Production of vector mesons within the color dipole picture

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Are hadrons fundamental objects?

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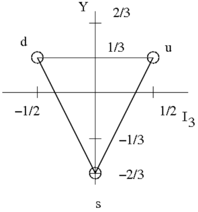
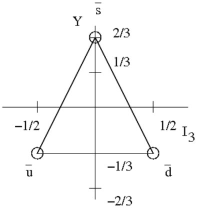
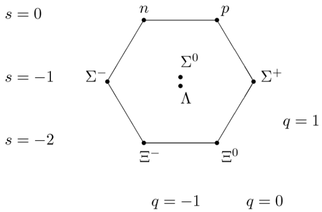
NO!

- **Additive quark model** (1964, Gell-Man, Zweig)
  - Hadrons can be arranged into SU(3) multiplets according to their spin, parity and baryon number, also mass and strangeness ordering emerges.
  - Multiplets are formed from fundamental representations of SU(3)
    $\rightarrow$ mesons: $3 \times \bar{3} = 8 + 1$
    $\rightarrow$ baryons: $3 \times 3 \times 3 = 10 + 8 + 8 + 1$
  - Gell-Man $\rightarrow$ "quarks" are just mathematical concept
  - Zweig $\rightarrow$ "aces" are fundamental particles, with $B = 1/3$ and fractional charge, experimental search should start
  - Extensions by accounting for spin, c quark, color...
- "Gluons" proposed by Nambu - interaction among quarks via exchange of 8 color fields – $\mathrm{SU(3)_C}$ symmetry.







- Probes inner structure of hadrons.
- DIS cross section

$$\frac{\mathrm{d}^2\sigma}{\mathrm{d}x\mathrm{d}Q^2} = \frac{4\pi\alpha^2}{Q^4}\left[y^2 F_1(x, Q^2) + (1-y)\frac{F_2(x, Q^2)}{x}\right] \quad (1)$$

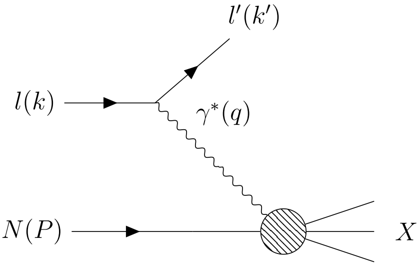
- $F_1, \ F_2$ – structure functions, include photon-proton interaction.

$$W^2_{\gamma^* p} = (P+q)^2$$

$$Q^2 = -q^2 = -(k-k')^2$$

$$x = \frac{Q^2}{2P\cdot q}$$

$$y = \frac{P\cdot Q}{P\cdot k}$$



- Scattering of γ^* on one of the constituent partons.
- Infinite momentum frame - incoming particles carry only longitudinal momentum.
- Partons carry fraction x of the proton momentum P.
- Electron-parton scattering cross section

$$\frac{\mathrm{d}^2\sigma}{\mathrm{d}x\mathrm{d}Q^2} = \frac{4\pi\alpha^2}{Q^4}\left[(1-y)+\frac{y^2}{2}\right]\sum_i e_i^2 f_i(x), \tag{2}$$

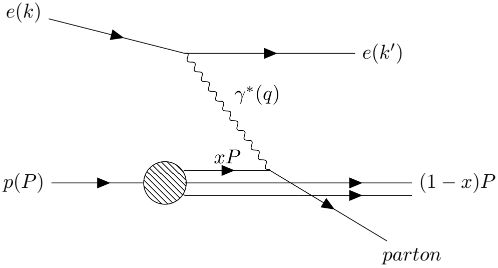
- If partons are ferminons:

$$F_1(x) = \frac{1}{2}\sum_i e_i^2 f_i(x)$$

$$F_2(x) = \sum_i e_i^2 x f_i(x)$$

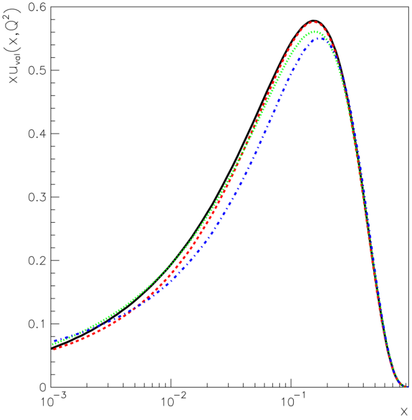
$$F_2(x) = 2xF_1(x).$$

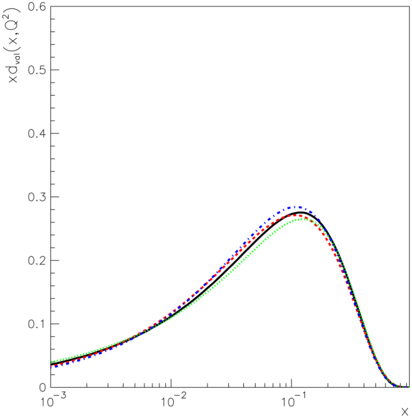
- Independence on Q^2 (Bjorken scaling)



Are there only valence quarks?

Something is clearly missing here! :(





Let's add sea quarks

- proton $= u_v + u_v + d_v + (u_s + \bar{u}_s) + (d_s + \bar{d}_s) + (s_s + \bar{s}_s)$ [1]

$$\frac{F_2^{ep}(x)}{x} = \frac{4}{9}\left[u^p(x) + \bar{u}^p(x)\right] + \frac{1}{9}\left[d^p(x) + \bar{d}^p(x)\right] + \frac{1}{9}\left[s^p(x) + \bar{s}^p(x)\right] \quad (3)$$

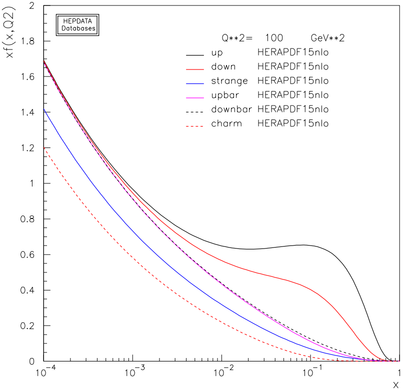
- Sum rules

$$\int_0^1 u_v(x)\mathrm{d}x = 2$$

$$\int_0^1 d_v(x)\mathrm{d}x = 1$$

$$\int_0^1 \left[q_s(x) - \bar{q}_s(x)\right]\mathrm{d}x = 0$$

This looks better. :)



- Fraction of the proton momentum carried by all q and $\bar{q}$ together

$$\int_0^1 x\Sigma(x)\mathrm{d}x = \frac{18}{5}\int_0^1 F_2^{eN}(x)\mathrm{d}x$$

- Naive expectation

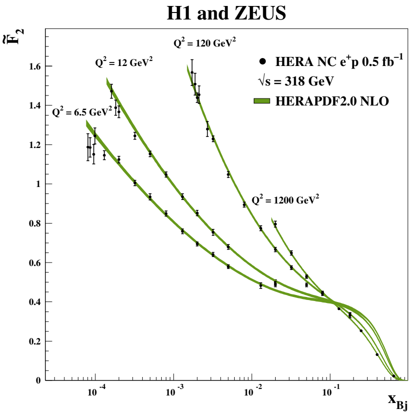
$$\int_0^1 x\Sigma(x)\mathrm{d}x = 1$$

- Experimental value

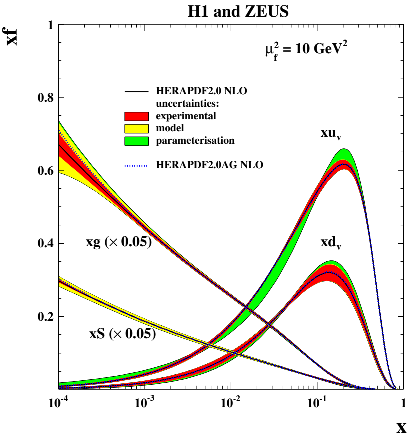
$$\int_0^1 x\Sigma(x)\mathrm{d}x \approx 0.5$$

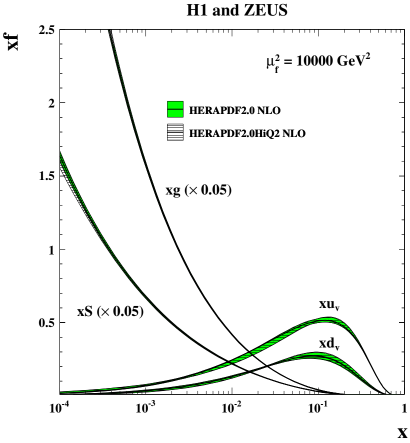
- Other, electrically neutral partons in proton → **gluons**

Also Bjorken scaling violation observed!



- Composition of the proton changes with x and Q^2.
- At low energies proton dominated by valence quarks.
- At large energies gluons dominate.





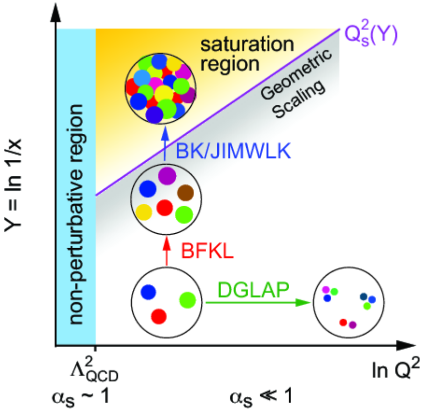


Figure: Diagram picturing the QCD evolution of the partonic structure of the proton.

C. Marquet, Nucl.Phys. A904-905 (2013) 294c-301c.

- Evolution with increasing Q^2 described by DGLAP equations.
- By fixing the scale of the process, one can fix the position in ln Q^2.
- Going to smaller x, one can reach the saturation scale $Q_S^2(x)$
  - Below $Q_S^2(x) \rightarrow$ dilute regime, linear evolution of the gluon density (BFKL).
  - Above $Q_S^2(x) \rightarrow$ dense regime, non-linear evolution of the gluon density (JIMWLK, BK).

- Energy dependence of dissociative J/ψ photoproduction as a signature of gluon saturation at the LHC
  J. Cepila, J. G. Contreras, J. D. Tapia Takaki
  Phys.Lett. B766 (2017) 186-191
- Coherent and incoherent J/ψ photonuclear production in an energy-dependent hot-spot model
  J. Cepila, J. G. Contreras, M. Krelina
  Phys. Rev. C 97 (2018), 024901
- Mass dependence of vector meson photoproduction off protons and nuclei within the energy-dependent hot-spot model
  J. Cepila, J. G. Contreras, M. Krelina, J. D. Tapia Takaki
  Nucl.Phys. B934 (2018) 330-340
- Dissociative production of vector mesons at electron-ion colliders
  D. Bendova, J. Cepila, J.G. Contreras
  arXiv:1811.06479; Submitted to PRD

What process is sensitive to the proton structure?

- We want to probe the partonic structure of hadrons.
- Easily observable final state is desirable.
- Exclusive and dissociative vector meson (VM) production fulfil both requirements.

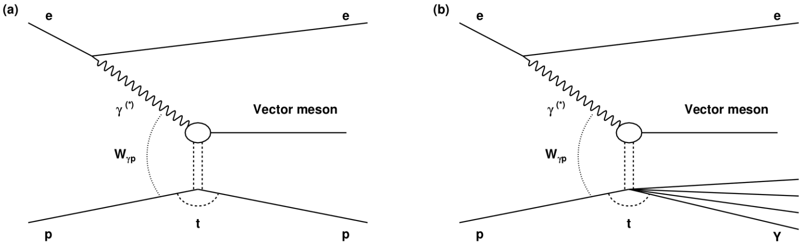
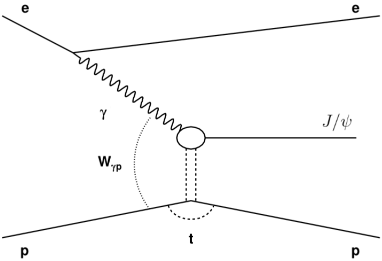


Figure: Diagrams for exclusive (a) and dissociative (b) production of vector mesons.

Exclusive production of J/ψ...

- J/ψ **meson**
  - $c\bar{c}$, $J^P = 1^-$
  - Large mass $M = 3.1\ \mathrm{GeV}$ (pQCD)
  - Clean experimental signal (leptonic decays, small width).
- Connected to the distribution of gluons in the transverse plane.
- Cross section

$$\left.\frac{\mathrm{d}\sigma^{\gamma p \rightarrow VMp}}{\mathrm{d}|t|}\right|_{T,L} = \frac{(R_g^{T,L})^2}{16\pi} |\langle \mathcal{A}_{T,L}^{\gamma p \rightarrow VMp} \rangle|^2$$



$$\Delta^2 = -t = -(P - P')^2$$

$$-t = p_t^2$$

$$W_{\gamma p}^2 = 2E_p M e^{|y|}$$

$$x = \frac{M^2 + Q^2}{W_{\gamma p}^2 + Q^2} \approx \frac{M^2}{W_{\gamma p}^2}$$

- The photon interacts via its $q\bar{q}$ Fock state with the proton in the target rest frame.
- At low x, lifetime of the fluctuation is larger than dipole-proton interaction time.
- After the interaction, J/ψ is formed from the dipole.

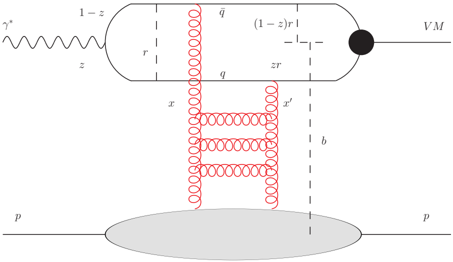


Figure: Schematic picture of vector meson production within the color dipole approach.

Scattering amplitude

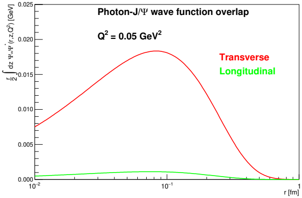
$$\mathcal{A}_{T,L}(x, Q^2, \vec{\Delta}) = i \int \mathrm{d}\vec{r} \int_0^1 \frac{\mathrm{d}z}{4\pi} \int \mathrm{d}\vec{b} |\Psi^*_{VM}\Psi_{\gamma^*}|_{T,L} \exp\left[-i\left(\vec{b} - (1-z)\vec{r}\right)\vec{\Delta}\right] \frac{\mathrm{d}\sigma_{q\bar{q}}}{\mathrm{d}\vec{b}}$$

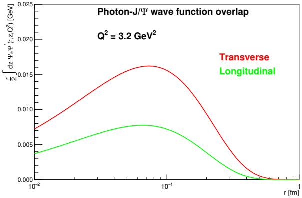
Wave functions

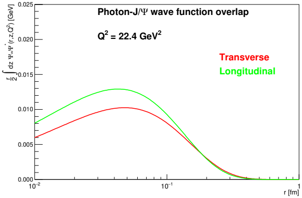
$$|\Psi^*_{VM}\Psi_{\gamma^*}|_T = \hat{e}_f e \frac{N_C}{\pi z(1-z)} \left[m_f^2 K_0(\epsilon r)\phi_T(r,z) - \left(z^2 + (1-z)^2\right) \epsilon K_1(\epsilon r)\partial_r \phi_T(r,z) \right]$$

$$|\Psi^*_{VM}\Psi_{\gamma^*}|_L = \hat{e}_f e \frac{N_C}{\pi} 2Qz(1-z)K_0(\epsilon r) \left[M\phi_L(r,z) + \delta \frac{m_f^2 - \nabla_r^2}{Mz(1-z)} \phi_L(r,z) \right]$$

$$\epsilon = z(1-z)Q^2 + m_f^2; \qquad r \equiv |\vec{r}|$$







Dipole-proton cross section

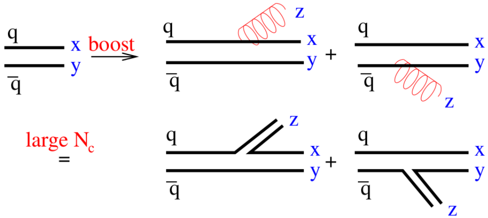
- From optical theorem

$$\frac{\mathrm{d}\sigma_{q\bar{q}}}{\mathrm{d}\vec{b}} = 2N(x, \vec{r}, \vec{b}) \tag{4}$$

- Dipole scattering amplitude $N(x, \vec{r}, \vec{b})$ from BK equation

$$\begin{aligned}\frac{\partial N(r, b, Y)}{\partial Y} = \int \mathrm{d}\vec{r}_1 K(r, r_1, r_2)[N(r_1, b_1, Y) + N(r_2, b_2, Y) \\ -N(r, b, Y) - N(r_1, b_1, Y)N(r_2, b_2, Y)]\end{aligned} \tag{5}$$

$$\vec{r}_2 = \vec{r} - \vec{r}_1; \qquad r \equiv |\vec{r}|$$



- We want to factorize impact-parameter dependence

$$\frac{\mathrm{d}\sigma_{q\bar{q}}}{\mathrm{d}\vec{b}} = 2N(x,\vec{r},\vec{b}) \rightarrow \sigma_0 N(x,\vec{r})\, T_p(\vec{b}). \tag{6}$$

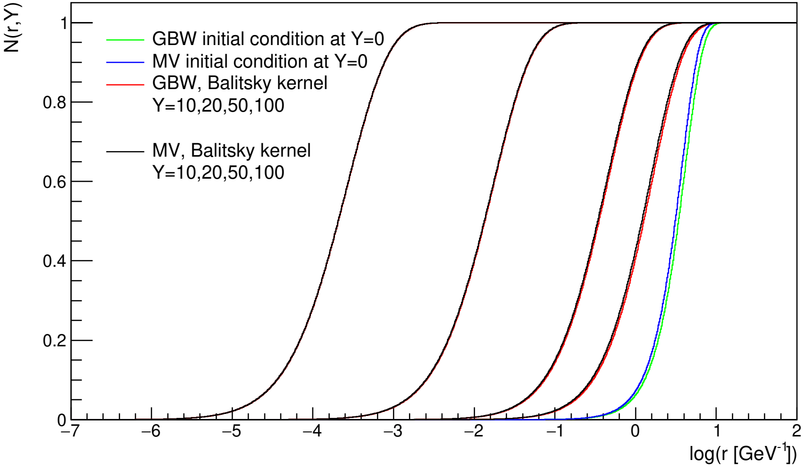
- $T_p(\vec{b})$ describes the proton profile in the impact-parameter plane
- σ_0 - normalization parameter
- Dipole amplitude $N(x,\vec{r})$ can be obtained as a solution of BK equation (b-independent) or from various parametrizations.
  - **GBW parametrization**[2]

$$N(x,\vec{r}) = 1 - \exp\left(-\frac{\vec{r}^2 Q_s^2(x)}{4}\right) \tag{7}$$

where $Q_s(x)$ denotes the x-dependent saturation scale

$$Q_s^2(x) = Q_0^2 \left(\frac{x_0}{x}\right)^{\lambda_{\mathrm{GBW}}} \;[\mathrm{GeV}^2]. \tag{8}$$

Dipole cross section: solution to BK equation



How to model proton?

- The simplest form is a step function

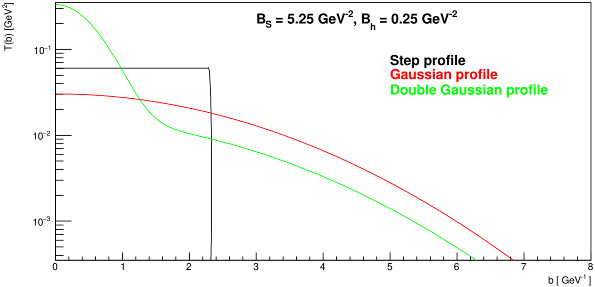
$$T_p(b) = \frac{1}{\pi B}\theta\left(\sqrt{B} - b\right). \tag{9}$$

- Widely used form is Gaussian distribution

$$T_p(b) = \frac{1}{2\pi B}\exp\left(-\frac{b^2}{2B}\right). \tag{10}$$

- Alternative form: Proton consists of a hard core surrounded by soft pion cloud

$$T_p(b) = \frac{1}{4\pi B_h}\exp\left(-\frac{b^2}{2B_h}\right) + \frac{1}{4\pi B_s}\exp\left(-\frac{b^2}{2B_s}\right) \tag{11}$$



Including inner structure of the proton

- We describe the proton profile using the **energy-dependent hot-spot model**[3].
  - Proton profile seen as a set of regions of high gluon density (hot spots) randomly placed in the impact parameter plane

$$T_p(\vec{b}) = \frac{1}{N_{hs}} \sum_{i=1}^{N_{hs}} T_{hs}\left(\vec{b} - \vec{b}_i\right). \tag{12}$$

  - Each hot spot has a Gaussian distribution

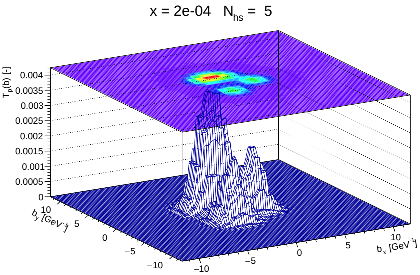
$$T_{hs}(\vec{b}) = \frac{1}{2\pi B_{hs}} \exp\left(-\frac{\vec{b}^2}{2B_{hs}}\right), \quad B_{hs} = 0.8\ \mathrm{GeV}^{-2}. \tag{13}$$

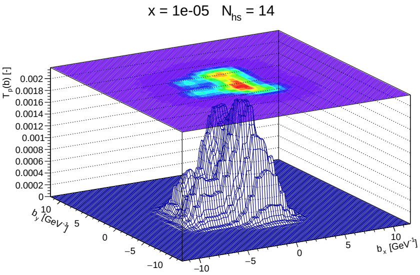
  - The positions of the hot spots in the transverse plane fluctuate event-by-event.
  - Number of hot spots depends on x as (grows with decreasing x)

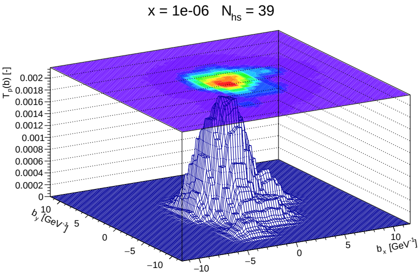
$$N_{hs} = p_0 x^{p_1}\left(1 + p_2\sqrt{x}\right) \tag{14}$$

  - Final N_{hs} is obtained using the Zero-truncated Poisson distribution with the mean value given by Eq. (14).

Examples of proton profiles in hot-spot model





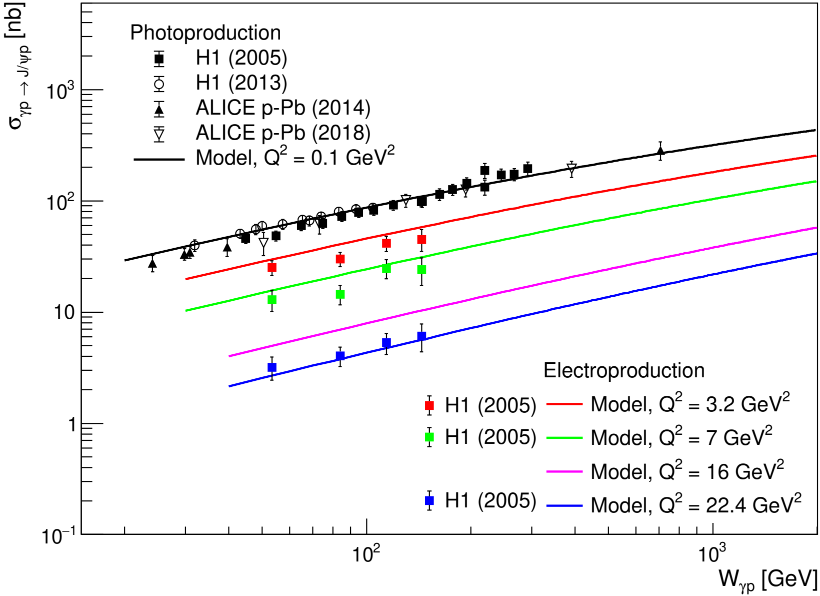


Let's put all the ingredients together...

Let’s put all the ingredients together...

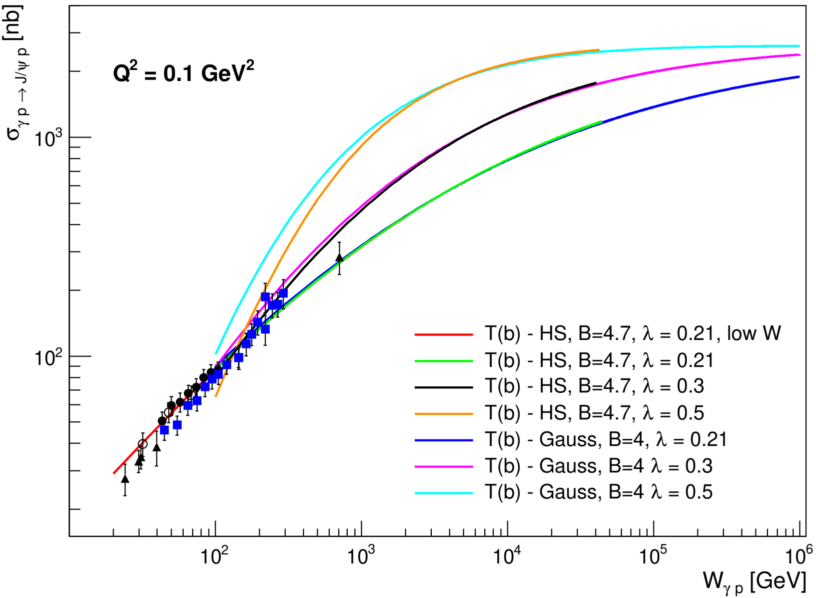
...and have a look at some results.

Resulting exclusive J/ψ cross section

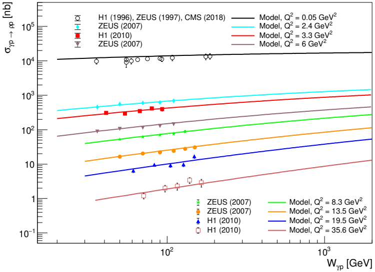


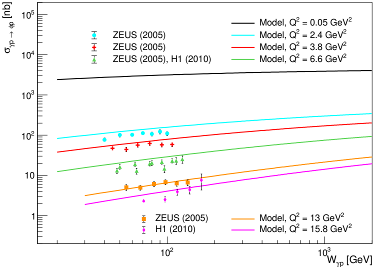
Where is the saturation?

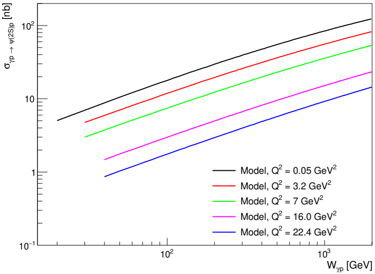
Resulting exclusive J/ψ cross section

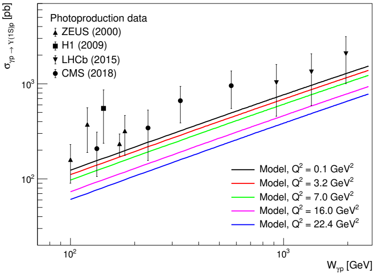


Other vector mesons

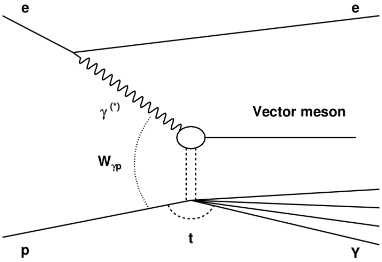








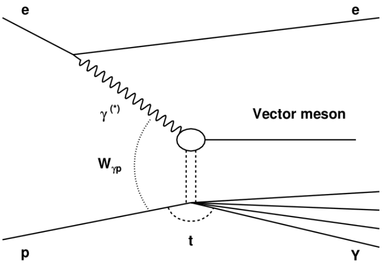
Dissociative vector meson production



$$\left.\frac{\mathrm{d}\sigma^{\gamma^* p\to VMY}}{\mathrm{d}|t|}\right|_{T,L} = \frac{\left(R_g^{T,L}\right)^2}{16\pi}\left(\langle|\mathcal{A}_{T,L}^{\gamma^* p\to VMp}|^2\rangle - |\langle\mathcal{A}_{T,L}^{\gamma^* p\to VMp}\rangle|^2\right) \tag{15}$$

Variance over different configurations!

Dissociative vector meson production



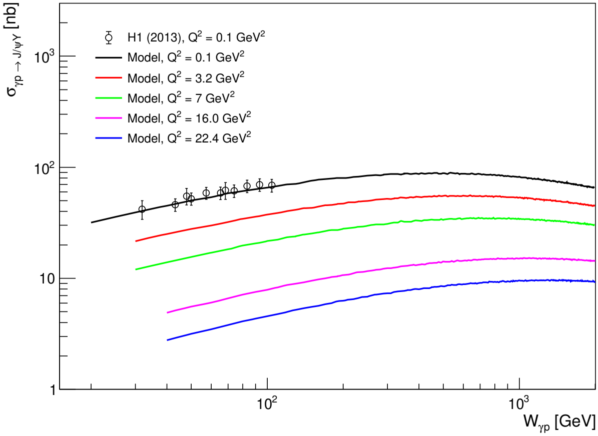
$$\left.\frac{\mathrm{d}\sigma^{\gamma^* p \to VMY}}{\mathrm{d}|t|}\right|_{T,L} = \frac{\left(R_g^{T,L}\right)^2}{16\pi}\left(\langle|\mathcal{A}_{T,L}^{\gamma^* p\to VMp}|^2\rangle - |\langle\mathcal{A}_{T,L}^{\gamma^* p\to VMp}\rangle|^2\right) \tag{16}$$

Variance over different configurations!

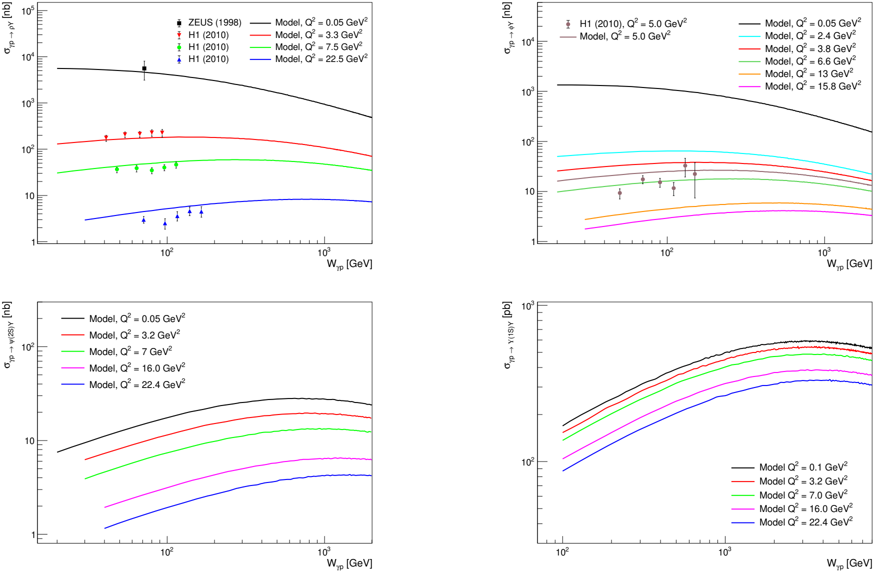
$\rightarrow$ should be sensitive to fluctuations in the proton structure.

Dissociative J/ψ cross section

- Maximum of the cross section at all Q^2.
- At a certain energy, available area in the proton is filled $\rightarrow$ hot spots overlap $\rightarrow$ all the possible configurations start to look alike $\rightarrow$ variance decreases.



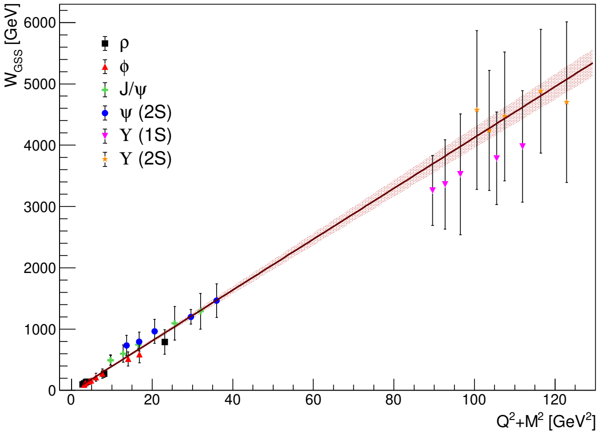
Again, let's have a look at other vector mesons



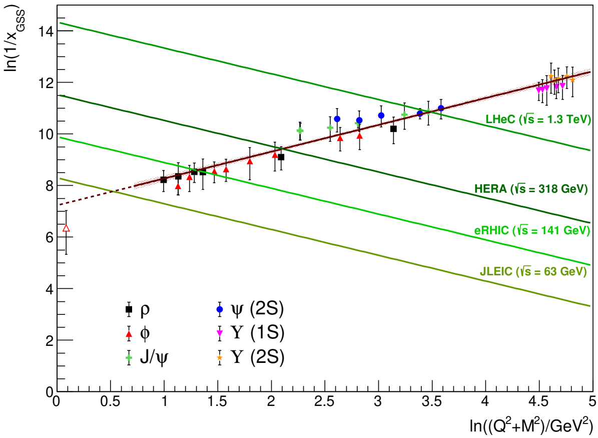
Is there some dependence?

Mass and scale dependence of the position of the dissociative maximum

- We investigate the energy W_{GSS} at which maximum is reached.
- Maximum is shifted towards higher W_{GSS} with increasing Q^2 and mass M of given vector meson $\rightarrow$ linear fit describes the behavior with a slope $(41 \pm 2)\ \mathrm{GeV}^{-1}$.



- We calculate $\ln(1/x_{GSS})$ and $\ln(Q^2 + M^2)$ for each VM at all the calculated Q^2.
- Dependence is described by a linear fit with slope (1.04 ± 0.07).
- Obtained result reminds of the saturation scale $Q_S^2(x)$, however it is of geometric origin coming from our model.



Conclusions

- Vector meson production can be treated using the color dipole approach.
- Prediction successfully describe the available data HERA and LHC experiments.
- Impact-parameter factorized form of the dipole-target cross section allows us to investigate transverse structure of the proton.
- Striking behavior of the dissociative cross section dependence on $W_{\gamma p}$
  - Cross section rises at low energies.
  - At a certain energy, available area in the proton is filled $\rightarrow$ hot spots overlap $\rightarrow$ all the possible configurations start to look alike $\rightarrow$ variance decreases.
  - After reaching a maximum at that energy, the cross section starts to decrease.
- Position of the dissociative maximum is directly connected to the vector meson mass and virtuality of the exchanged photon.
- We predict a power law behavior in $1/x_{GSS}$ for the geometrical saturation scale.
- Maxima seem to be within the reach of existing (LHC) and future (EIC) colliders.

BACKUP SLIDES

- Stages of $\gamma^* p$ scattering:
  - Incoming e^- radiates γ^* which can fluctuate into $q\bar{q}$ dipole (colorless).
  - Dipole then interacts with the proton.
  - After the interaction dipole collapses back to γ^*.
- Cross section for $\gamma^* p$ scattering and structure function F_2

$$\sigma_{T,L}^{\gamma^* p} = \sum_f \int \mathrm{d}^2 r \int \mathrm{d}z |\Psi^* \Psi|^f_{T,L} \sigma_{q\bar{q}}(\tilde{x}, r), \qquad F_2(x, Q^2) = \frac{Q^2}{4\pi^2 \alpha}(\sigma_T + \sigma_L).$$

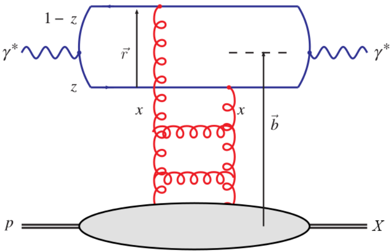
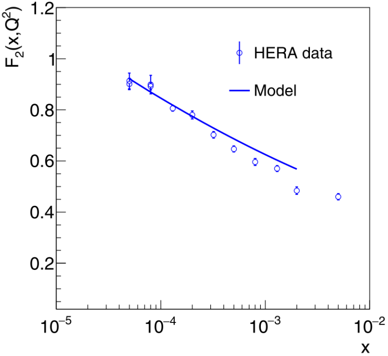


Figure: DIS in the dipole picture [?].

- Cross section for $\gamma^* p$ scattering and structure function F_2

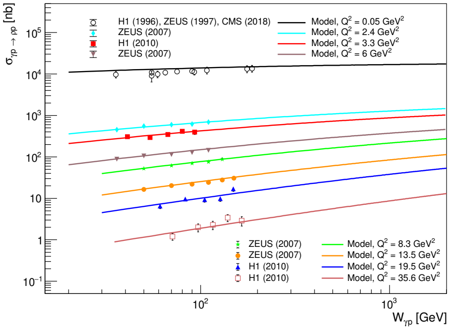
$$\sigma_{T,L}^{\gamma^* p} = \sum_f \int \mathrm{d}^2 r \int \mathrm{d}z |\Psi^* \Psi|_{T,L}^f \sigma_{q\bar{q}}(\tilde{x}, r), \qquad F_2(x, Q^2) = \frac{Q^2}{4\pi^2 \alpha}(\sigma_T + \sigma_L).$$

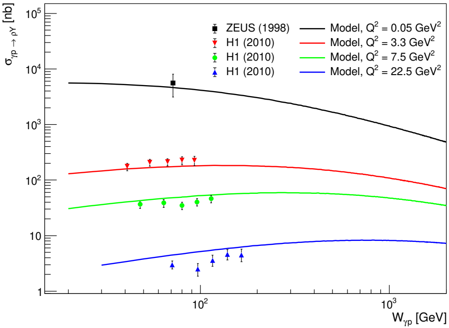
$$\tilde{x} = x \left(1 + \frac{4m_f^2}{Q^2}\right), \qquad Q^2 = 2.7 \ \mathrm{GeV}^2$$



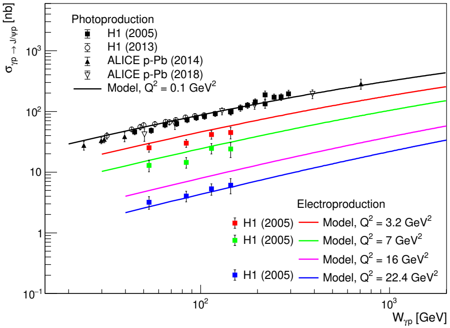
Predictions and comparison with data for cross sections of ρ meson

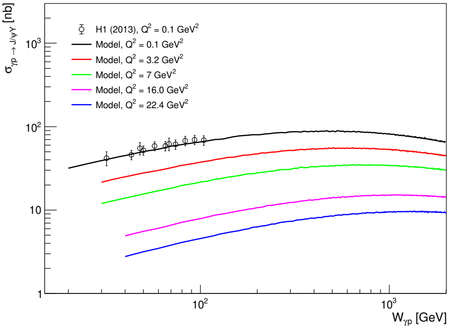
- Predictions compared to H1, ZEUS and preliminary CMS p–Pb data.
- Very good decription of electroproduction data for scales from $Q^2 = 2.4\ \mathrm{GeV}^2$ up to $Q^2 = 35.6\ \mathrm{GeV}^2$.
- For photoproduction B_p was changed[5] to $B_p = 8\ \mathrm{GeV}^{-2}$ in accordance with H1 measurements of the slope parameter b.[6]



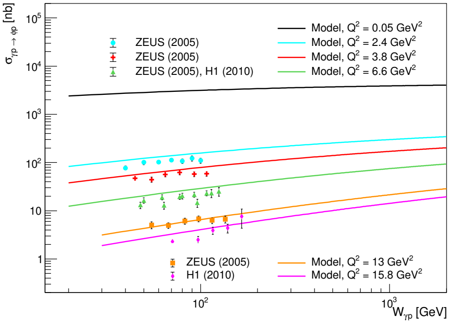


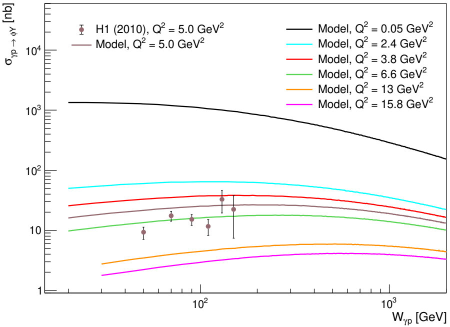
- Predictions compared to H1 and ALICE p–Pb data.
- Good agreement with the data.
- Dissociative maximum is clearly visible at all Q^2.





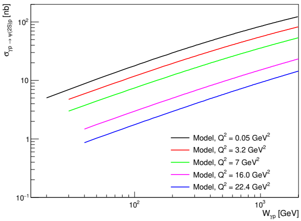
- Predictions compared to H1 and ZEUS data.
- Decription of the electroproduction data is satisfactory, however not as good as for ρ.
- Again, in photoproduction B_p was changed to $B_p = 8\ \mathrm{GeV}^{-2}$.

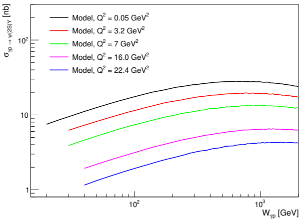


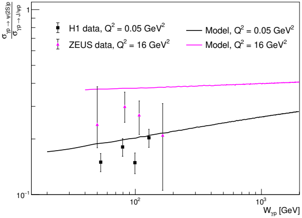


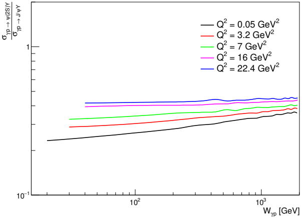
Predictions for cross sections of $\psi(2S)$ meson

- No data are available for cross sections.
- Exclusive $\psi(2S)/J/\psi$ ratios are in fair agreement with the data.



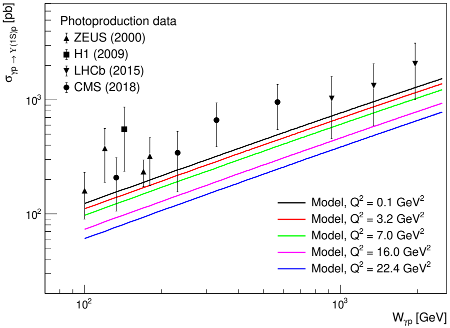


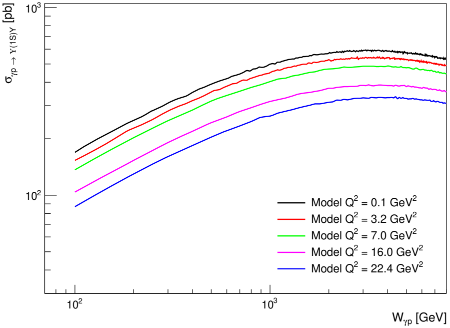




Predictions and comparison with data for cross sections of Υ meson

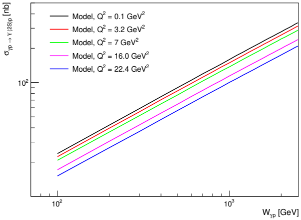
- Photoproduction predictions compared to H1, ZEUS, CMS and LHCb data.
- Description of the data is reasonable given the large uncertainties.
- No data are available for electroproduction nor for the dissociative process.

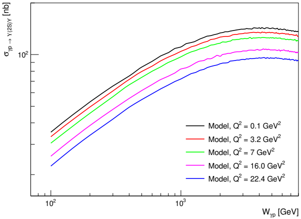


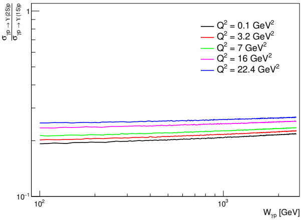


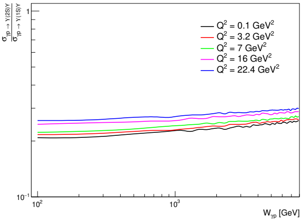
Predictions for cross sections of $\Upsilon(2S)$ meson

- No data are available for cross sections nor for the $\Upsilon(2S)/\Upsilon(1S)$ cross section ratios.









Exclusive and dissociative $|t|$-distribution of the J/ψ cross section[7]

- Compared with published HERA data.
- Used to tune $T_p(\vec{b})$ parameters.