Multiplicity dependence of quarkonia and open heavy flavor mesons

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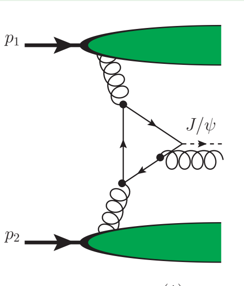
Eur.Phys.J.C 80 (2020) 6, 560.

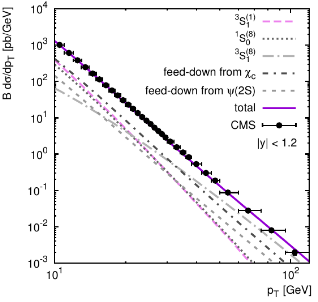
J/ψ production in pp collisions (short summary)

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

Color Singlet Model & NRQCD corrections



(1)



CSM (alone):

- Reasonable description for:
- small-p_T observables
- p_T-integrated observables
- Wrong behavior for

$p_T \gg m_{J/\psi}$

(EPJC 79 (2019) 241)

NRQCD:

- Description for large-p_T

(Reggeized) gluon=(cut) pomeron

Other mechanisms at large p_T ?

- Co-production ($J/\psi + \bar{Q}Q$, ...)

(PRL 101 (2008) 152001)

- Quark and gluon fragmentation

(EPJC 79 (2019) 241)

- ... ?

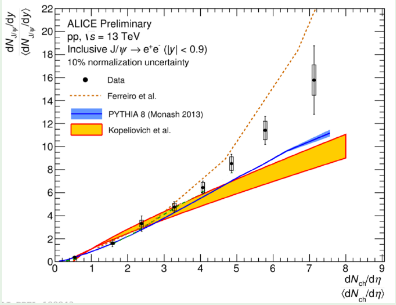
[Phys. Rev. D 96, no. 3, 034019 (2017)]:

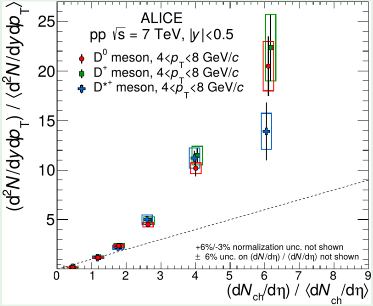
Challenge for NRQCD: LDMEs not universal ?!

	$\langle\mathcal{O}^{\psi}[^3S_1^{(1)}]\rangle/\mathrm{GeV}^3$	Color octet contributions $\langle\mathcal{O}^{\psi}[^1S_0^{(8)}]\rangle/\mathrm{GeV}^3$	$\langle\mathcal{O}^{\psi}[^3S_1^{(8)}]\rangle/\mathrm{GeV}^3$	$\langle\mathcal{O}^{\psi}[^3P_0^{(8)}]\rangle/\mathrm{GeV}^5$
kT-factorization				
A0	1.97	0.0	9.01×10^{-4}	0.0
JH	1.62	1.71×10^{-2}	2.83×10^{-4}	0.0
KMR	1.58	8.35×10^{-3}	2.32×10^{-4}	0.0
Collinear factorization				
[11]	1.32	3.04×10^{-2}	1.68×10^{-3}	-9.08×10^{-3}
[15]	1.16	9.7×10^{-2}	-4.6×10^{-3}	-2.14×10^{-2}

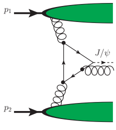
Multiplicity dependence of charmonia production [ALICE, 1811.01535]

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



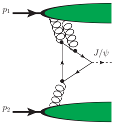


- Enhancement (deviation from linear) seen both for J/ψ and D mesons
- So far not clear if the effect exists for $\psi(2S)$, χ_c, Υ?



(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).
- Production on nuclei: $\sim A^{1/3}$ enhancement



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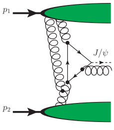


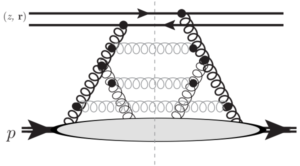
(3)

- We used CGC/Sat (color dipole) framework for our evaluations.
  - In the literature it is frequently assumed that the dipole cross-sections are universal object which already takes into account all possible interactions with the target.
  - Before we continue discussion, we'll stop briefly on what is included into dipole cross-section and what is not.
  - Also we'll consider how the heavy dipole scattering cross-section depends on the number of (charged) particles $dN_{\rm ch}$ produced per rapidity bin $d\eta$ during the scattering.

Dipole approach: what it includes and what doesn't

- BK equation for the rapidity evolution

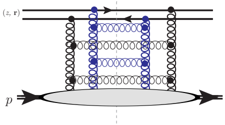
►effectively resums the fan-like diagrams as shown in the Figure



b-CGC parametrization:

► Constructed as interpolation of asymptotic solutions of BK equation

►extra gluon attachment to quarks which are **not** included in *b*-CGC:



High multiplicity events:

►Relation of saturation scale Q_s to observed multiplicity dependence

$$\frac{dN_{\rm ch}}{dy} \approx \text{const}\, N_P\, \frac{Q_s^2}{\bar{\alpha}_S\left(Q_s\right)}$$

▷N_P-number of cut pomerons

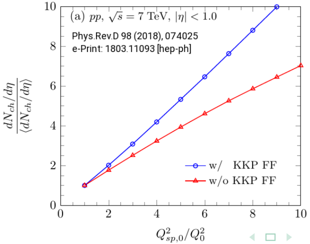
⇒ Modification of saturation scale:

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

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

(modulo small logarithmic corrections)

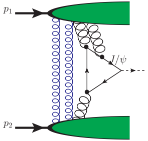
[Phys.Rev.D 98 (2018) 7, 074025, Phys.Lett.B 710 (2012) 125, Eur.Phys.J.C 71 (2011) 1699]



Multiplicity enhancement mechanisms

- Local Parton Hadron Duality: $dN_{\rm ch} \sim N_{\rm partons} \sim N_{IP}$ (number of cut pomerons)

►Pomerons disconnected from hard process (blue) after resummation give a common factor $P(n)$, same as in inclusive production without J/ψ



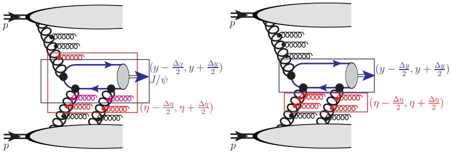
►Experimental results are given for self-normalized ratio

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

so $P(n)$ cancels

$\Rightarrow$ should focus only on cut pomerons connected to hard amplitude

The result for multiplicity depends if the bin used to collect charged particles (red in plot) overlaps with a bin used to collect quarkonia (blue in plot):



► If bins overlap, enhanced multiplicity is shared by all pomerons (summation over all possible partitions is implied)

► If bins are separated, enhanced multiplicity is shared by all pomerons

► If n is not very large, dipole size $\langle r\rangle \sim 1/m_Q$, so each cut pomeron contributes a factor $\sim (r\,Q_s)^{\gamma_{\rm eff}} \sim n_i^{\gamma_{\rm eff}}$

► If $n \gg 1$, dipole size $\langle r\rangle \sim 1/Q_s$, so the multiplicity dependence saturates

►Coupling of pomeron to heavy quarks $\sim \alpha_s\left(m_Q\right)/m_Q$, suppressed in $m_Q \to \infty$ limit

J/ψ production through 2-pomeron fusion

[PRC95 (2017), 065203]

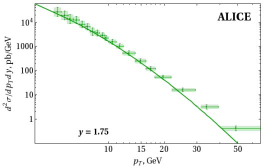
$$\frac{d\sigma_{pp}}{dy\, d^2p_T} = \frac{9}{8}\, g\left(x_1(y)\right) \int d^2\boldsymbol{b}\, e^{i\boldsymbol{p_T}\cdot\boldsymbol{b}} \int d\alpha_G d\alpha_1 d^2r_1\, d\alpha_2 d^2r_2\, d^2\rho$$

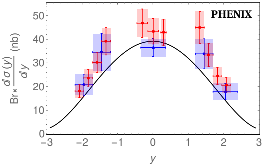
$$\times \underbrace{\Psi_M^*\left(\alpha_1\, r_1\right)\Psi_M\left(\alpha_2\, r_2\right)}_{\text{Meson WFs}} \sum_{n,n'=1}^{6} \underbrace{\eta_n\eta_{n'}}_{\text{numerical factor}} \underbrace{N\left(y,\, \boldsymbol{r_n}-\boldsymbol{r_{n'}}+\boldsymbol{b}\right)}_{\text{dipole cross-section}}$$

$$\times\ \mathrm{Tr}\left[\Lambda_M \Phi_{g\to\bar{Q}Q}\left(\epsilon_n,\, \vec{r}_n^{(1)}\right)\Phi_{Q\to Q\,g}\left(\delta_n,\, \vec{\rho}_n\right)\right]$$

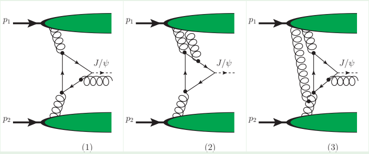
$$\times\ \mathrm{Tr}\left[\Lambda_M \Phi_{g\to\bar{Q}Q}\left(\epsilon_{n'},\, \vec{r}_{n'}^{(2)}\right)\Phi_{Q\to Q\,g}\left(\delta_{n'},\, \vec{\rho}_{n'}\right)\right]^*$$

- Λ_M-spin projector on meson WF
- $\Phi_{g\to\bar{Q}Q}$, $\Phi_{Q\to Q\,g}$ are evaluated perturbatively ($m_c\to\infty$ limit)
- $\vec{r}_n^{(1,2)} \approx \vec{r}_{1,2} + \delta\vec{r}_n\left(\alpha,\, \alpha_G,\, r,\, \rho\right)$, $\qquad \vec{\rho}_n \approx \vec{\rho} + \delta\vec{\rho}_n\left(\alpha,\, \alpha_G,\, r,\, \rho\right)$
- Sum over all possible gluon attachments in amplitude and its conjugate is implied
- Reasonable description of pp data:

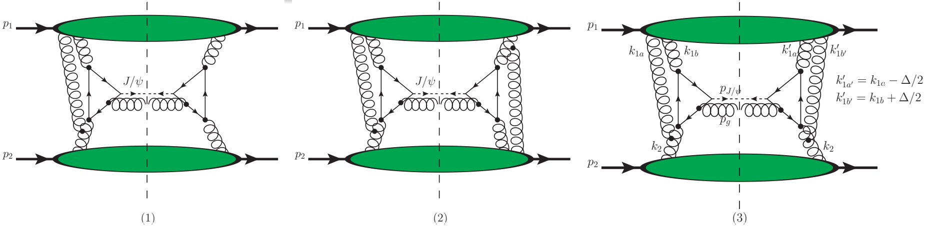




3-pomeron contributions



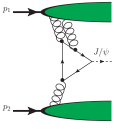
- Diagram (2) contributes additively to $d\sigma$
- Diagrams (1) and (3) might interfere:



- Diagrams (1) and (2) include Parton Distributions with odd number of gluons
- ... such distributions are sensitive if the proton is polarized [PLB 668 (2008), 216, PRD 78 (2008), 014024 , PRD 78 (2008), 114013].
- ... corresponding asymmetries are small, might neglect them [PHENIX Collaboration, PRD 82, 112008 (2010), PRD 86 (2012), 099904]

$\Rightarrow$Additive contribution to the LO cross-section, as shown in (3).

3-gluon fusion in dipole approach



(2)

$$\frac{d\sigma\left(Y,\,Q^2\right)}{dy\,d^2q_T} = 4\int\frac{d^2Q_T}{(2\pi)^2}\,S_h^2\left(Q_T\right)\;x_g G\left(x_g,\,M_{J/\psi}\right)$$

$$\times\int_0^1 dz\int_0^1 dz'\int\frac{d^2r}{4\pi}\,\frac{d^2r'}{4\pi}\,d^2b\;e^{-i\boldsymbol{q_T}\cdot\boldsymbol{b}}$$

$$\times\left\langle\Psi_g\left(r,z\right)\,\Psi_M\left(r,z\right)\right\rangle\left\langle\Psi_g\left(r',z'\right)\,\Psi_M\left(r',z'\right)\right\rangle\left(N\left(y;\,\boldsymbol{b}-\frac{1}{2}\left(\boldsymbol{r}-\boldsymbol{r}'\right)\right)\right.$$

$$\left.+N\left(y;\,\boldsymbol{b}+\frac{1}{2}\left(\boldsymbol{r}-\boldsymbol{r}'\right)\right)-N\left(y;\,\boldsymbol{b}+\frac{1}{2}\left(\boldsymbol{r}+\boldsymbol{r}'\right)\right)-N\left(y;\,\boldsymbol{b}-\frac{1}{2}\left(\boldsymbol{r}+\boldsymbol{r}'\right)\right)\right)^2$$

$$+\left(y\to Y-y\right)$$

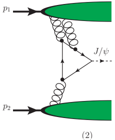
- Note: Results are defined up to nonperturbative normalization factor $\sim\int\frac{d^2Q_T}{(2\pi)^2}\,S_h^2\left(Q_T\right)$, related to Fourier image of cut pomeron Green function. This factor can be related to $\sigma_{\rm eff}$ which appears in models of DPDF & "pocket formula" for Double Parton Scattering,

$$\mathcal{F}\left(x_{1a},k_{1a,T},x_{1b},k_{1b,T}\right)\sim\frac{1}{\sigma_{\rm eff}}\mathcal{F}\left(x_{1a},\,k_{1a,T}\right)\mathcal{F}\left(x_{1b},\,k_{1b,T}\right),$$

$\Rightarrow\int\frac{d^2Q_T}{(2\pi)^2}\,S_h^2\left(Q_T\right)\sim({\rm const})\,\sigma_{\rm eff}^{-1}$

- Caveat: the "universal" value of $\sigma_{\rm eff}$ is not that universal; typical values are between 5 mb and 20 mb. [Eur.Phys.J. C77 (2017) no.2, 76]

Fixing uncertainty from diffractive photoproduction



$$\frac{d\sigma\left(Y,\,Q^2\right)}{dy} = \left(\int\dots\right)\left\langle\Psi_g\left(r,z\right)\,\Psi_{J/\psi}\left(r,z\right)\right\rangle\left\langle\Psi_g\left(r',z'\right)\,\Psi_{J/\psi}\left(r',z'\right)\right\rangle$$
$$\times\left(N\left(y;\,\frac{\mathbf{r}-\mathbf{r}'}{2}\right)-N\left(y;\,\frac{\mathbf{r}+\mathbf{r}'}{2}\right)\right)^2$$

- Use diffractive photoproduction ($\gamma^* p\to J/\psi\, X$) data to fix normalization:

$$\frac{d\sigma_{\rm diff}\left(Y,\,Q^2\right)}{dy} = \left(\int\dots\right)\left\langle\Psi_{\gamma^*}\left(r,z\right)\,\Psi_{J/\psi}\left(r,z\right)\right\rangle\left\langle\Psi_{\gamma^*}\left(r',z'\right)\,\Psi_{J/\psi}\left(r',z'\right)\right\rangle$$
$$\times N\left(y;\,\mathbf{r}\right)N\left(y;\,\mathbf{r}'\right)$$

For $Q^2\to\infty$, $m_c\to\infty$, $r\to 0$, can use pQCD expression for both $\Psi_{\gamma^*}\sim\Psi_g$.

- The dipole amplitude $N\left(y;\,\mathbf{r}\right)\sim\left(Q_s^2 r^2\right)^{\bar\gamma}$ at small r, so cross-secitons become proportional to each other⇒Can fix *hadro*production cross-section $d\sigma$ from diffractive *photo*production $d\sigma_{\rm diff}$ studied at HERA:

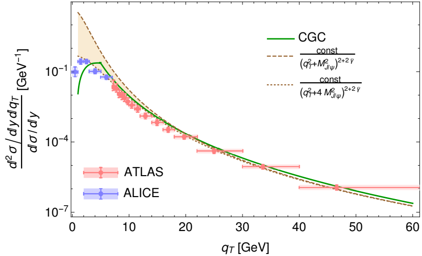
$d\sigma\left(y,\,Q^2\right)/dy$	Theoretical estimates	Experiment
$\sqrt{s}\approx 1.96$ TeV	2.1-2.6 μb	2.38 μb [67]
$\sqrt{s}\approx 7$ TeV	3.8-5.6 μb	5.8 μb [68]

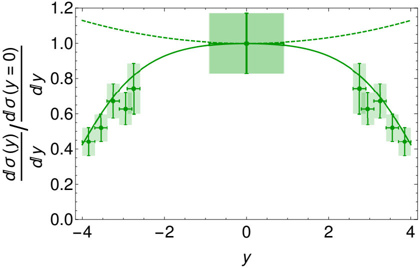
- Theoretical estimates: three-pomeron fusion gives sizeable contribution
- [Eur.Phys.J. C75 (2015) no.5, 213] (in k_T-fact): qualitatively agree; smaller due to larger $\sigma_{\rm eff}$

- In what follows will focus on shapes for p_T, rapidity, multiplicity dependence

3-pomeron J/ψ production with gluon emission

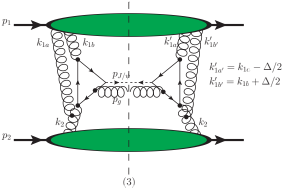
- Result for $g + gg \to J/\psi$





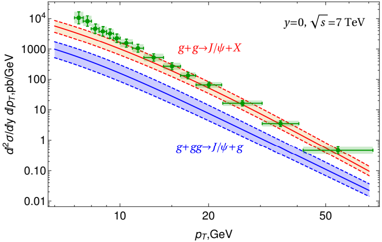
- BFKL: each gluon $\sim x^{\alpha}$ (dashed)
- Experiment: add endpoint suppression factor$\sim (1-x)^5$ (solid)

- Result for $g + gg \to g + J/\psi$



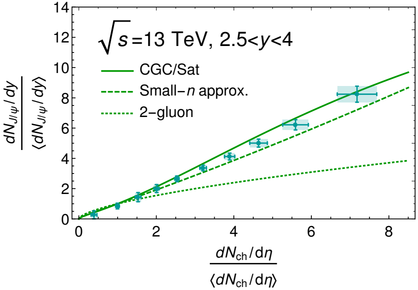
- ► Formally suppressed by α_s
- ► See [J.Phys.G 46 (2019) 6, 065002] for details

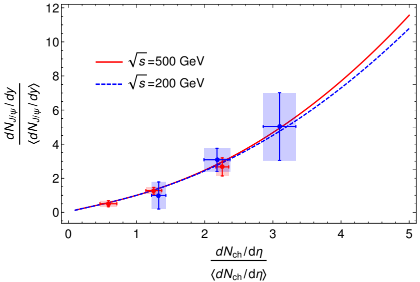
- Result for the cross-section:

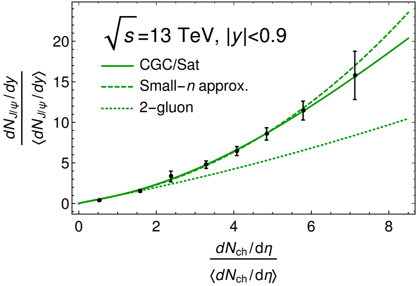


- $\Rightarrow$Contribution is sizeable, yet smaller than $g+gg \to J/\psi$ (due to $\mathcal{O}(\alpha_s(m_c))$)

Multiplicity dependence for J/ψ



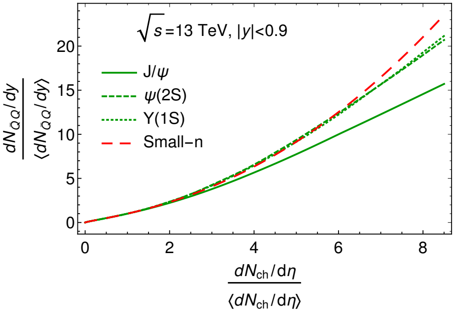


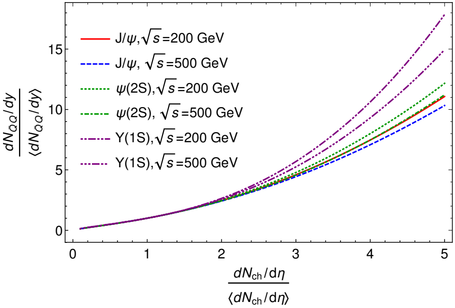


- Reasonable description of available data on multiplicity dependence from ALICE (both central & forward multiplicities) as well as STAR data at lower energies

- We believe that similar measurements of multiplicity dependencies might be done for $\psi(2S)$, $\Upsilon(nS)$. These data would help to confirm the role of the 3-pomeron mechanism in their formation.

Multiplicity dependence for other quarkonia (predictions)





Expected multiplicity dependence of other hadrons is similar to that of J/ψ:

► The typical dipole size $\langle r\rangle \sim \min\left(m_Q^{-1},\, Q_s^{-1}(x,\, n)\right)$, significantly smaller than the quarkonium size $\langle r_M\rangle \sim (m_Q\alpha_s(m_Q))^{-1}$.

⇒The quarkonium wave function might be approximated as $\psi_M(r) \approx \psi_M(0) + \mathcal{O}\left(r^2\right)$, cancels in self-normalized ratio

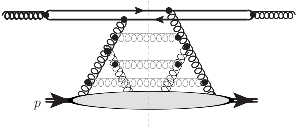
► The residual dependence on quarkonia is due to $\sim \mathcal{O}\left(\left\langle r^2\right\rangle \Big/ \left\langle r_M^2\right\rangle\right)$ corrections beyond the heavy quark mass limit

▷At small n, $\left\langle r^2\right\rangle \sim m_Q^{-2}$, so $\left\langle r^2\right\rangle \Big/ \left\langle r_M^2\right\rangle \sim \alpha_s^2\left(m_Q\right)$-no energy dependence, mild log-dependence on m_Q

▷At large n, $\left\langle r^2\right\rangle \sim 1/Q_s^2$, so $\left\langle r^2\right\rangle \Big/ \left\langle r_M^2\right\rangle \sim \left(m_Q^2\alpha_s^2\left(m_Q\right)/Q_s^2\right)$-pronounced dependence on m_Q and energy (through Q_s)

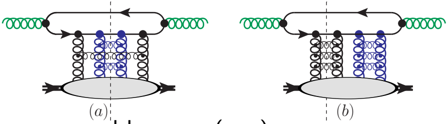
D- and B-mesons

- Leading order (2-Pomeron fusion):



► CGC/Sat (dipole) approach: the bCGC takes into account certain fan-like topologies

- 3-pomeron corrections:



- suppressed by $\sim \alpha_s (m_Q)$
- Two types of contributions:

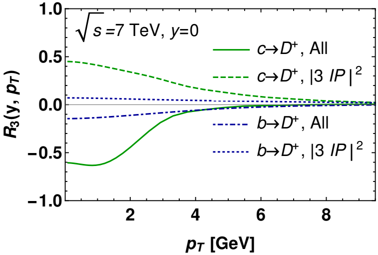
(a) "genuine" three-pomeron fusion, same as for J/ψ

(b) interference diagram

- Have opposite signs, comparable magnitude. Different number of cut pomerons is relevant for multiplicity dependence.

- Ratio of 3-pomeron to 2-pomeron contributions:

$$R^{(3)}(y,\ p_T) = \frac{d\sigma^{(3)}/dy\,dp_T}{d\sigma^{(2)}/dy\,dp_T}.$$



"3IP" is "genuine" contribution

"All" includes also interference diagrams

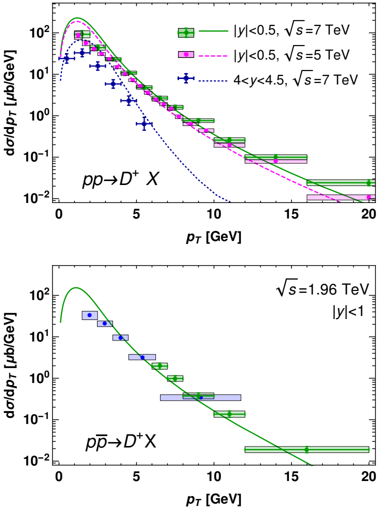
- Effect is sizeable for charm at small p_T

►Decreases at large p_T

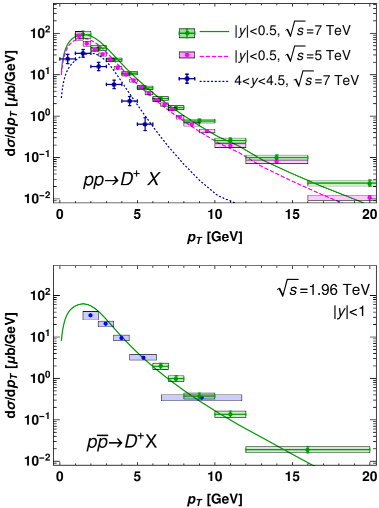
►Decreases as a function of mass m_Q (so for bottom quarks the 3-pomeron contribution is small)

3-pomeron contributions vs data

Results w/o 3-pomeron contribution:



Results with 3-pomeron contribution:

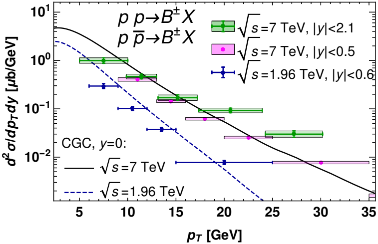


- *over*estimate the data by factor ~ 2 at $p_T \lesssim 3\,\mathrm{GeV}$ (dominant in p_T-integrated cross-section)

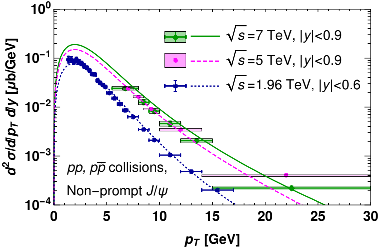
- Inclusion of 3-pomeron contribution definitely improves small-p_T description

Comparison with inclusive data

B-meson production

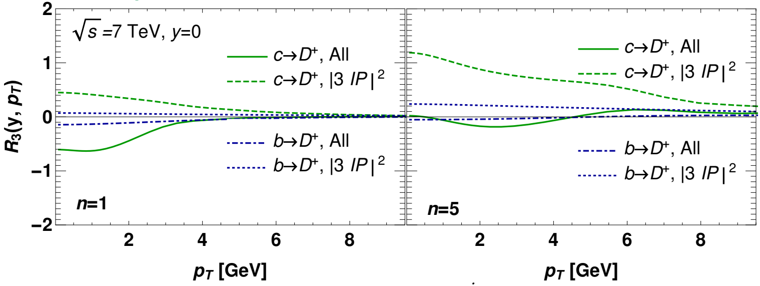


Non-prompt charmonia production



- Very reasonable description for *B*-mesons and non-prompt J/ψ achieved

Multiplicity dependence



- Ratio of 3-pomeron to 2-pomeron contributions which we defined earlier:

$$R^{(3)}\left(y,\ p_T\right)=\frac{d\sigma^{(3)}/dy\ dp_T}{d\sigma^{(2)}/dy\ dp_T}.$$

► "3$I\!P$" is "genuine" contribution

► "All" includes also interference diagram

►$n = (dN_{\rm ch}/dy)/\langle dN_{\rm ch}/dy\rangle$-relative enhancement of multiplicity

Multiplicity dependence

(*overlapping bins @central rapidity*):

►The leading twist contribution $\sim n^{2\gamma}$

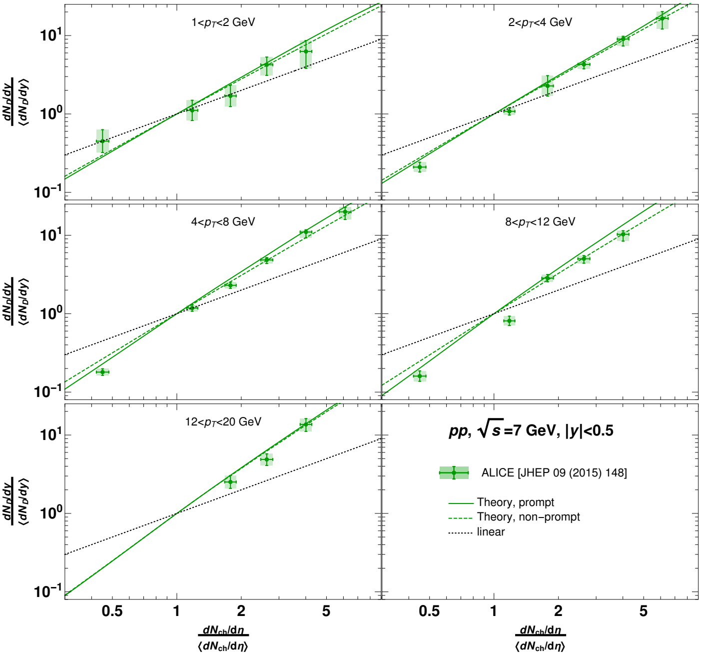
►The "genuine" tw-3 contribution grows as $\sim n^{3\gamma}$

►The interference term grows as $\sim n^{2\gamma}$. It is *negative*, for $n\sim 1$ is twice larger than genuine contribution

⇒The last two mechanisms partially cancel, for $n\sim 5$ almost complete cancellation

►For $n\gtrsim 6$ the "genuine" contribution becomes dominant, grows rapidly with n.

- Reasonable description of multiplicity dependence from ALICE
  - ▶ Theoretical curves include both 2- and 3-pomeron contributions



Summary

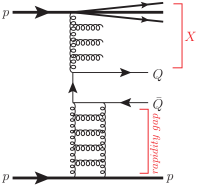
- We found that the three-pomeron terms give sizeable contribution in LHC kinematics, especially for charm in small-p_T kinematics.

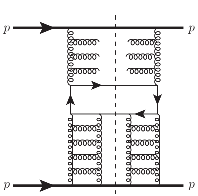
The inclusion of three-pomeron contributions:

►Improves description of inclusive data

►Allows to explain the multiplicity dependence seen both in open heavy flavor and quarkonia production, without additional model assumptions

- Possible way to measure the 3-pomeron fusion mechanism only: Single Diffractive production, $pp \to p + (\text{rapidity gap}) + \{D, B,\ J/\psi\}\, X$





► Evaluation is similar to inclusive production via 3-pomeron fusion (though differs in kinematical factors)

▷ See our recent arXiv:2008.12446 for details & predictions

Thank You for your attention!