J/ψ production in hadron scattering: three-pomeron contribution

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Based on:

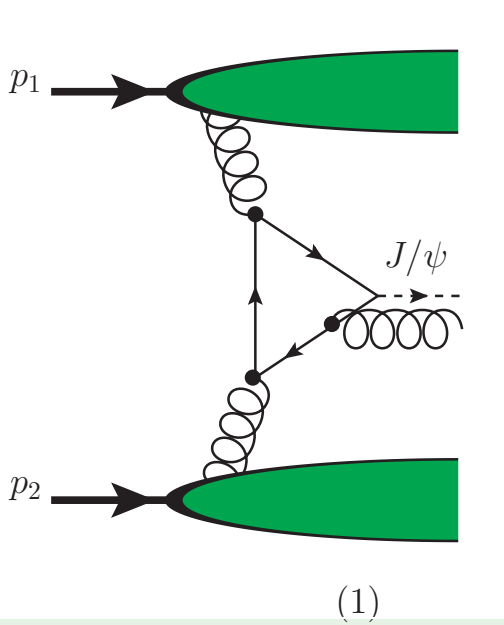
Eur.Phys.J. C79 (2019) no.5, 376,

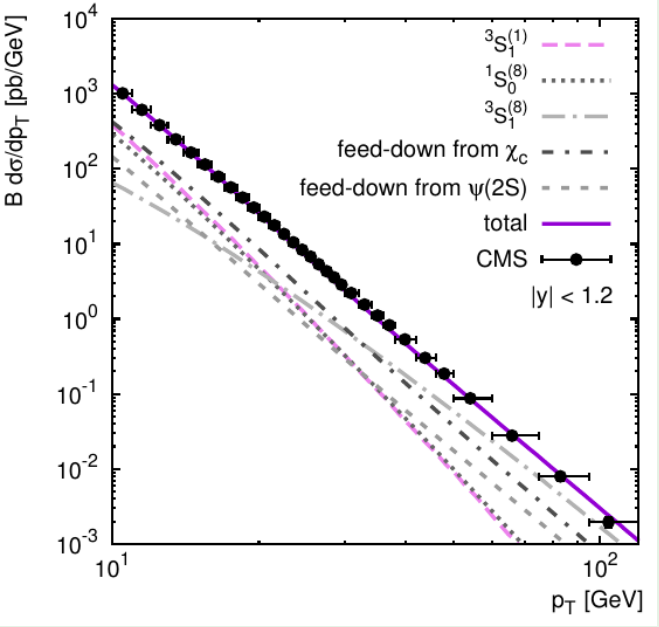
J.Phys. G46 (2019) no.6, 065002

J/ψ in pp collisions-how is it produced?

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

Color Singlet Model & NRQCD corrections





(CSM alone):

- Reasonable predictions for:
  - small-p_T observables
  - p_T-integrated observables
- Wrong behaviour 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)
- ... ?

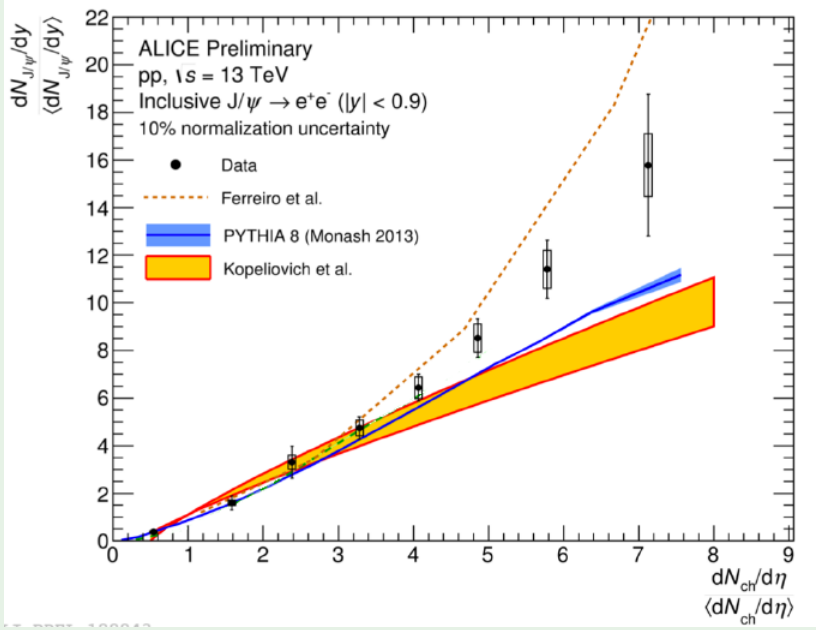
Challenge for NRQCD: LDMEs not universal ?!

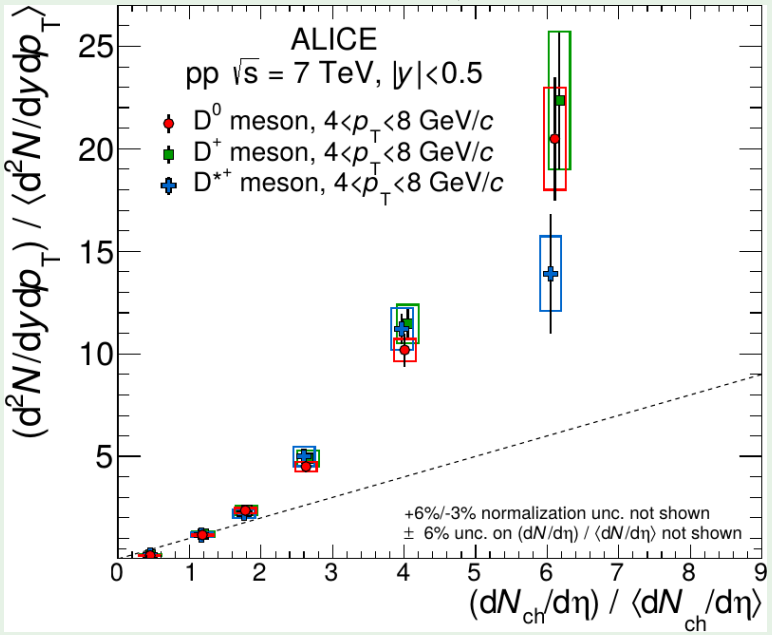
[Phys. Rev. D 96, no. 3, 034019 (2017)]:

	$\langle \mathcal{O}^\psi [^3S_1^{(1)}] \rangle$/GeV^3	Color octet contributions $\langle \mathcal{O}^\psi [^1S_0^{(8)}] \rangle$/GeV^3	$\langle \mathcal{O}^\psi [^3S_1^{(8)}] \rangle$/GeV^3	$\langle \mathcal{O}^\psi [^3P_0^{(8)}] \rangle$/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}

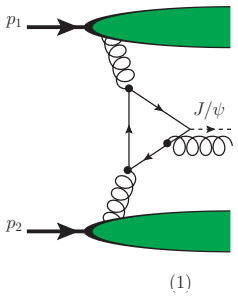
Multiplicity dependence of charmonia production [ALICE, 1811.01535]

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

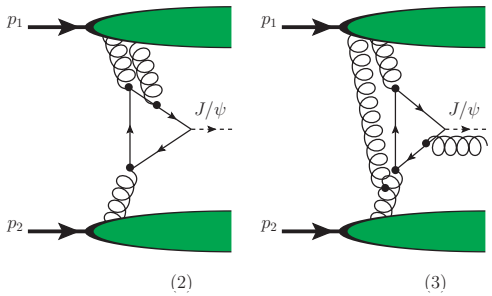




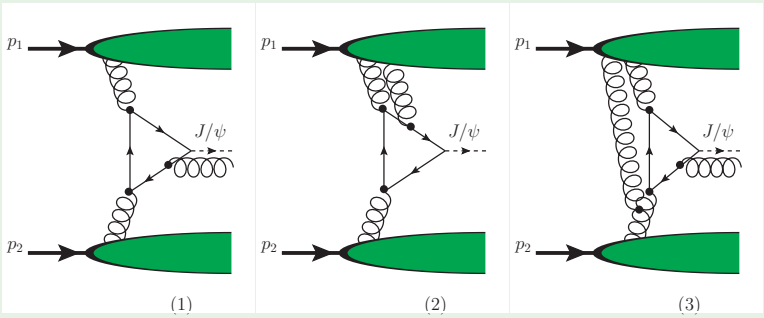
- Enhancement (deviation from linear) seen both for J/ψ and D mesons
- So far not clear if the effect exists for $\psi(2S)$, χ_c, Υ?



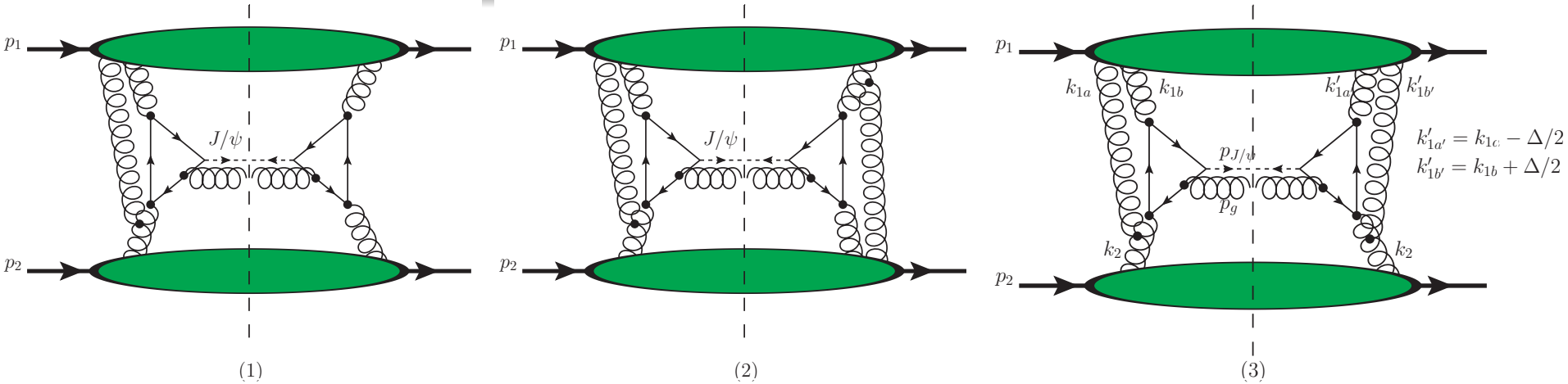
- Difficult to explain in terms of gluon-gluon fusion approach: if each reggeized gluon (cut pomeron) contributes approx. equal number $\bar{n}$ of charged hadrons, expect linear dependence
- Data hints that multipomeron mechanisms are pronounced (usually discarded as corrections).
- Production on nuclei: $\sim A^{1/3}$ enhancement



3-pomeron contributions



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

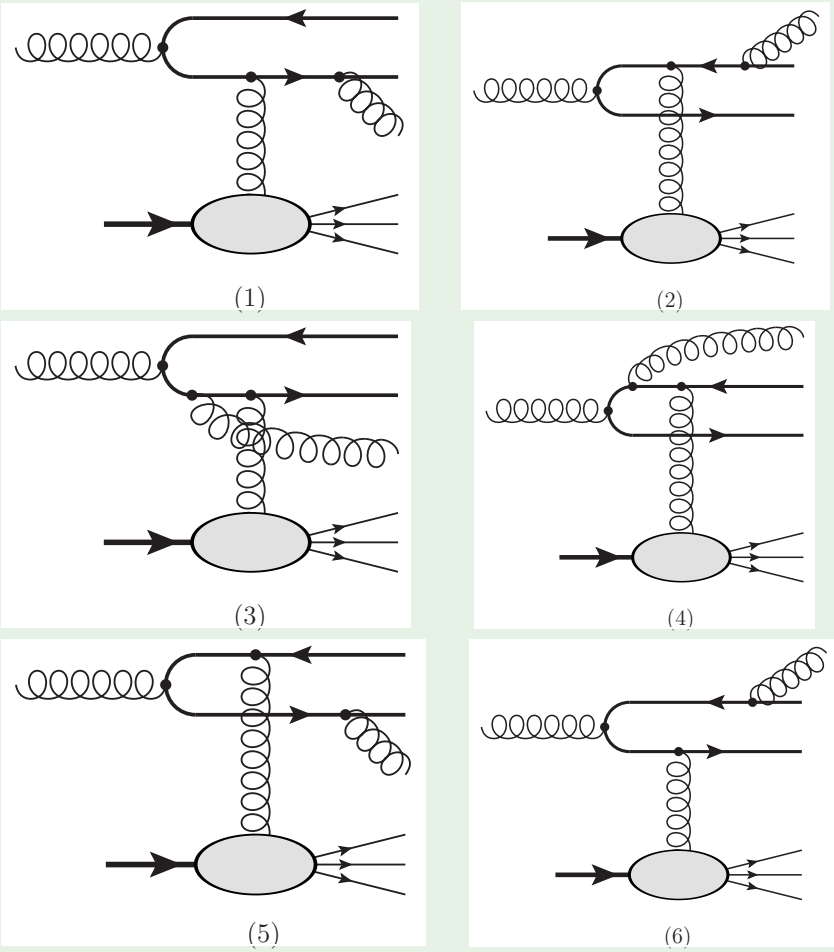


- Diagrams (1) and (2) include Parton Distributions with odd number of gluons
- ... such distributions are sensitive if the proton is polarized [PLB 668 (2008), 216, PRD 78 (2008), 014024 , PRD 78 (2008), 114013].
- ... corresponding asymmetries are small, might neglect them [PHENIX Collaboration, PRD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

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

CSM in dipole approach

LO diagrams



- Same diagrams as in k_T factorization, we just express everything in terms of dipole framework.

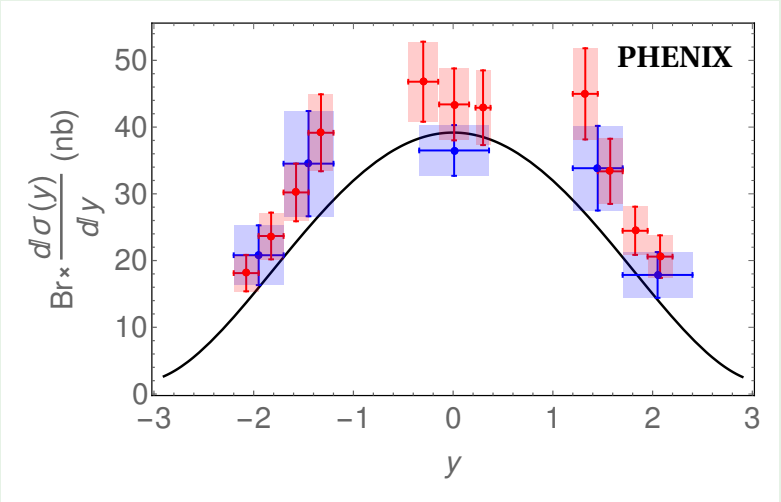
Large-m_Q limit

- Dipole cross-section related to $k_\perp$ uPDF, e.g. for color singlet

$$\sigma_d(x, r_\perp) = \int \frac{d^2 k_\perp}{(2\pi)^2} \mathcal{F}(x, k_\perp) \left(1 - e^{i k_\perp \cdot r_\perp}\right).$$

- Color octet dipole cross-section could be expressed as linear combinations of color singlets

Reasonable description of pp data



[PRC95 (2017), 065203]

J/ψ production cross-section in the dipole approach

[PRC95 (2017), 065203]

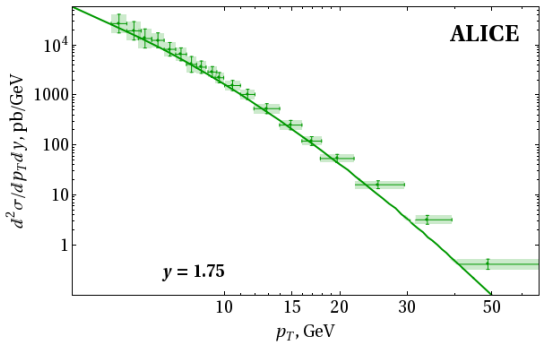
$$\frac{d\sigma_{pp}}{dy} = \frac{9}{8} g\left(x_1(y)\right) \int d\alpha_G d\alpha_1 d^2 r_1 \, d\alpha_2 d^2 r_2 \, d^2\rho \, \overbrace{\Psi^*_M\left(\alpha_1 r_1\right) \Psi_M\left(\alpha_2 r_2\right)}^{\text{Meson WFs}} \times$$

$$\times \sum_{n,n'=1}^{6} \underbrace{\eta_n \eta_{n'}}_{\text{numerical factor}} \quad \mathrm{Tr}\left[\Lambda_M \Phi_{g\to\bar{Q}Q}\left(\epsilon_n, \vec{r}_n^{(1)}\right) \Phi_{Q\to Q\,g}\left(\delta_n, \vec{\rho}_n\right)\right]$$

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

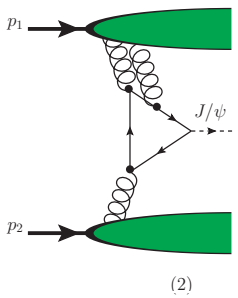
$$\times \quad \underbrace{\sigma\left(x_2, \vec{r}_n - \vec{r}_{n'}\right)}_{\text{dipole cross-section}}$$

- 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 6 diagrams in amplitude and its conjugate is implied



- For p_T-dependent cross-section, additional Fourier over difference of dipole impact parameter $\Delta\vec{b} = \vec{b}_1 - \vec{b}_2 \neq 0$; terms $\delta\vec{r}_n$, $\delta\vec{\rho}_n$ also depend on $\vec{b}_{1,2}$

3-gluon fusion in dipole approach



$$\frac{d\sigma\left(Y,\,Q^2\right)}{dy\,d^2q_T} = 4\int \frac{d^2Q_T}{(2\pi)^2}\,S_h^2\left(Q_T\right)\;\;x_g G\left(x_g,\,M_{J/\psi}\right)$$
$$\times\int_0^1 dz\int_0^1 dz'\int \frac{d^2r}{4\pi}\,\frac{d^2r'}{4\pi}\,d^2b\;e^{-i\boldsymbol{q_T}\cdot\boldsymbol{b}}$$

$$\times\left\langle\Psi_g\left(r,z\right)\,\Psi_{J/\psi}\left(r,z\right)\right\rangle\left\langle\Psi_g\left(r',z'\right)\,\Psi_{J/\psi}\left(r',z'\right)\right\rangle\left(N\left(y;\,\boldsymbol{b}-\frac{1}{2}\left(\boldsymbol{r}-\boldsymbol{r}'\right)\right)\right.$$
$$\left.+N\left(y;\,\boldsymbol{b}+\frac{1}{2}\left(\boldsymbol{r}-\boldsymbol{r}'\right)\right)-N\left(y;\,\boldsymbol{b}+\frac{1}{2}\left(\boldsymbol{r}+\boldsymbol{r}'\right)\right)-N\left(y;\,\boldsymbol{b}-\frac{1}{2}\left(\boldsymbol{r}+\boldsymbol{r}'\right)\right)\right)^2$$
$$+\left(y\to Y-y\right)$$

- 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. Can be related to $\sigma_{\rm eff}$ in DPDF.

Explanation of uncertainty in k_T-factorization language

- For gluon uPDF use KMR parametrization, $\mu_R = \mu_F = \sqrt{p_T^2 + M_{J/\psi}^2}$
- For DPDFs $\mathcal{F}^{c_1 c_2, c_1' c_2'}\left(x_{1a}, k_{1a,T}, x_{1b}, k_{1b,T}, \Delta\right)$ can have different color structures,

$$\mathcal{F}^{aa',bb'} = \frac{1}{64}\left[{}^1F\,\delta^{aa'}\delta^{bb'} - \frac{\sqrt{8}}{3}\,{}^AF\,f^{aa'c}f^{bb'c} + \frac{3\sqrt{8}}{5}\,{}^SF\,d^{aa'c}d^{bb'c} + \frac{4}{\sqrt{27}}\,{}^{27}F\,t_{27}^{aa',bb'} + \frac{2}{\sqrt{10}}\,{}^{10}F\left(t_{10}^{aa',bb'} + \left(t_{10}^{aa',bb'}\right)^*\right)\right],$$

- We *assume* that the parameterization is given by

$$\mathcal{F}^{c_1 c_2, c_1' c_2'}\left(x_{1a}, k_{1a,T}, x_{1b}, k_{1b,T}\right) \sim \mathcal{F}\left(x_{1a}, k_{1a,T}\right)\mathcal{F}\left(x_{1b}, k_{1b,T}\right),$$

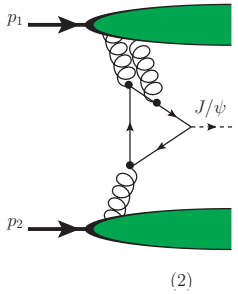
- ... reproduces "pocket formula" for DPS

$$d\sigma_{pp\to h_1 h_2 X} = \frac{1}{\sigma_{\rm eff}}\,d\sigma_{pp\to h_1 X}\,d\sigma_{pp\to h_2 X}.$$

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

- 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 in 3-gluon fusion cross-section



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

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

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

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

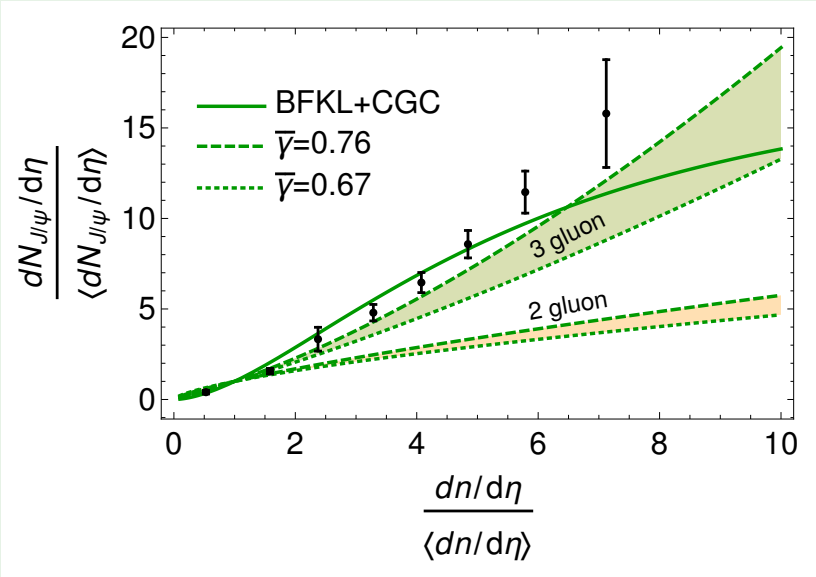
- The dipole amplitude $N\left(y;\,\boldsymbol{r}\right) \sim \left(Q_s^2 r^2\right)^{\bar{\gamma}}$ at small r, so rapidity dependence of $d\sigma$ and $d\sigma_{\rm eff}$ is the same⇒Can fix *hadro*production cross-section $d\sigma$ from diffractive *photo*production $d\sigma_{\rm diff}$ studied at 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 show only shapes for p_T, rapidity, multiplicity dependence

Contribution of $3g \to J/\psi$ to phenomenological observables

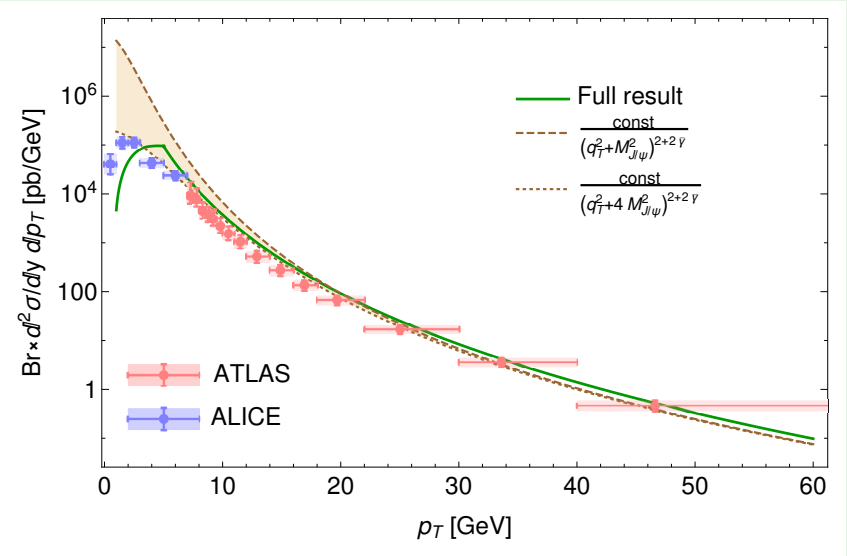
Multiplicity distributions

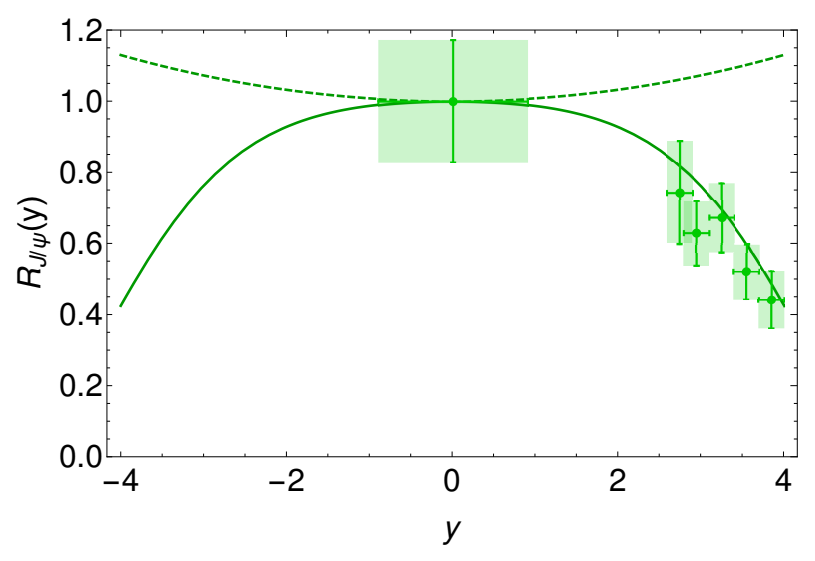


- BFKL: $\bar{\gamma} \approx 0.63$, phenomenology: $\bar{\gamma} \in [0.67, 0.76]$
- Data clearly favour 3-pomeron contribution.

- $\Rightarrow$Overall, reasonable description of pp data might be achieved

p_T- and rapidity distribution

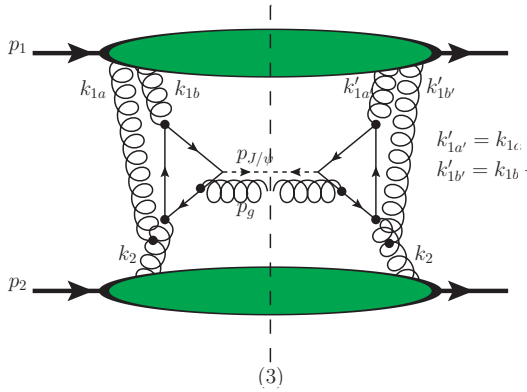




- BFKL: each gluon $\sim x^{\alpha}$ (dashed)
- Experiment: add $\sim (1-x)^5$ (solid)

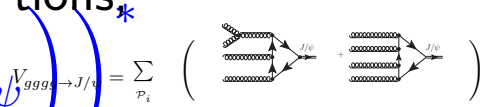
Contribution of the $g + gg \to g + J/\psi$ process

- Use k_T factorization, too difficult in dipole approach
  - Result expressed in terms of the gluon uPDFs and DPDFs of the proton



$$
\begin{aligned}
d\sigma \quad &= \frac{\pi \alpha_s^3(\mu)\, |\mathcal{R}(0)|^2}{(x_{1a} x_{1b} x_2 s)^2} \frac{d^2 k_{1a,T}}{\pi} \frac{d^2 k_{1b,T}}{\pi} \frac{d^2 k_{2,T}}{\pi} \\
&\times \frac{dy d^2 p_T}{\pi}\, d\Delta^+ \frac{d^2 \Delta_T}{\pi}\, dy_g\, dx_{1a} \\
&\times \mathcal{M}^{c_1 c_2,\, c_3}_{gg+g\to g\, J/\psi}\left(k_{1a},\, k_{1b},\, k_2,\, p_{J/\psi}\right) \\
&\times \left(\mathcal{M}^{c_1' c_2',\, c_3}_{gg+g\to g\, J/\psi}\left(k_{1a} - \frac{\Delta}{2},\, k_{1b} + \frac{\Delta}{2},\, k_2,\, p_{J/\psi}\right)\right)^* \\
&\times \underbrace{\mathcal{F}^{c_1 c_2, c_1' c_2'}\left(x_{1a}, k_{1a,T}, x_{1b}, k_{1b,T}, \Delta\right)}_{\text{DPDF}} \underbrace{\mathcal{F}\left(x_2,\, k_{2\perp}\right)}_{\text{uPDF}}
\end{aligned}
$$

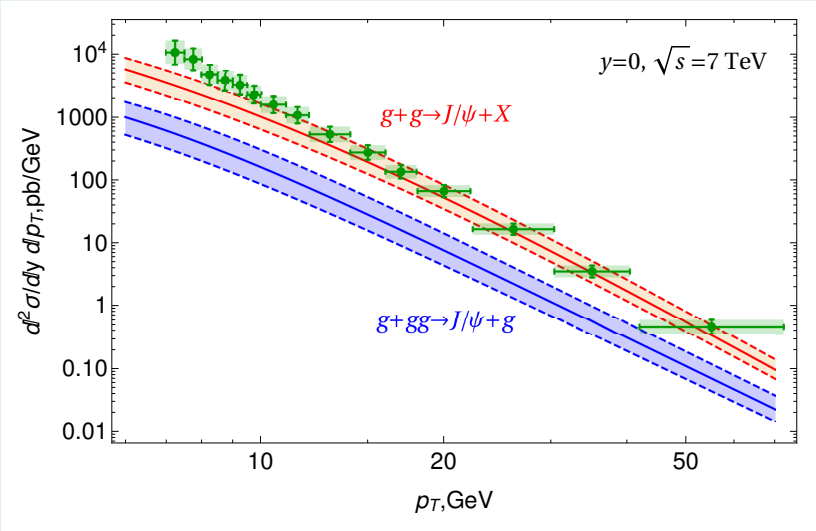
$\mathcal{M}$ =Sum over all possible permutations.



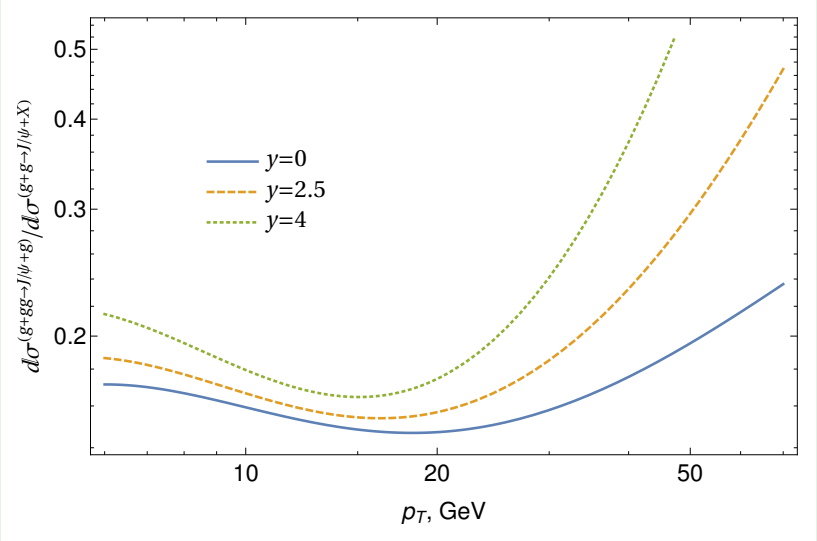
- For gluon uPDF use KMR parameterization.
- For gluon DPDF use factorized ansatz mentioned earlier

3-pomeron J/ψ production with gluon emission

- Result for the cross-section:

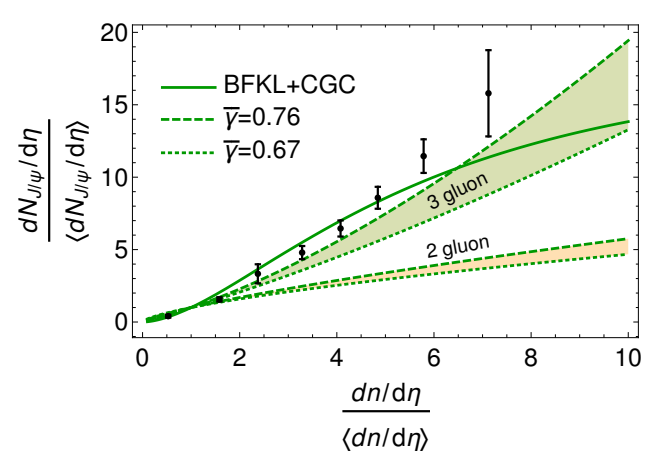


- Relative w.r.t. CSM+NRQCD



- $\Rightarrow$Similar to $g + gg \to J/\psi$, we get <u>sizeable</u> contribution from the three-pomeron fusion to J/ψ production (slightly smaller due to $\mathcal{O}(\alpha_s(m_c))$)

Summary



- The observed multiplicity of charged particles signals that 3-pomeron process gives a sizeable contribution to J/ψ production.
- We believe that similar studies of multiplicity dependencies for $\psi(2S)$, $\Upsilon(nS)$ should shed light on the role of the suggested mechanism in their formation.

Thank You for your attention