Recent results of Υ production measured with the STAR experiment

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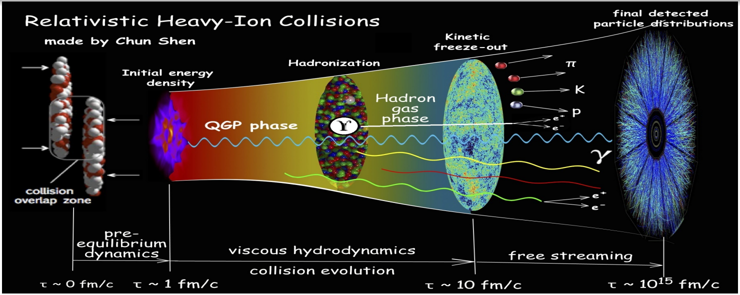
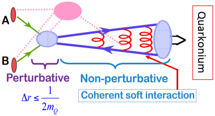
This work was also supported from European Regional Development Fund-Project "Center of Advanced Applied Science" No. CZ.02.1.01/0.0/0.0/16-019/0000778 and by the grant LTT18002 of Ministry of Education, Youth and Sports of the Czech Republic.

Outline

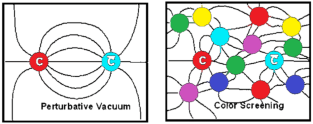
1. Introduction
2. STAR experiment
3. Υ in p+p
    - $\sqrt{s} = 200$ GeV
    - $\sqrt{s} = 500$ GeV
4. Υ production in p+Au
    - $\sqrt{s_{NN}} = 200$ GeV
5. Υ production in Au+Au
    - $\sqrt{s_{NN}} = 200$ GeV
6. Summary

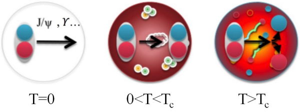
Υ - a probe of quark-gluon plasma





[E. Ferreiro, SQM 2019]





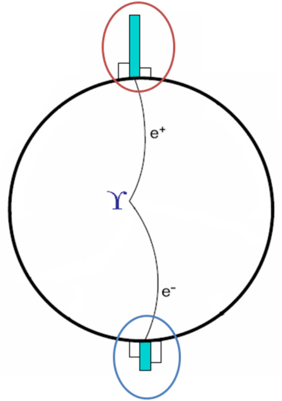
[A. Rothkopf, Hard Probes 2012]

Quark-gluon plasma studies with Υ states

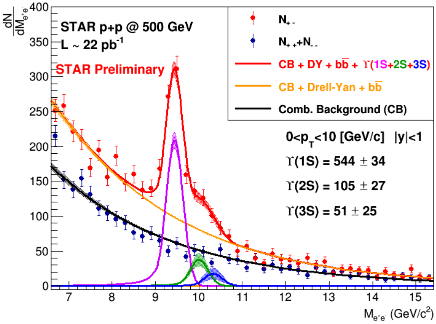
- QGP can be created in heavy-ion collisions and probed using Υ states
- $\Upsilon(nS)$ states $\Upsilon = b\bar{b}$ $(m_{u,d} << m_b)$:
  - Contain heavy quarks, created at the early stages of the collision
  - Dissociate at high T in QGP via Debye-like screening
    [T.Matsui, H.Satz, Phys.Lett.B 178(4),416-422(1986)]
  - Similar to J/ψ

Υ decay reconstruction

1. Upsilon mesons are reconstructed through $\Upsilon \to e^+e^-$ ($\Upsilon \to \mu^+\mu^-$) decays
2. Detect and select electrons and calculate invariant mass m_{ee} in order to obtain the Υ peak
   $m_{ee} = \sqrt{(E_1 + E_2)^2 - (\vec{p}_1 + \vec{p}_2)^2}$

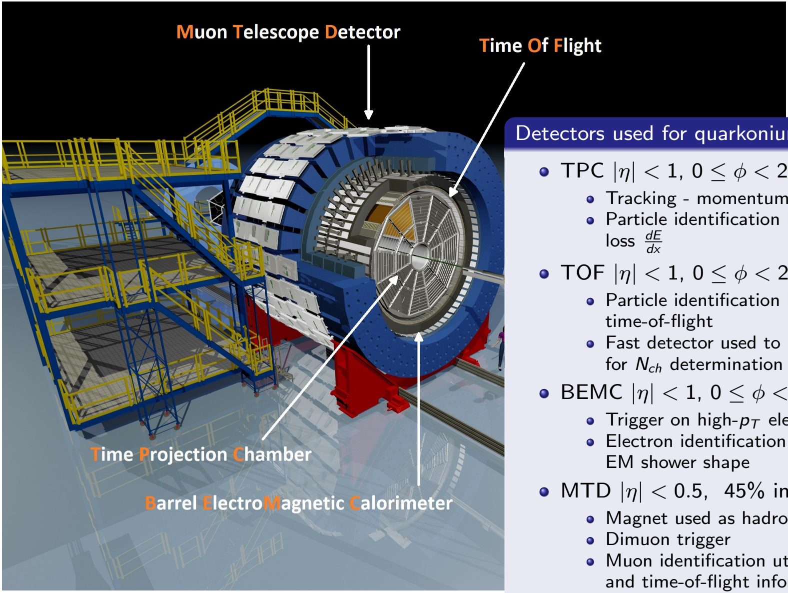


$\longmapsto$



3. Apply efficiency corrections to $e^+e^-(\mu^+\mu^-)$ obtained from simulated $\Upsilon \to e^+e^-(\Upsilon \to \mu^+\mu^-)$ decays

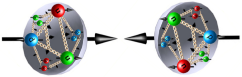
STAR experiment at RHIC collider



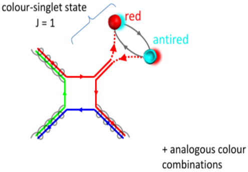
Detectors used for quarkonium studies

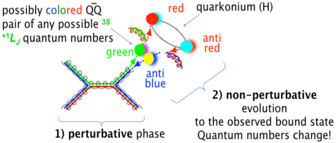
- TPC $|\eta| < 1,\ 0 \leq \phi < 2\pi$
    - Tracking - momentum measurement
    - Particle identification based on energy loss $\frac{dE}{dx}$
- TOF $|\eta| < 1,\ 0 \leq \phi < 2\pi$
    - Particle identification based on time-of-flight
    - Fast detector used to remove pile-up for N_{ch} determination
- 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 ϕ
    - Magnet used as hadron absorber
    - Dimuon trigger
    - Muon identification utilizing position and time-of-flight information
    - μ - less bremsstrahlung than e

Υ production in p+p collisions

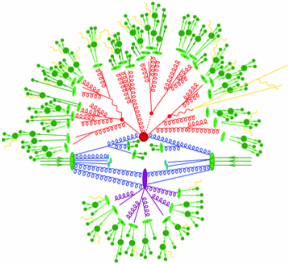


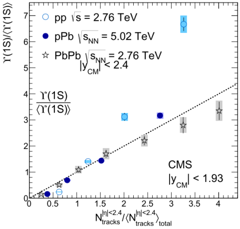
- Study of production mechanism: Color Singlet vs. Color Octet channels





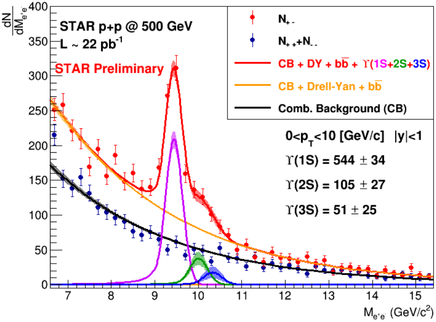
- Charged particle multiplicity N_{ch} dependence
  - Studied with $\Upsilon / <\Upsilon>$ vs $N_{ch} / <N_{ch}>$
  - Interesting stronger-than-linear increase observed at CMS
  - Investigates interplay between hard and soft processes





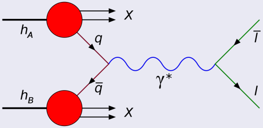
[L.Adamczyk, et al., J.Phys.Lett.B 735(2014)127]

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

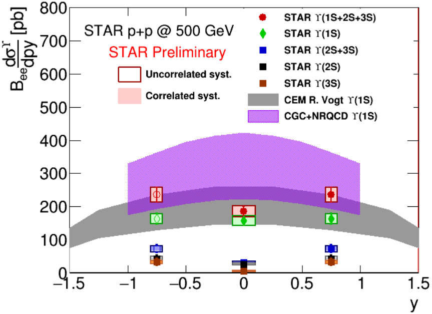


Signal extraction

- Challenging to extract individual $\Upsilon(nS)$ yields!
- Fit m_{ee} distributions with:
  - Signal lineshapes from STAR detector simulation
  - Backgrounds:
    - combinatorial
    - $b\bar{b} \rightarrow B\bar{B} \rightarrow e^+e^-$
    - Drell-Yan $q\bar{q} \rightarrow e^+e^-$



Υ rapidity dependence in p+p at 500 GeV

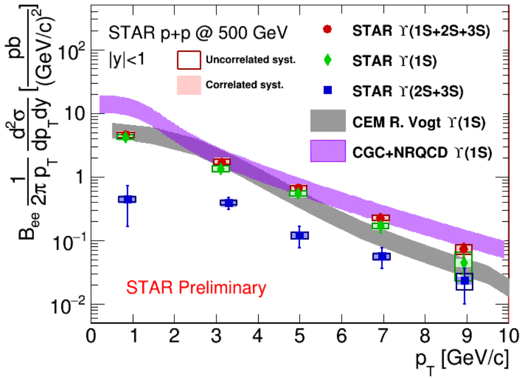


- Data reflected symmetrically around $y = 0$ ($y = \frac{1}{2} ln \frac{E+p_L c}{E-p_L c}$)
- Separate $\Upsilon(1S)$ and $\Upsilon(2S)$(NEW!),$\Upsilon(3S)$(NEW!) spectra.
- Flatter rapidity spectrum compared to $\sqrt{s} = 200\ \mathrm{GeV}$ (see backup: 27)
- Dip at mid-rapidity for Υ(2S+3S) $\approx 2\sigma$ level from flat
- CEM model (inclusive) consistent with the measurement for $\Upsilon(1S)$

  [R. Vogt, Phys.Rev.C 92 034909(2015)]
- CGC+NRQCD predictions for direct $\Upsilon(1S)$ are above the data for inclusive $\Upsilon(1S)$

  [H. Han, et al., Phys.Rev.D 94, 014028(2016)],[Y. Ma, R. Venugopalan, Phys.Rev.Lett. 113, 192301(2014)]

Υ p_T spectrum

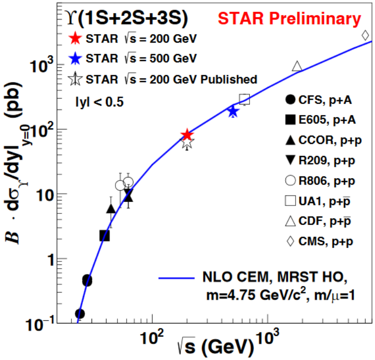


- Separate $\Upsilon(1S)$ and $\Upsilon(2S{+}3S)$ spectra.
- CEM calculation for inclusive $\Upsilon(1S)$

  [R. Vogt, Phys.Rev.C 92 034909(2015)]
  - Agree with data reasonably well
- CGC+NRQCD for direct Υ

  [H. Han, Phys.Rev.D 94, 014028(2016)] [Y. Ma, Phys.Rev.Lett. 113, 192301(2014)]
  - $\Upsilon(1S)$: model calculation is above the data points. Caveat: additional corrections (Sudakov resummation) are needed at low p_T according to authors.

Integrated Υ cross section in p+p collisions



STAR [L.Adamczyk, Phys.Lett.B 735,127–137(2014)]
CDF [D. Acosta et al., Phys.Rev.Lett. 88,161802(2002)]
CMS [V. Khachatryan et al., Phys.Rev.D 83,112004(2010)]
CFS [W. R. Innes et al., Phys.Rev.Lett. 39,1240-1242(1977)]
CFS [J. K. Yoh et al., Phys.Rev.Lett. 41,684–687(1978)]
CFS [K. Ueno et al., Phys.Rev.Lett. 42,486–489(1979)]
CFS [S. Childress et al., Phys.Rev.Lett. 55,1962–1964(1985)]
E605 [G. Moreno et al., Phys.Rev.D 43,2815–2835(1991)]
E605 [T. Yoshida et al., Phys.Rev.D 39,3516(1989)]
CCOR [A.L.S.Angelis et al., Phys.Lett.B 87,398–402(1979)]
L. Camilleri, T.B.W. Kirk, H.D.I. Abarbanel (Eds.)
E866 [L. Y. Zhu et al., Phys.Rev.Lett. 100,062301(2008)]
ISR [C.Kourkoumelis et al., Phys.Lett.B 91,481-486(1980)]

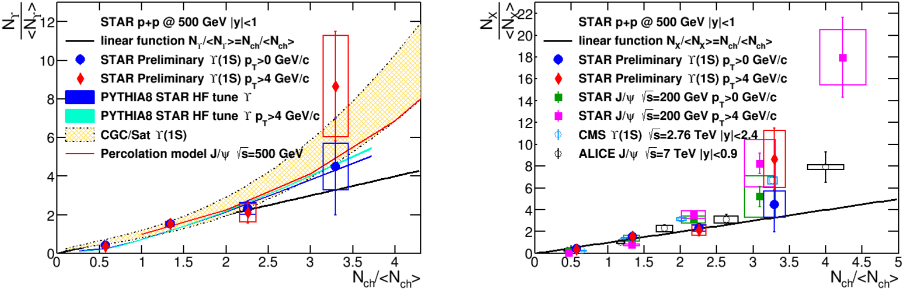
Integrated cross section

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

[A.D.Frawley et al., Phys.Rep. 462, pp.125–175(2008)]

Υ production vs. event activity

$$\Upsilon \to e^+e^-$$

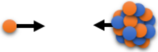


- Distributions of N_{ch} fully corrected using unfolding procedure. See backup: 26
- PYTHIA8 and String Percolation models reproduce the trend in the data

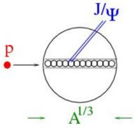
  [E. G. Ferreiro, C. Pajares, Phys.Rev.C, 86, 034903(2012)]
- CGC/Saturation model describes the data within large uncertainties

  [E. Levin, M. Siddikov, EPJC, 97(5), 376(2019)], [M. Siddikov, et al., arXiv:1910.13579 [hep-ph]]
- Similar trends at RHIC and LHC for Υ and J/ψ
- Suggest Υ production in MPI or saturation effects
- Prospects: large data sets coming from runs 2017+2022 - increased precision

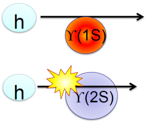
Υ production in p+A



p+A collisions (Cold Nuclear Matter (CNM) effects - assume no QGP effects):



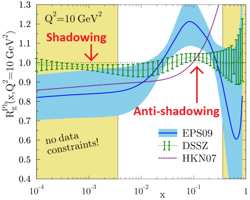
- Nuclear absorption: σ_{abs}
  - $\Upsilon + A \rightarrow X$



[L. Grandchamp, LBNL 2005]

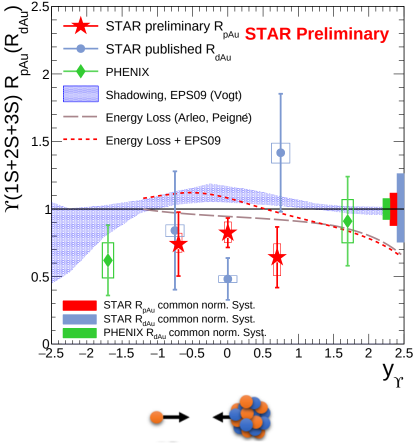
- Comover interactions - very small for $\Upsilon(1S)$

  [Z. Lin, C.M. Ko, Phys.Lett.B 503, 104(2001)]
  - $\Upsilon + h \rightarrow X$
- Modified nuclear PDFs with respect to free nucleons:
  - shadowing
  - anti-shadowing
- Studied by measuring Nuclear Modification Factor: $R_{pA} = \frac{\sigma_{inel}}{<N_{coll}>} \frac{\mathrm{d}^2 N_{p+Au}/\mathrm{d}p_T\mathrm{d}y}{\mathrm{d}^2\sigma_{pp}/\mathrm{d}p_T\mathrm{d}y}$



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

Υ production in p+Au at $\sqrt{s_{NN}} = 200$ GeV

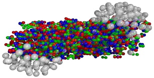


[L. Adamczyk et al., J.Phys.Lett.B 735(2014)127],
[A. Adare et al., Phys. Rev. C 87, 044909],
[F. Arleo, S. Peigné, JHEP 03, 122(2013)]

Υ(1S+2S+3S)

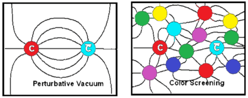
- Improved precision over published results of R_{dAu}
  - $\sim$ 50% smaller statistical uncertainty vs. y
  - $R_{pAu}|_{|y|<0.5} = 0.82 \pm 0.10(stat.)^{+0.08}_{-0.07}(syst.) \pm 0.10(glob.)$
- Indication of Υ(1S+2S+3S) suppression in p+Au collisions

Υ production in A+A



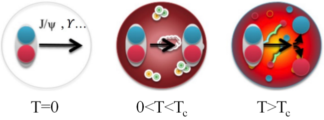
Heavy ion (A+A) collisions (QGP+CNM effects):

- Quarkonium states dissociate at high temperature in QGP via Debye-like screening
  [T.Matsui, H.Satz, Phys.Lett.B 178(4),416-422(1986)]
  - Provides information about QGP (interactions, temperature...)

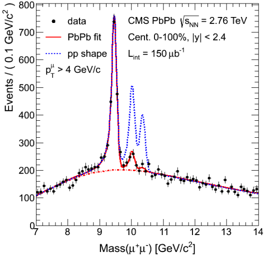


- Sequential suppression due to each $\Upsilon(nS)$ state dissociating at different T → estimate of T *[S. Digal, Phys.Rev.D 64, 094015(2001)]*

- Modified feed-down pattern

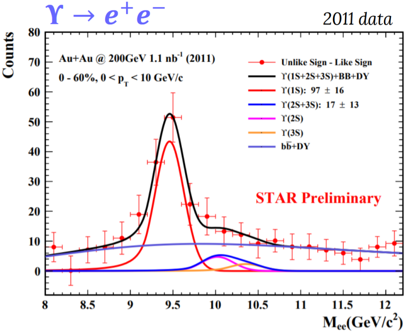


[A. Rothkopf, Hard Probes 2012]

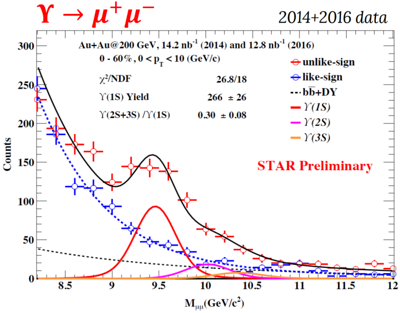


[S. Chatrchyan, et. al, Phys.Rev.Lett. 109(22), 222301]

Υ signal in Au+Au at $\sqrt{s_{NN}} = 200$ GeV


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

2011 data

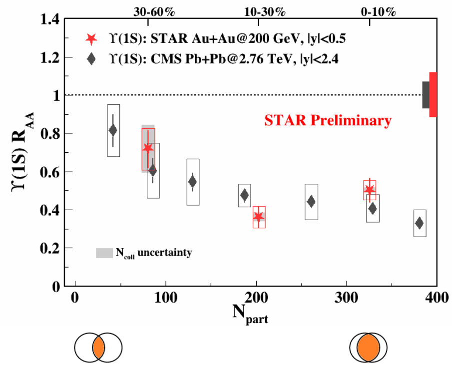

$\Upsilon \rightarrow \mu^+\mu^-$

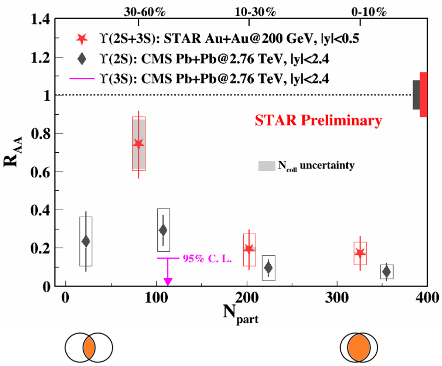
2014+2016 data

Υ signal

- Υ measured in both e^+e^- and $\mu^+\mu^-$
- Combined R_{AA} for better precision

Υ suppression - R_{AA}



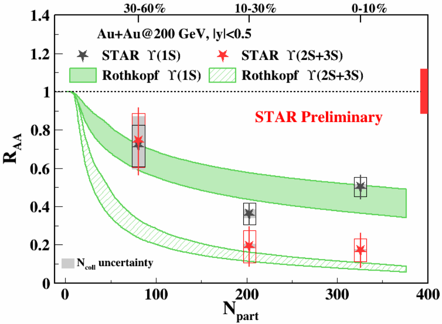


CMS: [V. Khachatryan et al., Phys.Lett.B 770, 357-379(2017)]

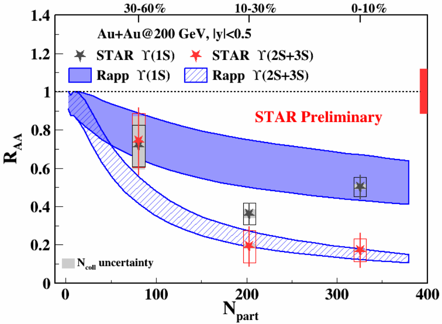
STAR vs. CMS

- Similar suppression for $\Upsilon(1S)$, despite higher medium temperature at the LHC
  - $R_{AA}(1S) \approx 0.4$ could be largely due to suppression of excited states contribution
  - Sequential suppression
  - Regeneration? Larger at LHC than at RHIC
  - CNM effects - need better constraints
- Indication of smaller suppression for $\Upsilon(2S+3S)$ at RHIC than at LHC

Υ: STAR vs. models



Rothkopf: [B. Krouppa et al., Phys.Rev.D 97, 016017(2018)]



Rapp: [X. Du et al., Phys.Rev.C 96,054901(2017)]

Models

- Kroupaa, **Rothkopf**, Strickland
  - QGP modeled by hydrodynamics + Debye-like screening
  - No regeneration, no CNM effects
- De, He, **Rapp**
  - QGP modeled by hydrodynamics + Debye-like screening
  - Includes both regeneration and CNM effects
- Both models agree with STAR $\Upsilon(1S)$ data
- Indication that Rothkopf's model underestimates the STAR Υ(2S+3S) results for 30 – 60% centrality

Summary

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

- $\Upsilon(1S)$ data reasonably described by CEM model, while overestimated by CGC+NRQCD
- Similar trends for J/ψ and Υ vs. $N_{ch}/ < N_{ch} >$ at RHIC and LHC

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

- Indication of Υ(1S+2S+3S) suppression

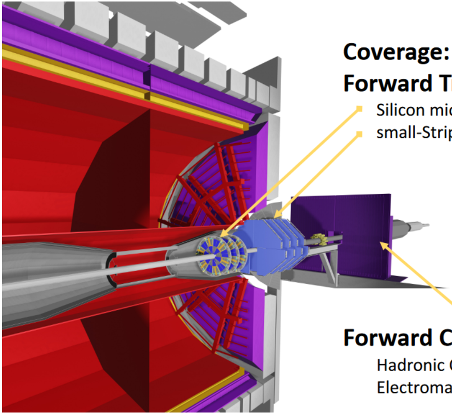
Υ in Au+Au collisions at $\sqrt{s_{NN}} = 200\ \mathrm{GeV}$

- Υ R_{AA} measured in dielectron and dimuon channels - combined for better precision
- Similar suppression of $\Upsilon(1S)$ at RHIC and LHC
- Stronger suppression of Υ(2S+3S) than $\Upsilon(1S)$ in central collisions
  - Sequential suppression
- $\Upsilon(1S)$, Υ(2S+3S) R_{AA} consistent with model calculations

Thank you for your attention!

BACKUP

Upgrades and plans for 2022+



Coverage: $2.5 < \eta < 4.0$

Forward Tracking System

Silicon microstrip sensors
small-Strip Thin Gap Chambers

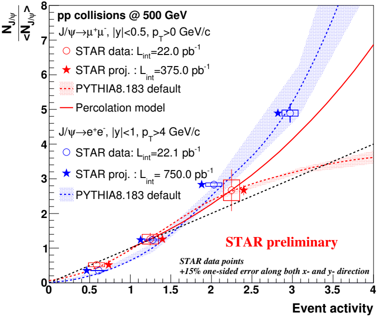
Forward Calorimetry System

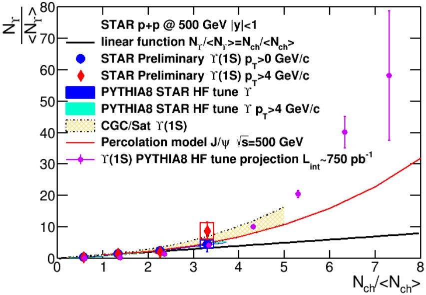
Hadronic Calorimeter
Electromagnetic Calorimeter

Future plans for STAR

- iTPC already running - improved momentum resolution
- Forward upgrade - new detectors
- High integrated luminosity for precision quarkonium production studies
- And more!

J/ψ and Υ in p+p projections 2017+2022

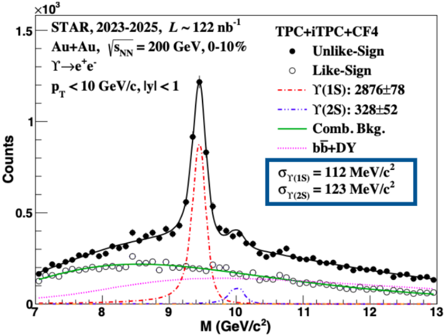


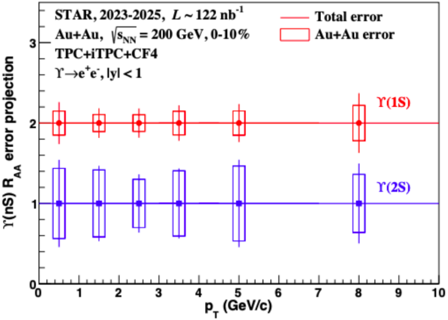


Projections 2017+2022

- High precision measurement of J/ψ and Υ dependence on normalized N_{ch}
- Very high integrated luminosity $\mathcal{L}_{int} \sim 750\,\mathrm{pb}^{-1}$ for BHT e and $\mathcal{L}_{int} \sim 375\,\mathrm{pb}^{-1}$ for $\mu\mu$ triggers
- Possible to discriminate different models

Υ R_{AA} projections 2023+

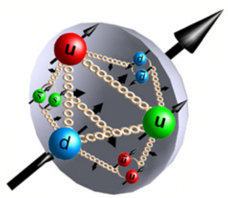


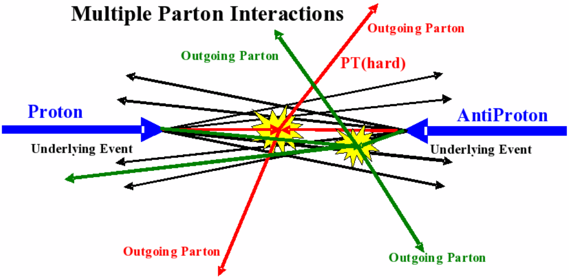


Projections 2023+

- High precision measurement:
  - High integrated luminosity $\mathcal{L}_{int} \sim 122\,\mathrm{nb}^{-1}$
  - Improved momentum resolution
  - Low material budget - less background
- R_{AA} of $\Upsilon(1S)$ and $\Upsilon(2S)$ vs:
  - centrality, p_T

Multiple parton interactions (MPI)



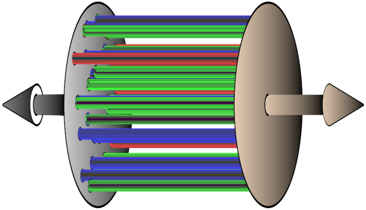


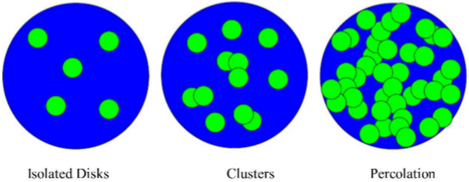
https://www.bnl.gov/rhic/images/proton-with-gluouns-300px.jpg

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





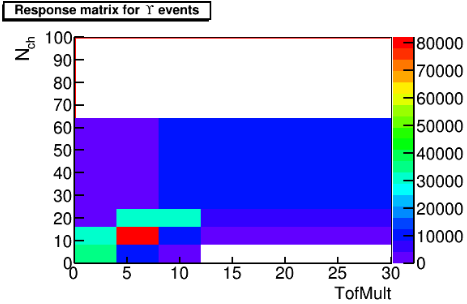
[F. Gelis et al., Ann.Rev.Nucl.Part.Sci.60, 463-489(2010)] [L. Kosarzewski, Proc.of SPIE, 100313U(2016)]

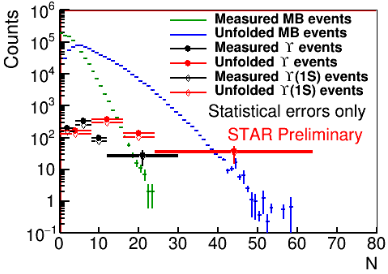
- Models particle production originating from strings of color field formed in $p+p$ collisions.
- Soft particle production dampened by interaction of overlapping strings.
- Predicts quadratic dependence of normalized yield for particles from hard processes vs. normalized charged particle multiplicity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

$$\frac{N_{hard}}{\langle N_{hard}\rangle} = \langle\rho\rangle \left(\frac{\frac{dN_{ch}}{d\eta}}{\left\langle \frac{dN_{ch}}{d\eta} \right\rangle} \right)^2$$

[E. G. Ferreiro, C. Pajares, Phys.Rev. C, 86, 034903 (2012)]

Multiplicity distribution via unfolding

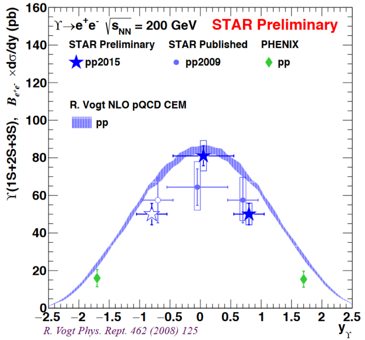




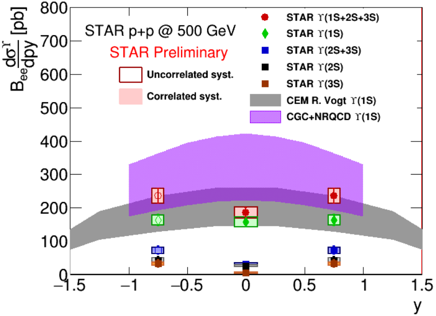
Unfolding method used for multiplicity dependent studies

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 using their respective response matrices
3. This procedure yields the unfolded (true) distribution
4. Similar procedure used for J/ψ
5. Measured N_{ch} distribution obtained from p+p $\sqrt{s} = 500\ \mathrm{GeV}$ 2009 data
6. Measured distribution of Υ events obtained from p+p $\sqrt{s} = 500\ \mathrm{GeV}$ 2011 data

Υ rapidity dependence in p+p at 200 and 500 GeV



R. Vogt Phys. Rept. 462 (2008) 125



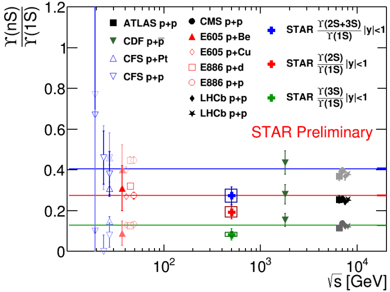
- $\sqrt{s} = 200$ GeV STAR data:
  - Slightly narrower than Color Evaporation Model (CEM)
- $\sqrt{s} = 500$ GeV data:
  - Data reflected symmetrically around $y = 0$ [1]
  - Separate $\Upsilon(1S)$ and $\Upsilon(2S)$(NEW!),$\Upsilon(3S)$(NEW!) spectra.
  - Flatter rapidity spectrum compared to $\sqrt{s} = 200$ GeV (see backup)
  - Dip at mid-rapidity for Υ(2S+3S) $\approx 2\sigma$ level from flat
  - CEM model (inclusive) consistent with the measurement for $\Upsilon(1S)$

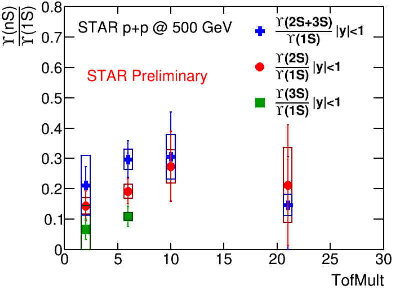
    [R. Vogt, Phys.Rev.C 92 034909(2015)]
  - CGC+NRQCD predictions for direct $\Upsilon(1S)$ are above the data for inclusive $\Upsilon(1S)$

    [H. Han et al., Phys.Rev.D 94, 014028(2016)],[Y. Ma, R. Venugopalan, Phys.Rev.Lett. 113, 192301(2014)]

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

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

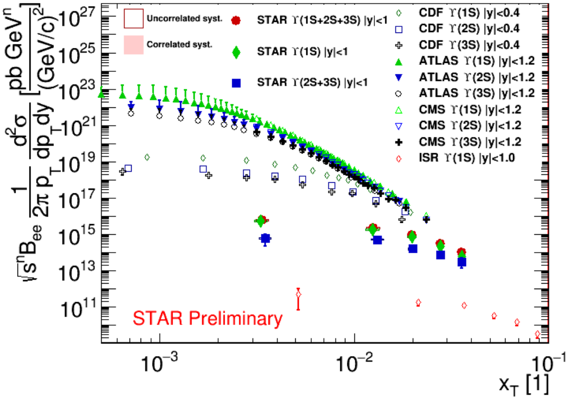




[W. Zha, et al, Phys.Rev.C 88,067901(2013)]

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

x_T dependence



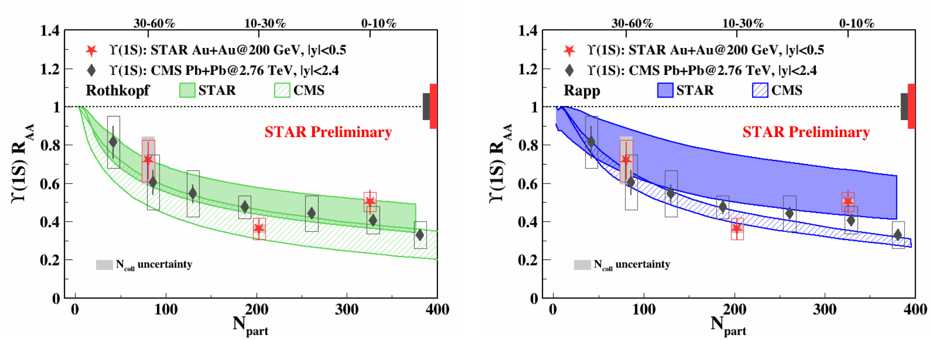
STAR $p+p$ $\sqrt{s} = 500$ GeV
ATLAS $p+p$ $\sqrt{s} = 7$ TeV
[G. Aad et al., Phys.Rev.D 87,052004(2013)]
CMS $p+p$ $\sqrt{s} = 7$ TeV
[V.Khachatryan et al., Phys.Lett.B 749,14-34(2015)]
CDF $p+\bar{p}$ $\sqrt{s} = 1.8$ TeV
[D. Acosta et al., Phys.Rev.Lett. 88,161802(2002)]
ISR $p+\bar{p}$ $\sqrt{s}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

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

  [F. Arleo et al., 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

  [L. Adamczyk et al., 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

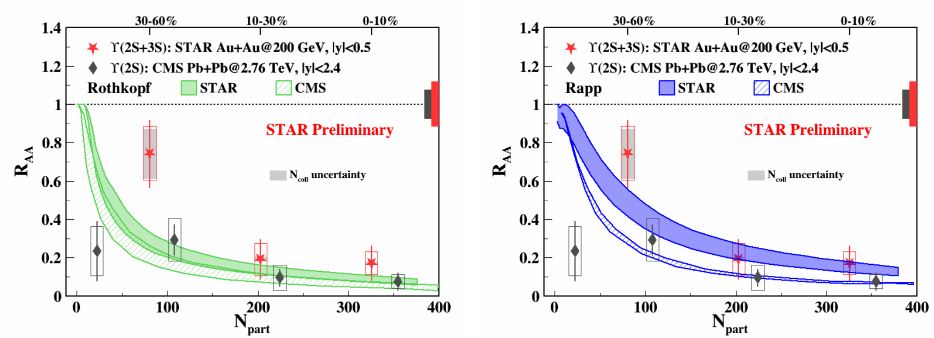


[B. KrouppaPhys et al., .Rev.D 97,(2018)016017], [X. Du et al., Phys.Rev.C 96,(2017)054901]

$\Upsilon(1S)$ vs. models

- Both models consistent with the data

STAR and CMS Υ(2S+3S) vs. models

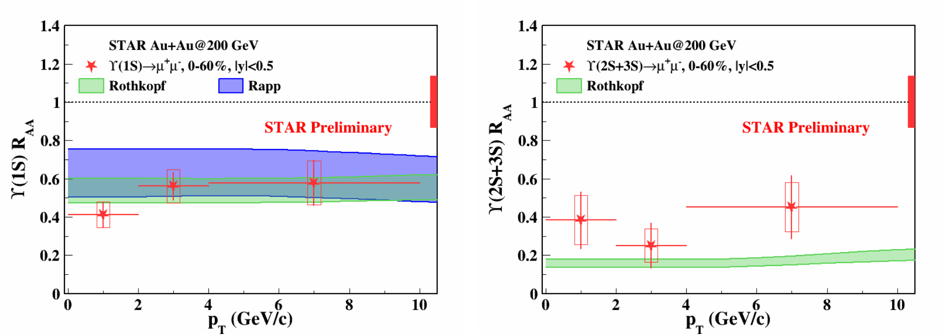


[B. Krouppa et al., Phys.Rev.D 97,016017(2018)], [X. Du et al., Phys.Rev.C 96,054901(2017)]

Υ(2S+3S) vs. models

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

R_{AA} vs. p_T vs. models

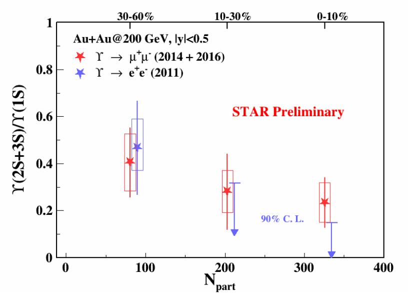


[B. Krouppa et al., Phys.Rev.D 97,016017(2018)], [X. Du et al., Phys.Rev.C 96,054901(2017)]

R_{AA} vs. p_T vs. models

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

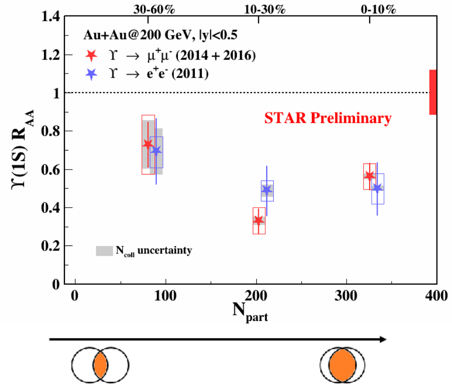
Ratio vs. N_{part}

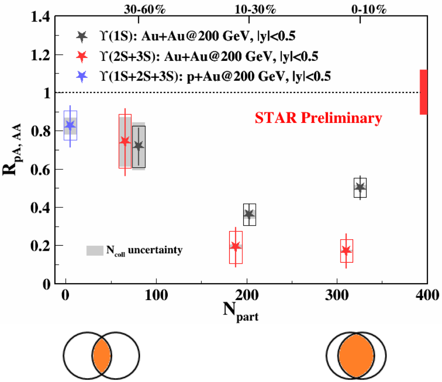


$\frac{\Upsilon(2S+3S)}{\Upsilon(1S)}$ vs. N_{part}

- Both channels consistent

Υ R_{AuAu} vs. N_{part}

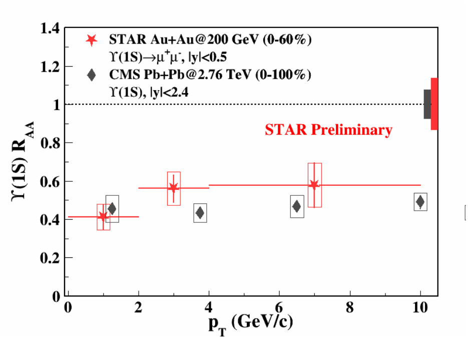


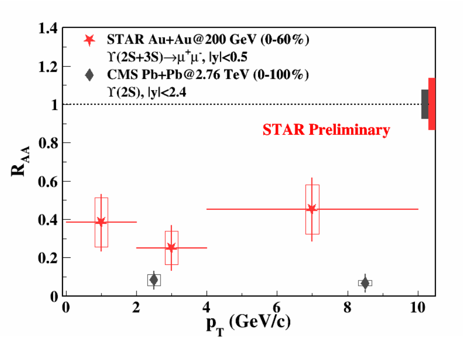


R_{AuAu} measured by STAR

- 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 Υ(2S+3S) than $\Upsilon(1S)$ in central collisions

Υ R_{AA} vs. p_T





CMS: [V.Khachatryan et al., 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 Υ(2S+3S) at LHC than at RHIC
- Both consistent with flat dependence vs. p_T