Overview of quarkonium production and suppression

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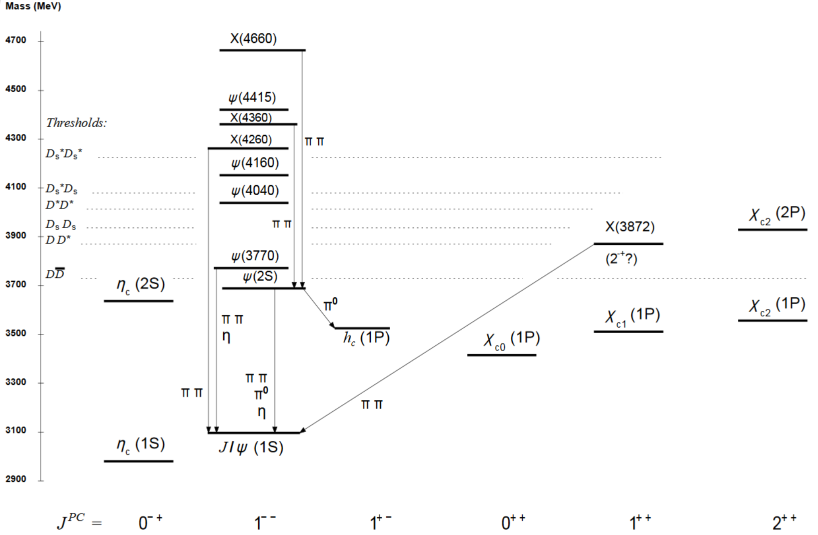
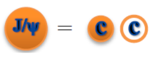
Outline

Charmonium family



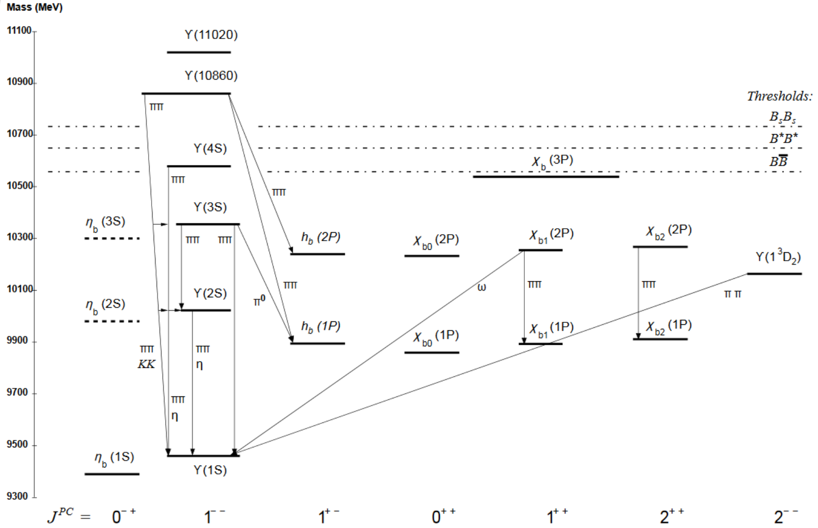
Decays - feed-down

- Only hadronic decays shown above
- Radiative decays: $\psi(nS) \rightarrow \chi_{cJ}(mP) + \gamma$, $\chi_{cJ}(1P) \rightarrow J/\psi + \gamma$



$n^{2S+1}L_J$

Bottomonium family



Decays - feed-down

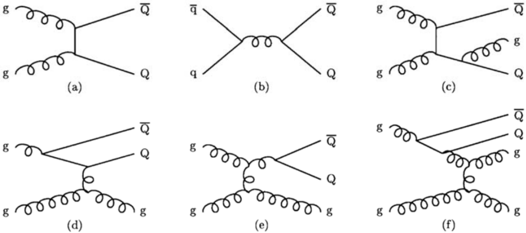
- Only hadronic decays shown above
- Radiative decays: $\Upsilon(nS) \rightarrow \chi_{bJ}(mP) + \gamma$, $\chi_{bJ}(nP) \rightarrow \Upsilon(mS) + \gamma$

$\Upsilon = b\bar{b}$ $n^{2S+1}L_J$

Quarkonium production mechanism

Heavy quark production

- Heavy quarks $Q = c, b$ have large mass $m_c = 1.28, \pm 0.03\,\mathrm{GeV}$, $m_b = 4.18^{+0.04}_{-0.03}$
- $Q\bar{Q}$ produced in hard collisions of partons $Q^2 \gg 1\,\mathrm{GeV}^2$
- Short timescales $\tau \ll 1\,\mathrm{fm/c}$ - before QGP formation
- At RHIC and LHC energy $Q\bar{Q}$ are mostly produced via gluon fusion
- This process depends on Parton Distribution Function(PDF)

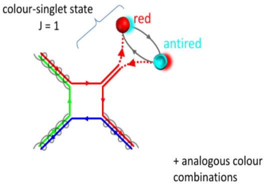


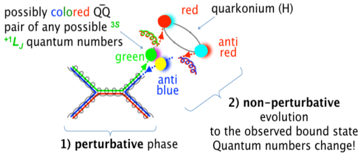
(a) gluon fusion, (b) quark-antiquark annihilation, (c) pair creation with gluon emission, (d) flavor excitation, (e) gluon splitting, (f) together gluon splitting and flavor excitation.

Quarkonium production models

Bound state formation

- Soft process and still not well understood
- $Q\bar{Q}$ pair can be produced in color-singlet(CS) or color-octet(CO) state
- A realistic model should include both channels CS+CO





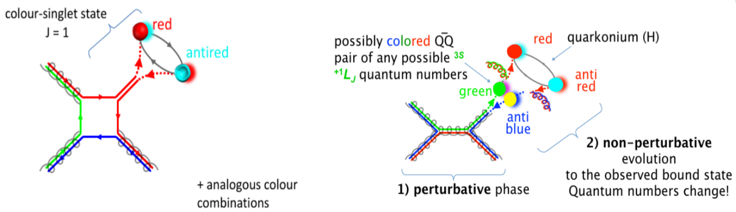
[B. Trzeciak, STAR Regional Meeting Prague, HQPC 2015]

Color Singlet Model [1, 2, 3]

- $Q\bar{Q}$ produced directly in a color neutral state(CS) in association with a gluon
- Quantum numbers compatible with a quarkonium nS state
- $f_{a/A}, f_{b/B}$ PDFs of projectile and target
- $d\sigma_{ab\to(Q\bar{Q})+X}$ parton level cross section
- $|\psi(0)|^2$ probability that $Q\bar{Q}$ forms a bound state nS, $\psi(0)$ - the quarkonium wave function

$$d\sigma_{Q_{Q\bar{Q}}+X} = \sum_{a,b}\int f_{a/A}(x_a,\mu_F)f_{b/B}(x_b,\mu_F)d\sigma_{ab\to(Q\bar{Q})+X}(s,\mu_F,\mu_R,\alpha_s)|\psi(0)|^2 \tag{1}$$

Quarkonium production models - Color Octet



[B. Trzeciak, STAR Regional Meeting Prague, HQPC 2015]

Color Octet Model [4, 5]

- $Q\bar{Q}$ can be produced in any colored or color-neutral state, with any quantum numbers $^{+1}L_J$
- $f_{a/A}$, $f_{b/B}$ PDFs of projectile and target
- $d\sigma_{ab\to(Q\bar{Q})_n+X}$ parton level cross section
- $\left\langle O^n_{Q_{Q\bar{Q}}} \right\rangle$ long distance matrix element(LDME), probability that particular $Q\bar{Q}$ pair can be found in a given quarkonium bound state
- LDMEs are assumed to be universal and are extracted from fits to the experimental data
- Often implemented in Non-relativistic QCD framework using an expansion in powers of v - quark velocity in the bound state
- Recently coupled with CGC formalism in order to describe $p_T < m_{QQ}$

$$d\sigma_{Q_{Q\bar{Q}}+X} = \sum_{a,b,n} \int f_{a/A}(x_a, \mu_F) f_{b/B}(x_b, \mu_F) d\sigma_{ab\to(Q\bar{Q})_n+X}(s, \mu_F, \mu_R, \mu_\Lambda, \alpha_s) \left\langle O^n_{Q_{Q\bar{Q}}} \right\rangle \tag{2}$$

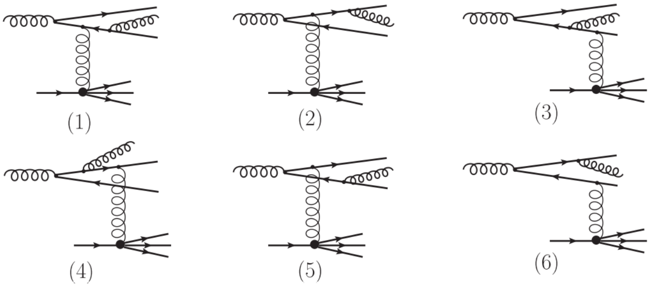
Quarkonium production models - Color Evaporation Model

Color Evaporation Model [6, 7, 8]

- $Q\bar{Q}$ quantum numbers are neglected
- Bound state is formed in an unspecified way as long as it can be described a fixed probability
- Quarkonium state is produced with some probability when the invariant mass of the $Q\bar{Q}$ pair is $2m_Q < m_{Q\bar{Q}} < 2m_H$
- m_Q is a mass of heavy quark
- m_H is a mass of the lightest open heavy flavor hadron eg: D or B meson
- $F_{Q_{Q\bar{Q}}}$ is a probability that $Q\bar{Q}$ forms a quarkonium, extracted from the fits to the experimental data
- An improved model ICEM introduces p_T dependence in quarkonium ratios [13]
- Recently, attempts to describe quarkonium polarization(spin aligment), where matrix elements are calculated separately for each J_z of the final state [12]

$$d\sigma_{Q_{Q\bar{Q}}} = F_{Q_{Q\bar{Q}}} \int_{2m_Q}^{2m_H} \frac{d\sigma_{Q\bar{Q}}}{dm_{Q\bar{Q}}} dm_{Q\bar{Q}} \tag{3}$$

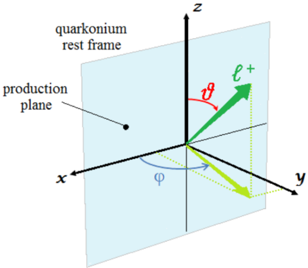
Quarkonium production models - Color Dipole

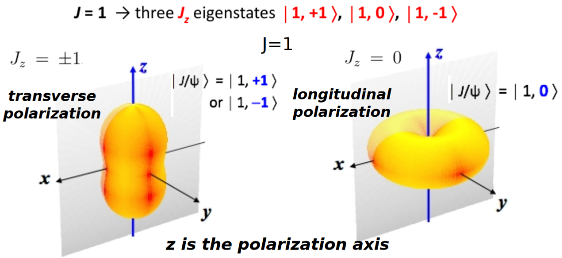


Color Dipole Model of quarkonium production

- $Q\bar{Q}$ pair is produced as a result of fluctuation in the form of a virtual gluon in a projectile hadron, which interacts with the color field of the target
- Only color-singlet channel needed, thanks to a rigorous QCD calculation
- Needs tests by studying quarkonium-hadron correlations in p+p collisions

Quarkonium production models - polarization





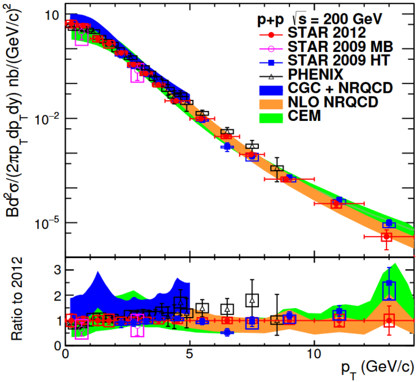
Polarization - spin aligment

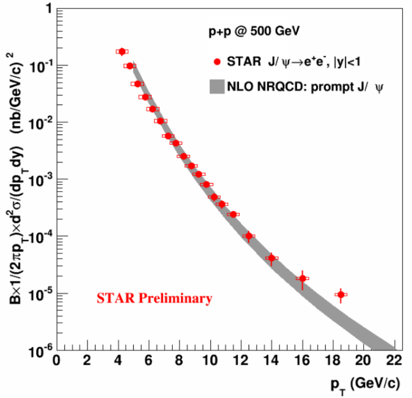
- Study of angular distribution of quarkonium decay daughters provides access to quarkonium polarization

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

- Polarization is dependent on the production mechanism
- Allows to distinguish between production models
- Can be measured in different frames:
  - Helicity frame
  - Collins-Soper frame

J/ψ production in p+p collisions

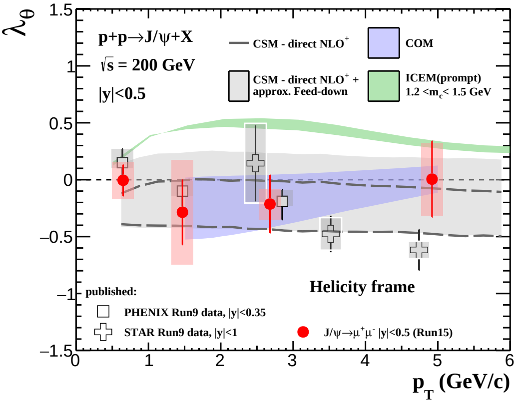




J/ψ production in p+p measured with STAR

- STAR data [9] at 200 GeV are reasonably well described by the CEM and NLO NRQCD calculations for prompt J/ψ
- CGC+NRQCD for prompt J/ψ is on the edge of the uncertainties at 200 GeV
- NLO NRQCD prompt J/ψ calculation also describes the data at 500 GeV [10]

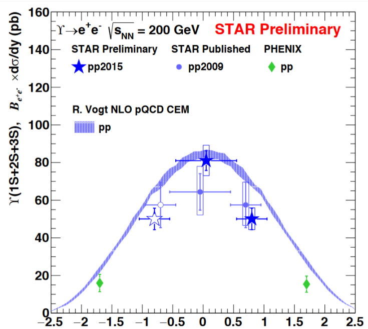
J/ψ production in p+p collisions - polarization



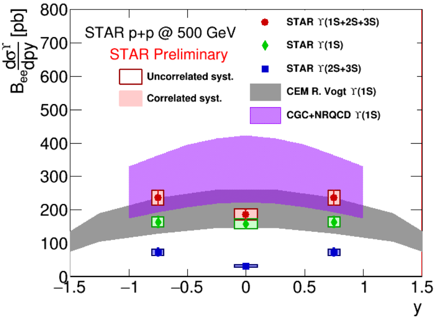
J/ψ polarization in p+p measured with STAR

- Color Singlet Model (CSM) and Color Octet Model (COM) calculations for direct J/ψ agree with the data
- CEM calculation is on the upper edge of uncertainty for some data points

Υ production in p+p - rapidity distribution



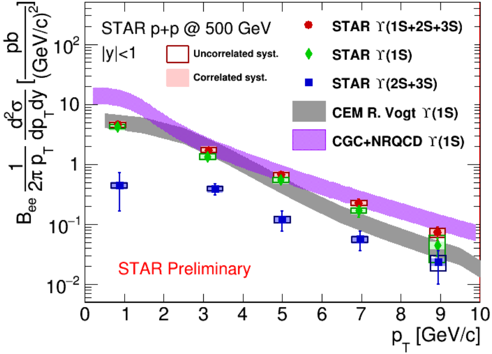
R. Vogt Phys. Rept. 462 (2008) 125



Υ rapidity distribution in p+p measured with STAR

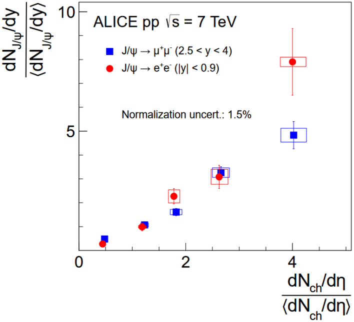
- STAR data slightly narrower than CEM model at $\sqrt{s} = 200$ GeV
- Flatter rapidity spectrum at $\sqrt{s} = 500$ GeV compared to $\sqrt{s} = 200$ GeV
  - CEM model (inclusive) consistent with the measurement for $\Upsilon(1S)$ [Phys.Rev. C92 (2015) 034909]
  - CGC+NRQCD (direct) predictions are above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

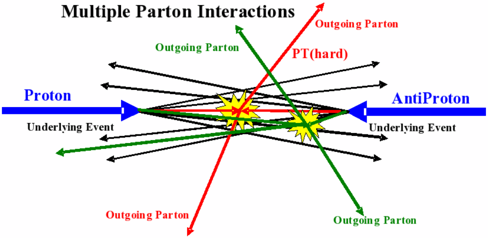
Υ production in p+p vs p_T



- 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.

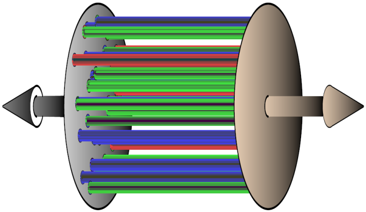
Event activity dependence

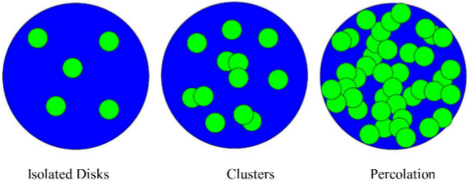




- ALICE first observed a strong increase of normalized J/ψ yield vs. normalized charged particle multiplicity
- It may be a result of J/ψ production happening in Multiple Parton Interactions(MPI)
- CMS has also measured double Υ production, possibly originating in Double Parton Scattering(DPS) [11]

String Percolation Model



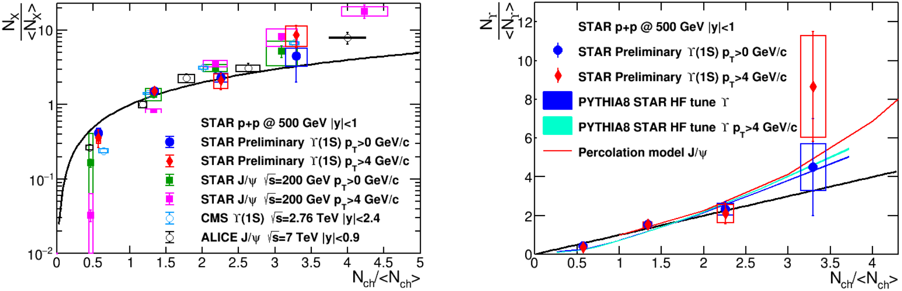


[Ann.Rev.Nucl.Part.Sci.60, 463-489(2010)] [Proceedings of SPIE, 100313U(2016)]

- 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.

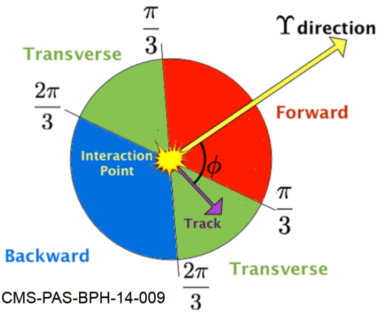
$$\frac{N_{hard}}{\langle N_{hard} \rangle} = \langle \rho \rangle \left(\frac{\frac{dN_{ch}}{d\eta}}{\left\langle \frac{dN_{ch}}{d\eta} \right\rangle} \right)^2$$ [Phys.Rev. C, 86, 034903 (2012)]

Event activity dependence

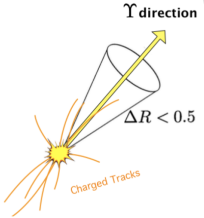


- Normalized Υ yield vs. normalized multiplicity (a measure of event activity)
- STAR results for inclusive $\Upsilon(1S+2S+3S)$ and $\Upsilon(1S)$ as well as high-p_T $\Upsilon(1S)$ with $p_T > 4\,\mathrm{GeV/c}$
- Data consistent with a linear rise, with a hint for stronger-than-linear rise for $\Upsilon(1S)$ above $p_T > 4\,\mathrm{GeV/c}$
- Similar trend 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)]
- Hints of interaction between strings of color field or Υ production in MPI [Phys.Rev. C, 86, 034903 (2012)]

Event activity dependence - new ideas



CMS-PAS-BPH-14-009



See talks

- Jan Fiete Grosse-Oetringhaus EJC2018 [18]
- Santona Tuli's Hot Quarks [17]

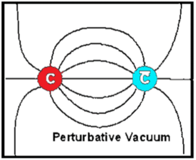
Problems

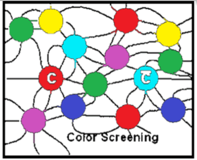
- Auto-correlation bias - we measure the multiplicity and quarkonium in the same phase space
- While we want to measure the underlying event

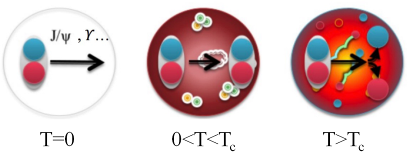
New methods

- 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

Quarkonium suppression in QGP

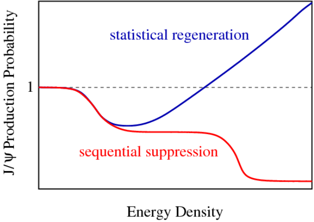


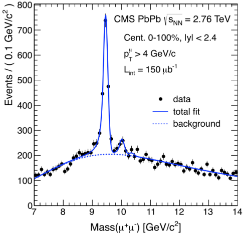


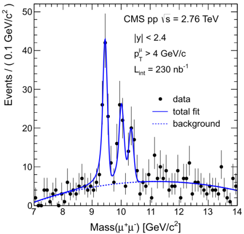


Suppression in QGP

- At high temperature or density in QGP the color charges are screened
- If the temperature is sufficiently high, the quarkonium states should dissociate if $r > r_D$ (Debye screening length)
- Quarkonium suppression is a signature of QGP formation [14]
- Since each of the quarkonium states has different characteristic radius and binding energy, we should expect a sequential pattern of suppression [15]
    - Observed by CMS for Υ in Pb+Pb collisions [16]
- Regeneration during QGP hadronization of uncorrelated $Q\bar{Q}$ pairs







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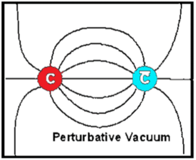

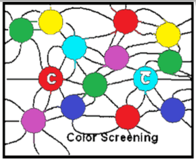

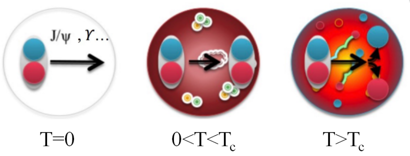

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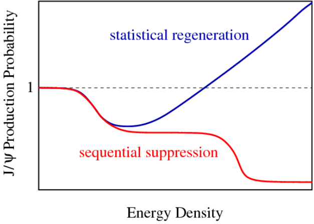
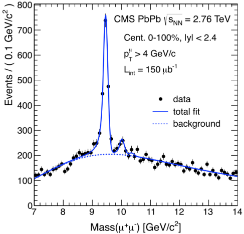
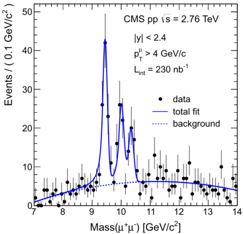
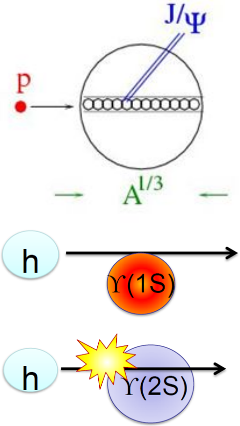
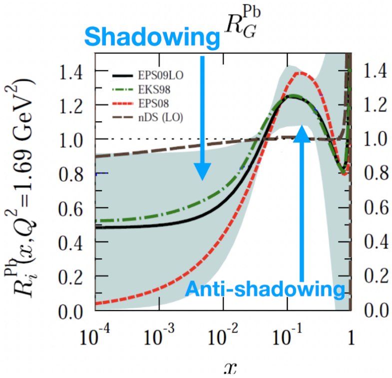






Cold Nuclear Matter effects

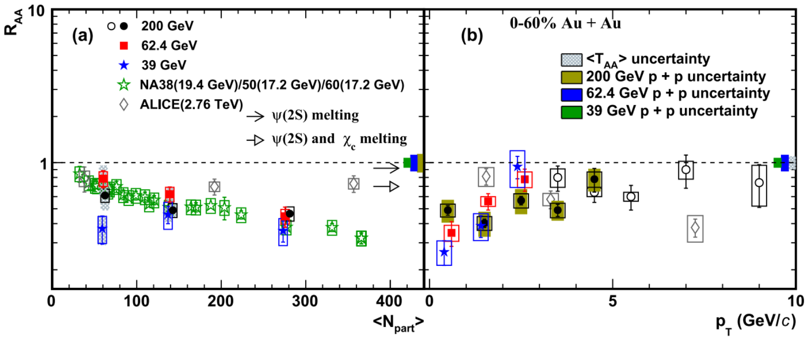




Cold Nuclear Matter effects

- Can be studied separately in $p + A$ or $d + A$ collision
- Nuclear absorption
- Comover interactions - very small for $\Upsilon(1S)$ [Phys.Lett.B 503, 104 (2001)]
- Modification of nuclear PDFs: shadowing, anti-shadowing

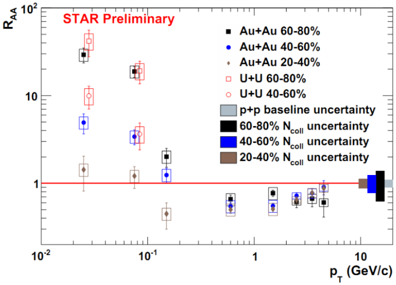
Energy dependence of J/ψ production in A+A



Energy dependence of J/ψ production in A+A

- No significant energy dependence observed

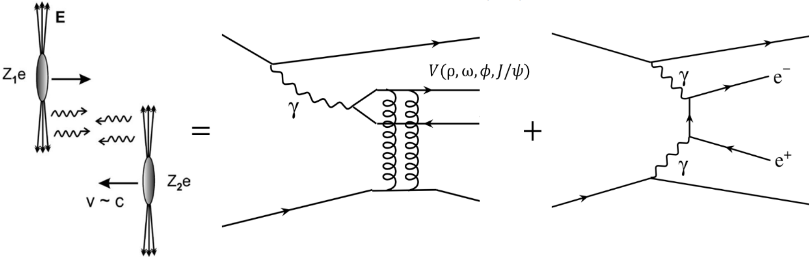
Low-p_T J/ψ excess in A+A



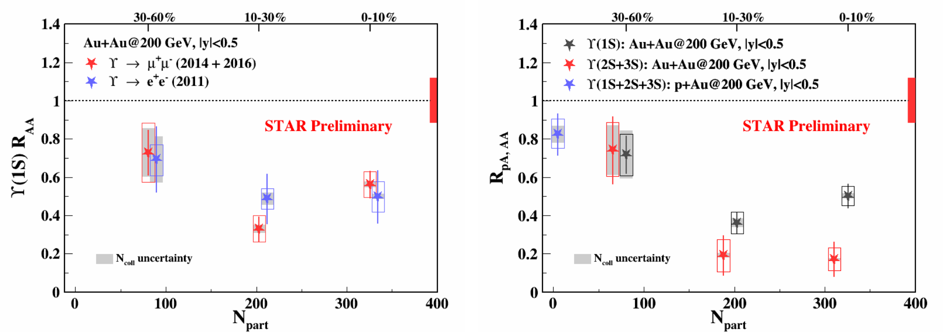
Low-p_T J/ψ excess in A+A

- First observed by ALICE [23]
- Now also measured in STAR - significant enhancement for $p_T < 0.1\,\mathrm{GeV}$
- No significant difference between results from Au+Au and U+U collisions
- May originate from coherent and incoherent photon interactions

C. Bertulani et al., Ann. Rev. Nucl. Part. Sci. 55 (2005) 271



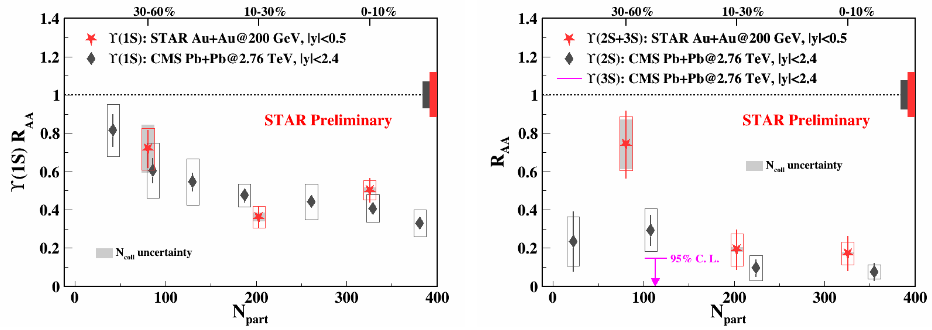
Υ R_{AuAu} vs. N_{part}



Υ R_{AuAu} measured by STAR in Au+Au

- Dielectron and dimuon results consistent with each other
- Both results combined for better precision
- Stronger suppression of $\Upsilon(2S+3S)$ than $\Upsilon(1S)$ in central collisions

Υ RHIC vs. LHC

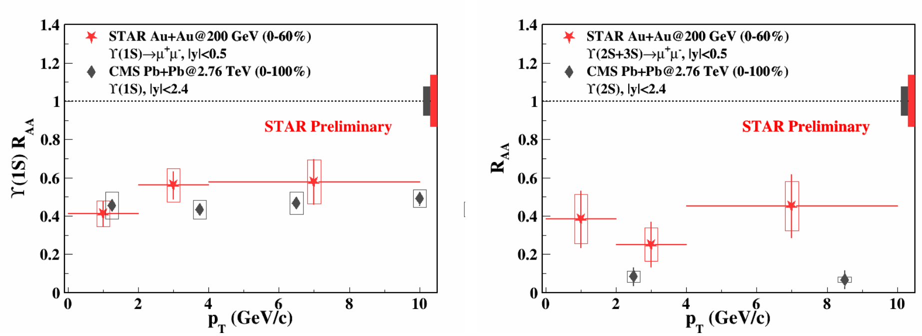


[Phys.Lett.B 770(2017)357-379]

Υ STAR vs. CMS

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

Υ R_{AA} vs. p_T

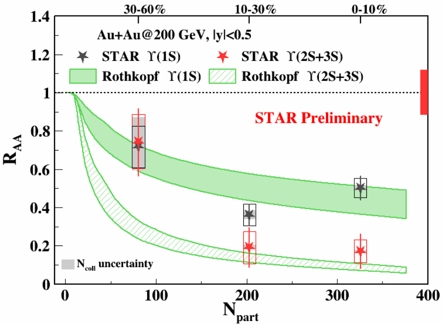


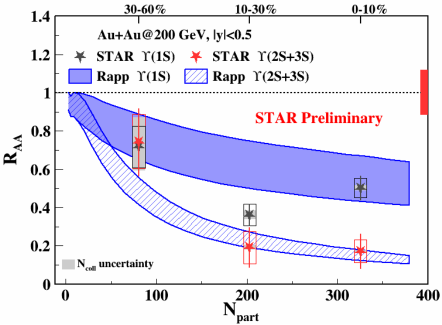
[Phys.Lett.B 770(2017)357-379]

Transverse momentum dependence

- Similar suppression for $\Upsilon(1S)$ at RHIC and LHC
- Indications of stronger suppression of high-p_T $\Upsilon(2S+3S)$ at LHC than at RHIC
- Both consistent with flat dependence vs. p_T

STAR vs. models

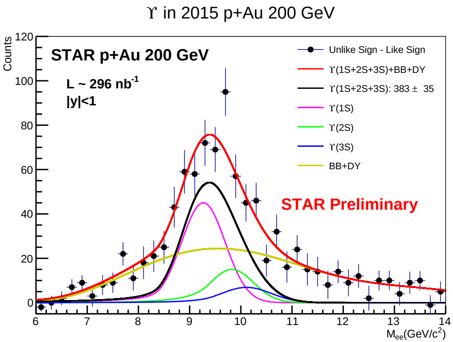


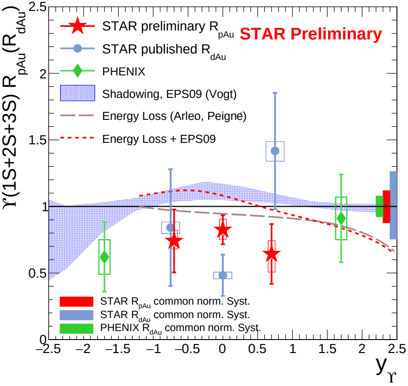


Models

- Kroupaa, **Rothkopf**, Strickland [Phys.Rev.D 97,(2018)016017]
  - Lattice QCD-vetted potential for heavy quarks in hydrodynamic-modeled medium
  - No regeneration, no CNM effects
- De, He, **Rapp** [Phys.Rev.C 96,(2017)054901]
  - 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
- Rothkopf's model underestimates the STAR $\Upsilon(2S+3S)$ results for $30-60\%$ centrality

Υ production in p+Au



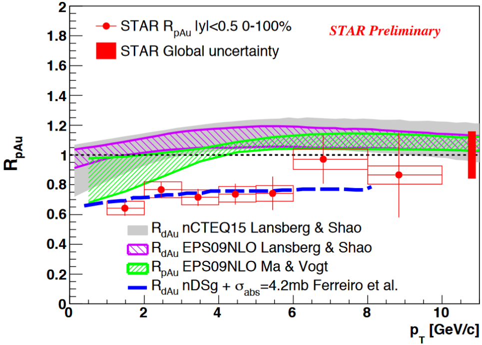


[Phys.Lett.B 735(2014)127], [Phys. Rev. C 87, 044909], [JHEP 03(2013)122]

$\Upsilon(1S + 2S + 3S)$

- Much better R_{pAu} precision than published R_{dAu} results
  - $R_{pAu}|_{|y|<0.5} = 0.82 \pm 0.10(stat.)^{+0.08}_{-0.07}(syst.) \pm 0.10(glob.)$
- Indication of $\Upsilon(1S + 2S + 3S)$ suppression in p+Au collisions

Υ R_{pAu} vs. p_T



EPS09+NLO:
[Ma & Vogt, Private Comm.]
nCTEQ, EPS09+NLO:
[Eur.Phys.J. C77 (2017) no.1, 1],
[Comp.Phys.Comm. 198 (2016) 238-259],
[Comp.Phys.Comm. 184 (2013) 2562-2570]

$\Upsilon(1S+2S+3S)$

- Models including only modified nuclear PDFs are above the data
- Model which incorporates nPDF and nuclear absorption can describe the data
  - $\sigma_{abs} = 4.2$ mb

Summary

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

- The J/ψ and $\Upsilon(1S)$ spectra can be reasonably described by CEM calculations.
- The J/ψ spectra can be described by NLO NRQCD model calculation.
- Flatter rapidity distribution for Υ at $\sqrt{s} = 500\,\mathrm{GeV}$ than at $\sqrt{s} = 200\,\mathrm{GeV}$.
- Both CS and CO models agree with the measured J/ψ polarization, CEM model on the edge of uncertainties
- Studied the dependence of quarkonium 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.

p+Au collisions at $\sqrt{s} = 200\,\mathrm{GeV}$

- Υ suppression
- Indication of nuclear absorption $\sigma_{abs} = 4.2\,\mathrm{mb}$ in addition to shadowing

Summary

A+A collisions at $\sqrt{s} = 200\ \mathrm{GeV}$

- No significant energy dependence of J/ψ production.
- Excess of low-p_T J/ψ observed both at RHIC and LHC
- Consistent Υ results from dielectron and dimuon channels - combined for better precision
- Similar suppression of $\Upsilon(1S)$ at RHIC and LHC
- Stronger suppression of $\Upsilon(2S+3S)$ than $\Upsilon(1S)$ in central collisions
  - Sequential suppression
  - Hint of smaller suppression at RHIC than at LHC
- Υ data consistent with model calculations

Thank you for your attention!

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BACKUP - links

BACKUP - links

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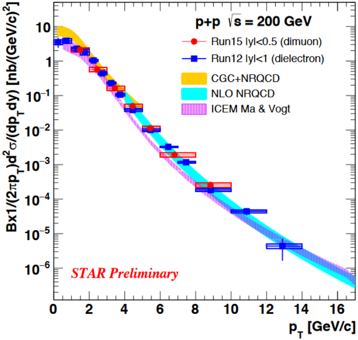
$J/\psi \to \mu\mu$ in p+p collisions



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NLO+NRQCD, Shao et al., JHEP 05 (2015) 103
ICEM, Ma & Vogt, PRD 94 (2016) 114029

J/ψ production measured with STAR

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