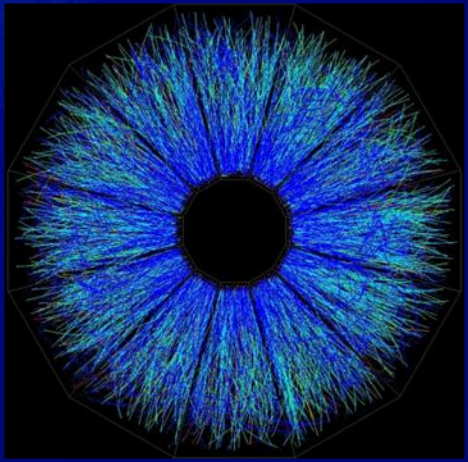
Open heavy flavor and quarkonia measurements in heavy ion collisions at RHIC



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International Conference on New Frontiers in Physics , Κρήτη, June 2012

Outline

- Motivation for heavy flavor physics
- Open heavy flavor
  - Charm mesons
  - Non-photonic electrons
- Quarkonia
  - J/ψ and Υ measurements
- Summary and Outlook

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Relativistic Heavy Ion Collider

RHIC site in BNL on Long Island - taking data from 2000

RHIC has been exploring nuclear matter at extreme conditions over the last 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
Cu+Au, U+U

Energies
$\sqrt{s_{NN}}$ = 20, 62, 130, 200 GeV (500 GeV)
+ 7.7, 11.5, 27, 39 GeV

Heavy quarks as a probe of QGP

- 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.

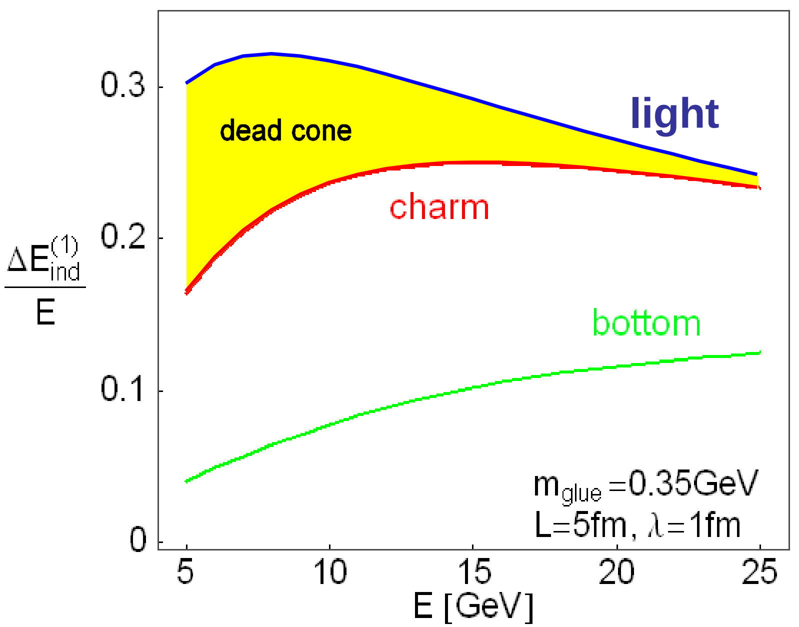
→ production rates calculable by pQCD.
M. Gyulassy and Z. Lin, PRC 51, 2177 (1995)

- heavy ion data:

- Studying energy loss of heavy quarks.

→ independent way to extract properties of the medium.

ENERGY LOSS



M.Djordjevic PRL 94 (2004)

Quarkonia states in A+A

Charmonia: J/ψ, Ψ', χ_c Bottomonia: Υ(1S), Υ(2S), Υ(3S)

Key Idea: Quarkonia melt in the QG plasma due to color screening of potential between heavy quarks

- Suppression of states is determined by T_C and their binding energy
- Lattice QCD: Evaluation of spectral functions $\Rightarrow T_{melting}$

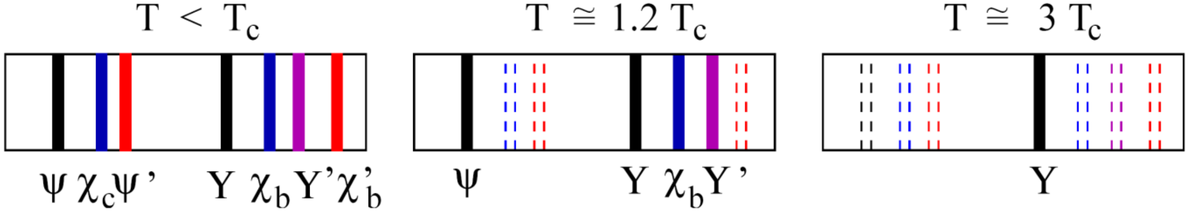
Sequential disappearance of states:

$\Rightarrow$ Color screening $\Rightarrow$ Deconfinement

$\Rightarrow$ QCD thermometer $\Rightarrow$ Properties of QGP

When do states really melt?

$T_{diss}(\psi') \approx T_{diss}(\chi_c) < T_{diss}(\Upsilon(3S)) < T_{diss}(J/\psi) \approx T_{diss}(\Upsilon(2S)) < T_{diss}(\Upsilon(1S))$

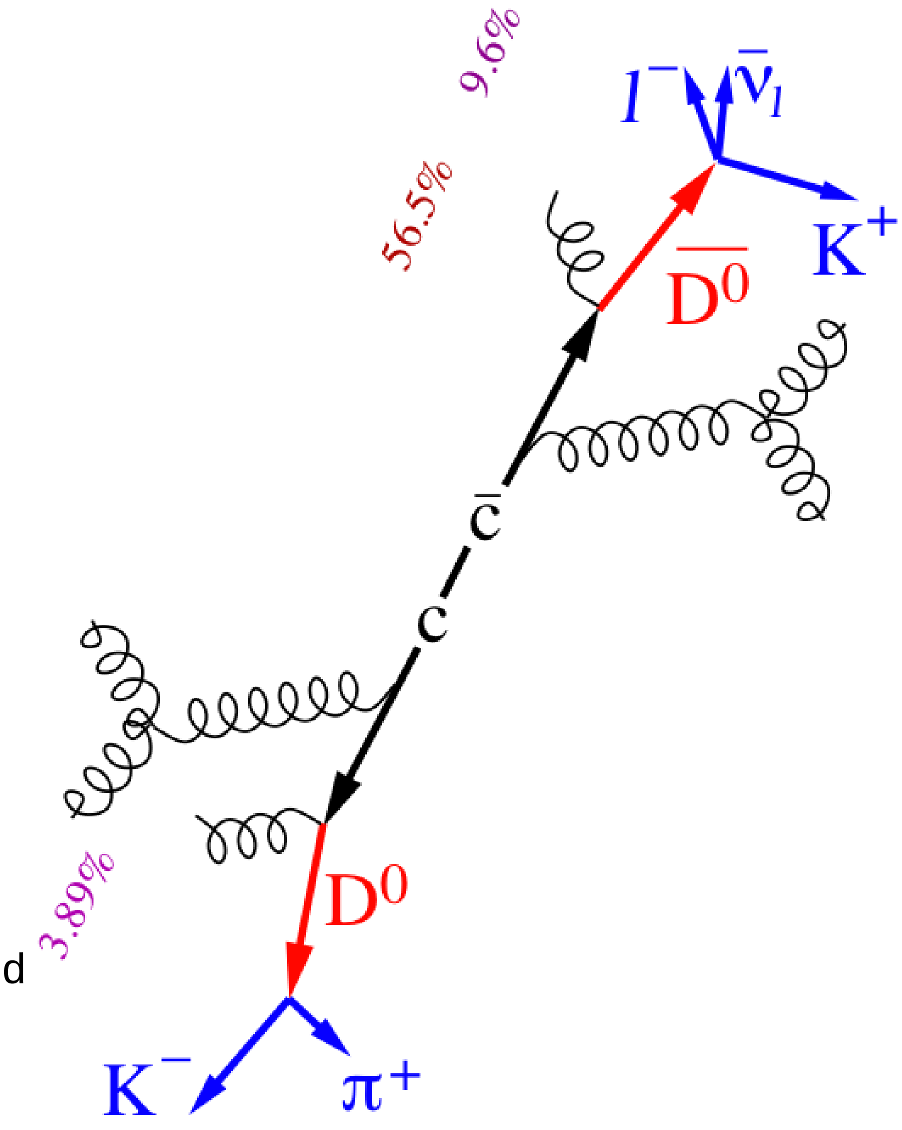


H. Satz, HP2006

Open heavy flavor

- **Direct reconstruction**
  - direct access to heavy quark kinematics
  - hard to trigger (high energy trigger only for correlation measurements)
  - smaller Branching Ratio (B.R.)
  - large combinatorial background (need handle on decay vertex)

- **Indirect measurements through decay leptons**
  - can be triggered easily (high p_T)
  - higher B.R.
  - indirect access to the heavy quark kinematics
  - mixing contribution from all charm and bottom hadron decays



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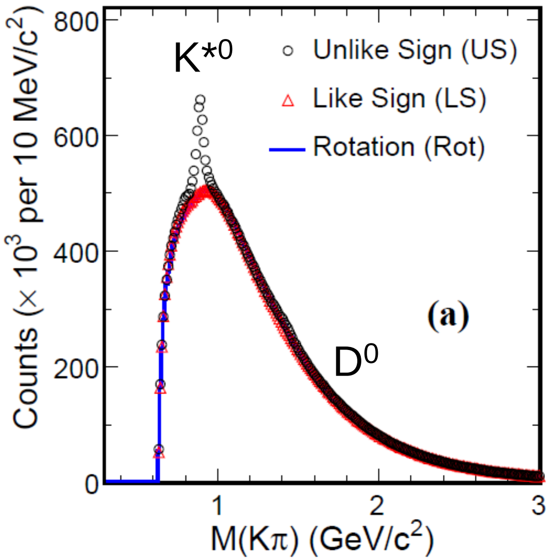
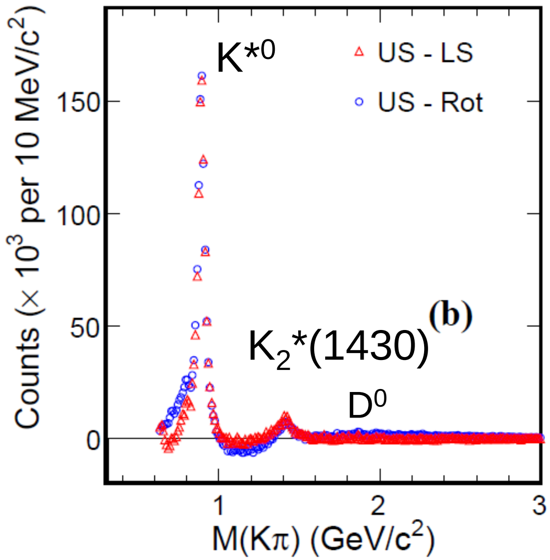
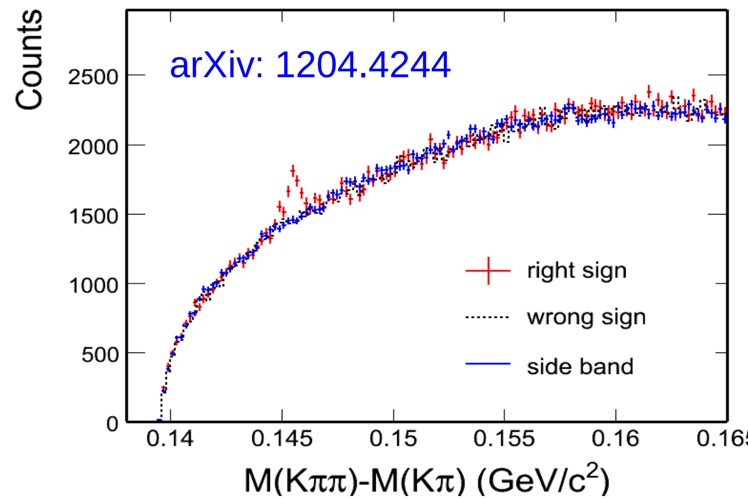
D^0 and D* signal in p+p and Au+Au 200 GeV

STAR arXiv: 1204.4244

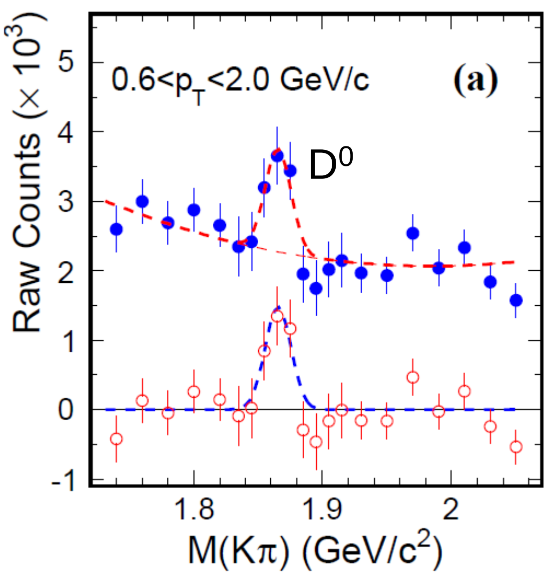




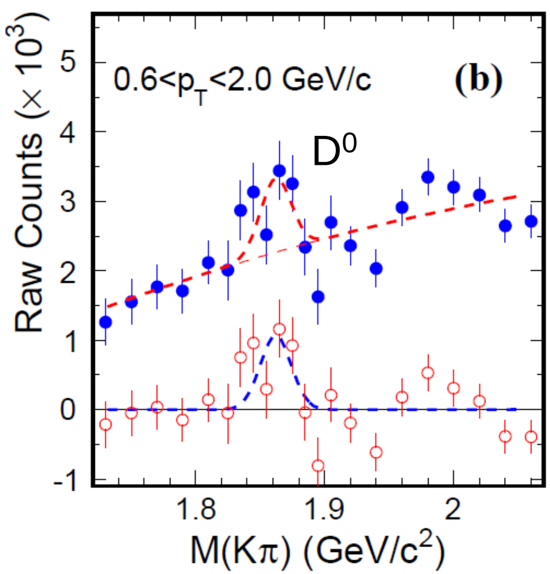
$$D^{*\pm} \rightarrow D^0(\overline{D^0}) + \pi^\pm \rightarrow K^\mp \pi^\pm \pi^\pm$$



D^0 mass window zoom



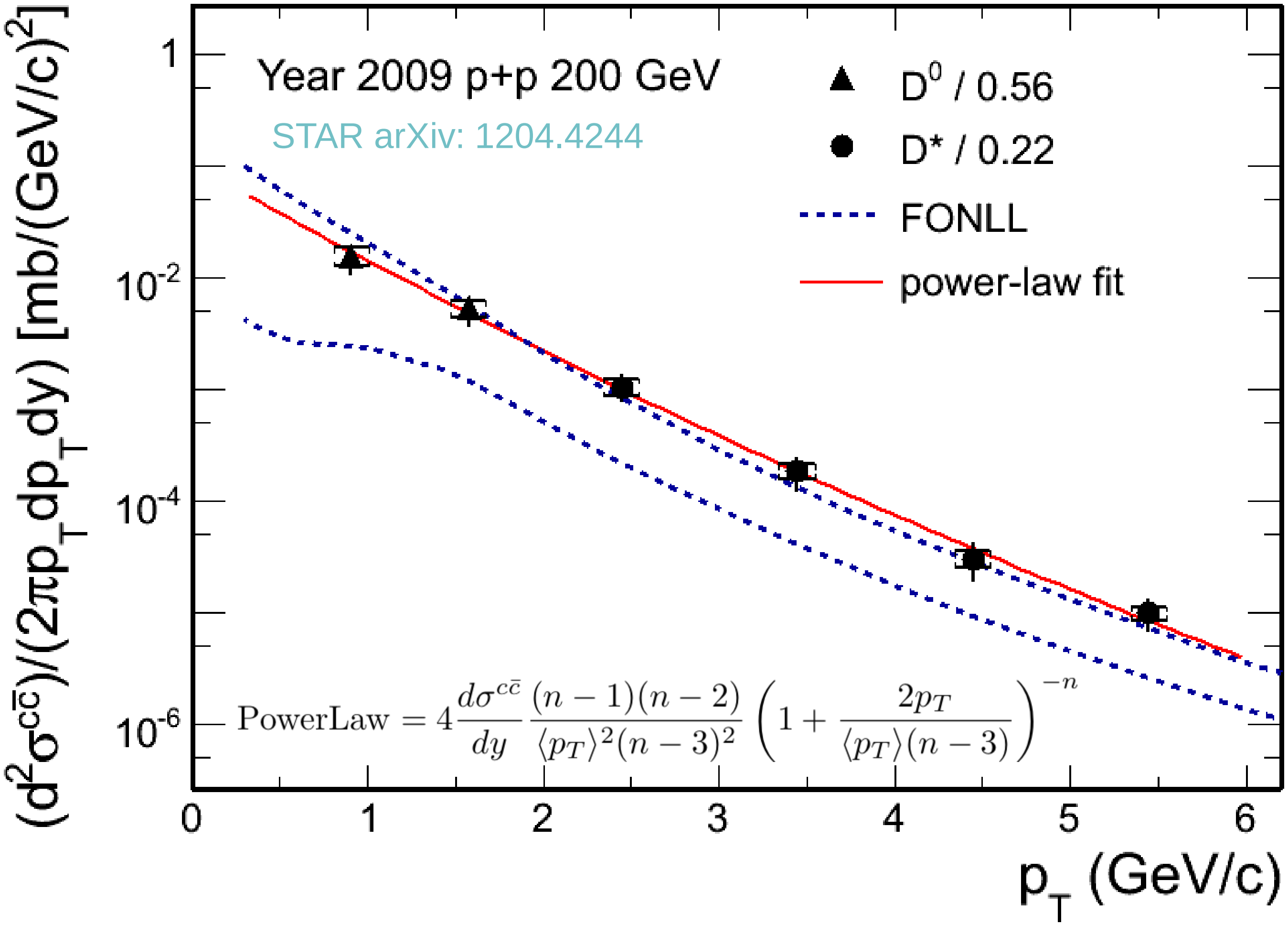
D^0 mass window zoom



Different methods reproduce combinatorial background.

Consistent results from two background methods.

D^0 and D* p_T spectra in p+p 200 GeV



D^0 scaled by N_{D0}/N_{cc}= 0.56[1]

D^* scaled by N_{D*}/N_{cc}= 0.22[1]

Consistent with FONLL[2] upper limit.

Xsec = $dN/dy|^{cc}_{y=0}$ * F * σ_{pp}

F = 4.7 ± 0.7 scale to full rapidity.

σ_{pp}(NSD) = 30 mb

The charm cross section at mid-rapidity is:

$$170 \pm 45(\text{stat.})^{+37}_{-51}(\text{sys.})\ \mu\text{b}$$

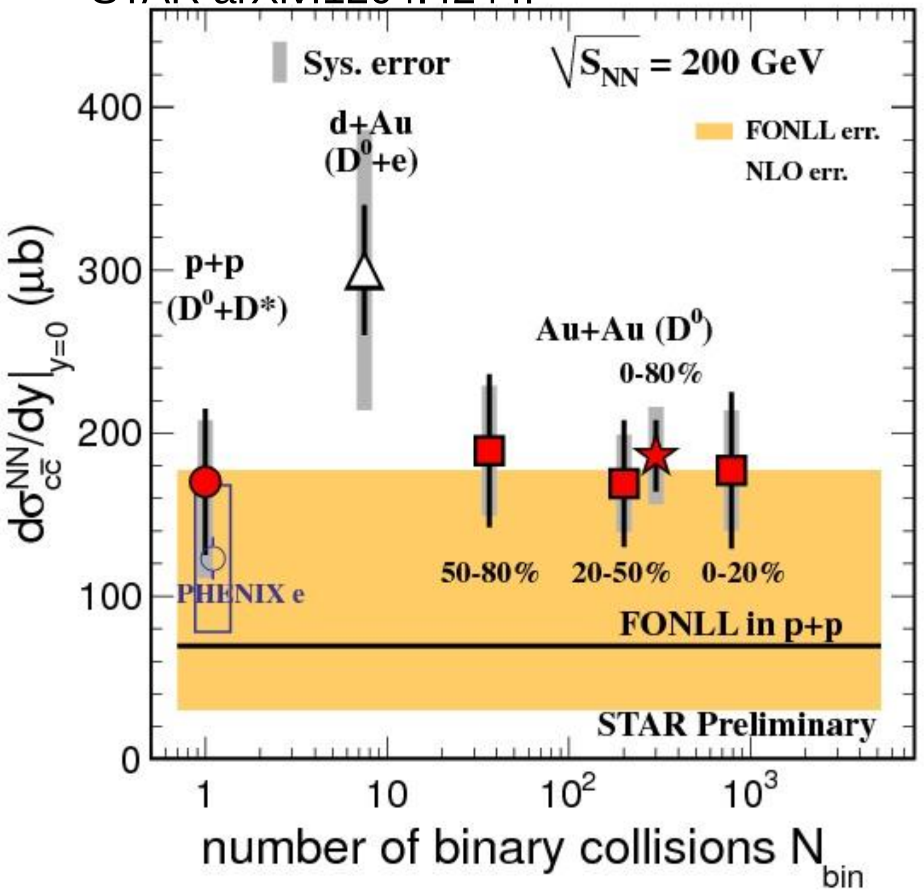
The charm total cross section is extracted as:

$$797 \pm 210(\text{stat.})^{+208}_{-262}(\text{sys.})\ \mu\text{b}$$

[1] C. Amsler et al. (Particle Data Group), PLB 667 (2008) 1.
[2] Fixed-Order Next-to-Leading Logarithm: M. Cacciari, PRL 95 (2005) 122001.

Charm cross section vs N_{bin}

YiFei Zhang, JPG 38, 124142 (2011)
STAR arXiv:1204.4244.



All of the measurements are consistent.

Year 2003 d+Au : D^0 + e

Year 2009 p+p : D^0 + D*

Year 2010 Au+Au: D^0

Assuming N_{D0} / N_{cc} = 0.56 does not change.

Charm cross section in Au+Au 200 GeV:

Mid-rapidity:

186 ± 22 (stat.) ± 30 (sys.) ± 18 (norm.) μb

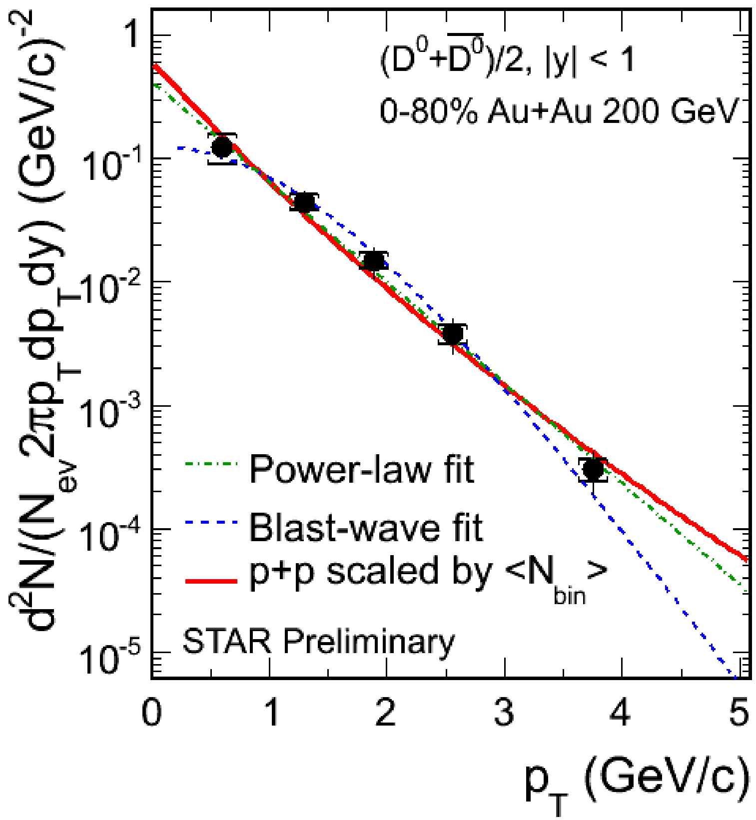
Total cross section:

876 ± 103 (stat.) ± 211 (sys.) μb

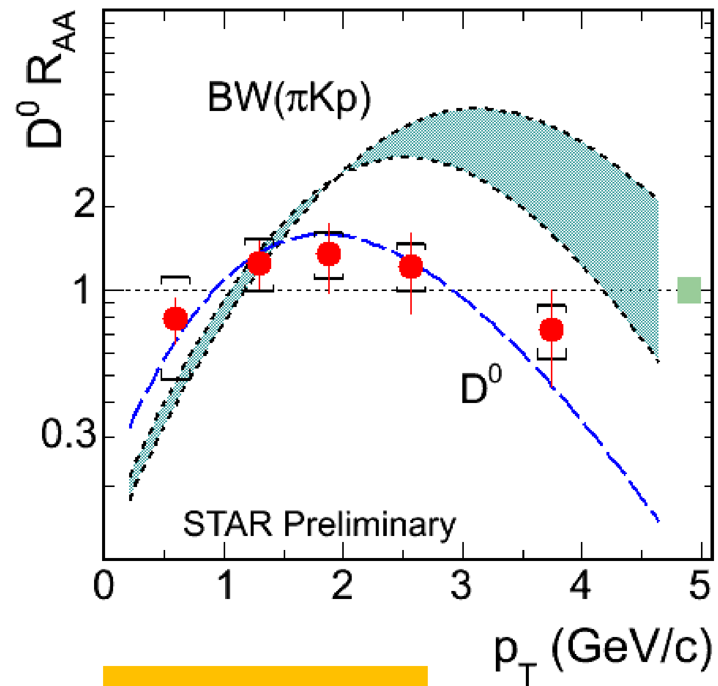
[1] STAR d+Au: J. Adams, et al., PRL 94 (2005) 62301
[2] FONLL: M. Cacciari, PRL 95 (2005) 122001.
[3] NLO: R. Vogt, Eur.Phys.J.ST 155 (2008) 213
[4] PHENIX e: A. Adare, et al., PRL 97 (2006) 252002.

Charm cross section follows number of binary collisions scaling =>
Charm quarks are mostly produced via initial hard scatterings.

D^0 nuclear modification factor Au+Au 200 GeV



BW (πKp): B. I. Abelev, et al., Phys. Rev. C 79 (2009) 34909.



STAR QM2011

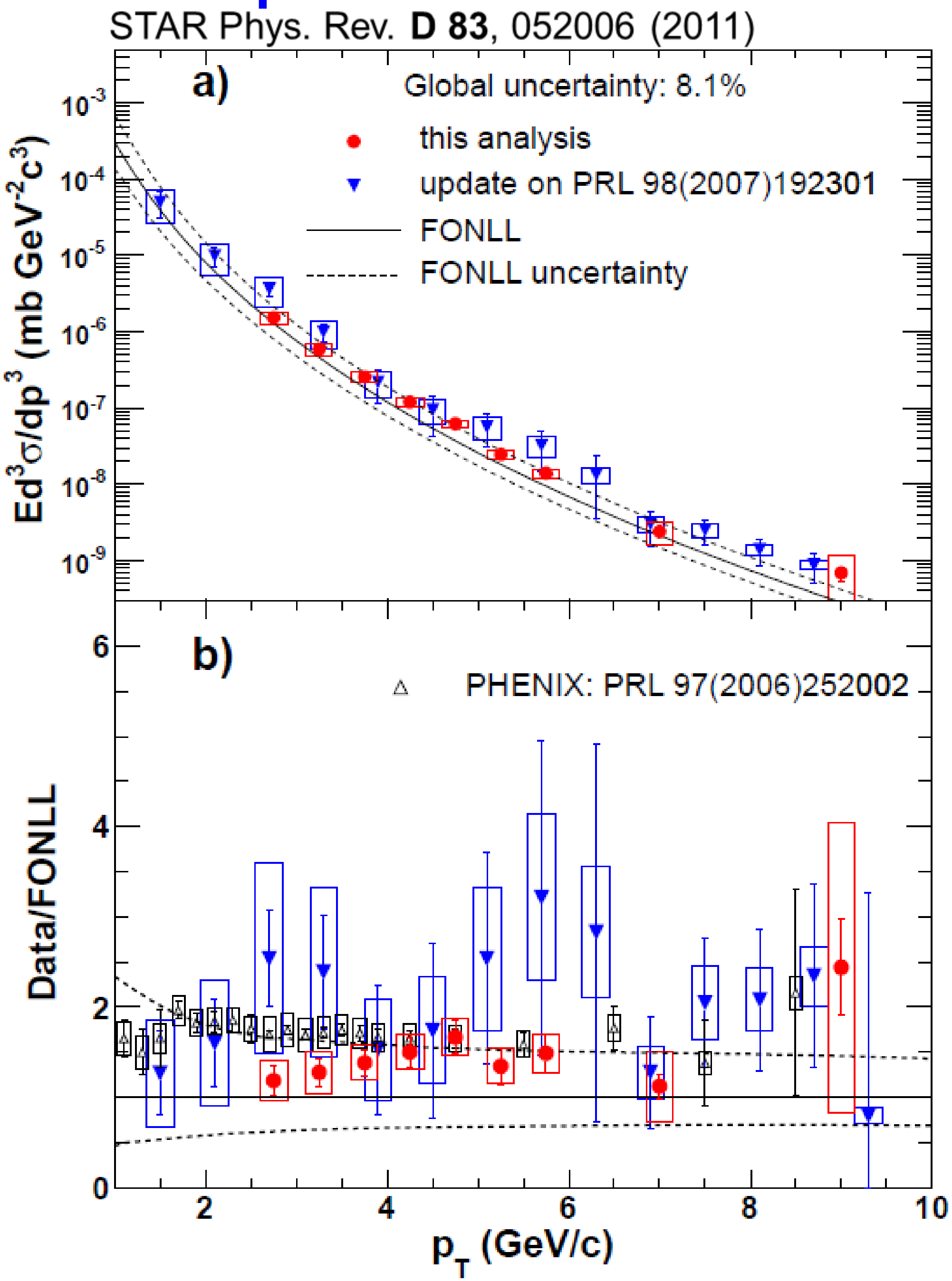
Au+Au 200 GeV:

- No obvious suppression at p_T < 3 GeV/c.

$$R_{AA}(p_T) = \frac{\text{Yield}_{AA}(p_T)}{\langle Nbin \rangle_{AA} \text{Yield}_{pp}(p_T)}$$

Non-photonic electrons

Non-photonic electrons in p+p 200GeV



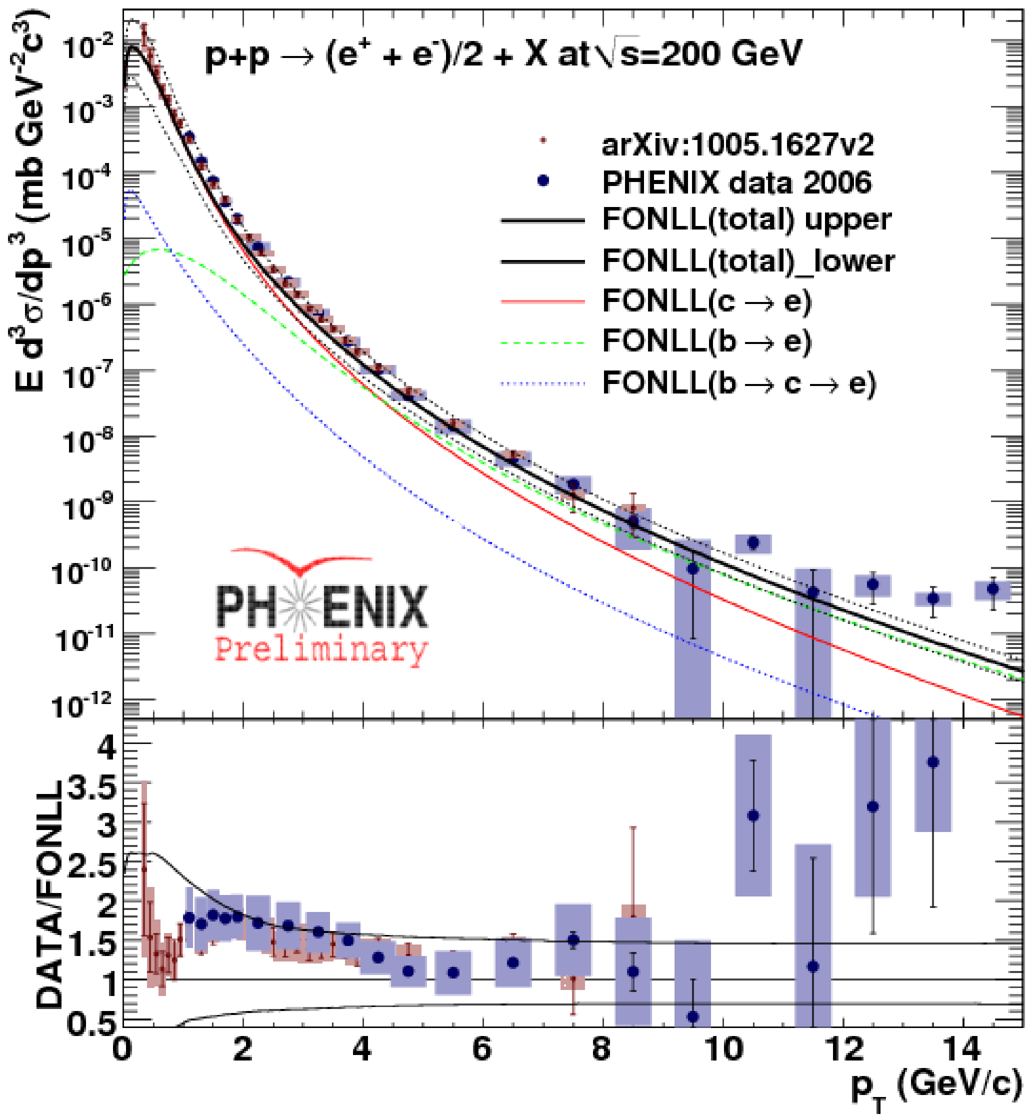
STAR and PHENIX NPE results in p+p 200GeV collisions

✓Are consistent within errors at pT > 2.5 GeV/c

NPE results are consistent with FONLL in p+p 200GeV collisions

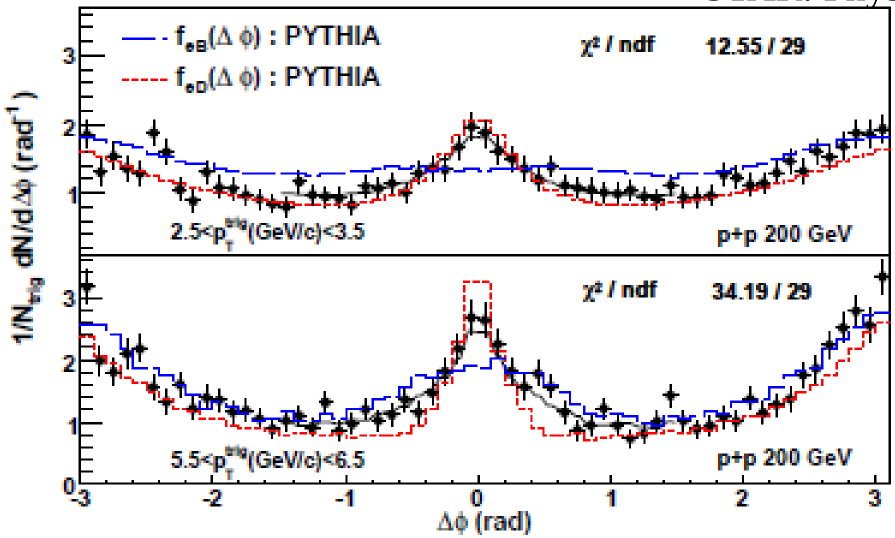
PHENIX update p+p 200 GeV

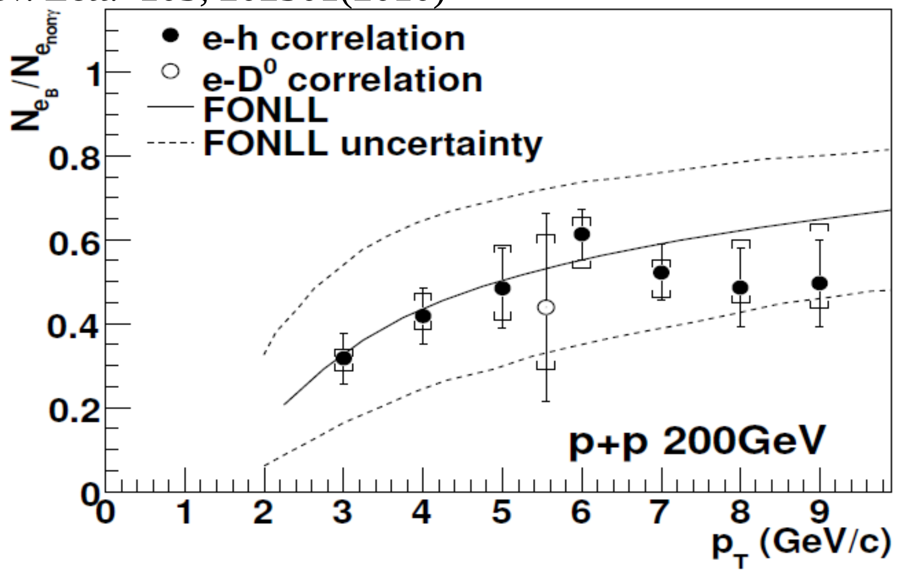
- Combined Run5 and Run6 p+p statistics
- Smaller uncertainties
  - Allows more precise R_{AA} comparisons
- Increased p_T range
- Consistent with previous results in overlap region



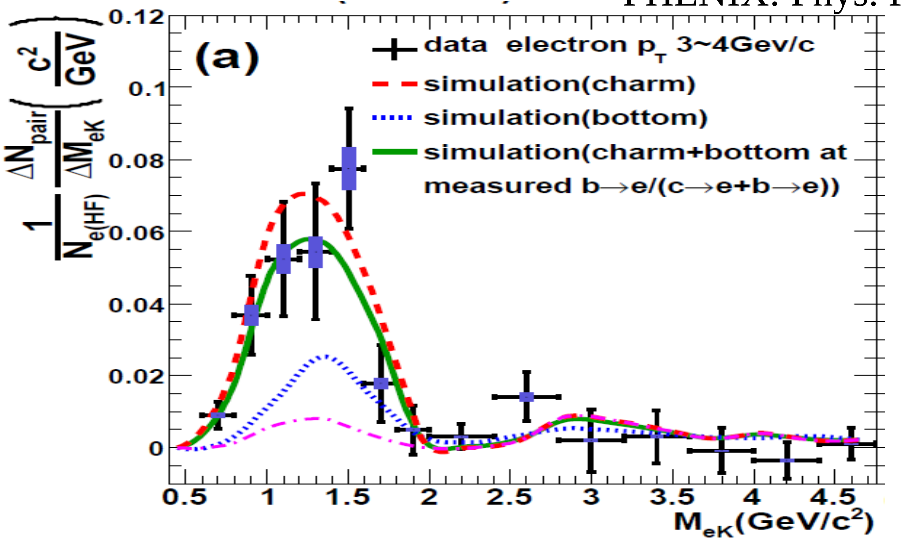
Separation of charm and bottom contribution

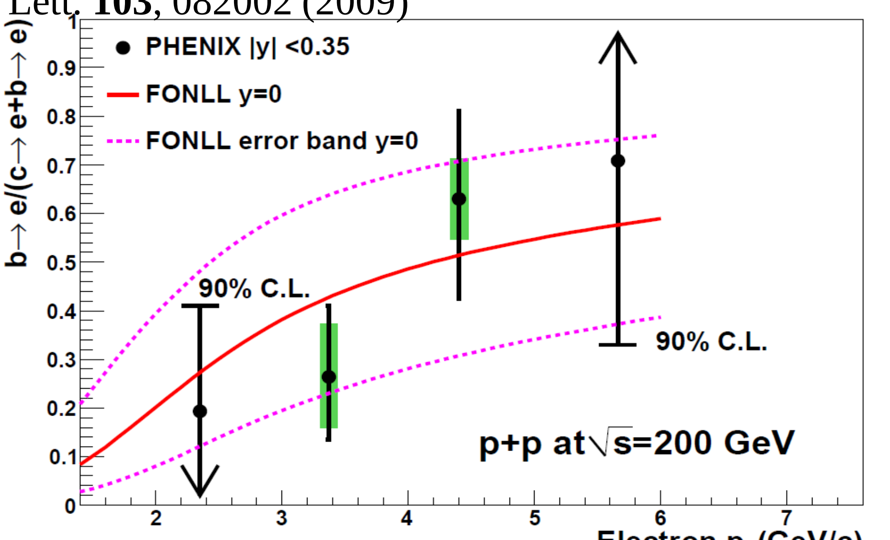
STAR: Phys. Rev. Lett. **105**, 202301(2010)





PHENIX: Phys. Rev. Lett. **103**, 082002 (2009)

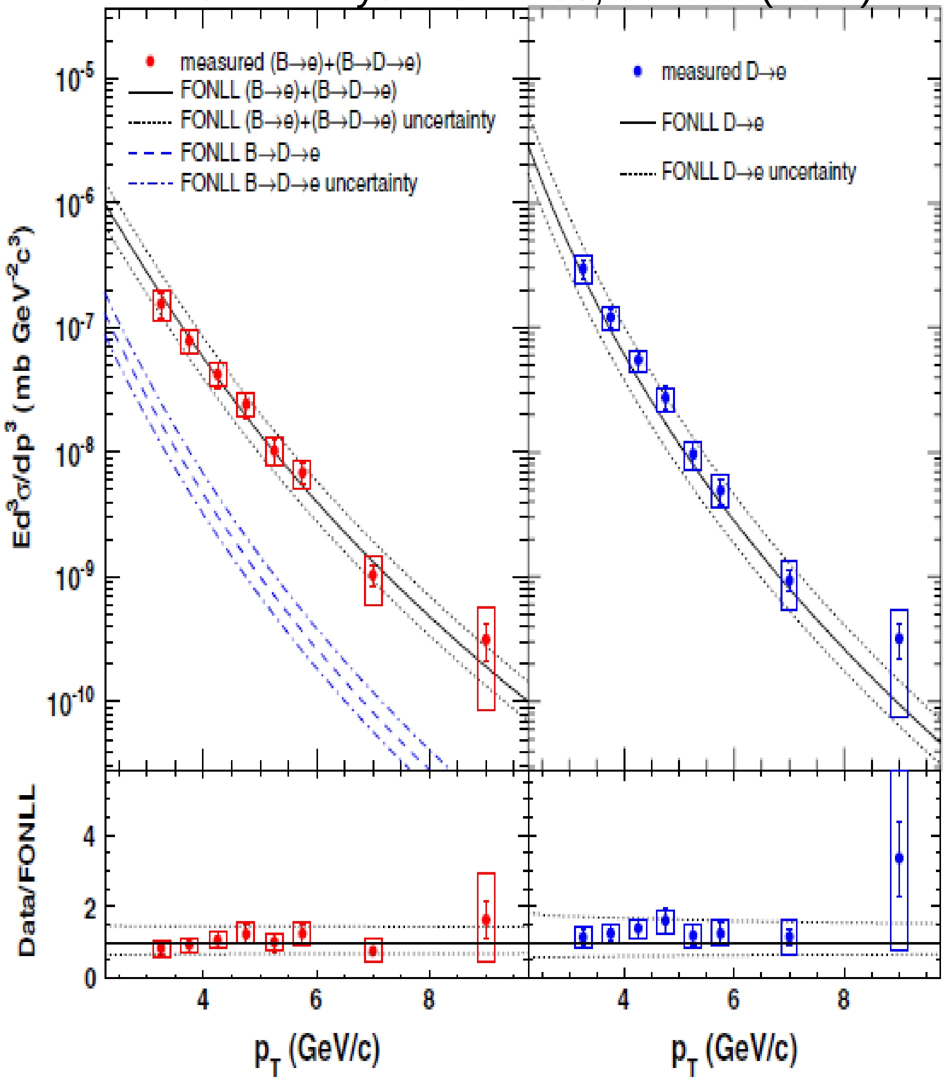




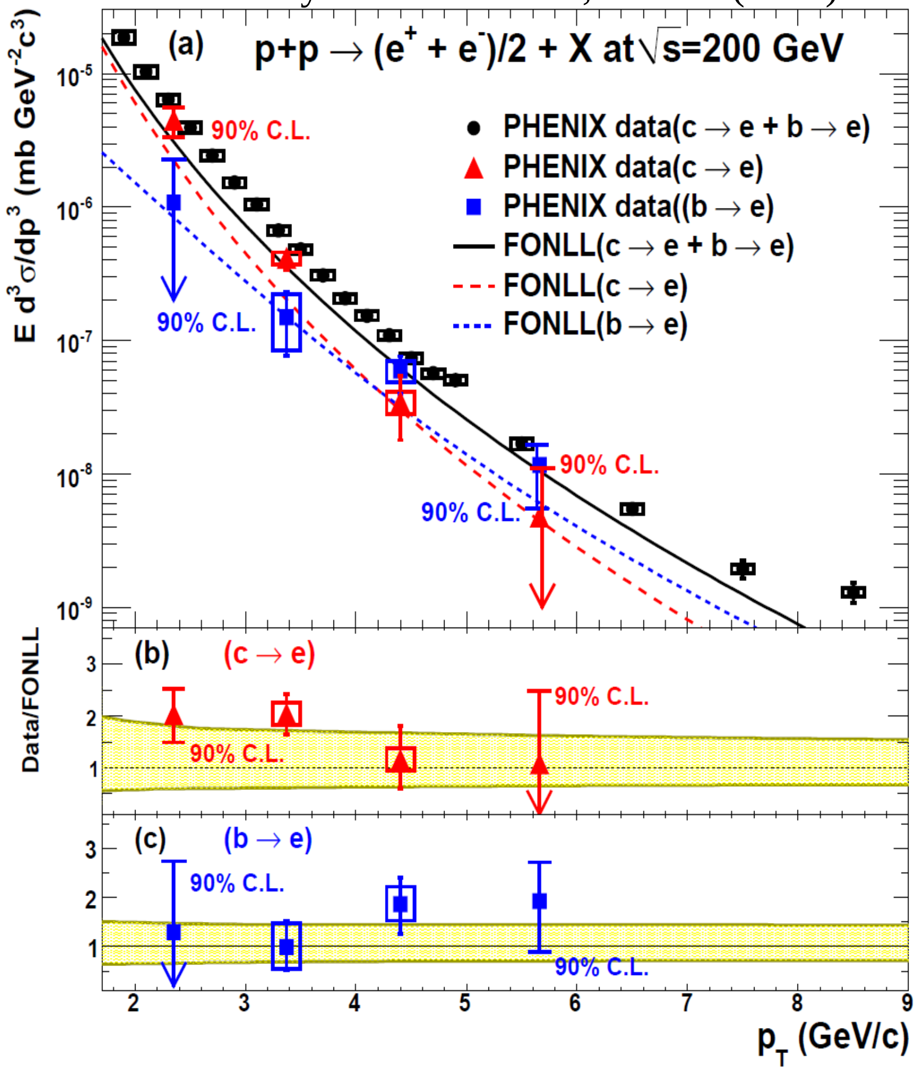
- ~30-60% of non-photonic electrons come from B meson in 200GeV p+p collisions.

Measurement of B and D meson spectra at RHIC

STAR Phys. Rev. **D 83**, 052006 (2011)

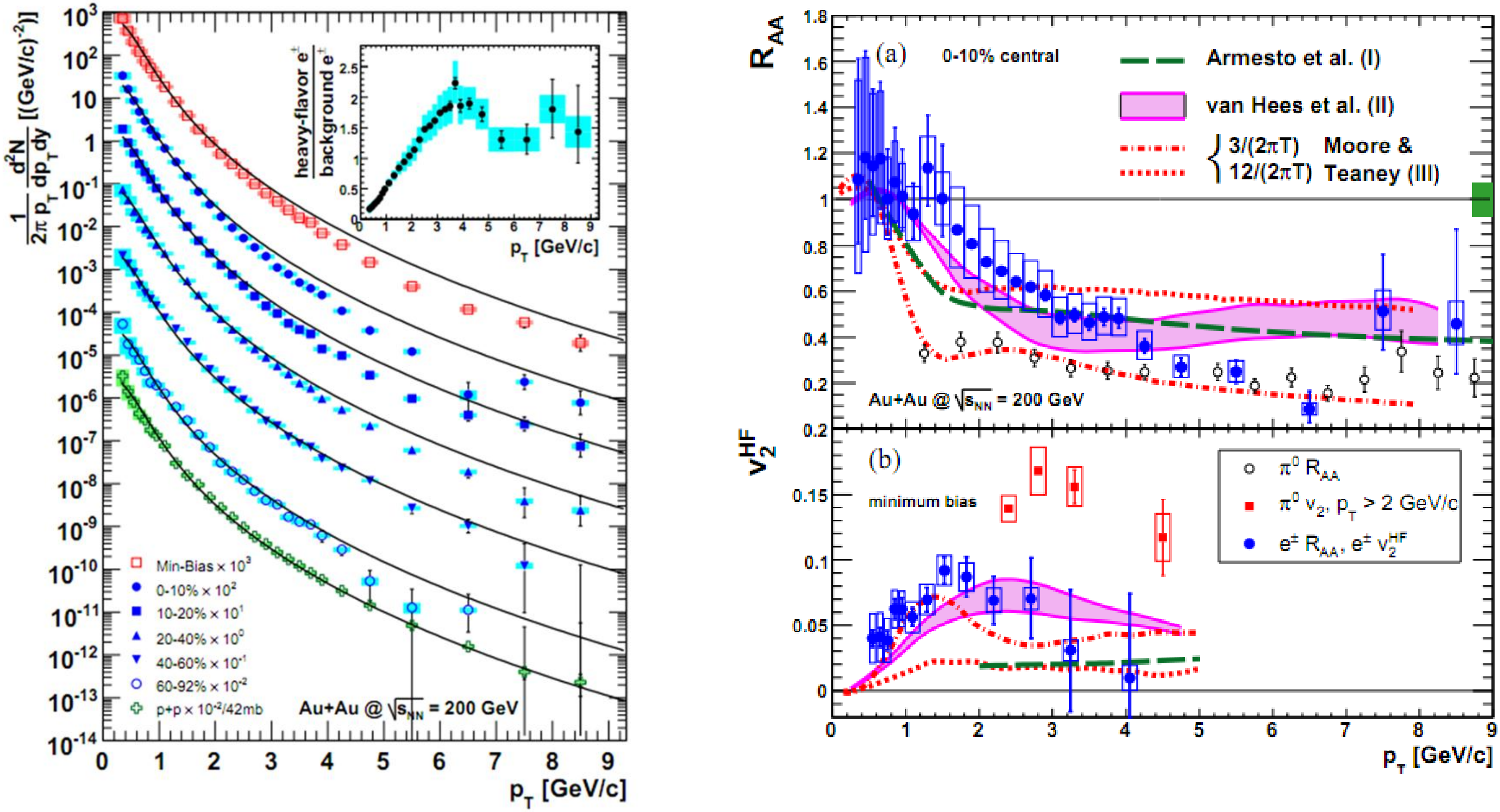


PHENIX Phys. Rev. Lett. **103**, 082002 (2009)



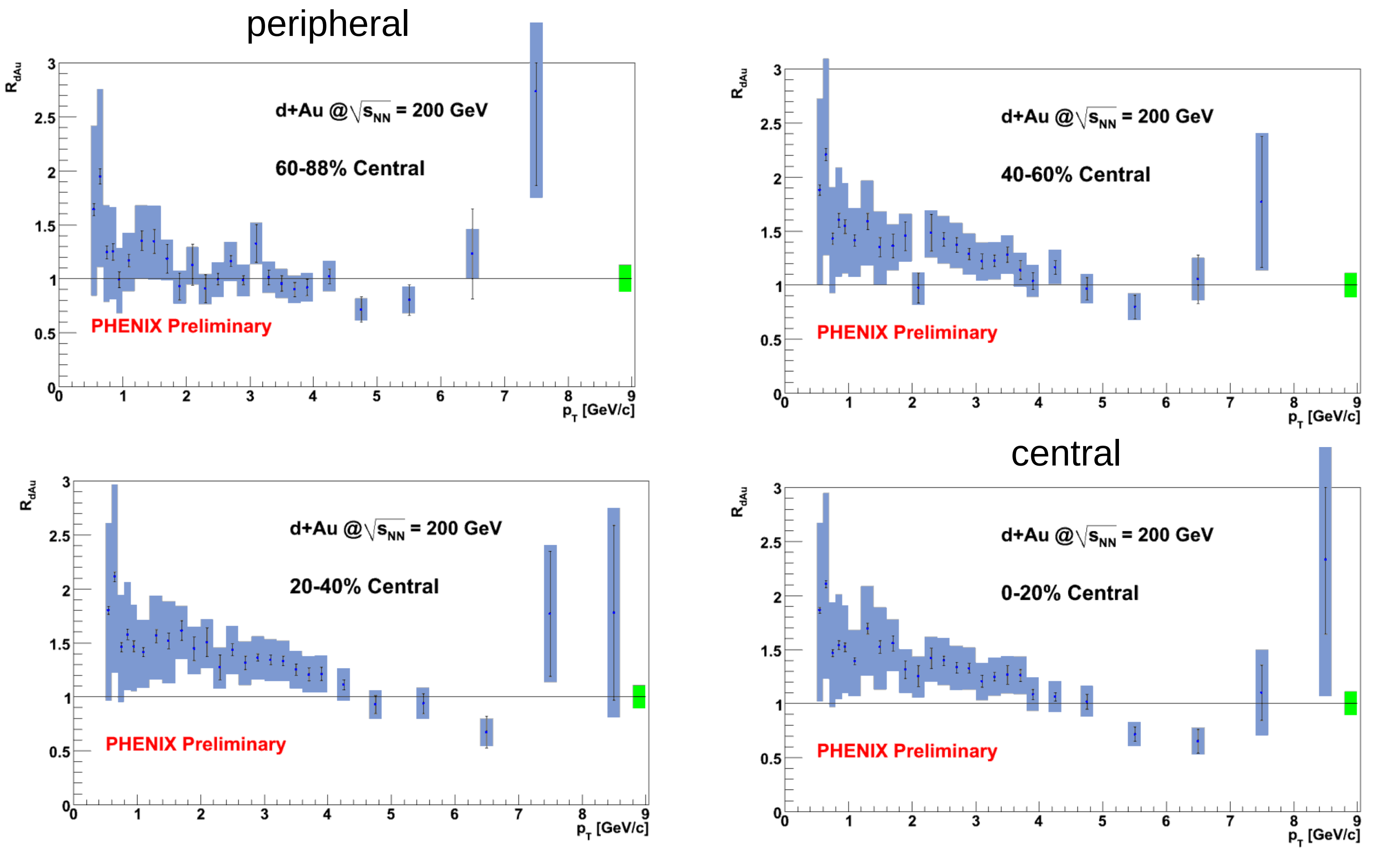
- p+p 200 GeV result
- ideal to get similar result from Au+Au but it's a lot harder.

Nuclear modification factor in Au+Au 200 GeV



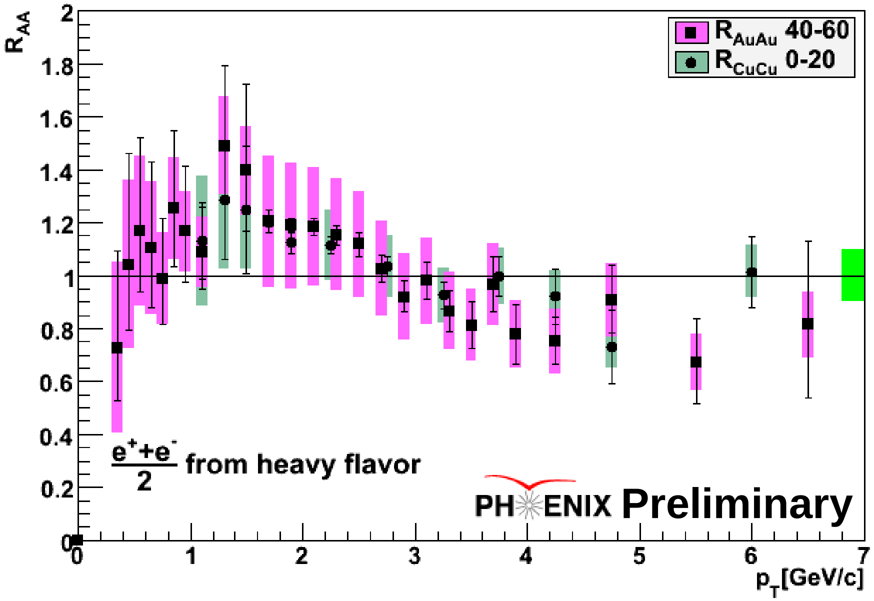
- Non-photonic electrons suppressed at high-p_T
- Flow of NPE was measured

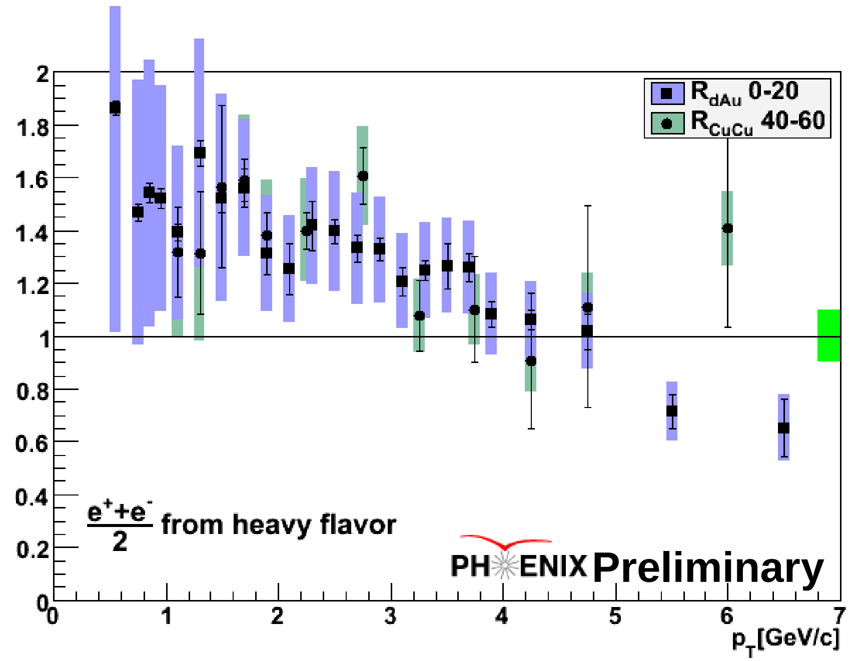
Non-photonic electrons in d+Au 200 GeV



- Peripheral R_{dAu} consistent with 1.0
- Evidence of CNM effects on open HF yields at $1<p_T<4$ GeV/c for more central collisions

d+Au/Au+Au and Cu+Cu





$\langle N_{coll} \rangle$ CuCu = 150

$\langle N_{coll} \rangle$ AuAu = 91

$\langle N_{coll} \rangle$ dAu = 15

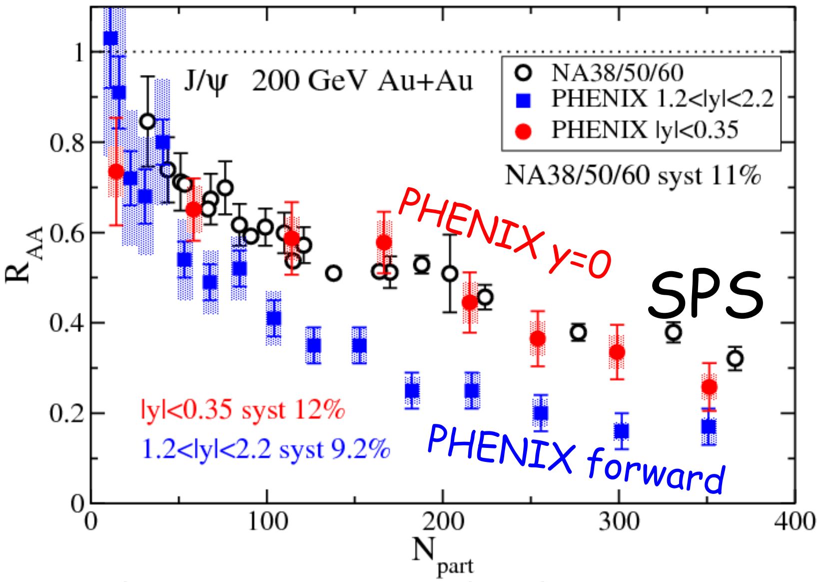
$\langle N_{coll} \rangle$ CuCu = 22.3

QUARKONIA

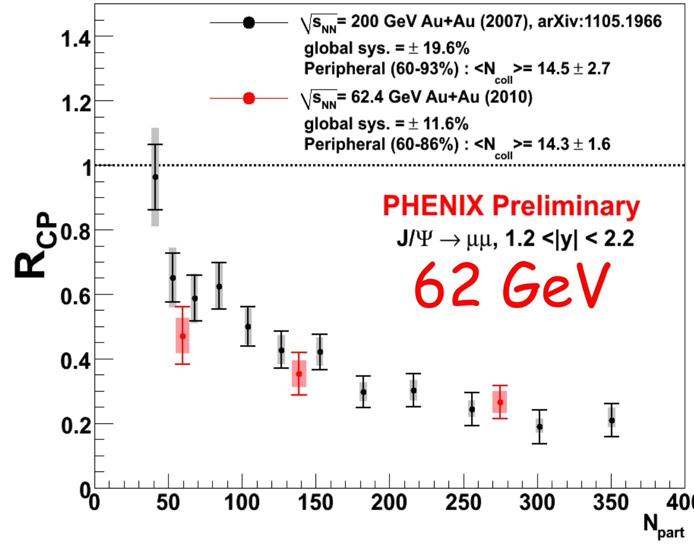
J/ψ

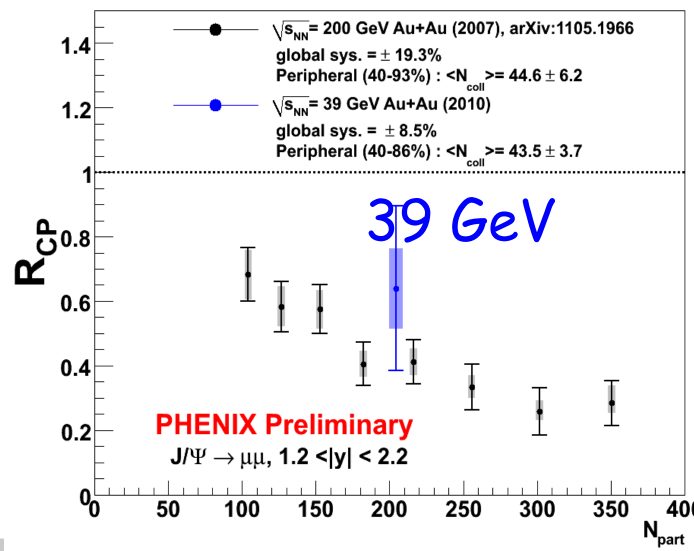
Charmonium suppression

PHENIX arXiv:1103.6269



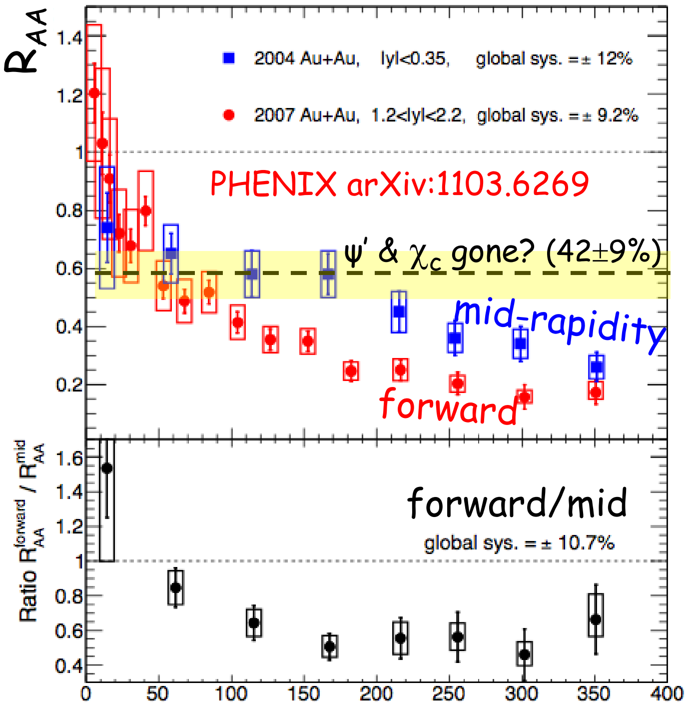
Phys. Rev. C 84, 054912 (2011)





- Overall suppression of J/ψ is nearly identical between RHIC (200,62,39 GeV), SPS (17.2 GeV) , (& LHC)
- Forward-rapidity is suppressed more than Mid-rapidity

Forward rapidity suppression



Phys. Rev. C 84, 054912 (2011)

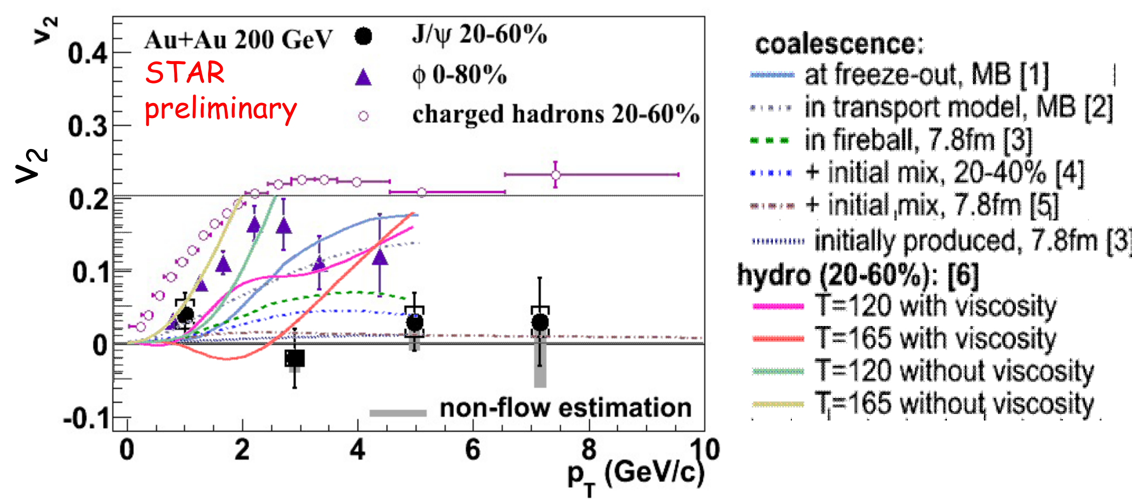
At RHIC - Forward-rapidity J/ψ's are suppressed more than Mid-rapidity – Why?

1) Stronger forward rapidity suppression due to CNM effects?

2) Regeneration at mid-rapidity reduces suppression relative to forward (and gives net suppression similar to SPS)?

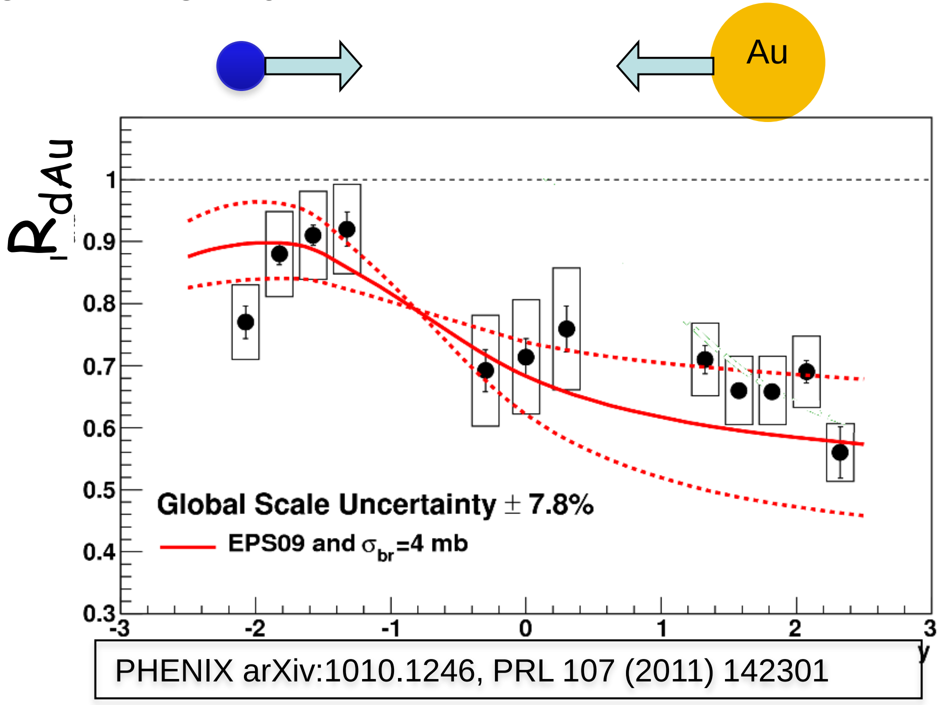
Small or no J/ψ flow at RHIC!

Many theoretical expectations & option #2 probably ruled out?



Cold nuclear matter effects – d+Au 200 GeV

CNM effects appear to provide a large fraction of the observed suppression; so difficult to conclude much w/o a thorough understanding of CNM and its extrapolation to A+A from d+A

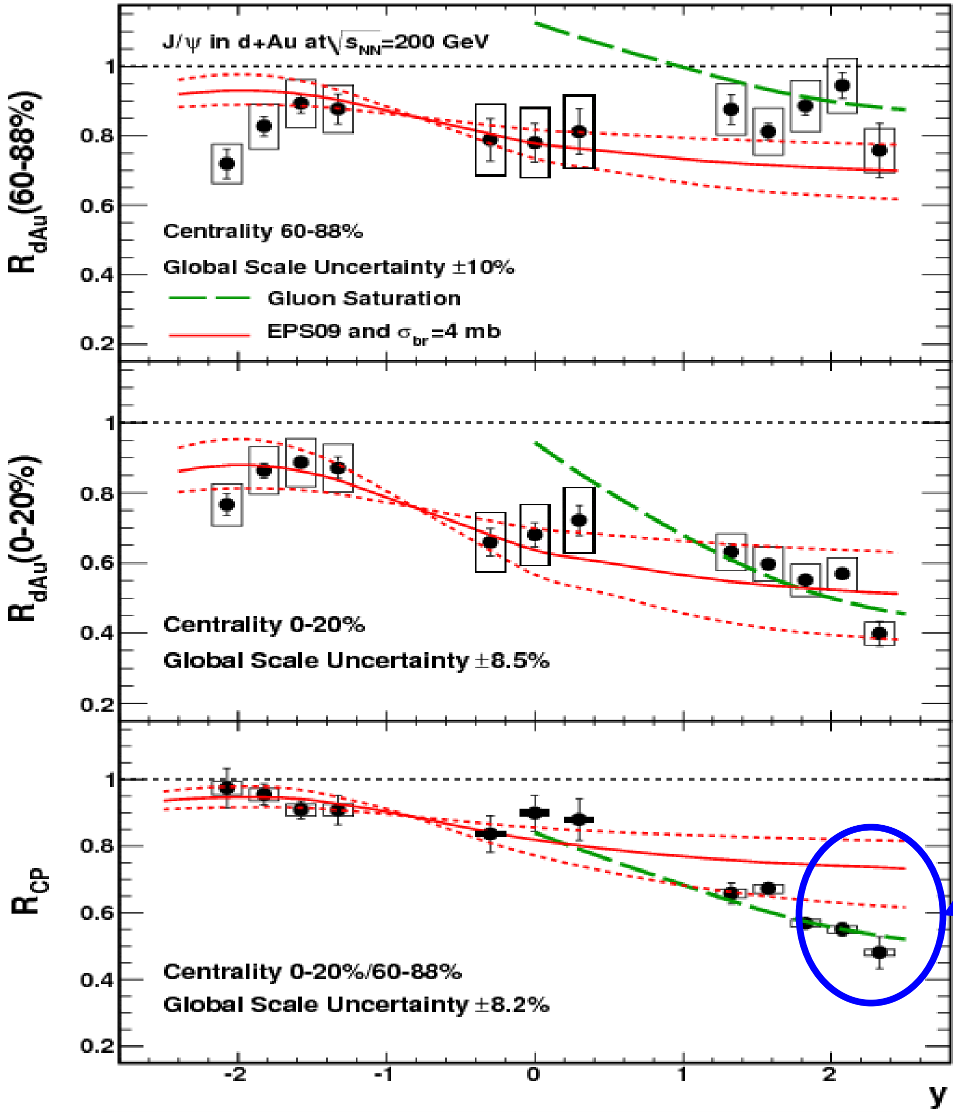


rapidity

- we have to understand CNM in a fundamental way in order to obtain reliable/quantitative extrapolations to A+A.

Cold nuclear matter effects – d+Au 200 GeV

centrality



PHENIX arXiv:1010.1246, , PRL 107 (2011) 142301

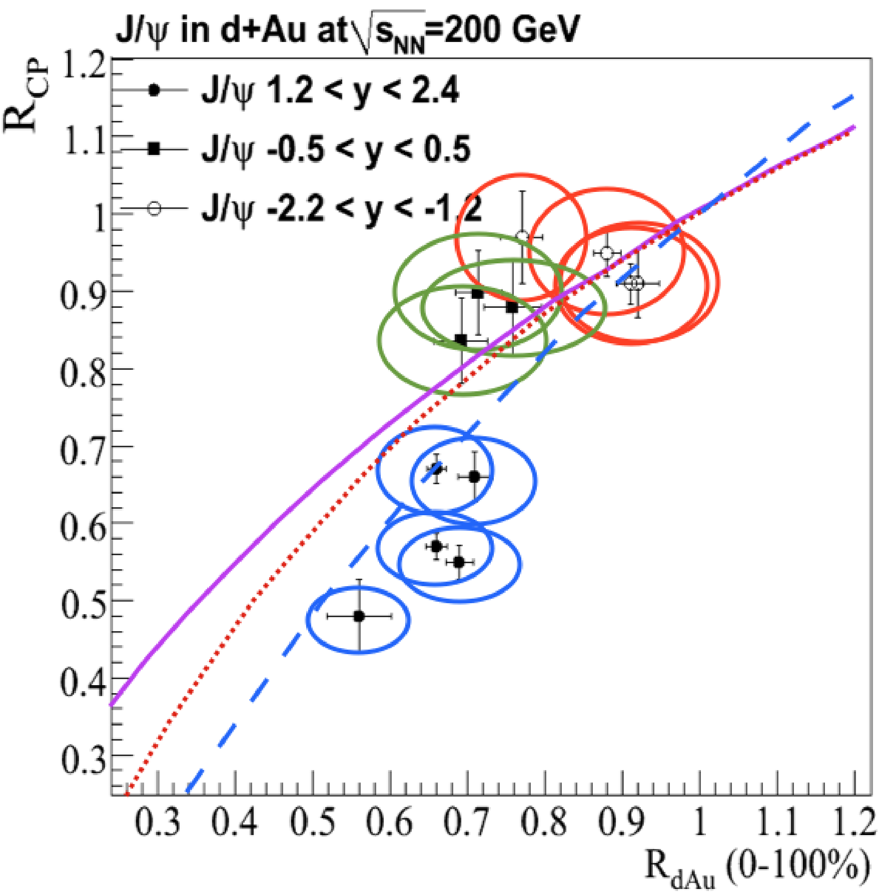
Reasonable agreement with EPS09 nPDF + σ_{br}=4 mb for central collisions but not peripheral

CGC calculations can't reproduce mid-rapidity (*Nucl. Phys. A 770(2006) 40*)

EPS09 with linear thickness dependence fails to describe centrality dependence of forward rapidity region.

Cold nuclear matter effects – d+Au 200 GeV

path-length dependence



PHENIX arXiv:1010.1246, , PRL 107 (2011) 142301

- Assume modification is dependent on the nuclear thickness

$$\Lambda(r_T) = \frac{1}{\rho_0}\int dz\,\rho(z, r_T)$$

Woods-Saxon

Exponential : $M(r_T) = e^{-a\Lambda(r_T)}$

Linear : $M(r_T) = 1 - a\Lambda(r_T)$

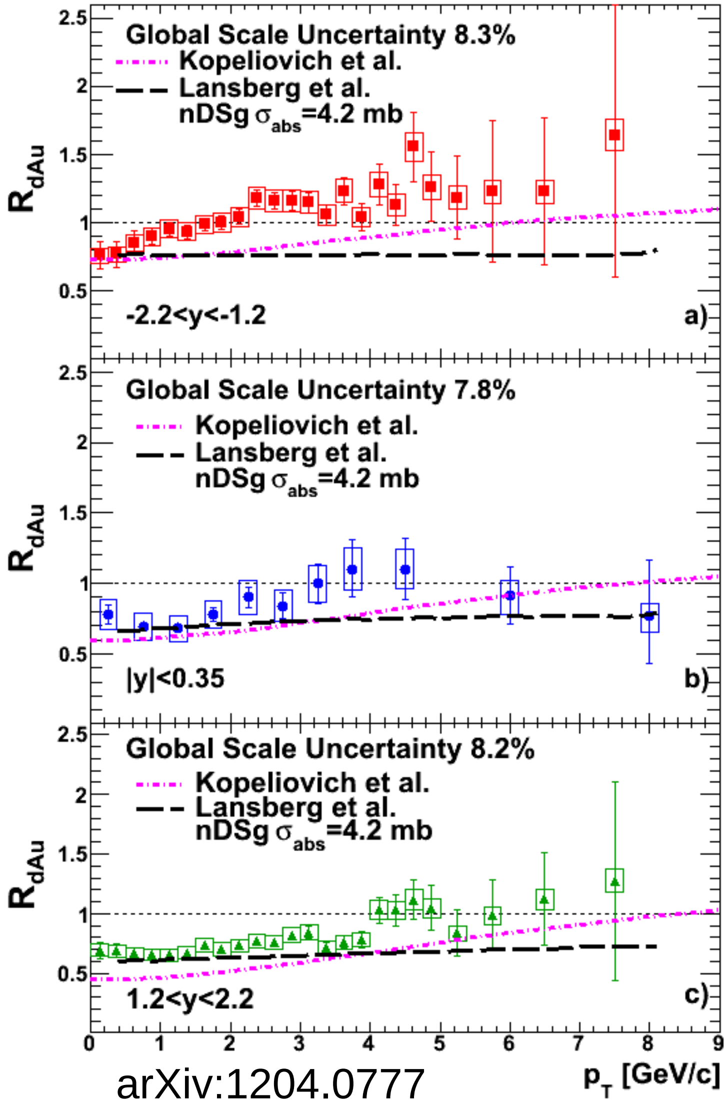
Quadratic : $M(r_T) = 1 - a\Lambda(r_T)^2$

- Break-up has exponential dependence
- EPS09 & initial-state dE/dx have unknown dependences

The forward rapidity points suggests a quadratic or higher geometrical dependence

Cold nuclear matter effects – d+Au 200 GeV

Transverse momentum



arXiv:1204.0777

- Similar suppression at **mid & forward rapidity**
- Suppression for $p_T < 4$ GeV/c
- $R_{dAu} \approx 1$ for $p_T > 4$ GeV/c
- Backward rapidity: $R_{dAu} > 1$ for $p_T > 2$ GeV/c

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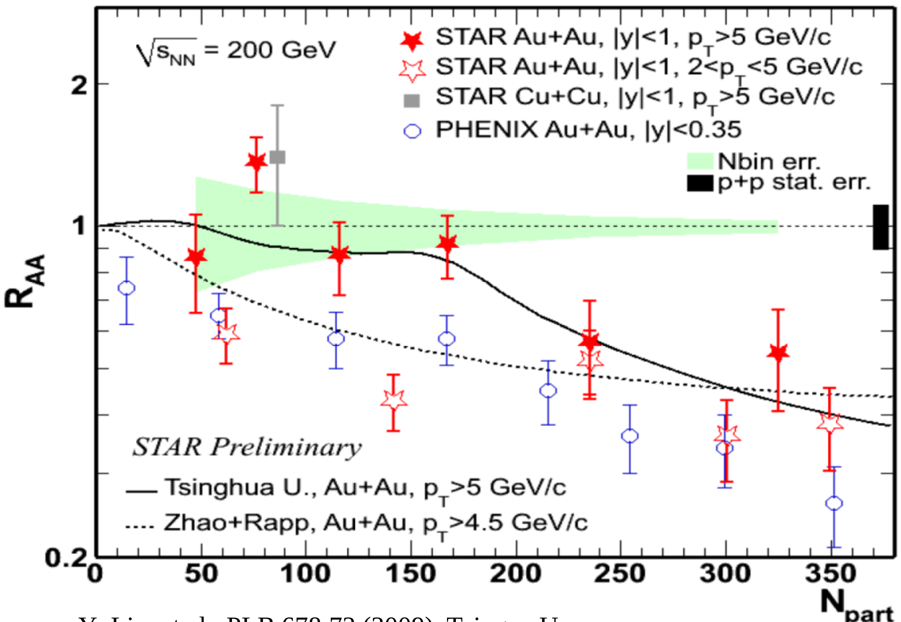
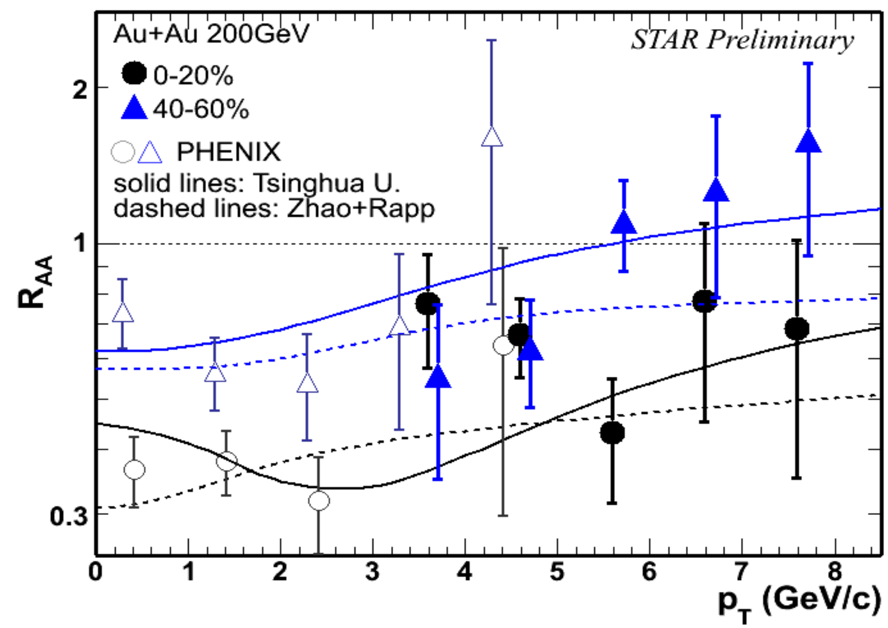
High-p_T J/ψ measurement Au+Au 200 GeV



Y. Liu, et al., PLB 678:72 (2009), Tsingua U.
X. Zhao and R.Rapp, PRC 82, 064905(2010)



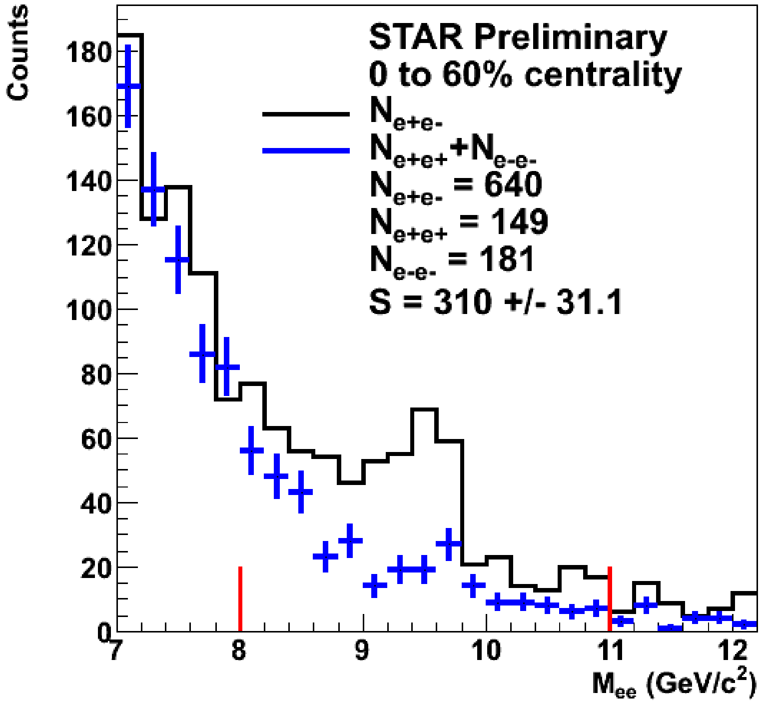
STAR CuCu: PRC80, 014922(R), PLB 678:72 (2009), PRC 82,064905(2010)
PHENIX: PRL98, 232301

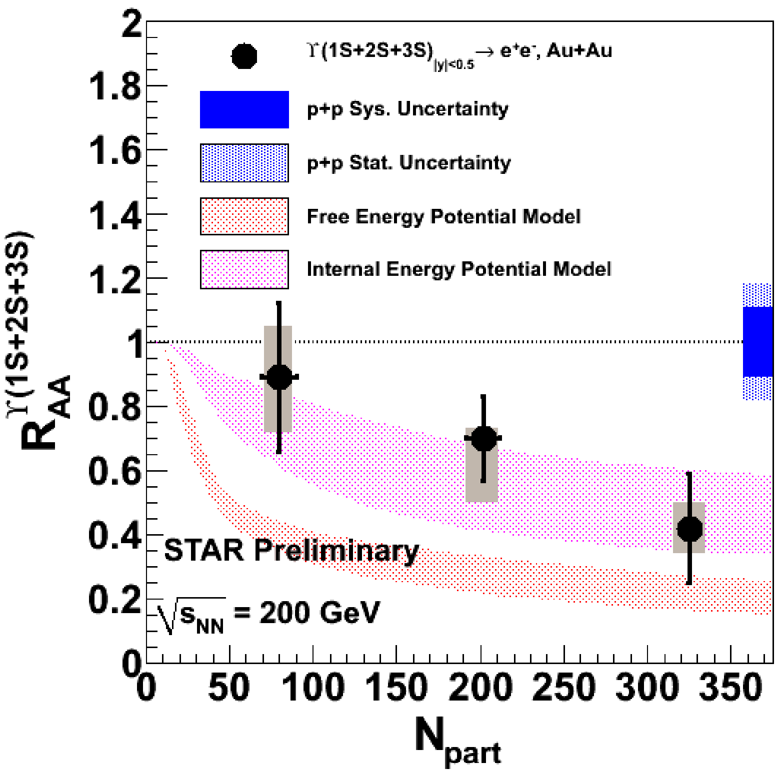
- Suppression of J/ψ in central and semi-central collisions is observed.
- R_{AA} increases with p_T and decreases with centrality.
- At high p_T suppression is present only in central collisions.

QUARKONIA

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

Upsilon in Au+Au 200 GeV





- R_{AA}: Observation of Upsilon suppression.
  (Including 2009 pp Preliminary dσ/dy)
  – Expect: Recombination: negligible, Hadronic co-mover absorption: negligible.
  – Suppression consistent with melting of excited states: **deconfinement effects**

Summary and outlook

- Heavy flavor is an important tool to understand medium properties.
- Results are interesting and challenging.

open charm measurement

- Charm hadrons; non-photonic electrons
- Charm production cross section.
- Separation of charm and bottom contribution.
- FONLL QCD describes the data rather well.

J/ψ

- SPS x RHIC   mid x forward rapidity suppression.
- Systematic study of Cold nuclear effects.
- Less suppression at high-p_T in STAR.

ϒ

- Suppression of ϒ(1S+2S+3S) in central Au+Au observed.

STAR/PHENIX upgrades: charm mesons flow; ϒ states separation
better charm/bottom separation

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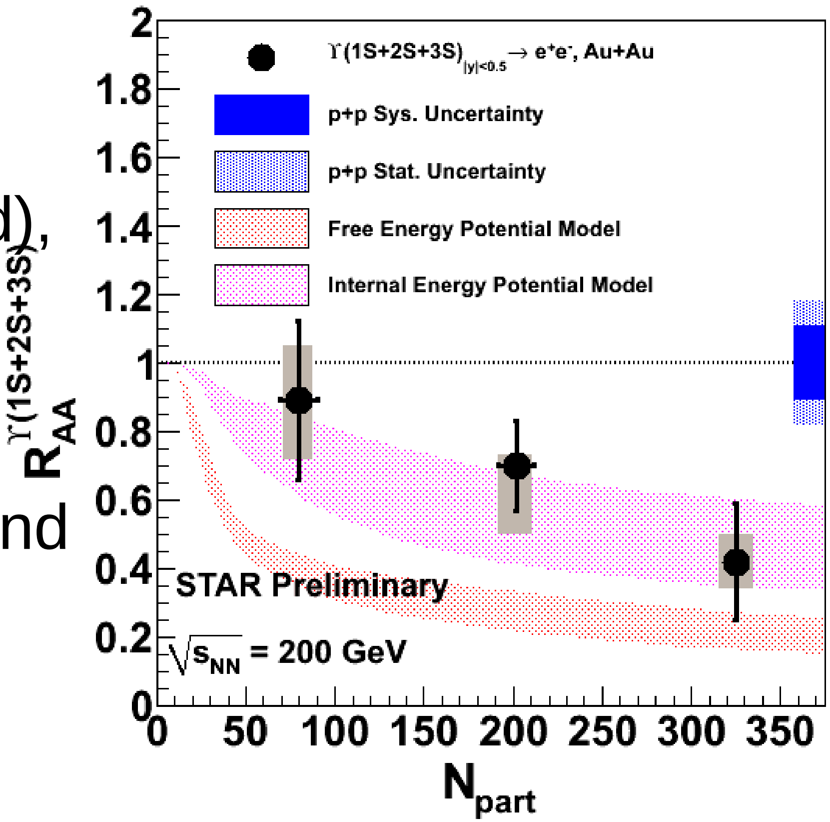
Υ model comparison

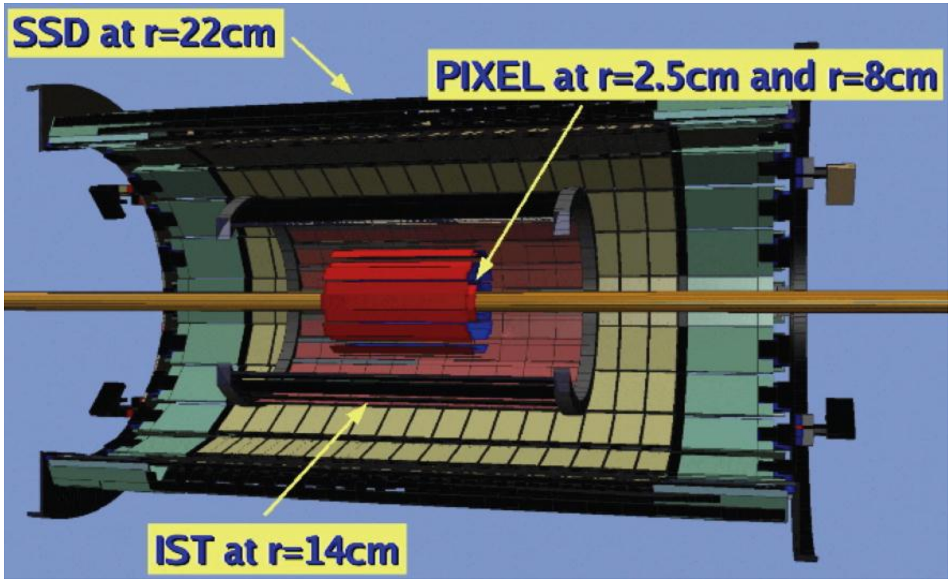
- Incorporating lattice-based potentials, including real and imaginary parts
  - A: Free energy (disfavored),
  - B: Internal energy (consistent with data vs. N_{part})
- Includes sequential melting and feed-down contributions
- Dynamical expansion, variations in initial conditions (T, η/S)
  - Data indicate: $428 < T_0 < 442$ MeV, $1 < 4\pi\eta/S < 3$

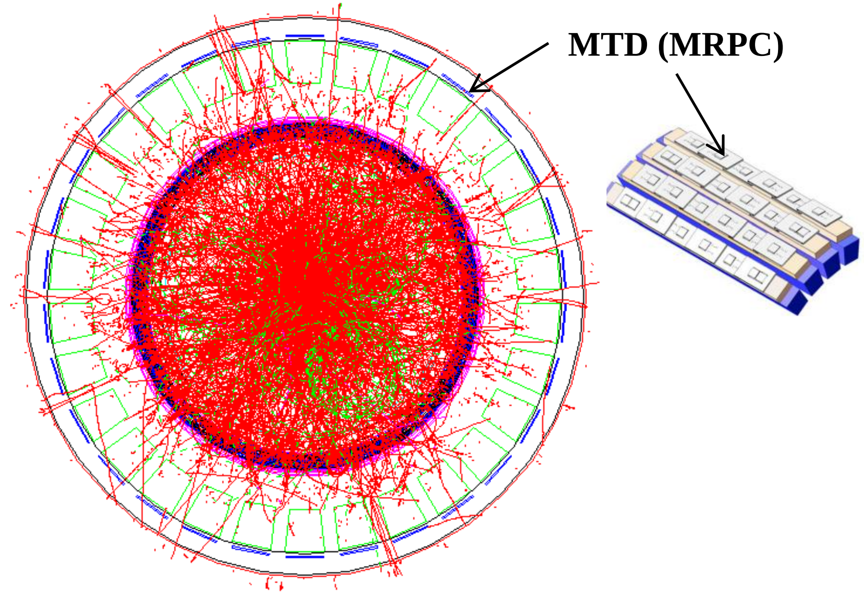


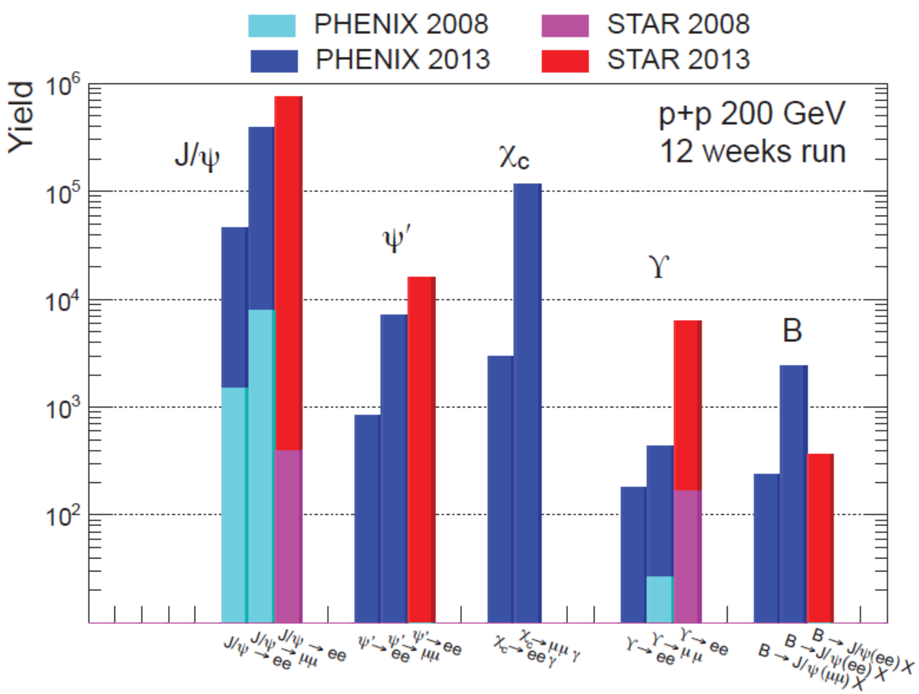
Models from M. Strickland and D. Bazow, arXiv:1112.2761v4

M. Strickland and D. Bazow, arXiv:1112.2761v4

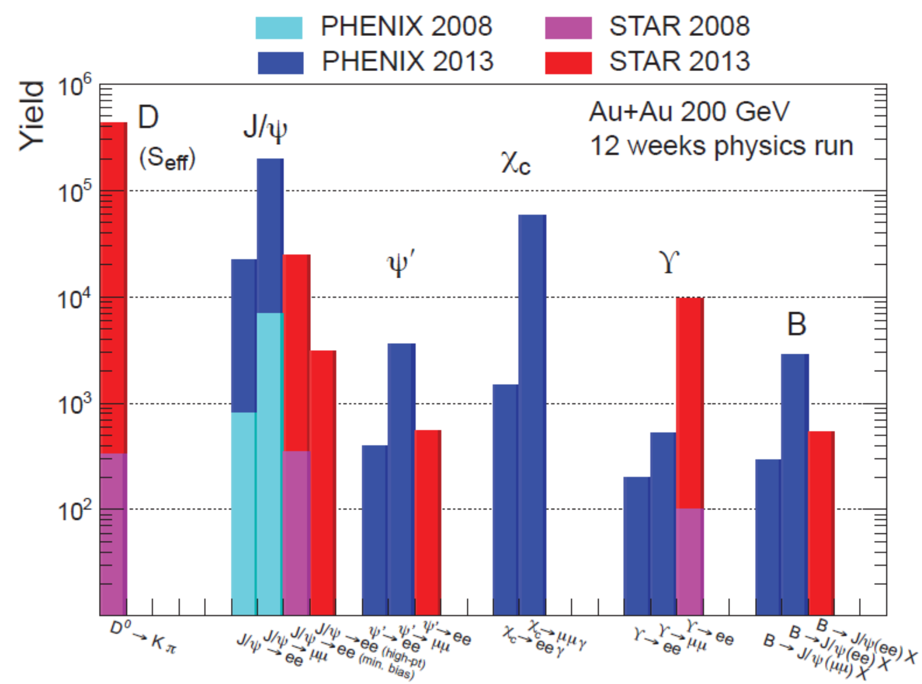
Future of Heavy Flavor Measurement at STAR







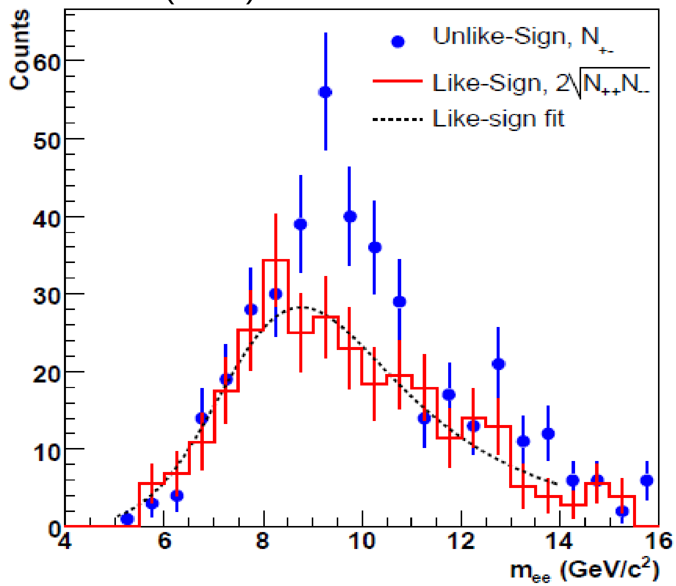
Source: Phys. Rept. 462: 125-175, 2008



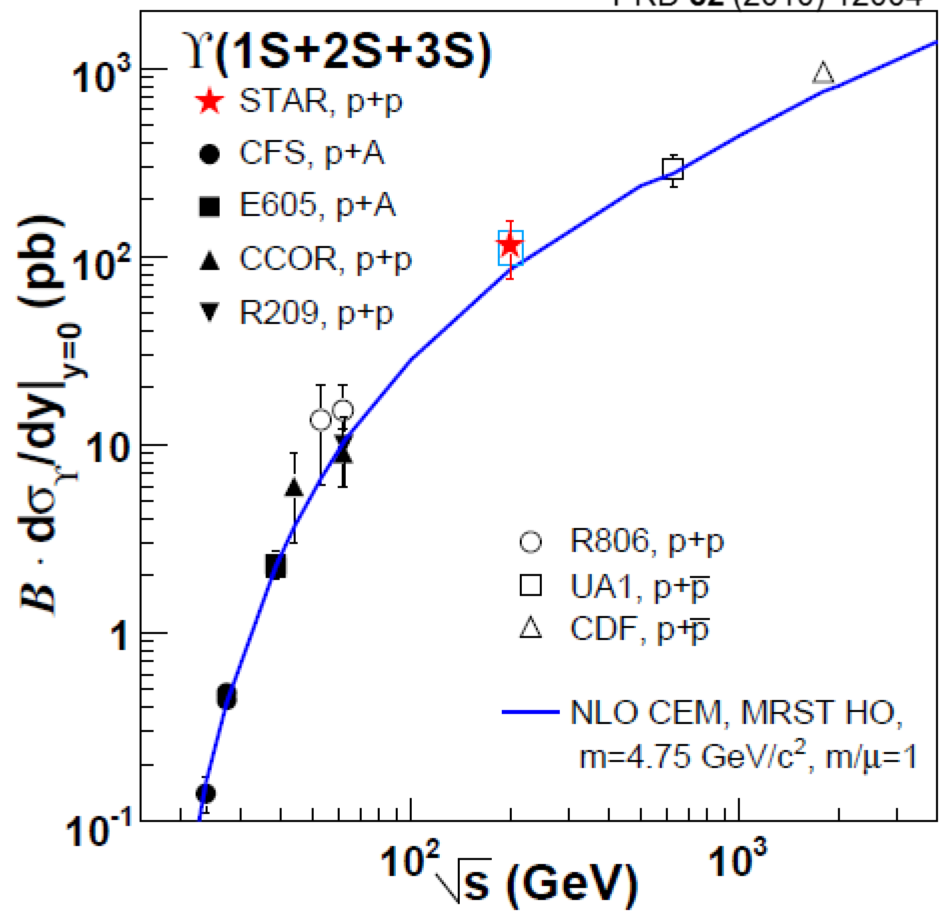
Source: Phys. Rept. 462: 125-175, 2008

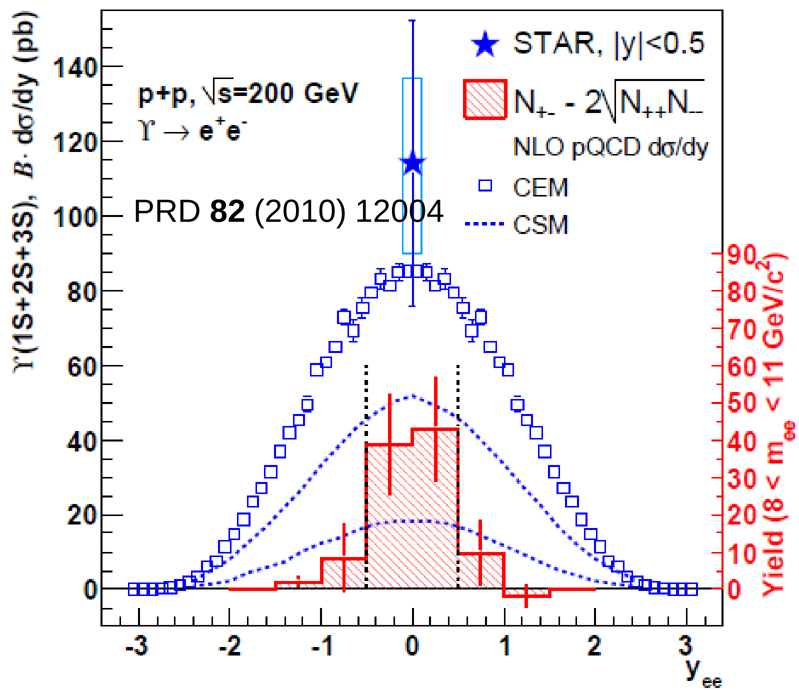
Upsilon in p+p 200GeV

PRD **82** (2010) 012004



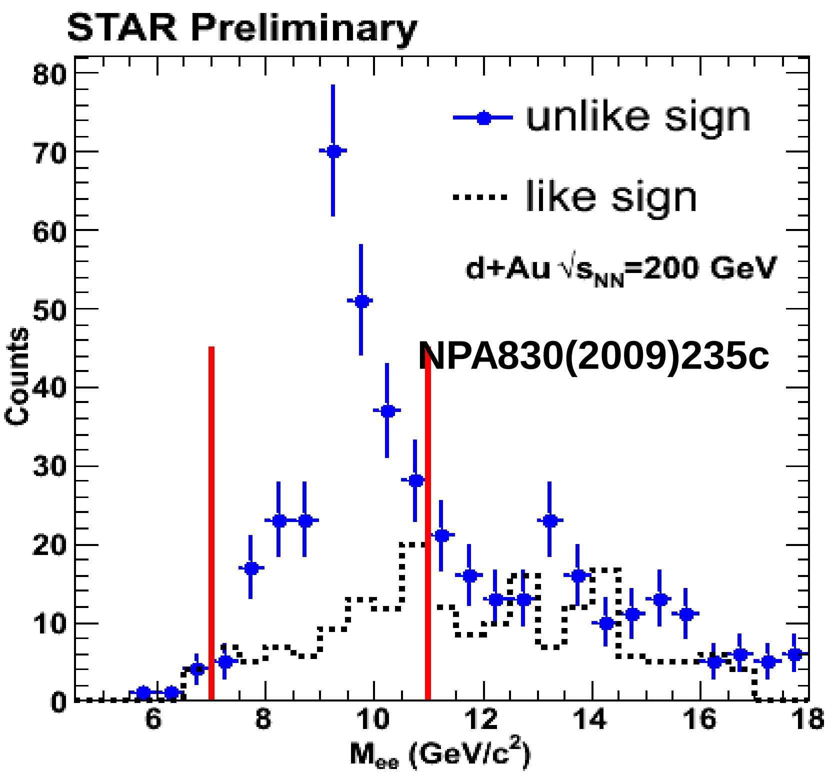
PRD **82** (2010) 12004

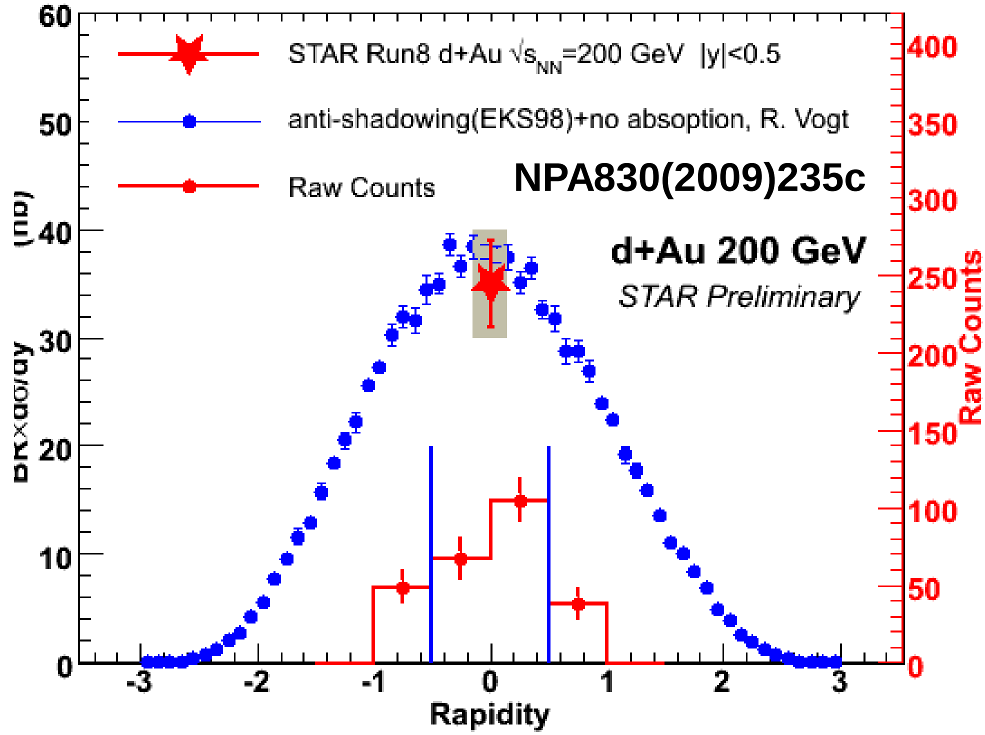




$$B_{ee}\frac{d\sigma}{dy}\bigg|_{y=0} = 114 \pm 38(stat)^{+23}_{-24}(sys) \quad \text{pb}$$

Upsilon in d+Au 200GeV



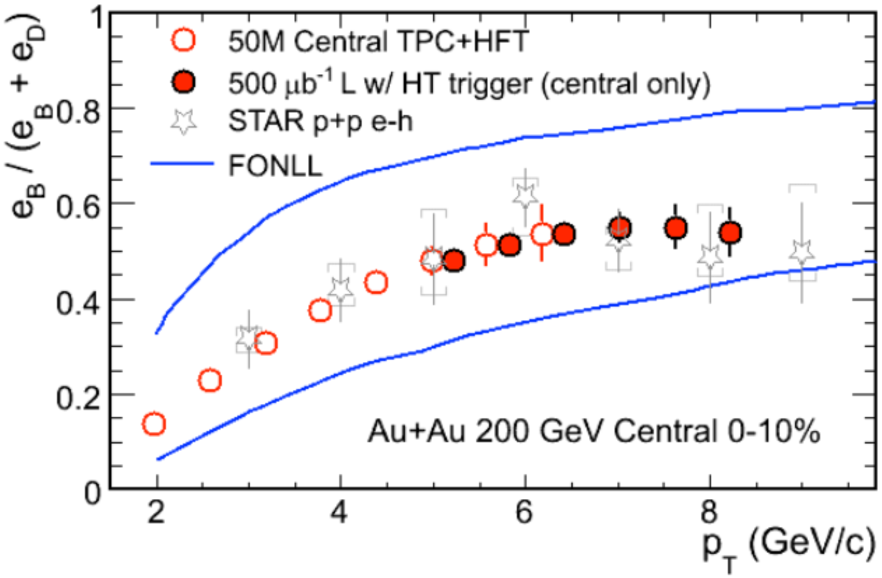


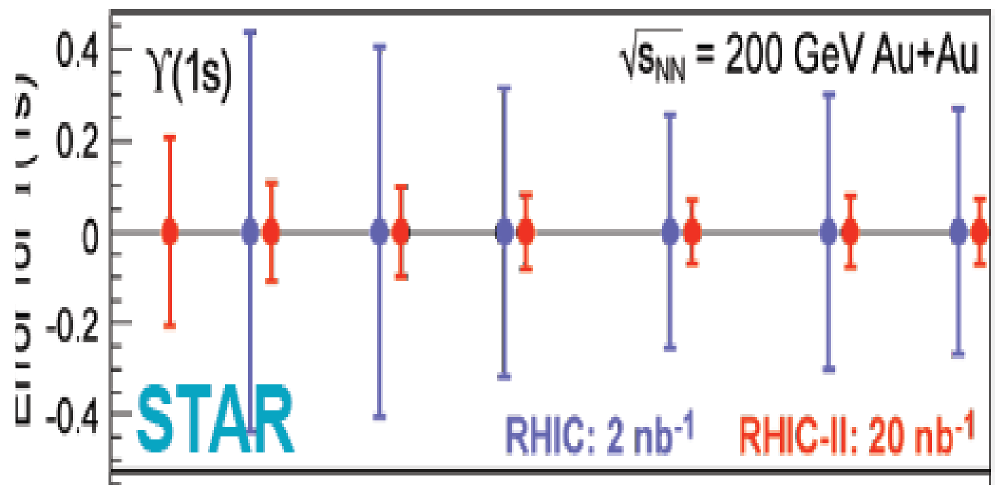
$$B_{ee}\frac{d\sigma}{dy}\bigg|_{y=0} = 35 \pm 4(stat) \pm 5(sys) \text{ nb}$$

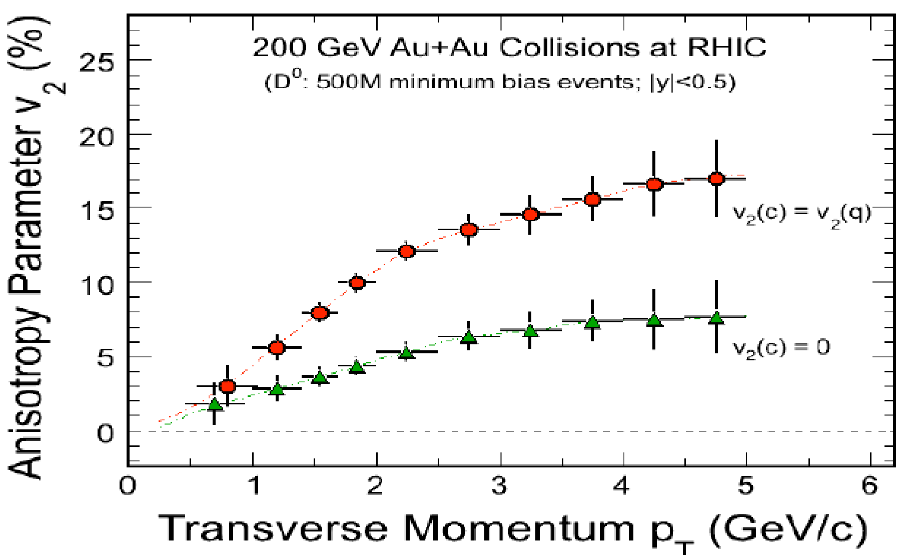
$$R_{dAu} = 0.8 \pm 0.3(stat) \pm 0.2(sys)$$

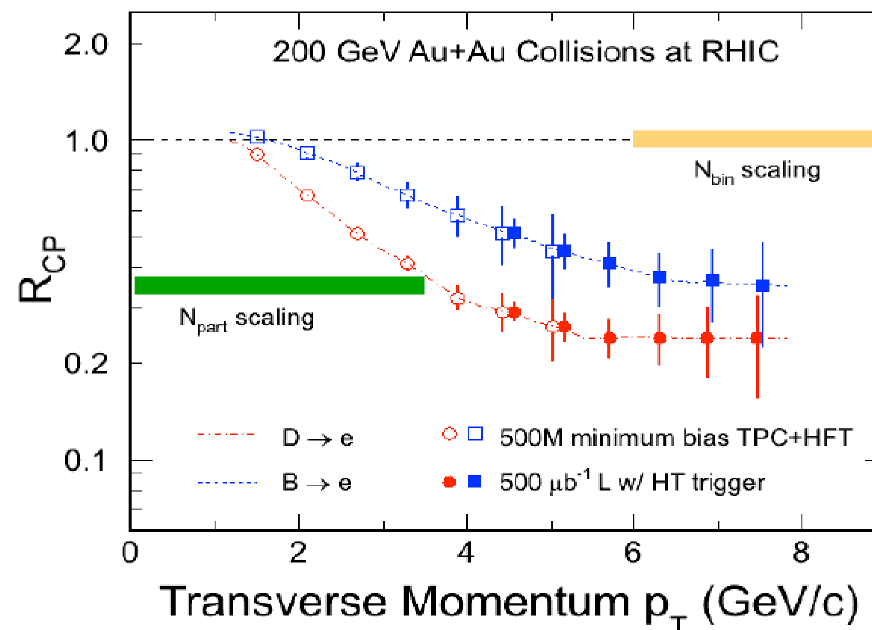
- Consistent with N_{bin} scaling of cross-section p+p - d+Au 200GeV

STAR with HFT

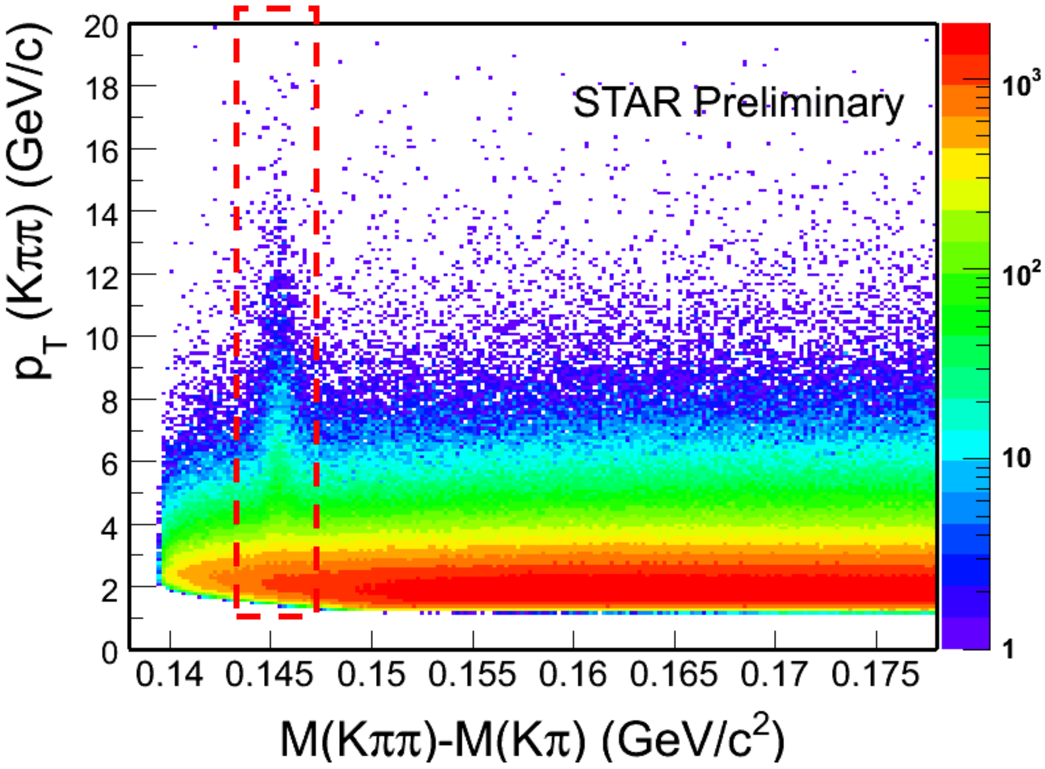


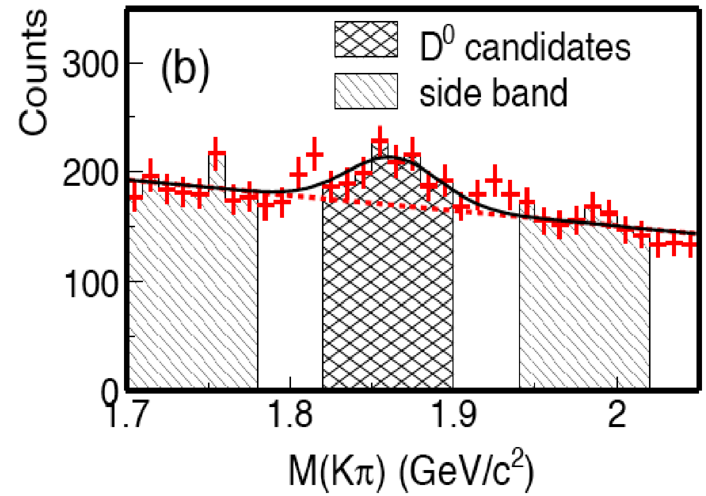






D* reconstruction





<u>Background combinations:</u>

Wrong sign:

D0 and π^-, D0bar and π^+

Side band:

1.72< M(Kπ) < 1.80 or

1.92 < M(Kπ) < 2.0 GeV/c^2

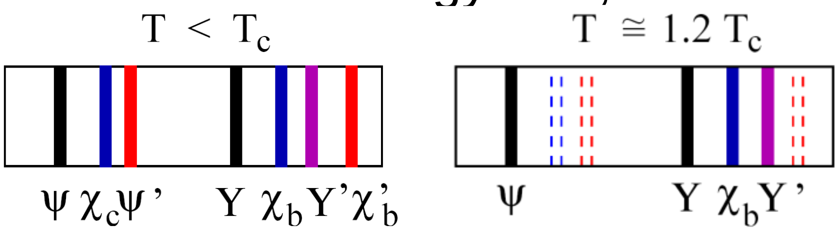
All triggers included.

More than 4σ signal at low p_T and very significant at high p_T - mostly from EMC-based high neutral energy triggers.

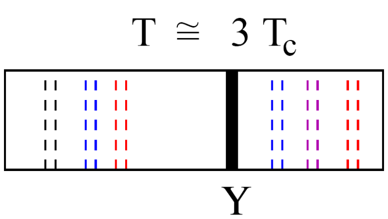
35

Charmonia in nuclear matter

- Production mechanism is not clear
- Observed J/ψ is a mixture of direct production + feeddown
  - All J/ψ ~ 0.6 J/ψ (Direct) + ~0.3 χ_c + ~0.1ψ'
- Suppression and enhancement in the "cold" nuclear medium
  - Nuclear Absorption, Gluon shadowing, initial state energy loss, Cronin effect and gluon saturation



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



- Hot/dense medium effect
  - J/ψ, Υ dissociation, i.e. suppression
  - Recombination from uncorrelated charm pairs

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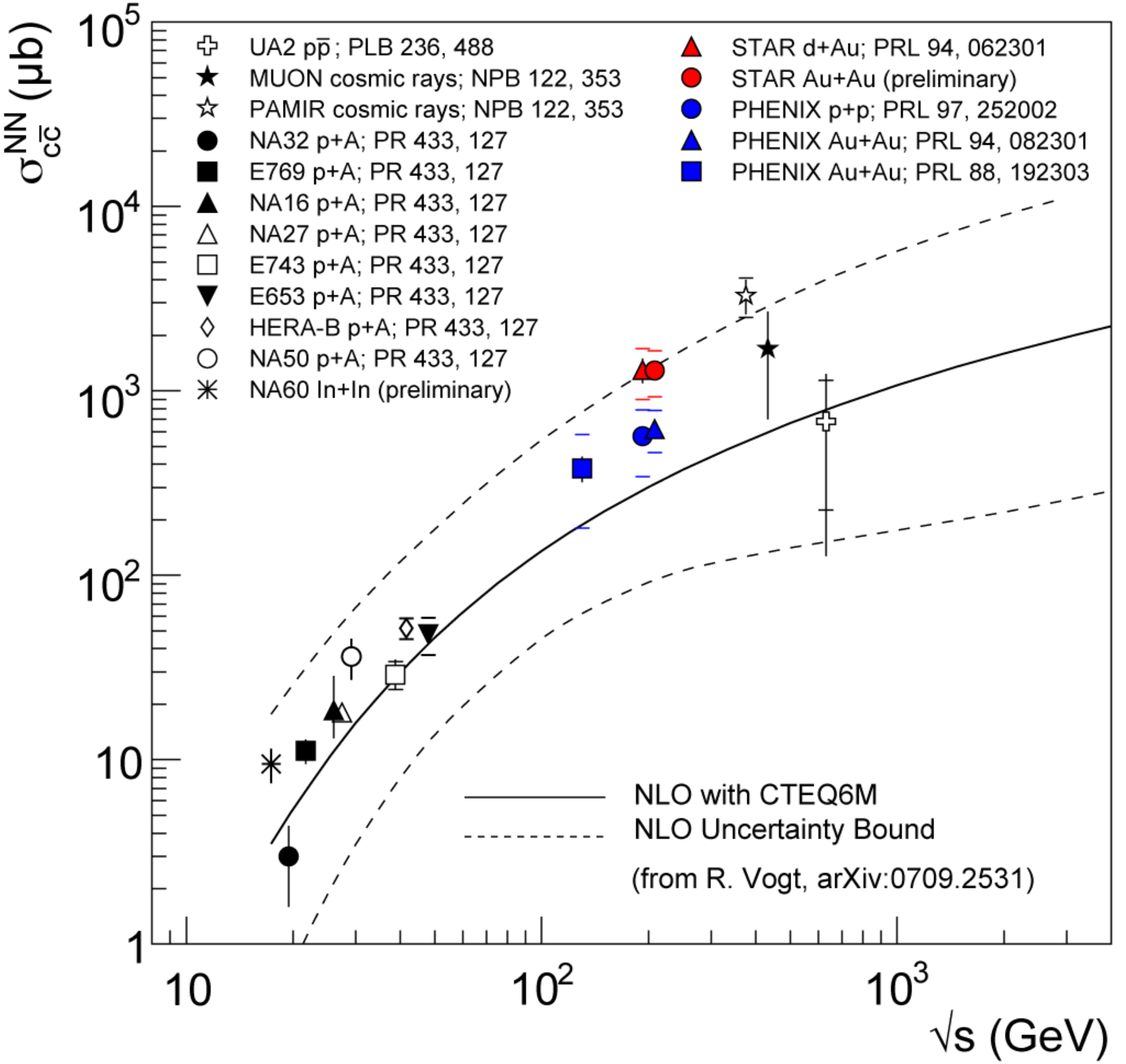
σ_{CC}: comparison with other measurements



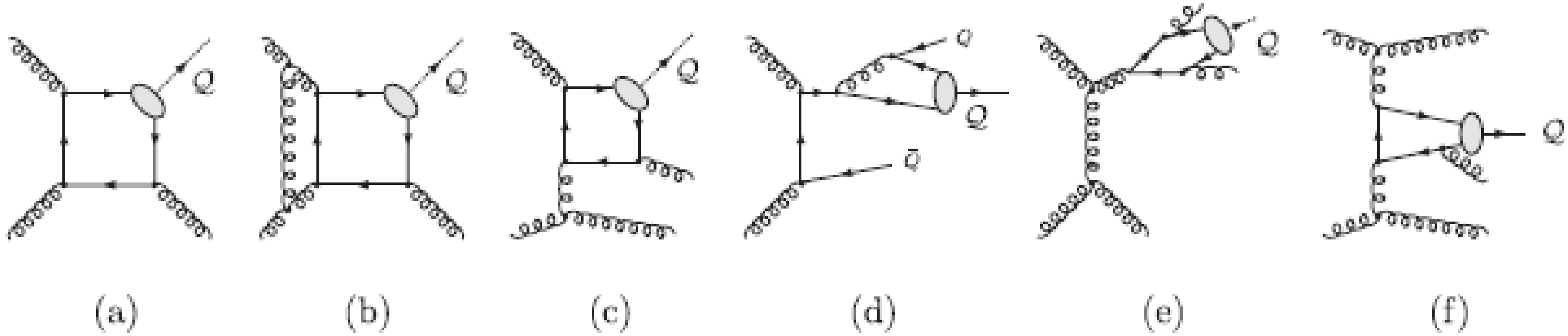
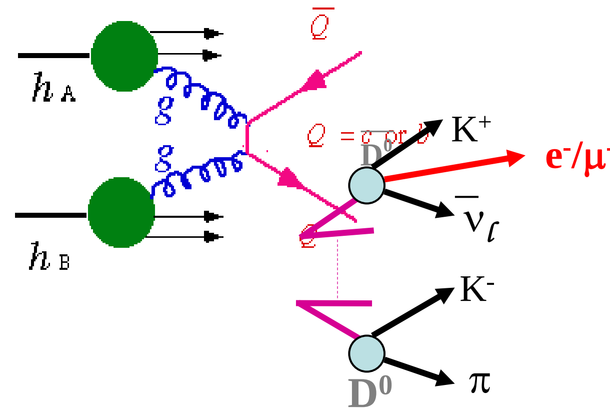
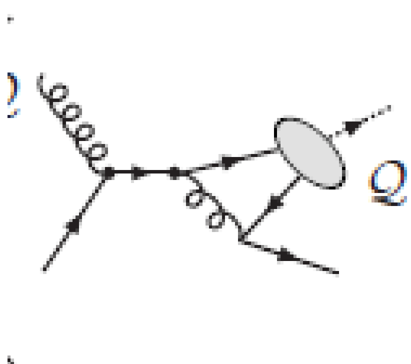
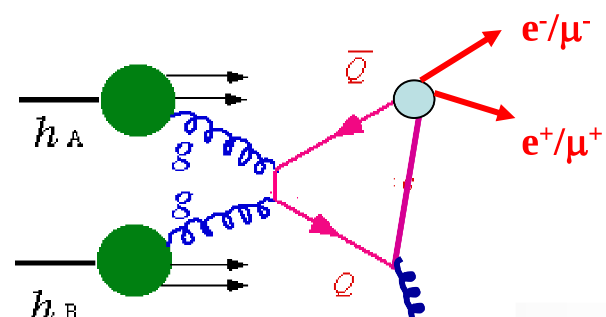


FIG. 1. Representative diagrams contributing to Υ hadroproduction at orders α_S^3 (a), α_S^4 (b,c,d), α_S^5 (e,f). See discussions in the text.



Open heavy flavor





Heavy quarkonia

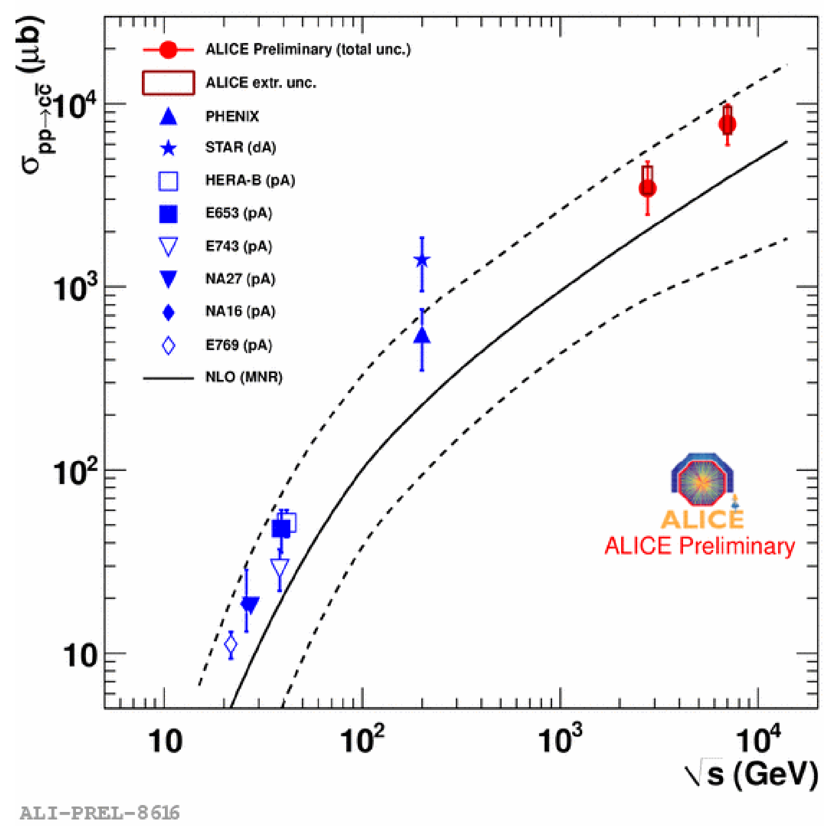
What can we learn at the LHC

- Higher c and b cross sections:
  - More abundant heavy flavour production
  - Better precision (reduced errors)

$$\sigma^{c\bar{c}}_{LHC} \approx 10 \cdot \sigma^{c\bar{c}}_{RHIC}$$

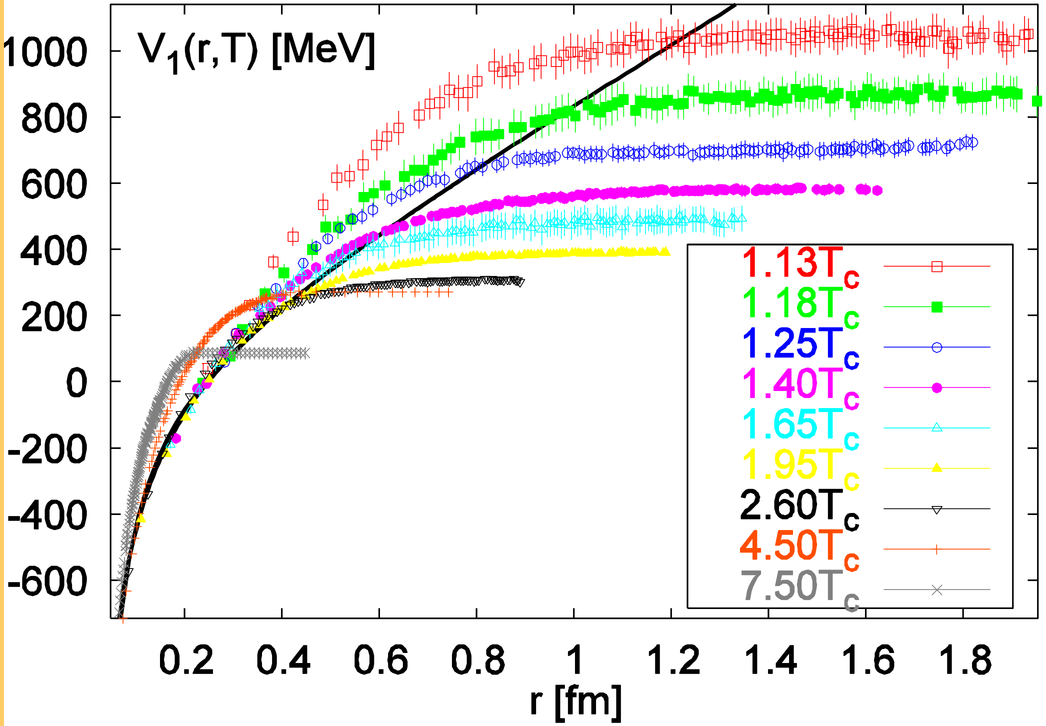
$$\sigma^{b\bar{b}}_{LHC} \approx 100 \cdot {}^{b\bar{b}}_{RHIC}$$

- High precision vertex detectors
  - Background removal
  - Separate c and b



High T: the potential between the quarks is modified.

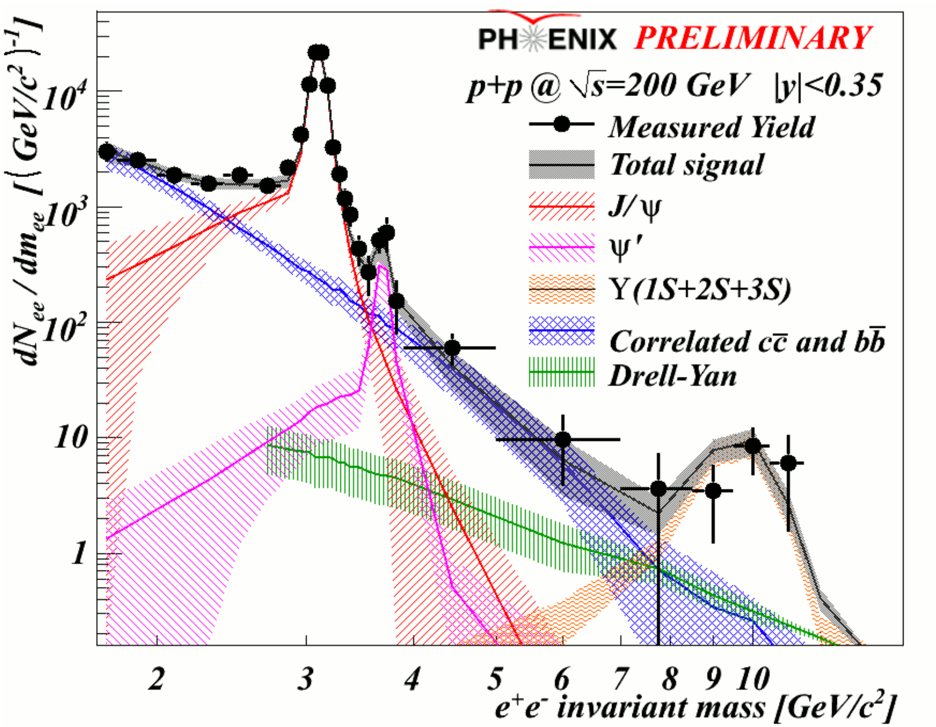
- Charmonium suppression: longstanding QGP signature
  - Original idea: High T leads to Debye screening
  - Screening prevents heavy quark bound states from forming!
  - **J/ψ suppression**:
    - Matsui and Satz, *Phys. Lett. B* **178** (1986) 416
  - lattice calculations confirm screening effects
    - **Nucl.Phys.Proc.Suppl.129: 560-562,2004**



O. Kaczmarek, et al., Nucl.Phys.Proc.Suppl.129:560-562,2004

Better Knowledge about the Baseline

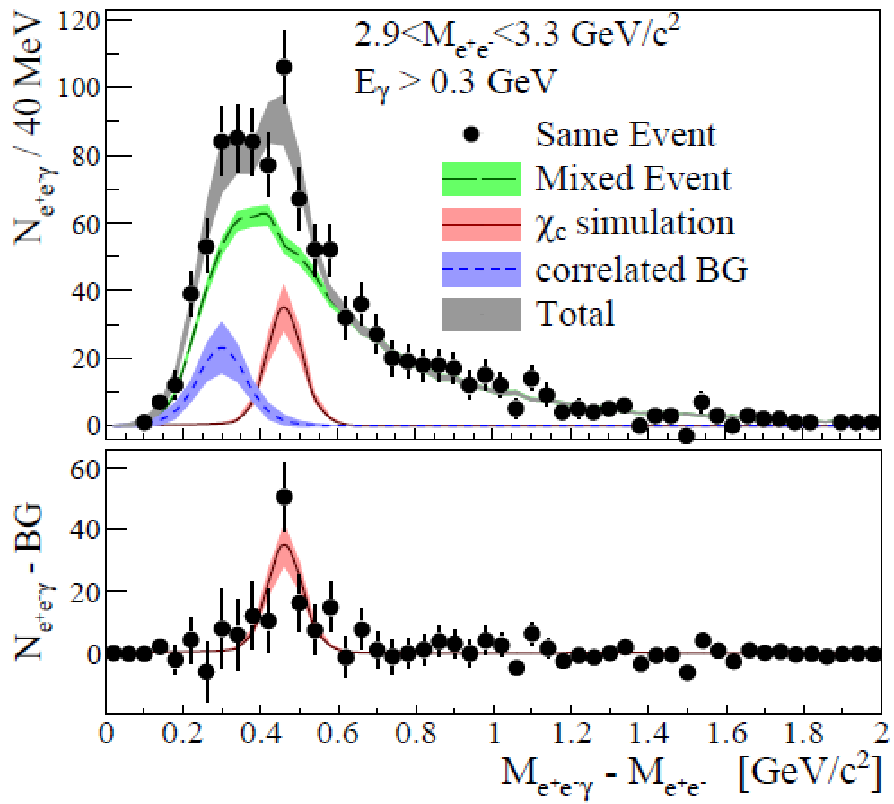
$\psi' \rightarrow e^+e^-$



$$F_{\Psi'}^{J/\Psi} = \frac{B_{J/\Psi}^{\Psi'}\sigma_{\Psi'}}{\sigma_{J/\Psi}} = (9.6 \pm 2.4)\%$$

Consistent with world average!!!

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



$$F_{\chi_c}^{J/\Psi} = \frac{N_{\chi_c}}{N_{J/\Psi}} \frac{1}{<\varepsilon_{\chi_c}/\varepsilon_{J/\Psi}>} = (32 \pm 9)\%$$

Non-photonic R_{AA} at RHIC

DGLV:
Djordjevic, PLB632, 81 (2006)

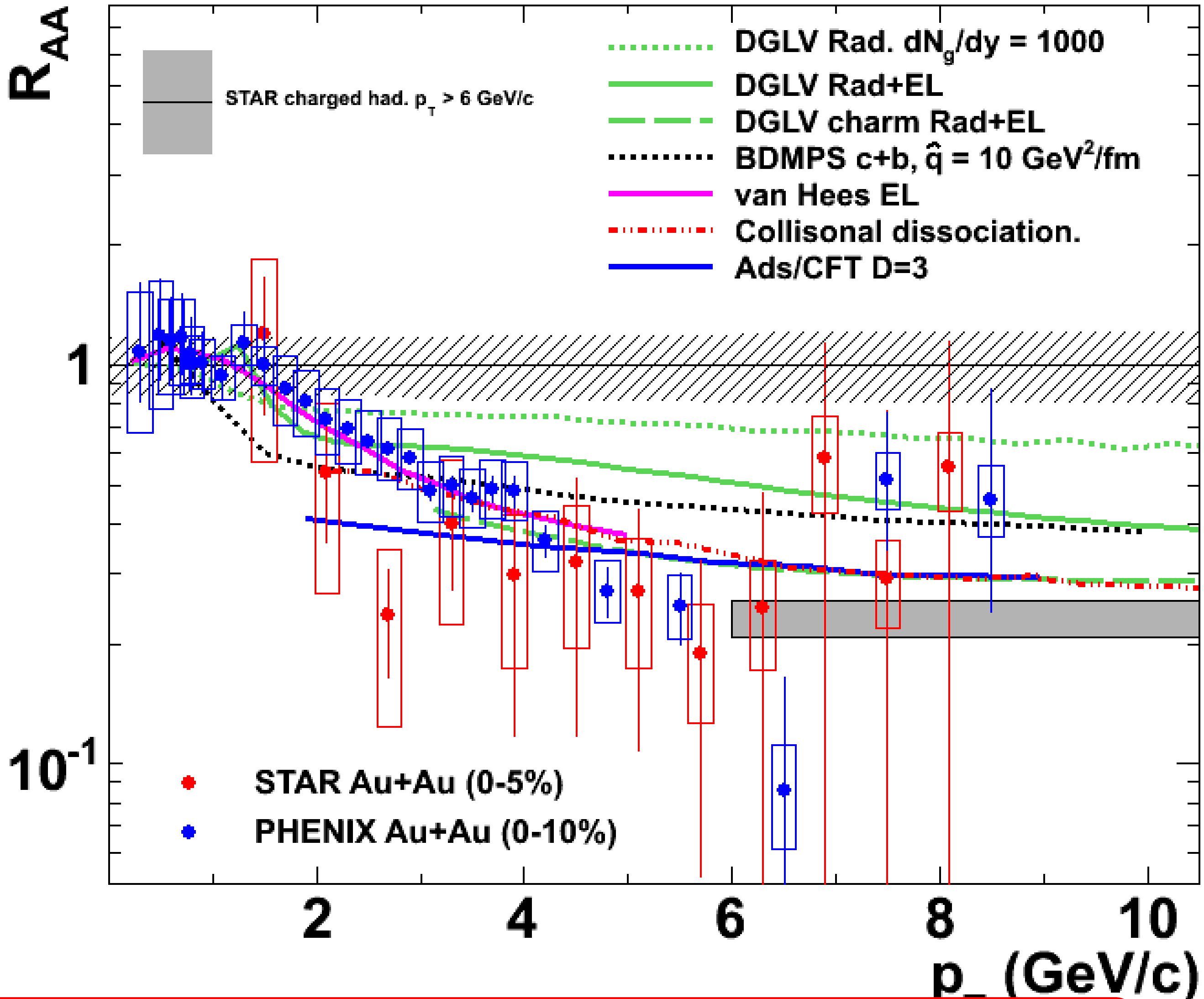
BDMPS:
Armesto, et al.,PLB637, 362 (2006)

T-Matrix:
Van Hees et al., PRL100,192301(2008).

Coll. Dissoc.
R. Sharma et al., PRC 80, 054902(2009).

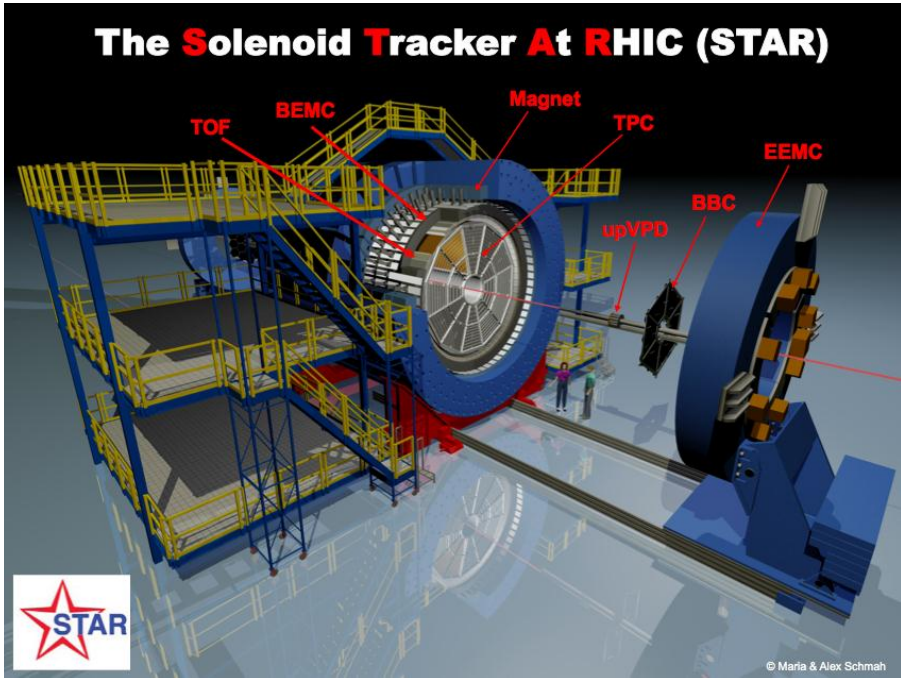
Ads/CFT:
W. Horowitz Ph.D thesis.

RL.+ Coll.
J. Aichelin et al., SQM11



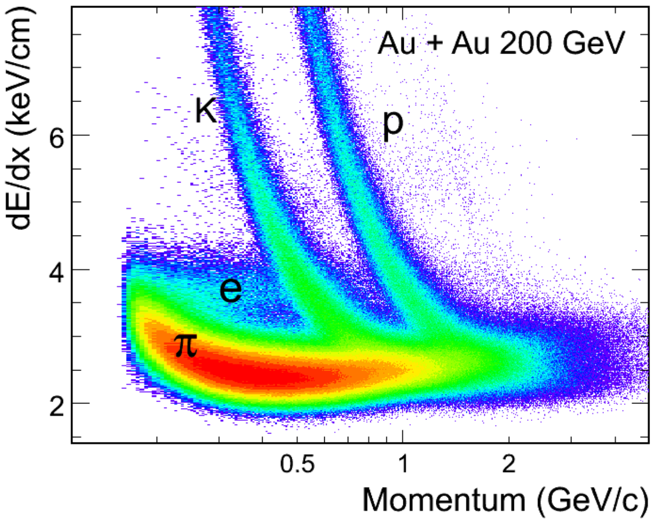
- ❑ Models with different or similar mechanisms can or can not describe the data
  - ➢ Which one is right and what are missing?

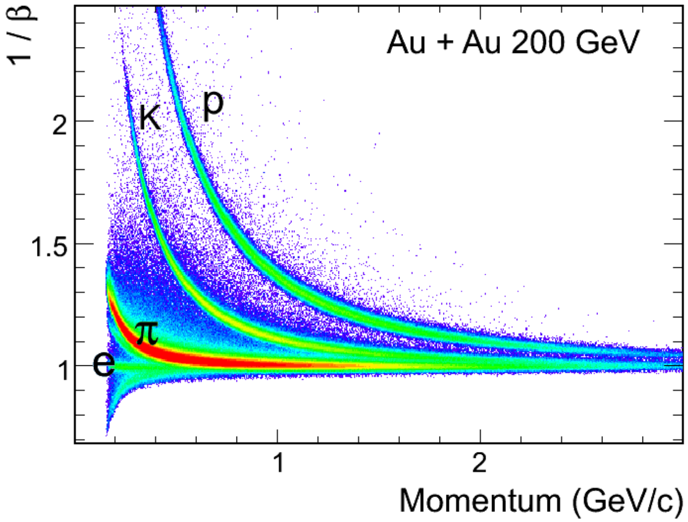
STAR detector and Particle ID



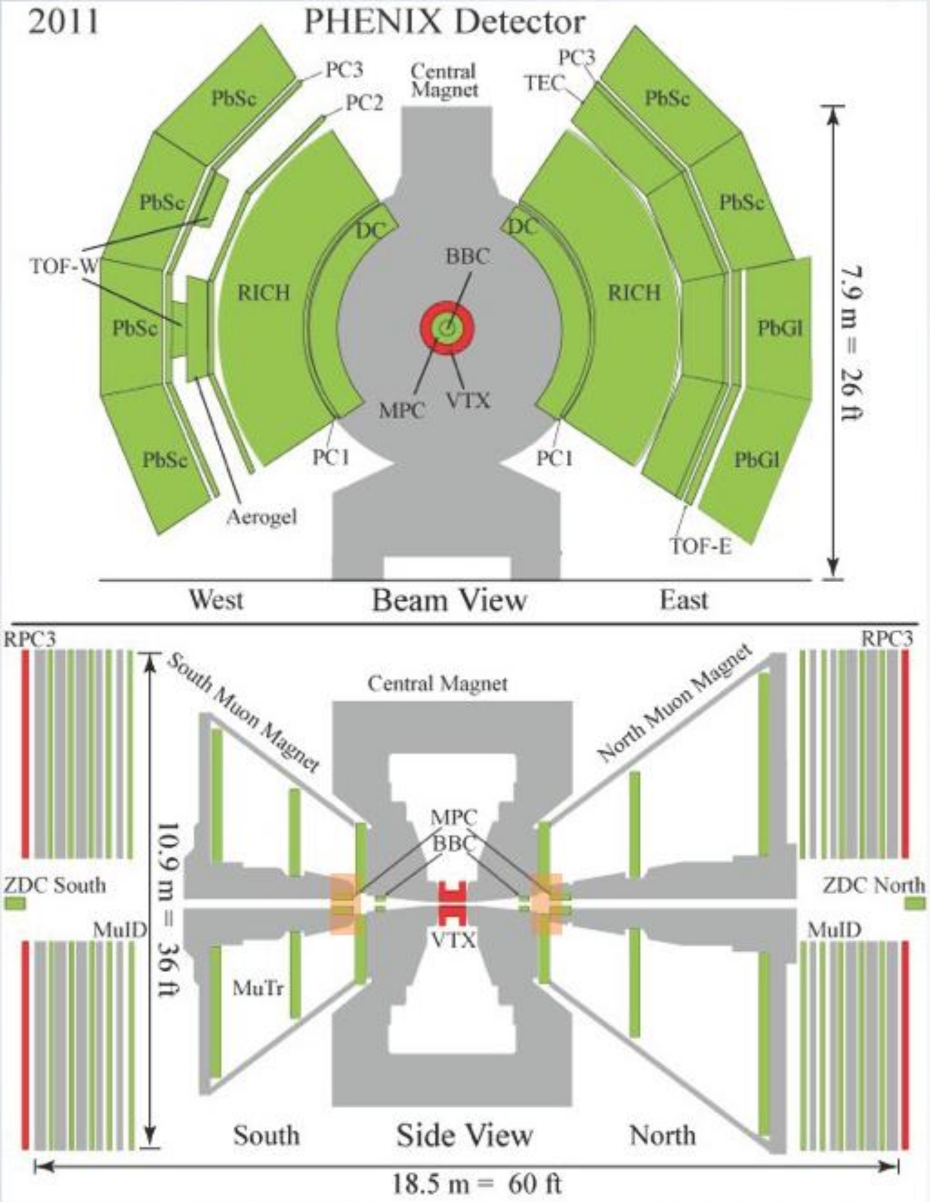
Large acceptance
$|\eta|<1$, $0<\phi<2\pi$

- Time Projection Chamber
  dE/dx, momentum
- Time Of Flight detector
  particle velocity $1/\beta$
- ElectroMagnetical Calorimeter
  E/p, single tower/topological Trigger





PHENIX detector and Particle ID



Central Arms $|\eta| < 0.35$

- Identified charged hadrons
- $e^{\pm}, \pi^0, \eta$
- Direct Photon
- $J/\Psi, \Psi', \chi_c$
- Heavy Flavor

Muon Arms $1.2 < |\eta| < 2.4$

- $J/\Psi, \Upsilon$
- Unidentified charged hadrons
- Heavy Flavor

MPC $3.1 < |\eta| < 3.9$

- π^0, η

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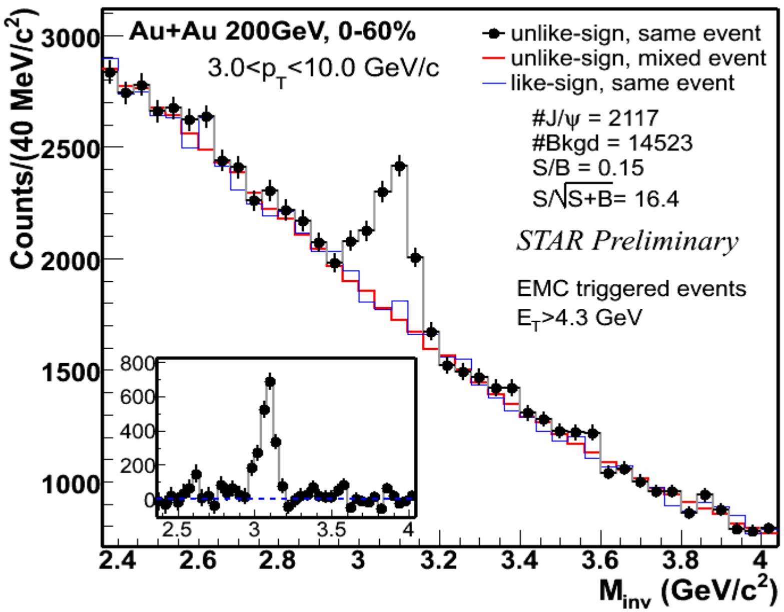
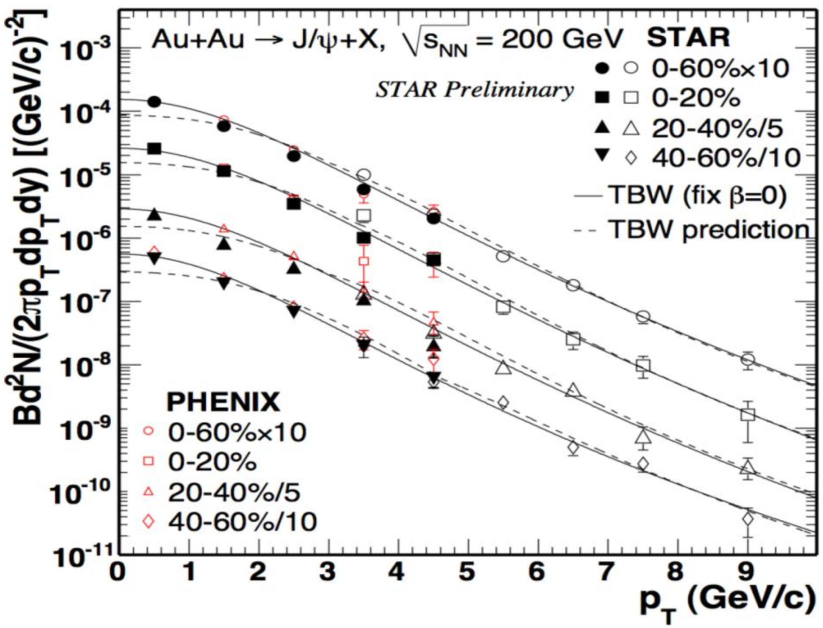
STAR J/ψ spectra in Au+Au 200GeV

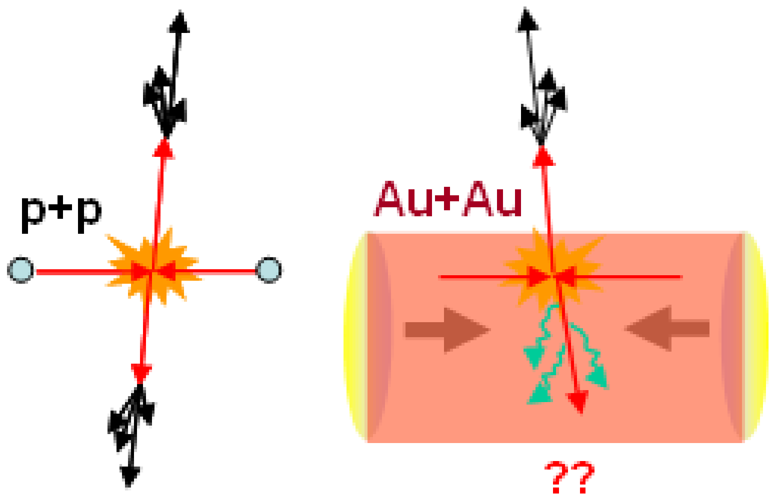


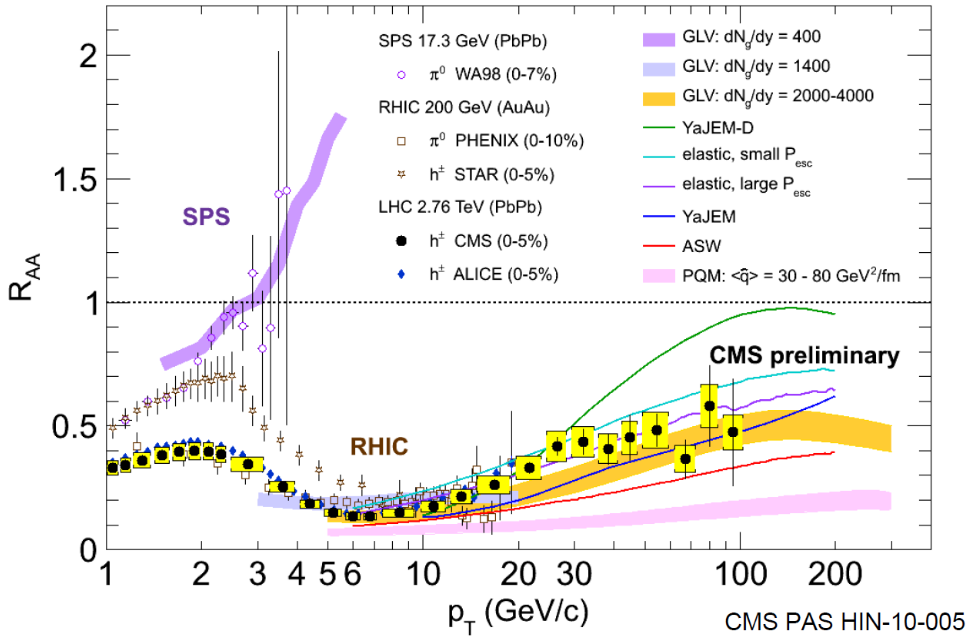


Phys. Rev. Lett. 98, 232301 (2007)
JPG 37, 085104 (2010)
ArXiv:1101.1912 (2011)

- Consistent with other RHIC measurements. Moreover we extend pT region up to 10GeV/c.

Nuclear modification factor





- **Hard probes** - produced in hard scatterings in initial phase of collision
- Nuclear matter influences the final particle production

  e.g. production of particles at given p_T

  supresion of particle production of particular type

- **Nuclear modification factor** - quantification of nuclear effects R_{AA}

$$R_{AA}(p_T) = \frac{\mathrm{Yield}_{AA}(p_T)}{\langle Nbin \rangle_{AA} \mathrm{Yield}_{pp}(p_T)}$$

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Cold nuclear matter effects

- **Nuclear Shadowing** – Modification of PDF's for nucleons bound in nuclei.
  Parametrizations of (mostly) DIS data (ex. EKS98, nDSg, EPS09).
- **Nuclear Break-up** – Break-up of cc pair through collisions with nucleons.
  Usually parametrized using break-up cross section.
- **Cronin Effect** – Broadening of the pT distribution through scattering of incoming partons.
- **Initial State Energy Loss** – decrease in parton momentum due to soft scatterings while propagating through colliding nucleus.

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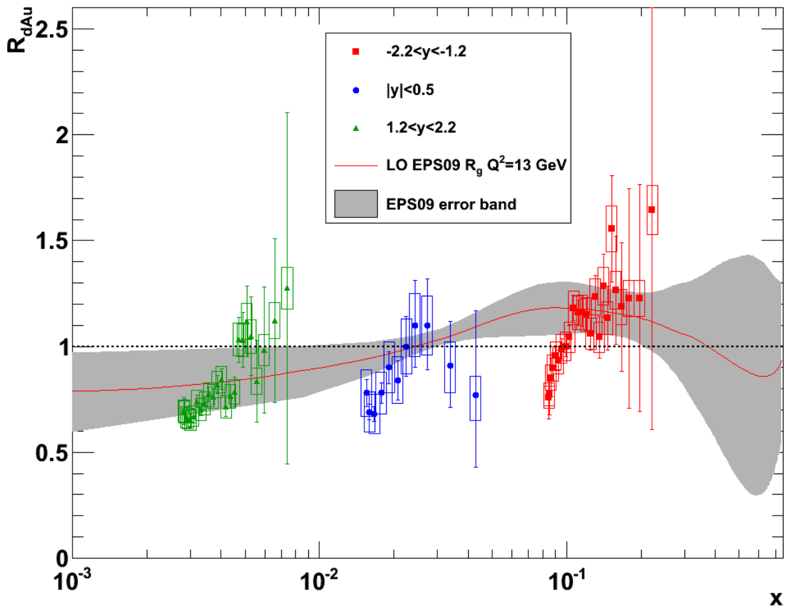
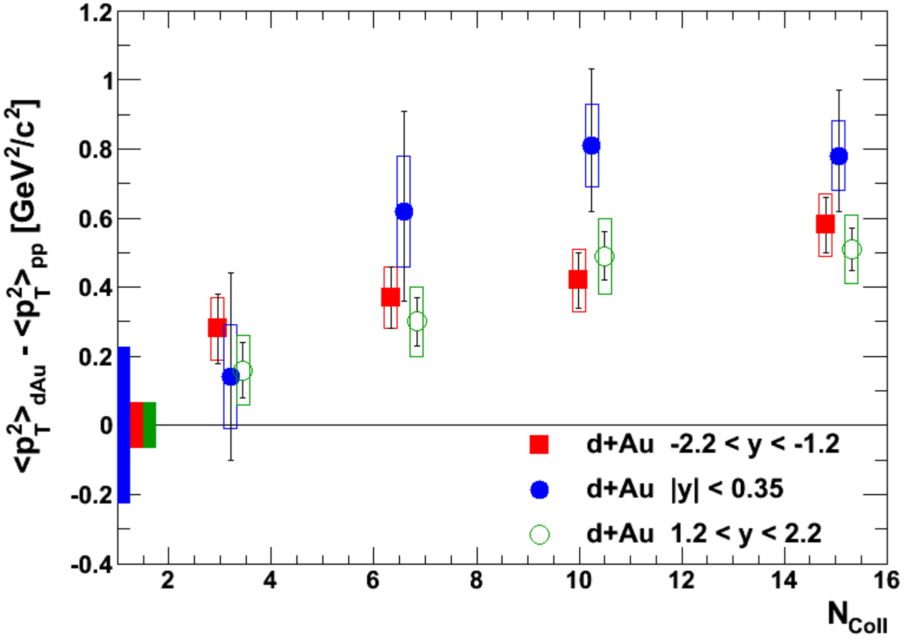
Cold nuclear matter effects





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