Photoproduction of vector mesons: from gamma-proton to nucleus-nucleus collisions

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Outline

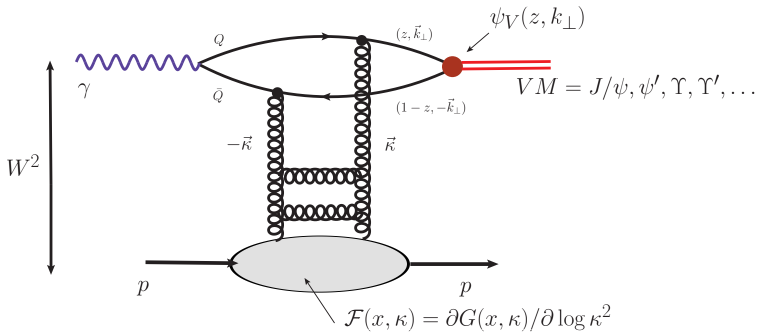
$\gamma p \to Vp$ at high energies

Exclusive production of vector mesons in hadron-hadron collisions

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

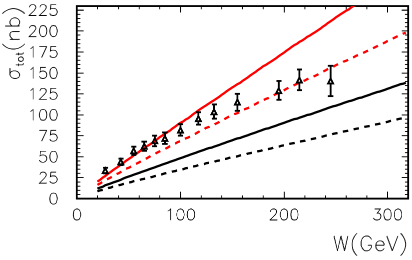
- W.S. & Antoni Szczurek Phys. Rev. D **76**, 094014 (2007).
- A. Rybarska, W.S. and A. Szczurek, Phys. Lett. B **668** (2008) 126.
- A. Cisek, W. S., A. Szczurek, Phys. Lett. **B690** (2010) 168-174.
- A. Cisek, P. Lebiedowicz, W. S., A. Szczurek, Phys. Rev. **D83** (2011) 114004.
- A. Cisek, W. S. and A. Szczurek, Phys. Rev **C86** (2012) 014905.
- S. Baranov, A. Cisek, M. Kłusek-Gawenda, W.S., A. Szczurek, arXiv:1208.5917.

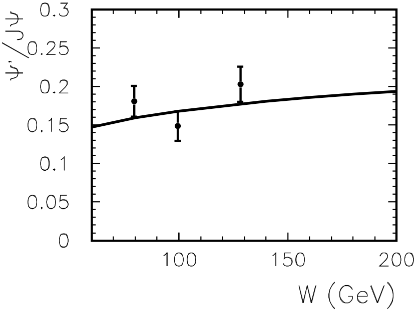
Diffractive Photoproduction $\gamma p \to Vp$



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

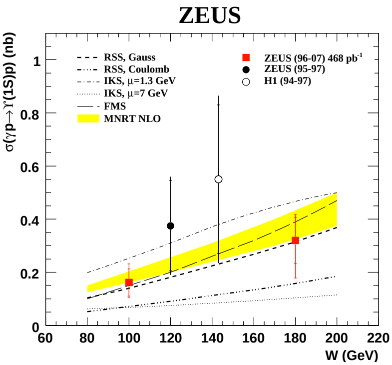
$\gamma p \longrightarrow J/\psi p, \Upsilon p$ and $\psi(2S)/J/\psi$ vs ZEUS data





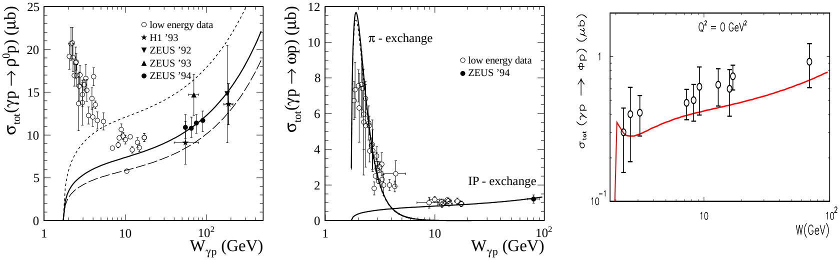
- dependence on wave function: **red:** Gaussian WF, **black**: Coulomb-type WF.
- dependence on LO/NLO treatment of decay width: dashed - LO width; solid - NLO width.
- suppression of the $\psi(2S)/J/\psi$ is a meson structure effect – the "node effect" Nemchik, Nikolaev et al. '94.
- calculation: A.Cisek,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

Light vector mesons: $\gamma p \longrightarrow \rho p, \omega p, \phi p$

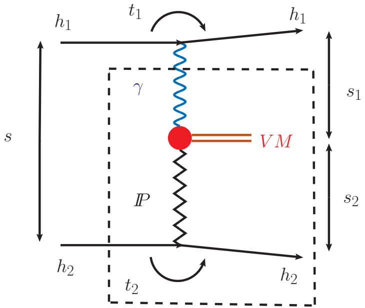


- with few free parameters– valence quark masses $m_{u,d}, m_s$ an extension into the soft regime is possible.
- A. Cisek, P. Lebiedowicz, WS, A. Szczurek Phys. Rev. D83 (2011);
  A. Cisek, WS, A. Szczurek Phys. Lett. B690(2010) .

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

Born Level Amplitudes

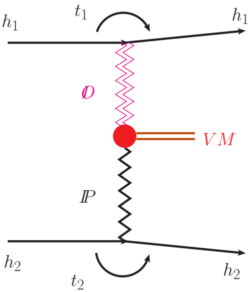
Photoproduction



Khoze-Martin-Ryskin '02; Klein & Nystrand '04

cross section ∼ nanobarns

Odderon–Pomeron fusion

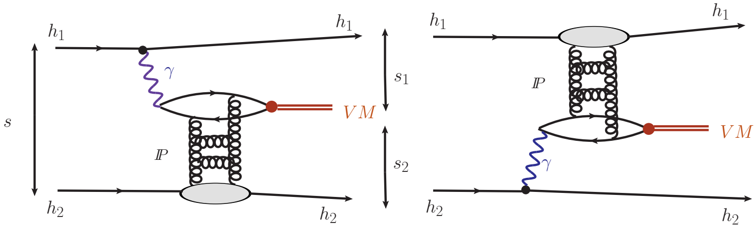


A. Schäfer, Mankiewicz & Nachtmann '91; Bzdak et al. '07

cross section ∼ 0.1÷few nanobarns (??)

Exclusive Photoproduction in Hadronic Collisions

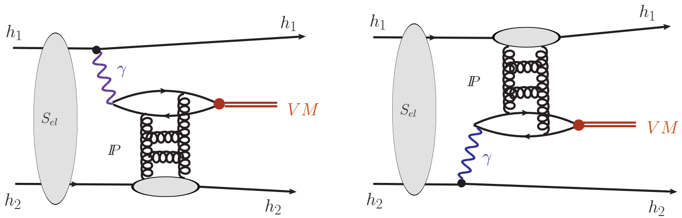
Born Level Amplitude



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

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

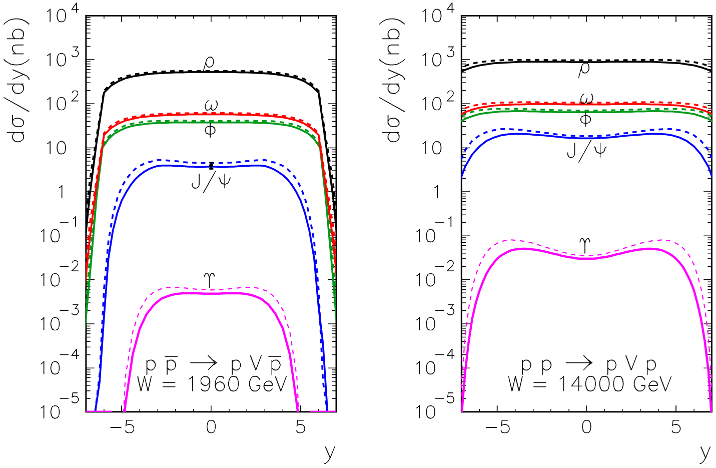
Absorptive Corrections



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

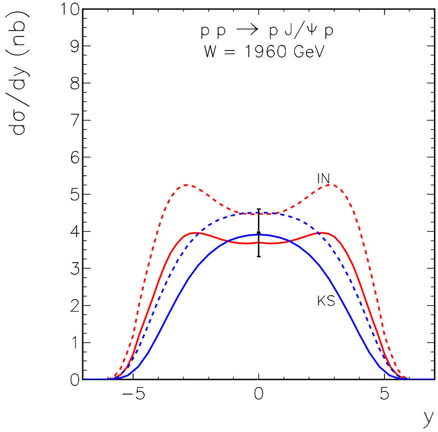
- Absorptive corrections depend on elastic $h_1 h_2$ Amplitude
  $\rightarrow$ taken from data.
- photon pole $\rightarrow$ peripheral interactions $\rightarrow$ Absorption at 20%–level.

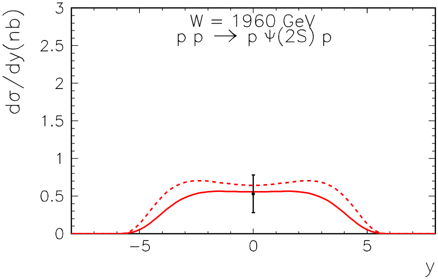
Rapidity spectra at Tevatron/LHC energies:



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

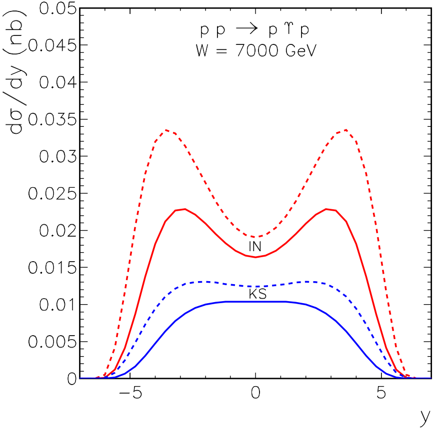
Rapidity spectra - comparison to Tevatron data:





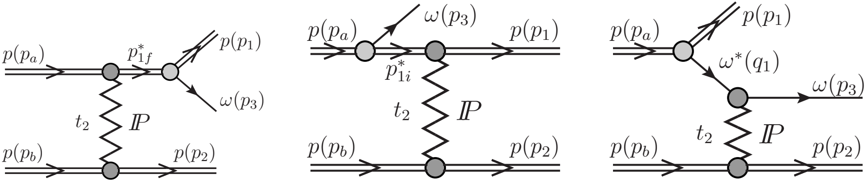
- CDF collaboration, T. Aaltonen et al. Phys. Rev. Lett. 102 (2009)
- in agreement with predictions from WS & A. Szczurek Phys. Rev. D76 (2007).
- calculations by A. Cisek, PhD thesis (2012), for two types of gluon distributions: Ivanov-Nikolaev, without explicit saturation effects, and Kutak- Staśto, with nonlinear evolution.
- dashed: no absorption, solid: with absorption.

Nonlinear vs linear glue: predictions for rapidity spectra



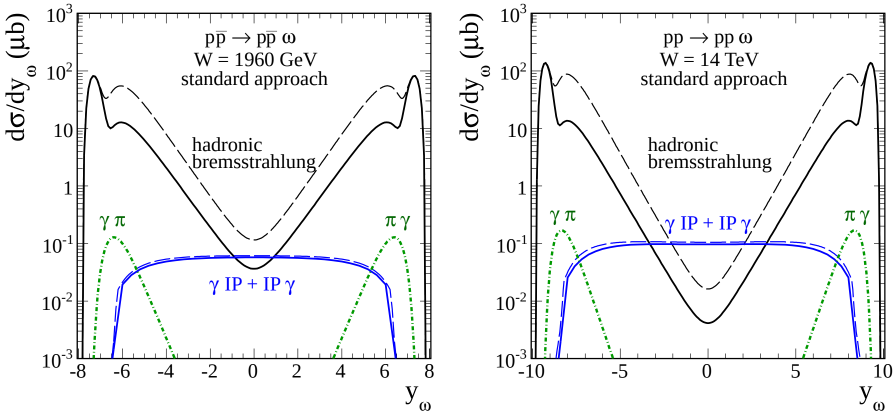
- $pp \to p\Upsilon p$ at LHC energy.
- calculations by A. Cisek, PhD thesis (2012), for two types of gluon distributions: Ivanov-Nikolaev, without explicit saturation effects, and Kutak- Staśto, with nonlinear evolution.
- dashed: no absorption, solid: with absorption.

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



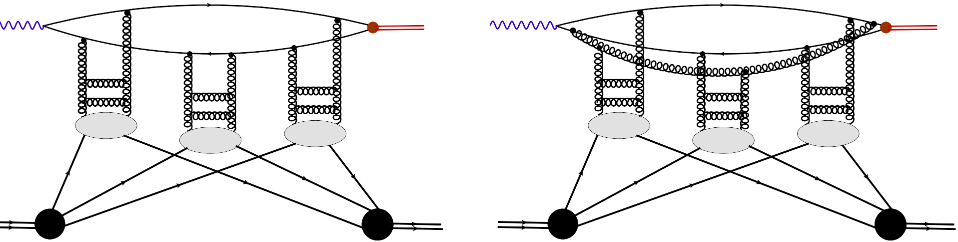
- "Bremsstrahlung"-type mechanism contributes in proton fragmentation regions
- t-channel exchange becomes reggeized
- subleading Regge pole, but **large** ωNN coupling, $g^2_{\omega NN}/4\pi \sim 10$.

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



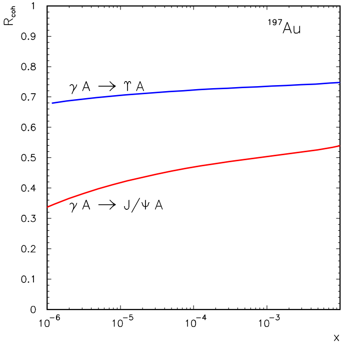
- dashed: without absorption, solid: with absorption
- need to go to very large energies to "dig out" photoproduction.
- A. Cisek, P. Lebiedowicz, WS, A. Szczurek Phys. Rev. D83 (2011)

VM photoproduction from nucleon to nucleus:



- large quark mass provides a hard scale for production of $J/\Psi, \Upsilon$
- for heavy nuclei rescattering/absorption effects are enhanced by the large nuclear size
- evaluate rescattering of $Q\bar{Q}$ and $Q\bar{Q}g$-Fock states by Glauber-Gribov theory in terms of free nucleon glue. (Nikolaev, WS, Schwiete, 2000).
- inclusion of the $Q\bar{Q}g$ term corresponds to the rednonlinear Balitsky-Kovchegov evolution of the nuclear glue.

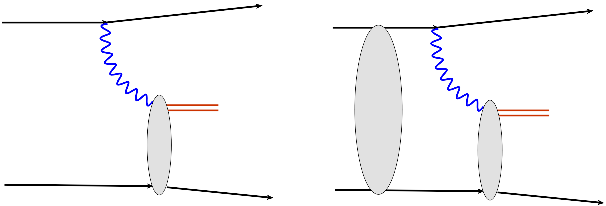
Coherent diffractive production of $J/\Psi, \Upsilon$ on ^{208}Pb



- A. Cisek, WS, A. Szczurek arXiv:1204.5381 [hep-ph].
- 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



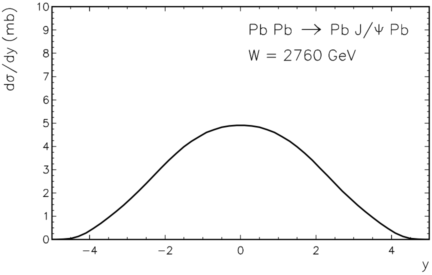
$$\sigma(A_1 A_2 \to A_1 A_2 f; s) = \int d\omega \frac{dN^{\rm eff}_{A_1}(\omega)}{d\omega} \sigma(\gamma A_2 \to f A_2; 2\omega\sqrt{s}) + (1 \leftrightarrow 2)$$

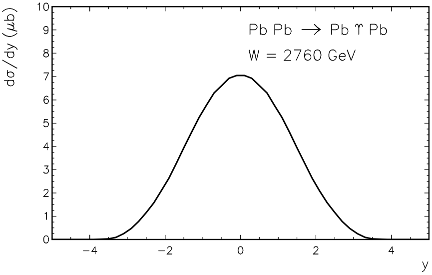
$$dN^{eff} = \int d^2\boldsymbol{b}\, S^2_{el}(\boldsymbol{b}) dN(\omega, \boldsymbol{b})$$

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

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

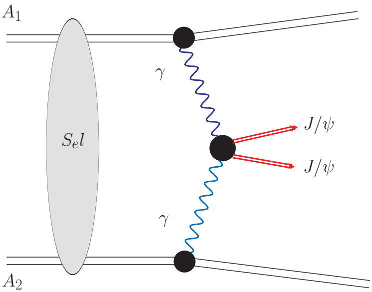
Coherent exclusive production in AA: rapidity distributions





- 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 → different rapidity shape than in *pp*.

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



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

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

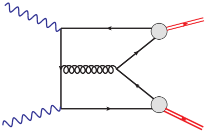
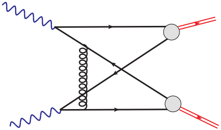
$$s_{\gamma\gamma} \equiv W^2 = x_1 x_2 s = 4\omega_1\omega_2$$

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

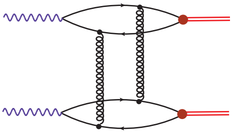
- survival probability:

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

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

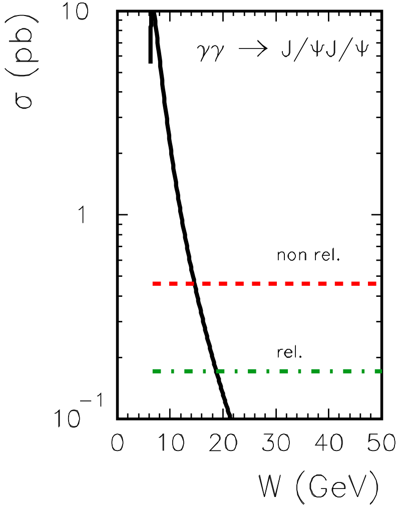
"Box"-diagrams: lowest order in α_S, dominate at low energies.
Fermion-antifermion exchange in crossed channels: die out with energy.



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

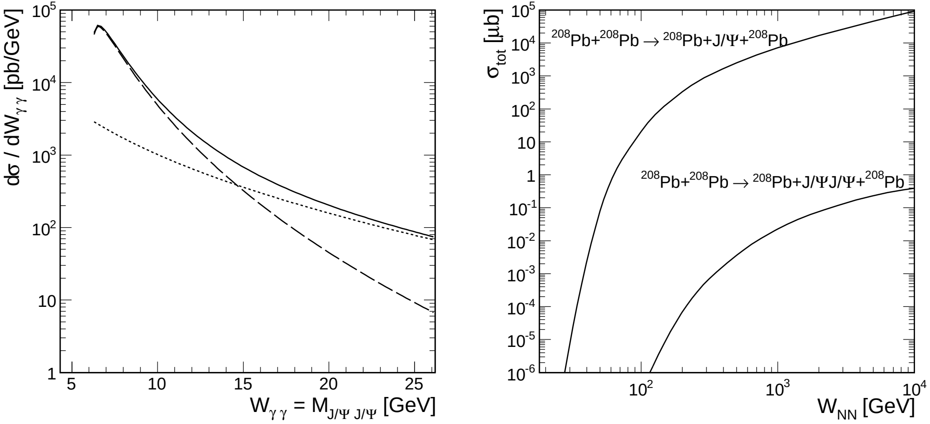


- solid curve: the box-diagram mechanisms
- red dashed: non-relativistic limit:

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

- 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.
- Cross sections for exclusive photoproduction of Quarkonia at colliders are of measurable size. Theory works at Tevatron energies.
- Exclusive VM's didn't help to discover the Odderon yet. Perhaps transverse-momentum distributions?
- At the LHC, a reach in energy beyond the HERA-domain possible.
  $\rightarrow$ Study the very small-x gluon distribution.
- 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 $(\gamma \mathbb{P} \rightarrow J/\psi) \otimes (\gamma \mathbb{P} \rightarrow J/\psi)$ may be important.