PHENIX Charmonium Measurements

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Outline

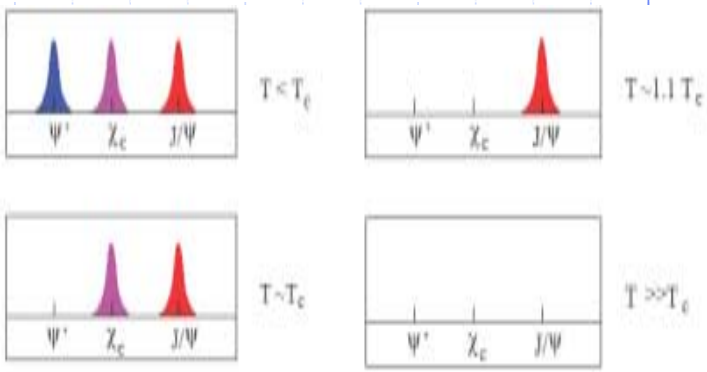
- Physics Motivation
- Charmonium in the Medium
  - Hot and dense medium and cold nuclear matter
- PHENIX Experiment
- PHENIX Charmonium Measurement
  - Base line Measurement from p+p
  - Cold Matter effect from d+Au
  - Hot and dense medium effect from A+A
- Current Conclusion of J/ψ production in A+A
- Other interesting results from PHENIX
- Summary

Physics Motivation

- Shed light on the study of the properties of QGP.
  - **Discovery the "strong coupled QGP".**
    - Early thermalization, Perfect Fluid
- **Hard Probe** is a powerful tool to study the initial stage of collisions and evolution of later hot and dense medium.
  - High p_T Jets → Discovery of "Jet Quenching"
    - ***Gluon Density*** (dN_g/dy) = 1000 ~ 1200
  - Heavy Quarks → Discovery of "strong suppression, flow"
    - Medium is ***dense and strong coupled*** even for heavy quarks!
  - Quarkonium
    - Probe to "measure" the ***Temperature*** *(Gluon density)* in the medium.

Quarkonium is "Thermometer"

- Color Debye Screening
  - Different T_{diss} for different quarkonia.
  - The quarkonium suppression pattern may be able to serve as a QGP thermometer.



H. Satz, J. Phys. **G32**, R25 (2006)

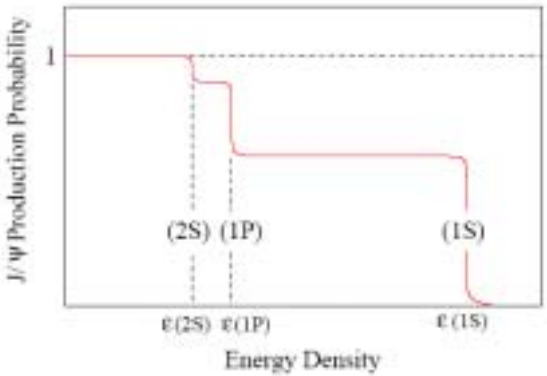
- Recent Lattice QCD results
  - J/ψ would survive at RHIC!?

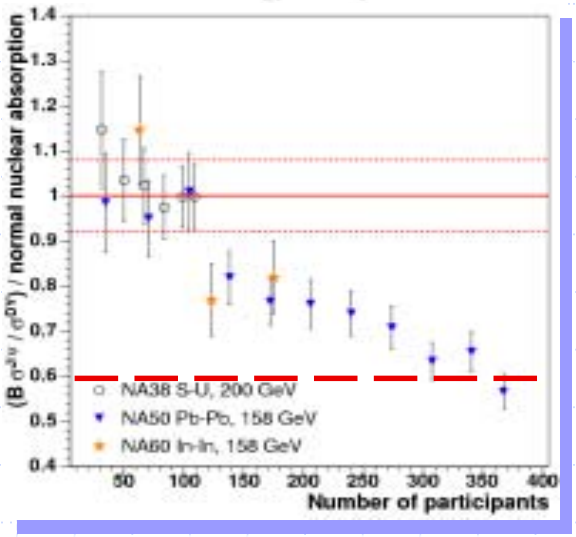
state	$J/\psi(1S)$	$\chi_c(1P)$	$\psi'(2S)$	$\Upsilon(1S)$	$\chi_b(1P)$	$\Upsilon(2S)$	$\chi_b(2P)$	$\Upsilon(3S)$
T_d/T_c	2.10	1.16	1.12	> 4.0	1.76	1.60	1.19	1.17

Datta & al, hep-lat/0409147
Alberico & al, hep-ph/0507084
Wong, hep-ph/0408020
← Satz, hep-ph/0512217

Feed Down Effect

- Without the direct measurement of ψ' and χ_c, we can extract the temperature in the medium!
- 40% J/ψ come from ψ' and χ_c.
  - $J/\psi \sim 0.6\ J/\psi + 0.3\chi_c + 0.1\psi'$
    - HERA-B exp. Phys. Lett. B 561(2003)
  - J/ψ suppression pattern gives the information of melting ψ' and (or) χ_c. (→ Temperature)
- J/ψ suppression at SPS can be described by feed down effect.

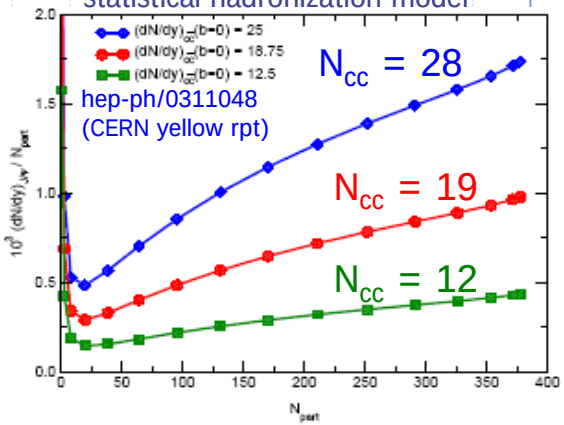




The story is not simple!

- New Scenario of J/ψ production in HIC at RHIC!
  - Negligible at SPS.
- Recombination of J/ψ from uncorrelated $c\bar{c}$ pairs.
  - Probability : N_{cc}^2/N_h
  - $N_{cc}(N_h)$ scales with $N_{col}(N_{part})$.
  - N_{cc} grows faster with CMS energy.

statistical hadronization model



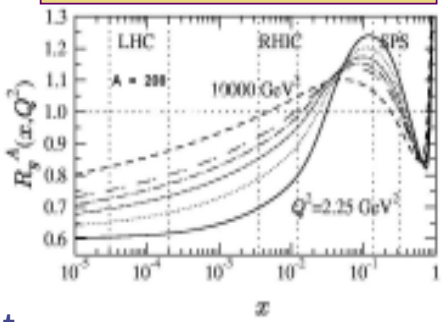
- Need to understand charm production and its modification in the medium.
  - Have strong impact to recombination
    - Cross section vs. Rapidity
    - Charm energy loss
    - Charm flow

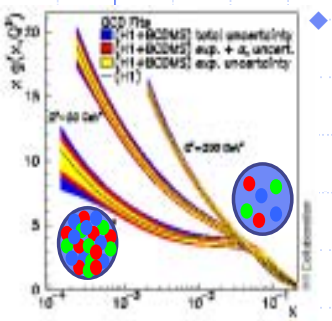
} Talked by R. Averbeck.

The story is not simple! (cont.)

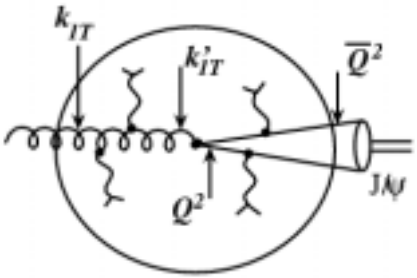
- J/ψ yield could be modified in cold nuclear matter.
  - From Initial conditions of nuclei:
    - Gluon Shadowing
      - Depletion of Gluon PDF in nuclei at small x.
    - Gluon Saturation (Color Glass Condensate)
      - High density gluons at small x in nucleon.
        - Saturation : gg → g process is dominant
        - Depletion of small x gluons.
        - Larger effect for Heavier nuclei.

Eskola et al. NP A696, 729 (2001)





  - From the nuclear environments after the collisions:
    - Nuclear Absorption
      - J/ψ or pre-resonance $c\bar{c}$ state vs. spectators
    - Cronin effect
      - Initial state multiple scattering of partons

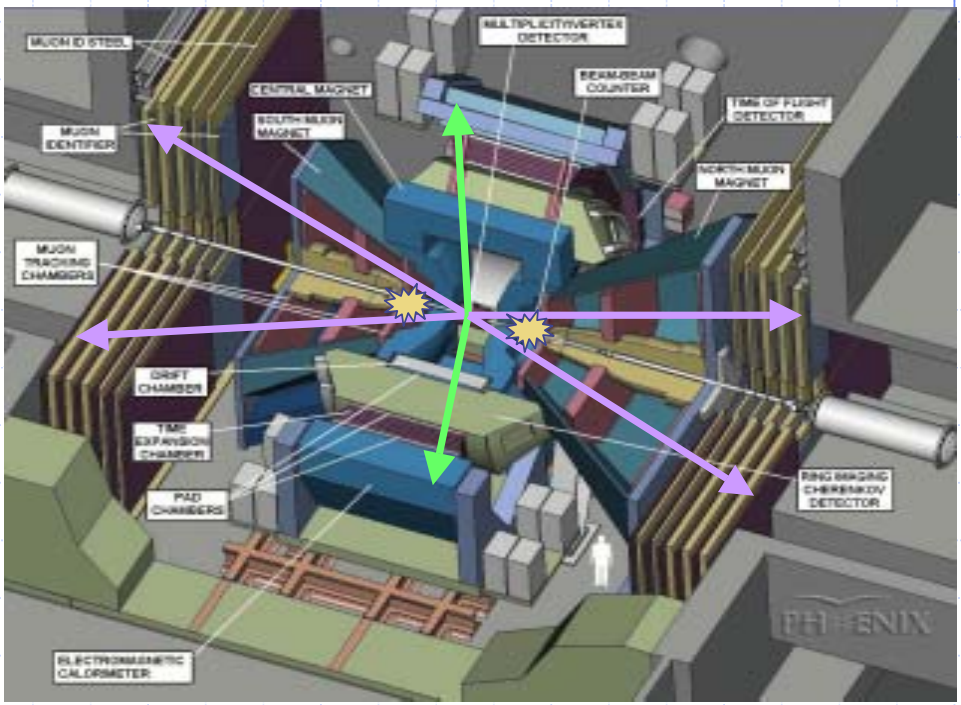


PHENIX Experiment

- PHENIX Can Measure J/ψ in wide y coverage.

Central Arms:
Hadrons, photons, electrons
- J/ψ → e+e-
- $|\eta|<0.35$
- $P_e > 0.2$ GeV/c
- $\Delta\phi = \pi$ (2 arms x $\pi/2$)

Muon Arms:
Muons at forward rapidity
- J/ψ → $\mu+\mu-$
- $1.2< |\eta| < 2.4$
- $P\mu > 2$ GeV/c
- $\Delta\phi = 2\pi$



[1] PRL92 (2004) 051802
[2] PRC69 (2004) 014901
[3] PRL96 (2006) 012304
[4] QM05, nucl-ex/0510051

Recorded data

- History of J/ψ measurement by PHENIX

Year	Ions	$\sqrt{s_{NN}}$	Luminosity	Status	J/ψ (ee + μμ)
2001	Au-Au	200 GeV	24 μb^{-1}	Central	13 + 0 [1]
2002	p-p	200 GeV	0.15 pb^{-1}	+ 1 muon arm	46 + 66 [2]
2002	d-Au	200 GeV	2.74 nb^{-1}	Central	360 + 1660 [3]
2003	p-p	200 GeV	0.35 pb^{-1}	+ 2 muon arms	130 + 450 [3]
2004	Au-Au	200 GeV	240 μb^{-1}	preliminary	~ 1000 + 5000 [4]
	Au-Au	63 GeV	9.1 μb^{-1}	analysis	~ 13
	p-p	200 GeV	324 nb^{-1}		
2005	Cu-Cu	200 GeV	4.8 nb^{-1}	preliminary	~ 1000 + 10000 [4]
	Cu-Cu	63 GeV	190 mb^{-1}	On Going	~ 60 + 200
	p-p	200 GeV	3.8 pb^{-1}	On Going	~ 1500 + 10000

J/ψ in p+p, d+Au and A+A

p+p collisions
- **Base line for all the measurements**

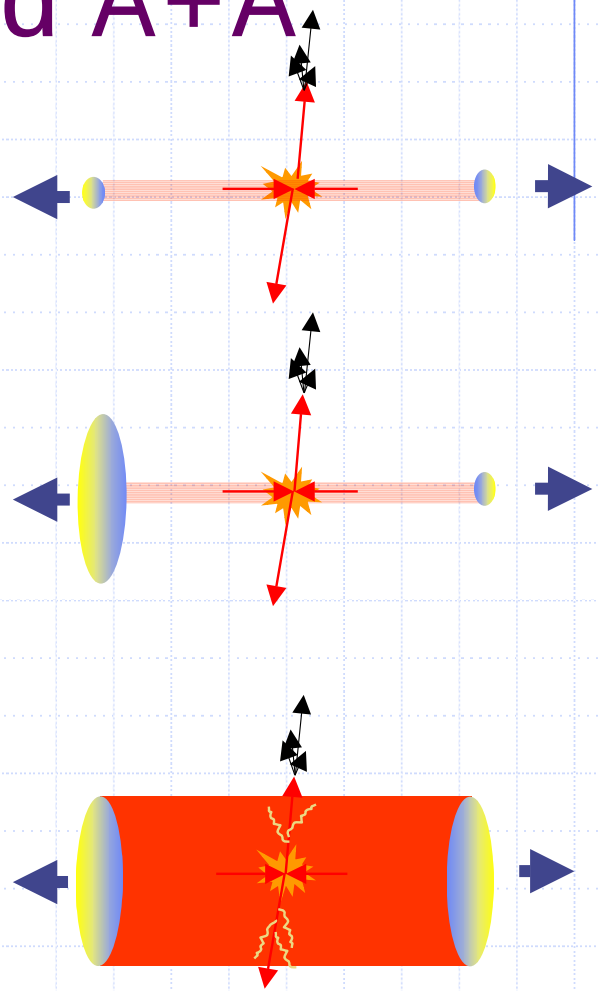
□$\sigma_{J/\psi}$ vs. ***rapidity, p_T***

d+Au collisions
- **Initial stage effect**
  - Gluon shadowing and Gluon Saturation
- **Nuclear medium effect**
  - Nuclear absorption and Cronin effect
- **Base Line for A+A collisions**

□$\sigma_{J/\psi}$ vs. ***rapidity, p_T, X_{Au}***

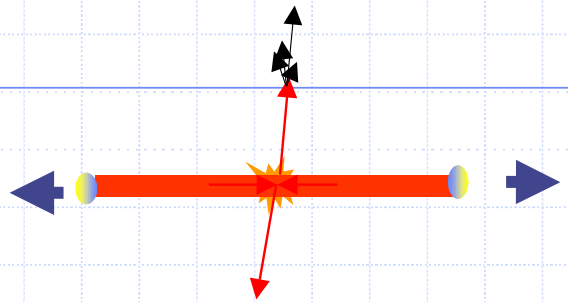
A+A collisions
- **Extract the medium effect**
  - Color screening and Recombination

□$\sigma_{J/\psi}$ (yield) vs. ***rapidity, p_T,***
collision centrality , species(Au/Cu)
collision energy(200/62.4 GeV)



J/ψ Measurement in p+p collisions

- Production Mechanism
- Base line of the J/ψ measurement in d+Au and A+A.

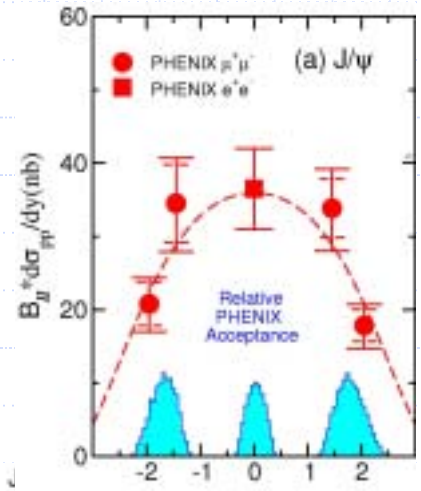


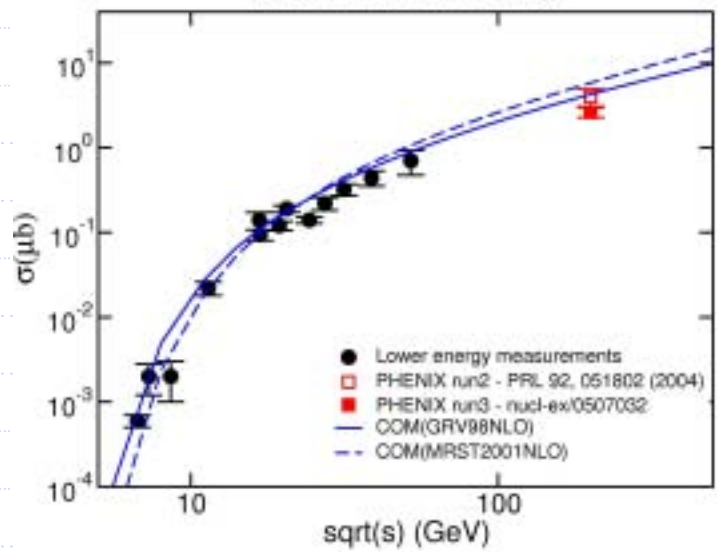
J/ψ production in p+p

- Cross section vs. y
  - Consistent with Pythia calculation
  - σ = 2.61+-0.20(fit)+-0.26(abs) μb
- Cross section vs. $\sqrt{s}$
  - Consistent with COM model
- Base Line for A+A
  - Nuclear modification factor

$$R_{AA} = \frac{dN_{J/\psi}^{AA}/dy}{dN_{J/\psi}^{pp}/dy \times \langle N_{coll} \rangle}$$

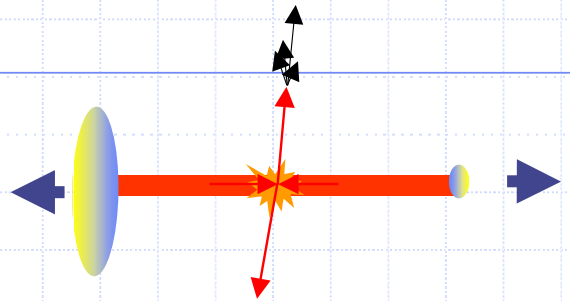
R_{AA} =1 (without medium effect)





J/ψ Measurement in d+Au collisions

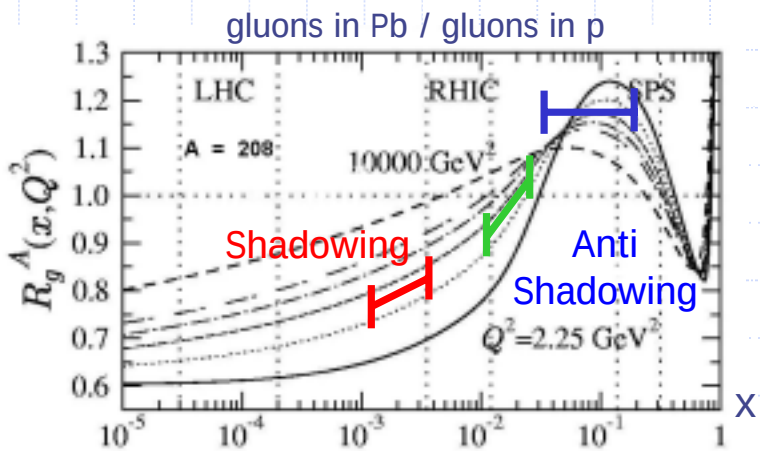
- Extraction of Cold Matter Effect
- What we have learned on Cold Matter Effect?



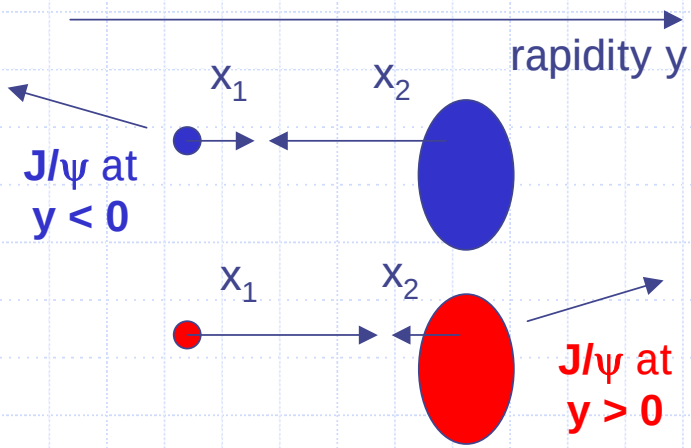
X_{Au} and Shadowing

- Three rapidity ranges probe different x of Au partons
  - South (y < -1.2) : large x_2 (in gold) ~ 0.090 (Anti-shadowing)
  - Central (y ~ 0) : intermediate x_2 ~ 0.020
  - North (y > 1.2) : small x_2 (in gold) ~ 0.003 (Shadowing)

An example of gluon shadowing prediction

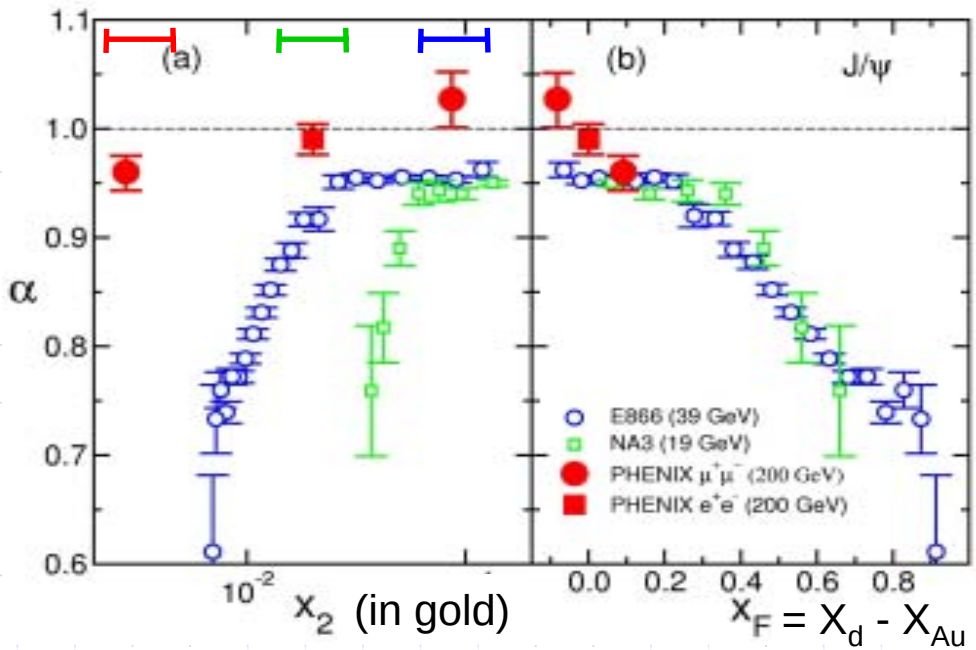


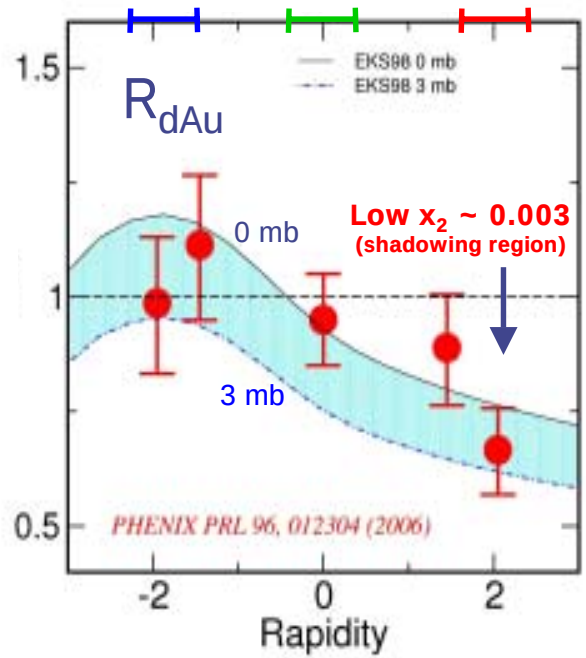
Eskola et al. NPA696 (2001) 729



Shadowing and Nuclear Absorption

- α vs. X_{Au}, X_F $\boxed{\sigma_{dAu} = \sigma_{pp}\,(2x197)^{\alpha}}$ R_{dAu} vs. Rapidity



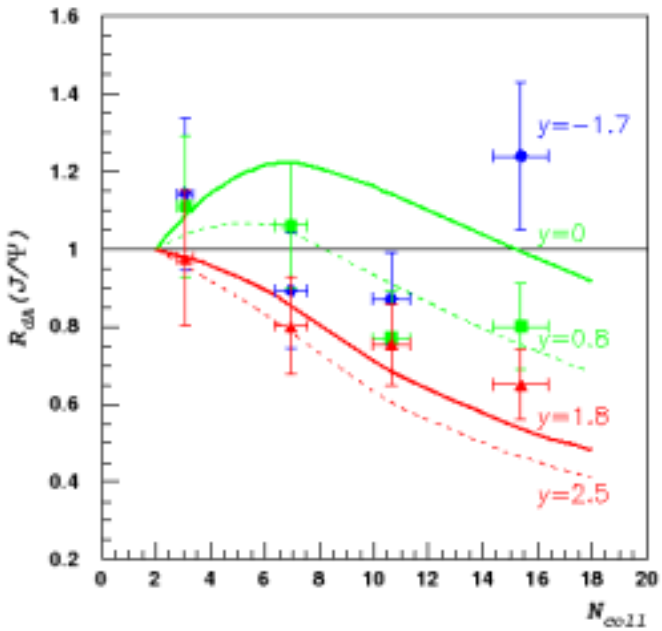


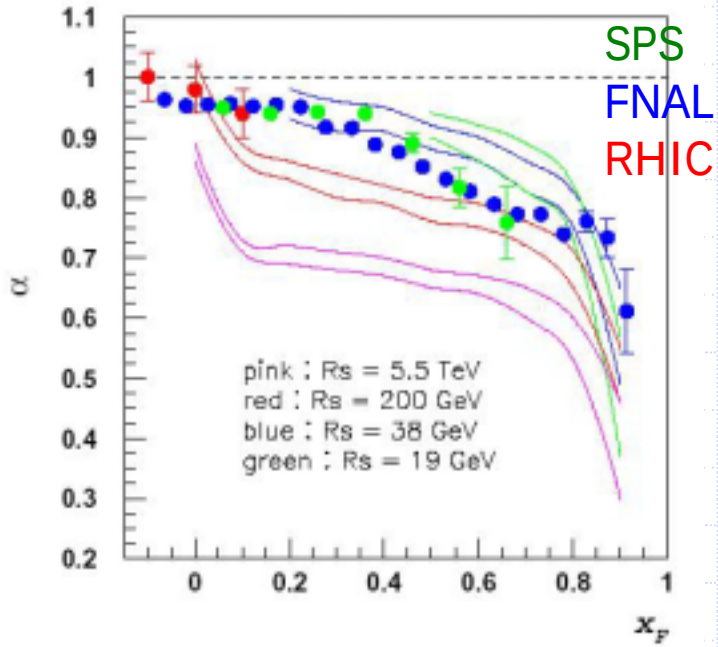
Shadowing and Absorption are weak at RHIC energy.

- α scales with X_F, not X_{au}. (gluon energy loss?, CGC?)
- σ_{abs} = 0-3 mb (4.18 +- 0.35 mb at SPS)

Color Glass Condensate

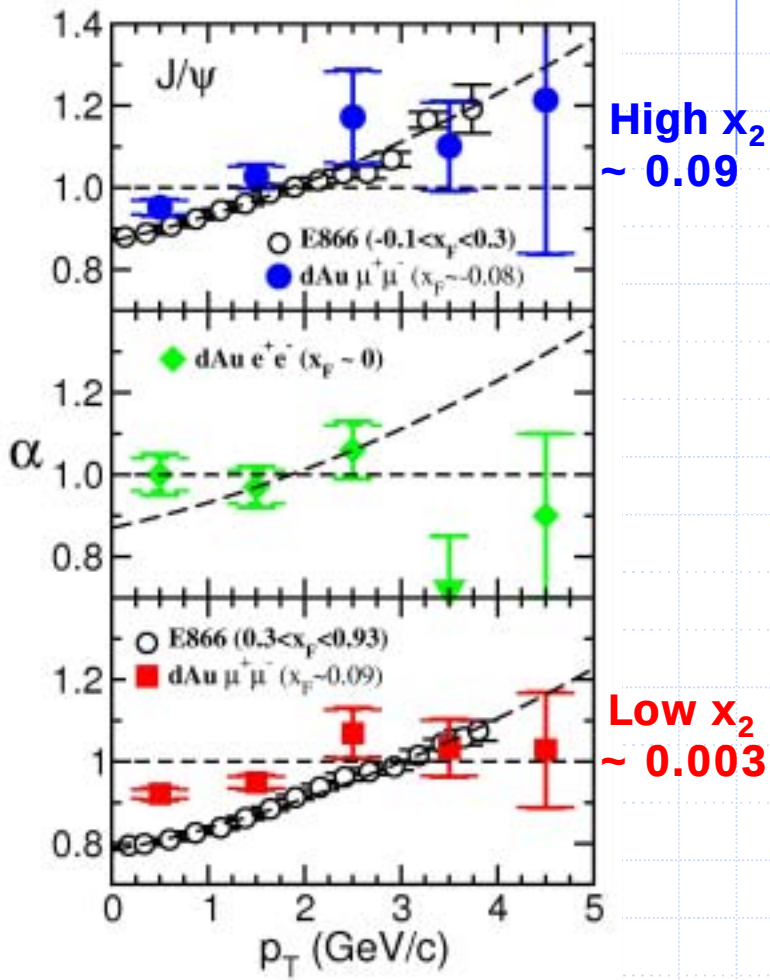
- At RHIC, coherent charm production in nuclear color field at y>0 ($Q_s > m_c$) and dominant at y>2.
  - Described well by Color Glass Condensate.
    - Approximate X_F scaling for SPS and FNAL





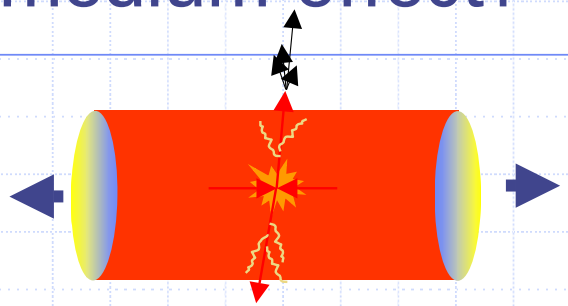
Cronin Effect (p_T broadening)

- α vs. pT for 3 x_{Au} region
- Comparison to lower energy results.
  - E866 at $\sqrt{s}$ = 39 GeV.
  - Trend of p_T broadening at RHIC is consistent With lower energy results.



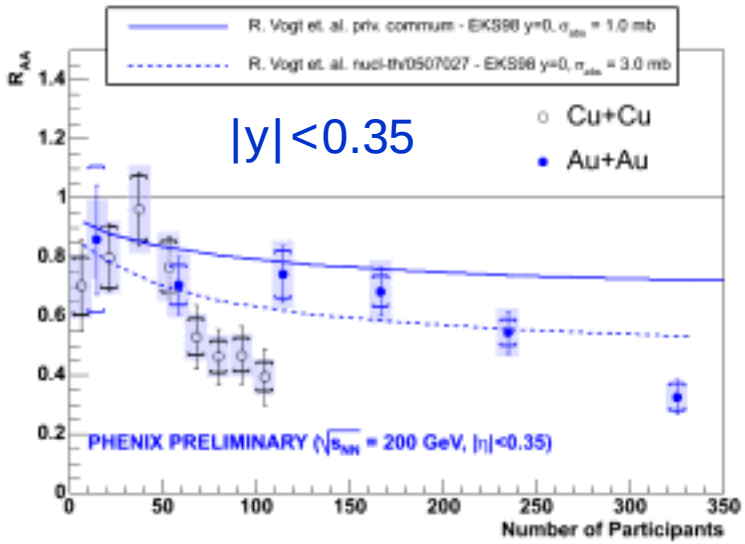
J/ψ Measurement in Au+Au and Cu+Cu collisions

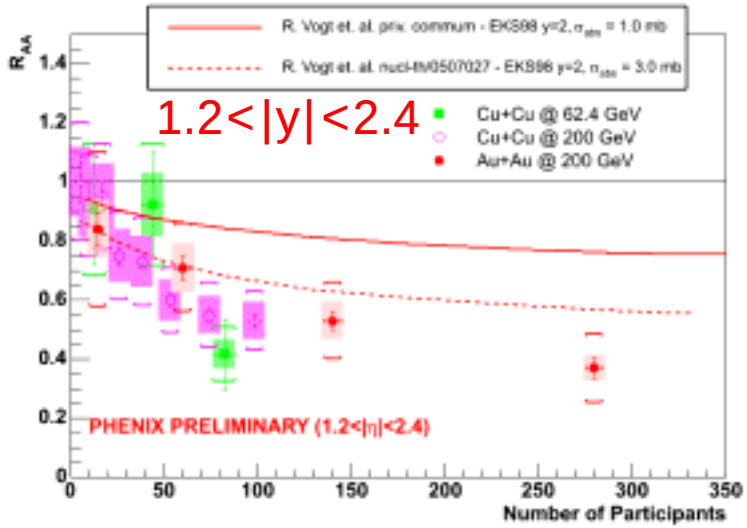
- Extraction of Hot and Dense Medium Effects.
- What we have learned on hot and dense medium effect?



R_{AA} vs. N_{part} in Au+Au/Cu+Cu

- Comparison to Cold Matter Effect
  - Extrapolated from Run3 d+Au results





Factor of 3 suppression at most central (Au+Au/Cu+Cu)

- Beyond the suppression from cold matter effect.

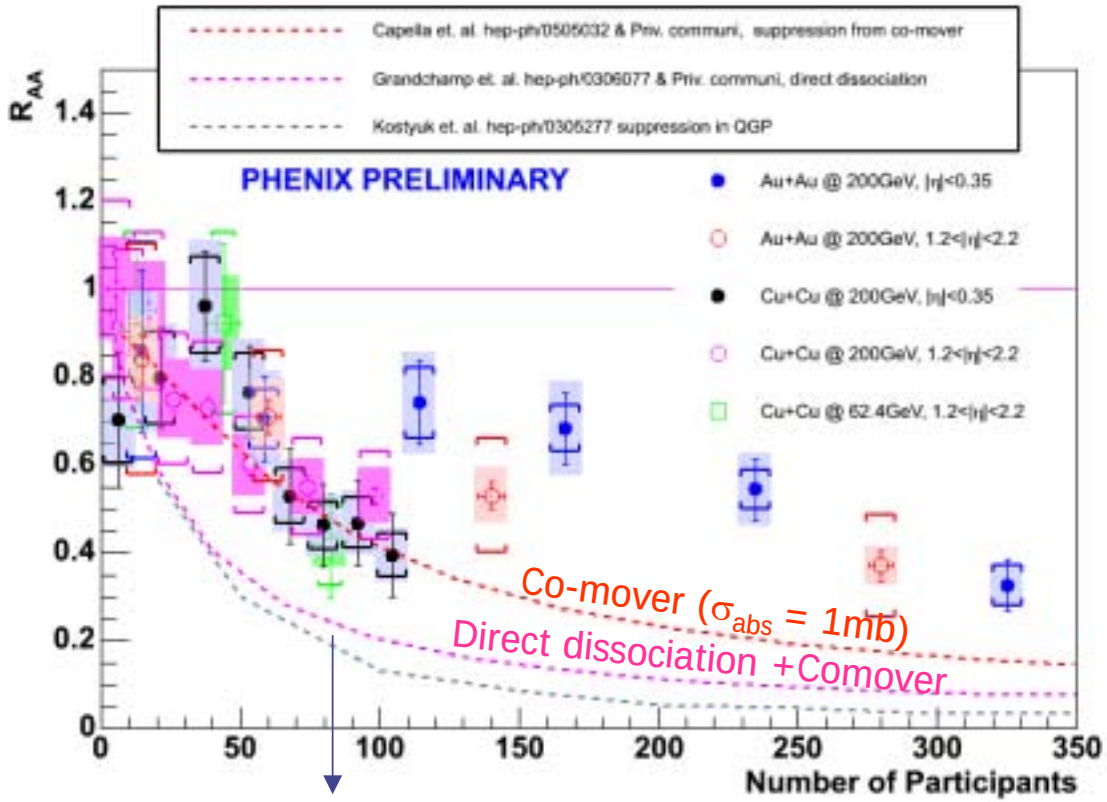
Same pattern at forward rapidity, but different in mid-rapidity.

Models which explain J/ψ suppression at RHIC.

- 1st : Dissociation + Recombination
  - Suppression due to Color Debye screening and comover scattering.
  - Recombination from uncorrelated cc-bar pairs at hadronization stage.
- 2nd : Sequence melting (Feed Down Effect)
  - Melt of only ψ' and χ_c. J/ψ still survives at RHIC.
- 3rd : J/ψ detailed transport in hydro QGP
  - Dissociation of J/ψ by gluons in QGP
    - QGP: Hydrodynamic equation.
    - J/ψ : Boltzmann transportation.
      - High p_T J/ψ escape the medium.

R_{AA} and NA50 suppression

- Comparison to the NA50 suppression models



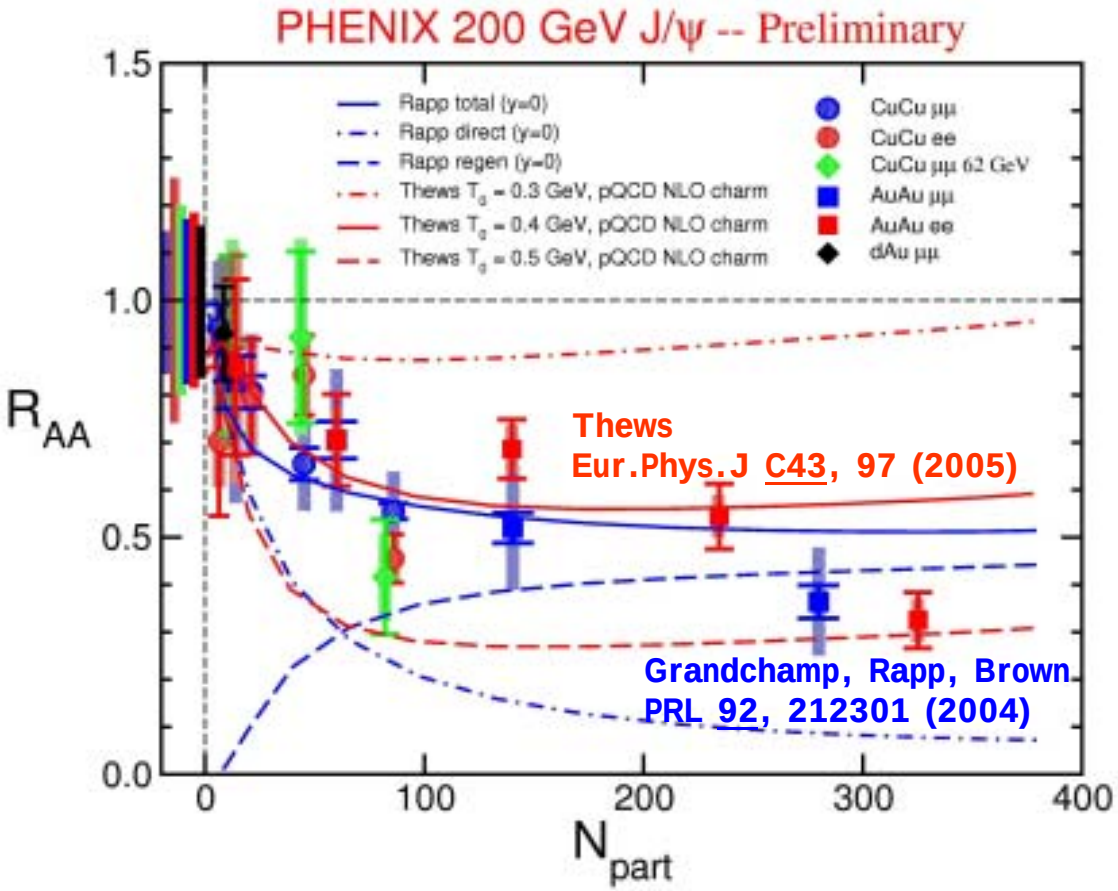
QGP screening + Comover + FeedDown

J/ψ suppression at RHIC is over-predicted by the suppression models that described SPS data successfully.

SPS → RHIC :
~10x collision energy
~2-3x gluon energy density

Include Recombination

- Dissociation + Recombination

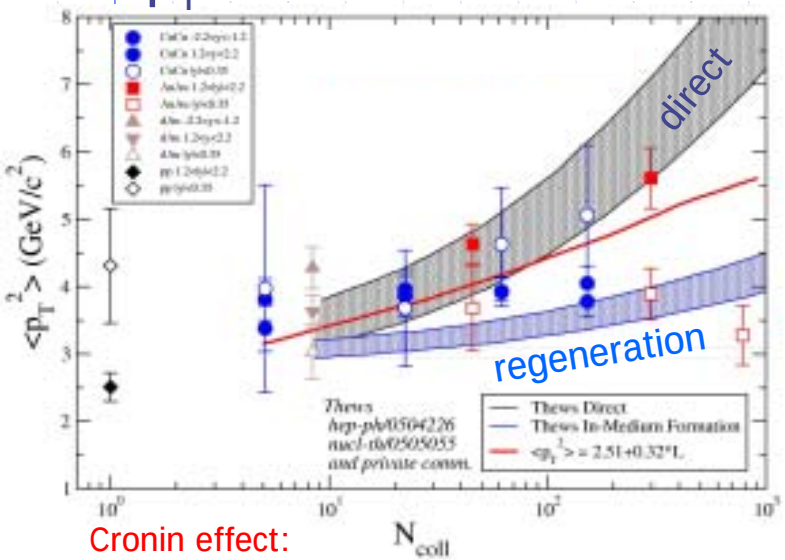


Models with recombination – single charm quarks combining in the hadronization stages to form J/ψ's – match the observed RHIC suppression much better!

Need to look at other observables. ($\langle p_T^2 \rangle$, y-shape)

$<p_T^2>$ and rapidity shape

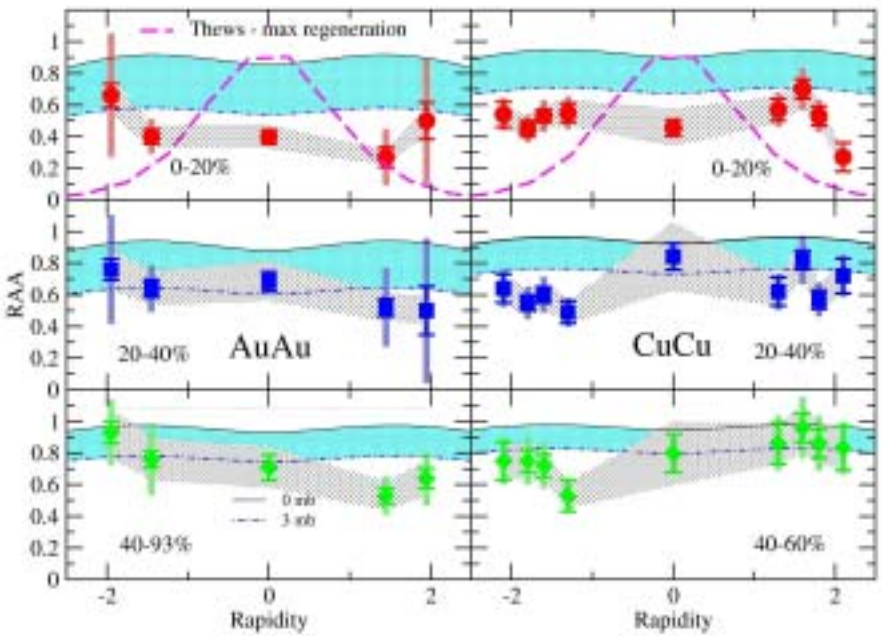
$<p_T^2>$



Cronin effect:
$<p_T^2> = 2.51+0.32*L$ from fit to dAu data vs L

Data points are lying between direct & Recombination. Suggesting some recombination!?

R_{AA} vs. y

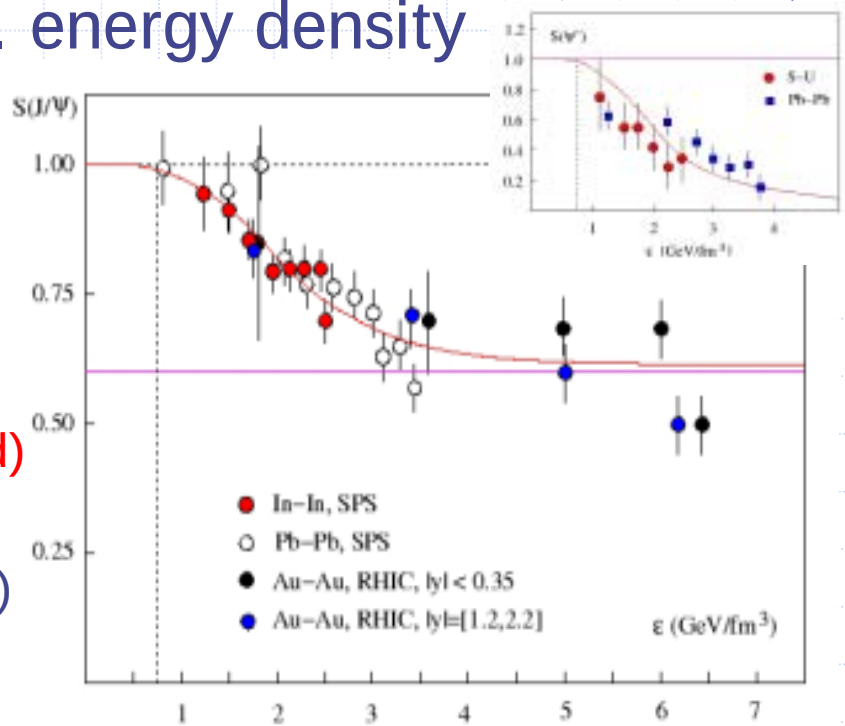


No significant difference in y-shape, while recombination predicts narrower rapidity shape.

But! Recombination models assume:
charm pT distribution, rapidity distribution, radial flow, (but no longitudinal flow) and thermalization of charm. Need to understand charm production at RHIC.

Sequential Melting

- Survival probability vs. energy density
  - $\tau_0 \sim 1$ fm/c
- Assuming Successive Melting.
  - $T_{diss}(\chi_c,\psi') \sim T_c$ (dissolved)
  - $T_{diss}(J/\psi) \sim 2T_c$ (un-dissolved)
  - $S(J/\psi) = 0.6 + 0.4*S(\psi')$
  - $S(\psi')$ from SPS (S-U, Pb+Pb)
- Support the Lattice QCD predictions.



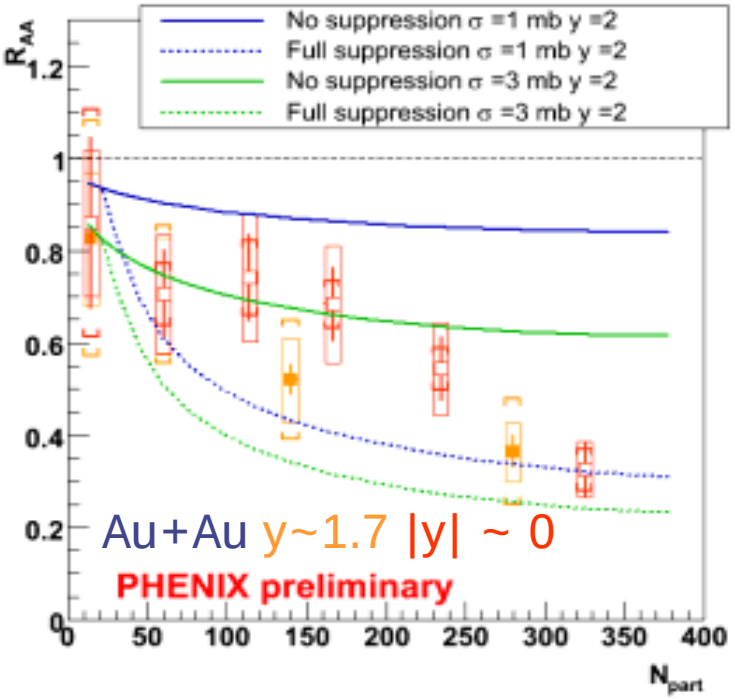
H. Satz, CERN Heavy Ion Forum, 10/06/2005

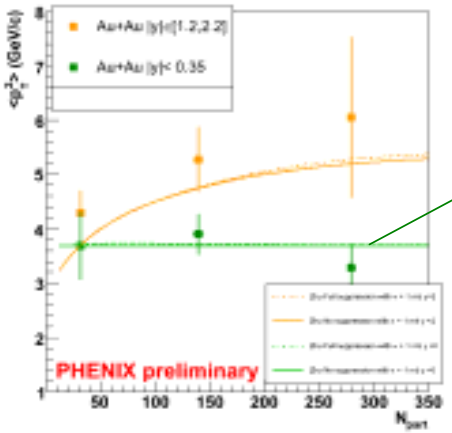
- *Q: 40% of feed down is still correct at RHIC?*

Transport Model

- QGP hydro (2+1D)
- Boltzman-type transport
- 40% feed down
- High p_T J/ψ escape
  - Suppression at low p_T J/ψ
- R_{AA} and $<p_T^2>$ match well

Results for y~2,
but similar for y~0



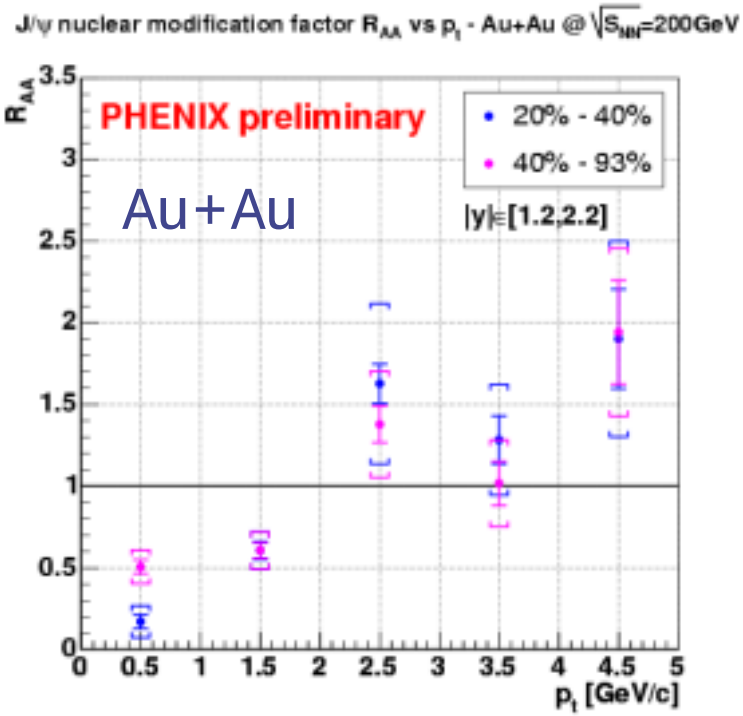


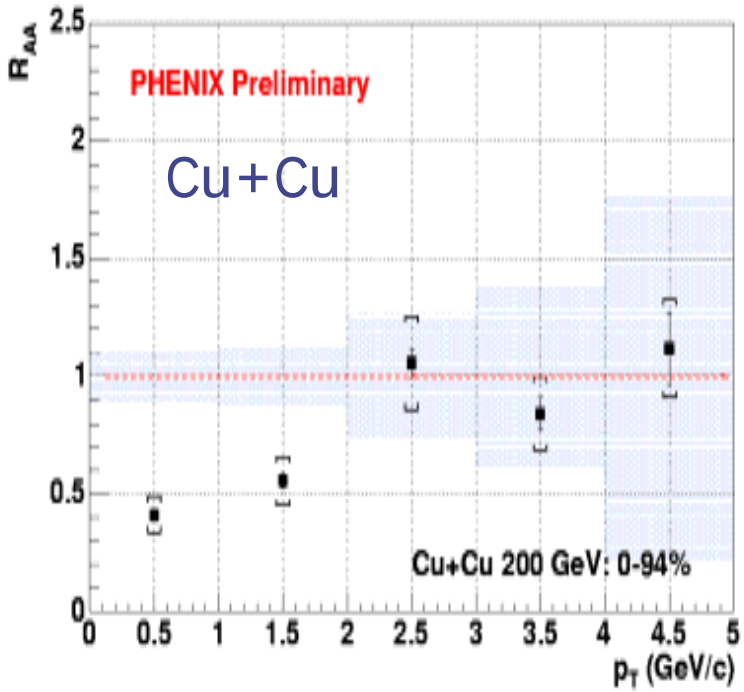
At mid-rapidity, Cronin effect is negligible (??) since $<p_T^2>_{pp} > <p_T^2>_{dAu}$

Zhu, Zhuang, Xu, PLB607 (2005) 107
+ private communications

High p_T J/ψ escape the medium!

- Results from forward rapidity.





Agreement with the transport picture.

This is same tendency as observed at NA50. [L.Ramello talk at QM05]

Azimuthal anisotropy of J/ψ

- Key to differentiate recombination and transport model.
  - Recombination :
    - 10% v2 @ 2GeV/c
      - If charm quark v2 is same as light quark v2.
  - Transport model:
    - 0.5% v2 @ 2GeV/c
      - More suppression of low pT J/ψ in the out-of-plane. (“Geometry only”)
- Need more statistics and good RP resolution.
  - RP detector at Run7

Zhu et al. PLB 607, 107 (2005)

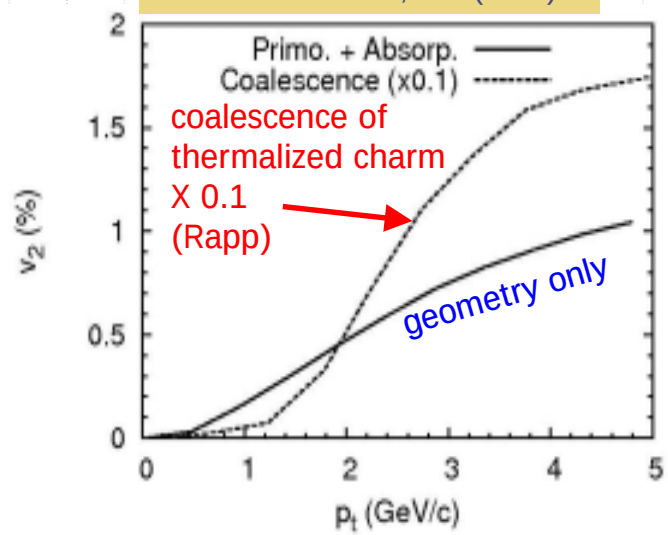


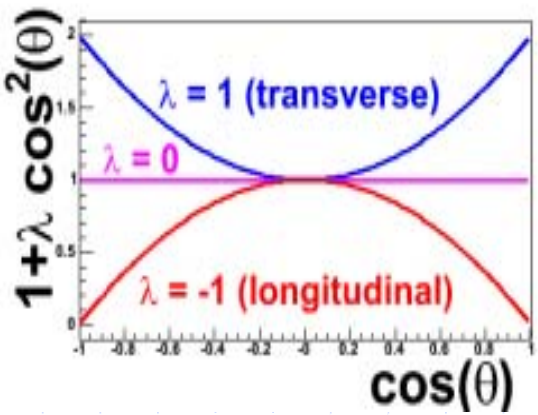
FIG. 4: The elliptical flow of J/ψ as a function of p_t at RHIC energy. The solid line is the maximal v_2 with impact parameter b=7.8 fm calculated in the frame of J/ψ transport, and the dashed line is the minimum-bias v_2 (scaled by a factor of 0.1) of the coalescence model with the assumption of complete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

Current Conclusion of J/ψ

- Cold Matter Effect:
  - Shadowing and Nuclear Absorption are weak.
  - Need more data to quantify the Cold Matter Effect.
- Hot and Dense Medium Effect:
  - R_{AA} in A+A collisions can be interpreted from:
    - Balance of Suppression + Recombination
      - But No strong sign of recombination from $<p_T^2>$ and y-shape
      - Need to understand charm production and its modification in medium.
      - Other observables such as v2 of J/ψ (10% at 2GeV, if v2 of charm is same as v2 of light quarks) and yields of Υ family are helpful.
    - Feed Down Effect
      - Melt of ψ' and χ_c. J/ψ is still not dissolved. Support the Lattice data.
      - How fraction of ψ' and χ_c go to J/ψ at RHIC energy? RHIC2!
    - Transport Model
      - $<p_T^2>$ also agrees. Suppression of low pT J/ψ agrees with this picture.
      - Finite v2 (0.5% at 2GeV/c) is predicted and v2 measurement is helpful.

J/ψ Polarization

- Sensitive to Production Mechanism



J/ψ production models predict different polarization.

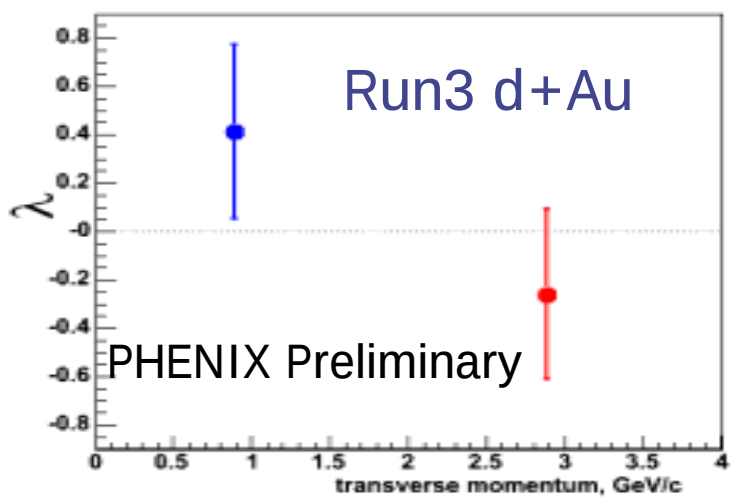
CEM and CSM: no polarization

COM: transverse at high P_T

Ioffe and Kharzeev, hep-ph/0306176: transverse (~0.35-0.40) at low P_T if QGP is formed

Khoze, Martin, Ryskin, and Stirling, hep-ph/0410020: longitudinal polarization at high P_T

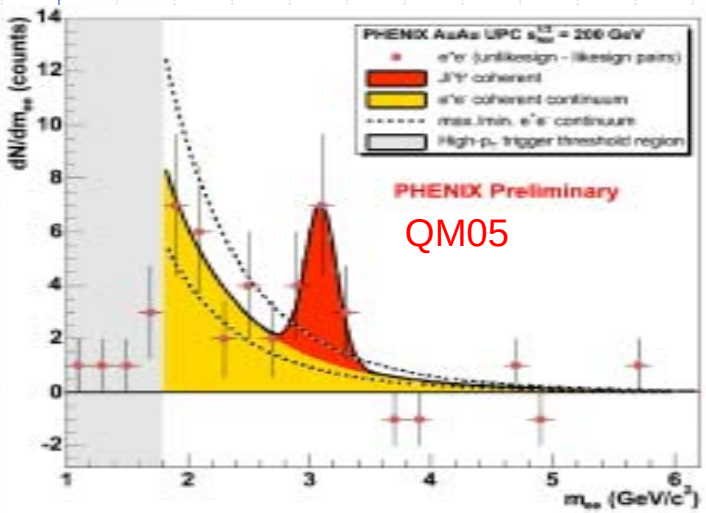
Results consistent with no polarization, large error bars due to low statistics.



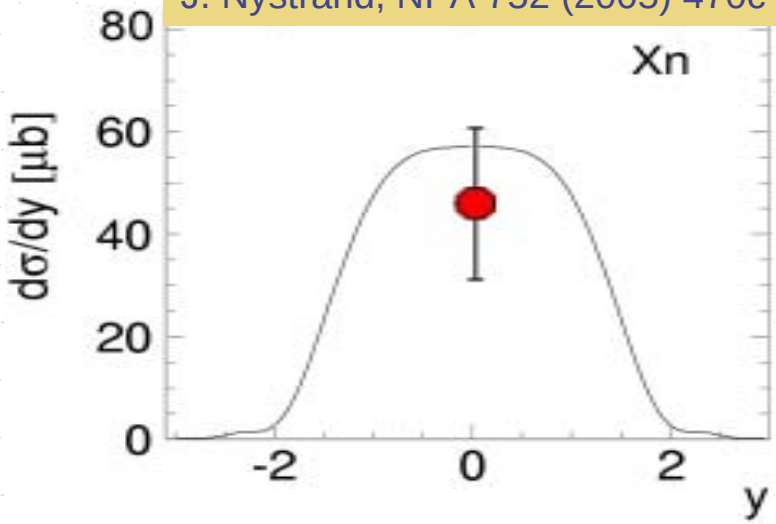
J/ψ in Ultra-Pheripheral Collisions

- Photo-production $\gamma p \rightarrow J/\psi p$:
  - Sensitive to Gluon distribution at small x.

$$\left.\frac{d\sigma(\gamma p \rightarrow V p)}{dt}\right|_{t=0} = \frac{\alpha_s^2 \Gamma_{ee}}{3\alpha M_V^5} 16\pi^3 \left[xG(x,Q^2)\right]^2 \quad \text{, with } Q^2 = M_V^2/4 \quad x = M_V^2/W_{\gamma p}^2$$



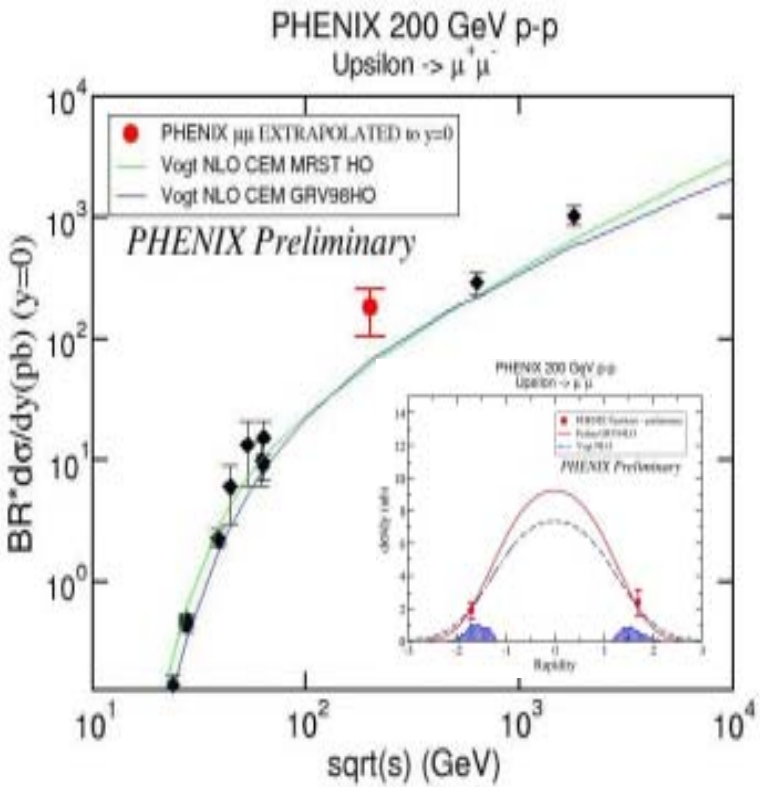
J. Nystrand, NPA 752 (2005) 470c

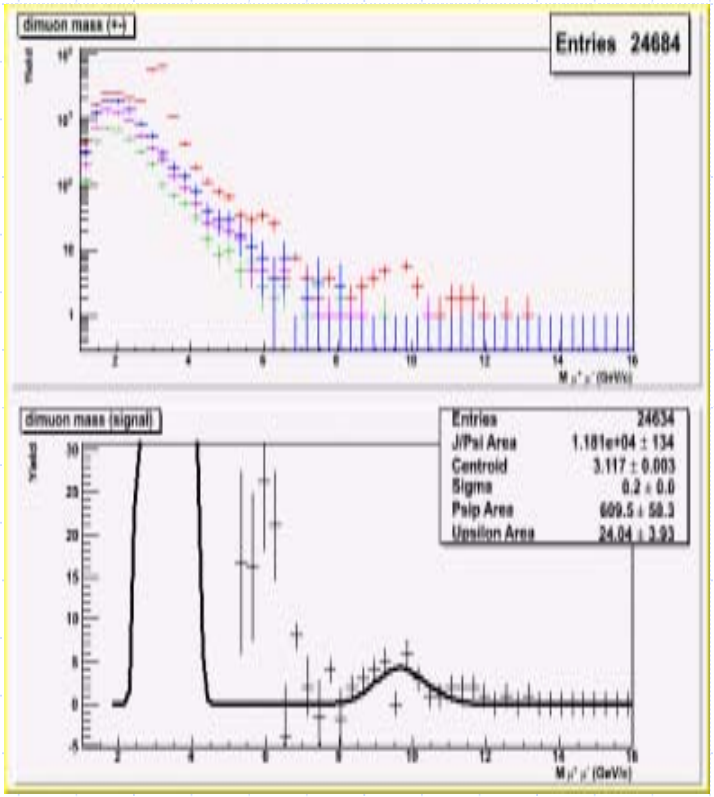


$d\sigma_{J/\psi}/dy|_{y=0}$ = 44 ± 16 (stat) ± 18 (syst) μb

First Υ measurements

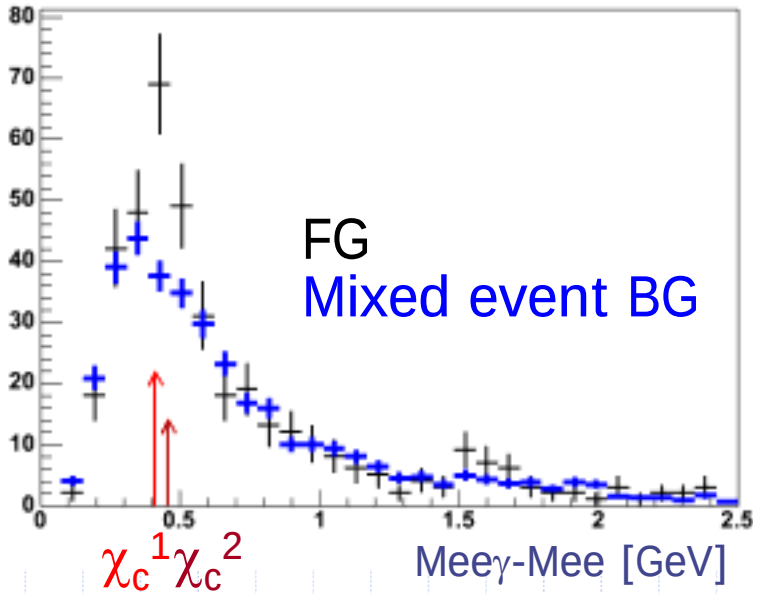
- Preliminary results from run5 p+p muon arms

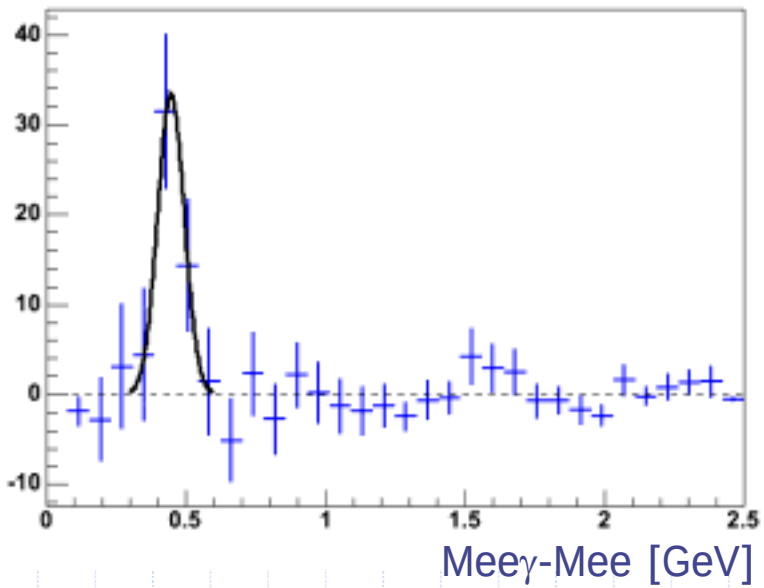




First χ_c observation

- From run5 p+p central arms
- Further analysis is on going.





Summary

- PHENIX Measured J/ψ in p+p, d+Au, Au+Au and Cu+Cu.
  - p+p collisions
    - Good Base Line for A+A Collisions.
    - High Stat. Data from Run5 p+p.
      - First Measurement of Υ and χ_c . Small error for R_{AA} calculation.
  - d+Au collisions
    - Nuclear Effect (Shadowing, Absorption) is weak
    - More Stat. is needed to quantify CNM effects.
  - A+A collisions
    - Suppression above CNM effects in most central collisions.
    - Suppression + recombination, Feed Down (Lattice), Transport model can explain observed suppression.
    - PHENIX is working on finalizing the results.
    - v2 measurement will clarify some of the different models.
    - RHIC2 high luminosity runs will be needed to differentiate these models with high stat. J/ψ data. (talk by T. Frawley)

PHENIX

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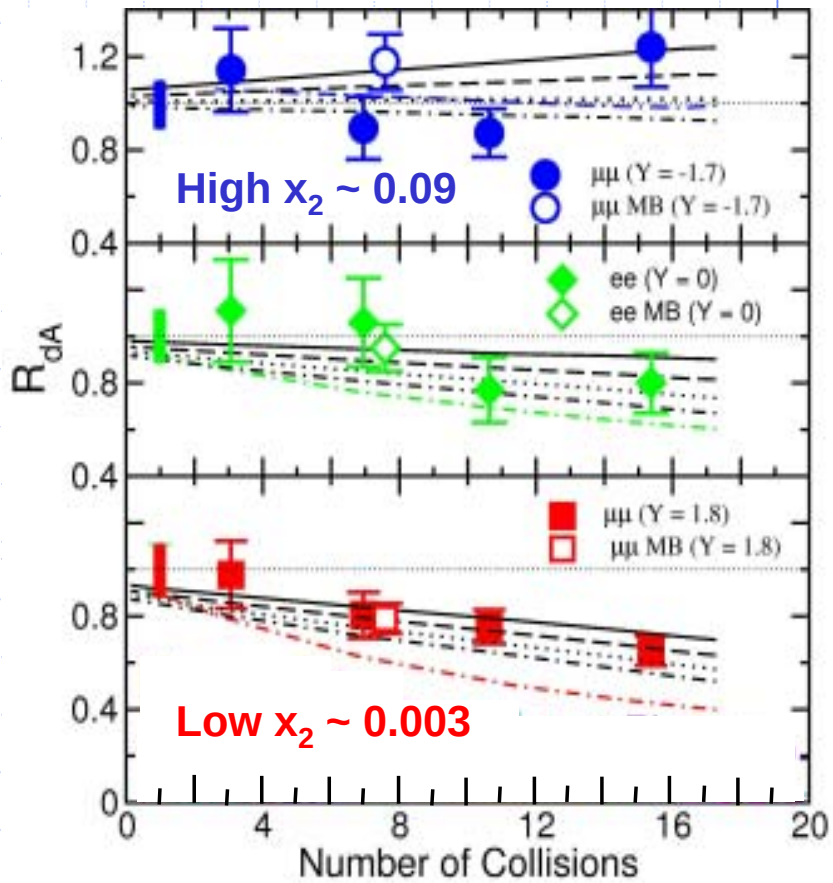
Back Up Slides

R_{dAu} vs. N_{col}

- Comparison to the prediction with :
  - EKS shadowing
  - σ_{abs} = 0-3 mb.
- Slopes consistent with shadowing model
  - Especially low x_2



Representing Nuclear Dependences

Typical fixed-target measurement where centrality not measured e.g. E772,E866:

$$R(W/Be)=\frac{(\sigma(W)/A_W)}{(\sigma(Be)/A_{Be})}$$

Power law representation of nuclear dependence when many nuclei are measured (especially useful when comparing different experiments that used different light and heavy targets):

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

Nuclear Modification factor typically used at RHIC:

$$R_{dAu}=\frac{Yield_{inv}^{dAu}}{<N_{coll}^{dAu}>Yield_{inv}^{pp}}$$

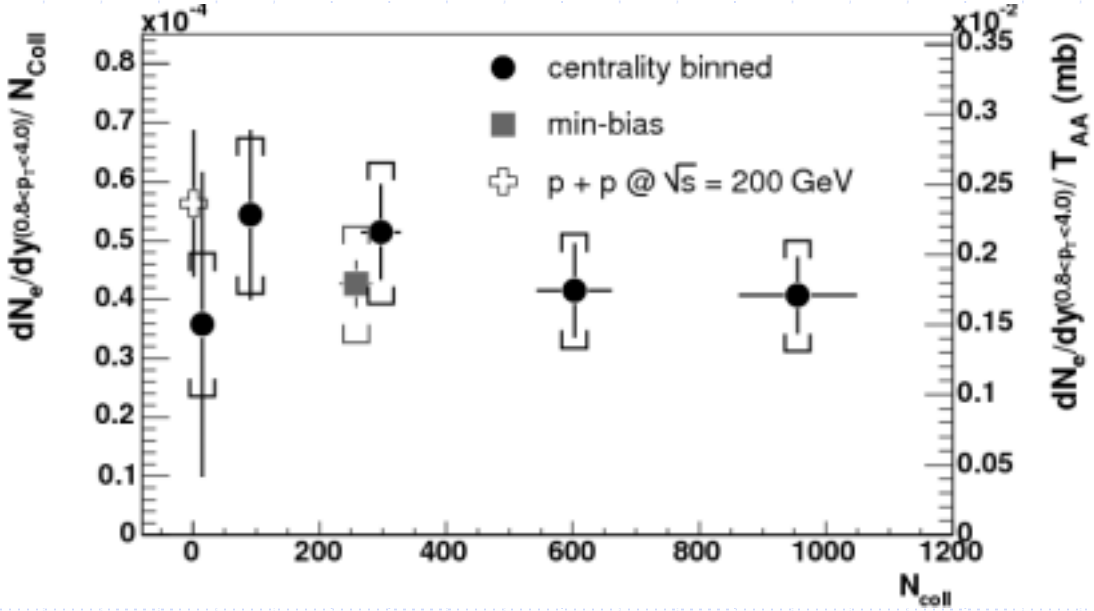
Where, when looking at non-centrality binned results, the latter is equivalent to:

$$R_{dAu}=\frac{\sigma_{dAu}}{(2\times 197)\sigma_{pp}}$$

Total Charm Yield

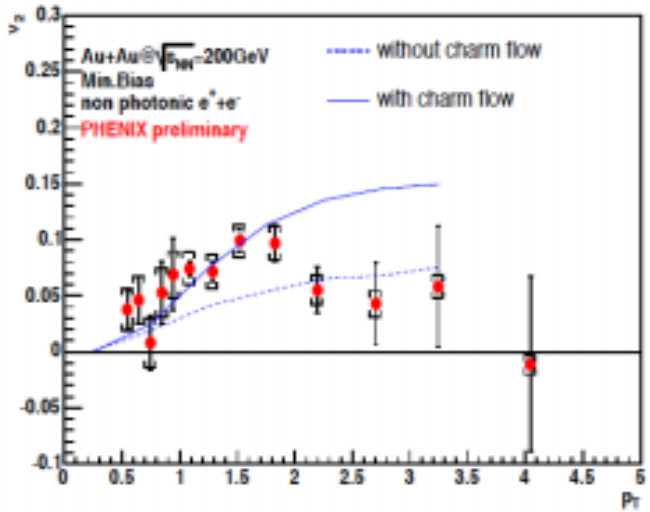
- PHENIX Run2 Au+Au
  - Binary scaling works well for total charm yield.
  - dN_e/dy is fit to AN_{coll}^{α}.

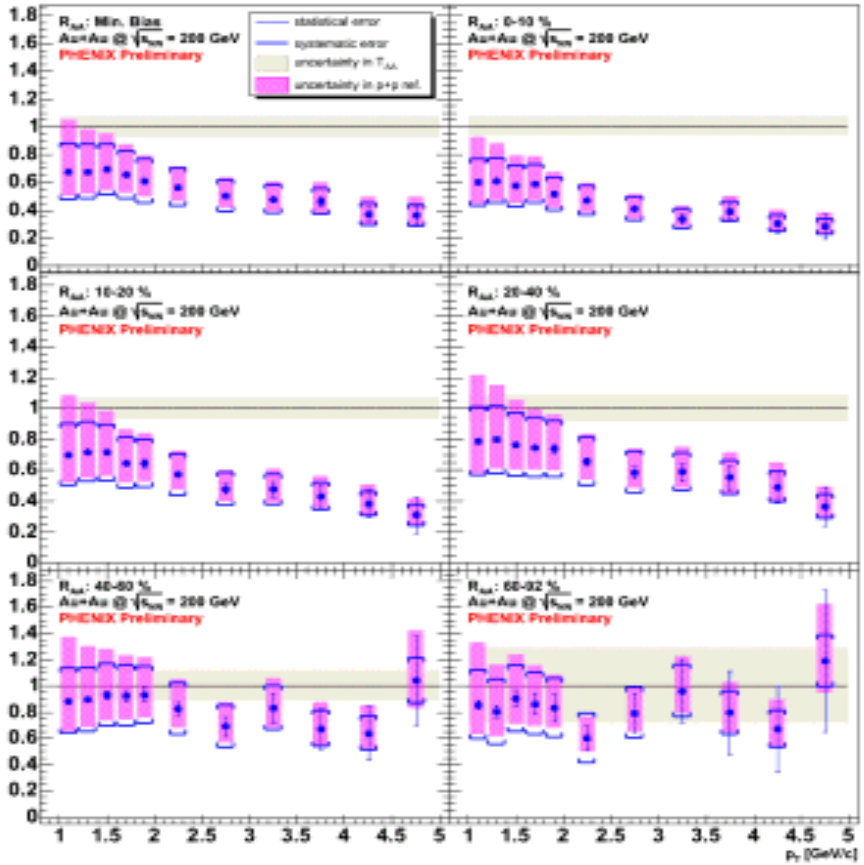
α = 0.938+/-0.075+/-0.0018



Charm in the medium

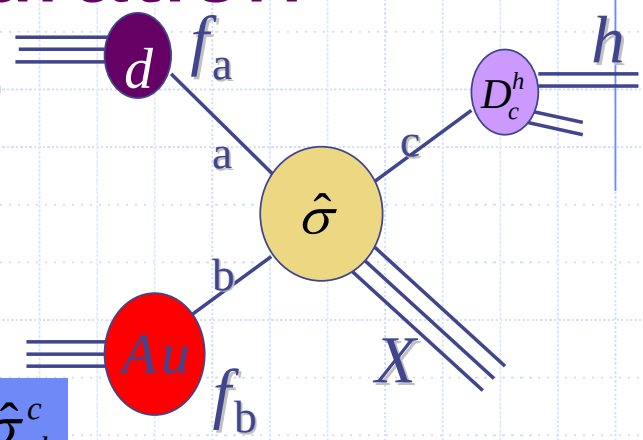
- V2 and R_{AA} of Non-photonic electrons in Au+Au (Run4)





Shadowing and Saturation

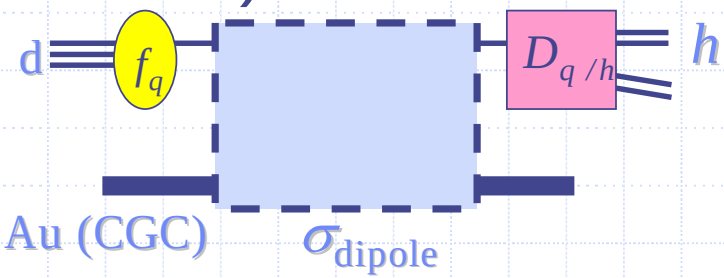
- Shadowing (pQCD approach)
  - 2→2 process
  - Leading Twist shadowing
    - Use nuclear PDF



$$d\sigma = \int dx_2 \int dx_1 \int dz \; f_a^d(x_1) \; f_b^{Au}(x_2) \; D_c^h(z) \; d\hat{\sigma}_{ab}^c$$

Leading Twist Gluon shadowing

- Parton Saturation (CGC framework)
  - 2→1 process
  - Including higher twist effect



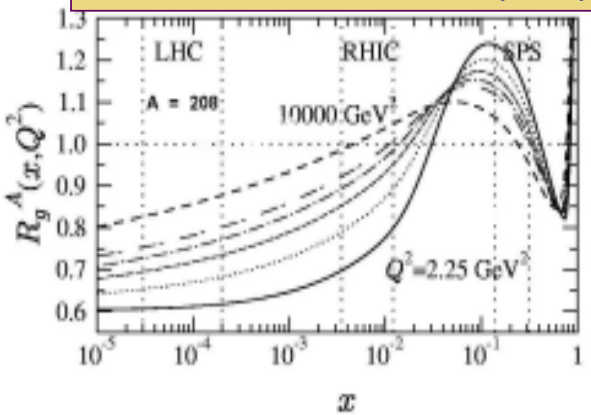
$$\sigma \sim \int dz \int d^2 r_\perp f_q^d(x_1) \sigma_{dipole}(x_2, r_\perp) D_{q/h}(z)$$

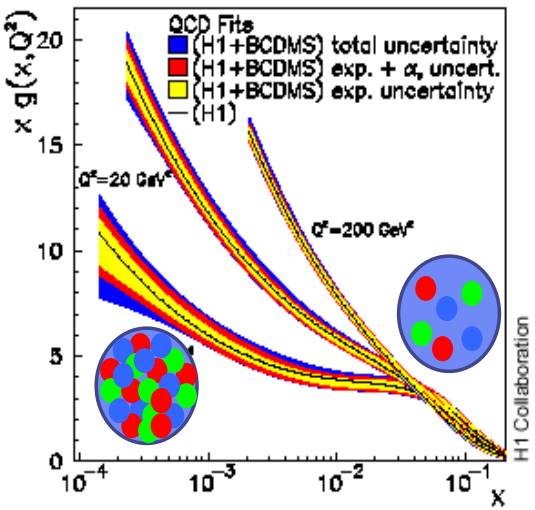
Valence quark distrib.

Cold Matter effect – Initial state

- Gluon shadowing
  - Depletion of gluon PDF at small x region
- Gluon saturation (CGC)
  - Breaking Bjorken scaling at small x (high energy scattering).
  - High density gluons at small x.
    - gg→g process is dominant
    - Depletion of small x gluons
  - Gluon density is ~ x 6 higher in Au than that in the nucleon.

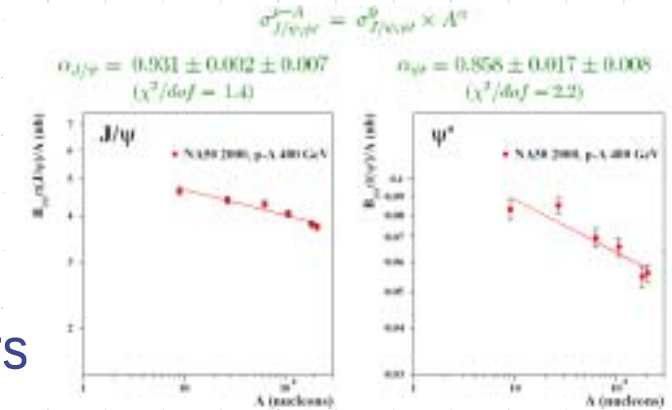
Eskola et al. NP A696, 729 (2001)

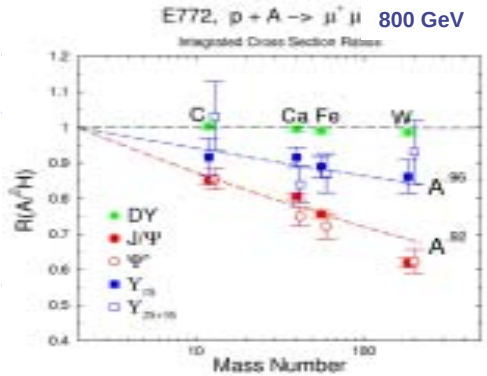


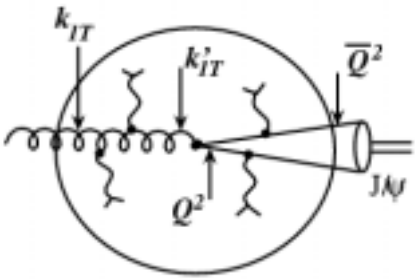


Cold Matter Effect – Nuclear Env.

- Nuclear Absorption
  - Break up interactions
    - J/ψ or $c\bar{c}$ pre-resonance vs. spectator nucleon
  - Multiple scattering of $c\bar{c}$ pairs
    - J/ψ is unlikely to produce at the production point.
    - Relative momentum of the pair
      - $\bar{Q}^2 > Q^2 \rightarrow$ suppression
  - "Hadronization time"
- Cronin effect
  - Initial state multiple Scattering of partons.
    - p_T Broadening



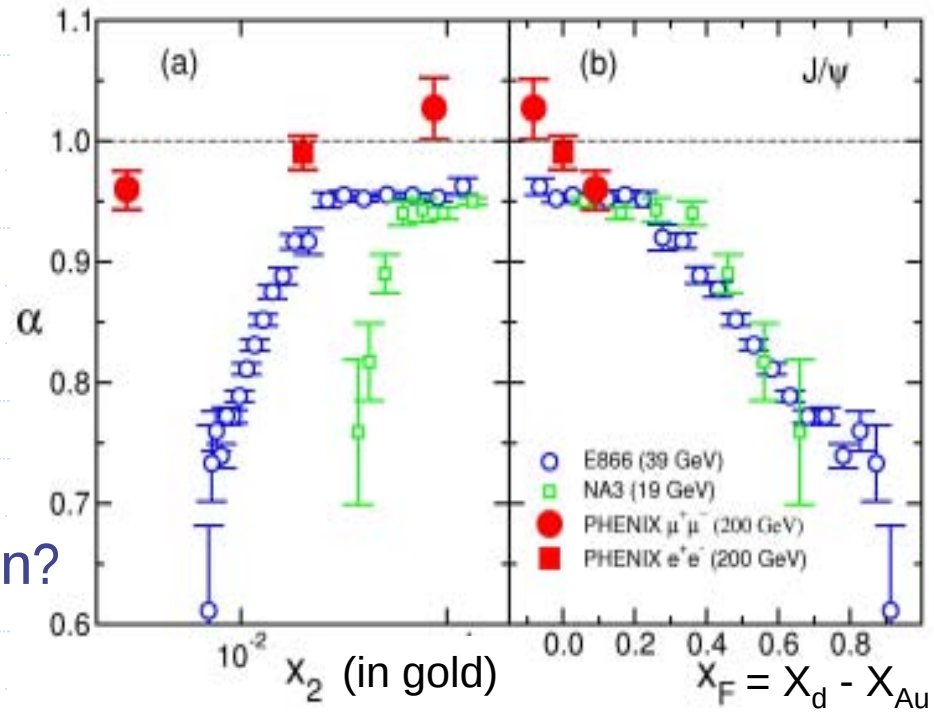




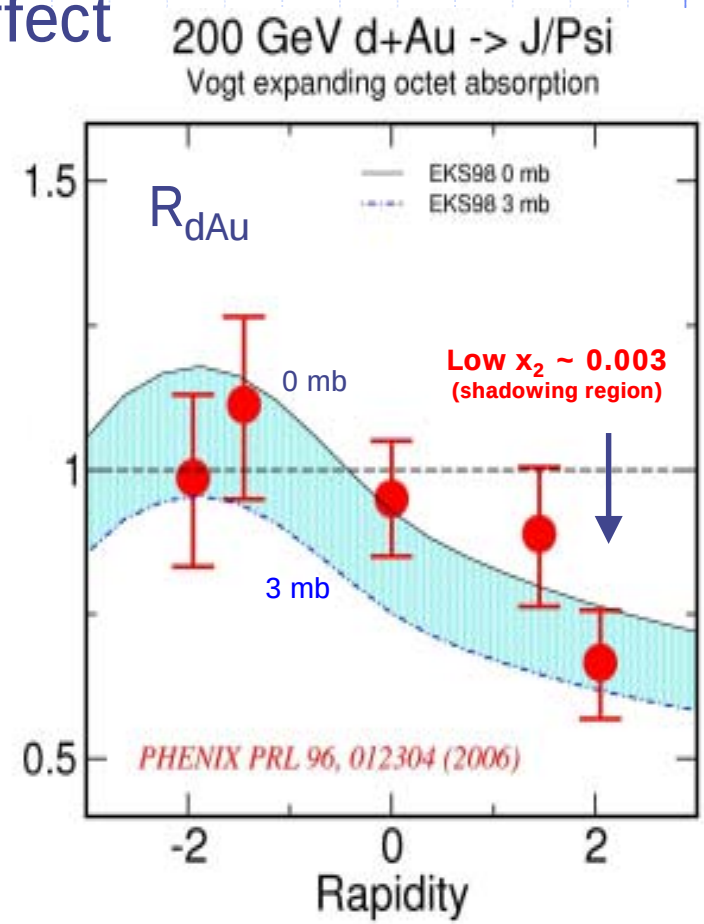
X_{Au}, X_F dependence of α

- Shadowing is weak.
- Not scaling with X_2 but scaling with X_F.
  - Coincidence?
    - Shadowing
    - Gluon energy loss
    - Nuclear Absorption
  - Sudakov Suppression?
    - hep-ph/0501260
  - Gluon Saturation?
    - hep-ph/0510358

$\sigma_{dAu} = \sigma_{pp} (2x197)^{\alpha}$



E866, PRL 84, (2000) 3256
NA3, ZP C20, (1983) 101
PHENIX, PRL96 (2006) 012304

R_{dAu} vs. Rapidity

- Extraction of shadowing effect and nuclear absorption
- Data favors :
  - Weak Shadowing
  - Weak Absorption
    - σ_{abs} ~ 0 – 3 mb
    - σ_{abs} = 4.18 +- 0.35 mb at SPS
- But with limited statistics difficult to disentangle nuclear effects !