# Single-diffractive production of heavy mesons in *pp* and *pA* collisions

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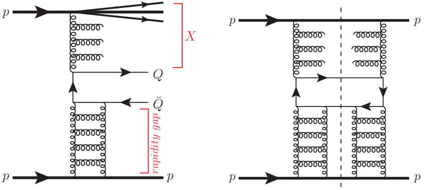
# Single-diffractive (SD) production

- Single Diffractive production, $pp \to p + (\text{rapidity gap}) + \{D, B, J/\psi\}\, X$




*Difference from inclusive*:

► Rapidity gap⇒interaction via *pomeron* ($I\!P$) exchange in *amplitude*. Cross-section:⇒3 $I\!P$ fusion

▷Ingelman-Schlein approach: introduces diffractive PDFs of gluons and quarks, $g_D$, $q_D$

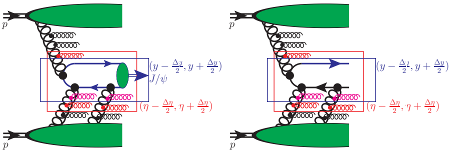
► Small-$x$ kinematics:

▷gluon densities grow rapidly, compensate $\mathcal{O}(\alpha_s)$-suppression of additional pomeron exchanges ("saturation")

▷Color dipole picture might be more accurate in this kinematics

***Motivation for SD studies at LHC***:

► Recent studies: for *inclusive* quarkonia and $D$-meson production the 3-pomeron contributions might be pronounced [EPJC **75** , 213; EPJC79, 376; PRD **101**, 094020; EPJC **80**, 560]




► The SD cross-section has similar structure, is dominated by the three-pomeron contributions only, so it allows to single out that contributions and study in detail

▷Should take into account certain additional (well-understood) effects & kinematic factors which diminish the SD cross-section.

# SD production in dipole picture

- ▶ We used the color dipole approach (well-justified for small-$x$ kinematics)
  - ▷ Cross-section fully determined, no free/unknown parameters

$$\frac{d\sigma_M}{dy\, d^2p_T} = \sum_i \int_{x_Q}^1 \frac{dz}{z^2} \underbrace{D_{i/M}\left(\frac{x_Q(y)}{z}\right)}_{\text{frag. function}} \frac{d\sigma_{\bar{Q}_i Q_i}}{dy^* d^2 p_T^*}$$

$$\frac{d\sigma_{\bar{Q}_i Q_i}\left(y,\sqrt{s}\right)}{dy\, d^2p_T} = \int d^2k_T x_1 g\left(x_1, \boldsymbol{p}_T - \boldsymbol{k}_T\right) \int_0^1 dz \int_0^1 dz'$$

$$\times \int \frac{d^2r_1}{4\pi} \int \frac{d^2r_2}{4\pi} e^{i(\boldsymbol{r}_1 - \boldsymbol{r}_2)\cdot \boldsymbol{k}_T} \underbrace{\Psi^\dagger_{\bar{Q}Q}\left(r_2, z, p_T\right) \Psi_{\bar{Q}Q}\left(r_1, z, p_T\right)}_{\text{(perturbative) wave functions of } g\to Q\bar{Q}}$$

$$\times N_M^{(\mathrm{SD})}\left(y;\, z,\, \vec{\boldsymbol{r}}_1,\, \vec{\boldsymbol{r}}_2\right) + \left(y \leftrightarrow -y\right),$$

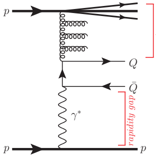
- ▷ Cross-section is expressed via $N_M^{(\mathrm{SD})}\left(y;\, z,\, \vec{\boldsymbol{r}}_1,\, \vec{\boldsymbol{r}}_2\right)$, which is bilinear combination of impact-parameter dependent *color singlet* dipole amplitudes $N\left(x,\, \boldsymbol{r}_i,\, \boldsymbol{b}\right)$ convoluted over $\int d^2\boldsymbol{b}$; $\boldsymbol{r}_i$ is some linear combination of $\boldsymbol{r}_1$, $\boldsymbol{r}_2$

⇒ All elements which contribute to $d\sigma_M$ are known from inclusive channels

# Challenges of SD production

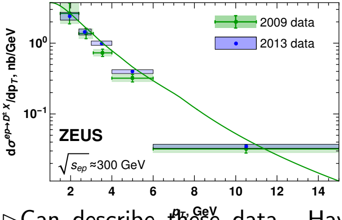
***Some challenges for SD studies***:

▶ Same final state as diffractive *photo*production:



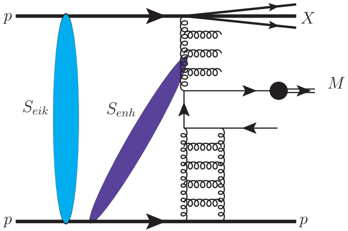

▷$\mathcal{O}(\alpha_{\rm em})$ suppressed, yet might contribute in ultraperipheral kinematics

▷Studied at HERA [EPJC 77, 550 (2017), EPJC 79 (2019) , 388, NPB 871, 1 (2013)]

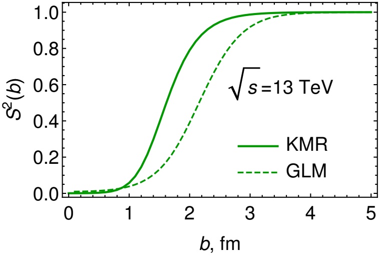



▷Can describe these data. Have also predictions for EIC kinematics

▶Should take into account gap survival factors $S^2$ (probability that gap won't be filled with debris of secondary processes) [EPJC 18, 167; JPG 36, 093001, EPJC 47, 655]




▷Suppresses cross-section significantly:




▷$b$=impact parameter between colliding $pp$

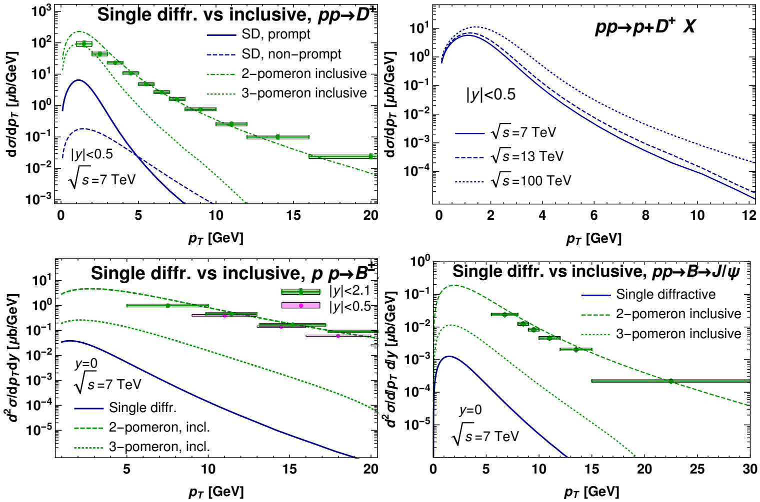
▷Central events ($b \lesssim 1$ fm) are suppressed

# Comparison with data & other approaches

- Almost no experimental SD data for comparison.
  - We'll compare with *inclusive* data and predictions for SD of other approaches (mostly Ingelman-Schlein)

# Comparison with inclusive production

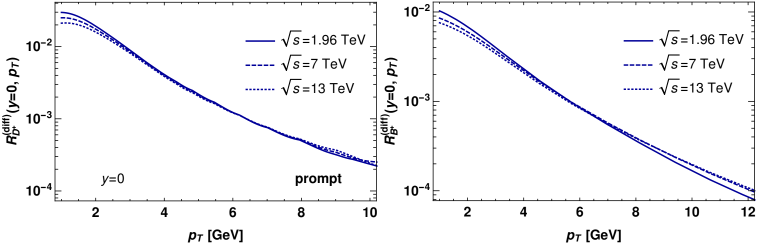
► Results for $D$-, $B$- and nonprompt $J/\psi$ mesons:




- At large $p_T$ SD is suppressed stronger than inclusive, in agreement with twist counting expectations (akin to 3-pomeron correction in inclusive channel)
- Difference of non-prompt $J/\psi$ and $B^{\pm}$ only due to fragmentation functions

# Comparison with Tevatron data

- Expectations for the ratio SD/inclusive ($p_T$-dependent) cross-sections. As discussed earlier, SD suppressed at large $p_T$




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

| $\sqrt{s}$ | $R^{(\mathrm{SD})}_{\bar{c}c}$ | $R^{(\mathrm{SD})}_{\bar{b}b}$ | $R^{(\mathrm{SD})}_{J/\psi,\,\mathrm{nonprompt}}$ |
|---|---|---|---|
| 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]:

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

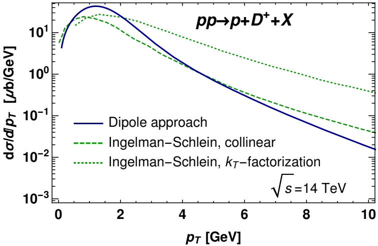
- No data from LHC as of now

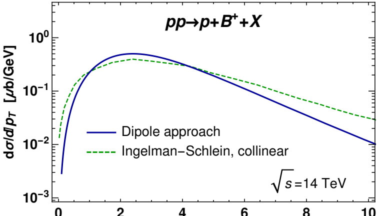
# Comparison with other approaches

▶ Comparison with Ingelman-Schlein approach

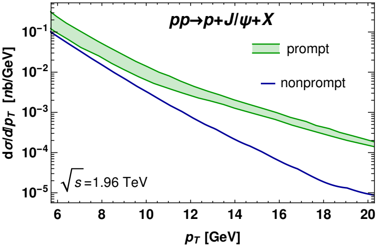
▷ $IP \to g_D$, $q_D$-diffractive PDFs; use collinear or $k_T$-fact. for evaluation of amplitudes

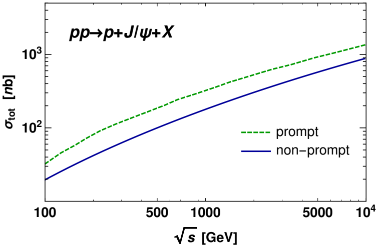
[PRD 91, no.5, 054024 (2015), JHEP 02, 089 (2017)]




▶ Comparison with prompt $J/\psi$ [PRD 57, 5658; PRD 58, 114016]




▶ Energy dependence is similar, $p_T$-dependence of prompt mechanism is milder

# Multiplicity observable

- Measures distribution of charged particle co-produced together with a given hadron
  - ▶ Can collect charged particles either in the same bin as meson $M$ or in separated bins (different observables, results for multiplicity might differ)
  - ▶ Local Parton Hadron Duality: $dN_{\rm ch} \sim dN_{\rm partons}$ (number of partons) $\Rightarrow$ information about partons in a given rapidity range
  - ▶ 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:

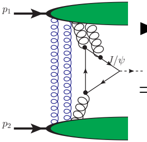
$$\frac{dN_M/dy}{\langle dN_M/dy\rangle}=\frac{d\sigma_M\left(y,\,\eta,\,\sqrt{s},\,n\right)/dy}{d\sigma_M\left(y,\,\eta,\,\sqrt{s},\,\langle n\rangle=1\right)/dy}\Bigg/\frac{d\sigma_{\rm ch}\left(\eta,\,\sqrt{s},\,Q^2,\,n\right)/d\eta}{d\sigma_{\rm ch}\left(\eta,\,\sqrt{s},\,Q^2,\,\langle n\rangle=1\right)/d\eta}$$

*-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*

▶In case of inclusive production ($J/\psi$, $D$) STAR & ALICE found experimentally that ratio grows faster than could be expected from 2-pomeron fusion, interpreted as signal of pronounced 3-pomeron contributions.

# Why multiplicity dependence matters?

- ► Various mechanisms of multiplicity production; gluon cascades ("pomerons") might be attached in different ways.




*(gluons are reggeized)*

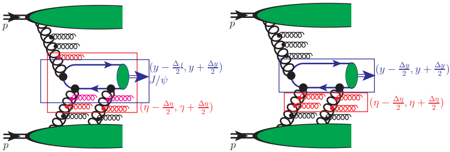
- ► Kinematic distributions of heavy mesons (in $y$ , $p_T$ ) not very informative.
- ► Multiplicity: "scans" density of partons in a given rapidity interval
- ► Pomerons disconnected from hard process (blue) after resummation give a common factor $P(n)$, same as in inclusive production
- ► For the self-normalized ratio $\frac{dN_M/dy}{\langle dN_M/dy \rangle}$ the common factor $P(n)$ cancels

$\Rightarrow$ Only cut pomerons connected to hard amplitude matter

- ► Multiplicity distribution for individual pomerons is known from BFKL

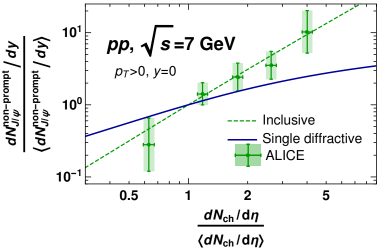
$\Rightarrow$ Multiplicity dependence *of a process* is sensitive to a number of pomerons attached to hard amplitude and stretching a given rapidity interval

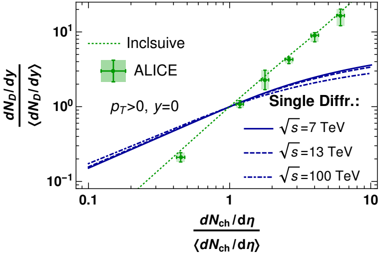
- ▷ Can consider different setups, e.g. the bins used to collect charged particles (red in plot) might overlap or not with a bin used to collect quarkonia (blue in plot)



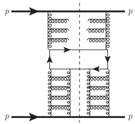

– If bins overlap, enhanced multiplicity is shared by all pomerons (summation over all partitions implied), otherwise only some of them matter.

# SD: Multiplicity dependence




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



- 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.

# SD: Nuclear dependence

- Could extend the process to $Ap \to A + (\text{rapidity gap}) + M\,X$

***Advantages***:

▷Cross-section enhanced by $\sim A^n \gg 1, \qquad n \lesssim 1.$

▷Sat-scale enhanced as

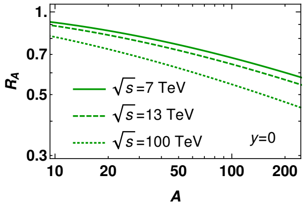
$$Q_{sA}^2(x) \approx Q_s^2(x)\,A^{1/3\delta}, \qquad \delta \approx 0.79 \pm 0.02.$$

access to deeply saturated regime (10-fold increase for $A \sim 208$)

▷Convenient to quantify the nuclear effects using the ratio

$$R_A(y) = \frac{d\sigma_{pA \to p\,M\,X}/dy}{A\,d\sigma_{pp \to p\,M\,X}/dy}.$$

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




$$R_A(y) \approx \frac{1}{A}\,\frac{\int d^2b \int d^2r\,\frac{J_1(r\,\mu_F)}{r}\nabla_r^2 N_A\left(y,\,\boldsymbol{r},\,\boldsymbol{b}/A^{1/3}\right)}{\int d^2b \int d^2r\,\frac{J_1(r\,\mu_F)}{r}\nabla_r^2 N\left(y,\,\boldsymbol{r},\,\boldsymbol{b}\right)},$$

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

# Summary

- We studied the single-diffractive production of heavy mesons $D$, $B$, $J/\psi$ in color dipole (CGC) framework in Tevatron & LHC kinematics

▷We believe that this channel presents interesting direction for study at HL-LHC and future colliders and could help to understand:

▷... the role of 3-pomeron mechanism in inclusive channel

▷... the multiplicity enhancement mechanisms in inclusive processes

►We also studied the diffractive electroproduction in EIC kinematics which has similar topology and could be studied in detail at EIC.

*Thank You for your attention!*