Exclusive vector mesons at high energies: from photon-proton to proton-proton and nucleus-nucleus collisions

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Outline

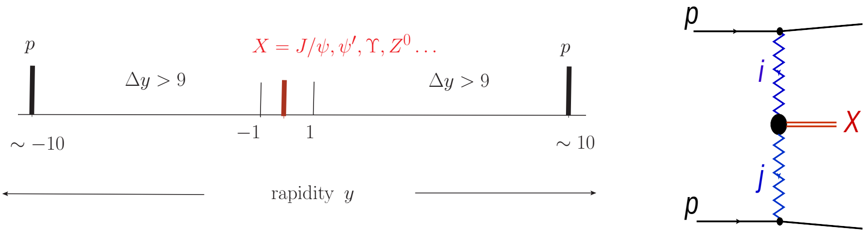
Central exclusive production

$\gamma p \to Vp$ **at high energies**

Predictions for LHC: proton-proton and nucleus-nucleus collisions

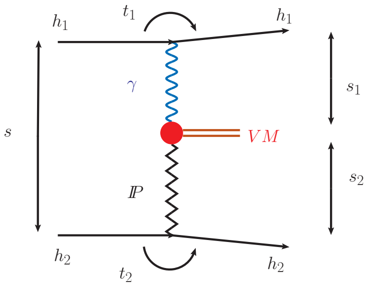
- W.S. & Antoni Szczurek Phys. Rev. D **76**, 094014 (2007).
- A. Rybarska, W.S. and A. Szczurek, Phys. Lett. B **668** (2008) 126.
- A. Cisek, W. S., A. Szczurek, Phys. Lett. **B690** (2010) 168-174.
- A. Cisek, P. Lebiedowicz, W. S., A. Szczurek, Phys. Rev. **D83** (2011) 114004.
- A. Cisek, W. S. and A. Szczurek, arXiv:1204.5381 [hep-ph].

Central Exclusive Production



- central exclusive production $\equiv$ very clean events.
- large rapidity gaps $\rightarrow$ strong constraints on t–channel exchanges:
- charge=0, color singlet
- (running) spin $J(t) \geq 1$
- even C-parity: Pomeron
- odd C-parity: photon, Odderon(?)
- $C_i \cdot C_j = C_X$
- First results from CDF/Tevatron for $X = J/\psi, \psi', \ldots$.

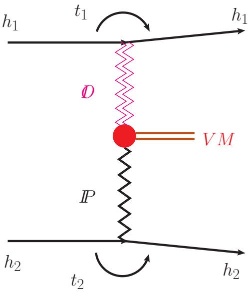
Photoproduction



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

cross section $\sim$ nanobarns

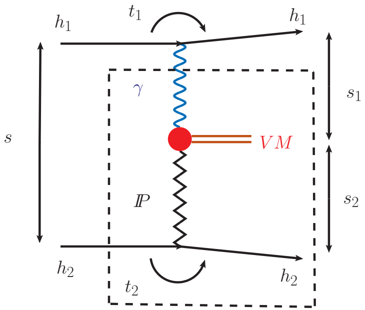
Odderon–Pomeron fusion



A. Schäfer, Mankiewicz & Nachtmann '91

cross section $\sim$ 0.1÷few nanobarns (??)

Photoproduction



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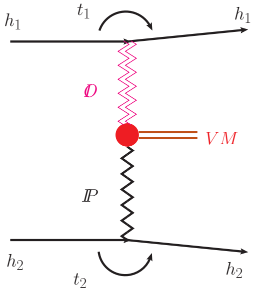

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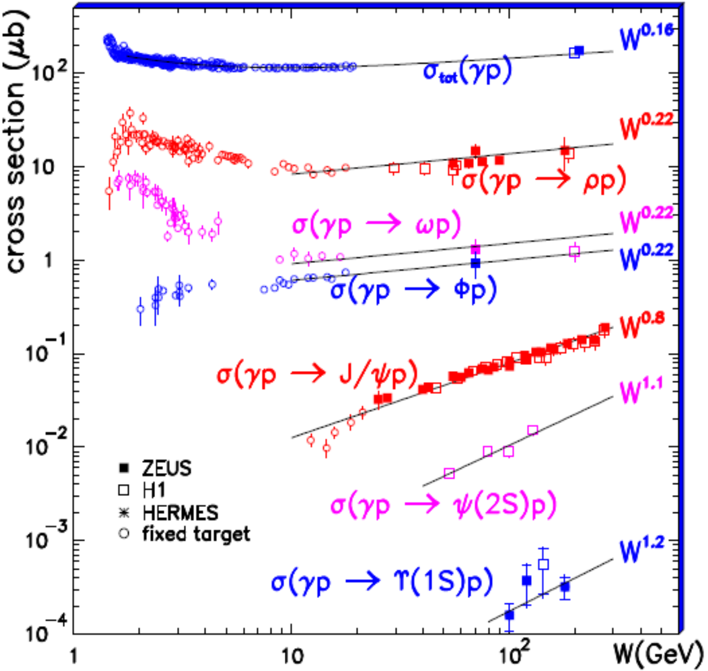
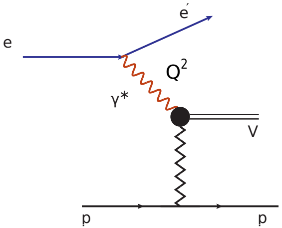
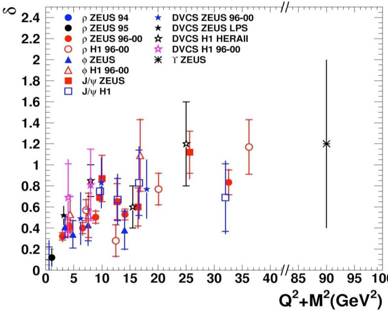
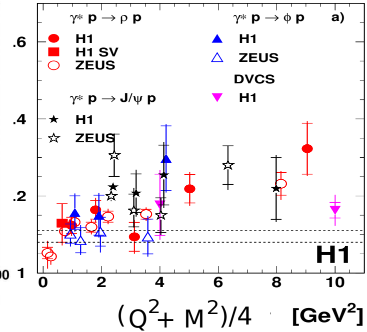


cross section (μb)
W(GeV)
σ_tot(γp)
σ(γp → ρp)
σ(γp → ωp)
σ(γp → φp)
σ(γp → J/ψp)
σ(γp → ψ(2S)p)
σ(γp → Υ(1S)p)
W^0.16
W^0.22
W^0.22
W^0.22
W^0.8
W^1.1
W^1.2
ZEUS
H1
HERMES
fixed target

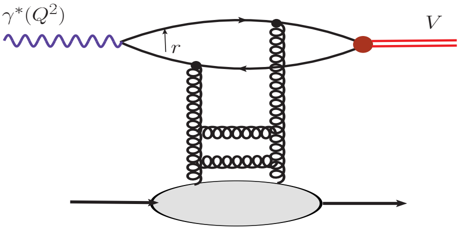


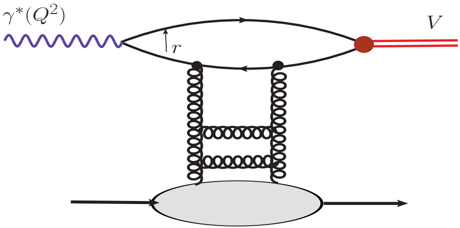




$$\sigma \approx W^{\delta} = W^{4(\alpha(0)-1)}$$

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

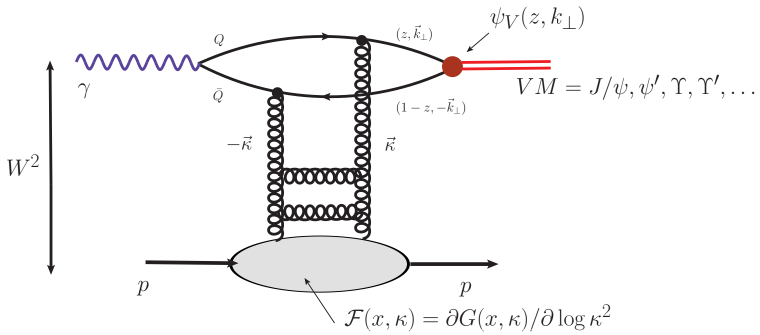
$$\sigma(x, r) = \frac{\pi^2}{3} r^2 \alpha_S(q^2) xg(x, q^2)\,,\; q^2 \approx \frac{10}{r^2}$$

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

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

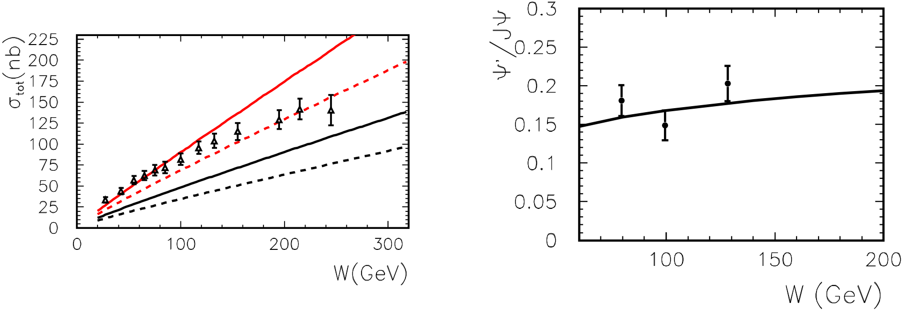
- probes the gluon distribution, which drives the energy dependence.
- From DGLAP fits: $xg(x, \mu^2) = (1/x)^{\lambda(\mu^2)}$ with $\lambda(\mu^2) \sim 0.1 \div 0.4$ for $\mu^2 = 1 \div 10^2 \mathrm{GeV}^2$.

Diffractive Photoproduction $\gamma p \to Vp$



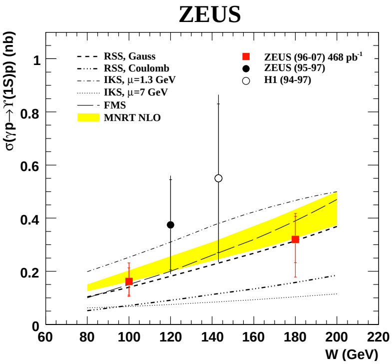
- $J/\psi = c\bar{c}$, $\Upsilon = b\bar{b}$: (almost) nonrelativistic bound states of heavy quarks. Wavefunctions constrained by their leptonic decay widths.
- Large quark mass $\to$ hard scale necessary for (perturbative) QCD.
- $\mathcal{F}(x,\kappa) \equiv$ unintegrated gluon density, $x \sim M_{VM}^2/W^2$, 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



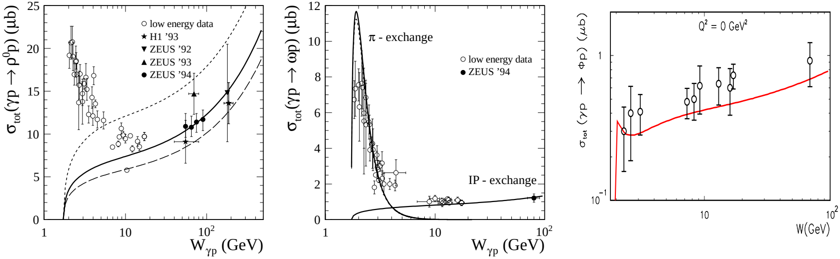
- dependence on wave function: **red:** Gaussian WF, **black**: Coulomb-type WF.
- dependence on LO/NLO treatment of decay width: dashed - LO width; solid - NLO width.
- suppression of the $\psi(2S)/J/\psi$ is a meson structure effect – the "node effect"
  Nemchik, Nikolaev et al. '94.
- calculation: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

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

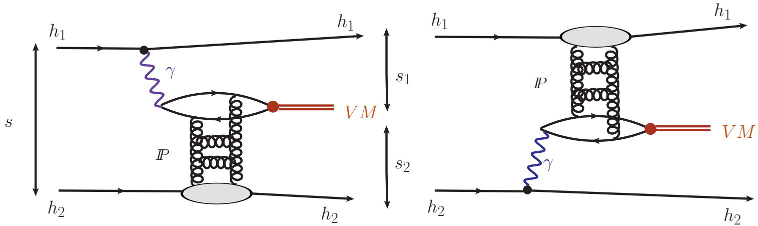


- various pQCD based approaches to Υ-production. They tend to agree better with the new data-points.
- also here, the Gaussian WF is preferred.
- A. Rybarska, WS, A. Szczurek Phys. Lett. B668(2008)

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



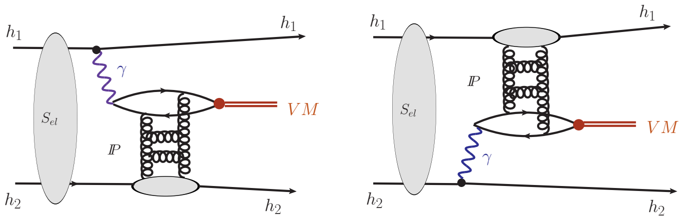
- with few free parameters– valence quark masses $m_{u,d}, m_s$ an extension into the soft regime is possible.
- A. Cisek, P. Lebiedowicz, WS, A. Szczurek Phys. Rev. D83 (2011);
  A. Cisek, WS, A. Szczurek Phys. Lett. B690(2010) .



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

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

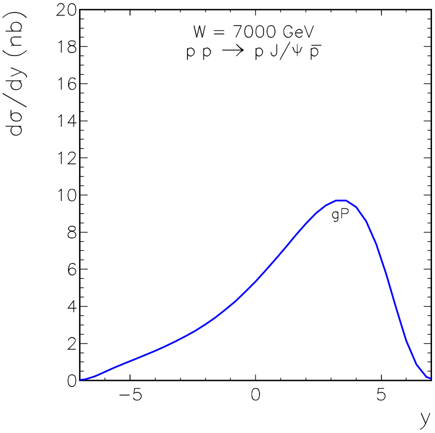
Absorptive Corrections



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

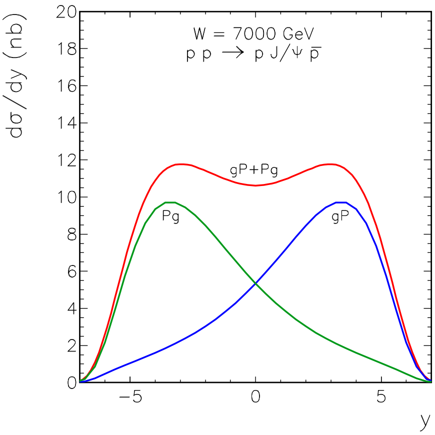
- Absorptive corrections depend on elastic $h_1 h_2$ Amplitude
  $\rightarrow$ taken from data.
- photon pole $\rightarrow$ peripheral interactions $\rightarrow$ Absorption at 20%–level.

Energy range in the γp subprocess:



- $y = -4 \to W_{\gamma p} \sim 20\,\mathrm{GeV}$
- $y = 0 \to W_{\gamma p} \sim 140\,\mathrm{GeV}$
- $y = +4 \to W_{\gamma p} \sim 1\,\mathrm{TeV}$

Energy range in the γp subprocess:



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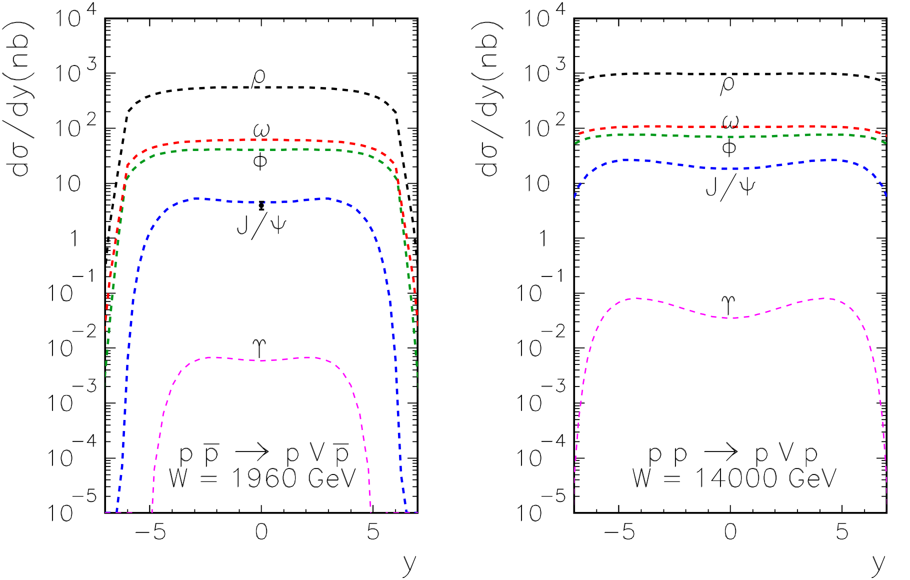
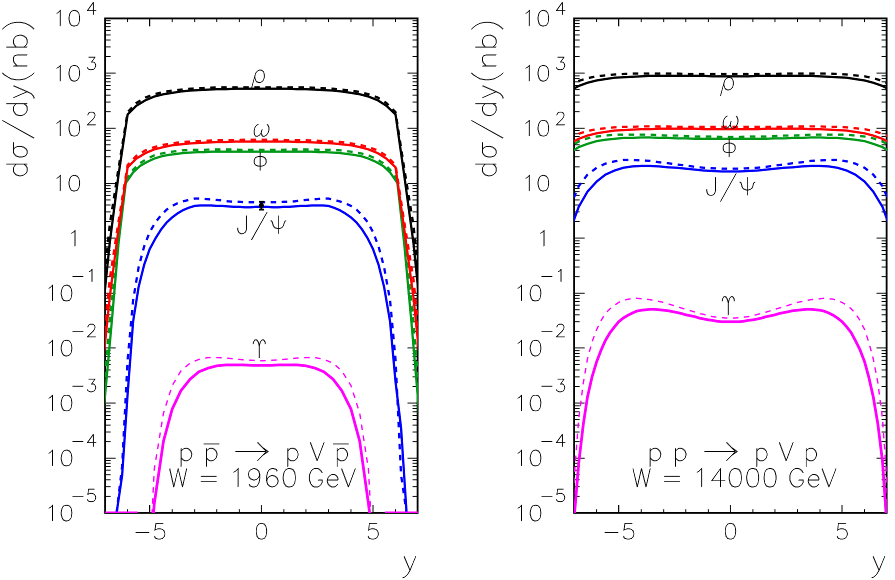
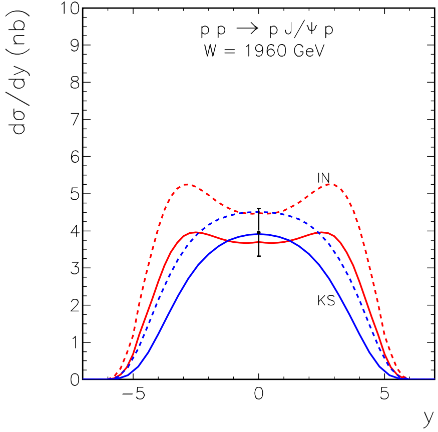
Rapidity spectra at Tevatron/LHC energies:

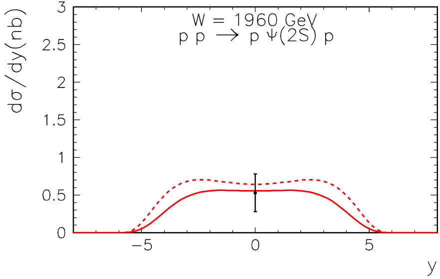


Rapidity spectra at Tevatron/LHC energies:



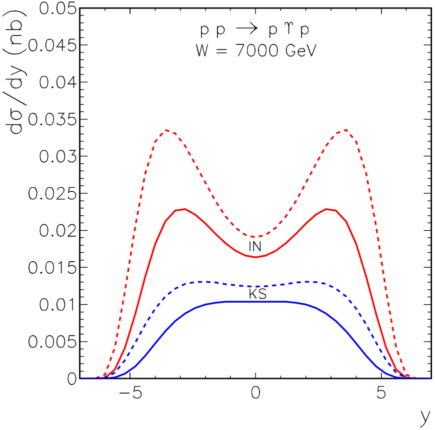
Rapidity spectra - comparison to Tevatron data:





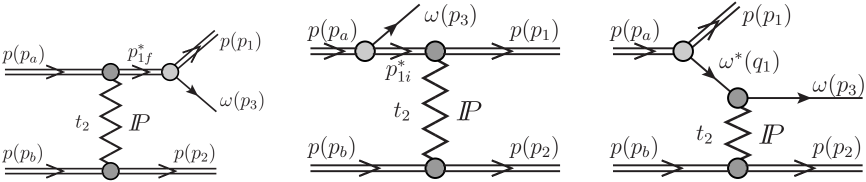
- CDF collaboration, T. Aaltonen et al. Phys. Rev. Lett. 102 (2009)
- in agreement with predictions from WS & A. Szczurek Phys. Rev. D76 (2007).
- calculations by A. Cisek, PhD thesis (2012), for two types of gluon distributions: Ivanov-Nikolaev, without explicit saturation effects, and Kutak- Staśto,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

Nonlinear vs linear glue: predictions for rapidity spectra



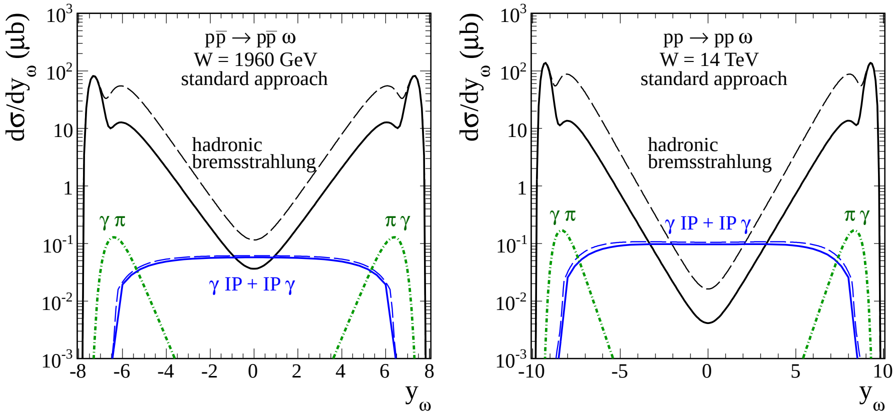
- $pp \to p\Upsilon p$ at LHC energy.
- calculations by A. Cisek, PhD thesis (2012), for two types of gluon distributions: Ivanov-Nikolaev, without explicit saturation effects, and Kutak- Staśto, with nonlinear evolution.
- dashed: no absorption, solid: with absorption.

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



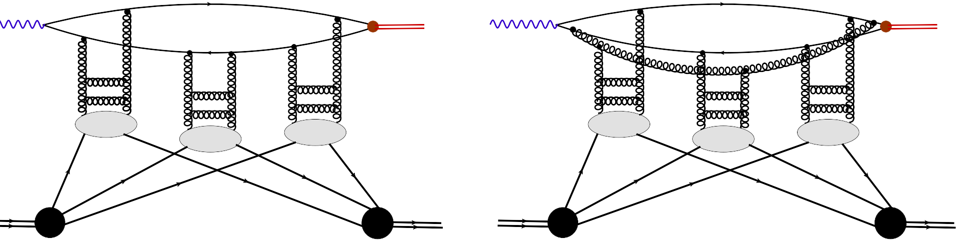
- "Bremsstrahlung"-type mechanism contributes in proton fragmentation regions
- t-channel exchange becomes reggeized
- subleading Regge pole, but **large** ωNN coupling, say $g^2_{\omega NN}/4\pi \sim 10$.

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



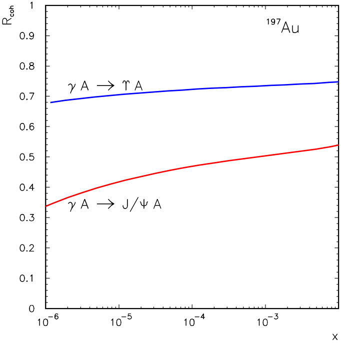
- dashed: without absorption, solid: with absorption
- need to go to very large energies to "dig out" photoproduction.
- A. Cisek, P. Lebiedowicz, WS, A. Szczurek Phys. Rev. D83 (2011)

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.
- the final state might as well be a (virtual) photon (total photoabsorption cross section) or a $q\bar{q}$-pair (inclusive low-mass diffraction).
- a probe of the saturated gluon distribution.

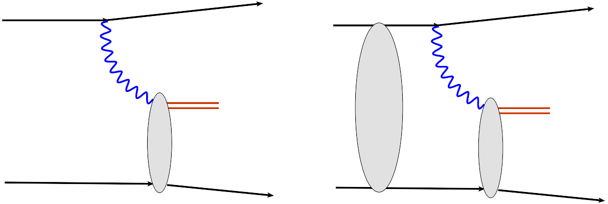
Coherent diffractive production of $J/\Psi, \Upsilon$ on ^{208}Pb



- 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



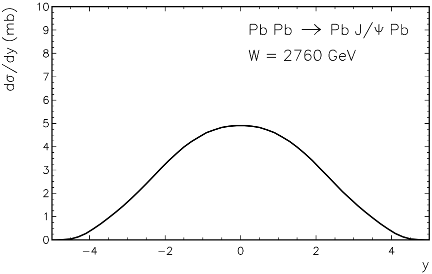
$$\sigma(A_1 A_2 \to A_1 A_2 f; s) = \int d\omega \frac{dN^{\rm eff}_{A_1}(\omega)}{d\omega} \sigma(\gamma A_2 \to f A_2; 2\omega\sqrt{s}) + (1 \leftrightarrow 2)$$

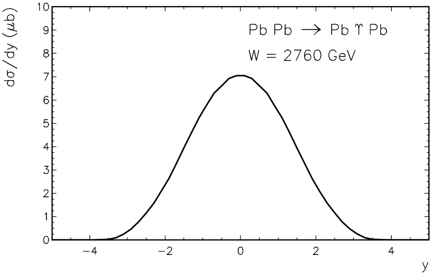
$$dN^{eff} = \int d^2\boldsymbol{b}\, S^2_{el}(\boldsymbol{b}) dN(\omega, \boldsymbol{b})$$

- $dN(\omega)$= 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 arXiv:1204.5381 [hep-ph].
- left column: J/Ψ, right column:Υ
- The large nuclear size cuts off the flux of hard photons severly → different rapidity shape tha in *pp*.

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.