Diffractive vector meson production from proton proton to ultraperipheral heavy ion collisions

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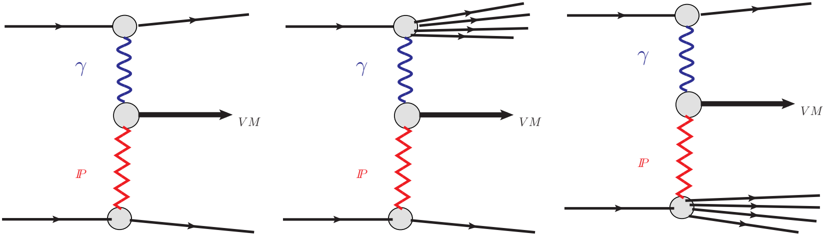
Outline

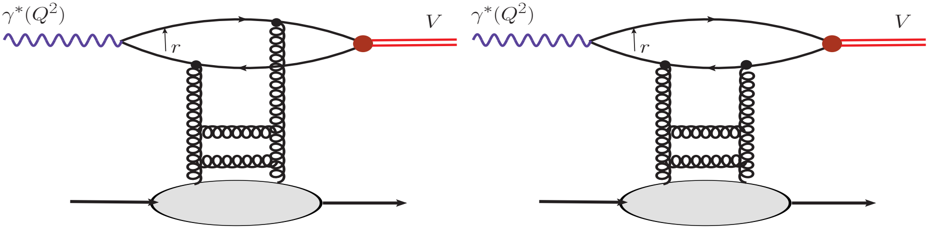
1. **Central exclusive production of vector mesons in pp collisions**
2. **Diffractive photoproduction with diffractive and electromagnetic dissociation**
3. **From photoproduction on the free nucleon to the nuclear target**

Anna Cisek, W. S., Antoni Szczurek, JHEP 1504, 159 (2015).
Anna Cisek, W. S. and Antoni Szczurek, arXiv:1611.08210 [hep-ph].



- 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.

Color dipole/ $k_\perp$-factorization approach



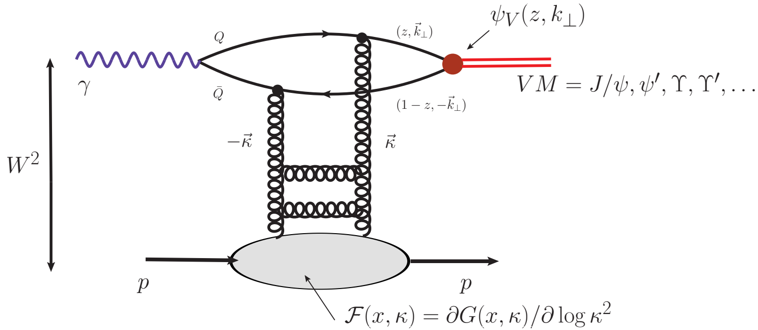
Color dipole representation of forward amplitude:

$$A(\gamma^*(Q^2)p \to Vp; W, t=0) = \int_0^1 dz \int d^2\boldsymbol{r}\, \psi_V(z,\boldsymbol{r})\, \psi_{\gamma^*}(z,\boldsymbol{r},Q^2)\, \sigma(x,\boldsymbol{r})$$

$$\sigma(x,\boldsymbol{r}) = \frac{4\pi}{3}\alpha_S \int \frac{d^2\boldsymbol{\kappa}}{\boldsymbol{\kappa}^4} \frac{\partial G(x,\boldsymbol{\kappa}^2)}{\partial \log(\boldsymbol{\kappa}^2)} \left[1 - e^{i\boldsymbol{\kappa}\boldsymbol{r}}\right], \; x = M_V^2/W^2$$

- impact parameters and helicities of high-energy q and $\bar{q}$ are conserved during the interaction.
- scattering matrix is "diagonal" in the color dipole representation.

Diffractive Photoproduction $\gamma p \to Vp$



- $J/\psi = c\bar{c}$, $\Upsilon = b\bar{b}$: (almost) nonrelativistic bound states of heavy quarks. Wavefunctions constrained by their leptonic decay widths.
- Large quark mass $\to$ hard scale necessary for (perturbative) QCD.
- $\mathcal{F}(x,\kappa) \equiv$ unintegrated gluon density, $x \sim M_{VM}^2/W^2$, constrained by HERA inclusive data.
- typical scale at which the gluon distribution is probed $\bar{Q}^2 \sim M_V^2/4$, i.e. $\bar{Q}^2 \sim 2.4\,\mathrm{GeV}^2$ for J/ψ and $\bar{Q}^2 \sim 20\,\mathrm{GeV}^2$ for Υ.
- topical subject: glue at small-x: nonlinear evolution, gluon fusion, saturation...

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

$$A_0(z, k^2) = m_c^2 + \frac{k^2 m_c}{M_{c\bar{c}} + 2m_c}\,, \quad M_{c\bar{c}}^2 = \frac{\boldsymbol{k}^2 + m_c^2}{z(1-z)}$$
$$A_1(z, k^2) = \left[z^2 + (1-z)^2 - (2z-1)^2 \frac{m_c}{M_{c\bar{c}} + 2m_c} \right] \frac{k^2}{k^2 + m_c^2}\,,$$
$$W_0(k^2, \kappa^2) = \frac{1}{k^2 + m_c^2} - \frac{1}{\sqrt{(k^2 - m_c^2 - \kappa^2)^2 + 4m_c^2 k^2}}\,,$$
$$W_1(k^2, \kappa^2) = 1 - \frac{k^2 + m_c^2}{2k^2} \left(1 + \frac{k^2 - m_c^2 - \kappa^2}{\sqrt{(k^2 - m_c^2 - \kappa^2)^2 + 4m_c^2 k^2}} \right).$$

- 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,

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

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

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

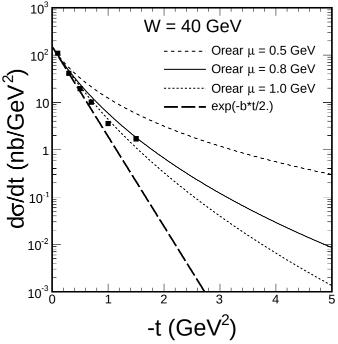
with: $b_0 = 4.88$, $\alpha'_{eff} = 0.164$ GeV^{-2} and $W_0 = 90$ GeV.
Within the diffraction cone:

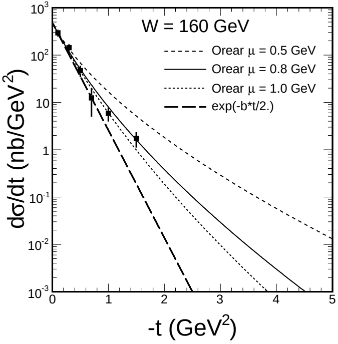
$$f(t,W) = \exp\left(\frac{1}{2}B(W)t\right),$$

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

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

- "**Gaussian**" parametrization:

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

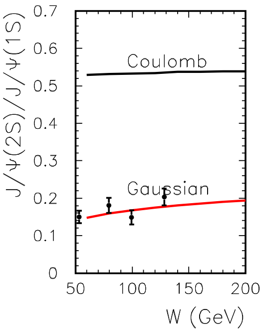
$$\psi_{2S}(z, \boldsymbol{k}) = C_2(\xi_0 - p^2 a_2^2) \exp\left(-\frac{p^2 a_2^2}{2}\right)$$

- "**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.

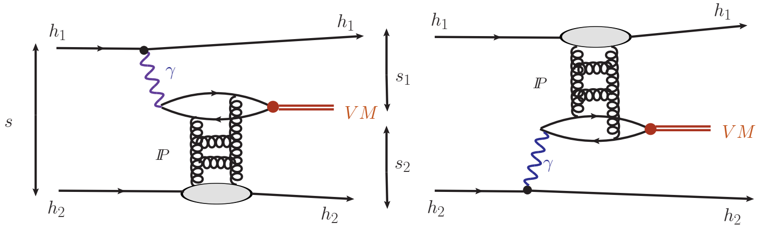


unintegrated gluon distributions:

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.

Exclusive Photoproduction in Hadronic Collisions

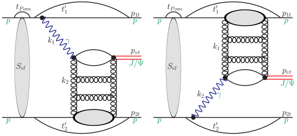
Born Level Amplitude



$$\begin{aligned} \boldsymbol{M}(\boldsymbol{p}_1, \boldsymbol{p}_2) &= e_1 \frac{2}{z_1} \frac{\boldsymbol{p}_1}{t_1} \mathcal{F}_{\lambda_1' \lambda_1}(\boldsymbol{p}_1, t_1) \mathcal{M}_{\gamma^* h_2 \to V h_2}(s_2, t_2, Q_1^2) \\ &+ e_2 \frac{2}{z_2} \frac{\boldsymbol{p}_2}{t_2} \mathcal{F}_{\lambda_2' \lambda_2}(\boldsymbol{p}_2, t_2) \mathcal{M}_{\gamma^* h_1 \to V h_1}(s_1, t_1, Q_2^2) \,. \end{aligned}$$

- $\boldsymbol{p}_1, \boldsymbol{p}_2 =$ transverse momenta of outgoing (anti–) protons.
- Interference induces azimuthal correlation $e_1 e_2 (\boldsymbol{p}_1 \cdot \boldsymbol{p}_2)$.

$pp \to p\ J/\psi(\psi')\ p$ with absorptive corrections



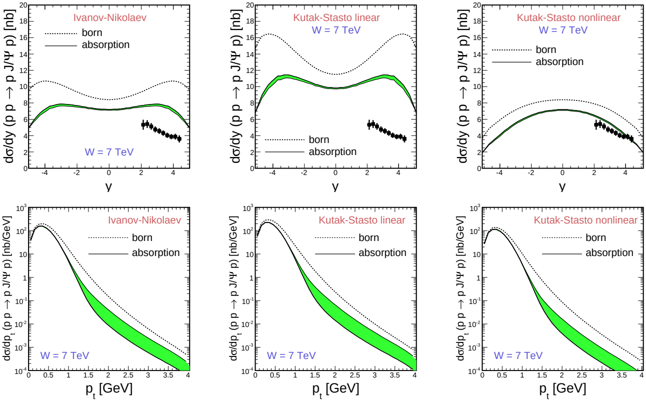
- absorption is accounted at the amplitude level and strongly depends on kinematics.
- elastic rescattering is only the simplest option – we will allow for an enhancement of absorption by a factor 1.4.
- possible competing mechanism: the Pomeron-Odderon fusion.

structure of e.m. current:

- pointlike fermion: 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:

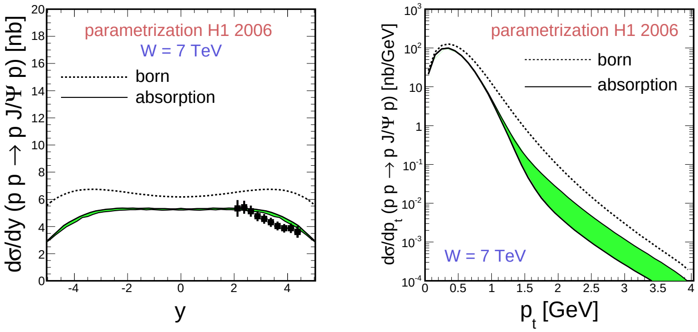
$$\langle p'_1, \lambda'_1 | J_\mu | p_1, \lambda_1 \rangle \epsilon^*_\mu(q_1, \lambda_V) = \frac{(\boldsymbol{e}^{*(\lambda_V)} \boldsymbol{q}_1)}{\sqrt{1-z_1}} \frac{2}{z_1} \cdot \chi^\dagger_{\lambda'} \Big\{ F_1(Q_1^2) - \frac{i\kappa_p F_2(Q_1^2)}{2m_p} (\boldsymbol{\sigma}_1 \cdot [\boldsymbol{q}_1,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

Comparison to LHCb data



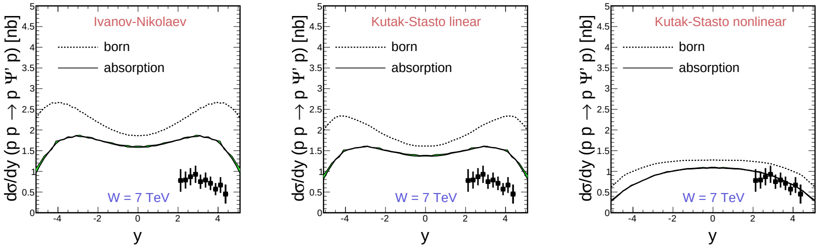
- R. Aaij et al. (LHCb collaboration), J.Phys. G41 (2014) 055002
- the band shows variation in strength of absorption. Substantial uncertainty in the large p_t region.
- all the gluons shown here do describe the Tevatron data!

Extrapolation of the HERA data



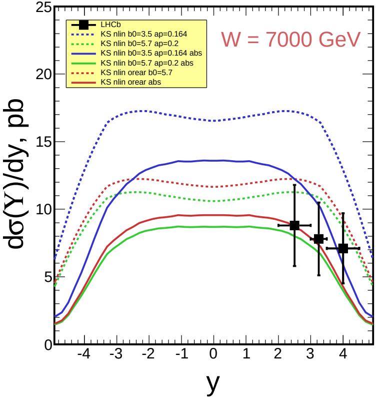
Cross section for $\gamma p \to J/\psi p$ parametrized in the power-like form fitted to HERA data

Excited state ψ'



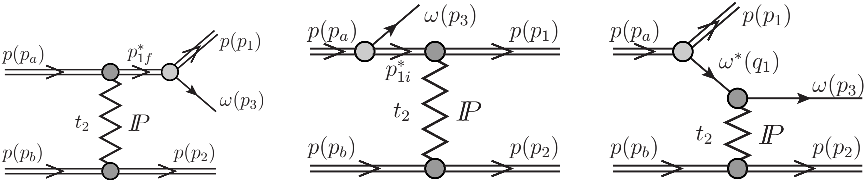
- R. Aaij et al. (LHCb collaboration), J.Phys. G41 (2014) 055002
- note: the ratio of $\psi(2S)/J/\psi$ is reasonably well described by all the gluon distributions.

Exclusive Υ in pp



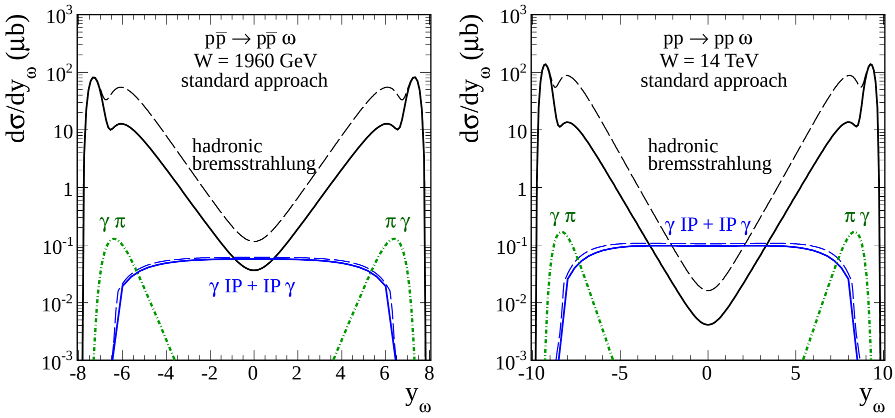
- LHCb Collaboration, JHEP 1509 (2015) 084
- diffractive slope of $\gamma p \to \Upsilon p$ known only with large uncertainty.

A soft process: $pp \to pp\omega$



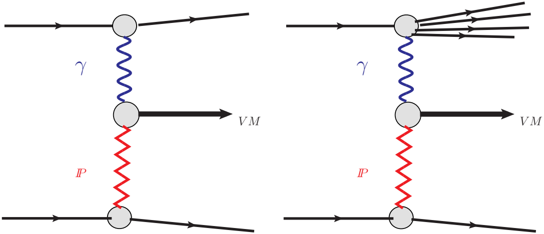
- "Bremsstrahlung"-type mechanism contributes in proton fragmentation regions
- *t*-channel exchange becomes reggeized
- subleading Regge pole, but **large** ωNN coupling, $g^2_{\omega NN}/4\pi \sim 10$.

A soft process: $pp \to pp\omega$



- dashed: without absorption, solid: with absorption
- need to go to very large energies to "dig out" photoproduction.
- A. Cisek, P. Lebiedowicz, WS, A. Szczurek Phys. Rev. D83 (2011)

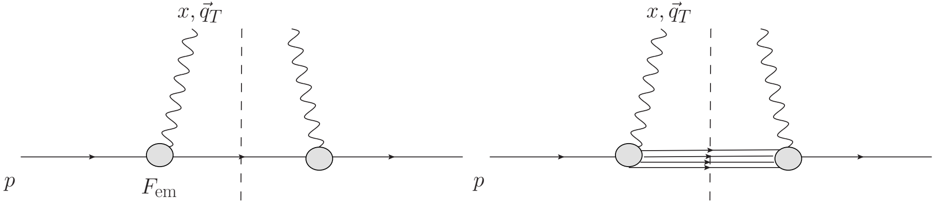
Diffractive production with electromagnetic dissociation



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

- $z_\pm = e^{\pm y}\sqrt{\boldsymbol{p}^2 + m_V^2}/\sqrt{s}$
- 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

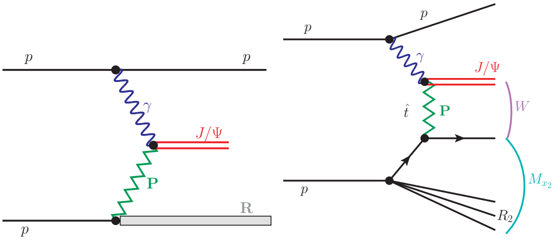


$$\mathcal{F}^{(\rm el)}_{\gamma/p}(z, \boldsymbol{q}^2) = \frac{\alpha_{\rm em}}{\pi}(1-z)\left[\frac{\boldsymbol{q}^2}{\boldsymbol{q}^2 + z^2 m_p^2}\right]^2 \frac{4m_p^2 G_E^2(Q^2) + Q^2 G_M^2(Q^2)}{4m_p^2 + Q^2}\,.$$

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

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

Diffractive dissociation of one of the protons



- Dissociation into nucleon resonances/low mass continuum states. Dominated by $N^*(1680)$, $J^P = \frac{5}{2}^+$, $N^*(2220)$, $J^P = \frac{9}{2}^+$, $N^*(2700)$, $J^P = \frac{13}{2}^+$. A model by L.L. Jenkovszky, O.E. Kuprash, J.W. Lämsa, V.K. Magas and R. Orava (2011).
- large p_T: diffractive scattering off partons, as in the large-t mechanism of Ryskin, Forshaw et al. Large diffractive masses are possible here.

Ratio of dissociative to exclusive cross section

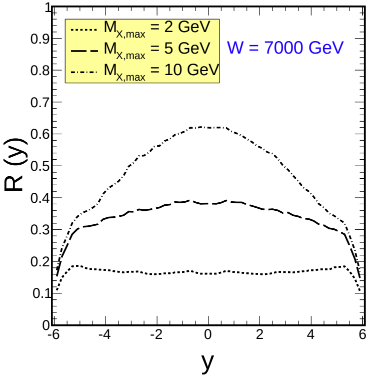
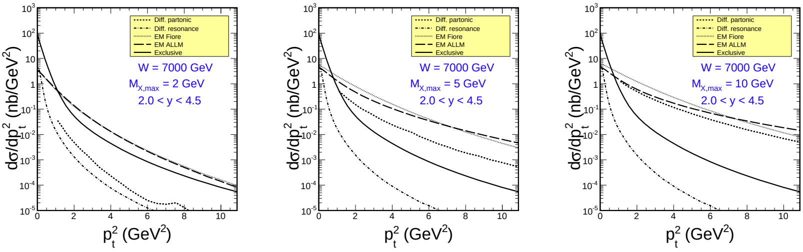


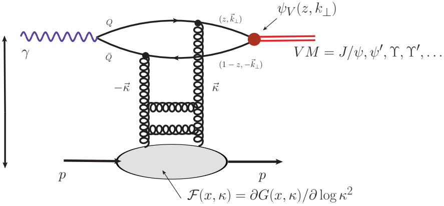
Figure : $R(y)$ as a function of J/ψ rapidity for different ranges of M_X. Both electromagnetic and diffractive excitations are included here.

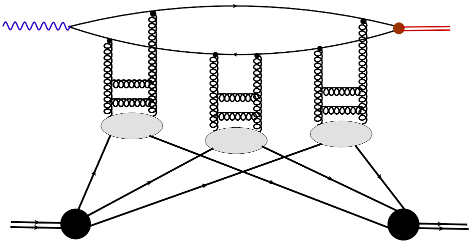
Results for LHCb cuts



- Clear emergence of two different slopes. Electromagnetic dissociation dominates!

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

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

Nuclear unintegrated glue at $x \sim x_A$

- at not too small $x \sim x_A = (R_A m_p)^{-1} \sim 0.01$ only the $\bar{q}q$ state is coherent over the nucleus, and $\Gamma(\boldsymbol{b}, x, \boldsymbol{r})$ can be constructed from Glauber-Gribov theory:

$$\Gamma(\boldsymbol{b}, x_A, \boldsymbol{r}) = 1 - \exp[-\sigma(x_A, \boldsymbol{r}) T_A(\boldsymbol{b})/2] = \int d^2\boldsymbol{\kappa}[1 - e^{i\boldsymbol{\kappa r}}]\phi(\boldsymbol{b}, x_A, \boldsymbol{\kappa}).$$

- nuclear coherent glue per unit area in impact parameter space:

$$\phi(\boldsymbol{b}, x_A, \boldsymbol{\kappa}) = \sum w_j(\boldsymbol{b}, x_A) f^{(j)}(x_A, \boldsymbol{\kappa}) \,, \; f^{(1)}(x, \boldsymbol{\kappa}) = \frac{4\pi\alpha_S}{N_c} \frac{1}{\boldsymbol{\kappa}^4} \frac{\partial G(x, \boldsymbol{\kappa}^2)}{\partial \log(\boldsymbol{\kappa}^2)}$$

- collective glue of j overlapping nucleons :

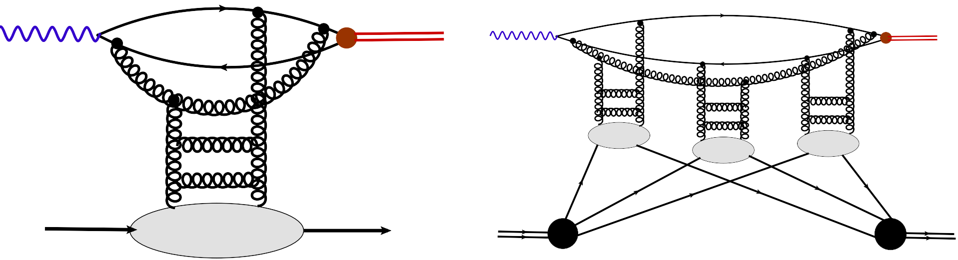
$$f^{(j)}(x_A, \boldsymbol{\kappa}) = \int \Big[\prod^{j} d^2\boldsymbol{\kappa}_i f^{(1)}(x_A, \boldsymbol{\kappa}_i)\Big] \delta^{(2)}(\boldsymbol{\kappa} - \sum \boldsymbol{\kappa}_i)$$

- probab. to find j overlapping nucleons

$$w_j(\boldsymbol{b}, x_A) = \frac{\nu_A^j(\boldsymbol{b}, x_A)}{j!} \exp[-\nu_A(\boldsymbol{b}, x_A)] \,, \; \nu_A(\boldsymbol{b}, x_A) = \frac{1}{2}\alpha_S(q^2)\, \sigma_0(x_A) T_A(\boldsymbol{b}) \,,$$

- impact parameter $\boldsymbol{b} \to$ effective opacity ν_A, q^2 = the relevant hard scale.

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 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” $\mu_G \sim .7\,\mathrm{GeV}$.

Properties of the nonlinear term:

- first piece of the nonlinear term looks like a diffractive cut of a triple-Pomeron vertex Nikolaev & WS '05:

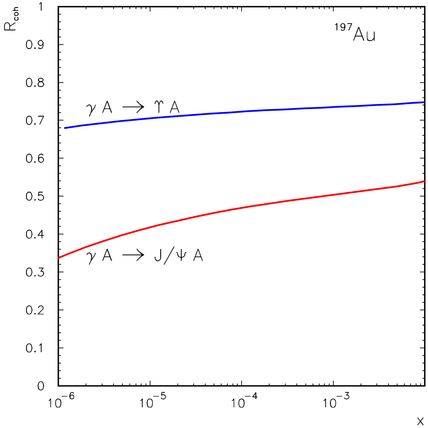
$$\int d^2\boldsymbol{q} d^2\boldsymbol{\kappa} \phi(\boldsymbol{b}, x, \boldsymbol{q}) \Big[K(\boldsymbol{p}+\boldsymbol{\kappa}, \boldsymbol{p}+\boldsymbol{q}) - K(\boldsymbol{p}, \boldsymbol{\kappa}+\boldsymbol{p}) - K(\boldsymbol{p}, \boldsymbol{q}+\boldsymbol{p}) \Big] \phi(\boldsymbol{b}, x, \boldsymbol{\kappa})$$
$$= -2K_0 \Big| \int d^2\boldsymbol{\kappa}\, \phi(\boldsymbol{b}, x, \boldsymbol{\kappa}) \Big[\frac{\boldsymbol{p}}{\boldsymbol{p}^2 + \mu_G^2} - \frac{\boldsymbol{p}+\boldsymbol{\kappa}}{(\boldsymbol{p}+\boldsymbol{\kappa})^2 + \mu_G^2} \Big] \Big|^2$$

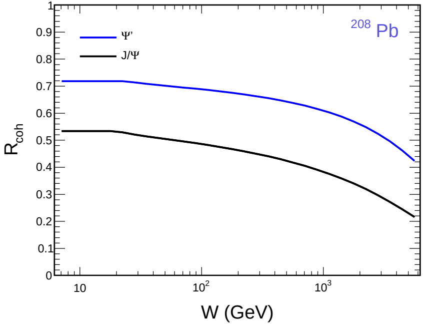
- at large $\boldsymbol{p}^2$ the nonlinear term is dominated by the 'anticollinear' region $\boldsymbol{\kappa}^2 > \boldsymbol{p}^2$. (see also Bartels & Kutak (2007)) It cannot be written as a square of the integrated gluon distribution.

$$\mathcal{Q}[\phi](\boldsymbol{b}, x, \boldsymbol{p}) \approx -\frac{2K_0}{\boldsymbol{p}^2} \Big| \int_{\boldsymbol{p}^2} \frac{d^2\boldsymbol{\kappa}}{\boldsymbol{\kappa}^2} \phi(\boldsymbol{b}, x, \boldsymbol{\kappa}^2) \Big|^2$$
$$-2K_0 \phi(\boldsymbol{b}, x, \boldsymbol{p}^2) \int_{\boldsymbol{p}^2} \frac{d^2\boldsymbol{\kappa}}{\boldsymbol{\kappa}^2} \int_{\boldsymbol{\kappa}^2} d^2\boldsymbol{q} \phi(\boldsymbol{b}, x, \boldsymbol{q}^2)$$

- in that regard it differs from the earlier Mueller-Qiu and Gribov-Levin-Ryskin gluon fusion corrections.

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

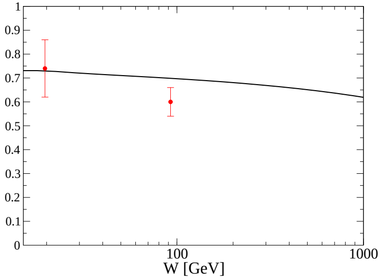




- left panel A. Cisek, WS, A. Szczurek Phys. Rev **C86** (2012) 014905.
- Ratio of coherent production cross section to impulse approximation

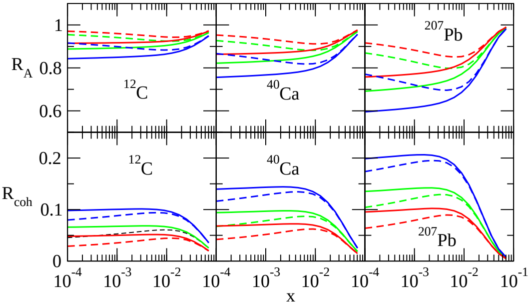
$$R_{\rm coh}(W) = \frac{\sigma(\gamma A \to VA; W)}{\sigma_{IA}(\gamma A \to VA; W)} \;,\; \sigma_{IA} = 4\pi \int d^2\boldsymbol{b}\, T_A^2(\boldsymbol{b}) \, \frac{d\sigma(\gamma N \to VN)}{dt}_{|t=0}$$

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": $R_G = \sqrt{R_{\rm coh}(x \sim 10^{-3})} \sim 0.7$.
- Whether our result should be interpreted as a shadowing of the DGLAP evolving glue is a seperate issue.

Predictio



- Predictions for a future EIC: $Q^2 = 1, 5, 20\,\mathrm{GeV}^2$
- $R_A = \frac{\sigma(\gamma^* A)}{A\sigma(\gamma^* p)}$, $R_{coh} = \frac{\text{coherent diffraction}}{\text{total}}$
- calculation from Nikolaev, WS, Zoller & Zakharov '07
- dashed $= q\bar{q}$, solid $= q\bar{q} + q\bar{q}g$ contributions
- Remember, that $16\pi d\sigma(\gamma^* p \to Xp)/dt = \langle\sigma^2(\boldsymbol{r})\rangle$ for low-mass diffraction $\to$ *elastic scattering of dipoles.*

Summary

- The k_T-factorization approach applied to the LHCb ($pp \longrightarrow p\ J/\psi(\psi')\ p$) gives the best description when using a glue that includes nonlinear evolution.
- Absorptive corrections in $pp \to ppJ/\psi$ 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.
- "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 a slightly stronger effect $R_G(10^{-3}, m_c^2) \div 0.6$.
- EIC: large coherent diffraction in DIS on large nuclei.