Heavy quarkonium production at the STAR experiment

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Outline

- Motivation: QGP and quarkonia
- The STAR experiment at RHIC
- J/ψ production in p+p collisions
- Energy dependence of J/ψ R_{AA} in Au+Au collisions
- ϒ and J/ψ in U+U collisions
- Conclusions

Quarkonia as a probe of QGP

- Large masses of c, b quarks
  - created during initial stages of collision
- Color screening of quark potential in QGP
  quarkonium dissociation is expected

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

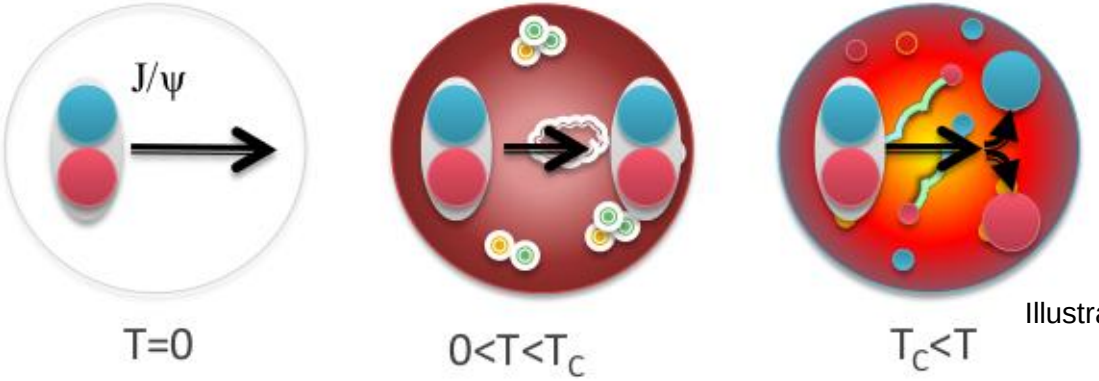

Illustration: A.Rothkopf

Charmonia ($c\bar{c}$):
J/ψ, ψ', χ_c

Bottomonia ($b\bar{b}$):
Υ(1S), Υ(2S), Υ(3S), χ_B

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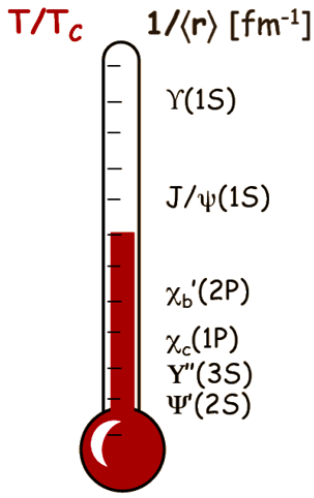
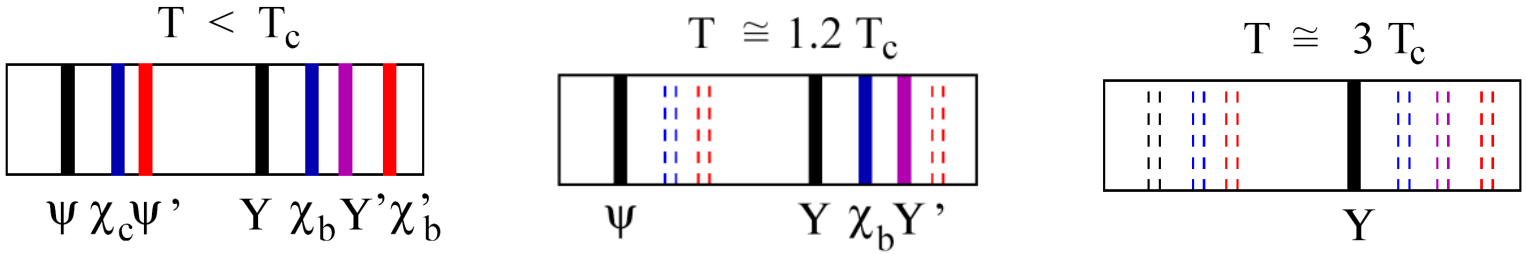


- Suppression determined by medium temperature and quarkonium binding energy.

Á. Mócsy, P. Petreczky, Phys. Rev. D77, 014501 (2008)



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

STAR quarkonium systematics

J/ψ measurements

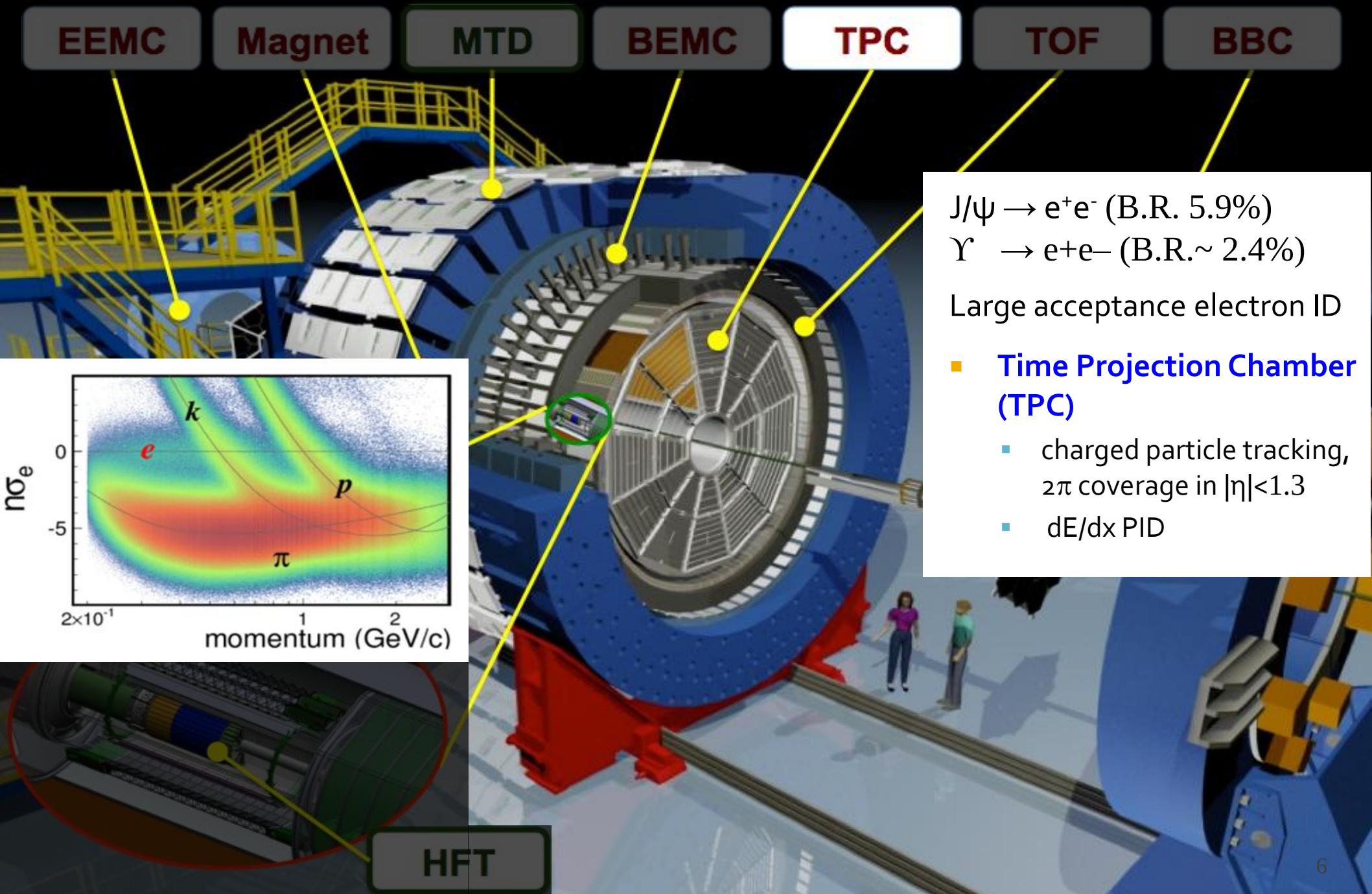
- Different collision systems
  p+p : baseline, **J/ψ production mechanism**
  d+Au : **cold nuclear matter** (CNM) effects
  Au+Au, U+U: **hot plasma effects**, different energy densities
- **Beam energy scan**:
  Different collision energy - different temperature reached
  -> vary contribution of direct production and regeneration
- High-p_T J/ψ
  smaller influence of regeneration and **CNM effects**

ϒ measurements

- **co-mover absorption → negligible**
  ϒ(1S): tightly bound, larger kinematic threshold.
  Expect σ~ 0.2 mb, 5-10 times smaller than for J/ψ
  Lin & Ko, PLB 503 (2001) 104
- **recombination → negligible**
  at RHIC: σ_{cc} ~800μb >> σ_{bb} ~(1-2)μb
- Excited states: expect **sequential suppression** of ϒ(1S), ϒ(2S), ϒ(3S) states
- **Challenge**: low rate, rare probe
  Need large acceptance, efficient trigger

ϒ -cleaner probe compared to J/ψ

Electron ID at STAR



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

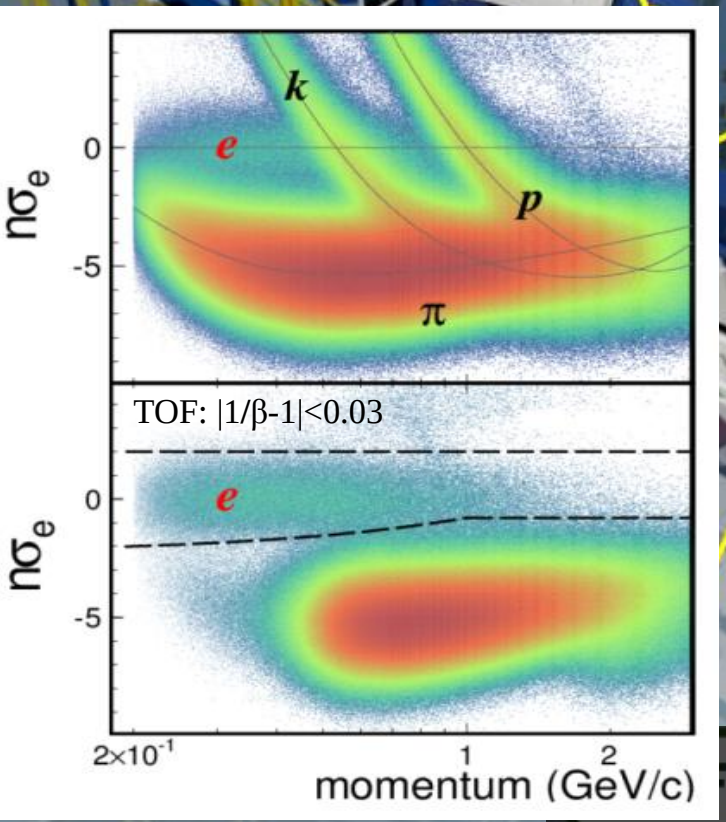
$\Upsilon \rightarrow e^+e^-$ (B.R.~ 2.4%)

Large acceptance electron ID

- **Time Projection Chamber (TPC)**
  - charged particle tracking, 2π coverage in $|\eta|<1.3$
  - dE/dx PID

Electron ID at STAR

EEMC | Magnet | MTD | BEMC | TPC | TOF | BBC



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- **Time Projection Chamber (TPC)**
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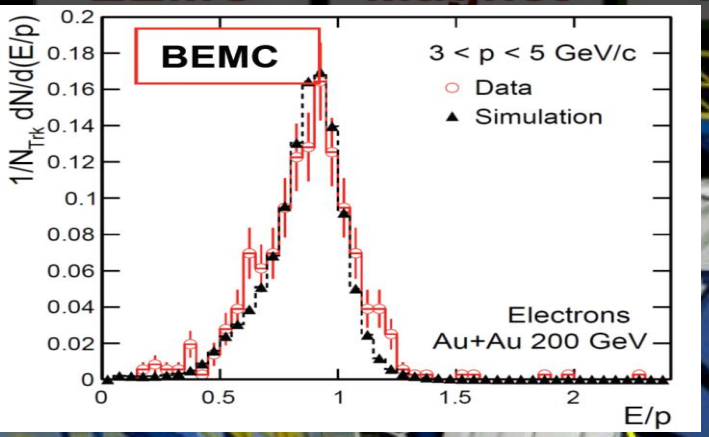
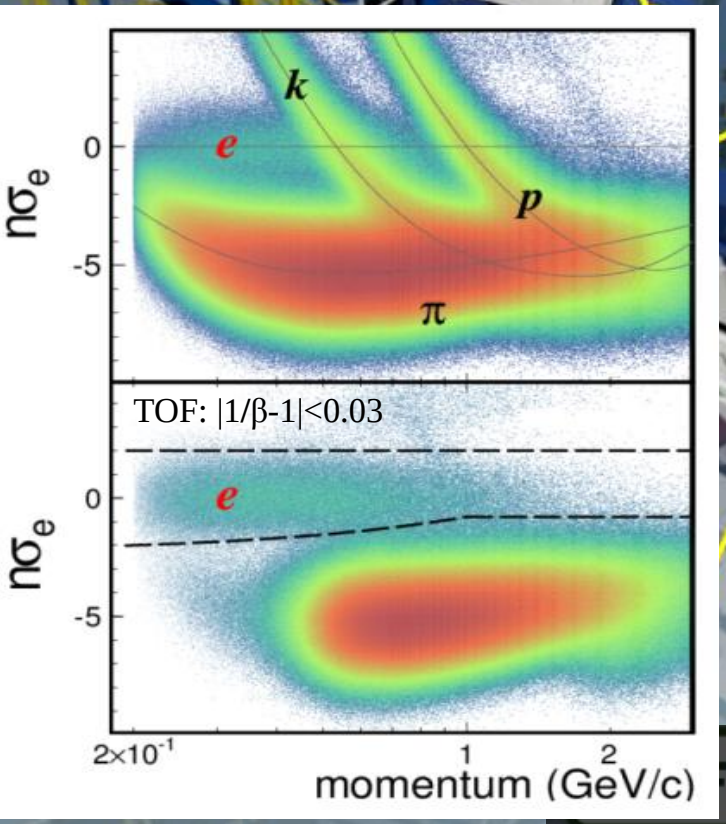
  - dE/dx PID
- **Time Of Flight(TOF)**
  - Timing resolution <100 ps
  - $1/\beta$ PID
  - e purity >90%

Electron ID





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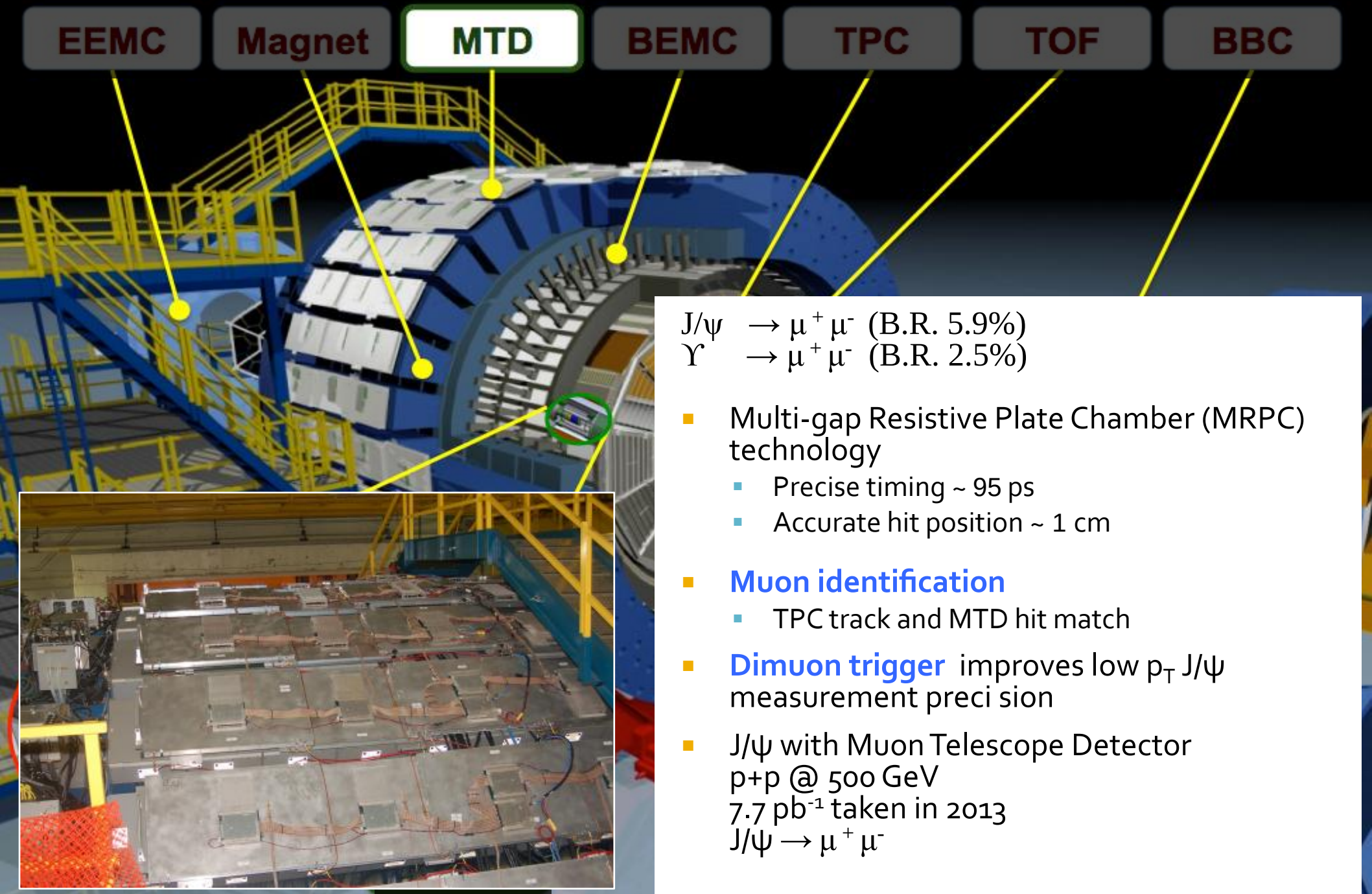
Large acceptance electron ID

- **Time Projection Chamber (TPC)**
  - charged particle tracking, 2π coverage in $|\eta|<1.3$
  - dE/dx PID
- **Time Of Flight(TOF)**
  - Timing resolution <100 ps
  - $1/\beta$ PID
  - e purity >90%
- **EM Calorimeter**
  - 2π coverage in $|\eta|<1$
  - Electron ID via E/p ~ 1
  - Triggering capability

Muon ID at STAR



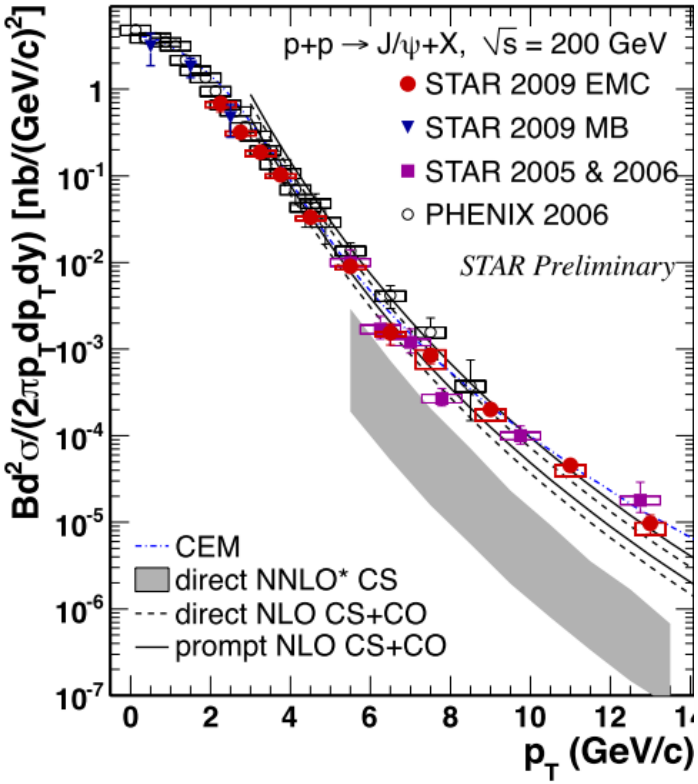
$J/\psi \rightarrow \mu^+\mu^-$ (B.R. 5.9%)
$\Upsilon \rightarrow \mu^+\mu^-$ (B.R. 2.5%)

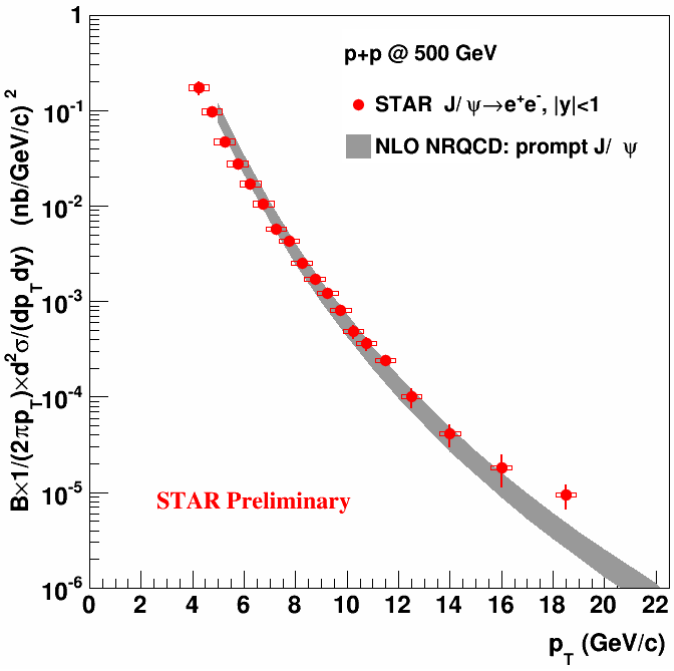
- Multi-gap Resistive Plate Chamber (MRPC) technology
  - Precise timing ~ 95 ps
  - Accurate hit position ~ 1 cm
- **Muon identification**
  - TPC track and MTD hit match
- **Dimuon trigger** improves low p_T J/ψ measurement preci sion
- J/ψ with Muon Telescope Detector
  p+p @ 500 GeV
  7.7 pb^{-1} taken in 2013
  $J/\psi \rightarrow \mu^+\mu^-$

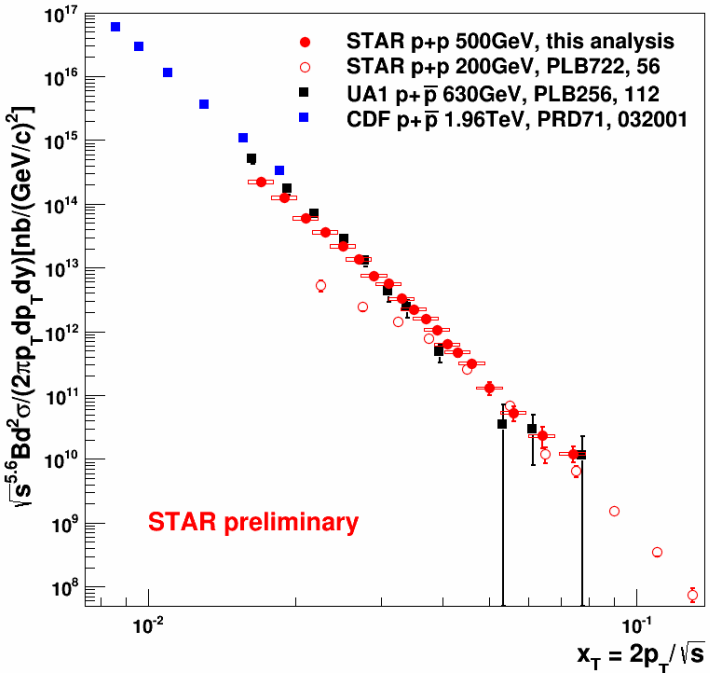
J/ψ in p+p collisions

JPG38,124107(2011), PRC80,041902(R) (2009), PRC82,012001(2010)

see talk of B. Trzeciak on quarkonia polarization …







- NNLO* CS(color singlet), direct production
  - misses high-p_T part
- prompt color evaporation model (CEM) can reasonably describe the p_T spectra
- NLO NRQCD, prompt production, describes the data for p_T > 4 GeV/c

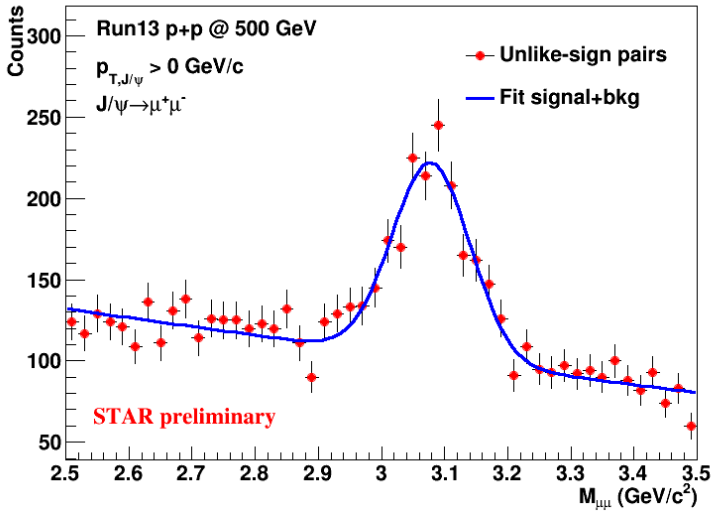
- p_T > 5 GeV/c – J/ψ production follows the x_T scaling of cross-section at mid-rapidity, with n ~ 5.
- x_T scaling breaking - transition from hard to soft processes

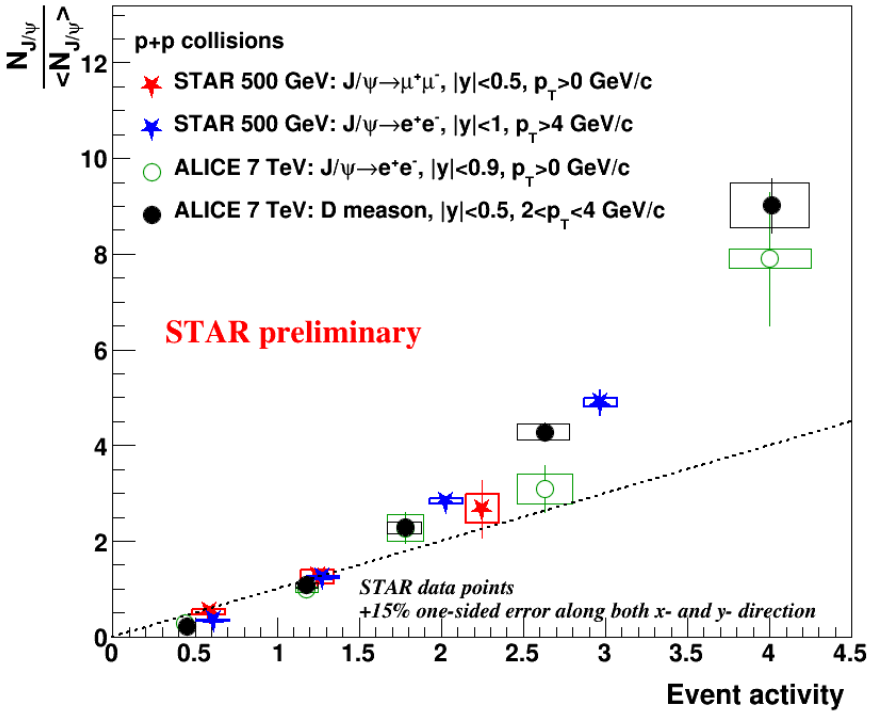
NLO NRQCD: Phys.Rev.Lett. 106 (2011) 042002, Phys Rev. D84 (2011) 114001, JHEP 1505 (2015) 103, and priv. communication

J/ψ yield vs event activity in p+p 500 GeV

- MTD dimuon trigger greatly improves low p_T J/ψ measurement precision

$J/\psi \rightarrow e^+e^-$ with BEMC 22 pb^{-1} taken in 2011
$J/\psi \rightarrow \mu^+\mu^-$ with MTD 7.7 pb-1 taken in 2013





Correlation between quarkonium yields and multiplicity in pp

- Faster rise for higher p_T
- Similar trend at LHC for J/ψ and open charm production

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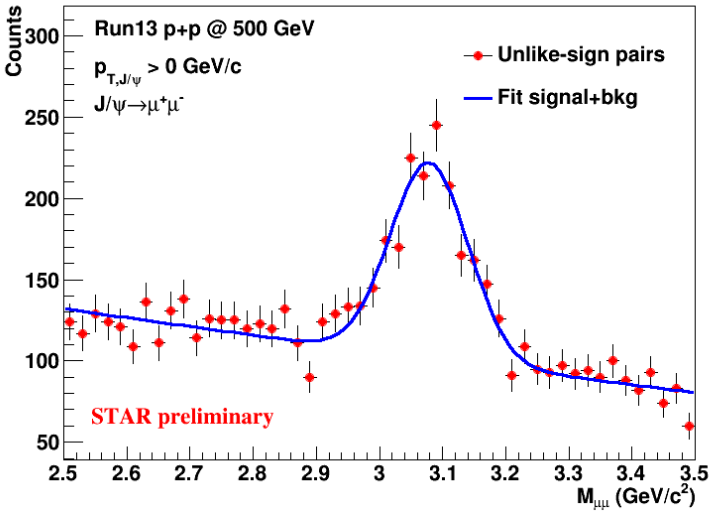
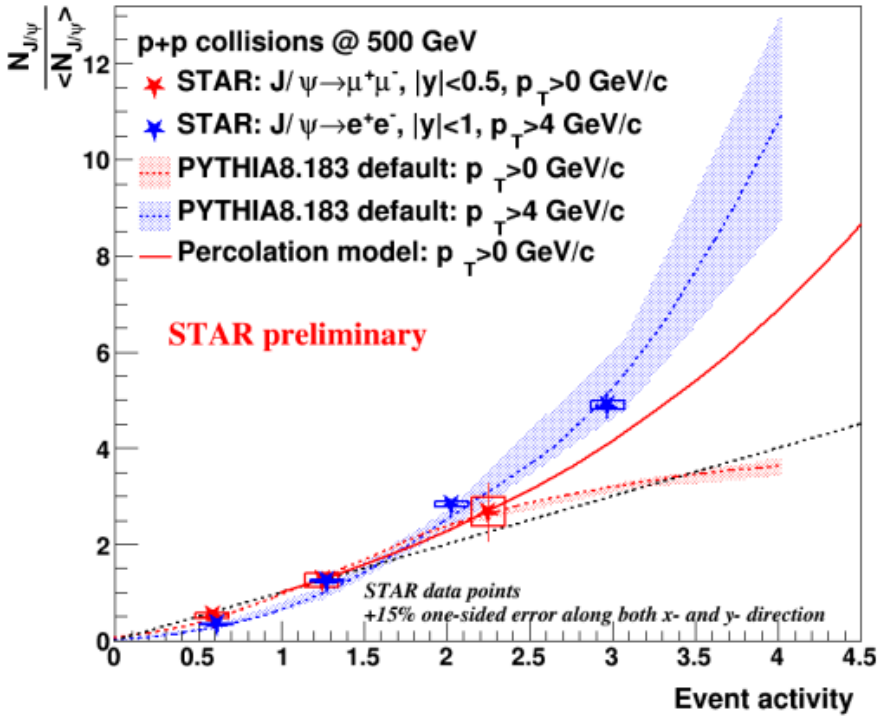




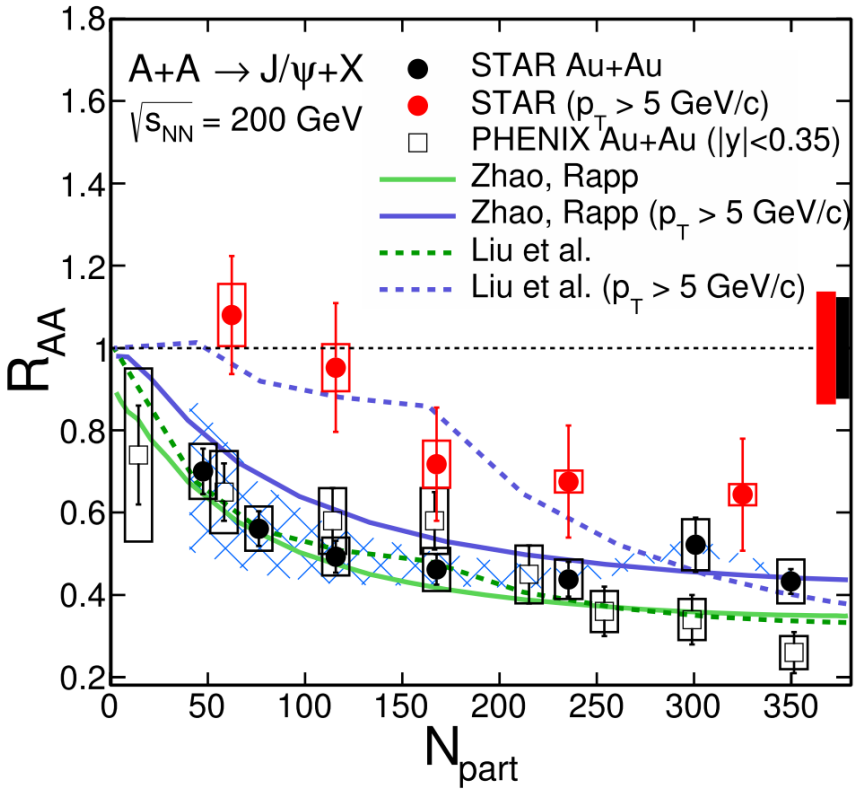
Possible explanations:

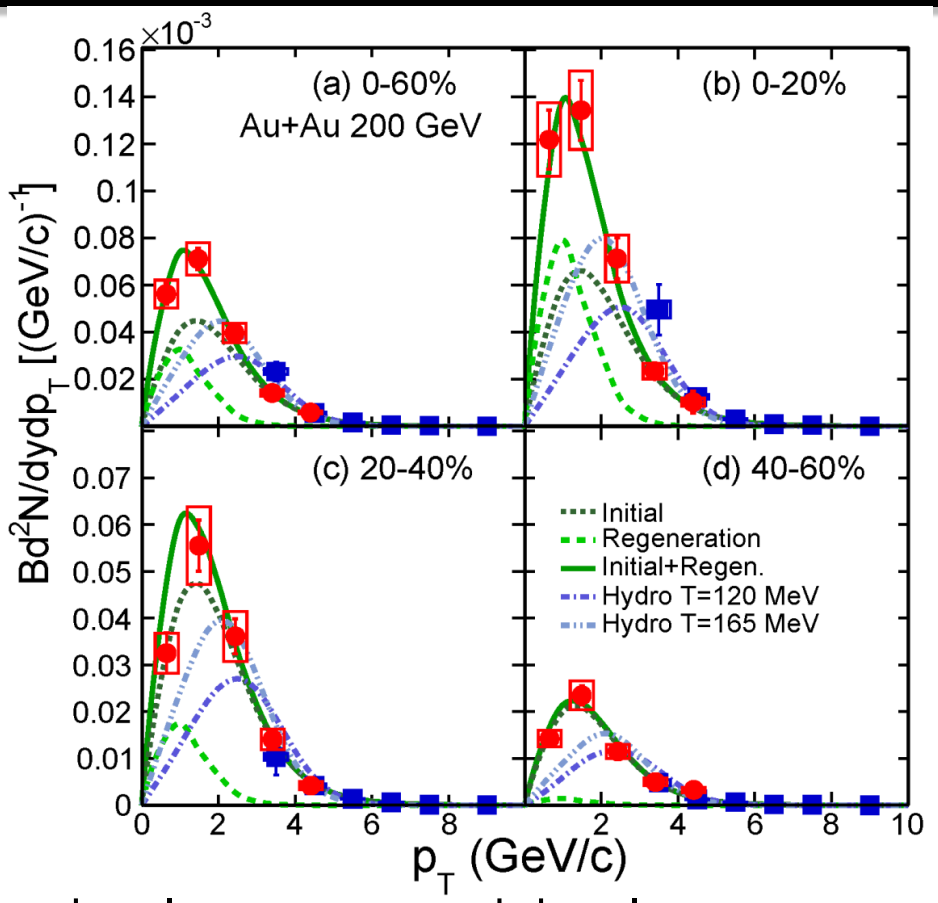
- Multiple parton-parton interactions - PYTHIA 8
- String screening – percolation model, PRC 86 (2012) 034903, and priv. communication
- Hadronic activity associated with J/ψ production

J/ψ in Au+Au at 200 GeV

- Models with suppression of **initial production and recombination** reasonably describe the J/ψ production

Liu et al., PLB 678, 72 (2009)
Zhao and Rapp, PRC 82, 064905(2010) ; PLB 664, 253 (2008)
U. W. Heinz and C. Shen (2011), private communication.

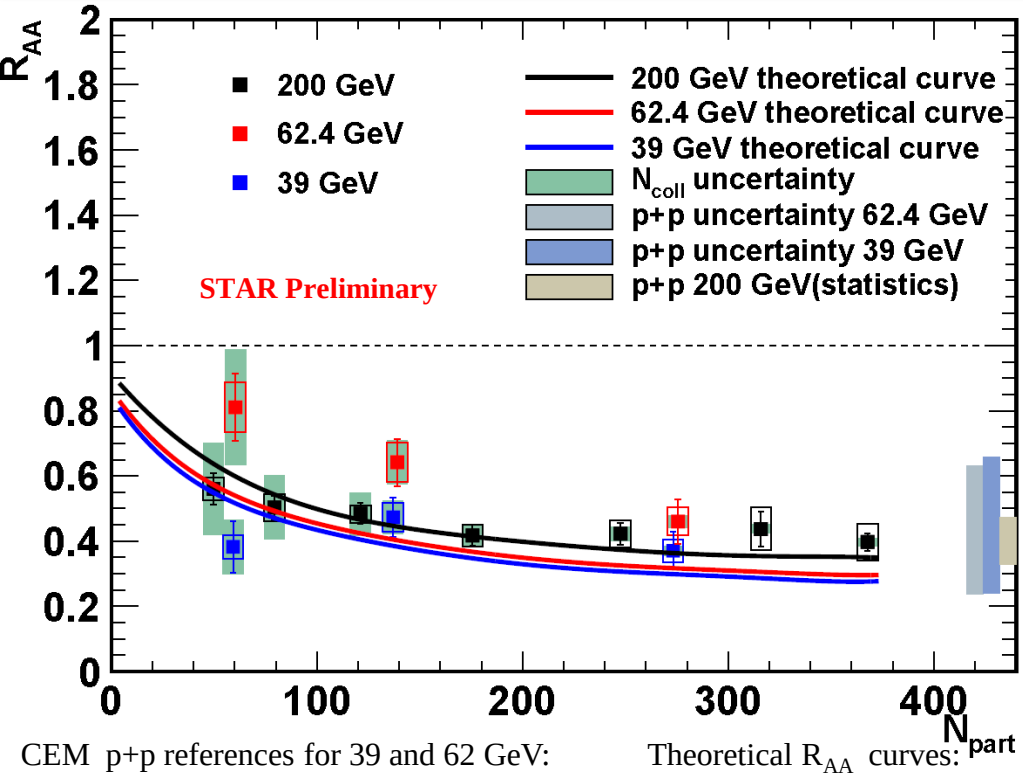


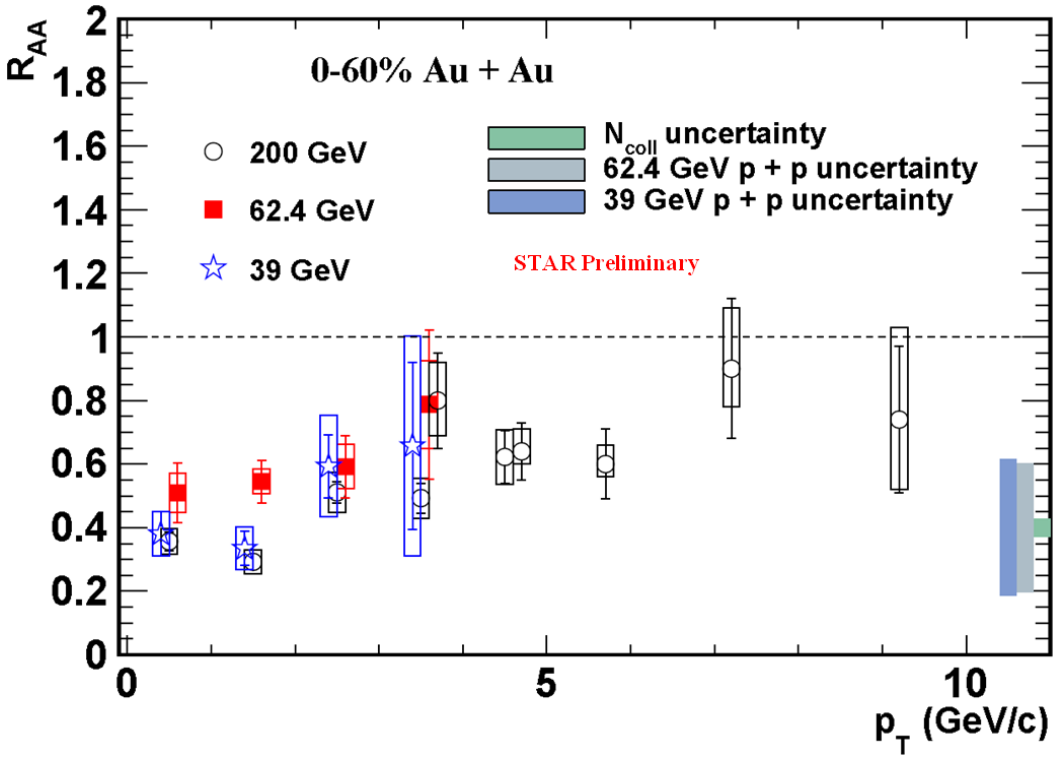


- High p_T data less suppressed than low p_T
  - Smaller influence of recombination and CNM effects in this region
  - May indicate QGP effects.

Beam Energy Scan – changing contribution of different effects

Energy dependence of J/ψ R_{AA}



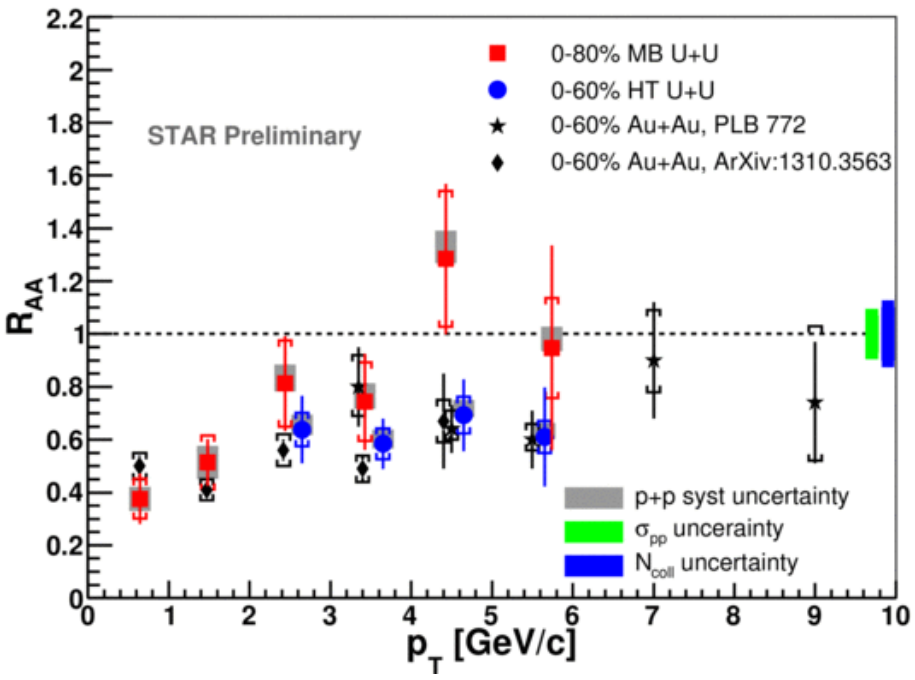


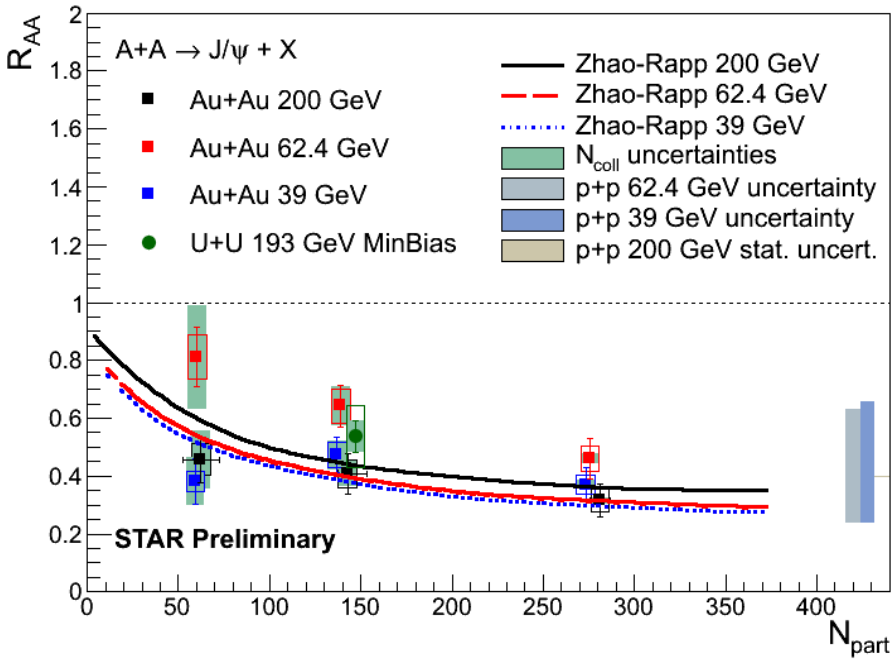
CEM p+p references for 39 and 62 GeV:
Nelson, Vogt et al., PRC87, 014908 (2013)

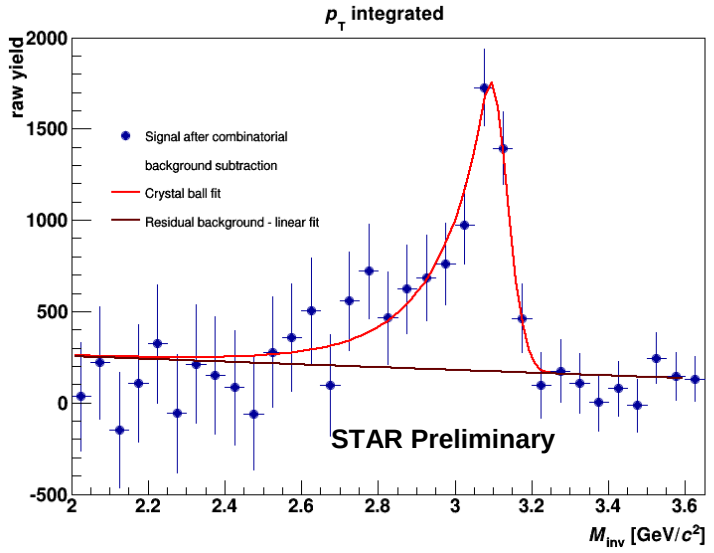
Theoretical R_{AA} curves:
Zhao, Rapp PRC82, 064905 (2010)

- Similar suppression in Au+Au at 200, 62.4 and 39 GeV
  - p+p reference is based on CEM calculations
  - Large theoretical uncertainty
- Consistent with theoretical calculations
  - Almost **compensating interplay of melting and recombination**?

J/ψ R_{AA} in U+U



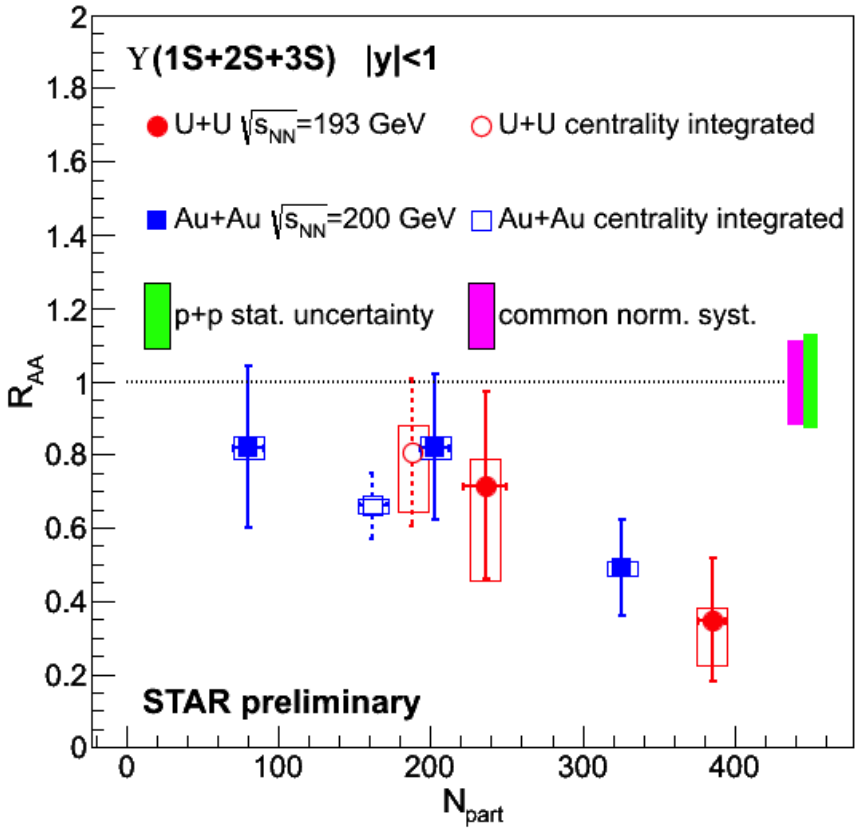


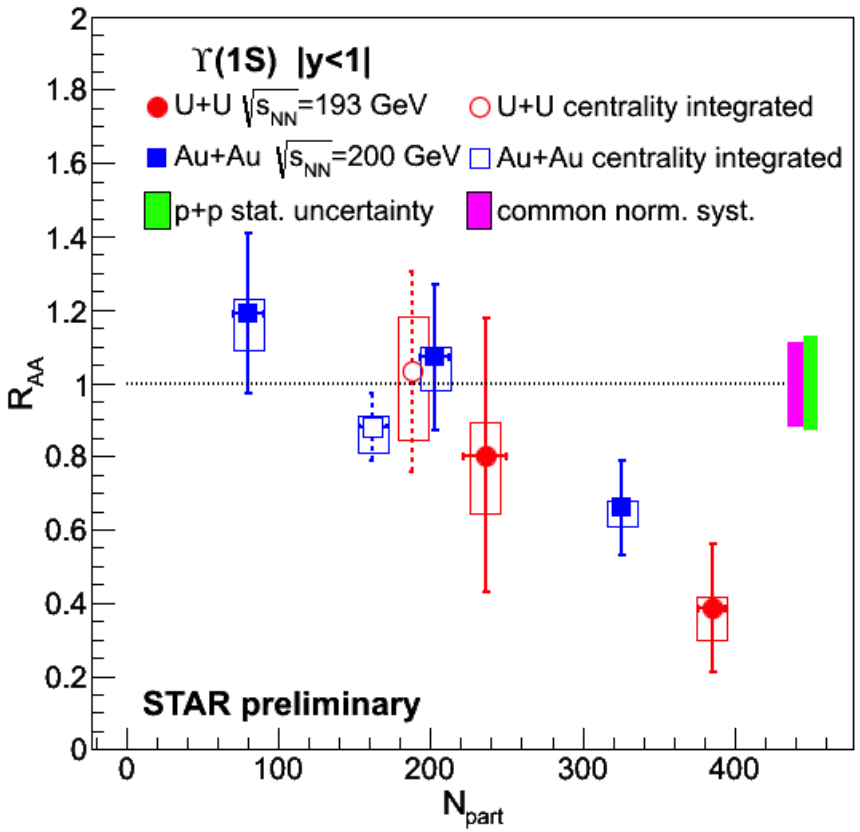


- U+U collisions
  - higher energy density
  - number of binary collisions
- Nuclear modification factor as a function of p_T similar to Au+Au
  - p+p reference from 200 GeV used
- Centrally triggered data under study

..see poster of J. Fodorova

ϒ suppression: Au+Au and U+U



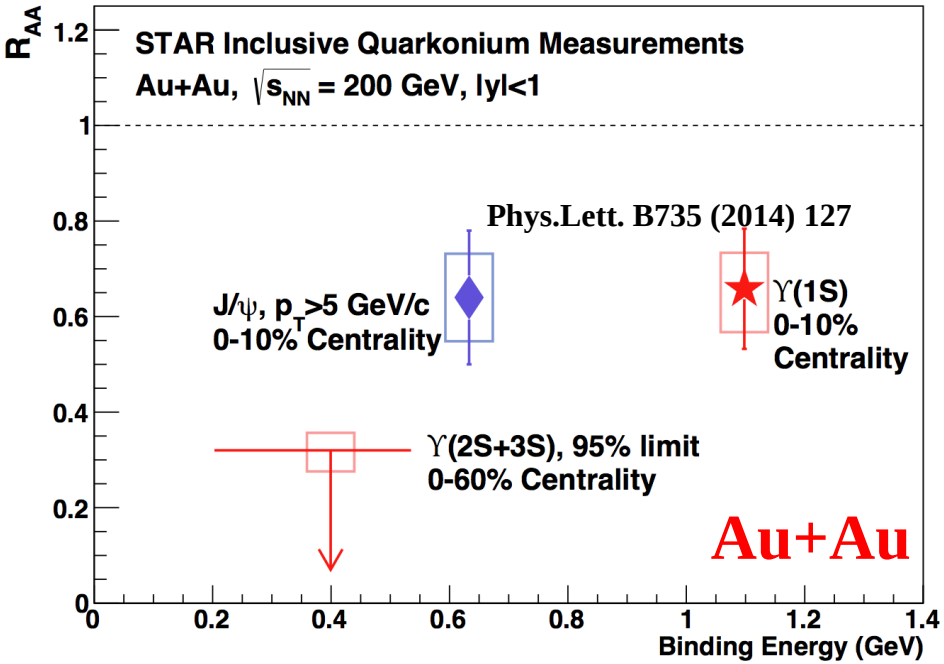


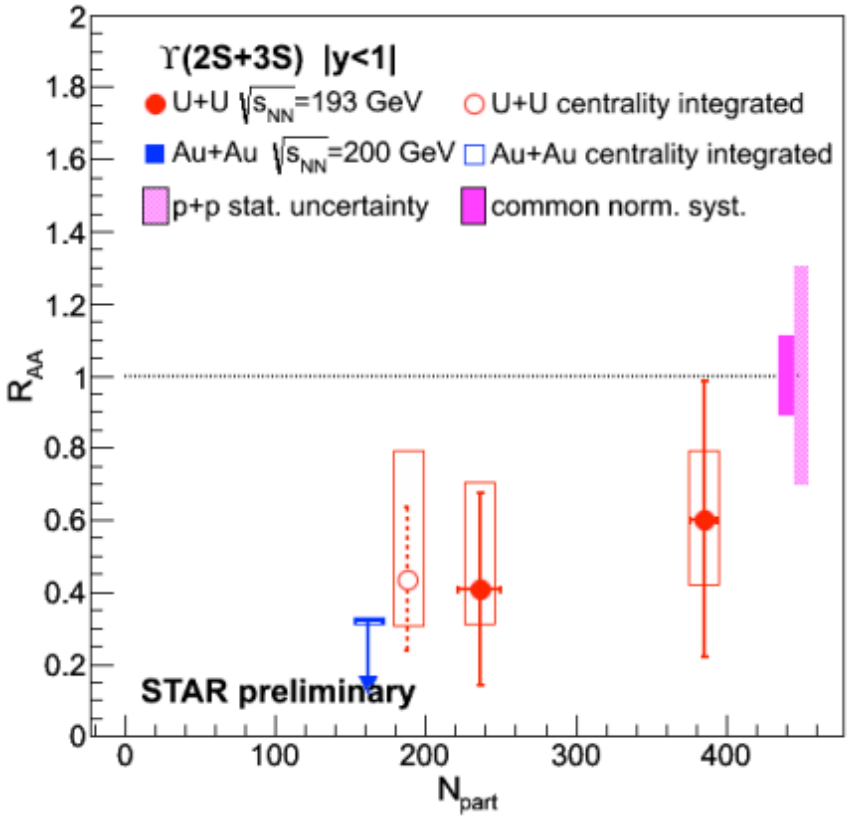
- Peripheral :
  consistent with no suppression
- Central :
  significant suppression

- Central ϒ(1S)
  U+U: significant suppression

Similar ϒ suppression trend in Au+Au and U+U collisions

Supression of Υ states





Central Au+Au:

- Excited states Υ (2S) and Υ (3S) consistent with complete melting
- Υ(1S) suppression is similar to high-p_T J/ψ

U+U: consistent with Au+Au

Υ suppression pattern supports sequential melting

Summary

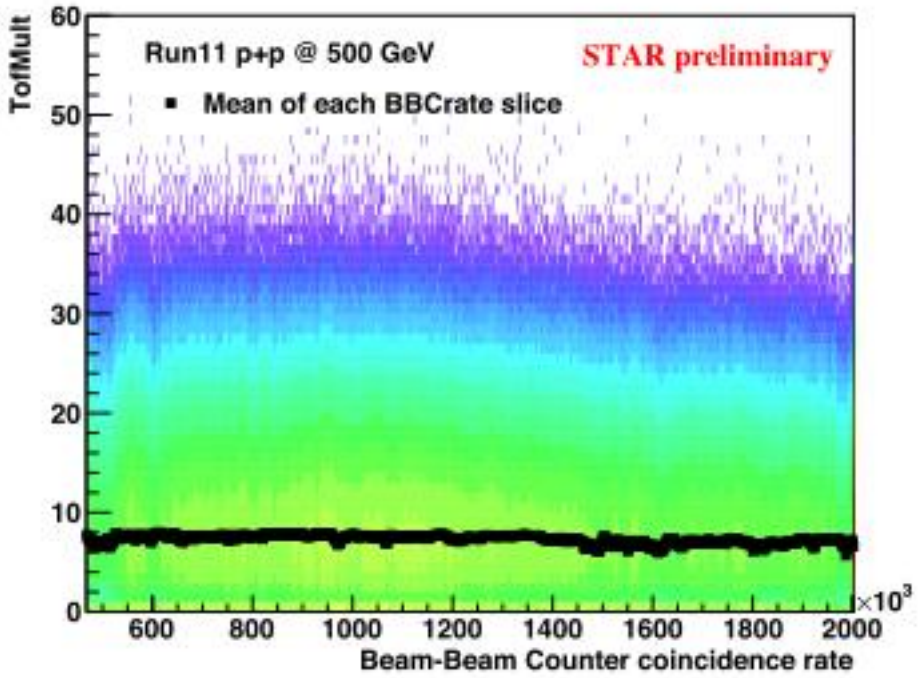
- **J/ψ in p+p** 200 and 500 GeV
  - J/ψ p_T spectra described well by NRQCD
  - Increase of relative J/ψ yield with relative charged-particle multiplicity in p+p at 500 GeV
    - Stronger than linear rise at higher multiplicities at $p_T > 4$ GeV/c
- **J/ψ in Au+Au** at 39 GeV and 62.4 GeV **and U+U** collisions at 193 GeV
  - Similar suppression as in Au+Au 200 GeV within uncertainties
  - Consistent with interplay of melting and regeneration
- **ϒ in Au+Au** at 200 GeV and **and U+U** at 193 GeV - hot medium effects
  - Significant suppression of ϒ states in central collisions
  - U+U extends the Au+Au observations – similar suppression pattern
  - ϒ(1S) is similarly suppressed as high- p_T J/ψ
  - ϒ(2S) and ϒ(3S) suppression is stronger than ϒ(1S)

- BACKUPS

Characterize event activity

- Time of Flight based event activity
  - Multiplicity of TOF matched tracks $|\eta|<0.9$

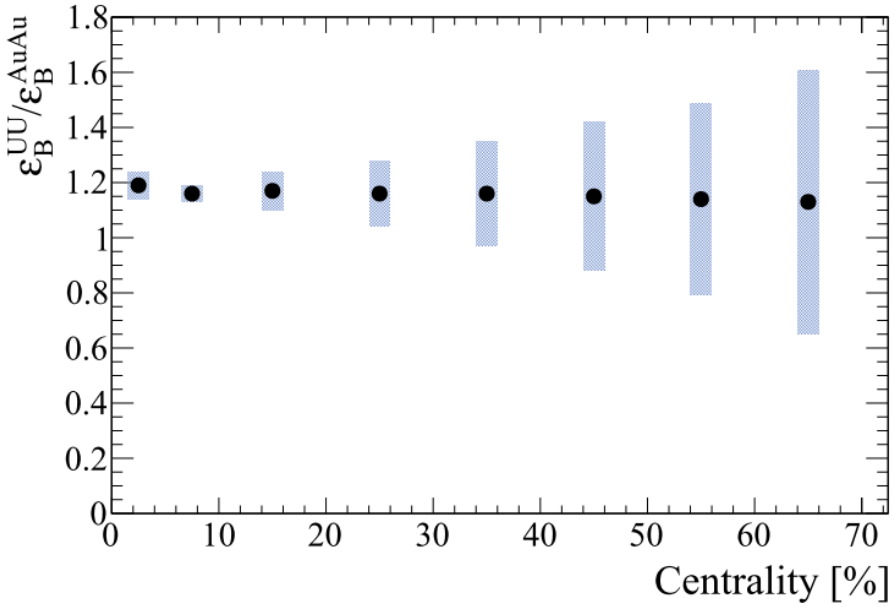
$$\text{Event activity} = \frac{\text{TofMult}}{<\text{TofMult}>}$$



Insensitive to pile-up effects

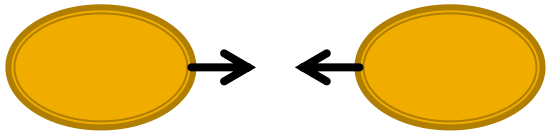
U+U collisions at 193 GeV

- Uranium nucleus is larger than Au and non-spherical
- U+U collisions provide higher energy density then Au+Au
  - Tip-to-tip collisions - highest energy density
- Larger number of binary collisions
  - Increased charm production and recombination
- These two effects go in opposite directions

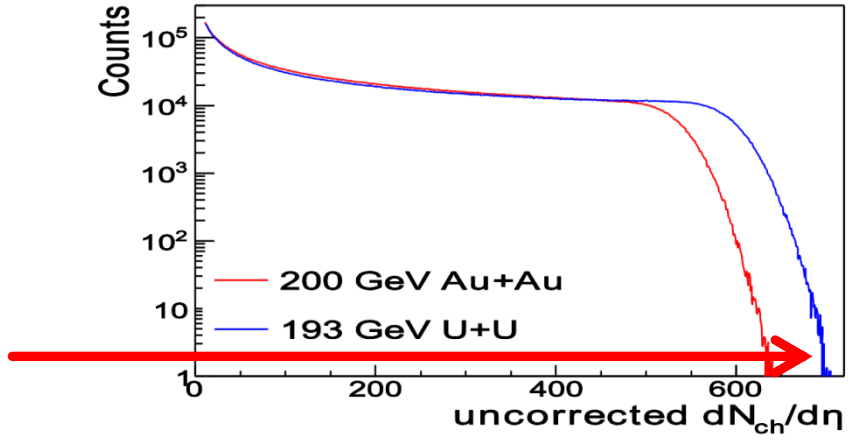


Kikola, Odyniec, Vogt, Phys. Rev. C 84, 054907

U+U collisions: study of interplay between color screening and recombination

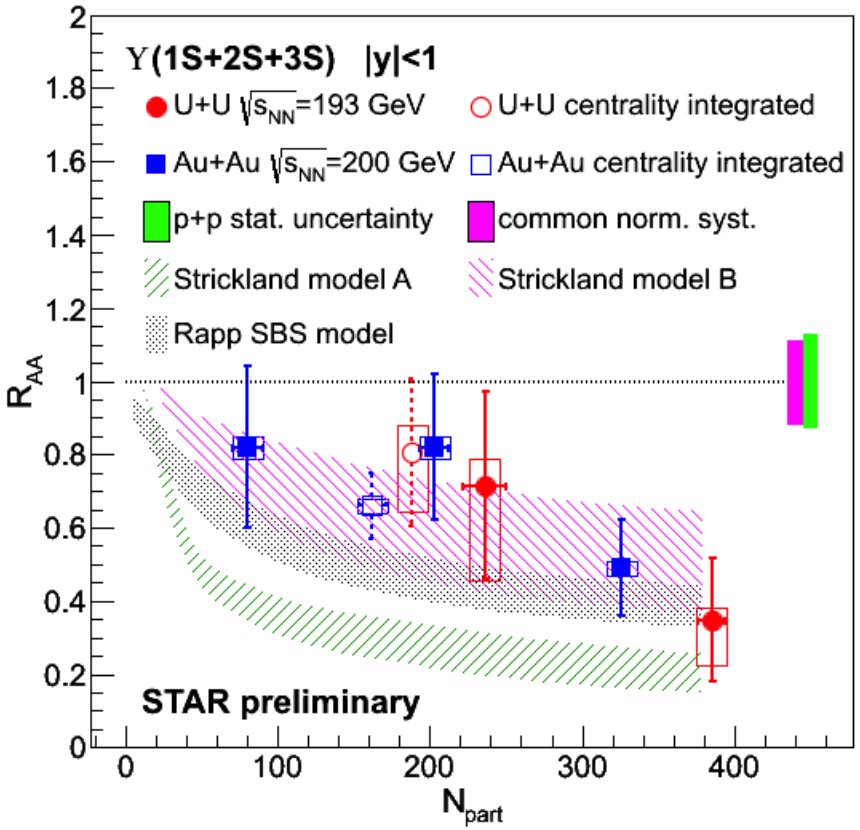


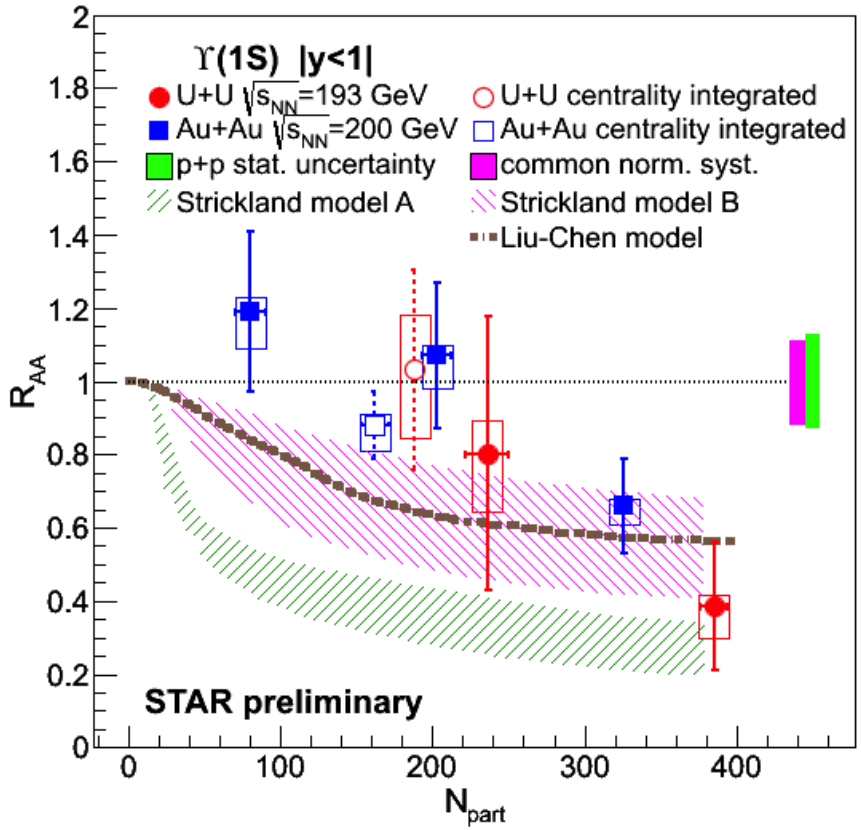
Tip-to-tip collision



STAR Collaboration: arXiv 1310.3563 (2013)

Υ R_{AA} : data vs. models





Strickland, Bazov, Nucl.Phys.A 879, 25 (2012)

- No CNM effects, 428<T<443 MeV
- Potential model 'B' based on **heavy quark internal energy**
- Potential model 'A' based on heavy quark free energy (disfavored)

Liu, Chen, Xu, Zhuang, Phys.Lett.B 697, 32 (2011)

- Potential model, no CNM effects
- T=340 MeV, only excited states dissociate

Emerick, Zhao, Rapp, Eur.Phys.J A48, 72 (2012)

- **CNM effects** included
- Strong binding scenario

Suppression indicates Υ melting in a deconfined medium