Quarkonium production measured by the STAR experiment

Leszek Kosarzewski, BEng, Ph.D.
for the STAR collaboration

Faculty of Nuclear Sciences and Physical Engineering
Czech Technical University in Prague

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Development and Education

MINISTRY OF EDUCATION,
YOUTH AND SPORTS

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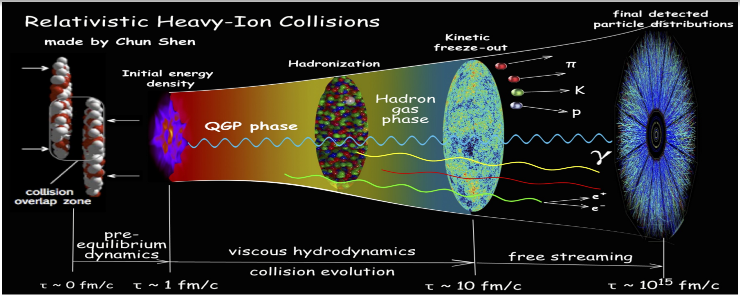
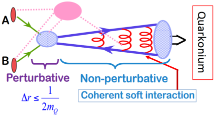
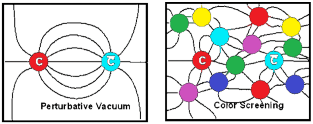
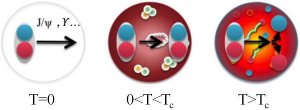
Outline





[E. Ferreiro, SQM 2019]



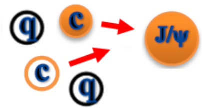


[A. Rothkopf, Hard Probes 2012]

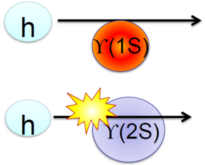
Quark-gluon plasma studies with quarkonium states

- QGP can be created in heavy-ion collisions and studied using quarkonium states
- Quarkonium states $J/\psi = c\bar{c}, \Upsilon = b\bar{b}$ ($m_{u,d} << m_c < m_b$):
  - Contain heavy quarks, created at the early stages of the collision
  - Dissociate at high T in QGP via Debye-like screening *[Phys.Lett.B 178(4),416-422(1986)]*
  - Sequential suppression due to each state dissociating at different $T \rightarrow$ estimate of T *[Phys.Rev.D 64, 094015(2001)]*

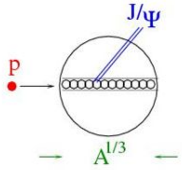
Regeneration



Comover interactions



Nuclear absorption σ_{abs}

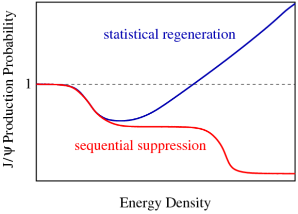


[L. Grandchamp, LBNL 2005]

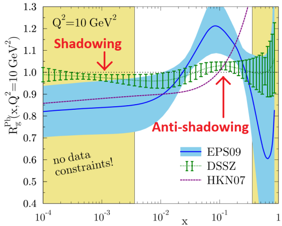
Other modifications to quarkonium production

- 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 $\chi_{cJ} \to \gamma J/\psi$
- Regeneration relevant for J/ψ at low p_T, but very small for Υ at RHIC

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



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



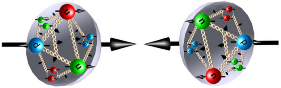
[Nucl.Phys.A 926 24-33(2014)]

Measure and disentangle hot and cold matter effects

Measure nuclear modification factor R_{AA} in different colliding systems. Disentangle different effects by comparing with model calculations.

$$R_{AA} = \frac{1}{N_{coll}} \frac{\mathrm{d}^2\sigma_{Au+Au}/\mathrm{d}p_T\mathrm{d}y}{\mathrm{d}^2\sigma_{pp}/\mathrm{d}p_T\mathrm{d}y}$$

p+p



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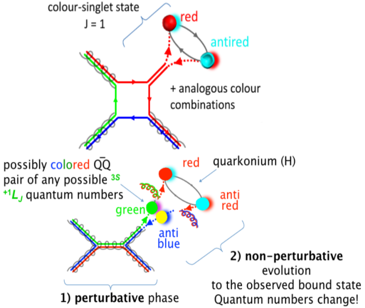
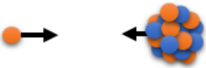


- Production mechanism

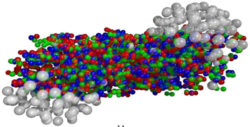
p+A



$\Downarrow$

- Cold Nuclear Matter effects
  - Nuclear absorption cross section σ_{abs}
  - Effect of nuclear PDFs

A+A



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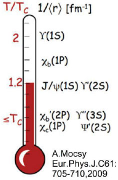
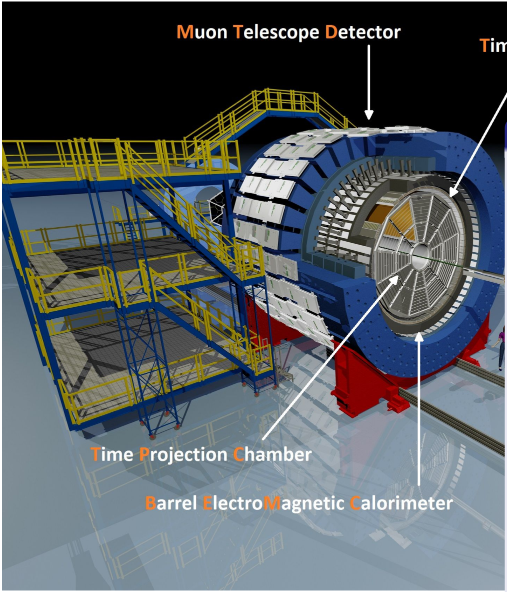


- Suppression in QGP due to high temperature
- Estimate of the temperature T

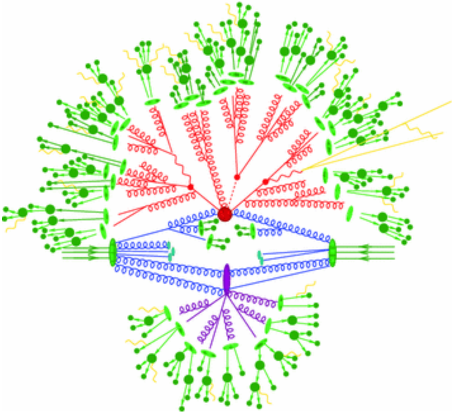
STAR experiment - detectors



Detectors used for quarkonium studies

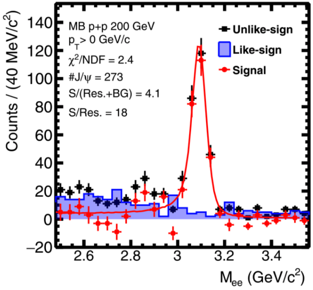
- TPC $|\eta| < 1$, $0 \leq \phi < 2\pi$
  - Tracking - momentum measurement
  - Particle identification based on energy loss $\frac{dE}{dx}$
- BEMC $|\eta| < 1$, $0 \leq \phi < 2\pi$
  - Trigger on high-p_T electrons
  - Electron identification via E/p and EM shower shape
- MTD $|\eta| < 0.5$, 45% in $0 \leq \phi < 2\pi$
  - 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
  - Fast detector used to remove pile-up for N_{ch} determination

Quarkonium production in p+p at $\sqrt{s} = 200$, 500 and 510 GeV



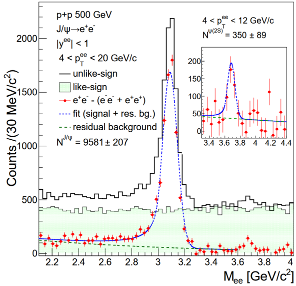
J/ψ signal in p+p at $\sqrt{s} = 200$, 500 and 510 GeV

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



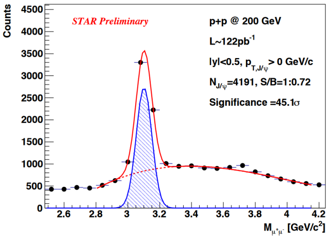
[Phys.Lett.B 786,87-93(2018)]

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

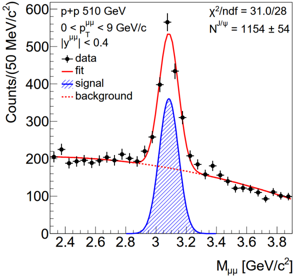


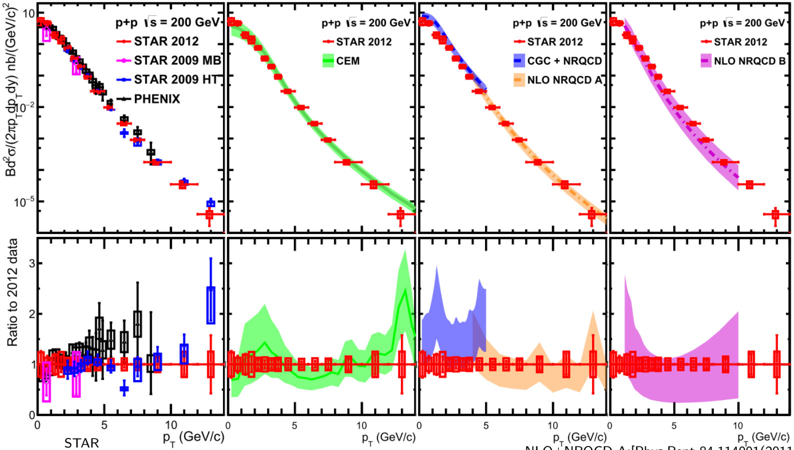
[arXiv:1905.06075] submitted to PRD

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



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





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

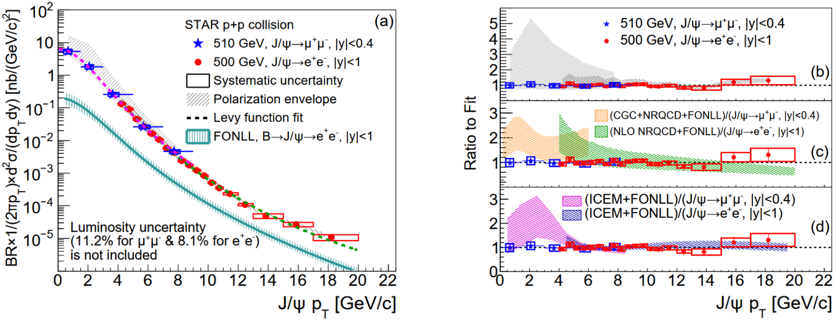
PHENIX: [Phys.Rev.D 82,012001(2010)]
CEM:[Phys.Rept 462,125-175(2008)]

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 the relevant 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



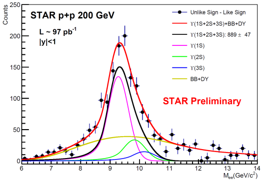
[arXiv:1905.06075] submitted to PRD

J/ψ p_T spectrum vs. models

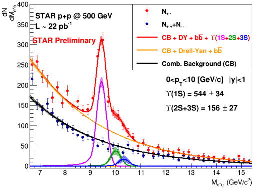
- Precise measurement covering a wide range of $0 < p_T < 20$ GeV/c
- All model calculations for prompt J/ψ, with the addition of $B \to J/\psi$ contribution based on FONLL calculation, provide a good description of data at high p_T

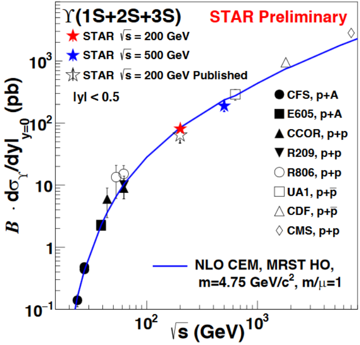
$\Upsilon \to e^+e^-$ cross section in p+p at 200 and 500 GeV

$\Upsilon \to e^+e^-$ in 2015
p+p $\sqrt{s} = 200$ GeV



$\Upsilon \to e^+e^-$ in 2011
p+p $\sqrt{s} = 500$ GeV





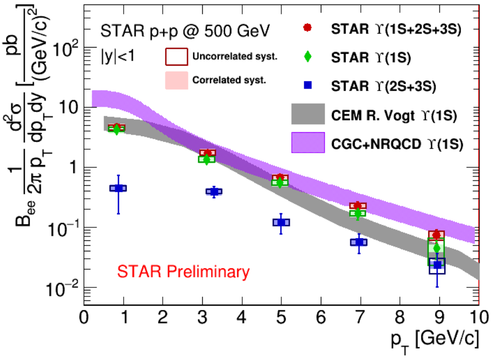
Integrated cross section

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

  [Phys.Rep. 462, pp.125–175(2008)]

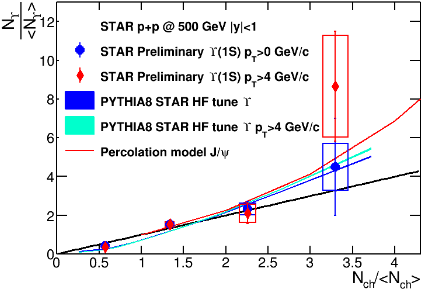
STAR [Phys.Lett.B 735,127–137(2014)]
CDF [Phys.Rev.Lett. 88,161802(2002)]
CMS [Phys.Rev.D 83,112004(2010)]
CFS [Phys.Rev.Lett. 39,1240-1242(1977)]
CFS [Phys.Rev.Lett. 41,684–687(1978)]
CFS [Phys.Rev.Lett. 42,486–489(1979)]
CFS [Phys.Rev.Lett. 55,1962–1964(1985)]
E605 [Phys.Rev.D 43,2815–2835(1991)]
E605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

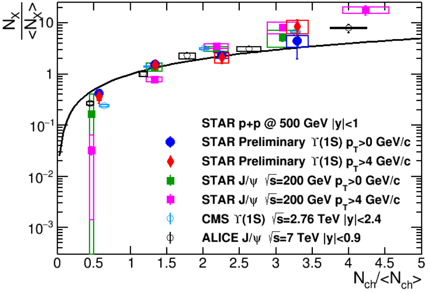
Υ differential cross section vs p_T



- 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.

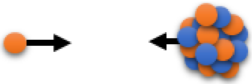
Υ production vs. event activity



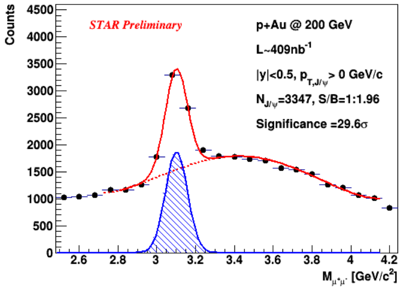


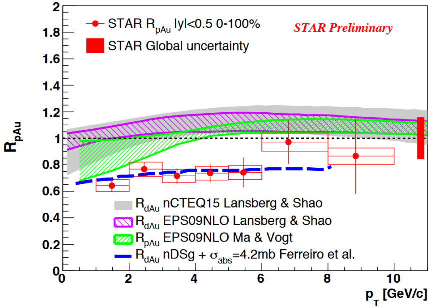
- Normalized $\Upsilon(1S)$ yield vs. normalized multiplicity (a measure of event activity)
- Data consistent with a linear rise(black line), with a hint for stronger-than-linear rise for $\Upsilon(1S)$ above $p_T > 4\,\mathrm{GeV/c}$
- Similar trend at RHIC and LHC for Υ and J/ψ
  [JHEP04,103(2014)],[Nucl.and 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



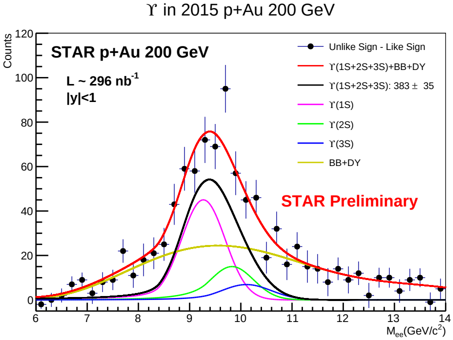


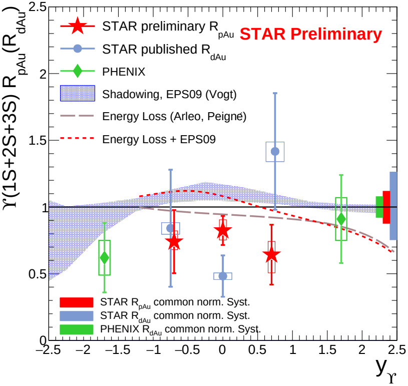
EPS09+NLO:
[Ma & Vogt, Private Comm.]
nCTEQ, EPS09+NLO:
[Eur.Phys.J. C77 (2017) no.1, 1],
[Comp.Phys.Comm. 198 (2016) 238-259],
[Comp.Phys.Comm. 184 (2013) 2562-2570]

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

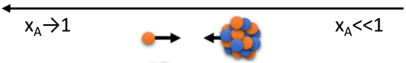
- Models including only nuclear PDFs are higher than the data at lower p_T
- Model which incorporates nPDF and nuclear absorption can better describe the data for $p_T < 6\ \mathrm{GeV/c}$
  - $\sigma_{abs} = 4.2\ \mathrm{mb}$

Υ production in p+Au





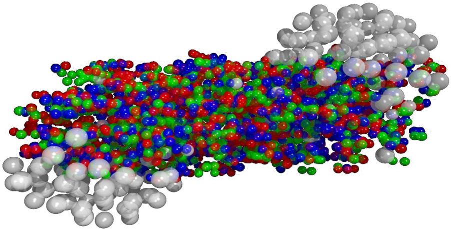
[J.Phys.Lett.B 735(2014)127],
[Phys. Rev. C 87, 044909],
[JHEP 03, 122(2013)]



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

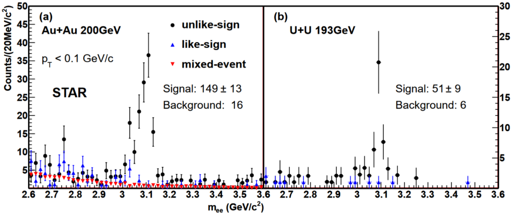
- Improved precision over published results from R_{dAu}
  - $R_{pAu}|_{|y|<0.5} = 0.82 \pm 0.10(stat.)^{+0.08}_{-0.07}(syst.) \pm 0.10(glob.)$
- Indication of $\Upsilon(1S+2S+3S)$ suppression in p+Au collisions

Quarkonium production in A+A



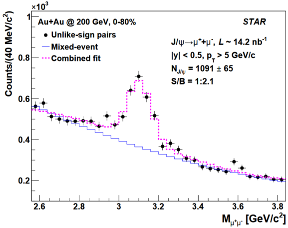
J/ψ and Υ signals in A+A

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



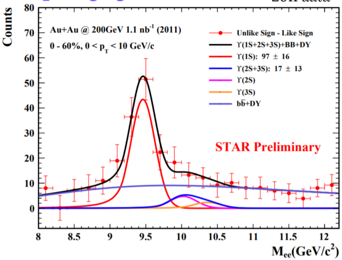
[arXiv:1904.11658] submitted to PRL

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

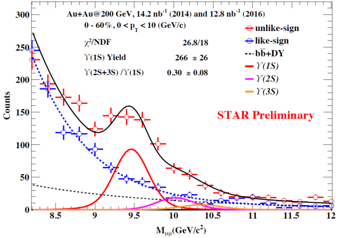


[arXiv:1905.13669] submitted to PLB

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

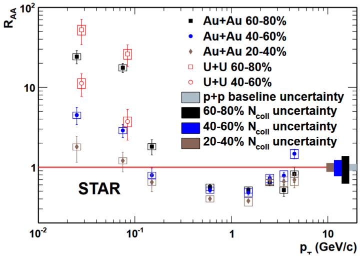


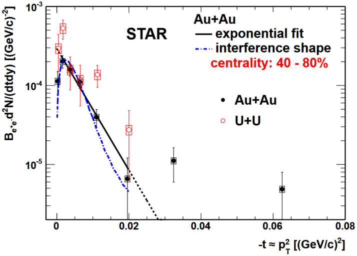
$\Upsilon \rightarrow \mu^+\mu^-$ *2014+2016 data*



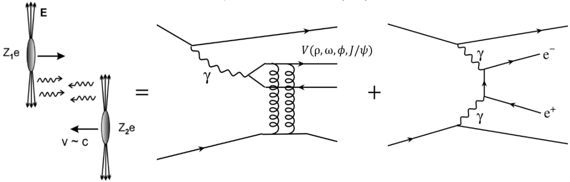
J/ψ and Υ signals

- J/ψ measured in Au+Au (e^+e^- and $\mu^+\mu^-$) and U+U collisions (e^+e^-)
- Υ measured in both e^+e^- and $\mu^+\mu^-$ - combined for better precision





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

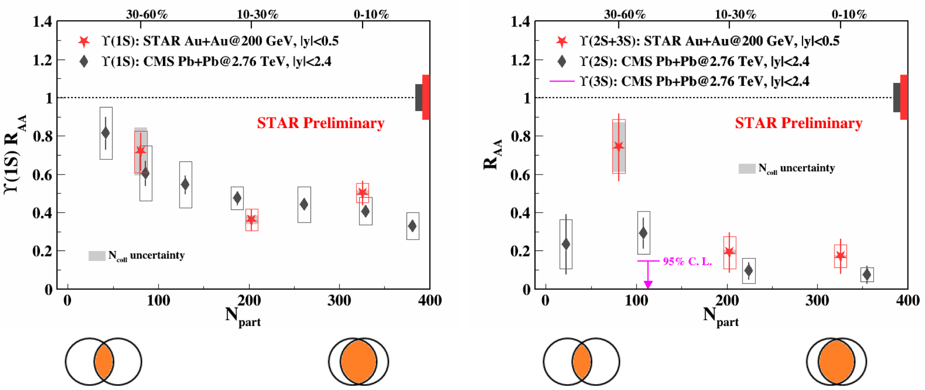


[arXiv:1904.11658] submitted to PRL

$J/\psi \to e^+e^-$ 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 likely coming from coherent(mostly) and incoherent(small contribution) photoproduction
- No significant difference between Au+Au and U+U collisions

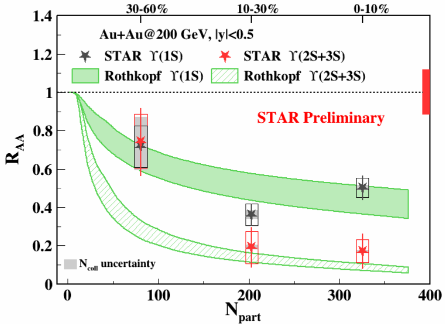
Υ RHIC vs. LHC



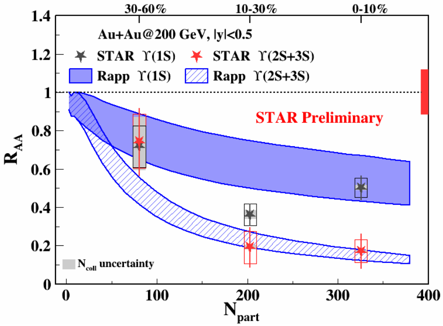
CMS: [Phys.Lett.B 770, 357-379(2017)]

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



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 $\sqrt{s} = 200$ GeV and $\sqrt{s} = 500$ GeV

- NLO NRQCD and CEM models can reasonably describe the J/ψ and $\Upsilon(1S)$ data
- 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 in the data.

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

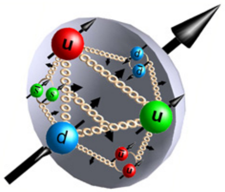
- Measured R_{pAu} vs. p_T for J/ψ ($R_{pAu} \approx 0.7$ for $p_T < 6$ GeV/c)
  - Nuclear absorption $\sigma_{abs} = 4.2$ mb in addition to nPDF favored by the data
- Indication of $\Upsilon(1S+2S+3S)$ suppression $R_{pAu}|_{|y|<0.5} = 0.82 \pm 0.10(stat.)^{+0.08}_{-0.07}(syst.) \pm 0.10(glob.)$

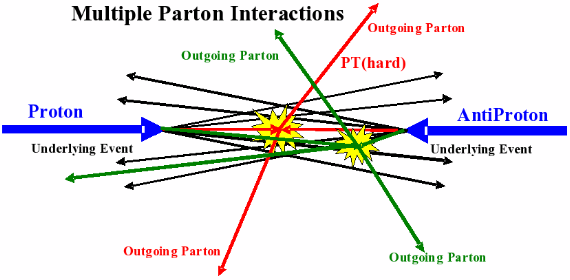
A+A collisions at $\sqrt{s_{NN}} = 200$ GeV

- Strong excess of J/ψ production for $p_T < 0.1$ GeV/c
  - Due to coherent and a small fraction of incoherent photoproduction
- Consistent quarkonium R_{AA} measured in dielectron and dimuon channels
  - Υ results 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
- $\Upsilon(1S)$, $\Upsilon(2S+3S)$ R_{AA} consistent with model calculations

Thank you for your attention!

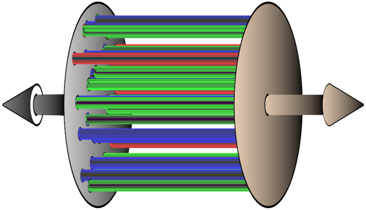
BACKUP

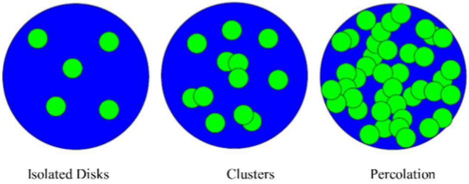




https://www.bnl.gov/rhic/images/proton-with-gluouns-300px.jpg
http://www.desy.de/~jung/multiple-interactions/may06/mi-rick.gif

- 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.

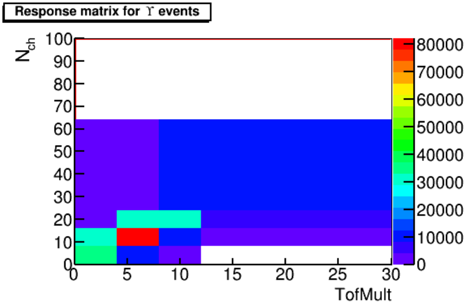


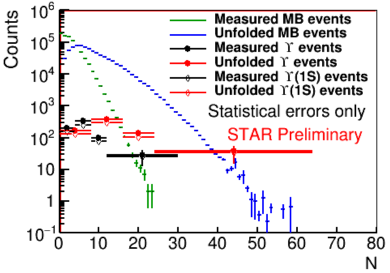


[Ann.Rev.Nucl.Part.Sci.60, 463-489(2010)] [Proc.of SPIE, 100313U(2016)]

- 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.

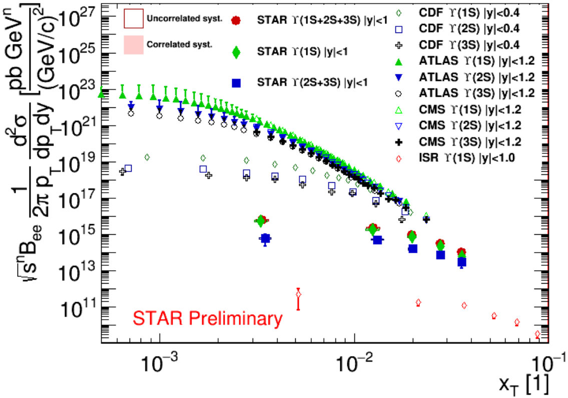
$$\frac{N_{hard}}{\langle N_{hard} \rangle} = \langle \rho \rangle \left(\frac{\frac{dN_{ch}}{d\eta}}{\left\langle \frac{dN_{ch}}{d\eta} \right\rangle} \right)^2$$ [Phys.Rev. C, 86, 034903 (2012)]





Unfolding method used for multiplicity dependent studies

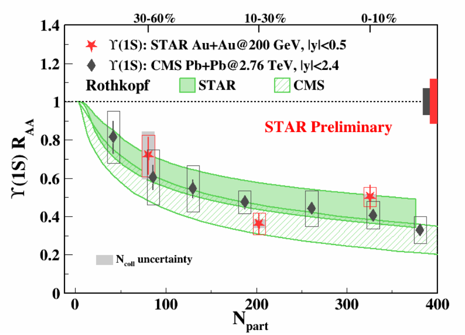
1. A response matrix is obtained using the PYTHIA8 event generator for both min-bias and Υ events taking into account reconstruction efficiency
2. The measured distributions are unfolded with their respective response matrices
3. This procedure yields the unfolded (true) distribution

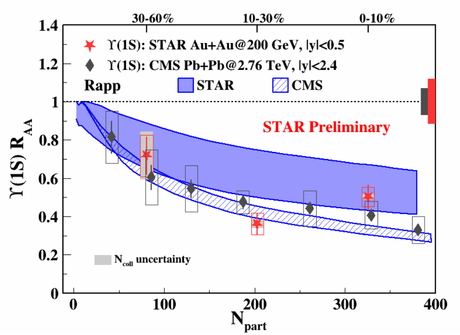


STAR $p+p$ $\sqrt{s} = 500$ GeV
ATLAS $p+p$ $\sqrt{s} = 7$ TeV
[Phys.Rev.D 87,052004(2013)]
CMS $p+p$ $\sqrt{s} = 7$ TeV
[Phys.Lett.B 749,14-34(2015)]
CDF $p+\bar{p}$ $\sqrt{s} = 1.8$ TeV
[Phys.Rev.Lett. 88,161802(2002)]
ISR $p+\bar{p}$ $\sqrt{s} = 53, 63$ GeV
[Phys.Lett.B 91,481-486(1980)]

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



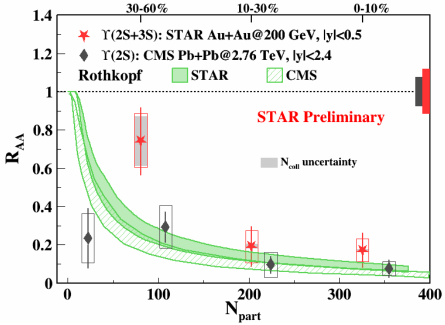


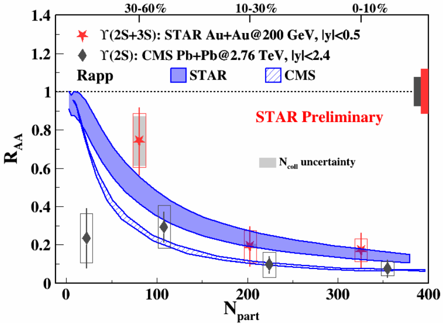
[Phys.Rev.D 97,(2018)016017], [Phys.Rev.C 96,(2017)054901]

$\Upsilon(1S)$ vs. models

- Both models consistent with the data

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

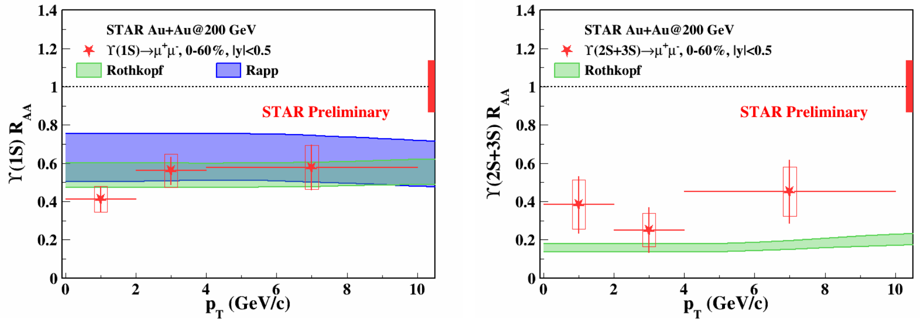




[Phys.Rev.D 97,016017(2018)], [Phys.Rev.C 96,054901(2017)]

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

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

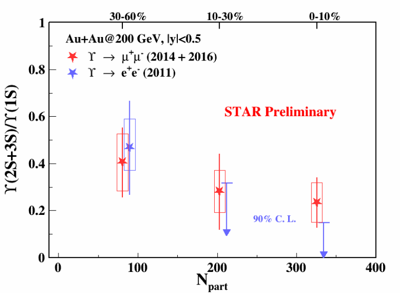


[Phys.Rev.D 97,016017(2018)], [Phys.Rev.C 96,054901(2017)]

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

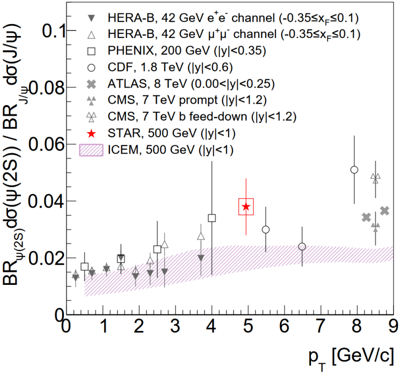
Ratio vs. N_{part}



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

- Both channels consistent

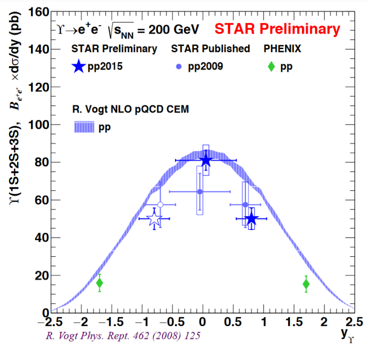
$\psi(2S)/J/\psi$ cross section ratio vs. p_T

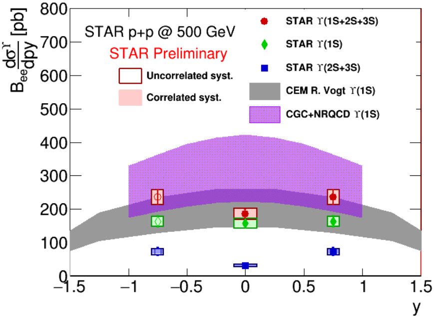


STAR: [arXiv:1905.06075] submitted to PRD
ICEM: [Phys.Rev.D 94, 114029(2016)]

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

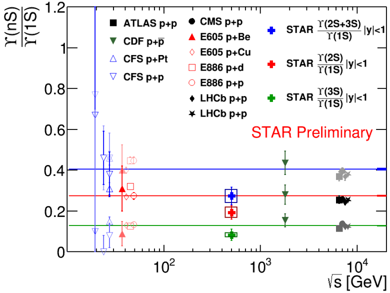
- STAR measured ratio consistent with the results from other experiments
- ICEM model calculation describes the data trend reasonably well

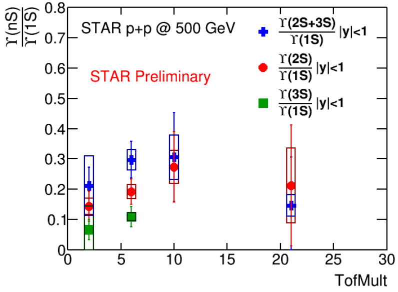




- STAR data slightly narrower than Color Evaporation Model (CEM) at $\sqrt{s} = 200$ GeV
- Flatter rapidity spectrum at $\sqrt{s} = 500$ GeV compared to $\sqrt{s} = 200$ GeV
  - Dip at mid-rapidity for $\Upsilon(2S+3S) \approx 2\sigma$ level from flat
  - CEM model (inclusive) consistent with the measurement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

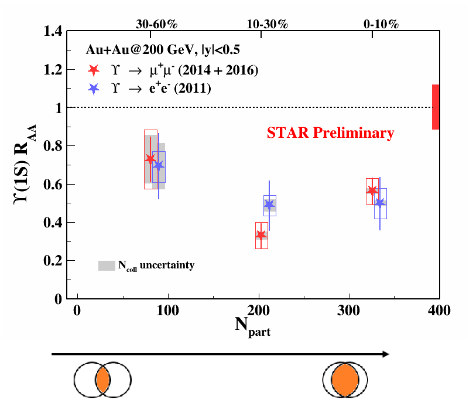
Cross section ratios: $\Upsilon(nS)/\Upsilon(1S)$

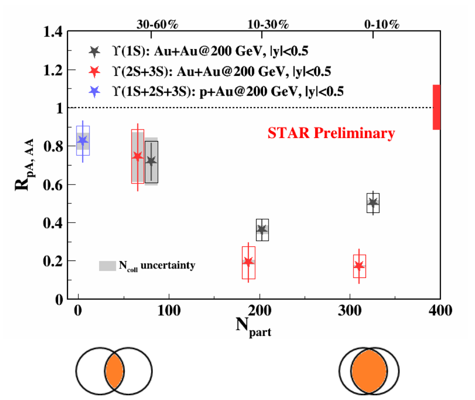




[Phys.Rev.C 88,067901(2013)]

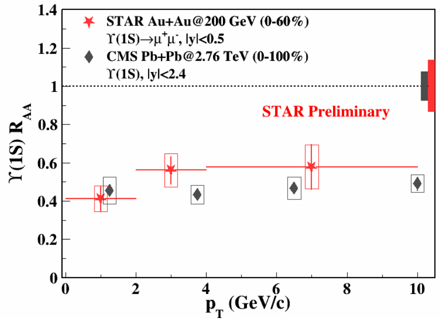
- TofMult: number of tracks matched to TOF within $|\eta| < 1$, $p_T > 0.2\,\mathrm{GeV/c}$
- Boxes correspond to uncorrelated systematic uncertainties (correlated uncertainties largely cancel out)
- Left plot: cross section ratios measured in 500 GeV p+p collisions are slightly below (within 2σ) world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

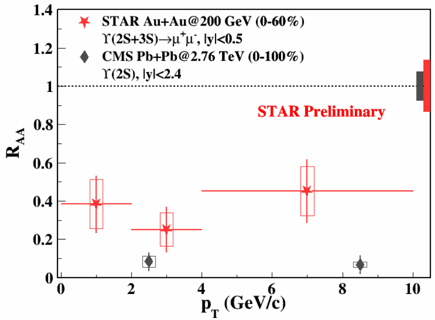




R_{AuAu} measured by STAR

- 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



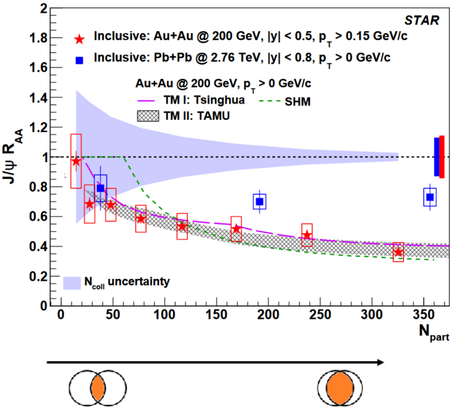


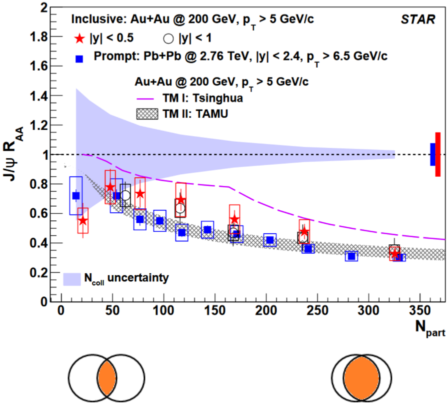
CMS: [Phys.Lett.B 770, 357-379(2017)]

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

J/ψ R_{AA} in Au+Au





[[arXiv:1905.13669] submitted to PLB]

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