PHENIX results on quarkonia

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Hard Probes
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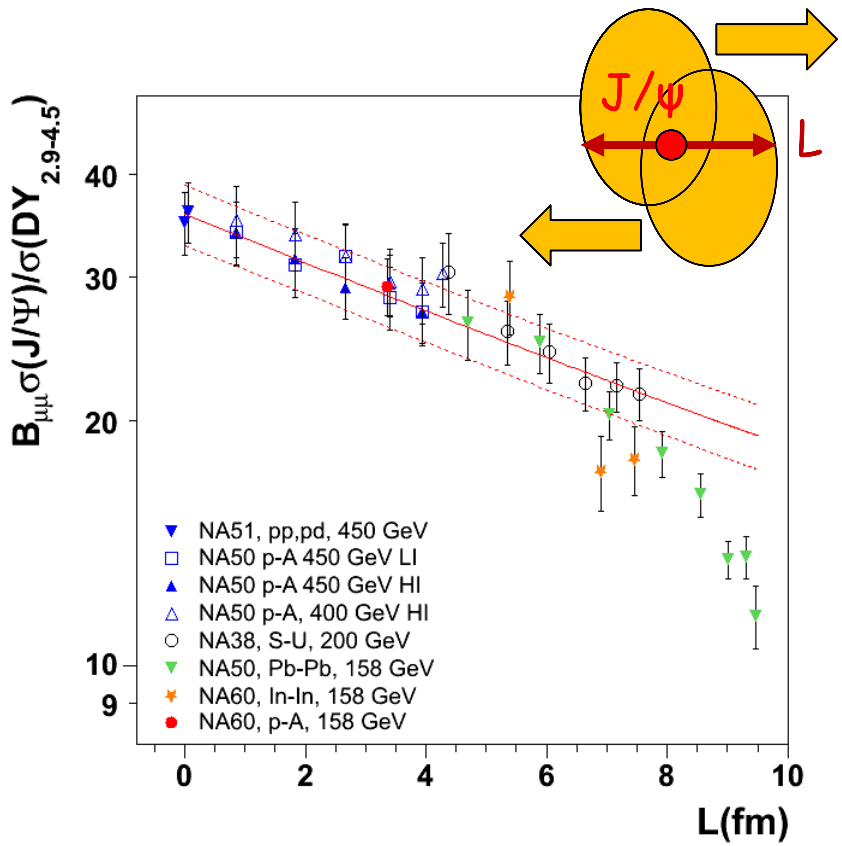
Probing QGP with quarkonia

- The start:
  - J/ψ anomalously suppressed in heavy ion collisions due to color screening if Quark Gluon Plasma is formed (Matsui & Satz PL B178 (1986) 416)
  - The NA38, NA50 and NA60 experiments at CERN SPS measured J/ψ suppression in a variety of systems
- Anomalous suppression
  - 'measured/expected' J/ψ yield for light-light and heavy-light type collisions follow a universal scaling as a function of L
  - Trend is broken by central heavy-heavy type collisions
  - Models with no QGP have reproduced this behavior, so further investigation is needed



J/ψ detection in PHENIX

Central Arms:

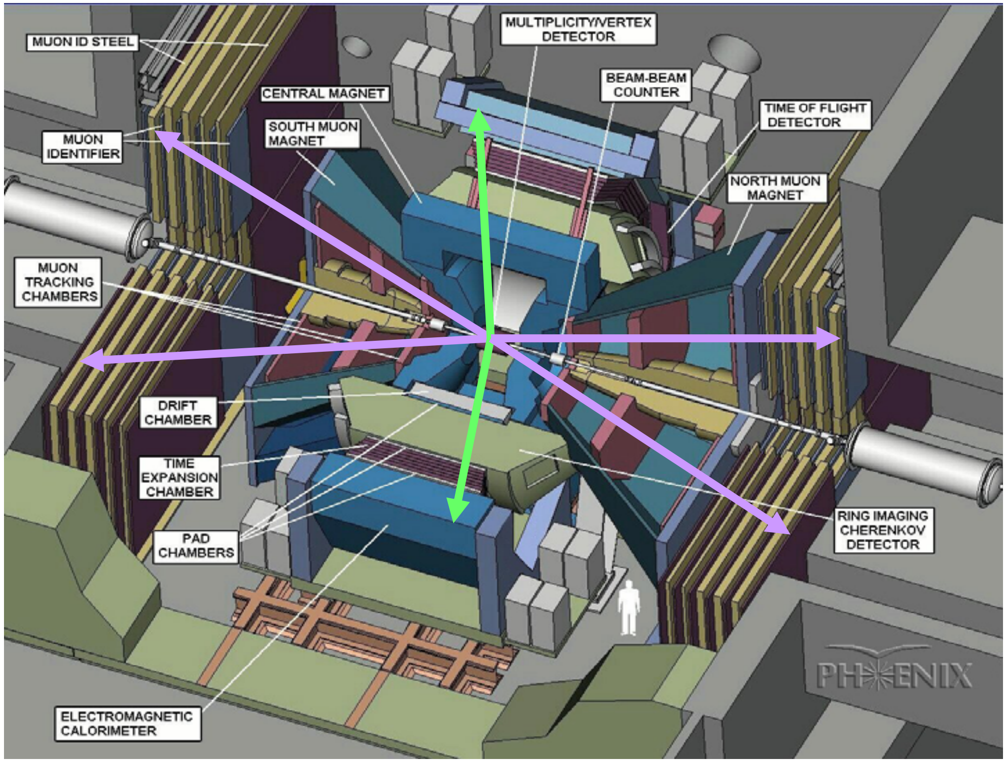
Hadrons, photons, electrons

- $J/\psi \rightarrow e^+e^-$
- $|\eta|<0.35$
- $p_e > 0.2$ GeV/c
- $\Delta\phi = \pi$ (2 arms x $\pi/2$)

Forward rapidity Arms:

Muons

- $J/\psi \rightarrow \mu^+\mu^-$
- $1.2<|\eta|<2.2$
- $p_\mu > 1$ GeV/c
- $\Delta\phi = 2\pi$



Global detectors

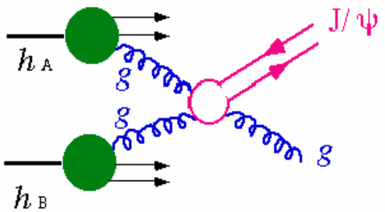
Beam-Beam Counter (BBC)

Zero Degree Calorimeter (ZDC)

Reaction Plane Detector (RxNP)

Contributions to J/ψ yield in HICs

- Production (RHIC energies)
  - Mainly by gluon fusion ($gg \rightarrow J/\psi$)
    - Very early in nucleon-nucleon hard scatterings
  - Feed down from excited states of charmonia, multiple measurements
    - HERA-B : ($\chi_c \rightarrow J/\psi X$) ~ 21±5% and ($\psi' \rightarrow J/\psi X$) ~ 7±0.4% (*)
    - PHENIX prelim.: ($\chi_c \rightarrow J/\psi X$) <42%(90% CL) and ($\psi' \rightarrow J/\psi X$) ~ 8.6 ± 2.5%
    - …



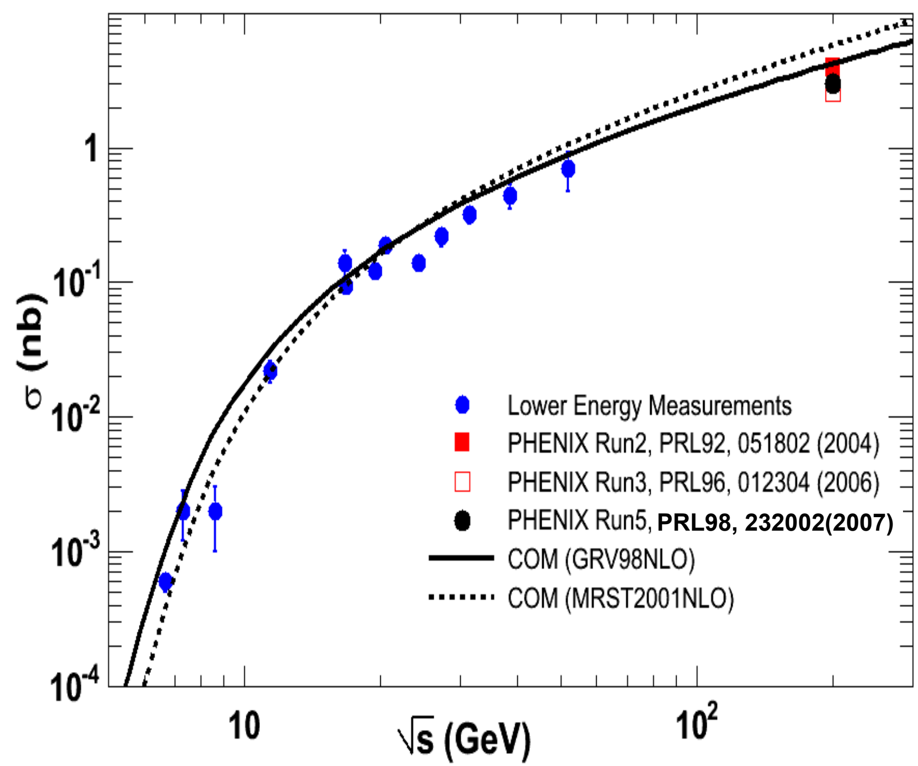
- Gluon shadowing: modification of PDFs in nuclei
- Suppression
  - Breakup by scattering on nucleons from initial heavy ions ($J/\psi + N \rightarrow X$)
  - Melting in QGP/dissociation by comovers
- Enhancement
  - Possible recombination from <u>uncorrelated</u> c and $\bar{c}$ quarks

J/ψ measurements in p+p collisions

- Why J/ψ in p+p?
  - Constrain J/ψ production models
  - Baseline to heavy ion yields
    - Compared to a superposition of independent pp collisions

$$R_{AB}(y,p_t) = \frac{d^2N_{AB}/dydp_t}{<N_{coll}> \times d^2N_{pp}/dydp_t}$$

Nuclear modification factor



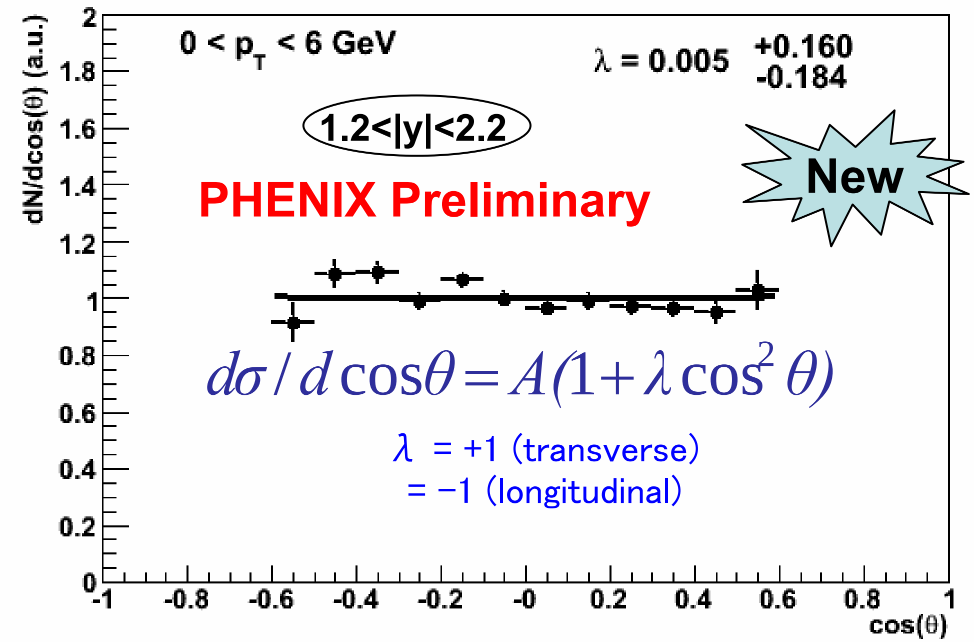
Total cross section:

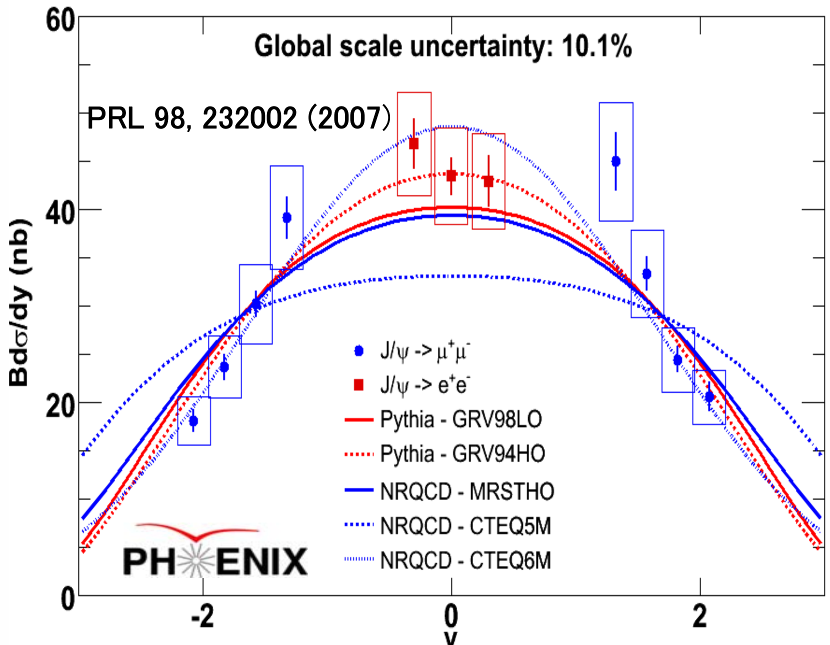
$$BR_{ll} \cdot \sigma_{tot} = 178 \pm 3^{stat} \pm 53^{sys} \pm 18^{norm} \text{ nb}$$

B_{ll} is the J/ψ dilepton branching ratio (~12%)

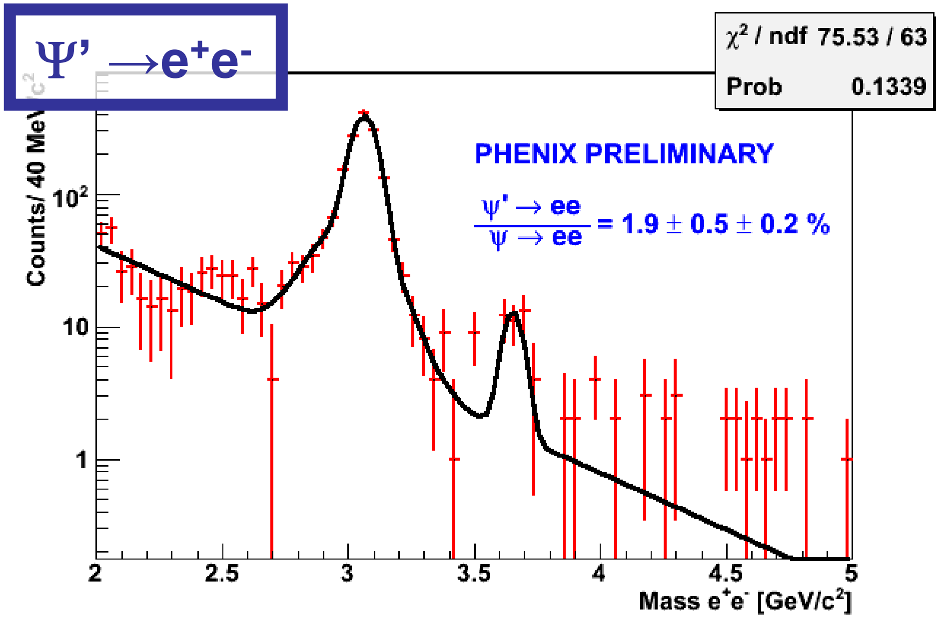
J/ψ production mechanism

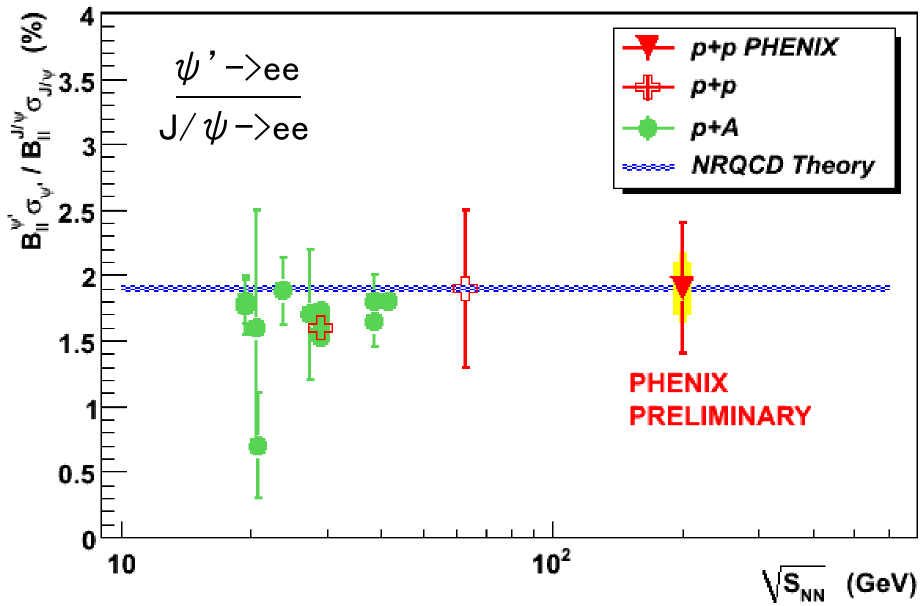
- Constraints from data
  - Most color singlet models underestimate total cross section
    - A new approach allowing off-shell and non static heavy quarks to form quarkonium reproduces total cross section and polarization
      (PRL 100, 032006 (2008) cf. Talk by J-P. Lansberg)
  - Color octet model, gets good cross section, but predicts transverse polarization at high pt, not seen yet
  - Precision on rapidity dependence is starting to become good enough to bring useful constraint





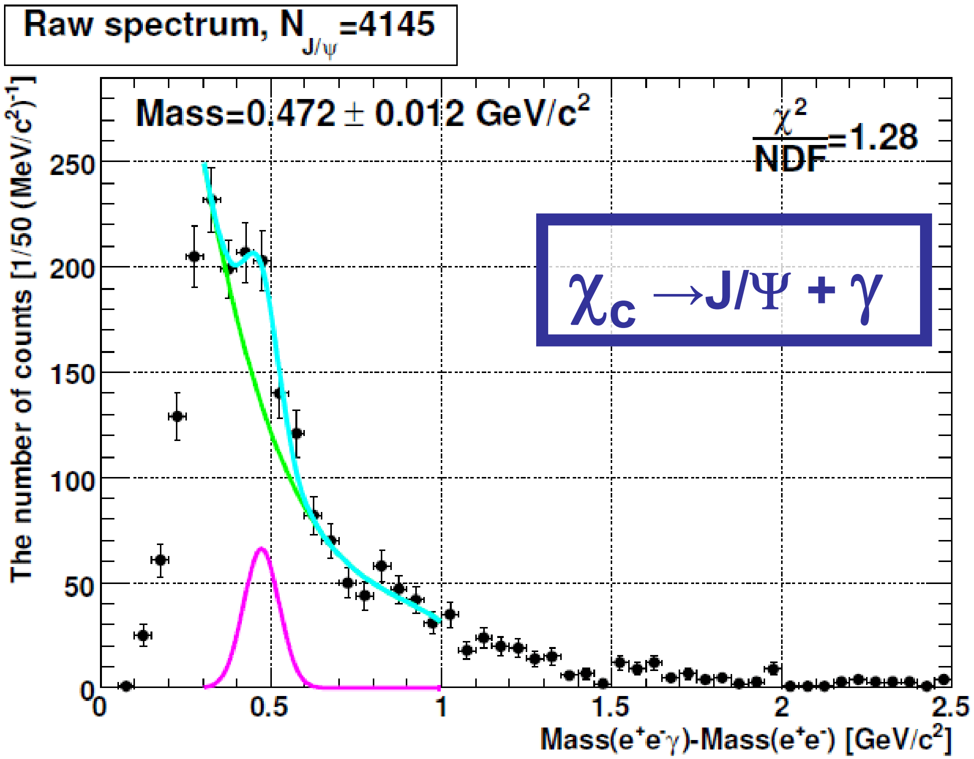
J/ψ from ψ'

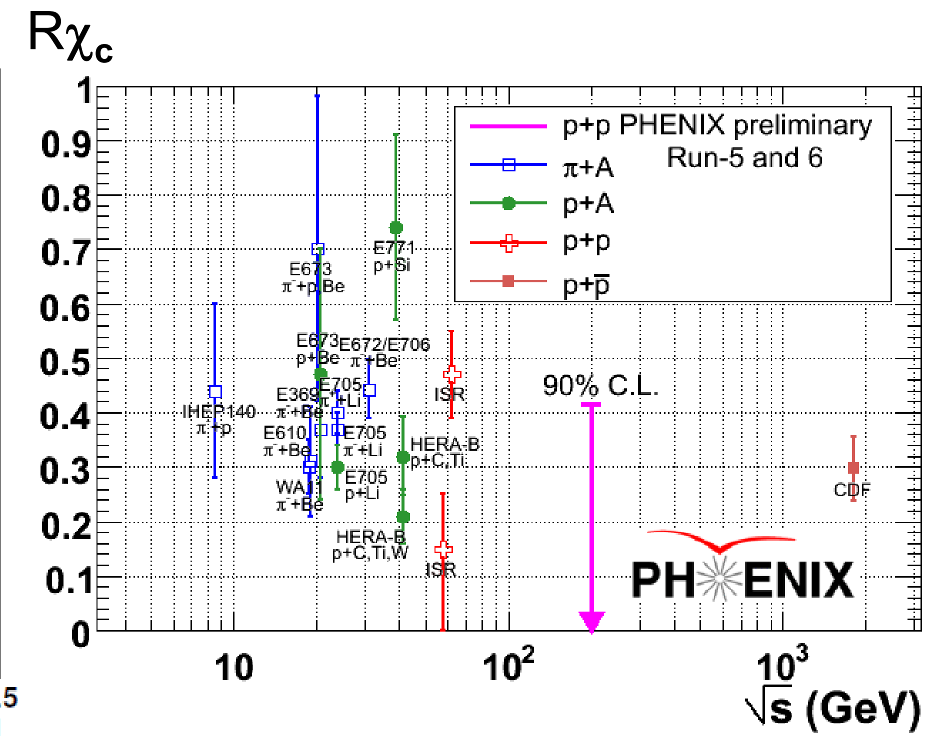




	PHENIX	Theory
J/ψ from ψ'	0.086±0.025	0.08 Digal et al., Phys. Rev. D 64 (2001) 94015

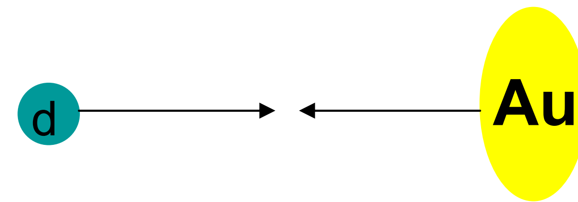
J/ψ from χ_c





	PHENIX	Theory
J/ψ from χ_c	<0.42(90% CL)	0.30 Digal et al., Phys. Rev. D 64 (2001) 94015

Cold nuclear matter (CNM) effects

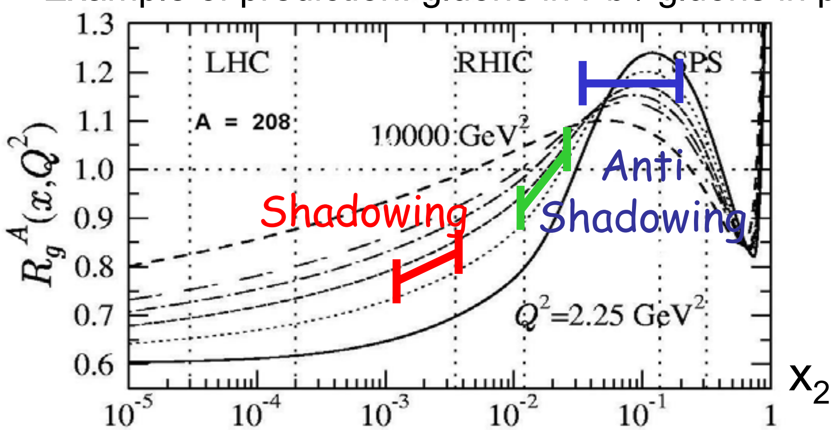


- J/ψ suppression in d+Au:
  - Study CNM effects
    - Shadowing, absorption/breakup

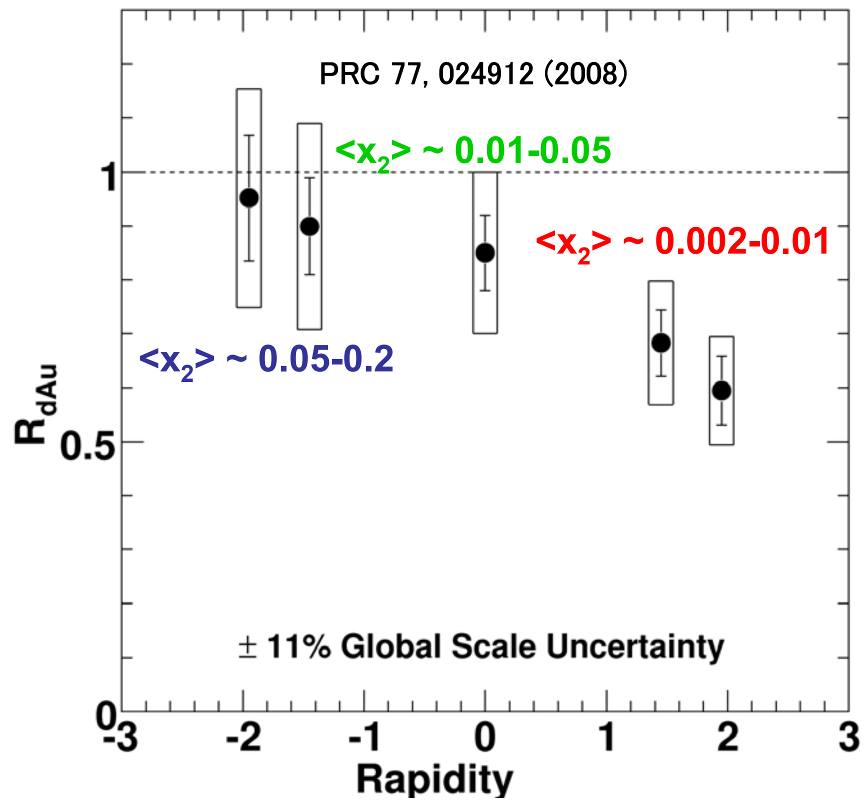
$$R_{dAu}(y) = \frac{dN_{dAu}/dy}{< N_{coll} > \times dN_{pp}/dy}$$

$N_{coll}(dAu) = 7.6 \pm 0.3$

Example of prediction: gluons in Pb / gluons in p



K.J. Eskola et al. Nucl. Phys. B535 (1998) 351



x_2 : Momentum fraction in nucleus

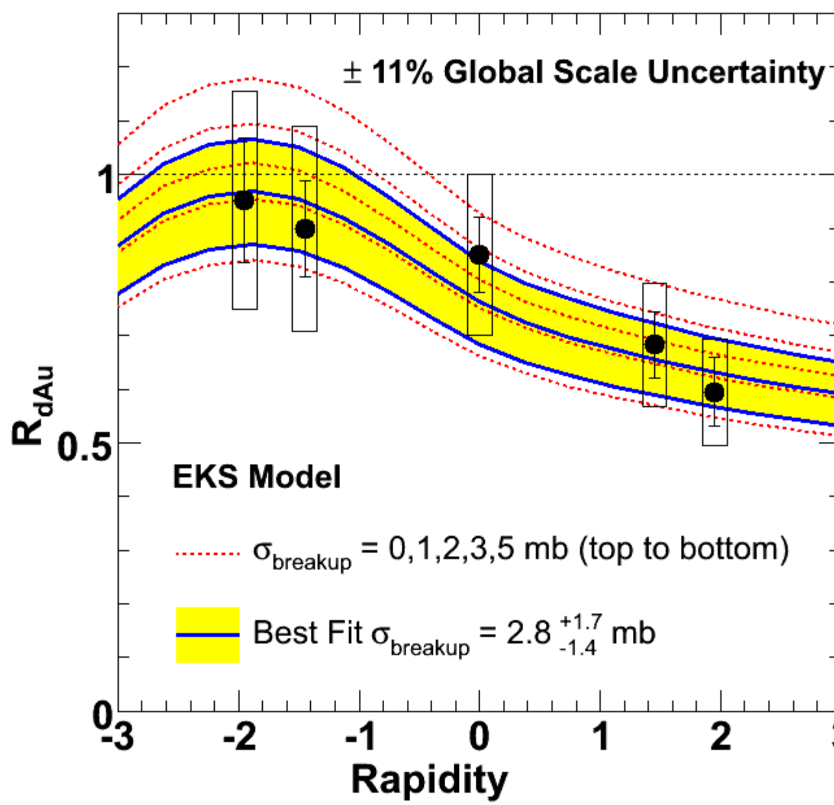
Breakup cross-section

- Extraction method
  - Rapidity dependence of R_{dAu} calculated (*) assuming a shadowing model EKS (**) or NDSG (#)
  - Any additional suppression is accounted for by a single free parameter : break up cross-section ($\sigma_{breakup}$)
    - EKS => $\sigma_{breakup} = 2.8_{-1.4}^{+1.7}$ mb
    - NDSG => $\sigma_{breakup} = 2.2_{-1.5}^{+1.6}$ mb
  - Compatible with SPS (##):

    $\sigma_{abs} = 4.2 \pm 0.5$ mb

    (Anti shadowing effect not taken into account in SPS calculation)

PRC 77 024912 (2008)



(*) R. Vogt, PRC, 71 054902 (2005)

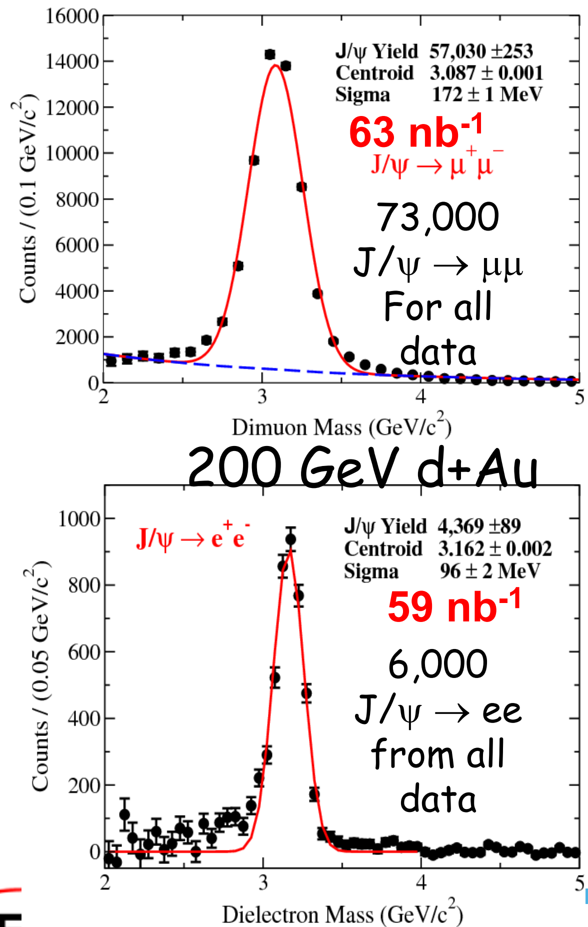
(**) K.J. Eskola et al., Nucl. Phys. A 696, 729 (2001)

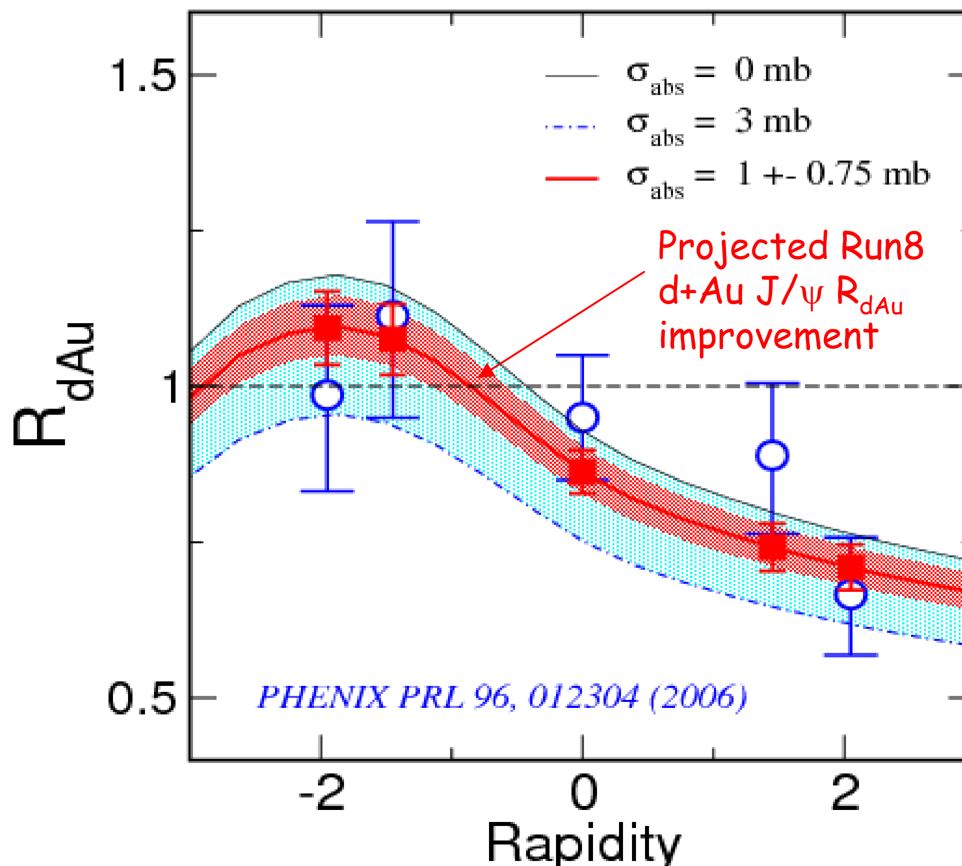
(#) D. deFlorian et al., PRD, 69 074028 (2004)

(##) B. Alessandro et al., Euro. Phys. J. C48, 329 (2006)

Coming up…

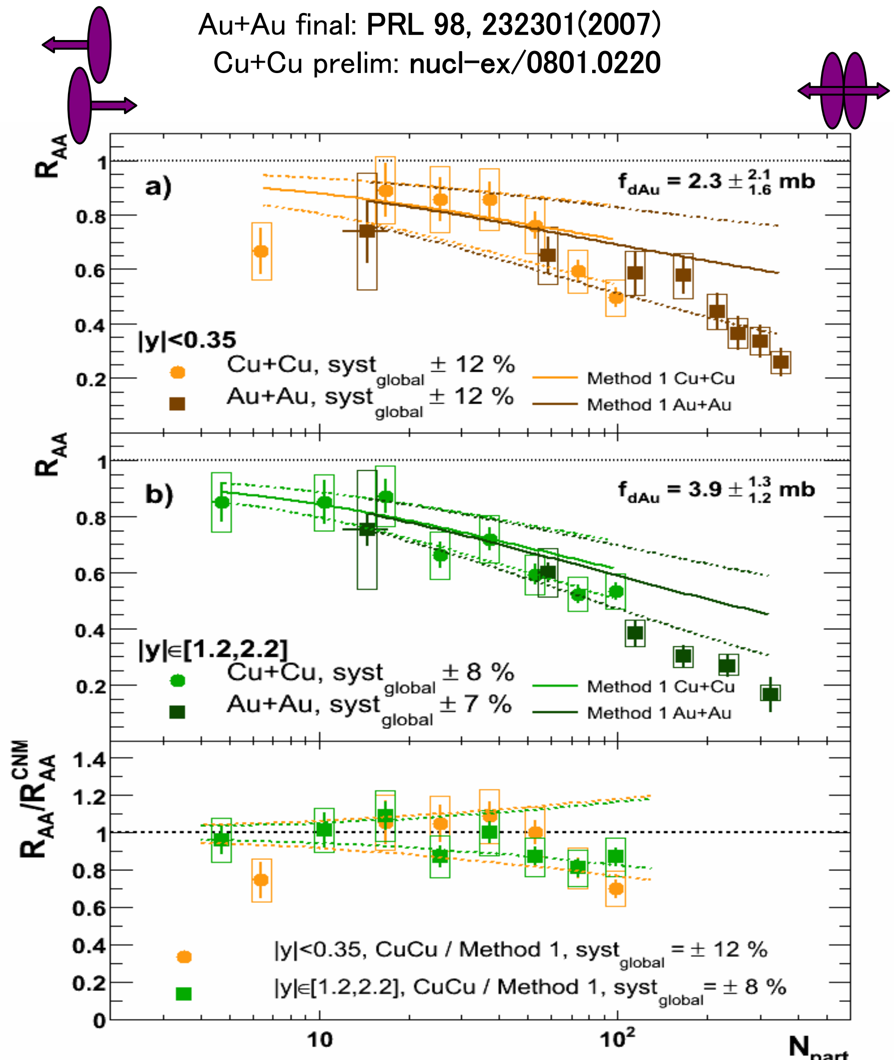
- New d+Au from very high luminosity run
  - 30x the previously available statistics ($80 nb^{-1}$)
  - Will bring a much stronger constraint on CNM





Au+Au and Cu+Cu collisions

Au+Au final: PRL 98, 232301(2007)
Cu+Cu prelim: nucl-ex/0801.0220



Bar: stat. + uncorrelated syst. errors
Band: correlated syst. Errors

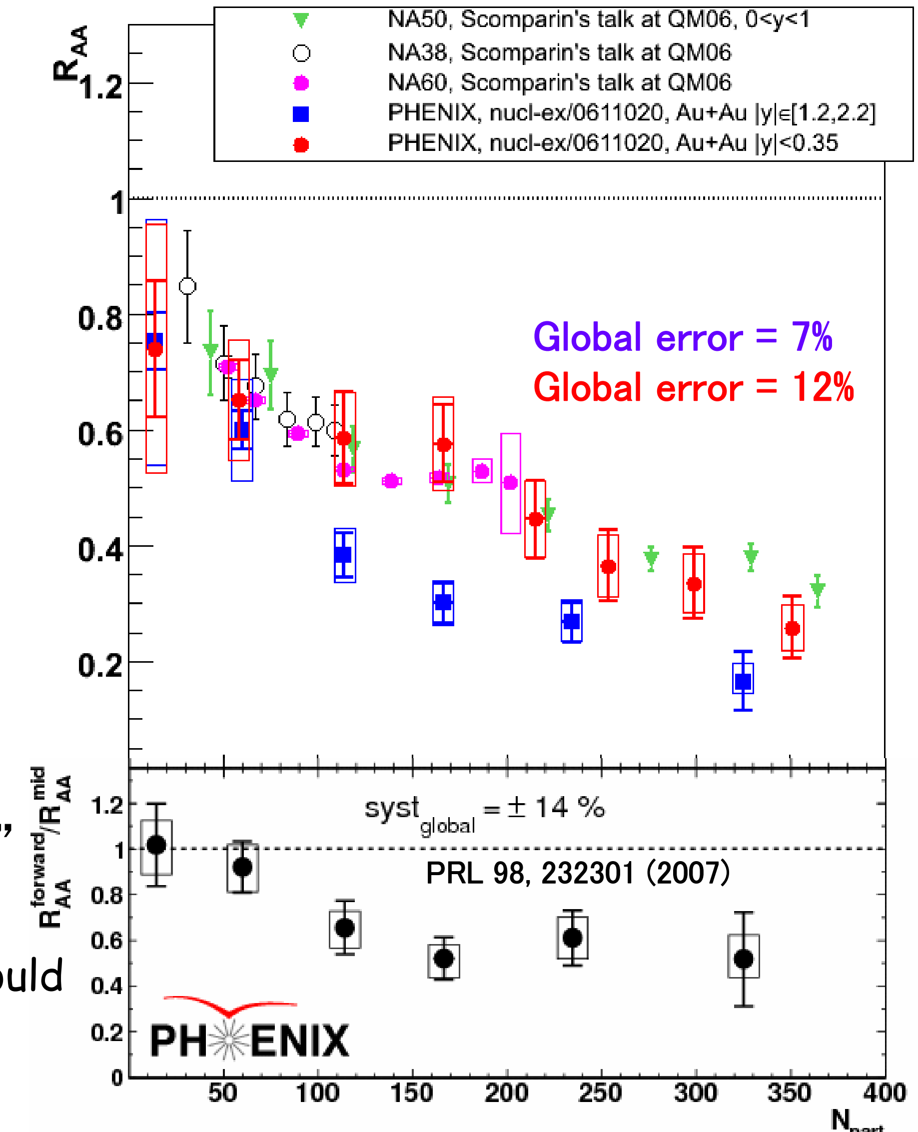
- R_{AA} summary plot :
  - J/ψ suppression measurements in Au+Au and Cu+Cu collisions at $\sqrt{s_{NN}}$=200GeV
  - Curves show the CNM constraint from d+Au data
  - Suppression in most central Au+Au goes as far as by a factor of 5 at forward rapidity

Two surprises

- Comparison to SPS
  - R_{AA} (RHIC, (|y|<.35) ≈ R_{AA} (SPS)
  - Not what's expected from

    $\varepsilon_{SPS} < \varepsilon_{RHIC}$
  - Caution:
    - Rapidity ranges not same

      $0 < y_{sps} < 1$
    - Different CNM effects
- Rapidity trend
  - R_{AA} (|y|<.35) > R_{AA} (1.2<|y|<2.2)
  - Challenge to most "local density" based suppression models
    - More matter at mid rapidity, should lead to more suppression there

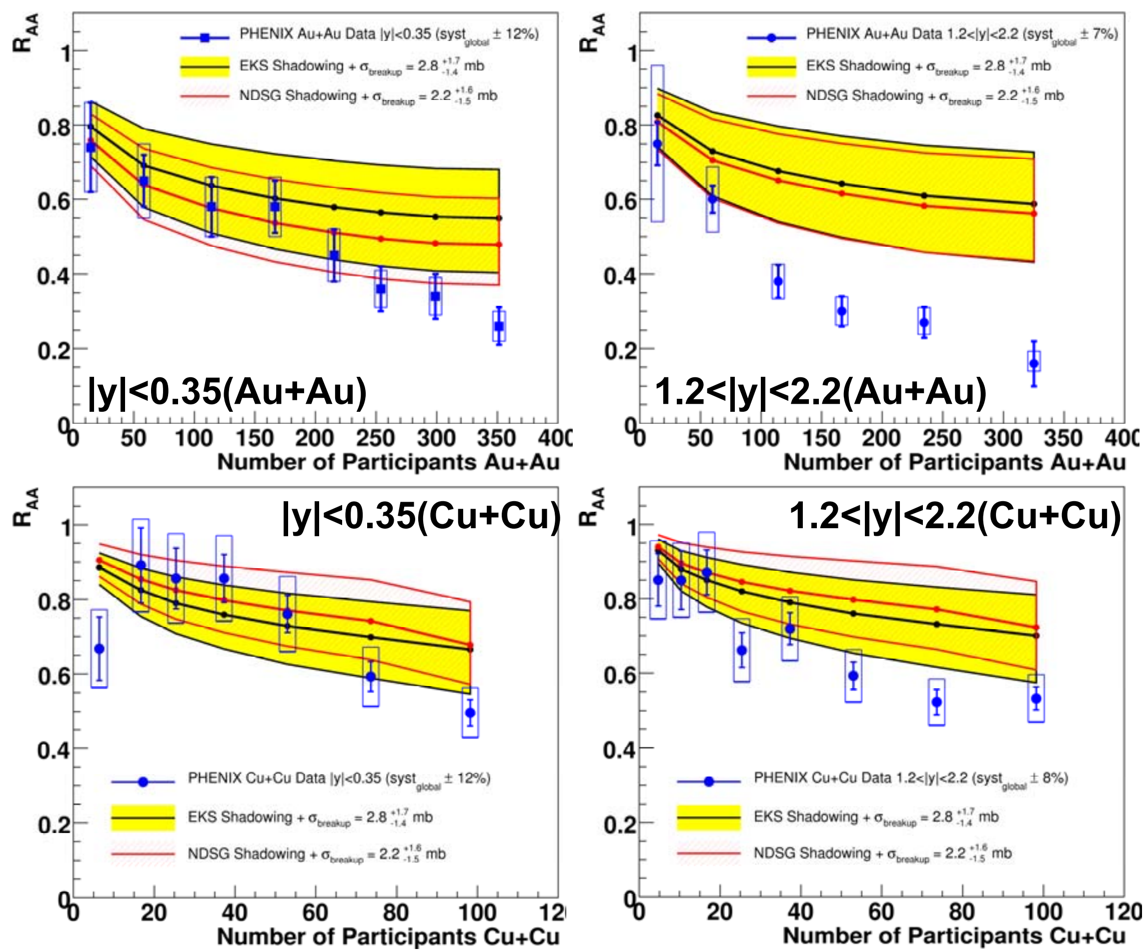


Scomparin (proc. QM06) : nucl-ex/0703030

Model dependent extrapolation from d+Au

- Shadowing + $\sigma_{breakup}$ from R_{dAu} fit used to get R_{AA}
  - Same theoretical framework as one used for R_{dAu}
- Observations
  - Statistically significant suppression observed at forward rapidity in AuAu
  - Less clear in other cases
  - Forward and mid extrapolation uncertainties correlated
  - According to these models, anomalous suppression is higher at forward rapidity in Au+Au

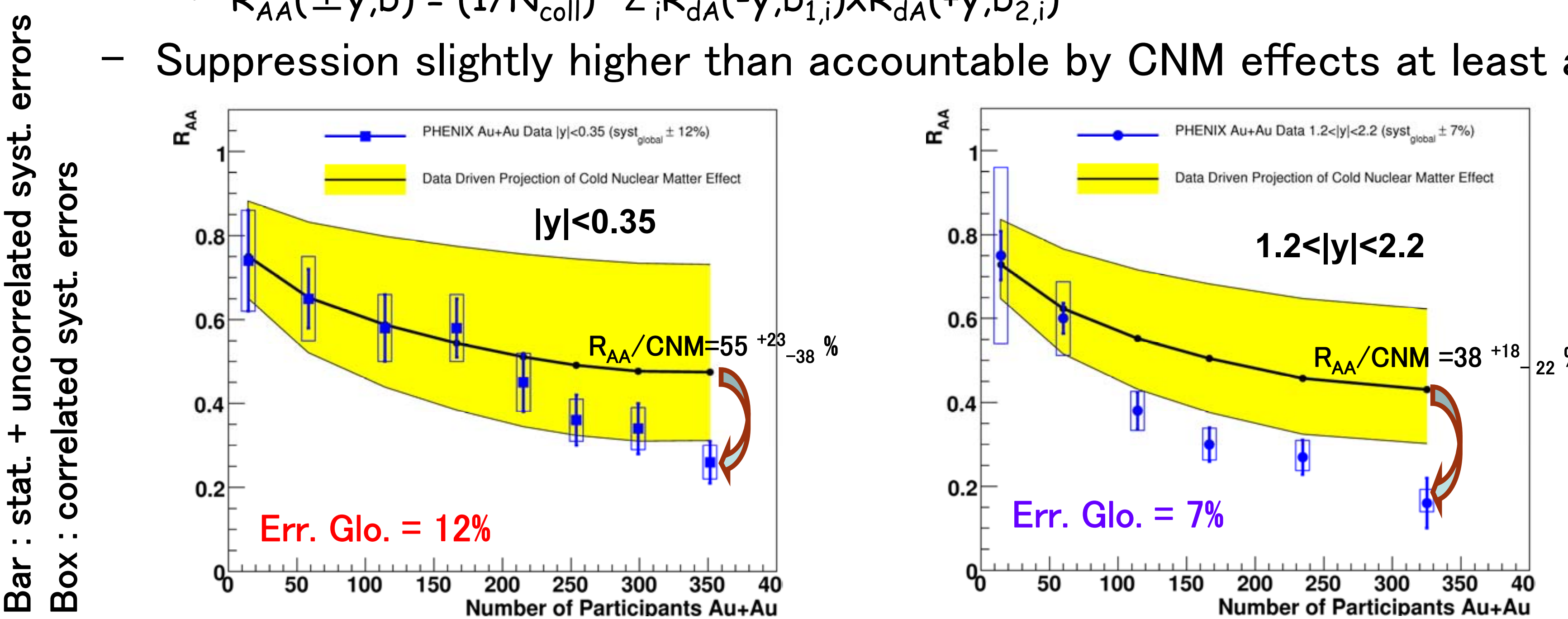
PRC 77, 024912 (2008)



Data driven extrapolation from d+Au

PRC 77, 024912 (2008)

- Minimal model dependence
  - Modification depends only on local impact parameter
  - Glauber model + rapidity symmetrization of d+Au points (*)
    - $R_{AA}(\pm y,b) = (1/N_{coll})^* \Sigma_i R_{dA}(-y,b_{1,i}) \times R_{dA}(+y,b_{2,i})$
  - Suppression slightly higher than accountable by CNM effects at least at y=0



If we want minimal model dependence, R_{AA}/CNM doesn't exclude the same anomalous suppression at forward and mid rapidities.

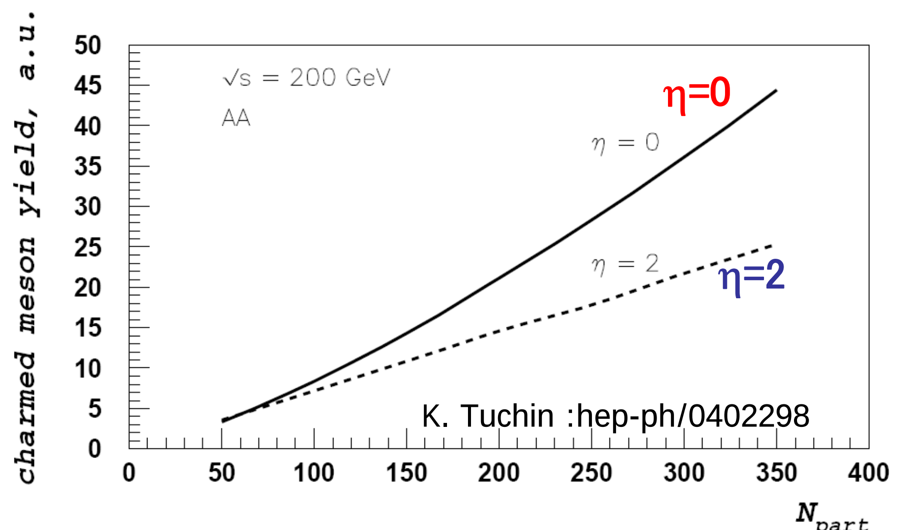
PHENIX

(*) For method cf. R. Granier de Cassagnac, J.Phys.G34:S955-958,2007

Alternate explanation

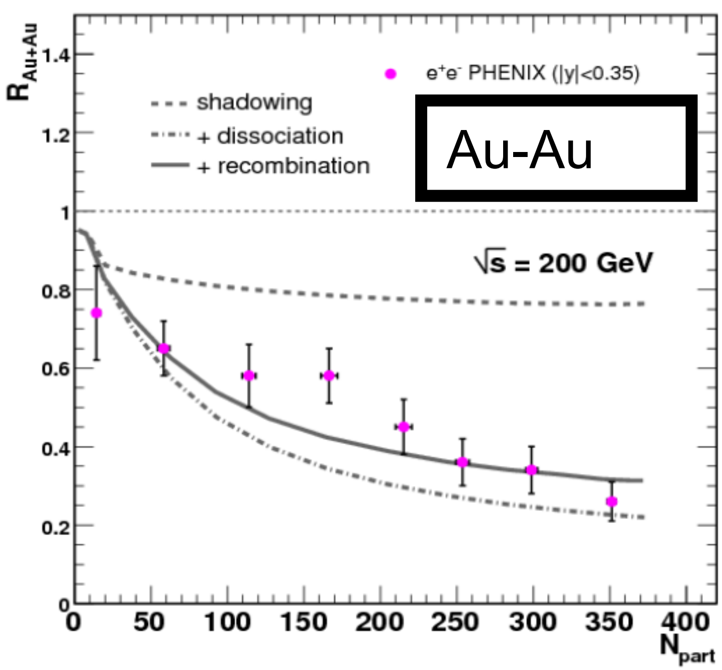
- Lattice QCD results suggest :
  - No J/ψ suppression for T as high as 2.1Tc ($\gtrsim$ 10GeV/fm3)
  - ψ' and χc start melting at around 1.1Tc (attained both at RHIC & SPS)
  - Suppression seen at RHIC & SPS may be only the feed down part
- Color Glass Condensate
  - Charmed meson calculations based on CGC give higher mid rapidity yields (no final prediction for J/ψ)
  - If valuable for J/ψ this should partly explain the forward/mid tendency, but is challenged by the saturating Forward/Mid rapidity RAA
  - Quantitative prediction for J/ψ in d+Au and Au+Au is indispensable to draw conclusion

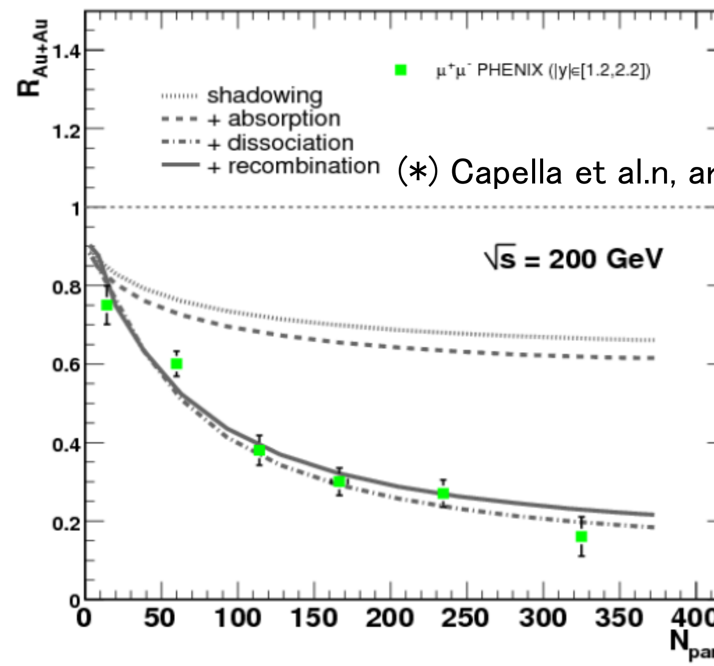
state	$J/\psi(1S)$	$\chi_c(1P)$	$\psi'(2S)$	$\Upsilon(1S)$	$\chi_b(1P)$	$\Upsilon(2S)$	$\chi_b(2P)$	$\Upsilon(3S)$
T_d/T_c	2.10	1.16	1.12	> 4.0	1.76	1.60	1.19	1.17



Yet another explanation: regeneration

- Why regeneration explains rapidity trend?
  - Uncorrelated c and $\bar{c}$ quarks coalesce at hadronization
  - At mid rapidity, more charm quarks => enhance the direct J/ψ yield
  - Just an example below (*), a number of other models do as good a job (**)



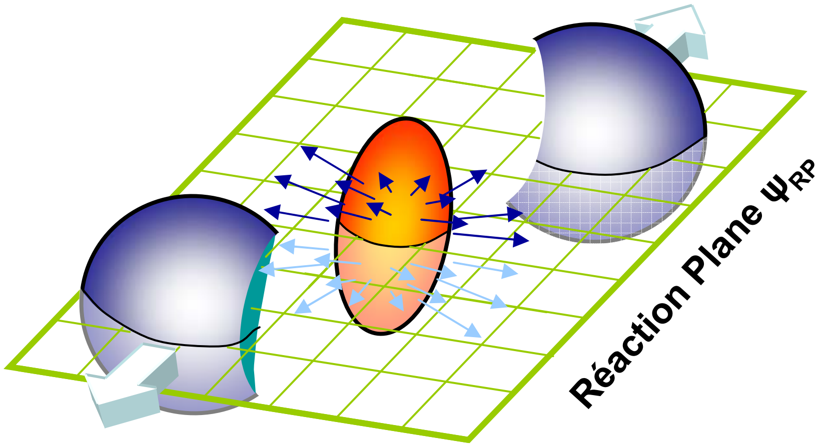


(*) Capella et al.n, arXiv:0712.4331

cf. Talks by R. Thews and K. Tywoniuk

(**) Without being exhaustive some of these models are listed below :
O. Linnyk et. al. arXiv:0801.4282; R. Thews et. al. Eur.Phys. JC43, 97 (2005); Yan et al. PRL 97, 232301 (2006); Andronic et. al. NPA789, 34(2007), Ravagli et al. arXiv:0705:0021; Zhao et. al. arXiv:0712.2450,

Testing regeneration with J/ψ flow



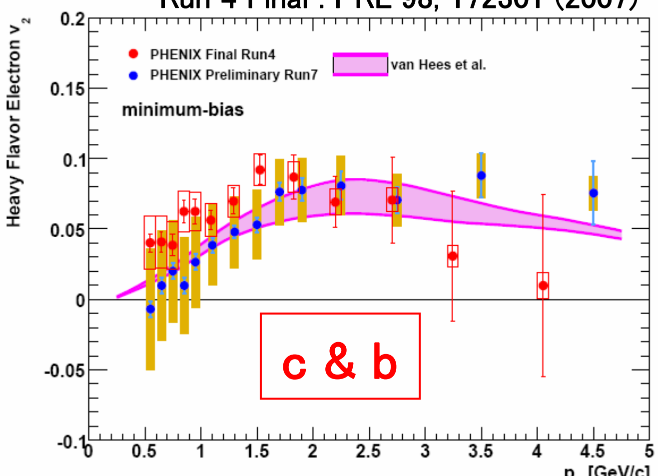
- Elliptic flow
  - In non central collisions, almond shaped interaction region results in a pressure gradient
  - More particles are emitted 'in plane' than 'out of plane'
  - Magnitude measured by v_2

$$\frac{dN}{dp_t dy d\phi} \approx \frac{dN}{dp_t dy}\left[1+2v_2\cos\left(2\left(\phi-\Psi_{RP}\right)\right)\right]$$

$$where \quad v_2 = \left\langle \cos\left(2\times\left(\phi-\Psi_{RP}\right)\right)\right\rangle$$

- J/ψ flow : promising test of regeneration
  - **Electrons from open c and b semileptonic decays show large nonzero elliptic flow**
  - J/ψ regenerated from c quarks should inherit their flow

Run 4 Final : PRL 98, 172301 (2007)



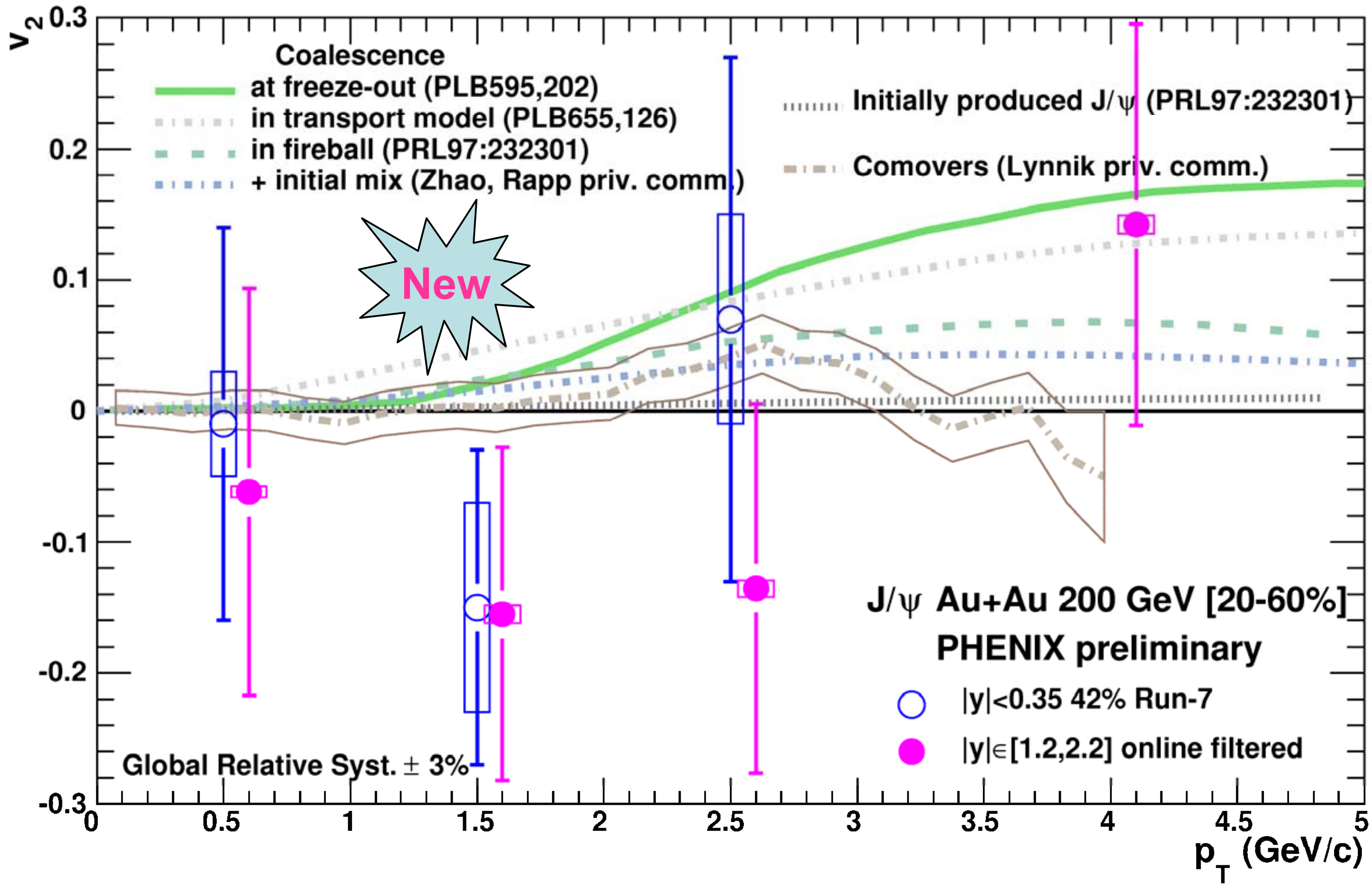
(cf. Talk by A. Dion)

J/ψ flow results (1/2)

Bar : stat. + uncorrelated syst. errors
Band : correlated syst. errors

- Preliminary results

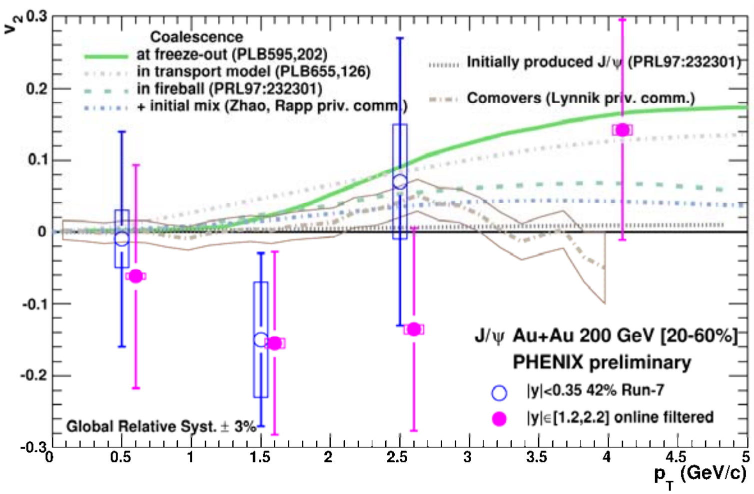
cf. Talk by C. Silvestre



J/ψ flow results (2/2)

- Preliminary results
  - This is more of a proof of principle that the measurement is feasible
  - Completely independent measurement techniques at forward & mid rapidity
    - A slightly negative v_2 observed at intermediate p_T in both measurements
    - Highest p_t data points are compatible with zero to maximum flow predictions within errors
  - Current precision doesn't allow to draw strong conclusions. Much larger data sample, expected to be available in future runs, is required.

cf. Talk by C. Silvestre

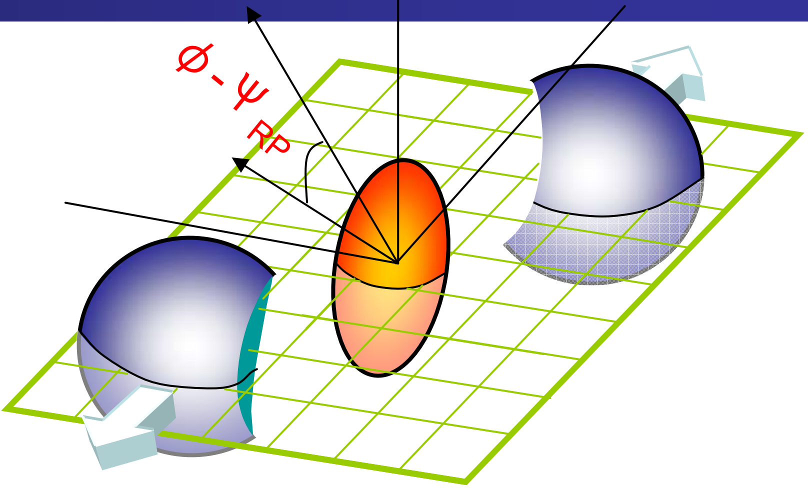


Summary

- Reviewed PHENIX results on quarkonia
  - In p+p collisions, production baseline is measured
    - J/ψ feed-down ratios from ψ' and χ_c constrained from data
  - In d+Au collisions, despite lack of statistics, data is used to extract
    - J/ψ CNM $\sigma_{breakup}$, comparable within errors to SPS measurement
    - Extrapolation to Au+Au and Cu+Cu collisions
  - In Au+Au and Cu+Cu measurements:
    - Very similar suppression to SPS at mid rapidity
    - Higher suppression at forward rapidity than at mid rapidity
    - R_{AA}/CNM (abnormal suppression) difference b/n mid and forward not very clear
  - Regeneration is a possible scenario to explain rapidity trend
    - Many models describe data satisfactorily when regeneration is allowed
    - A promising experimental test : J/ψ v_2, so far limited by statistics
- Outlook
  - New d+Au data set (30x more statistics), better constraint on CNM effect
  - Better precision on J/ψ v_2 from larger statistics in future runs

Backup

Measuring J/ψ flow (central rapidity)



- Estimate reaction plane
  - New detector for event by event reaction plane determination
- Measure v_2
  - $N_{sig}*v_{2,J/\psi} = N_{fg}*v_{2,fg} - N_{bg}*v_{2,bg}(M_{J/\psi})$
  - $v_{2,fg} = \langle\cos(2*(\phi-\Psi_{RP}))\rangle$ of unlike sign pairs in J/ψ mass window
  - $v_{2,bg}$ at $M_{j/\psi}$ is interpolated from a polynomial fit outside of J/ψ mass window of like sign $v_2(m)$
- Correct for finite resolution
  - $v_2 = v_{2,meas} / \sigma_{RP}$, where

$$\sigma_{RP} = 2\times\sqrt{\left\langle\cos\left(2\times\left(\Psi_{RP,1A}-\Psi_{RP,1B}\right)\right)\right\rangle}$$

24 segment plastic scintillator
$1 < \eta < 2.8$

Centrality classes

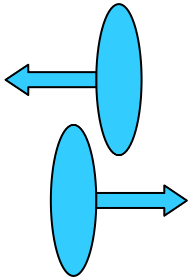
- Dividing total cross section according to centrality
  - Use BBC charge vs. ZDC energy
  - N_{coll} : number of binary inelastic N–N collisions
  - N_{part} : number of nucleons that undergo inelastic collisions
  - Glauber model + detector response simulation => $\langle N_{part} \rangle$ & $\langle N_{coll} \rangle$

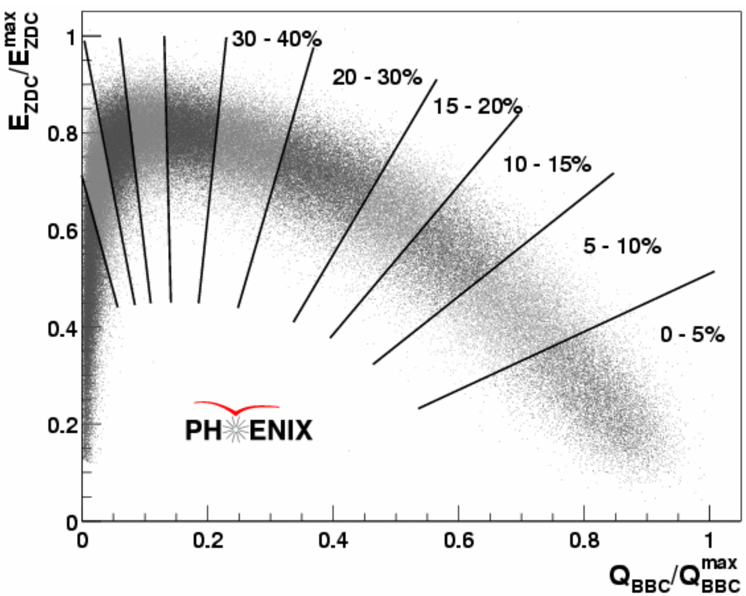
Most peripheral

80 – 92.2%

$\langle N_{part} \rangle = 6.3 \pm 1.2$

$\langle N_{coll} \rangle = 4.9 \pm 1.2$



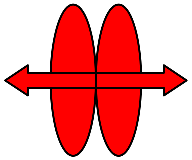


Most central

0 – 5 %

$\langle N_{part} \rangle = 351.4 \pm 2.9$

$\langle N_{coll} \rangle = 1065 \pm 105$

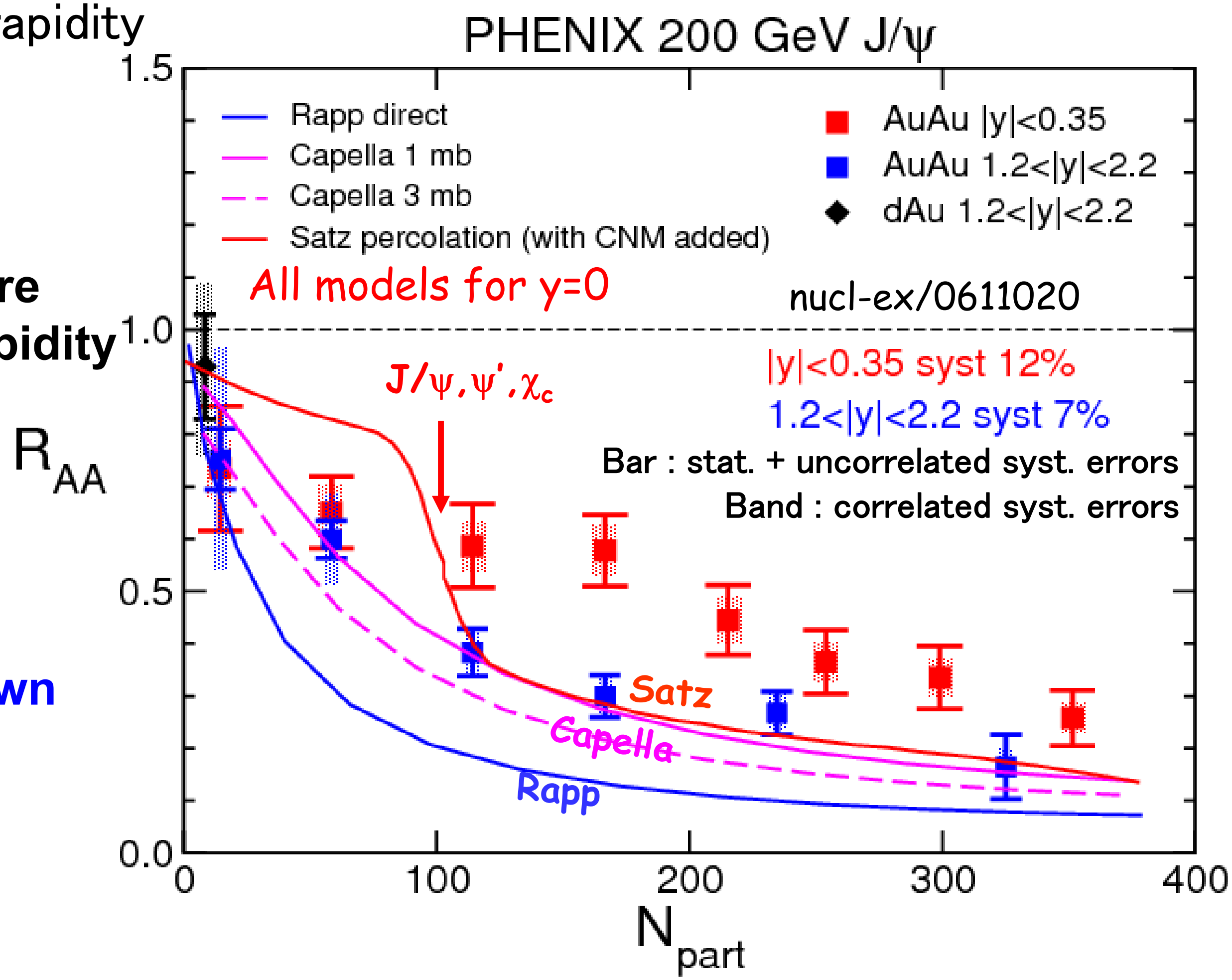


Indirect comparisons to SPS

- Test with RHIC data models that worked at SPS
  - Most models are strongly challenged by the rapidity trend, and less suppression at mid rapidity

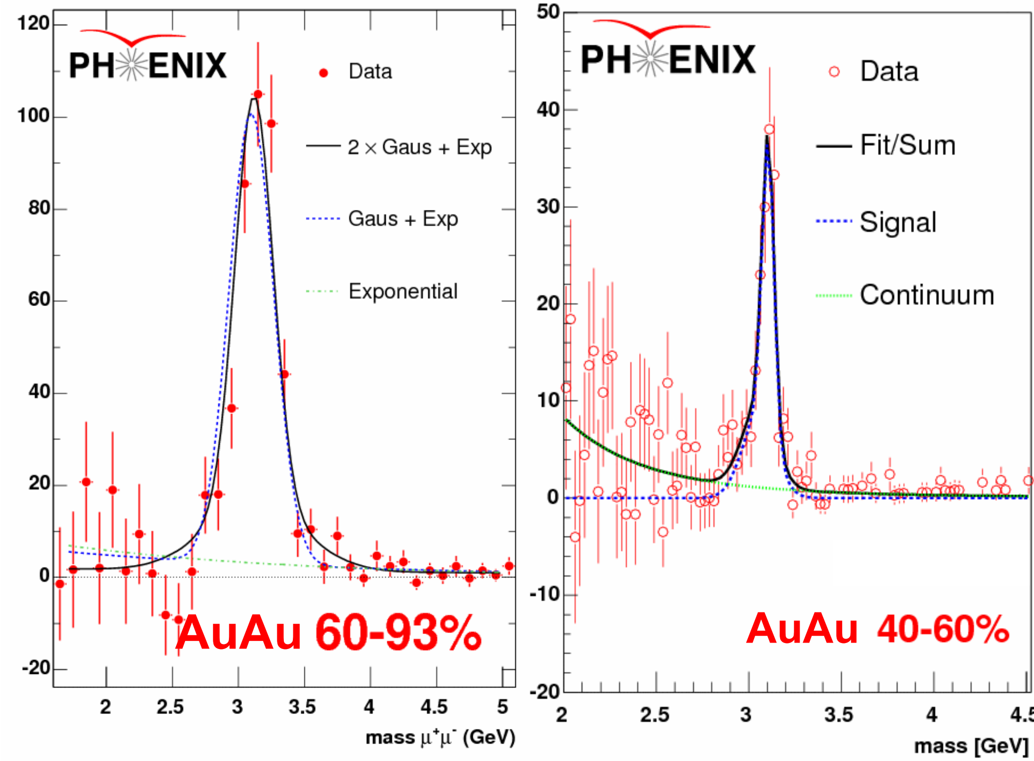
All calculations shown here give predictions at mid rapidity

- **Digal, Fortunato, Satz**
  - **hep-ph/0310354**
- **Capella, Ferreiro**
  - **hep-ph/0505032**
- **Grandchamp, Rapp, Brown**
  - **hep-ph/0306077**



Signal extraction

- Invariant mass spectra of $\mu^+\mu^-$ and e^+e^- (J/ψ branching ratio ~ 6% each)
- Combinatorial background subtracted by event mixing
- Fitted with:
  - Gaussians for the mass peak
  - Exponentials for physical background (heavy flavor decay and/or Drell-Yan)
  - Average value of various fits used as J/ψ count
  - Dispersion is included in systematic errors.



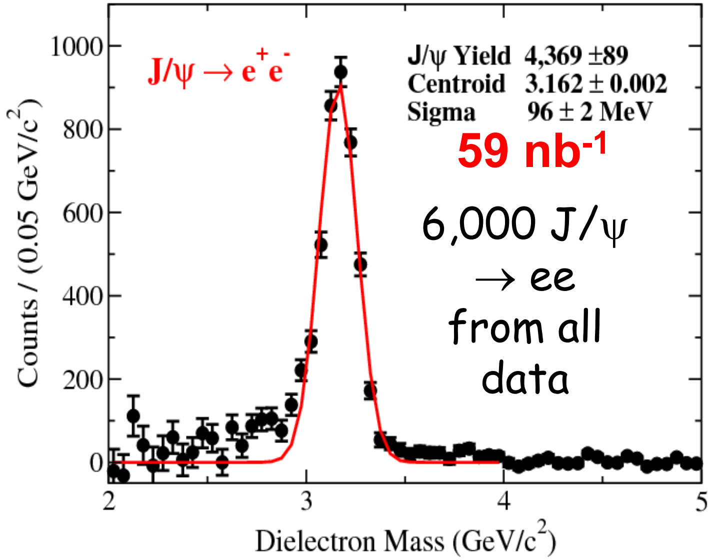
$J/\psi \rightarrow \mu^+\mu^-$ $J/\psi \rightarrow e^+e^-$

PHENIX J/ψ measurements summary

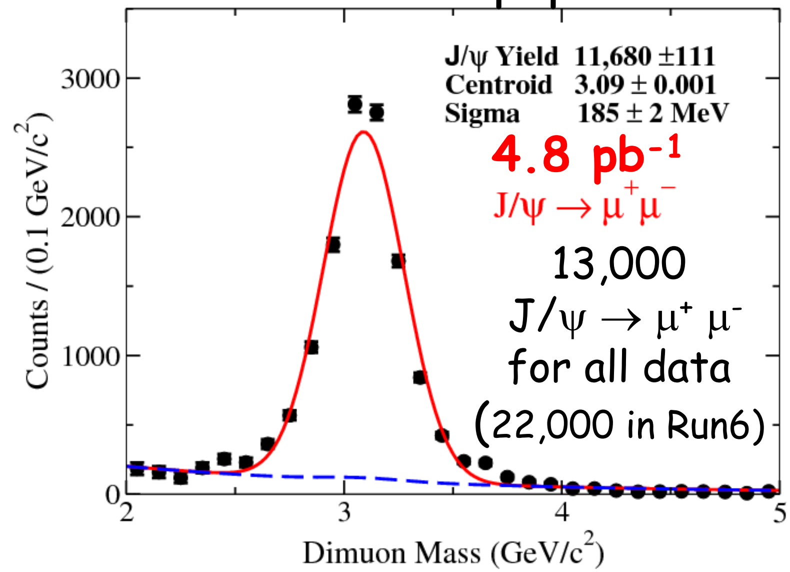
Run	Species	$\sqrt{s_{NN}}$[GeV]	∫Ldt	J/ψ counts (|y|<0.35)	J/ψ counts (1.2<|y|<2.2)	Reference
1	Au+Au	130	1μb-1			
2	Au+Au	200	24μb^{-1}	~13		
	p+p	200	0.15pb^{-1}	46	66	PRC69, 014901(2004)
3	d+Au	200	2.74nb^{-1}	360	1200	PRL92, 051802(2004)
	p+p	200	0.35pb^{-1}	130	450	PRL96, 012304 (2006)
4	Au+Au	200	241μb^{-1}	1000	4500	PRL 98, 232301(2007)
	Au+Au	63	9μb^{-1}			
	p+p	200	350nb^{-1}			
5	Cu+Cu	200	3nb^{-1}	2000	9000	arXiv:0801.0220
	Cu+Cu	62	0.19μb^{-1}		~146	
	Cu+Cu	22.5	2.7μb^{-1}			
	p+p	200	3.8pb^{-1}	1500	8000	PRL98,232002(2007)
6	p+p	200	10.7pb^{-1}	~2300	~27000	
	p+p	62	0.1pb^{-1}			
7	Au+Au	200	800μb^{-1}			
8	d+Au	200	80nb-1	~4400	~57000	
	p+p	200				

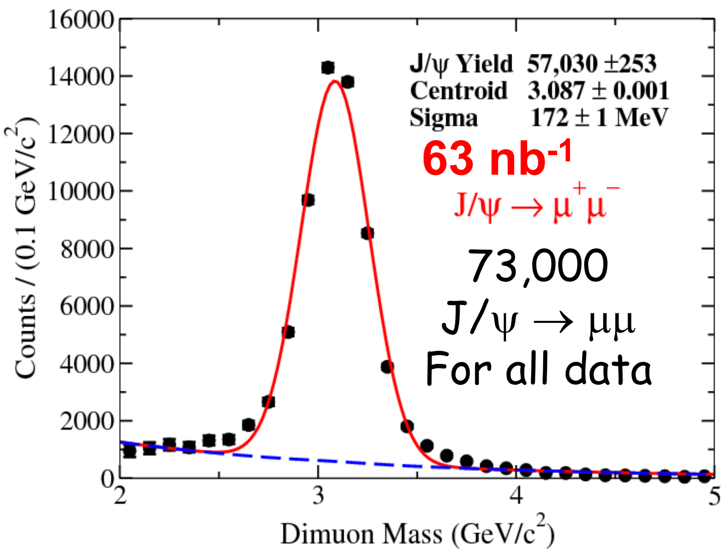
PHENIX J/ψ's from Run8

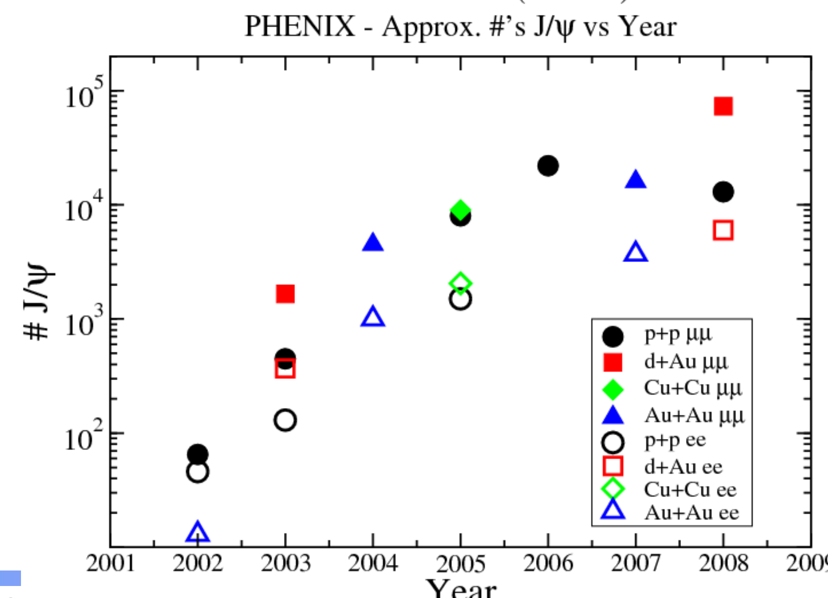
200 GeV d+Au



200 GeV p+p

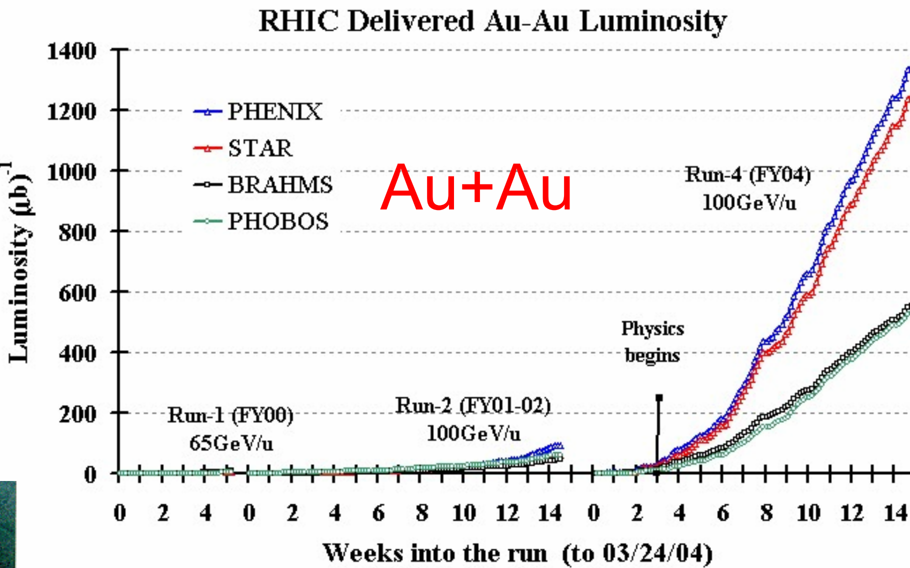


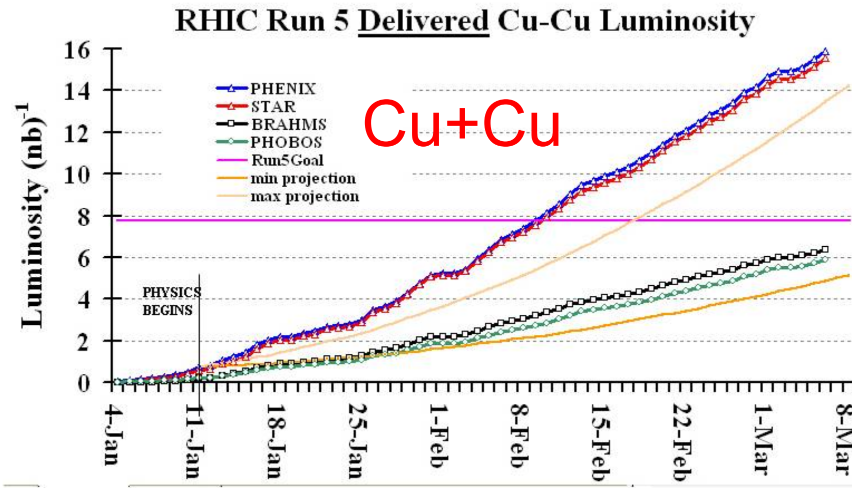




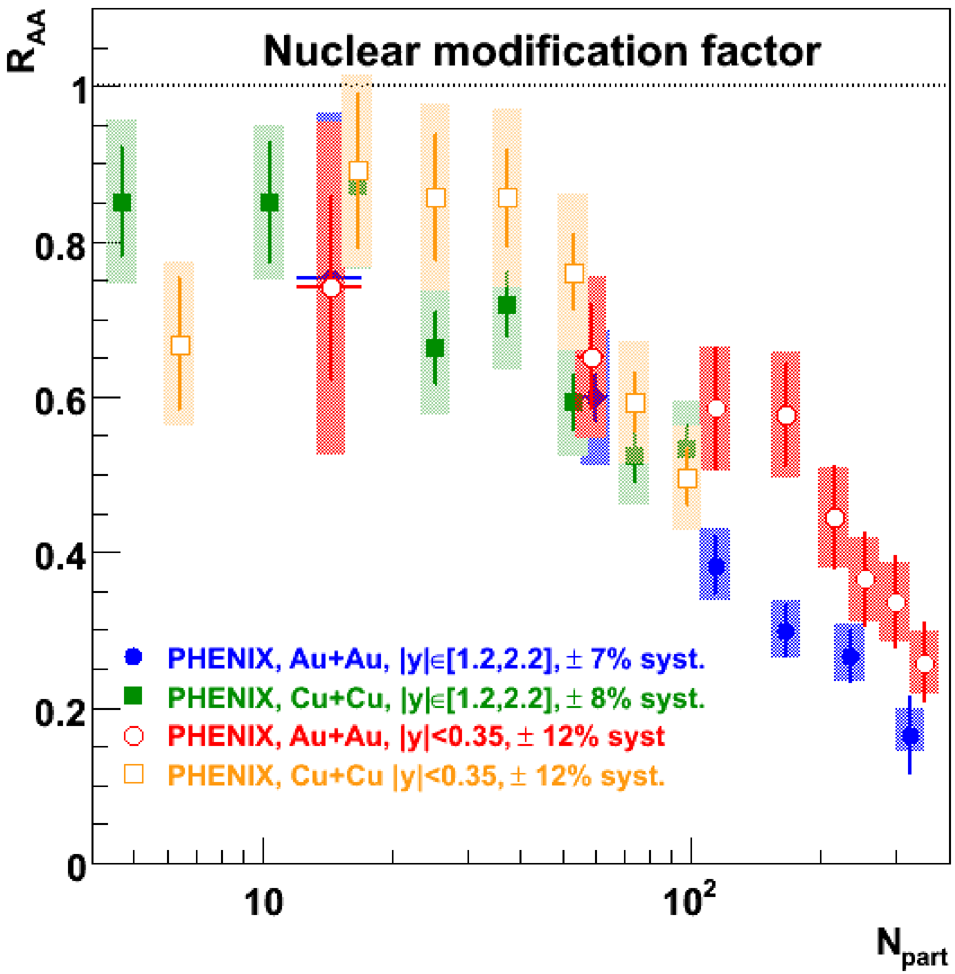
RHIC

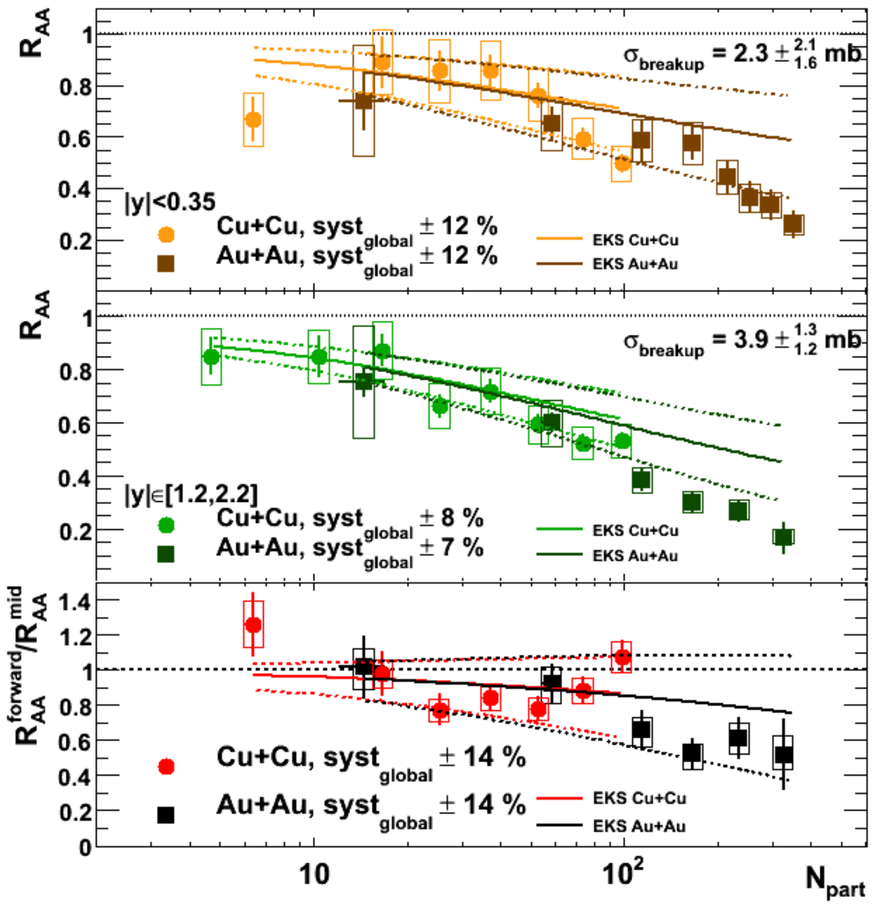
- Heavy ion and polarized proton colliding machine
  - 4 species: p+p, d+Au, Au+Au, Cu+Cu
  - 6 energies: 9.2 GeV, 19 GeV, 22.5 GeV, 62.4 GeV, 130 GeV, 200 GeV





R_{AA} vs. N_{part} summary





Au+Au final: PRL 98, 232301(2007)
Cu+Cu prelim: nucl-ex/0801.0220