χ_c and χ_b meson production in high multiplicity events

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arXiv:**2012.08284** (to appear in PRD)

Introduction

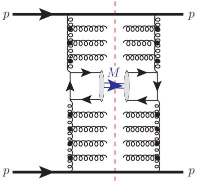
- Our goal: study the hadroproduction of P-wave quarkonia (χ_c and χ_b)

$$pp \to M\,X,$$
$$M = \chi_{cJ},\, \chi_{bJ}, \quad J = 0, 1, 2$$

analyze dependence on multiplicity of co-produced states X

- Conventional picture of inclusive production (collinear and k_T-fact. approaches): gluon-gluon fusion

$$|\mathcal{A}|^2 \sim$$

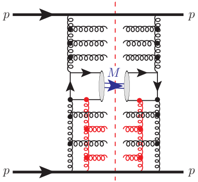


► Final state M might include quarkonia + soft gluons

►Gluons ⇒gluon cascades

▷ reggeization⇒ pomerons

- Diagrams with more than two pomerons (t-channel vertical gluon ladders) are usually disregarded:



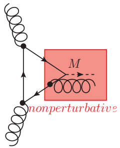
►Suppressed by $\alpha_s\,(\mu_F)$ or if gluon densities are not large

►*In small-x regime* ($x_i \ll 1$) *gluon densities grow vigorously, compensate all suppression factors, so have saturation*

► *CGC/Color Dipole approach: dipole amplitude essentially takes into account multiple gluon connections to one of the hadrons*

Challenges of quarkonia production

(see QWG review, Eur.Phys.J. C71 (2011) 1534)



- ► Final state might (and in case of S-wave must) include soft gluons
  - ▷ Essentially nonperturbative contribution
    - – Use NRQCD for systematic description
    - – Soft gluon emission ⇒ nonperturbative Long Distance Matrix Elements (LDMEs), extracted from phenomenology

Some challenges of NRQCD:

► Challenge 1: LDMEs significantly depend on technical details of the fit [PRD 96, 034019 (2017), ...]

▷ LDMEs of different quarkonia vary considerably. For ($2S$, $1P$, all $\bar{b}b$) are compatible with zero, yet larger for J/ψ

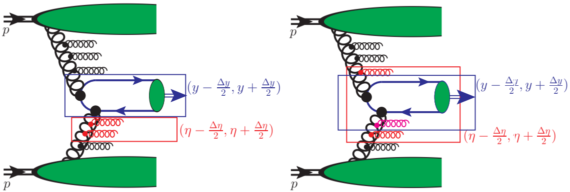
► Challenge 2: Implement possible contributions of other mechanisms, *e.g.*: co-production (PRL 101 (2008) 152001) ..., fragmentation (EPJC 79 (2019) 241) ...

► Challenge 3: Some data (*e.g.* multiplicity dependence) suggest that multigluon fusion might give sizeable contributions [EPJC 79, 376; EPJC 80, 560]. This should be taken into account in the phenomenological analyses.

⇒ *Understanding of quarkonia production still is not complete*

Why multiplicity dependence matters?

- The distributions of quarkonia over rapidity, transverse momentum are important, yet the information which they provide is not exhaustive:
  - ▷ ... many possible production mechanisms
  - ▷ ... potentially can attribute possible discrepancy between data and theory to some new soft process at quarkonia formation stage
- Dependence on multiplicity of co-produced particles⇒new tool for testing of production mechanisms
  - ▷ The bins used to collect quarkonia and light hadrons might be separated to exclude possible contributions of hadronization debris:



- ► Local Parton Hadron Duality: $dN_{\rm ch} \sim dN_{\rm partons}$ (number of partons)
- ► The multiplicity distribution in each *individual* pomeron is known from BFKL

⇒the multiplicity dependence of the ***process*** might be used to probe the role of multipomeron mechanisms (recall AGK ideas)

Multiplicity observable

► Probability $P\left(N_{\rm parton}\right)$ of large multiplicity fluctuations is exponentially suppressed at large $N_{\rm parton}$ for all processes,

$$P\left(N_{\rm parton}\right)\sim\exp\left(-\lambda\,n\right),\;\; n=\frac{N_{\rm parton}}{\langle N_{\rm parton}\rangle}$$

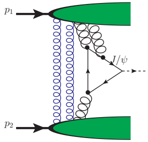
-average $\langle N_{\rm parton}\rangle$ depends on energy $\sqrt{s}_{pp}$.

►More common observable is the self-normalized yield:

$$\frac{dN_M/dy}{\langle dN_M/dy\rangle}=\frac{d\sigma_M\left(y,\,\eta,\,\sqrt{s},\,n\right)/dy}{d\sigma_M\left(y,\,\eta,\,\sqrt{s},\,\langle n\rangle=1\right)/dy}\Bigg/\frac{d\sigma_{\rm ch}\left(\eta,\,\sqrt{s},\,Q^2,\,n\right)/d\eta}{d\sigma_{\rm ch}\left(\eta,\,\sqrt{s},\,Q^2,\,\langle n\rangle=1\right)/d\eta}\qquad\textbf{(1)}$$

-if cross-section $d\sigma_M$ ∼probability to produce final state M, then self-normalized ratio∼conditional probability produce M if $N_{\rm ch}$ hadrons are produced

- Now we'll discuss relation between multiplicity of process & of individual pomerons



►Pomerons disconnected from hard process (blue) after re-summation give a common factor $P(n)$, same as in inclusive process w/o M

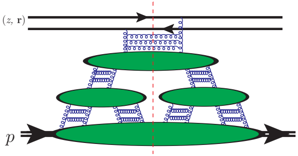
►In the ratio **(1)** these factors $P(n)$ cancel

⇒The ratio **(1)** probes only cut pomerons connected to hard amplitude

Dipole approach at high multiplicity

- In small-x_B kinematics gluon densities are enhanced, so we used color dipole ("CGC") approach

▷Dipole amplitude satisfies BK equations, effectively resums fan-like diagrams shown in the Figure



▷Couplings to *heavy quarks* $\mathcal{O}\left(\alpha_s(m_Q)\right)$, but not to gluons

▷Dipole amplitude⇔gluon shower

CGC in high multiplicity events:
[Phys.Rev.D 98 (2018) 7, 074025, Phys.Lett.B 710 (2012) 125, Eur.Phys.J.C 71 (2011) 1699]

⇒ Modification of saturation scale:

$$Q_s^2\left(x,\,b;\,n\right)\;\approx\;n\,Q^2\left(x,\,b\right),$$

$$n = dN_{\rm ch}\Big/\langle dN_{\rm ch}\rangle$$

▷Asymptotics of dipole amplitude for small $r\sim m_Q^{-1}$:

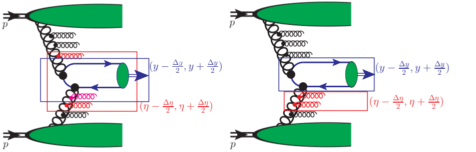
$$N(x,\,\boldsymbol{r})\sim\left(r\,Q_s\right)^{2\gamma_{\rm eff}}$$

⇒expected multiplicity dependence $\sim n_i^{\gamma_{\rm eff}}$ for each pomeron

⇒ Multiplicity dependence of multipomeron mechanism:

$$\frac{dN_M/dy}{\langle dN_M/dy\rangle}\lesssim\left(\frac{n}{k}\right)^{k\,\gamma_{\rm eff}},$$

where k is the number of cut pomerons which might contribute in a given rapidity bin:



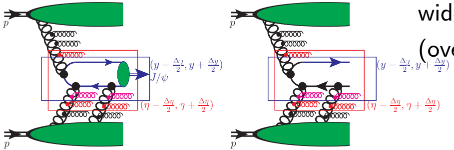
If bins overlap, enhanced multiplicity is shared by all pomerons, otherwise only by one of them.

► More accurate evaluation: averaging over all possible partitions, yields similar results

Multiplicity enhancement mechanisms

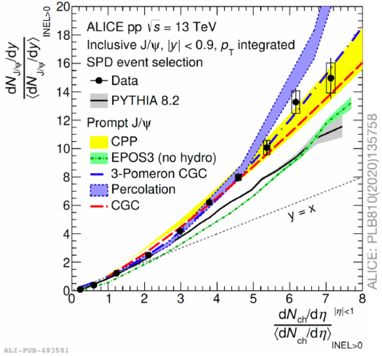
► Experimental data (STAR, ALICE): Multiplicity dependence of J/ψ, $D^{\pm}$ faster than for pomeron-pomeron fusion

▷ One of the possible (plausible) explanations: 3-pomeron contributions:



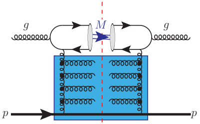
– Can describe multiplicity dependence in a wide range, in different bin configurations (overlapping, separated by rapidity, etc)

► There are also other explanations of multiplicity enhancement, so it is desirable to study multiplicity dependence of other quarkonia in order to choose the right explanation



▷ Possible tool: P-wave quarkonia, dominated by 2-pomeron mechanism, 3-pomeron contributions are suppressed at high energies

Production of P-wave quarkonia (χ_c, χ_b)



- Leading contribution: 2-pomeron fusion
  - ▷ ... 3-pomeron is suppressed at high energies
  - ▷Dipole picture: BK-pomeron (gluon shower) ⇒ dipole amplitude

- Cross-section is expressed as superposition of forward dipole amplitudes (N_M), convoluted with overlaps of wave functions

$$\frac{d\sigma_M\left(y,\,\sqrt{s}\right)}{dy\,d^2p_T} = \int d^2k_T x_1 \underbrace{g\left(x_1,\,\boldsymbol{p}_T-\boldsymbol{k}_T\right)}_{\text{gluon uPDF}} \times$$

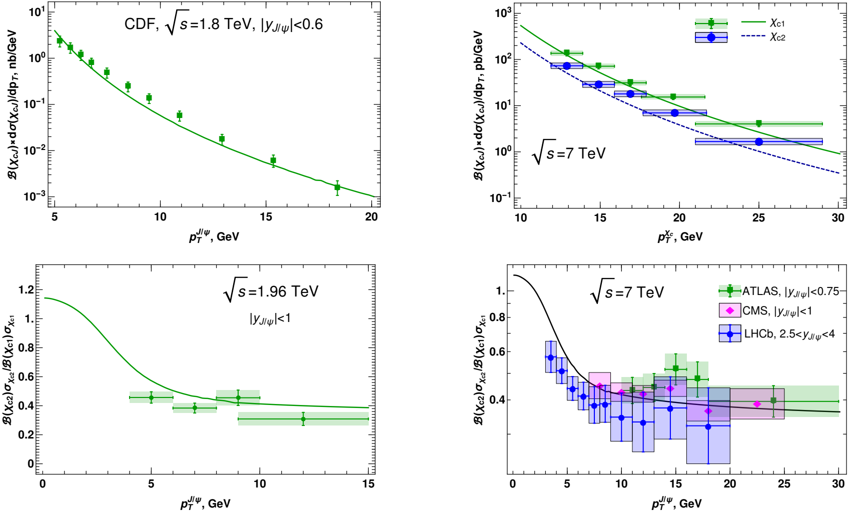
$$\times \int_0^1 dz_1 \int_0^1 dz_2 \int \frac{d^2 r_1}{4\pi} \int \frac{d^2 r_2}{4\pi} \int d^2\boldsymbol{b}_{21} e^{i\boldsymbol{b}_{21}\cdot\boldsymbol{k}_T} \times$$

$$\times \underbrace{\left\langle \Psi^\dagger_{\bar{Q}Q}\left(r_1,\,z_1\right)\,\Psi_M\left(r_1,\,z_1\right)\right\rangle}_{\text{wave functions}} \underbrace{\left\langle \Psi^\dagger_{\bar{Q}Q}\left(r_2,\,z_2\right)\,\Psi_M\left(r_2,\,z_2\right)\right\rangle}_{\text{wave functions}} \times$$

$$\times N_M\left(x_2;\,z_1,\,\boldsymbol{r}_1;\,z_2,\,\boldsymbol{r}_2;\,\boldsymbol{b}_{21}\right) + \left(x_1 \leftrightarrow x_2\right),$$

- The wave functions of quarkonia are evaluated in potential models in their rest frame; use proper Clebsch for spins and evaluation of overlaps with WF of incident gluon
- Phenomenology: NRQCD Color octet LDMEs $\mathcal{O}^\chi\left[{}^3S_1^{(8)}\right]$, $\mathcal{O}^\chi\left[{}^3P_J^{(8)}\right]$, $\mathcal{O}^\chi\left[{}^3P_J^{(8)}\right]$ are small for χ_c and χ_b [PRD 90, 074021; PRD 93, 094012; PRD 93, 054033]., so can disregard them as first approximation

Comparison with experimental data (CDF, LHC)



- Good description of the available data achieved without color octet LDMEs

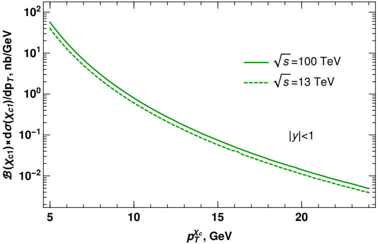
▷ χ_c is detected via $\chi_c \to \gamma J/\psi \to \gamma\mu^+\mu^-$, that's why some experiments use $y_{J/\psi}$, $p_T^{J/\psi}$

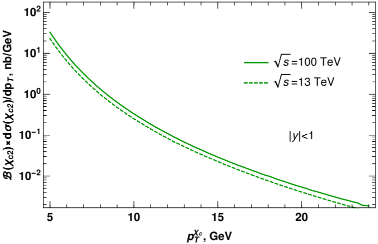
▷ Ratio of χ_{c1} and χ_{c2} -sensitive test of spin-orbital structure of the wave function

▷ No published data for χ_{c0}(might be due to significantly smaller branchings)

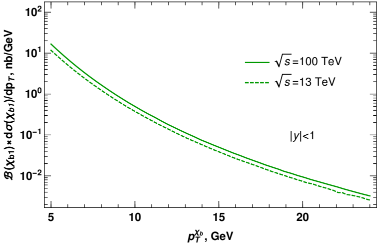
Predictions for higher energies

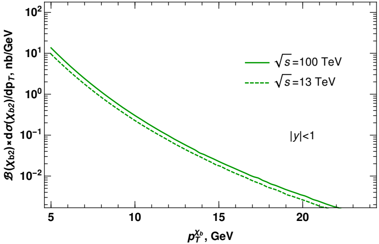
► Cross-sections of χ_{c1}, χ_{c2}:





► Cross-sections of χ_{b1}, χ_{b2}:

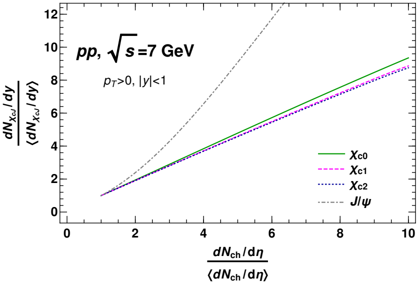


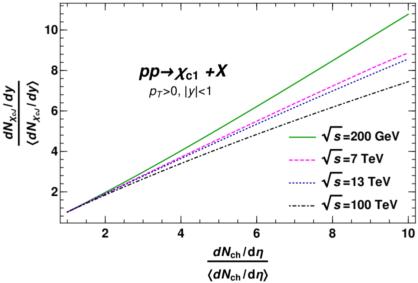


► Qualitatively the same behaviour, increase of energy scales up the cross-section.

► Cross-sections for χ_{c0}, χ_{b0} look very similar (available in paper). However, since branching $\mathcal{B}$ is just $\sim 5-10\%$ of $J=1, 2$, the expected rates are smaller.

Multiplicity dependence for P-wave quarkonia (χ_c, χ_b)





Expected multiplicity dependence of 1P quarkonia is *milder* than that of J/ψ:

►Two-pomeron fusion is dominant mechanism, three-pomeron is suppressed at high energies

▷Each cut pomeron≈factor $\sim n^{\gamma_{\rm eff}}$.

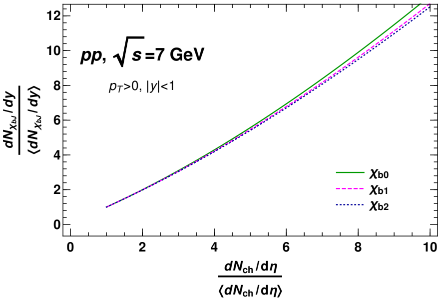
▷$\gamma_{\rm eff}$ slightly *decreases* with energy due to higher order corrections (approaches asymptotic constant value),

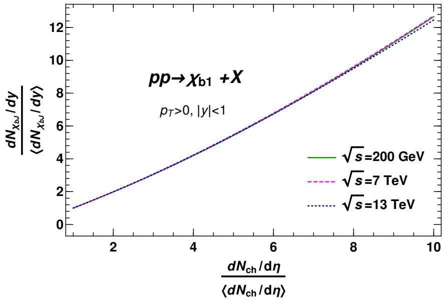
$$\gamma_{\rm eff}(s) \approx \gamma_s + \frac{\rm const}{\ln(\sqrt{s})} \ln\left(\frac{2}{\langle r\rangle\ Q_s}\right)$$

▷ Average dipole size $\langle r\rangle \sim m_Q^{-1}$, slightly changes depending on quarkonium numbers⇒ minor differences of $\gamma_{\rm eff}$ for χ_c states with different J^P.

▷ At very large $n \gtrsim 20$ observe saturation: $\langle r\rangle \sim Q_s^{-1} \ll m_Q^{-1}$, so dipole amplitude $N \sim (r\, Q_s)^{\gamma_{\rm eff}}$ becomes (almost) n-independent. However this regime not achievable even at HL-LHC (recall that probability of fluctuation $P(n) \sim e^{-\lambda\, n}$)

Multiplicity dependence for P-wave quarkonia (χ_c, χ_b)





- ► For χ_b-mesons expected multiplicity is slightly faster than for χ_c because average dipole size $\langle r\rangle \sim m_Q^{-1}$ is smaller. However, it remains much slower than for $1S$ quarkonia ($\Upsilon(1S)$, J/ψ, ...)

- ▷ Expected energy dependence is very mild, so expect the same results for self-normalized yields from STAR and LHC

- ▷ In general the multiplicity measurements with b-quarks is more challenging than for c-quarks, since the cross-section is expected to scale as $\sim (m_c/m_b)^{2\gamma_{\rm eff}}$. However, theoretically it is cleaner (less corrections from higher twists)

Summary

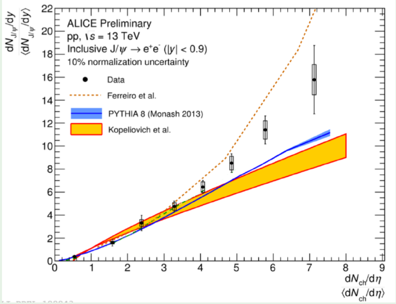
- We analyzed production of χ_c and χ_b mesons in a wide energy range (from RHIC to LHC) using color dipole ("CGC") approach
  - ▶ The approach can describe kinematical distributions of χ_{cJ} without color octet contributions.
  - ▶ **Multiplicity dependence should be much weaker than for $1S$ quarkonia since 3-pomeron mechanism is suppressed**
    - ▷ *If confirmed experimentally, this finding would constitute strong evidence that multiplicity enhancement seen both in $D^{\pm}$- and J/ψ-meson production is due to 3-pomeron contributions, rather than any other effects*

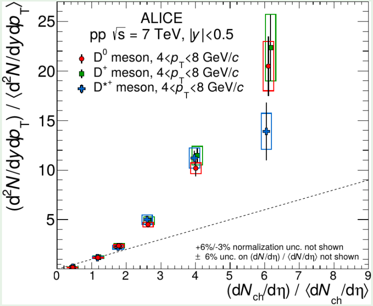
Thank You for your attention!

Appendix: Multiplicity dependence of J/ψ, D

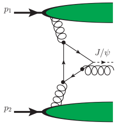
[ALICE, 1811.01535]

- Observable: $J/\psi+$ charged hadrons, study multiplicity $dN_{J/\psi}$ vs. dN_{ch}



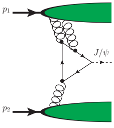


- Enhancement (deviation from linear) seen both for J/ψ and D mesons
- So far not clear if the effect exists for $\psi(2S)$, χ_c, Υ?

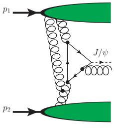


(1)

- Difficult to explain in terms of gluon-gluon fusion approach: if each reggeized gluon (cut pomeron) contributes approx. equal number $\bar{n}$ of charged hadrons, expect milder dependence
- Data hints that multipomeron mechanisms are pronounced (usually discarded as corrections)



(2)



(3)

Appendix: Full expression for cross-section

▷Cross-section:

$$\frac{d\sigma_M\left(y,\,\sqrt{s}\right)}{dy\,d^2p_T} = \int d^2k_T x_1\,\underbrace{g\left(x_1,\,\boldsymbol{p}_T-\boldsymbol{k}_T\right)}_{\text{gluon uPDF}}\times$$

$$= \int_0^1 dz_1 \int_0^1 dz_2 \int \frac{d^2r_1}{4\pi}\int \frac{d^2r_2}{4\pi}\int d^2\boldsymbol{b}_{21}e^{i\boldsymbol{b}_{21}\cdot\boldsymbol{k}_T}\times$$

$$\times\quad \underbrace{\left\langle \Psi^\dagger_{\bar{Q}Q}\left(r_1,\,z_1\right)\,\Psi_M\left(r_1,\,z_1\right)\right\rangle}_{\text{wave functions}}\underbrace{\left\langle \Psi^\dagger_{\bar{Q}Q}\left(r_2,\,z_2\right)\,\Psi_M\left(r_2,\,z_2\right)\right\rangle}_{\text{wave functions}}\times$$

$$\times N_M\left(x_2;\,z_1,\,\boldsymbol{r}_1;\,z_2,\,\boldsymbol{r}_2;\,\boldsymbol{b}_{21}\right)+\left(x_1\leftrightarrow x_2\right),$$

$$N_M\left(x;\,z_1,\,\boldsymbol{r}_1;\,z_2,\,\boldsymbol{r}_2;\,\boldsymbol{b}_{21}\right) = N\left(x,\,\boldsymbol{b}_{21}+\bar{z}_2\boldsymbol{r}_2+\bar{z}_1\boldsymbol{r}_1\right)+N\left(x\,\boldsymbol{b}_{21}-z_1\boldsymbol{r}_1-z_2\boldsymbol{r}_2\right)-$$

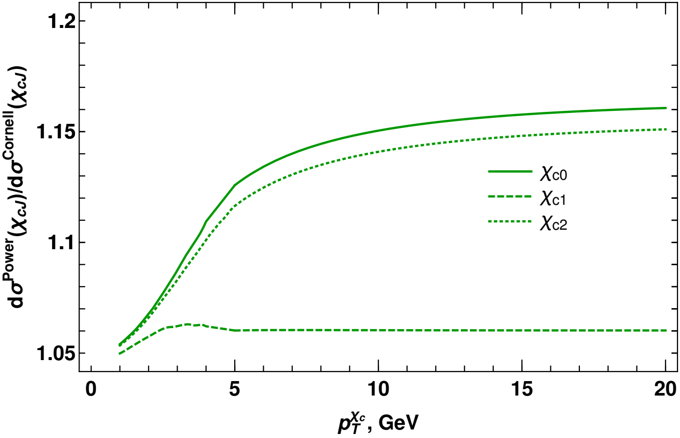
$$-N\left(x,\,\boldsymbol{b}_{21}+\bar{z}_2\boldsymbol{r}_2-z_1\boldsymbol{r}_1\right)-N\left(x,\,\boldsymbol{b}_{21}-\bar{z}_1\boldsymbol{r}_1-z_2\boldsymbol{r}_2\right)$$

$$x_{1,2} \approx \frac{\sqrt{m_M^2+\left\langle p^2_{\perp M}\right\rangle}}{\sqrt{s}}e^{\pm y}$$

▷Ψ_M -WF of quarkonium, from potential models
▷$\Psi_{\bar{Q}Q}$ -WF of gluon ($\bar{Q}Q$ component), evaluated perturbatively
▷$N(x,\,\boldsymbol{b},\,\boldsymbol{r})$ -impact parameter dependent forward dipole amplitude

Appendix: Potential model dependence for χ_c

▶ Dependence of the cross-section on the choice of the wave function of final state



▷ Dependence is mild, $\lesssim$ 15% for χ_{c0}, χ_{c2}, $\lesssim$ 6% for χ_{c1} . In the small-p_T domain and the p_T-integrated cross-section the dependence does not exceed 10%