# Heavy flavor at RHIC


## Jaroslav Bielčík

**Czech Technical University**

**NPI AS CR**

**Prague**


Excited QCD 2010, Stará Lesná, Slovensko

# Outline

- Heavy ion program at RHIC in BNL
- Motivation for heavy flavor physics
- Open heavy flavor
  - Charm mesons: $D^0$
  - Non-photonic electrons
- Quarkonia
  - $J/\psi$ and $\Upsilon$ measurements

# Relativistic Heavy Ion Collider

RHIC site in BNL on Long Island, USA

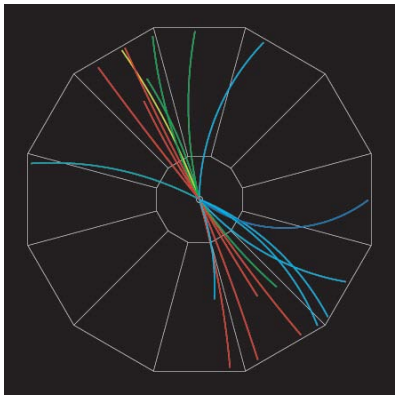

**RHIC has been exploring nuclear matter at extreme conditions over the last few years**

Lattice QCD predicts a phase transition from hadronic matter to a deconfined state, the **Quark-Gluon Plasma**

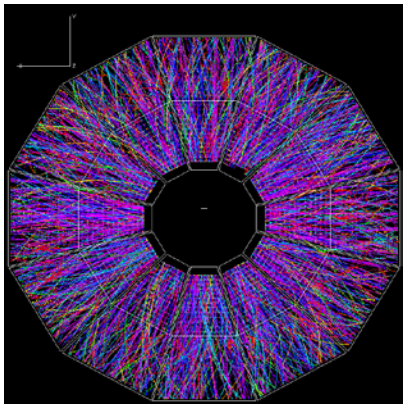
Colliding systems:
p↑+p↑, d+Au, Cu+Cu, Au+Au
Energies
$\sqrt{s_{NN}}$ = 20, 62, 130, 200GeV

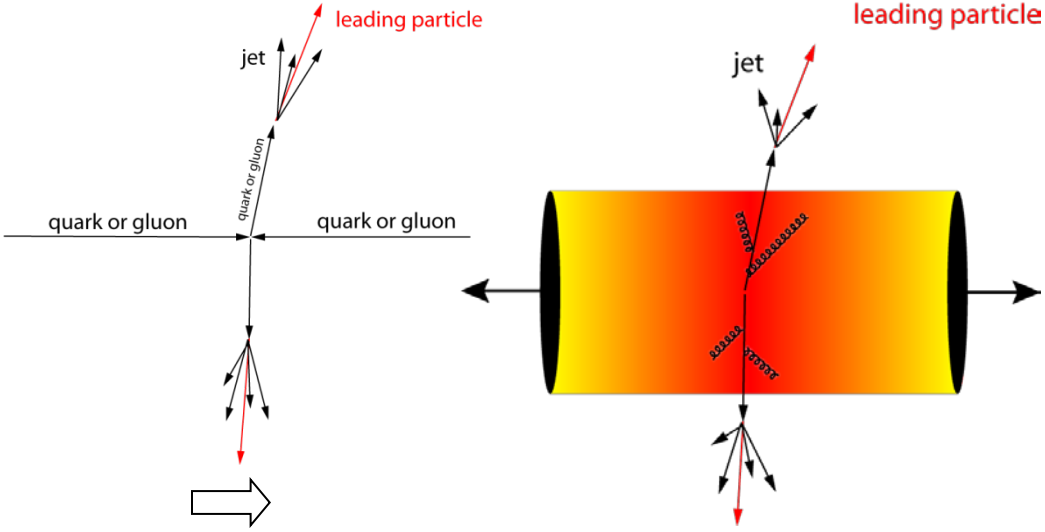
# Probing of Dense Matter with jets

p+p Collision



Au+Au Collision





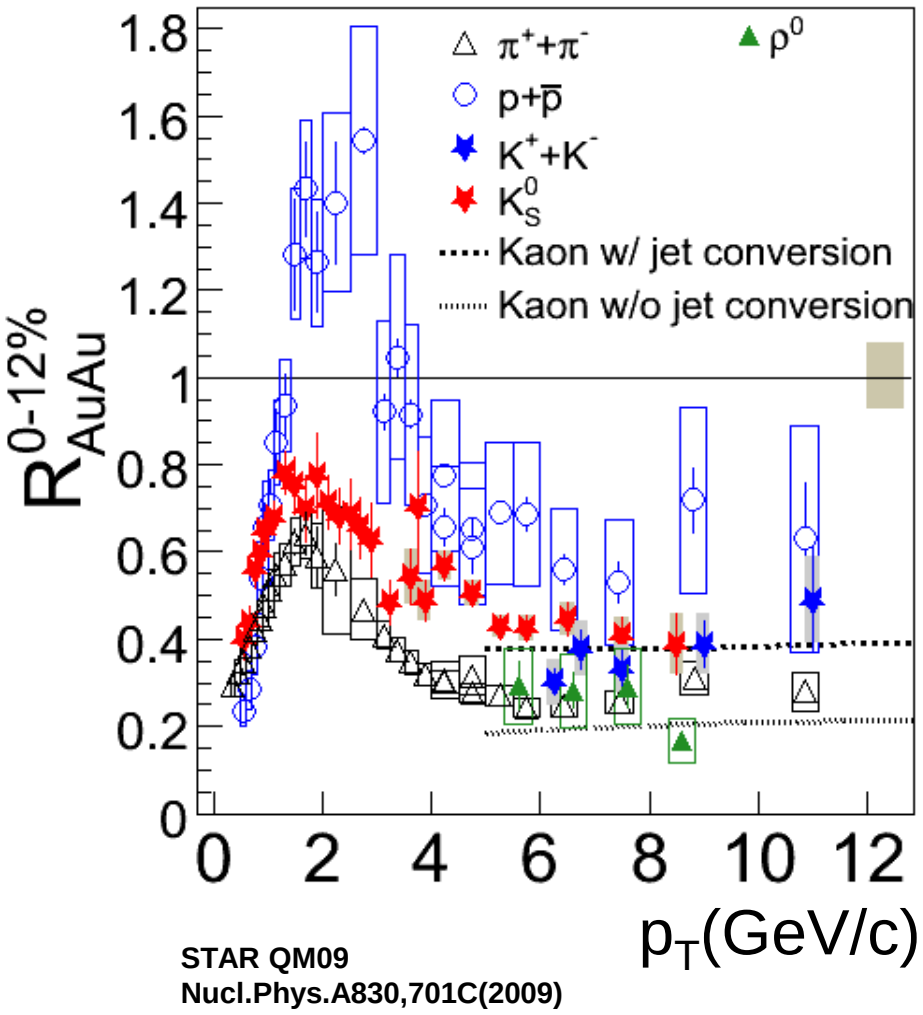

- nuclear modification factor $R_{AA}$ :

$$R_{AA}(p_T) = \frac{Yield(A+A)}{Yield(p+p) \times \langle N_{coll} \rangle}$$

Average number of NN collisions in AA collision

- No "Effect" of nuclear matter: $R_{AA} = 1$ at higher momenta where hard processes dominate
- Suppression: $R_{AA} < 1$
- Partons interact with medium gluon radiation/energy loss
- measuring high-$p_T$ particles in Au+Au vs. p+p to extract the properties of medium

# Hadron suppression in central Au+Au



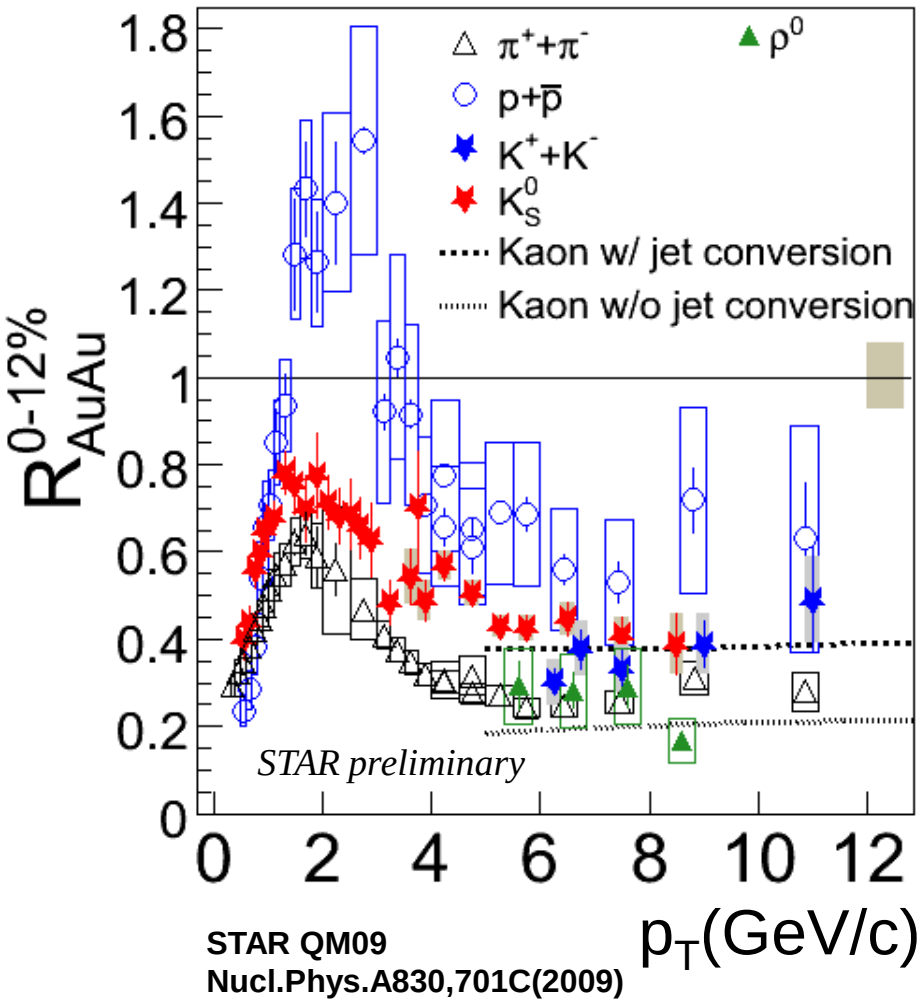

STAR QM09
Nucl.Phys.A830,701C(2009)

- **Hadron yields:**
  **strongly suppressed**
  **in central Au+Au at 200 GeV**

- **Large energy loss of light partons in the formed nuclear matter**

**Energy loss depends on**
**properties of medium**
**(gluon densities, size)**
**properties of "probe"**
**(color charge, mass)**

# Hadron suppression in central Au+Au




**STAR QM09**
**Nucl.Phys.A830,701C(2009)**

$$\langle \Delta E \rangle \sim \alpha_s C \langle \hat{q} \rangle L^2$$

- Color charge dependence: g /q ($C_A/C_F$=9/4)
- Gluons loose more energy than quarks
- At high-$p_T$ protons are produced mainly from gluon jets
- At high-$p_T$ pions are produced mainly from quark jets

=> Expected $R_{AA}$(g->p) < $R_{AA}$(q->$\pi$)

# Heavy quarks as a probe

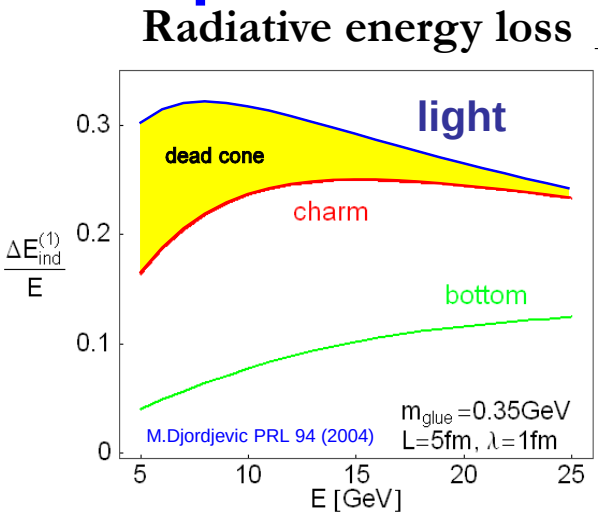
- p+p data:

→ baseline of heavy ion measurements
→ test of pQCD calculations

- Due to their large mass heavy quarks are primarily produced by gluon fusion in early stage of collision

→ production rates calculable by pQCD

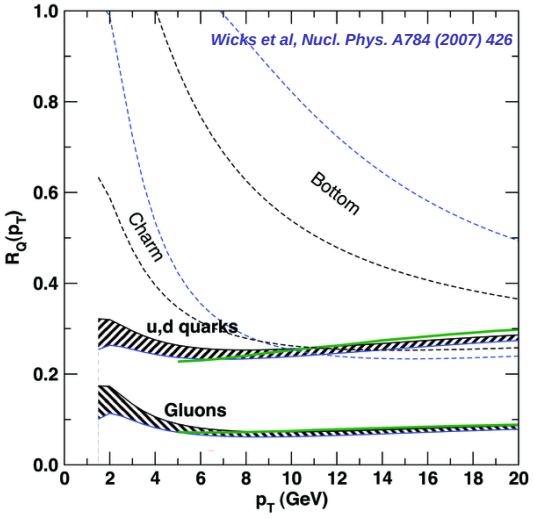
M. Gyulassy and Z. Lin, PRC 51, 2177 (1995)




- heavy ion data:

- Studying energy loss of heavy quarks

→ independent way to extract properties of the medium



# Open heavy flavor

**Direct:** reconstruction of all decay products

$$D^0 \to K^-\pi^+, \overline{D}^0 \to K^+\pi^-,$$

$$B.R. = 3.80 \pm 0.07\%$$

**Indirect:** charm and beauty via electrons

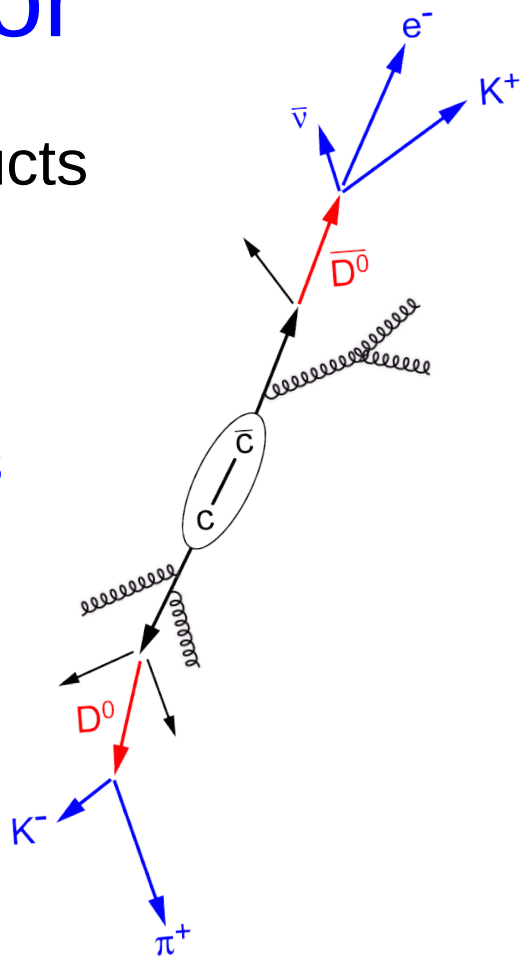
$c \to e^+ +$ anything (B.R.: 9.6%)

$b \to e^+ +$ anything (B.R.: 10.9%)

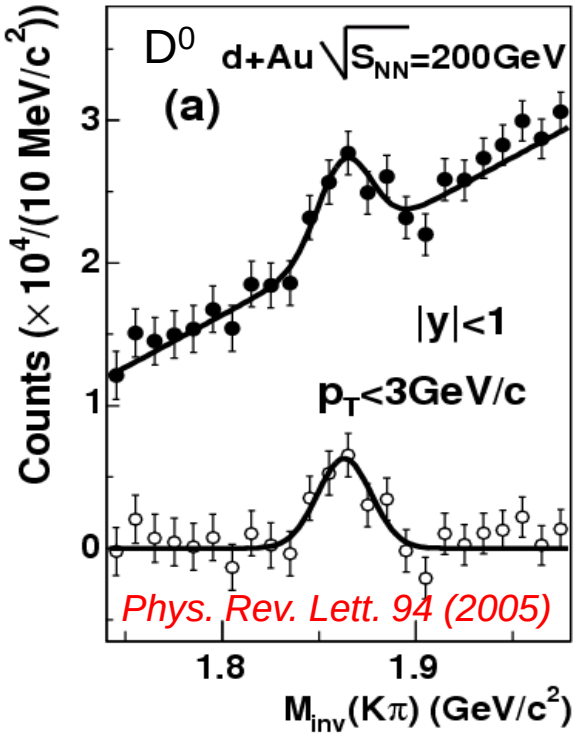
issue of photonic background

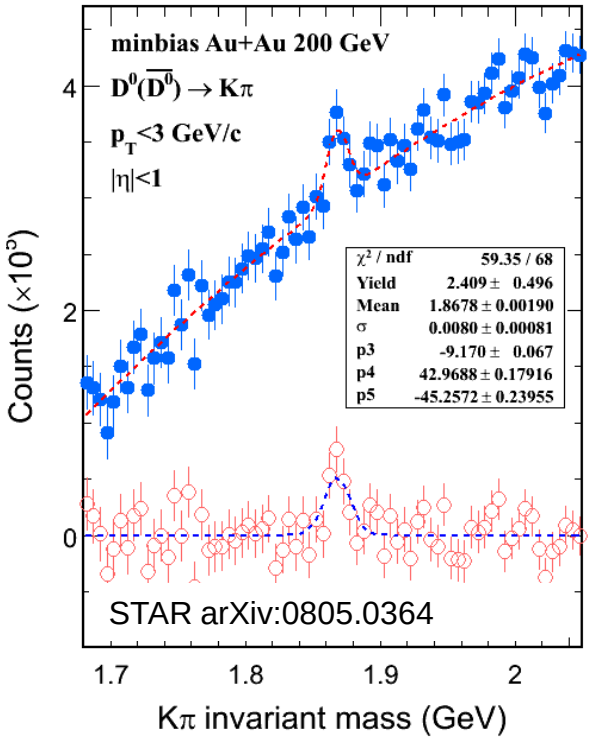
charm (and beauty) via muons

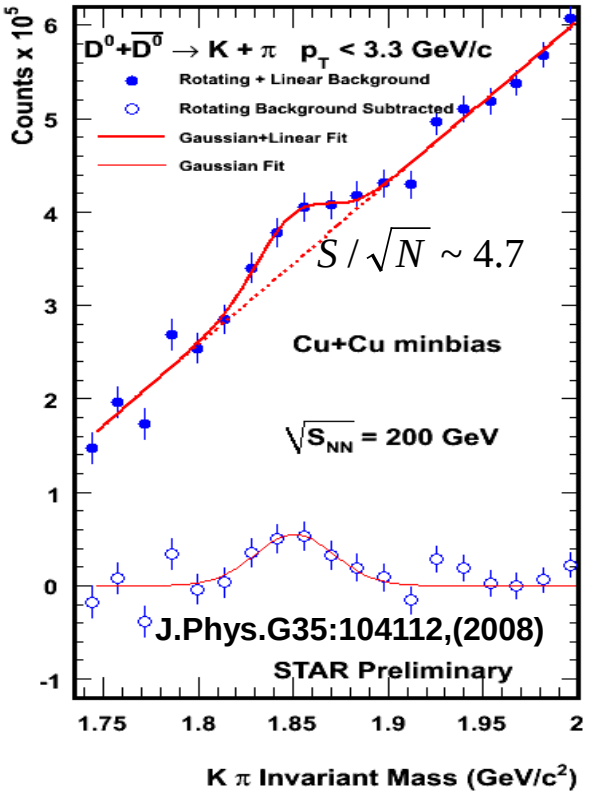
$c \to \mu+ +$ anything (B.R.: 9.5%)



# Direct D-meson reconstruction at STAR

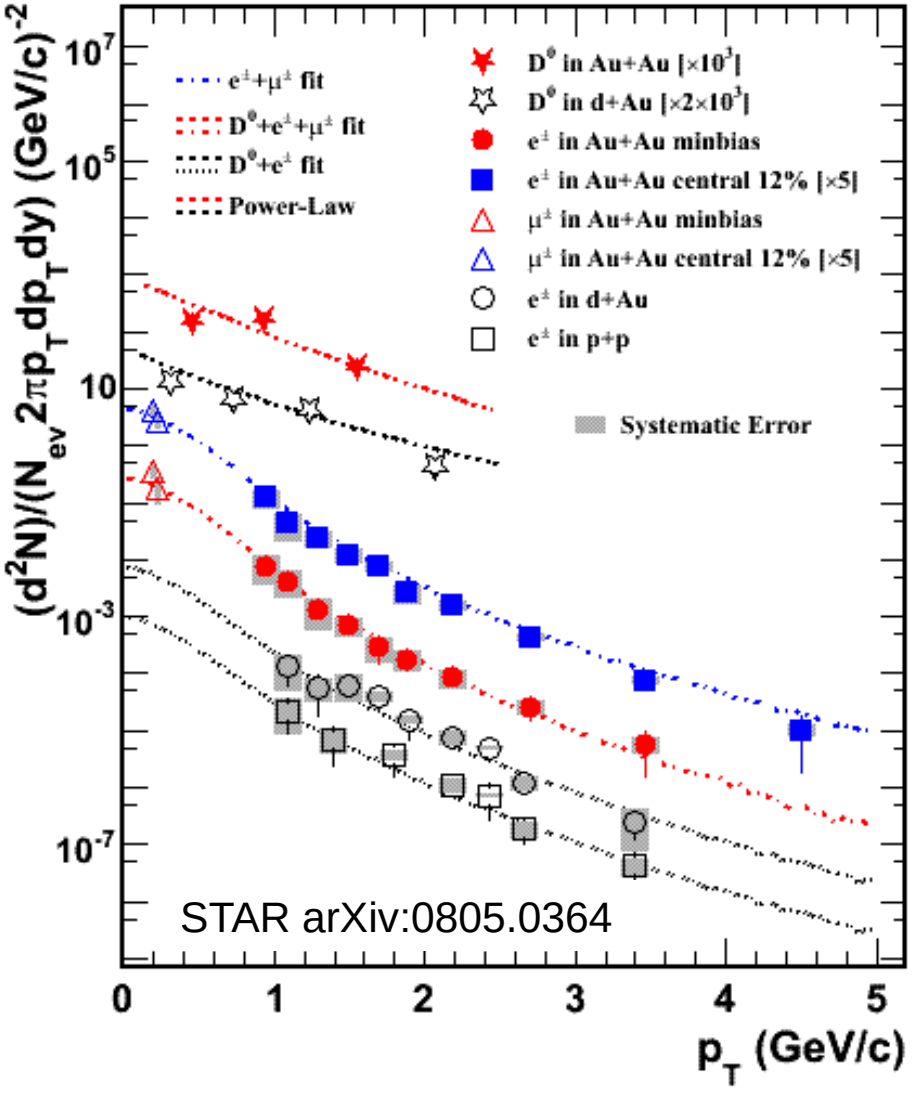



- Kπ invariant mass distribution in d+Au, Au+Au minbias, Cu+Cu minbias at 200 GeV collisions
- No displaced vertex used for open heavy flavor

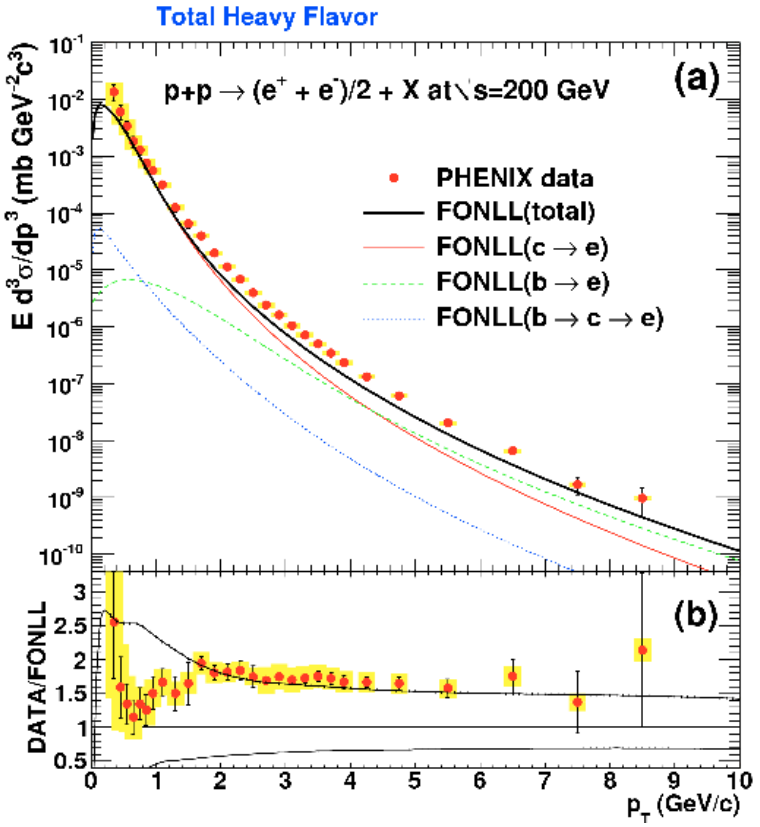
# Measurement of charm STAR



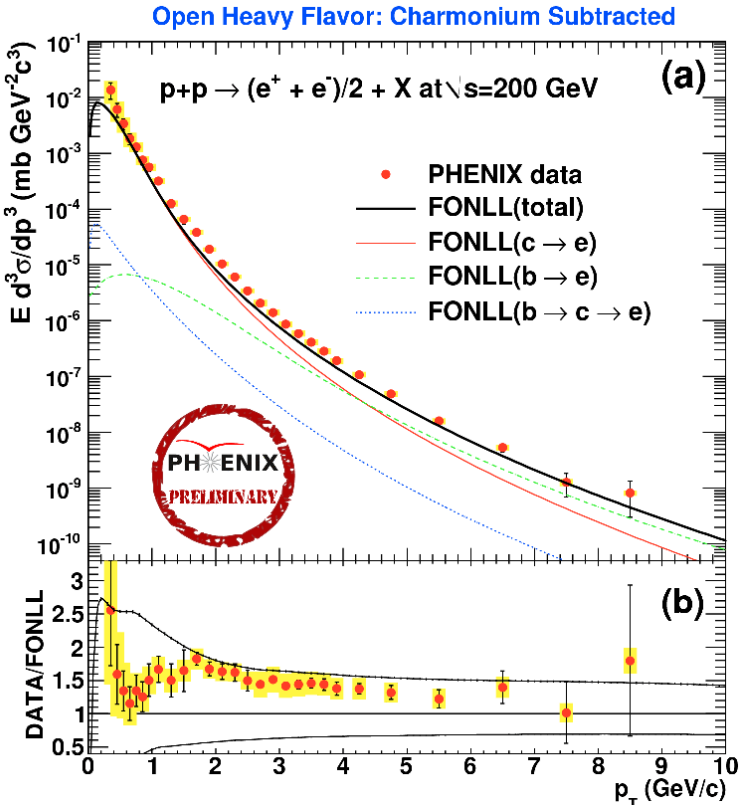

STAR charm measurement:

- $D^0$ in d+Au, Au+Au, Cu+Cu 200GeV
- low $p_T$ muon in Au+Au 200GeV
- non-photonic electrons in p+p, d+Au, Cu+Cu, Au+Au 200GeV
- 90% of charm total kinematic range covered

# Measurement of charm PHENIX




**Phys. Rev. Lett. 97, 252002 (2006)**



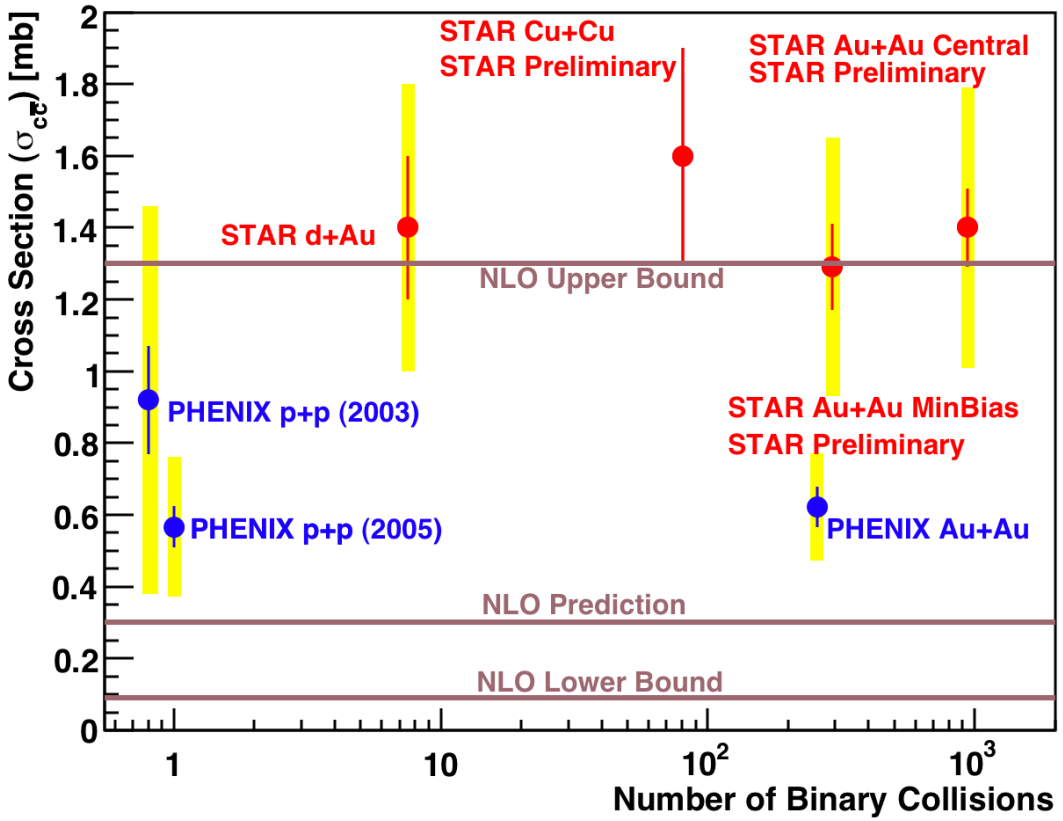

•New study takes J/y→ e± contribution into account

**PHENIX QM09: Nucl.Phys.A830:765C(2009)**



jaroslav.bielcik@fjfi.cvut.cz

# Open Charm Cross-section




STAR:

$D^0$, electrons

PRL 94(2005) 062301

$D^0$, muons

arXiv:0805.0364

PHENIX:

Single electrons

PRL 97(2006) 252002

Electron pairs

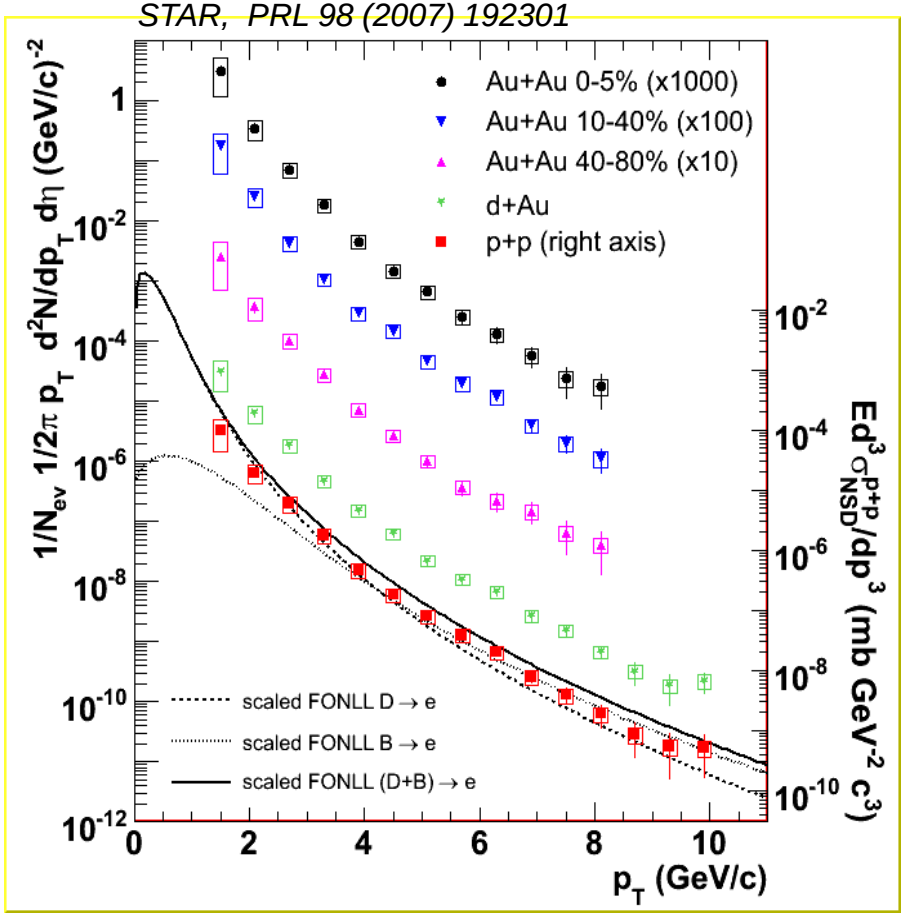
544 ± 39(stat) ± 142 (syst) ± 200 (model)

PLB 670 (2009) 313

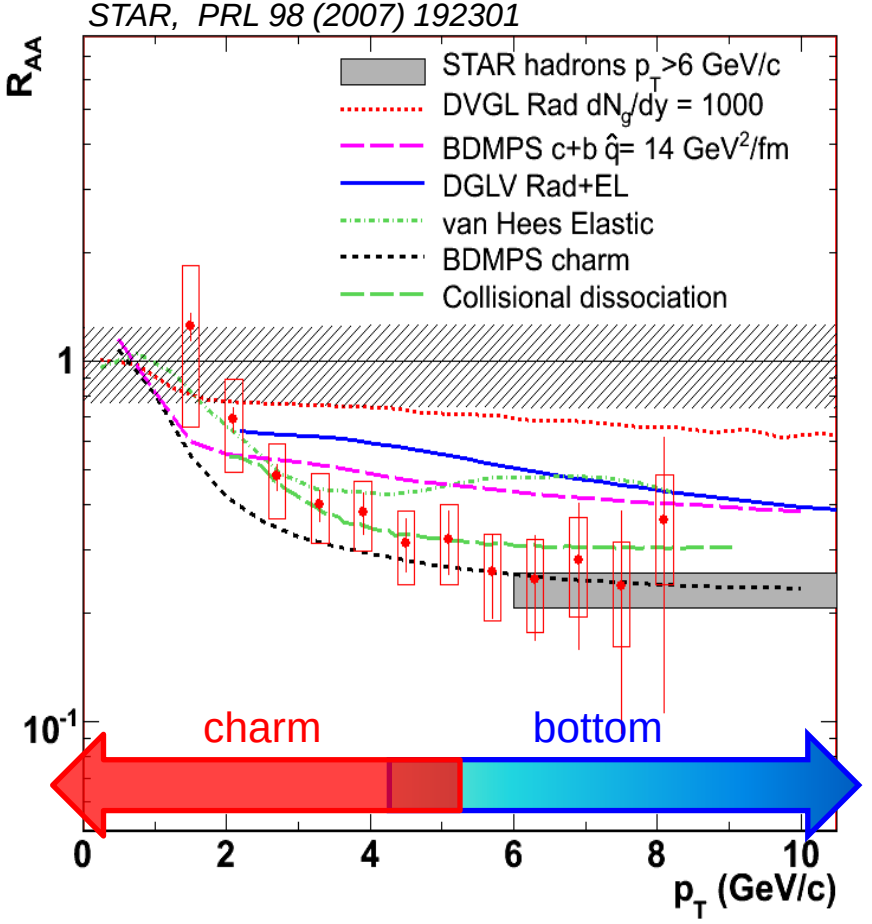
- Large discrepancy between extracted total cross-section from STAR and PHENIX
- Large theoretical uncertainties

# Suppression of non-photonic electrons

STAR, PRL 98 (2007) 192301




STAR, PRL 98 (2007) 192301



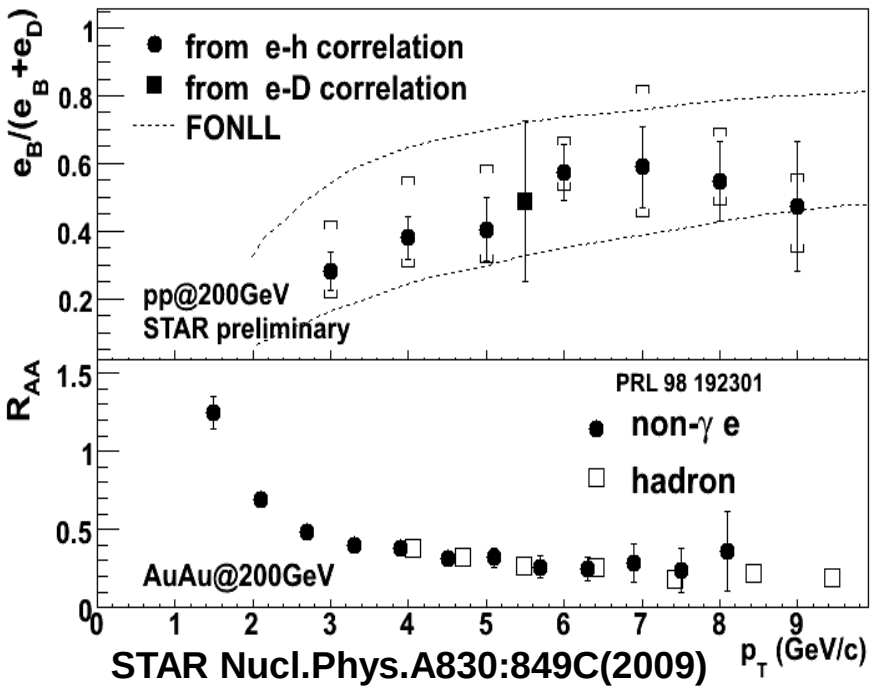

- Large suppression of non-photonics electrons similar to hadrons
- No satisfactory theoretical description yet

$$R_{AA}(p_t) = \frac{1}{N_{coll}} \times \frac{dN_{AA}/dp_t}{dN_{pp}/dp_t}$$

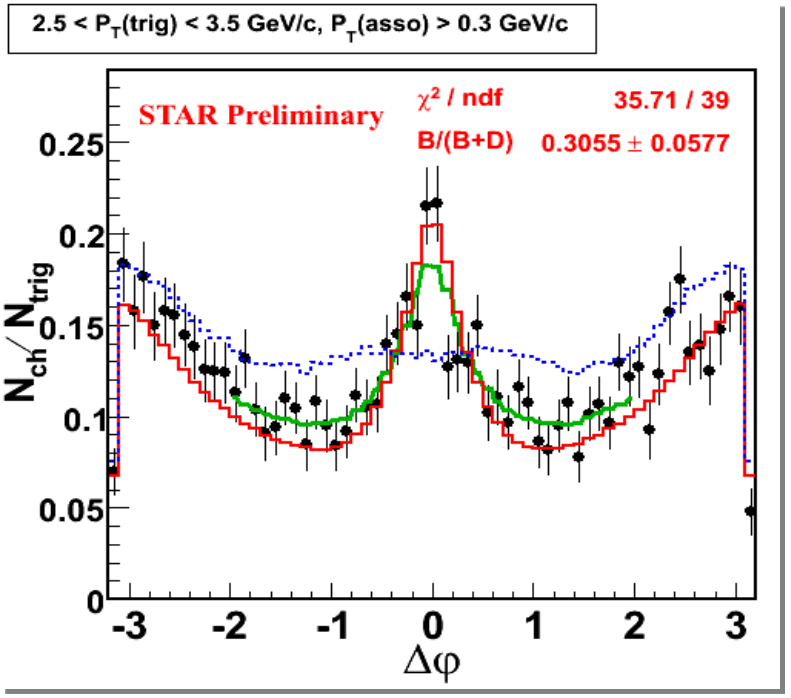


jaroslav.bielcik@fjfi.cvut.cz

# Bottom contribution to electron spectrum

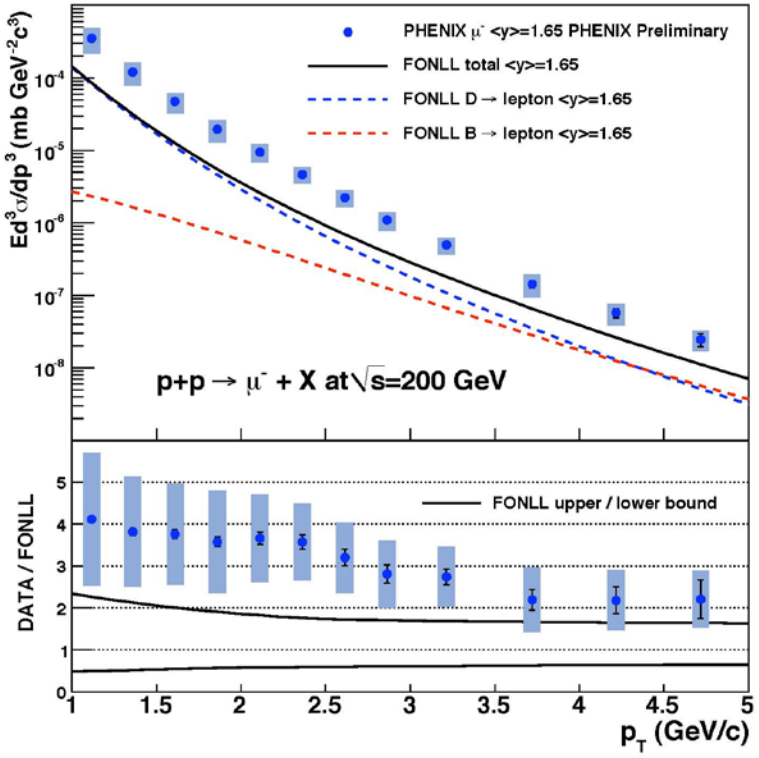


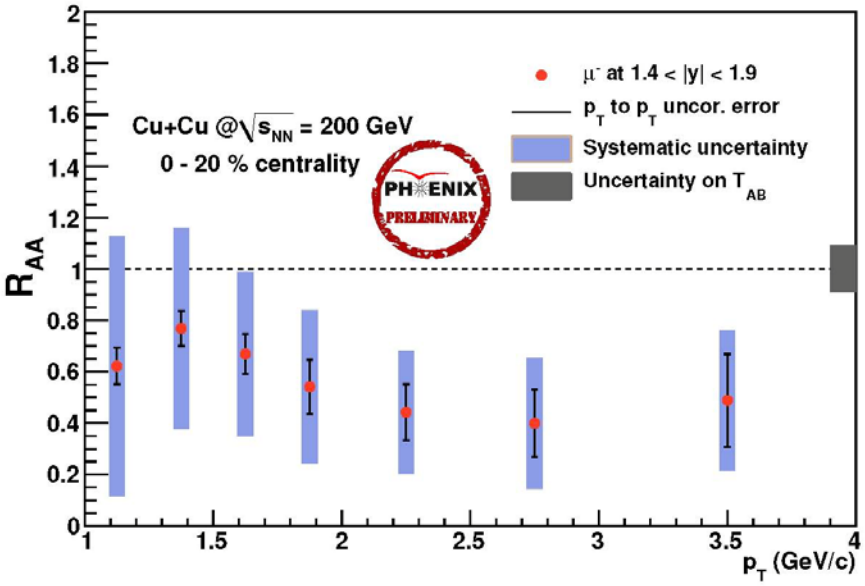

STAR Nucl.Phys.A830:849C(2009)




- Difficult to interpret suppression without the knowledge of charm/bottom
- **Data** show non-zero **B contribution** consistent with FONLL
- Charm and bottom contribution comparable at $p_T$ of 5 GeV
- B meson is also suppressed

# PHENIX forward muons



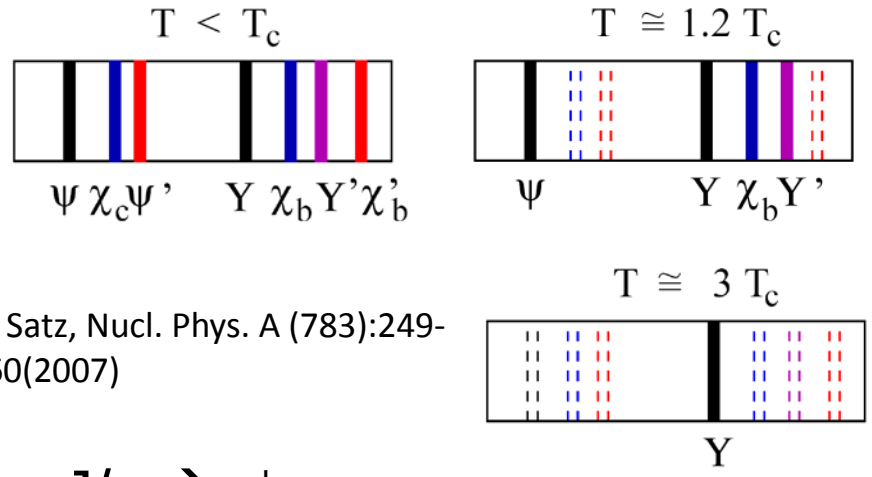




- Significant forward heavy flavor suppression
- Smaller than at midrapidity

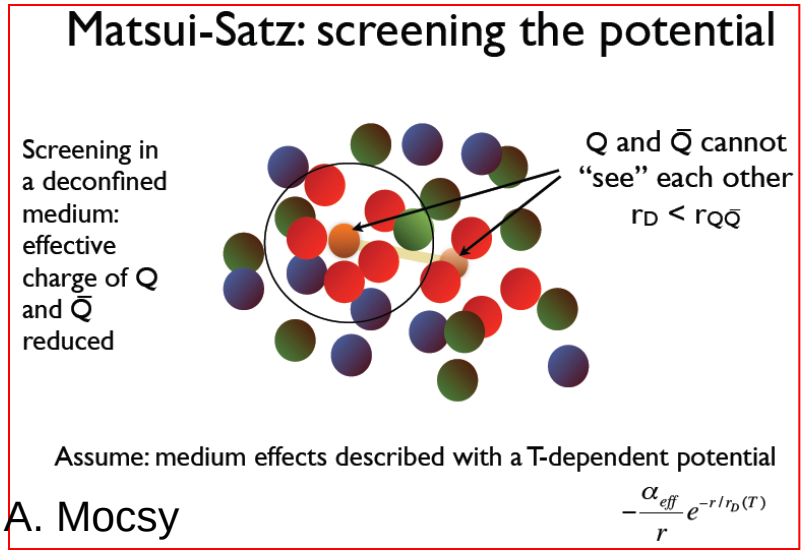
- Factor 4 larger yield than FONLL at low $p_T$

**PHENIX QM09: Nucl.Phys.A830:765C(2009)**

# Quarkonia




H. Satz, Nucl. Phys. A (783):249-260(2007)

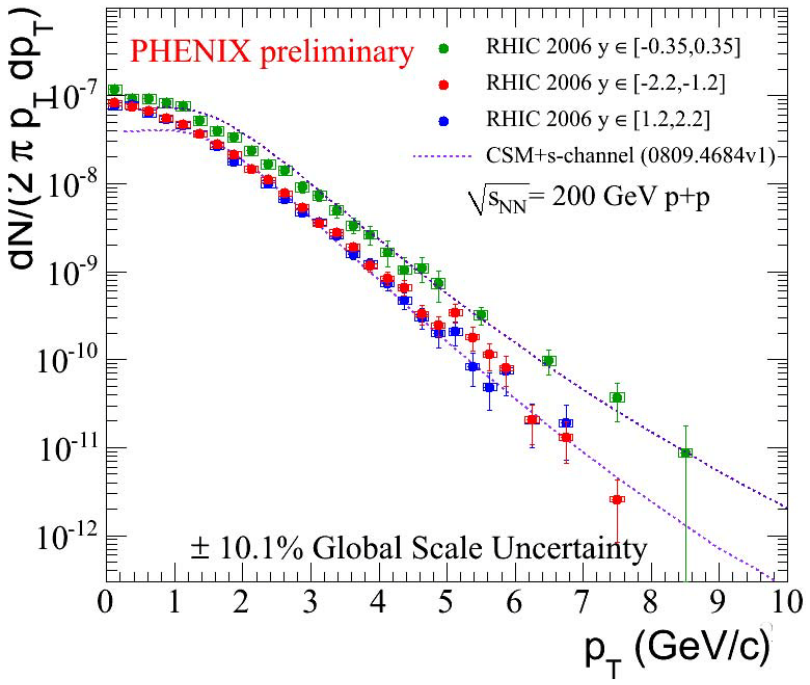


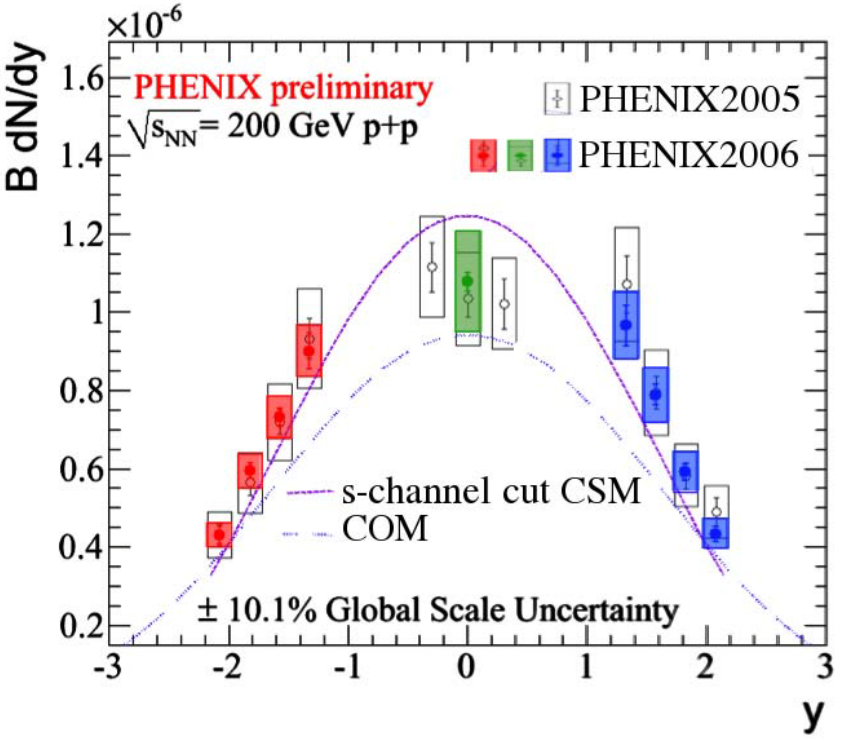

$J/\psi \rightarrow e^+e^-$

$\Upsilon \rightarrow e^+e^-$

- How they melt in hot/dense nuclear matter?
- What is production mechanism at RHIC?

# PHENIX J/$\psi$ in p+p 200 GeV

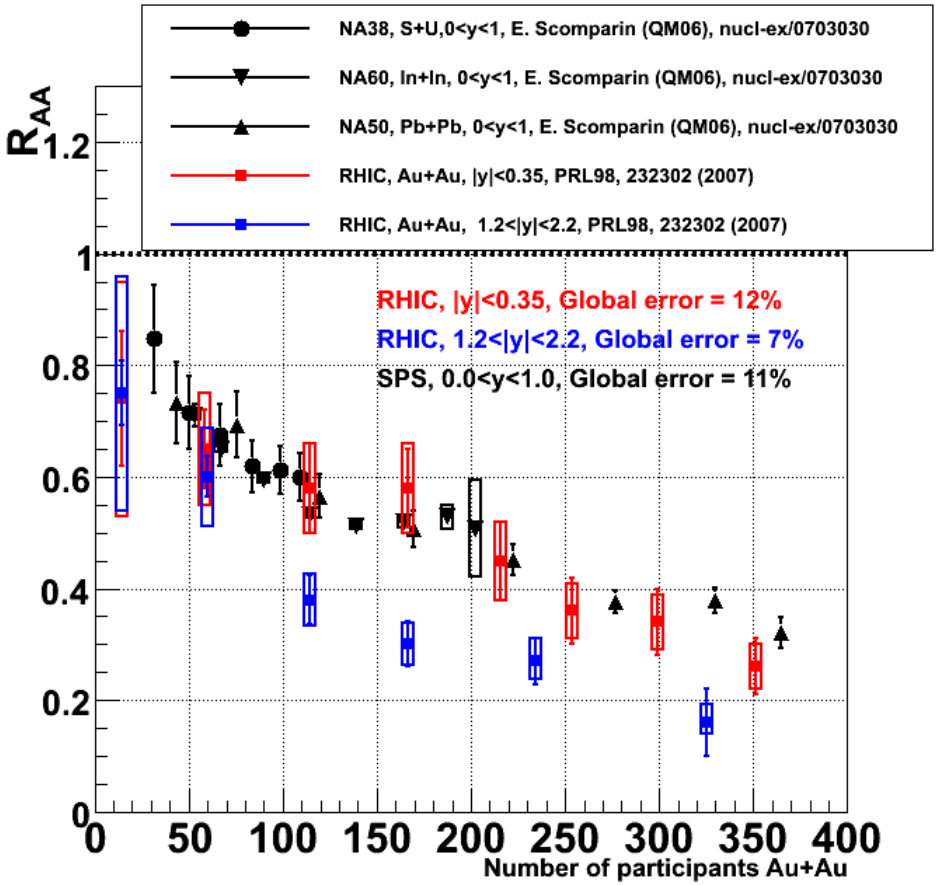



PHENIX QM09 arXiv:0907.4696

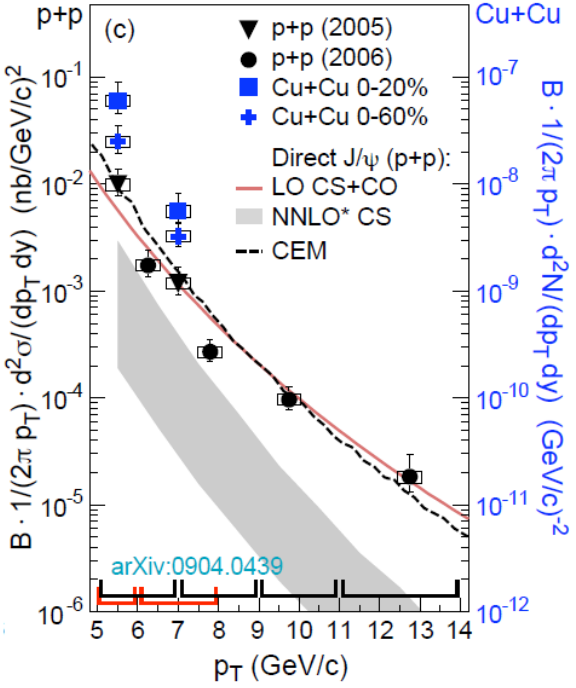
- both mid and forward results well described by the s-channel cut Color Singlet Model (CSM)

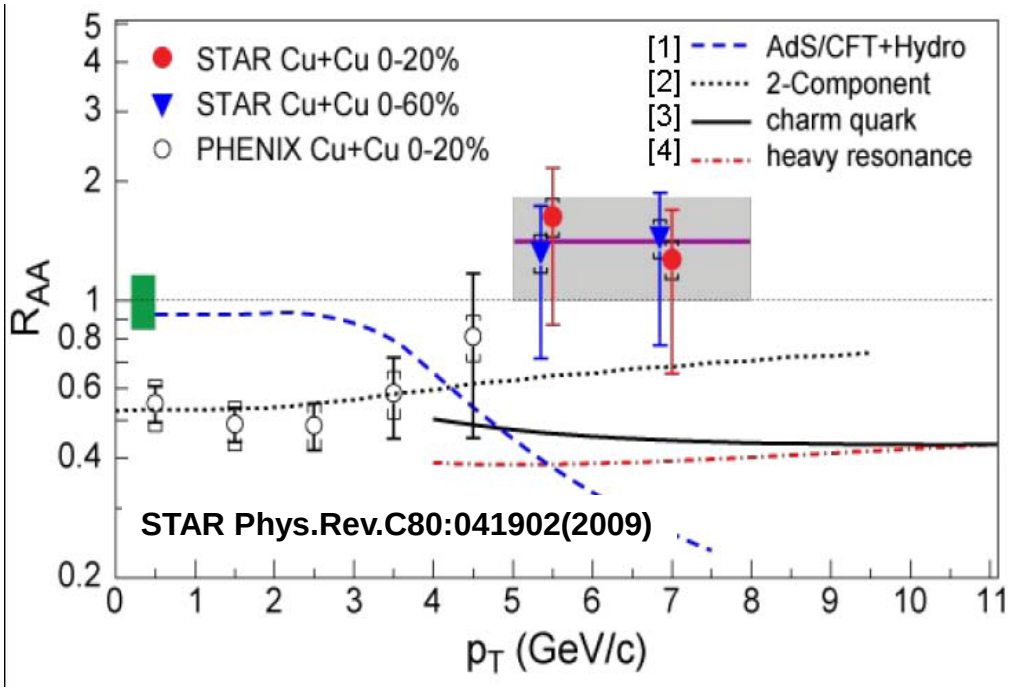
# The "RHIC J/$\psi$ puzzle"




- Suppression doesn't increase with local density
  - $R_{AA}$ (|y|<0.35) > $R_{AA}$ (1.2<|y|<2.2)
  - $R_{AA}$ (RHIC, |y|<0.35) ≈ $R_{AA}$ (SPS)
- Possible candidates
  - Suppression (gluon diss.)
  - Sequential melting
  - Regeneration
  - Gluon saturation
  - Some combination of all
- Obviously only part of the suppression is anomalous

# J/ψ in p+p and Cu+Cu 200 GeV



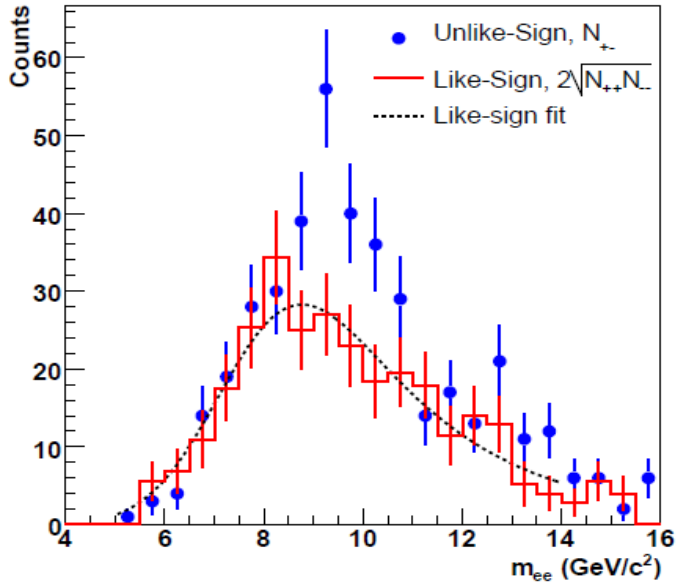

- **$R_{AA}(p_T>5$ GeV/c) = 1.4± 0.4±0.2**
- Consistent with no suppression at high $p_T$
- Expectation of J/ψ suppression at high $p_T$ from strong open charm suppression from color octet model

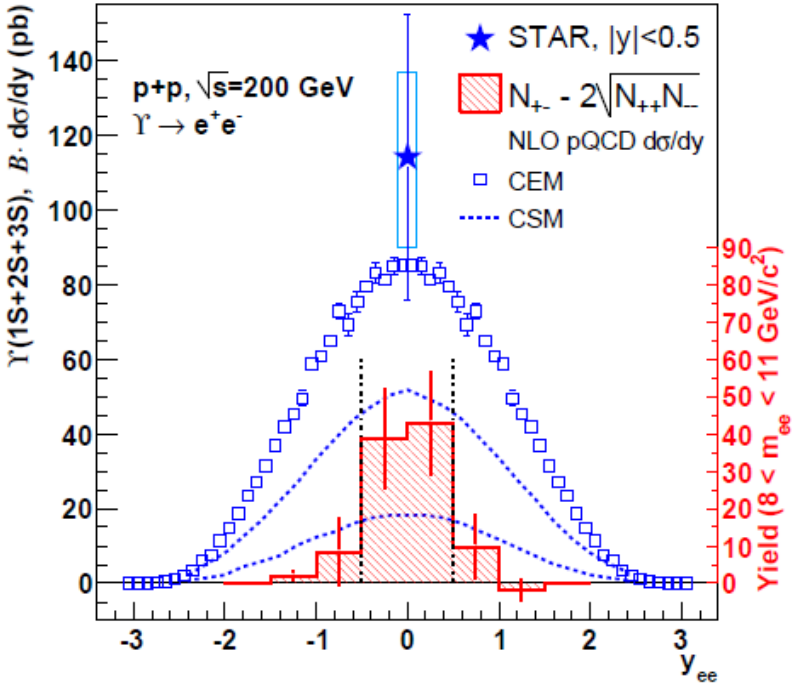
A. Adil and I. Vitev, Phys.Lett. B649, 139 (2007), private c.
S. Wicks et al., Nucl. Phys. A784, 426 (2007), and W. A. Horowitz private communication.

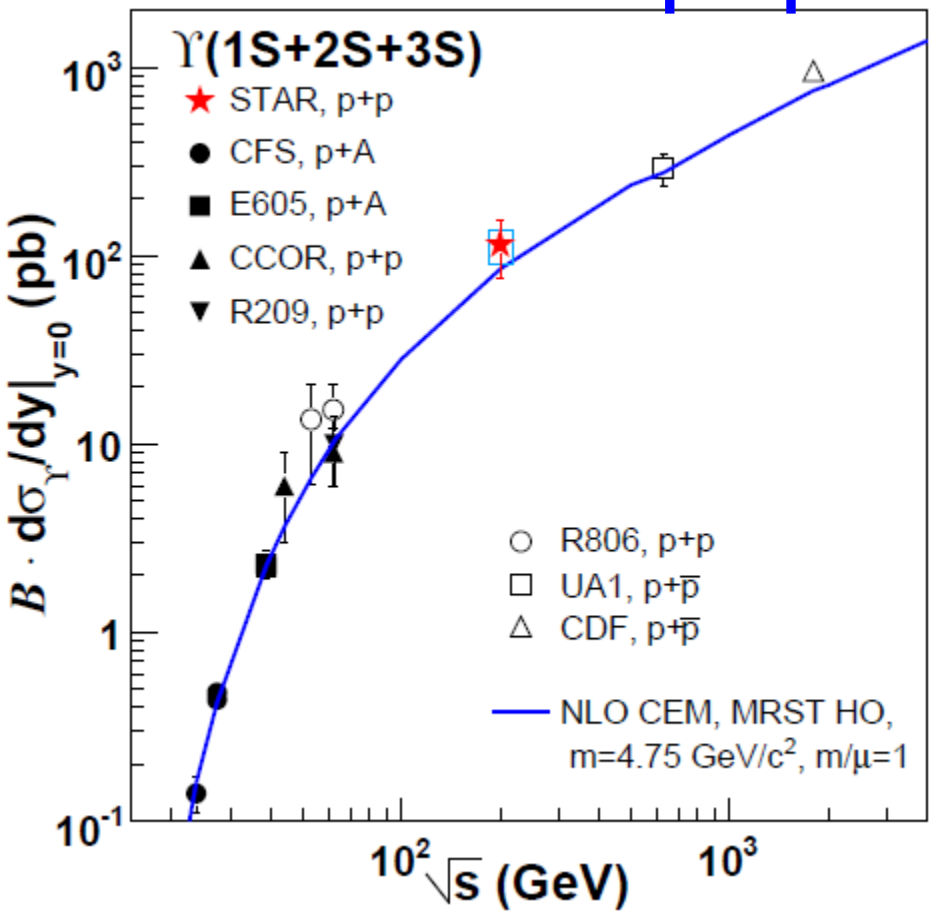
- Two component model+J/ψ form. time+ B feeddown describes the trend well

R. Rapp, X. Zhao, nucl-th/0806.1239

# STAR $\Upsilon$ measurements in p+p



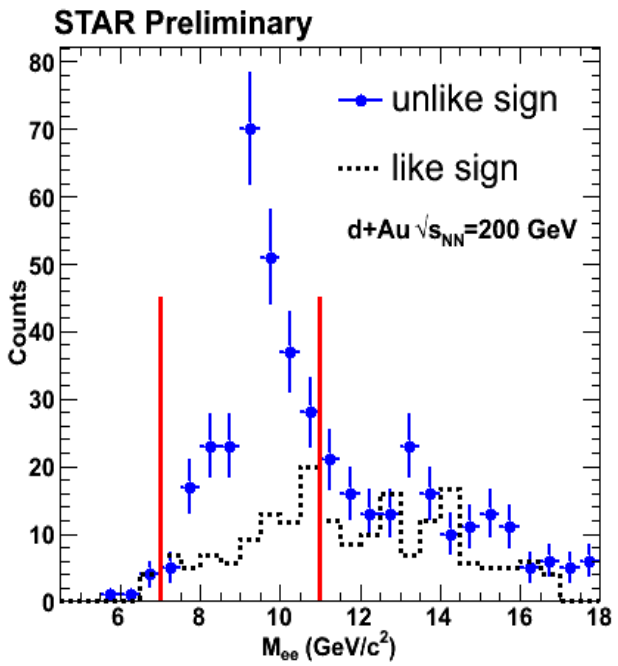



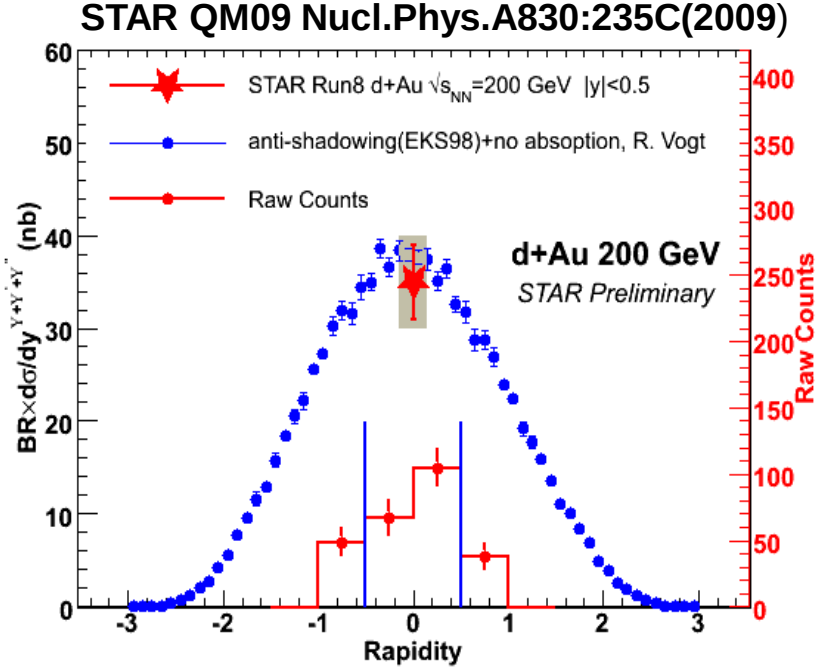

$$B_{ee}\left.\frac{d\sigma}{dy}\right|_{y=0} = 114 \pm 38(stat)^{+23}_{-24}(sys) \quad \text{pb}$$



**NEW STAR: arXiv:1001.2745**

# ϒ signal in d+Au 200 GeV collisions




- Strong signal (8σ significance) extracted

$$B_{ee} \times \left( \frac{d\sigma}{dy} \right)_{y=0}^{Y+Y'+Y''} = 35 \pm 4(stat.) \pm 5(syst.)\ pb$$

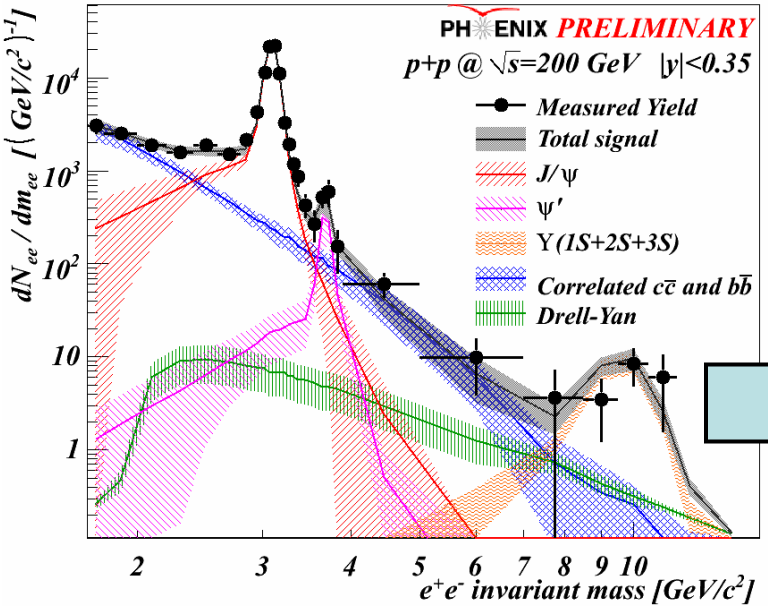
$$R_{dAu} = 0.98 \pm 0.32\ (stat.) \pm 0.28\ (sys.)$$

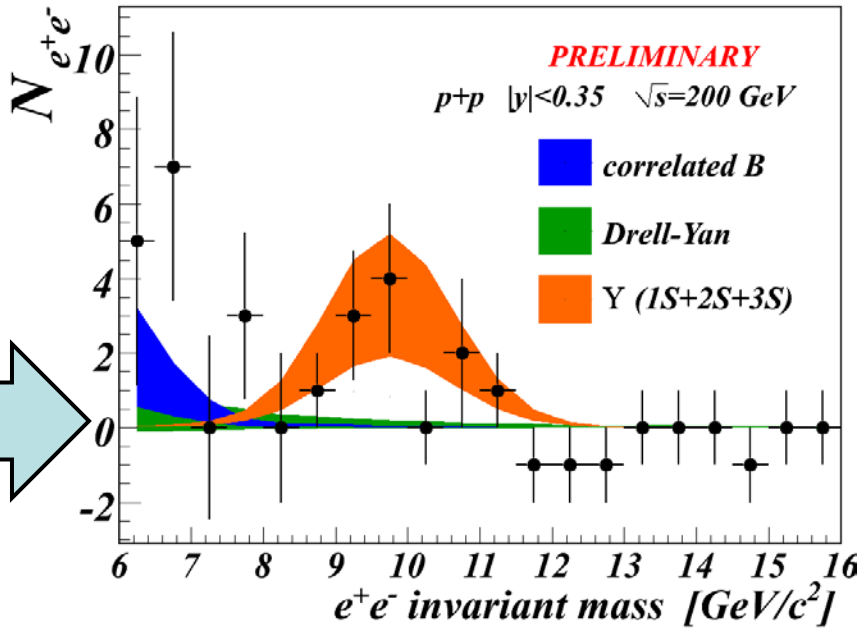
- Consistent with $N_{bin}$ scaling of cross-section p+p ⟶ d+Au 200GeV



jaroslav.bielcik@fjfi.cvut.cz

# Quarkonia Production & Suppression – Upsilons in p+p

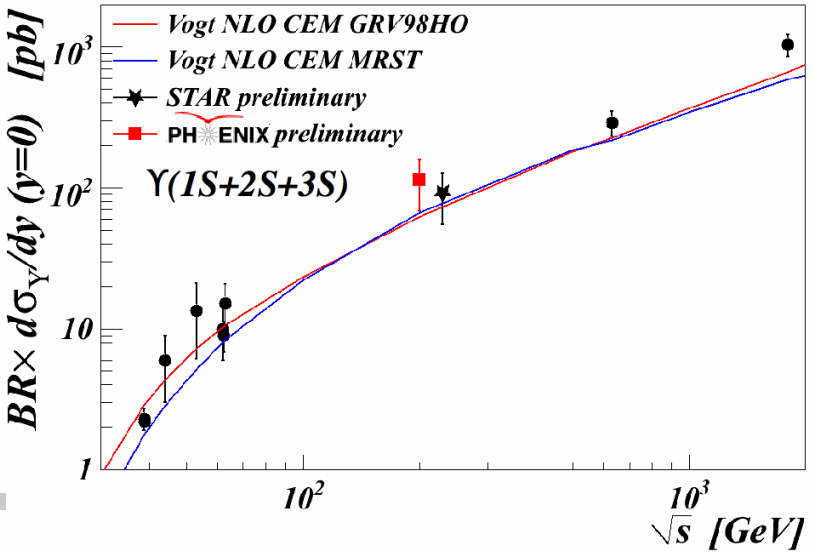


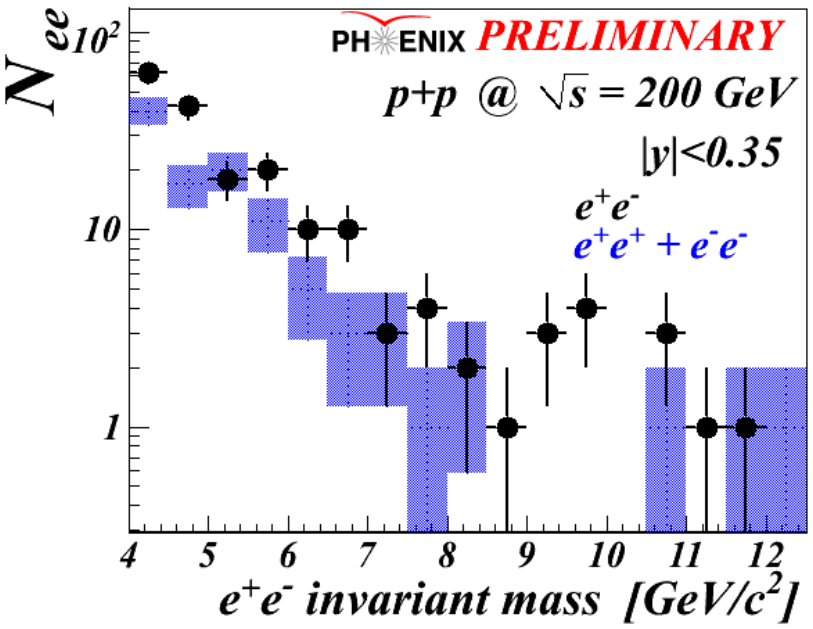

Nucl.Phys.A830:331C,(2009)

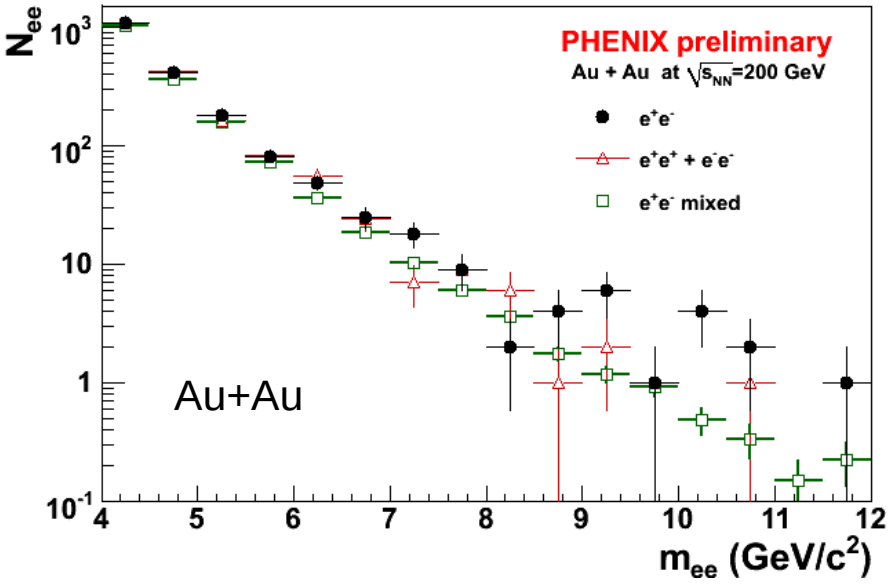
- Cross section follows world trend
- Baseline for Au+Au

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

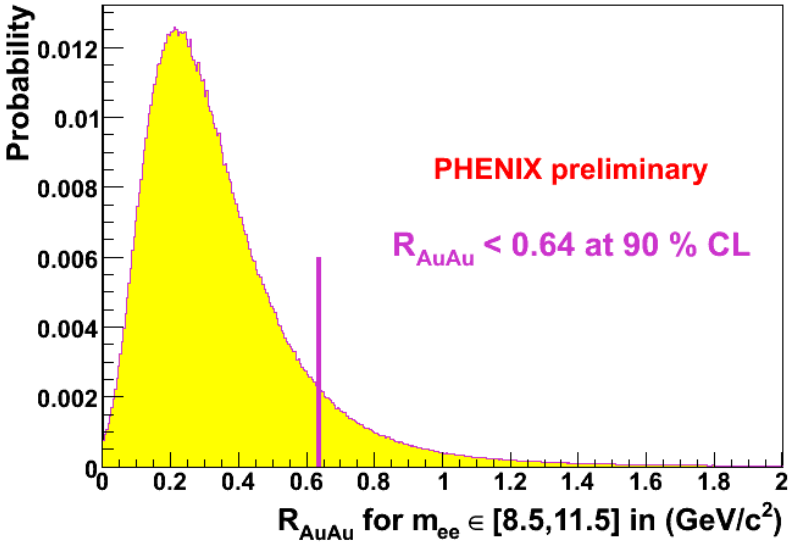


# Upsilons Suppressed in Au+Au




$R_{AuAu}$ [8.5,11.5] < 0.64 at 90% C.L.




Nucl.Phys.A830:331C,(2009)

# Conclusions

- Heavy flavor is an important tool to understand medium properties
- **RHIC** results are interesting and challenging

**charm measurement**

- STAR x PHENIX cross section not settled

**non-photonic electrons**

- Bottom  relative contribution consistent with FONLL
- Strong high-$p_T$ suppression in Au+Au
- Heavy quark energy loss not  fully understood

**muons forward y**

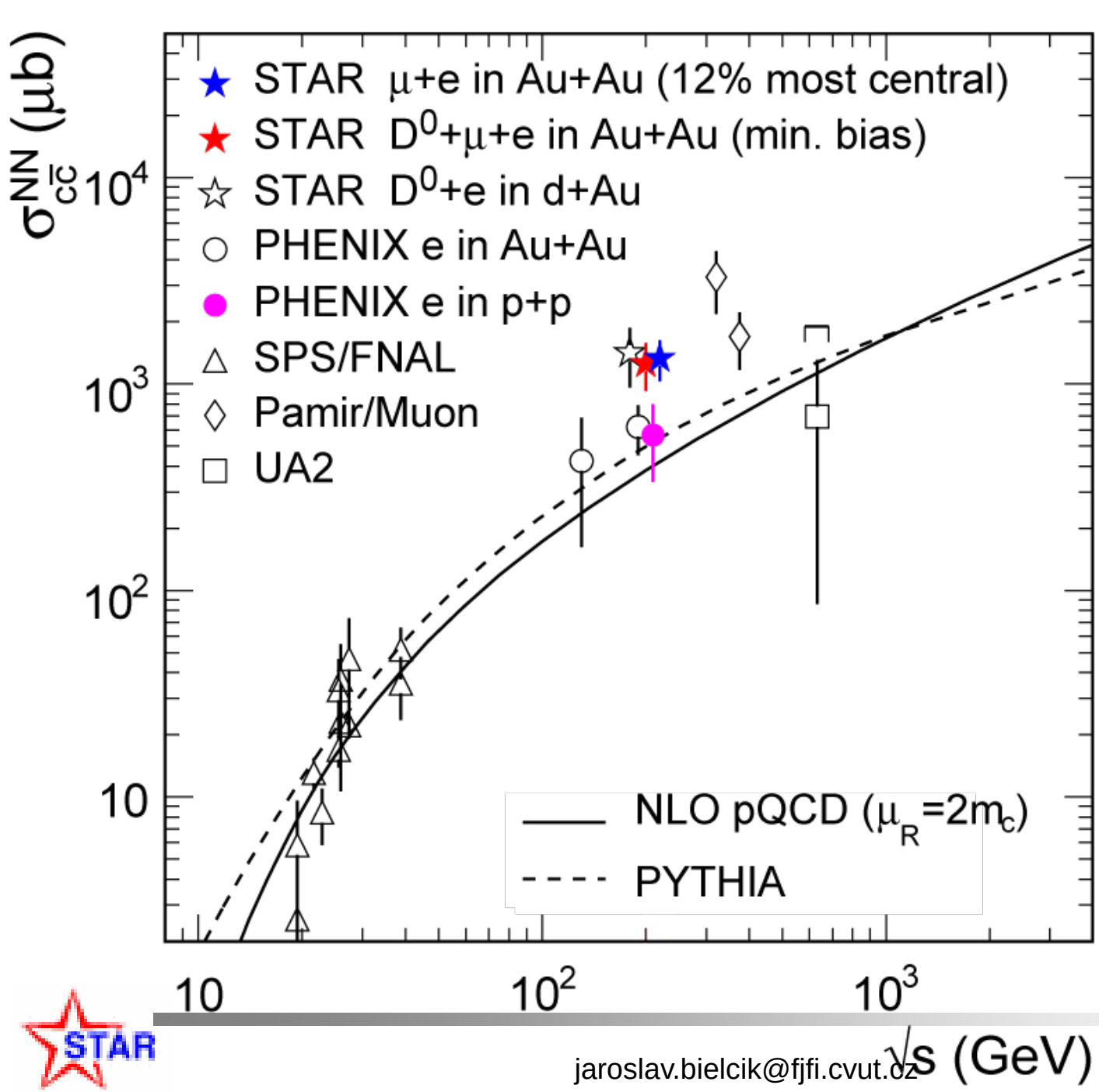
- FONNL 4x higher than PHENIX

**J/Psi**

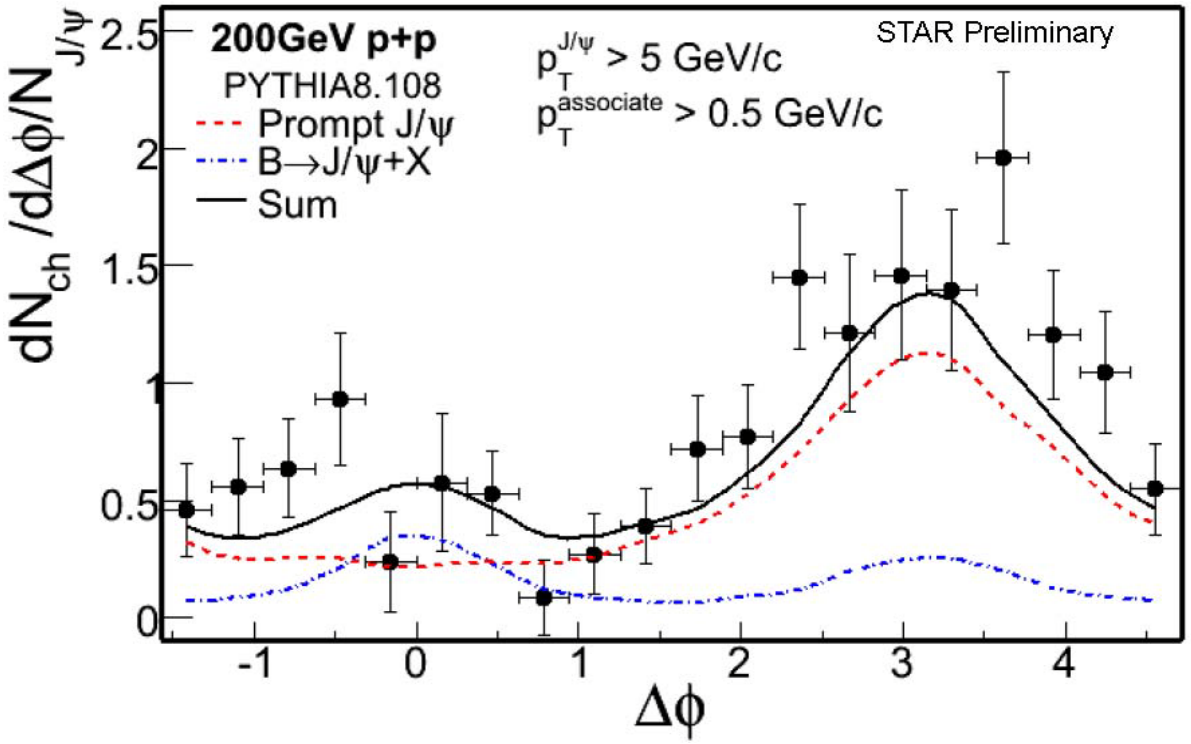
- suppression puzzle
- Cu+Cu consistent with no suppression at high-$p_T$

**Upsilon**

- Cross section measurement in p+p and dAu
- Follows $N_{bin}$ scaling
- Au+Au possible suppression

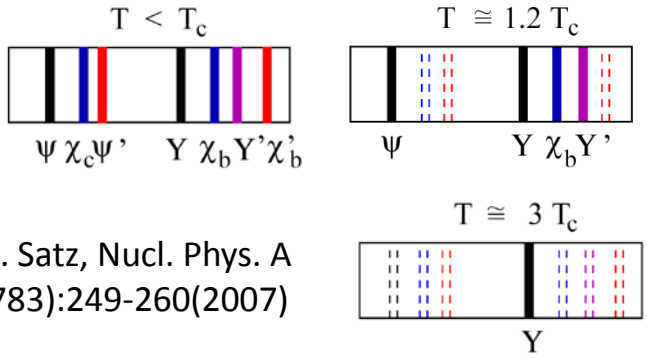

STAR μ+e in Au+Au (12% most central)
STAR D0+μ+e in Au+Au (min. bias)
STAR D0+e in d+Au
PHENIX e in Au+Au
PHENIX e in p+p
SPS/FNAL
Pamir/Muon
UA2
NLO pQCD (μR=2mc)
PYTHIA
σccNN (μb)
10
10^2
10^3
10^4
√s (GeV)

# High-$p_T$ J/$\psi$ - hadron correlations




- Near-side correlation due dominantly to **B → J/ψ+X**
- B-meson feeddown to inclusive J/$\psi$ production of **13%± 5%** at $p_T$ > 5 GeV/c.

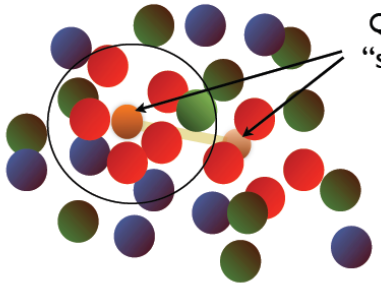
# Color screening and sequential suppression of quarkonia




H. Satz, Nucl. Phys. A (783):249-260(2007)

## Matsui-Satz: screening the potential

Screening in a deconfined medium: effective charge of Q and $\bar{Q}$ reduced



Q and $\bar{Q}$ cannot "see" each other $r_D < r_{Q\bar{Q}}$

Assume: medium effects described with a T-dependent potential

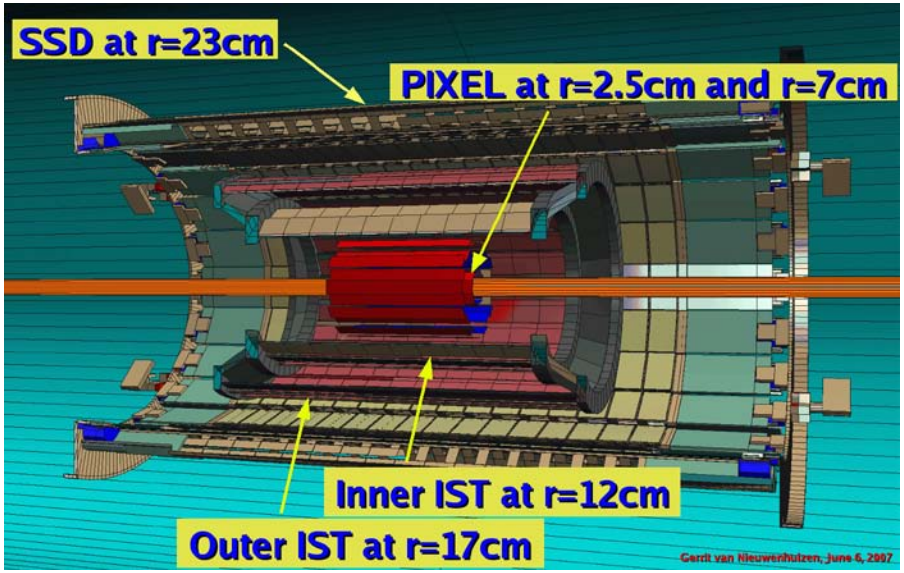
A. Mocsy

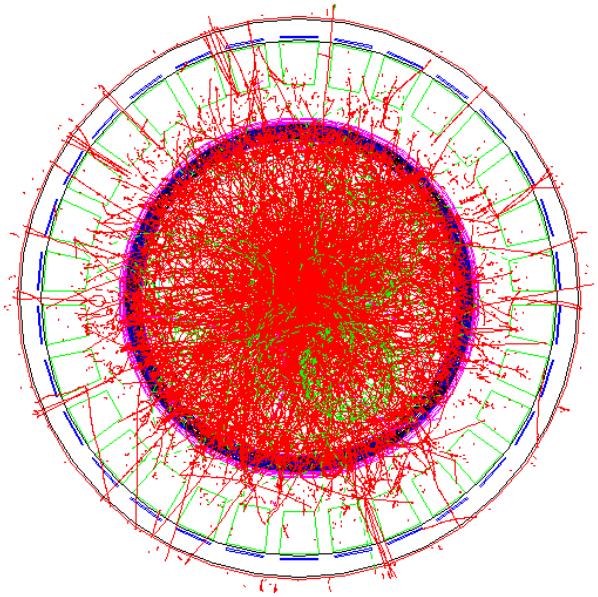
$$-\frac{\alpha_{eff}}{r} e^{-r/r_D(T)}$$

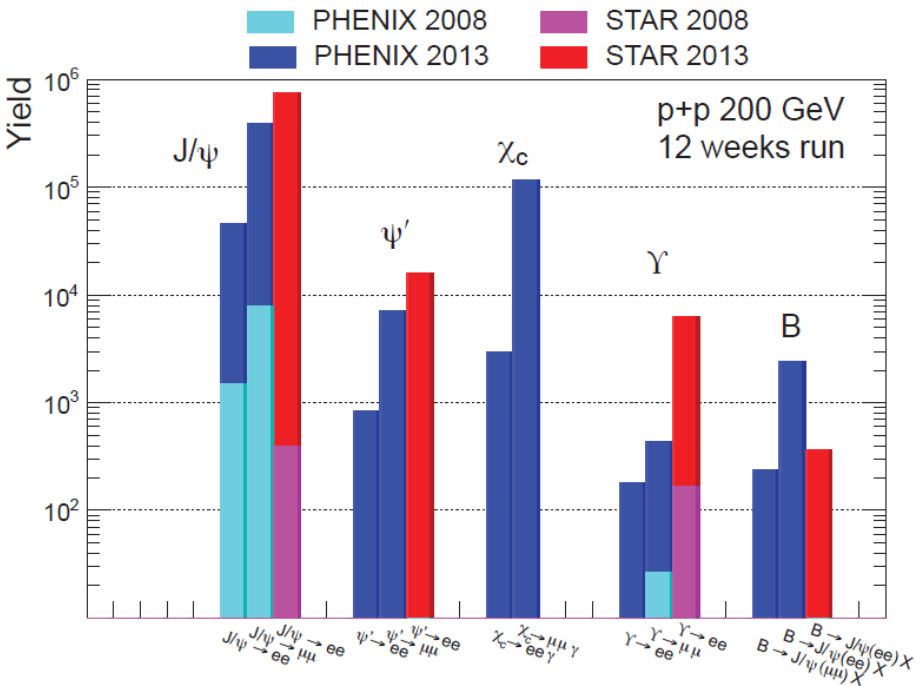
**J/ψ suppression at low $p_T$ maybe from excited stats (ψ', $\chi_c$)** F. Karsch, D. Kharzeev and H. Satz, PLB 637, 75 (2006); B. Alessandro et al. (NA50), Eur. Phys. J. C 39 (2005) 335; R. Arnaldi et al. (NA60), Quark Matter 2005; PHENIX: Phys.Rev.Lett.98, 232301,2007.

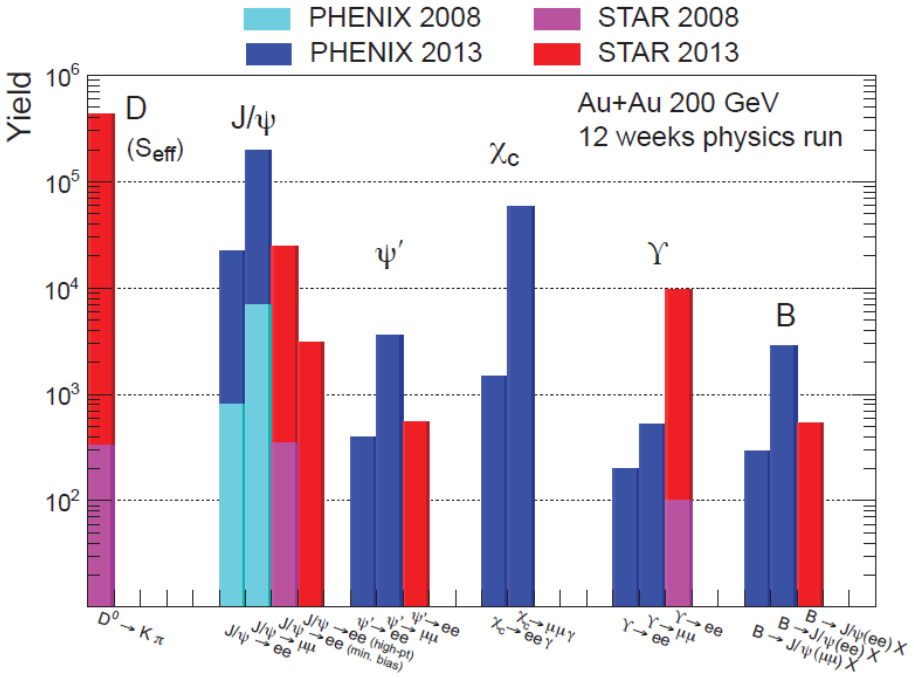
**60% from direct J/ψ: not suppressed**
**30% $\chi_c$ and 10% ψ': dissociated**

# Future of Heavy Flavor Measurement at STAR






Source: Phys. Rept. 462: 125-175, 2008

Courtesy of T. Ullirich

Source: Phys. Rept. 462: 125-175, 2008

# Examples of Future Measurements