Vector meson photoproduction: selected topics

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References

Diffractive VMs at large Q^2

Helicity flip effects in $d\sigma/dt$ in ρ photoproduction

Central exclusive production of J/ψ and $\psi'(2S)$ in pp and collisions

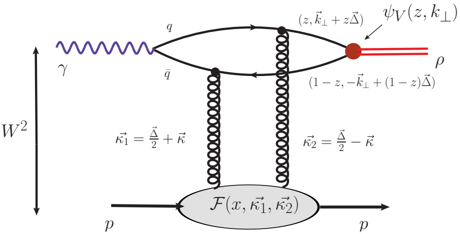
A. Cisek, W. Schäfer and A. Szczurek, Phys. Lett. B **836** (2023), 137595 doi:10.1016/j.physletb.2022.137595 [arXiv:2209.06578 [hep-ph]].

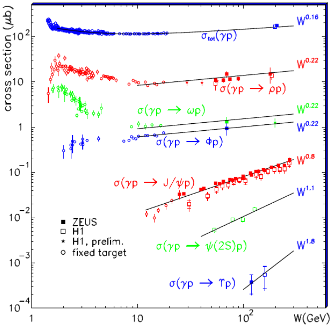
A. D. Bolognino, F. G. Celiberto, D. Y. Ivanov, A. Papa, W. Schäfer and A. Szczurek, Eur. Phys. J. C **81** (2021) no.9, 846 doi:10.1140/epjc/s10052-021-09593-9 [arXiv:2107.13415 [hep-ph]].

A. D. Bolognino, A. Szczurek and W. Schäfer, Phys. Rev. D **101** (2020) no.5, 054041 doi:10.1103/PhysRevD.101.054041 [arXiv:1912.06507 [hep-ph]].

A. Cisek, W. Schäfer and A. Szczurek, JHEP **04** (2015), 159 doi:10.1007/JHEP04(2015)159 [arXiv:1405.2253 [hep-ph]].

Diffractive (virtual) photoproduction of vector mesons



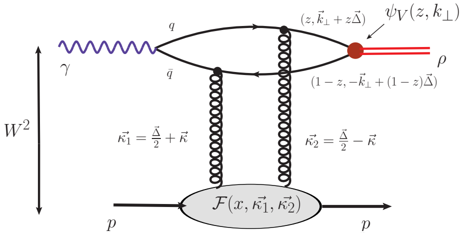


- diffractive (photoproduction) photoproduction is the archetypical Pomeron-exchange process.
- sharp forward peak, approximate conservation of s–channel helicity
- photon virtuality Q^2 or heavy quark mass m_Q allow us to go from **soft** to **hard** diffraction.
- a puzzling **process dependent Pomeron intercept** can be accounted for in the dipole picture, where small dipoles probe the gluon distribution of the target:

$$\sigma(x, \mathbf{r}) \approx \mathbf{r}^2 \frac{\pi^2 \alpha_S}{N_c} xg(x, \frac{1}{\mathbf{r}^2})$$

- **QCD gluon Wigner function**
- gluon saturation effects at very high energies?

Factorization of the diffractive amplitude



- dipole factorization in impact parameter space $\leftrightarrow$ k_T–factorization in momentum space
- **ingredients:** light-front wave function of the vector meson $\psi(z, k_\perp)$ and unintegrated gluon distribution(UGD) /GTMD.
- $t \sim -\mathbf{\Delta}^2$.

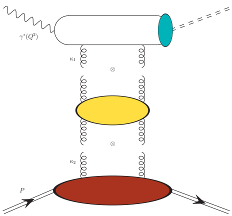
diffractive amplitude:

$$\Im m\, \mathcal{M}_{\lambda_V,\lambda_\gamma}(W, \mathbf{\Delta}) = W^2 \frac{c_V \sqrt{4\pi\alpha_{em}}}{4\pi^2} \int \frac{d\kappa^2}{\kappa^4} \alpha_S(q^2) \mathcal{F}(x, \frac{\mathbf{\Delta}}{2} + \boldsymbol{\kappa}, \frac{\mathbf{\Delta}}{2} - \boldsymbol{\kappa}) \times \int \frac{dz d^2\mathbf{k}}{z(1-z)} I(\lambda_V, \lambda_\gamma; z, \boldsymbol{\kappa}, \mathbf{k}, \mathbf{\Delta}) \psi_V(z, k)$$

$$\mathcal{F}(x, \frac{\mathbf{\Delta}}{2} + \boldsymbol{\kappa}, \frac{\mathbf{\Delta}}{2} - \boldsymbol{\kappa}) \propto \int d^2\mathbf{b} d^2\mathbf{r} e^{-i\boldsymbol{\kappa}\mathbf{r}} e^{-i\mathbf{\Delta}\mathbf{b}} \langle p| 1 - U(Y, \mathbf{b} + \frac{\mathbf{r}}{2}) U^\dagger(Y, \mathbf{b} - \frac{\mathbf{r}}{2}) |p\rangle, \; Y = \log(1/x)$$

generalized TMD (GTMD)/Wigner function

Small-x factorization at large Q^2



- Color dipole factorization is closely related to factorization into impact factors and gluon Green's function in the BFKL approach.
- At large Q^2, transverse momentum in the LFWF can be integrated out and collinear **distribution amplitudes (DAs)** appear.
- **Longitudinal γ^*:** standard leading twist DA.
- **Transverse γ^*:** higher twist DA + $q\bar{q}g$ contribution. Anikin et al. (2010)

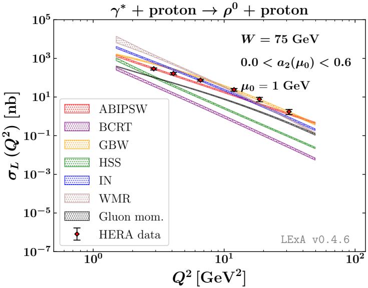
$$\Im m T_{\lambda_V \lambda_\gamma}(s, Q^2) = s \int \frac{d^2\boldsymbol{\kappa}}{(\boldsymbol{\kappa}^2)^2} \Phi^{\gamma^* \to V}_{\lambda_V, \lambda_\gamma}(\boldsymbol{\kappa}^2, Q^2) \mathcal{F}(x, \boldsymbol{\kappa}^2). \quad x = \frac{Q^2}{s}.$$

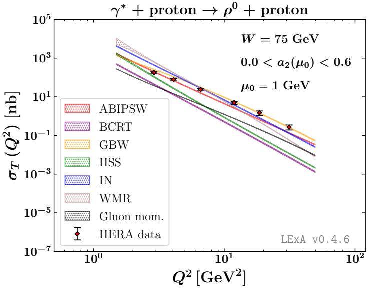
Impact factors

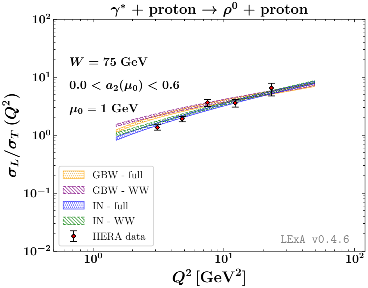
$$\Phi^{\gamma^* \to V}_{0,0}(\boldsymbol{\kappa}^2, Q^2) = \frac{4\pi\alpha_S(\mu_r^2) e_q \sqrt{4\pi\alpha_{\rm em}} f_V}{N_c Q} \int_0^1 dy\, \varphi_1(y; \mu^2) \left(\frac{\alpha}{\alpha + y\bar{y}} \right),$$

$$\begin{aligned}\Phi^{\gamma^* \to V}_{+,+}(\boldsymbol{\kappa}^2, Q^2) &= \frac{2\pi\alpha_S(\mu_r^2) e_q \sqrt{4\pi\alpha_{\rm em}} f_V m_V}{N_c Q^2} \\ &\times \left\{ \int_0^1 dy \frac{\alpha(\alpha + 2y\bar{y})}{y\bar{y}(\alpha + y\bar{y})^2} \left[(y - \bar{y})\varphi_1^T(y; \mu^2) + \varphi_A^T(y; \mu^2) \right] + [q\bar{q}g] \right\}\end{aligned}$$

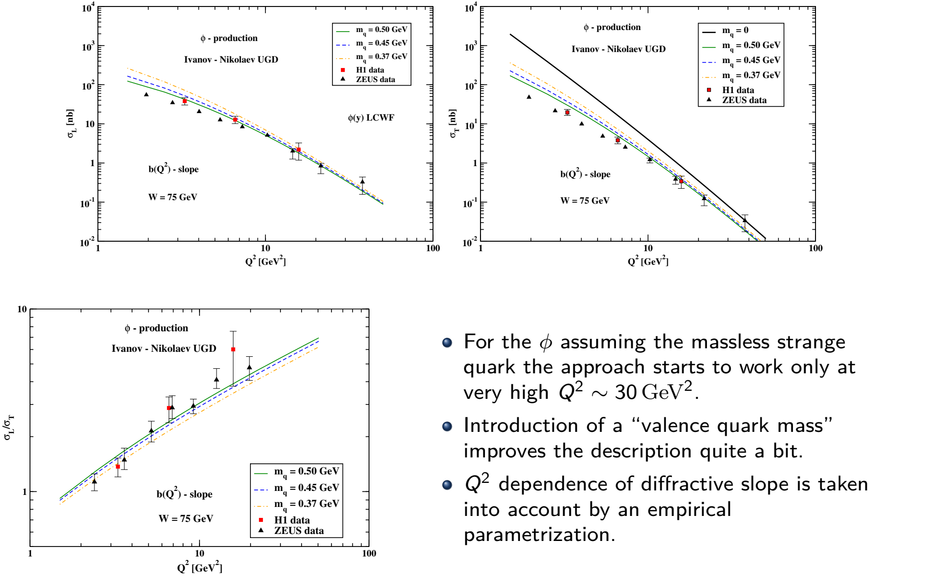
σ_T and σ_L as probes of the UGD: ρ–meson







σ_T and σ_L as probes of the UGD: ϕ–meson



- For the ϕ assuming the massless strange quark the approach starts to work only at very high $Q^2 \sim 30\,\mathrm{GeV}^2$.
- Introduction of a "valence quark mass" improves the description quite a bit.
- Q^2 dependence of diffractive slope is taken into account by an empirical parametrization.

Helicity dependence in ρ meson photoproduction.

diffractive amplitude:

$$\Im m\, \mathcal{M}_{\lambda_V,\lambda_\gamma}(W,\boldsymbol{\Delta}) = W^2 \frac{c_V\sqrt{4\pi\alpha_{em}}}{4\pi^2} \int \frac{d\kappa^2}{\kappa^4}\alpha_S(q^2)\mathcal{F}(x,\frac{\boldsymbol{\Delta}}{2}+\boldsymbol{\kappa},\frac{\boldsymbol{\Delta}}{2}-\boldsymbol{\kappa}) \times \int \frac{dz d^2\boldsymbol{k}}{z(1-z)} I(\lambda_V,\lambda_\gamma;z,\boldsymbol{\kappa},\boldsymbol{k},\boldsymbol{\Delta})\psi_V(z,k)$$

- Regge models of soft scattering often adhere to the principle of s–channel helicity conservation for the Pomeron exchange, which is supported empirically.
- The dipole approach gives a natural possibility for the presence of **helicity flip transitions**. helicity of quark and antiquark is **exactly conserved by gluon exchanges**, but the two-gluon exchange can change the **orbital angular momentum component** L_z.

$$J_z^{\rm VM} = S_z^{q\bar{q}} + L_z^{q\bar{q}}\,.$$

- **double helicity flip** proceeds through the $S_z = 0$ state.
- helicity flips vanish in the forward direction as $|\boldsymbol{\Delta}|^{|\lambda_\gamma-\lambda_V|} \propto |t - t_{\rm min}|^{|\lambda_\gamma-\lambda_V|}$

Helicity conserving & flip amplitudes

1. The s-channel helicity conserving $T \to T$ transition, where $\lambda_\gamma = \lambda_V$: ,

$$I(T,T)_{(\lambda_V=\lambda_\gamma)} = m_q^2 \Phi_2 + \left[z^2 + (1-z)^2\right](\boldsymbol{k}\boldsymbol{\Phi}_1) + \frac{m_q}{M+2m_q}\left[\boldsymbol{k}^2\Phi_2 - (2z-1)^2(\boldsymbol{k}\boldsymbol{\Phi}_1)\right] .$$

2. the helicity flip by one unit, i.e. from the transverse photon $\lambda_\gamma = \pm 1$ to the longitudinally polarized meson, $\lambda_V = 0$.

$$I(L,T) = -2Mz(1-z)(2z-1)(\boldsymbol{e}\boldsymbol{\Phi}_1)\left[1 + \frac{(1-2z)^2}{4z(1-z)}\frac{2m_q}{M+2m_q}\right] + \frac{Mm_q}{M+2m_q}(2z-1)(\boldsymbol{e}\boldsymbol{k})\Phi_2 .$$

3. the helicity flip by two units, from the transverse photon $\lambda_\gamma = \pm 1$ to the transversely polarized meson with $\lambda_V = \mp 1$:

$$I(T,T)_{(\lambda_V=-\lambda_\gamma)} = 2z(1-z)(\Phi_{1x}k_x - \Phi_{1y}k_y) - \frac{m_q}{M+2m_q}\left[(k_x^2 - k_y^2)\Phi_2 - (2z-1)^2(k_x\Phi_{1x} - k_y\Phi_{1y})\right] .$$

$$\Phi_2 = -\frac{1}{(\boldsymbol{r}+\boldsymbol{\kappa})^2+\varepsilon^2} - \frac{1}{(\boldsymbol{r}-\boldsymbol{\kappa})^2+\varepsilon^2} + \frac{1}{(\boldsymbol{r}+\boldsymbol{\Delta}/2)^2+\varepsilon^2} + \frac{1}{(\boldsymbol{r}-\boldsymbol{\Delta}/2)^2+\varepsilon^2} ,$$

$$\boldsymbol{\Phi}_1 = -\frac{\boldsymbol{r}+\boldsymbol{\kappa}}{(\boldsymbol{r}+\boldsymbol{\kappa})^2+\varepsilon^2} - \frac{\boldsymbol{r}-\boldsymbol{\kappa}}{(\boldsymbol{r}-\boldsymbol{\kappa})^2+\varepsilon^2} + \frac{\boldsymbol{r}+\boldsymbol{\Delta}/2}{(\boldsymbol{r}+\boldsymbol{\Delta}/2)^2+\varepsilon^2} + \frac{\boldsymbol{r}-\boldsymbol{\Delta}/2}{(\boldsymbol{r}-\boldsymbol{\Delta}/2)^2+\varepsilon^2} , \quad \boldsymbol{r} = \boldsymbol{k} + (z - \frac{1}{2})\boldsymbol{\Delta}$$

Off forward gluon distribution (GTMD)

$$\mathcal{F}\left(x, \frac{\boldsymbol{\Delta}}{2} + \boldsymbol{\kappa}, \frac{\boldsymbol{\Delta}}{2} - \boldsymbol{\kappa}\right) = f(x, \boldsymbol{\kappa})\, G(\boldsymbol{\Delta}^2)\,,$$

where $f(x, \boldsymbol{\kappa})$ is an unintegrated gluon distribution, which in the perturbative domain at large $\boldsymbol{\kappa}^2$ is related to the standard gluon distribution as

$$f(x, \boldsymbol{\kappa}) \to \frac{\partial xg(x, \boldsymbol{\kappa}^2)}{\partial \log \boldsymbol{\kappa}^2}\,.$$

For the function $G(\boldsymbol{\Delta}^2)$, which satisfies $G(0) = 1$ and takes into account the momentum transfer dependence of the proton-Pomeron coupling, we adopt two options:

1. an exponential parametrization:

$$G(\boldsymbol{\Delta}^2) = \exp\left[-\frac{1}{2} B \boldsymbol{\Delta}^2\right],$$

   with a diffraction slope of $B = 4\,\mathrm{GeV}^{-2}$.

2. a dipole form factor parametrization often used in nonperturbative Pomeron models

$$G(\boldsymbol{\Delta}^2) = \frac{4m_p^2 + 2.79\boldsymbol{\Delta}^2}{4m_p^2 + \boldsymbol{\Delta}^2} \frac{1}{\left(1 + \frac{\boldsymbol{\Delta}^2}{\Lambda^2}\right)^2},$$

   with $\Lambda^2 = 0.71\,\mathrm{GeV}^2$.

Impact parameter space: dipole orientation

The elastic scattering amplitude for a color dipole of size $\vec{r}_\perp$ at impact parameter $\vec{b}_\perp$ is related to the familiar dipole cros section:

$$\sigma(x, \vec{r}_\perp) = 2 \int d^2\vec{b}_\perp\, N(Y, \vec{r}_\perp, \vec{b}_\perp)\,. \quad Y = \log(1/x)$$

Its relation with the GTMD involves a specific combination of phases:

$$\begin{aligned} N(Y, \vec{r}_\perp, \vec{b}_\perp) &= \int d^2\vec{q}_\perp d^2\vec{\kappa}_\perp\, f\left(Y, \frac{\vec{q}_\perp}{2} + \vec{\kappa}_\perp, \frac{\vec{q}_\perp}{2} - \vec{\kappa}_\perp\right) \exp[i\vec{q}_\perp \cdot \vec{b}_\perp] \\ &\times \left\{ \exp\left[i\frac{1}{2}\vec{q}_\perp \cdot \vec{r}_\perp\right] + \exp\left[-i\frac{1}{2}\vec{q}_\perp \cdot \vec{r}_\perp\right] - \exp[i\vec{\kappa}_\perp \cdot \vec{r}_\perp] - \exp[-i\vec{\kappa}_\perp \cdot \vec{r}_\perp] \right\}. \end{aligned}$$

Now the "uncorrelated", factorized ansatz

$$f\left(Y, \frac{\vec{q}_\perp}{2} + \vec{\kappa}_\perp, \frac{\vec{q}_\perp}{2} - \vec{\kappa}_\perp\right) = f(x, \vec{\kappa}_\perp)\, G(\vec{q}_\perp)$$

leads to the amplitude with $\vec{r}_\perp \cdot \vec{b}_\perp$ correlations:

$$N(Y, \vec{r}_\perp, \vec{b}_\perp) = \frac{1}{4}\left\{ t_N\left(\vec{b}_\perp + \frac{\vec{r}_\perp}{2}\right) + t_N\left(\vec{b}_\perp - \frac{\vec{r}_\perp}{2}\right) - 2t_N(\vec{b}_\perp) \right\} \sigma_0(x) + \frac{1}{2} t_N(\vec{b}_\perp) \sigma(x, \vec{r}_\perp)\,,$$

where

$$t_N(\vec{b}_\perp) = \int \frac{d^2\vec{q}_\perp}{(2\pi)^2} \exp(-i\vec{q}_\perp \cdot \vec{b}_\perp) G(\vec{q}_\perp)\,.$$

ρ meson photoproduction: helicity dependence

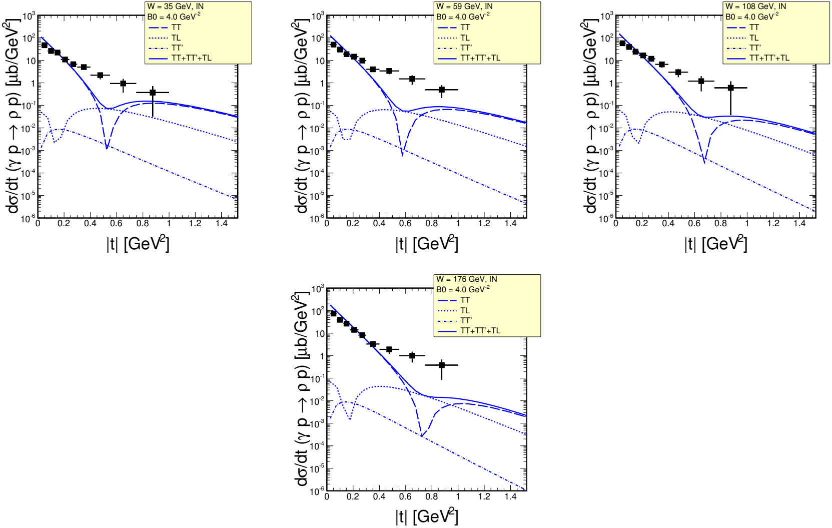


Figure: Distribution in t, the four-momentum transfer squared in the $\gamma p \to \rho p$ reaction for different energies and the Ivanov-Nikolaev UGD. Here the exponential parametrization of the form factor $G(\mathbf{\Delta}^2)$ was used.
Data from *pPb* UPC by CMS: Eur. Phys. J. C, 79 (2019), p. 702.

ρ meson photoproduction: helicity dependence

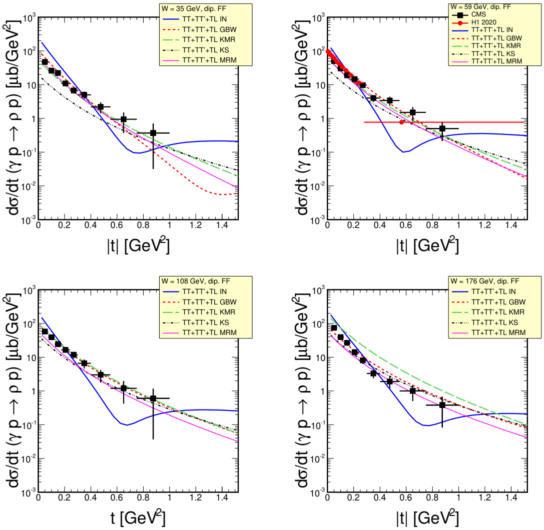
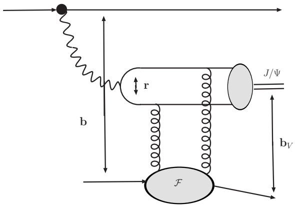
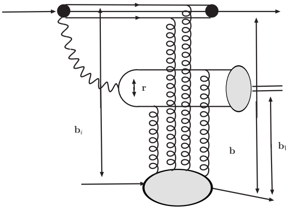


Figure: Distribution in t for different energies for the different UGDs. Data from CMS and H1 (Eur. Phys. J. C, 80 (2020), p. 1189).

$pp \to pJ/\psi p$ - diffractive excitation of the Weizsäcker-Williams photons





- Born: $\Gamma^{(0)}(\boldsymbol{r}, \boldsymbol{b}_V) = \frac{1}{2}\,\sigma(\boldsymbol{r})\, t_N(\boldsymbol{b}_V)$
- Absorbed:

$$\begin{aligned}\Gamma(\boldsymbol{r}, \boldsymbol{b}_V, \boldsymbol{b}) &= \Gamma^{(0)}(\boldsymbol{r}, \boldsymbol{b}_V) - \frac{1}{4}\sigma(\boldsymbol{r})\sigma_{qqq}(\{\boldsymbol{b}_i\})t_N(\boldsymbol{b}_V)t_N(\boldsymbol{b}) \\ &= \Gamma^{(0)}(\boldsymbol{r}, \boldsymbol{b}_V)\left(1 - \frac{1}{2}\sigma_{qqq}(\{\boldsymbol{b}_i\})t_N(\boldsymbol{b})\right) \to \Gamma^{(0)}(\boldsymbol{r}, \boldsymbol{b}_V) \cdot S_{el}(\boldsymbol{b})\end{aligned}$$

W.S. & A. Szczurek (2007).

- strong spectator interactions are short-range in $\boldsymbol{b}$-space, but γ-exchange is long-range $\to$ smallish absorptive corrections

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,

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

dependence on momentum transfer $t=-\Delta^2$ is parametrized by the function $f(\Delta^2,W)$, which dependence on energy derives from the Regge slope

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

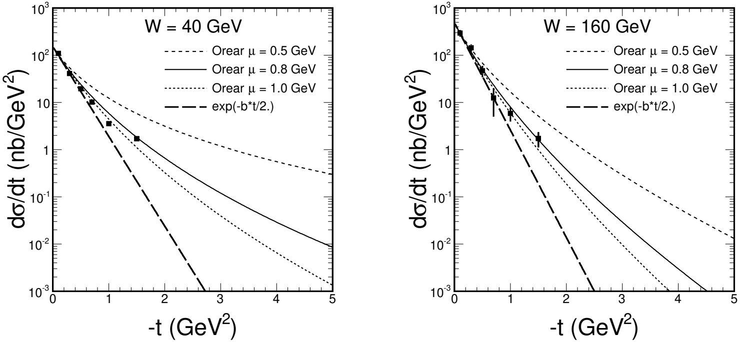
with: $b_0 = 4.88$, $\alpha'_{eff} = 0.164$ GeV^{-2} and $W_0 = 90$ GeV.
Within the diffraction cone:

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

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

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

ZEUS data on $d\sigma/dt(\gamma p \to J/\psi p)$: fit to t-dependence



Parameters/input to the diffractive amplitude

- frame-independent radial LCWF depends on the invariant

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

- "**Gaussian**" parametrization:

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

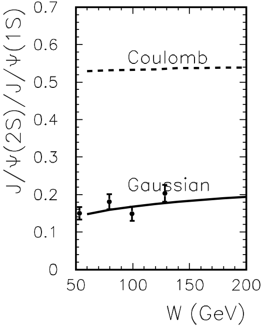
$$\psi_{2S}(z,\mathbf{k}) = C_2(\xi_0 - p^2 a_2^2)\exp\left(-\frac{p^2 a_2^2}{2}\right)$$

- "**Coulomb**" parametrization:

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

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

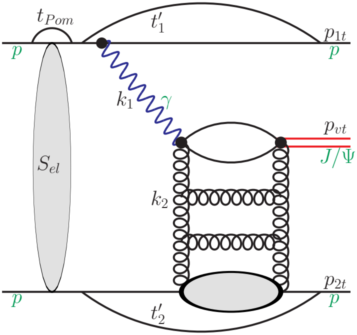
- parameters fixed through: leptonic decay width & orthonormality.



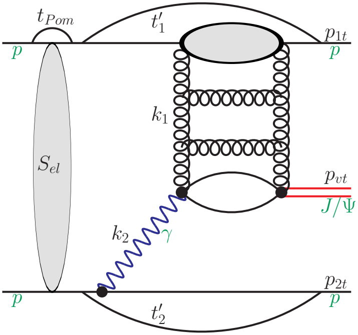
unintegrated gluon distributions:

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



photon-Pomeron



Pomeron-photon

- absorption is accounted at the amplitude level and strongly depends on kinematics.
- elastic rescattering is only the simplest option – we will allow for an enhancement of absorption by a factor 1.4.
- possible competing mechanism: the Pomeron-Odderon fusion.

Helicity conserving and helicity flip amplitudes

structure of e.m. current:

- pointlike fermion: γ_μ vertex conserves helicity at high energies.
- proton has also Pauli-coupling, which leads to a nonvanishing spin-flip at high energies.
- For photons with $z \ll 1$ we can write:

$$\langle p_1', \lambda_1' | J_\mu | p_1, \lambda_1 \rangle \epsilon_\mu^*(q_1, \lambda_V) = \frac{(\boldsymbol{e}^{*(\lambda_V)} \boldsymbol{q}_1)}{\sqrt{1 - z_1}} \, \frac{2}{z_1} \cdot \chi_{\lambda'}^\dagger \left\{ F_1(Q_1^2) - \frac{i \kappa_p F_2(Q_1^2)}{2 m_p} (\boldsymbol{\sigma}_1 \cdot [\boldsymbol{q}_1, \boldsymbol{n}]) \right\} \chi_\lambda$$

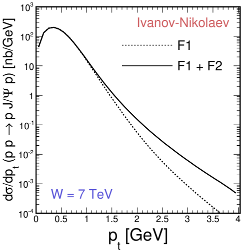
- we neglect the possible helicity flip in the Pomeron-proton coupling, due to the smallness of r_5.

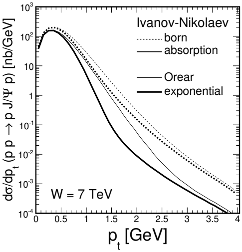
$$\mathcal{M}_{h_1 h_2 \to h_1 h_2 V}^{\lambda_1 \lambda_2 \to \lambda_1' \lambda_2' \lambda_V}(s, s_1, s_2, t_1, t_2) = \mathcal{M}_{\gamma \mathbf{P}} + \mathcal{M}_{\mathbf{P} \gamma}$$

$$= \langle p_1', \lambda_1' J_\mu p_1, \lambda_1 \rangle \epsilon_\mu^*(q_1, \lambda_V) \frac{\sqrt{4\pi\alpha_{em}}}{t_1} \mathcal{M}_{\gamma^* h_2 \to V h_2}^{\lambda_{\gamma^*} \lambda_2 \to \lambda_V \lambda_2}(s_2, t_2, Q_1^2)$$

$$+ \langle p_2', \lambda_2' J_\mu p_2, \lambda_2 \rangle \epsilon_\mu^*(q_2, \lambda_V) \frac{\sqrt{4\pi\alpha_{em}}}{t_2} \mathcal{M}_{\gamma^* h_1 \to V h_1}^{\lambda_{\gamma^*} \lambda_1 \to \lambda_V \lambda_1}(s_1, t_1, Q_2^2)$$

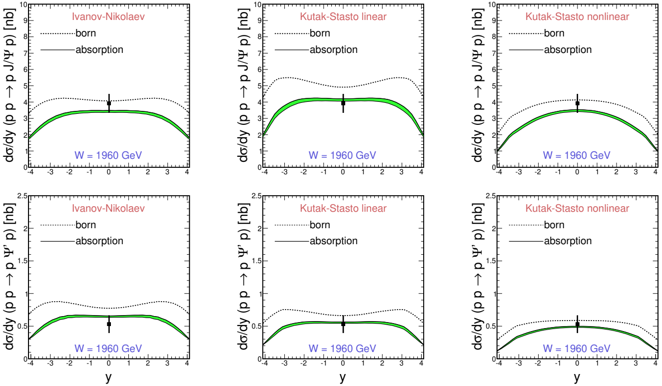
Dirac vs Pauli form factors (Born), exponential vs. "Orear"





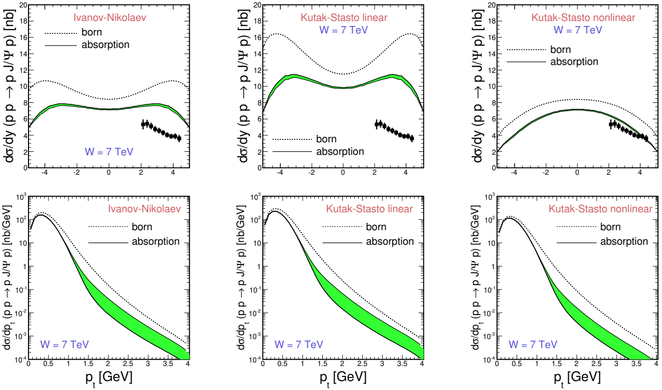
- Pauli form factor changes the p_t-shape of elastic contribution at larger p_t. Significant effect for $p_t \gtrsim 1.5\,\mathrm{GeV}$.
- At very large p_t we get an enhancement factor of the cross section of order of 10.
- p_t distribution is an important tool for the Odderon searches.

Comparison of J/ψ and ψ' central exclusive to Tevatron data



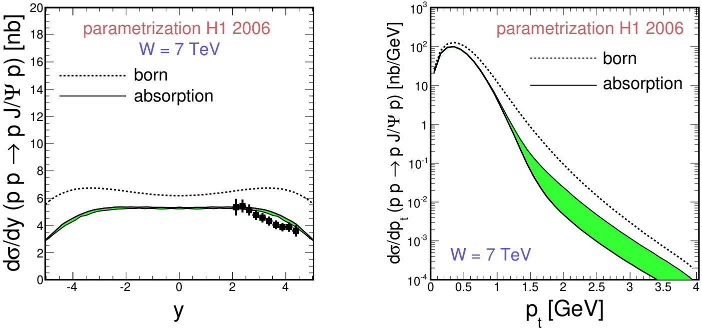
- CDF Collaboration, T.Aaltonen et al., Phys. Rev. Lett. 102 (2009)

Comparison to LHCb data



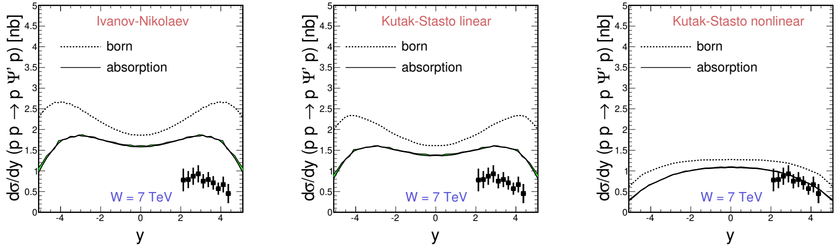
- R. Aaij et al. (LHCb collaboration), arXiv:1401.3288 [hep-ex], J.Phys.G 41 (2014) 055002
- the band shows variation in strength of absorption. Substantial uncertainty in the large p_t region.

Extrapolation of the HERA data



- Cross section for $\gamma p \to J/\psi p$ parametrized in the power-like form fitted to HERA data.
- Also calculations at NLO pQCD using DGLAP evolving glue without saturation effects describe LHCb data. S. Jones, A.D. Martin, M. Ryskin, T. Teubner JHEP 2013.

Excited state ψ'



- R. Aaij et al. (LHCb collaboration), arXiv:1401.3288 [hep-ex], J.Phys.G 41 (2014) 055002

Summary:

1. Diffractive (virtual) photoproduction of vector mesons probes the dynamics of the QCD Pomeron from **soft to hard** interactions.
2. In electroproduction, the Q^2–dependence of the cross sections σ_L and σ_T (and their ratio) are a sensitive probe of the **gluon UGD**.
3. The t–dependence of VM production gives additional access to GTMDs/Wigner function.
4. Photoproduction in *pp* collisions displays interesting new phenomena. It must be well understood, if we want to identify a possible Odderon contribution.