

Exclusive production of vector mesons from pp to AA collisions

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Outline

Diffractive photoproduction of vector mesons

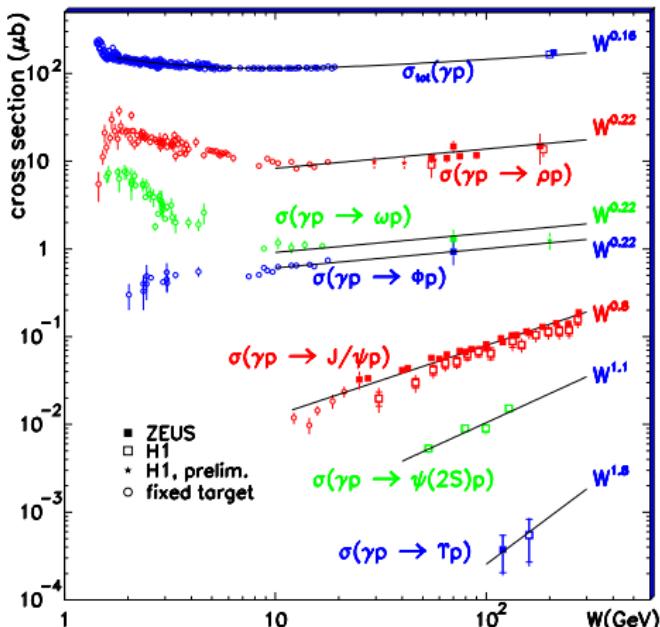
Central Exclusive Production at Colliders (Tevatron/LHC)

Photoproduction on nuclei

Summary and outlook

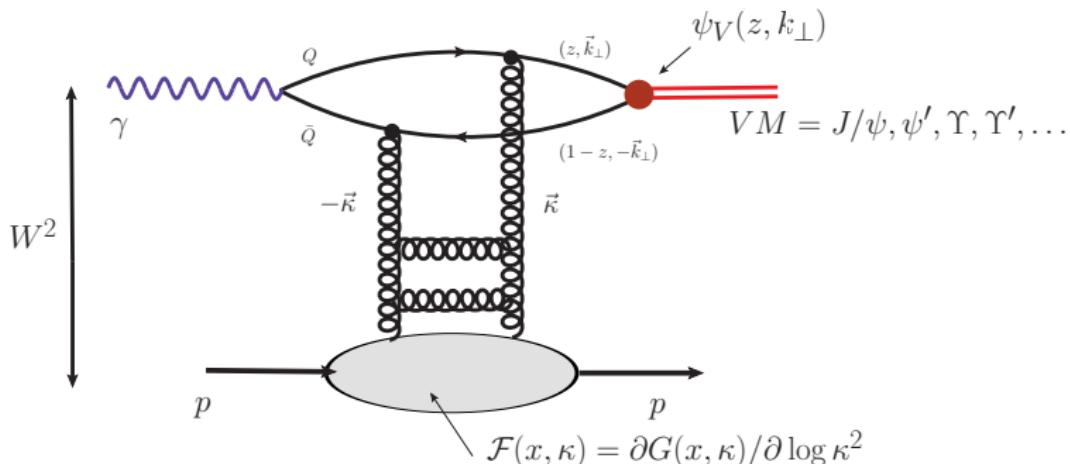
-  W.S. & Antoni Szczurek Phys. Rev. D **76**, 094014 (2007).
-  A. Rybarska, W.S. and A. Szczurek, Phys. Lett. B **668** (2008) 126.
-  A. Cisek, W.S. and A. Szczurek, Phys. Rev. D **80** (2009) 074013.
-  A. Cisek, W. S., A. Szczurek, Phys. Lett. **B690** (2010) 168-174.
[arXiv:1004.0070 [hep-ph]].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

Total exclusive photoproduction cross sections



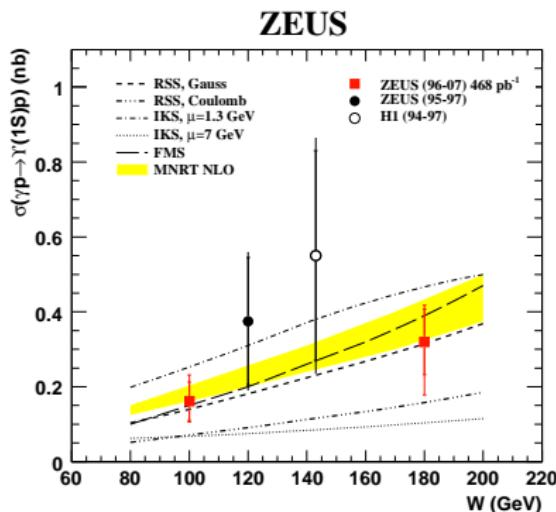
- VM photoproduction from light to heavy mesons
- the QCD Pomeron from soft to hard

Diffractive Photoproduction $\gamma p \rightarrow Vp$



- $J/\psi = c\bar{c}$, $\Upsilon = b\bar{b}$: (almost) nonrelativistic bound states of heavy quarks.
Wavefunctions constrained by their leptonic decay widths.
- Large quark mass \rightarrow **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.

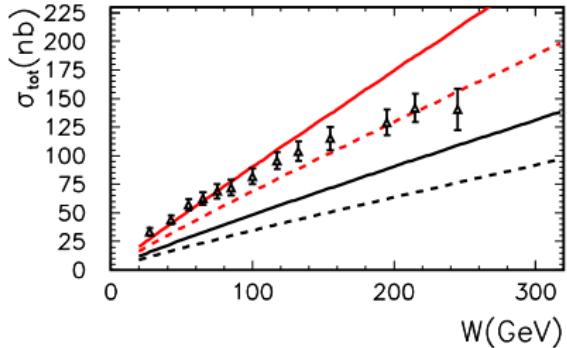
Total cross section for $\gamma p \rightarrow \gamma p$



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

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

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

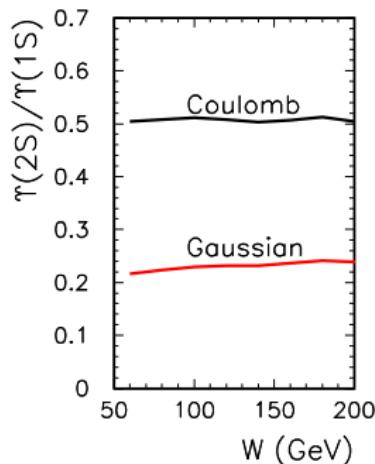
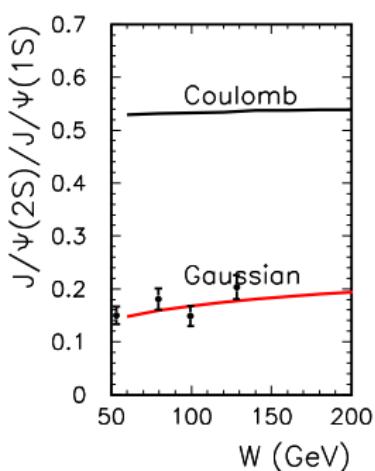


- $\Psi_V - \text{Gauss}, K_{NLO} \neq 1$
- - $\Psi_V - \text{Gauss}, K_{NLO} = 1$
- $\Psi_V - \text{Coulomb}, K_{NLO} \neq 1$
- - $\Psi_V - \text{Coulomb}, K_{NLO} = 1$

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

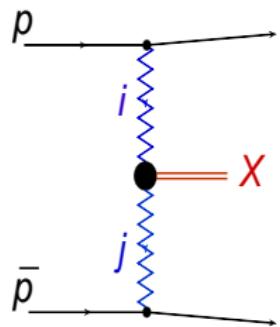
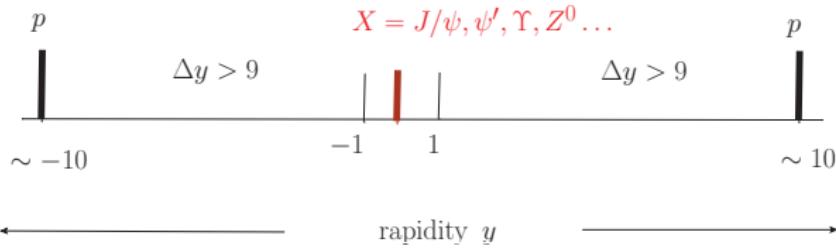
Radial excitations

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



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

Central Exclusive Production

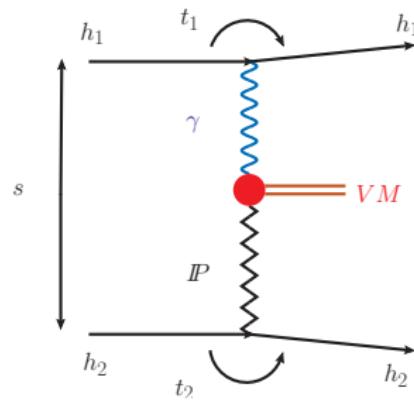


- central exclusive production \equiv very clean events.
- large rapidity gaps \rightarrow strong constraints on t -channel exchanges:
 - charge = 0, color singlet
 - spin $J \geq 1$: photon, Pomeron, Odderon(?). $C_i \cdot C_j = C_X$

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

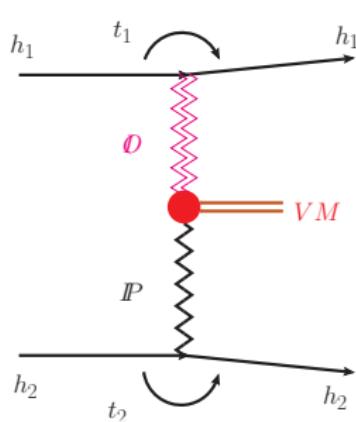
Born Level Amplitudes

Photoproduction



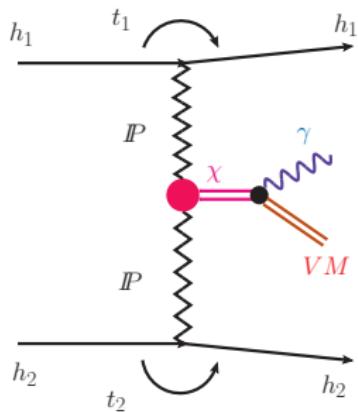
Khoze-Martin-Ryskin '02; Klein & Nystrand '04
cross section \sim nanobarns

Odderon–Pomeron fusion



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

Radiative Decay of χ

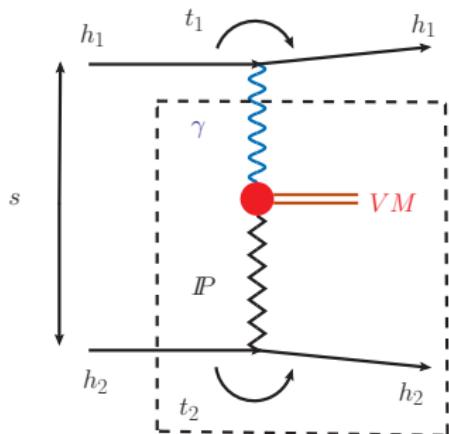


e.g. Szczurek, Pasechnik & Teryaev '07 find
 < 1 nb.

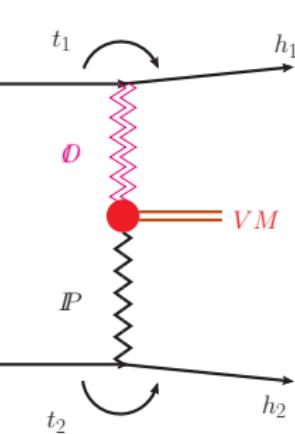
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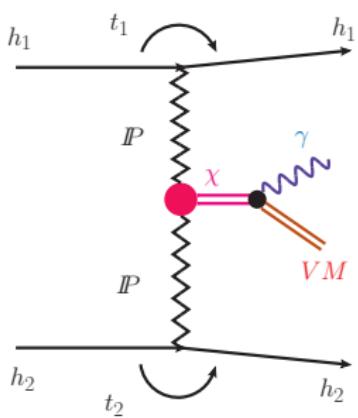
Photoproduction



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Radiative Decay of χ



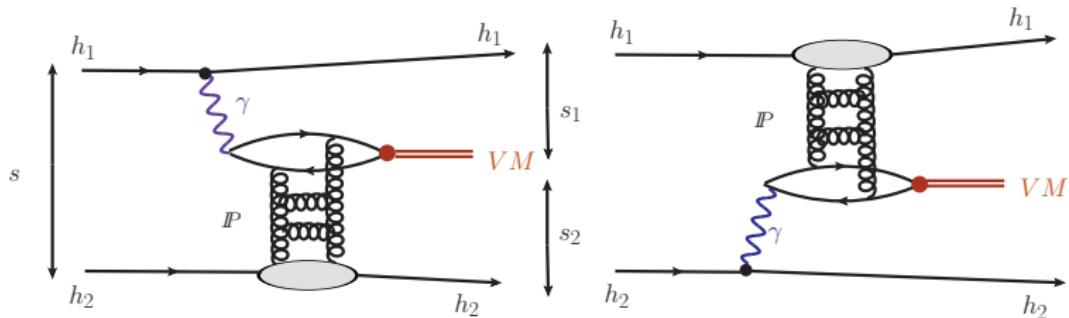
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Exclusive Photoproduction in Hadronic Collisions

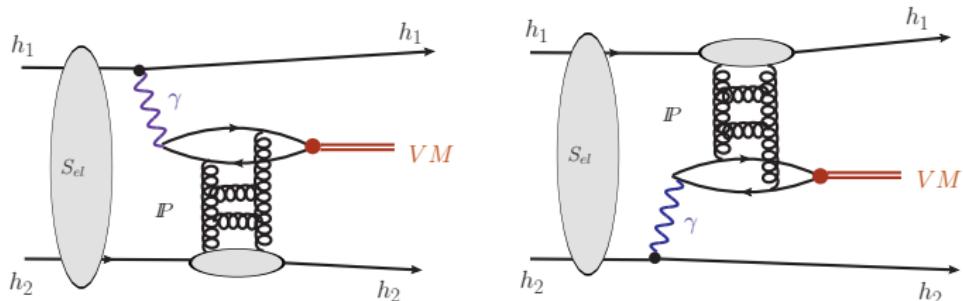
Born Level Amplitude



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

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

Absorptive Corrections



$$M(p_1, p_2) = \int \frac{d^2 k}{(2\pi)^2} S_{el}(k) M^{(0)}(p_1 - k, p_2 + k)$$

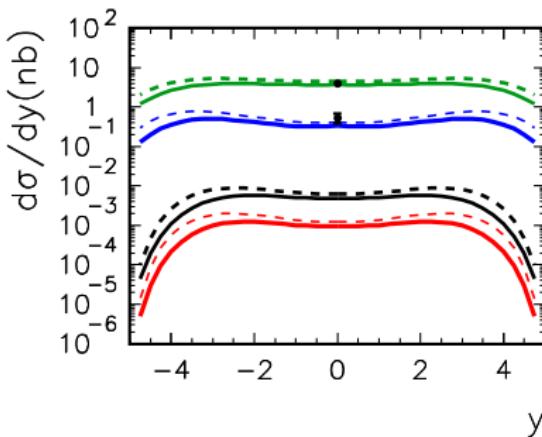
- Absorptive corrections depend on elastic $h_1 h_2$ Amplitude
→ taken from data.
- photon pole → peripheral interactions → Absorption at 20%-level.

Rapidity distribution

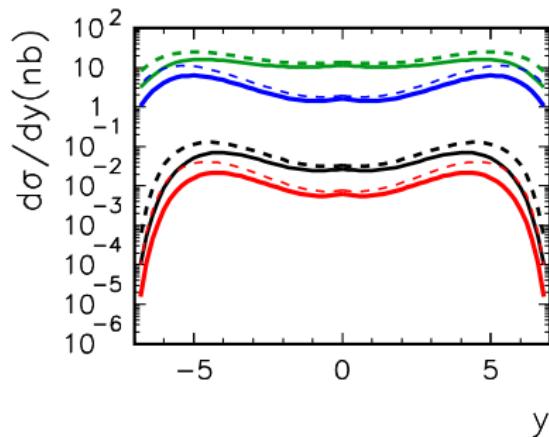
vs. data from CDF/Tevatron (2008)

dashed: no Absorption, solid: with Absorption

Tevatron:



LHC:



J/ψ

Ψ'

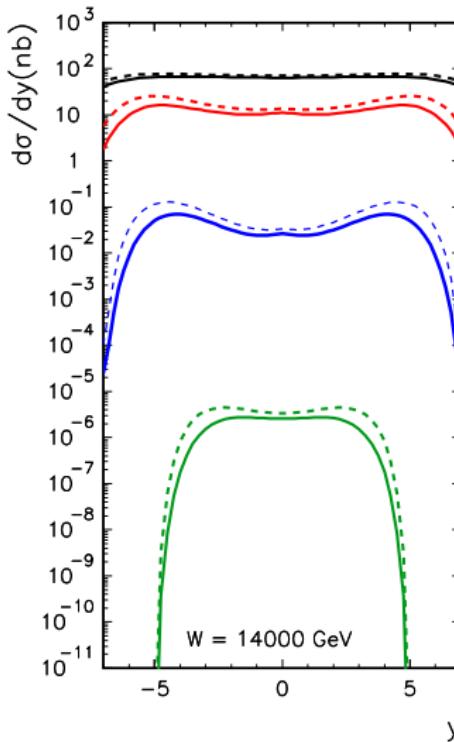
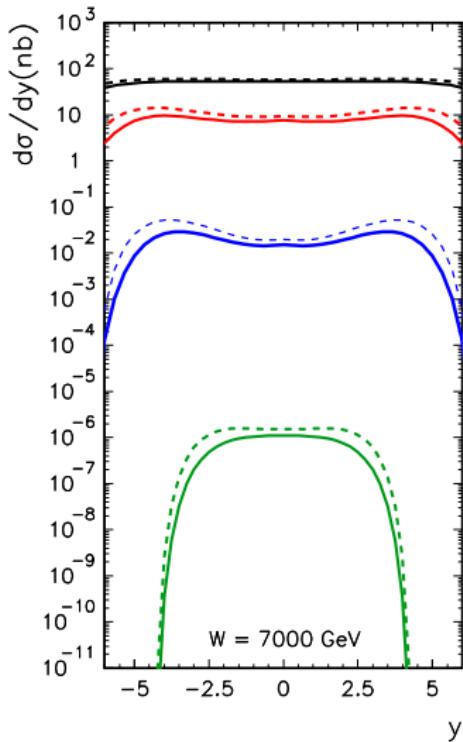
$\Upsilon(1S)$

$\Upsilon(2S)$

e.g. Υ at LHC ($\sqrt{s} = 14 \text{ TeV}$):

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

Rapidity distributions at LHC energies



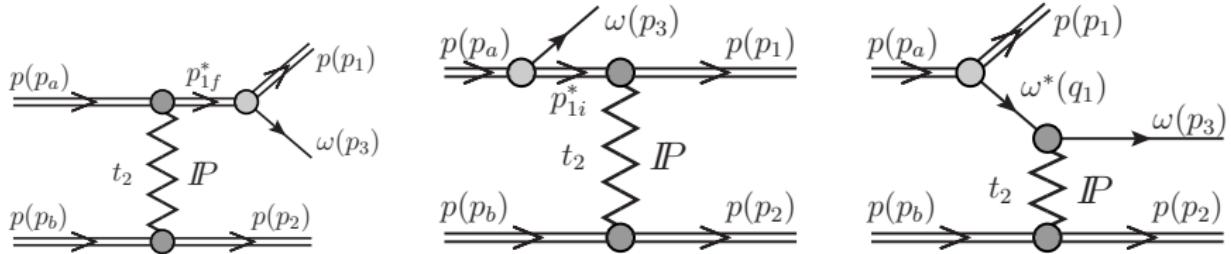
φ

J/ψ

Υ

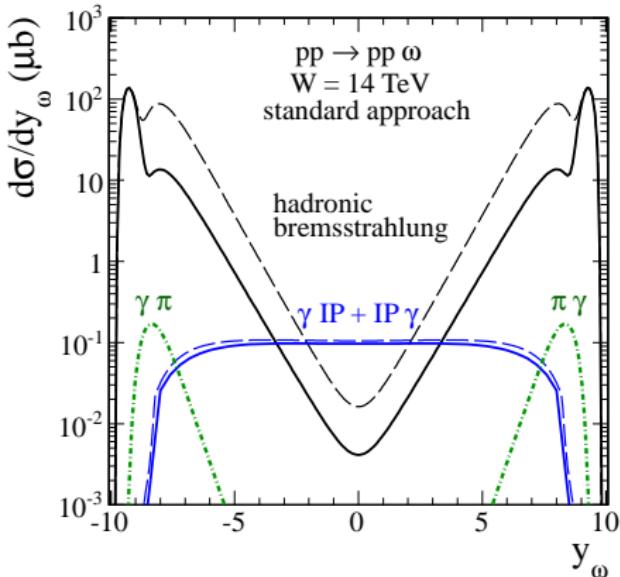
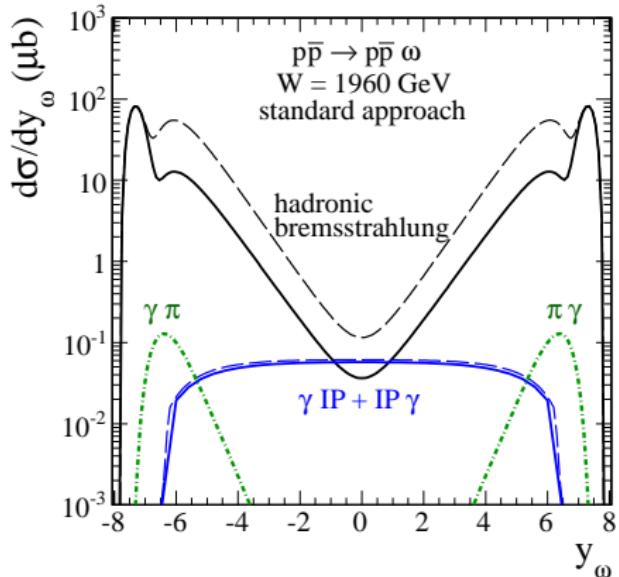
Z^0

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



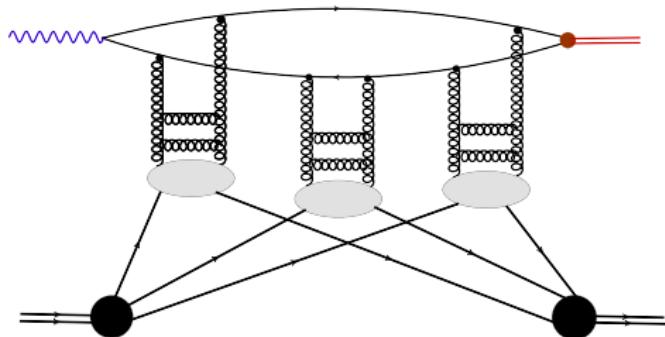
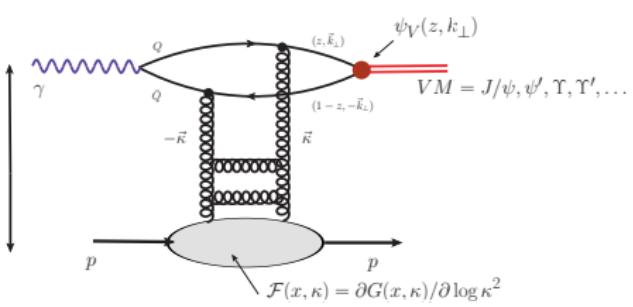
- "bremsstrahlung"-type mechanism contributes in proton fragmentation regions
- t -channel exchange becomes reggeized
- subleading Regge pole, but **large** ωNN coupling

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



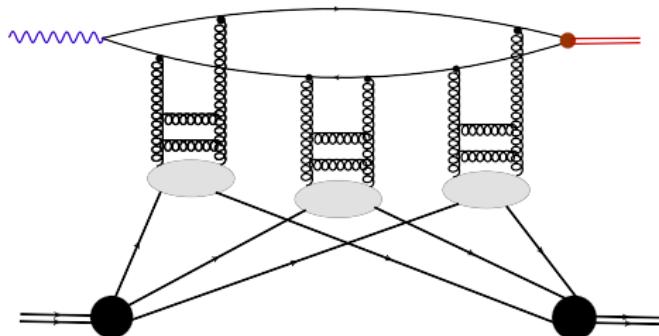
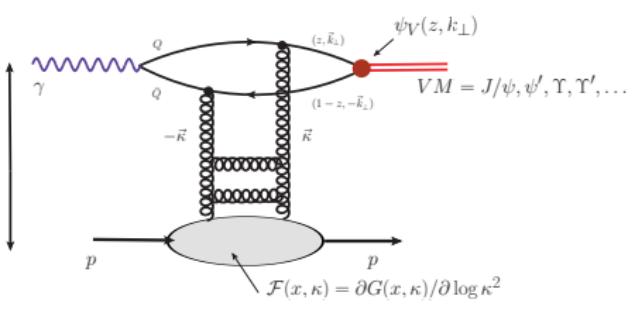
- dashed: without absorption, solid: with absorption
- need to go to very large energies to "dig out" photoproduction.

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:

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

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

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 $\Gamma(\mathbf{b}, x, \mathbf{r})$ can be constructed from Glauber-Gribov theory:

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

- nuclear coherent glue per unit area in impact parameter space:

$$\phi(\mathbf{b}, x_A, \kappa) = \sum w_j(\mathbf{b}, x_A) f^{(j)}(x_A, \kappa), \quad f^{(1)}(x, \kappa) = \frac{4\pi\alpha_S}{N_c} \frac{1}{\kappa^4} \frac{\partial G(x, \kappa^2)}{\partial \log(\kappa^2)}$$

- collective glue of j overlapping nucleons :

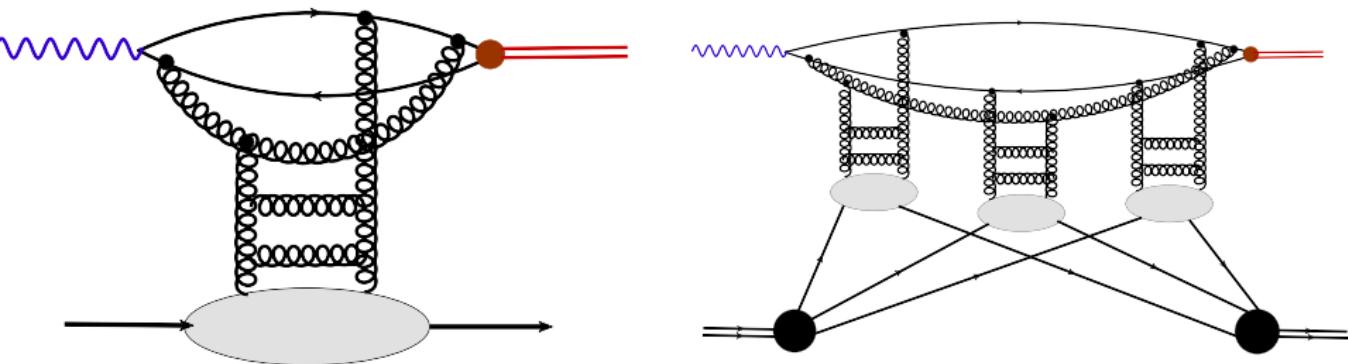
$$f^{(j)}(x_A, \kappa) = \int \left[\prod_{i=1}^j d^2\kappa_i f^{(1)}(x_A, \kappa_i) \right] \delta^{(2)}(\kappa - \sum \kappa_i)$$

- probab. to find j overlapping nucleons

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

- impact parameter $\mathbf{b} \rightarrow$ effective opacity ν_A , $q^2 =$ the relevant hard scale.

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

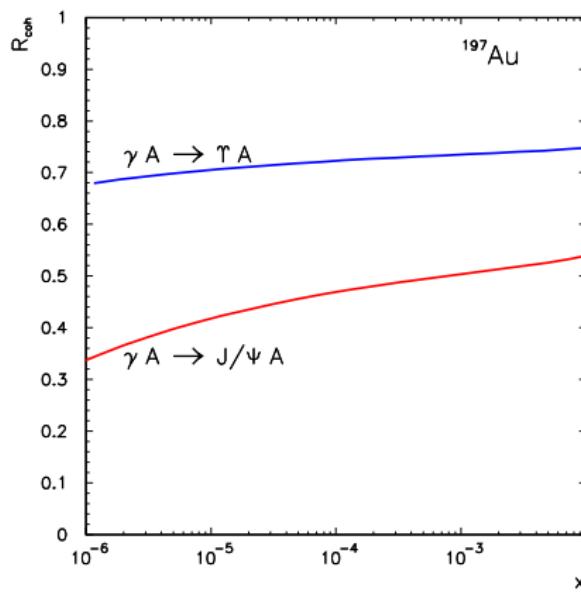


- the effect of higher $q\bar{q}g$ -Fock-states is absorbed into the x -dependent dipole-nucleus interaction **Nikolaev, Zakharov, Zoller / Mueller '94**
- evolution of **unintegrated glue** Balitsky – Kovchegov '96 – '98:

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

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

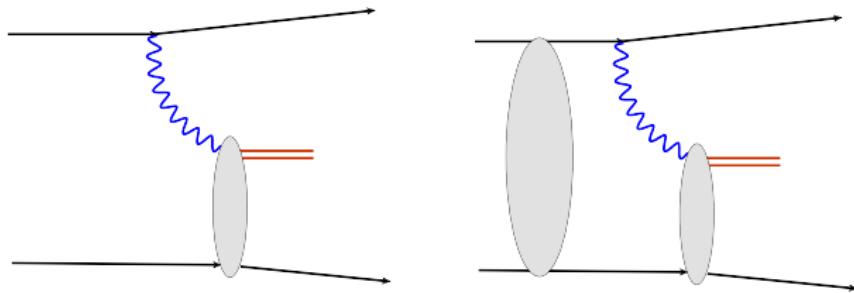
Coherent diffractive production of J/ψ , Υ on ^{208}Pb



- Ratio of coherent production cross section to impulse approximation

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

Absorption corrected flux of photons



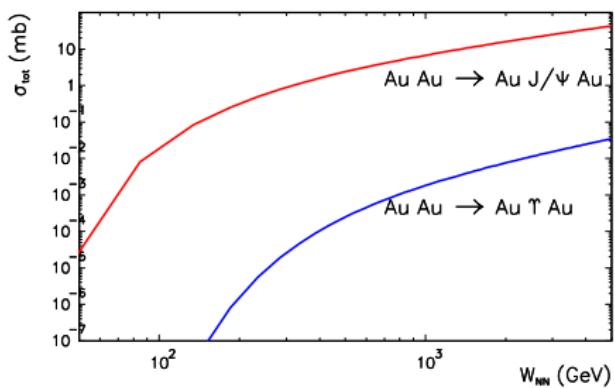
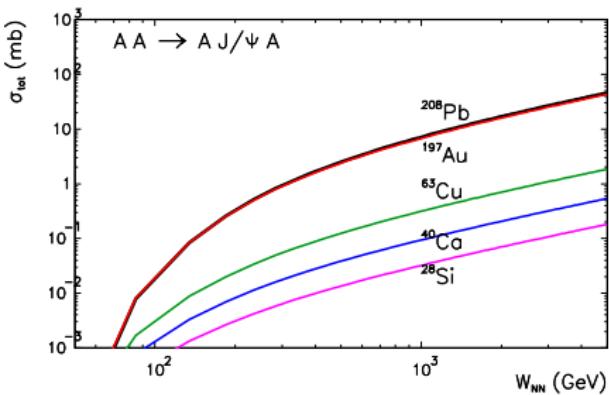
$$\sigma(A_1 A_2 \rightarrow A_1 A_2 f; s) = \int d\omega \frac{dN_{A_1}^{\text{eff}}(\omega)}{d\omega} \sigma(\gamma A_2 \rightarrow f A_2; 2\omega\sqrt{s}) + (1 \leftrightarrow 2)$$

$$dN^{\text{eff}} = \int d^2 \mathbf{b} S_{el}^2(\mathbf{b}) dN(\omega, \mathbf{b})$$

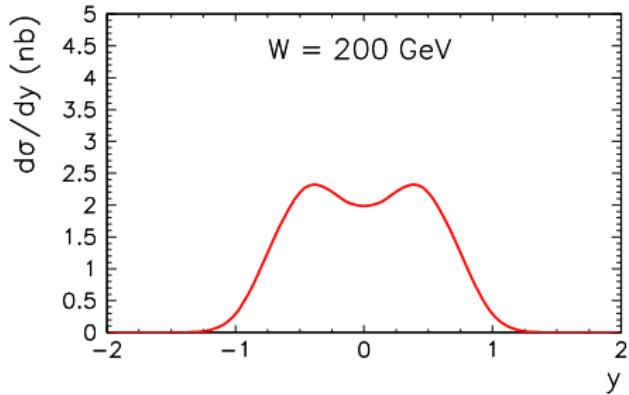
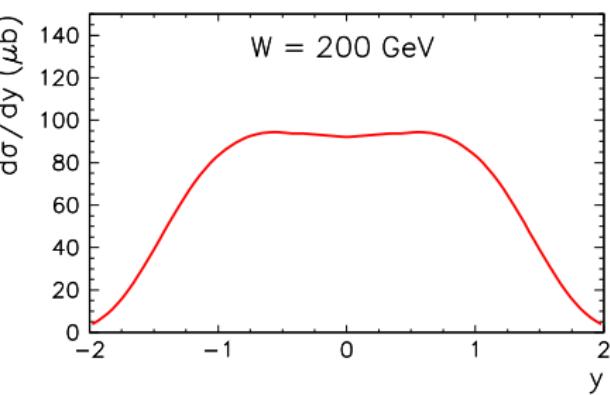
- $dN(\omega)$ = Weizsäcker-Williams flux
- **survival probability:**

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

Coherent exclusive production in AA: total cross sections

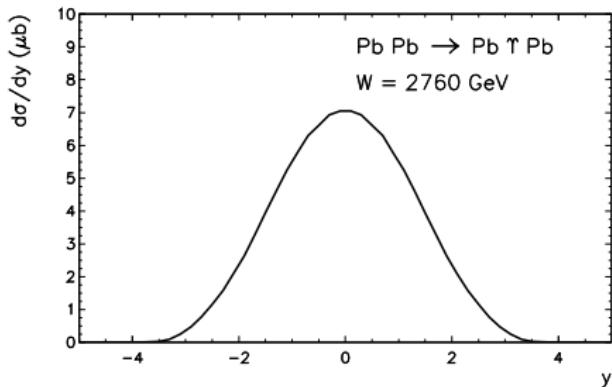
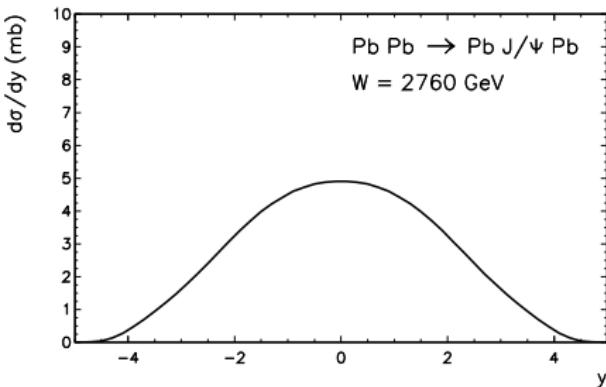


Coherent exclusive production in AA: rapidity distributions



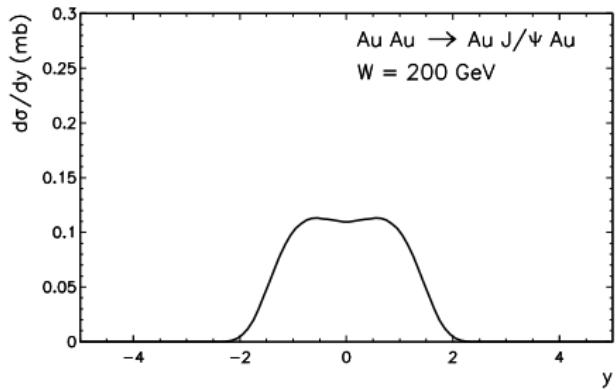
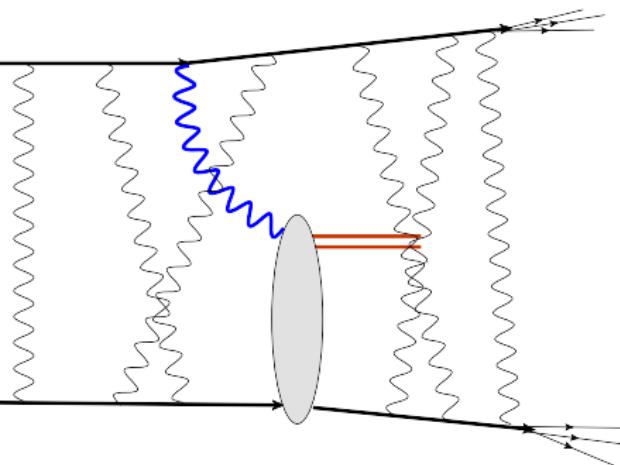
- left column: J/Ψ , right column: Υ

Coherent exclusive production in AA: rapidity distributions



- left column: J/ψ , right column: Υ

Few-neutron topological cross sections



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

- for the integrated case Klein and Nystrand estimate a suppression of 0.55
- exp. result: [PHENIX Collab. \(2009\)](#):

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

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.
→ **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.