J/ψ production at the STAR experiment

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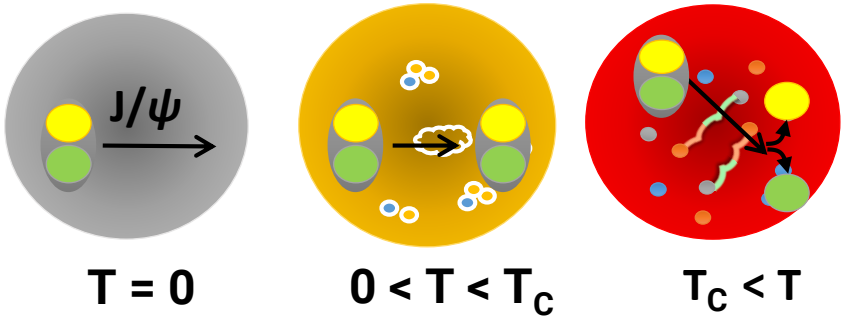
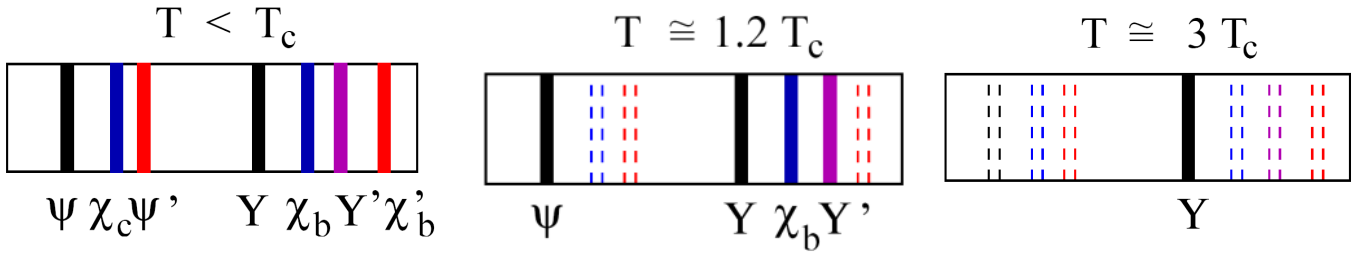
Motivation for heavy quarkonium studies

- **Heavy quarkonium suppression in heavy-ion collisions** due to the color screening in the quark-gluon plasma (QGP)

  T. Matsui, H. Satz, Phys.Lett. B178, 416 (1986)



- Sequential melting of different quarkonium states = **QGP thermometer** Á. Mócsy, P. Petreczky , Phys. Rev. D77, 014501 (2008)



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

Nuclear modification factor

- Modification of heavy quarkonium production in nucleus+nucleus collisions (A+A) compared with p+p collisions is usually quantified by the **nuclear modification factor :**

$$R_{AA} = \frac{1}{\langle N_{bin} \rangle} \frac{d^2 N_{AA}/dp_T\, dy}{d^2 N_{pp}/dp_T\, dy}$$

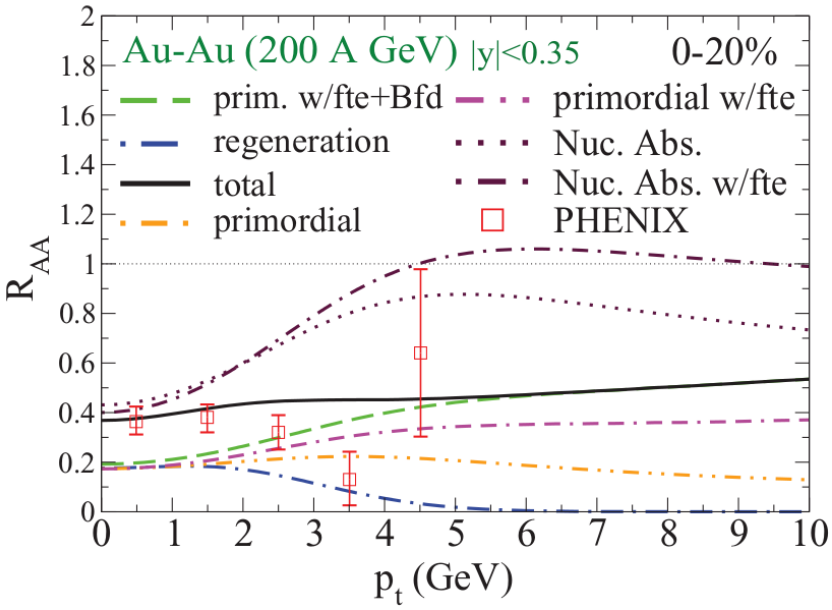
$\langle N_{bin} \rangle$ ... the average number of binary collisions

U+U collisions:
centrality 0-5 % ... $\langle N_{bin} \rangle \approx 1\,280$
centrality 40-45 % ... $\langle N_{bin} \rangle \approx 160$

$R_{AA} > 1$ ... enhancement
$R_{AA} = 1$ ... no medium effects
$R_{AA} < 1$ ... suppression

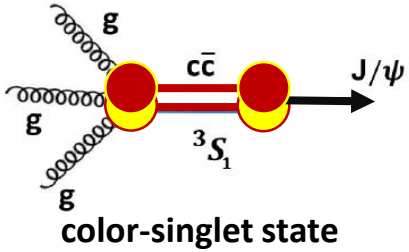
Challenges

- Modification of the quarkonium production due to the **other effects:**
  - Recombination of dissociated charm quarks
  - Feed-down effects
  - Cold-nuclear-matter effects (CNM)

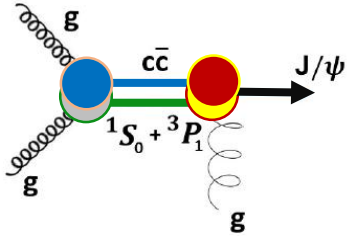


X .Zhao and R.Rapp, Phys. Rev. C82, 064905 (2010)

- **Quarkonium production mechanism in elementary collisions not fully understood**



color-singlet state



colored cc̄ pair → J/ ψ

Challenges

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  - Feed-down effects
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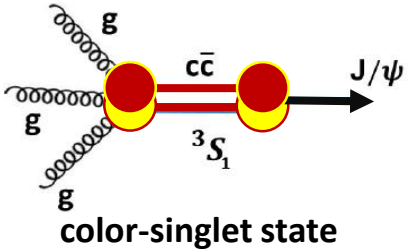
Heavy quarkonium measurements in **different colliding systems, at different centralities and collision energies** help to understand these different processes

- **Quarkonium production mechanism in elementary collisions not fully understood**



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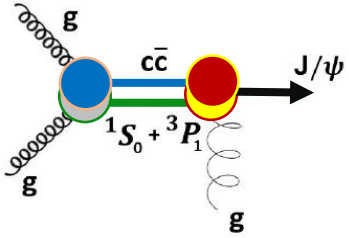

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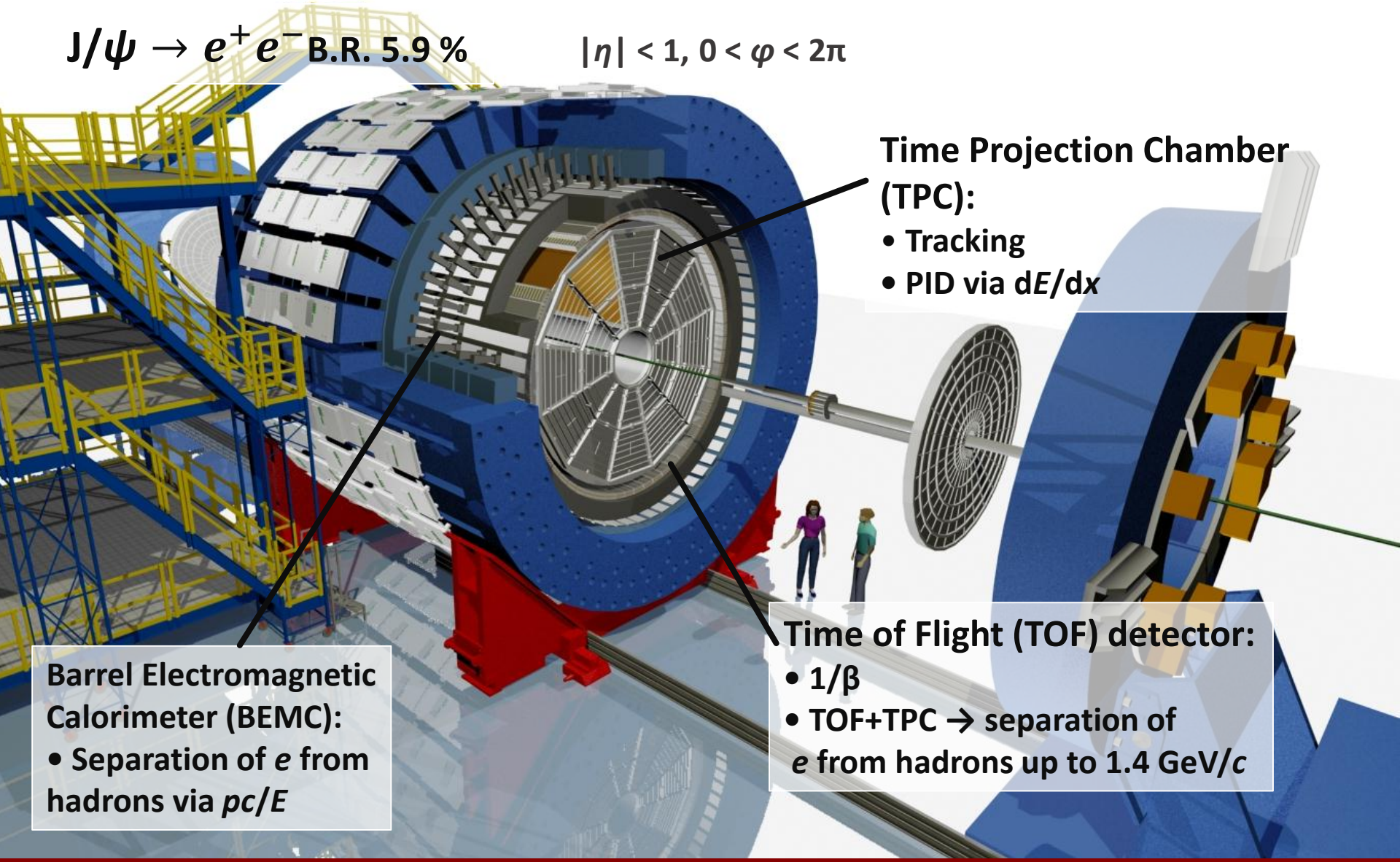
- **Quarkonium production mechanism in elementary collisions not fully understood**

Quarkonium **polarization measurements** further constrain models

J/ψ at the STAR experiment

$J/\psi \rightarrow e^+e^-$ B.R. 5.9 %

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



Time Projection Chamber (TPC):
- Tracking
- PID via d*E*/d*x*

Time of Flight (TOF) detector:
- 1/β
- TOF+TPC → separation of *e* from hadrons up to 1.4 GeV/*c*

Barrel Electromagnetic Calorimeter (BEMC):
- Separation of *e* from hadrons via *pc*/*E*

J/ψ at the STAR experiment

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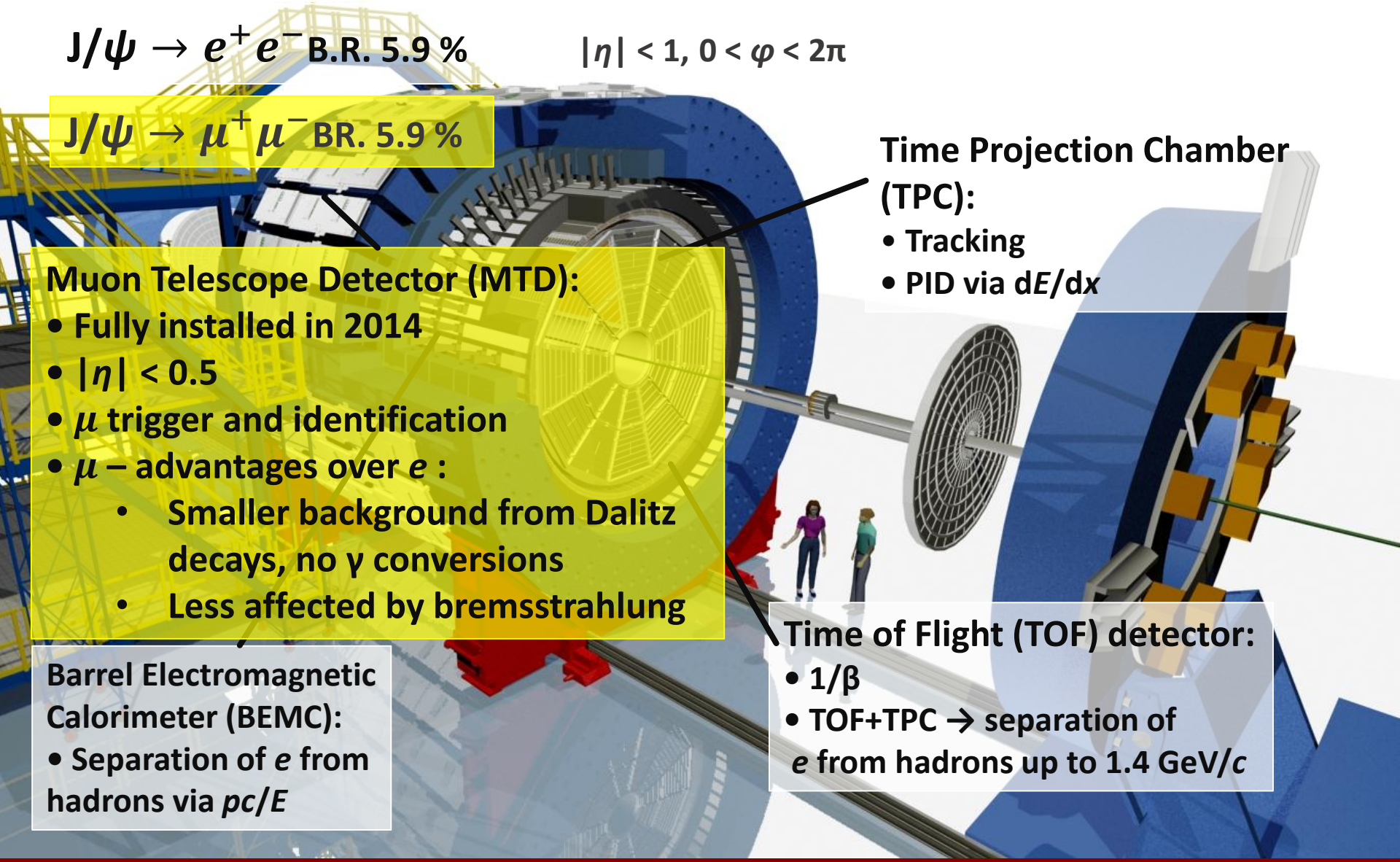


Time Projection Chamber (TPC):
- Tracking
- PID via d*E*/d*x*

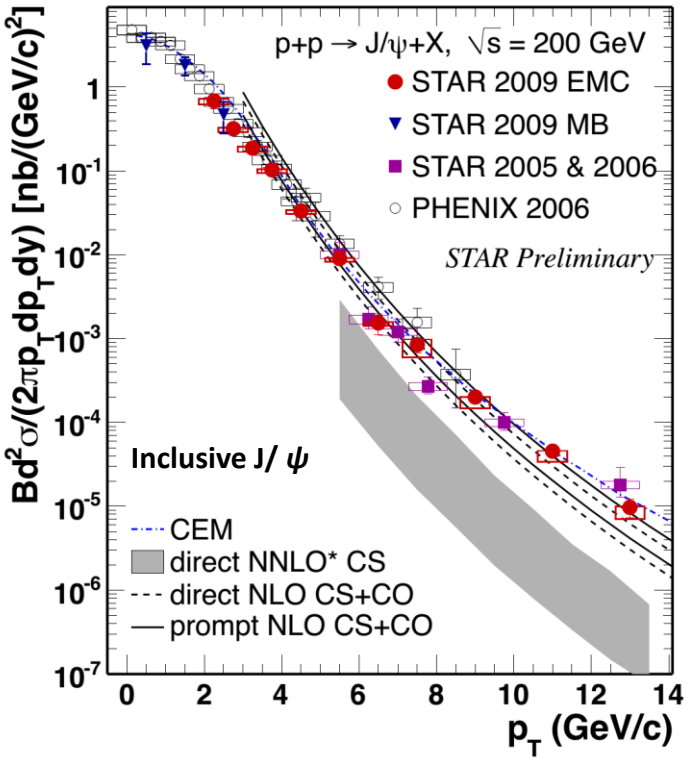
Muon Telescope Detector (MTD):
- Fully installed in 2014
- $|\eta| < 0.5$
- μ trigger and identification
- μ – advantages over *e* :
  - Smaller background from Dalitz decays, no γ conversions
  - Less affected by bremsstrahlung

Time of Flight (TOF) detector:
- 1/β
- TOF+TPC → separation of *e* from hadrons up to 1.4 GeV/*c*

Barrel Electromagnetic Calorimeter (BEMC):
- Separation of *e* from hadrons via *pc*/*E*

J/ψ in p+p collisions

200 GeV

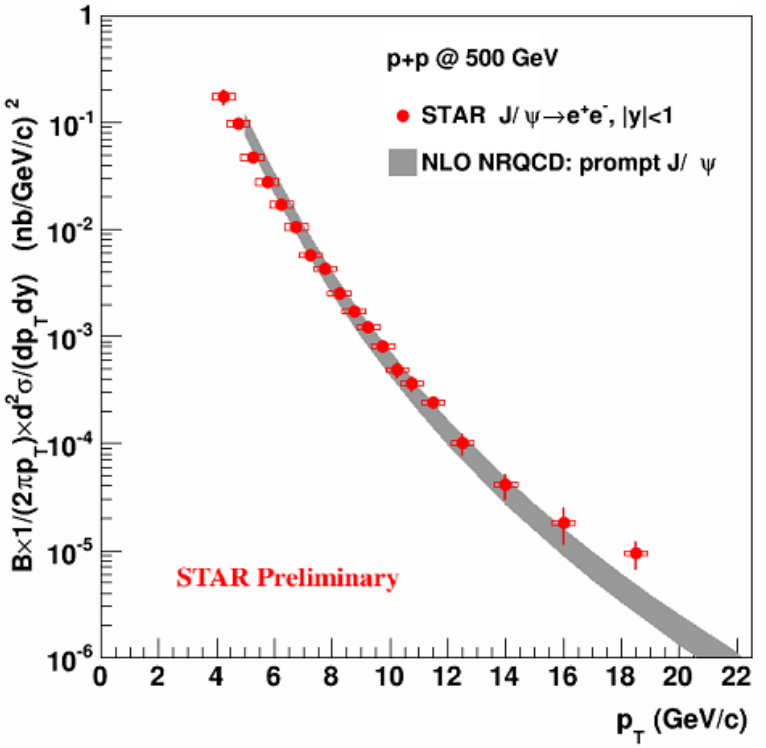


CEM: A.D.Fawley, T.Ullrich, R.Vogt, Phys.Rept. 462, 125 (2008)
direct NNLO* CS: P. Artoisenet et al., Phys. Rev. Lett. 101, 152001 (2008)
NLO CS+CO: Y.-Q. Ma, K. Wang and K.T. Chao, Phys. Rev. D 84, 51 114001 (2011)

STAR EMC: Phys.Lett. B 722, 55 (2013)
STAR MB: Acta Phys. Polonica B Vol.5, No2, 543 (2012)
STAR 2005 & 2006: Phys. Rev. C80, 041902 (R) (2009)
PHENIX: Phys.Rev. D 85, 092004 (2012)

- p+p at 200 GeV: different models (CEM, NLO CS+CO for $p_T > 4$ GeV/c) describe the data well
- Direct NNLO* CS misses high p_T data

500 GeV



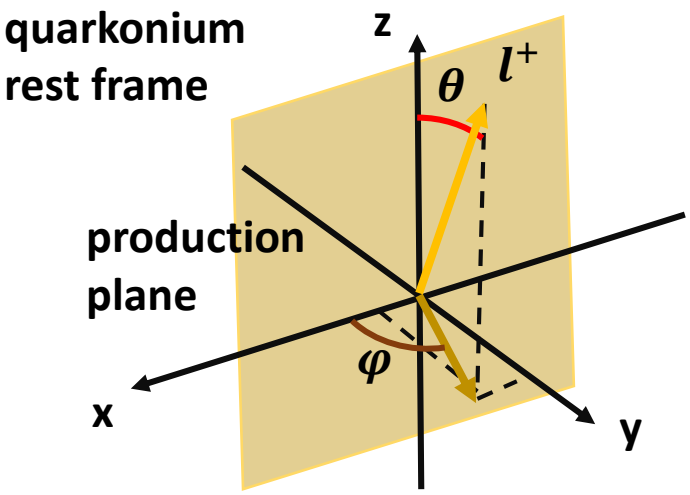
NLO NRQCD: Phys.Rev.Lett. 106 042002 (2011), Phys Rev. D84 114001 (2011), JHEP 1505 , 103 (2015)

- p+p at 500 GeV: NLO NRQCD for prompt J/ψ describes the data for $p_T > 4$ GeV/c

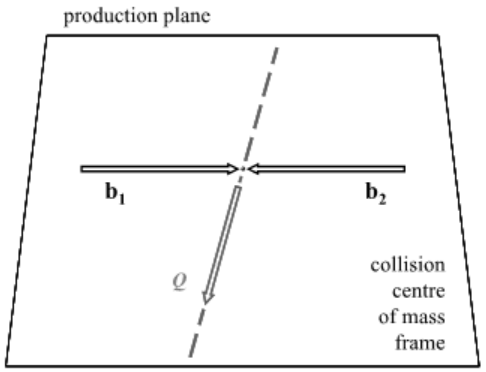
J/ψ polarization

- Can be studied via the angular distribution of the decay lepton pair:

$$\frac{d^2\sigma}{d\cos\theta\, d\varphi} \propto 1 + \lambda_\theta \cos^2\theta + \lambda_{\theta\varphi} \sin 2\theta \cos\varphi + \lambda_\varphi \sin^2\theta \cos 2\varphi$$



- **Helicity (HX) frame:** polarization z axis along the J/ψ momentum in the center of mass of the colliding beams
- **Collins-Soper (CS) frame**: bisector of the angle formed by one beam direction and the opposite direction of the other beam in the J/ψ rest frame



P. Faccioli et al., Eur. Phys. J. C 69, 657 (2010)

J/ψ polarization

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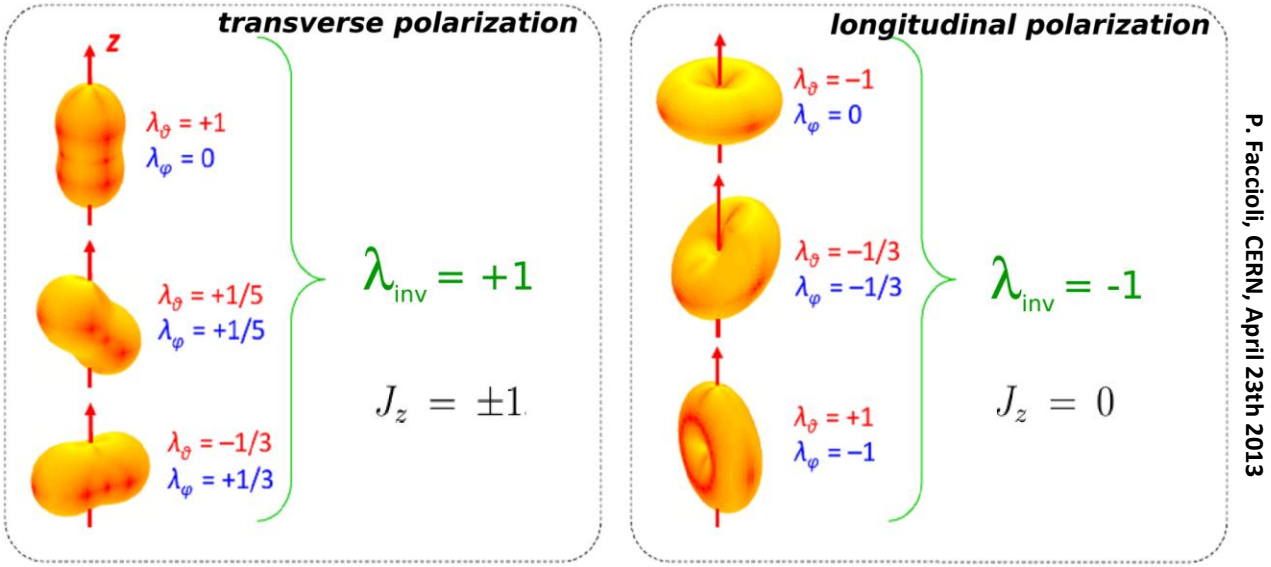
- Frame invariant quantity:

$$\lambda_{inv} = \frac{\lambda_\theta + 3\lambda_\varphi}{1 - \lambda_\varphi}$$



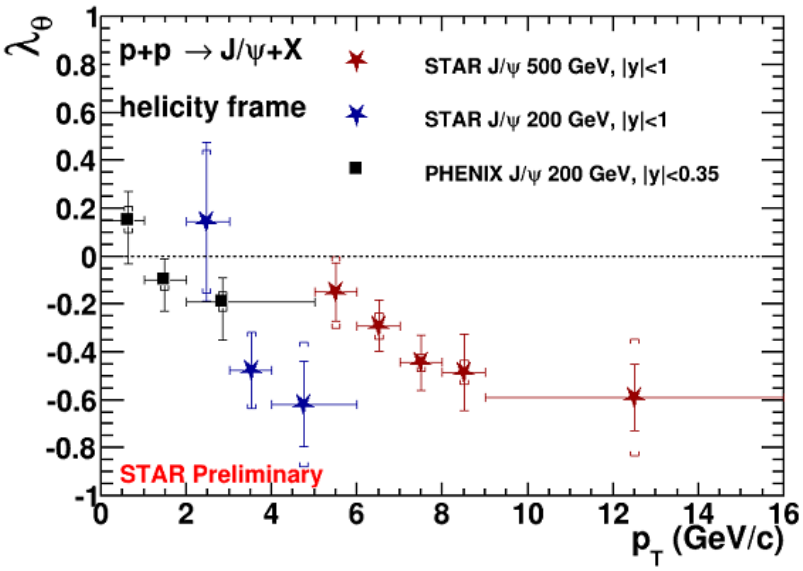
P. Faccioli, CERN, April 23th 2013

J/ψ polarization

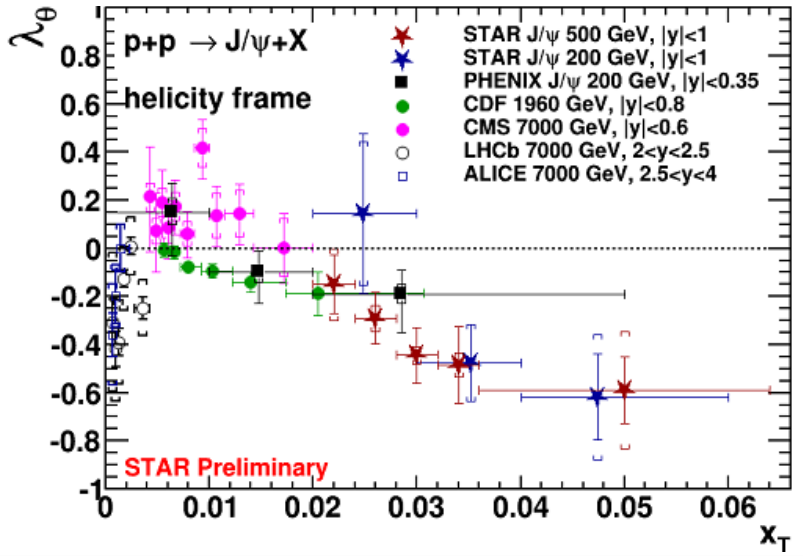
- **J/ψ polarization in new 500 GeV p+p collisions**
  - Measurement extended to higher p_T range
  - **λ_θ in helicity frame**
    - 500 GeV data show similar trend as 200 GeV data: towards longitudinal polarization with increasing p_T

- λ_θ in helicity frame as a function of x_T at different experiments
  - Common trend towards negative λ_θ with increasing x_T

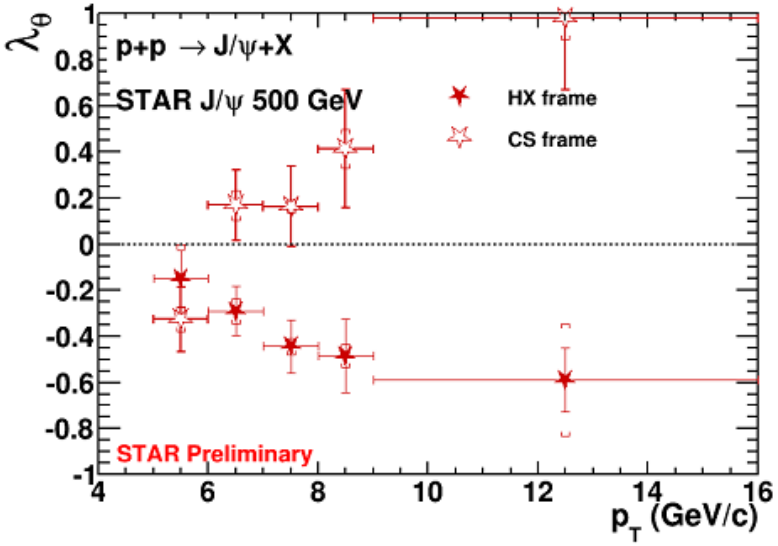
$$x_T = 2\,p_T\,/\sqrt{s}$$

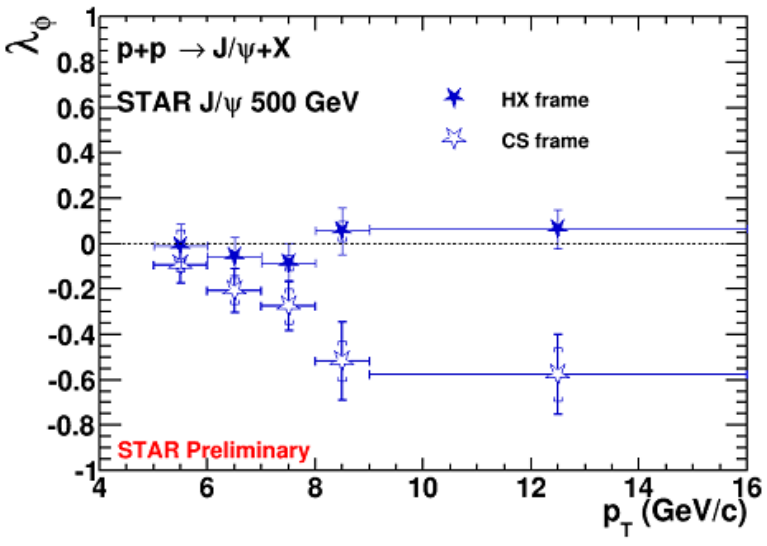


PHENIX: Phys. Rev. D 82, 012001 (2010)
STAR 200 GeV: Phys.Lett. B739, 180 (2014)



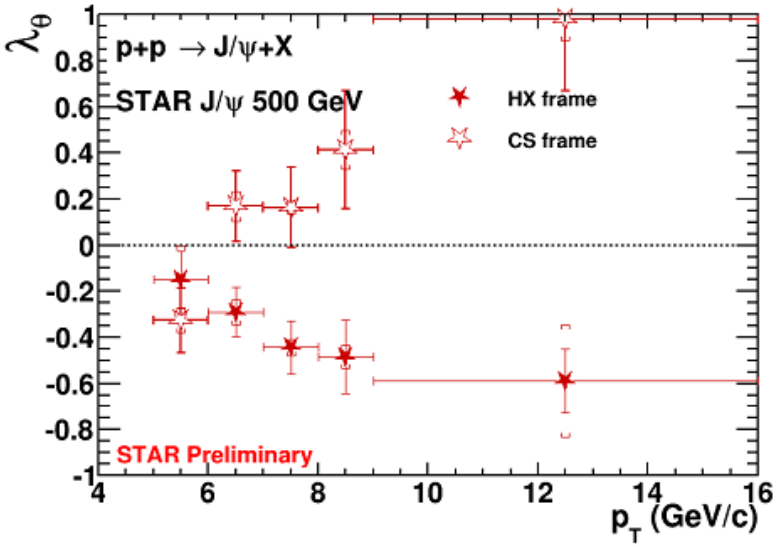
J/ψ polarization

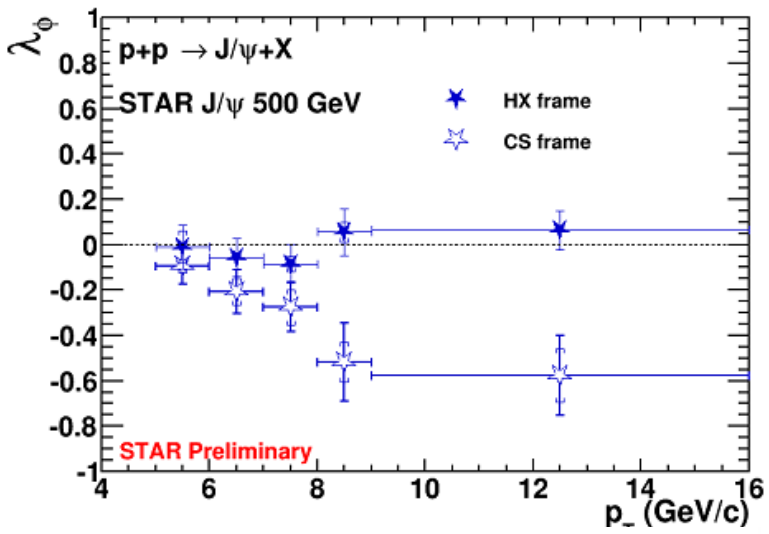


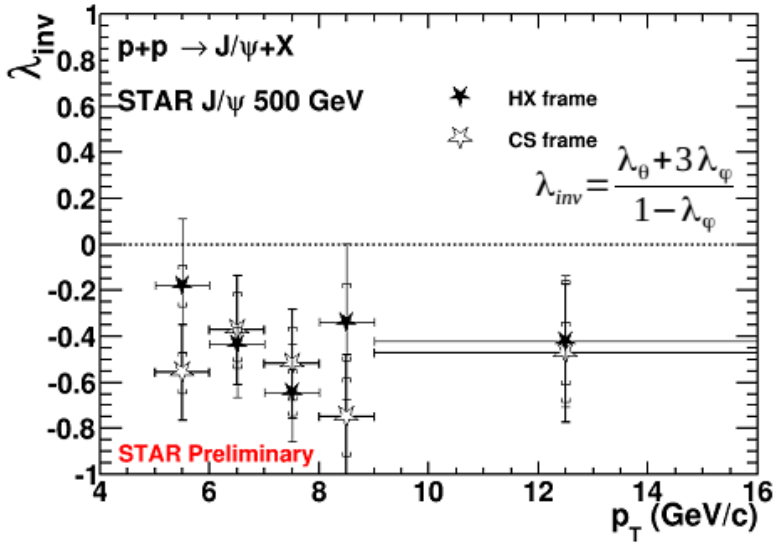


- **J/ψ polarization in new 500 GeV p+p collisions**
  - Helicity frame vs. Collins-Soper frame
  - Higher statistics allows to extract λ_Φ

J/ψ polarization



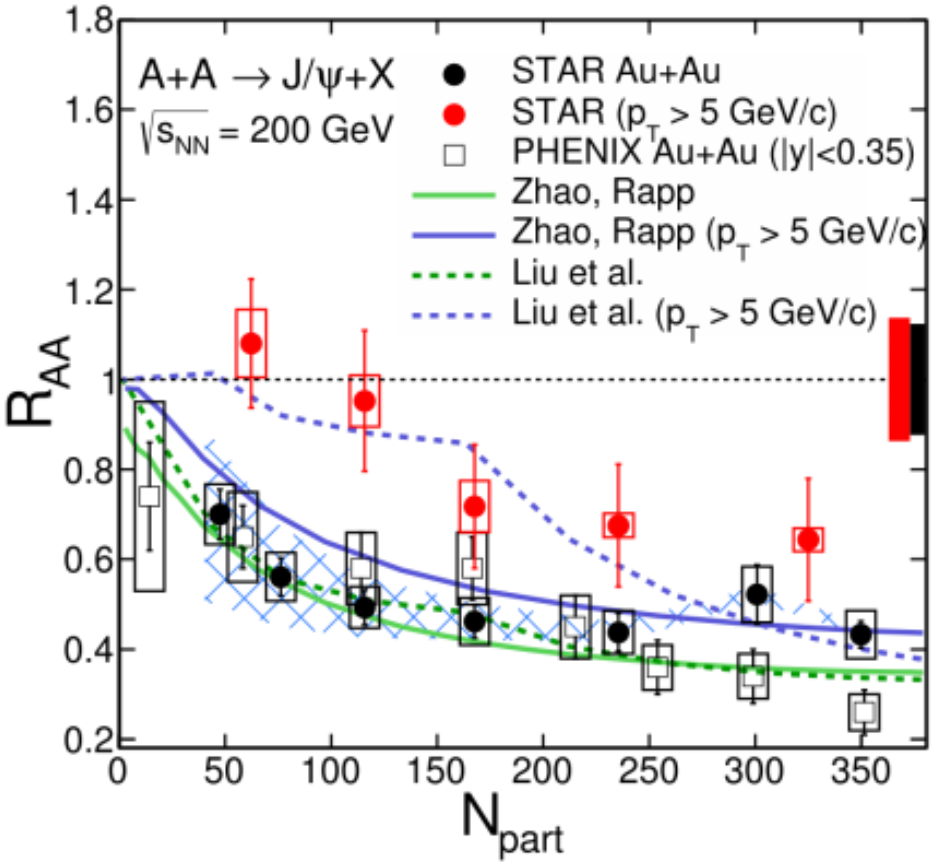




- **J/ψ polarization in new 500 GeV p+p collisions**
  - Helicity frame vs. Collins-Soper frame
  - Higher statistics allows to extract λ_Φ
  - **λ_{inv} consistent in both frames**
  - **trend towards longitudinal polarization with increasing p_T**

J/ψ in Au+Au collisions

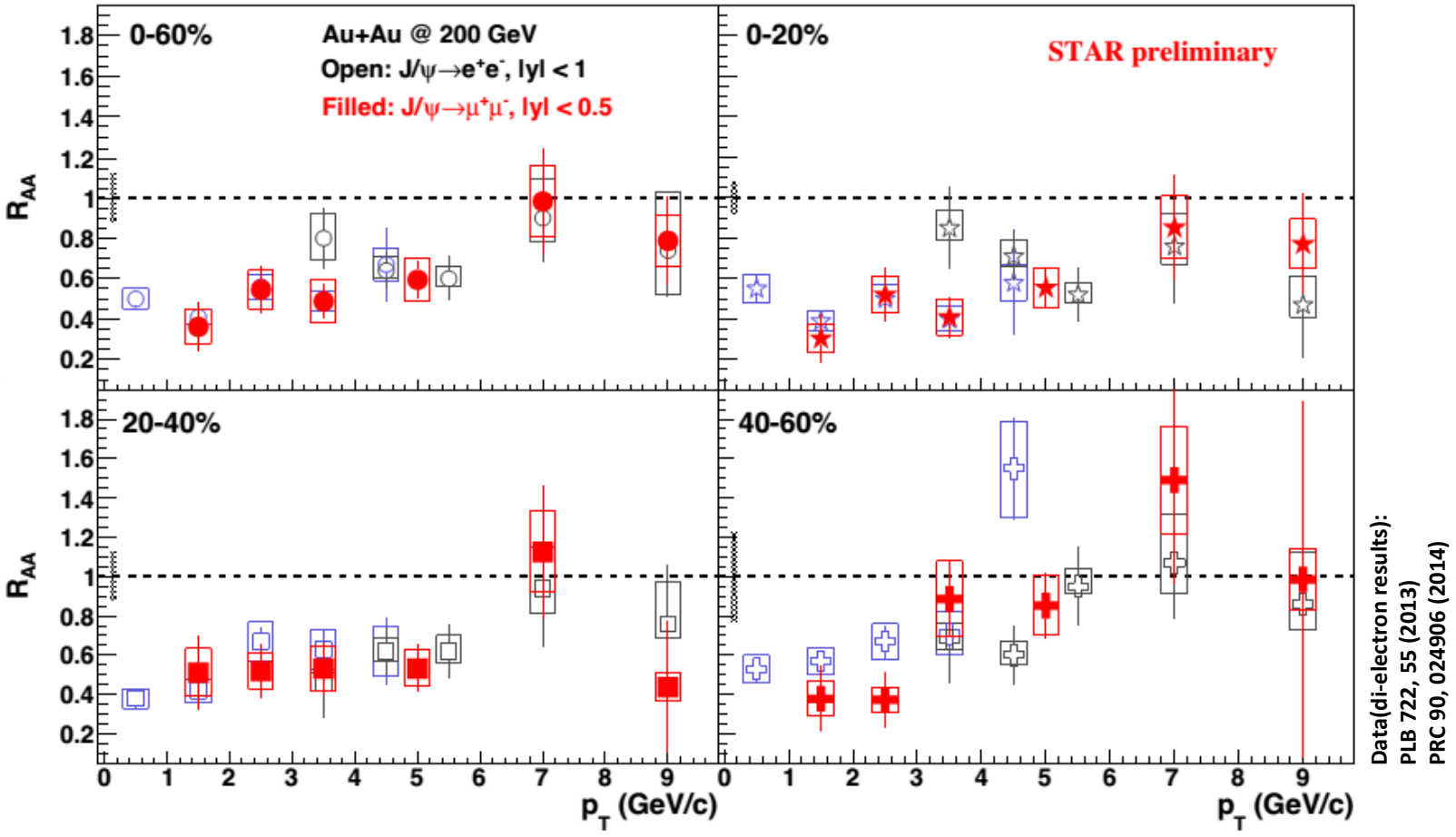
- e^+e^- channel
- Suppression increases with centrality
- **High-p_T J/ψ**
  - Higher R_{AA}, significant suppression in central collisions
  - Smaller influence of regeneration and CNM effects
- Models:
  - Liu et al. : direct production with color screening + recombination
  - Zhao, Rapp: + J/ψ formation time and B meson feed-down
- Both models describe the data well at low p_T , Zhao, Rapp underestimates high-p_T R_{AA}



STAR high-p_T: Phys. Lett. B722, 55 (2013)
STAR low-p_T: Phys. Rev. C90, 24906 (2014)
Y.Liu et al., Phys. Lett. B678, 72 (2009)
Zhao, Rapp, Phys. Rev. C82, 06490 (2010)

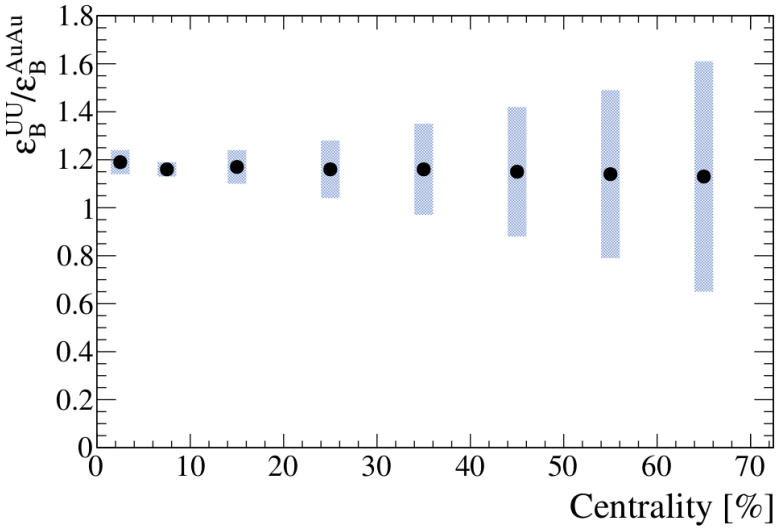
J/ψ in Au+Au collisions

- $\mu^+\mu^-$ channel
- R_{AA} increases towards higher p_T and peripheral collisions (as in di-electron channel)

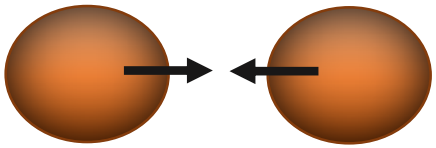


J/ψ in U+U collisions

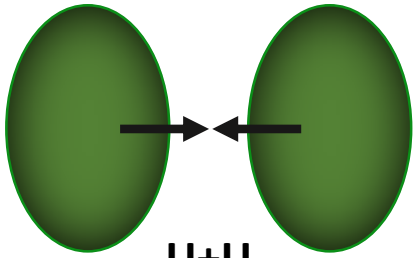
- U nuclei are non-spherical and **larger** than Au nuclei
- **In U+U** collisions the **energy density** of the created medium is expected to be **higher than in Au+Au** collisions
- Central U+U collisions – important tool for testing of the color screening hypothesis



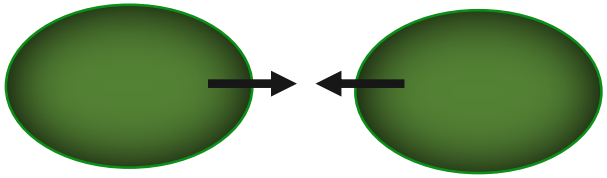
Kikola, Odyniec, Vogt, Phys. Rev. C 84, 054907



Au+Au



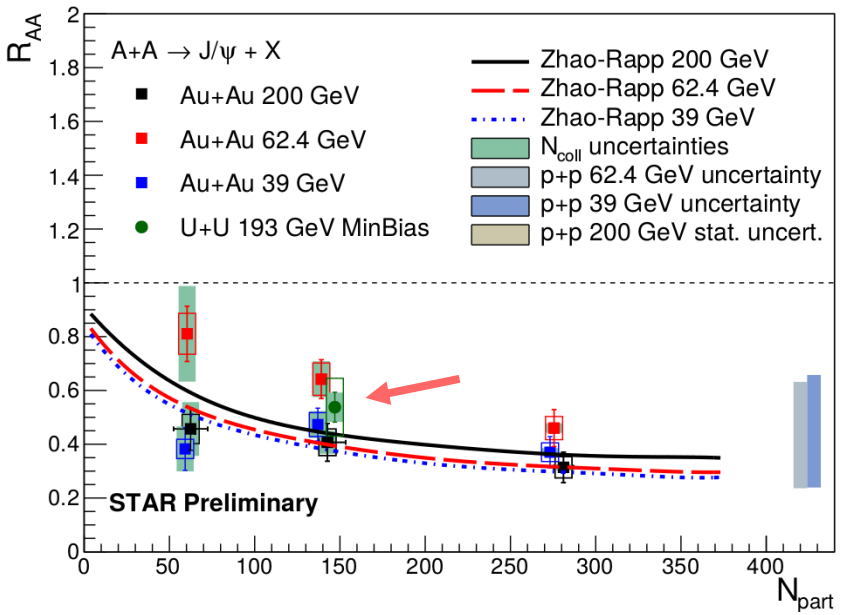
U+U
side+side



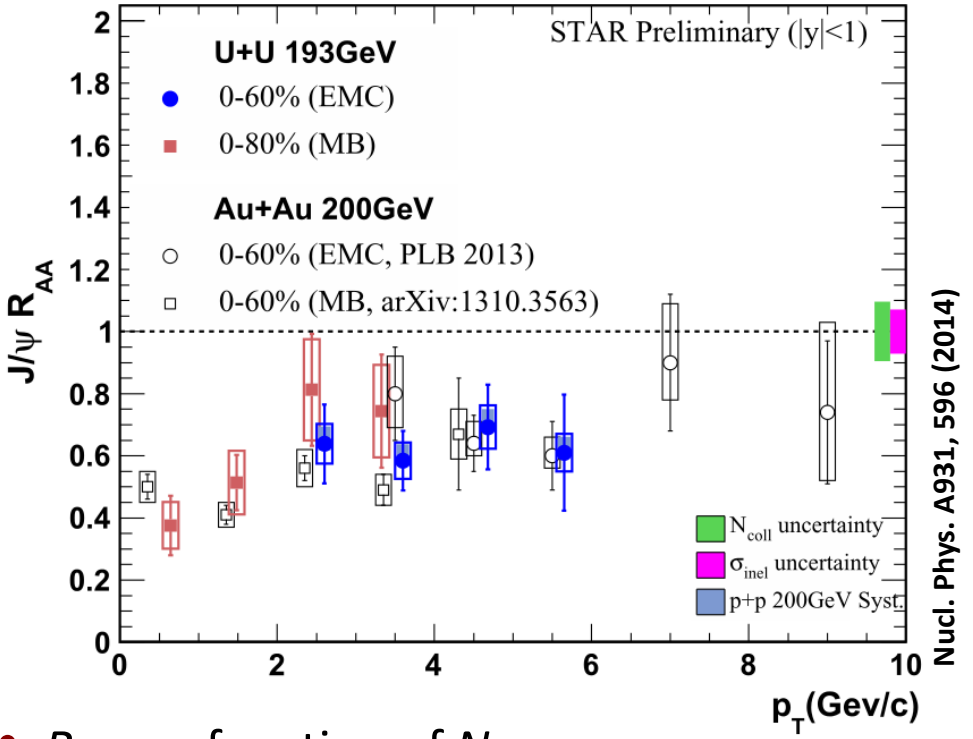
U+U
tip+tip

J/ψ in U+U collisions

- Suppression of J/ψ production in minimum-bias (MB) 193 GeV U+U collisions (Run 12) is similar to that observed in 200 GeV Au+Au collisions
  - p+p reference from 200 GeV



theoretical calculation: X. Zhao, R. Rapp, Phys. Rev. C82, 064905 (2010)
CEM: R. E. Nelson, R. Vogt and A. D. Frawley, Phys. Rev. C87, 014908 (2013)



- R_{AA} as a function of N_{part}
  - No significant energy dependence observed in Au+Au at 39, 62.4 and 200 GeV
  - **U+U MB data** is consistent with Au+Au results with similar N_{part}

J/ψ in U+U collisions

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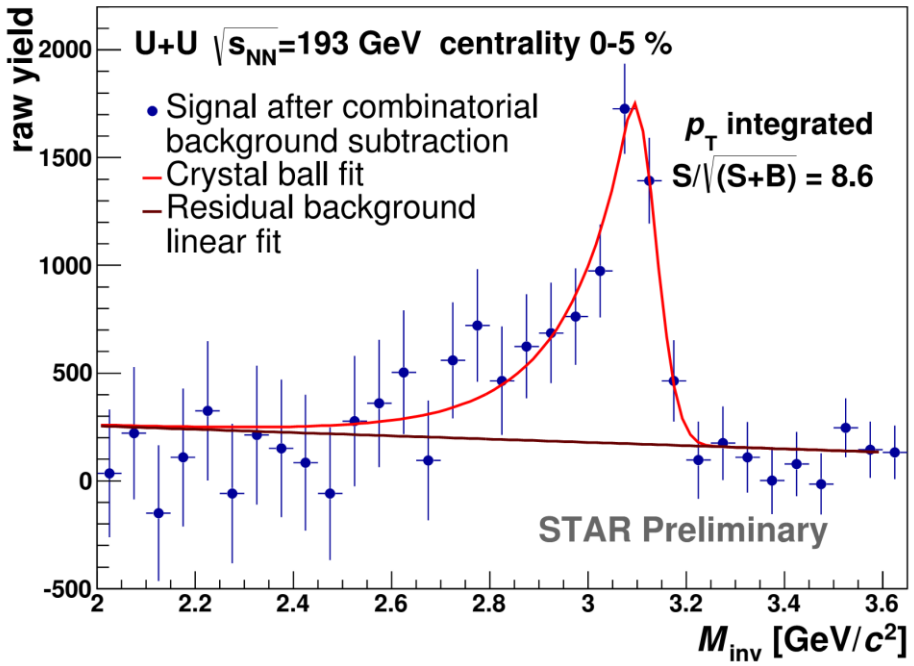

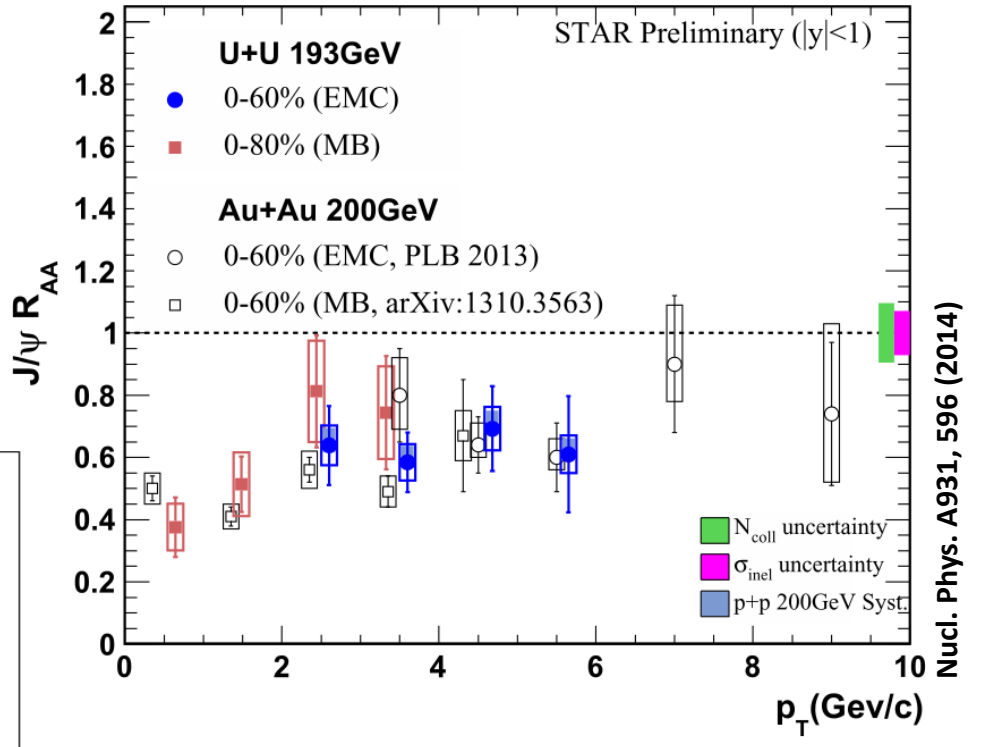

- Study of J/ψ suppression in central U+U collisions is underway

Summary

- **J/ψ production and polarization in 500 GeV p+p collisions:**
  - p_T spectrum described well by NRQCD prediction
  - Trend towards longitudinal polarization with increasing p_T

- **J/ψ R_{AA} from di-electron decay channel in Au+Au at 39, 62.4 and 200 GeV and U+U at 193 GeV collisions:**
  - No significant energy dependence observed in Au+Au collisions
  - 200 GeV Au+Au: high p_T J/ψ supressed in central Au+Au collisions at 200 GeV
  - Suppression seen in U+U collisions is similar to that observed in 200 GeV Au+Au collisions

- **New results on J/ψ R_{AA} via di-muon decay channel using MTD:**
  - Consistent with results from di-electron decay channel

Thank you for your attention !