DVCS at Collider Energies

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Introduction

$$e + p \to e + p + \gamma$$

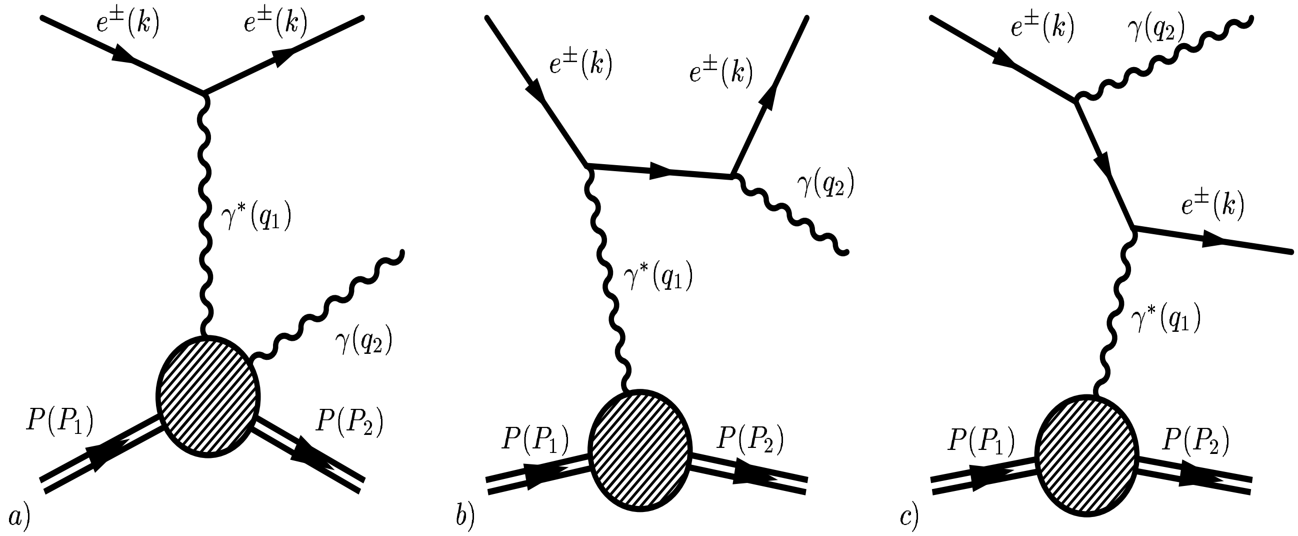

Figure 1: a) DVCS graph, b) BH with photon from final state lepton and c) with photon from initial state lepton.

- Process best suited to access Generalized Parton Distributions(GPDs).
- Proven Factorization Theorem.
- Interference with Bethe-Heitler process directly singles out hadronic amplitudes.
- Experimentally measured:
  - H1/ZEUS results on $\sigma(\gamma^* p)$ agree with NLO QCD results.
  - HERMES and CLAS results on the Single Spin Asymmetry (SSA) and Hermes on the Charge Asymmetry (CA) agree too.

Definition of Observables

General structure of observables:

$$\frac{d\sigma}{dx dQ^2 d|t| d\phi} = \text{DVCS} \mp \text{Interference} + \text{BH}$$

$$\propto \left(|\mathcal{T}_{DVCS}|^2 \mp \mathcal{T}_{DVCS}\mathcal{T}^{BH} + \mathcal{T}^2_{BH} \right)$$

DVCS :

$$f(x, Q^2, t, \phi) \sim f\left(|M|^2_{\text{Tw-2,4}}\right) + \cos(\phi) f\left(M_{\text{Tw-2}}, M_{\text{Tw-3}}\right)$$

$$+ \cos(2\phi) f\left(M_{\text{Tw-2}}, M_{\text{Tw-4}}\right) + \lambda\Big[\sin(\phi) f\left(M_{\text{Tw-2}}, M_{\text{Tw-3}}\right)$$

$$+ \sin(2\phi) f\left(M_{\text{Tw-2}}, M_{\text{Tw-4}}\right)\Big]$$

Interference :

$$f_1(x, Q^2, t, \phi) \sim \frac{1}{P_1(\phi) P_2(\phi)}\Big[\cos(\phi) f\left(\text{Re } M_{\text{Tw-2}}\right)$$

$$+ \cos(2\phi) f\left(\text{Re } M_{\text{Tw-3}}\right) + \cos(3\phi) f\left(\text{Re } M_{\text{Tw-2}}\right)$$

$$+ \lambda\Big(\sin(\phi) f\left(\text{Im } M_{\text{Tw-2}}\right) + \sin(2\phi) f\left(\text{Im } M_{\text{Tw-3}}\right)\Big)\Big]$$

BH : $f_2(x, Q^2, t, \phi)$ with a very complicated ϕ dependence which simplifies drastically at small x_{bj} and t.

Single Spin Asymmetry:

$$\Delta\sigma = d\sigma^{+} - d\sigma^{-}$$

$$\text{SSA} = \frac{2\int_0^{2\pi} d\phi\ \sin(\phi)\Delta\sigma}{\int_0^{2\pi} d\phi\ d\sigma^{\text{tot}}} \sim f\left(\text{Im}\ M_{\text{Tw-2}}\right)$$

Charge Asymmetry:

$$\Delta d\sigma^{\text{unpol}} = d\sigma^{-,\text{tot}} - d\sigma^{+,\text{tot}}$$

$$\text{CA} = \frac{2\int_0^{2\pi}\ \cos(\phi)\Delta d\sigma^{\text{tot}}}{\int_0^{2\pi} d\phi\ d\sigma^{\text{tot}}} \sim f\left(\text{Re}\ M_{\text{Tw-2}}\right)$$

$\sigma_{DVCS}(\gamma^* p \to \gamma p)$ at small x:

$$\frac{d^2\sigma(ep \to ep\gamma)}{dy dQ^2} = \frac{\alpha_{e.m.}(1+(1-y)^2)}{2\pi y Q^2}\sigma_{DVCS}(\gamma^* p \to \gamma p)$$

$$\sigma_{DVCS}(\gamma^* p \to \gamma p) = \frac{\alpha^2 x^2 \pi}{Q^4 B\left(Q^2\right)}|M_{DVCS}|^2|_{t=0}$$

$$B(Q^2) = B_0\left(1 - 0.15\ln\frac{Q^2}{2}\right)\ \Rightarrow\ B_0 \leftarrow \text{slope depends on target}$$

DVCS Amplitude:

$$M = T \otimes H + \text{terms } O(m/Q, \sqrt{-t}/Q)$$

T's and evolution of GPDs (H) known in LO and NLO.

Specifications of GPD model:

→ DGLAP region: $H^{S,NS,g}(X,\zeta) \equiv q^{S,NS,g}\left(\frac{X-\zeta/2}{1-\zeta/2}\right)/(1-\zeta/2)$

→ ERBL region: Simple analytical form respecting polynomiality:

$$H^{g,NS}(X,\zeta) = H^{g,NS}(\zeta)\left[1 + A^{g,NS}(\zeta)C^{g,NS}(X,\zeta)\right],$$

$$H^{S}(X,\zeta) = H^{S}(\zeta)\left(\frac{X-\zeta/2}{\zeta/2}\right)\left[1 + A^{S}(\zeta)C^{S}(X,\zeta)\right]$$

$$C^{g,NS}(X,\zeta) = \frac{3}{2}\frac{2-\zeta}{\zeta}\left(1 - \left(\frac{X-\zeta/2}{\zeta/2}\right)^2\right),$$

$$C^{S}(X,\zeta) = \frac{15}{2}\left(\frac{2-\zeta}{\zeta}\right)^2\left(1 - \left(\frac{X-\zeta/2}{\zeta/2}\right)^2\right)$$

C's vanish at $X=\zeta$ to guarantee continuity of the GPDs.

Forward PDFs used from now on:

MRST2001 ($Q_0 = 1$ GeV) and CTEQ6 ($Q_0 = 1.3$ GeV)

DVCS in ep scattering

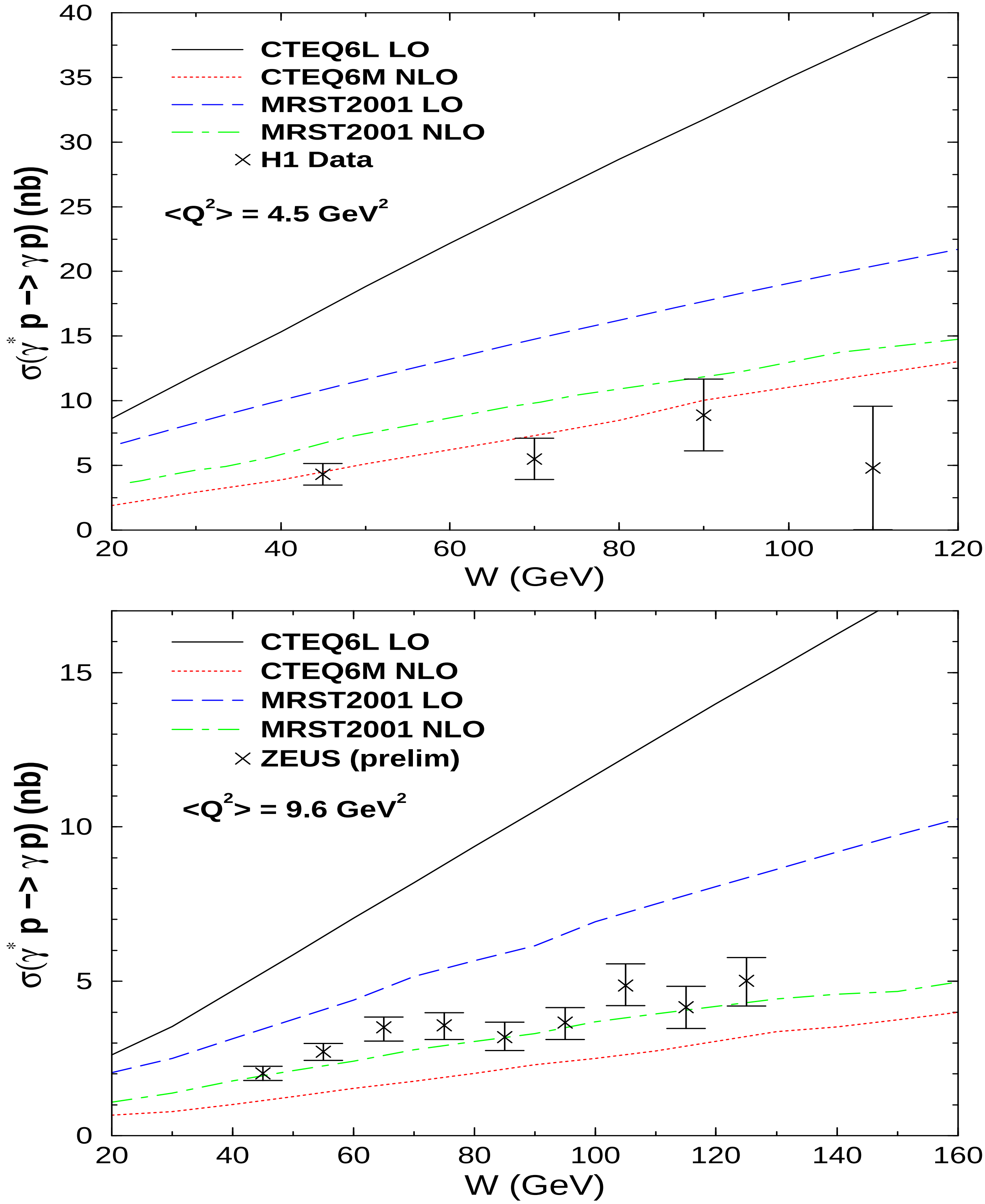

Figure 2: Photon level cross section $\sigma(\gamma^* P \to \gamma P)$, vs. W at $Q^2 = 4.5$ GeV^2 (H1, upper plot), and at $Q^2 = 9.6$ GeV^2 (ZEUS, lower plot) for $B = 6.5$ GeV^{-2} with AJ/FM ansatz.

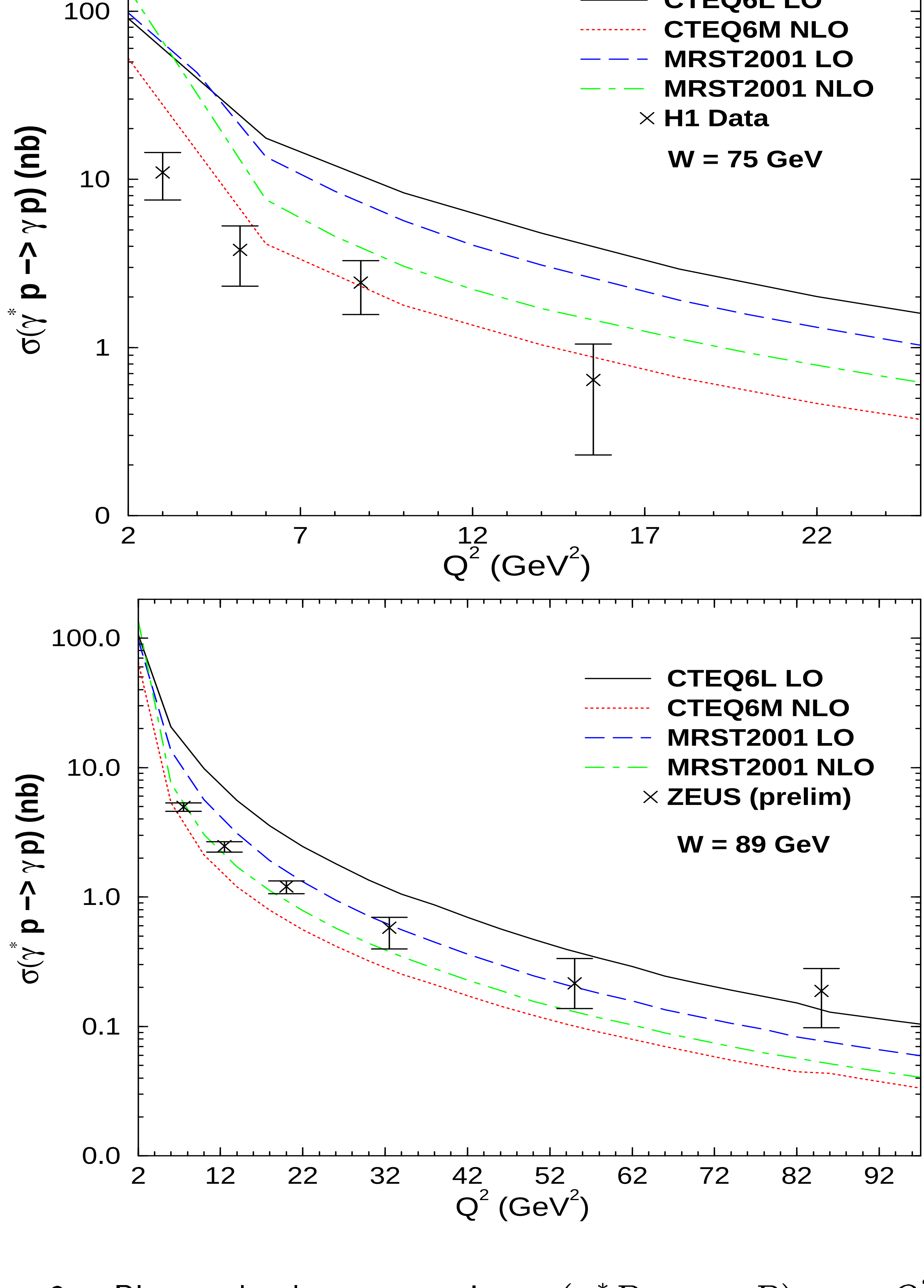

Figure 3: Photon level cross section $\sigma(\gamma^* P \to \gamma P)$, vs. Q^2 at $W = 75$ GeV (H1, upper plot), and at $W = 89$ GeV (ZEUS, lower plot) for $B = 6.5$ GeV^{-2} with AJ/FM ansatz.

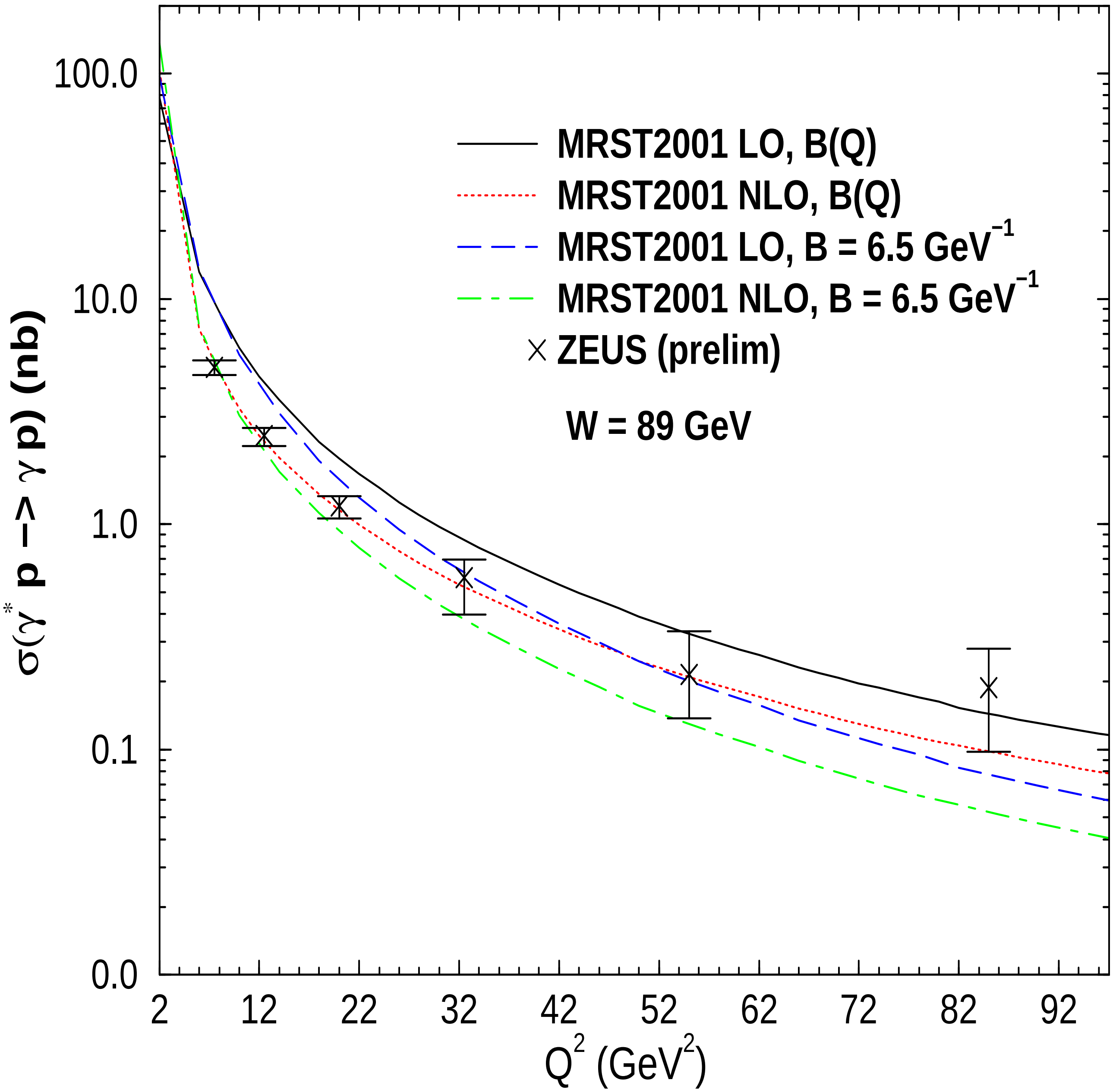

Figure 4: The effect on the DVCS cross section, in the average kinematics of the ZEUS data, of introducing a simple Q^2-dependent model for B.

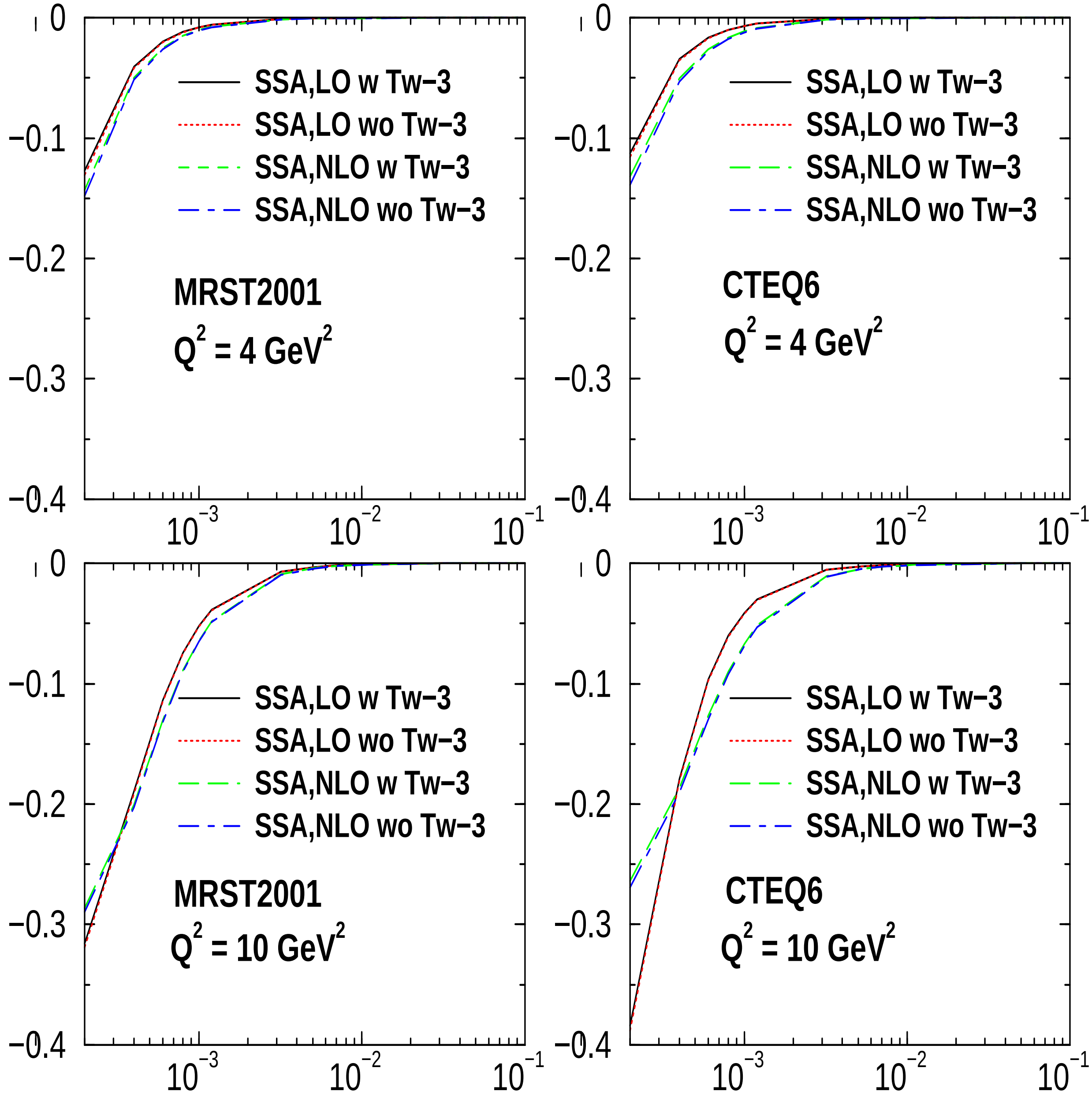

Figure 5: The SSA for HERA in $x = \zeta$ for integrated t and fixed Q^2.

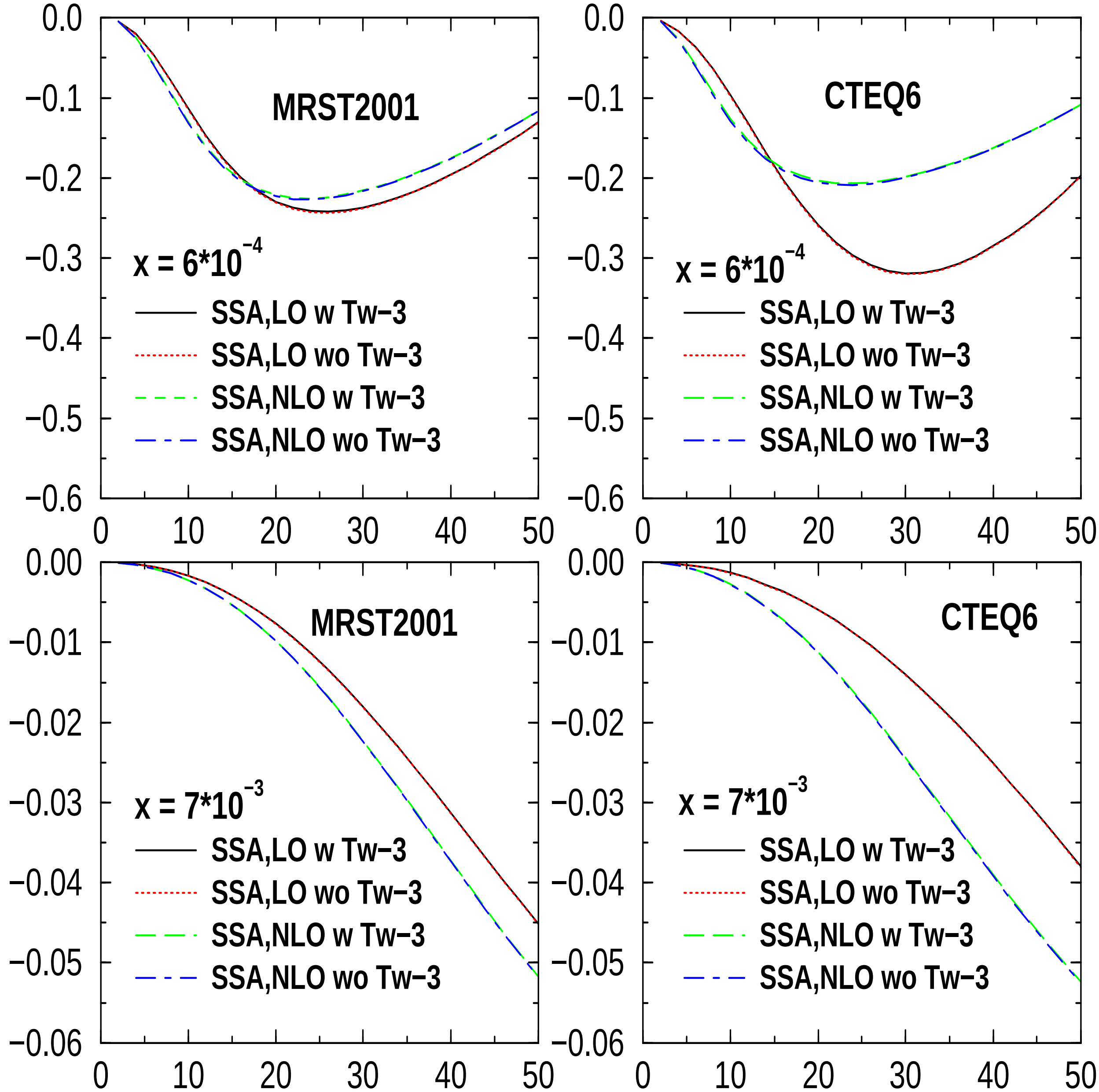

Figure 6: The SSA for HERA in Q^2 for integrated t and fixed $x = \zeta$.

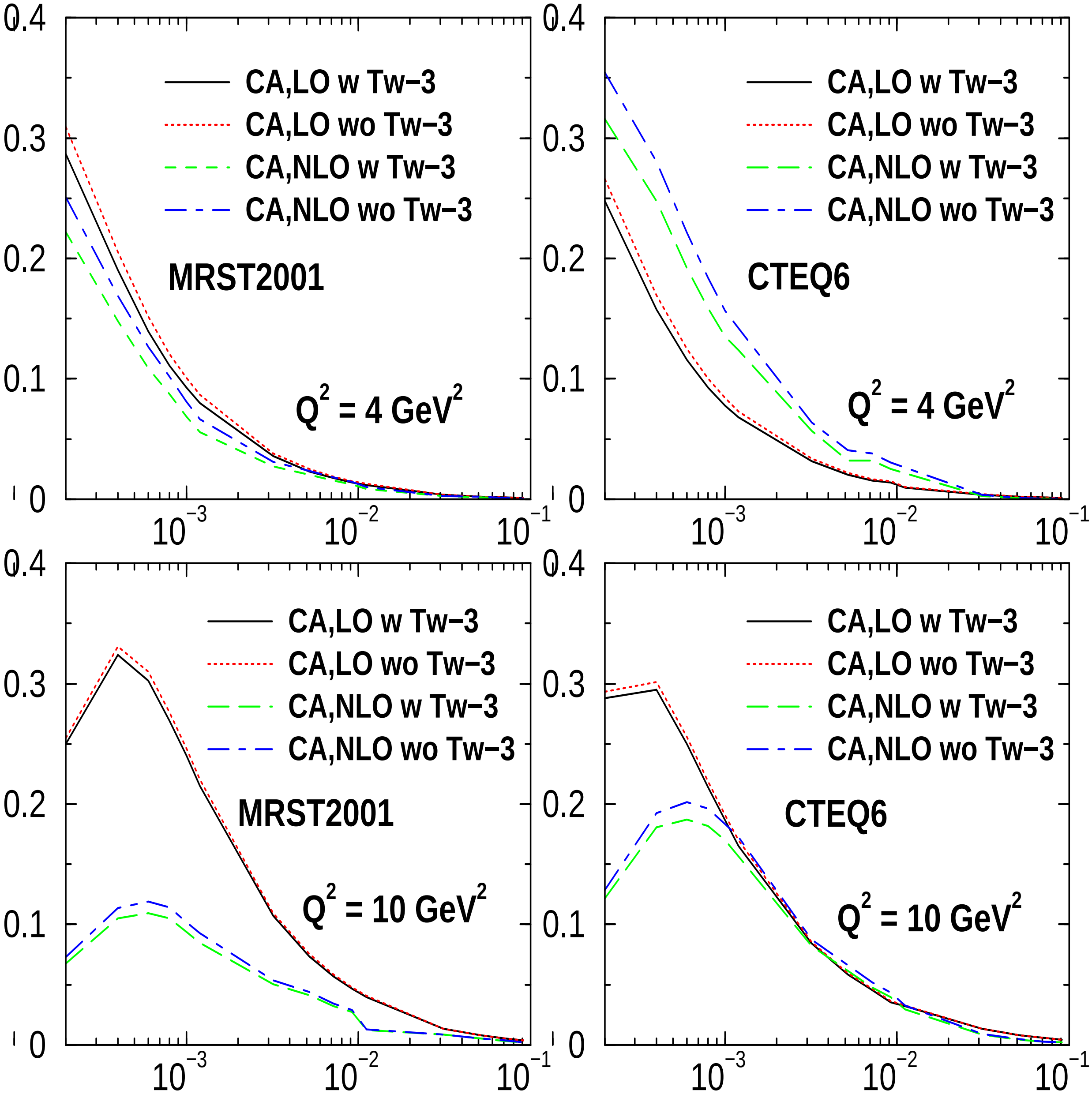

Figure 7: The CA for HERA in $x = \zeta$ for integrated t and fixed Q^2.

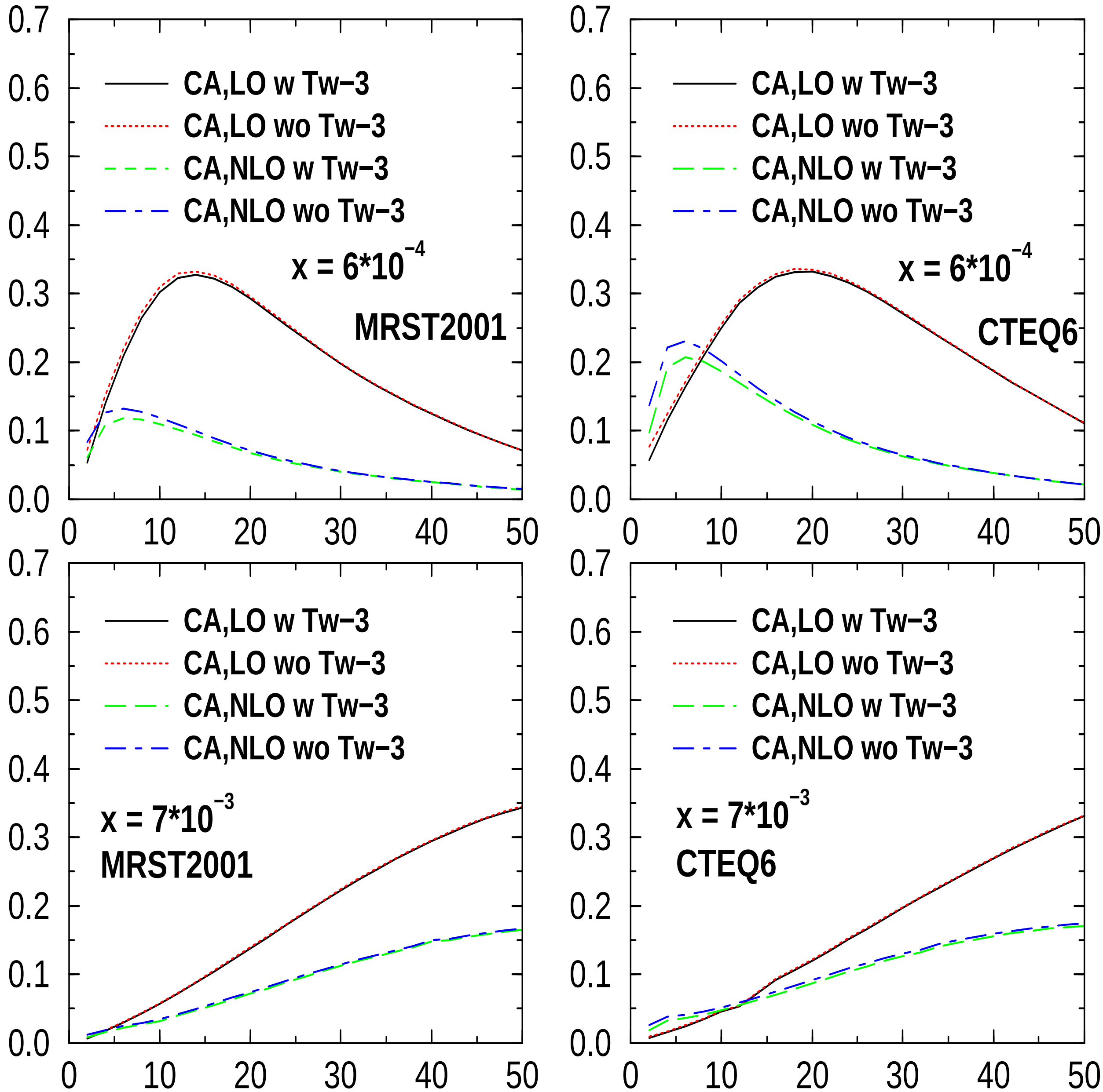

Figure 8: The CA for HERA in Q^2 for integrated t and fixed $x = \zeta$.

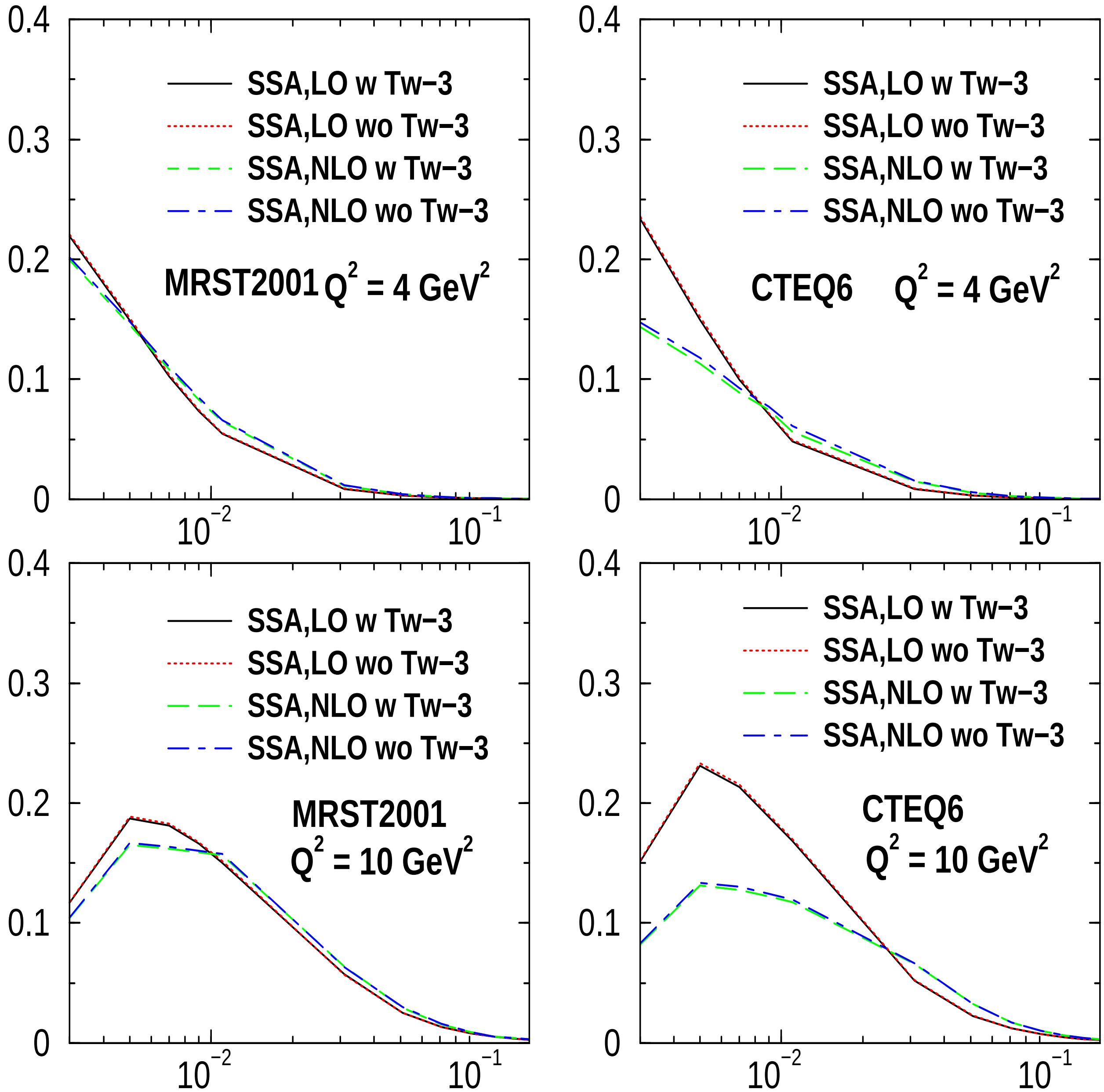

Figure 9: The SSA for EIC in $x = \zeta$ for integrated t and fixed Q^2.

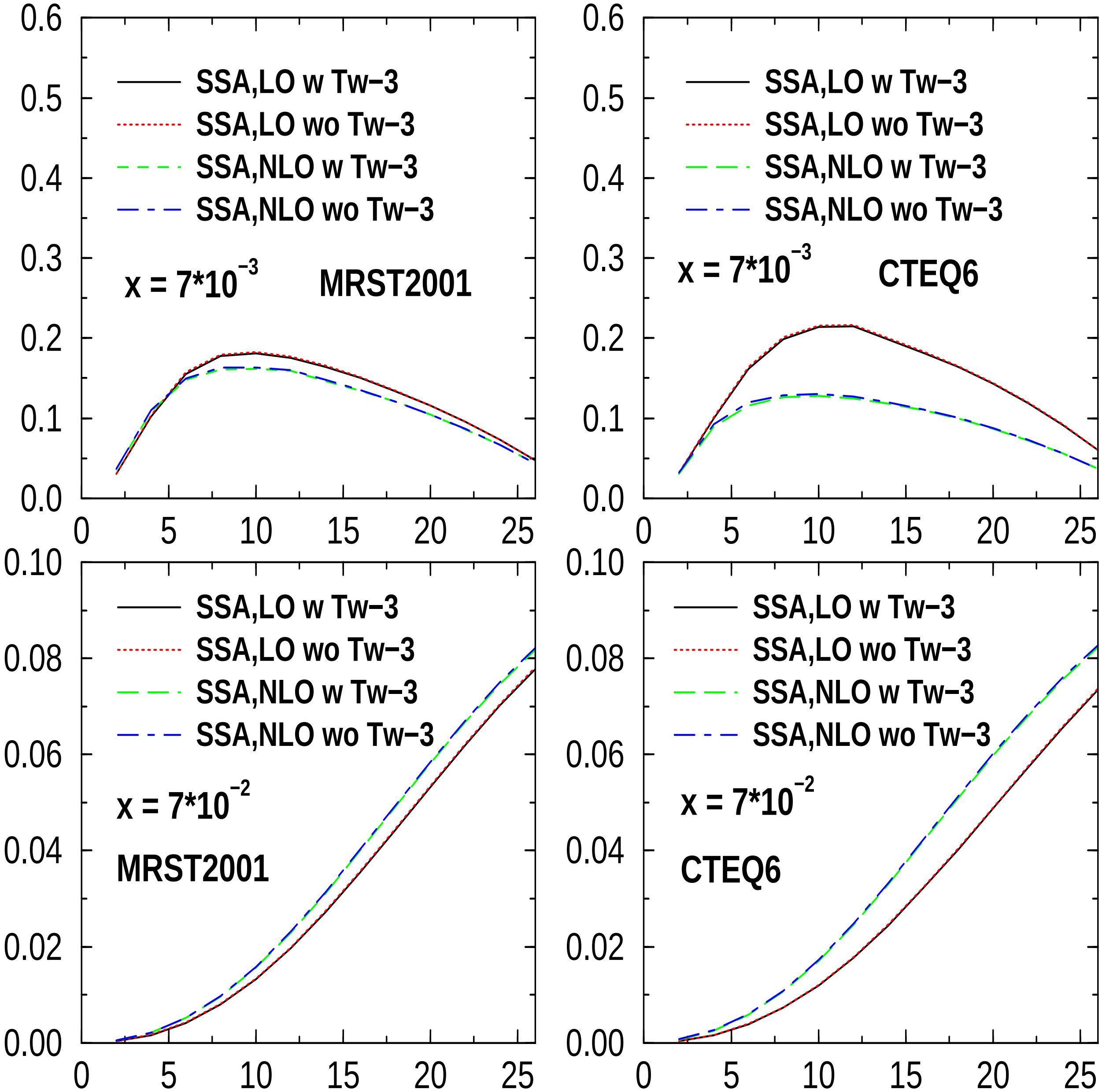

Figure 10: The SSA for EIC in Q^2 for integrated t and fixed $x = \zeta$.

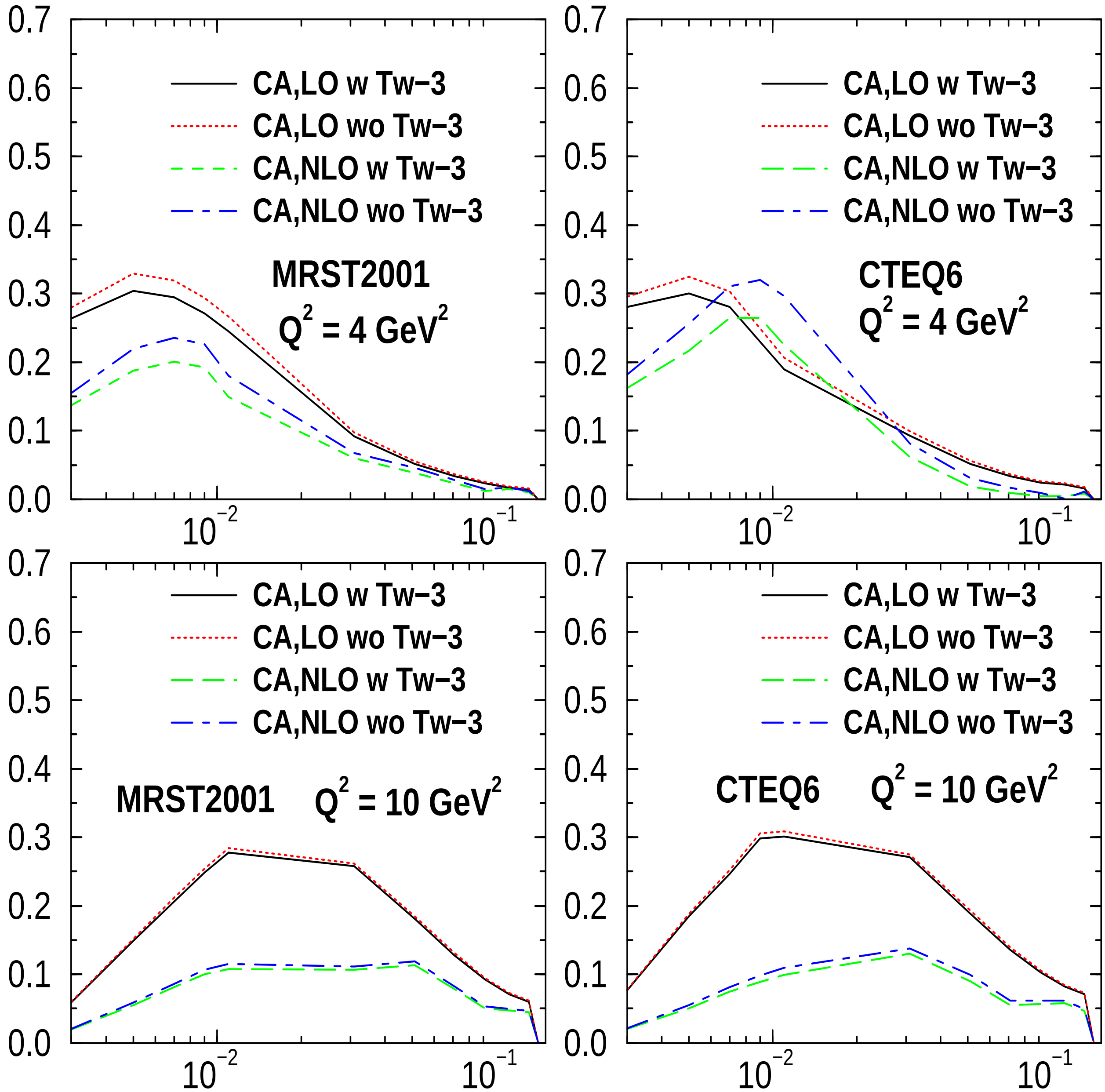

Figure 11: The CA for EIC in $x = \zeta$ for integrated t and fixed Q^2.

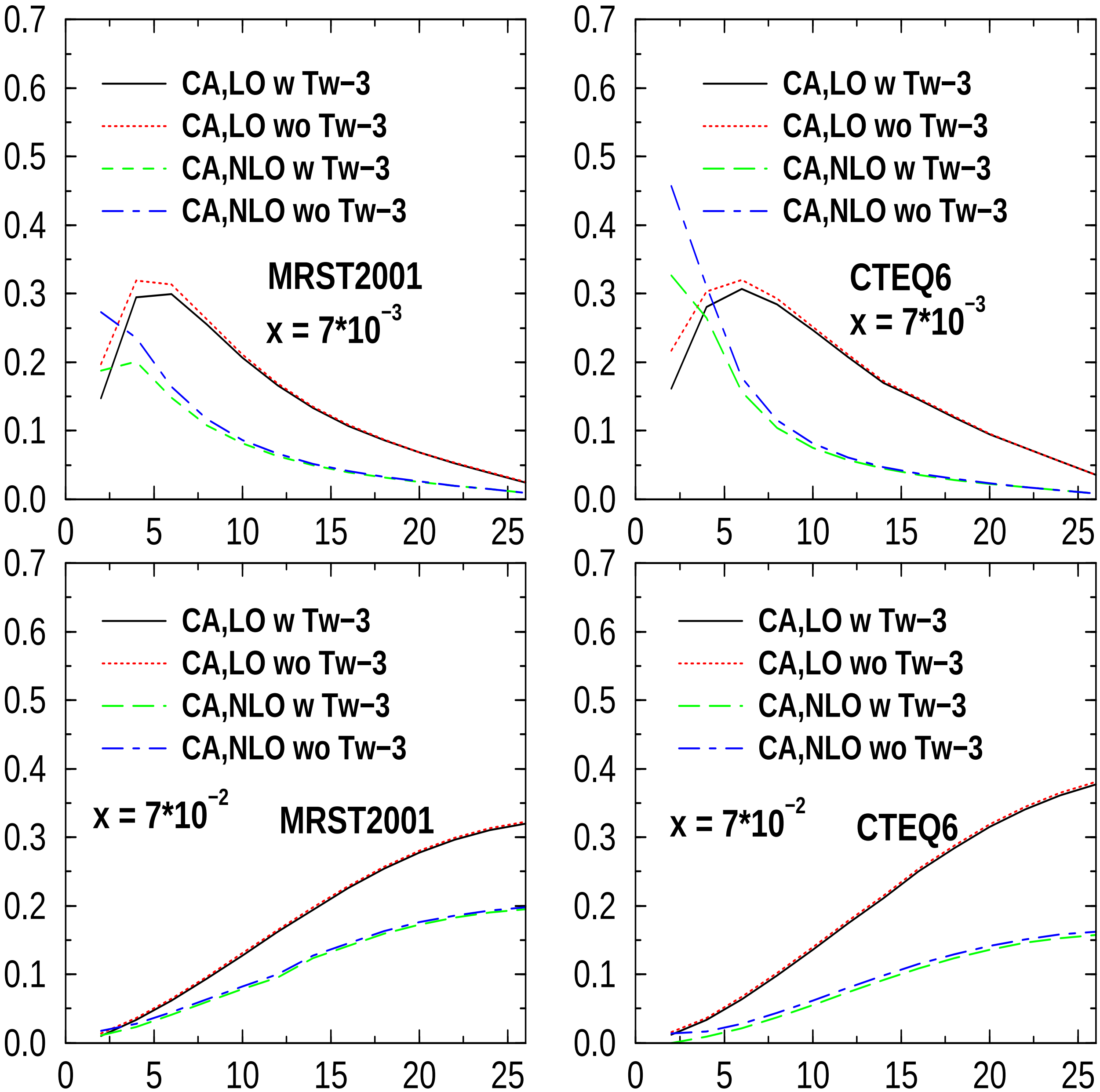

Figure 12: The CA for EIC in Q^2 for integrated t and fixed $x = \zeta$.

Experimental requirements:

- Generally: Increase in statistics i.e. more Lumi + better γ Id at lower energies!
- Need t dependence: 5 bins in $-t$ between 0 and 1 GeV^2 for reasonable statistics lumi between $200 - 600$ pb^{-1} depending on γ ID. $\rightarrow$ improved VFPS of some sort!
- SSA $\simeq 5 - 30\%$ for HERA & EIC kinematics. Current lumi enough for measurement!
- CA $\simeq 5 - 40\%$. Current lumi enough for measurement.
- Asymmetry measurements serve as cross chek to future GPD fits to $\sigma(\gamma^* p)$.
- Flexible MC generator for detector studies is now complete.

DVCS in eA scattering

- Observables: Same as in ep scattering!
- t-dependence is different for both DVCS and BH! Much steeper!
- A dependence helps offset steeper t-dependence since

$$d\sigma^A \propto A^2 |\mathcal{T}_{DVCS}|^2 \;\Rightarrow\; \frac{d\sigma^A}{A} \propto A |\mathcal{T}_{DVCS}|^2$$

- Model for nuclear GPDs ($O-16, Ca-40, Pd-110, Pb-206$):
  - DGLAP region:

    $$\mathcal{F}^{S,NS,g}(X,\zeta) \equiv R^{S,NS,g}(z) q^{S,NS,g}(z) / (1-\zeta/2)$$

    with $z = \frac{X-\zeta/2}{1-\zeta/2}$ and $R(z) = \frac{q^A(z)}{Aq(z)} \leftarrow$ supplied by V. Guzey.
  - ERBL region: Simple analytical form (as in ep) respecting polynomiality
- same $B(Q^2)$ as for proton just with different B_0.

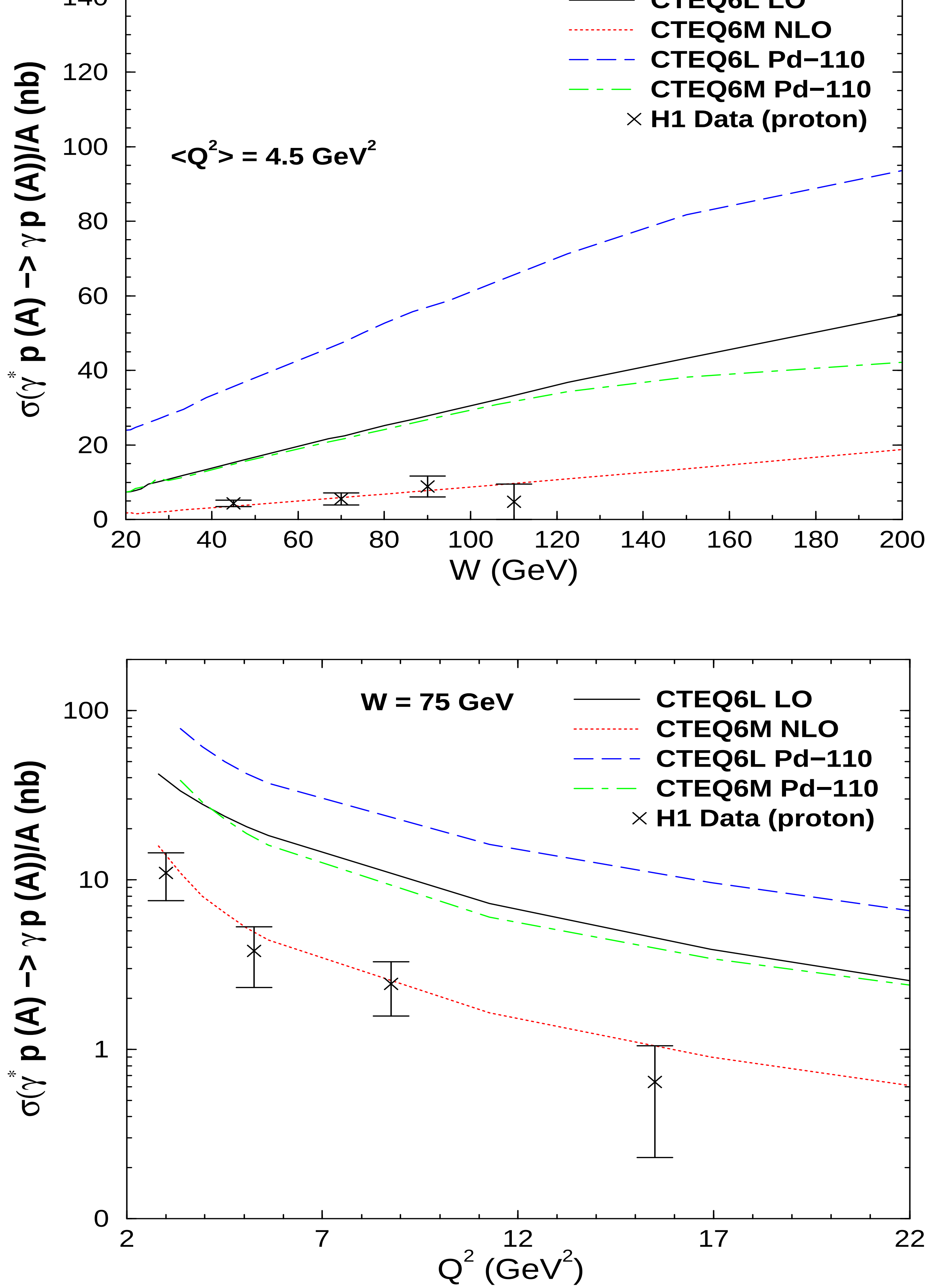

Figure 13: Photon level cross section of Pd-110 at the EIC.

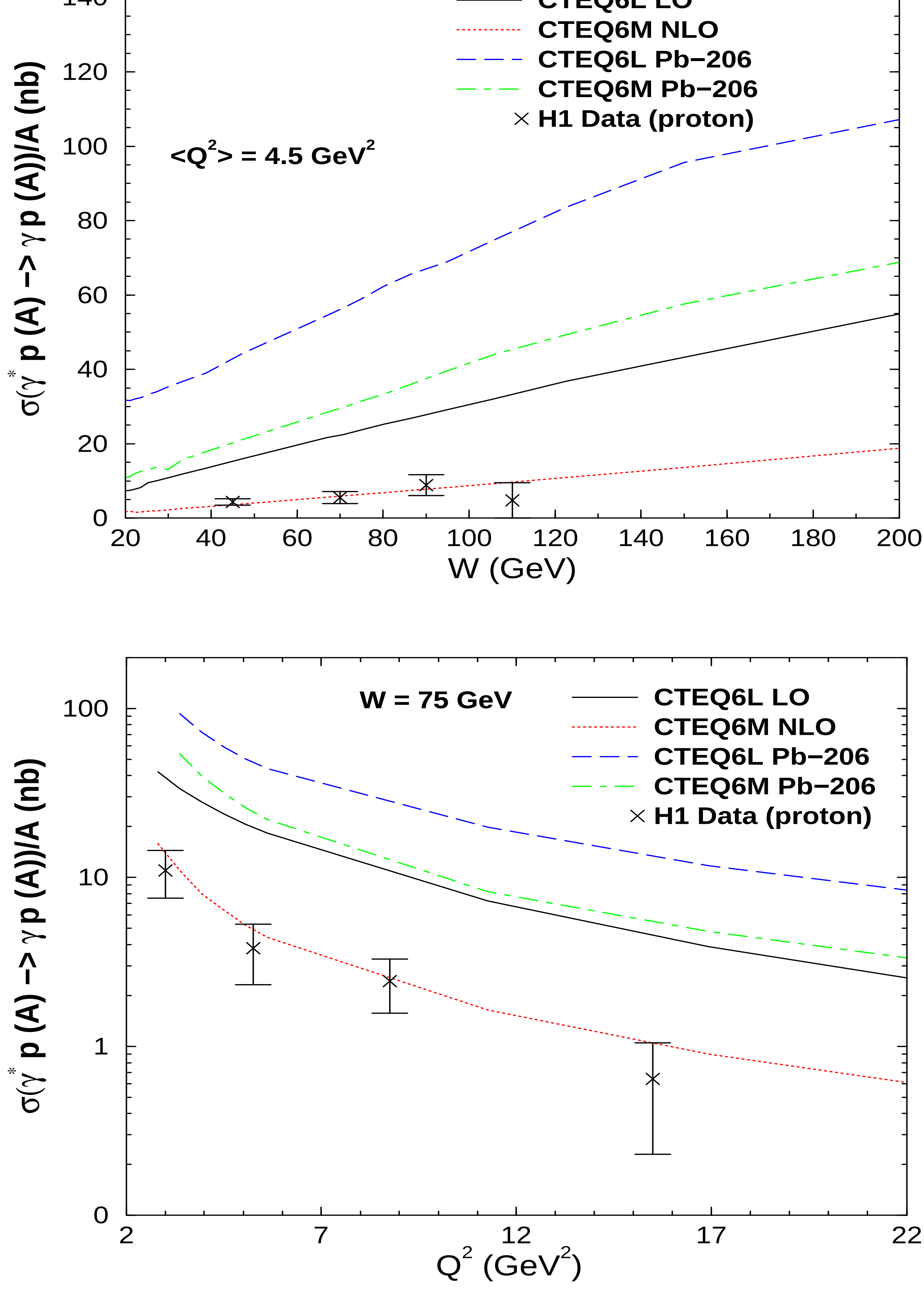

Figure 14: Photon level cross section of Pb-206 at the EIC.

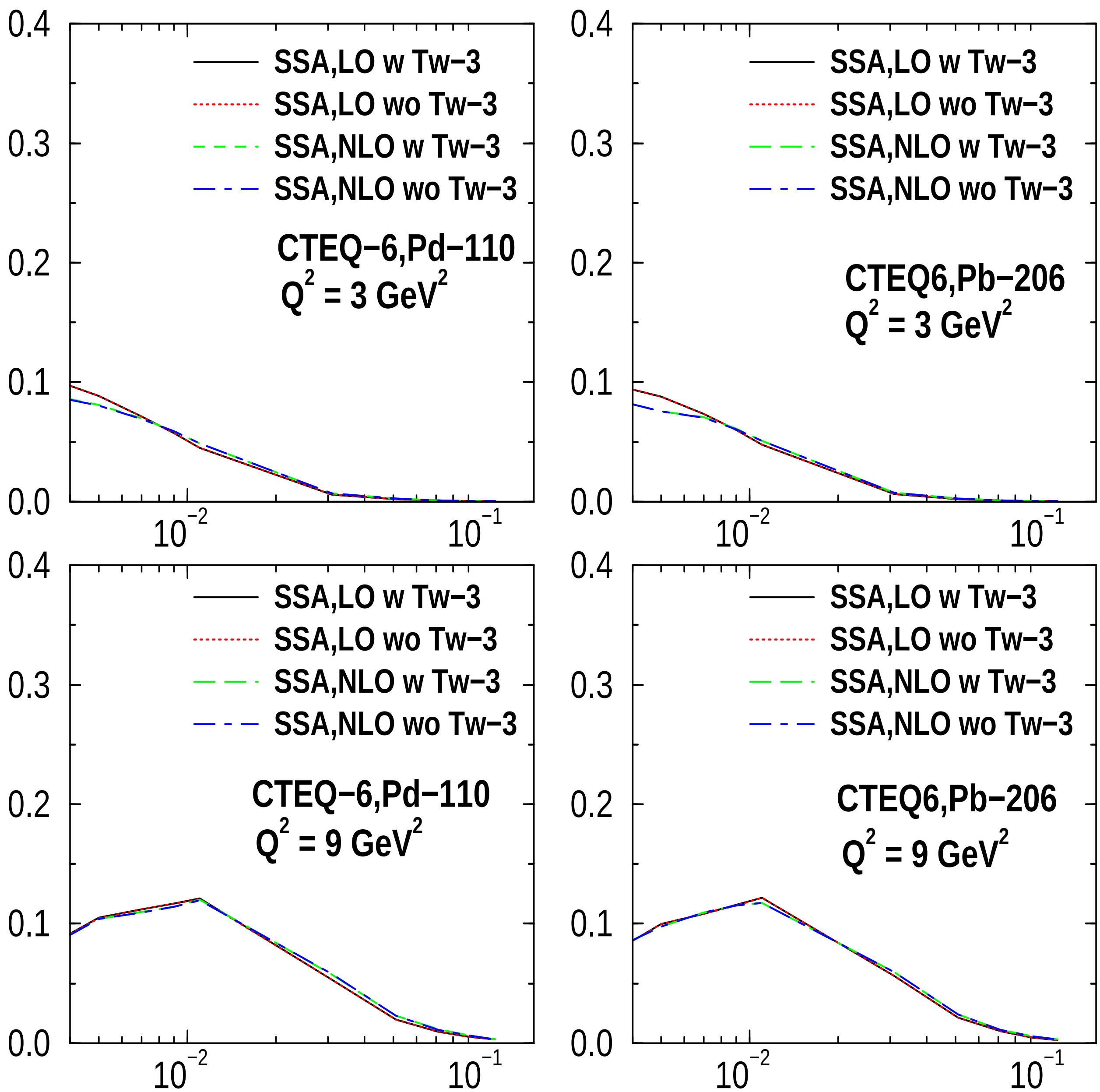

Figure 15: The SSA for EIC in $x = \zeta$ for integrated t and fixed Q^2.

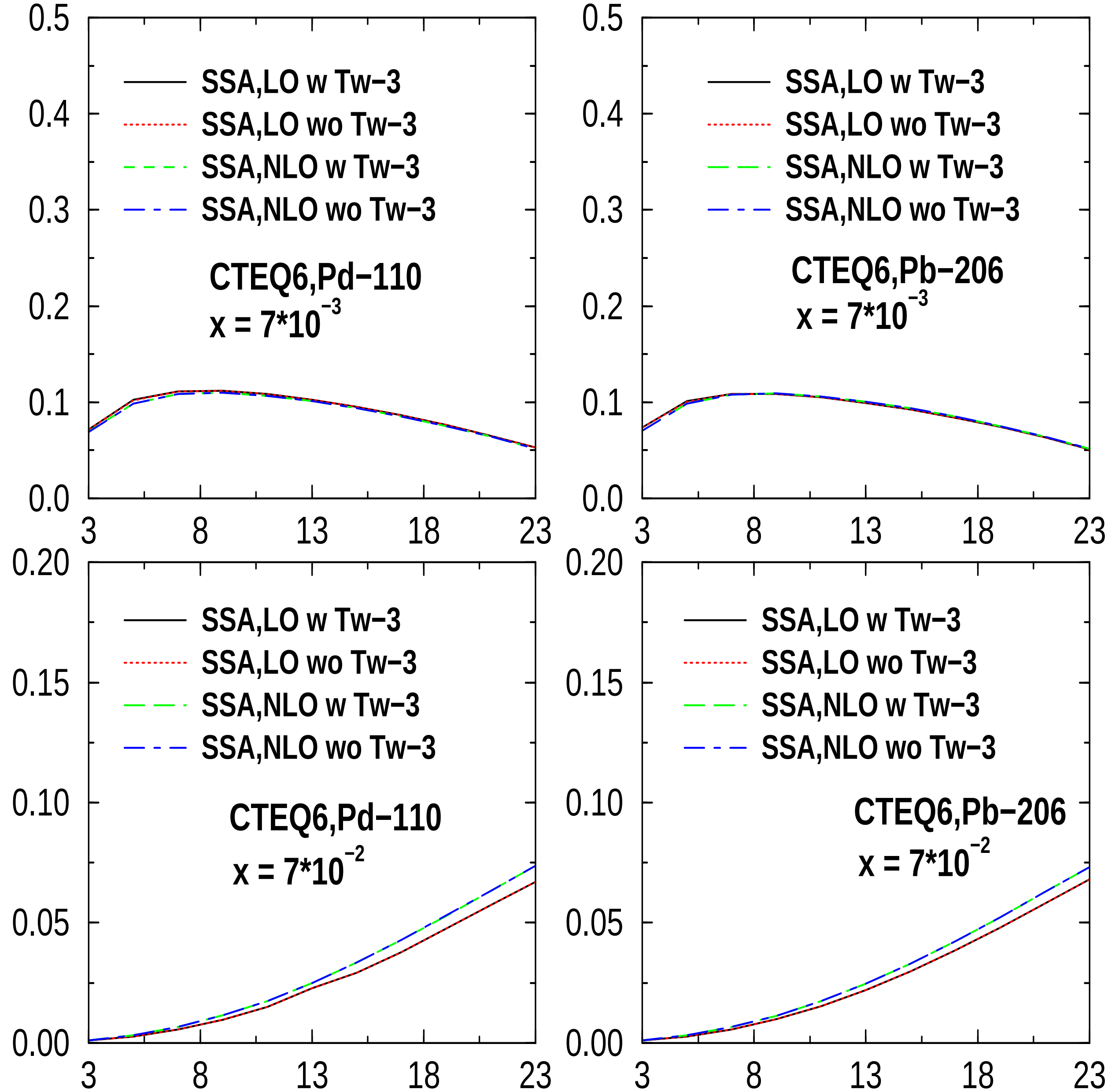

Figure 16: The SSA for EIC in Q^2 for integrated t and fixed $x = \zeta$.

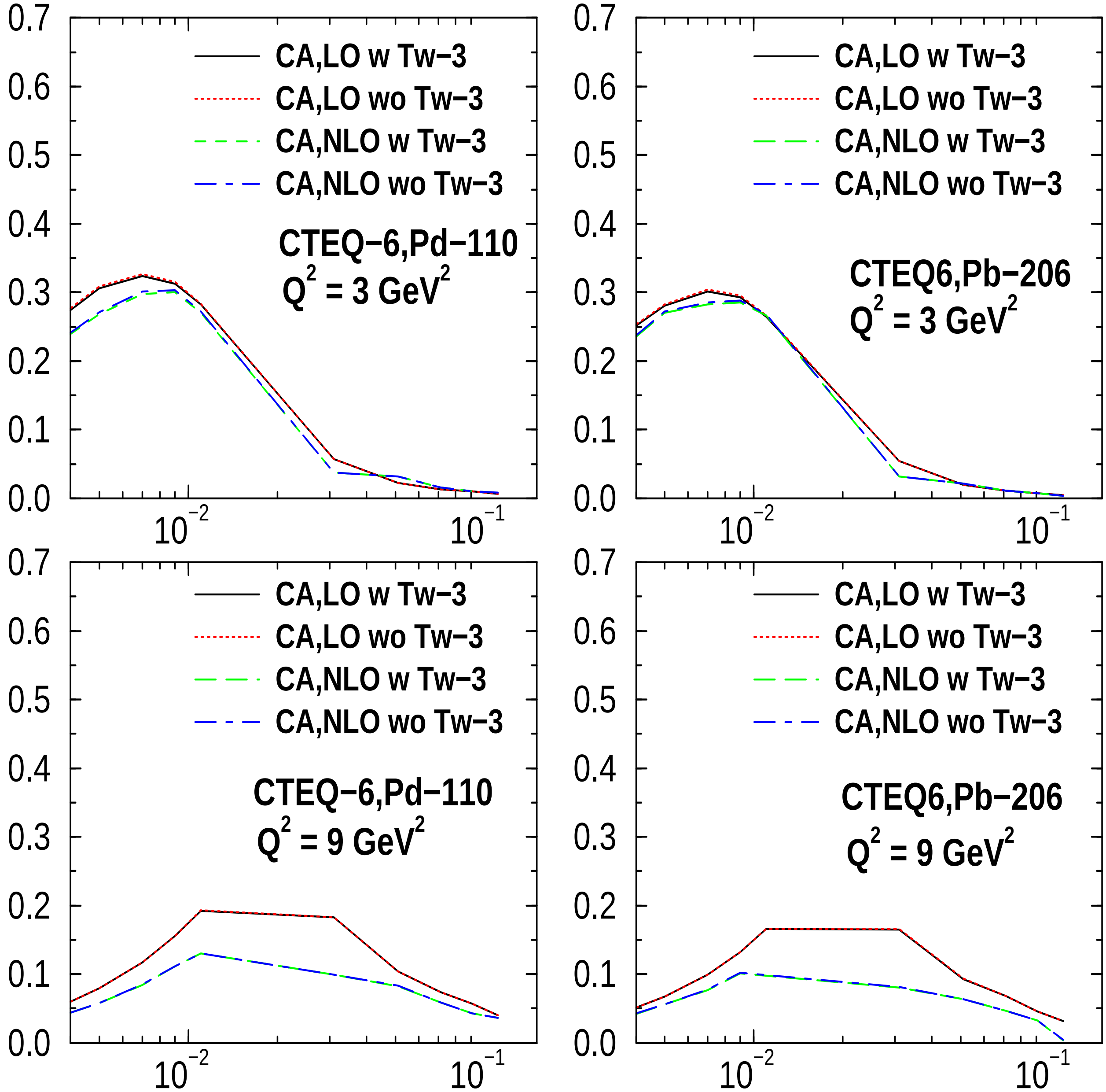

Figure 17: The CA for EIC in $x = \zeta$ for integrated t and fixed Q^2.

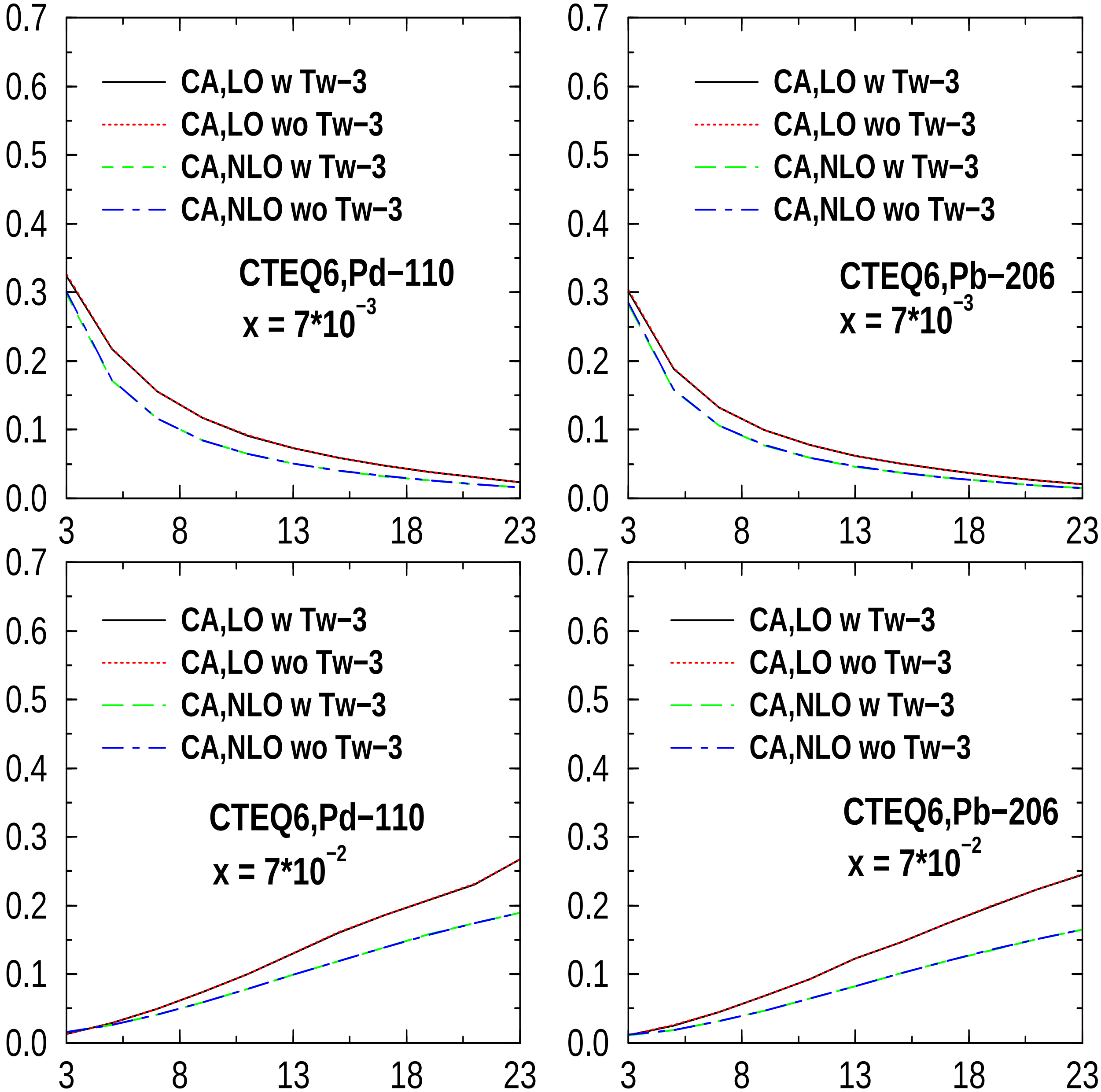

Figure 18: The CA for EIC in $x = \zeta$ for integrated t and fixed Q^2.

Experimental requirements:

- High Lumi $+$ higher cross section $+$ better γ Id at lower energies $\rightarrow$ high precision data $\rightarrow$ extraction of nuclear GPDs with high precision possible!
- Asymmetries are reduced $(5 - 20\%)$ but still sizeable!
- Relevant $< -t >$-values between $0.01 - 0.1$ GeV^2 $=>$ most likely no experimental determination of t-dependence possible!
- MC generator from the proton already for isoscalar nuclei.
- Excellent opportunity to study nuclear shadowing in exclusive reactions!

Exclusive saturation observables

Why exclusive observables ?. . . bad statistics, need specific detector configuration and delicate triggers!!

True, BUT exclusive processes are directly sensitive to particle correlations in target due to specific final state!

$\Rightarrow$ greater sensitivity to saturation (particle correlation) effects + many exclusive processes already measured at HERA as for example . . .

$$d\sigma_{DVCS} \propto |Im\ M_{DVCS}|^2 \simeq |H^S(\zeta,\zeta)|^2$$

$\Rightarrow$ DVCS directly probes long distances on the light cone! Why?

$H(X=\zeta,\zeta) \equiv$ one parton has momentum fraction $X=\zeta$ (fast) and other one $X-\zeta \simeq 0$ (slow) $\equiv$ large light-like separations (LLLS) probed in GPD independent of $\zeta = x_{bj}$!

$\rightarrow$ LLLSs in PDFs only for $x_{bj} \rightarrow 0$ where sea dominates and one expects saturation to set in!

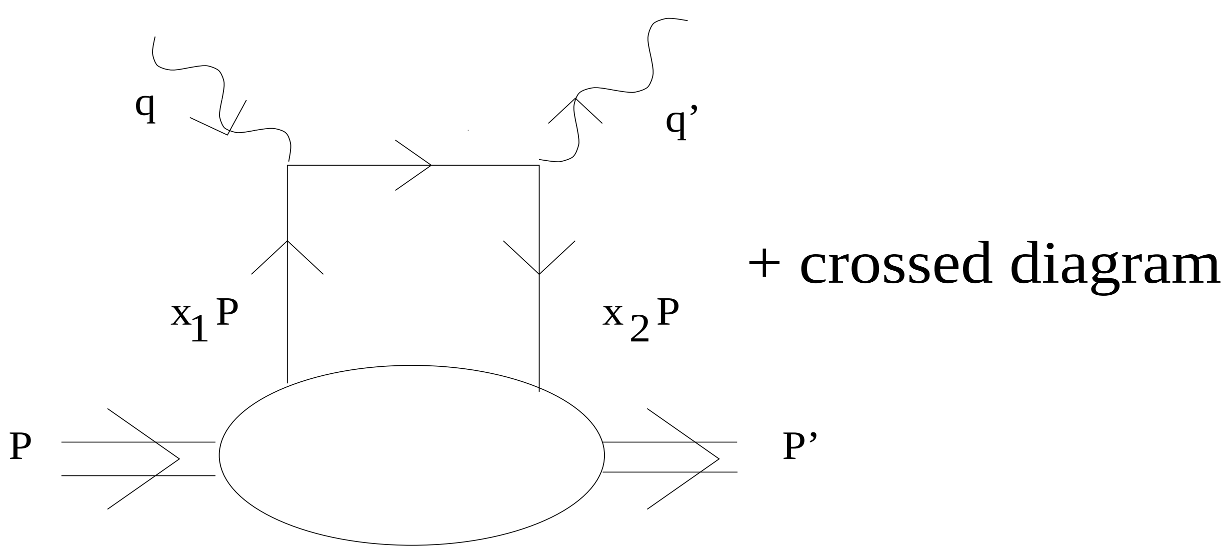

Figure 19: LO handbag diagram for DVCS. Here $x_1 = X$ and $x_2 = X - \zeta$.

- $\sigma_{DVCS}(\gamma^* p) \propto |Im\ M_{DVCS}|^2$ should exhibit geometric scaling as F_2^p.

- Scaling curves should be different for different t! $\leftarrow$ Determination of black disc radius from change in curves!

- Geometric scaling should extend to larger x_{bj} i.e. earlier onset of saturation!

  Why ?

  Input: $H^S(X,\zeta) \propto q^S\left(\frac{X-\zeta/2}{1-\zeta/2}\right)$ describes H1/ZEUS/HERMES data in NLO QCD.

  $\Rightarrow$ DVCS sensitive to smaller momentum fractions than DIS!!!

- σ_{DVCS} in eA should show geometric scaling too, as well as stronger nuclear shadowing compared to DIS at same x_{bj}. Reason as above!

- Further observables (in ep and ea):

  - Single Spin Asymmetry $\propto Im\ M_{DVCS}$ (pol. beam/unpol. target)
  - Charge Asymmetry $\propto Re\ M_{DVCS}$

  $\Rightarrow$ Also geometric scaling for real part ? Nuclear shadowing the same as for imaginary part ? $\leftarrow$ real part sensitive to ERBL region!!

- Similar statements true for $\sigma(\gamma^* p)$ in vector meson production in ep and eA!

Conclusions

- $\sigma(\gamma^* p)$, SSA, CA are measurable at HERA & EIC with enough precision to extract GPDs with fairly high precision in a LO and NLO QCD analysis!
- There are GPD input parametrizations which describe all the available DVCS data in a NLO QCD analysis.
- Need higher lumi, better γ id and improved VFPS to measure t-dependence which is a must!
- DVCS in eA is measurable for the EIC with high statistics (nuclear shadowing, EMC effect etc.)
- Lumi is much better than for HERA $\rightarrow$ much better statistics!
- DVCS observables are perfect place to look for saturation $\rightarrow$ more sensitive to particle correlations and to smaller relative x than DIS.
- t-dependence will allow one to determine "black" and "grey" areas of target.