Heavy Flavour at RHIC

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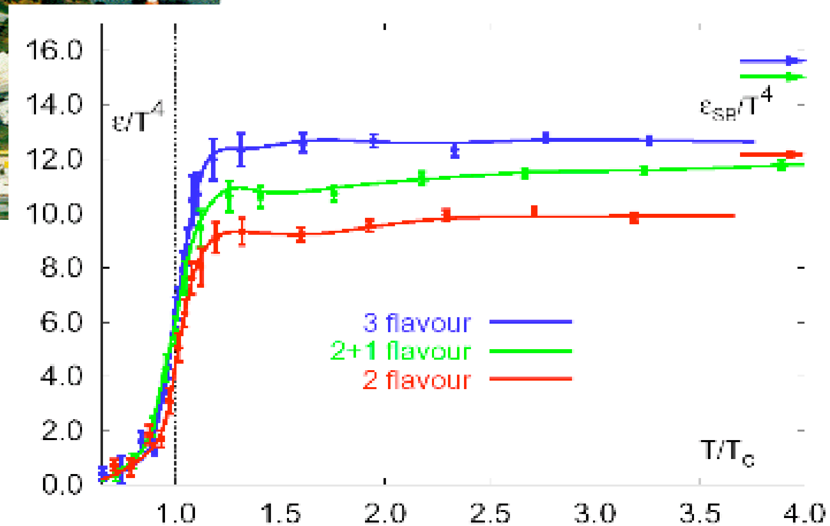
Outline

1. Introduction
2. Open heavy flavour
   - Charm meson reconstruction and non photonic electrons
   - R(AA) and elliptic flow
   - Disentangling Beauty and Charm
3. Hidden heavy flavour
   - J/Psi
   - Y
4. Conclusions

Introduction
Relativistic Heavy Ion Collider

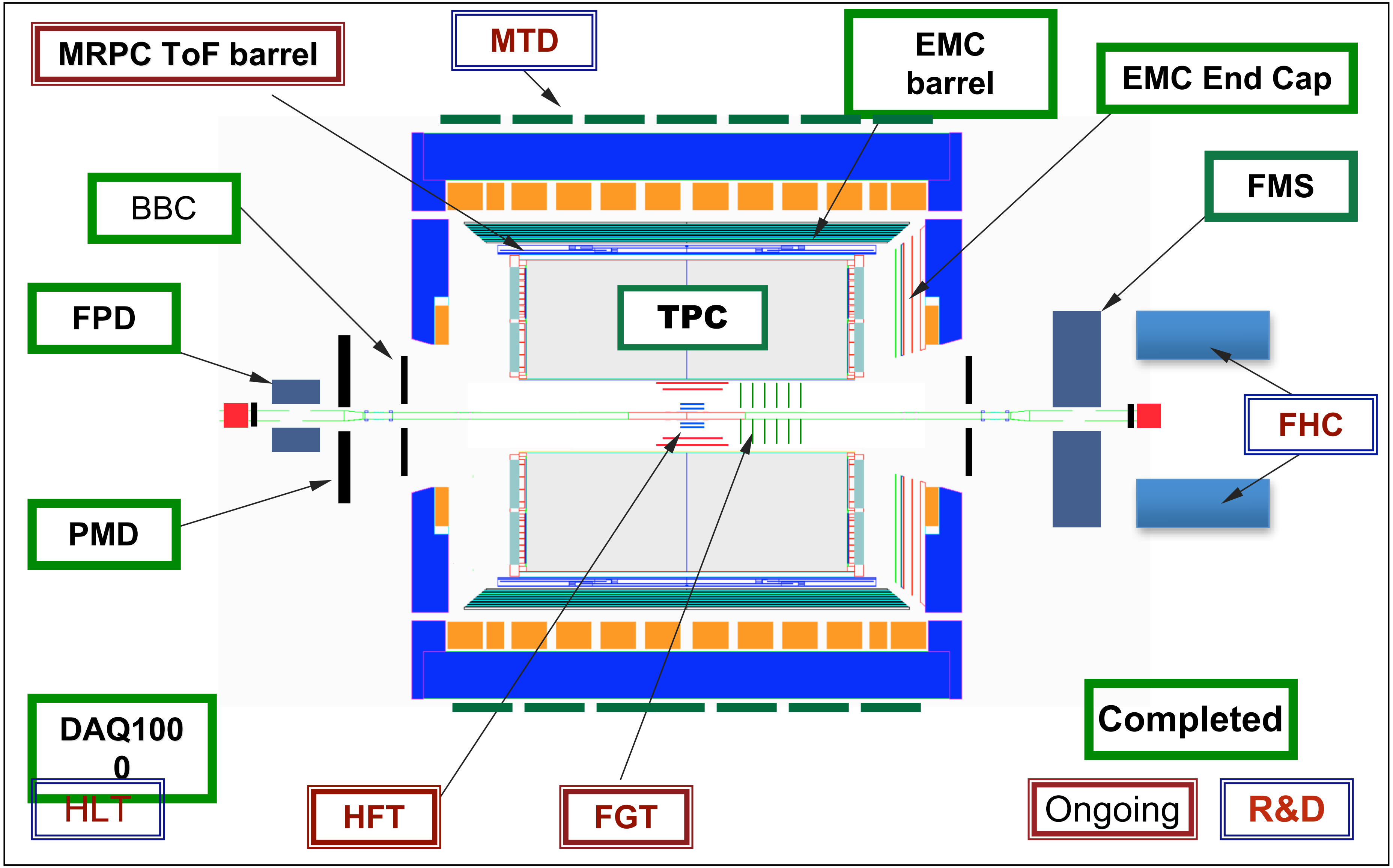
RHIC site in BNL on Long Island, USA

RHIC has been exploring nuclear matter at extreme conditions over the last decade 2000-2011



Colliding systems:
p↑+p↑, d+Au, Cu+Cu, Au+Au
Energies A+A :
$\sqrt{s_{NN}}$ = 62, 130, 200 GeV
and low energy scan

The STAR Detector



The PHENIX detector

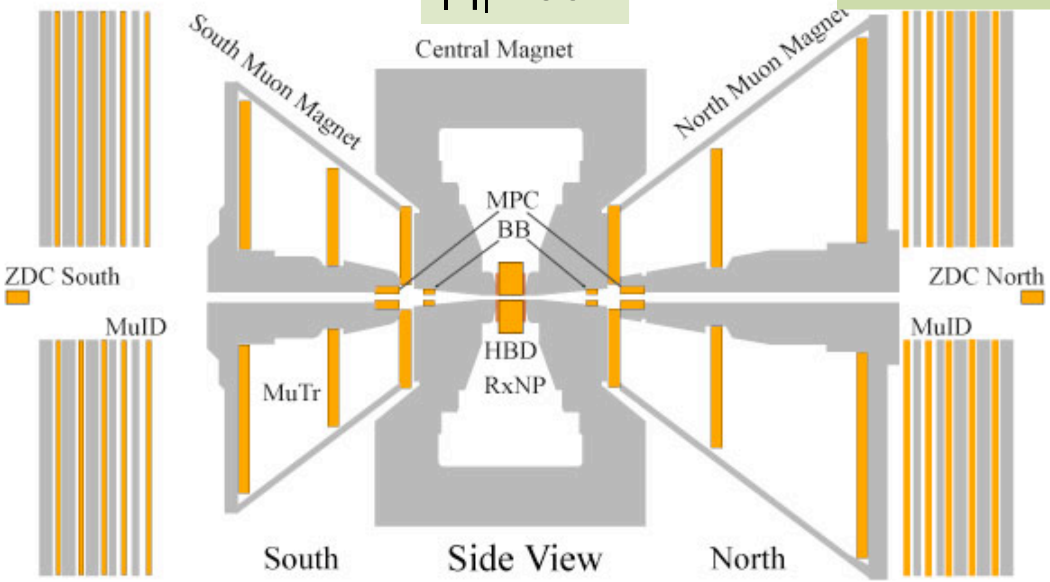
$\mu^+\mu^-$

e^+e^-

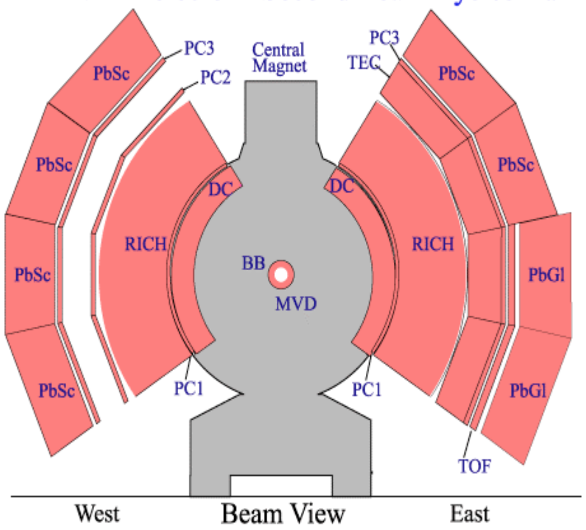
$|\eta|<.35$

$\mu^+\mu^-$

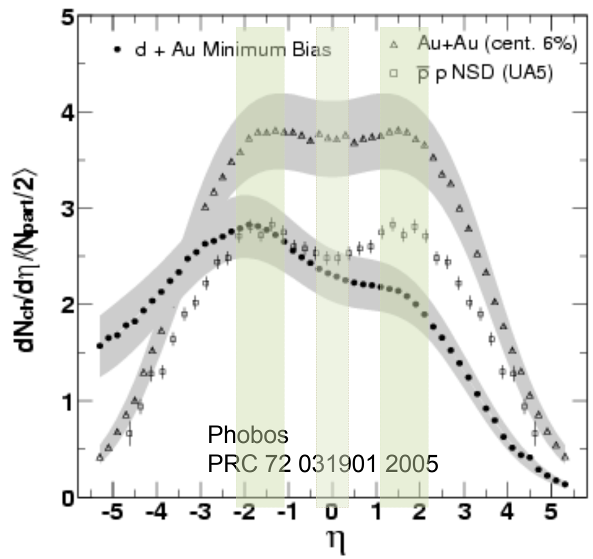
$1.2>\eta>2.2$



PHENIX Detector - Second Year Physics Run



Phenix acceptance shown with the vertical bands :



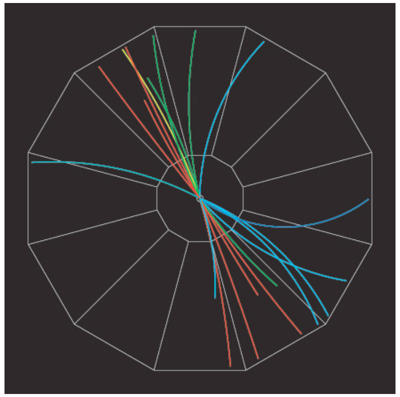
Denis Jouan ,
Renc de Moriond
QCD 2010

PHENIX

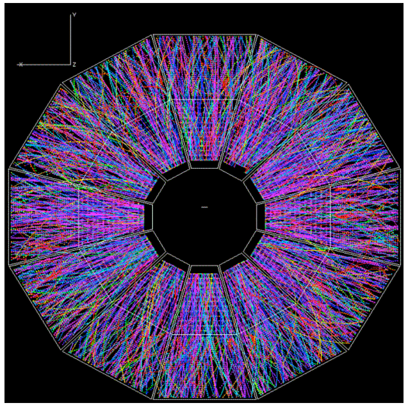
Energy in calorimeter
electron ID in RICH
Tracking in Drift chamber

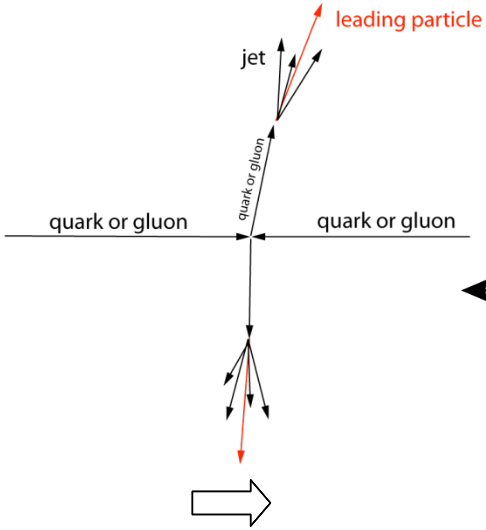
Probing of Dense Matter with jets

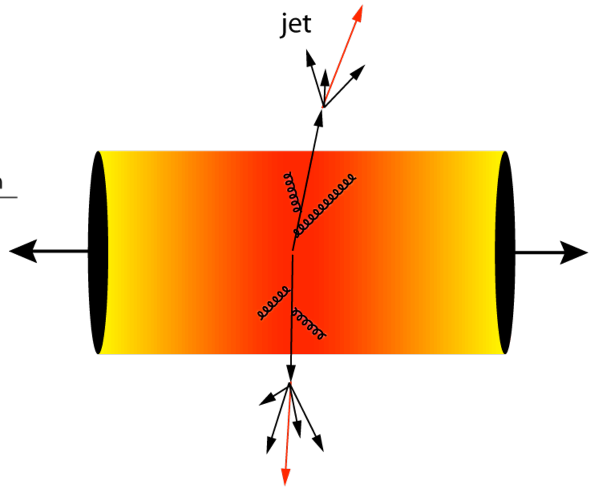
p+p Collision



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

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)

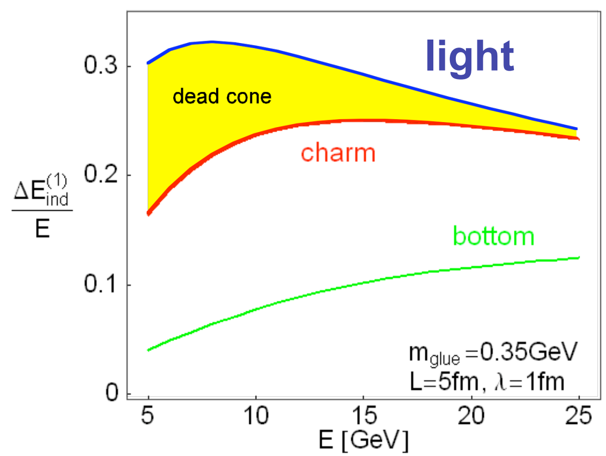
•heavy ion data:

- Study energy loss of heavy quarks

→ independent way to extract properties of the medium

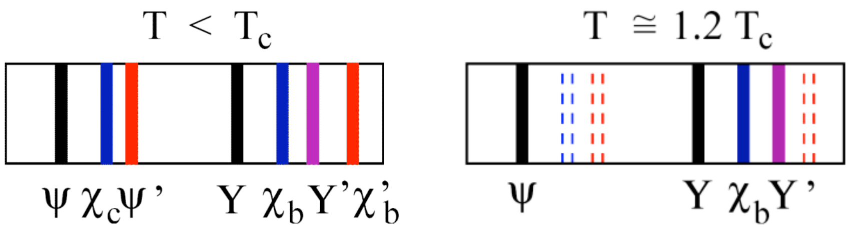
Radiative energy loss

M.Djordjevic PRL 94 (2004)

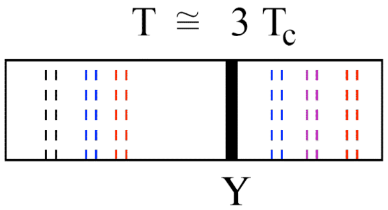


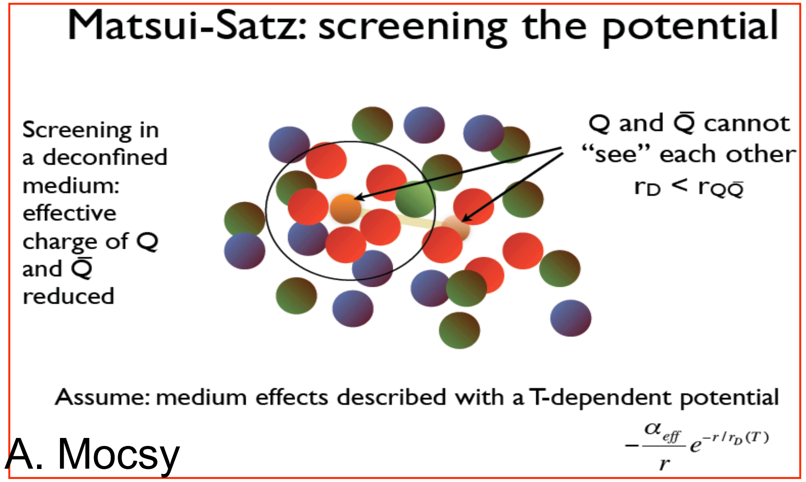
-> Flavour dependence of jet quenching

Quarkonia



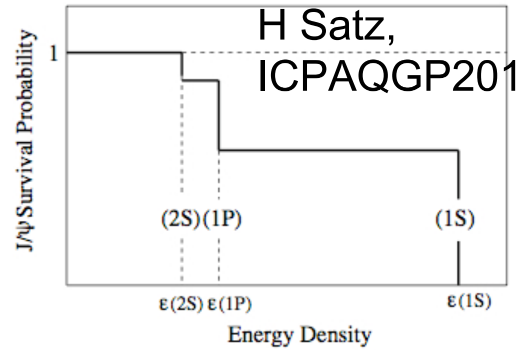
H. Satz, Nucl. Phys. A (783):249-260(2007)





A. Mocsy

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



H Satz, ICPAQGP2010

Quarkonia: Thermometer of QGP through hierarchy of T(dissociation)

Many effects play a role: dissociation in QGP - cold matter absorbtion - recombination/coalescence from c, cbar - heavy resonances ...

Open Heavy Flavour

Charm meson reconstruction and non photonic electrons

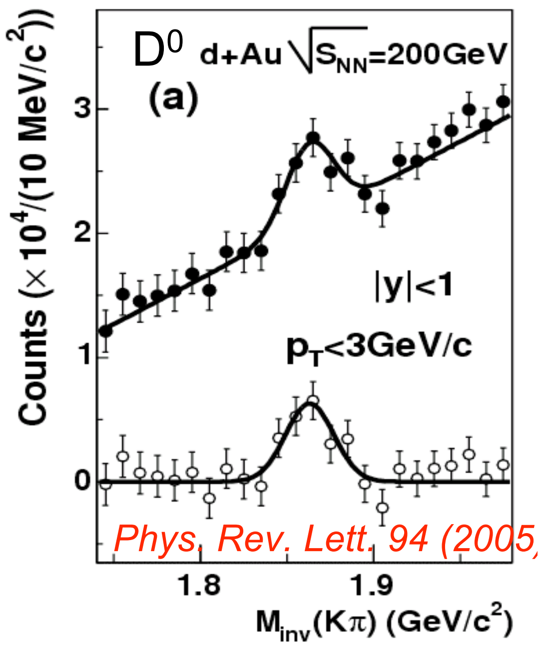
Open heavy flavor

Direct: reconstruction of all decay products

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

STAR

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



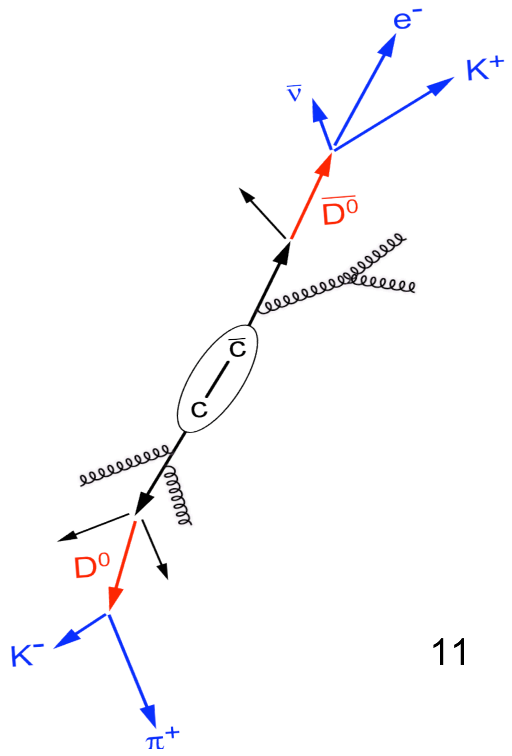
Indirect: charm and beauty via electrons

c → e^+ + anything (B.R.: 9.6%)
b → e^+ + anything (B.R.: 10.9%)
issue of photonic background

charm (and beauty) via muons

c → μ+ + anything (B.R.: 9.5%)

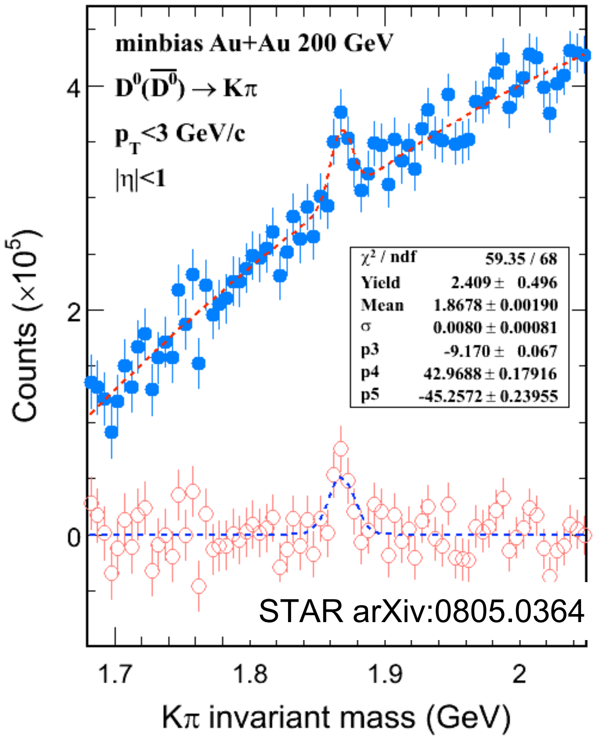
STAR and PHENIX

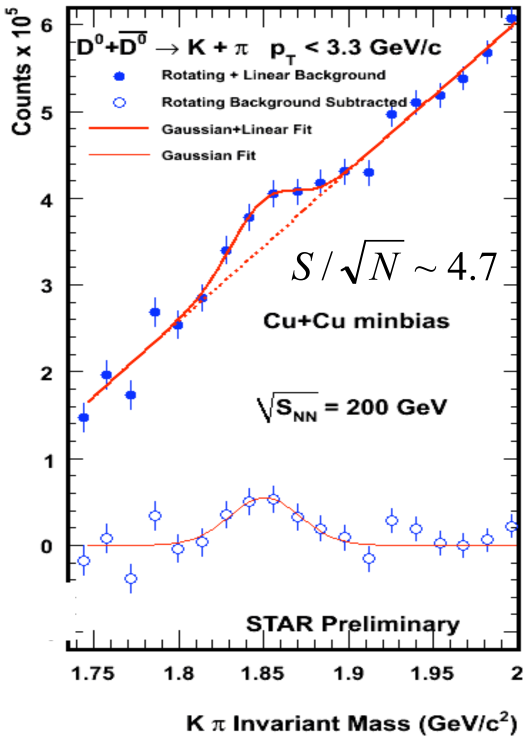


See talk by S. Margetis on open charm

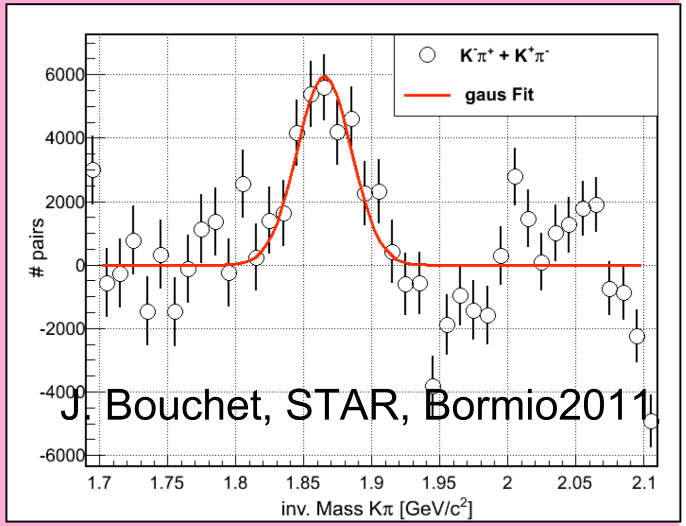
direct reconstruction, eQCD2011

Direct D-meson reconstruction at STAR



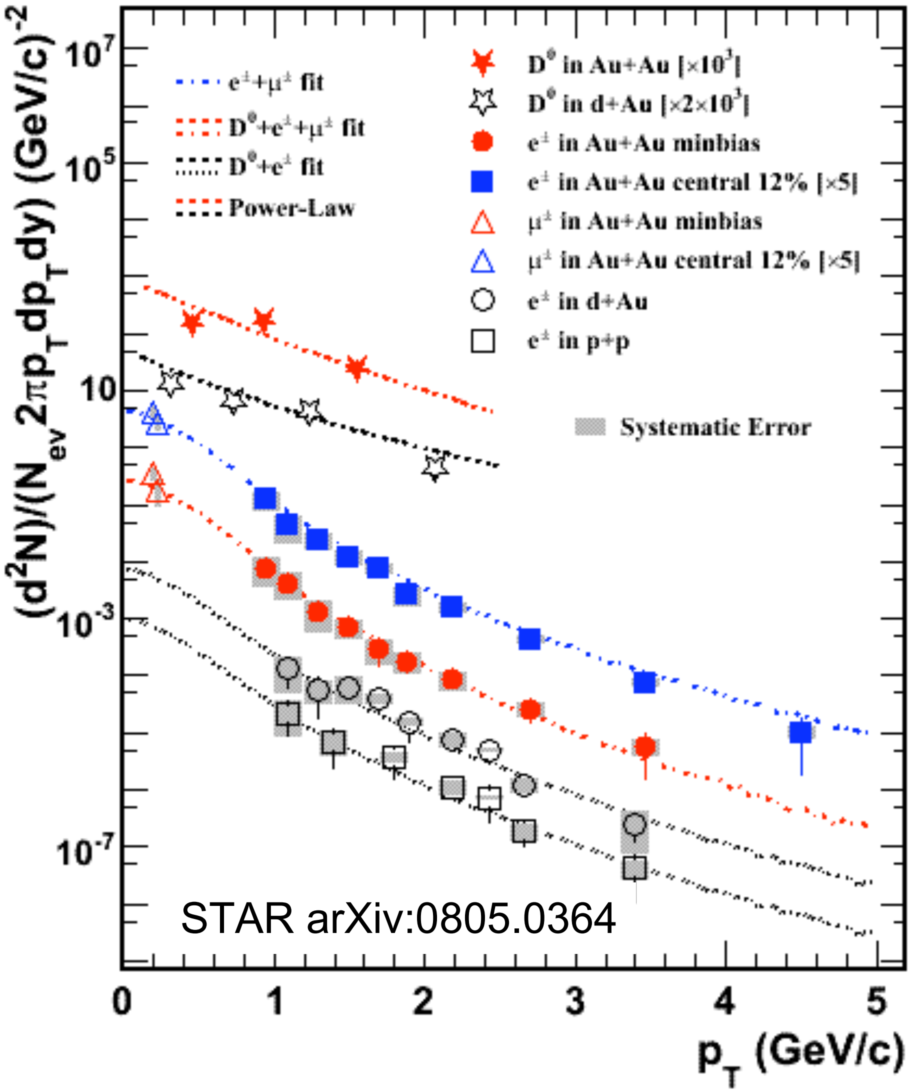


D0 recon. with the help of silicon detectors in STAR (preliminary)



- Kπ invariant mass distribution in d+Au, Au+Au minbias, Cu+Cu minbias at 200 GeV collisions

Measurement of charm STAR



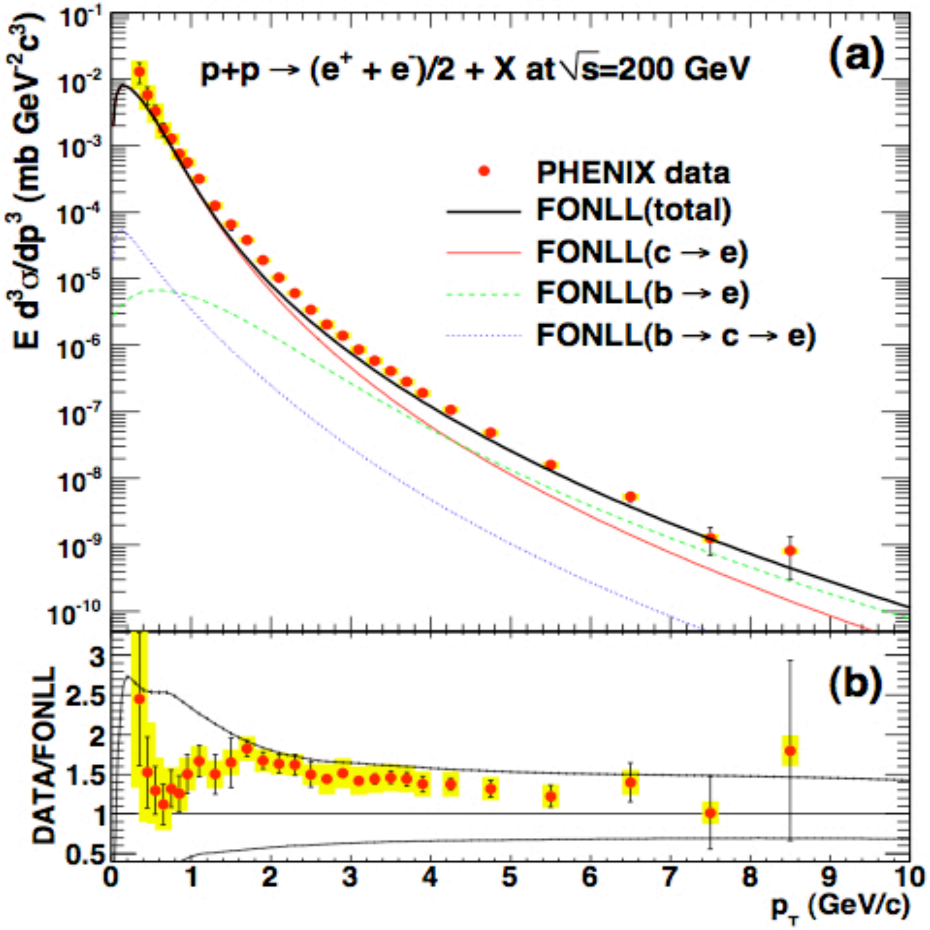
STAR charm measurement:

- 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

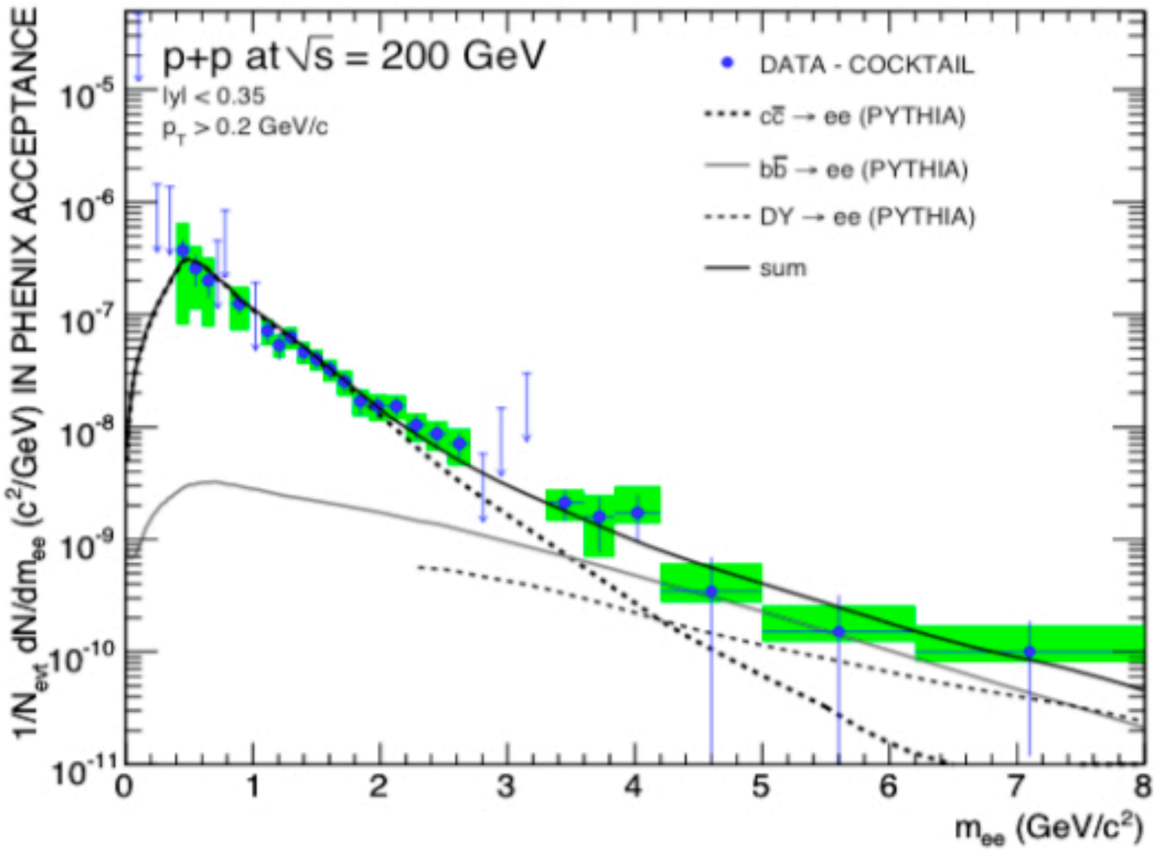
- 90% of charm total kinematic range covered

Measurement of charm PHENIX

Non photonic electrons PHENIX, arXiv:1005.1627



Open heavy flavour from di-electron spectrum (PHENIX)



arXiv:0802.0050 (PHENIX)
Published

measured correlated e^-e^+ pairs

Independent cross-check for calculation charm and bottom quark cross sections:

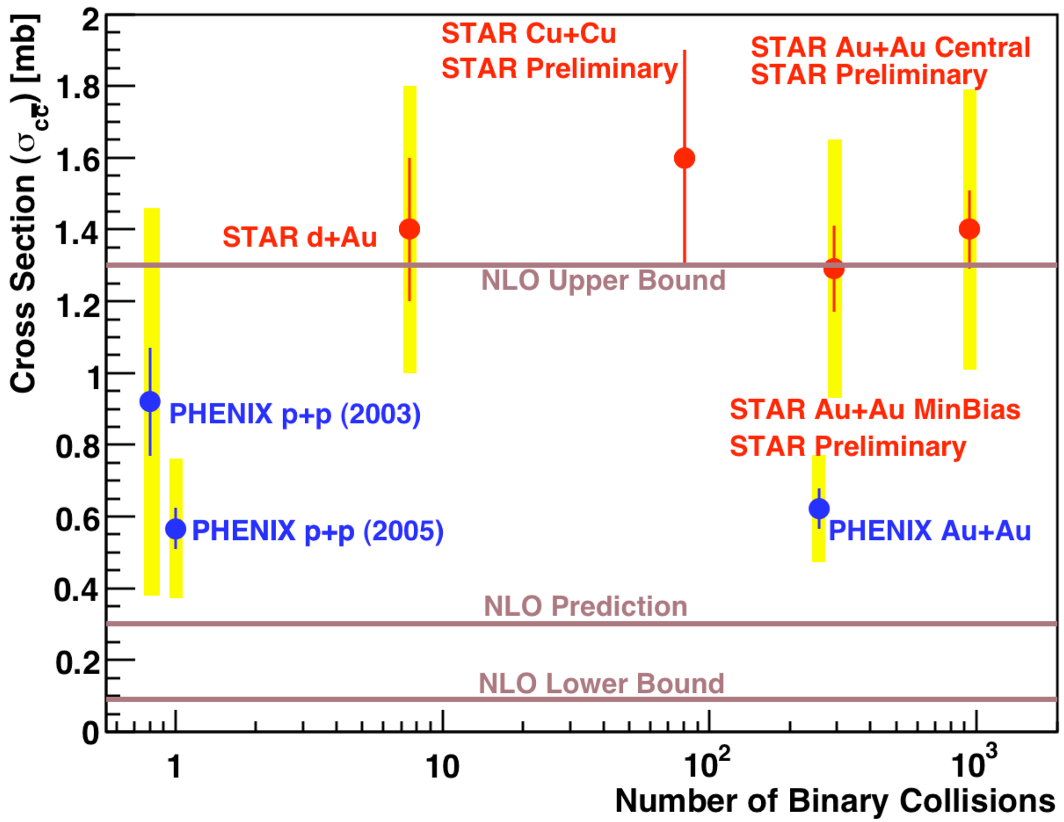
σ_{cc}= 544 ± 39(stat) ± 142(sys) ± 200(model) mb

σ_{bb}= 3.9 ± 2.5(stat) ± $^{3}_{2}$ (sys)

Good agreement with single heavy flavor electron results.

I. Garishvili, PHENIX, Purdue workshop Jan 2011

Open Charm Cross-section and STAR-PHENIX discrepancy



STAR:

D^0, electrons
PRL 94(2005) 062301

D^0, muons
arXiv:0805.0364

PHENIX:

Single electrons
PRL 97(2006) 252002

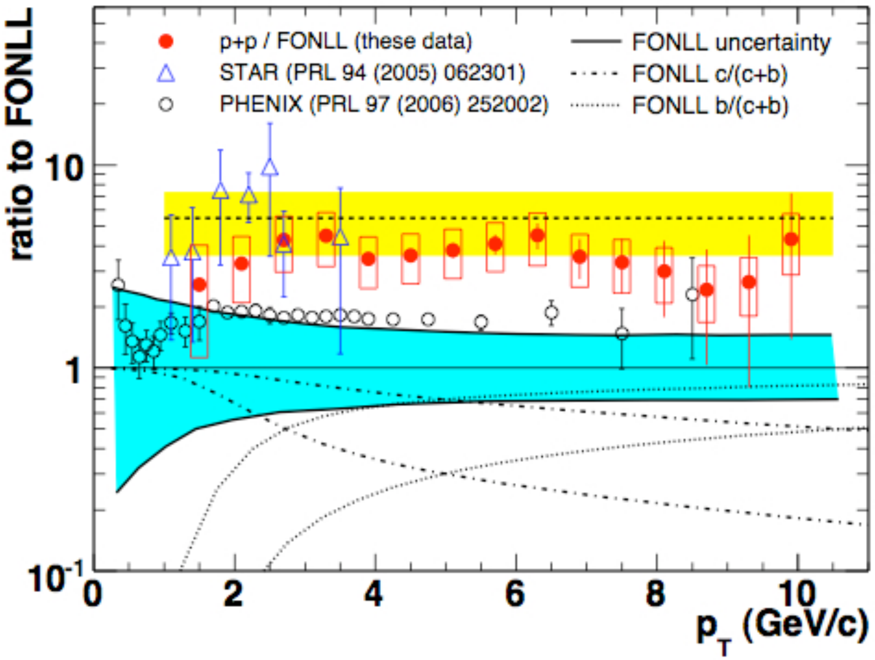
Electron pairs
544 ± 39(stat) ± 142 (syst) ± 200 (model)
PLB 670 (2009) 313

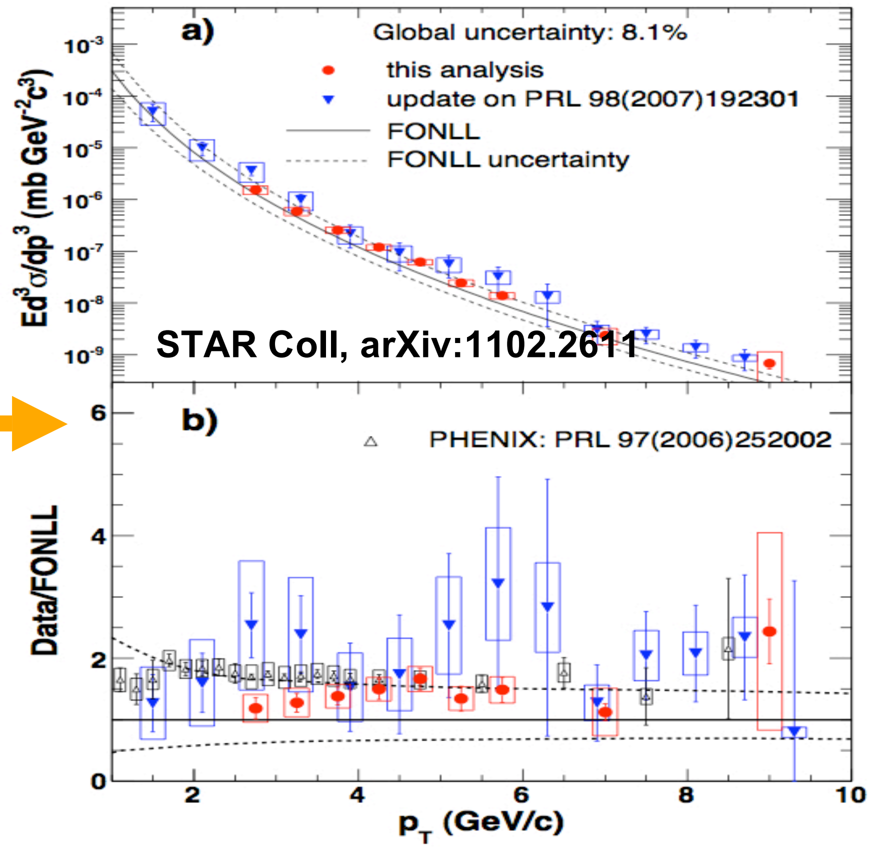
- Discrepancy between extracted total cross-section from STAR and PHENIX

Resolution of the high pT NPE STAR-PHENIX discrepancy

Discrepancy : STAR Coll, PRL98 (2007) 192301 (old result, now updated --> see right plot)

Resolution: STAR 2011 update of PRL98 (2007) 192301 (blue) and new data (red)





* STAR and PHENIX NPE results in 200 GeV p+p collisions are consistent within errors at pt > 2.5 GeV/c

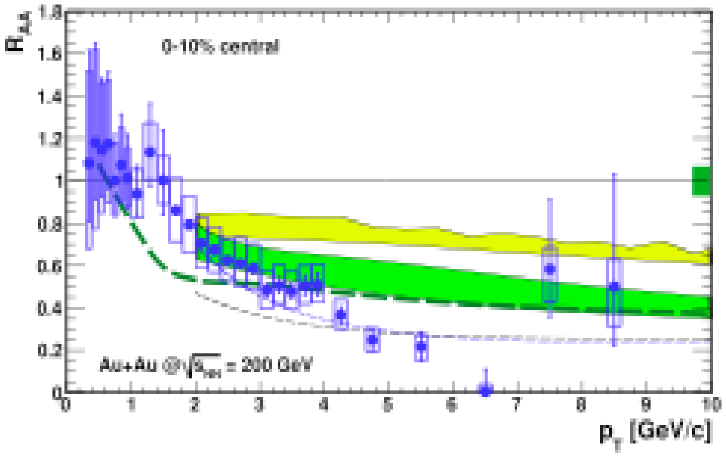
* STAR and PHENIX NPE results are consistent with FONLL in 200GeV p+p collisions

R(AA) and elliptic flow

Large suppression of Non-Photonic-Electrons

A Adare et al, PHENIX, arXiv:1005.1627

Au+Au 200 GeV 0-10% central



Thick dashed line: BDMPS (D,B)->e

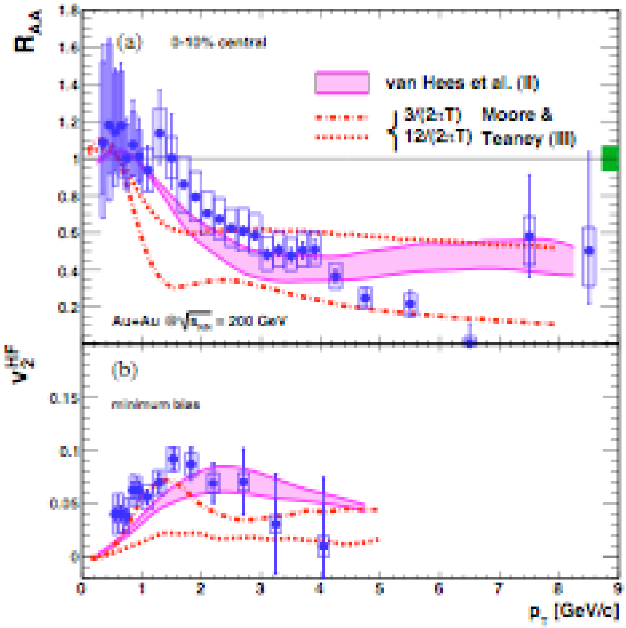
Upper band: DGLV (D<B)->e radiative dedx

Lower band: DGLV collisional+rad. dedx

Thin dashed curves: DGLV only D->e+X

NPE R_AA puzzle: Larger suppression (c+b) than expected for radiative dedx/dead cone effect

Adding collisional dedx improves agreement



Van Hees et al PRL100 (2008) 192301

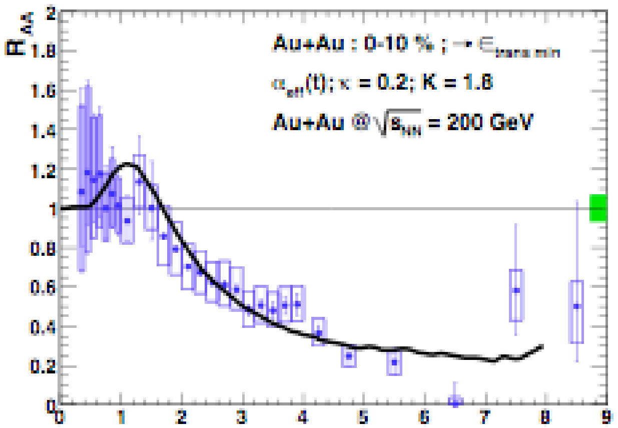
Dedx by elastic scattering mediated by resonance excitation of D and B-like states in the medium

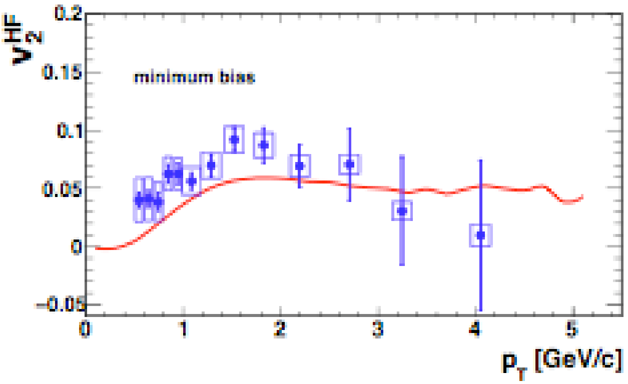
Describes ~ both R_AA, v2(NPE)

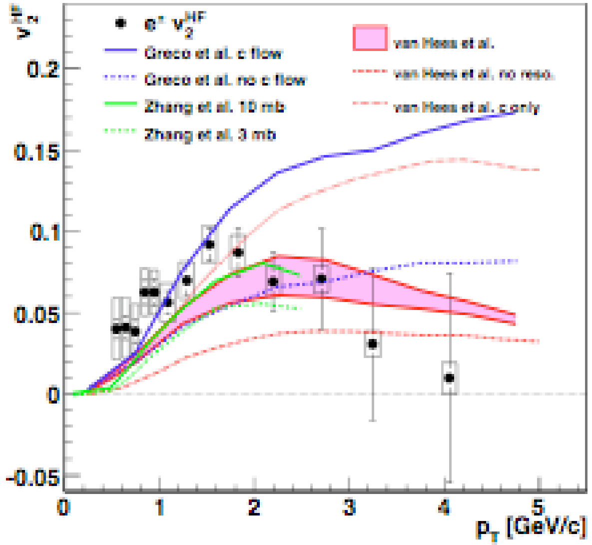
R_AA(NPE) and v2(NPE)

P. Gossiaux, J Aichelin, PRC78 (2008) 014904, 0901.2462, 0901.0946

A Adare et al, PHENIX, arXiv:1005.1627







Collisional dedx+

running coupling constant,

Greco et al: c flow assumes v2(c)=v2(u,d)

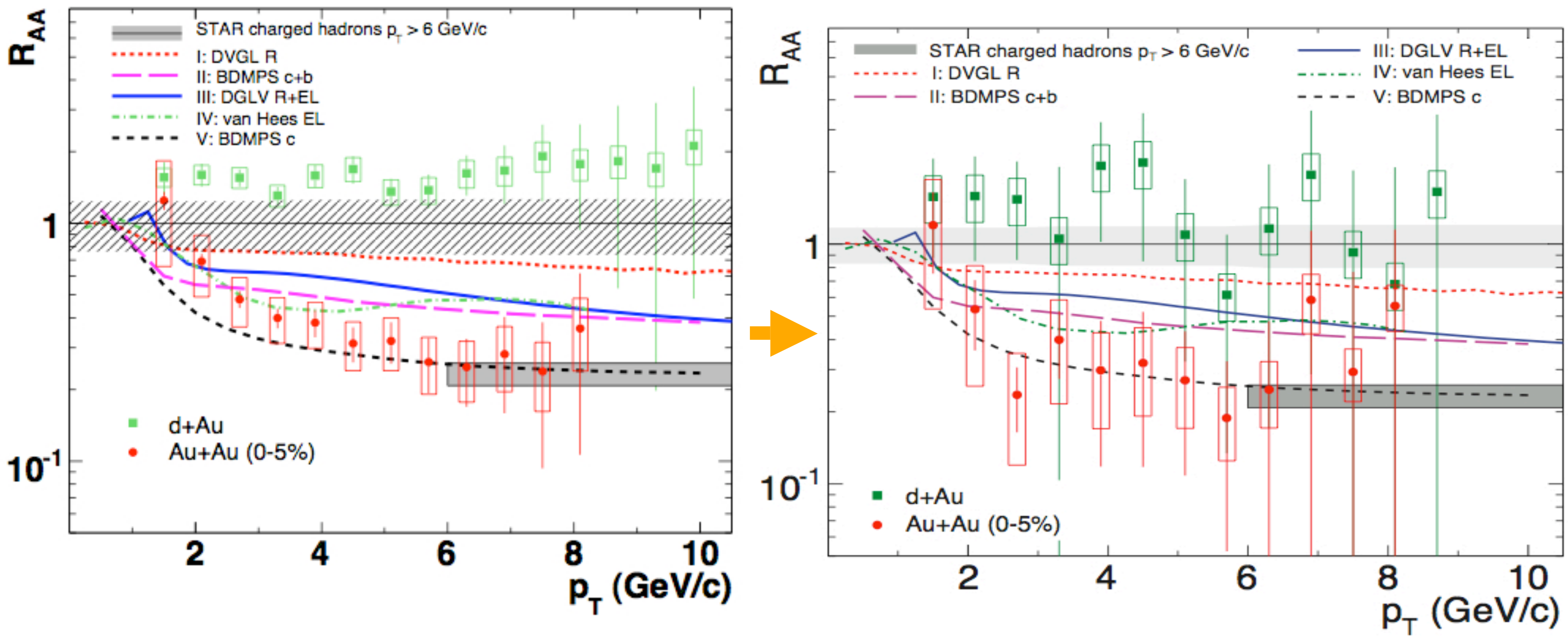
no c flow assumes v2(c)=0

Zhang et al: HIJING+(parton cascade)+(hadron cascade) for two charm quark scattering cross sections

Van Hees et al: resonant interaction in strongly interacting QGP and parton coalescence of c,b --> Reduction or flatening of v2 at high pT requires b contribution

Resonances required at low pT

Recent update of STAR R(AA) NPE Au+Au 200 GeV (2007 paper erratum)



Physics message remains the same as in original publication

Elliptic flow v2(NPE)

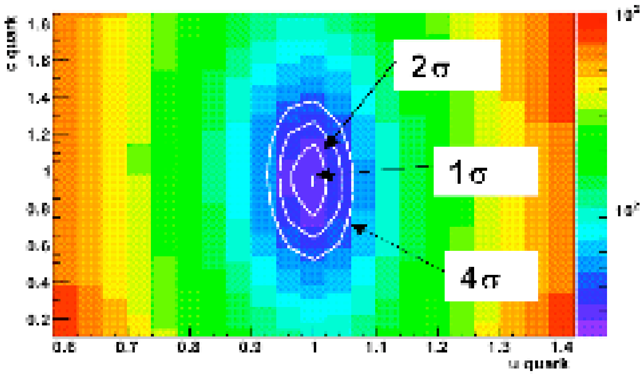
A Adare et al, PHENIX, arXiv:1005.1627

R_AA(NPE) suppression and sizable v2(NPE) :

Heavy quarks lose energy in the medium, while acquiring a substantial component of the medium's collective flow

Compare v2(NPE) to the expected v2(D) from coalescence production.

pT< 2 GeV to be sensitive only to c and not b



chi^2 for v2(c) vs v2(u)

both normalized to measured v2(u)

calculated from measured v2(light quarks) and v2(NPE)

→ v2(c) ~ v2(u)

→ the coalescence assumption for D seems supported

→ indicates common quark collectivity

Disentangling Beauty and Charm

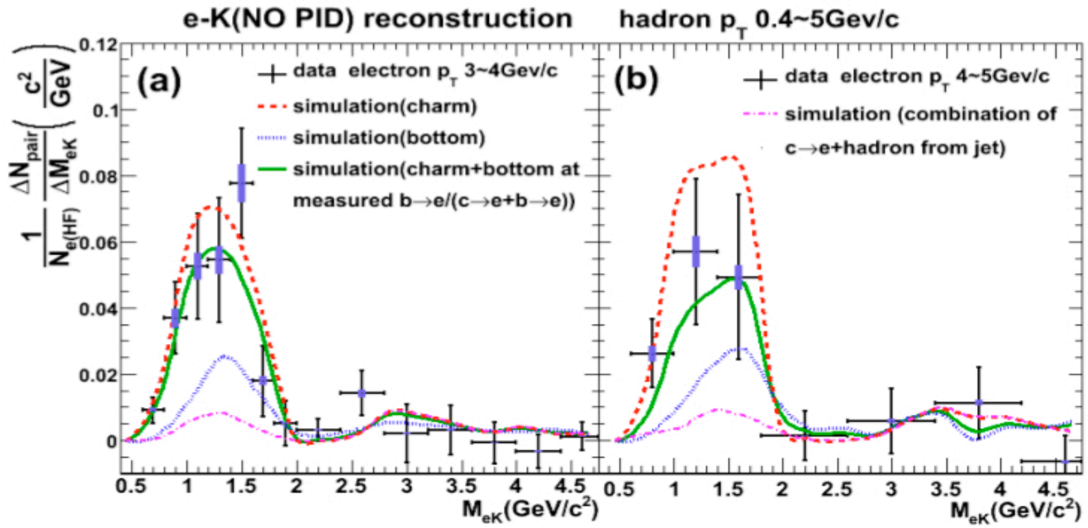
Beauty to charm ratio in p+p collisions

PHENIX :

Reconstruction of e-K (K unidentified) invariant mass

Fit with PYTHIA simulation varying the b/(c+b) ratio

Phenix Coll, PRL103, 082002, 2009.

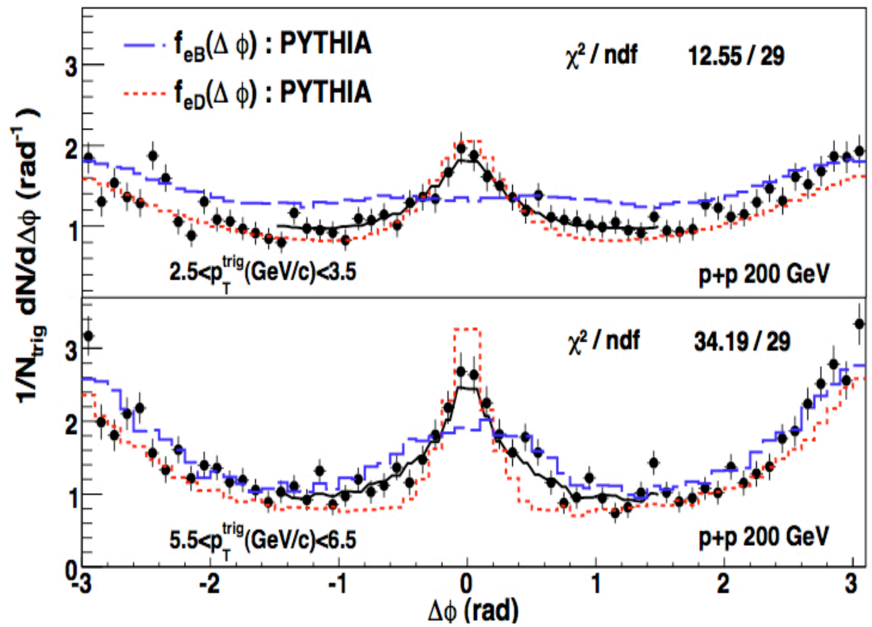


STAR and PHENIX :

e-hadron azimuthal correlations -->

different widths for NPE coming from Charm and Beauty decays

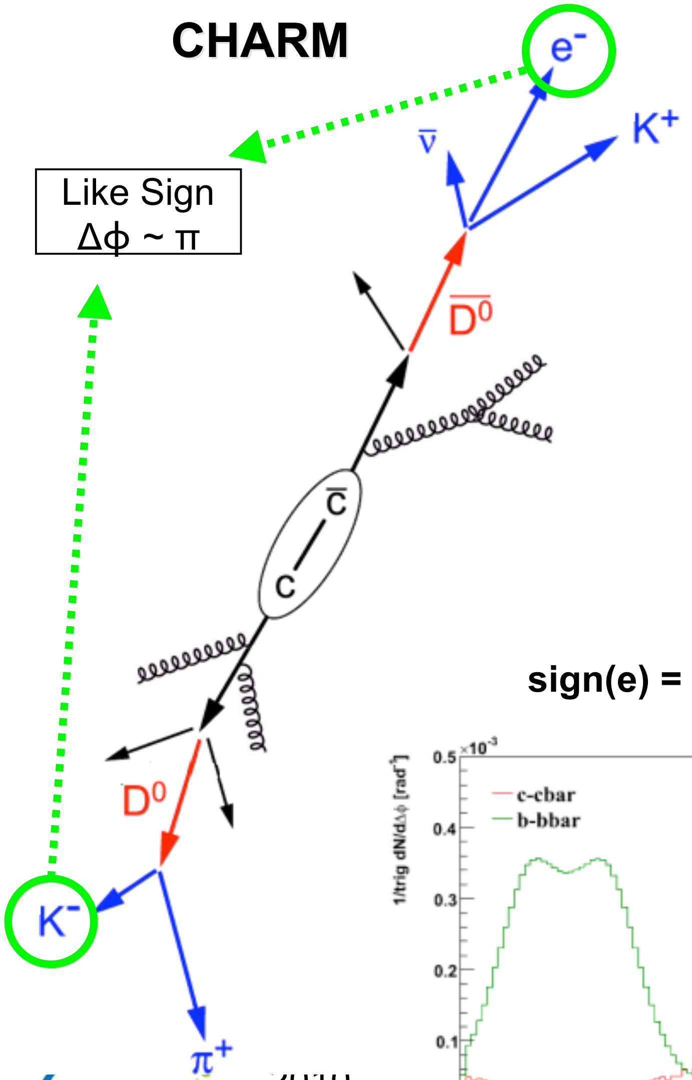
Fit with PYTHIA simulation varying the b/(c+b) ratio

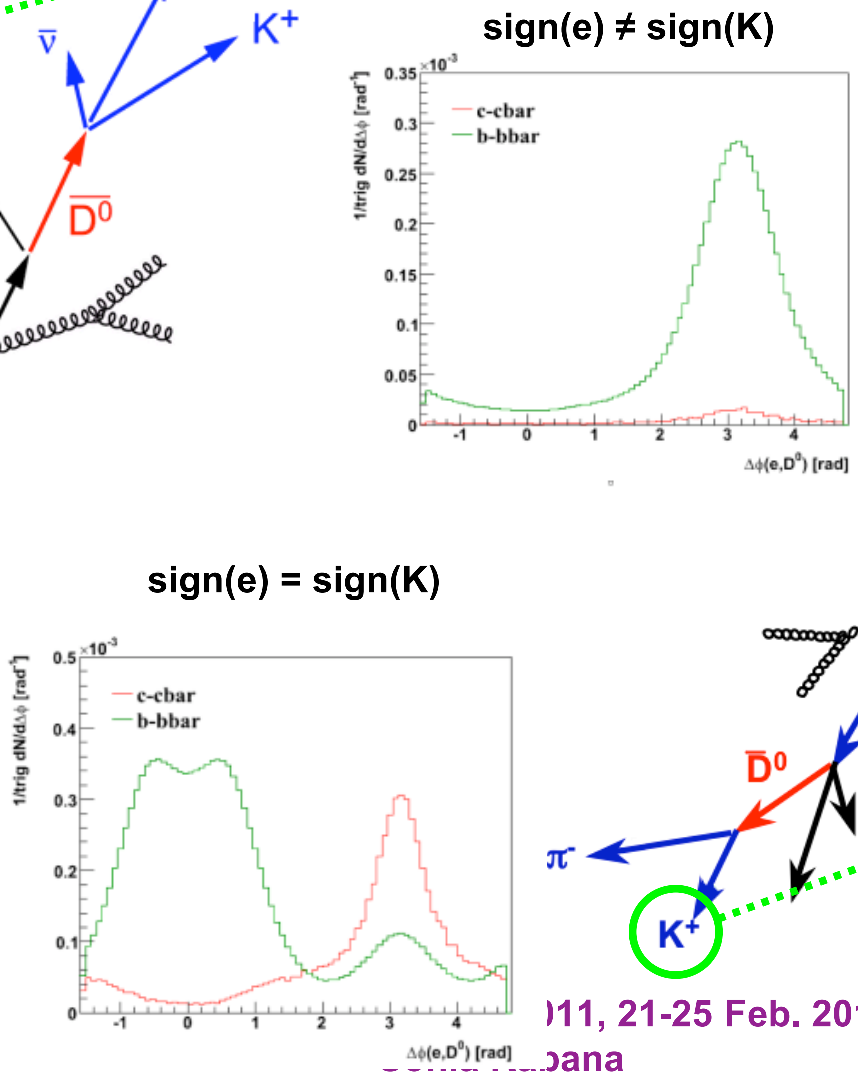


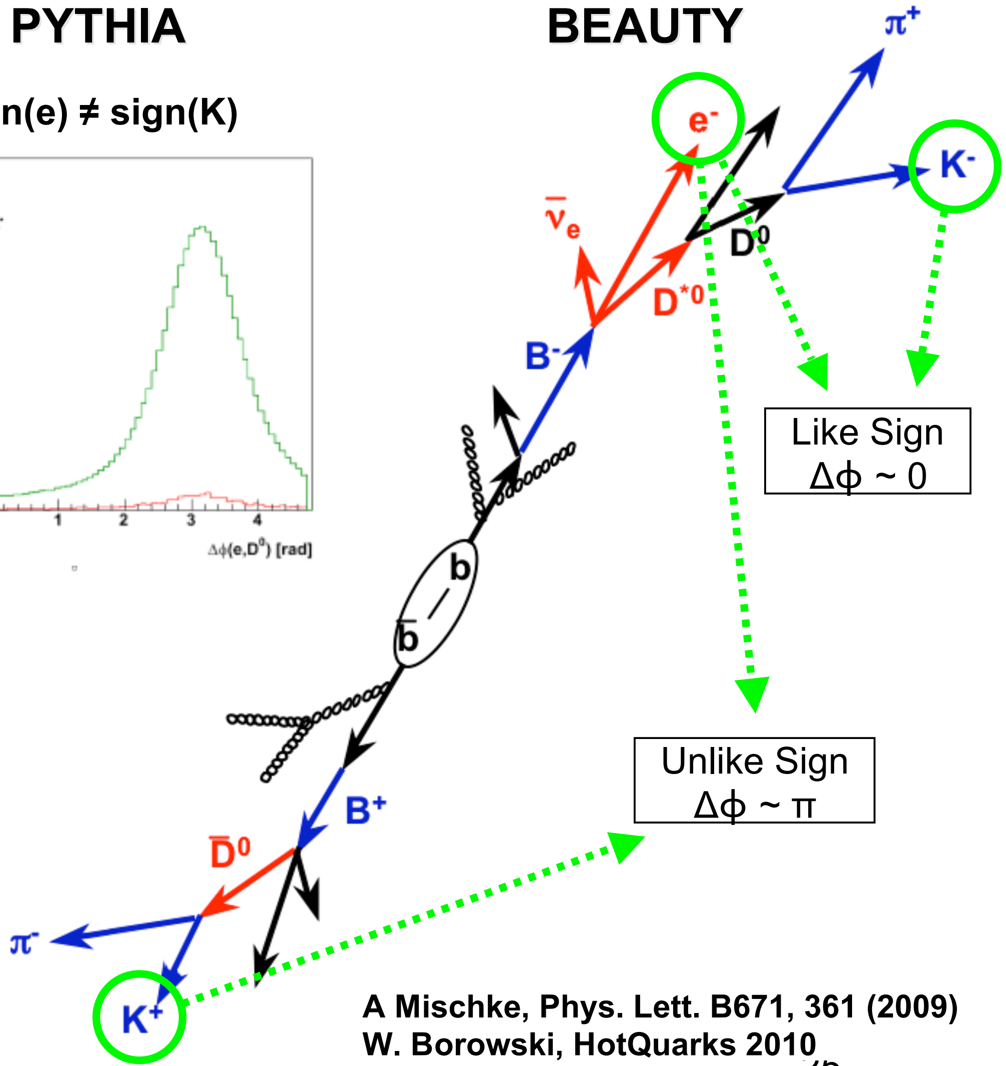
STAR Coll. PRL105, 202301, 2010.

STAR : Charm and beauty from e-D0 azimuthal correlations

See talk by W. Borowski, eQCD2011

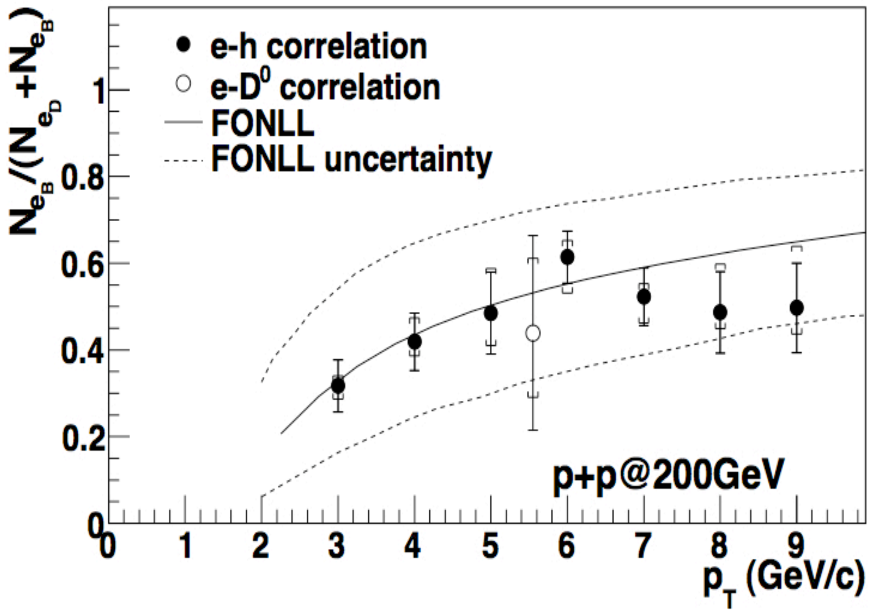




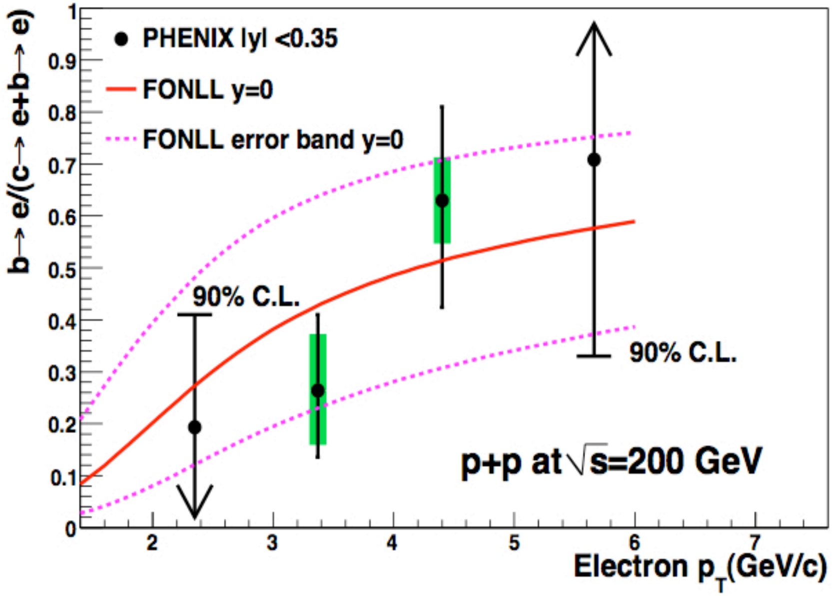


A Mischke, Phys. Lett. B671, 361 (2009)
W. Borowski, HotQuarks 2010

Beauty contribution to electron spectrum in p+p at 200 GeV



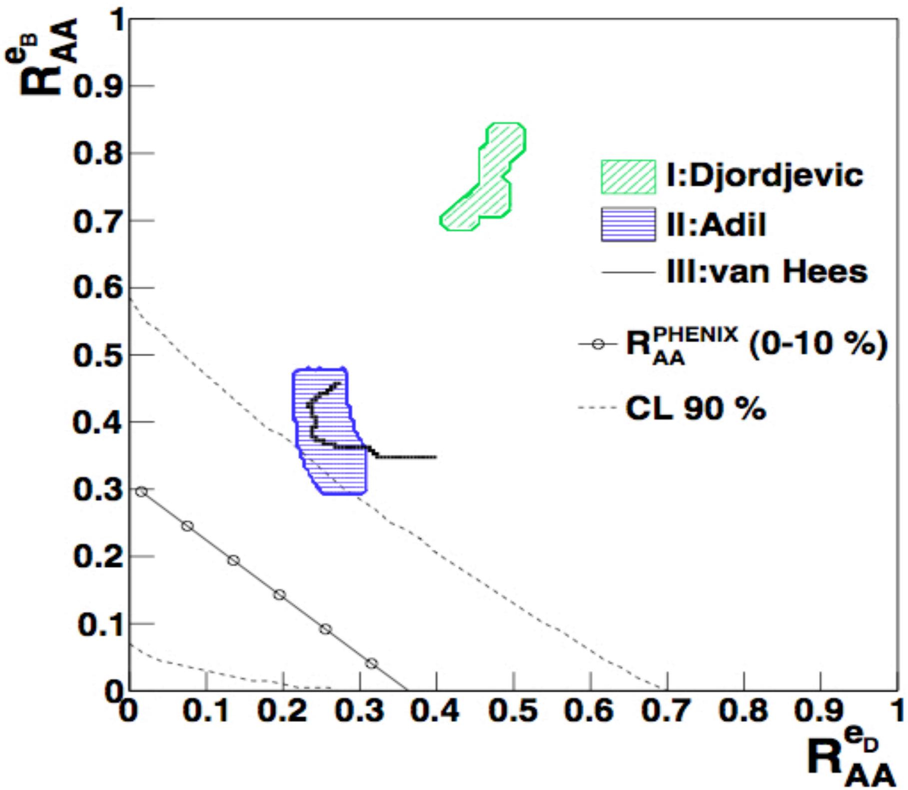
STAR Coll., PRL105, 202301,2010, arXiv:1007.1200



PHENIX Coll., PRL103, 082002, 2009.

* The beauty component in NPE in p+p collisions (r_B) enhances with pT and becomes comparable to Charm at pT~5 GeV.
* PHENIX and STAR data on B/(B+C) ratio vs pT, agree within errors
  STAR results from e-h and e-D0 correlations agree within errors
  --> 3 diferent methods give consistent results on B/(B+C) vs pT
* Data agree with FONLL predictions.

Beauty and Charm nuclear modification factors in Au+Au collisions at 200 GeV



M Aggarwal et al, STAR, arXiv:1007.1200

Confidence level contours for the nuclear modification factor R_AA for beauty and charm are determined from R_AA of NPE (Phenix) and the B/(C+B) measurement from e-h and e-D0 correlations for pT>5 GeV (STAR).

Models

I: (M.Djordjevic et al, PLB 632, 81, 2006) radiative energy loss with initial g density dN/dy(g)=1000. This model is excluded by the data.

II: (Adil, Vitev,PLB649,139,2007) collisional dissociation of D and B mesons in the QGP causes suppression of R_AA.

III: (van Hees et al,PRC73,034913,2006) Large elastic scattering cross section associated with resonance states of D and B mesons in the QGP.

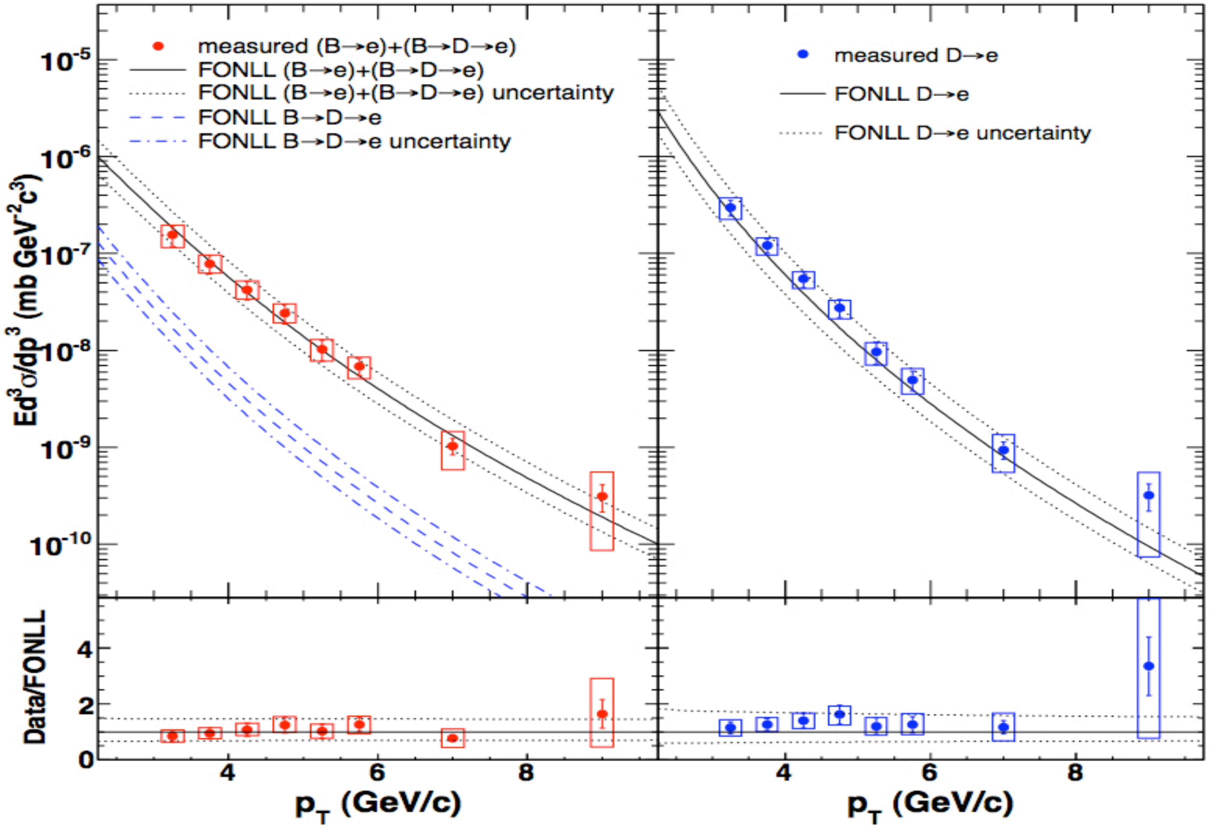
Beauty is also suppressed in Au+Au collisions. R_AA of e from Beauty is < 1 even if R_AA of e from Charm is zero.

Beauty and Charm are both suppressed in Au+Au collisions

-> Measurements of R_AA of B and C separately in Au+Au are crucial

C and B cross sections in p+p collisions at 200 GeV at high pT (STAR 2011)

STAR Coll., arXiv:1102.2611 (Feb 2011)



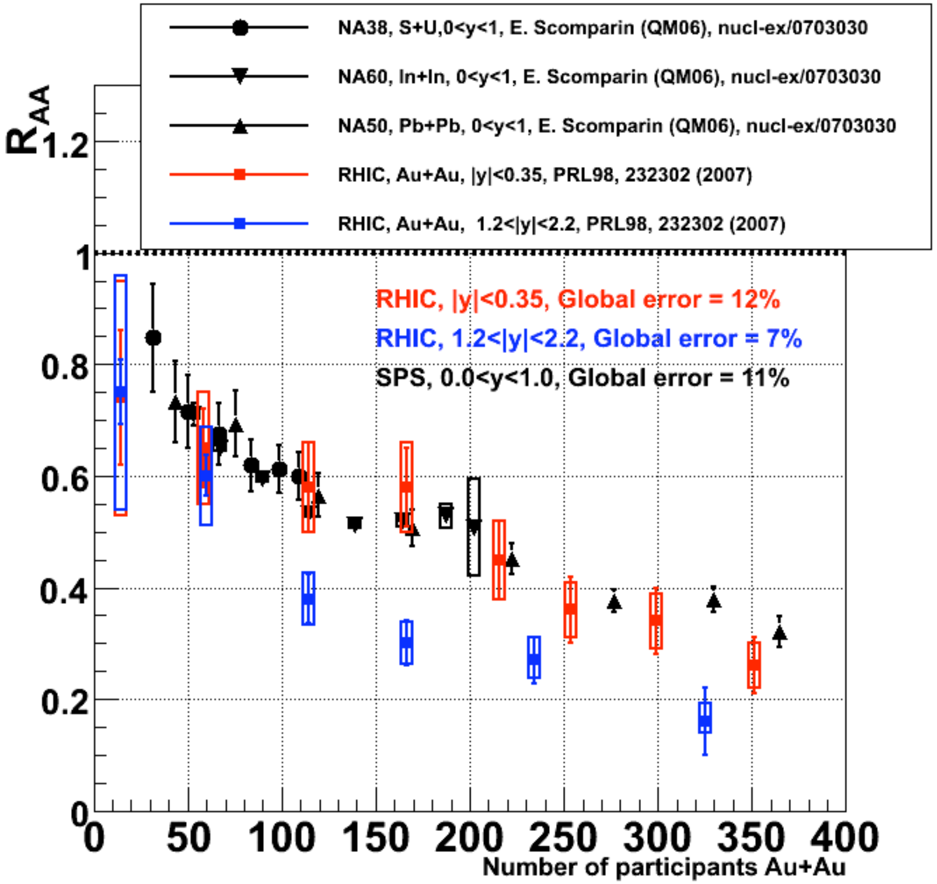
$$\frac{d\sigma_{(B\to e)+(B\to D\to e)}}{dy_e}\bigg|_{y_e=0} = 4.0 \pm 0.5(\text{stat.}) \pm 1.1(\text{syst.})\text{nb}$$

$$\frac{d\sigma_{D\to e}}{dy_e}\bigg|_{y_e=0} = 6.2 \pm 0.7(\text{stat.}) \pm 1.5(\text{syst.})\text{nb.}$$

--> Using the measured ratio e(B)/NPE, cross sections for B and C for 3 GeV <pT<10 GeV in p+p collisions at 200 GeV have been extracted

Hidden Heavy Flavour

The “RHIC J/ψ puzzle” : y-dependence

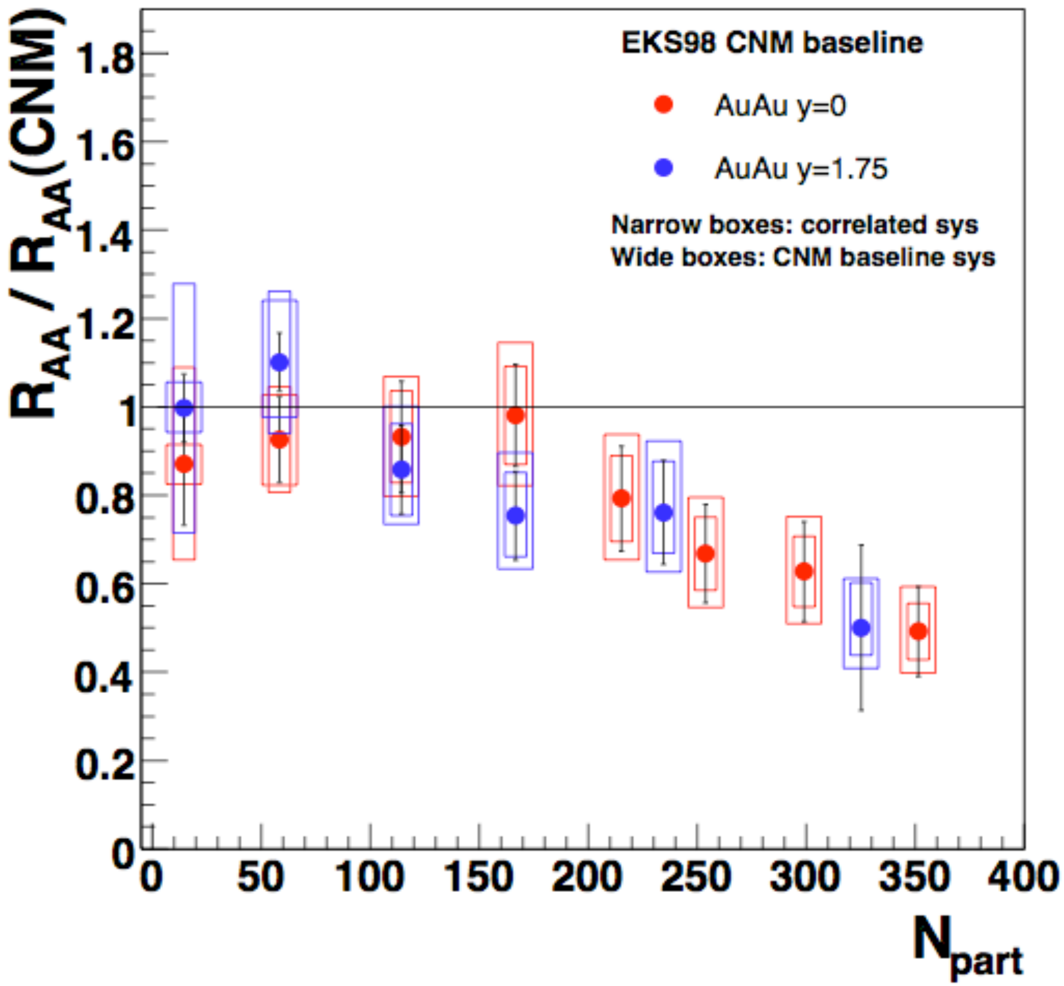


- Suppression doesn't increase with local density
  - R_{AA} (|y|<0.35) > R_{AA} (1.2<|y|<2.2)
  - R_{AA} (RHIC, |y|<0.35) ≈ R_{AA} (SPS)

R_AA is < 1 also for low N_part where J/Psi (meas./expect) of NA50 was = 1

--> need to correct R_AA for cold nuclear matter effect like done by NA50 with p+A

RHIC J/Psi "y"-puzzle



T Frawley, (PHENIX) workshop ECT*,Trento, May 24-29 2009

Linden-Levy, (PHENIX), WWND2011 and ICHEO2010

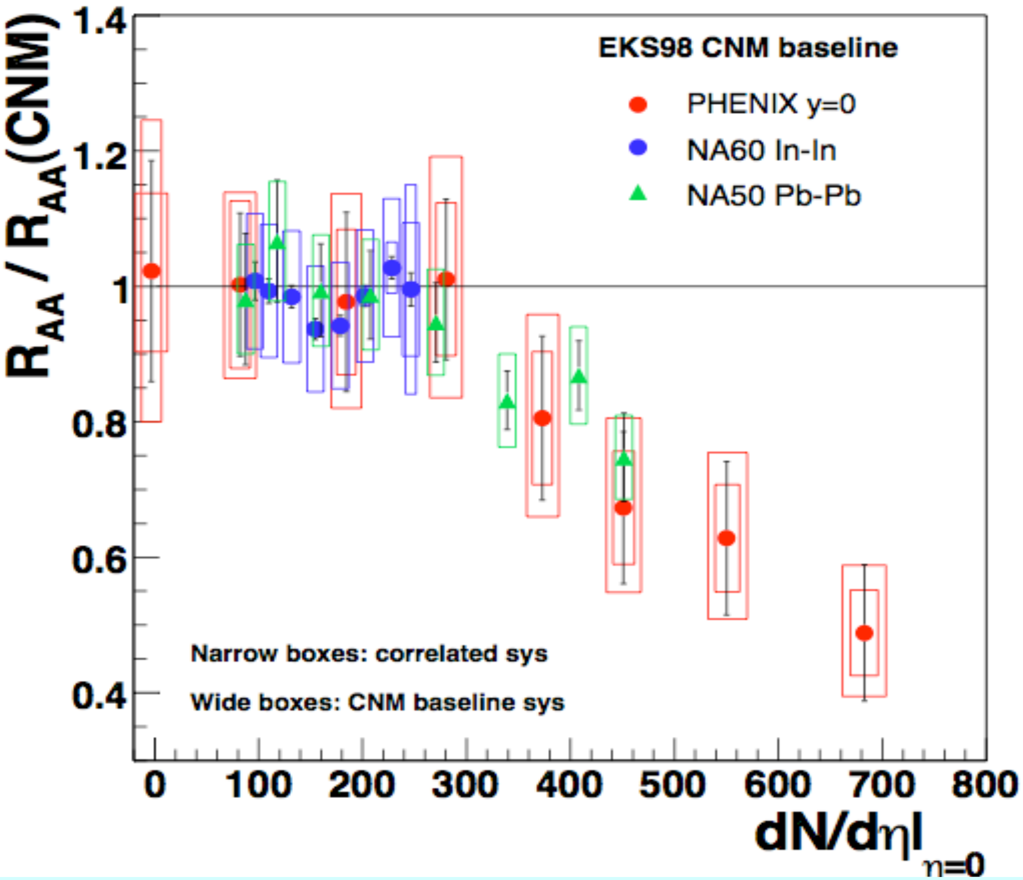
Analysis of d+Au data of run 2009 in terms of sigma_abs to account for all nuclear matter effects

(recent paper PHENIX, arXiv:1010.1246)

→sigma_abs increases from midrapidity to forward rapidity

→ Agreement of J/Psi R_AA/R_AA(Cold Nuclear Matter) at y=0 and y=1.75

The J/Psi RHIC-SPS-comparison -puzzle



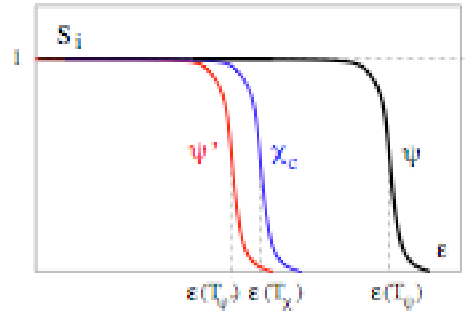
R Arnaldi, D Frawley, Trento 25-29 may 2009

-Divide out cold nuclear matter effects using not model but data (d+Au, p=Au)

- Plot as a function of dN/deta|eta=0 takes into account differences in energy in contrast to N_part.

---> Cold nuclear matter absorbtion effect up to dN/deta|eta=0 = 300

---> Suppression of J/Psi above 300



J/ψ suppression at low p_T maybe from excited stats (ψ', χ_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% of all J/Psi comes from direct J/ψ. While 30% of all J/Psi come from χ_c and 10% ψ'

χ_c and ψ' T(dissociation) ~Tc, while J/Psi T(dissociation)~ 2.1 T_c

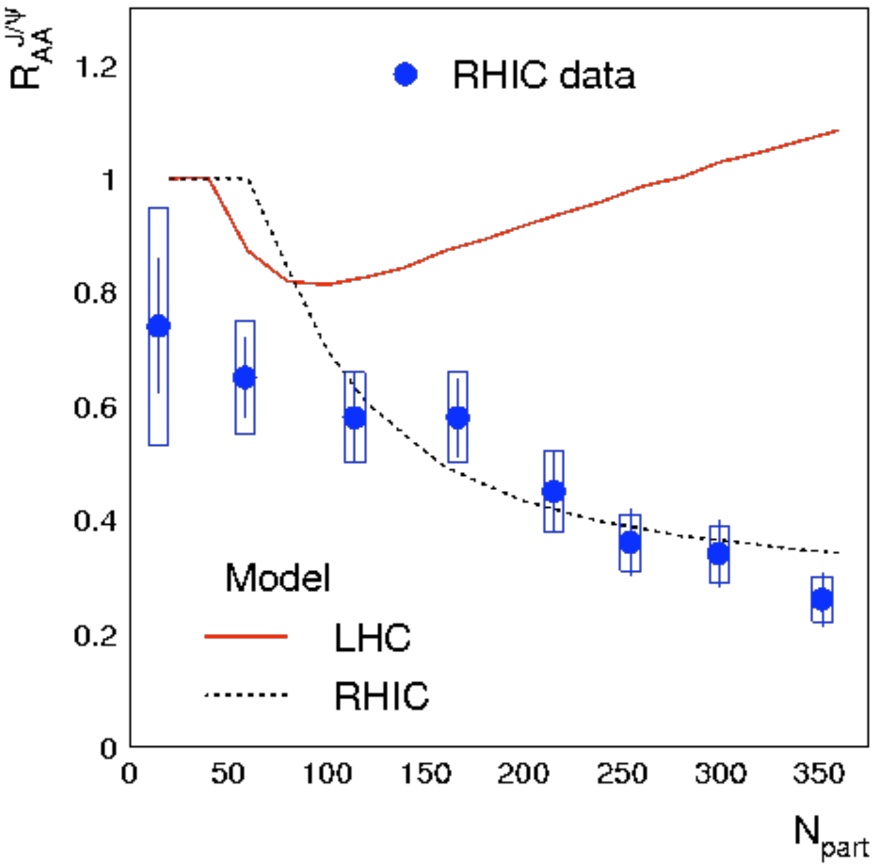
--> suppression of J/Psi observed, maybe due to χ_c and ψ' dissociation

--> directly produced J/Psi may not be suppressed at all at RHIC

--> expect more suppression at LHC due to direct J/Psi dissociation

(but must account for c,cbar coalescence-> J/Psi)

J/Psi assumed completely suppressed and resurrected by c,cbar "coalescence"



A Andronic et al, Phys Lett B 652 2007, p 259

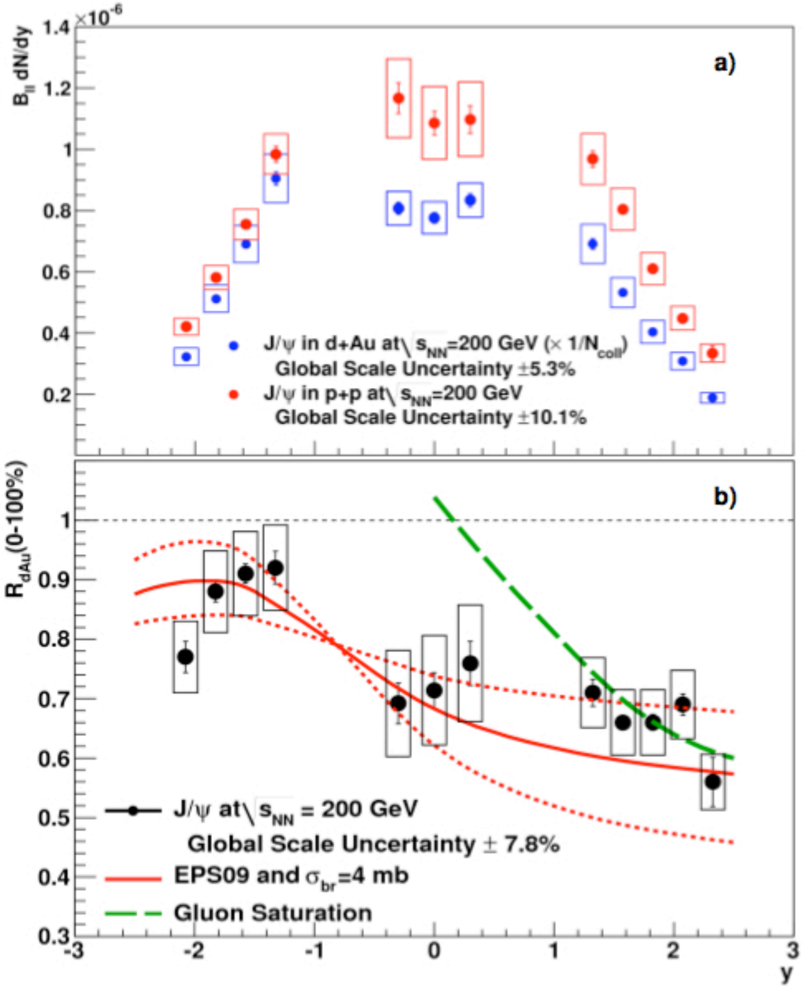
-J/Psi is assumed to be completely suppressed at RHIC

- R_AA(J/Psi) is then estimated for the process of c, cbar coalescence to J/Psi, within a thermal model

→This estimate agrees with R_AA(J/Psi) at RHIC

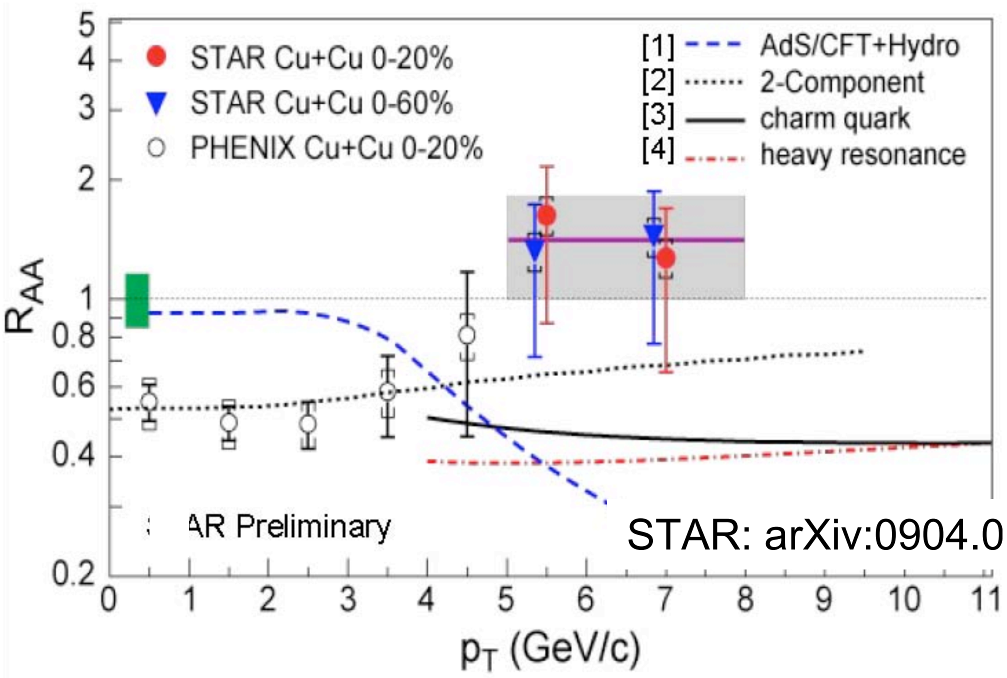
→ It predicts a great enhancement of R_AA(J/Psi) at LHC

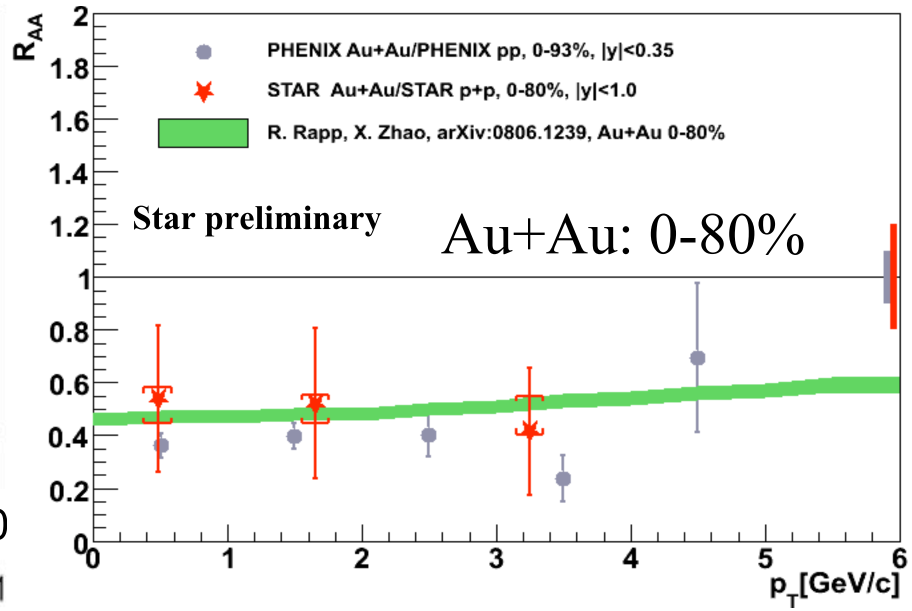
J/Psi in d+Au at 200 GeV (PHENIX, oct 2010)



PHENIX, arXiv:1010.1246

J/ψ in Au+Au and Cu+Cu 200 GeV pT dependence





D. Prindle et al, STAR coll., ICPAQGP2010

- **R_{AA}(Cu+Cu, p_T>5 GeV/c) = 1.4± 0.4±0.2**
- Cu+Cu: Consistent with no suppression at high p_T

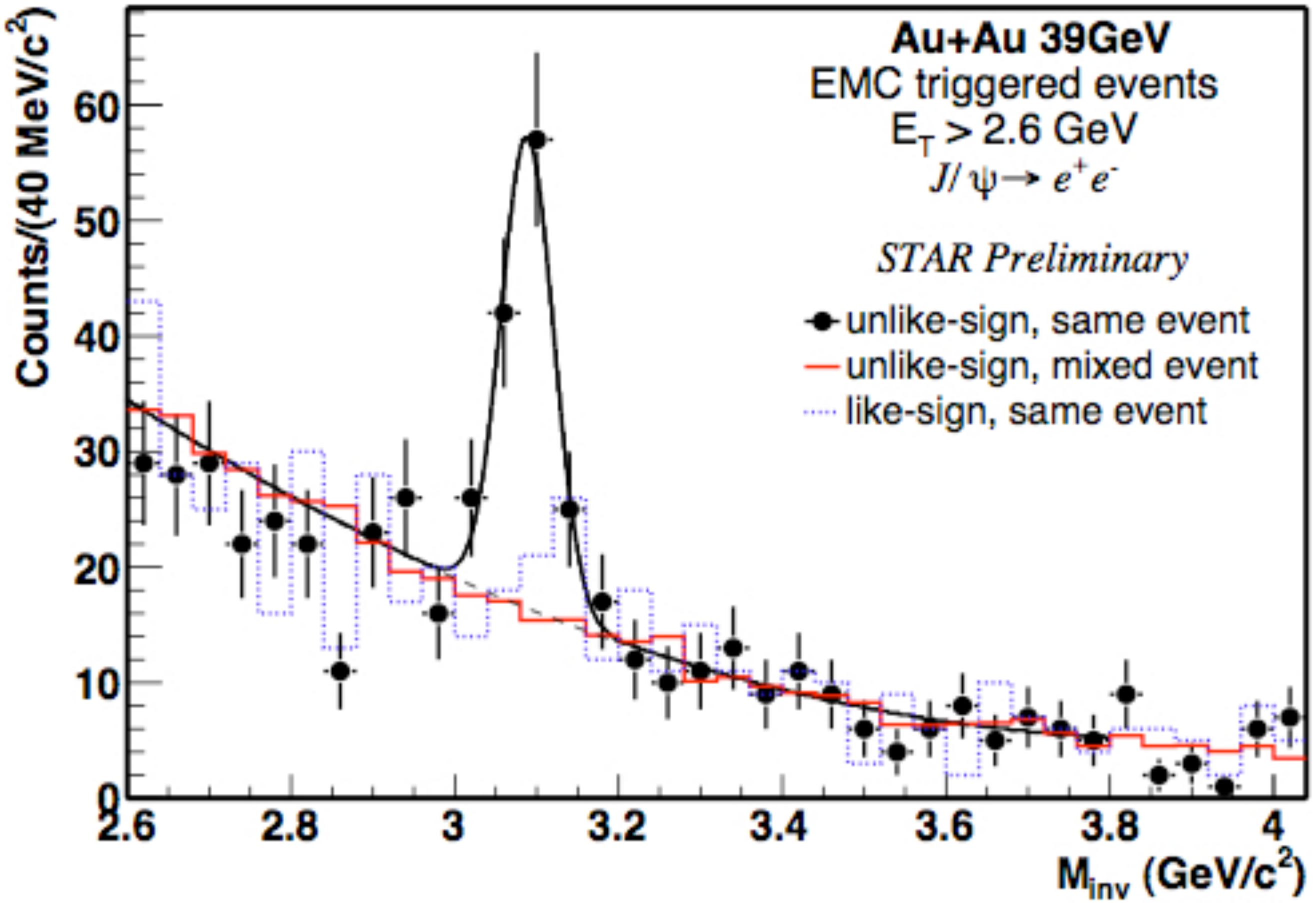
A. Adil and I. Vitev, Phys.Lett. B649, 139 (2007),
S. Wicks et al., Nucl. Phys. A784, 426 (2007)

- Cu+Cu: Inconsistent with AdS/CFT+Hydro and “heavy resonance” models

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

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

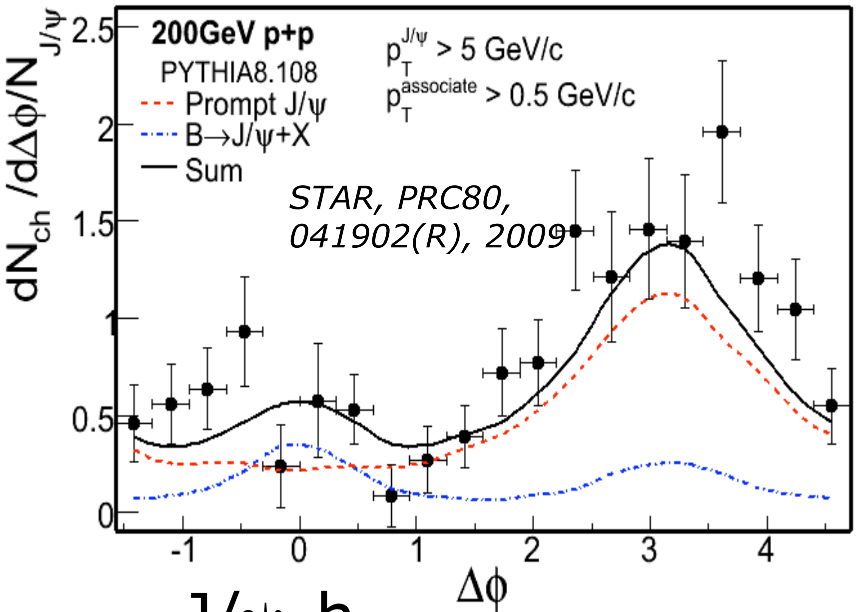
J/Psi in Au+Au at 39 GeV (STAR)



Z Tang, STAR, Nucl Phys A (2010) 1-4, arXiv:1012.0233

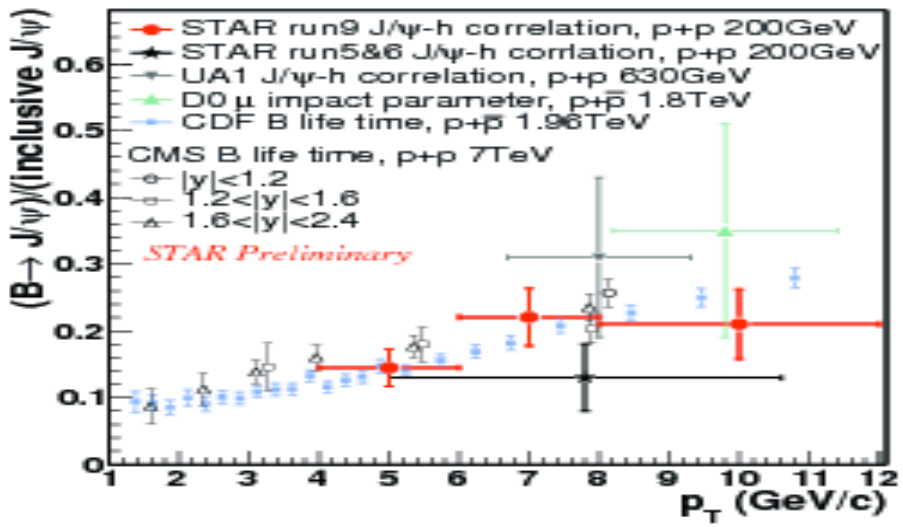
B --> J/Psi

D Prindle et al, STAR, ICPAQGP, Goa, India 2010



J/ψ-h

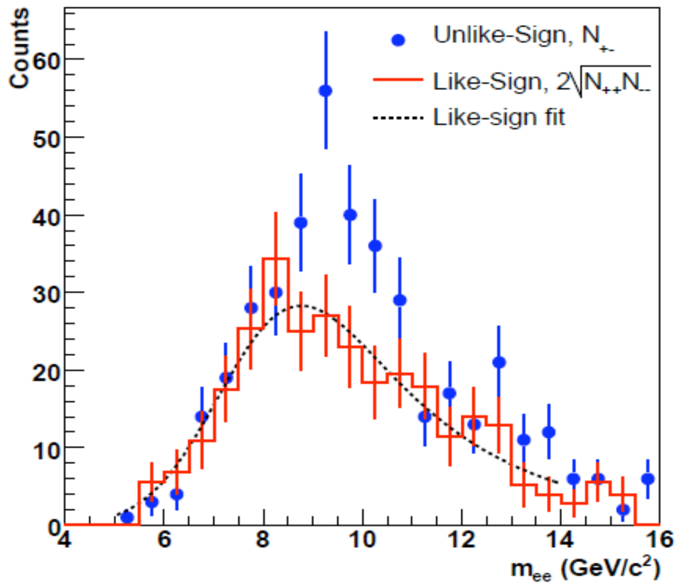
(B→J/ψ) / (inclusive J/ψ)

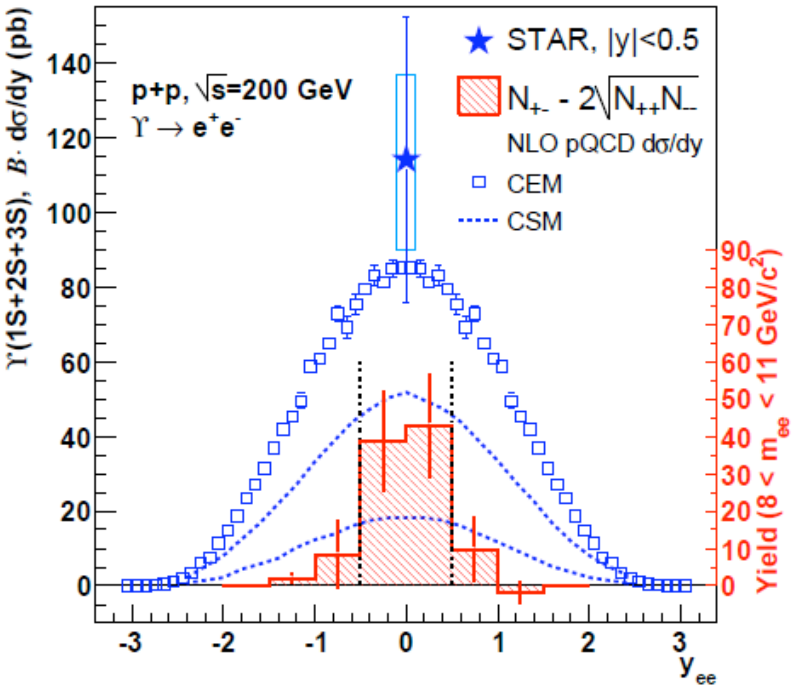


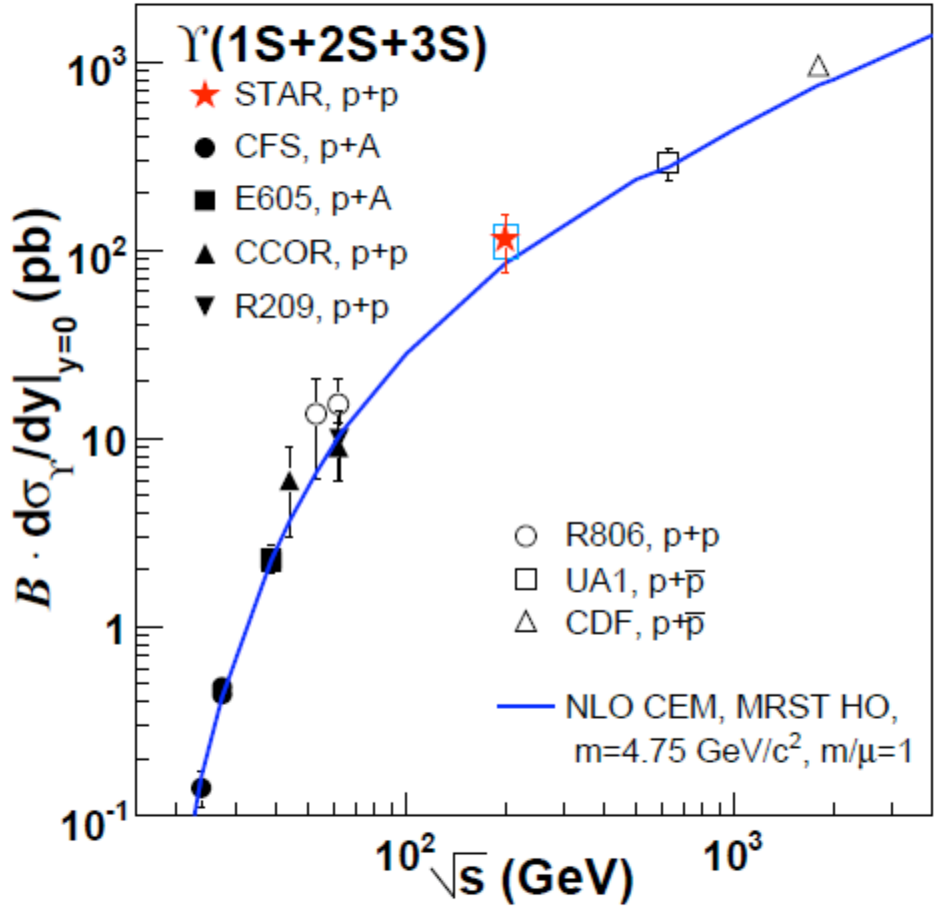
B contribution to J/ψ is the same at 200 GeV and 7 TeV

Υ

STAR ϒ measurements in p+p



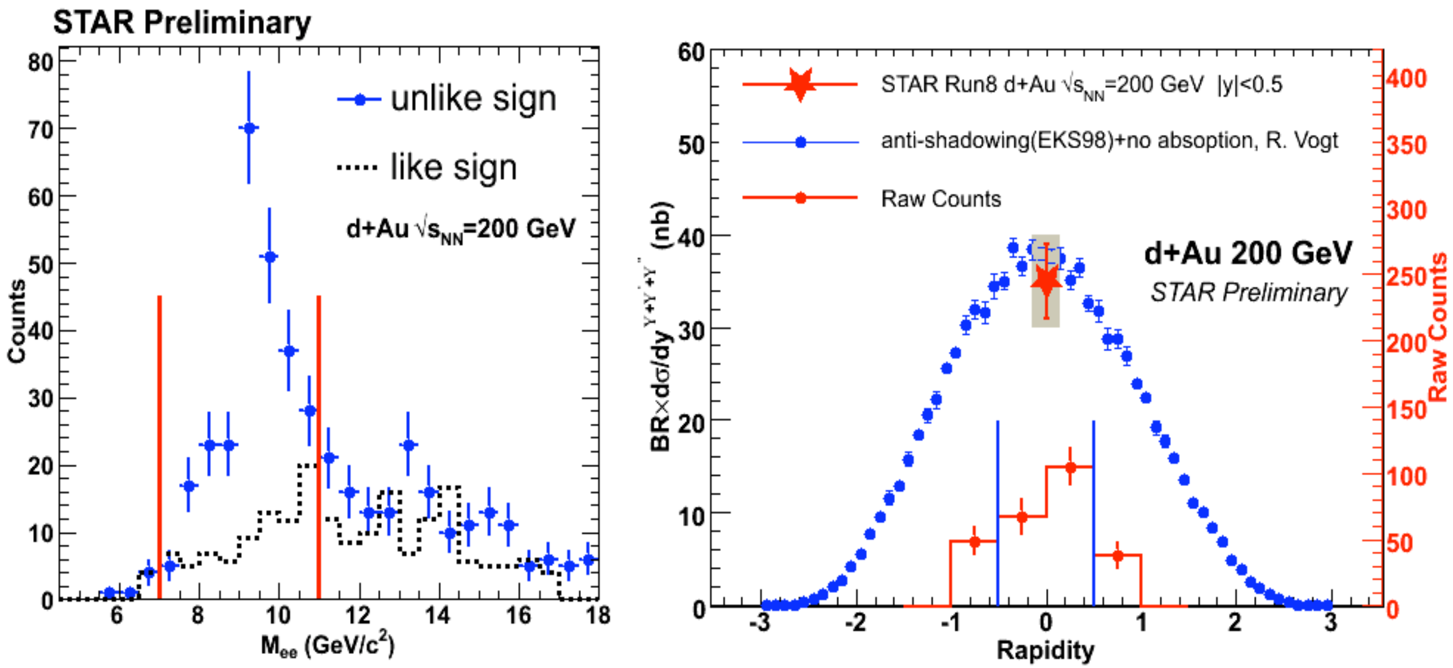




STAR: arXiv:1001.2745

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

Υ signal in d+Au 200 GeV collisions

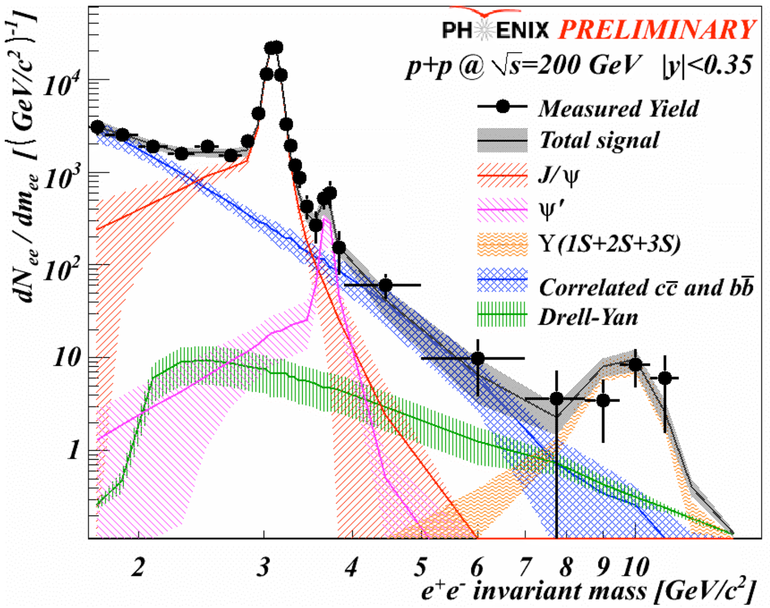


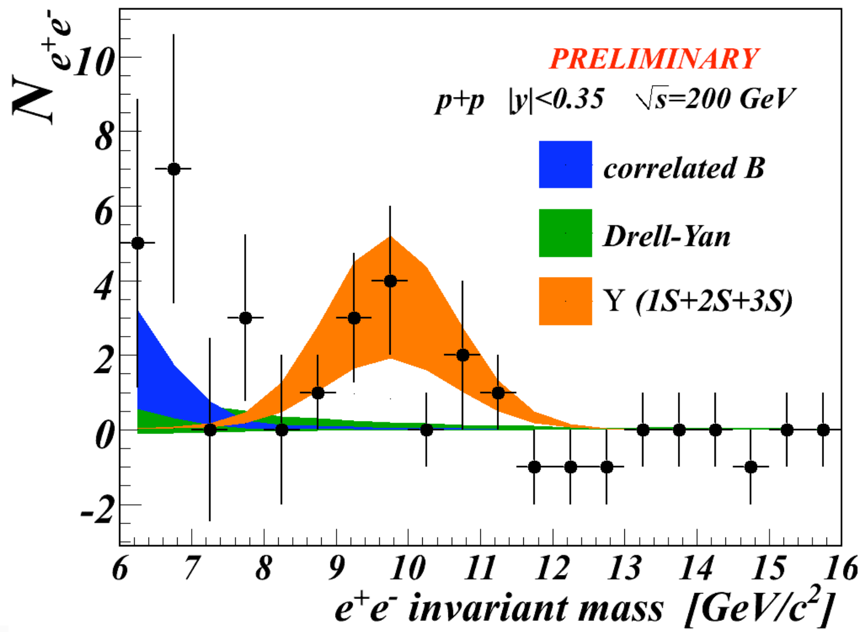
- Strong signal (8σ significance) extracted

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

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

Upsilons in p+p - PHENIX

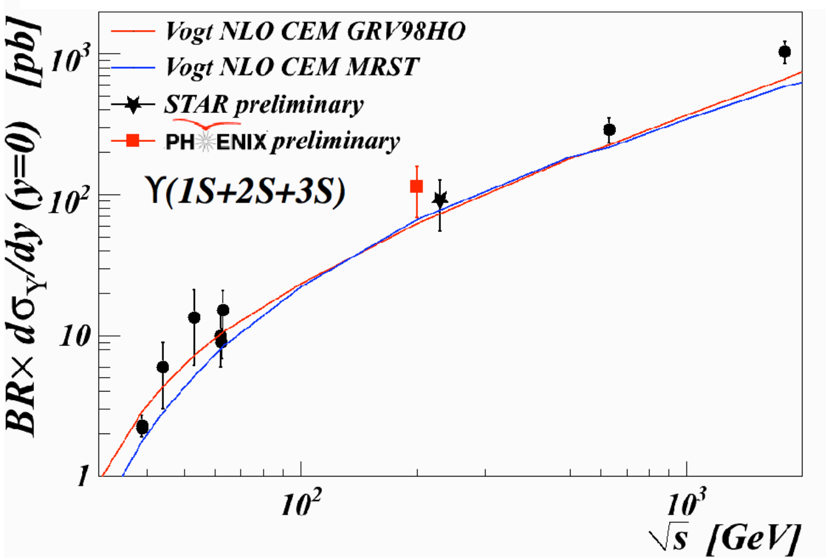




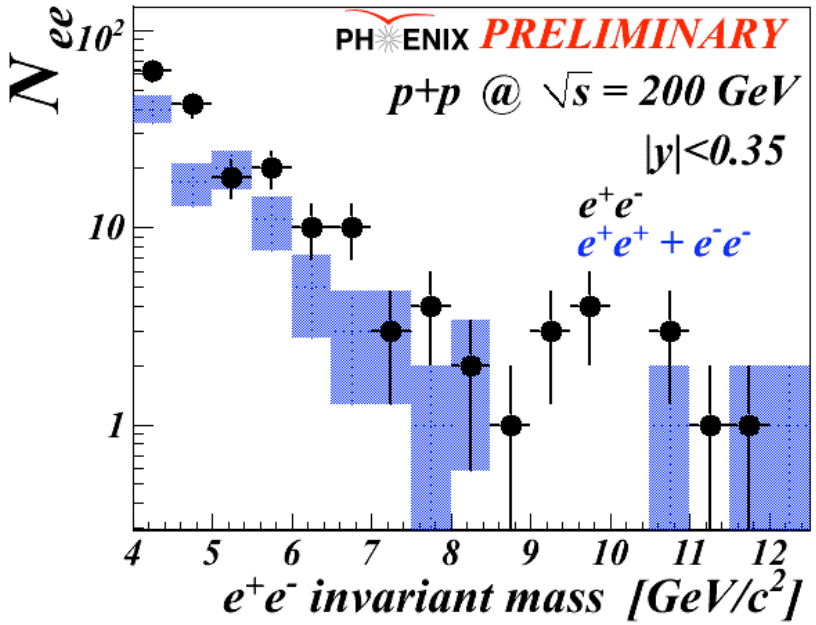
Nucl.Phys.A830:331C-334C,2009.

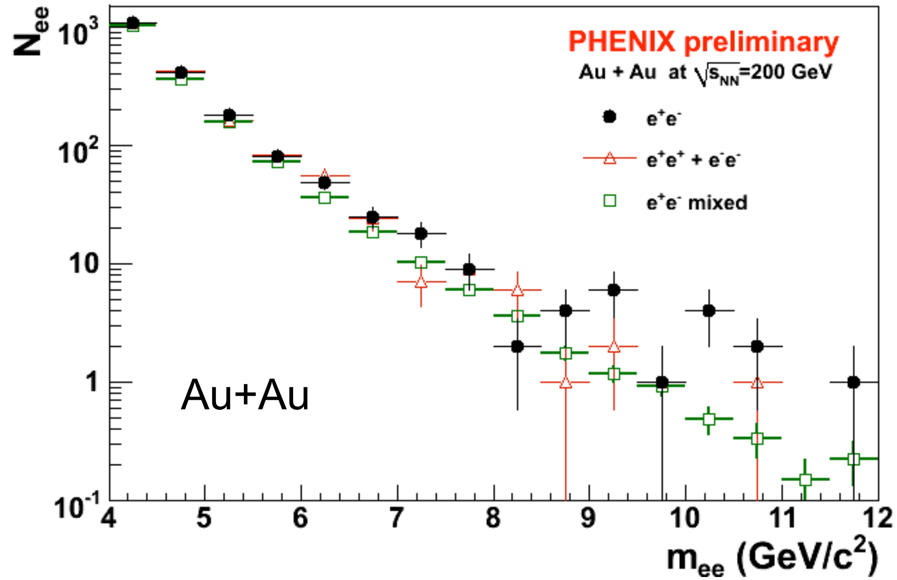
- Cross section follows world trend
- Baseline for Au+Au

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

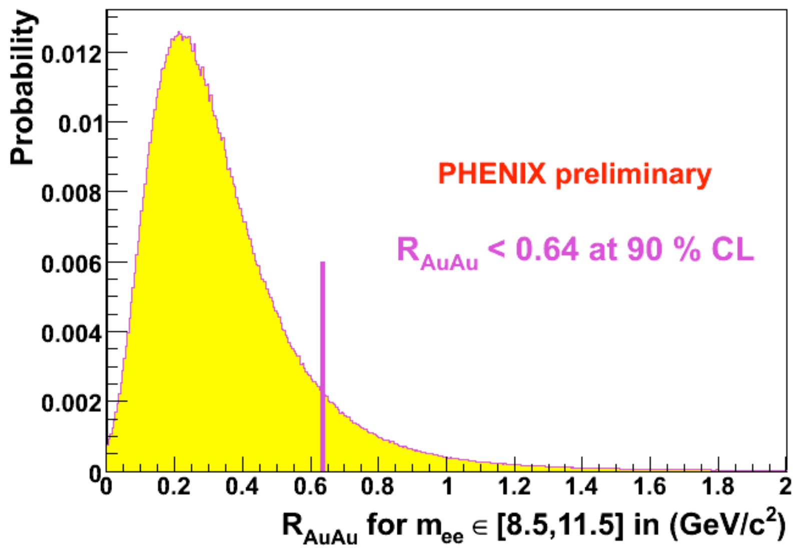


Upsilons Suppressed in Au+Au - PHENIX





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



Nucl.Phys.A830:331C-334C,2009.

Conclusions

* Large R_AA and flow of NP electrons in central Au+Au collisions at 200 GeV
Heavy quarks lose energy in the medium, while acquiring a substantial component of the medium's collective flow

* e-h, e-D0 correlations : In p+p at 200 GeV c~b contribution at pT ~5 GeV

c/b contribution in p+p is consistent with FONLL

b is also suppressed in Au+Au at 200 GeV

* J/Psi y-puzzle can be possibly attributed to cold nuclear matter absorbtion

* J/Psi sqrt(s) dependence from SPS to RHIC : remains to be understood

Chi_c, psi' suppressed, direct J/Psi not suppressed at RHIC ?

Direct J/Psi also suppressed at RHIC and produced through c,cbar coalescence?

* High pT J/Psi is consistent with no suppression (Cu+Cu 200 GeV)

* Y measured in p+p, d+Au, Au+Au

Outlook

•2009/2010 STAR run with full TOF , low material -> improve c,b ID

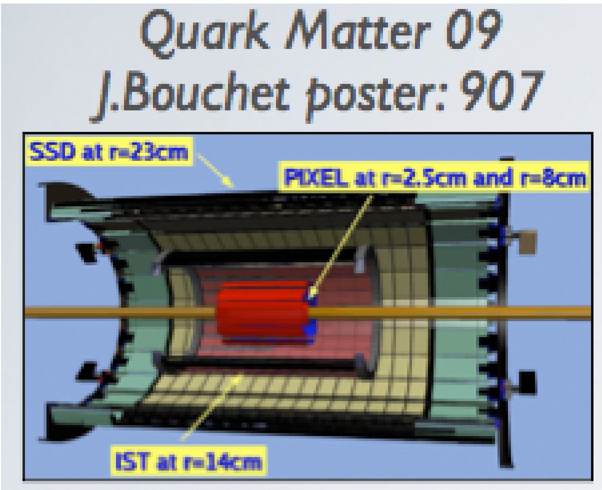
• D mesons with microvertexing - cross section coming soon

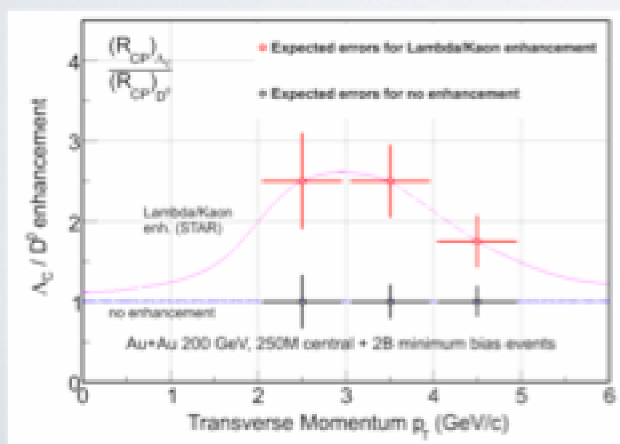
• Phenix : new silicon tracker commissioned right now

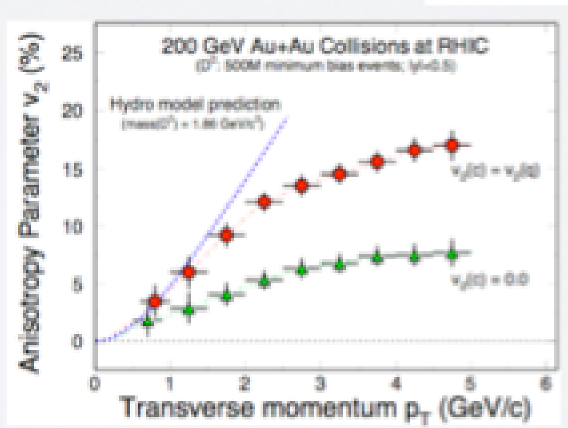
• STAR : plans for new silicon vertex tracker to measure Heavy Flavour with great accuracy (HFT)

--> Heavy Flavour substantial element of RHIC plans

STAR Heavy Flavour Tracker : ~2014








Thank you very much