Charged particle multiplicity dependence of quarkonium production measured by the STAR experiment

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

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

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MINISTRY OF EDUCATION,
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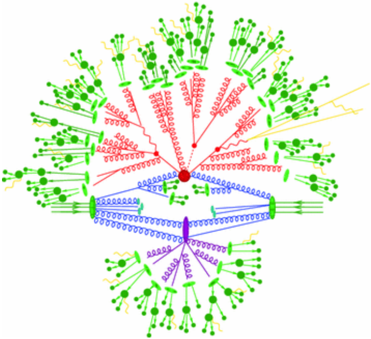
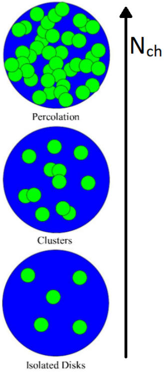
Outline

1. Introduction
   - Quarkonium production vs. multiplicity in p+p
2. STAR experiment
3. Results
   - J/ψ in p+p $\sqrt{s} = 200$ GeV
   - J/ψ in p+p $\sqrt{s} = 500$ GeV
   - Υ in p+p $\sqrt{s} = 500$ GeV
4. Summary

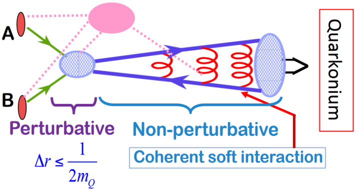
Quarkonium production vs. multiplicity in p+p

Charged particle multiplicity
$\propto$ "'event activity"'
soft QCD processes



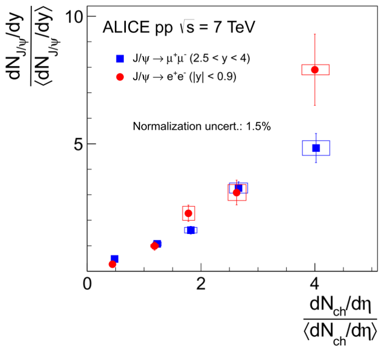


Quarkonium production
hard QCD process

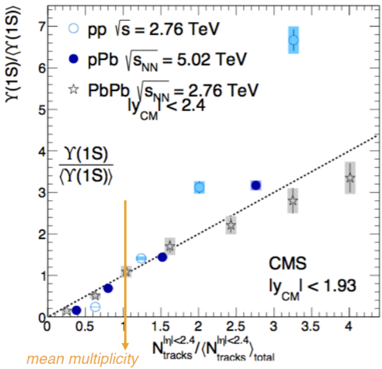


[E. Ferreiro, SQM 2019]

- Quarkonium production vs. multiplicity provides insight into initial conditions
- Study of interplay between hard and soft QCD processes
- At high multiplicity:
  - QGP in small systems?
  - Saturation effects, CGC?
- Study by measuring self-normalized yields $\frac{N_x}{\langle N_x \rangle}$ vs. $\frac{\frac{dN_{ch}}{d\eta}}{\left\langle \frac{dN_{ch}}{d\eta} \right\rangle}$

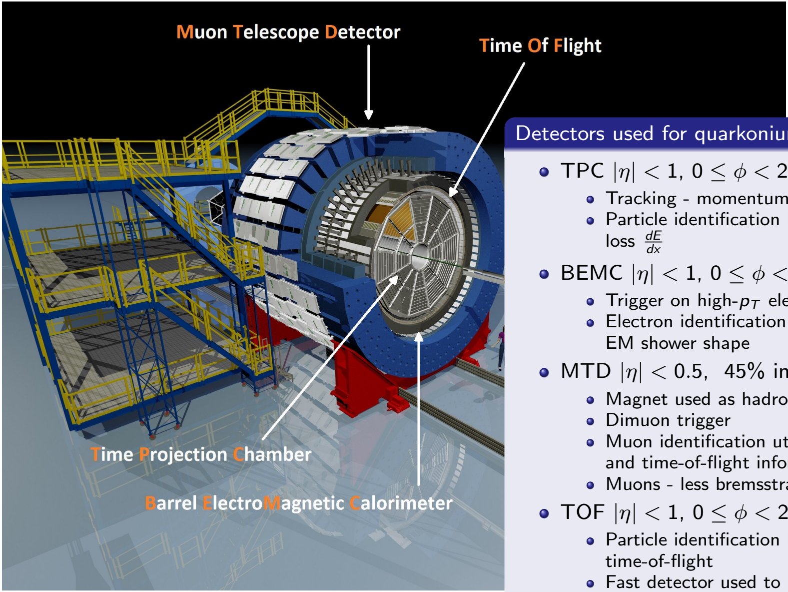


[Phys.Lett.B 712,165–175(2012)]



[JHEP04,103(2014)]

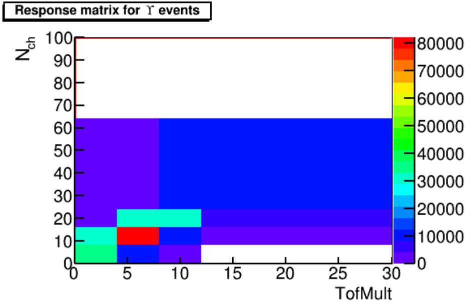
- Linear increase for J/ψ vs. N_{ch} at both mid- and forward rapidity *[Phys.Lett.B 712,165–175(2012)]*
  - Stronger slope at mid-rapidity
- Strong increase of $\Upsilon(1S)$ self normalized yields observed at LHC *[JHEP04,103(2014)]*
- Need to investigate for J/ψ and Υ at RHIC energy
- Study the p_T dependence

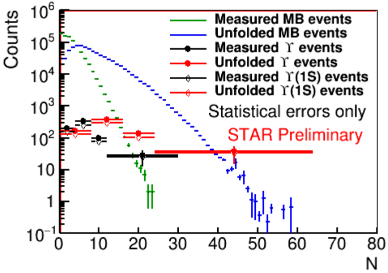


Detectors used for quarkonium studies

- TPC $|\eta| < 1$, $0 \leq \phi < 2\pi$
  - Tracking - momentum measurement
  - Particle identification based on energy loss $\frac{dE}{dx}$
- BEMC $|\eta| < 1$, $0 \leq \phi < 2\pi$
  - Trigger on high-p_T electrons
  - Electron identification via E/p and EM shower shape
- MTD $|\eta| < 0.5$, 45% in ϕ
  - Magnet used as hadron absorber
  - Dimuon trigger
  - Muon identification utilizing position and time-of-flight information
  - Muons - less bremsstrahlung
- TOF $|\eta| < 1$, $0 \leq \phi < 2\pi$
  - Particle identification based on time-of-flight
  - Fast detector used to remove pile-up for N_{ch} determination

Multiplicity distribution via unfolding



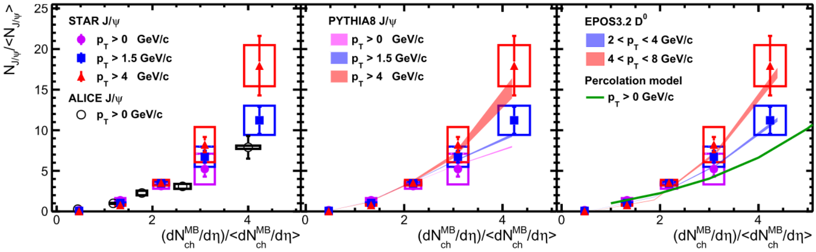


Unfolding method used for multiplicity dependent studies

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

p+p $\sqrt{s} = 200\,\mathrm{GeV}$ 2012 dataset

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

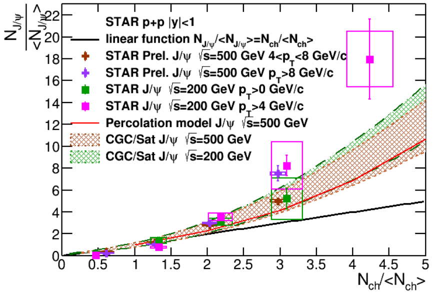


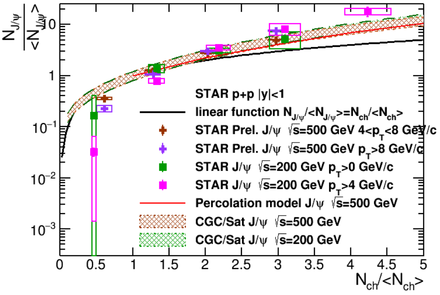
[Phys.Lett.B 786,87-93(2018)]

- Similar trend seen by STAR and ALICE *[Phys.Lett.B 712,165–175(2012)]*
- Qualitatively described by PYTHIA8, Percolation model and EPOS3 for D mesons

J/ψ production vs. event activity - models

p+p $\sqrt{s} = 200, 500$ GeV 2012, 2011 datasets
$J/\psi \rightarrow e^+e^-$

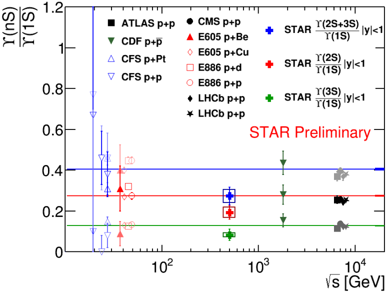


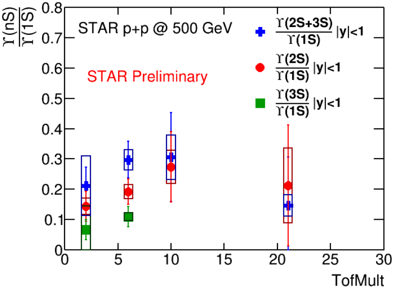


- Percolation model: *[E. G. Ferreiro, C. Pajares, Phys.Rev.C, 86, 034903(2012)]*
  - Low-p_T data are well described
  - High-p_T data are above the model at high N_{ch}. Note that the model if for $p_T > 0\,\mathrm{GeV/c}$
- CGC/Saturation model: *[E. Levin, M. Siddikov, EPJC, 97(5), 376(2019)], [M. Siddikov, et al, arXiv:1910.13579 [hep-ph]]*
  - Describes the data, however uncertainties are large
  - Data are slightly above the model at high p_T. Note that the model if for $p_T > 0\,\mathrm{GeV/c}$

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

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

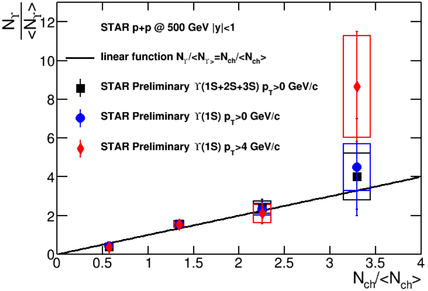


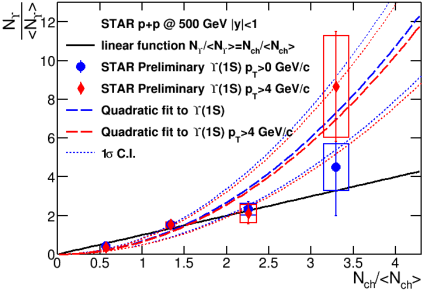


[W. Zha, et al, Phys.Rev.C 88,067901(2013)]

- 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 $|\eta| < 1$, $p_T > 0.2$ GeV/c (uncorrected)

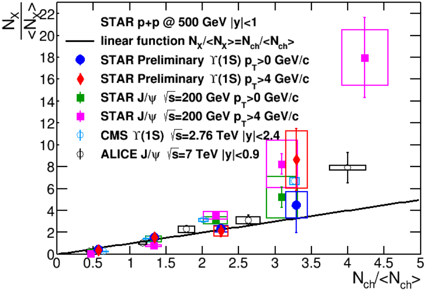
p+p $\sqrt{s} = 500$ GeV 2011 dataset
$\Upsilon \to e^+e^-$

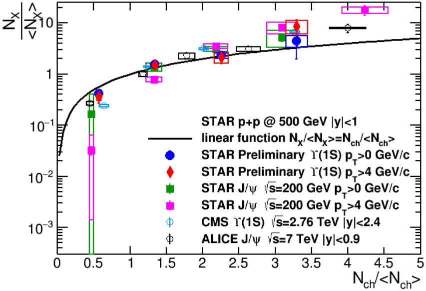




- Self-normalized yield vs. self-normalized multiplicity in p+p $\sqrt{s} = 500$ GeV measured for $\Upsilon(1S + 2S + 3S)$ and $\Upsilon(1S)$
- Data consistent with a linear rise (black line), with a hint for stronger-than-linear rise for $\Upsilon(1S)$ above $p_T > 4$ GeV/c
- Percolation model predicts quadratic dependence $\frac{N_{hard}}{\langle N_{hard}\rangle} = \langle\rho\rangle \left(\frac{\frac{dN_{ch}}{d\eta}}{\left\langle\frac{dN_{ch}}{d\eta}\right\rangle}\right)^2$ at high multiplicity [E. G. Ferreiro, C. Pajares, Phys.Rev. C, 86, 034903 (2012)]
- Quadratic fit $y = ax^2$ describes the data

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

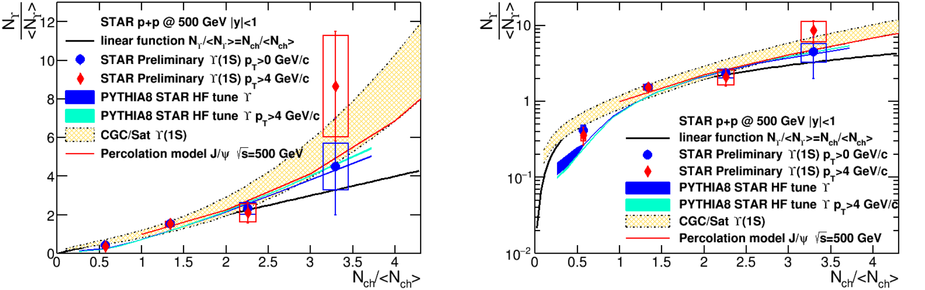




[JHEP04,103(2014)],[Nucl.and Part.Phys. Proc., 276-278, pp.261–264(2016)],[Phys.Lett.B 712,165–175(2012)],[Phys.Lett.B 786,87-93(2018)]

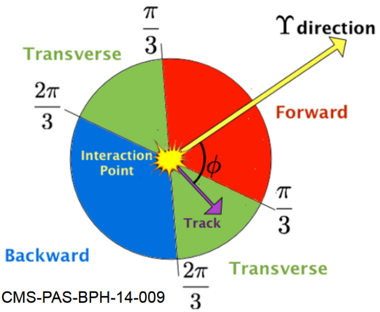
- Similar trend at RHIC and LHC for Υ and J/ψ

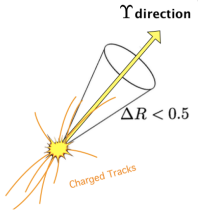
p+p $\sqrt{s} = 500\ \mathrm{GeV}$ 2011 dataset
$\Upsilon \rightarrow e^+e^-$



- PYTHIA8 and 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. LevinM. Siddikov, EPJC, 97(5), 376(2019)], [M. Siddikov, et al, arXiv:1910.13579 [hep-ph]]*

Event activity dependence - new ideas





See talks:

- [Jan Fiete Grosse-Oetringhaus EJC2018]
- [Santona Tuli, Hot Quarks 2018]

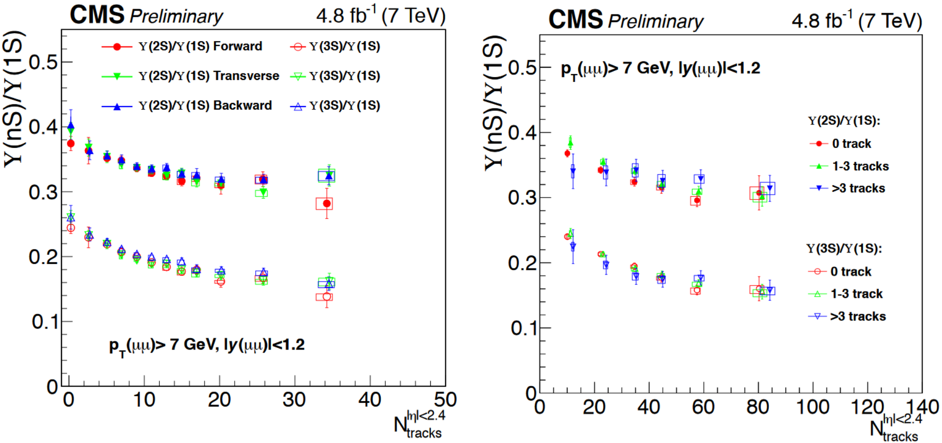
Problems

- Auto-correlation bias - we measure the multiplicity and quarkonium in the same phase space
- We want to characterize the underlying event

New methods

- Measure charged particle multiplicity in the transverse region with respect to quarkonium emission angle
  - This is related to underlying event, while not affected by particles produced in association with the quarkonium
- Measure particles in a cone around quarkonium momentum direction

Υ ratios vs. event activity - CMS



[Santona Tuli, Hot Quarks 2018]

Υ ratios vs. N_{ch}

- Similar trend in transverse, forward and backward regions
- More flat dependence of $\Upsilon(2S)/\Upsilon(1S)$ for > 3 particles in a $\Delta R < 0.5$ cone
  - Opposite to expectation from comover interactions
- Need to test it at RHIC energy as well

Summary

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

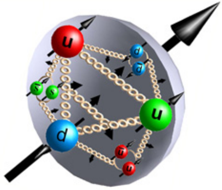
- Dependence of quarkonium production on event activity measured by STAR for J/ψ and Υ.
- Similar trends observed for J/ψ and $\Upsilon(1S)$ at RHIC and LHC.
- Predictions from PYTHIA8 and Percolation model can qualitatively describe the trend in the data.
- CGC/Saturation model describes the data within large uncertainties
- 10x more data at high p_T available from STAR 2017 run, may allow to distinguish between the models
- Cross section ratios $\Upsilon(nS)/\Upsilon(1S)$:
  - $\approx 2\sigma$ below world data average
  - No strong dependence on multiplicity visible, within large uncertainties

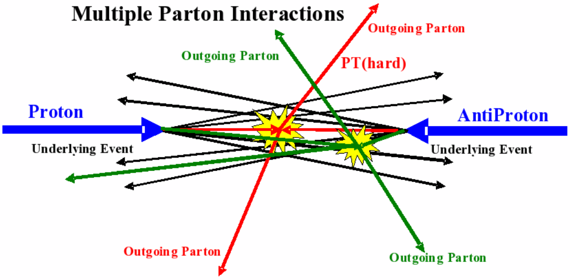
Open questions:

- Which scenario is seen in the data?
- Do models describe the N_{ch} distribution?
- What is the dependence on event activity at forward rapidity at RHIC?
- How does ratios behave vs. N_{ch} measured in:
  - a cone around quarkonium?
  - transverse to quarkonium emission angle in ϕ?

Thank you for your attention!

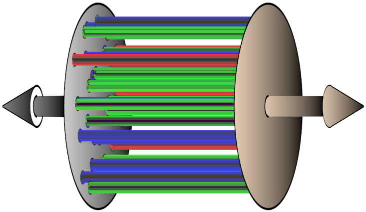
BACKUP

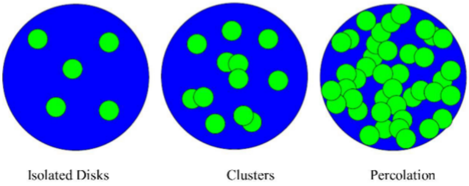




https://www.bnl.gov/rhic/images/proton-with-gluouns-300px.jpg
http://www.desy.de/~jung/multiple-interactions/may06/mi-rick.gif

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





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

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

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