Quarkonium production and MPI effects in p+p collisions at RHIC

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Quarkonia as Tools 9-15.1.2022, Centre Paul Langevin, Aussois, France

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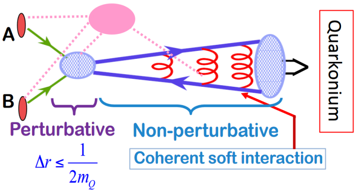
Outline

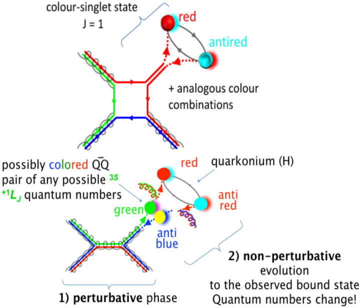
1. Motivation
2. Quarkonium spectra at RHIC
   - J/ψ in p+p $\sqrt{s} = 200\ \mathrm{GeV}$ by STAR
   - J/ψ in p+p $\sqrt{s} = 500\ \mathrm{GeV}$ and $\sqrt{s} = 510\ \mathrm{GeV}$ by STAR
   - J/ψ in p+p $\sqrt{s} = 200\ \mathrm{GeV}$ and $\sqrt{s} = 510\ \mathrm{GeV}$ by PHENIX
   - Υ in p+p $\sqrt{s} = 500\ \mathrm{GeV}$ by STAR
3. Multiplicity dependence - introduction
4. Multiplicity dependence - results
   - J/ψ in p+p $\sqrt{s} = 200\ \mathrm{GeV}$
   - J/ψ in p+p $\sqrt{s} = 500\ \mathrm{GeV}$
   - Υ in p+p $\sqrt{s} = 500\ \mathrm{GeV}$
5. Prospects
6. Summary

- Measure quarkonium production in order to study the production mechanism by comparing to model calculations
- Quarkonium production is often assumed to factorize into:
  - Production of heavy $Q\bar{Q}$ pair in a hard scattering (mostly through gluon fusion at RHIC)
  - Evolution and formation of a bound state (non-perturbative)



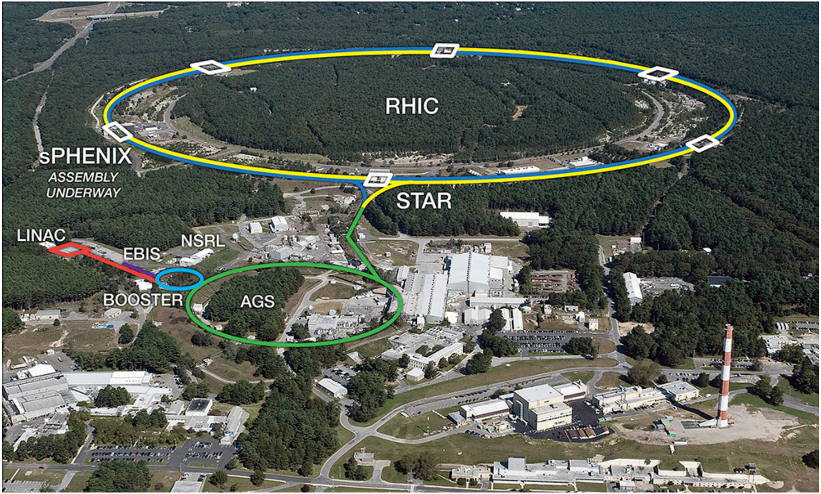
[E. Ferreiro, SQM 2019]

- Quarkonium production mechanism:
  - Describes the bound state formation
  - Still not fully understood
  - Consists of color singlet (CS) and color octet (CO) channels
  - Implemented in:
    - Non-relativistic QCD (+CGC EFT) *[PRD 51(3)(1995)],[JHEP01(2014)056]*
    - Color Evaporation Model *[Phys.Lett.B 67(2), 217–221(1977)]*
    - Color Dipole Model *[PoS(EPS-HEP2015),191]*
    - ...



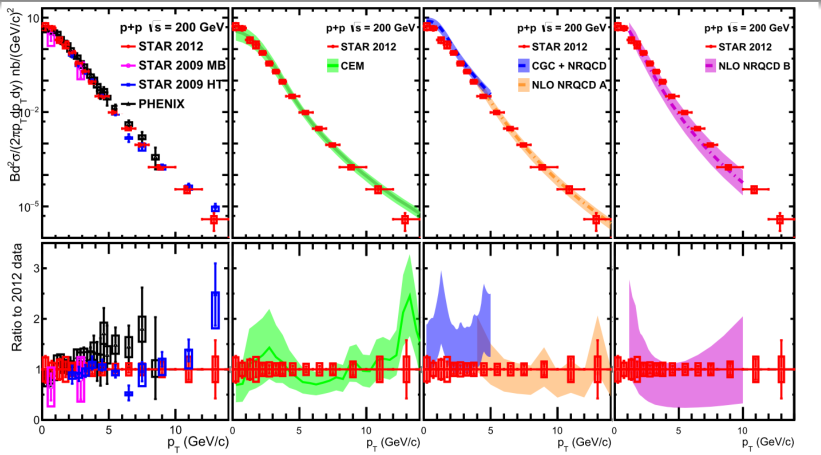
[B. Trzeciak, Prague, HQPC 2015]

- CS - color neutral
- CO - any color and quantum numbers possible



[https://www.bnl.gov/newsroom/news.php?a=119262]

J/ψ measured by STAR at $\sqrt{s} = 200$ GeV

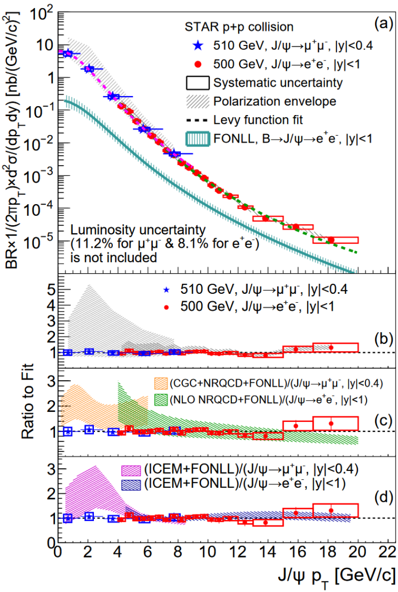


[Phys. Lett. B, 786, 87–93]

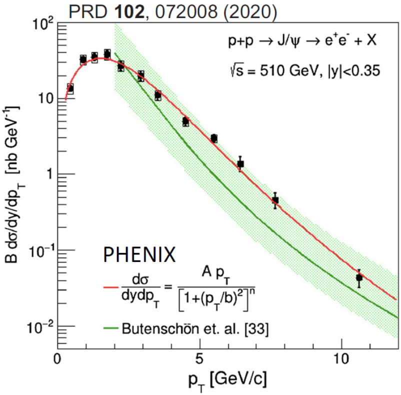
- Precise measurements performed by STAR at mid-rapidity with $0 < p_T < 15\,\mathrm{GeV/c}$
- Data are well described by CEM and NLO+NRQCD B calculations for direct J/ψ
- NLO+NRQCD A model calculations for prompt J/ψ also rather well describe the data
- Prompt CGC+NRQCD above the data, but on the edge of uncertainties
- $B \to J/\psi$ contribution not included in models

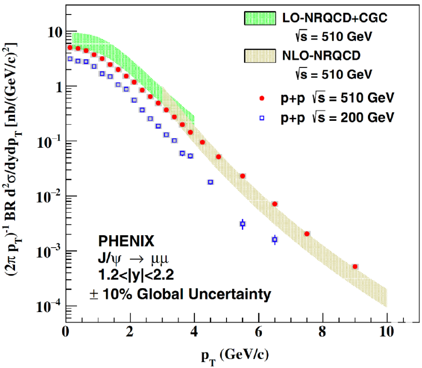
J/ψ measured by STAR at $\sqrt{s} = 500$ GeV and $\sqrt{s} = 510$ GeV

- Precise results over wider $0 < p_T < 20$ GeV/c range
- Model calculations include $B \to J/\psi$ feed-down calculated with FONLL
- Inclusive CGC+NRQCD and ICEM above the data at low p_T, but on the verge of uncertainties
- NLO NRQCD and ICEM at high p_T for inclusive J/ψ describe the data



[Physical Review D, 100(5), 052009]

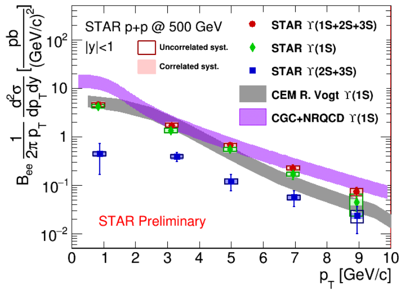




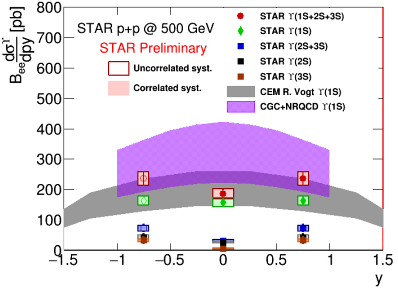
[Phys. Rev. D, 101(5), 052006]

- Data overestimated by LO-NRQCD+CGC calculation at low p_T
- Prompt NLO-NRQCD calculation describes the data, but overestimates at high $p_T > 5\,\mathrm{GeV/c}$

Υ production measured by STAR

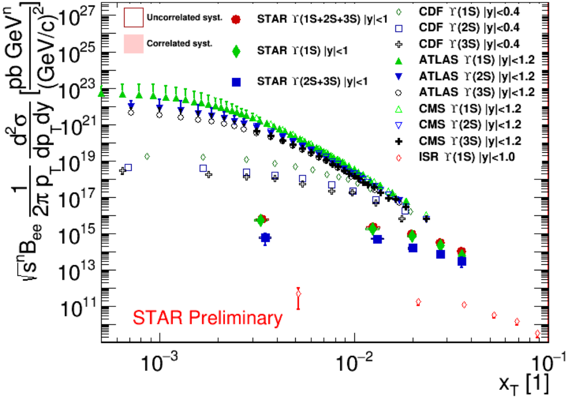


[J. Phys.: Conf. Ser., 1667(1), 012022]



[L. Kosarzewski, 20th Conference of Czech and Slovak Physicists]

- Both p_T and rapidity spectra measured by STAR
  - Separated $\Upsilon(2S)$ and $\Upsilon(3S)$ states vs. y
- $\Upsilon(1S)$ data are:
  - Well described by inclusive CEM calculation
  - Overestimated by direct CGC+NRQCD calculation



[L. Kosarzewski, 20th Conference of Czech and Slovak Physicists]

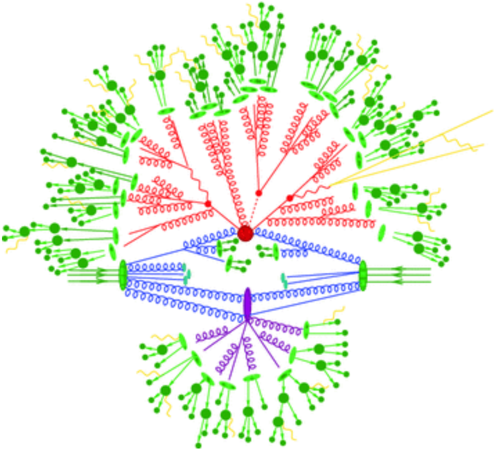
STAR $p+p$ $\sqrt{s} = 500$ GeV
ATLAS $p+p$ $\sqrt{s} = 7$ TeV
[G. Aad et al., Phys.Rev.D 87,052004(2013)]
CMS $p+p$ $\sqrt{s} = 7$ TeV
[V.Khachatryan et al., Phys.Lett.B 749,14-34(2015)]
CDF $p+\bar{p}$ $\sqrt{s} = 1.8$ TeV
[D. Acosta et al., Phys.Rev.Lett. 88,161802(2002)]
ISR $p+\bar{p}$ $\sqrt{s}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

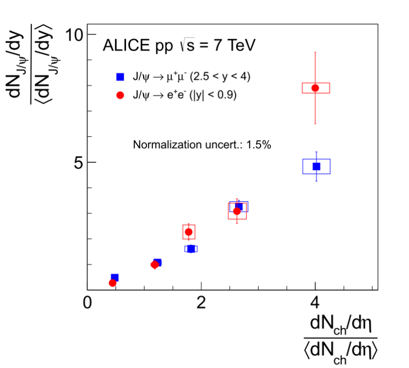
- $x_T = \frac{2p_T}{\sqrt{s}}$, $\sigma^{inv} \equiv E\frac{d^3\sigma}{d^3p} = \frac{F(x_T)}{p_T^{n(x_T,\sqrt{s})}} = \frac{F'(x_T)}{\sqrt{s}^{n(x_T,\sqrt{s})}}$

  [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

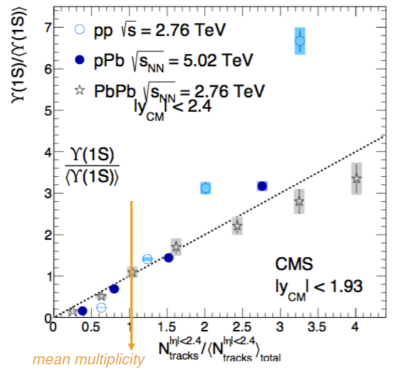
  [L. Adamczyk et al., Phys.Rev.C 80, 041902(2009)]
- No clear scaling observed, some indication for LHC data at high p_T

Multiplicity dependence of quarkonium production



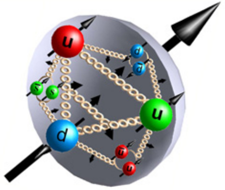


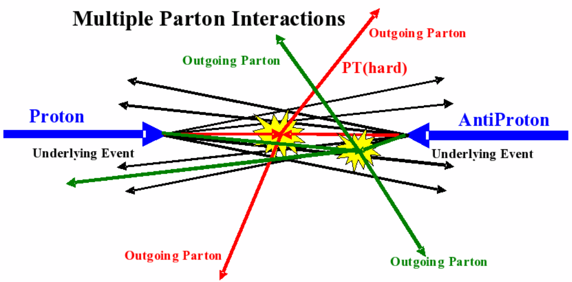
[Phys.Lett.B 712,165–175(2012)]



[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 increase at mid-rapidity in high-N_{ch} events
- Strong increase of $\Upsilon(1S)$ self normalized yields observed at LHC *[JHEP04,103(2014)]*
- Can similar effect be seen at RHIC energy? What is the cause of the effect?
- Expectation: quarkonium production $\propto N_{MPI}$, $N_{ch} \propto$ energy density
- Way to study interesting interplay between hard and soft QCD processes

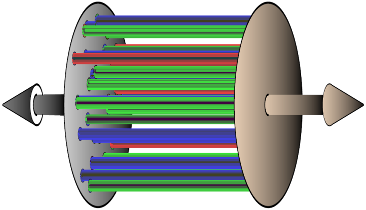


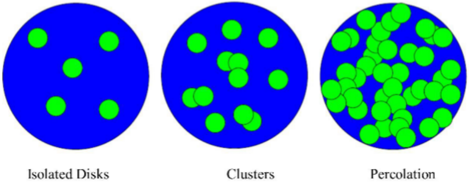


https://www.bnl.gov/rhic/images/proton-with-gluouns-300px.jpg

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.
- Charged particle multiplicity $N_{ch} \propto$ energy density

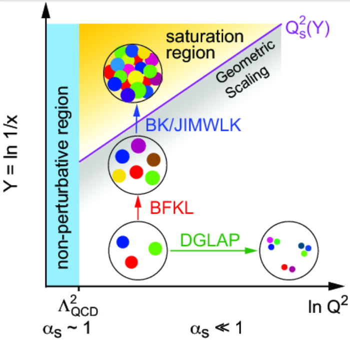


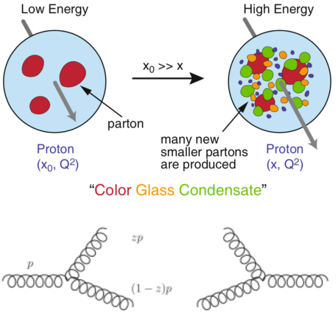


[Ann.Rev.Nucl.Part.Sci.60, 463-489(2010)] [Proc.of SPIE, 100313U(2016)]

- Models particle production originating from strings of color field formed in $p + p$ collisions.
- Soft particle production dampened by interaction of overlapping strings with transverse size $r_T \propto 1/m_T$
- A simple model inspired by Color Glass Condensate approach
- Quarkonium production $\propto N_{MPI}$, while $N_{ch} \propto$ energy density
- 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)]

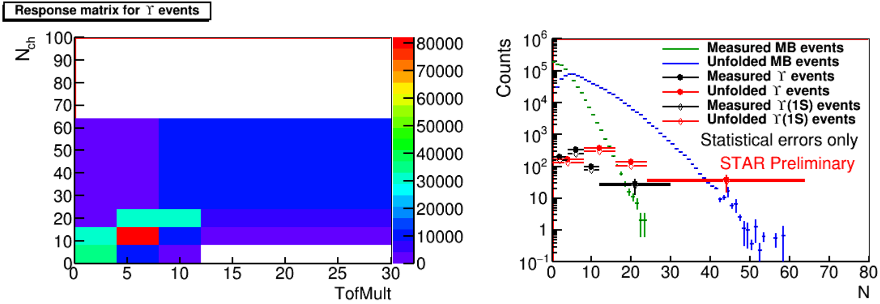




[Ann.Rev.Nucl.Part.Sci.60, 463-489(2010)] [D. Boer, EICUG Meeting 2019, Paris]

- Color Glass Condensate (CGC) is a high density state of gluonic matter [arXiv:hep-ph/0104285]
- Due to time dilation the gluons move slowly - they are "frozen" like in a glass
- Constant splitting and merging of gluons causes gluon density to saturate
- CGC EFT models relativistic hadron collisions by treating low-x partons as classical fields
- Saturation affects N_{ch}
- Implemented in CGC/Saturation model *[E. Levin, M. Siddikov, EPJC 97(5), 376(2019)], [EPJC 80(6), 560(2020)]*

Multiplicity distribution via unfolding



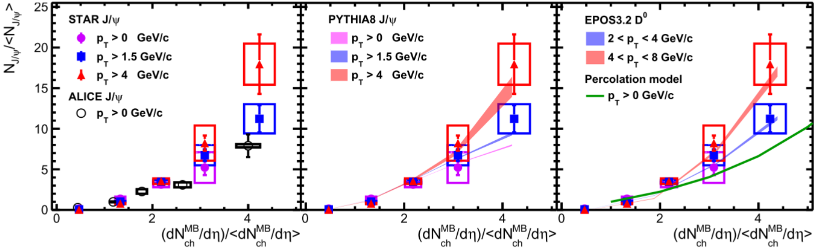
[L. Kosarzewski, MPI2019, Prague]

Unfolding method used to obtain corrected N_{ch}

1. A response matrix is obtained using the PYTHIA8 event generator for both min-bias and quarkonium events taking into account tracking efficiency
2. Use tracks matched to fast detector (TOF) to remove pileup
3. The measured distributions are unfolded using their respective response matrices
4. This procedure yields the unfolded (true) distribution

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

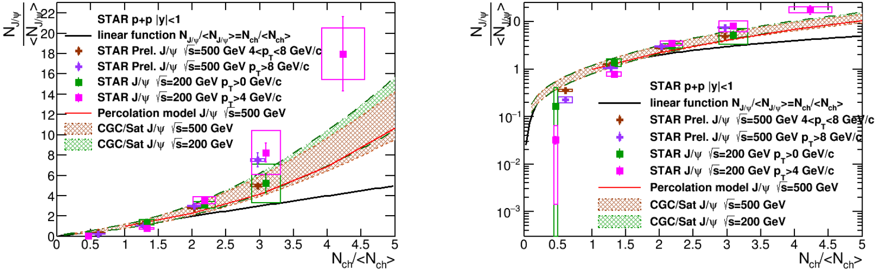
$J/\psi \to e^+e^-$



[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

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

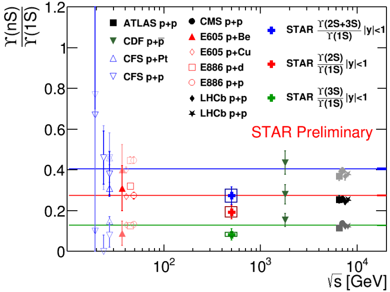


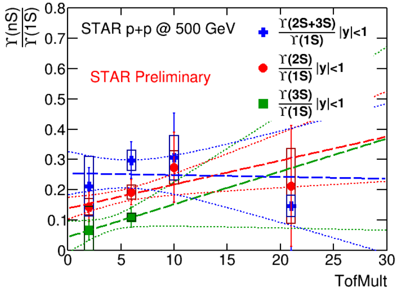
[L. Kosarzewski, MPI2019, Prague]

- 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 calculation is for $p_T > 0$ GeV/c
- CGC/Saturation model: *[E. Levin, M. Siddikov, EPJC 97(5), 376(2019)], [EPJC 80(6), 560(2020)]*
  - Describes the data, however uncertainties are large
  - Data are slightly above the model at high p_T. Note that the calculation is for $p_T > 0$ GeV/c

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

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



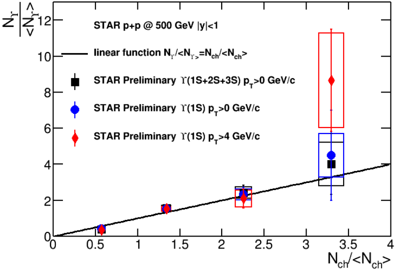


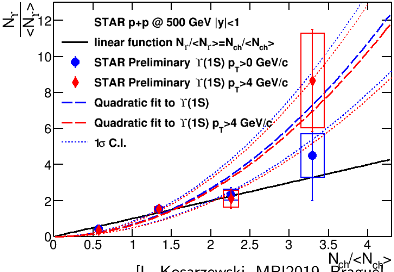
[L. Kosarzewski, MPI2019, Prague]

[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)

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

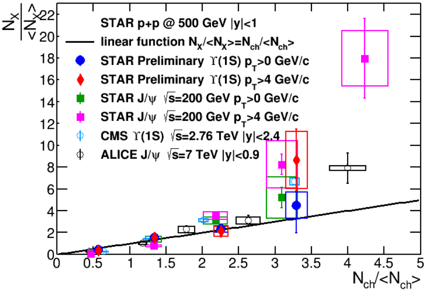


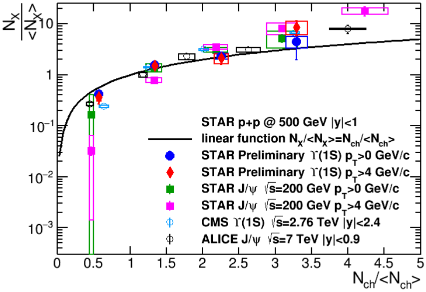


[L. Kosarzewski, MPI2019, Prague]

- Self-normalized yield vs. self-normalized multiplicity in p+p $\sqrt{s} = 500\ \mathrm{GeV}$ 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 $p_T > 4\ \mathrm{GeV/c}$
- 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
$\Upsilon \rightarrow e^{+}e^{-}$



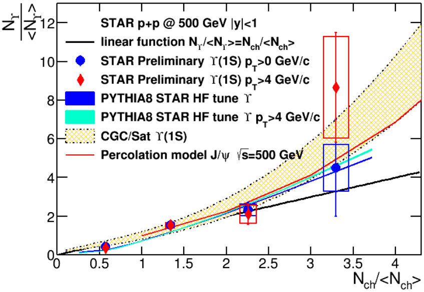


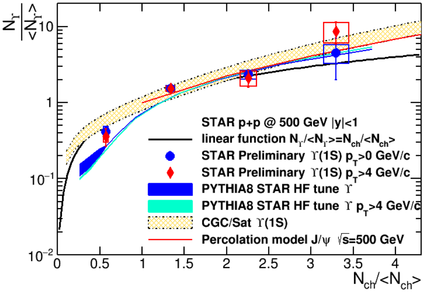
[L. Kosarzewski, MPI2019, Prague]
[JHEP04,103(2014)],[Nucl.and Part.Phys. Proc., 276-278, pp.261–264(2016)],[Phys.Lett.B 712,165–175(2012)],[Phys.Lett.B 786,87-93(2018)]

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

Υ production vs. event activity - models

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

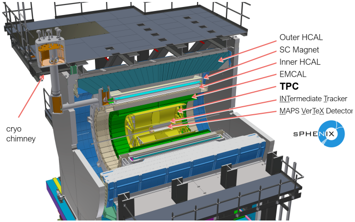


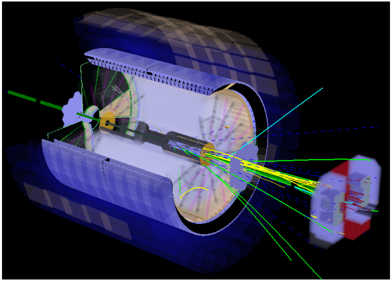


[L. Kosarzewski, MPI2019, Prague]

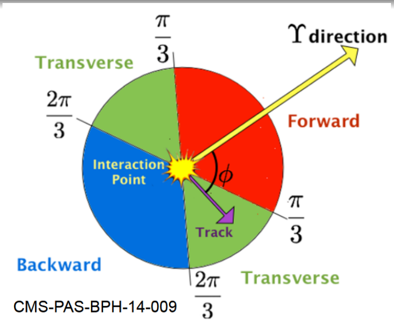
- PYTHIA8 and Percolation models reproduce the trend in the data *[E. G. Ferreiro, C. Pajares, Phys.Rev.C, 86, 034903(2012)]*
- CGC/Saturation model describes the data within large uncertainties *[E. Levin M. Siddikov, EPJC, 97(5), 376(2019)], [EPJC 80(6), 560(2020)]*

Prospects

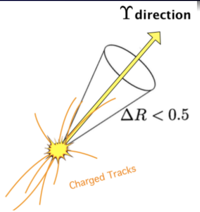

Outer HCAL
SC Magnet
Inner HCAL
EMCAL
TPC
INTermediate Tracker
MAPS VerTeX Detector
cryo
chimney
sPHENIX



Event activity dependence - new ideas



CMS-PAS-BPH-14-009



See talks:

- [Jan Fiete Grosse-Oetringhaus EJC2018]
- [JHEP11(2020)001]

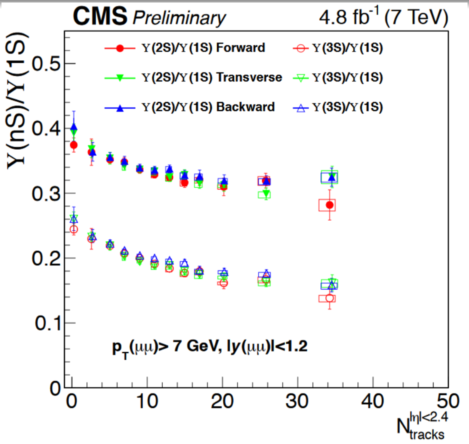
Problems

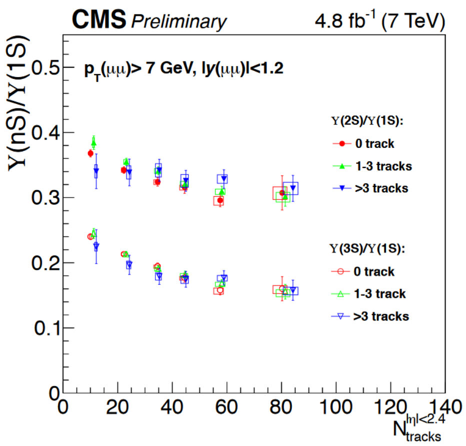
- Auto-correlation bias - we measure the multiplicity and quarkonium in the same phase space
- We want to characterize the underlying event

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



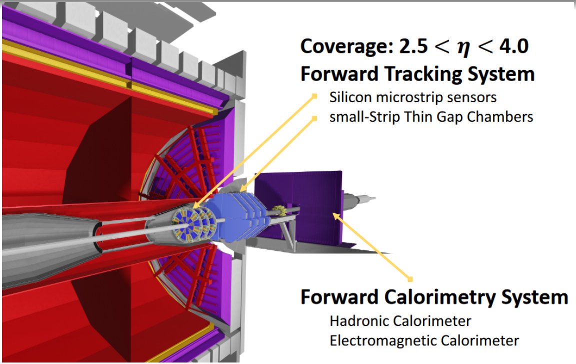


[Santona Tuli, Hot Quarks 2018]

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

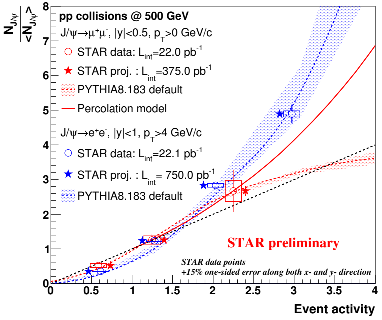
STAR Upgrades and plans for 2022+

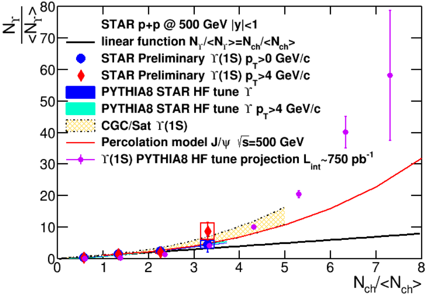


[D. Brandenburg: Hard Probes 2020]

Future plans for STAR

- iTPC already running - improved momentum resolution
- Forward upgrade $2.5 < y < 4$
  `https://drupal.star.bnl.gov/STAR/starnotes/public/sn0648`
  - Silicon detectors (FST) - tracking
  - small-strip Thin Gap Chambers (sTGC) - tracking
  - Electromagnetic and hadronic calorimeters
- High integrated luminosity for precision quarkonium production studies both at mid and forward rapidity



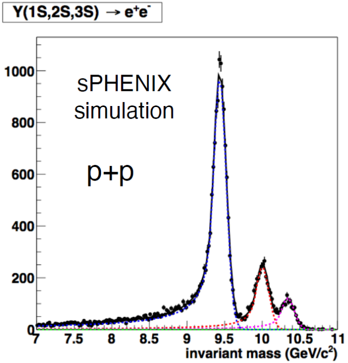


[L. Kosarzewski, 20th Conference of Czech and Slovak Physicists, 2020]

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 Barrel High Tower triggered e - high energy electrons
  - $\mathcal{L}_{int} \sim 375\,\mathrm{pb}^{-1}$ for $\mu\mu$ triggers
- Possible to discriminate different models
- 2017 data is already 10x more than 2011

sPHENIX quarkonium program in p+p



sPHENIX Beam Use Proposal (BUP) sPH-TRG-2020-001, August 31, 2020.

Year	Species	$\sqrt{s_{NN}}$ [GeV]	Cryo Weeks	Physics Weeks	Rec. Lum. $\lvert z\rvert < 10$ cm	Samp. Lum. $\lvert z\rvert < 10$ cm
2023	Au+Au	200	24 (28)	9 (13)	3.7 (5.7) nb^{-1}	4.5 (6.9) nb^{-1}
2024	$p^{\uparrow}p^{\uparrow}$	200	24 (28)	12 (16)	0.3 (0.4) pb^{-1} [5kHz] 4.5(6.2) pb^{-1} [10%-str]	45 (62) pb^{-1}
2024	$p^{\uparrow}$+Au	200	–	5	0.003 pb^{-1} [5kHz] 0.02 pb^{-1} [10%-str]	0.11 pb^{-1}
2025	Au+Au	200	24 (28)	20.5 (24.5)	13 (15) nb^{-1}	21 (25) nb^{-1}

[A. Frawley, Physics Opportunity with Heavy Quarkonia at the EIC, 2021]

- Focused on heavy-ion reference and cold QCD
- Only dielectron channel
- Good separation between Υ states
- Smaller integrated luminosity than STAR
- TPC allows to measure charged particle multiplicity dependence

Summary

Quarkonium spectra

- CEM and NLO NRQCD models describe the data well
- CGC+NRQCD overestimates the data J/ψ and $\Upsilon(1S)$ at low p_T

Multiplicity dependence of quarkonium production

- Similar trend observed for J/ψ and Υ at RHIC and LHC
- Percolation Model, PYTHIA and CGC/Sat models qualitatively describe the data
  - Indication of quarkonium production in MPI
  - Possible effect of parton saturation

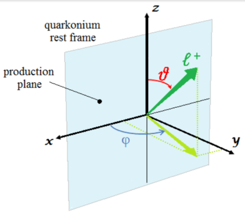
Prospects

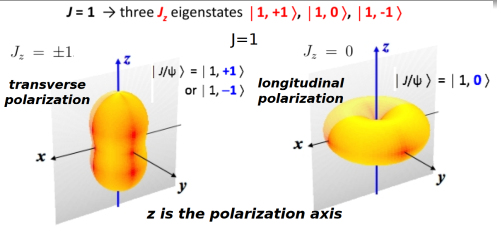
- More precise data are needed to distinguish between event activity models
- 10x more data available now for STAR
- 20x more data after 2024

Thank you for your attention!

BACKUP

Polarization





Quarkonium polarization (spin alignment)

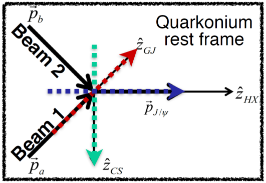
- **Is a tool to study the quarkonium production mechanism in more detail**

$$\frac{d\sigma}{d(cos(\theta))d\phi} \propto 1 + \boldsymbol{\lambda}_\theta cos^2(\theta) + \boldsymbol{\lambda}_{\theta\phi} sin(2\theta)cos(\phi) + \boldsymbol{\lambda}_\phi sin^2(\theta)cos(2\phi)$$

  - It can be studied by measuring the angular distribution of the decay daughters
  - Provides access to J_z eigenstates and their relative contributions

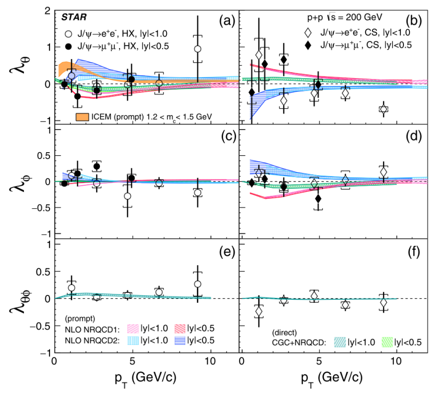
Measured in quarkonium rest frame w.r.t:

- Helicity (HX) - quarkonium momentum direction
- Collins-Soper (CS) - bisector of the angle between beams
- Gottfried-Jackson (GJ): - direction of one beam

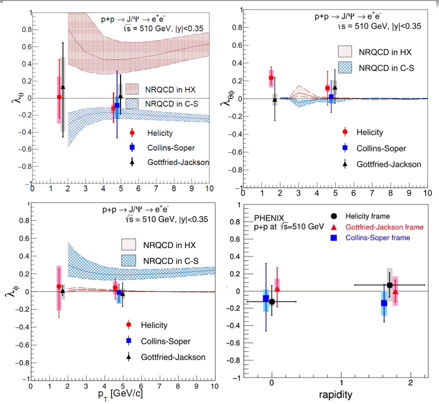


[A. Stahl, SQM 2021]

J/ψ polarization at RHIC

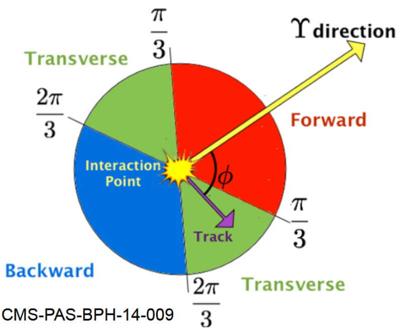


[Phys. Rev. D 102, 092009]

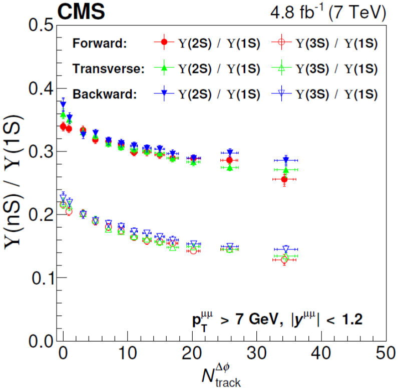


[Phys. Rev. D 102, 072008]

- All polarization coefficients measured by STAR and PHENIX in (almost) all frames
    - Consistent results in different frames
    - Consistent with no J/ψ polarization (except λ_θ at high-p_T in $|y| < 0.5$)
- Data best described by CGC+NRQCD calculation
    - Other models hard to rule out due to large uncertainties
- No difference between forward $1.2 < y < 2.2$ and mid-rapidity $|y| < 0.35$ measured by PHENIX

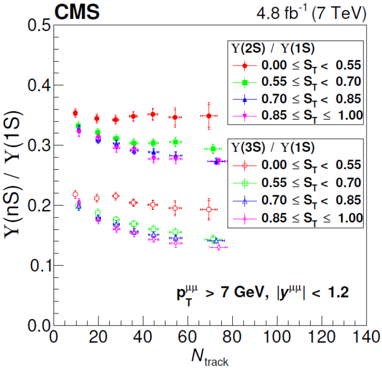


[JHEP, 2020(11), 1]



[JHEP, 2020(11), 1]

- Same behavior in forward/backward/transverse regions
  - Decrease in ratios related to UE event



[JHEP, 2020(11), 1]

- No dependence on N_{ch} for each $\Upsilon(nS)$ state in events with $S_T < 0.55$
  - Same multiplicity for each state
  - No link between multiplicity dependence and mass difference
  - Source - UE event