Los Alamos

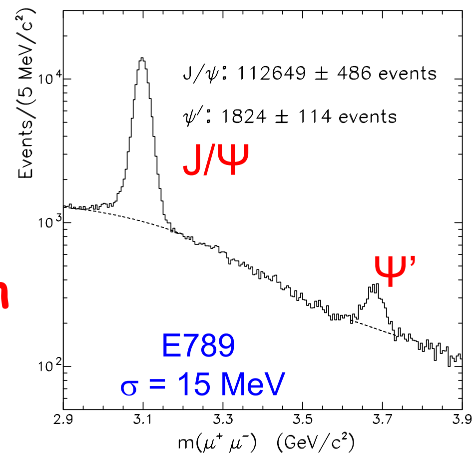
Quarkonia Production in pp, p(d)A & AA Collisions

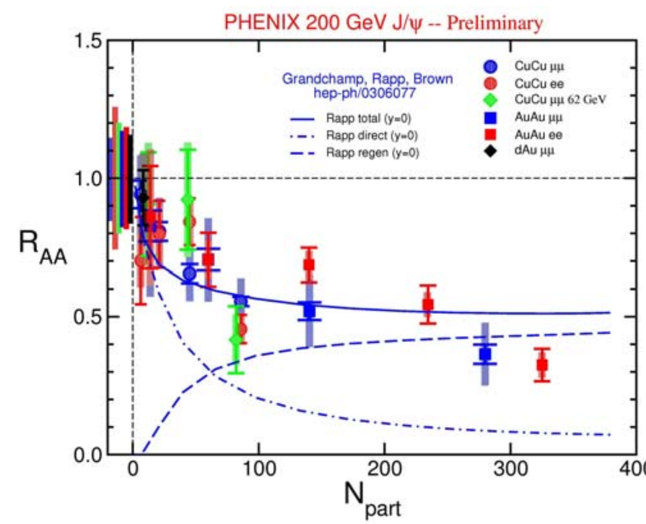
Mike Leitch – LANL - leitch@lanl.gov

LBL – 29 November 2005

- production
  - mechanisms
  - cross section & polarization
  - complications
- cold nuclear matter
  - shadowing and/or saturation
  - p_T broadening
  - absorption
  - parton energy loss
  - contrasting open & closed charm
- hot-dense matter in A-A collisions
  - PHENIX results
  - cold-nuclear matter effects in A-A
  - suppression & recombination
- future prospects
- summary

800 GeV





J/ψ & open-charm production, parton level structure & dynamics

Production of heavy vector mesons, e.g. J/Ψ,Ψ' and Υ

• gluon fusion dominates (NLO calculations add more complicated diagrams but still mostly with gluons)

• production: color singlet or octet $c\bar{c}$: absolute cross section and polarization?

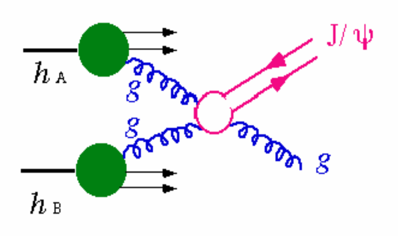
• hadronization time (important for pA nuclear effects)

• complications due to substantial feed-down from higher mass resonances, e.g. from χ_c

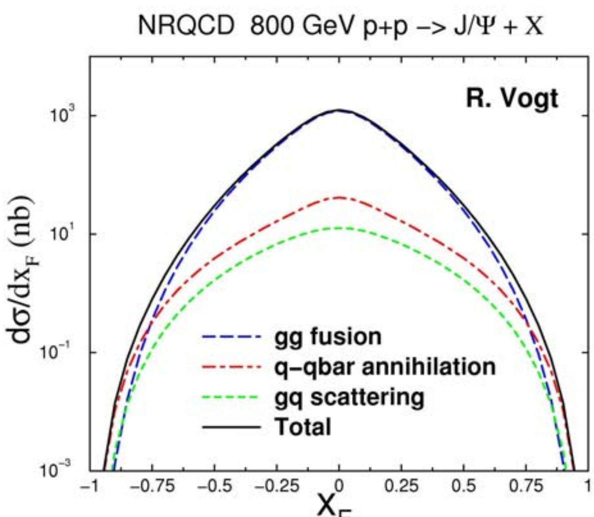
Open charm

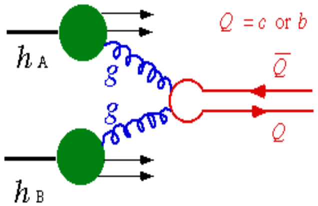
• shares sensitivity to gluon distributions and initial-state effects such as p_T broadening, initial-state energy loss

• but different final-state effects



Phys.Rev. C61 (2000) 035203





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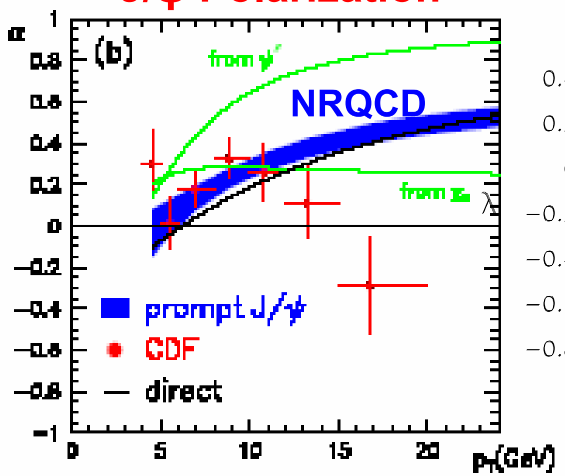
J/ψ Production—Polarization

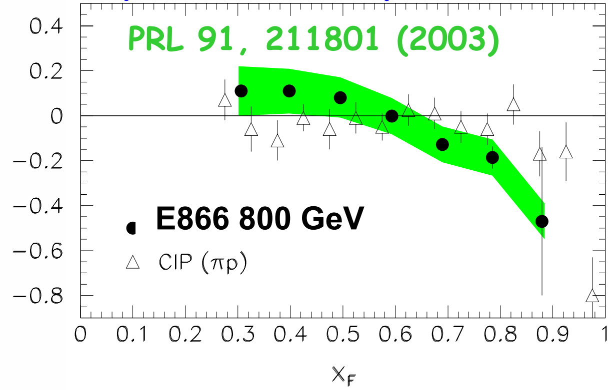
Color Octet Model predicts J/ψ polarization at large p_T - NOT SEEN in data

J/ψ Polarization



E866

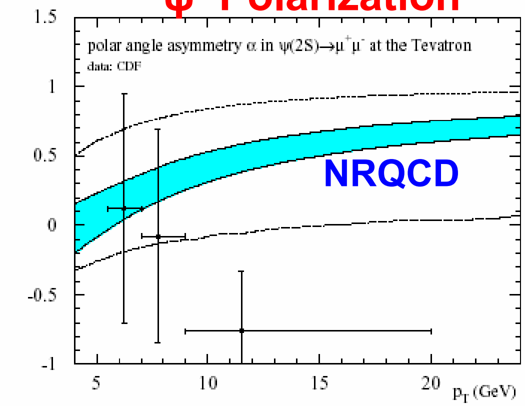
very small J/ψ polarization



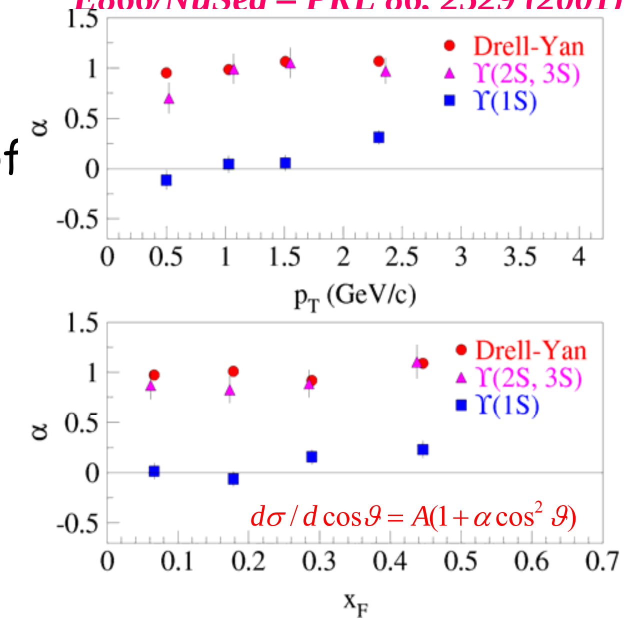
λ = +1 (transverse)

= -1 (longitudinal)

ψ' Polarization



E866/NuSea – PRL 86, 2529 (2001)

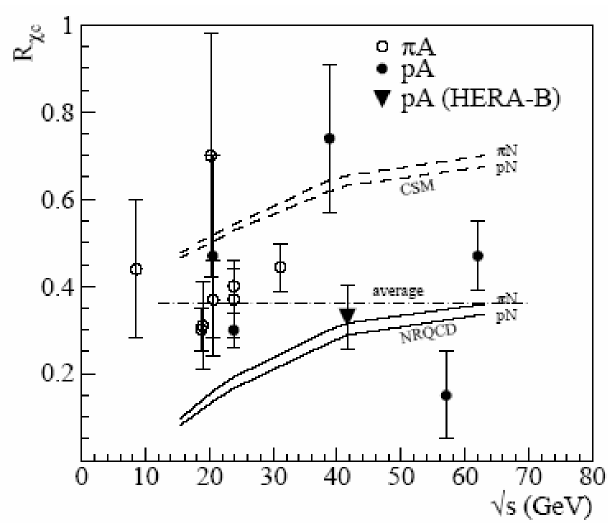


$d\sigma / d\cos\vartheta = A(1 + \alpha \cos^2 \vartheta)$

- CDF and Fermilab E866 data show little polarization of J/ψ & opposite trend from predictions
  - NRQCD (with octet) predicts:

    $0.25 < \lambda < 0.7$ [Beneke & Rothstein, PRD 54, 2005 (1996)].
- But Υ maximally polarized for (2S+3S), but NOT (1S)
- Is feed-down washing out polarization? (~50% of 1S from feed-down)

Feeding of J/ψ's from Decay of Higher Mass Resonances

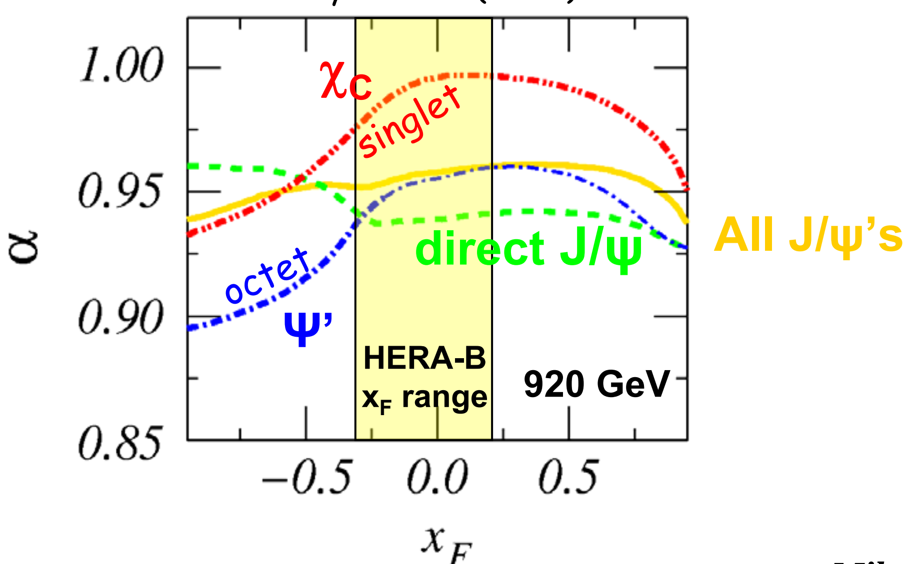


HERA-B Phys.Lett. B561 (2003) 61-72 & E705 @ 300 GeV/c, PRL 70, 383 (1993)

Large fraction of J/ψ's are not produced directly

	Proton	Pion
$\chi_{,1,2} \rightarrow J/\Psi$	~30%	37%
$\Psi' \rightarrow J/\Psi$	5.5%	7.6%

R. Vogt, NRQCD calculations
Nucl. Phys. A700 (2002) 539

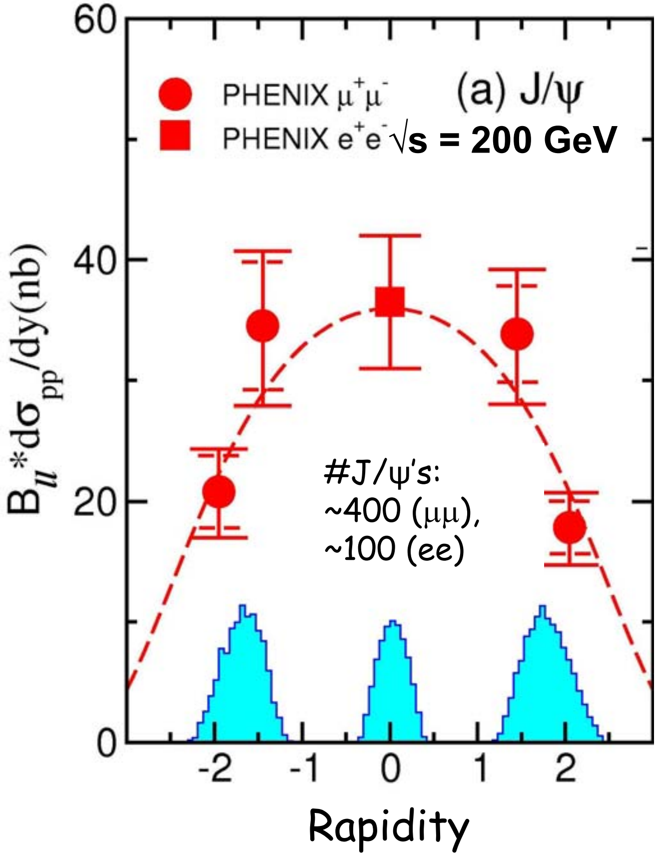


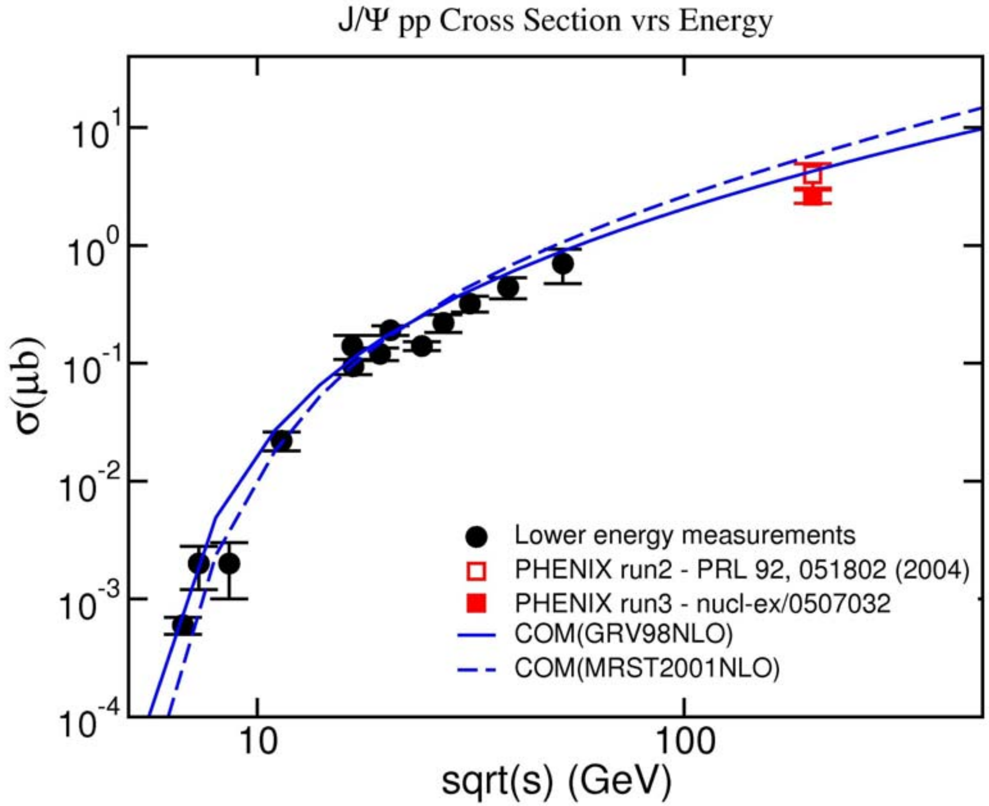
Effect on Nuclear dependence:

- Nuclear dependence of parent resonance, e.g. χ_C is probably different than that of the J/ψ
- e.g. in proton production ~21-30% of J/ψ's will have different effective absorption because they were actually χ_C's while in the nucleus

PHENIX - J/ψ cross section versus rapidity & √s

nucl-ex/0507032





More pp J/ψ's coming from PHENIX - ~5k/arm in 2005 run

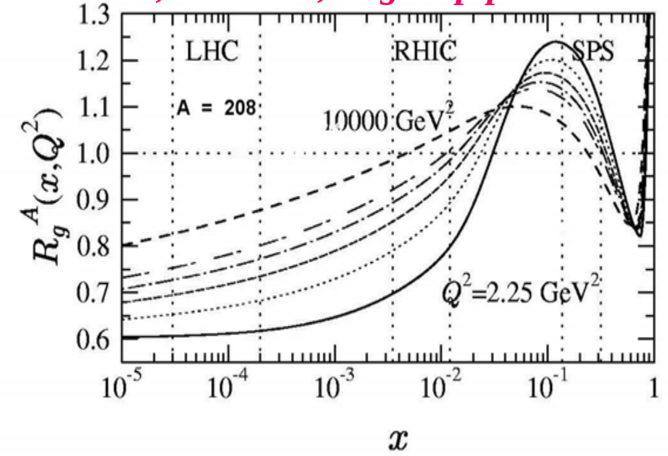
(Ψ' is, so far, out of reach with present RHIC luminosities)

Nuclear modification of parton level structure & dynamics

Modification of parton momentum distributions of nucleons embedded in nuclei

- shadowing – depletion of low-momentum partons (gluons)
- coherence & dynamical shadowing
- gluon saturation – e.g. color glass condensate, a specific/fundamental model of gluon saturation which gives shadowing in nuclei

Eskola, Kolhinen, Vogt hep-ph/0104124

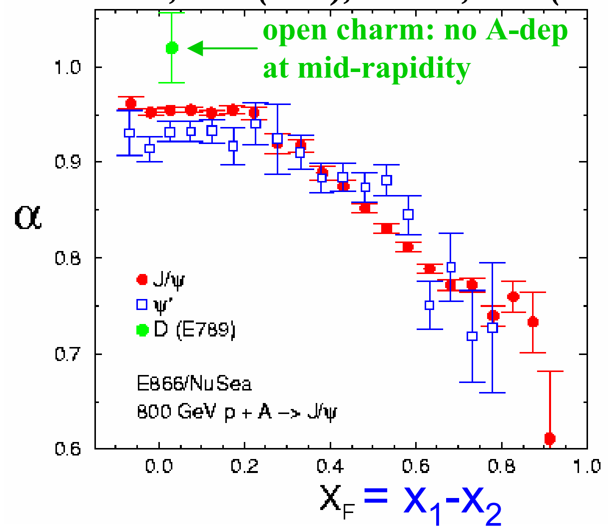


Nuclear effects on parton "dynamics"

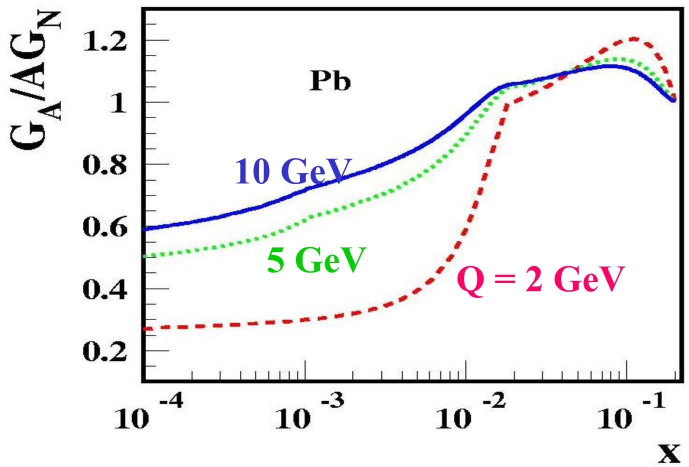
- energy loss of partons as they propagate through nuclei
- and (associated?) multiple scattering effects (Cronin effect)
- absorption of J/ψ on nucleons or co-movers; compared to no-absorption for open charm production

800 GeV p-A (FNAL) $\sigma_A = \sigma_p * A^\alpha$

PRL 84, 3256 (2000); PRL 72, 2542 (1994)

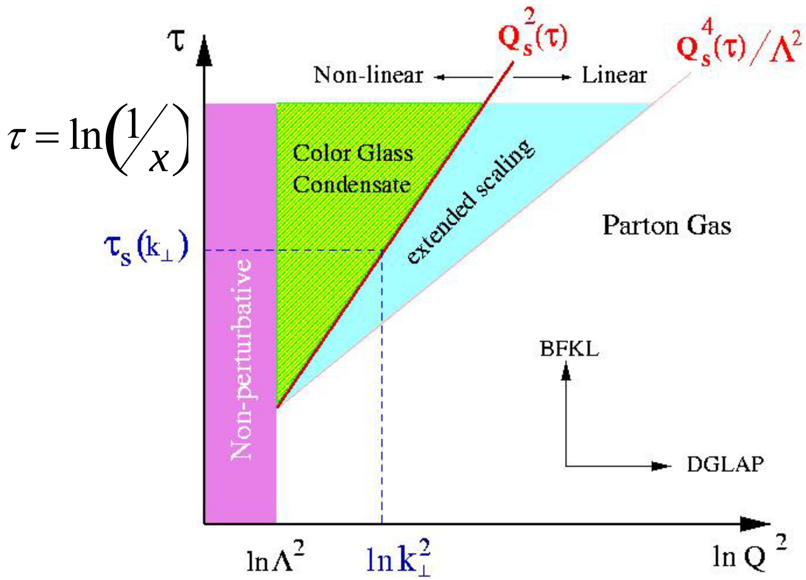


Gluon Shadowing and Saturation



Leading twist gluon shadowing, e.g.:
- Gerland, Frankfurt, Strikman, Stocker & Greiner (hep-ph/9812322)
- phenomenological fit to DIS & DY data, Eskola, Kolhinen, Vogt hep-ph/0104124
- and many others

Amount of gluon shadowing differs by up to a factor of three between diff models!



Iancu and Venugopalan hep-ph/0303204

Saturation or Color Glass Condensate (CGC)
- At low x there are so many gluons, that the quantum occupation numbers get so large that the situation looks classical
- Nuclear amplification: $x_A G(x_A) = A^{1/3} x_p G(x_p)$, i.e. gluon density is ~6x higher in Gold than the nucleon

Large variations of predicted Gluon Shadowing!

from
hep-ph/0308248
N. Armesto &
C. Salgado

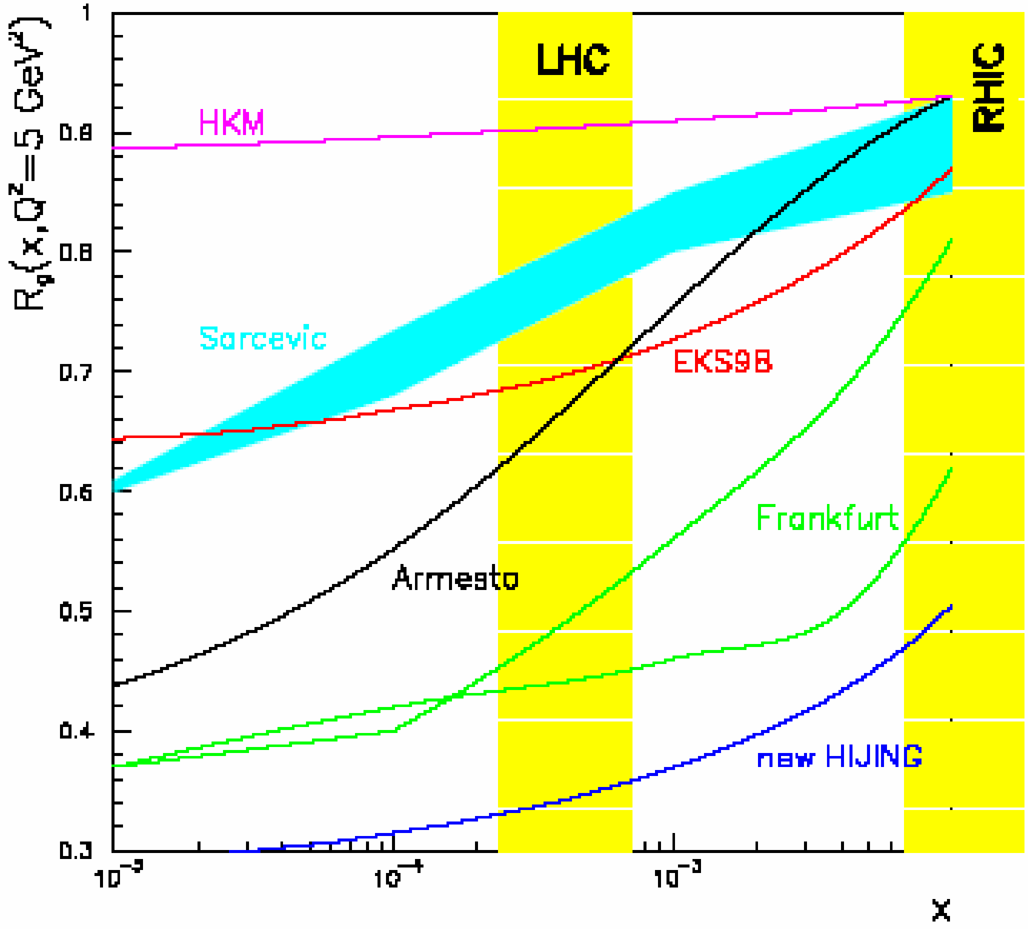
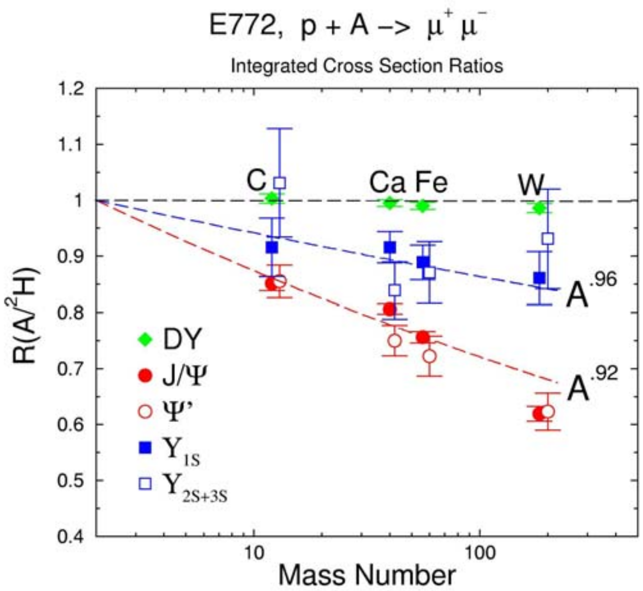
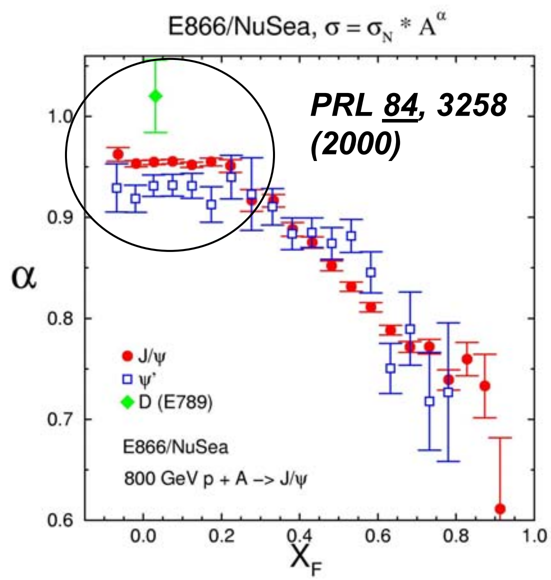
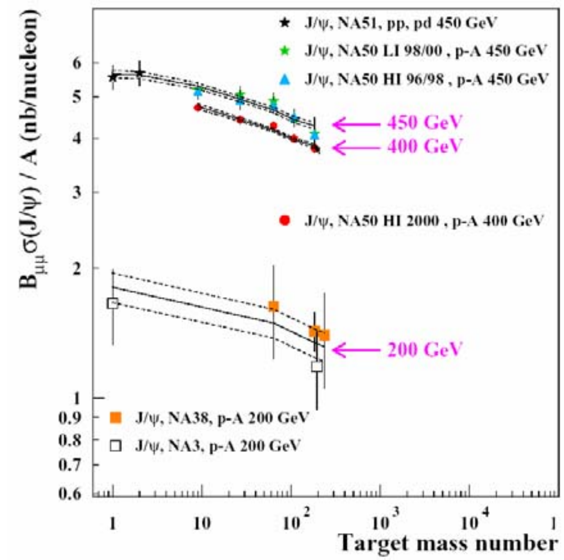


Fig. 13: Ratios of gluon distribution functions from different models at $Q^2 = 5$ GeV^2; HKM refers to the results from Ref. [29], Sarcevic, Ref. [107], EKS98, Refs. [27, 28], Frankfurt, Ref. [103], Armesto, Refs. [89, 106] and new HIJING, Ref. [66]. The bands represent the ranges of $x = (Q/\sqrt{s})e^y$ for processes with $|y| \leq 0.5$, $Q^2 = 5$ GeV^2 at RHIC ($\sqrt{s} = 200$ GeV) and LHC ($\sqrt{s} = 5.5$ TeV).

J/ψ at fixed target: Absorption at mid-rapidity







Breakup by nucleus of J/ψ or pre-J/ψ ($c\bar{c}$) as it exits nucleus

Power law parameterization $\sigma = \sigma_N * A^{\alpha}$

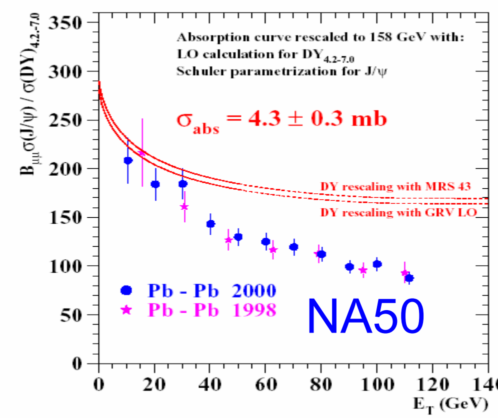
$\alpha = 0.954 \pm 0.003$ E866/NuSea @ x_F=0

$\alpha = 0.941 \pm 0.004$ NA50, QM04

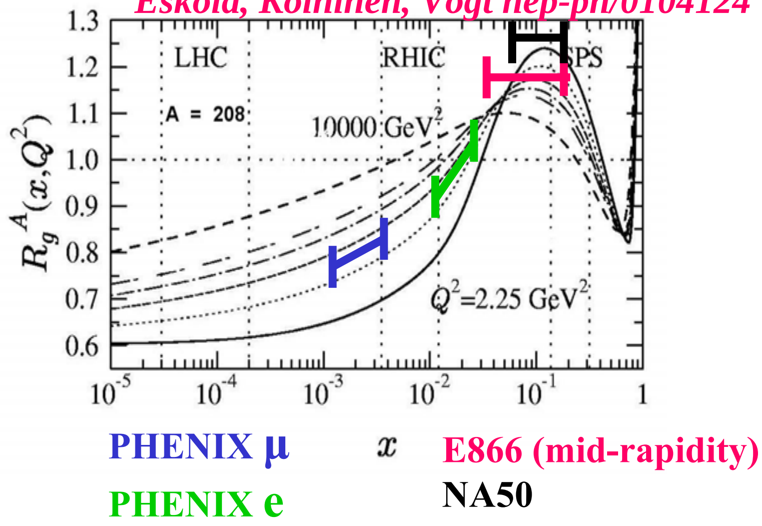
Absorption model parameterization (from pA)

$\sigma_{J/\psi} = 4.18 \pm 0.35$ mb NA50 QM05

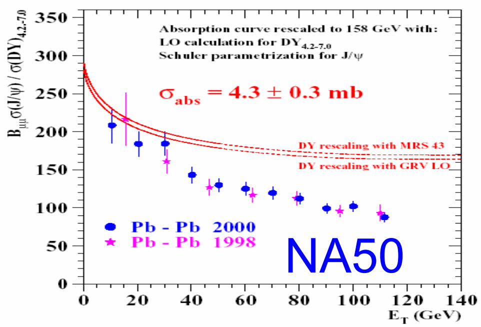
$\sigma_{\psi'} = 7.6 \pm 1.1$ mb



Absorption of J/ψ's not so simple?



Set	P_{lab}	N_0 (nb)	σ_{abs} (mb)
NA50	450 GeV	5.6±0.1	4.1±0.4
NA50	400 GeV	5.1±0.1	
NA38 (corrected)	400 GeV	5.5±0.2	

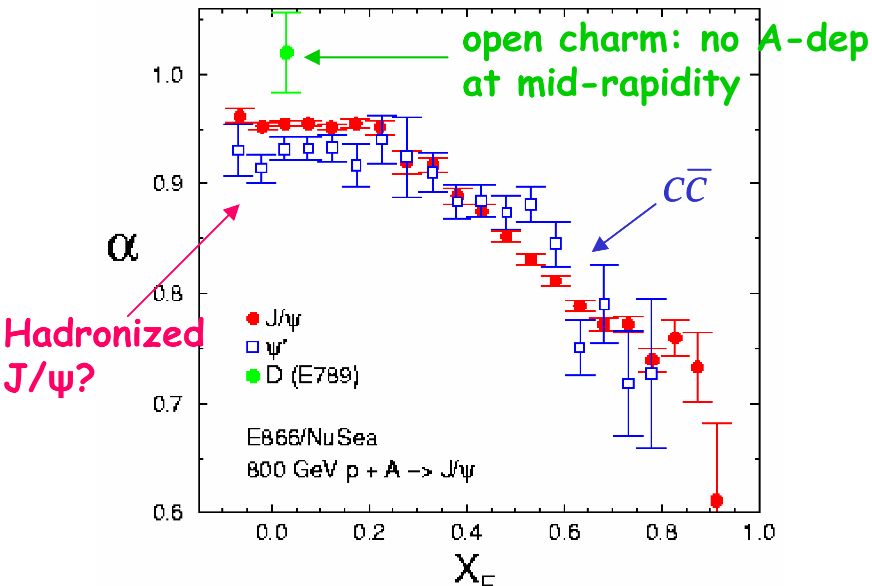


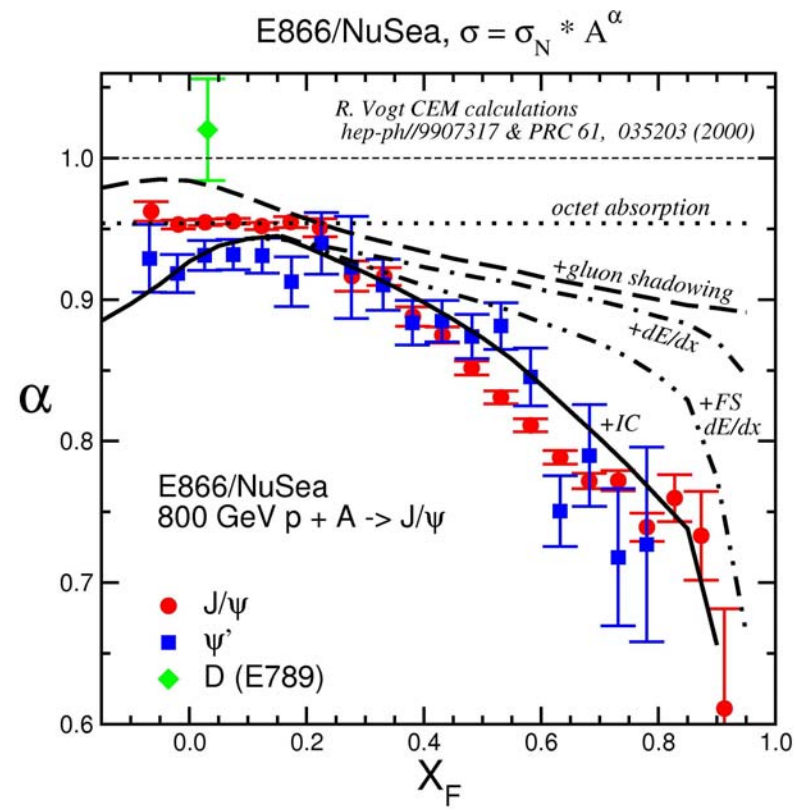
- What really is $\sigma_{abs}^{J/\psi}$?
  - An effective quantity
  - What is crossing the nucleus and how does it evolve?
    - pre-resonant $c\bar{c}$ state, fully formed resonance?
  - Are we measuring primary J/ψ?
    - feed-down from ψ' and χ_c
    - will fraction of feed-down change in AA collisions?
  - Does anti-shadowing make absorption appear smaller than it is?

J/ψ suppression in pA fixed-target

800 GeV p-A (FNAL)

PRL 84, 3256 (2000); PRL 72, 2542 (1994)

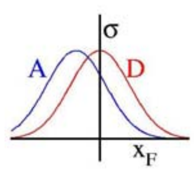




- J/Ψ and Ψ' similar at large x_F where they both correspond to a $c\bar{c}$ traversing the nucleus
- but Ψ' absorbed more strongly than J/Ψ near mid-rapidity (x_F ~ 0) where the resonances are beginning to be hadronized in nucleus
- open charm not suppressed at x_F ~ 0; what about at higher x_F?

Many ingredients to explain the J/ψ nuclear dependence – R. Vogt

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



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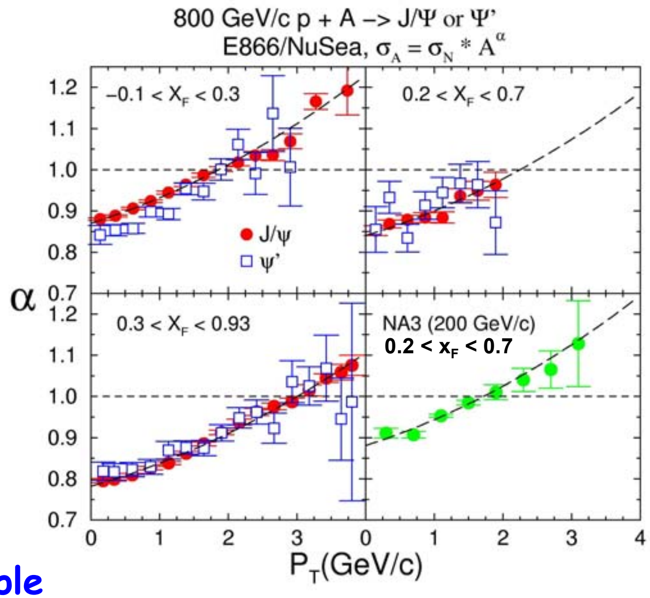
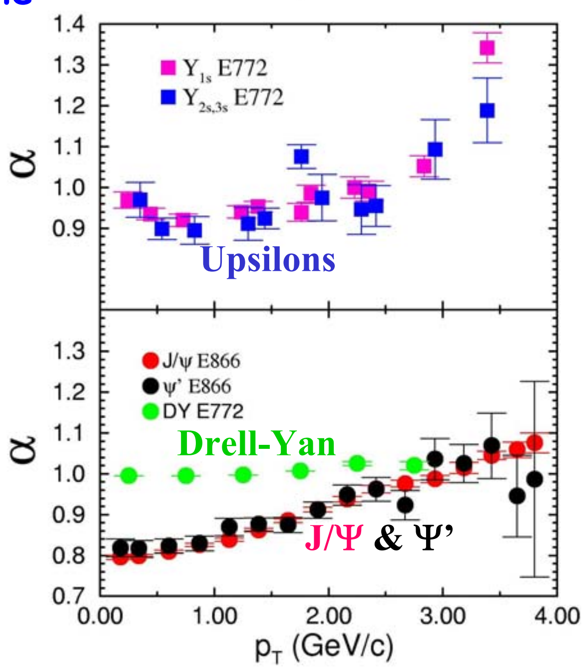
P_T Broadening for J/ψ's

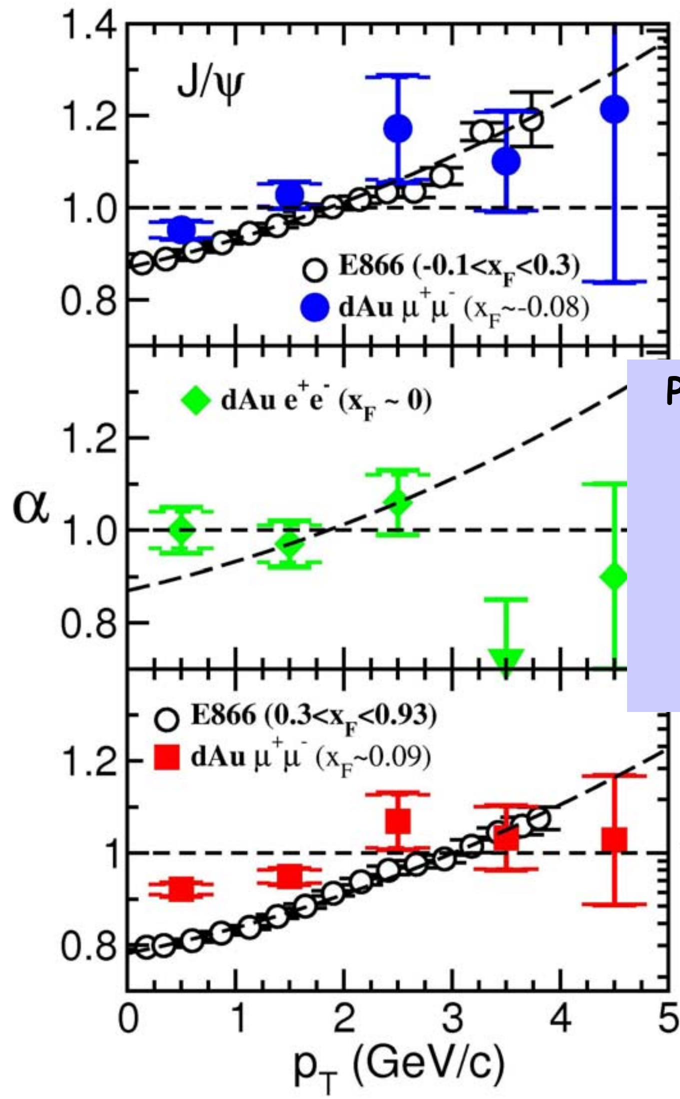
$$\sigma_A = \sigma_N A^{\alpha}$$

nucl-ex/0507032



Usually interpreted as initial-state multiple scattering





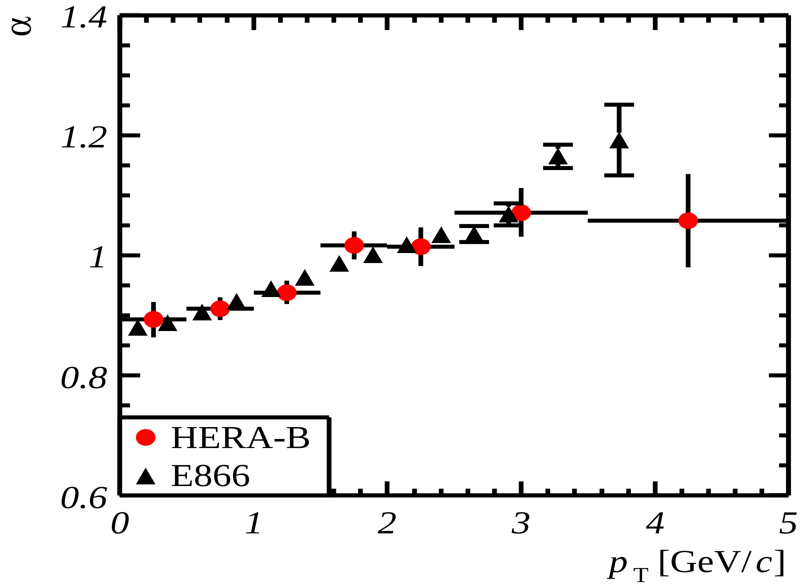
High x_2 ~ 0.09

PHENIX 200 GeV results show p_T broadening comparable to lower energy ($\sqrt{s}$=39 GeV in E866)

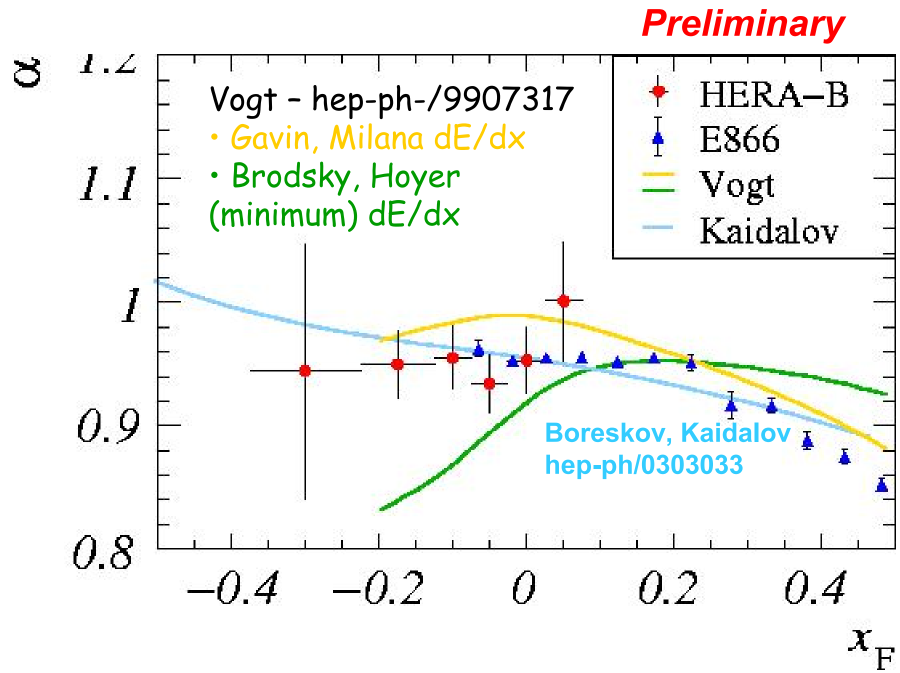
Low x_2 ~ 0.003

HERA-B - J/ψ A dependence

$$\sigma_A = \sigma_N A^{\alpha}$$

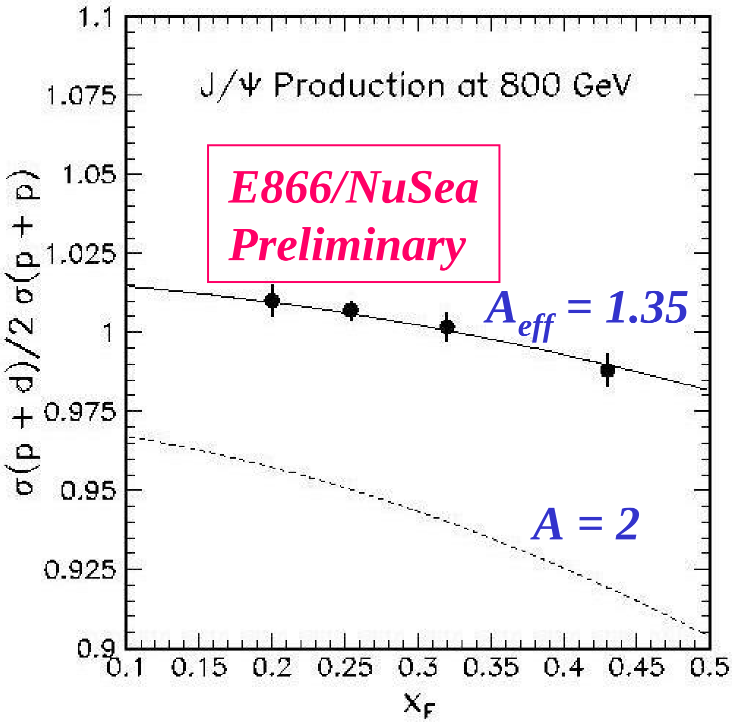


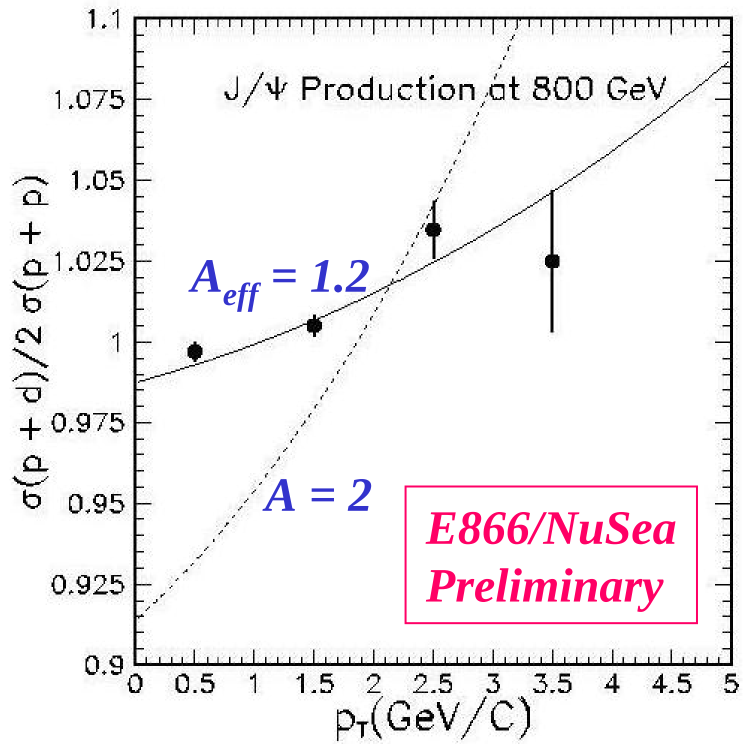
A. Zoccoli (HERA-B) – talk @ Hard Probes 2004



- Previous result of FNAL E866 extended to x_F = −0.35
- Result from 15% of full $\mu^+ \mu^-$ sample, statistical uncertainties only, similar results for e^+e^-
- Work on systematics ongoing. Complete the analysis on the full data sample.

J/ψ Nuclear dependence seen even for Deuterium/Hydrogen!



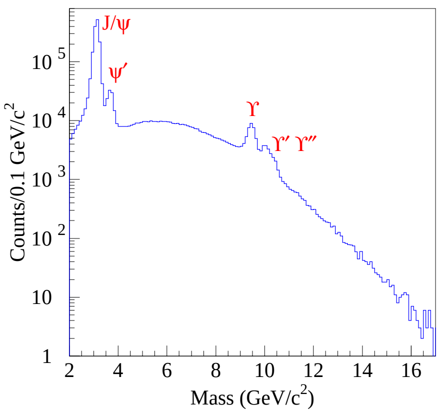


Nuclear dependence in deuterium seems to follow the systematics of larger nuclei, but with an effective A, A_{eff}, smaller than two.

From fits to E866/NuSea p + Be, Fe, W data: $\sigma_{pA} \sim \sigma_{pp} A^{\alpha}$

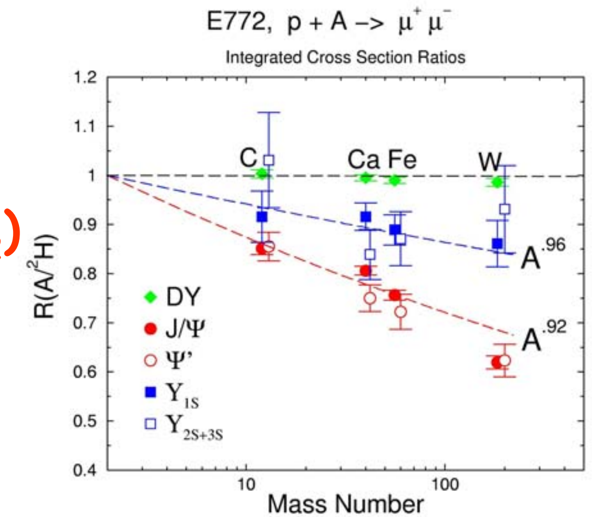
$$\alpha(x_F) \propto 1 - 0.052 x_F - 0.034 x_F^2$$
$$\alpha(p_T) \propto 0.06 p_T + 0.011 p_T^2$$

Contrasting ϒ's with J/ψ's

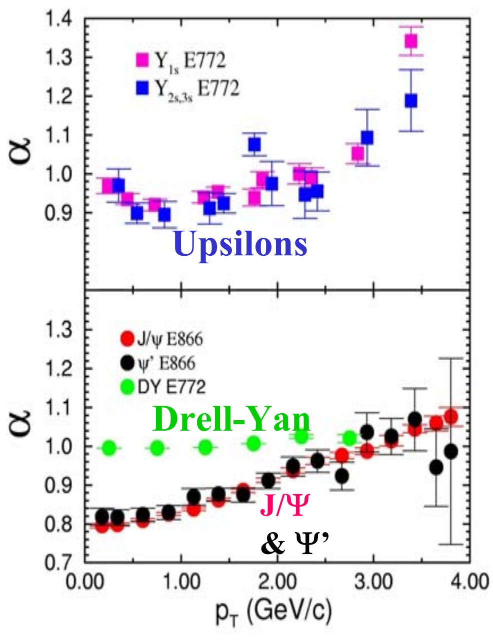


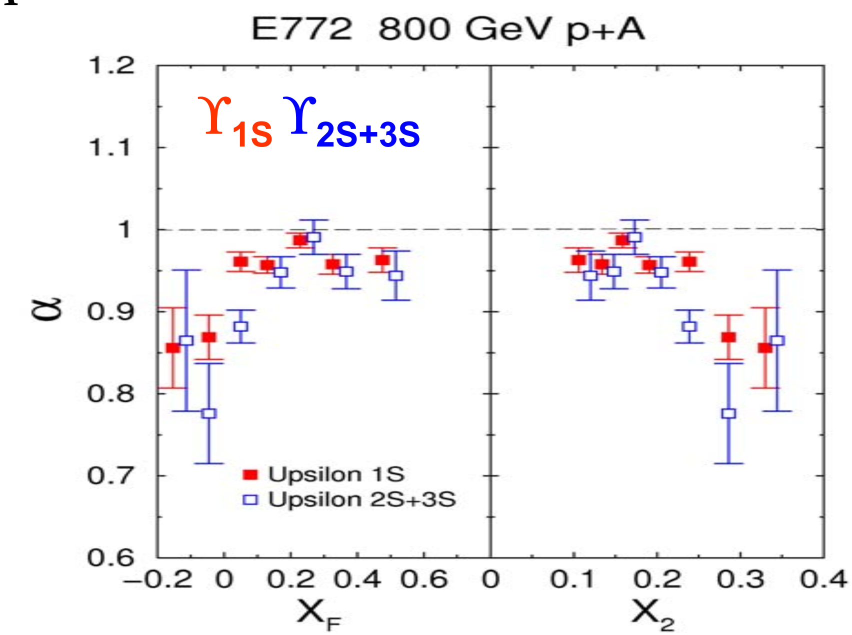
At √S = 39 GeV (E772/E866)

- less absorption
- not in shadowing region (large x_2)
- similar p_T broadening
- Υ_{2S+3S} have large transverse polarization (unlike Υ_{1S} or J/ψ)

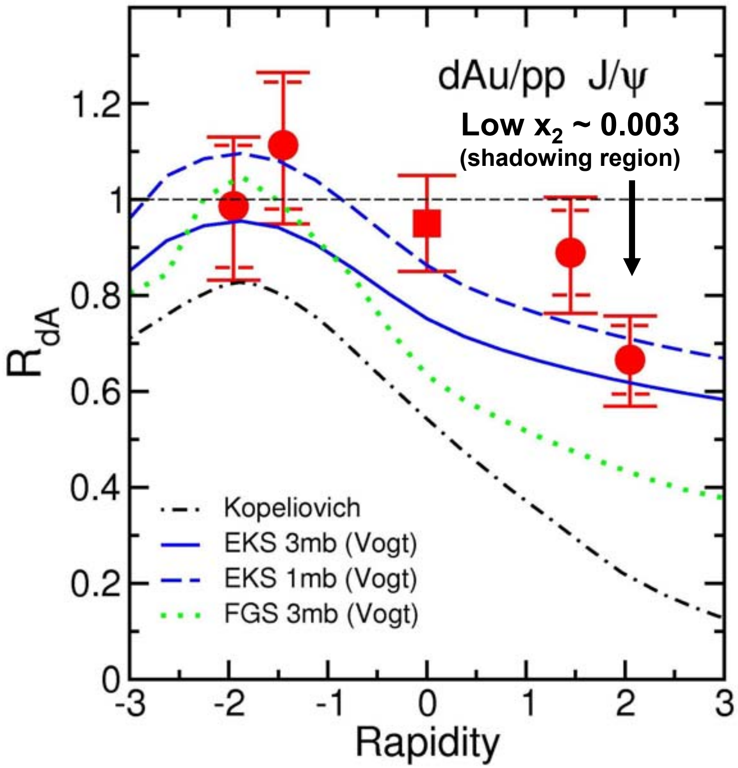


$$\sigma_A = \sigma_N A^{\alpha}$$

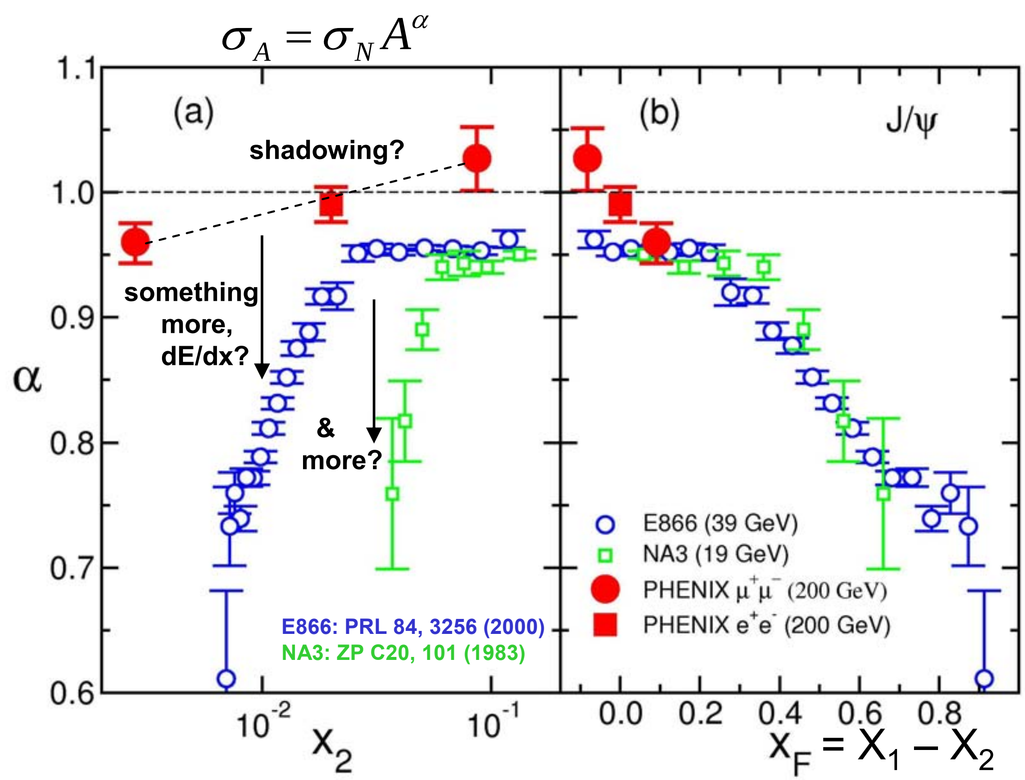




PHENIX J/ψ Nuclear Dependence
For 200 GeV pp and dAu collisions - nucl-ex/0507032



Klein,Vogt, PRL 91:142301,2003
Kopeliovich, NP A696:669,2001



Data favors (weak) shadowing + (weak) absorption (α > 0.92)

With limited statistics difficult to disentangle nuclear effects

Will need another dAu run! (more pp data also)

Not universal versus X_2 : shadowing is not the main story.

BUT does scale with x_F ! - why?

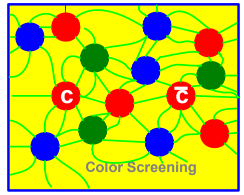
(Initial-state gluon energy loss -which goes as x_1~x_F - expected to be weak at RHIC energy)

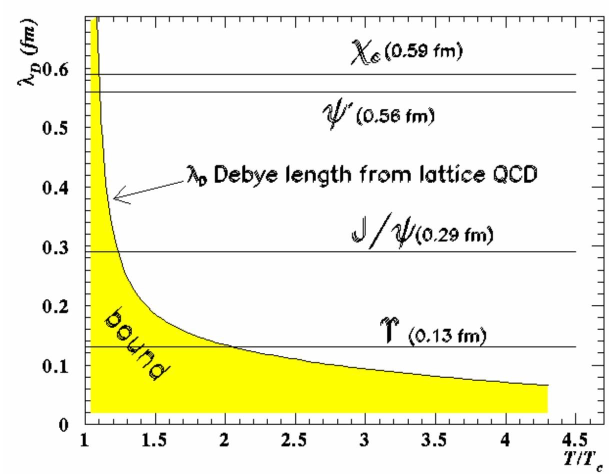
Sudakov suppression (energy conservation)?

→ Kopeliovich, hep-ph/0501260

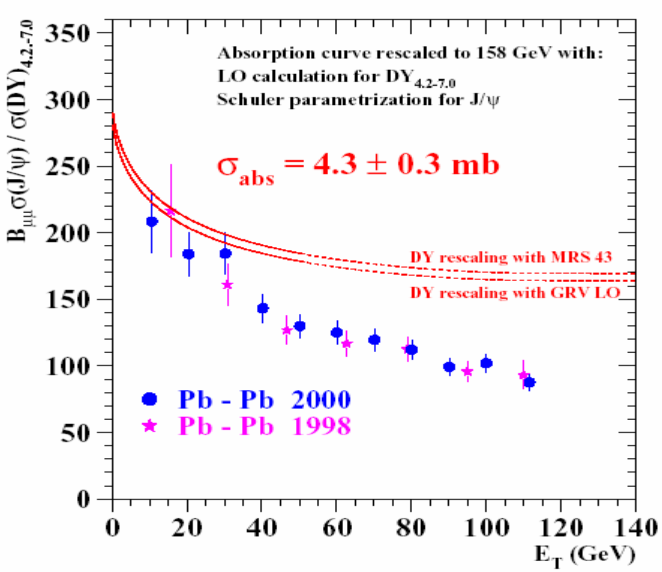
AuAu J/ψ's - Quark Gluon Plasma (QGP) signature?

- Debye screening predicted to destroy J/ψ's in a QGP
- Different states "melt" at different temperatures due to different binding energies.
- but recent charm recombination models might instead cause an enhancement?

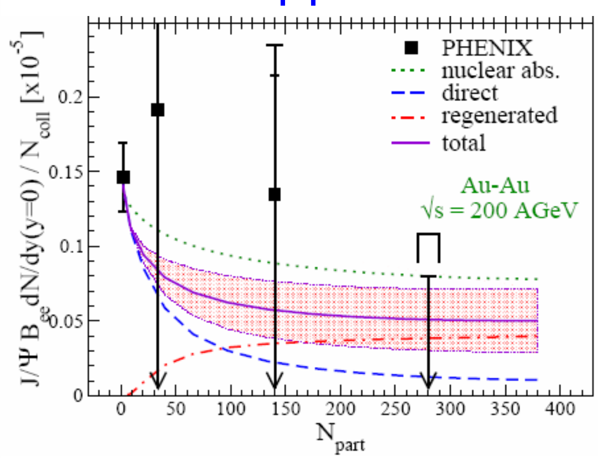




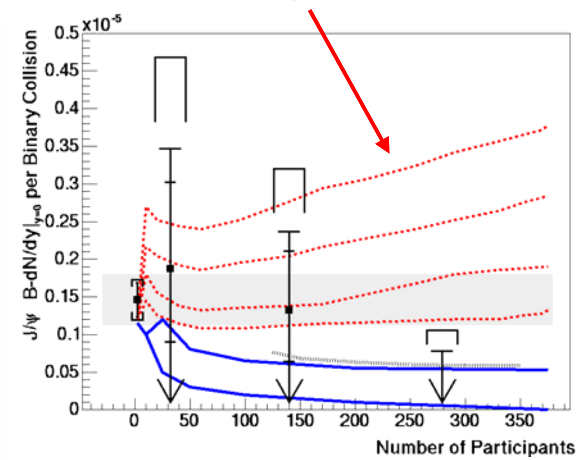
NA50



Grandchamp, Rapp, Brown hep-ph/0403204



R. L. Thews, M. Schroedter, J. Rafelski, Phys Rev C 63, 054905



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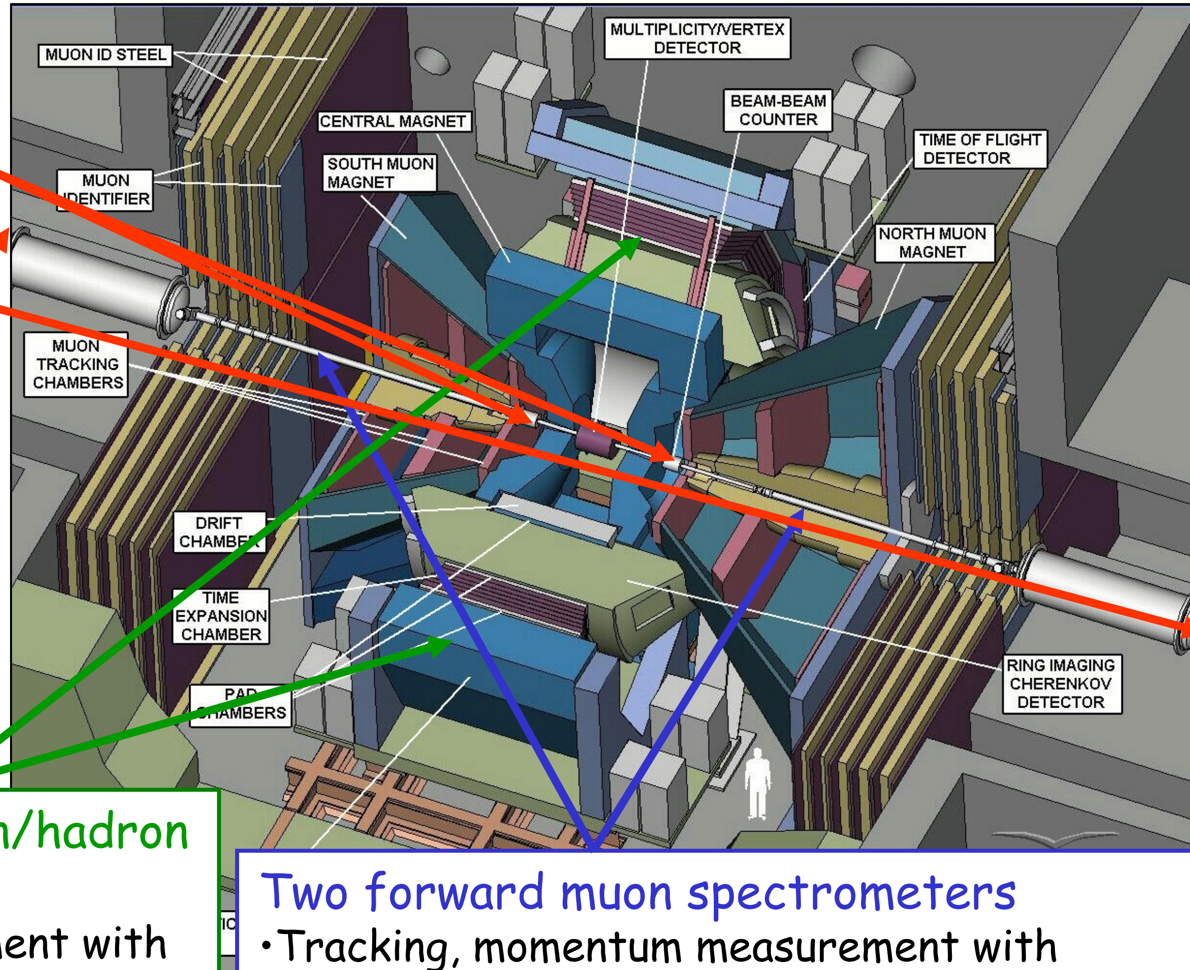
PHENIX at RHIC



Two sets of forward-rapidity detectors for event characterization

- Beam-beam counters measure particle production in $3.0<|\eta|<3.9$. Luminosity monitor + vertex determination.
- Zero-degree calorimeters measure forward-going neutrons.
- Correlation gives centrality

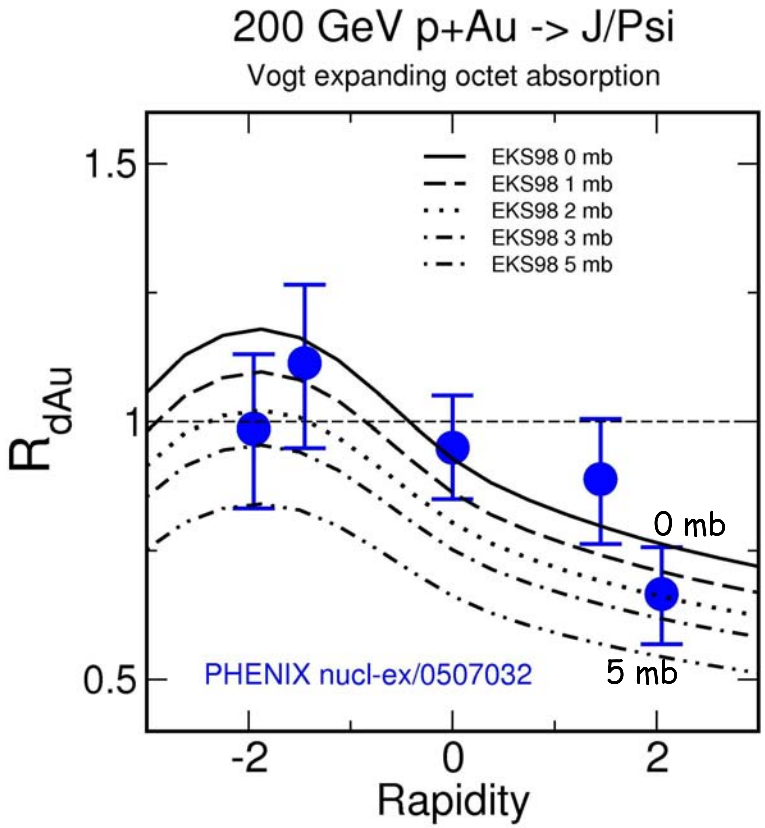
Two central electron/photon/hadron spectrometers:

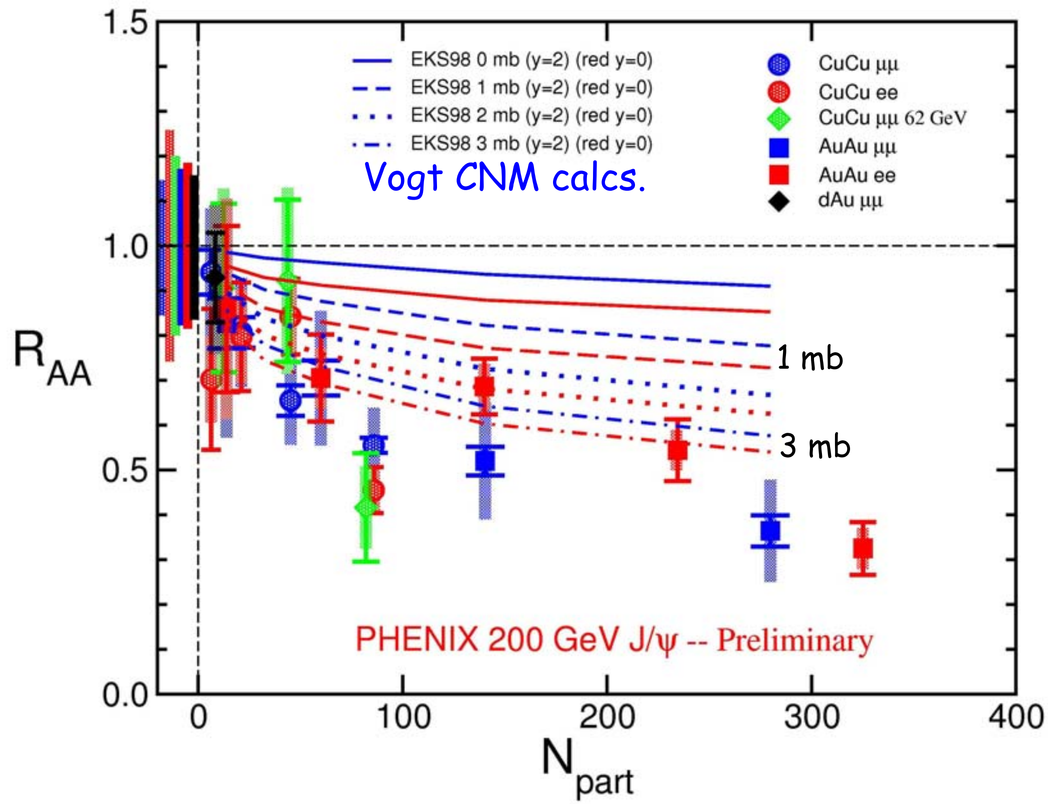
- Tracking, momentum measurement with drift chamber, pixel pad chambers
- e ID with E/p ratio in EmCAL + good ring in RICH counter.

Two forward muon spectrometers

- Tracking, momentum measurement with cathode strip chambers
- μ ID with penetration depth / momentum match

J/ψ suppression in AA collisions & CNM baseline

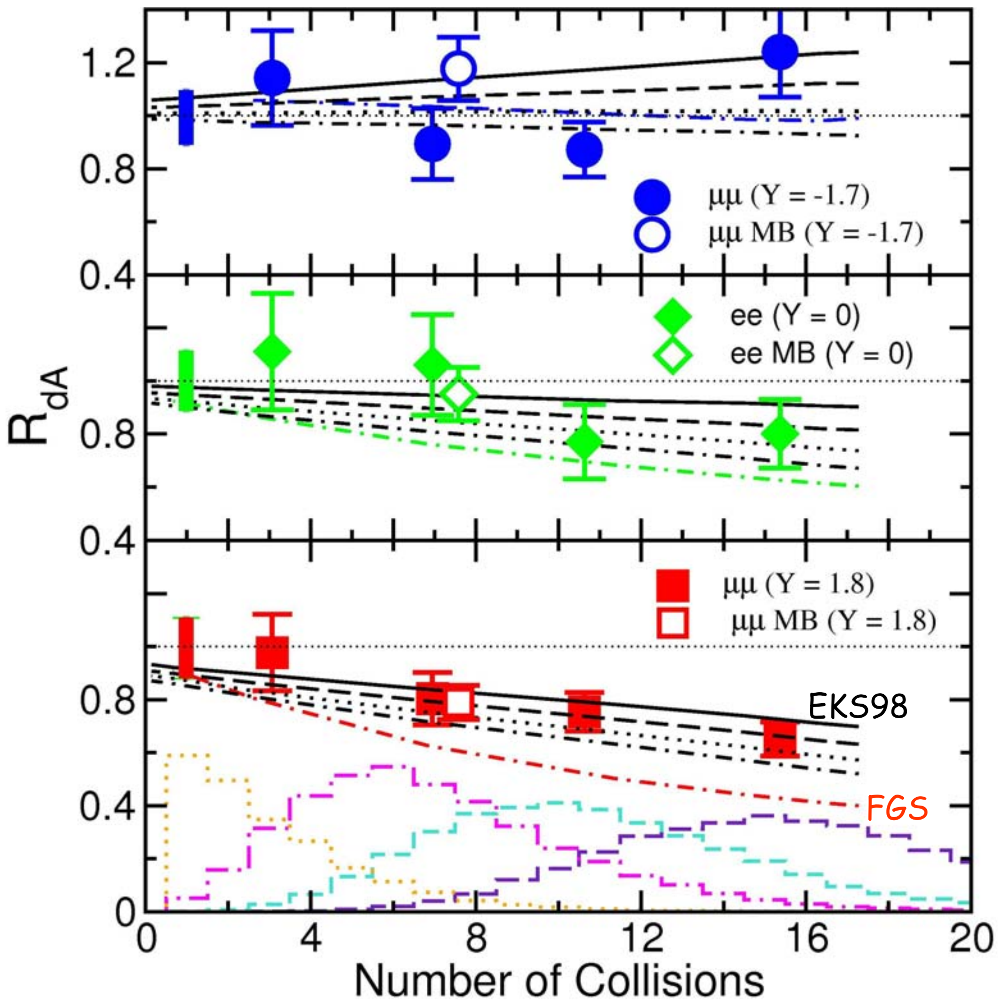




- CNM calculations with shadowing and absorption appear to be most consistent with weaker shadowing models and weak absorption
- but present dAu data probably only constrains absorption to: $\sigma_{ABS} \sim$ 1-3 mb

- AA suppression is somewhat stronger than CNM calculations predict
- but really need more precise dAu constraint!

Centrality dependence of dAu CNM calculations compared to data



Centrality dependence in dAu collisions can also be compared to theory, but uncertainties in dAu data accuracy, and in ability to experimentally define distinct bins in centrality are pretty limiting

Theory from Ramona Vogt with absorption and shadowing:

- black curves for EKS98 shadowing an $\sigma_{ABS} = 0$ to 3 mb
- red curve for FGS shadowing and $\sigma_{ABS} = 3$ mb

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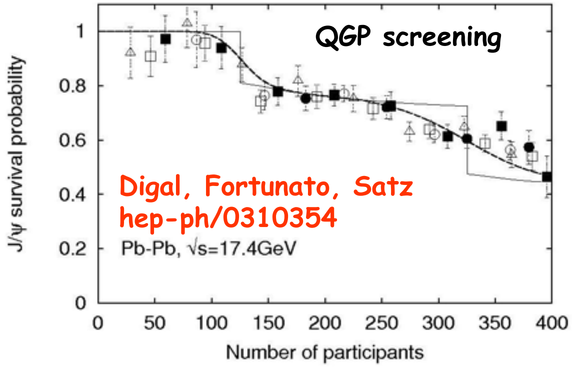
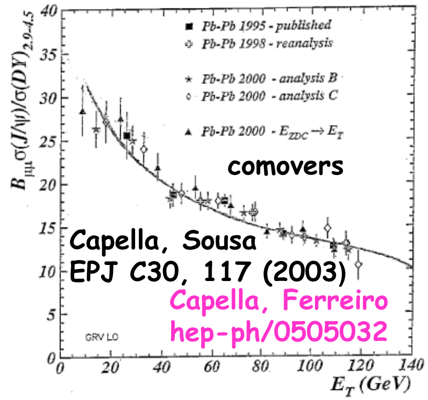
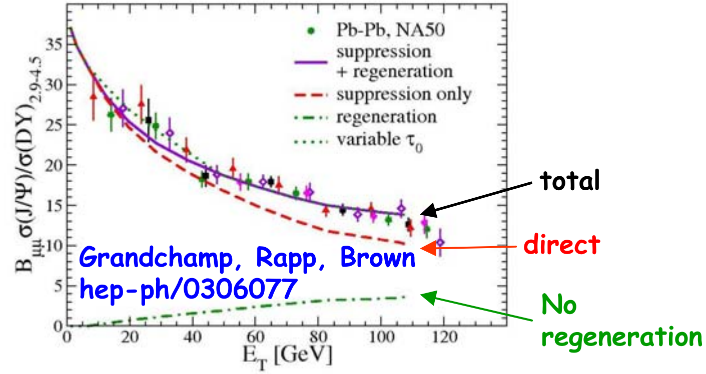
Models without regeneration

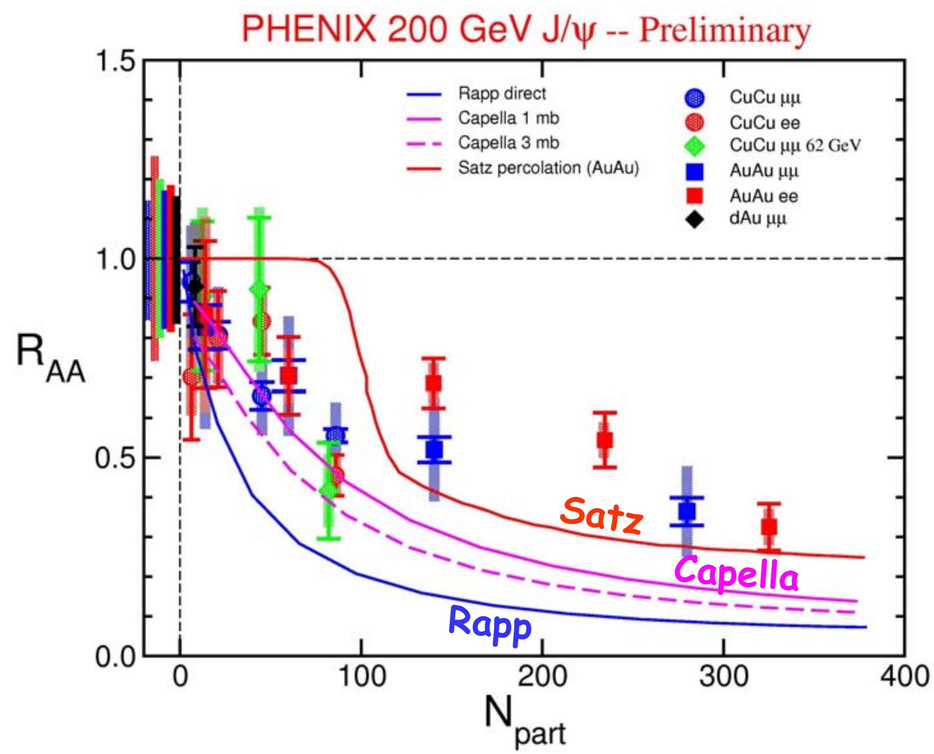






Models that reproduce NA50 results at lower energies preduct too much suppression at RHIC!

- Satz - color screening in QGP (percolation model)
- Capella – comovers with normal absorption and shadowing
- Rapp – direct production with CNM effects needs very little regeneration to match NA50 data

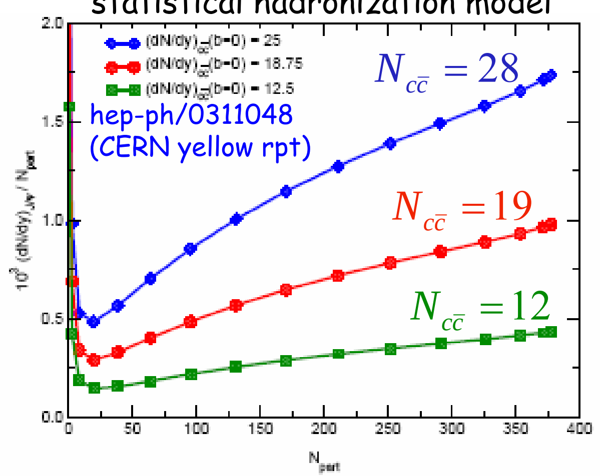


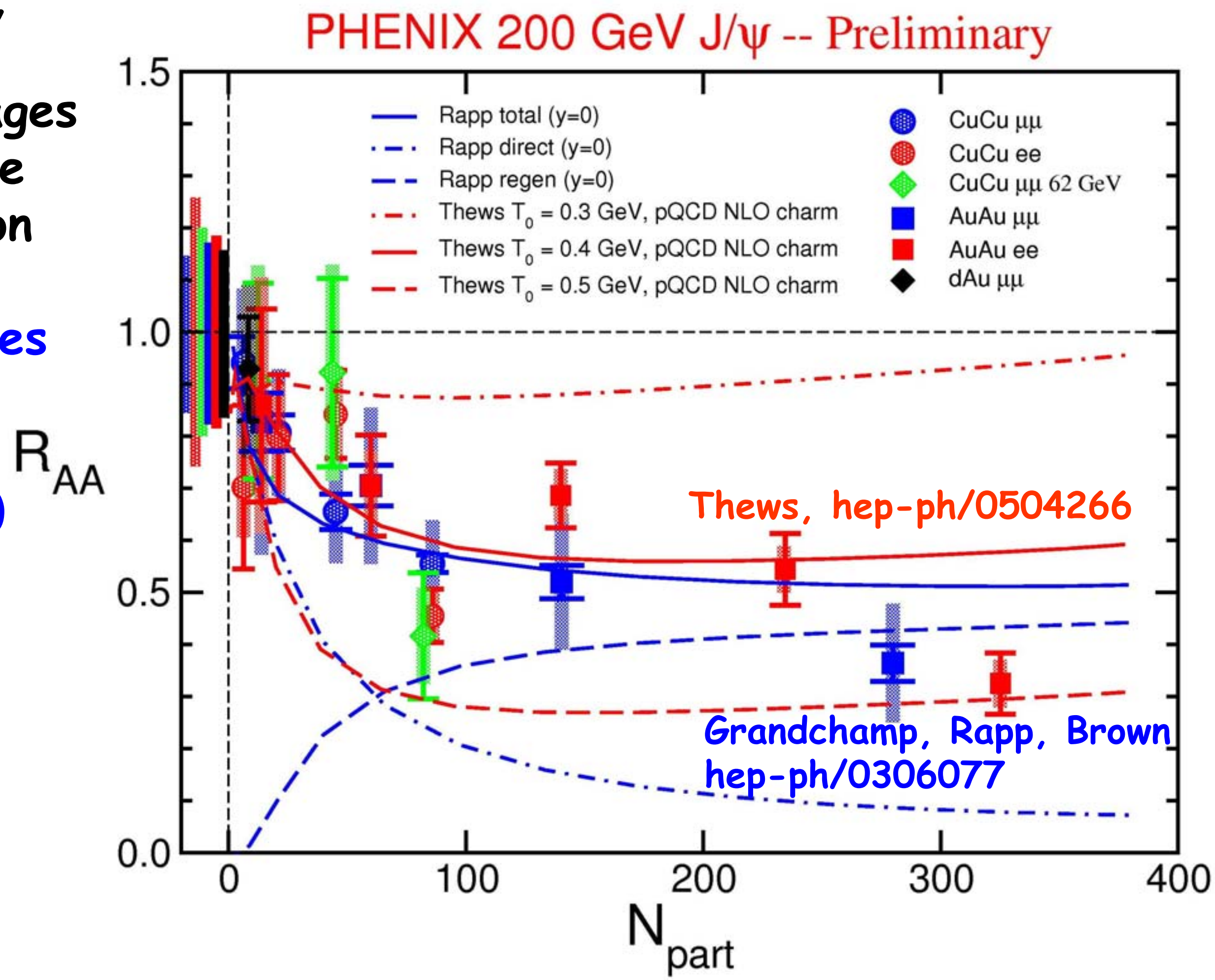
Models with screening & regeneration

Models with regeneration, i.e. single charm quarks combining in the later stages to form J/ψ's – match the observed RHIC suppression much better!

- **but the regeneration goes as $\sigma_{c\bar{c}}^{2}$ - which is still poorly known at RHIC (& that's another story..)**

statistical hadronization model

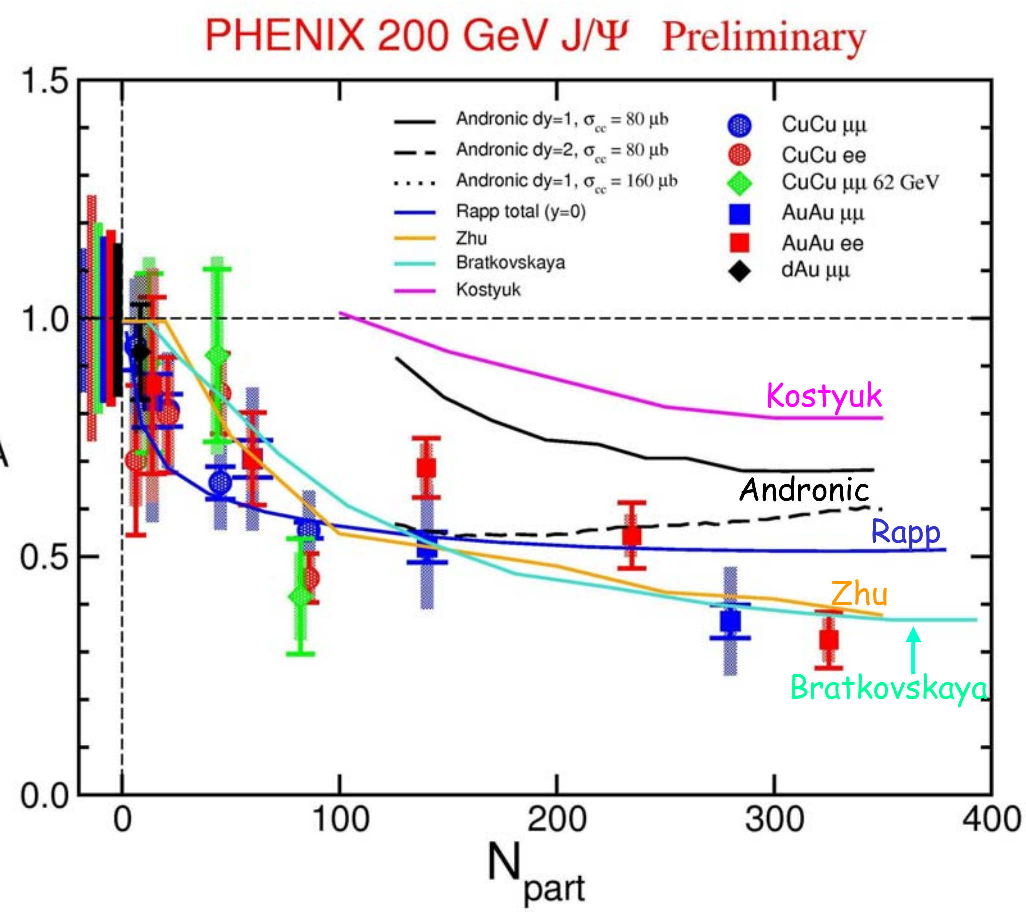




More Models for RHIC J/ψ suppresion in CuCu & AuAu collisions

All have suppression + various regeneration mechanisms

- Rapp (see prev. slide)
- Andronic (nucl-th/0303036)
  - statistical hadronization model
  - ΔY & σ_{ccbar} varied
  - Complete screening of primordial J/ψ's
  - formed at chemical freezeout from thermalized c-cbar's
- Zhu (nucl-th/0411093)
  - J/ψ transport in QGP
  - gluon interactions…
- Bratkovskaya (nucl-th/0402042)
  - hadron-string dynamics transport
- Kostyuk (hep-ph/0305277)
  - statistical coalescence model (SCM)



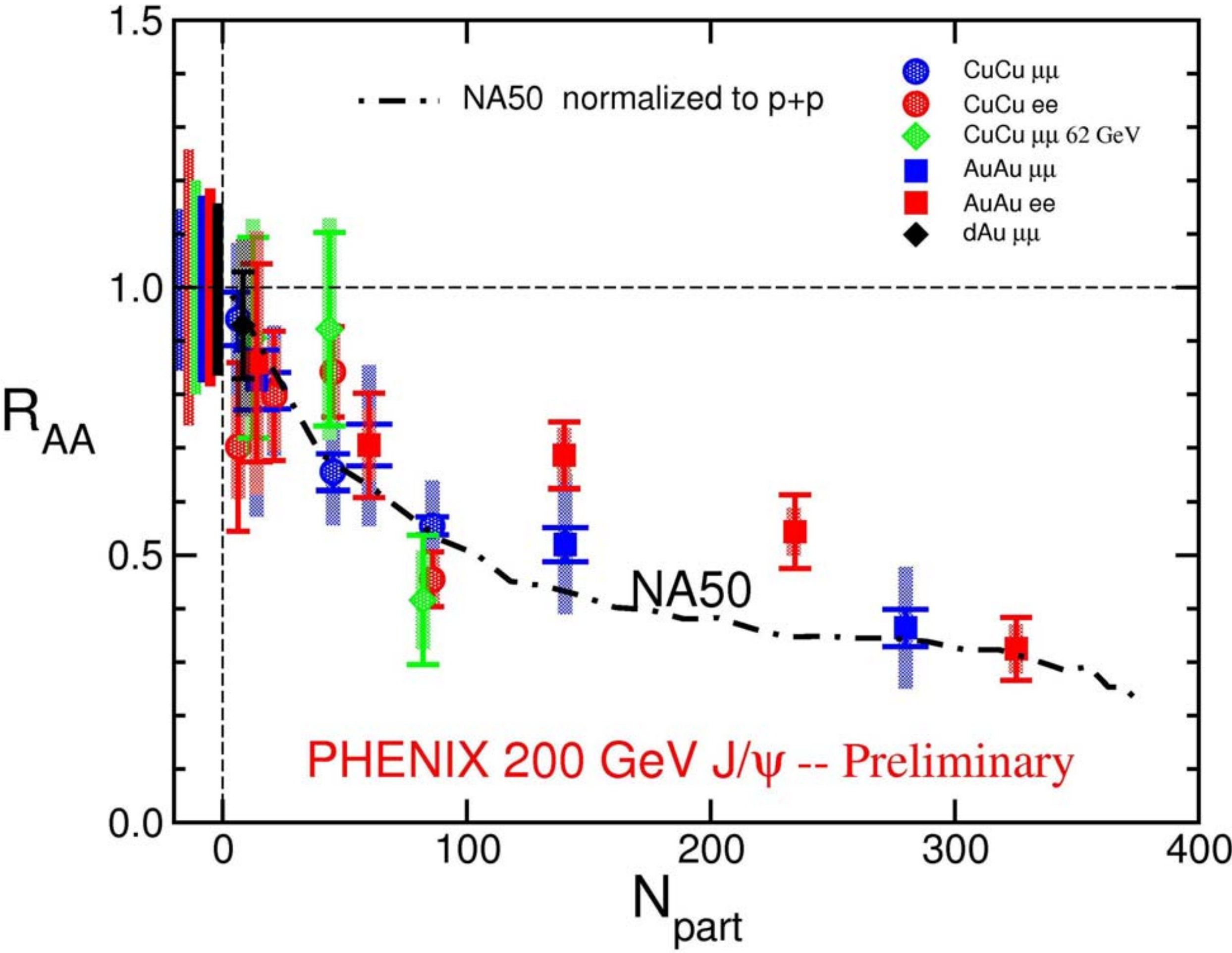
Direct comparision to lower energy NA50 measurement

Suppression at RHIC ($\sqrt{s}$=200 GeV) looks VERY similar to that seen at NA50

- but ~10x collision energy & ~2-3x gluon energy density
- why should it be the same??

Apparently because regeneration compensates for stronger primordial suppression

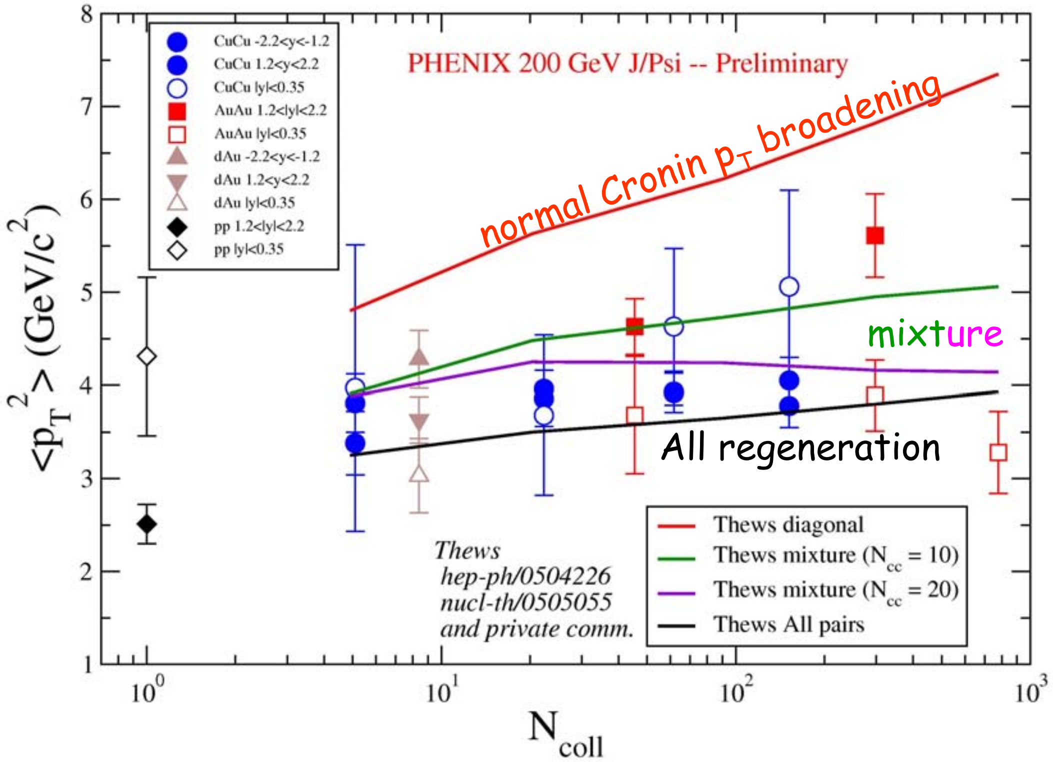
- if so, this effect should be huge at LHC !



Is it really regeneration (at RHIC)?

Regeneration should give narrowing of p_T and rapdity:

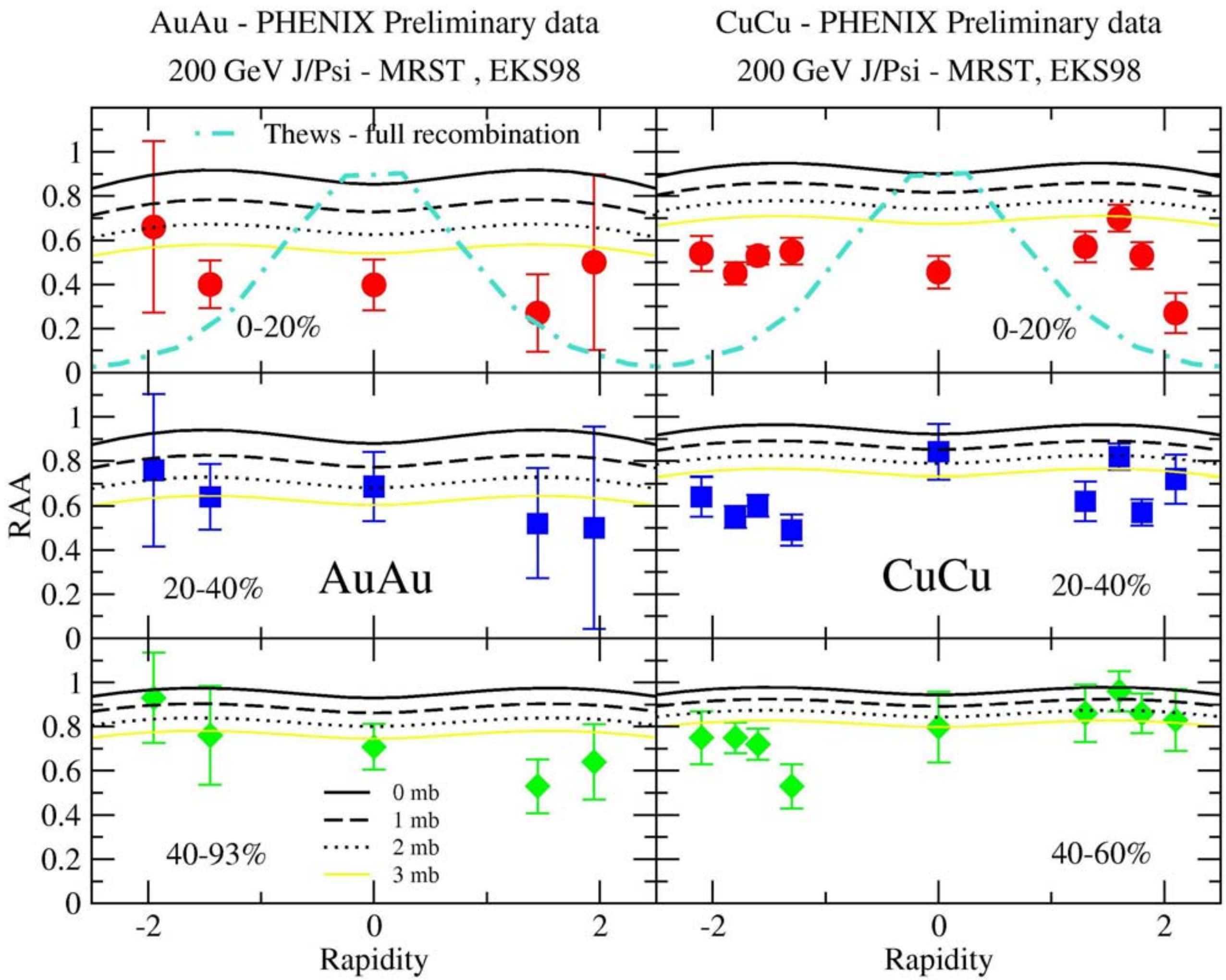
- some evidence of this in $<p_T^2>$ vs centrality
    - narrowing compensates for normal Cronin broadening resulting in more constant $<p_T^2>$(ncoll)
- Bob Thews calculations shown, but data uncertainties make conclusion somewhat weak
- What about rapidity → next slide



Rapidity dependence of ratio for different centrality ranges

Rapidity dependence of central AA collisions (top panels) shows no narrowing – i.e. peaked ratios as in the Thews regeneration calculation shown

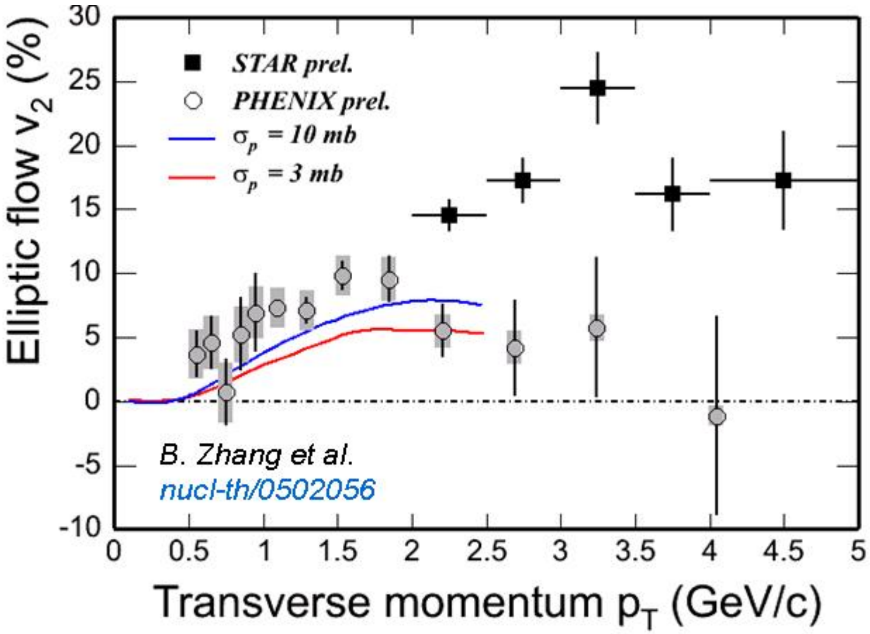
- Thews calculation shown here is extreme – if all production was regeneration, realistic calculation would be less peaked
- but uncertainties in data limit the sensitivity to such an effect



Flow of J/ψ's?

Need to look for J/ψ flow – if regeneration dominates, the J/ψ's should inherit flow from charm quarks

- open charm has recently been seen to flow (at least at some p_T values)
- but what about geometrical absorption effects, which could also give asymmetry wrt reaction plane?



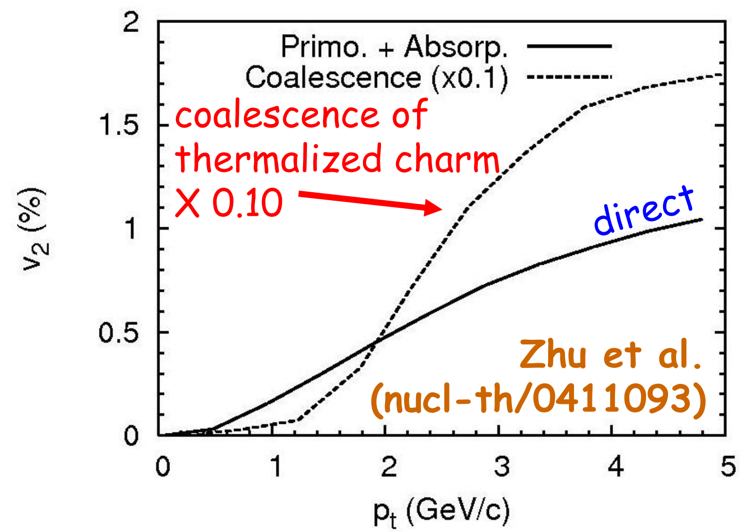


FIG. 4: The elliptical flow of J/ψ as a function of p_t at RHIC energy. The solid line is the maximal v_2 with impact parameter b=7.8 fm calculated in the frame of J/ψ transport, and the dashed line is the minimum-bias v_2 (scaled by a factor of 0.1) of the coalescence model with the assumption of complete charm quark thermalization.

Summary & Comments

Progress on onia production cross sections and polarizations but still doesn't seem to be well understood

• causes uncertainties in the understanding of nuclear effects (e.g. J/ψ absorption)

Weak shadowing has been observed at RHIC for the J/ψ in dAu collisions

• but scaling with x_F (and not with x_2) is still a puzzle!

AA collisions at RHIC suggest substantial contributions from regeneration

• suppression observed is very similar to NA50 at lower energies but more suppression would be expected from QGP since gluon densities are 2-3x larger at RHIC

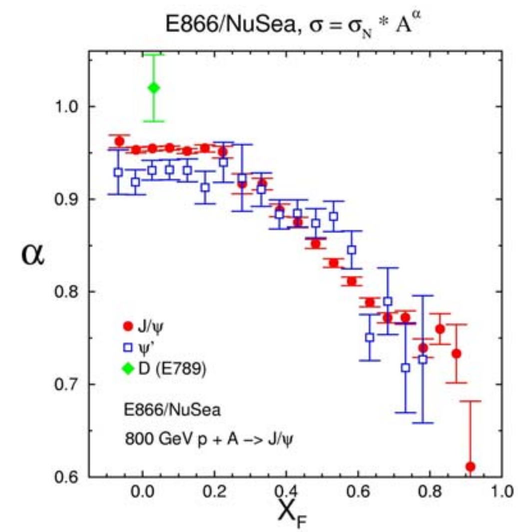
• however large charm cross section & regeneration may compenstate – not a very appealing picture, but might be true

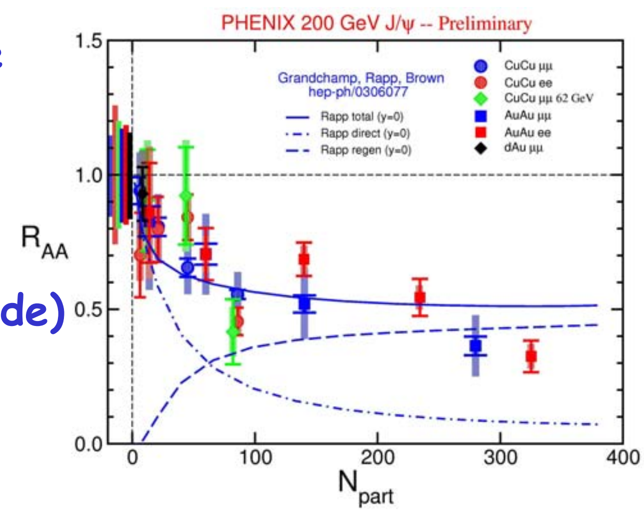
• need careful quantitative analysis of dAu and AA to establish level of CNM effects in AA

• need higher more accurate dAu & AA J/ψ data (higher luminosities and cleaner spectra with silicon vertex upgrade)

• need accurate charm cross section to constrain regeneration

• need flow measurement for J/ψ





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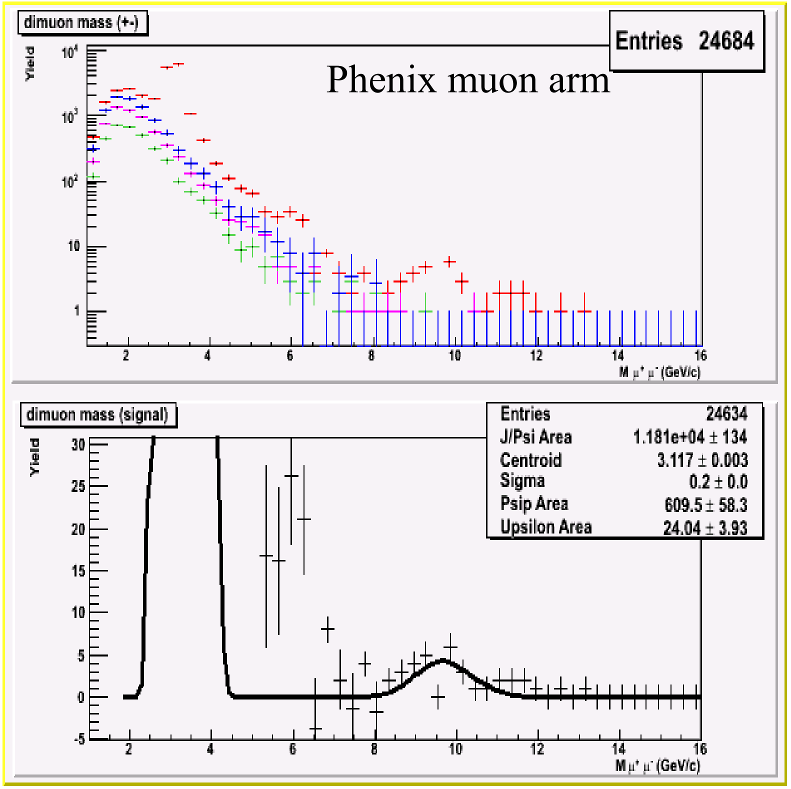
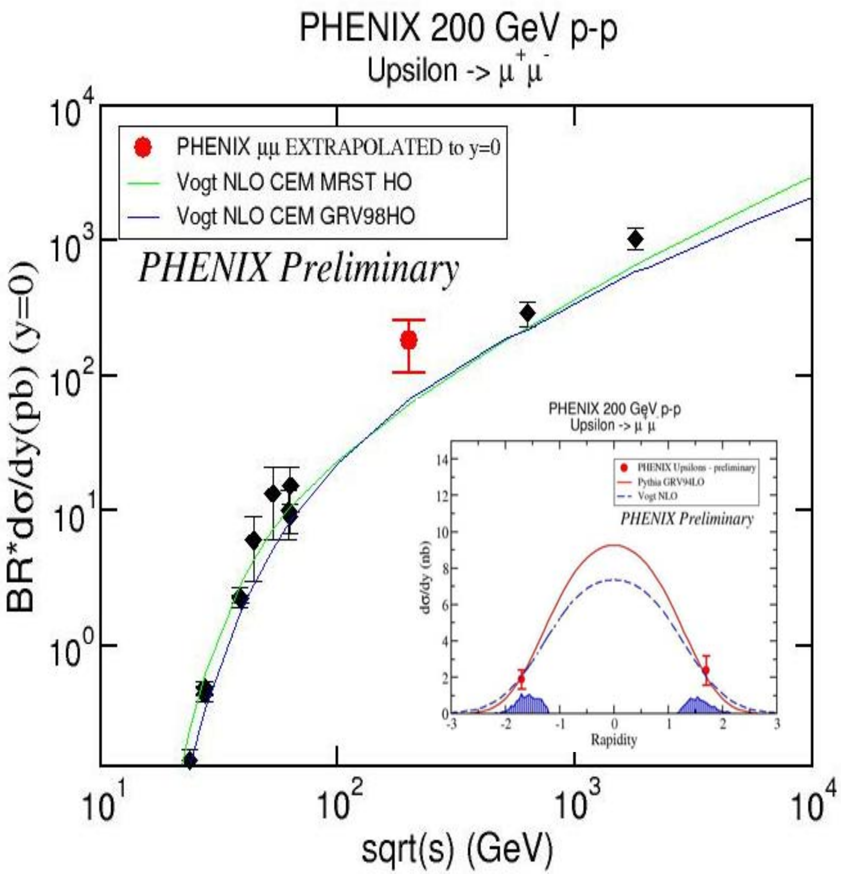
Υ in *pp* – Much More to Come!



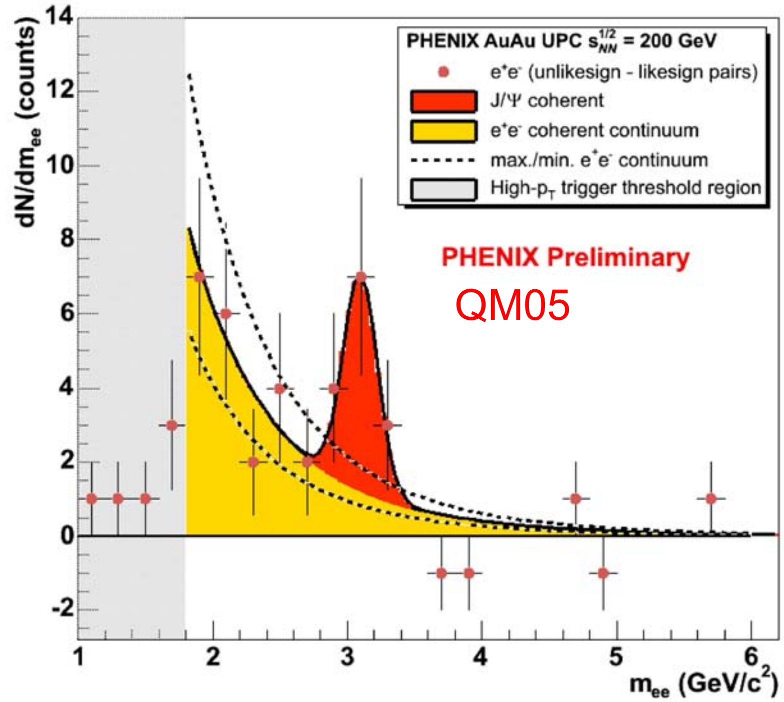


1st Upsilons at RHIC from ~3pb^{-1} collected during the 2005 run.

Ultra-peripheral Collisions (UPC's)

Can Ultra-peripheral reactions (UPC's) at forward rapidity probe small-x gluon shadowing or saturation?

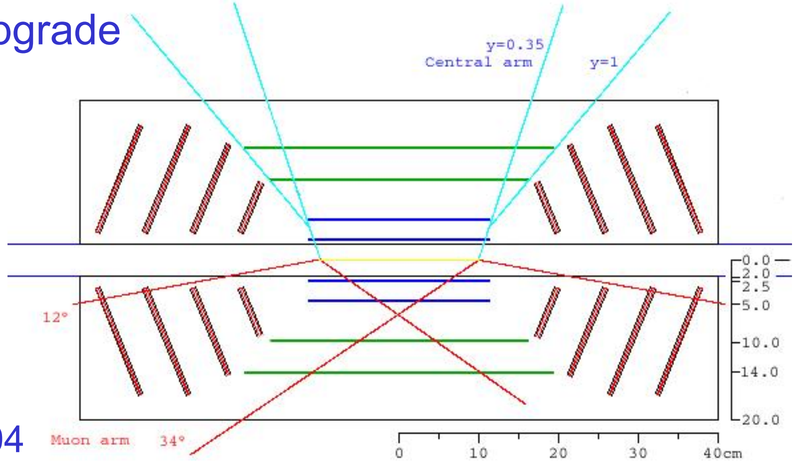
- e.g. J/ψ production probes gluon distributions of nuclei (private comm. Mark Strikman)



Some comments about the future at RHIC/PHENIX

- Present p-p in "Run5" is supposed to bring ~4.1 pb^{-1}
  - would give ~13k J/ψ, 400 ψ', 6 ϒ (in 2 muon arms) & ~5k $J/\psi \rightarrow e^+e^-$
  - compared to ~0.2 pb^{-1} in Run3 with ~450 $J/\psi \rightarrow \mu^+\mu^-$
  - and ~0.2 pb^{-1} in Run4 with ~850 $J/\psi \rightarrow \mu^+\mu^-$ (?)
- A new higher luminosity d-Au run (by 2009?) needed
  - projected to give ~39 nb^{-1}
  - which would give ~50k $J/\psi \rightarrow \mu^+\mu^-$ & ~12k J/ψ→e+e-
  - compared to ~1.5 nb^{-1} in "Run3" which gave ~1.7k $J/\psi \rightarrow \mu^+\mu^-$ (~400 J/ψ→e+e-)
- Muon arm performance also is improved:
  - better efficiency with reduced beam backgrounds, by as much as a factor of two (see Run4 vrs Run3 pp above)
  - better mass resolution σ ~ 200 MeV → 150 MeV or better
- Silicon vertex upgrade to PHENIX will improve mass resolution further
- ϒ is tough without a luminosity (RHIC-II) upgrade

Vector meson	Lepton pair	1.5 nb^{-1} Au-Au	30 nb^{-1} Au-Au RHIC-II
ψ'	ee	100	2k
	μμ	1.4k	28k
ϒ	ee	8	155
	μμ	35	700

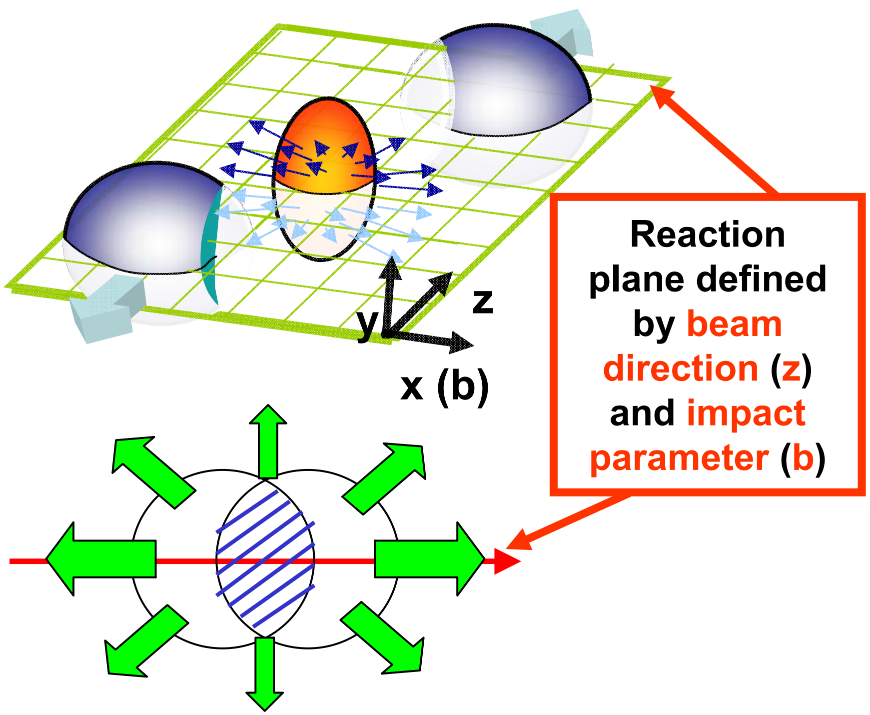


From Axel Drees CAARI 2004

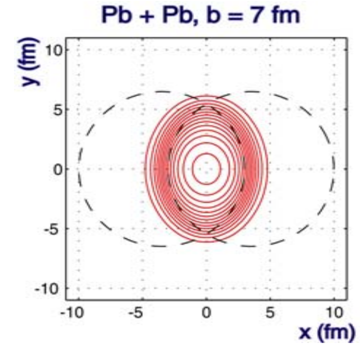
RHIC-II & LHC rate comparisons (RHIC: 12 weeks of AuAu; LHC: 1 month of PbPb). From Tony Frawley, Santa Fe RHIC Planning Meeting, 29-30 Oct 2005 http://www.phenix.bnl.gov/WWW/publish/abhay/panic05/frawley.pdf

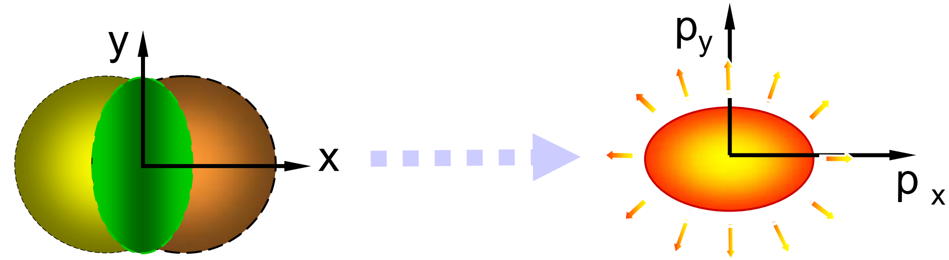
	RHIC-II				LHC Heavy Ions					
Signal	PHENIX	$\lvert\eta\rvert$	STAR	$\lvert\eta\rvert$	ALICE	$\lvert\eta\rvert$	CMS	$\lvert\eta\rvert$	ATLAS	$\lvert\eta\rvert$
$J/\psi \to ee$	45k	<0.35	220k	<1	9.5k	<0.9				
$J/\psi \to \mu\mu$	395k	1.2-2.4			380k	2.5-4	40k	<2.4	8-100k	<2.5
$\psi' \to ee$	800	<0.35	4k	<1	190	<0.9				
$\psi' \to \mu\mu$	7.1k	1.2-2.4			6.9k	2.5-4	731	<2.4	140-1800	<2.5
$\chi_C \to ee\gamma$	2.8k	<0.35								
$\chi_C \to \mu\mu\gamma$	117k	1.2-2.4								
$\Upsilon \to ee$	400	<0.35	11.2k	<1	1.9k	<0.9				
$\Upsilon \to \mu\mu$	1.04k	1.2-2.4			4.2k	2.5-4	8.2k	<2.4	15k	<2
$B \to J/\psi \to ee$	570	<0.35	2.5k	<1						
$B \to J/\psi \to \mu\mu$	5.7k	1.2-2.4								
$D \to K\pi$	?		30k	<1	8k	<0.9				

Reaction plane definition



Initial coordinate space anisotropy
→pressure anisotropy
→momentum space anisotropy.
(P = ρRT → dP ~ dρ)





What we measure:

Particle distributions in coordinate space (*due to momentum space anisotropy*).

v_1: directed

v_2: elliptical