



Nuclear DVCS at high energies within the color dipole approach

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Outline

- Motivation
- Deeply Virtual Compton Scattering (DVCS) at small- x
- The DVCS process in the color dipole approach
- Phenomenology for DVCS on a nucleon (cross check)
- The DVCS on nuclei in the color dipole approach
- Phenomenology for DVCS on a nucleus at high energies
- Summary

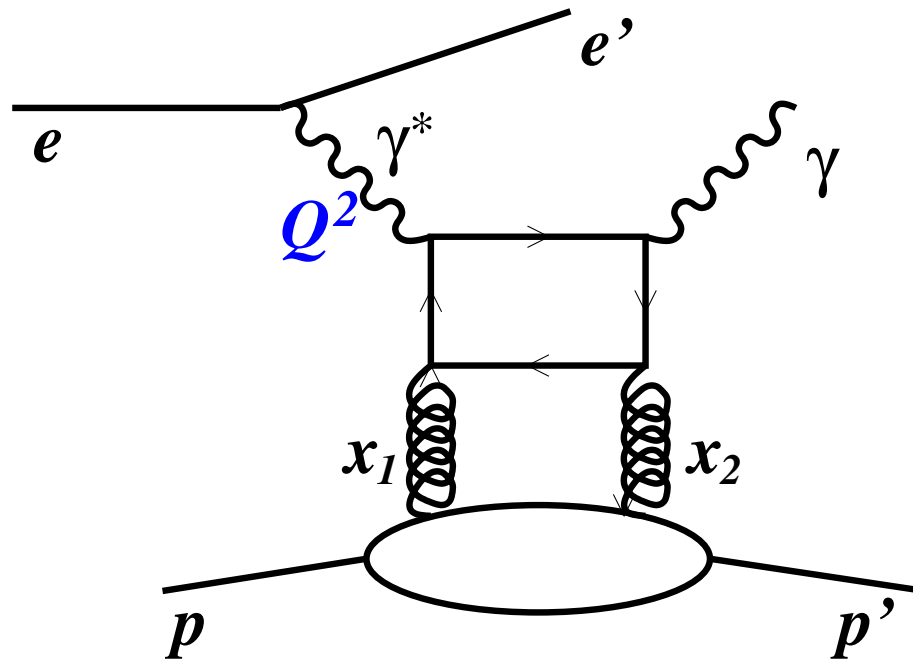
Motivation

- DVCS ($ep \rightarrow ep\gamma$) 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 or two quarks at larger x carrying different fractions of the initial proton momentum (**skewedness**).
- DVCS thus gives information on **generalized parton distributions** (**GPDs**) which depends on two momentum fractions x and x' and on the four-momentum transfer t at the proton vertex: $H_f(x, x', Q^2, t)$.
- Similar process also occurs in **eA colliders** (e.g., at the **LHeC**), $eA \rightarrow eA\gamma$, 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 CLAS experiment 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 **LHeC proposal**.

Kinematics for DVCS on a proton

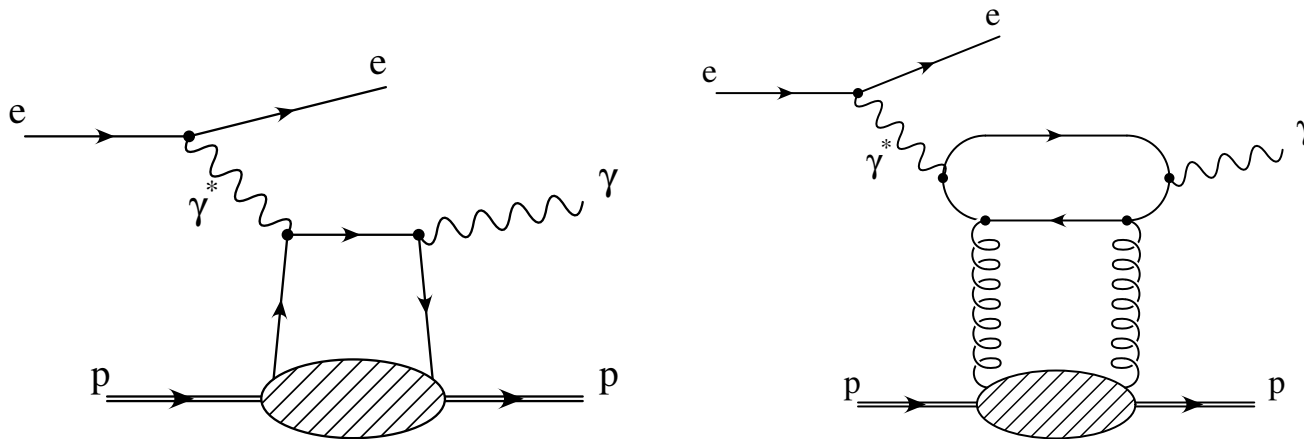


- Q^2 is the virtuality of incoming photon.
- W is the photon-proton center-of-mass energy.
- t is the four-momentum transfer at the proton vertex.
- Bjorken variable is $x = \frac{Q^2}{W^2 + Q^2}$.

DVCS - theoretical description

- Conventional partonic description of DVCS, $\gamma^* + p \rightarrow \gamma + p$, is described within the **QCD factorization framework**.
- Cross section at photon level is given by the convolution of hard coefficient functions and the corresponding **GPDs** (see e.g, L. Schoeffel/D. Mueller/J. Wagner talks).

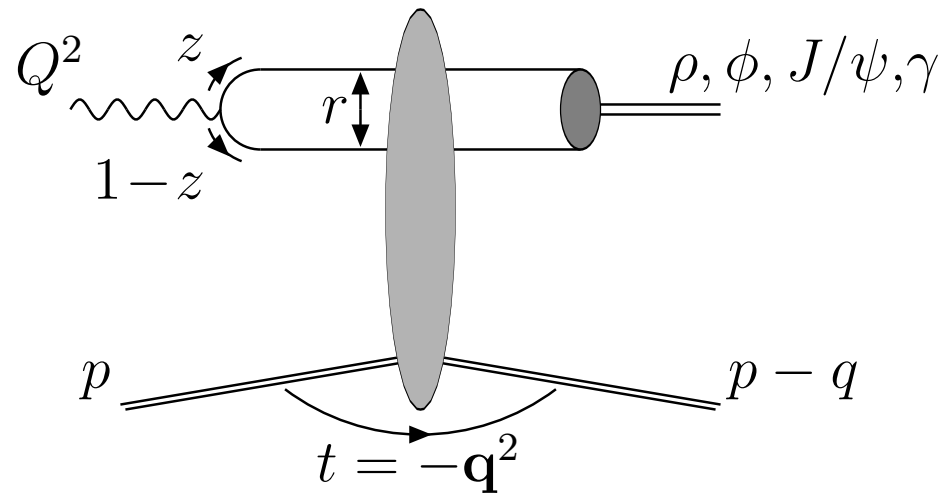
$$\sigma(\gamma^* p \rightarrow \gamma p) \propto C_f(Q^2, Q_0^2) \otimes H_f(x_1, x_2, Q^2, t; Q_0^2)$$



- 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:

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

- $\Psi_{h\bar{h}}(r, z, Q)$ 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,

$$\begin{aligned} (\Psi_\gamma^* \Psi_{\gamma^*})_T^f &= \frac{N_c \alpha_{\text{em}} e_f^2}{2\pi^2} \{ [z^2 + \bar{z}^2] \varepsilon_1 K_1(\varepsilon_1 r) \varepsilon_2 K_1(\varepsilon_2 r) \\ &+ m_f^2 K_0(\varepsilon_1 r) K_0(\varepsilon_2 r) \} \end{aligned}$$

- 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 $Q_1^2 = Q^2$ (incoming virtual photon) and $Q_2^2 = 0$ (outgoing real photon).
- The **elastic diffractive cross section** is then given by,

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

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.

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

- Dipole amplitude saturates for dipoles sizes larger than $1/Q_{sat}$, where $Q_{sat} \propto x^{-\lambda}$ 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.

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

- The t dependence of the **saturation scale** is parametrised as

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

- The scaling function N is:

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

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

Elementary dipole scattering amplitude

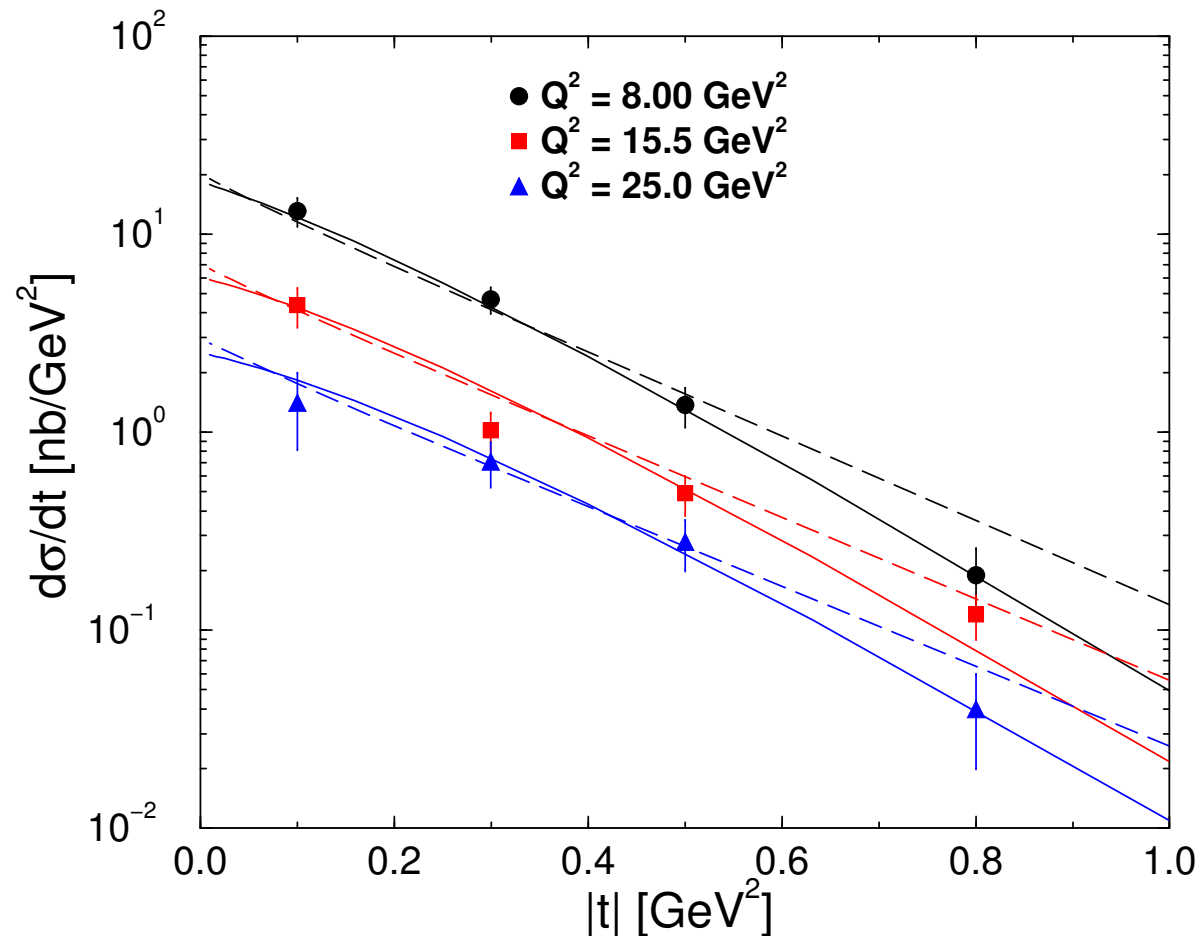
- For comparison, we use the **impact parameter saturation model** (H. Kowalski, L. Motyka and G. Watt, (2006) - b-SAT model).
- Differential dipole cross section is written in the impact parameter space.

$$\frac{d\sigma_{q\bar{q}}}{d^2b} = 2 \left[1 - \exp \left(-\frac{\pi^2}{2N_c} r^2 \alpha_S(\mu^2) xg(x, \mu^2) T(b) \right) \right],$$

- 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 $T(b)$.

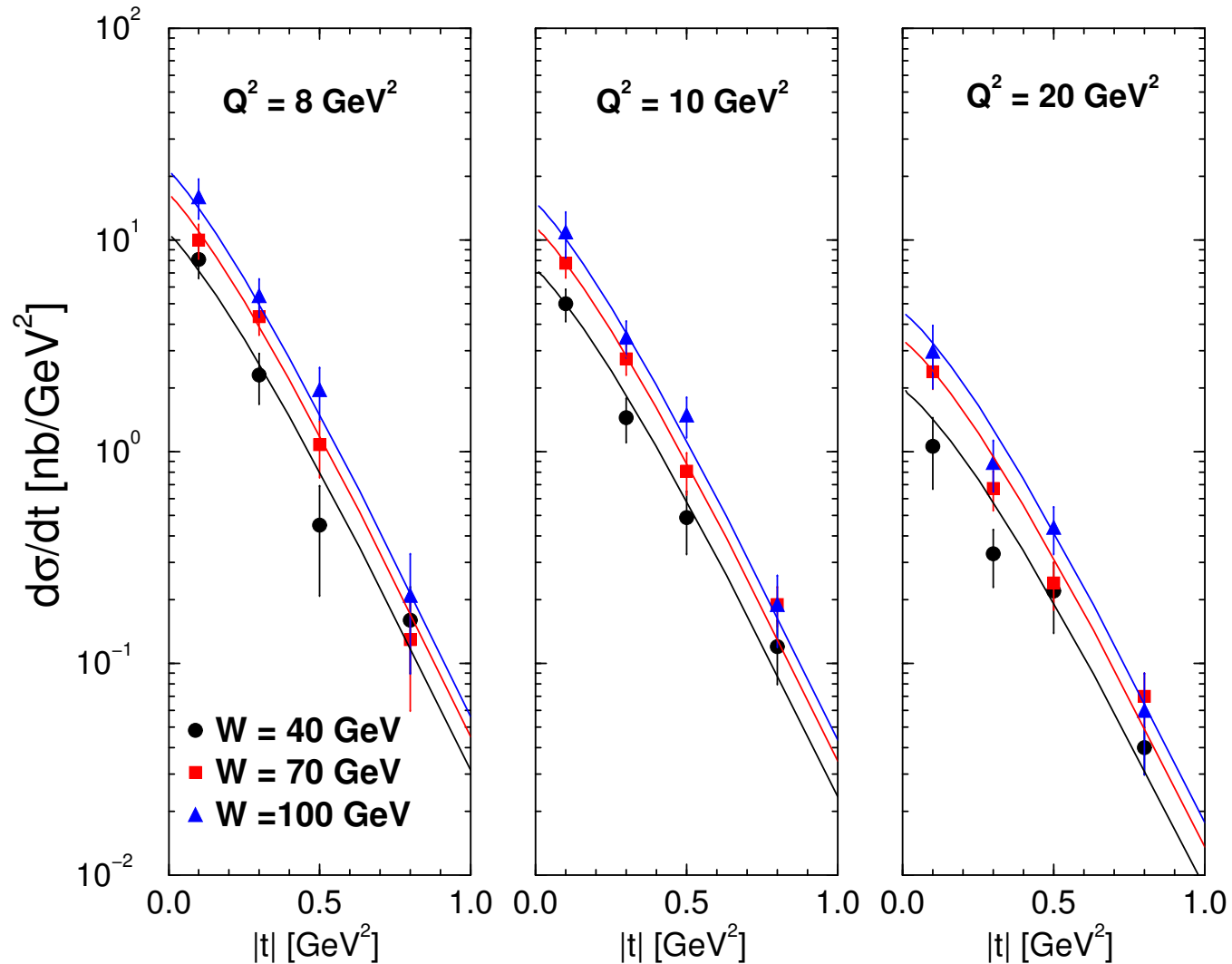
Phenomenology for DVCS on a nucleon

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



More results (cross check) . . .

- 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 **pQCD factorization scheme** (for instance, A. Freund and M. Strikman/ V. Guzey investigations).

Coherent scattering

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

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

- **Challenge**: how to implement a **nuclear version** of elementary dipole amplitude ?
- (*) Use Glauber-Gribov formalism to obtain nuclear shadowing corrections.
- (**) For saturation models we can rely on **Geometric Scaling** arguments (see N. Armesto's plenary talk).
- See: Armesto, Salgado and Wiedemann, PRL94 (2005).

Coherent scattering

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

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

- For b-SAT model in nuclear case, we can use Glauber approximation (see, e.g. T. Lappi's talk).
- It should be stressed that we are considering the limit of long coherence time, that is $l_c \gg R_A$.

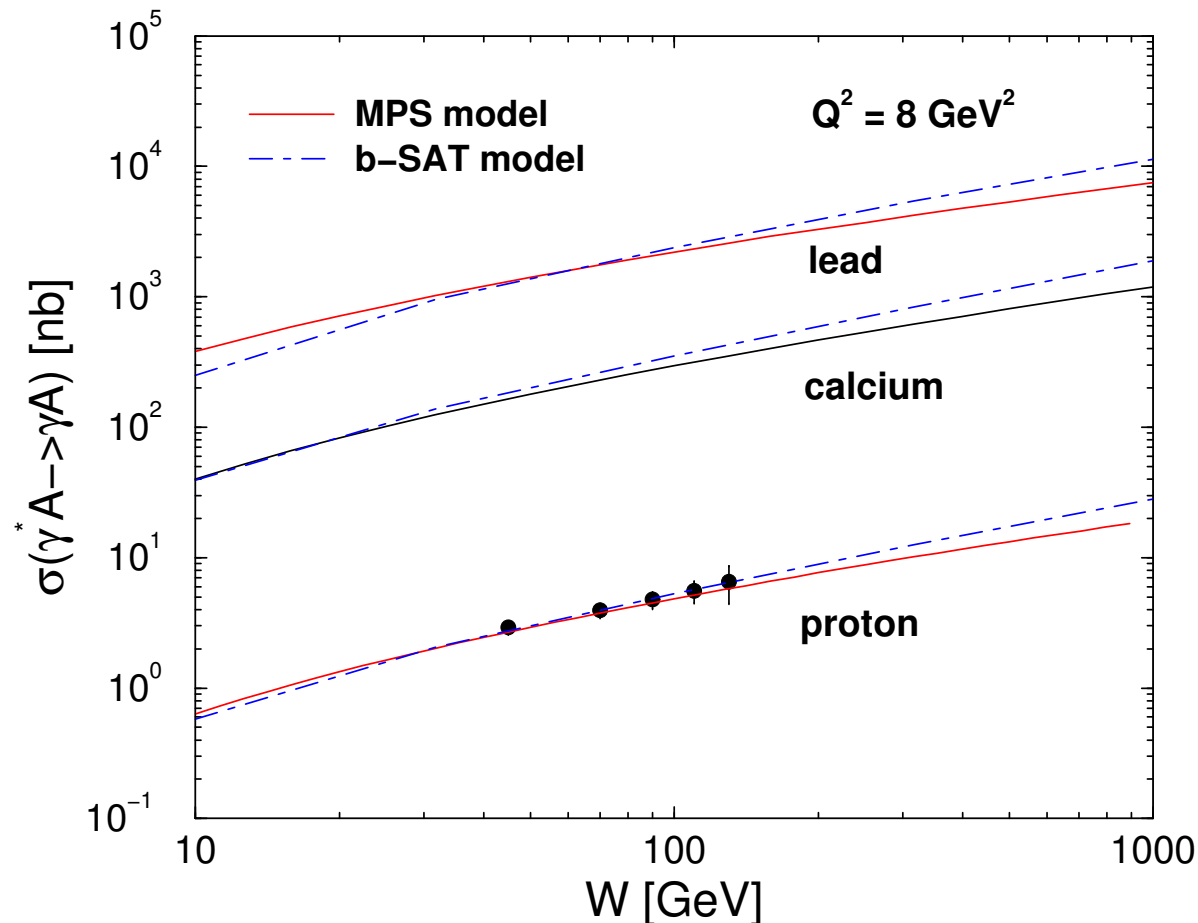
$$\frac{d\sigma_{q\bar{q}}^A}{d^2b} = 2 \left[1 - \exp \left(-\frac{\pi^2}{2N_c} r^2 \alpha_S(\mu^2) x g(x, \mu^2) T_A(b) \right) \right]$$

Phenomenology for nuclear targets

- The coherent DVCS cross section will take the form

$$\frac{d\sigma_{\text{coh}}}{dt} \approx A^2 F_A^2(t) \frac{d\sigma_N}{dt}.$$

- The total coherent cross section (integrated over $|t|$) has an approximate **A-dependence** given by $\sigma_{\text{coh}} \propto A^{4/3} \sigma_N$.



Incoherent scattering

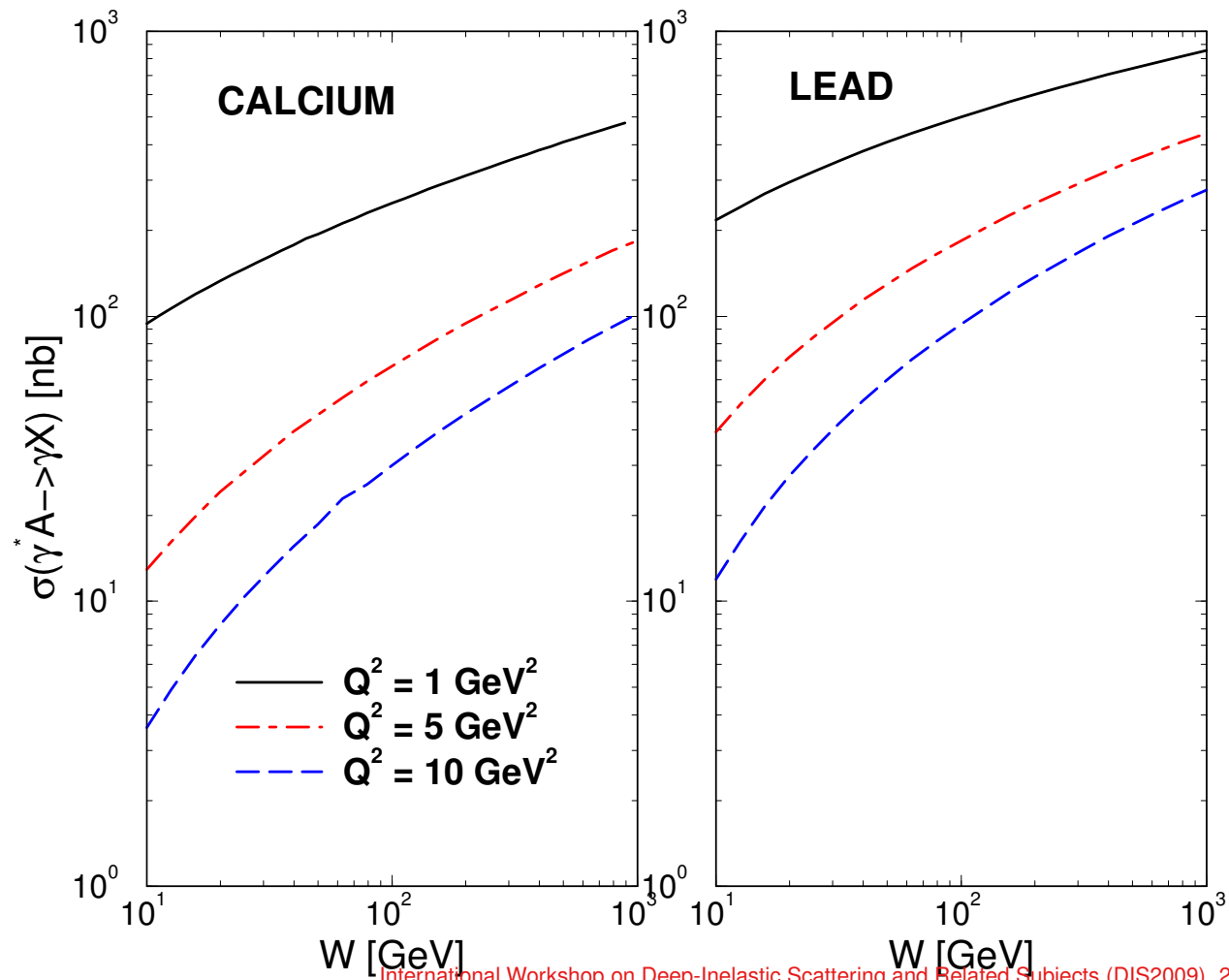
- In **incoherent** (**quasi-elastic**) production of direct photons off nuclei, $\gamma^* A \rightarrow \gamma X$, one sums over all final states of the target nucleus except those which contain particle creation.
- We consider the high energy regime where the coherence length, $\ell_c = 2\omega/Q^2$,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

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

- Here, $\sigma_{dip}(x, r) = \mathcal{A}_{q\bar{q}}(x, r, \Delta = 0)$
- $T_A(b) = \int_{-\infty}^{+\infty} dz \rho(b, z)$ is the nuclear thickness function.
- The brackets denote integration on phase space variables.

Phenomenology for nuclear targets

- Incoherent DVCS cross section behaves like $\frac{d\sigma_{\text{incoh}}}{dt} \approx A \frac{d\sigma}{dt}$, 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 nuclei at small- x .
- Such an approach is powerful and describes a wide class of exclusive processes measured at DESY-HERA.
- 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.