Exclusive photoproduction of J/ψ and $\psi(2S)$ in pp and AA collisions

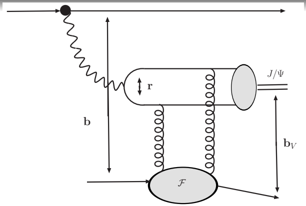
Wolfgang Schäfer [1]

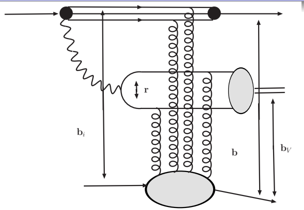
[1] Institute of Nuclear Physics, PAN, Kraków

Diffraction 2014
Primosten, Croatia, 10-16 September 2014

Anna Cisek, W.S. and Antoni Szczurek, arxiv:1405.2253

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

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

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

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

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

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

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

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

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

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

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

Cross section for $\gamma p \to J/\psi(\psi')\ p$

The full amplitude:

$$\mathcal{M}_T(W,\Delta^2) = (i+\rho_T)\,\Im m \mathcal{M}_T(W,\Delta^2=0,Q^2=0)\,\exp(-B(W)\Delta^2/2)\,.$$

where

$$\rho_T = \frac{\Re e \mathcal{M}_T}{\Im m \mathcal{M}_T} = \frac{\pi}{2}\,\frac{\partial \log\left(\Im m \mathcal{M}_T/W^2\right)}{\partial \log W^2} = \frac{\pi}{2}\,\Delta_{\mathbf{P}}\,,$$

$$B(W) = B_0 + 2\alpha'_{eff}\log\left(\frac{W^2}{W_0^2}\right)\,.$$

Total cross section can be written as:

$$\sigma_T(\gamma p \to J/\psi p) = \frac{1+{\rho_T}^2}{16\pi B(W)}\left|\frac{\Im m \mathcal{M}_T(W,\Delta^2=0,Q^2=0)}{W^2}\right|^2$$

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:

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

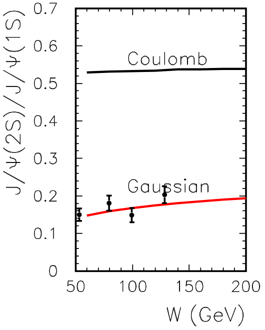
$$\psi_{2S}(z,\boldsymbol{k}) = C_2(\xi_0 - p^2 a_2^2) \exp\left(-\frac{p^2 a_2^2}{2}\right)$$

- "**Coulomb**" parametrization:

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

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

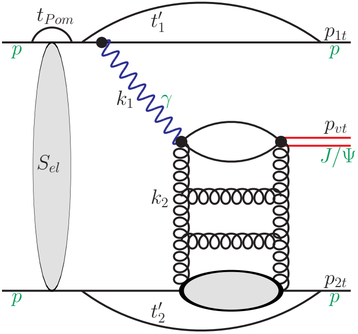
- parameters fixed through: leptonic decay width & orthonormality.



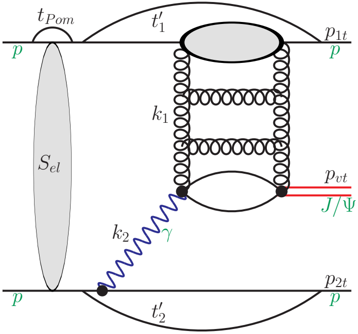
unintegrated gluon distributions:

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



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:

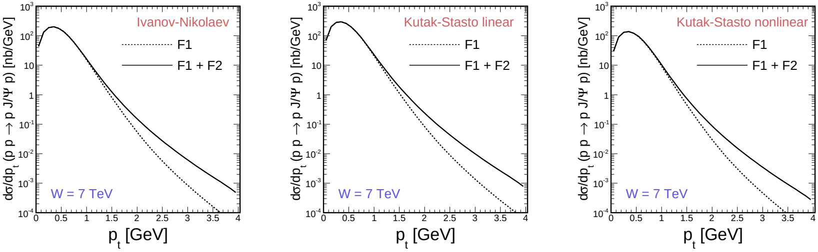
$$\langle p_1', \lambda_1' | J_\mu | p_1, \lambda_1 \rangle \epsilon_\mu^*(q_1, \lambda_V) = \frac{(\boldsymbol{e}^{*(\lambda_V)} \boldsymbol{q}_1)}{\sqrt{1 - z_1}} \frac{2}{z_1} \cdot \chi^\dagger_{\lambda'} \Big\{ F_1(Q_1^2) - \frac{i\kappa_p F_2(Q_1^2)}{2m_p} (\boldsymbol{\sigma}_1 \cdot [\boldsymbol{q}_1,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

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

The full amplitude for the $pp \to pVp$ process can be written as:

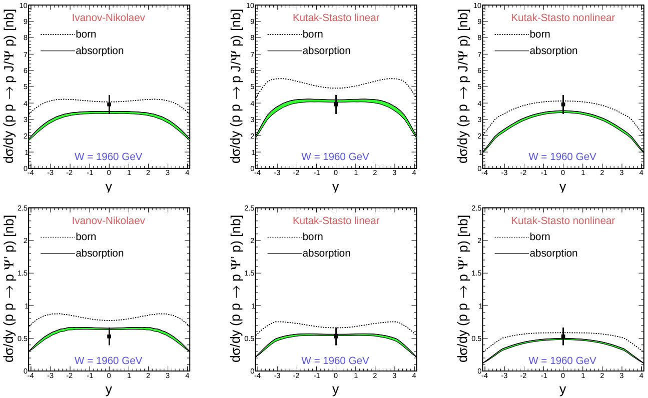
$$\mathcal{M}^{\lambda_1 \lambda_2 \to \lambda_1' \lambda_2' \lambda_V}_{h_1 h_2 \to h_1 h_2 V}(s, s_1, s_2, t_1, t_2) = \mathcal{M}_{\gamma \mathbf{P}} + \mathcal{M}_{\mathbf{P} \gamma}$$
$$= \langle p_1', \lambda_1' | J_\mu | p_1, \lambda_1 \rangle \epsilon_\mu^*(q_1, \lambda_V) \frac{\sqrt{4\pi\alpha_{em}}}{t_1} \mathcal{M}^{\lambda_{\gamma^*} \lambda_2 \to \lambda_V \lambda_2}_{\gamma^* h_2 \to V h_2}(s_2, t_2, Q_1^2)$$
$$+ \langle p_2', \lambda_2' | J_\mu | p_2, \lambda_2 \rangle \epsilon_\mu^*(q_2, \lambda_V) \frac{\sqrt{4\pi\alpha_{em}}}{t_2} \mathcal{M}^{\lambda_{\gamma^*} \lambda_1 \to \lambda_V \lambda_1}_{\gamma^* h_1 \to V h_1}(s_1, t_1, Q_2^2)$$

Dirac vs Pauli form factors (Born)



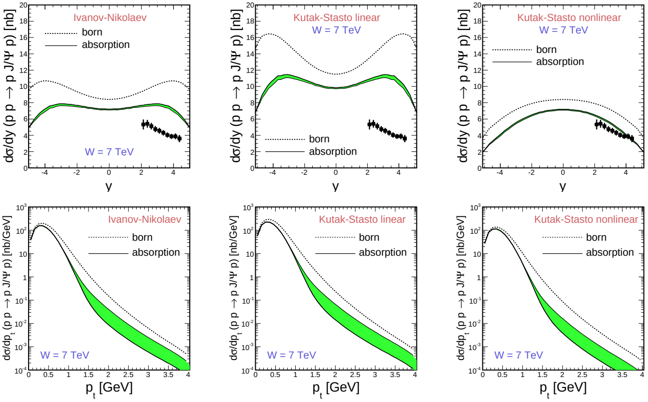
- Pauli form factor changes the p_t-shape of elastic contribution at larger p_t. Significant effect for $p_t \gtrsim 1.5\,\mathrm{GeV}$.
- At very large p_t we get an enhancement factor of the cross section of order of 10.
- p_t distribution is an important tool for the Odderon searches.

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



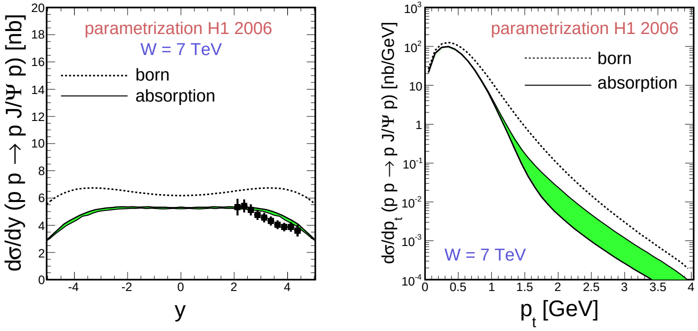
- CDF Collaboration, T.Aaltonen et al., Phys. Rev. Lett. 102 (2009)

Comparison to LHCb data



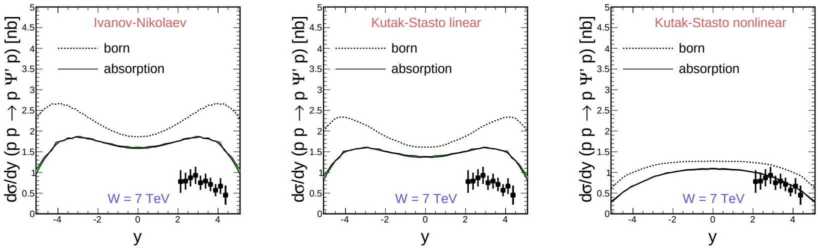
- R. Aaij et al. (LHCb collaboration), arXiv:1401.3288 [hep-ex]
- the band shows variation in strength of absorption. Substantial uncertainty in the large p_t region.

Extrapolation of the HERA data



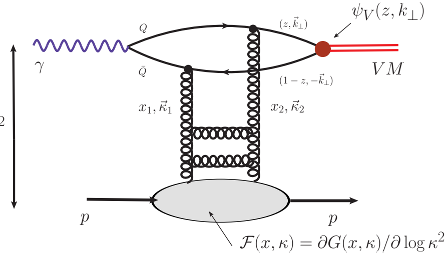
Cross section for $\gamma p \to J/\psi p$ parametrized in the power-like form fitted to HERA data

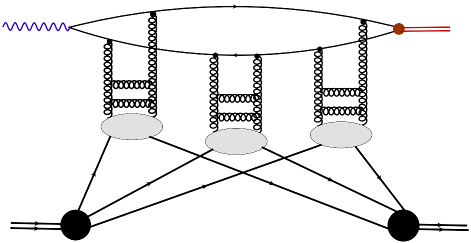
Excited state ψ'



- R. Aaij et al. (LHCb collaboration), arXiv:1401.3288 [hep-ex]
- Absorption may be bigger

VM photoproduction from nucleon to nucleus:

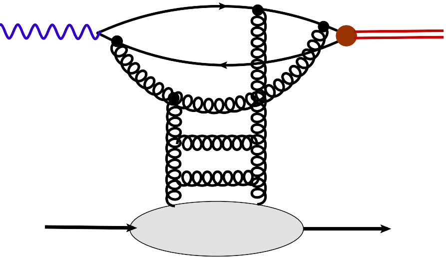


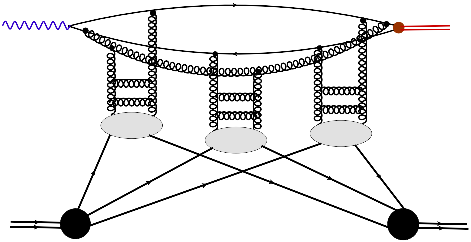


- for heavy nuclei rescattering/absorption effects are enhanced by the large nuclear size
- $q\bar{q}$ rescattering is easily dealt with in impact parameter space
- the final state might as well be a (virtual) photon (total photoabsorption cross section) or a $q\bar{q}$-pair (inclusive low-mass diffraction).
- Color-dipole amplitude

$$\Gamma(\boldsymbol{b}, x, \boldsymbol{r}) = 1 - \frac{\langle A| Tr[S_q(\boldsymbol{b}) S_q^\dagger(\boldsymbol{b}+\boldsymbol{r})]|A\rangle}{\langle A| Tr[\mathbb{1}]|A\rangle}$$

Small-x evolution: adding $q\bar{q}(ng)$ Fock-states



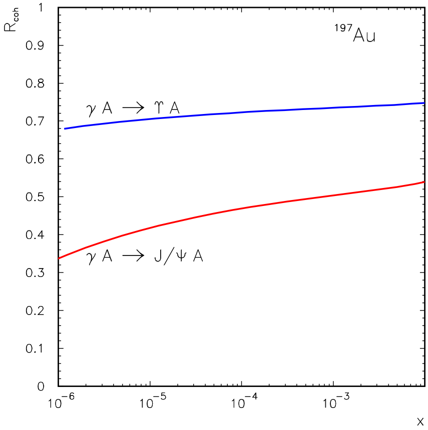


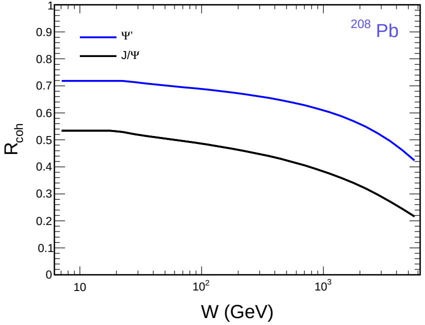
- the effect of higher $q\bar{q}g$-Fock-states is absorbed into the x–dependent dipole-nucleus interaction Nikolaev, Zakharov, Zoller / Mueller '94
- evolution of unintegrated glue $\mathrm{Balitsky-Kovchegov\ '96 -' 98}$:

$$\frac{\partial \phi(\boldsymbol{b}, x, \boldsymbol{p})}{\partial \log(1/x)} = \mathcal{K}_{BFKL} \otimes \phi(\boldsymbol{b}, x, \boldsymbol{p}) + \mathcal{Q}[\phi](\boldsymbol{b}, x, \boldsymbol{p})$$

- corresponds to taking the contribution to shadowing from high–mass diffraction into account $\leftrightarrow$ Gribov's unitarity relation between nuclear shadowing and diffraction on the nucleon.
- contains a "gluon mass" $\mu_G \sim .7\,\mathrm{GeV}$.

Coherent diffractive production of $J/\Psi, \psi(2S), \Upsilon$ on ^{208}Pb

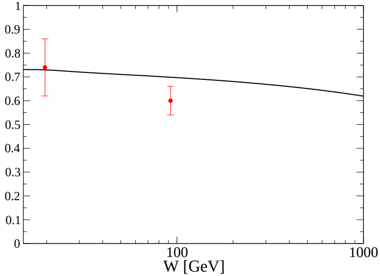




- left panel A. Cisek, WS, A. Szczurek Phys. Rev **C86** (2012) 014905.
- Ratio of coherent production cross section to impulse approximation

$$R_{\rm coh}(W) = \frac{\sigma(\gamma A \to VA; W)}{\sigma_{IA}(\gamma A \to VA; W)} \;, \; \sigma_{IA} = 4\pi \int d^2\boldsymbol{b} T_A^2(\boldsymbol{b}) \frac{d\sigma(\gamma N \to VN)}{dt}_{|t=0}$$

The putative gluon shadowing: $\sqrt{R_{\rm coh}}$



- an extraction of $\sqrt{R_{\rm coh}}$ from ALICE $PbPb \to J/\psi PbPb$ data by Guzey et al. (2013).
- in the collinear approach: "gluon shadowing": $R_{\rm coh} \sim [g_A(x, \bar{Q}^2)/(A \cdot g_N(x, \bar{Q}^2))]^2$.
- the putative "gluon shadowing": $R_G = \sqrt{R_{\rm coh}(x \sim 10^{-3})} \sim 0.7$.
- for illustration: $R_G(x, m_c^2) \equiv g_A(x, m_c^2)/(A \cdot g_N(x, m_c^2))$ from popular DGLAP fits:
- EPS09: $R_G(10^{-3}, m_c^2) \sim 0.6$, EPS08: $R_G(10^{-3}, m_c^2) \sim 0.3$
- Inclusive dijet observables depend on unintegrated nuclear glue nonlinearly.

Conclusions

- We have compared our results with recent HERA ($\gamma p \longrightarrow J/\psi(\psi')\ p$) and LHCb ($pp \longrightarrow p\ J/\psi(\psi')\ p$) data.
- In photoproduction of heavy quarkonia, the large quark mass ensures dominance of small dipoles $\to$ pQCD.
- 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.
- Coherent diffraction on the nucleus is a sensitive probe of the (unintegrated) gluon distribution of the target nucleus. Rescattering/saturation effects entail that the unintegrated glue enters inclusive dijet observables nonlinearly.
- "gluon shadowing" is included via the rescattering of higher $Q\bar{Q}g$ Fock states. The effective "gluon shadowing" ratio $R_G(x, m_c^2) \sim 0.74 \div 0.62$. For $x \sim 10^{-2} \div 10^{-5}$. ALICE data appear to indicate somewhat stronger effect $R_G(10^{-3}, m_c^2) \div 0.6$.
- smaller nuclear suppression for $\psi'(2S)$ appears to be a possibility.