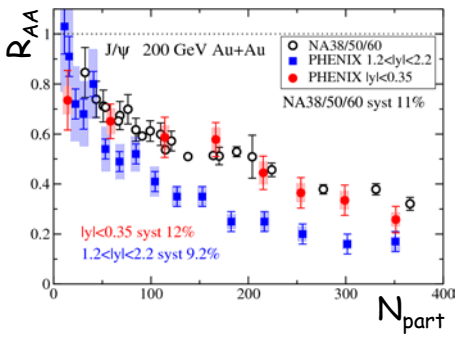
Landscape of the Quarkonia Puzzle

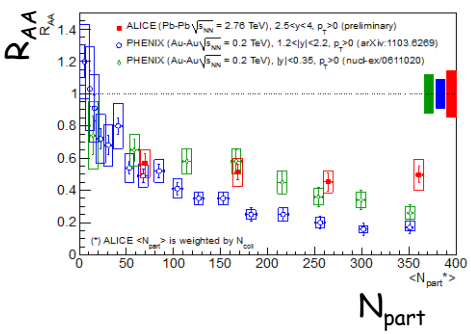
Quarkonia in Deconfined Matter Workshop

Acitrezza, Italy - Sep 28-30, 2011

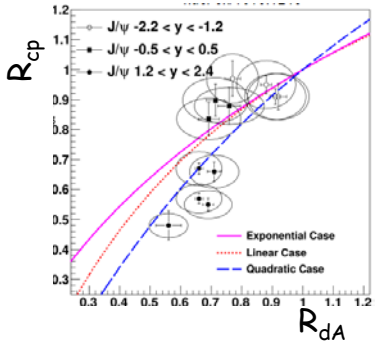
Mike Leitch, LANL



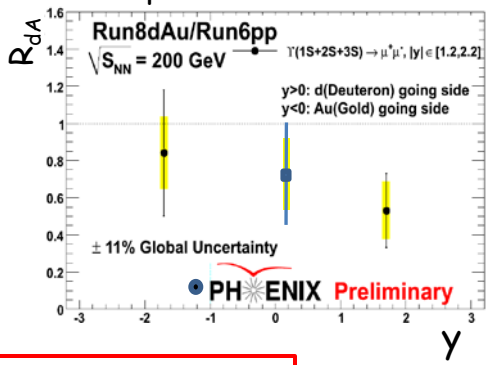
Energy dependence of Quarkonia suppression



Non-linear CNM effects



Upsilon CNM effects



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

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??

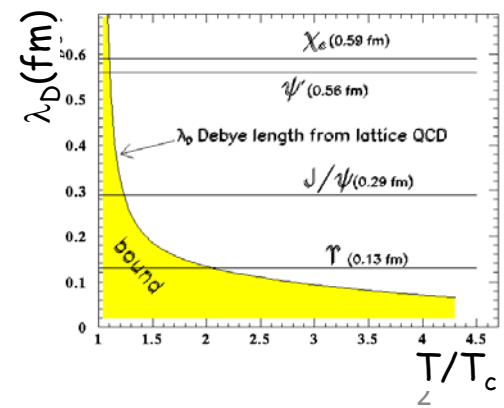
Matsui and Satz, Phys. Lett. B 178 (1986) 416:

"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."

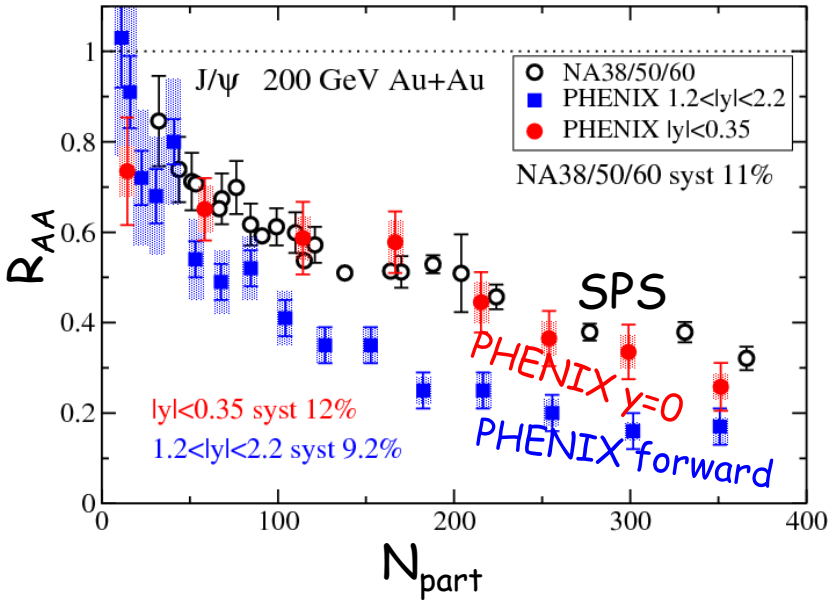
Debye screening predicted to destroy J/ψ's in a QGP with other states "melting" at different temperatures due to different sizes or binding energies.

Satz, 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

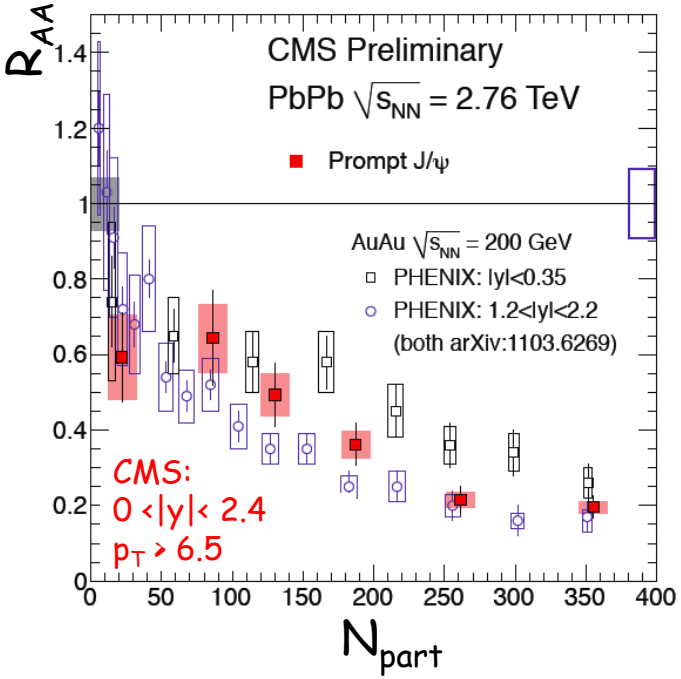


Quarkonia Suppression in A+A Collisions – key observations and questions

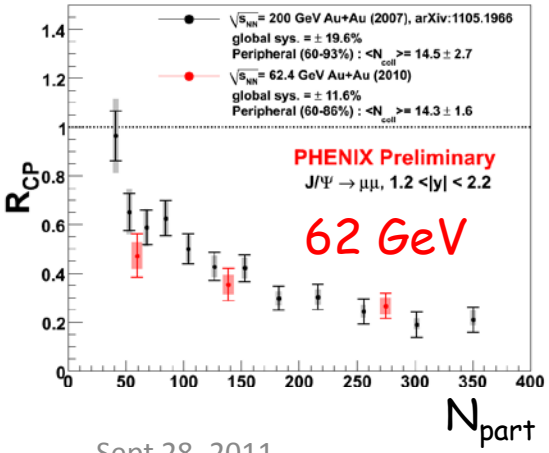


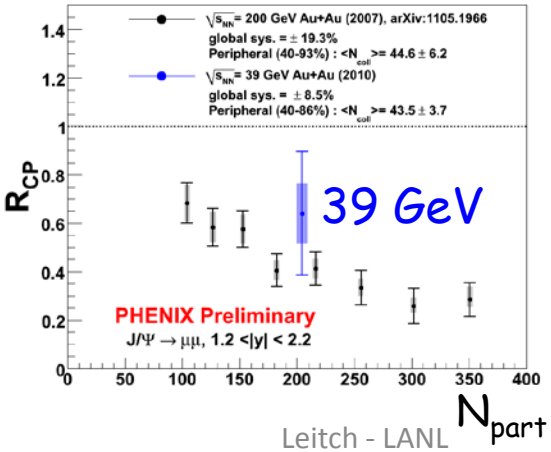
Overall suppression of J/ψ is very similar between:

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

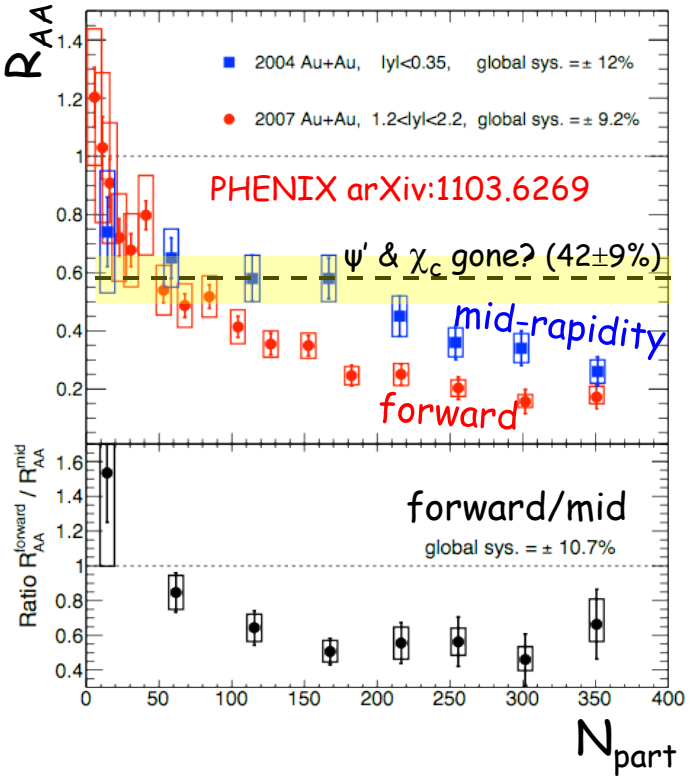


(more on LHC in a minute)





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



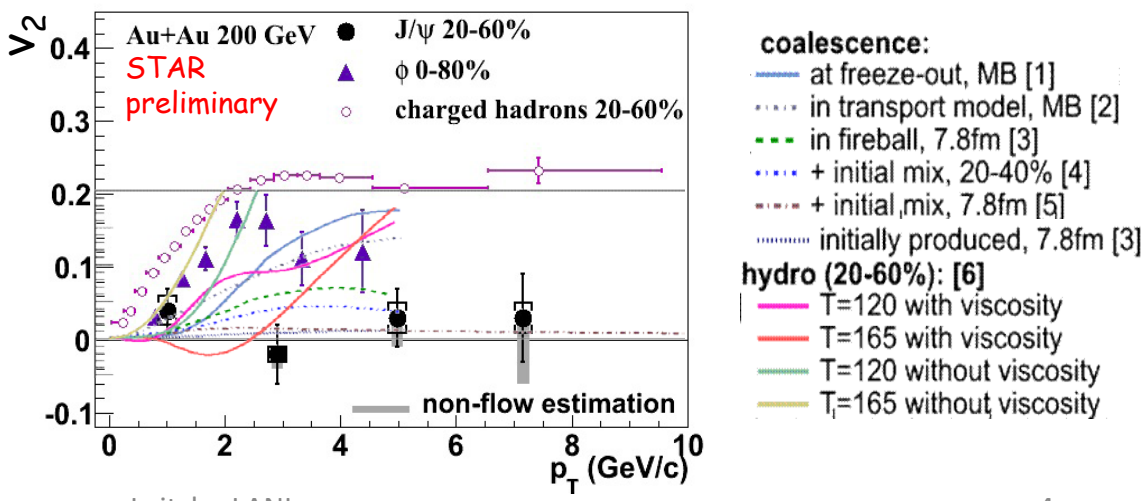
At RHIC - Forward-rapidity J/ψ's are suppressed more than Mid-rapidity – Why?

1) Stronger forward rapidity suppression due to CNM effects?

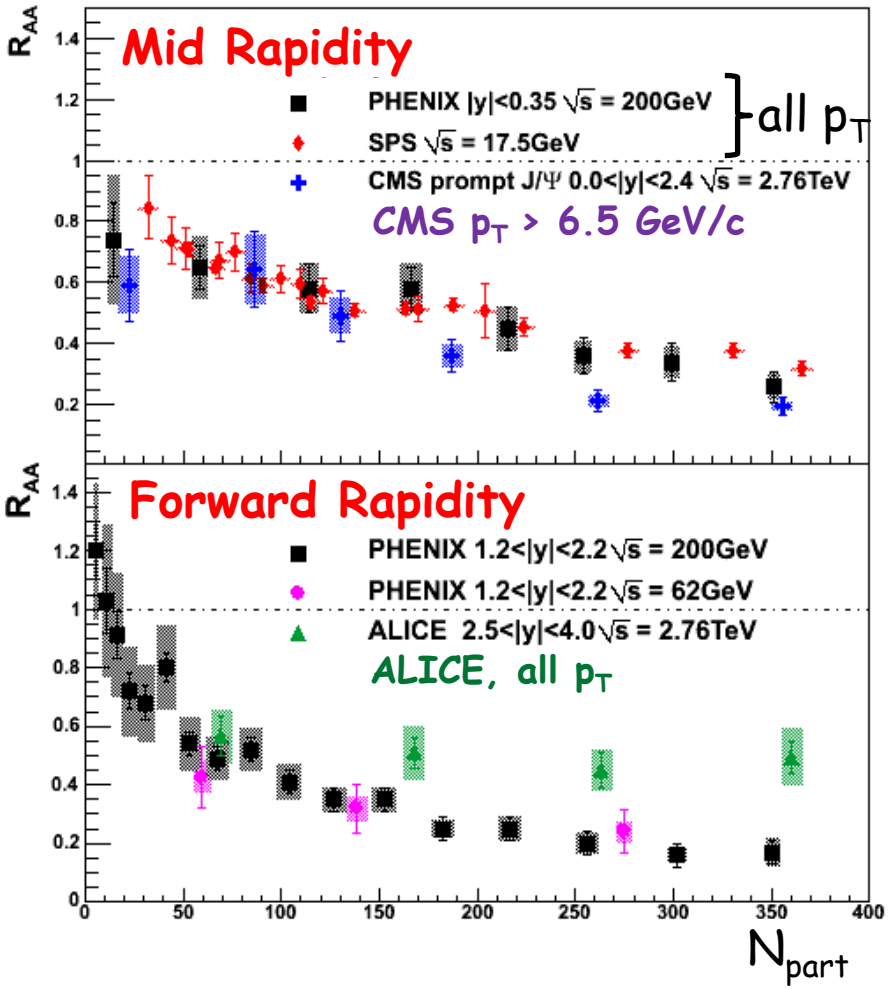
2) Regeneration at mid-rapidity reduces suppression relative to forward (and gives net suppression similar to SPS)?

Small or no J/ψ flow at RHIC!

Many theoretical expectations & option #2 probably ruled out?



Quarkonia Suppression in A+A Collisions – comparing RHIC & LHC



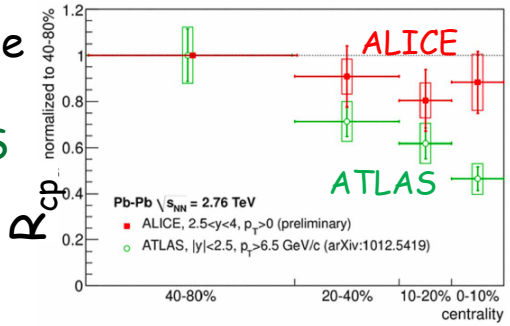
Missing LHC data – y~0, p_T→ 0 R_{AA}?
(where regeneration may be rather large)

caution *caution*

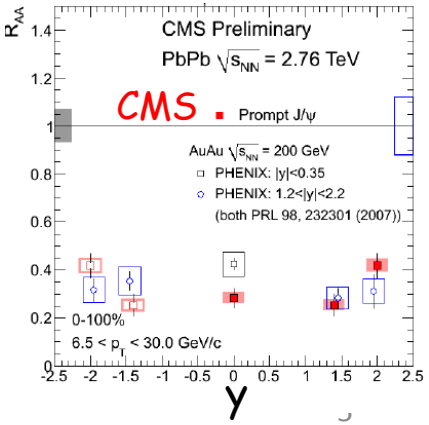
- LHC suppressed more than RHIC at y~0 (but CMS is p_T→ 6.5 GeV/c)
- LHC suppressed less than RHIC at forward y (here ALICE is p_T→ 0)

Features expected from regeneration, which is concentrated at small p_T

High-p_T suppressed more than low p_T (but ALICE y~3; ATLAS y~0)

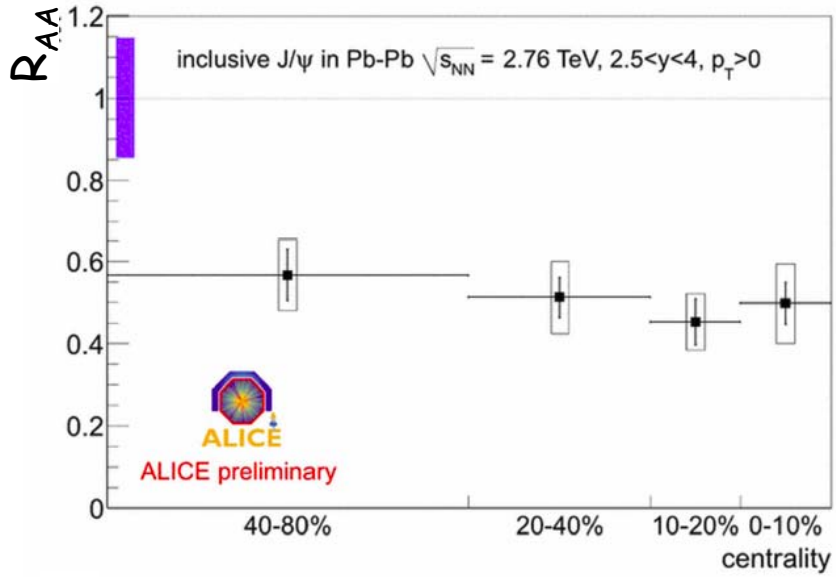


However suppression roughly flat with rapidity for p_T→6.5

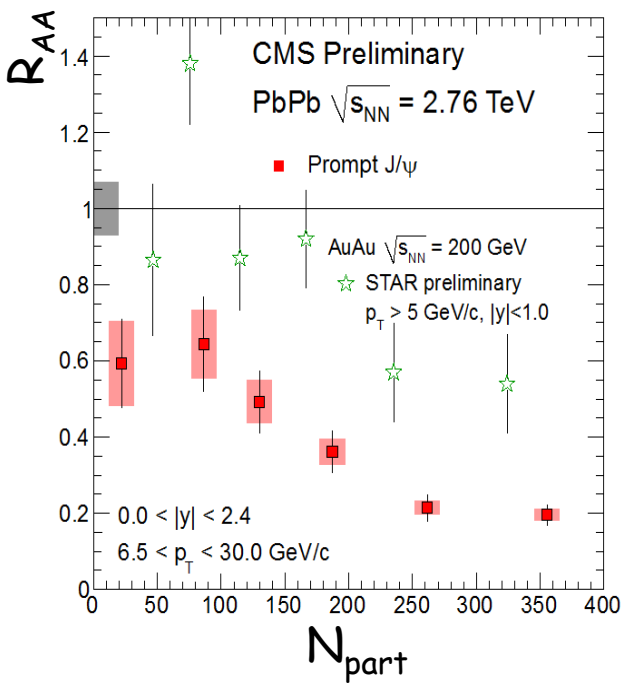


So may also be consistent with regeneration at small p_T

Quarkonia Suppression in A+A Collisions – comparing RHIC & LHC



Regeneration could cause suppression to be flat with centrality, as seen by ALICE (forward rapidity, all p_T)

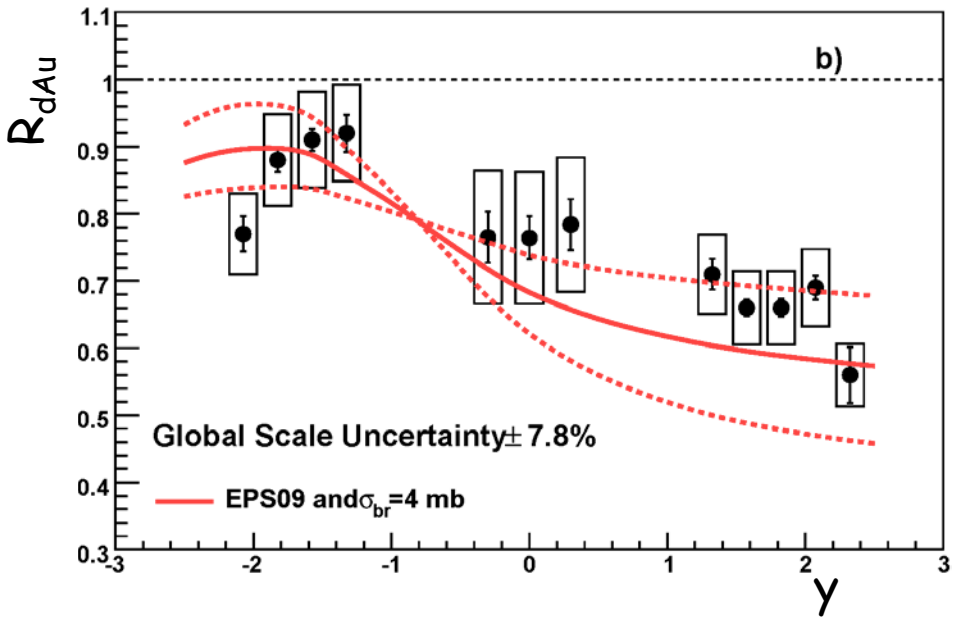


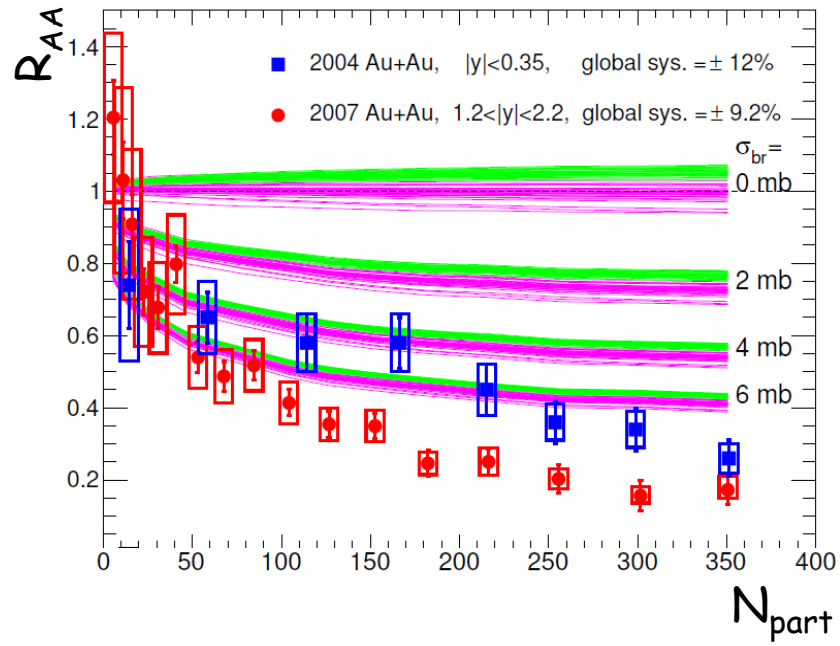
CMS more suppressed than STAR at high p_T where regeneration should not be important – stronger screening/QGP suppression at the LHC?

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



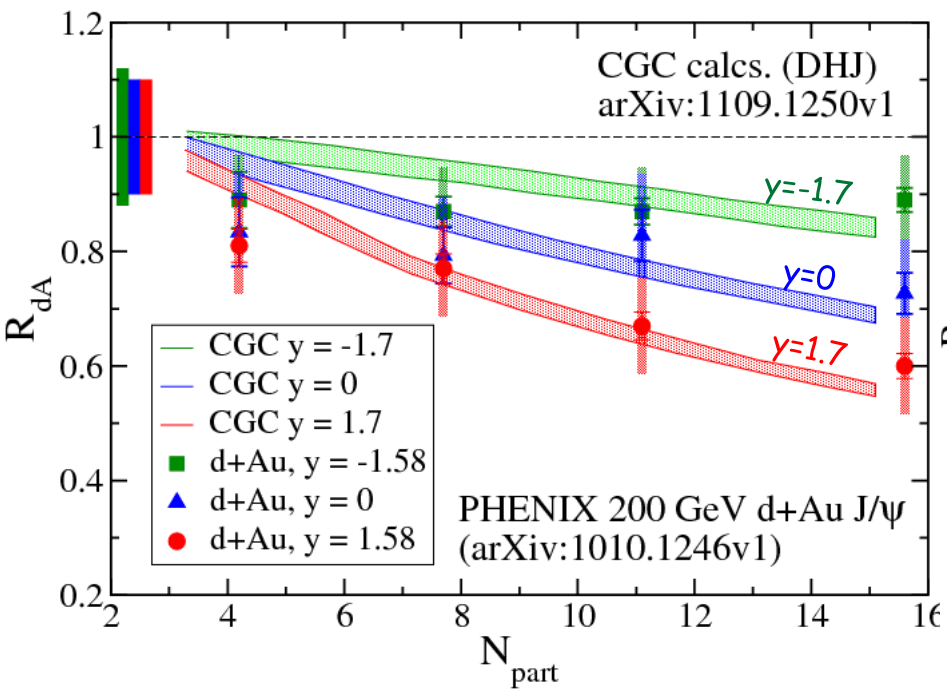


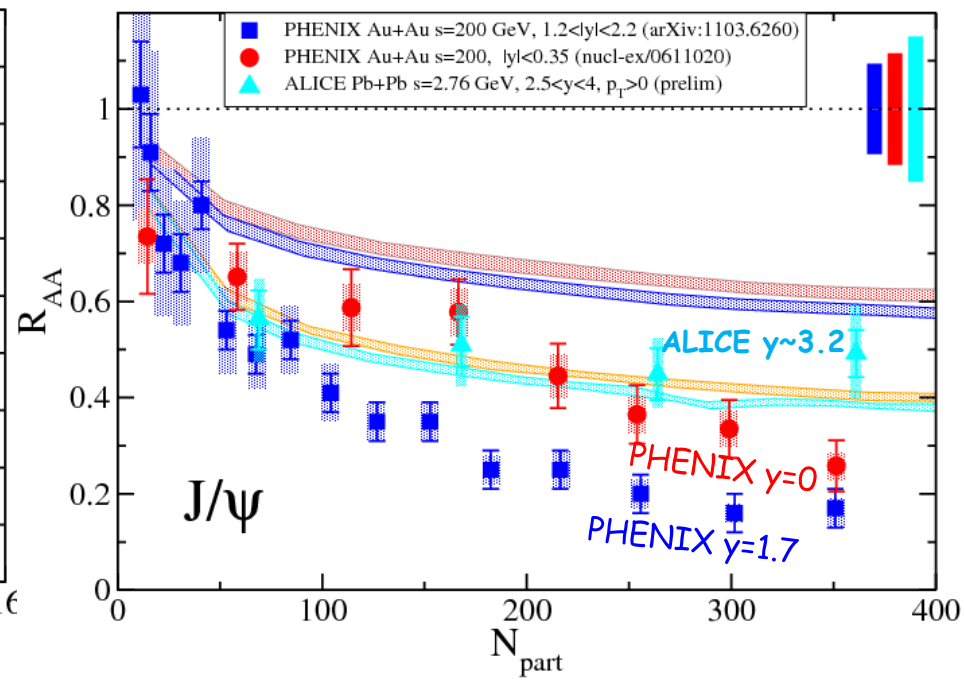
Probably have to understand CNM in a fundamental way in order to extrapolate to A+A correctly

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

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

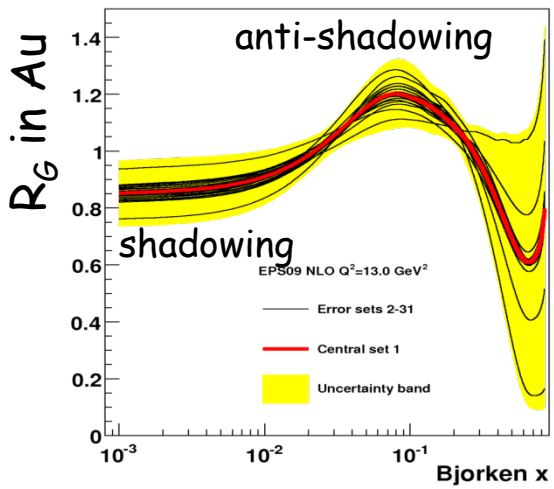
- However, they do not help explain the stronger suppression at forward rapidity in A+A

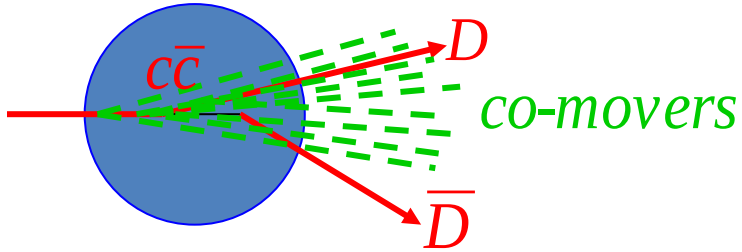




What are the CNM effects that are so strong in Quarkonia production?

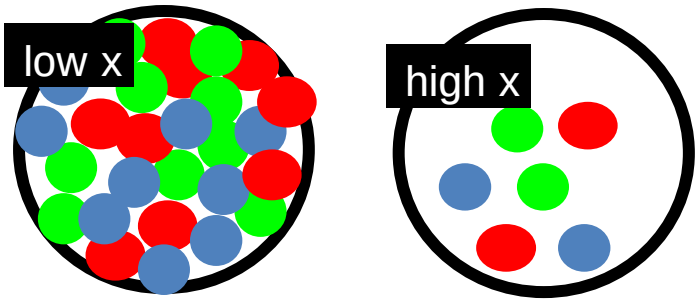
Traditional shadowing from fits to DIS or from coherence models



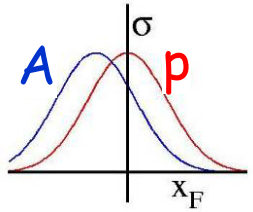


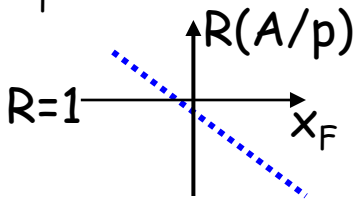
Absorption (or dissociation) of $c\bar{c}$ into two D mesons by nucleus or co-movers

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





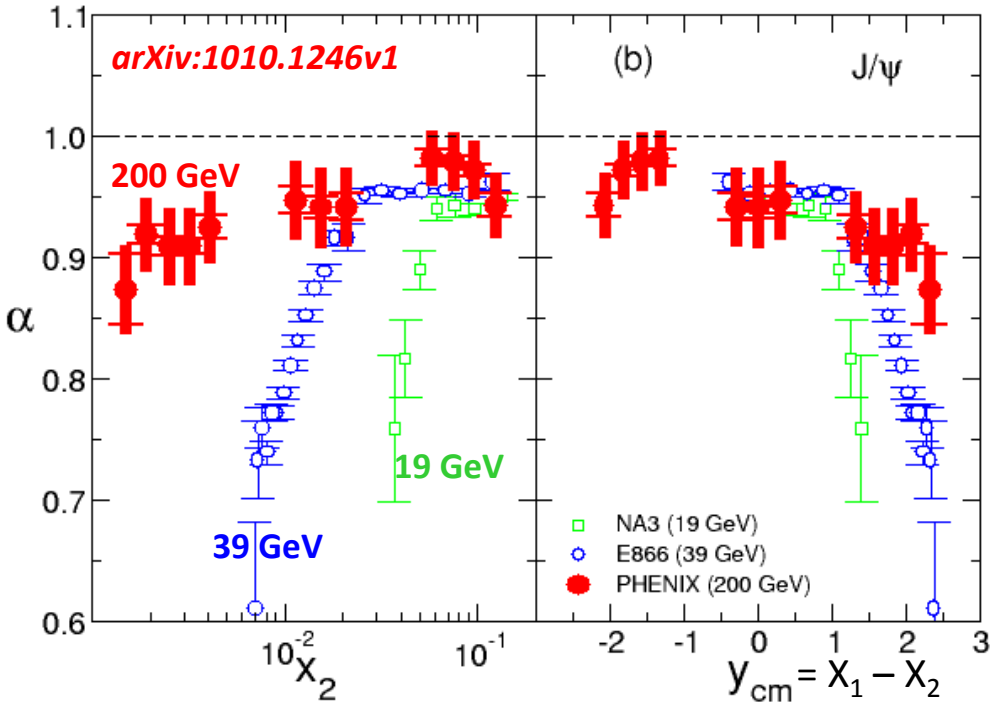
What are the CNM effects that are so strong in Quarkonia production?

Scaling between measurements at different Energies

PHENIX, E866, NA3 Comparison

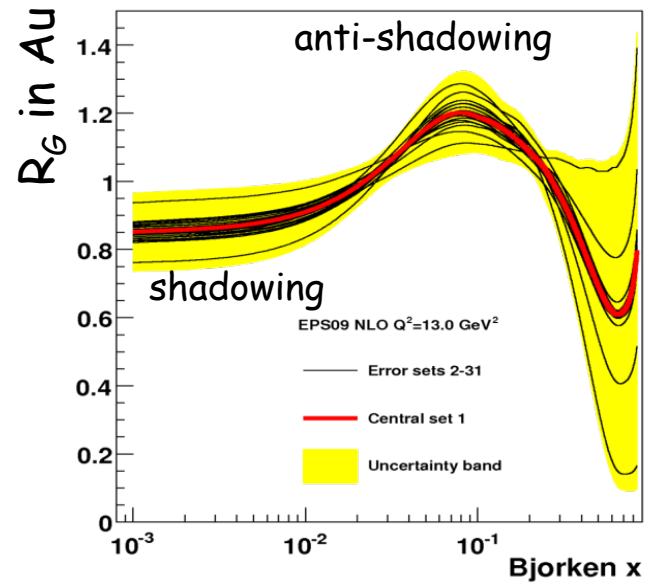
$$\sigma_{pA} = \sigma_{pp} A^{\alpha}$$

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

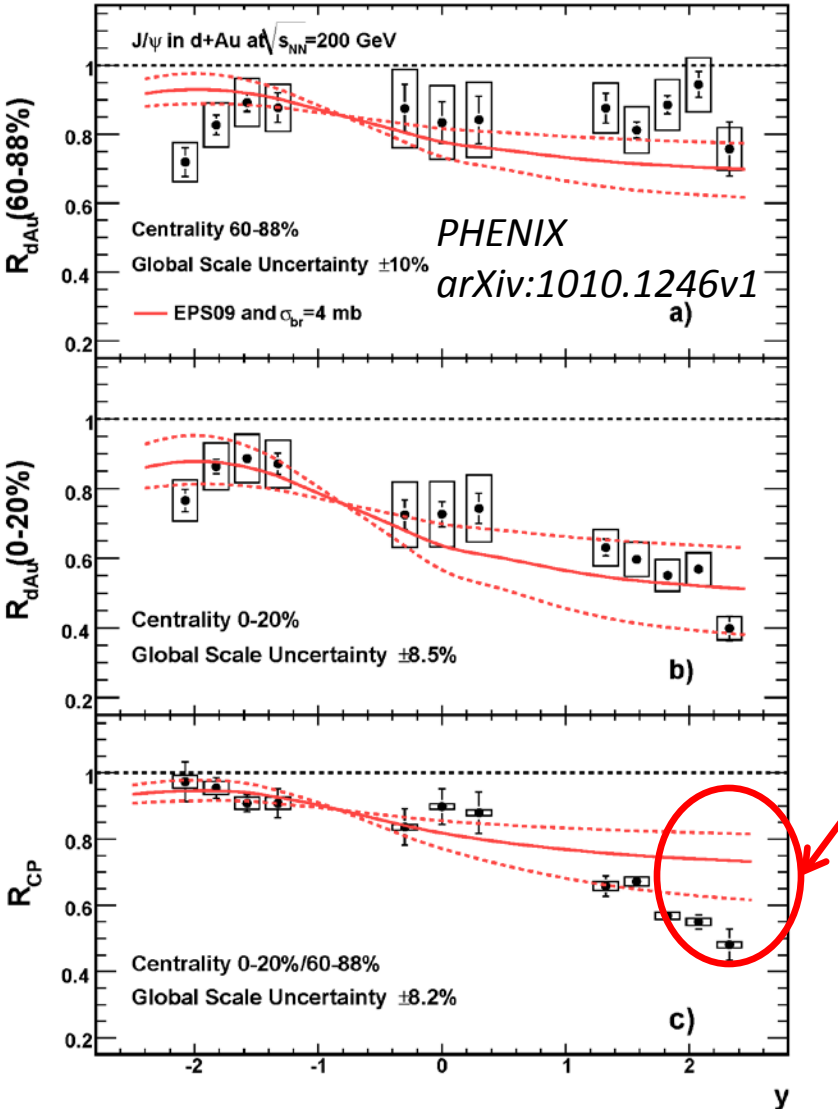


Closer to scaling with x_F or rapidity

- 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

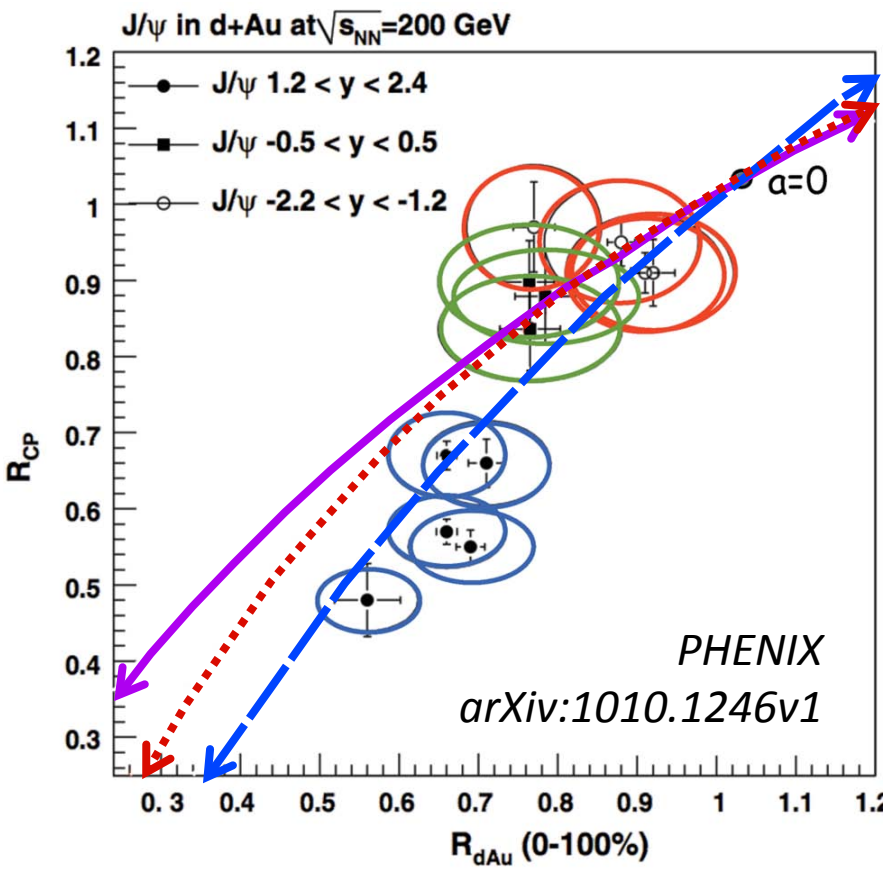


Reasonable agreement with EPS09 nPDF + σ_{br}=4 mb for central collisions but not peripheral

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

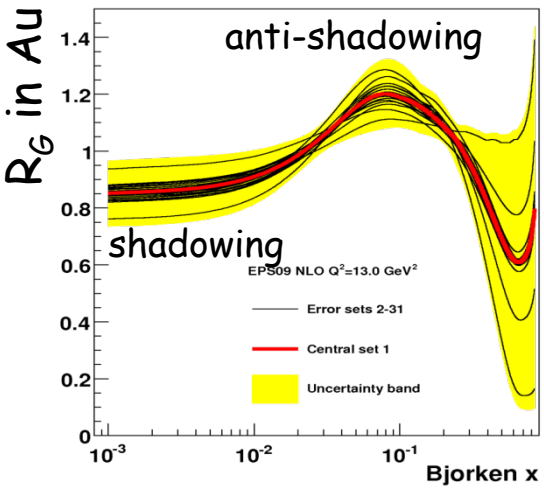
The forward rapidity points suggests a quadratic or higher geometrical dependence

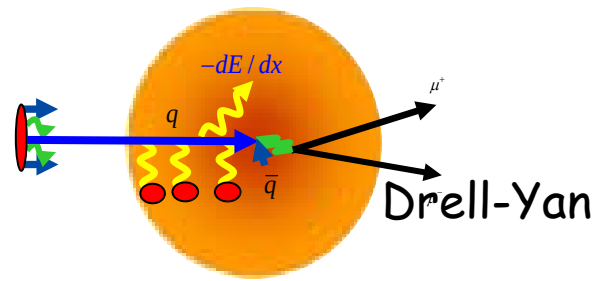
What are the CNM effects that are so strong in Quarkonia production?

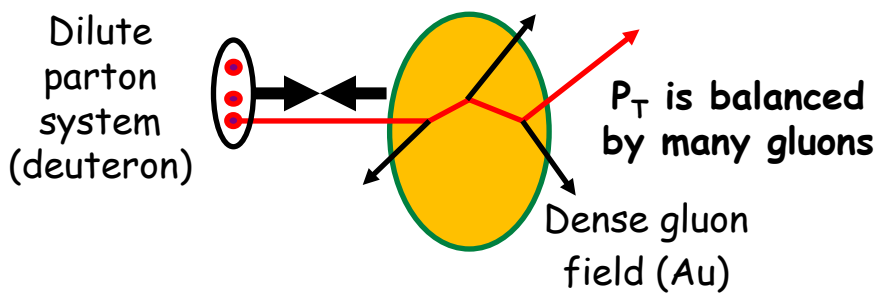
The various CNM effects are difficult to disentangle experimentally – multiple probes, types & energies of collisions, wide kinematic coverage are key

- 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







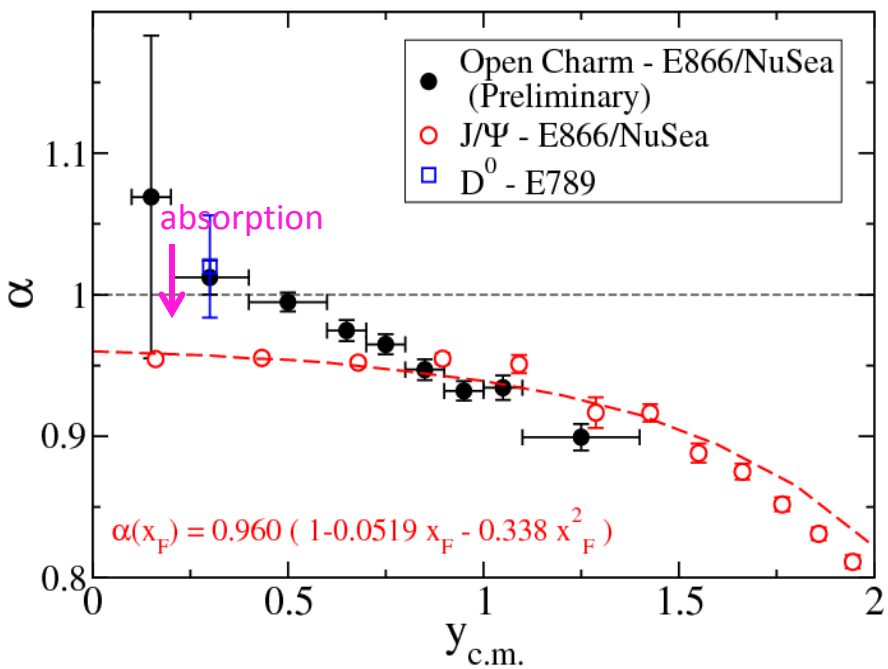
What are the CNM effects that are so strong in Quarkonia production?

Open-heavy suppression – Isolates initial-state effects

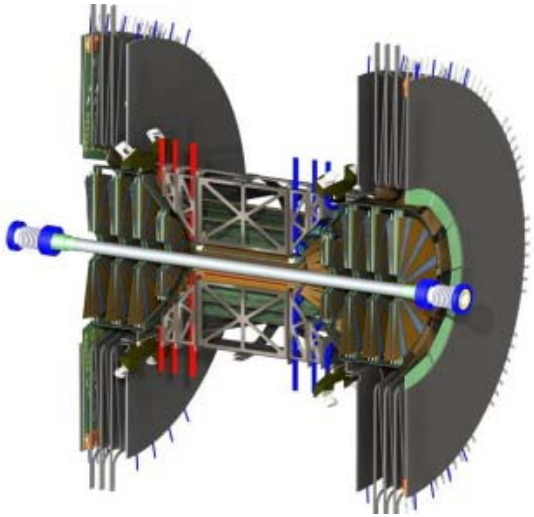
Open-charm p+A nuclear dependence (single-μ p_T > 1 GeV/c) – very similar to that of J/Ψ (E866/NuSea, 39 GeV):

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

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

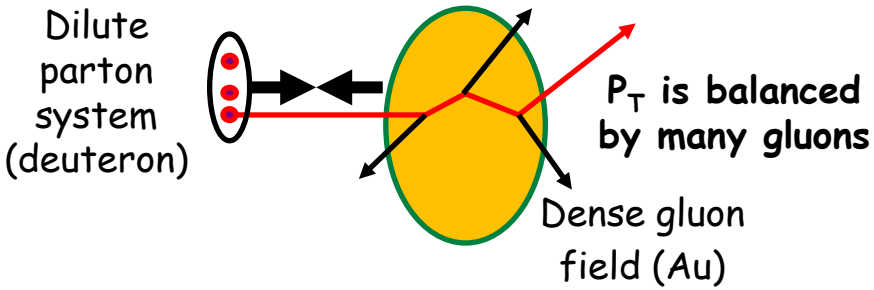


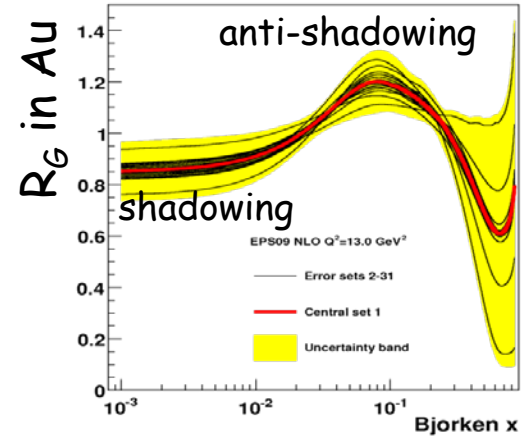
Soon new PHENIX c,b measurements with VTX/FVTX to isolate initial & final-state effects via precision comparisons with Quarkonia (and later STAR HFT)



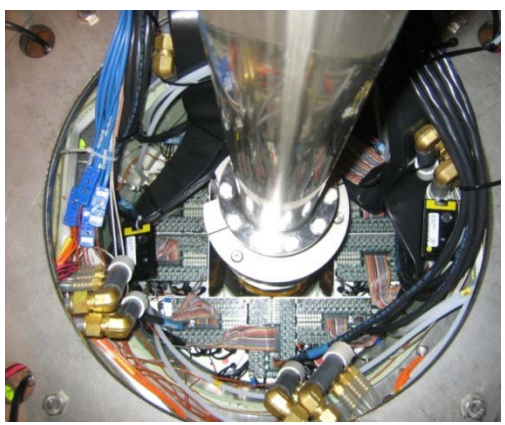
What are the CNM effects that are so strong in Quarkonia production?

Other probes of shadowing & gluon saturation – Forward hadrons

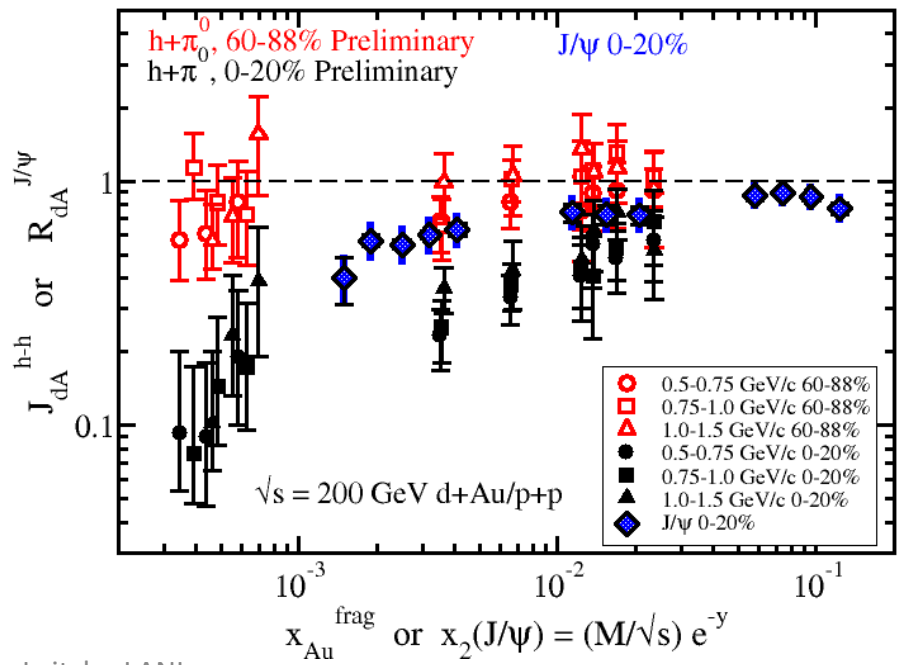




Mono-jets in the gluon saturation (CGC) picture give suppression of pairs per trigger and some broadening of correlation
Kharzeev, NPA 748, 727 (2005)



PHENIX MPC

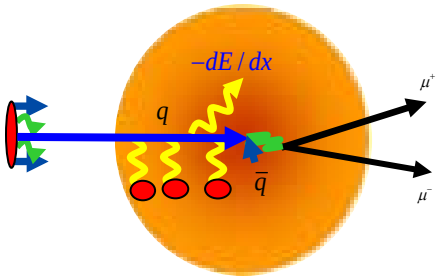


What are the CNM effects that are so strong in Quarkonia production?

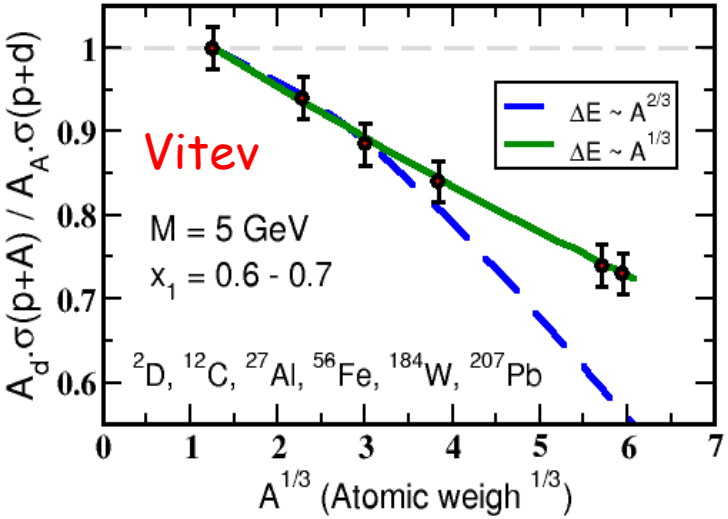
Drell-Yan to constrain parton energy loss in CNM

FNAL E906/Seaquest – Drell Yan

Drell-Yan

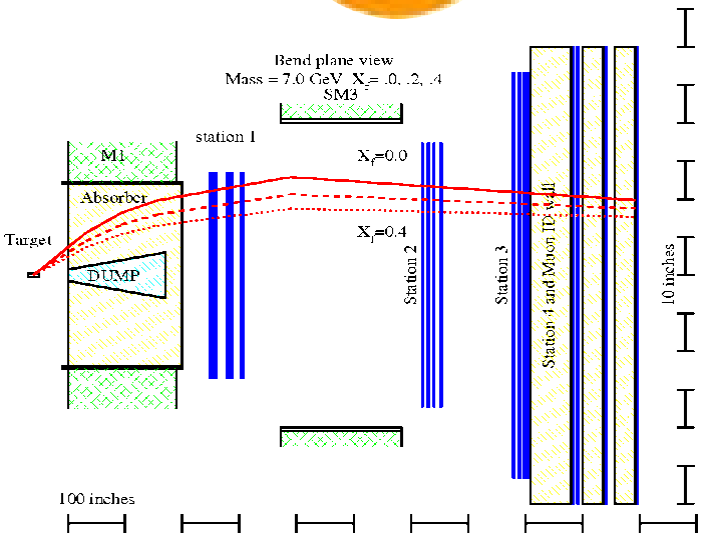


In E906 at 120 GeV, nuclear suppression in Drell-Yan should only be from dE/dx (x_2 > 0.1)



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

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

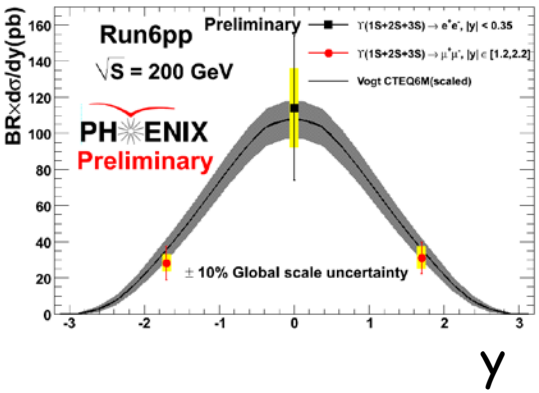


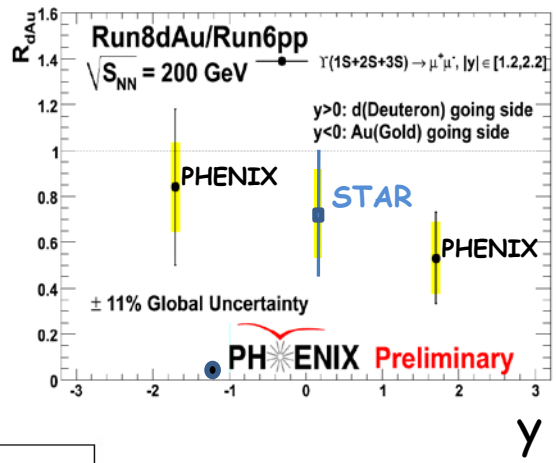
- Distinguish radiative from collisional (L^2 vs L)
- then "extrapolate with theory" to energy loss of gluons for quarkonia production

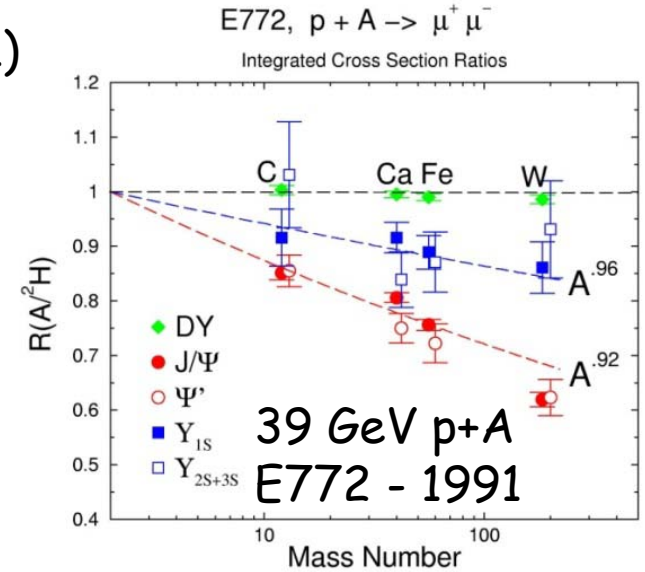
First E906 data expected in 2012

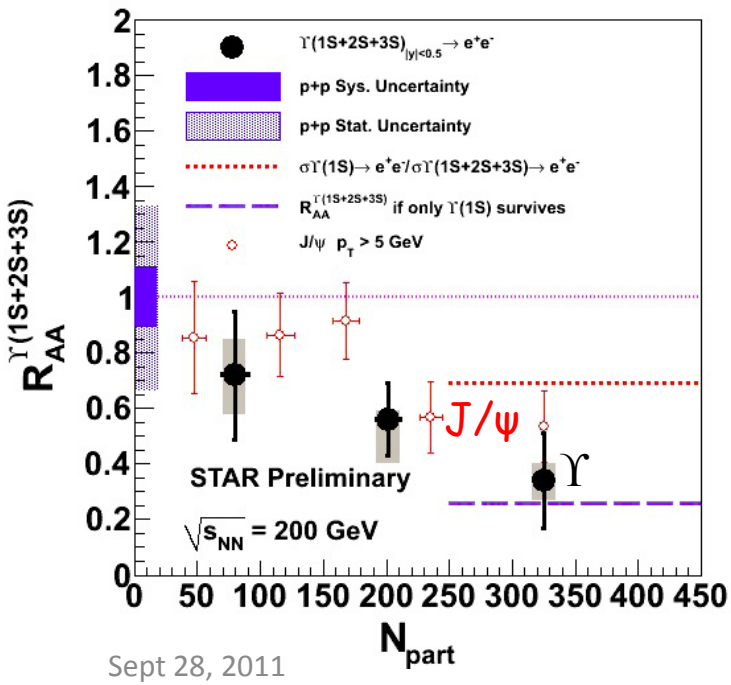
Heavier Quarkonia - Upsilons

Upsilons suppressed in CNM at RHIC (& at FNAL)



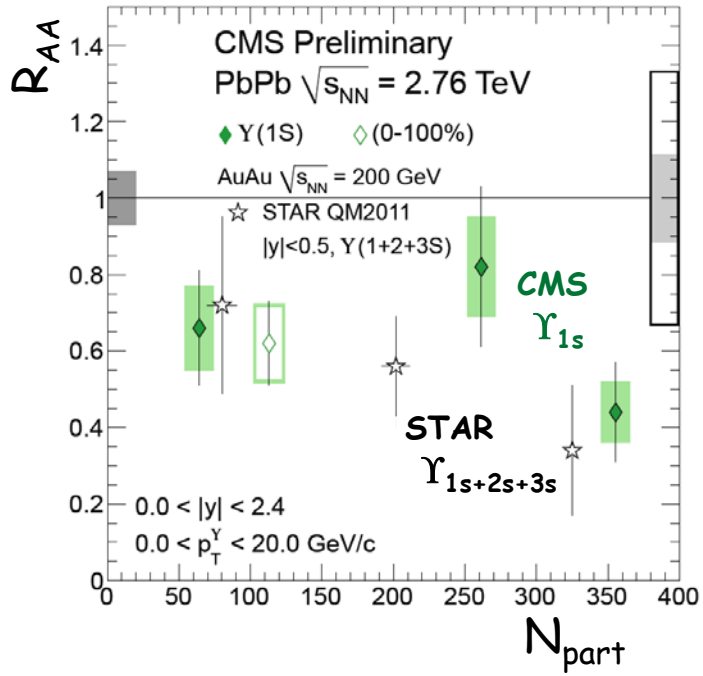




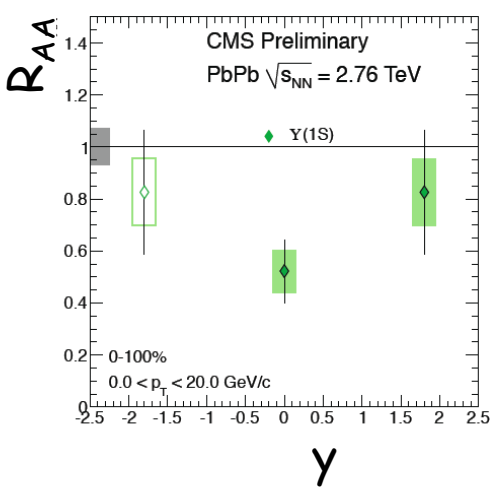


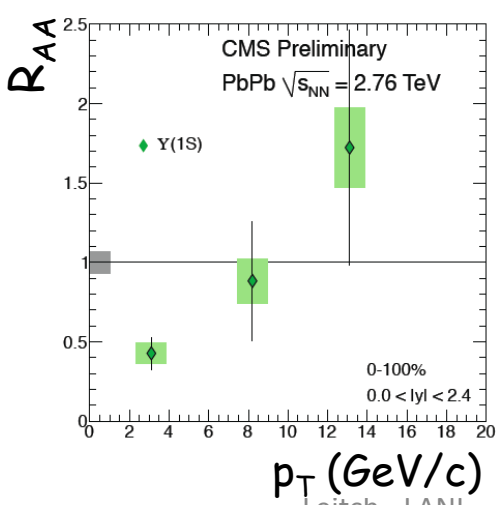
Upsilon suppression in Au+Au at RHIC – watch out for CNM suppression (as usual)!

Heavier Quarkonia - Upsilons



Upsilon suppression at RHIC & LHC similar

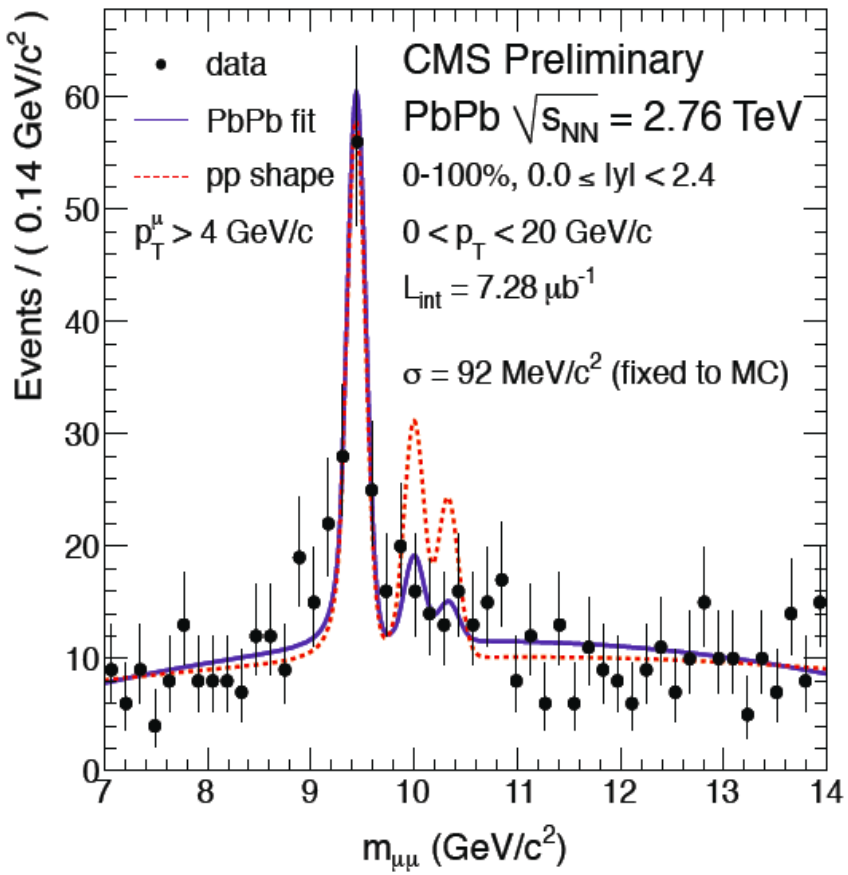




Upsilons at LHC in Pb+Pb

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

Heavier Quarkonia - Upsilons

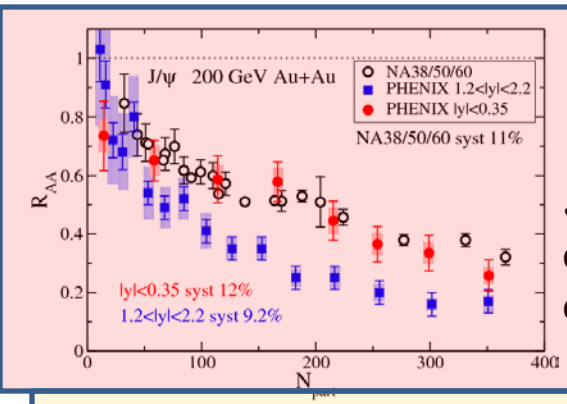


CMS - Upsilon 2S+3S suppressed more than 1S

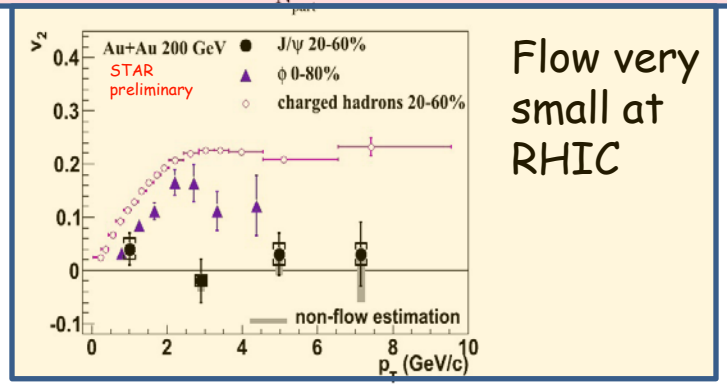
$$\frac{\Upsilon(2S+3S)/\Upsilon(1S)\big|_{PbPb}}{\Upsilon(2S+3S)/\Upsilon(1S)\big|_{pp}} = 0.31^{+0.19}_{-0.15} \pm 0.03$$

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

Summary

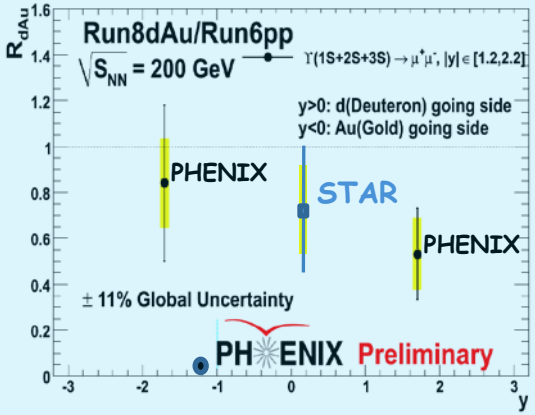


J/ψ suppression almost same at all energies

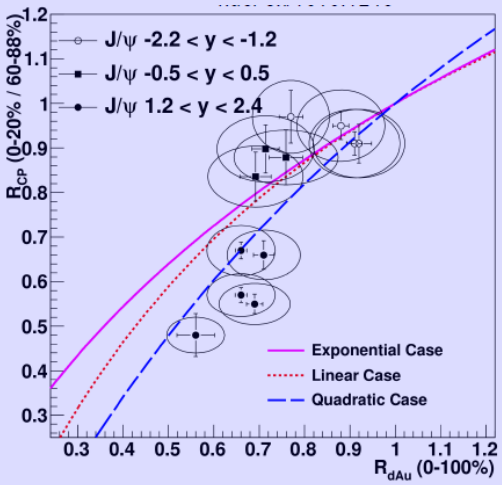


Flow very small at RHIC

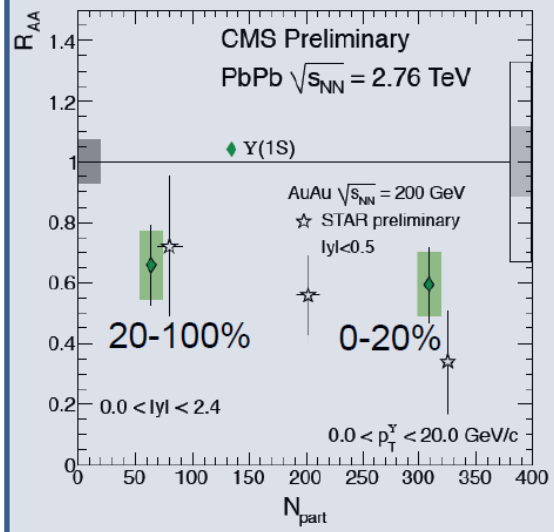
Strong CNM effects for Upsilon too



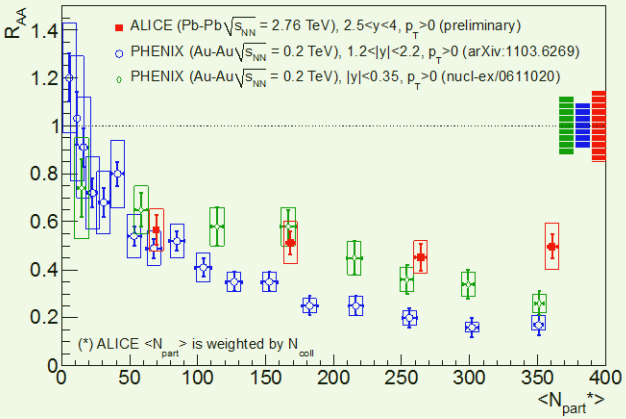
CNM suppression of J/ψ has stronger than linear dependence on density-weighted thickness



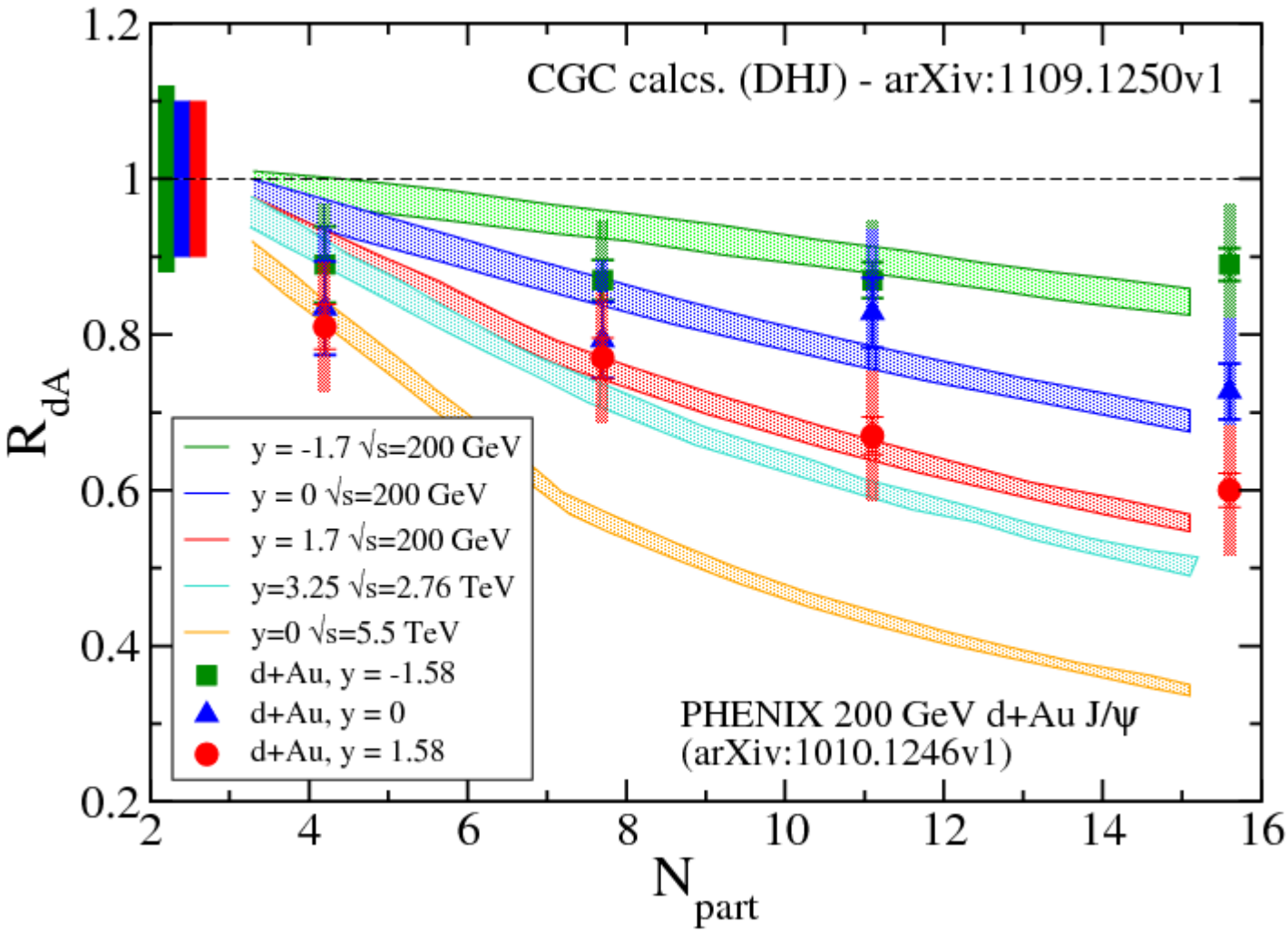
Upsilon suppression at RHIC & LHC similar

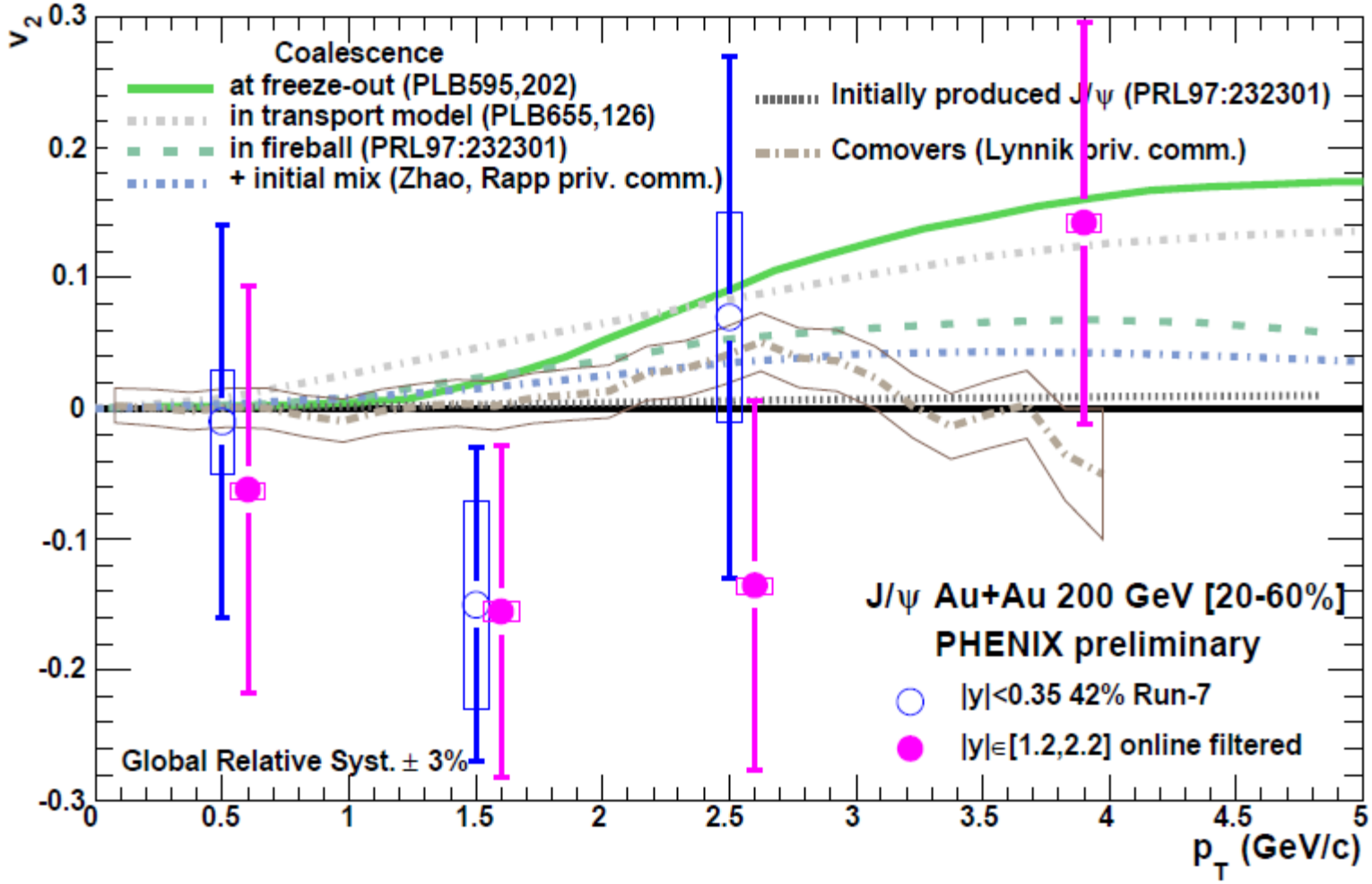


Hint of regeneration at LHC?



Extra Slides


CGC calcs. (DHJ) - arXiv:1109.1250v1
y = -1.7 √s=200 GeV
y = 0 √s=200 GeV
y = 1.7 √s=200 GeV
y=3.25 √s=2.76 TeV
y=0 √s=5.5 TeV
d+Au, y = -1.58
d+Au, y = 0
d+Au, y = 1.58
PHENIX 200 GeV d+Au J/ψ
(arXiv:1010.1246v1)
R_dA
N_part
1.2
1
0.8
0.6
0.4
0.2
2
4
6
8
10
12
14
16

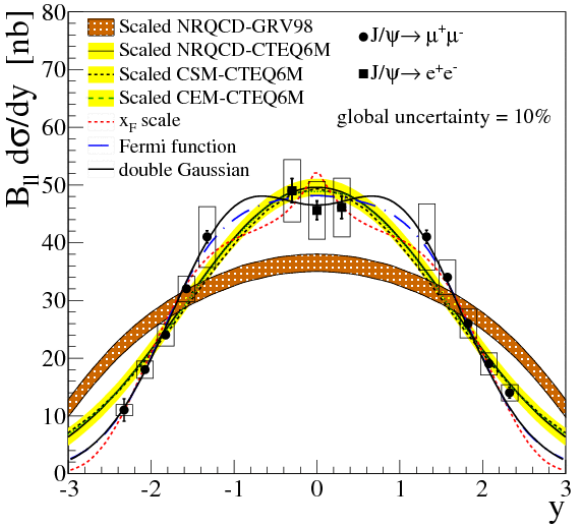

Coalescence
at freeze-out (PLB595,202)
in transport model (PLB655,126)
in fireball (PRL97:232301)
+ initial mix (Zhao, Rapp priv. comm.)
Initially produced J/ψ (PRL97:232301)
Comovers (Lynnik priv. comm.)
J/ψ Au+Au 200 GeV [20-60%]
PHENIX preliminary
|y|<0.35 42% Run-7
|y|∈[1.2,2.2] online filtered
Global Relative Syst. ± 3%
v2
pT (GeV/c)
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5

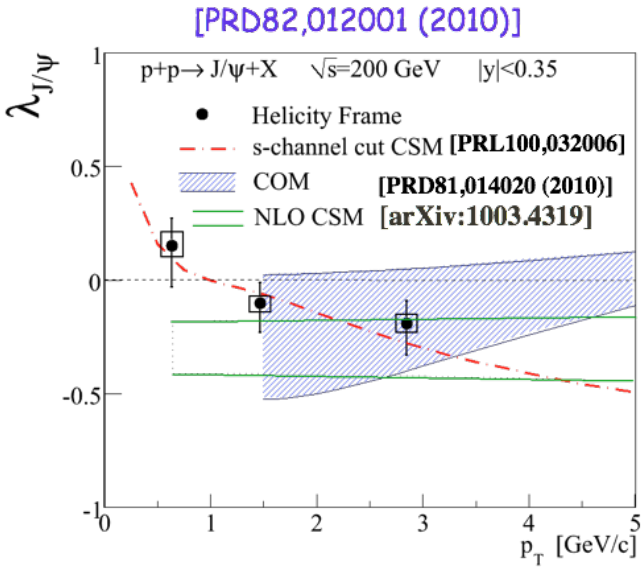
Production mechanism uncertainty - underlies everything else

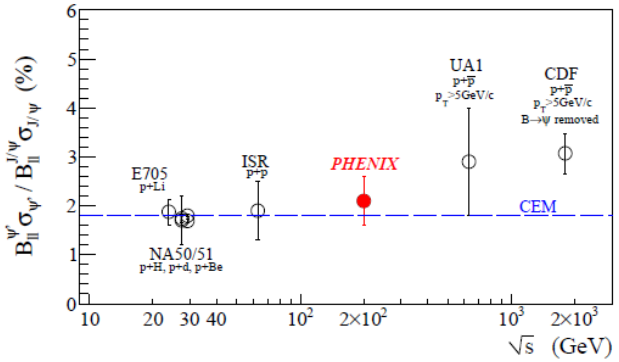
- What kind of state is the precursor heavy-quark pair that eventually forms a quarkonia; this effects how it interacts with the media
- What happens to other charmonium states & how much feeddown do they give to the J/ψ

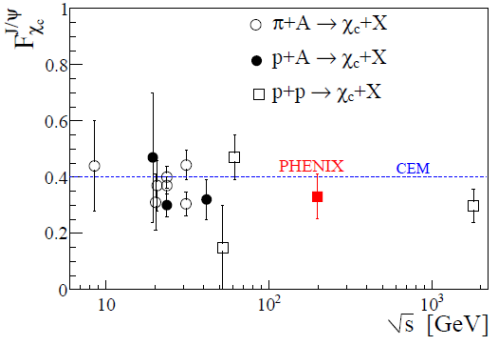
Feedown fractions from PHENIX for 200 GeV, y=0

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









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

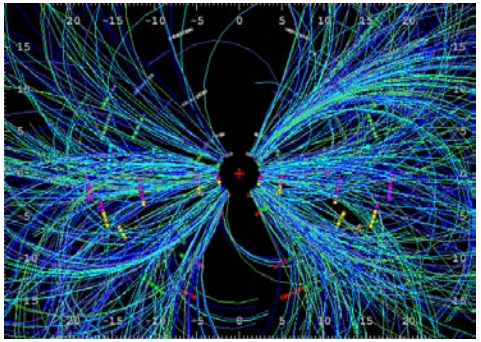


Table B.1: PHENIX run plan for the years 2010–2015. Longitudinal polarization is indicated by (L), transverse by (T).

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

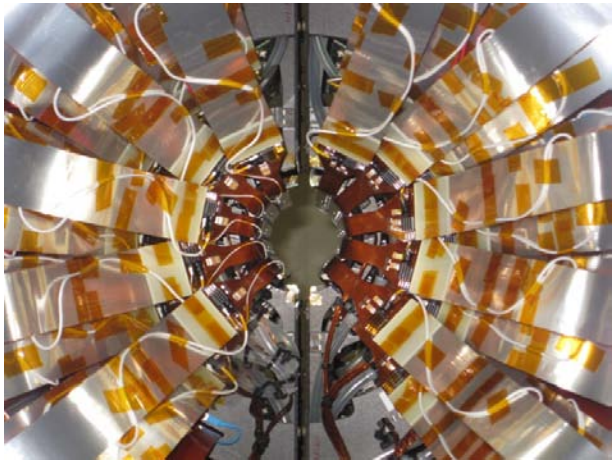
Projected Luminosities & (Evolving) Strawman PHENIX Run Plan

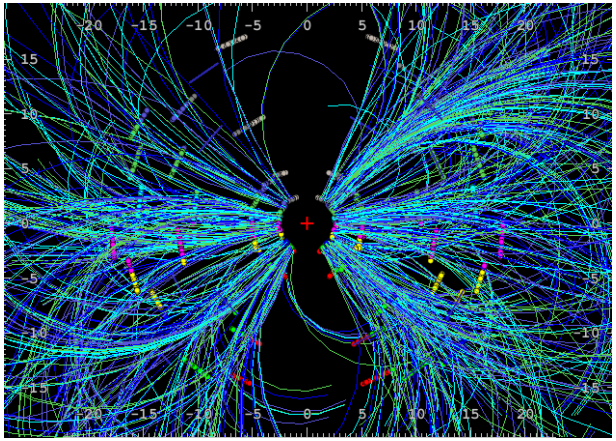
Run	Species	√s	Wks	±30 cm	±10 cm	Pol	Comments
11	p+p	500	10	27 pb^{-1}		50%(L)	W program + ΔG
	Au+Au	19.6	1.5	13.7M MB evts			energy scan
	Au+Au	200	7	915 μb^{-1}	790 μb^{-1}		heavy flavor (VTX)
	Au+Au	27	1	5.2 μb^{-1}			energy scan
12	p+p	200	5	13.1 pb^{-1}	4.7 pb^{-1}	60%(T)	HI ref. + transv. spin
	p+p	500	7	90 pb^{-1}	30 pb^{-1}	50%(L)	W program + ΔG
	Cu+Au	200	5		2.4 nb^{-1}		geometry
	U+U	200	3		0.4 nb^{-1}		explore geometry
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
	Au+Au	200	7		800 μb^{-1}		Heavy flavor (FVTX/VTX)
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
	d+Cu	200	?				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)

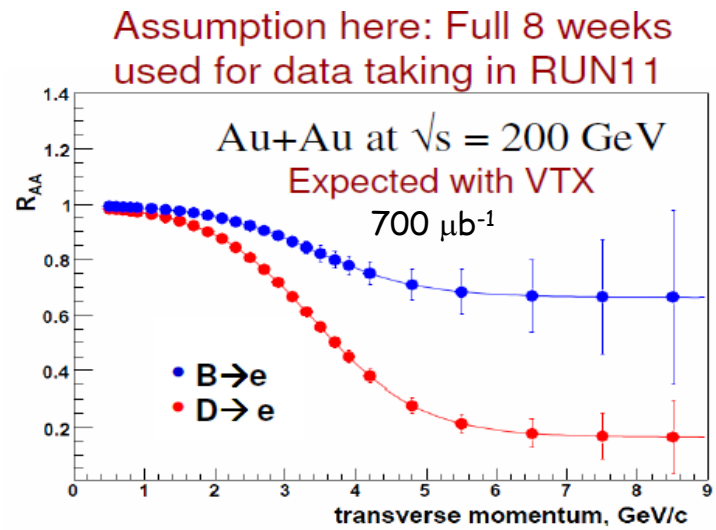
- Running now: charm, beauty; improved Upsilon resolution

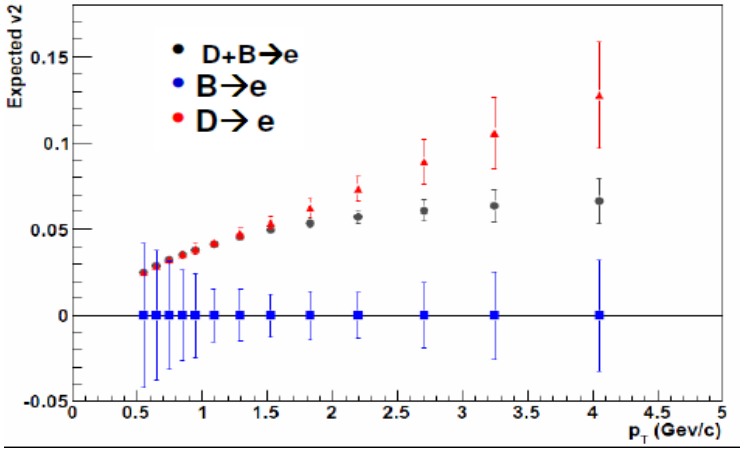




VTX endview: detector (top); Au+Au event (bottom)

Expectations for open-charm and beauty with VTX

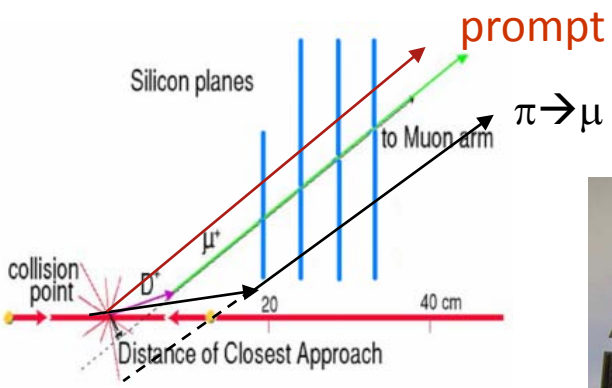


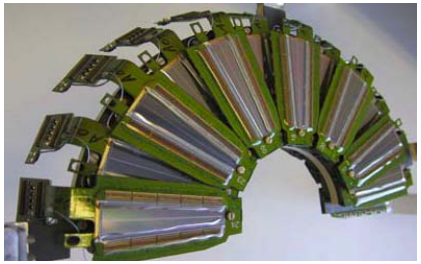


Quarkonia – looking to the Future

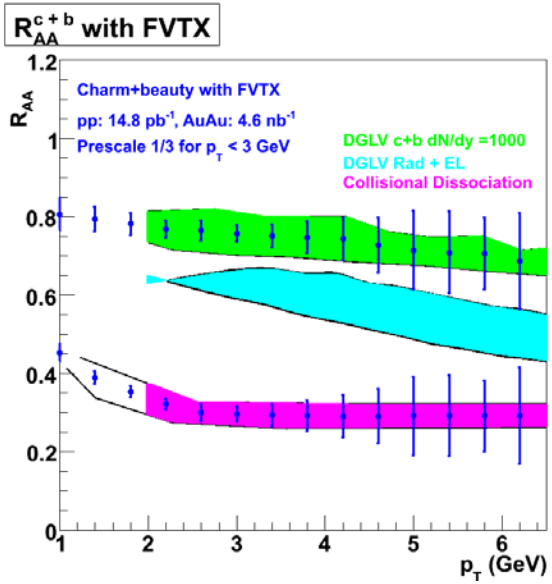
PHENIX Forward-rapidity Vertex Detector (FVTX)

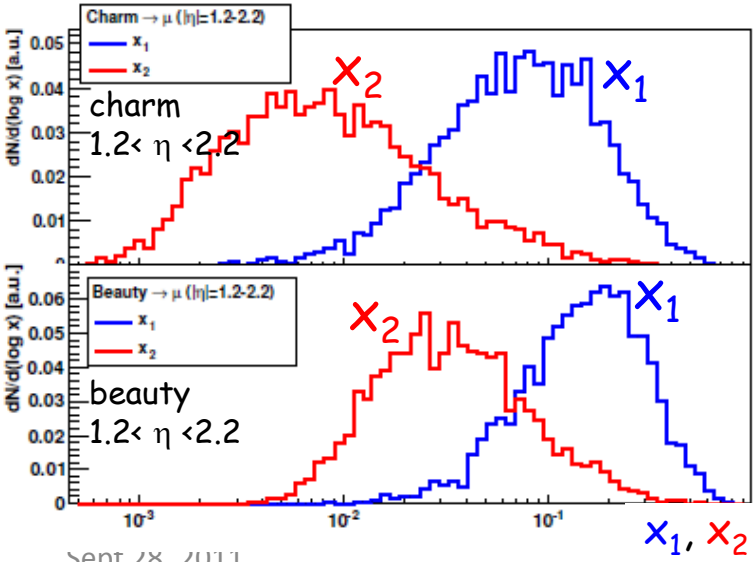
- Runs in 2012; forward charm, beauty; improved J/ψ resolution





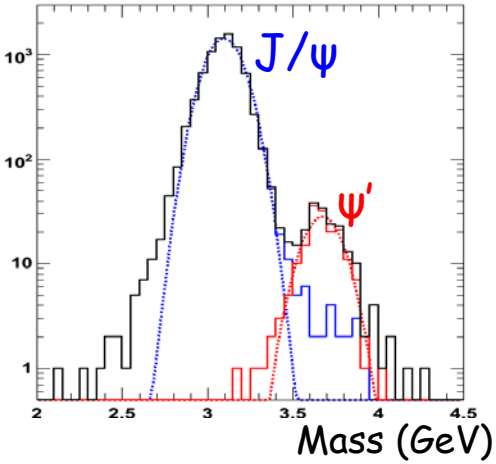
Resolving radiative & collisional dE/dx with the FVTX





x coverage for open-charm and beauty with FVTX

Improved separation of ψ'



Quarkonia – looking to the Future

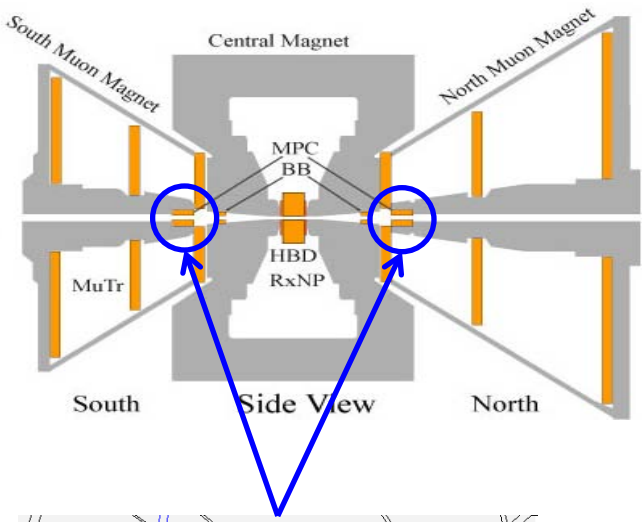
The MPC Extension (MPC-EX)

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

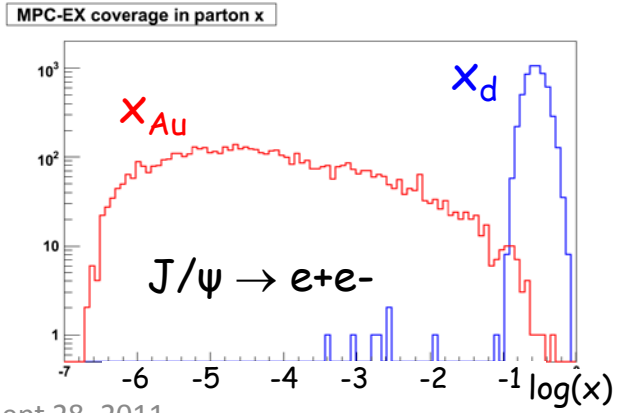
Technology:

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

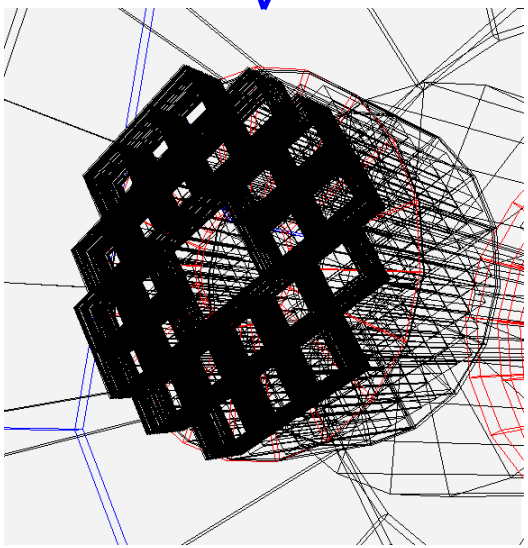


Projections for J/ψ (acceptance only, no efficiencies!):

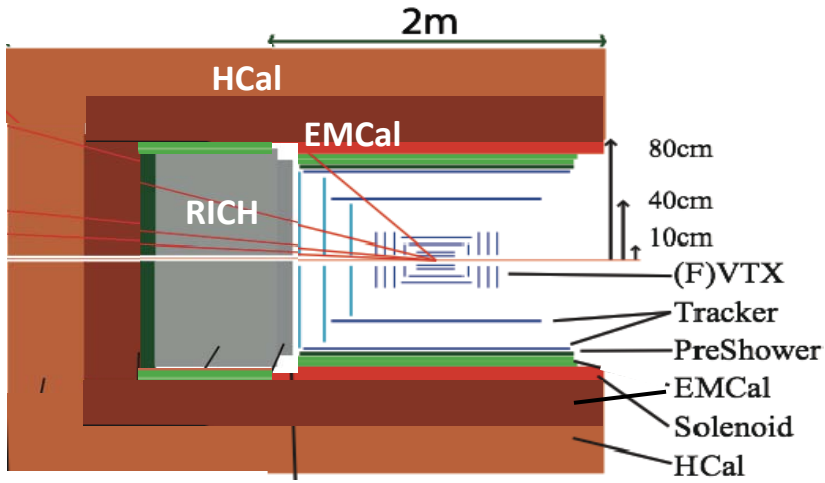
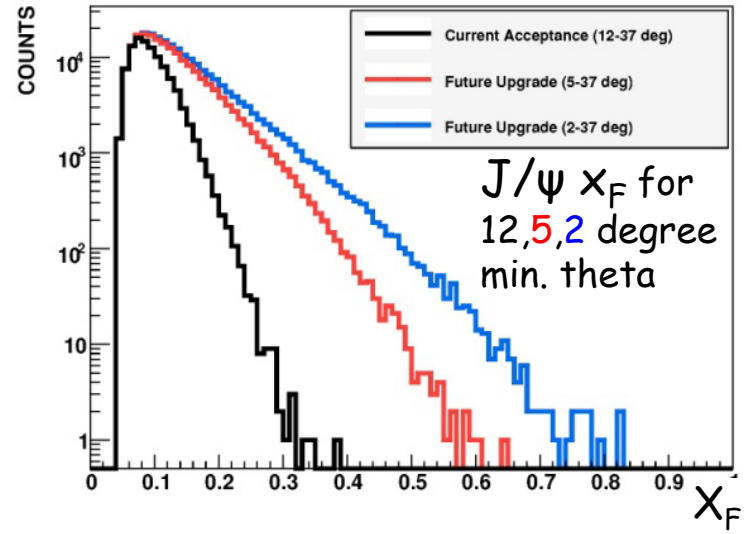
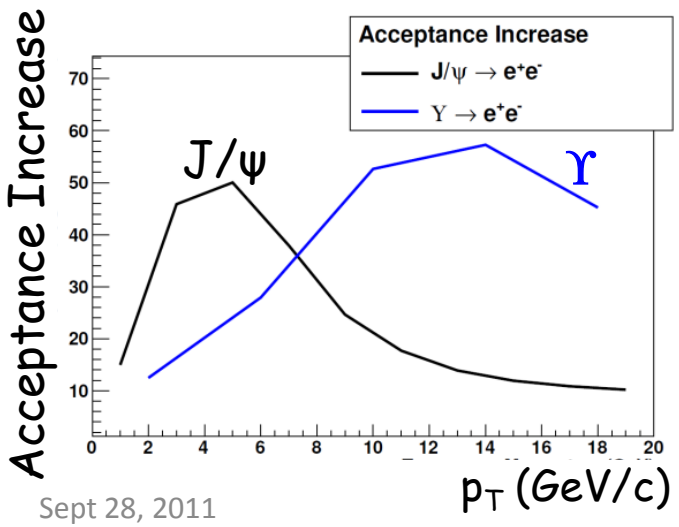
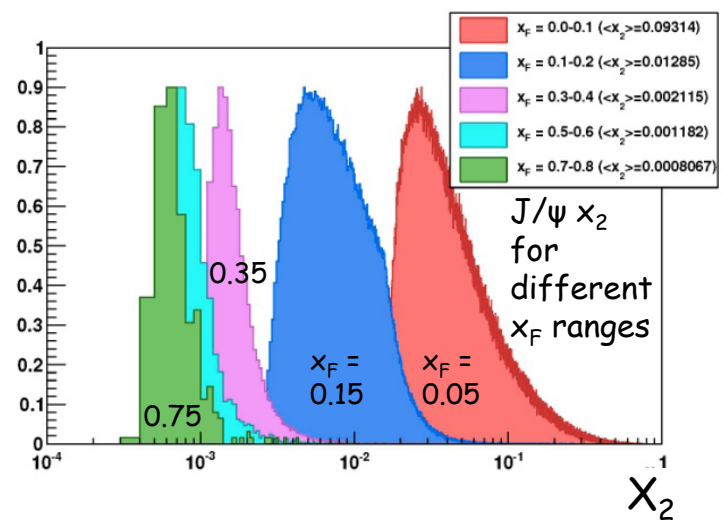
- 260 nb^{-1} d+Au run: ~9.7k J/ψ -> $e^+ e^-$ in North MPC
- 34 pb^{-1} 200 GeV p+p run ~3.6k J/ψ sum for two arms



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