Quarkonium Measurements in p+p, p+Au and Au+Au Collisions at $\sqrt{s_{NN}} = 200$ GeV with the STAR Experiment

Zaochen Ye (Rice University)

at HENPIC Seminar

Outline

- Quarkonium as a Probe of QGP
- RHIC and STAR Experiment
- Charmonium
- Bottomonium
- Summary

Quarkonium as a Probe of QGP

Quarkonium: charmonium($c\bar{c}$) and bottomonium ($b\bar{b}$):

- **$m_c = 1.2\text{-}1.4\ \mathrm{GeV}/c^2$, $m_b = 4.6\text{-}4.9\ \mathrm{GeV}/c^2 > \Lambda_{QCD}$ dominantly produced at early stage**

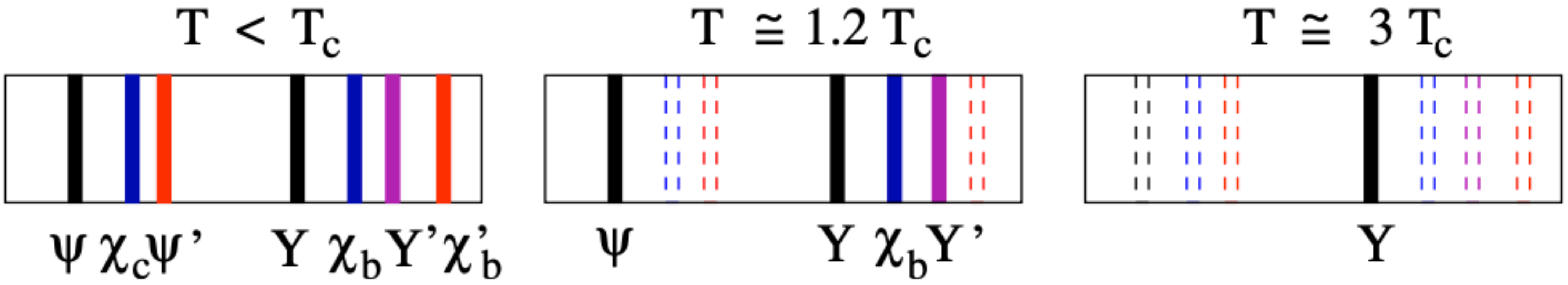
Quarkonium suppression, was suggested as a signature of the QGP formation in heavy-ion collisions:

Matsui, Satz; PLB 178 (1986) 416

- **Color screening:** quark-antiquark potential is color-screened by the surrounding partons

  ➔ **Suppression** of quarkonium

- **"Thermometer"**: different states dissociate at different temperature ➔ **Sequential melting**

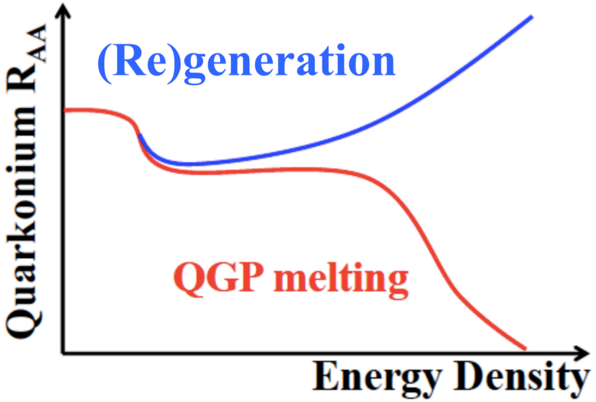


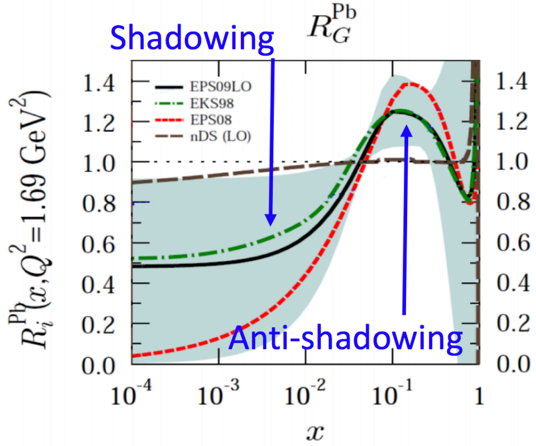
H. Satz, Nucl. Phys. A 783 (2007)

Quarkonium as a Probe of QGP

However, various effects complicate the picture:

- **Regeneration:**
  - **Recombination of deconfined quarks**

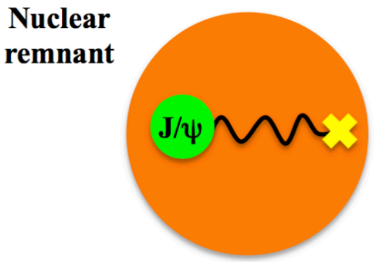




Ferreiro et al., PRC 81 (2010) 064911

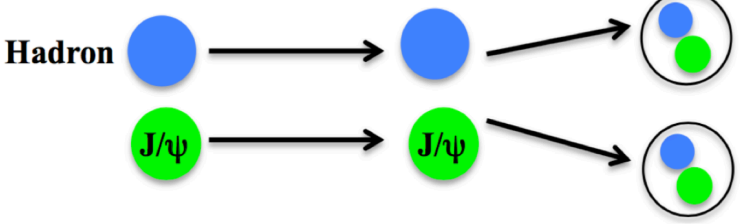
- **Cold Nuclear Matter (CNM) effects:**
  - nPDF: shadowing/anti-shadowing
  - Energy loss
  - Nuclear absorption
  - Interaction with co-movers…

Nuclear absorption



Gavin et al.,
PRL 78 (1997) 1006

Co-Movers



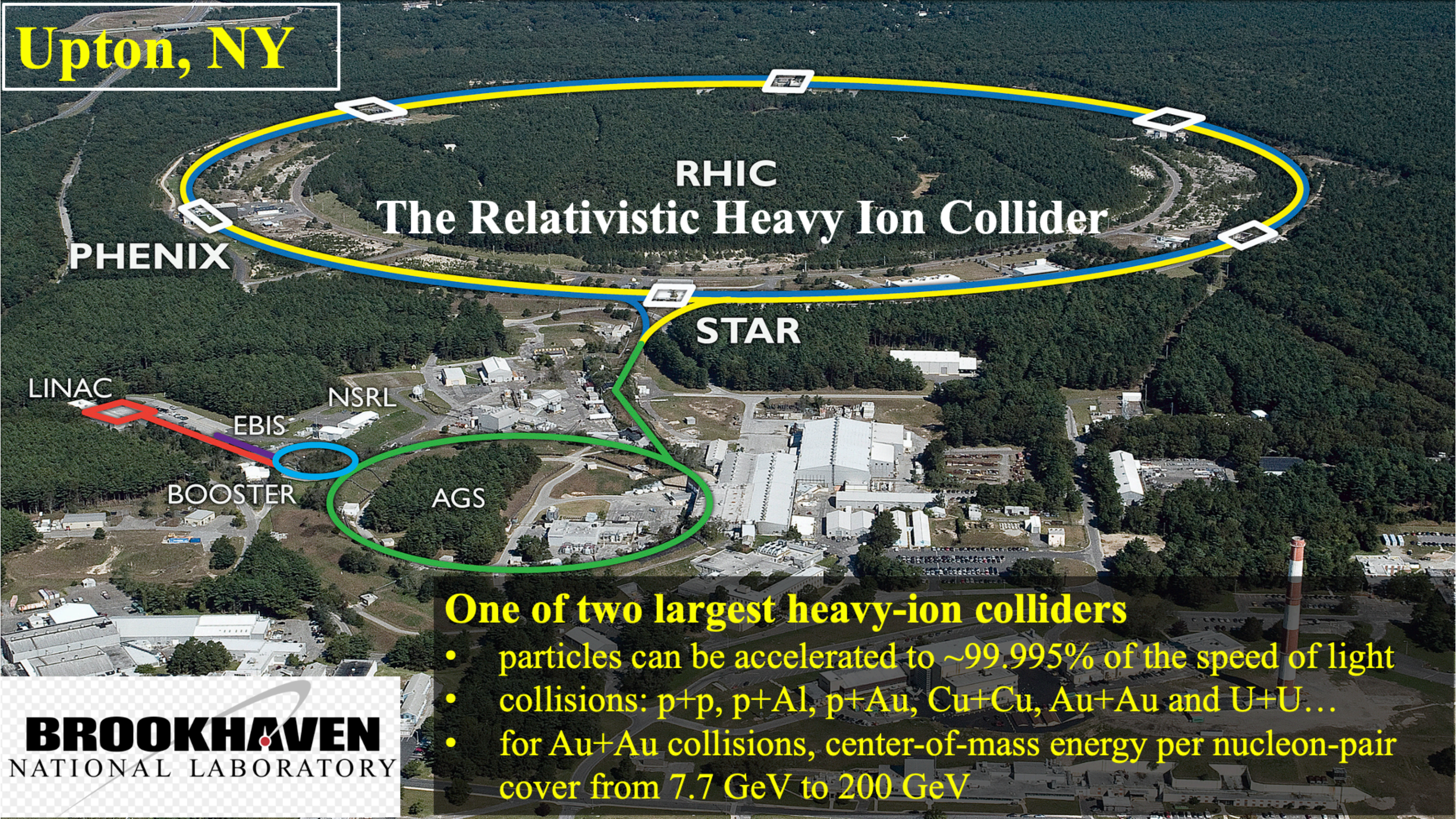
Capella and Ferreiro, EPJC 42 (2005) 419

- **Feed–down contributions:**

	direct	from χ_{c1}	from χ_{c2}	from $\psi(2S)$
"low" P_T J/ψ	79.5 ± 4 %	8 ± 2 %	6 ± 1.5 %	6.5 ± 1.5 %
"high" P_T J/ψ	64.5 ± 5 %	23 ± 5 %	5 ± 2 %	7.5 ± 0.5 %

J.-P. Lansberg, arXiv:1903.09185

Upton, NY

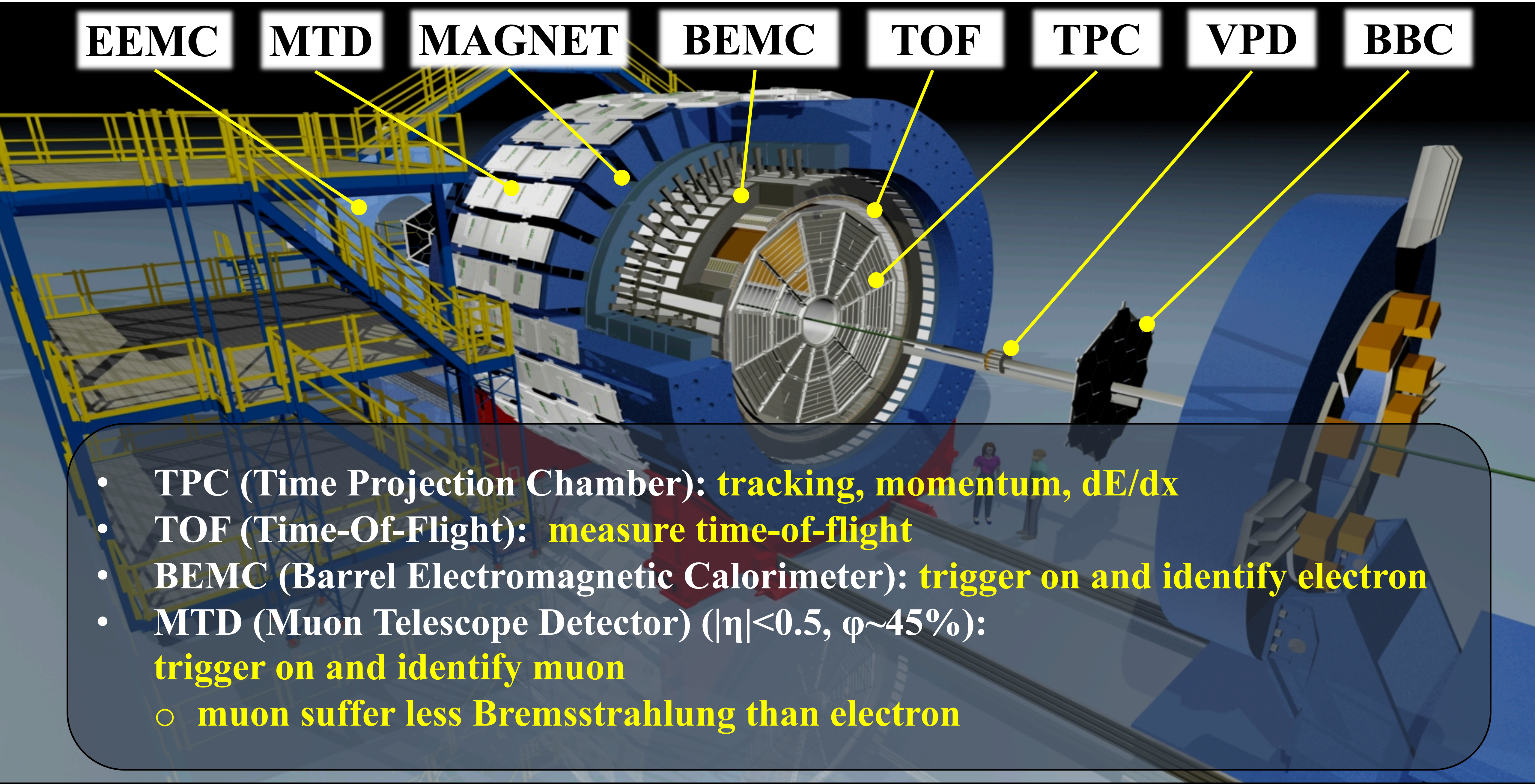


BROOKHAVEN
NATIONAL LABORATORY

One of two largest heavy-ion colliders

- particles can be accelerated to ~99.995% of the speed of light
- collisions: p+p, p+Al, p+Au, Cu+Cu, Au+Au and U+U…
- for Au+Au collisions, center-of-mass energy per nucleon-pair cover from 7.7 GeV to 200 GeV

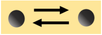
The Solenoidal Tracker At RHIC (STAR)



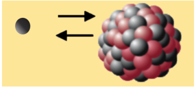
- TPC (Time Projection Chamber): tracking, momentum, dE/dx
- TOF (Time-Of-Flight): measure time-of-flight
- BEMC (Barrel Electromagnetic Calorimeter): trigger on and identify electron
- MTD (Muon Telescope Detector) ($|\eta|<0.5$, φ~45%): trigger on and identify muon
    - muon suffer less Bremsstrahlung than electron

Charmonium production at 200 GeV in different systems:

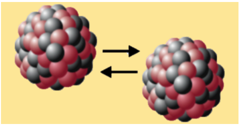
1. p+p collisions



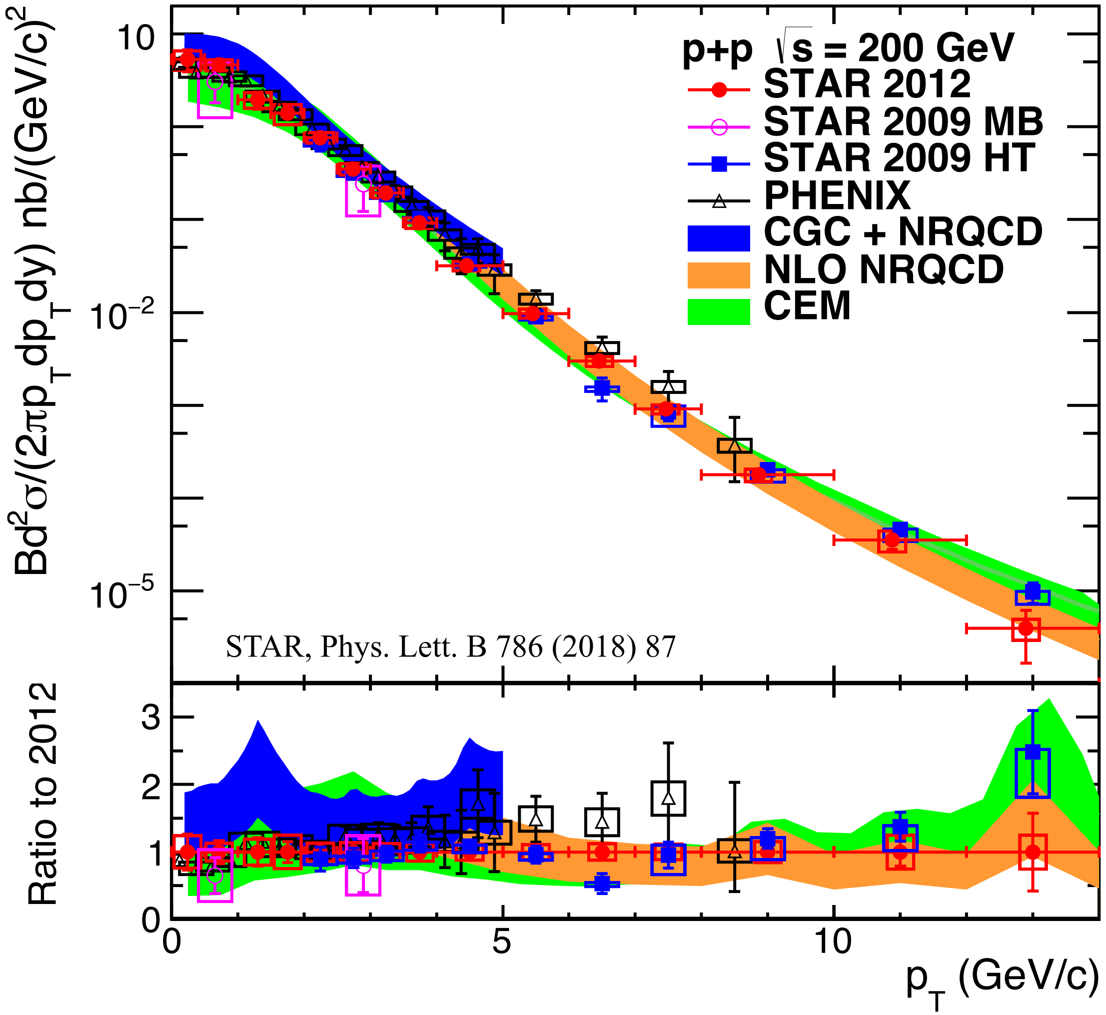
2. p+Au collisions



3. Au+Au collisions



J/ψ in p+p collisions



STAR, Phys. Lett. B 786 (2018) 87

CGC+NRQCD, Ma & Venugopalan, PRL 113 (2014) 192301
NLO+NRQCD, Shao et al., JHEP 05 (2015) 103
CEM, V. D. Barger. W. Y. Keung, and R. J. Phillips, PLB 91 (1980) 253

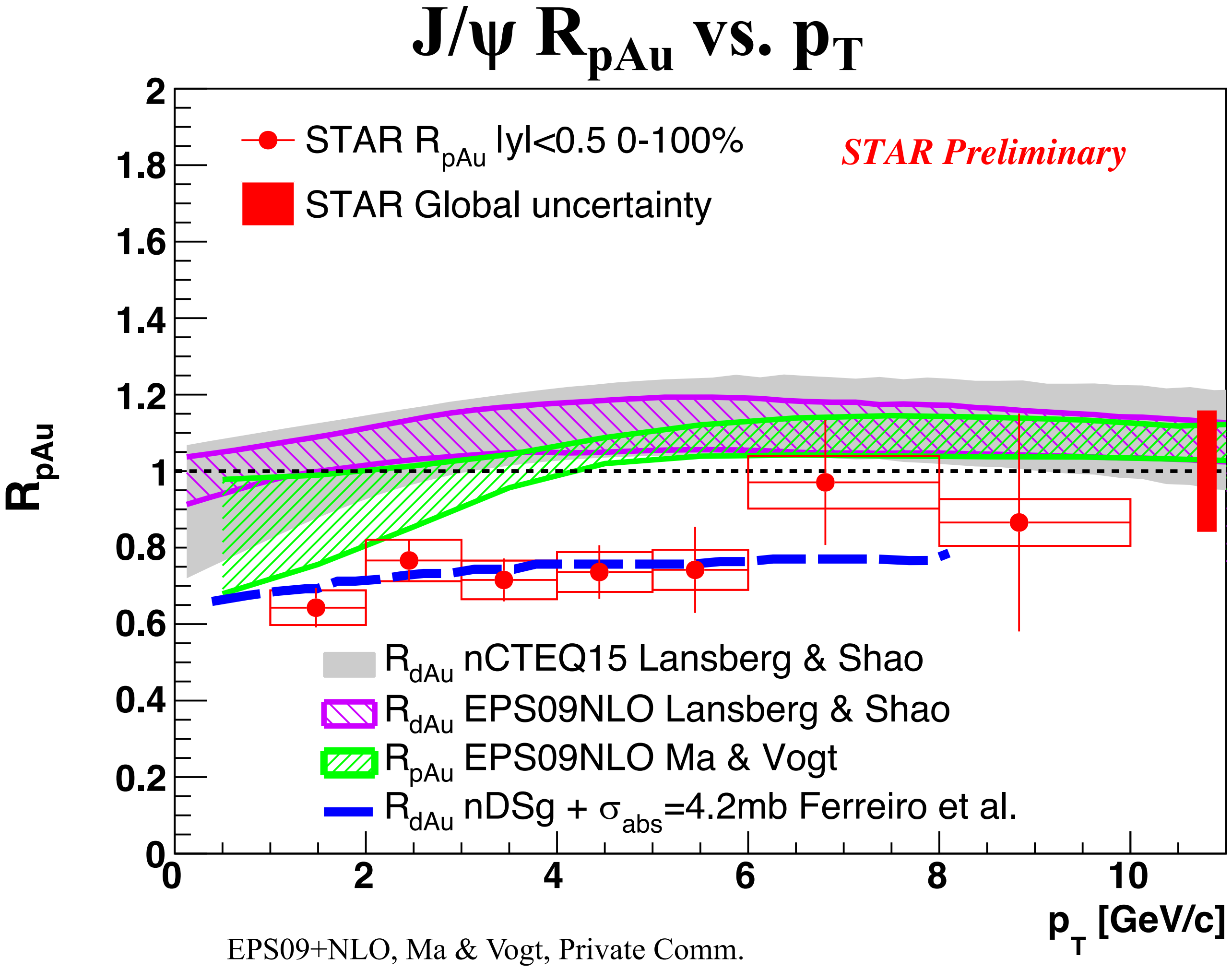
Inclusive J/ψ cross-section measured in $0<p_T<14$ GeV/c:

- ➢ **Consistent with previous measurements but with a better precision**

- ➢ **CEM and NLO NRQCD calculations**
  - **describe the data well for the applicable p_T ranges**

- ➢ **CGC + NRQCD calculations**
  - **lower boundary touches data within uncertainties**

J/ψ in p+Au collisions


J/ψ R_{pAu} vs. p_T

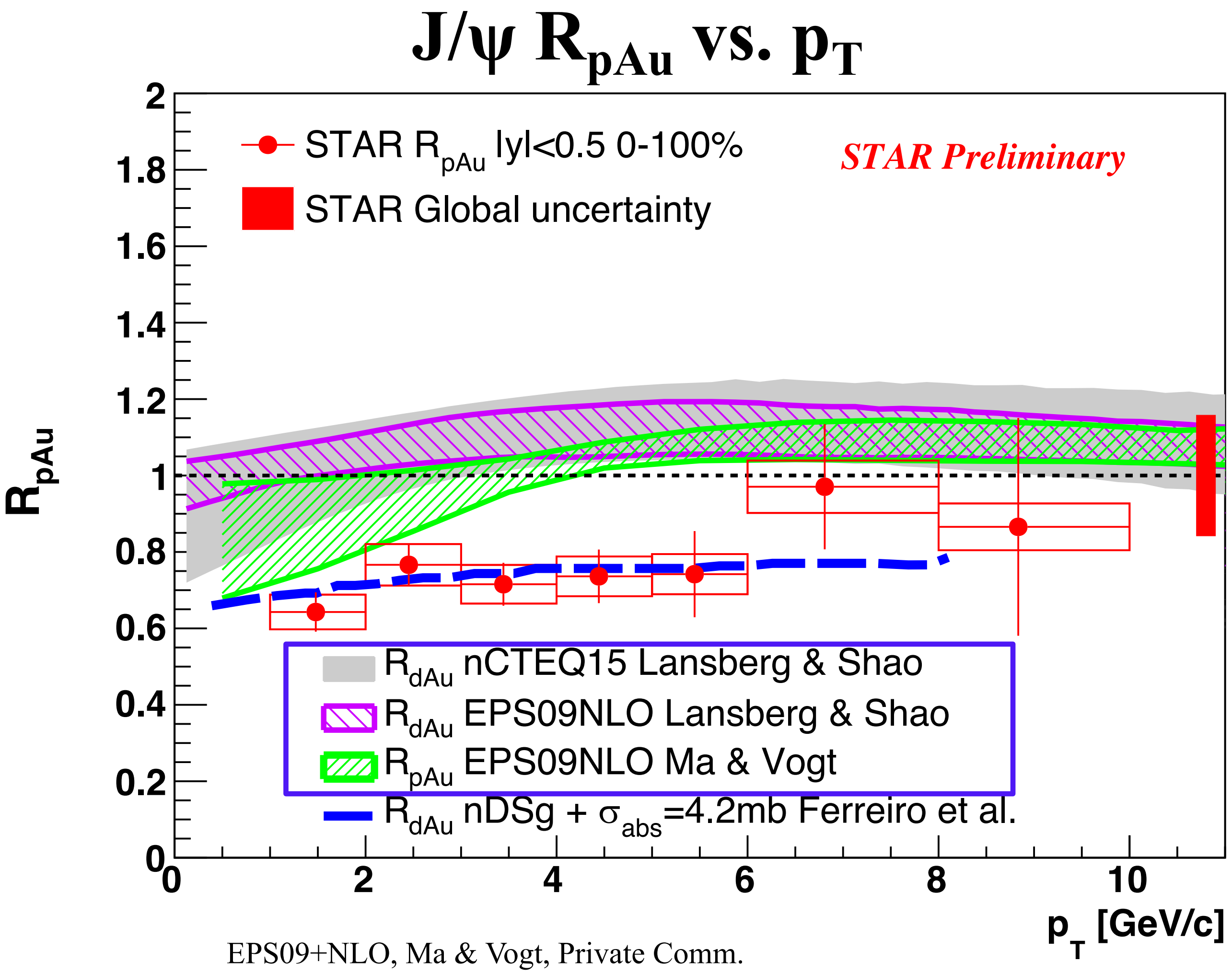
EPS09+NLO, Ma & Vogt, Private Comm.
nCTEQ, EPS09+NLO, Lansberg & Shao, Eur. Phys. J. C77 (2017) 1
Comp. Phys. Comm. 198 (2016) 238
Comp. Phys. Comm. 184 (2013) 2562
Ferreriro et al., Few Body Syst. 53 (2012) 27

$$R_{pAu} = \frac{\sigma_{pp}^{inel}\ d^2N_{pAu}/dydp_T}{\langle N_{coll}\rangle\ d^2\sigma_{pp}/dydp_T}$$

The J/ψ R_{pAu} measurement at RHIC:

- J/ψ suppressed due to the CNM effects

J/ψ in p+Au collisions



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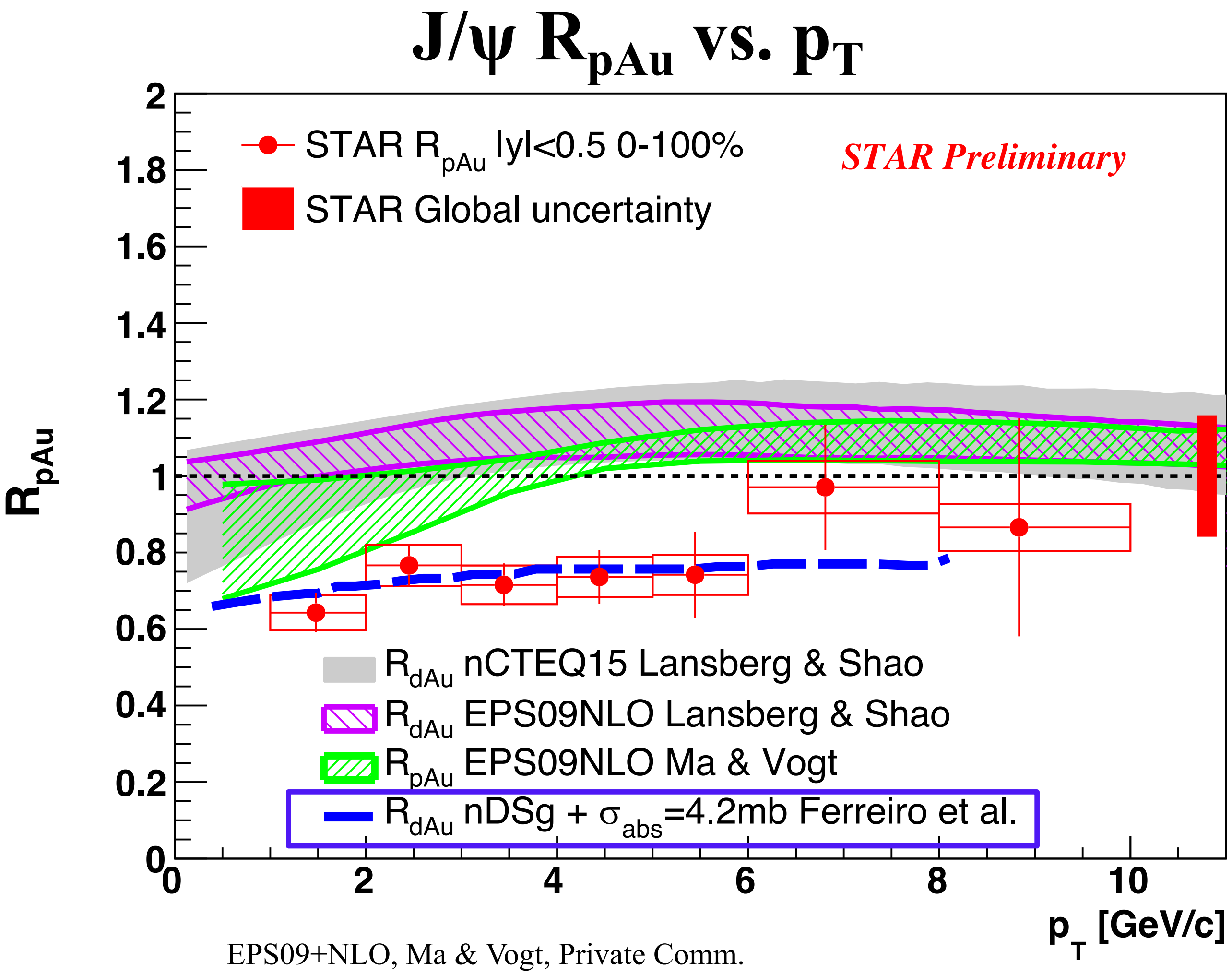
J/ψ in p+Au collisions



EPS09+NLO, Ma & Vogt, Private Comm.
nCTEQ, EPS09+NLO, Lansberg & Shao, Eur. Phys. J. C77 (2017) 1
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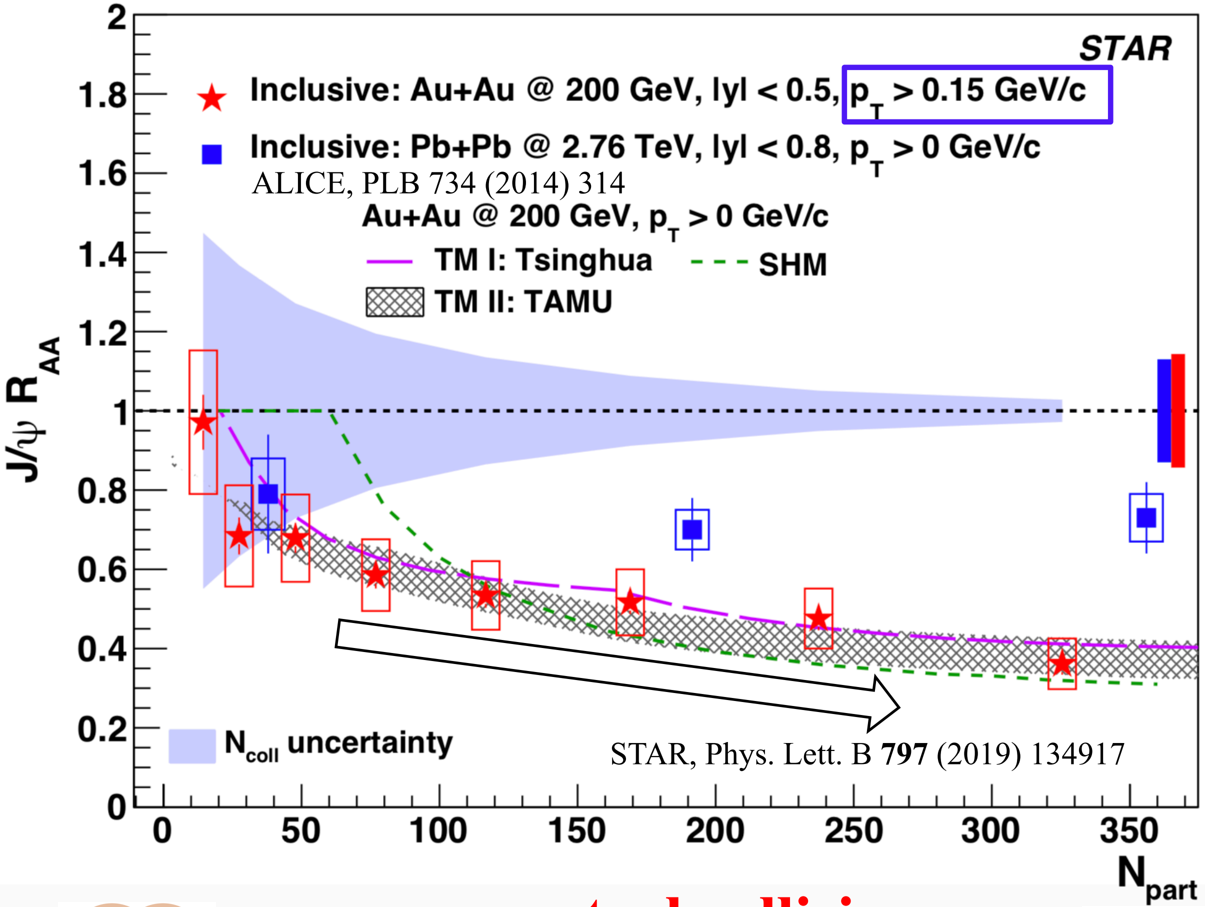
The J/ψ R_{pAu} measurement at RHIC:

- **J/ψ suppressed due to the CNM effects**
- **Models only considering nPDF + energy loss effects can not well describe data**
- **Model with additional nuclear absorption is favored by data**

J/ψ in Au+Au collisions

Low p_T J/ψ

R_{AA} vs. Centrality



STAR, Phys. Lett. B **797** (2019) 134917

more central collision

peripheral

central

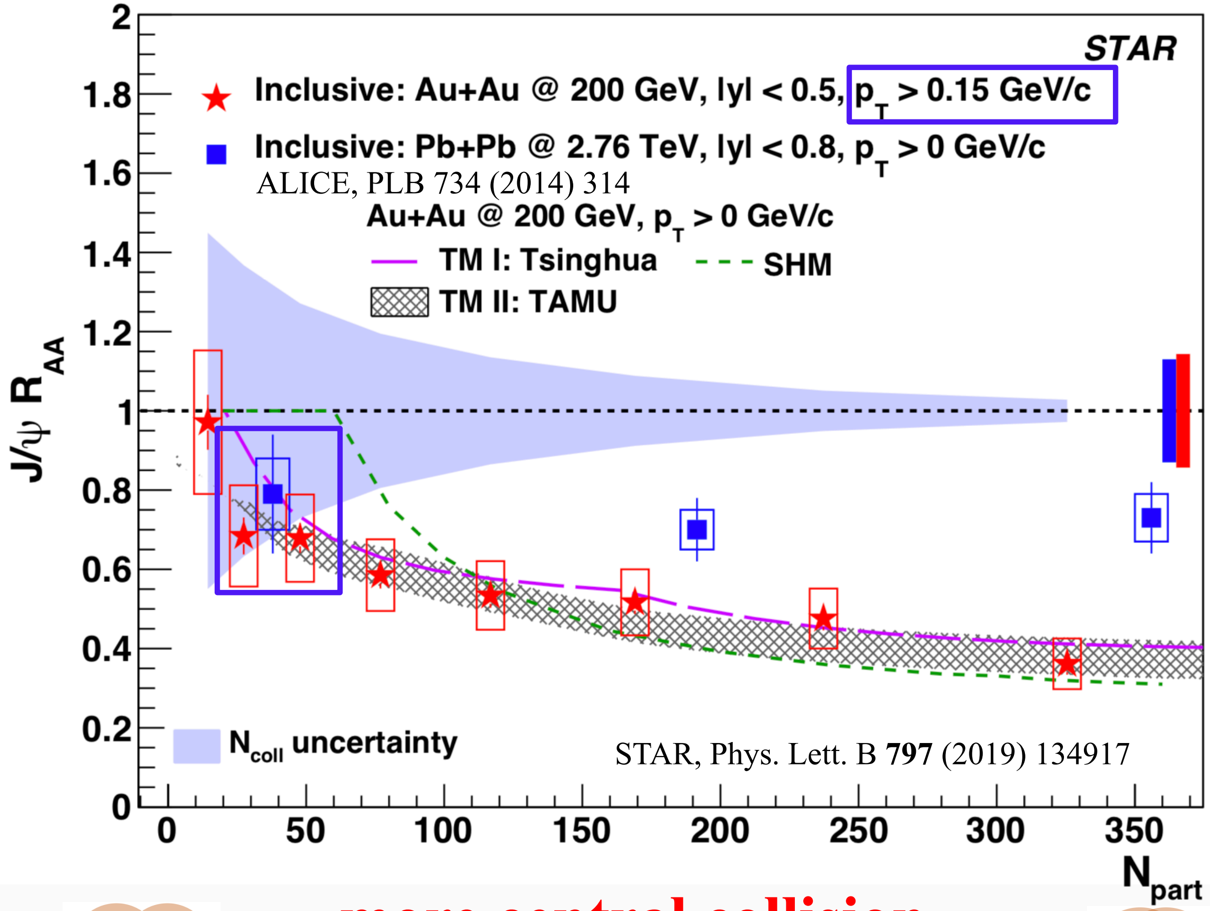
$$R_{AA} = \frac{\sigma_{pp}^{inel}\ d^2N_{AuAu}/dydp_T}{\langle N_{coll}\rangle\ d^2\sigma_{pp}/dydp_T}$$

- **More suppression towards central collisions**
  - **Interplay of CNM effects, dissociation, and regeneration**

J/ψ in Au+Au collisions

Low p_T J/ψ

R_{AA} vs. Centrality



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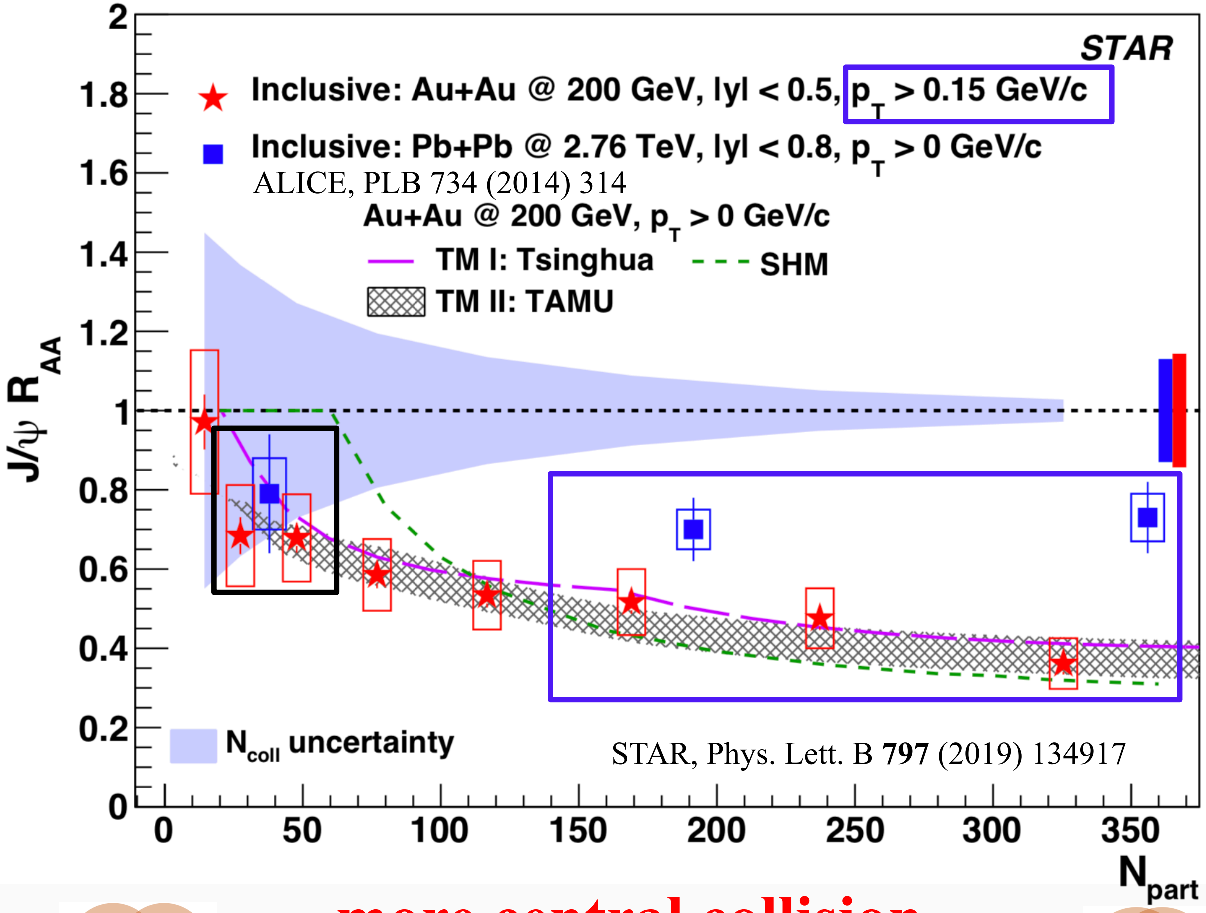
- **At peripheral collisions, similar suppression at RHIC as at LHC**

J/ψ in Au+Au collisions

Low p_T J/ψ

R_{AA} vs. Centrality



ALICE, PLB 734 (2014) 314

STAR, Phys. Lett. B **797** (2019) 134917

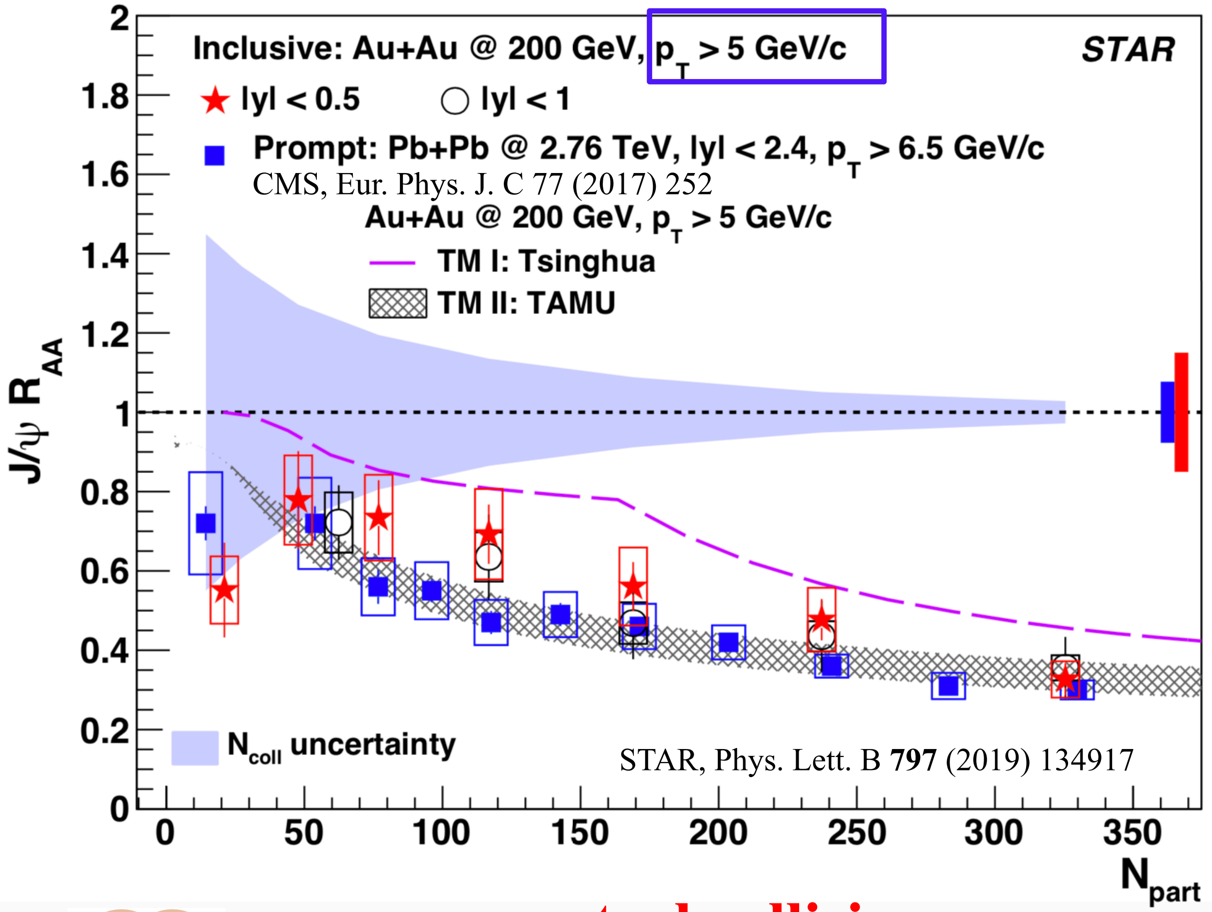
$$R_{AA} = \frac{\sigma_{pp}^{inel} \; d^2N_{AuAu}/dydp_T}{\langle N_{coll}\rangle \; d^2\sigma_{pp}/dydp_T}$$

- ➢ More suppression towards central collisions
  - Interplay of CNM effects, dissociation, and regeneration
- ➢ At peripheral collisions, similar suppression at RHIC as at LHC
- ➢ At semi-central and central collisions, more suppressed at RHIC than at LHC

J/ψ in Au+Au collisions

High p_T J/ψ

R_{AA} vs. Centrality



CMS, Eur. Phys. J. C 77 (2017) 252

STAR, Phys. Lett. B **797** (2019) 134917

peripheral

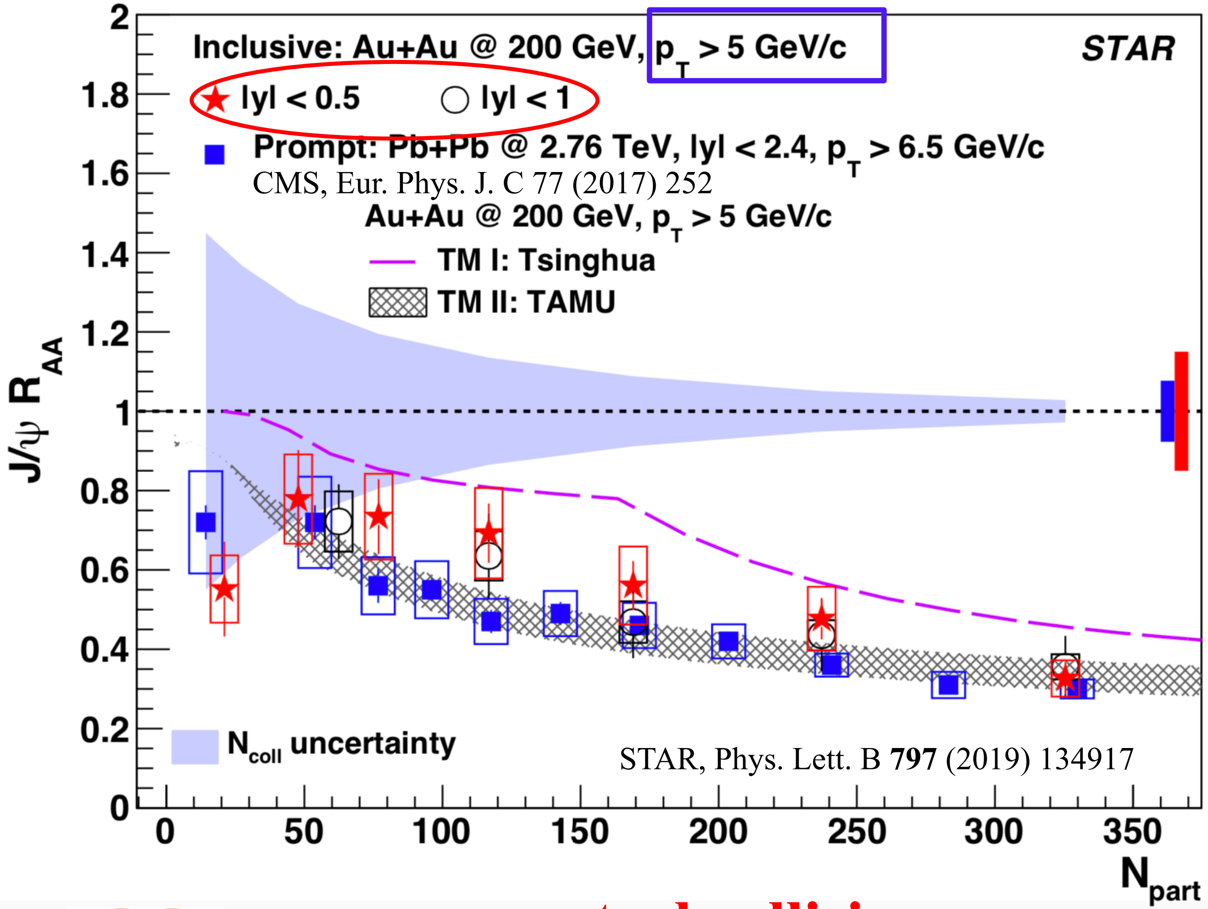
central

- **CNM** and **regeneration** effects are small, **color screening effect** dominant !!!

J/ψ in Au+Au collisions

High p_T J/ψ

R_{AA} vs. Centrality



STAR, Phys. Lett. B **797** (2019) 134917

more central collision

peripheral

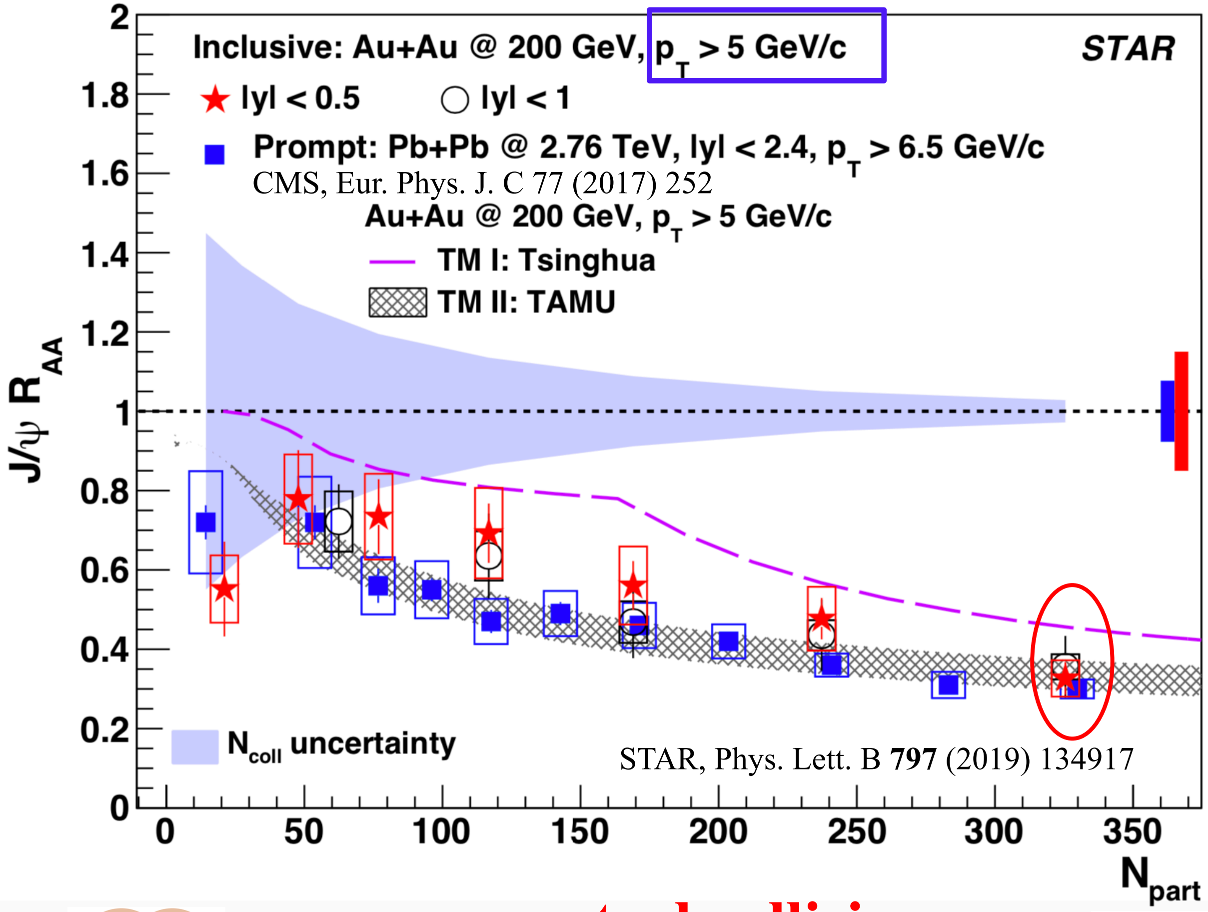
central

- ➢ **Results from dimuon and dielectron channel are consistent**
  - **More suppression towards central collisions, similar trend as at LHC**

J/ψ in Au+Au collisions

High p_T J/ψ

R_{AA} vs. Centrality



more central collision

peripheral

central

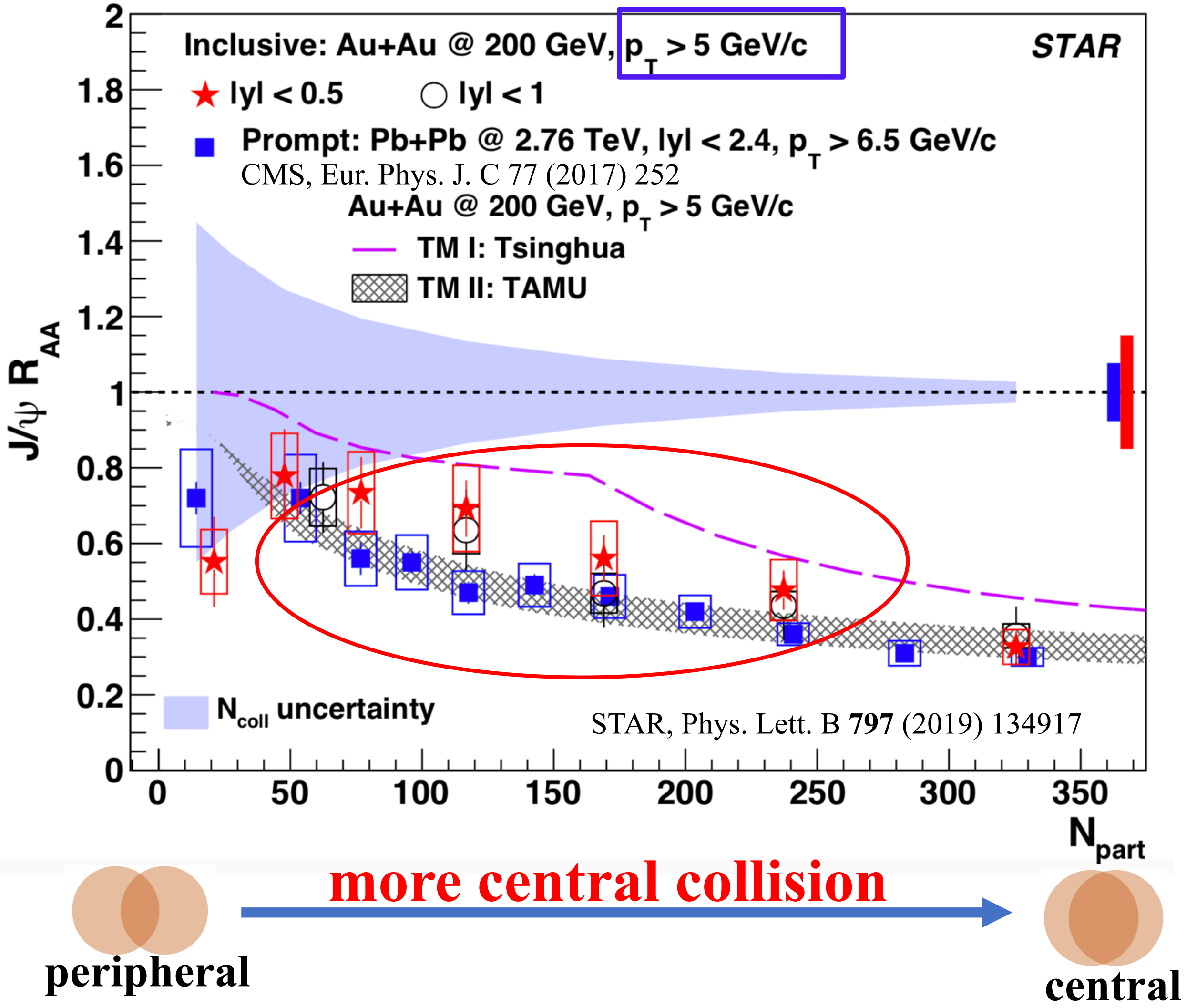
- ➢ **Results from dimuon and dielectron channel are consistent**
  - **More suppression towards central collisions, similar trend as at LHC**

- ➢ **At most central collisions:**
  - **A factor of 3.1 (~8.5 σ) suppression → a strong evidence of dissociation due to the color screening effect**

J/ψ in Au+Au collisions

High p_T J/ψ

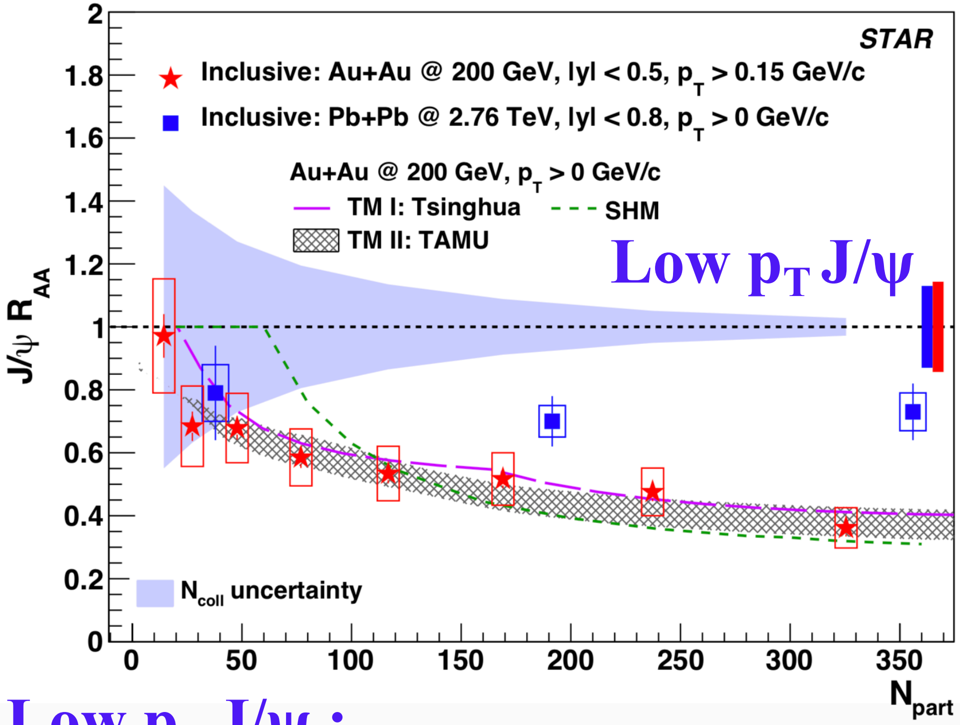
R_{AA} vs. Centrality

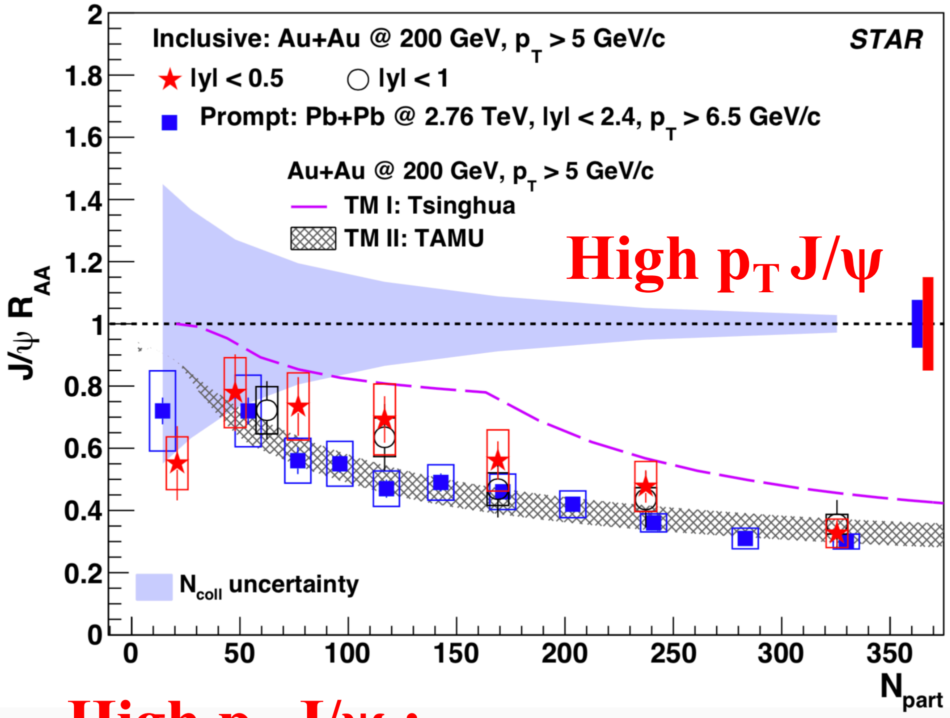


STAR, Phys. Lett. B **797** (2019) 134917

- Results from dimuon and dielectron channel are consistent
  - More suppression towards central collisions, similar trend as at LHC
- At most central collisions:
  - A factor of 3.1 (~8.5 σ) suppression → a strong evidence of dissociation due to the color screening effect
- At semi-central collisions:
  - Systematically less suppressed than at LHC ←→ lower dissociation rate due to lower temperature at RHIC than at LHC

J/ψ in Au+Au collisions





Low p_T J/ψ :

- ➢ Both transport models (Tsinghua and TAMU) can well describe the data
- ➢ Statistical Hadronization Model fails to describe the peripheral collisions

High p_T J/ψ :

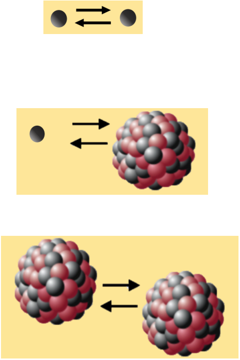
- ➢ Both transport models (Tsinghua and TAMU) show clear deviation to data

Tsinghua Model: PLB 678 (2009) 72m, Tsinghua at LHC: PRC 89 (2014) 054911
TAMU Model: PRC 82 (2010) 064905, TAMU at LHC: NPA 859 (2011) 114
SHM: Nature 561 (7723) (2018) 321–330

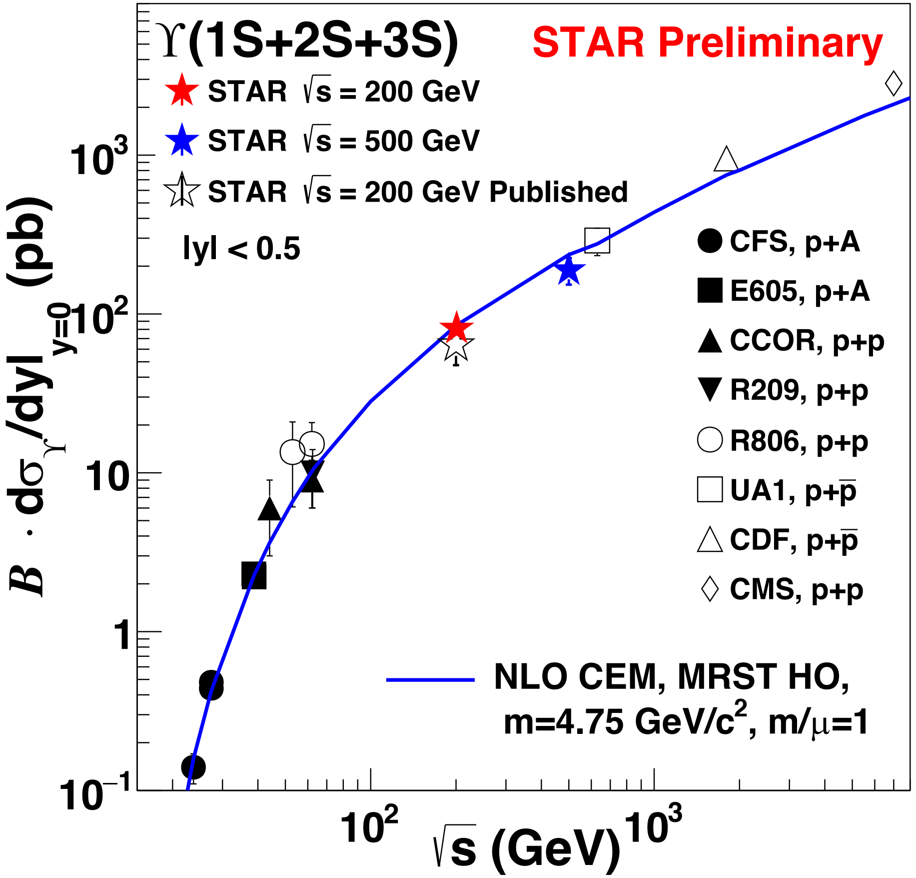
Both Transport Models include the regeneration and feed-down contributions, $T_0^{QGP} \sim 330\ MeV$
Tsinghua Model: gluon-dissociate mechanism, dissociate rate = 100% when $T >\sim T_{dissociate}$, hydrodynamically evolving medium
TAMU Model: quasi-free dissociation mechanism + energy loss, T-dependent dissociate rate, fireball medium, CNM effects
SH Model: feed-down from higher excited states is included, but from b hadron is not included, hydrodynamically evolving medium

Bottomonium production at 200 GeV in different systems:

1. p+p collisions
2. p+Au collisions
3. Au+Au collisions

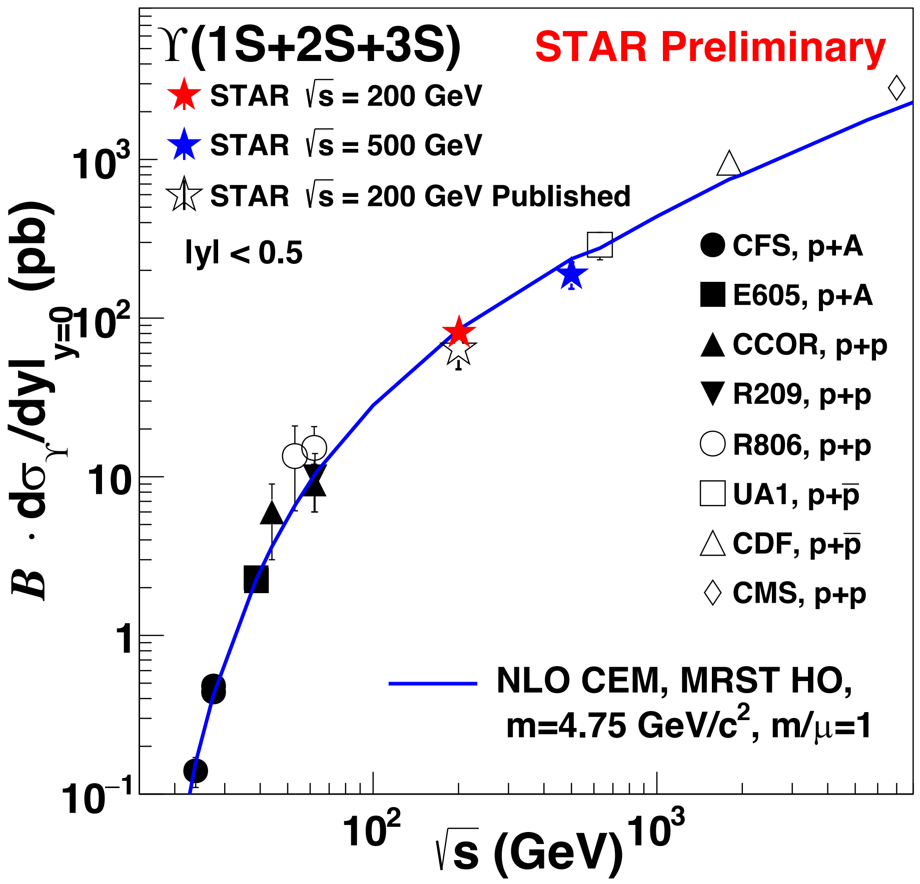


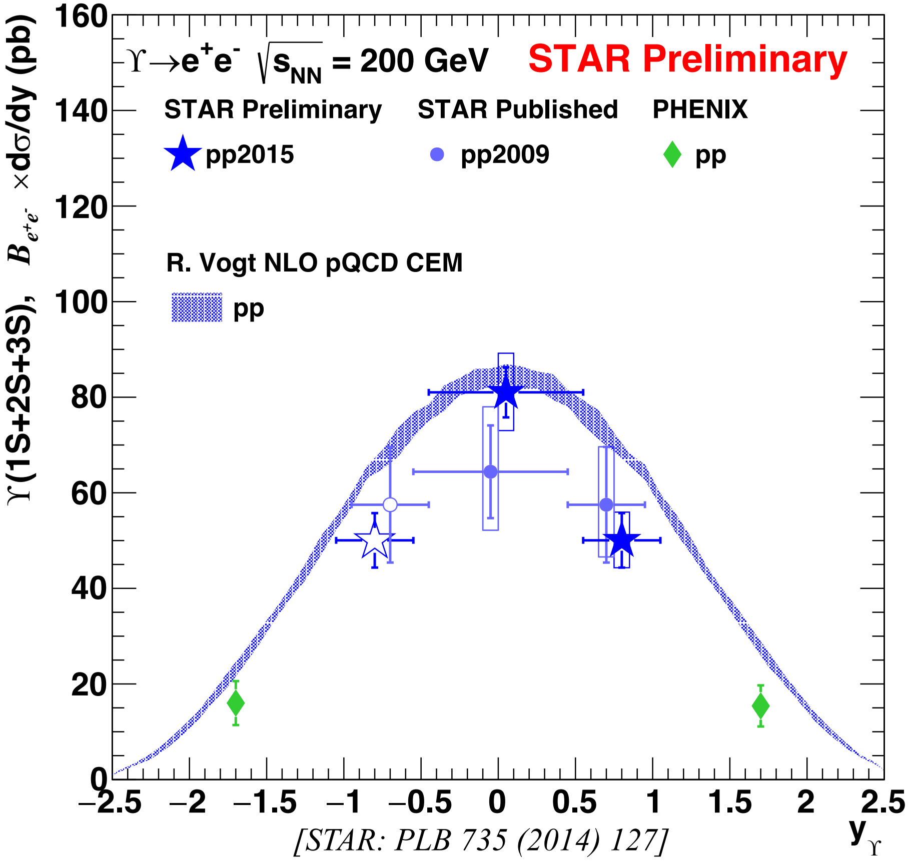
Υ in p+p collisions at 200 GeV



- **Follows the trend predicted by NLO pQCD + CEM calculations**
- **Provide a precise base line for Υ study in p+Au and Au+Au collisions**

Υ in p+p collisions at 200 GeV



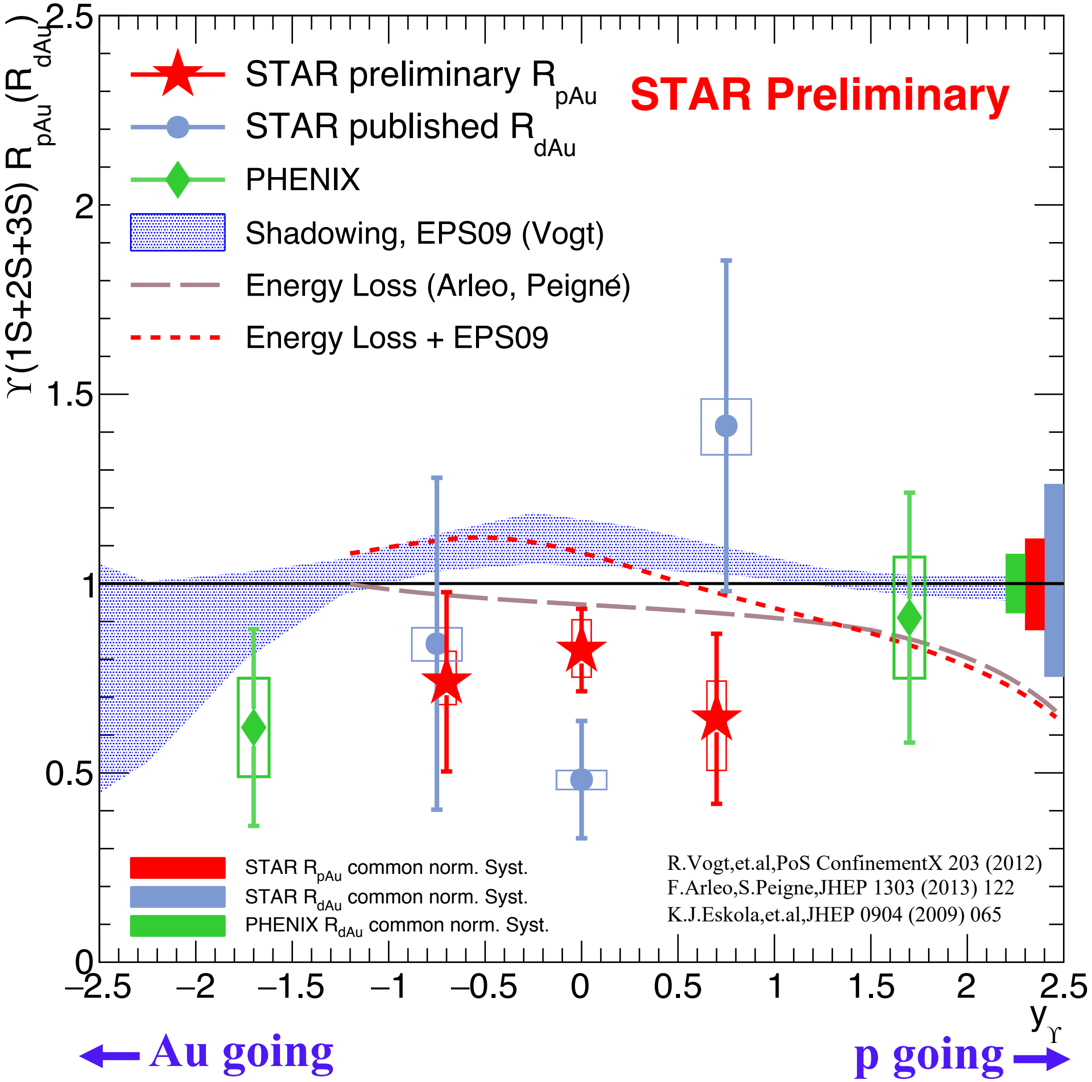


[STAR: PLB 735 (2014) 127]

[PHENIX: PRC 87 (2013) 044909]

- **Follows the trend predicted by NLO pQCD + CEM calculations**
- **Provide a precise base line for Υ study in p+Au and Au+Au collisions**
- **Narrower rapidity distribution than NLO CEM calculation**

Υ R_{pA} from RHIC

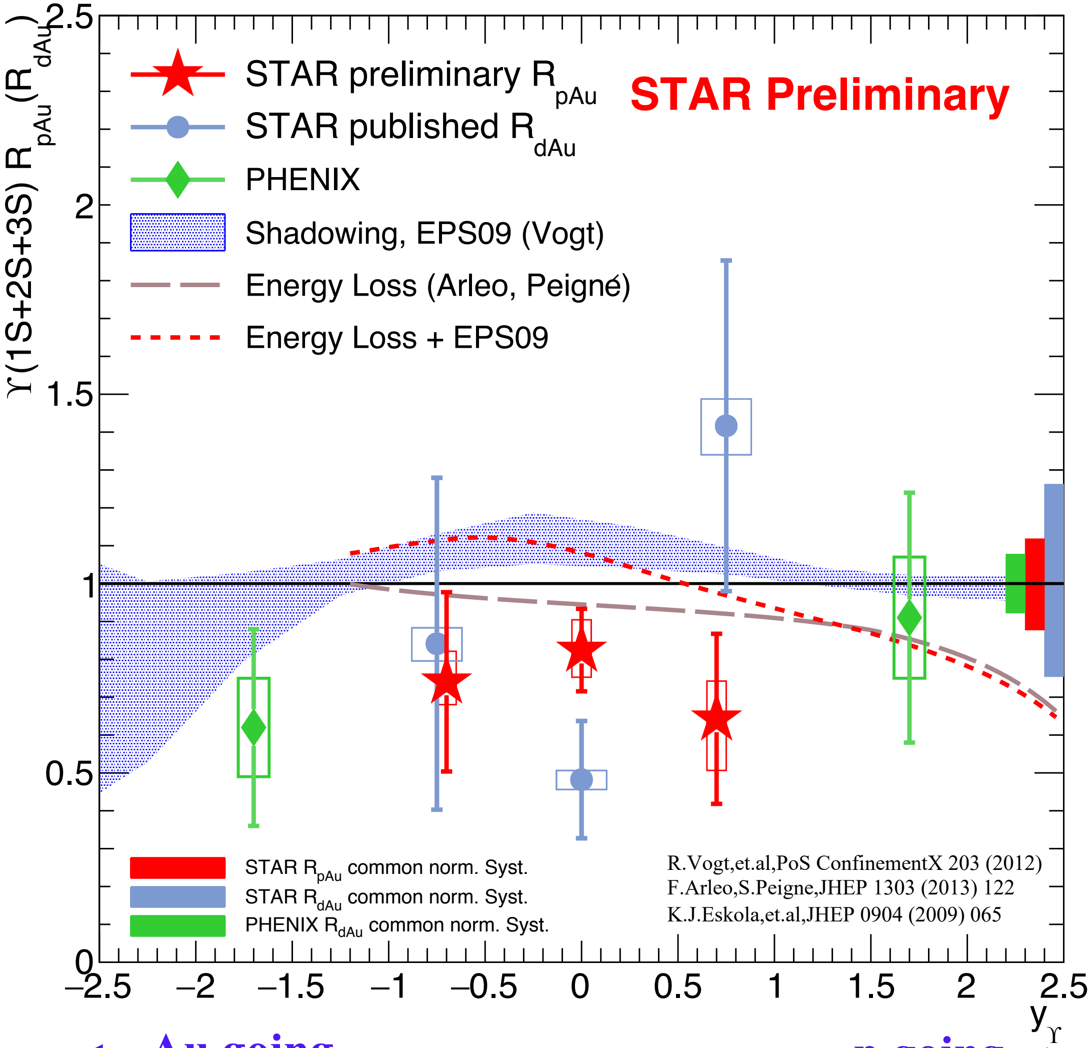


R.Vogt,et.al,PoS ConfinementX 203 (2012)
F.Arleo,S.Peigne,JHEP 1303 (2013) 122
K.J.Eskola,et.al,JHEP 0904 (2009) 065

The first measurement of Υ R_{pAu} at RHIC:

- Better precision compared to published data

Υ R_{pA} from RHIC

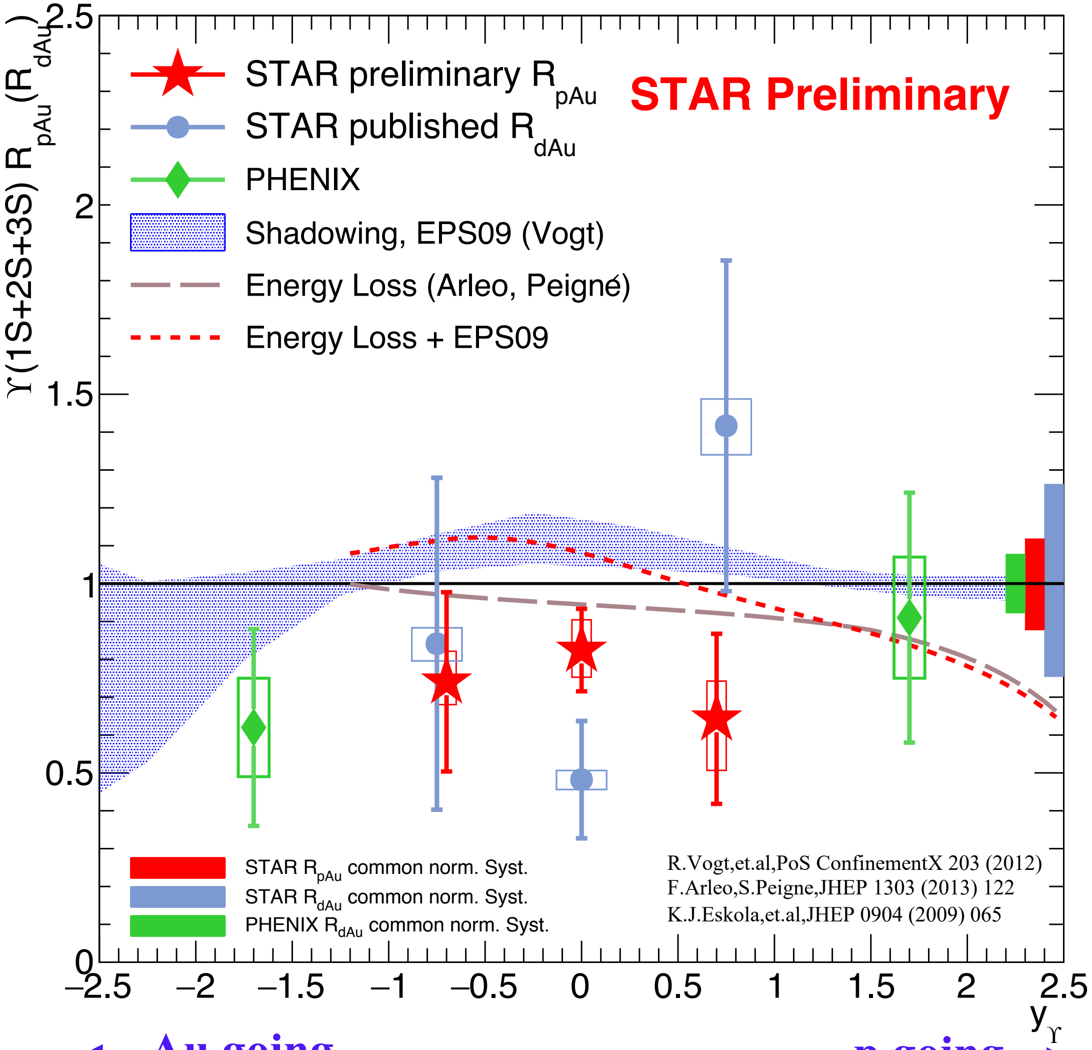


← **Au going** **p going** →

The first measurement of Υ R_{pAu} at RHIC:

- **Better precision compared to published data**
- **Indication of Υ suppression due to CNM**
  - **No clear rapidity dependence**

Υ R_{pA} from RHIC



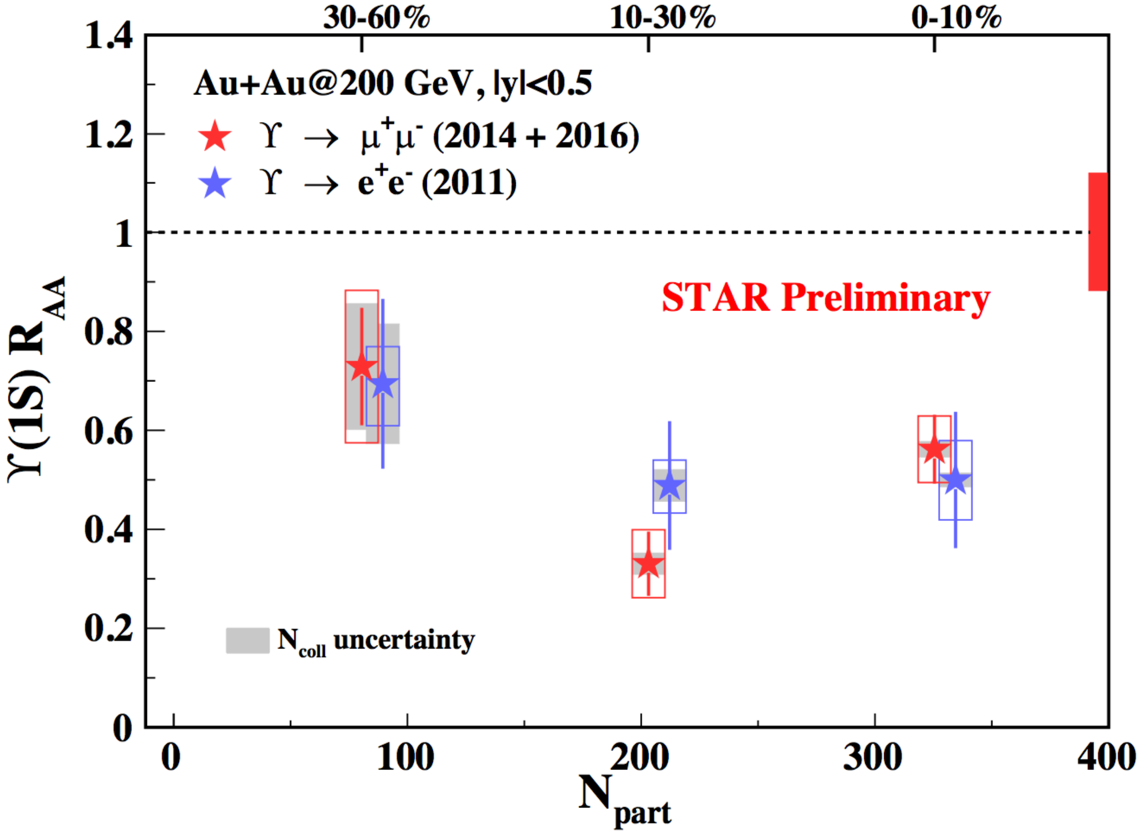
← Au going

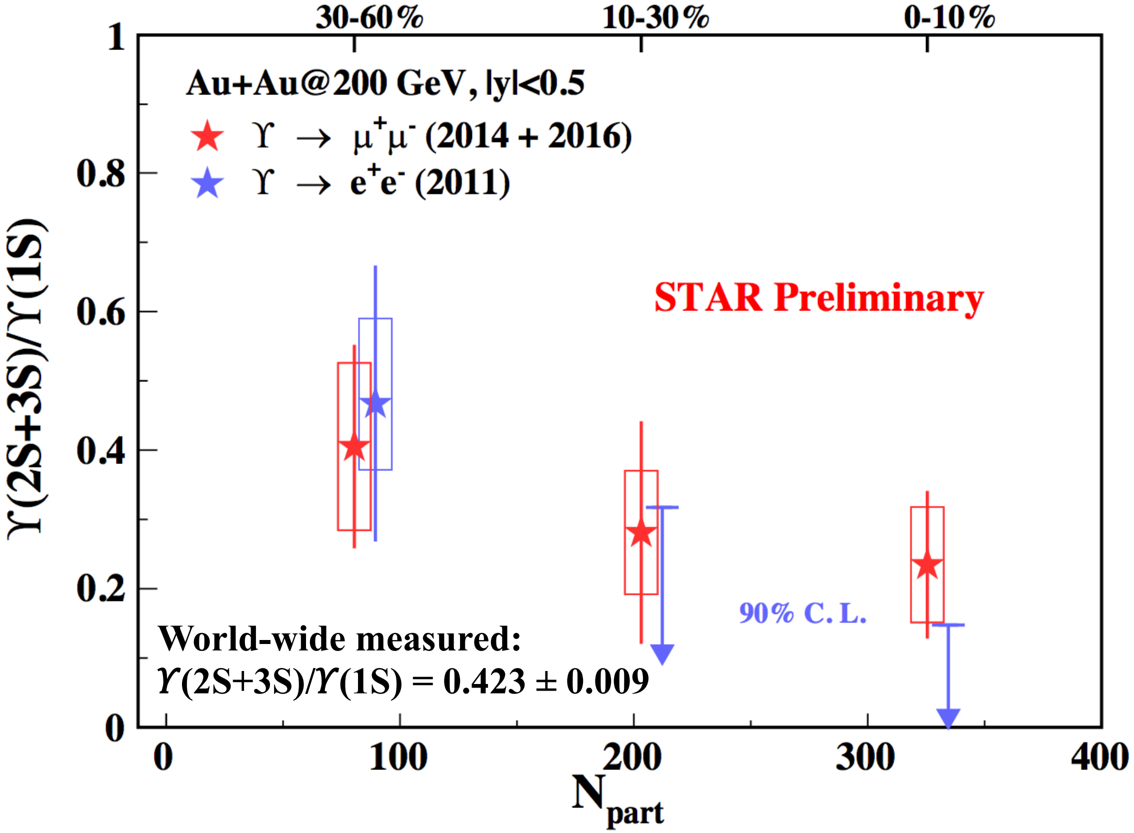
p going →

The first measurement of Υ R_{pAu} at RHIC:

- **Better precision compared to published data**
- **Indication of Υ suppression due to CNM**
  - **No clear rapidity dependence**
- **Model calculations only considering nPDF and energy loss effects can not well describe data**
  - **Other effects are needed**

Υ results in Au+Au collisions from: dielectron vs. dimuon

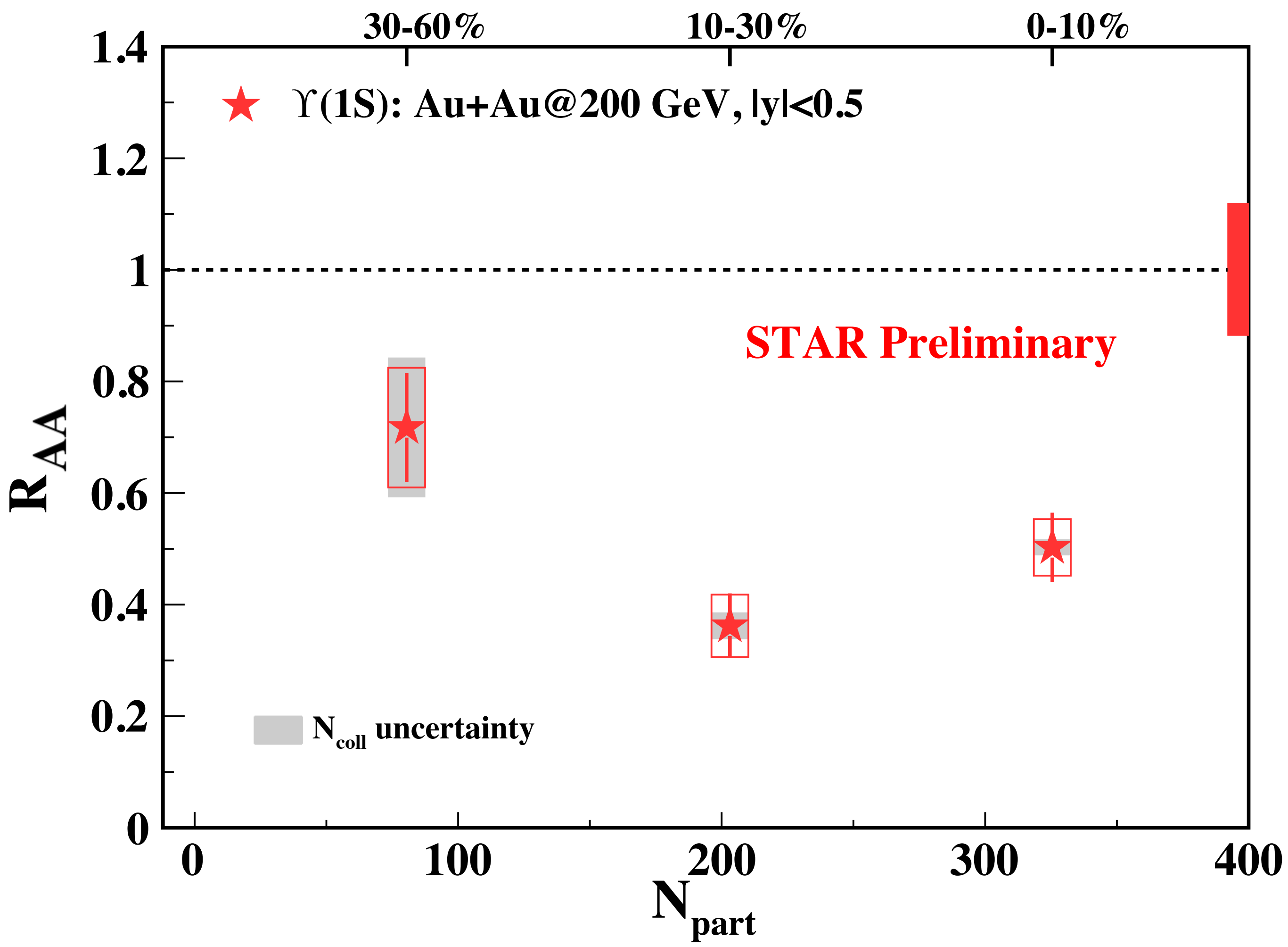




- ➢ Results from di-muon and di-electron channels are consistent within uncertainty

➔ Combine results from two decay channels

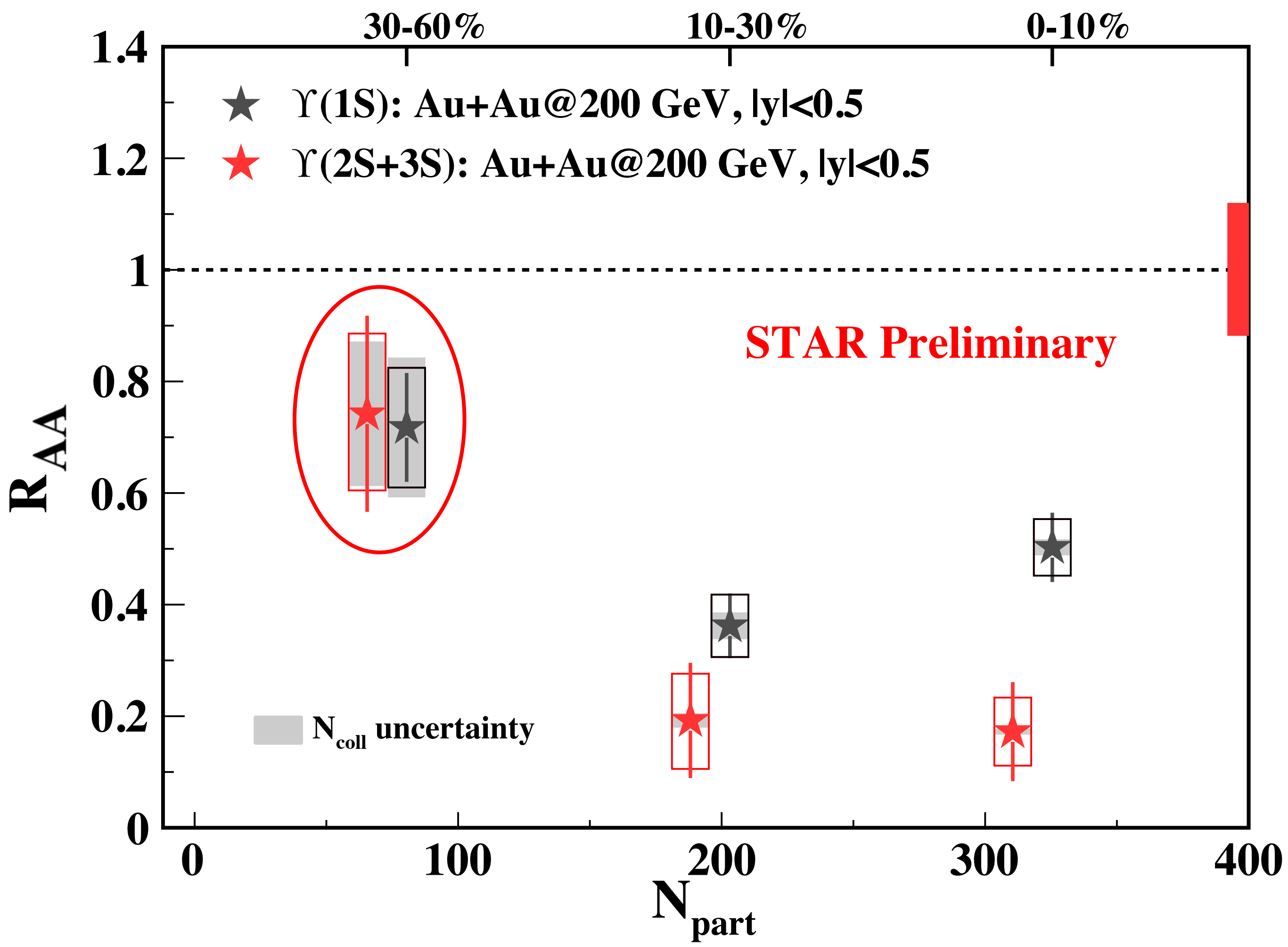
R_{AA}: Υ(1S)



Υ(1S):

- **Stronger suppression in semi-central and central collisions**

R_{AA}: Υ(1S) vs. Υ(2S+3S)



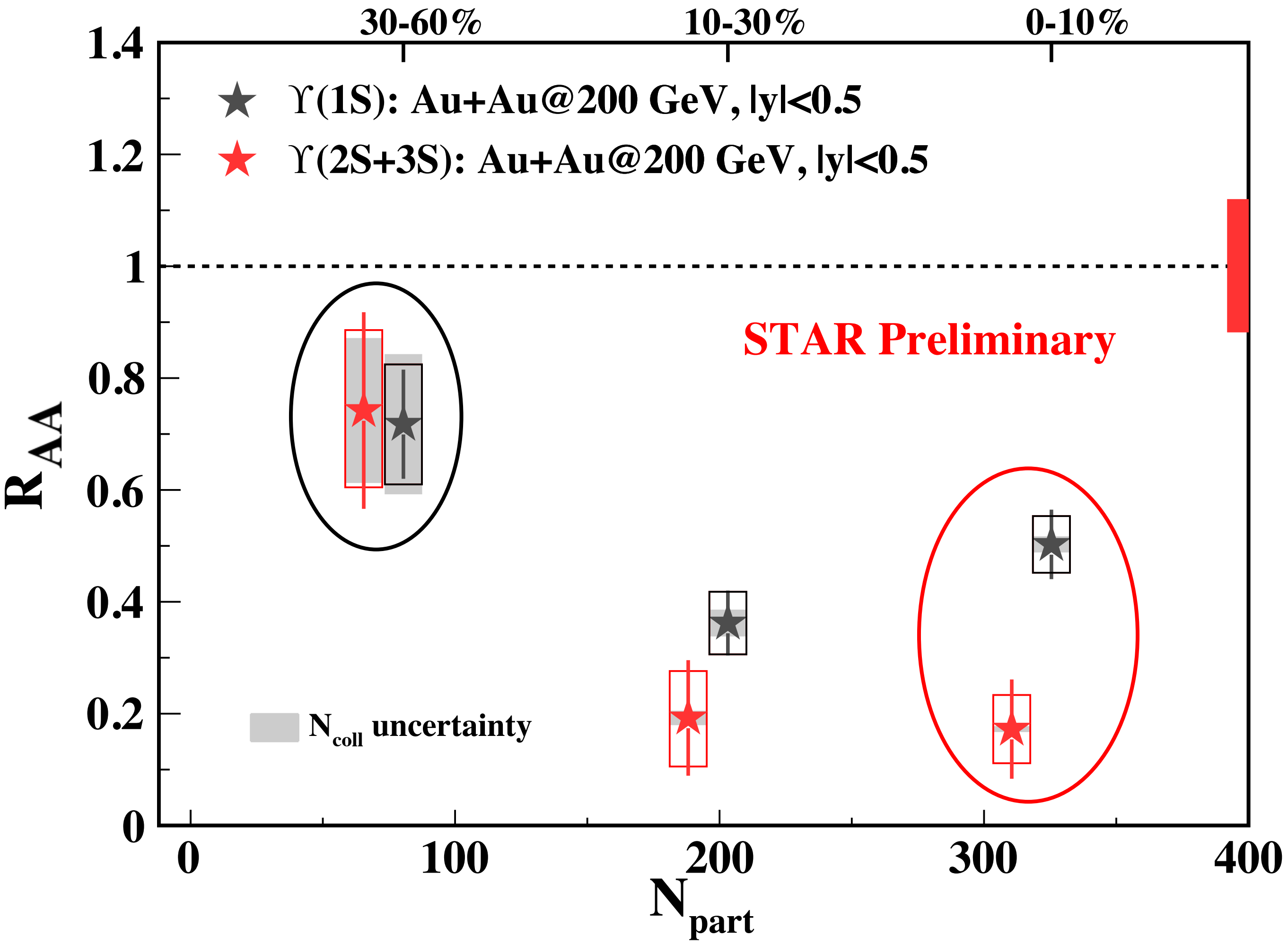
Υ(1S):

- Stronger suppression in semi-central and central collisions

Υ(2S+3S):

- Similar suppression as Υ(1S) in peripheral collisions

R_{AA}: Υ(1S) vs. Υ(2S+3S)



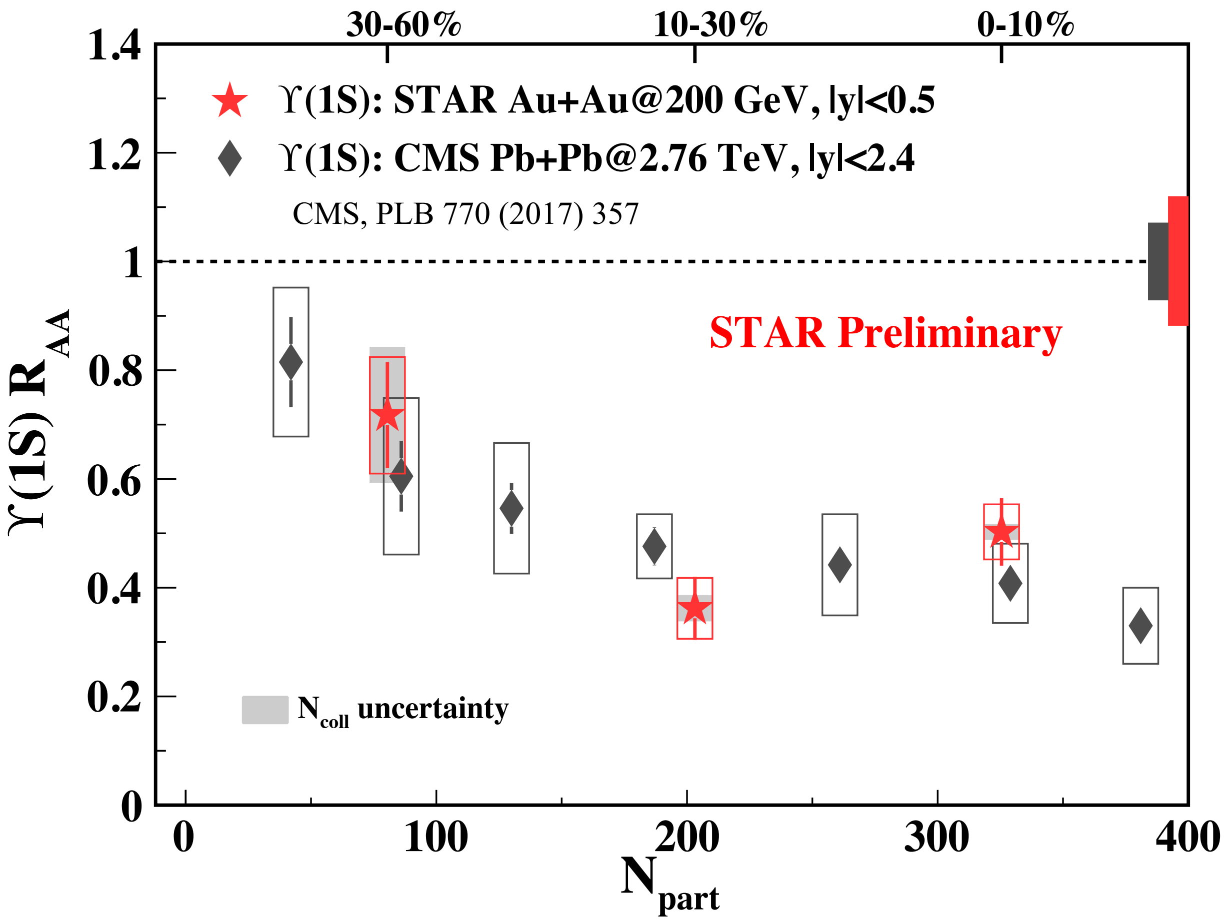
Υ(1S):

- **Stronger suppression in semi-central and central collisions**

Υ(2S+3S):

- **Similar suppression as Υ(1S) in peripheral collisions**
- **More suppression than Υ(1S) in most central collisions ⇔ "sequential melting"**

Υ(1S) R_{AA}: RHIC vs. LHC



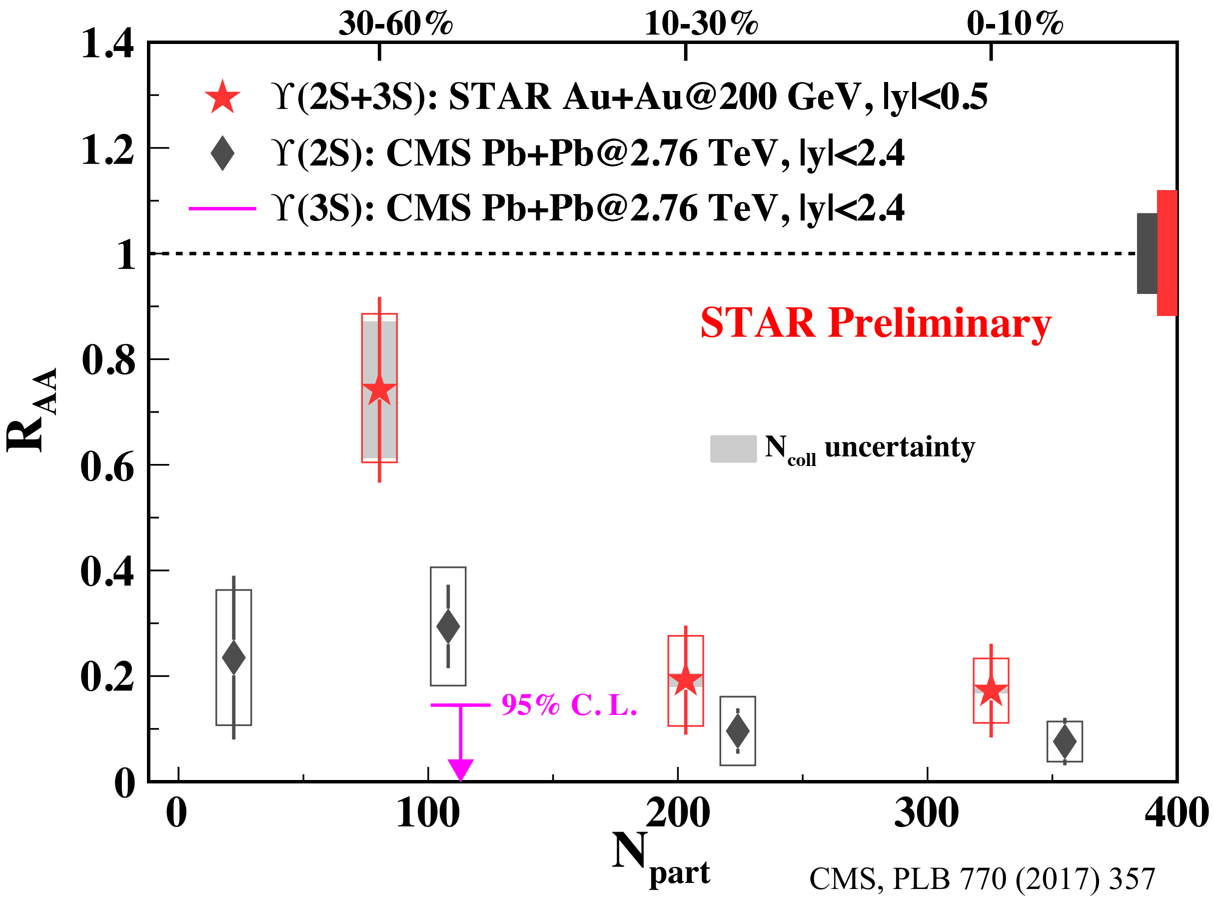
Υ(1S) suppression is similar at RHIC and LHC energy !

- $T^{RHIC} < T^{LHC}$, $Rate^{RHIC}_{diso.} < Rate^{LHC}_{diso.}$
- $Rate^{RHIC}_{recomb.} < Rate^{LHC}_{recomb.}$
- **Feed-down?**
- **CNM effects?**

Prompt $\Upsilon(1s)$	$\sim 51\%$
$\Upsilon(1s)$ from $\chi_b(1P)$ decays	$\sim 27\%$
$\Upsilon(1s)$ from $\chi_b(2P)$ decays	$\sim 10\%$
$\Upsilon(1s)$ from $\Upsilon(2S)$ decays	$\sim 11\%$
$\Upsilon(1s)$ from $\Upsilon(3S)$ decays	$\sim 1\%$

CDF, PRL 84 (2000) 2094

Excited Υ states R_{AA}: RHIC vs. LHC



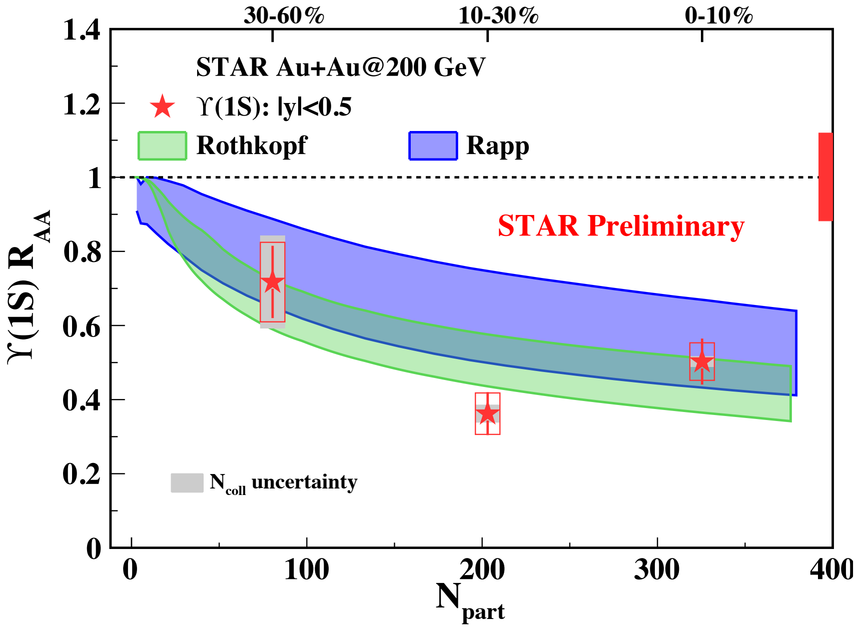
CMS, PLB 770 (2017) 357

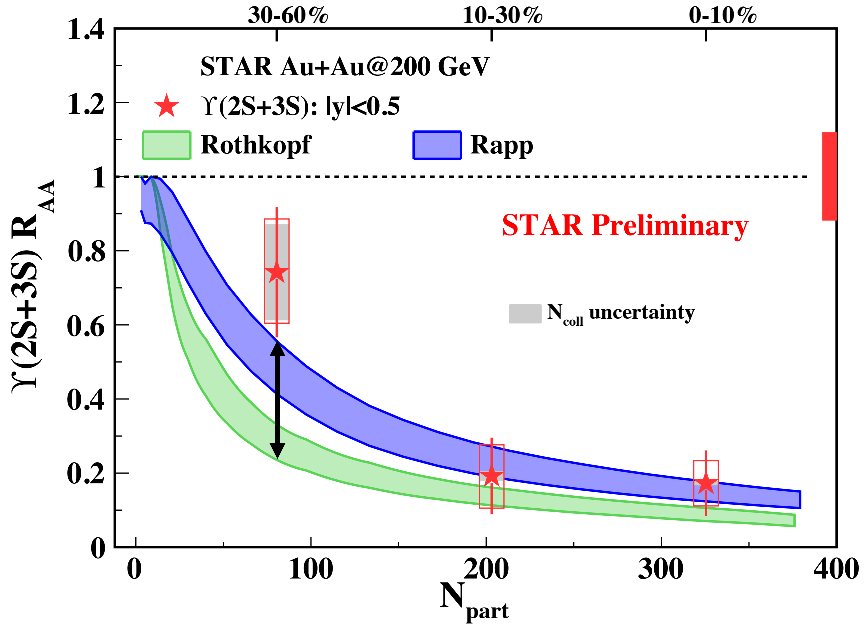
Υ(2S+3S) R_{AA} at RHIC compared to Υ(2S), Υ(3S) R_{AA} at LHC:

- **Similar suppression at semi-central and central collisions**
- **Indication of less suppression at RHIC than at LHC for the most peripheral collisions**

STAR: Υ(2S+3S) R_{AA}: 0.35 ± 0.08 (stat.) ± 0.10 (sys.) (0 < pT < 10 GeV/c, 0-60%.)
CMS: Υ(2S) R_{AA}: 0.08 ± 0.05 (stat.) ± 0.03 (sys.) (0 < pT < 5 GeV/c, 0-100%)

Compared to models





- **Both models show good agreement with $\varUpsilon$(1S) R_{AA}**
- **Rothkopf model seems to underestimate the $\varUpsilon$(2S+3S) R_{AA} in 30-60% centrality**

Rothkopf Model: Krouppa, Rothkopf, Strickland, PRD 97, 016017 (2018)

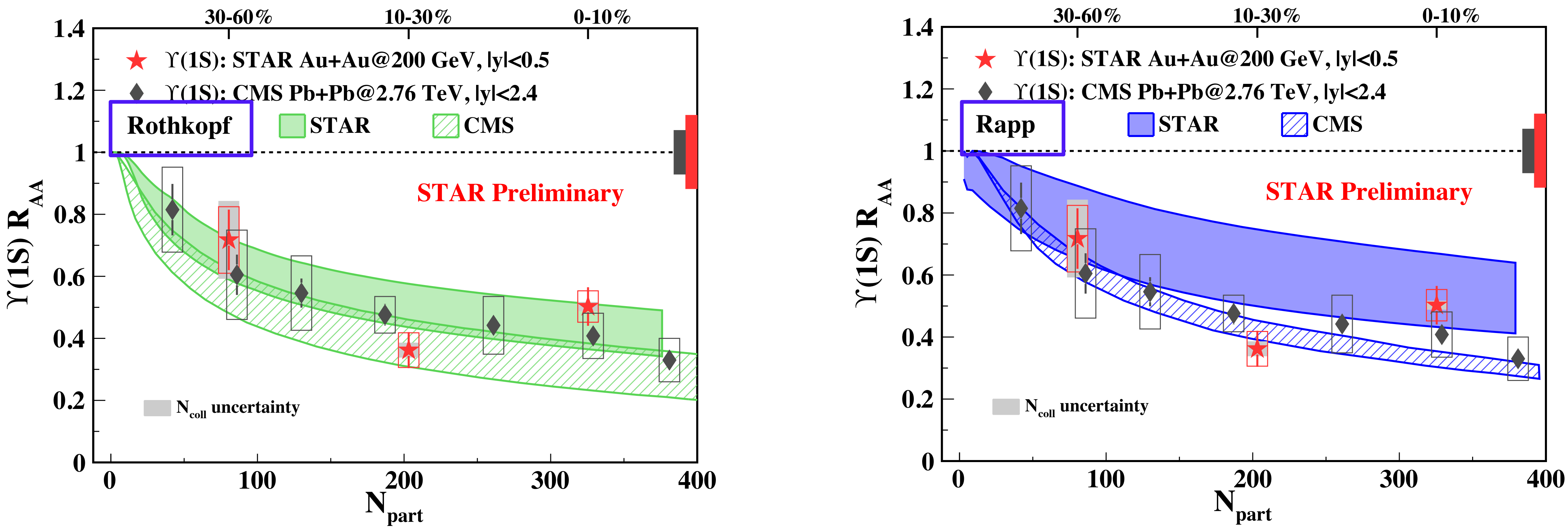
- **lattice QCD vetted potential embedded in hydrodynamically evolving medium**
- **no CNM or regeneration effects**
- **$\varUpsilon$(1S), $\varUpsilon$(2S), $\varUpsilon$(3S) melt at T = 600, 230, 170 MeV**

Rapp Model: X. Du, M. He, and R. Rapp, PRC 96, 054901 (2017)

- **both quasi-free and gluo-dissociate mechanism**
- **binding energies predicted by thermodynamic T-matrix calculations with internal energy potentials**
- **include CNM and regeneration effects**
- **$\varUpsilon$(1S), $\varUpsilon$(2S), $\varUpsilon$(3S) melt at T = 500, 240, 190 MeV**

	RHIC (0.2 TeV)	LHC (2.76 TeV)
T_0^{QGP} (Rothkopf)	439-442	544-552 MeV
T_0^{QGP} (Rapp)	313	520-750 MeV

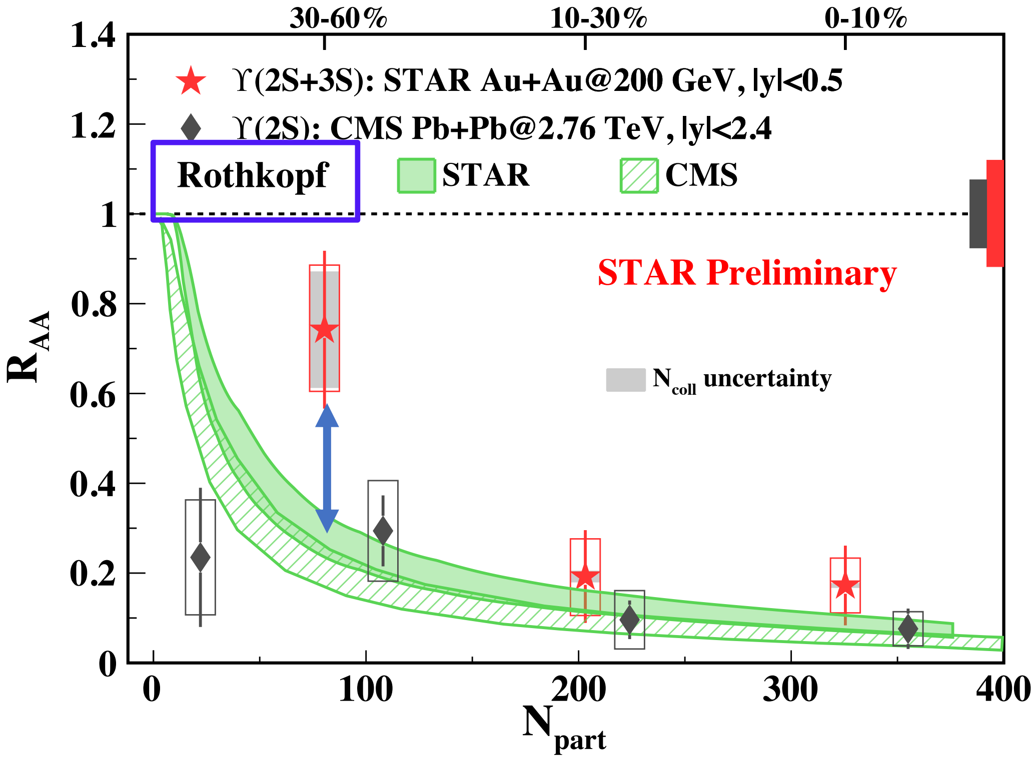
Can models consistently describe Υ(1S) R_{AA} at RHIC and LHC?

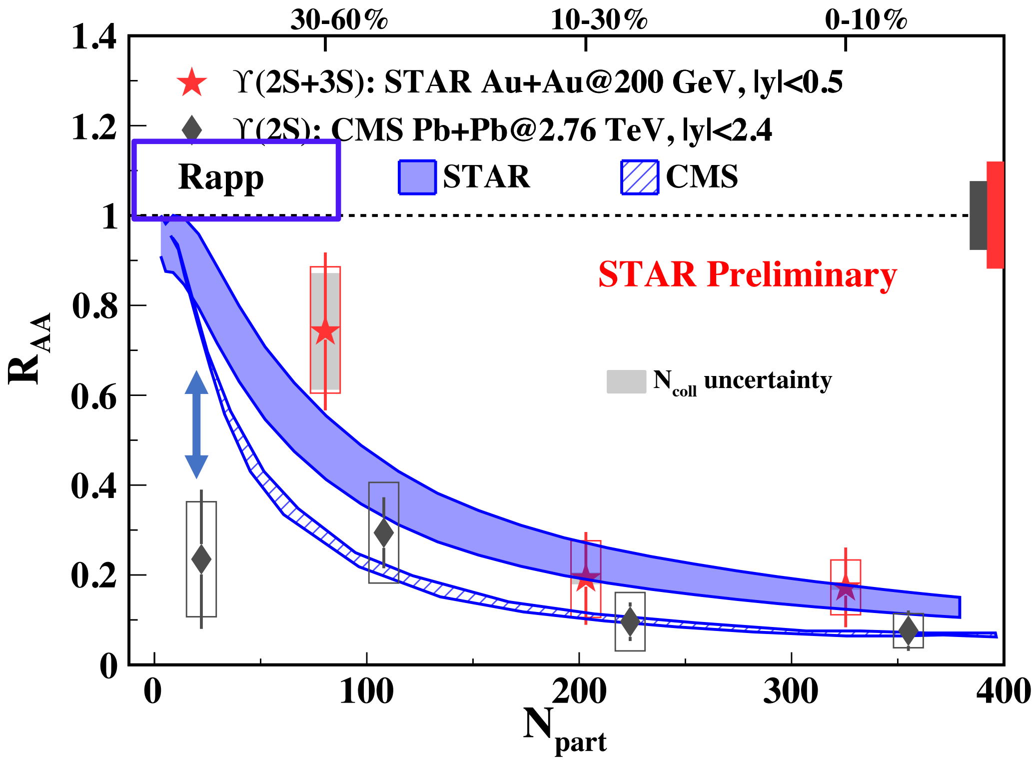


CMS: PLB 770, 357 (2017)
X. Du, M. He, and R. Rapp: PRC 96, 054901 (2017)
B. Krouppa, A. Rothkopf, M. Strickland: PRD 97, 016017 (2018)

- **Both Rapp and Rothkopf models can consistently describe the suppression of Υ(1S) from RHIC to LHC energies**

Can models consistently describe excited Υ states R_{AA} at RHIC and LHC?





CMS: PLB 770, 357 (2017)
X. Du, M. He, and R. Rapp: PRC 96, 054901 (2017)
B. Krouppa, A. Rothkopf, M. Strickland: PRD 97, 016017 (2018)

- **Both Rapp and Rothkopf models can consistently describe the suppression of excited Υ states in semi-central and central collisions from RHIC to LHC energies**
- **Rothkopf model underestimates Υ(2S+3S) R_{AA} in 30-60% centrality at RHIC**
- **Rapp model overestimate Υ(2S) R_{AA} at most peripheral collisions at LHC**

Summary

- **p+p collisions at $\sqrt{s} = 200$ GeV:**
  - **Cross section can be described by CEM and NLO NRQCD**

Summary

- p+p collisions at $\sqrt{s} = 200$ GeV:
  - Cross section can be described by CEM and NLO NRQCD

- p+Au collisions at $\sqrt{s_{NN}} = 200$ GeV:
  - J/ψ, ϒ suppressed due to CNM effects, nPDF + energy loss + additional effects

Summary

- **p+p collisions at $\sqrt{s} = 200$ GeV:**
  - **Cross section can be described by CEM and NLO NRQCD**
- **p+Au collisions at $\sqrt{s_{NN}} = 200$ GeV:**
  - **J/ψ, ϒ suppressed due to CNM effects, nPDF + energy loss + additional effects**
- **Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV:**
  - **low p_T J/ψ more suppressed at RHIC than at LHC ⇐⇒ Less regeneration at RHIC**
  - **high p_T J/ψ less suppressed at RHIC than at LHC ⇐⇒ Lower temperature at RHIC**

Summary

- **p+p collisions at $\sqrt{s} = 200$ GeV:**
  - **Cross section can be described by CEM and NLO NRQCD**

- **p+Au collisions at $\sqrt{s_{NN}} = 200$ GeV:**
  - **J/ψ, ϒ suppressed due to CNM effects, nPDF + energy loss + additional effects**

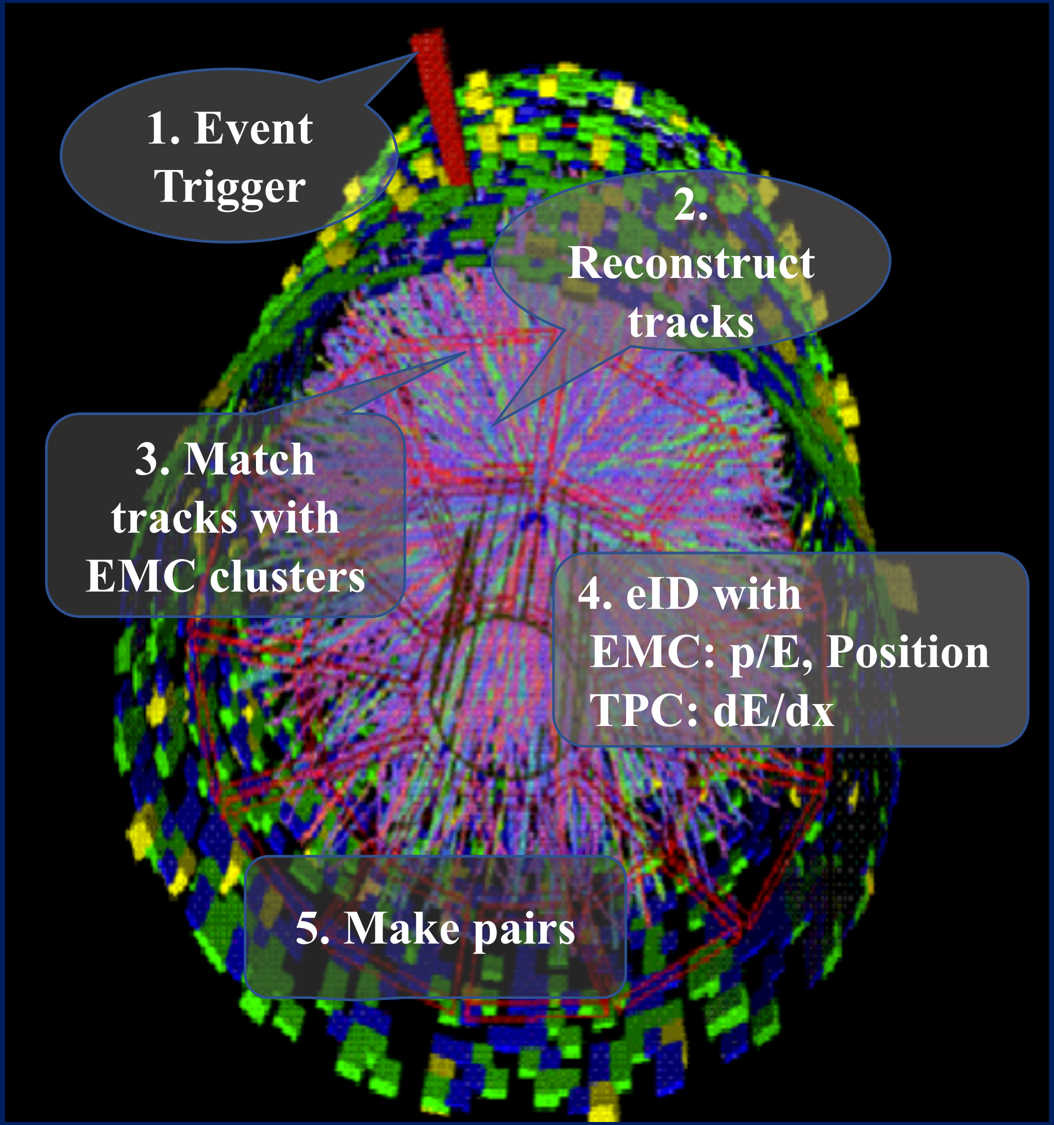
- **Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV:**
  - **low p_T J/ψ more suppressed at RHIC than at LHC ⇔ Less regeneration at RHIC**
  - **high p_T J/ψ less suppressed at RHIC than at LHC ⇔ Lower temperature at RHIC**
  - **ϒ(2S+3S) more suppressed than ϒ(1S) in central collisions ⇔ Sequential melting**
  - **ϒ(1S) similar suppression at RHIC and LHC, ϒ(2S+3S) less suppressed at RHIC than at LHC ⇔ interplay of cold/hot nuclear matter effects on direct + feed-down contributions**

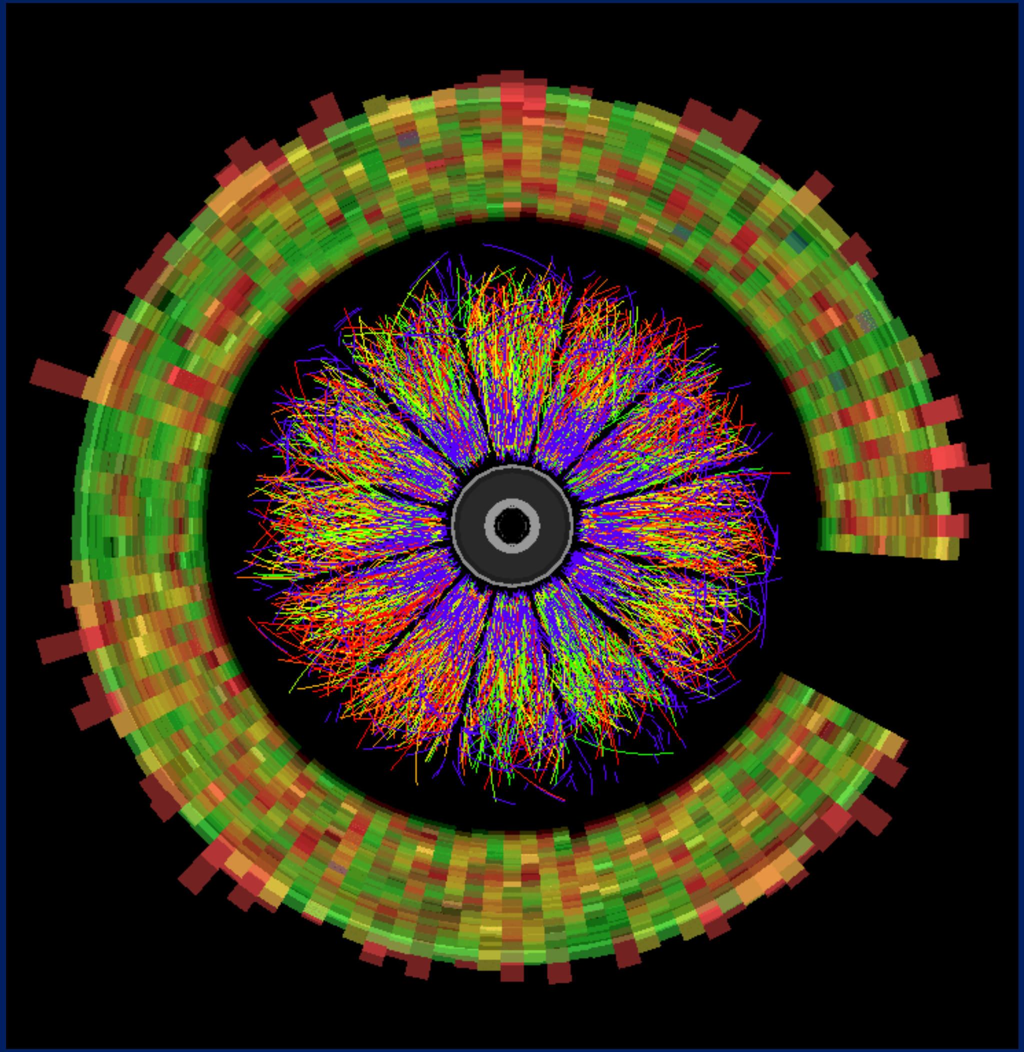
THANK YOU !!

Be Safe !!!

Backup

Upsilon reconstruction via $\Upsilon \rightarrow e^{+}e^{-}$





The high tower trigger is to trigger on those events with high energy particles hitting on BEMC

Advantage and Challenge of Υ Measurements at RHIC

At central AA collisions	RHIC (200 GeV)	LHC (2.76 GeV)
$\#c\bar{c}/event$	~13	~115
$\#b\bar{b}/event$	~0.1	3

https://indico.cern.ch/event/355454/contributions/838966/

➢ Advantages:

- ❑ **Less recombination contributions**

  [A. Emerick, X. Zhao and R. Rapp: EPJ A48, 72 (2012)]
  [X. Du, M. He, and R. Rapp: PRC 96, 054901 (2017)]

- ❑ **Pre-Υ ($b\bar{b}$) has higher chance to survive than pre-J/ψ ($c\bar{c}$) when passing through the nuclear remnant:**

$$\sigma_{\text{eff}}^{\Upsilon} \sim \left(\frac{m_c}{m_b}\right)^2 \sigma_{\text{eff}}^{J/\psi} \simeq 0.1\, \sigma_{\text{eff}}^{J/\psi}$$

E. Ferreiro, et al., PoS 157 (2012) 159

- ❑ **Υ(1S) is less affected by co-mover absorption than J/ψ**

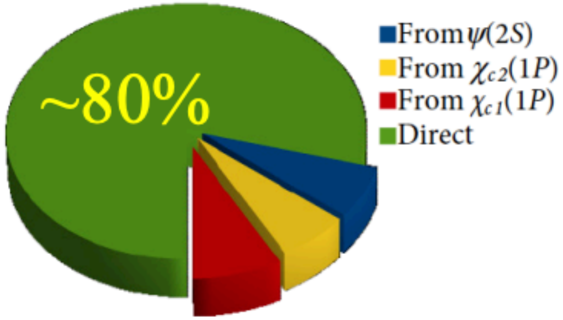
Z. Lin, C. Ko, PLB 503 (2001) 104

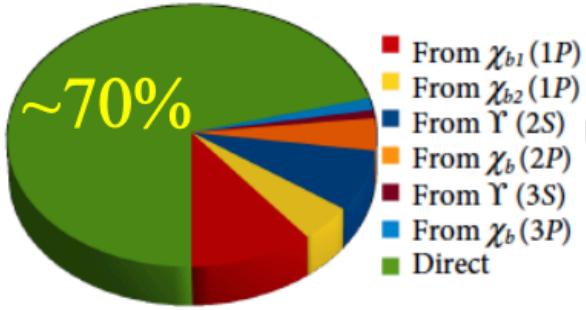
→ A cleaner probe at RHIC

➢ Challenge: **small production cross section**

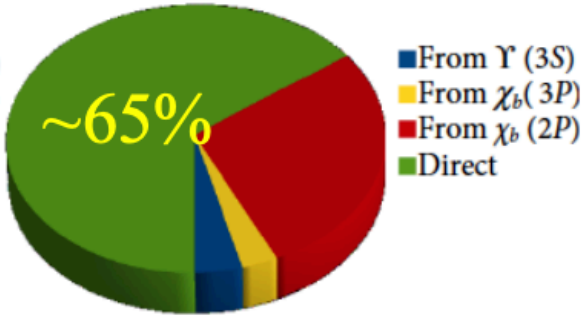
Feeddown to Prompt Quarkonia in p+p

J/ψ Υ(1S) Υ(2S) Υ(3S)

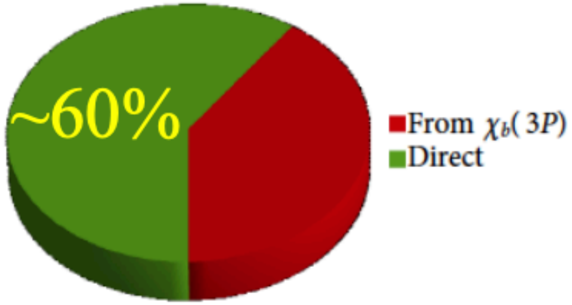




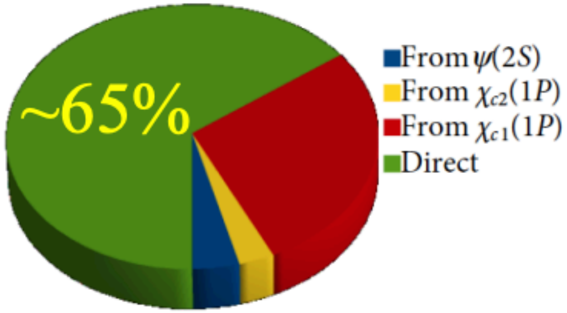
(a) Low P_T $\Upsilon(1S)$

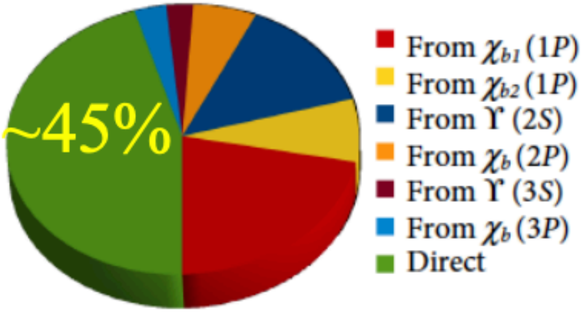


(b) Low P_T $\Upsilon(2S)$

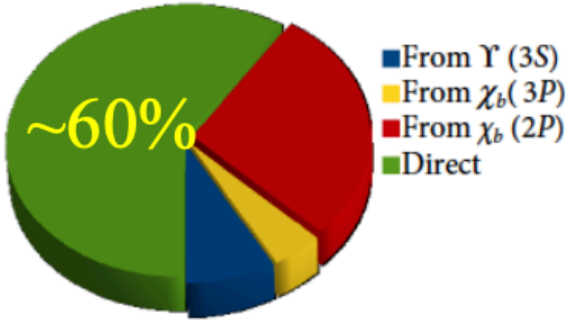


(c) Low P_T $\Upsilon(3S)$

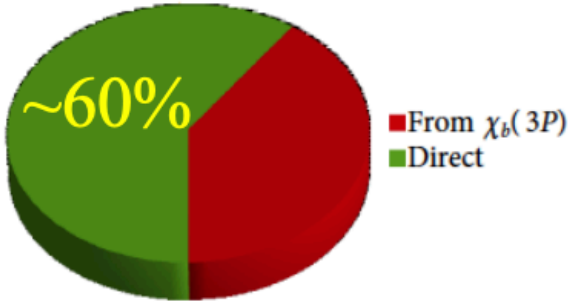




(d) High P_T $\Upsilon(1S)$



(e) High P_T $\Upsilon(2S)$

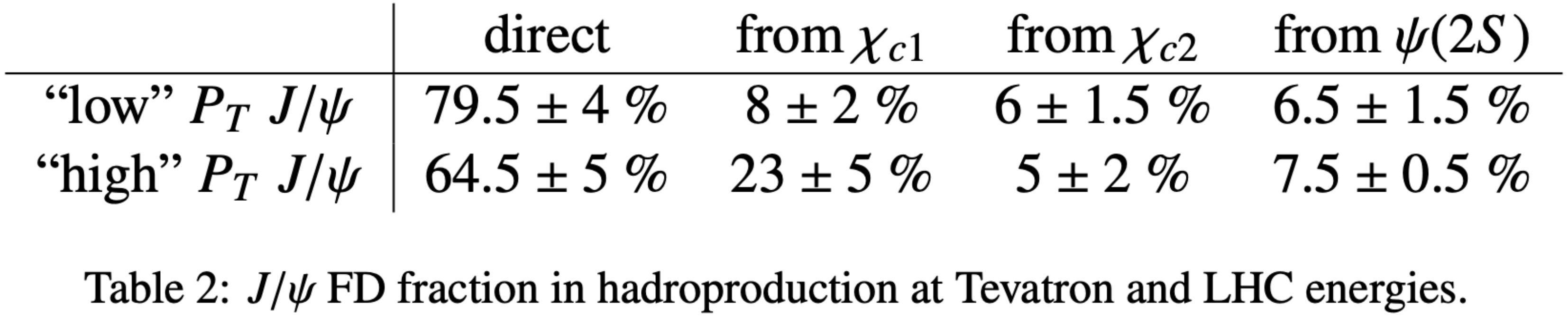


(f) High P_T $\Upsilon(3S)$

Green: direct production

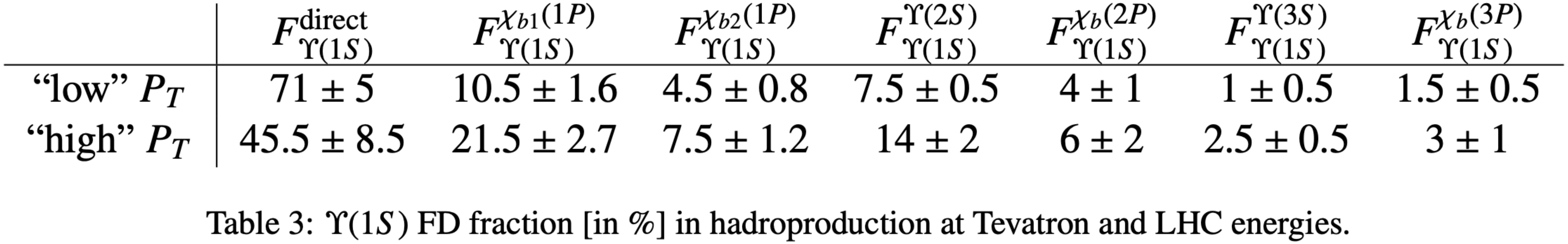
Feeddown need always be taken into account

J.-P. Lansberg, arXiv:1903.09185



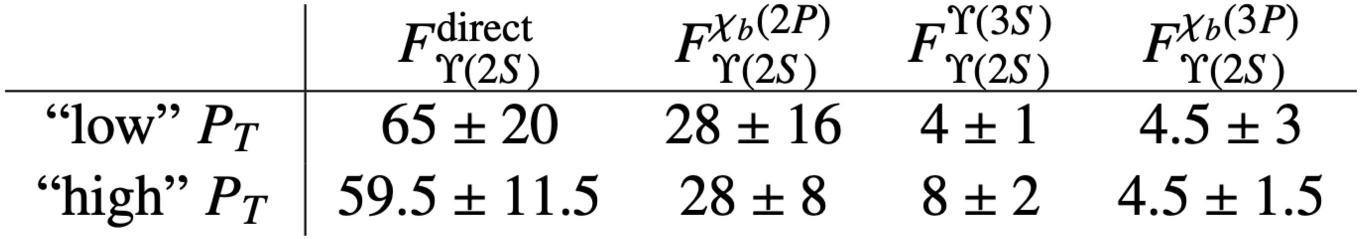
	direct	from χ_{c1}	from χ_{c2}	from $\psi(2S)$
"low" P_T J/ψ	79.5 ± 4 %	8 ± 2 %	6 ± 1.5 %	6.5 ± 1.5 %
"high" P_T J/ψ	64.5 ± 5 %	23 ± 5 %	5 ± 2 %	7.5 ± 0.5 %

Table 2: J/ψ FD fraction in hadroproduction at Tevatron and LHC energies.

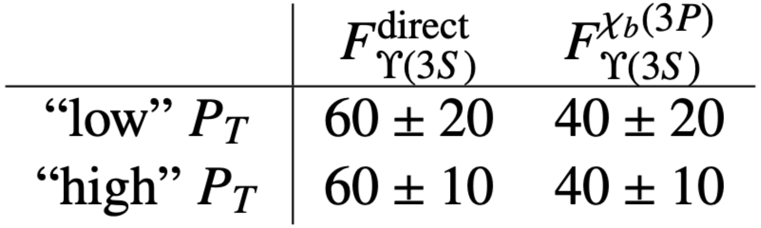


	$F_{\Upsilon(1S)}^{\text{direct}}$	$F_{\Upsilon(1S)}^{\chi_{b1}(1P)}$	$F_{\Upsilon(1S)}^{\chi_{b2}(1P)}$	$F_{\Upsilon(1S)}^{\Upsilon(2S)}$	$F_{\Upsilon(1S)}^{\chi_b(2P)}$	$F_{\Upsilon(1S)}^{\Upsilon(3S)}$	$F_{\Upsilon(1S)}^{\chi_b(3P)}$
"low" P_T	71 ± 5	10.5 ± 1.6	4.5 ± 0.8	7.5 ± 0.5	4 ± 1	1 ± 0.5	1.5 ± 0.5
"high" P_T	45.5 ± 8.5	21.5 ± 2.7	7.5 ± 1.2	14 ± 2	6 ± 2	2.5 ± 0.5	3 ± 1

Table 3: $\Upsilon(1S)$ FD fraction [in %] in hadroproduction at Tevatron and LHC energies.

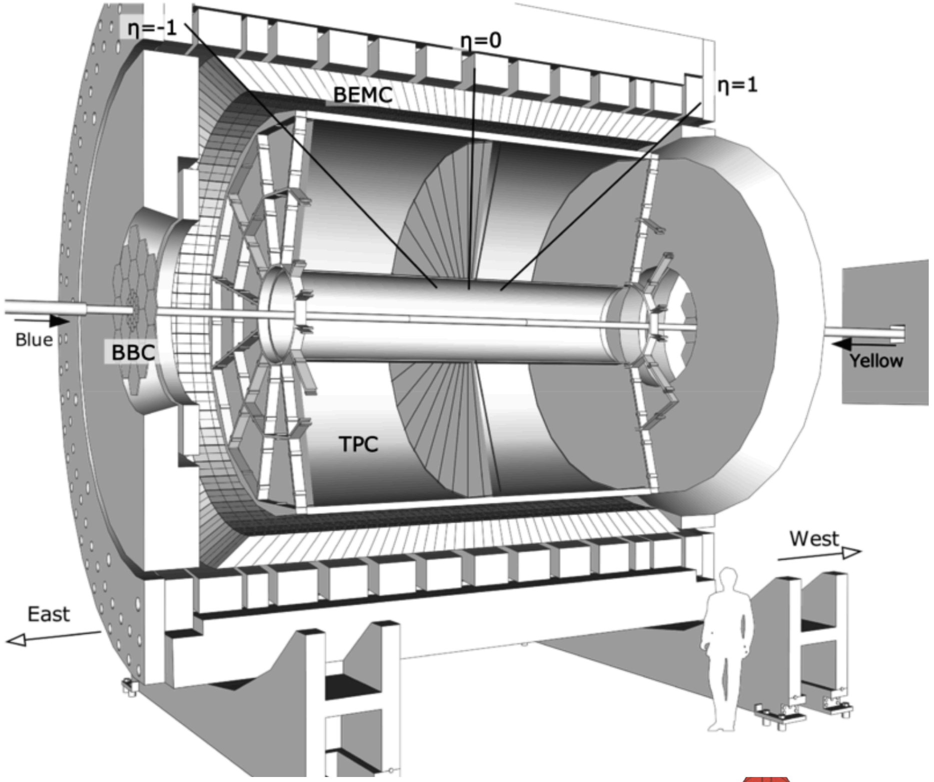


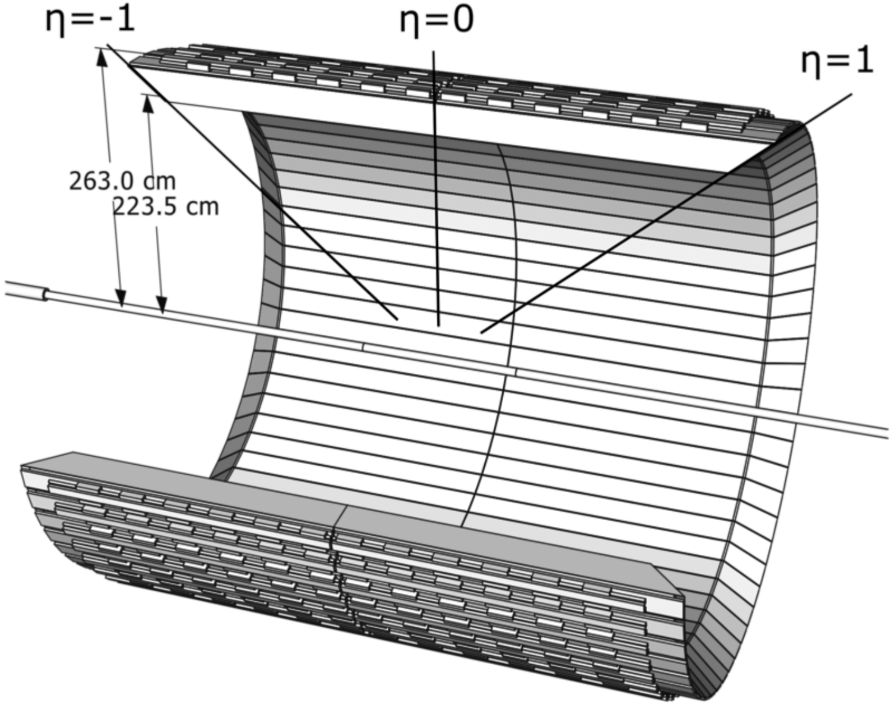
	$F_{\Upsilon(2S)}^{\text{direct}}$	$F_{\Upsilon(2S)}^{\chi_b(2P)}$	$F_{\Upsilon(2S)}^{\Upsilon(3S)}$	$F_{\Upsilon(2S)}^{\chi_b(3P)}$
"low" P_T	65 ± 20	28 ± 16	4 ± 1	4.5 ± 3
"high" P_T	59.5 ± 11.5	28 ± 8	8 ± 2	4.5 ± 1.5



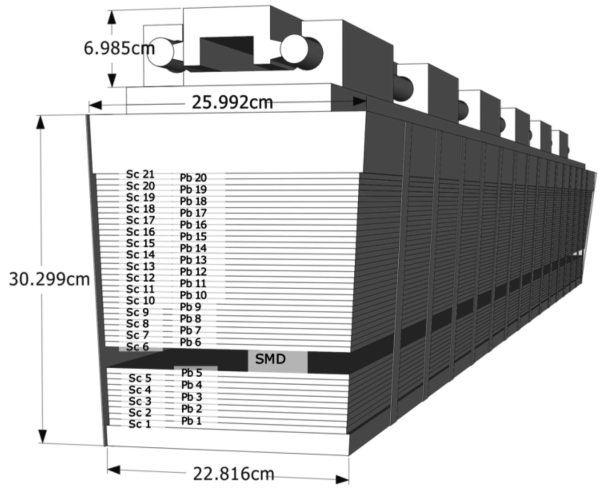
	$F_{\Upsilon(3S)}^{\text{direct}}$	$F_{\Upsilon(3S)}^{\chi_b(3P)}$
"low" P_T	60 ± 20	40 ± 20
"high" P_T	60 ± 10	40 ± 10

The Barrel Electromagnetic Calorimeter (BEMC)





A BEMC Module



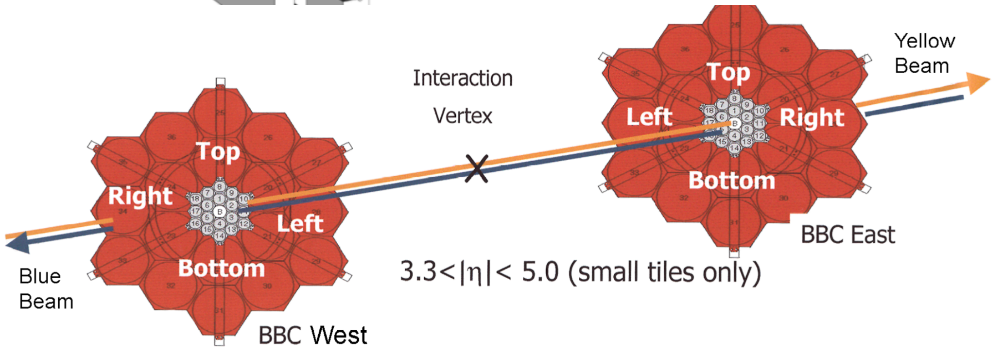


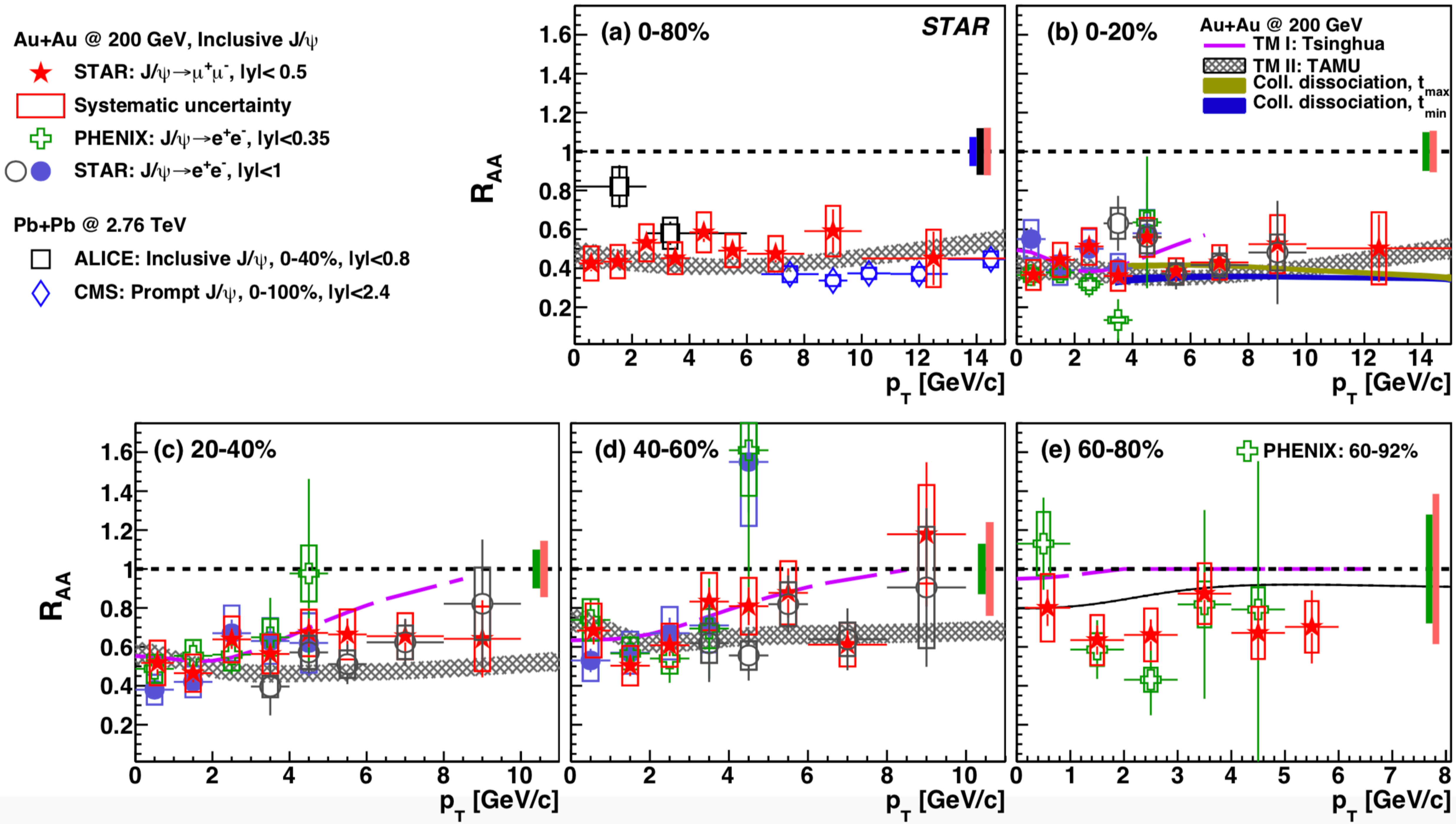
FIGURE 5.1. The STAR BBC is divided into two identical detectors on the east and west sides of the interaction region. The each BBC detector contains two inner annuli of smaller scintillators and two outer annuli of larger scintillators [**17**].

Beam Beam Counter(BBC):

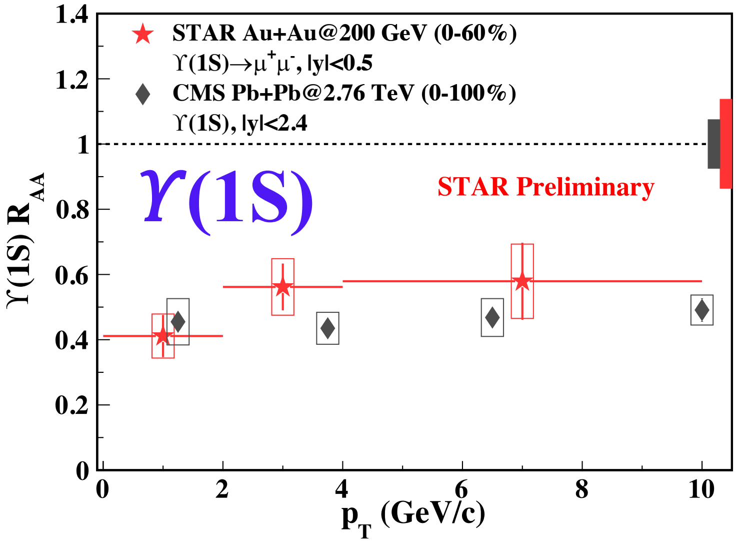
- high-Eta particles
- MB trigger, coincidence between BBC-East and BBC-West

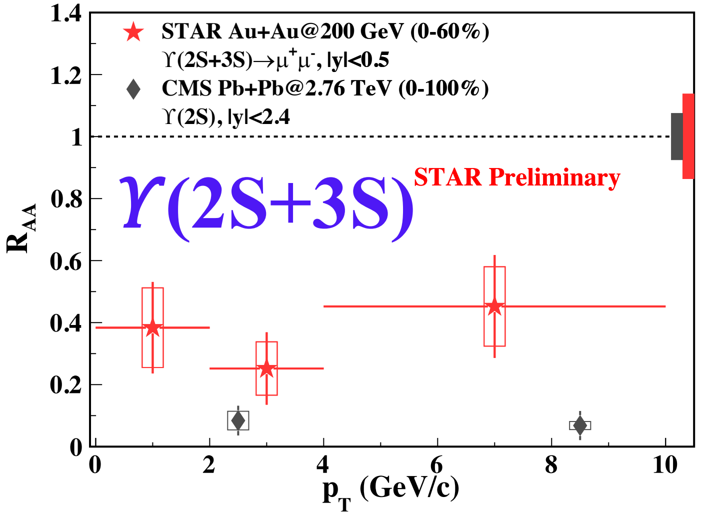
Vertex Position Detector (VPD):

- Pb+scintillator+photo-multiplier tubes
- Resolution: 4cm(120ps) in pp, 1.6cm(54ps) in dAu, 7mm(23ps) in AuAu


Au+Au @ 200 GeV, Inclusive J/ψ
STAR: J/ψ→μ⁺μ⁻, |y|< 0.5
Systematic uncertainty
PHENIX: J/ψ→e⁺e⁻, |y|<0.35
STAR: J/ψ→e⁺e⁻, |y|<1
Pb+Pb @ 2.76 TeV
ALICE: Inclusive J/ψ, 0-40%, |y|<0.8
CMS: Prompt J/ψ, 0-100%, |y|<2.4
(a) 0-80%
STAR
(b) 0-20%
Au+Au @ 200 GeV
TM I: Tsinghua
TM II: TAMU
Coll. dissociation, t_max
Coll. dissociation, t_min
(c) 20-40%
(d) 40-60%
(e) 60-80%
PHENIX: 60-92%
R_AA
p_T [GeV/c]
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
0
2
4
6
8
10
12
14
1
3
5
7

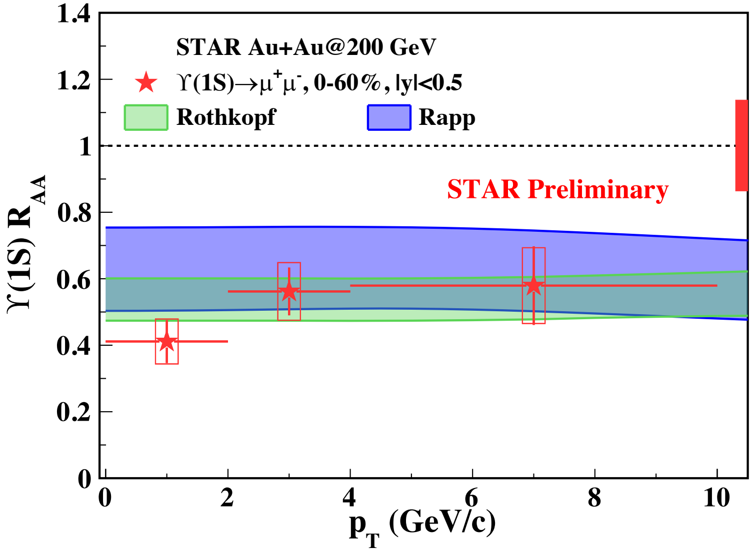
Upsilon R_{AA} vs. p_T

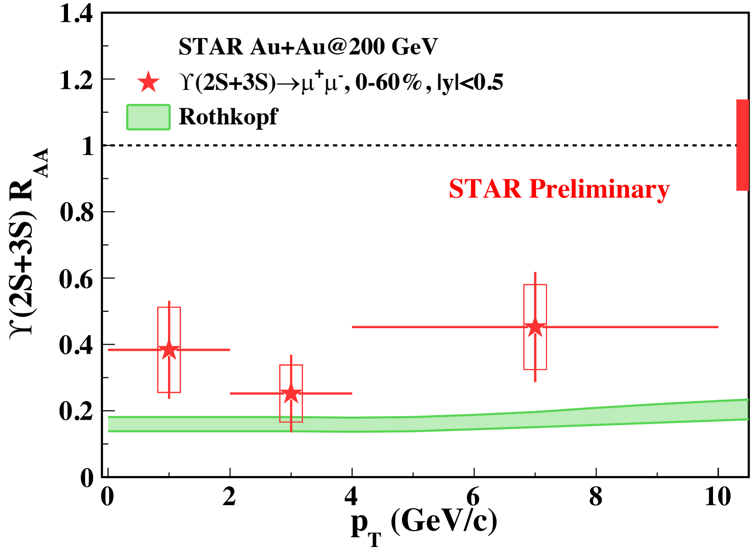




Υ(1S), Υ(2S+3S) R_{AA}:

- No significant p_T dependence
- 1S consistent with LHC results
- 2S+3S less suppressed than LHC

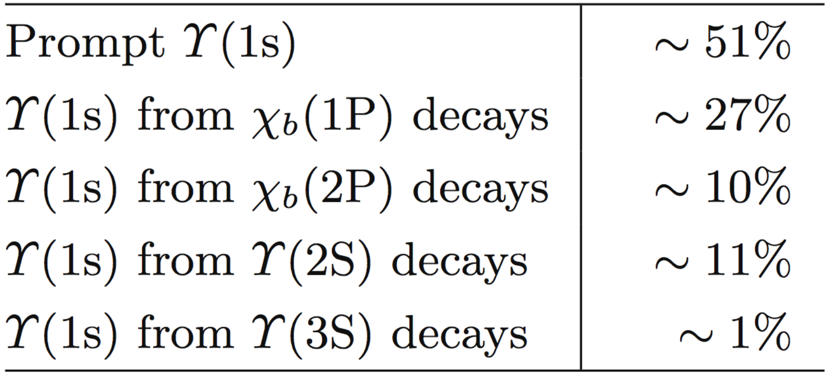




https://indico.cern.ch/event/355454/contributions/838966/

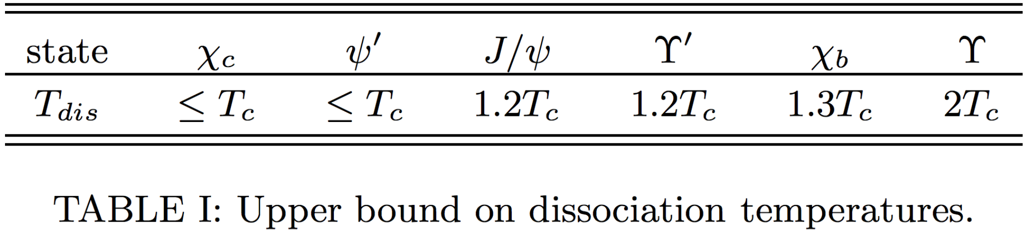
At central AA collisions	RHIC (200 GeV)	LHC (2.76 GeV)
$\#c\bar{c}/event$	~13	~115
$\#b\bar{b}/event$	~0.1	3

Upsilon(1S) feed down fractions measured at High p_T (p_T>8 GeV/c) CDF, PRL 84 (2000) 2094



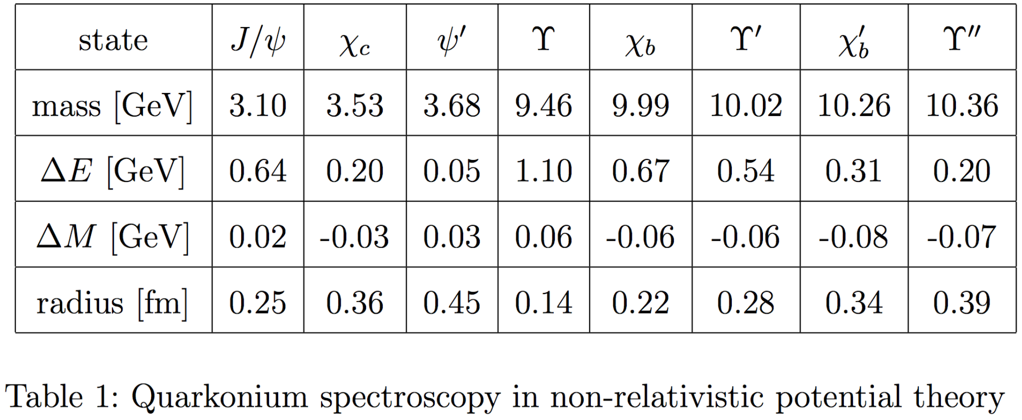
Prompt $\Upsilon(1s)$	$\sim 51\%$
$\Upsilon(1s)$ from $\chi_b(1P)$ decays	$\sim 27\%$
$\Upsilon(1s)$ from $\chi_b(2P)$ decays	$\sim 10\%$
$\Upsilon(1s)$ from $\Upsilon(2S)$ decays	$\sim 11\%$
$\Upsilon(1s)$ from $\Upsilon(3S)$ decays	$\sim 1\%$

PhysRevLett.99.211602



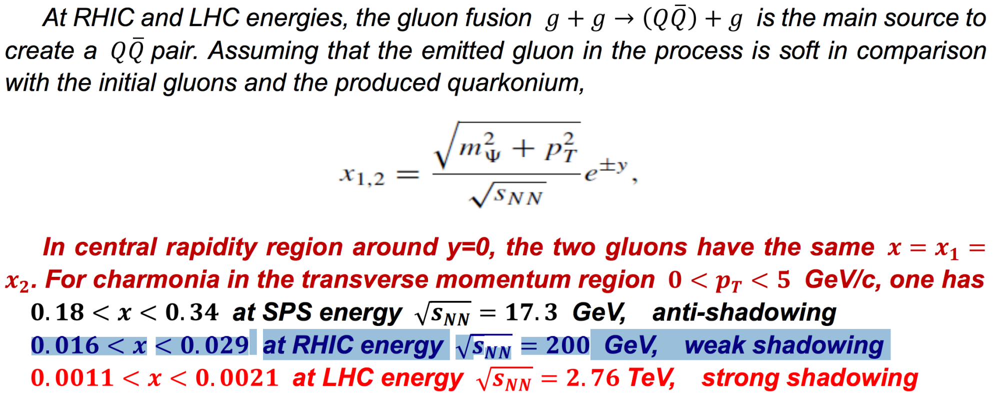
state	χ_c	ψ'	J/ψ	Υ'	χ_b	Υ
T_{dis}	$\leq T_c$	$\leq T_c$	$1.2T_c$	$1.2T_c$	$1.3T_c$	$2T_c$

TABLE I: Upper bound on dissociation temperatures.



state	J/ψ	χ_c	ψ'	Υ	χ_b	Υ'	χ_b'	Υ''
mass [GeV]	3.10	3.53	3.68	9.46	9.99	10.02	10.26	10.36
ΔE [GeV]	0.64	0.20	0.05	1.10	0.67	0.54	0.31	0.20
ΔM [GeV]	0.02	-0.03	0.03	0.06	-0.06	-0.06	-0.08	-0.07
radius [fm]	0.25	0.36	0.45	0.14	0.22	0.28	0.34	0.39

Table 1: Quarkonium spectroscopy in non-relativistic potential theory



At RHIC and LHC energies, the gluon fusion $g+g \to (Q\bar{Q})+g$ is the main source to create a $Q\bar{Q}$ pair. Assuming that the emitted gluon in the process is soft in comparison with the initial gluons and the produced quarkonium,

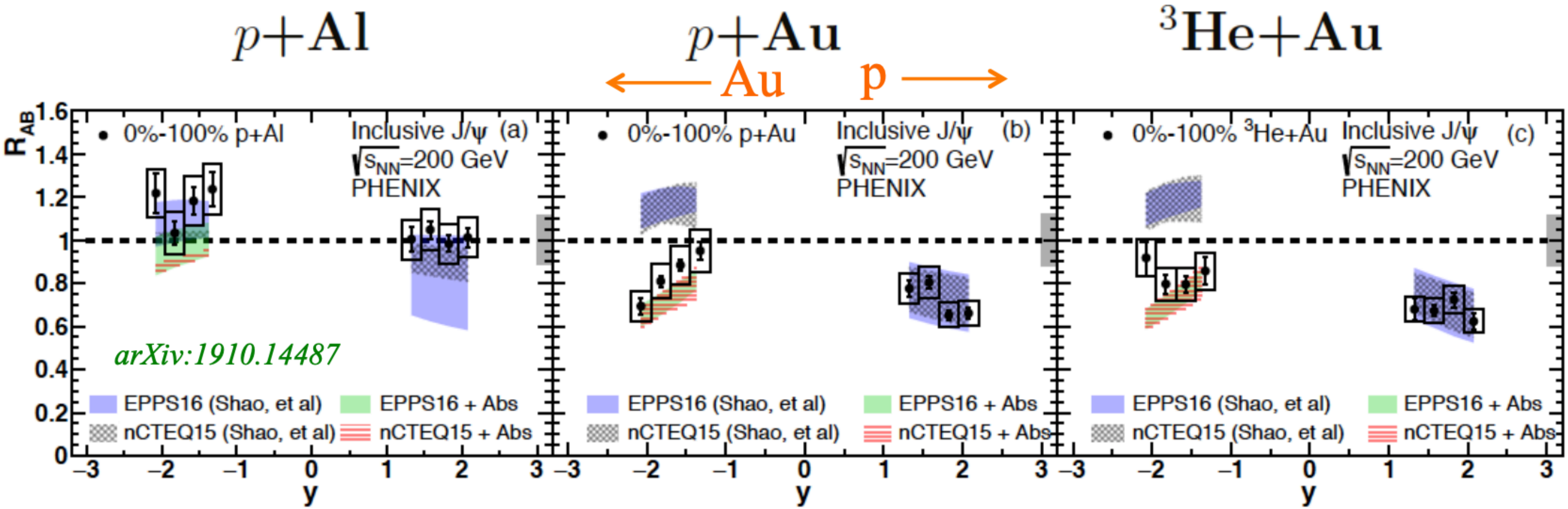
$$x_{1,2} = \frac{\sqrt{m_\Psi^2 + p_T^2}}{\sqrt{s_{NN}}} e^{\pm y},$$

In central rapidity region around y=0, the two gluons have the same $x = x_1 = x_2$. For charmonia in the transverse momentum region $0 < p_T < 5$ GeV/c, one has

$0.18 < x < 0.34$ at SPS energy $\sqrt{s_{NN}} = 17.3$ GeV, anti-shadowing

$0.016 < x < 0.029$ at RHIC energy $\sqrt{s_{NN}} = 200$ GeV, weak shadowing

$0.0011 < x < 0.0021$ at LHC energy $\sqrt{s_{NN}} = 2.76$ TeV, strong shadowing

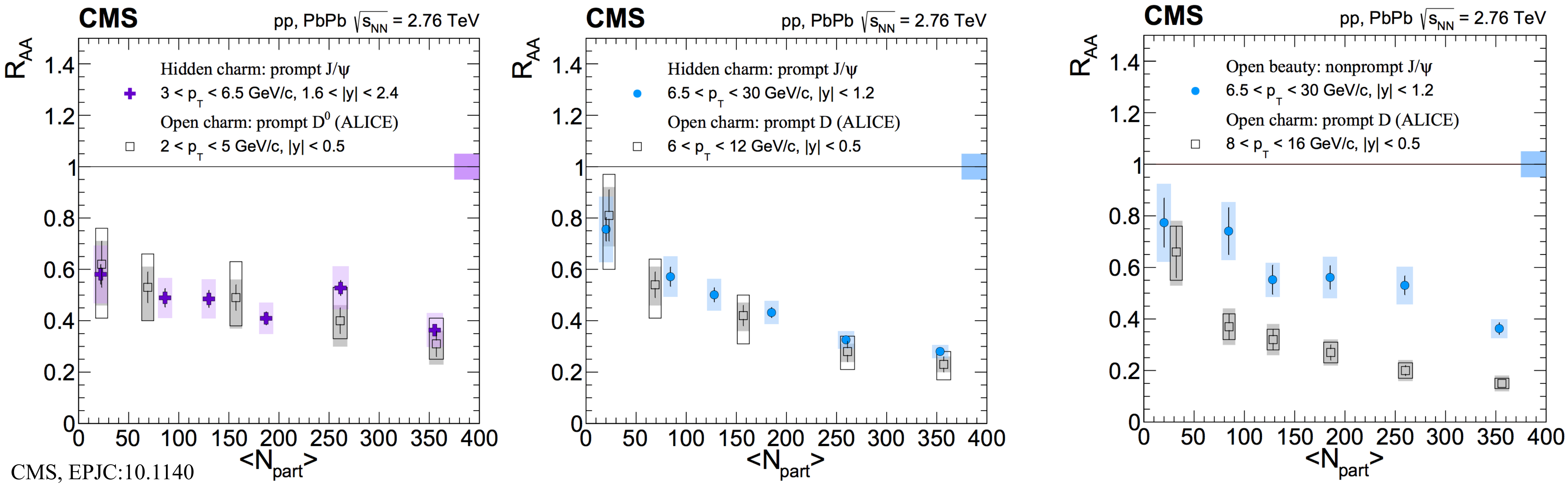


Suppression in both forward and backward rapidity with Au beam

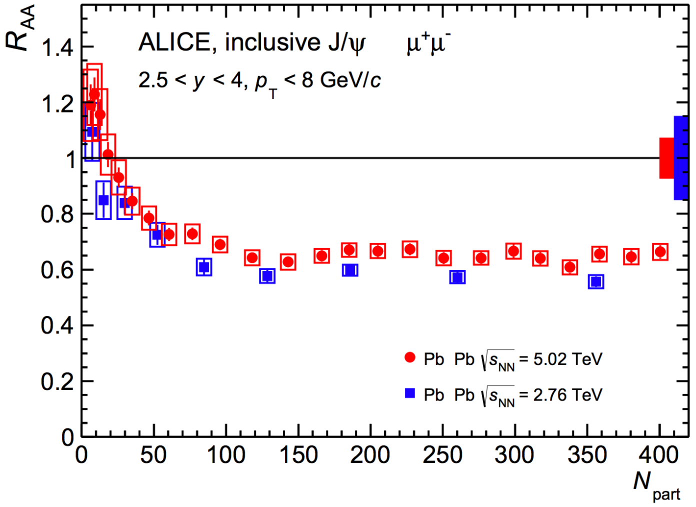
Forward rapidity: nPDFs alone describe data reasonably well

Backward rapidity: Nuclear absorption in addition is needed

Jpsi measurements at LHC

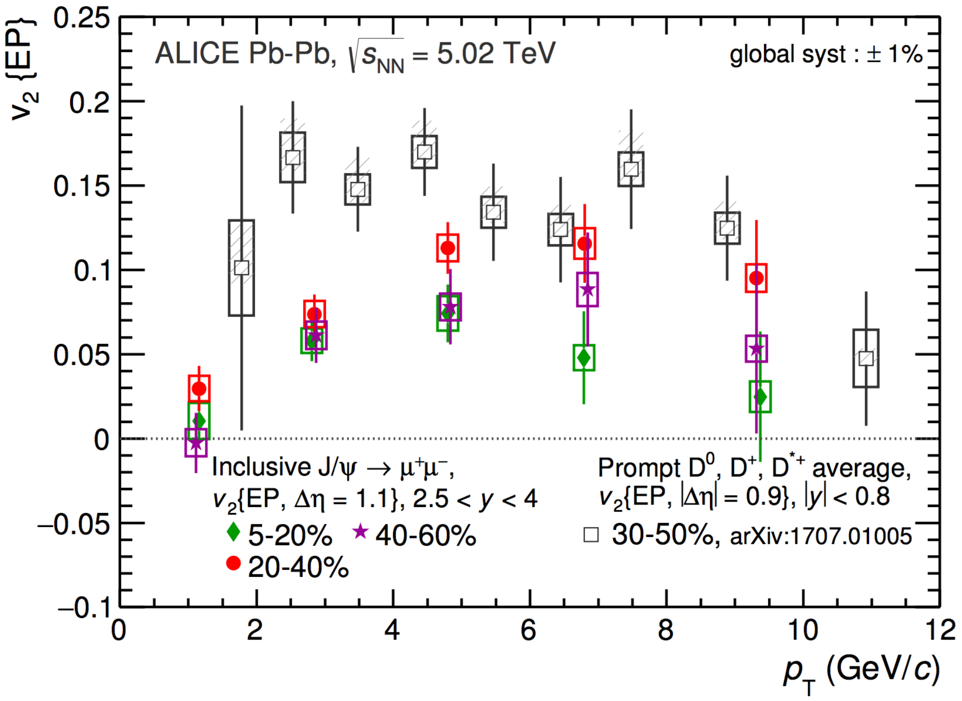


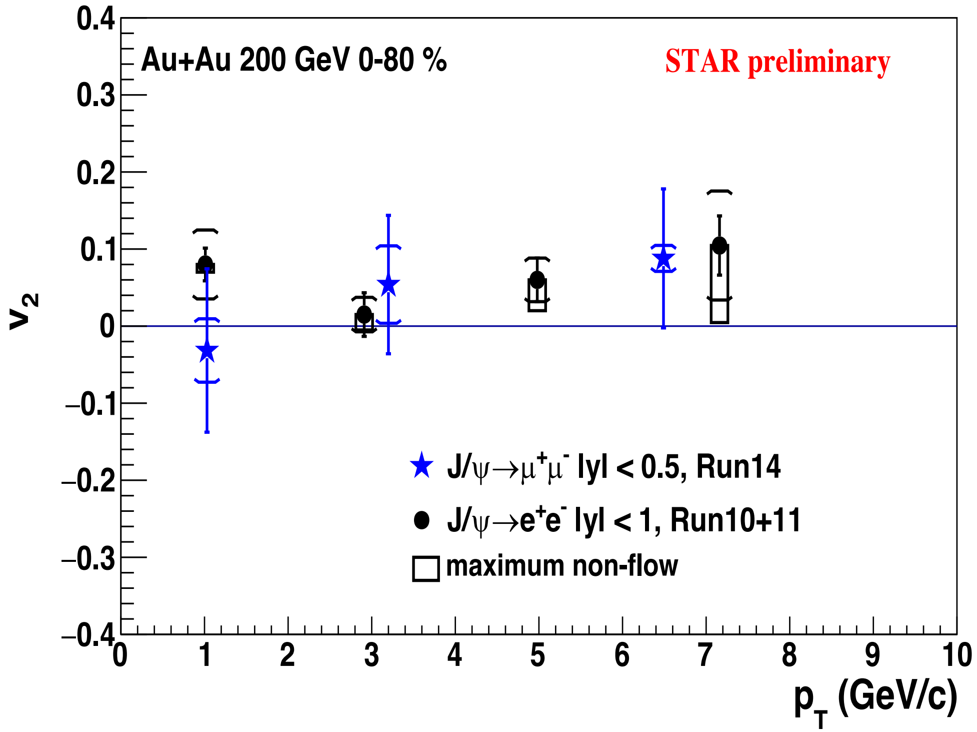
CMS, EPJC:10.1140
(PLB 766 (2017), 212)



Elliptic flow:

J/ψ from recombination should inherit the charm flow ➔ positive v_2



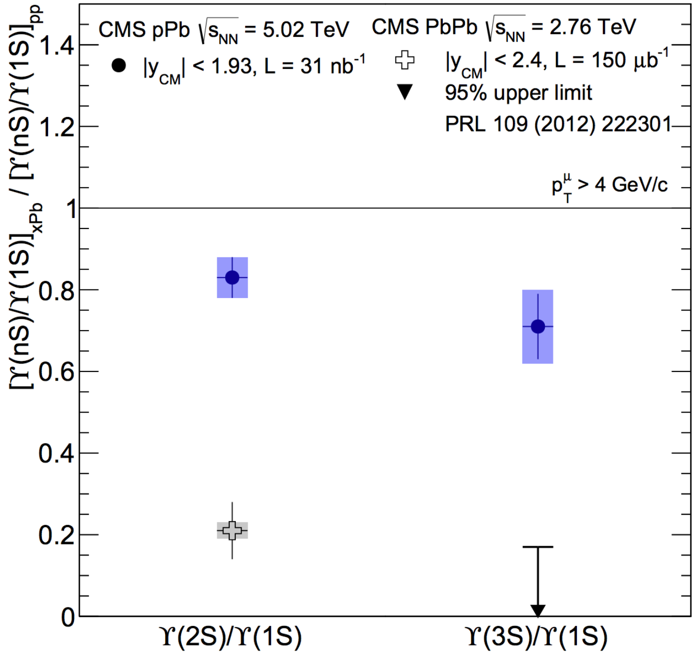


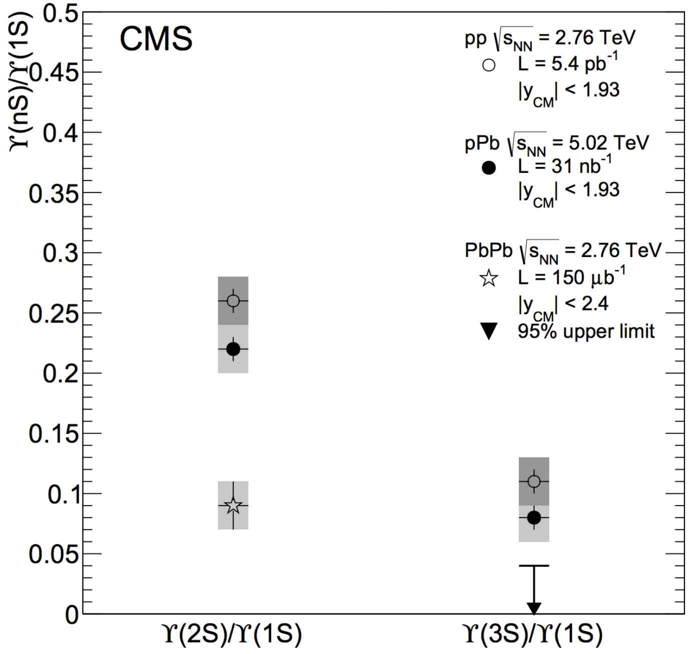
At LHC:

- **Signs of significant kinetic equilibration of charm with the medium: a finite elliptic J/psi flow**

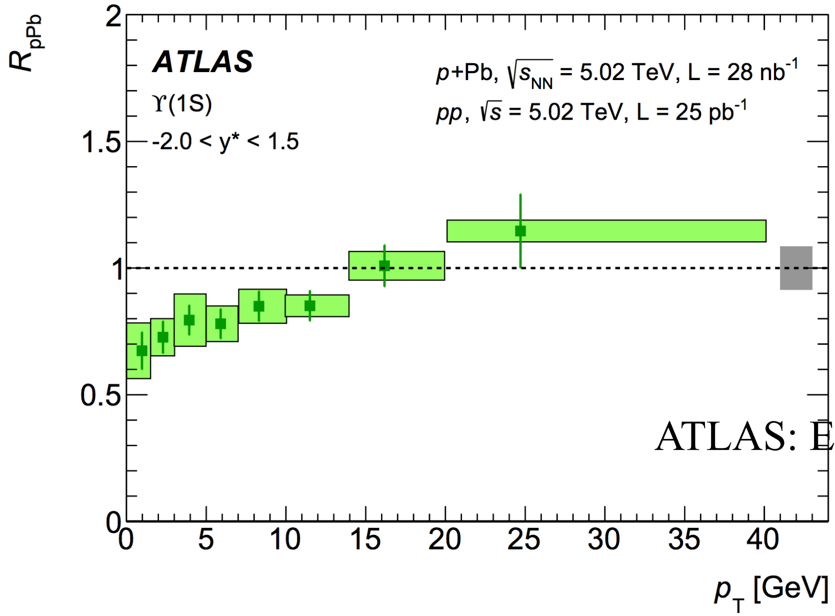
At RHIC:

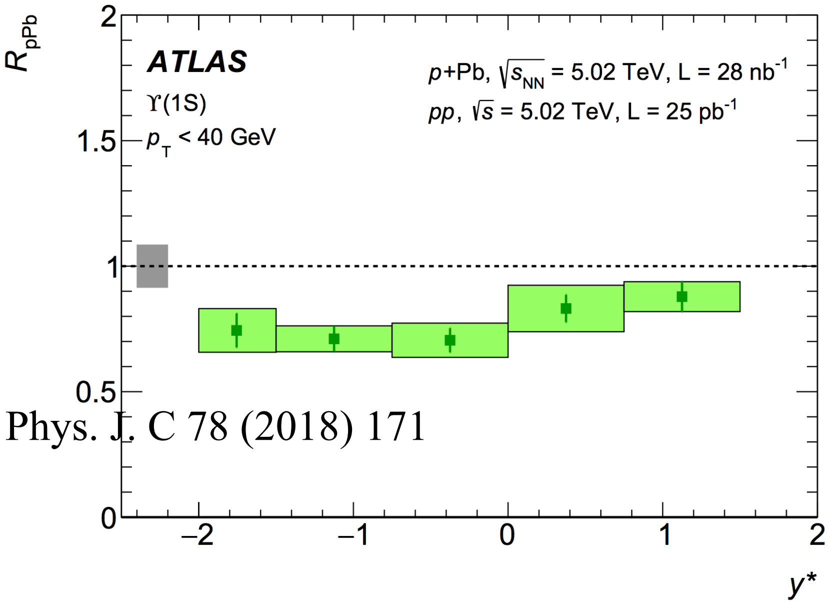
- **No significant sign of equilibration observed: Elliptic flow consistent with zero**





JHEP 04, 103 (2014), CMS-HIN-13-003





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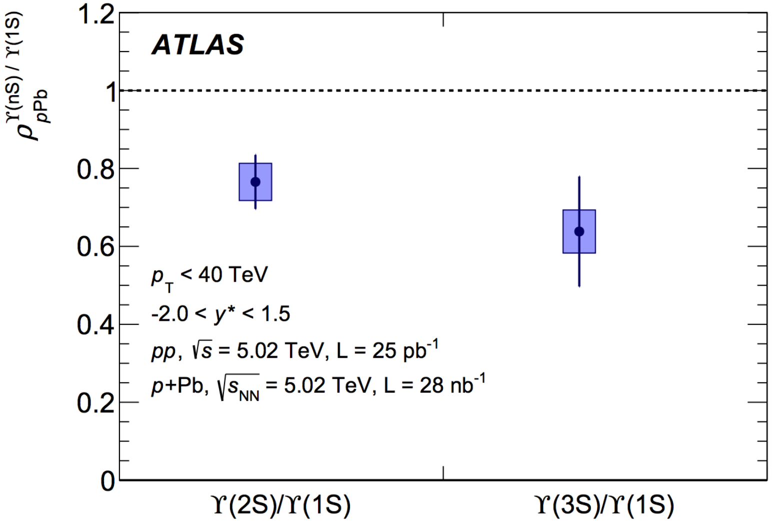
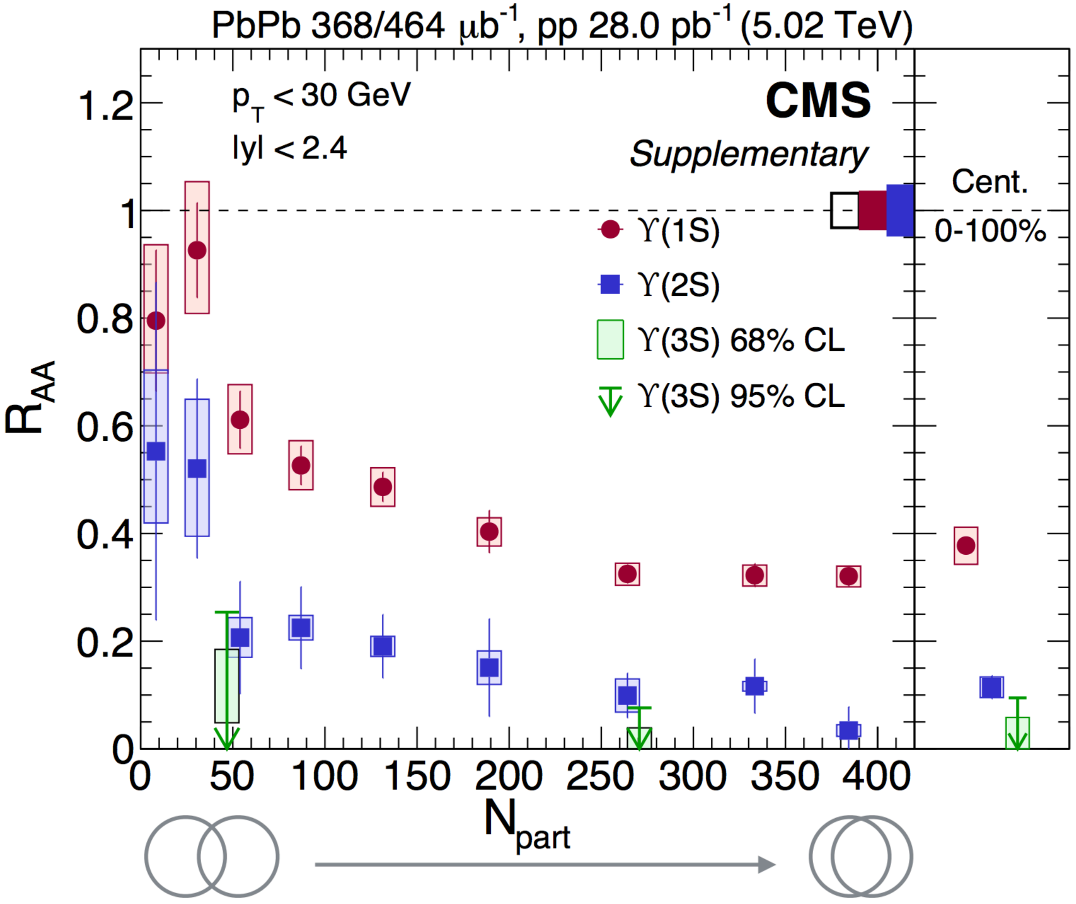
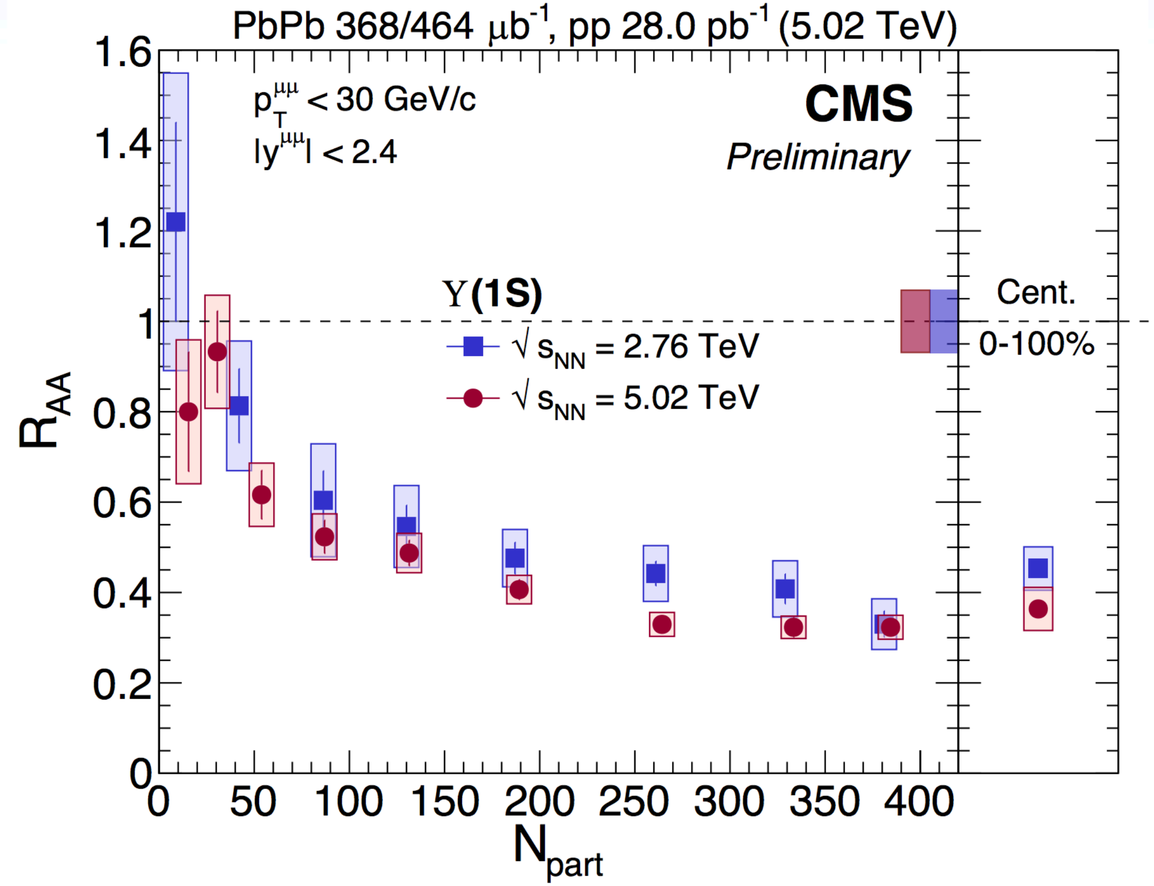




- **Stronger suppression towards mores central collisions**
- **Excited states suppressed more than ground state, consist with sequential suppression picture**



More suppression with higher collision energy

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