Exclusive production of one and two heavy quarkonia in nuclear collisions

Wolfgang Schäfer [1]

[1] Institute of Nuclear Physics, PAN, Kraków

XXI. International Workshop on Deep-Inelastic Scattering and Related Subjects, Marseille, France, 22.-26. April 2013

Outline

1. **Exclusive production of vector mesons in hadron-hadron collisions**

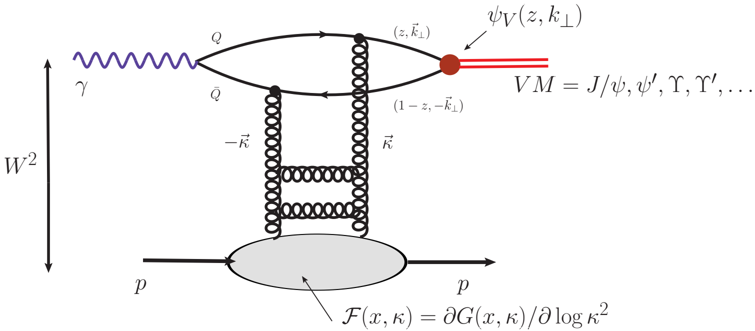
2. **From diffraction on heavy nuclei to $AA \to AAV$**

3. $AA \to AAJ/\psi J/\psi$ **via** $\gamma\gamma \to J/\psi J/\psi$

A. Cisek, W. S. and A. Szczurek, Phys. Rev **C86** (2012) 014905.

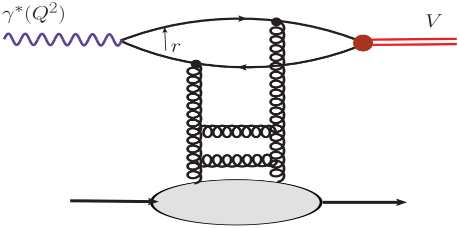
S. Baranov, A. Cisek, M. Kłusek-Gawenda, W.S., A. Szczurek, Eur. Phys. J. C **73** (2013), 2335.

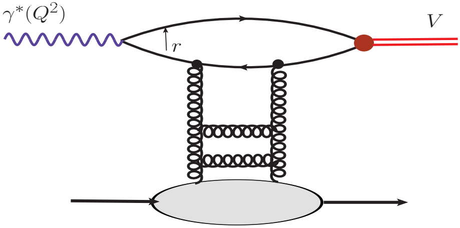
Diffractive Photoproduction $\gamma p \to Vp$



- $J/\psi = c\bar{c}$, $\Upsilon = b\bar{b}$: (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...

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

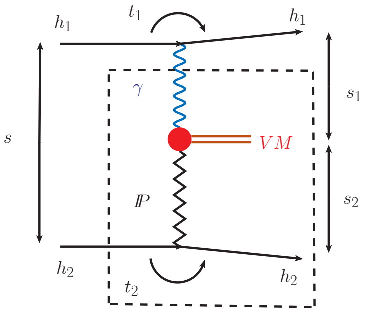
$$A(\gamma^* p \to Vp) \propto r_S^2 \sigma(x, r_S) \propto \frac{1}{Q^2 + M_V^2} \times \frac{1}{Q^2 + M_V^2}\, xg(x, Q^2 + M_V^2)$$

- 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 $\mu^2 = 1 \div 10^2 \mathrm{GeV}^2$.

Exclusive Production of $J/\psi, \Upsilon$ in Hadronic Collisions

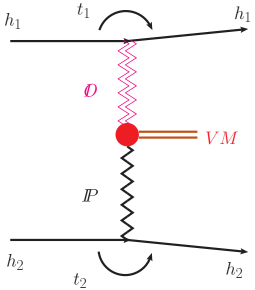
Born Level Amplitudes

Photoproduction



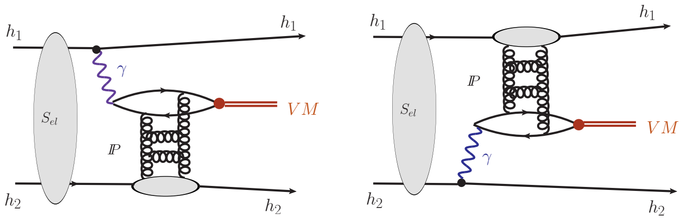
Khoze-Martin-Ryskin '02; Klein & Nystrand '04
cross section $\sim$ nanobarns

Odderon–Pomeron fusion



A. Schäfer, Mankiewicz & Nachtmann '91; Bzdak et al. '07
cross section $\sim$ 0.1÷few nanobarns (??)

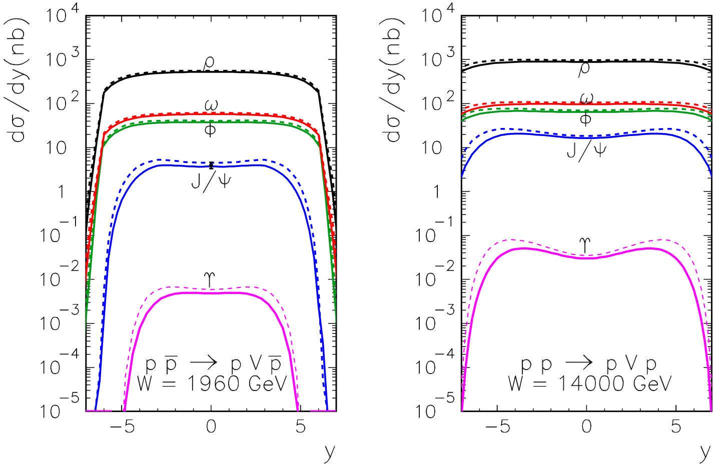
Absorptive Corrections



$$\boldsymbol{M}(\boldsymbol{p}_1, \boldsymbol{p}_2) \quad = \quad \int \frac{d^2\boldsymbol{k}}{(2\pi)^2} \, S_{el}(\boldsymbol{k}) \, \boldsymbol{M}^{(0)}(\boldsymbol{p}_1 - \boldsymbol{k}, \boldsymbol{p}_2 + \boldsymbol{k})$$

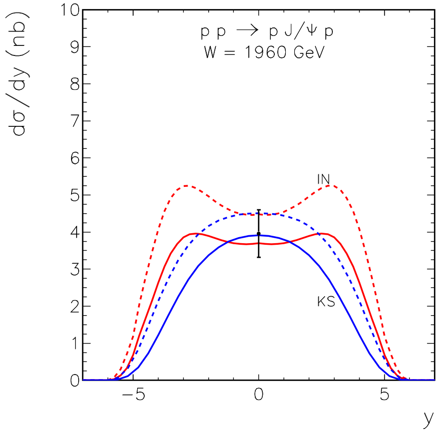
- Absorptive corrections depend on elastic $h_1 h_2$ Amplitude
  $\to$ taken from data.
- photon pole $\to$ peripheral interactions $\to$ Absorption at 20%–level.

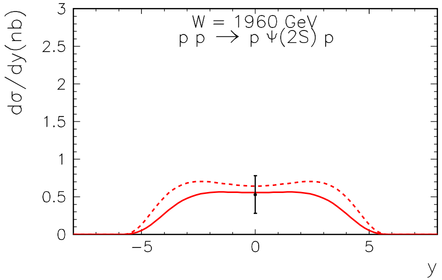
Rapidity spectra at Tevatron/LHC energies:



e.g. Υ at LHC: $y \sim 0$ probes glue at $x \sim 10^{-3} \div 10^{-4}$; $y \sim 5$ probes $x \sim 10^{-5} \div 10^{-6}$.

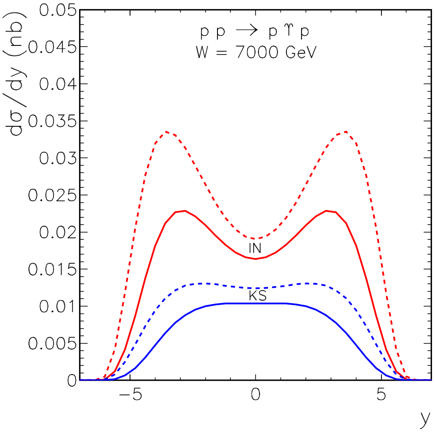
Rapidity spectra - comparison to Tevatron data:





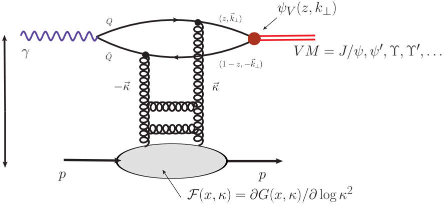
- CDF collaboration, T. Aaltonen et al. Phys. Rev. Lett. 102 (2009)
- in agreement with predictions from WS & A. Szczurek Phys. Rev. D76 (2007).
- calculations by A. Cisek, PhD thesis (2012), for two types of gluon distributions: Ivanov-Nikolaev, without explicit saturation effects, and Kutak- Staśto, with nonlinear

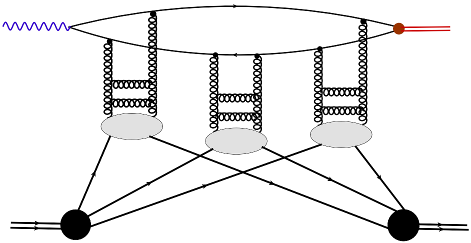
Nonlinear vs linear glue: predictions for rapidity spectra



- $pp \to p\Upsilon p$ at LHC energy.
- calculations by A. Cisek, PhD thesis (2012), for two types of gluon distributions: Ivanov-Nikolaev, without explicit saturation effects, and Kutak- Staśto, with nonlinear evolution.

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 :

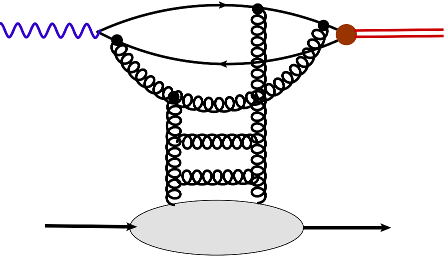
$$f^{(j)}(x_A, \boldsymbol{\kappa}) = \int \Big[\prod^{j} d^2\boldsymbol{\kappa}_i f^{(1)}(x_A, \boldsymbol{\kappa}_i)\Big] \delta^{(2)}(\boldsymbol{\kappa} - \sum \boldsymbol{\kappa}_i)$$

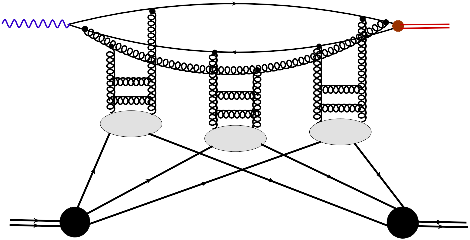
- probab. to find j overlapping nucleons

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

- 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

properties of the nonlinear term:

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

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

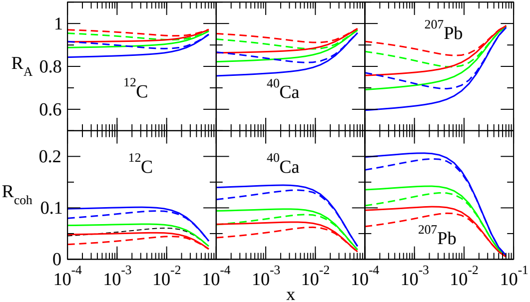
$$= -2K_0 \Big| \int d^2\boldsymbol{\kappa}\, \phi(\boldsymbol{b},x,\boldsymbol{\kappa}) \Big[\frac{\boldsymbol{p}}{\boldsymbol{p}^2+\mu_G^2} - \frac{\boldsymbol{p}+\boldsymbol{\kappa}}{(\boldsymbol{p}+\boldsymbol{\kappa})^2+\mu_G^2} \Big] \Big|^2$$

- 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.

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

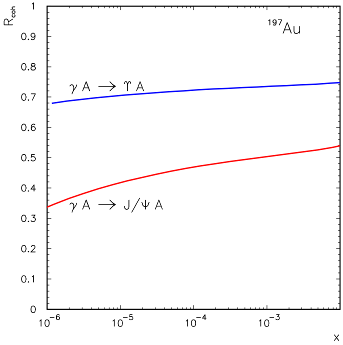
- in that regard it differs from the earlier Mueller-Qiu and Gribov-Levin-Ryskin gluon fusion corrections.

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

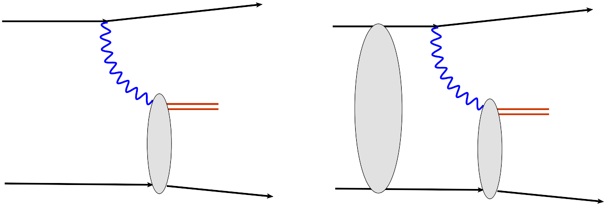
Coherent diffractive production of $J/\Psi, \Upsilon$ on ^{208}Pb



- 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



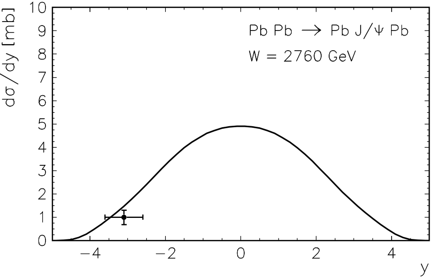
$$\sigma(A_1 A_2 \to A_1 A_2 f; s) = \int d\omega \frac{dN^{\rm eff}_{A_1}(\omega)}{d\omega} \sigma(\gamma A_2 \to f A_2; 2\omega\sqrt{s}) + (1 \leftrightarrow 2)$$

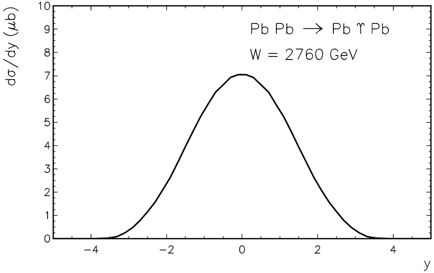
$$dN^{eff} = \int d^2\boldsymbol{b}\, S^2_{el}(\boldsymbol{b}) dN(\omega, \boldsymbol{b})$$

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

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

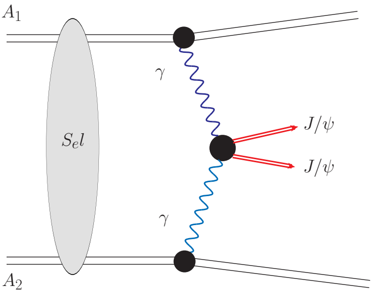
Coherent exclusive production in AA: rapidity distributions





- 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*.
- data point: B. Abelev *et al.* [ALICE Collaboration], Phys. Lett. B **718** (2013) 1273

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



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

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

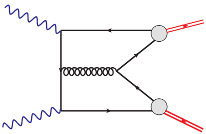
$$s_{\gamma\gamma} \equiv W^2 = x_1 x_2 s = 4\omega_1\omega_2$$

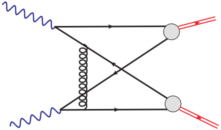
$$\sigma(A_1 A_2 \to A_1 A_2 f; s) = \int d^2\boldsymbol{b}\, S_{el}^2(\boldsymbol{b}) \int \frac{dx_1}{x_1}\frac{dx_2}{x_2}\, n_{\gamma\gamma}(x_1, x_2, \boldsymbol{b})\, \sigma(\gamma\gamma \to f; x_1 x_2 s)$$

- survival probability:

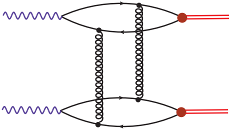
$$S_{el}^2(\boldsymbol{b}) = \exp\Big(-\sigma_{NN} T_{A_1 A_2}(\boldsymbol{b})\Big) \sim \theta(|\boldsymbol{b}| - (R_1 + R_2))$$

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





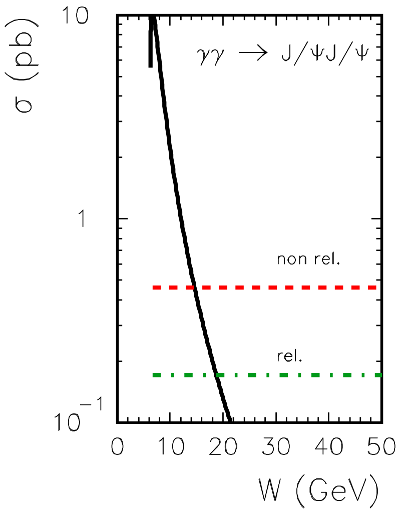
"Box"-diagrams: lowest order in α_S, dominate at low energies.
Fermion-antifermion exchange in crossed channels: die out with energy.



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

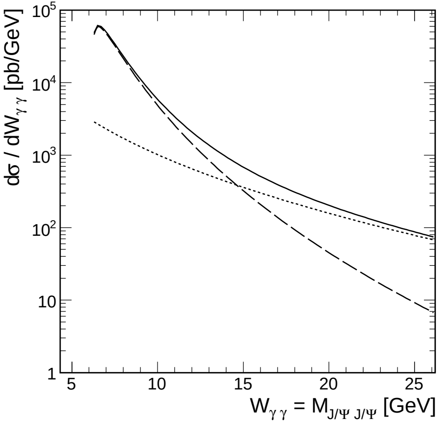


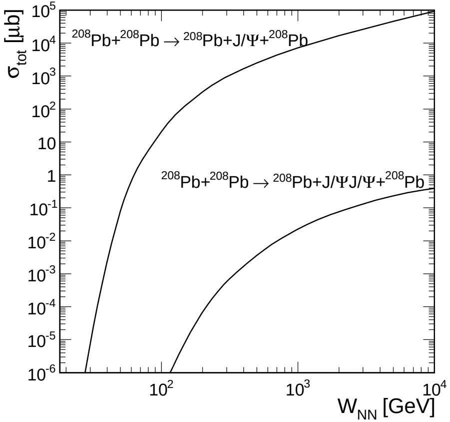
- solid curve: the box-diagram mechanisms
- red dashed: non-relativistic limit:

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

- 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.