Overview of Υ production studies performed with the STAR experiment

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MINISTRY OF EDUCATION,
YOUTH AND SPORTS

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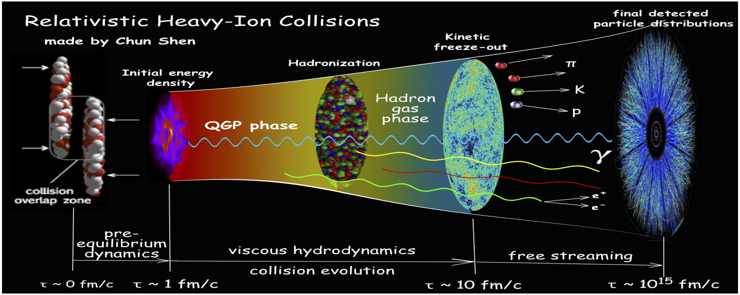
ČESKÉ VYSOKÉ UČENÍ TECHNICKÉ V PRAZE

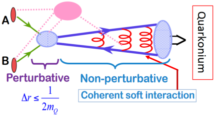
The work was also supported from European Regional Development Fund-Project "Center of Advanced Applied Science" No. CZ.02.1.01/0.0/0.0/16-019/0000778 and by the grant LTT18002 of Ministry of Education, Youth and Sports of the Czech Republic.

Outline

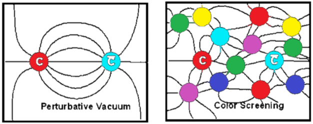
1. Introduction
2. STAR experiment
3. Υ in p+p
   - $\sqrt{s} = 200$ GeV
   - $\sqrt{s} = 500$ GeV
4. Υ production in p+Au
   - $\sqrt{s_{NN}} = 200$ GeV
5. Υ production in Au+Au
   - $\sqrt{s_{NN}} = 200$ GeV
6. Projections for 2022+ runs
7. Summary

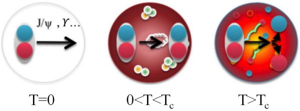
Υ - a probe of quark-gluon plasma





[E. Ferreiro, SQM 2019]

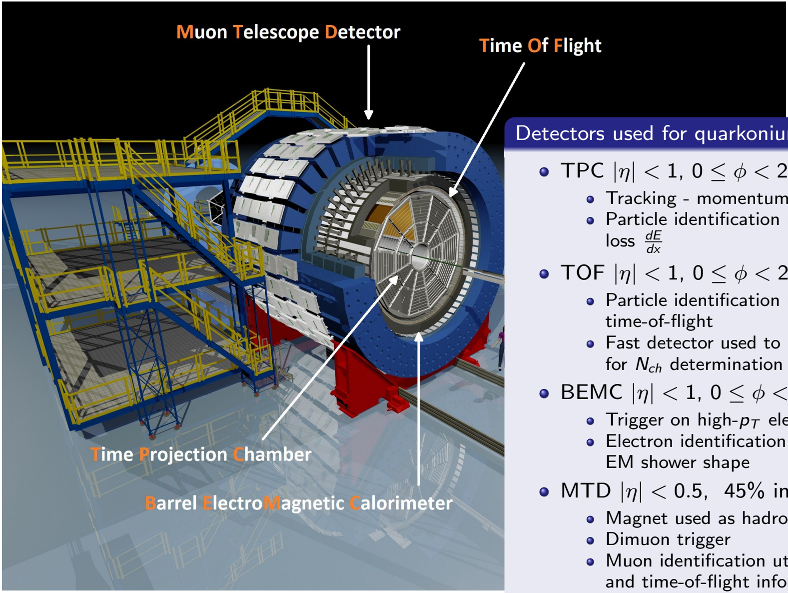




[A. Rothkopf, Hard Probes 2012]

Quark-gluon plasma studies with Υ states

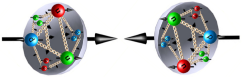
- QGP can be created in heavy-ion collisions and probed using Υ states
- $\Upsilon(nS)$ states $\Upsilon = b\bar{b}$ ($m_{u,d} << m_b$):
  - Contain heavy quarks, created at the early stages of the collision
  - Dissociate at high T in QGP via Debye-like screening *[Phys.Lett.B 178(4),416-422(1986)]*



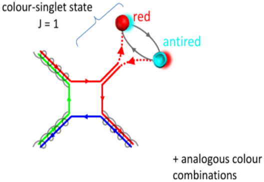
Detectors used for quarkonium studies

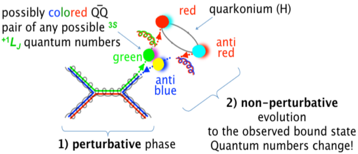
- TPC $|\eta| < 1$, $0 \leq \phi < 2\pi$
  - Tracking - momentum measurement
  - Particle identification based on energy loss $\frac{dE}{dx}$
- TOF $|\eta| < 1$, $0 \leq \phi < 2\pi$
  - Particle identification based on time-of-flight
  - Fast detector used to remove pile-up for N_{ch} determination
- 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

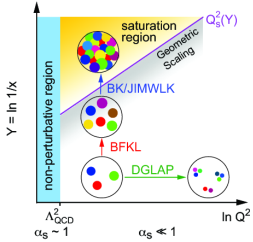


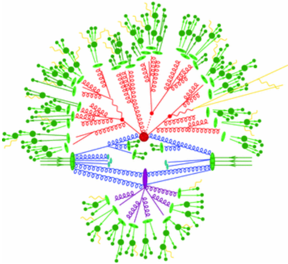
- Study of production mechanism: Color Singlet vs. Color Octet channels





- Events with high charged particle multiplicity
  - Interplay between hard and soft processes
  - Saturation effects/multiple parton interactions

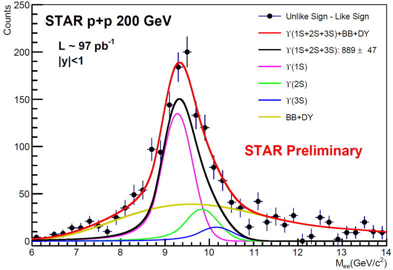




[Nuclear Physics A 904-905 (2013): 294c–301c]

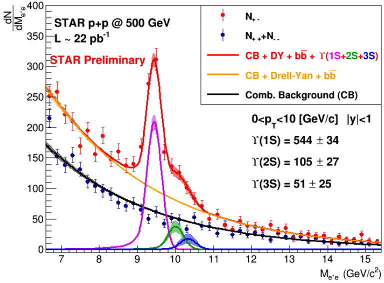
$\Upsilon \rightarrow e^+e^-$ in 2015

p+p $\sqrt{s} = 200$ GeV



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

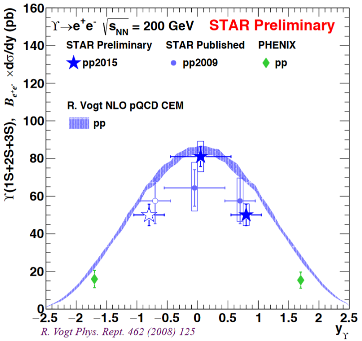
p+p $\sqrt{s} = 500$ GeV

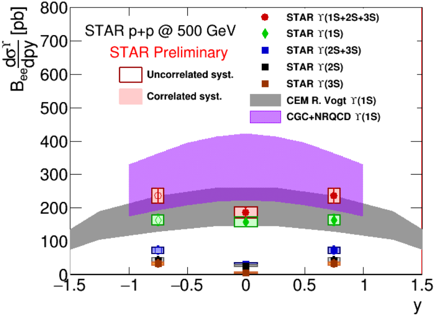


Signal extraction

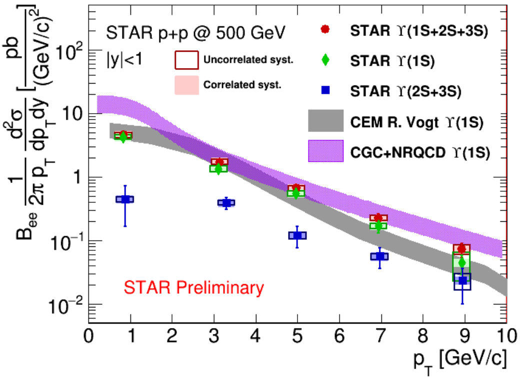
- Challenging to extract individual $\Upsilon(nS)$ yields!
- Fit m_{ee} histograms with:
  - Signal lineshapes from STAR detector simulation
  - Backgrounds: combinatorial, $b\bar{b}$, Drell-Yan

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



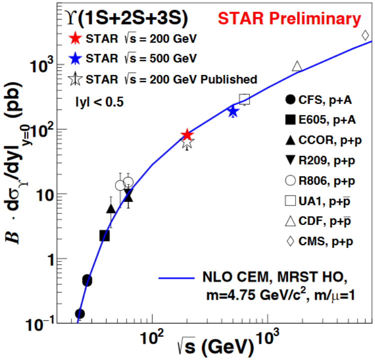


- $\sqrt{s} = 200$ GeV STAR data:
  - Slightly narrower than Color Evaporation Model (CEM)
- $\sqrt{s} = 500$ GeV data:
  - Separate $\Upsilon(1S)$ and $\Upsilon(2S)$(NEW!),$\Upsilon(3S)$(NEW!) spectra.
  - Flatter rapidity spectrum compared to $\sqrt{s} = 200$ GeV
  - Dip at mid-rapidity for Υ(2S+3S) $\approx 2\sigma$ level from flat, mostly due to low $\Upsilon(3S)$ yield
  - 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 inclusive $\Upsilon(1S)$ *[Phys.Rev.D 94, 014028(2016)],[Phys.Rev.Lett. 113, 192301(2014)]*



- Separate $\Upsilon(1S)$ and $\Upsilon(2S+3S)$ spectra.
- 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.

$\Upsilon \to e^+e^-$ integrated cross section in p+p



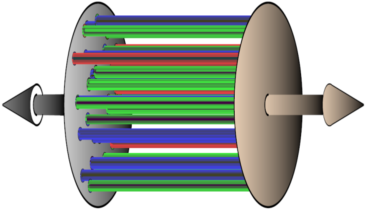
STAR [Phys.Lett.B 735,127–137(2014)]
CDF [Phys.Rev.Lett. 88,161802(2002)]
CMS [Phys.Rev.D 83,112004(2010)]
CFS [Phys.Rev.Lett. 39,1240-1242(1977)]
CFS [Phys.Rev.Lett. 41,684–687(1978)]
CFS [Phys.Rev.Lett. 42,486–489(1979)]
CFS [Phys.Rev.Lett. 55,1962–1964(1985)]
E605 [Phys.Rev.D 43,2815–2835(1991)]
E605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

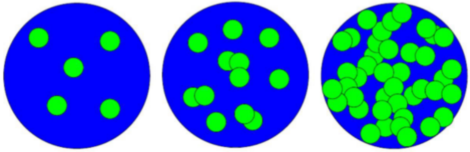
Integrated cross section

- $B_{ee}\frac{d\sigma}{dy}|_{|y|<0.5} = 81 \pm 5(stat) \pm 8(syst)$ 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)]

Event activity in Percolation model

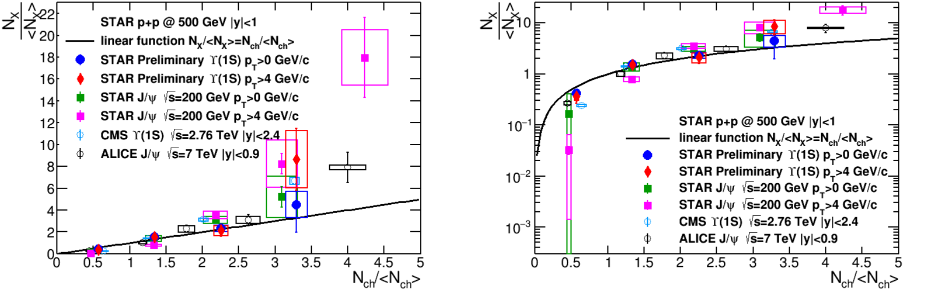




[Ann.Rev.Nucl.Part.Sci.60, 463-489(2010)] [Proc.of SPIE, 100313U(2016)]

- Pairs of partons form elongated strings of color field
- In high charged particle multiplicity (N_{ch}) events, many strings overlap and interact (percolation)
  - Interactions lower N_{ch} - yield from soft processes
  - Hard processes mostly unaffected - increase faster with N_{ch}
- Click to see backup slide 26 for more info!
- Similar to CGC

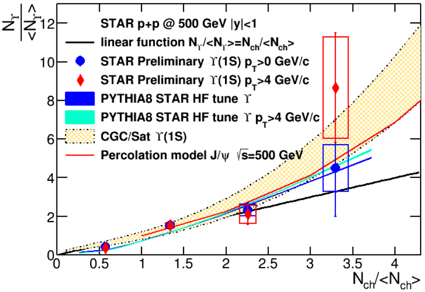
$\Upsilon \rightarrow e^+e^-$

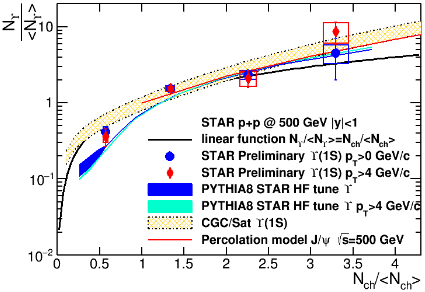


[JHEP04,103(2014)],[Nucl.and Part.Phys. Proc., 276-278, pp.261–264(2016)],[Phys.Lett.B 712,165–175(2012)],[Phys.Lett.B 786,87-93(2018)]

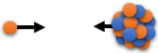
- Distributions of N_{ch} fully corrected using unfolding procedure. See backup: 27
- Similar trends at RHIC and LHC for Υ and J/ψ

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

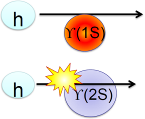




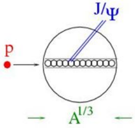
- PYTHIA8 and String Percolation models reproduce the trend in the data *[E. G. Ferreiro, C. Pajares, Phys.Rev.C, 86, 034903(2012)]*
- CGC/Saturation model describes the data within large uncertainties *[E. Levin, M. Siddikov, EPJC, 97(5), 376(2019)], [M. Siddikov, et al, arXiv:1910.13579 [hep-ph]]*
- Suggest Υ production in MPI or saturation effects



p+A collisions (Cold Nuclear Matter (CNM) effects):

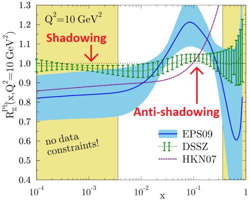


- Comover interactions - very small for $\Upsilon(1S)$
  [Phys.Lett.B 503, 104(2001)]



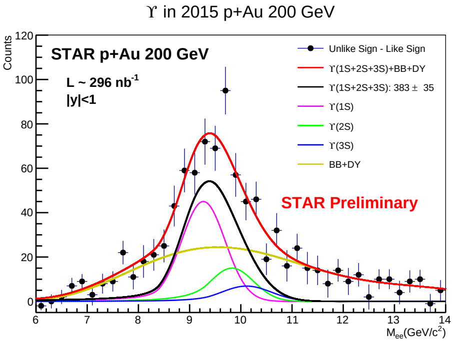
[L. Grandchamp, LBNL 2005]

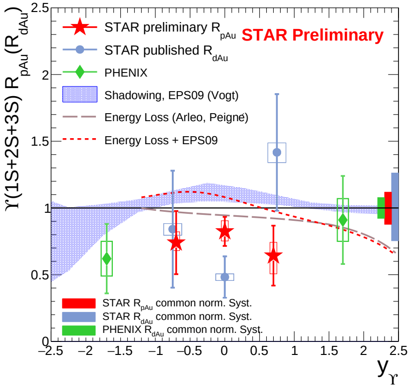
- Nuclear absorption: σ_{abs}

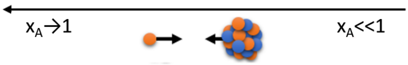


[Nucl.Phys.A 926 24-33(2014)]

- Nuclear PDFs: shadowing, anti-shadowing
- Studied by measuring Nuclear Modification Factor: $R_{pA} = \frac{\sigma_{inel}}{<N_{coll}>} \frac{\mathrm{d}^2 N_{p+Au}/\mathrm{d}p_T\mathrm{d}y}{\mathrm{d}^2\sigma_{pp}/\mathrm{d}p_T\mathrm{d}y}$







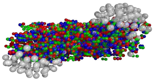
[J.Phys.Lett.B 735(2014)127],

[Phys. Rev. C 87, 044909],

[JHEP 03, 122(2013)]

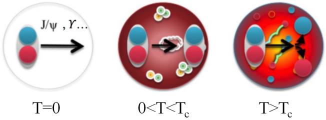
Υ(1S+2S+3S)

- Improved precision over published results from 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



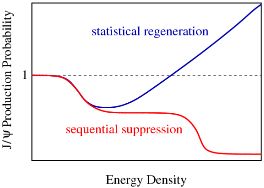
Heavy ion (A+A) collisions (QGP+CNM effects):

- Quarkonium states dissociate at high temperature in QGP via Debye-like screening *[Phys.Lett.B 178(4),416-422(1986)]*



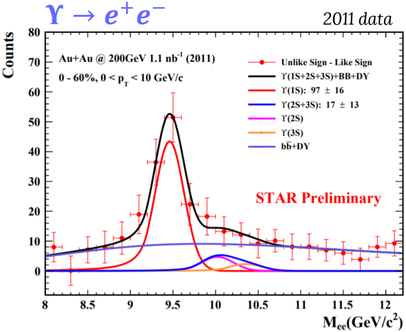
[A. Rothkopf, Hard Probes 2012]

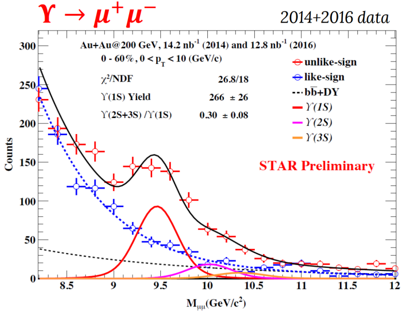
- Sequential suppression due to each $\Upsilon(nS)$ state dissociating at different T $\rightarrow$ estimate of T *[Phys.Rev.D 64, 094015(2001)]*



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

- Modified feed-down pattern
- Regeneration negligible at RHIC!

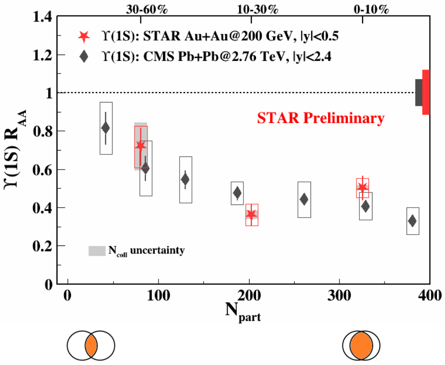


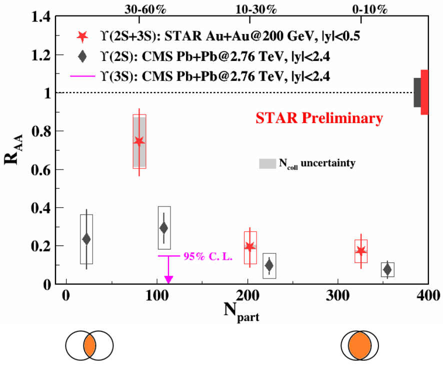


Υ signal

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

Υ suppression - R_{AA}



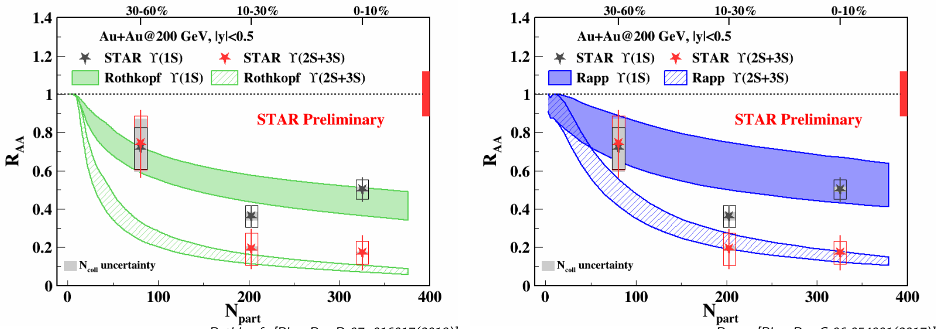


CMS: [Phys.Lett.B 770, 357-379(2017)]

STAR vs. CMS

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

Υ: STAR vs. models

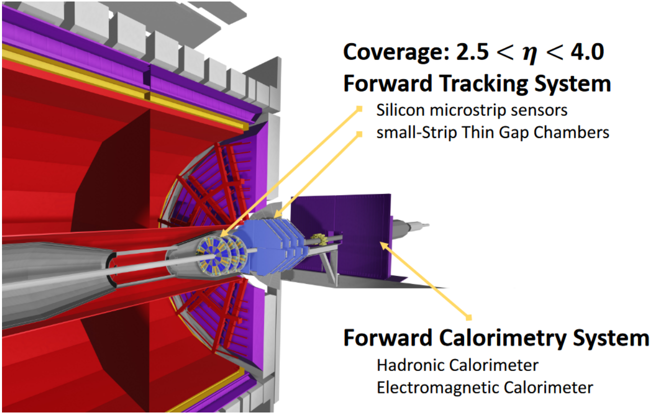


Rothkopf: [Phys.Rev.D 97, 016017(2018)]

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

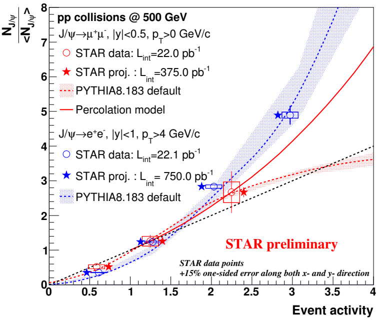
Models

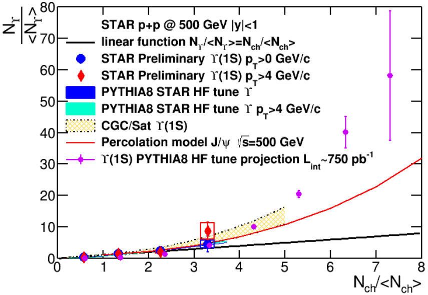
- Kroupaa, **Rothkopf**, Strickland
  - Lattice QCD-vetted potential for heavy quarks in hydrodynamic medium
  - No regeneration, no CNM effects
- De, He, **Rapp**
  - Quarkonium in-medium binding energy described by thermodynamic T-matrix calculations with internal energy potential (strongly bound scenario)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



Future plans for STAR

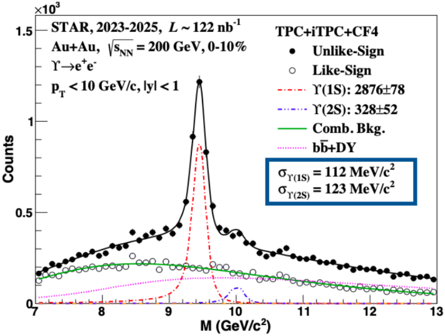
- iTPC already running - improved momentum resolution
- Forward upgrade - new detectors
- High integrated luminosity for precision quarkonium production studies
- And more!

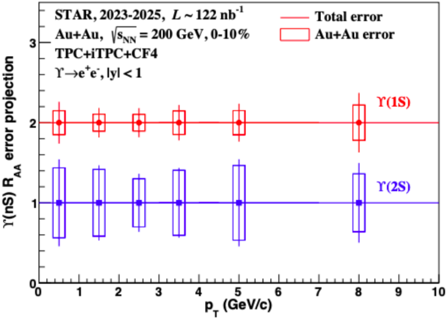




Projections 2017+2022

- 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





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

Summary

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

- $\Upsilon(1S)$ data reasonably described by CEM model, while overestimated by CGC+NRQCD
- Rapidity spectrum flatter at $\sqrt{s} = 500$ GeV than at $\sqrt{s} = 200$ GeV
- Similar trends for J/ψ and Υ vs. $N_{ch}/ < N_{ch} >$ at RHIC and LHC
  - Qualitatively reproduced by the models - may be discriminated with 2017+2022 datasets

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

- Indication of Υ(1S+2S+3S) suppression
  $R_{pAu}|_{|y|<0.5} = 0.82 \pm 0.10(stat.)^{+0.08}_{-0.07}(syst.) \pm 0.10(glob.)$

Υ in Au+Au collisions at $\sqrt{s_{NN}} = 200$ 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
  - Hint of smaller Υ(2S+3S) suppression at RHIC than at LHC
- $\Upsilon(1S)$, Υ(2S+3S) R_{AA} consistent with model calculations
- High precision $\Upsilon(1S)$, $\Upsilon(2S)$ R_{AA} measurements vs. p_T and centrality beyond 2023+

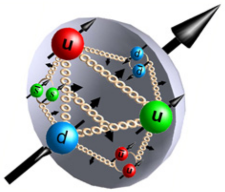
Thank you for your attention!

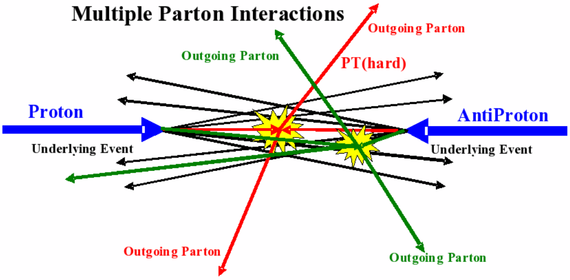
STAR presentations at ICHEP 2020

- 976. Measurements of J/ψ photoproduction in ultra-peripheral collisions at RHIC
  - Jaroslav Adam, 29 July 2020 (Wednesday), 19:18
- 1052. Central exclusive production of charged particle pairs in proton-proton collisions at $\sqrt{s} = 200\,\mathrm{GeV}$ with the STAR detector at RHIC
  - Rafal Sikora, 30 July 2020 (Thursday), 10:25
- 537. Measurements of open charm hadrons in Au+Au collisions at $\sqrt{s_{NN}} = 200\,\mathrm{GeV}$ by the STAR experiment
  - Lukáš Kramárik, 30 July 2020 (Thursday), 12:12
- 414. Production of $D^{\pm}$ mesons in Au+Au collisions at $\sqrt{s_{NN}} = 200\,\mathrm{GeV}$ at the STAR experiment
  - Jan Vaněk(poster), 30 July 2020 (Thursday), 13:39
- 611. Geometry and Dynamics in Heavy-ion Collisions Seen by the Femtoscopy Method in the STAR experiment
  - Prof. Hanna Zbroszczyk, 31 July 2020 (Friday), 8:30
- 686. Study of the central exclusive production of $\pi^+\pi^-$ K^+K^- and $p\bar{p}$ pairs in proton-proton collisions at $\sqrt{s} = 510\,\mathrm{GeV}$ with the STAR detector at RHIC
  - Tomáš Truhlář(poster), 31 July 2020 (Friday), 13:30

BACKUP

Multiple parton interactions (MPI)

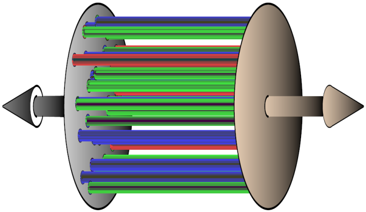


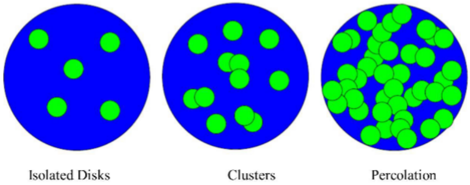


https://www.bnl.gov/rhic/images/proton-with-gluouns-300px.jpg

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.

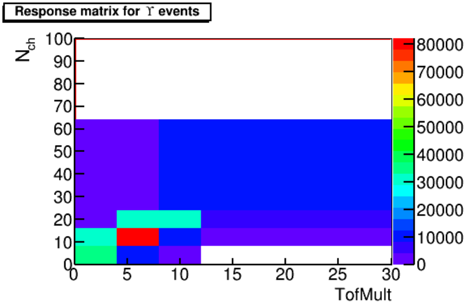


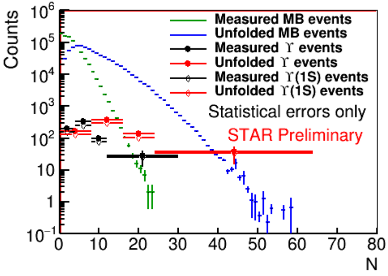


[Ann.Rev.Nucl.Part.Sci.60, 463-489(2010)] [Proc.of SPIE, 100313U(2016)]

- 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)]



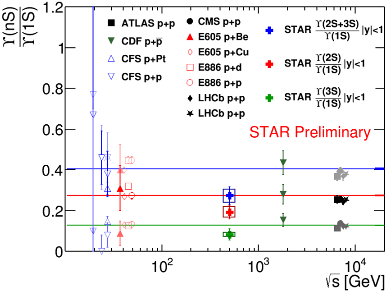


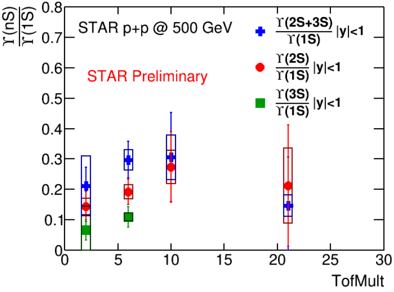
Unfolding method used for multiplicity dependent studies

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 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 $\sqrt{s} = 500$ GeV 2009 data
6. Measured distribution of Υ events obtained from p+p $\sqrt{s} = 500$ GeV 2011 data

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

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

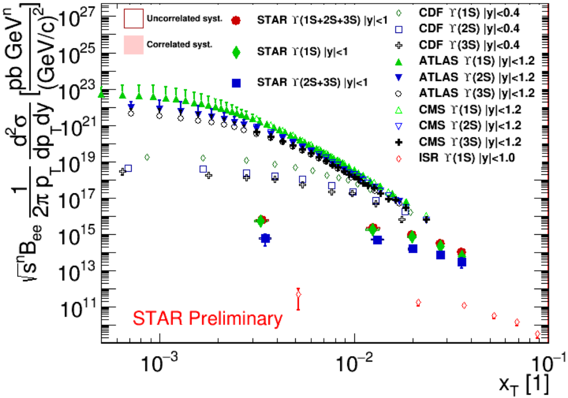




[W. Zha, et al, Phys.Rev.C 88,067901(2013)]

- Left plot: cross section ratios measured in 500 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
[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)]

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

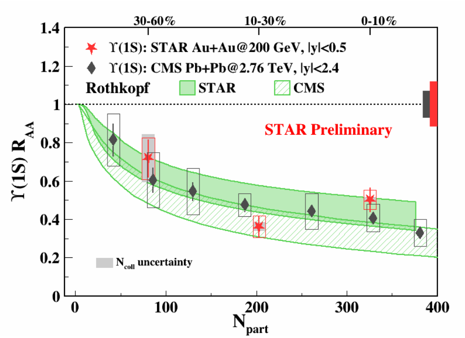
  [JHEP06,035(2010)]

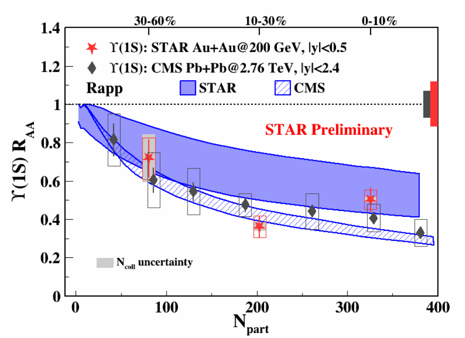
- pQCD predicts that spectra of hard processes should follow x_T scaling - check with $n = 5.6$ (number of partons taking active part in the process) obtained for J/ψ

  [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



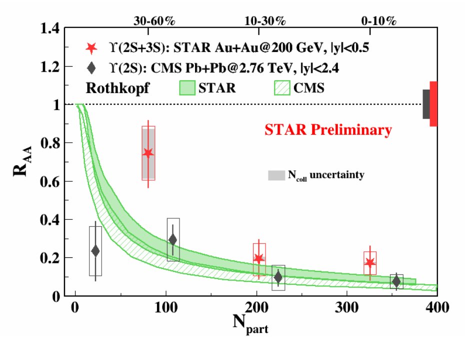


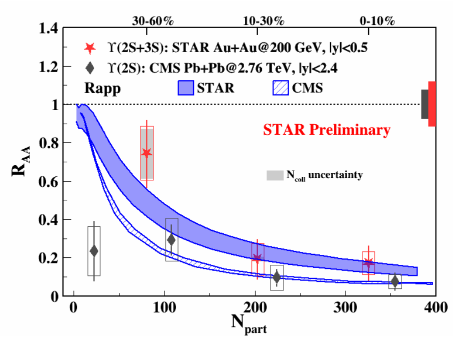
[Phys.Rev.D 97,(2018)016017], [Phys.Rev.C 96,(2017)054901]

$\Upsilon(1S)$ vs. models

- Both models consistent with the data

STAR and CMS Υ(2S+3S) vs. models

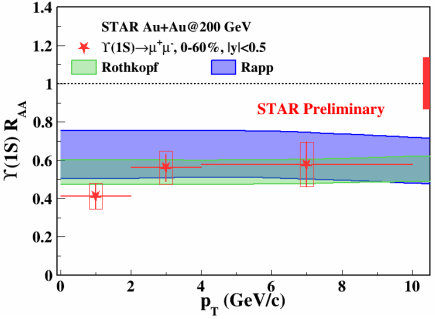


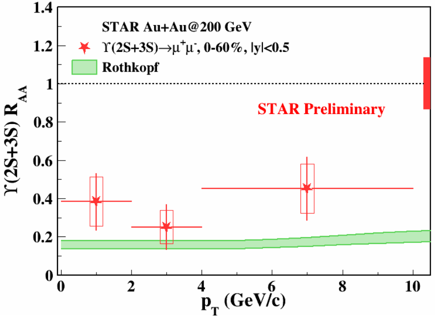


[Phys.Rev.D 97,016017(2018)], [Phys.Rev.C 96,054901(2017)]

Υ(2S+3S) vs. models

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



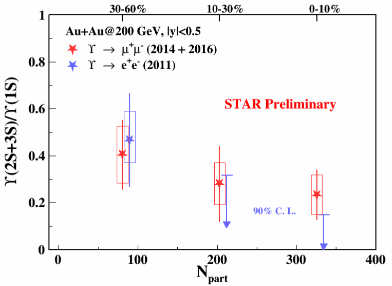


[Phys.Rev.D 97,016017(2018)], [Phys.Rev.C 96,054901(2017)]

R_{AA} vs. p_T vs. models

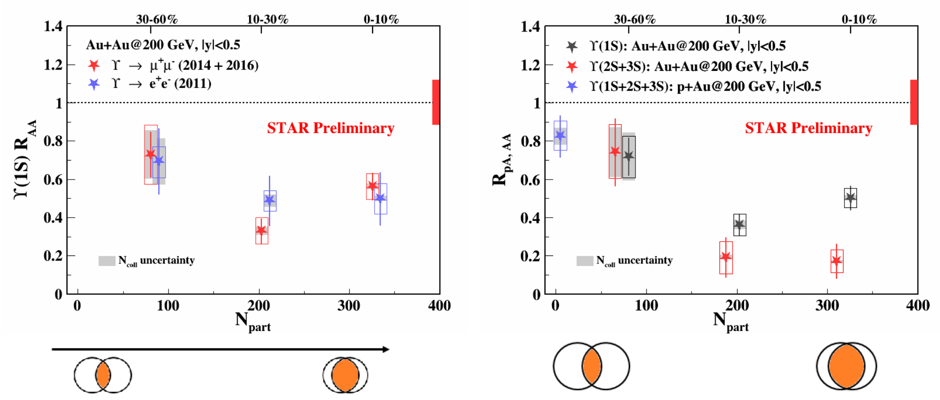
- Both models consistent with the data
- Rothkopf's model slightly lower than Υ(2S+3S)
- Flat vs. p_T

Ratio vs. N_{part}



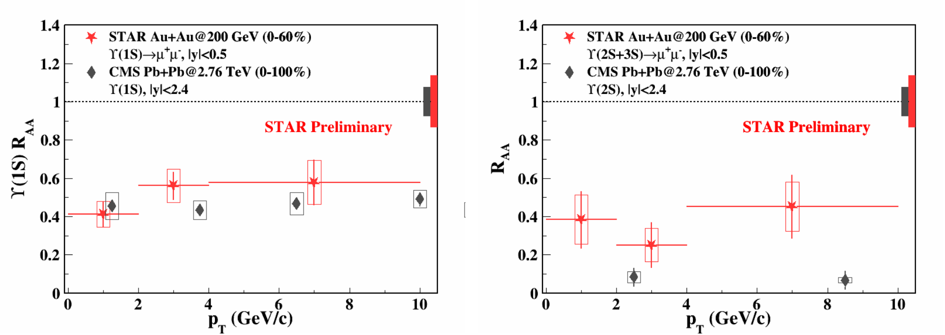
$\frac{\Upsilon(2S+3S)}{\Upsilon(1S)}$ vs. N_{part}

- Both channels consistent



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



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 Υ(2S+3S) at LHC than at RHIC
- Both consistent with flat dependence vs. p_T