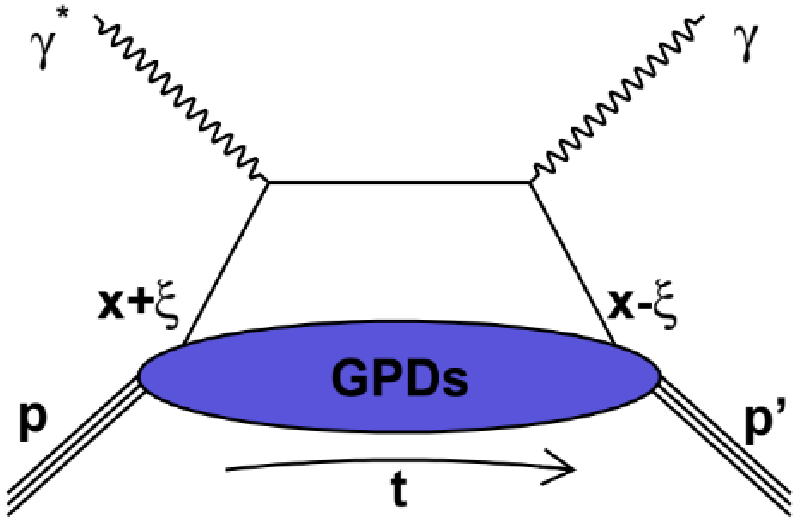
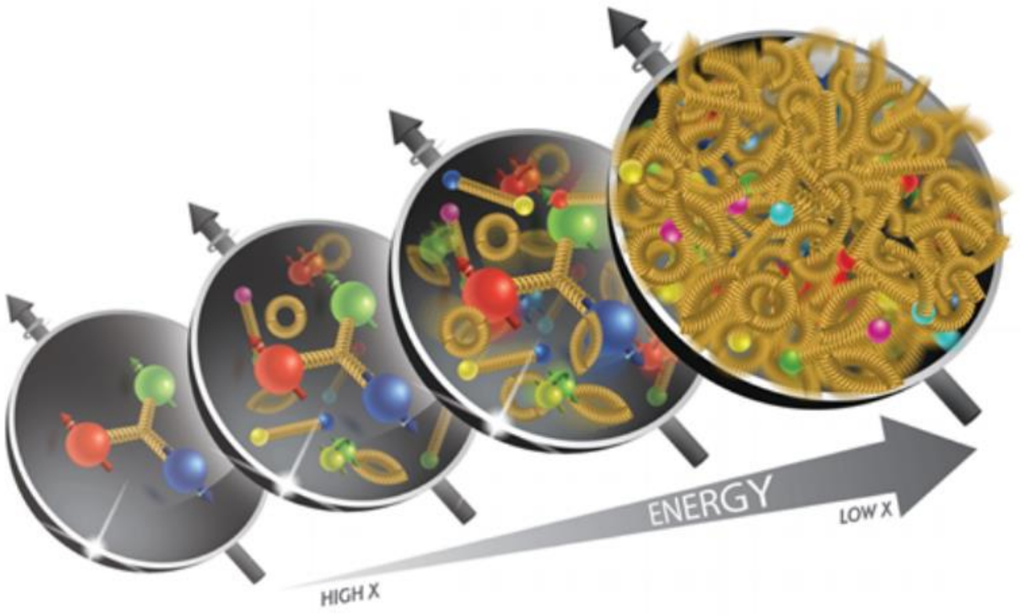
Deeply Virtual Compton Scattering and Spatial Imaging





Lecture 2

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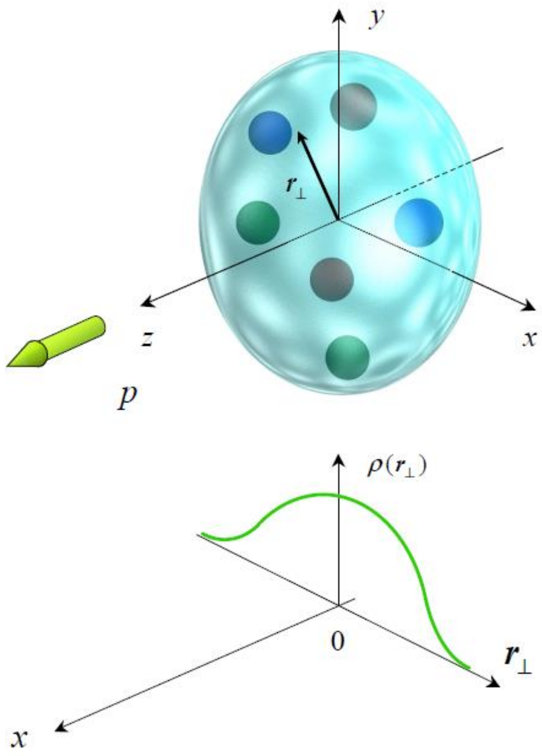
IJCLab-Orsay (CNRS/IN2P3, France)

Outline

- Lecture 1: Introduction
  - Elastic scattering, form factors (FFs)
  - Deep Inelastic scattering, parton distribution functions (PDFs)
  - Exclusive reactions, Generalized Parton Distributions (GPDs)
- Lecture 2: Deeply Virtual Compton Scattering
  - Experimental results on proton targets
  - Flavor separation using quasi-free neutrons
- Lecture 3: Deeply Virtual Meson Production & GPD models
  - Rosenbluth separation
  - Access to transversity GPDs
  - GPD models and parametrizations
- Lecture 4: GPDs at JLab12 and beyond
  - Review of GPD programs in other facilities worldwide
  - Future experiments at JLab at 12 GeV
- Lecture 5: Electron-Ion Collider
  - Imaging gluons inside the nucleon
  - The EIC project

Reminder lecture 1

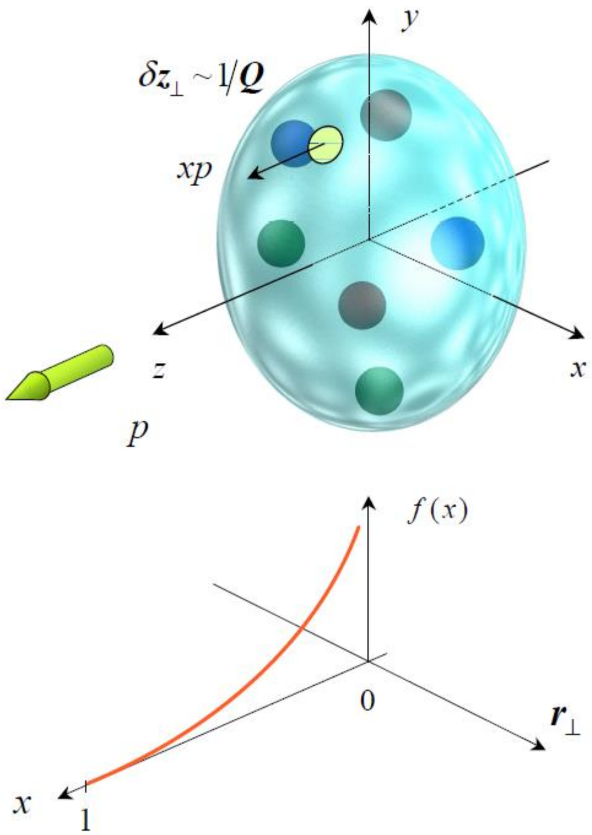
Elastic scattering



Form factors

Nobel prize, 1961

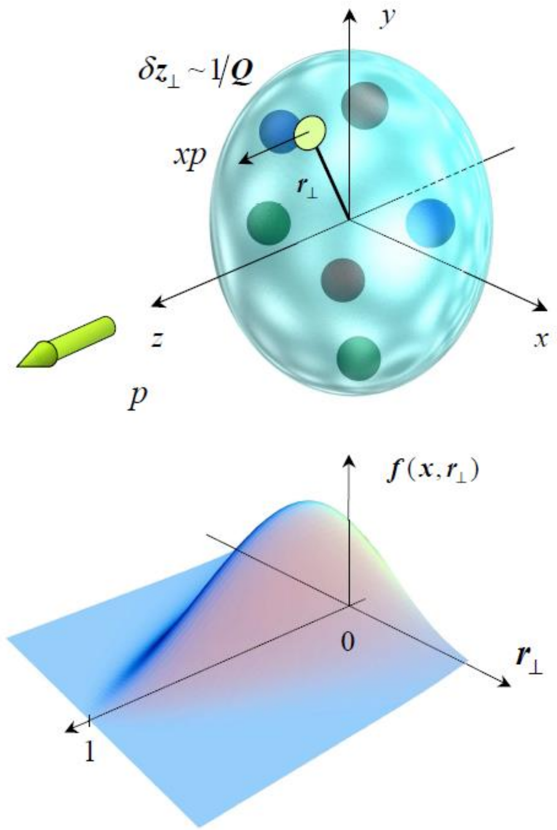
Deeply Inelastic Scattering



Parton distributions

Nobel prize, 1969
Nobel prize, 1990

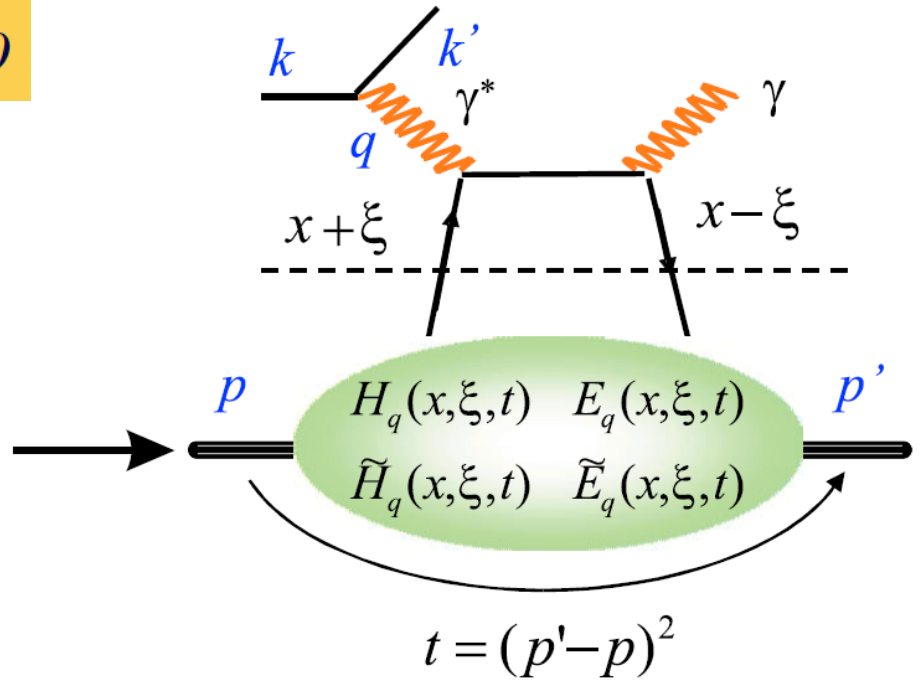
Hard exclusive processes



Generalized Parton Distributions (GPDs)

Deeply Virtual Compton Scattering (DVCS)

$\gamma^* \, p \rightarrow \gamma \, p$



Handbag diagram

High Q^2
Perturbative QCD

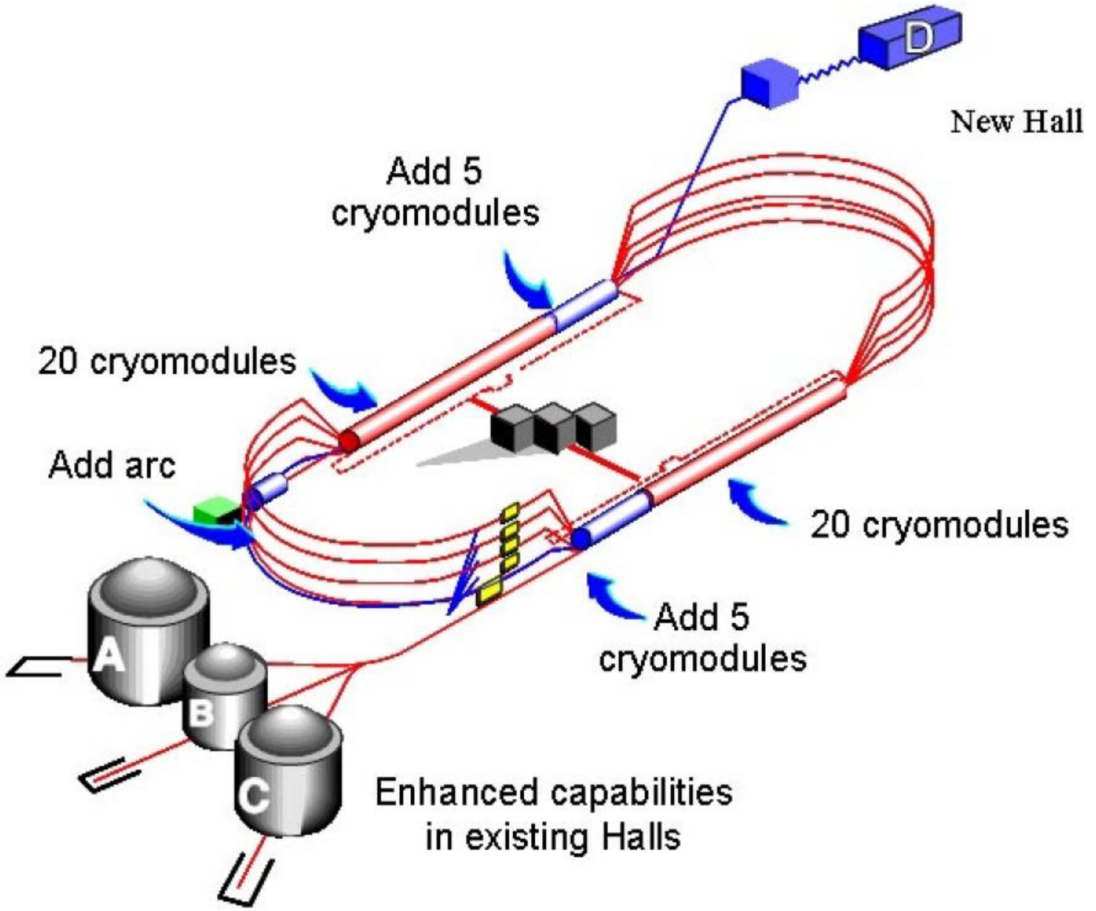
Non-perturbative
GPDs

Bjorken limit :

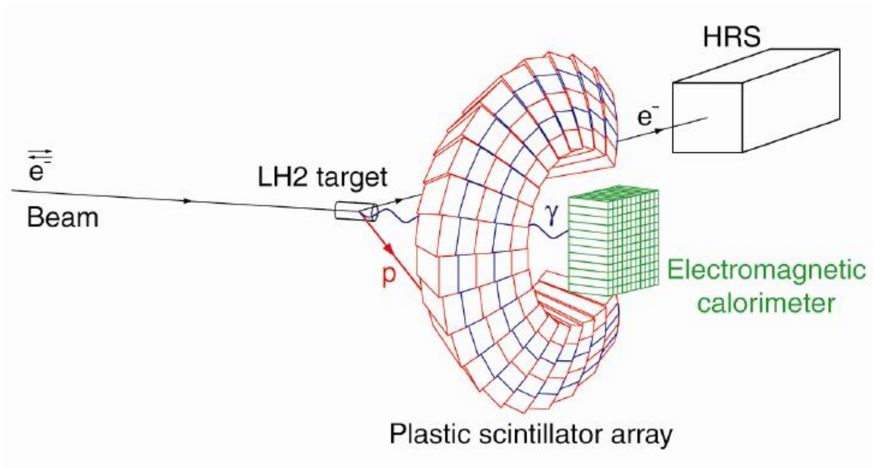
$$Q^2 = -q^2 \rightarrow \infty, \quad \nu \rightarrow \infty \quad \Big\} \quad x_B = \frac{Q^2}{2M\nu} \text{ fixed}$$

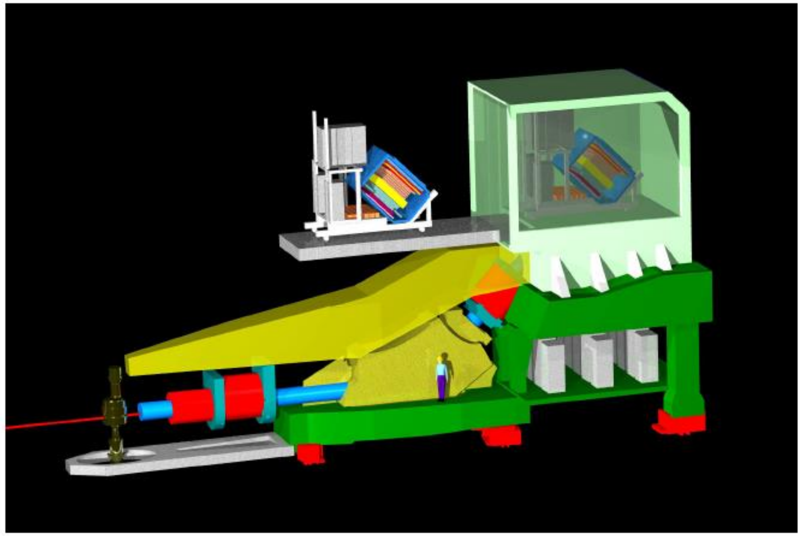
Jefferson Lab

- 6-12 GeV longitudinally polarized (>85%) continuous electron beam
- High intensity (>100 μA): luminosities $> 10^{38}\,\mathrm{s}^{-1}\,\mathrm{cm}^{-2}$
- 3 experimental Halls (A, B, C) w/ fixed target and dedicated detectors

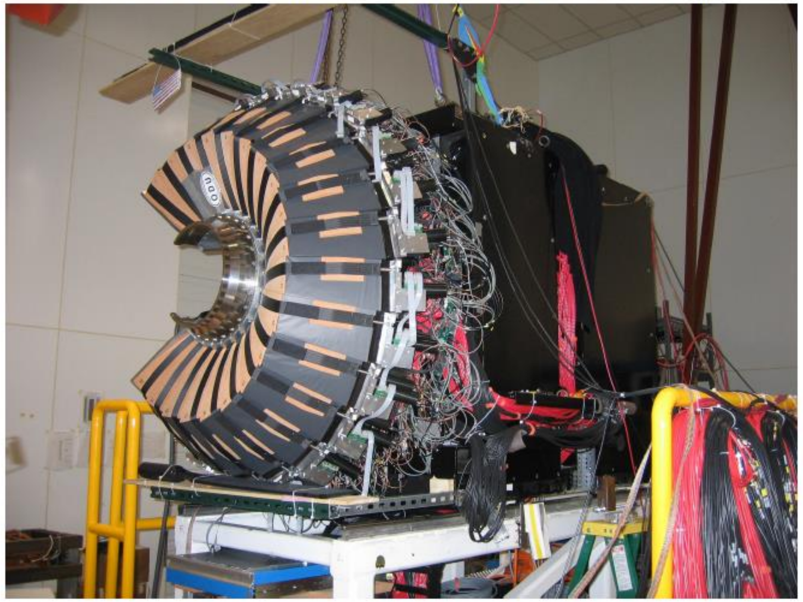


DVCS experiment: example of a setup



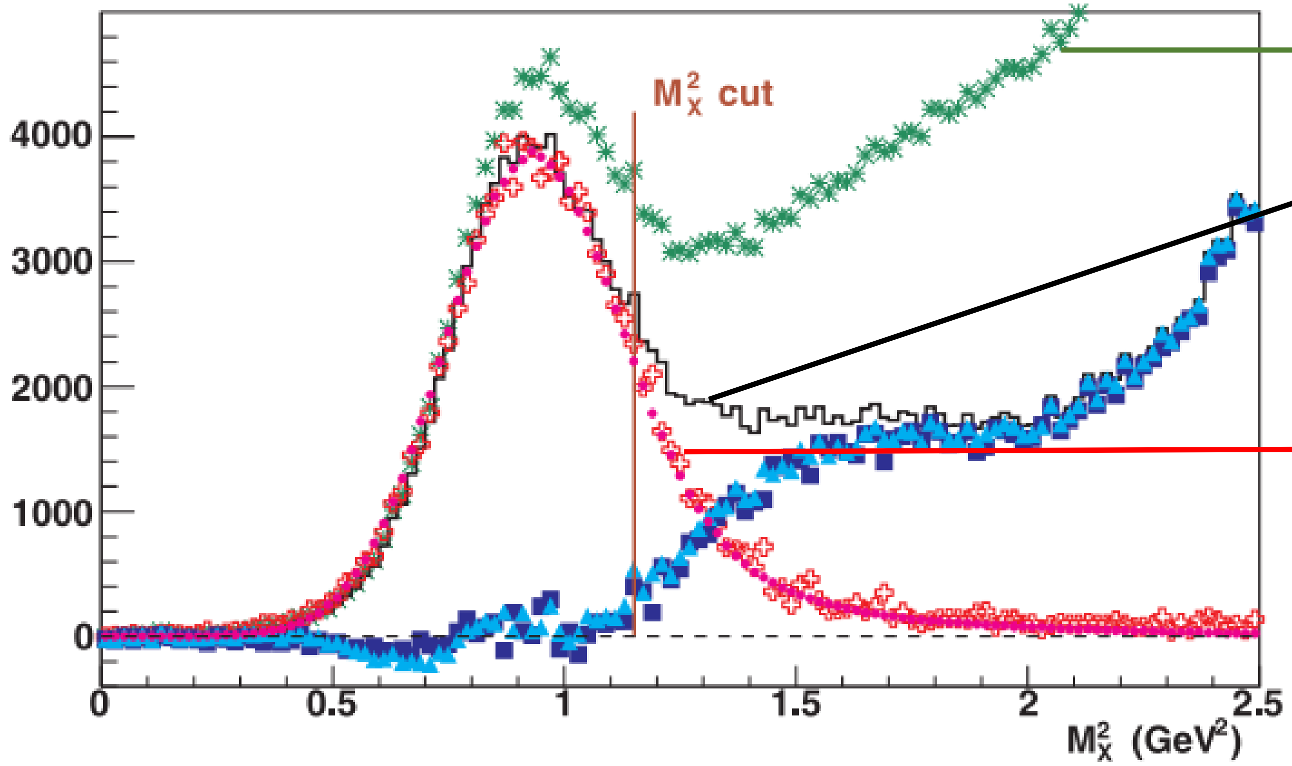


100-channel scintillator array



132-block PbF_2 electromagnetic calorimeter

DVCS: experimental exclusivity



ep→eγX raw data

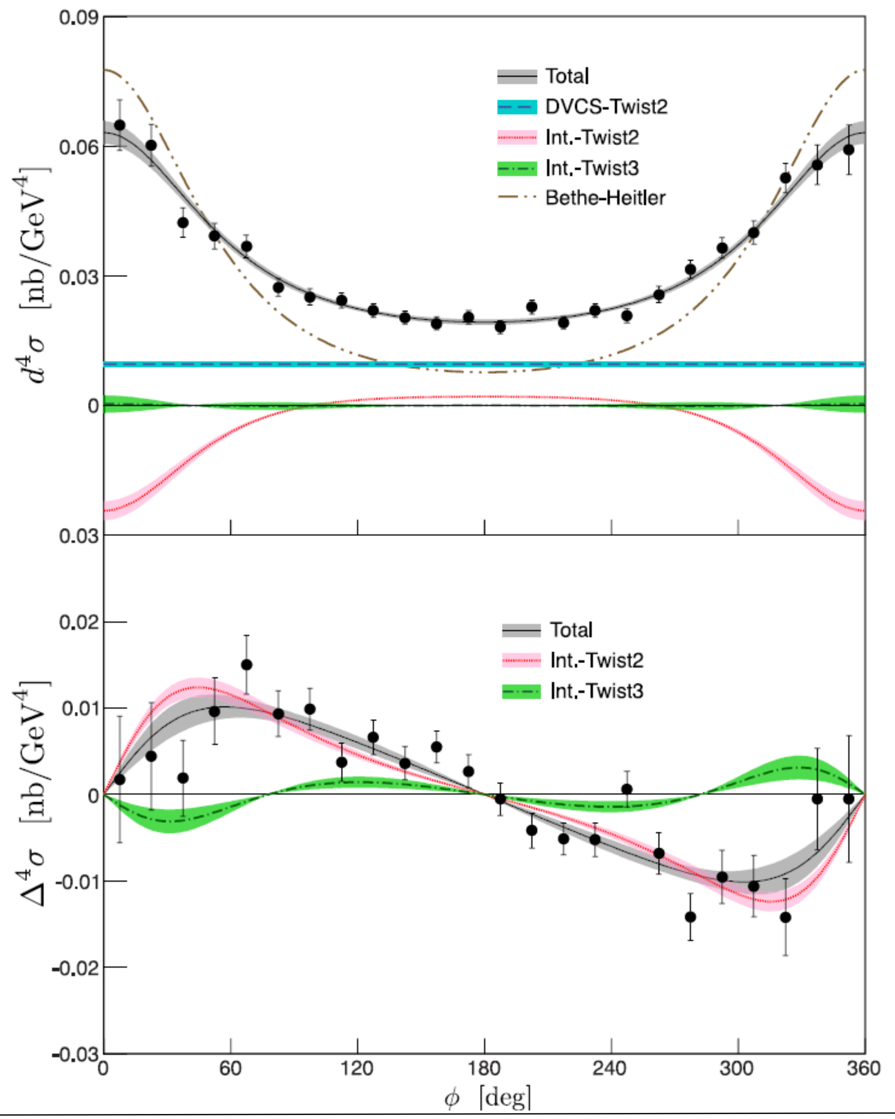
Background subtracted

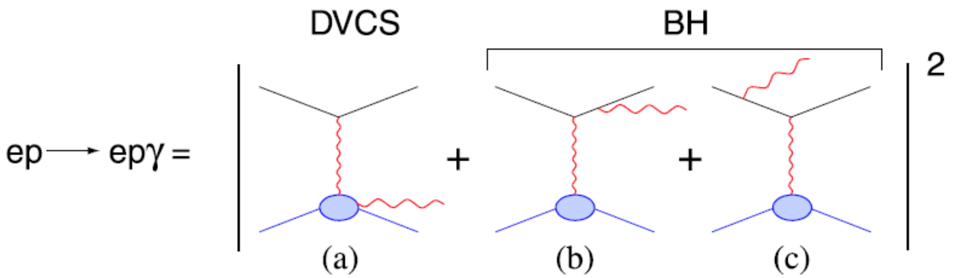
Fully exclusive events (crosses data; dots simulation)

Missing mass squared: $M_X{}^2=(e+p-e'-q')^2$

A sample of typical results

$Q^2 = 2.36$ GeV^2, $x_B = 0.37$, $-t = 0.32$ GeV^2





$$d^4\sigma = \mathcal{T}_{\text{BH}}^2 + \mathcal{T}_{\text{BH}}\mathcal{R}e(\mathcal{T}_{\text{DVCS}}) + \mathcal{T}_{\text{DVCS}}^2$$

$$\mathcal{R}e(\mathcal{T}_{\text{DVCS}}) \sim c_0^{\mathcal{I}} + c_1^{\mathcal{I}} \cos\phi + c_2^{\mathcal{I}} \cos 2\phi$$

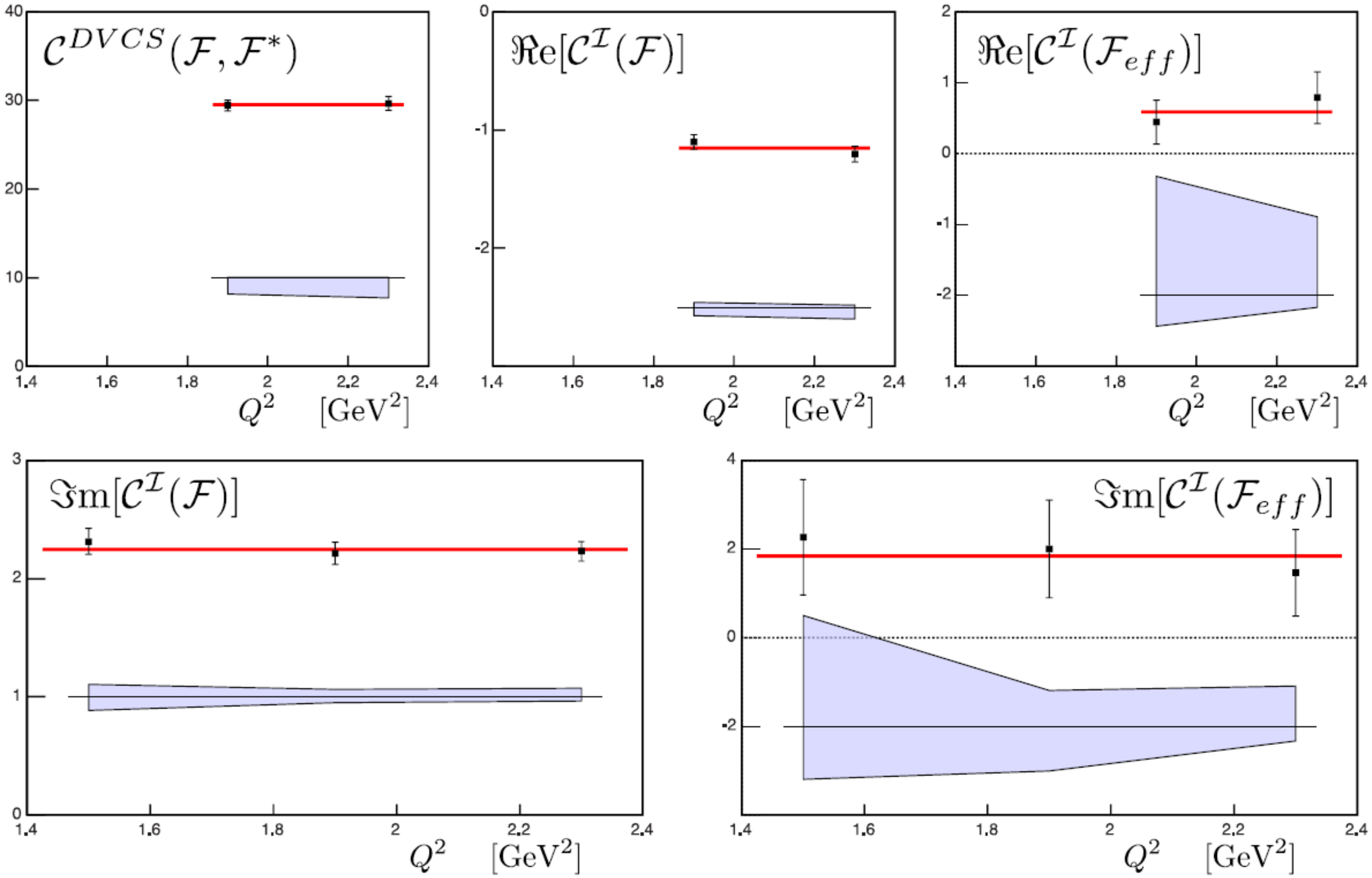
$$\mathcal{T}_{\text{DVCS}}^2 \sim c_0^{\text{DVCS}} + c_1^{\text{DVCS}} \cos\phi$$

$$\Delta^4\sigma = \frac{d^4\overrightarrow{\sigma} - d^4\overleftarrow{\sigma}}{2} = \mathcal{I}m(\mathcal{T}_{\text{DVCS}})$$

$$\mathcal{I}m(\mathcal{T}_{\text{DVCS}}) \sim s_1^{\mathcal{I}} \sin\phi + s_2^{\mathcal{I}} \sin 2\phi$$

M. Defurne *et al.* Phys. Rev. C 92, 055202

DVCS cross sections: Q^2-dependence

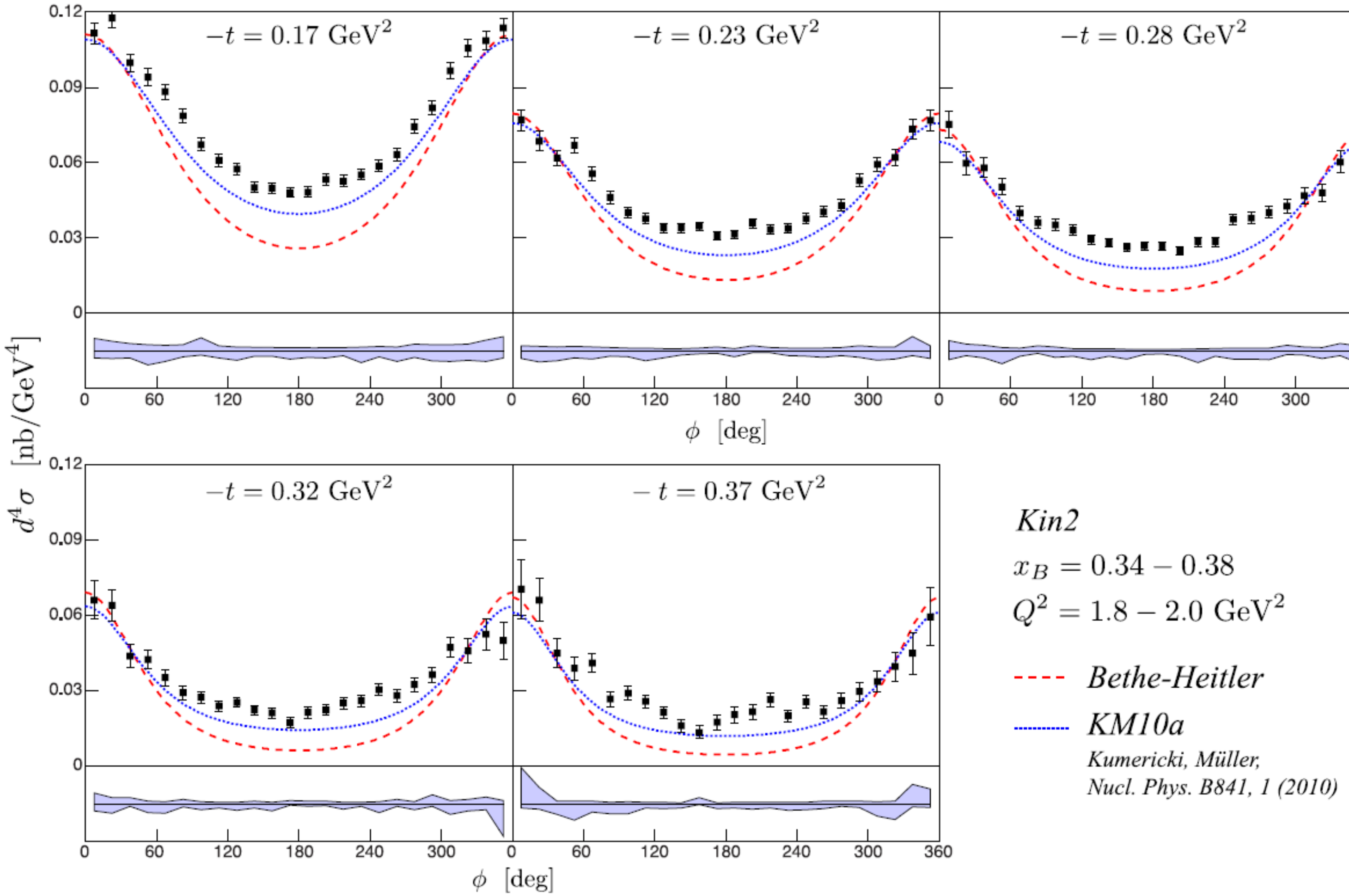


- No Q^2-dependence observed
- Supports scattering off a single quark

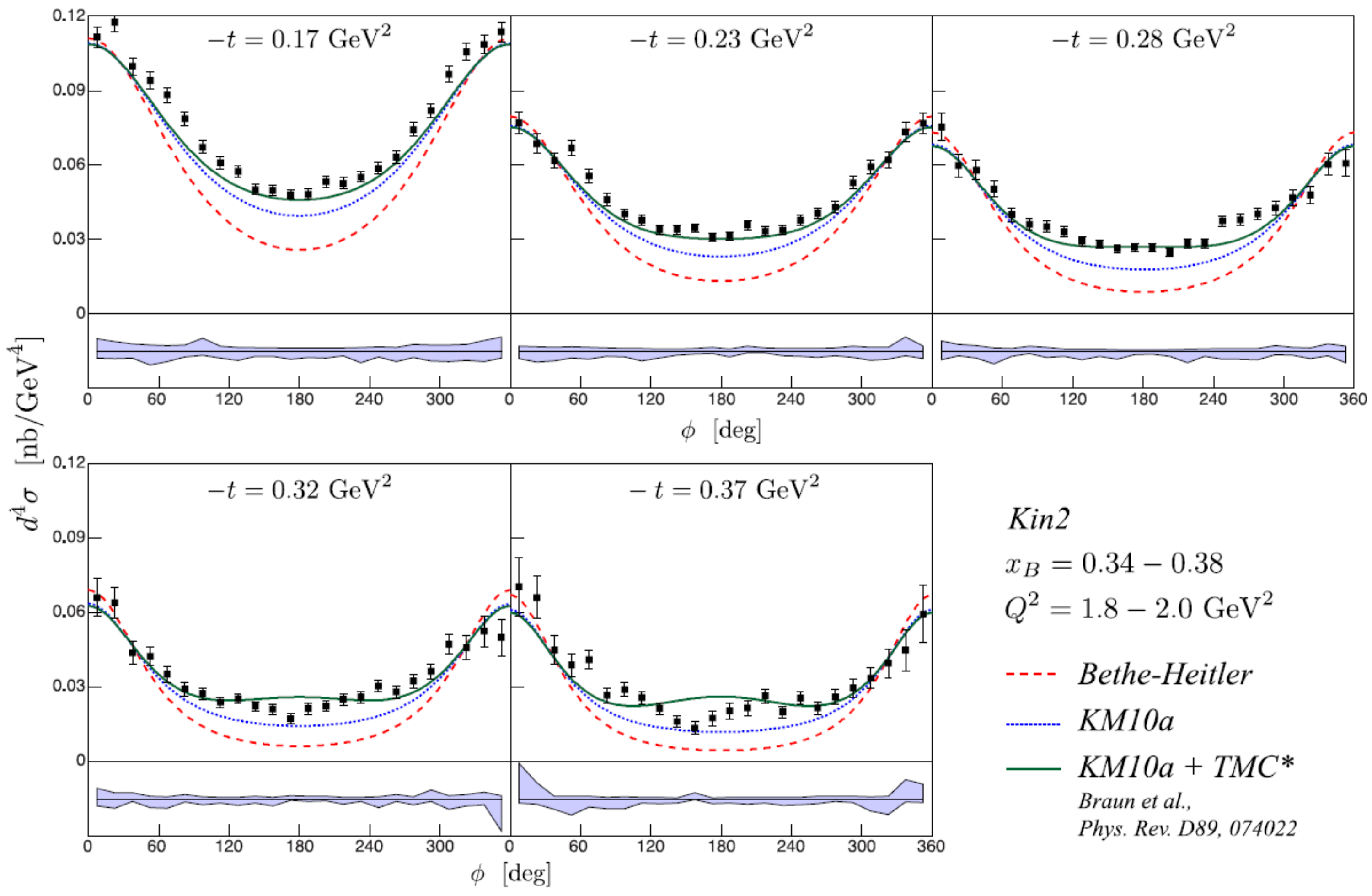
(handbag diagram, leading twist dominance)

- Limited range in Q^2

DVCS cross sections: ϕ-dependence



DVCS cross sections: ϕ-dependence



- Target-mass corrections (TMC): $\sim \mathcal{O}(M^2/Q^2)$ and $\sim \mathcal{O}(t/Q^2)$

Braun, Manashov, Mueller and Pirnay (2014)

DVCS cross sections: first experimental conclusions

- DVCS cross section significant higher than Bethe-Heitler
- Q2-dependence indicates leading twist dominance (scattering off a single quark)
- Exact description of the ϕ-dependence requires higher order corrections

Rosenbluth-like separation of the DVCS cross section

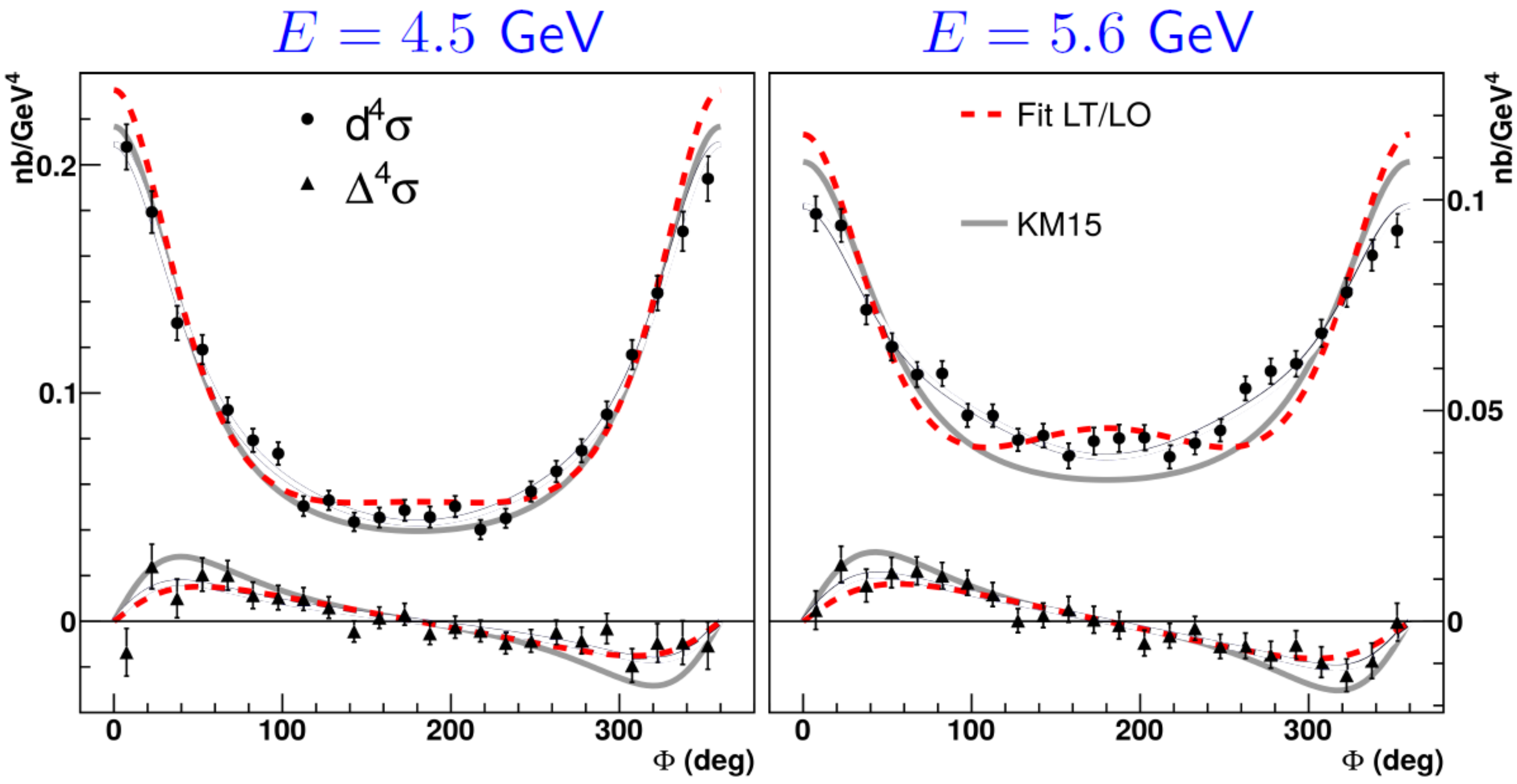
$$\sigma(ep \to ep\gamma) = \underbrace{|BH|^2}_{\text{Known to} \sim 1\%} + \underbrace{\mathcal{I}(BH \cdot DVCS)}_{\text{Linear combination of GPDs}} + \underbrace{|DVCS|^2}_{\text{Bilinear combination of GPDs}}$$

$$\mathcal{I} \propto 1/y^3 = (k/\nu)^3,$$

$$\left|\mathcal{T}^{DVCS}\right|^2 \propto 1/y^2 = (k/\nu)^2$$

Energy dependence of the DVCS cross section

- Cross section measured at 2 beam energies and constant Q^2, x_B, t



➢ Leading-twist and leading order fit of cross sections at both beam energies does not reproduce the data

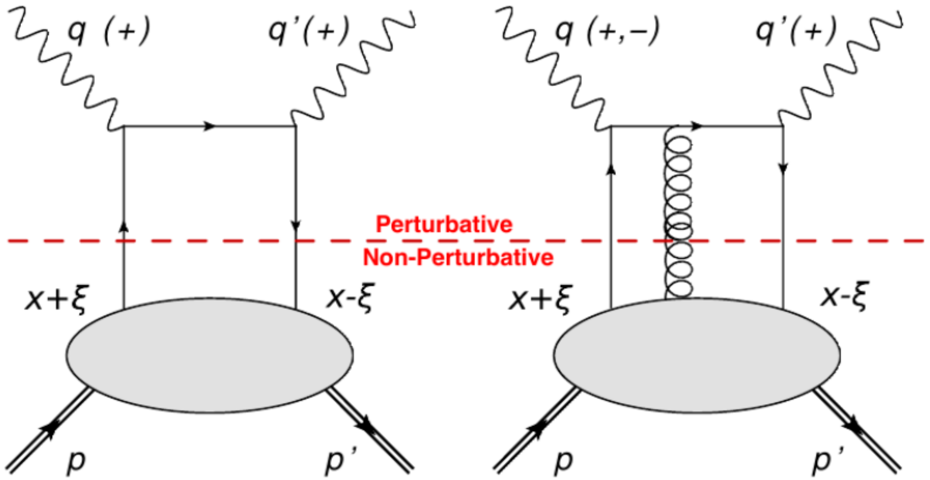
Higher order corrections to handbag diagram

Two fit-scenarios:

Light-cone axis in the (q,q') plane (Braun et al.)

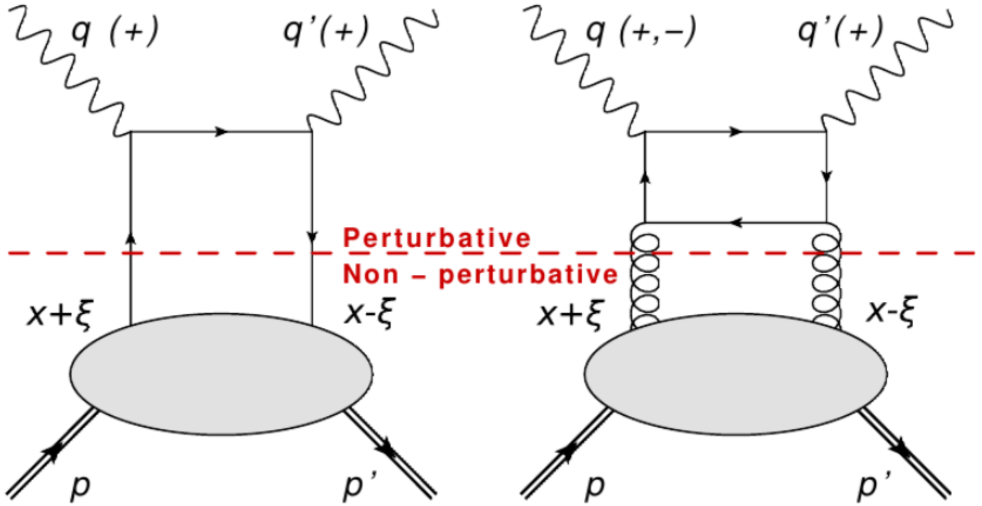
LO/LT + HT

$\mathbb{H}_{++}, \widetilde{\mathbb{H}}_{++}, \mathbb{H}_{0+}, \widetilde{\mathbb{H}}_{0+}$



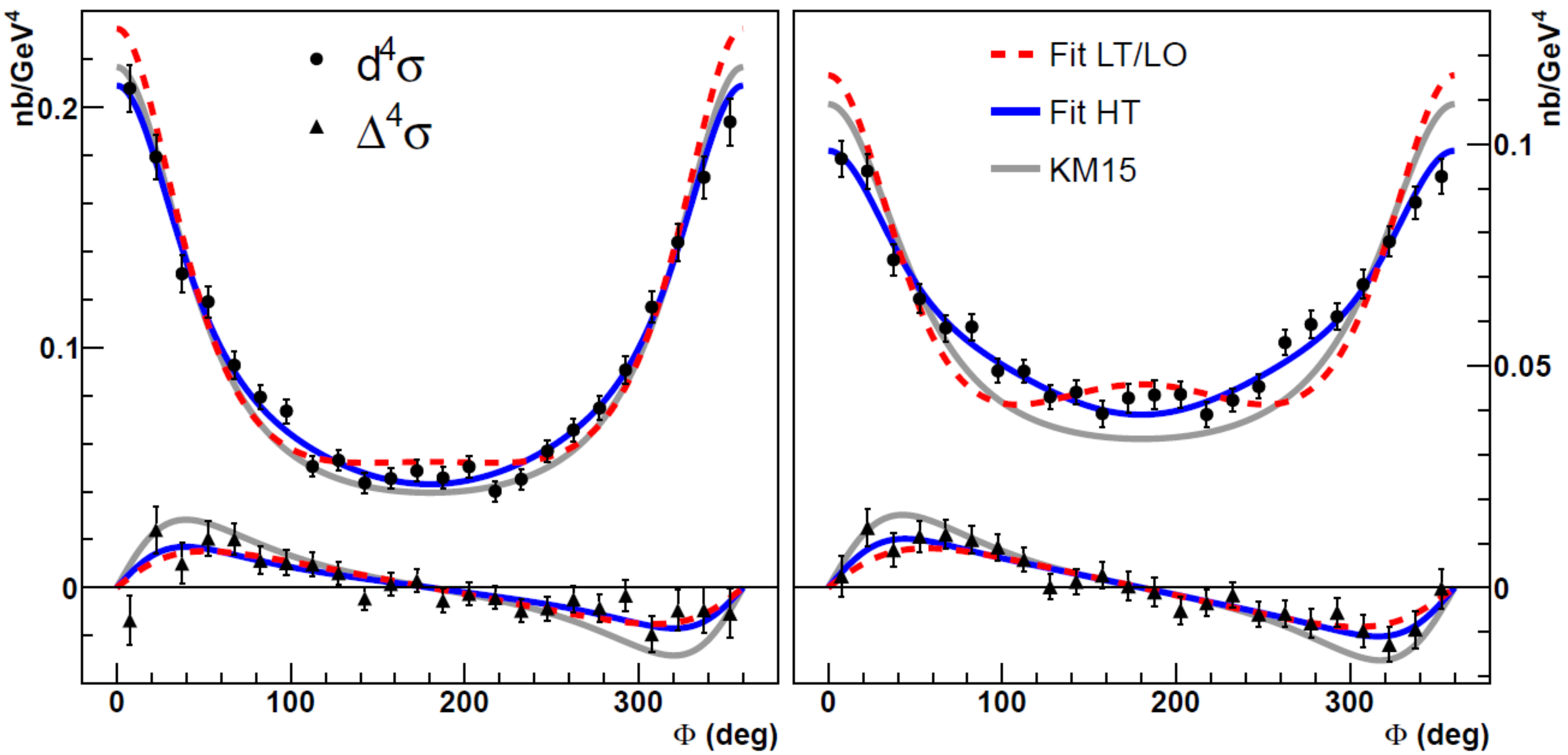
LO/LT + NLO

$\mathbb{H}_{++}, \widetilde{\mathbb{H}}_{++}, \mathbb{H}_{-+}, \widetilde{\mathbb{H}}_{-+}$



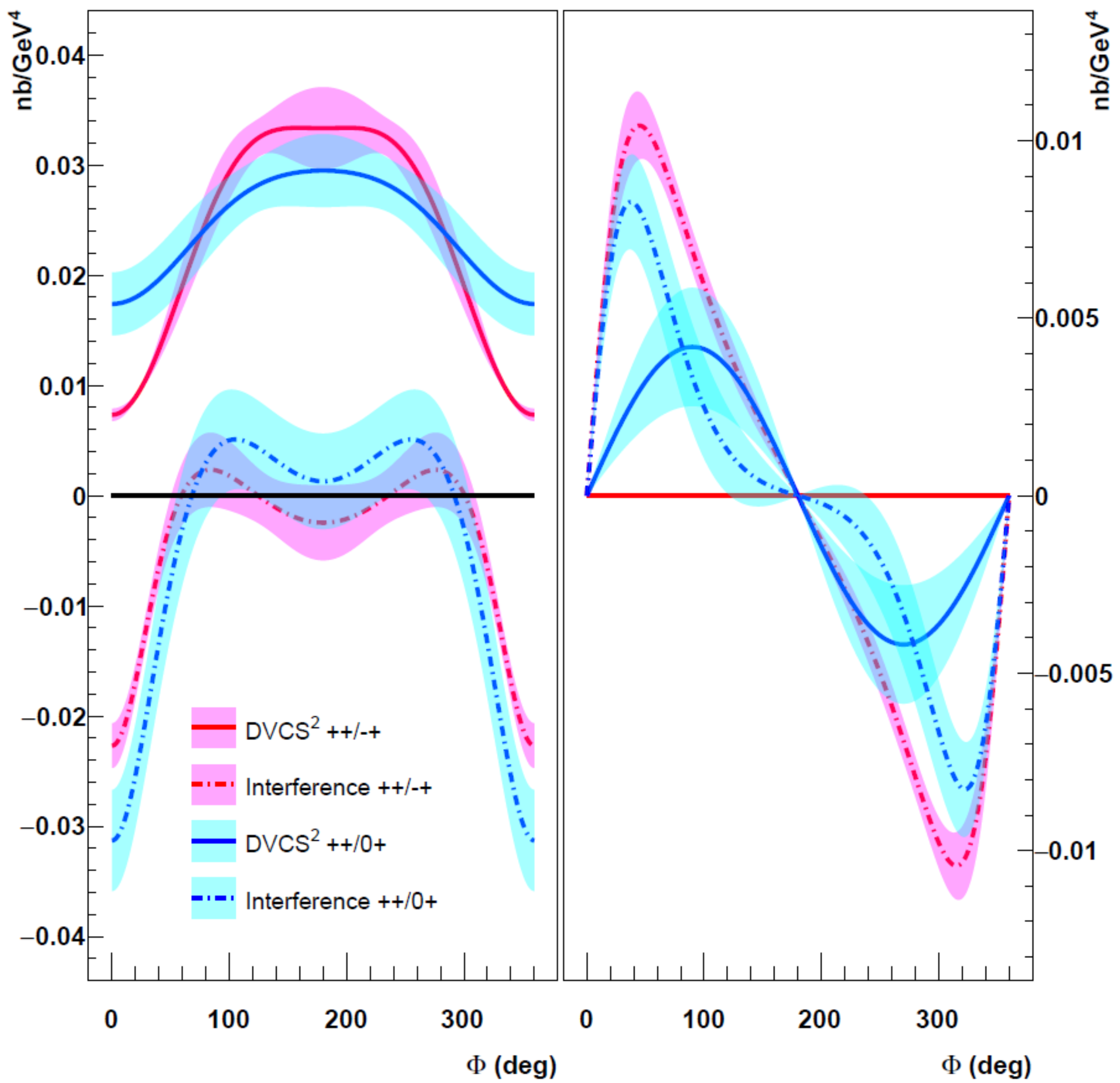
Energy dependence of the DVCS cross section

- Cross section measured at 2 beam energies and constant Q^2, x_B, t



- ➢ Leading-twist and leading order fit of cross sections at both beam energies does not reproduce the data
- ➢ Including either next-to-leading order or higher-twist effects (blue line) satisfactorily reproduces the angular dependence

Separation of the DVCS² and BH-DVCS interference



- DVCS2 & interference significantly different in each scenario
- Sizeable DVCS2 contribution in the higher-twist scenario in the helicity-dependent cross section

Nature Communications 8, 1408 (2017)

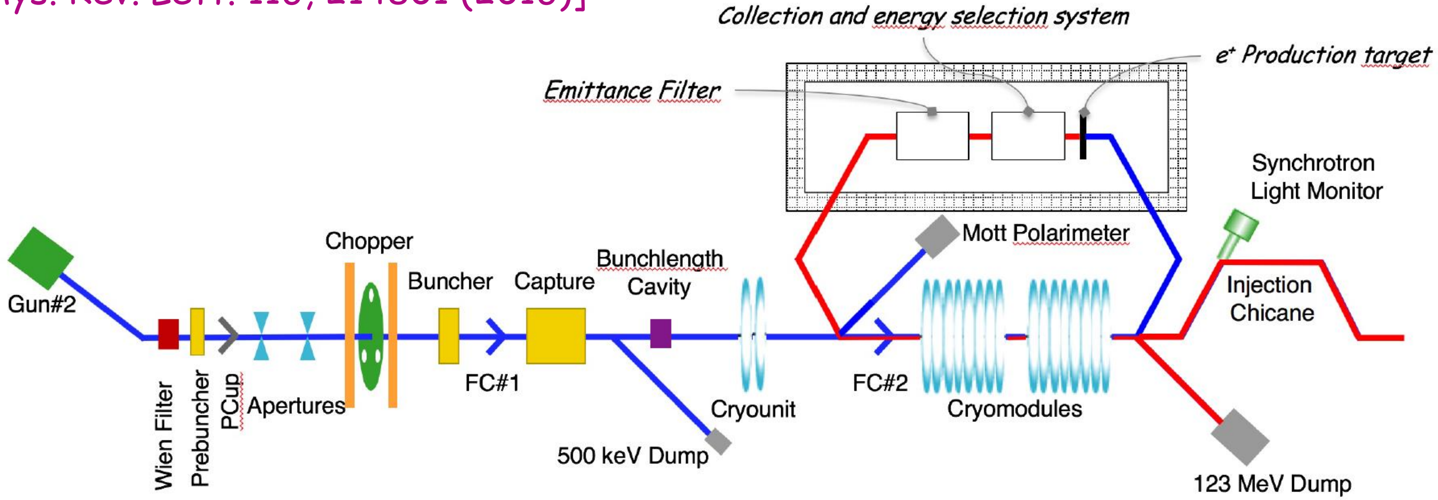
Separation of the DVCS² and BH-DVCS interference: positrons

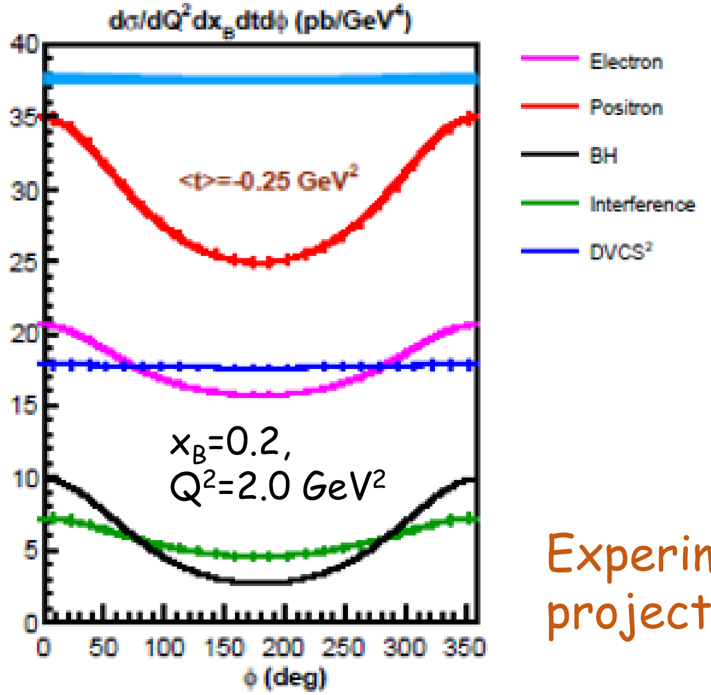
$$|\mathcal{T}(\pm ep \to \pm ep\gamma)|^2 = |\mathcal{T}^{BH}|^2 + |\mathcal{T}^{DVCS}|^2 \mp \mathcal{I}$$

Opposite sign for e- & e+

Experiment proposal submitted in 2020

JLab injector modifications
[based on PEPPo experiment:
Phys. Rev. Lett. 116, 214801 (2016)]





Experimental projections

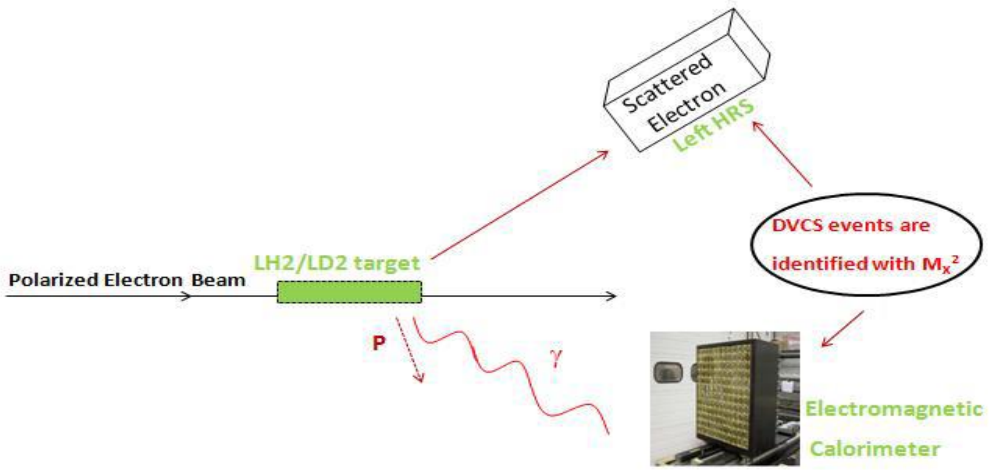
Flavor separation: DVCS off the neutron

- Proton: 2 up quarks, 1 down quark
- Neutron: 1 up quark, 2 down quarks

$$\sigma^{\rightarrow} - \sigma^{\leftarrow} = \Gamma(A \sin\varphi + \dots)$$

LD$_2$ target ($F_2^n(t) \gg F_1^n(t)$!)

$$C^{\mathcal{I}} = F_1(t)\mathcal{H} + \frac{x_B}{2-x_B}[F_1(t)+F_2(t)]\tilde{\mathcal{H}} - \underbrace{\frac{t}{4M^2} \cdot F_2(t) \cdot \mathcal{E}}_{\text{Main contribution for neutron}}$$

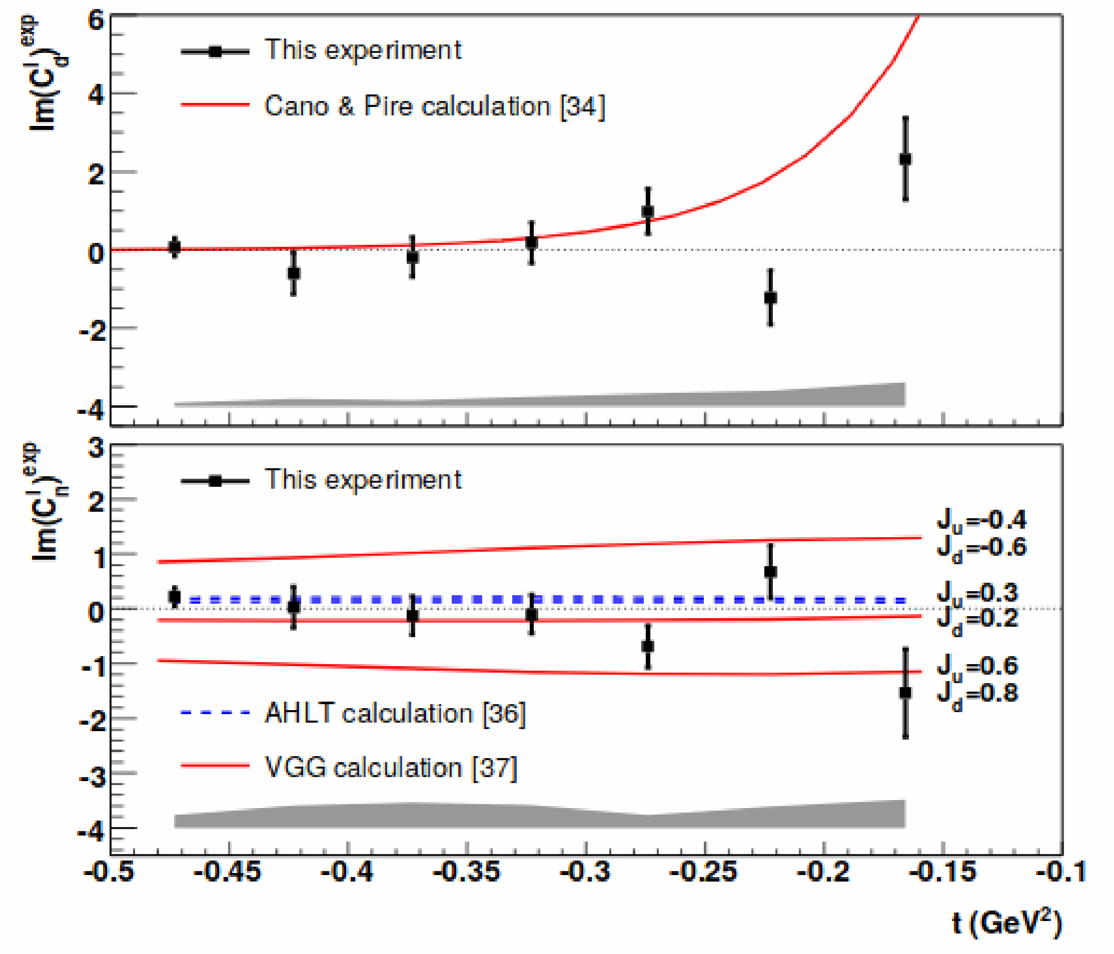


DVCS off the neutron

Polarized cross section difference
Q^2=1.91 GeV^2, x_B=0.36, E_b=5.75 GeV

- $d\sigma^{\rightarrow} - d\sigma^{\leftarrow}$ found compatible with zero within uncertainties
- Used to provide a model-dependent constraint in J_u & J_d

Unpolarized cross section
not measured
(experimental calibration issues
→ next experiment E08-025)



M. Mazouz *et al.*, Phys. Rev. Lett. 99:242501, 2007

DVCS off the neutron: experimental upgrades

1. Frequent swap between LH_2 & LD_2 targets

   $\rightarrow$ **better proton data substraction**

2. Calorimeter upgrade:

   - Larger detector ($11\times12 \rightarrow 13\times16$ 3x3 cm^2 PbF_4 crystals)
   - Lower energy threshold

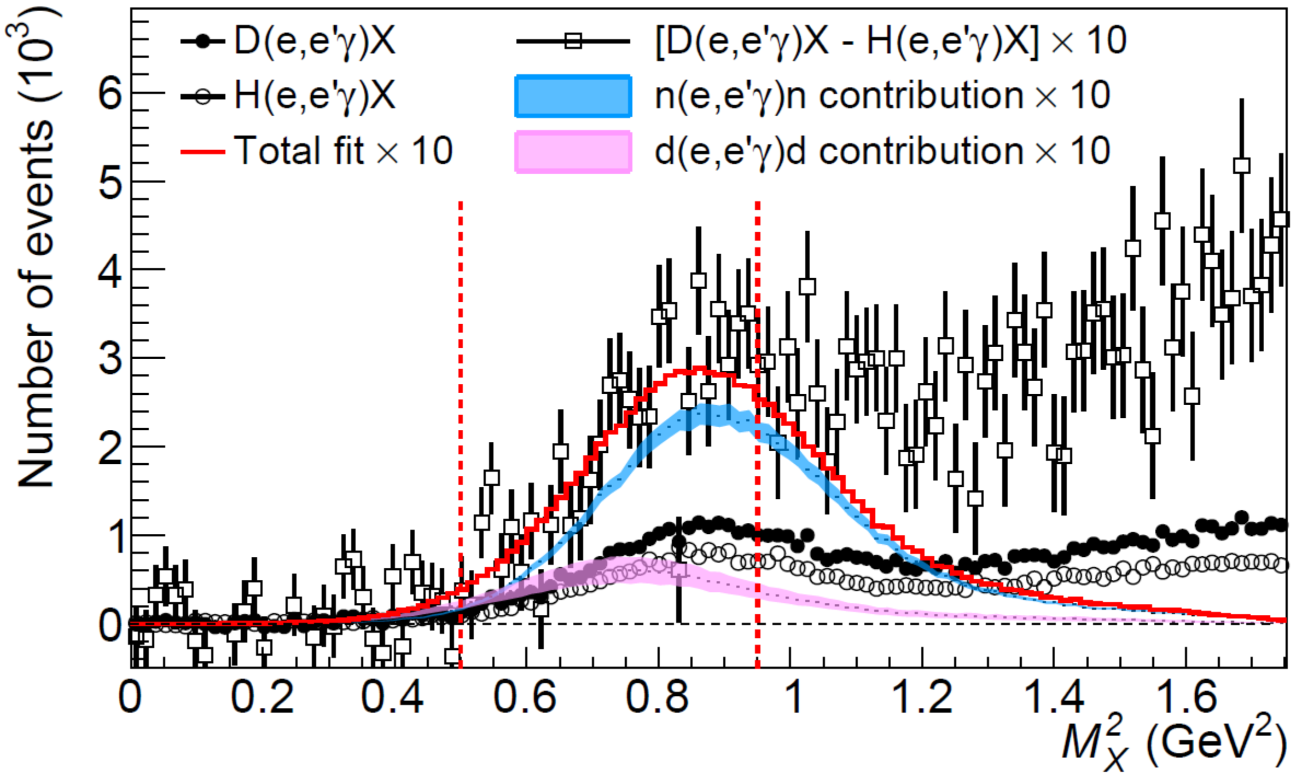
   $\rightarrow$ **Better π^0 substraction**

DVCS off the neutron: exclusivity

LD_2 & LH_2 $ep \to ep\gamma X$ missing mass squared

Impulse approximation:

$$D(e,e'\gamma)X - H(e,e'\gamma)X = n(e,e'\gamma)n + d(e,e'\gamma)d + \dots$$

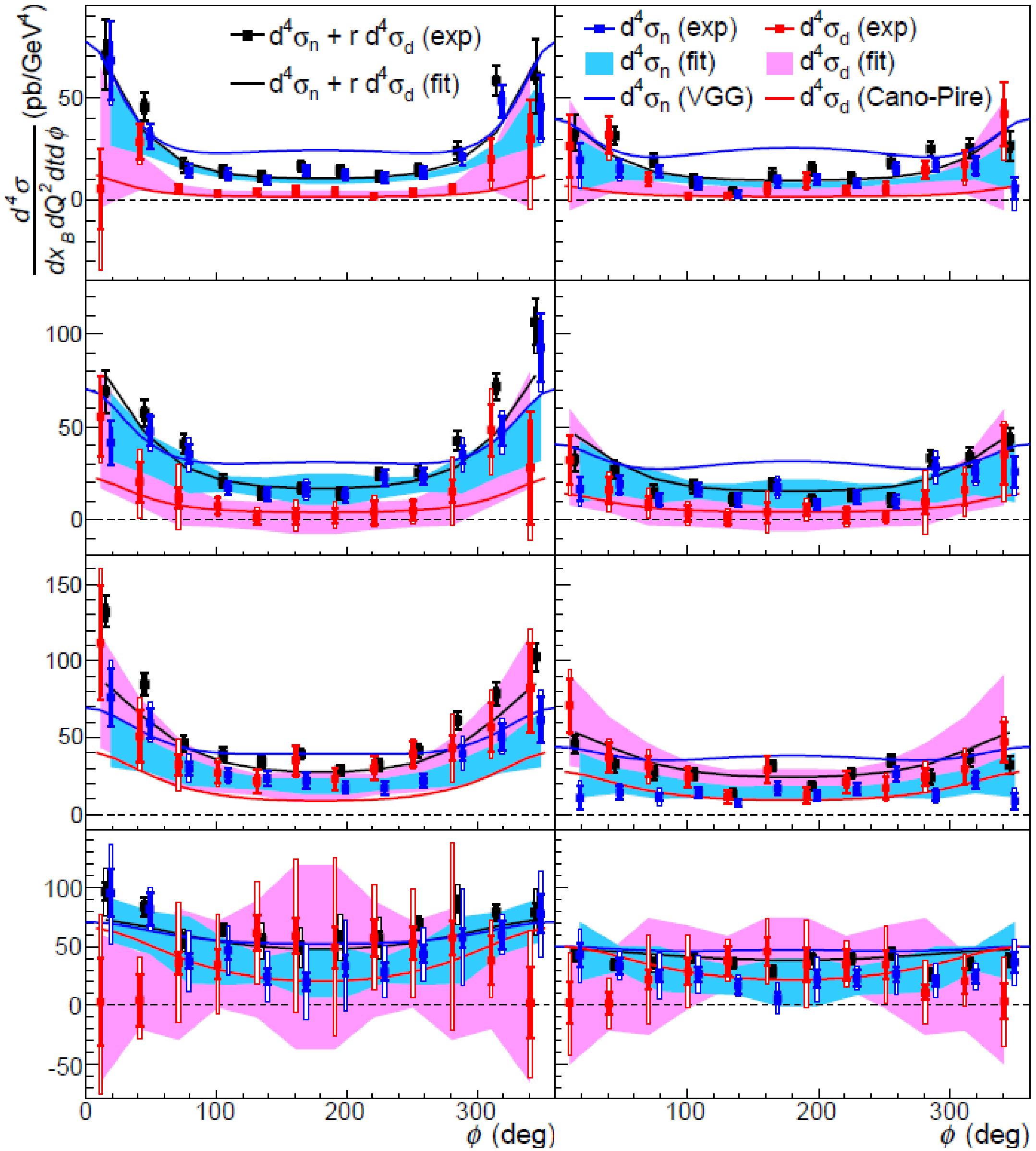


nDVCS and dDVCS shifted by $t/2$ in M^2_X

DVCS off the neutron: cross sections

nDVCS and coherent dDVCS separated through M^2_X shift:

- large correlations at low $-t$
- good separation at larger $-t$



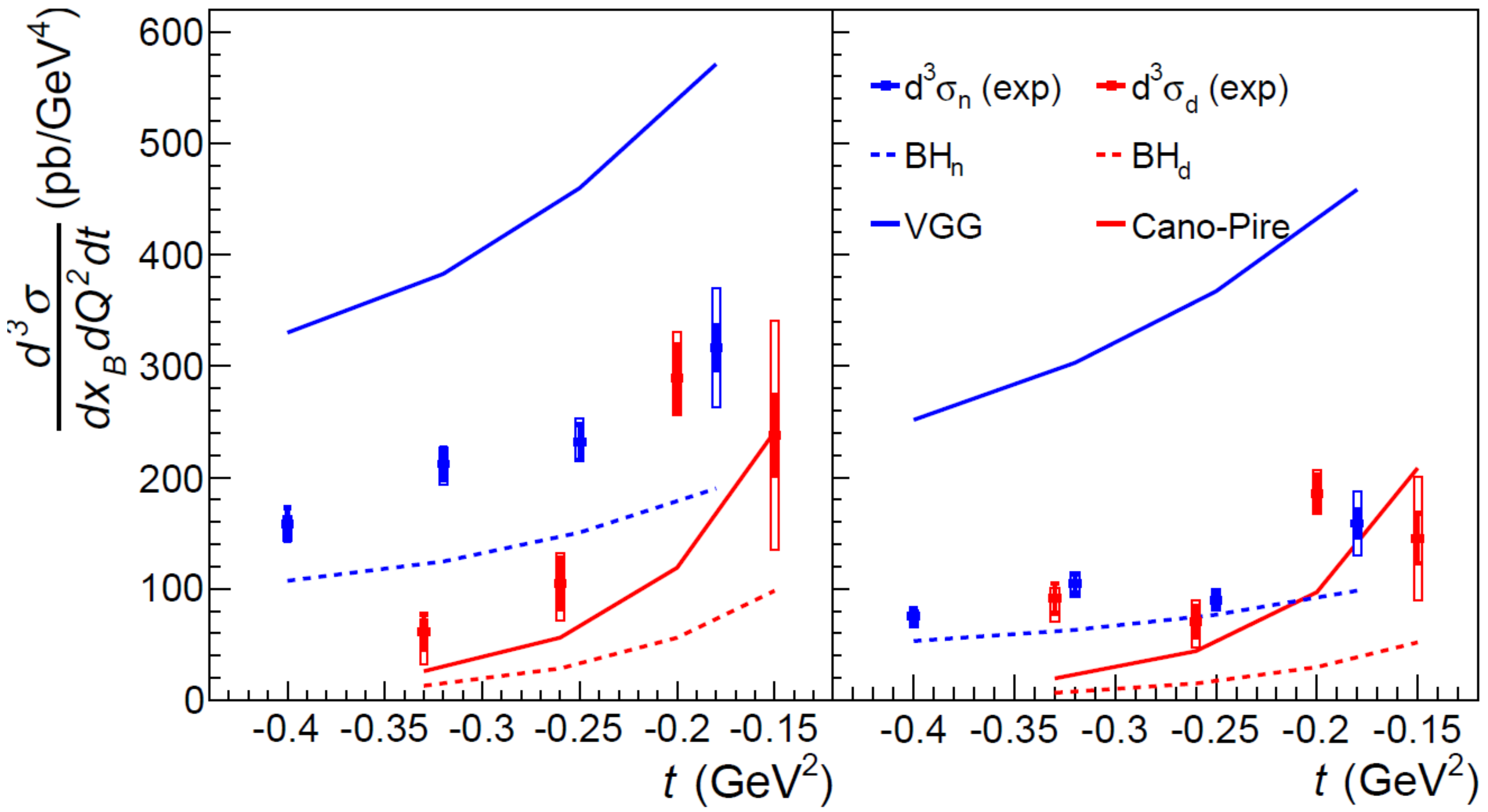
✓ dDVCS very small (compatible with theory)

✓ nDVCS significant signal

(first observation of DVCS off the neutron)

M. Benali *et al.*, Nature Physics 16, 191(2020)

DVCS off the neutron: t-dependence



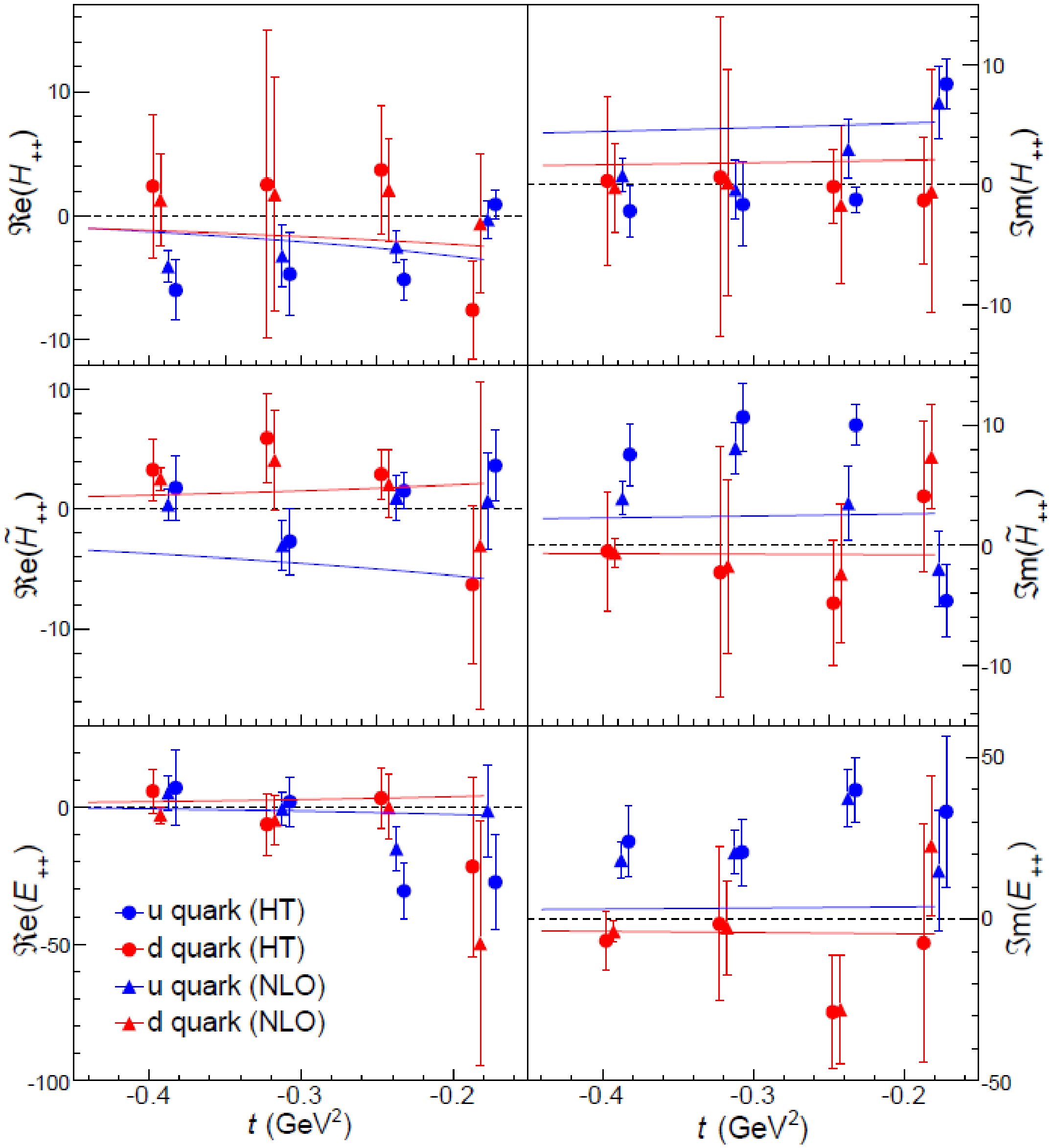
- First experimental determination of the unpolarized $en \to e\gamma n$ cross section
- $\sigma(en \to e\gamma n) > \sigma(BH_n)$: **Sizeable DVCS off the neutron**

M. Benali *et al.*, Nature Physics 16, 191(2020)

DVCS off the neutron: flavor-separated CFFs

Global fit of all Hall A DVCS data off proton and neutron, with CFFs of up and down quarks as free parameters

- ✓ .H^u and H^d: same sign (as forward & large-N_c limits, models…)
- ✓ .Ht^u and Ht^d: opposite sign (as forward & large N_c limit, models…)
- ✓ Data suggest same sign for Re (E^u) and Re (E^d) (against predictions from the large N_c limit)



M. Benali *et al.*, Nature Physics 16, 191(2020)

Summary lecture 2

- DVCS data show indications of leading twist dominance at relatively small values of Q^2 (~2 GeV^2)
- A good description of the precise azimuthal dependence of the cross section may require the inclusion of higher order effects (power corrections)
- Beam energy dependence of the cross section allows to (partially) separate the $DVCS^2$ term from the BH-DVCS interference contribution (ultimately one would need positrons)
- First observation of DVCS off the neutron and initial flavor separation of Compton Form Factors