



Quarkonium production in $p+p$ collisions in the STAR experiment

Leszek Kosarzewski

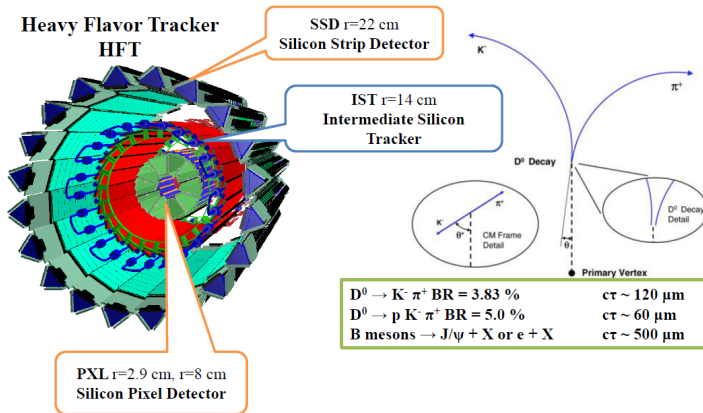
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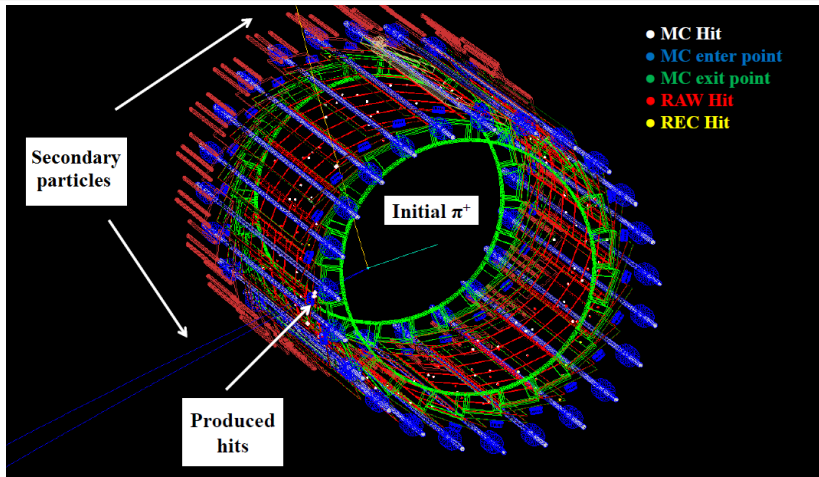
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- 7-10.2009 - "EU summer student" internship
 - MC studies of hadron spectra vs. reaction plane in ALICE experiment
- 8-11.2010 - Lawrence Berkeley National Laboratory ,summer internship
 - J/ψ production studies in $p+p$ $\sqrt{s} = 200$ GeV in the STAR experiment
- 2-5.2014 - Brookhaven National Laboratory, Service work for the STAR experiment
 - Development of response simulator for Intermediate Silicon Tracker, part of Heavy Flavor Tracker upgrade
- 6-8.2014 University of California Davis, WUT CAS internship
 - Υ production studies in $p+p$ $\sqrt{s} = 500$ GeV in the STAR experiment
- 23.9.2016-21.1.2017 University of California Davis, ETIUDA 3 internship
 - Υ production studies in $p+p$ $\sqrt{s} = 500$ GeV in the STAR experiment
- 9.2016-7.2017 Scholarship for best PhD students, 2-nd best PhD student of Faculty of Physics



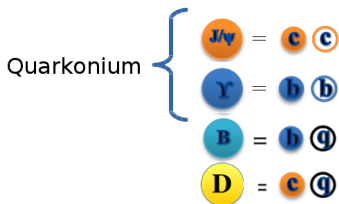
Heavy Flavor Tracker

- Designed to provide precise $\sigma \approx 20 \mu\text{m}$ tracking and vertex resolution $\sigma \approx 40 \mu\text{m}$
- Used for direct reconstruction of heavy flavor D, B decays [Phys.Rev.Lett. 118(4),212301(2017)]
- Development of IST response simulator - my task



Heavy Flavor Tracker

- Working simulator, integrated into official STAR simulation software
- Performed basic tests in pure simulation and embedding mode (data+MC)
- Used visualization to help testing



$$m_c = 1.28 \pm 0.03 \text{ GeV}/c^2$$

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

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

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

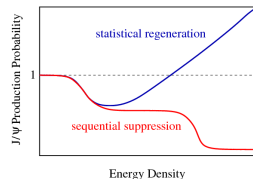
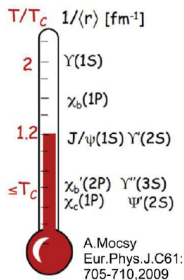
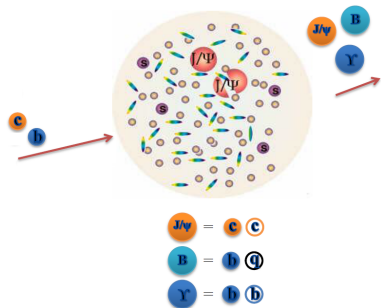
$$m_{\Upsilon(2S)} = 10023.26 \pm 0.31 \text{ MeV}/c^2$$

$$m_{\Upsilon(3S)} = 10355.2 \pm 0.5 \text{ MeV}/c^2$$

[Chinese Physics C 2016 vol: 40(10) 100001]

Upsilon

- Part of quarkonium family ($Q\bar{Q}$)
- Much heavier than $J/\psi \Rightarrow$ very rare
- At RHIC energy, heavy quarks are mainly produced in hard scatterings of partons at early stages of a collision ($\tau < 1 \text{ fm}/c$)



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

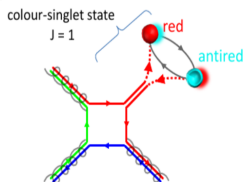
- J/ψ suppression was suggested as signature of Quark-Gluon Plasma (QGP) formation [T. Matsui, H. Satz, Phys. Lett. B 178(4), 416-422(1986)]
 - Recombination, feeddown and cold nuclear matter effects complicate the picture
- Similar to J/ψ , Y mesons also melt in the QGP at high temperature due to the color-screening effect.
 - Less recombination for Y than for J/ψ
- Each of the quarkonium states has a different binding energy \Rightarrow dissociates at a different temperature \Rightarrow sequential suppression [Phys. Lett B 637(1-2), 75-80(2006)]
- To fully understand the quarkonium behavior in the QGP, it is important to understand its production mechanism in elementary p+p collisions.

Production mechanism

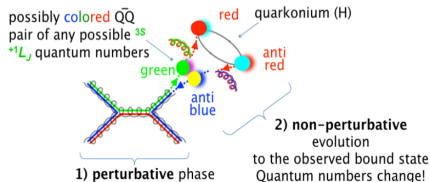
- Still not well understood: hard scattering+non-perturbative hadronization
- Quarkonium measurements provide tests of production models, and thus help to understand QCD

Quarkonium production models

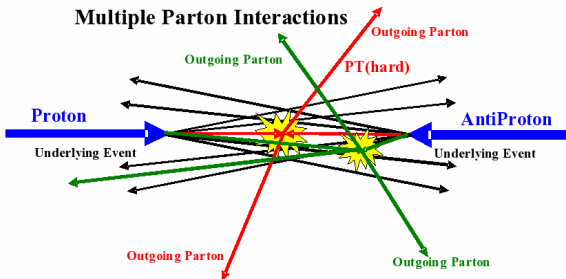
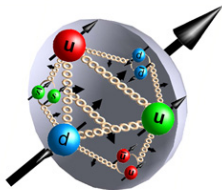
- Color Singlet - $Q\bar{Q}$ produced directly in a color neutral state
- Color Octet - $Q\bar{Q}$ produced in a colored state. Gluon emissions are needed to neutralize color. This is described by long-distance matrix elements (LDMEs) which are assumed universal.
- Color Evaporation Model - color irrelevant.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



+ analogous colour combinations



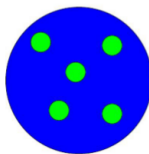
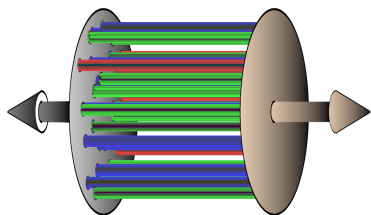
[B. Trzeciak, HQPC 2015]



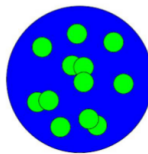
<https://www.bnl.gov/rhic/images/proton-with-gluons-300px.jpg>

<http://www.desy.de/~jung/multiple-interactions/may06/mi-rick.gif>

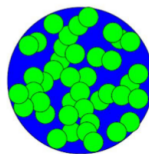
- Protons are complex objects consisting of constituent quarks, sea quarks and gluons.
- Multiple parton interactions (MPI) may happen in $p + p$ collision - implemented in PYTHIA.
 - Besides the main hard process, there may be additional hard and soft processes in MPI.
- As implemented in PYTHIA8, heavy 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.



Isolated Disks



Clusters

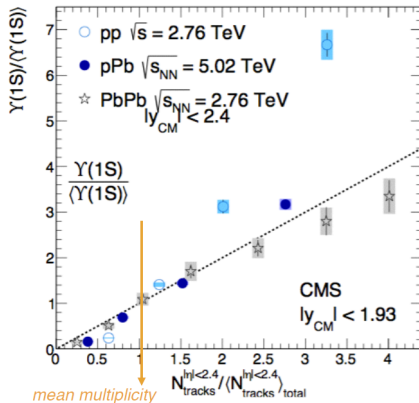
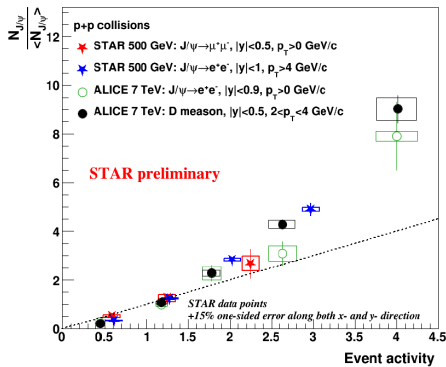


Percolation

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

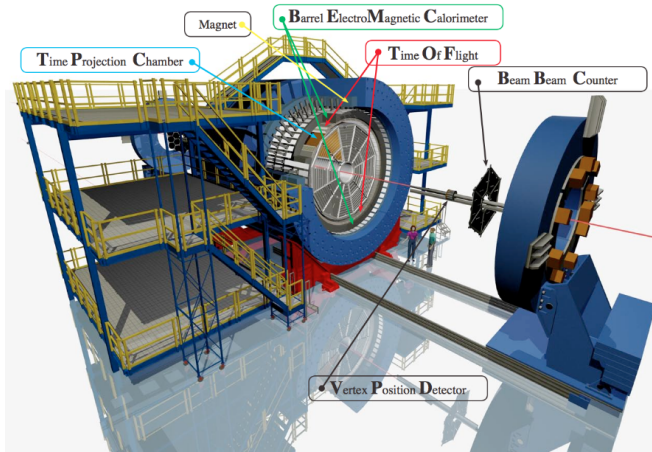
- Models particle production originating from strings of color field formed in $p + p$ collisions.
- Soft particle production dampened by interaction of overlapping strings.
- Predicts quadratic dependence of normalized yield for particles from hard processes vs. normalized charged particle multiplicity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

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



- A strong rise of normalized yield vs. normalized event multiplicity was observed for J/ψ by ALICE and STAR [Phys.Lett.B 712,165–175(2012)], [Nucl.and Part.Phys. Proc., 276–278, pp.261–264(2016)]
- A strong rise for Υ as well at the LHC energy [JHEP04,103(2014)]
- Is there a similar effect for Υ at RHIC energy?

Solenoidal Tracker At RHIC : $-1 < \eta < 1, 0 < \phi < 2\pi$



Time Projection Chamber (TPC)

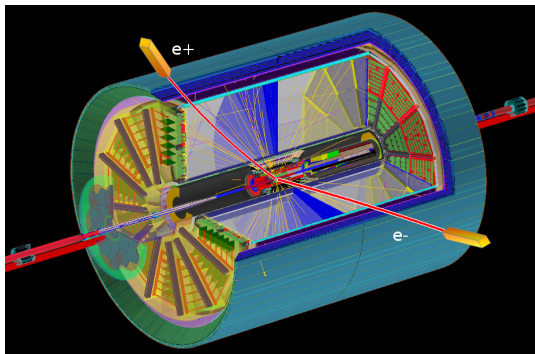
Particle identification via dE/dx and tracking.

Barrel Electromagnetic Calorimeter (BEMC)

Particle identification via E/p and shower shape. It also provides online High Tower trigger.

Time-Of-Flight detector (TOF)

Particle identification via time of flight. Fast detector used to reject pile-up tracks.



Υ decay reconstruction

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

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

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

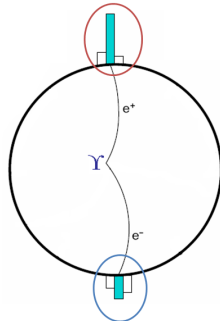
[Chinese Physics C 2016 vol: 40(10) 100001]

Dataset

Analyzed 160M 500 GeV p+p events triggered by High Tower trigger ($\mathcal{L} \approx 22 \text{ pb}^{-1}$), which contain a track with $E_T > 4.6 \text{ GeV}$

Vertex selection

$$|V_z| < 40 \text{ cm}$$



Trigger track:

Matched to the BEMC tower that fired the High Tower trigger

Partner track:

$$p > 1 \text{ GeV}/c$$

Electron identification:

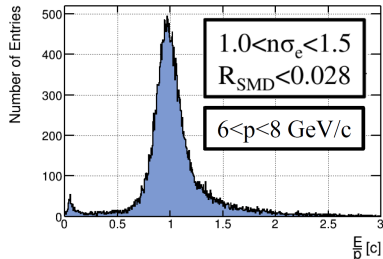
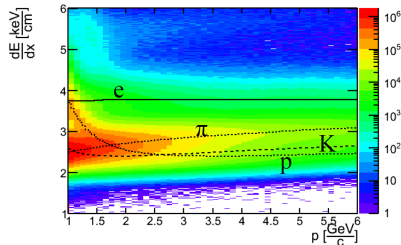
$$-1.2 < n\sigma_e < 3$$

$$\frac{E_{TOW}}{E_{CLU}} > 0.5$$

$$0.55 < \frac{E_{CLU}}{pc} < 1.45$$

$$R_{SMD} < 0.028$$

dEdx vs p all



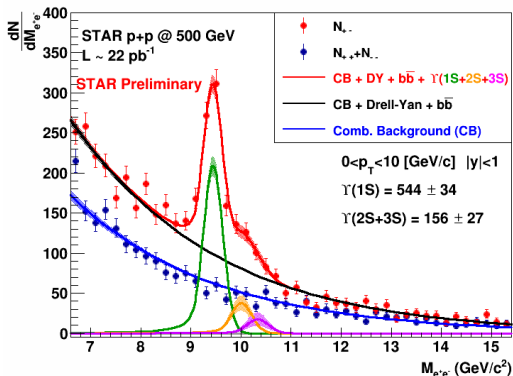
J. Phys.: Conf. Ser. 612 012022

Normalized dE/dx :

$$n\sigma_e = \ln \left(\frac{\frac{dE}{dx} |_{Measured}}{\frac{dE}{dx} |_{Expected}} \right) / \sigma$$

$$R_{SMD} = \sqrt{\Delta\eta^2 + \Delta\phi^2}$$

Distance between a track projection on BEMC SMD and the center of the associated BEMC cluster



Systematic uncertainties estimated by:

- Including difference to the fit method (signal from bin-counting vs. fit)
- Parameter B is fixed to $B = 30$ and varied by ± 15
- $\frac{\Upsilon(2S)}{\Upsilon(3S)}$ set free vs. fixed

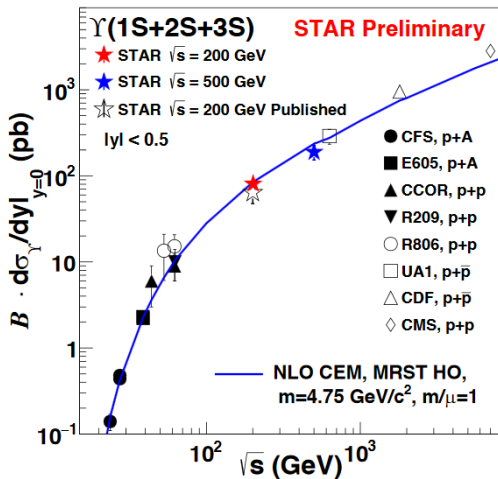
- Simultaneous fit of like-sign and unlike-sign distributions using RooFit

- Υ signal shapes modeled by 3 Crystal-Ball functions

- Fit to **Unlike-sign (red)** distribution consists of:

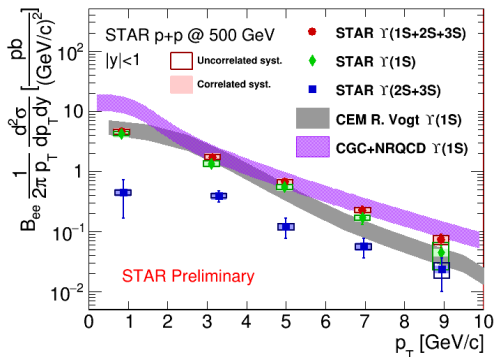
- 3 Crystal-Ball functions ($1S, 2S, 3S$ states)
- $b\bar{b}$ +DY correlated background (black): $f_{b\bar{b}} = N \frac{m^A}{(1 + \frac{m}{B})^C}$
- Combinatorial background (blue) - an exponential function simultaneously fitted to like-sign distribution: $f_{CB} = N \cdot \exp(\frac{-m}{Exp1})$

[Nucl.Phys.A 967, pp.600–603(2017)]

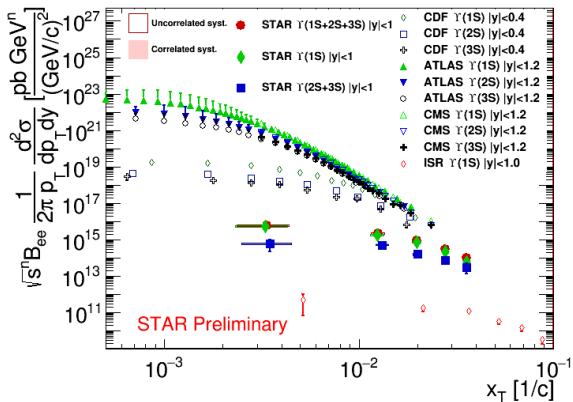


STAR
 [Nucl.Phys.A 967,600–603(2017)]
 [Phys.Lett.B 735,127–137(2014)]
 CDF
 [Phys.Rev.Lett. 88,161802(2002)]
 CMS
 [Phys.Rev.D 83,112004(2010)]
 CFS
 [Phys.Rev.Lett. 39,1240–1242(1977)]
 [Phys.Rev.Lett. 41,684–687(1978)]
 [Phys.Rev.Lett. 42,486–489(1979)]
 [Phys.Rev.Lett. 55,1962–1964(1985)]
 E605
 [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)]

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

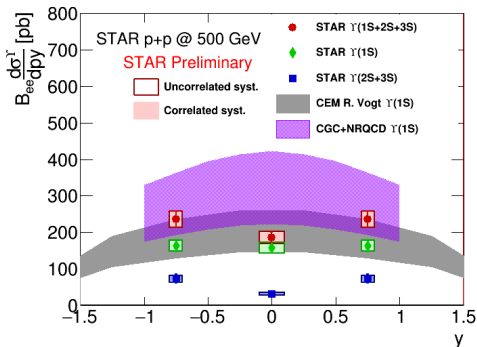
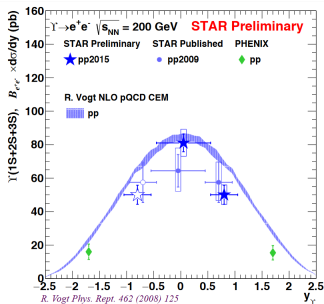


- Color Evaporation Model (CEM) calculation for inclusive $\Upsilon(1S)$ [Phys.Rev. C92 (2015) 034909]
 - Agree with data reasonably well
- Non-relativistic Quantum Chromodynamics coupled with the Color-Glass Condensate formalism (CGC+NRQCD) for direct Υ [PRD 94, 014028 (2016)] [PRL 113, 192301 (2014)]
 - $\Upsilon(1S)$: model calculation is above the data points. Caveat: additional corrections are needed at low p_T according to authors.



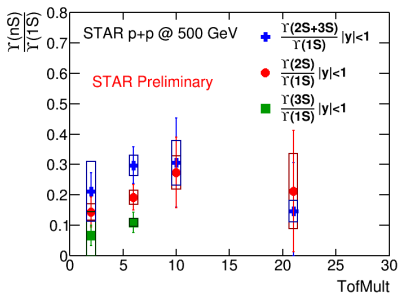
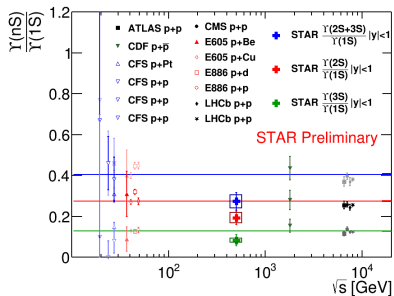
ATLAS
[Phys.Rev.D 87,052004(2013)]
CMS
[Phys.Lett.B 749,14-34(2015)]
CDF
[Phys.Rev.Lett. 88,161802(2002)]
ISR
[Phys.Lett.B 91,481-486(1980)]

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



- STAR data slightly narrower than CEM model at $\sqrt{s} = 200$ GeV
- Flatter rapidity spectrum at $\sqrt{s} = 500$ GeV compared to $\sqrt{s} = 200$ GeV
 - CEM model (inclusive) consistent with the measurement for $\Upsilon(1S)$ [Phys.Rev. C92 (2015) 034909]
 - CGC+NRQCD (direct) predictions are above the data [PRD 94, 014028 (2016)], [PRL 113, 192301 (2014)]

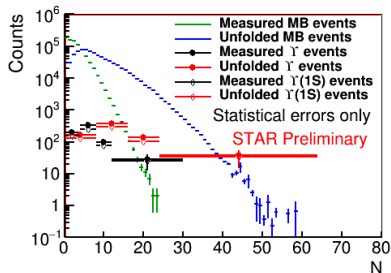
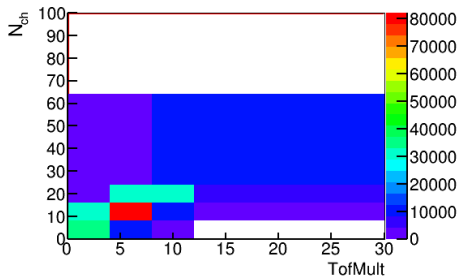
Cross section ratios: $\Upsilon(nS)/\Upsilon(1S)$



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

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

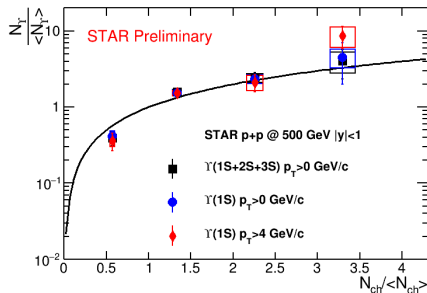
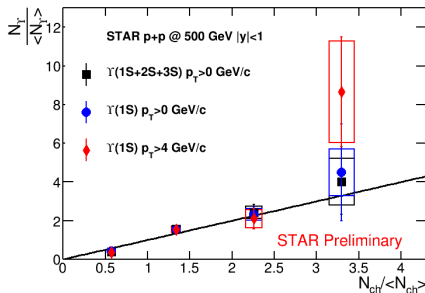
Response matrix for Υ events



Unfolding method used for multiplicity dependent studies

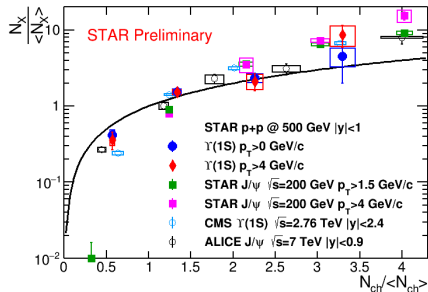
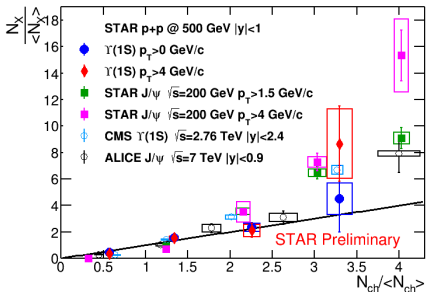
- 1 A response matrix is obtained using the PYTHIA8 event generator for both min-bias and Υ events taking into account reconstruction efficiency
- 2 The measured distributions are unfolded with their respective response matrices
- 3 This procedure yields the unfolded (true) distribution

Υ production vs. event activity



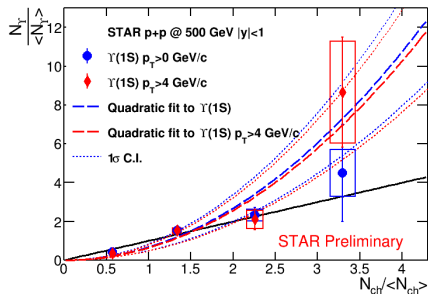
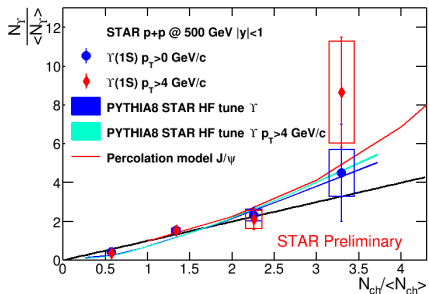
- Normalized Υ yield vs. normalized multiplicity (a measure of event activity)
- STAR results for inclusive $\Upsilon(1S + 2S + 3S)$ and $\Upsilon(1S)$ as well as high- p_T $\Upsilon(1S)$ with $p_T > 4$ GeV/c
- Boxes correspond to systematic uncertainties both for $\frac{N_\Upsilon}{\langle N_\Upsilon \rangle}$ and $\frac{N_{ch}}{\langle N_{ch} \rangle}$
- Data consistent with a linear rise, with a hint for stronger-than-linear rise for $\Upsilon(1S)$ above $p_T > 4$ GeV/c

Υ production vs. event activity - world data

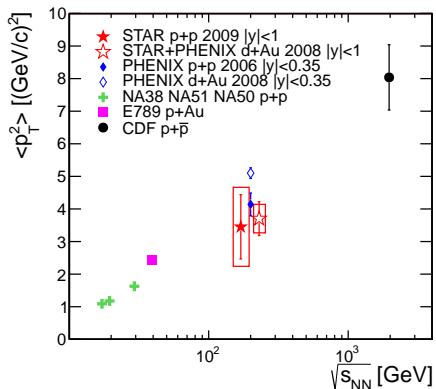
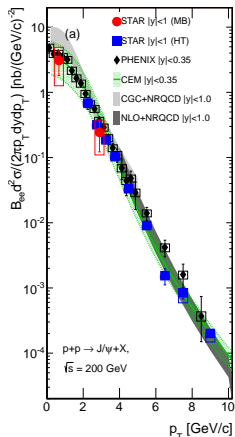


- A similar trend observed at RHIC and LHC for Υ and J/ψ [JHEP04,103(2014)], [Nucl. and Part. Phys. Proc., 276-278, pp.261-264(2016)], [Phys.Lett.B 712,165-175(2012)]

Υ production vs. event activity - models



- Consistent with models and quadratic fit $f(x) = ax^2$ taking into account statistical errors only
- Hints of interaction between strings of color field or Υ production in MPI



- Low- p_T ($p_T < 4$ GeV/c) J/ψ production in p+p collisions at $\sqrt{s} = 200$ GeV - published [Phys.Rev.C 93,064904(2016)]
- NLO NRQCD [Phys.Rev.Lett 106,042002(2011)] and CGC+NRQCD models [Phys.Rev.Lett 113,192301(2014)] describe the data
- CEM model also describes the data [Phys.Rev.C 87,014908(2013)]
- $\langle p_T^2 \rangle$ consistent with PHENIX data and follows the world data trend

- Presented first measurements of Υ production in p+p collisions at $\sqrt{s} = 500$ GeV.
- The $\Upsilon(1S)$ spectrum can be reasonably described by CEM calculations.
- Flatter rapidity distribution for Υ at $\sqrt{s} = 500$ GeV than at $\sqrt{s} = 200$ GeV.
- Presented $\frac{\Upsilon(nS)}{\Upsilon(1S)}$ vs. multiplicity - no strong dependence.
 - Ratios slightly lower than world data.
- Studied the dependence of Υ production on event activity.
 - A similar trend observed for J/ψ and Υ at RHIC and LHC.
 - Predictions from PYTHIA8 and Percolation model can qualitatively describe the trend observed in data.
- Measured J/ψ p_T spectrum in p+p collisions at $\sqrt{s} = 200$ GeV
 - Described by CEM, NRQCD and CGC+NRQCD calculations.