Review of Quarkonia at RHIC

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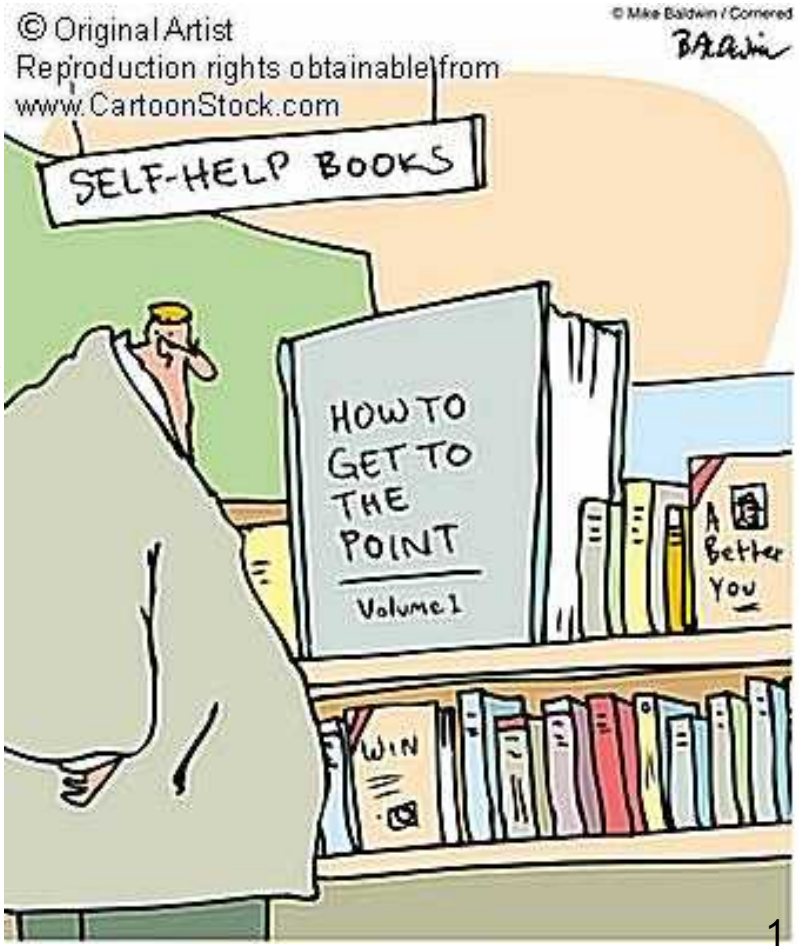
Warning, the speaker has found this be his most important reference.



The speaker expresses the his thanks for the sources of many slides showing these results.
1. From PHENIX, thanks to Mike Leitch and Matt Durham.
2. From STAR, thanks to Xin Dong.

Outline

1. Review quarkonia studies at RHIC.
   Sorry, can't be done in one talk. Well, at least not by me!

2. PHENIX and STAR detectors have many results, but are becoming more sophisticated, so expect much more to come.

3. RHIC has unique abilities to collide different species, such as Cu-Au.

Comment:

Many of these measurement lie in the area of non-perturbative QCD.
I have a strong bias that we MUST make these type of measurements.

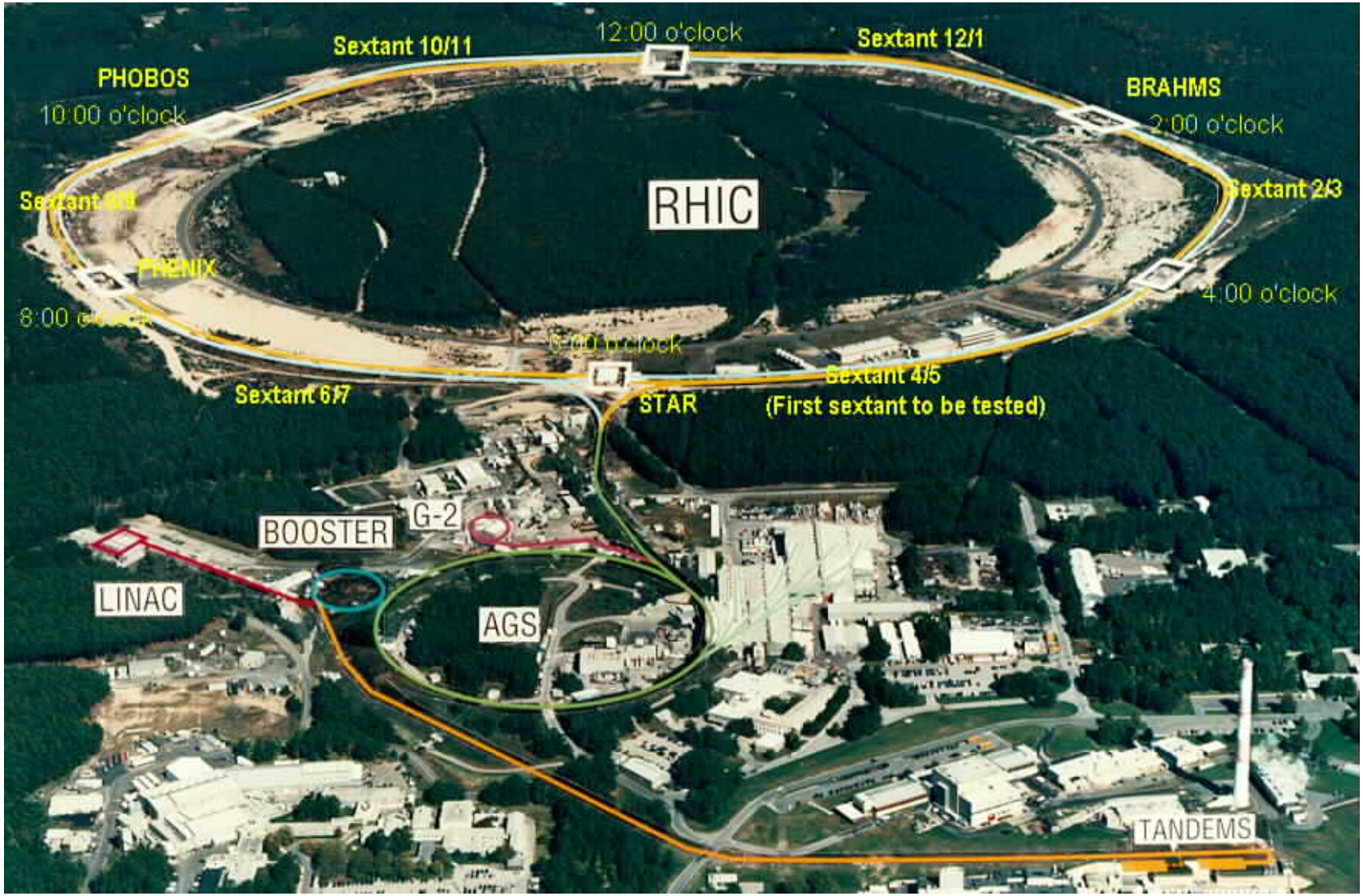
Only if we accumulate a high quality data set do we provide the basis for a rigorous explanation for WHY we find these results.
(Probably by a young physicist, untainted by the "We can't calculate that," mantra.)

*Theory can guide us, but it can also **bias** us.*

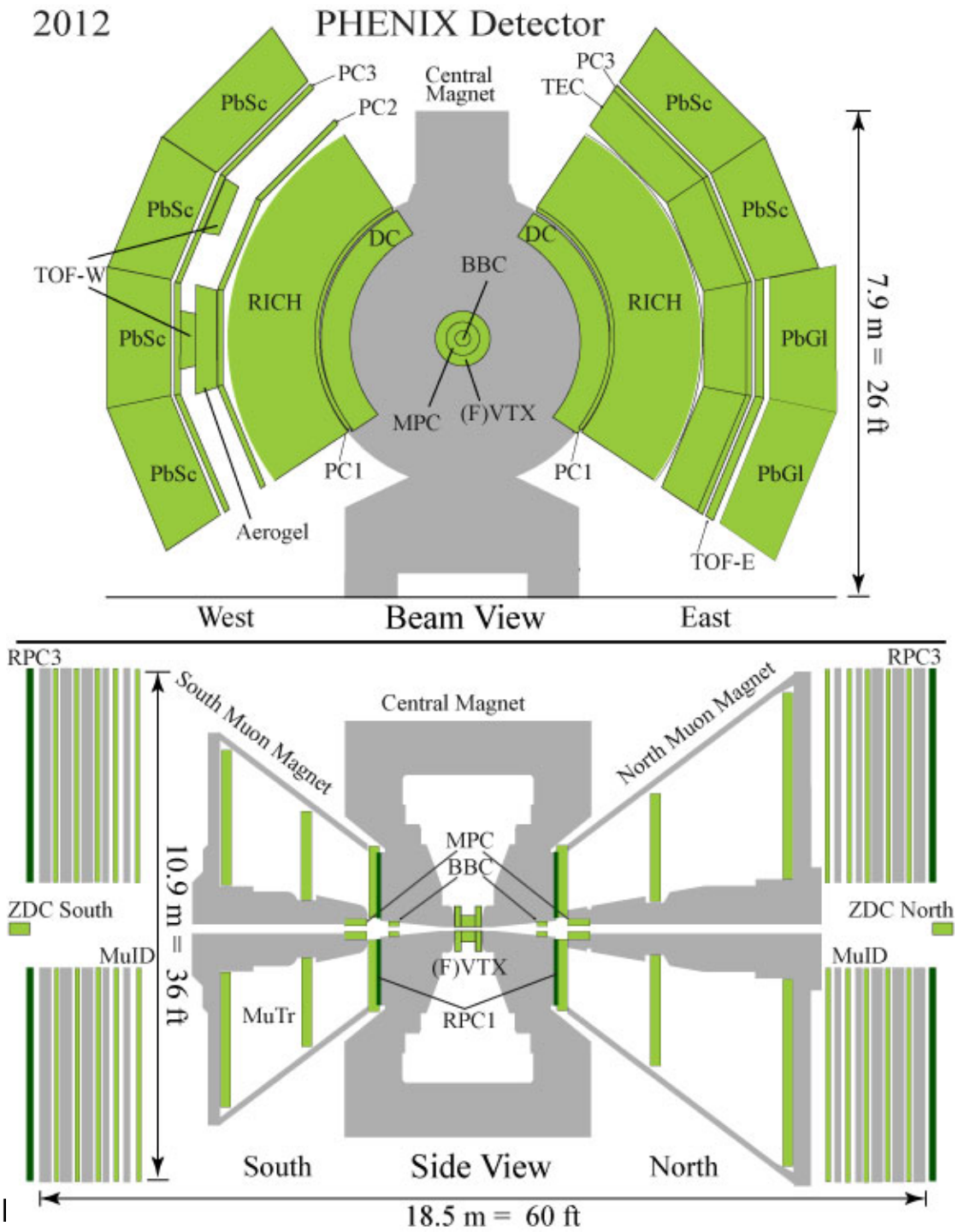
The starting point of the study of just exactly how protons, neutrons, and nuclei are made.

How to put a nucleus together.

RHIC Facility at Brookhaven National Lab



PHENIX as set up in RUN 12

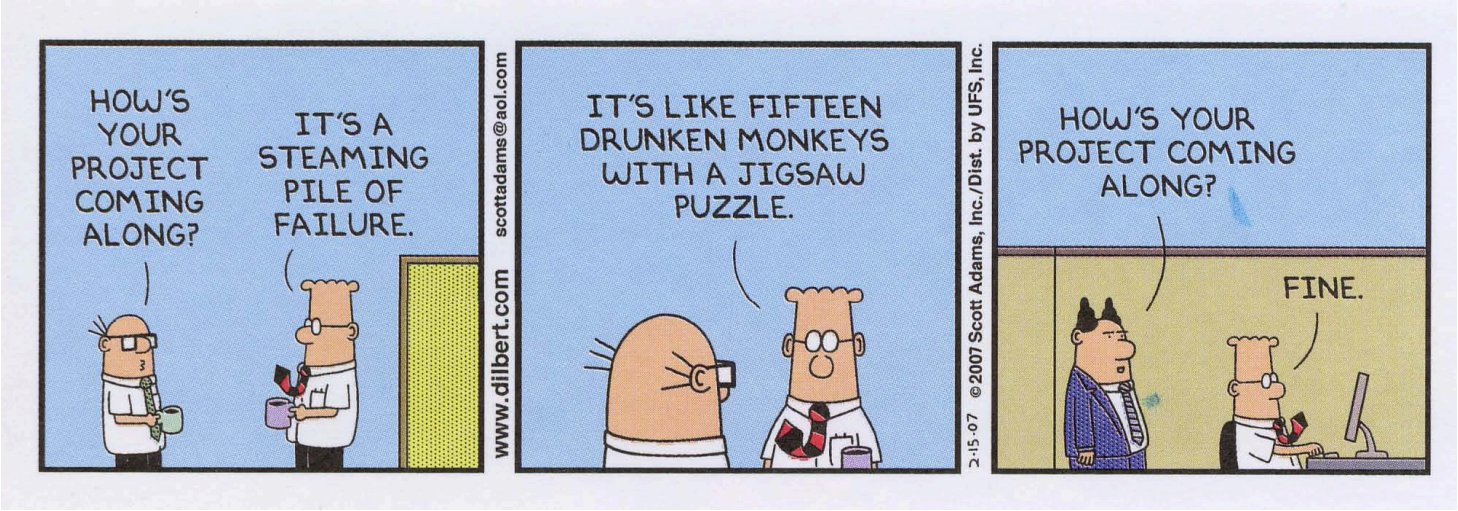


We have some things we would really like to have in a detector.

Accessibility - Ease of operation - Ease of calibration - Ease of trouble shooting

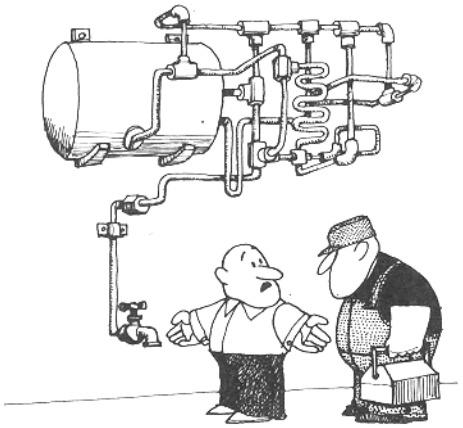
But we are often dealing with detectors that are more like this.

Collaboration internal reports. Reports to outsiders.

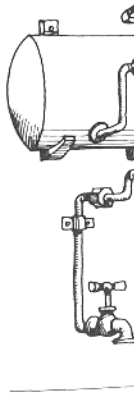


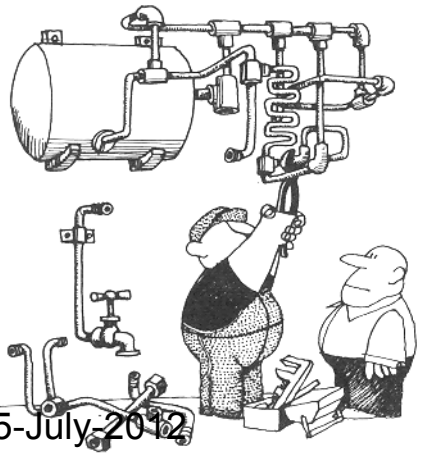
The reality is that there are a number of very talented, hard working people who manage do get things working and get the **physics results**.

If we can make it hard on the theorists, hopefully it is because **the physics is done right**!



How you feel working on it after you put it together sometimes.





Quarkonia Suppression in A+A Collisions – Screening

For the hot-dense medium (QGP) created in A+A collisions

- Large quark energy loss in the medium implies high densities
- Flow scales with number of quarks
- Is there deconfinement? → Quarkonia screening??

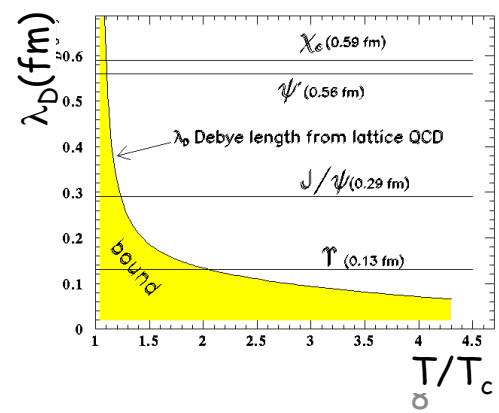
Matsui and Satz, Phys. Lett. B 178 (1986) 416:

"If high energy heavy ion collisions lead to the formation of a hot quark-gluon plasma, then colour screening prevents ccbar binding in the deconfined interior of the interaction region … … It is concluded that J/Ψ suppression in nuclear collisions should provide an unambiguous signature of quark-gluon plasma formation."

Debye screening predicted to destroy J/ψ's in a QGP with other states "melting" at different temperatures due to different sizes or binding energies.

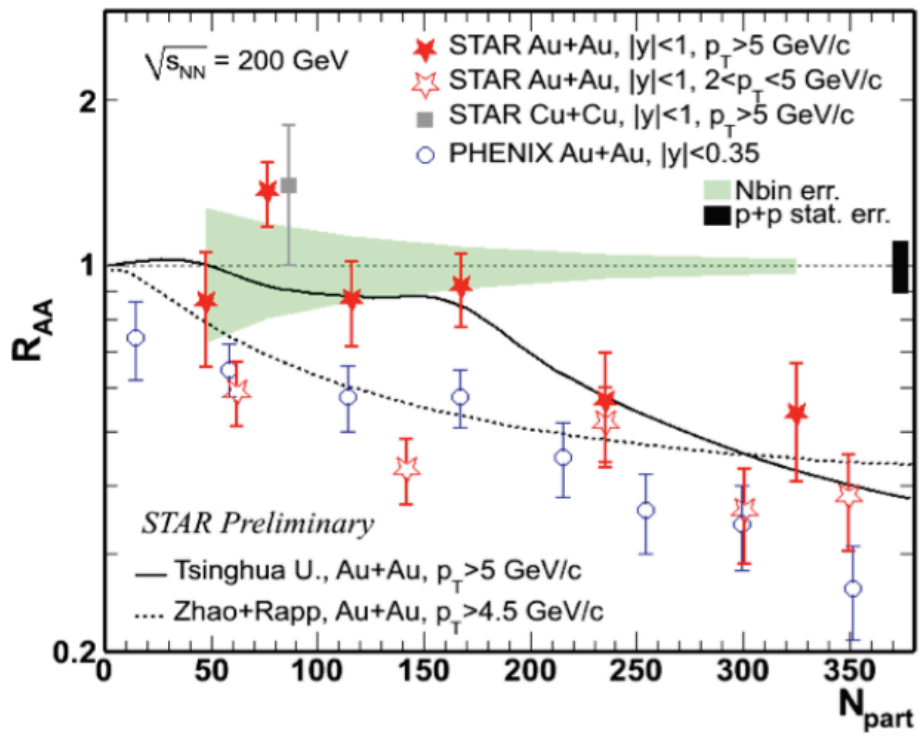
Satz, J.Phys.G32:R25,2006

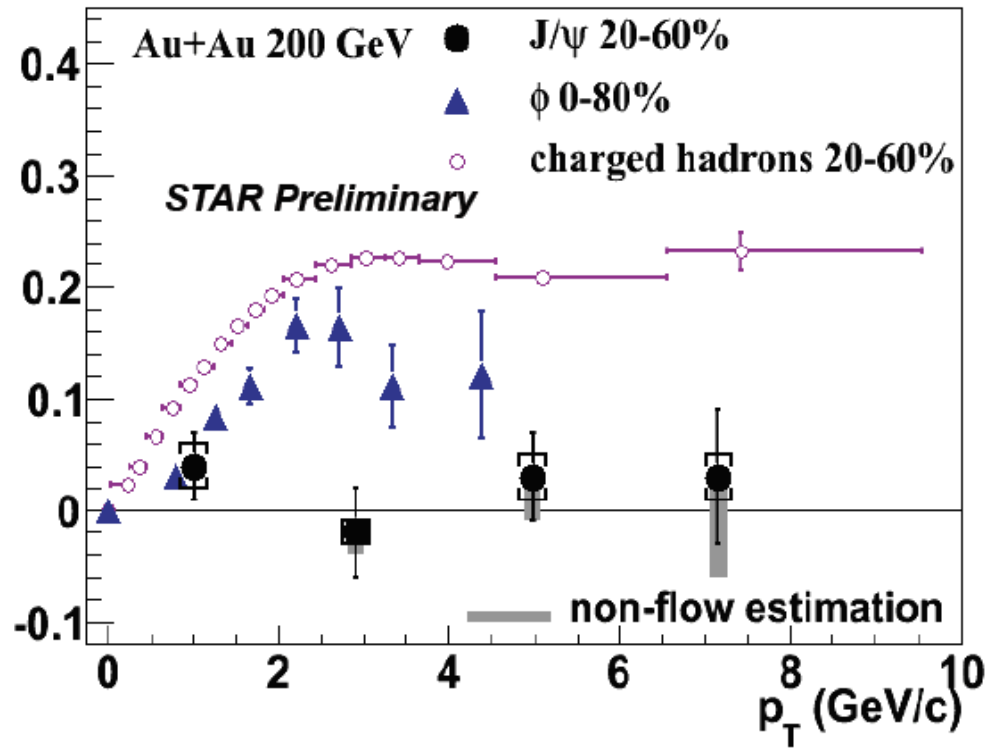
state	$J/\psi(1S)$	$\chi_c(1P)$	$\psi'(2S)$	$\Upsilon(1S)$	$\chi_b(1P)$	$\Upsilon(2S)$	$\chi_b(2P)$	$\Upsilon(3S)$
T_d/T_c	2.10	1.16	1.12	> 4.0	1.76	1.60	1.19	1.17



Slide provided by STAR – The speaker thanks Xin Dong!

J/ψ production in the heavy ion collisions





Quarkonia suppression – color screening: "classic" QGP signature

Multiple mechanisms will influence J/ψ production in heavy ion collisions:

- Initial production (and nuclear shadowing)
- Suppression due to cold nuclear absorption
- Recombination from sQGP medium …

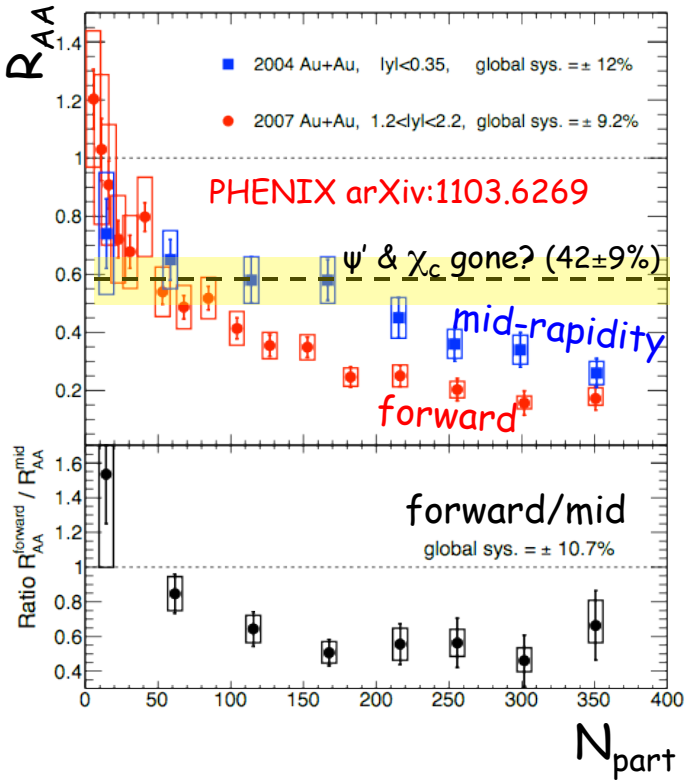
R_{AA} increases with p_T, and is smaller in central collisions

- start to probe initial sQGP suppression at high p_T?

v_2 is consistent with 0

- disfavor J/ψ is produced via recombination from thermalized charm quarks

Looking at the Suppression at a different rapidity – add PHENXIX muon detector

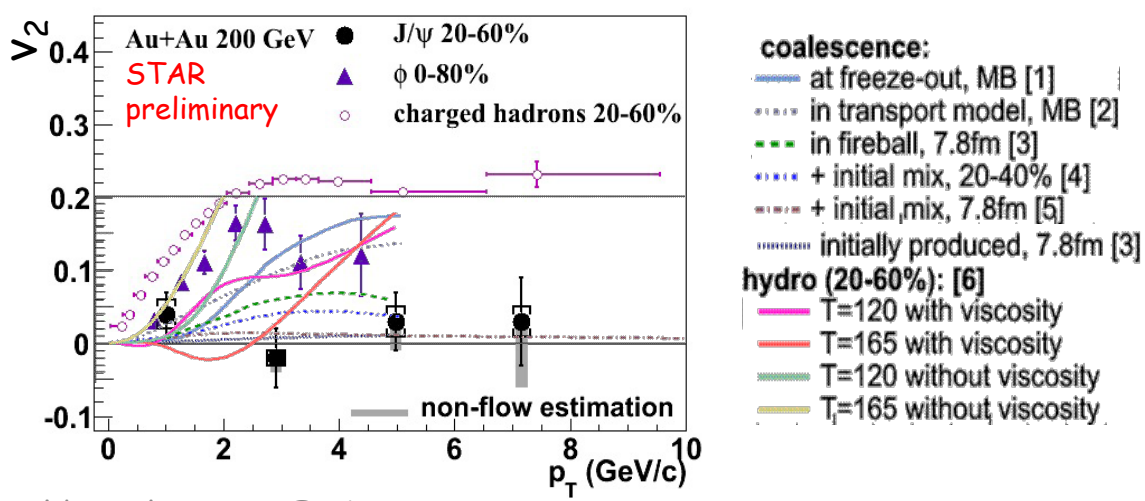


At RHIC - Forward-rapidity J/ψ's are suppressed more than Mid-rapidity – Why?

1) Stronger forward rapidity suppression due to CNM effects?

2) Regeneration at mid-rapidity reduces suppression relative to forward (and gives net suppression similar to SPS)?

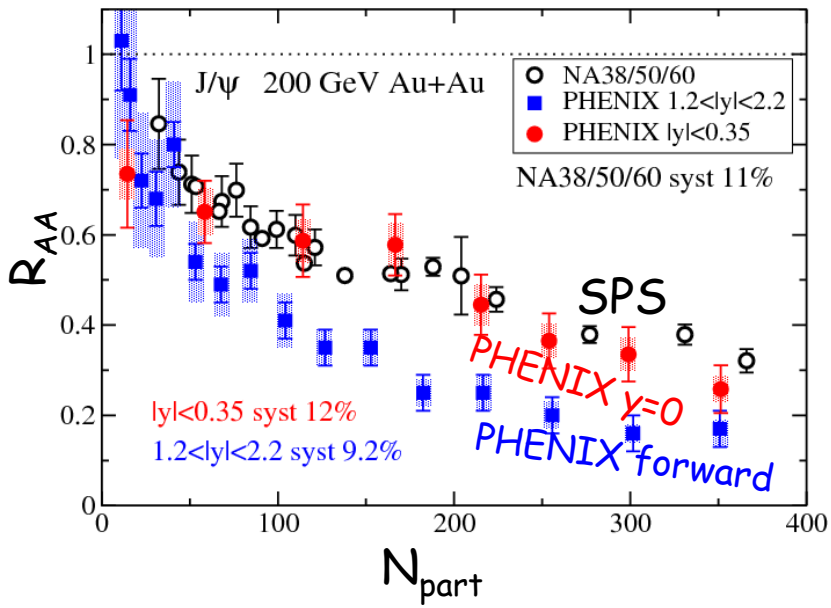
The upper left plot shows the value in having complementary detectors at RHIC.



Small or no J/ψ flow at RHIC!

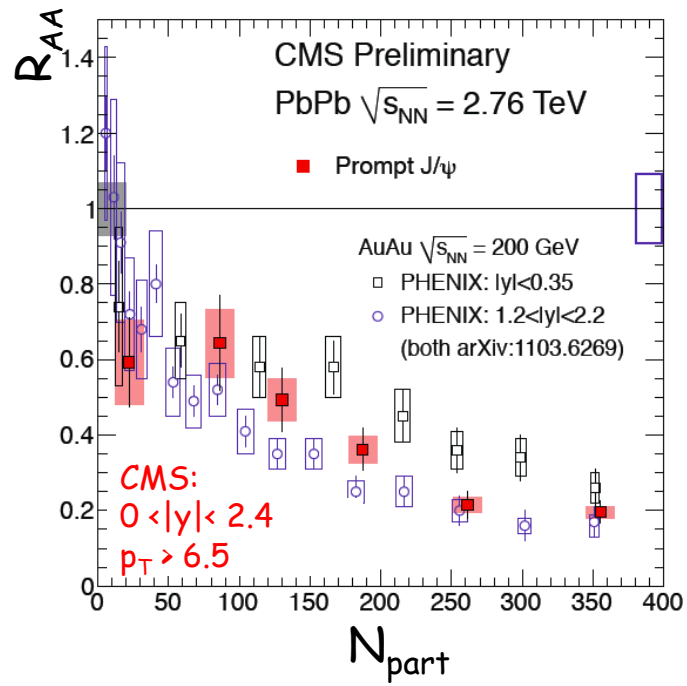
Many theoretical expectations & option #2 probably ruled out?

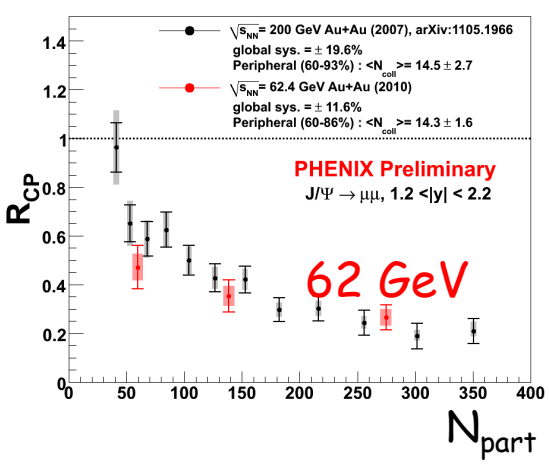
Quarkonia Suppression in A+A Collisions – key observations and questions

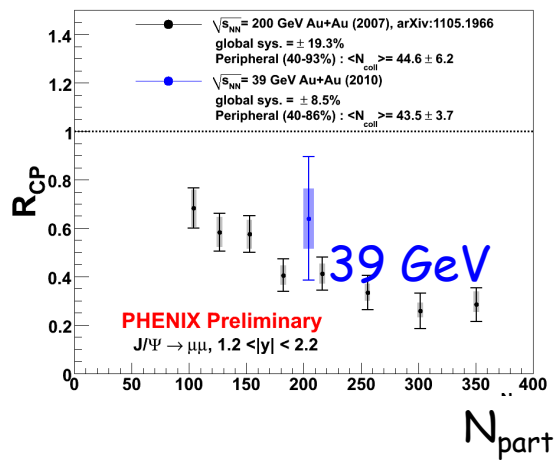


Overall suppression of J/ψ is very similar between:

- SPS (17.2 GeV)
- RHIC (200,62,39 GeV)
- and LHC (2.76 TeV)





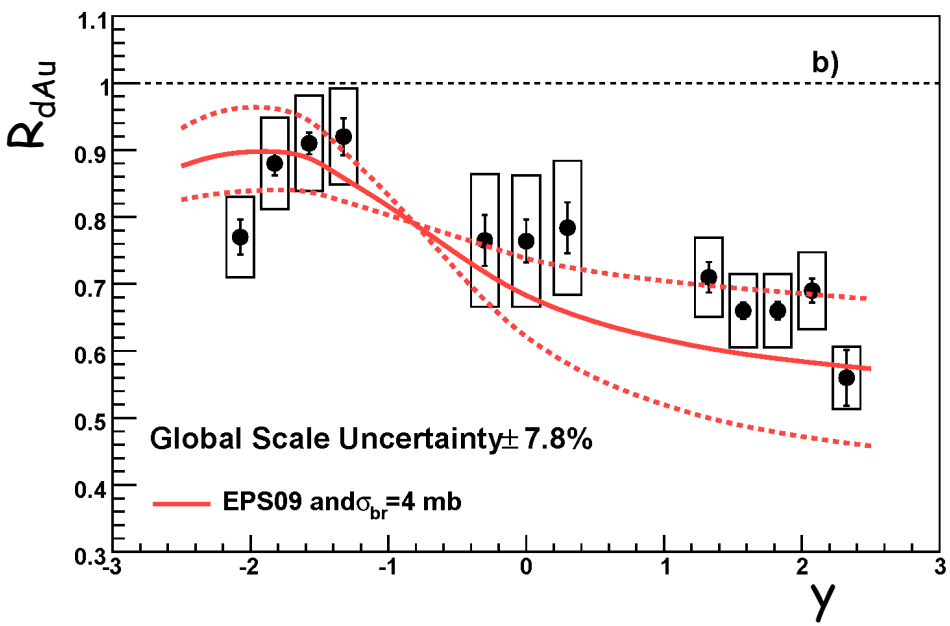


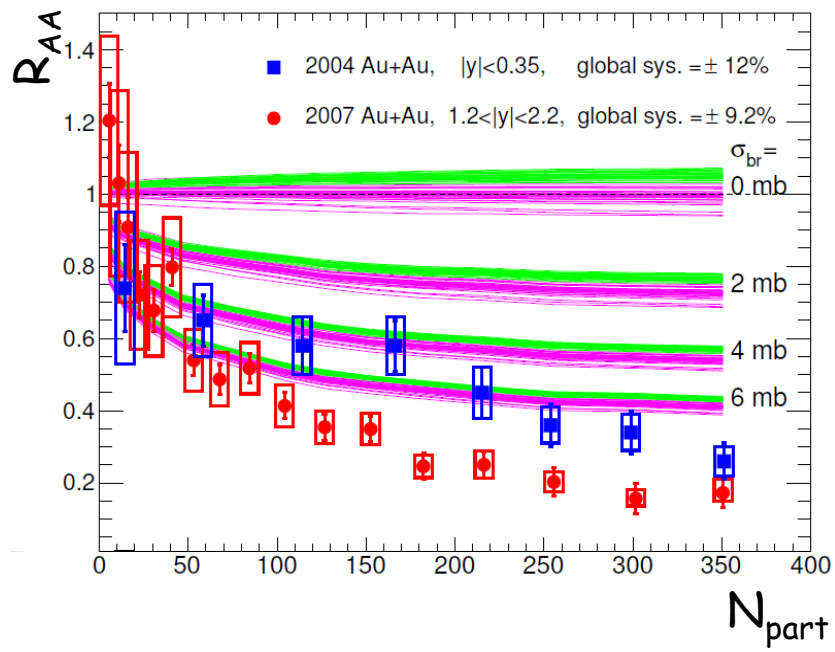
This in some ways complicates explanations.

Quarkonia Suppression in A+A Collisions – key observations and questions

Cold Nuclear Matter (CNM) effects appear to provide a large fraction of the observed suppression.

- So difficult to conclude much w/o a thorough understanding of CNM and its extrapolation to A+A from d+A. *Keeps us busy!*



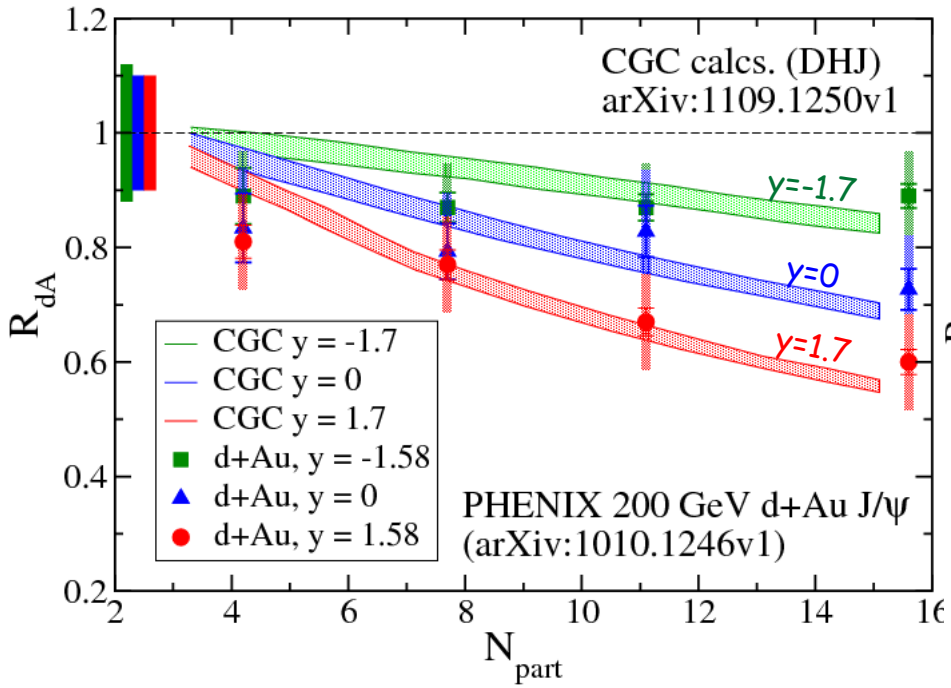


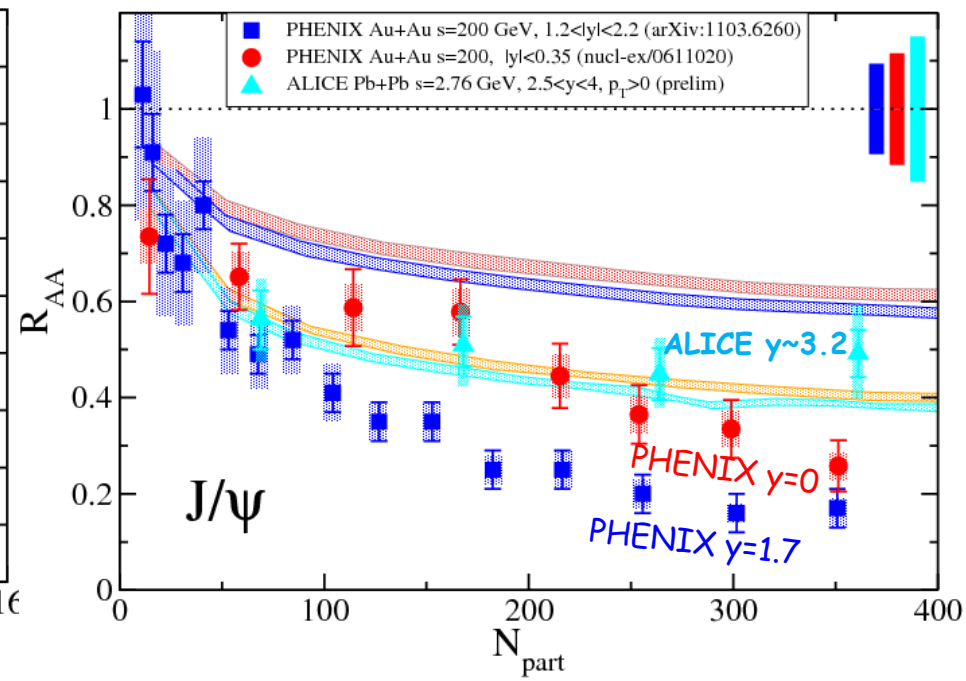
Probably have to understand CNM in a fundamental way in order to extrapolate to A+A correctly. *This should not come as a surprise!*

Quarkonia Suppression in A+A Collisions – more observations and questions

Recent Gluon Saturation (CGC) calculations (arXiv:1109.1250v1) also leave room for QGP effects in A+A collisions.

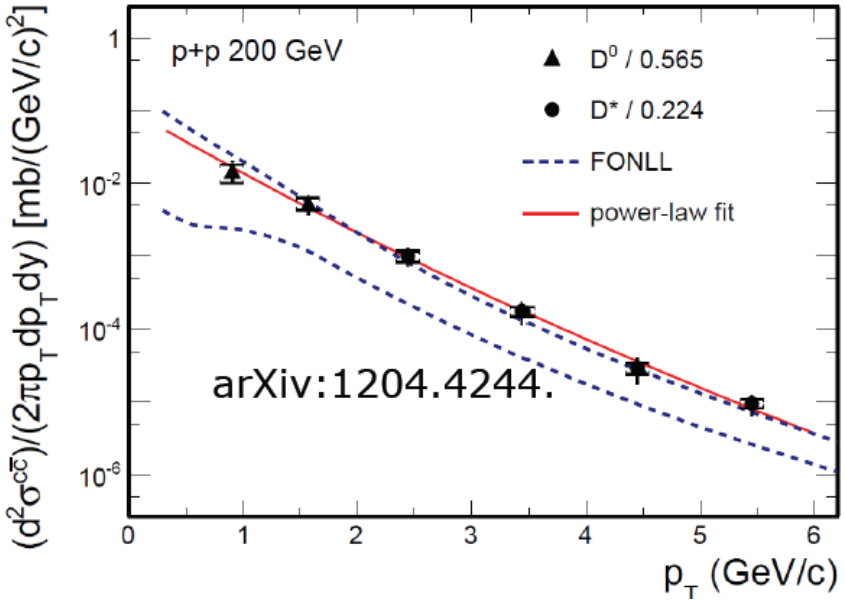
- However, they do not help explain the stronger suppression at forward rapidity in A+A.

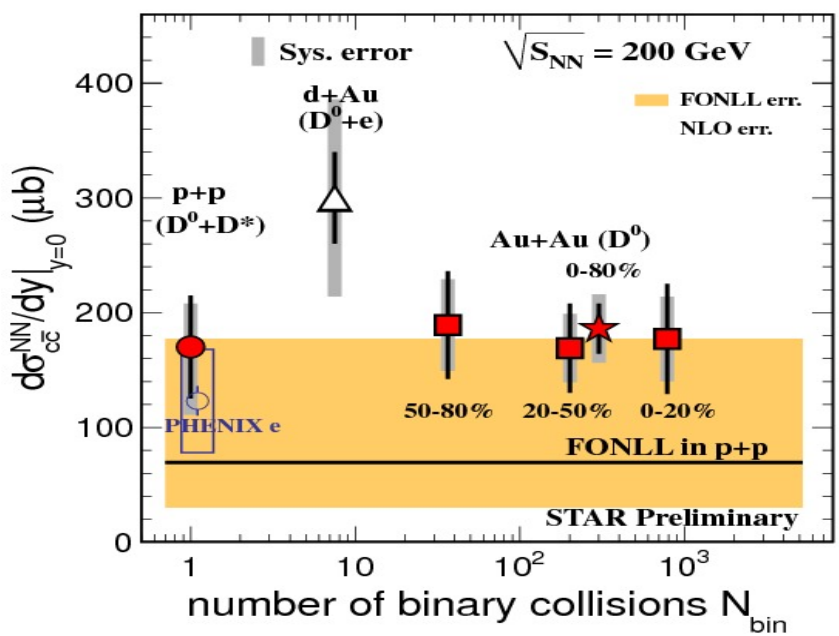




Slide provided by STAR – The speaker thanks Xin Dong!

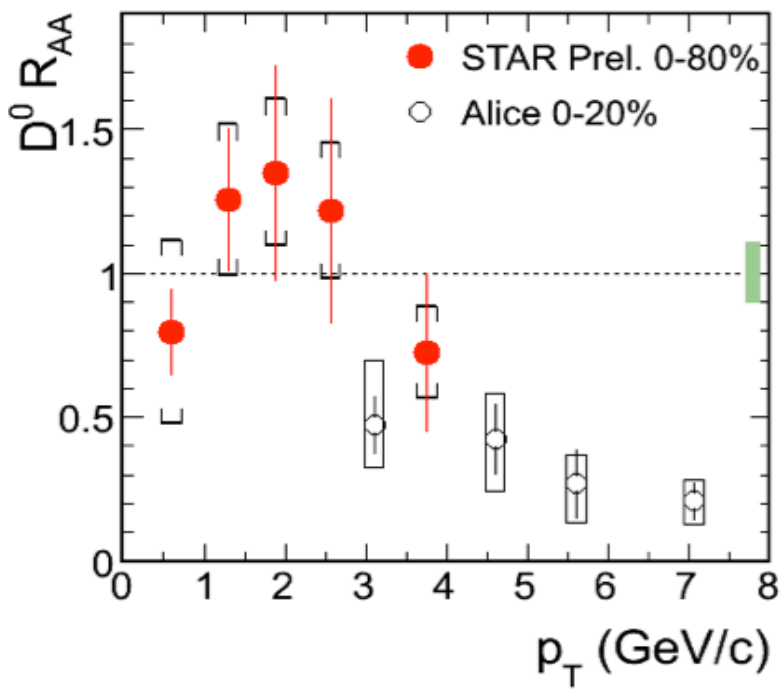
Open charm hadrons – Probe the sQGP properties





Low p_T: interacting with bulk medium – test medium thermalization

High p_T: parton energy loss mechanism in sQGP

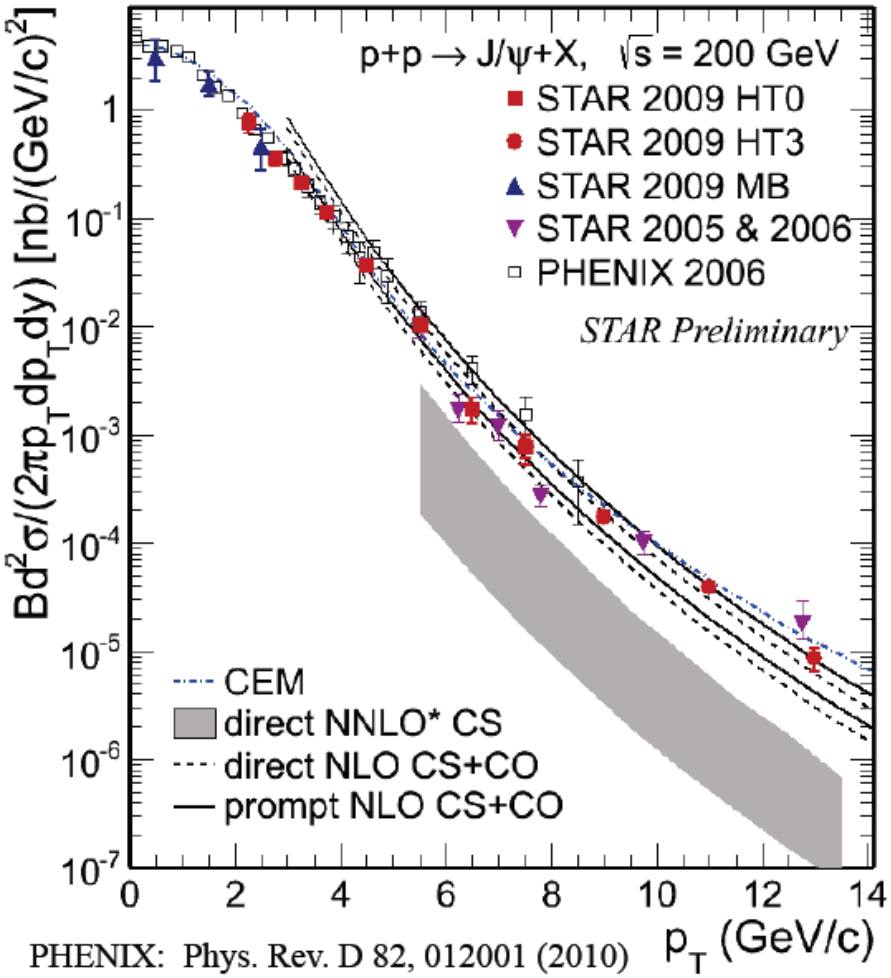


- Charm hadron production cross section in p+p collisions is consistent with the upper bound of FONLL pQCD calculation.
- Charm cross section in A+A collisions approximately follows N_{bin} scaling.

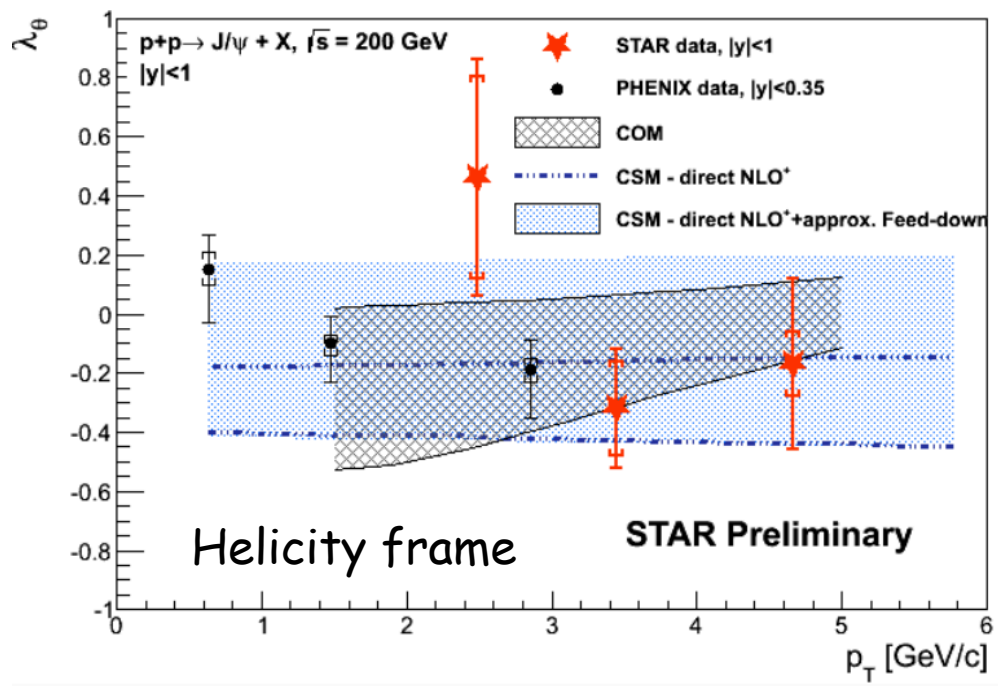
  Charm created from initial hard scatterings.

Slide provided by STAR – The speaker thanks Xin Dong!

J/ψ production mechanism in hadron collisions



PHENIX: Phys. Rev. D 82, 012001 (2010)
STAR: Phys. Rev. C80, 041902(R) (2009)



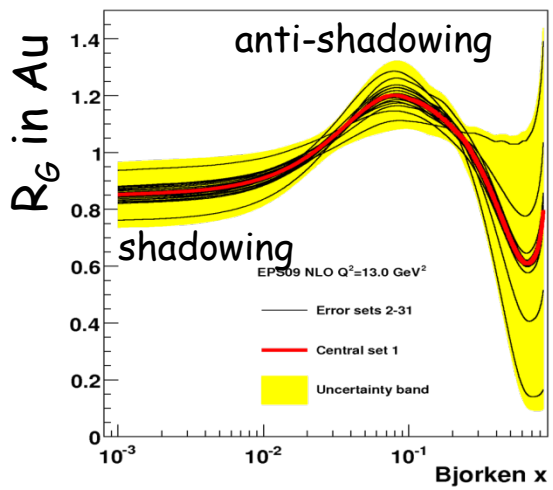
A wide range of p_T coverage
Multi observables:
cross section, polarization

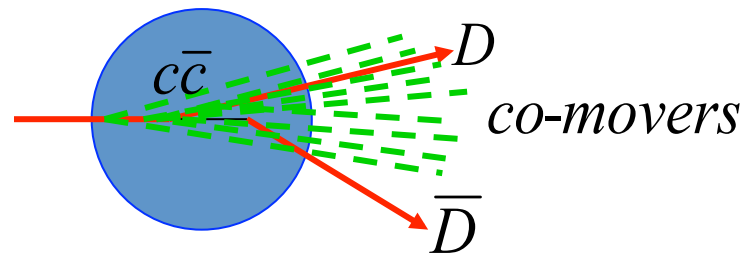
Constrain the production mechanism in hadron collisions

Note again the advantage of STAR showing the value of complementary detectors! D.I.

What are the CNM effects that are so strong in Quarkonia production?

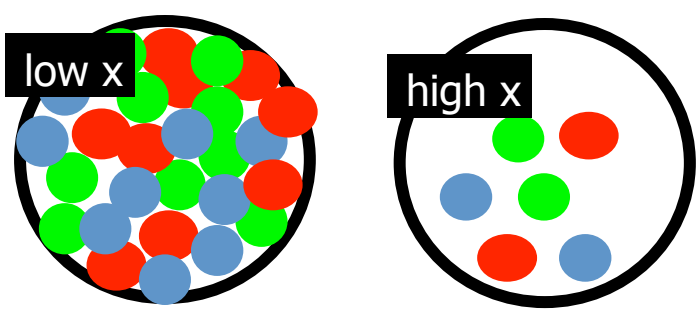
Traditional shadowing from fits to DIS or from coherence models



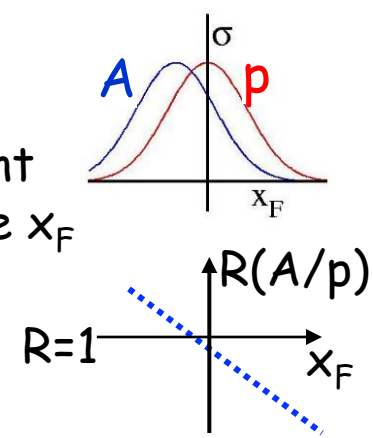


Absorption (or dissociation) of $c\bar{c}$ into two D mesons by nucleus or co-movers

Gluon saturation from non-linear gluon interactions for the high density at small x - Amplified in a nucleus.



Energy loss of incident gluon shifts effective x_F and produces nuclear suppression which increases with x_F

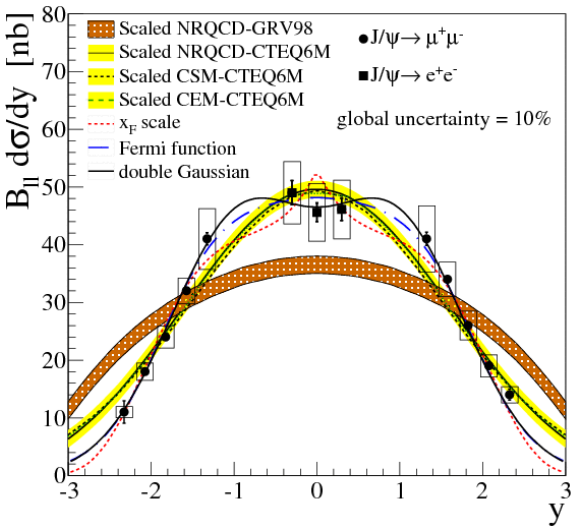


Production mechanism uncertainty - underlies everything else

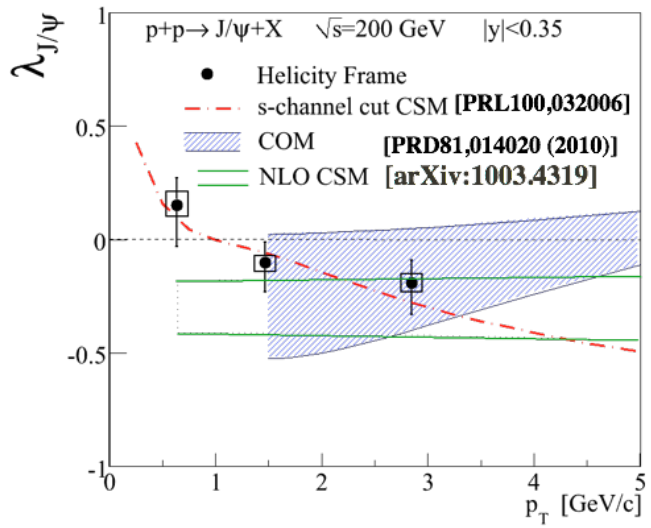
- What kind of state is the precursor heavy-quark pair that eventually forms a quarkonia; this effects how it interacts with the media
- What happens to other charmonium states & how much feeddown do they give to the J/ψ

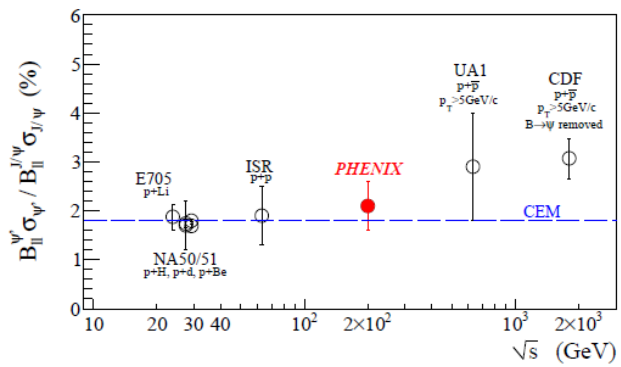
Feedown fractions from PHENIX for 200 GeV, y=0

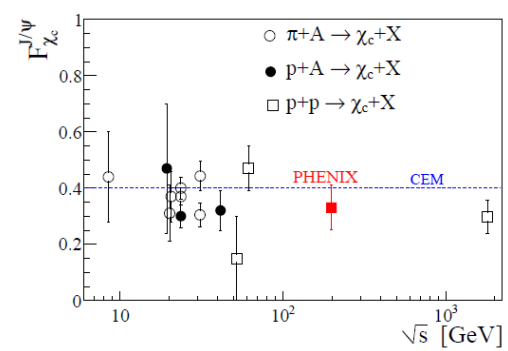
- *arXiv:1105.1966*: 9.6 ± 2.4% (ψ'), 32 ± 9% (χ_c)



[PRD82,012001 (2010)]







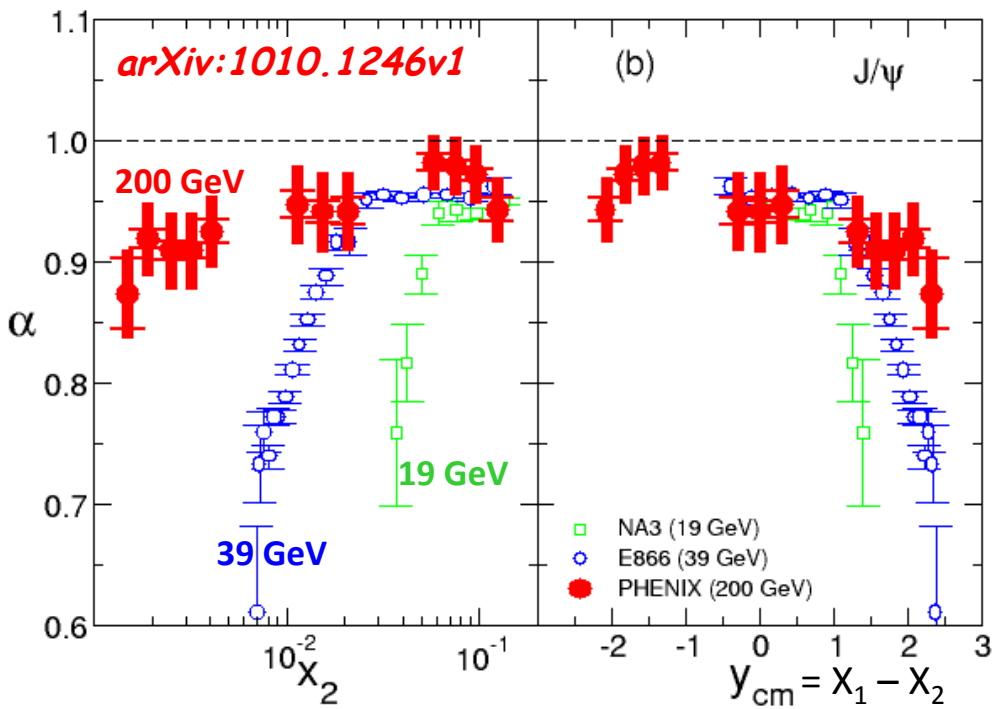
What are the CNM effects that are so strong in Quarkonia production?

Scaling between measurements at different Energies

PHENIX, E866, NA3 Comparison

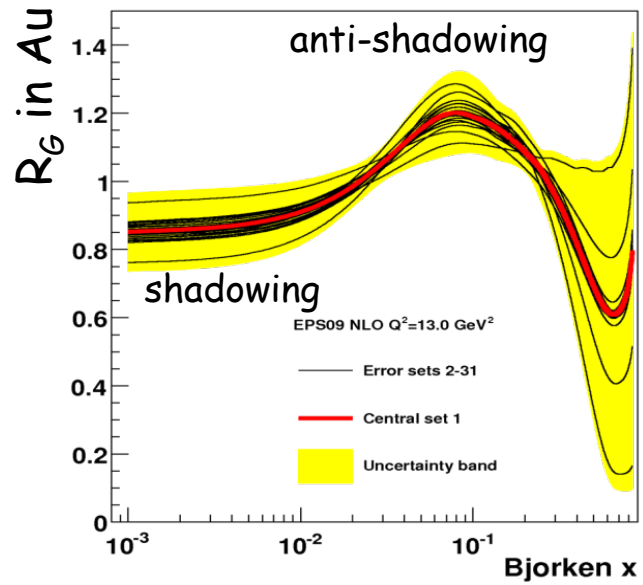
$$\sigma_{pA} = \sigma_{pp} A^{\alpha}$$

J/ψ α for different √s collisions
E866 p+A & lower-energy NA3 at CERN



(x_2 is x in the nucleus)

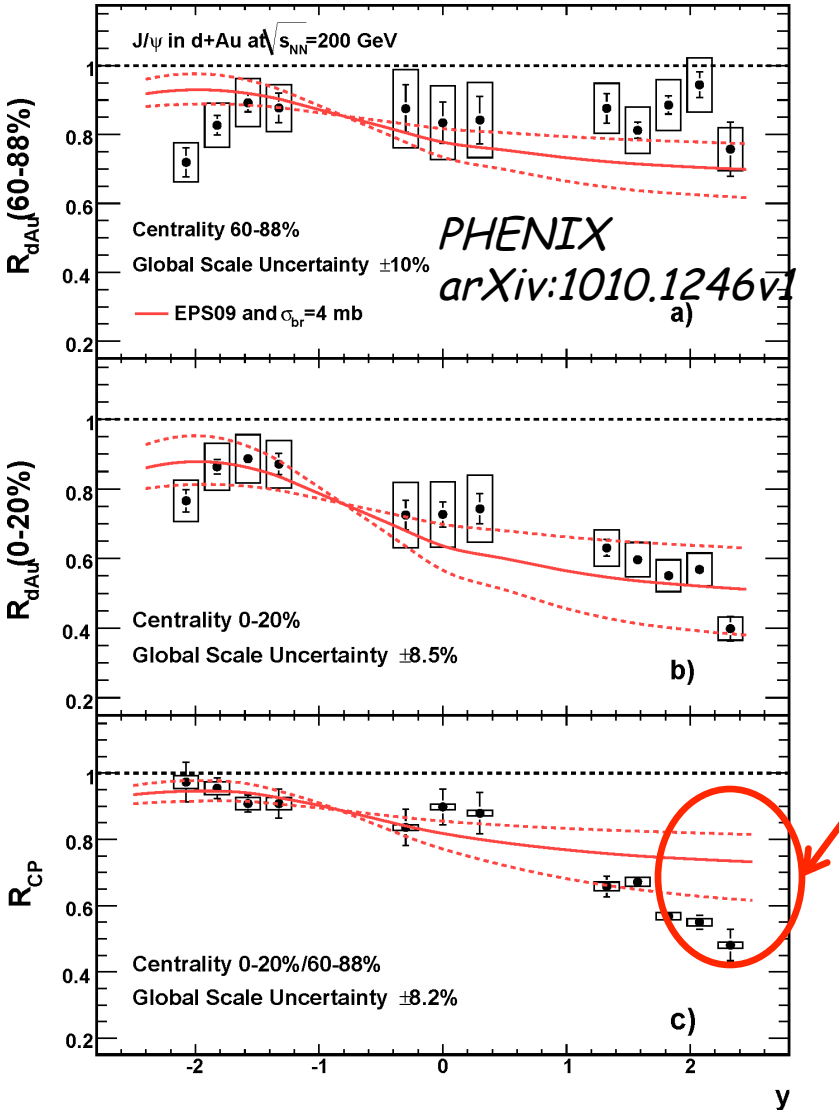
Suppression not universal vs x_2 as expected for shadowing



Closer to scaling with x_F or rapidity
- initial-state gluon energy loss?
- or gluon saturation?

What are the CNM effects that are so strong in Quarkonia production?

J/ψ in d+Au – learning about CNM thickness dependence

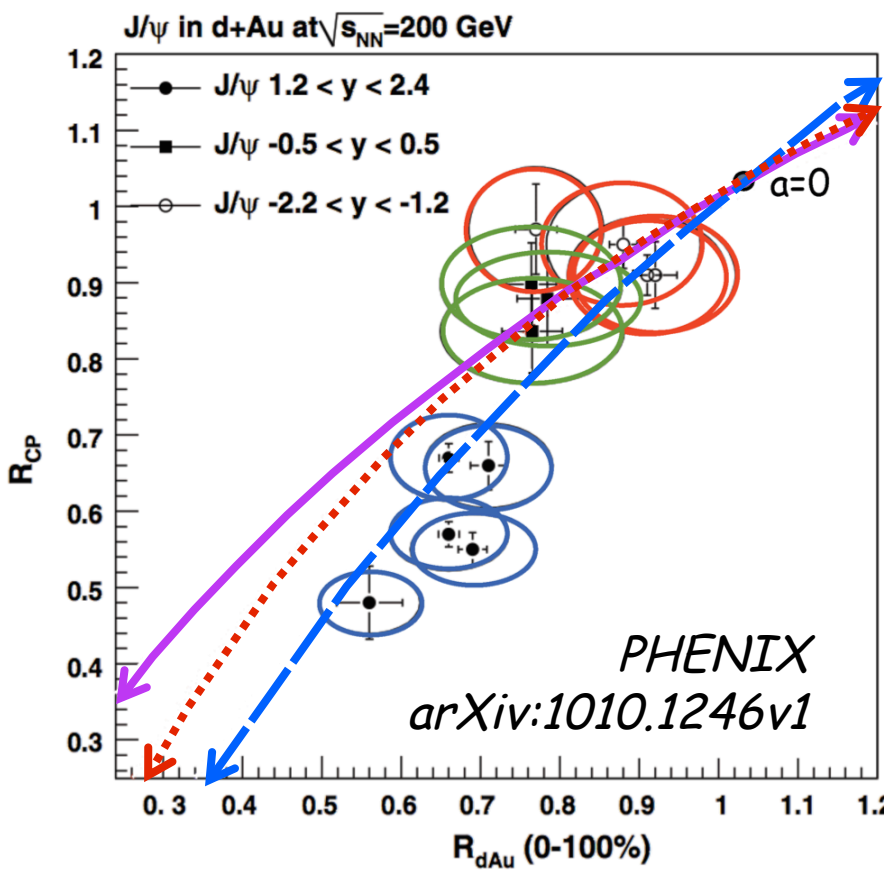


Reasonable agreement with EPS09 nPDF + σ_{br}=4 mb for central collisions but not peripheral

EPS09 with linear thickness dependence fails to describe centrality dependence of forward rapidity region.

What are the CNM effects that are so strong in Quarkonia production?

J/ψ in d+Au – learning about CNM thickness dependence



Vary the strength of suppression (a) & see what relationship between R_{dAu} and R_{CP} is given strictly by Glauber geometry for different dependences on density-weighted thickness

$$\Lambda(r_T) = \frac{1}{\rho_0}\int dz\rho(z, r_T)$$

Woods-Saxon

$$\text{Exponential}: \; M(r_T) = e^{-a\Lambda(r_T)}$$

$$\text{Linear}: \; M(r_T) = 1 - a\Lambda(r_T)$$

$$\text{Quadratic}: \; M(r_T) = 1 - a\Lambda(r_T)^2$$

- Break-up has exponential dependence
- EPS09 & initial-state dE/dx have unknown dependences

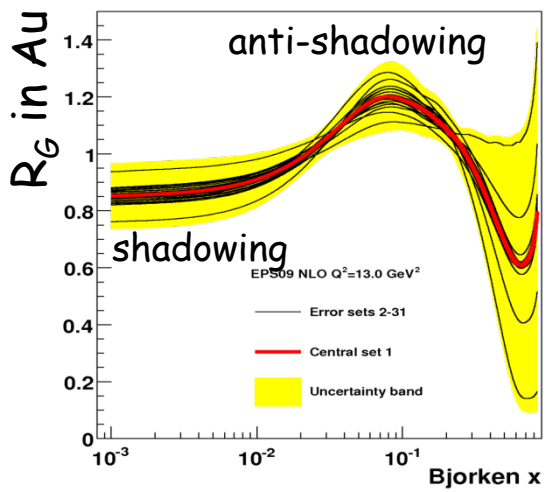
The forward rapidity points suggests a quadratic or higher geometrical dependence

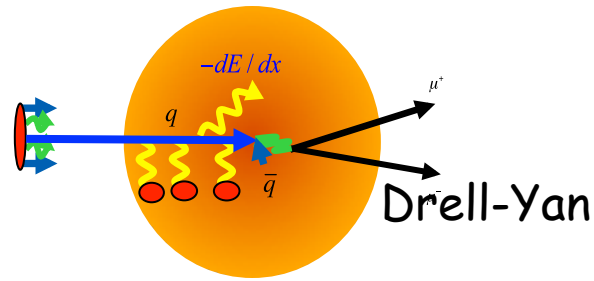
What are the CNM effects that are so strong in Quarkonia production?

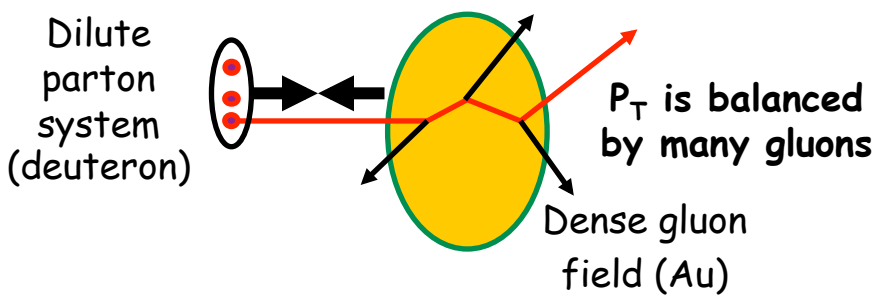
The various CNM effects are difficult to disentangle experimentally – multiple probes, types & energies of collisions, wide kinematic coverage are key

- open-heavy suppression – isolates initial-state effects
- other probes of shadowing & gluon saturation – forward hadrons, etc.
- Drell-Yan to constrain parton energy loss in CNM

And strong theoretical guidance & analysis – not just for certain measurements but for the ensemble of measurements







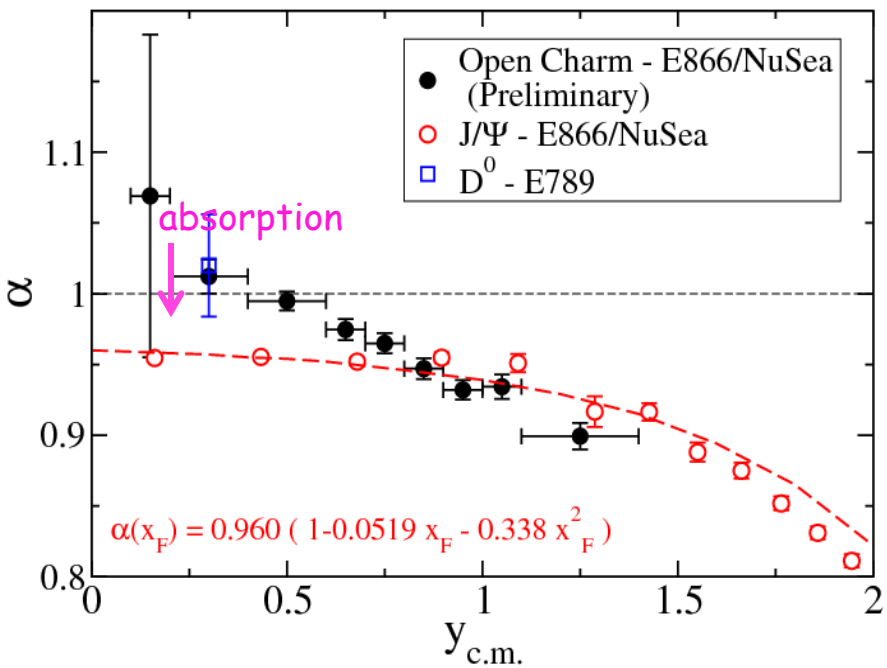
What are the CNM effects that are so strong in Quarkonia production?

Open-heavy suppression – Isolates initial-state effects

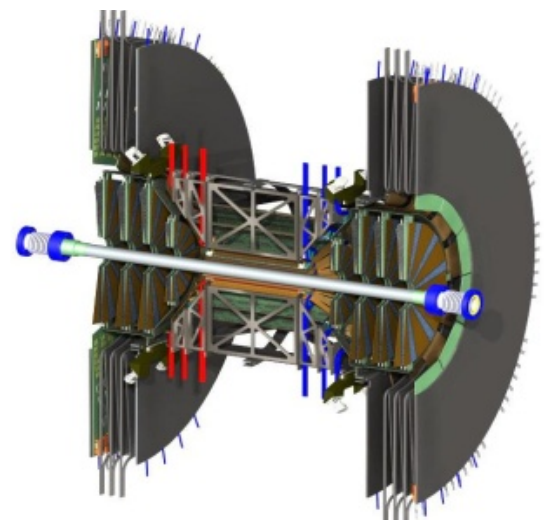
Open-charm p+A nuclear dependence (single-μ p_T > 1 GeV/c) – very similar to that of J/Ψ (E866/NuSea, 39 GeV):

- implies that dominant effects are in the initial state
  - e.g. dE/dx

$$\sigma_{pA} = \sigma_{pp} A^{\alpha}$$

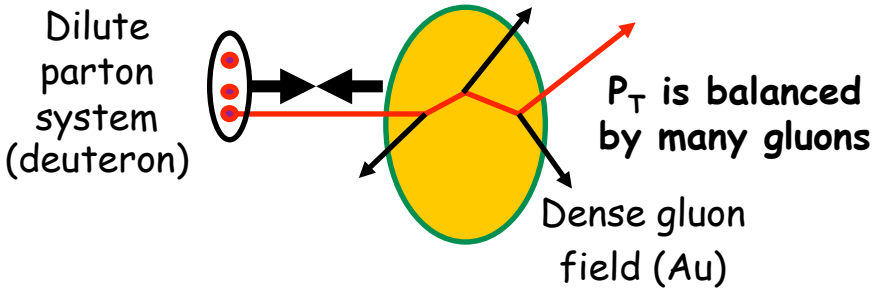


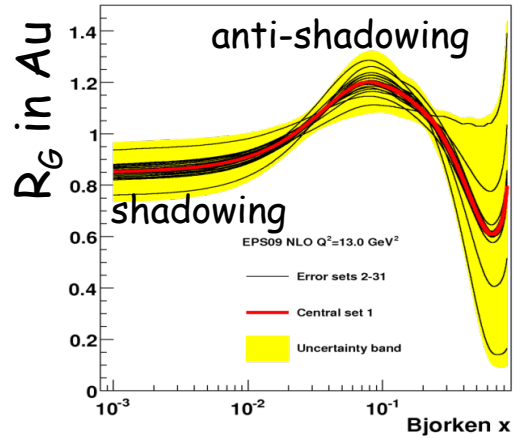
Soon new PHENIX c,b measurements with VTX/FVTX to isolate initial & final-state effects via precision comparisons with Quarkonia (and later STAR HFT)



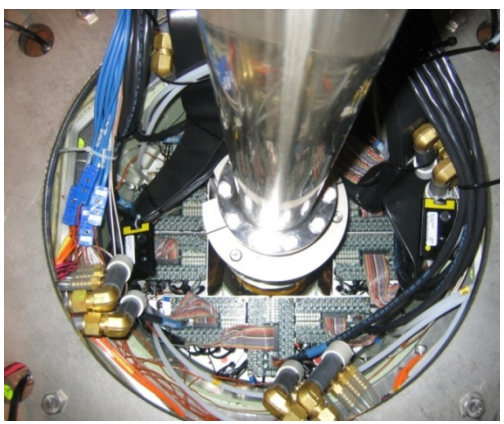
What are the CNM effects that are so strong in Quarkonia production?

Other probes of shadowing & gluon saturation – Forward hadrons

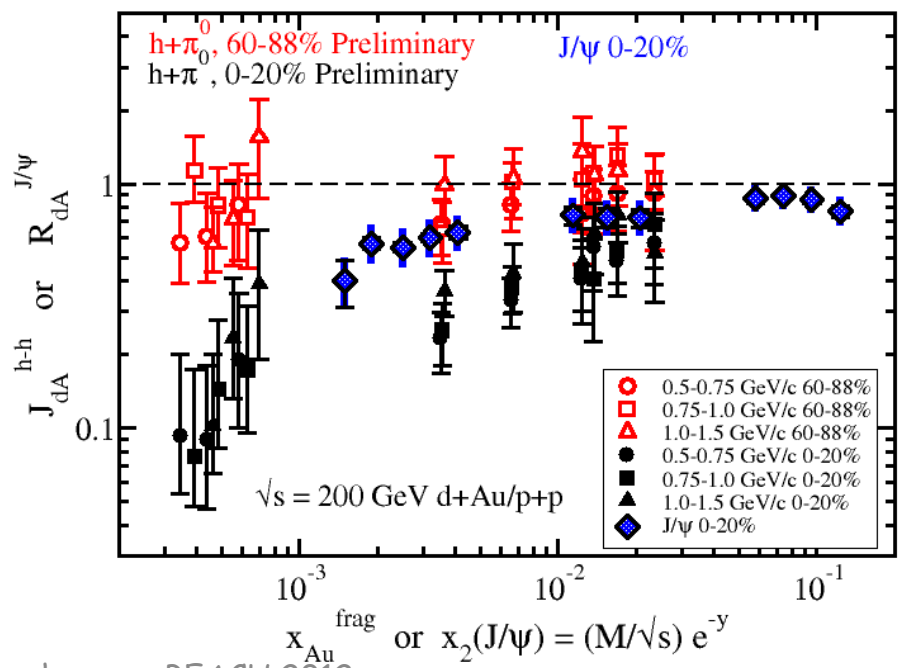




Mono-jets in the gluon saturation (CGC) picture give suppression of pairs per trigger and some broadening of correlation
Kharzeev, NPA 748, 727 (2005)



PHENIX MPC

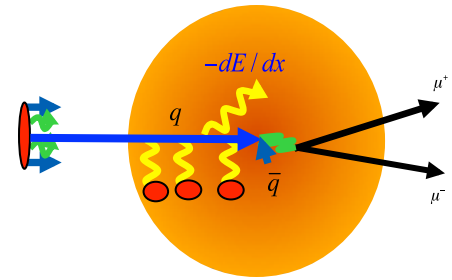


What are the CNM effects that are so strong in Quarkonia production?

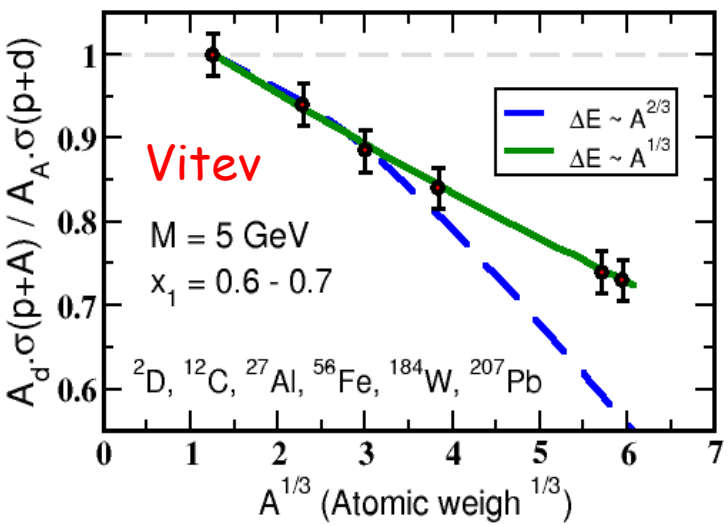
Drell-Yan to constrain parton energy loss in CNM

FNAL E906/SeaQuest – Drell Yan

Drell-Yan

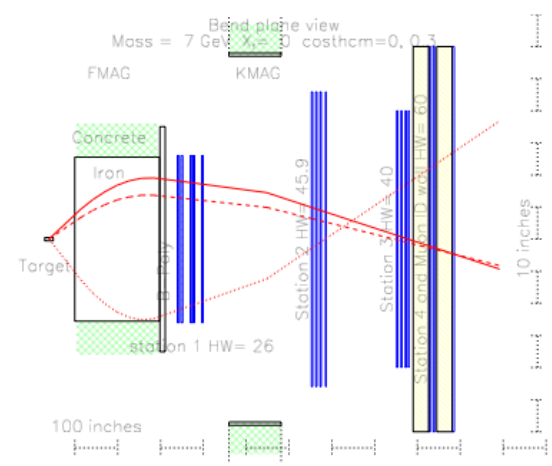


In SeaQuest at 120 GeV, nuclear suppression in Drell-Yan should only be from dE/dx (x_2 > 0.1)



$$\frac{\Delta E}{E} \propto \frac{\mu^2 L^2}{\lambda_g} \frac{\ln E/Q_0}{E}$$

$$\frac{\Delta E}{E} \propto \frac{L}{\lambda_g} \ln \frac{E}{Q_0}$$



SeaQuest, not drawn to scale.

- Distinguish radiative from collisional (L^2 vs L)
- then "extrapolate with theory" to energy loss of gluons for quarkonia production

First SeaQuest data taken in 2012

<u>Whoa!</u>
Seems like a digression is needed here.

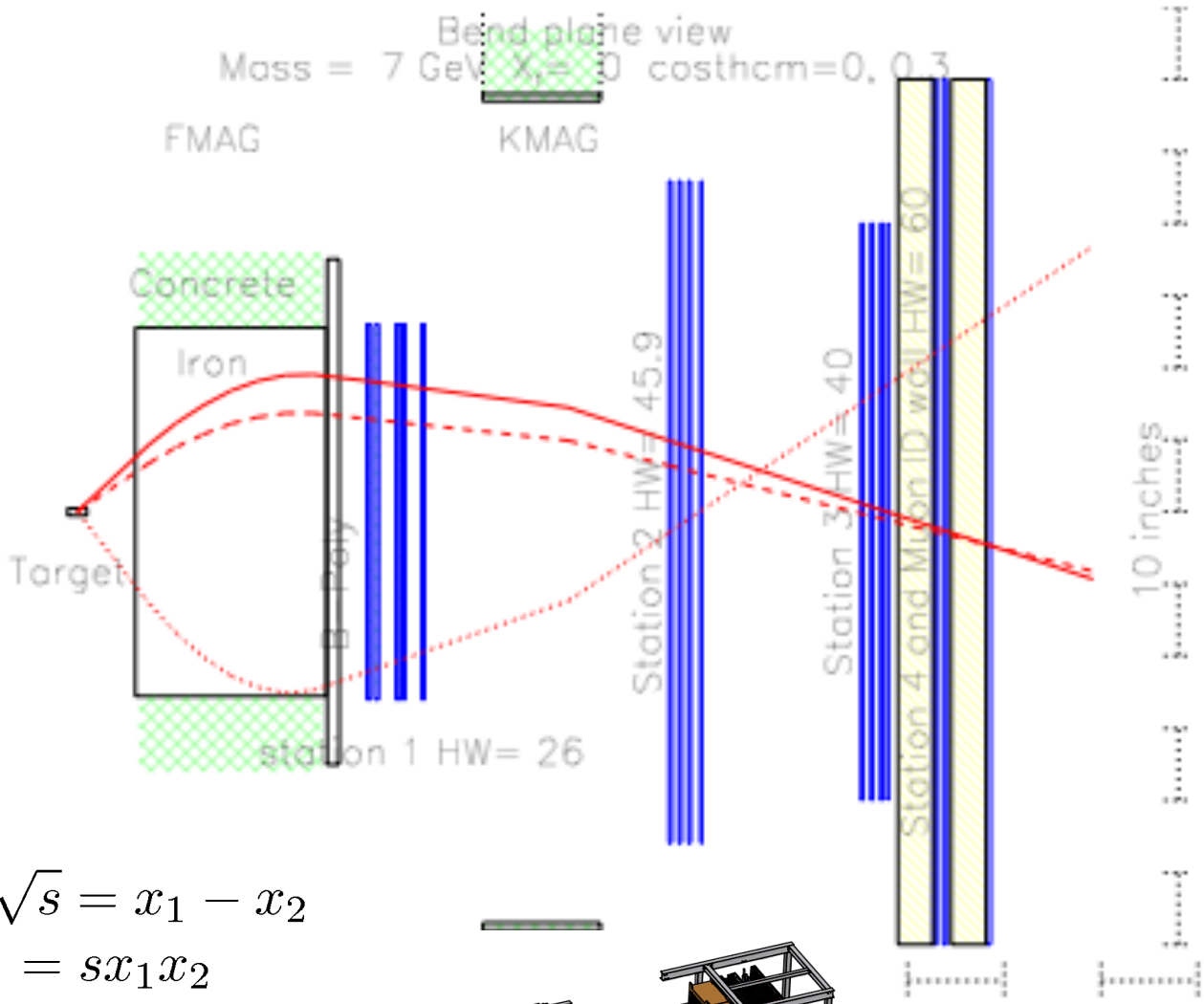
OK, I've spent a long time getting ready to run Fermilab SeaQuest, so I'm biased.

If we are going to study quarkonia in Heavy Ions,
then we need to know something about them in a "simple" nucleon.

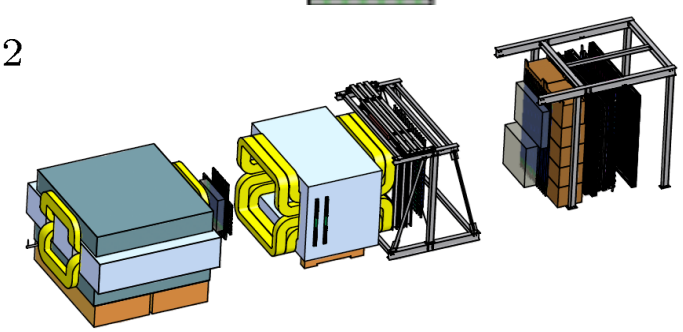
Fermilab E772 and E866/NuSea dealt with this topic.

Following slides show what those experiments found,
and what SeaQuest (Fermilab E906) will provide.

SeaQuest: Solid Fe + Open Magnet Spectrometer (not to scale)



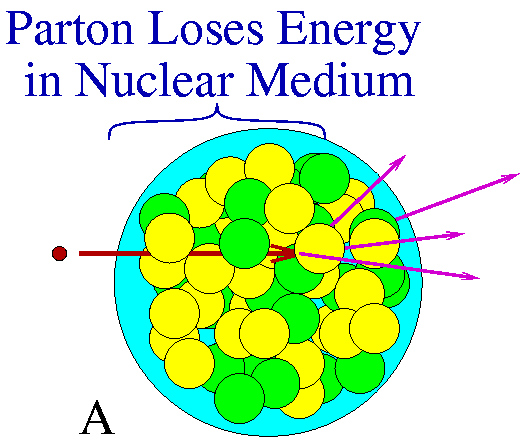
$$x_F \approx 2p_L/\sqrt{s} = x_1 - x_2$$
$$M^2_{\mu^+\mu^-} = s x_1 x_2$$

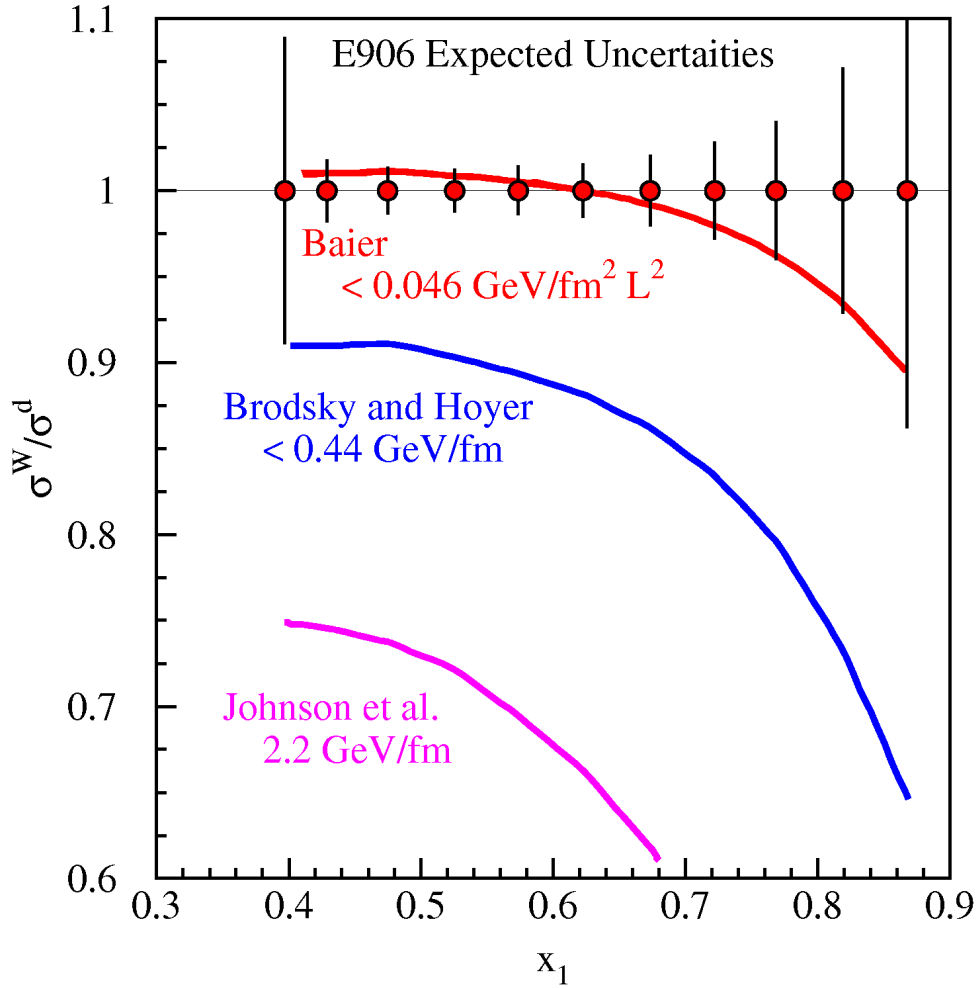


Detector is in place in NM4, old KTeV hall.

SeaQuest has finished commissioning run.

Parton Energy Loss





- Colored parton moving in strongly interacting media.
- Only initial state interactions are important—*no final state strong interactions*.

- Important to understand HI data.

Structure of the nucleon: What is d-bar/u-bar in the proton?

Why?

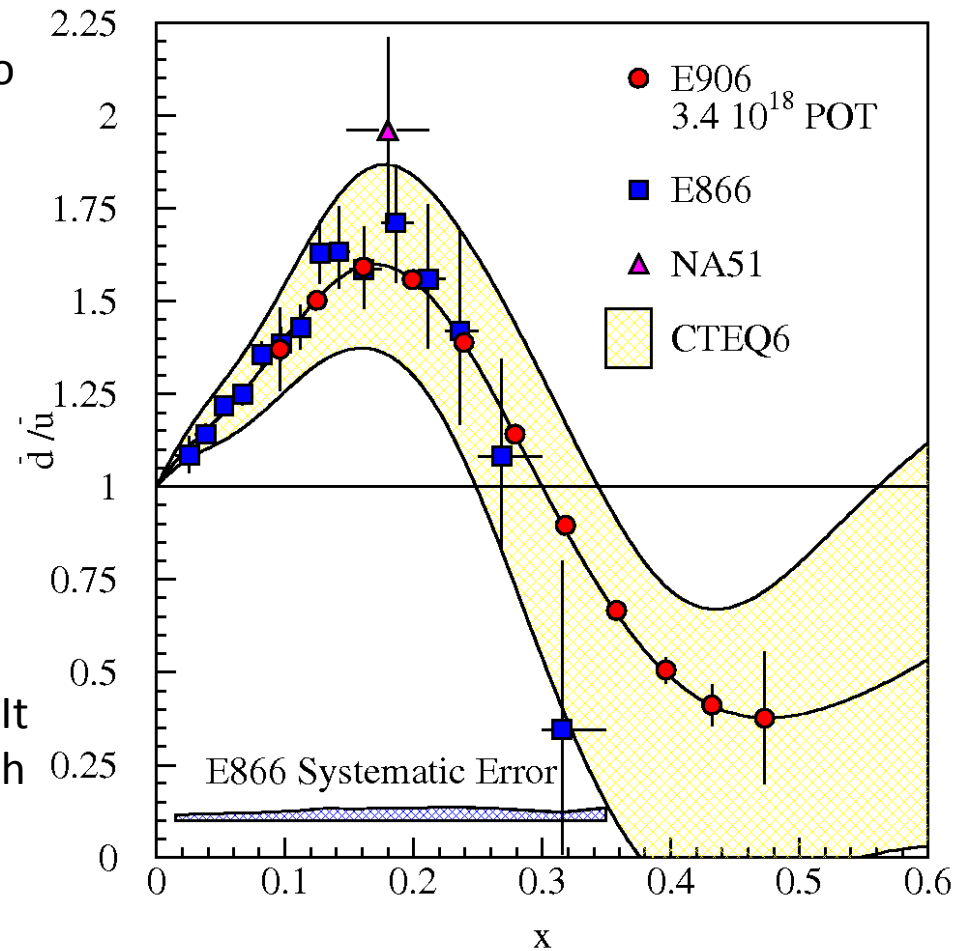
Parton Distributions

- Study ratio of cross sections for deuterium to hydrogen

$$\left.\frac{\sigma^{pd}}{2\sigma^{pp}}\right|_{x_b \gg x_t} \approx \frac{1}{2}\left[1 + \frac{\bar{d}(x_t)}{\bar{u}(x_t)}\right]$$

(In analysis, we use a full Next-to-Leading order cross section calculation with both terms)

- PDF fits are and uncertainties completely dominated by E866.
- E906 will significantly extend these measurements and improve on uncertainty. It uses 120 GeV Fermilab Main Injector to reach higher x region.



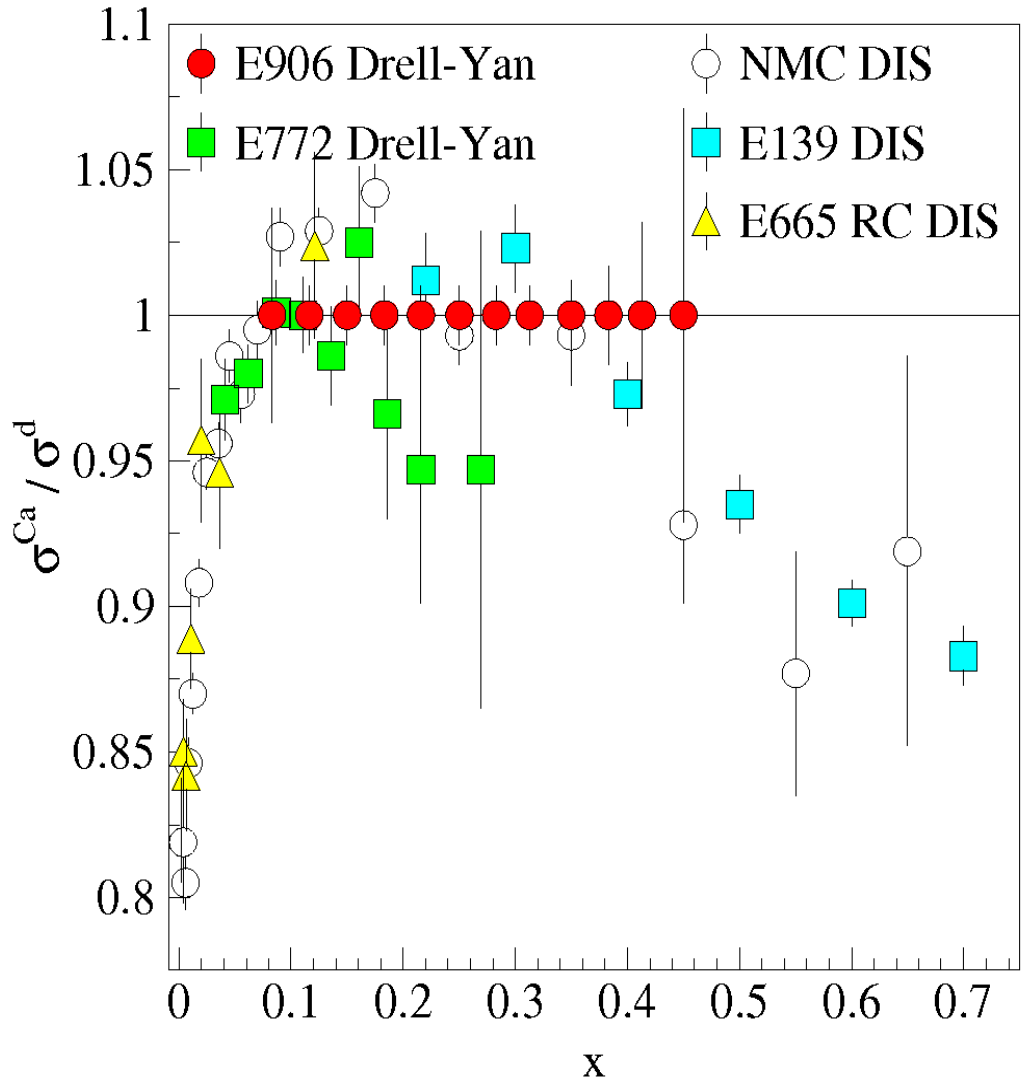
Impact

- Collider/LHC sensitivity for tests of the Standard Model—Background.
- Origins of the Proton Sea—Models explain d-bar > u-bar. No theory (model) expects the results seen for x > 0.3.

Structure of nucleonic matter: How do sea quark distributions differ in a nucleus?

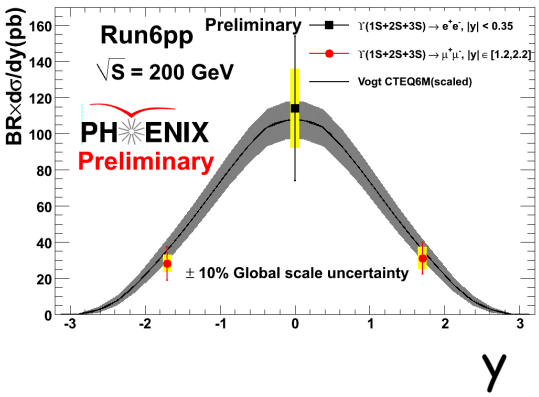
Comparison with Deep Inelastic Scattering (DIS)

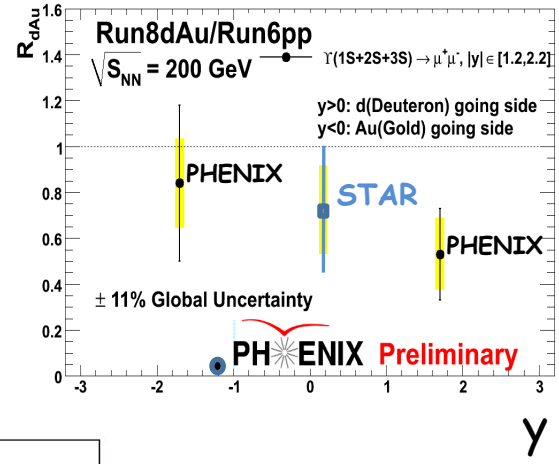
- Antishadowing not seen in Drell-Yan—Valence only effect?—better statistical precision needed, thus SeaQuest (E906).
- Intermediate-*x sea* PDF's set by ν-DIS on iron—unknown nuclear effects.
- If we are going to understand quark production in a collisions of nucleons, it would seem like a good idea to understand its light quark structure.

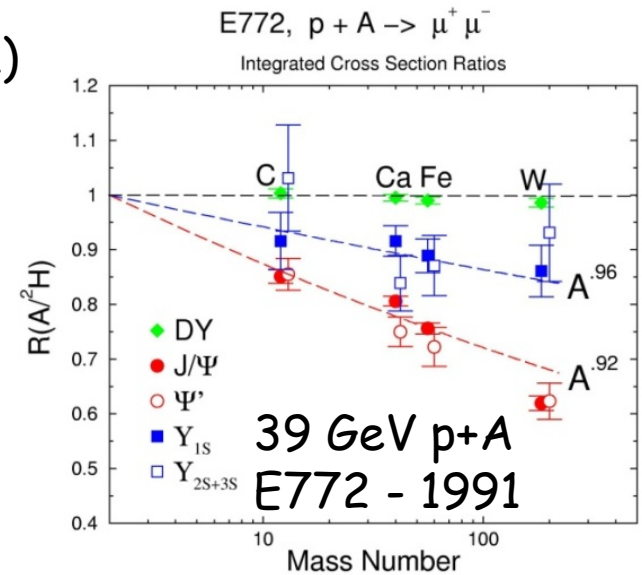


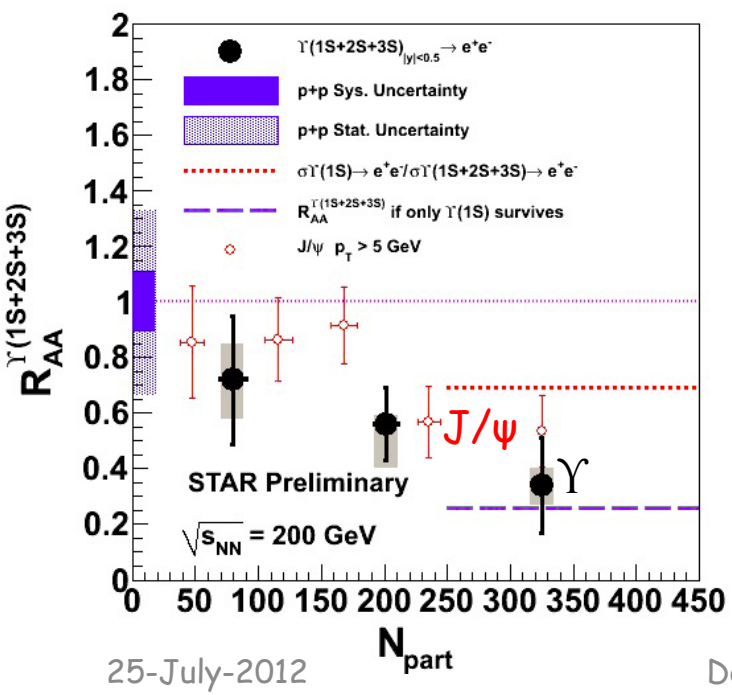
Heavier Quarkonia - Upsilons

Upsilons suppressed in CNM at RHIC (& at FNAL)





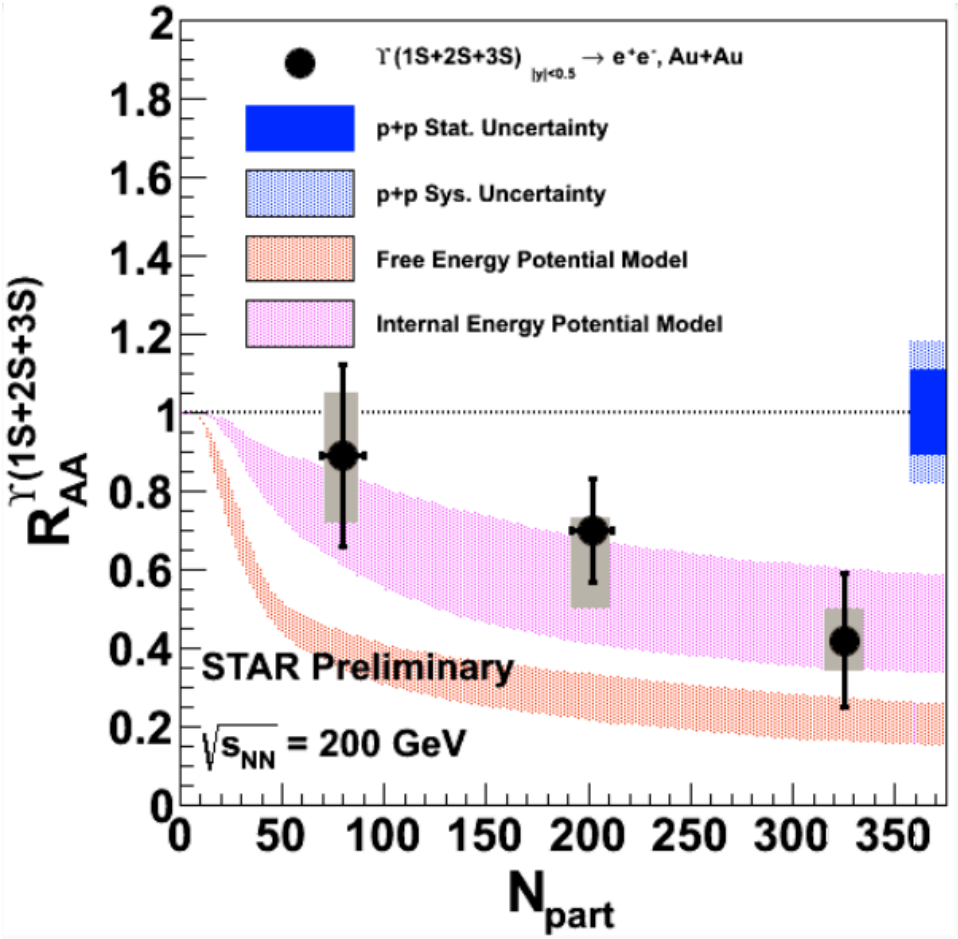


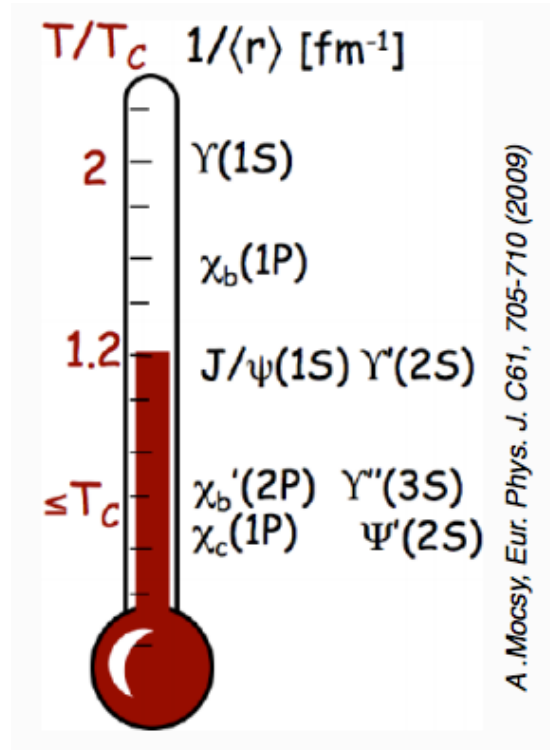


Upsilon suppression in Au+Au at RHIC – watch out for CNM suppression (as usual)!

Slide provided by STAR – The speaker thanks Xin Dong!

Upsilon production in the heavy ion collisions

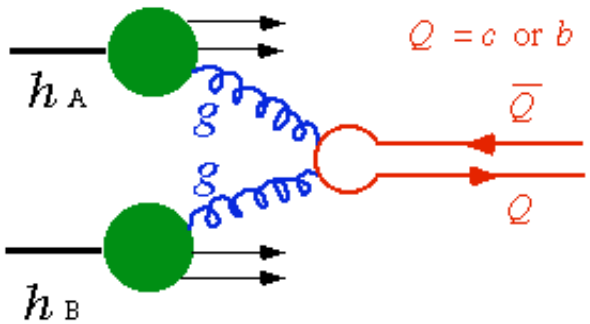




- Upsilons – cleaner probe to the sQGP
  - cold nuclear absorption and recombination from sQGP are small.
- R_{AA} of Upsilon(1S+2S+3S) in central collisions is consistent with melting of all excited bottomonia states.
- Systematic studies on quarkonia suppression pattern – QGP thermometer!

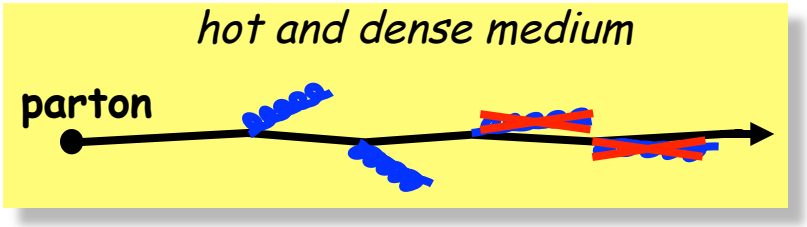
Heavy Quarks (charm and bottom)

- Produced by gluon fusion in early stages of collisions
- Experience full medium evolution



- Expected to lose less energy in medium
  - "Dead cone effect" suppresses gluon radiation at small angles $\theta < m_Q/E_Q$

Y. Dokshitzer, D. Kharzeev, PLB 519, 199 (2001), hep-ph/0106202



Expectation from dead cone:

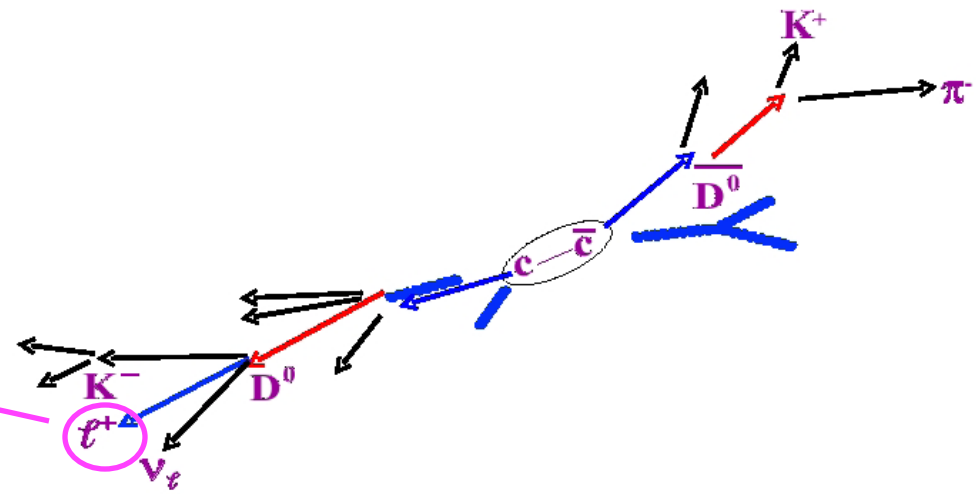
$$R_{AA}^{bottom} > R_{AA}^{charm} > R_{AA}^{u,d}$$

Open Heavy Flavor at RHIC

Most measurements rely on semileptonic decays of *D, B* mesons

$$e^{\pm}_{HF} : |y| < 0.35$$

$$\mu^{\pm}_{HF} : 1.5 < y < 1.8$$



N_{coll} = 1

N_{coll} ~ 1000

p+p

PRL97, 252002 (2006)

PRD 83 (2011) 52006

PHENIX Preliminary

d+Au

PHENIX Preliminary

Cu+Cu

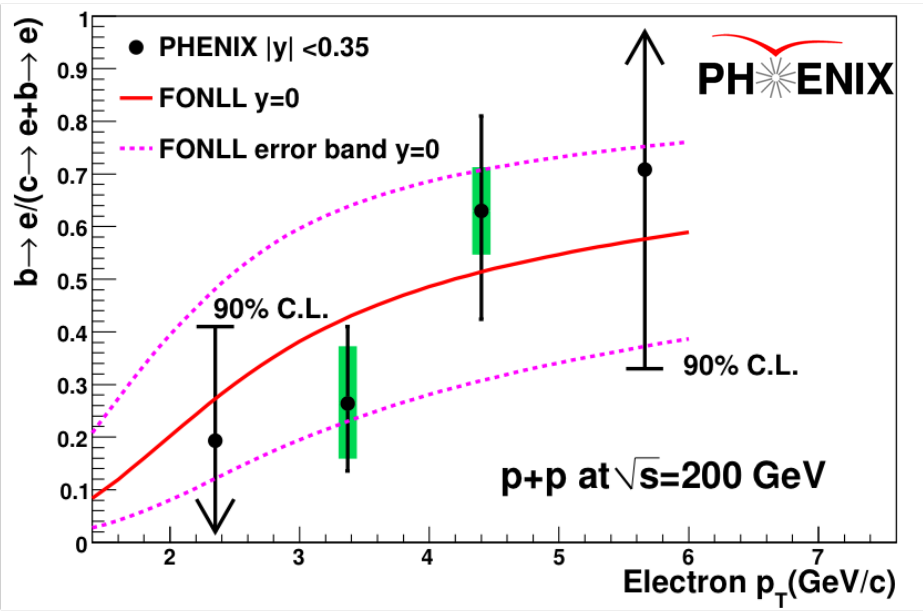
PHENIX Preliminary

Au+Au

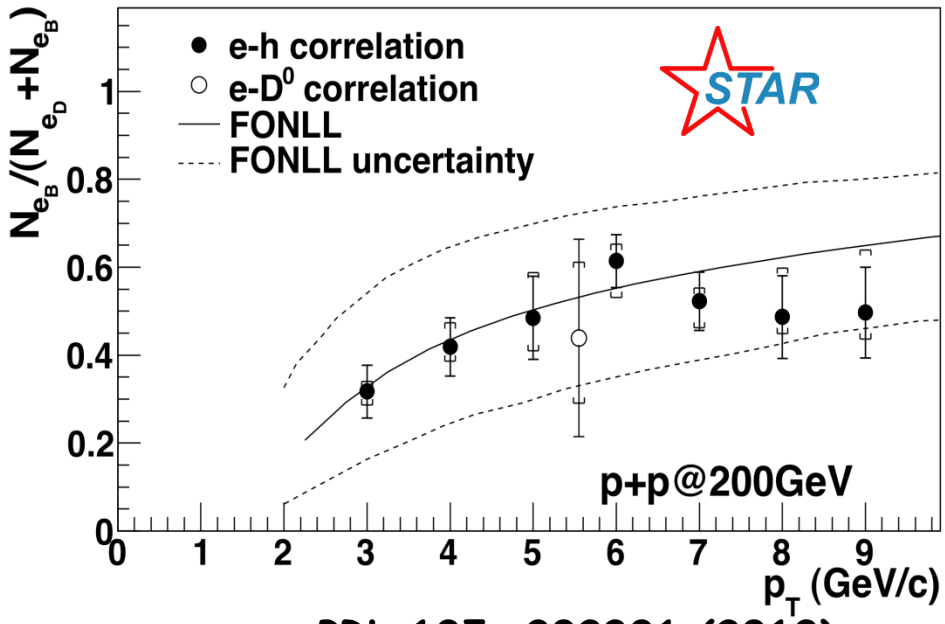
PRL 98, 172301 (2007)

PRL **98** (2007) 192301

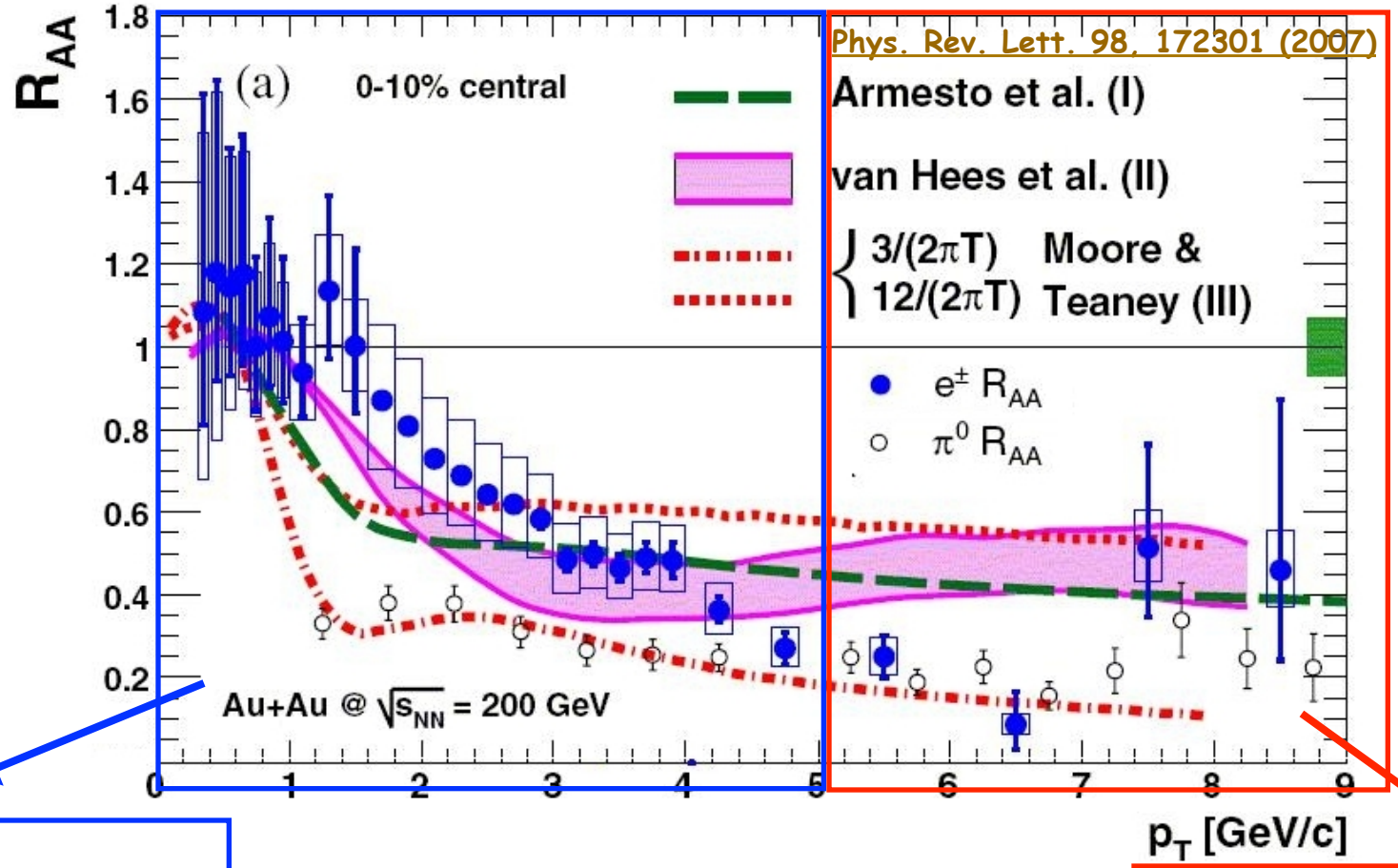
Charm/bottom Separation



PRL 103, 082002 (2009)



PRL 105, 202301 (2010)



At p_T< 5 GeV/c:

$$R_{AA}^{e^{\pm}_{HF}} > R_{AA}^{\pi^0}$$

Mostly *charm*

$$R_{AA}^{bottom} < R_{AA}^{charm}$$

Opposite of expectation

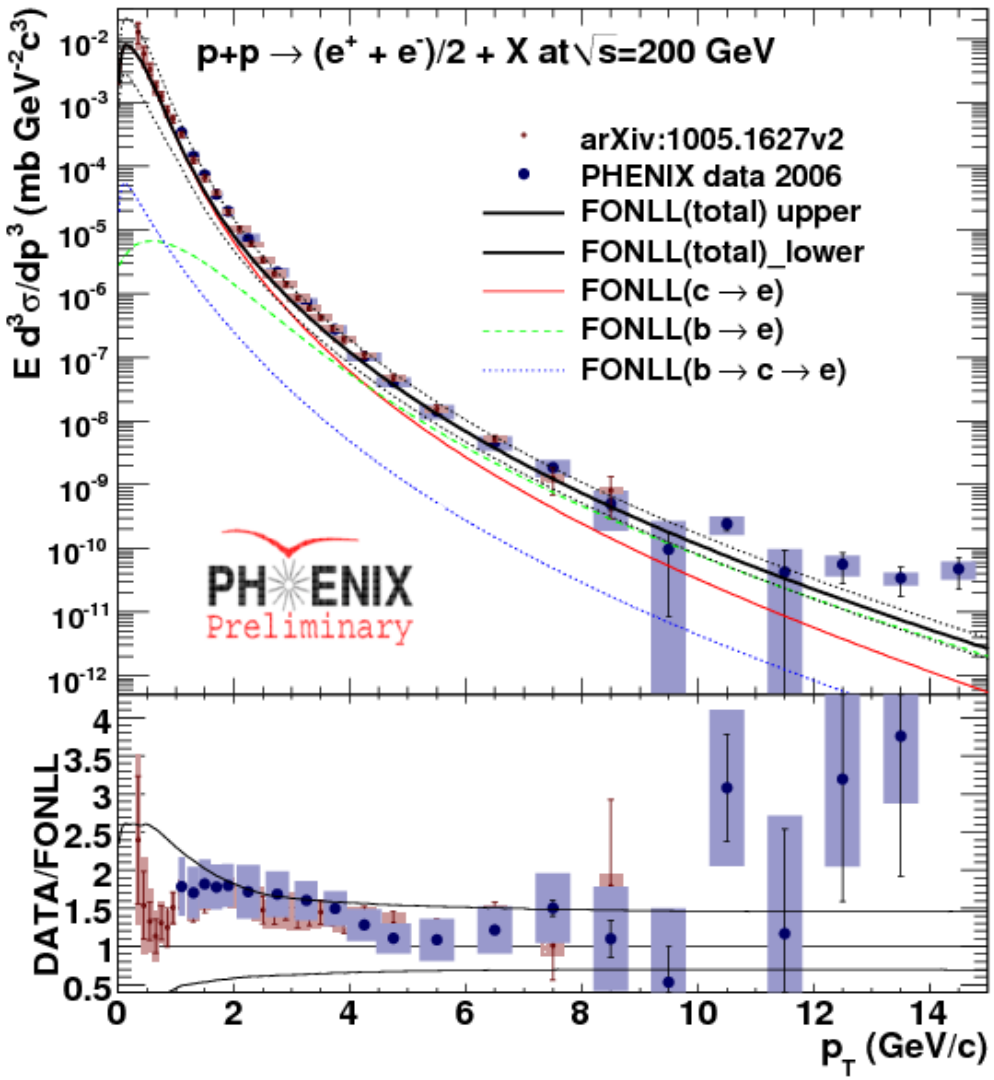
At p_T> 5 GeV/c:

$$R_{AA}^{e^{\pm}_{HF}} \approx R_{AA}^{\pi^0}$$

Mostly *bottom*

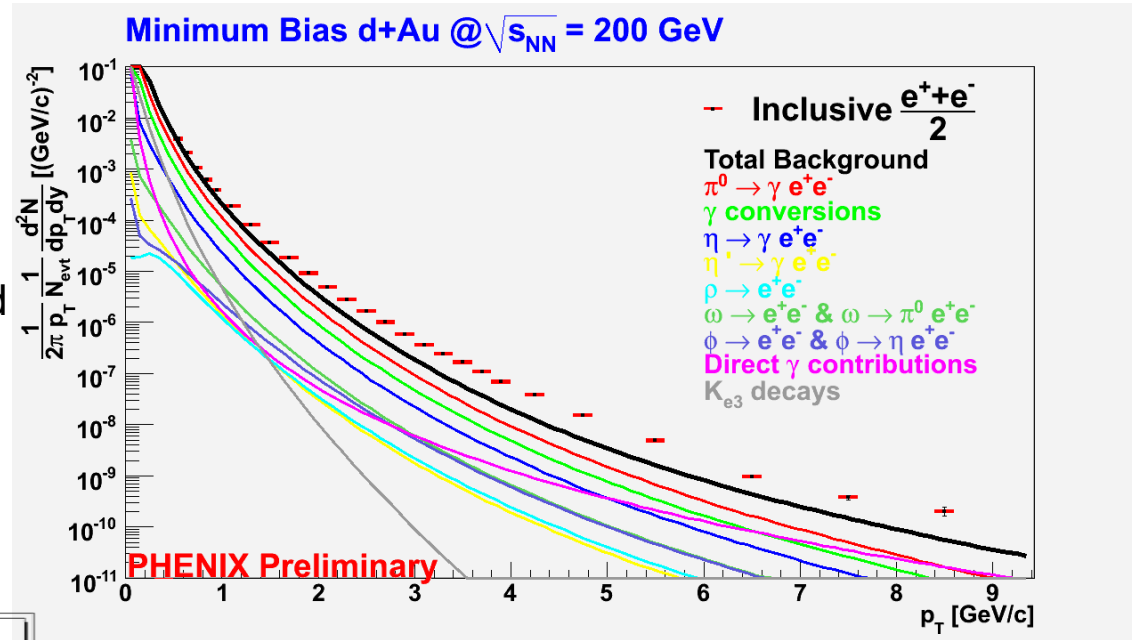
Improved p+p Baseline

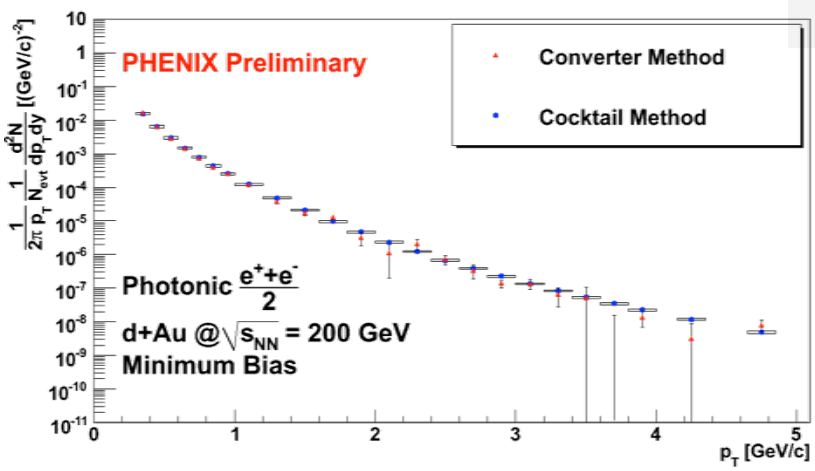
- Combined Run5 and Run6 p+p statistics
- Smaller uncertainties
  - Allows more precise R_{AA} comparisons
- Increased p_T range
- Consistent with previous results in overlap region



Run -8 *d*+Au – CNM Baseline

- Combination of background subtraction methods
  - Cocktail subtraction
  - Photonic components scaled to match converter method

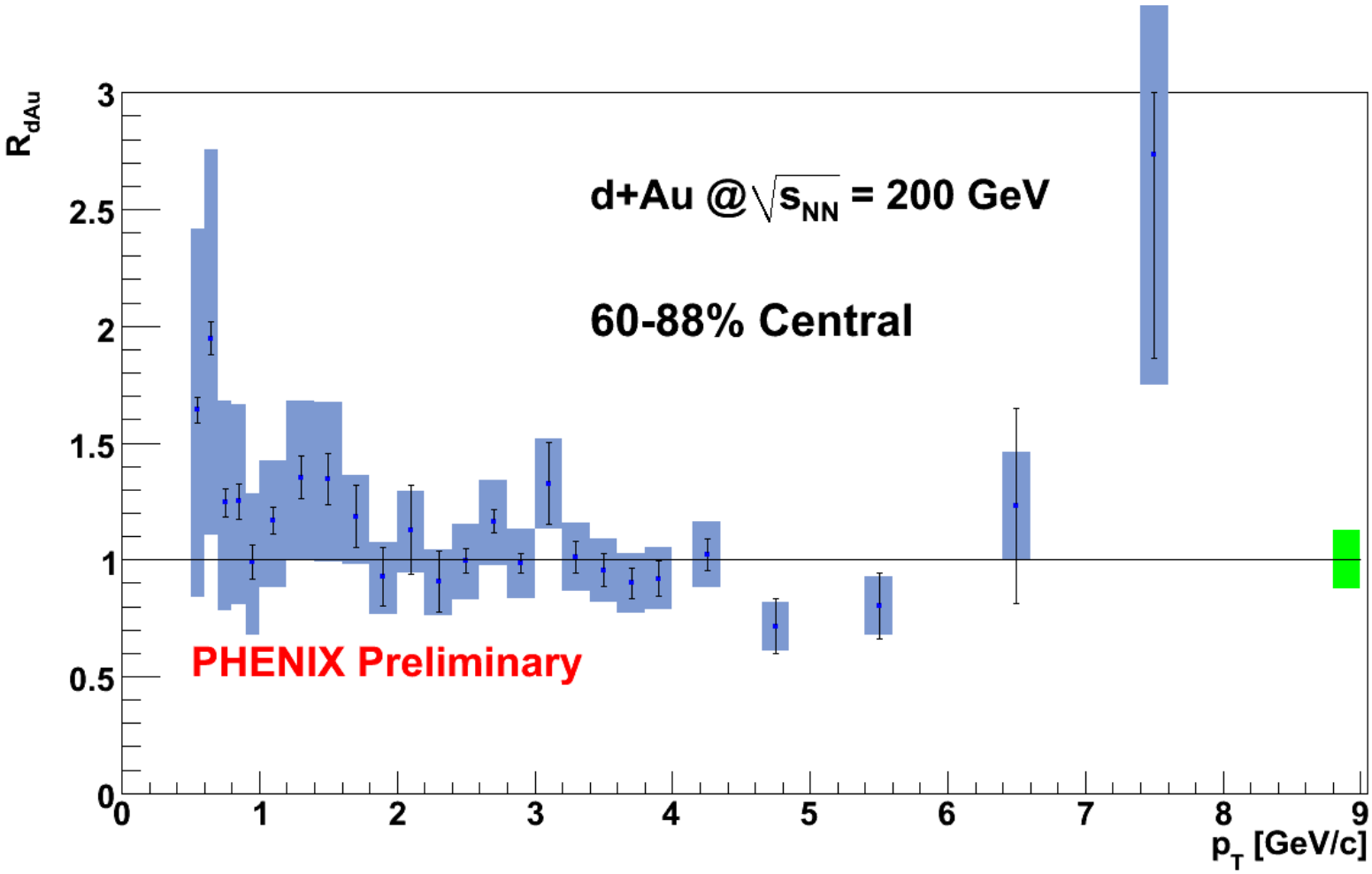




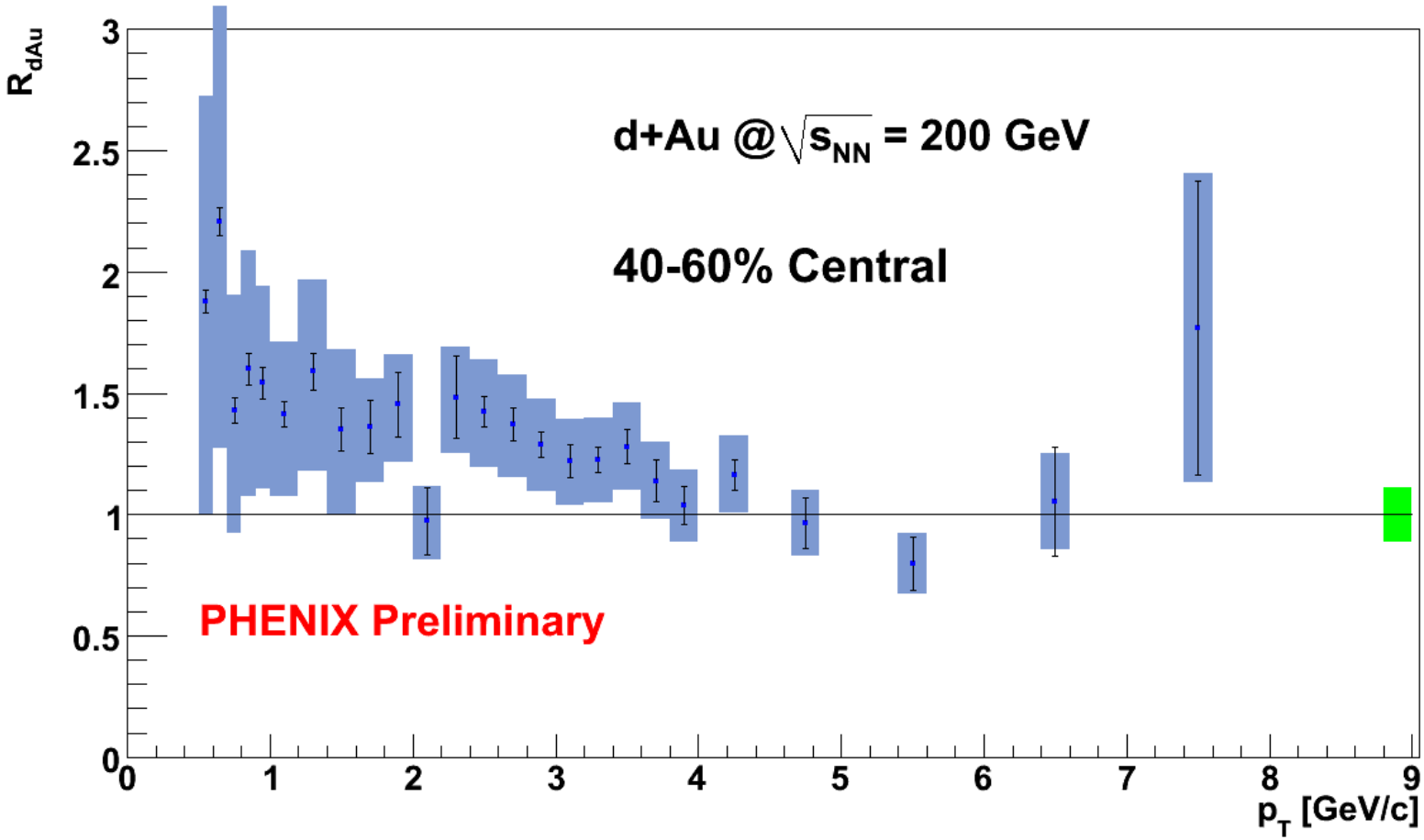
Difference in cocktail and converter photonic background ~5-10% for each centrality

Note: Cocktail is term that refers to combining different Monte Carlo packages that compensates for problems using a single one.

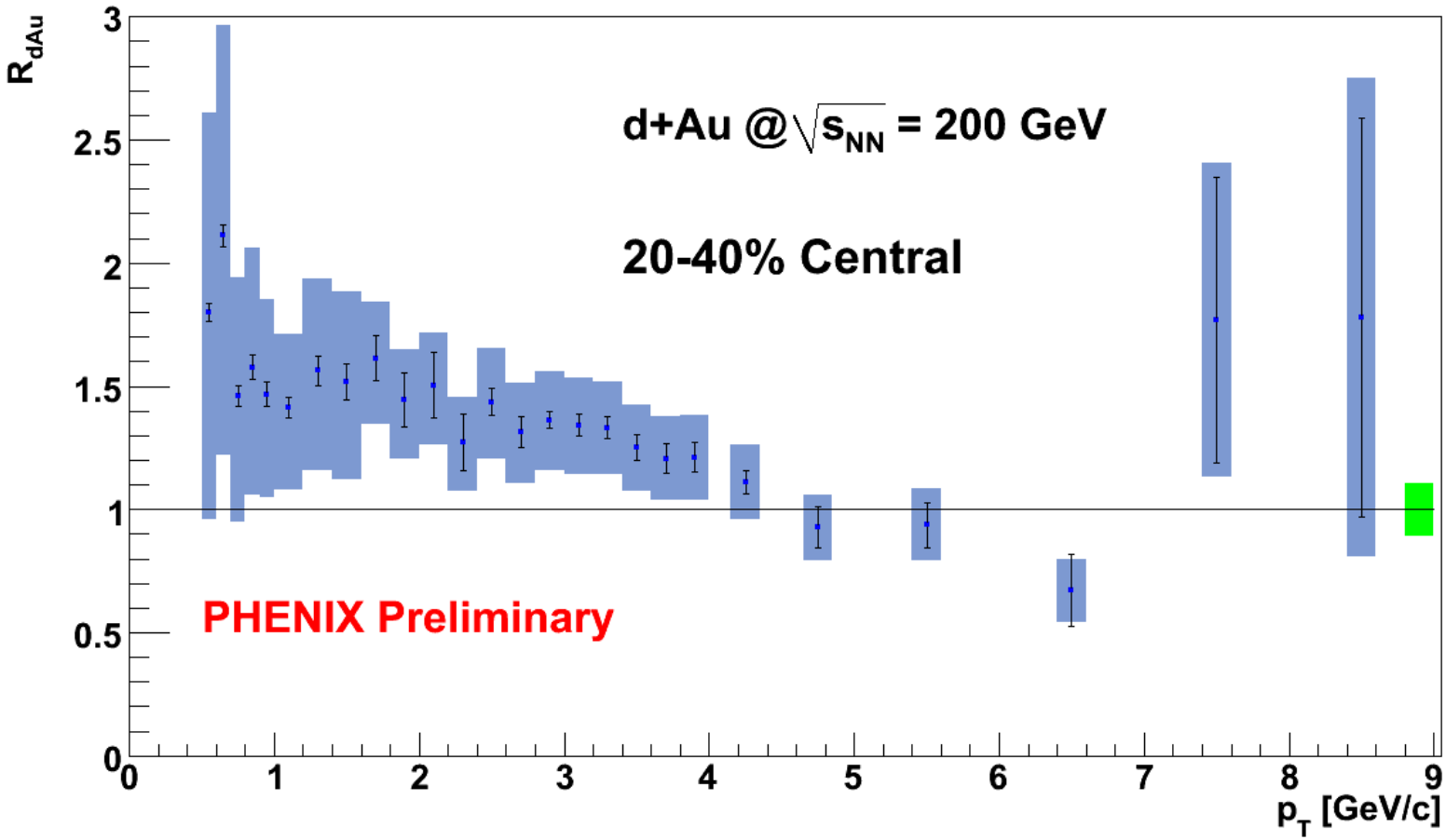
Peripheral R_{dA}



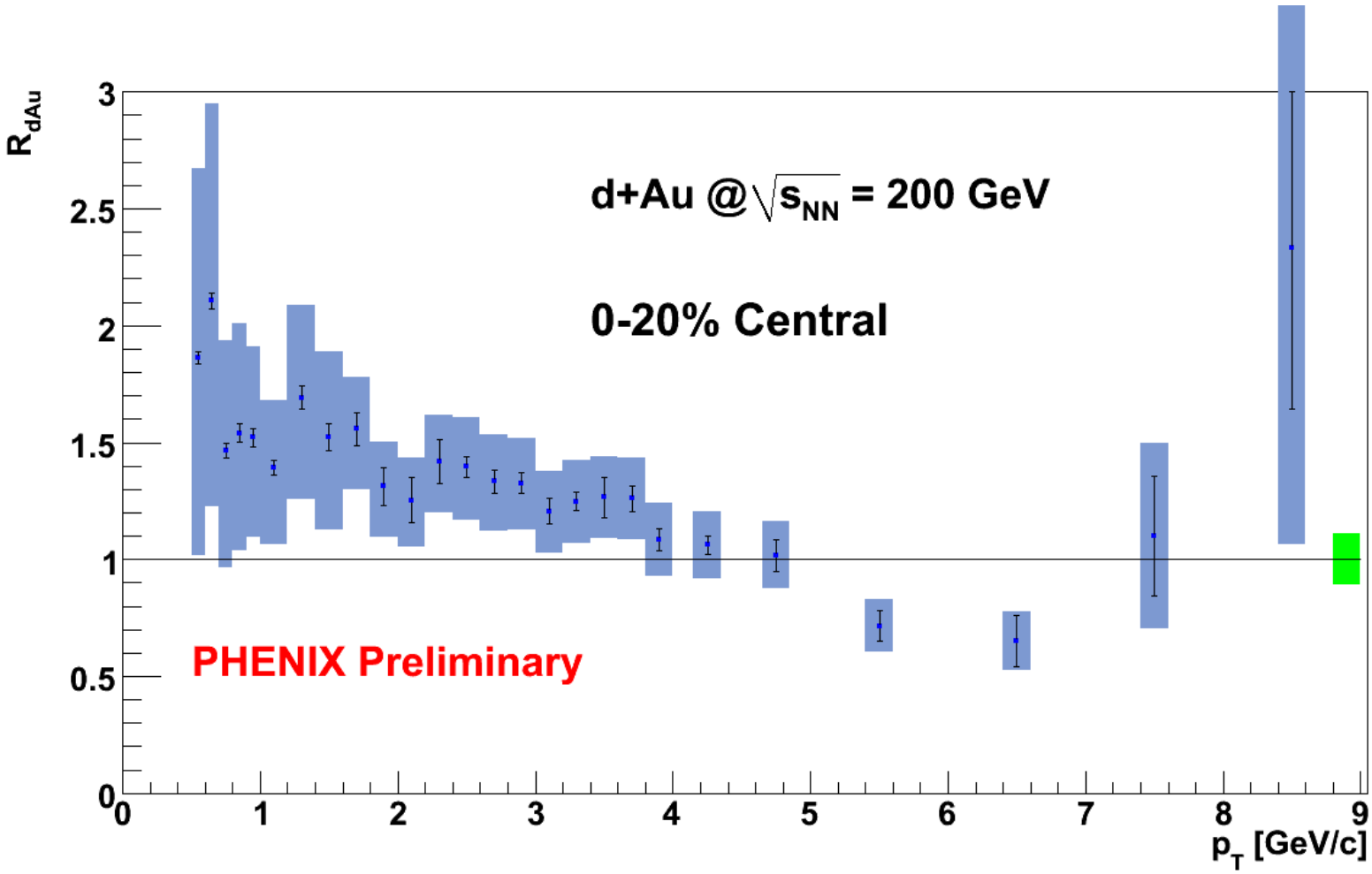
Semi-Peripheral R_{dA}



Semi-Central R_{dA}

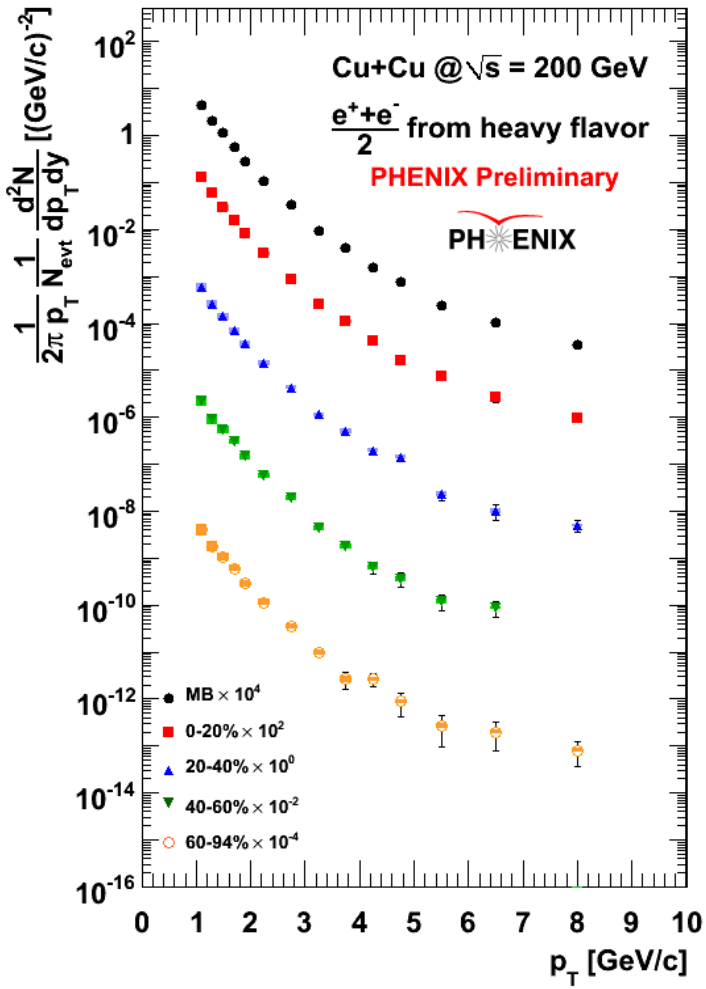


Central R_{dA}

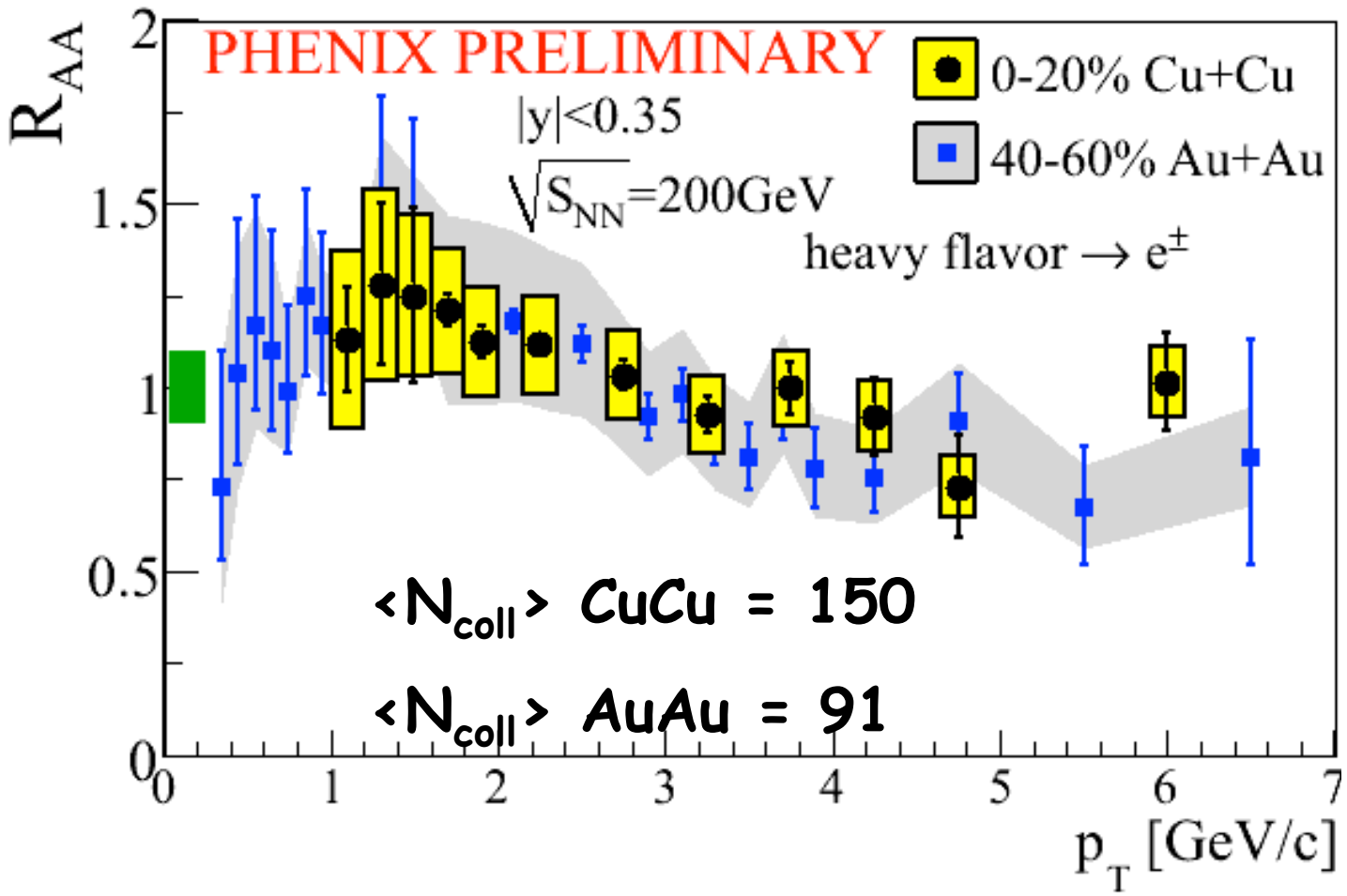

R_{dAu}
3
2.5
2
1.5
1
0.5
0
0
1
2
3
4
5
6
7
8
9
p_T [GeV/c]
d+Au @$\sqrt{s_{NN}}$ = 200 GeV
0-20% Central
PHENIX Preliminary

A few comments on R_{dA}

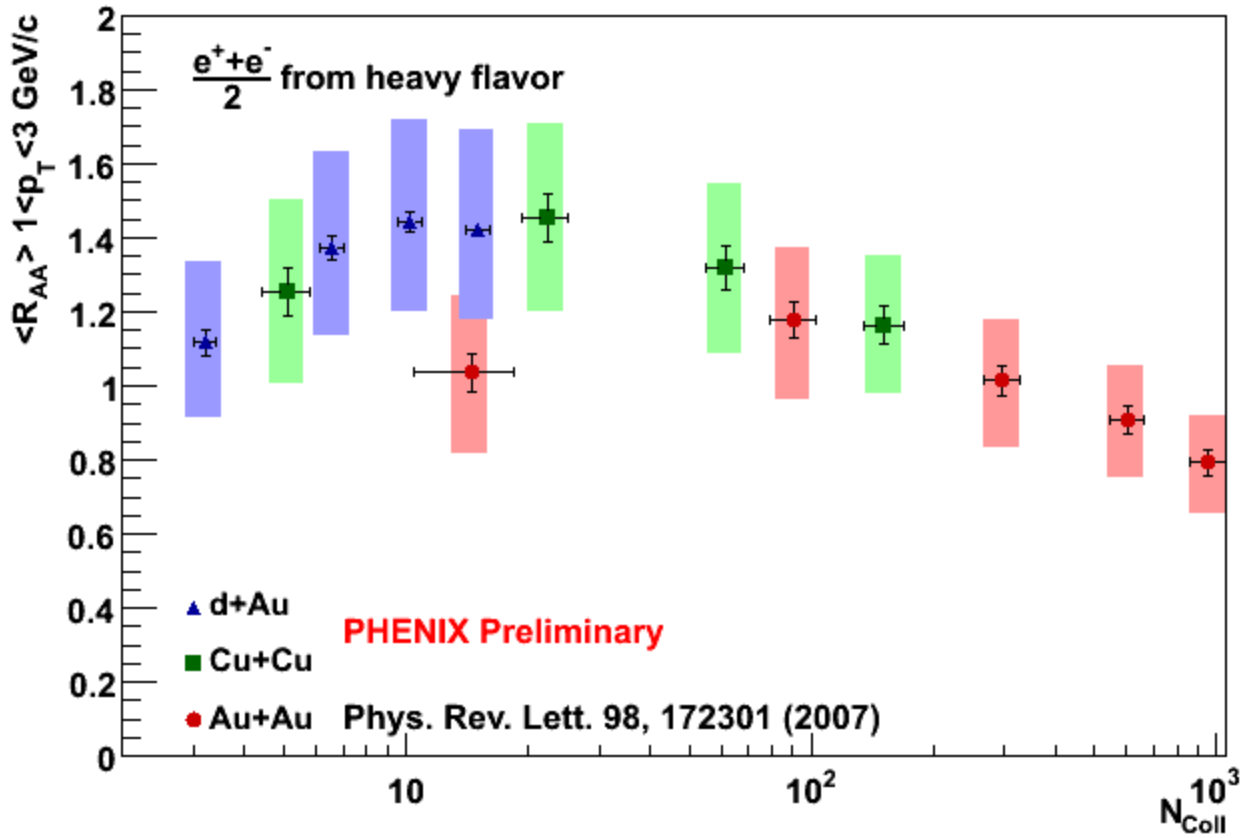
- Peripheral R_{dA} consistent with p+p
- Evidence of CNM effects on open HF yields at $1<p_T<4$ GeV/c for more central collisions
  - With large systematic uncertainties from cocktail
- Cu+Cu examines N_{coll} region between d+A and central Au +Au (up to ~200)



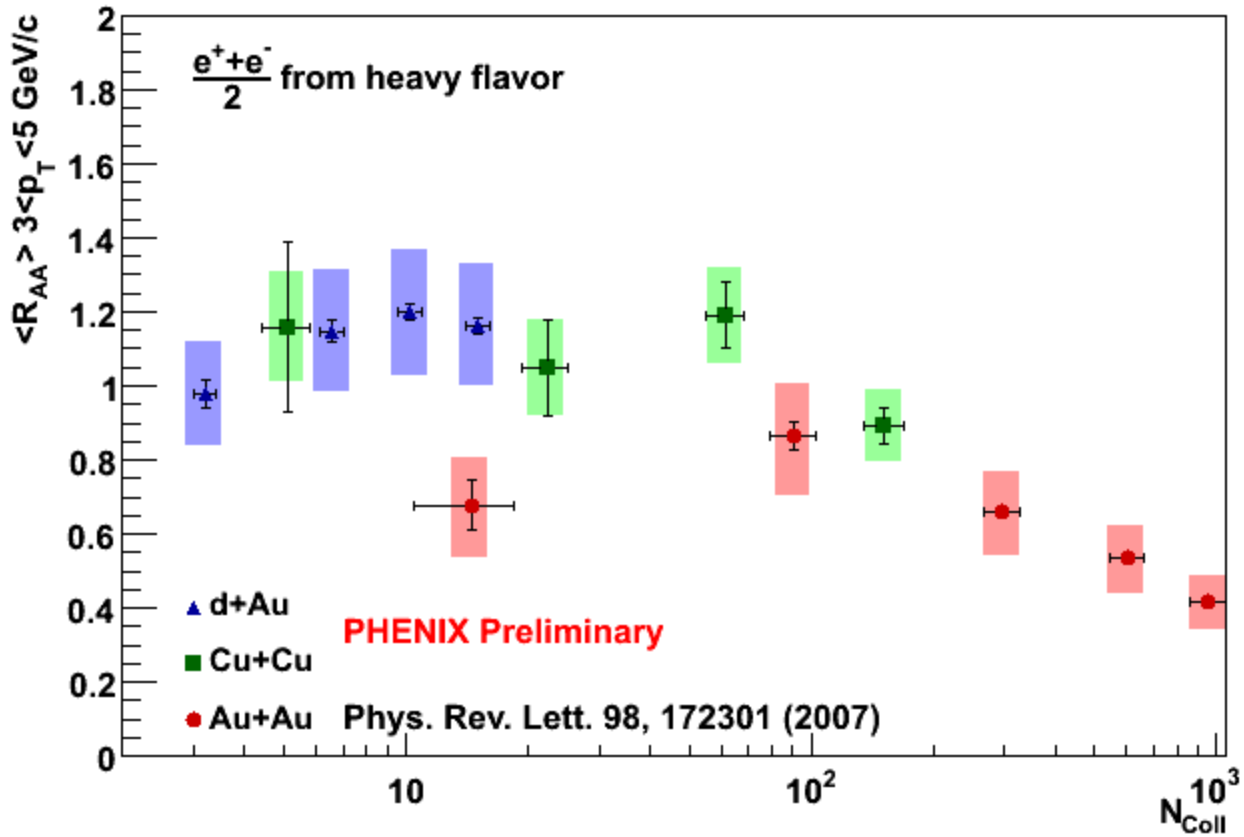
Cu+Cu and Au+Au



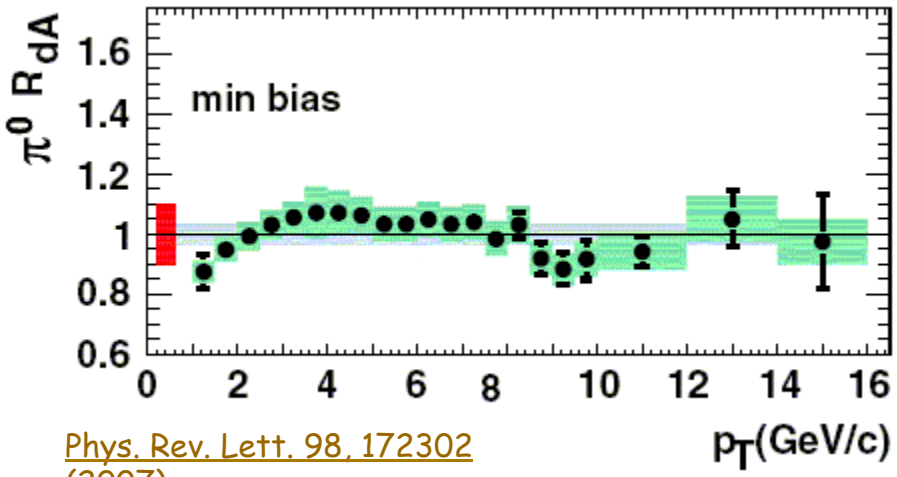
Trend with $\langle N_{coll} \rangle$



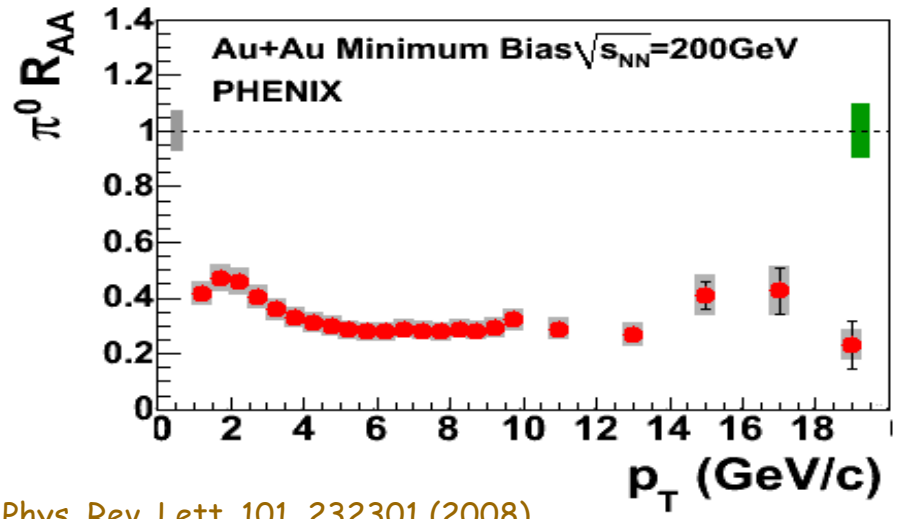
Trend with $\langle N_{coll} \rangle$



Light Quarks

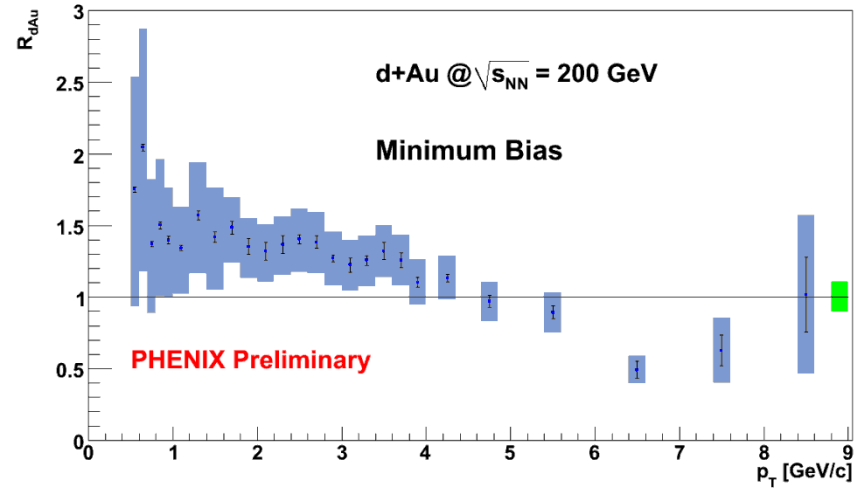


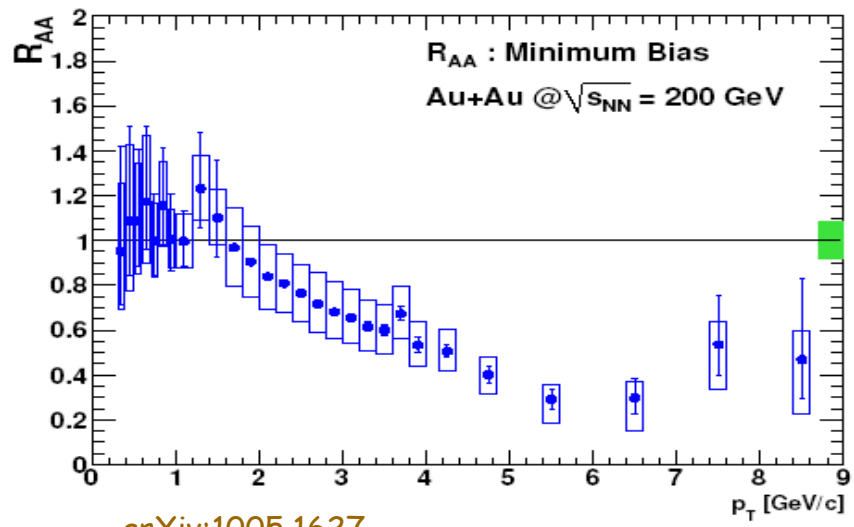
Phys. Rev. Lett. 98, 172302 (2007)



Phys. Rev. Lett. 101, 232301 (2008)

Heavy Quarks





arXiv:1005.1627

Quarkonia – looking to the Future

- Heavy-quark motivated detector upgrades at RHIC – e.g. the vertex detectors at PHENIX & STAR; forward calorimeters (MPC-EX) to extend to larger rapidity

- A new d+Au run with above upgrades – to understand CNM effects & provide the reliable extrapolation to A+A that we desperately need

- Comprehensive comparison of results from RHIC (at various energies), SPS, and emerging results from the LHC

- Increasing luminosity at RHIC (and LHC) to allow more quantitative measurements of the rarest quarkonia, and over wider kinematics

- Constraints from Drell-Yan on quark energy loss in CNM (E906)

VTX Au+Au event

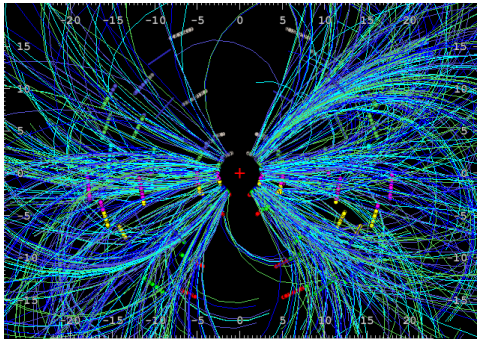


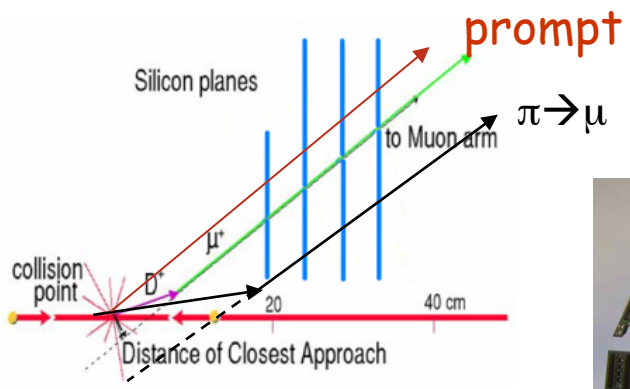
Table B.1: PHENIX run plan for the years 2010–2015. Longitudinal polarization is indicated by (L), transverse by (T).

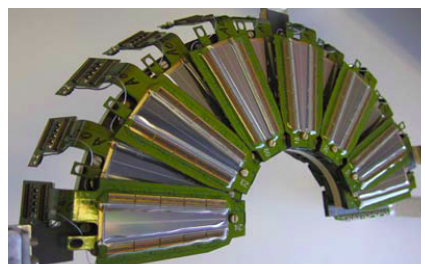
run	Species	$\sqrt{s_{NN}}$	Wks	$\int L\,dt$ $\lvert z\rvert < 30$ cm	$\int L\,dt$ $\lvert z\rvert < 10$ cm	Pol.	Comments
11	$p+p$	500	10	$50\,pb^{-1}$	$20\,pb^{-1}$	50% (L)	W program + ΔG
	Au+Au	200	8		$0.7\,nb^{-1}$		heavy flavor (VTX)
12	$p+p$	200	5	$13.1\,pb^{-1}$	$4.7\,pb^{-1}$	60% (T)	HI comparison, $\perp$ spin
	$p+p$	500	8	$100\,pb^{-1}$	$35\,pb^{-1}$	50% (L)	W program + ΔG
	Au+Au	200	7		$0.8\,nb^{-1}$		heavy flavor (F/VTX)
	U+U	193	1.5		$0.03\,nb^{-1}$		explore geometry
	Au+Au	27	1	$5.2\,\mu b^{-1}$			energy scan
13	$p+p$	500	10	$200\,pb^{-1}$	$74\,pb^{-1}$	60% (L)	W program
	$p+p$	200	5	$20\,pb^{-1}$	$4.7\,pb^{-1}$	60% (T)	HI comparison
	Cu+Au	200	5		$2.4\,nb^{-1}$		control geometry
	U+U	193	5		$0.57\,nb^{-1}$		explore geometry
14	$p+p$	200	10	$34\,pb^{-1}$	$12\,pb^{-1}$	65% (T)	HI comp., transv.
	$p+p$	62	3	$0.6\,pb^{-1}$	$0.2\,pb^{-1}$	60% (T/L)	HI comp., transv.
	$d+$Au	200	8	$260\,nb^{-1}$	$150\,nb^{-1}$		CNM/FOCAL
	$d+$Au	62	2	$6.5\,nb^{-1}$	$3.8\,nb^{-1}$		CNM/FOCAL
15	Au+Au	200	10		$2.8\,nb^{-1}$		High Bandwidth
	Au+Au	62	4		$0.13\,nb^{-1}$		HF vs $\sqrt{s_{NN}}$
	$p+{}^3$He	132	5			(T)	Test Run

Quarkonia – looking to the Future

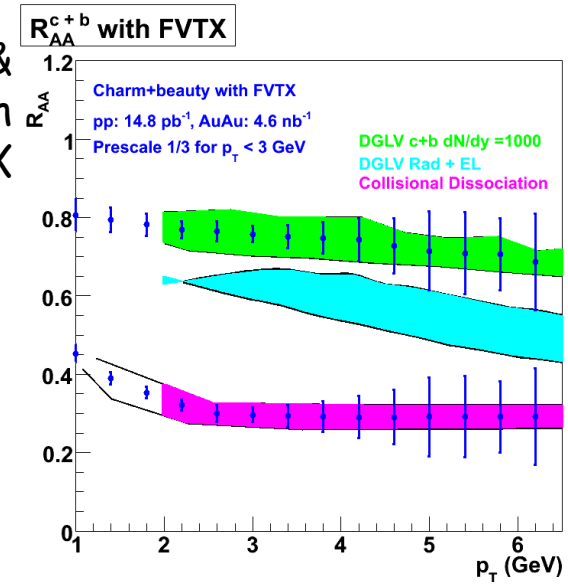
PHENIX Forward-rapidity Vertex Detector (FVTX)

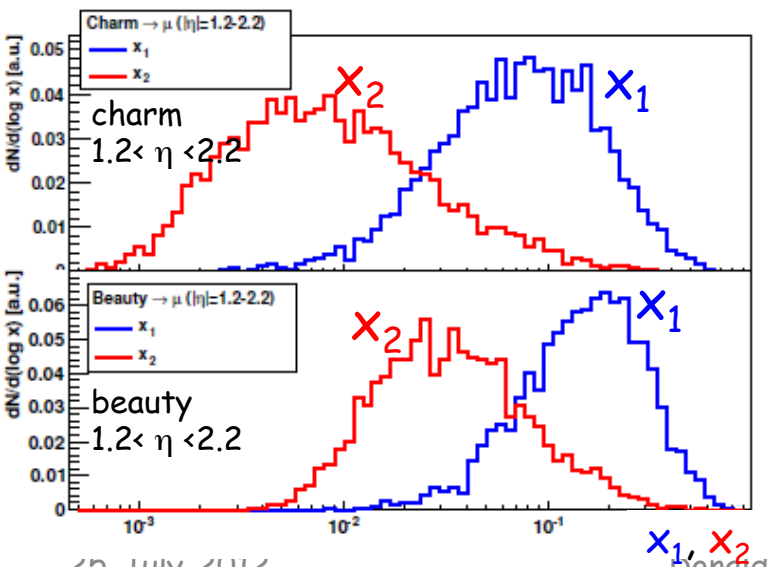
- Used in 2012 Run; forward charm, beauty; improved J/ψ resolution





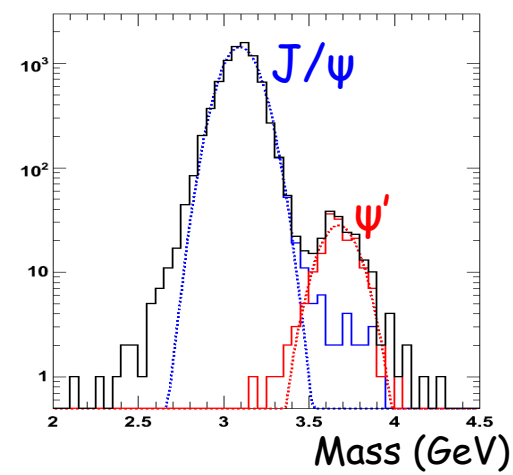
Resolving radiative & collisional dE/dx with the FVTX





x coverage for open-charm and beauty with FVTX

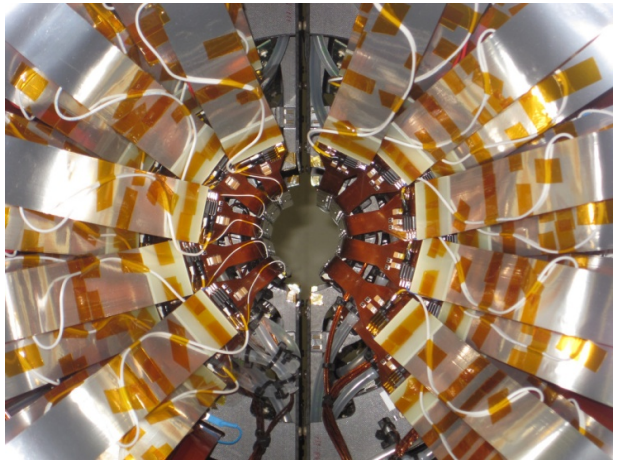
Improved separation of ψ'

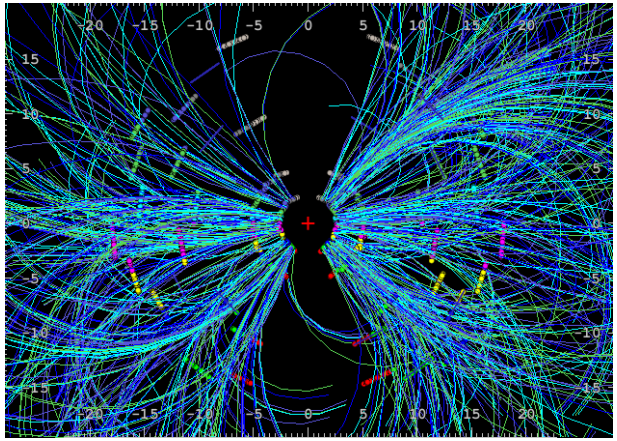


Quarkonia – looking to the Future

PHENIX Mid-rapidity Vertex Detector (VTX)

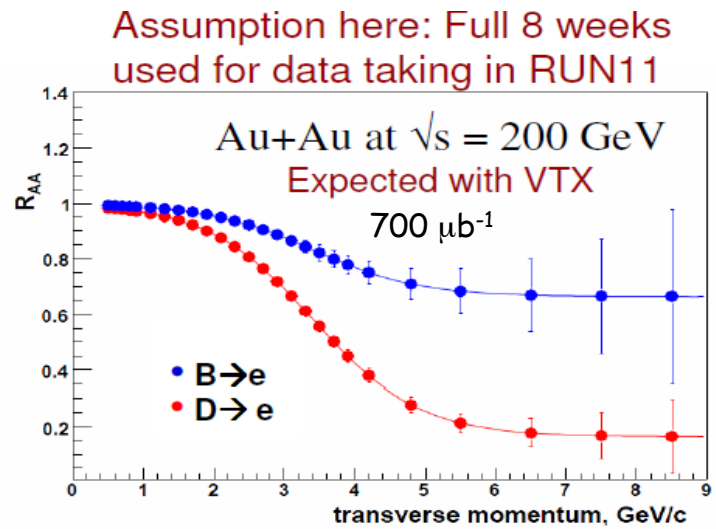
- Running now: charm, beauty; improved Upsilon resolution

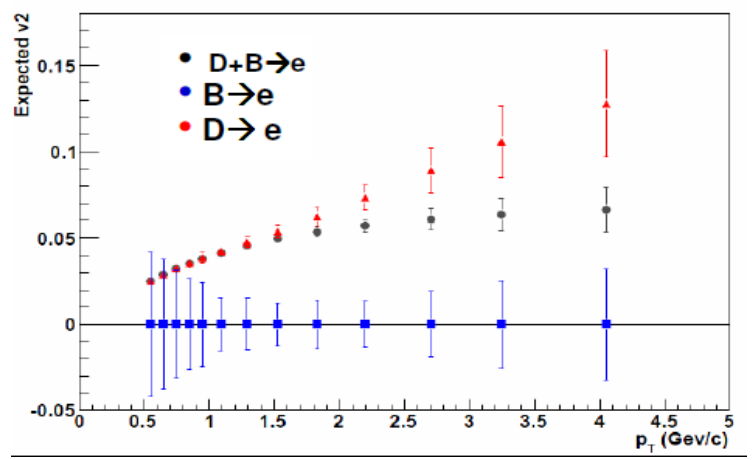




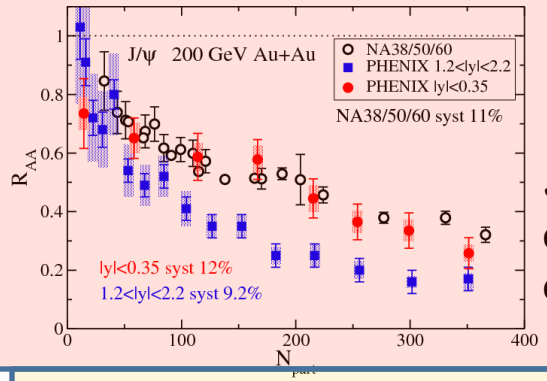
VTX endview: detector (top); Au+Au event (bottom)

Expectations for open-charm and beauty with VTX

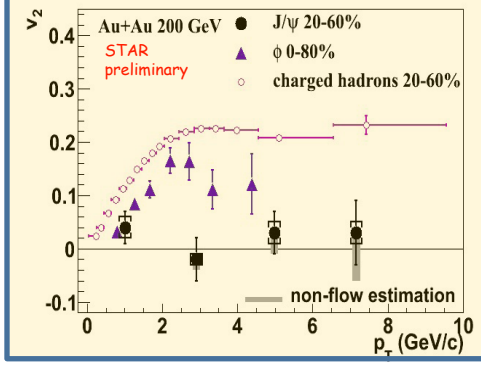




Summary

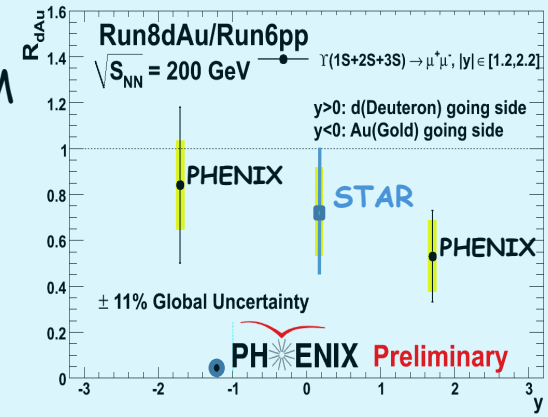


J/ψ suppression almost same at all energies

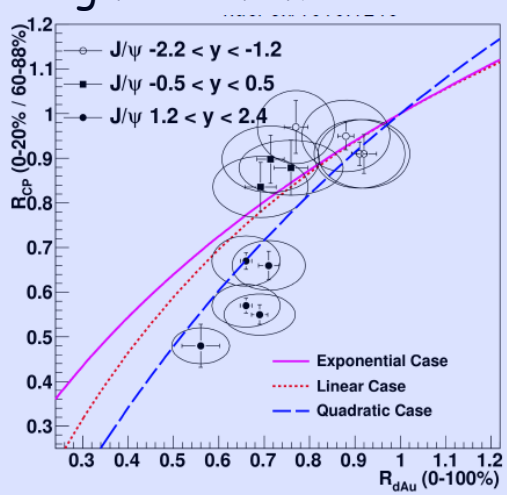


Flow very small at RHIC

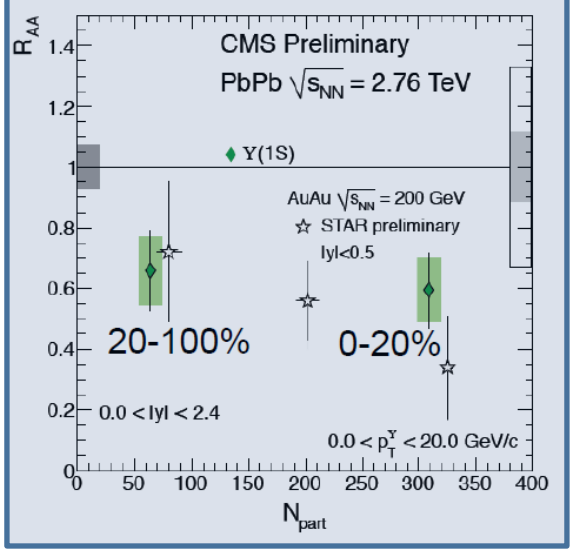
Strong CNM effects for Upsilon too



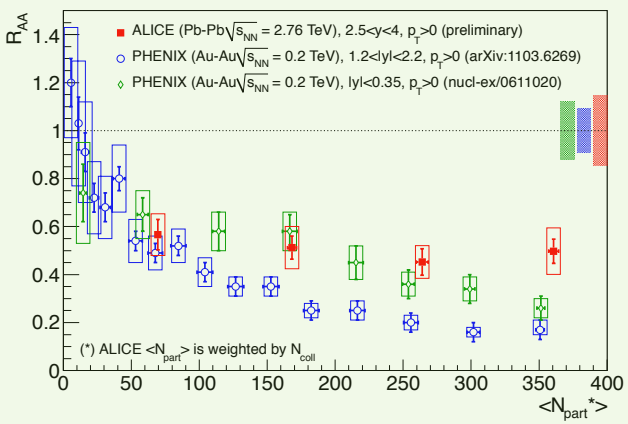
CNM suppression of J/ψ has stronger than linear dependence on density-weighted thickness



Upsilon suppression at RHIC & LHC similar



Hint of regeneration at LHC?



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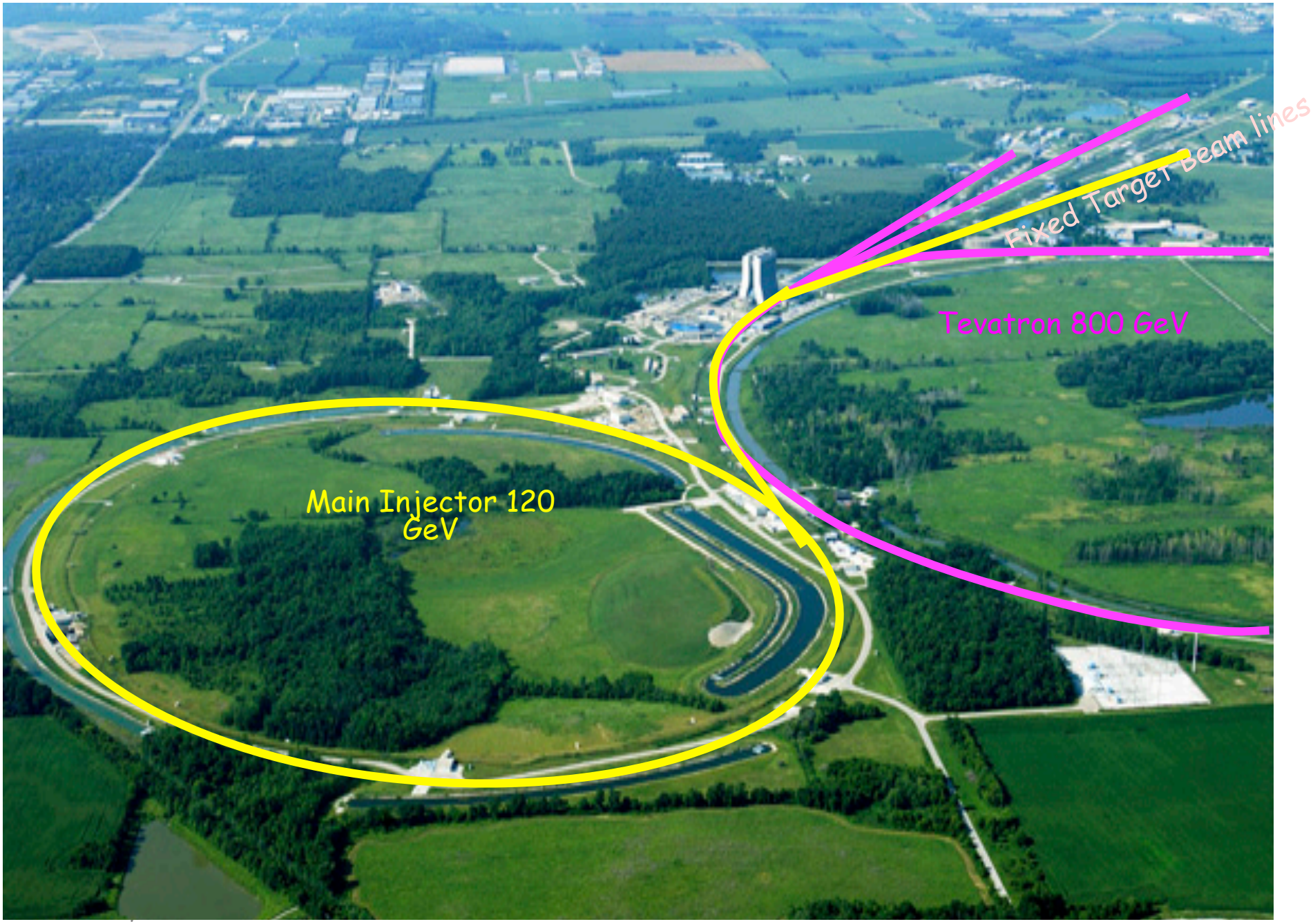
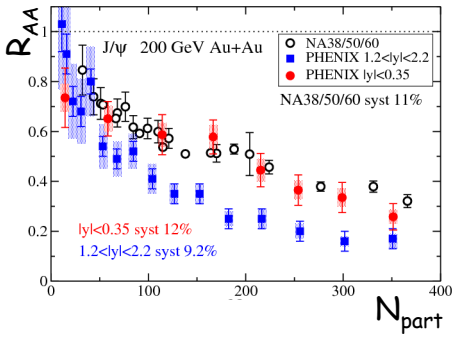

Fixed Target Beam lines
Tevatron 800 GeV
Main Injector 120 GeV

Landscape of the Quarkonia Puzzle

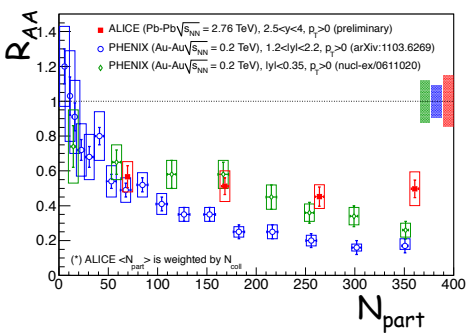
Quarkonia in Deconfined Matter Workshop

Acitrezza, Italy - Sep 28-30, 2011

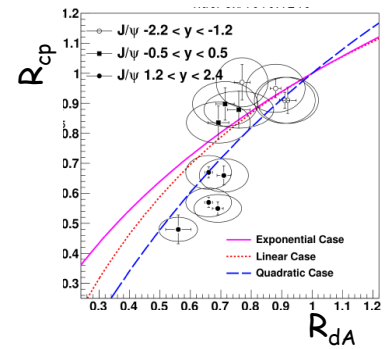
Mike Leitch, LANL



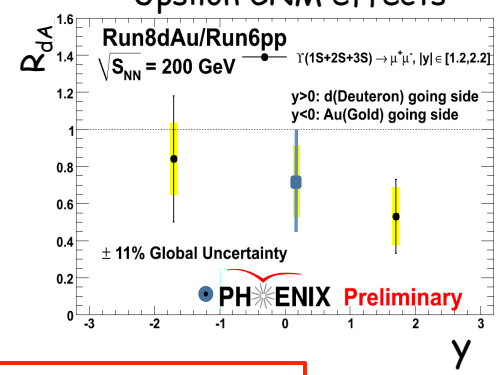
Energy dependence of Quarkonia suppression



Non-linear CNM effects



Upsilon CNM effects

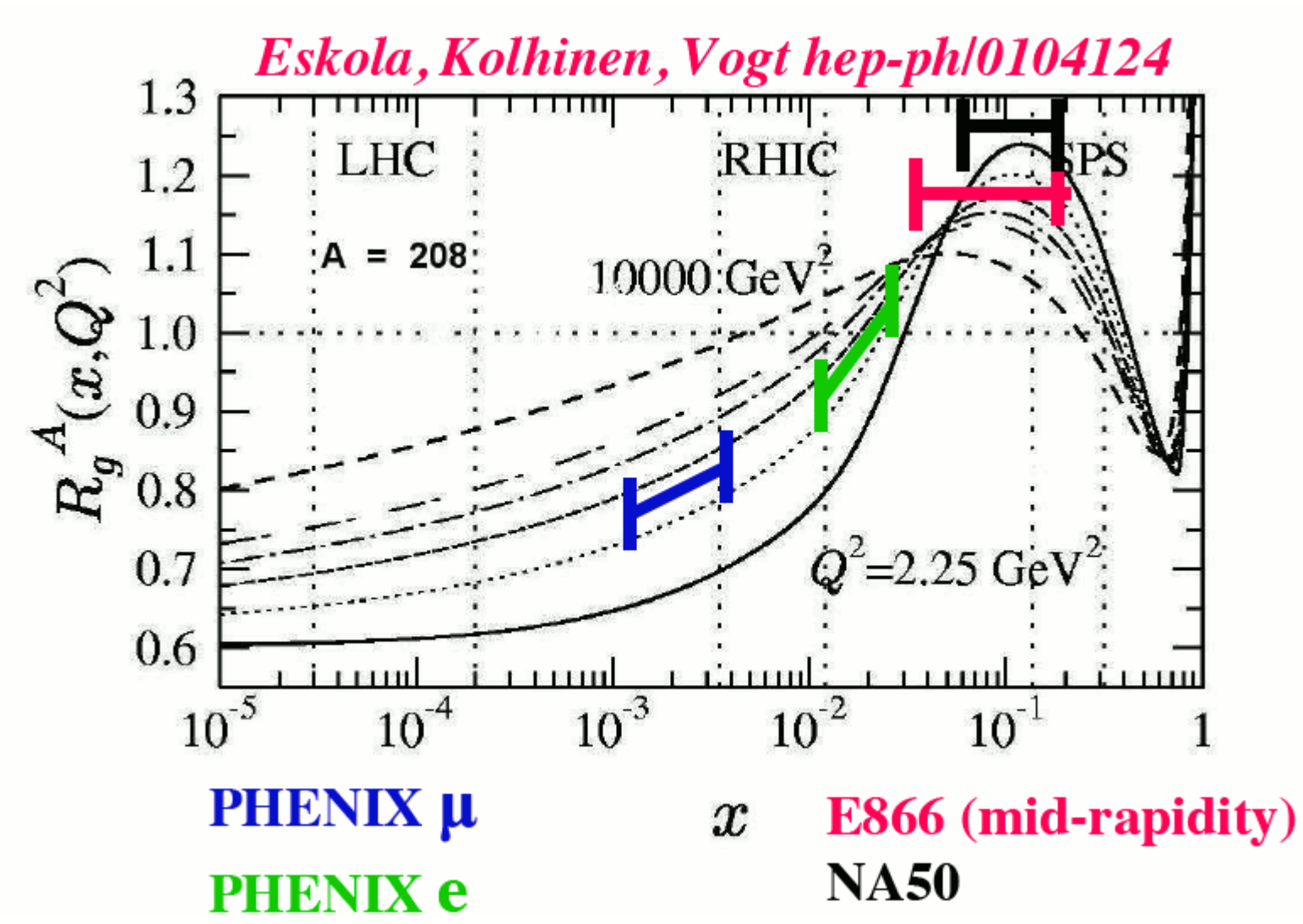


- Charmonia Suppression in A+A Collisions
- (Strong) Cold Nuclear Matter (CNM) effects
- Heavier Quarkonia - Upsilons

Recent Open Heavy Flavor Results from PHENIX

J. Matthew Durham
for the PHENIX Collaboration
Stony Brook University

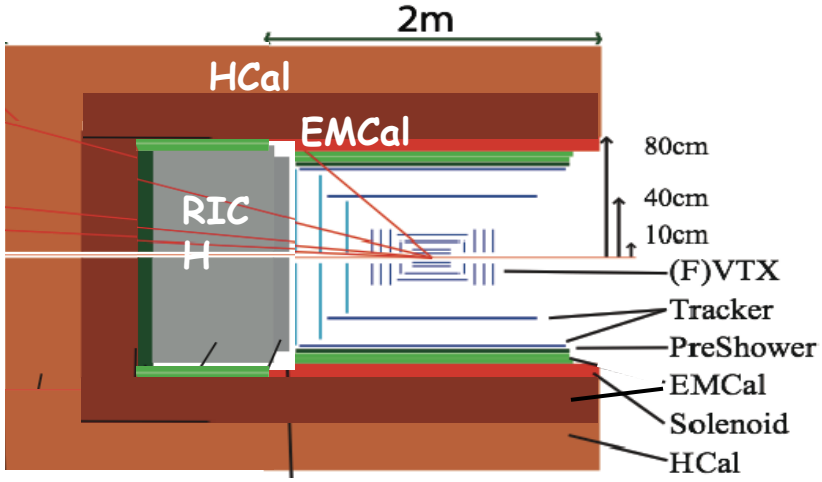
durham@skipper.physics.sunysb.edu

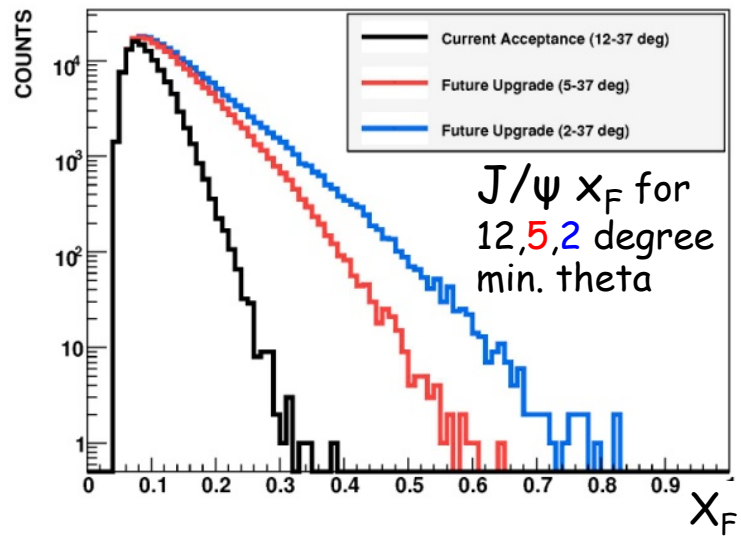

Eskola, Kolhinen, Vogt hep-ph/0104124
LHC
RHIC
SPS
A = 208
10000 GeV^2
Q^2=2.25 GeV^2
$R_g^A(x,Q^2)$
1.3
1.2
1.1
1.0
0.9
0.8
0.7
0.6
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1
x
PHENIX μ
PHENIX e
E866 (mid-rapidity)
NA50

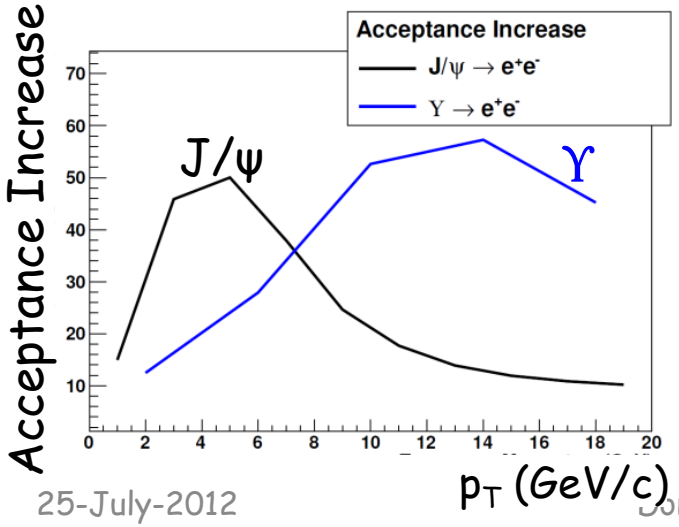
Quarkonia – looking to the Future

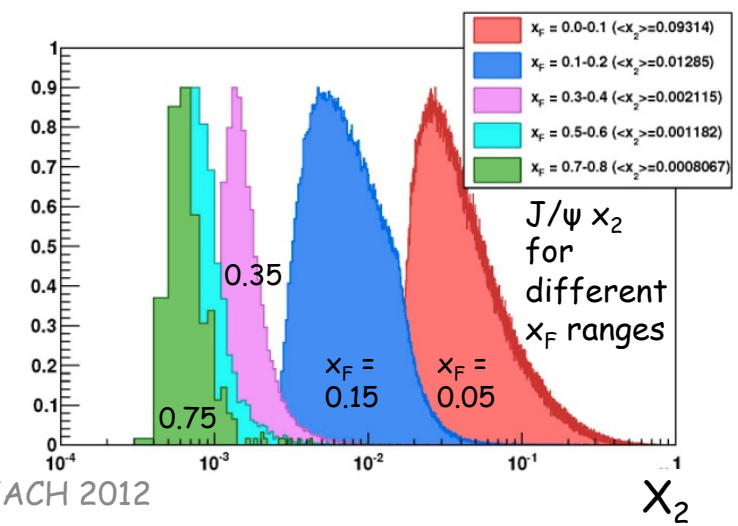
Decadal upgrades of RHIC detectors; at PHENIX:

- Larger acceptance and luminosity for rarest (quarkonia) probes
- Very forward rapidity constraints on CNM









Quarkonia – looking to the Future

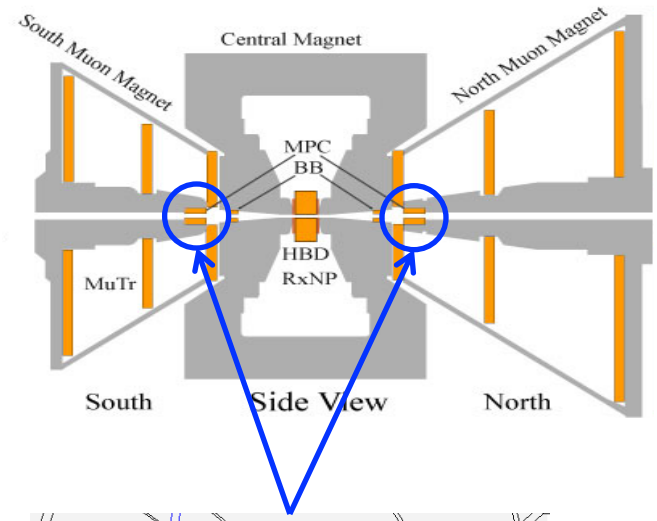
The MPC Extension (MPC-EX)

Enhance the forward direction ($3 < \eta < 3.8$) in PHENIX with a <u>combined</u> preshower and tracking device

- Enable J/ψ measurements in MPC with low background
- Enable reconstruction of π^0's in the MPC out to high p_T
- Measurement of direct photons
- Reconstruction of jet direction with charged hadrons

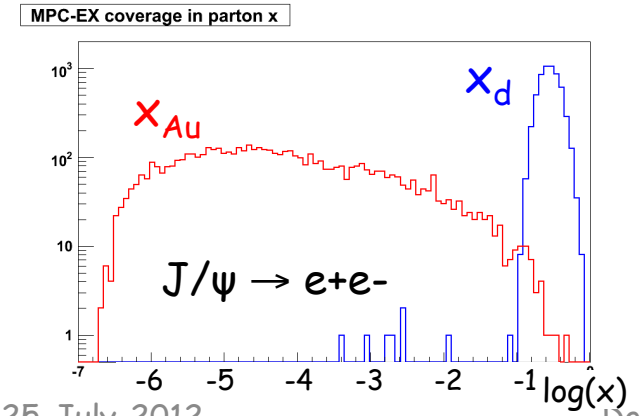
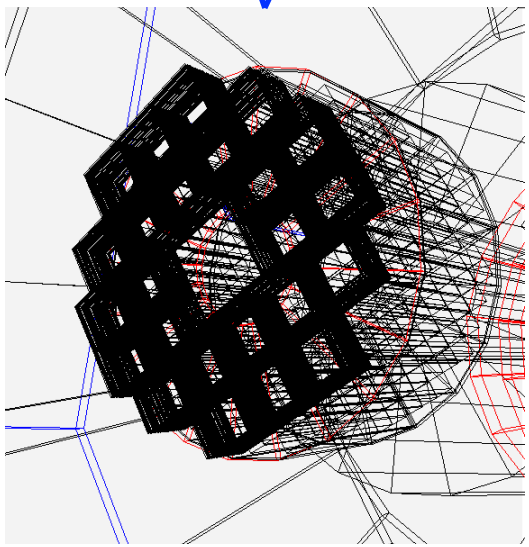
Technology:

- Si detectors (pad and 500 mm strips) plus W absorber



Projections for J/ψ (acceptance only, no efficiencies!):

- 260 nb^{-1} d+Au run: ~9.7k J/ψ -> $e^+ e^-$ in North MPC
- 34 pb^{-1} 200 GeV p+p run ~3.6k J/ψ sum for two arms



Ready for next d+Au in 2014?