# Photoproduction of $J/\psi$ and $\Upsilon$ in exclusive and proton dissociative diffractive events

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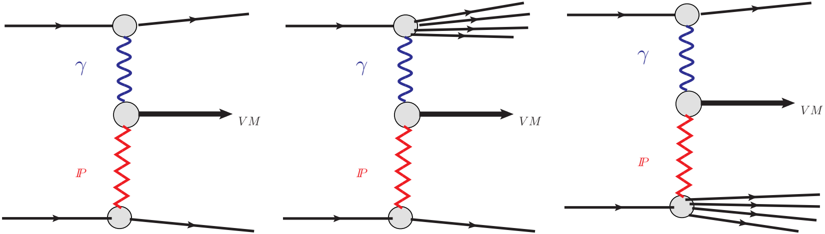
# Outline

1. Motivation/Introduction
2. Central exclusive production of $J/\psi$ and $\psi'$ in pp collisions
3. Diffractive photoproduction with electromagnetic dissociation

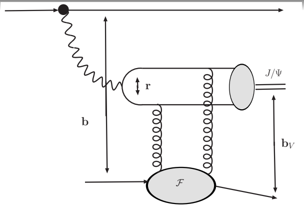
Anna Cisek, W.S, Antoni Szczurek, JHEP 1504, 159 (2015).

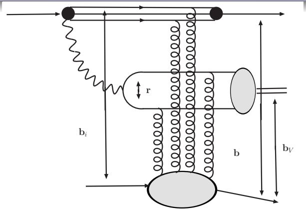
Marta Łuszczak, W.S., Antoni Szczurek, Phys. Rev. D93 (2016) no.7, 074018




- 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.

# $pp \to pJ/\psi p$ - 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:

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

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

- strong spectator interactions are short-range in $\boldsymbol{b}$-space, but $\gamma$-exchange is long-range $\to$ smallish absorptive corrections
- dipole cross section $\leftrightarrow$ unintegrated glue

$$\sigma(x, \boldsymbol{r}) = \frac{4\pi}{3}\int \frac{d^2\boldsymbol{\kappa}}{\boldsymbol{\kappa}^4}[1 - \exp(-i\boldsymbol{\kappa}\boldsymbol{r})]\alpha_S\,\mathcal{F}(x, \boldsymbol{\kappa})\,,\ \mathcal{F}(x, \boldsymbol{\kappa}) = \frac{\partial xg(x, \boldsymbol{\kappa}^2)}{\partial \log \boldsymbol{\kappa}^2}$$

- $$\bar{Q}^2 \sim (Q^2 + M_V^2)/4 \leftrightarrow r \sim r_S \approx \frac{1}{\bar{Q}}\,,\ \mathrm{for} J/\psi : \bar{Q}^2 \sim 2.5\,\mathrm{GeV}^2\ \mathrm{Kopeliovich, Nikolaev, Zakharov'93}$$

# The production amplitude for $\gamma p \to J/\psi p$

**The imaginary part of the amplitude can be written as:**

$$\Im m \, \mathcal{M}_{\mathcal{T}}(W, \Delta^2 = 0, Q^2 = 0) = W^2 \frac{c_v \sqrt{4\pi\alpha_{em}}}{4\pi^2} \int_0^1 \frac{dz}{z(1-z)} \int_0^\infty \pi dk^2 \psi_V(z, k^2)$$

$$\int_0^\infty \frac{\pi d\kappa^2}{\kappa^4} \alpha_S(q^2) \mathcal{F}(x_{eff}, \kappa^2) \Big( A_0(z, k^2) \; W_0(k^2, \kappa^2) + A_1(z, k^2) \; W_1(k^2, \kappa^2) \Big)$$

where

$$A_0(z, k^2) = m_c^2 + \frac{k^2 m_c}{M_{c\bar{c}} + 2m_c}, \quad M_{c\bar{c}}^2 = \frac{\mathbf{k}^2 + m_c^2}{z(1-z)}$$

$$A_1(z, k^2) = \left[ z^2 + (1-z)^2 - (2z-1)^2 \frac{m_c}{M_{c\bar{c}} + 2m_c} \right] \frac{k^2}{k^2 + m_c^2},$$

$$W_0(k^2, \kappa^2) = \frac{1}{k^2 + m_c^2} - \frac{1}{\sqrt{(k^2 - m_c^2 - \kappa^2)^2 + 4m_c^2 k^2}},$$

$$W_1(k^2, \kappa^2) = 1 - \frac{k^2 + m_c^2}{2k^2} \left( 1 + \frac{k^2 - m_c^2 - \kappa^2}{\sqrt{(k^2 - m_c^2 - \kappa^2)^2 + 4m_c^2 k^2}} \right).$$

- the pure $S$-wave bound state. See the review I.Ivanov, N. Nikolaev, A. Savin (2005).

# 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,

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

The 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

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

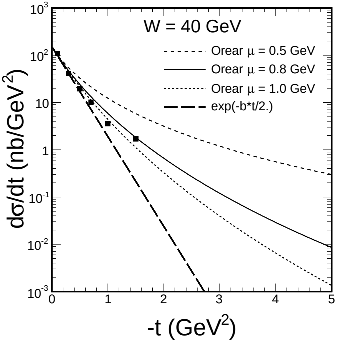
with: $b_0 = 4.88$, $\alpha'_{eff} = 0.164$ GeV$^{-2}$ and $W_0 = 90$ GeV. Within the diffraction cone:

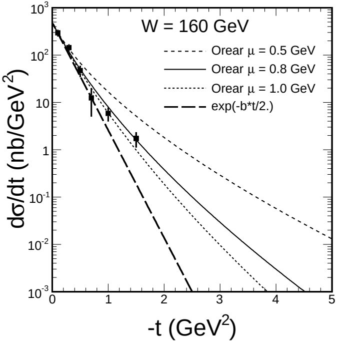
$$f(t,W) = \exp\left(\frac{1}{2}B(W)t\right),$$

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

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

# 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

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

- "**Gaussian**" parametrization:

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

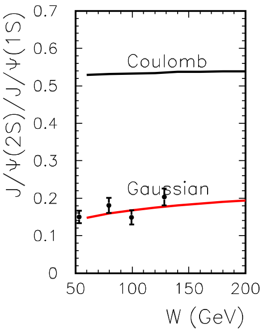
$$\psi_{2S}(z, \boldsymbol{k}) = C_2(\xi_0 - p^2 a_2^2) \exp\left(-\frac{p^2 a_2^2}{2}\right)$$

- "**Coulomb**" parametrization:

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

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

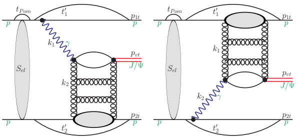
- parameters fixed through: leptonic decay width & orthonormality.




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



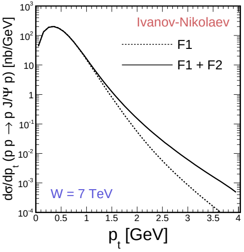

- absorption is accounted at the amplitude level and strongly depends on kinematics.
- elastic rescattering is only the simplest option – we will allow for an enhancement of absorption by a factor 1.4.
- possible competing mechanism: the Pomeron-Odderon fusion.

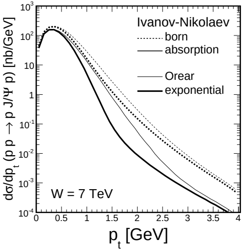
structure of e.m. current:

- pointlike fermion: $\gamma_\mu$ 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:

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

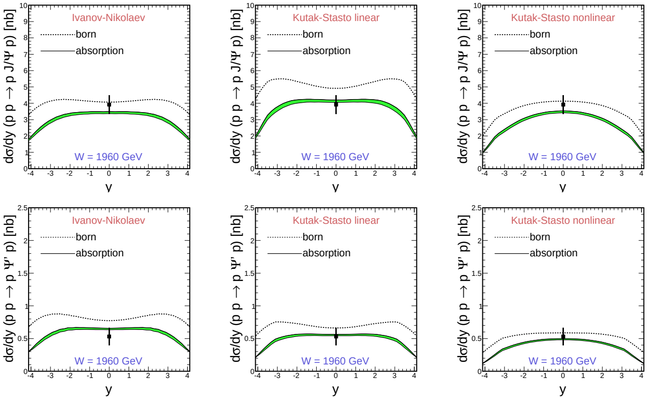
# Dirac vs Pauli form factors (Born), exponential vs. "Orear"



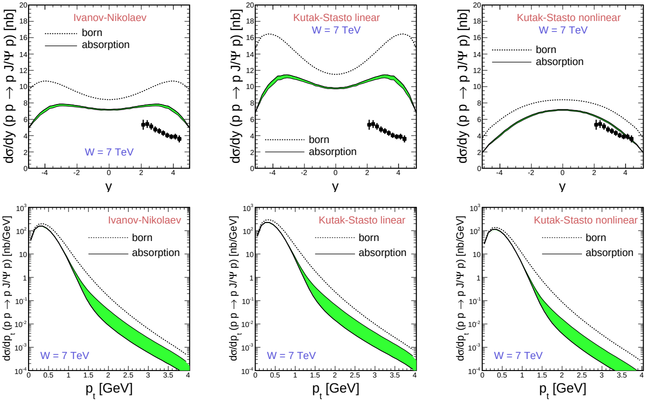

- Pauli form factor changes the $p_t$-shape of elastic contribution at larger $p_t$. Significant effect for $p_t \gtrsim 1.5\,\mathrm{GeV}$.
- At very large $p_t$ we get an enhancement factor of the cross section of order of 10.
- $p_t$ distribution is an important tool for the Odderon searches.

# Comparison of $J/\psi$ and $\psi'$ central exclusive to Tevatron data



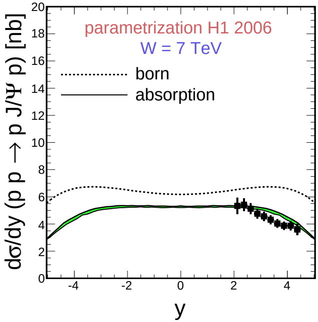

- CDF Collaboration, T.Aaltonen et al., Phys. Rev. Lett. 102 (2009)

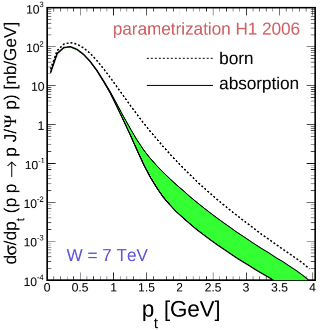
# Comparison to LHCb data




- R. Aaij et al. (LHCb collaboration), J.Phys. G41 (2014) 055002
- the band shows variation in strength of absorption. Substantial uncertainty in the large $p_t$ region.
- all the gluons shown here do describe the Tevatron data!

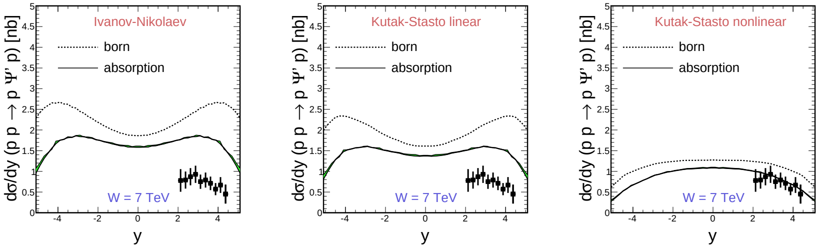
# Extrapolation of the HERA data



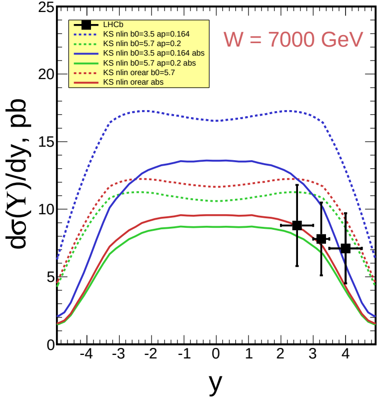

Cross section for $\gamma p \to J/\psi p$ parametrized in the power-like form fitted to HERA data

# Excited state $\psi'$

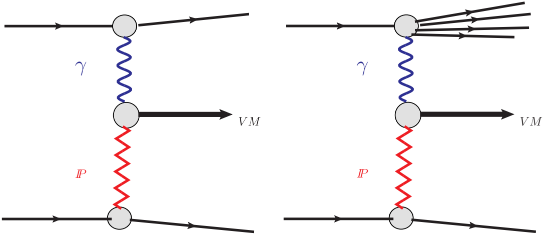



- R. Aaij et al. (LHCb collaboration), J.Phys. G41 (2014) 055002
- note: the ratio of $\psi(2S)/J/\psi$ is reasonably well described by all the gluon distributions.

# Exclusive $\Upsilon$ in $pp$



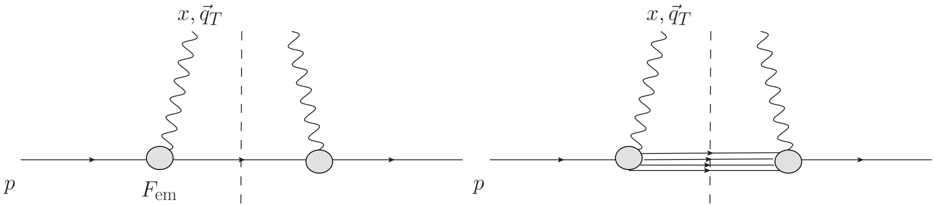

- LHCb Collaboration, JHEP 1509 (2015) 084
- diffractive slope of $\gamma p \to \Upsilon p$ known only with large uncertainty.




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

- $z_\pm = e^{\pm y} \sqrt{\boldsymbol{p}^2 + m_V^2} / \sqrt{s}$
- generalization of the Weizsäcker-Williams flux to dissociative processes.
- must in principle add contributions of longitudinal photons. Negligible for heavy mesons as long as $Q^2 \ll m_V^2$.

# Unintegrated photon fluxes in the high energy limit

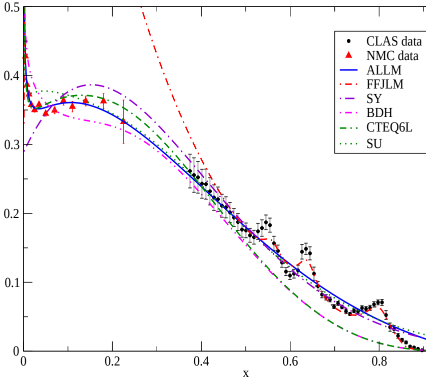


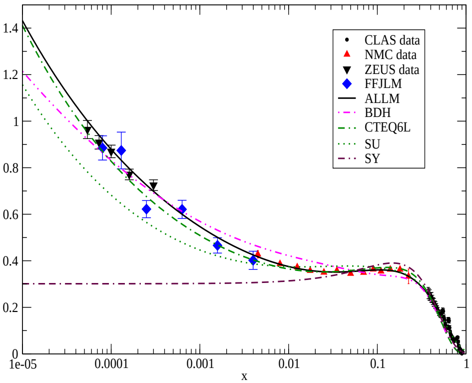

$$\mathcal{F}^{(\rm el)}_{\gamma/p}(z, \boldsymbol{q}^2) = \frac{\alpha_{\rm em}}{\pi}(1-z)\left[\frac{\boldsymbol{q}^2}{\boldsymbol{q}^2 + z^2 m_p^2}\right]^2 \frac{4m_p^2 G_E^2(Q^2) + Q^2 G_M^2(Q^2)}{4m_p^2 + Q^2} \, .$$

$$\mathcal{F}^{(\rm inel)}_{\gamma/p}(z, \boldsymbol{q}^2) = \frac{\alpha_{\rm em}}{\pi}(1-z)\int_{M^2_{\rm thr}}^{\infty} \frac{dM_X^2 F_2(x_{Bj}, Q^2)}{M_X^2 + Q^2 - m_p^2}\left[\frac{\boldsymbol{q}^2}{\boldsymbol{q}^2 + z(M_X^2 - m_p^2) + z^2 m_p^2}\right]^2 .$$

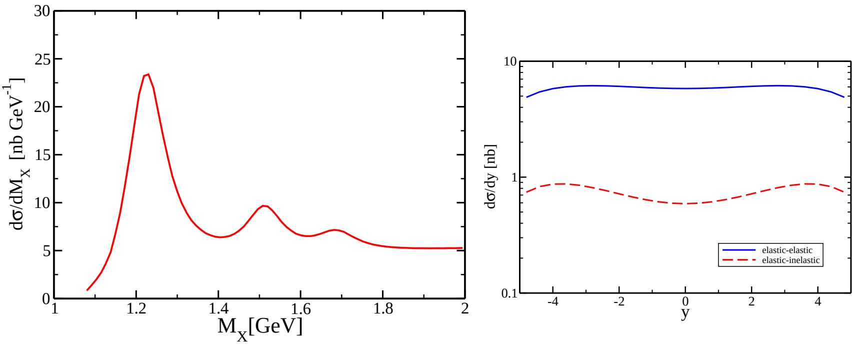
$$Q^2 = \frac{1}{1-z}\left[\boldsymbol{q}^2 + z(M_X^2 - m_p^2) + z^2 m_p^2\right], x_{Bj} = \frac{Q^2}{Q^2 + M_X^2 - m_p^2}$$

# Fits to the $F_2(x, Q^2)$ structure function, $Q^2 = 2.5\,\mathrm{GeV}^2$



# $J/\psi$-photoproduction with e.m. dissociation




- $F_2$ from Fiore, Flachi, Jenkovszky, Lengyel, Magas (2002). A parametrization which describes very well photoabsorption in the resonance region from low to large $Q^2$. Excellent description of JLAB data.
- rapidity spectrum for $M_X < 2\,\mathrm{GeV}$.
- dissociative contamination stronger at larger rapidities.

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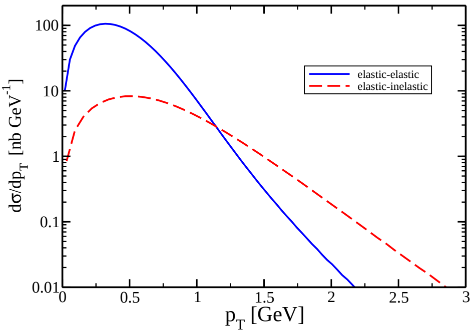


- $F_2$ from Fiore, Flachi, Jenkovszky, Lengyel, Magas (2002). A parametrization which describes very well photoabsorption in the resonance region from low to large $Q^2$. Excellent description of JLAB data.
- rapidity spectrum for $M_X < 2\,\mathrm{GeV}$.
- $p_T$ distribution somewhat smeared out wrt. purely elastic events.

# Conclusions

- In photoproduction of heavy quarkonia, the large quark mass ensures dominance of small dipoles $\rightarrow$ pQCD.
- We have compared our $k_\perp$-factorization results with recent and LHCb ($pp \longrightarrow p\ V\ p$) data, for $VM = J/\psi, \psi(2S), \Upsilon$. Best description is obtained for a glue which does contain saturation effects.
- Absorptive corrections are a strong function of kinematics. At large $p_T$, relevant for Odderon searches, the Pauli coupling needs to be included. There is a sizeable uncertainty due to absorption in the $p_T$ distribution.
- Proton dissociation is a background to exclusive processes. Electromagnetic dissociation is calculable from $F_2$, excited states $M_X < 2\mathrm{GeV}$ make a contribution of $10 \div 15\%$ of the exclusive cross section for $J/\psi$.