Measurements of Υ production in p+p, p+Au and Au+Au collisions with the STAR experiment

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3-rd Heavy Flavor Meet, Indian Institute of Technology Indore 20.3.2019

EUROPEAN UNION
European Structural and Investment Funds
Operational Programme Research,
Development and Education

MINISTRY OF EDUCATION,
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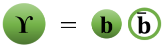
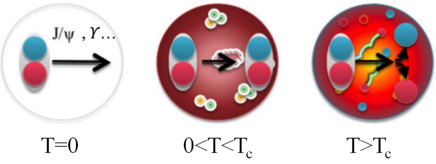
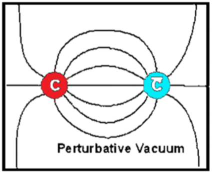
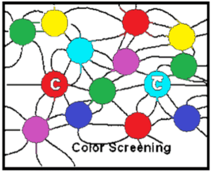
Supported by the Ministry of Education, Youth and Sports of the Czech Republic under grant CZ.02.2.69/0.0/0.0/16_027/0008465





[A. Rothkopf, Hard Probes 2012]





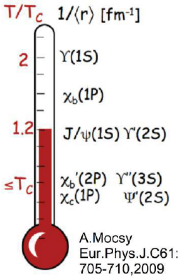
High mass - produced early

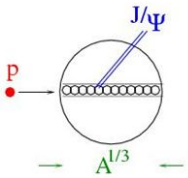
$$m_b = 4.18^{+0.04}_{-0.03}\ \mathrm{GeV/c^2}$$
$$m_{\Upsilon(1S)} = 9460.30 \pm 0.26\ \mathrm{MeV/c^2}$$
$$m_{\Upsilon(2S)} = 10023.26 \pm 0.31\ \mathrm{MeV/c^2}$$
$$m_{\Upsilon(3S)} = 10355.2 \pm 0.5\ \mathrm{MeV/c^2}$$

[Phys.Rev.D 98, 030001 (2018)]

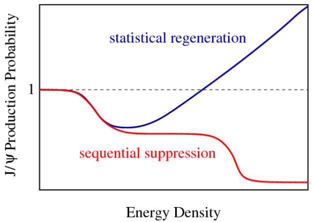
Υ as a probe of quark-gluon plasma

- Υ is sensitive to the QGP properties similarly to J/ψ
  [Phys.Lett.B 178(4),416-422(1986)]
- Dissociation due to Debye-like screening when $r_\Upsilon > r_{Debye} \propto T^{-1}$
- Suppression observed at RHIC and LHC
  [Phys.Lett.B 735,127-137(2014)], [Phys.Lett.B. 770,357-359(2017)]
- Sequential suppression, due to lower binding energy for excited Υ states, expected and observed
  [Phys.Rev.D 64, 094015(2001)], [Phys.Rev.Lett 109, 222301(2012)]

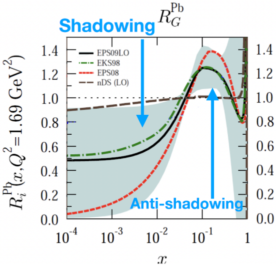




[L. Grandchamp, LBNL 2005]



[Nucl.Phys.B (Proc.Suppl.) 214, 3-36(2011)]



[Phys.Rev.C 81 064911(2010)]

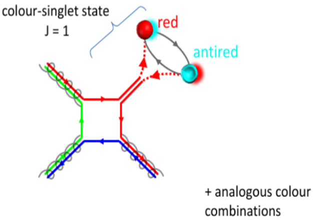
Other modifications to Υ production

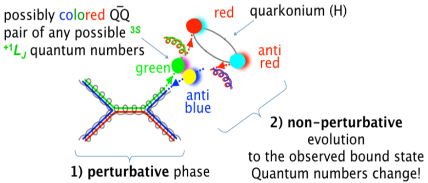
- Regeneration very small for Υ at RHIC
  [Phys.Rev.C 96, 054901(2017)]
- Feed-down from excited states $\Upsilon(nS) \to \Upsilon(1S)\pi^+\pi^-$ and $\chi_{bn} \to \gamma\Upsilon(1S)$
- Cold Nuclear Matter effects - can be studied separately in $p+A$ or $d+A$ collision
  - nuclear absorption
  - comover interactions - very small for $\Upsilon(1S)$
    [Phys.Lett.B 503, 104(2001)]
  - nuclear PDFs: shadowing, anti-shadowing

- Still not well understood: hard scattering+non-perturbative hadronization
- Quarkonium measurements provide tests of production models, and thus help to understand QCD

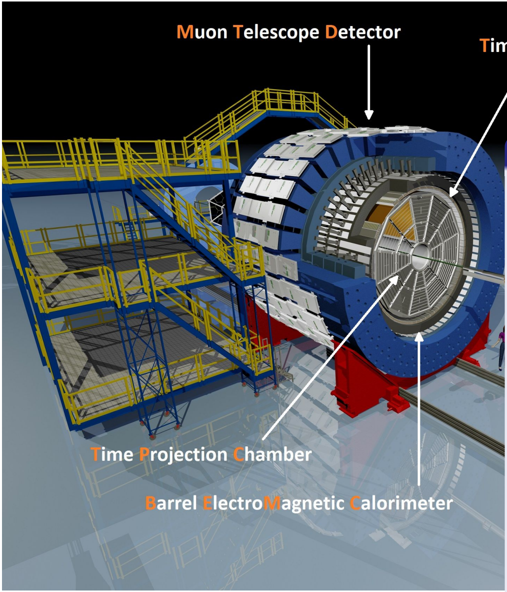
Quarkonium production models

- Color Singlet - only $Q\bar{Q}$ produced directly in a color neutral state can bind to form quarkonia
- Color Octet - $Q\bar{Q}$ produced in a colored state. Gluon emissions are needed to neutralize color. This is described by long-distance matrix elements (LDMEs) which are assumed universal.
- Color Evaporation Model - color irrelevant. Fixed fractions of $Q\bar{Q}$ pairs evolve into various quarkonium states.



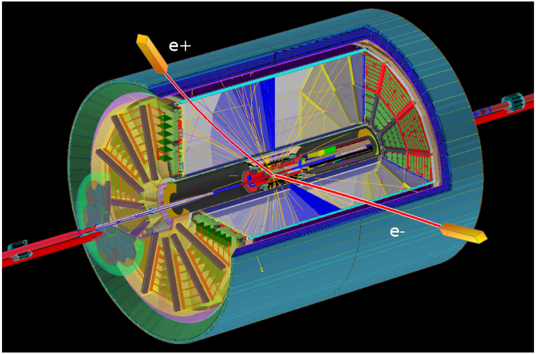


[P. Faccioli, Polarization in LHC physics, Course on Physics at the LHC 2014]



Detectors used for Υ studies

- TPC $|\eta| < 1$, $0 < \phi < 2\pi$
  - Tracking - momentum measurement
  - Particle identification based on energy loss $\frac{dE}{dx}$
- BEMC $|\eta| < 1$, $0 < \phi < 2\pi$
  - Trigger on high-p_T electrons
  - Electron identification via E/p and EM shower shape
- MTD $|\eta| < 0.5$, 45% in $0 < \phi < 2\pi$
  - Dimuon trigger
  - Muon identification with time-of-flight
  - Magnet used as hadron absorber
  - Muons - less bremsstrahlung
- TOF $|\eta| < 1$, $0 < \phi < 2\pi$
  - Particle identification based on time-of-flight - not used for Υ
  - Fast detector used to remove pile-up for N_{ch} determination



Detectors used

- TPC+BEMC(+TOF for N_{ch})

STAR datasets for $\Upsilon \to e^+e^-$ NEW

- Au+Au $\sqrt{s_{NN}} = 200$ GeV: **2011**, 2010
- p+Au $\sqrt{s_{NN}} = 200$ GeV: **2015**
- d+Au $\sqrt{s_{NN}} = 200$ GeV: 2008
- p+p $\sqrt{s} = 500$ GeV: **2011**
- p+p $\sqrt{s} = 200$ GeV: **2015**, 2009

Υ decay reconstruction in e^+e^- channel

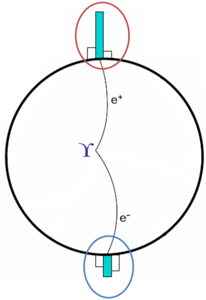
$\Upsilon(1S) \to e^+e^-$, $B_{ee}^{\Upsilon(1S)} = 2.38 \pm 0.11\%$

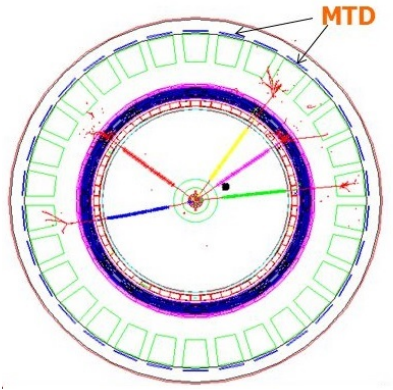
$\Upsilon(2S) \to e^+e^-$, $B_{ee}^{\Upsilon(2S)} = 1.91 \pm 0.16\%$

$\Upsilon(3S) \to e^+e^-$, $B_{ee}^{\Upsilon(3S)} = 2.18 \pm 0.20\%$

[Phys.Rev.D 98, 030001(2018)]

- Project TPC track to the high-energy tower in BEMC, which fired the trigger, and reconstruct a cluster
- Find a partner track and project it to BEMC cluster





Υ decay reconstruction in $\mu^+\mu^-$ channel

$\Upsilon(1S) \rightarrow \mu^+\mu^-, \ B_{\mu\mu}^{\Upsilon(1S)} = 2.48 \pm 0.05\%$

$\Upsilon(2S) \rightarrow \mu^+\mu^-, \ B_{\mu\mu}^{\Upsilon(2S)} = 1.93 \pm 0.17\%$

$\Upsilon(3S) \rightarrow \mu^+\mu^-, \ B_{\mu\mu}^{\Upsilon(3S)} = 2.18 \pm 0.21\%$

[Phys.Rev.D 98, 030001 (2018)]

Detectors used

- TPC+MTD

STAR MTD datasets for $\Upsilon \rightarrow \mu^+\mu^-$

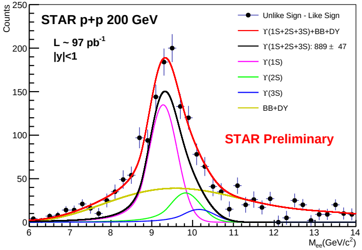
- 2016 Au+Au $\sqrt{s_{NN}} = 200$ GeV
- 2014 Au+Au $\sqrt{s_{NN}} = 200$ GeV

Track projection to MTD hits

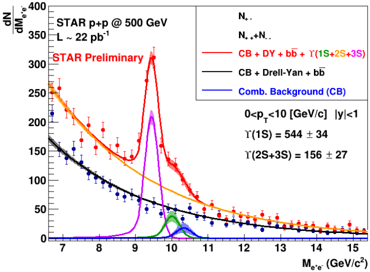
- Tracks are projected from TPC to MTD and matched to hits
- Energy loss in the magnet is included in the track projection procedure

$\Upsilon \rightarrow e^+e^-$ signal in p+p

Υ in 2015 p+p 200 GeV

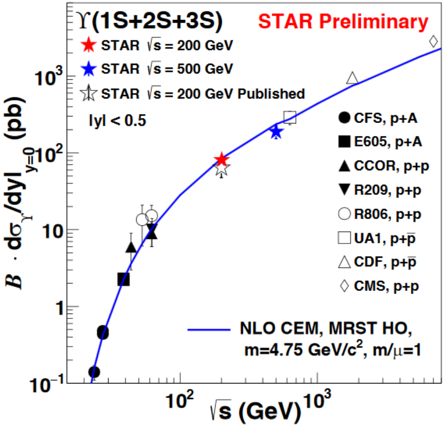


$\Upsilon \rightarrow e^+e^-$ in 2011 p+p 500 GeV



Signal fitting $\Upsilon \rightarrow e^+e^-$

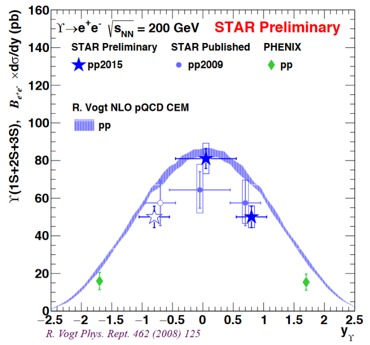
- Υ signal shapes modeled by 3 Crystal-Ball functions
- Fit to Unlike-sign (red) distribution consists of:
  - 3 Crystal-Ball functions (1S,2S,3S states) - fixed using MC simulation
  - $b\bar{b}$+Drell-Yan correlated background (orange) determined using MC simulation

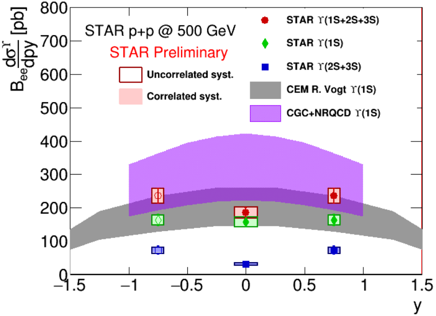


STAR
[Phys.Lett.B 735,127–137(2014)]
CDF
[Phys.Rev.Lett. 88,161802(2002)]
CMS
[Phys.Rev.D 83,112004(2010)]
CFS
[Phys.Rev.Lett. 39,1240–1242(1977)]
[Phys.Rev.Lett. 41,684–687(1978)]
[Phys.Rev.Lett. 42,486–489(1979)]
[Phys.Rev.Lett. 55,1962–1964(1985)]
E605
[Phys.Rev.D 43,2815–2835(1991)]
[Phys.Rev.D 39,3516(1989)]
CCOR
[Phys.Lett.B 87,398–402(1979)]
L. Camilleri, T.B.W. Kirk, H.D.I. Abarbanel (Eds.)
E866
[Phys.Rev.Lett. 100,062301(2008)]
ISR
[Phys.Lett.B 91,481-486(1980)]

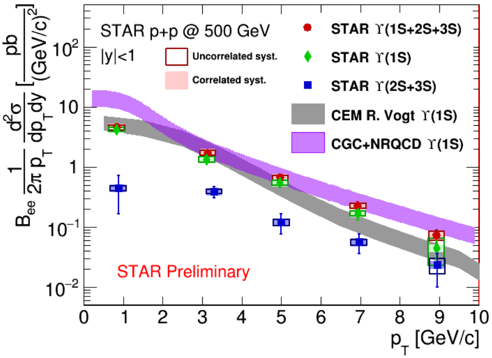
- $B_{ee}\frac{d\sigma}{dy}|_{|y|<0.5} = 81 \pm 5(stat) \pm 8(syst)\,\mathrm{pb}$ in p+p collisions at $\sqrt{s} = 200\,\mathrm{GeV}$
- $B_{ee}\frac{d\sigma}{dy}|_{|y|<0.5} = 186 \pm 14(stat) \pm 33(syst)\,\mathrm{pb}$ in p+p collisions at $\sqrt{s} = 500\,\mathrm{GeV}$
- STAR results follow the world data trend
- Consistent with the Color Evaporation Model calculation
  [Phys.Rep. 462, pp.125–175(2008)]

Rapidity dependence in p+p

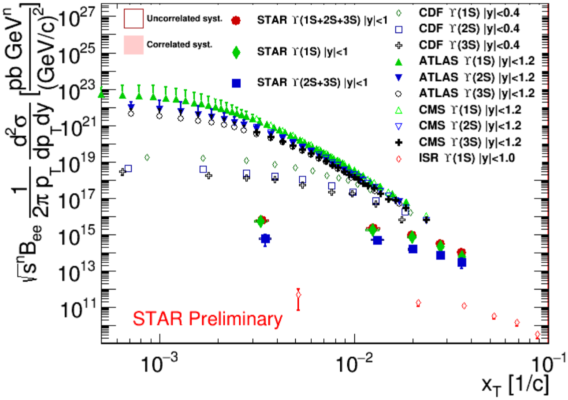




- STAR data slightly narrower than Color Evaporation Model (CEM) at $\sqrt{s} = 200$ GeV
- Flatter rapidity spectrum at $\sqrt{s} = 500$ GeV compared to $\sqrt{s} = 200$ GeV
  - Dip at mid-rapidity for $\Upsilon(2S + 3S) \approx 2\sigma$ level from flat
  - CEM model (inclusive) consistent with the measurement for $\Upsilon(1S)$ *[Phys.Rev.C 92 034909(2015)]*
  - Non-relativistic Quantum Chromodynamics coupled with the Color-Glass Condensate formalism (CGC+NRQCD) predictions for direct $\Upsilon(1S)$ are above the data for $\Upsilon(1S)$ *[Phys.Rev.D 94, 014028(2016)],[Phys.Rev.Lett. 113, 192301(2014)]*

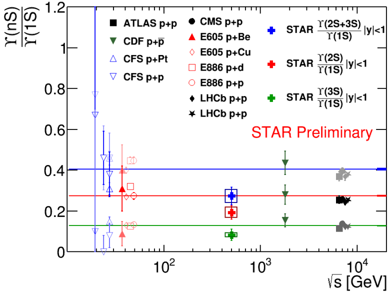


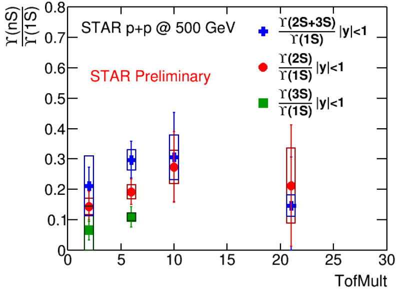
- CEM calculation for inclusive $\Upsilon(1S)$
  [Phys.Rev.C 92 034909(2015)]
  - Agree with data reasonably well
- CGC+NRQCD for direct Υ
  [Phys.Rev.D 94, 014028(2016)] [Phys.Rev.Lett. 113, 192301(2014)]
  - $\Upsilon(1S)$: model calculation is above the data points. Caveat: additional corrections are needed at low p_T according to authors.



ATLAS
[Phys.Rev.D 87,052004(2013)]
CMS
[Phys.Lett.B 749,14-34(2015)]
CDF
[Phys.Rev.Lett. 88,161802(2002)]
ISR
[Phys.Lett.B 91,481-486(1980)]

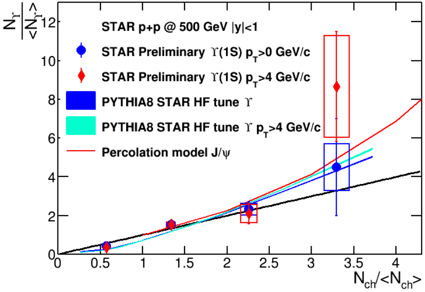
- $x_T = \frac{2p_T}{\sqrt{s}}$, $\sigma^{inv} \equiv E\frac{d^3\sigma}{d^3p} = \frac{F(x_T)}{p_T^{n(x_T,\sqrt{s})}} = \frac{F'(x_T)}{\sqrt{s}^{n(x_T,\sqrt{s})}}$
  [JHEP06,035(2010)]
- pQCD predicts that spectra of hard processes should follow x_T scaling - check with $n = 5.6$ (number of partons taking active part in the process) obtained for J/ψ
  [Phys.Rev.C 80, 041902(2009)]
- No clear scaling observed

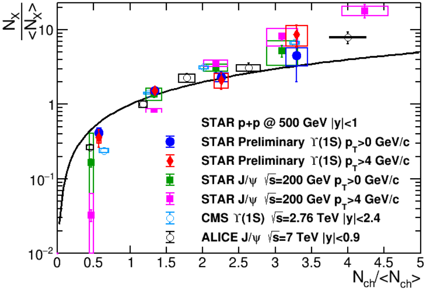




[Phys.Rev.C 88,067901(2013)]

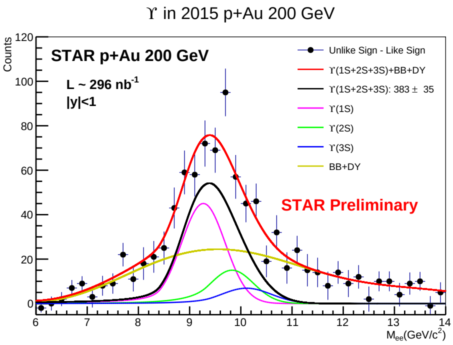
- TofMult: number of tracks matched to TOF within $|\eta| < 1$, $p_T > 0.2\,\mathrm{GeV/c}$
- Boxes correspond to uncorrelated systematic uncertainties (correlated uncertainties largely cancel out)
- Cross section ratios measured in 500 GeV p+p collisions are slightly below (within 2σ) world data average, shown as solid lines in the left plot.
- Right plot: No strong multiplicity dependence observed.

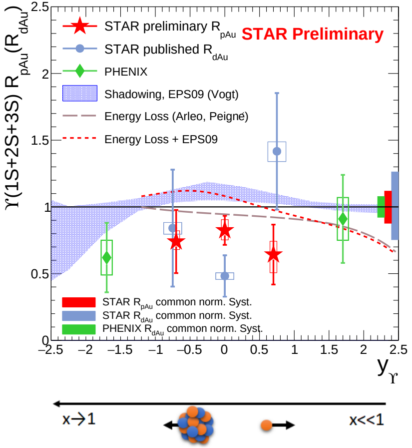




- Normalized $\Upsilon(1S)$ yield vs. normalized multiplicity (a measure of event activity)
- Data consistent with a linear rise(black line), with a hint for stronger-than-linear rise for $\Upsilon(1S)$ above $p_T > 4\ \mathrm{GeV/c}$
- Similar trend at RHIC and LHC for Υ and J/ψ *[JHEP04,103(2014)],[Nucl.and Part.Phys. Proc., 276-278, pp.261–264(2016)],[Phys.Lett.B 712,165–175(2012)]*
- Indication of Υ production in MPI or soft particle production being suppressed by interactions of strings of color field in high-N_{ch} collisions compared to quarkonium yield *[Phys.Rev.C, 86, 034903(2012)]*
  - Need more data to distinguish between the 2 scenarios

Υ production in p+Au

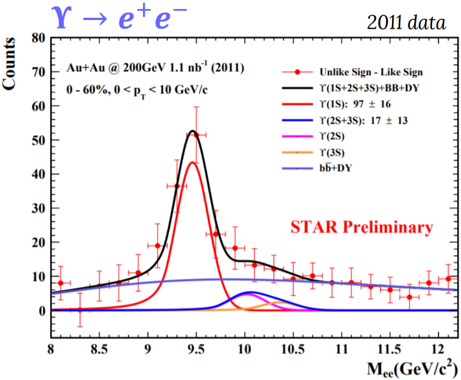


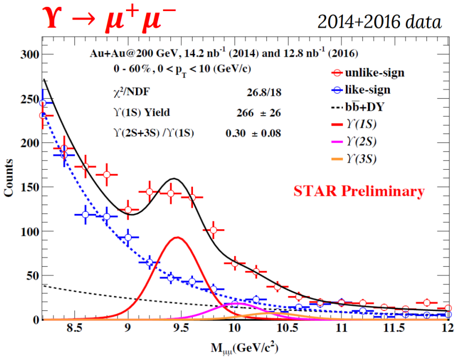


[J.Phys.Lett.B 735(2014)127],
[Phys. Rev. C 87, 044909],
[JHEP 03, 122(2013)]

$\Upsilon(1S + 2S + 3S)$

- Significantly improved precision over published results from R_{dAu}
  - $R_{pAu}|_{|y|<0.5} = 0.82 \pm 0.10(stat.)^{+0.08}_{-0.07}(syst.) \pm 0.10(glob.)$
- Indication of $\Upsilon(1S + 2S + 3S)$ suppression in p+Au collisions

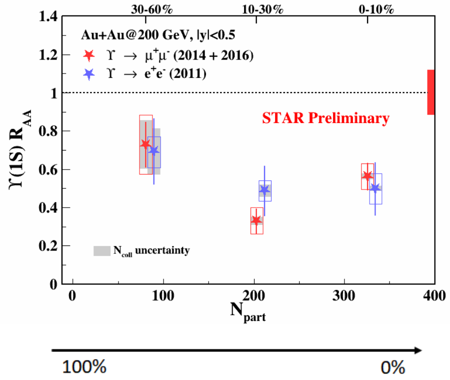


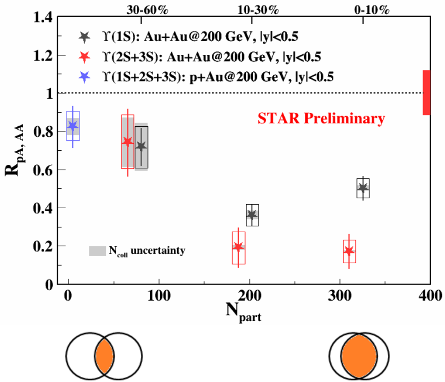


[Pengfei Wang, QM2018]

Signal fits

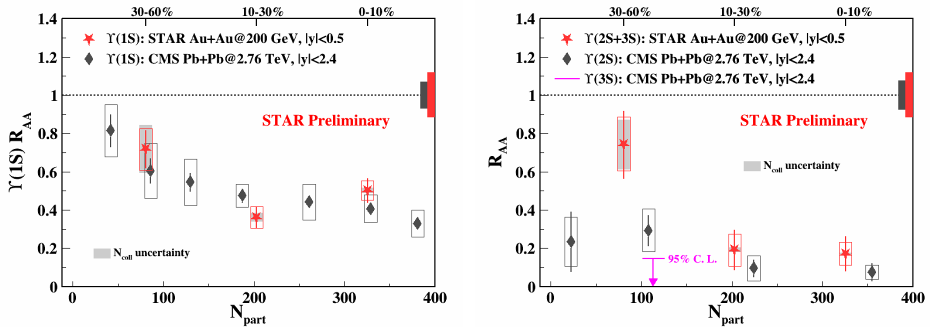
- 3 Crystal Ball fits for $\Upsilon \to e^+e^-$
- 3 Gaussian fits for $\Upsilon \to \mu^+\mu^-$, because of less bremsstrahlung





R_{AuAu} measured by STAR

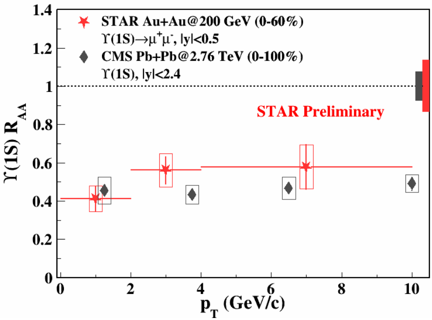
- Consistent results from dielectron and dimuon channels
- Both results combined in order to achieve better precision
- Similar level of suppression in peripheral collisions as in $p + Au$
- Stronger suppression of $\Upsilon(2S + 3S)$ than $\Upsilon(1S)$ in central collisions

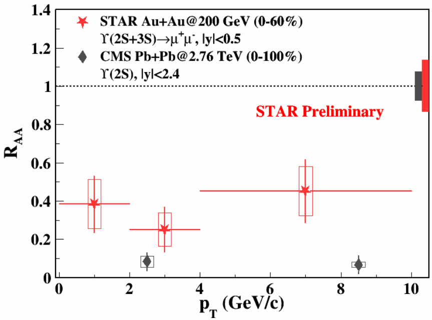


[Phys.Lett.B 770, 357-379(2017)]

STAR vs. CMS

- Similar suppression for $\Upsilon(1S)$, despite higher medium temperature at the LHC
  - Regeneration? Larger at LHC than at RHIC
  - CNM effects
- Indication of smaller suppression for $\Upsilon(2S+3S)$ at RHIC than at LHC

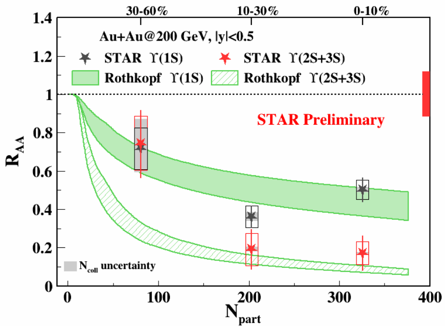




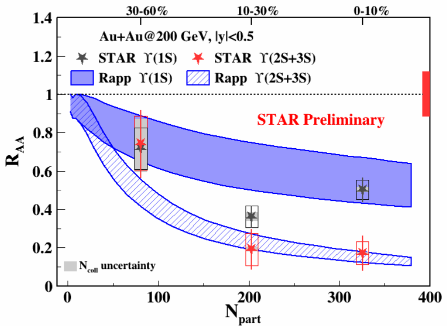
[Phys.Lett.B 770, 357-379(2017)]

Transverse momentum dependence

- Similar suppression for $\Upsilon(1S)$ at RHIC and LHC
- Indications of stronger suppression of high-p_T $\Upsilon(2S+3S)$ at LHC than at RHIC
- Both consistent with flat dependence vs. p_T



[Phys.Rev.D 97, 016017(2018)]



[Phys.Rev.C 96,054901(2017)]

Models

- Kroupaa, **Rothkopf**, Strickland
  - Lattice QCD-vetted potential for heavy quarks in hydrodynamic-modeled medium
  - No regeneration, no CNM effects
- De, He, **Rapp**
  - Quarkonium in-medium binding energy described by thermodynamic T-matrix calculations with internal energy potential (strongly bound scenario)
  - Includes both regeneration and CNM effects
- Both models agree with STAR $\Upsilon(1S)$ data
- Rothkopf's model underestimates the STAR $\Upsilon(2S + 3S)$ results for $30 - 60\%$ centrality

Summary

p+p collisions at $\sqrt{s} = 200$ GeV and $\sqrt{s} = 500$ GeV

- The $\Upsilon(1S)$ spectra can be reasonably described by CEM calculations.
- Flatter rapidity distribution for Υ at $\sqrt{s} = 500$ GeV than at $\sqrt{s} = 200$ GeV.
- Measured $\frac{\Upsilon(nS)}{\Upsilon(1S)}$ vs. multiplicity at 500 GeV - no strong dependence.
  - Ratios slightly lower than world data.
- Dependence of Υ production on event activity.
  - Similar trends observed for J/ψ and Υ at RHIC and LHC.
  - Predictions from PYTHIA8 and Percolation model can qualitatively describe the trend observed in data.

p+Au collisions at $\sqrt{s} = 200$ GeV

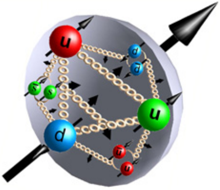
- Indication of Υ suppression

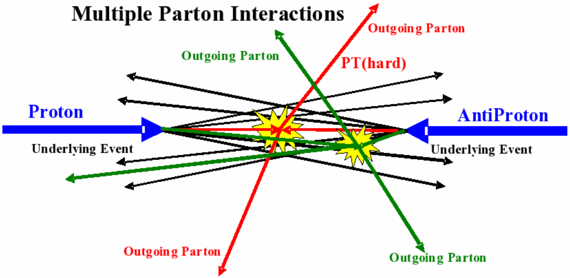
A+A collisions at $\sqrt{s} = 200$ GeV

- Consistent results from dielectron and dimuon channels - combined for better precision
- Similar suppression of $\Upsilon(1S)$ at RHIC and LHC
- Stronger suppression of $\Upsilon(2S + 3S)$ than $\Upsilon(1S)$ in central collisions
  - Sequential suppression
  - Hint of smaller suppression at RHIC than at LHC
- Data consistent with model calculations

Thank you for attention!

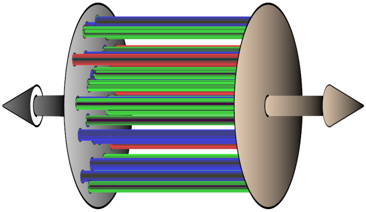
Multiple parton interactions (MPI)

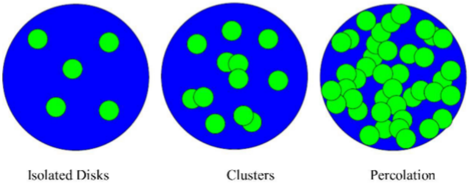




https://www.bnl.gov/rhic/images/proton-with-gluouns-300px.jpg
http://www.desy.de/~jung/multiple-interactions/may06/mi-rick.gif

- Protons are complex objects consisting of constituent quarks, sea quarks and gluons.
- Multiple parton interactions (MPI) may happen in $p + p$ collison - implemented in PYTHIA.
  - Besides the main hard process, there may be additional hard and soft processes in MPI.
- As implemented in PYTHIA8, heavy quarks can also be produced during MPI.
- MPI together with initial- (ISR), final-state radiation (FSR) and beam remnants define the event activity, which can be characterized experimentally using the charged particle multiplicity.



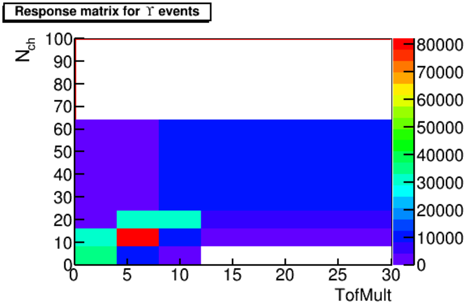


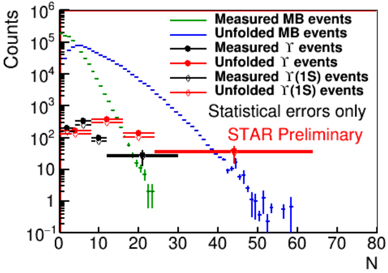
[Ann.Rev.Nucl.Part.Sci.60, 463-489(2010)] [Proc.of SPIE, 100313U(2016)]

- Models particle production originating from strings of color field formed in $p+p$ collisions.
- Soft particle production dampened by interaction of overlapping strings.
- Predicts quadratic dependence of normalized yield for particles from hard processes vs. normalized charged particle multiplicity in high multiplicity events.

$$\frac{N_{hard}}{\langle N_{hard}\rangle} = \langle\rho\rangle \left(\frac{\frac{dN_{ch}}{d\eta}}{\left\langle\frac{dN_{ch}}{d\eta}\right\rangle}\right)^2$$ [Phys.Rev. C, 86, 034903 (2012)]

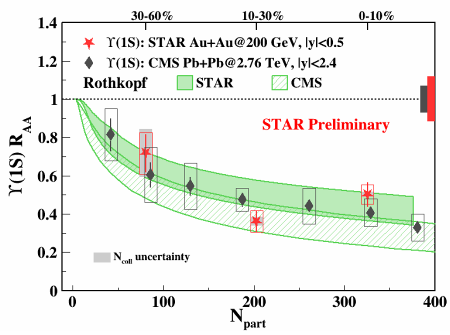
Multiplicity distribution via unfolding

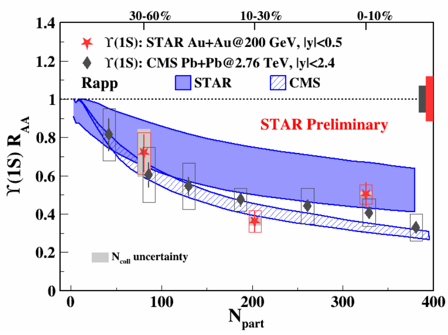




Unfolding method used for multiplicity dependent studies

1. A response matrix is obtained using the PYTHIA8 event generator for both min-bias and Υ events taking into account reconstruction efficiency
2. The measured distributions are unfolded with their respective response matrices
3. This procedure yields the unfolded (true) distribution



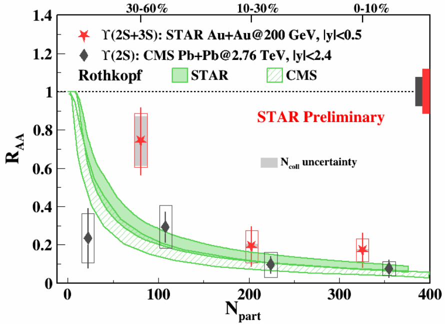


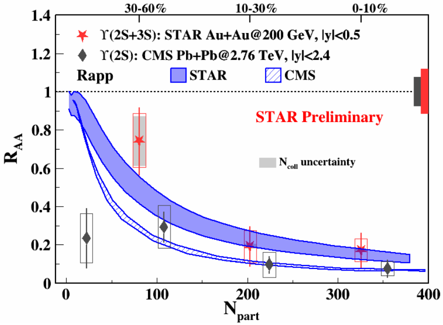
[Phys.Rev.D 97,(2018)016017], [Phys.Rev.C 96,(2017)054901]

$\Upsilon(1S)$ vs. models

- Both models consistent with the data

STAR and CMS $\Upsilon(2S+3S)$ vs. models



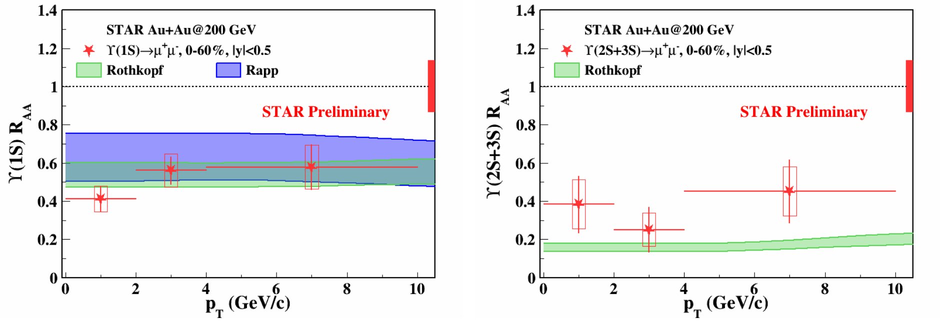


[Phys.Rev.D 97,016017(2018)], [Phys.Rev.C 96,054901(2017)]

$\Upsilon(2S+3S)$ vs. models

- Both models consistent with the data in central and semi-central collisions

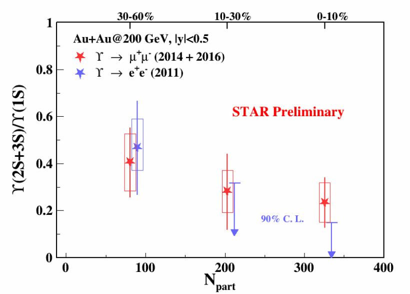
R_{AA} vs. p_T vs. models



[Phys.Rev.D 97,016017(2018)], [Phys.Rev.C 96,054901(2017)]

R_{AA} vs. p_T vs. models

- Both models consistent with the data
- Rothkopf's model slightly lower than $\Upsilon(2S+3S)$
- Flat vs. p_T



$\frac{\Upsilon(2S+3S)}{\Upsilon(1S)}$ vs. N_{part}

- Both channels consistent