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Dissociative charmonia photoproduction as a signal of gluon saturation

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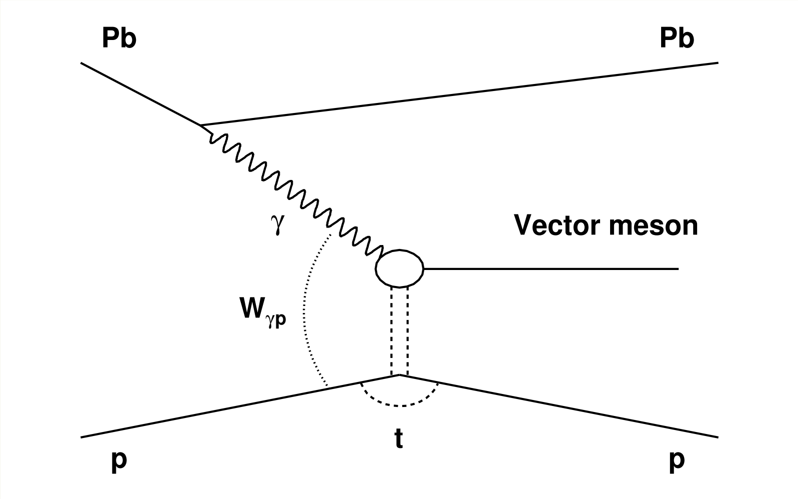
J. Cepila, J.G. Contreras, D.T. Takaki, Phys. Lett. B 766 (2017)
arXiv:1608.07559

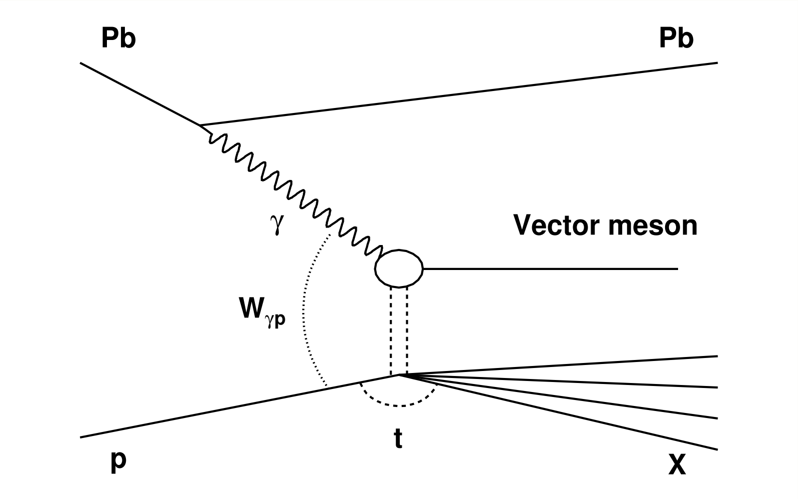
Outline of the talk

- Motivation of the model
- Kinematics
- Color dipole approach
- Wave function
- Dipole cross-section
- Results
- Parameters discussion
- Conclusions

Motivation

- Inclusive processes (e.g. DIS) give a good qualitative picture on the evolution of the gluon structure of a proton - but they are inconclusive regarding the gluon saturation
- Exclusive and dissociative processes can be a better probe to the gluon structure of a proton - not dependent only on the number of gluons but also on the geometry
- Exclusive and dissociative vector meson photoproduction is sensitive to the distribution of gluons in the impact parameter plane through the t-distribution

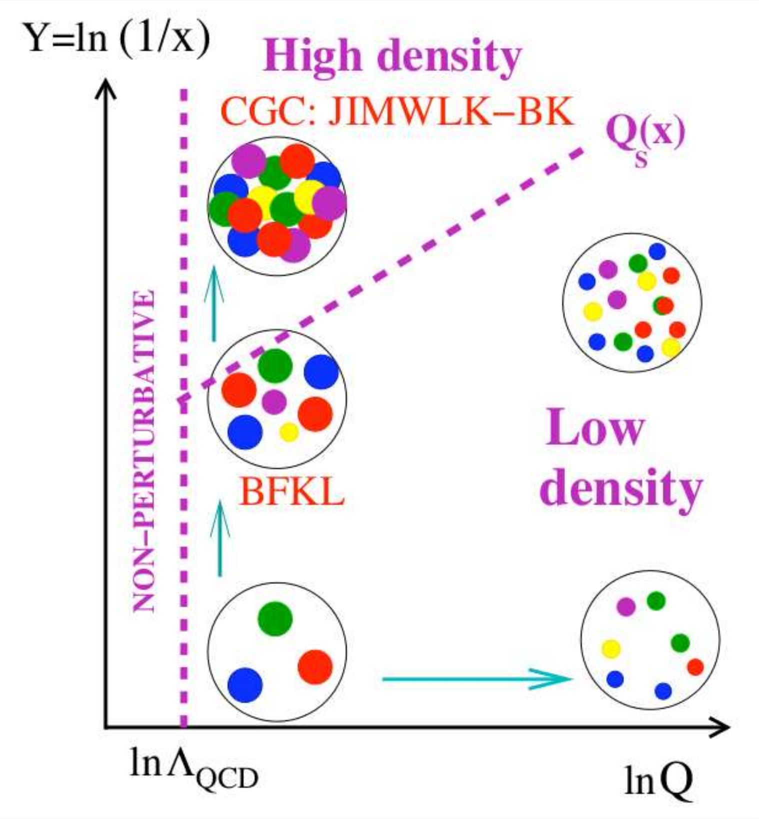




- Exclusive cross-section = average over many geometrical configurations
- Dissociative cross-section = variance over many geometrical configurations

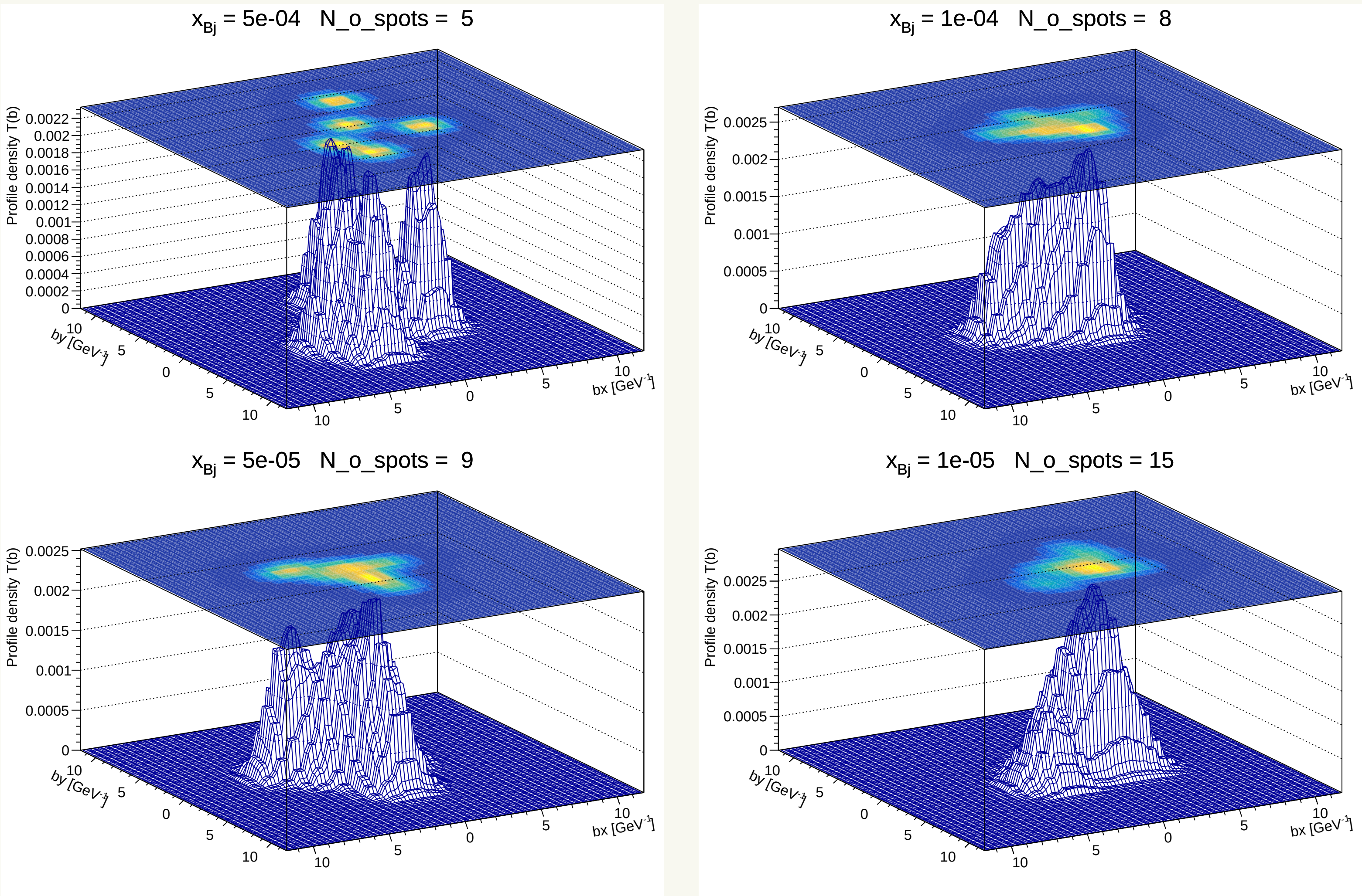
Motivation

- Why is the gluon geometry of the proton important? - onset of parton saturation
- BFKL linear evolution in $\ln \frac{1}{x}$ - if you accelerate parton, it will radiate more gluons
- Gluons may overlap in the transverse plane and, eventually, interact due to non-abelian character of colored QCD
- Dynamical balance between two processes - gluon fusion and BFKL gluon radiation
- Up to the saturation scale $Q_s(x)$(dilute regime) more gluons are produced than fuse - from $Q_s(x)$ on(dense regime) fusion is dominant and suppresses the growth of the density leading to non-linear evolution = **parton saturation**



- We show that including geometrical fluctuations a clear signal of saturation can be seen in the energy dependence of dissociative vector meson production off protons at LHC energies.

- We generate hot spots inside the proton according to approx. rise with energy given by PDF parametrizations.
- As one moves to the saturated region, variance diminishes and the dissociative cross-section drops.



Kinematics

- Consider a photon emitted from the incident particle with energy

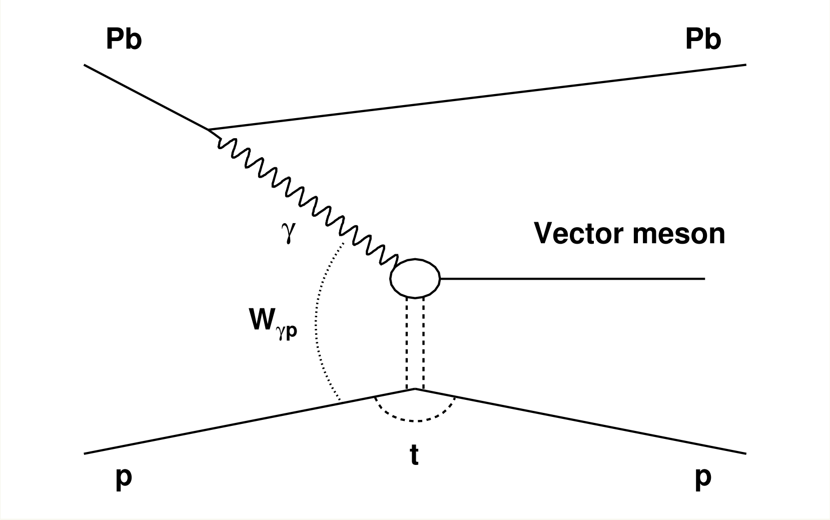
$$w_{\pm} = \frac{M_V}{2}\exp(\pm|y|)$$

  M_V is the mass of the vector meson, y is the rapidity of the vector meson in the lab frame

- After an interaction, the energy of the meson in the cms of the photon-proton system is

$$W_{\pm}^2 = 2w_{\pm}\sqrt{s}$$

  $\sqrt{s}$ is the invariant cms energy of the collision



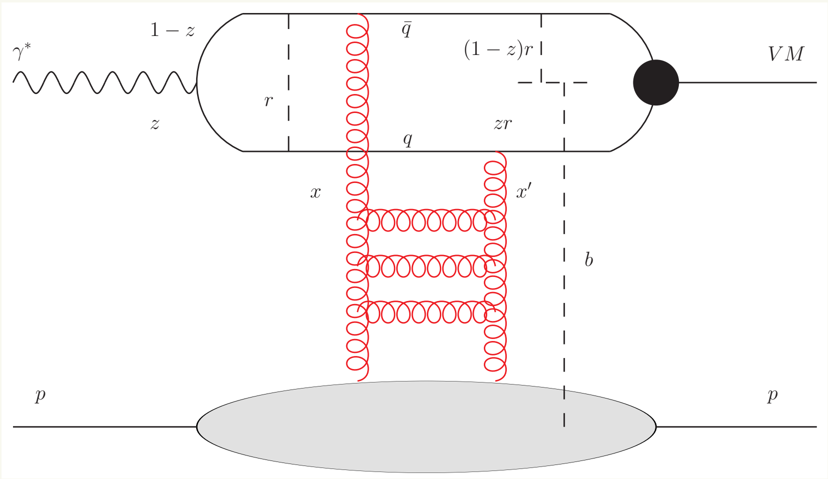
- Bjorken-x of produced meson is

$$x_{Bj} = \frac{M_V^2}{W_{\pm}^2} = \frac{M_V}{\sqrt{s}}\exp(\mp|y|)$$

- Mandelstam variable $t = (p' - p)^2$ is the square of four-momentum transferred at the proton vertex

Color dipole approach

- Light-cone color dipole approach allows to factorize the scattering amplitude at $x \ll 1$
- In the rest frame of the target a photon interacts via it's $q\bar{q}$ Fock component with the target's static color field



- The scattered dipole collapses into the vector meson after a formation time
- z is the fraction of the original momenta of the photon carried by the dipole quark, r is the transverse width of the dipole, b is the impact parameter of the γp collision
- The scattering amplitude is given by the convolution of photon Ψ_{γ^*} and meson Ψ_M wave functions with the dipole cross-section $\mathrm{d}\sigma_{q\bar{q}}/\mathrm{d}^2b$

$$\mathcal{A}_{T,L}^{\gamma^* p \to Mp}(x,Q,\Delta) = i \int \mathrm{d}^2 r \int_0^1 \frac{\mathrm{d}z}{4\pi} \int \mathrm{d}^2 b \, \Psi_M^* \Psi_{\gamma^*} \Big|_{T,L} e^{-i(\vec{b}-(1-z)\vec{r})\Delta} \frac{\mathrm{d}\sigma_{q\bar{q}}}{\mathrm{d}^2 b}$$

H. Kowalski, L. Motyka, and G. Watt, Phys.Rev. D74, 074016 (2006)

$\Delta = \sqrt{-t}$ and T,L denote the trans. and longit. degrees of freedom of the photon

Wave function

- Overlap of a virtual photon and vector meson wave function of the $|q\bar{q}\rangle$ Fock state

$$\Psi_M^*\Psi_{\gamma^*}\Big|_T = e_f\delta_{f\bar{f}}e\frac{N_c}{\pi z(1-z)}\left(m_f^2K_0(\varepsilon r)\Phi_T(r,z) - (z^2+(1-z)^2)\varepsilon K_1(\varepsilon r)\partial_r\Phi_T(r,z)\right)$$

$$\Psi_M^*\Psi_{\gamma^*}\Big|_L = e_f\delta_{f\bar{f}}e\frac{N_c}{\pi}2Qz(1-z)K_0(\varepsilon r)\left(M_V\Phi_L(r,z)+\delta\frac{m_f^2-\nabla_r^2}{M_V z(1-z)}\Phi_L(r,z)\right)$$

$$\varepsilon^2 = z(1-z)^2Q^2+m_f^2$$

G. P. Lepage and S. J. Brodsky, Phys.Rev. D22, 2157 (1980); K.Golec-Biernat and M.Wusthoff, Phys. Rev. D **59**, 014017 (1999)

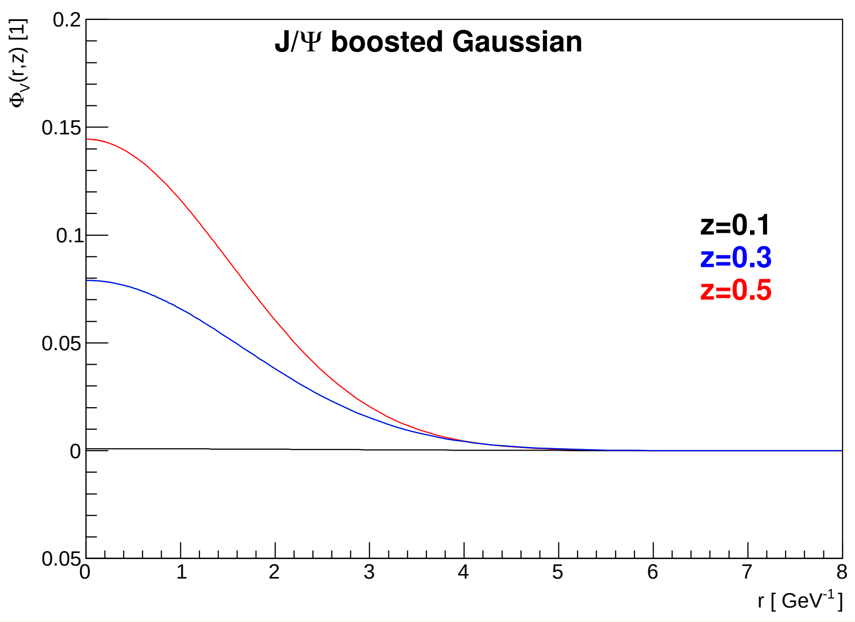
- Photon wave function can be calculated from QED for number of flavours f fixed by $m_f < Q$
- Vector meson wave function is modelled with the presumption that vector meson is predominantly a quark-antiquark state and the spin and polarization structure is the same as in the photon case.
- δ is a switch that enables to include the non-local part of the wave function
- $e=\sqrt{4\pi\alpha_{em}}$, $e_f\delta_{ff}$ is an effective charge of the meson, N_c is the number of color degrees of freedom

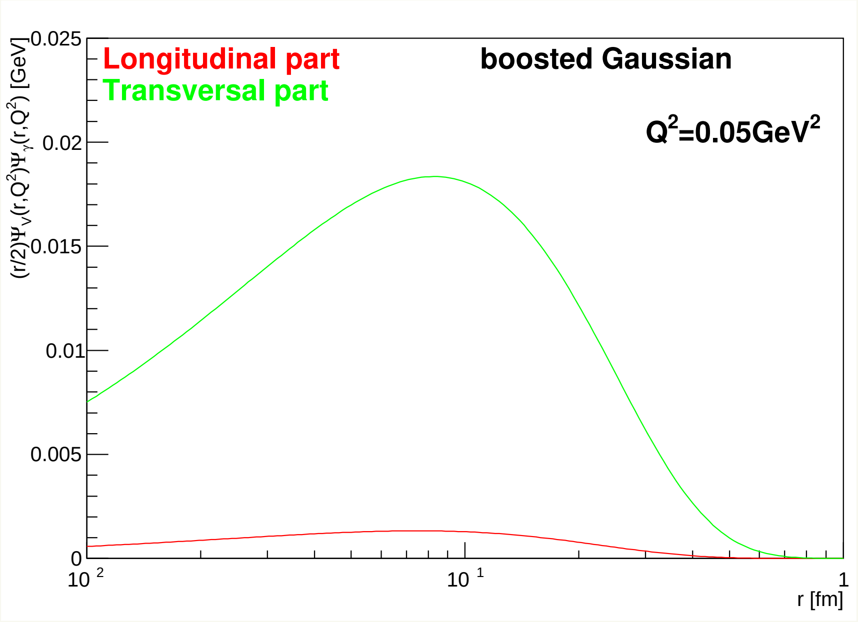
Wave function

- The scalar part $\Phi_{T,L}$ of the vector meson wave function is model dependent
- In the photon case the scalar part is given by modified Bessel functions
- Boosted Gaussian model - assumes $\delta = 1$ and that the $q\bar{q}$ dipole wave function in the rest frame is modelled with Gaussian shape and boosted to proper frame

$$\Phi_{T,L}(r,z) = N_{T,L}z(1-z)e^{-\frac{m_f^2R^2}{8z(1-z)} - \frac{2z(1-z)r^2}{R^2} + \frac{m_f^2R^2}{2}}$$

K.Golec-Biernat and M.Wusthoff, Phys. Rev. D **59**, 014017 (1999); B. E. Cox, J. R. Forshaw, and R. Sandapen, JHEP 06, 034 (2009)





Dipole cross-section

- Dipole cross-sections cannot be calculated from first principles - usually fit to data
- Due to this, they incorporate higher order effects and even non-perturbative effects
- Data are integrated over impact parameter - we can access only $\sigma_{dip}(x,r)$ - impact parameter dependence has to be modelled

$$\frac{\mathrm{d}\sigma_{q\bar{q}}}{\mathrm{d}^2 b} = 2N(x,r,b) = 2N(x,r)T(b)$$

$$\sigma_{dip}(x,r) = 2\int d^2 bN(x,b,r) \sim 2N(x,r)\int d^2 bT(b) = \sigma_0 N(x,r)$$

- σ_0 is the model dependent normalization
- $N(x,r)$ is dipole scattering amplitude of a dipole with separation r
- $T(b)$ is a transverse profile of a proton

- Golec-Biernat and Wusthoff model

$$N(x,r) = \left(1 - e^{-r^2 Q_s^2(x)/4}\right) \qquad Q_s^2(x) = Q_0^2(x)\left(\frac{x_0}{x}\right)^{\lambda}$$

K.J. Golec-Biernat, M. Wusthoff, Phys. Rev. D 59 (1998) 014017, arXiv:hep-ph/9807513

Dipole cross-section

- The proton is a quantum object, so its structure fluctuates from interaction to interaction - the cross-section is an average over many events with different structure!
- Each hot-spot in the proton can be taken as a small Gaussian distribution with the width $B_{hs} = 0.8\text{GeV}^{-2}$ put in an arbitrary position generated from 2-D Gaussian distribution centered at (0,0) with the width $B_p = 4.7\text{GeV}^{-2}$

$$T_{hs}(\vec{b}-\vec{b}_i) = \frac{1}{2\pi B_{hs}} e^{-\frac{(\vec{b}-\vec{b}_i)^2}{2B_{hs}}}$$

- The number of gluons has to grow with energy - let's take a simple form of gluon growth

$$N_{hs}(x) = p_0 x^{p_1}(1+p_2\sqrt{x}) \quad p_0 = 0.011 \quad p_1 = -0.58 \quad p_2 = 250$$

- Final gluon profile is

$$T(\vec{b}) = \frac{1}{N_{hs}(x)} \sum_{i=1}^{N_{hs}(x)} T_{hs}(\vec{b}-\vec{b}_i)$$

- Similar to H. Mäntysaari and B. Schenke model, but with the number of gluon spots growing with decreasing x.

H. Mäntysaari, B. Schenke, Phys. Rev. Lett. 117 (5) (2016) 052301

Color dipole approach

- Skewedness correction - gluons attached to quarks in the $q\bar{q}$ dipole carry different light-front momenta fractions x and x' of the proton - the skewness effect

$$R_g^{T,L}(\lambda) = \frac{2^{2\lambda^{T,L}+3}}{\sqrt{\pi}} \frac{\Gamma(\lambda^{T,L}+5/2)}{\Gamma(\lambda^{T,L}+4)} \qquad \lambda^{T,L} = \frac{\partial \ln \mathcal{A}_{T,L}^{\gamma^* p \to Mp}}{\partial \ln \frac{1}{x}}$$

A.G. Shuvaev, K.J. Golec-Biernat, A.D. Martin, M.G. Ryskin, Phys. Rev. D 60 (1999) 014015

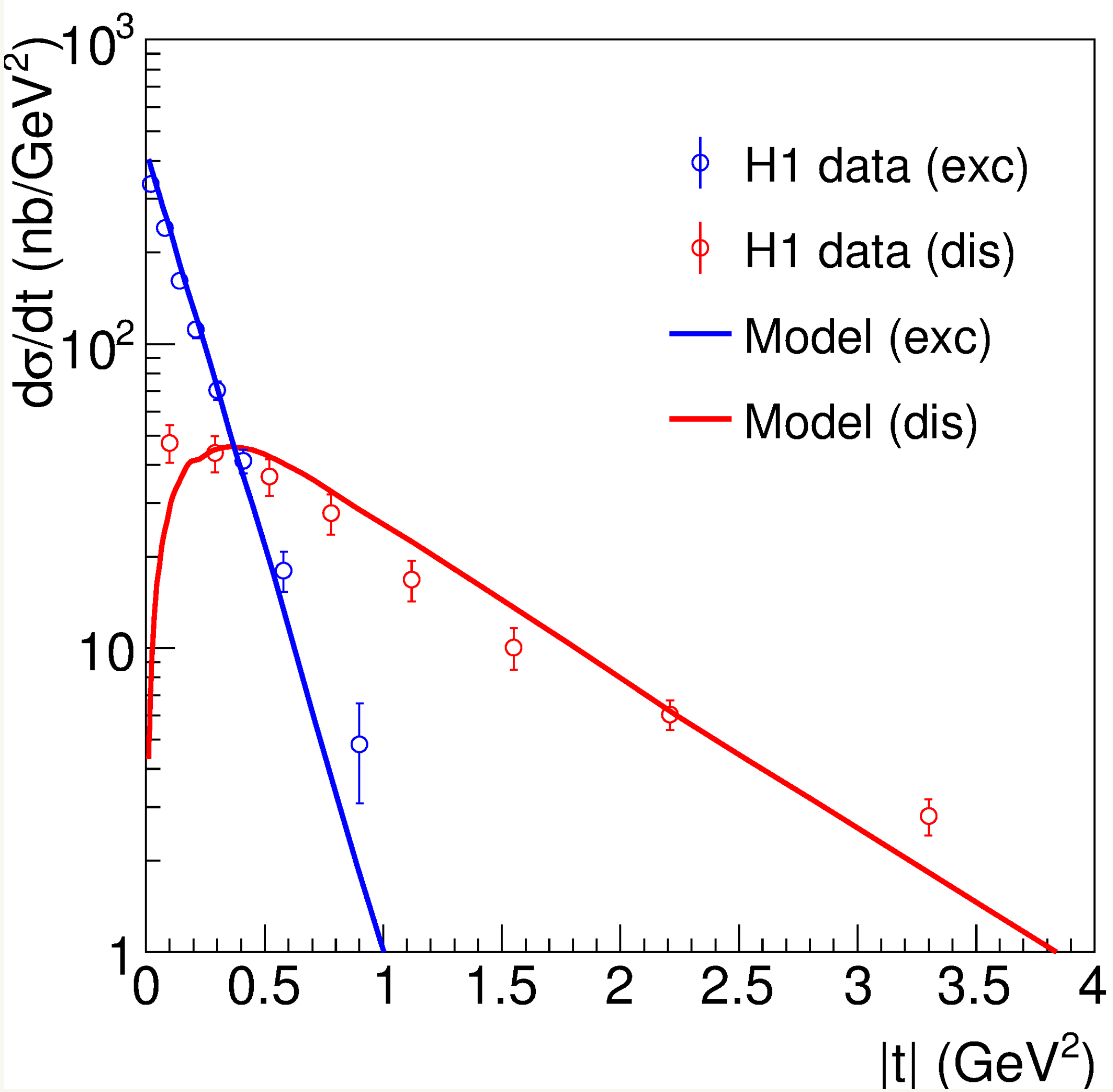
- Final formula for exclusive production is

$$\frac{d\sigma_{T,L}^{\gamma^* p \to Mp}}{d|t|} = \frac{1}{16\pi} \left| \left\langle \mathcal{A}_{T,L}^{\gamma^* p \to Mp} R_g^{T,L} \right\rangle \right|^2$$

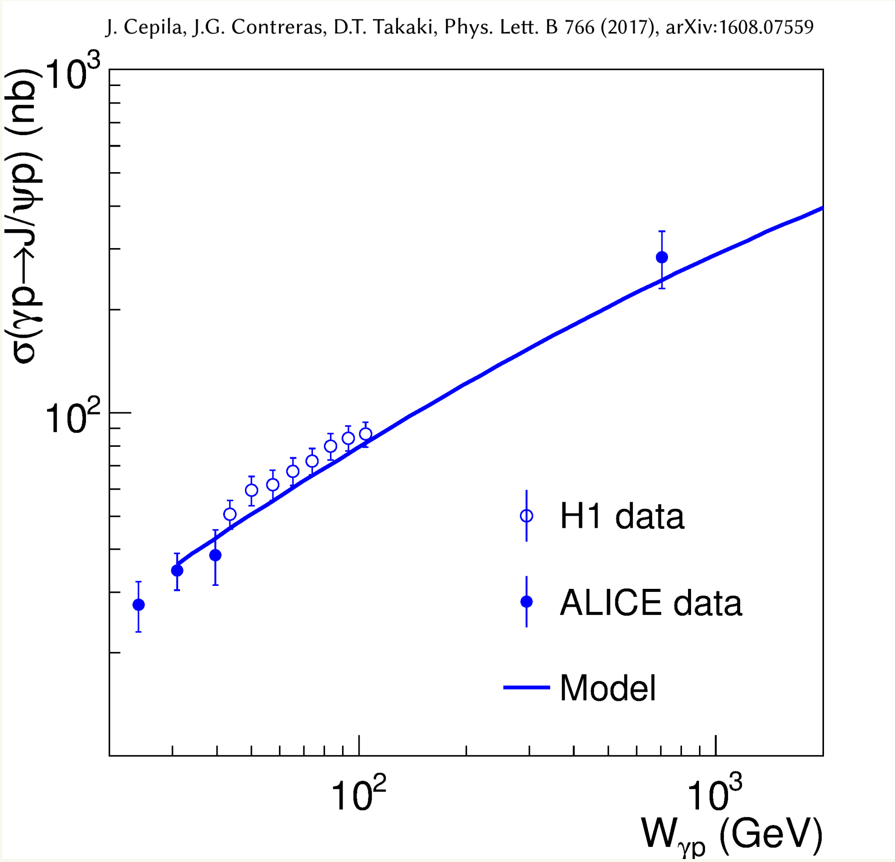
- Final formula for dissociative production is

$$\frac{d\sigma_{T,L}^{\gamma^* p \to MX}}{d|t|} = \frac{1}{16\pi} \left(\left\langle \left| \mathcal{A}_{T,L}^{\gamma^* p \to Mp} R_g^{T,L} \right|^2 \right\rangle - \left| \left\langle \mathcal{A}_{T,L}^{\gamma^* p \to Mp} R_g^{T,L} \right\rangle \right|^2 \right)$$

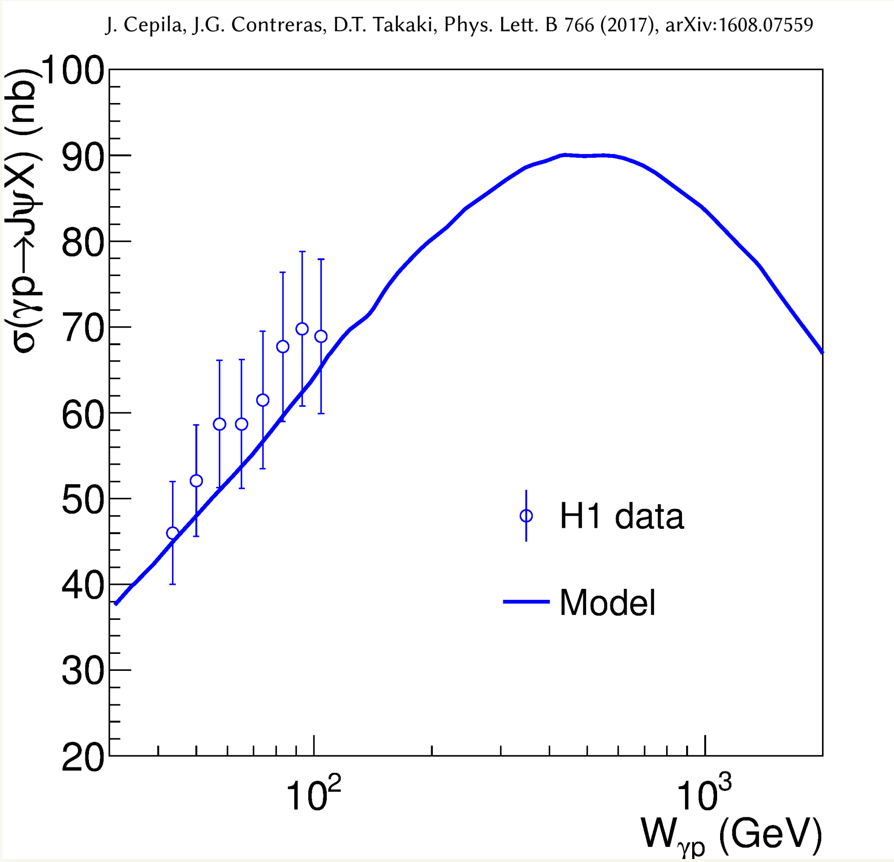
J. Cepila, J.G. Contreras, D.T. Takaki, Phys. Lett. B 766 (2017), arXiv:1608.07559



Results



J. Cepila, J.G. Contreras, D.T. Takaki, Phys. Lett. B 766 (2017), arXiv:1608.07559
σ(γp→J/ψp) (nb)
10^3
10^2
10^2
10^3
W_γp (GeV)
H1 data
ALICE data
Model



J. Cepila, J.G. Contreras, D.T. Takaki, Phys. Lett. B 766 (2017), arXiv:1608.07559
σ(γp→JψX) (nb)
100
90
80
70
60
50
40
30
20
10^2
10^3
W_γp (GeV)
H1 data
Model

- We did a test of the model prediction for DIS, also. Here is the result compared to data at $Q^2 = 2.7\text{GeV}^2$

$$F_2(x,Q^2) = \frac{Q^2}{4\pi^2\alpha_{em}}\left(\sigma_T^{\gamma^* p}(x,Q^2) + \sigma_L^{\gamma^* p}(x,Q^2)\right)$$

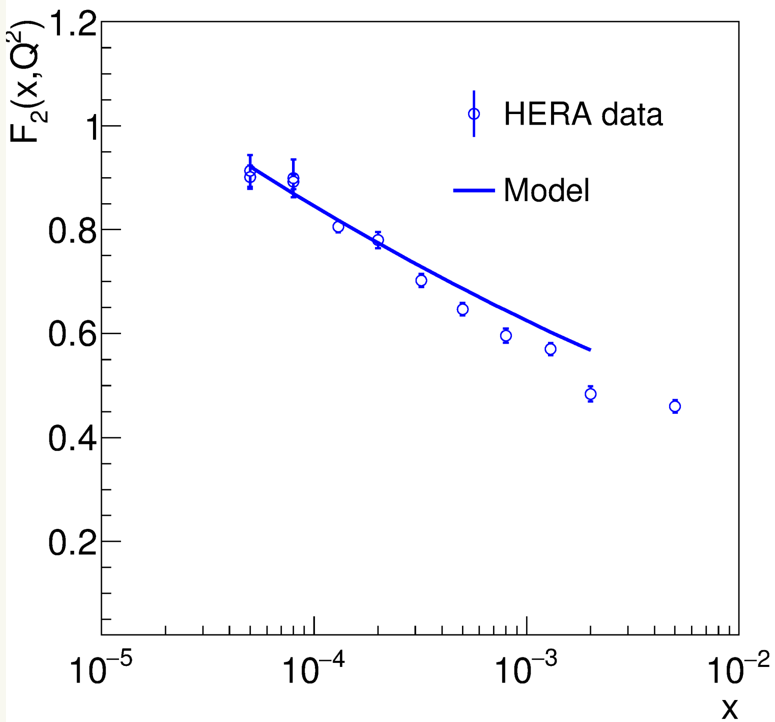
$$\sigma_{T,L}^{\gamma^* p}(x,Q^2) = \sigma_0 \int d\vec{r} \int_0^1 dz \left|\Psi_{T,L}^{\gamma^* \to q\bar{q}}(z,r,Q^2)\right|^2 N(r,\tilde{x})$$

- $\tilde{x} = x(1 + (4m_f^2)/Q^2)$

K.Golec-Biernat and M.Wusthoff, Phys. Rev. D **59**, 014017 (1999)

- $N(r,\tilde{x})$ taken from the GBW model
- m_f is an effective mass for light quarks set to 140 MeV and for charm quark to 1.4 GeV
- $\Psi_{T,L}^{\gamma^* \to q\bar{q}}$ is the wave function for the splitting of the photon into a quark-antiquark pair

J. Cepila, J.G. Contreras, D.T. Takaki, Phys. Lett. B 766 (2017), arXiv:1608.07559



Discussion

- The numerical values were chosen according to the following arguments:
- The average square of the proton radius $B_p = 4.7\text{GeV}^{-2}$ is similar to that measured at HERA
- The value of the average square of the hot spot radius $B_{hs} = 0.8\text{GeV}^{-2}$ corresponds to a hot spot radius of 0.35 fm, quite close to the values around 0.3 fm found in several papers on soft QCD structure
- The value of $\lambda = 0.21$ is constrained by the energy dependence of exclusive J/Ψ photoproduction, similar to the value found at HERA for a scale $Q^2 \sim 2$–3GeV^2
- Due to factorized form of the dipole cross-section we can set $\sigma_0 = 4\pi B_p$.
- We related the number of hot spots with the number of gluons available for the interaction - we follow simple functional form for the gluon distribution motivated by PDF parametrizations
- Coefficients of this form were varied to find best agreement with energy dependence of H1 data of dissociative J/Ψ photoproduction. The chosen normalization is the one that yields a correct simultaneous description of the available data for total and differential cross-section.

Summary and conclusions

- We have presented a model for the exclusive and dissociative J/Ψ photoproduction cross section.
- The model incorporates a fluctuating hot spot structure of the proton in the impact parameter plane, with the number of hot spots growing with decreasing x.
- The model describes correctly the behaviour of F_2 at the relevant scale, as well as the W and t distribution of the exclusive and dissociative J/Ψ photoproduction cross section as measured by H1 and ALICE.
- The model predicts that the energy dependence of the dissociative process increases from low energies up to $W_{\gamma p} \sim 500$ GeV and then decreases steeply.
- Physical explanation according to the parton saturation phenomenon is that the growth of the number of scattering centers provides the growth of the exclusive and dissociative cross-section . However, at some point the number of hot spots is so large that they overlap. When the overlap is large enough, different configurations look the same and the variance diminishes and so does the dissociative cross-section.

J. Cepila, J.G. Contreras, D.T. Takaki, Phys. Lett. B 766 (2017), arXiv:1608.07559