# The latest STAR results on quarkonium production

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*Czech Technical University in Prague*

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european social fund in the czech republic
EUROPEAN UNION
MINISTRY OF EDUCATION, YOUTH AND SPORTS
OP Education for Competitiveness
INVESTMENTS IN EDUCATION DEVELOPMENT

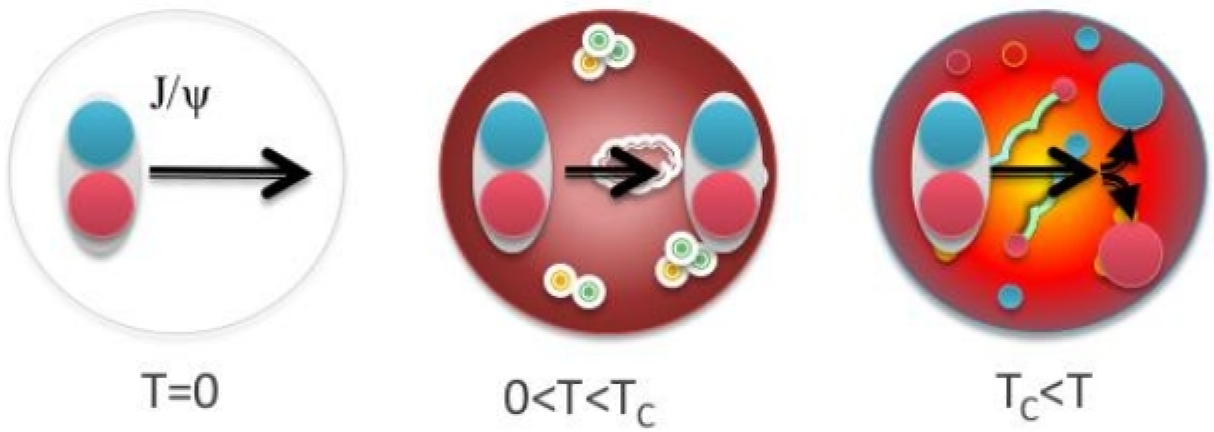
# Quarkonia at RHIC - Motivation

<u>Charmonia</u>: $J/\psi$, $\psi(2S)$, $\chi_C$ <u>Bottomonia</u>: $\Upsilon(1S)$, $\Upsilon(2S)$, $\Upsilon(3S)$, $\chi_B$

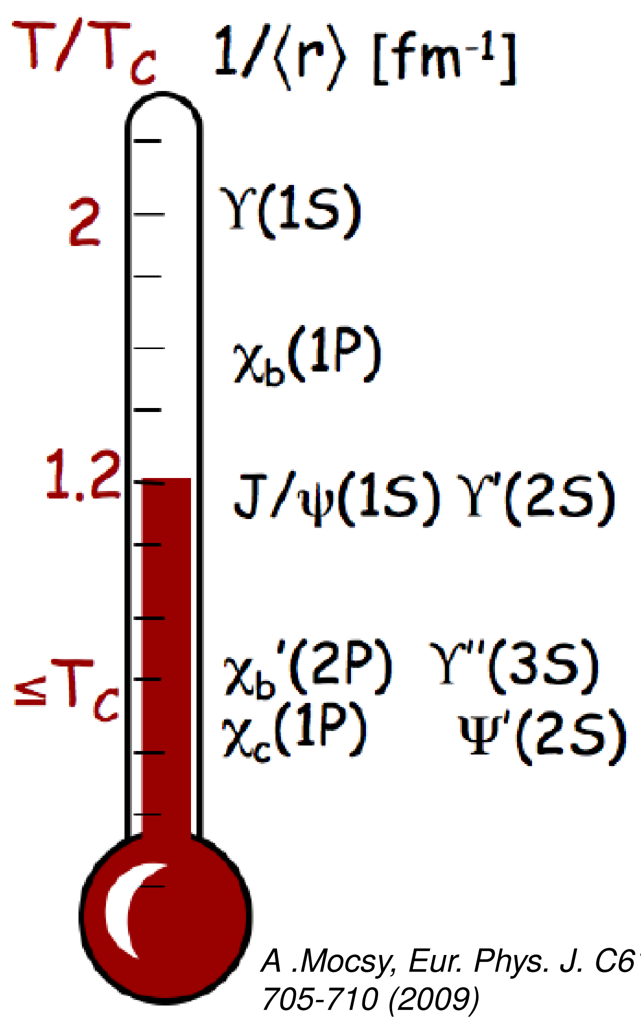
## First ideas:

- ✓ **color screening** - quarkonium suppression in QGP in heavy-ion collisions

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




- ✓ **QGP thermometer** - suppression of different states is determined by T and their binding energies




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

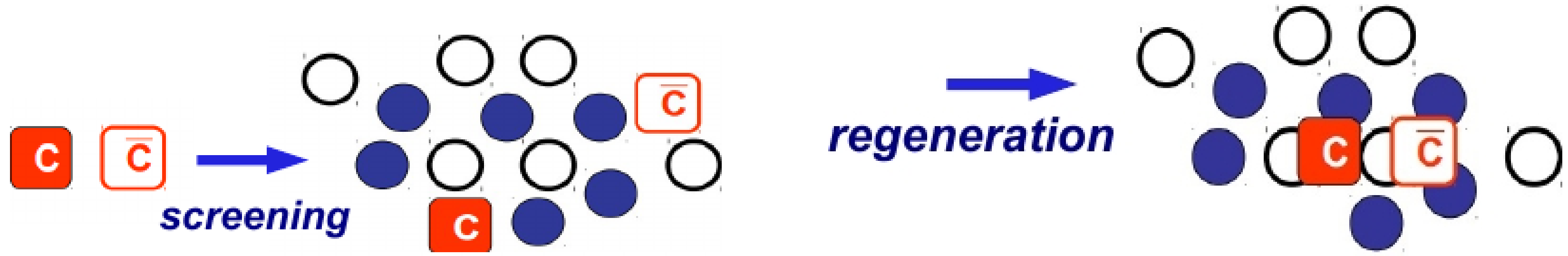
*<u>Screening radius:</u>*

$r_D(T) \propto 1/T$

# Quarkonia – other effects

## *But there are additional complications:*

- Still unclear ***production mechanism*** in elementary collisions
- ***Feed-down:***
  - prompt: *direct* J/ψ (~*60%*) + *feed down* from ψ(2S) and $\chi_C$ (~40%); non-prompt: B-mesons feed-down (up to 25% at 12 GeV/c, Phys. Lett. B722 (2013) 55)
  - ~*50%* of ϒ(1S) originates from excited states feed-down (Phys. Rev. Lett. 84 (2000) 2094)
- ***Cold Nuclear Matter (CNM) effects*** - nuclear (anti-)shadowing, Cronin effect, nuclear absorption, …
- Other ***Hot Nuclear Matter effects*** - regeneration, …

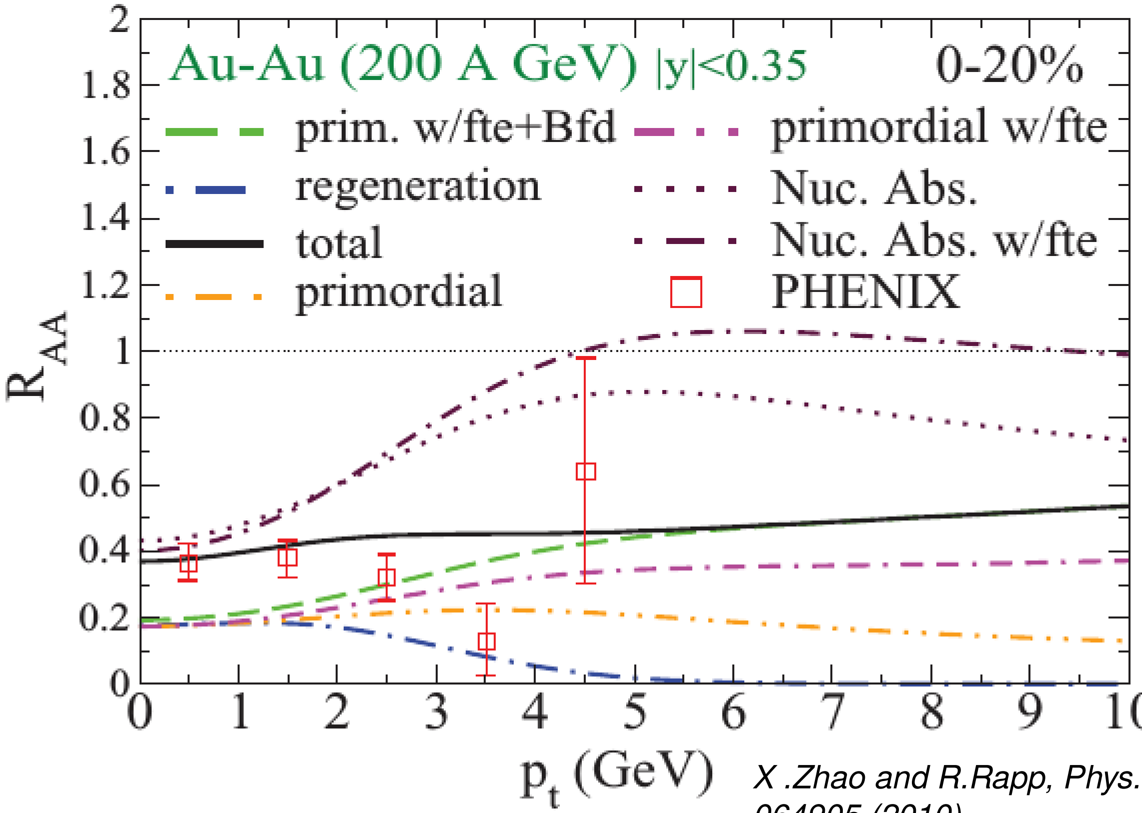


# Strategy

- ***High-$p_T$ J/ψ and ϒ – cleaner probes***

  - High-$p_T$ J/ψ - almost not affected by CNM effects and recombination
  - ϒ - negligible co-mover absorption and recombination

    at RHIC: $\sigma_{cc}$ ~800μb >> $\sigma_{bb}$ ~(1-2)μb




*X .Zhao and R.Rapp, Phys. Rev. C82, 064905 (2010)*

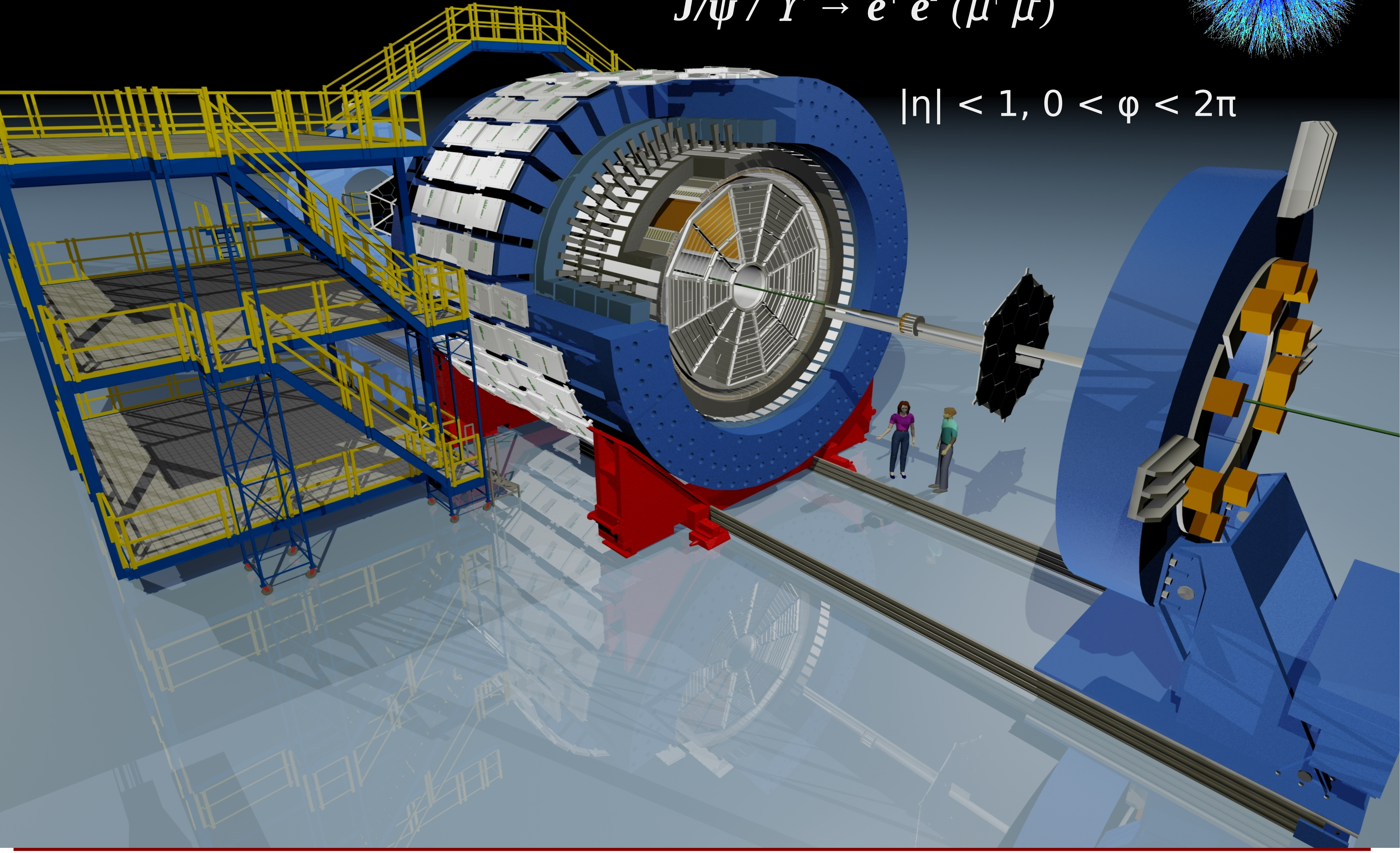
  - Energy dependence of quarkonium production - varying relative contributions

$$R_{AA} = \frac{1}{\langle N_{coll} \rangle} \frac{dN/dy^{A+A}}{dN/dy^{p+p}}$$

- ***Measure quarkonia at different colliding systems and energies, in different kinematic regions***

# Quarkonia in the STAR Experiment

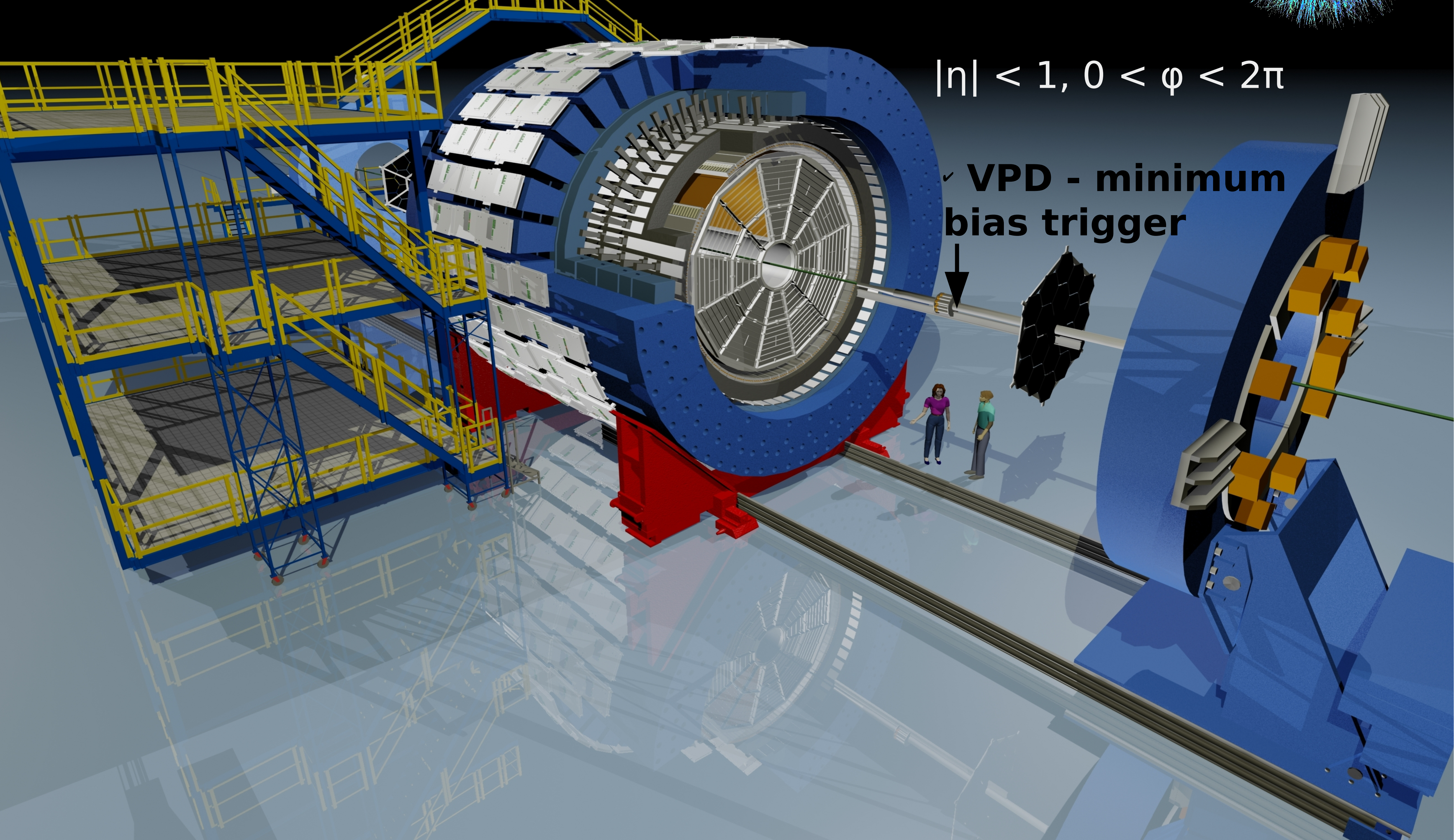
$J/\psi \,/\, \Upsilon \rightarrow e^{+} e^{-} \; (\mu^{+} \mu^{-})$



$|\eta| < 1, \; 0 < \varphi < 2\pi$

# Quarkonia in the STAR Experiment

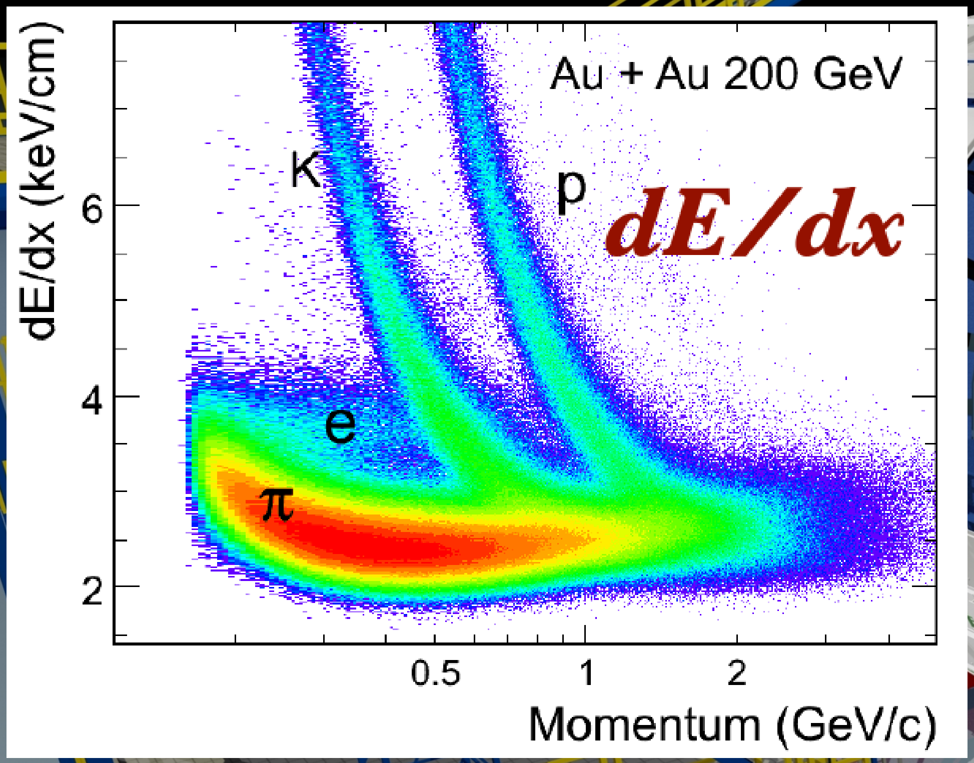
$J/\psi \,/\, \Upsilon \rightarrow e^+ e^- \; (\mu^+ \mu^-)$



# Quarkonia in the STAR Experiment

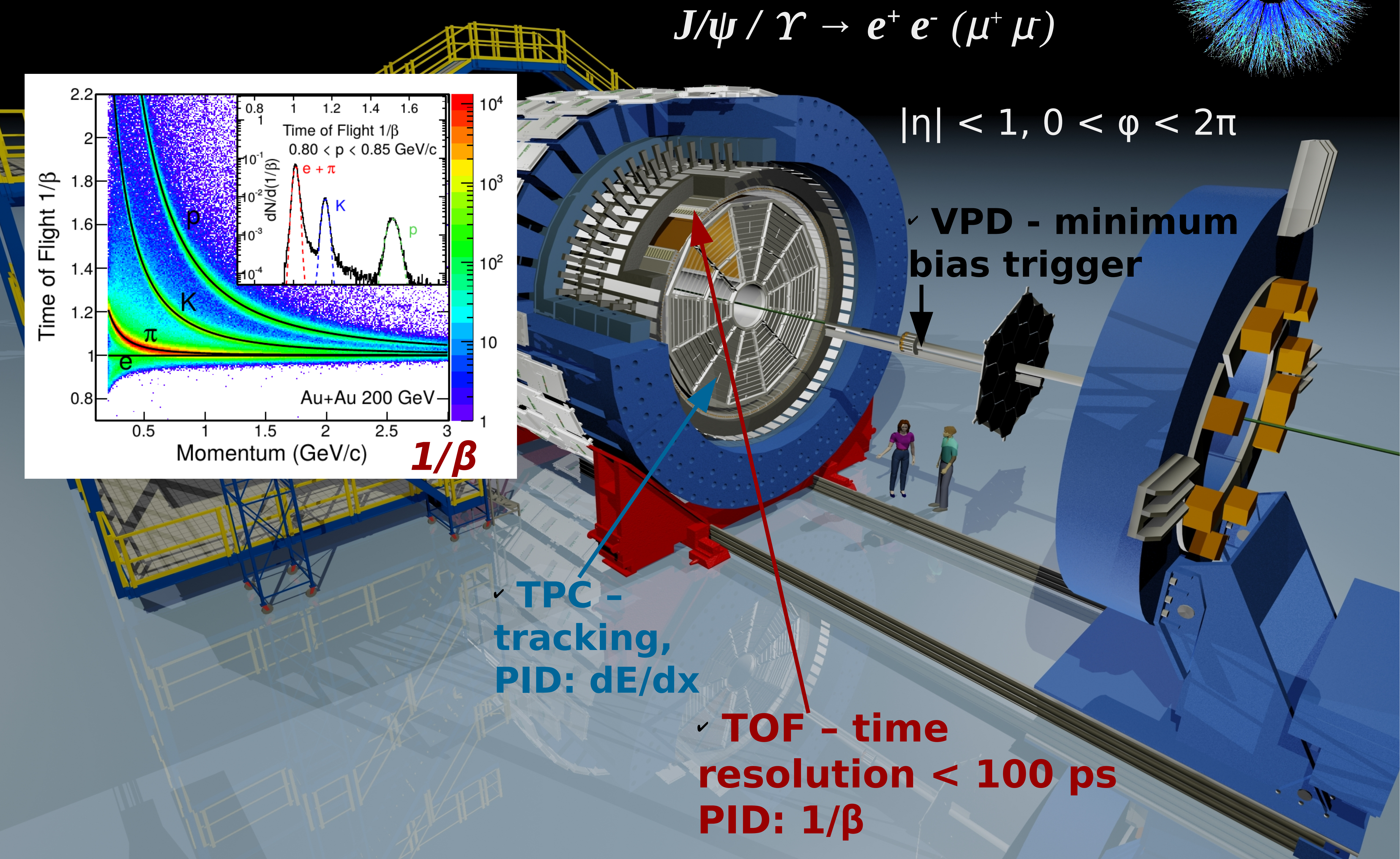
$J/\psi$ / $\Upsilon \rightarrow e^+ e^-$ ($\mu^+ \mu^-$)

$|\eta| < 1$, $0 < \varphi < 2\pi$




- VPD - minimum bias trigger
- TPC – tracking, PID: dE/dx

# Quarkonia in the STAR Experiment



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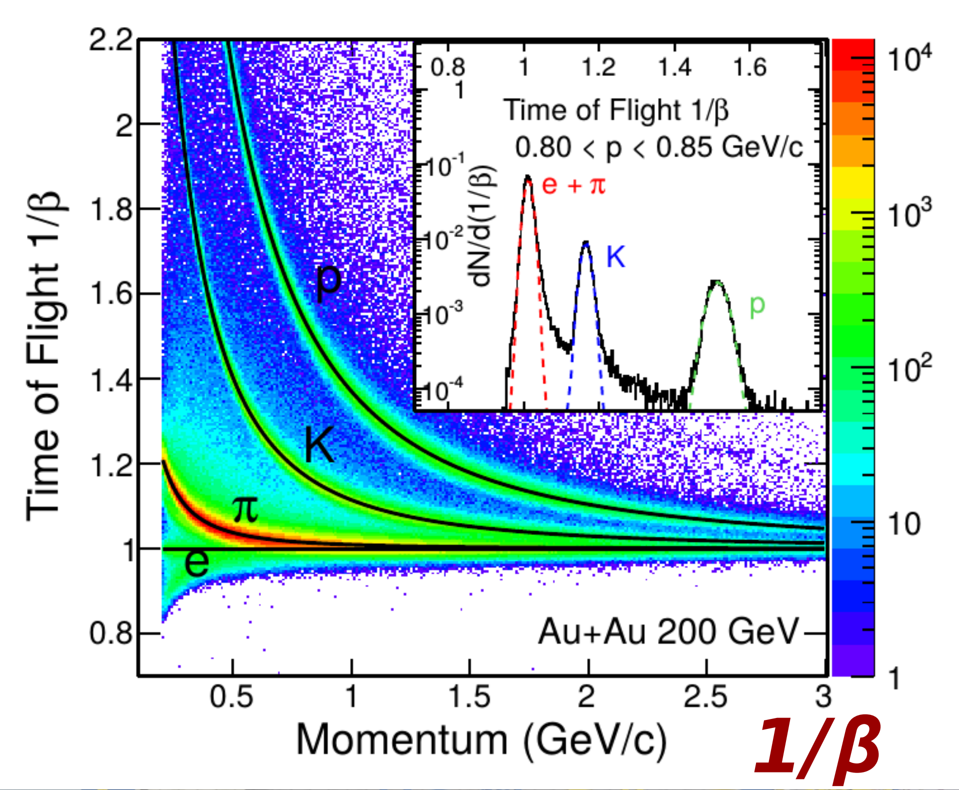
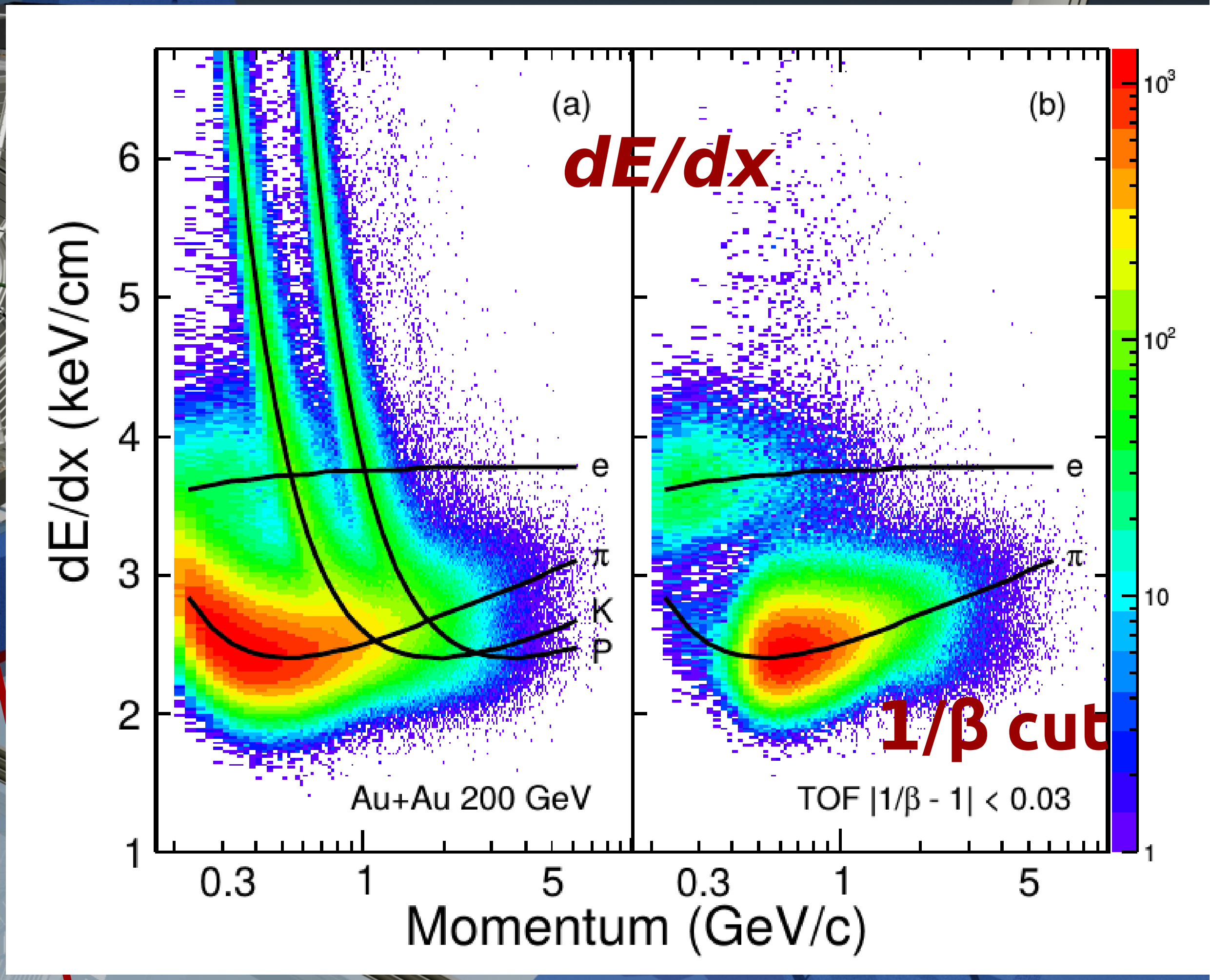


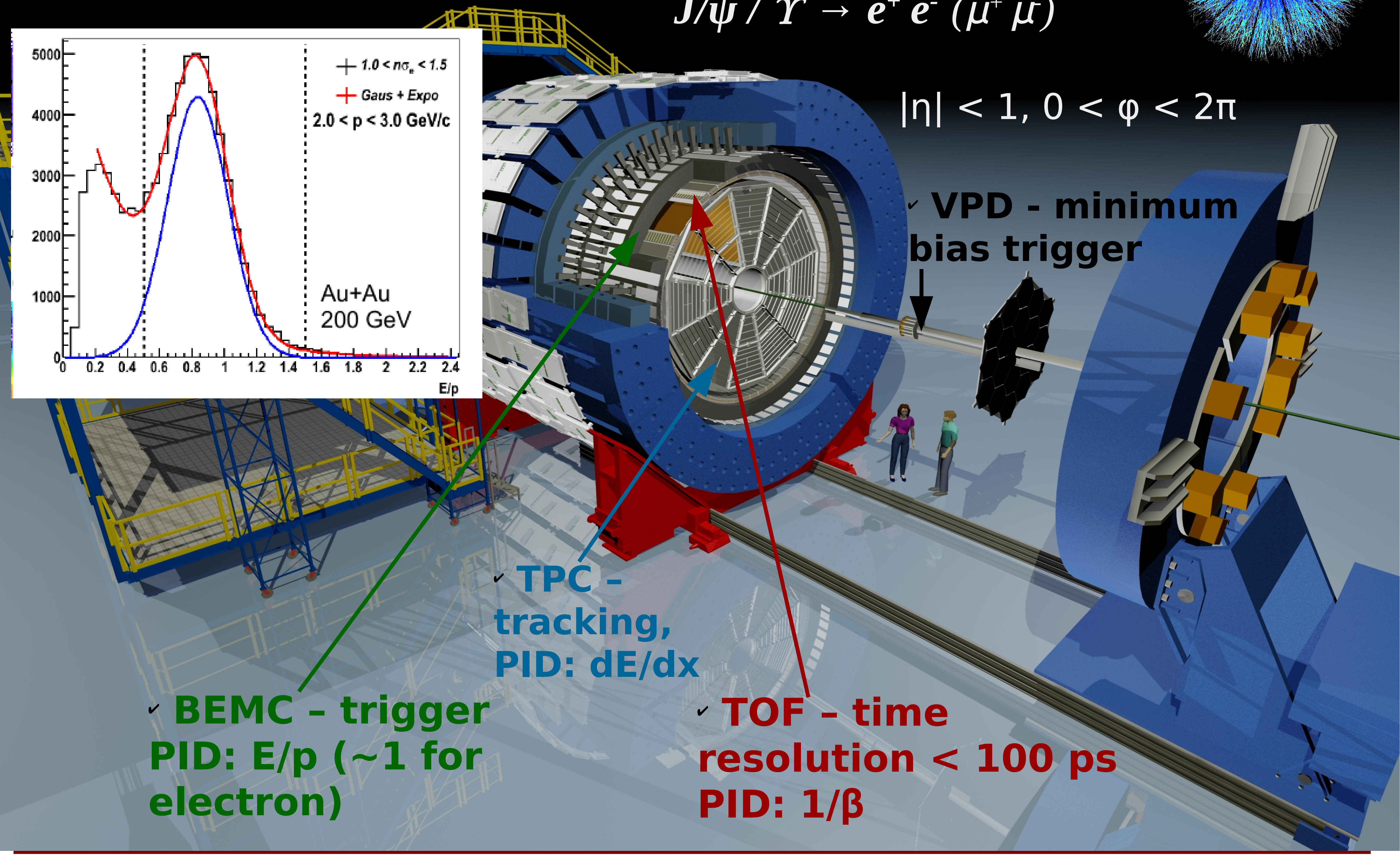




- **TPC – tracking, PID: dE/dx**
- **TOF – time resolution < 100 ps PID: 1/β**

# Quarkonia in the STAR Experiment

$J/\psi$ / $\Upsilon \rightarrow e^+ e^-$ ($\mu^+ \mu^-$)

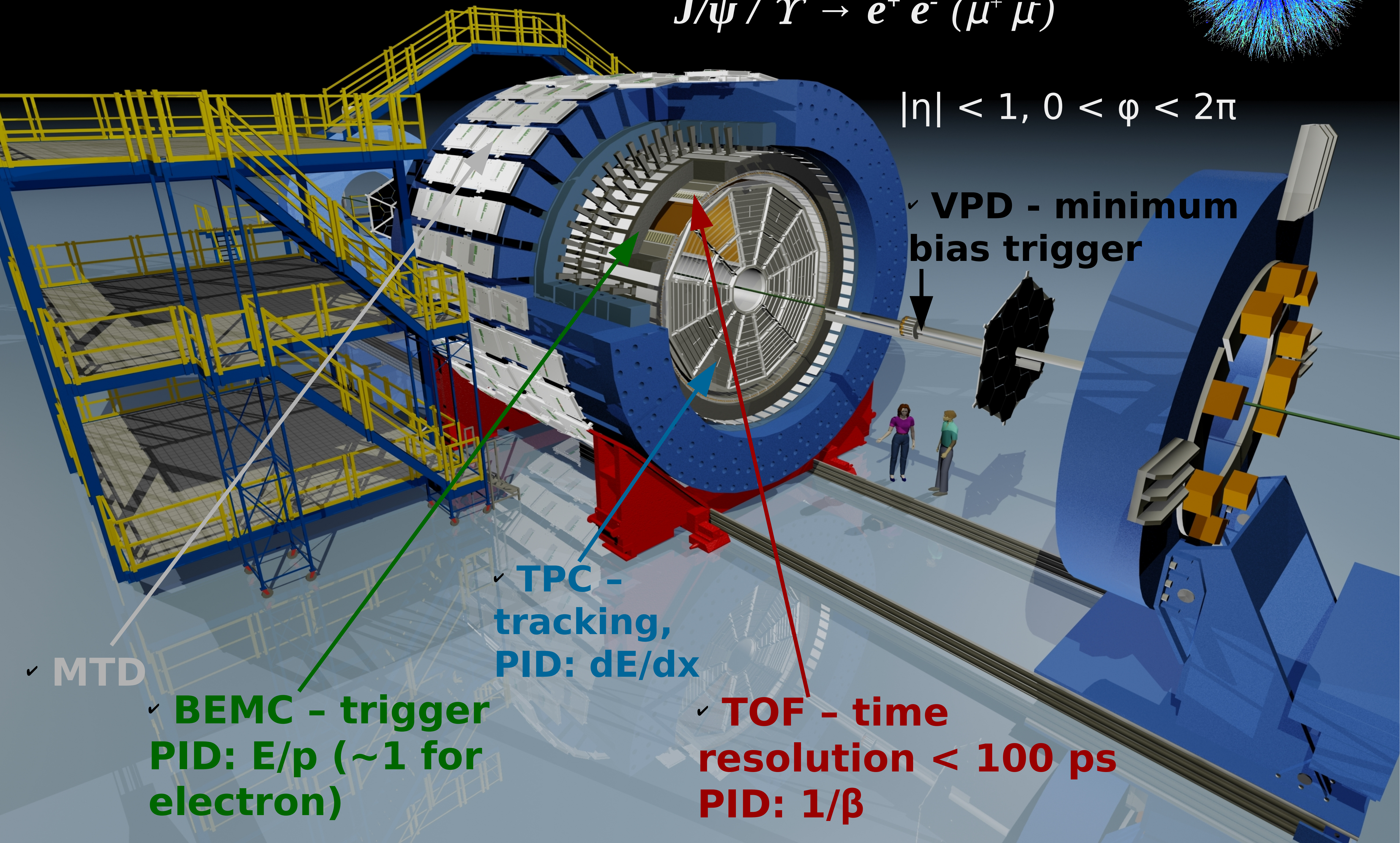
$|\eta| < 1$, $0 < \varphi < 2\pi$




- VPD - minimum bias trigger
- TPC – tracking, PID: dE/dx
- BEMC – trigger PID: E/p (~1 for electron)
- TOF – time resolution < 100 ps PID: 1/β

# Quarkonia in the STAR Experiment

$J/\psi\ /\ \Upsilon \rightarrow e^+ e^-\ (\mu^+ \mu^-)$



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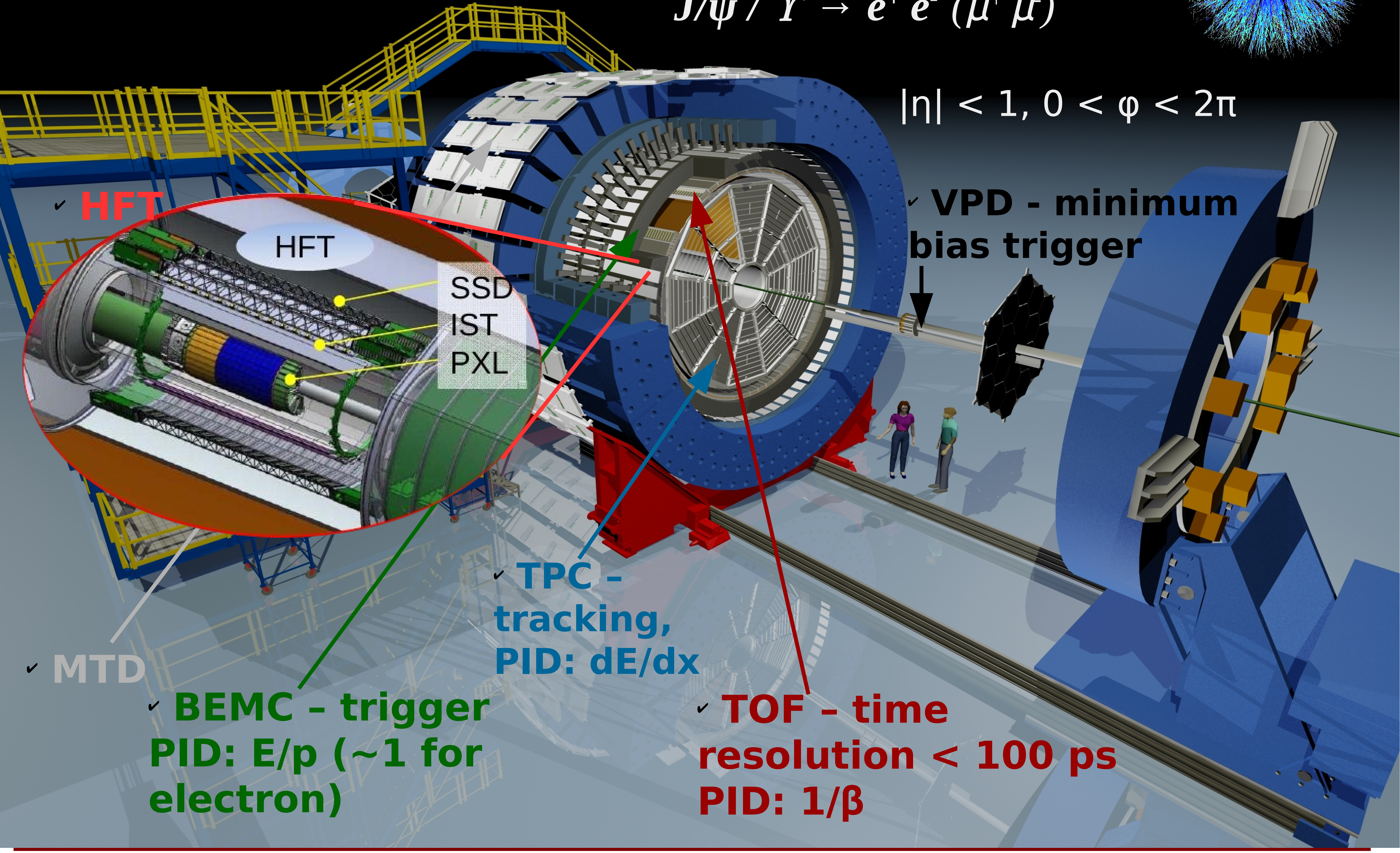
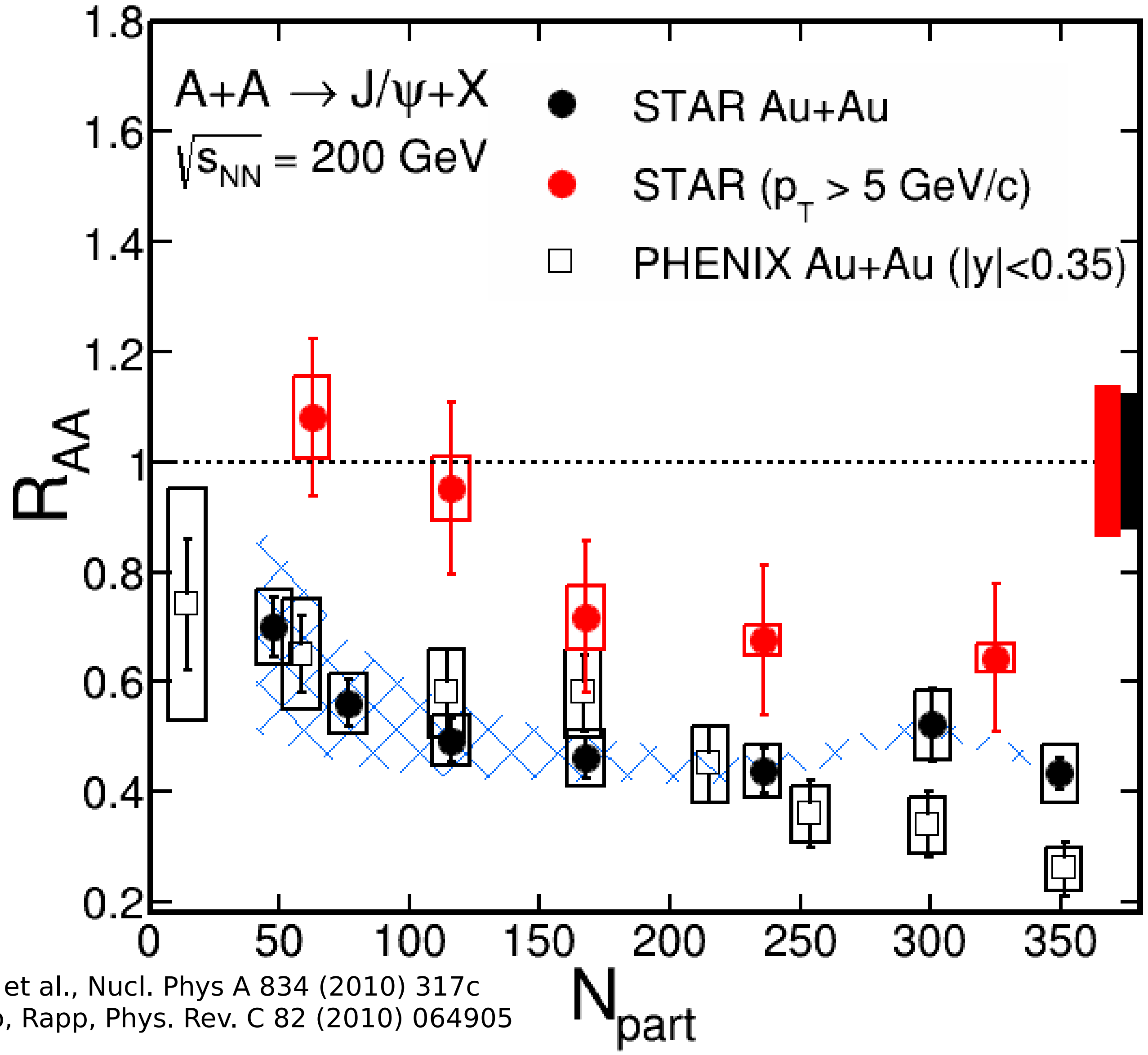


# J/ψ $R_{AA}$ in Au+Au 200 GeV



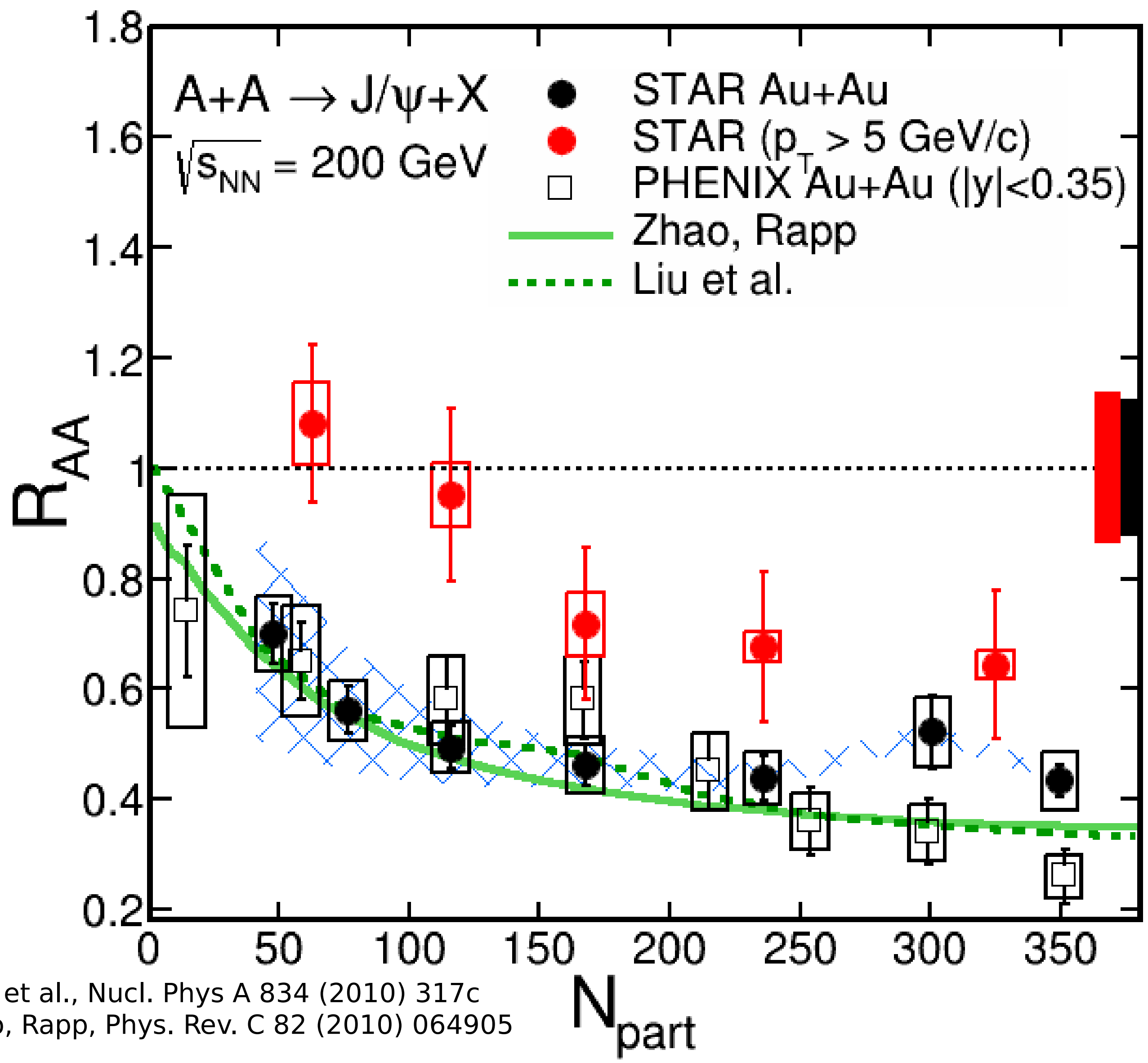

Y.Liu et al., Nucl. Phys A 834 (2010) 317c
Zhao, Rapp, Phys. Rev. C 82 (2010) 064905

STAR high-$p_T$ : Phys. Lett. B 722 (2013) 55
STAR low-$p_T$ : Phys. Rev. C 90 (2014) 24906

- ✓ Suppression increases with collision centrality
- ✓ High-$p_T$ $R_{AA}$ is systematically higher
  - J/ψ at high-$p_T$ almost not affected by CNM effects and recombination *X .Zhao and R.Rapp, Phys. Rev. C82, 064905 (2010)*
- ✓ High-$p_T$ J/ψ suppressed in central collisions
  - → May indicate QGP effects

$$R_{AA} = \frac{1}{\langle N_{coll} \rangle} \frac{dN/dy^{A+A}}{dN/dy^{p+p}}$$

# $J/\psi$ $R_{AA}$ in Au+Au 200 GeV

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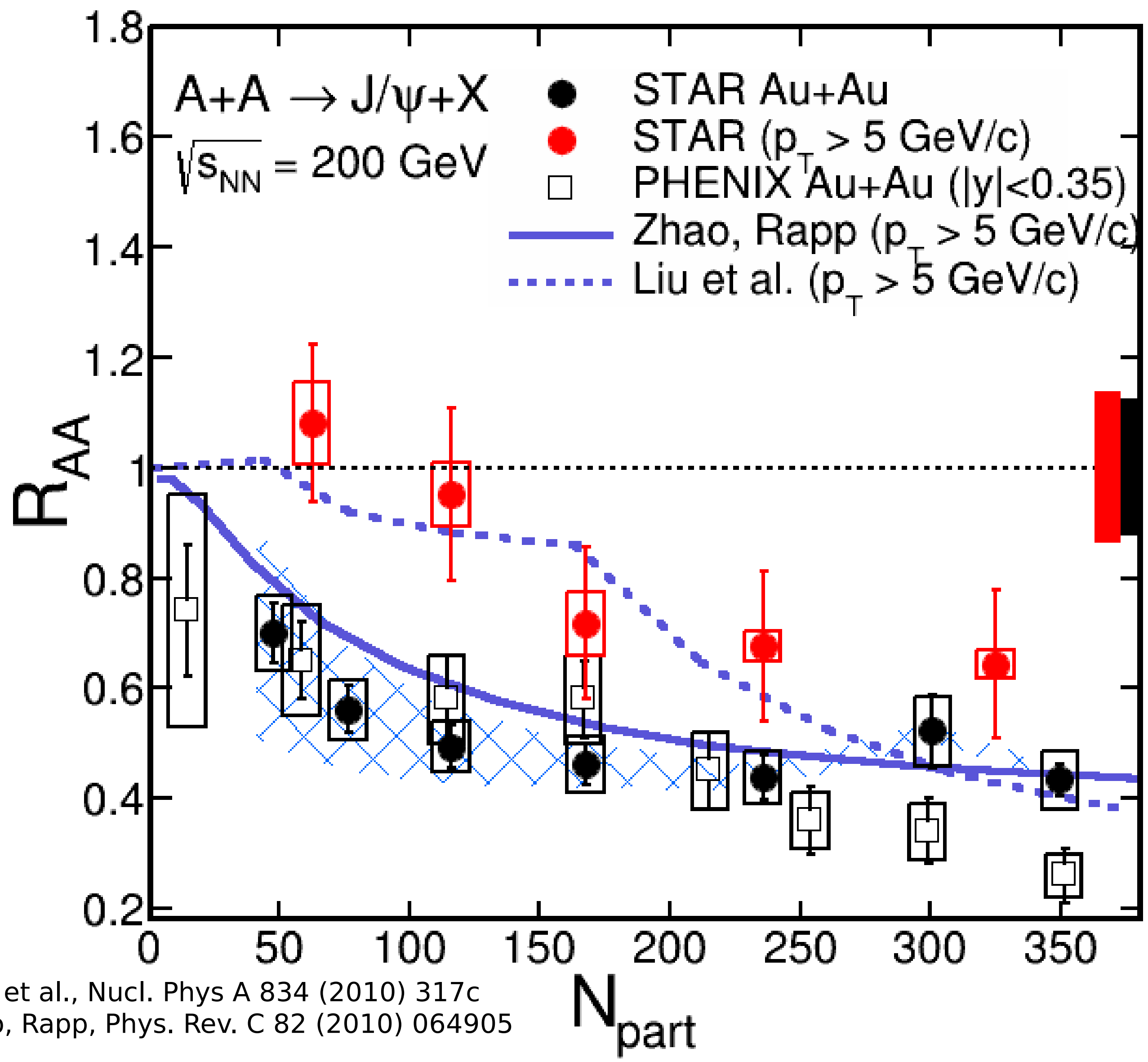
- ✓ Suppression increases with collision centrality
- ✓ High-$p_T$ $R_{AA}$ is systematically higher
- ➔ High-$p_T$ $J/\psi$ suppressed in central collisions

- Models of *Zhao et al.* and *Liu et al.*: direct $J/\psi$ production with color screening + recombination

  *Zhao et al.:* + $J/\psi$ formation time effect and B-meson feed-down

➔ Both models *(Zhao et al., Liu et al.)* describe the data well at low $p_T$

# $J/\psi$ $R_{AA}$ in Au+Au 200 GeV

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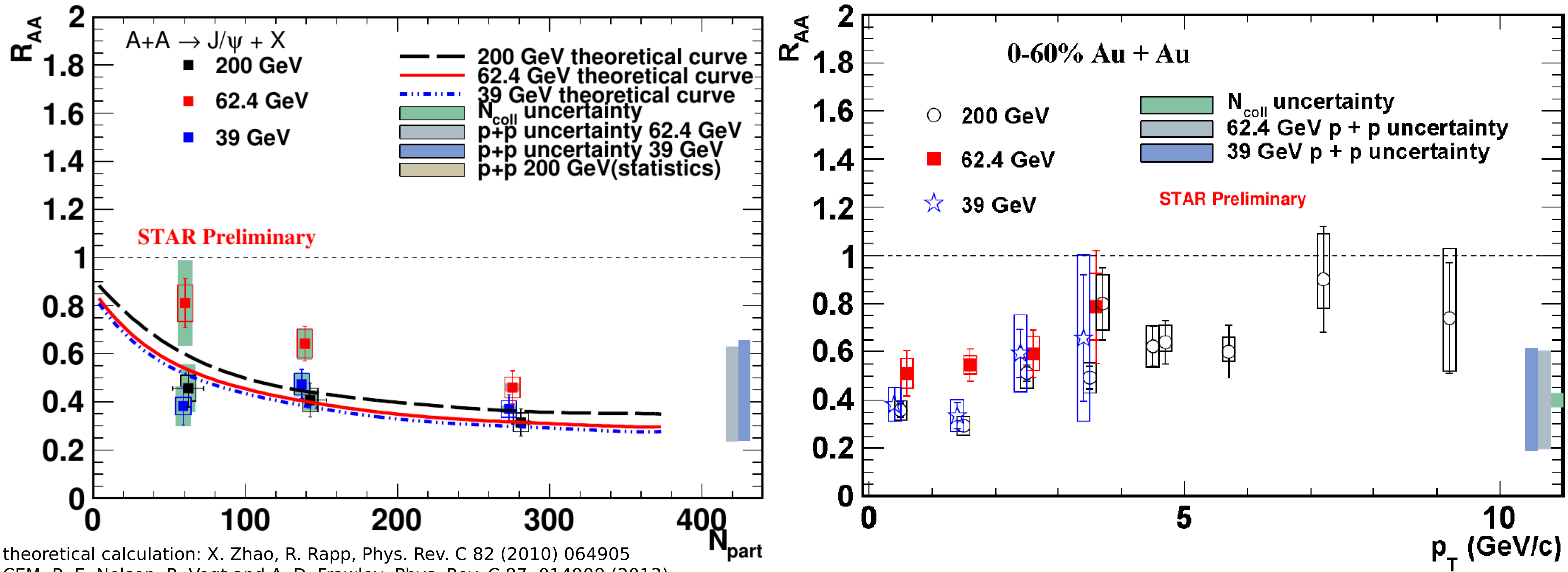
- <u>Models of *Zhao et al.* and *Liu et al.*:</u> direct $J/\psi$ production with color screening + recombination

  *Zhao et al.:* + $J/\psi$ formation time effect and B-meson feed-down

➔ 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 $R_{AA}$

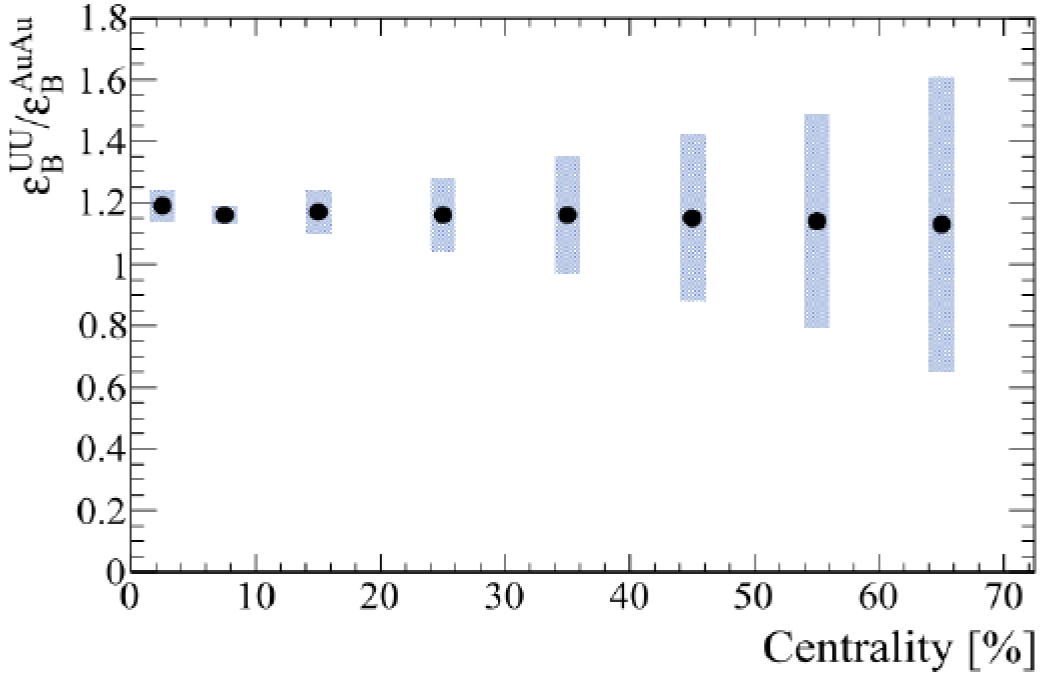



theoretical calculation: X. Zhao, R. Rapp, Phys. Rev. C 82 (2010) 064905
CEM: R. E. Nelson, R. Vogt and A. D. Frawley, Phys. Rev. C 87, 014908 (2013).

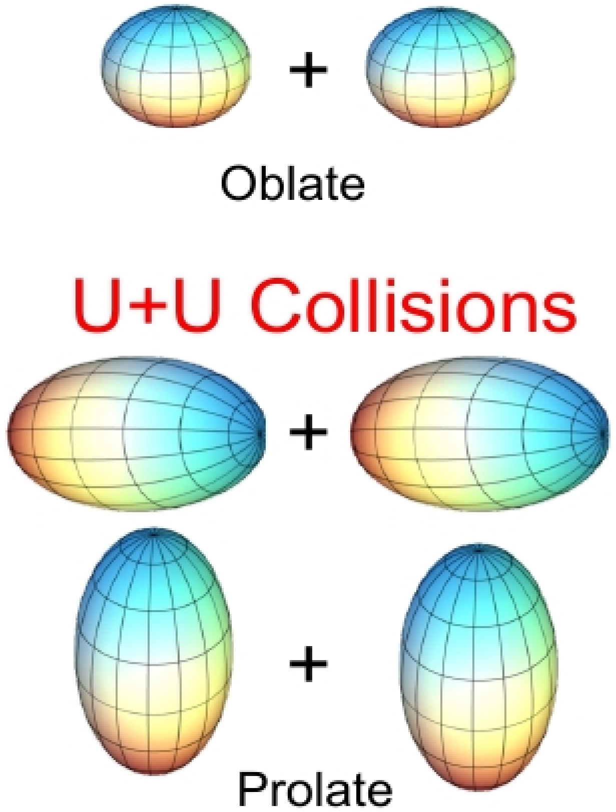
- ✓ Suppression observed for all energies: 200, 62.4 and 39 GeV, similar trend in $p_T$
  - ➔ No strong energy dependence of J/ψ $R_{AA}$ within uncertainties
- ➔ Data agrees with the prediction of the two-component model
  - *p+p reference for 62.4 and 39 GeV data from Color Evaporation Model (CEM) - large theoretical uncertainties*

# $J/\psi$ in U+U 193 GeV

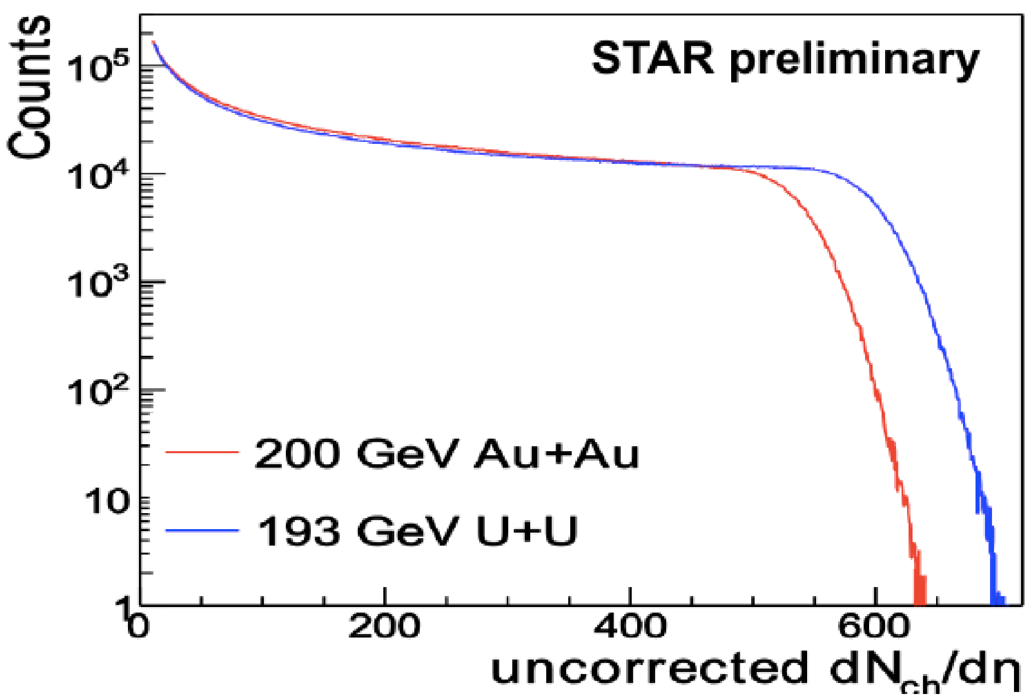
- Higher energy density can be reached in U+U collisions, at the same centrality

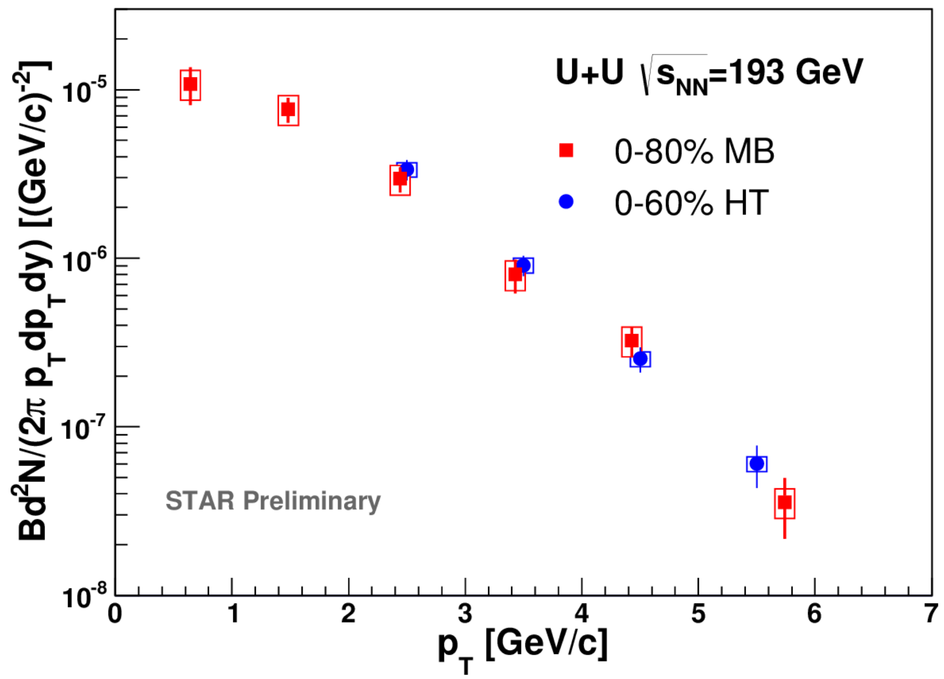



Kikola, Odyniec, Vogt, Phys. Rev. C 84, 054907

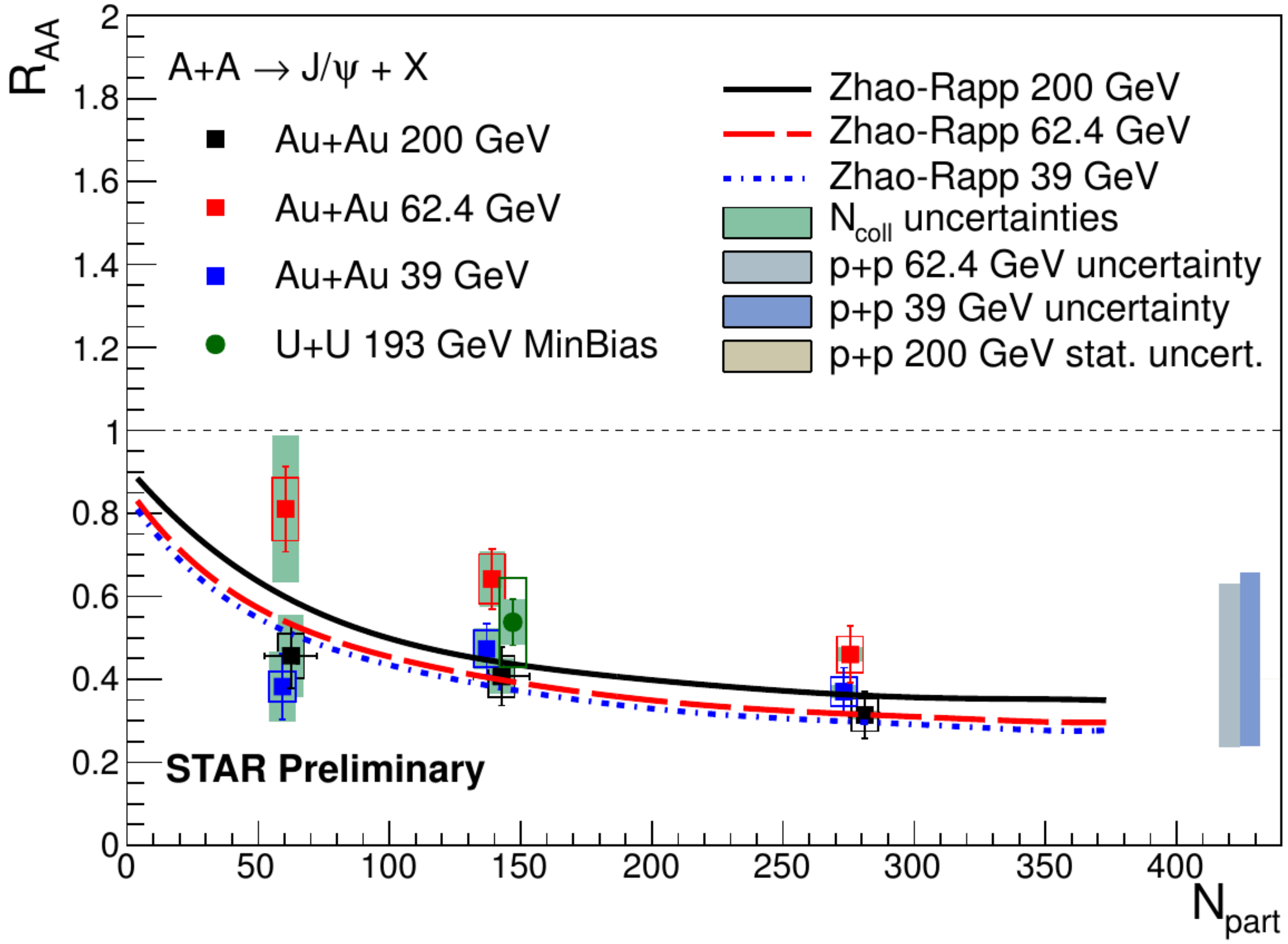



- Higher $N_{part}$



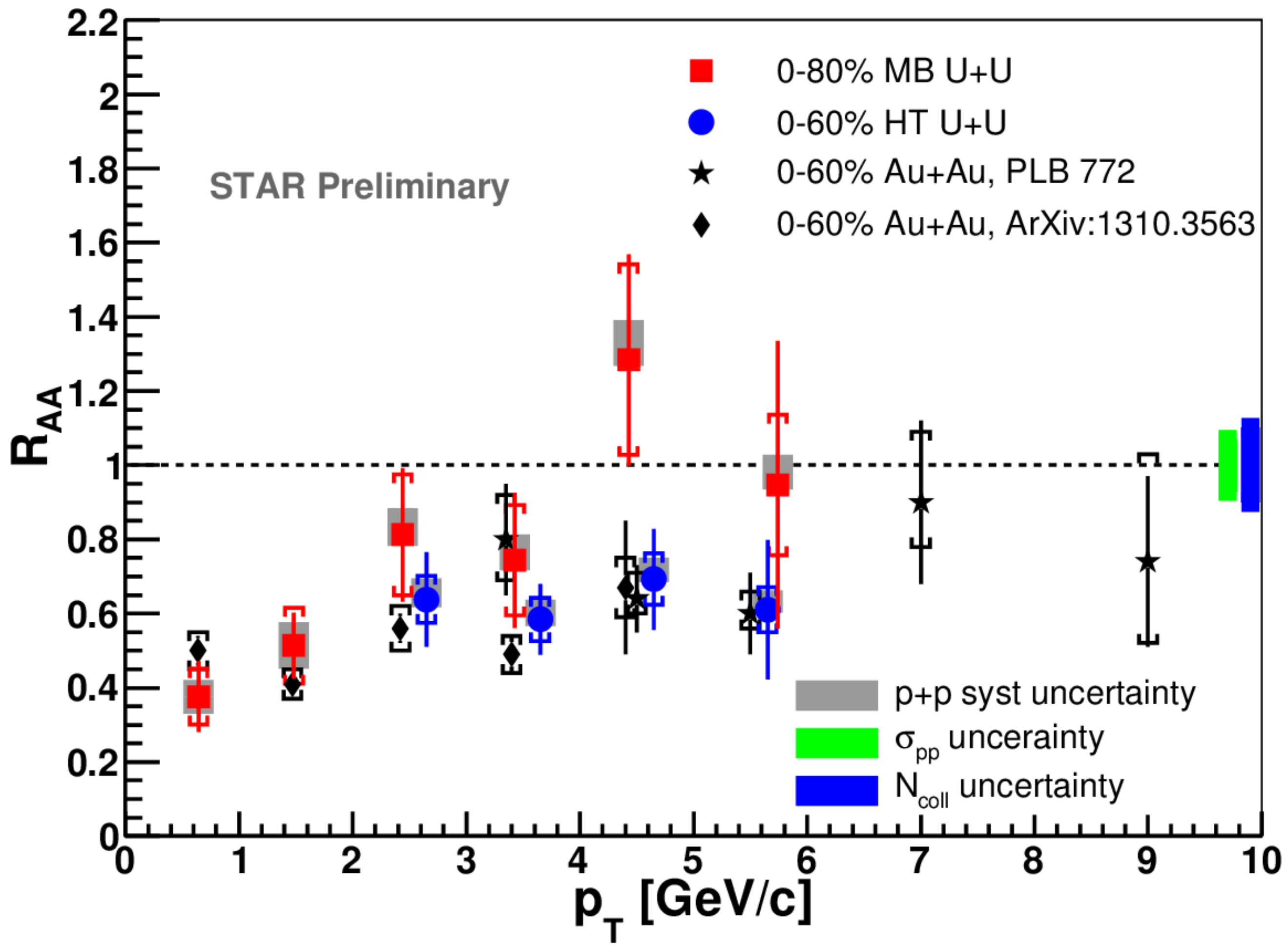



# $J/\psi$ in U+U 193 GeV

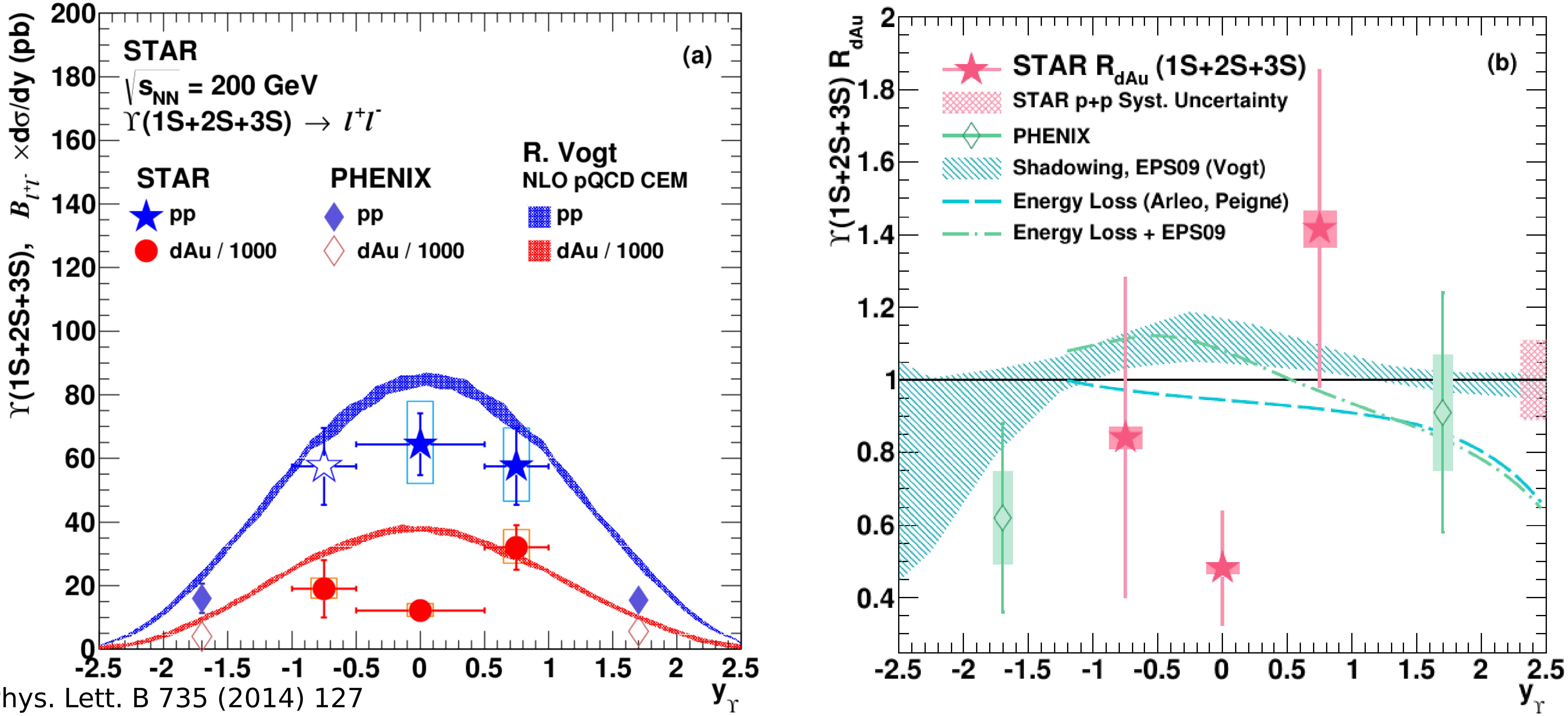



- Similar suppression pattern in U+U and Au+Au collisions, similar $p_T$ trend

*(p+p reference from 200 GeV)*



# $\Upsilon$ in d+Au 200 GeV, CNM effects

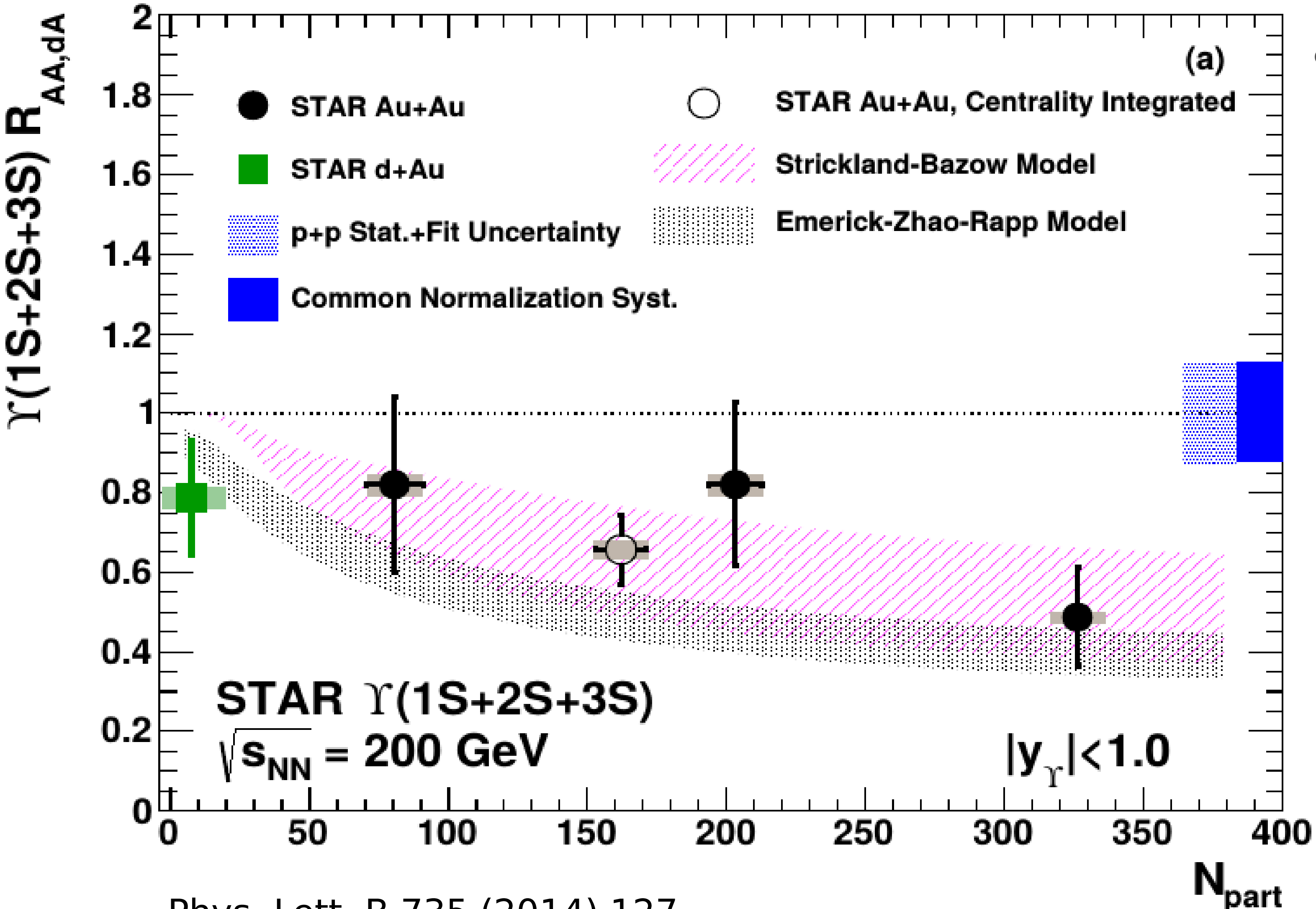



Phys. Lett. B 735 (2014) 127

- Agreement with models except y~0
  - Suppression at y~0, in addition to shadowing and initial state parton energy loss

*($\Upsilon$ - negligible co-mover absorption and recombination)*

# $\Upsilon$ $R_{AA}$ in Au+Au 200 GeV




Phys. Lett. B 735 (2014) 127

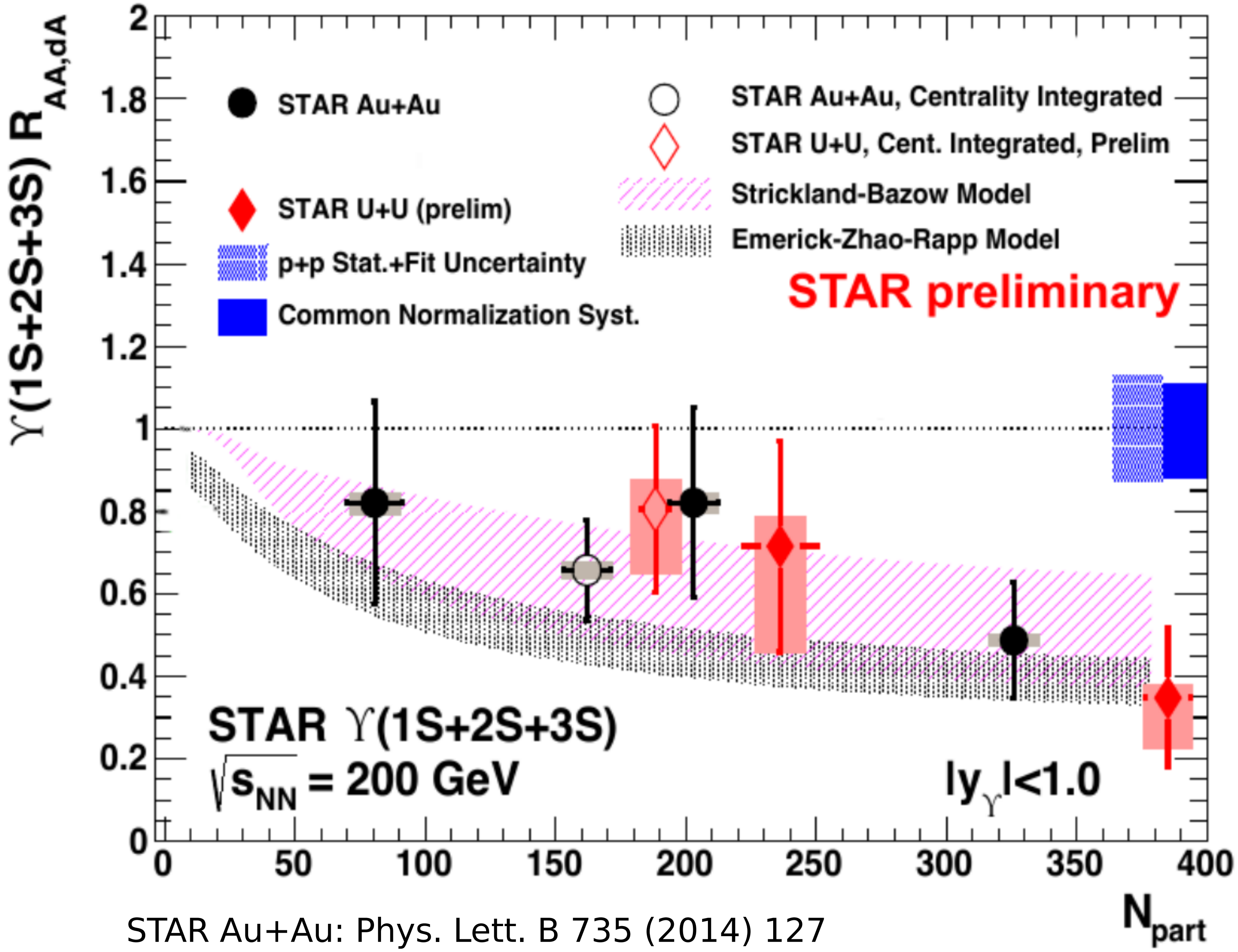
- *Strickland-Bazow Model* *(Nucl. Phys. A879, 25 (2012))*: 428 < T < 442 MeV, internal energy potential
- *Emerick-Zhao-Rapp Model* *(Eur. Phys. J A48, 72 (2012))*: CNM effects included, strong binding scenario

✓ Suppression increases with collision centrality

✓ Strong suppression in central collisions

➔ Agreement with models that include presence of QGP

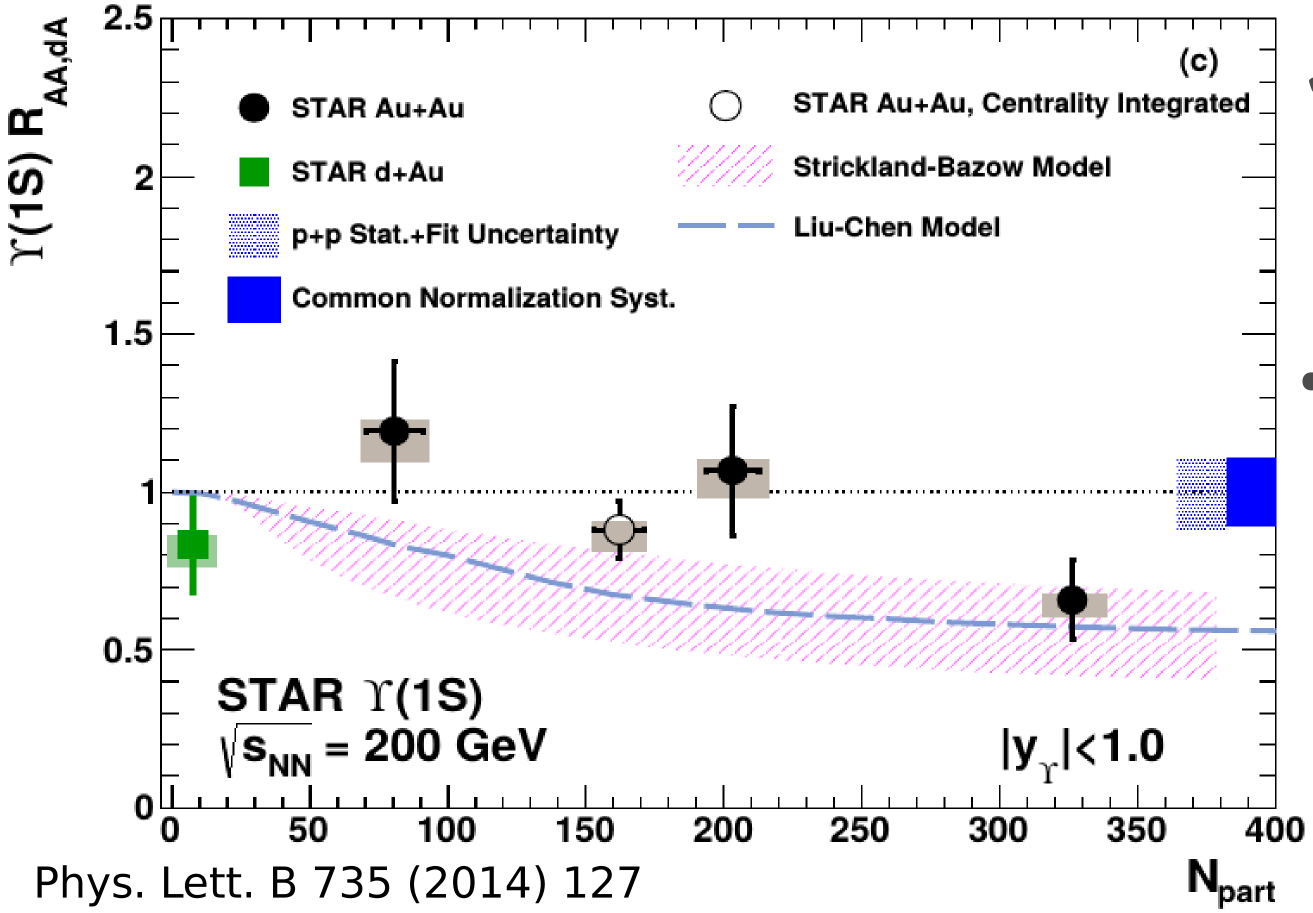
# $\Upsilon$ in U+U 193 GeV




STAR Au+Au: Phys. Lett. B 735 (2014) 127

- ✓ The same trend in Au+Au and U+U collisions

# Suppression of Υ states in Au+Au

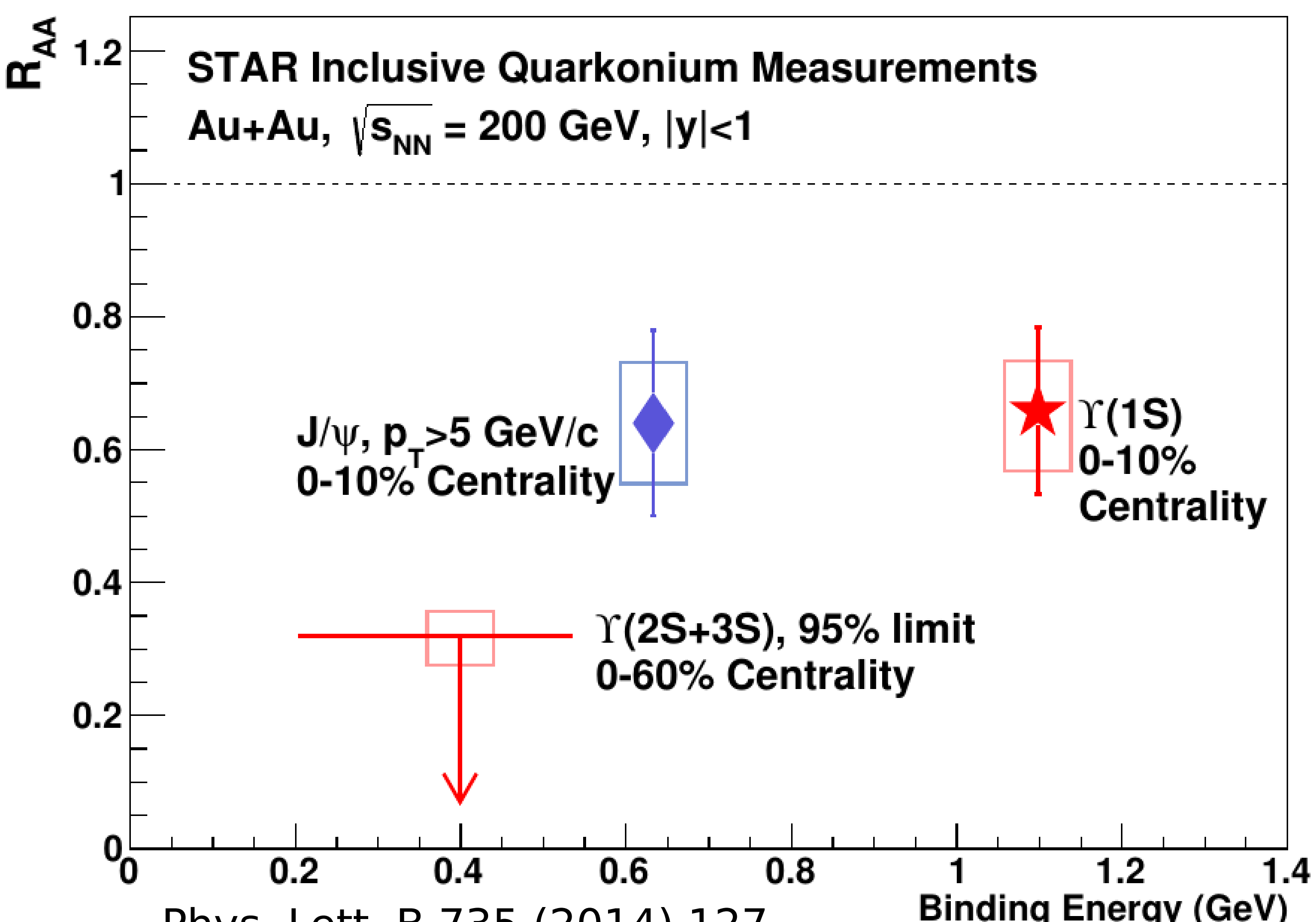



Phys. Lett. B 735 (2014) 127
S-B Model:Nucl. Phys. A879, 25 (2012)
Liu-Chen Model: Phys. Lett. B697 (2011) 32

- ✓ Suppression of Υ(1S) in central collisions consistent with model predictions
- *Liu et al. Model* – suppression mostly due to dissociation of the excited states (CNM effects not included)

➢ Central collisions

- ✓ Indication of complete Υ(2S+3S) suppression
- ✓ Suppression of Υ(1S) similar to high-$p_T$ J/ψ




Phys. Lett. B 735 (2014) 127

# Upgrades

**Fully installed and take data since 2014**

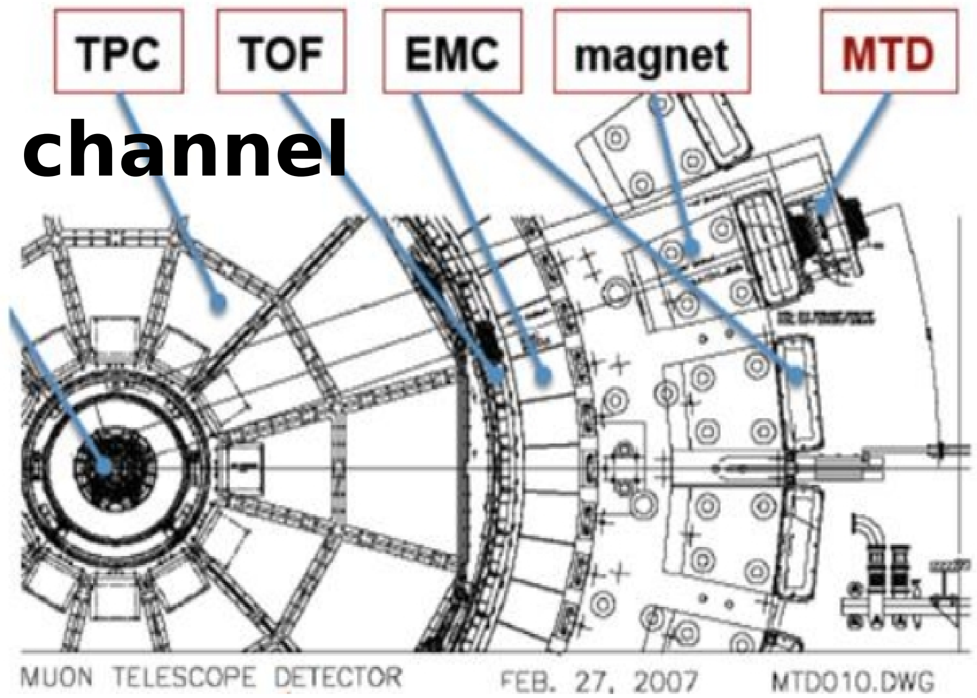
STAR

## Muon Telescope Detector (MTD)

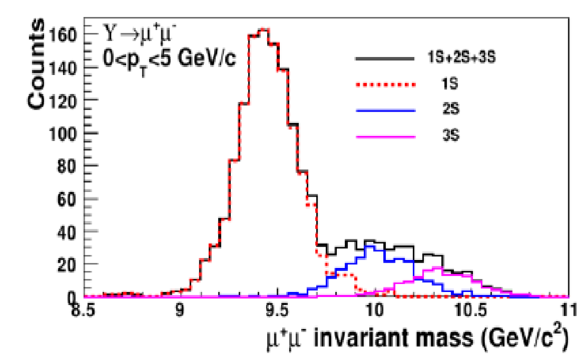
**Precision quarkonium measurements via di-μ channel**

*μ advantages over e:*

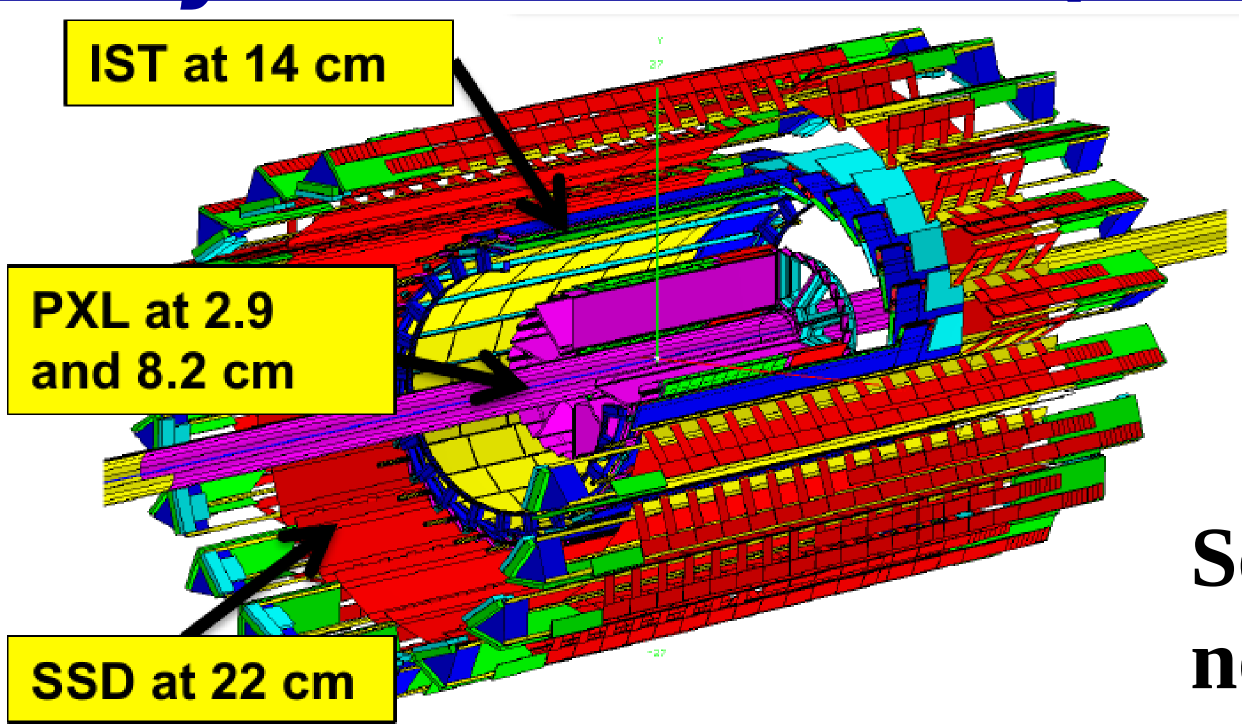
- No γ conversion
- Much less Dalitz decay contribution
- Less affected by radiative loses in the detector material




- Acceptance: 45% at $|\eta| < 0.5$
- Multi-gap Resistive Plate Chamber (MRPC) - gas detector
- Long-MRPCs




## Heavy Flavor Tracker (HFT)




Inner tracking system with 3 sub-systems

**Precise pointing resolution**

$$B \to J/\psi + X$$

**Separate prompt J/ψ production from non-prompt one, from B decays**

# Summary

- No strong energy dependence of J/ψ suppression in Au+Au 200, 62.4, 39 GeV
- Similar J/ψ and ϒ suppression in Au+Au and U+U
- ϒ and high-$p_T$ J/ψ suppressed in central Au+Au 200 GeV
- Indication for complete ϒ(2S) and ϒ(3S) suppression in central collisions

➔ Signals of the QGP presence

- *HFT and MTD since 2014 – significant improvement of quarkonium measurements*

**This work was supported by the European social fund within the framework of realizing the project „Support of inter-sectoral mobility and quality enhancement of research teams at Czech Technical University in Prague", CZ.1.07/2.3.00/30.0034.**

INVESTMENTS IN EDUCATION DEVELOPMENT

*Thank you !*

# Quarkonia Measurements

## $J/\psi$

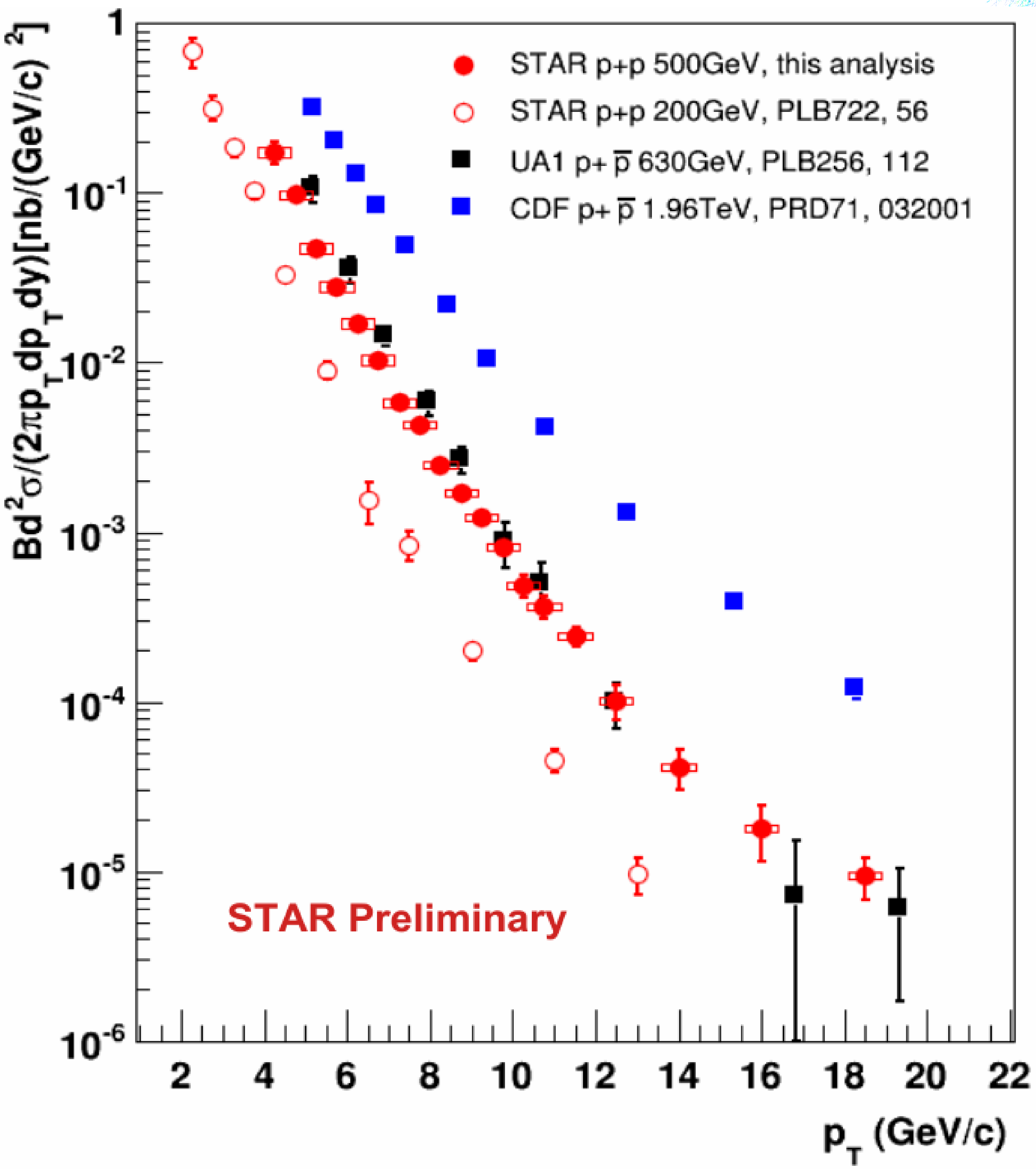
- p+p, $\sqrt{s}$ = 500 GeV, and $\psi(2S)$
- Au+Au, $\sqrt{s_{NN}}$ = 200, 62.4, 39 GeV
- U+U, $\sqrt{s_{NN}}$ = 193 GeV

## Upsilon

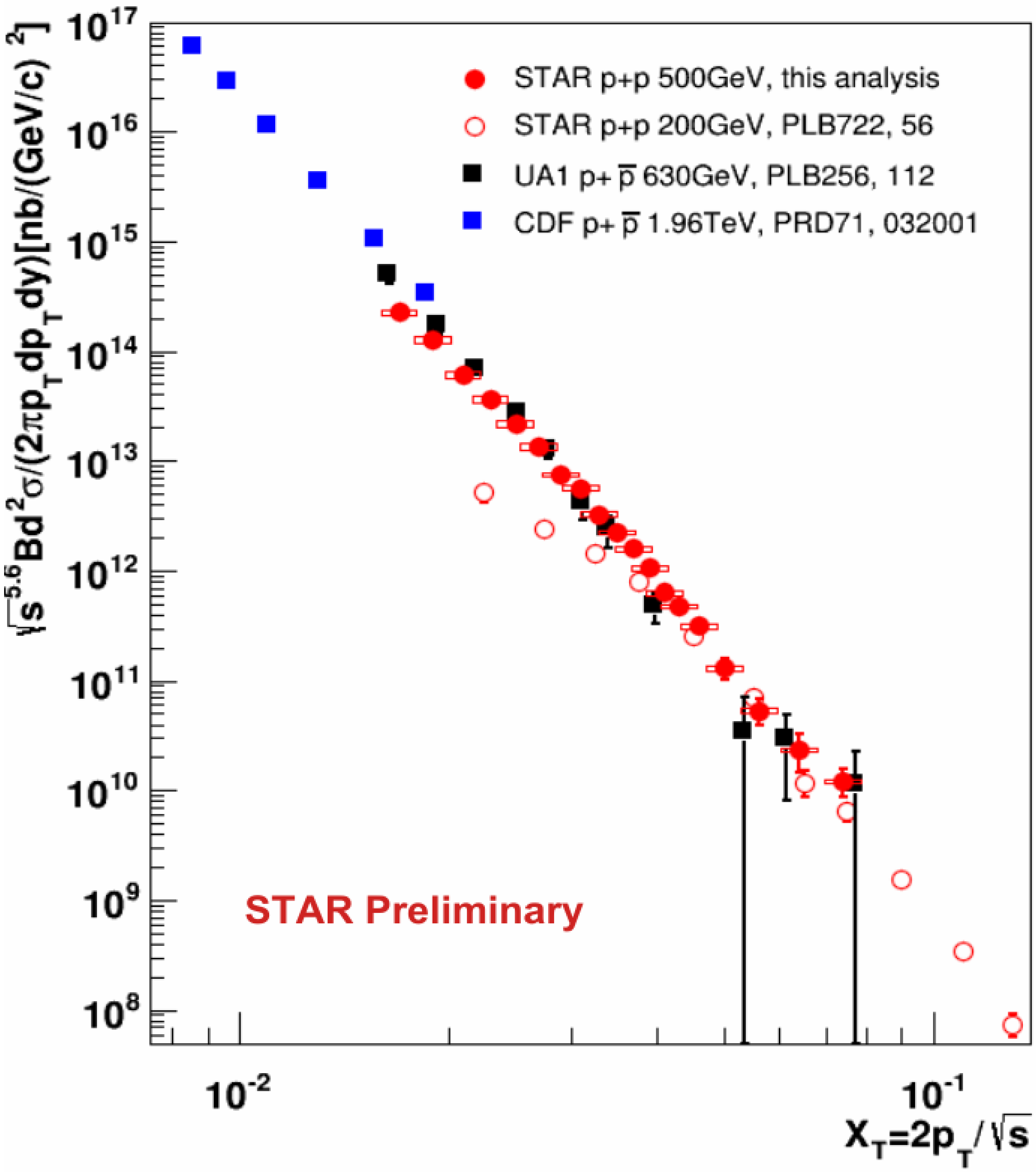
- p+p, $\sqrt{s}$ = 200 GeV
- d+Au, $\sqrt{s_{NN}}$ = 200 GeV
- Au+Au, $\sqrt{s_{NN}}$ = 200 GeV
- U+U, $\sqrt{s_{NN}}$ = 193 GeV
- $\Upsilon(1S)$ at $\sqrt{s_{NN}}$ = 200 GeV

# $J/\psi$ $p_T$ spectrum in p+p 500 GeV

- ✓ Precise J/ψ measurement at new beam energy, up to $p_T$ = 20 GeV/c



# $J/\psi\ x_T$ scaling



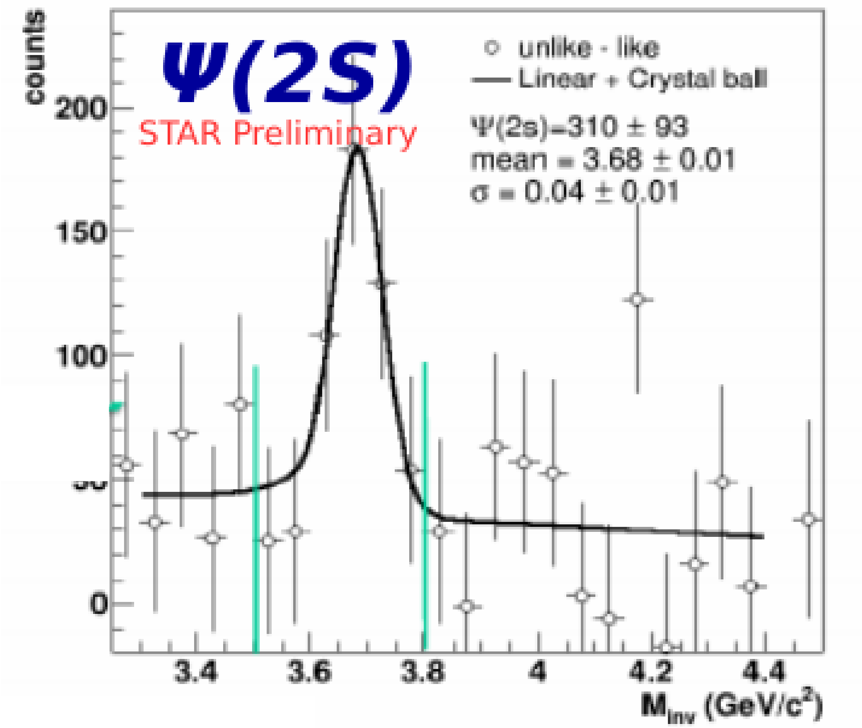

$$\frac{d^2\sigma}{2\pi\, p_T\, dp_T\, dy} = g(x_T)/(\sqrt{s})^n$$

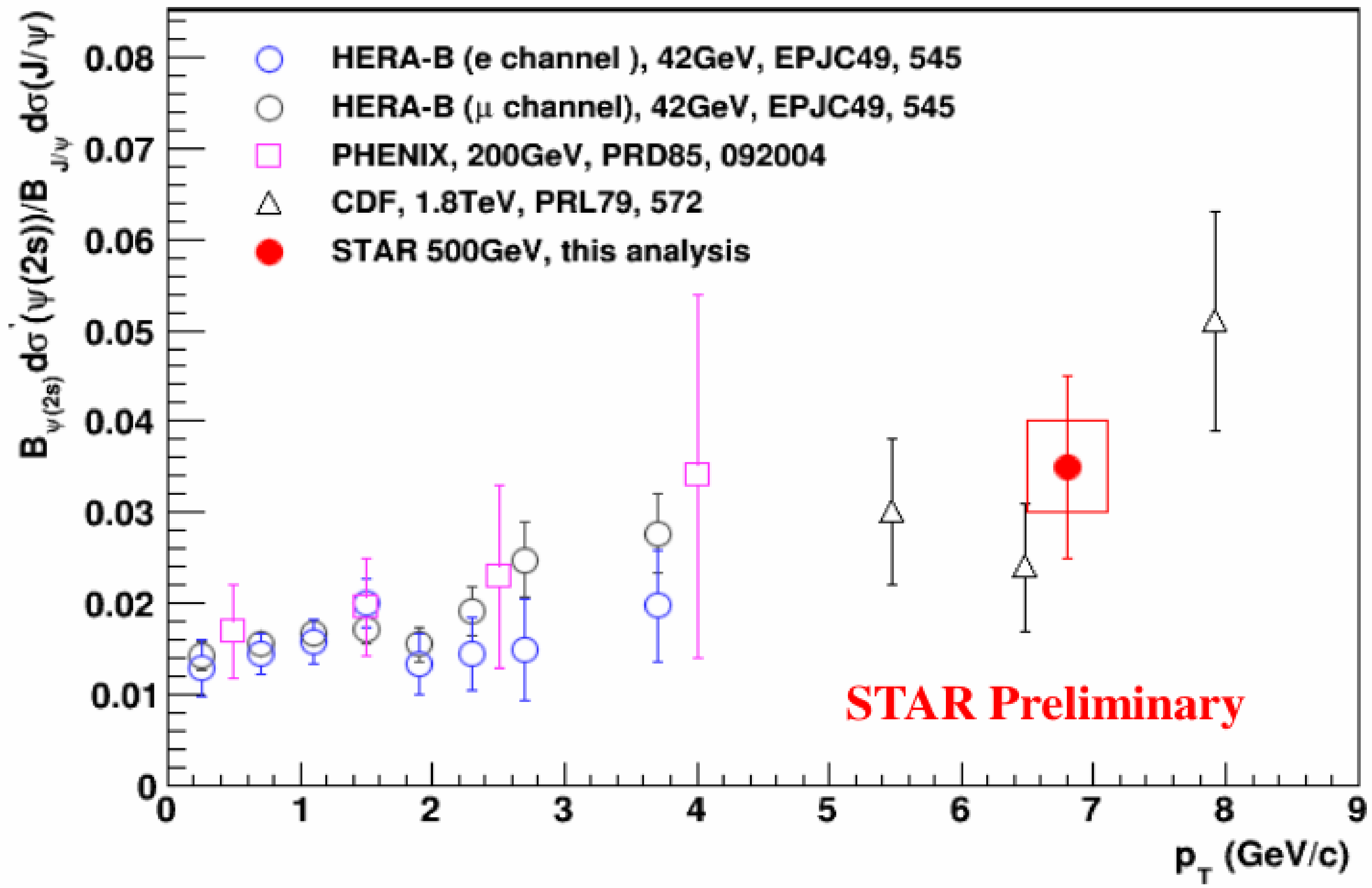
- ✓ In p+p 200 GeV $J/\psi$ production follows the $x_T$ scaling of cross-section at mid-rapidity at high $p_T$, with $\underline{n = 5.6 \pm 0.2}$ (Phys. Rev. C 80, 041902 (2009))
- ✓ $x_T$ scaling observed also in 500 GeV data
  - ➔ $x_T$ scaling breaking - transition from hard to soft process

*n – number of constituents taking an active role in hadron production*

# ψ(2S) in p+p 500 GeV

- Constrain ψ(2S) feed-down contribution to inclusive J/ψ production



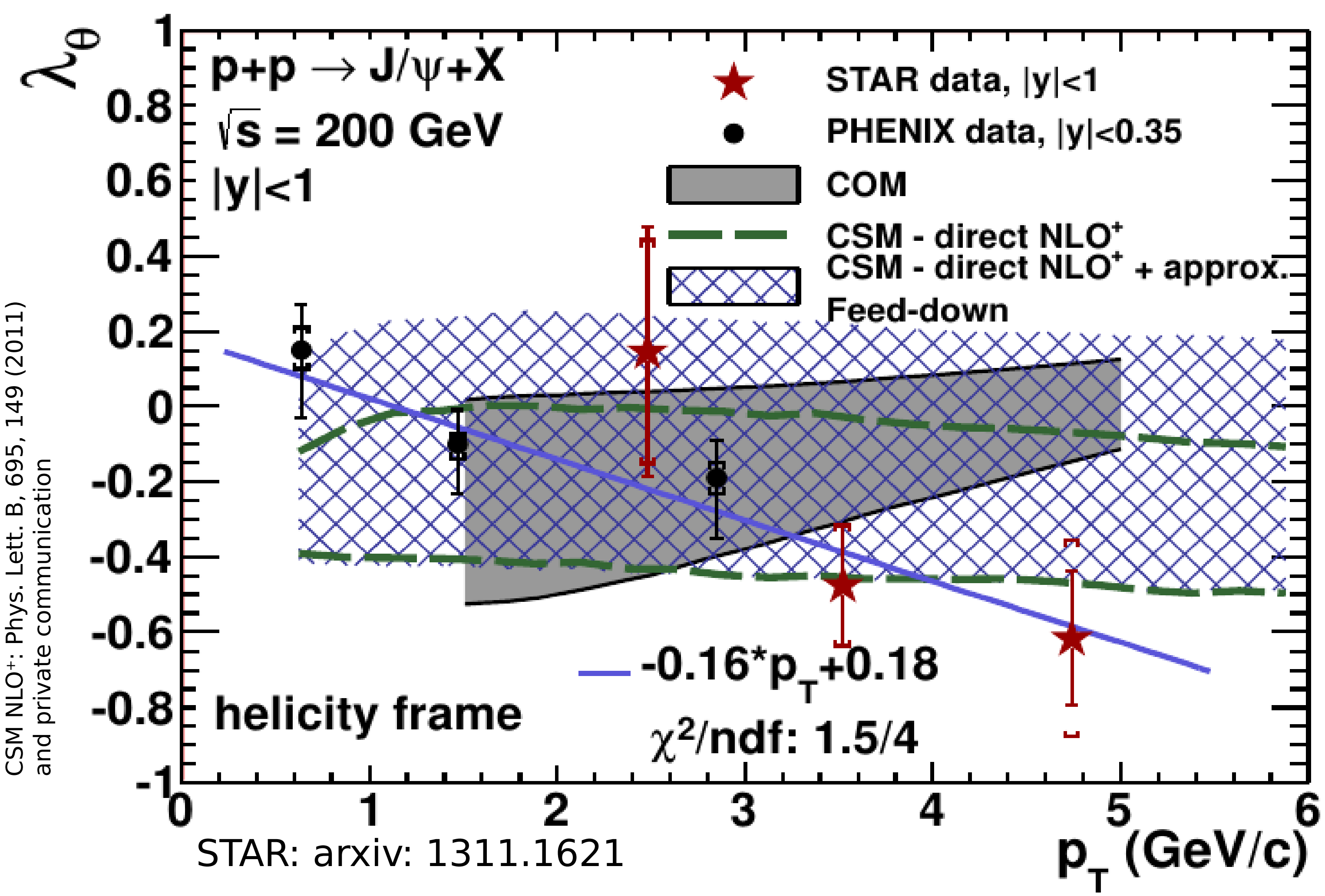




✓ First measurement of (ψ(2S) / J/ψ) ratio in p+p at 500 GeV

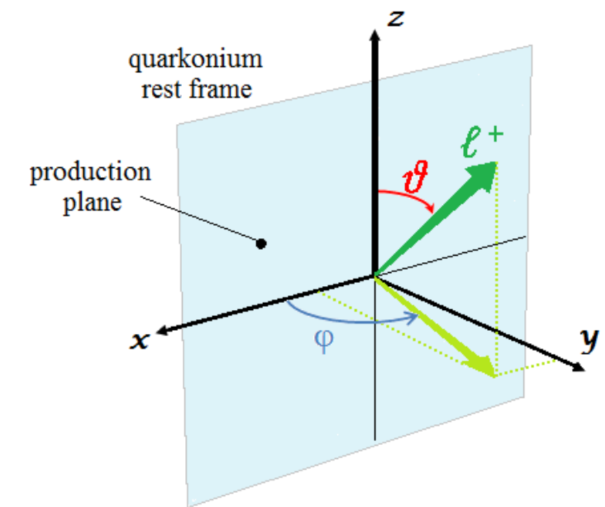
- Consistent with other experiments
- No collision energy dependence observed

# J/ψ polarization in p+p 200 GeV

PHENIX: Phys. Rev. D 82, 012001 (2010)
COM: Phys. Rev. D 81, 014020 (2010)
CSM NLO+: Phys. Lett. B, 695, 149 (2011)
and private communication




STAR: arxiv: 1311.1621




The angular distribution integrated over the azimuthal angle:

$$W(cos\theta) \propto 1 + \lambda_\theta cos^2\theta$$

*$\lambda_\theta$ – polarization parameter*

$\lambda_\theta$ = -1- longitudinal polarization

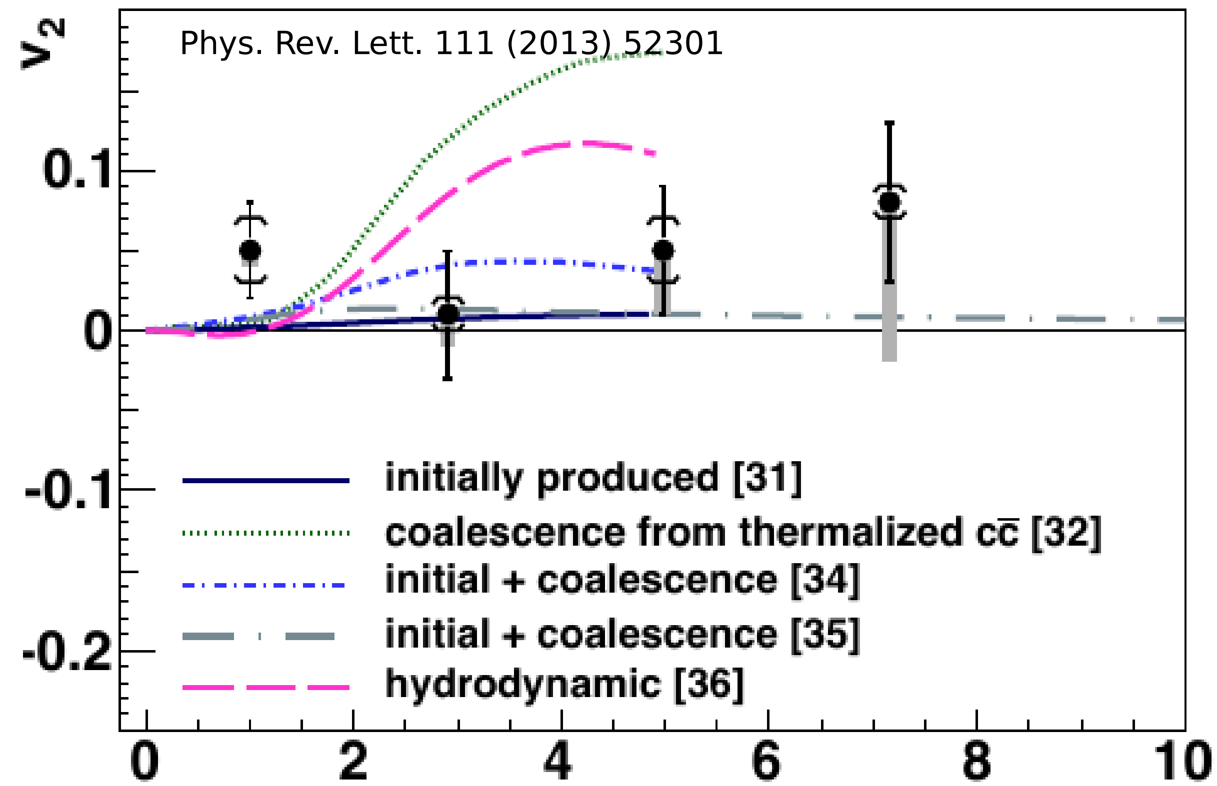
$\lambda_\theta$ = 1 - transverse polarization

- ✓ Polarization parameter $\lambda_\theta$ is measured in the helicity frame at |y| < 1 and 2 < $p_T$ < 6 GeV/c
  - ➔ RHIC data indicate trend towards longitudinal polarization with increasing $p_T$
  - ➔ The result is consistent with NLO+ CSM

# *J/ψ $v_2$ in Au+Au 200 GeV*

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

- Disfavors the model with J/ψ production via thermalized (anti-)charm coalescence

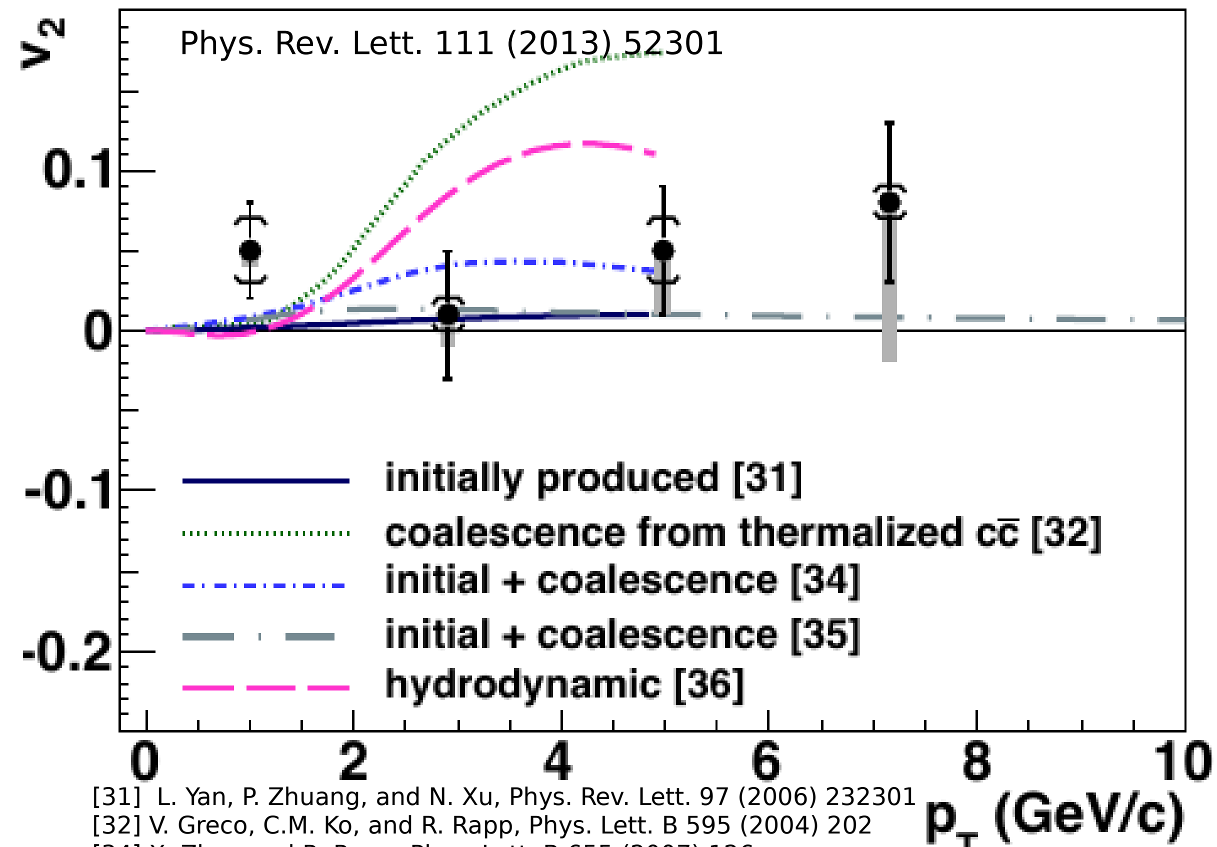




[31] L. Yan, P. Zhuang, and N. Xu, Phys. Rev. Lett. 97 (2006) 232301
[32] V. Greco, C.M. Ko, and R. Rapp, Phys. Lett. B 595 (2004) 202
[34] X. Zhao and R. Rapp, Phys. Lett. B 655 (2007) 126
[35] Y. Liu, N. Xu, and P. Zhuang, Nucl. Phys. A 834 (2010) 317c
[36] U. W. Heinz and C. Chen, private communication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

# $J/\psi$ $v_2$ and $p_T$ spectra in Au+Au 200 GeV

- ✓ $J/\psi$ $v_2$ is consistent with zero at $p_T$ > 2 GeV/c
  - ➔ Disfavors the model with $J/\psi$ production via thermalized (anti-)charm coalescence




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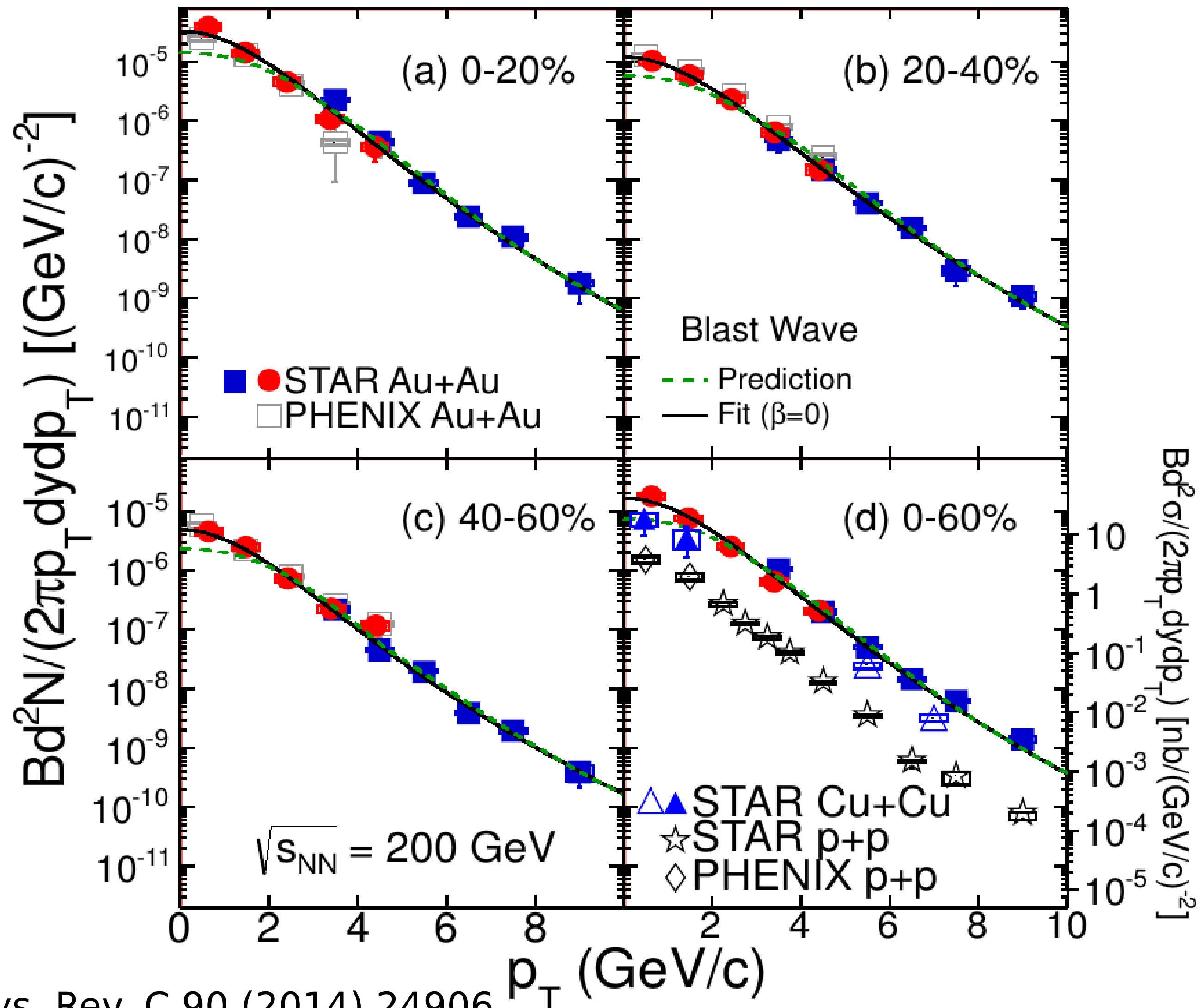
[34] X. Zhao and R. Rapp, Phys. Lett. B 655 (2007) 126
[35] Y. Liu, N. Xu, and P. Zhuang, Nucl. Phys. A 834 (2010) 317c
[36] U. W. Heinz and C. Chen, private communication (2012)

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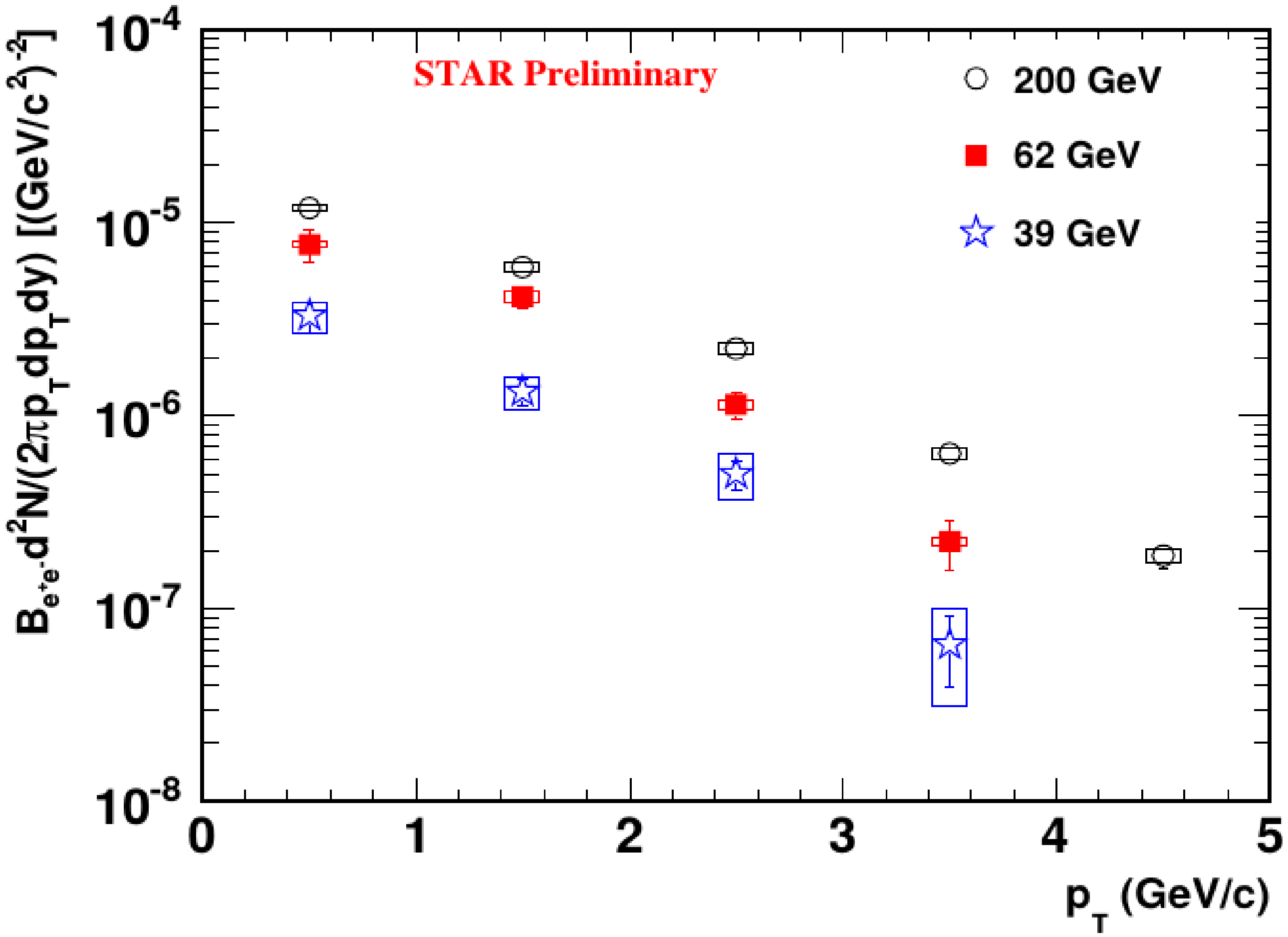
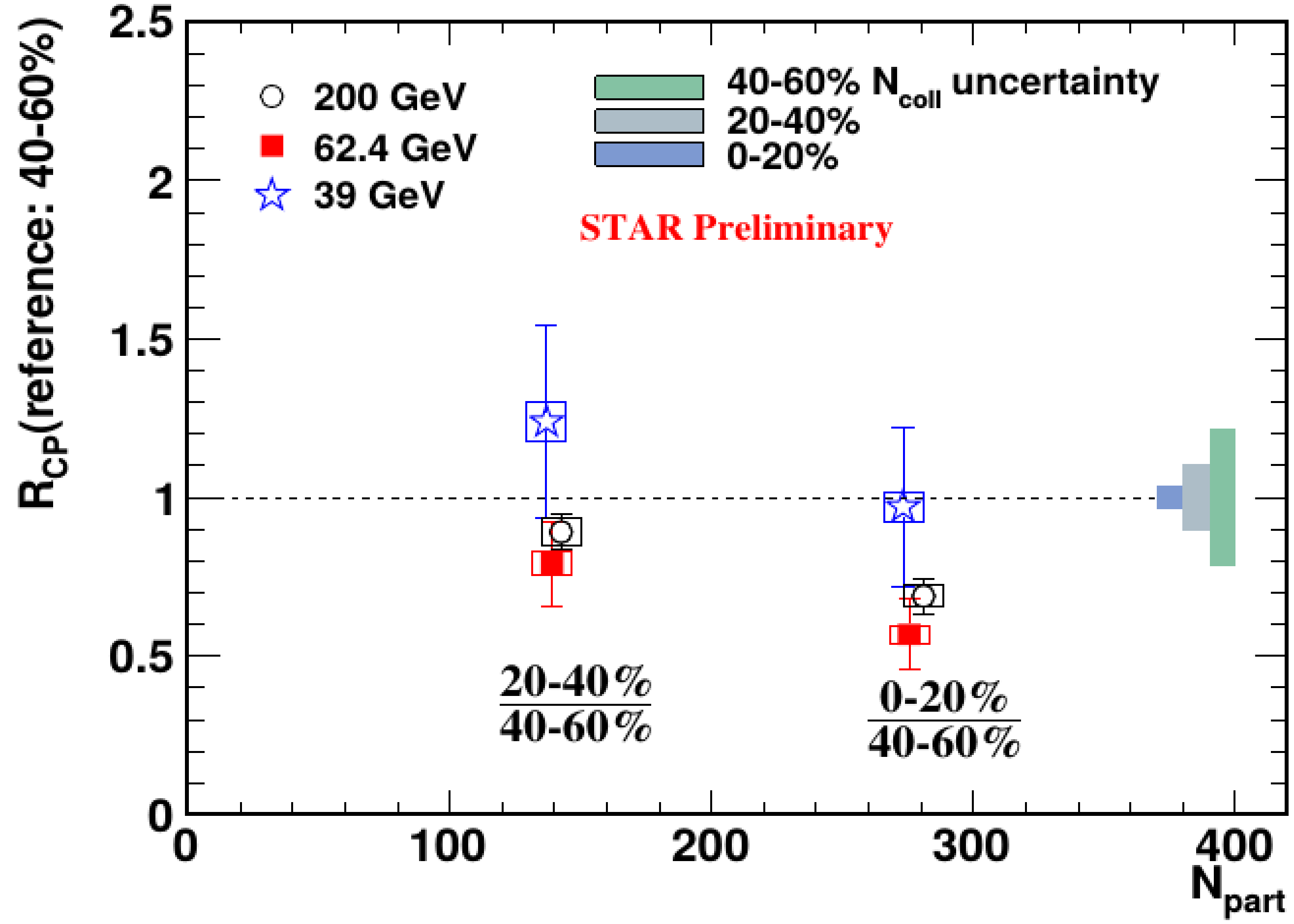
- ✓ At low $p_T$ $J/\psi$ spectra softer than the *TBW* prediction from light hadron
  - ➔ small radial flow ?
  - ➔ regeneration at low $p_T$ ?

# J/ψ BES results

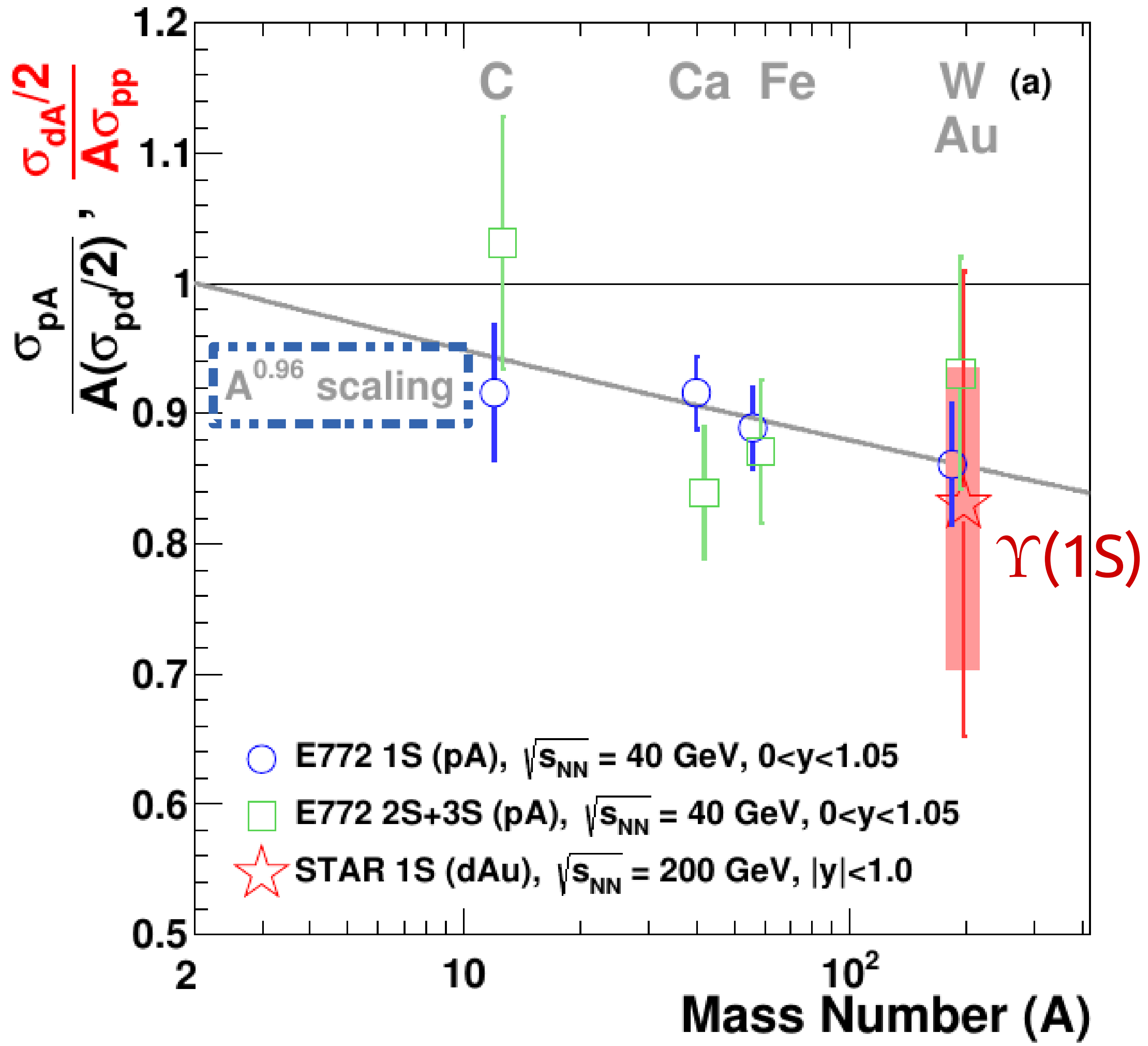



- ✓ Larger invariant yields at larger center-of-mass energy



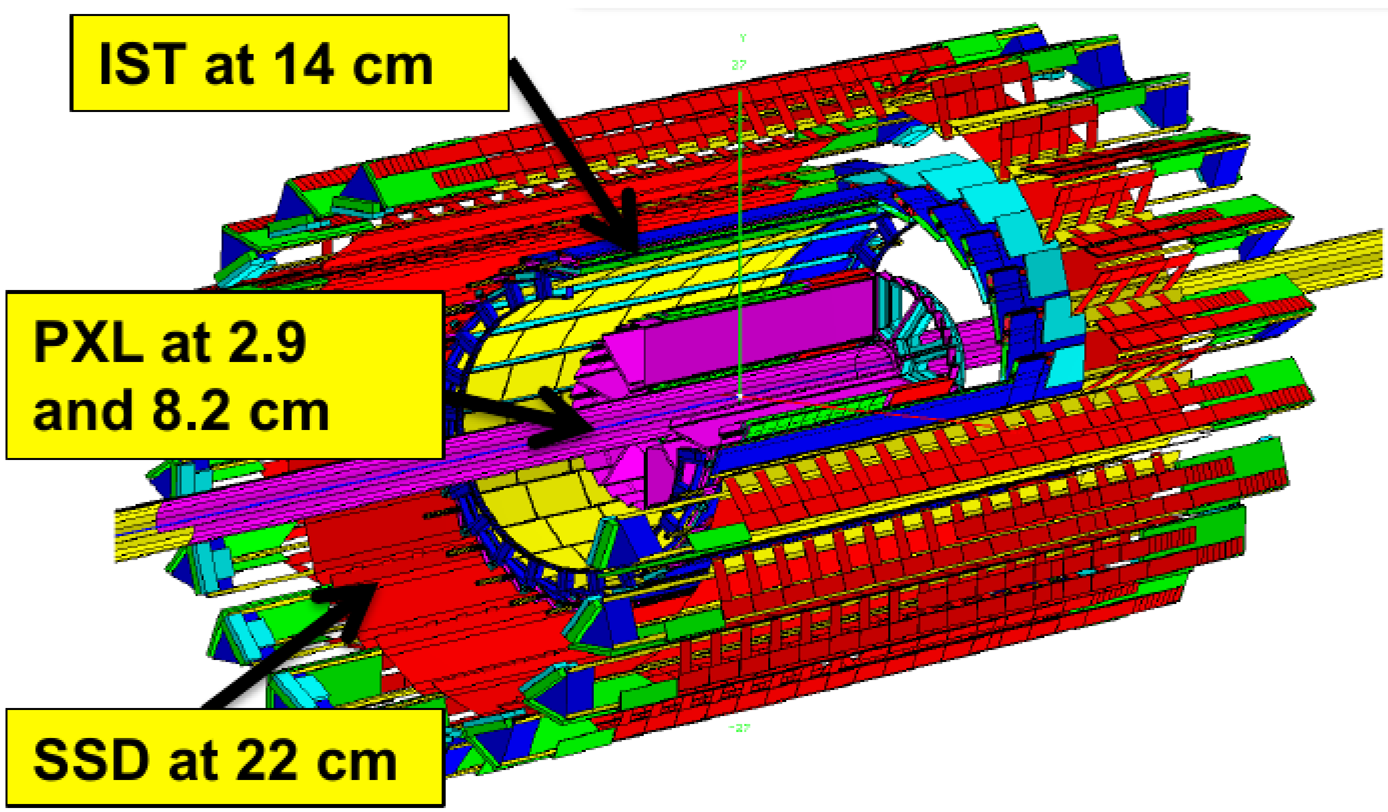

- ✓ Similar $R_{CP}$ in 62.4 and 200 GeV collisions
- ✓ Large uncertainties of 39 GeV result
  - *Reference: 40-60% centrality*

# *Upsilon in d+Au 200 GeV, CNM effects*




- Similar suppression seen at E772
  - *Better understanding of CNM effects needed*

# Heavy Flavor Tracker (HFT)

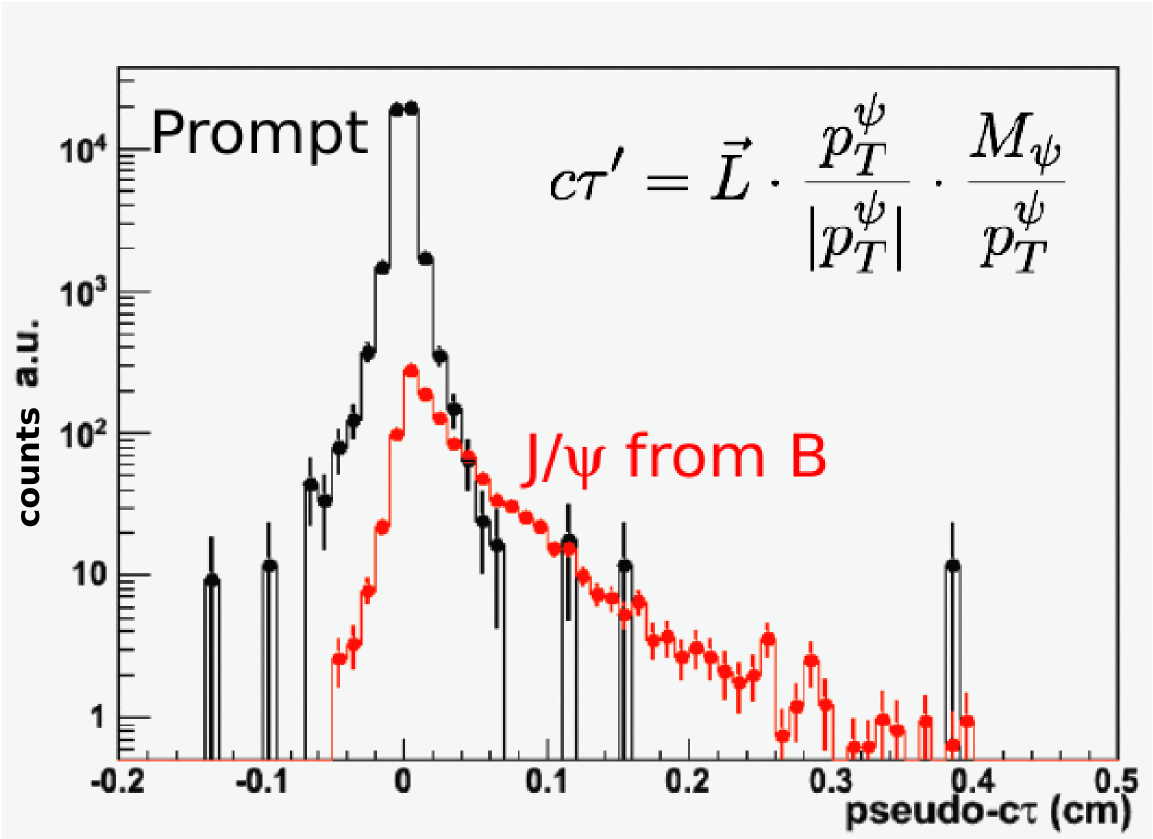



- Inner tracking system with 3 sub-systems
- Direct topological reconstruction of a decay vertex

**Precise pointing resolution**

$$B \rightarrow J/\psi + X$$

**Separate <u>prompt J/ψ</u> production from non-prompt one, from B decays**




**Fully installed and takes data since 2014**

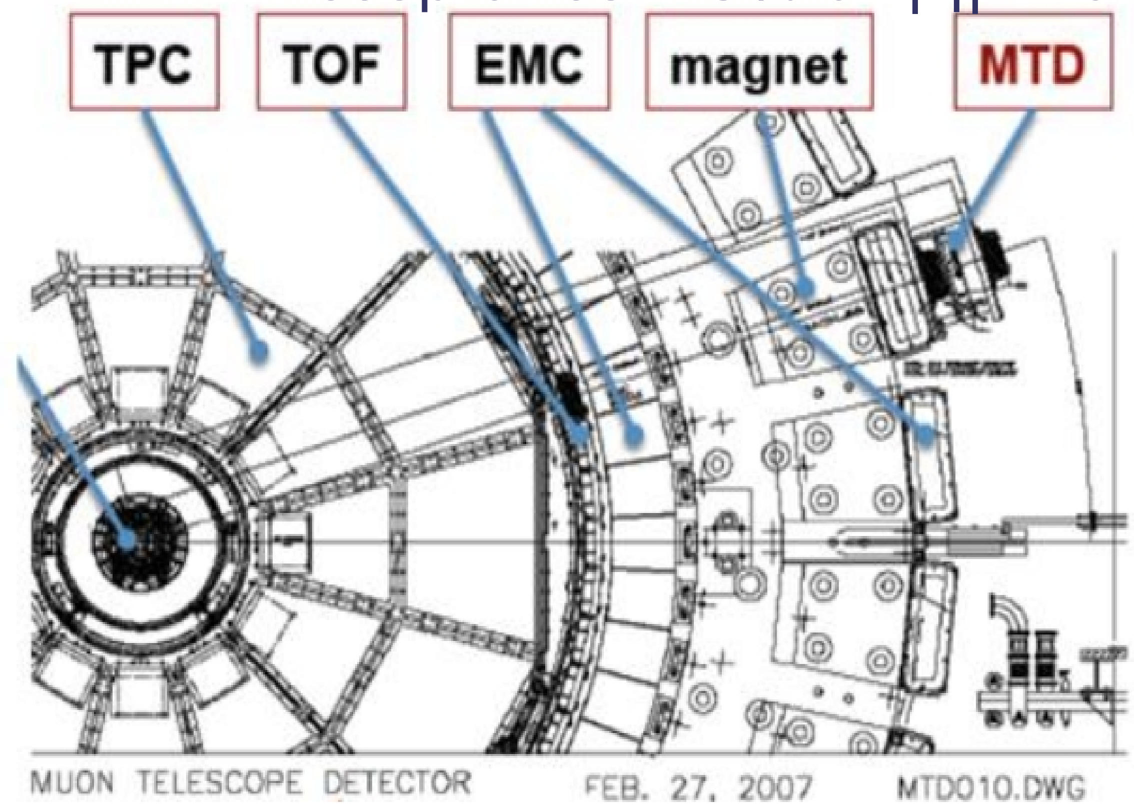
# Muon Telescope Detector (MTD)

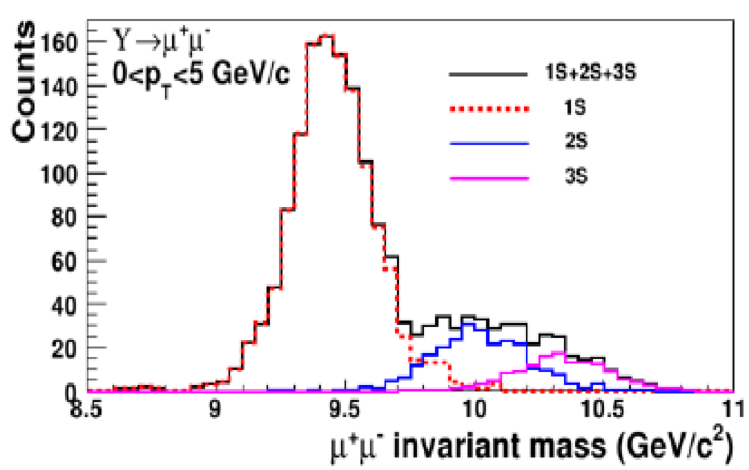
## Precision quarkonium measurements via di-μ channel

*μ advantages over e:*

- No γ conversion
- Much less Dalitz decay contribution
- Less affected by radiative loses in the detector material

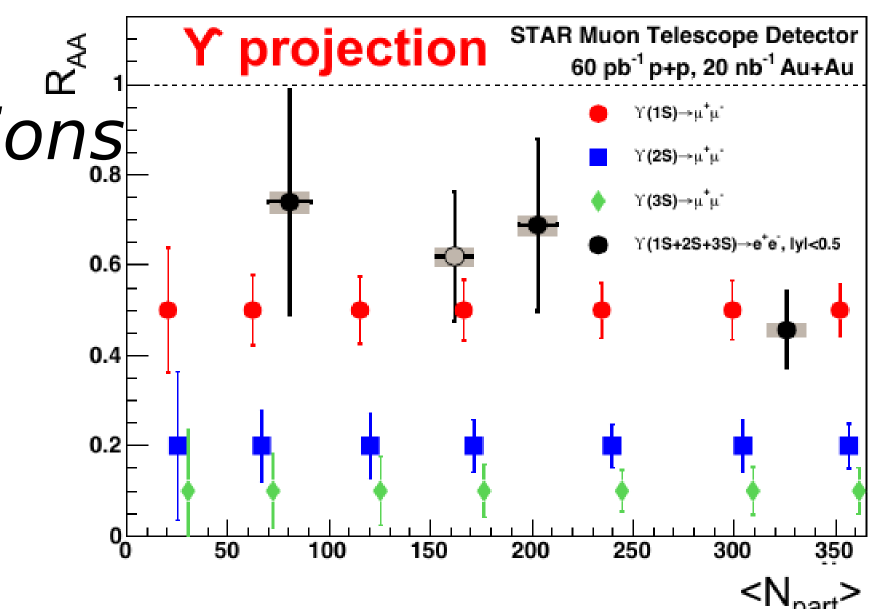
Acceptance: 45% at |η| < 0.5

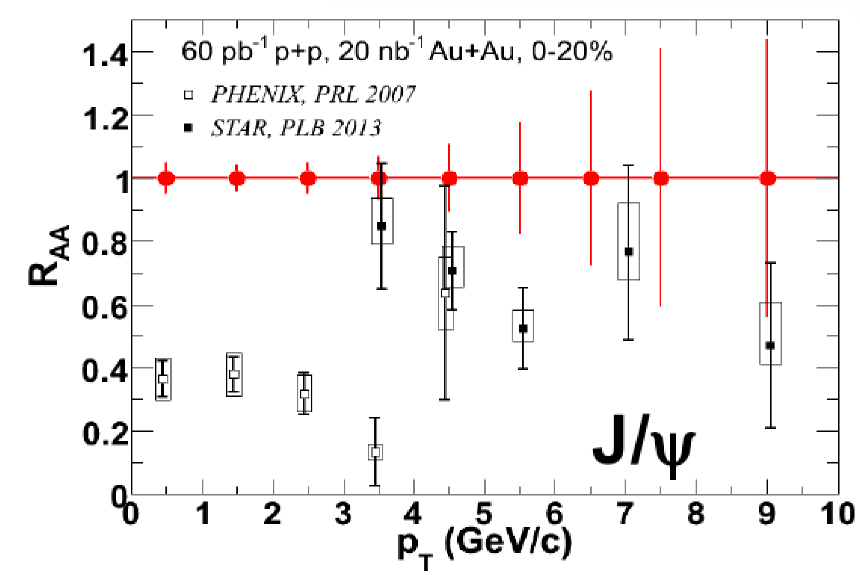



- Multi-gap Resistive Plate Chamber (MRPC) - gas detector
- Long-MRPCs

*simulations*




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

**Fully installed and takes data since 2014**