Production mechanisms of open heavy flavor mesons and quarkonia in high-multiplicity events

Marat Siddikov

Universidad Técnica Federico Santa María

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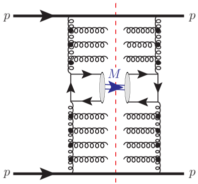
Introduction

- Conventional picture of inclusive production in high energy process:

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



► Red line is unitarity cut

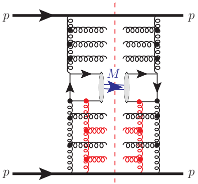
► Final state M might include one or more hadrons

► Gluons ⇒gluon showers

▷ reggeization⇒ pomerons

⇒Cross-section is dominated by pomeron-pomeron fusion

- Diagrams with more than two pomerons are usually disregarded:



► Suppressed if gluon densities are not large

► Suppressed if $\alpha_s(\mu_F) \ll 1$

► Frequently additional ("higher twist") suppression,

$$\alpha_s(\mu_F) \to \frac{\Lambda_{\rm soft}^2}{\mu_F^2} \ll \alpha_s(\mu_F)$$

► *Caution in small-x regime ($x_i \ll 1$):*

▷ *gluon densities grow vigorously, might compensate all suppression factors*

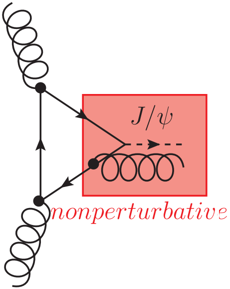
▷ *situation ambiguous up to now, from inclusive production difficult to judge*

▷ *I am going to demonstrate that data on multiplicity dependence could help to clarify situation ...*

▷ *I will consider heavy quarks ("cleanest" channel, hard scale $\mu_F \gtrsim m_Q$)*

J/ψ production in pp collisions (short summary)

(see QWG review, Eur.Phys.J. C71 (2011) 1534)
(see also talks in yesterday session)



Color Singlet Model (CSM):

- Emission of at least one gluon required due to quantum numbers of J/ψ (essentially nonperturbative)
- Reasonable description for small-p_T & p_T-integrated observables
- Wrong behavior for $p_T \gg m_{J/\psi}$ (EPJC 79 (2019) 241)

NRQCD:

- Soft gluon emission $\Rightarrow$ nonperturbative Long Distance Matrix Elements (LDMEs), systematic approach

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

▷ LDMEs for other quarkonia ($2S$, $1P$, all $\bar{b}b$) are negligibly small. Why J/ψ is so different?

► Challenge 2: Implement possible contributions of other mechanisms, *e.g.*:

▷ Co-production ($J/\psi + \bar{Q}Q$, ...) (PRL 101 (2008) 152001) ...

▷ Quark and gluon fragmentation (EPJC 79 (2019) 241) ...

$\Rightarrow$ *Understanding of J/ψ production still is not complete*

Multiplicity observable

- The kinematic distributions of a J/ψ alone cannot clarify the role of 3-pomeron mechanisms:

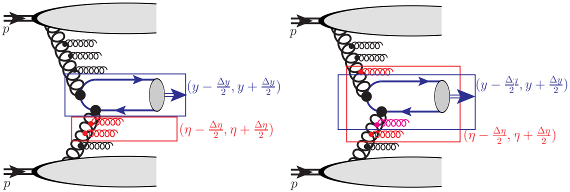
 ▷always can attribute possible discrepancy between data and 2-pomeron production to some new soft process at J/ψ formation stage

- Fortunately, nowadays it is possible to study collective production:

► In case of *inclusive* processes $pp \to M$ the final quarkonium is not produced alone, always accompanied with avalanche of co-produced particles

⇒Makes sense to study the distribution of these co-produced hadrons

▷ The bins used to collect J/ψ and light hadrons might either overlap or not, to exclude possible contributions of hadronization debris:



- The contribution of 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

- Local Parton Hadron Duality: $dN_{\rm ch} \sim dN_{\rm partons}$ (number of partons)
- Probability $P\left(N_{\rm parton}\right)$ of large multiplicity flucuations 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 $\sqrt{s}_{pp}$.

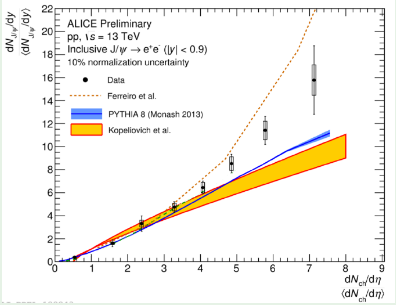
- More common variable is the self-normalized yield:

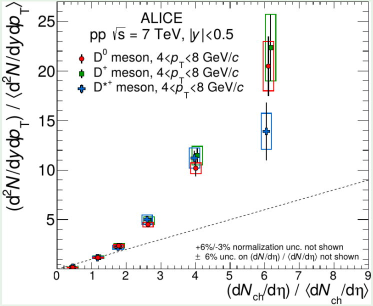
$$\frac{dN_M/dy}{\langle dN_M/dy\rangle} = \frac{d\sigma_M\left(y,\,\eta,\,\sqrt{s},\,n\right)/dy}{d\sigma_M\left(y,\,\eta,\,\sqrt{s},\,\langle n\rangle = 1\right)/dy} \Bigg/ \frac{d\sigma_{\rm ch}\left(\eta,\,\sqrt{s},\,Q^2,\,n\right)/d\eta}{d\sigma_{\rm ch}\left(\eta,\,\sqrt{s},\,Q^2,\,\langle n\rangle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

-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

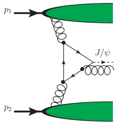
Multiplicity dependence of charmonia production [ALICE, 1811.01535]

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



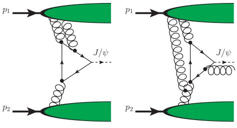


- Enhancement (deviation from linear) seen both for J/ψ and D mesons
- So far not clear if the effect exists for $\psi(2S)$, χ_c, Υ?



(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).
- Originally seen in AA, touted as QGP signal



(2) (3)

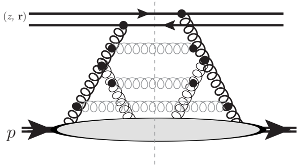
Now we are going to stop briefly on multipomeron mechanisms and some technical details related to evaluations

- We used CGC/Sat (color dipole) framework for our evaluations.
  - ►In the literature it is frequently assumed that the dipole cross-section is universal object which already takes into account all possible interactions with the target.
  - ►Before we continue discussion, we need to revisit what is included into dipole cross-section and what is not.
  - ►Also we'll discuss 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 rapidity evolution

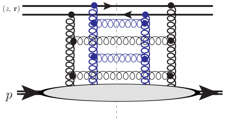
►effectively resums the fan-like diagrams as shown in the Figure



b-CGC parametrization:

► Constructed as interpolation of asymptotic solutions of BK equation

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



⇒Need to take them into account

High multiplicity events:

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

►Relation of saturation scale Q_s to observed multiplicity dependence

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

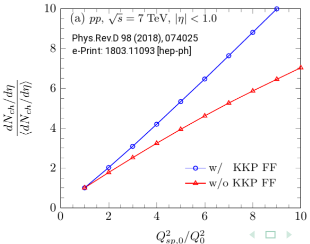
▷N_P-number of cut pomerons

⇒ Modification of saturation scale:

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

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

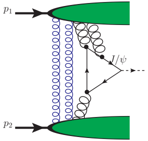
(modulo small logarithmic corrections)



Multiplicity enhancement mechanisms

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

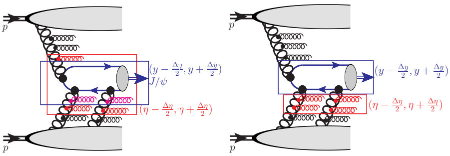
$$\frac{dN_M/dy}{\langle dN_M/dy\rangle} = \frac{d\sigma_M\left(y,\eta,\sqrt{s},n\right)/dy}{d\sigma_M\left(y,\eta,\sqrt{s},\langle n\rangle{=}1\right)/dy}$$

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

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

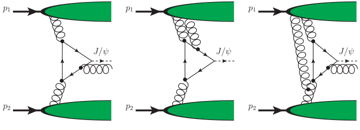
► If n is not very large, dipole size $\langle r\rangle \sim 1/m_Q$, so each cut pomeron contributes a factor $\sim (r\,Q_s)^{\gamma_{\rm eff}} \sim n_i^{\gamma_{\rm eff}}$, $\gamma_{\rm eff}(r,\sqrt{s}) \approx 0.7-0.75$

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

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

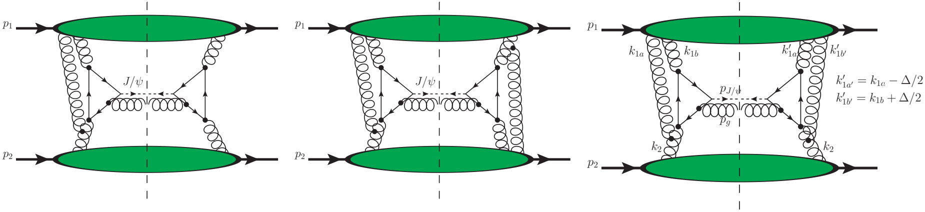
2- vs. 3-pomeron contributions for 1S quarkonia

- For 1S quarkonia have two complementary 3-pomeron mechanisms (diags 2 & 3):



(1) (2) (3)

- 2-pomeron: CSM + color octet contributions
- Diagram (2) contributes additively to $d\sigma$
- Diagrams (1) and (3) might interfere:



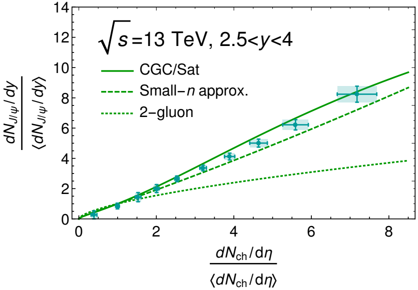
(1) (2) (3)

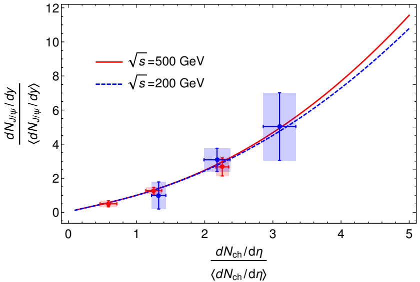
- Diagrams (1) and (2) include Parton Distributions with odd number of gluons
- ... such distributions contribute if the proton is polarized [PLB 668 (2008), 216, PRD 78 (2008), 014024 , PRD 78 (2008), 114013].
- ... corresponding asymmetries are small, might neglect them [PHENIX Collaboration, PRD 82,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

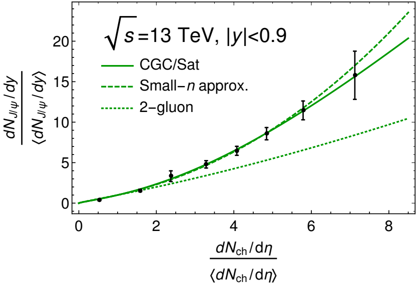
⇒Additive contribution to the LO cross-section.

► Numerically 3-pomeron contributions are smaller than 2-pomeron fusion, but become important in high-multiplicity events

Multiplicity dependence for J/ψ





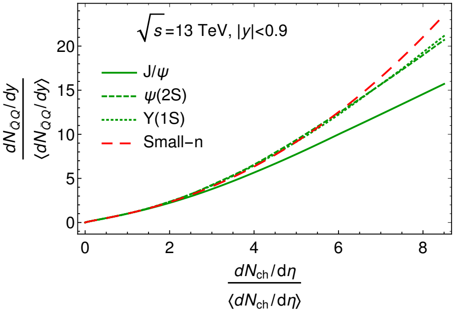


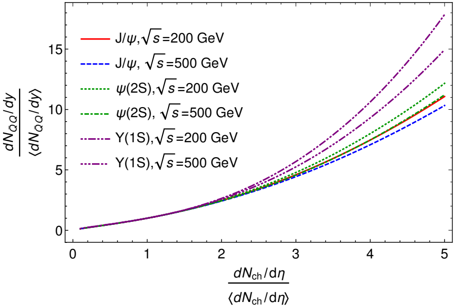
- Reasonable description of available data on multiplicity dependence from ALICE (both central & forward multiplicities) as well as STAR data

►Very roughly, each cut pomeron=multiplicative factor $\sim n^{\gamma_{\rm eff}}$, $\gamma_{\rm eff} \approx 0.7 - 0.75$, so clearly can distinguish 2- and 3-pomeron mechanisms

- Similar measurements can be done for multiplicity dependencies of $\psi(2S)$, $\Upsilon(nS)$, χ_c, χ_b.

Multiplicity dependence for other S-wave quarkonia





Expected multiplicity dependence of other 1S quarkonia 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 $\langle r_M \rangle \sim \left(m_Q \alpha_s(m_Q)\right)^{-1}$.

⇒The quarkonium WF

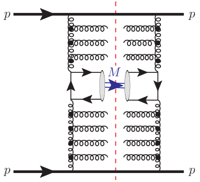
$$\psi_M(r) \approx \psi_M(0) + \mathcal{O}\left(r^2\right),$$

cancels in self-normalized ratio

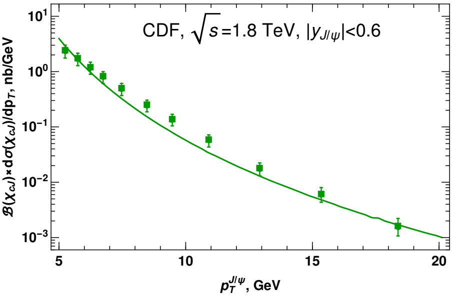
► The residual dependence on quarkonia, energy from r, $\sqrt{s}$ -dependence of $\gamma_{\rm eff}(r,\, \sqrt{s})$. in $\sim n^{\gamma_{\rm eff}}$ -factors for each pomeron

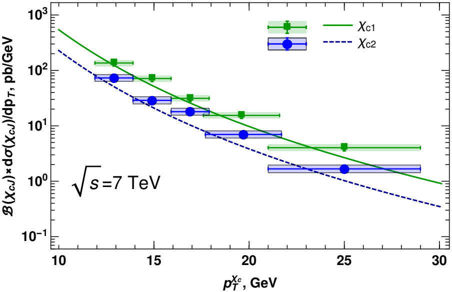
Production of P-wave quarkonia (χ_c, χ_b)

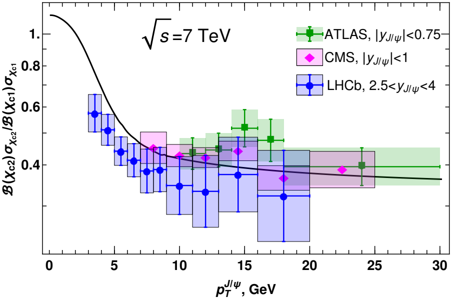
- Leading contribution: 2-Pomeron fusion



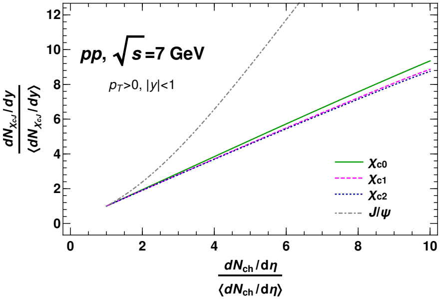
- Good description of the data from CDF and LHC:

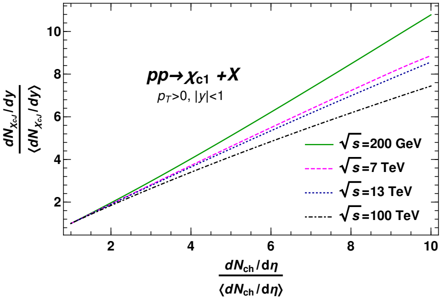


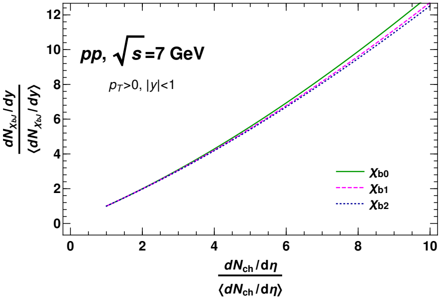




Multiplicity dependence for P-wave quarkonia (χ_c, χ_b)







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

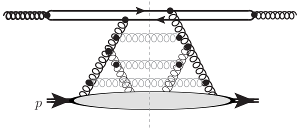
▷Each cut pomeron≈factor $\sim n^{\gamma_{\rm eff}}$.

►Higher order corrections are suppressed significantly

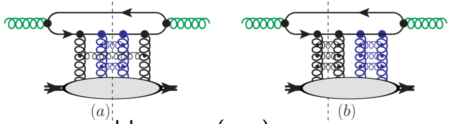
Confirmation of this result would help to clarify the role of three-pomeron mechanism in quarkonia formation

Production of 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:

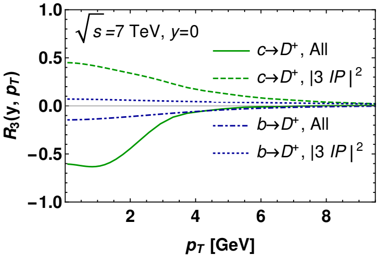
(a) "genuine" three-pomeron fusion, same as for J/ψ

(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

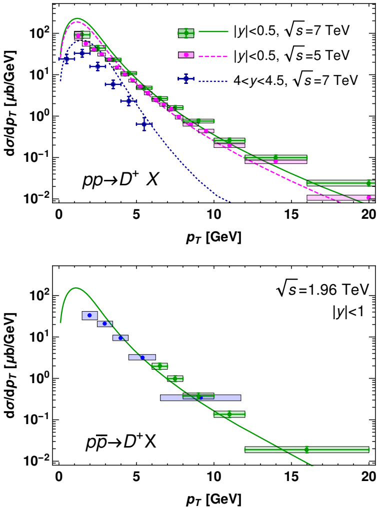
- Effect is sizeable for charm at small p_T

►Decreases at large p_T

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

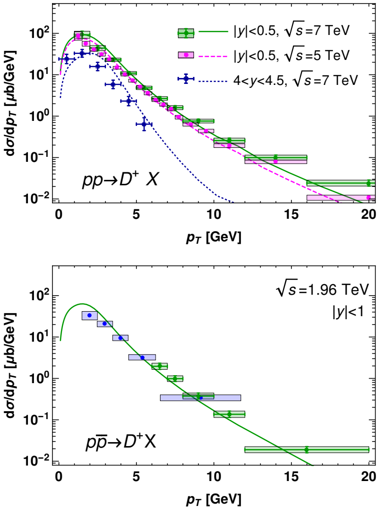
3-pomeron contributions vs data

Results w/o 3-pomeron contribution:



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

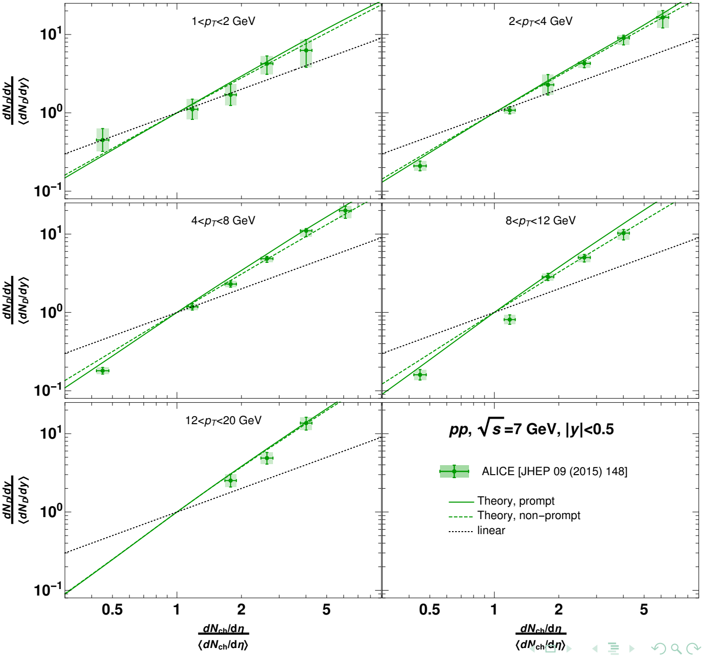
Results with 3-pomeron contribution:



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

Multiplicity dependence for D- and B-mesons

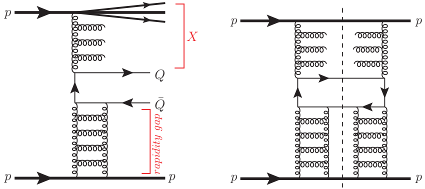
- Evaluation similar to quarkonia
  - ►For D-mesons 3-pomeron correction $\sim$ 40% at small p_T and integrated cross-section
  - ►For B-mesons does not exceed 10% event at small p_T
- Reasonable description of multiplicity dependence from ALICE (2- and 3-pomerons included)



Single-diffractive production

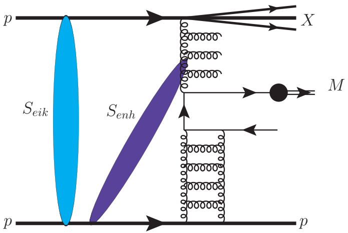
- Possible way to measure the 3-pomeron mechanism only:
Single Diffractive production, $pp \to p + (\text{rapidity gap}) + \{D, B, J/\psi\}\, X$

►Telltale signal: rapidity gap between heavy meson and one of the protons

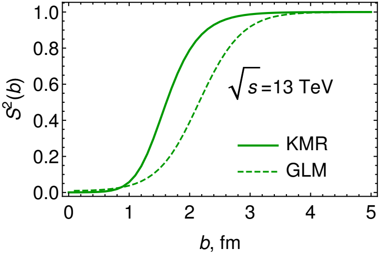


► Evaluation is similar to inclusive production via 3-pomeron fusion (though differs in kinematical factors)
►Only one pomeron is cut
⇒Should have milder dependence on multiplicity

►Should take into account gap survival factors S^2 (probability that gap won't be filled with debris)



▷Suppresses cross-section significantly:



▷b=impact parameter between colliding pp
▷Dominant contribution from $b \lesssim 1$ fm

Single-diffractive (SD) production

- Expectations for the ratio SD/inclusive (p_T-integrated) cross-sections

$$R_M^{(\mathrm{SD})}(s,\, y,\, p_T) \equiv \frac{d\sigma_M^{\mathrm{SD}}/dy}{d\sigma_M^{\mathrm{incl}}/dy}, \quad M = D^{\pm}, B^{\pm}, \ldots,$$

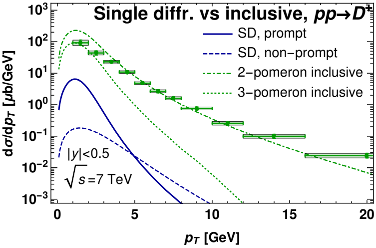
$\sqrt{s}$	$R_{\bar{c}c}^{(\mathrm{SD})}$	$R_{\bar{b}b}^{(\mathrm{SD})}$	$R_{J/\psi,\,\mathrm{nonprompt}}^{(\mathrm{SD})}$
1.8 TeV	2.20 %	0.40 %	0.57%
7 TeV	1.87 %	0.33 %	0.45%
13 TeV	1.59 %	0.30 %	0.40%

►In reasonable agreement with Tevatron data [PRL **84** (2000), 232]:

$$R_{\bar{b}b}^{(\mathrm{SD.})} = (0.62 \pm 0.19 \pm 0.16)\,\%.$$

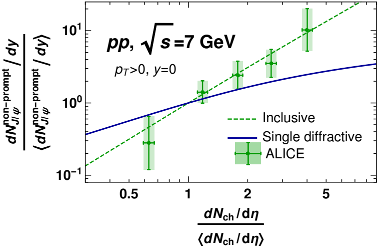
►No data for SD from LHC so far

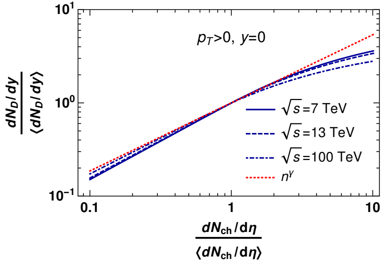
- At large p_T SD suppressed stronger than inclusive production, in agreement with twist counting expectations



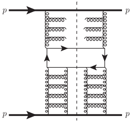
- See Phys.Rev.D 102 (2020) 076020 for $B^{\pm}$, J/ψ plots & predictions for higher energies

Single-diffractive production





- Multiplicity dependence is milder than for inclusive production, since have only one cut pomeron which contributes to the yields of charged particles $\Rightarrow$



- For p_T-integrated cross-section the multiplicity dependence given by a common factor for all possible SD-production channels of heavy mesons

$$\frac{dN_M/dy}{\langle dN_M/dy\rangle} = \frac{\int d^2r\, \frac{J_1(r\,\mu_F)}{r} \nabla_r^2 N\left(y,\, \boldsymbol{r},\, n\right)}{\int d^2r\, \frac{J_1(r\,\mu_F)}{r} \nabla_r^2 N\left(y,\, \boldsymbol{r},\, 1\right)},$$

where $N(\ldots)$ is the forward dipole amplitude.

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 $D^{\pm}$- and J/ψ-meson production, without additional model assumptions

- Our **pre**dictions:
 ►Other S-wave quarkonia ($\psi(2S)$, $\psi(3S)$,$\Upsilon(1S)$, $\Upsilon(2S)$) should have the same rapid multiplicity dependence as J/ψ & $D^{\pm}$ (modulo small corrections)
 ►For P-wave quarkonia (χ_c, χ_b) dependence is much weaker than for $1S$ quarkonia since 3-pomeron mechanism can't contribute
 ►For Single Diffractive production, $pp \to p + (\text{rapidity gap}) + \{D, B, J/\psi\} X$ expect much milder dependence on multiplicity since only one of the pomerons can contribute

Thank You for your attention!