Incoherent diffractive photoproduction of J/ψ and Υ on heavy nuclei

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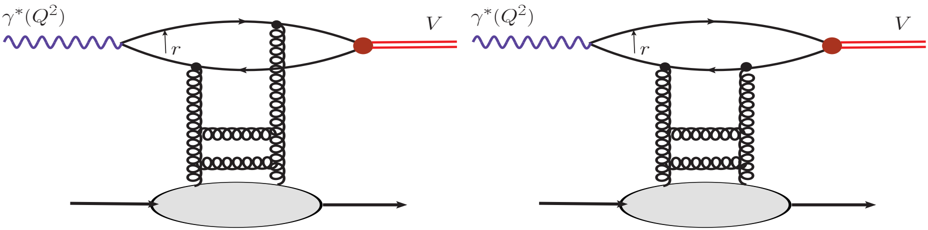
Outline

1. Exclusive photoproduction of vector mesons in γp collisions
2. Diffractive processes on the nuclear target & multiple scattering expansion
3. Incoherent diffraction in ultraperipheral and peripheral heavy ion collisions

Agnieszka Łuszczak, W.S. "Incoherent diffractive photoproduction of J/ψ and Υ on heavy nuclei in the color dipole approach," Phys. Rev. C **97**, no. 2, 024903 (2018) [arXiv:1712.04502 [hep-ph]].

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.

When do small dipoles dominate ?

- the photon shrinks with Q^2 - photon wavefunction at large r:

$$\psi_{\gamma^*}(z, \mathbf{r}, Q^2) \propto \exp[-\varepsilon r]\,,\; \varepsilon = \sqrt{m_f^2 + z(1-z)Q^2}$$

- the integrand receives its main contribution from

$$r \sim r_S \approx \frac{6}{\sqrt{Q^2 + M_V^2}}$$

Kopeliovich, Nikolaev, Zakharov '93

- a large quark mass (bottom, charm) can be a hard scale even at $Q^2 \to 0$.
- for small dipoles we can approximate

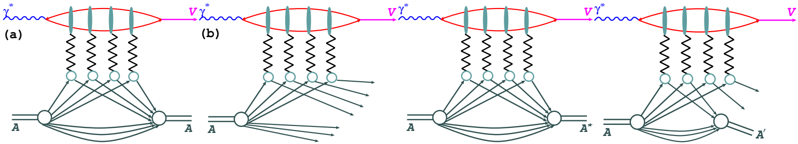
$$\sigma(x, r) = \frac{\pi^2}{3} r^2 \alpha_S(q^2) xg(x, q^2)\,,\; q^2 \approx \frac{10}{r^2}$$

- for $\varepsilon \gg 1$ we then obtain the asymptotics

$$A(\gamma^* p \to Vp) \propto r_S^2 \sigma(x, r_S) \propto \frac{1}{Q^2 + M_V^2} \times \frac{1}{Q^2 + M_V^2} xg(x, Q^2 + M_V^2)$$

- probes the gluon distribution, which drives the energy dependence.
- From DGLAP fits: $xg(x, \mu^2) = (1/x)^{\lambda(\mu^2)}$ with $\lambda(\mu^2) \sim 0.1 \div 0.4$ for $\mu^2 = 1 \div 10^2 \mathrm{GeV}^2$.

Diffractive processes on the nuclear target



diffractive processes on nuclear targets:

- coherent diffraction – nucleus stays in the ground state
- complete breakup of the nucleus, final state free protons & neutrons
- intact nucleus, but an excited state
- partial breakup of the nucleus, a variety of possible fragments

they all have in common:

- large rapidity gap between vector meson and nuclear fragments
- lack of production of additional particles

See e.g. A. Caldwell and H. Kowalski, Phys. Rev. C **81** (2010) for prospects at an electron-ion collider

Off-forward amplitude

Amplitude at finite transverse momentum transfer $\boldsymbol{\Delta}$

$$\mathcal{A}(\gamma^* A_i \to V A_f^*; W, \Delta) = 2i \int d^2\boldsymbol{B} \exp[-i\boldsymbol{\Delta}\boldsymbol{B}] \langle V | \langle A_f^* | \hat{\Gamma}(\boldsymbol{b}_+, \boldsymbol{b}_-) | A_i \rangle | \gamma \rangle$$

$$= 2i \int d^2\boldsymbol{B} \exp[-i\boldsymbol{\Delta}\boldsymbol{B}] \int_0^1 dz \int d^2\boldsymbol{r} \Psi_V^*(z, \boldsymbol{r}) \Psi_\gamma(z, \boldsymbol{r}) \langle A_f^* | \hat{\Gamma}(\boldsymbol{B} - (1-z)\boldsymbol{r}, \boldsymbol{B} + z\boldsymbol{r}) | A_i \rangle.$$

$$\boldsymbol{B} = z\boldsymbol{b}_+ + (1-z)\boldsymbol{b}_- = \boldsymbol{b} - (1-2z)\frac{\boldsymbol{r}}{2}$$

$$\mathcal{A}(\gamma^* A_i \to V A_f^*; W, \Delta) = 2i \int d^2\boldsymbol{b} \exp[-i\boldsymbol{b}\boldsymbol{\Delta}] \int d^2\boldsymbol{r} \rho_{V\gamma}(\boldsymbol{r}, \boldsymbol{\Delta}) \langle A_f^* | \hat{\Gamma}(\boldsymbol{b} + \frac{\boldsymbol{r}}{2}, \boldsymbol{b} - \frac{\boldsymbol{r}}{2}) | A_i \rangle ,$$

$$\rho_{V\gamma}(\boldsymbol{r}, \boldsymbol{\Delta}) = \int_0^1 dz \exp[i(1-2z)\frac{\boldsymbol{r}\boldsymbol{\Delta}}{2}] \Psi_V^*(z, \boldsymbol{r}) \Psi_\gamma(z, \boldsymbol{r}) .$$

Incoherent diffraction: summing over nuclear states

$$\frac{d\sigma_{\rm incoh}}{d\boldsymbol{\Delta}^2} = \sum_{A_f \neq A} \frac{d\sigma(\gamma A_i \to V A_f^*)}{d\boldsymbol{\Delta}^2} \,.$$

Closure in the sum over nuclear final states:

$$\sum_{A \neq A_f} |A_f\rangle\langle A_f| = 1 - |A\rangle\langle A|,$$

$$\frac{d\sigma_{\rm incoh}}{d\boldsymbol{\Delta}^2} = \frac{1}{4\pi} \int d^2\boldsymbol{r} d^2\boldsymbol{r}' \rho^*_{V\gamma}(\boldsymbol{r}', \boldsymbol{\Delta}) \rho_{V\gamma}(\boldsymbol{r}, \boldsymbol{\Delta}) \Sigma_{\rm incoh}(\boldsymbol{r}, \boldsymbol{r}', \boldsymbol{\Delta}) \,,$$

$$\Sigma_{\rm incoh}(\boldsymbol{r}, \boldsymbol{r}', \boldsymbol{\Delta}) = \int d^2\boldsymbol{b} d^2\boldsymbol{b}' \exp[-i\boldsymbol{\Delta}(\boldsymbol{b} - \boldsymbol{b}')] \mathcal{C}\Big(\boldsymbol{b}' + \frac{\boldsymbol{r}'}{2}, \boldsymbol{b}' - \frac{\boldsymbol{r}'}{2}; \boldsymbol{b} + \frac{\boldsymbol{r}}{2}, \boldsymbol{b} - \frac{\boldsymbol{r}}{2}\Big)$$

Only ground state nuclear averages:

$$\mathcal{C}(\boldsymbol{b}'_+, \boldsymbol{b}'_-; \boldsymbol{b}_+, \boldsymbol{b}_-) = \langle A|\hat{\Gamma}^\dagger(\boldsymbol{b}'_+, \boldsymbol{b}'_-)\hat{\Gamma}(\boldsymbol{b}_+, \boldsymbol{b}_-)|A\rangle - \langle A|\hat{\Gamma}(\boldsymbol{b}'_+, \boldsymbol{b}'_-)|A\rangle^* \langle A|\hat{\Gamma}(\boldsymbol{b}_+, \boldsymbol{b}_-)|A\rangle \,.$$

Nuclear averages as in Glauber & Matthiae

$$\hat{\Gamma}(\boldsymbol{b}_+, \boldsymbol{b}_-) = 1 - \prod_{i=1}^{A} [1 - \hat{\Gamma}_{N_i}(\boldsymbol{b}_+ - \boldsymbol{c}_i, \boldsymbol{b}_- - \boldsymbol{c}_i)] \,,$$

in the limit of the dilute uncorrelated nucleus all we need are:

$$M(\boldsymbol{b}_+, \boldsymbol{b}_-) = \int d^2\boldsymbol{c}\, T_A(\boldsymbol{c}) \Gamma_N(\boldsymbol{b}_+ - \boldsymbol{c}, \boldsymbol{b}_- - \boldsymbol{c})$$

$$\Omega(\boldsymbol{b}'_+, \boldsymbol{b}'_-; \boldsymbol{b}_+, \boldsymbol{b}_-) = \int d^2\boldsymbol{c}\, T_A(\boldsymbol{c}) \Gamma^*_N(\boldsymbol{b}'_+ - \boldsymbol{c}, \boldsymbol{b}'_- - \boldsymbol{c}) \Gamma_N(\boldsymbol{b}_+ - \boldsymbol{c}, \boldsymbol{b}_- - \boldsymbol{c})$$

$$\begin{aligned} \mathcal{C}(\boldsymbol{b}'_+, \boldsymbol{b}'_-; \boldsymbol{b}_+, \boldsymbol{b}_-) &= \left[1 - \frac{1}{A}\Big(M^*(\boldsymbol{b}'_+, \boldsymbol{b}'_-) + M(\boldsymbol{b}_+, \boldsymbol{b}_-)\Big) + \frac{1}{A}\Omega(\boldsymbol{b}'_+, \boldsymbol{b}'_-; \boldsymbol{b}_+, \boldsymbol{b}_-)\right]^A \\ &\quad - \left[\Big(1 - \frac{1}{A}M^*(\boldsymbol{b}'_+, \boldsymbol{b}'_-)\Big)\Big(1 - \frac{1}{A}M(\boldsymbol{b}_+, \boldsymbol{b}_-)\Big)\right]^A \end{aligned}$$

Multiple scattering expansion of the incoherent cross section

Diffraction cone of the free nucleon: $B \ll R_A^2$

$$\sigma(x, \boldsymbol{r}, \boldsymbol{\Delta}) = \sigma(x, r) \exp[-\frac{1}{2} B \boldsymbol{\Delta}^2]$$

Multiple scattering expansion for $\boldsymbol{\Delta}^2 R_A^2 \gg 1$

$$\frac{d\sigma_{\rm incoh}}{d\boldsymbol{\Delta}^2} = \sum_n \frac{d\sigma^{(n)}}{d\boldsymbol{\Delta}^2} = \frac{1}{16\pi} \sum_n w_n(\boldsymbol{\Delta}) \int d^2\boldsymbol{b}\, T_A^n(\boldsymbol{b}) |I_n(x, \boldsymbol{b})|^2 \,,$$

$$w_n(\boldsymbol{\Delta}) = \frac{1}{n \cdot n!} \cdot \left(\frac{1}{16\pi B} \right)^{n-1} \cdot \exp\left(- \frac{B}{n} \boldsymbol{\Delta}^2 \right) ,$$

and

$$\begin{aligned} I_n(x, \boldsymbol{b}) &= \langle V | \, \sigma^n(x, r) \exp[-\frac{1}{2} \sigma(x, r) T_A(\boldsymbol{b})] | \gamma \rangle \\ &= \int_0^1 dz \int d^2\boldsymbol{r}\, \Psi_V^*(z, \boldsymbol{r}) \Psi_\gamma(z, \boldsymbol{r})\, \sigma^n(x, r) \underbrace{\exp[-\frac{1}{2} \sigma(x, r) T_A(\boldsymbol{b})]}_{\text{nuclear absorption}} \,. \end{aligned}$$

Dipole cross section from Xfitter

BGK-form of the dipole cross section

$$\sigma(x,r) = \sigma_0 \left(1 - \exp\left[-\frac{\pi^2 r^2 \alpha_s(\mu^2) xg(x,\mu^2)}{3\sigma_0}\right]\right), \mu^2 = C/r^2 + \mu_0^2$$

- the *soft* ansatz, as used in the original BGK model

$$xg(x,\mu_0^2) = A_g x^{-\lambda_g}(1-x)^{C_g},$$

- the *soft* + *hard* ansatz

$$xg(x,\mu_0^2) = A_g x^{-\lambda_g}(1-x)^{C_g}(1 + D_g x + E_g x^2),$$

- fit I: BGK fit with fitted valence quarks for σ_r for H1ZEUS-NC data in the range $Q^2 \geq 3.5$ GeV^2 and $x \leq 0.01$. NLO fit. *Soft gluon*.
- fit II: BGK fit with valence quarks for σ_r for H1ZEUS-NC data in the range $Q^2 \geq 0.35$ GeV^2 and $x \leq 0.01$. NLO fit. *Soft + hard gluon*.
- fits from A. Łuszczak and H. Kowalski, Phys. Rev. D **95** (2017).

Further input to our calculation

Overlap of light-cone wave functions

$$\Psi_V^*(z,\boldsymbol{r})\Psi_\gamma(z,\boldsymbol{r}) = \frac{e_Q\sqrt{4\pi\alpha_{\rm em}}N_c}{4\pi^2 z(1-z)}\Big\{m_Q^2 K_0(m_Q r)\psi(z,r) - [z^2+(1-z)^2]m_Q K_1(m_Q r)\frac{\partial\psi(z,r)}{\partial r}\Big\}.$$

- "boosted Gaussian" wave functions as in Nemchik et al. ('94)

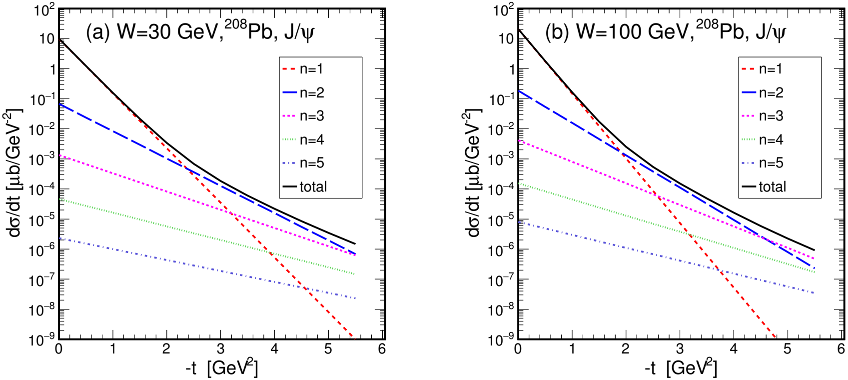
$$\psi(z,r) \propto z(1-z)\exp\left[-\frac{M_Q^2 R^2}{8z(1-z)} - \frac{2z(1-z)r^2}{R^2}\right]$$

- parameters m_Q, R & normalization as in Kowalski et al. (2006) for J/ψ and Cox et al. (2008) for Υ.

diffractive slope on a free nucleon:

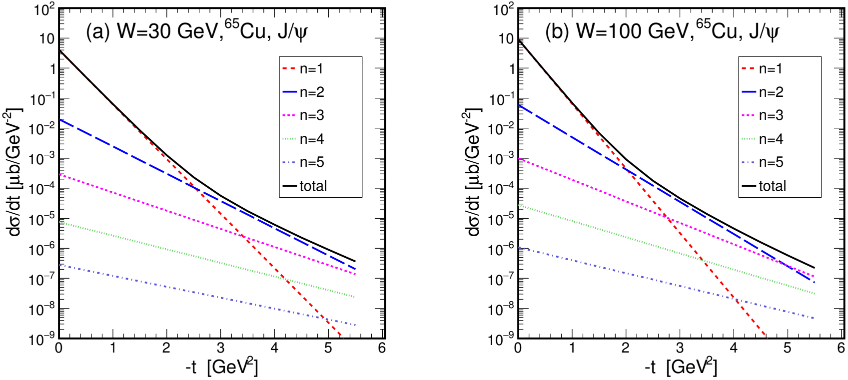
$B = B_0 + 4\alpha' \log(W/W_0)$ with $W_0 = 90\,\mathrm{GeV}$, and $\alpha' = 0.164\,\mathrm{GeV}^{-2}$.
We take $B_0 = 4.88\,\mathrm{GeV}^{-2}$ for J/ψ and $B_0 = 3.68\,\mathrm{GeV}^{-2}$ for Υ.

Diffractive incoherent photoproduction on the nuclear target

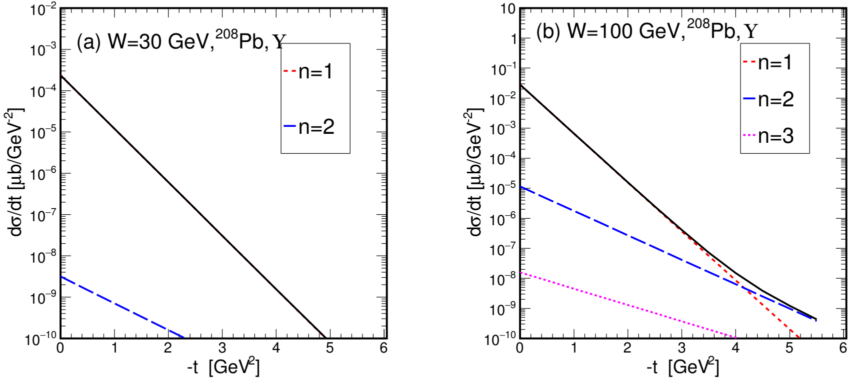


$-t = \mathbf{\Delta}^2$, single scattering has the same diffractive slope as on the free nucleon, multiple scatterings have smaller slopes.

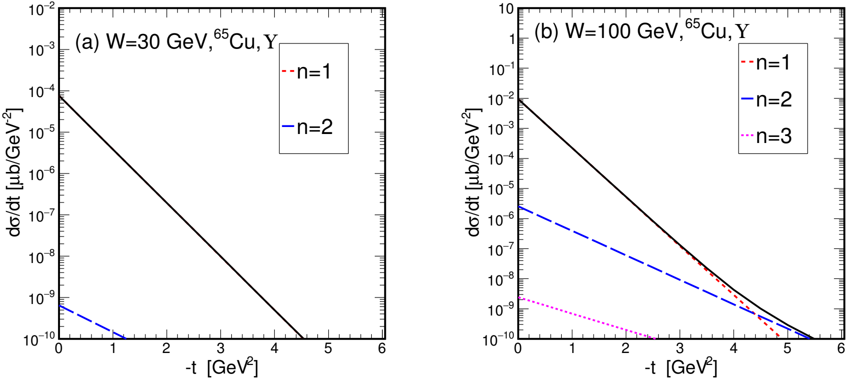
Diffractive incoherent photoproduction on the nuclear target



Diffractive incoherent photoproduction on the nuclear target



Diffractive incoherent photoproduction on the nuclear target



Incoherent difffraction at low $\mathbf{\Delta}^2$

at low $\mathbf{\Delta}^2$ the single scattering dominates, and one should rather use its exact form:

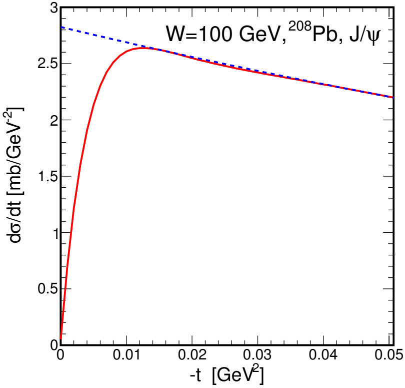
$$\frac{d\sigma_{\rm incoh}}{d\mathbf{\Delta}^2} = \frac{1}{16\pi}\left\{ w_1(\mathbf{\Delta}) \int d^2\mathbf{b}\, T_A(\mathbf{b}) |I_1(x,\mathbf{b})|^2 - \underbrace{\frac{1}{A}\left| \int d^2\mathbf{b}\, \exp[-i\mathbf{\Delta}\mathbf{b}]\, T_A(\mathbf{b}) I_1(x,\mathbf{b}) \right|^2}_{\text{vanishes for } \mathbf{\Delta}^2 \mathrm{R}_\mathrm{A}^2 \gg 1} \right\}.$$

$$I_1(x,\mathbf{b}) \quad = \quad \langle V|\, \sigma(x,r) \underbrace{\exp[-\frac{1}{2}\sigma(x,r)\, T_A(\mathbf{b})]}_{\text{nuclear absorption}} |\gamma\rangle$$

If we were to neglect intranuclear absorption, we would obtain for small $\mathbf{\Delta}^2$:

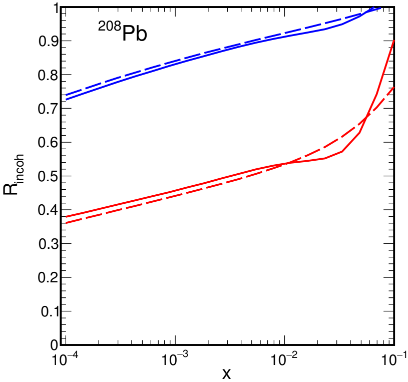
$$\frac{d\sigma_{\rm incoh}}{d\mathbf{\Delta}^2} = A \cdot \frac{d\sigma(\gamma N \to VN)}{d\mathbf{\Delta}^2}\Big|_{\mathbf{\Delta}^2=0} \cdot \Big\{ 1 - \mathcal{F}_A(\mathbf{\Delta}^2) \Big\}.$$

Diffractive processes on the nuclear target



- solid line: exact single scattering
- dashed: large $|t|$-limit of single scattering
- exact result merges into the large $|t|$ limit quickly, the latter is a good approximation in a broad range of t.
- cross section dips, but does not vanish at $t \to 0$.
- note: in the small to intermediate t region nuclear correlations may play a role.

Diffractive processes on the nuclear target



- blue: Υ, red: J/ψ
- dashed line: dipole fit I (soft gluon),
- solid line: dipole fit II (soft+hard gluon)
- dependence on dipole cross section in its "applicability region" is rather small.
- nuclear absorption cannot be neglected, even for heavy vector mesons.

$$R_{\rm incoh}(x) = \frac{d\sigma_{\rm incoh}/d\boldsymbol{\Delta}^2}{A \cdot d\sigma(\gamma N \to VN)/d\boldsymbol{\Delta}^2} = \frac{\int d^2\boldsymbol{b}\, T_A(\boldsymbol{b}) \Big| \langle V|\sigma(x,r)\exp[-\frac{1}{2}\sigma(x,r)T_A(\boldsymbol{b})]|\gamma\rangle \Big|^2}{A \cdot \Big| \langle V|\sigma(x,r)|\gamma\rangle \Big|^2} .$$

Corrections for real part and skewedness

numerically important corrections:

- real part of the diffractive amplitude:

$$\sigma(x,r) \to (1 - i\rho(x))\sigma(x,r)\,,\ \rho(x) = \tan\left(\frac{\pi\Delta_{\mathbf{P}}}{2}\right), \Delta_{\mathbf{P}} = \frac{\partial \log\Big(\langle V|\sigma(x,r)|\gamma\rangle\Big)}{\partial \log(1/x)}$$

- amplitude is non-forward also in the longitudinal momenta. Correction factor (Shuvaev et al. (1999)):

$$R_{\rm skewed} = \frac{2^{2\Delta_{\mathbf{P}}+3}}{\sqrt{\pi}} \cdot \frac{\Gamma(\Delta_{\mathbf{P}} + 5/2)}{\Gamma(\Delta_{\mathbf{P}} + 4)}\,.$$

- apply K-factor to the cross section:

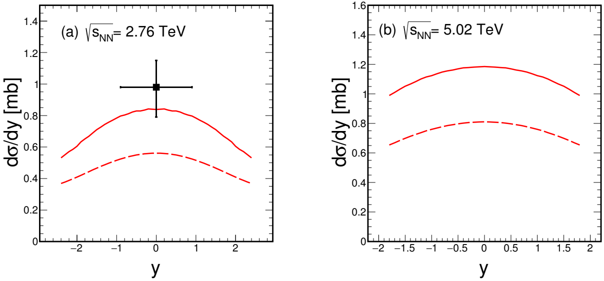
$$K = (1 + \rho^2(x)) \cdot R^2_{\rm skewed}\,.$$

Note: absorption factor is really:

$$\int d^2\boldsymbol{b}\, T_A^n(\boldsymbol{b}) \exp\Big[-\frac{1}{2}\Big(\sigma^*(x,\boldsymbol{r}') + \sigma(x,\boldsymbol{r})\Big) T_A(\boldsymbol{b})\Big]$$

so that we neglect a real part in the absorption exponentials

Incoherent diffraction in ultraperipheral heavy ion collisions



solid line: with K-factor
dashed line: without K-factor
data point from ALICE
Eur. Phys. J. C **73** (2013)

Cross section for AA collision uses Weizsäcker-Williams photon fluxes:

$$\frac{d\sigma_{\rm incoh}(AA \to VAX)}{dy} = n_{\gamma/A}(z_+)\sigma_{\rm incoh}(W_+) + n_{\gamma/A}(z_-)\sigma_{\rm incoh}(W_-)\,,$$

$$z_\pm = \frac{m_V}{\sqrt{s_{NN}}} e^{\pm y}, \;\; W_\pm = \sqrt{z_\pm s_{NN}}\,.$$

From ultraperipheral to peripheral nuclear collisions

Recently, the ALICE collaboration has observed a large enhancement of J/ψ mesons carrying very small $p_T < 300\,\mathrm{MeV}$ in the centrality classes corresponding to peripheral collisions.

Centrality class $70 \div 90\%$:

$13\,\mathrm{fm} < b < 15\,\mathrm{fm}$, photon fluxes by Contreras Phys. Rev. C **96** (2017)

$$\begin{aligned} \frac{d\sigma_{\rm incoh}(AA \to VX|70 \div 90\%)}{dy} &= n_{\gamma/A}(z_+|70 \div 90\%)\sigma_{\rm incoh}(W_+|p_T < p_T^{\rm cut}) \\ &+ n_{\gamma/A}(z_-|70 \div 90\%)\sigma_{\rm incoh}(W_-|p_T < p_T^{\rm cut}) \\ &\approx 15\,\mu\mathrm{b}\,, \end{aligned}$$

The ALICE measurement is [Phys. Rev. Lett. **116** (2016)]:

$$\frac{d\sigma(AA \to VX|70 \div 90\%; 2.5 < |y| < 4.0)}{dy} = 59 \pm 11 \pm 8\,\mu\mathrm{b}\,.$$

For an estimate of the coherent contribution, see: M. Kłusek-Gawenda and A. Szczurek, Phys. Rev. C **93** (2016)

Conclusions

- we have presented the Glauber-Gribov theory for incoherent photoproduction of vector mesons on heavy nuclei within the color dipole approach.
- We have developed the multiple scattering expansion which involves matrix elements of the operator $\sigma^n(x,r)\exp[-\frac{1}{2}\sigma(x,r)T_A(\boldsymbol{b})]$. We performed calculations for J/ψ and Υ photoproduction. Multiple scatterings lead to extended tails in the t-distributions.
- multiple scattering terms are only important at large t, beyond the free-nucleon diffraction cone.
- We use the dipole cross section obtained in the Xfitter framework. Our calculations are in agreement with data from ALICE in ultraperipheral lead-lead collisions at $\sqrt{s_{\rm NN}} = 2.76\,\mathrm{TeV}$.
- Incoherent diffractive production also contributes to the J/ψ yield in peripheral inelastic heavy-ion collisions. Rough estimates using photon fluxes of Contreras give about $\sim 25\%$ of the cross section measured by ALICE.
- In the future: extension to light vector mesons, as well as to finite Q^2 (electron-ion collider).