A glimpse of gluon through Deeply Virtual Compton Scattering on the proton

J. Roche (Ohio University)

- Hard exclusive reactions allow the study of the 3D structure of nucleon through the measure of Generalized Parton Distributions that goes beyond what can be achieved with Elastic and Deep Inelastic Scattering.

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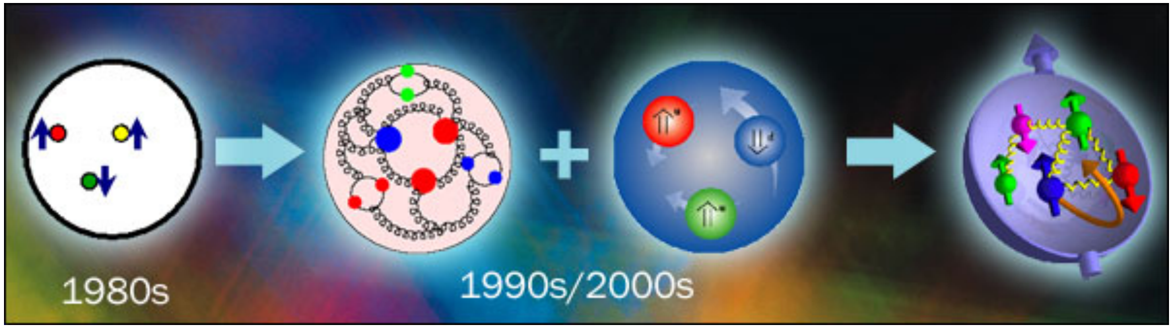
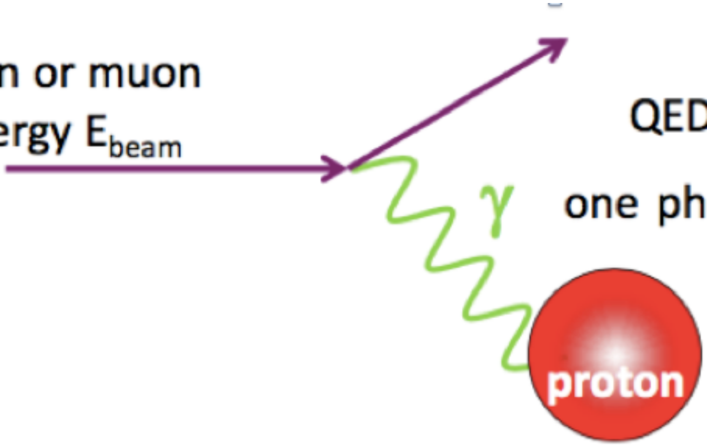
APS April 2018

Nucleons are perfect laboratories for studying QCD .



Lepton beams are well understood probes of their internal structure.



Lepton : electron or muon
of energy E_{beam}

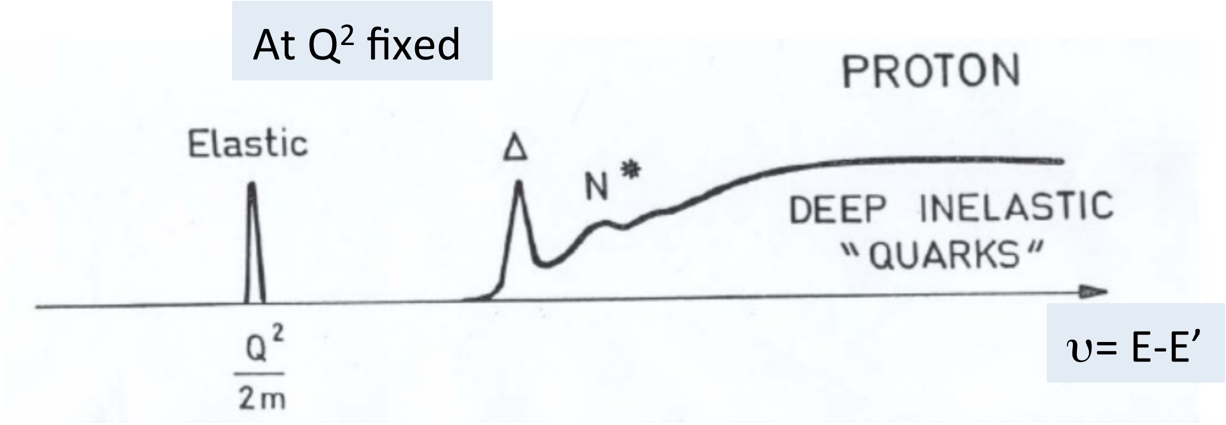
QED: $\alpha=1/137$

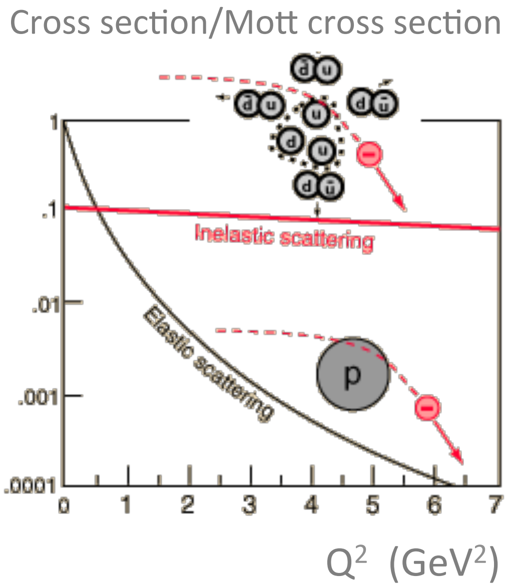
one photon exchange dominates

momentum $\vec{q}$ and energy υ

$Q^2 = \upsilon^2 - q^2$ and $x_B \overset{lab}{=} Q^2/2m\upsilon$

How is the structure of the nucleon studied?





Point like fermion

$$\frac{\mathbf{d}\sigma_{\mathbf{ep\to e'X}}}{\mathbf{d\Omega}} = \frac{\mathbf{d}\sigma_{\mathbf{Mott}}}{\mathbf{d\Omega}} \times \mathbf{F(Q^2, x_B)}$$

Elastic:

$$F(Q^2, x_B = 1)$$

Form factors:
Transverse spatial structure

Deep Inelastic:

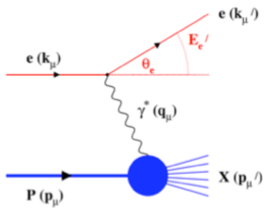
$$F(Q^2 \text{ independent}, x_B)$$

Parton distribution functions:
Longitudinal momentum structure

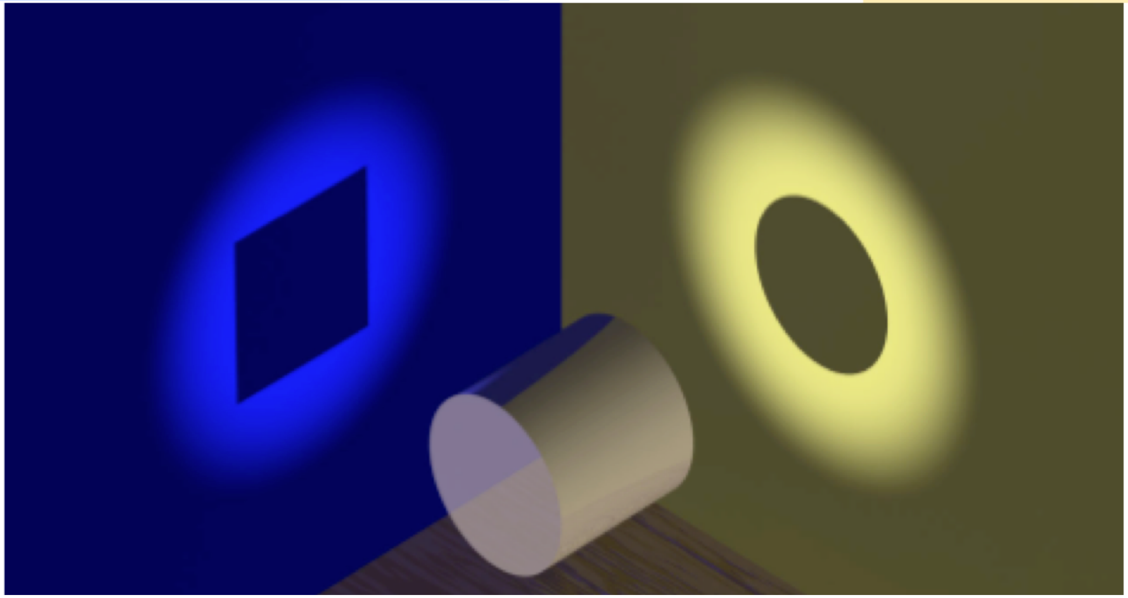
3D picture of the nucleon

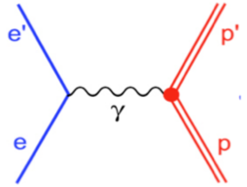
DIS Parton Distribution Functions

Elastic Form Factors



No information on the spatial location of the constituents

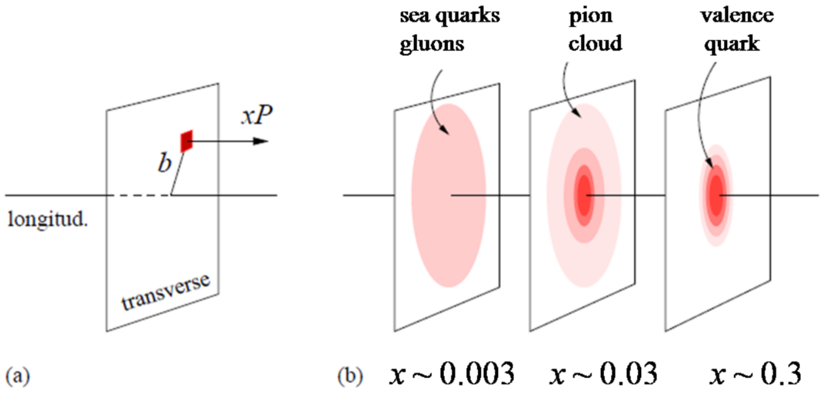




No information about the underlying dynamics of the system

Generalized Parton Distribution Function :

3-D imaging of the nucleon with access to **correlations** between **transverse spatial distribution and longitudinal momentum distributions.**



Slide from S. Stepanyan, GHP April ‘15

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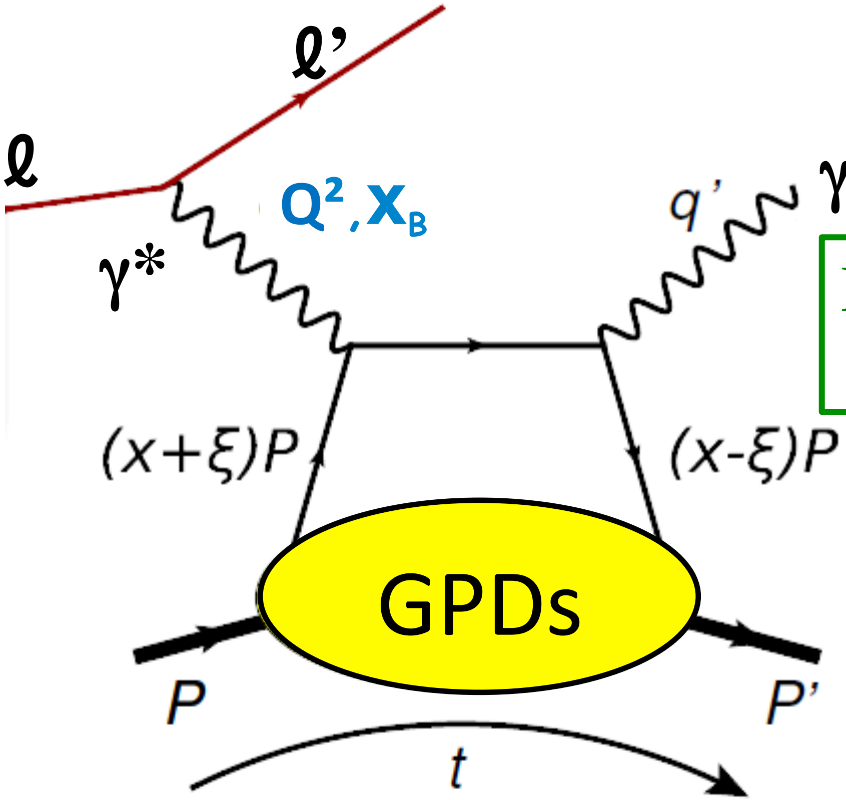
Exclusive reactions: handbag diagram



γ or $\pi, \rho, \phi, J/\psi, \ldots$

DVCS: **$\ell p \rightarrow \ell' p' \gamma$** (golden channel)
HEMP: **$\ell p \rightarrow \ell' p' \pi$ or ρ or ϕ or $J/\psi, \ldots$**

Definition of variables:

x: average long. momentum - NOT ACCESSIBLE

ξ: long. mom. difference $\simeq x_B/(2 - x_B)$

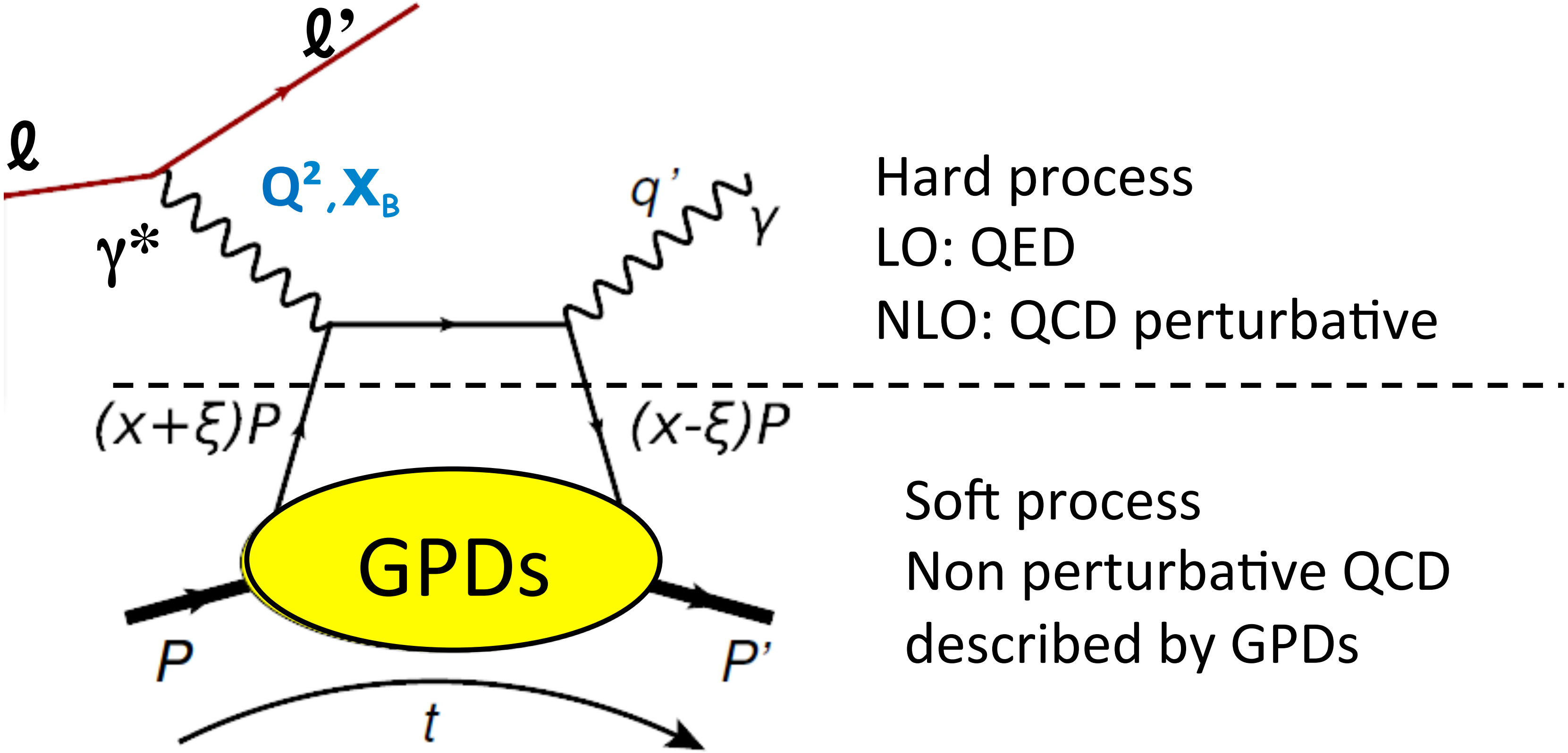
t: four-momentum transfer
related to $b_\perp$ via Fourier transform

Slide from N d'Hose, Tranversity 2014

GPDs and factorization

D. Mueller *et al*, Fortsch. Phys. 42 (1994)
X.D. Ji, PRL 78 (1997), PRD 55 (1997)
A. V. Radyushkin, PLB 385 (1996), PRD 56 (1997)

In the Bjorken limit: $$\left.\begin{array}{rcl} Q^2 = -q^2 & \rightarrow & \infty \\ \nu & \rightarrow & \infty \end{array}\right\} \quad x_B = \frac{Q^2}{2M\nu} \quad \text{fixed}$$



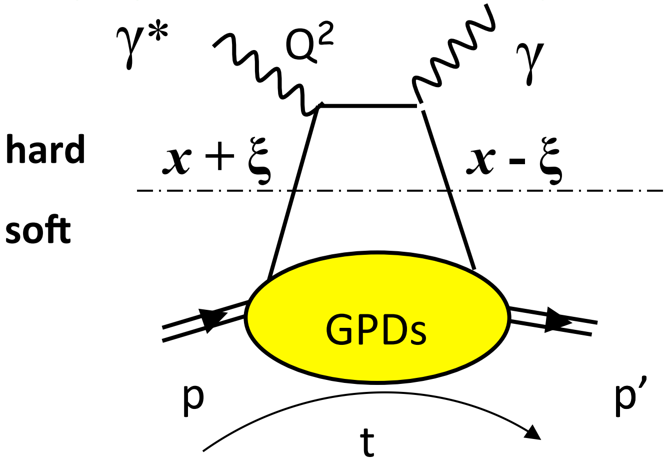
Hard process
LO: QED
NLO: QCD perturbative

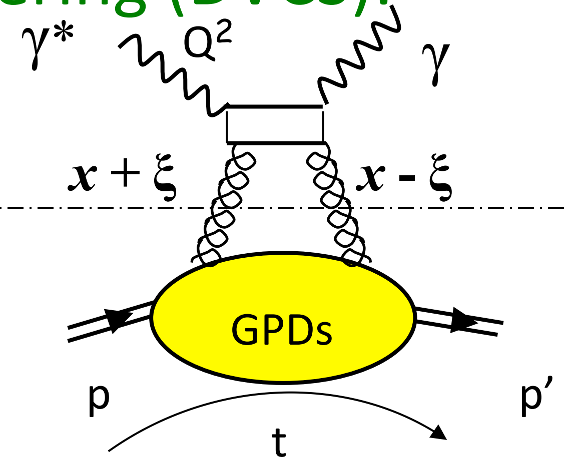
Soft process
Non perturbative QCD
described by GPDs

The minimal Q^2 at which the factorization holds **must be tested** and established by **experiments**

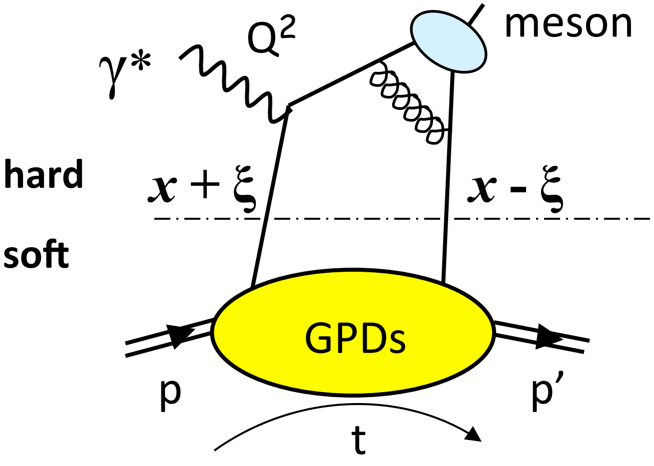
Exclusive reactions

Deeply Virtual Compton Scattering (DVCS):

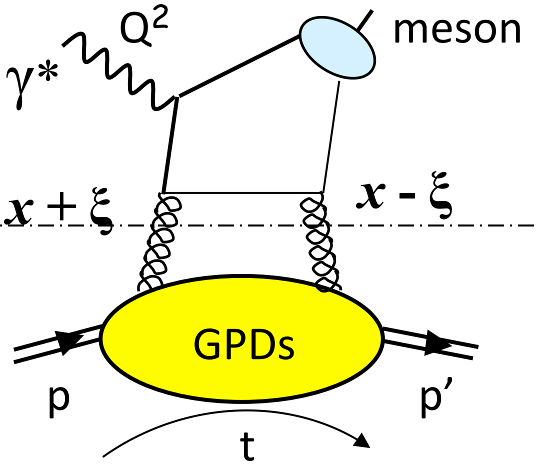




Hard Exclusive Meson Production (HEMP):



Quark contribution



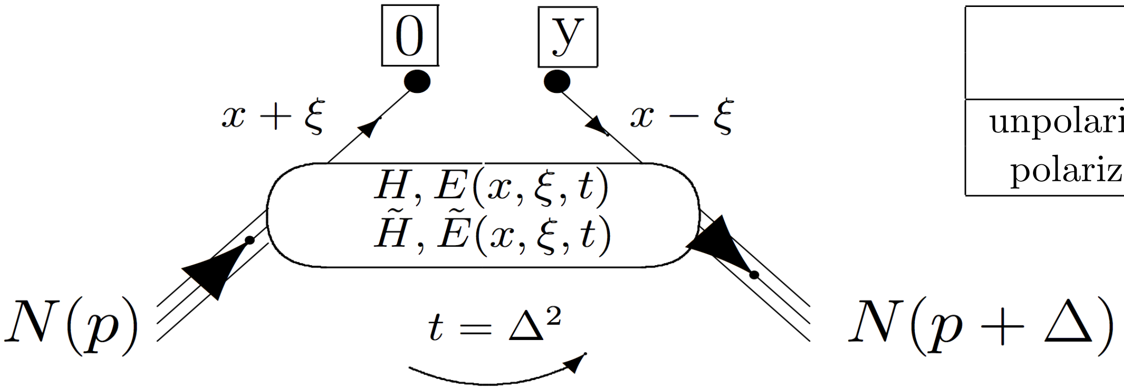
Gluon contribution

γ_L^* factorization

Meson w.f.
Very slow scaling

Slide from N d'Hose, Tranversity 2014

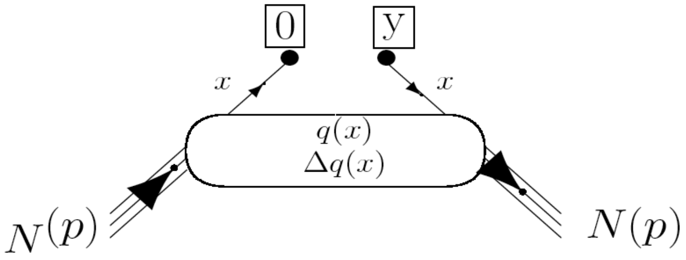
Generalized Parton Distributions



	Nucleon Helicity	
	conserving	non-conserving
unpolarized GPD	H	E
polarized GPD	$\tilde{H}$	$\tilde{E}$

$$\lim_{t\to 0}(GPD) \to PDF$$

DIS

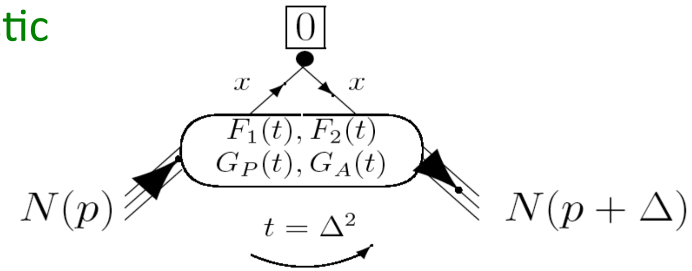


$$H^q(x,0,0) = q(x), -\bar{q}(-x)$$

$$\tilde{H}^q(x,0,0) = \Delta q(x), \Delta\bar{q}(-x)$$

GPD first moments → Form Factors

Elastic



$$\int_{-1}^{+1} dx H^q(x,\xi,t) = F_1^q(t) \quad \int_{-1}^{+1} dx \tilde{H}^q(x,\xi,t) = g_A^q(t)$$

$$\int_{-1}^{+1} dx E^q(x,\xi,t) = F_2^q(t) \quad \int_{-1}^{+1} dx \tilde{E}^q(x,\xi,t) = h_A^q(t)$$

No relation for the GPD E and $\tilde{E}$

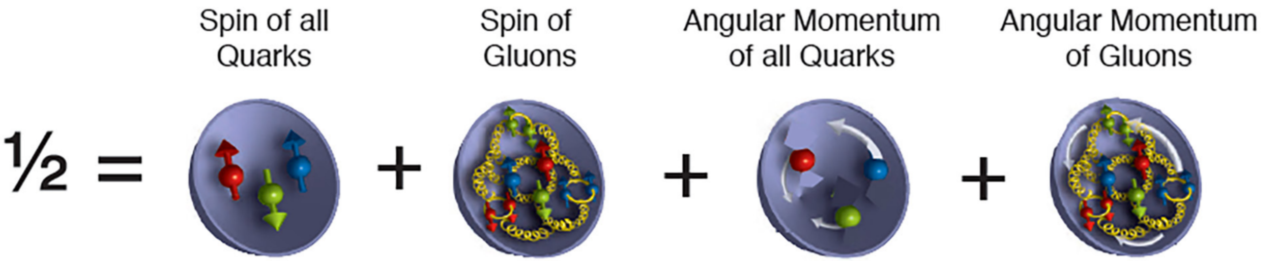
RPP 76(2013) 066202

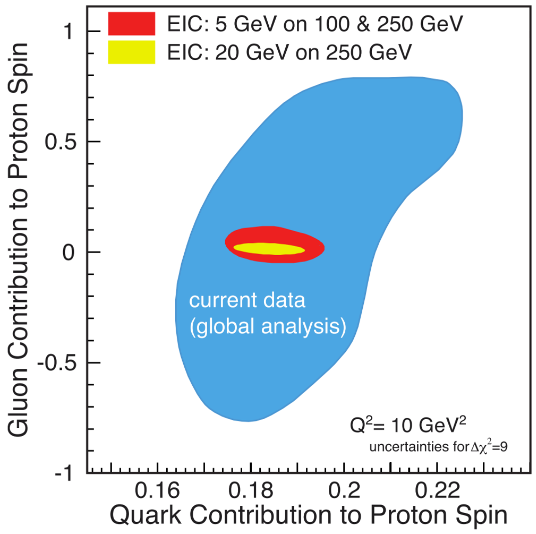
The “Holy grail” of GPDs physics

Contribution of the **angular momentum of quarks** to proton spin:

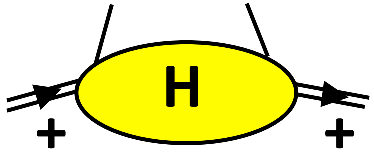
$$\frac{1}{2} = \underbrace{\frac{1}{2}\Delta\Sigma + L_q}_{J_q} + J_g \quad \Rightarrow \quad J_q = \frac{1}{2}\int_{-1}^{1} dx\, x[H^q(x,\xi,0) + E^q(x,\xi,0)]$$

Ji’s sum rule

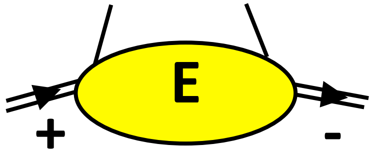




RHIC spin physics results (LRP 2015)



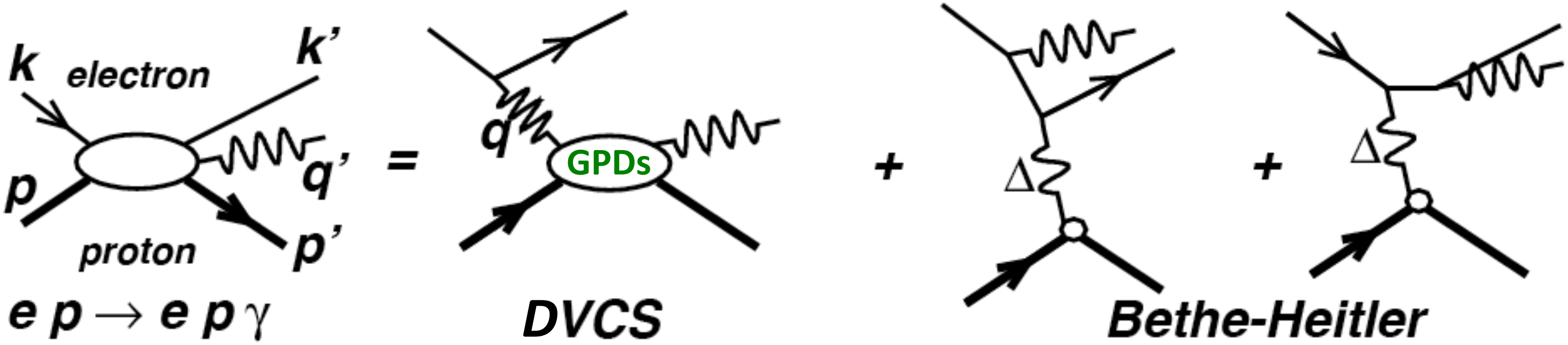
GPD H connects to the PDFs (symmetric initial-final states)
Known from polarized DIS data



GPD E is the unknown

Experimentally, producing enough data to support the integration over the whole x range is a challenge.

Measuring DVCS to access GPDs information



When only considering the handbag diagram (at leading twist)

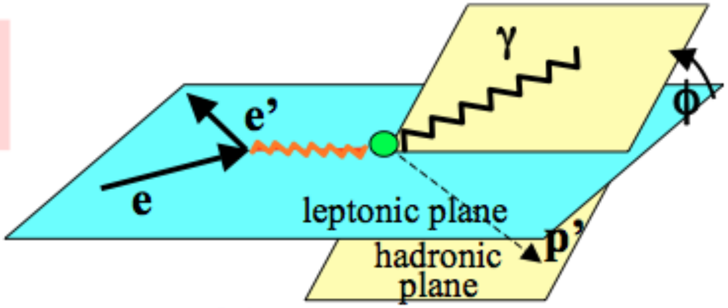
$$d^5\overrightarrow{\sigma} - d^5\overleftarrow{\sigma} = \Im m\,(T^{BH}\cdot T^{DVCS})$$

$$d^5\overrightarrow{\sigma} + d^5\overleftarrow{\sigma} = \underbrace{|BH|^2}_{\text{Known to 1\%}} + \Re e\,(\underbrace{T^{BH}\cdot T^{DVCS}}_{\text{Linear combinations of GPDs}}) + \underbrace{|DVCS|^2}_{\text{Bilinear combinations of GPDS}}$$

DVCS sensitivities to GPDs

$$\Delta\sigma = d^5\overrightarrow{\sigma} - d^5\overleftarrow{\sigma}$$

$\xi = x_B/(2-x_B)$
$k = -t/4M^2$



Polarized beam, unpolarized proton target:

$$\Delta\sigma_{LU} \sim \sin\phi\, \mathbf{Im}\{F_1 H + \underset{\uparrow}{\xi}(F_1+F_2)\widetilde{H} + \underset{\uparrow}{k}F_2 E\}d\phi \quad\Rightarrow\quad H_p, \widetilde{H}_p, E_p$$

Kinematically suppressed

Unpolarized beam, longitudinal proton target:

$$\Delta\sigma_{UL} \sim \sin\phi\, \mathbf{Im}\{F_1\widetilde{H} + \xi(F_1+F_2)(H + \ldots\}d\phi \quad\Rightarrow\quad H_p, \widetilde{H}_p$$

Unpolarized beam, transverse proton target:

$$\Delta\sigma_{UT} \sim \sin\phi\, \mathbf{Im}\{k(F_2 H - F_1 E) + \ldots..\}d\phi \quad\Rightarrow\quad H_p, E_p$$

Polarized beam, unpolarized neutron target:

$$\Delta\sigma_{LU} \sim \sin\phi\, \mathbf{Im}\{F_1 H + \xi(F_1+F_2)\widetilde{H} - kF_2 E\}d\phi \quad\Rightarrow\quad H_n, \widetilde{H}_n, E_n$$

Suppressed because $F_1(t)$ is small

Suppressed because of cancellation between PPD's of u and d quarks

$$H_p(x, \xi, t) = 4/9\, H_u(x, \xi, t) + 1/9\, H_d(x, \xi, t)$$
$$H_n(x, \xi, t) = 1/9\, H_u(x, \xi, t) + 4/9\, H_d(x, \xi, t)$$

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The DVCS program worldwide

Experimental timeline

- Pioneering results from non-dedicated experiments (Hall B and Hermes): ~2001
- First round of dedicated experiments (Hall A/B, Hermes, H1&ZEUS): ~ 2005
- Second round of dedicated experiments (Halls A/B): ~2010
- Compelling DVCS program at JLab-12 GeV and Compass: 2015 and later
- EIC program…

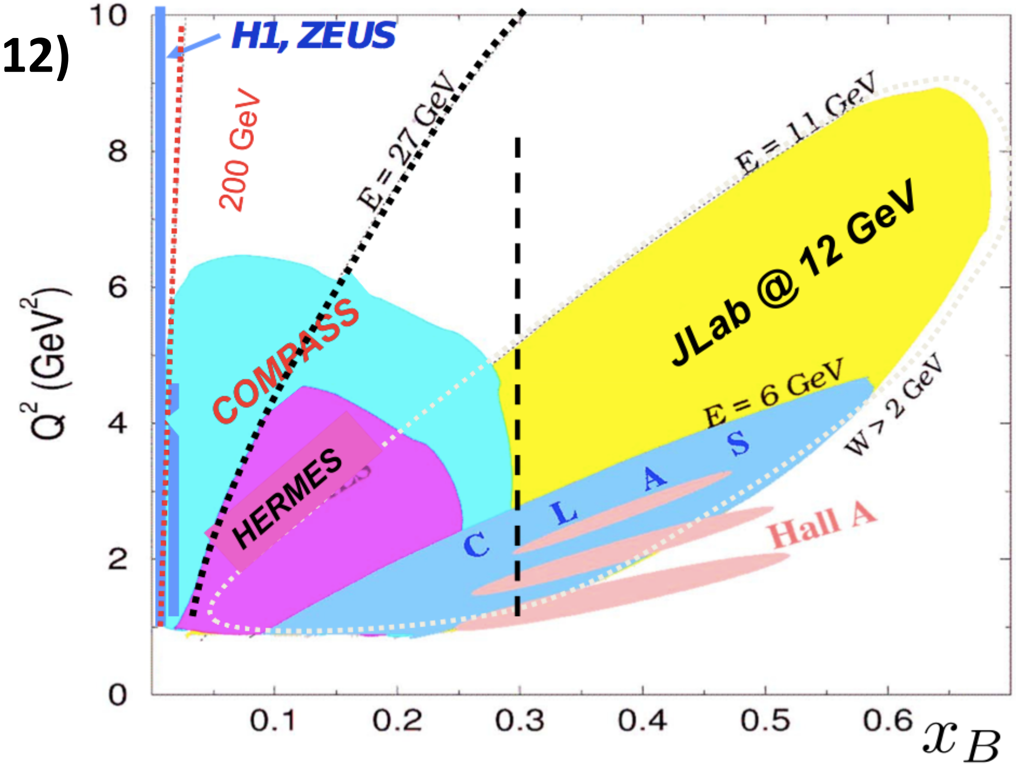
In the valence region (JLab 6 and JLab 12)

Partially complimentary, overlapping

- Hall A/C:
  - high accuracy (~5%)
  - limited kinematic

  Test the validity of the formalism
- Hall B:
  - limited accuracy (15+%)
  - wide kinematic range

  Map the GPDS



The ideal experiment

High beam energy

ensure hard regime and large kinematic domain

polarized beam

availability of **positive** and **negative** leptons

variable energy for:

L/T separation for pseudo scalar production

ε separation for DVCS^2 and Interference (DVCS+BH)

H_2, D_2, Longitudinaly and Transversely Polarized Target

High luminosity

small cross section

fully differential analysis (x_B, Q^2, t, ϕ)

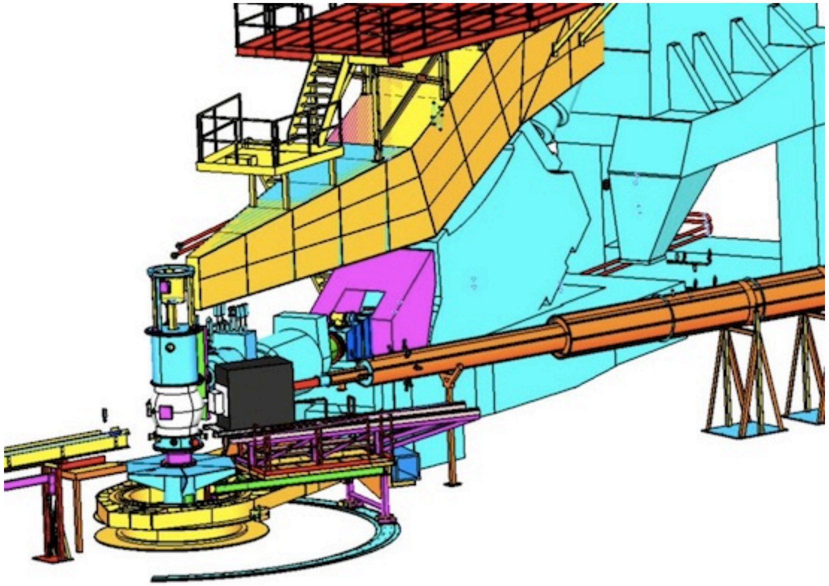
Hermetic detectors

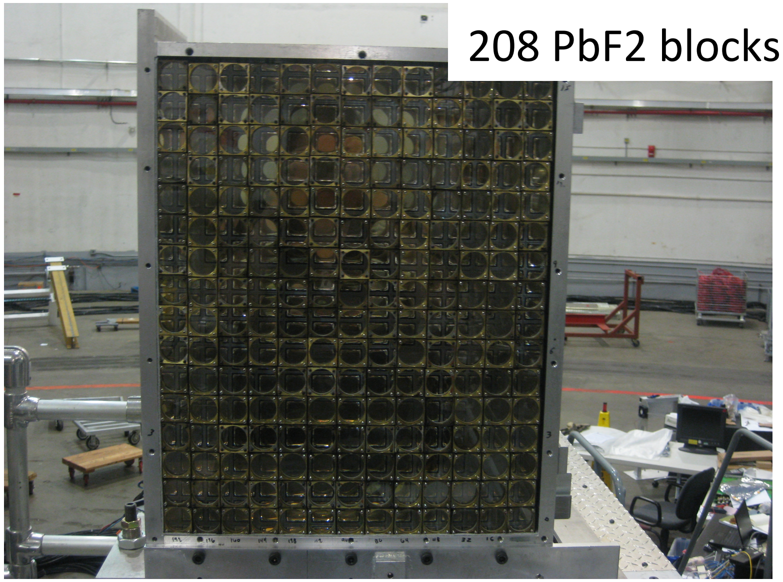
ensure exclusivity

but does not exist (yet)

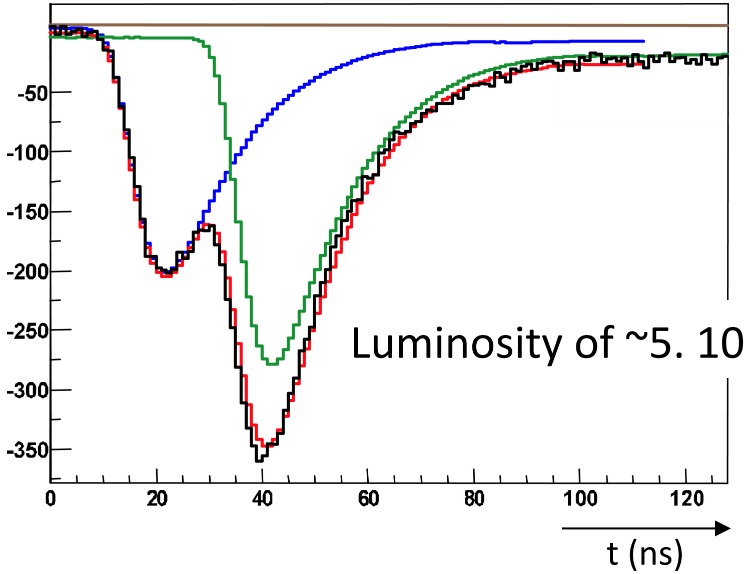
Slide from N d'Hose, Tranversity 2014

Dedicated apparatus eg the Hall A scheme

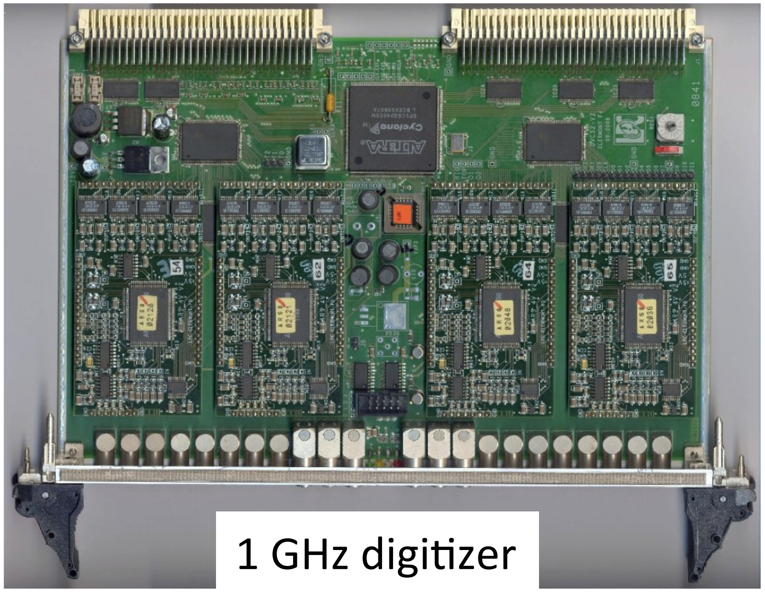




208 PbF2 blocks



Luminosity of ~5. 10^{37} Hz/cm^2

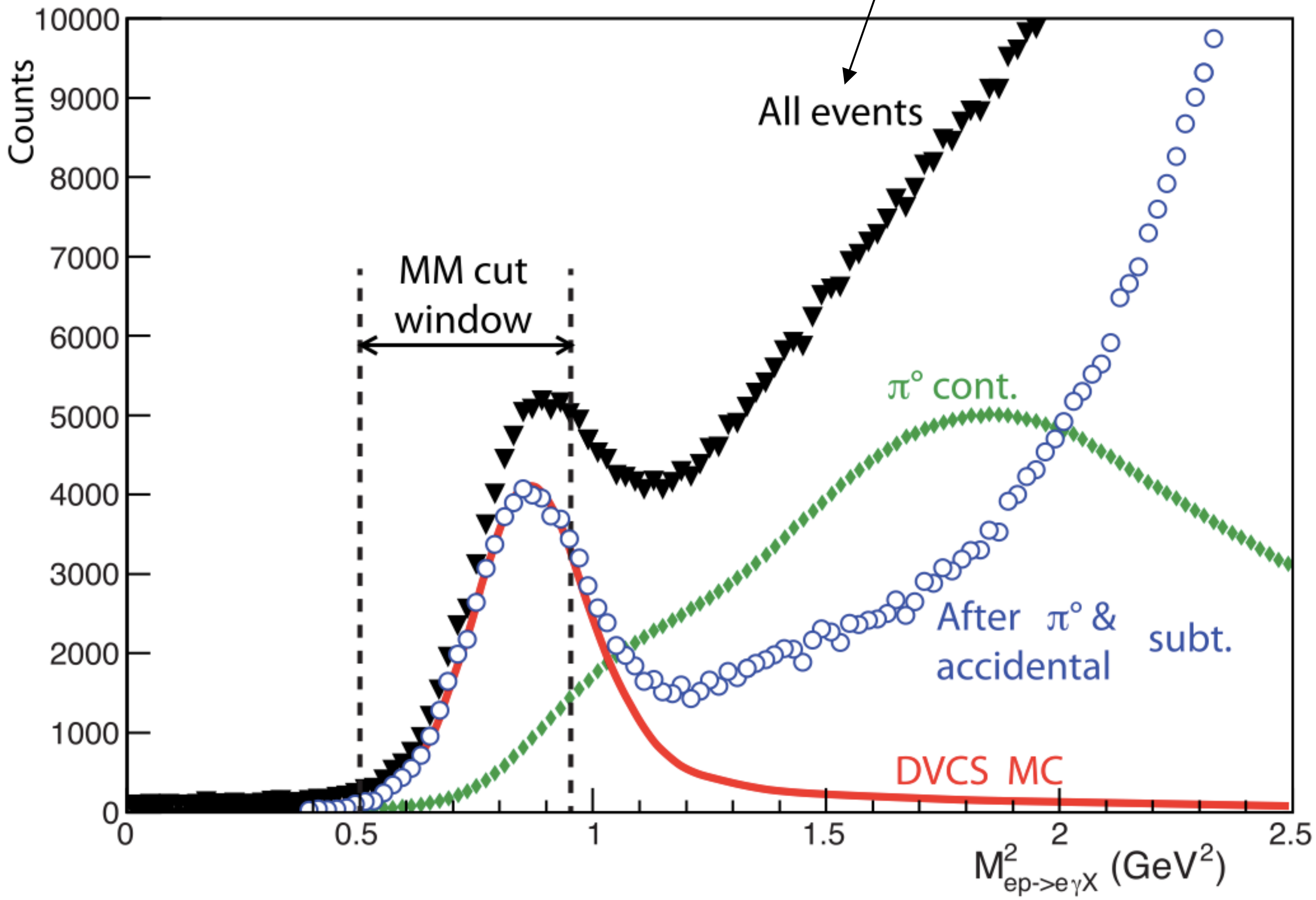


1 GHz digitizer

Exclusivity
eg Hall A 2004 data

H(e,e'γ)X
X can be
- p : ep -> epγ
- γp : ep -> epπ^0, π^0->γγ
- Nπ: ep -> eNγπ

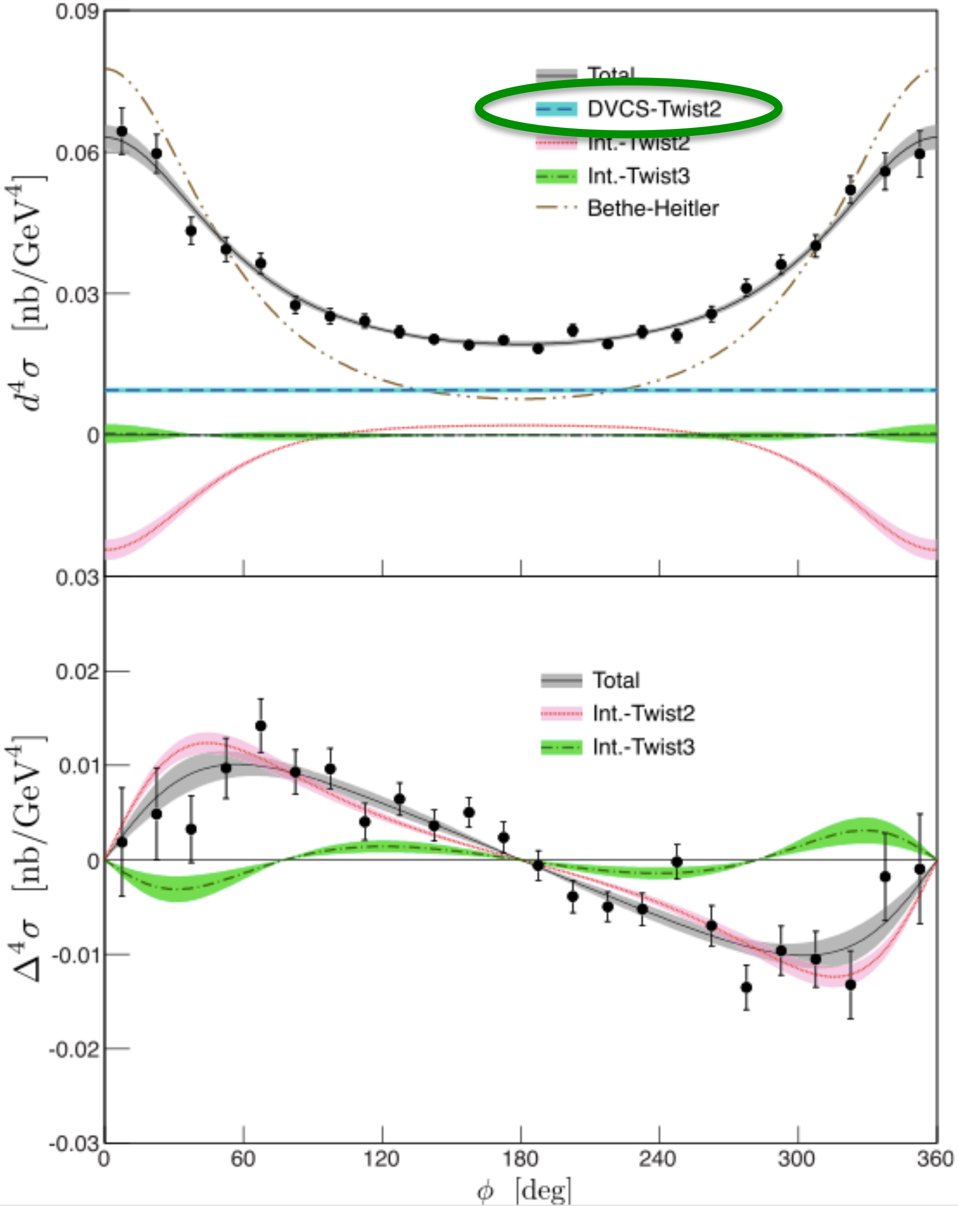
…

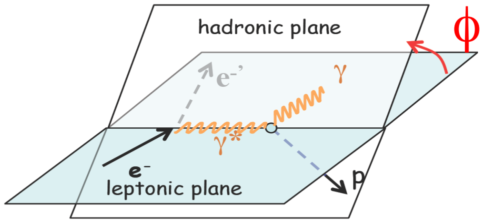


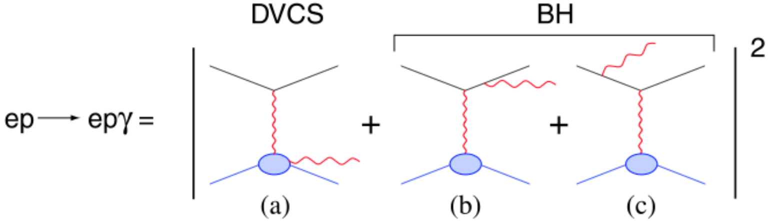
Hall A E00-110: cross section **azimuthal analysis**

$x_B = 0.37, \quad Q^2 = 2.36\ \mathrm{GeV}^2, \quad -t = 0.32\ \mathrm{GeV}^2$

Final paper PRC C92, Nov ‘15







$$d^4\sigma = \mathcal{T}_{\mathrm{BH}}^2 + \mathcal{T}_{\mathrm{BH}}\mathcal{Re}(\mathcal{T}_{\mathrm{DVCS}}) + \mathcal{T}_{\mathrm{DVCS}}^2$$

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

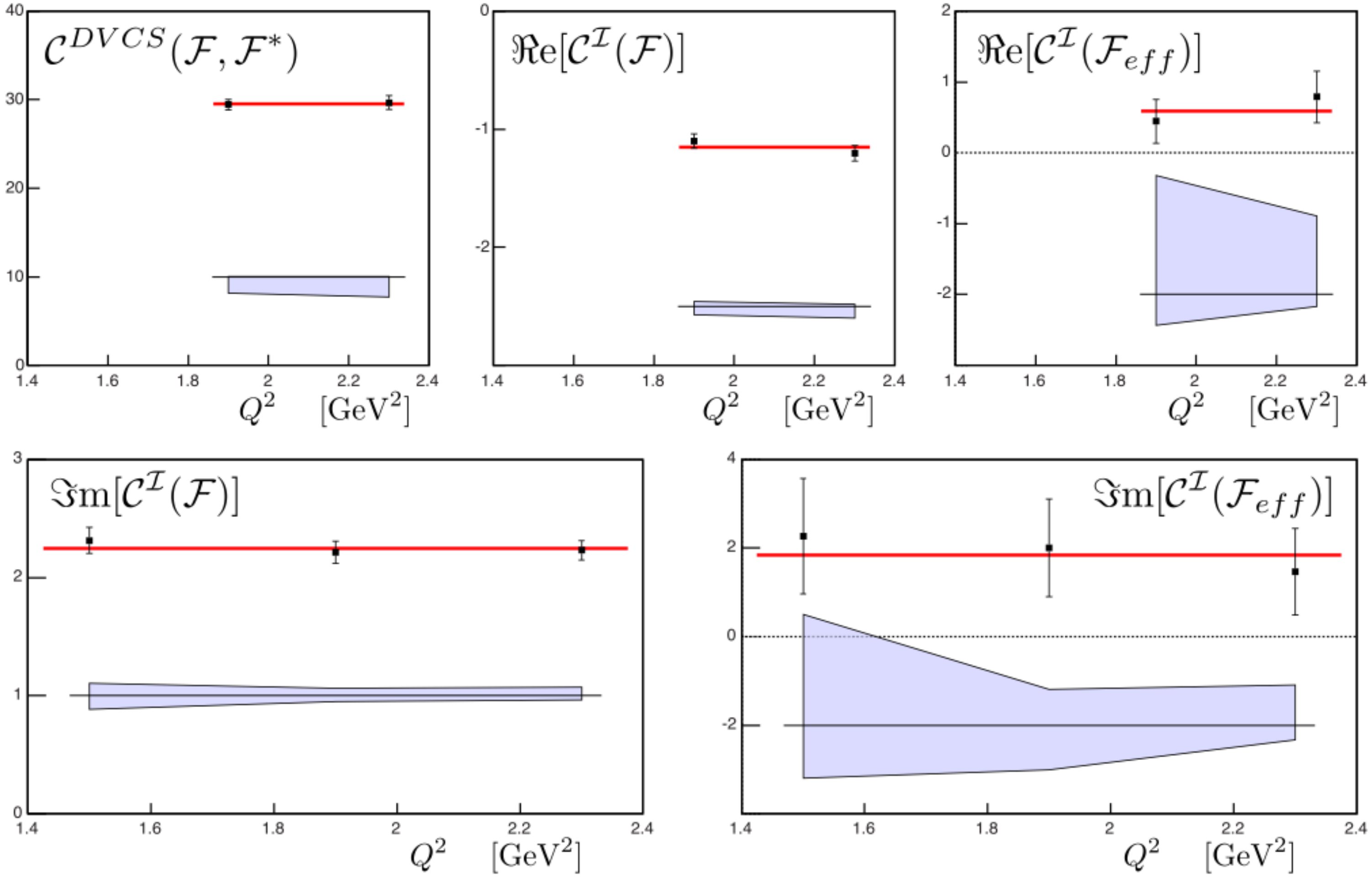
$$\mathcal{T}_{\mathrm{DVCS}}^2 \sim c_0^{\mathrm{DVCS}}$$

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

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

Hall A E00-110: cross section **Q^2 dependence**

PRC C92, Nov ‘15



No Q^2 dependence within this limited range => leading twist dominance
Need to be checked over a larger Q^2 bite

Hall A E07-007: a glimpse of gluons through DVCS

Goal:

To separate the BH.DVCS interference contribution from the DVCS^2 contribution.

Altmetric: 19

More detail »

Article | OPEN

A glimpse of gluons through deeply virtual compton scattering on the proton

M. Defurne, A. Martí Jiménez-Argüello, [...] P. Zhu

Nature Communications **8**,
Article number: 1408 (2017)
doi:10.1038/s41467-017-01819-3

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Experimental nuclear physics

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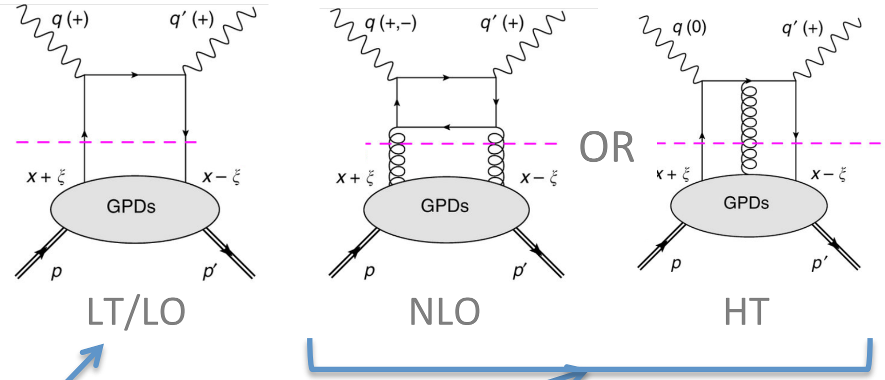
Accepted: 18 October 2017

Hall A E07-007: a glimpse of gluons through DVCS

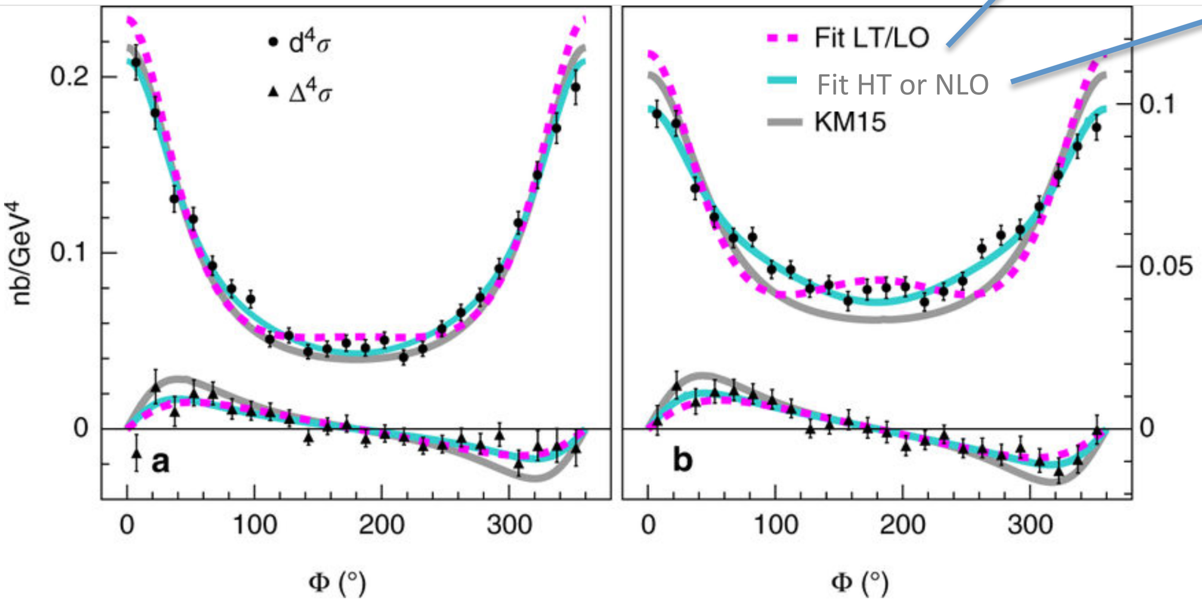
Goal:

To separate the BH.DVCS interference contribution from the DVCS^2 contribution.

	Kin 1		Kin 2		Kin3	
Q^2 (GeV^2)	1.5		1.75		2.0	
X_B	0.36		0.36		0.36	
E_{beam} (GeV)	3.36	5.55	4.45	5.55	4.45	5.55

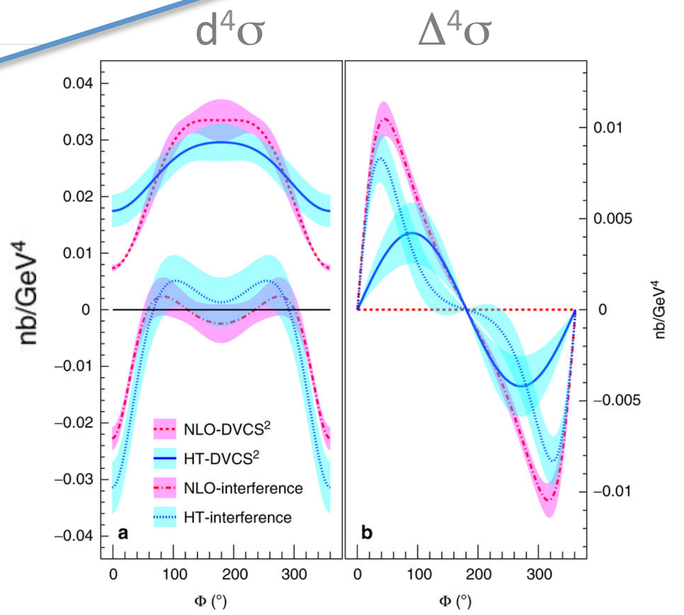


Q^2=1.75 GeV^2, t=-0.30 GeV^2



E_{beam}=4.455 GeV

E_{beam}=5.55 GeV

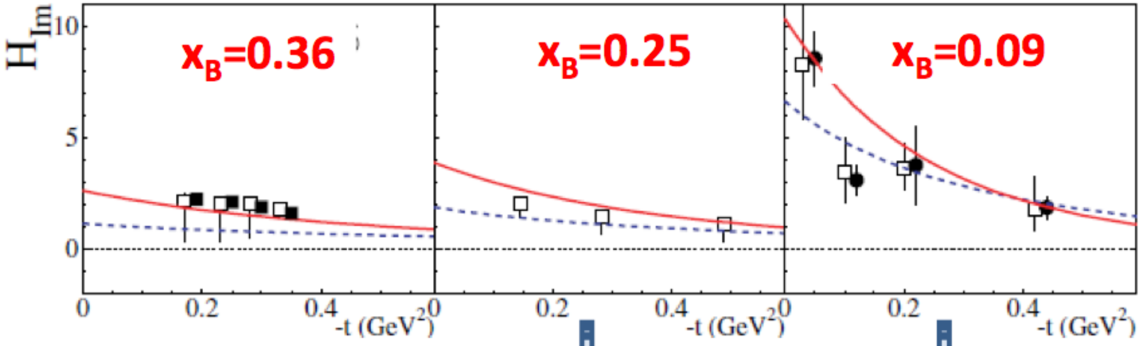


Towards the 3D Structure of the Proton (past 10 years)

the CFF H in *Im* DVCS

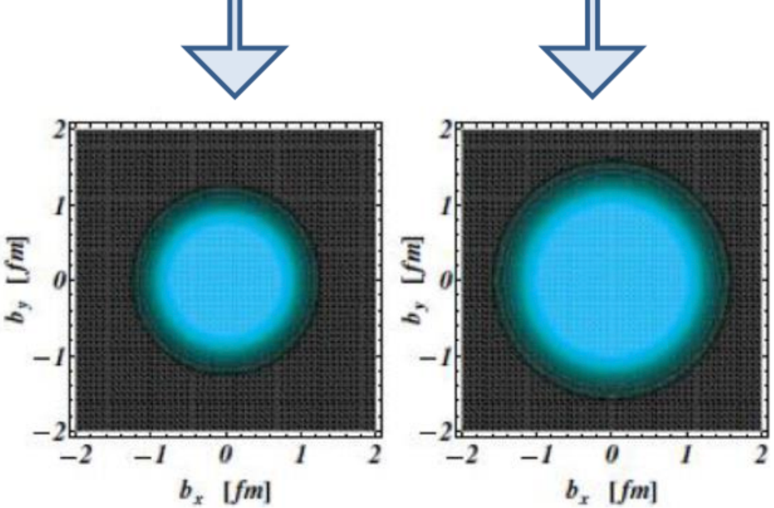
●○■□ Different local fits
— VGG model
- - - KM10 global fit on the world data ranging from H1,ZEUS to HERMES, JLab

e⁻ 6 GeV		e± 27 GeV
Jlab Hall A	**Jlab CLAS**	**HERMES**
Beam Spin Diff	Beam Spin Asym	Beam Spin Asym
Beam Spin Sum	Long Pol targ Asym	Beam Charge Asym



To "extract the GPDs", one can:

- Compare data to models of the GPDs
- Extract GPDs from data:
  - world-wide data fitted at once (8 quantities varying with x_B and t),
  - fit data points versus ϕ at one kinematic point choosing a limited set of GPDs.

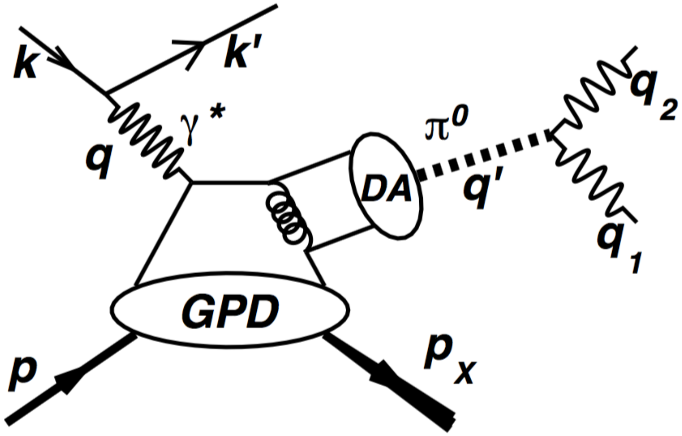


Guidal, Moutarde, Vanderhaeghen, Rept. Prog. Phys. 76 (2013)

An encouraging proof of concept: one is looking forward to much refined data and analysis.

L/T pion production separation: E07-007

M. Defurne et al. PRL 117, 26 (2015)

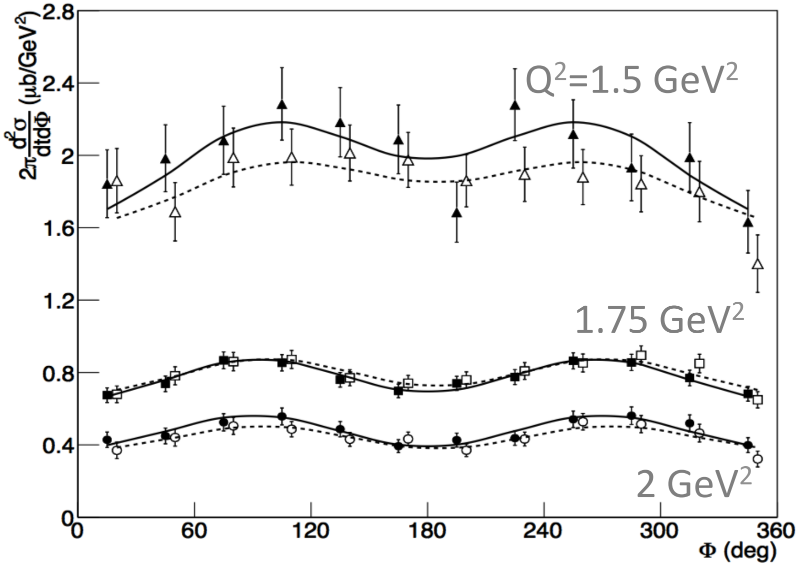


4 chiral-even GPDs
4 chiral-odd GPDS (not seen in DVCS)

Leading twist , leading order factorization is only proven for $d\sigma_L/dt$

$$\frac{d^4\sigma}{dt\,d\phi\,dQ^2\,dx_B} = \frac{1}{2\pi}\Gamma_{\gamma^*}(Q^2, x_B, E_e)\left[\frac{d\sigma_T}{dt} + \epsilon\frac{d\sigma_L}{dt} + \sqrt{2\epsilon(1+\epsilon)}\frac{d\sigma_{TL}}{dt}cos(\phi) + \epsilon\frac{d\sigma_{TT}}{dt}cos(2\phi)\right]$$

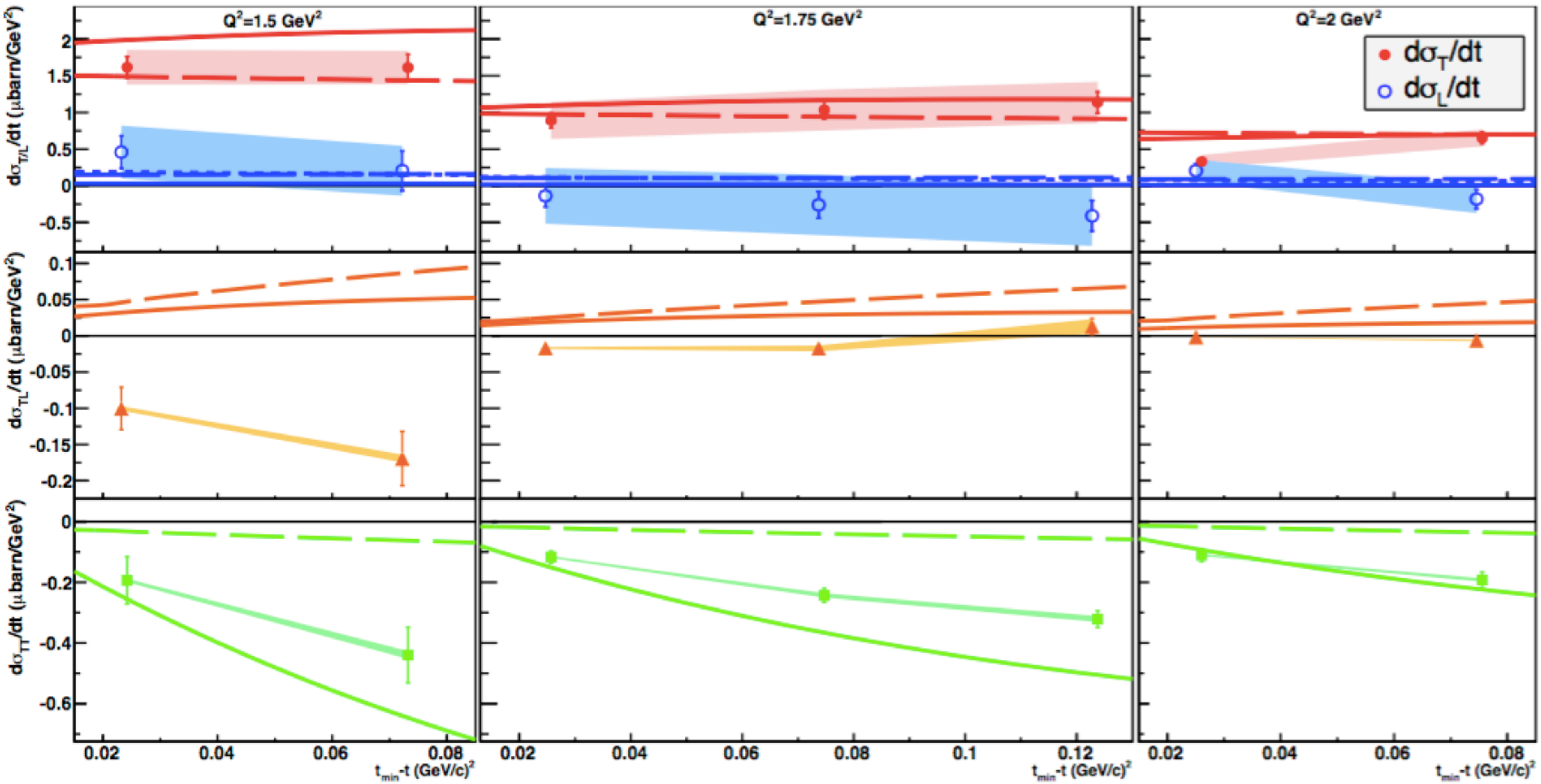
Setting	E (GeV)	Q^2 (GeV^2)	x_B	ϵ
2010-Kin1	(3.355 ; 5.55)	1.5	0.36	(0.52 ; 0.84)
2010-Kin2	(4.455 ; 5.55)	1.75	0.36	(0.65 ; 0.79)
2010-Kin3	(4.455 ; 5.55)	2	0.36	(0.53 ; 0.72)



Dominance of $d\sigma_T/dt$ observed like at

- Hermes & Hall C π^+
- Hall B, Hall A π^0

E07-007: π^0 fully separated contributions



Models with $d\sigma_T$ factorization scheme

– – – G-H-L (JPG:NPP39 ‘12)

—— G-K (EPJA47 ‘11)

Small $d\sigma_L$, large $d\sigma_T$: models ok on these
Wrong sign and t dependence on $d\sigma_{TL}$ and $d\sigma_{TT}$
$d\sigma_{TL}$ sizeable => $d\sigma_L$ is small but not null

A glimpse of gluon through Deeply Virtual Compton Scattering on the proton

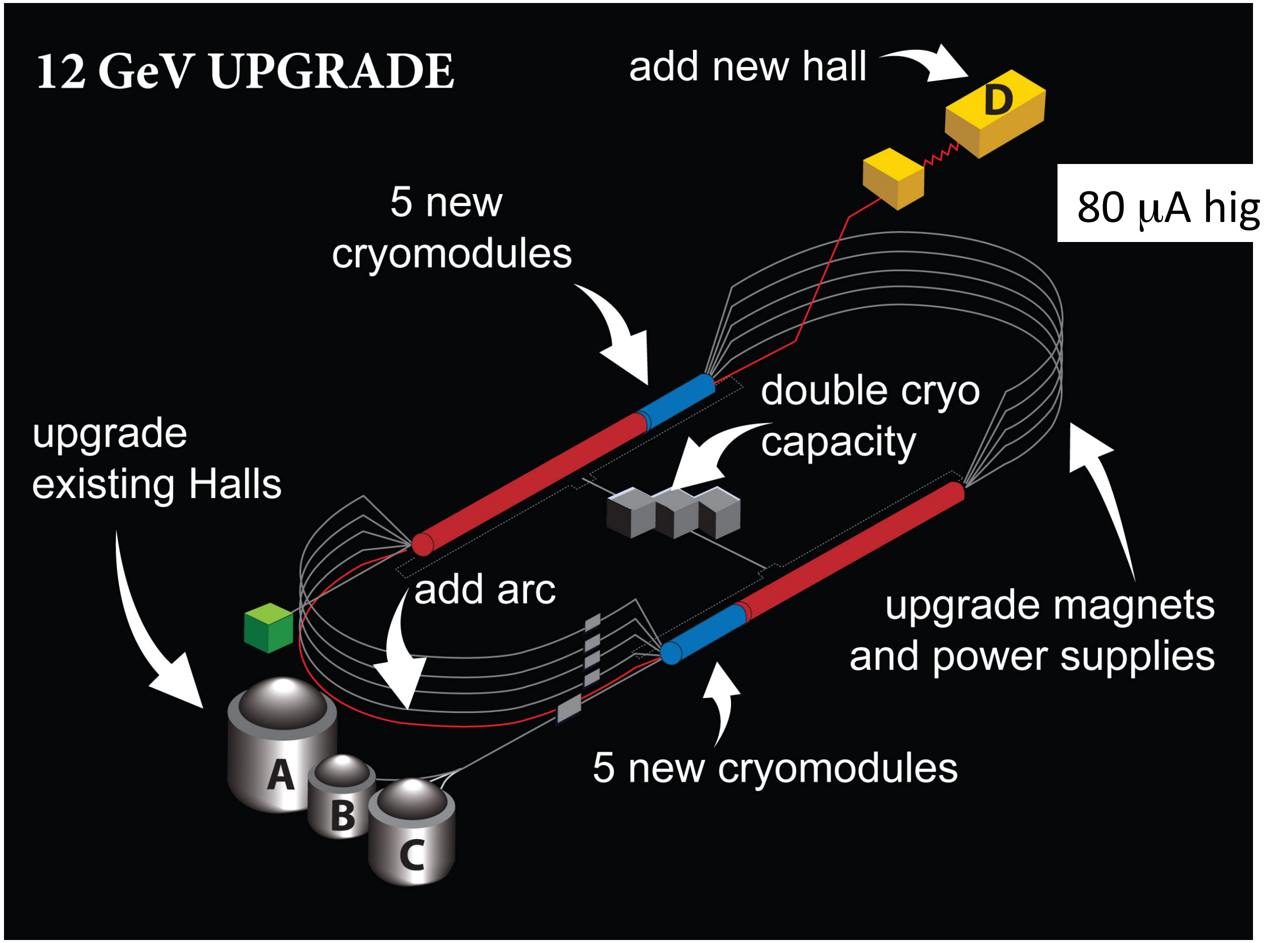
J. Roche (Ohio University)

- Hard exclusive reactions allow the study of the 3D structure of nucleon through the measure of Generalized Parton Distributions that goes beyond what can be achieved with Elastic and Deep Inelastic Scattering.

- Dedicated experiments are conducted world-wide. In the valence region, the growing set of existing results is helping refine our approach to extracting the GPDs from the data.

- DVCS experiments are an essential part of the comprehensive GPD program with the 12 GeV CEBAF beam and the EIC.

JLab



80 μA highly polarized beam

Physics topics:

- Search for exotic mesons
- Search for Physics beyond the Standard Model
- Study of the spin and flavor dependence of valence PDFs
- Study of modification of the quark structure in dense nuclear medium
- Study of the 3-D structure of the nucleon (GPDs-TMDs)

Overall JLab 12 GeV DVCS proposals

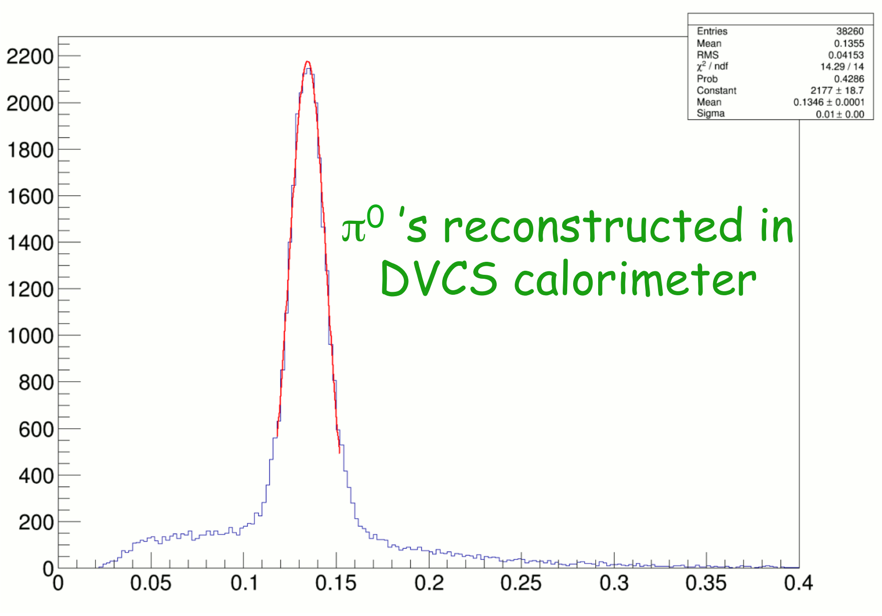
- E12-06-114: Hall A unpolarized protons

Q^2 scans at various x_B

(data taking “completed” at the end of 2016)

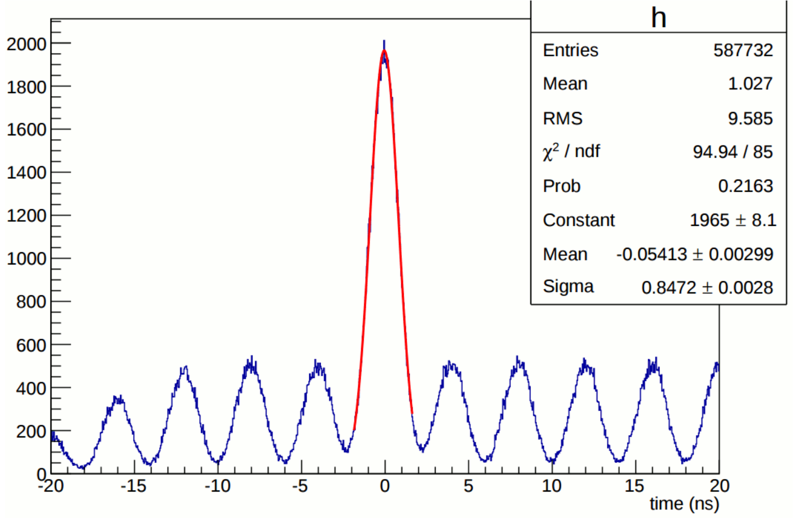
- E12-06-119: Hall B unpolarized protons
- E12-11-003: Hall B unpolarized neutrons
- E12-06-119: Hall B long polarized protons
- E12-12-010: Hall B tran polarized protons
- E12-13-010: Hall C unpolarized protons

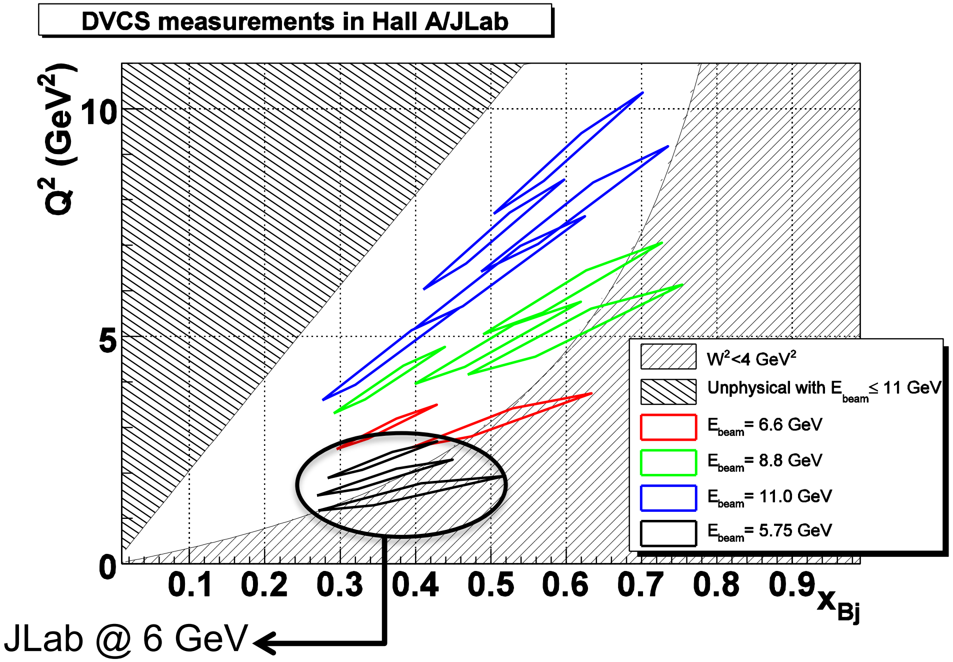
E12-06-114 DVCS/Hall A experiment at 11 GeV

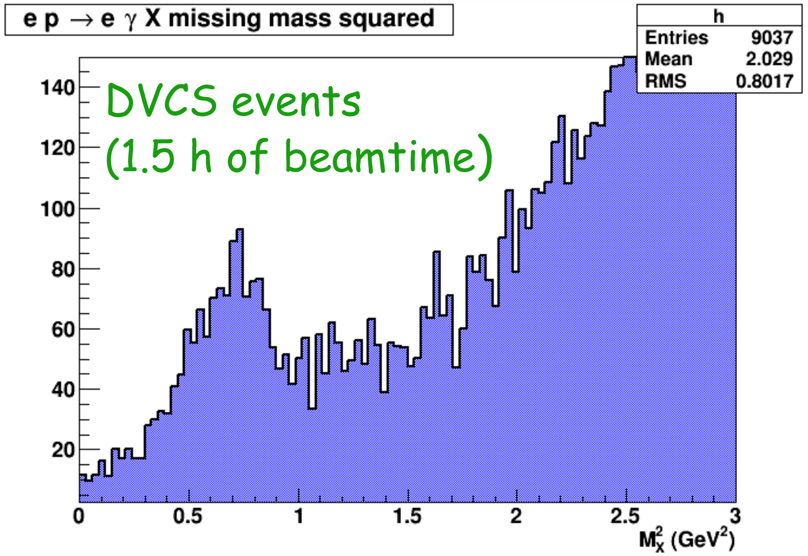


π^0 's reconstructed in DVCS calorimeter

Excellent coincident time resolution:
250 MHz beam structure





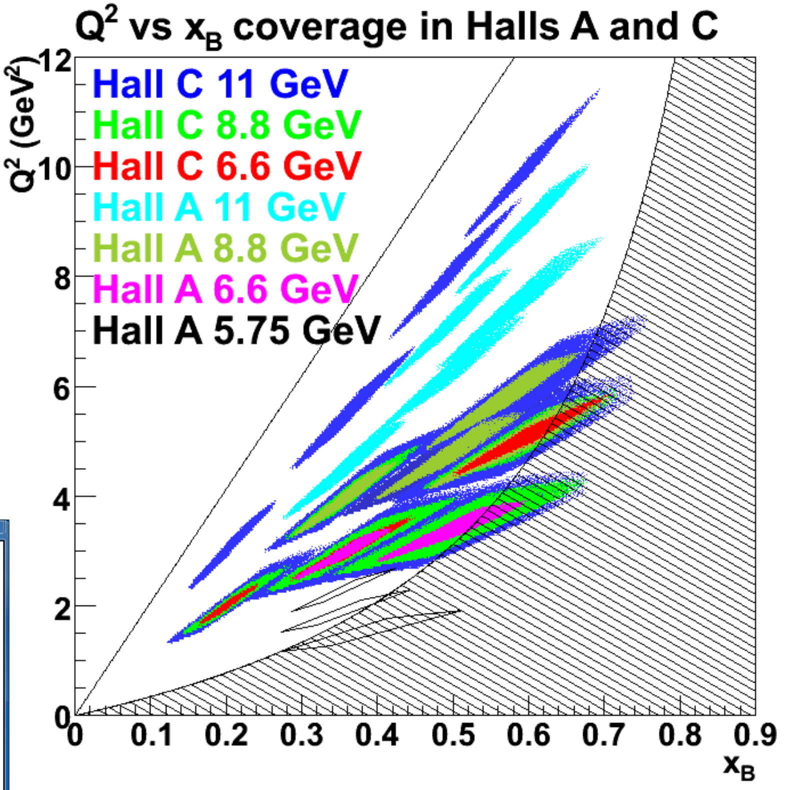


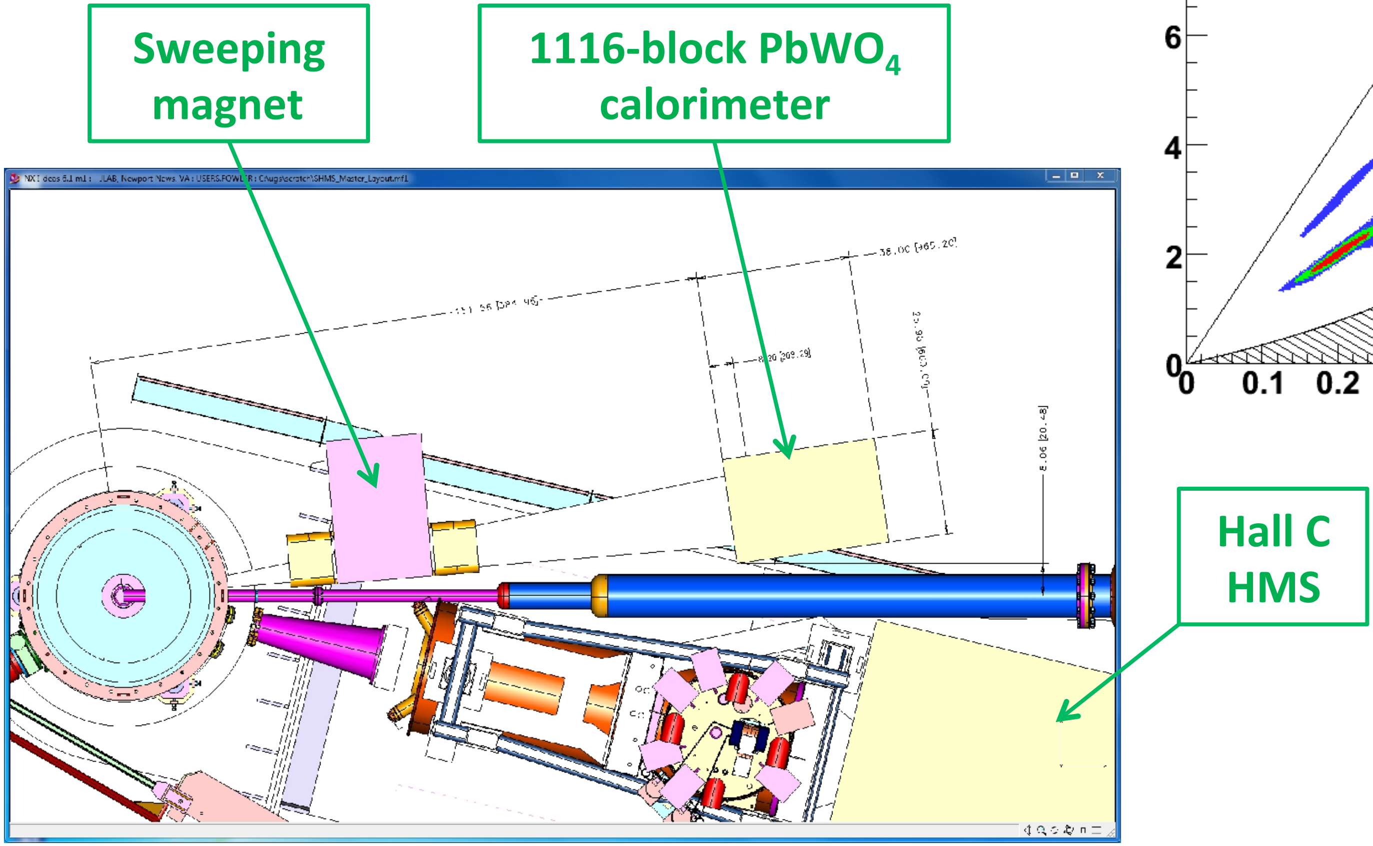
DVCS events
(1.5 h of beamtime)

Some preliminary results on π^0

E12-13-010: DVCS at 11 GeV in Hall C

- Energy separation of the DVCS cross section
- Higher Q^2: measurement of higher twist contributions
- Low x_B extension (thanks to sweeping magnet)





Sweeping magnet

1116-block $PbWO_4$ calorimeter

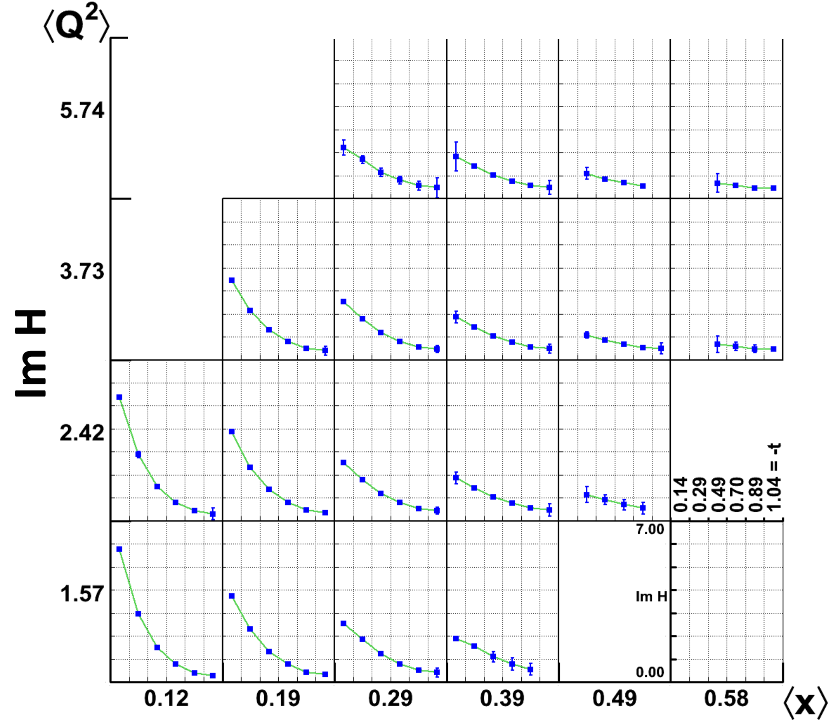
Hall C HMS

Calorimeter under constructrion

Towards the 3D Structure of the Proton (next 7 years?)

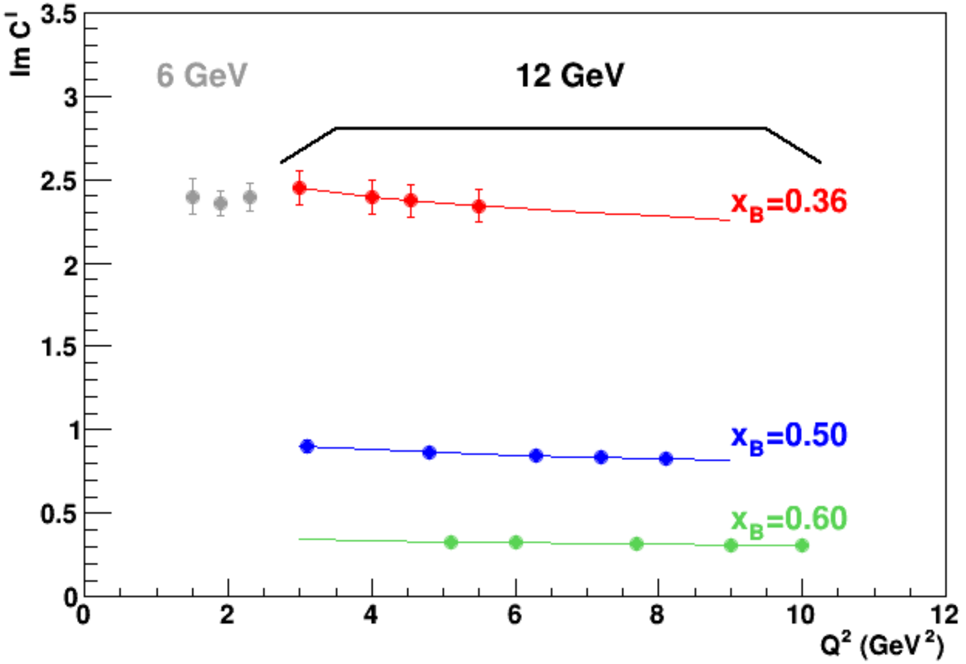
6 GeV data:
Hall B beam-spin asymmetries and cross sections data show potential for imaging studies from analysis in x, Q^2 and t.

12 GeV projections for Hall B:
(beam-spin and target-spin asymmetries)
transverse spatial maps



6 GeV data:
Hall A data over *limited* Q^2 range agree with hard-scattering

12 GeV projections for Hall A/C:
confirm formalism



A glimpse of gluon through Deeply Virtual Compton Scattering on the proton

- Hard exclusive reactions allow the study of the 3D structure of nucleon through the measure of Generalized Parton Distributions that goes beyond what can be achieved with Elastic and Deep Inelastic Scattering.
- Dedicated experiments are conducted world-wide. In the valence region, the growing set of existing results is helping refine our approach to extracting the GPDs from the data.
- DVCS experiments are an essential part of the comprehensive GPD program with the 12 GeV CEBAF beam and the EIC.

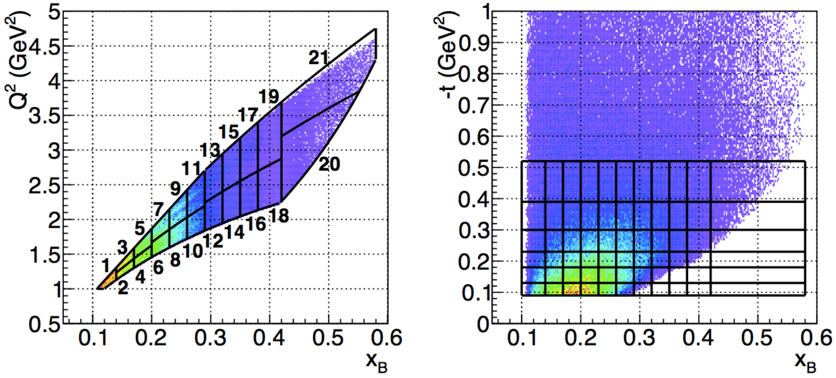
Thank you for your attention

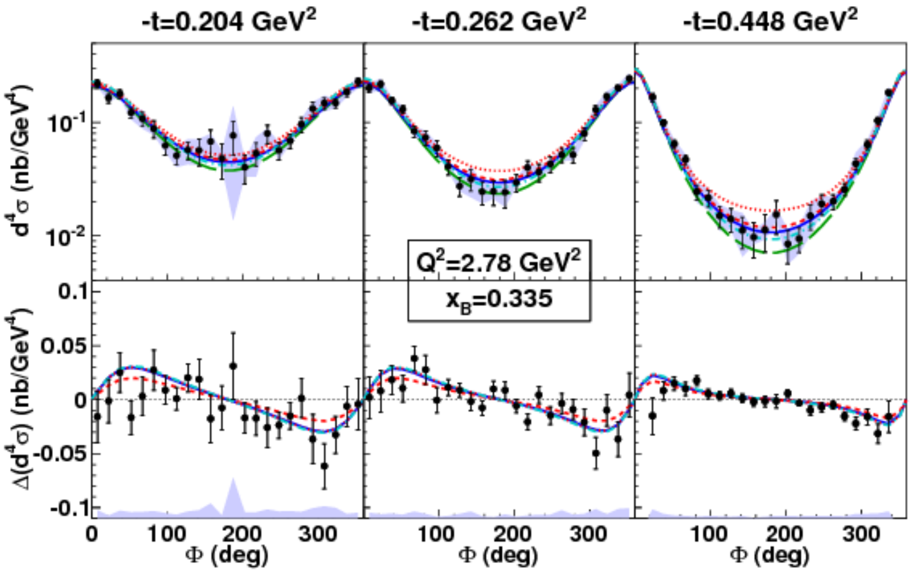
Hall B E01-113 cross sections

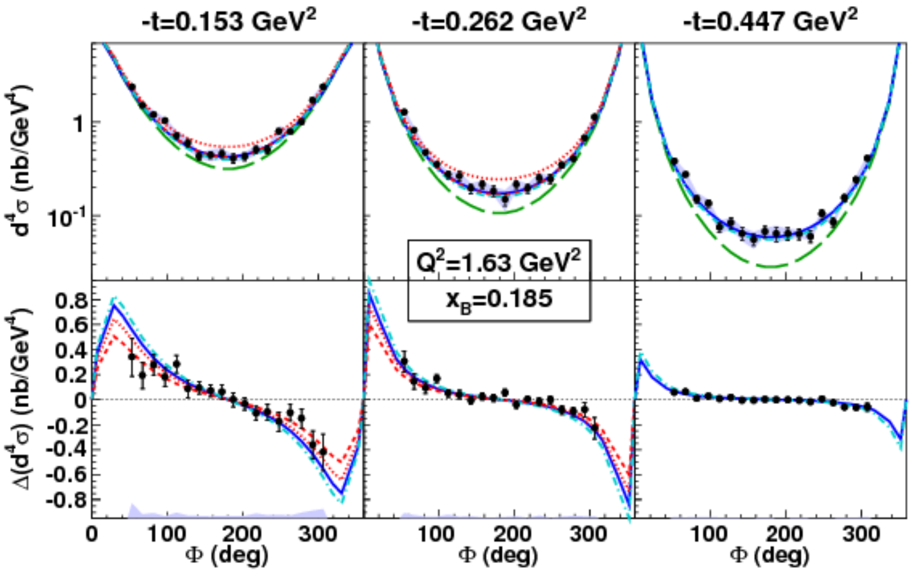
$$\mathrm{BSA} = \frac{\Delta^4\sigma}{d^4\sigma}\ \mathrm{(PRL\ 2006)} \quad \Rightarrow \quad \Delta^4\sigma \quad \mathrm{and} \quad d^4\sigma\ (\mathrm{PRL}\,\mathbf{115},\ \mathrm{Nov\ 2015})$$

110 bins in (x_B, Q^2 and t)

- Compatible with Hall A results in overlapping regions
- Leading twist models describe the data within uncertainties (more than 15%)







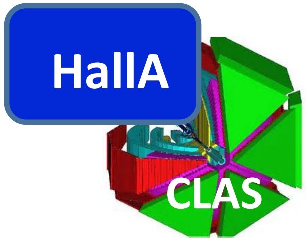
The past and future experiments

Collider mode e-p forward fast proton

Polarised 27 GeV e-/e+
Unpolarised 920 GeV p
~ Full event reconstruction

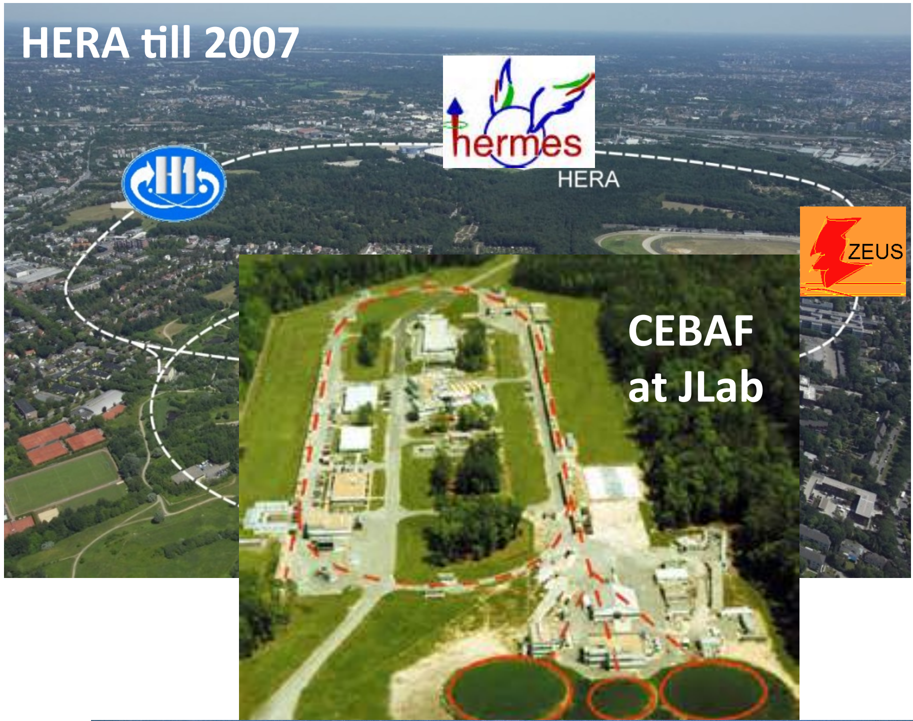
Fixed target mode slow recoil proton

Polarised 27 GeV e-/e+
Long, Trans polarised p, d target
Missing mass technique
2006-07 with recoil detector



High lumi, highly polar. 6 & **12 GeV e-**
Long, (Trans) polarised p, d target
Missing mass technique

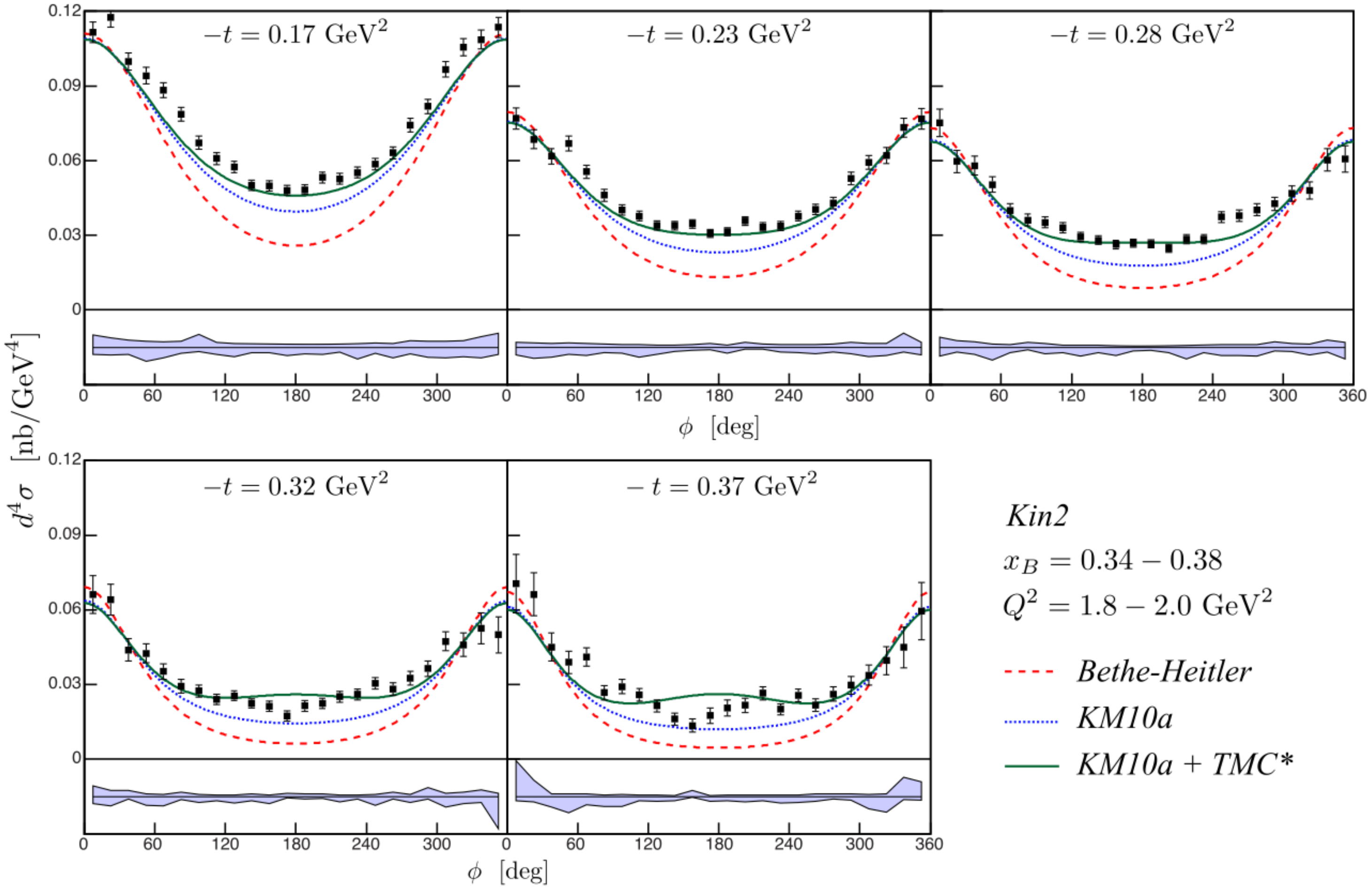
Highly polarised **160 GeV μ+/μ-**
p target, (Trans) polarised target
with recoil detection



Slide from N d'Hose, Tranversity 2014

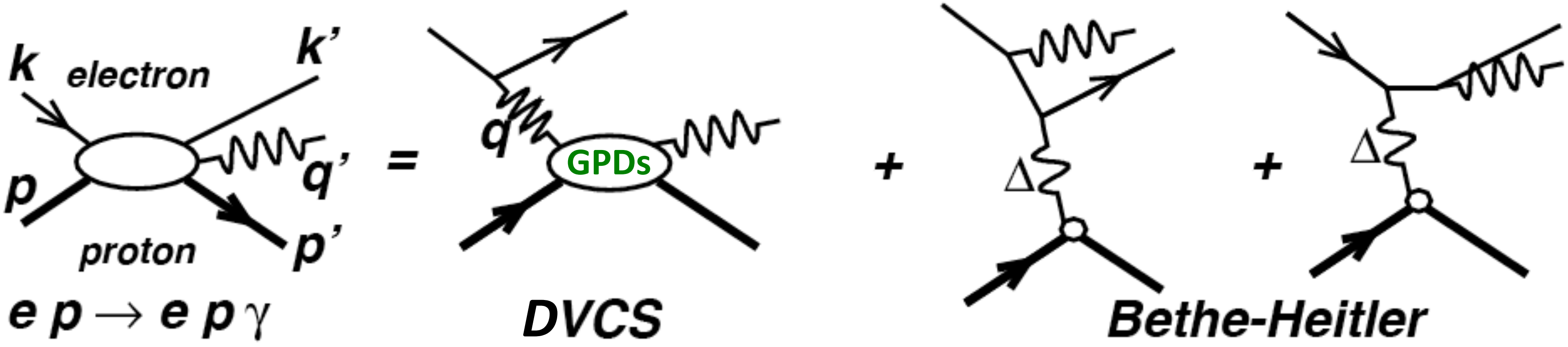
Hall A E00-110 cross sections: **higher twist corrections**

PRC C92, Nov ‘15

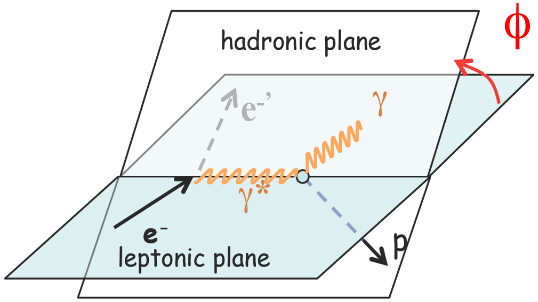


Higher twist corrections might be necessary to fully explain experimental data
Confirmation of the significant deviation from BH => Need to measure T^2_{DVCS}

Measuring DVCS to access GPDs information



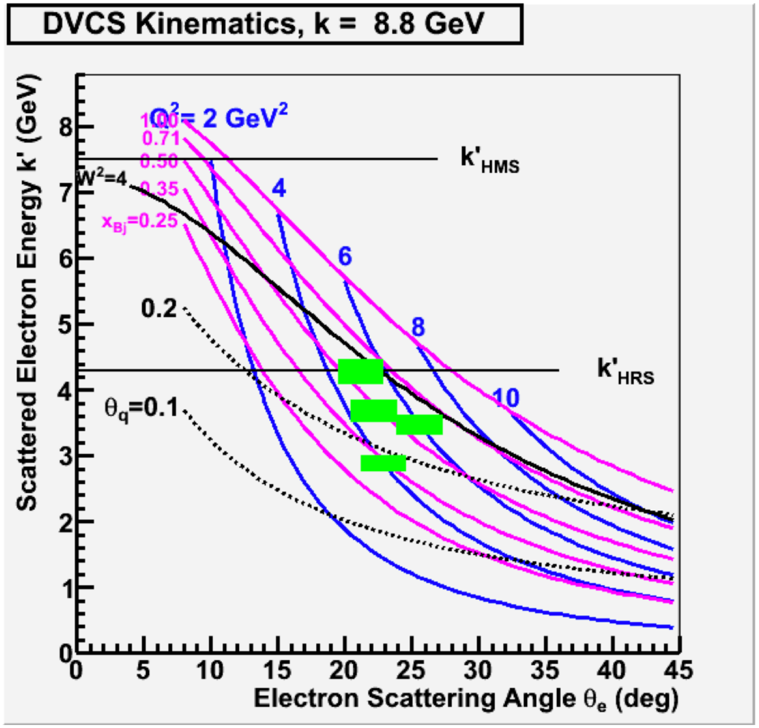
$$\frac{\mathbf{d^4\sigma(lp \to lp\gamma)}}{\mathbf{dx_B dQ^2 d|t|d\phi}} = \mathbf{d\sigma^{BH}} + \mathbf{d\sigma^{DVCS}_{unpol}} + \mathbf{P_l}\ \mathbf{d\sigma^{DVCS}_{pol}} + \mathbf{e_l}\,(\mathbf{Re(I)} + \mathbf{P_l Im(I)})$$

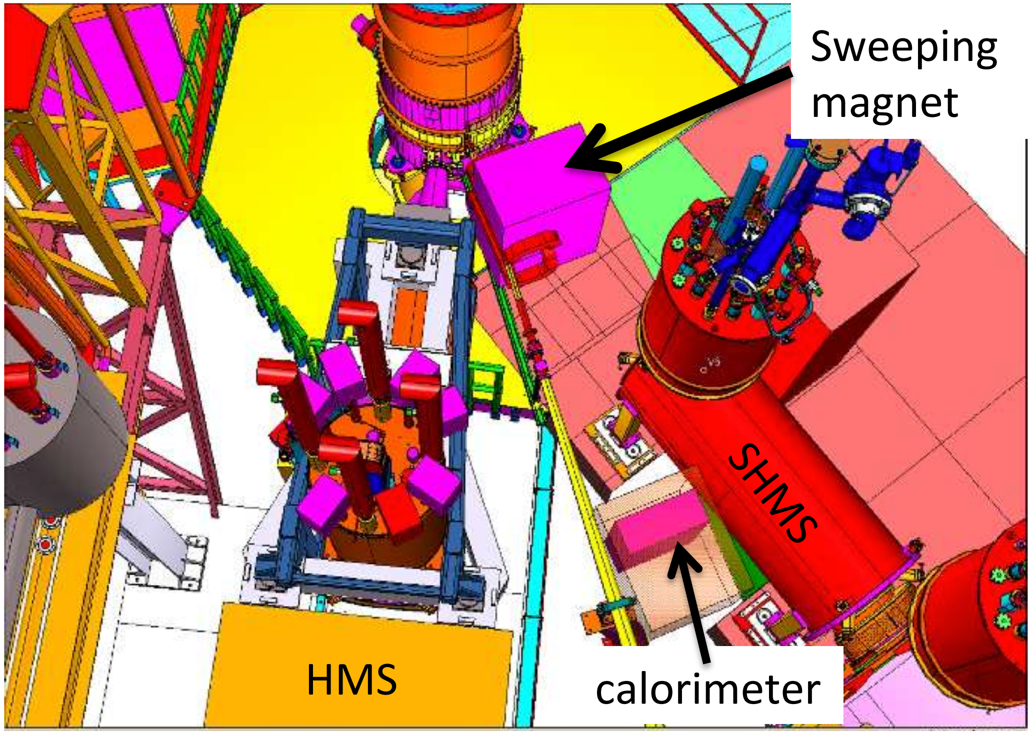


P_l : polarization target or beam

e_l : charge of the lepton beam

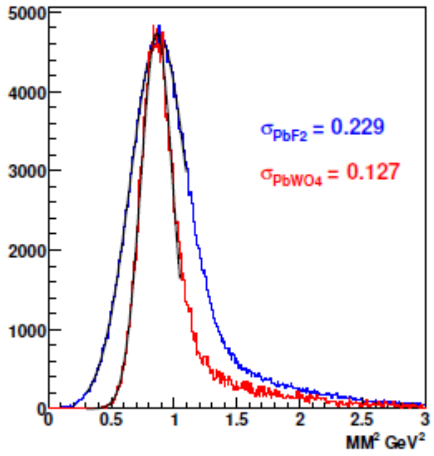
Moving from Hall A to Hall C: E12-13-007





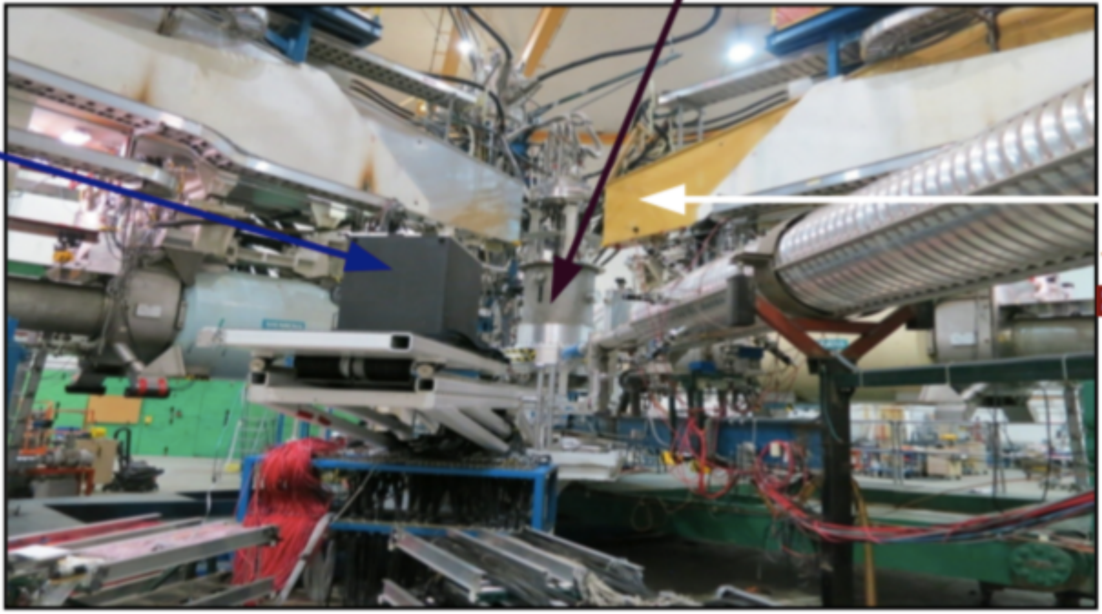
New Calorimeter

- 25 ms at 4m (two times larger than DVCS Hall A)
- PW0$_4$ (larger light yield-better energy resolution) or PbF$_2$ (Cerenkov light- no need to temperature control)
- Radiation hardness is a must (expect dose in excess of 2 Mrad)



Hall A/JLab

$p(e,e'\gamma)p'$

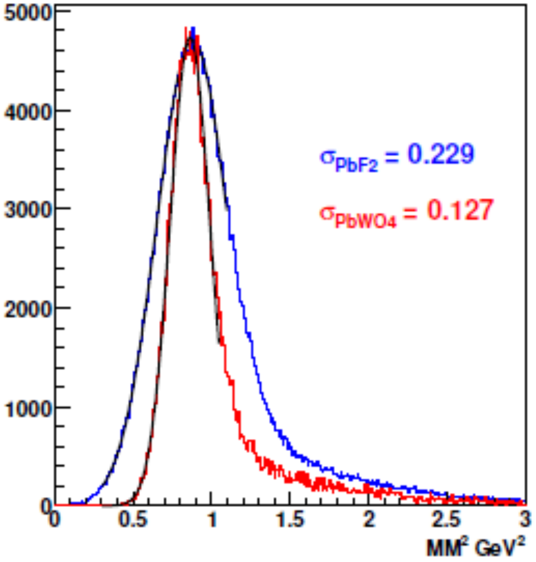


TARGET

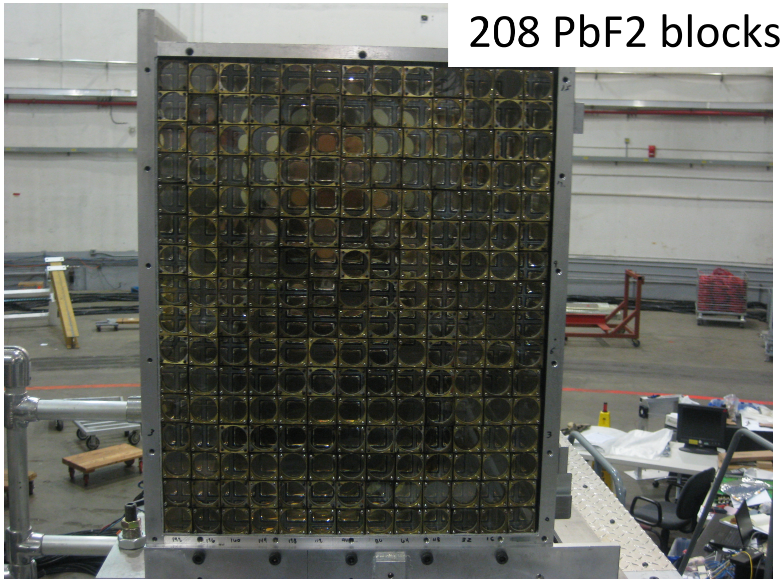
CALORIMETER
- → 208 PbF_2 blocks
- → $\Delta q/q \sim 3\%$
- → Calorimeter energy resolution is our limiting factor in the missing mass reconstruction

HRS
→ $\delta p/P \sim 10^{-4}$
Excellent!

Simulated M_X^2 resolution



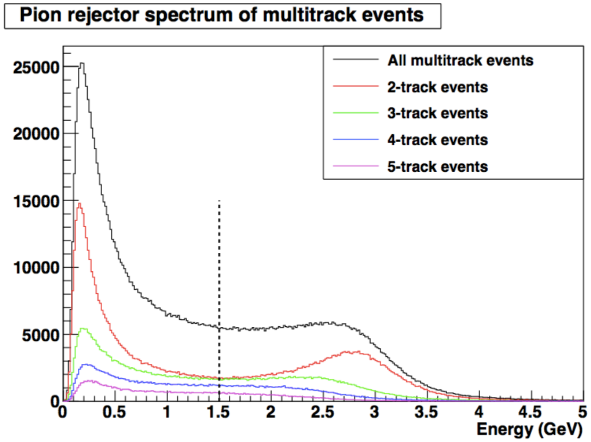
PbF2
3X3X18 cm block
~1000 pe
for 1 GeV outgoing photon



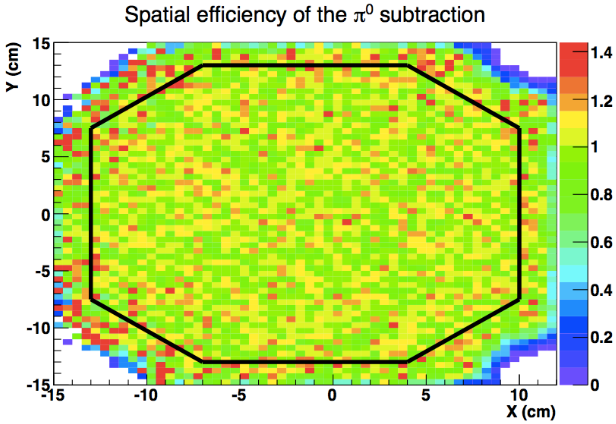
208 PbF2 blocks

Preliminary: re-analysis of 2006 data

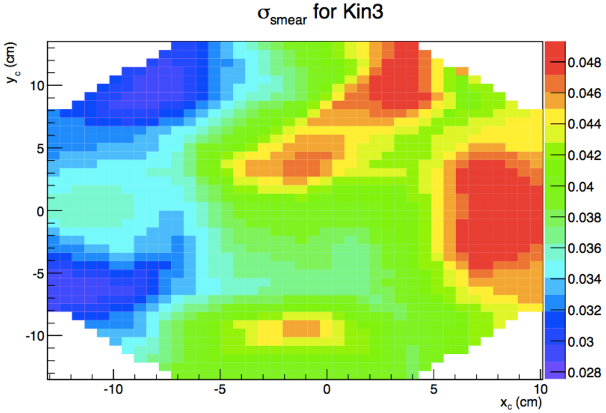
(by grad student M. Defurne – CEA Saclay)



Better correction for events lost in reconstruction algorithm for VCD



Fiducial cuts on calorimeter to take into account π^0 subtraction efficiency



Better description of the energy resolution of the calorimeter.

Cross-sections have changed some, but the conclusions from the first article hold:

- Large contribution from the DVCS^2
- No contribution from the twist 3 part of the interference.

Extracting Compton form factor from the data

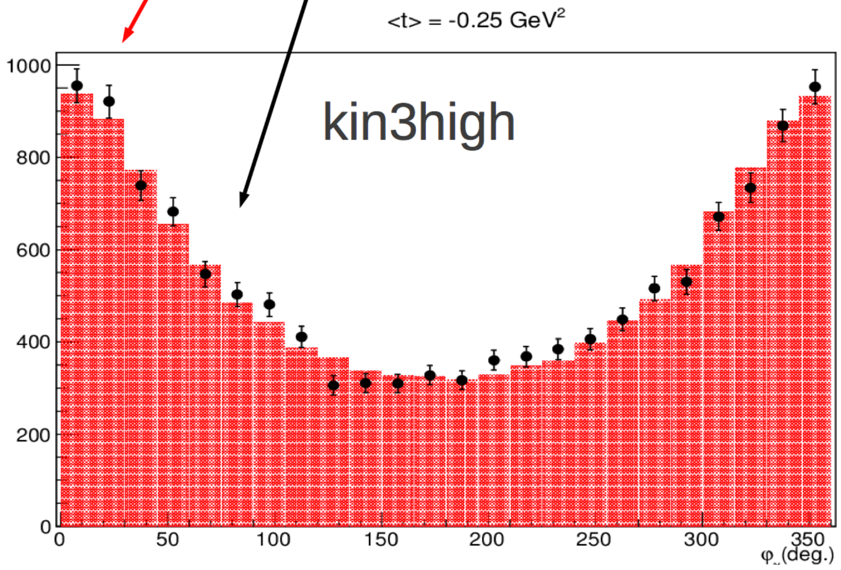
$$\frac{d^4\sigma}{dx_b\,dt\,d\phi_\gamma\,dQ^2} = \Gamma^G|BH|^2 + \Gamma^1\mathcal{C}^{\mathcal{I}}(\mathcal{F}) + \Gamma^2\Delta\mathcal{C}^{\mathcal{I}}(\mathcal{F}) + \Gamma^3\mathcal{C}^{\mathcal{I}}(\mathcal{F}^{eff})$$

Γ^i : kinematic factors (calculable in experimental setup simulation)

C^i $(= C^I, \Delta C^I, C^I_{eff})$: Compton Form Factors obtained by fit on the data

$$\chi^2 = \frac{(N^{MC} - N^{Exp})^2}{\sigma^2} \longrightarrow N^{MC} = \int \frac{d\sigma}{d\Omega}\, d\Omega = \sum_{i=1}^{3} \left(\int \Gamma^i\, d\Omega\right)\boxed{C^i}$$

$$\frac{\delta\chi^2}{\delta C^i} = 0 \rightarrow \begin{Bmatrix} C^I \\ \Delta C^I \\ C^I_{eff} \end{Bmatrix}$$



Black dot: data / Red histogram: MC fit

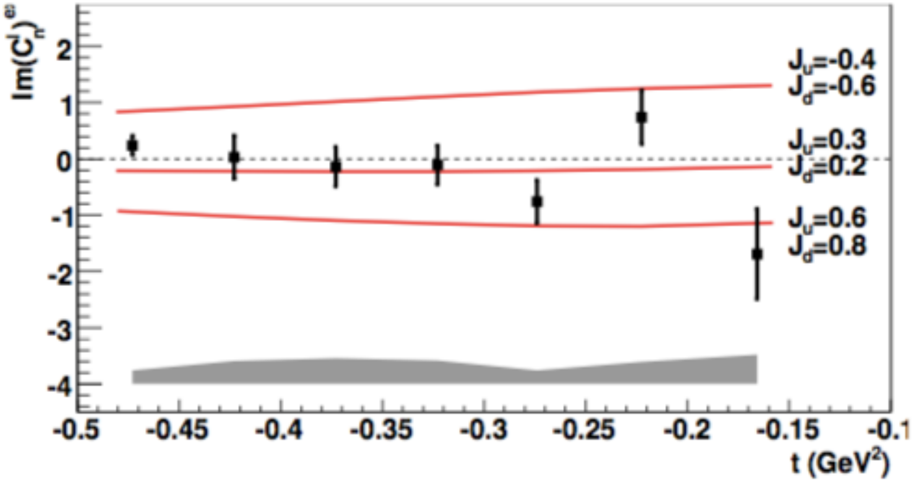
Status:

- Independent cross-check completed
- Rosenbluth-type fits in progress
  (add a C^{DVCS} term)

Slide from C. Desnault

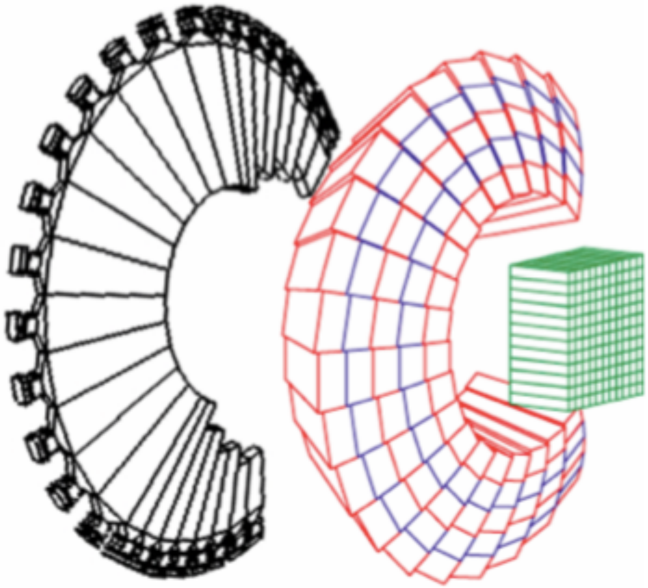
DVCS on the neutron: experiment E03-106 at JLab

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



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

Charged particle veto
in front of scintillator array

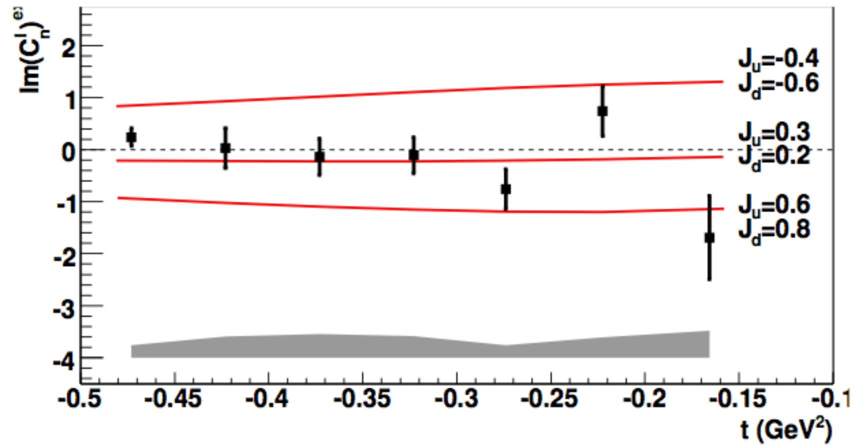


$$A = F_1(t)\mathcal{H} + \frac{x_B}{2-x_B}[F_1(t)+F_2(t)]\tilde{\mathcal{H}} - \underbrace{\frac{t}{4M^2}\cdot F_2(t)\cdot \mathcal{E}}_{\text{Main contribution for neutron}}$$

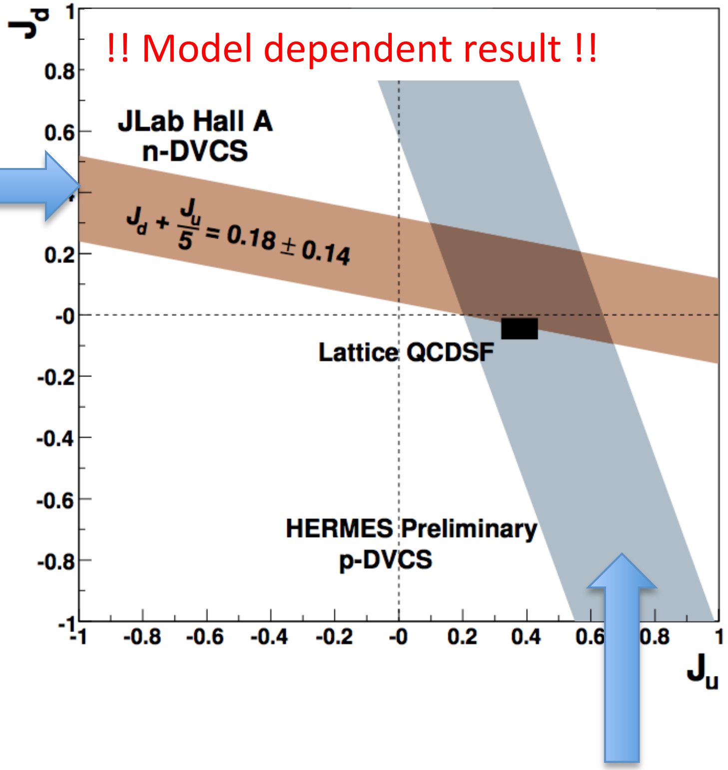
Ji's sum rule on the fraction of the proton spin carried by quarks:

$$\frac{1}{2} = J_q + J_g \quad \text{and} \quad J_q = \lim_{t \to 0} \int_{-1}^{+1} dx\, x\, [H_q(x,\xi,t) + E_q(x,\xi,t)]$$

Hall A DVCS on neutron PRL 99: 242501 (2007)



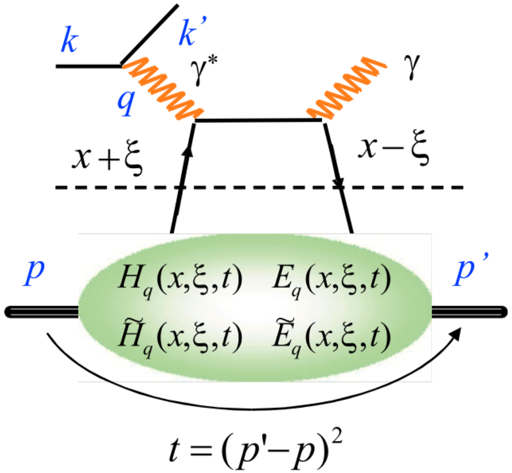
VGG model with various parameters defining the GPD E (-> different values of J_u and J_d)


!! Model dependent result !!

Hermes:
Unpolarized beam, transversely polarized proton target

Ji, PRL 78:610 (97) VGG, Phys Rev D 60: 094017 (99) Lattice, PRL 92:042002 (04) Hermes, Eur Phys J C46:729 (06)

Multipole expansion of the amplitude



The full DVCS amplitude (ep->epγ) is

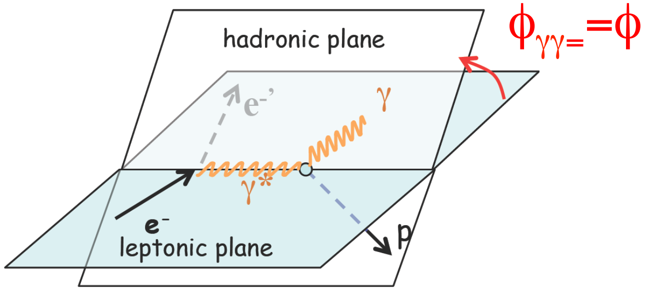
$$\mathcal{T}_{\mathrm{VCS}}(e^{\pm}) = \overline{u}(k',\lambda)\gamma_\mu u(k,\lambda)\frac{(\pm e)}{q^2}H^{\mu\nu}\epsilon_\nu^\dagger$$

The hadronic tensor is

$$H^{\mu\nu}_{\mathrm{LO,twist\,2}} = \frac{1}{2}(-g^{\mu\nu})_\perp \overline{U}(p')\left[(n\cdot\gamma)\mathcal{H}(\xi,t)+\frac{i}{2M}n_\kappa\sigma^{\kappa\lambda}\Delta_\lambda\mathcal{E}(\xi,t)\right]U(p)$$
$$-(\epsilon^{\mu\nu})_\perp \overline{U}(p')\left[(n\cdot\gamma\gamma_5)\widetilde{\mathcal{H}}(\xi,t)+(\gamma_5 n\cdot\Delta)\widetilde{\mathcal{E}}(\xi,t)\right]U(p)\ ,$$

CFFs

In practice, one exploits the azimuthal modulation of the DVCS(and its interference)



$$|\mathcal{T}_{\mathrm{DVCS}}|^2 = \frac{e^6(s_e-M^2)^2}{x_{\mathrm{Bj}}^2Q^6}\left\{\sum_{n=0}^{2}c_n^{\mathrm{DVCS}}\cos(n\phi_{\gamma\gamma})+\sum_{n=1}^{2}s_n^{\mathrm{DVCS}}\sin(n\phi_{\gamma\gamma})\right\}$$

$$c_0^{DVCS} = f(kine)\left\{4(1-x_{Bj})\mathcal{H}\mathcal{H}^* + 4\left(1-x_{Bj}+\frac{2Q^2+t}{Q^2+x_{Bj}t}\,\frac{\epsilon^2}{4}\right)\tilde{\mathcal{H}}\tilde{\mathcal{H}}^*+...\right\}$$

Harmonic coefficients

CFFs

$$c^I_{unp} = g(kine)\left\{F_1\mathcal{H}-\frac{t}{4M^2}F_2\mathcal{E}+\frac{x_{Bj}}{2-x_{Bj}+x_{Bj}\frac{t}{Q^2}}(F_1+F_2)\tilde{\mathcal{H}}+...\right\}$$

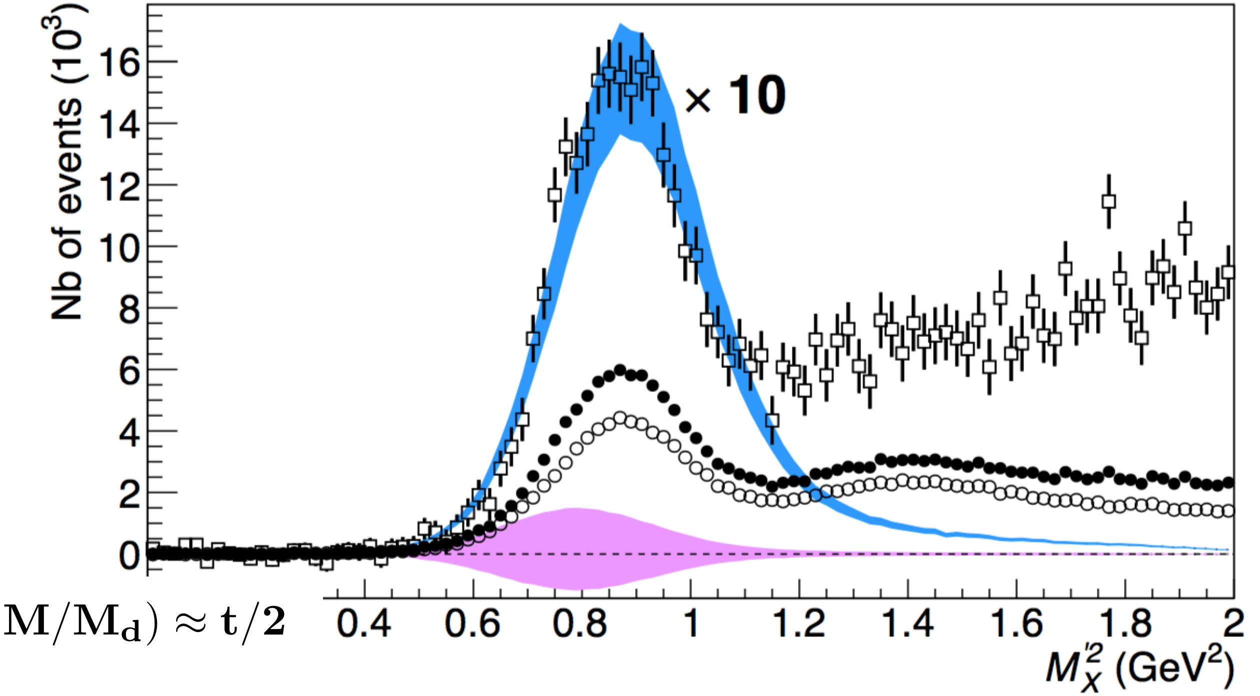
DVCS2 results neutron data

M. Mazouz PRL 118 (2017) 22, 222002

At Q^2=1.75 GeV^2 and x_B=0.36 , half of the data taken on a LD2 target.

Below the two pions threshold:

$$D(e,e'\pi^0)X = d(e,e'\pi^0)d + n(e,e'\pi^0)n + \overbrace{p(e,e'\pi^0)p}^{\text{From LH2, add Fermi smearing}}.$$



- ● LD2
- ○ LH2
- □ LD2-LH2

- 🟪 d(e,e'π^0)d
- 🟦 n(e,e'π^0)n

separated by

$$\mathbf{\Delta M_X^2 = t(1 - M/M_d) \approx t/2}$$

Computed for n(e,e'π^0)X

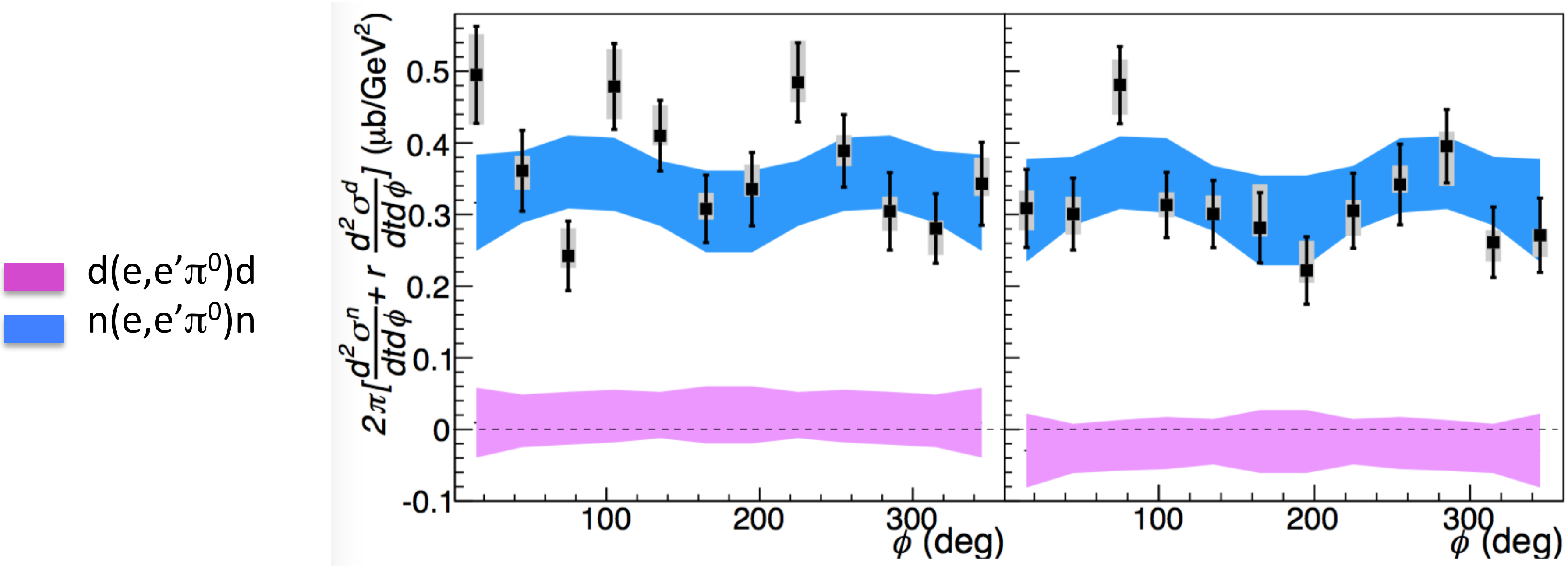
Events with missing mass squared below 0.95 GeV^2:

- are divided in 12 x 2 x 5 x 30 bins in ϕ, E, t and M_x^2

  ϕ, E allow for L, T, LT and TT separation
  M_x^2 allows for the n/d separation

- fitted with eight cross-section function structure

$$\mathbf{d}\sigma_{\mathbf{\Lambda}}^{\mathbf{n,d}}(\mathbf{t}) \qquad \mathbf{\Lambda} = \mathrm{T, L, LT, TT}$$



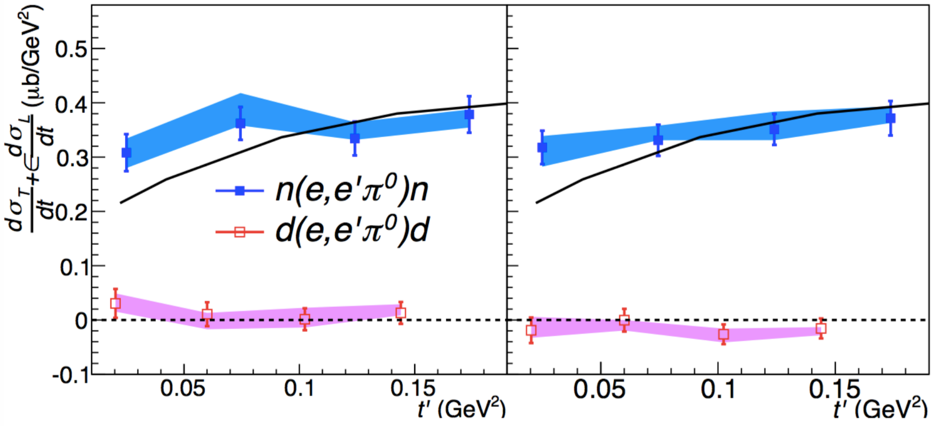
Q^2=1.75 GeV^2 and x_B=0.36

E=4.45 GeV
<t'>= 0.025 GeV^2

E=5.55 GeV
<t'>=0.021 GeV^2

DVCS2n results: fully separated contributions

Q^2=1.75 GeV^2 and x_B=0.36

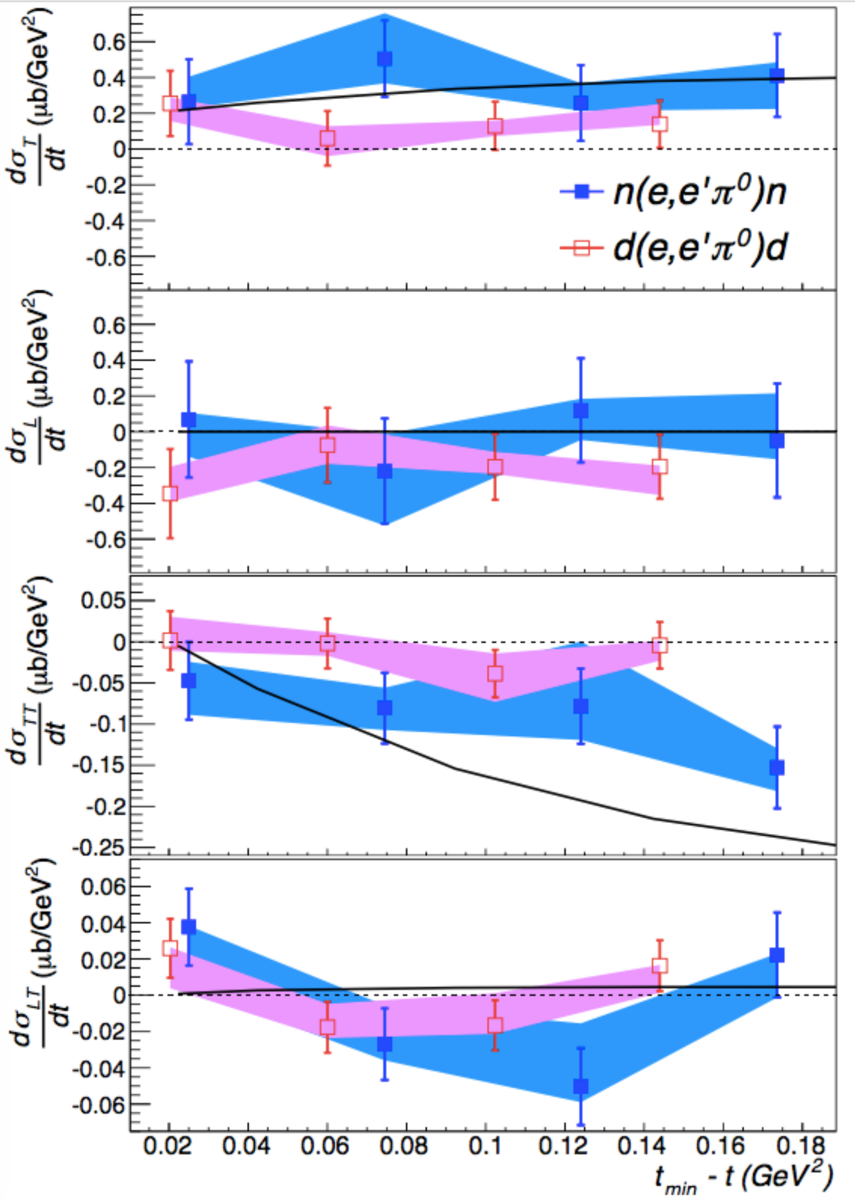


— Goloskokov and Kroll
Eur Phys J A47 (2012)

$$\frac{d\sigma_T}{dt} = \Lambda \left[\left(1-\xi^2\right) \left|\langle H_T\rangle\right|^2 - \frac{t'}{8M^2} \left|\langle \bar{E}_T\rangle\right|^2 \right]$$

$$\frac{d\sigma_{TT}}{dt} = \Lambda \, \frac{t'}{8M^2} \left|\langle \bar{E}_T\rangle\right|^2 .$$

$$\bar{E}_T = 2\tilde{H}_T + E_T$$



DVCS2n results: flavor separation

$$|\langle H_T^{p,n}\rangle|^2 = \frac{1}{2}\left|\frac{2}{3}\left\langle H_T^{u,d}\right\rangle + \frac{1}{3}\left\langle H_T^{d,u}\right\rangle\right|^2$$

🟪🟩 account for the unknown phase variation between u and the d amplitude $\gamma^* q \to q' \pi^0$ convoluted with $(H,E)_T$

Goloskokov and Kroll
Eur Phys J A47 (2012)

—— u quark
------ d quark

Q^2=1.75 GeV^2 , x_B=0.36