Exclusive photoproduction of dileptons at high energy

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Outline

- Motivation
- Dilepton photoproduction in color dipole approach
- Phenomenology for γp process (dipole cross sections)
- Some words about the photonuclear case
- Photoproduction of dileptons in pp collisions
- Summary

Motivation

- Recently, electromagnetic interactions in pp and AA collisions extend the physics program of photon induced processes beyond energies reached at DESY-HERA.
- LHC detector configurations can explore small-x hard phenomena with nuclei and nucleons at photon-nucleon energies above 1 TeV.
- Possible to probe diffractive/inclusive PDFs in nuclei using several processes: for instance, the interaction of small dipoles with protons/nuclei can be investigated in diffractive meson production (J/ψ, Υ and high t ρ^0).
- Electromagnetic interactions can also be studied with beams of p or $\bar{p}$, but there is then no Z^2-enhancement in the photon flux in contrast to AA collisions.

Motivation

- Several analysis on central exclusive production are currently being done at Tevatron:
- For instance, CDF is analyzing the exclusive production of muon pairs at lower invariant masses.
- The two main contributions to these events are, as with heavy-ion beams, $\gamma\gamma \to \mu^+ + \mu^-$ and $\gamma + IP \to J/\Psi(\mathrm{or}\,\Psi')$.
- Here, we use color dipole approach (valid at high energies) to study the exclusive photoproduction of lepton pairs, $\gamma N \to \gamma^*(\to \ell^+\ell^-)\, N$ (with $N = p,\ A$). Such a process could be a contribution for lepton pair production.
- Use of recent models for elementary dipole-hadron scattering amplitude that capture main features of the dependence on A, energy and momentum transfer t.

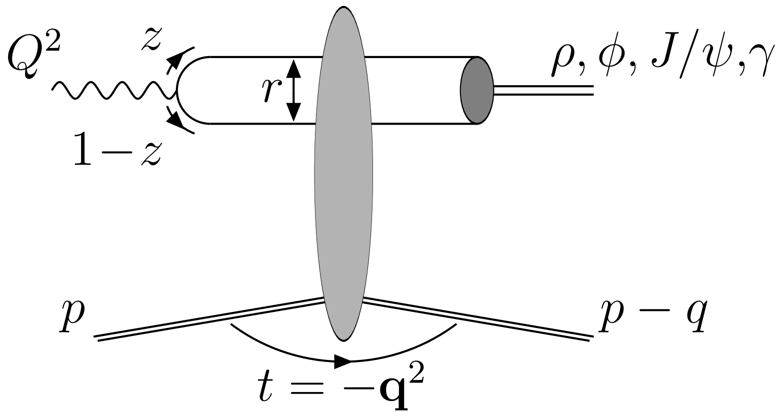
Timelike Compton scattering

- Conventional partonic description of timelike Compton scattering (TCS), $\gamma + p \to \gamma^* + p$, considers the relevant generalized parton distributions (GPDs).
- TCS process has been studied at LO in the collinear factorization framework in terms of the quark GPDs and sub-processes initiated by quarks (handbag diagrams).
- E.R. Berger, M. Diehl and B. Pire (2002). B. Pire, L. Szymanowski and J. Wagner, arXiv:0805.1589.
- TCS process at small t and large timelike virtuality of the outgoing photon shares many features of DVCS, $\gamma^* p \to \gamma p$.
- Here, we use alternative framework . . .

TCS on the dipole approach

- Color dipole approach provides good description of data on γp inclusive/diffractive processes at small-x region.
- In particular, deeply virtual Compton scattering (DVCS) cross section is nicely reproduced in several implementations of the dipole cross section.
- In dipole frame TCS process proceeds in three stages:
- (1) first the incoming real photon fluctuates into a $q\bar{q}$ pair, (2) then this pair scatters elastically on the proton, and finally (3) the $q\bar{q}$ pair recombines to form a virtual photon (which subsequently decays into lepton pairs).
- We can use current rich phenomenology at small-x region.

TCS on dipole approach



$$\mathcal{A}^{\gamma p \to \gamma^* p} = \sum_f \sum_{h,\bar{h}} \int \mathrm{d}^2 r \int_0^1 \mathrm{d}z \, \Psi^*_{h\bar{h}}(r, z, Q) \mathcal{A}_{q\bar{q}}(x, r, \Delta) \Psi_{h\bar{h}}(r, z, 0)$$

- $\Psi_{h\bar{h}}(r, z, Q)$ denotes the amplitude for a photon to fluctuate into a $q\bar{q}$ dipole with helicities h and $\bar{h}$ and flavor f.
- $\mathcal{A}_{q\bar{q}}(x, r, \Delta)$ is the elementary amplitude for the scattering of a dipole of size r on the proton, Δ is the transverse momentum lost by the outgoing proton (with $t = -\Delta^2$), x is the scaling variable and Q^2 is the photon virtuality.

TCS on dipole approach

- Summed over the quark helicities, for a given quark flavour f one obtains for corresponding overlap function,

$$
\begin{aligned}
(\Psi^*_{\gamma^*}\Psi_\gamma)^f_T &= \frac{N_c\,\alpha_{\mathrm{em}} e_f^2}{2\pi^2}\left\{\left[z^2+\bar{z}^2\right]\varepsilon_1 K_1(\varepsilon_1 r)\varepsilon_2 K_1(\varepsilon_2 r)\right. \\
&+ \left. m_f^2 K_0(\varepsilon_1 r) K_0(\varepsilon_2 r)\right\}
\end{aligned}
$$

- Quantities $\varepsilon_{1,2} = \sqrt{z\bar{z}\,Q_{1,2}^2 + m_f^2}$ and $\bar{z} = (1-z)$.
- Accordingly, the photon virtualities are $Q_1^2 = 0$ (incoming real photon) and $Q_2^2 = -Q^2$ (outgoing virtual photon).
- The elastic diffractive cross section is then given by,

$$
\frac{\mathrm{d}\sigma^{\gamma p\to\gamma^* p}}{\mathrm{d}t} = \frac{1}{16\pi}\left|\mathcal{A}^{\gamma p\to\gamma^* p}(x,Q,\Delta)\right|^2
$$

Elementary dipole scattering amplitude

- We consider the non-forward saturation model (C. Marquet, R. Peschanski and G. Soyez (2007) - MPS model), which gives directly the t dependence.

$$\mathcal{A}_{q\bar{q}}(x,r,\Delta) = 2\pi R_p^2\, e^{-B|t|} N(rQ_{\rm sat}(x,|t|),x)$$

- The t dependence of the saturation scale is parametrised as

$$Q_{\rm sat}^2\,(x,|t|) = Q_0^2\,(1+c|t|)\,\left(\frac{1}{x}\right)^{\lambda}$$

- The scaling function N is:

$$N\,(x,\boldsymbol{r}) = \begin{cases} \mathcal{N}_0\left(\frac{\boldsymbol{r}^2 Q_{\rm sat}^2}{4}\right)^{\gamma_{\rm eff}\,(x,\,r)}\,, & \text{for } \boldsymbol{r}Q_{\rm sat} \leq 2\,, \\ 1-\exp\left[-a\,\ln^2\,(b\boldsymbol{r}Q_{\rm sat})\right]\,, & \text{for } \boldsymbol{r}Q_{\rm sat} > 2\,, \end{cases}$$

where $\gamma_{\rm eff}\,(x,\,r) = \gamma_{\rm sat} + \frac{\ln(2/\tilde{\tau})}{\kappa\,\lambda\,Y}$ ($\gamma_{\rm sat} = 0.63$ or free).

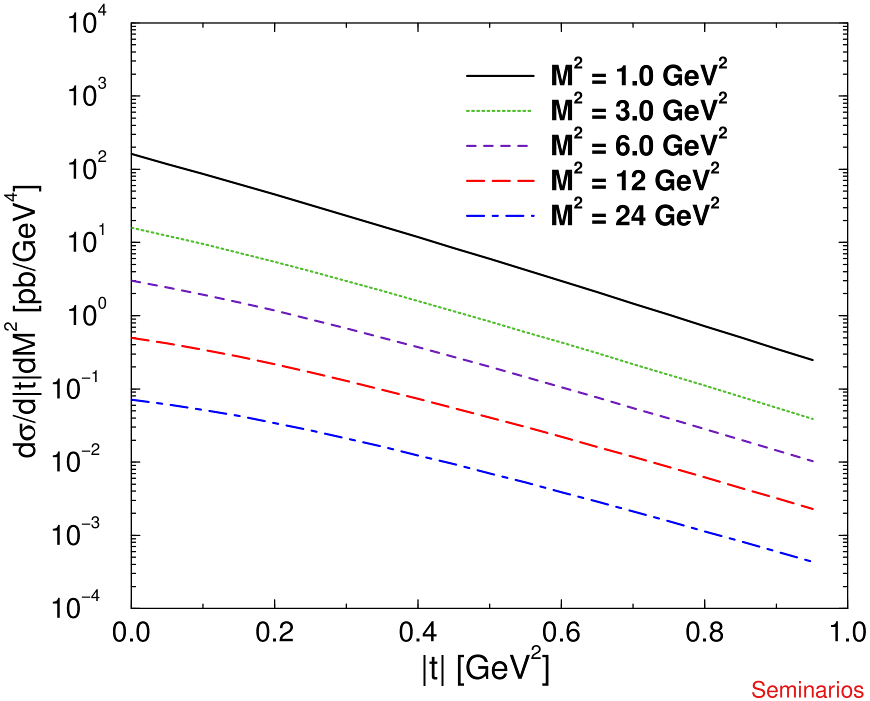
Technicalities and approximations . . .

- The quark-antiquark light-cone wavefunctions of timelike photons has been derived recently by L. Motyka and G. Watt (2008).
- It was shown that is needed to deal with imaginary arguments for the modified Bessel functions and this fact leads to wildly oscillatory r-integrand.
- In the following calculations, (uncorrect) space-like kinematics is used and we expect that the numeric impact of this procedure to be reasonably small.

Phenomenology for TCS at high energie

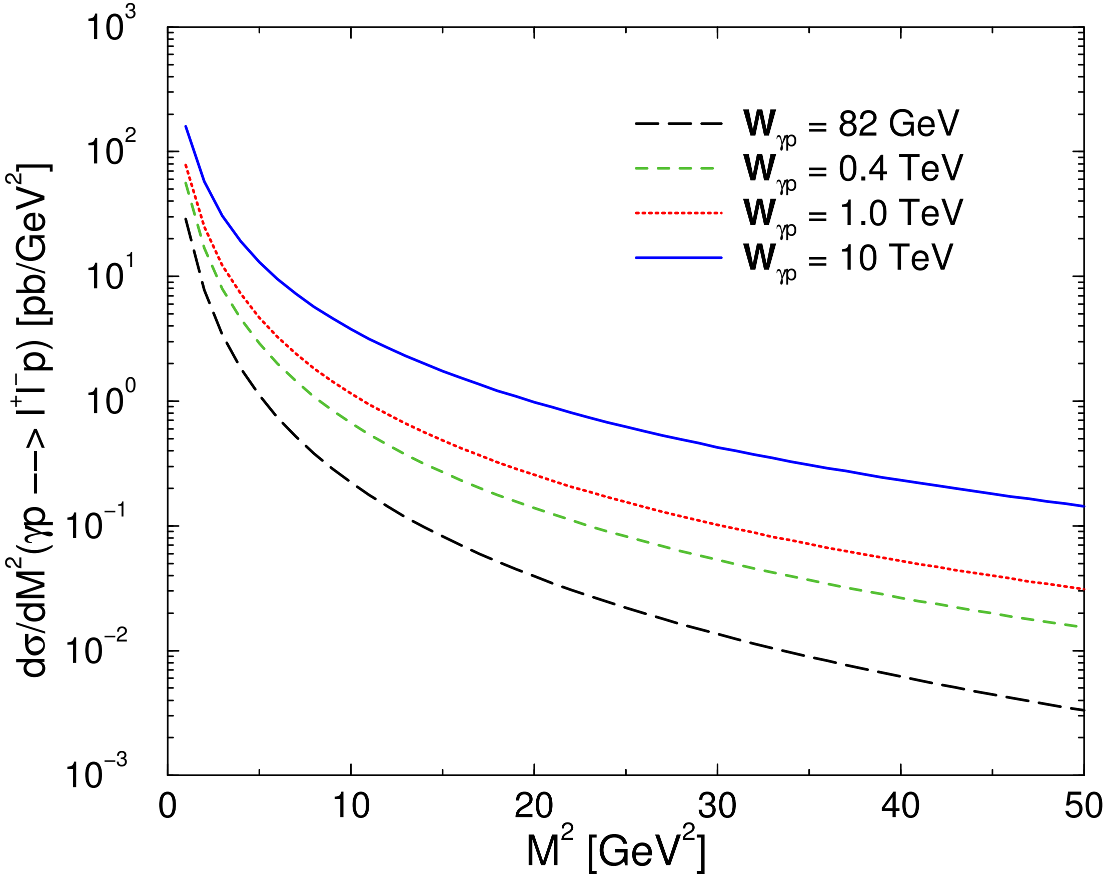
- We investigate the exclusive photoproduction of a heavy timelike photon which decays into a lepton pair, $\gamma p \to \ell^+\ell^- p$.
- Therefore, for the $\ell^+\ell^-$ invariant mass distribution from the virtual γ^* decay we have (with $Q^2 = M^2_{\ell^+\ell^-}$),

$$\frac{d\sigma}{dM^2_{\ell^+\ell^-}}\left(\gamma p \to \ell^+\ell^- p\right) = \frac{\alpha_{em}}{3\pi M^2_{\ell^+\ell^-}}\,\sigma\left(\gamma p \to \gamma^* p\right)$$



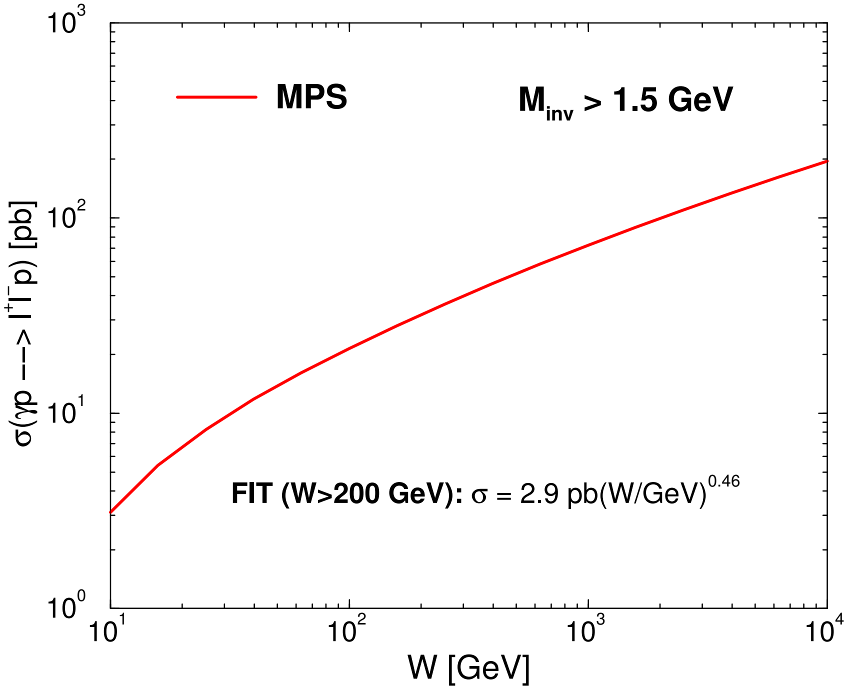
More results . . .

- Differential cross section, $d\sigma/dM^2$, as a function of dilepton invariant mass for fixed values of energy (integrated over $|t| < 1$ GeV^2).



More results . . .

- Integrated cross section ($M_{\ell^+\ell^-} \geq 1.5$ GeV and $|t| \leq 1$ GeV^2) as a function of photon-nucleon energy.



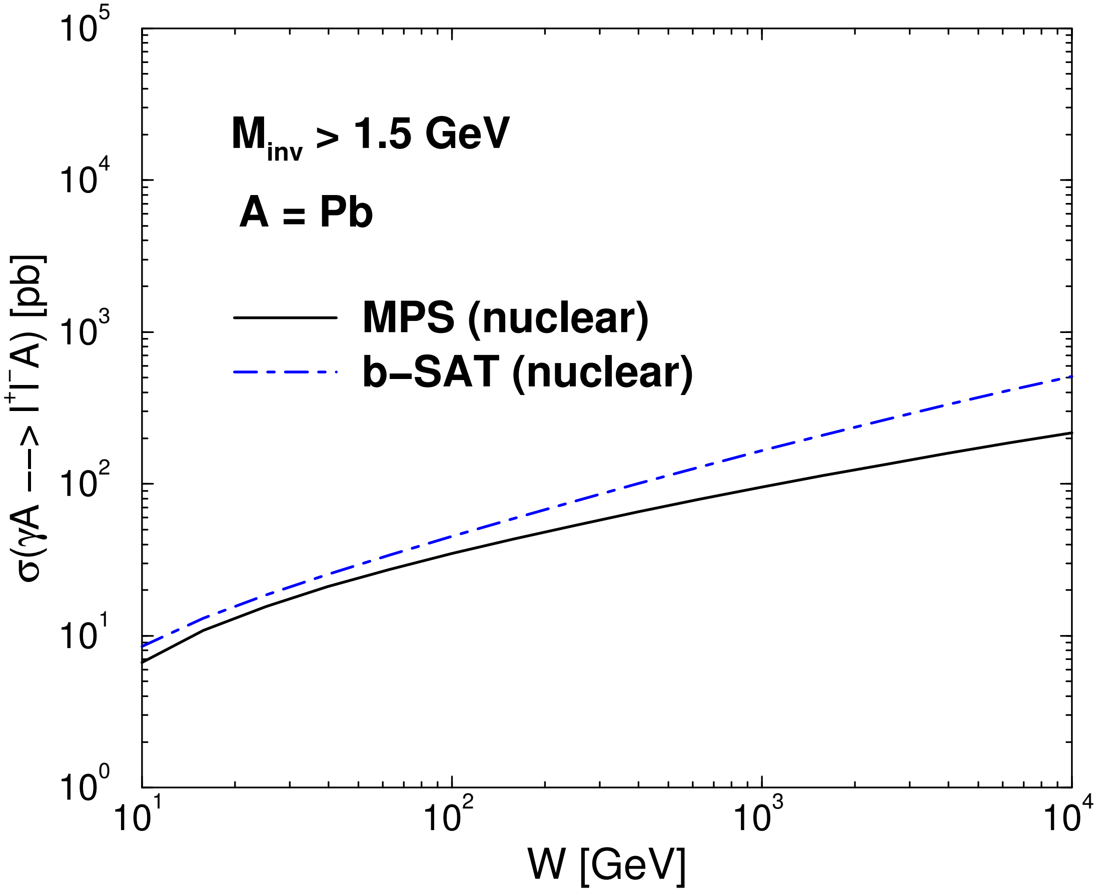
- Calculations using other saturation models are distinct mostly at low energy (different threshold behavior) and extrapolation to very high energy (different saturation scales/QCD evolutions).

Phonomenology for nuclear targets

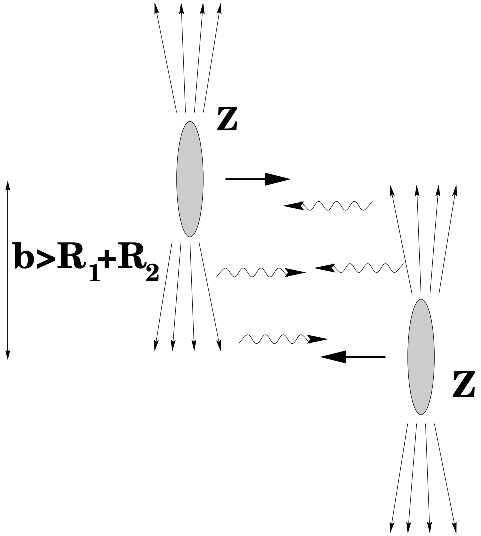
- We consider now the process $\gamma A \to \gamma^*(\to \ell^+\ell^-)\, A$ which is the coherent contribution to nuclear TCS, where the nucleus remains intact.
- Following geometric scaling arguments, for MPS model we take $R_p \to R_A$ and $Q^2_{\mathrm{sat},p}(x,t=0) \to (AR_p^2/R_A^2)^{\Delta}\, Q^2_{\mathrm{sat},p}$.
- When $\Delta = 1$ such a replacement becomes the usual assumption for nuclear saturation scale, $Q^2_{\mathrm{sat},A} = A^{1/3}\, Q^2_{\mathrm{sat},p}$.
- For simplicity, we replace the form factor $F(t) = \exp(-B|t|)$ by corresponding nuclear form factor $F_A(t) = \exp(-\frac{R_A^2}{6}|t|)$.
- In order to check procedure, we compare it with nuclear version of impact parameter saturation model (H. Kowalski, L. Motyka and G. Watt (2006) - b-SAT).

Numerical results . . .

- The photonuclear cross section per nucleon as a function of energy for a lead nucleus.

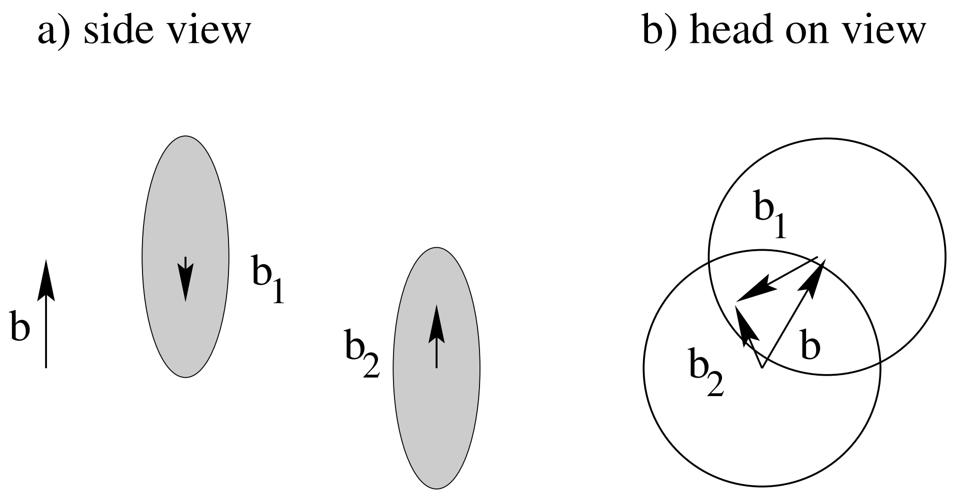


γ's in relativistic nuclei or protons



- Relativistic nuclei (or protons) having strong electromagnetic field, viewed as a cloud of virtual photons.
- They obey the condition of coherence, $Q^2 \leq 1/R_A^2$ (final state particles with low transverse momenta).
- Maximum energy of quasireal photons is $\omega_{max} \approx \gamma_L/R_A$. Examples in heavy-ions: RHIC ($\gamma_L \approx 100$, $\omega_{max}^{\rm RHIC} \approx 3$ GeV); LHC ($\gamma_L \approx 3000$, $\omega_{max}^{\rm LHC} \approx 80$ GeV).

Weissacker-Williams approximation



- Equivalent photon spectrum for relativistic particle (charge Ze, velocity v, impact parameter b)

$$N_\gamma(\omega,b) = \frac{Z^2\alpha}{\pi^2\,b^2}\left(\frac{c}{v}\right)^2 x^2\left[K_1^2(x)+\frac{1}{\gamma_L^2}K_0^2(x)\right], \quad x=\frac{\omega b}{\gamma_L v}$$

- The number of equivalent photons:

$$n\,(\omega) = \int_{R_{\min}}^{\infty} d^2b\, N_\gamma(\omega,b)\,, \qquad R_{\min} = R_{A1} + R_{A2}$$

Number of equivalent γ's

- Number of equivalent photons on nuclei:

$$\begin{aligned} n_{\rm nucleus}(\omega) &= \frac{2\,Z^2\alpha}{\pi\,\omega}\left[\bar{\eta}\,K_0(\bar{\eta})\,K_1(\bar{\eta}) + \frac{\bar{\eta}^2}{2}\left(K_1^2(\bar{\eta}) - K_0^2(\bar{\eta})\right)\right], \\ \bar{\eta} &= 2\omega\,R_A/\gamma_L\,, \qquad\qquad n(\omega) \approx \frac{2\,Z^2\,\alpha}{\pi}\ln\left(\frac{\gamma_L}{\omega\,R_{\rm min}}\right) \end{aligned}$$

- Number of equivalent photons on energetic protons:

$$\begin{aligned} n_{\rm proton}(\omega) &= \frac{\alpha_{\rm em}}{2\pi\,\omega}F(\omega)\left(\ln\Omega - \frac{11}{6} + \frac{3}{\Omega} - \frac{3}{2\,\Omega^2} + \frac{1}{3\,\Omega^3}\right), \\ F(\omega) &= \left[1 + \left(1 - \frac{2\,\omega}{\sqrt{S_{NN}}}\right)^2\right], \quad \Omega \approx 1 + \left(\frac{0.71\gamma_L^2}{\omega^2}\right) \end{aligned}$$

γ-scattering on nuclei or protons

- The photonuclear cross section is given by,

$$\sigma^{\text{photonuc}}_{A\,A\rightarrow(?)AA}(\sqrt{s_{NN}}) = \int \frac{d\,\omega}{\omega}\, n_{\text{nucleus}}\,(\omega)\,\sigma_{\gamma\,A\rightarrow(?)\,X}\,(\omega)$$

- The photoproduction cross section on protons reads,

$$\sigma^{\text{photo}}_{pp\rightarrow(?)pp}(\sqrt{s_{pp}}) = \int \frac{d\,\omega}{\omega}\, n_{\text{proton}}\,(\omega)\,\sigma_{\gamma\,p\rightarrow(?)\,X}\,(\omega)$$

- Allow to study photoproduction with energies reaching $W_{\gamma N} \simeq 930$ GeV at LHC (at DESY-HERA, $W_{\gamma p} \simeq 200$ GeV).
- Accurate theoretical predictions for the subprocesses $\gamma p(A) \rightarrow (?)X$ at very high energies are required!

Dilepton photoproduction on pp collisio

- Photoproduction of dileptons can be computed for pp collisions using equivalent-photon approximation.
- Such processes are characterized by the photon-hadron interaction, with the photon stemming from the electromagnetic field of one of the two colliding hadrons.
- Cross section for the $h\,h \to h \otimes \ell^+\ell^- \otimes h$ process is:

$$\frac{d^2\sigma}{d\omega dM^2_{\ell^+\ell^-}}(hh \to \ell^+\ell^-\,hh) = 2\frac{dN_\gamma}{d\omega}\,\frac{d\sigma}{dM^2_{\ell^+\ell^-}}\left(\gamma h \to \ell^+\ell^-\,h\right),$$

- ω is the photon energy and $\frac{dN_\gamma}{d\omega}$ is the equivalent flux of photons from a charged hadron.
- Moreover, γ_L is the Lorentz boost of a single beam, $W^2_{\gamma h} = 2\,\omega\sqrt{S_{\mathrm{NN}}}$ and $\sqrt{S_{\mathrm{NN}}}$ is the c.m.s energy of the hadron-hadron system.

Numerical results

Collider	($M_{\ell^+\ell^-} > 1.2$ GeV)	($3 < M_{\ell^+\ell^-} < 4$ GeV)
Tevatron	7 pb	400 fb
LHC	25 pb	—

- Rough estimation of cross section.
- Very small cross sections compared to contribution from two-photon process and vector meson decays.
- For instance, $\sigma(p\bar{p} \rightarrow p\bar{p} + \mu^+\mu^-[M_{inv} > 1.5\,GeV]) = 2.4$ nb [J. Nystrand (2007)].

Summary

- Using the color dipole formalism, dilepton photoproduction was investigated. Such an approach is robust in describing a wide class of exclusive processes at small-x.
- Using current phenomenology for the elementary dipole-hadron scattering, we estimate the order of magnitude of the exclusive photoproduction of lepton pairs.
- We also investigate the photonuclear cross section, focusing on the nuclear coherent scattering.
- These calculations can be used to compute dilepton photoproduction in pp (small cross section) and AA.