

Heavy Flavor and  
Quarkonia Production at  
PHENIX

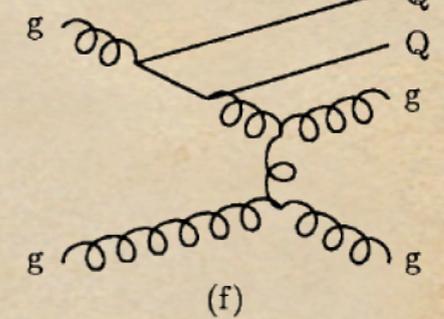
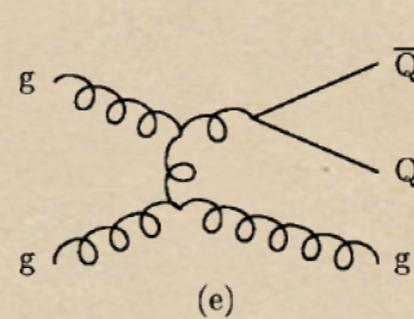
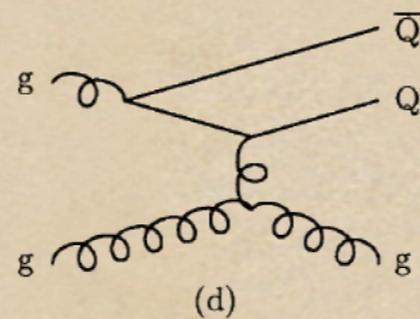
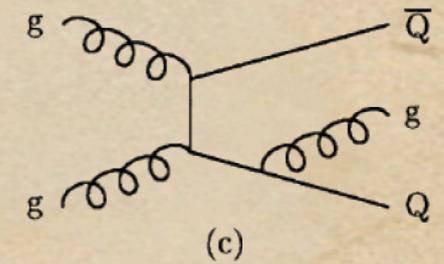
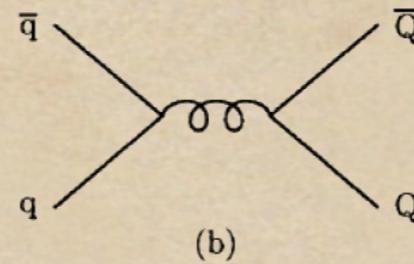
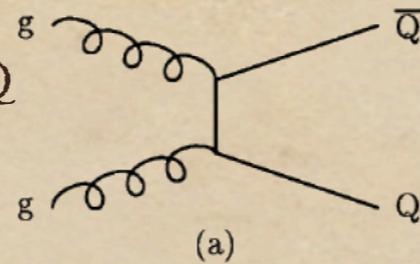
Cesar Luiz da Silva - Iowa State University

For the PHENIX Collaboration

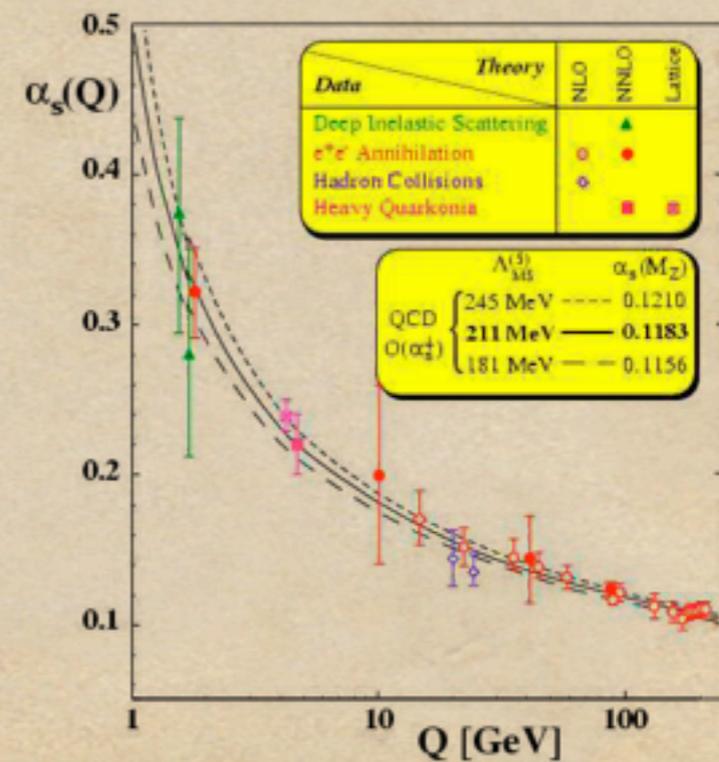
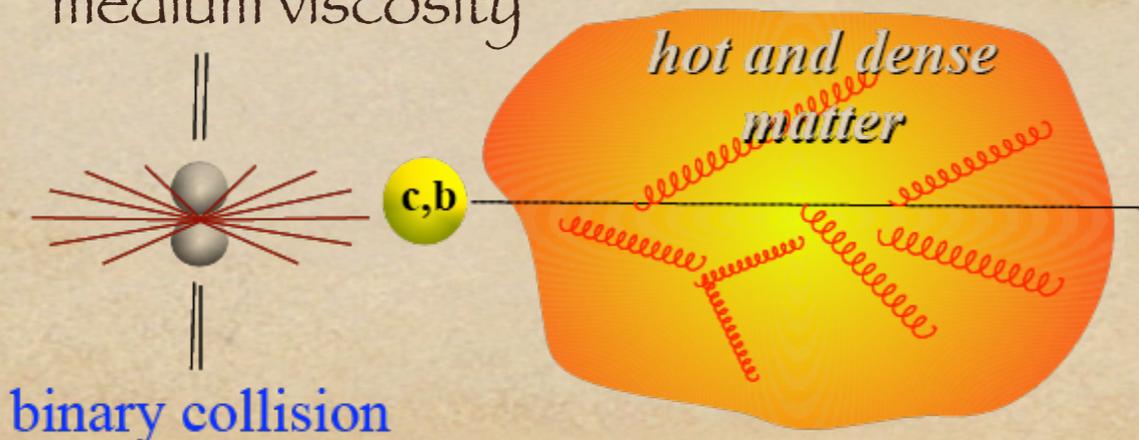
DIFFRACTION 2008 - La Londe-les-Maures - France

# What we can learn with heavy quarks ?

- ◆ heavy quark ( $M_{HQ} \gg \Lambda_{QCD}$ ) production demands high  $Q$
- ◆ good test for pQCD
- ◆  $p_T$  dependence of HQ modification factors in A+A compared to p+p collisions complement the gluon radiation picture in hot and dense medium

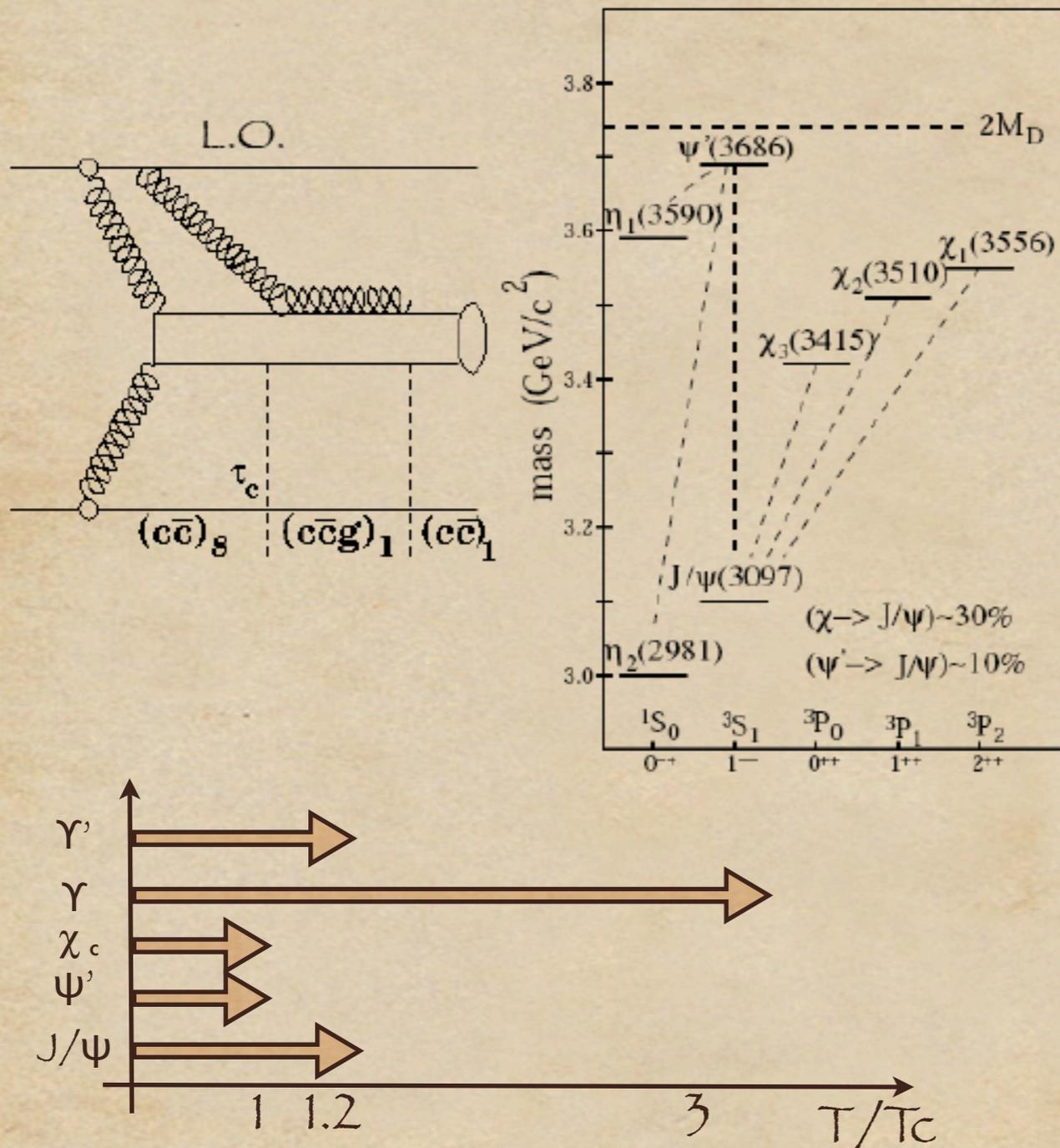


- ◆ HQ motion is sensitive to the medium viscosity



# And what about Quarkonia ?

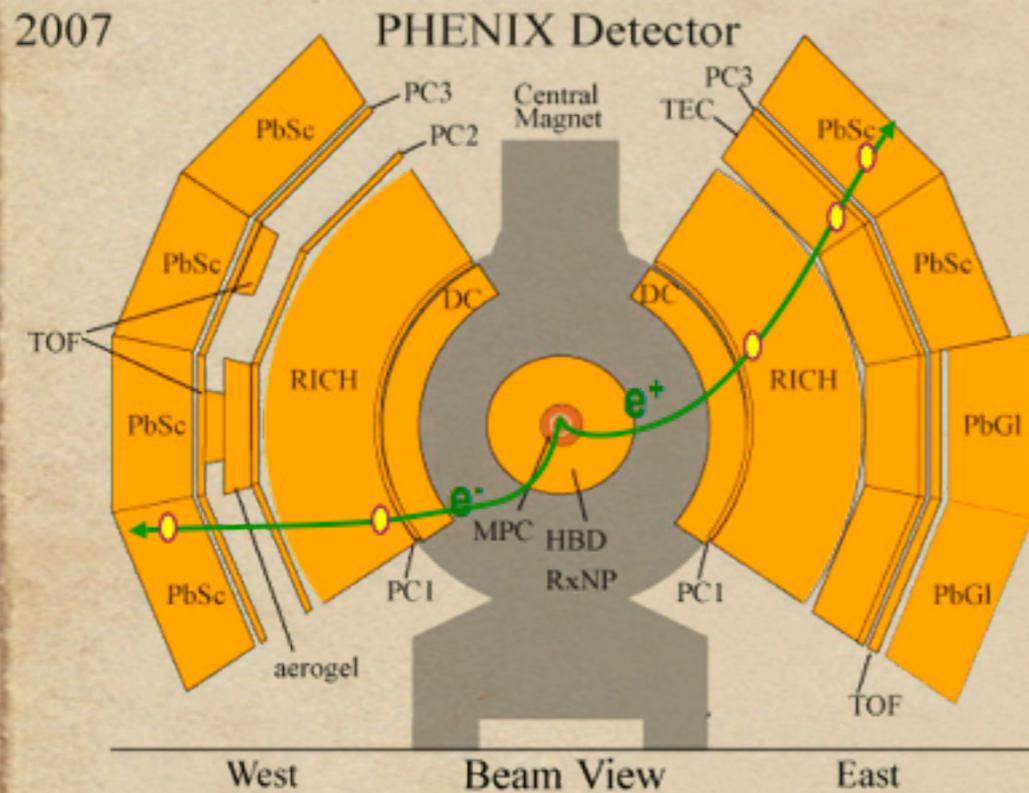
- ◆ weak coupling with light mesons
- ◆ small size
- ◆ strong binding
- ◆ nevertheless production is non-perturbative and its calculation is challenging
- ◆ can gauge initial states effects like parton distribution modifications
- ◆ complete dissociation in AA collisions is triggered by specific temperatures for different quarkonia states



# Heavy Quark Measurements

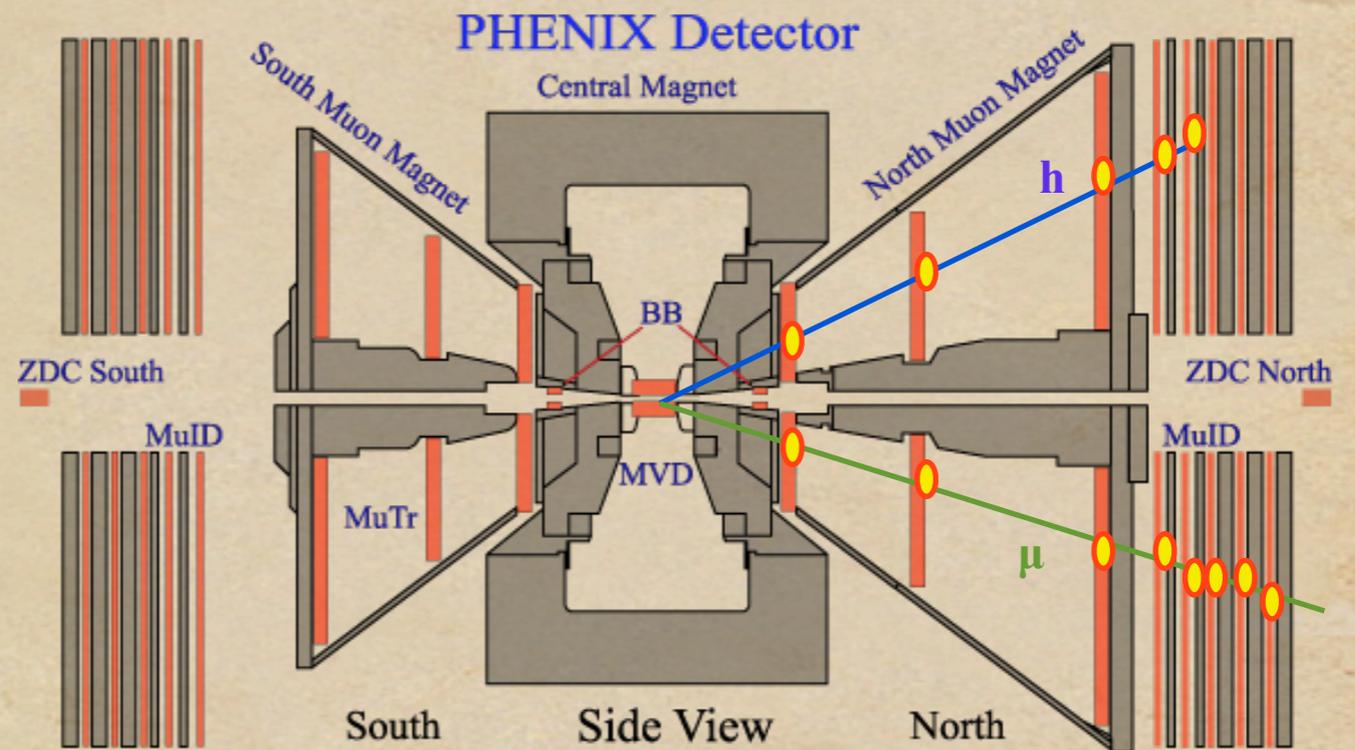
# PHENIX abilities to measure HQ

## Central Arms

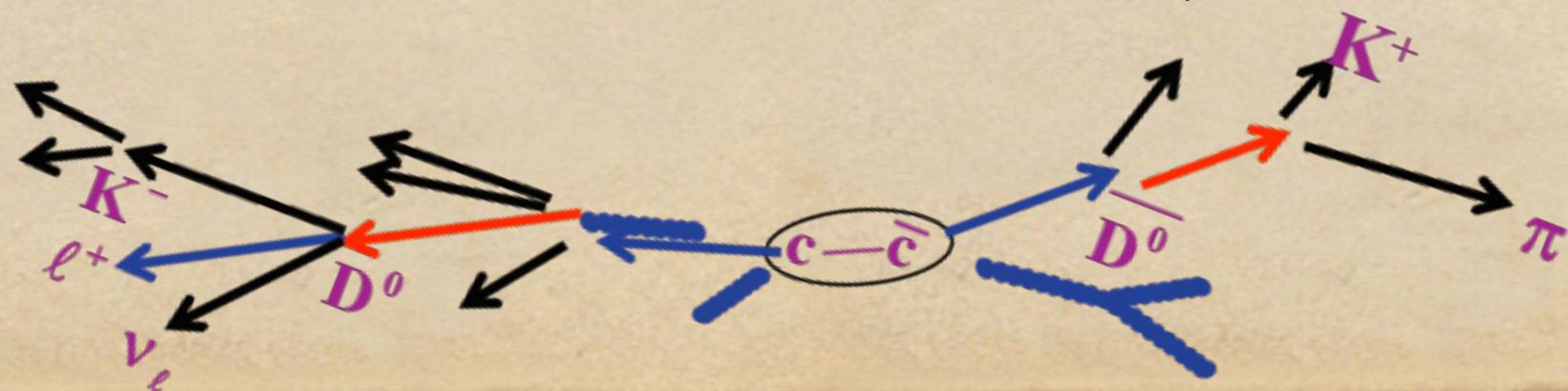


$|\eta| < 0.35$   $\Delta\Phi = 2 \times \pi/2$   
 electrons decays  $p > 0.15$  GeV/c  
 amount of material in run4 = 0.4%  $X_0$

## Forward Arms



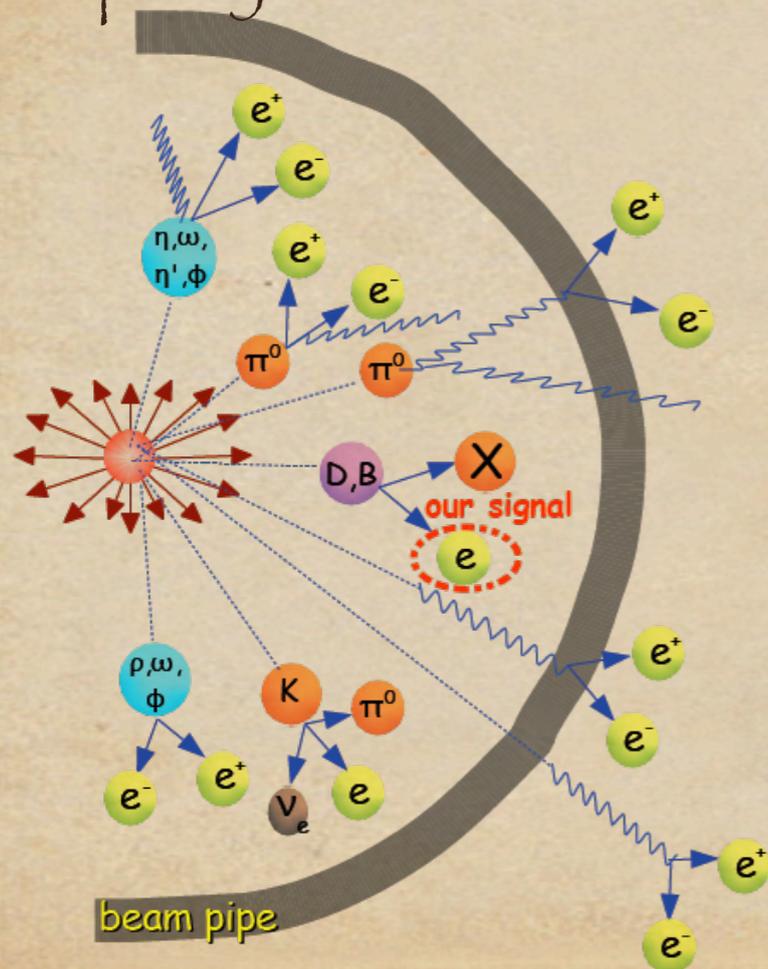
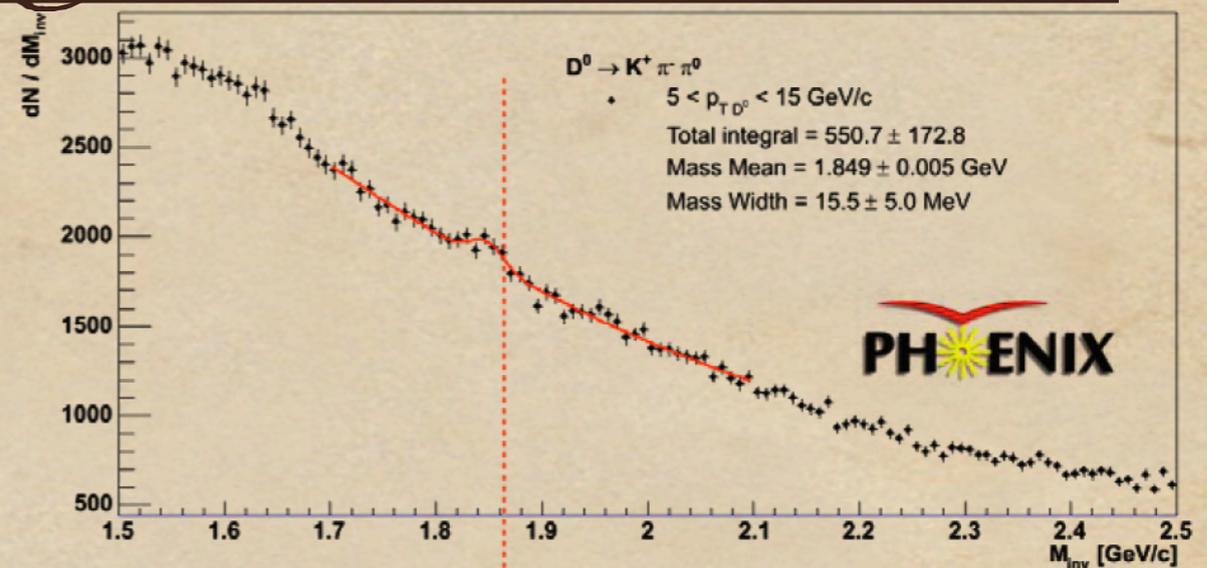
$-2.2 < \eta < -1.2$   $1.2 < \eta < 2.2$   $\Delta\Phi = 2\pi$   
 muons decays  $p > 2$  GeV/c  
 common accepted  $\pi/\mu \sim 10^{-4}$



# Experimental challenges to measure HQ

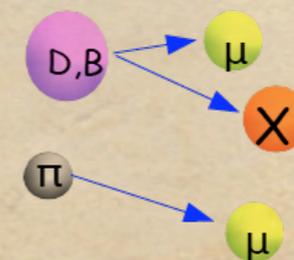
~ full reconstruction of D and B decays is currently dominated by background.

~ the installation of the Silicon Vertex Detector in 2010 will make direct reconstruction feasible even in high multiplicity events

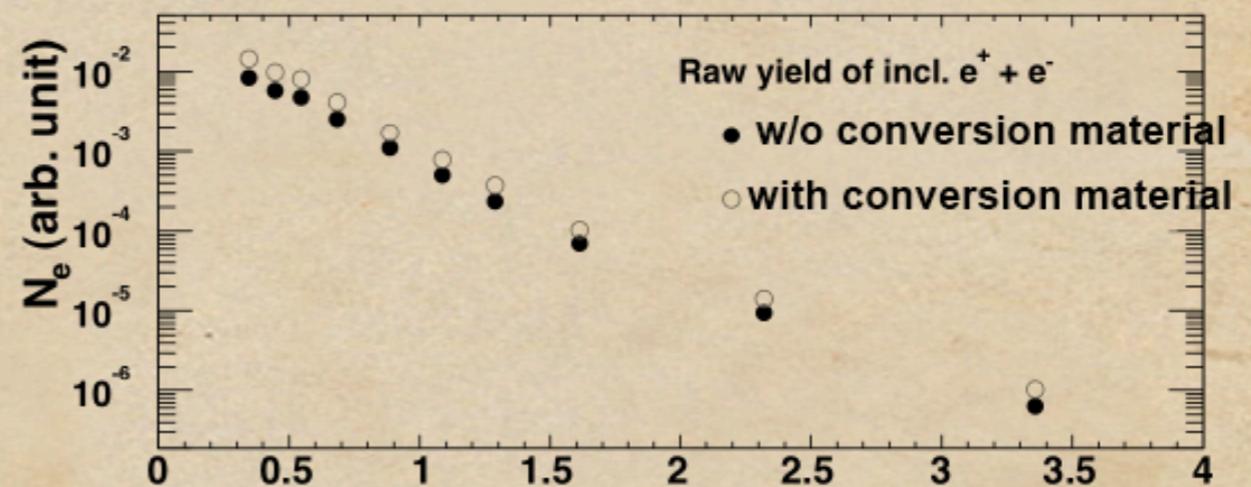
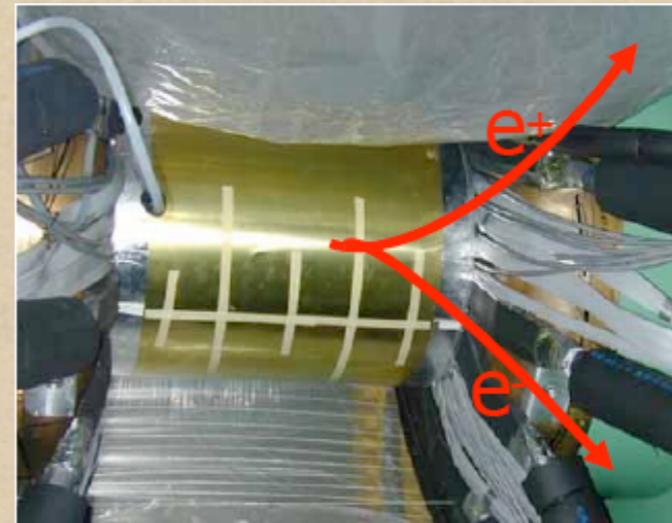
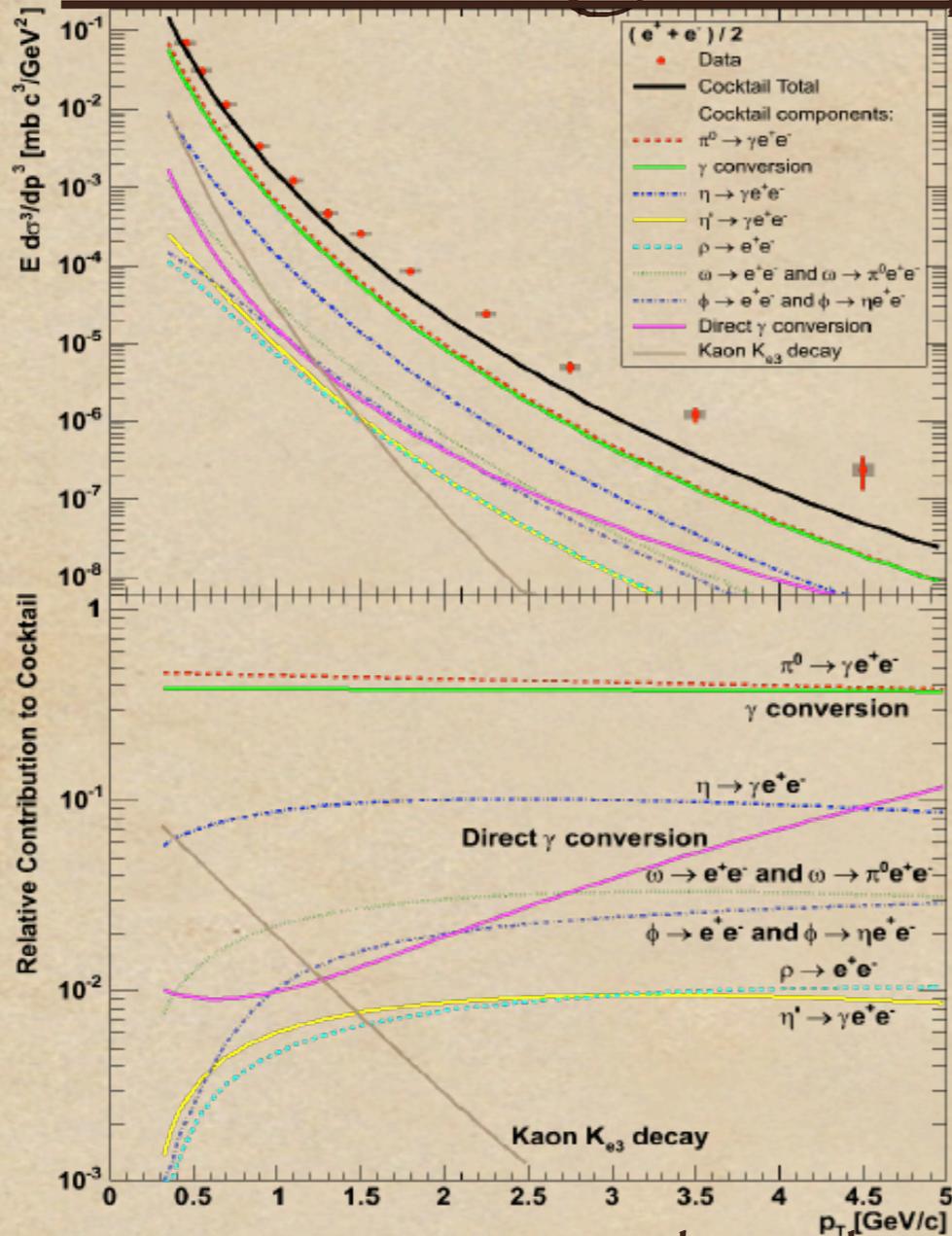


~ requires precise measurements of all electron sources to discriminate HQ semi-electronic decays out of large amount of photonic contributions

~ demands well knowledge of hadron contamination and fraction of hadrons which decays in muons before reach absorbers



# Extracting non-photonic contribution



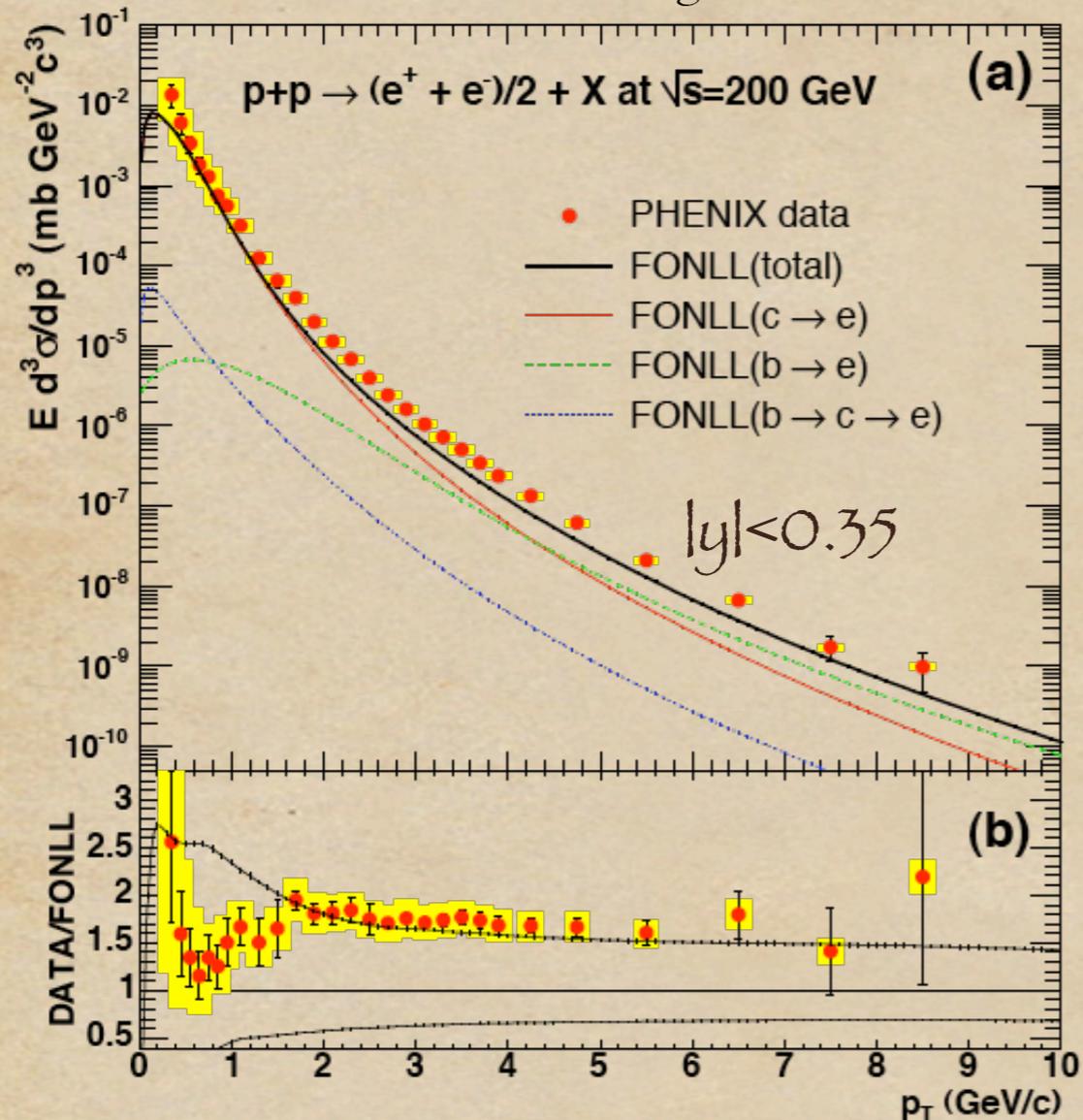
PHENIX can use measured  $\gamma$  and neutral meson production as input for the photonic contribution to high  $p_T$  electron yield. Measured kaon yield is also a input parameter.

In the low  $p_T$  range the photonic contribution is measured by introducing a known amount of material.

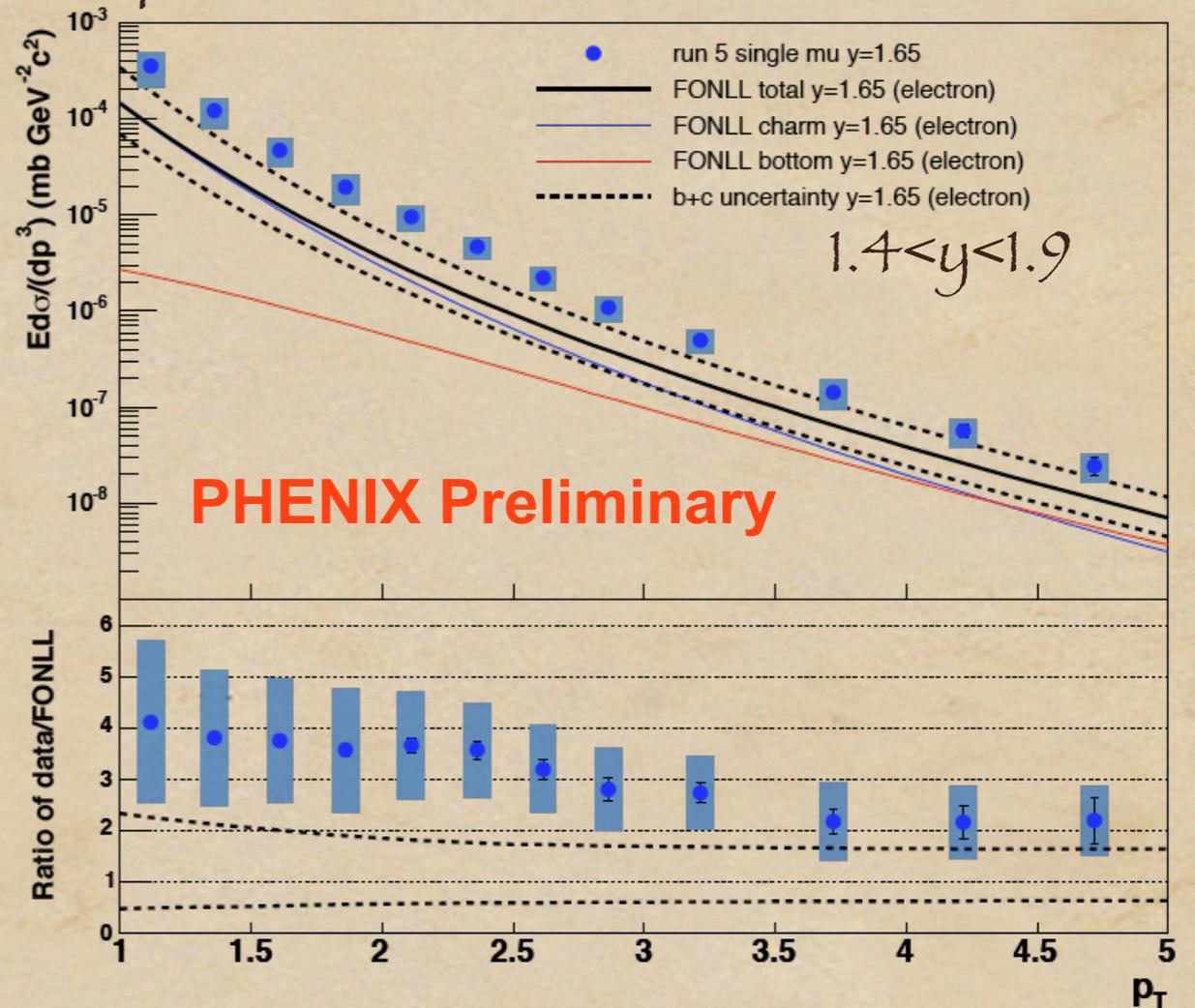
# Results in p+p collisions at $s^{1/2}=200$ GeV

PRL 97, 252002 (2006)

FONLL: M. Cacciari, P. Nason, R. Vogt PRL95,122001 (2005)



In agreement with previous PHENIX publication PRD 76, 092992 (2007)

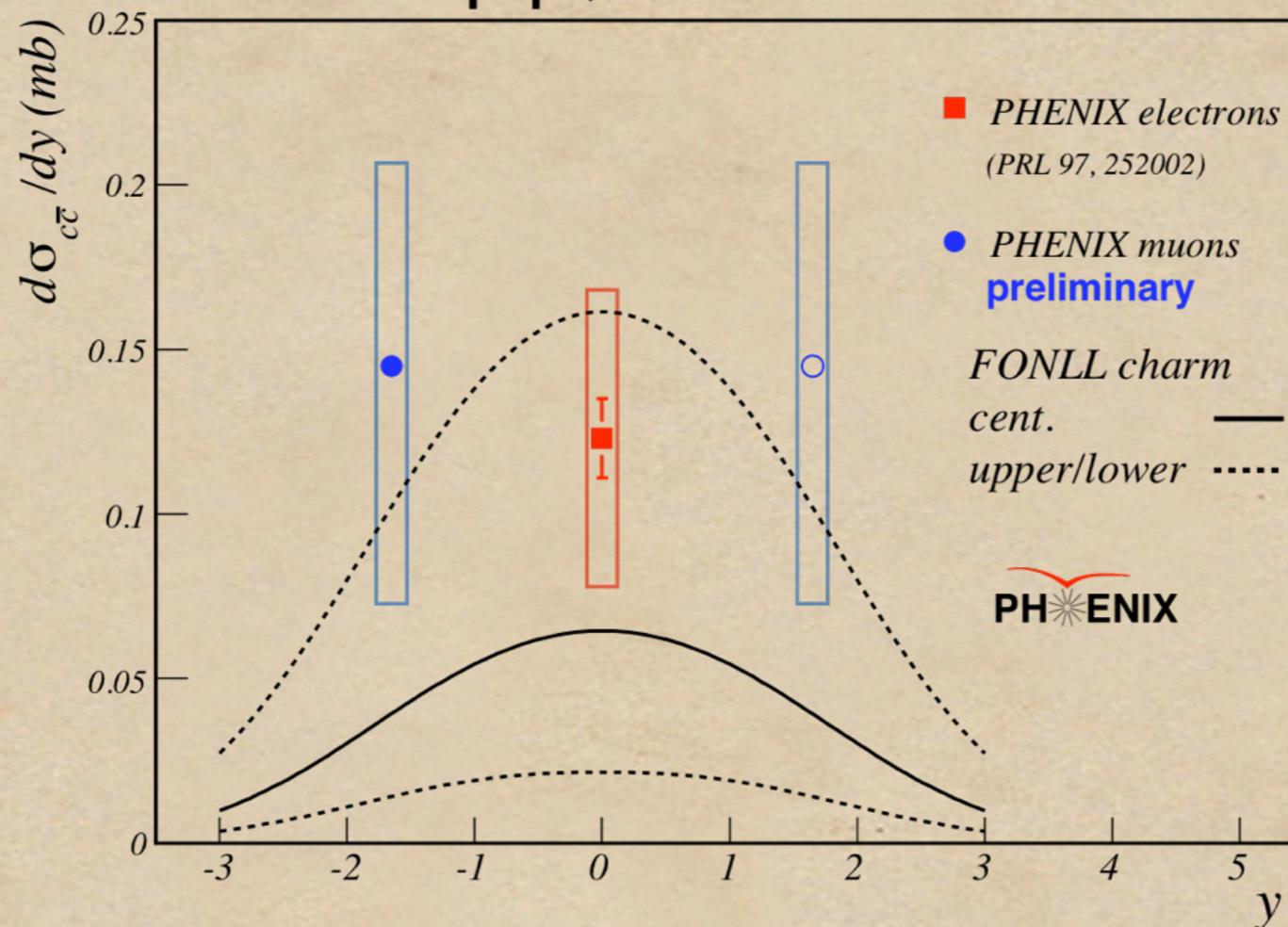


PHENIX Preliminary

Non-photonic electrons are dominated by D and B decays.  
 Mid-rapidity measurement in agreement with state of the art pQCD calculations.  
 Measurement at forward rapidity agrees for  $p_T > 3.5$  GeV/c where S/B is better.

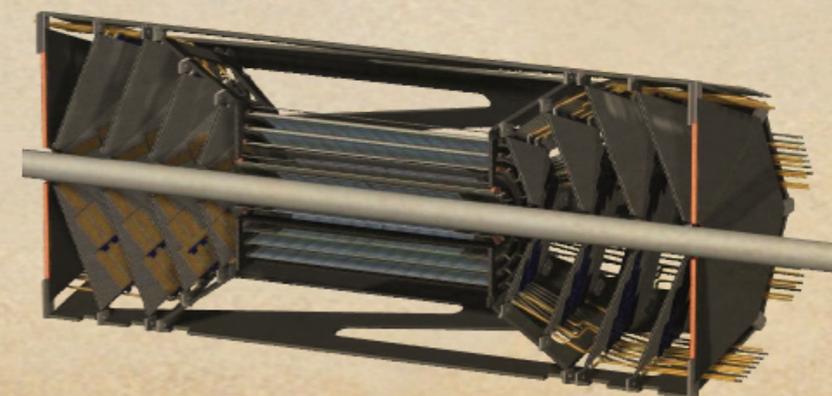
# Rapidity dependence of HQ

p+p  $\sqrt{s} = 200$  GeV



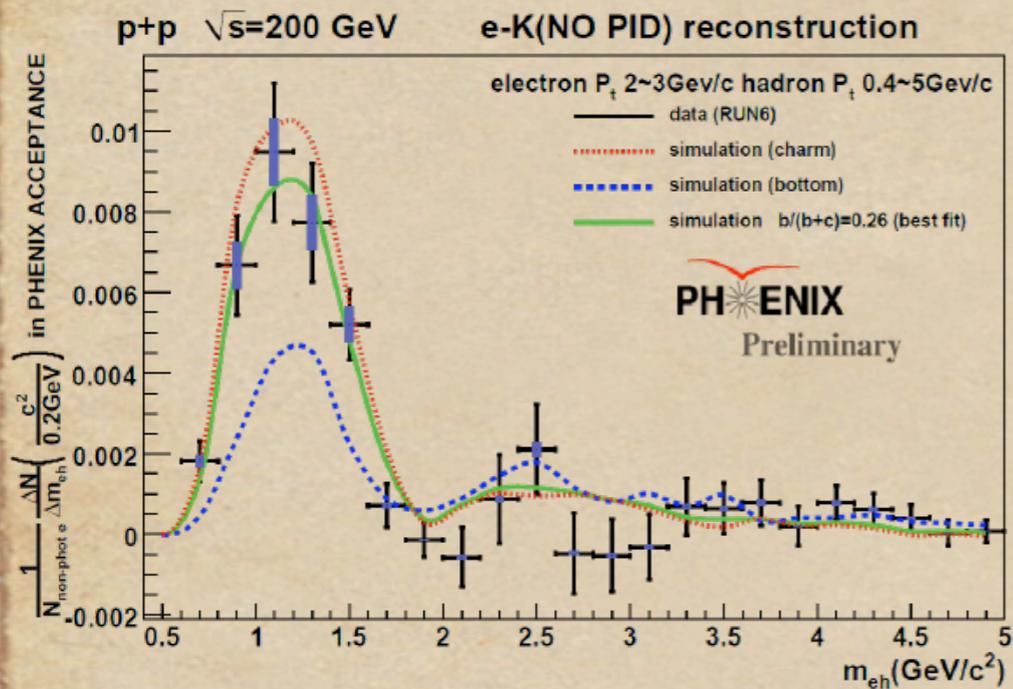
Uncertainties dominated by background systematic errors.

Better measurements will be possible with fully reconstructed D and B decays expected to happen with the installation of the Silicon Vertex detector.

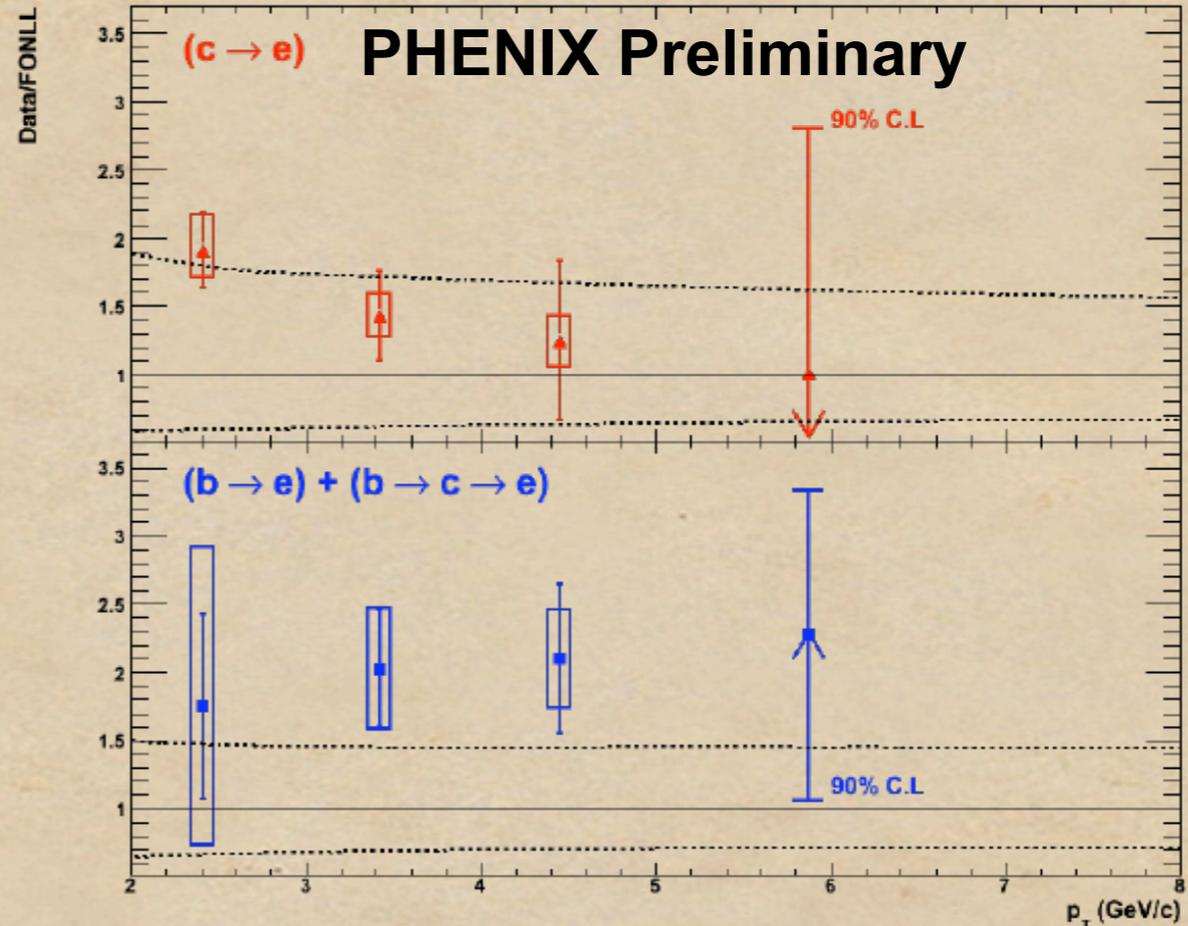


# D and B separation

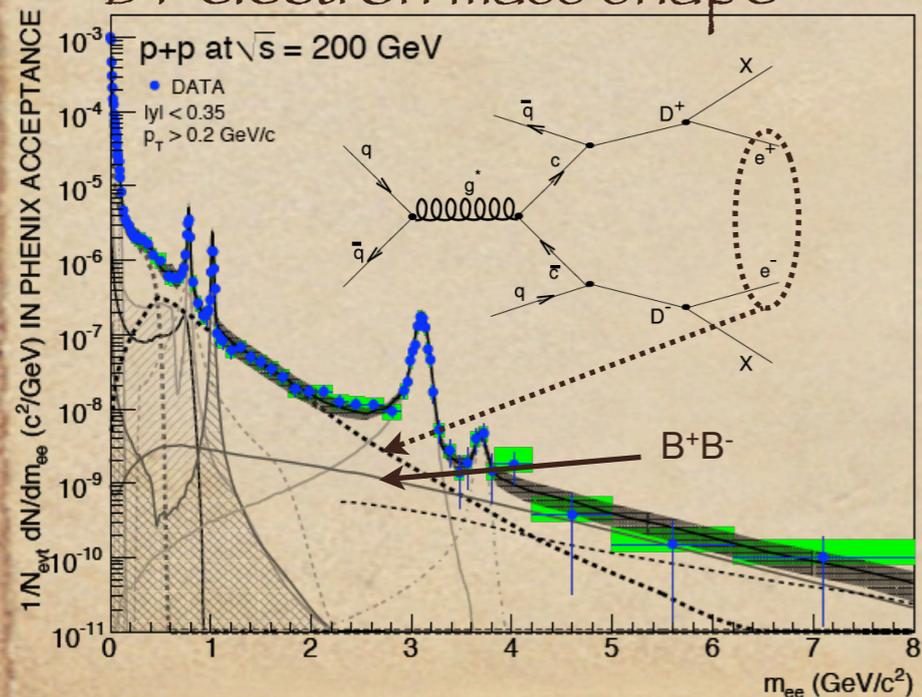
## Electron-hadron correlation



p+p  $\rightarrow (e^+ + e^-)/2 + X$  at  $\sqrt{s}=200$  GeV



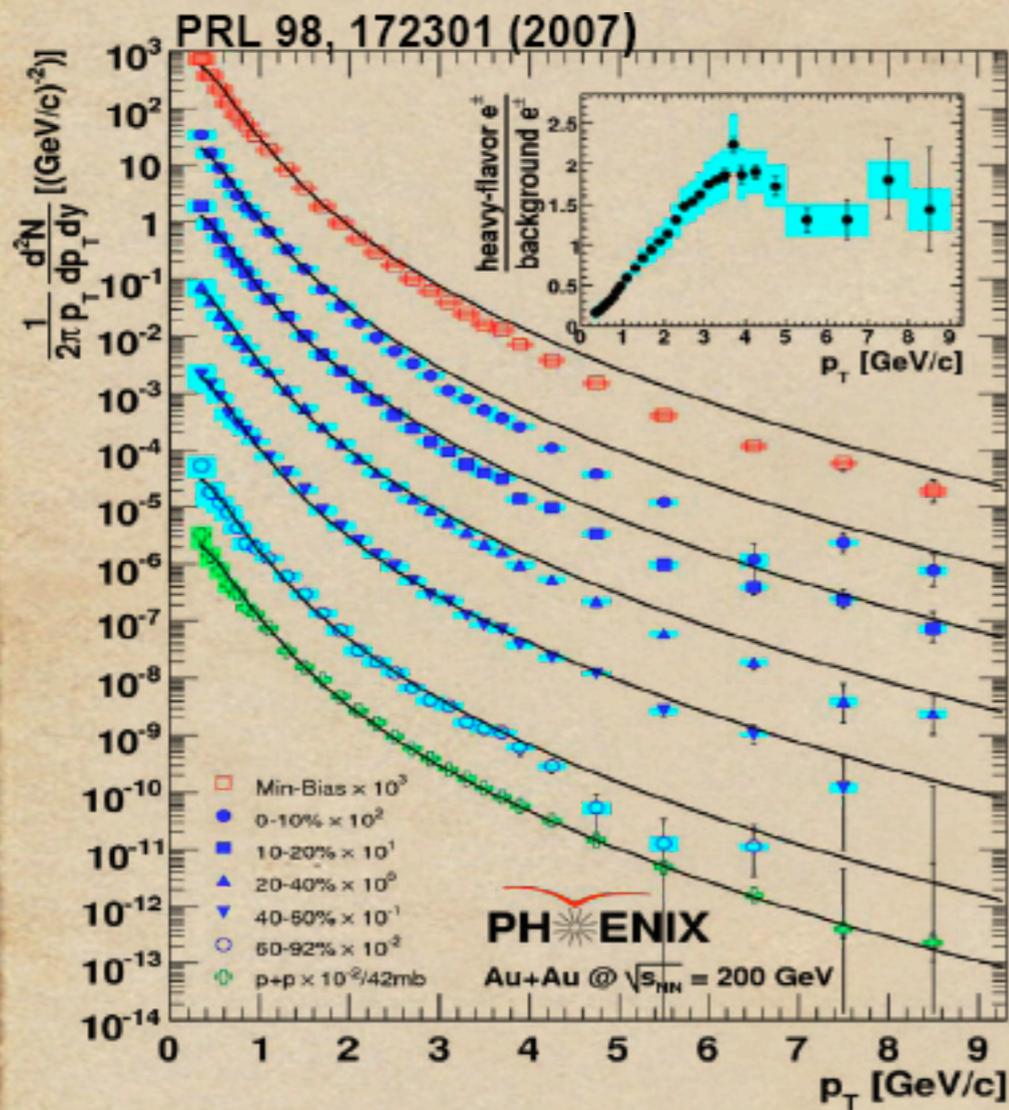
## Di-electron mass shape



	e-h correlation	di-electron
$\sigma_{cc}$	$567 \pm 57(\text{stat}) \pm 224(\text{sys}) \mu\text{b}$	$518 \pm 47(\text{stat}) \pm 135(\text{sys}) \pm 190(\text{model}) \mu\text{b}$
$\sigma_{bb}$	$4.61 \pm 1.31(\text{stat})^{+2.57}_{-2.22}(\text{sys}) \mu\text{b}$	$3.9 \pm 2.5(\text{stat})^{+3}_{-2}(\text{sys}) \pm 1.4(\text{model}) \mu\text{b}$

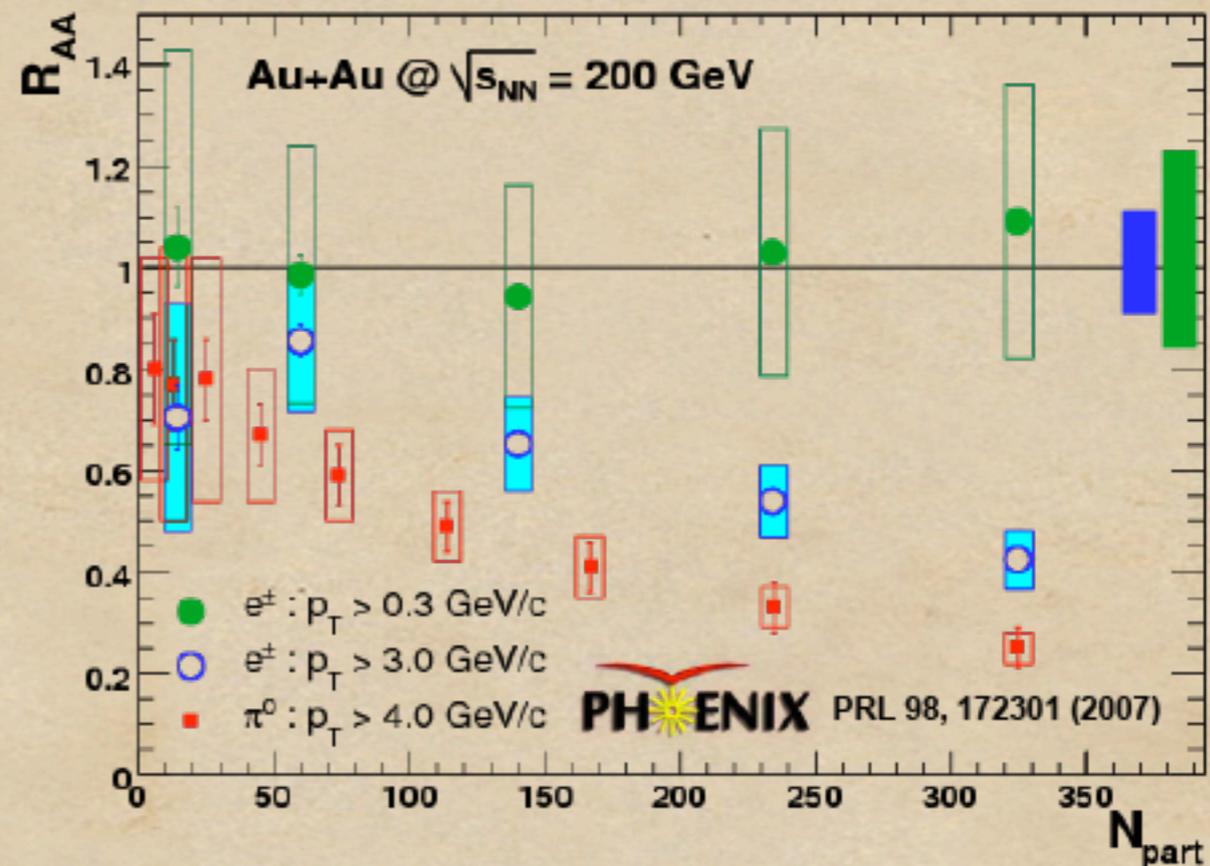
Better measurement w/ future Silicon  
Vertex Detector

# HQ production in Au+Au at $s^{1/2}=200$ GeV



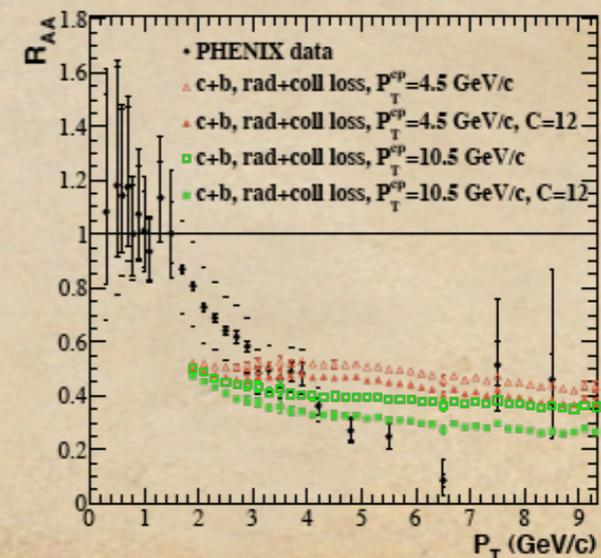
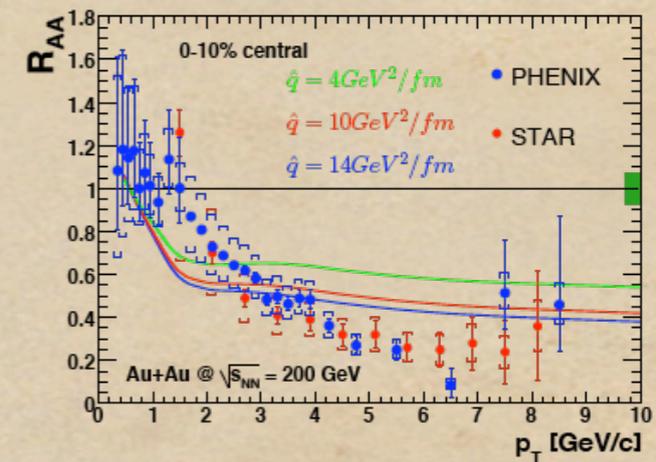
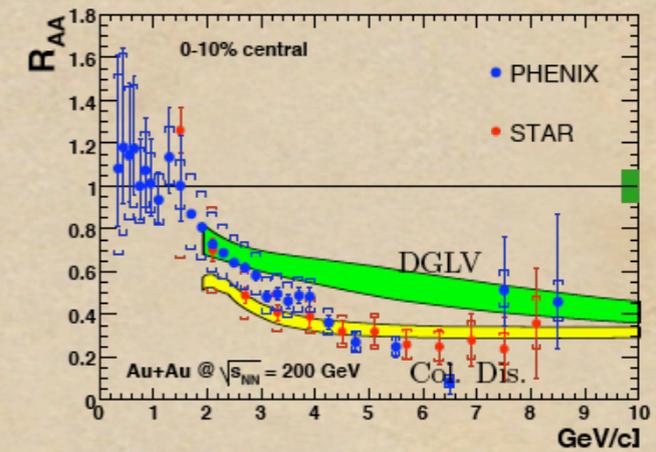
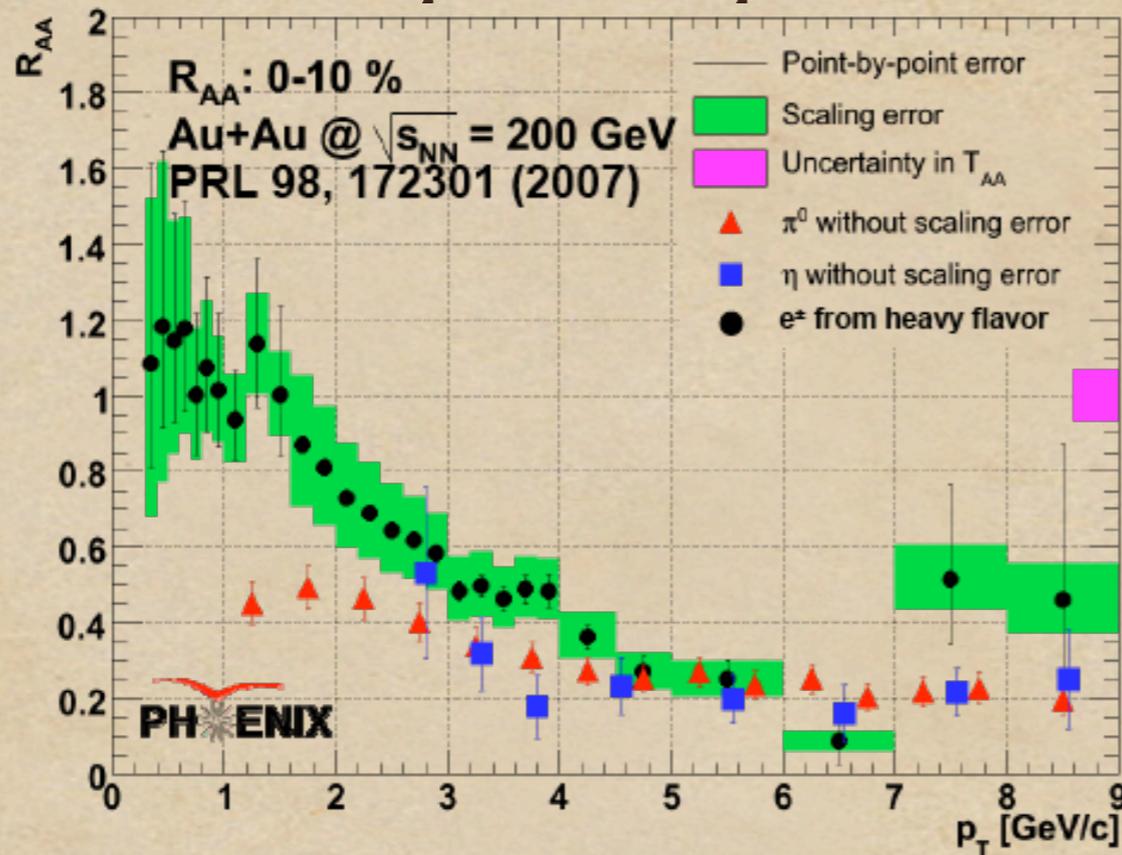
Nuclear Modification Factor

$$R_{AA} = \frac{dN_{Au+Au}}{\langle T_{AA} \rangle \times d\sigma_{p+p}}$$



- ~ Binary scaling works for total non-photonic electrons as expected from heavy quarks produced by hard scattering
- ~ yield suppressed for high  $p_T$  indicating medium effects in HQ yield

# $p_T$ dependence of $R_{AA}$



~ intermediate  $p_T$  suppression compatible with scenario where the radiative energy loss is larger for light mesons

(Dokshitzer and Kharzeev, PLB 519(2001)199)

~ theoretical challenge to describe high  $p_T$

~ elastic contribution in radiation - PLB 632(2006)81, PLB 637(2006)362

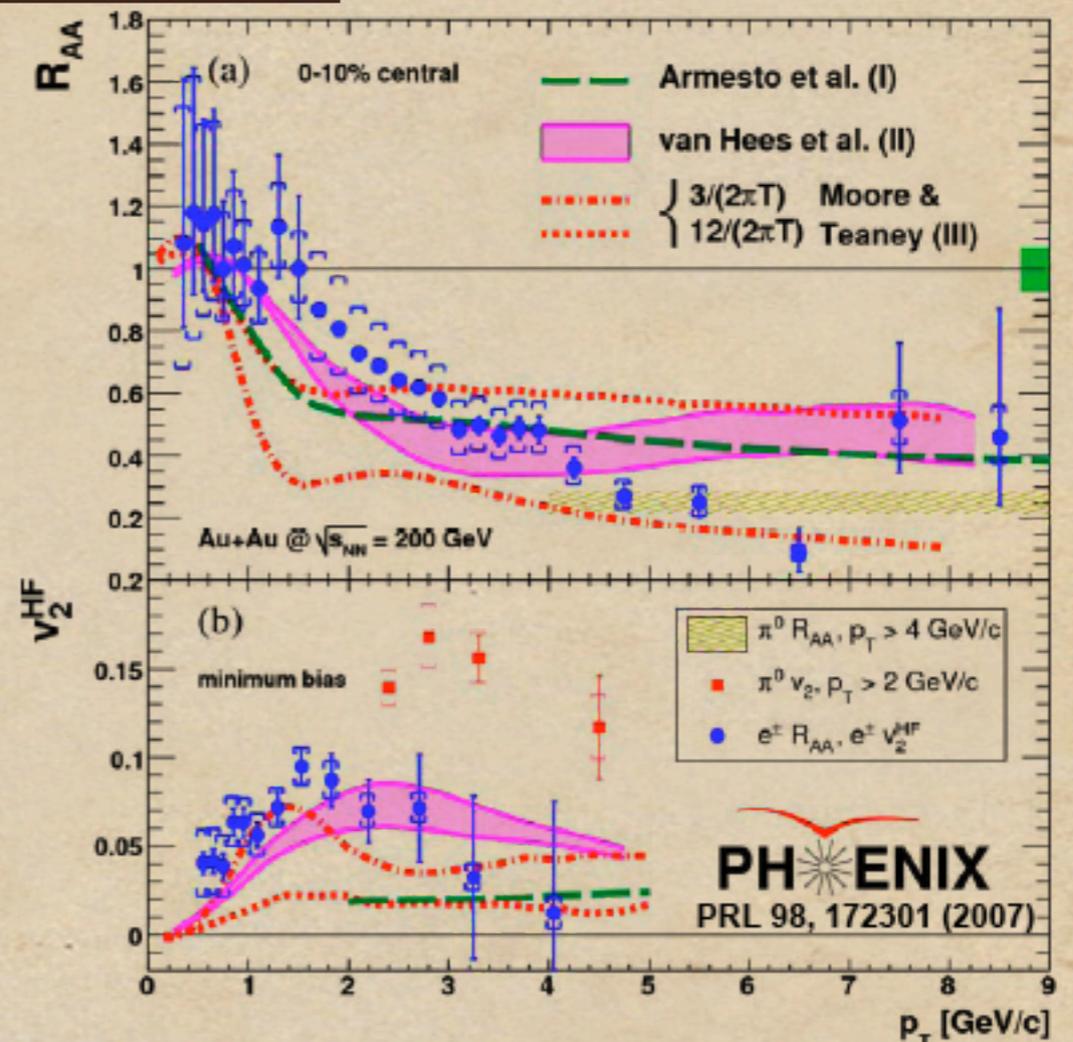
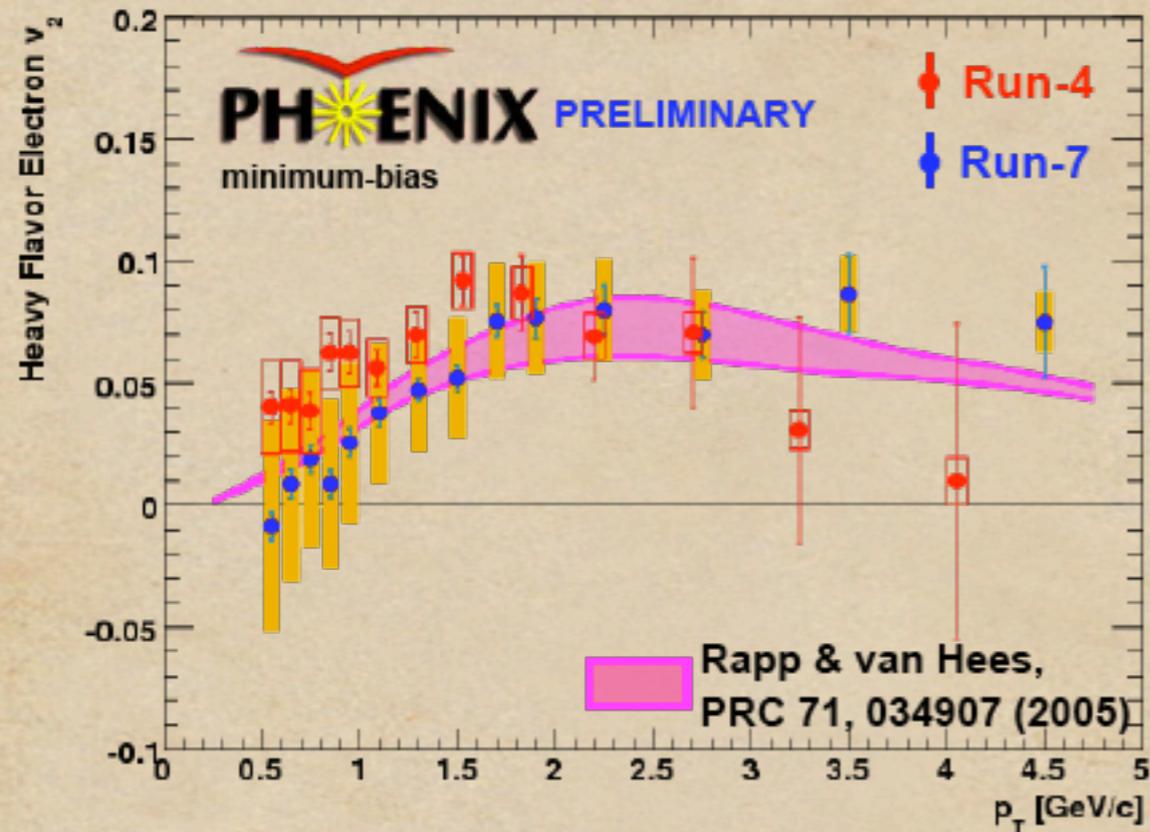
~ collisional included - NPA 784(2007)426, PRC 73(2006)034913

~ collisional dissociation of heavy mesons - PLB 649(2007)139

~ baryon enhancement - PRC 74(2006)024902

~ needs to distinguish charm and bottom contributions

# HQ Elliptic Flow



Transport models try to describe suppression and elliptic flow simultaneously

~ Rapp & Van Hees - PRC 71, 034907 (2005)

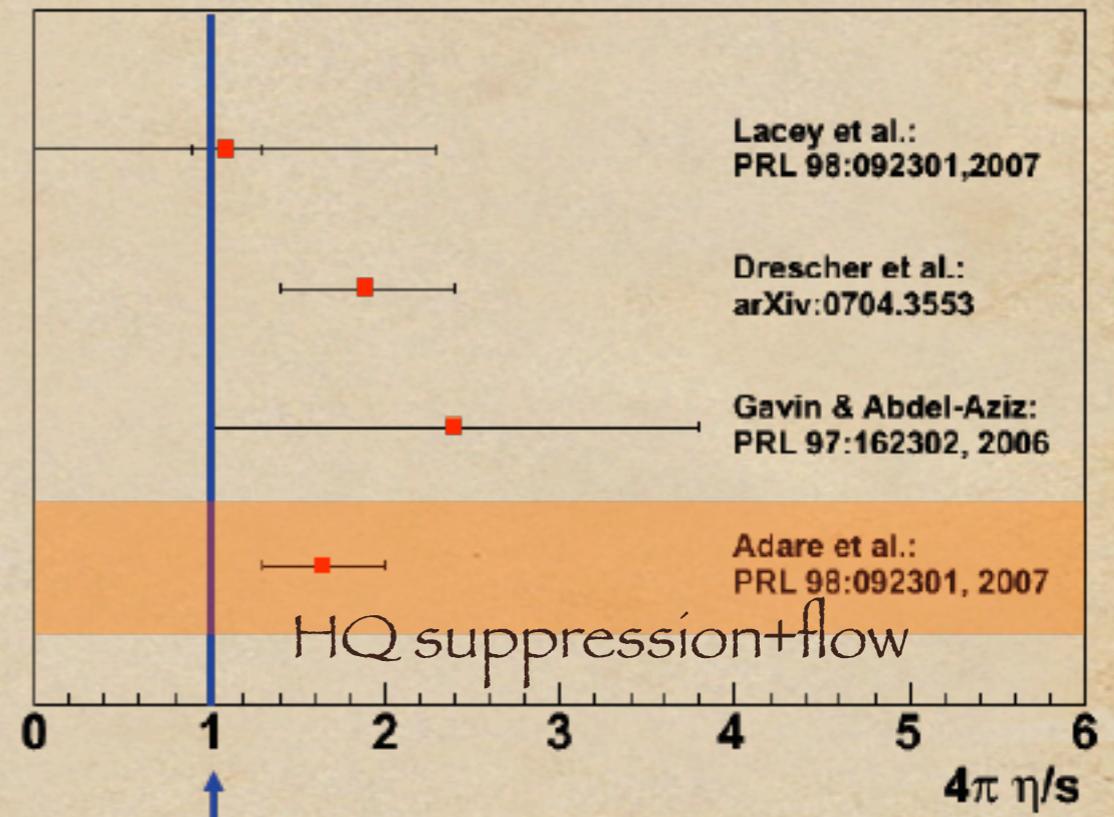
~ Moore & Teaney - PRC 71, 064904 (2005)

The models extracted from data can be used to calculate viscosity/entropy of the medium formed

# Liquid perfectness at RHIC

Conjecture quantum limit motivated by AdS/CFT\* and derived by P. Kovtun, D.T. Son, A.O. Starinets (PRL 94, 111601 - 2005) for the minimum viscosity suggest

$$\frac{\eta}{s} \geq \frac{\hbar}{4\pi}$$



Viscosity/entropy suggested by HQ measurement and transport models is

$$\eta/s_{\text{calculation using HQ}} \approx (1.3-2.0)/4\pi$$

This estimation agrees with other estimations at RHIC.

For comparison

~ for water at normal conditions is  $380 \hbar/4\pi$

~ for helium is  $> 9 \hbar/4\pi$

\* AdS/CFT stands for Anti de Sitter space / Conformal Field Theory, first mentioned in (J. Maldacena: Adv. Theor. Math. Phys. 2, 231, 1998)

# Quarkonia Measurements

# Charmonium Cross Section Calculations

Binding energy are not large enough to allow a perturbative calculation.

Methods to calculate the cross section include:

~ Non-relativistic QCD (NRQCD) :  $\sigma_{ij}(\hat{s}, Q^2) = \sum_n \frac{C_n(\Lambda)}{m_{d_n}^4} \langle \mathcal{O}_n^H(\Lambda) \rangle$   
 PLB167 (1986) 437, PRD43 (1991) 196, empirical

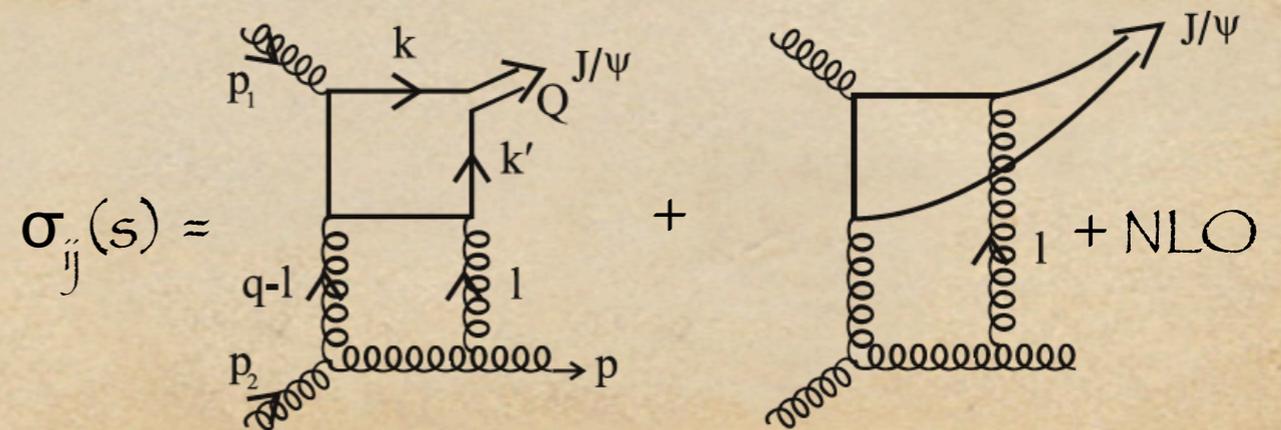
PRD51 (1995) 1125.

Effective field theory where the production is a combination of singlet and octet states.

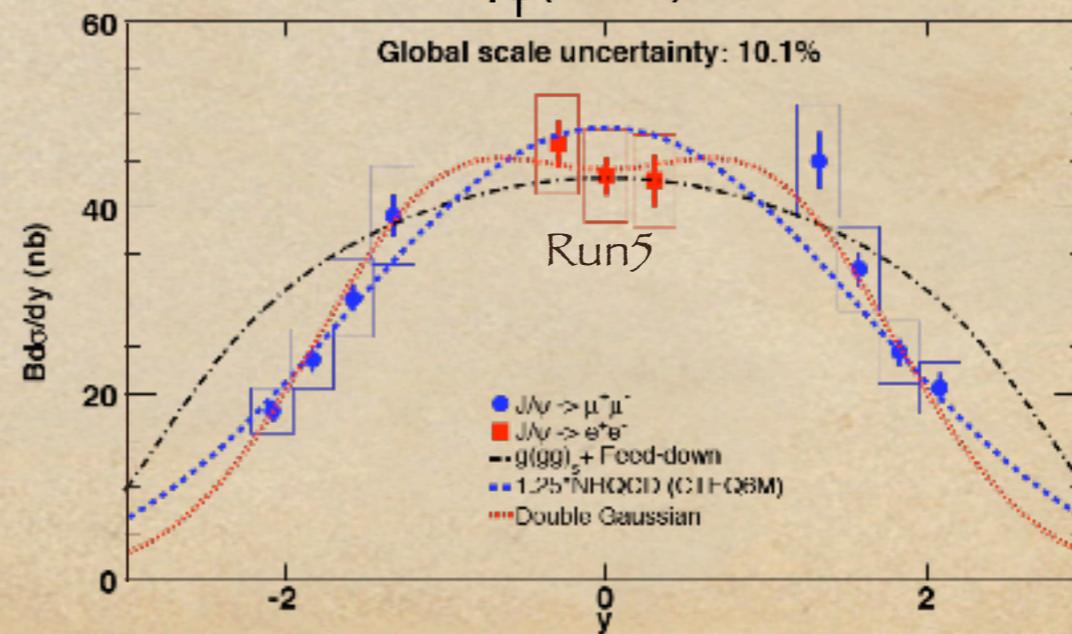
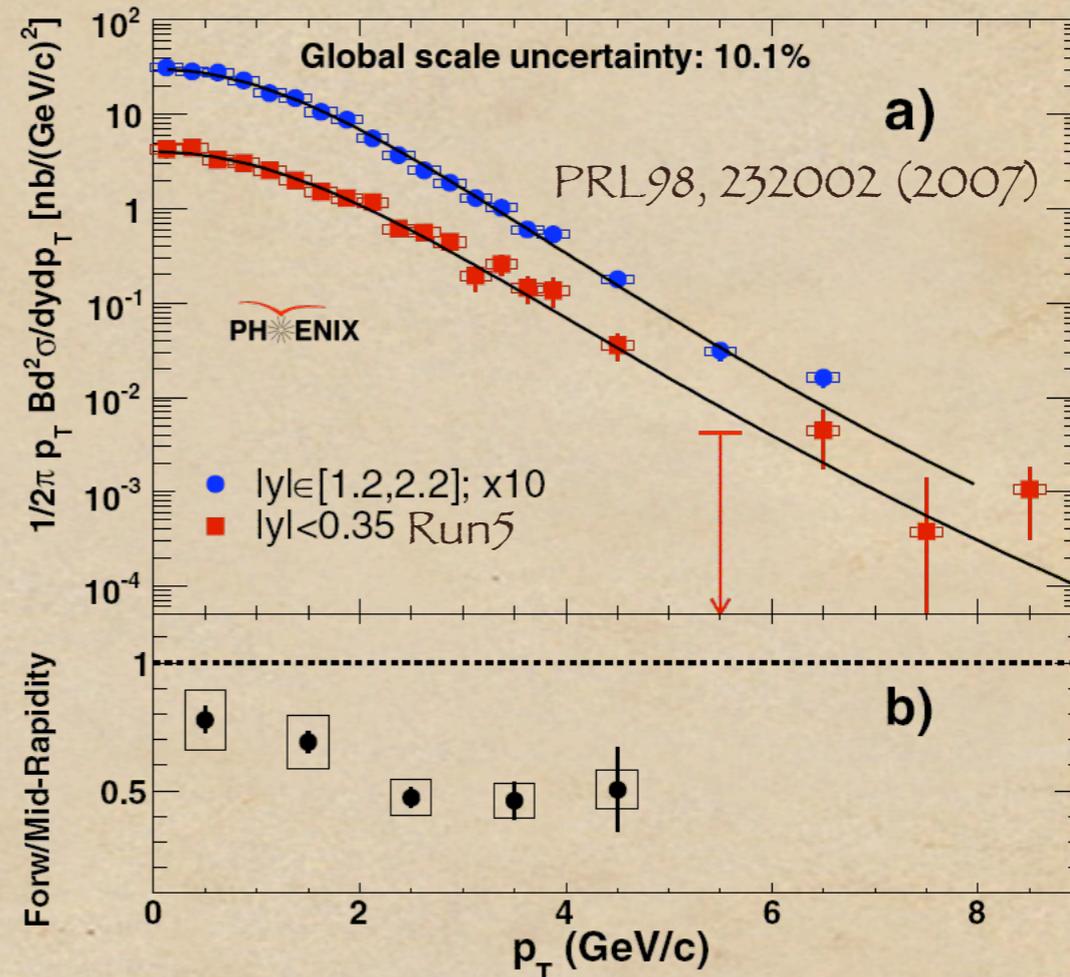
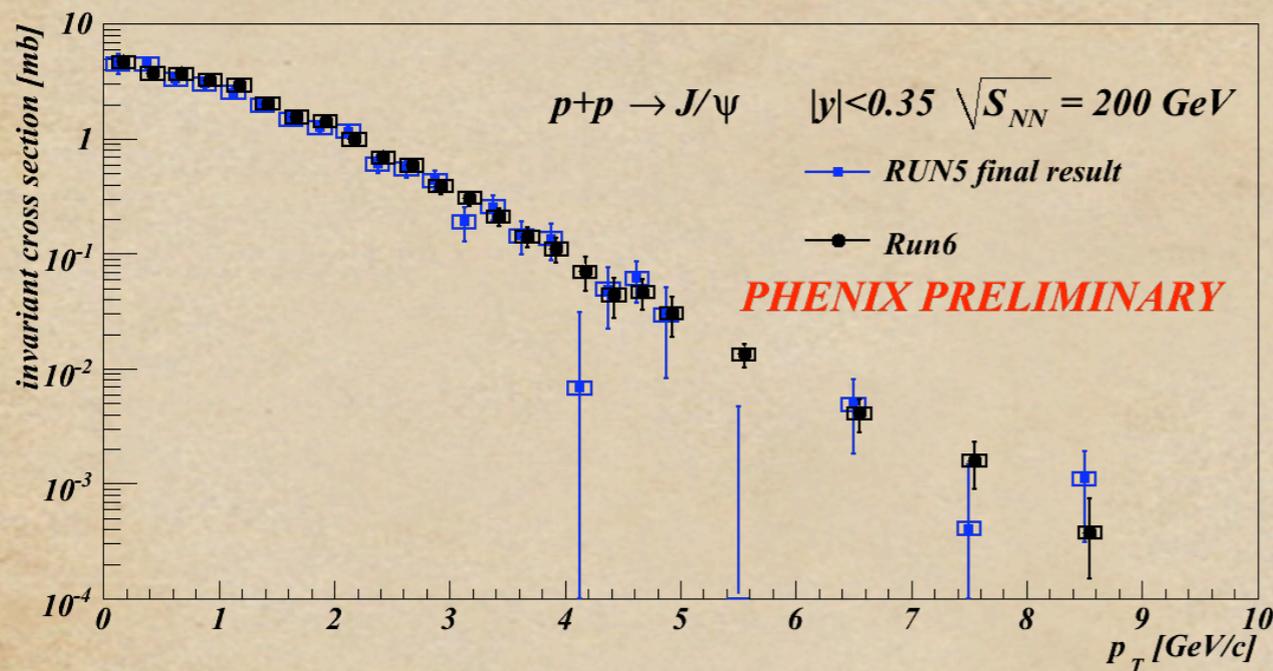
~ Color Evaporation Model (CEM) :  $\sigma_{ij}(\hat{s}, Q^2) = F_H \int_{2m_c}^{2m_D} d\hat{s} \frac{d\sigma_{ij}(\hat{s}, Q^2)}{d\hat{s}}$   
 Int. J. Mod. Phys. A 10 (1995) 3043 empirical pQCD

Production is a empirical fraction of QQ heavy quark cross section integrated over  $2m_c$  and  $2m_D$ . Color octet turns to singlet by soft gluon evaporation.

~ pQCD w/ 3-gluon fusion :  
 Eur. Phys. J. C 39, 163-171 (2005)  
 Formation done by  $(gg)_8 + g$  fusion.  
 Complete perturbative treatment.



# J/ψ in p+p collisions at $s^{1/2}=200$ GeV

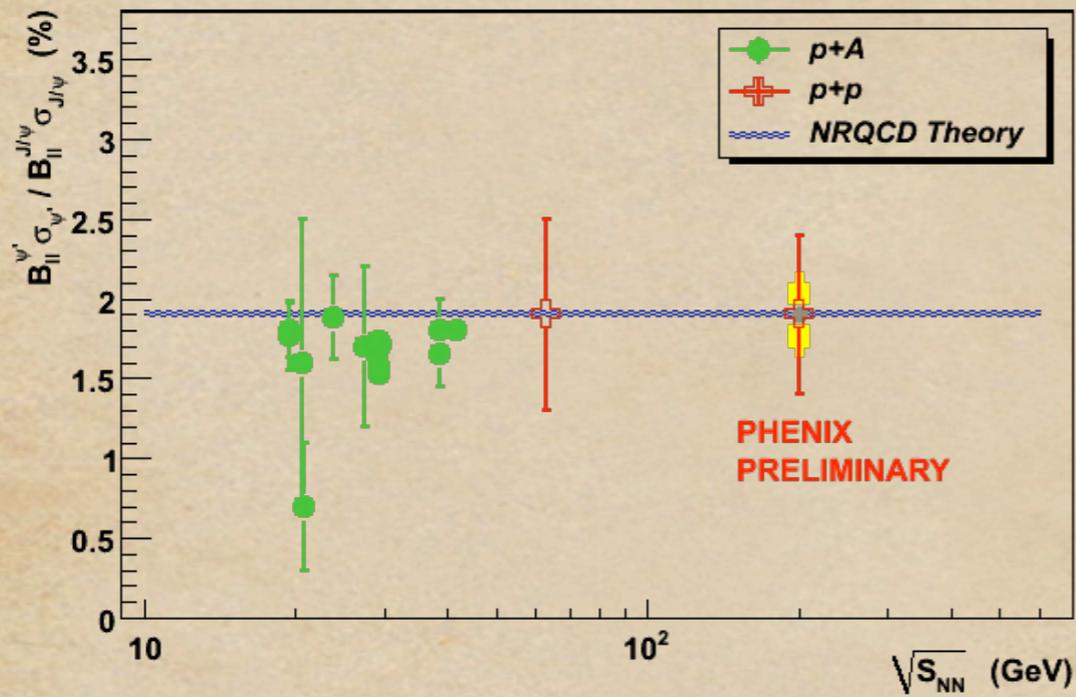


- ~ Brand new yield measurement from larger luminosity Run6 agrees with published results
- ~ Total cross section calculated by integration of different fits to  $y$  dependence
- ~ Inclusive measurement: includes feed down
- ~ Different models fit to the p+p data returning a total cross section:

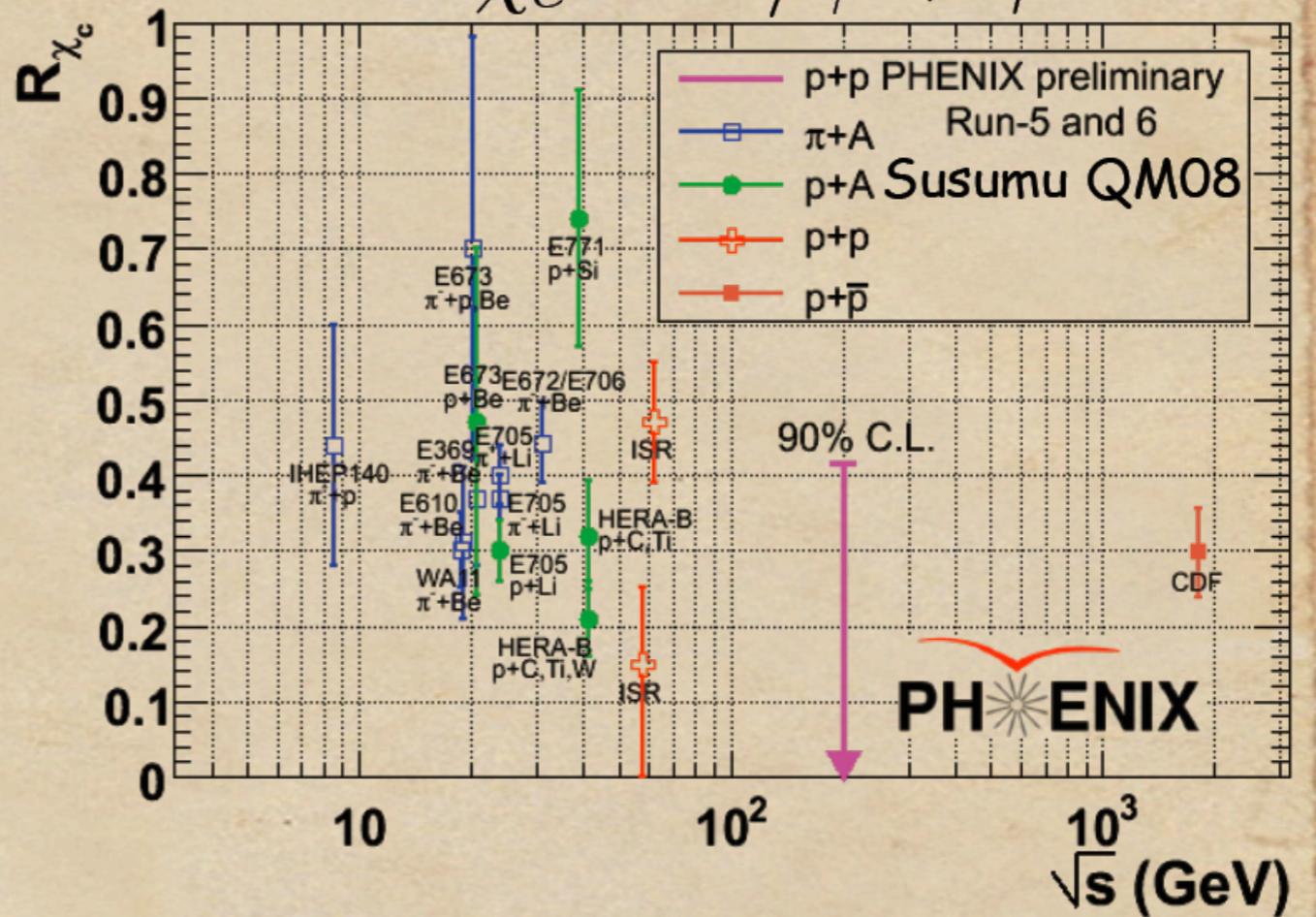
$$\text{BR}_{\parallel} \sigma_{pp} (p+p \rightarrow J/\psi + X) = 178 \pm 3 (\text{stat}) \pm 53 (\text{sys}) \pm 18 (\text{norm}) \text{ nb}$$

# Feed down contribution to $J/\psi$

$$\psi' \rightarrow e^+e^-$$



$$\chi_c \rightarrow J/\psi + \gamma$$



e-h correlation  $\rightarrow$  B cross section

$$\sigma_{b\bar{b}} = 4.61 \pm 1.31(stat)^{+2.57}_{-2.22} nb$$

$$BR(b \rightarrow J/\psi + X) = 1.16 \pm 0.10\%$$

decay	PHENIX	theory
$\psi' \rightarrow J/\psi$	$0.086 \pm 0.025$	$0.08^*$
$\chi_c \rightarrow J/\psi$	$< 0.42$ (90% CL)	$0.30^*$
$B \rightarrow J/\psi$	$0.036^{+0.025}_{-0.023}$	$0.02 \pm 0.01^{**}$

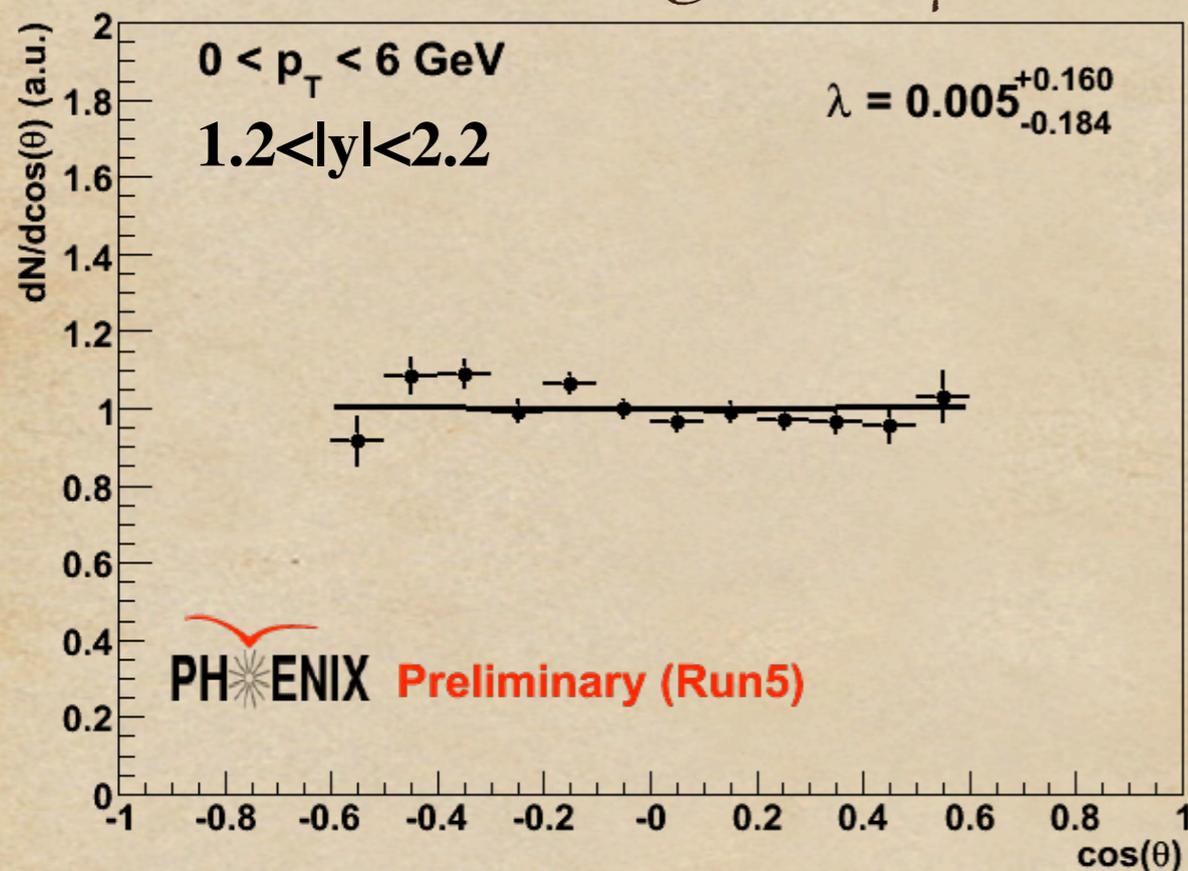
# Polarization in p+p collisions

$$dN/d\cos(\theta) = A[1 + \lambda \cos^2\theta]$$

$\theta$  = angle between  $l^+$  and  $J/\psi$  direction in its rest frame

$\lambda > 0$  transverse polarization

$\lambda < 0$  longitudinal polarization



~ NRQCD predicts:

~ transverse for octet states with  $p_T \gg M_{J/\psi}$

~ longitudinal for singlet states with  $p_T \gg M_{J/\psi}$

~ CEM expect no polarization.

~ 3-gluon fusion expect transverse polarization

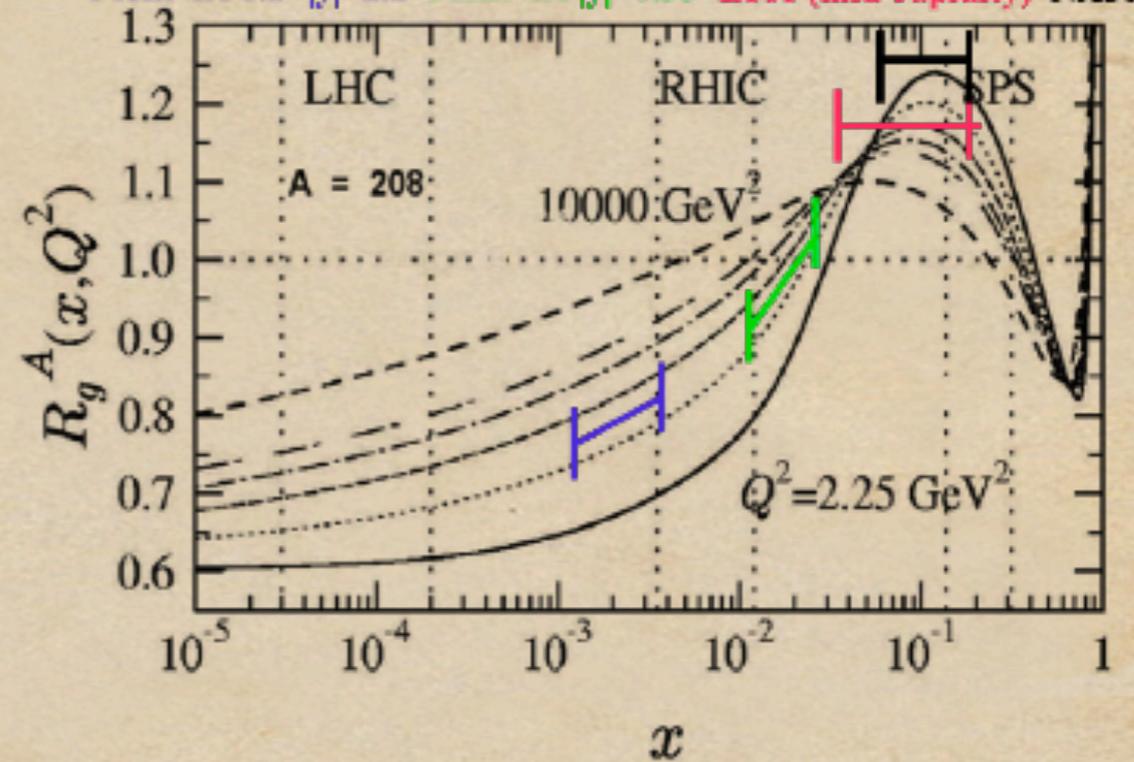
~ for low  $p_T$  and longitudinal for  $p_T \gg M_{J/\psi}$

Needs more statistics, principally for  $p_T \gg M_{J/\psi}$  to disentangle production mechanisms

# J/ψ in AA collisions

K.J.Eskola, V.J.Kolhinen, R. Vogt, *Nucl.Phys. A696,729*

PHENIX  $1.2 < |y| < 2.2$  PHENIX  $|y| < 0.35$  E866 (mid-rapidity) NA50

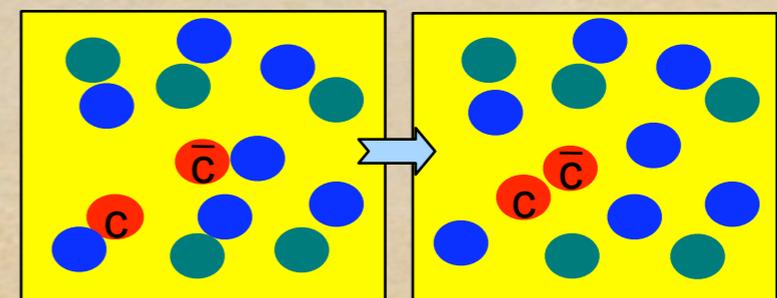
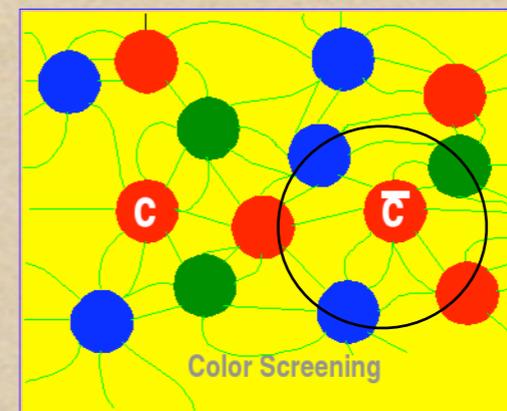


● The bound or pre-resonant charmonium state is sensitive to:

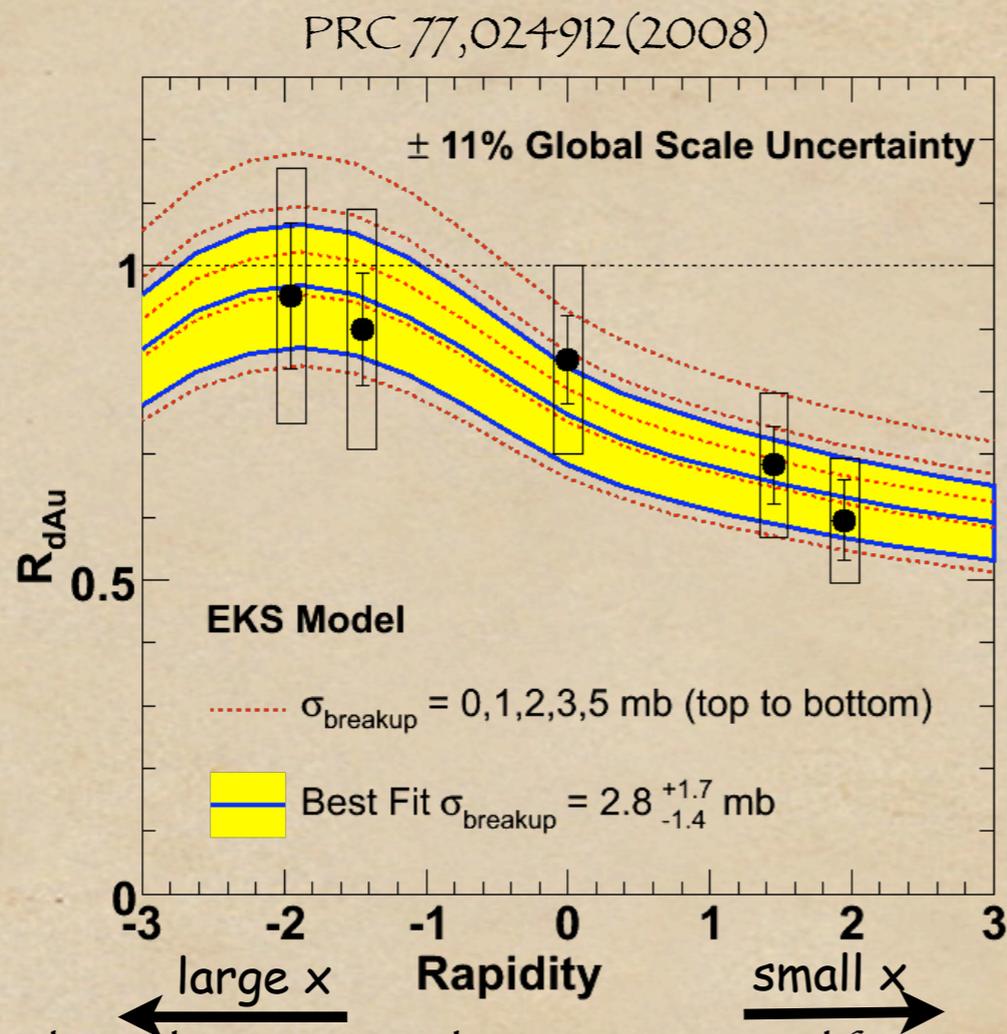
- “Cold” nuclear matter (CNM) effects
- Parton distribution modifications in nucleus
- $c\bar{c}$  breakup in hadrons

● Hot and dense matter effects, sometimes called “anomalous” effect

- Dissociation due to color screening
- Recombination of open charms in charmonium, feasible at RHIC due to the large amount of D mesons

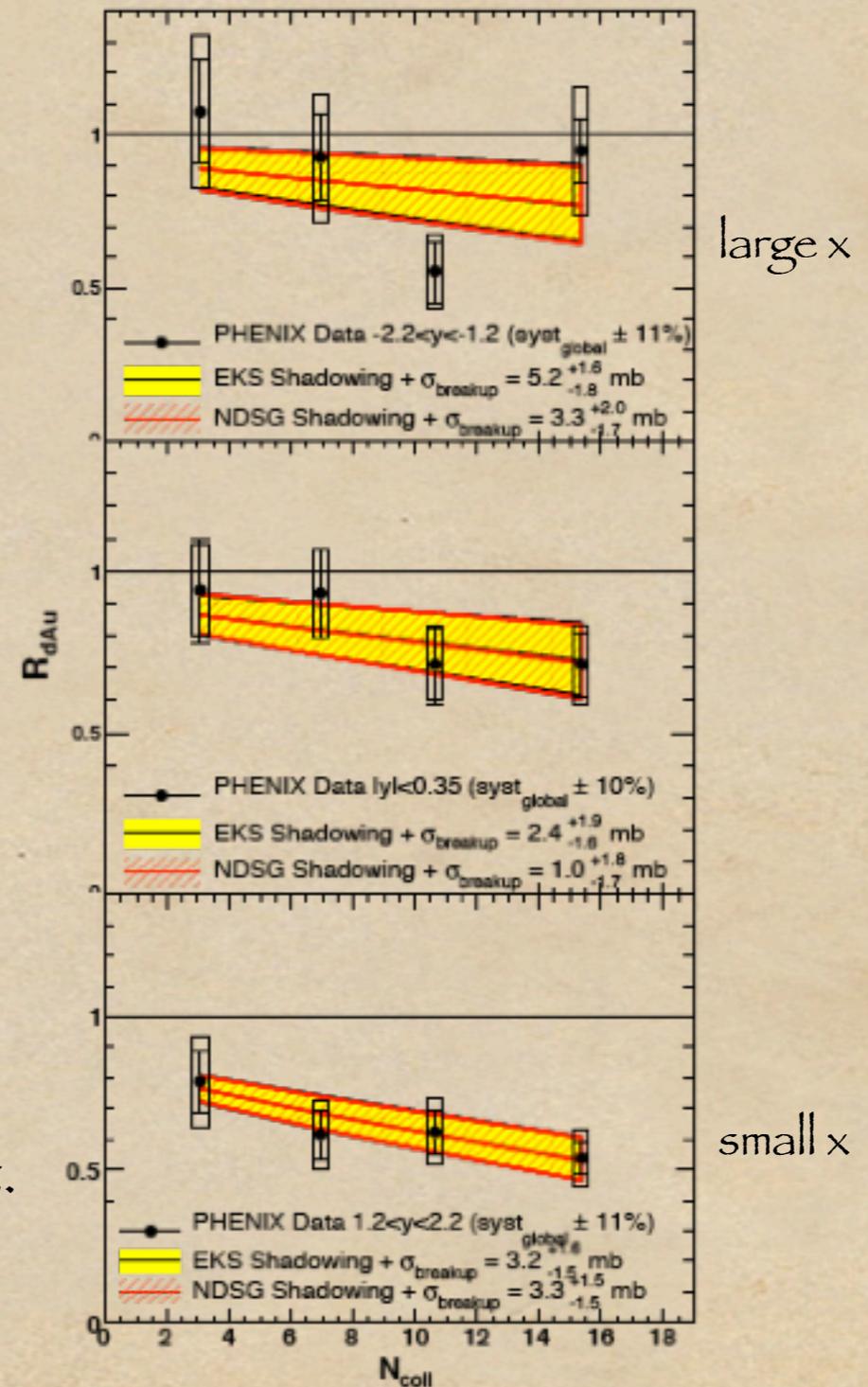


# CNM Effects measured in d+Au collisions



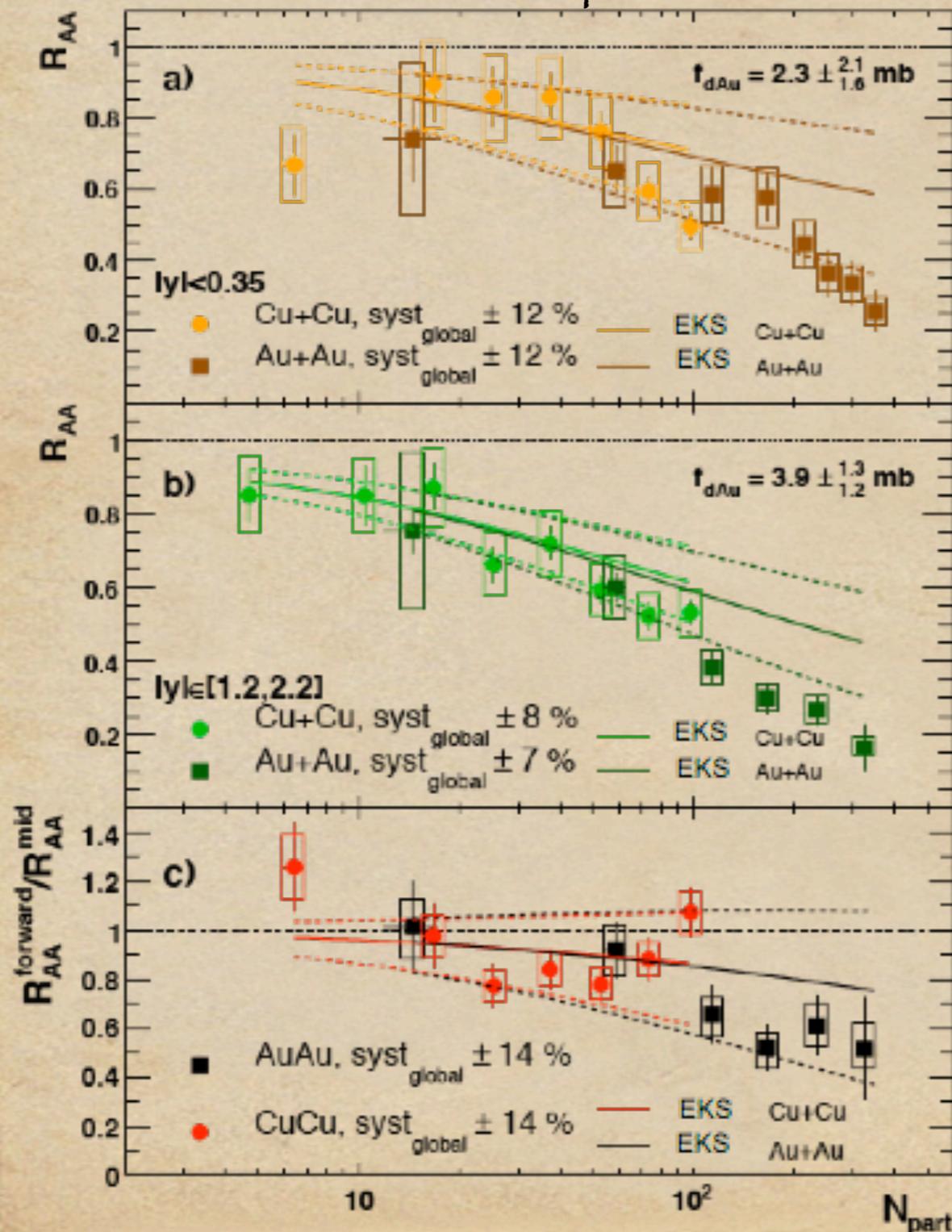
Fits based on CEM and EKS Parton modification  
[Vogt, PRC 71, 054902 (2005)]

Breakup cross section not well constrained yet.  
10x more d+Au data under analysis now



# Extrapolation of fitted CNM to A+A

arxiv:0801.0220 to be published in PRL

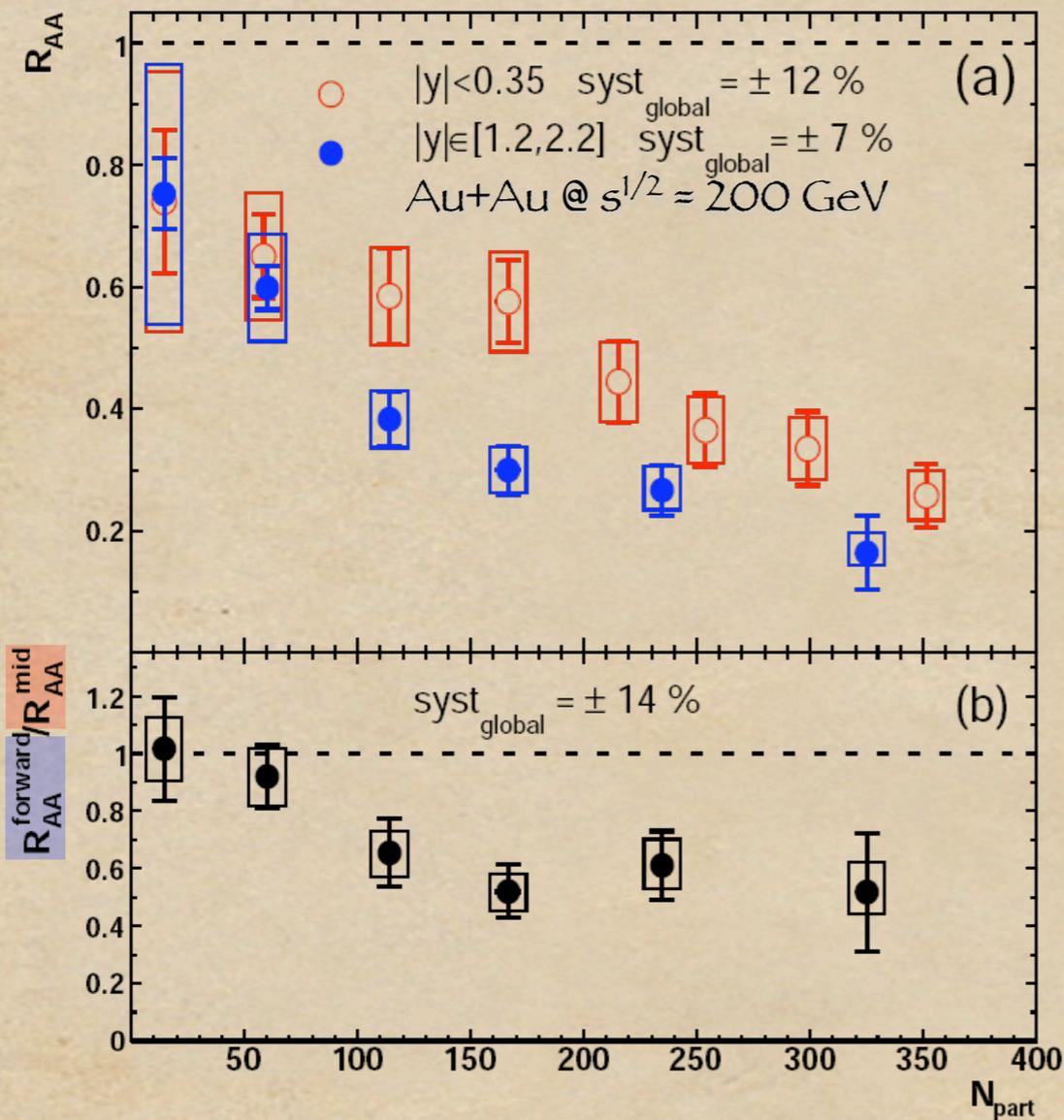


$f_{dAu}$  = breakup(absorption) cross section

- ~ good agreement btw. Cu+Cu and Au+Au  $R_{AA}$
- ~ there is a large room for CNM effects
- ~ anomalous suppression is considerable at least at forward rapidity
- ~ but the CNM is not enough constrained yet for a serious calculation of anomalous suppression  $R_{AA}/\text{CNM}$

# Suppression in forward and mid rapidity

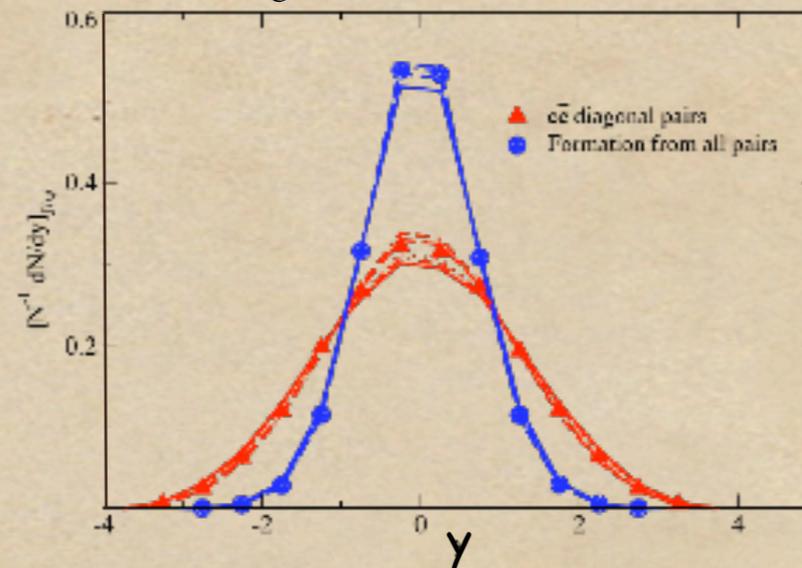
PRL 98, 232301 (2007)



Stronger suppression at forward rapidities:

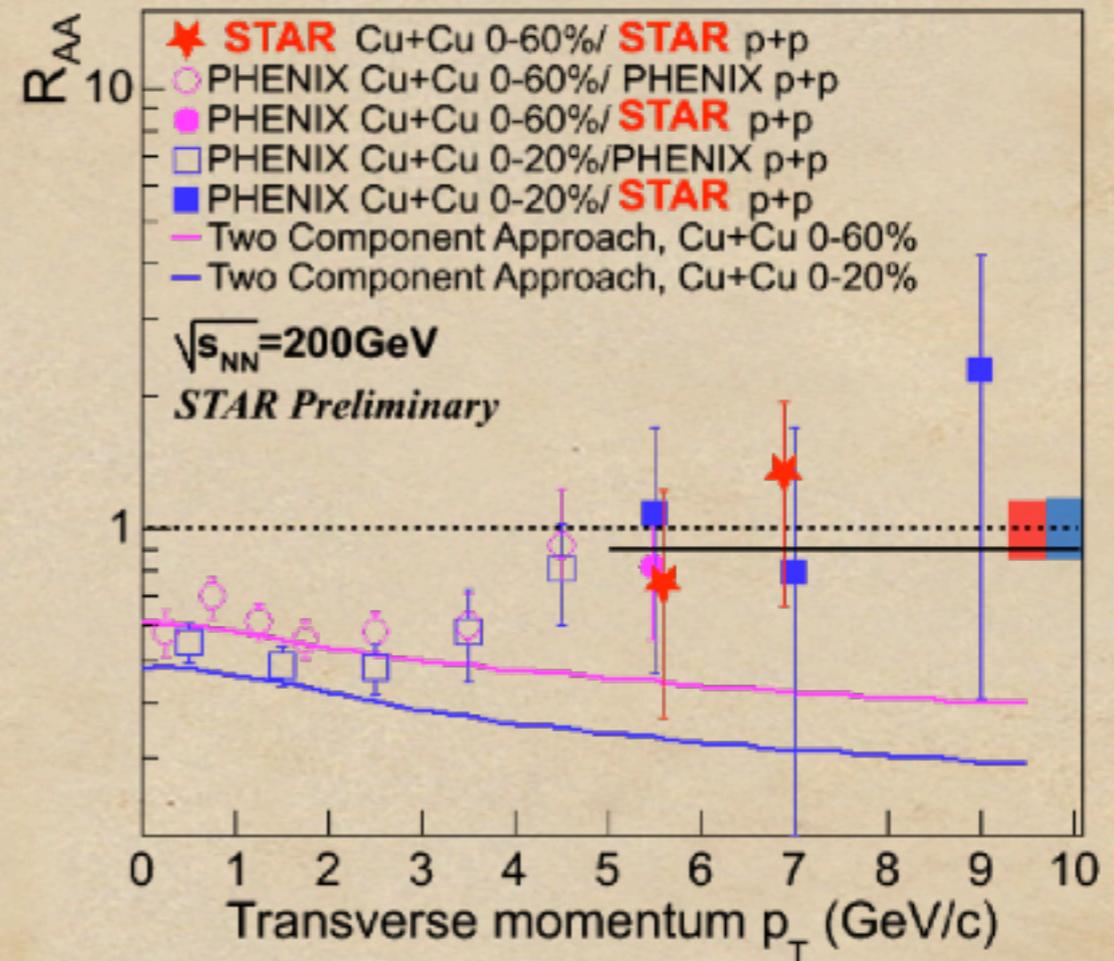
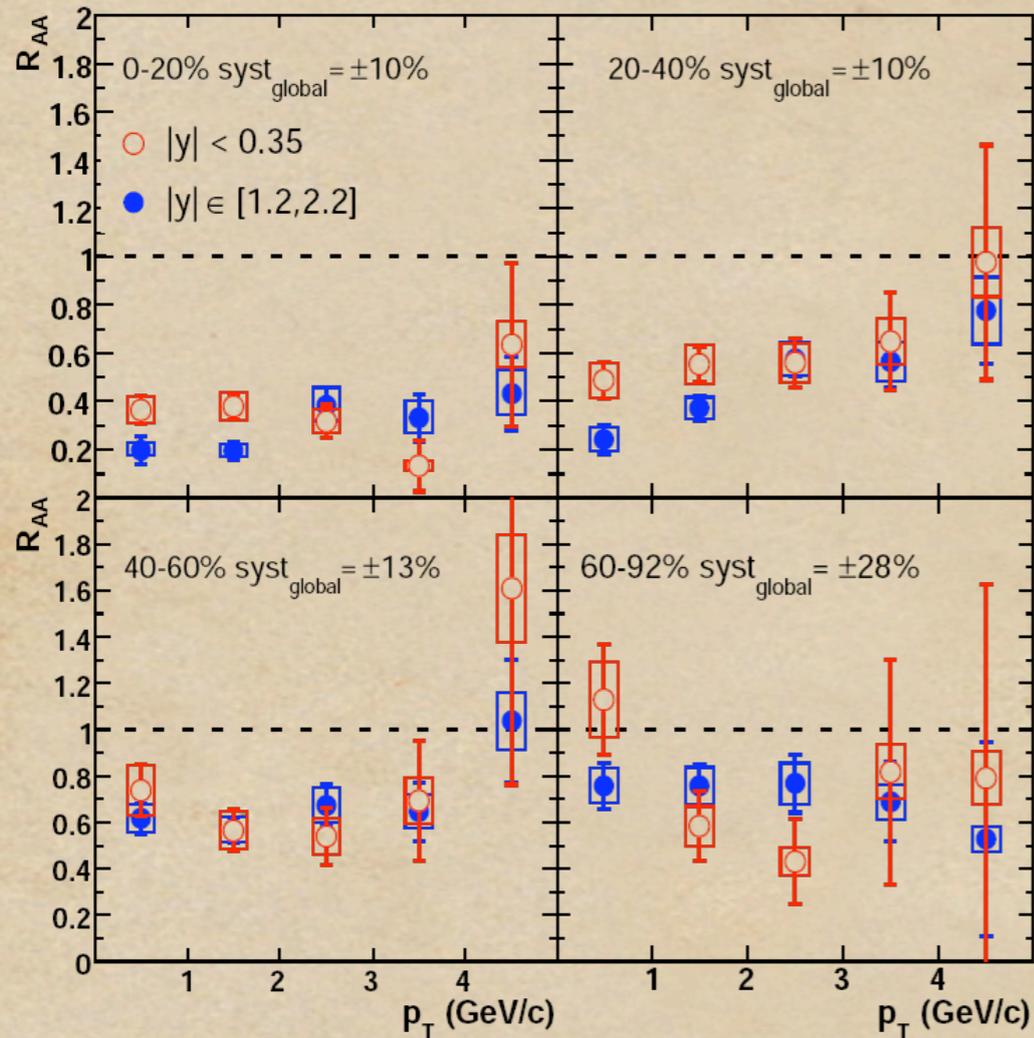
- ~ Different charmonium absorption ?
- ~ Shadowing or CGC ?
- ~ regeneration at mid-rapidity ?

R.L.Tews, Phys.Rev.C73 (2006) 014904



# $p_T$ dependence of $R_{AA}$

PRL 98, 232301 (2007)  
Au+Au @  $s^{1/2} = 200$  GeV



Behavior at high  $p_T$  can provide interesting information but currently it is inconclusive (need more statistics).

Results from Run7 with higher luminosity and released new p+p reference will give a more precise  $R_{AA} \times$  centrality  $\times$   $p_T$  picture.

# Comparison with SPS

Same suppression as found in SPS

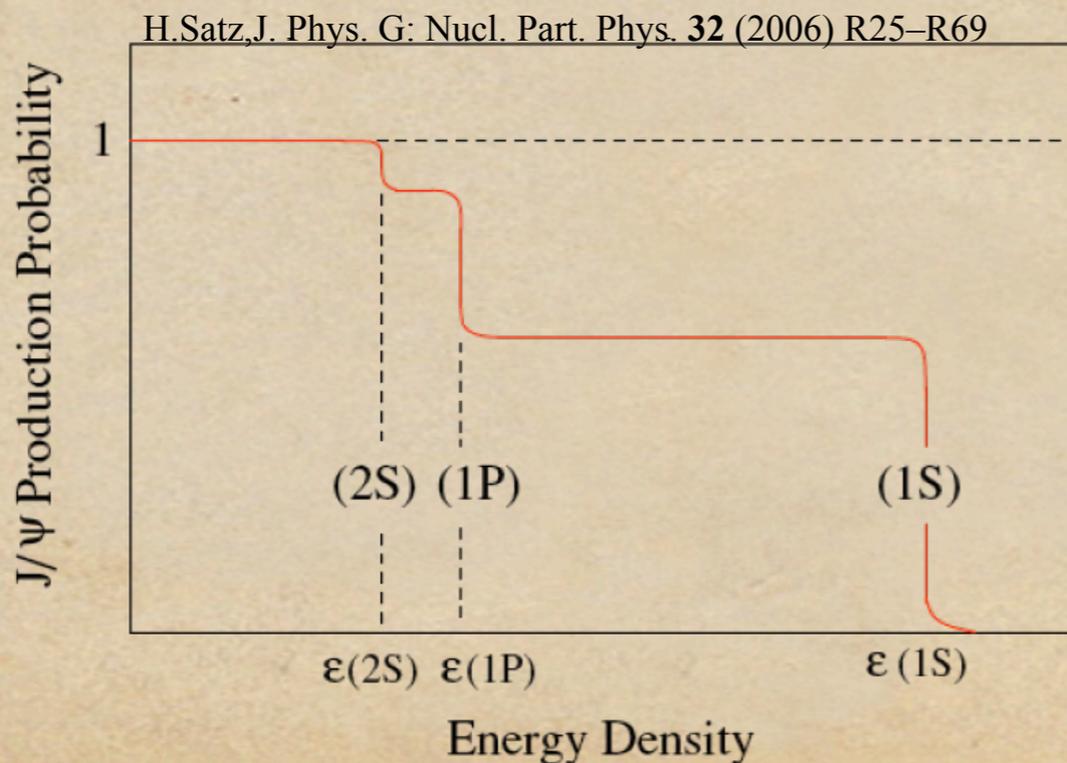
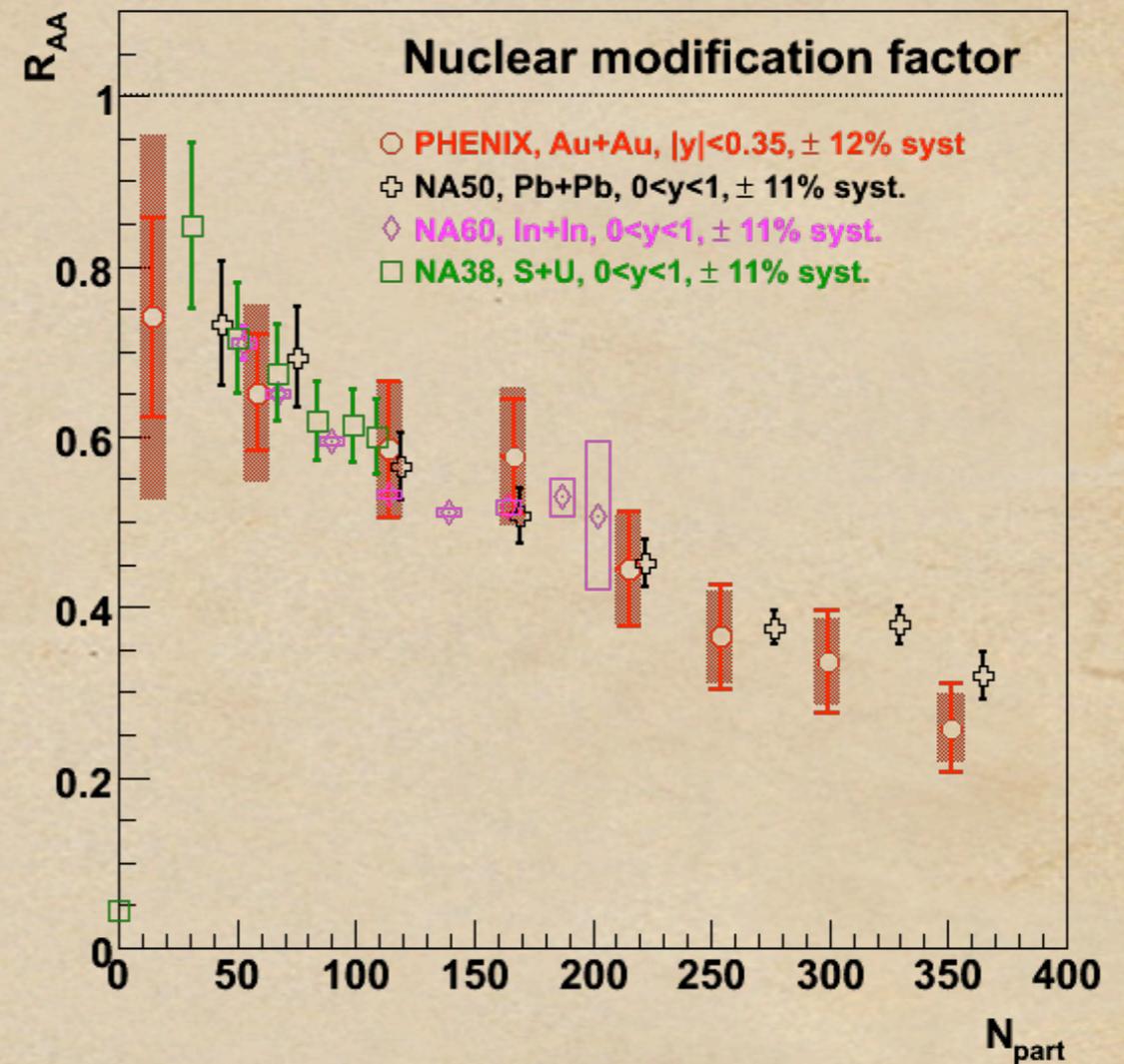
Caveat:

- ~ different CNM ?
- ~ stronger QGP suppression at RHIC ?
- ~ recombination at RHIC ?
- ~ melting of different feed down sources of  $J/\psi$ s ?

NA50 @  $\sqrt{S_{NN}} = 17\text{GeV}$

NA60 @  $\sqrt{S_{NN}} = 17\text{GeV}$

NA38 @  $\sqrt{S_{NN}} = 20\text{GeV}$

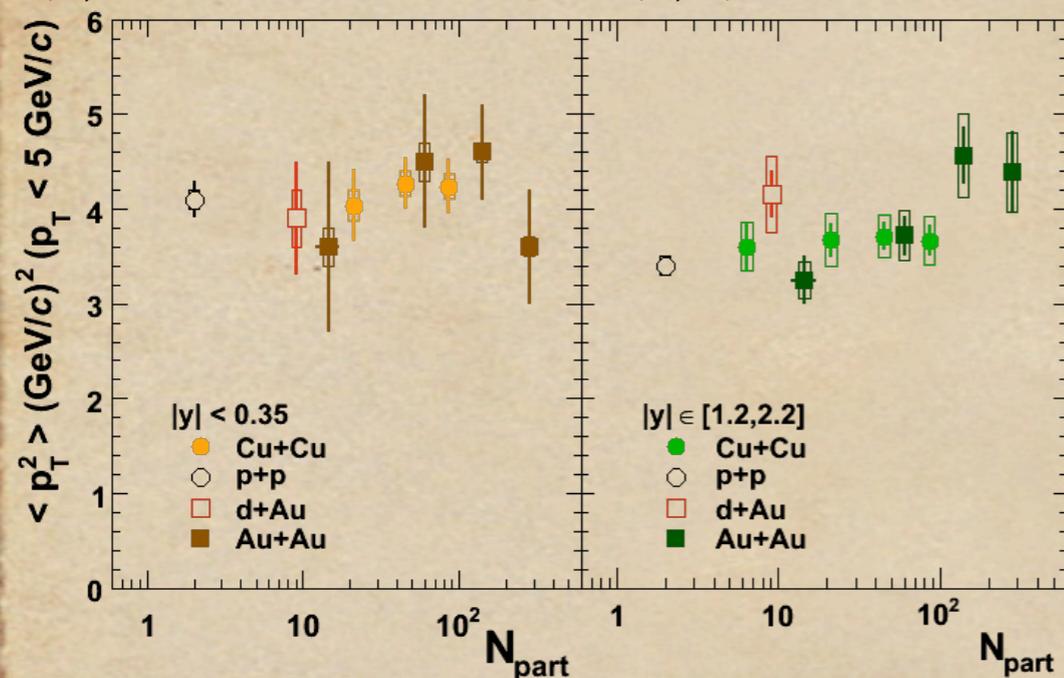


Needs  $R_{AA}(X_c)$ ,  $R_{AA}(\psi')$  measurements.

# Detecting $c\bar{c}$ recombination coalescence

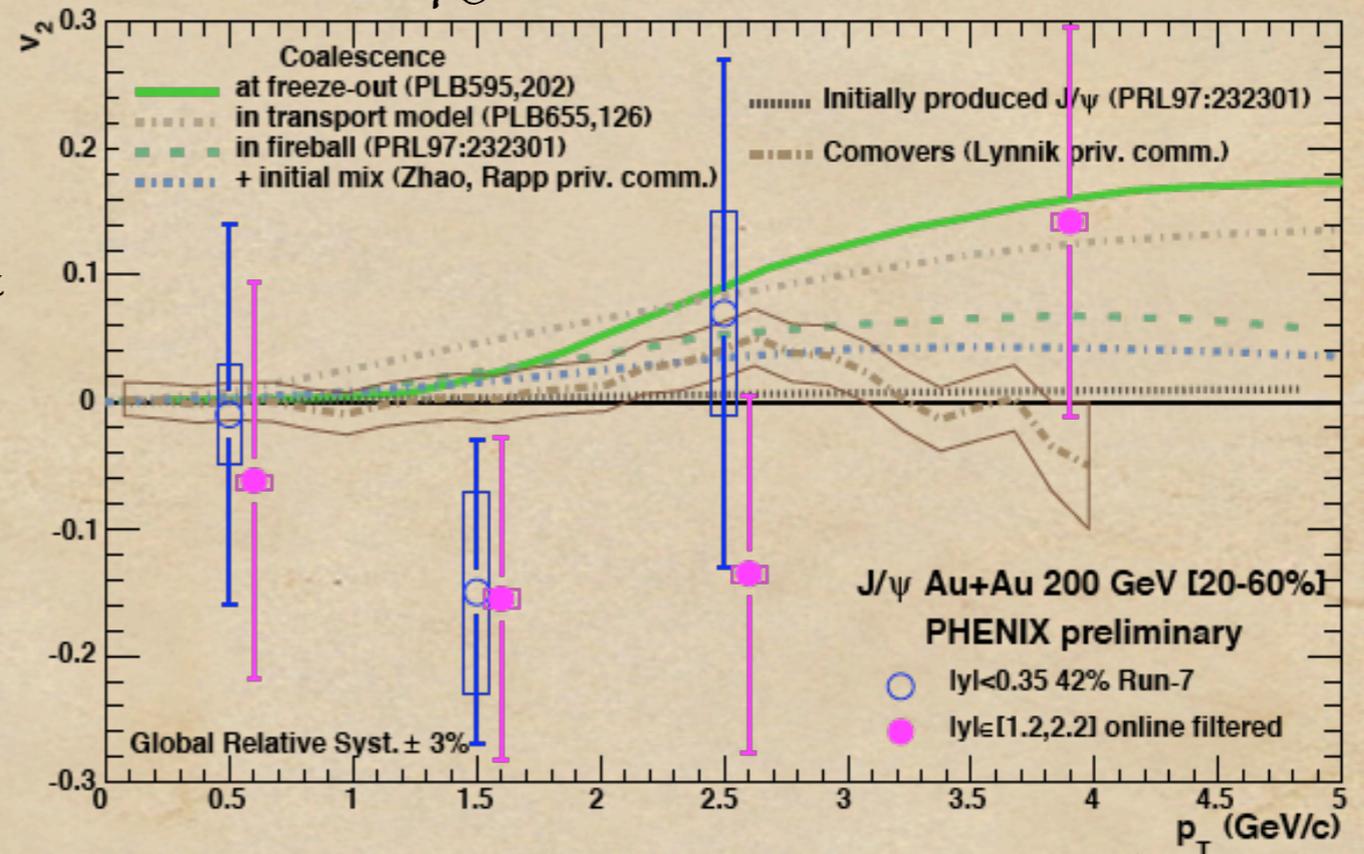
- ~ Cronin effect broaden the  $p_T$  of primary  $J/\psi$ s
- ~  $J/\psi$ s from recombined charm quarks are not affected by Cronin effect and  $\langle p_T^2 \rangle$  should be flat

$\langle p_T^2 \rangle$  obtained directly from  $p_T$  spectra  $<5\text{GeV}/c$



- ~ there is a trend for  $p_T$  broadening at forward rapidity, but not conclusive

- ~ primary  $J/\psi$ s have isotropic momentum
- ~ open charms flow
- ~  $J/\psi$ s from these charm quarks should show similar anisotropy



- ~ partial data is inconclusive regarding the coalescence

- ~ still finishing Run7 analysis and waiting for much higher luminosity at RHICII

# Conclusions and Outlook

- ~ non-photonic electron measurement provided valuable information about heavy quark production and interaction with media
- ~ remaining questions rely on fully reconstructed D and B mesons which will be feasible once the silicon vertex detector starts to operate
- ~ quarkonia production mechanism still needs more theoretical and experimental constraints to be understood
- ~ suppression has been observed but we are still learning its components:  
CNM, recombination, feed down
- ~  $R_{AA}$  measurement is not sufficient to separate the suppression components
- ~ other measurements which are on the way:
  - ~ extended momentum distributions
  - ~ elliptic flow
  - ~ polarization
- ~ suppression measurements of charmonium excited states can spot a light in production and nuclear modification mechanisms

# BACKUP SLIDES

# PHENIX-STAR HQ production in p+p

