Diffractive production of heavy vector mesons in pp and AA collisions

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Exclusive and Diffractive Processes at High Energy Proton-proton and Nucleus-nucleus Collisions
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Outline

Diffractive photoproduction of vector mesons

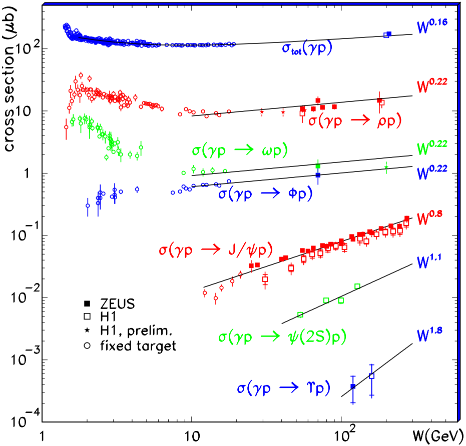
Central Exclusive Production at Colliders (Tevatron/LHC)

Photoproduction on nuclei

Summary and outlook

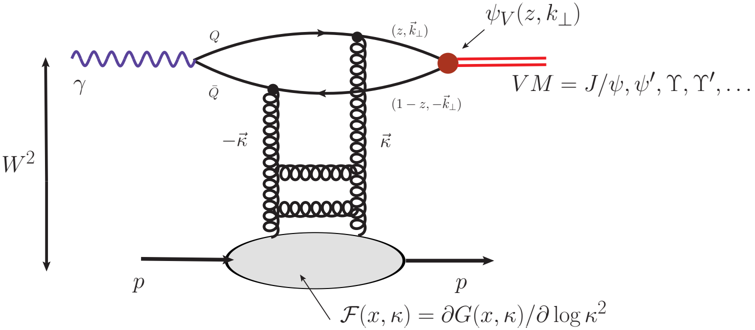
- W.S. & Antoni Szczurek Phys. Rev. D **76**, 094014 (2007).
- A. Rybarska, W.S. and A. Szczurek, Phys. Lett. B **668** (2008) 126.
- A. Cisek, W.S. and A. Szczurek, Phys. Rev. D **80** (2009) 074013.
- A. Cisek, W. S., A. Szczurek, Phys. Lett. **B690** (2010) 168-174. [arXiv:1004.0070 [hep-ph]].
- A. Cisek, P. .Lebiedowicz, W. S., A. Szczurek, Phys. Rev. **D83** (2011) 114004. [arXiv:1101.4874 [hep-ph]].

Total exclusive photoproduction cross sections



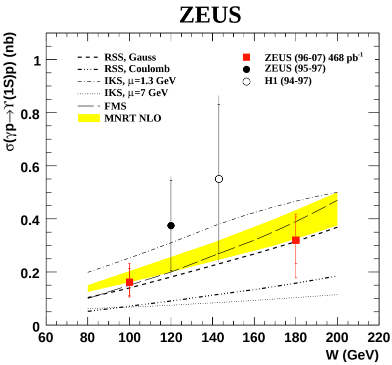
- VM photoproduction from light to heavy mesons
- the QCD Pomeron from soft to hard

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.

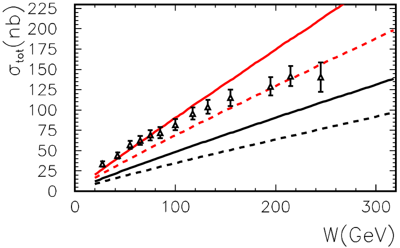
Total cross section for $\gamma p \longrightarrow \Upsilon p$



- FMS - Frankfurt, McDermott, Strikman (CTEQ4L)
- IKS - Ivanov, Krasnikov, Szymanowski
- MNRT NLO - Martin, Nockles, Ryskin, Teubner
- RSS - Rybarska, Schäfer, Szczurek

- experimental data $\rightarrow$ ZEUS Collaboration, Phys.Lett.B680:4-12 (2009)
- unintegrated glue from Ivanov & Nikolaev (2002).

$\gamma p \longrightarrow J/\Psi p$ vs ZEUS data



$\Psi_V -$ Gauss, $K_{NLO} \neq 1$

$\Psi_V -$ Gauss, $K_{NLO} = 1$

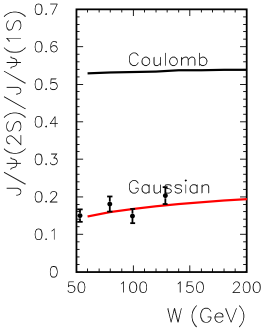
$\Psi_V -$ Coulomb, $K_{NLO} \neq 1$

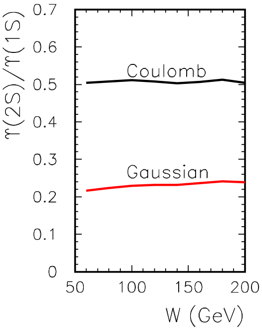
$\Psi_V -$ Coulomb, $K_{NLO} = 1$

- dependence on wave function and LO/NLO treatment of decay width

Radial excitations

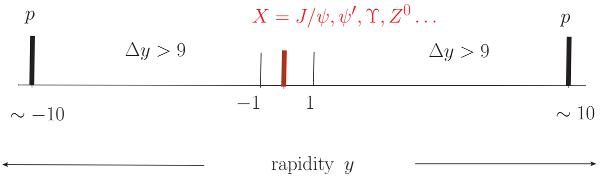
$$\sigma(\gamma p \to V(2S)p)/\sigma(\gamma p \to V(1S)p):$$

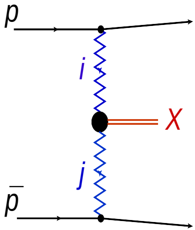




- strong dependence on the wave function
- data → H1 Collaboration, published in Phys.Lett.B541:251-264 (2002)

Central Exclusive Production



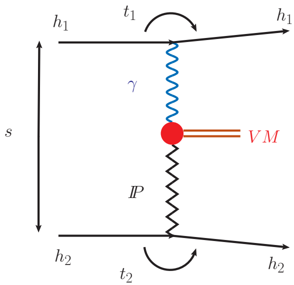


- central exclusive production $\equiv$ very clean events.
- large rapidity gaps $\rightarrow$ strong constraints on t–channel exchanges:
  - charge $= 0$, color singlet
  - spin $J \geq 1$: photon,Pomeron,Odderon(?). $C_i \cdot C_j = C_X$

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

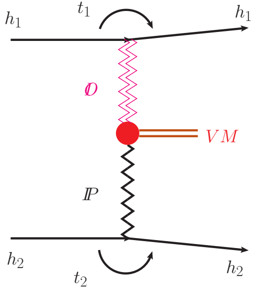
Born Level Amplitudes

Photoproduction



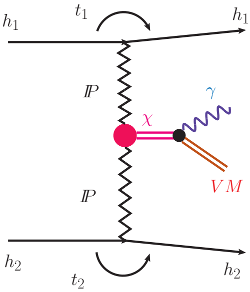
Khoze-Martin-Ryskin '02; Klein & Nystrand '04
cross section $\sim$ nanobarns

Odderon–Pomeron fusion



A. Schäfer, Mankiewicz & Nachtmann '91
cross section $\sim$ 0.1$\div$few nanobarns (??)

Radiative Decay of χ

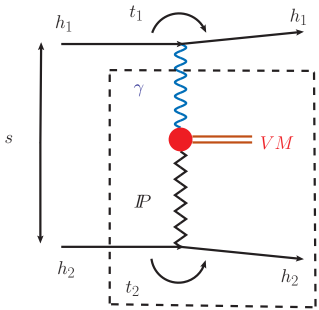


e.g. Szczurek, Pasechnik & Teryaev '07 find $<$ 1 nb.

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

Born Level Amplitudes

Photoproduction



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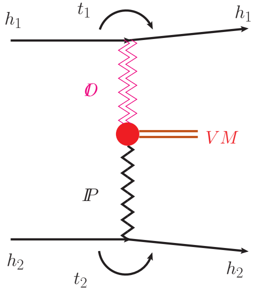
Odderon–Pomeron fusion



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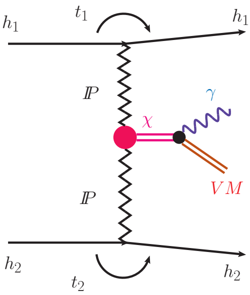
Radiative Decay of χ



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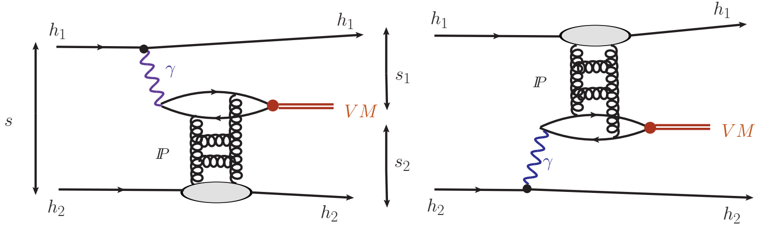
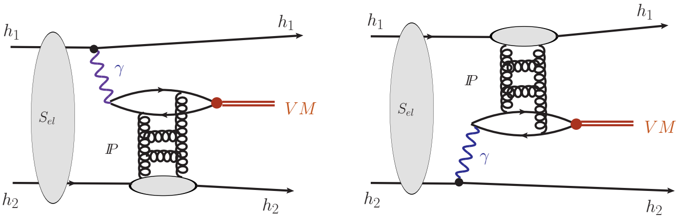


$$\begin{aligned} \boldsymbol{M}(\boldsymbol{p}_1, \boldsymbol{p}_2) &= e_1 \frac{2}{z_1} \frac{\boldsymbol{p}_1}{t_1} \mathcal{F}_{\lambda_1' \lambda_1}(\boldsymbol{p}_1, t_1) \mathcal{M}_{\gamma^* h_2 \to V h_2}(s_2, t_2, Q_1^2) \\ &+ e_2 \frac{2}{z_2} \frac{\boldsymbol{p}_2}{t_2} \mathcal{F}_{\lambda_2'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

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

Absorptive Corrections

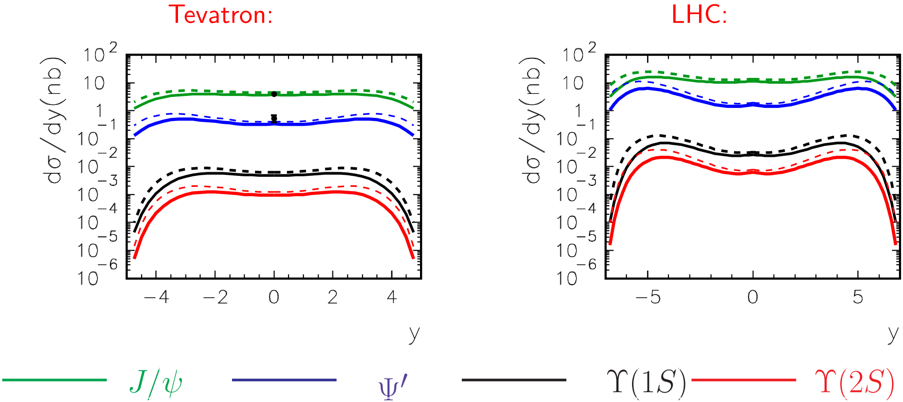


$$\boldsymbol{M}(\boldsymbol{p}_1, \boldsymbol{p}_2) = \int \frac{d^2\boldsymbol{k}}{(2\pi)^2} S_{el}(\boldsymbol{k})\, \boldsymbol{M}^{(0)}(\boldsymbol{p}_1 - \boldsymbol{k}, \boldsymbol{p}_2 + \boldsymbol{k})$$

- 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 distribution

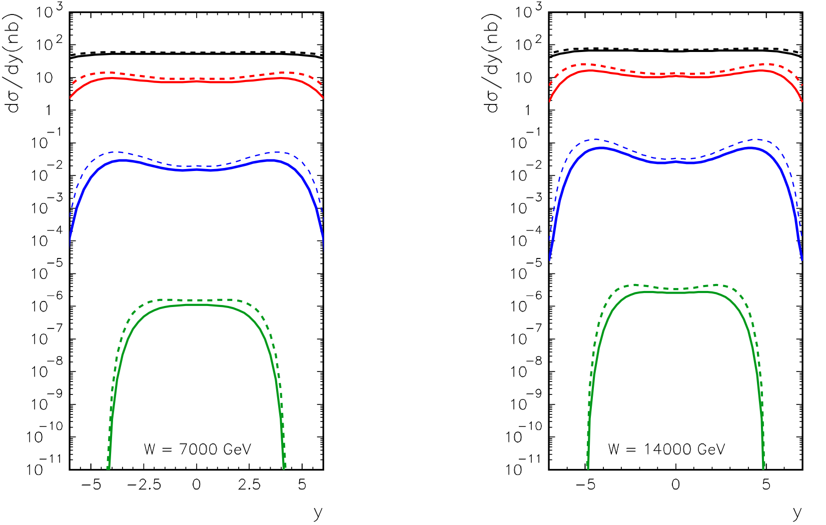
vs. data from CDF/Tevatron (2008)
dashed: no Absorption, solid: with Absorption



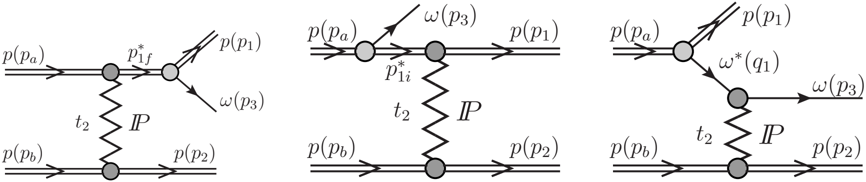
e.g. Υ at LHC ($\sqrt{s} = 14$ TeV):

- $y \sim 0$ probes the glue at $x \sim 10^{-3} \div 10^{-4}$ $\sim$ HERA
- $y \sim 5$ probes the glue at $x \sim 10^{-5} \div 10^{-6}$

Rapidity distributions at LHC energies

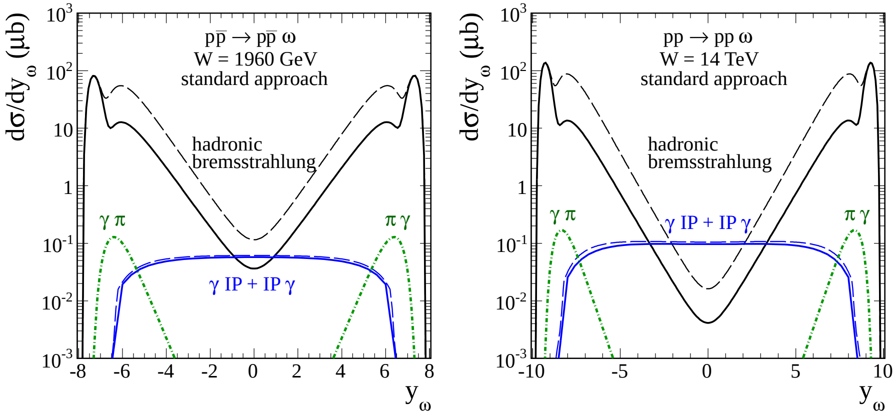


A soft process: $pp \to pp\omega$



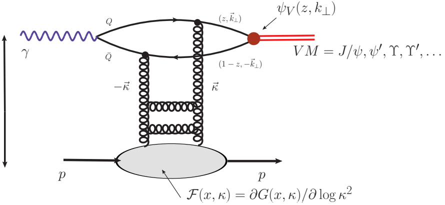
- "bremsstrahlung"-type mechanism contributes in proton fragmentation regions
- t-channel exchange becomes reggeized
- subleading Regge pole, but **large** ωNN coupling

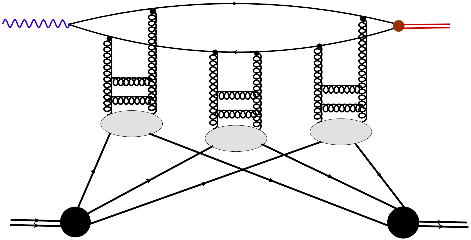
A soft process: $pp \to pp\omega$



- dashed: without absorption, solid: with absorption
- need to go to very large energies to "dig out" photoproduction.

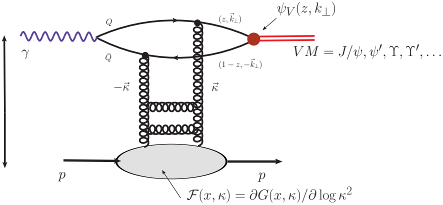
VM photoproduction from nucleon to nucleus:

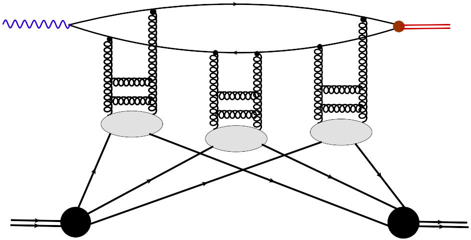




- large quark mass provides a hard scale for production of $J/\Psi, \Upsilon$
- for heavy nuclei rascattering/absorption effects are enhanced by the large nuclear size
- the final state might as well be a (virtual) photon (total photoabsorption cross section) or a $q\bar{q}$-pair (inclusive low-mass diffraction).

VM photoproduction from nucleon to nucleus:





Color dipole representation of forward amplitude:

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

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

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 :

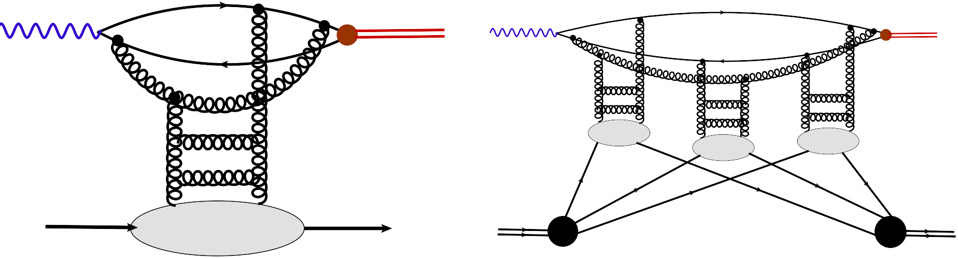
$$f^{(j)}(x_A, \boldsymbol{\kappa}) = \int \Big[\prod^{j} d^2\boldsymbol{\kappa}_i f^{(1)}(x_A, \boldsymbol{\kappa}_i)\Big] \delta^{(2)}(\boldsymbol{\kappa} - \sum \boldsymbol{\kappa}_i)$$

- 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

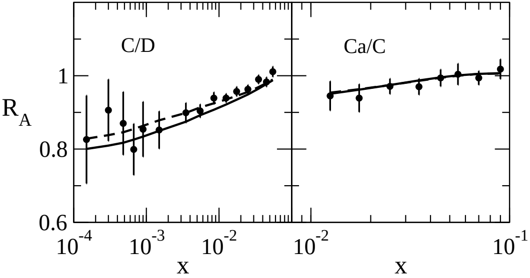


- the effect of higher $q\bar{q}g$-Fock-states is absorbed into the $x-$-dependent dipole-nucleus interaction Nikolaev, Zakharov, Zoller / Mueller '94
- evolution of unintegrated glue Balitsky – Kovchegov '96 –' 98:

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

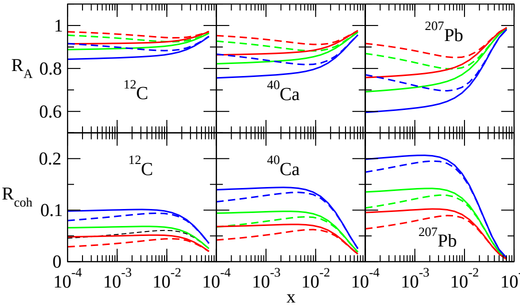
- corresponds to taking the contribution to shadowing from high–mass diffraction into account

Shad



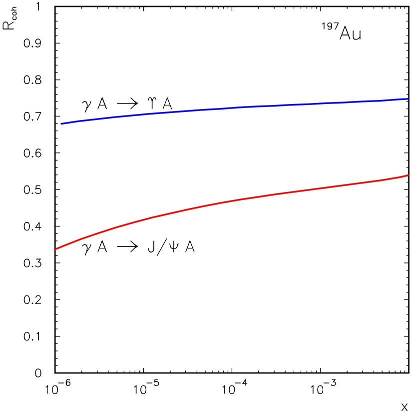
- $R_A = \frac{A_2 \sigma(\gamma^* A_1)}{A_1 \sigma(\gamma^* A_2)}$
- data from NMC Collab. ('95)
- x and Q^2 are correlated
- calculation from Nikolaev, WS, Zoller & Zakharov '07
- dashed $= q\bar{q}$, solid $= q\bar{q} + q\bar{q}g$ contributions

Predicti



- 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

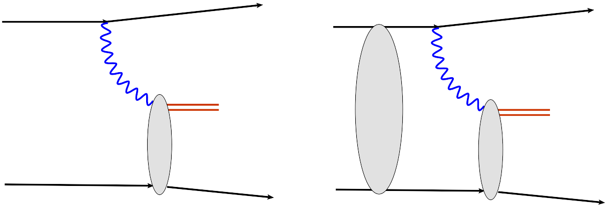
Coherent diffractive production of $J/\Psi, \Upsilon$ on ^{208}Pb



- 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



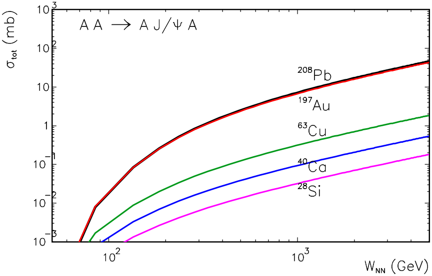
$$\sigma(A_1 A_2 \to A_1 A_2 f; s) = \int d\omega \frac{dN^{\rm eff}_{A_1}(\omega)}{d\omega} \sigma(\gamma A_2 \to f A_2; 2\omega\sqrt{s}) + (1 \leftrightarrow 2)$$

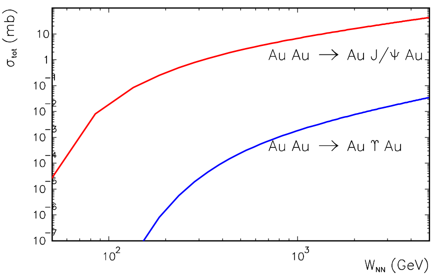
$$dN^{eff} = \int d^2\boldsymbol{b}\, S^2_{el}(\boldsymbol{b}) dN(\omega, \boldsymbol{b})$$

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

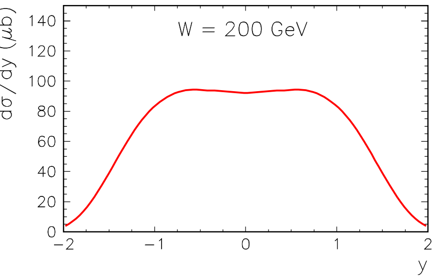
$$S^2_{el}(\boldsymbol{b}) = \exp\Big(-\sigma_{NN} T_{A_1 A_2}(\boldsymbol{b})\Big) \sim \theta(|\boldsymbol{b}| - (R_1 + R_2))$$

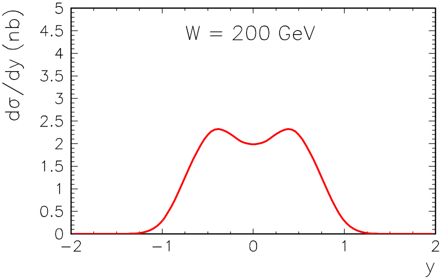
Coherent exclusive production in AA: total cross sections





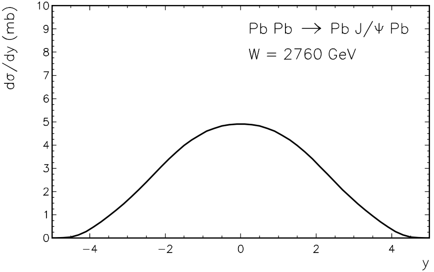
Coherent exclusive production in AA: rapidity distributions

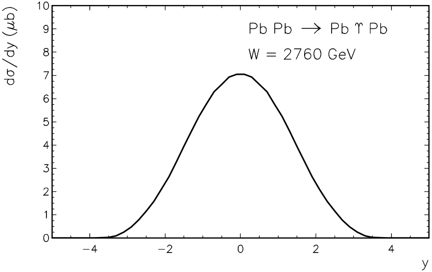




- left column: J/Ψ, right column:Υ

Coherent exclusive production in AA: rapidity distributions





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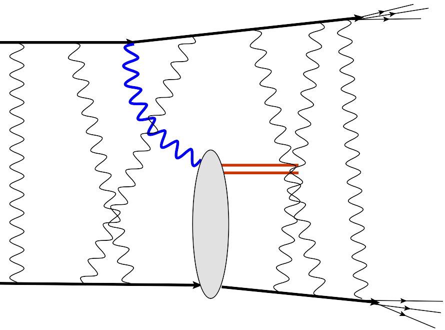
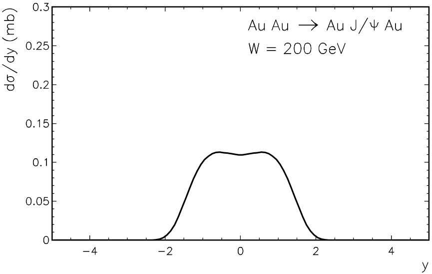
Few-neutron topological cross sections





$$d\sigma(AA \to V(Xn)(Yn)) = \int d^2\boldsymbol{b}\, d\sigma(AA \to VAA; \boldsymbol{b}) \times P(AA \to (Xn)(Yn); \boldsymbol{b})$$

- for the integrated case Klein and Nystrand estimate a suppresion of 0.55
- exp. result: PHENIX Collab. (2009):

$$\frac{d\sigma(AuAu \to J/\Psi Xn)}{dy}(y = 0) = 76 \pm 33 \pm 11\ \mu b$$

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.
- 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.