Quarkonium measurements at the STAR experiment

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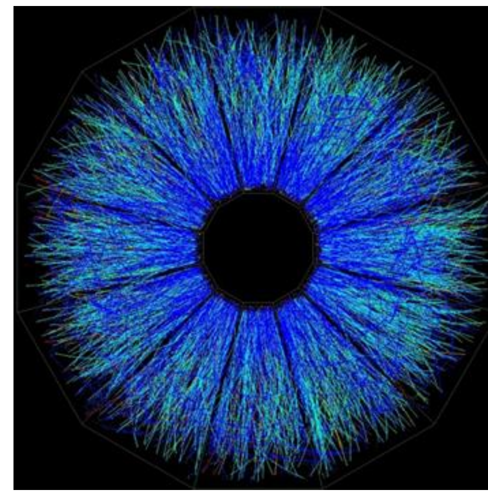

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MINISTRY OF EDUCATION,
YOUTH AND SPORTS

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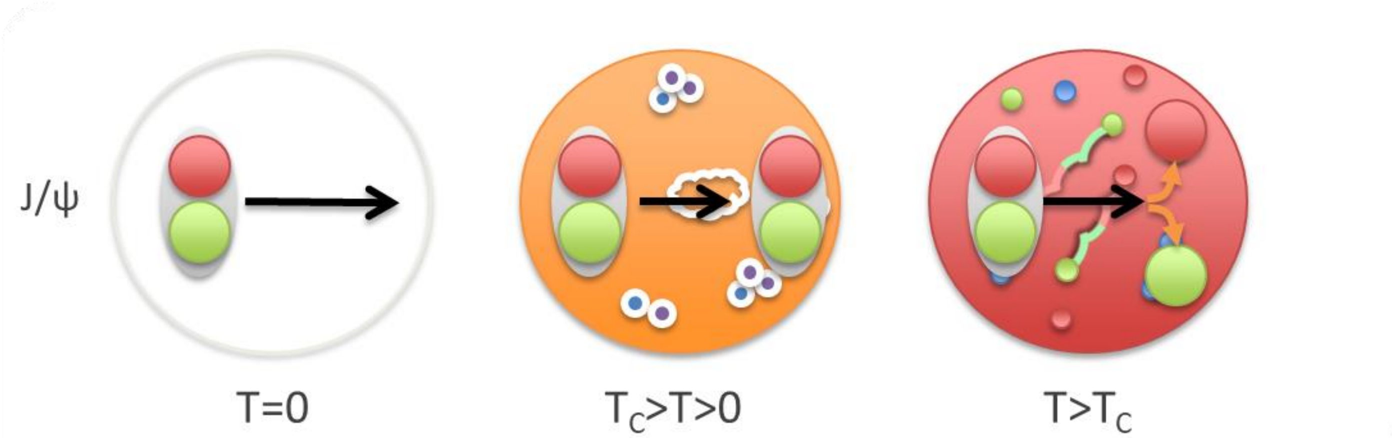
Quarkonium in nuclear matter

- In heavy ion collisions at RHIC hot and dense quark gluon plasma is created
- Heavy-flavor quarks are good probes for studying QGP
  - $m_{c,b} >> T_C, \Lambda_{QCD}, m_{u,d,s}$: produced dominantly by high-Q^2 scatterings in the early stage
- Due to color screening of quark potential in QGP quarkonium dissociation is expected

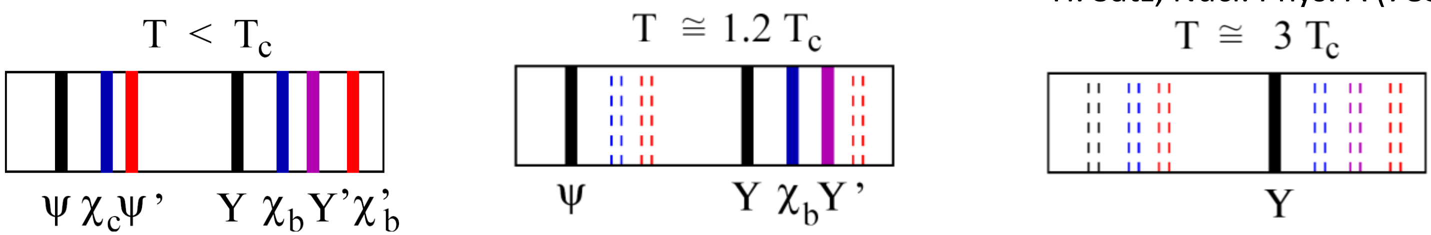


A.Rothkopf HP12

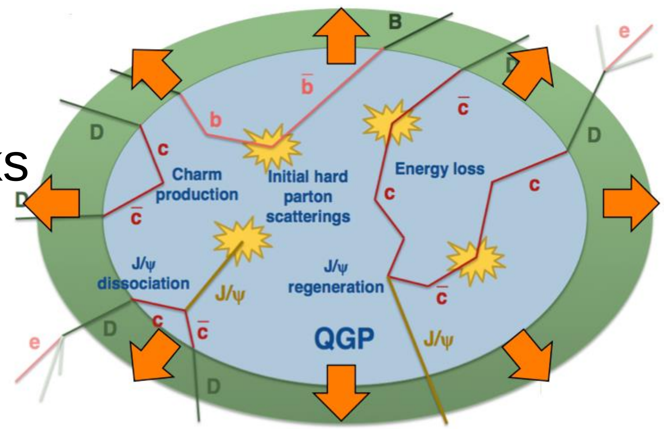
Quarkonium in nuclear matter

- Sequential melting: suppression of different states is determined by medium temperature and their binding energy - QGP thermometer

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



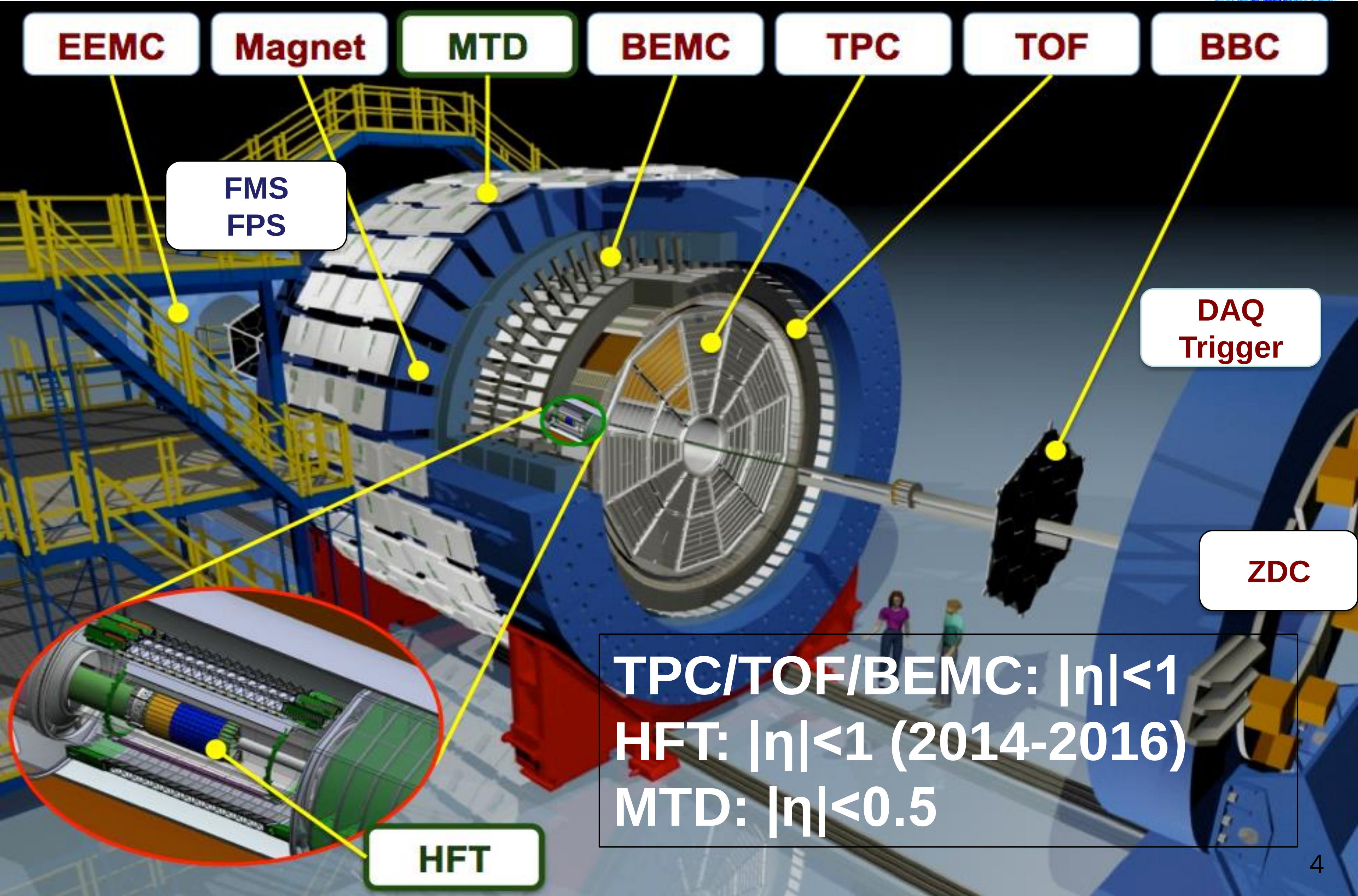
- Hot nuclear matter effects
  - Dissociation
  - Regeneration from deconfined quarks
  - Medium-induced energy loss
  - Formation time effect



https://indico.cern.ch/event/443462/images/6069-hf_cartoon1.png

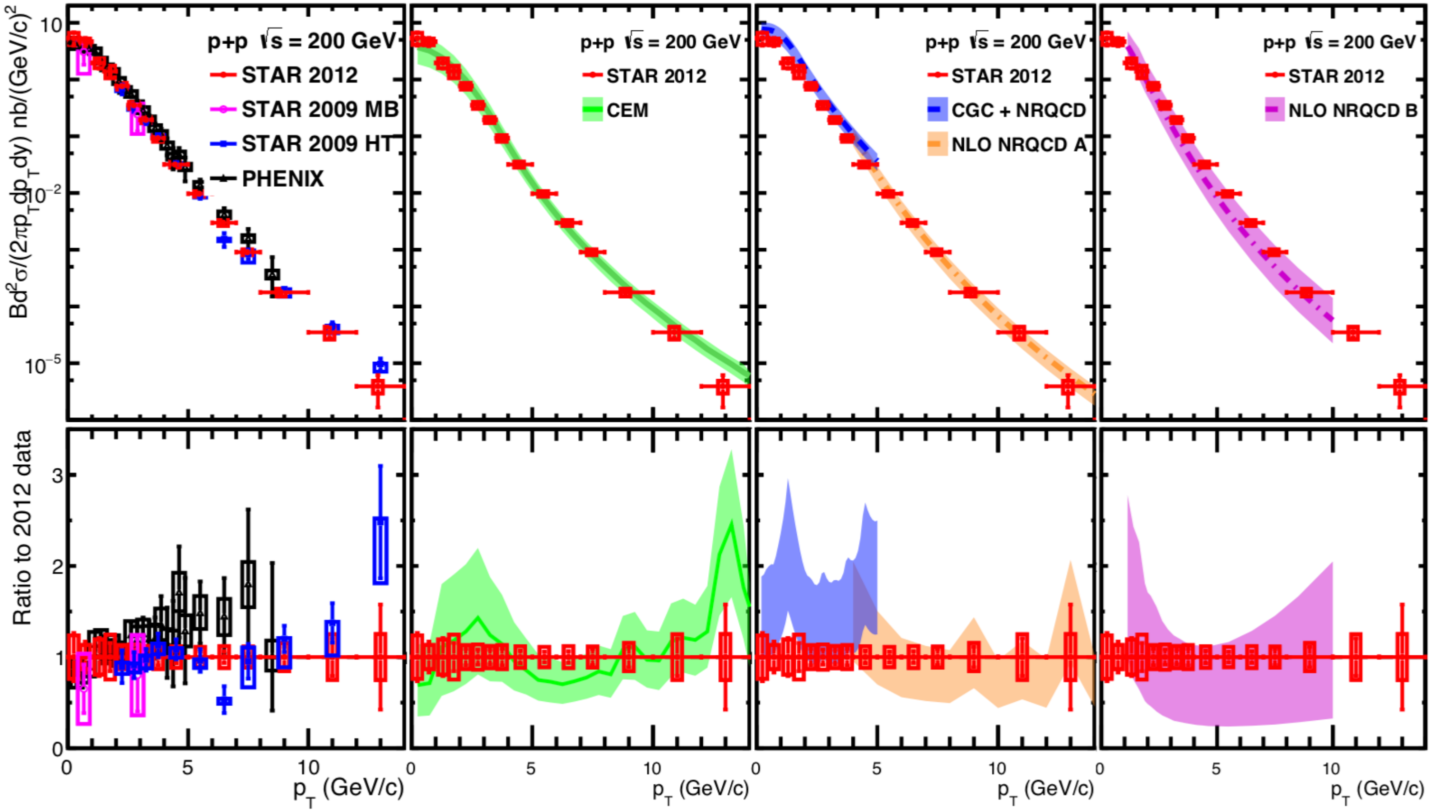
- Cold nuclear matter effects
  - Nuclear absorption, gluon shadowing, initial state energy loss, Cronin effect and gluon saturation.
- Feed-down from excited states and B-hadrons

STAR experiment



TPC/TOF/BEMC: |η|<1
HFT: |η|<1 (2014-2016)
MTD: |η|<0.5

J/ψ production in 200 GeV p+p collisions

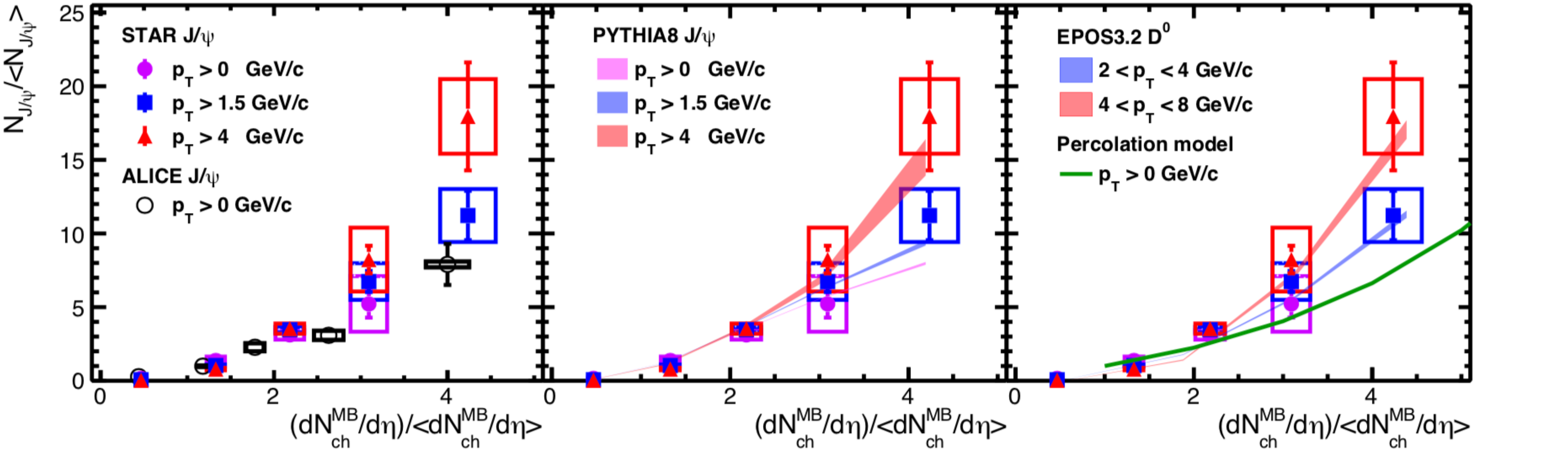


STAR 2012: PLB 786 (2018) 87-93
STAR 2009: PLB 722 (2013) 55;
PRC 93 (2016) 064904
PHENIX: PRD 82 (2010) 012001
CEM: Phys. Rept. 462 (2008) 125;
R. Vogt private communication (2009)
NLO+NRQCD A: PRD 84 (2011) 114001
CGC+NRQCD: PRL 113 (2014) 192301
NLO+NRQCD B: PRL 108 (2012) 172002

- Precision measurement of J/ψ production cross-section for p_T= 0 to 14 GeV/c
- Consistent with CEM (direct J/ψ production only) and NLO NRQCD (prompt J/ψ)
- CGC+NRQCD seems to overestimate the data in the low p_T

J/ψ production vs. event activity in p+p collisions

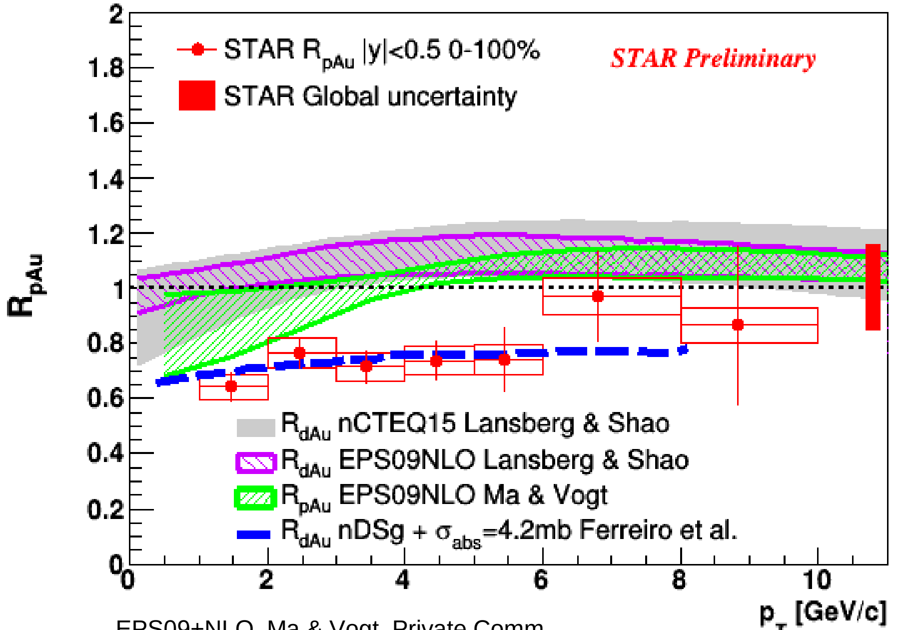
STAR 2012: PLB 786 (2018) 87-93



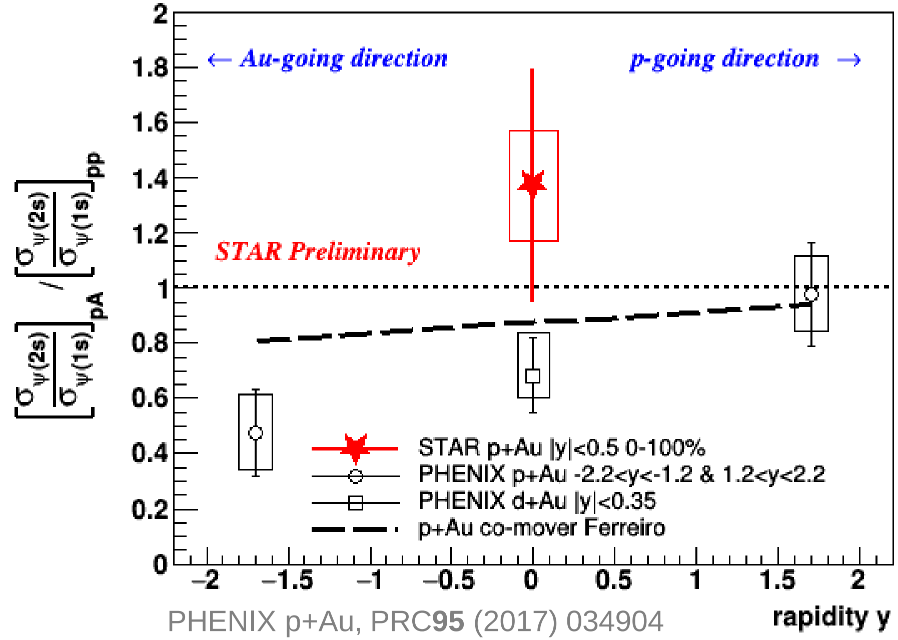
- Relative J/ψ yields as a function of event activity N_{ch} rises faster than a linear function
  - Similar trend at different collision energies

- PYTHIA, EPOS3 and Percolation model can qualitatively describe the rising trend

J/ψ and ψ(2s) production in 200 GeV p+Au collisions



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

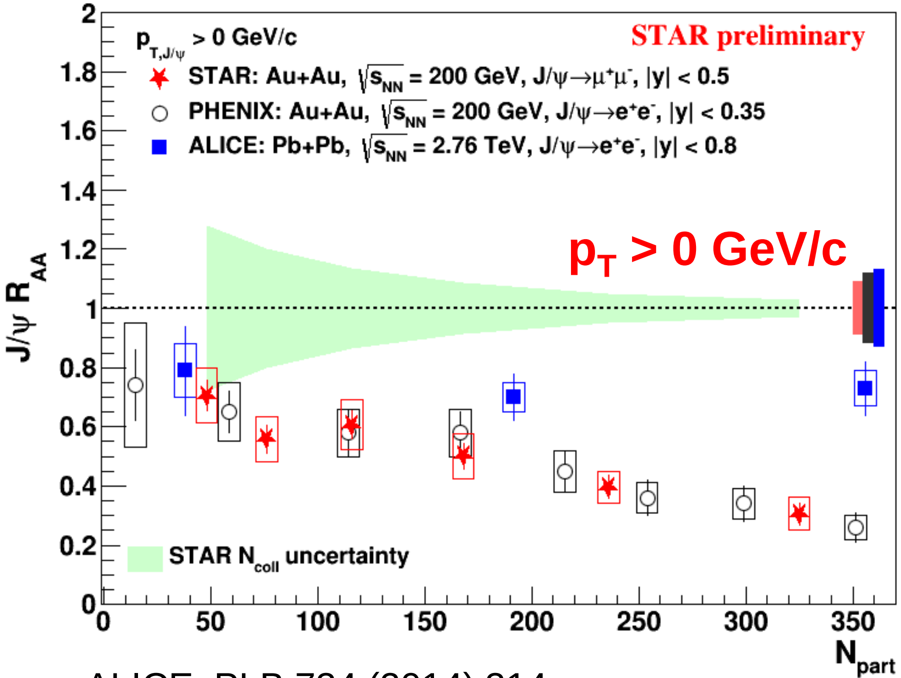


PHENIX p+Au, PRC**95** (2017) 034904
PHENIX d+Au, PRL**111** (2013) 202301
Co-mover calculation, Ferreiro, private comm.

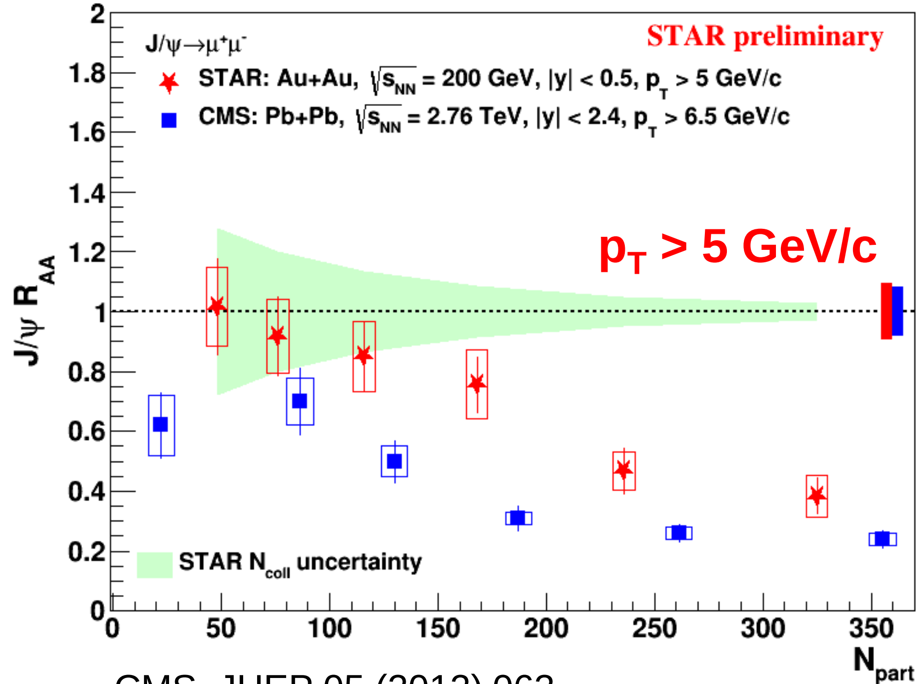
- Models with only nPDF effects describe the data at high p_T, but underpredicts the suppression at low p_T
  - Additional nuclear absorption is favored by data

- First ψ(2S) to J/ψ double ratio measurement from STAR between p+Au and p+p at midrapidity at RHIC: **1.37 ±0.42(stat.) ±0.19(syst.)**

J/ψ production in 200 GeV Au+Au collisions



ALICE, PLB 734 (2014) 314
PHENIX, PRL 98 (2007) 232301

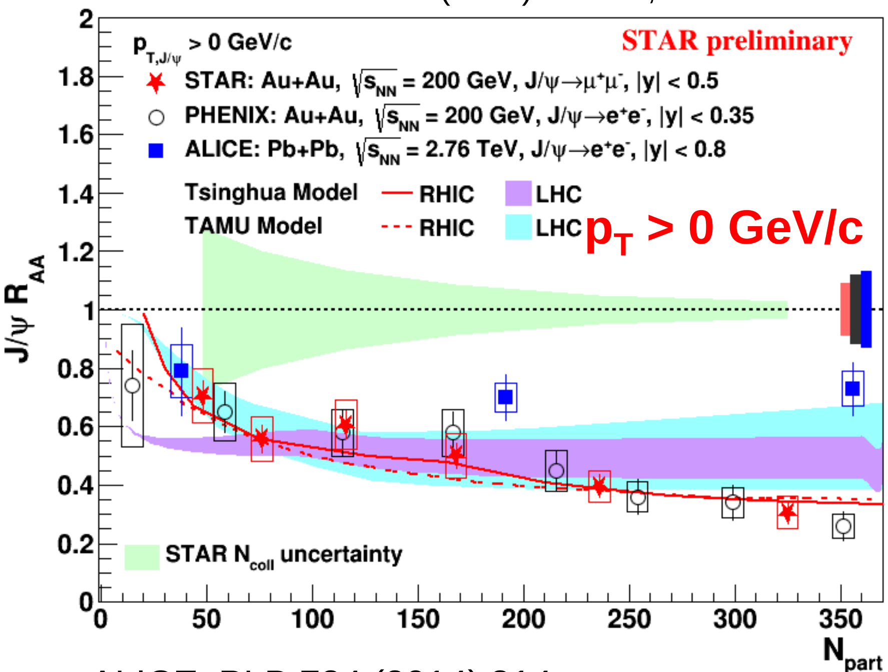


CMS, JHEP 05 (2012) 063

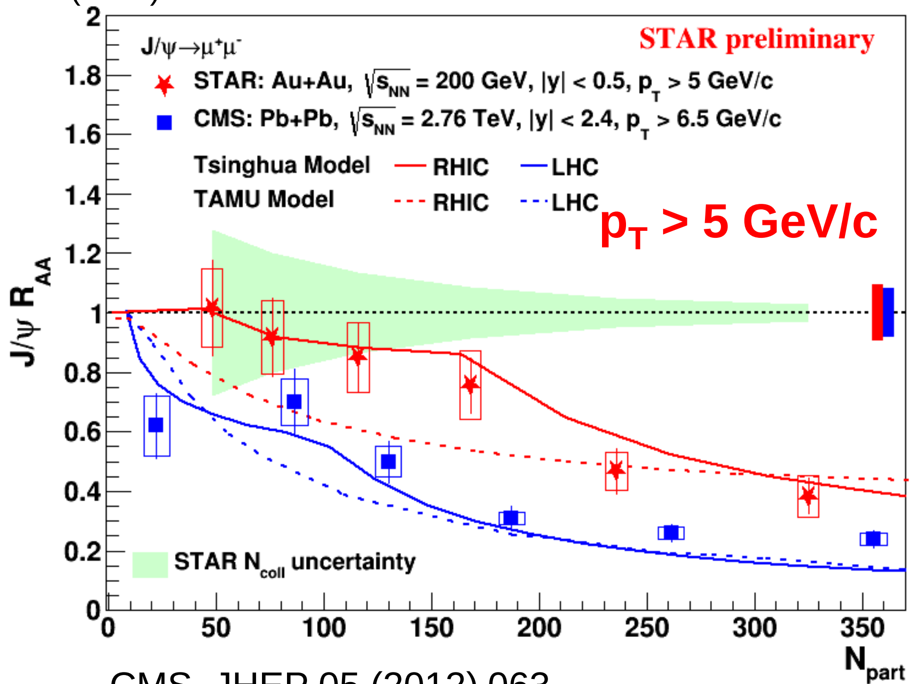
- Suppression in central collisions at low p_T:
  - dissociation, Cold Nuclear Matter (CNM) effects, regeneration
- Suppression in central collisions at high p_T: due to dissociation
- LHC vs RHIC:
  - More regeneration at LHC leads to less suppression at low p_T
  - Higher temperature at LHC, higher dissociation leads to more suppression at high p_T

J/ψ production in 200 GeV Au+Au collisions

Tsinghua at RHIC: PLB 678 (2009) 72, Tsinghua at LHC: PRC 89 (2014) 054911
TAMU at RHIC: PRC 82 (2010) 064905, TAMU at LHC: NPA 859 (2011) 114



ALICE, PLB 734 (2014) 314
PHENIX, PRL 98 (2007) 232301



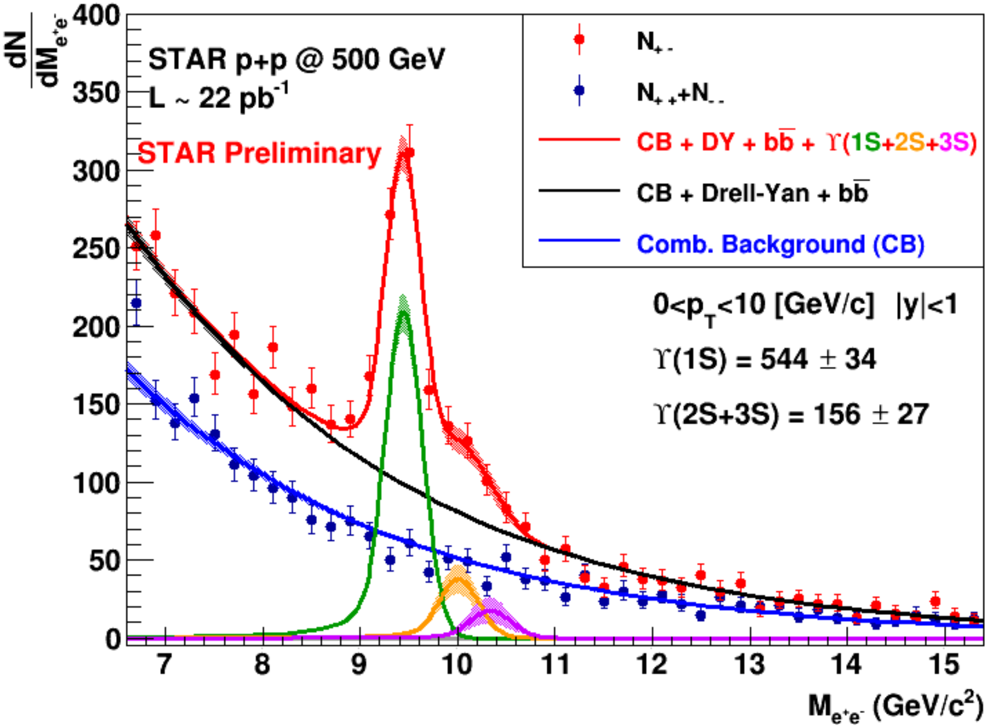
CMS, JHEP 05 (2012) 063

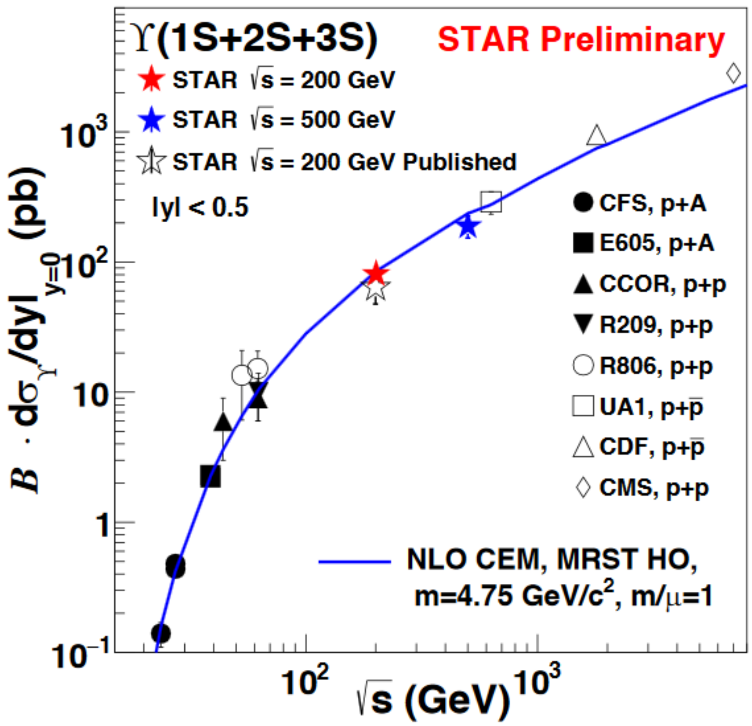
- Models can describe centrality dependence at RHIC, but overestimate suppression at the LHC at low p_T
- At high p_T both models can qualitatively describe data at RHIC and LHC

Bottomnia $\Upsilon(1S)$, $\Upsilon(2S)$, $\Upsilon(3S)$

- Recombination effects
  - J/ψ : Evidence for large effects.
  - Υ: Expecting negligible contribution.
    - σ_{cc} @ RHIC: 797 ± 210 $^{+208}_{-295}$ μb. (PRD 86, 072013(2012))
    - $\sigma_{b\bar{b}}$ @ RHIC: ~ 1.34 – 1.84 μb (PRD 83 (2011) 052006)
- Co-mover absorption effects
  - 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

Υ(1S,2S,3S) in 200GeV and 500GeV p+p collisions

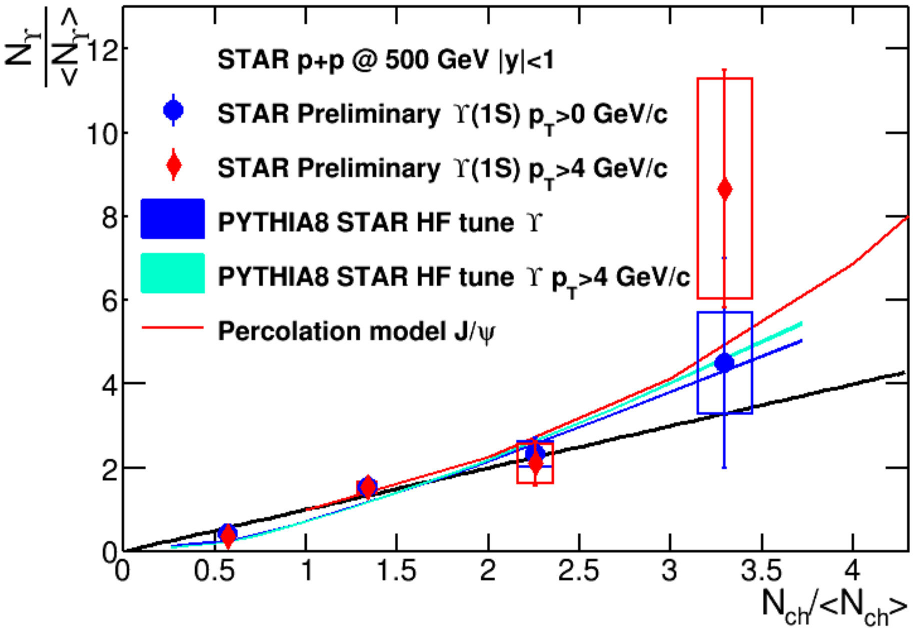


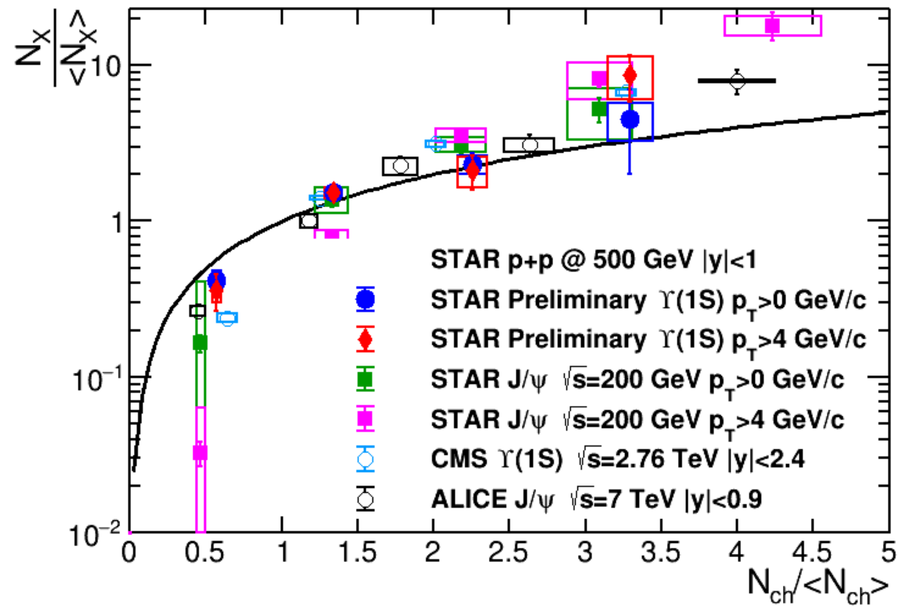


- Υ signal shapes modeled by 3 Crystal-Ball functions
- bb+Drell-Yan correlated background determined using MC simulation
- STAR results follow the world data trend
- Consistent with the Color Evaporation Model calculation

[Phys.Rep. 462, pp.125-175(2008)]

Υ(1S) and event activity





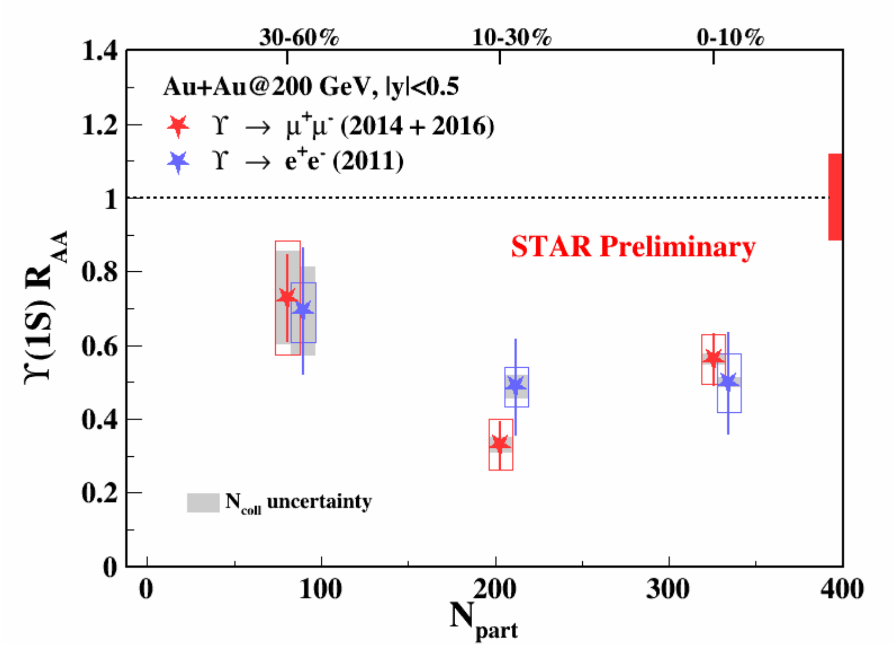
- Data consistent with a linear rise(black line), with a hint for stronger than linear rise for Υ(1S) above $p_T > 4$ GeV/c
- Similar trend at RHIC and LHC for Υ(1S) and J/ψ

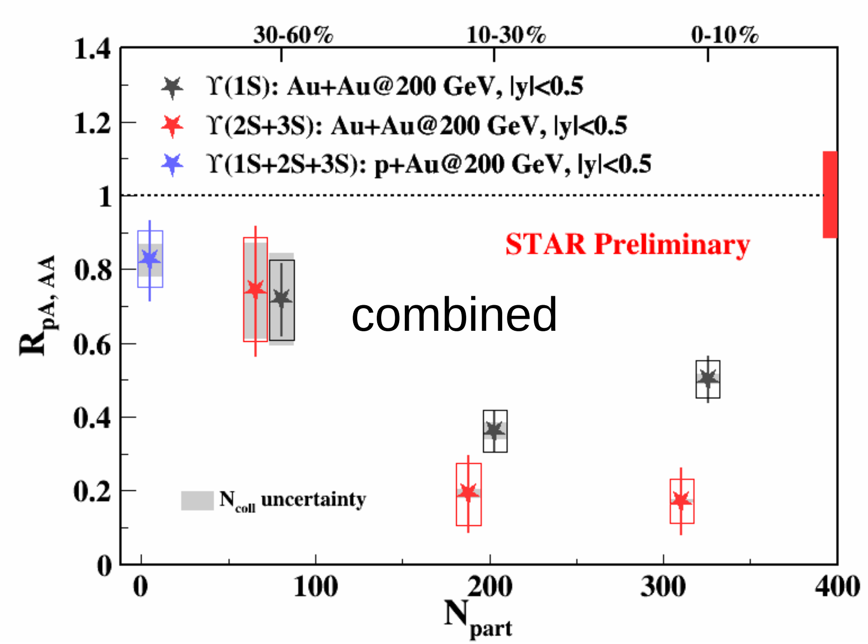
[JHEP04,103(2014)],[Nucl.and Part.Phys. Proc., 276-278, pp.261-264(2016)],[Phys.Lett.B 712,165-175(2012)]

- Hints of interaction between strings of color field in high multiplicity collisions or production in MPI

[Phys.Rev. C, 86, 034903 (2012)]

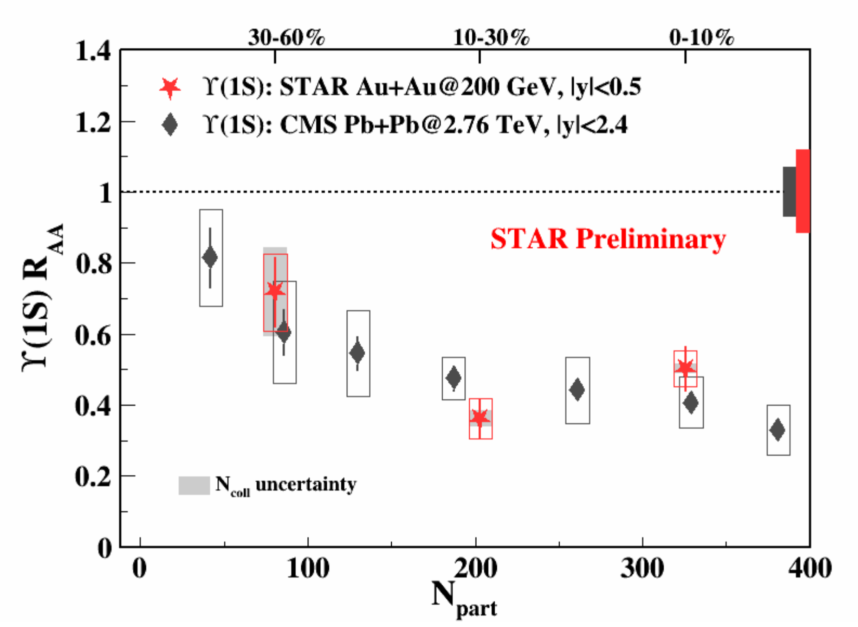
Υ(1S,2S,3S) in 200 GeV Au+Au collisions

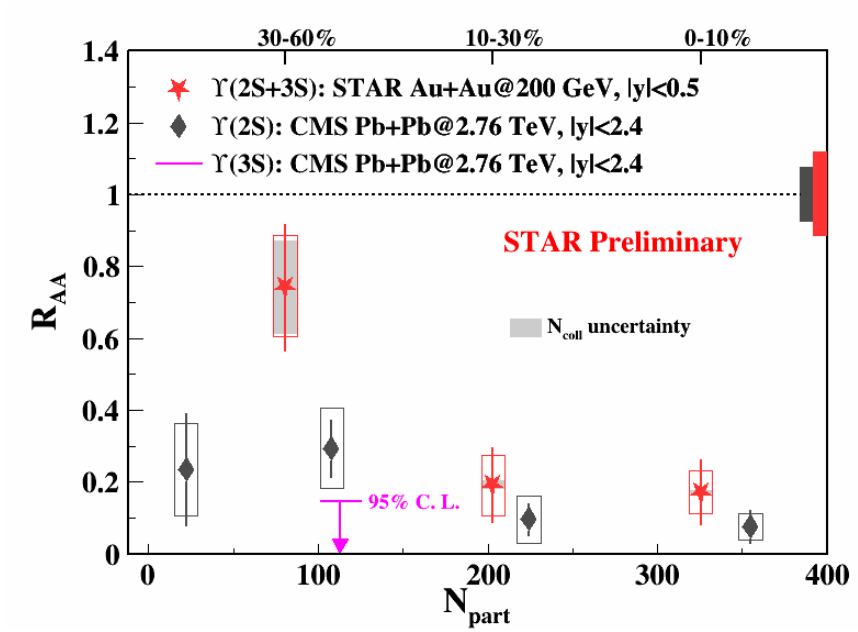




- Dielectron and dimuon results consistent with each other
- Stronger suppression of Υ(2S + 3S) than Υ(1S) in central coll.
  - Consistent with sequential melting expectations

ϒ at RHIC and LHC





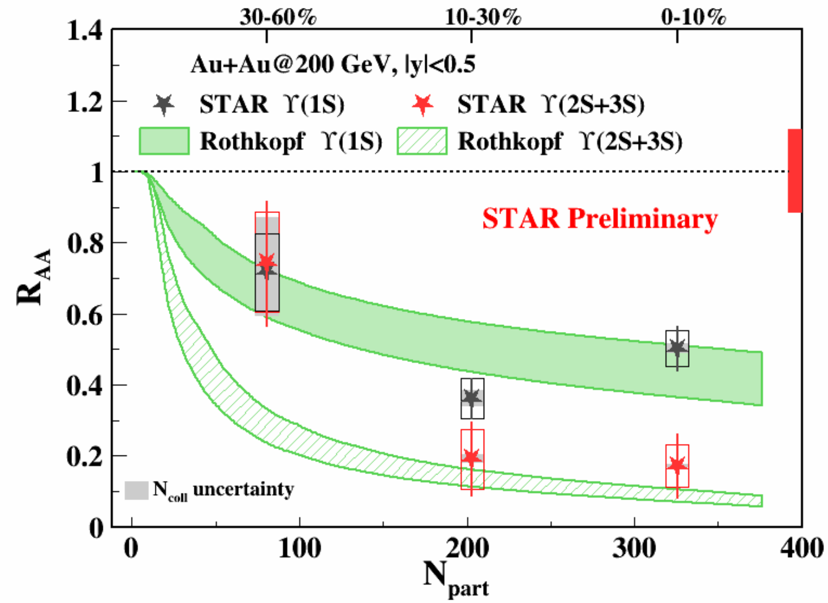
Phys. Lett. B 770(2017) 357

- Similar suppression for ϒ(1S), despite higher medium temperature at the LHC
  - Regeneration? Larger at LHC than at RHIC
  - CNM effects

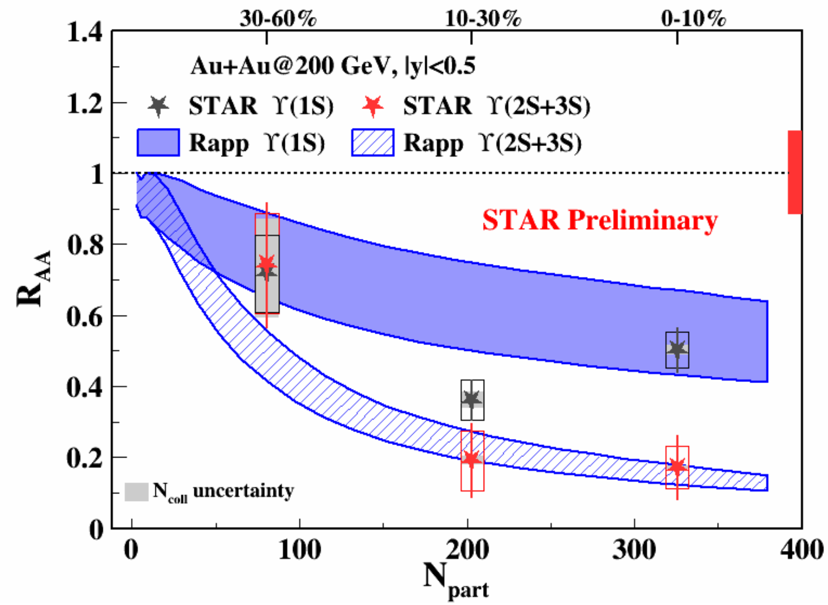
- Indication of smaller suppression for ϒ(2S+3S) at RHIC than at LHC

Data to model comparison

- Kroupaa, Rothkopf, Strickland
  Phys. Rev. D **97**, 016017
- Lattice QCD-vetted potential for heavy quarks in hydrodynamic-modeled medium
- No regeneration, no CNM efects



- De, He, Rapp
  Phys. Rev. C 96, 054901
- Quarkonium in-medium binding energy described by thermodynamic T-matrix calculations with internal energy potential (strongly bound scenario)
- Includes both regeneration and CNM efects



- **ϒ**(1S) well described;
- **ϒ**(2S+3S) underestimated in 30-60% centrality by Rothkopf model

Summary

- **J/ψ in p+p at 200GeV**
  - Models describe the charmonium production cross-section well
  - Relative J/ψ yield as a function of event activity rises faster than a linear function

- **J/ψ in p+Au at 200GeV**
  - R_{pAu} favors additional nuclear absorption on top of nPDF

- **J/ψ in Au+Au at 200GeV**
  - R_{AA} described qualitatively by models including dissociation and regeneration
  - Suppression observed at p_T>5GeV/c due to dissociation

- **ϒ** production in **p+p at 200 GeV** and **500GeV** follow the world data trend

- **ϒ** production in **Au+Au at 200GeV**
  - Stronger suppression of **ϒ**(2S + 3S) than **ϒ**(1S)
  - Consistent with sequential melting