Nuclear DVCS within the QCD color dipole formalism

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Outline

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- The DVCS process in the color dipole approach
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- Phenomenology for DVCS on a nucleus at high energies
- Summary

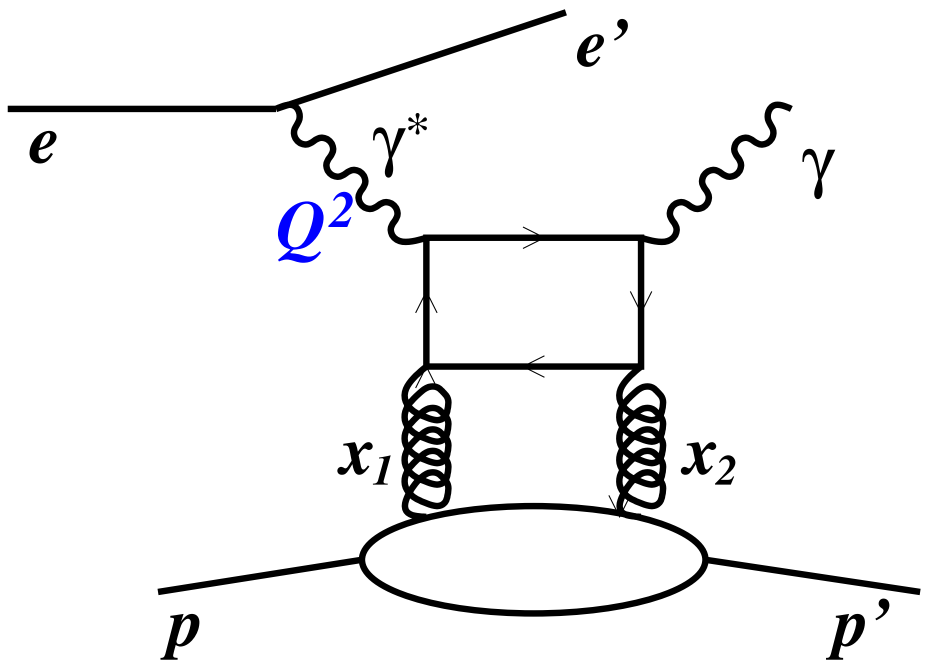
Motivation

- DVCS ($ep \to ep\gamma$) is a nice probe of hadronic matter, where a parton in the proton absorbs the virtual photon, emits a real photon and the proton ground state is restored.
- Relevant QCD diagrams involves two gluons exchange at low x (at collider experiments) or two quarks at larger x (as in fixed target experiments) carrying different fractions of the initial proton momentum (skewedness).
- DVCS thus measures generalized parton distributions (GPDs) which depends on two momentum fractions x and x', as well as on Q^2 and the four-momentum transfer t at the proton vertex: $H_f(x, x', Q^2, t)$.
- Similar process also occurs in eA colliders (the so called EICs), $eA \to eA\gamma$, which is extremely sensitive to the corresponding nuclear parton distributions.

Where DVCS is currently measured ?

- DVCS on nucleons has been studied at high energies (small Bjorken-x) by H1 and ZEUS Collaborations at DESY-HERA.
- At low energies, DVCS has been measured in the experiment CLAS at the Jefferson Laboratory (JLAb).
- Initial experimental investigations of nuclear DVCS has been reported by CLAS at low energies.
- At high energies, it is expected to investigate nuclear DVCS on future electron-ion colliders (EICs) and on ultraperipheral heavy ion AA collisions.
- Among the planned eA colliders we recall the eRHIC project and the more recent LHeC proposal.

Kinematics for DVCS on a proton

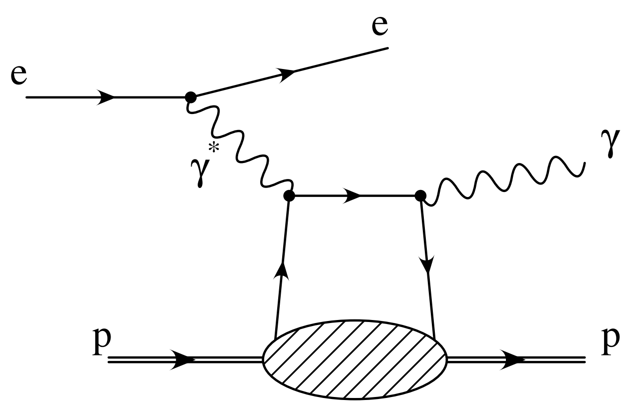


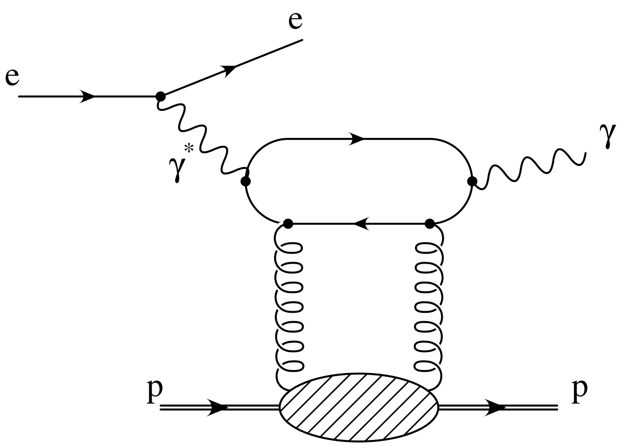
- Q^2 is the virtuality of incoming photon.
- W is the photon-proton center-of-mass energy.
- t is the four-momentum transfer at the proton vertex.
- Bjorken variable is $x = \frac{Q^2}{W^2+Q^2}$.

DVCS - theoretical description

- Conventional partonic description of DVCS, $\gamma^* + p \to \gamma + p$, is described within the collinear factorization framework.
- Cross section at photon level is given by the convolution of hard coefficient functions and the corresponding generalized parton distributions (GPDs).

$$\sigma(\gamma^* p \to \gamma p) \propto C_f(Q^2, Q_0^2) \otimes H_f(x_1, x_2, Q^2, t; Q_0^2)$$

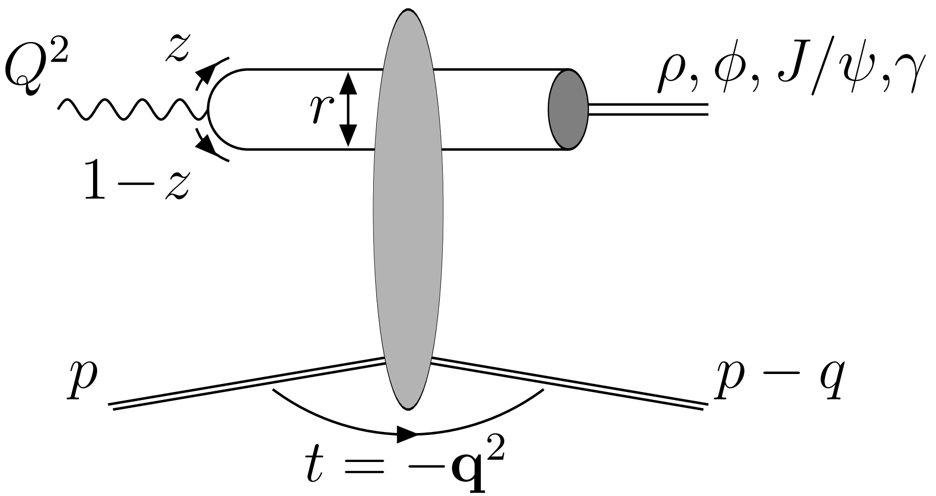




- DVCS has been studied at LO and NLO in terms of the quark/gluon GPDs and sub-processes initiated by quarks.

DVCS on the color dipole approach

- Color dipole approach provides good description of data on γp inclusive/diffractive processes at small-x region.
- In particular, DVCS cross section is nicely reproduced in several implementations of the dipole cross section.



- In dipole frame DVCS process proceeds in three stages:
- (1) first the incoming virtual 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 real photon.

DVCS on color dipole approach

- DVCS cross section is expressed in a factorized way:

$$\mathcal{A}^{\gamma^* p \to \gamma p} = \sum_f \sum_{h,\bar{h}} \int \mathrm{d}^2 r \int_0^1 \mathrm{d}z \, \Psi^*_{h\bar{h}}(r, z, Q_2) \mathcal{A}_{q\bar{q}}(x, r, \Delta) \Psi_{h\bar{h}}(r, z, Q$$

- $\Psi_{h\bar{h}}(r, z, Q)$ 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.
- We can use current rich phenomenology at small-x region.
- Some nice models (mostly saturation models) for the elementary dipole amplitude available at the market.

DVCS on color dipole approach

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

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

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

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

Elementary dipole scattering amplitude

- The forward elementary dipole amplitude is basically Fourier-transform of unintegrated gluon distribution.
- Theoretically, unintegrated gluon function is solution of BFKL equation (linear QCD evolution equation).
- Recently, saturation models (which include unitarization corrections) have appeared.

$$\mathcal{A}_{q\bar{q}}(x,r,\Delta=0) \equiv \sigma_{dip}(x,r) \longrightarrow 2\pi R_p^2 \left[1-\exp\left(-\frac{r^2 Q_{\rm sat}^2}{4}\right)\right]$$

- Dipole amplitude saturates for dipoles sizes larger than $1/Q_{\rm sat}$, where $Q_{\rm sat} \propto x^{-\lambda}$ is the so-called saturation scale.
- The saturation scale is energy dependent and sets the transverse momentum scale where unitarization corrections start to be important.

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

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

- The scaling function N is:

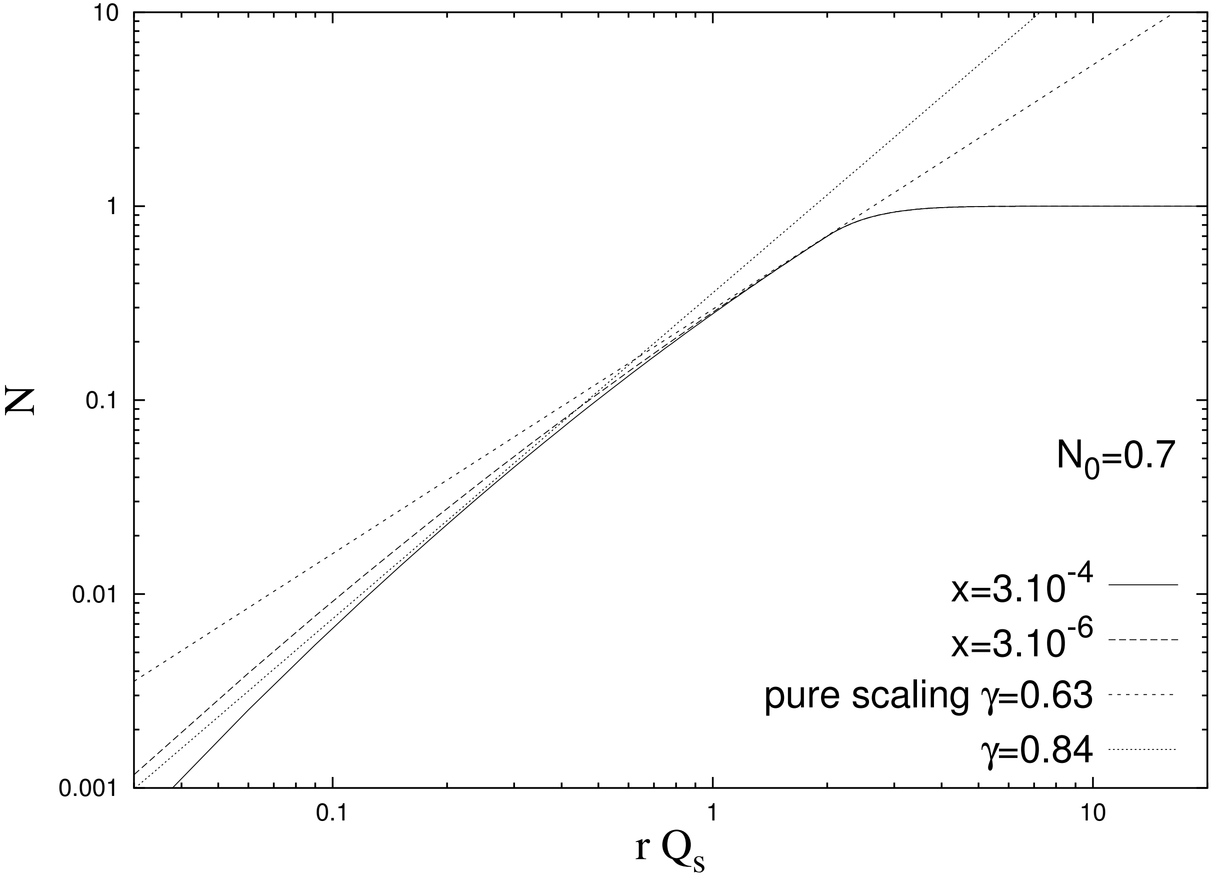
$$N\,(x, \boldsymbol{r}) = \begin{cases} \mathcal{N}_0 \left(\frac{\boldsymbol{r}^2 Q^2_{\rm sat}}{4}\right)^{\gamma_{\rm eff}\,(x,r)}, & \text{for } \boldsymbol{r}Q_{\rm sat} \le 2\,, \\ 1 - \exp\left[-a\,\ln^2\,(b\boldsymbol{r}Q_{\rm sat})\right], & \text{for } \boldsymbol{r}Q_{\rm sat} > 2\,, \end{cases}$$

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

The MPS model

- Example: r-dependence of dipole cross section

  $\sigma_{dip}(x, r) = \mathcal{A}_{q\bar{q}}(x, r, \Delta = 0)$



- Taming of dipole cross section takes place at $rQ_{\rm sat} \simeq 1$.

Elementary dipole scattering amplitude

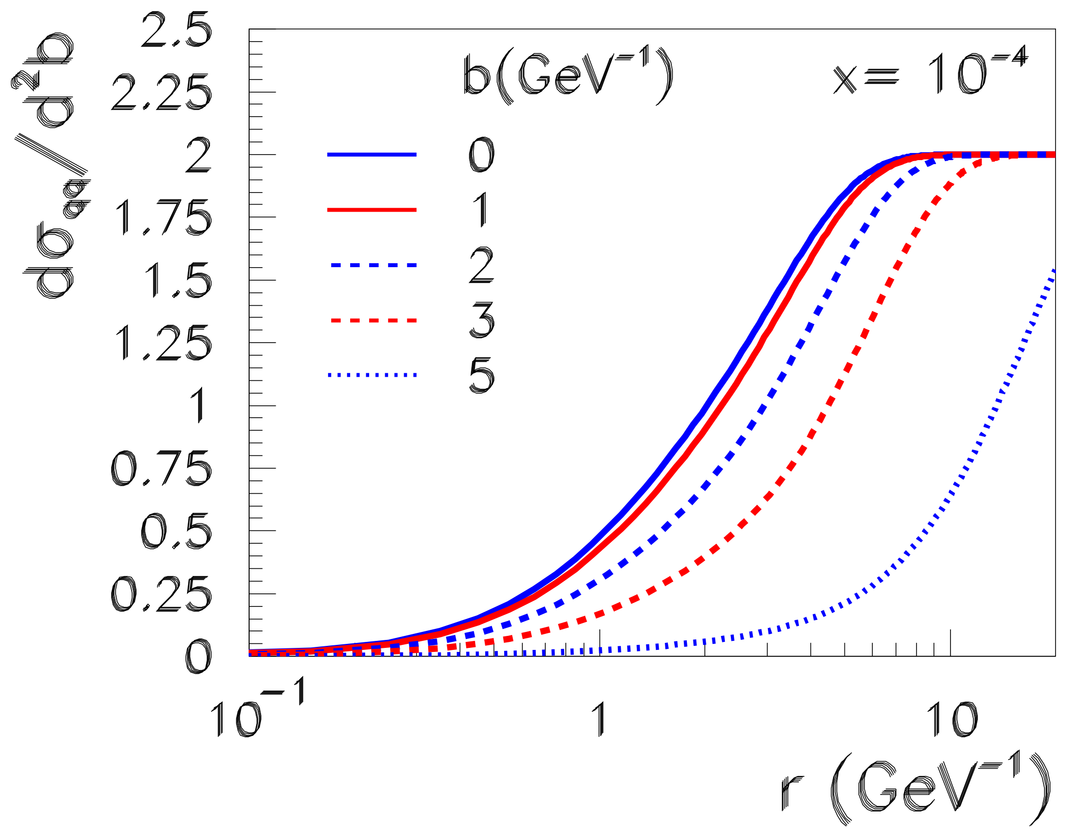
- For comparison, we use the impact parameter saturation model (H. Kowalski, L. Motyka and G. Watt, (2006) - b-SAT model), where the dipole scattering amplitude is written in the impact parameter space.
- In the b-SAT model the S-matrix element is given by:

$$S(x,r,b) = \exp\left[-\frac{\pi^2}{2N_c} r^2 \alpha_S(\mu^2)\, xg(x,\mu^2)\, T(b)\right],$$

- The scale μ^2 is related to the dipole size r by $\mu^2 = 4/r^2 + \mu_0^2$.
- The gluon density, $xg(x,\mu^2)$, is evolved from a scale μ_0^2 up to μ^2 using LO DGLAP evolution without quarks.
- The proton shape function $T(b)$ is normalized so that $\int d^2b\, T(b) = 1$ and one considers a Gaussian form for $T(b)$.

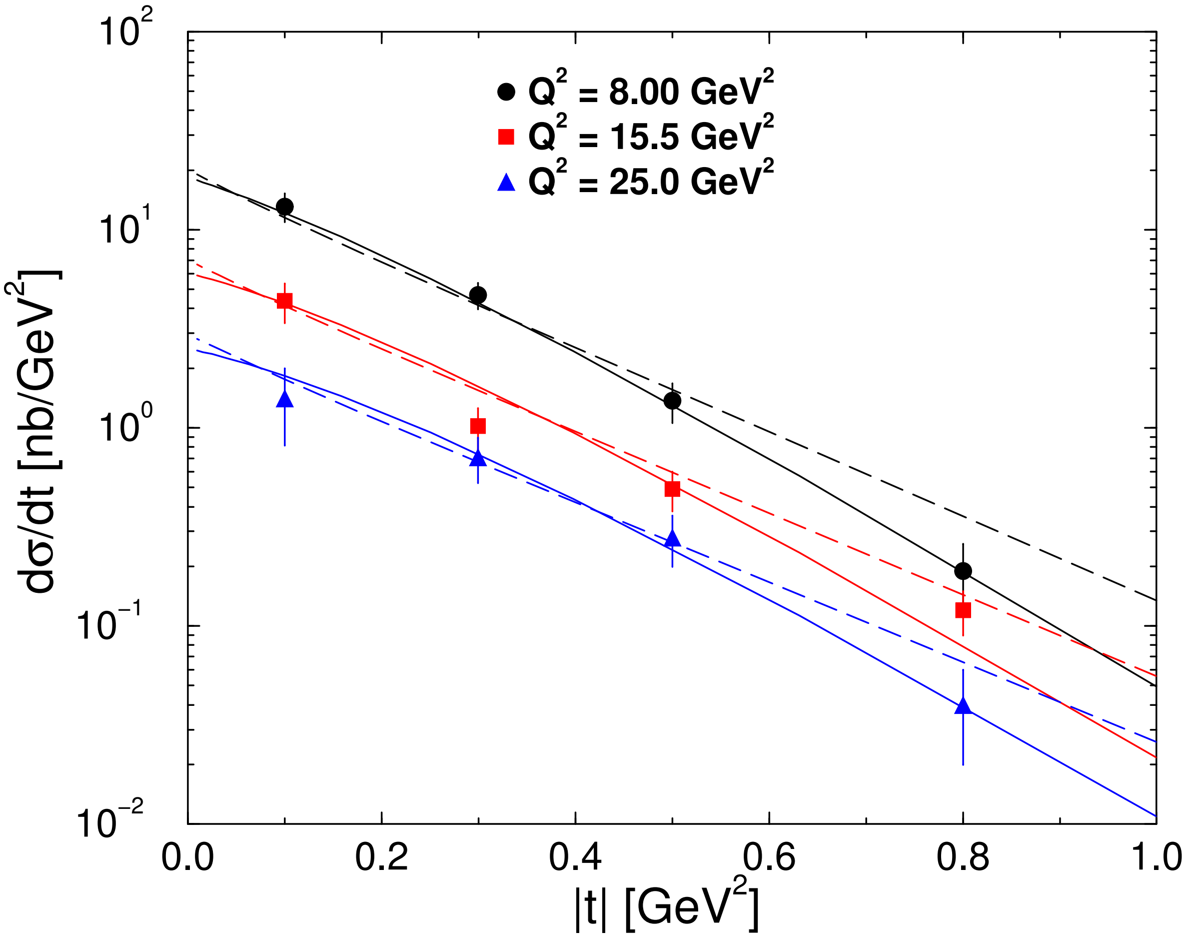
The b-SAT model

- Example: r-dependence of dipole cross section $\frac{d\sigma_{dip}}{d^2b} = 2\left[1 - S\left(x, r, b\right)\right]$.



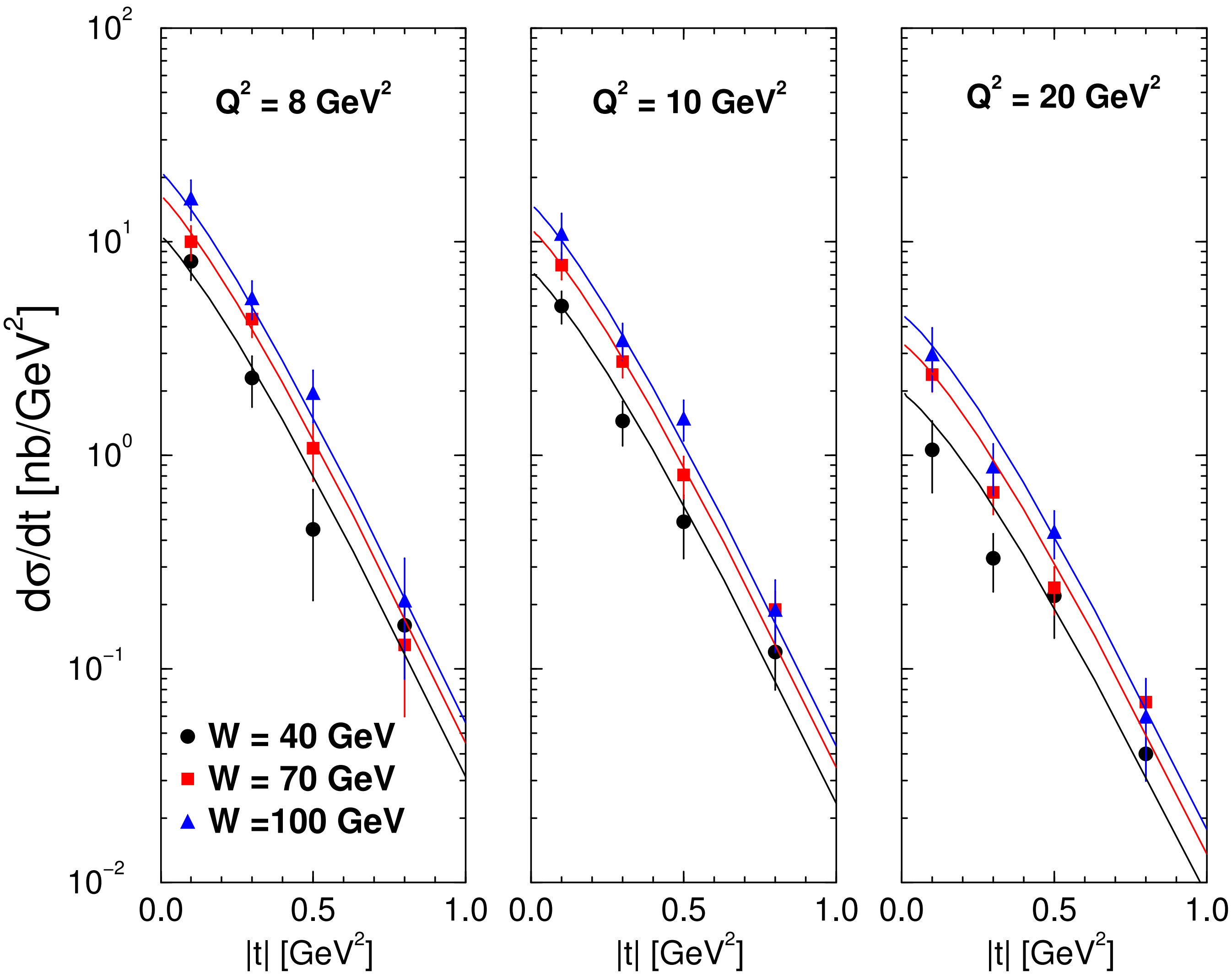
Phenomenology for DVCS on a nucleon

- The description of DVCS on a nucleon at DESY-HERA is very nice (model parameters are fixed).
- MPS model (solid lines) vs. b-SAT model (dashed lines) .



More results . . .

- DVCS cross section for several virtualities and energies (recent data from DESY-HERA/MPS model).



DVCS on nuclei

- In situation when the recoiled nucleus is not detected, measurements of DVCS observables with nuclear targets involves the coherent and incoherent contributions.
- The coherent scattering corresponds to the case in which the nuclear target remains intact (dominates at small t).
- The incoherent scattering occurs when the initial nucleus of atomic number A transforms into the system of $(A-1)$ spectator bound/free nucleons and one interacting nucleon (dominates at large t).
- There are a few calculations for nuclear DVCS using the QCD factorization scheme (for instance, A. Freund and M. Strikman/ V. Guzey investigations).

Coherent scattering

- Lets start by the coherent (elastic) nuclear DVCS contribution, $\gamma^* A \to \gamma A$, where the recoiled nucleus is intact.

$$\mathcal{A}^{\gamma^* A \to \gamma A} \propto \int d^2 r \int_0^1 dz\, \Psi^*_{h\bar{h}}(r, z, Q_2) \mathcal{A}^{nuc}_{q\bar{q}}(x, r, \Delta; A) \Psi_{h\bar{h}}(r, z, Q_1)$$

- Challenge: how to impplement a nuclear version of elementary dipole amplitude ?
- (*) Use Glauber-Gribov formalism to obtain nuclear shadowing corrections.
- (**) For saturation models we can relay on Geometric Scaling arguments and just replace $R_p \to R_A$ and $Q^2_{\text{sat},A}(x, t = 0) \to A^{\delta}\, Q^2_{\text{sat},p}(x, t = 0)$.
- Armesto, Salgado and Wiedemann, PRL94 (2005).

Coherent scattering

- Using the MPS model, we replace $2\pi R_p^2 \to 2\pi R_A^2$ and put $Q^2_{\mathrm{sat},A} = (A R_p^2/R_A^2)^{\Delta}\, Q^2_{\mathrm{sat},p}$.
- When $\Delta = 1$ such a replacement becomes the usual assumption for nuclear saturation scale, $Q^2_{\mathrm{sat},A} = A^{1/3}\, Q^2_{\mathrm{sat},p}$.

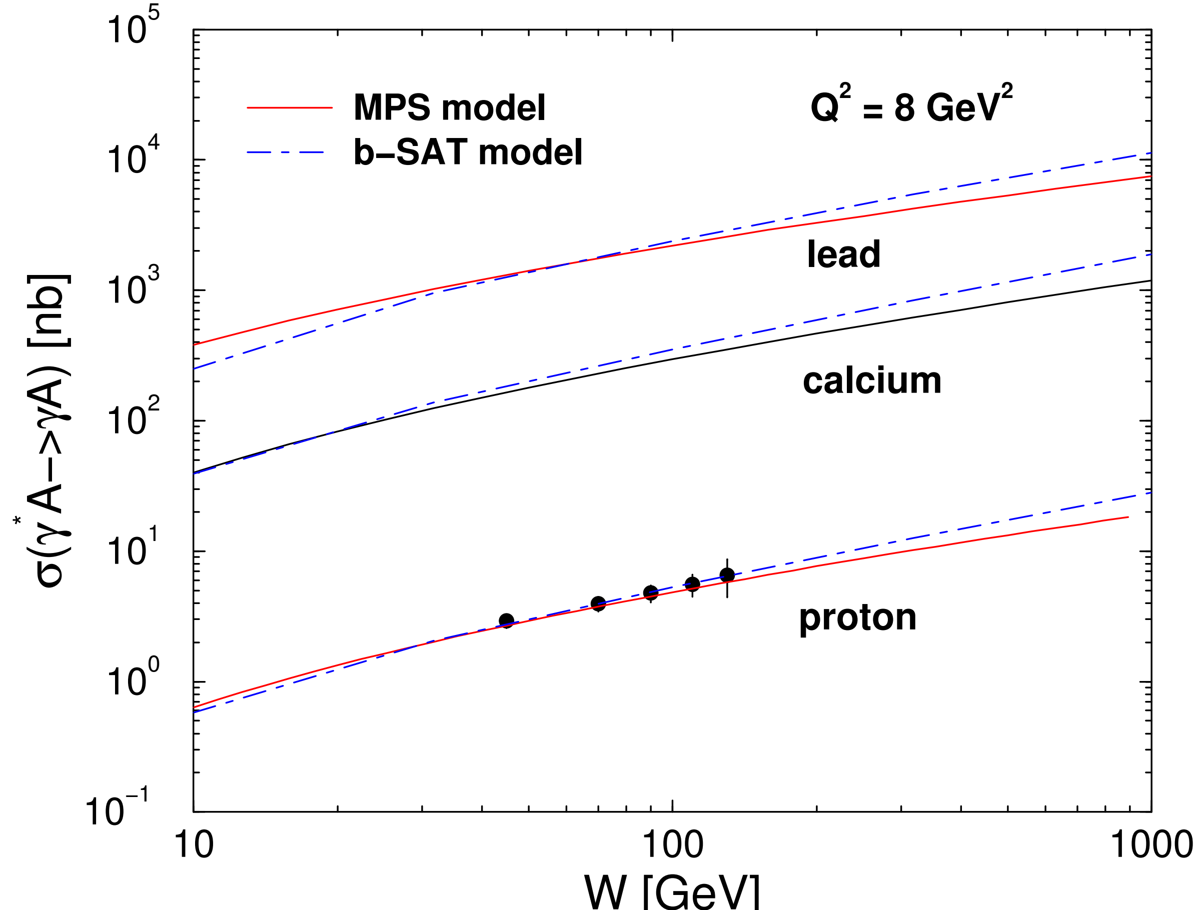
$$\mathcal{A}^{\mathrm{nuc}}_{q\bar{q}}(x,r,\Delta) = 2\pi R_A^2\, F_A(t)\, N\,(rQ_{\mathrm{sat},\,A};\, x)$$

- For b-SAT model, we replace the proton shape by the corresponding nuclear profile $T_A(b)$ (Wood-Saxon).
- It should be stressed that we are considering the limit of long coherence time, that is $l_c \gg R_A$.

$$S_A(x,r,b) = \exp\left[-\frac{\pi^2}{2N_c} r^2 \alpha_S(\mu^2)\, xg(x,\mu^2)\, T_A(b)\right]$$

Phonomenology for nuclear targets

- The coherent DVCS cross section will take the form $\frac{d\sigma_{\rm coh}}{dt} \approx A^2 F_A^2(t) \frac{d\sigma_N}{dt}$.
- The total coherent cross section (integrated over $|t|$) has an approximate A-dependence given by $\sigma_{\rm coh} \propto A^{4/3}\sigma_N$.



Incoherent scattering

- In incoherent (quasi-elastic) production of direct photons off nuclei, $\gamma^* A \to \gamma X$, one sums over all final states of the target nucleus except those which contain particle creation.
- We consider the high energy regime where the coherence length, $\ell_c = 2\omega/Q^2$, is large such that $\ell_c \gg R_A$ (ω is the energy of the virtual photon in the rest frame of the nucleus).

$$\left.\frac{d\sigma^{T,L}}{dt}\right|_{t=0} = \int d^2b\, T_A(b) \left| \left\langle \Psi_{\gamma}^{T,L} \middle| \sigma_{dip} \exp\left[-\frac{1}{2}\sigma_{dip}\, T_A(b)\right] \middle| \Psi_{\gamma^*}^{T,L} \right\rangle \right.$$

- $T_A(b) = \int_{-\infty}^{+\infty} dz\, \rho(b,z)$ is the nuclear thickness function.
- The brackets denote integration on phase space variables.

Incoherent scattering

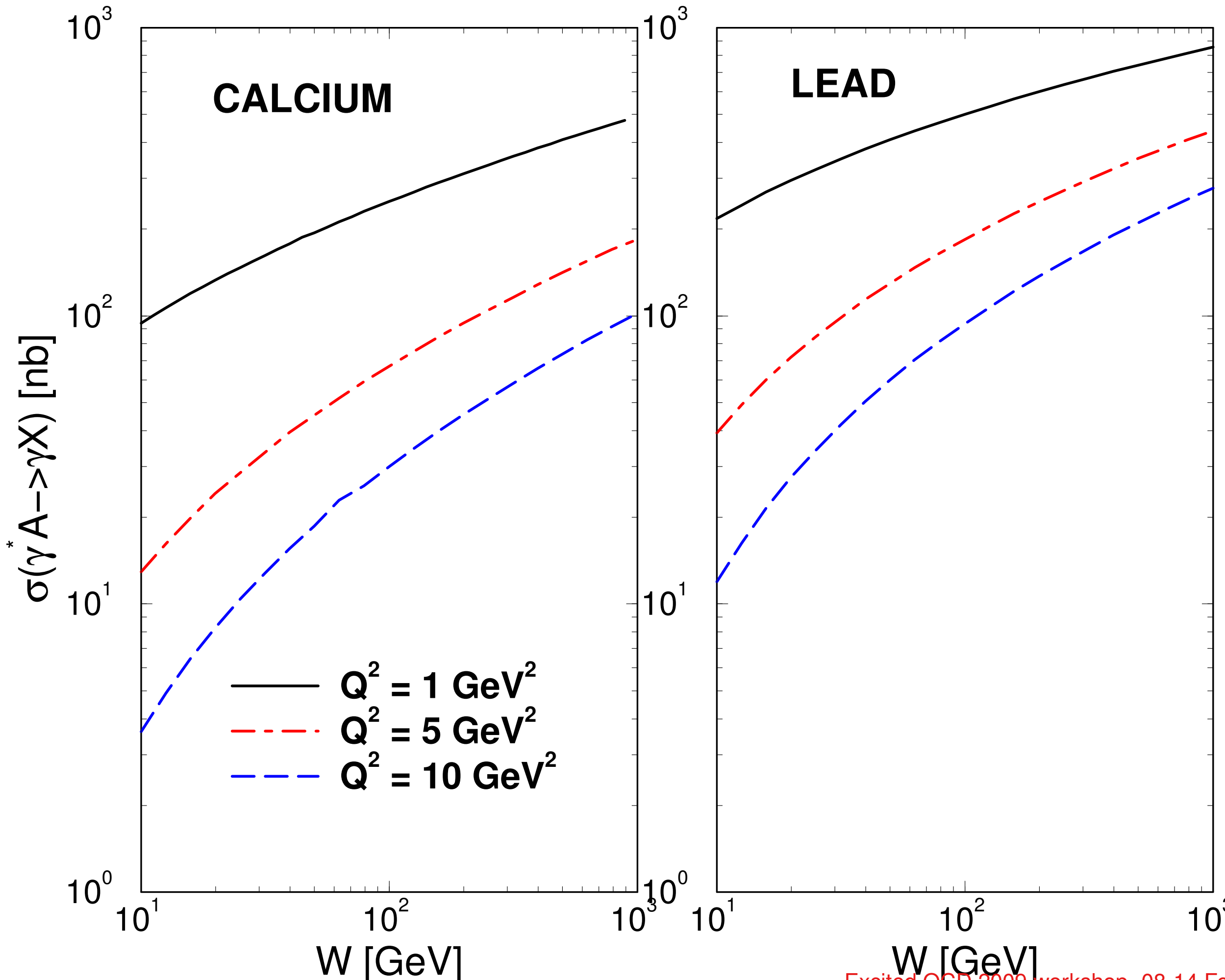
- The total incoherent DVCS cross section is given by $\sigma_{\rm incoh} = \frac{|\mathcal{A}(\gamma^* A \to \gamma X)|^2}{16\pi B_{\rm DVCS}}$, where $B_{\rm DVCS}$ is the t-slope in the DVCS on nucleons.
- The forward scattering amplitude gives:

$$\left.\frac{d\sigma^{\gamma^* A\to\gamma X}}{dt}\right|_{t=0} = \int d^2b\, T_A(b)$$
$$\times \left| \int d^2r \int dz\, \Phi_{\gamma^*\gamma}\, \sigma_{dip}(x,r)\ \exp\left[-\frac{1}{2}\sigma_{dip}(x,r) T_A(b)\right]\right|^2$$

- $\Phi_{\gamma^*\gamma}(z,r,Q^2;m_f)$ is the overlap function (wavefunctions for incoming/outgoing photons).

Phonomenology for nuclear targets

- Incoherent DVCS cross section behaves like $\frac{d\sigma_{\rm incoh}}{dt} \approx A \frac{d\sigma}{dt}$, where $\frac{d\sigma}{dt}$ denotes the cross section for quasi-free nucleon.
- It scales as A versus a A^2 scaling in the coherent case.



Summary

- DVCS off nuclei is a very promising tool to investigate the partonic structure of nuclei and it can be useful to clarify physics issues related to planned EICs (e.g., LHeC).
- Using color dipole formalism, we studied the DVCS process on nucleons and nuclei.
- Such an approach is powerful and describes a wide class of exclusive processes measured at DESY-HERA and at the experiment CLAS (Jeferson Lab.).
- The theoretical uncertainties are smaller in contrast to the exclusive vector meson production.
- We provide estimations for the coherent and incoherent DVCS cross section, investigating their energy and atomic number dependences.