

# Heavy Quark Measurements at RHIC by PHENIX Experiment

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# Introduction

Heavy quark production study is important for both high energy and relativistic nuclear physics

in p+p

- stringent test of pQCD
- valuable reference for heavy ion collisions

in Au+Au

- quarkonia suppression due to Debye screening a signature of QGP
- comparison to light quarks provides valuable information about QGP properties (e.g. strong coupling of the medium)

*In this talk:*

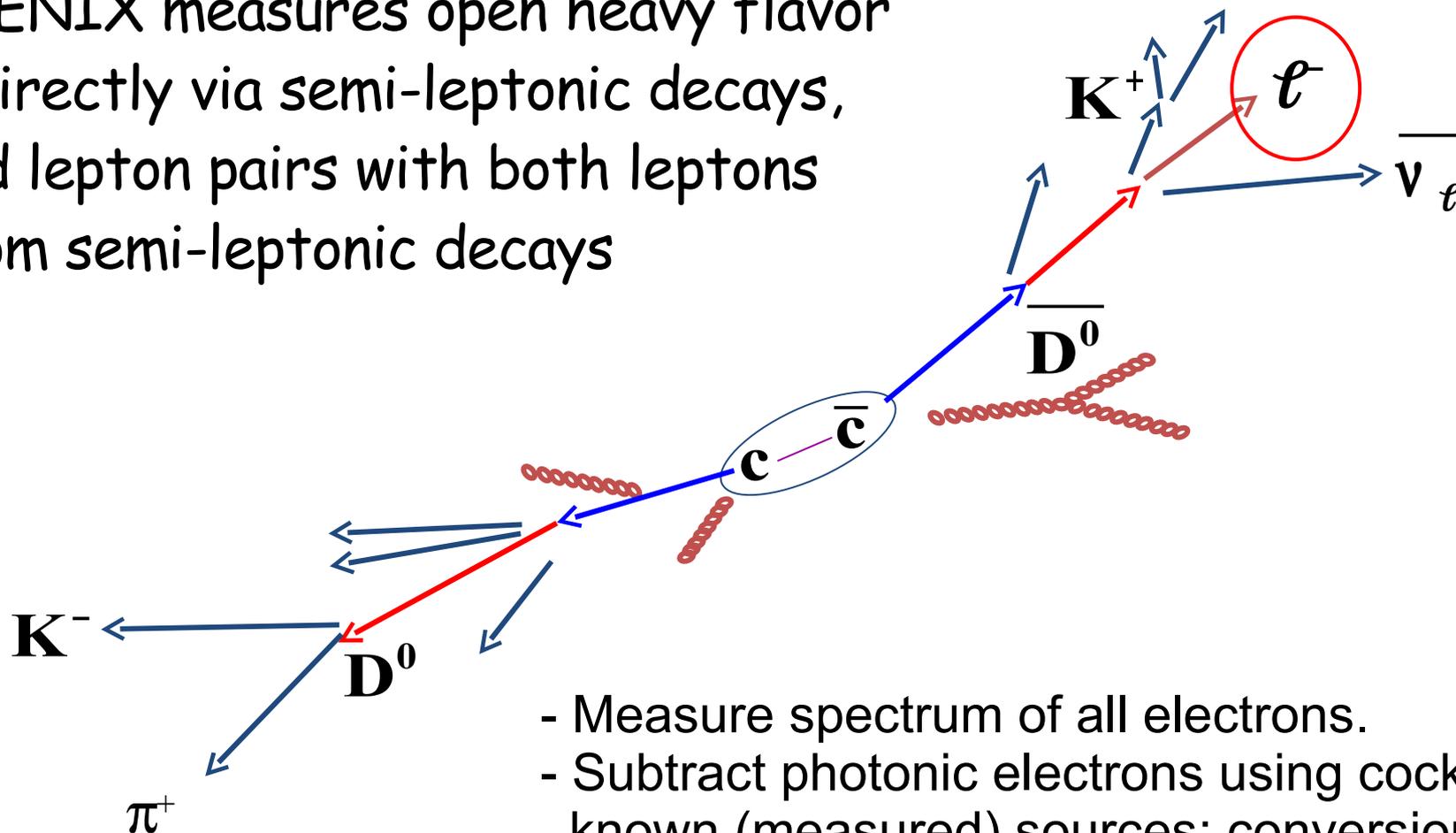
- *Open heavy flavor and quarkonia in leptonic channel by PHENIX*
- *Emphasis on p+p collisions with some glimpses of Au+Au*



# Open Charm and Beauty

# Open Heavy Flavor Measurement in PHENIX

PHENIX measures open heavy flavor indirectly via semi-leptonic decays, and lepton pairs with both leptons from semi-leptonic decays



- Measure spectrum of all electrons.
- Subtract photonic electrons using cocktail of known (measured) sources: conversions, Dalitz decays of  $\pi^0$  and  $\eta$ , etc.
- Additional subtraction of quarkonia contribution.
- Cross-check of photonic contribution by inserting converter.

# Heavy Flavor Electrons

Good agreement with FONLL

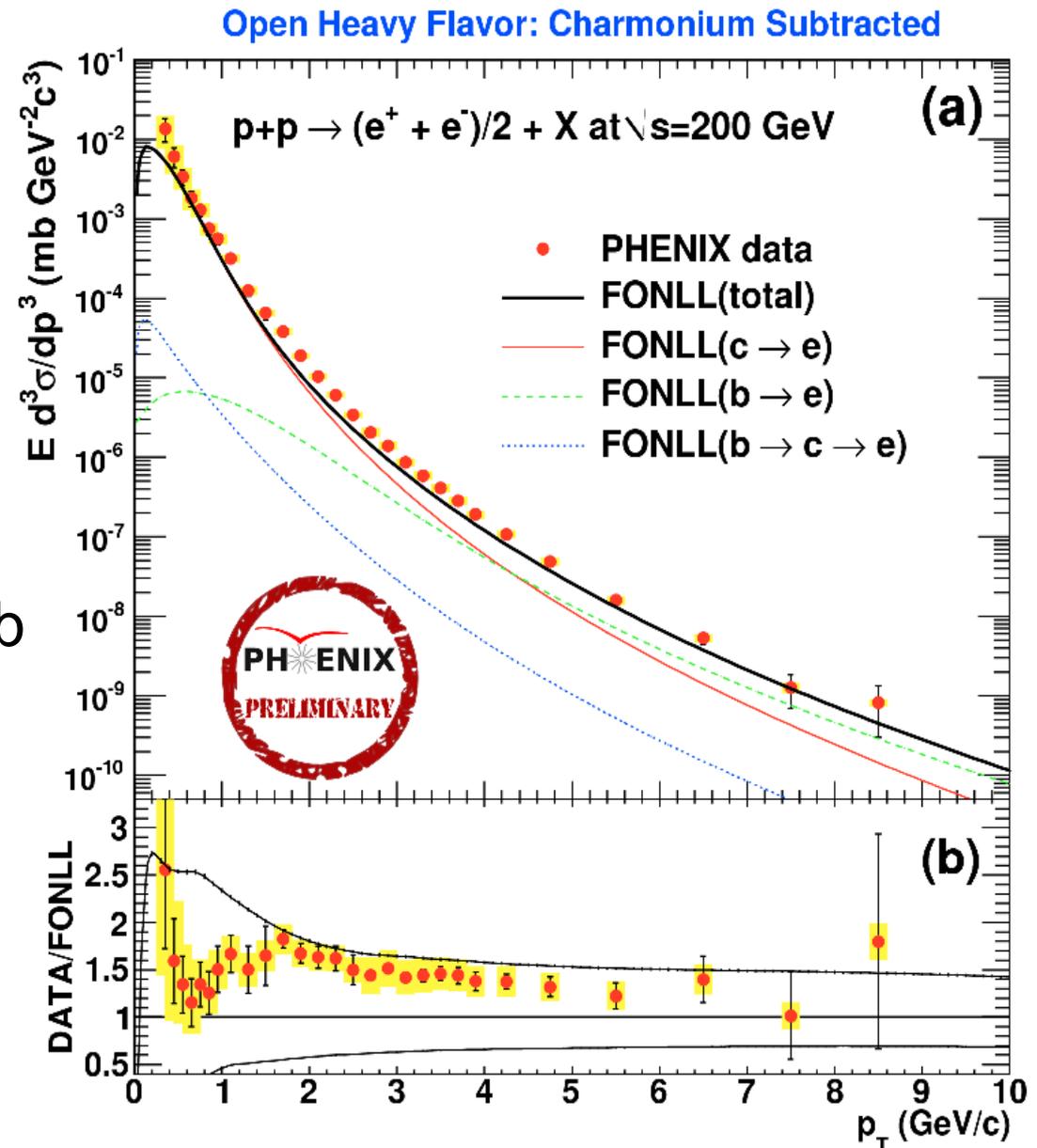
Charm dominates low  $p_T$  region  
and total cross-section

Derived charm cross-section:

$$\sigma_{cc} = 567 \pm 57(\text{stat}) \pm 224(\text{sys}) \mu\text{b}$$

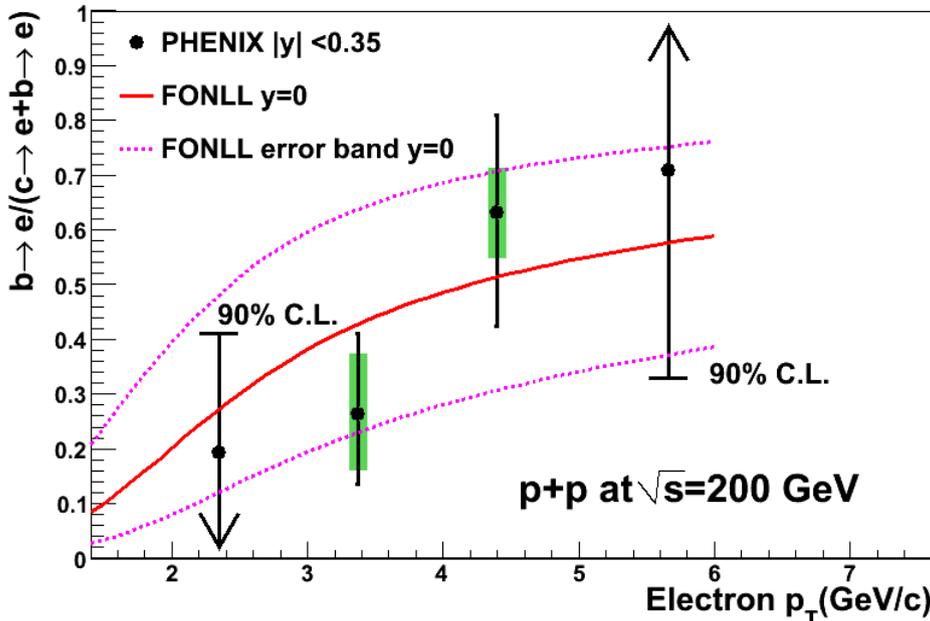
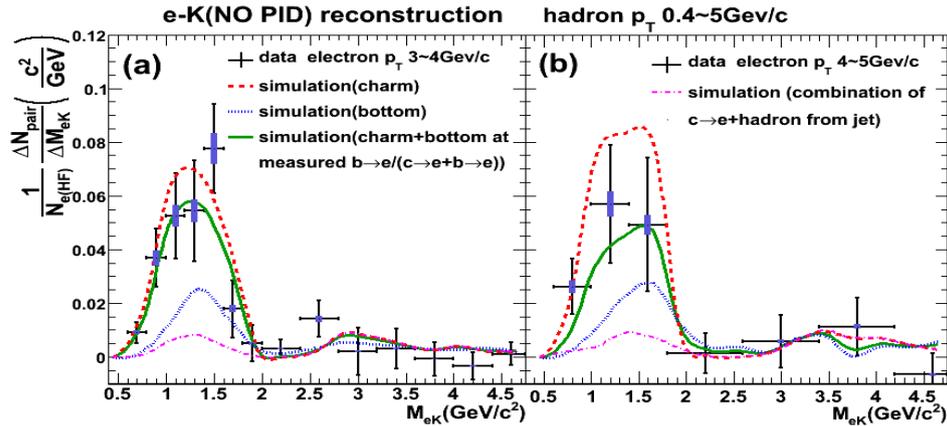
(PRL97 (2006) 252002)

How to extract beauty  
cross-section?



# c/(c+b) from e-h correlations

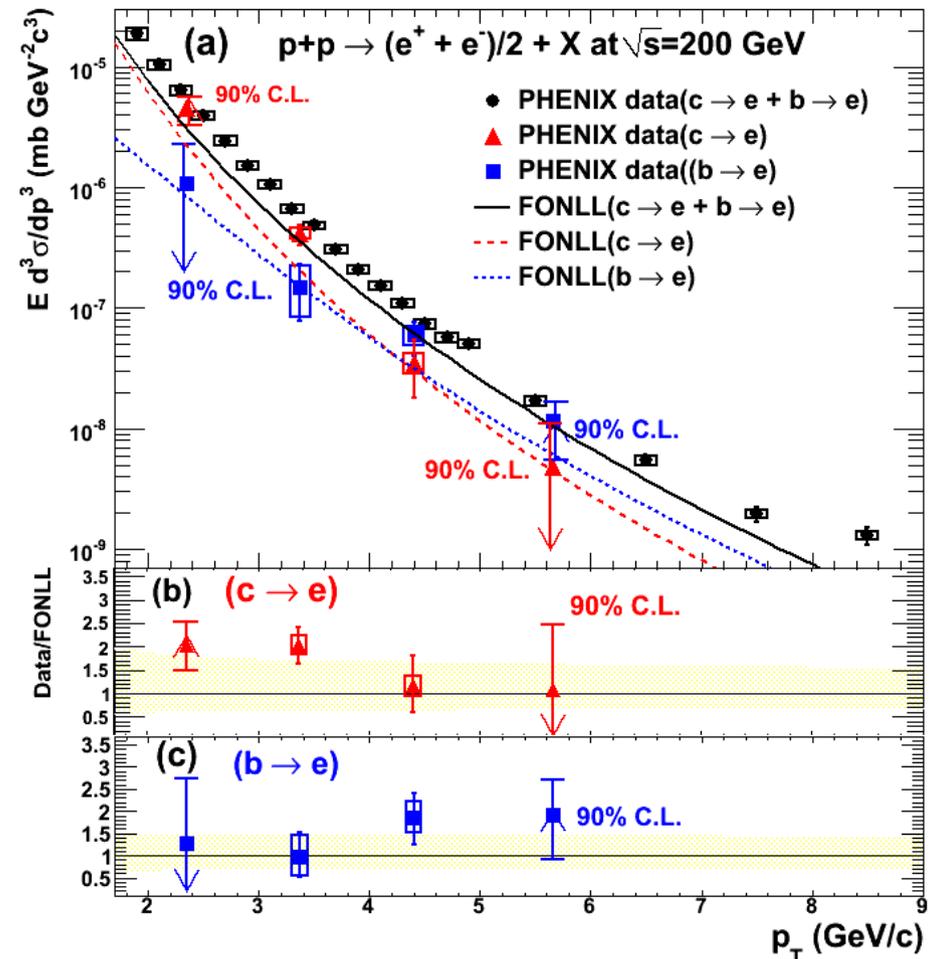
e-hadron invariant mass (per electron) is different for B and D meson decays (arXiv:0903.4851, submitted to PRL)



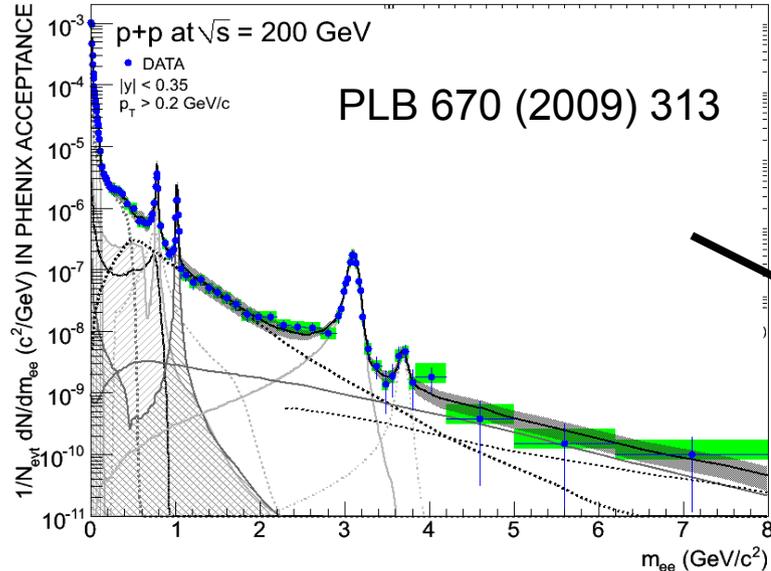
Combining with single electron spectra, obtain c and b distributions

Derived beauty cross-section:

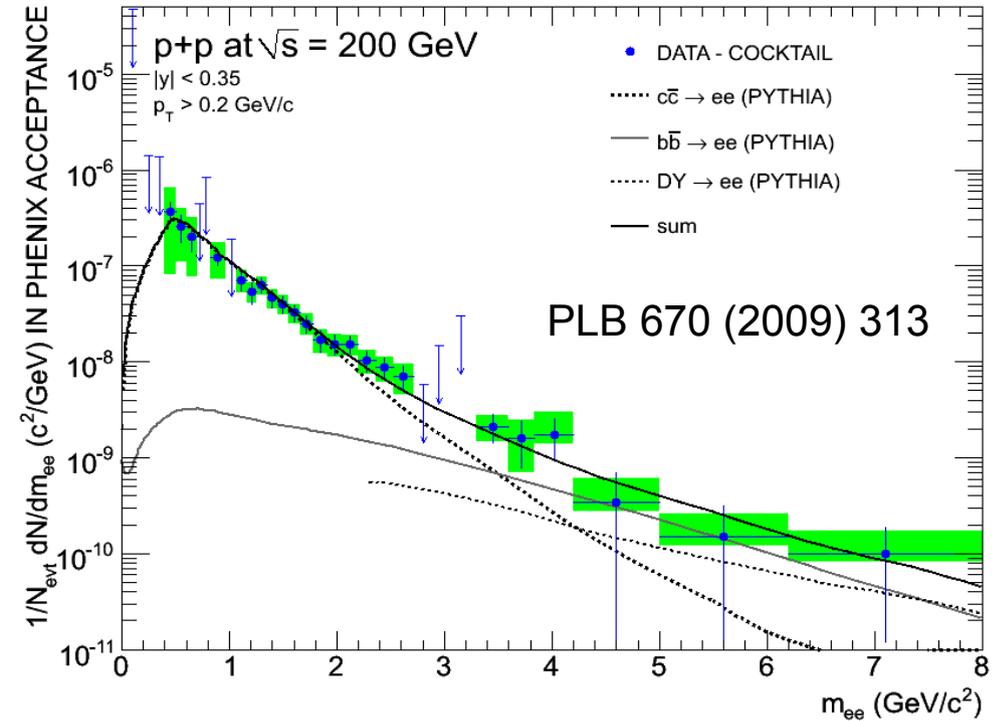
$$\sigma_{b\bar{b}} = 3.2^{+1.2}_{-1.1}(\text{stat})^{+1.4}_{-1.3}(\text{sys}) \mu\text{b}$$



# Charm and beauty from di-electron spectra



After subtraction of all hadronic sources of dielectrons



- A different way to separate c and b
- Model (PYTHIA) dependent
- Agrees well with single electron results

$$\sigma_{c\bar{c}} = 518 \pm 47(\text{stat}) \pm 135(\text{sys}) \pm 190(\text{model}) \mu\text{b}$$

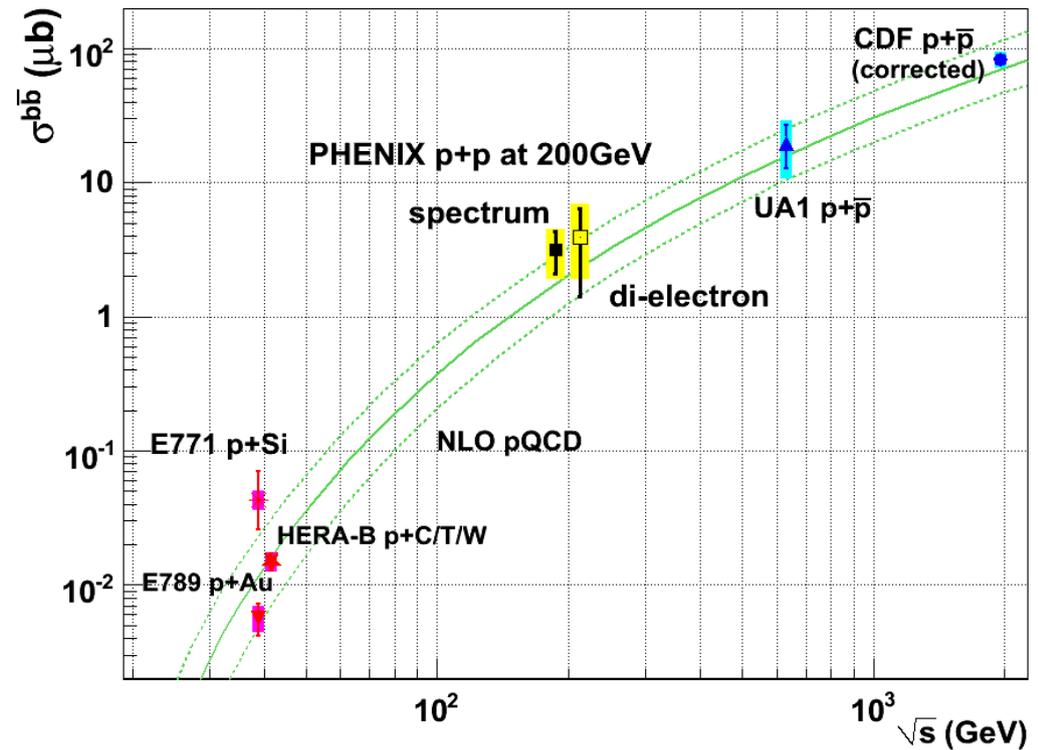
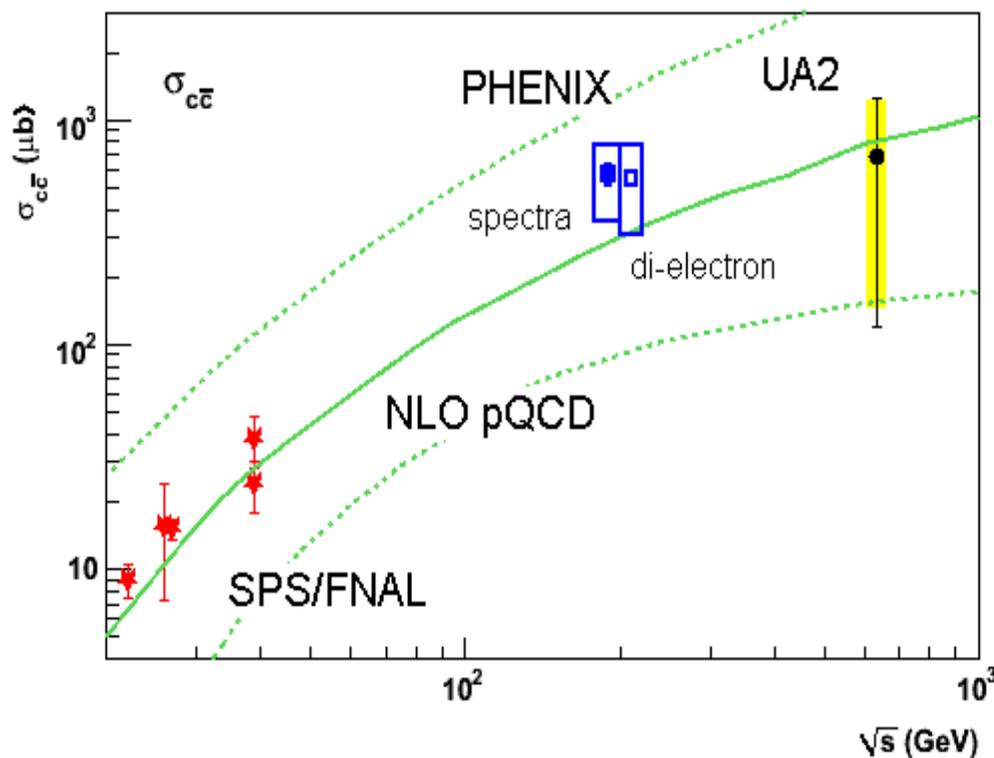
$$\sigma_{b\bar{b}} = 3.9 \pm 2.4 +3/-2 \mu\text{b}$$

(PLB 670 (2009) 313)

# Charm and beauty cross-sections

$\sigma_{cc\bar{c}}$  and  $\sigma_{bb\bar{b}}$  from single electrons and di-electrons agree with each other and NLO pQCD calculation.

First measurement of beauty cross-section at RHIC energy



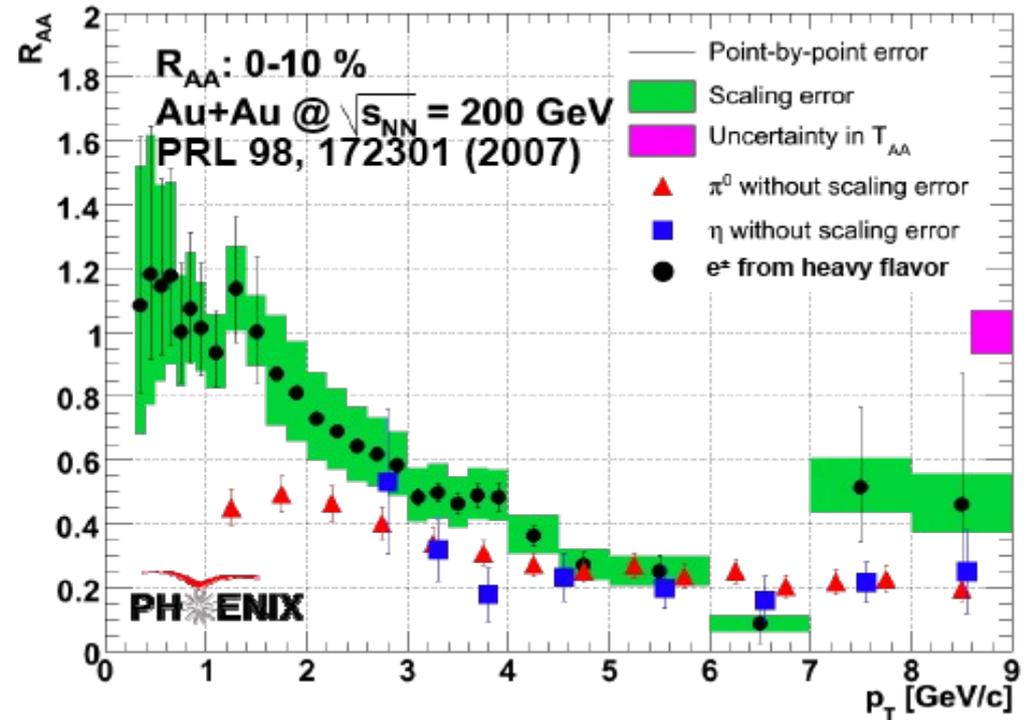
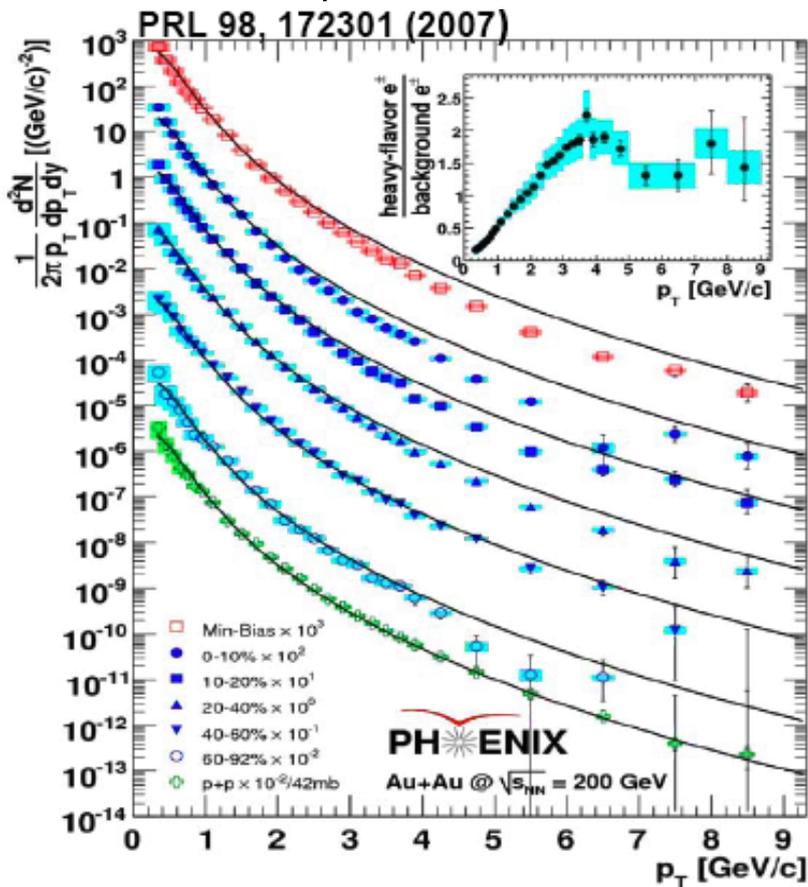
PHENIX results at the same energy; shifted for clarity

# Open heavy flavor in Au+Au

Nuclear Modification Factor:  $R_{AA} = \text{Yield in Au+Au} / N_{\text{COLL}} / \text{Yield in p+p}$

where  $N_{\text{COLL}}$  is number of binary collisions calculated using Glauber model

Heavy flavor electrons from Au+Au compared to  $N_{\text{COLL}}$  scaled p+p (FONLL x 1.71)



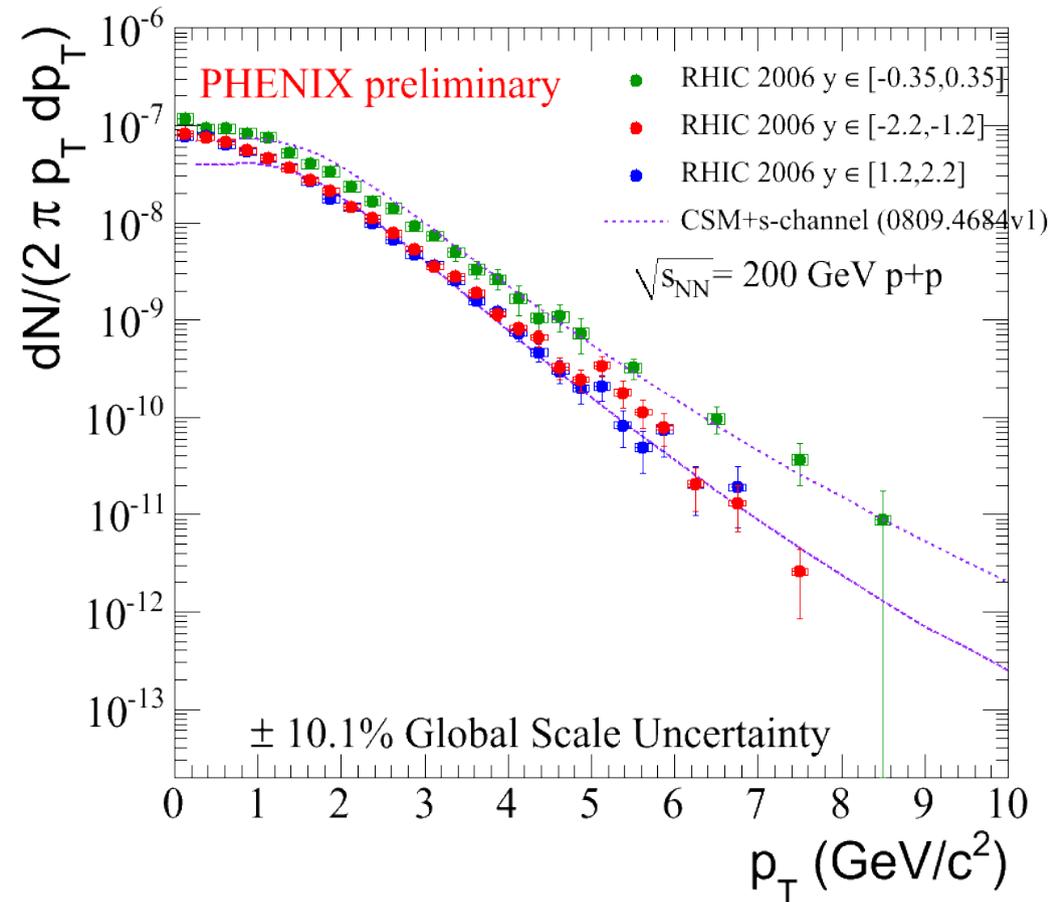
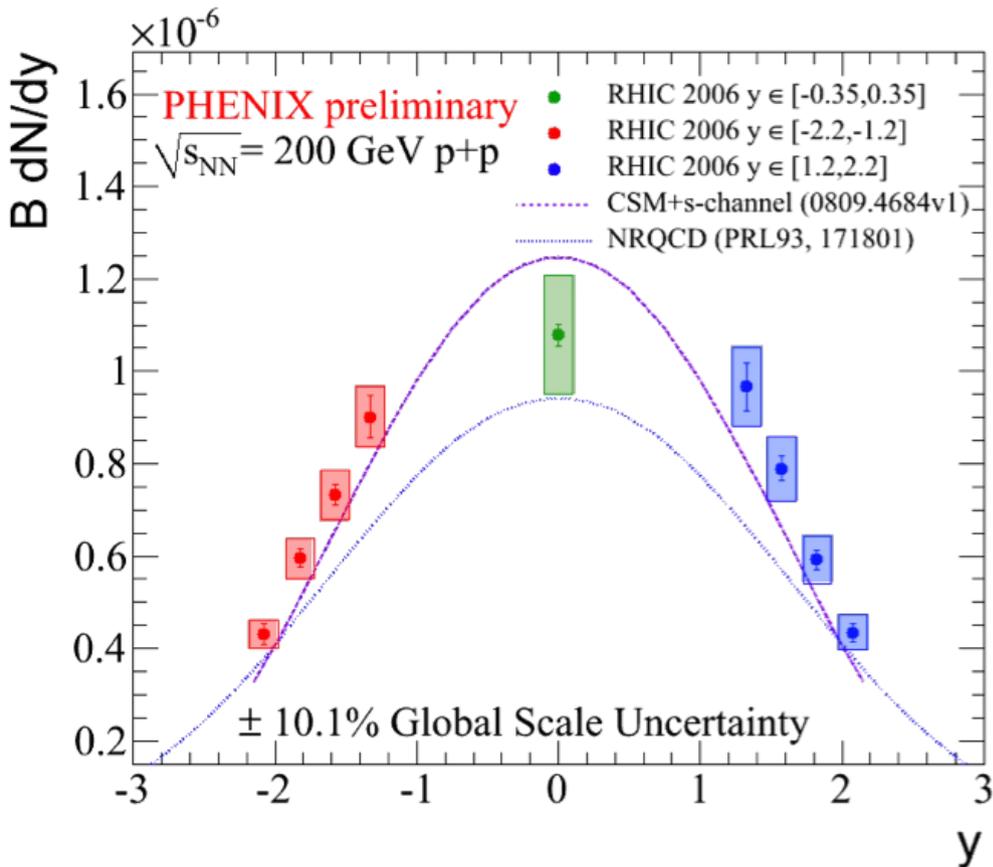
Same methods as in p+p

Suppression level is almost the same as for light quarks at high  $P_T$ !

# Quarkonia

# J/ψ in p+p

Models have absolute normalization

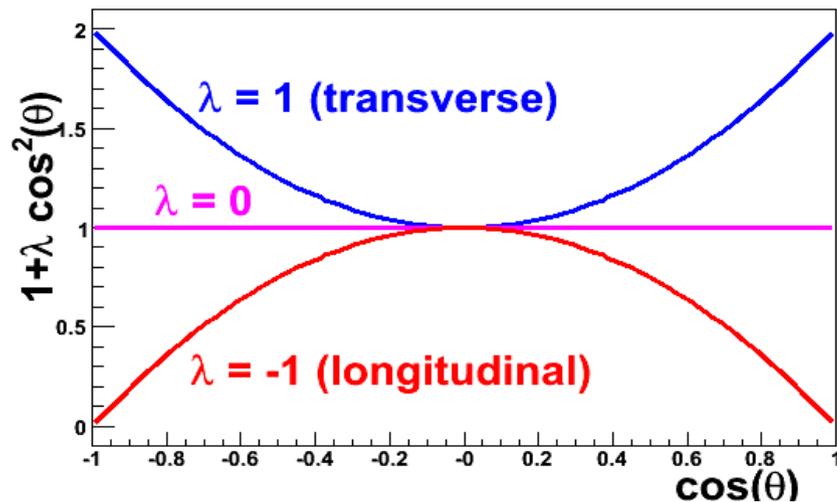


- New “s-channel cut” Color Singlet Model better agrees with the data  
(Haberzettl, Lansberg, PRL 100 (2008) 032006)
- Good baseline for Au+Au

# J/ψ polarization

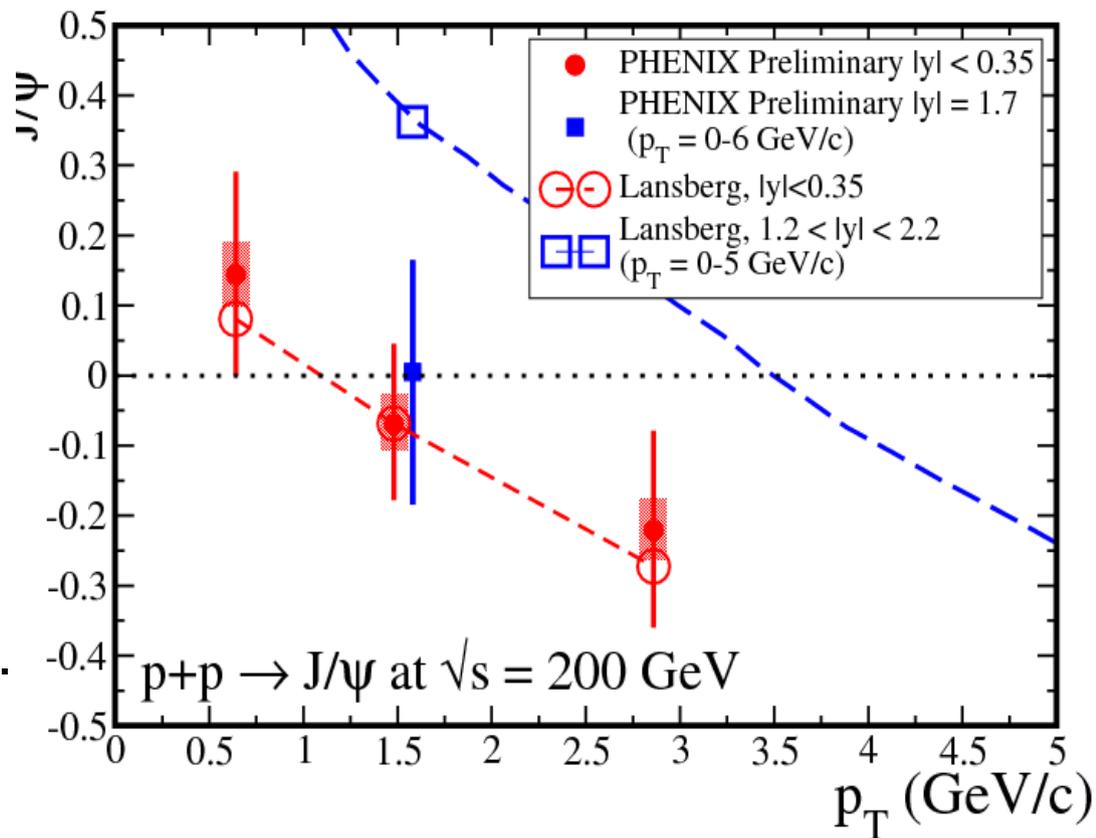
Measure decay lepton angle ( $\theta$ ) in J/ψ rest frame relative to J/ψ momentum in lab frame.  
Helicity frame - correlation between J/ψ spin and momentum.

$$\frac{dN}{d \cos \theta} = A(1 + \lambda \cos^2 \theta)$$



New “s-channel cut” Color Singlet Model agrees with PHENIX at  $y=0$  but disagrees ( $2-3 \sigma$ ) at forward rapidity.

Work in progress on polarization in Gottfried-Jackson frame (correlation between J/ψ spin and colliding partons momenta).



# J/ψ in Au+Au

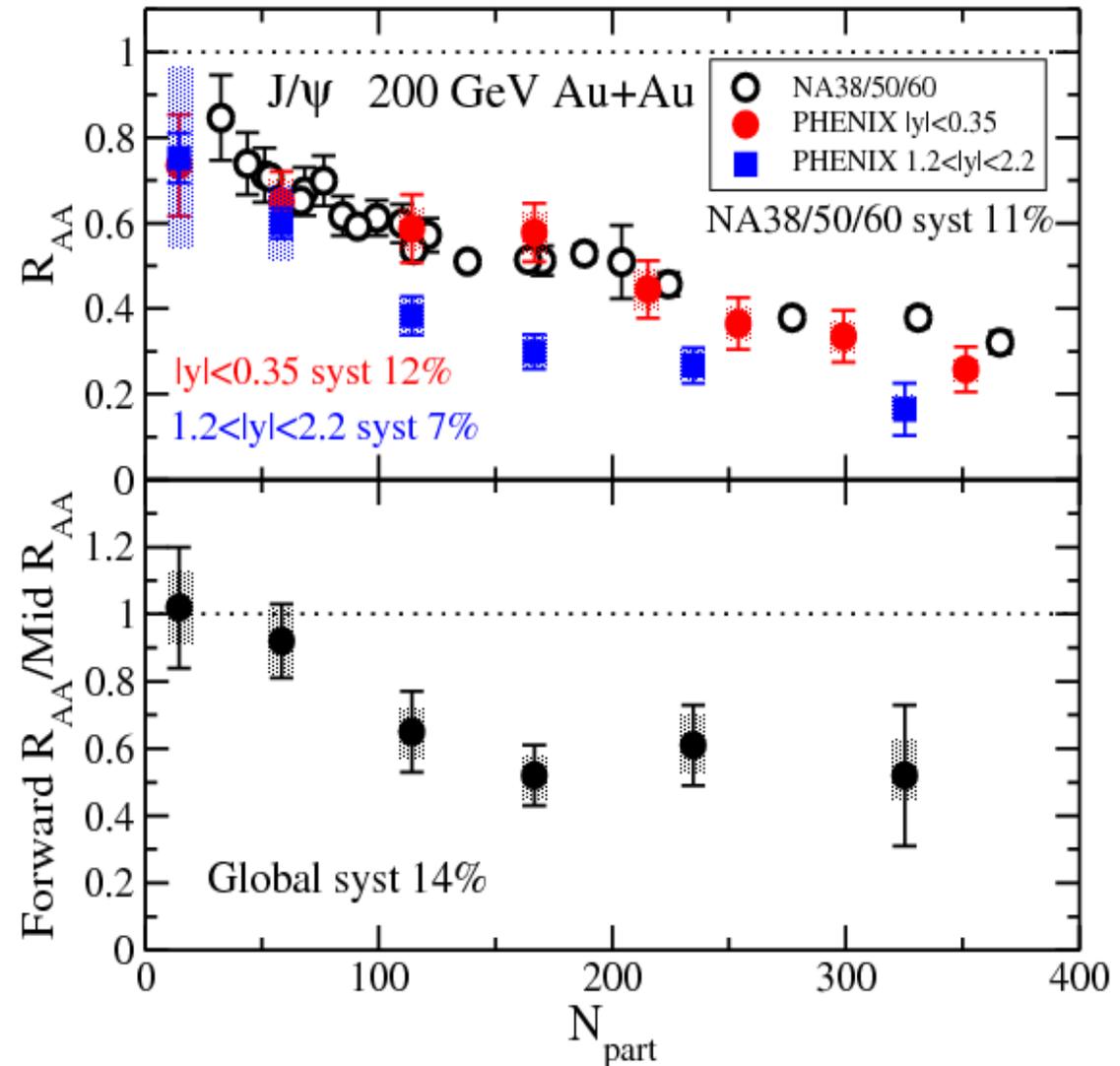
Quarkonia suppression is similar to open charm suppression

Suppression at RHIC similar to one observed at SPS at mid-rapidity, but stronger at forward rapidity.

Many different interpretations exist (“cold nuclear matter” effects, re-generation, etc.)

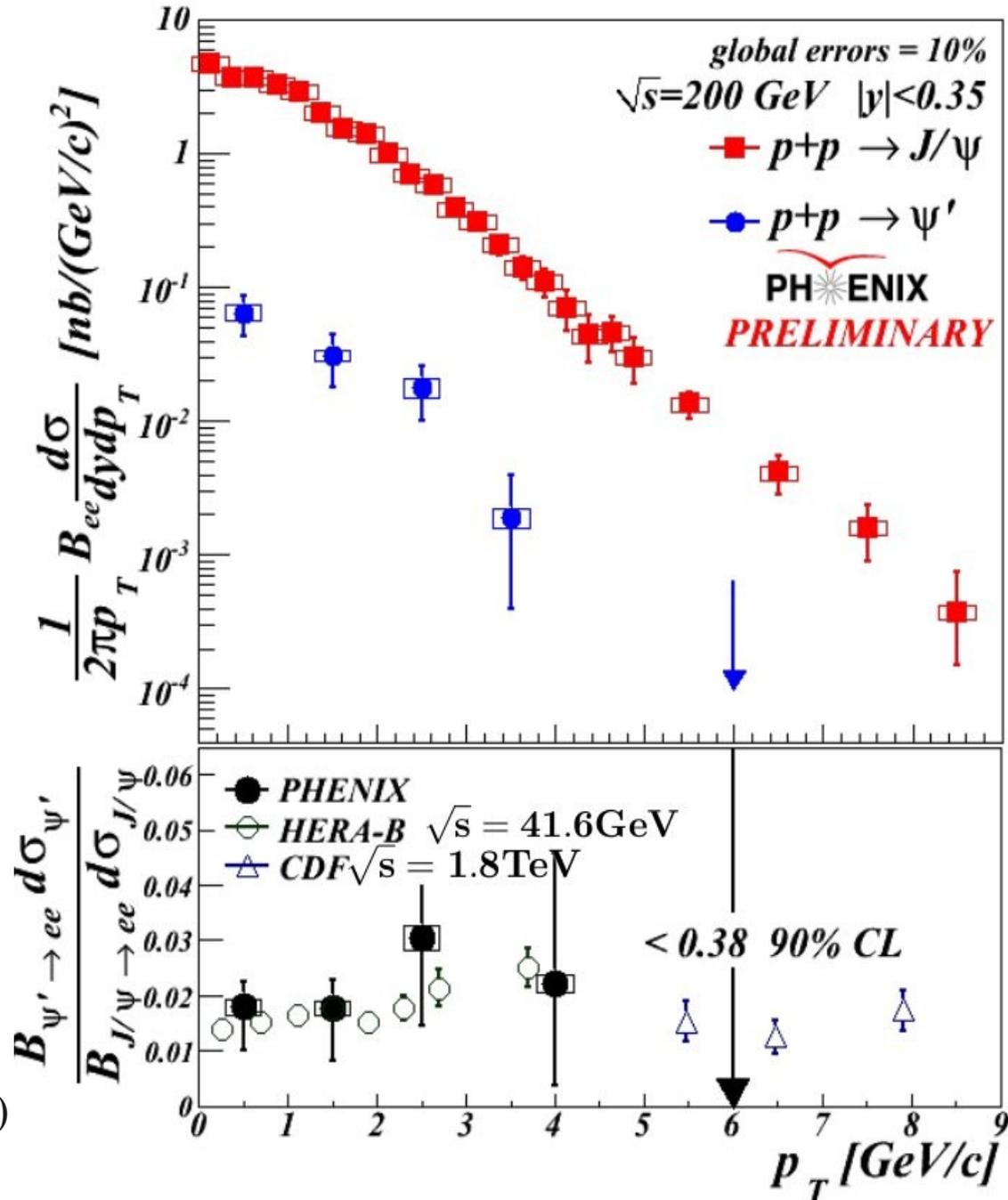
**Exact picture is still unclear**

$$R_{AA} = \text{Yield in Au+Au} / N_{\text{coll}} / \text{Yield in p+p}$$



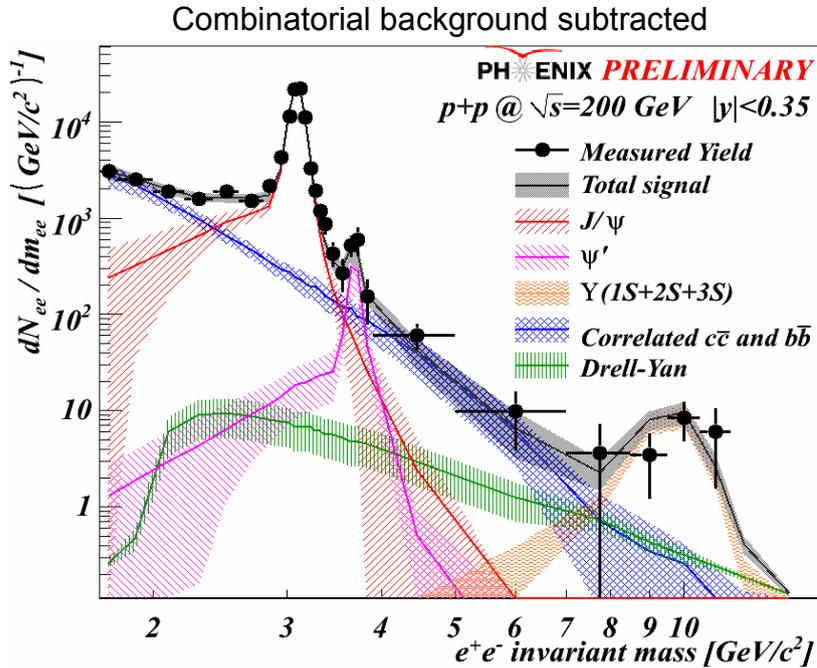
# $\psi'$ in $p+p$

- $J/\psi$  to  $\psi'$  ratio of order of 2%
- Same as at higher and lower energies
- No strong  $P_T$  dependence
- Feed down to  $J/\psi$   
= 8.6%  $\pm$  2.5%

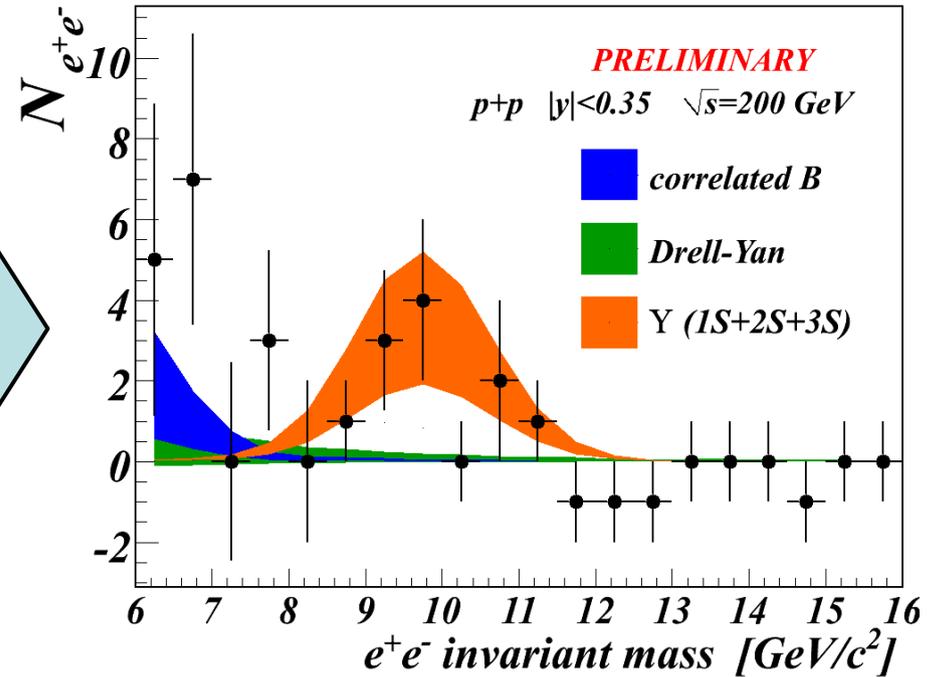


HERA-B: Eur. Phys. J. C49, 545 (2007)  
 CDF: PRL 79, 572 (1997)

# Upsilon in p+p



Zoom on Upsilon



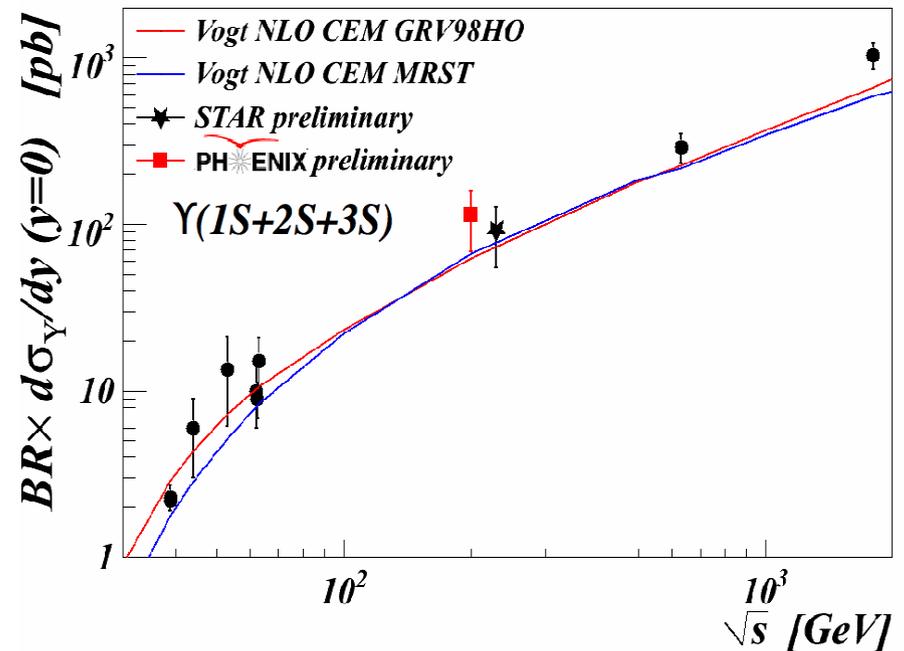
In 8.5-11.5 GeV mass range

$$N_{\text{OPP}} = 12; N_{\text{SAME}} = 1;$$

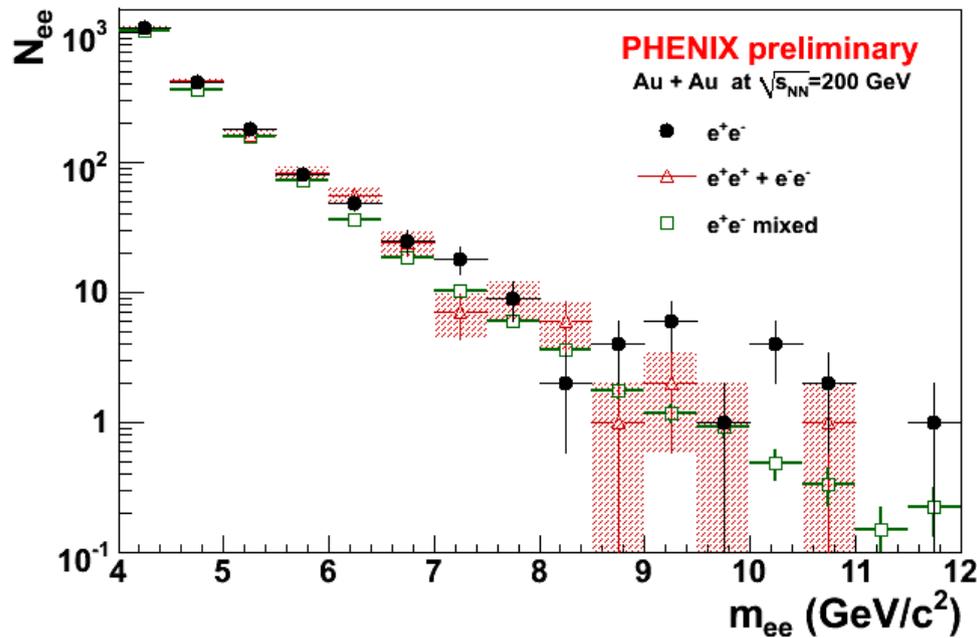
Continuum contribution is <15%  
under Upsilon peak

Cross-section follows world trend

$$BR * \frac{d\sigma}{dy} \Big|_{|y|<0.35} = 114^{+46}_{-45} \text{ pb}$$



# Upsilon's in Au+Au

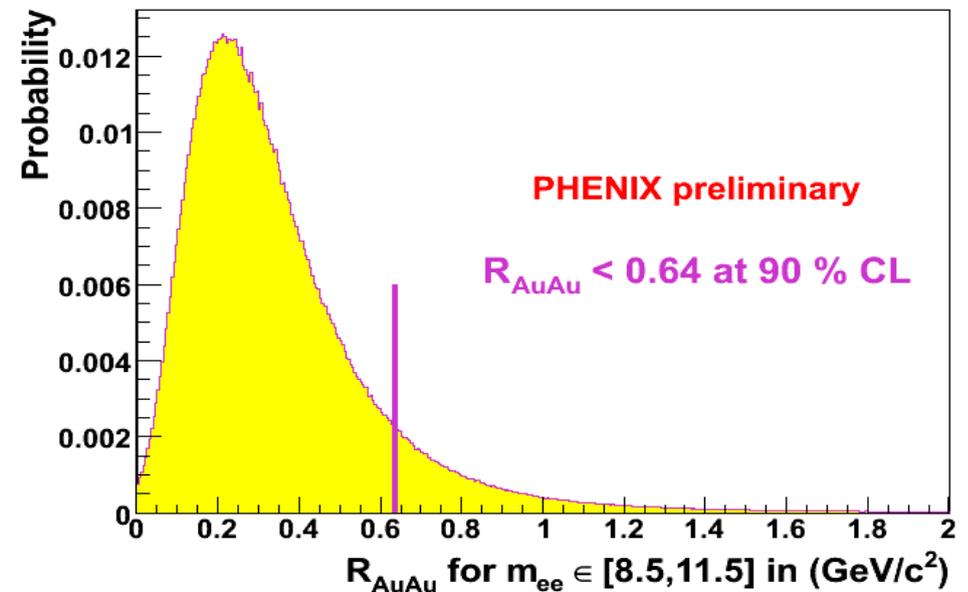


**High mass unlike sign di-electrons are suppressed!**

(background from DY and correlated open heavy flavor not subtracted)

In 8.5-11.5 GeV mass range  
 $N_{OPP} = 17$ ;  $N_{SAME} = 5$ ;

After careful statistical analysis  
upper limit on  $R_{AA}$  was calculated



Feed-down from  $\chi_b$ ? Cold nuclear matter effects?

# Conclusions

- PHENIX has excellent capability to study heavy quarks in p+p, p+A, and A+A collisions.
- Open charm in p+p is in good agreement with FONLL
- Open charm/beauty separated; both cross-sections in agreement with NLO pQCD calculation
- In Au+Au open charm suppression similar to that of light quarks
- $J/\psi$  in p+p are well described by new “s-channel cut” Color Singlet Model, except for forward rapidity polarization
- $J/\psi$  to  $\psi'$  ratio, and  $\psi'$  feed-down to  $J/\psi$  similar to other energies
- Upsilon cross-section in p+p follows world trend vs  $\sqrt{s}$
- Upsilon in Au+Au appear to be suppressed