Heavy Flavor production in the STAR experiment

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Outline:

- Open Heavy Flavor
- Quarkonia
- Prospects

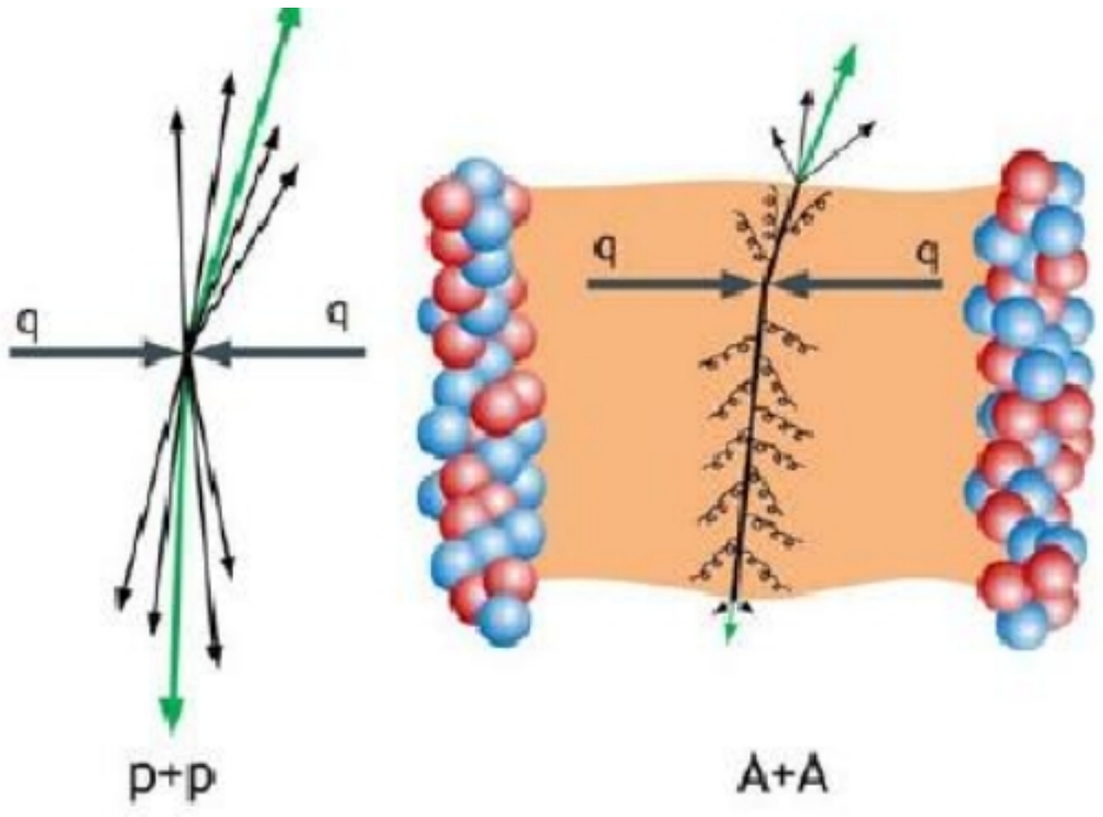
The 30th Winter Workshop on Nuclear Dynamics
6-10 April 2014
Galveston, Texas USA

Open Heavy Flavor

Heavy quarks

✓ c and b quarks are produced in initial hard scattering

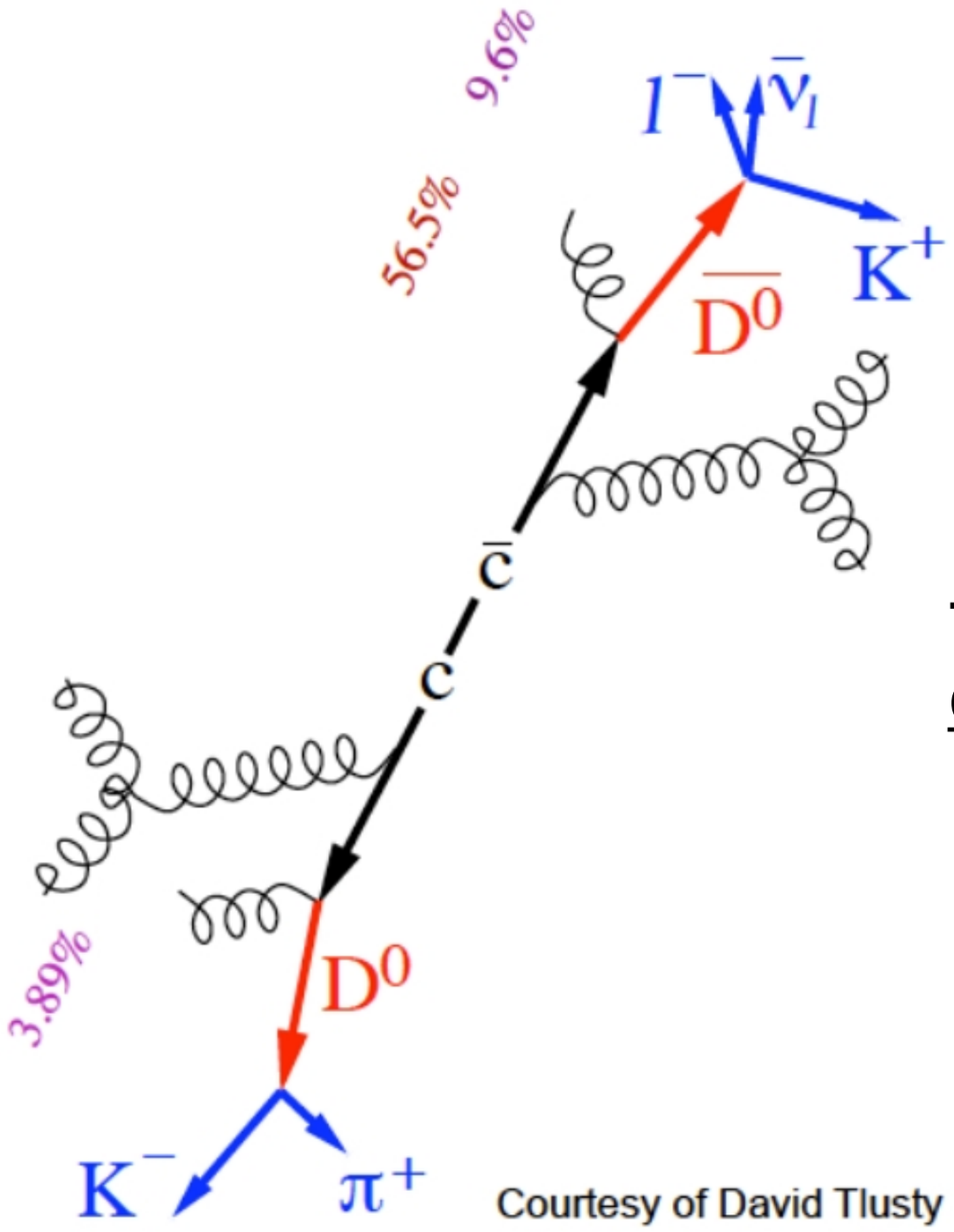
- Cross-sections calculable within pQCD
- Unique probes of QGP properties



- Degree of medium thermalization – production and elliptic flow sensitive to dynamics of the medium
- Parton energy loss mechanism

$\Delta E_g > \Delta E_q > \Delta E_c > \Delta E_b$?

Open Heavy Flavor in STAR



Courtesy of David Tlusty

➔ Non-photonic electrons (NPE)

– *electrons from semi-leptonic HF hadron decays*

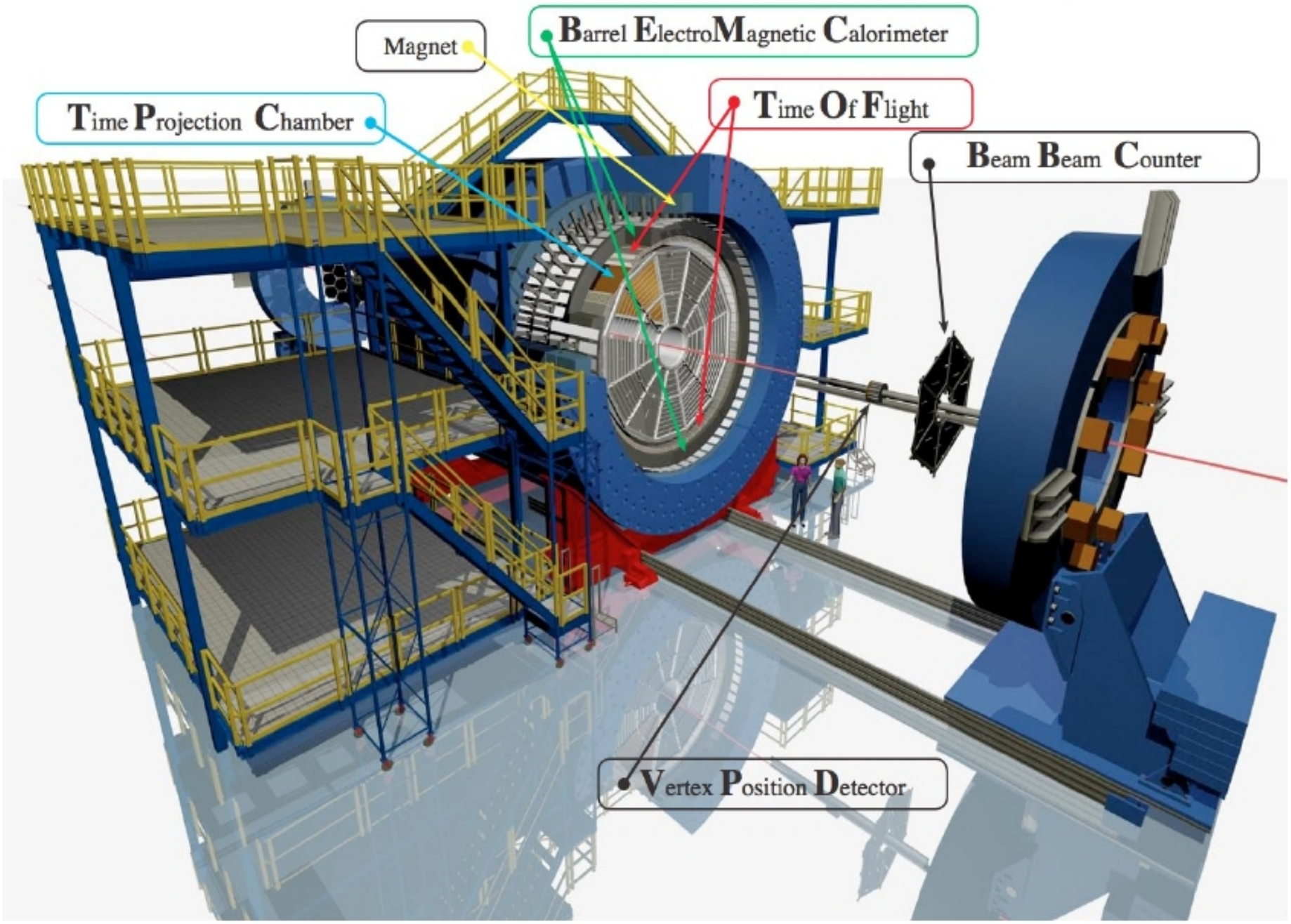
- ✔ higher branching ratio
- ✔ easy to trigger
- ✗ indirect access to heavy quark kinematics
- ✗ contribution from c and b

➔ Direct reconstruction of open charm

- ✔ direct access to heavy quark kinematics
- ✗ high statistics compete with large combinatorial background w/o good vertex resolution
- ✗ difficult to trigger

STAR Experiment

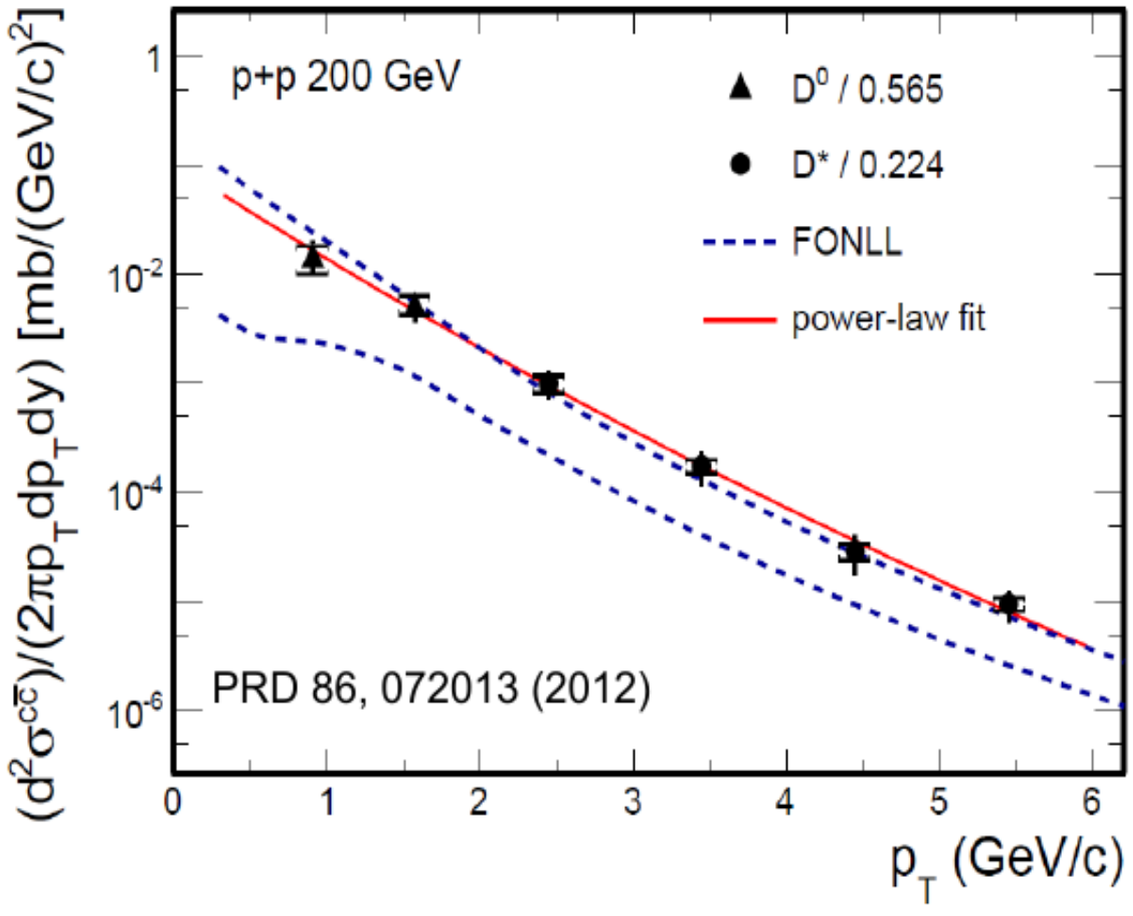
Large acceptance: $|\eta| < 1$, $0 < \varphi < 2\pi$



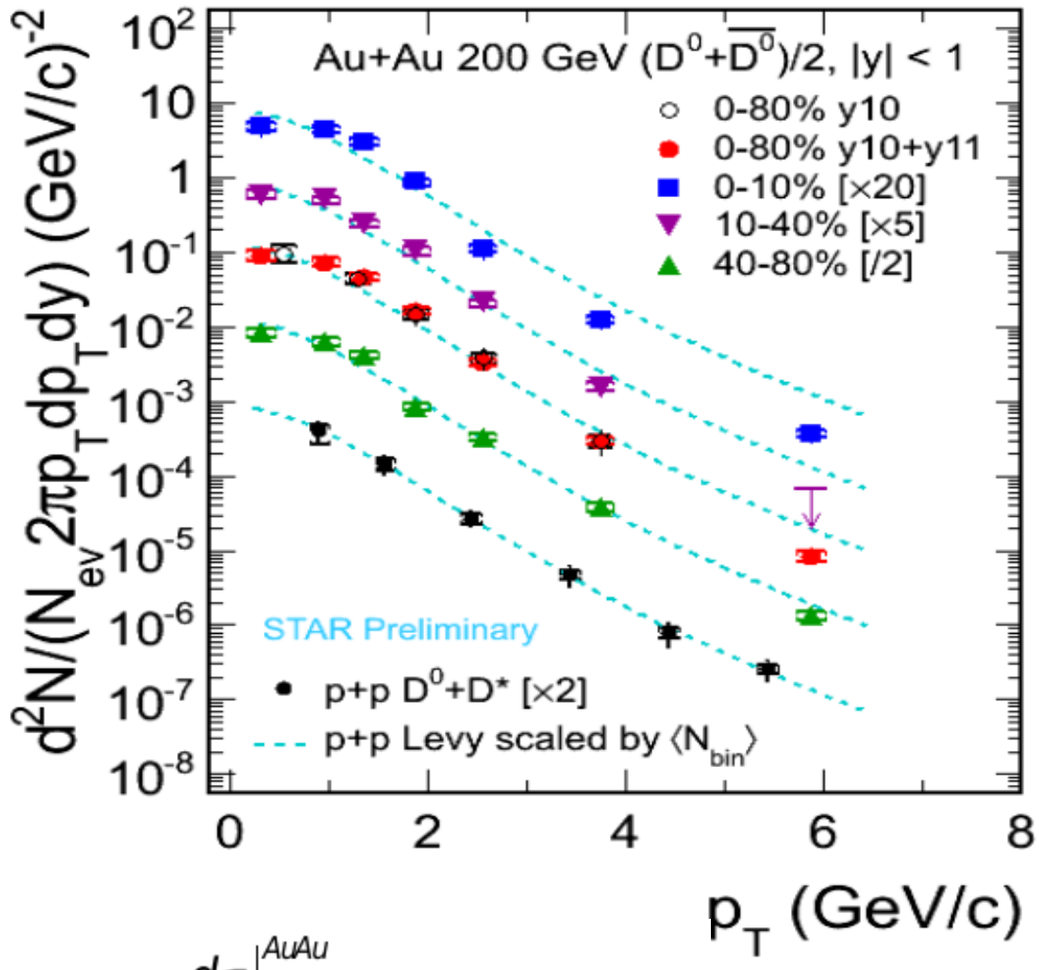
- VPD minimum bias trigger
- TPC – PID: dE/dx, tracking
- TOF – PID: 1/β
- EMC – PID: E/p, trigger

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

p+p



Au+Au



Charm cross section at mid-rapitiy:

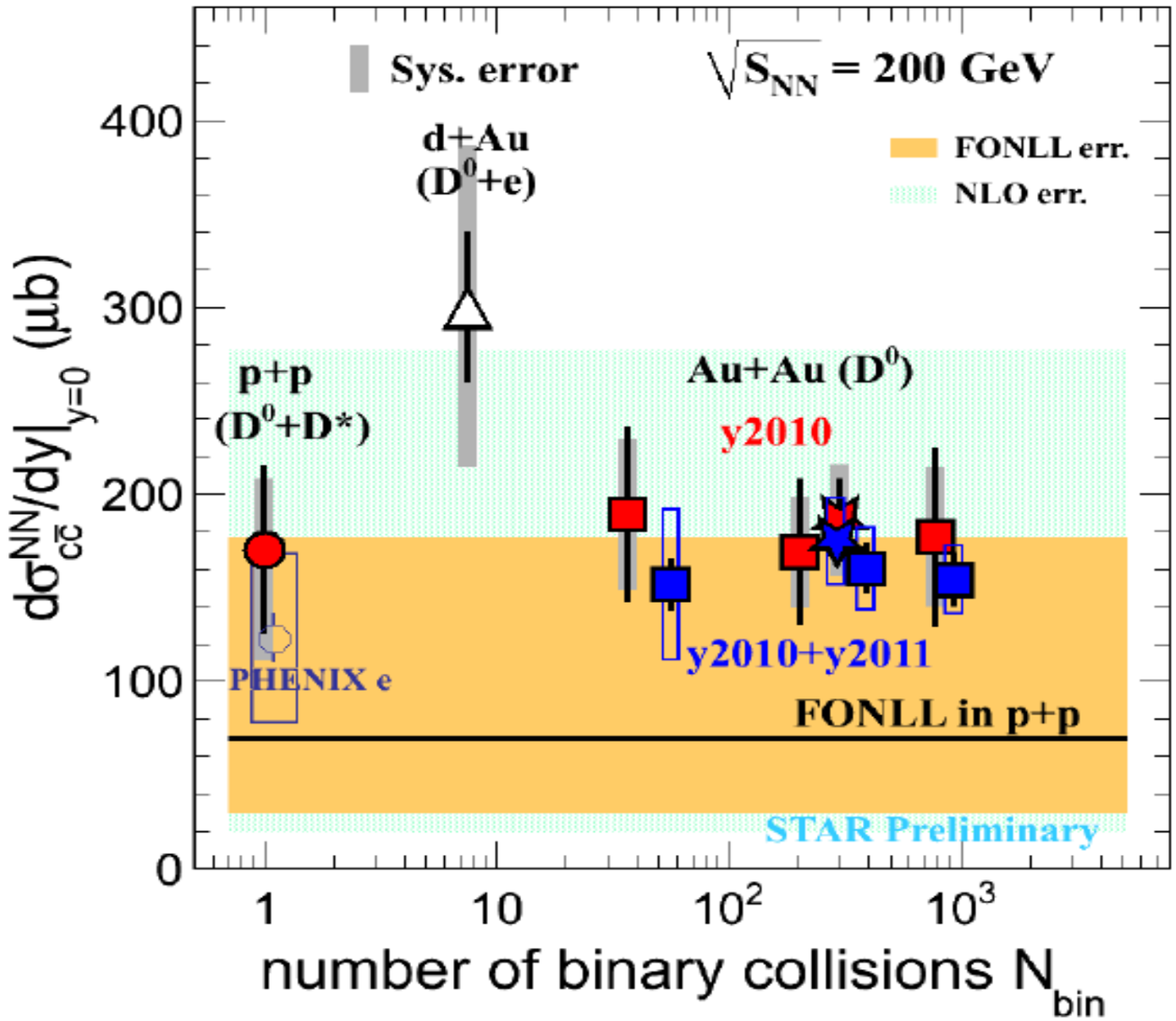
$$\left.\frac{d\sigma}{dy}\right|_{y=0}^{pp} = 170 \pm 45^{+38}_{-59}\,\mu b$$

$$\left.\frac{d\sigma}{dy}\right|_{y=0}^{AuAu} = 175 \pm 13 \pm 23\,\mu b$$

- ✓ Consistency with FONLL upper limit
- ✓ Better precision - new 2010+2011 data

FONLL: R. Nelson, R. Vogt, A. D. Frawley, arXiv: 1210.4610

Charm cross section at 200 GeV



Total charm cross section:

$$\sigma_{c\bar{c}}^{pp} = 797 \pm 210^{+208}_{-295} \mu b$$

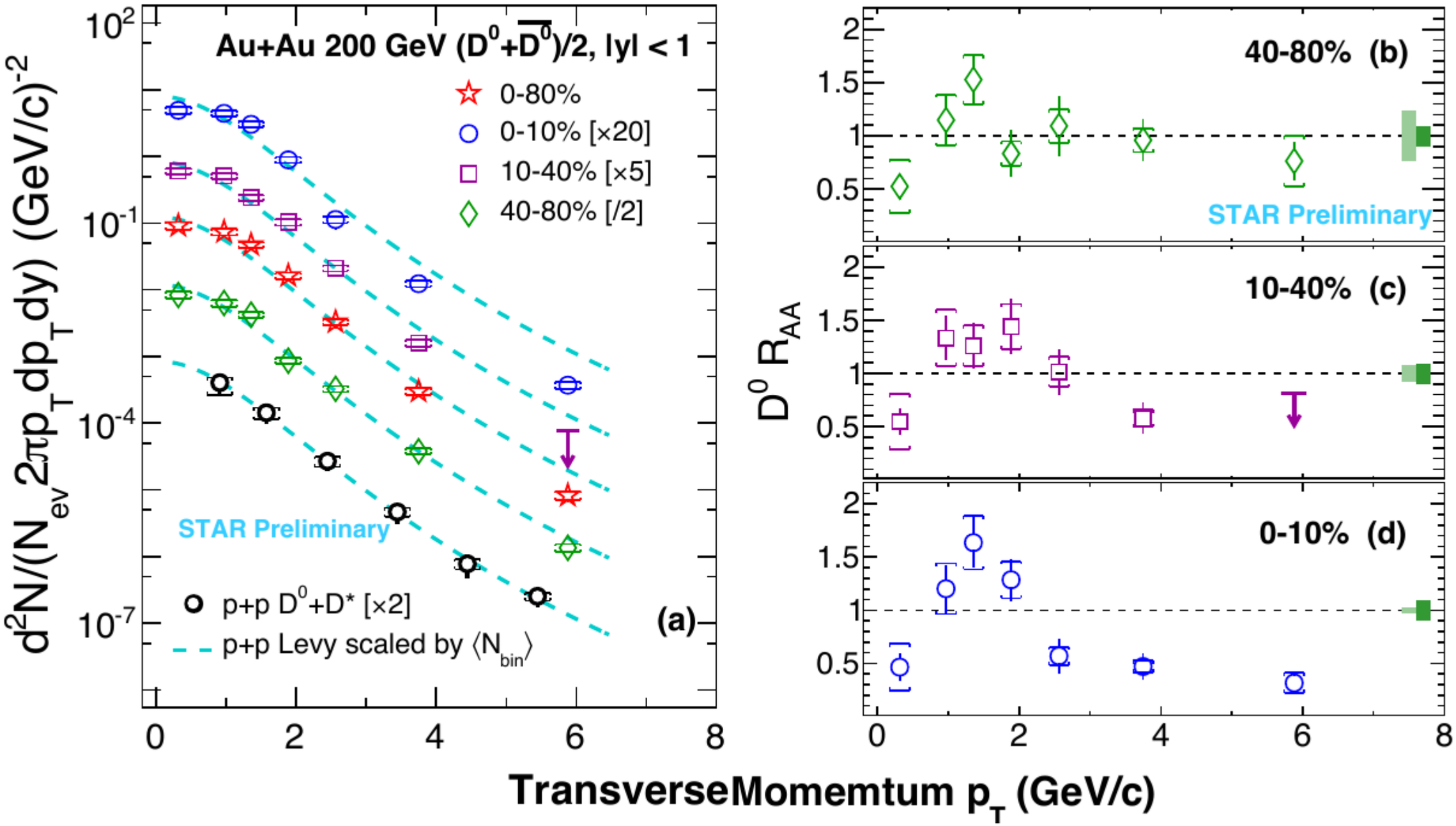
$$\sigma_{c\bar{c}}^{AuAu} = 822 \pm 62 \pm 192 \mu b$$

assuming charm fragmentation ratio to D meson is the same for p+p, d+Au and Au+Au

extrapolation to full rapidity from Pythia

- ✓ Total charm production follows number-of-binary-collision scaling

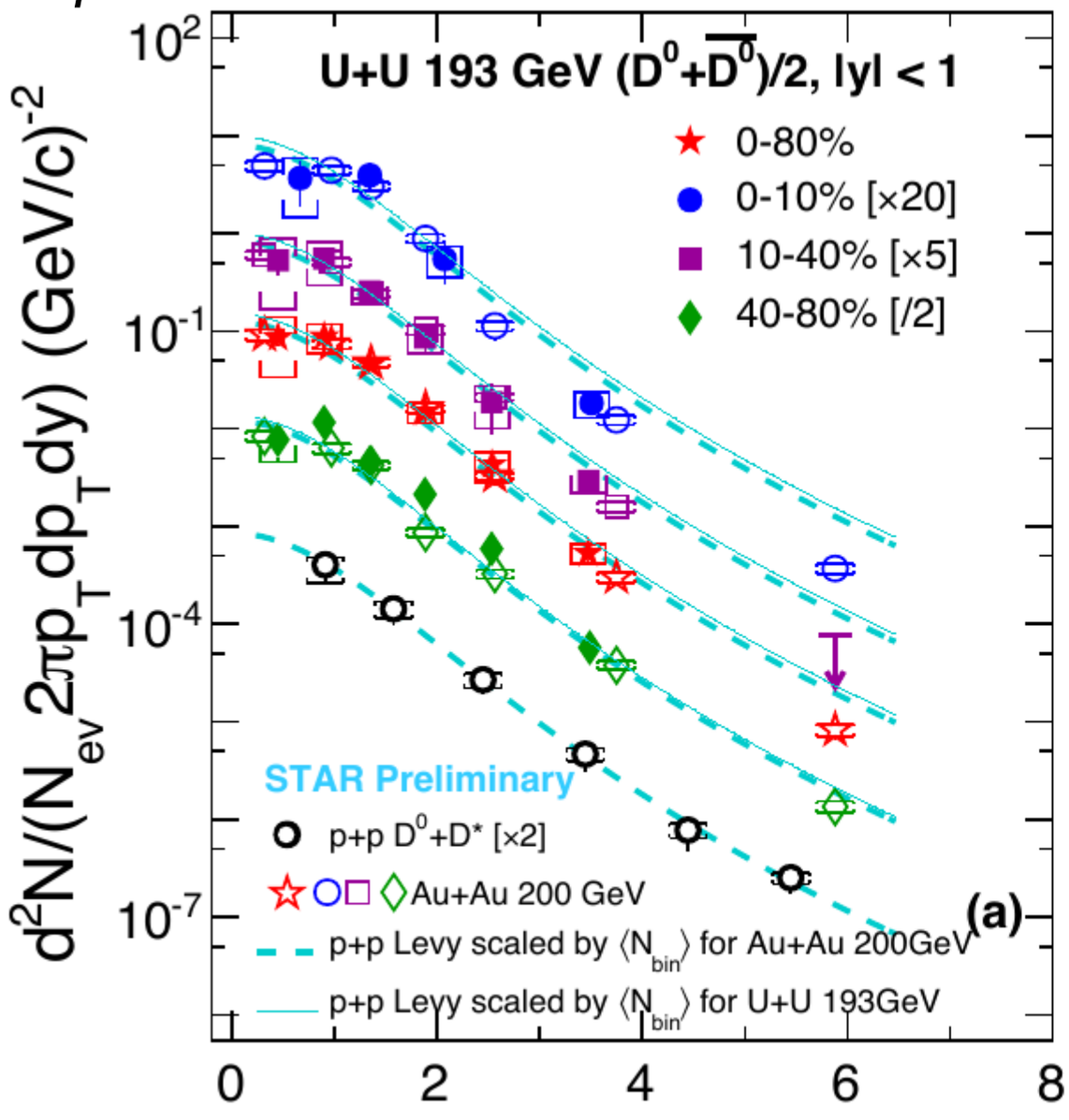
D^0 in Au+Au 200 GeV

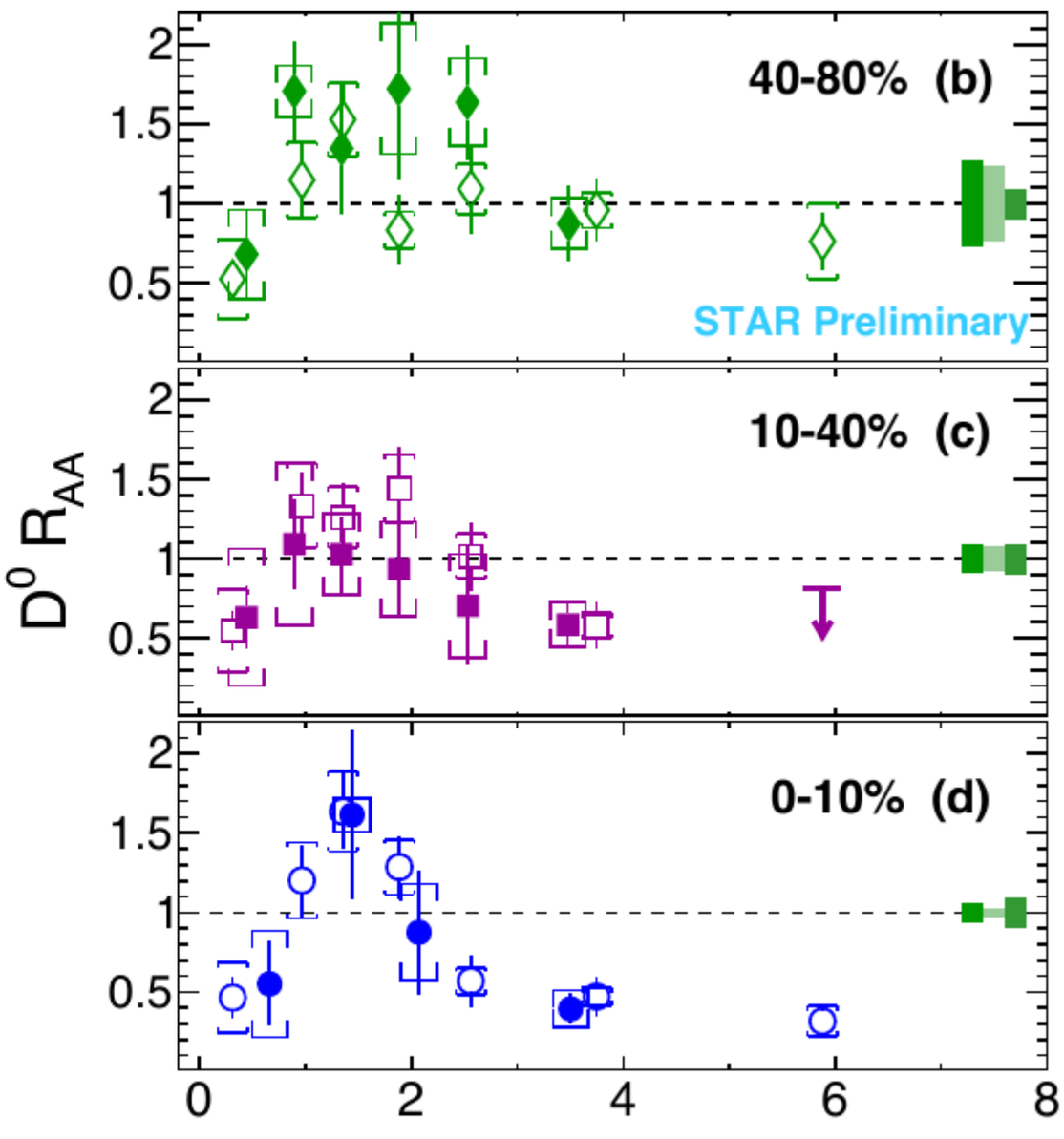


- ✓ In central collisions strong suppression at high p_T

D^0 in U+U 193 GeV

Higher energy density compared with Au+Au

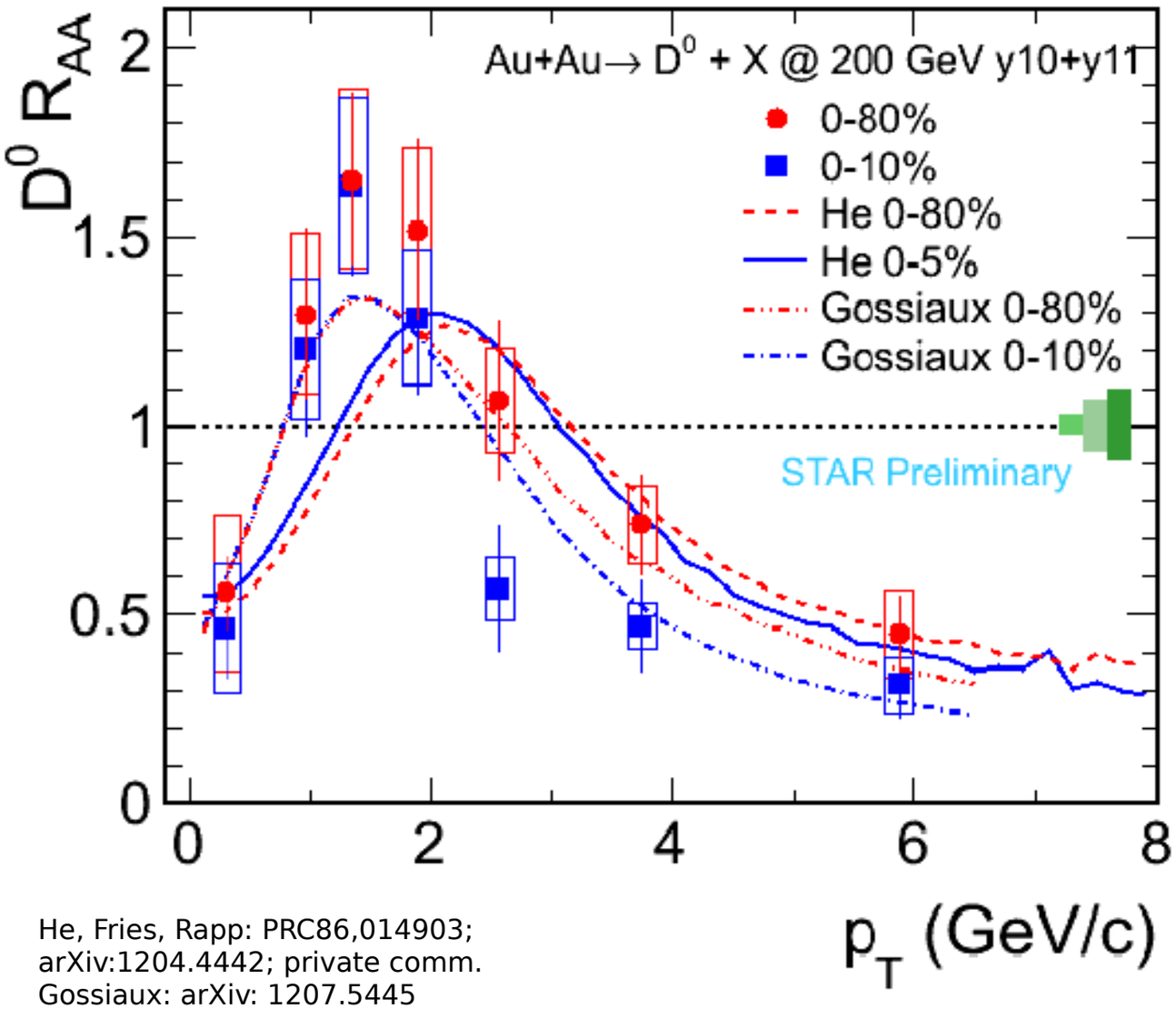




TransverseMomemtum p_T (GeV/c)

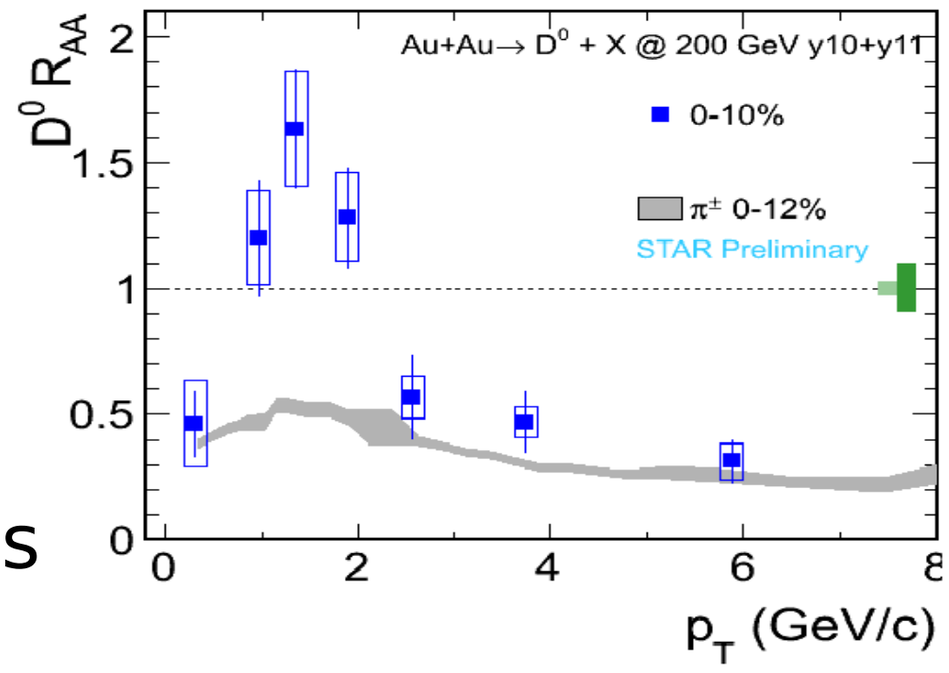
✓ Similar behavior in U+U and Au+Au collisions

D^0 R_{AA} in Au+Au 200 GeV



He, Fries, Rapp: PRC86,014903; arXiv:1204.4442; private comm.
Gossiaux: arXiv: 1207.5445

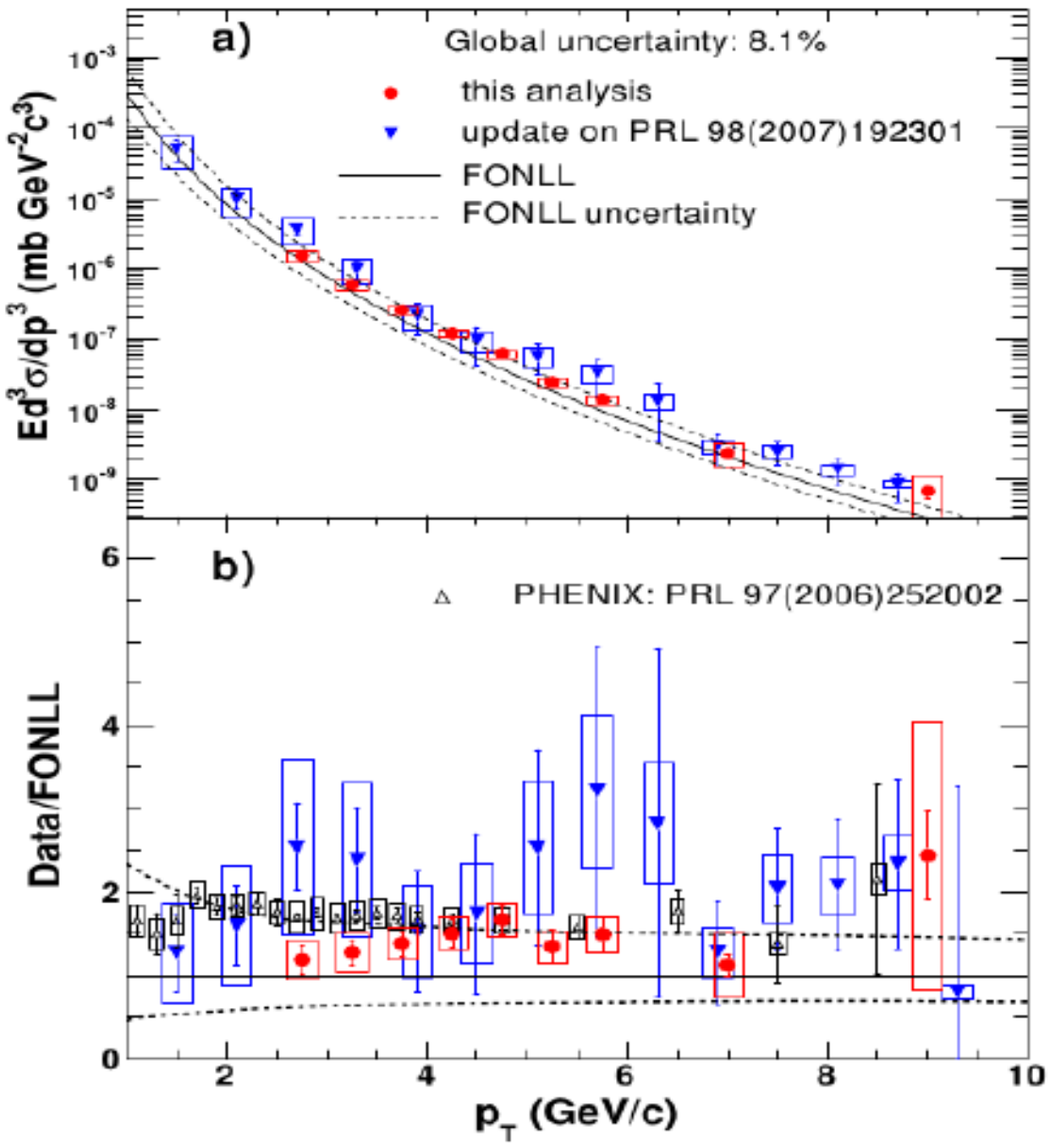
- ✓ Suppression at high p_T
- ✓ Enhancement at intermediate p_T
  - Cronin ?
  - radial flow ?
- ➔ *Enhancement described by models with light-quark coalescence with charm*



- ✓ At high p_T central collisions suppression similar to light hadrons

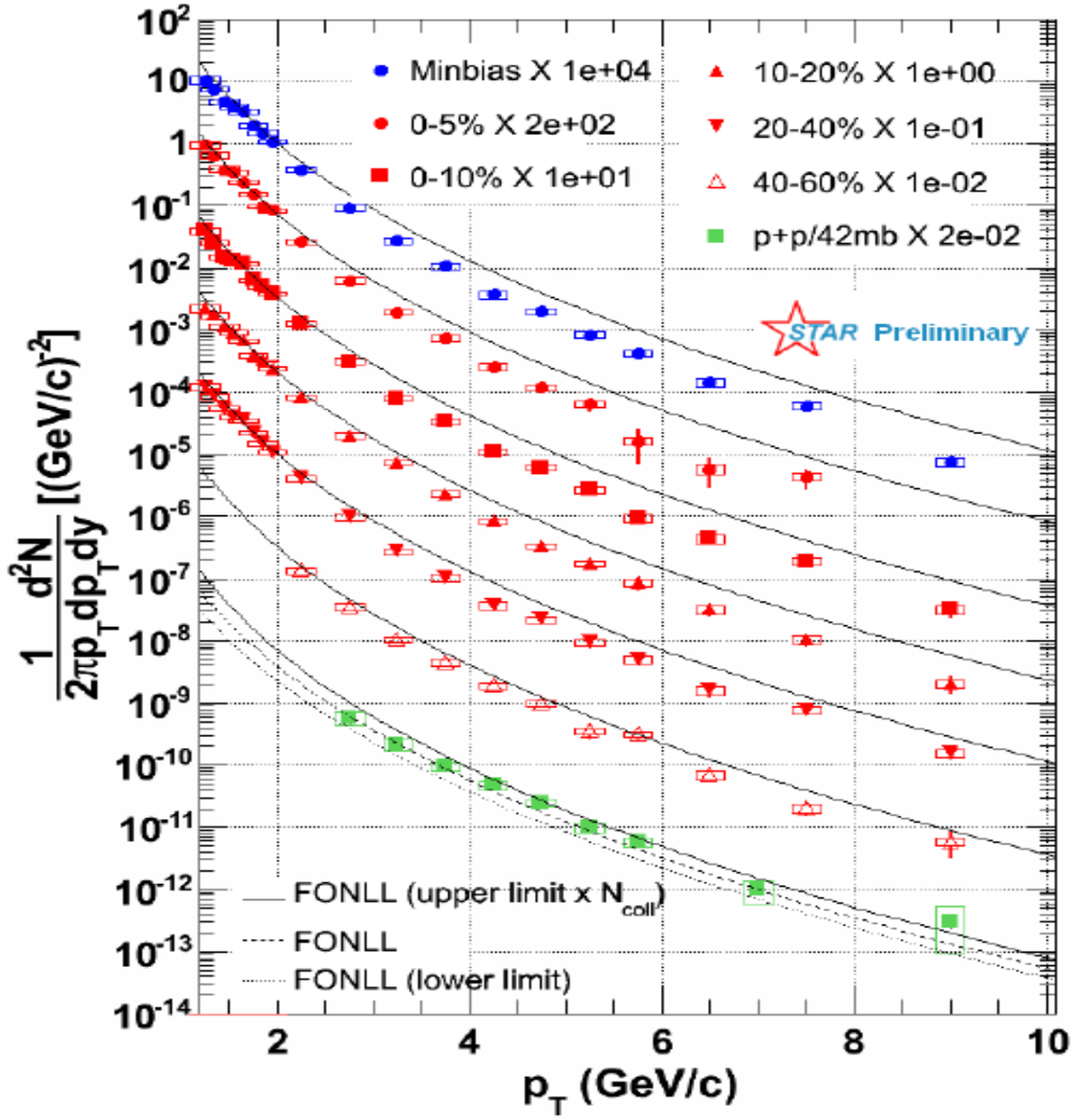
NPE in p+p and Au+Au 200 GeV

p+p



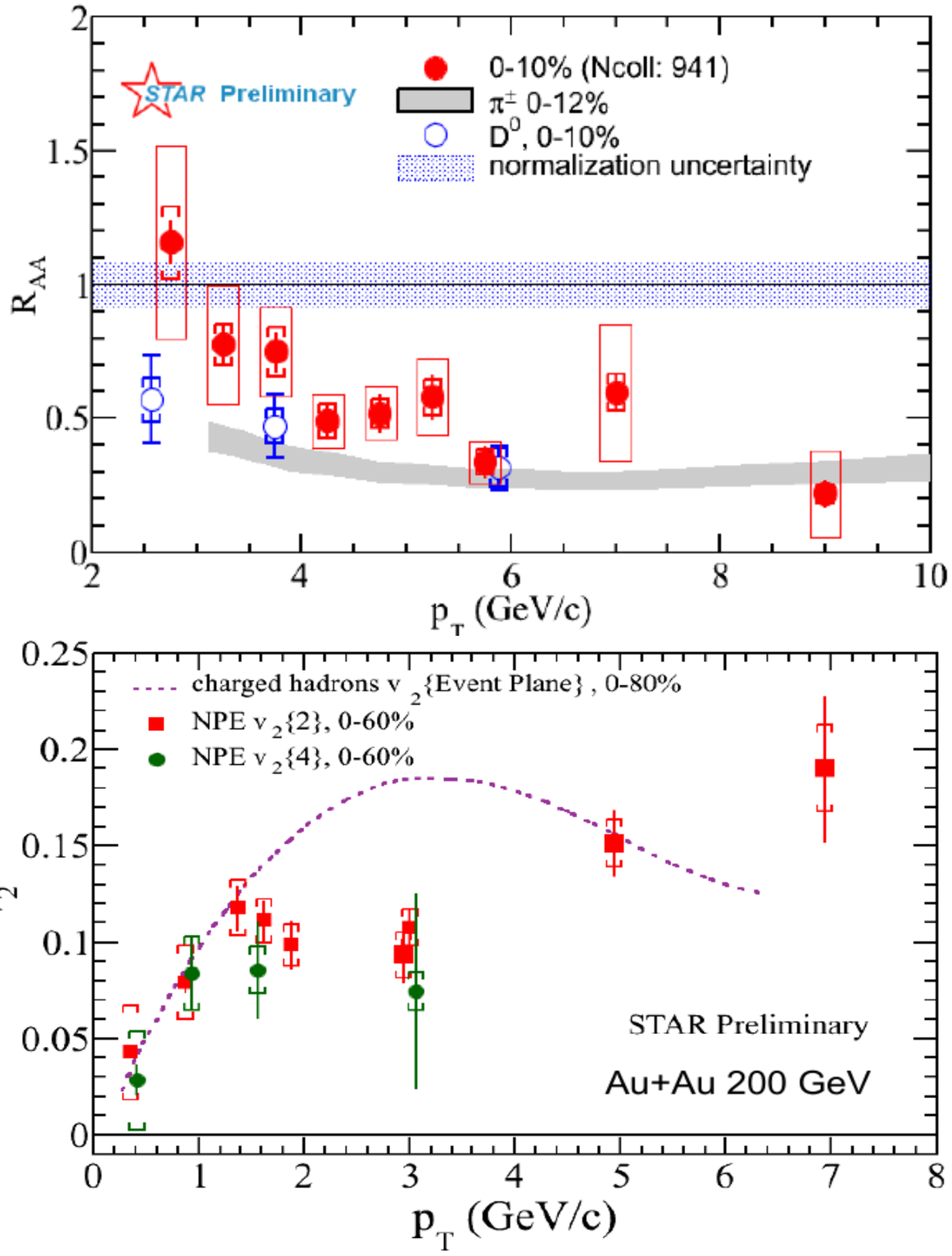
- ✓ Consistency with FONLL upper limit

Au+Au



- ✓ Suppression at high p_T comparing to FONLL

NPE in Au+Au 200 GeV

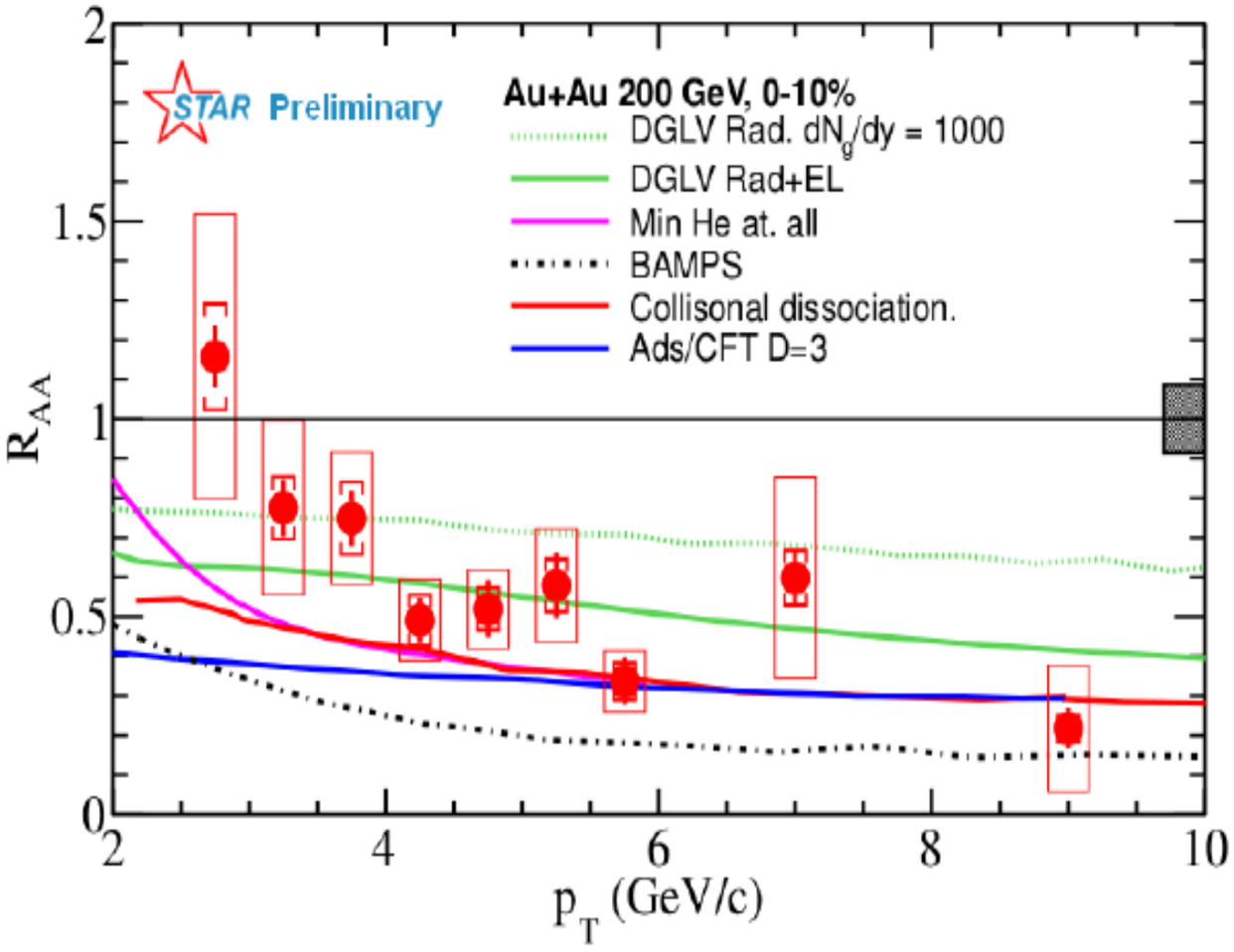


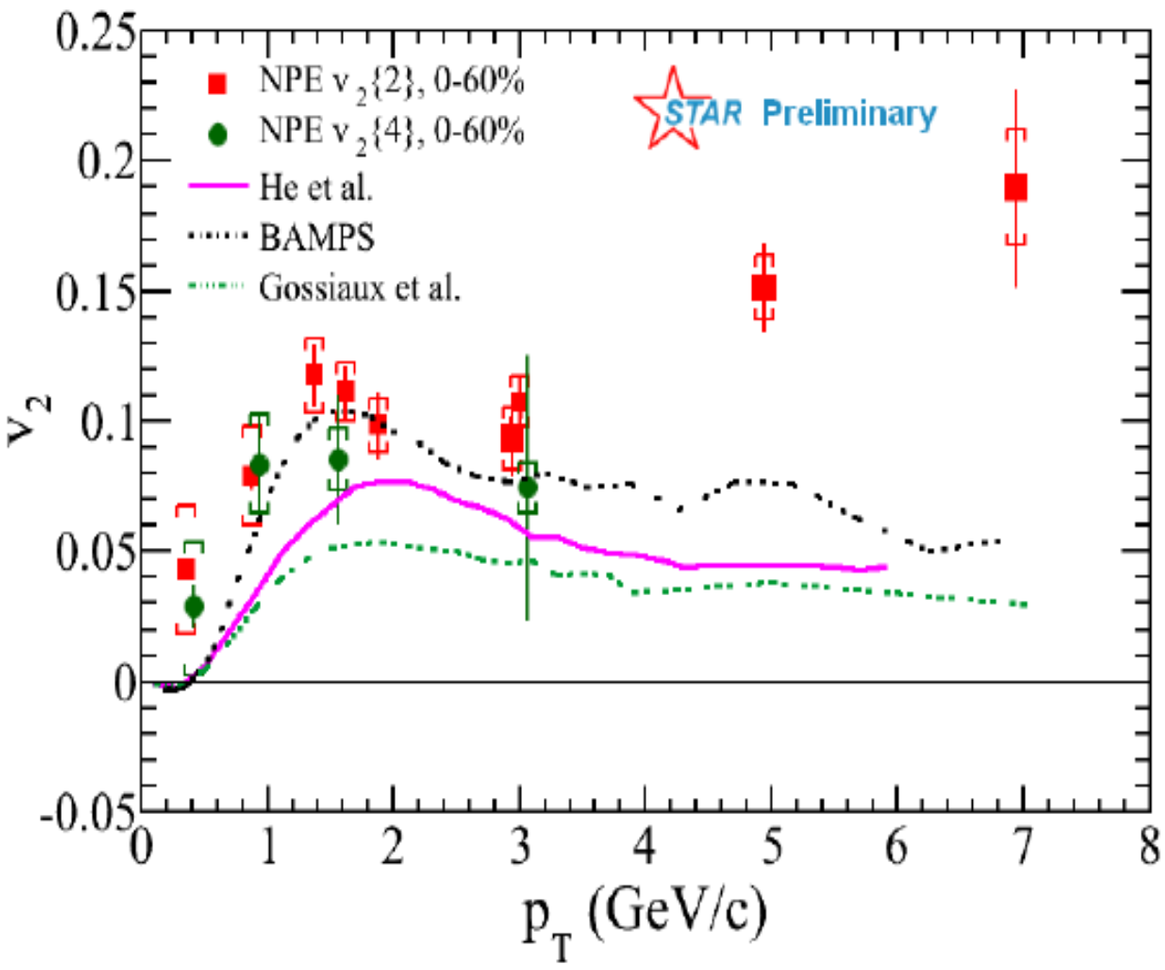
- ✓ Strong suppression at high p_T
  - ✓ Similar to D^0 mesons and light hadrons suppression

NPE includes both c and b

- ✓ Finite v_2 at low and intermediate p_T
  - ➔ Suggests strong charm-medium interaction, but more precise measurements of D^0 v_2 are needed
- Increase of v_2 with p_T can be due to jet-like correlations or path length of energy loss

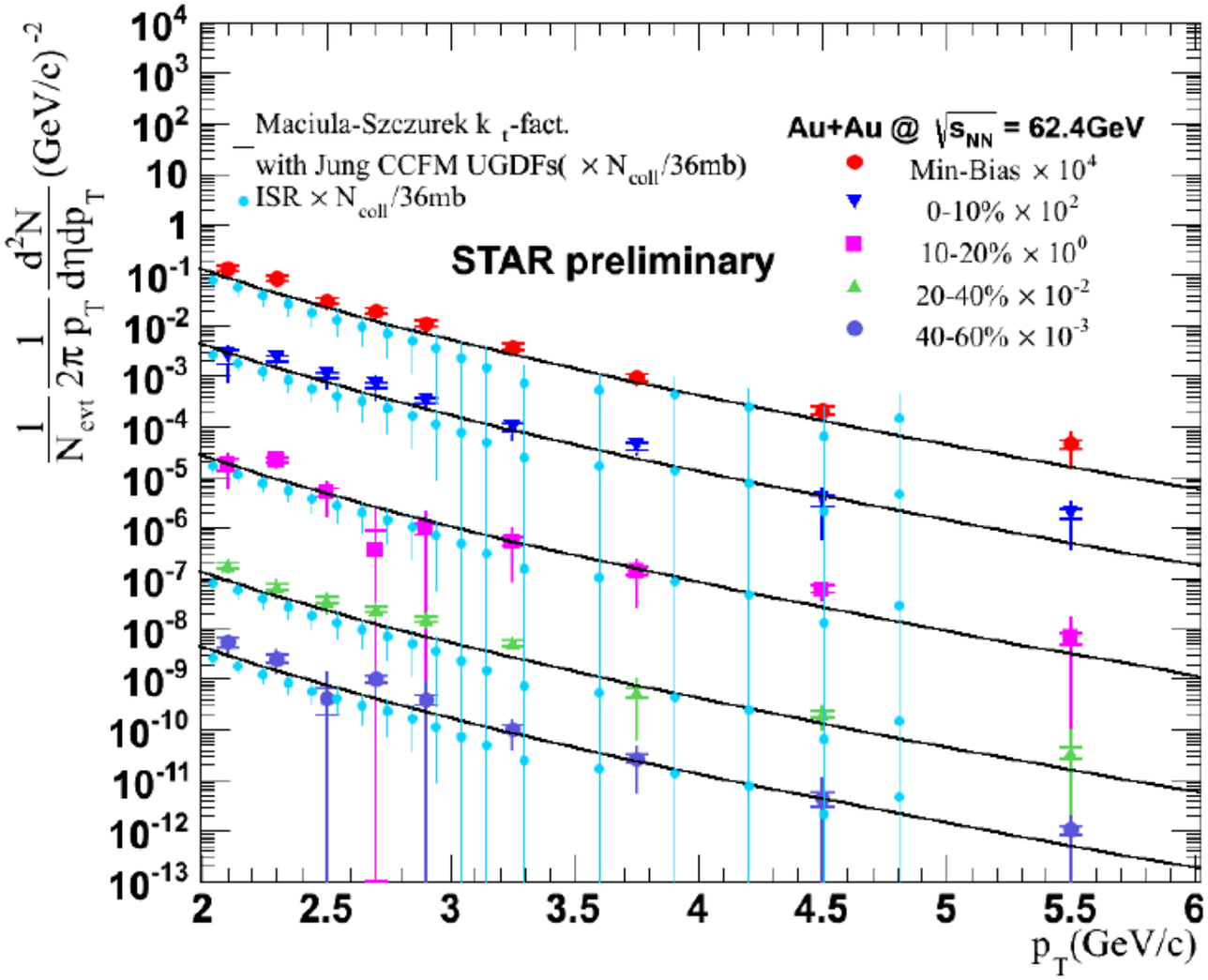
NPE in Au+Au 200 GeV – model comparison





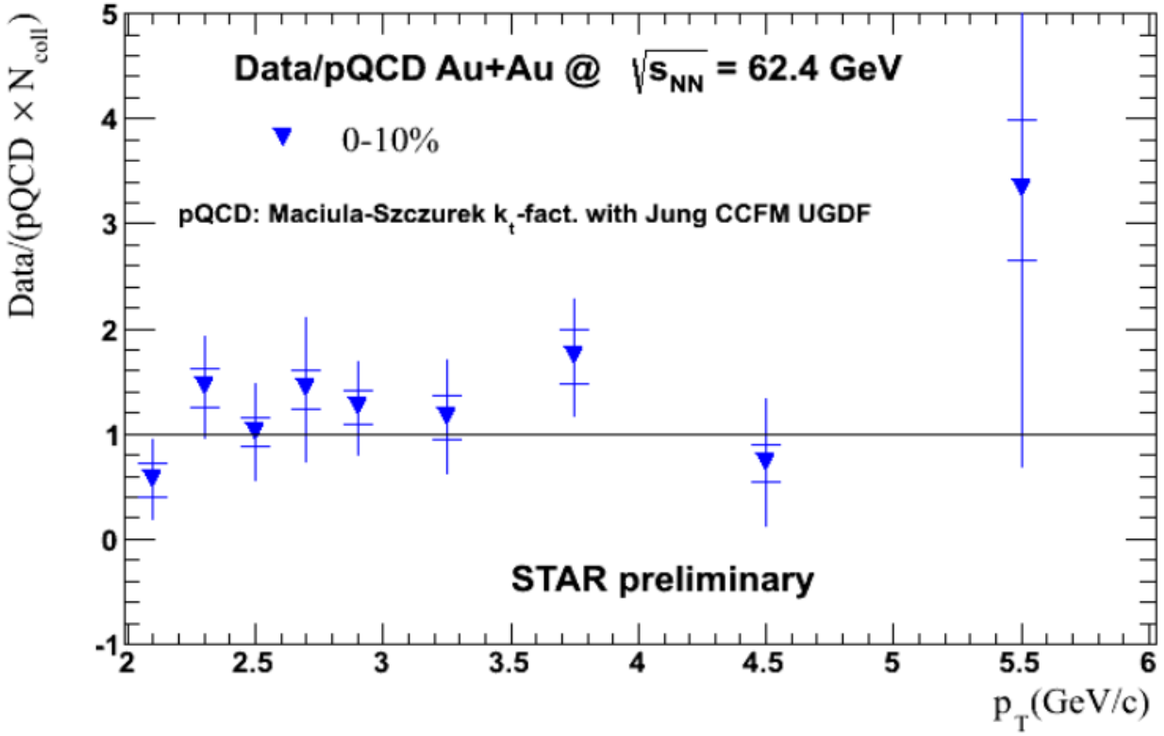
- ✓ Gluon radiation scenario alone fails to describe large NPE suppression
- ✓ No model can successfully explain the suppression and v_2 simultaneously

NPE in Au+Au 62.4 GeV



- ✓ No NPE suppression at 62.4 GeV - compared to pQCD calculations at $p_T < 5.5$ GeV

not corrected yet for J/ψ
Drell-Yan



Quarkonia

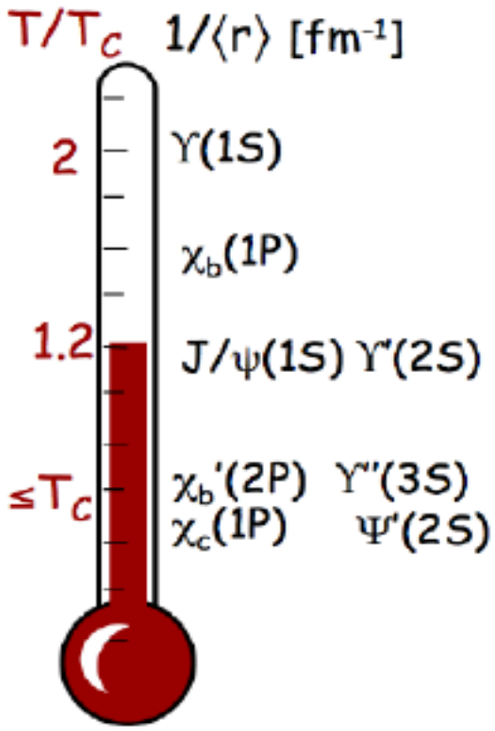
Quarkonia at RHIC - Motivation

Charmonia: J/ψ, ψ', χ_c — $J/\psi \rightarrow e^+e^-$ (BR 5.9%)

Bottomonia: $\Upsilon(1S)$, $\Upsilon(2S)$, $\Upsilon(3S)$, χ_b — $\Upsilon \rightarrow e^+e^-$ (BR 2.4%)

- ✓ Quarkonia suppression in QGP in heavy-ion collisions due to ***color screening***
- ✓ Suppression of different states is determinate by T_C and their binding energy - QGP thermometer

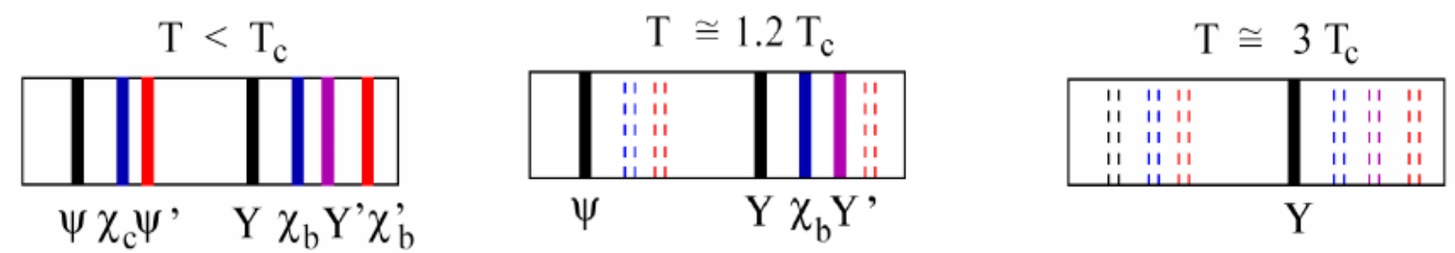
The QGP Thermometer



A .Mocsy, Eur. Phys. J. C61, 705-710 (2009)

Screening radius:

$r_D(T) \propto 1/T$



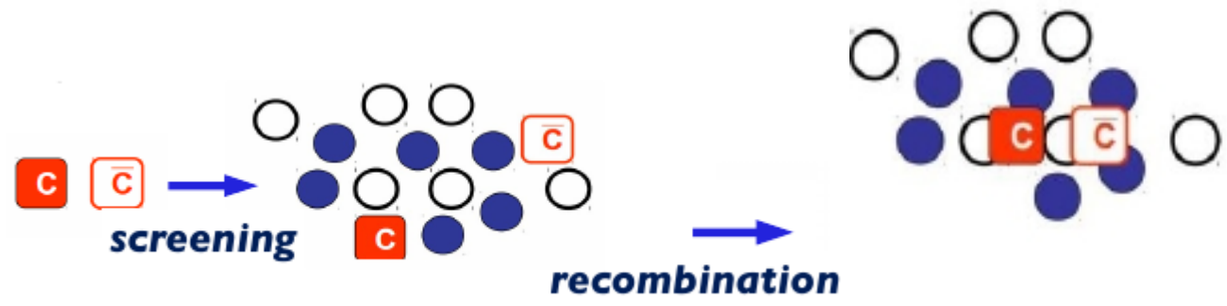
Quarkonia spectral lines as thermometer

H.Satz, Nucll. Phys. A 783, 249 (2007)

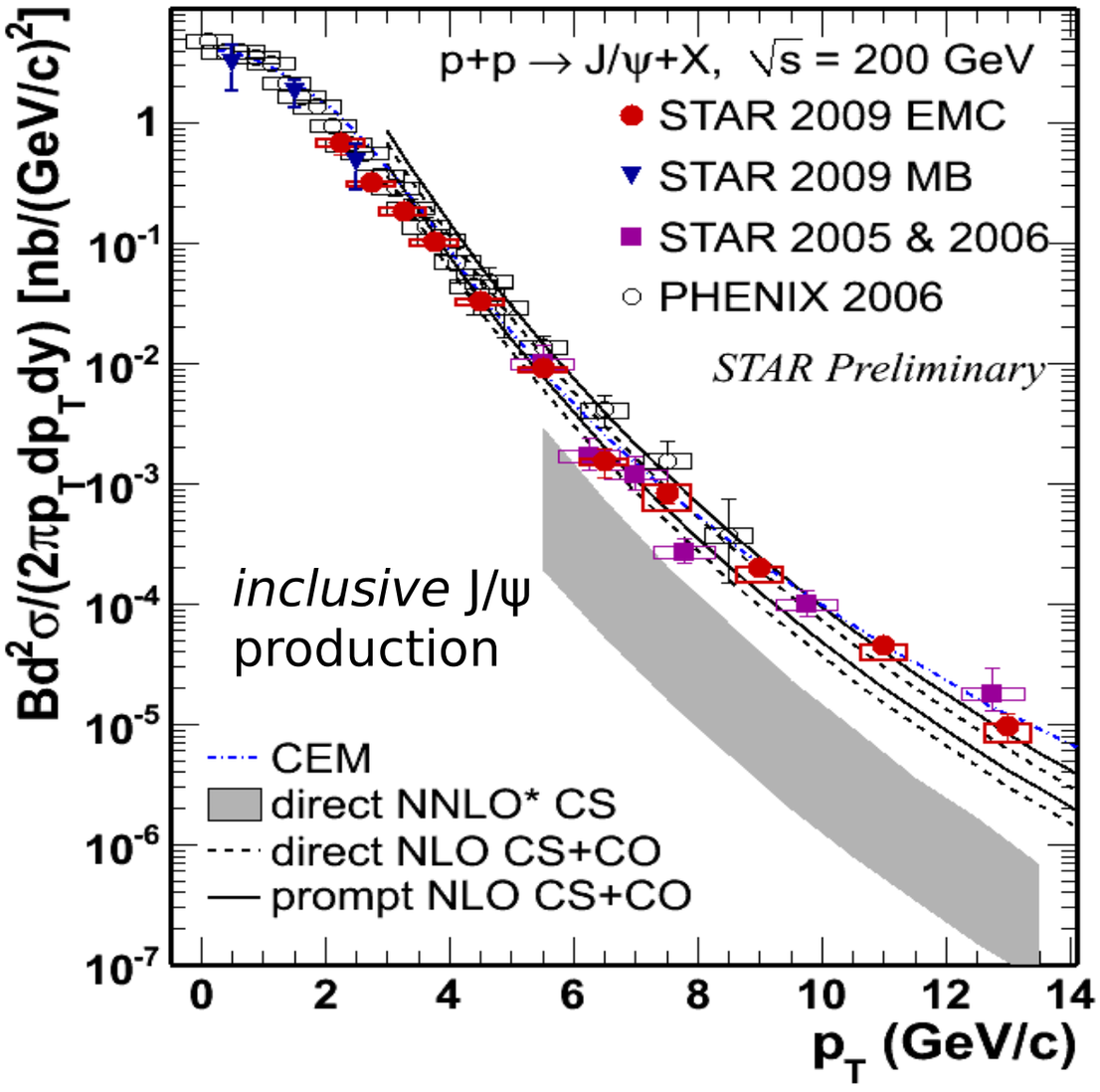
Quarkonia - Other effects

But there are more complications:

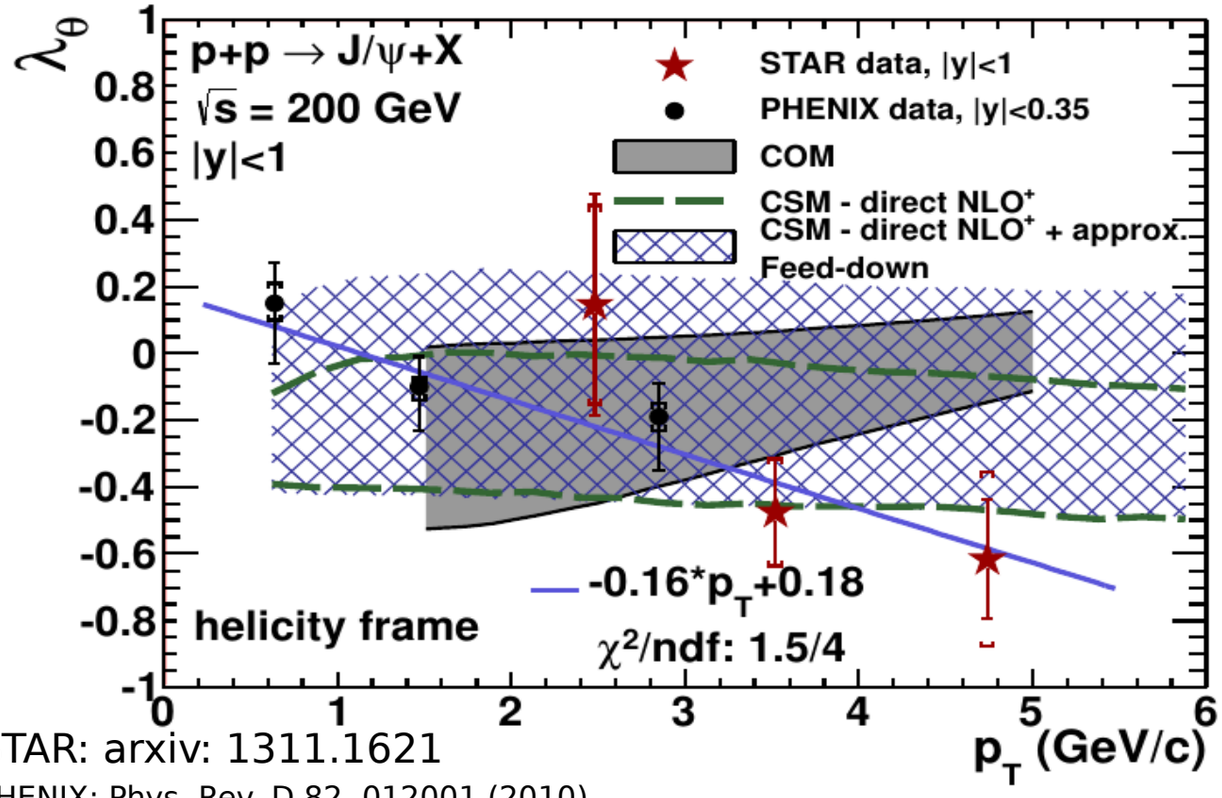
- Still unknown ***production mechanism*** in elementary collisions - measure p_T spectra and polarization
- ***Feed-down:***
  - *prompt J/ψ* production - ***direct J/ψ*** (~60%), feed down from **ψ'** (~10%) and χ_c (~30%) decays
  - *non-prompt* - **B-mesons** feed-down (10-25% at 4-12 GeV/c, STAR, Phys. Lett. B722 (2013) 55)
- ***Cold Nuclear Matter (CNM) effects*** - nuclear shadowing, Cronin effect, nuclear absorption, ...
- Other ***Hot Nuclear Matter effects*** - recombination, ...



J/ψ in p+p 200 GeV



STAR EMC : Phys. Lett. B 722 (2013) 55
STAR MB: Acta Phys. Polonica B Vol.5, No 2 (2012), 543
PHENIX: Phys. Rev. D 85, 092004 (2012)

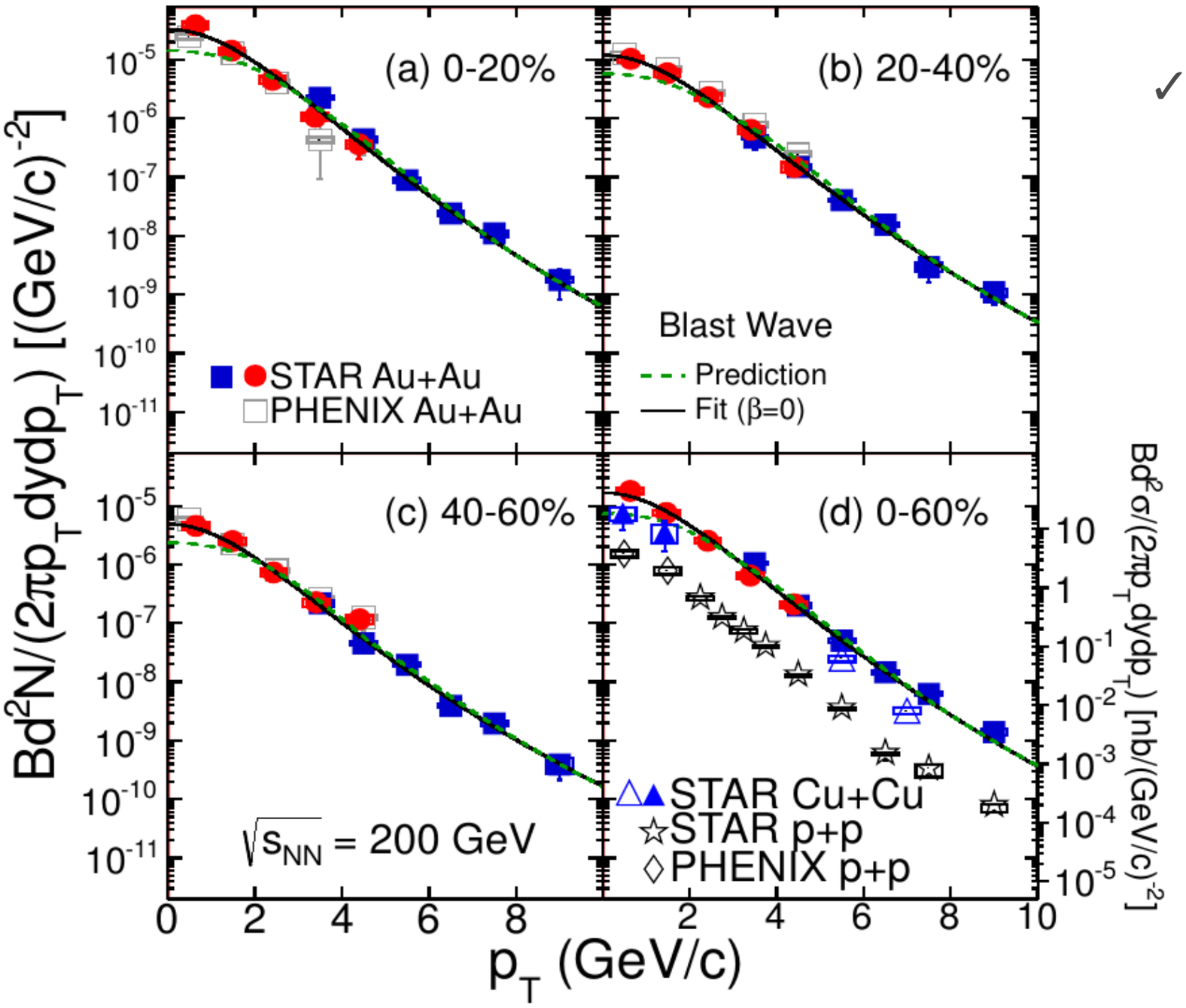


STAR: arxiv: 1311.1621
PHENIX: Phys. Rev. D 82, 012001 (2010)

- ✓ Trend towards longitudinal polarization in the HX frame

- ✓ It's challenging to describe both J/ψ p_T spectrum and polarization

J/ψ p_T spectra in Au+Au 200 GeV



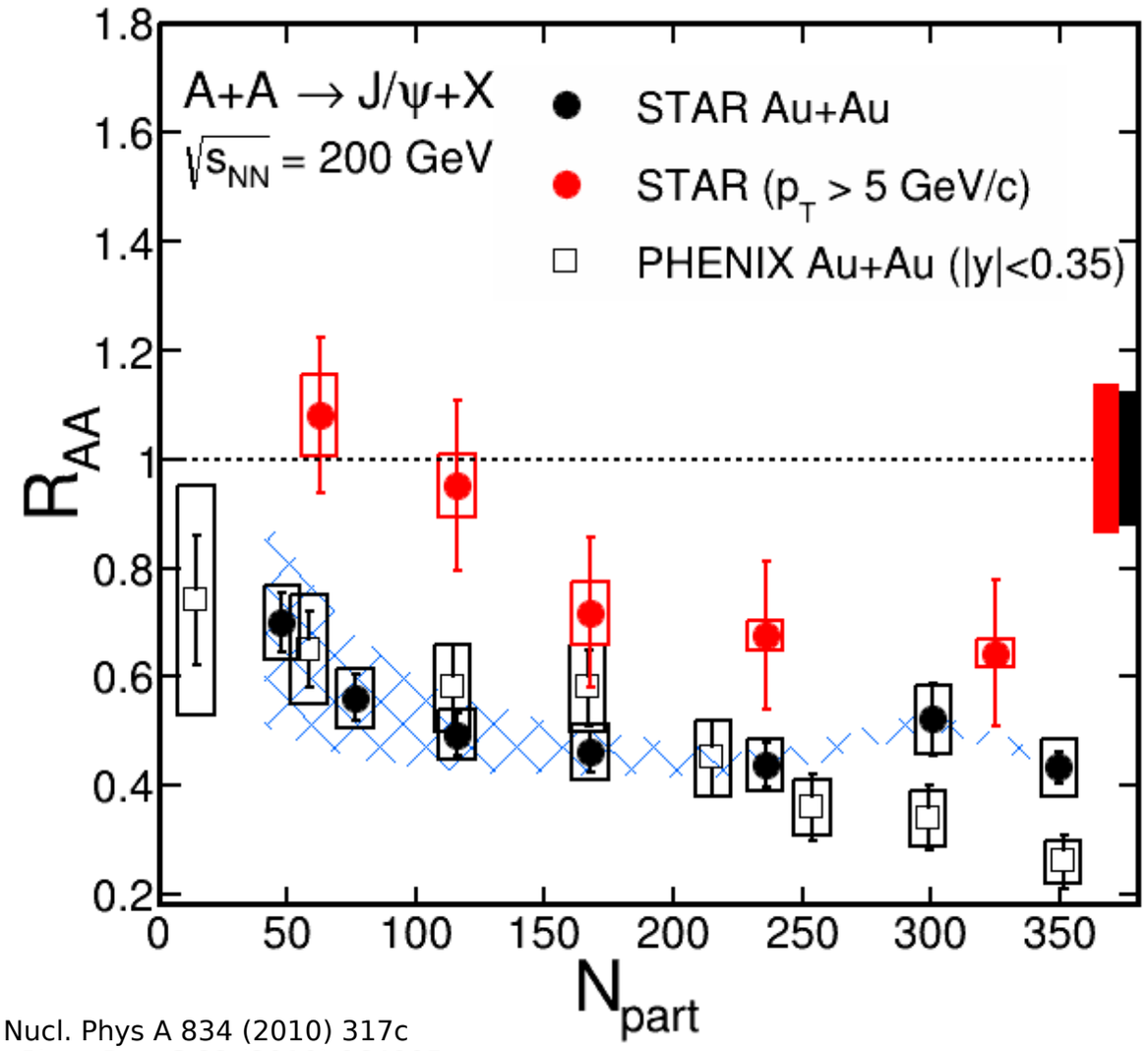
- ✓ At low p_T J/ψ spectra softer than the TBW prediction from light hadron
  - small radial flow ?
  - recombination at low p_T ?

J/ψ p_T range extended to 0-10 GeV/c

Tsallis Blast-Wave model:
Phys. Rev. C 79 (2009) 051901
Chin. Phys. Lett. 30 (2013) 031201

STAR high-p_T : Phys. Lett. B 722 (2013) 55
STAR low-p_T : arxiv:1310.3563
STAR high-p_T Cu+Cu : Phys. Rev. C 80 (2009) 041902

J/ψ R_{AA} in Au+Au 200 GeV



Y.Liu et al., Nucl. Phys A 834 (2010) 317c
Zhao, Rapp, Phys. Rev. C 82 (2010) 064905

- ✓ Suppression increases with collision centrality
- ✓ High-p_T R_{AA} is systematically higher
- ✓ High-p_T J/ψ suppressed in central collisions
  - QGP effects ?

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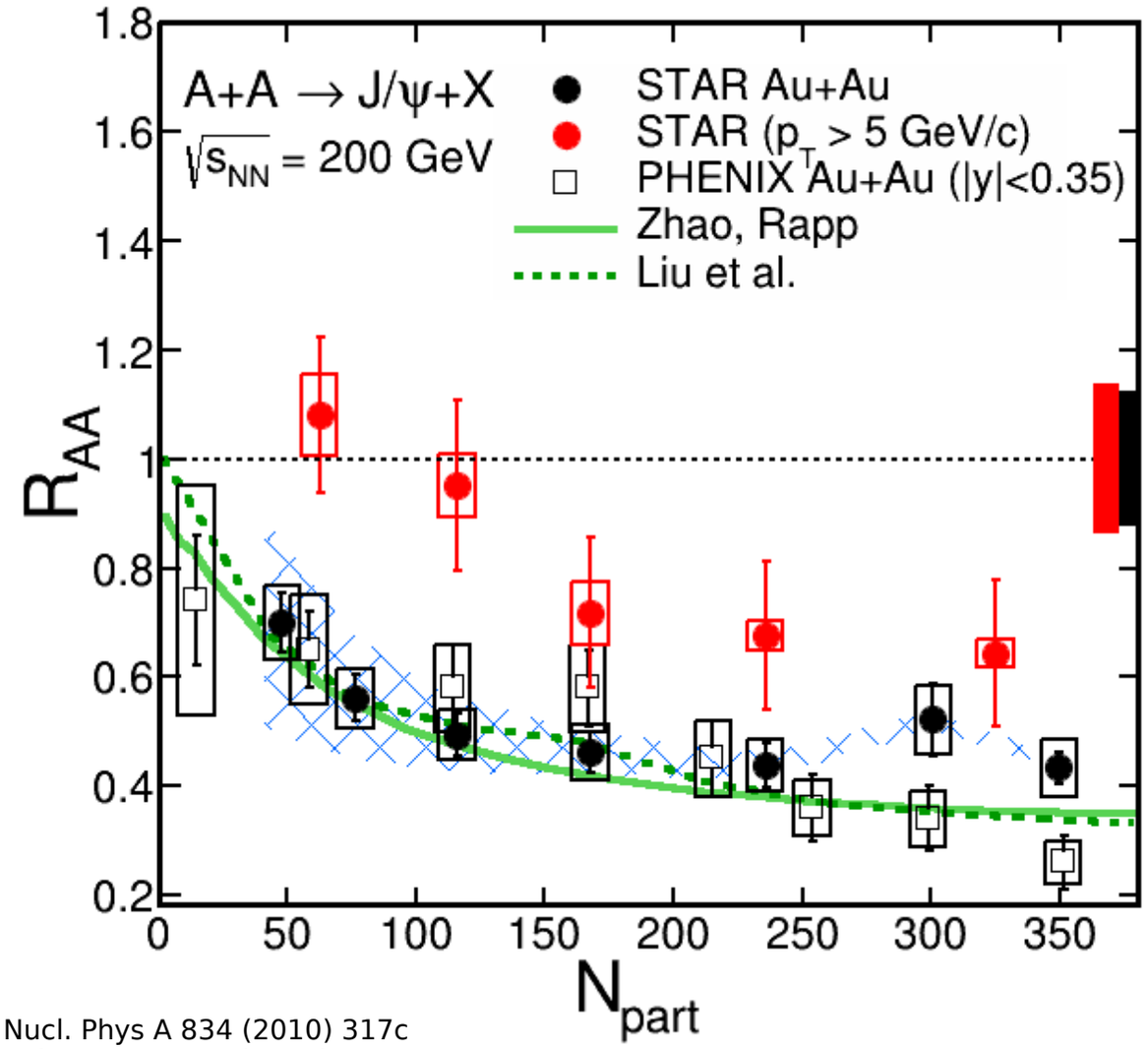

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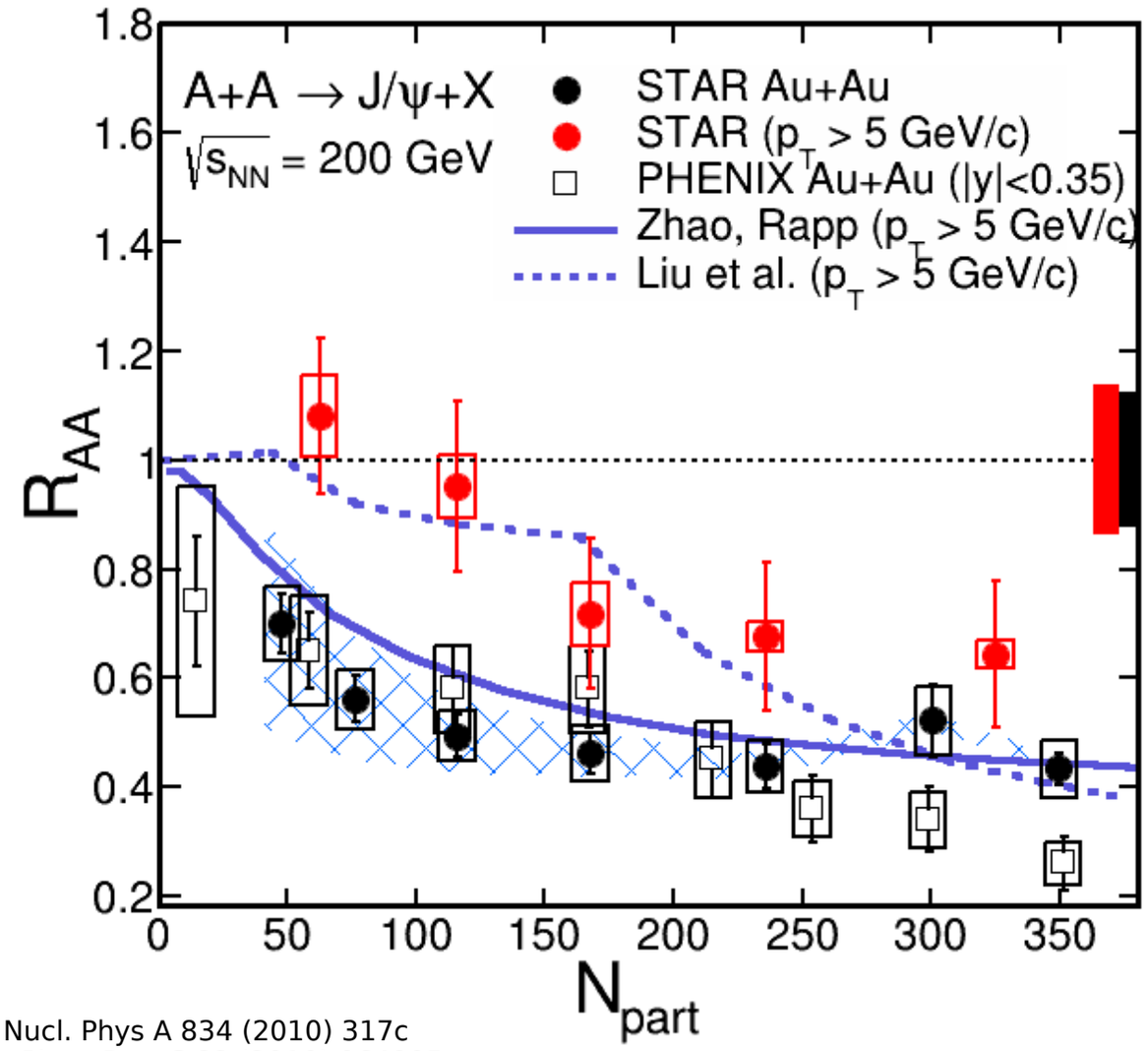
STAR high-p_T : Phys. Lett. B 722 (2013) 55
STAR low-p_T : arxiv:1310.3563

➔ Both models – *color screening + statistical regeneration* - describe the data well at low p_T

J/ψ R_{AA} in Au+Au 200 GeV



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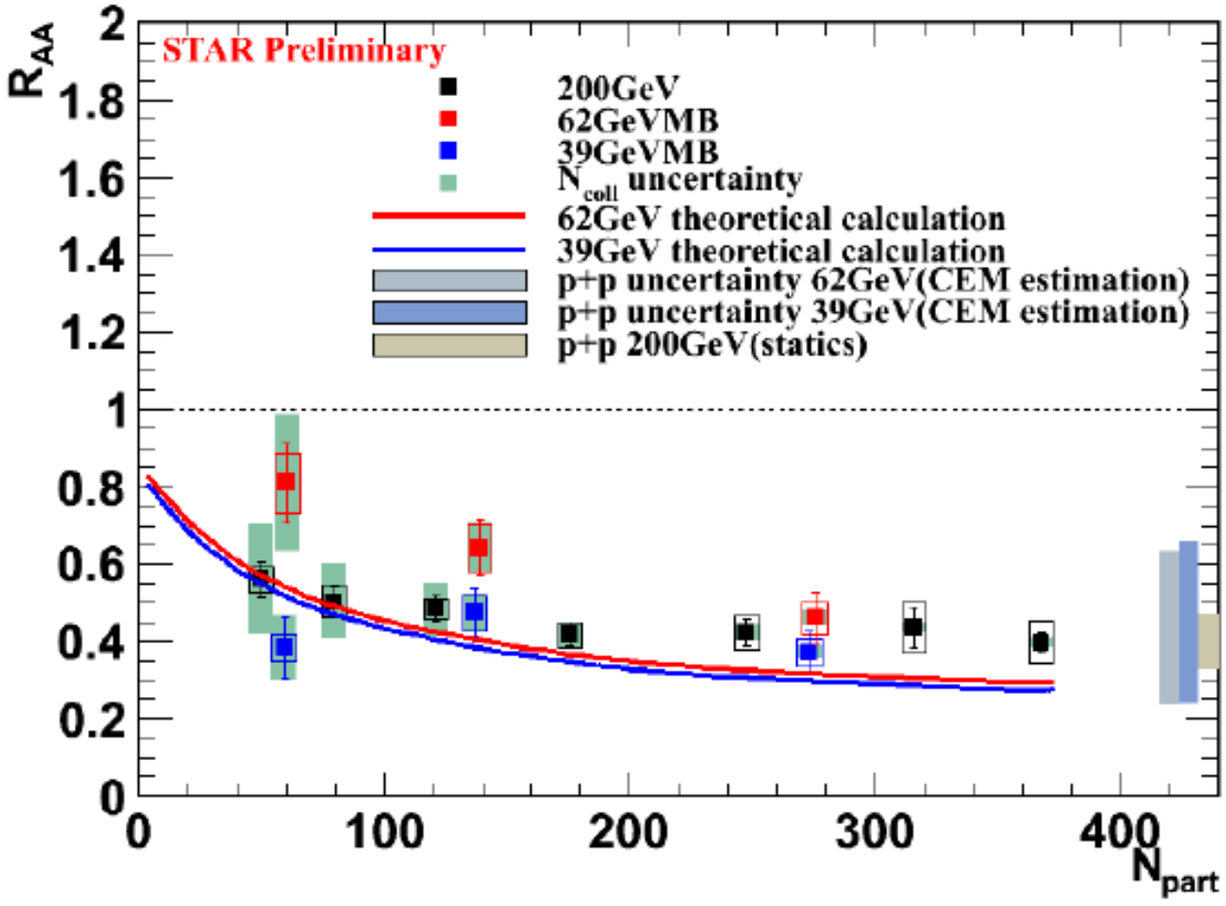
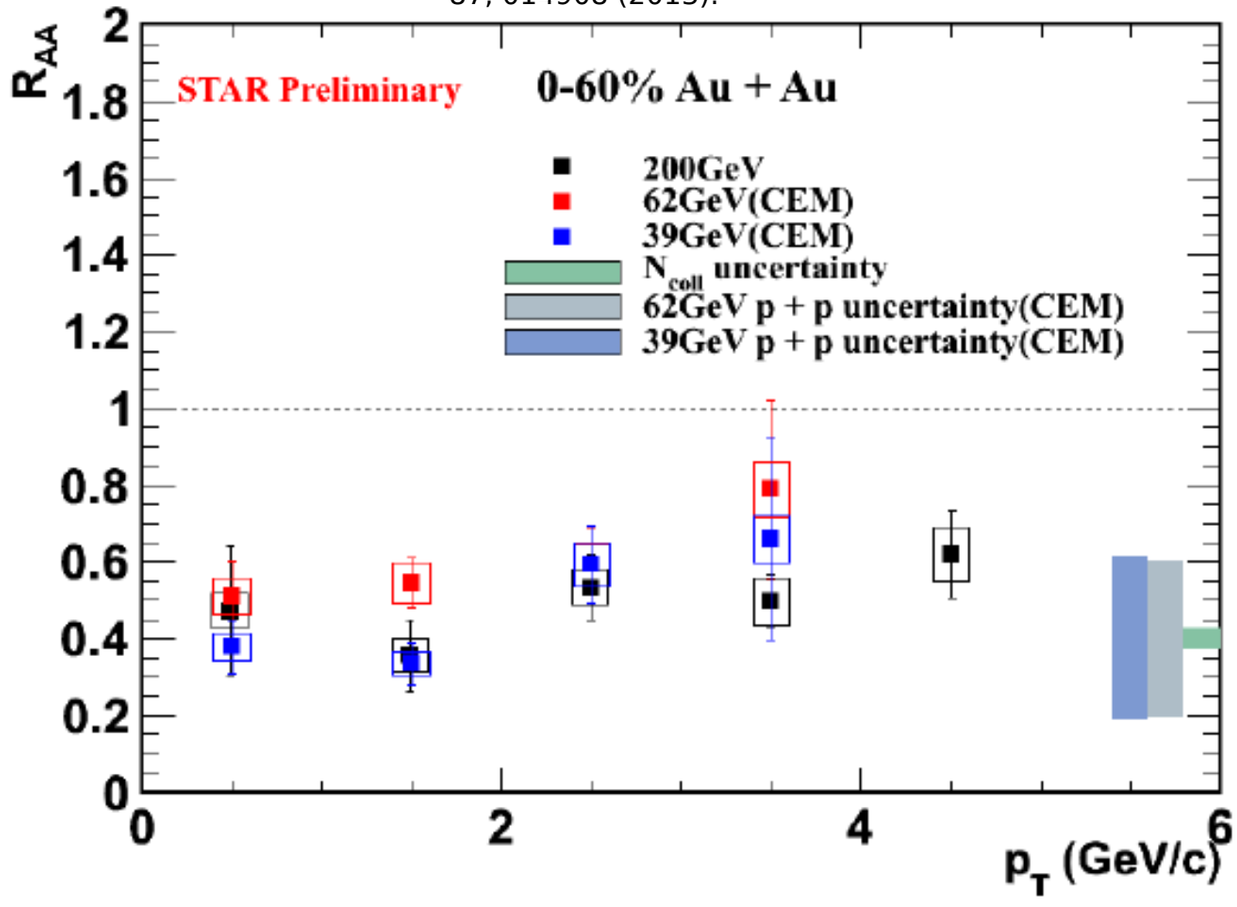
STAR high-p_T : Phys. Lett. B 722 (2013) 55
STAR low-p_T : arxiv:1310.3563

➔ At high p_T Liu et al. model describes the data well, while Zhao et. al model underpredicts the R_{AA}

Energy dependence of J/ψ R_{AA}

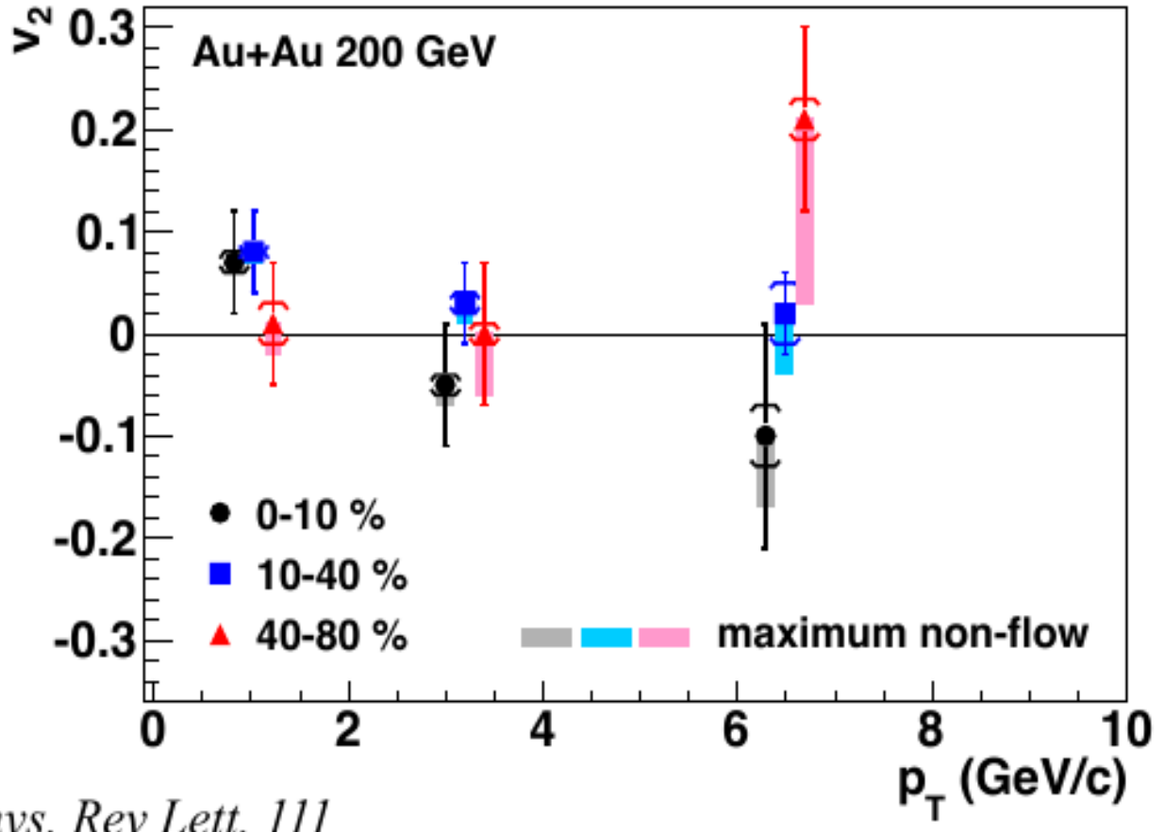
theoretical calculation: X. Zhao, R. Rapp, Phys. Rev. C 82 (2010) 064905
CEM: R. E. Nelson, R. Vogt and A. D. Frawley, Phys. Rev. C 87, 014908 (2013).



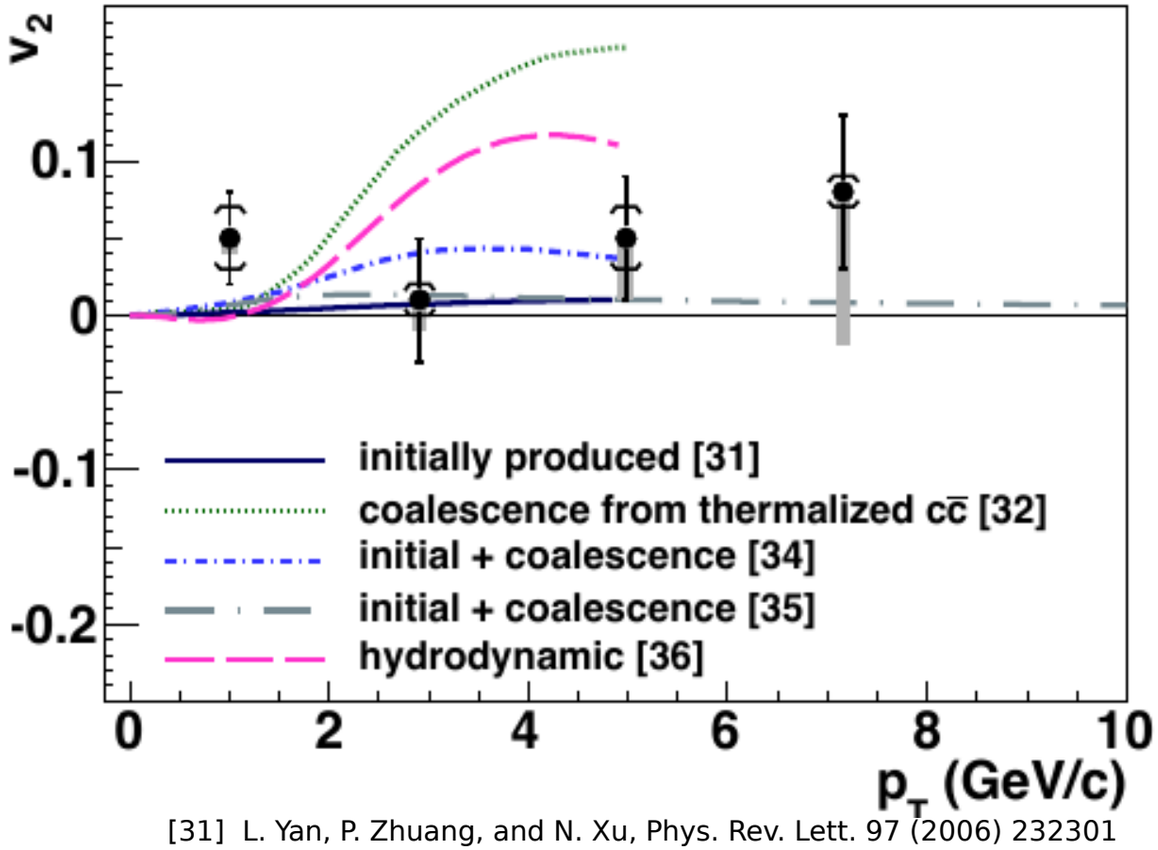


- ✓ Suppression of J/ψ at 62.4 and 39 GeV - no strong energy dependence of J/ψ R_{AA}
- ➔ Data agrees with the prediction of the two-component model
  - p+p reference for 62.4 and 39 GeV data from Color Evaporation Model (CEM) - large theoretical uncertainties

J/ψ v_2 in Au+Au 200 GeV



Phys. Rev Lett. 111 (2013) 52301

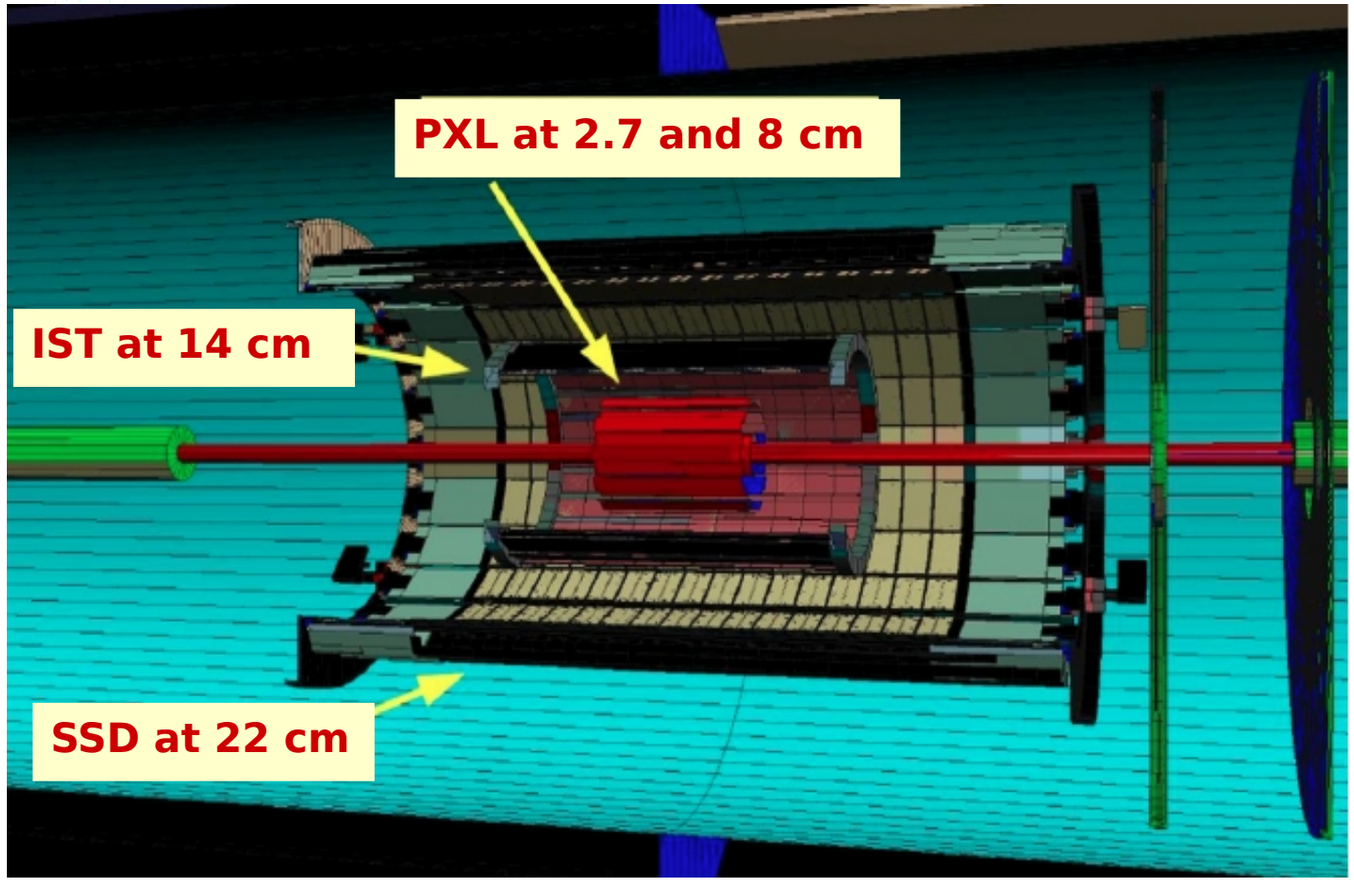


[31] L. Yan, P. Zhuang, and N. Xu, Phys. Rev. Lett. 97 (2006) 232301
[32] V. Greco, C.M. Ko, and R. Rapp, Phys. Lett. B 595 (2004) 202
[34] X. Zhao and R. Rapp, Phys. Lett. B 655 (2007) 126
[35] Y. Liu, N. Xu, and P. Zhuang, Nucl. Phys. A 834 (2010) 317c
[36] U. W. Heinz and C. Chen, private communication (2012)

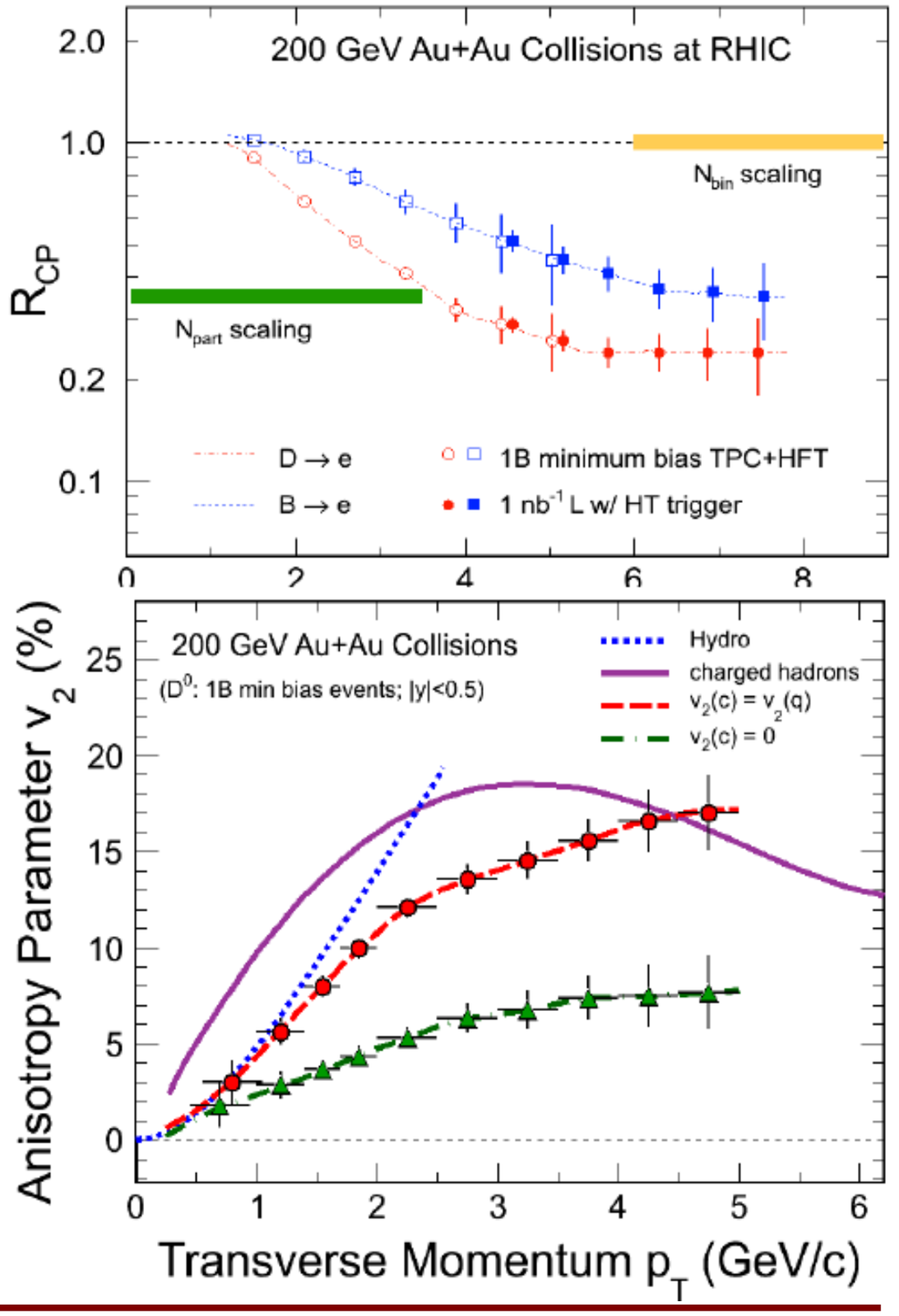
- ✓ J/ψ v_2 is consistent with zero at $p_T > 2$ GeV/c

  → disfavors the case that J/ψ with $p_T > 2$ GeV/c are produced dominantly by coalescence from thermalized (anti-)charm quarks

Heavy Flavor Tracker (HFT)



simulations



Precision open heavy flavors v_2 and R_{AA} measurements

Non-prompt J/ψ: $\boldsymbol{B \rightarrow J/\psi + X}$

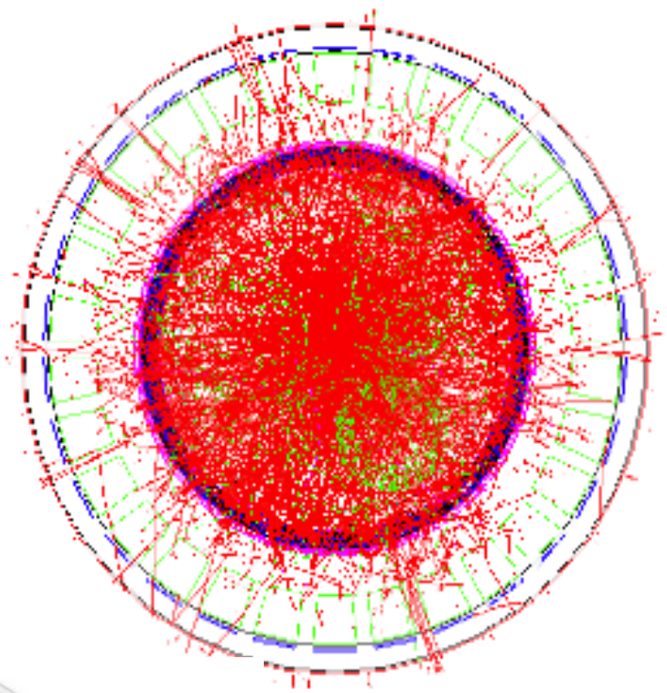
Muon Telescope Detector (MTD)

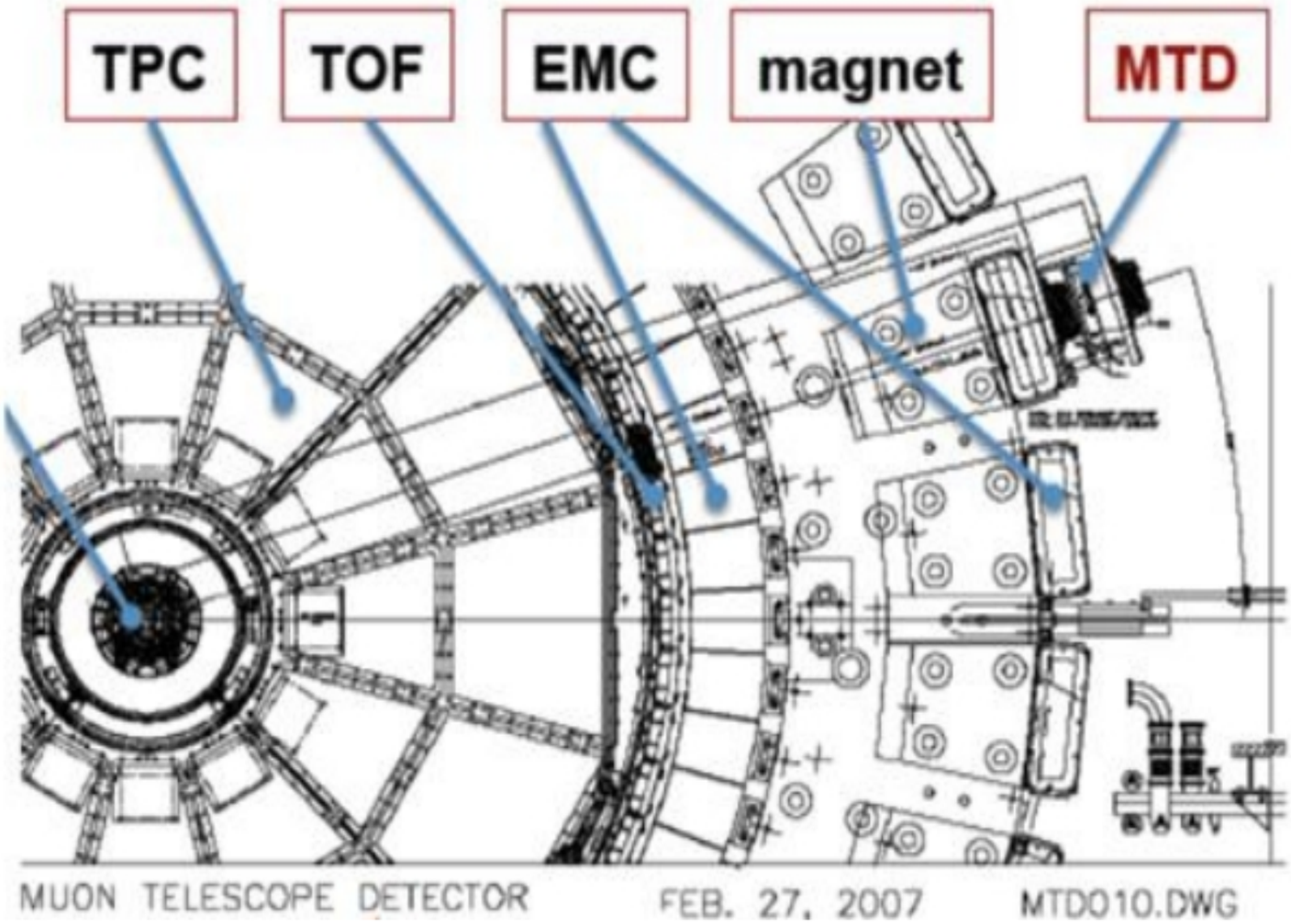
Multi-gap Resistive Plate Chamber (MRPC) - gas detector

Acceptance: 45% at $|\eta| < 0.5$

Long-MRPCs

Electronics same as in STAR TOF





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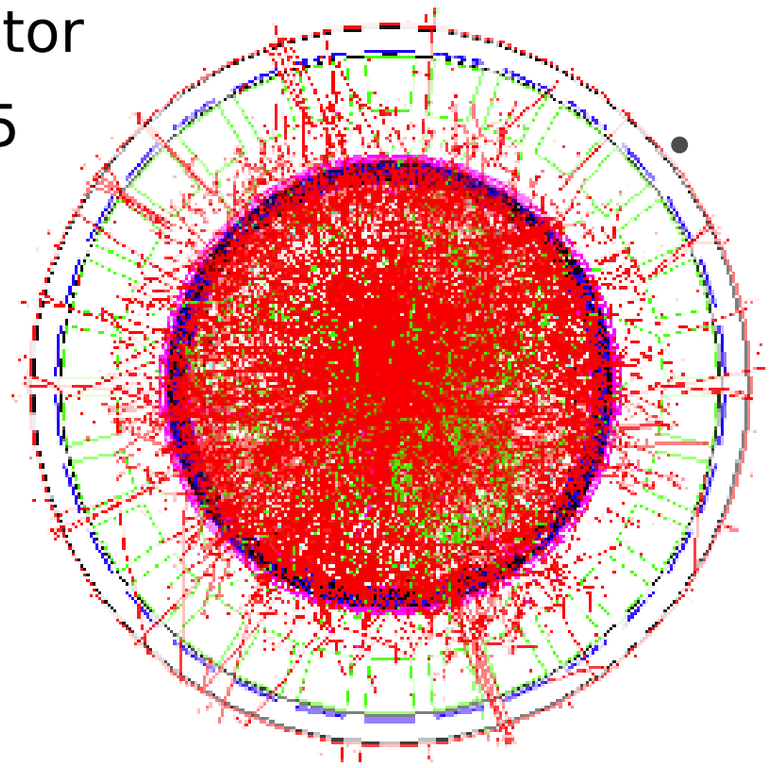
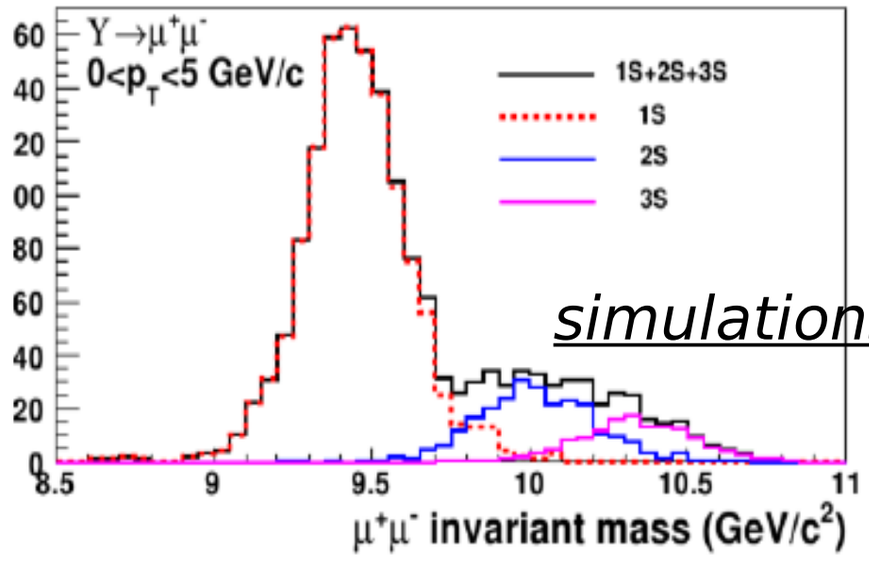
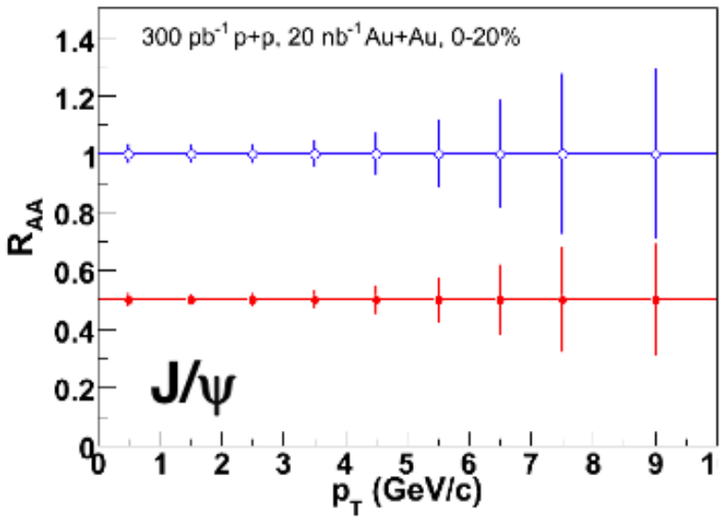
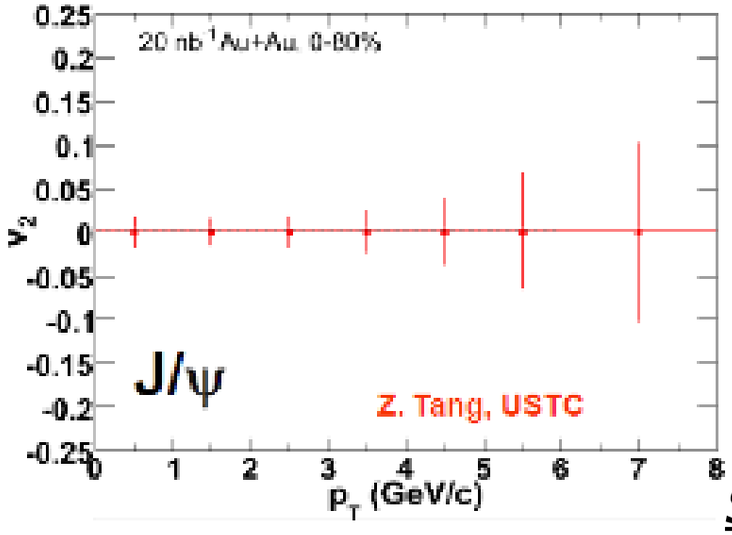


- No γ conversion
- Much less Dalitz decay contribution
- Less affected by radiative looses in the materials



simulations





- Excellent mass resolution
- Trigger capability for low and high p_T J/ψ in central Au+Au

simulations

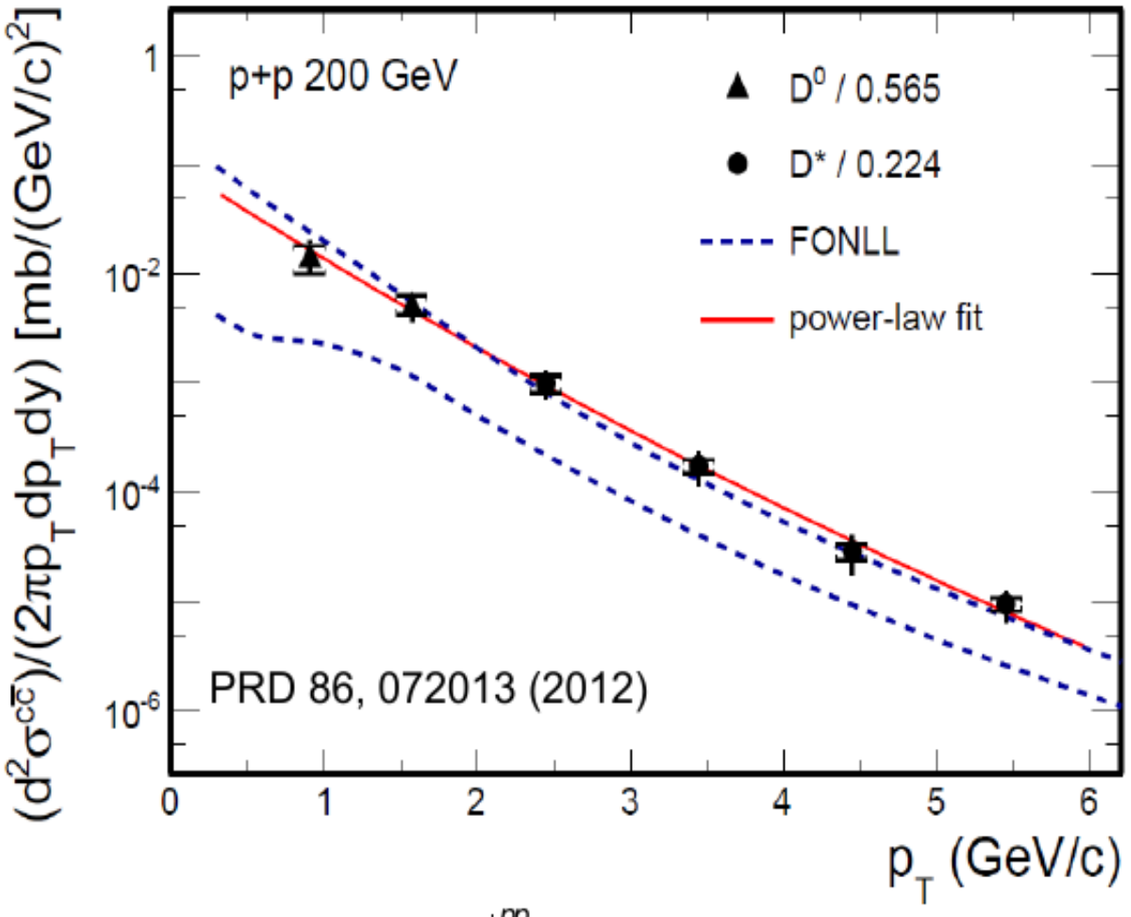
Summary

- NPE and D^0 suppression at high p_T Au+Au 200 GeV
- No NPE suppression at 62.4 GeV Au+Au collisions
- D^0 R_{AA} – similar behavior in Au+Au and U+U collisions
- High p_T J/ψ suppressed in central Au+Au 200 GeV
- No strong energy dependence of J/ψ suppression in Au+Au 200, 62.4, 39 GeV
- HFT and MTD since 2014

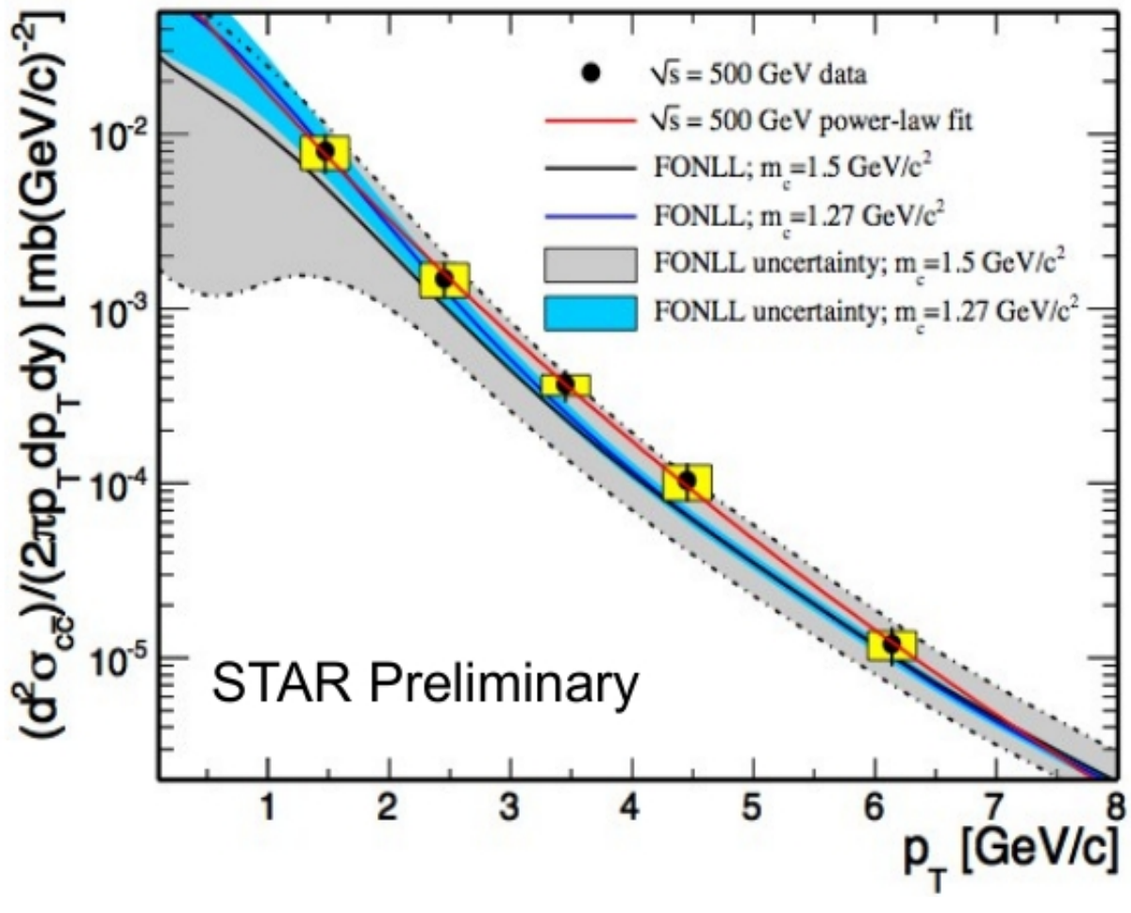
Thank you !

Backup

D^0, D* in p+p 200 and 500 GeV



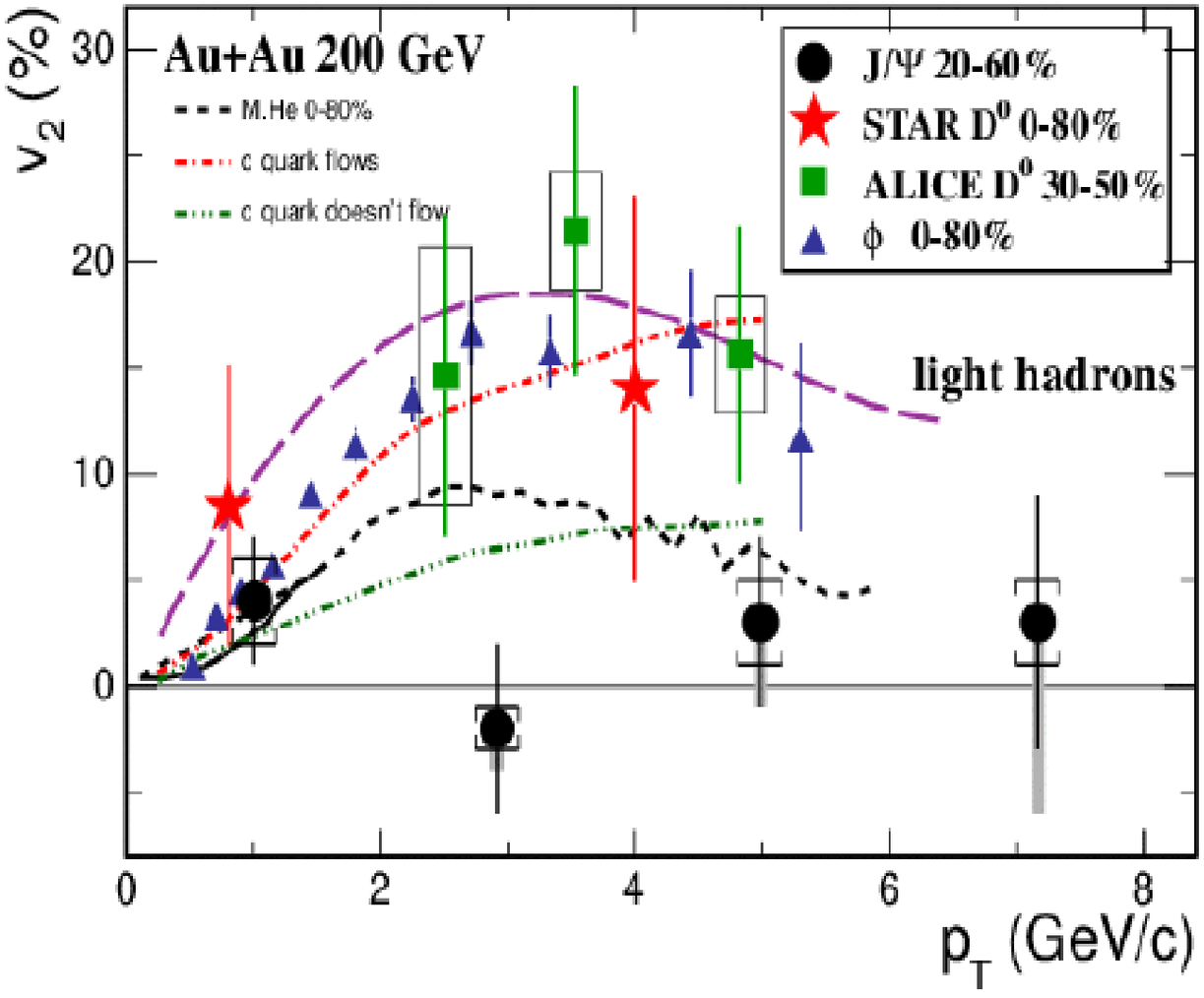
$$\left.\frac{d\sigma}{dy}\right|_{y=0}^{pp} = 170 \pm 45^{+38}_{-59}\,\mu b$$

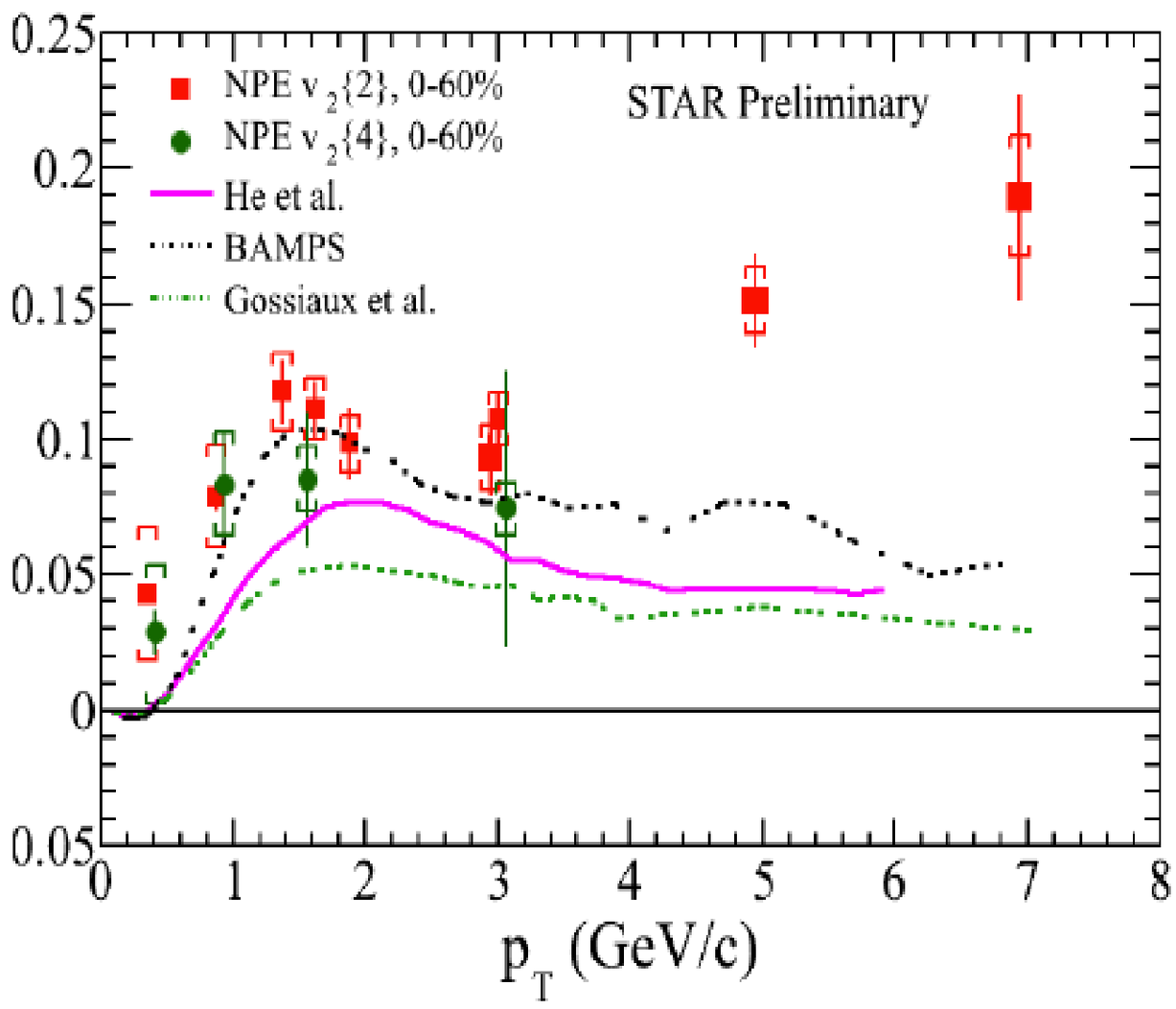


$$\left.\frac{\mathrm{d}\sigma_{c\bar{c}}}{\mathrm{d}y}\right|_{y=0}^{\sqrt{s}=500\mathrm{GeV}} = 217 \pm 86(\mathrm{stat.}) \pm 73(\mathrm{sys.})\ \mu\mathrm{b}$$

- ✓ Consistency with FONLL upper limit

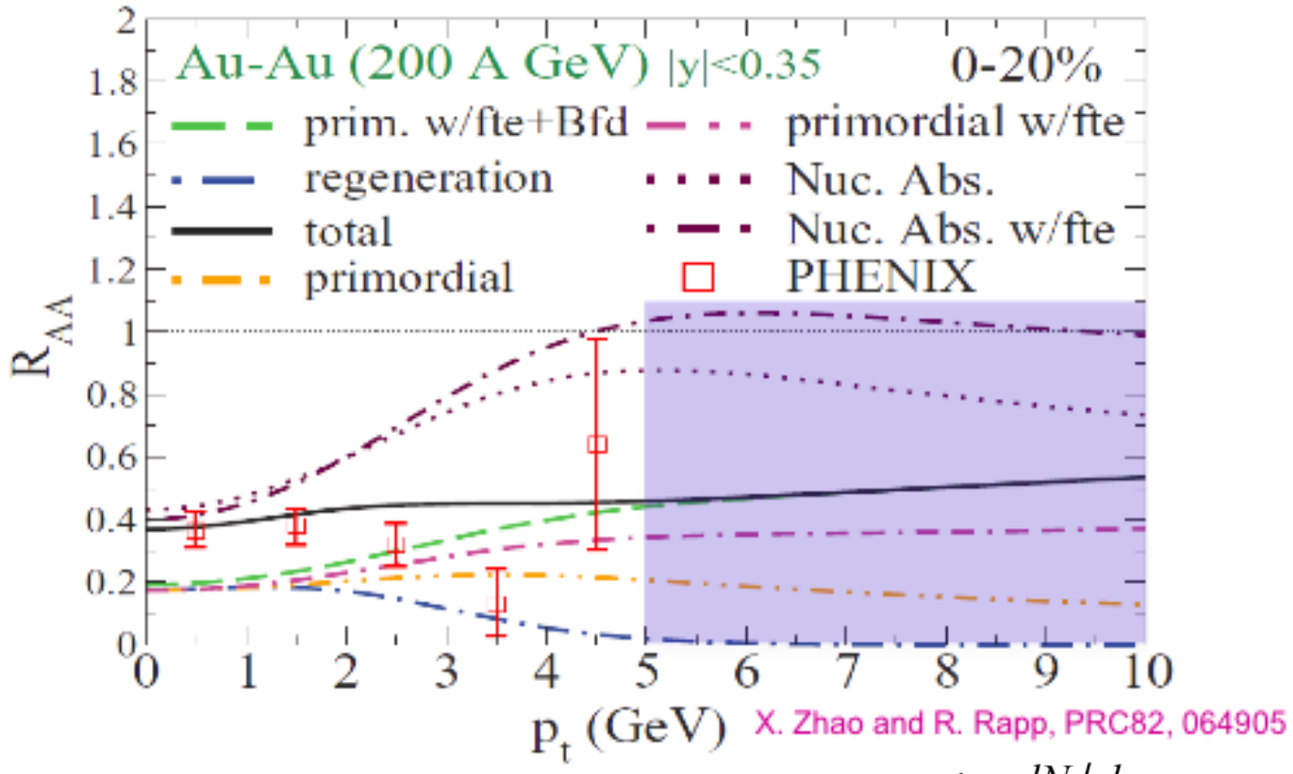
Open Heavy Flavor flow Au+Au 200 GeV





How to disentangle color screening vs CNM effect vs recombination

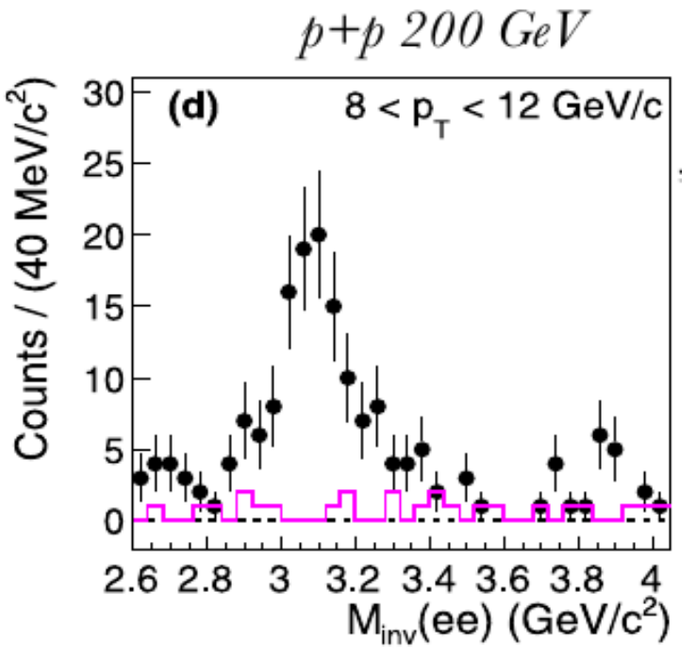
- Energy dependence of the J/ψ production - varying relative contributions
- High-p_T J/ψ - almost not affected by CNM effects and recombination

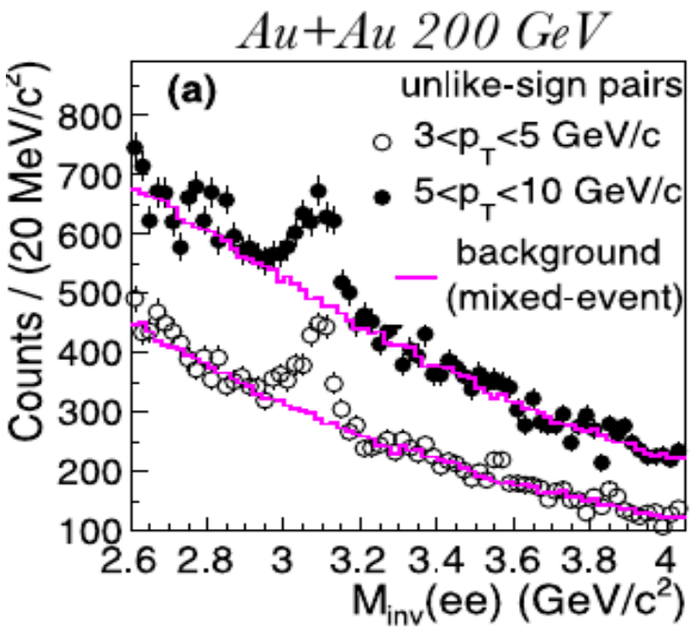


X. Zhao and R. Rapp, PRC82, 064905

$$R_{AA} = \frac{1}{N_{coll}} \frac{dN/dy_{A+A}}{dN/dy_{p+p}}$$

STAR high-p_T signal:





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Measure J/ψ p_T spectra, R_{AA}, polarization, elliptic flow …

J/ψ-hadron correlations in p+p 200 GeV

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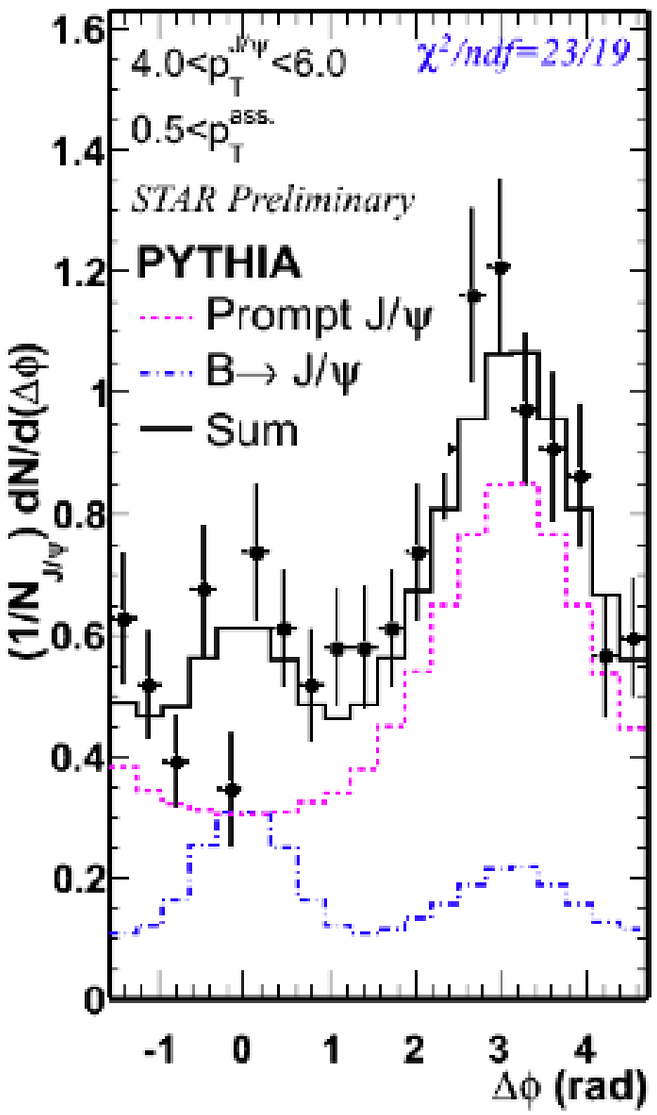
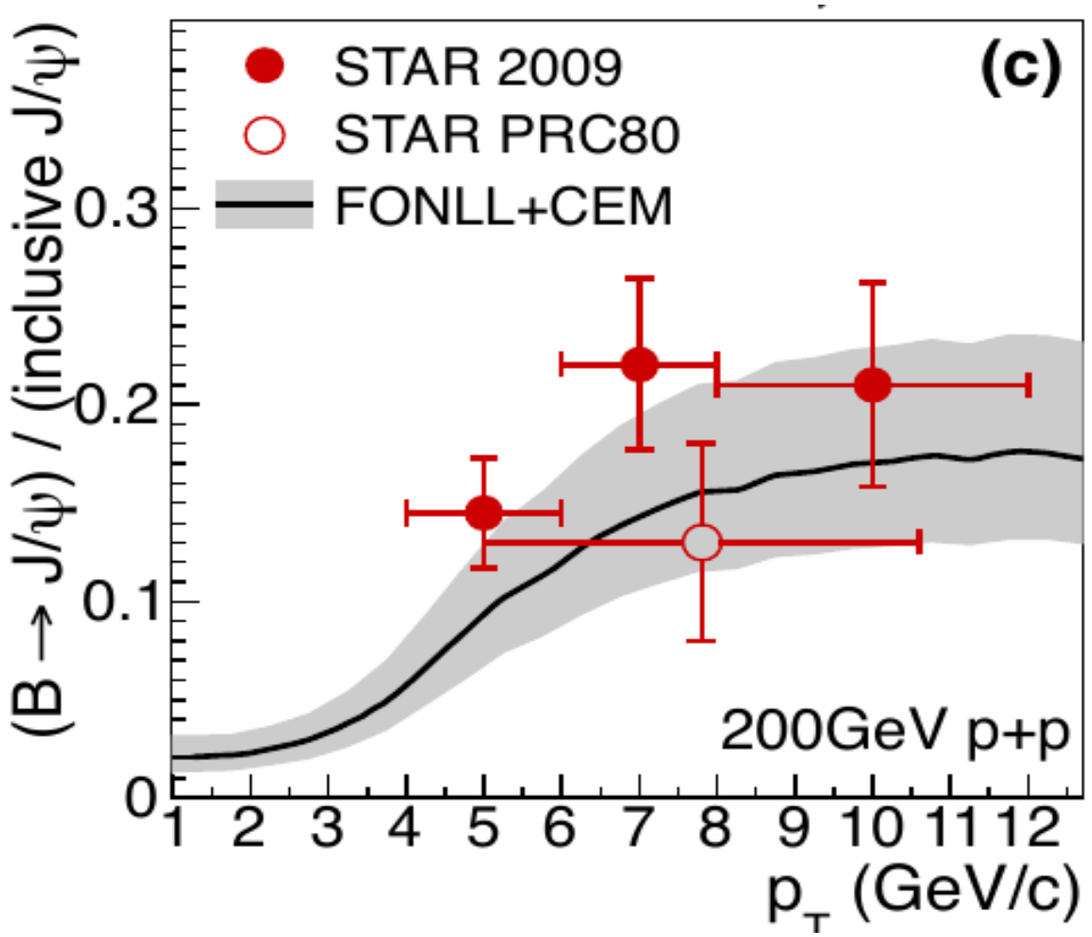
B → J/ψ feed-down

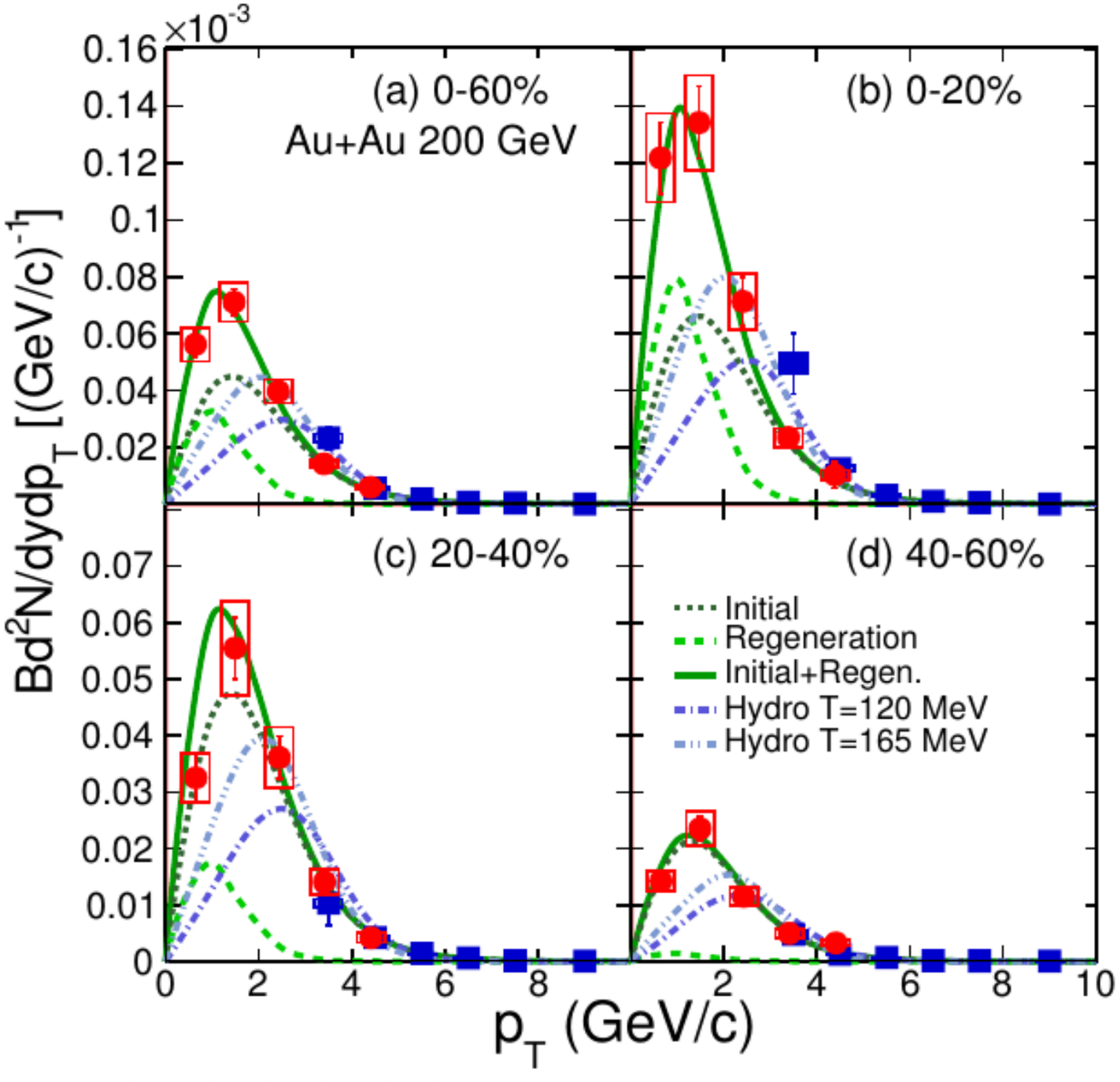
Model based extraction using PYTHIA





- ✓ Extracted from near side J/ψ-h correlation
- ✓ B-hadron feed-down contribution of 10-25% at 4-12 GeV/c
- ✓ Result consistent with FONLL+CEM calculation

J/ψ in Au+Au 200 GeV - comparison to models



- ✓ ***Viscous hydrodynamics***
- prediction for two J/ψ decoupling temperatures: T = 120 MeV and T = 165 MeV

Fails to describe the low-p_T J/ψ yield (< 2 GeV/c) and J/ψ elliptic flow at p_T > 2 GeV/c

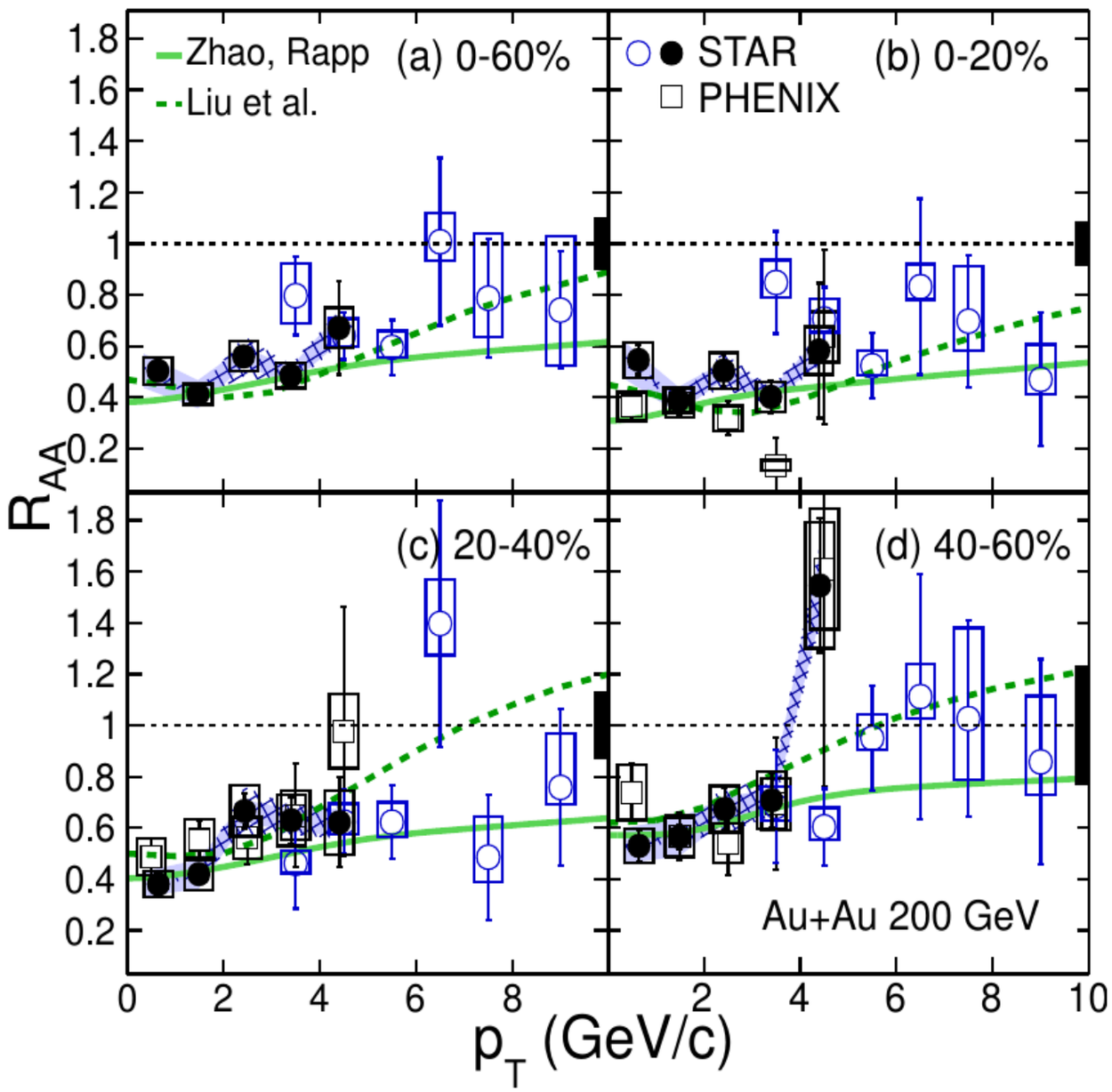
- ✓ ***Liu et. al.***
- J/ψ suppression due to color screening + statistical regeneration + B-meson feed-down + formation-time effects

Describes the p_T spectrum

Hydro: U. W. Heinz and C. Shen (2011), private communication
Liu et. all: Y. Liu,Z. Qu, N. Xu, and P. Zhuang, Phys. Lett. B 678 (2009) 72

STAR high-p_T : Phys. Lett. B 722 (2013) 55
STAR low-p_T : arxiv:1310.3563

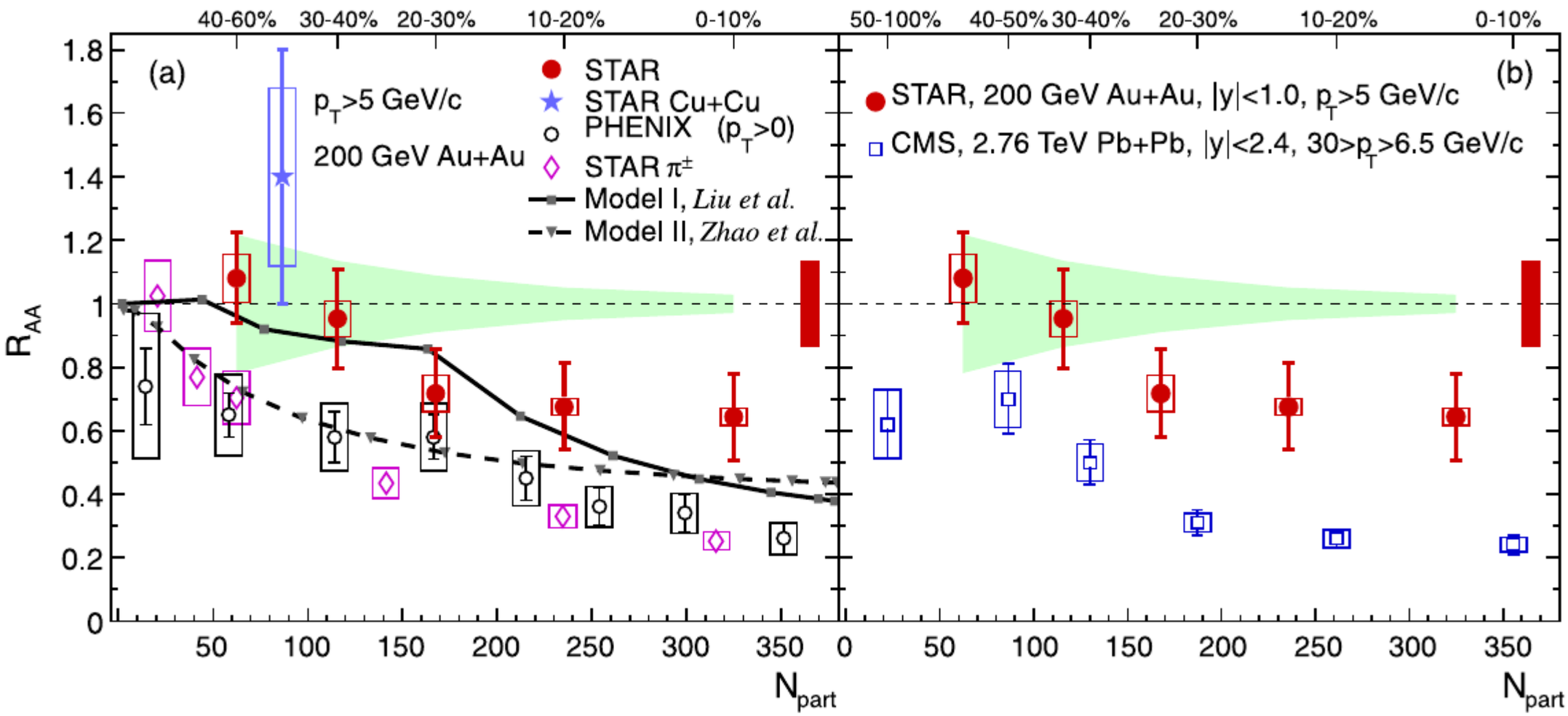
J/ψ R_{AA} vs p_T in Au+Au collisions at 200 GeV



- ✓ J/ψ suppression decreases with increasing p_T across the centrality range
- ✓ Strong suppression at low p_T (< 3 GeV/c) for all centralities
- ✓ At high-p_T:
  - suppression for central collisions
  - R_{AA} consistent with unity in (semi-)peripheral collisions
- ✓ Data agrees with theoretical calculations
  - color screening + statistical regeneration
    - Zhao et. al: + formation-time effect and B-hadron feed-down

Y.Liu et al., Phys. Lett. B, 678 (2009) 72
Zhao, Rapp, Phys. Rev. C 82 (2010) 064905
PHENIX: Phys. Rev. Lett. 98 (2007) 232301
STAR high-p_T : Phys. Lett. B 722 (2013) 55
STAR low-p_T : arxiv:1310.3563

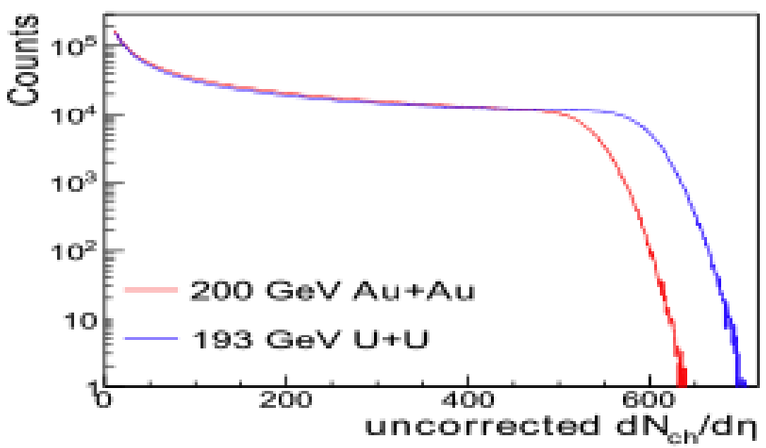
J/ψ R_{AA} vs N_{part} in Au+Au collisions at 200 GeV

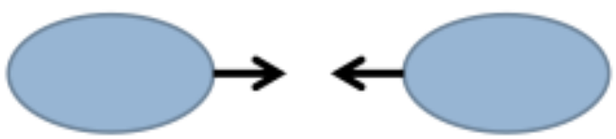


- ✓ Higher R_{AA} for STAR than CMS for all centralities

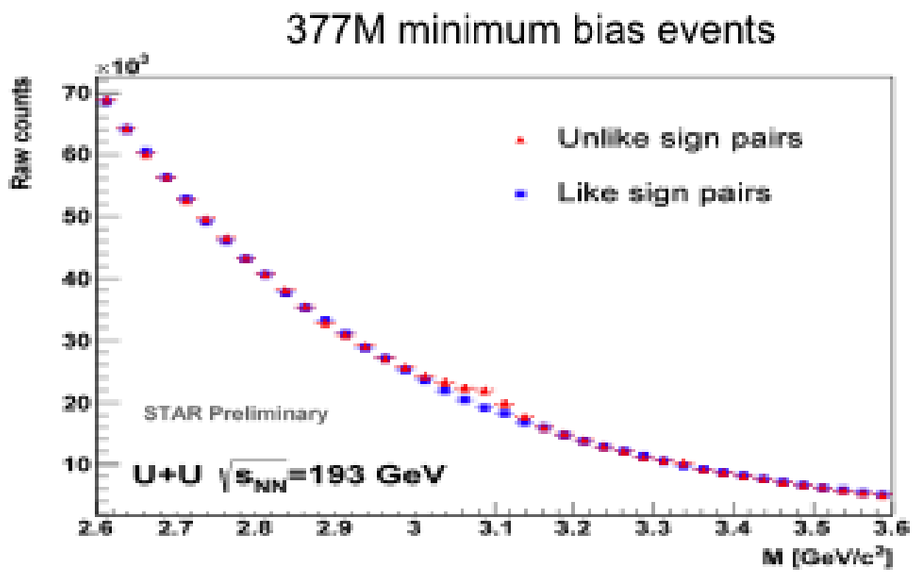
J/ψ in U+U collisions at 193 GeV

- ✓ Non- spherical nucleus - higher initial energy density

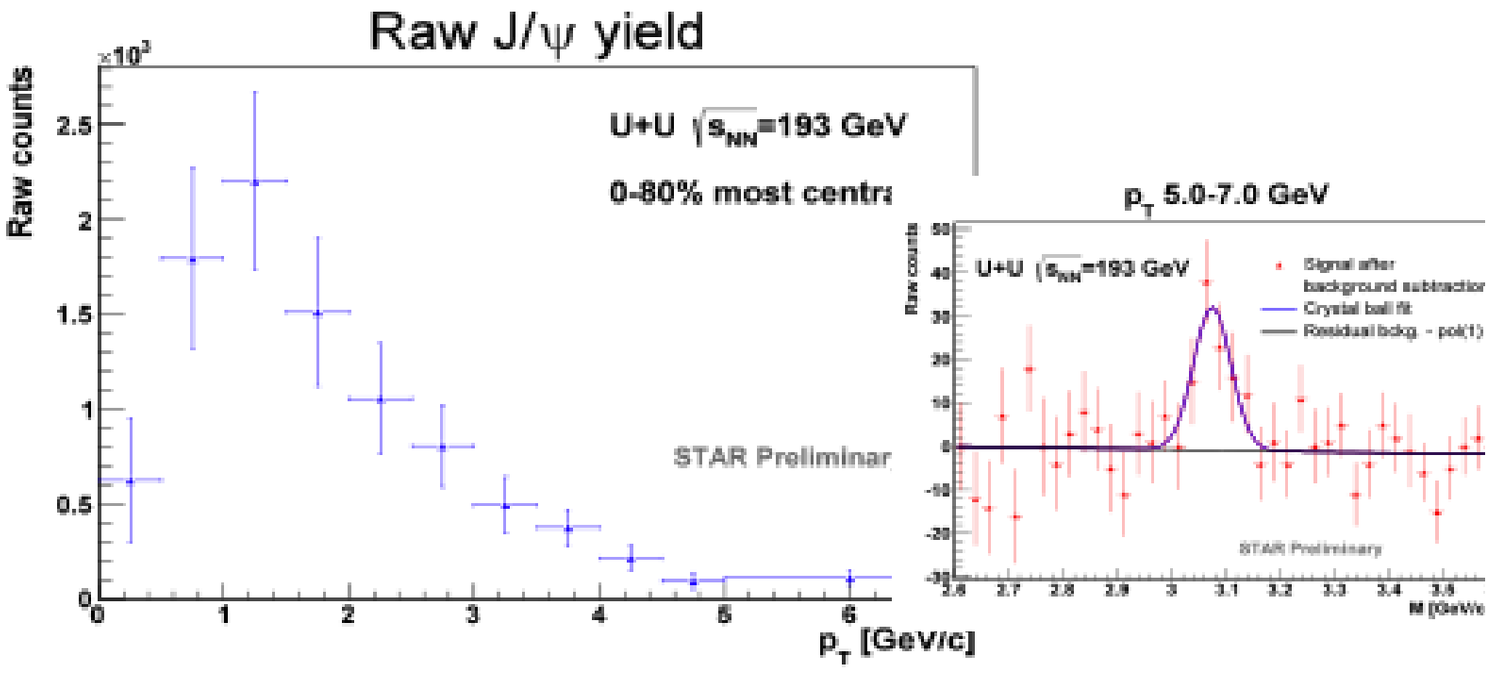




Tip-to-tip collision

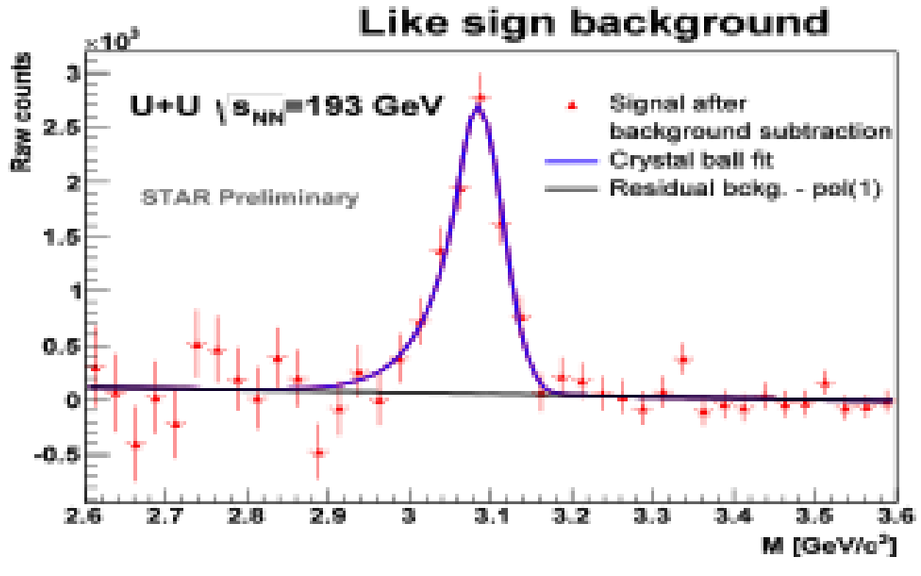


Can divide signal into 11 p_T bins up to 6 GeV/c

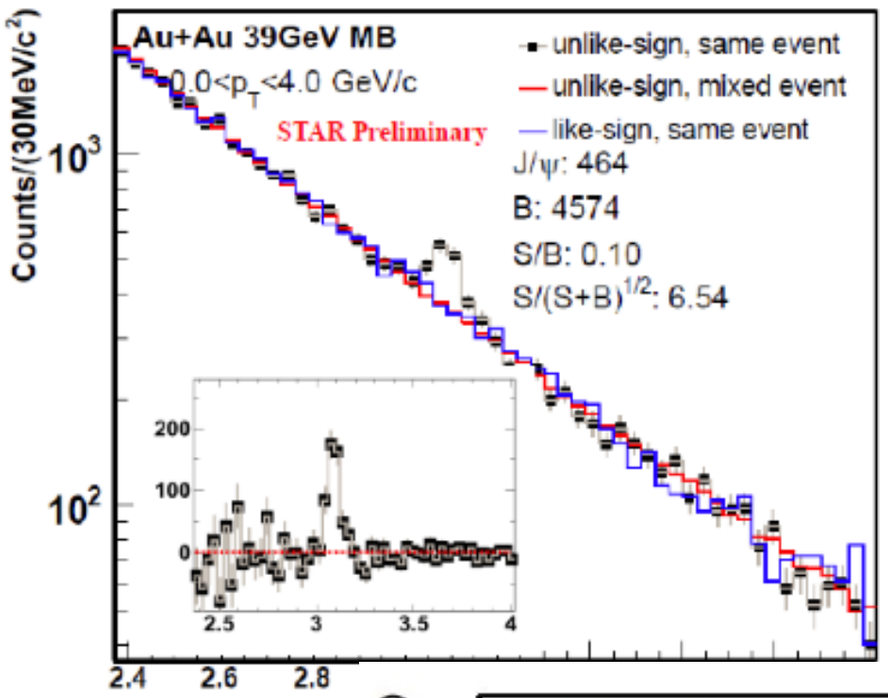


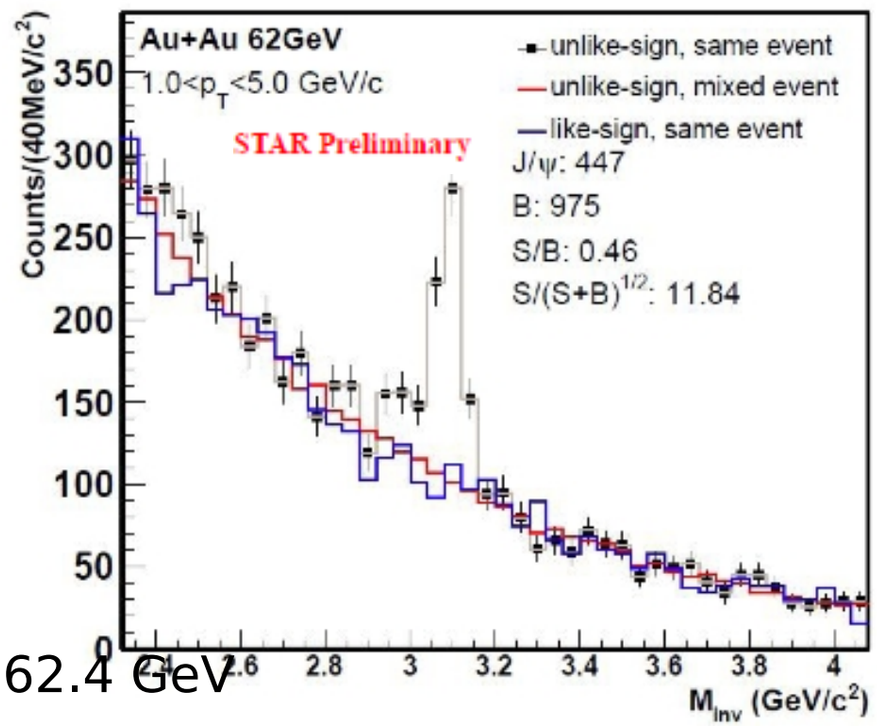
S = 9440 ± 640 in (2.9-3.2) GeV/c^2

significance ~ 13

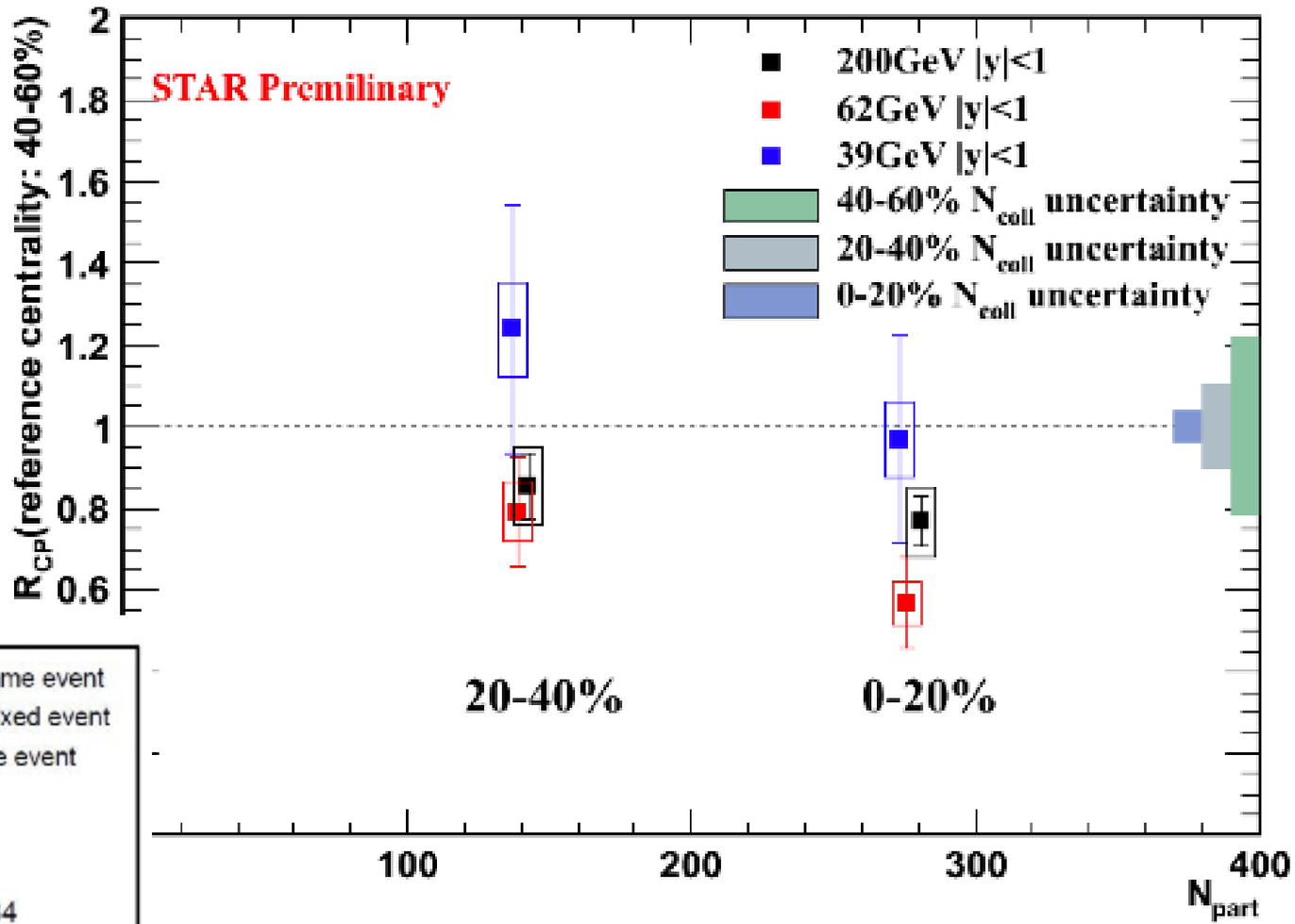


Energy dependence of J/ψ R_{CP}





62.4 GeV



Significant suppression at 200 and 62.4 GeV in central collisions