Photoproduction of $J/\psi$ with and without proton dissociation

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

Born: $\Gamma^{(0)}(r, b_V) = \frac{1}{2} \sigma(r) t_N(b_V)$

Absorbed:

$$\Gamma(r, b_V, b) = \Gamma^{(0)}(r, b_V) - \frac{1}{4} \sigma(r) \sigma_{qqq}(\{b_i\}) t_N(b_V) t_N(b)$$

$$= \Gamma^{(0)}(r, b_V) \left(1 - \frac{1}{2} \sigma_{qqq}(\{b_i\}) t_N(b)\right) \rightarrow \Gamma^{(0)}(r, b_V) \cdot S_{el}(b)$$


- strong spectator interactions are short-range in $b$-space, but $\gamma$-exchange is long-range $\rightarrow$ smallish absorptive corrections

- dipole cross section $\leftrightarrow$ unintegrated glue

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

$$\bar{Q}^2 \sim (Q^2 + M_V^2)/4 \leftrightarrow r \sim r_S \approx \frac{1}{Q} \quad \text{for} J/\psi : \bar{Q}^2 \sim 2.5 \text{ GeV}^2 \quad \text{Kopeliovich, Nikolaev, Zakharov'93}$$
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The production amplitude for $\gamma p \rightarrow J/\psi p$

The imaginary part of the amplitude can be written as:

$$\Im m M_{\tau}(W, \Delta^2 = 0, Q^2 = 0) = W^2 \frac{c_v \sqrt{4\pi \alpha_{em}}}{4\pi^2} \int_0^1 \frac{dz}{z(1-z)} \int_0^\infty \pi dk^2 \psi V(z, k^2)$$

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

where

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

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

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

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

◮ 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:

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

The real part of the amplitude is restored from analyticity,

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

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

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

with: $b_0 = 4.88$, $\alpha'_{\text{eff}} = 0.164$ 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 $|t| \sim 1 \div 2$ 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 $d\sigma/dt(\gamma p \rightarrow J/\psi p)$: fit to $t$-dependence
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Parameters/input to the diffractive amplitude

- frame-independent radial LCWF depends on the invariant
  \[ p^2 = \frac{1}{4} \left( \frac{k^2 + m_c^2}{z(1-z)} - 4m_c^2 \right) \]

- **“Gaussian”** parametrization:
  \[ \psi_{1S}(z, k) = C_1 \exp(-\frac{p^2 a_1^2}{2}) \]
  \[ \psi_{2S}(z, k) = C_2 (\xi_0 - p^2 a_2)^2 \exp(-\frac{p^2 a_2^2}{2}) \]

- **“Coulomb”** parametrization:
  \[ \psi_{1S}(z, k) = \frac{C_1}{\sqrt{M}} \frac{1}{(1 + a_1^2 p^2)^2} \]
  \[ \psi_{2S}(z, k) = \frac{C_2}{\sqrt{M}} \frac{\xi_0 - a_2^2 p^2}{(1 + a_2^2 p^2)^3} \]

- 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.

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$pp \to p \ J/\psi(\psi') \ p$ 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:

$$
\langle p_1', \lambda_{1}' | J_\mu | p_1, \lambda_1 \rangle e^*_{\mu}(q_1, \lambda_V) = \frac{(e^*(\lambda_V) q_1)}{\sqrt{1 - z_1}} \frac{2}{z_1} \cdot \chi_{\lambda'}^{\dagger} \left\{ F_1(Q_1^2) - \frac{i\kappa_p F_2(Q_1^2)}{2m_p}(\sigma_1 \cdot [q_1, n]) \right\} \chi_\lambda
$$

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Pauli form factor changes the $p_t$-shape of elastic contribution at larger $p_t$. Significant effect for $p_t \gtrsim 1.5$ 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.

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 $\gamma p \rightarrow J/\psi p$ parametrized in the power-like form fitted to HERA data.
Excited state $\psi'$

- note: the ratio of $\psi(2S)/J/\psi$ is reasonably well described by all the gluon distributions.
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**Exclusive $\Upsilon$ in pp**

![Graph showing differential cross section $d\sigma(\Upsilon)/dy$ in pb for different models and data points at $W = 7000$ GeV.]

- LHCb Collaboration, JHEP 1509 (2015) 084
- Diffractive slope of $\gamma p \rightarrow \Upsilon p$ known only with large uncertainty.
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\[
\frac{d\sigma(pp \rightarrow XVp; s)}{dyd^2p} = \int \frac{d^2q}{\pi q^2} F^{(\text{in})}_{\gamma/p}(z_+, q^2) \frac{1}{\pi} \frac{d\sigma^{* p \rightarrow VP}}{dt}(z+s, t = -(q - p)^2) + (z_+ \leftrightarrow z_-)
\]

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

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Unintegrated photon fluxes in the high energy limit

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

\[ F_{\gamma/p}^{(\text{inel})}(z, q^2) = \frac{\alpha_{\text{em}}}{\pi} (1 - z) \int_{M_{X\text{thr}}^2}^{\infty} \frac{dM_X^2 F_2(x_{Bj}, Q^2)}{M_X^2 + Q^2 - m_p^2} \left[ \frac{q^2}{q^2 + z(M_X^2 - m_p^2) + z^2 m_p^2} \right]^2. \]

\[ Q^2 = \frac{1}{1 - z} \left[ q^2 + z(M_X^2 - m_p^2) + z^2 m_p^2 \right], \quad x_{Bj} = \frac{Q^2}{Q^2 + M_X^2 - m_p^2} \]
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Fits to the $F_2(x, Q^2)$ structure function, $Q^2 = 2.5 \text{ GeV}^2$

Most useful for our purposes are the parametrizations of Fiore, Flachi, Jenkovszky, Lengyel, Magas (2002) and Abramowicz, Levy, Levin & Maor ('91,'97).
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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 $M_X < 2$ GeV.
- dissociative contamination stronger at larger rapidities.
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**$J/\psi$-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 $M_X < 2$ GeV.
- $p_T$ distribution somewhat smeared out wrt. purely elastic events.
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$F_2$ from Fiore, Flachi, Jenkovszky, Lengyel, Magas (2002) and Abramowicz, Levy, Levin & Maor ('91,'97).

- ALLM smoothly interpolates the resonances.
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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 ($pp \rightarrow p V p$) 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 $M_X < 2\text{GeV}$ make a contribution of $10 \div 15\%$ of the exclusive cross section for $J/\psi$. 