Measurements of Υ production in $p+p$ collisions at $\sqrt{s} = 500\ \mathrm{GeV}$ with the STAR experiment

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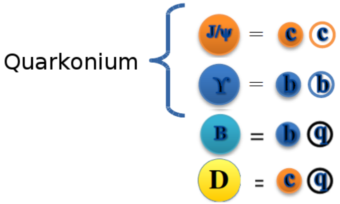
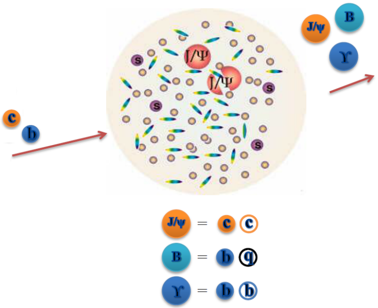


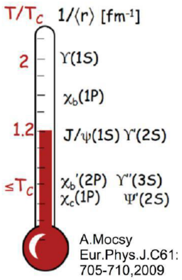
$m_c = 1.28 \pm 0.03\ \mathrm{GeV}/c^2$
$m_b = 4.18^{+0.04}_{-0.03}\ \mathrm{GeV}/c^2$
$m_{J/\psi} = 3096.900 \pm 0.006\ \mathrm{MeV}/c^2$
$m_{\Upsilon(1S)} = 9460.30 \pm 0.26\ \mathrm{MeV}/c^2$
$m_{\Upsilon(2S)} = 10023.26 \pm 0.31\ \mathrm{MeV}/c^2$
$m_{\Upsilon(3S)} = 10355.2 \pm 0.5\ \mathrm{MeV}/c^2$
[Chinese Physics C 2016 vol: 40(10) 100001]

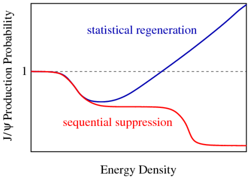
Upsilon

- 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 ($\tau < 1\ fm/c$)

Quarkonium in the quark-gluon plasma







[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, Υ mesons also melt in the QGP at high temperature due to the color-screening effect.
  - Less recombination for Υ 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.

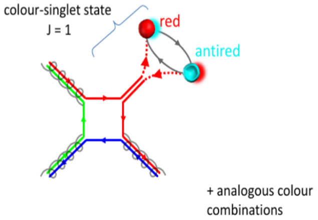
Production mechanism

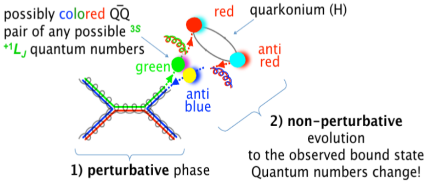
Production mechanism

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

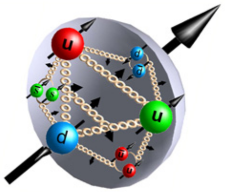
Quarkonium production models

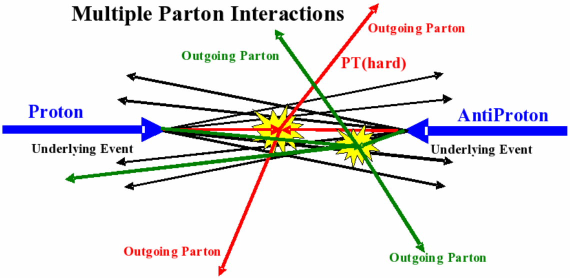
- Color Singlet - $Q\bar{Q}$ produced directly in a color neutral state
- Color Octet - $Q\bar{Q}$ produced in a colored state. Gluon emissions are needed to neutralize color. This is described by long-distance matrix elements (LDMEs) which are assumed universal.
- Color Evaporation Model - color irrelevant.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





[B. Trzeciak, HQPC 2015]

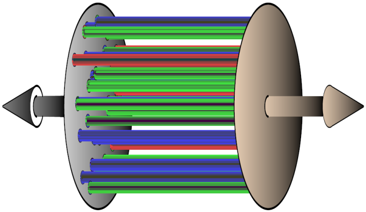


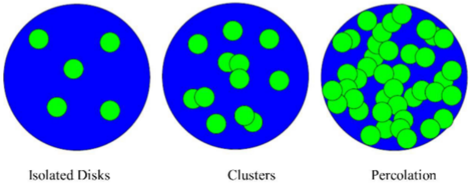


https://www.bnl.gov/rhic/images/proton-with-gluouns-300px.jpg
http://www.desy.de/~jung/multiple-interactions/may06/mi-rick.gif

- Protons are complex objects consisting of constituent quarks, sea quarks and gluons.
- Multiple parton interactions (MPI) may happen in $p + p$ collison - implemented in PYTHIA.
  - Besides the main hard process, there may be additional hard and soft processes in MPI.
- As implemented in PYTHIA8, heavy quarks can also be produced during MPI.
- MPI together with initial- (ISR), final-state radiation (FSR) and beam remnants define the event activity, which can be characterized experimentally using the charged particle multiplicity.

String Percolation Model

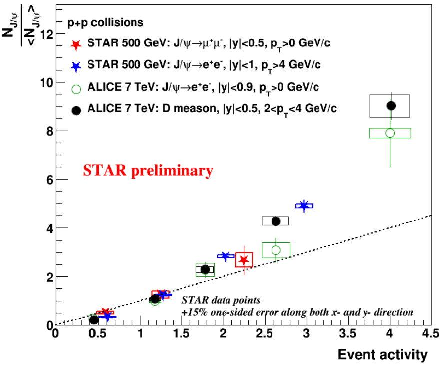


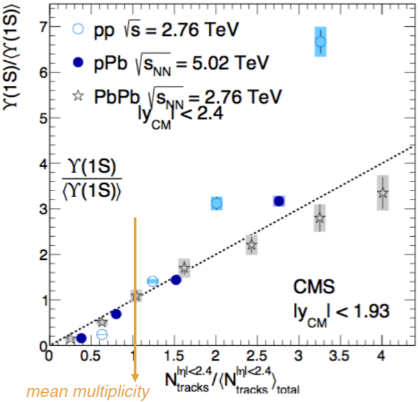


[Ann.Rev.Nucl.Part.Sci.60, 463-489(2010)] [Proceedings of SPIE, 100313U(2016)]

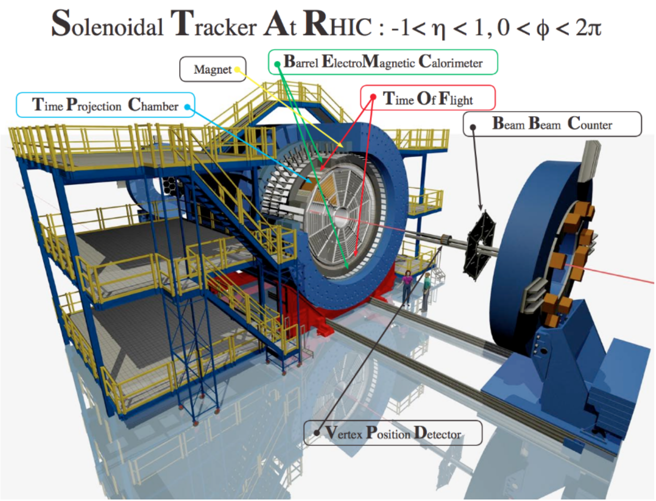
- Models particle production originating from strings of color field formed in $p + p$ collisions.
- Soft particle production dampened by interaction of overlapping strings.
- Predicts quadratic dependence of normalized yield for particles from hard processes vs. normalized charged particle multiplicity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

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



Time Projection Chamber (TPC)

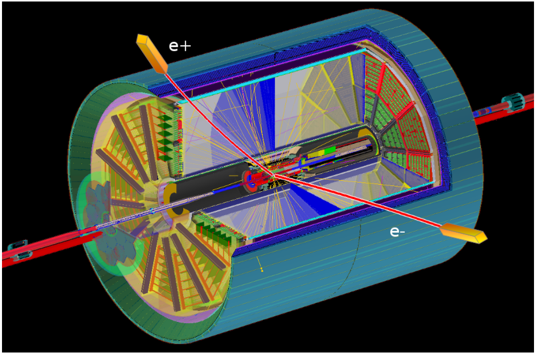
Particle identification via dE/dx and tracking.

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.

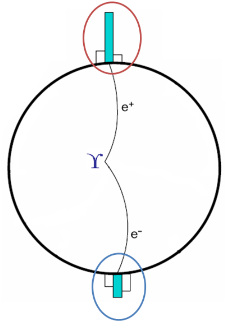


Dataset

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

Vertex selection

$|V_z| < 40\ cm$



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]

Trigger track:

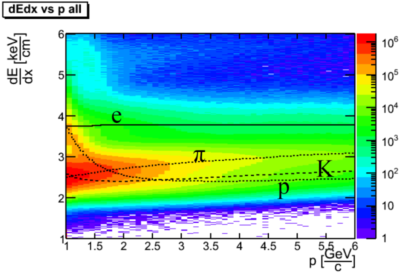
Matched to the BEMC tower that fired the High Tower trigger

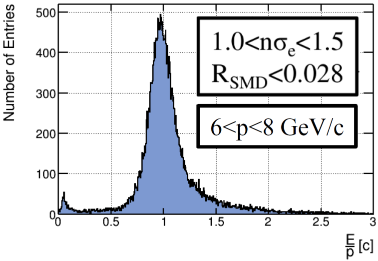
Partner track:

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

Electron identification:

$$-1.2 < n\sigma_e < 3$$
$$\frac{E_{TOW}}{E_{CLU}} > 0.5$$
$$0.55 < \frac{E_{CLU}}{pc} < 1.45$$
$$R_{SMD} < 0.028$$





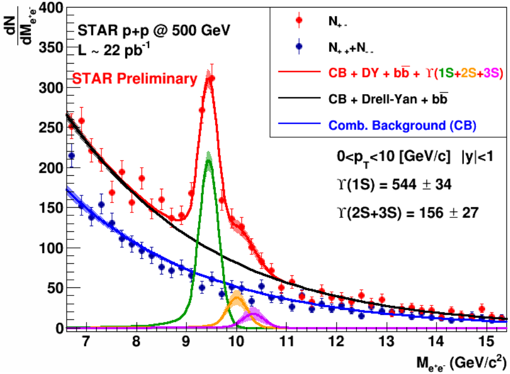
J. Phys.: Conf. Ser. 612 012022

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

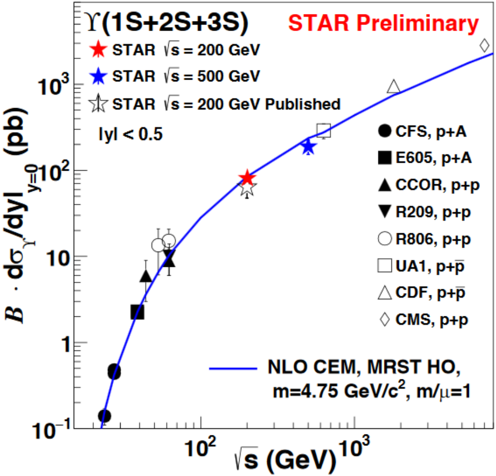


- Simultaneous fit of like-sign and unlike-sign distributions using RooFit
- Υ signal shapes modeled by 3 Crystal-Ball functions
- Fit to Unlike-sign (red) distribution consists of:
  - 3 Crystal-Ball functions (1S,2S,3S states)
  - $b\bar{b}$+DY correlated background (black): $f_{b\bar{b}} = N\frac{m^A}{(1+\frac{m}{B})^C}$
  - Combinatorial backround (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)]

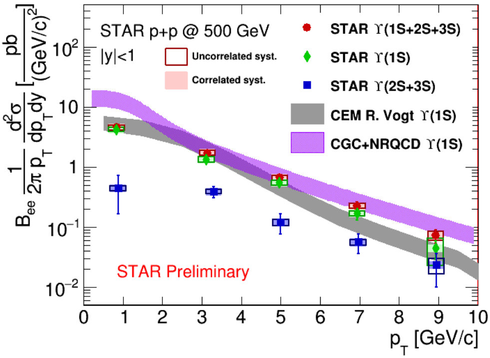
Systematic uncertainties estimated by:

- 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

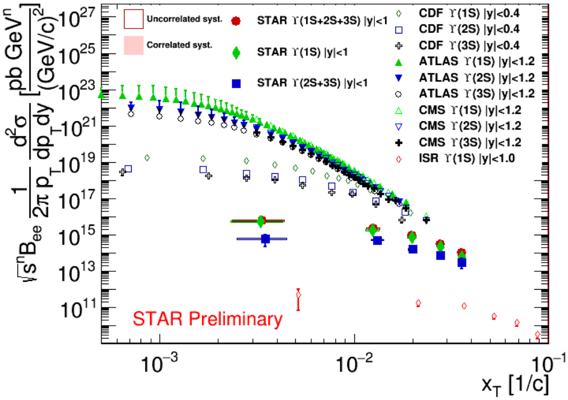


STAR
[Nucl.Phys.A 967,600–603(2017)]
[Phys.Lett.B 735,127–137(2014)]
CDF
[Phys.Rev.Lett. 88,161802(2002)]
CMS
[Phys.Rev.D 83,112004(2010)]
CFS
[Phys.Rev.Lett. 39,1240-1242(1977)]
[Phys.Rev.Lett. 41,684–687(1978)]
[Phys.Rev.Lett. 42,486–489(1979)]
[Phys.Rev.Lett. 55,1962–1964(1985)]
E605
[Phys.Rev.D 43,2815–2835(1991)]
[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)]

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



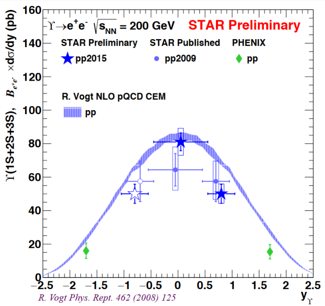
- Color Evaporation Model (CEM) calculation for inclusive $\Upsilon(1S)$ [Phys.Rev. C92 (2015) 034909]
  - Agree with data reasonably well
- Non-relativistic Quantum Chromodynamics coupled with the Color-Glass Condensate formalism (CGC+NRQCD) for direct Υ [PRD 94, 014028 (2016)] [PRL 113, 192301 (2014)]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

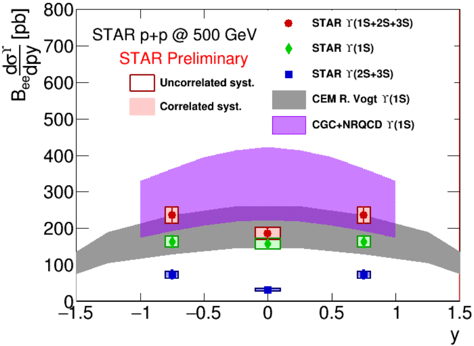


ATLAS
[Phys.Rev.D 87,052004(2013)]
CMS
[Phys.Lett.B 749,14-34(2015)]
CDF
[Phys.Rev.Lett. 88,161802(2002)]
ISR
[Phys.Lett.B 91,481-486(1980)]

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

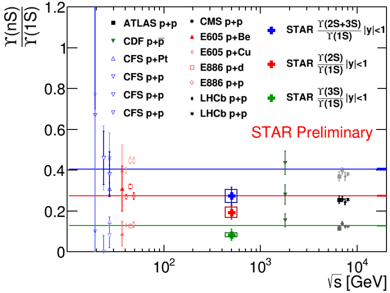
Rapidity dependence

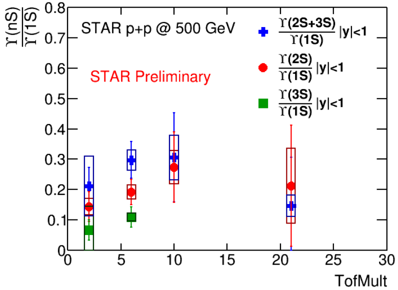




- STAR data slightly narrower than CEM model at $\sqrt{s} = 200$ GeV
- Flatter rapidity spectrum at $\sqrt{s} = 500$ GeV compared to $\sqrt{s} = 200$ GeV
  - CEM model (inclusive) consistent with the measurement for $\Upsilon(1S)$ [Phys.Rev. C92 (2015) 034909]
  - CGC+NRQCD (direct) predictions are above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

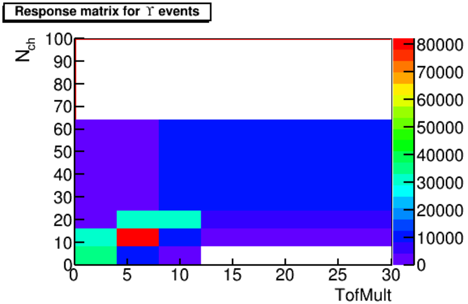
Cross section ratios: $\Upsilon(nS)/\Upsilon(1S)$

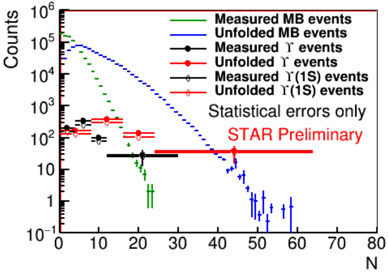




[Phys.Rev.C 88,067901(2013)]

- TofMult: number of tracks matched to TOF with $|\eta| < 1$, $p_T > 0.2\,\mathrm{GeV/c}$
- 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.

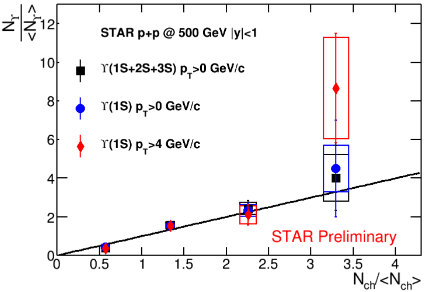


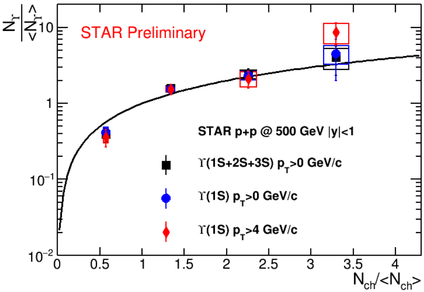


Unfolding method used for multiplicity dependent studies

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

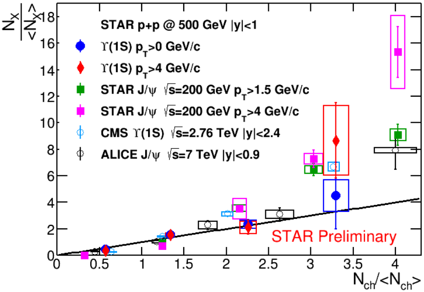
Υ production vs. event activity

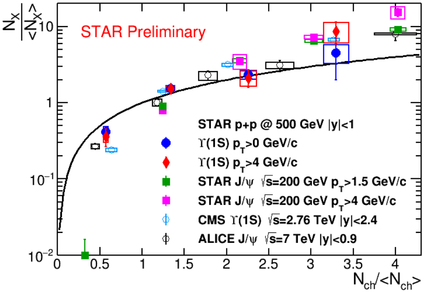




- Normalized Υ yield vs. normalized multiplicity (a measure of event activity)
- STAR results for inclusive $\Upsilon(1S + 2S + 3S)$ and $\Upsilon(1S)$ as well as high-p_T $\Upsilon(1S)$ with $p_T > 4\,\mathrm{GeV/c}$
- Boxes correspond to systematic uncertainties both for $\frac{N_\Upsilon}{\langle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

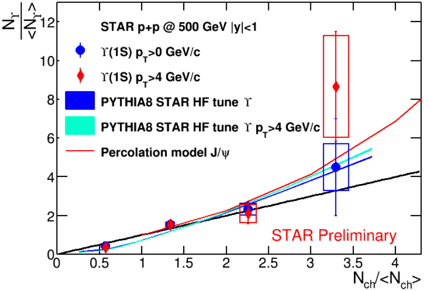
Υ production vs. event activity - world data

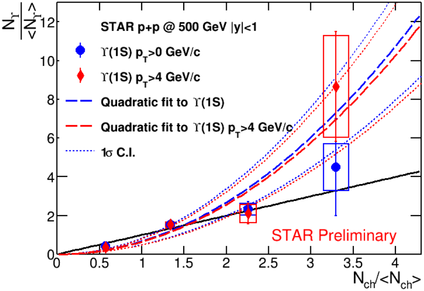




- A similar trend observed at RHIC and LHC for Υ and J/ψ [JHEP04,103(2014)],[Nucl.and Part.Phys. Proc., 276-278, pp.261–264(2016)],[Phys.Lett.B 712,165–175(2012)]

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

Summary

- Presented first measurements of Υ production in p+p collisions at $\sqrt{s} = 500\ \mathrm{GeV}$.
- The $\Upsilon(1S)$ spectrum can be reasonably described by CEM calculations.
- Flatter rapidity distribution for Υ at $\sqrt{s} = 500\ \mathrm{GeV}$ than at $\sqrt{s} = 200\ \mathrm{GeV}$.
- 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.