Exclusive coherent production of heavy vector mesons in nucleus-nucleus collisions

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Outline

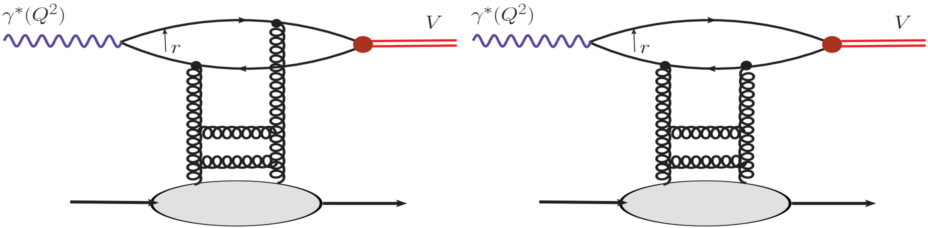
$\gamma p \to Vp$ at high energies

From diffraction on heavy nuclei to $AA \to AAV$

$AA \to AAJ/\psi J/\psi$ via $\gamma\gamma \to J/\psi J/\psi$

- W.S. & Antoni Szczurek Phys. Rev. D **76**, 094014 (2007).
- A. Rybarska, W.S. and A. Szczurek, Phys. Lett. B **668** (2008) 126.
- A. Cisek, W. S. and A. Szczurek, Phys. Rev **C86** (2012) 014905.
- S. Baranov, A. Cisek, M. Kłusek-Gawenda, W.S., A. Szczurek, arXiv:1208.5917.

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:

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

- 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

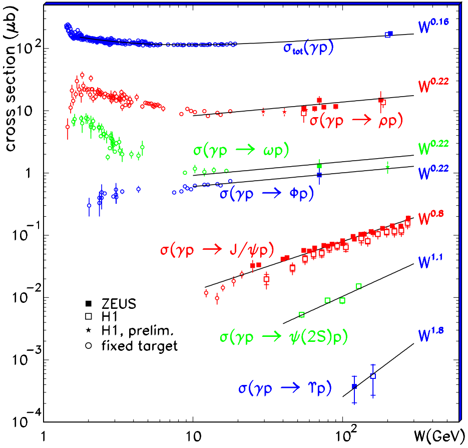
$$\sigma(x, r) = \frac{\pi^2}{3} r^2 \alpha_S(q^2) x g(x, q^2)\,,\ q^2 \approx \frac{10}{r^2}$$

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

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

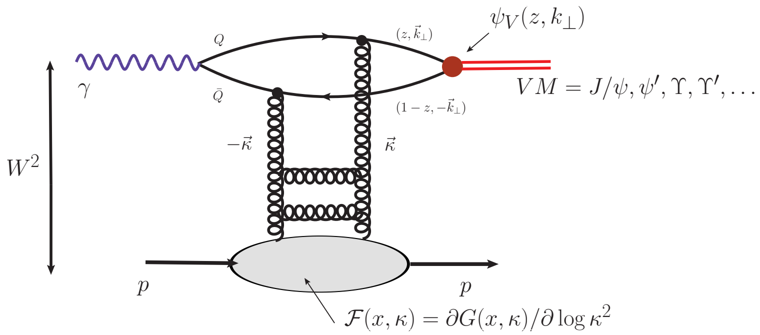
- probes the gluon distribution, which drives the energy dependence.
- From DGLAP fits: $xg(x, \mu^2) = (1/x)^{\lambda(\mu^2)}$ with $\lambda(\mu^2) \sim 0.1 \div 0.4$ for $\mu^2 = 1 \div 10^2 \mathrm{GeV}^2$.

Total photoproduction cross sections



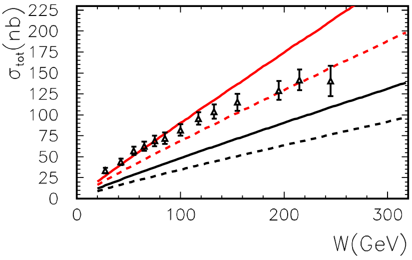
$$G(x, Q^2) \propto (1/x)^{\lambda(Q^2)}\,, \quad \lambda(Q^2) = 0.1 \div 0.4 \;\text{ for }\; Q^2 = 1 \div 10^2$$

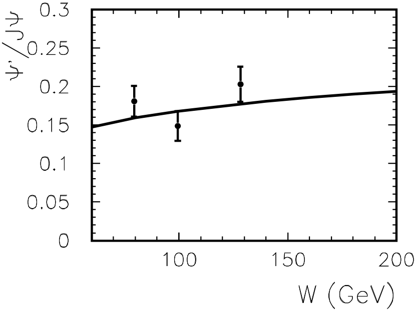
Diffractive Photoproduction $\gamma p \to Vp$



- $J/\psi = c\bar{c}$, $\Upsilon = b\bar{b}$: (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.
- for an extensive phenomenology, see Ivanov, Nikolaev, Savin (2006)
- topical subject: glue at small-x: nonlinear evolution, gluon fusion, saturation...

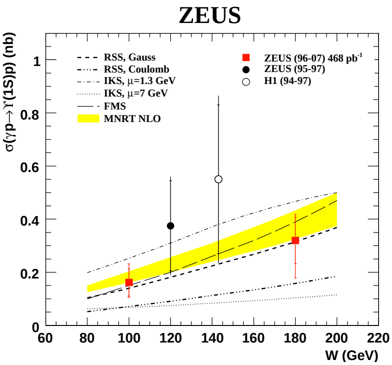
$\gamma p \longrightarrow J/\psi p, \Upsilon p$ and $\psi(2S)/J/\psi$ vs ZEUS data





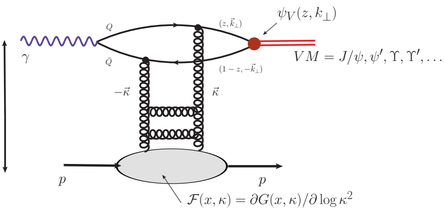
- dependence on wave function: **red:** Gaussian WF, **black**: Coulomb-type WF.
- dependence on LO/NLO treatment of decay width: dashed - LO width; solid - NLO width.
- suppression of the $\psi(2S)/J/\psi$ is a meson structure effect – the "node effect" Nemchik, Nikolaev et al. '94.
- calculation: A.Cisek, PhD thesis (2012).

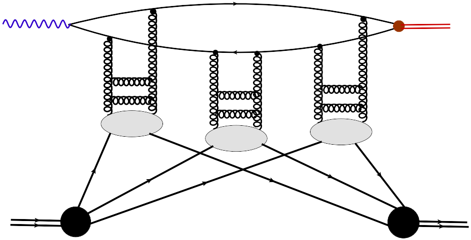
Total cross section for $\gamma p \longrightarrow \Upsilon p$



- various pQCD based approaches to Υ-production. They tend to agree better with the new data-points.
- also here, the Gaussian WF is preferred.
- A. Rybarska, WS, A. Szczurek Phys. Lett. B668(2008)

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:

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

- 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 :

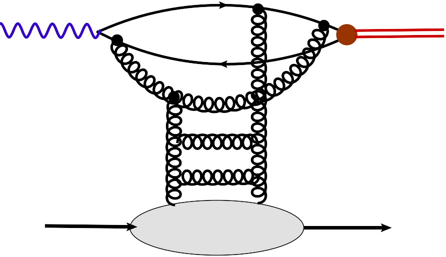
$$f^{(j)}(x_A, \boldsymbol{\kappa}) = \int \Big[\prod^{j} d^2\boldsymbol{\kappa}_i f^{(1)}(x_A, \boldsymbol{\kappa}_i) \Big] \delta^{(2)}(\boldsymbol{\kappa} - \sum \boldsymbol{\kappa}_i)$$

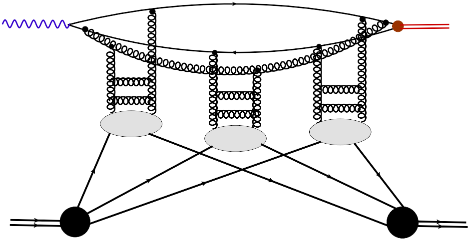
- probab. to find j overlapping nucleons

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

- 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 $\mathrm{Balitsky-Kovchegov~'96-'98}$:

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

- corresponds to taking the contribution to shadowing from high–mass diffraction into account

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

Nikolaev & Zakharov '94, Mueller '94

- as we increase energy Fock states $q\bar{q}g, q\bar{q}gg, \dots q\bar{q}(ng)$ with strongly ordered light–cone momenta $z_n \ll \dots \ll z_2 \ll z_1 \ll 1$ will be coherent over the target.
- their effect can be resummed and absorbed into the x–dependent dipole cross section:

$$\frac{\partial \sigma(x, \boldsymbol{r})}{\partial \log(1/x)} = \int d^2\rho K(\boldsymbol{\rho}, \boldsymbol{\rho} + \boldsymbol{r}) \Big[\sigma_{q\bar{q}g}(x, \boldsymbol{\rho}, \boldsymbol{r}) - \sigma(x, \boldsymbol{r}) \Big]$$

$$\sigma_{q\bar{q}g}(x, \boldsymbol{\rho}, \boldsymbol{r}) = \frac{N_c^2}{N_c^2 - 1} [\sigma(x, \boldsymbol{\rho}) + \sigma(x, \boldsymbol{\rho} + \boldsymbol{r})] - \frac{1}{N_c^2 - 1} \sigma(x, \boldsymbol{r})$$

$$K(\boldsymbol{\rho}, \boldsymbol{\rho} + \boldsymbol{r}) \propto \Big| \psi(\boldsymbol{\rho}) - \psi(\boldsymbol{\rho} + \boldsymbol{r}) \Big|^2, \; \psi(\boldsymbol{\rho}) = \frac{\boldsymbol{\rho}}{\boldsymbol{\rho}^2} F(\mu_G \boldsymbol{\rho})$$

- $\mu_G^2 \sim 0.5\,\mathrm{GeV}^2$, 'gluon mass' - a smooth cutoff for long wavelength gluons, which respects 'gauge cancellations'.

. . . in momentum space it is BFKL:

- the equivalence of dipole and momentum space approaches extends to the small-x evolution:

$$\begin{aligned} \frac{\partial f(x,\boldsymbol{p})}{\partial \log(1/x)} &= 2\int d^2\boldsymbol{\kappa}\, K(\boldsymbol{p},\boldsymbol{p}+\boldsymbol{\kappa})\, f(x,\boldsymbol{\kappa}) - f(x,\boldsymbol{p}) \int d^2\boldsymbol{\kappa}\, K(\boldsymbol{\kappa},\boldsymbol{\kappa}+\boldsymbol{p}) \\ &= \mathcal{K}_{BFKL} \otimes f(x,\boldsymbol{p}) \end{aligned}$$

- the kernel:

$$K(\boldsymbol{p}_1,\boldsymbol{p}_2) = K_0 \cdot \left| \frac{\boldsymbol{p}_1}{\boldsymbol{p}_1^2+\mu_G^2} - \frac{\boldsymbol{p}_2}{\boldsymbol{p}_2^2+\mu_G^2} \right|^2, \, K_0 = \frac{C_A \alpha_S}{2\pi^2}$$

- nonperturbative parameters: μ_G, freezing of α_S.

Nuclear unintegrated glue: small-x evolution

- again, add the $q\bar{q}g$ Fock-state:
- small–x evolution Nikolaev,Zakharov,Zoller/Mueller '94:

$$\Gamma_{q\bar{q},A}(\boldsymbol{b},x_A,\boldsymbol{r}) \to \Gamma_{q\bar{q},A}(\boldsymbol{b},x_A,\boldsymbol{r}) + \log(x_A/x)\delta\Gamma_{q\bar{q},A}(\boldsymbol{b},\boldsymbol{r})$$

$$\delta\Gamma_{q\bar{q},A}(\boldsymbol{b},\boldsymbol{r}) \propto \int d^2\rho K(\boldsymbol{\rho},\boldsymbol{\rho}+\boldsymbol{r})\Big(\Gamma_{q\bar{q}g,A}(\boldsymbol{b},\boldsymbol{\rho},\boldsymbol{r}) - \Gamma_{q\bar{q},A}(\boldsymbol{b},\boldsymbol{r})\Big)$$

$$\Gamma_{q\bar{q}g,A}(\boldsymbol{b},\boldsymbol{\rho},\boldsymbol{r}) = \Gamma_{q\bar{q},A}(\boldsymbol{b},\boldsymbol{\rho}) + \Gamma_{q\bar{q},A}(\boldsymbol{b},\boldsymbol{\rho}+\boldsymbol{r}) - \Gamma_{q\bar{q},A}(\boldsymbol{b},\boldsymbol{\rho})\Gamma_{q\bar{q},A}(\boldsymbol{b},\boldsymbol{\rho}+\boldsymbol{r})$$

- evolution of unintegrated glue Balitsky–Kovchegov '96–'98:

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

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

$$-\phi(\boldsymbol{b},x,\boldsymbol{p})\Big[K(\boldsymbol{\kappa},\boldsymbol{\kappa}+\boldsymbol{q}+\boldsymbol{p}) - K(\boldsymbol{\kappa},\boldsymbol{\kappa}+\boldsymbol{p})\Big]\Big\} nonumber \quad (1)$$

properties of the nonlinear term:

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

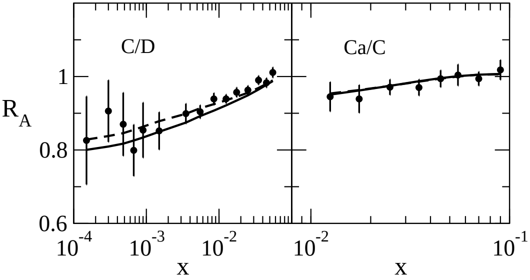
$$\int d^2\boldsymbol{q} d^2\boldsymbol{\kappa} \phi(\boldsymbol{b},x,\boldsymbol{q}) \Big[K(\boldsymbol{p}+\boldsymbol{\kappa},\boldsymbol{p}+\boldsymbol{q}) - K(\boldsymbol{p},\boldsymbol{\kappa}+\boldsymbol{p}) - K(\boldsymbol{p},\boldsymbol{q}+\boldsymbol{p}) \Big] \phi(\boldsymbol{b},x,\boldsymbol{\kappa})$$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

- at large $\boldsymbol{p}^2$ the nonlinear term is a pure higher twist, it 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.

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

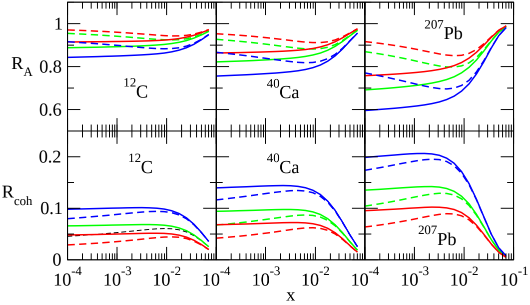
- in that regard it differs from the earlier Mueller-Qiu and Gribov-Levin-Ryskin gluon fusion corrections.

Shadowing of nuclear structure functions



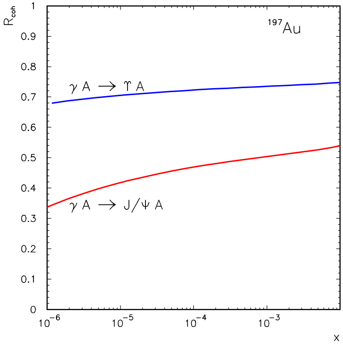
- $R_A = \frac{A_2 \sigma(\gamma^* A_1)}{A_1 \sigma(\gamma^* A_2)}$
- data from NMC Collab. ('95)
- x and Q^2 are correlated
- calculation from Nikolaev, WS, Zoller & Zakharov '07
- dashed $= q\bar{q}$, solid $= q\bar{q} + q\bar{q}g$ contributions

Prediction



- 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

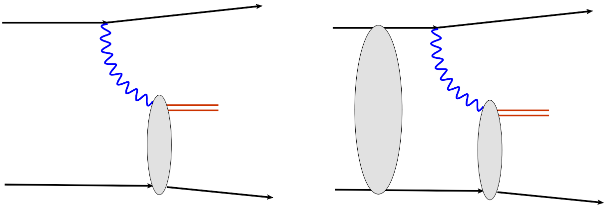
Coherent diffractive production of $J/\Psi, \Upsilon$ on ^{208}Pb



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

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

Absorption corrected flux of photons



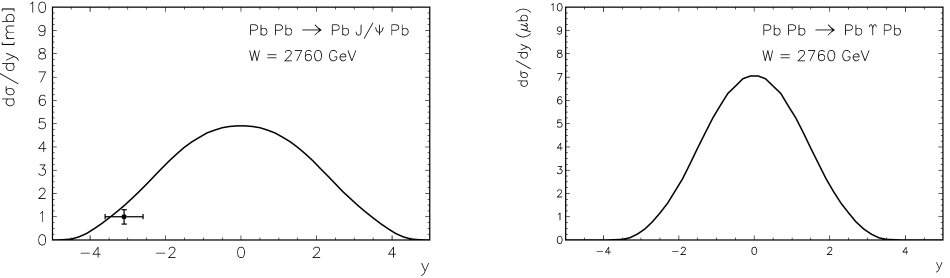
$$\sigma(A_1 A_2 \to A_1 A_2 f; s) = \int d\omega \frac{dN^{\rm eff}_{A_1}(\omega)}{d\omega} \sigma(\gamma A_2 \to f A_2; 2\omega\sqrt{s}) + (1 \leftrightarrow 2)$$

$$dN^{eff} = \int d^2\boldsymbol{b}\, S^2_{el}(\boldsymbol{b}) dN(\omega, \boldsymbol{b})$$

- $dN(\omega)$= Weizsäcker-Williams flux
- survival probability:

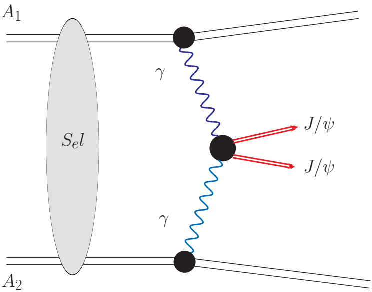
$$S^2_{el}(\boldsymbol{b}) = \exp\Big(- \sigma_{NN} T_{A_1 A_2}(\boldsymbol{b}) \Big) \sim \theta(|\boldsymbol{b}| - (R_1 + R_2))$$

Coherent exclusive production in AA: rapidity distributions



- A. Cisek, WS, A. Szczurek, Phys. Rev **C86** (2012) 014905.
- left column: J/Ψ, right column: Υ
- The large nuclear size cuts off the flux of hard photons severly $\rightarrow$ different rapidity shape than in *pp*.

Absorbed photon fluxes for $\gamma\gamma$-collisions



$$x_i = \frac{2\omega_i}{\sqrt{s}}\,,\ \frac{\omega_i}{\gamma_i} = x_i M_{A_i}$$

$$q_i \approx x_i p_i + q_i^{\perp}$$

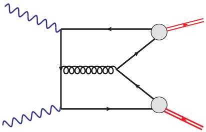
$$s_{\gamma\gamma} \equiv W^2 = x_1 x_2 s = 4\omega_1\omega_2$$

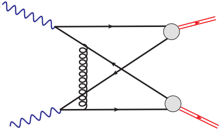
$$\sigma(A_1 A_2 \to A_1 A_2 f; s) = \int d^2\boldsymbol{b}\, S_{el}^2(\boldsymbol{b}) \int \frac{dx_1}{x_1}\frac{dx_2}{x_2}\, n_{\gamma\gamma}(x_1, x_2, \boldsymbol{b})\, \sigma(\gamma\gamma \to f; x_1 x_2 s)$$

- survival probability:

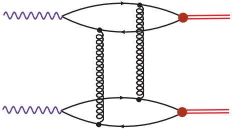
$$S_{el}^2(\boldsymbol{b}) = \exp\Big(- \sigma_{NN}\, T_{A_1 A_2}(\boldsymbol{b})\Big) \sim \theta(|\boldsymbol{b}| - (R_1 + R_2))$$

Production mechanisms for $\gamma\gamma \to J/\psi J/\psi$





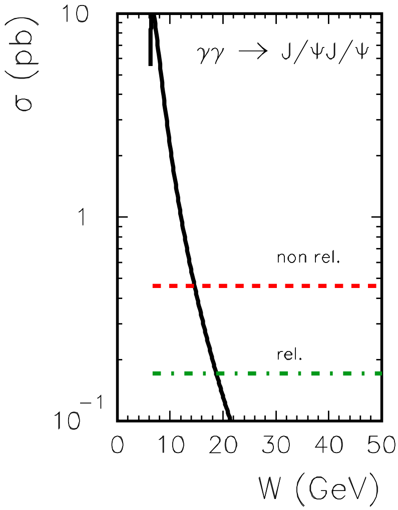
"Box"-diagrams: lowest order in α_S, dominate at low energies.
Fermion-antifermion exchange in crossed channels: die out with energy.



Two-gluon exchange is formally of higher order in α_S, but does not die out with energy.
The $\gamma \to J/\psi$ transition is governed by the same wavefunction as for photoproduction $\gamma p \to J/\psi p$.
First evaluation by Ginzburg, Panfil & Serbo 1988 in the extreme nonrelativistic limit for the $Q\bar{Q}$ bound-state.

Most of the literature concentrates on improvements of the two-gluon exchange mechanism (BFKL-rise of the cross section etc.). But for present day energies, the box mechanisms dominate.

Production mechanisms for $\gamma\gamma \to J/\psi J/\psi$: results

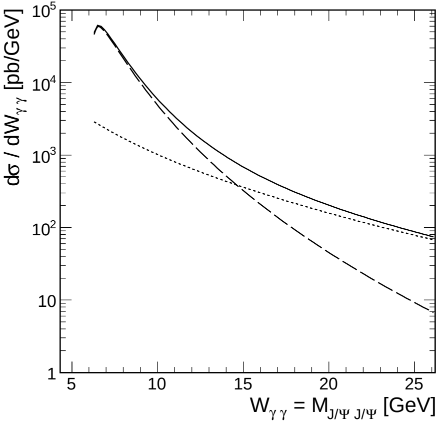


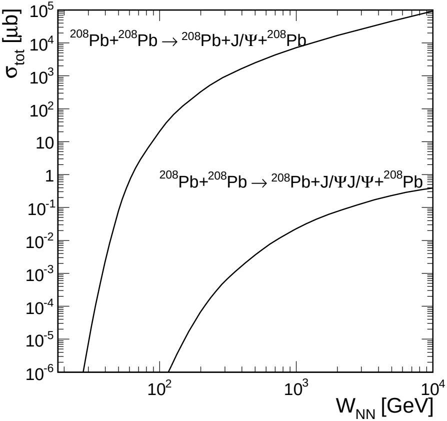
- solid curve: the box-diagram mechanisms
- red dashed: non-relativistic limit:

$$\psi(z, \boldsymbol{k}) = C\,\delta(z - 1/2)\delta^{(2)}(\boldsymbol{k})$$

- dot dashed: Fermi-motion effects included (Gaussian wavefunction).
- inclusion of a gluon mass $\mu_G \sim 0.7$ GeV will introduce another suppression factor ~ 0.45. (see also Gay-Ducati & Sauter (2001))

Results for $AA \to AAJ/\psi J/\psi$





- dashed: box-mechanism; dotted: two-gluon exchange

Summary

- In photoproduction of heavy quarkonia, the large quark mass ensures dominance of small dipoles.
- a sensitive probe of the (unintegrated) gluon distribution of the target.
- "gluon shadowing" is included via the rescattering higher $Q\bar{Q}g$ Fock states.
- heavy nuclei are of special interest in view of the scarcity of probes of the nuclear glue. Here saturation effects are enhanced by the nuclear size.
- J/ψ-pair production in via $\gamma\gamma$ fusion in AA is dominated by the "box-diagram" mechanisms. Multiple interactions of the type $(\gamma \mathbb{P} \to J/\psi) \otimes (\gamma \mathbb{P} \to J/\psi)$ may be important.