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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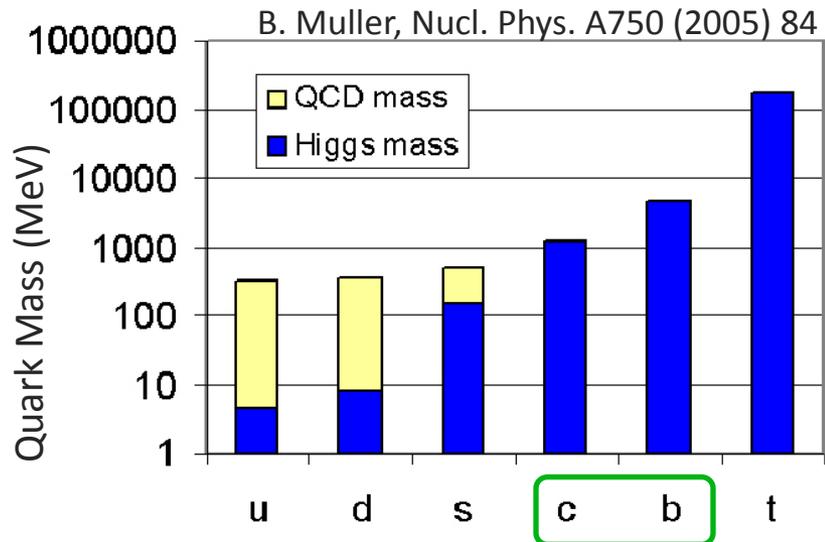


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Heavy Flavors: Ideal Probes of Nuclear Matter

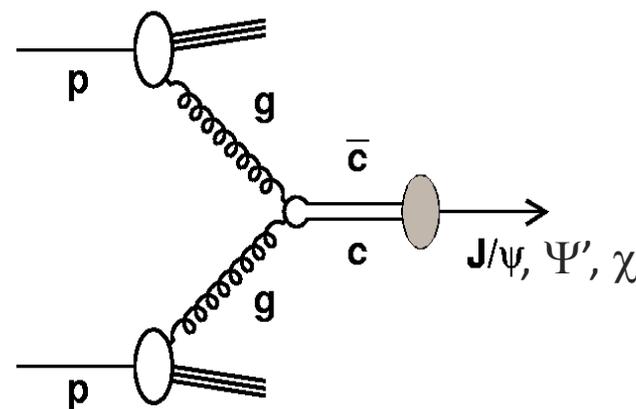
- ❖ Symmetry breaking
 - Higgs mass: electroweak symmetry breaking
→ **current quark mass**
 - QCD mass: chiral symmetry breaking
→ **constituent quark mass**
- ❖ Charm and beauty quark masses are not affected by QCD vacuum
→ **ideal probes to study QGP**



- ❖ 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

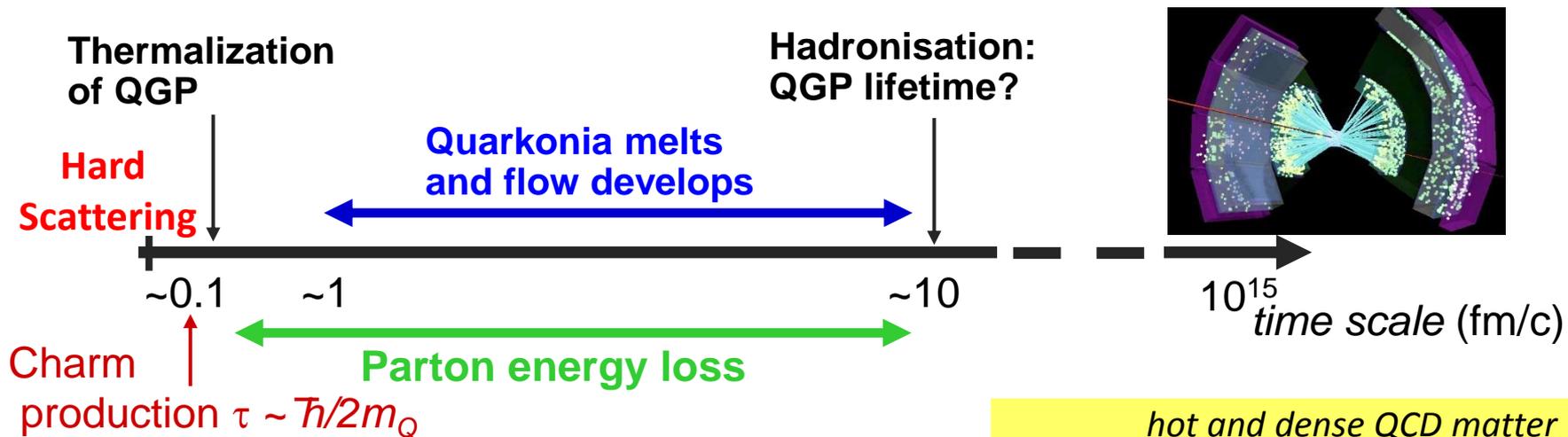
- ❖ Due to their mass ($m_Q \gg T_{\text{cri}}, \Lambda_{\text{QCD}}$)
→ **higher penetrating power**
- ❖ Gluon fusion dominates
→ **sensitive to initial state gluon distribution**



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



Heavy Flavors Energy Loss

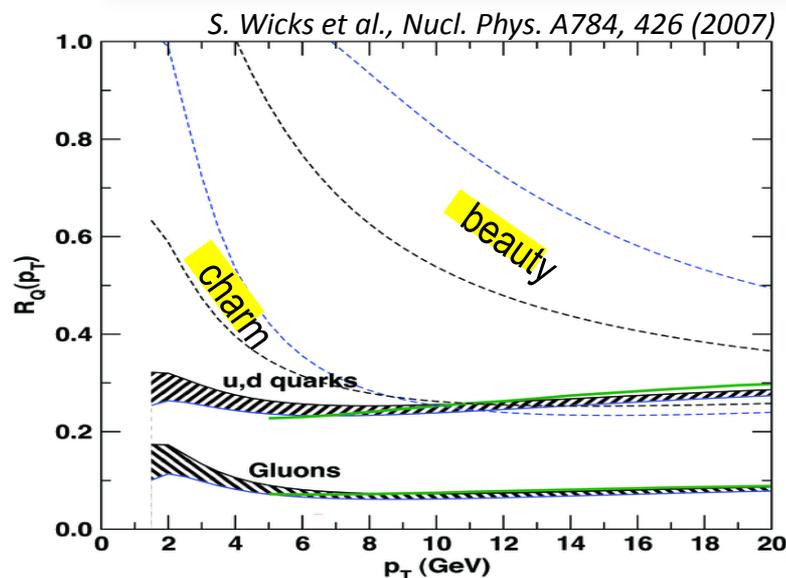
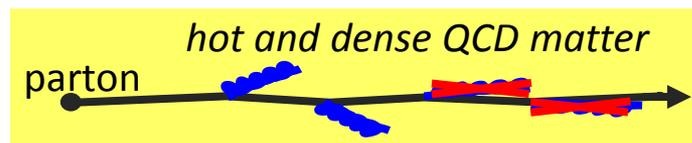


- (1) **Radiative parton energy loss** is color charge dependent (Casimir coupling factor C_R)
R. Baier et al., Nucl. Phys. B483, 291 (1997) ("BDMPS")

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

- (2) **Dead-cone effect:** gluon radiation suppressed at small angles ($\theta < m_Q/E_Q$)
Y. Dokshitzer et al. PLB 519, 199 (2001)

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





Challenge: Medium Effects “Hot versus Cold Nuclear matters”

- **p+p data:**

- baseline of heavy ion measurements
- test of pQCD calculation:
- $m_c \sim 1.3 \text{ GeV}, m_b \sim 4.8 \text{ GeV} \gg T_c, \Lambda_{\text{QCD}}$
- less affected than light quarks

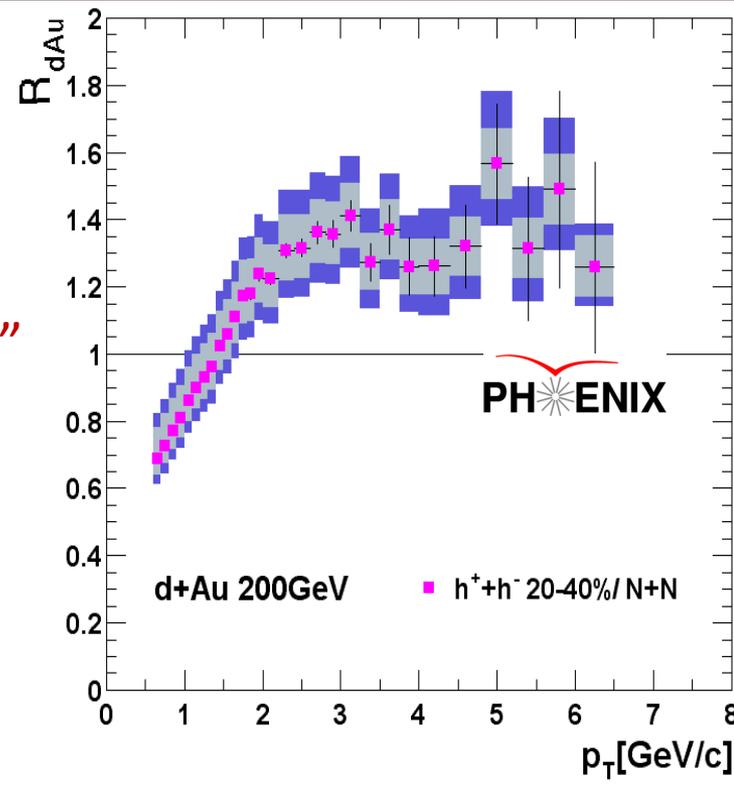
- **Heavy ion data: “Hot nuclear matter i.e. Au+Au”**

- 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
- **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
- **Absorption** — **final-state effect**, after $c\bar{c}$ that forms the J/ψ has been produced, pair breaks up in matter due to interactions with nucleons

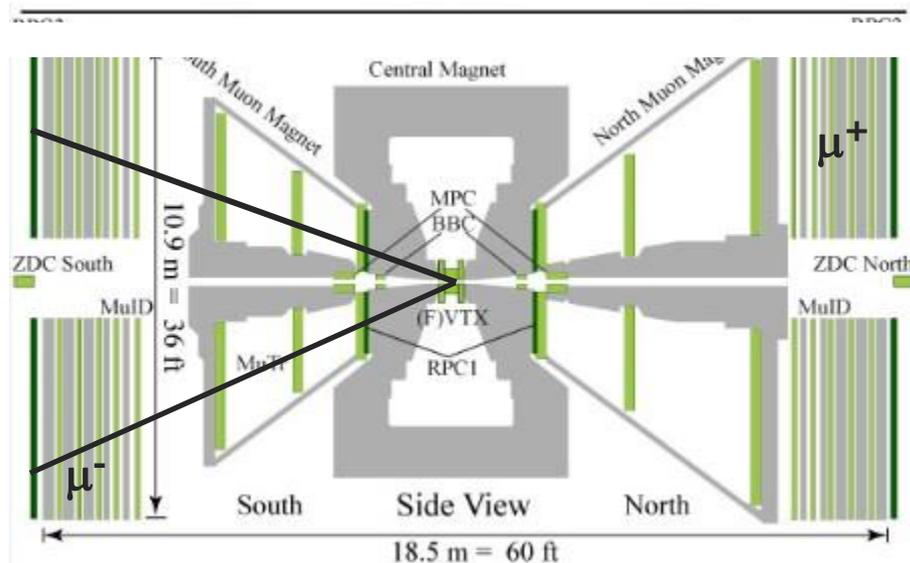
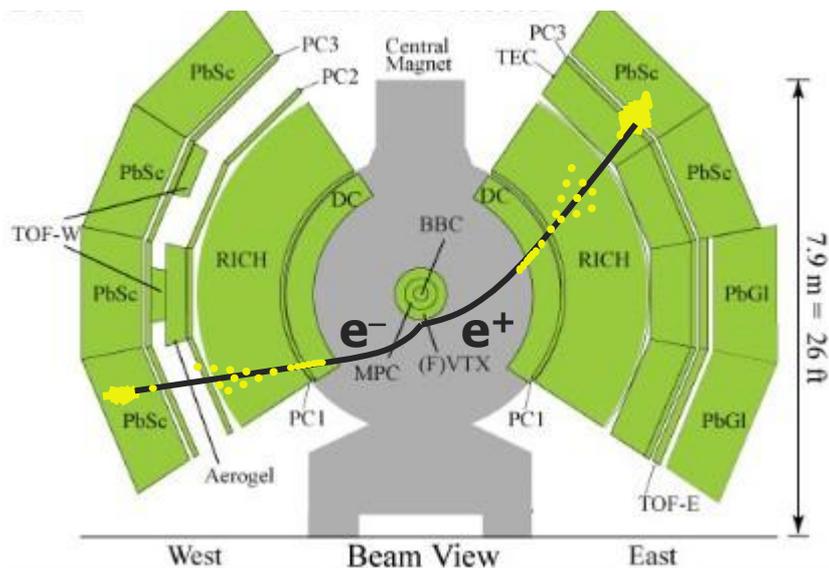




Measuring Heavy Flavor in PHENIX

PHENIX: optimized to measure leptons:

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



Mid-rapidity: $J/\psi, \Upsilon \rightarrow e^+ e^-$

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

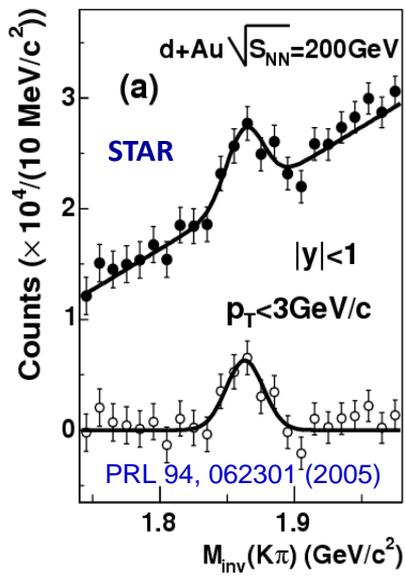
Forward rapidity: $J/\psi, \Upsilon \rightarrow \mu^+ \mu^-$

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

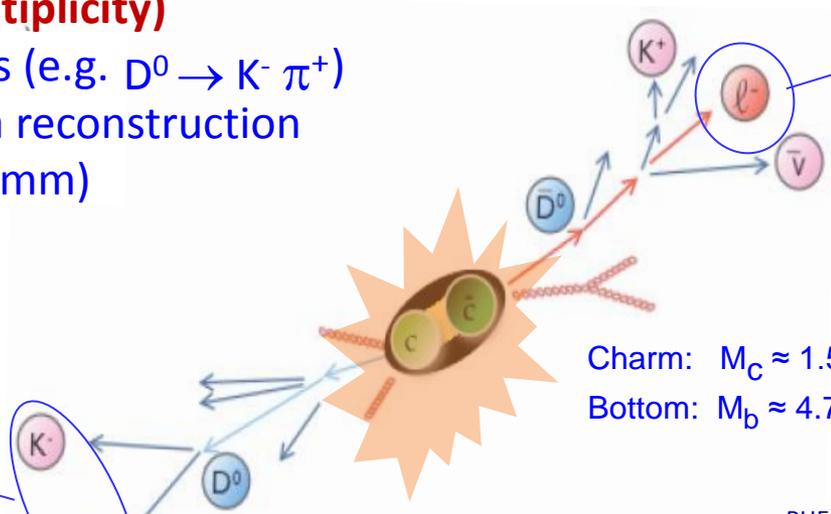
How to Measure Heavy Flavours

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)

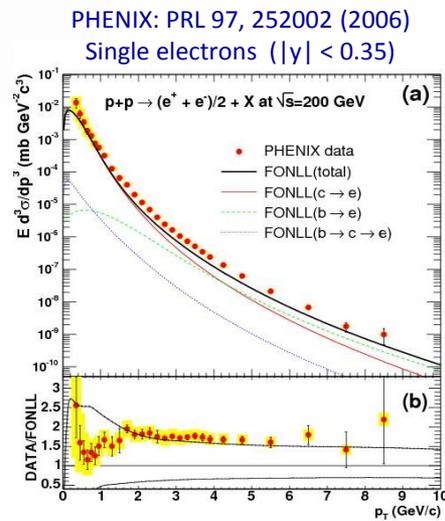
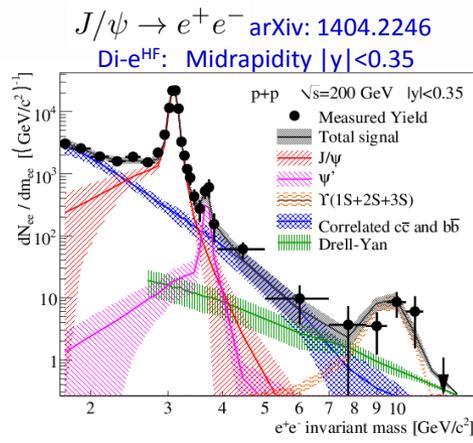


Direct measurement



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 $D^0 \rightarrow K\pi$	$(3.85 \pm 0.10) \%$
BR $D \rightarrow e+X$	17.2 (6.7) %
BR $D \rightarrow \mu+X$	17.2 (6.6) %

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

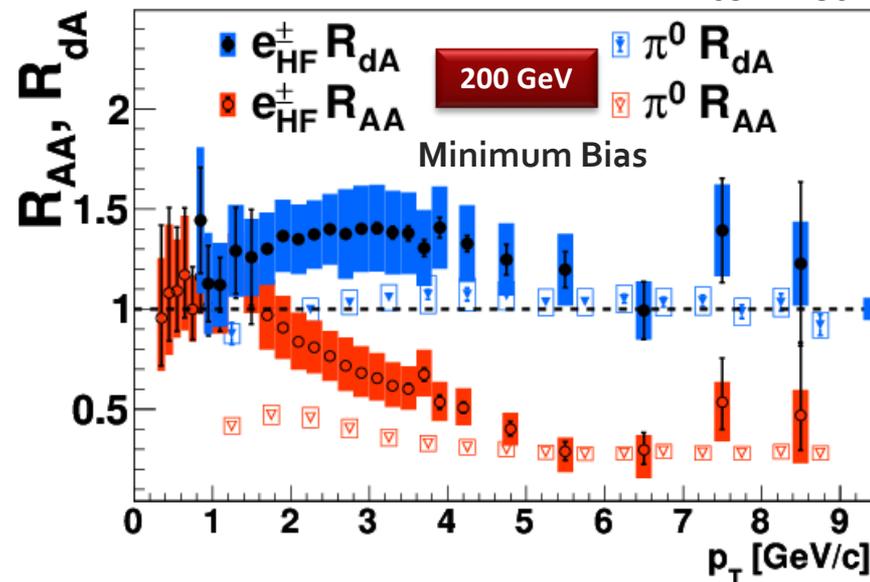
1) Au + Au at 200 GeV

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

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

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

PHENIX: PRL 109 242301



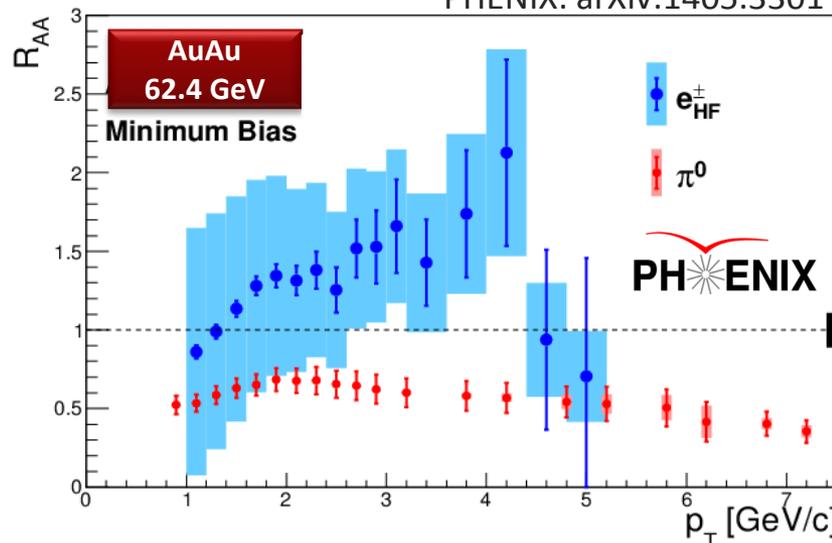
2) d + Au at 200 GeV

no suppression observed over p_T

→ e^{HF}, π^0 are quenched due to the hot nuclear
medium created in Au+Au at 200 GeV

→ final state effect

PHENIX: arXiv:1405.3301



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!



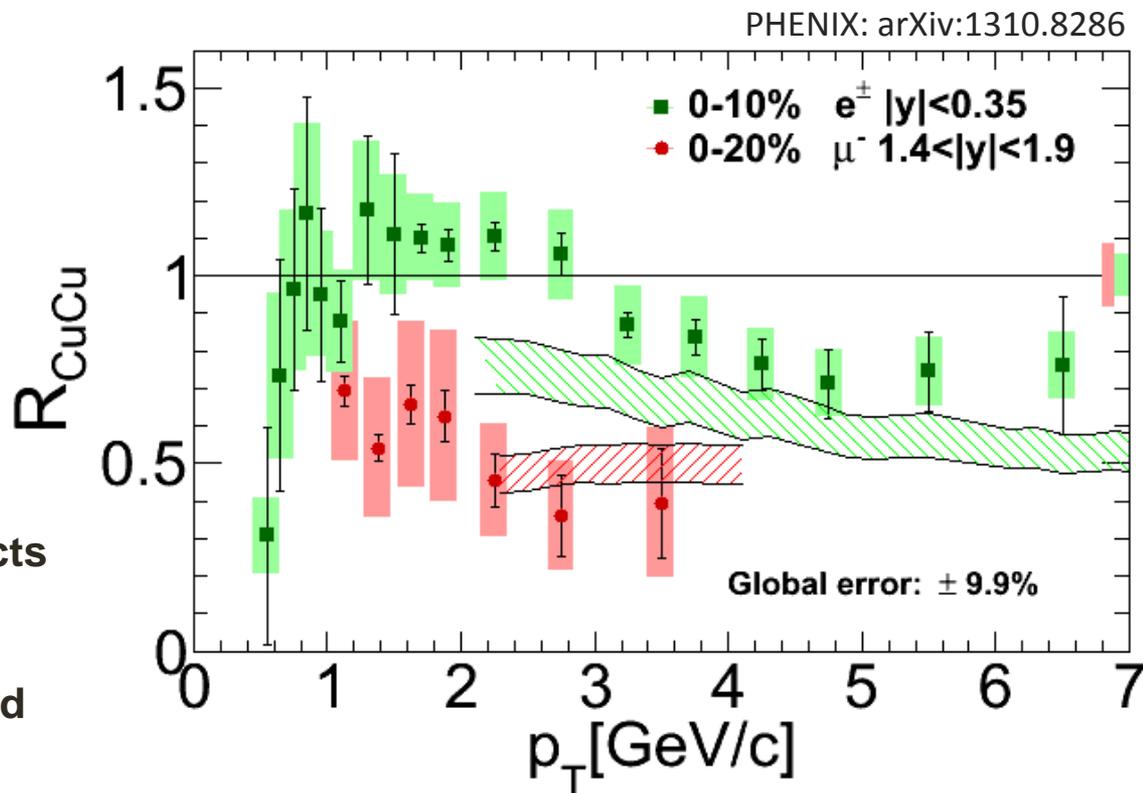
Open Heavy Flavor (single e^{HF}) in Cu+Cu at 200 GeV

Single electrons e^{HF} vs single muons μ^{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



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 $\mu^+\mu^-$

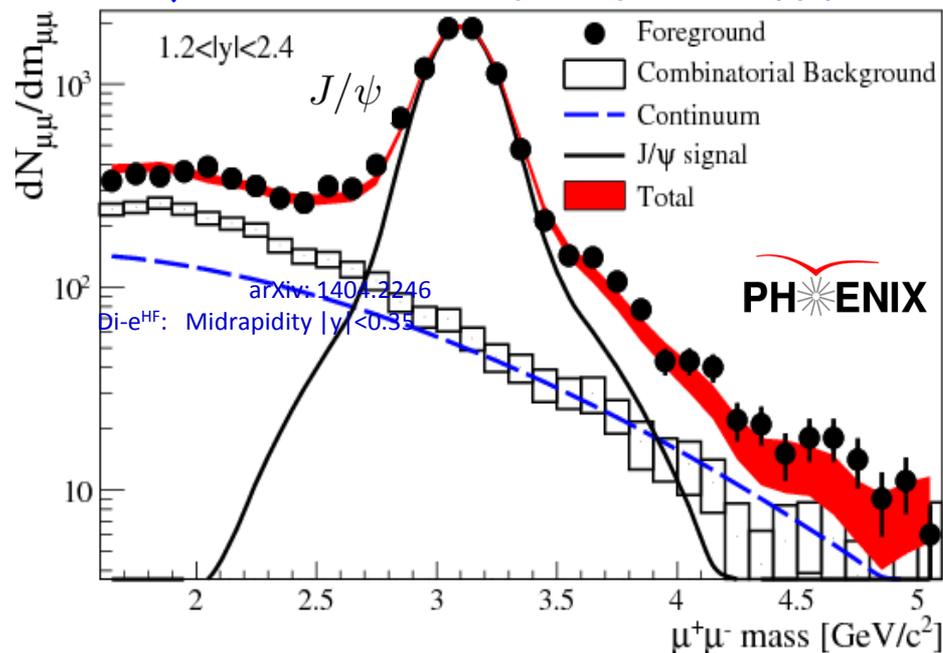
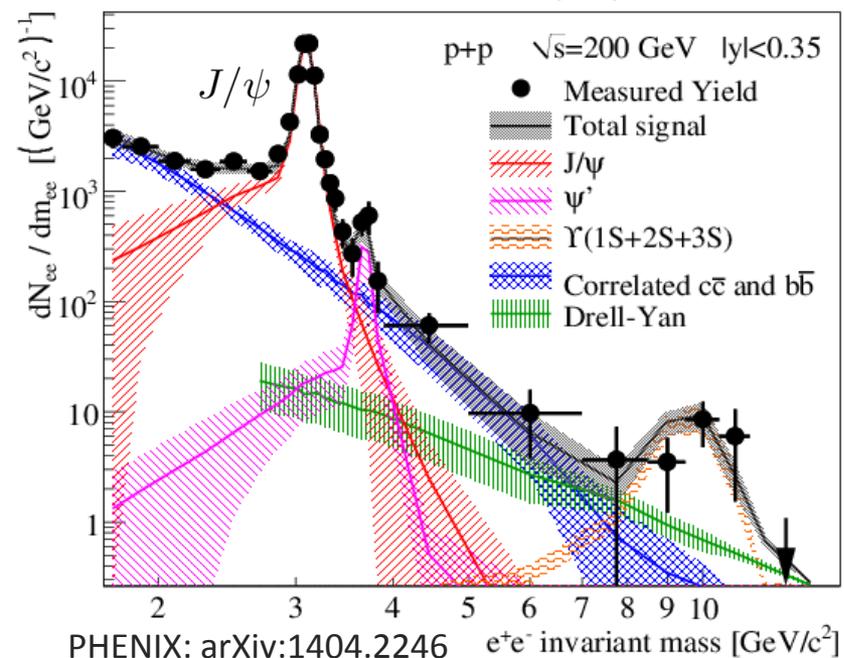
$$J/\psi \rightarrow e^+e^-$$

p+p at 200 GeV

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

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

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

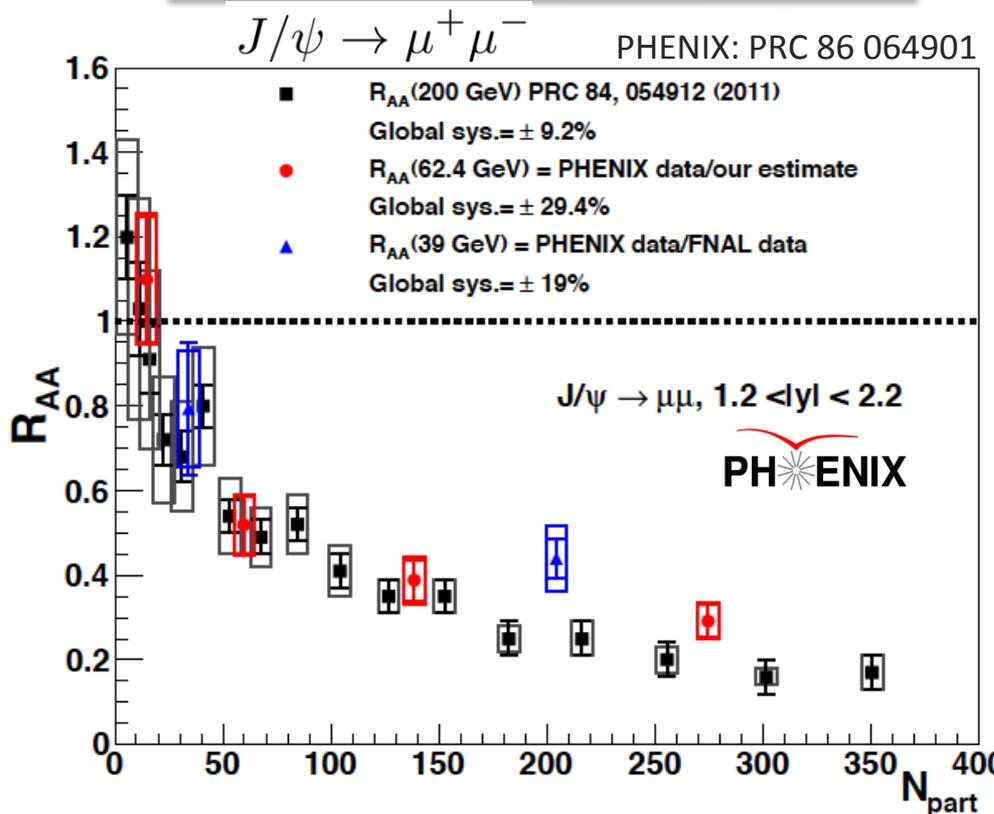


PHENIX has excellent capabilities of measuring different quarkonia states in di-electron and di-muon channels.



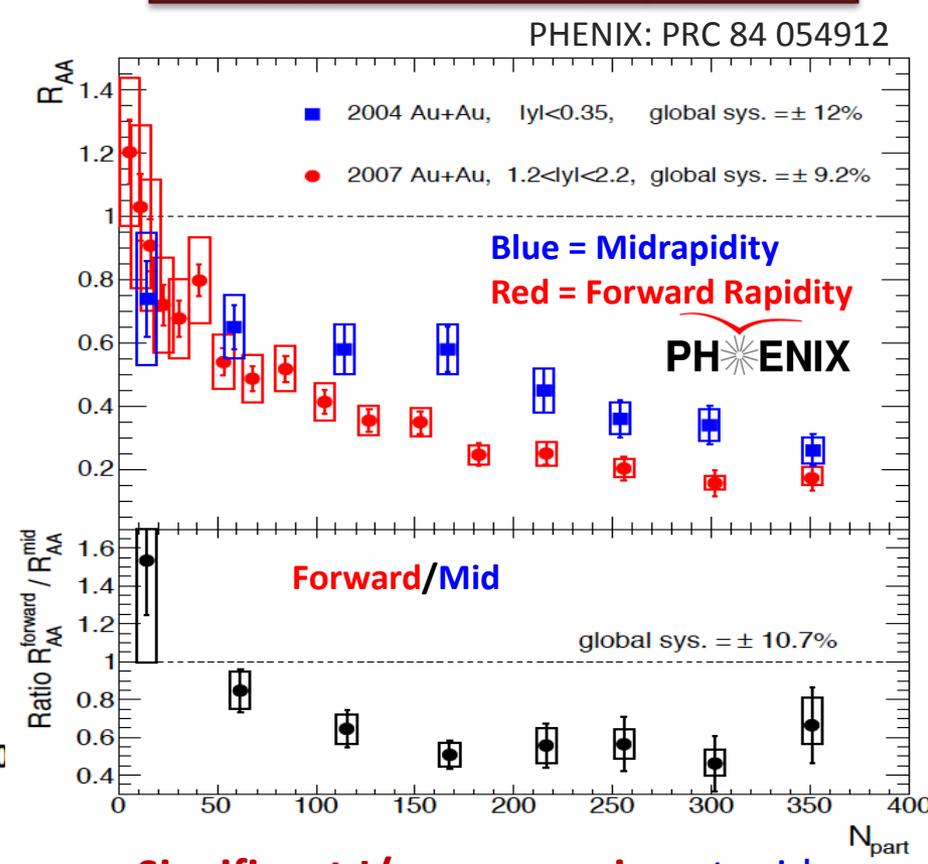
Bound Heavy Flavor: J/ψ R_{AA}

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



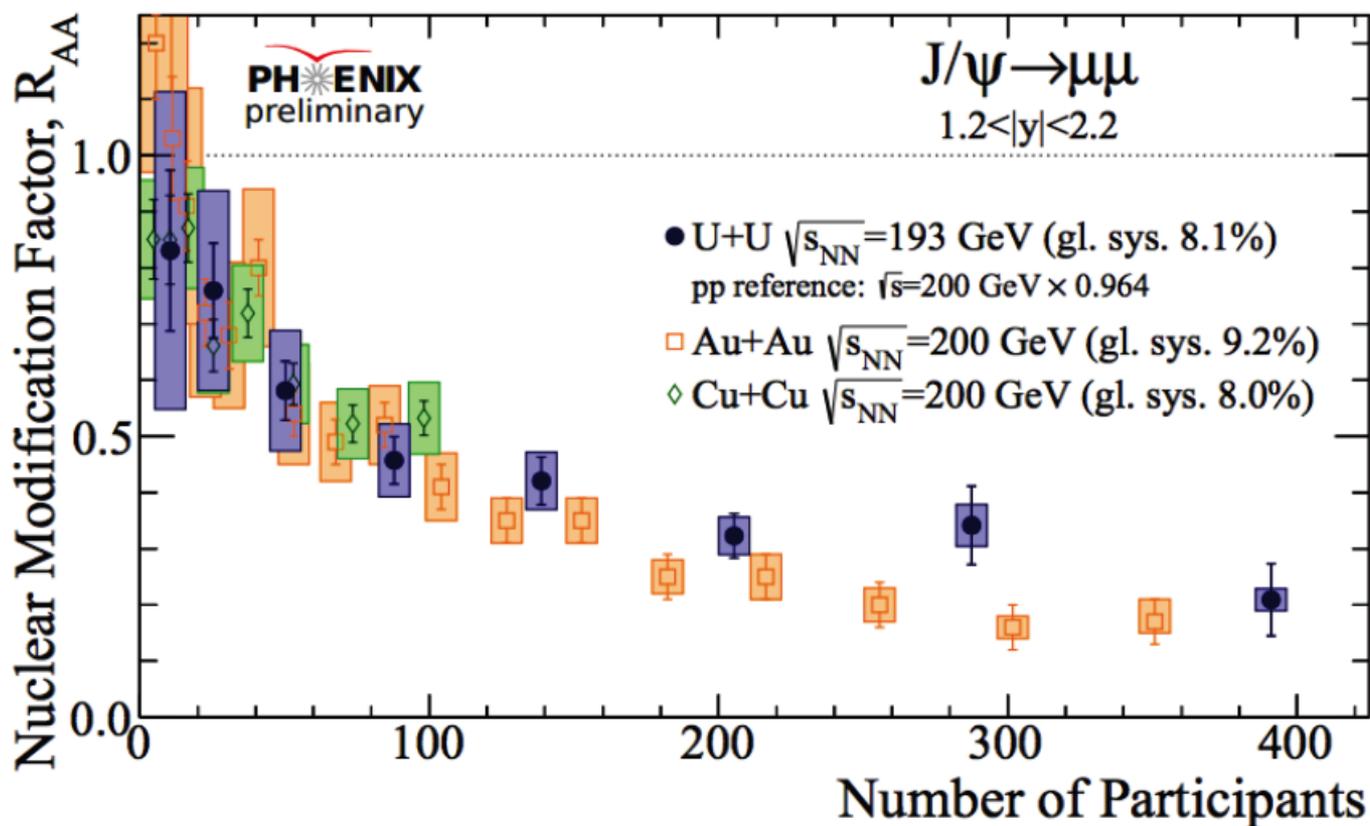
Significant J/ψ suppression at mid- and forward rapidity regions is observed in central Au + Au collisions
 R_{AA} decreases with increasing N_{part}



Bound Heavy Flavor: J/ψ R_{AA}

System Size study: Cu+Cu, Au+Au and U+U ≈ 200 GeV

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

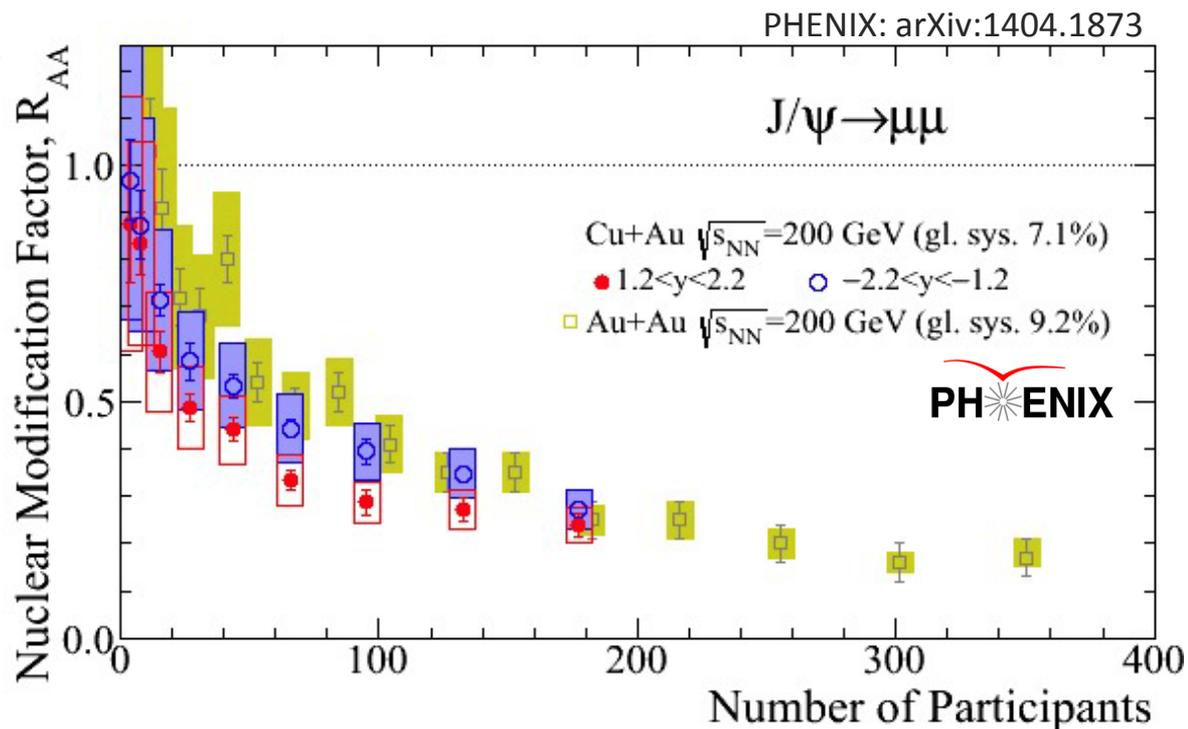
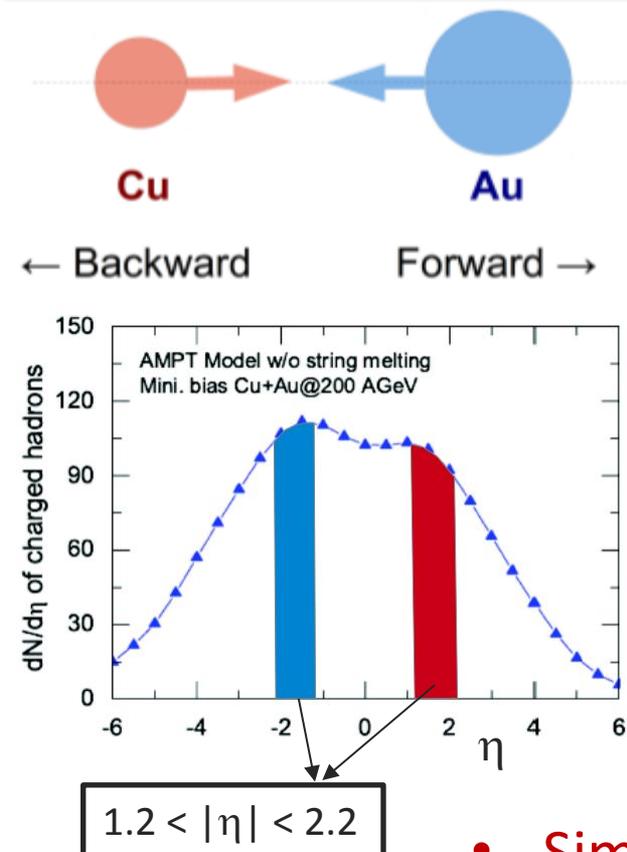
Is this what we expected?



Bound Heavy Flavor: J/ψ R_{AA}

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

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

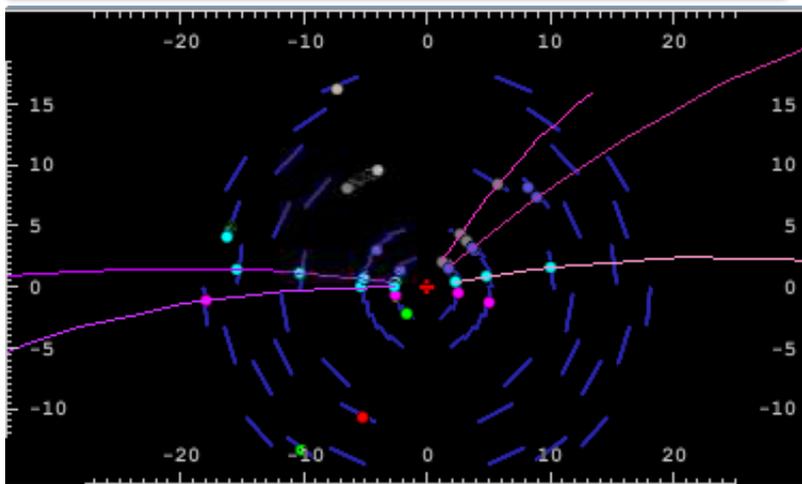


- Similar suppression in Cu+Au compared to Au+Au
- Forward (Cu-going) more suppressed than Backward
 → CNM effects?

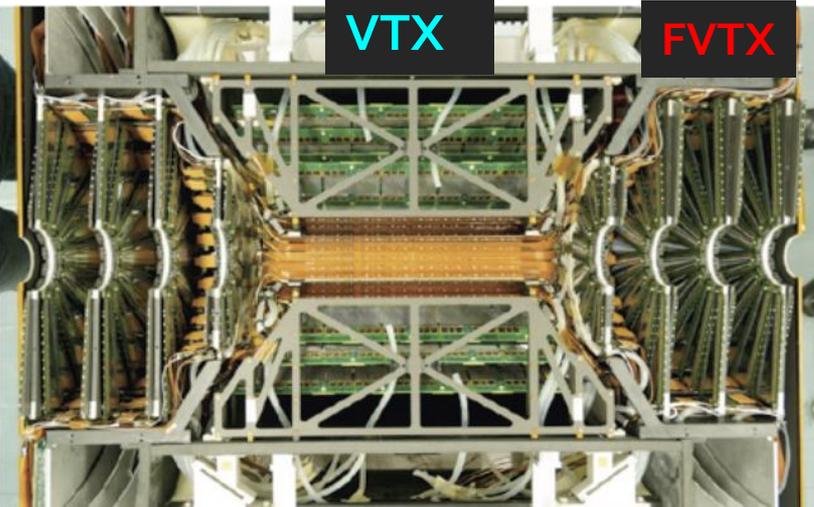


Charm/Bottom Separation with VTX/FVTX: Coming Soon

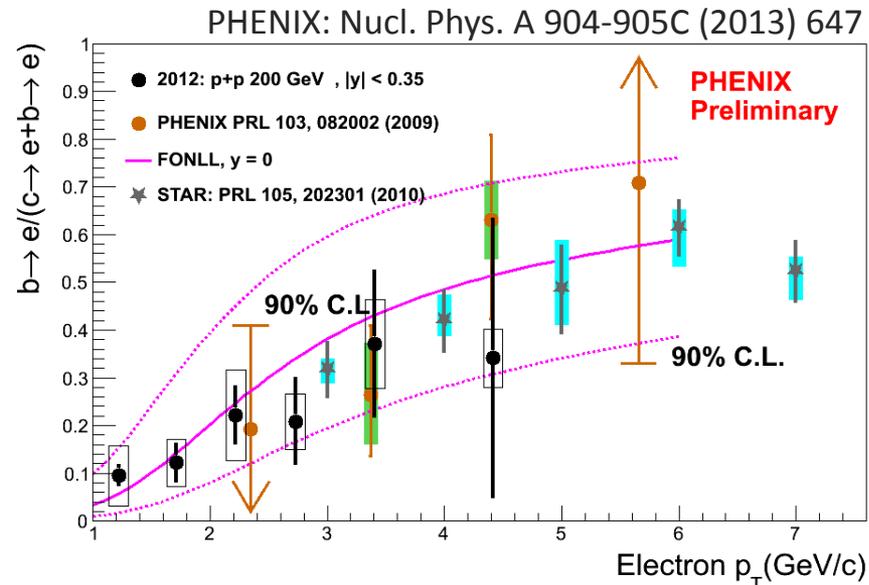
VTX in Run 2012: p+p at 200 GeV



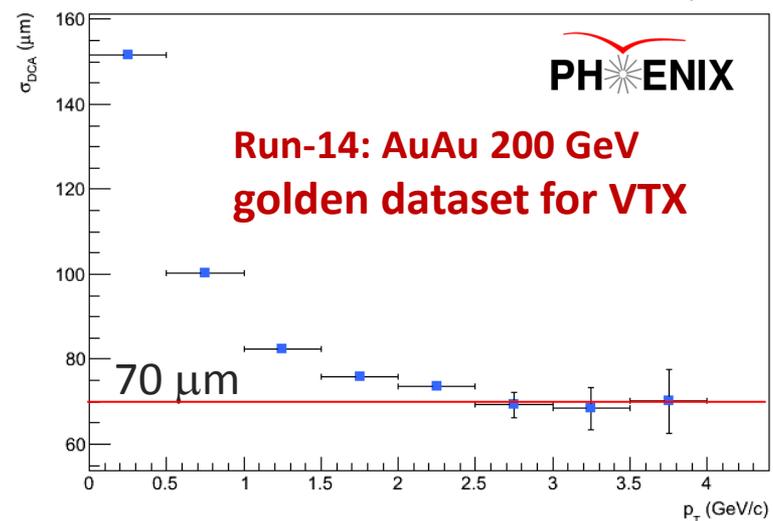
- Alignment of VTX for Run-14 is ongoing and almost done



STAR indirect measurement consistent with our results

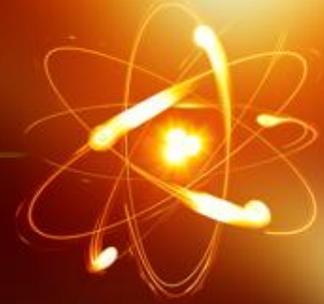


Resolution of DCA in X-Y plane versus p_T



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 (π^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: $R_{\text{AA}}(J/\psi)$ show similar suppression at different collision energies: 200, 62.4 and 39 GeV
- Varying system size does not appear to have much effect on $R_{\text{AA}}(J/\psi)$: 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



Auxiliary Slides

Extraction of Heavy Flavor Signal

- **Electron:** measuring first inclusive electrons:
 - **Background subtracted method:** using background cocktail composed of electron sources measured at PHENIX: **photonic** and **non-photonic** sources:
 - Conversion of photons from hadron decays in material
 - Dalitz decays of light mesons (π^0 , η , ω , η' , ϕ)
 - Ke3 : $K^\pm \rightarrow \pi^0 e^\pm \nu_e$
 - vector meson decays: ρ , ω , $\phi \rightarrow e^+ e^-$
 - heavy quarkonia decay
 - **Converter subtract method:** adds material of known thickness around beam pipe, measures conversion electrons by extra yield produced. Used at lower p_T .

Both cocktail and converter methods agree

- **Muon:** measuring first inclusive muons:
 - **Background subtracted method:** background removed through hadronic cocktail subtraction. Backgrounds include:
 - decay muons: resulting from light hadron decay.
 - Punchthrough hadrons: hadrons that are not absorbed in steel absorber, look identical to muons.