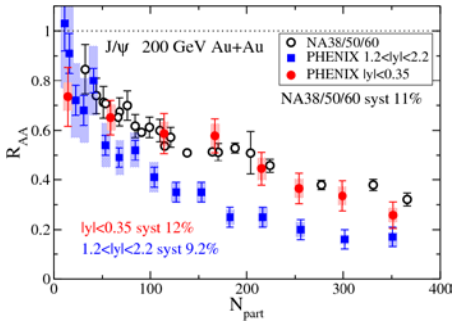
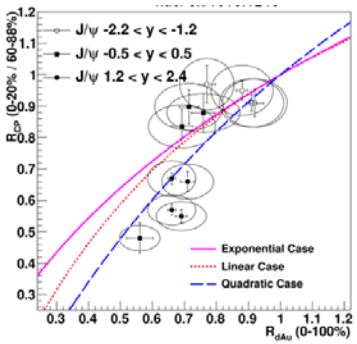
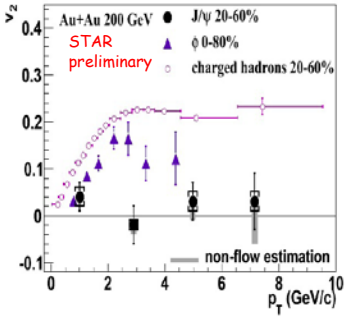
Landscape of the Quarkonia Puzzle

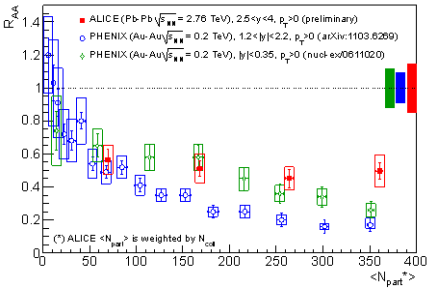
QWG at BNL – June 6-18, 2011

Mike Leitch, LANL

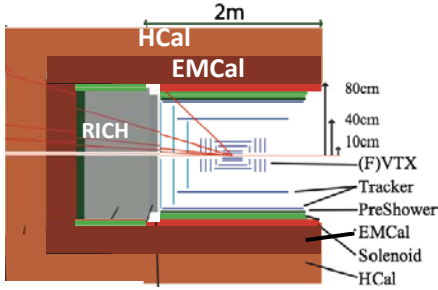








- Charmonia Suppression in A+A Collisions
- (Strong) CNM effects
- Production uncertainties
- Heavier Quarkonia
- Future



Quarkonia Suppression in A+A Collisions – Debye Screening

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

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

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

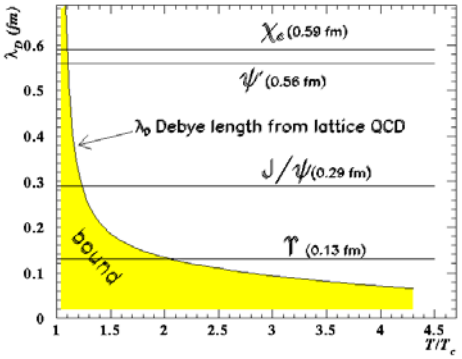
"If high energy heavy ion collisions lead to the formation of a hot quark-gluon plasma, then colour screening prevents ccbar binding in the deconfined interior of the interaction region … … It is concluded that J/Ψ suppression in nuclear collisions should provide an unambiguous signature of quark-gluon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

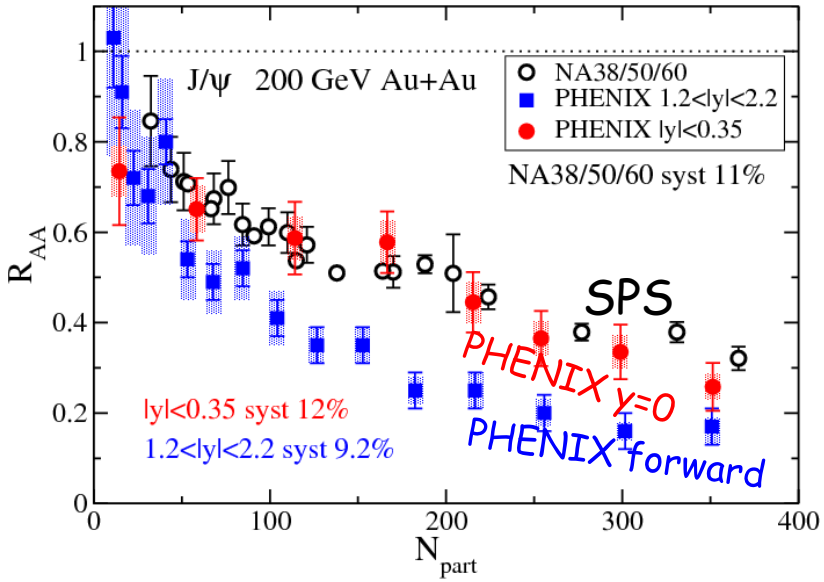
Different lattice calculations do not agree on whether the J/ψ is screened or not – measurements will have to tell!

Satz, hep-ph/0512217

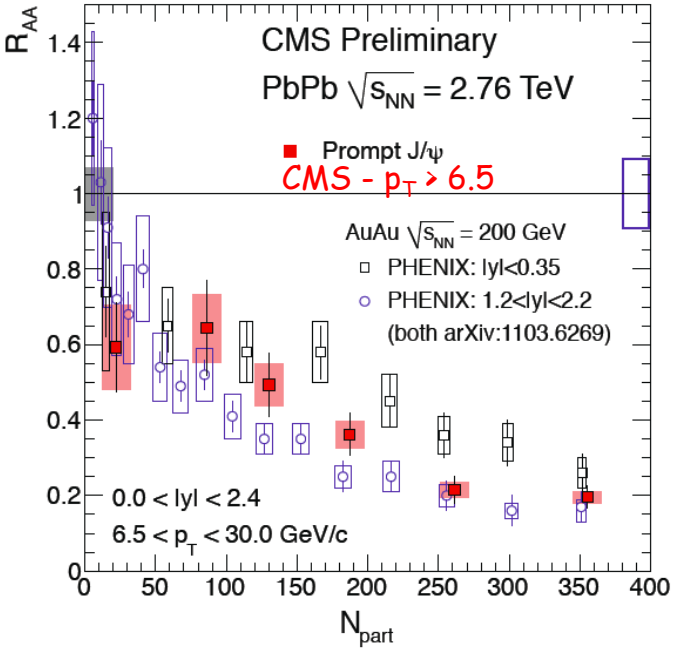
state	$J/\psi(1S)$	$\chi_c(1P)$	$\psi'(2S)$	$\Upsilon(1S)$	$\chi_b(1P)$	$\Upsilon(2S)$	$\chi_b(2P)$	$\Upsilon(3S)$
T_d/T_c	2.10	1.16	1.12	> 4.0	1.76	1.60	1.19	1.17

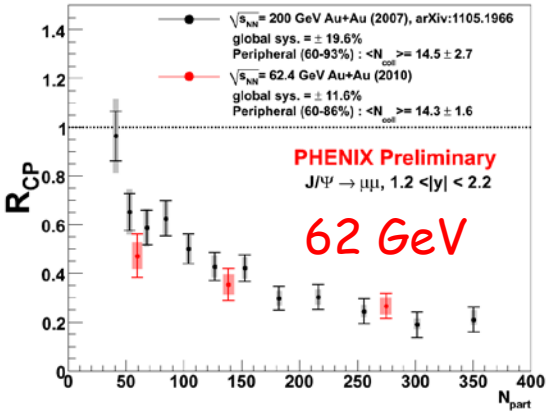


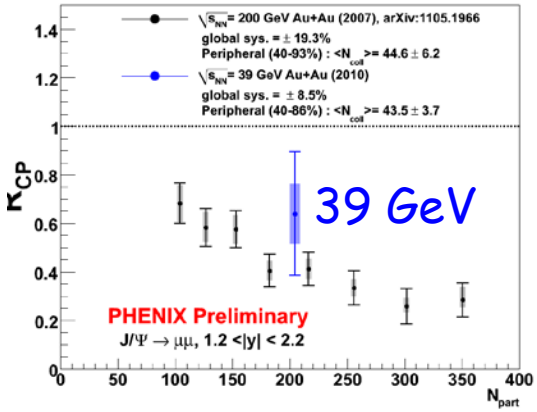
Quarkonia Suppression in A+A Collisions – key observations and questions



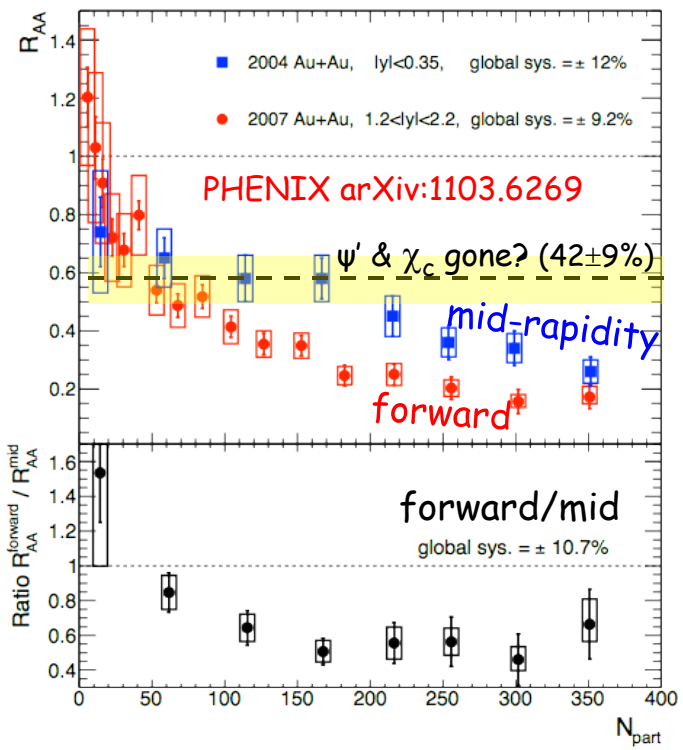
Overall suppression of J/ψ is nearly identical between RHIC, SPS, & LHC







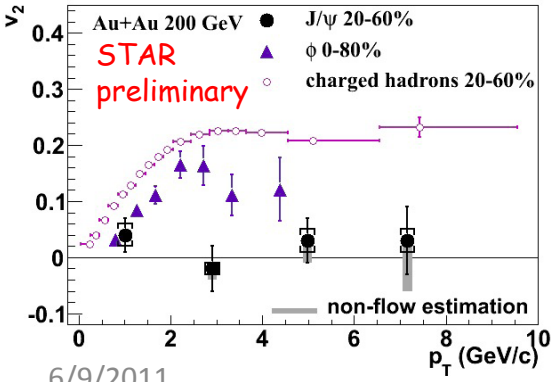
Quarkonia Suppression in A+A Collisions – key observations and questions



Forward-rapidity is suppressed more than Mid-rapidity

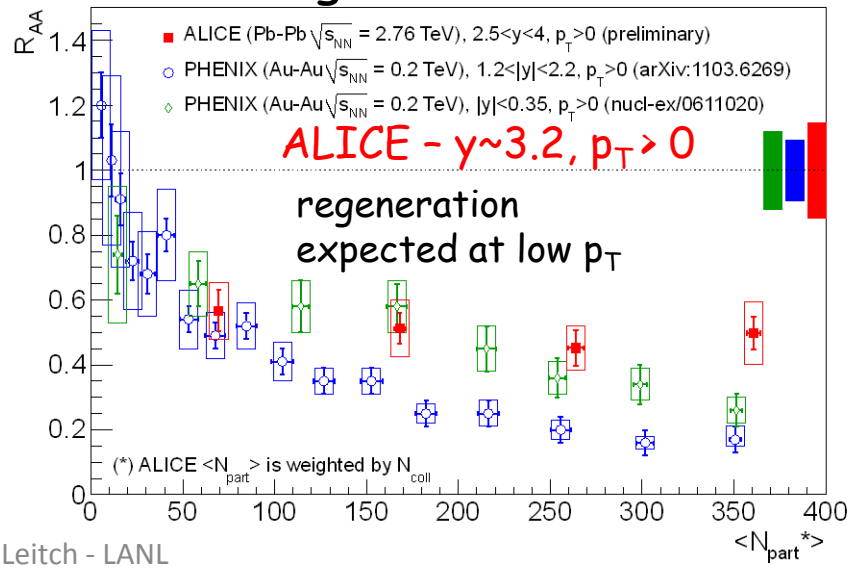
Stronger forward rapidity suppression due to CNM effects?

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



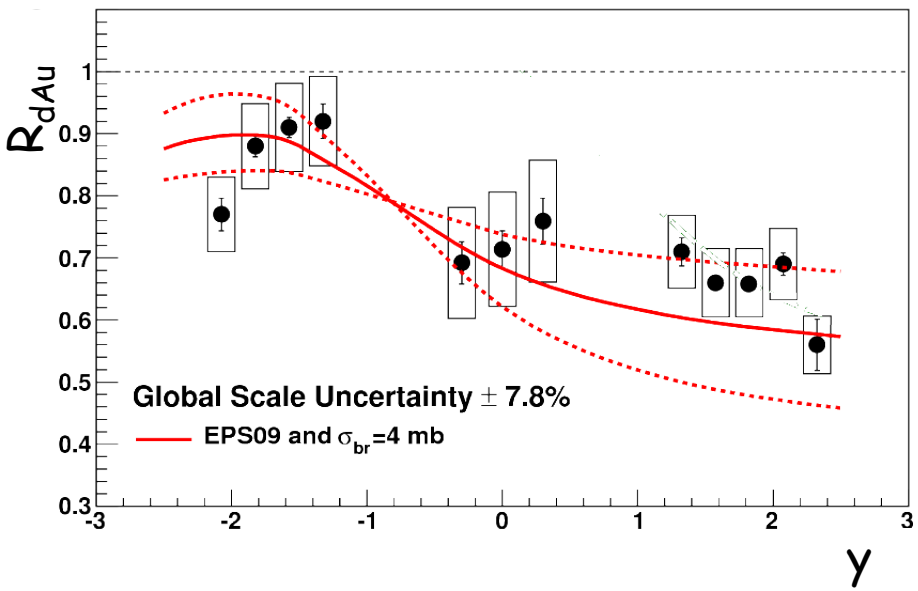
no J/ψ flow at RHIC!

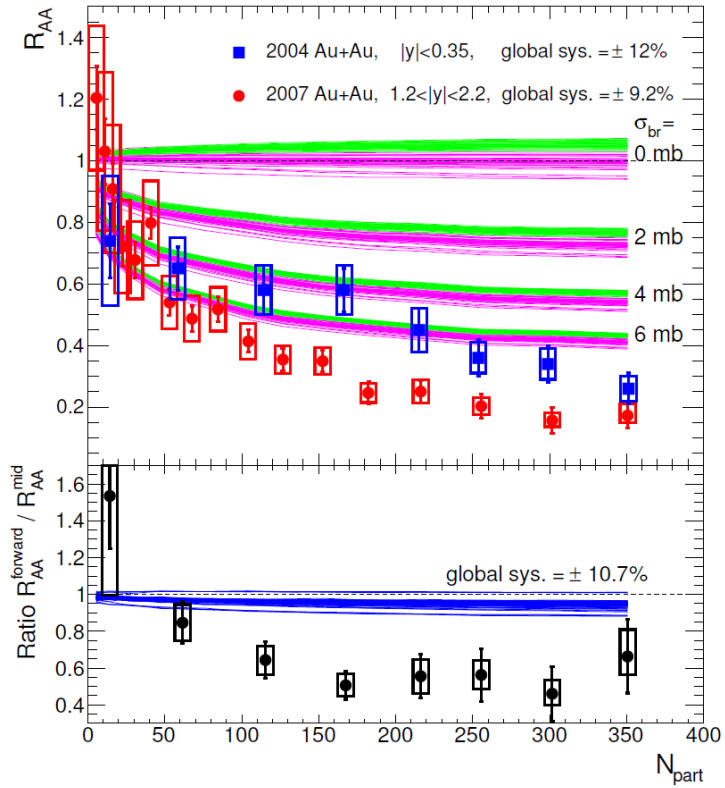
Hint of regeneration at ALICE?



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

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

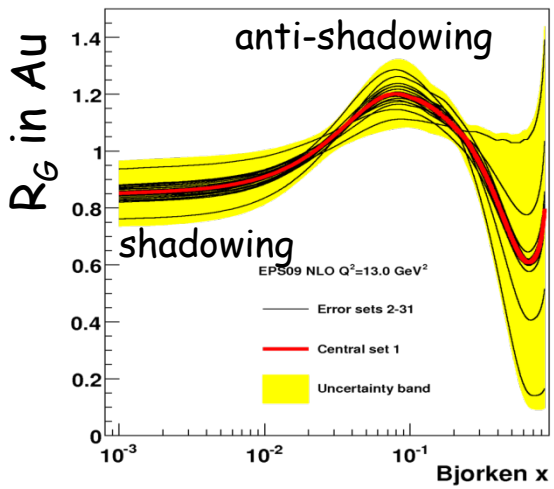


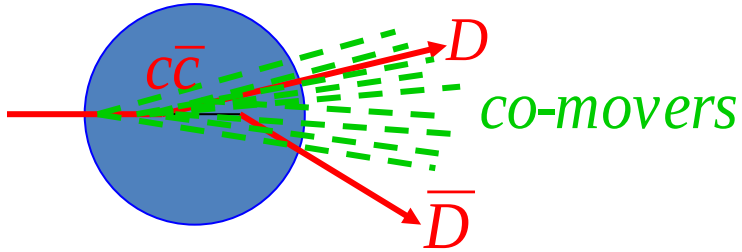


- Probably have to understand CNM in a fundamental way in order to obtain reliable/quantitative extrapolations to A+A
- Only then can we be quantitative about the suppression effects of the QGP

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

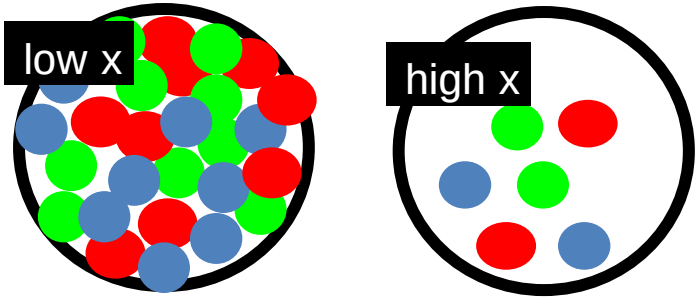
Traditional shadowing from fits to DIS or from coherence models



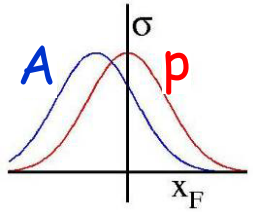


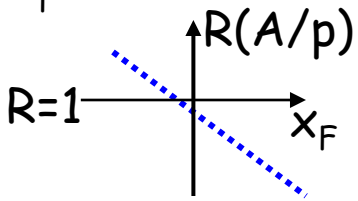
Absorption (or dissociation) of $c\bar{c}$ into two D mesons by nucleus or co-movers

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





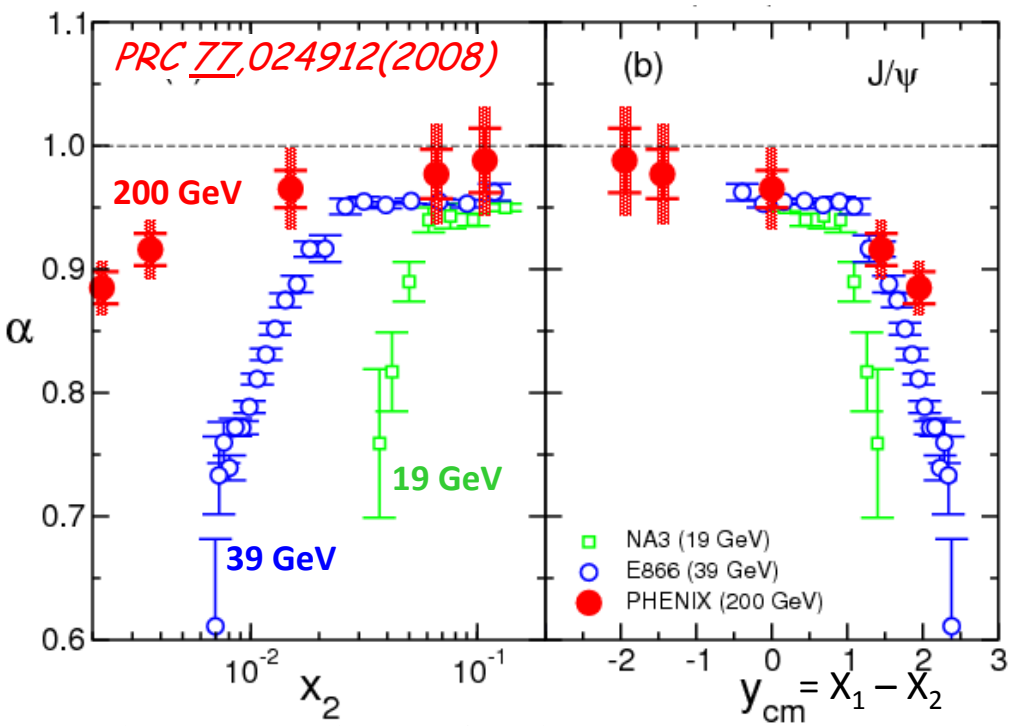
What are the CNM effects that are so strong in Quarkonia production?

Scaling between measurements at different Energies

PHENIX, E866, NA3 Comparison

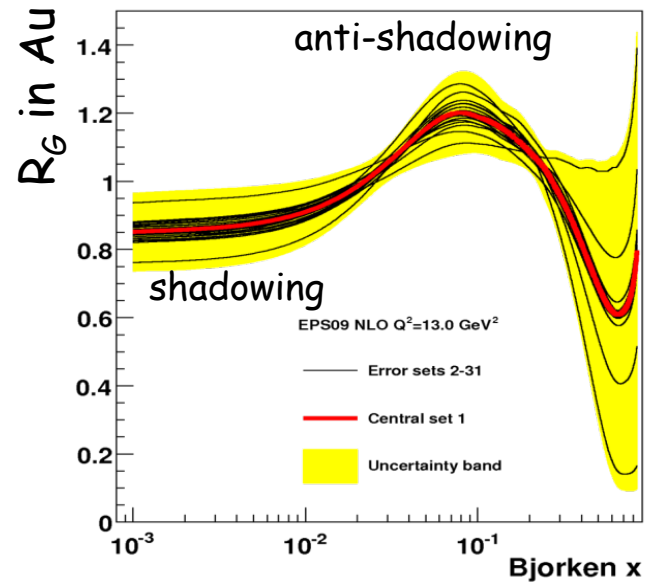
$$\sigma_{pA} = \sigma_{pp} A^{\alpha}$$

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

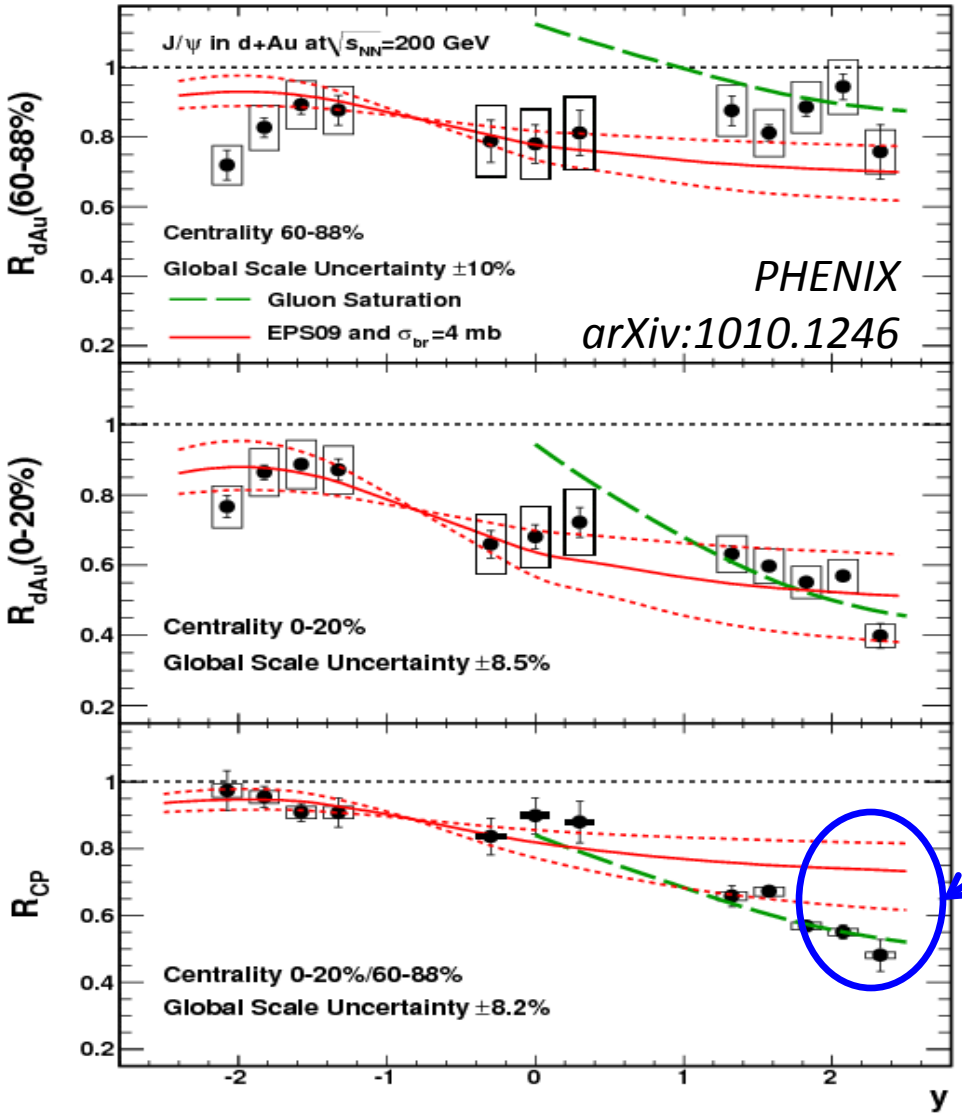


Closer to scaling with x_F or rapidity

- 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



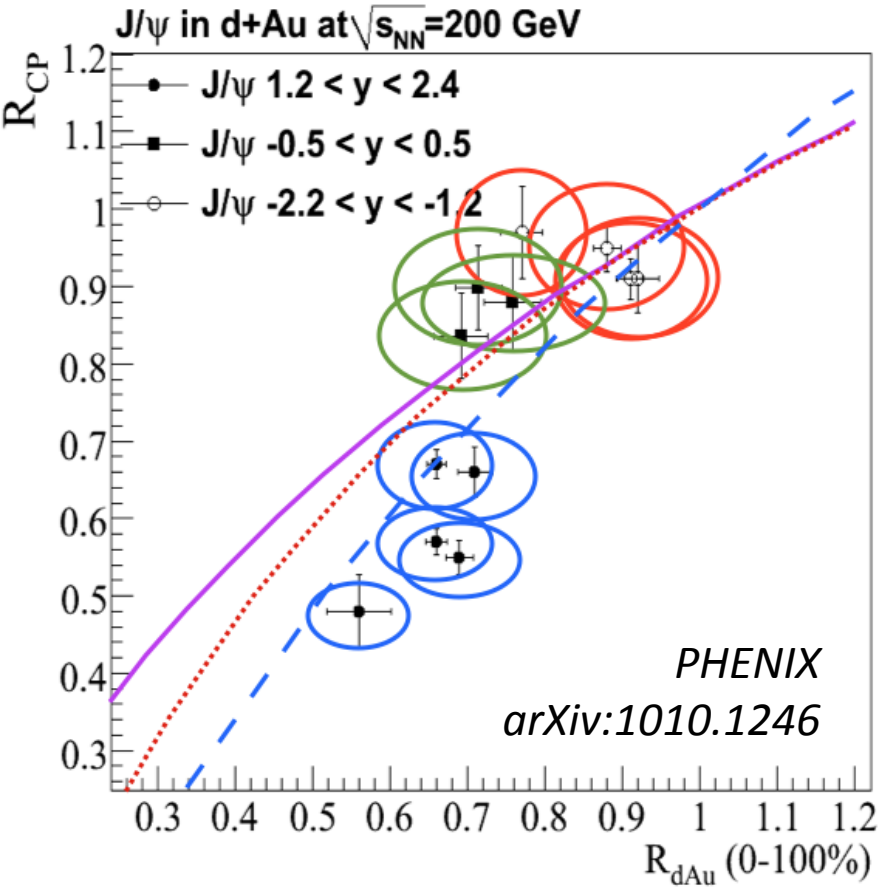
Reasonable agreement with EPS09 nPDF + σ_{br}=4 mb for central collisions but not peripheral

CGC calculations can't reproduce mid-rapidity (*Nucl. Phys. A 770(2006) 40*)

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

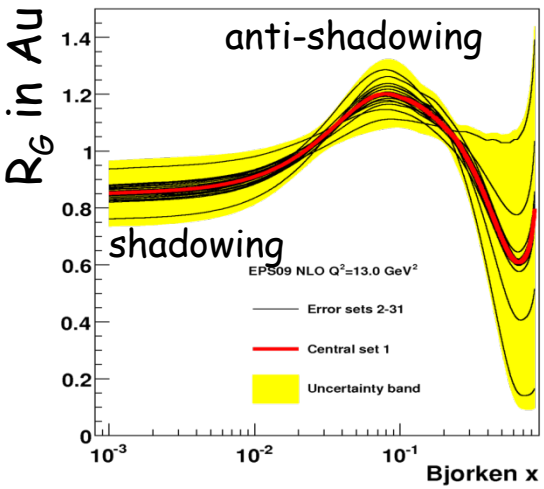
The forward rapidity points suggests a quadratic or higher geometrical dependence

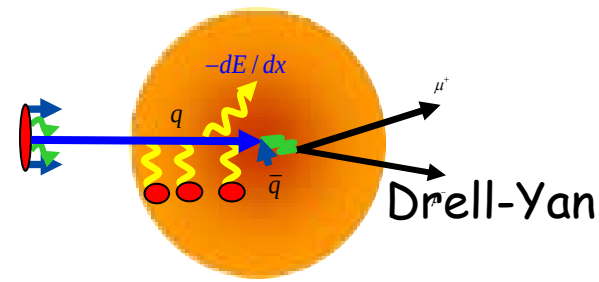
What are the CNM effects that are so strong in Quarkonia production?

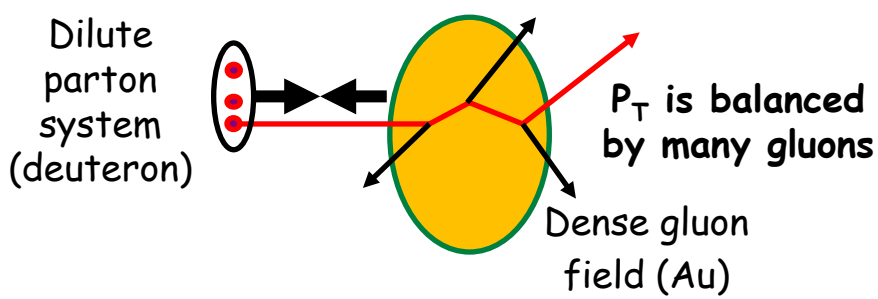
The various CNM effects are difficult to disentangle experimentally – multiple probes, types & energies of collisions, wide kinematic coverage are key

- 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





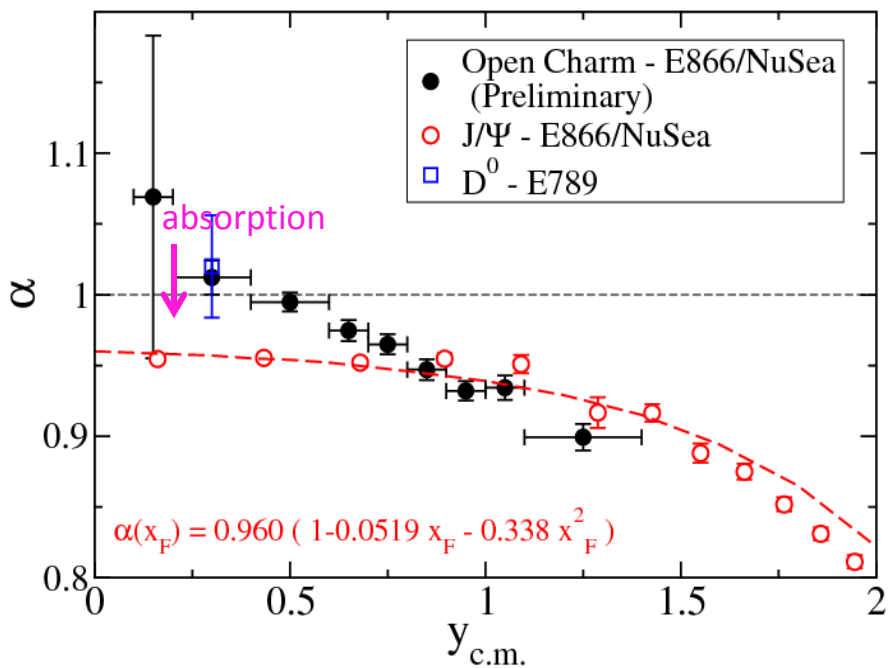


What are the CNM effects that are so strong in Quarkonia production?

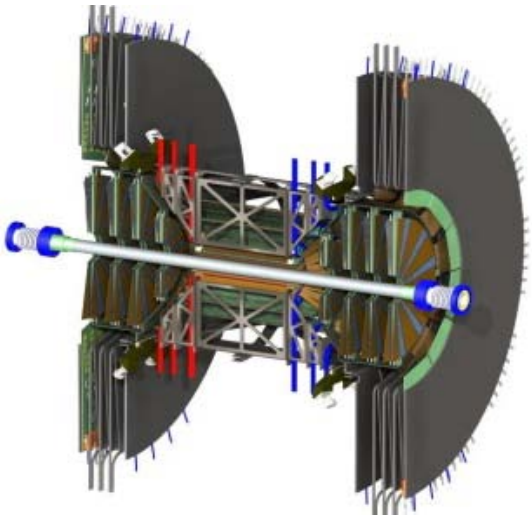
open-heavy suppression – isolates initial-state effects

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

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

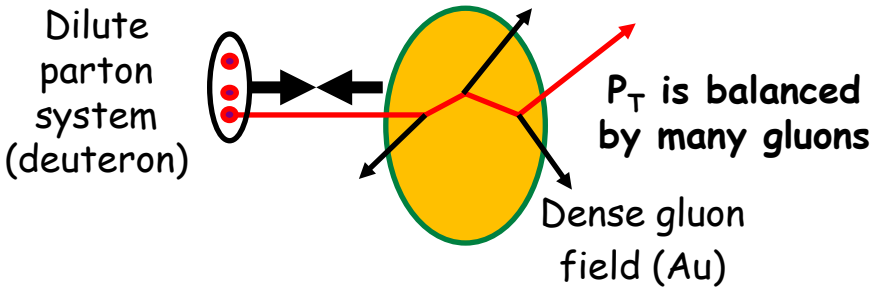


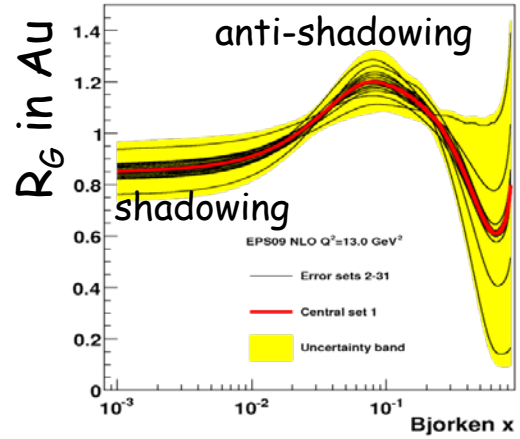
Include new PHENIX c,b measurements with VTX/FVTX to isolate initial & final-state effects via comparisons with quarkonia



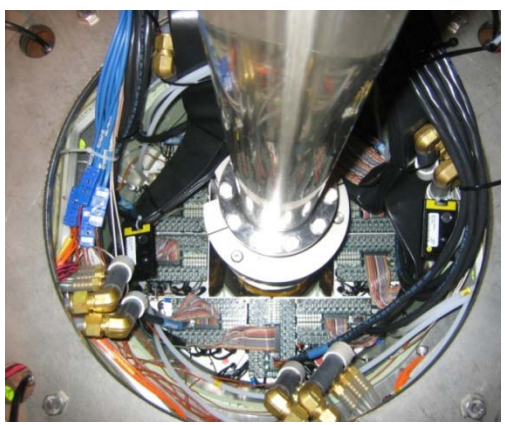
What are the CNM effects that are so strong in Quarkonia production?

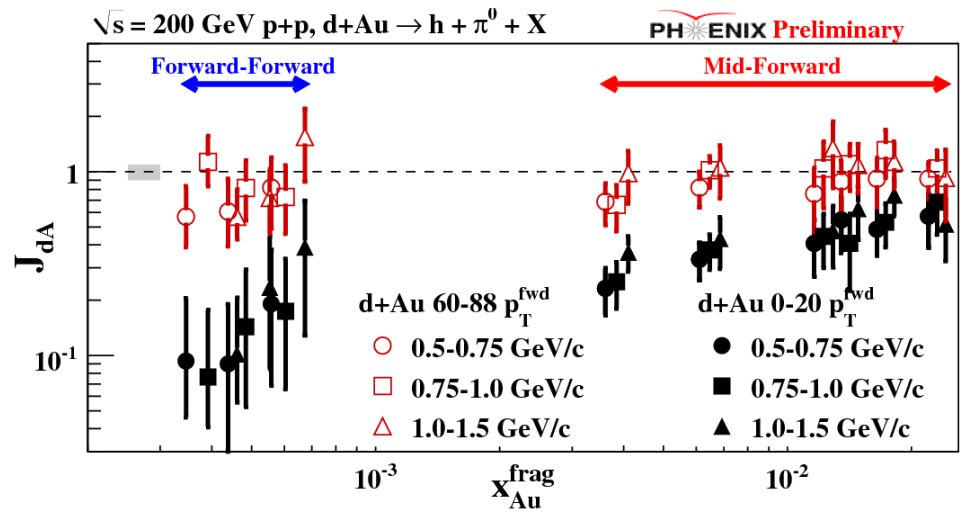
other probes of shadowing & gluon saturation – forward hadrons





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





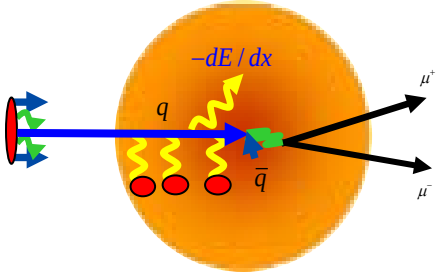
$$x_{Au}^{frag} = \frac{< p_{T1} > e^{-<\eta_1>} + < p_{T2} > e^{-<\eta_2>}}{\sqrt{s}}$$

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

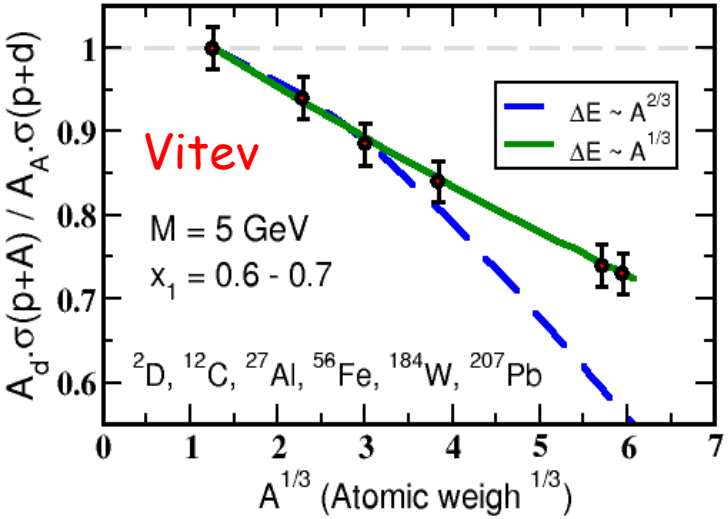
Drell-Yan to constrain parton energy loss in CNM

FNAL E906 – Drell Yan

Drell-Yan

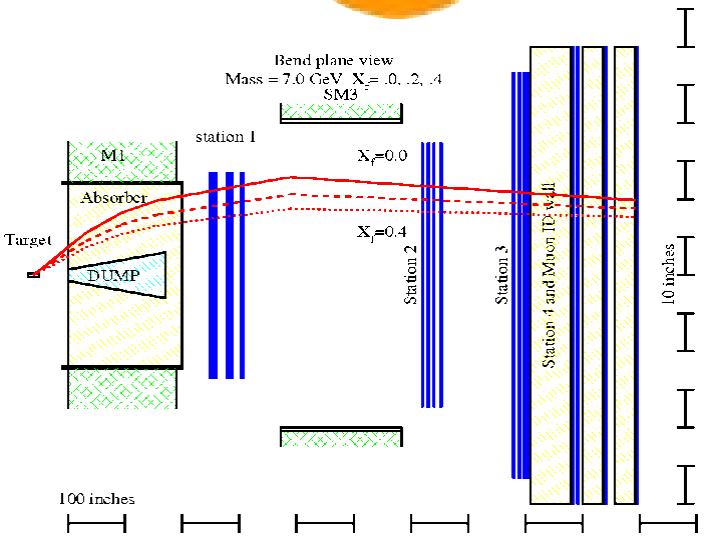


In E906 at 120 GeV, nuclear suppression in Drell-Yan should only be from dE/dx (x_2 > 0.1)



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

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



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

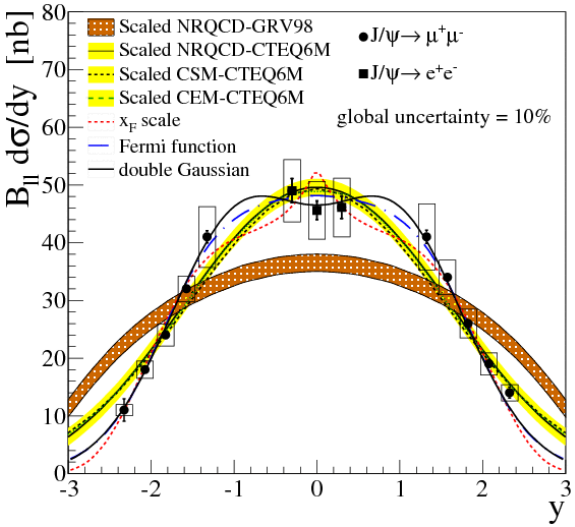
First data expected late 2011

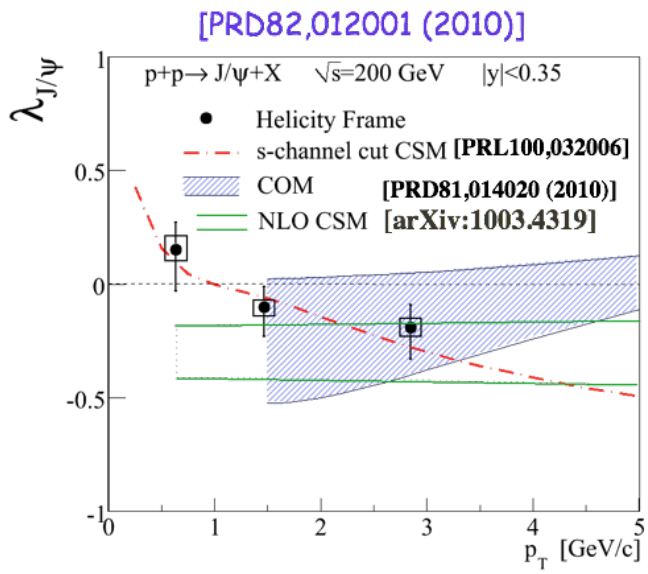
Production mechanism uncertainty - underlies everything else

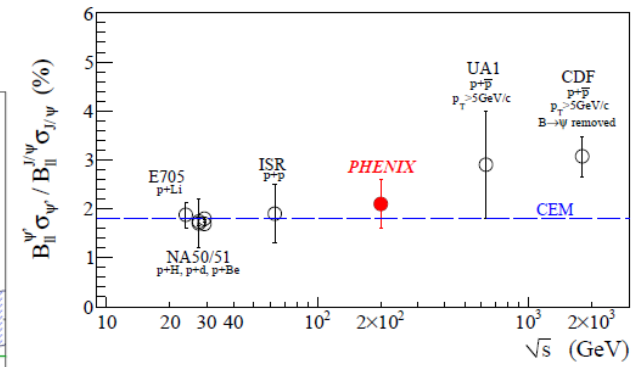
- What kind of state is the precursor heavy-quark pair that eventually forms a quarkonia; this effects how it interacts with the media
- What happens to other charmonium states & how much feeddown do they give to the J/ψ

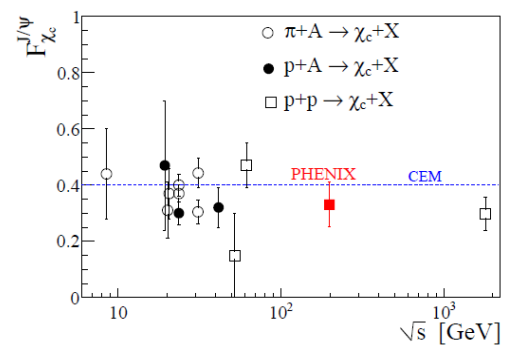
Feedown fractions from PHENIX for 200 GeV, y=0

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



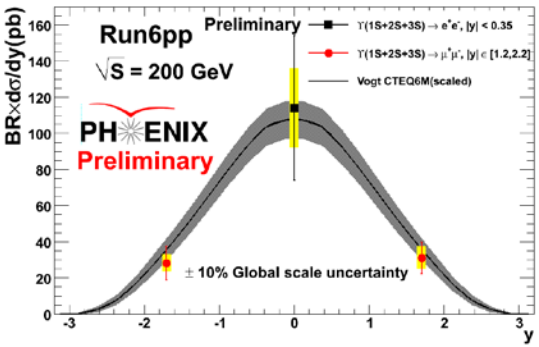


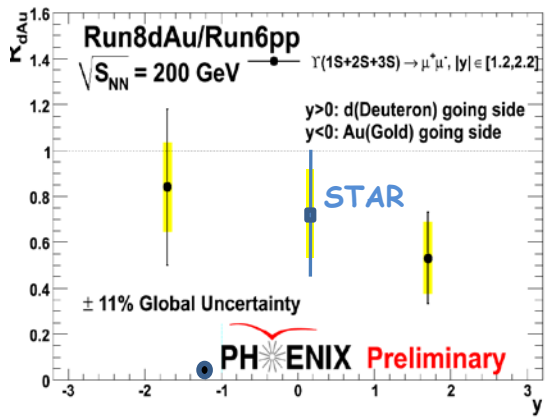


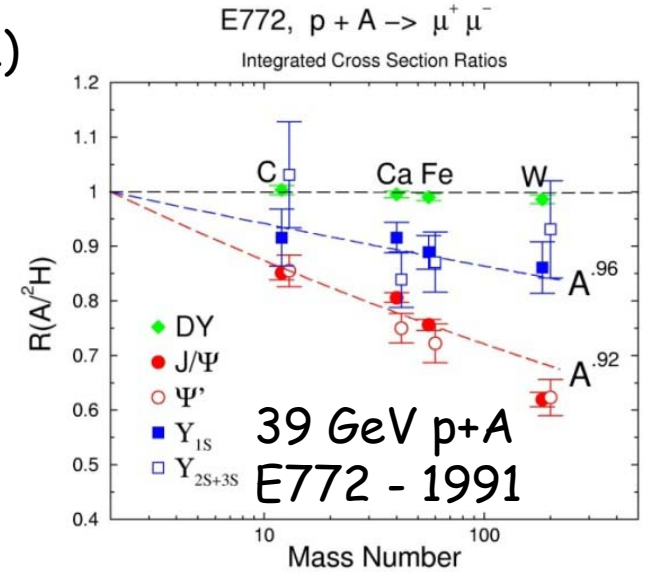


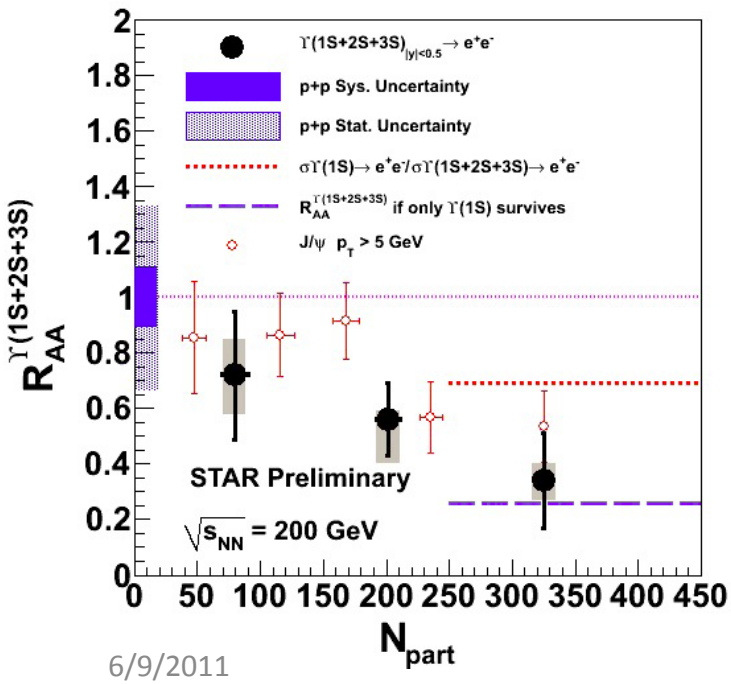
Heavier Quarkonia - Upsilons

Upsilons suppressed in CNM at RHIC (& at FNAL)



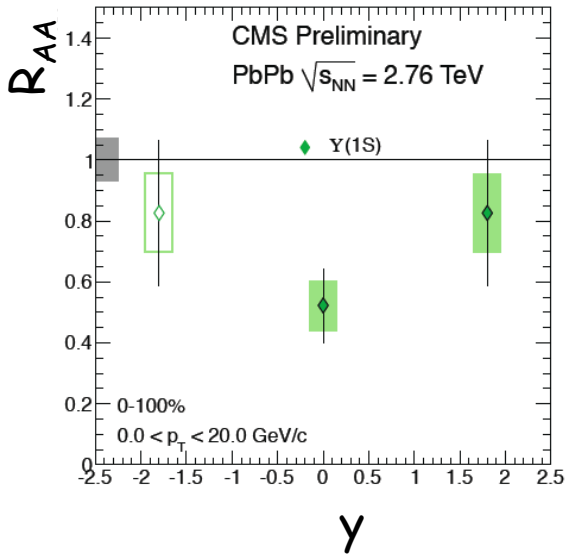


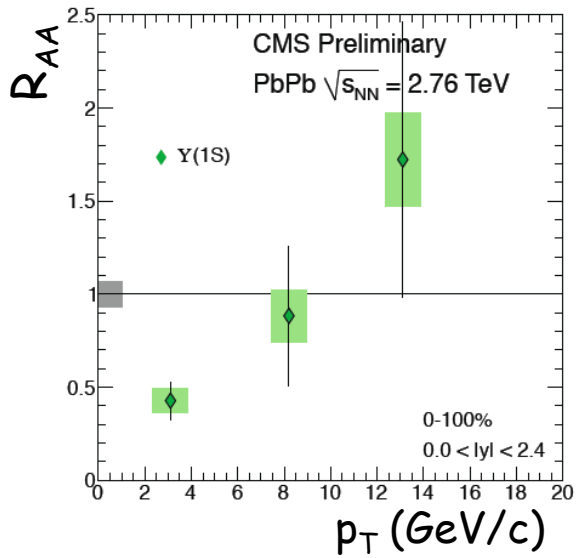




Upsilon suppression in Au+Au at RHIC – watch out for CNM suppression (as usual)!

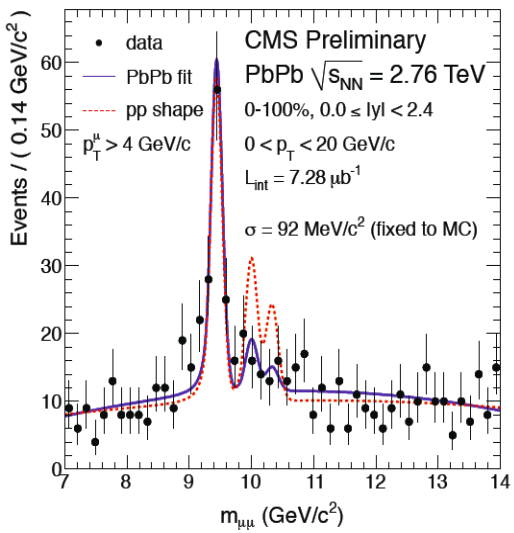
Heavier Quarkonia - Upsilons





Upsilons at LHC

- suppressed more at mid-rapidity
- show classic Cronin (p_T broadening) effect



Upsilon 2S+3S suppressed more than 1S

$$\frac{\Upsilon(2S+3S)/\Upsilon(1S)\big|_{PbPb}}{\Upsilon(2S+3S)/\Upsilon(1S)\big|_{pp}} = 0.31^{+0.19}_{-0.15} \pm 0.03$$

"Probability to obtain measured value, or lower, if the real double ratio is unity, has been calculated to be less than 1%"

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

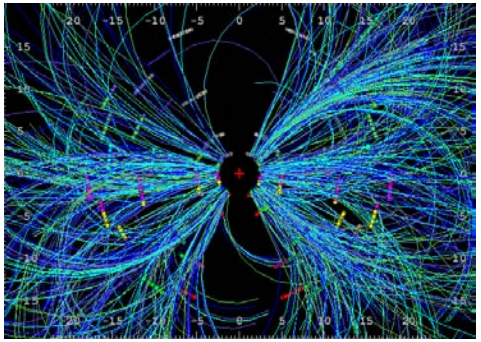


Table B.1: PHENIX run plan for the years 2010–2015. Longitudinal polarization is indicated by (L), transverse by (T).

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)	
	$d+$Au	200	8	$260\,nb^{-1}$	$150\,nb^{-1}$		CNM/FOCAL
	$d+$Au	62	2	$6.5\,nb^{-1}$	$3.8\,nb^{-1}$		
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

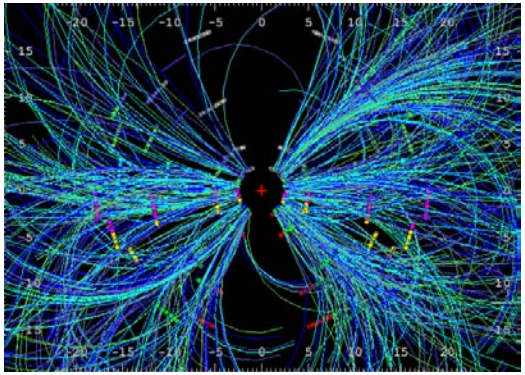
Projected Luminosities & Strawman PHENIX Run Plan

Run	Species	√s	Wks	±30 cm	±10 cm	Pol	Comments
11	p+p	500	10	27 pb^{-1}		50%(L)	W program + ΔG
	Au+Au	19.6	1.5	13.7M MB evts			energy scan
	Au+Au	200	8		700 μb^{-1}		heavy flavor (VTX)
12	p+p	200	5	13.1 pb^{-1}	4.7 pb^{-1}	60%(T)	HI ref. + transv. spin
	p+p	500	8	100 pb^{-1}	35 pb^{-1}	50%(L)	W program + ΔG
	Au+Au	200	7		800 μb^{-1}		Heavy flavor (FVTX/VTX)
	U+U	200	1.5		0.3 nb^{-1}		explore geometry
	Au+Au	27	1	5.2 μb^{-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 ref. + transv. spin
	Cu+Au	200	5		2.4 nb^{-1}		geometry
	U+U	200	5		0.57 nb^{-1}		geometry
14	p+p	200	10	34 pb^{-1}	12 pb^{-1}	65%(T)	HI ref. + transv. spin
	p+p	62	3	0.6 pb^{-1}	0.2 pb^{-1}	60%(T/L)	HI ref. + transv. spin
	d+Au	200	8	260 nb^{-1}	150 nb^{-1}		CNM
	d+Au	62	2	6.5 nb^{-1}	3.8 nb^{-1}		CNM
15	Au+Au	200	10		2.8 nb^{-1}		high bandwidth
	Au+Au	62	4		0.13 nb^{-1}		HF vs √s
	p+^{3}He	132	5			(T)	test run

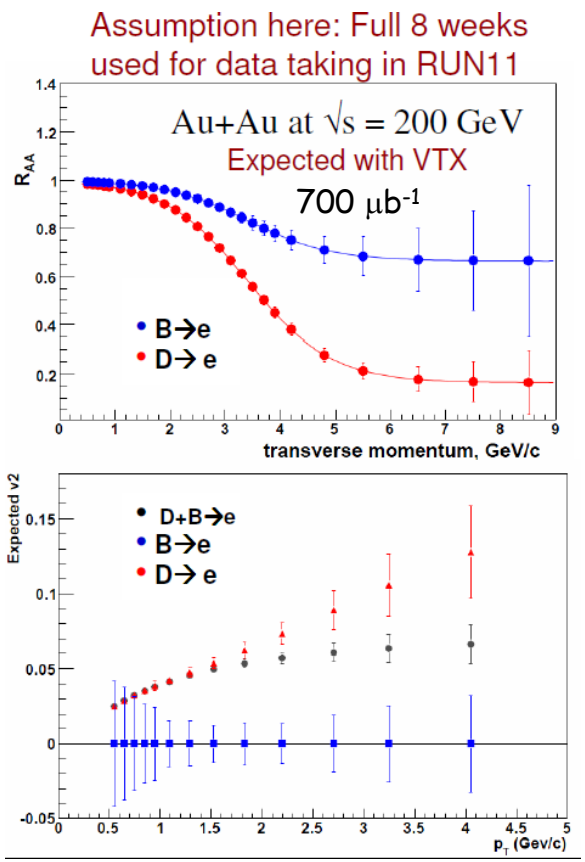
Quarkonia – looking to the Future

PHENIX Mid-rapidity Vertex Detector (VTX)

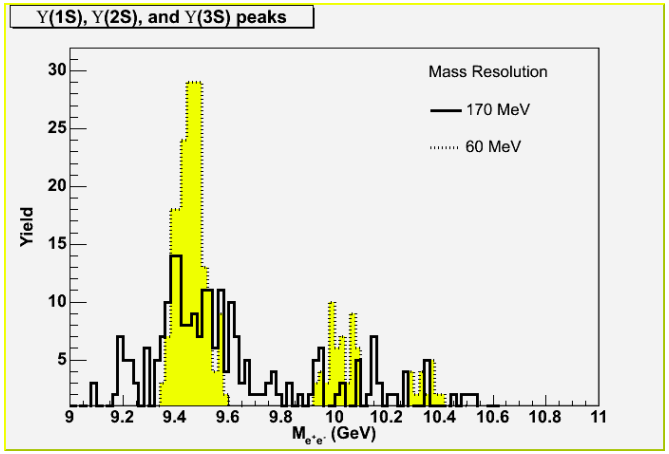
- Running now: charm, beauty; improved Upsilon resolution



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



Expectations for open-charm and beauty with VTX

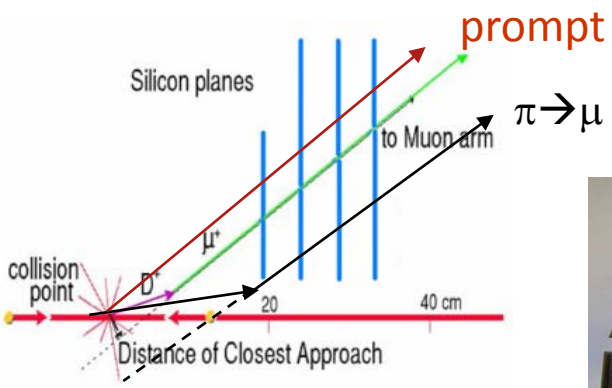


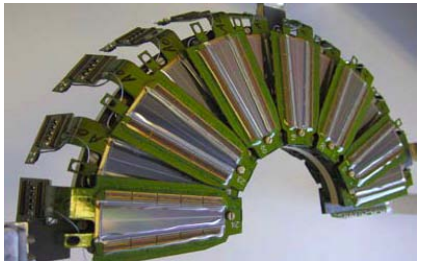
Improved separation of Upsilon states

Quarkonia – looking to the Future

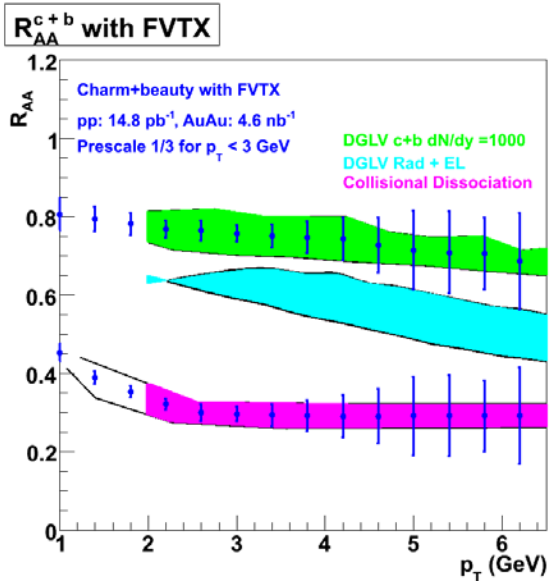
PHENIX Forward-rapidity Vertex Detector (FVTX)

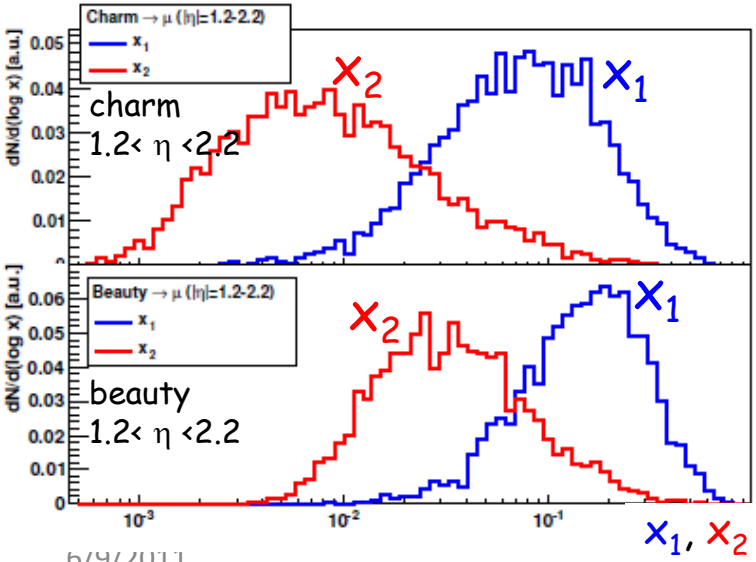
- Runs in 2012; forward charm, beauty; improved J/ψ resolution





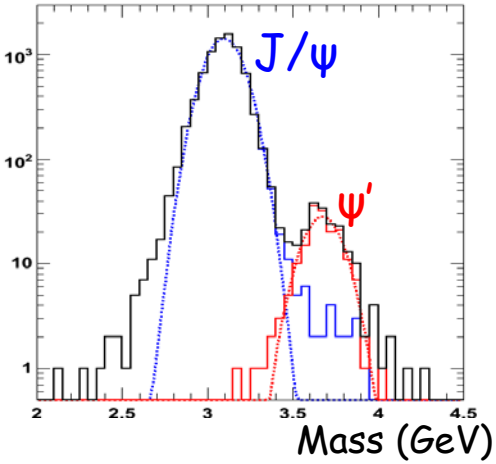
Resolving radiative & collisional dE/dx with the FVTX





x coverage for open-charm and beauty with FVTX

Improved separation of ψ'



Quarkonia – looking to the Future

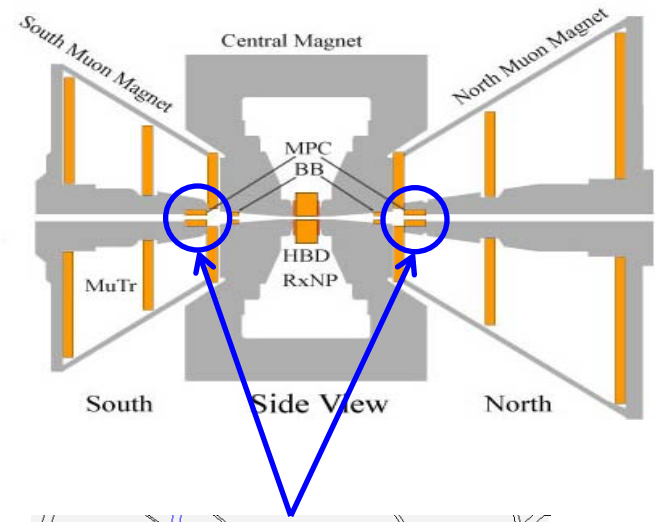
The MPC Extension (MPC-EX)

Enhance the forward direction ($3 < \eta < 3.8$) in PHENIX with a combined 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

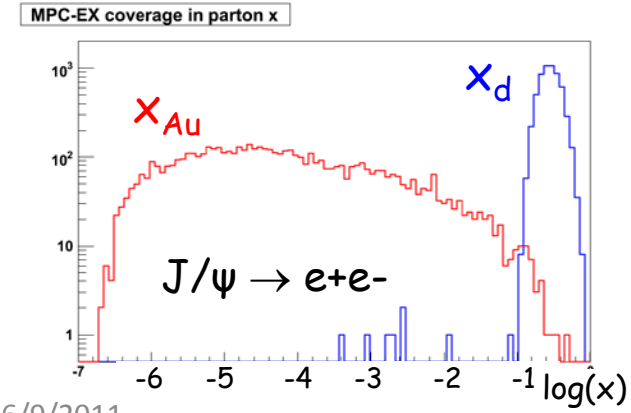
Technology:

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

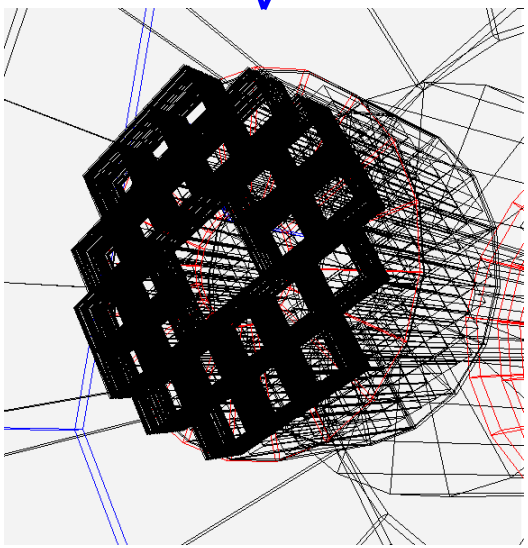


Projections for J/ψ (acceptance only, no efficiencies!):

- 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



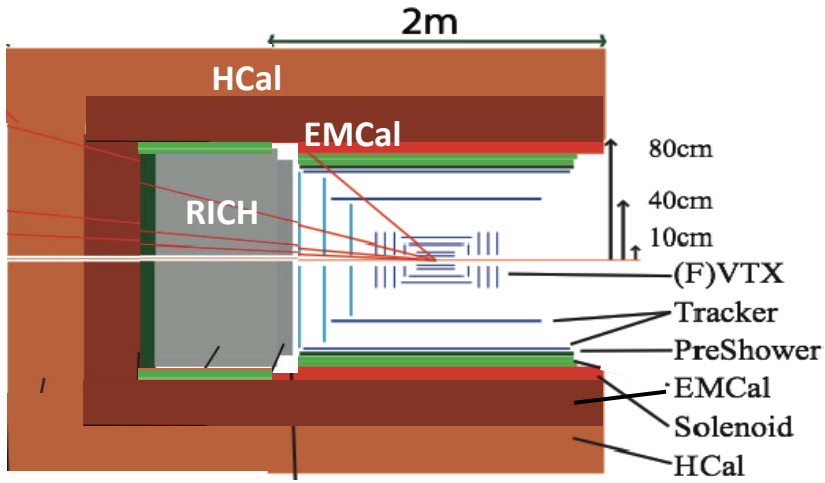
Ready for next d+Au in 2014?

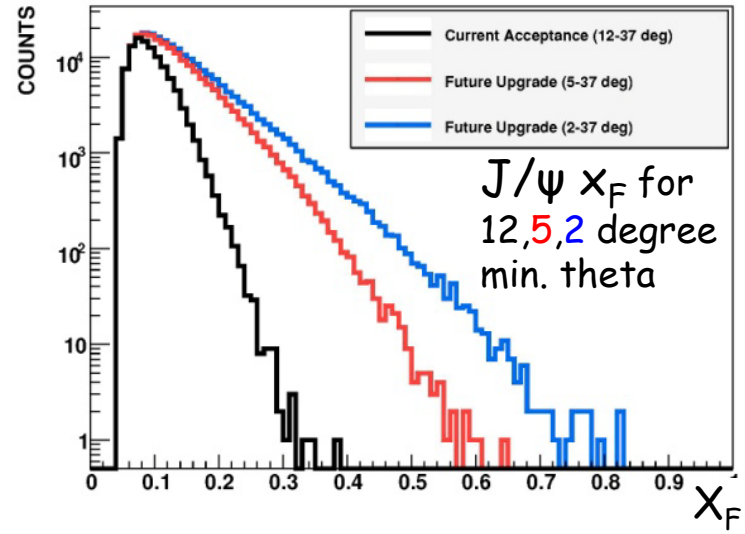


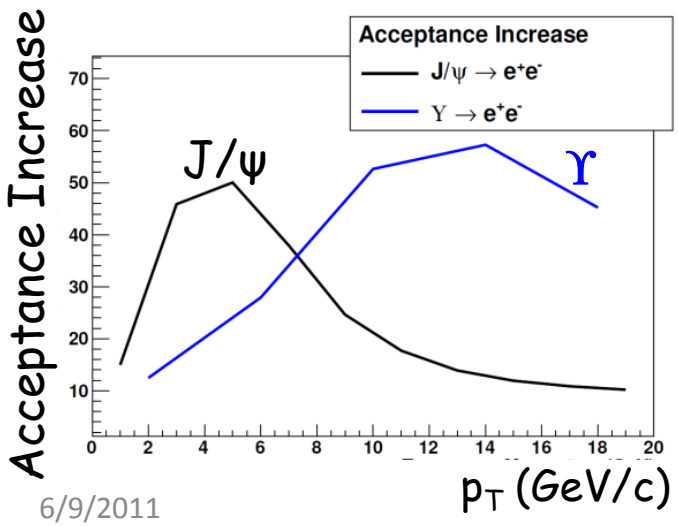
Quarkonia – looking to the Future

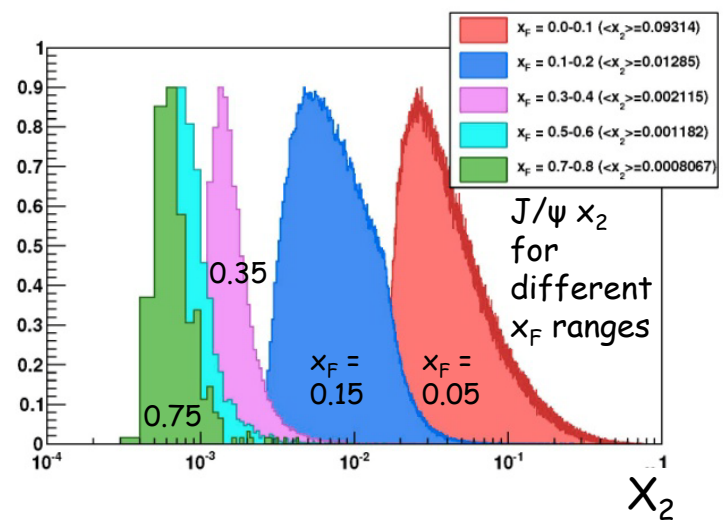
Decadal upgrades of RHIC detectors; at PHENIX:

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

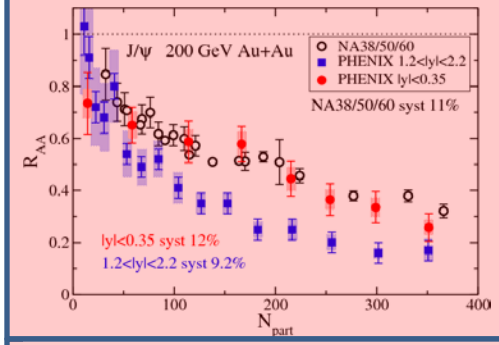




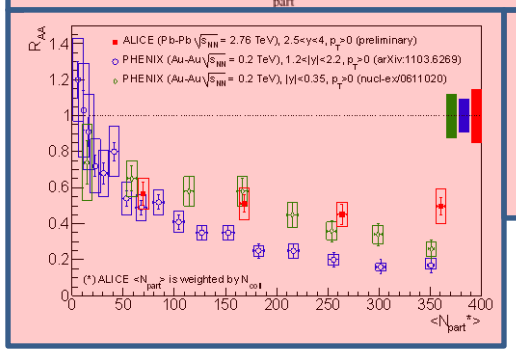




Summary

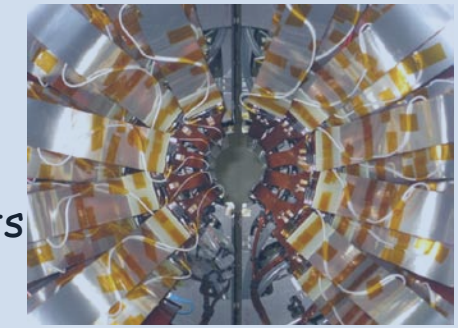


J/ψ suppression almost same at all energies

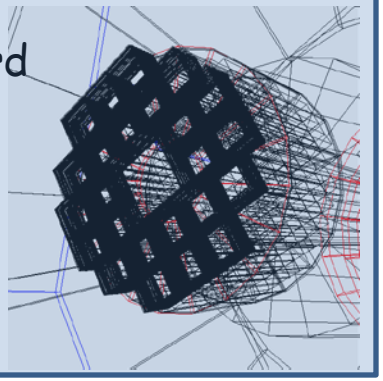


Hint of regeneration at LHC?

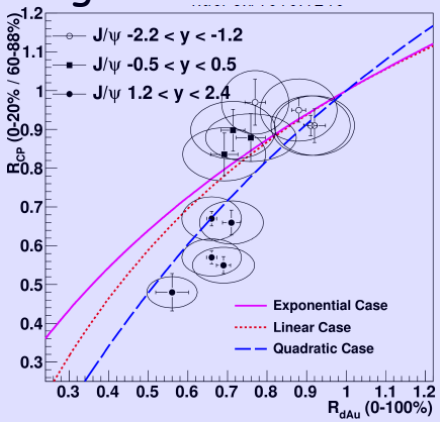
Vertex detectors for robust open-heavy measurements



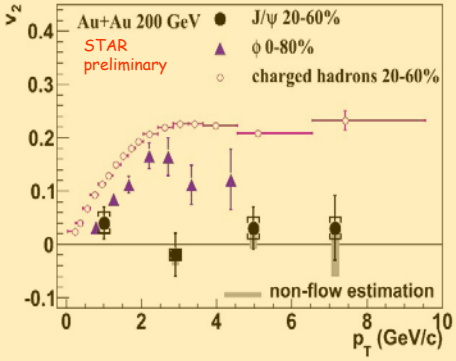
MPC-EX – improved forward calorimetry & small-x physics



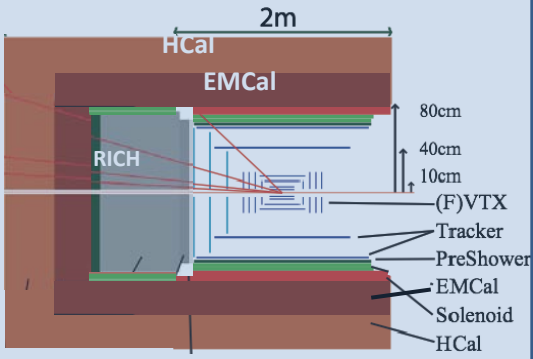
CNM suppression of J/ψ has stronger than linear dependence on density-weighted thickness



Flow not seen at RHIC



Decadal Upgrades to the RHIC detectors



Extra Slides

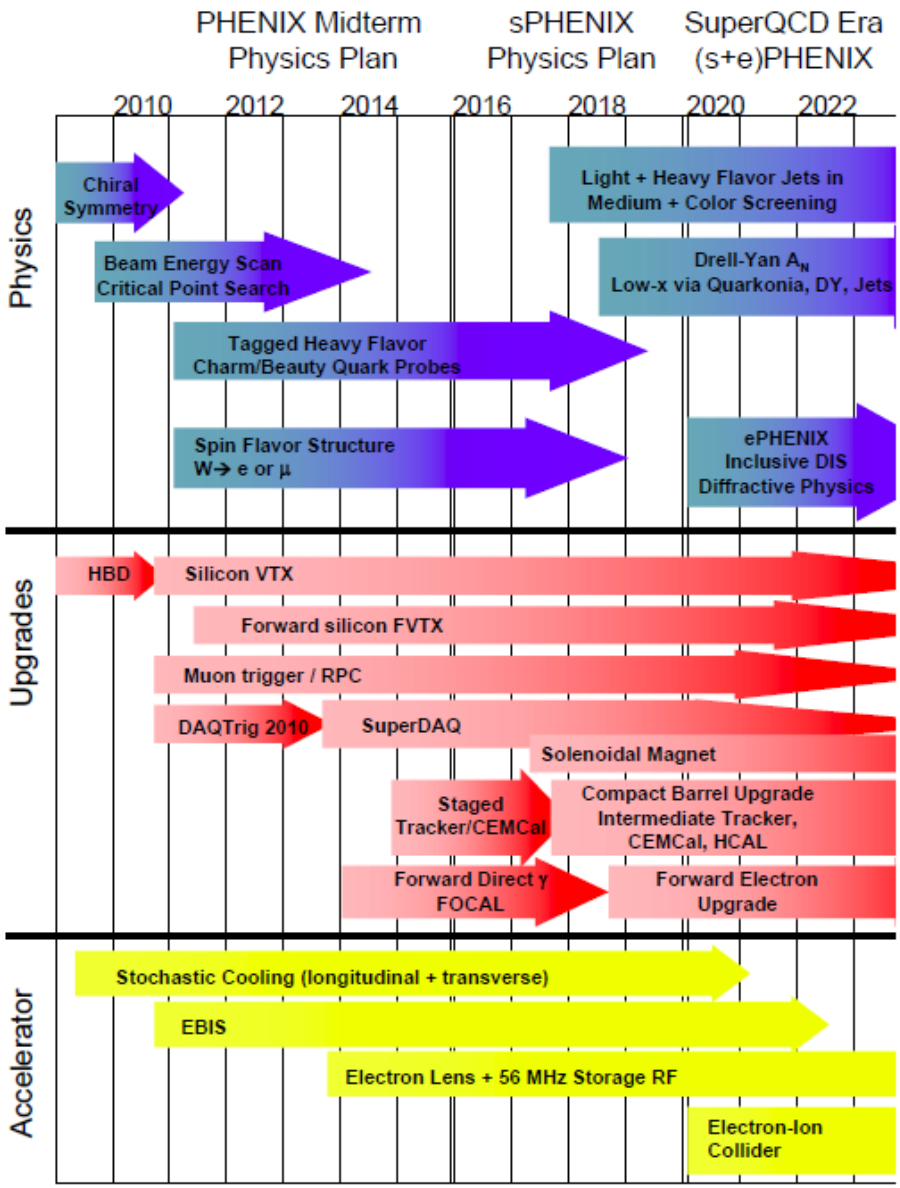
from PHENIX Decadal Plan – Quarkonia in the 5++ yr timescale

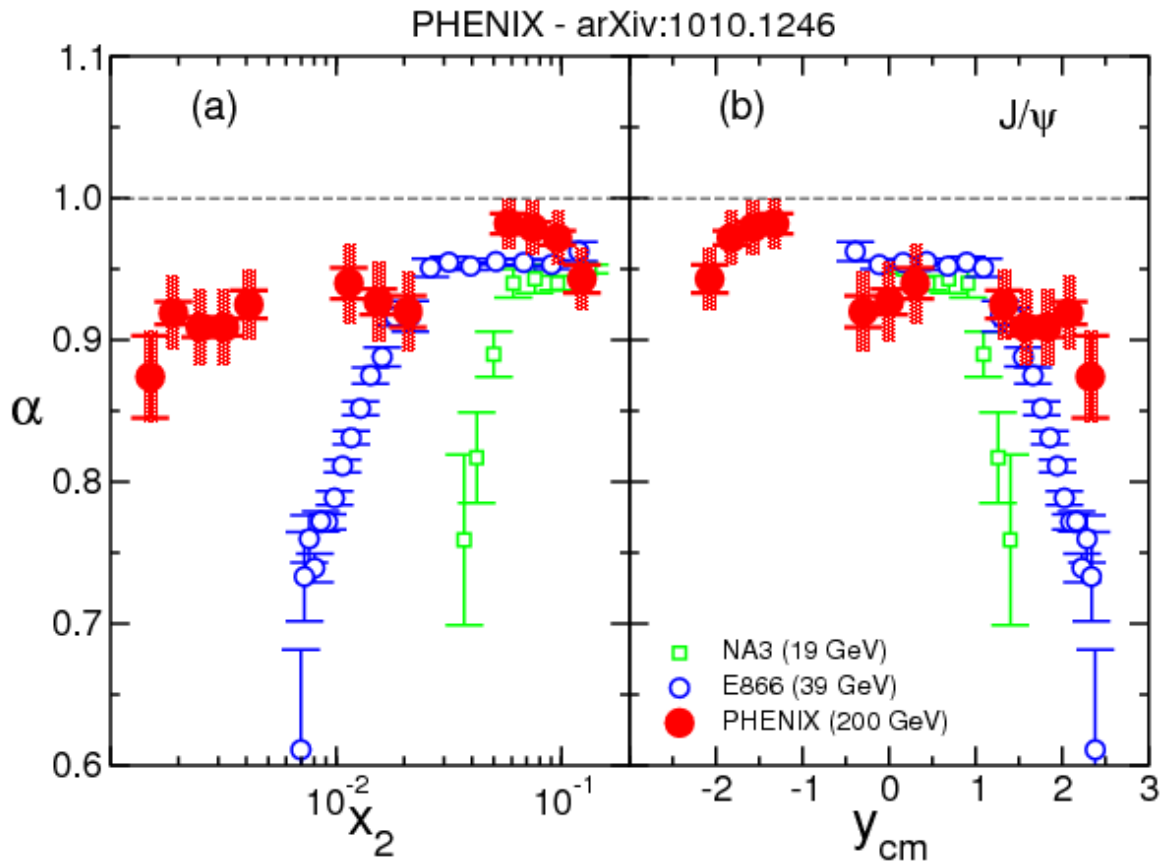
- Vary the temperature and lifetime of the QGP medium by changing the collision energy between $\sqrt{s_{NN}}$=62 GeV to 200 GeV (at RHIC) and 5.5 TeV (at the LHC), which changes the initial temperature from about 1.5Tc to about 4Tc and increases the lifetime by a factor of two to three

- Vary the size of the quarkonia states by observing the three bound states at LHC and RHIC, as well as the ψ' and possibly the χ_c

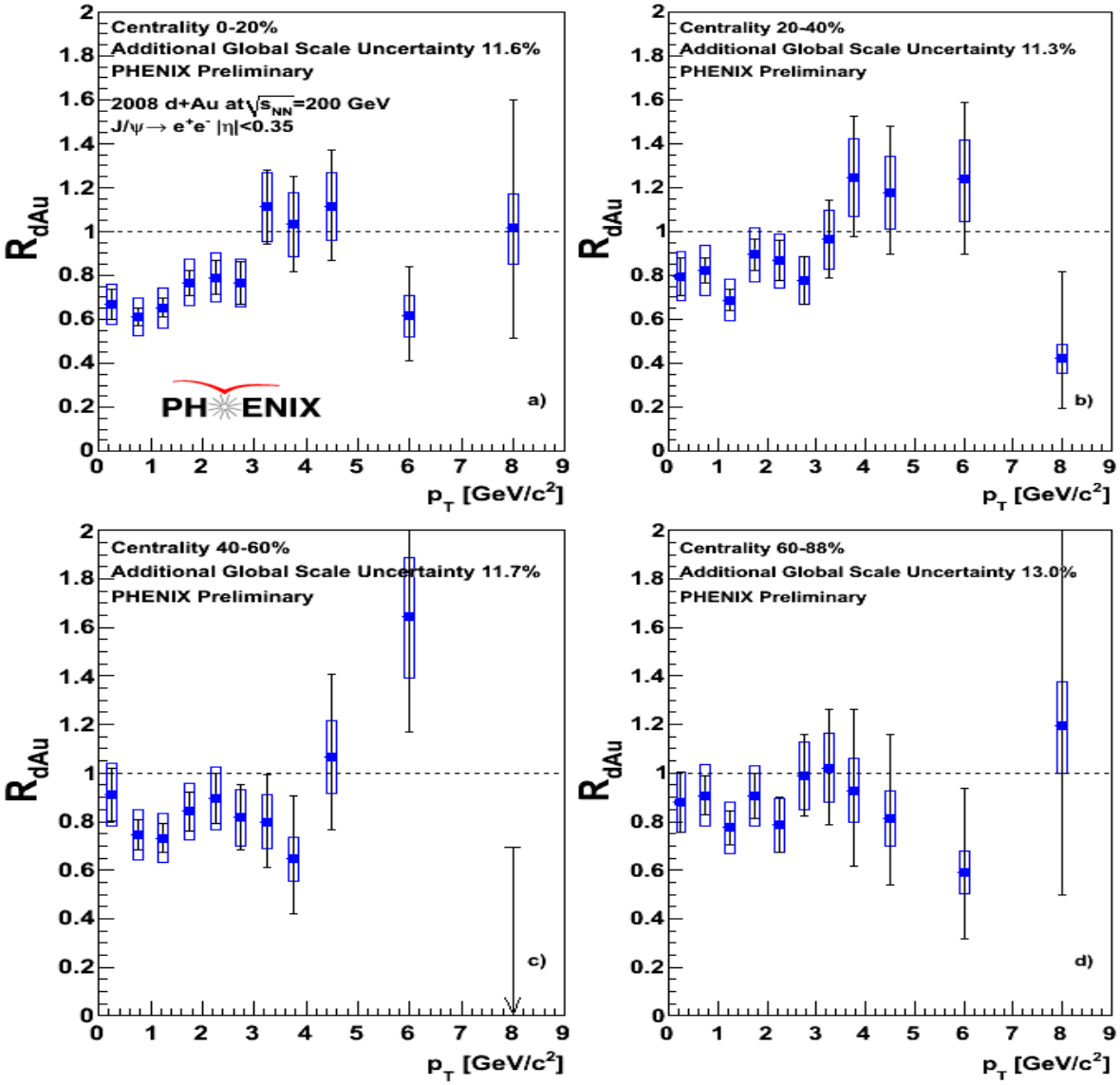
- Vary the underlying heavy quark production cross sections by observing charmonium and bottomonium produced at $\sqrt{s_{NN}}$=62 and 200 GeV and 5.5 TeV. The open charm and bottom cross sections are, respectively, about 15 and 100 times higher at LHC energy than at RHIC energy of 200 GeV
- When RHIC lowers the energy from 200 to 62 GeV, the charm production cross section is reduced by 1/3 and the beauty cross section by more than a factor of 10

With higher luminosities, larger acceptance, and more uniform reconstruction:
- High-pT J/ψ over a range from pT= 0–20 GeV/c.
- J/ψ elliptic flow (v2) over a range of pT= 0–10 GeV/c.
- J/ψ polarization in multiple frames, encoding information on the production mechanisms.
- Feed-down contribution to the J/ψ from the ψ' and χ_c.
- J/ψ-hadron and J/ψ-jet correlations.


PHENIX Midterm Physics Plan
sPHENIX Physics Plan
SuperQCD Era (s+e)PHENIX
2010
2012
2014
2016
2018
2020
2022
Physics
Chiral Symmetry
Beam Energy Scan Critical Point Search
Tagged Heavy Flavor Charm/Beauty Quark Probes
Spin Flavor Structure W→ e or μ
Light + Heavy Flavor Jets in Medium + Color Screening
Drell-Yan A_N Low-x via Quarkonia, DY, Jets
ePHENIX Inclusive DIS Diffractive Physics
Upgrades
HBD
Silicon VTX
Forward silicon FVTX
Muon trigger / RPC
DAQTrig 2010
SuperDAQ
Solenoidal Magnet
Staged Tracker/CEMCal
Compact Barrel Upgrade Intermediate Tracker, CEMCal, HCAL
Forward Direct γ FOCAL
Forward Electron Upgrade
Accelerator
Stochastic Cooling (longitudinal + transverse)
EBIS
Electron Lens + 56 MHz Storage RF
Electron-Ion Collider


PHENIX - arXiv:1010.1246
(a)
(b)
J/ψ
α
1.1
1.0
0.9
0.8
0.7
0.6
10^{-2}
10^{-1}
x_2
-2
-1
0
1
2
3
y_{cm}
NA3 (19 GeV)
E866 (39 GeV)
PHENIX (200 GeV)

New p_T dependence of R_{dAu}



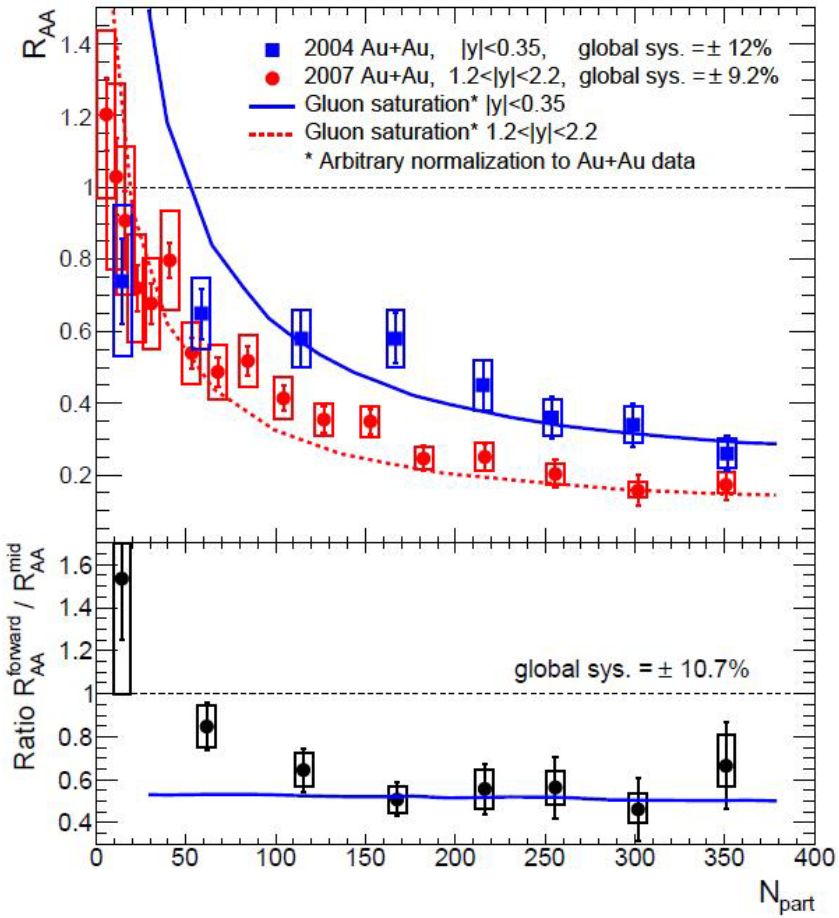
- R_{dAu} at midrapidity $|y|<0.35$.
- Convoluted shadowing + Cronin effect.
- Proper geometry dependence of shadowing needed.

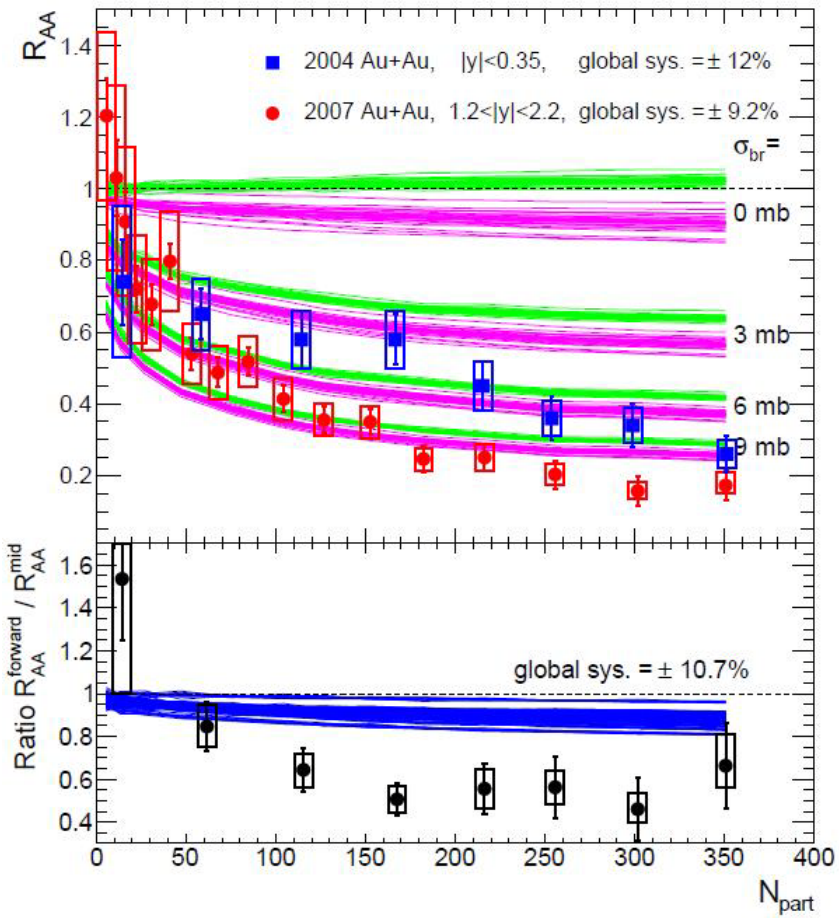
See Darren McGlinchey's Poster

J/ψ R_{AA} vs N_{part} in A+A

New 2007 data

More comparisons are shown at arXiv:1103.6269

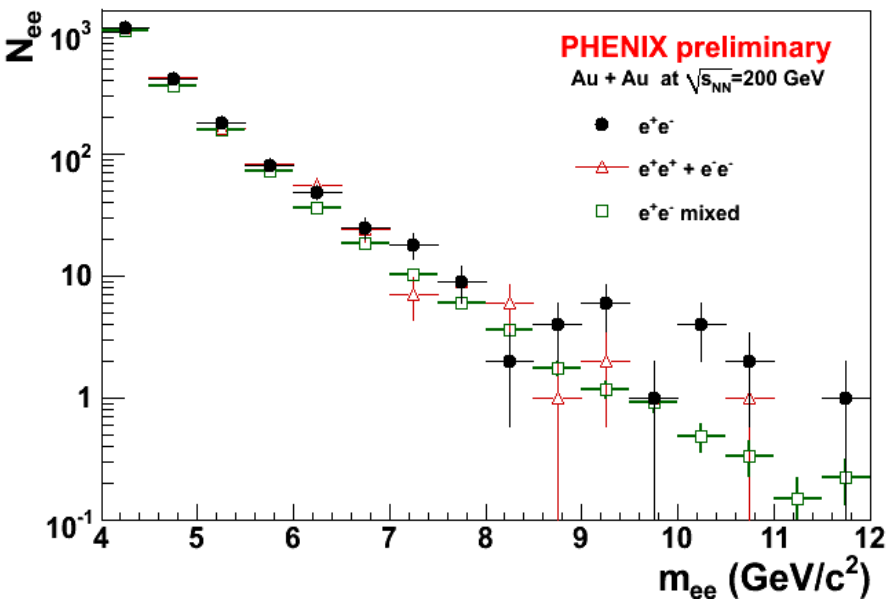


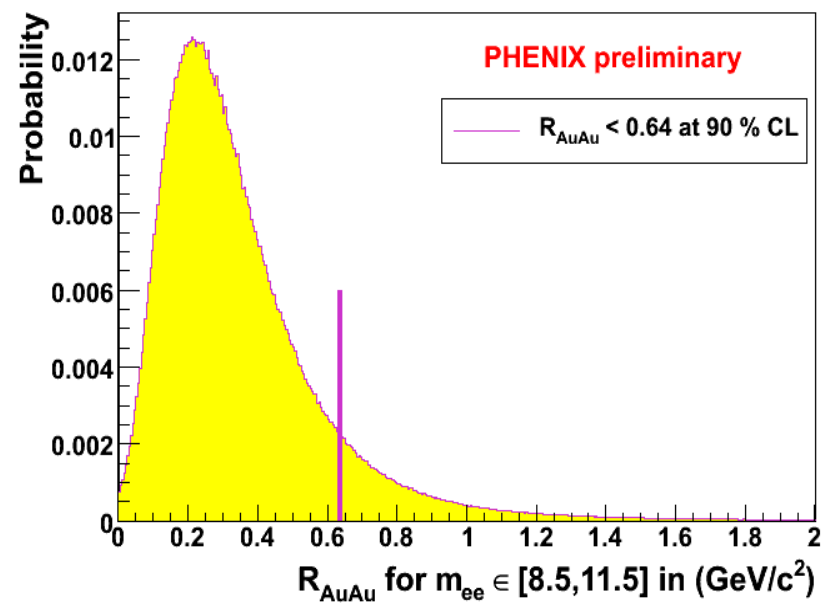


Color Glass Condensate(CGC)
Arbitrary normalization by mid rapidity

Shadowing/Nuclear absorption/Initial state parton energy loss

ϒ (or rather: high mass di-leptons) R_{AA} in A+A





-0.35 < y < 0.35

R_{AuAu} [8.5,11.5] < 0.64 at 90% C.L.

- Derived a 90% C.L. for high-mass dileptons R_{AA}