Overview of quarkonium production studies in the STAR experiment

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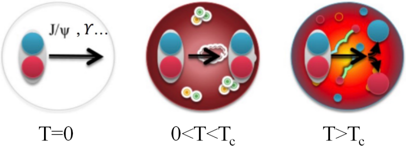
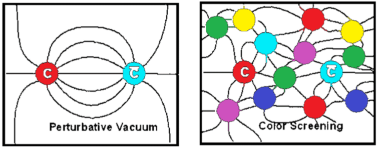
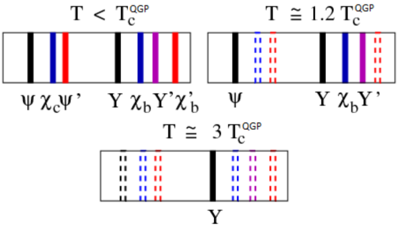
Probing quark-gluon plasma with quarkonium

$J/\psi = c\,\bar{c}$



[A. Rothkopf, Hard Probes 2012]





$\Upsilon = b\,\bar{b}$

High mass - produced early

$$m_c = 1.275^{+0.025}_{-0.035}\ \mathrm{GeV}/c^2$$

$$m_b = 4.18^{+0.04}_{-0.03}\ \mathrm{GeV}/c^2$$

$$m_{J/\psi} = 3096.900 \pm 0.006\ \mathrm{MeV}/c^2$$

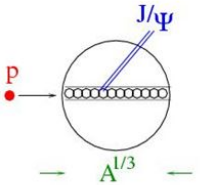
$$m_{\Upsilon(1S)} = 9460.30 \pm 0.26\ \mathrm{MeV}/c^2$$

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

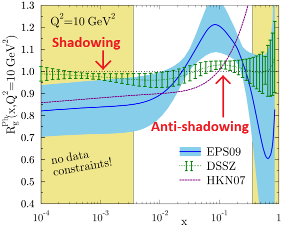
Quarkonium as a probe of quark-gluon plasma

- J/ψ is sensitive to the QGP properties *[Phys.Lett.B 178(4),416-422(1986)]*
- Dissociation due to Debye-like screening when $r_{J/\psi} > r_{Debye} \propto T^{-1}$
- 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 quarkonium states, expected, and have been observed at LHC *[Phys.Rev.D 64, 094015(2001)], [Phys.Rev.Lett 109, 222301(2012)]*

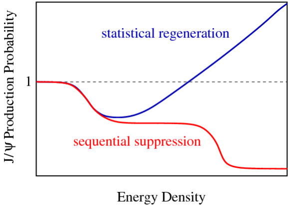
Other effects



[L. Grandchamp, LBNL 2005]



[Nucl.Phys.A 926 24-33(2014)]



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

Other modifications to quarkonium production

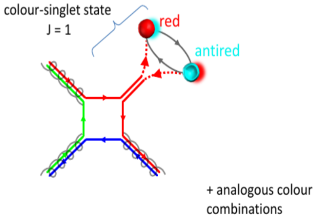
- Regeneration relevant for J/ψ at low p_T, but very small for Υ at RHIC
  [Phys.Rev.C 96, 054901(2017)]
- Feed-down from excited states (examples):
  - $\Upsilon(nS) \to \Upsilon(1S)\pi^+\pi^-$, $\Upsilon(nS) \to \Upsilon(1S)\pi^0\pi^0$ and $\chi_{bJ} \to \gamma\Upsilon(1S)$
  - $\psi(nS) \to J/\psi\pi^+\pi^-$, $\psi(nS) \to J/\psi\pi^0\pi^0$ and $\chi_{cJ} \to \gamma J/\psi$
- 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

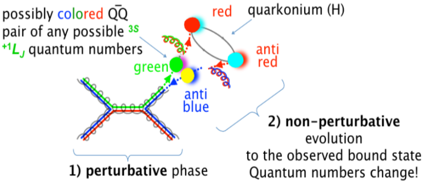
Quarkonium production mechanism

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

Quarkonium production models

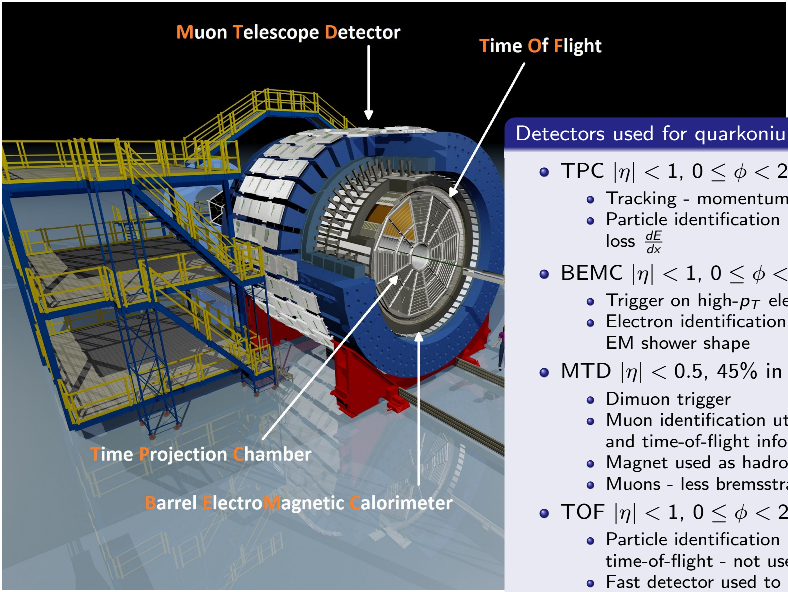
- Color Singlet - only $Q\bar{Q}$ produced directly in a color neutral state can bind to form quarkonia
- Color Octet - $Q\bar{Q}$ produced in a colored state. Gluon emissions are needed to neutralize color. This is described by long-distance matrix elements (LDMEs) which are assumed universal.
- Color 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]

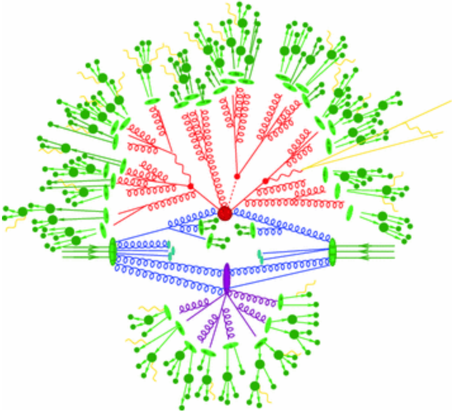
STAR experiment - detectors



Detectors used for quarkonium studies

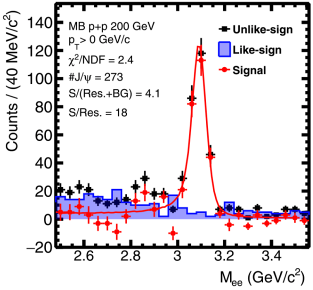
- TPC $|\eta| < 1,\ 0 \leq \phi < 2\pi$
  - Tracking - momentum measurement
  - Particle identification based on energy loss $\frac{dE}{dx}$
- BEMC $|\eta| < 1,\ 0 \leq \phi < 2\pi$
  - Trigger on high-p_T electrons
  - Electron identification via E/p and EM shower shape
- MTD $|\eta| < 0.5$, 45% in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

Quarkonium production in p+p at 200,500 and 510 GeV



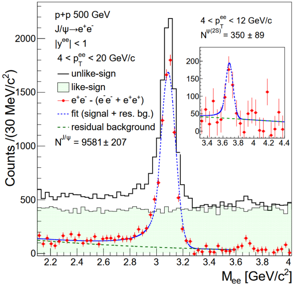
J/ψ signal in p+p at 200,500 and 510 GeV

$J/\psi \rightarrow e^+e^- \quad \sqrt{s} = 200$ GeV



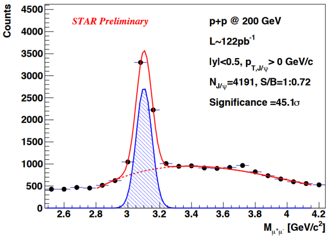
[Phys.Lett.B 786,87-93(2018)]

$J/\psi \rightarrow e^+e^- \quad \sqrt{s} = 500$ GeV

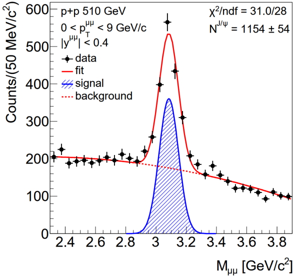


[arXiv:1905.06075] submitted to PRD

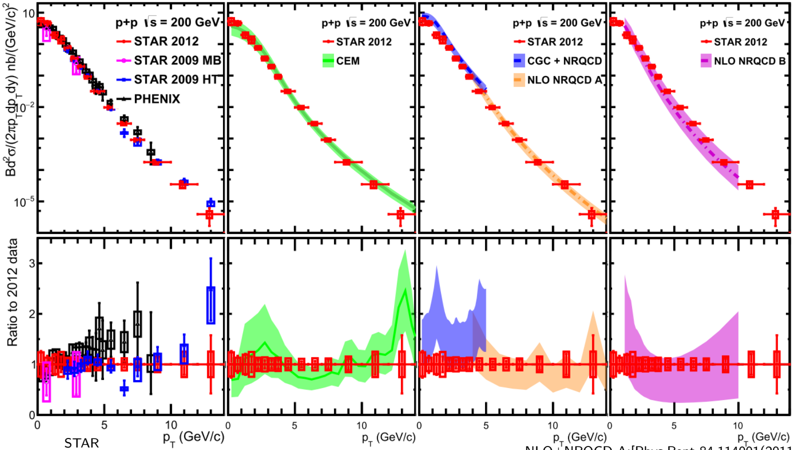
$J/\psi \rightarrow \mu^+\mu^- \quad \sqrt{s} = 200$ GeV



$J/\psi \rightarrow \mu^+\mu^- \quad \sqrt{s} = 510$ GeV



J/ψ p_T spectrum at $\sqrt{s} = 200$ GeV



STAR
[Phys.Lett.B 786,87-93(2018)]
[Phys.Rev.C 722,064904(2016)]
[Phys.Lett.B 722,55-62(2013)]

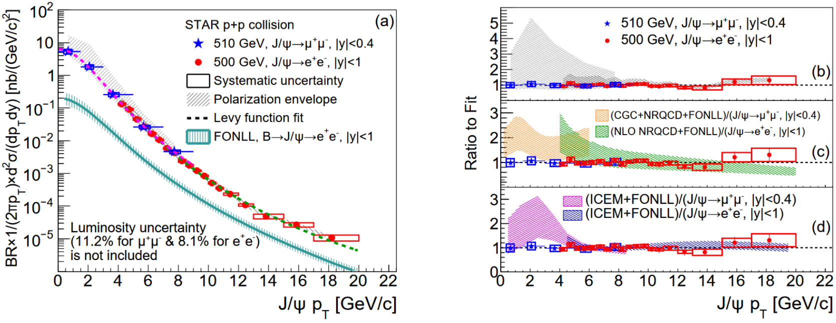
PHENIX: [Phys.Rev.D 82,012001(2010)]
CEM:[Phys.Rept 462,125-175(2008)]

NLO+NRQCD A:[Phys.Rept 84,114001(2011)]
NLO+NRQCD B:[Phys.Rev.Lett. 108,172002(2012)]
CGC+NRQCD:[Phys.Rept 113,192301(2014)]

$J/\psi \to e^+e^-$ p_T spectrum vs. models

- Data are reasonably well described by both CEM (direct J/ψ) and NLO NRQCD (prompt J/ψ) model calculations in their corresponding p_T ranges
- CGC+NRQCD (prompt J/ψ) calculation above the data, but on the edge of uncertainties

J/ψ p_T spectrum at $\sqrt{s} = 500, 510$ GeV

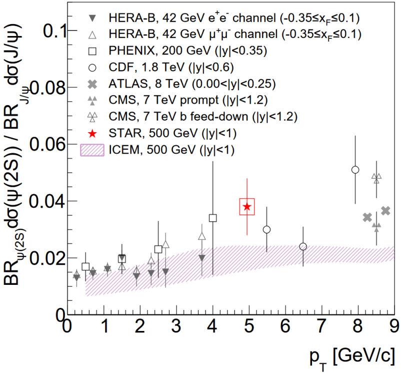


[arXiv:1905.06075] submitted to PRD

J/ψ p_T spectrum vs. models

- Precise measurement covering a wide range of $0 < p_T < 20\,\mathrm{GeV}/c$
- All model calculations for prompt J/ψ, with the addition of $B \to J/\psi$ contribution based on FONLL calculation, provide a good description of data at high p_T
  - Worse description at low p_T

$\psi(2S)/J/\psi$ cross section ratio vs. p_T



STAR: [arXiv:1905.06075] submitted to PRD

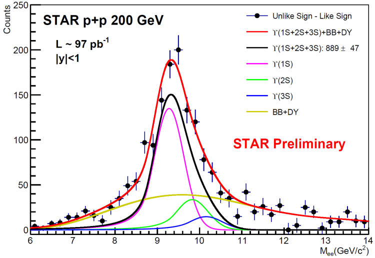
ICEM: [Phys.Rev.D 94, 114029(2016)]

$\psi(2S)/J/\psi$ ratio vs. models

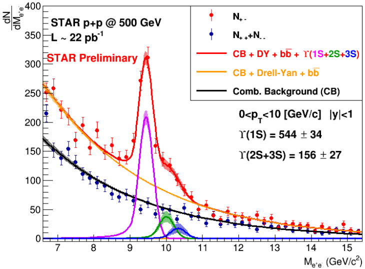
- STAR measured ratio consistent with the results from other experiments
- ICEM model calculation describes the data trend reasonably well

$\Upsilon \rightarrow e^+e^-$ signal in p+p at 200 and 500 GeV

$\Upsilon \rightarrow e^+e^-$ in 2015 p+p 200 GeV



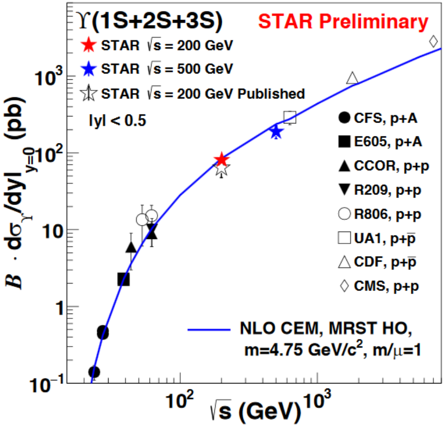
$\Upsilon \rightarrow e^+e^-$ in 2011 p+p 500 GeV



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

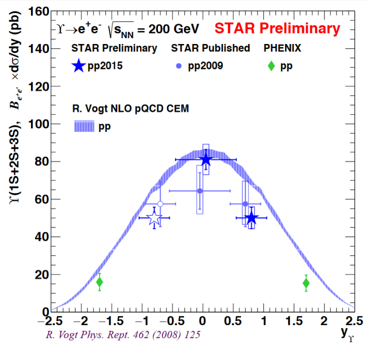
Integrated Υ cross section in p+p

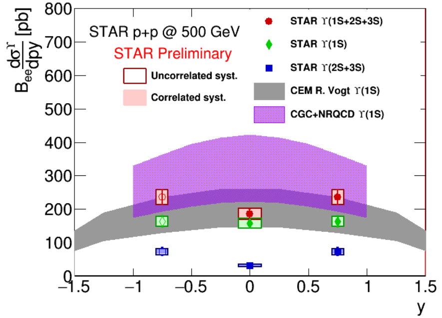


STAR
[Phys.Lett.B 735,127–137(2014)]
CDF
[Phys.Rev.Lett. 88,161802(2002)]
CMS
[Phys.Rev.D 83,112004(2010)]
CFS
[Phys.Rev.Lett. 39,1240-1242(1977)]
[Phys.Rev.Lett. 41,684–687(1978)]
[Phys.Rev.Lett. 42,486–489(1979)]
[Phys.Rev.Lett. 55,1962–1964(1985)]
E605
[Phys.Rev.D 43,2815–2835(1991)]
[Phys.Rev.D 39,3516(1989)]
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)]

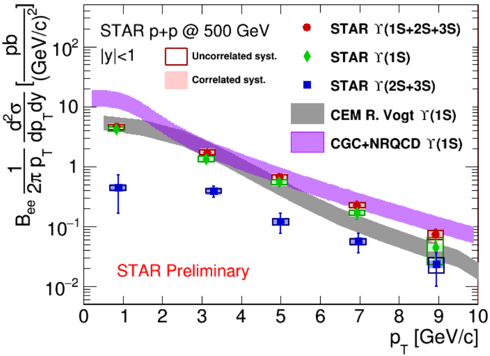
Υ rapidity dependence in p+p





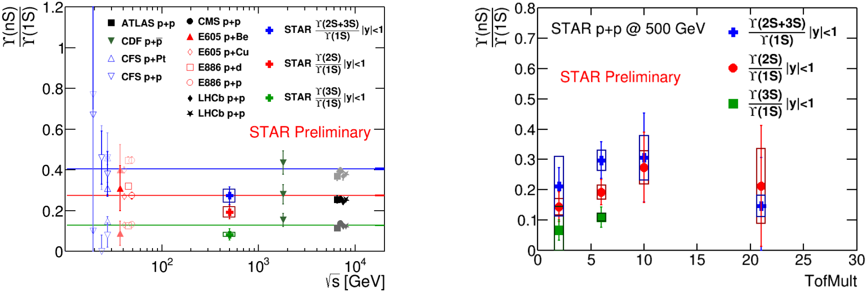
- STAR data slightly narrower than Color Evaporation Model (CEM) at $\sqrt{s} = 200\,\mathrm{GeV}$
- Flatter rapidity spectrum at $\sqrt{s} = 500\,\mathrm{GeV}$ compared to $\sqrt{s} = 200\,\mathrm{GeV}$
  - Dip at mid-rapidity for $\Upsilon(2S+3S) \approx 2\sigma$ level from flat
  - CEM model (inclusive) consistent with the measurement for $\Upsilon(1S)$ *[Phys.Rev.C 92 034909(2015)]*
  - 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)]*

Υ differential cross section vs p_T



- 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.

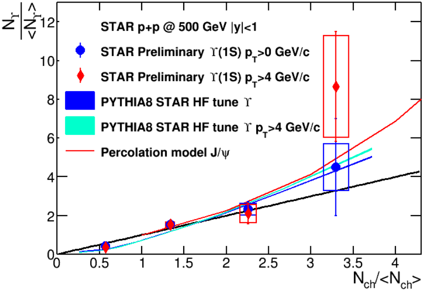
Cross section ratios: $\Upsilon(nS)/\Upsilon(1S)$

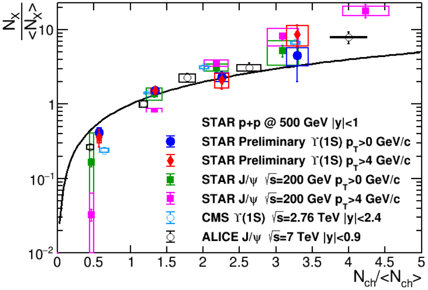


[Phys.Rev.C 88,067901(2013)]

- 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)
- Left plot: 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.

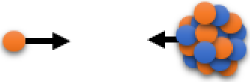
Υ production vs. event activity



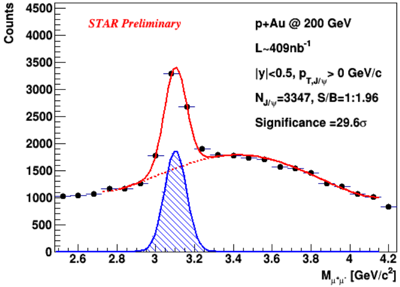


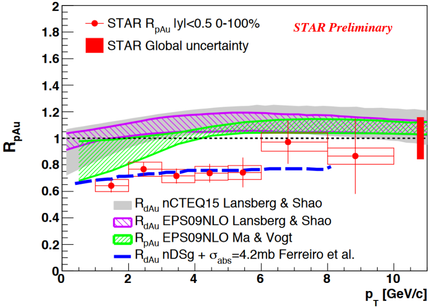
- Normalized $\Upsilon(1S)$ yield vs. normalized multiplicity (a measure of event activity)
- Data consistent with a linear rise(black line), with a hint for stronger-than-linear rise for $\Upsilon(1S)$ above $p_T > 4\,\mathrm{GeV/c}$
- Similar trend at RHIC and LHC for Υ and J/ψ *[JHEP04,103(2014)],[Nucl.and Part.Phys. Proc., 276-278, pp.261–264(2016)],[Phys.Lett.B 712,165–175(2012)],[Phys.Lett.B 786,87-93(2018)]*
- 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

Quarkonium production in p+Au



J/ψ R_{pAu} vs. p_T



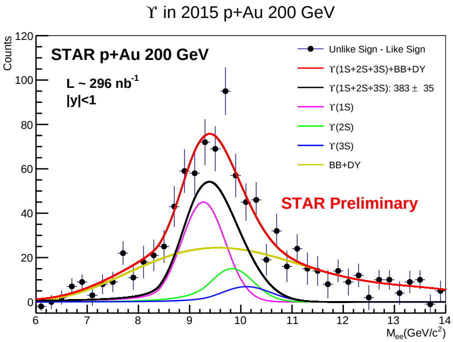


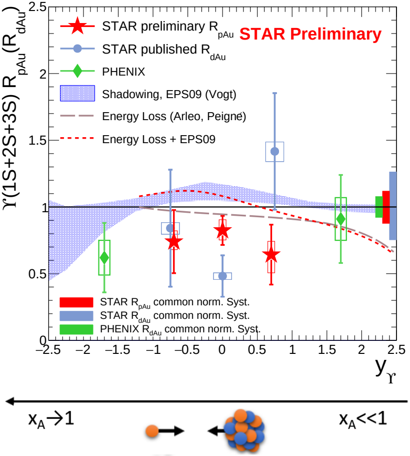
EPS09+NLO:
[Ma & Vogt, Private Comm.]
nCTEQ, EPS09+NLO:
[Eur.Phys.J. C77 (2017) no.1, 1],
[Comp.Phys.Comm. 198 (2016) 238-259],
[Comp.Phys.Comm. 184 (2013) 2562-2570]

$J/\psi \rightarrow e^+e^-$ R_{pAu}

- Models including only nuclear PDFs are higher than the data at lower p_T
- Model which incorporates nPDF and nuclear absorption can better describe the data for $p_T < 6\,\mathrm{GeV/c}$
  - $\sigma_{abs} = 4.2\,\mathrm{mb}$

Υ production in p+Au



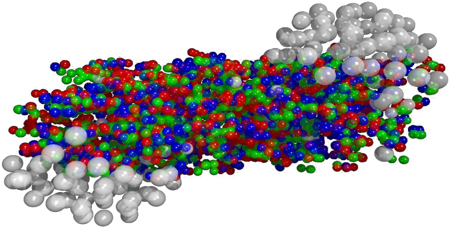


[J.Phys.Lett.B 735(2014)127],
[Phys. Rev. C 87, 044909],
[JHEP 03, 122(2013)]

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

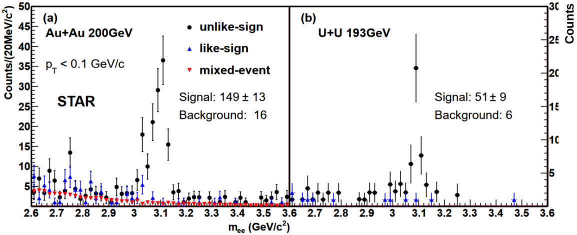
- Improved precision over published results from R_{dAu}
  - $R_{pAu}|_{|y|<0.5} = 0.82 \pm 0.10(stat.)^{+0.08}_{-0.07}(syst.) \pm 0.10(glob.)$
- Indication of $\Upsilon(1S + 2S + 3S)$ suppression in p+Au collisions

Quarkonium production in A+A

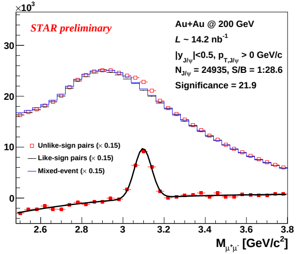


J/ψ signal in A+A

$J/\psi \rightarrow e^+e^-$



$J/\psi \rightarrow \mu^+\mu^-$

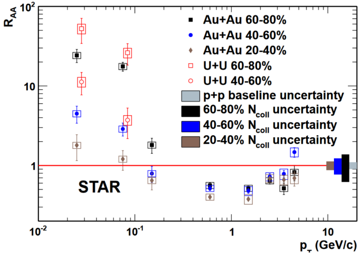


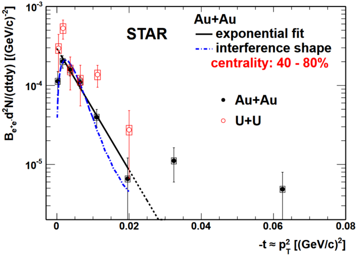
[arXiv:1904.11658] submitted to PRL

J/ψ signals

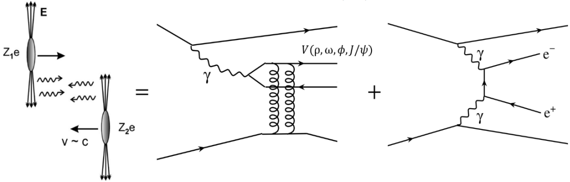
- Measured in Au+Au and U+U collisions
- Au+Au results obtained via both e^+e^- and $\mu^+\mu^-$ channels

Low-p_T J/ψ excess





C. Bertulani et al., Ann. Rev. Nucl. Part. Sci. 55 (2005) 271

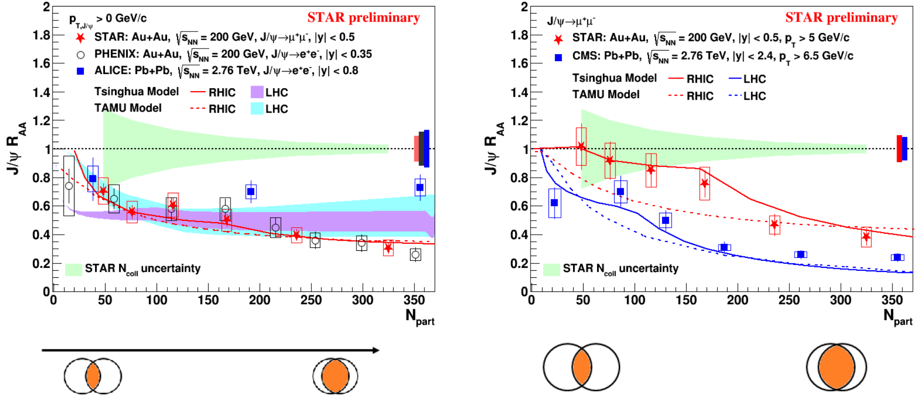


[arXiv:1904.11658] submitted to PRL

$J/\psi \to e^+e^-$ excess in R_{AA} vs. p_T at low p_T

- Very strong enhancement below $p_T < 0.1\,\mathrm{GeV}/c$
- Right plot: J/ψ yield after subtracting expected yield from hadronic interactions
    - Observed excess coming from coherent(mostly) and incoherent(small contribution) photon interactions
- No significant difference between Au+Au and U+U collisions

J/ψ R_{AA} in Au+Au

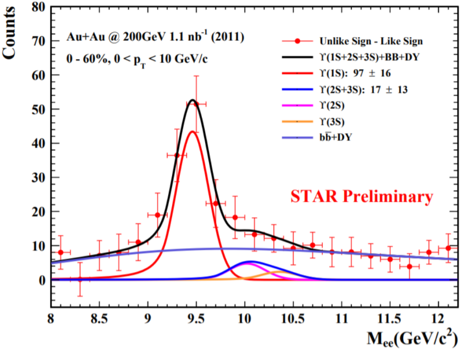


$J/\psi \rightarrow \mu^+\mu^-$ R_{AA} vs. N_{part}

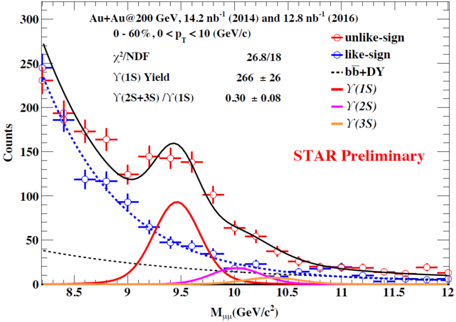
- Stronger suppression at RHIC than LHC for low p_T
  - Probably because of less regeneration at RHIC due to lower $c\bar{c}$ production cross section
- Less suppression at RHIC than LHC at high p_T
  - Higher QGP temperature at LHC causes higher dissociation rate of J/ψ or excited states

Υ signal in Au+Au

$\Upsilon \rightarrow e^+e^-$ 2011 data



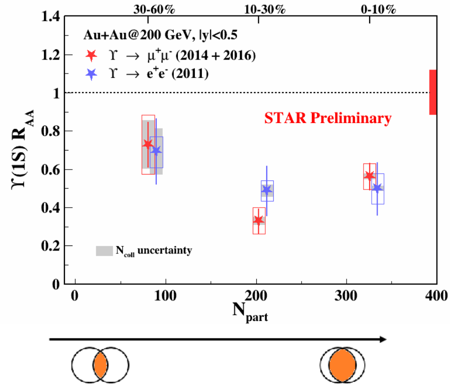
$\Upsilon \rightarrow \mu^+\mu^-$ 2014+2016 data

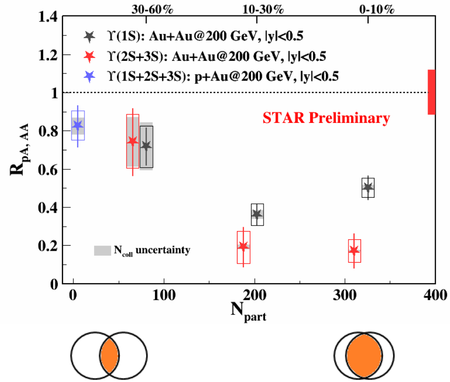


Signal fits

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

Υ R_{AuAu} vs. N_{part}

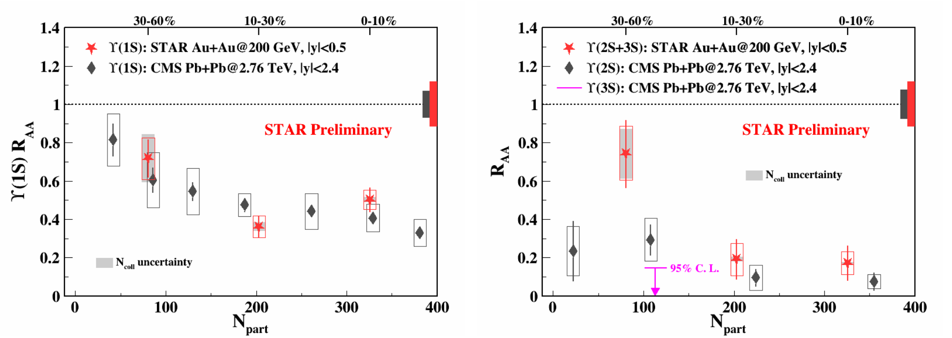




R_{AuAu} measured by STAR

- 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

Υ RHIC vs. LHC

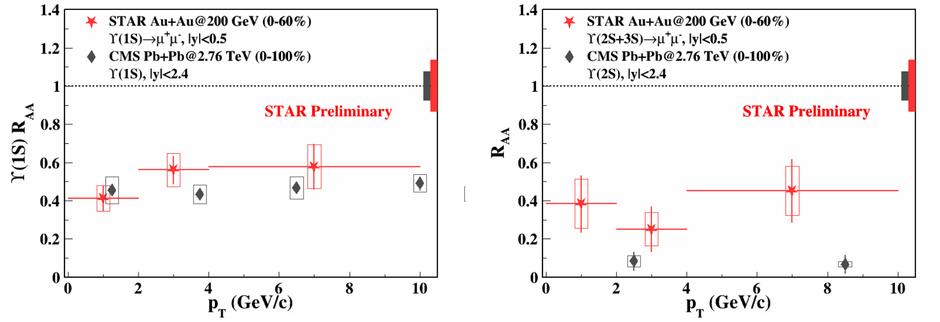


CMS: [Phys.Lett.B 770, 357-379(2017)]

STAR vs. CMS

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

Υ R_{AA} vs. p_T

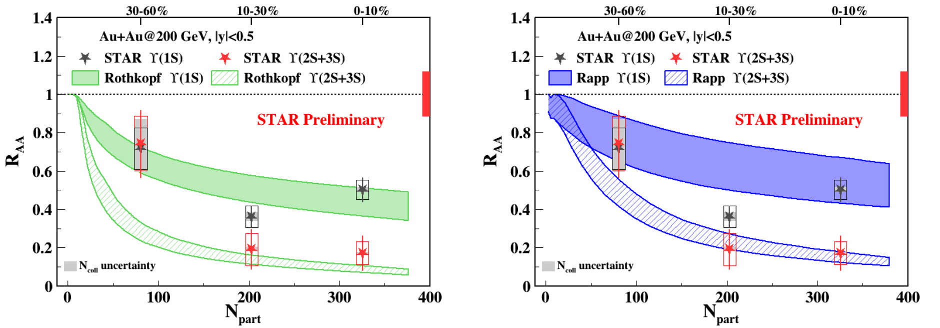


CMS: [Phys.Lett.B 770, 357-379(2017)]

Transverse momentum dependence

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

Υ: STAR vs. models



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

Rapp: [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 $\sqrt{s} = 200\ \mathrm{GeV}$ and $\sqrt{s} = 500\ \mathrm{GeV}$

- NLO NRQCD and CEM models can reasonably describe the J/ψ and $\Upsilon(1S)$ data
- $\frac{\psi(2S)}{J/\psi}$ ratio consistent with other experiments.
- Measured $\frac{\Upsilon(nS)}{\Upsilon(1S)}$ vs. multiplicity at $500\ \mathrm{GeV}$ - no strong dependence.
- Dependence of quarkonium production on event activity.
  - Similar trends observed for J/ψ and $\Upsilon(1S)$ at RHIC and LHC.
  - Predictions from PYTHIA8 and Percolation model can qualitatively describe the trend observed in data.

p+Au collisions at $\sqrt{s_{NN}} = 200\ \mathrm{GeV}$

- Measured $R_{pAu} \approx 0.7$ vs. p_T for J/ψ
  - Nuclear absorption $\sigma_{abs} = 4.2\ \mathrm{mb}$ in addition to nPDF favored by the data
- Indication of $\Upsilon(1S + 2S + 3S)$ suppression
  $R_{pAu}|_{|y|<0.5} = 0.82 \pm 0.10(stat.)^{+0.08}_{-0.07}(syst.) \pm 0.10(glob.)$

Summary and outlook

A+A collisions at $\sqrt{s_{NN}} = 200\,\mathrm{GeV}$

- Strong excess of J/ψ production for $p_T < 0.1\,\mathrm{GeV/c}$
  - Due to coherent and incoherent photon interactions
  - Due to coherent and a small fraction of incoherent photon interactions
- Stronger J/ψ suppression at RHIC than at LHC at low p_T
  - More regeneration at LHC
- Less J/ψ suppression at RHIC than at LHC at high p_T
  - Lower medium temperature at RHIC
- 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
- $\Upsilon(1S)$, $\Upsilon(2S+3S)$ R_{AA} consistent with model calculations

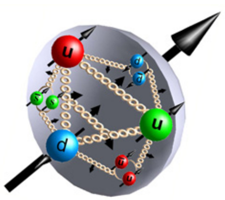
Outlook - more data

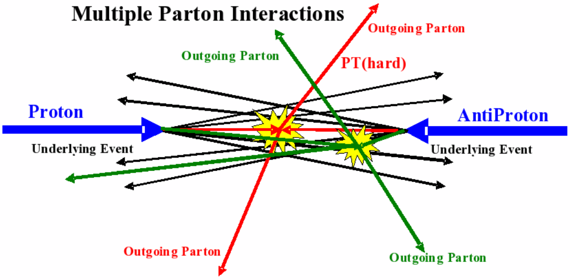
- p+p $\sqrt{s} = 500\,\mathrm{GeV}$ 2017 10× more data for high-p_T J/ψ, Υ
- d+Au $\sqrt{s_{NN}} = 200\,\mathrm{GeV}$ 2016

Thank you for your attention!

BACKUP

Multiple parton interactions (MPI)



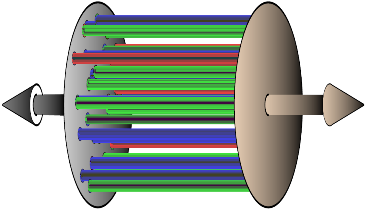


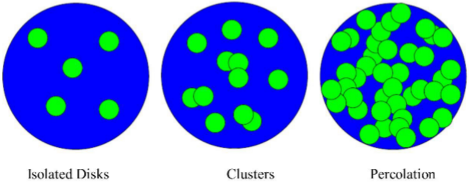
`https://www.bnl.gov/rhic/images/proton-with-gluouns-300px.jpg`

`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.

String Percolation Model



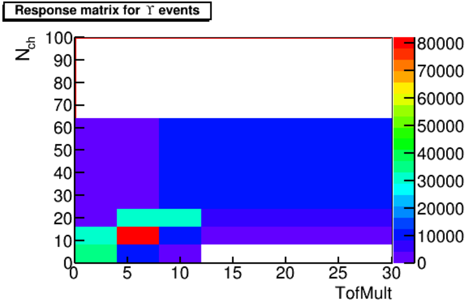


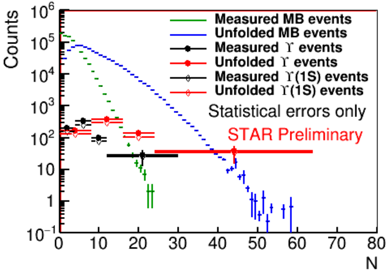
[Ann.Rev.Nucl.Part.Sci.60, 463-489(2010)] [Proc.of SPIE, 100313U(2016)]

- 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

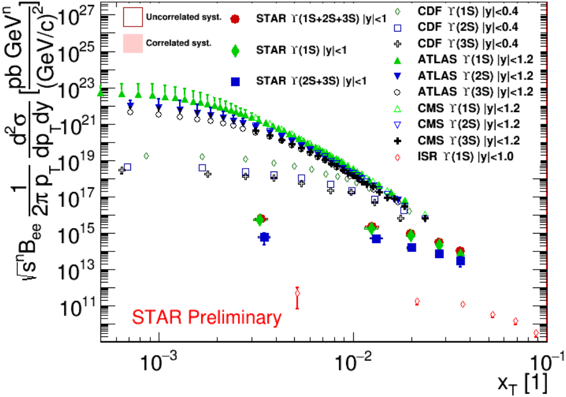




Unfolding method used for multiplicity dependent studies

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

x_T dependence

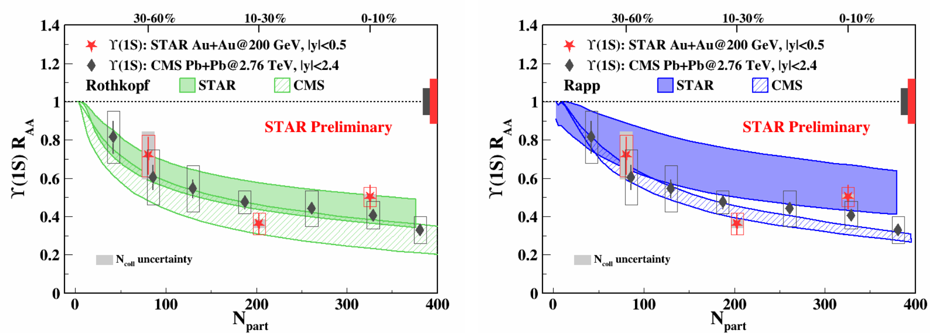


STAR $p+p$ $\sqrt{s} = 500$ GeV
ATLAS $p+p$ $\sqrt{s} = 7$ TeV
[Phys.Rev.D 87,052004(2013)]
CMS $p+p$ $\sqrt{s} = 7$ TeV
[Phys.Lett.B 749,14-34(2015)]
CDF $p+\bar{p}$ $\sqrt{s} = 1.8$ TeV
[Phys.Rev.Lett. 88,161802(2002)]
ISR $p+\bar{p}$ $\sqrt{s} = 53, 63$ GeV
[Phys.Lett.B 91,481-486(1980)]

- $x_T = \frac{2p_T}{\sqrt{s}}$, $\sigma^{inv} \equiv E\frac{d^3\sigma}{d^3p} = \frac{F(x_T)}{p_T^{n(x_T,\sqrt{s})}} = \frac{F'(x_T)}{\sqrt{s}^{n(x_T,\sqrt{s})}}$

  [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, some indication for LHC data at high p_T

STAR and CMS $\Upsilon(1S)$ vs. models

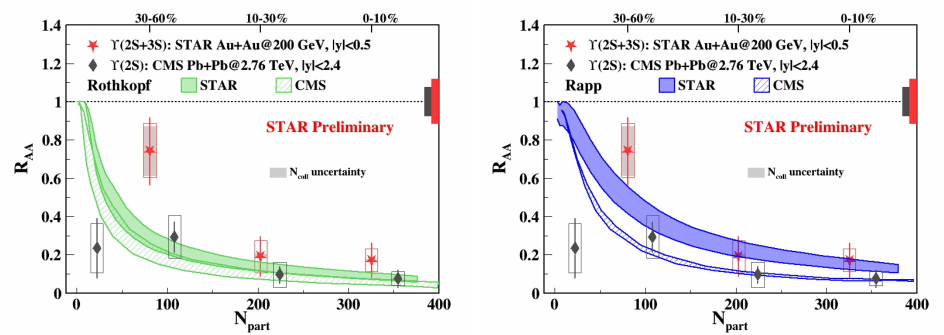


[Phys.Rev.D 97,(2018)016017], [Phys.Rev.C 96,(2017)054901]

$\Upsilon(1S)$ vs. models

- Both models consistent with the data

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

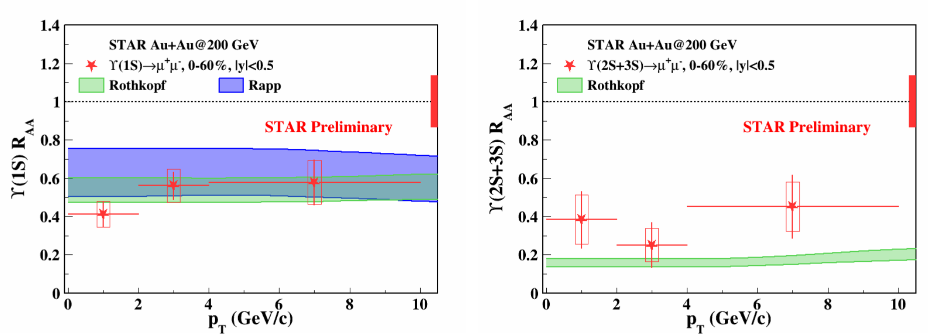


[Phys.Rev.D 97,016017(2018)], [Phys.Rev.C 96,054901(2017)]

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

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

R_{AA} vs. p_T vs. models

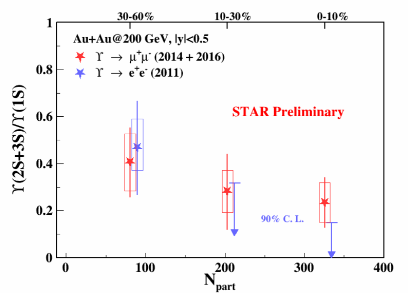


[Phys.Rev.D 97,016017(2018)], [Phys.Rev.C 96,054901(2017)]

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

Ratio vs. N_{part}



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

- Both channels consistent