Some new aspects of quarkonia production at the LHC: diffractive J/ψ, inclusive χ_c-pair production

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Outline

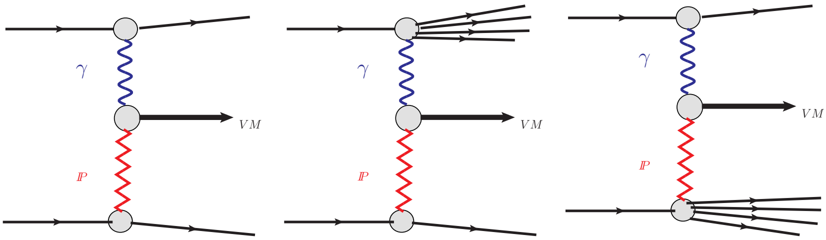
1. **Exclusive photoproduction of $J/\psi, \psi'$ in pp collisions**
2. **Semiexclusive photoproduction with diffractive and electromagnetic dissociation**
3. **Inclusive $\chi_c \chi_c$ production: mechanisms contributing at large rapidity separations**

Anna Cisek, W. S., Antoni Szczurek, JHEP 1504, 159 (2015).

Anna Cisek, W. S. and Antoni Szczurek, Phys.Lett. B769 (2017) 176-186.

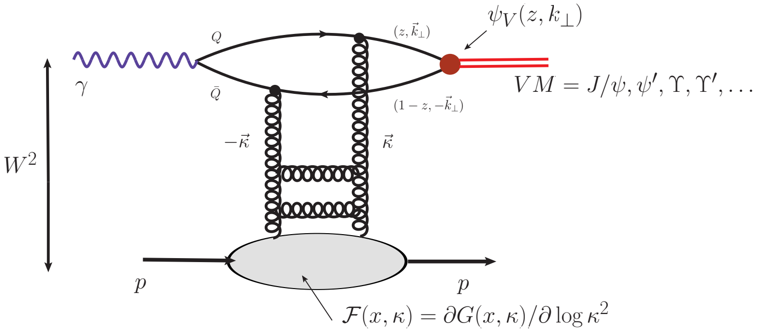
Anna Cisek, W. S. and Antoni Szczurek, "Double χ_c production in k_T -factorization", in preparation

Exclusive and semiexclusive diffractive photoproduction of vector mesons in pp



- large rapidity gaps: no exchange of charge or color. t-channel exchanges with the (running) spin $J(t) \geq 1$.
- C-parity constraint: $C_X = C_1 \times C_2$. even: Pomeron, odd: Odderon, photon.
- we often have to deal with diffractive reactions which include excitation of incoming protons. Instead of fully inclusive final states: gap cross sections, gap vetos or even only vetos on additional tracks(!) from a production vertex.
- large rapidity gaps $\Leftrightarrow M_X^2/s \ll 1$, for the mass of excited system M_X.

Diffractive Photoproduction $\gamma p \to Vp$



- $J/\psi = c\bar{c}$, $\Upsilon = b\bar{b}$: (almost) nonrelativistic bound states of heavy quarks. Node structure of light-cone wavefunctions affects production of radial excitations.
- Large quark mass $\to$ hard scale necessary for (perturbative) QCD.
- $\mathcal{F}(x, \kappa) \equiv$ unintegrated gluon density, $x \sim M_{VM}^2/W^2$, constrained by HERA inclusive data.
- typical scale at which the gluon distribution is probed $\bar{Q}^2 \sim M_V^2/4$, i.e. $\bar{Q}^2 \sim 2.4\,\mathrm{GeV}^2$ for J/ψ and $\bar{Q}^2 \sim 20\,\mathrm{GeV}^2$ for Υ.
- topical subject: glue at small-x: nonlinear evolution, gluon fusion, saturation...

The full amplitude

The full amplitude, at finite momentum transfer is given by:

$$\mathcal{M}(W,\Delta^2) = (i+\rho)\,\Im m\mathcal{M}(W,\Delta^2=0,Q^2=0)\cdot f(\Delta^2,W)\,,$$

The real part of the amplitude is restored from analyticity,

$$\rho = \frac{\Re e\mathcal{M}}{\Im m\mathcal{M}} = \tan\left(\frac{\pi}{2}\,\frac{\partial\log\left(\Im m\mathcal{M}/W^2\right)}{\partial\log W^2}\right).$$

two option for dependence on momentum transfer $t=-\Delta^2$

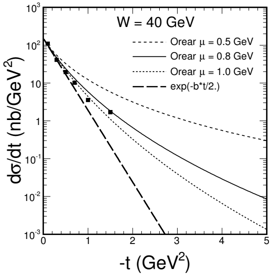
$$f(t,W) = \exp\left(\frac{1}{2}B(W)t\right),$$

extension to larger $|t|\sim 1\div 2\,\mathrm{GeV}^2$: "stretched exponential" parametrization

$$f(t,W) = \exp(\mu^2 B(W)) \times \exp\left(-\mu^2 B(W)\sqrt{1-t/\mu^2}\right),$$

with

$$B(W) = b_0 + 2\alpha'_{eff}\log\left(\frac{W^2}{W_0^2}\right).$$



data from ZEUS collaboration

Parameters/input to the diffractive amplitude

- frame-independent radial LCWF depends on the invariant

$$p^2 = \frac{1}{4}\left(\frac{\boldsymbol{k}^2 + m_c^2}{z(1-z)} - 4m_c^2\right)$$

- "**Gaussian**" parametrization:

$$\psi_{1S}(z,\boldsymbol{k}) = C_1 \exp\left(-\frac{p^2 a_1^2}{2}\right)$$

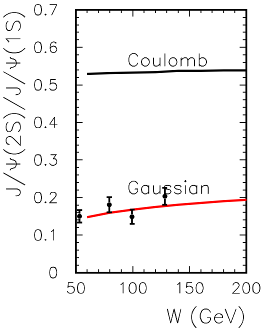
$$\psi_{2S}(z,\boldsymbol{k}) = C_2(\xi_0 - p^2 a_2^2) \exp\left(-\frac{p^2 a_2^2}{2}\right)$$

- "**Coulomb**" parametrization:

$$\psi_{1S}(z,\boldsymbol{k}) = \frac{C_1}{\sqrt{M}} \frac{1}{(1+a_1^2 p^2)^2}$$

$$\psi_{2S}(z,\boldsymbol{k}) = \frac{C_2}{\sqrt{M}} \frac{\xi_0 - a_2^2 p^2}{(1+a_2^2 p^2)^3}$$

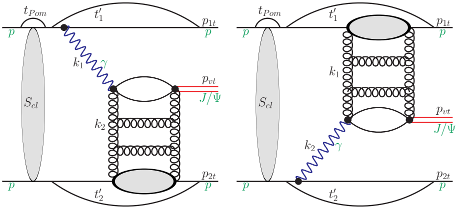
- parameters fixed through: leptonic decay width & orthonormality.



unintegrated gluon distributions:

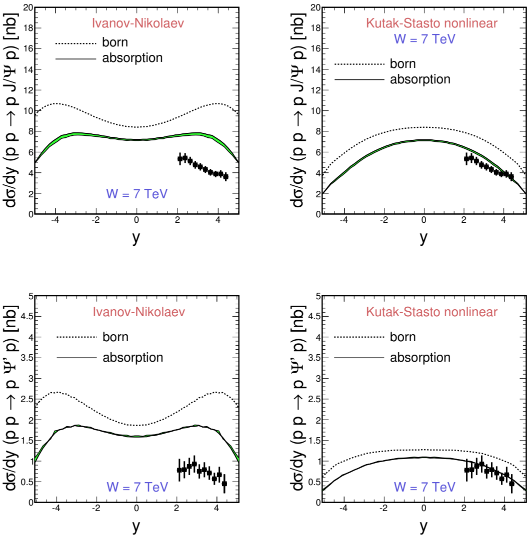
1. **Ivanov-Nikolaev**: hybrid glue with soft and hard components. Fitted to HERA F_2 data.
2. **Kutak-Staśto linear**, a solution to BFKL-type evol. with kinematic constraints
3. **Kutak-Staśto nonlinear**, includes a BK gluon fusion term.

$pp \to p\ J/\psi(\psi')\ p$ with absorptive corrections



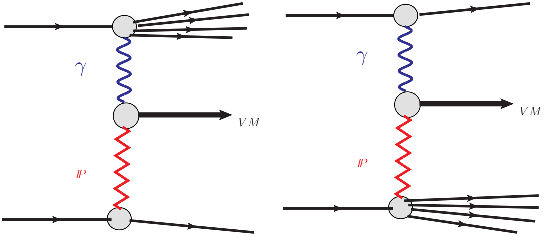
- in pp collisions each of protons can be emitter of photon $\to$ two interfering amplitudes. (Klein & Nystrand (2004), WS & Szczurek (2007)).
- Need to account for absorptive corrections. Roughly: in impact parameter space, multiply by probability amplitude of protons passing through each other $S_{\rm el}(\boldsymbol{b})$.
- thus absorption is accounted at the amplitude level and strongly depends on kinematics. It accounts for gap survival probability.
- long range photon exchange helps keeping absorptive corrections small.

Comparison to LHCb data



- R. Aaij et al. (LHCb collaboration), J.Phys. G41 (2014) 055002
- all the gluons shown here do describe the earlier Tevatron data!

Diffractive production with electromagnetic dissociation

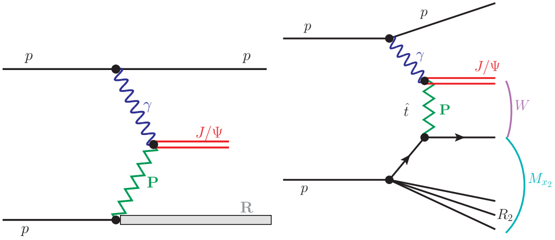


electromagnetic dissociation:

$$\frac{d\sigma(pp \to XVp; s)}{dy d^2\boldsymbol{p}} = \int \frac{d^2\boldsymbol{q}}{\pi \boldsymbol{q}^2} \mathcal{F}^{(\mathrm{in})}_{\gamma/p}(z_+, \boldsymbol{q}^2) \frac{1}{\pi} \frac{d\sigma^{\gamma^* p \to Vp}}{dt}(z_+ s, t = -(\boldsymbol{q} - \boldsymbol{p})^2) + (z_+ \leftrightarrow z_-)$$

- $z_\pm = e^{\pm y} \sqrt{\boldsymbol{p}^2 + m_V^2} / \sqrt{s}$
- generalization of the Weizsäcker-Williams flux to dissociative processes. Calculable from inelastic proton structure functions F_2, F_1.
- data driven approach (Silveira, Forthomme, Piotrzkowski, Szczurek & WS (2014), Łuszczak, Szczurek & WS (2015)).
- must in principle add contributions of longitudinal photons. Negligible for heavy mesons as long as $Q^2 \ll m_V^2$.

Diffractive dissociation of one of the protons



- small p_T: dissociation into $I = 1/2$ nucleon resonances/low mass continuum states. Dominated by $N^*(1680)$, $J^P = \frac{5}{2}^+$, $N^*(2220)$, $J^P = \frac{9}{2}^+$, $N^*(2700)$, $J^P = \frac{13}{2}^+$. A model by L.L. Jenkovszky, O.E. Kuprash, J.W. Lämsa, V.K. Magas and R. Orava (2011).
- large p_T: incoherent sum of diffractive scatterings off partons. Large diffractive masses are possible here. Note: The limit of very large p_T is interesting in its own right, see e.g. pQCD large-t mechanism of Ryskin, Forshaw et al.

Ratio of dissociative to exclusive cross section

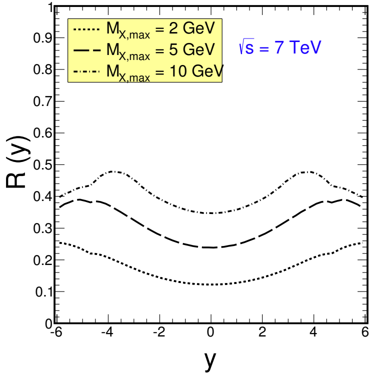
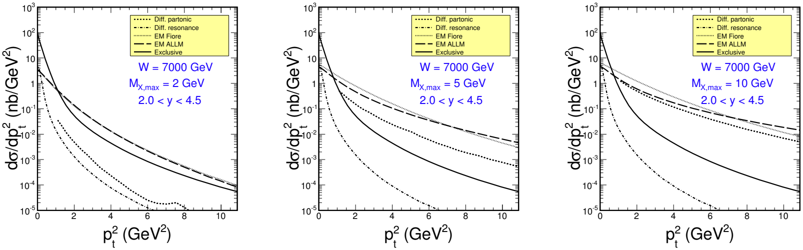


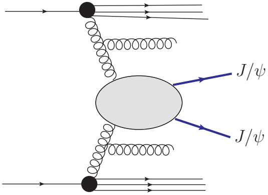
Figure: $R(y)$ as a function of J/ψ rapidity for different ranges of M_X. Both electromagnetic and diffractive excitations are included here.

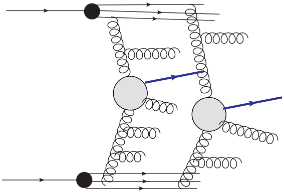
Results for LHCb cuts



- Clear emergence of two different slopes. Electromagnetic dissociation dominates!

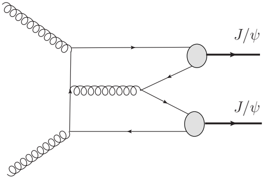
Inclusive J/ψ-pair production: SPS vs. DPS

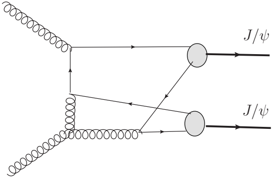


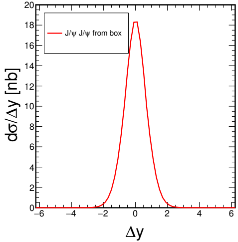


- Single parton scattering (SPS) production through gluon-gluon fusion. LO ($\mathcal{O}(\alpha_S^4)$) mechanism well known. k_T-factorization by Baranov, Zotov et al.
- Double parton scattering expected sizeable (Kom, Kulesza & Stirling '11). Recall also large DPS in open charm (Łuszczak, Maciuła & Szczurek '11).
- $\sigma(\mathrm{DPS}) = \frac{1}{2}\frac{\sigma^2(\mathrm{SPS})}{\sigma_{\mathrm{eff}}}$. σ_{eff} from quarkonia production seems to be systematically smaller than $\sigma_{\mathrm{eff}} \sim 15\,\mathrm{mb}$
- DPS $\rightarrow$ large rapidity differences between J/ψ's.

The SPS "box"-mechanism



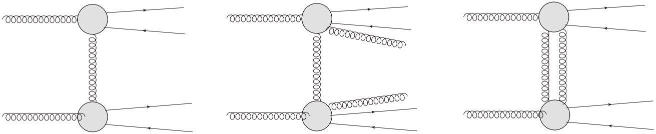




$$\frac{d\sigma(pp \to J/\psi J/\psi X)}{dy_1 dy_2 d^2p_{1t} d^2p_{2t}} = \frac{1}{16\pi^2 (x_1 x_2 s)^2} \int \frac{d^2 q_{1t}}{\pi} \frac{d^2 q_{2t}}{\pi} \overline{|\mathcal{M}^{\mathrm{off-shell}}_{g^* g^* \to J/\psi J/\psi}|^2}$$
$$\times \; \delta^2 \left(\vec{q}_{1t} + \vec{q}_{2t} - \vec{p}_{1t} - \vec{p}_{2t} \right) \mathcal{F}_g(x_1, q_{1t}^2, \mu_F^2) \mathcal{F}_g(x_2, q_{2t}^2, \mu_F^2) \; .$$

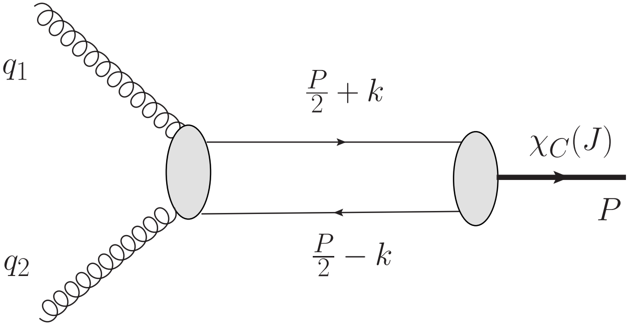
- we restrict ourselves to the color singlet model. This is consistent with k_T-factorization analysis of single-inclusive quarkonia by Baranov et al.
- we use everywhere the NRQCD nonrelativistic limit. Coupling $c\bar{c}J/\psi$ is given by the radial wavefunction at the origin $R(0)$.
- k_T factorization takes into account (part of) the collinear NLO corrections and allows to explore full phasespace (azimuthal correlations, total p_T of the pair).

Production mechanisms that don't vanish at large Δy



- gluon- and multigluon exchange in the t-channel gives rise to parton-level cross sections that stay constant at large Δy .
- We can't produce $c\bar{c}$ states in the $^{2S+1}L_J = ^3 S_1$ state by single-gluon exchange, but $^3P_J, J = 0, 1, 2$ is allowed (i.e. χ_c-states)!
- diagrams with additional gluon emission can give J/ψ's, but are extremely small.
- "quasi-diffractive" two-gluon exchange can also produce J/ψ-pairs. Note that the crossed channel gluons are in a symmetric color-octet state. (Baranov, Snigirev, Zotov, Szczurek & WS 2013.)
- $Br(\chi_c(0) \to J/\psi\gamma) = 1.26 \pm 0.06\%$, $Br(\chi_c(1) \to J/\psi\gamma) = 33.9 \pm 1.2\%$, $Br(\chi_c(2) \to J/\psi\gamma) = 19.2 \pm 0.7\%$

χ_c production: preparations



$$V^{ab}_{\mu\nu}(J, J_z; q_1, q_2) = 4\pi\alpha_S \frac{\mathrm{Tr}[t^a t^b]}{\sqrt{N_c}} \sqrt{\frac{2}{M}} \sum_{S_z, L_z} \int \frac{d^4 k}{(2\pi)^3} \delta(k^0 - \frac{\vec{k}^2}{M}) \Psi_{1,L_z}(\vec{k})$$

$$\times \langle 1, S_z; 1, L_z | J, J_z \rangle \cdot \mathrm{Tr}[A_{\mu\nu} \Pi_{1,S_z}],$$

- NRQCD: expand in the relative momentum k.
- external gluons off-shell with spacelike virtualities, but beyond "Regge kinematics". Essentially a QED problem.

$\chi_c(1)$: axial vector, $J^{PC} = 1^{++}$

$$T_{\mu\nu}(1, J_z; q_1, q_2) = \frac{i}{\sqrt{2}M} \frac{1}{2(q_1 \cdot q_2)} \Big\{ 2(q_1^2 - q_2^2) \Big(\epsilon_{\mu\nu\alpha\beta} q_1^\alpha \epsilon^\beta(J_z) + \epsilon_{\mu\nu\alpha\beta} q_2^\alpha \epsilon^\beta(J_z) \Big) + 4(a_\nu q_{1\mu} - a_\mu q_{2\nu}) - \frac{q_1^2 + q_2^2}{2(q_1 \cdot q_2)} 4(q_{2\mu} a_\nu - q_{1\nu} a_\mu) \Big\} ,$$

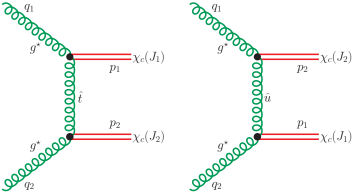
$$a_\mu = \epsilon_{\mu\rho\alpha\beta} q_1^\rho q_2^\alpha \epsilon^\beta(J_z) .$$

- Landau-Yang theorem forbids $\mathrm{Vector} \to \gamma\gamma$.
- Indeed, for $q_i^2 \to 0$:

$$T_{\mu\nu}(1, J_z; q_1, q_2) \propto a_\nu q_{1\mu} - a_\mu q_{2\nu} ,$$

which vanishes, when contracted with the polarization vectors of on-shell photons/gluons

$g^*g^* \to \chi_c(J_1)\chi_c(J_2)$ amplitudes

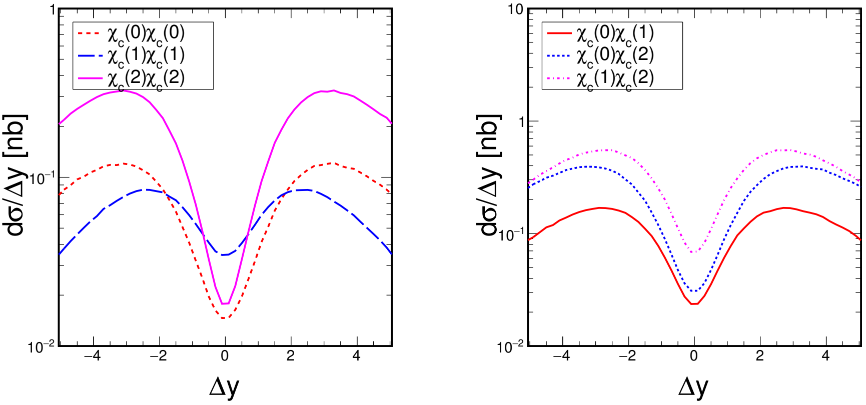


$$\begin{aligned}\mathcal{M}^{ab}_{\mu\nu}(J_1, J_{1z}, J_2, J_{2z}) &= V^{ac}_{\mu\alpha}(J_1, J_{1z}; q_1, p_1 - q_1)\,\frac{-g^{\alpha\beta}\delta_{cd}}{\hat{t}}\,V^{db}_{\beta\nu}(J_2, J_{2z}; p_2 - q_2, q_2) \\ &+ V^{ac}_{\mu\alpha}(J_2, J_{2z}; q_1, p_2 - q_1)\,\frac{-g^{\alpha\beta}\delta_{cd}}{\hat{u}}\,V^{db}_{\beta\nu}(J_1, J_{1z}; p_1 - q_2, q_1)\,,\end{aligned}$$

where $\hat{t} = (p_1 - q_1)^2 = (p_2 - q_2)^2$, $\hat{u} = (p_2 - q_1)^2 = (p_1 - q_2)^2$.

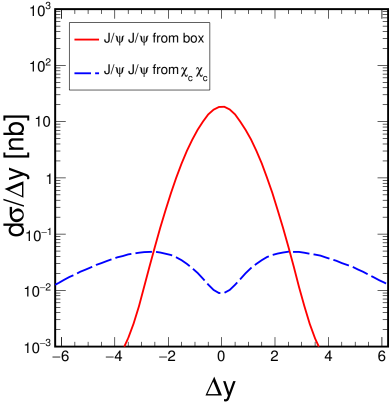
- Vertices enter in *off-shell* kinematics.
- $q_1 = q_1^+ n^+ + q_1^\perp$, $q_2 = q_2^- n^- + q_2^\perp$.

Rapidity separation, pp collision at $\sqrt{s} = 8$ TeV, $-5 < y_{\chi_i} < 5$.



- broad Δy distributions. Dip at $\Delta y = 0 \rightarrow$ neglibible if experimental coverage doesn't allow for large rapidity distances (e.g. LHCb).

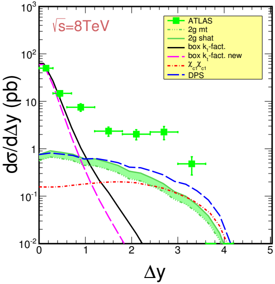
Contribution to $J/\psi J/\psi$



- $J/\psi J/\psi$ from box diagrams and sum over all $\chi_c\chi_c$ contributions into $J/\psi J/\psi$.

Comparison to recent ATLAS data, preliminary calculations

- M. Aaboud *et al.* [ATLAS Collaboration], "Measurement of the prompt J/ ψ pair production cross-section in pp collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector," Eur. Phys. J. C **77**, no. 2, 76 (2017)
- cuts on J/ψ: $|y^{J/\psi}| < 2.1$, $p_T^{J/\psi} > 8.5\,\mathrm{GeV}$.
- additional muon cuts: $|\eta^{\mu}| < 2.3$, $p_T^{\mu} > 2.5\,\mathrm{GeV}$, $2.8 < M_{\mu\mu} < 3.4\,\mathrm{GeV}$.



Conclusions

- We applied the k_T-factorization approach to the LHCb ($pp \longrightarrow p\ J/\psi(\psi')\ p$). We include interference effects and calculate absorptive corrections at the amplitude level.
- The best description is obtained for an unintegrated glue that includes nonlinear evolution. Reasonable description of J/psi as well as $\psi(2S)$.
- Dissociative events are a sizeable fraction of large-gap cross section. Clear distinction in the p_T^2-slope. Electromagnetic dissociation is calculable and dominates under generic conditions over diffractive dissociation.
- We calculated inclusive double-χ_c production in k_T-factorization for all combinations of $J = 0, 1, 2$. Single gluon exchange naturally leads to broad Δy-distributions $\rightarrow$ "mimics" behaviour of double parton scattering contribution to $J/\psi J/\psi$.