DVCS and exclusive neutral pion at Jefferson Laboratory: Accomplishments and future developments

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8th workshop of the APS Topical Group on Hadronic Physics
Denver, Colorado
Tuesday, April 11th 2019

Reminder on Generalized Parton Distributions (GDPs):

- **Nucleon spin puzzle and GPDs**
- **Experimental access to GPDs**
  - **Deeply Virtual Compton Scattering**
  - **Deeply Virtual Meson Production (π^0)**

DVCS/π^0 program at Jefferson Lab:

- **Measurements at 6 GeV (p-DVCS, n-DVCS, $ep \rightarrow ep\pi^0$, $en \rightarrow en\pi^0$):**
  - **Results: Highlights and open questions;**
- **Measurements at 12 GeV:**
  - **A taste of Hall A (preliminary) results**
  - **Ongoing and upcoming measurements and projections**

Reminder on Generalized Parton Distributions (GPDs)
Nucleon spin puzzle and GPDs

Nucleon Spin puzzle:

$S_N = \frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_q + L_g$ => $\Delta\Sigma \sim 0.3$, $\Delta G \sim 0.1$ (ep experiments), $L_{q,g}$ ***unknown***

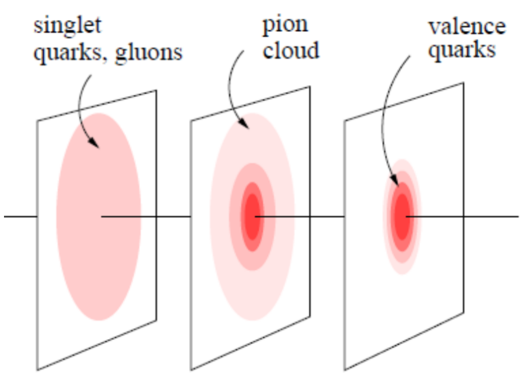
Nucleon spin is more than the sum of the spins of its constituents!

Generalized Parton Distributions (GPDs)

=> Correlation $r_\perp \leftrightarrow x$P

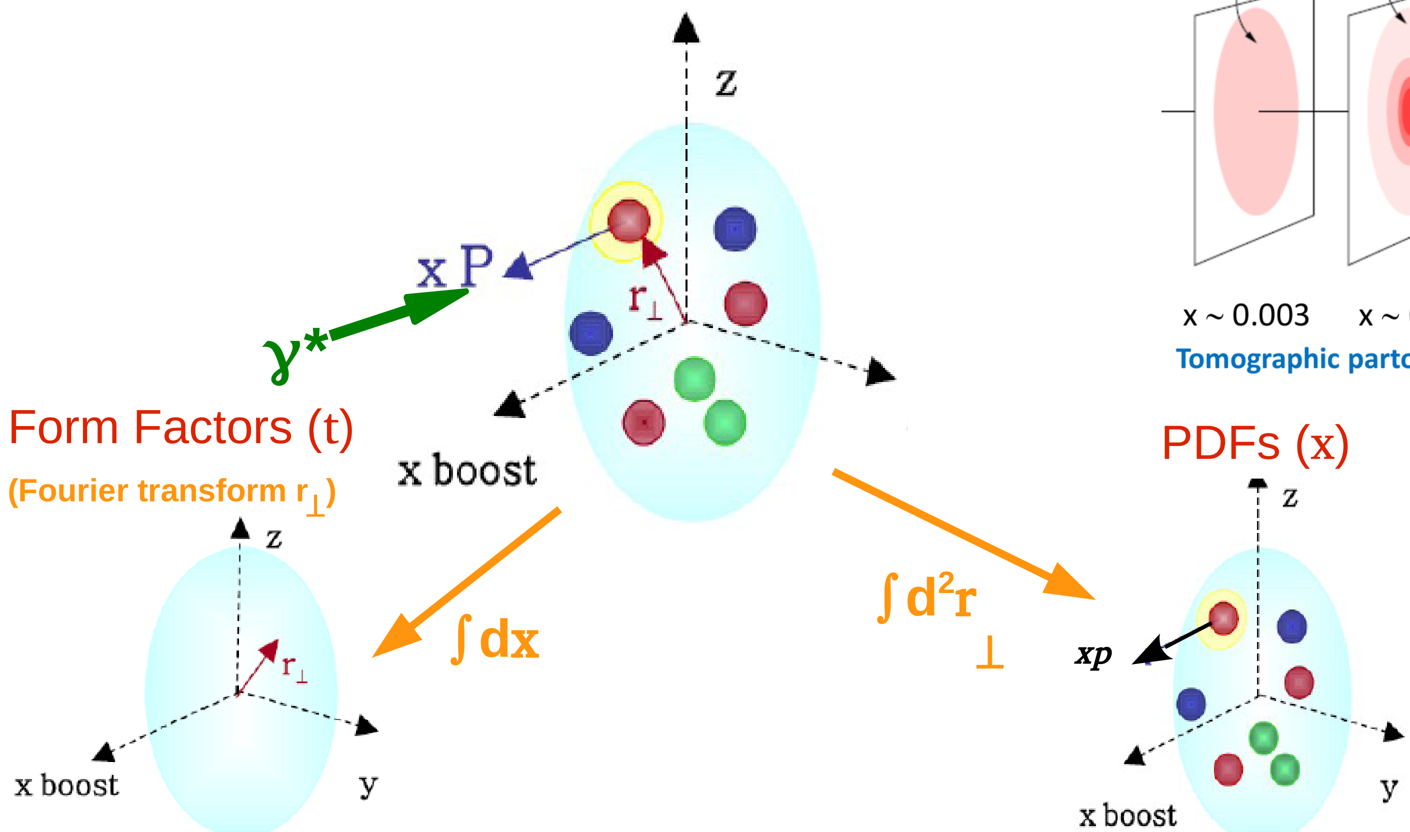
=> constraint on partons Orbital Angular Momentum $L_{q,g}$

=> *Nucleon tomography*



x ~ 0.003 x ~ 0.03 x ~ 0.3

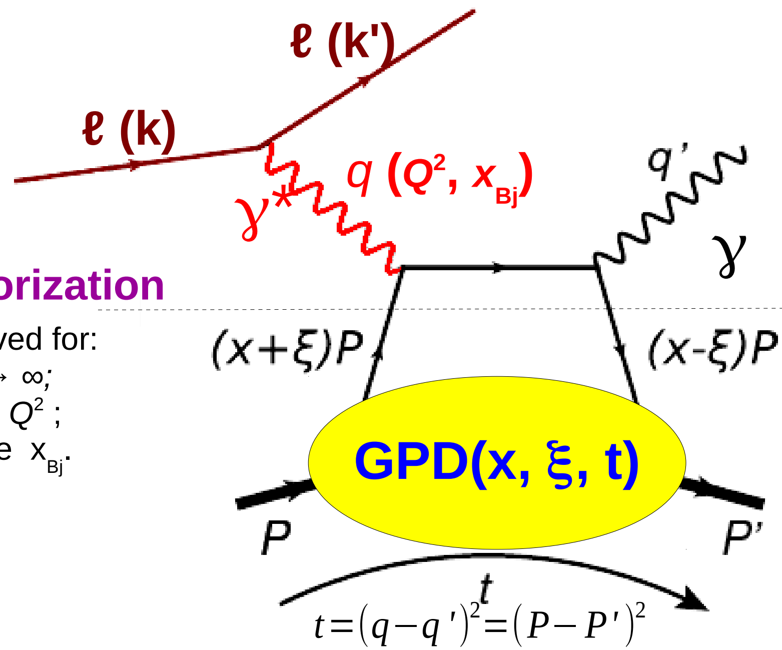
Tomographic parton images of the nucleon



Introduction to Generalized Parton Distributions (GPDs)
Experimental access

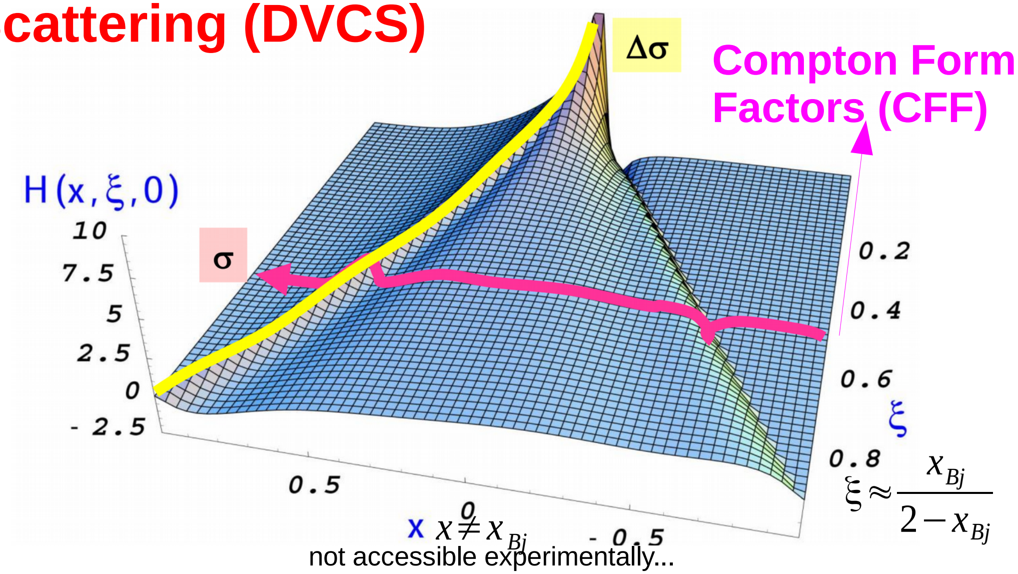
Deeply Virtual Compton Scattering (DVCS)

Exclusive reactions
(DVCS: ℓp → ℓpγ, DVMP: ℓp → ℓph)



Factorization

proved for:
$Q^2 \to \infty$;
$t << Q^2$;
finite x_{Bj}.

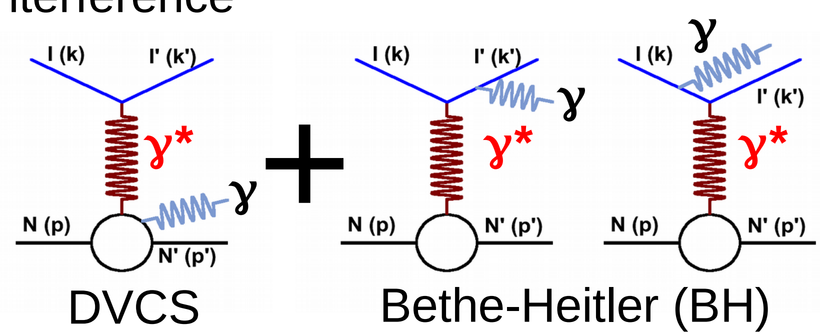


4 "chiral-even" GPD: $H, E, \tilde{H}, \tilde{E}$

\+ Measurement on: (p) $(p^{\downarrow\uparrow}, n)$

4 "chiral-odd" GPD$_T$: $H_T, E_T, \tilde{H}_T, \tilde{E}_T$

Advantages of DVCS measurement:
- "clean" (no other non-perturbative quantity than GPDs)
- DVCS amplitude accessible with DVCS/BH interference



$$\sigma^{lp \to lp\gamma} \propto \left[|BH|^2 + |DVCS|^2 + 2|DVCS||BH| \right]$$

=> Access to total angular momentum ***J = L+S***
via *Ji sum rule*: $\int dx\, x\, [H+E](t=0) = 2J$
[X. Ji, Phys. Rev. Lett. **78**, 610-613 (1997)]

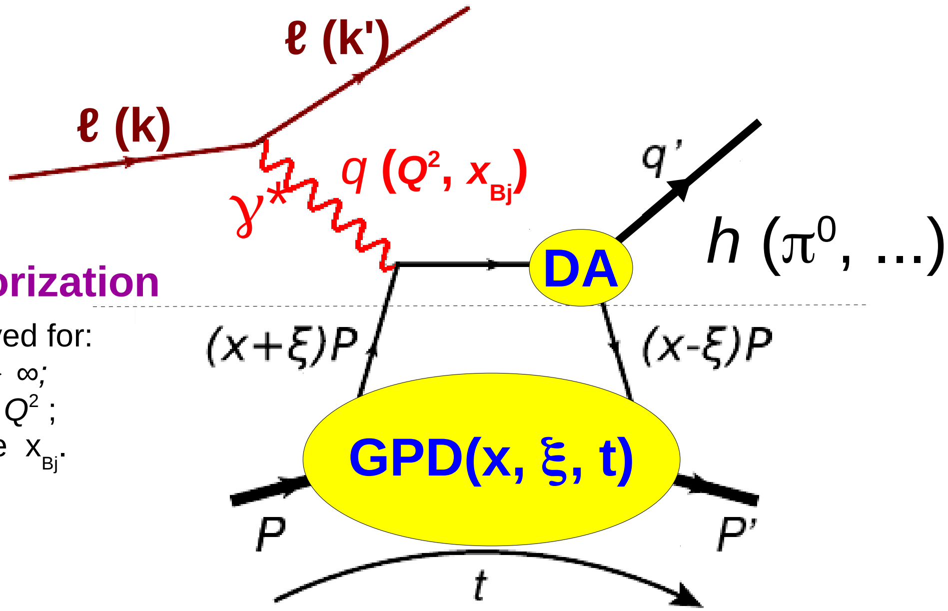
Generalized Parton Distributions : Experimental access (cont'd)

Deeply Virtual Meson Production (DVMP) => π^0

Exclusive reactions

(DVCS: $\ell p \rightarrow \ell p \gamma$, DVMP: $\ell p \rightarrow \ell p h$)

(ou HEMP.. mais j'ai décidé de ne pas faire cette blague)



Factorization

proved for:
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4 "chiral-even" GPD: $H, E, \widetilde{H}, \widetilde{E}$

+

4 "chiral-odd" GPD_T: $H_T, E_T, \widetilde{H}_T, \widetilde{E}_T$

=> Access to total angular momentum ***J***
via *Ji sum rule*: $\int dx\, x\, [H+E](t=0) = 2J$

DVMP measurements:
 * not as "clean" as DVCS: depends on distribution amplitude (DA)

Advantages:
 * ***Flavor decomposition***
(depending on meson quark content)
 * different combinations of GPDs
(depends on meson quantum numbers)

Meson electroproduction:
GPD => σ_L (α 1/Q^6);
GPD_T => σ_T: **NLO** but *significant contribution* (see π^0 results)

Here, will focus on π^0 measurements;
Come "for free" with (*i.e.*, significant contamination of) DVCS measurements (comparable final state and phase space)

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DVCS/π^0 program at Jefferson Lab:

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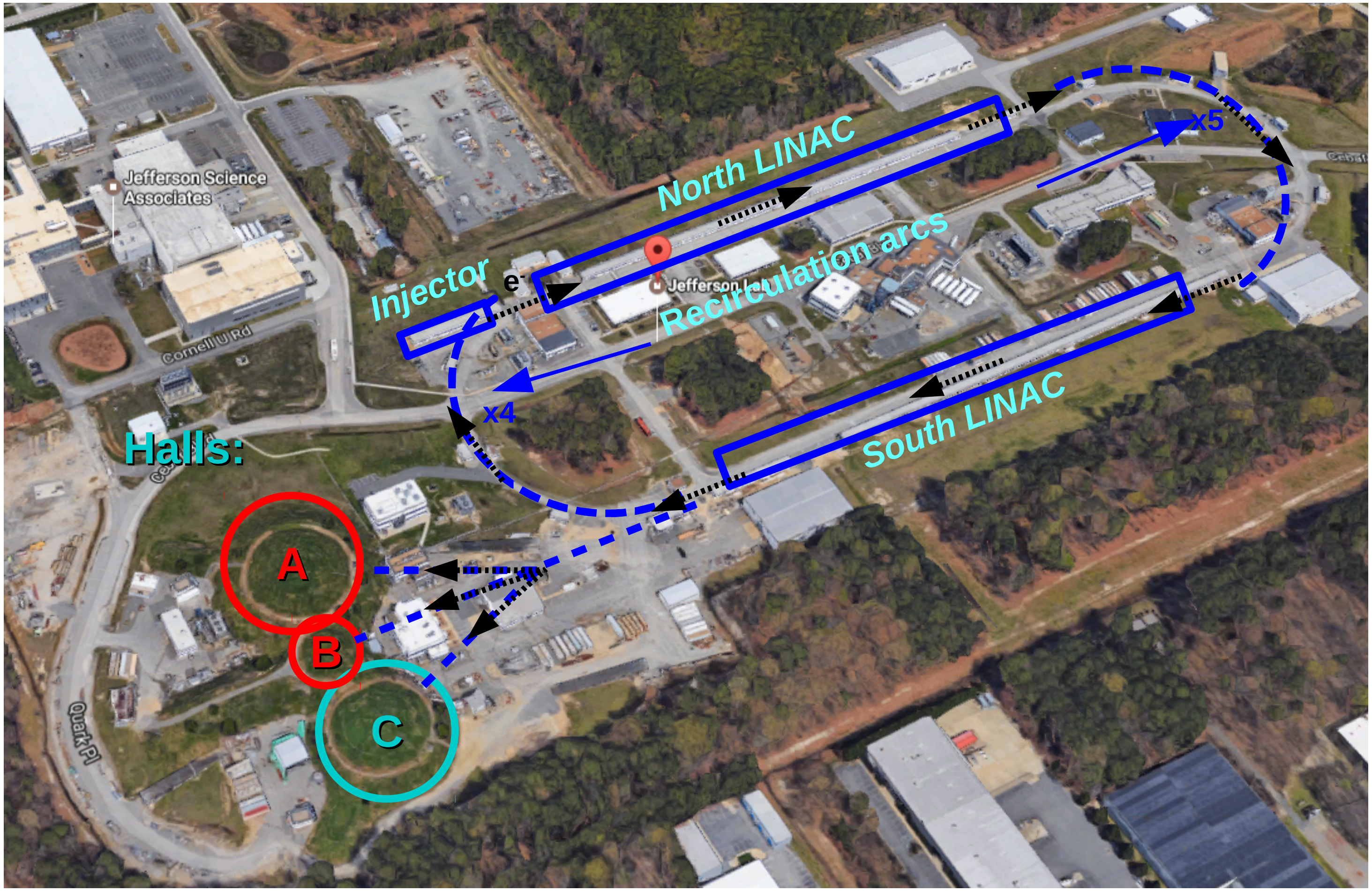
DVCS/π^0 program at Jefferson Lab:
6 GeV era

Jefferson Lab @ 6 GeV: E_{max} ~ 6 GeV in Halls A, B, C

Continuous wave electron beam, **High luminosity (I_{max}~200 μA), high polarization (≥ 85 %),**

=> Great facility for DVCS/DVMP measurements in valence region



DVCS/π^0 measurements in Halls A, B

Measurements at 6 GeV
experimental setups

Hall A:
- **High luminosity**: ($\mathcal{L}$ ~10^{37} cm^{-2} s^{-1})
- **High resolution equipements**:

High Resolution Spectrometer (HRS)
+ *PbF_2 Calorimeter*

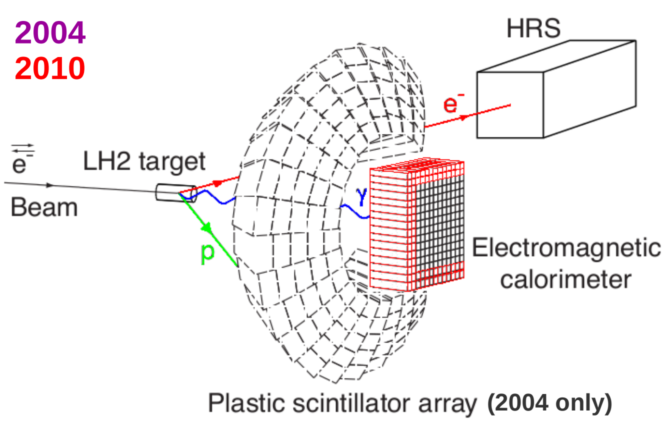
High precision measurements

CLAS (Hall B):
- **CEBAF Large Acceptance Spectrometer**

+ *inner calorimeter*

Measurements on large kinematic coverage

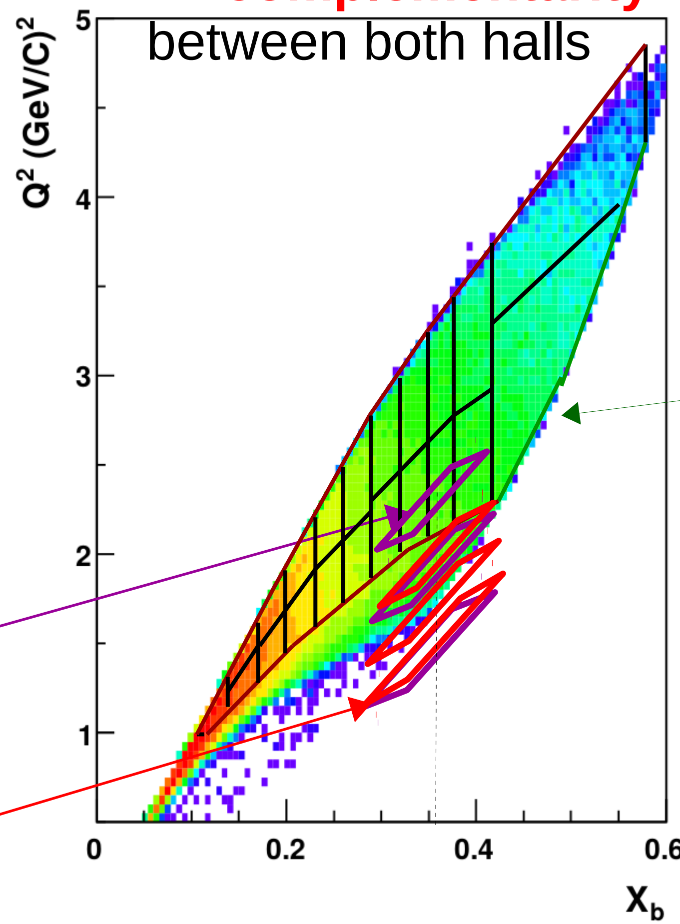
=> complementarity
between both halls

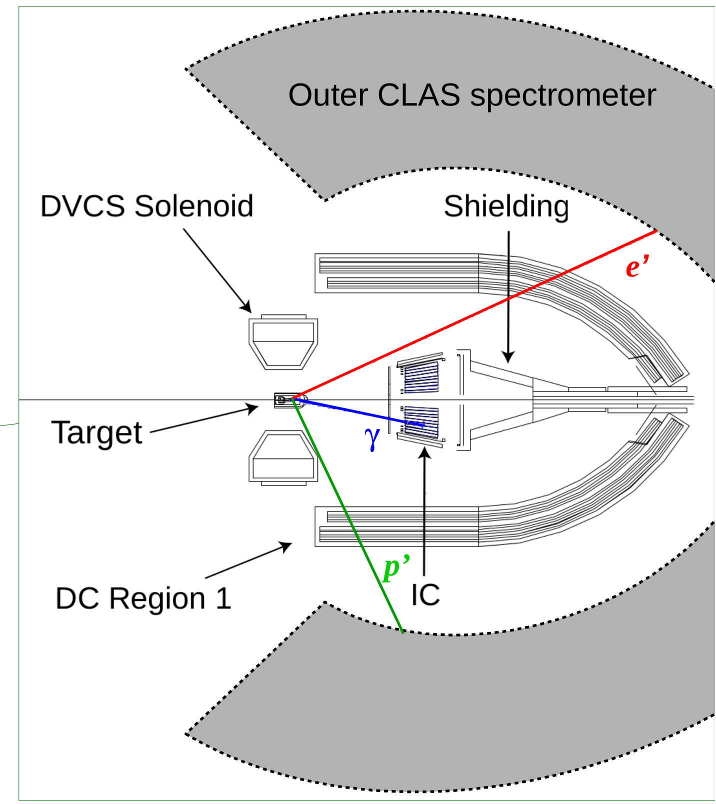


2 runs (LH_2, LD_2): **x_{Bj} = 0.36**

2004: E_{beam} = 5.75 GeV,
Q^2 = 1.5, 1.9, 2.3 GeV^2;

2010: Rosenbluth separation
(2 $\boldsymbol{E}_{beam}$ / kin,
DVCS^2/DVCS-BH, σ_T/σ_L):
Q^2 = 1.5, 1.75, 2.0 GeV^2





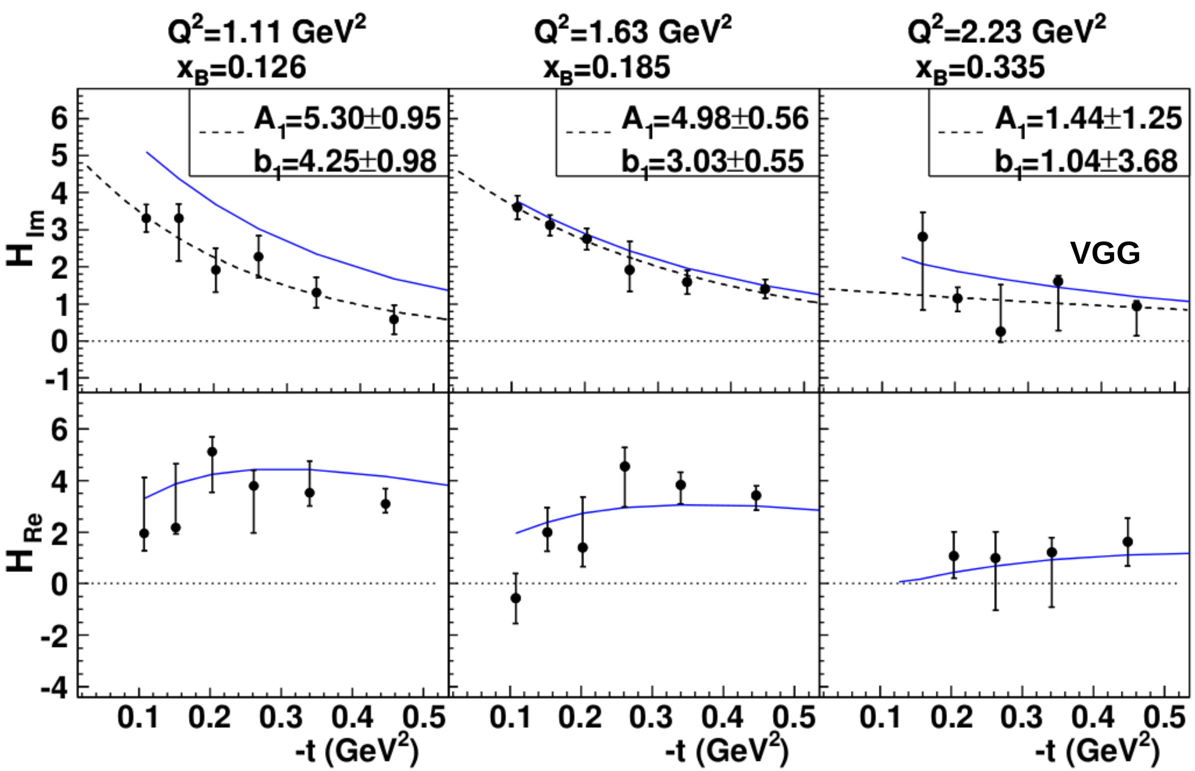
2 runs:
e1-dvcs (proton);
eg1-dvcs (L polarized proton)

6 GeV measurements
Results: DVCS on proton

CLAS

First evidence of DVCS with Beam Spin Asymmetry (BSA) (ex aequo with HERMES)
[Stepanyan *et al.*: Phys. Rev. Lett. **87** (2001) 182002]
*Other **BSA** data:* [Girod *et al.*: Phys. Rev. Lett. **100** (2008) 162002, Gavalyan *et al.*: Phys. Rev. **C80** (2009) 035206]

Compton Form Factor $\mathcal{H}$ from ***cross sections*** [Jo *et al.*: Phys. Rev. Lett. **115** (2015), 212003]
[Hirlinger-Saylor *et al.*: Phys. Rev. **C 98** (2018) 045203]



CFF $\mathcal{H}$: VGG in fair agreement w/ data

CFFs $\mathcal{E}$, $\tilde{\mathcal{E}}$ neglected

VGG:
Vanderhaeghen, Guichon, Guidal,
Phys. Rev. **D60**, 094017 (1999)

Large data sets over
large kinematic coverage

+ DVCS off longitudinally polarized proton target => GPD $\tilde{H}$

Target single spin asymmetry [Seder *et al.*: Phys.Rev.Lett. **114** (2015), 032001]
Double spin asymmetries [Pisano *et al.*: Phys.Rev. **D91** (2015), 052014]

p-DVCS GPD *H* Hall A 6 GeV

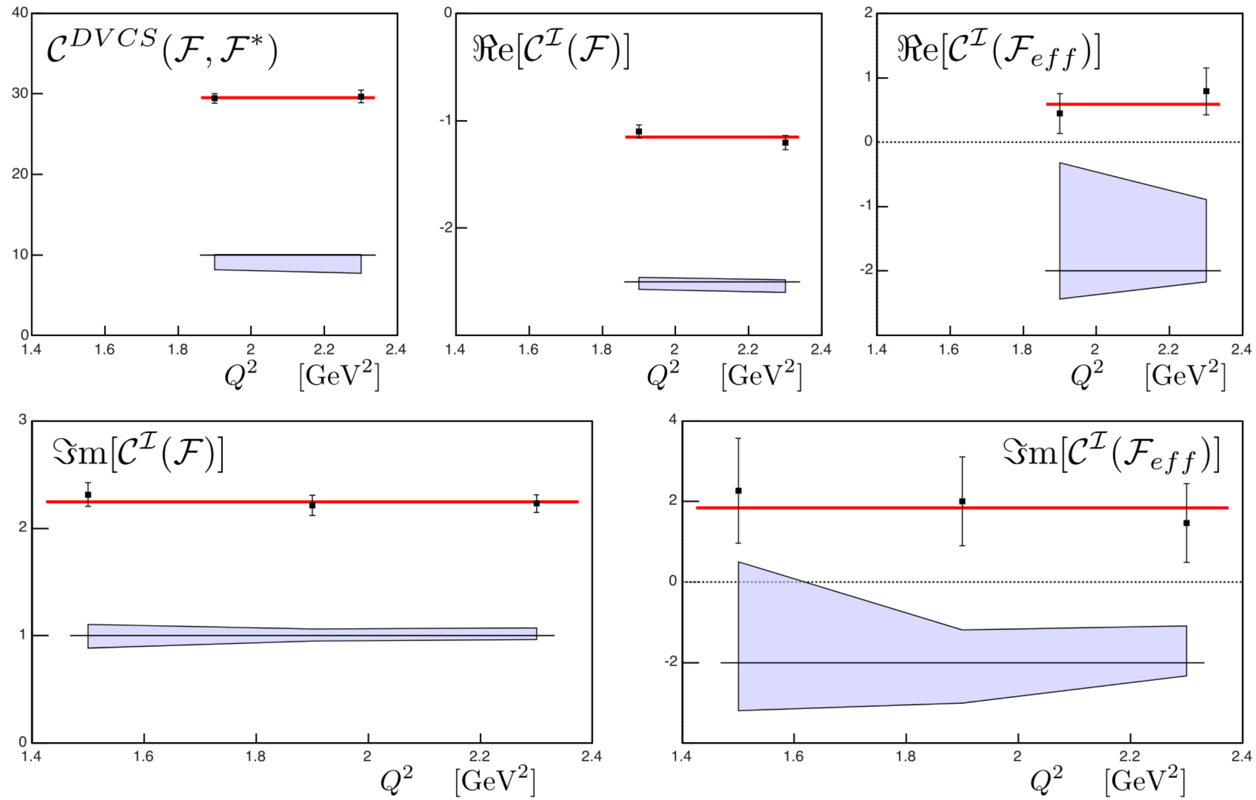
6 GeV measurements
Results: DVCS on proton

Hall A

First DVCS cross sections published in valence region: [Munoz *et al.*: Phys. Rev Lett. **97** (2006), 262002] *reanalyzed in 2015* [Defurne *et al.*: Phys. Rev. C 92, 055202 (2015)]

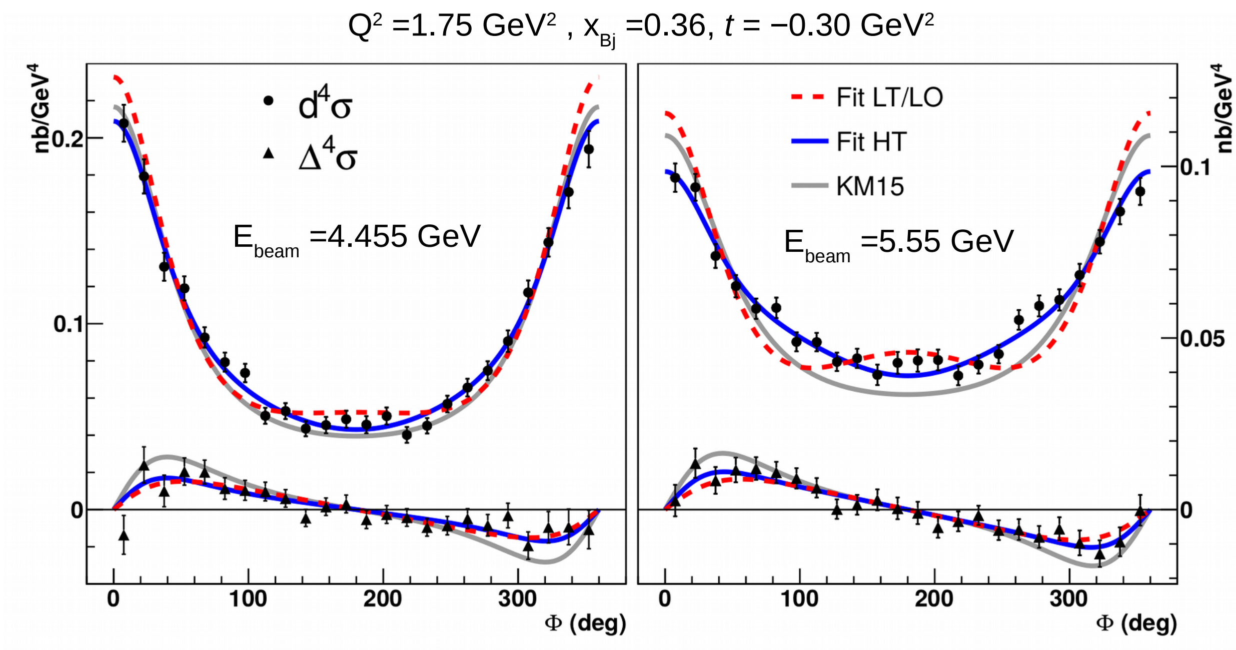
Compton Form Factors (x_{Bj} = 0.36) extracted from ***high precision cross sections*** measurements (Defined in Belitski, Mueller, PRD82 (2010), 074010)

=> ***no deviation from Q^2 scaling.***

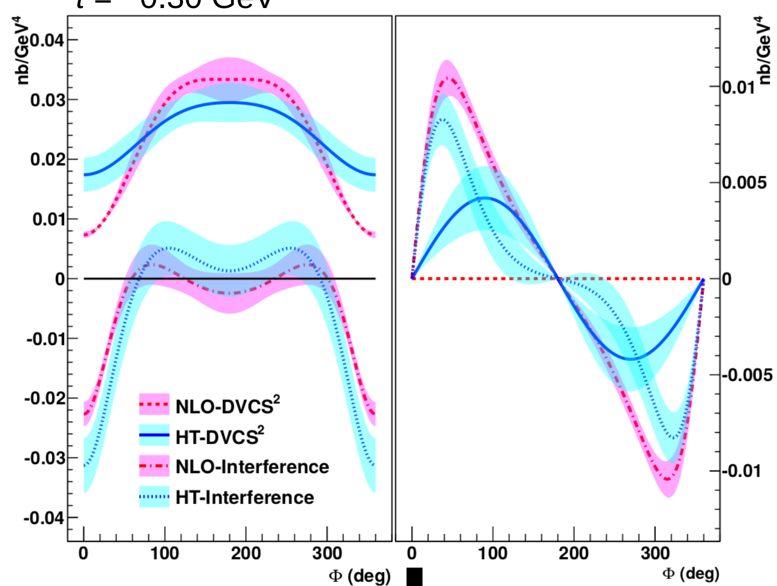


6 GeV measurements
Results / open questions: DVCS on proton

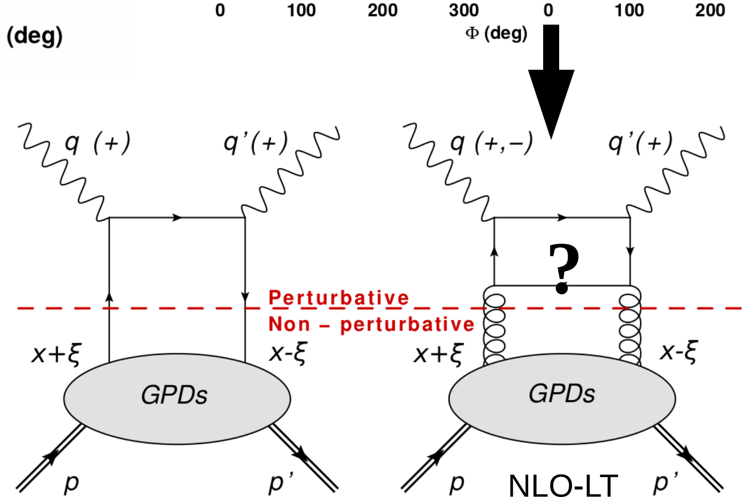
“Generalized Rosenbluth” (DVCS^2/DVCS-BH) separation data:
Evidence of contribution beyond leading order/leading twist (gluons ?)
[Defurne *et al.* Nature Commun. 8 (2017) no. 1, 1408]



E_{beam} =5.55 GeV, Q^2 =1.75 GeV^2 , x_{Bj} =0.36,
t = −0.30 GeV^2



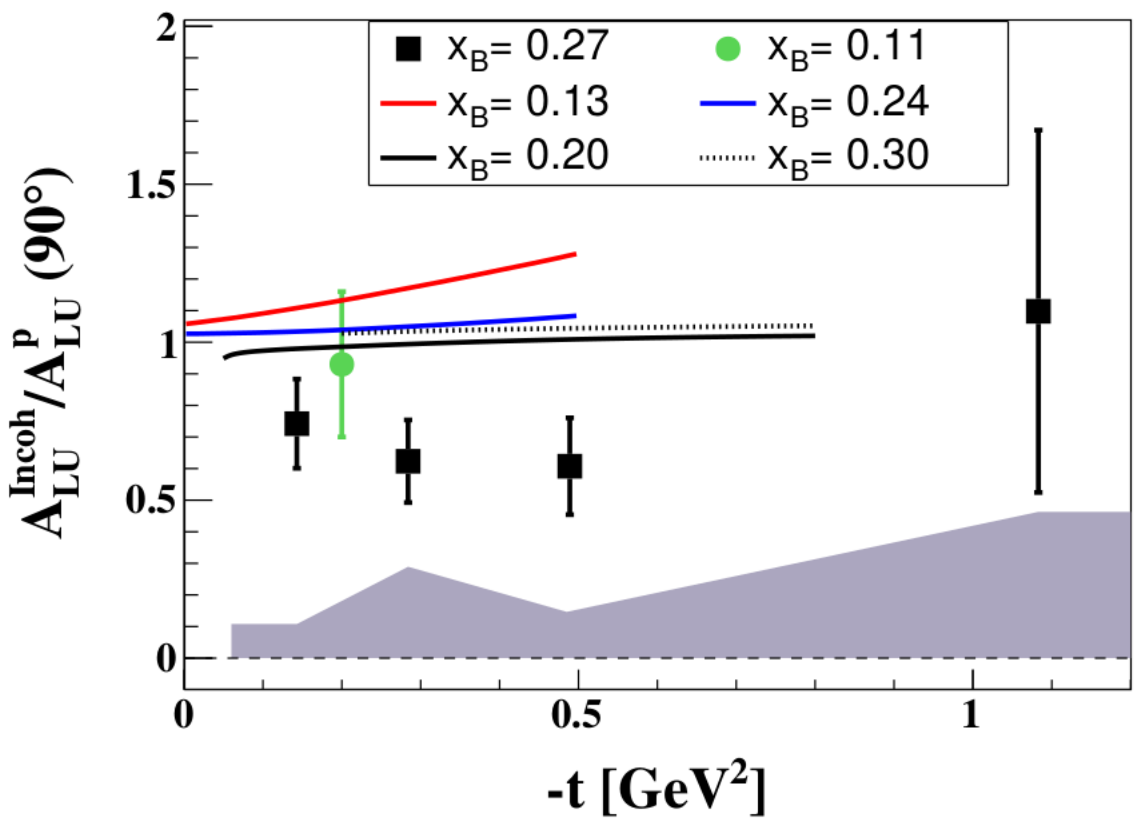
Lingering ambiguity on what this higher order contribution is



6 GeV measurements
Highlights / open questions: *p*-DVCS off ^{4}He

Coherent ^{4}He-DVCS data [Hattawy *et al.*, Phys. Rev. Lett. **119** (2017) no.20, 202004]
Well described by LO/LT calculations

Incoherent *p*-DVCS off ^{4}He [Hattawy *et al.*, arXiv:1812.07628 [nucl-ex]]
Suppressed wrt free *p*-DVCS (EMC-like effect) No existing model describes this



For more details on EMC, check F. Hauenstein's slides from Wednesday, session: "Production and Decays"

Solide curves: Off shell calculations: [S. Liuti and K. Taneja, Phys. Rev. **C 72**, 032201 (2005)]
Dashed curve: [V. Guzey, A. W. Thomas and K. Tsushima, Phys. Lett. **B 673**, 9 (2009)]

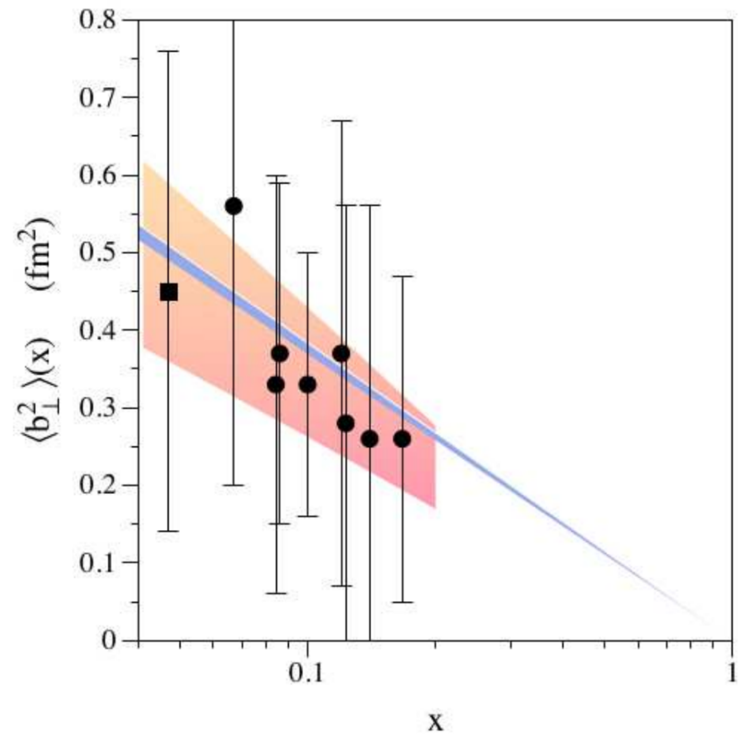
6 GeV measurements
Highlights: global *p*-DVCS analysis

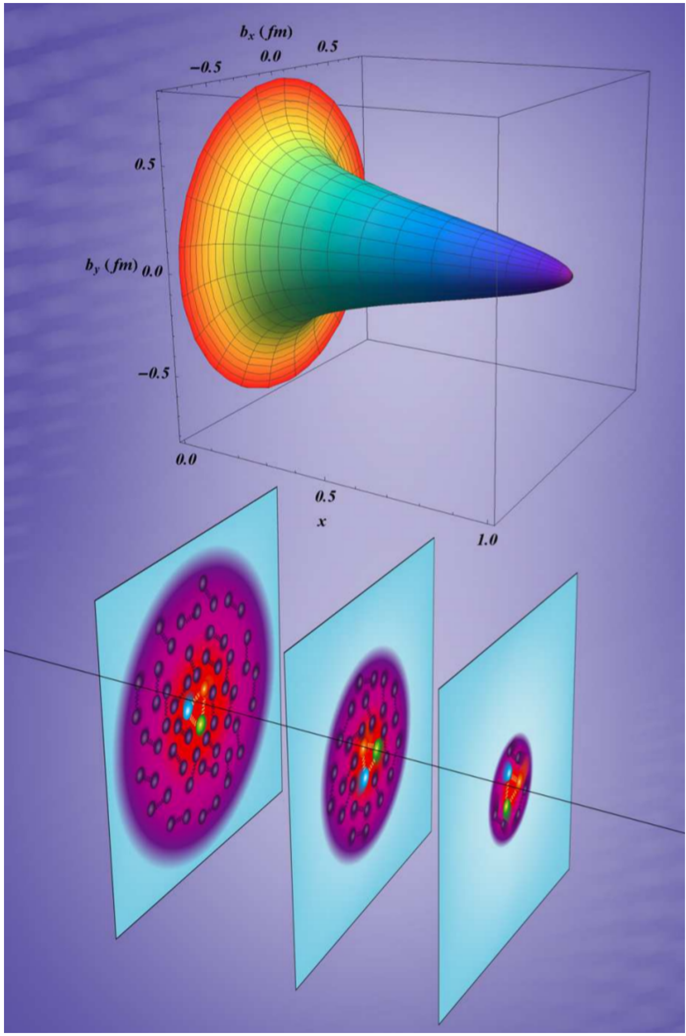
Proton tomography:
Transverse spatial distribution of partons = f(partons momentum x)

$$H_{-}^{q}(x,0,t)=q_{v}(x)\,e^{B_{-}^{0}(x)t} \quad => \quad \langle b_{\perp}^{2}\rangle^{q}(x)=4\,B_{-}^{0}(x)$$

[Dupré, Guidal, Vanderhaeghen, Phys. Rev. **D95** (2017) no.1, 011501]
[Dupré, Guidal, Niccolai Vanderhaeghen, Eur. Phys. J. **A53** (2017) no.8, 171]

Model dependent **extraction of GPD *H* from *p*-DVCS data using VGG**
[Vanderhaeghen, Guichon, Guidal, Phys. Rev. **D60,** 094017 (1999)]





Proton shrinks with increasing parton momentum

NB: COMPASS/HERA has performed a similar work, but with a different method
(see N. d'Hose talk on Friday, session "GPDs and TMDs")

***p*-DVCS**
GPD *H*
6 GeV

6 GeV measurements
Highlights: global *p*-DVCS analysis

Proton Pressure Distribution

Gravitational Form Factors evaluated with DVCS data, *exploiting the relations between GPDs and proton momentum-energy tensor:*
[Burkert, Elouadrhiri, Girod, Nature volume **557**, pages 396–399 (2018)]

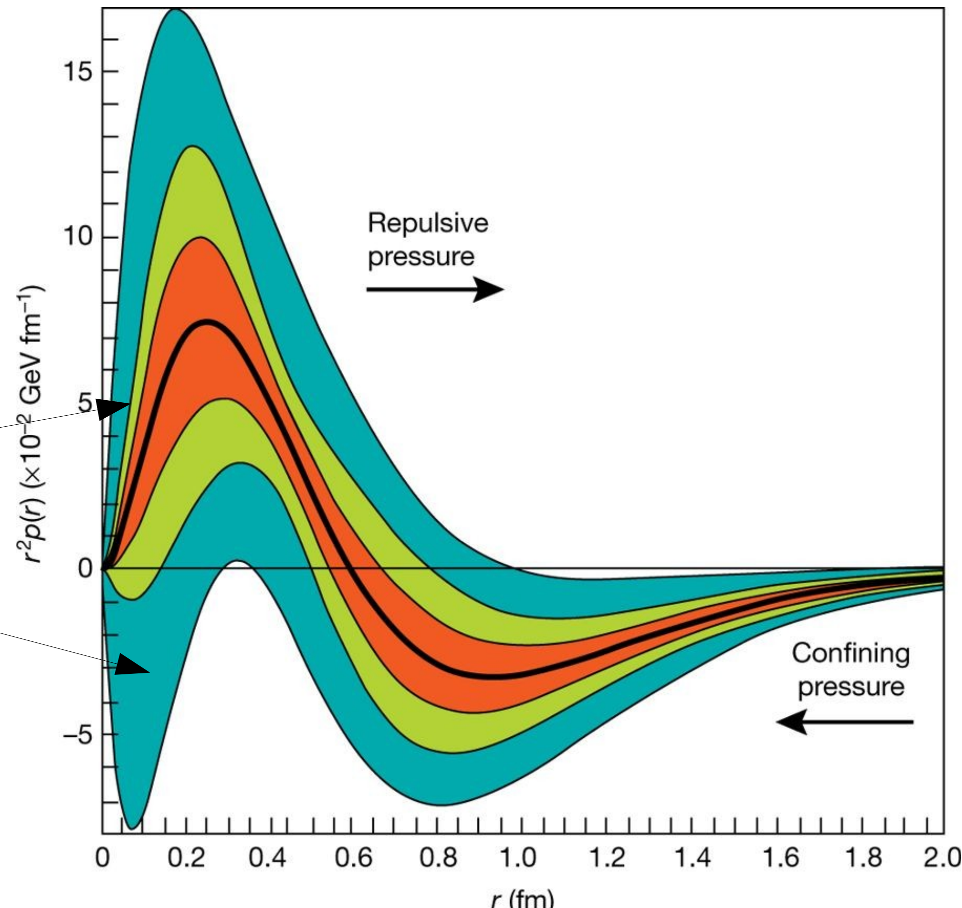
$$\int x\,H(x,\xi,t)\,dx = M_2(t) + 4/5\,\xi^2 d_1(t)$$

$d_1(t)$: shear force and pressure distribution term;
$M_2(t)$: mass term ($M_2(0) = M_p$)

Model dependent
extraction of GPD *H* from *p*-DVCS data using VGG
[Vanderhaeghen, Guichon, Guidal, Phys. Rev. **D60,** 094017 (1999)]

Statistical uncertainty with projected 12 GeV data

Statistical uncertainty with 6 GeV data



See V. Burkert's slides from Wednesday, 1st plenary session, for more details

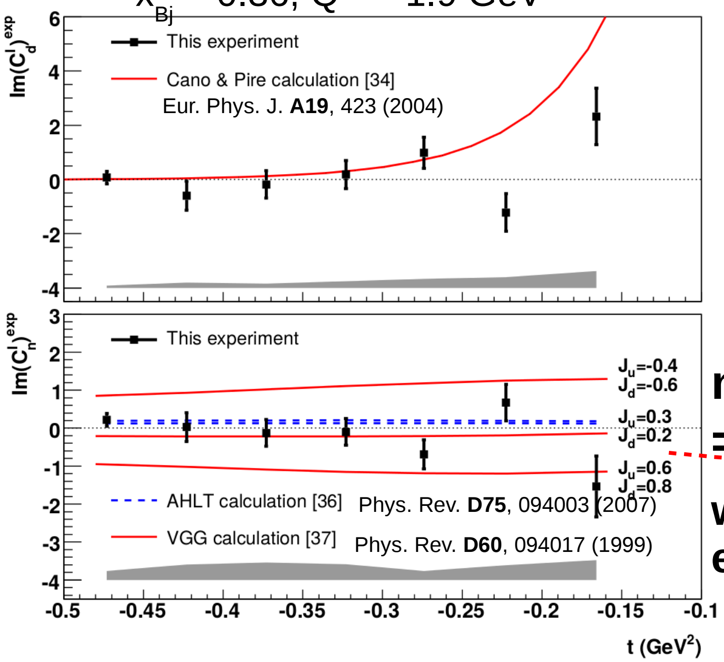
Proton Internal pressure > pressure in neutron stars!!!

6 GeV measurements
Results / highlights: DVCS on neutron

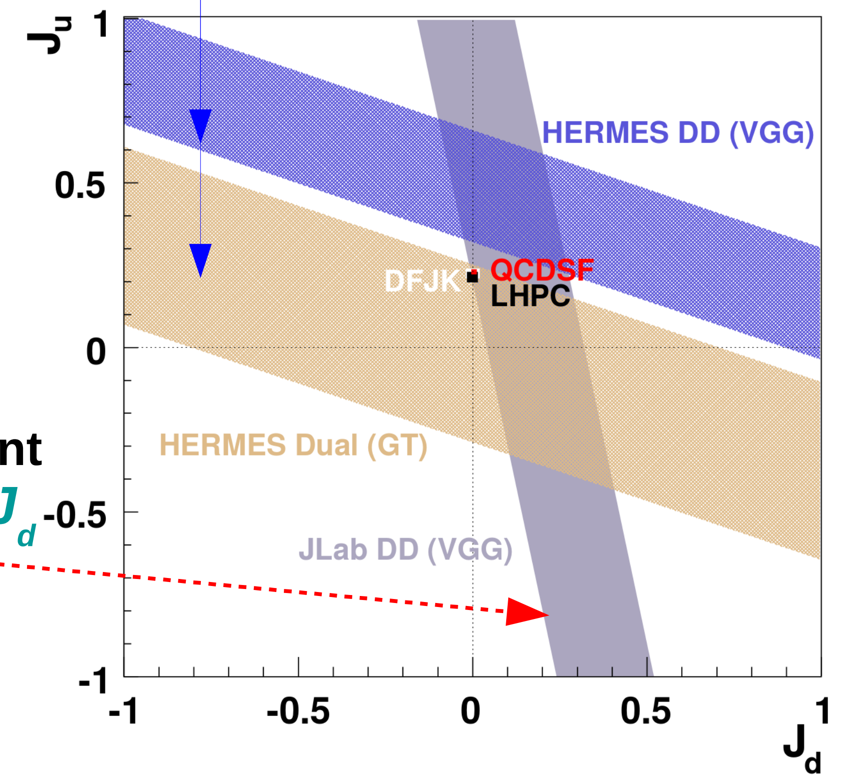
n-DVCS => GPD *E*

Compton Form Factors extracted from ***cross sections***
[Mazouz and Hall A coll. : Phys. Rev. Lett. **99**, (2007) 242501]

x_{Bj} = 0.36, Q^2 = 1.9 GeV^2



+HERMES TTSA on proton: ($J_{u,d}$)
[HERMES coll.: J. High Energy Phys. **0806** (2008) 066]



nDVCS measurement
=> Constraint on J_d
w/ model-dependent evaluation using VGG

n-DVCS analysis with Rosenbluth separation *not finalized*, but evidence for a positive *n*-DVCS signal

VGG: Vanderhaeghen, Guichon, Guidal, Phys. Rev. **D60**, 094017 (1999)
GT: Guzey, Teckentrup, Phys. Rev. **D74** (2006) 054027.
QCDSF/UKQCD Coll.: Eur. Phys. J. **A32** (2007) 445.
LHPC Coll.: Phys. Rev. **D77** (2008) 094502.
Diehl, Feldmann, Jakob, Kroll, Eur. Phys. J. **C39** (2005) 1.

L-QCD

6 GeV measurements

Results: $ep \rightarrow ep\pi^0$

Hall A

First π^0 cross section in valence region

[**EF** *et al.*, Phys. Rev. **C83** (2011), 025201]

=> unsatisfactory description by GPD models w/o GPD_T + suspicion of $\sigma_T(\pi^0)$ dominance

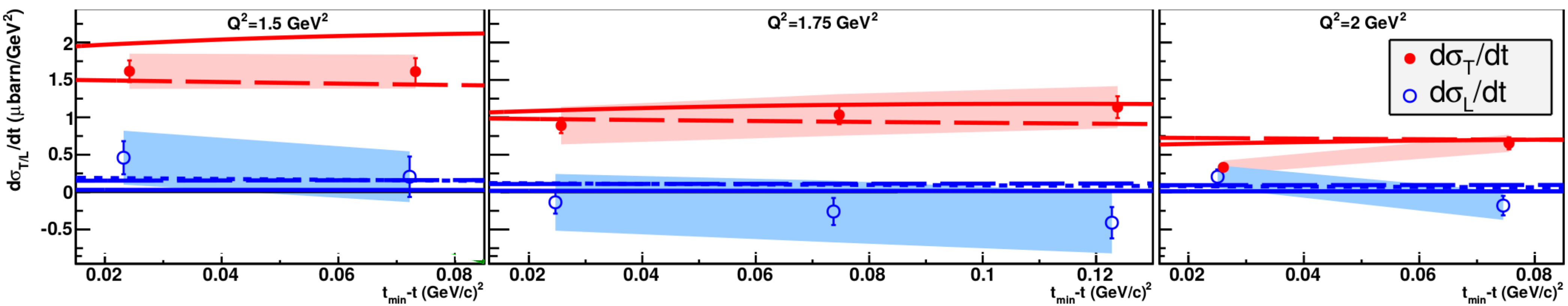
(reinforced by suprisingly large $\sigma_T(\pi^+)$ from Hall C data [T. Horn *et al.*, Phys. Rev. **C78** (2008), 058201])

$ep \rightarrow ep\pi^0$ with Rosenbluth (σ_T/σ_L) separation:

[Defurne *et al.*, Phys.Rev.Lett. **117** (2016) no.26, 262001]

Experimental confirmation:

dominance of $\sigma_T(\pi^0)$ + need of GPD_T for description of $ep \rightarrow ep\pi^0$.



Right: calculations with chiral odd GPDs (**GPD_T**) ***agree pretty well with data***

Solid: [S. Goloskokov and P. Kroll, Eur. Phys. J. **A 47**, (2011) 112]

dashed: [Goldstein, Gonzalez-Hernandez, Liuti, Phys. Rev. **D84**, 034007 (2011)]

n-DVMP
GPD_T
Hall A 6 GeV

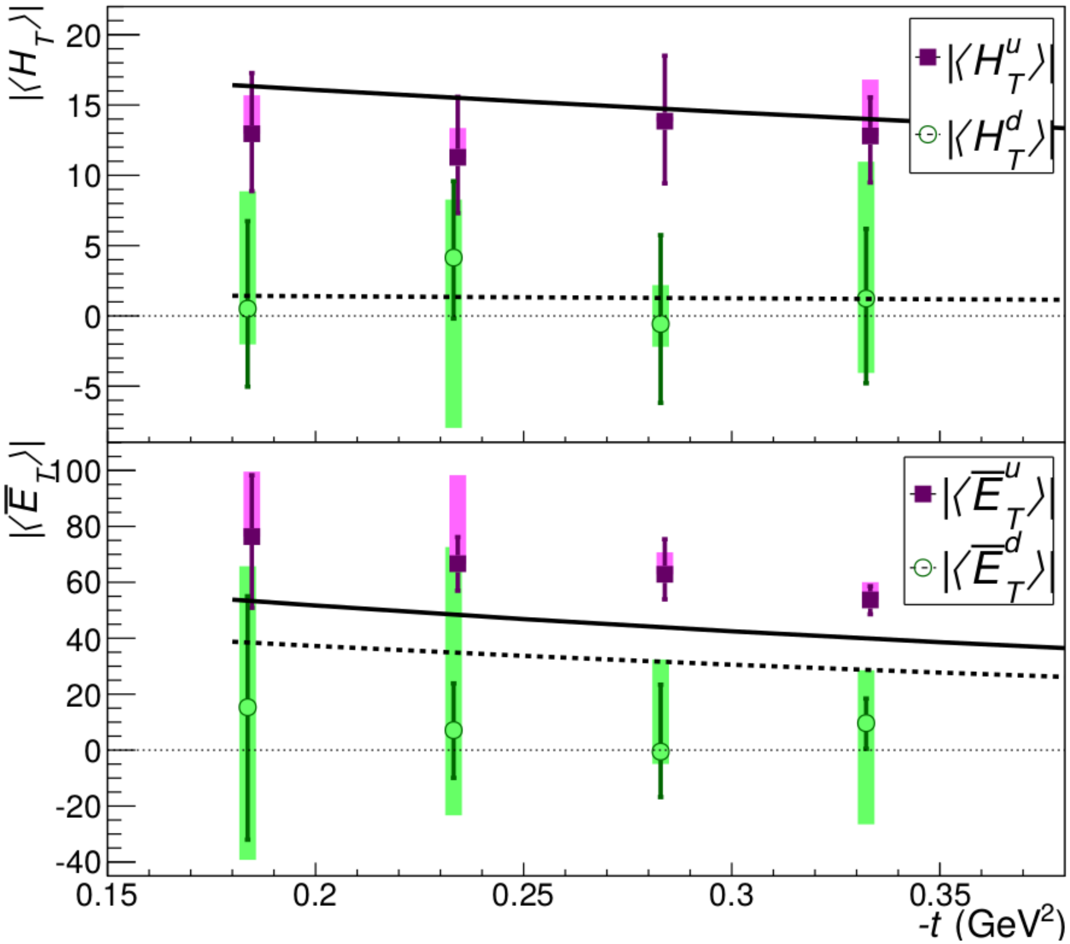
6 GeV measurements

Results: highlights / open questions: $en \to en\pi^0$

$en \to en\pi^0$ cross sections w/ Rosenbluth separation:

Combination with proton data: first flavor separation

[Mazouz *et al.*, Phys.Rev.Lett. **118** (2017) no.22, 222002]



Curves: [Goloskokov, Kroll, Eur. Phys. J. **A 47**, (2011) 112] (solid: *u*; dashed: *d*)

Fair agreement of these calculations with Hall A data.

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

Uncertainty of the relative phase between u and d

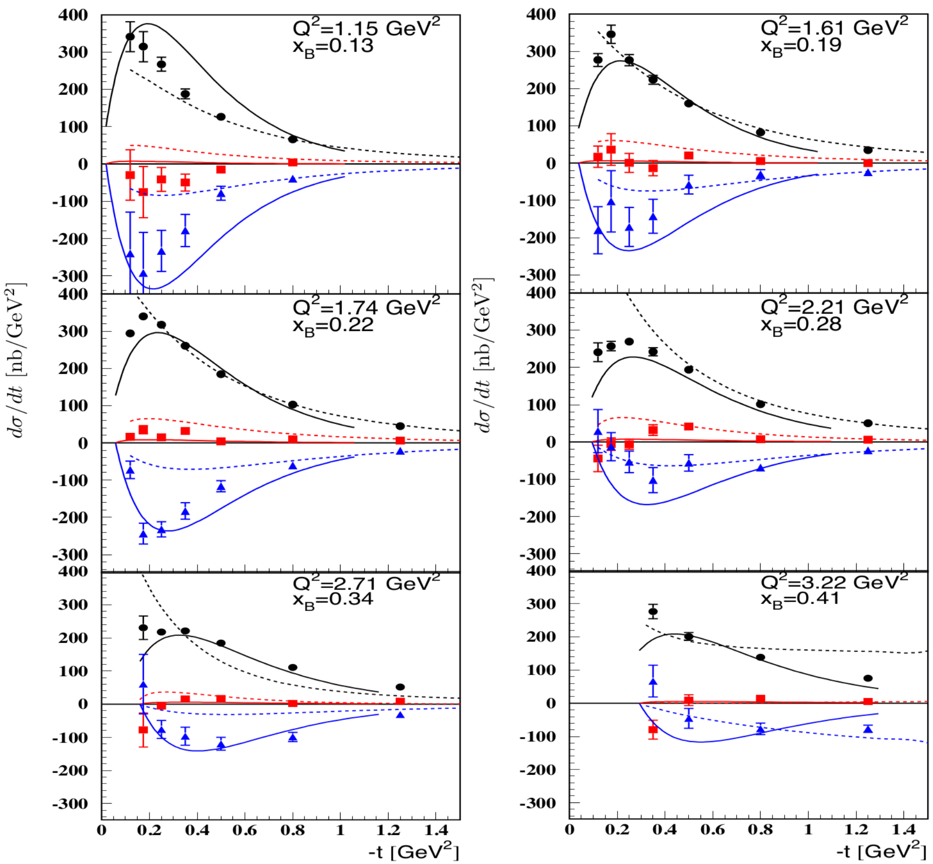
Would need a η measurement at similar kinematic (Hall A PbF_2 too small)

p-DVMP
GPD_T
Hall B 6 GeV

6 GeV measurements
Results: $ep \to ep\pi^0$

CLAS

First π^0 Beam Spin Asymmetry [De Masi *et al.*, Phys. Rev. **C77**, 042201 (2008)]
Cross sections [Bedlinskiy *et al.*: Phys. Rev. Lett. **109** (2012) 112001; Phys.Rev. **C90** (2014) 025205]



+***Target Spin Assymetries***,
Double Spin Asymmetries with
longitudally polarized target
[Kim *et al.*: Phys.Lett. **B768** (2017) 168-173]

Large data sets over
large kinematic coverage
Confirms **need of GPD_T for**
$ep \to ep\pi^0$ description

More details in A. Kim's talk
(17:30 today, this session)

Curves: *calculations with chiral-odd GPDs* => **mainly contribute to σ_T**
Solid: [S. Goloskokov and P. Kroll, Eur. Phys. J. **A 47**, (2011) 112]
dashed: [Goldstein, Gonzalez-Hernandez, Liuti, Phys. Rev. **D84**, 034007 (2011)]
Good agreement between these calculations and CLAS data.

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Measurements at 12 GeV:
experimental setups/kinematic coverage

11 GeV polarized e^- beam in Halls A, B, C

HALL A+C

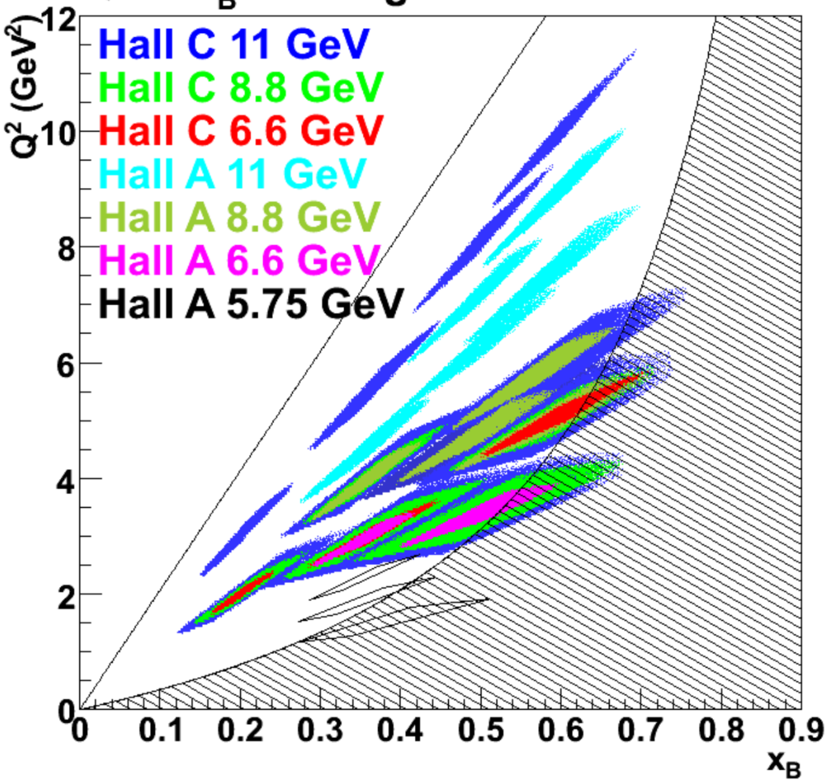
High precision measurements

Novelty wrt 6 GeV :

Hall C HMS + NPS allowing

Rosenbluth separation

(DVCS^2/DVCS-BH, σ_T/σ_L)



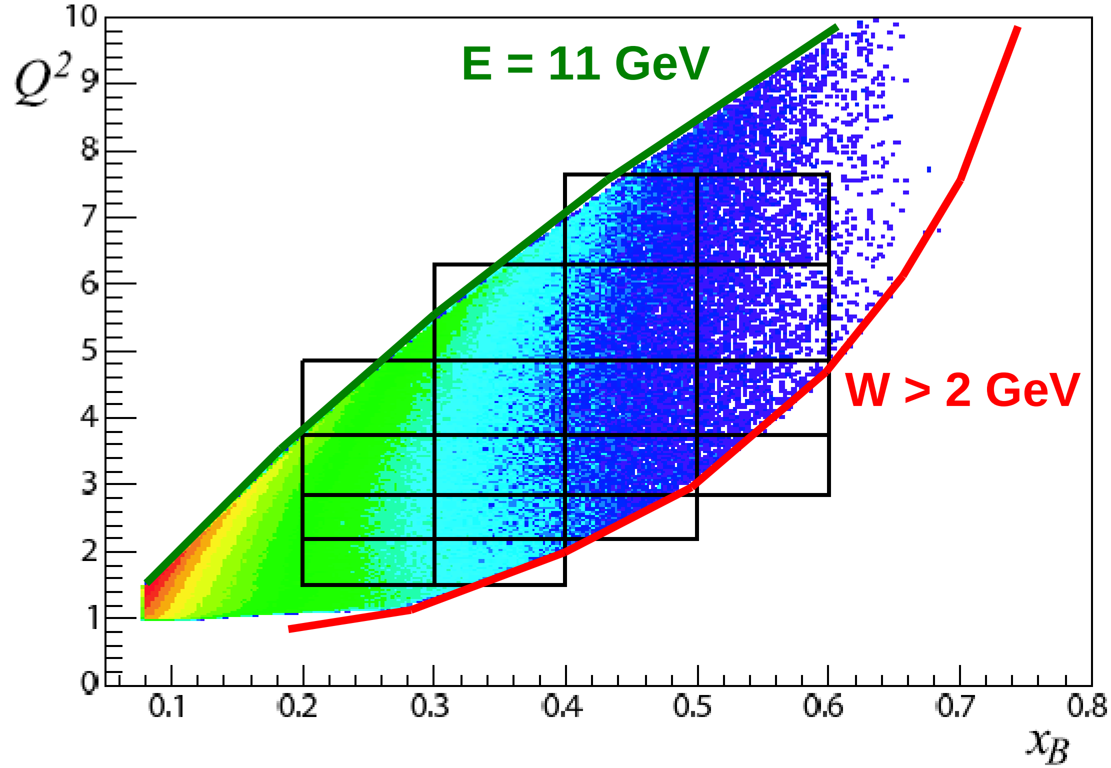
CLAS 12 (Hall B)

Measurements on large kinematic coverage

Novelties: - Central neutron detector + LD$_2$ tgt

- ALERT + D$_2$, ^{4}He targets

=> *n*-DVCS (GPD *E*), nuclei GPDs



=> complementarity between both halls

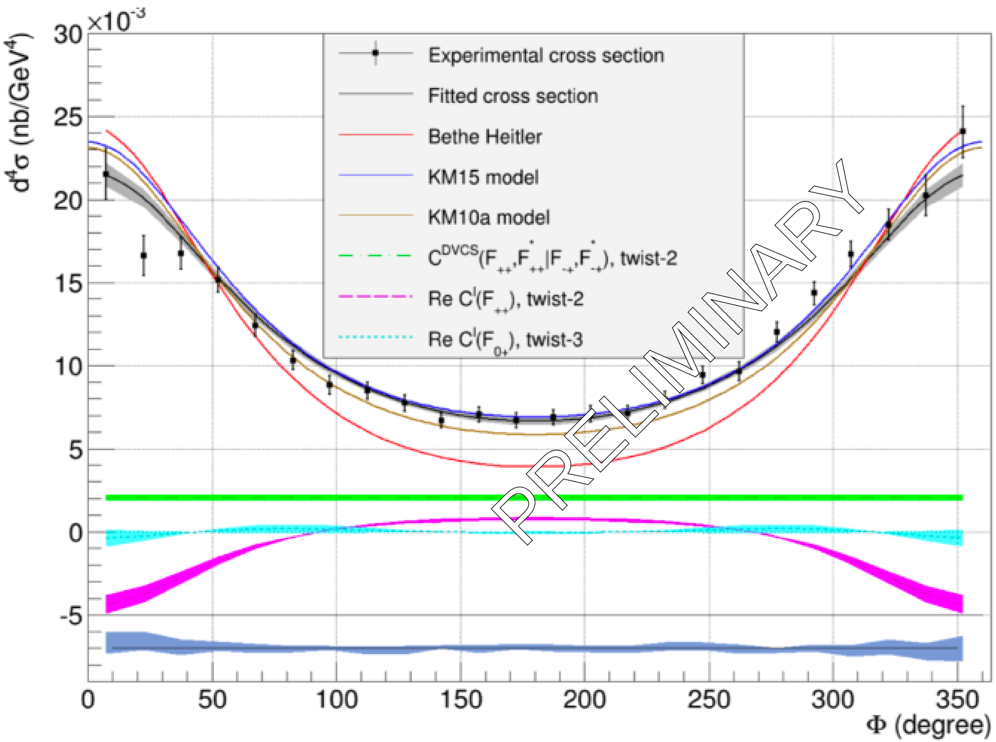
p-DVCS
GPD *H*
Hall A
12 GeV

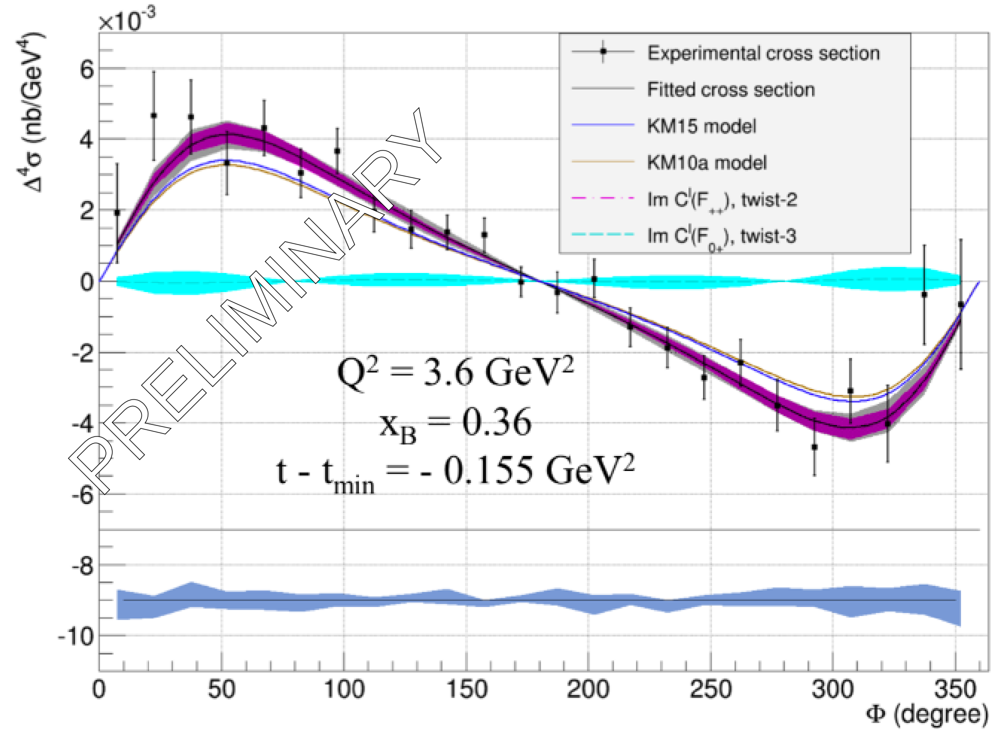
12 GeV measurements:
A taste of Hall A 12 GeV *preliminary* DVCS results

High precision DVCS cross section measurement
Analysis credit: F. Georges (IPN Orsay)
Presented at Jefferson Lab Hall A collaboration meeting 2019 (1/30/2019) by H. Rashad (ODU)

$$d^4\sigma = \frac{d^4\overrightarrow{\sigma} + d^4\overleftarrow{\sigma}}{2} = |T_{BH}|^2 + |T_{DVCS}|^2 + \Re(\mathscr{T})$$

$$\Delta^4\sigma = \frac{d^4\overrightarrow{\sigma} - d^4\overleftarrow{\sigma}}{2} = \Im(\mathscr{T})$$



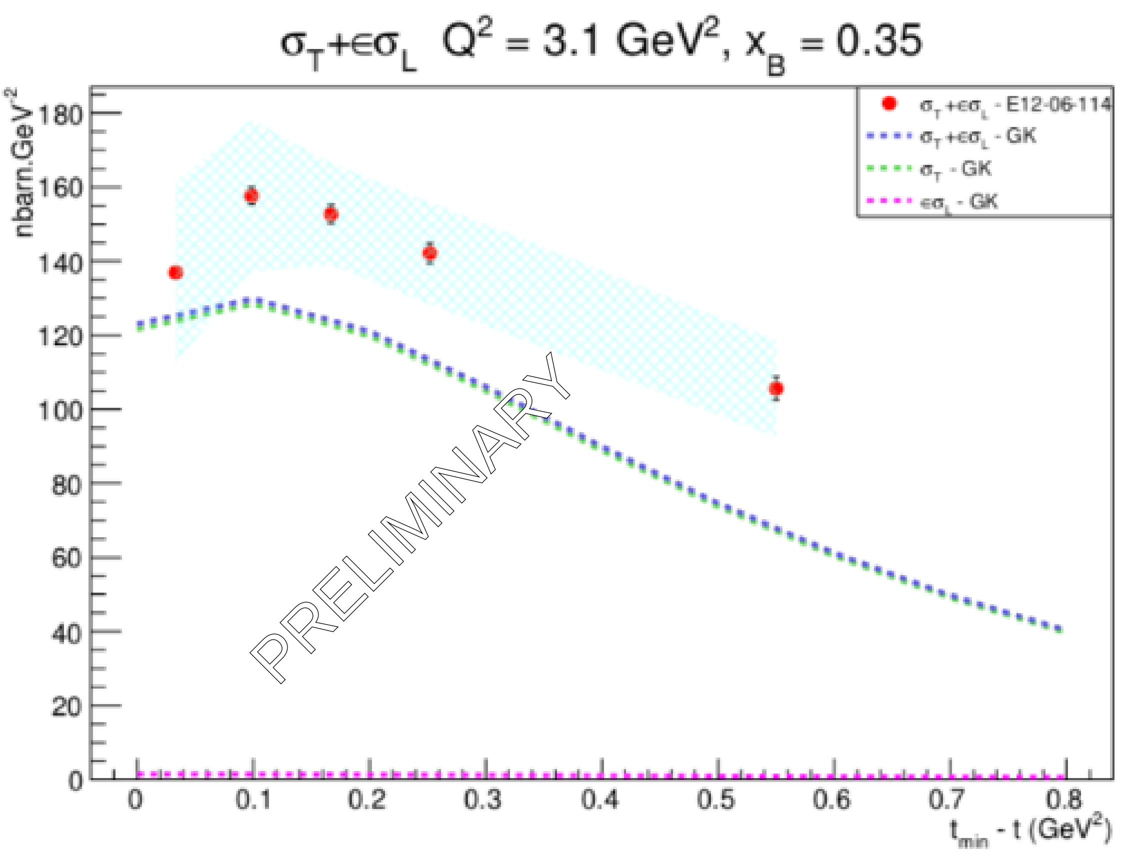


(As of current analysis, Q^2 scaling of CFF seems to hold)

p-DVMP
GPD H
Hall A
12 GeV

12 GeV measurements:
A taste of Hall A 12 GeV *preliminary* $ep \rightarrow ep\pi^0$ results

High precision π^0 cross section measurement
Analysis credit: M. Dlamini (Ohio U.)
Presented at Jefferson Lab Hall A collaboration meeting 2019 (1/30/2019) by H. Rashad (ODU)



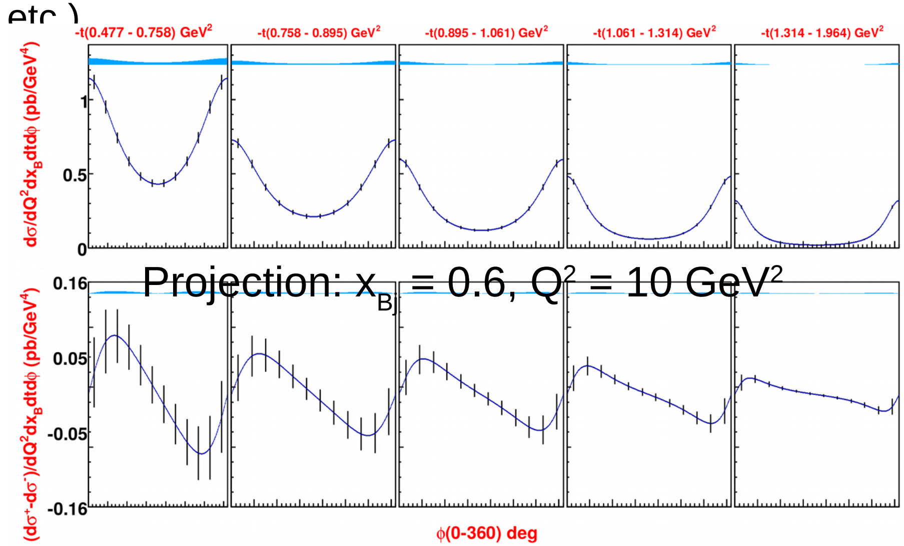
As of current analysis, σ_T dominance can still be infered from data
(with comparison with GK model [S. Goloskokov and P. Kroll, Eur. Phys. J. **A 47**, (2011) 112]) .

p-DVCS/MP
GPD H
Hall C
12 GeV

12 GeV upcoming measurements:
Upcoming experiments: p-DVCS/π^0 with Hall C HMS/NPS

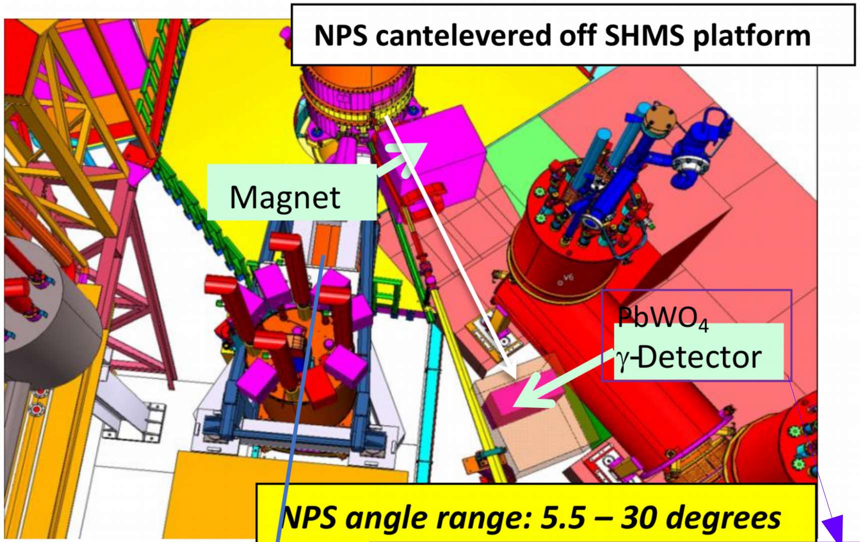
NPS: Neutral Particle Spectrometer (calorimeter + sweeping magnet)

DVCS/π^0 proposal (*Munoz*, Paremuzian, Horn, Hyde, Roche):
https://www.jlab.org/exp_prog/proposals/13/PR12-13-010.pdf
NB: Other measurements planned with NPS (**TCS**, WACS, SIDIS, etc.)



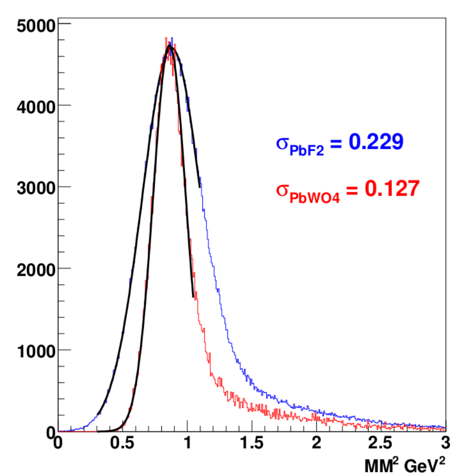
NPS layout on SHMS carriage

- DVCS H(e,e' γ)p, Deep H(e,e' π^0)p



e- to HMS
(High Momentum Spectrometer)

PbF$_2$ → PbWO$_4$:
Better calorimeter resolution



Capability for good statistical accuracy at high Q^2, x_{Bj}.

=> potential to confirm/infirm gluon contribution in valence region evidenced by Hall A Rosenbluth separation data.

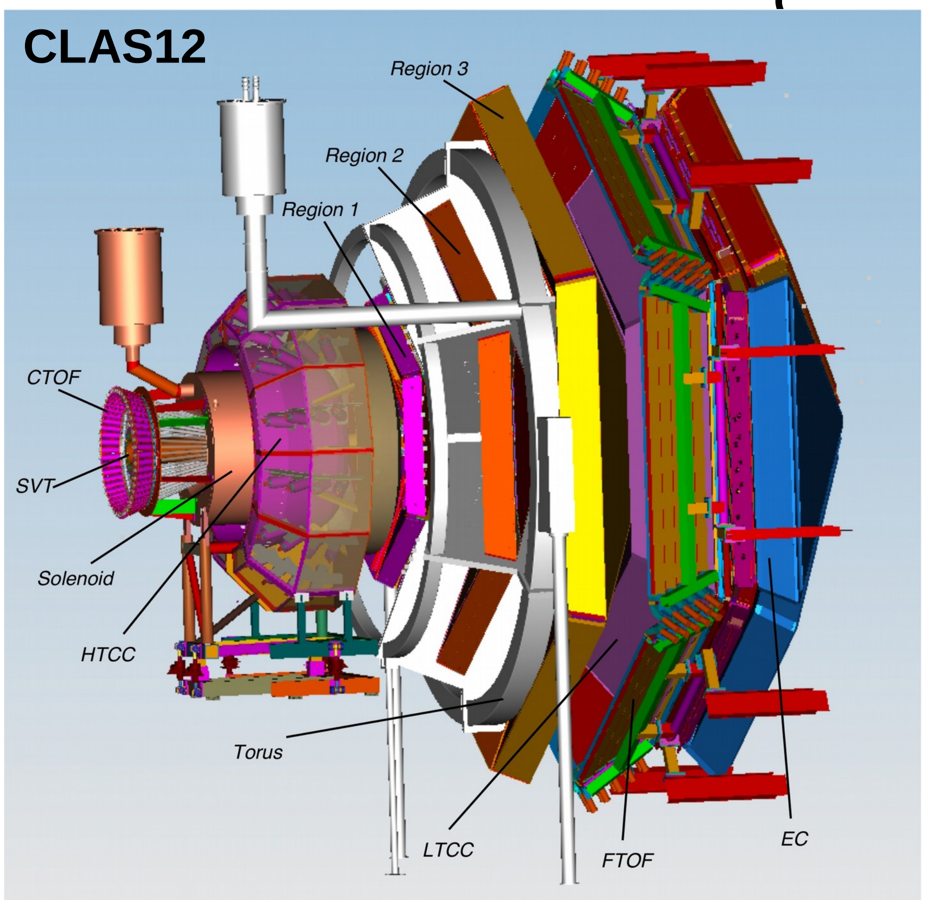
p-DVCS/MP
GPD *H*
Hall B
12 GeV

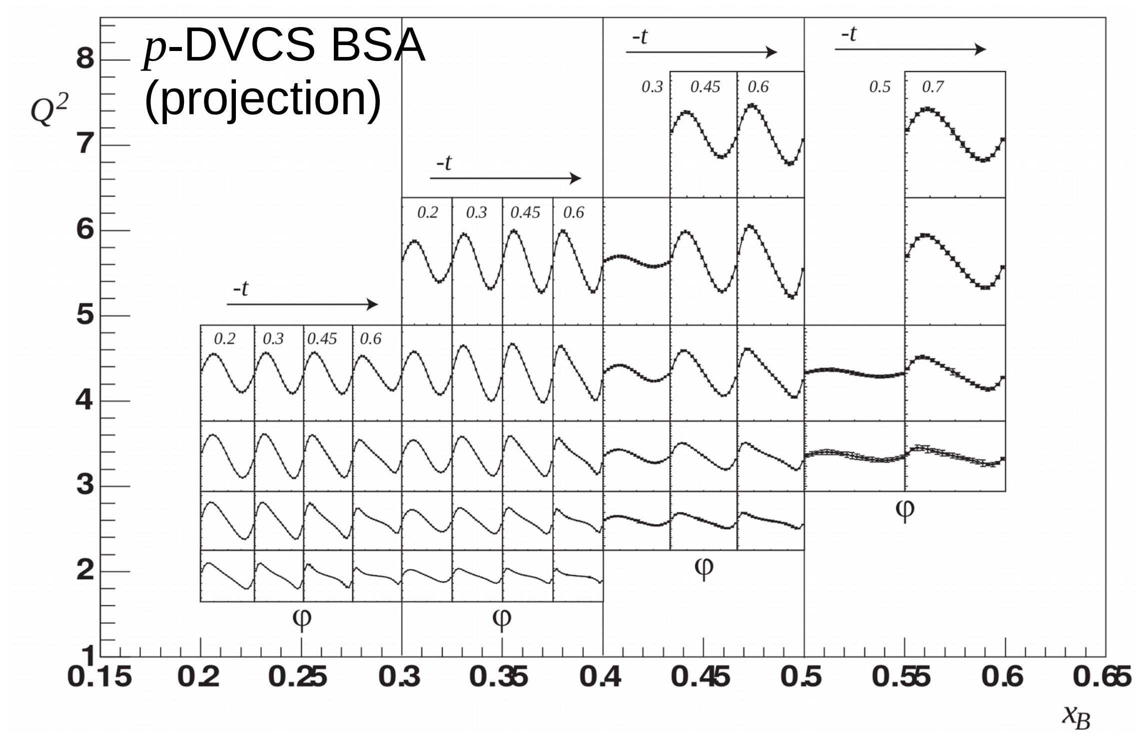
12 GeV upcoming measurements:
Ongoing/upcoming experiments: *p*-DVCS/π^0 with CLAS12

DVCS measurement on proton (U+L)
(*Sabatie*, Biselli, Egiyan, Elouadrhiri, Holtrop, Ireland, Kim)
https://www.jlab.org/exp_prog/proposals/06/PR12-06-119.pdf

π^0/η measurement on proton
(*Stoler*, Joo, Kubarovsky, Ungaro, Weiss)
https://www.jlab.org/exp_prog/proposals/06/PR12-06-108.pdf

New DVCS/π^0/η measurements on large kinematic coverage





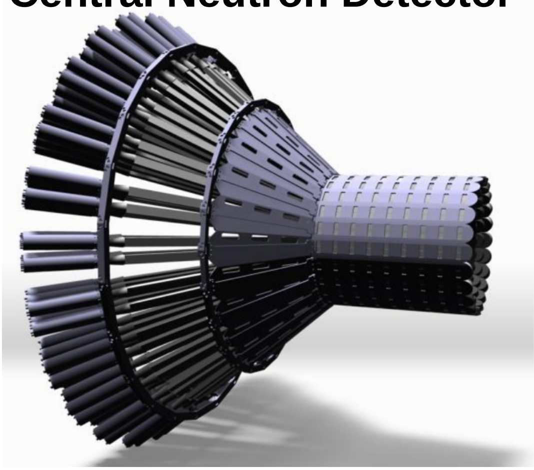
Improve statistical accuracy on:
* **proton tomography;**
* **proton pressure distribution;**

12 GeV upcoming measurements:
Upcoming experiments: *n*-DVCS/π^0 with CLAS12

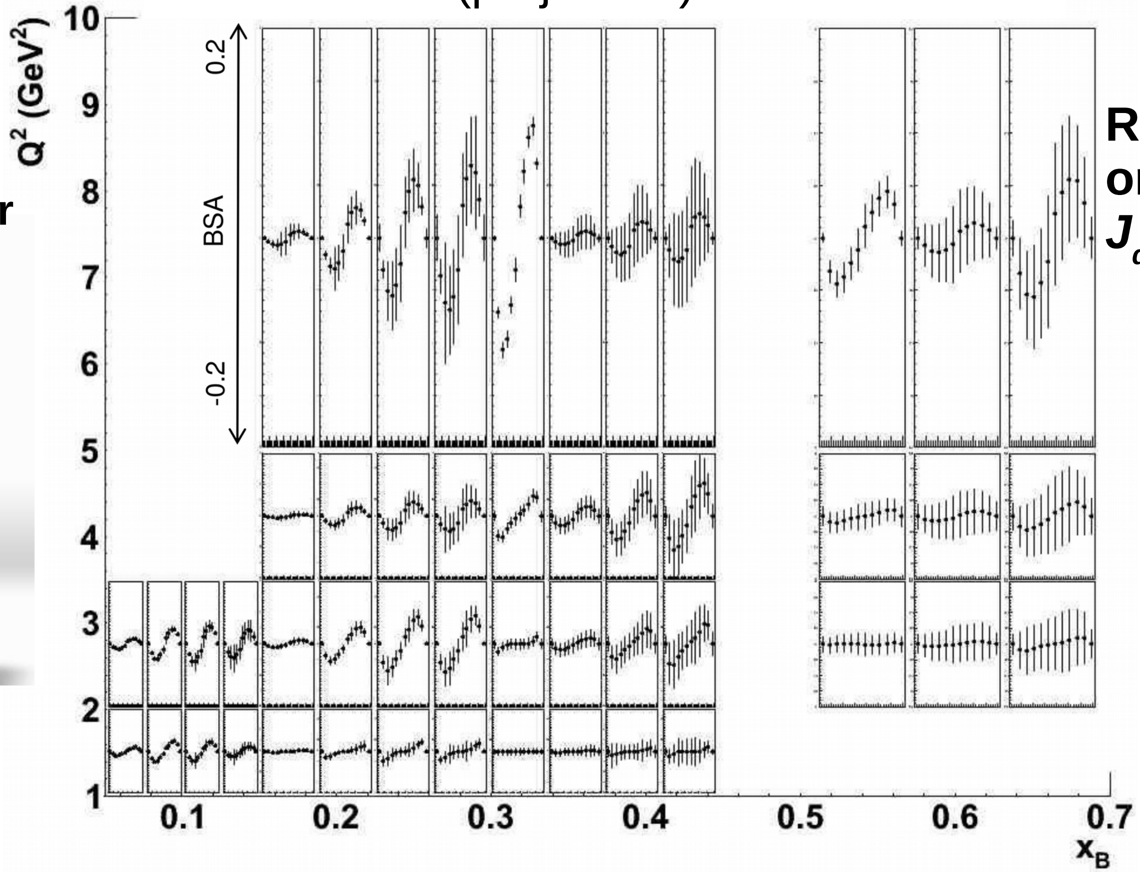
DVCS measurement on (unp) D_2 with recoil neutron detection (*Niccolai*, Sokhan)
https://www.jlab.org/exp_prog/proposals/11/PR12-11-003.pdf
DVCS measurement on (L. pol) D_2 with recoil neutron detection
(*Niccolai*, Biselli, Keith, Pisano, Sokhan)
https://www.jlab.org/exp_prog/proposals/16/E12-06-109A.pdf

***n*-DVCS measurements on large kinematic coverage** (mostly unexplored for n-DVCS)

Central Neutron Detector



n-DVCS BSA (projection)



Reduce systematics on the evaluation of J_d from data

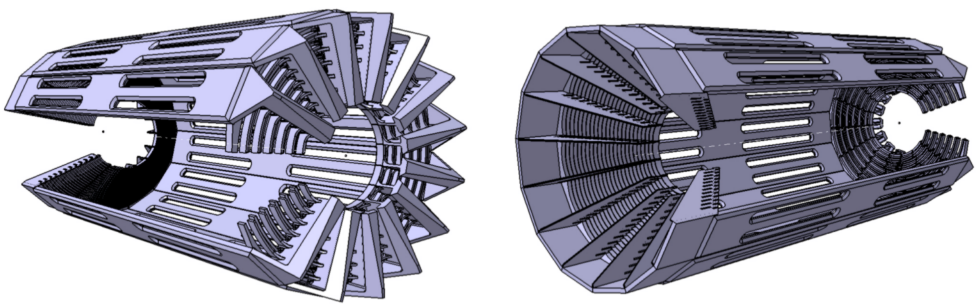
***n/A*-DVCS**
GPD *E*
Hall B
12 GeV

12 GeV upcoming measurements:
Upcoming experiments: CLAS12 with ALERT

DVCS (π^0) measurements on D_2, ^{4}He, with recoil/ measurement

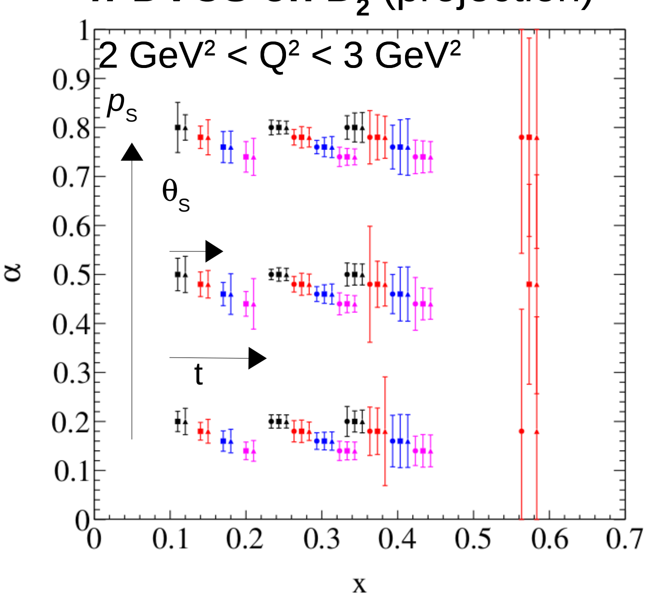
Coherent measurements (Hadifi, Hattawy, Dupré, *Meziani*, Paolone)
https://www.jlab.org/exp_prog/proposals/17/PR12-17-012.pdf
Incoherent measurement (*Armstrong*, Hadifi, Dupré, Meziani)
https://www.jlab.org/exp_prog/proposals/17/PR12-17-012B.pdf

ALERT: *A Low Energy Recoil Tracker*

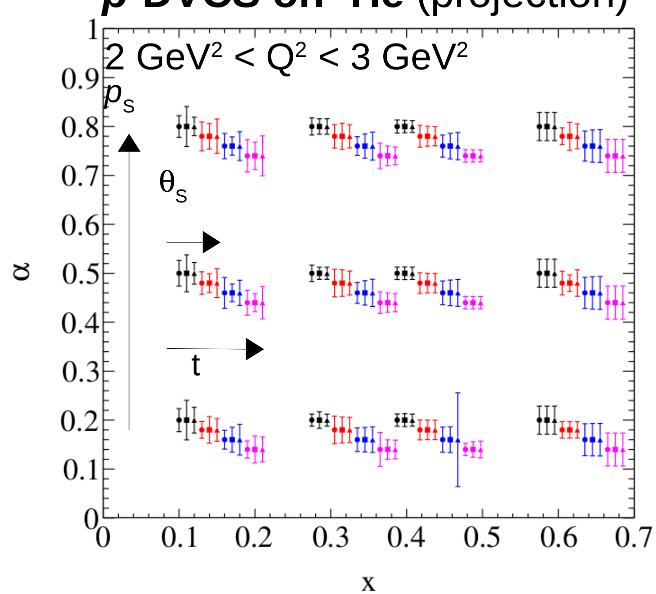


Detection of low energy p, ^{3}H, ^{3}He, ^{4}He:
=> Recoil detection / spectator tagging
=> Unambiguous identification of coherent and incoherent DVCS
=> reduced systematics on *n*-DVCS and bound *p*-DVCS

***n*-DVCS on D_2** (projection)



***p*-DVCS on ^{4}He** (projection)



=> Study in more detail the “EMC-like” effect evidenced by existing *p*-DVCS measurement off ^{4}He.

For more details on coherent DVCS and ALERT, check Z.E. Meziani’s slides from today, session: “3D imaging”

GPDs: promising tool to solve the nucleon spin puzzle;

Jefferson Lab is a great facility to study GPDs (high luminosity, beam polarization)

A wealth of DVCS/π^0 data produced at Jefferson Lab 6 GeV, which lead to improved knowledge on nucleon structure:

=> constraint on J_d/J_u

=> Nucleon tomography in valence region

=> Pressure distribution in the proton

=> Role of transverse GPDs in meson production

=> First flavor separation of GPDs

Yet data did not address or raise many other questions:

=> Role of gluons in valence region

=> Ambiguities on GPD flavor separation

=> Suppression of CFF in incoherent DVCS off nuclei

By extending kinematic coverage of existing measurements, or allowing new ones, Jefferson Lab at 12 GeV will help address these questions

I could not talk about: * other DVMP channels (DVϕP);
* EIC program
* etc...

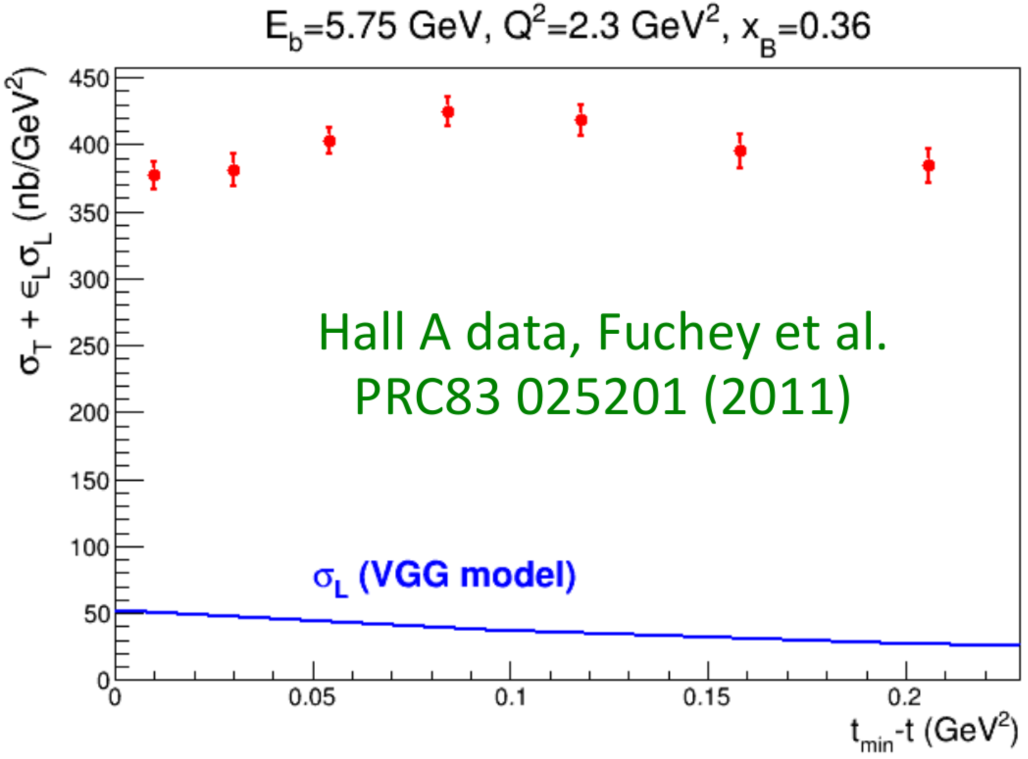
Thank you for your attention !

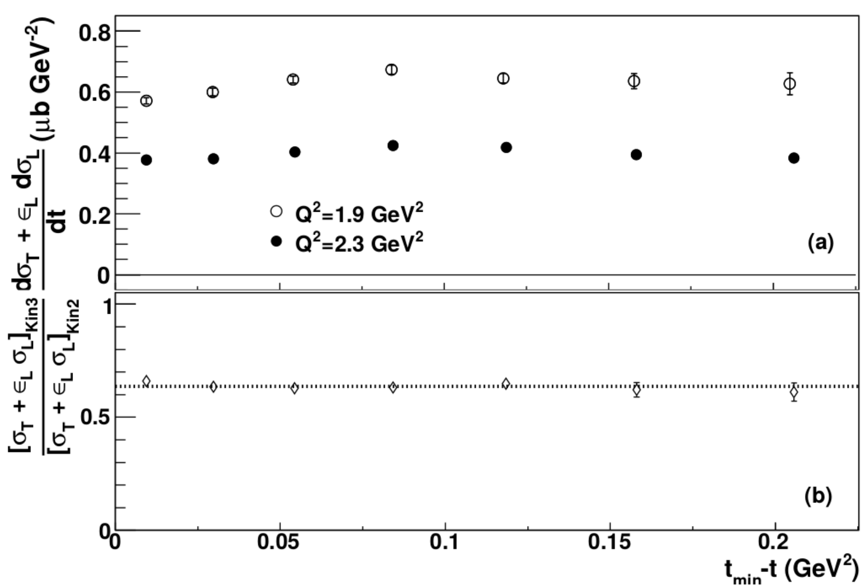
p-DVMP
GPD$_T$
Hall A 6 GeV

6 GeV measurements
Results: $ep \rightarrow ep\pi^0$

Hall A

First π^0 cross section in valence region [**EF** *et al.*, Phys. Rev. **C83** (2011), 025201]
=> unsatisfactory description by LO GPD models + Suspicion of $\sigma_T(\pi^0)$ dominance
(reinforced by suprisingly large $\sigma_T(\pi^+)$ from Hall C data [T. Horn *et al.*, Phys. Rev. **C78** (2008), 058201])



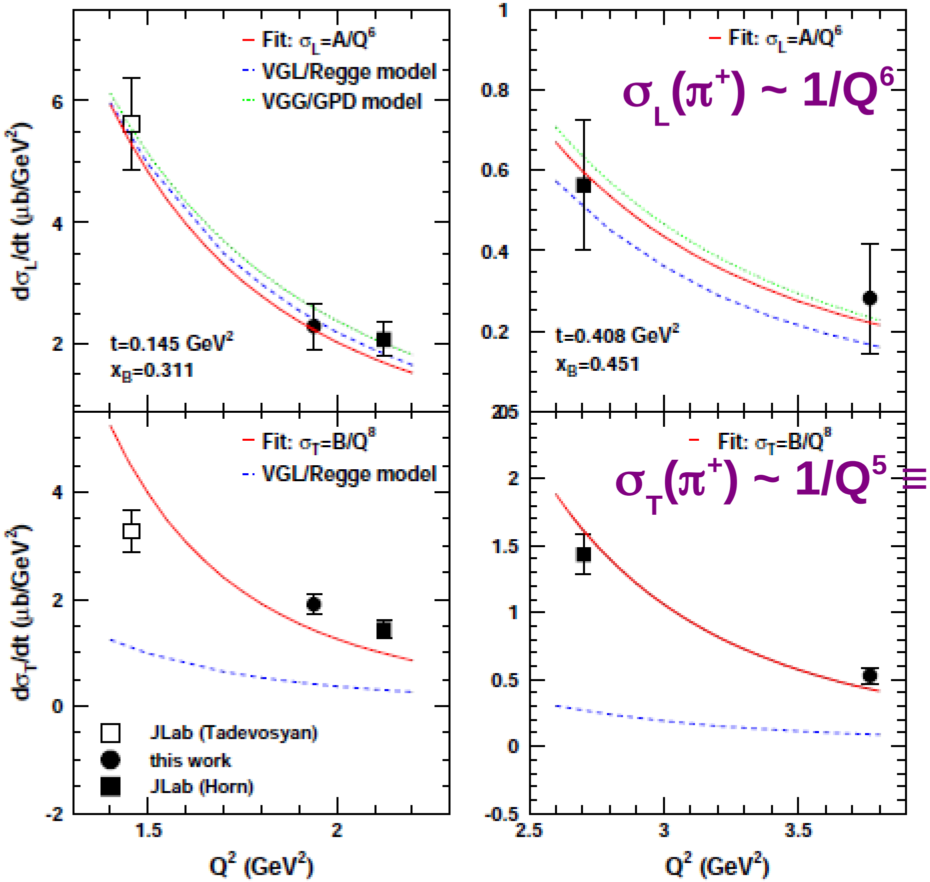


Curves: *left*: VGG: [Vanderhaeghen, Guichon, Guidal, Phys. Rev. **D60**, 094017 (1999)]
Right: calculations with chiral odd GPDs (**GPD$_T$**) ***agree pretty well with data***

$ep \to ep\pi^0$ analysis in Hall A:
Comparison with $ep \to en\pi^+$

$ep \to en\pi^+$ in Hall C

[T. Horn et al., Phys. Rev. C78 (2011), 025125]



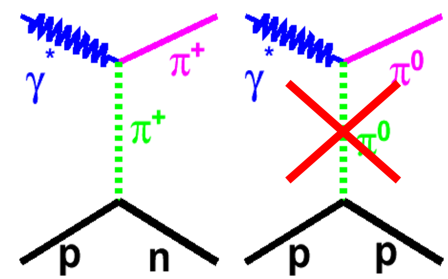
$\sigma_L(\pi^+) \sim 1/Q^6$

$\sigma_T(\pi^+) \sim 1/Q^5 \equiv \sigma_T + \varepsilon\sigma_L(\pi^0)$ **+**

A priori

$\sigma_L^{\pi 0} \ll$

$\sigma_L^{\pi +}$



=> $\sigma_T(\pi^0)$ dominant ?

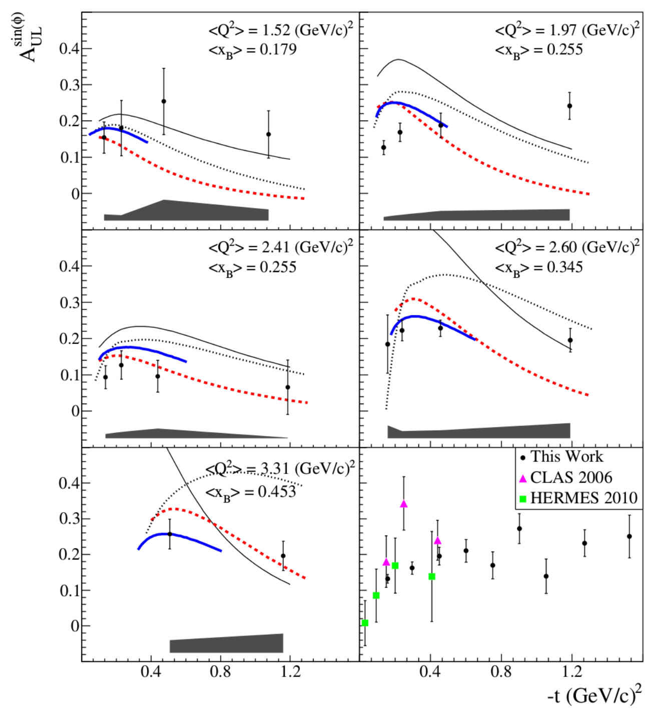
VGG: Vanderhaeghen, Guichon, Guidal, Phys. Rev. **D60**, 094017 (1999)
VGL: Vanderhaeghen, Guidal, Laget, Phys. Rev. **C57**, 1454 (1998)

6 GeV measurements

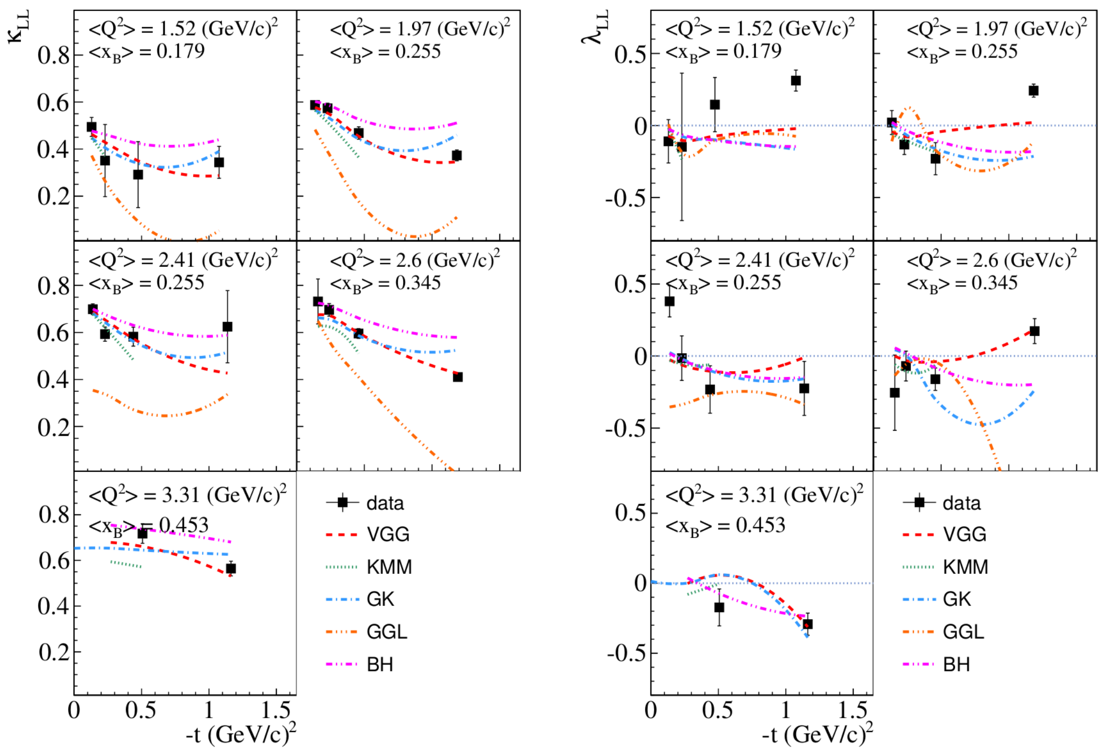
Highlights: DVCS on longitudinally polarized proton

Longitudinally polarized proton target => GPD $\tilde{H}$

Target single spin assymetry
[Seder *et al.*: Phys.Rev.Lett. **114** (2015), 032001]



Double spin asymmetries
[Pisano *et al.*: Phys.Rev. **D91** (2015), 052014]



VGG } GPDs
GK
KMM (Hybrid GPD fit model) Kumericki, Müller, Murray, Phys. Part. Nucl. **45**, 723 (2014)
GGL (quark-diquark model) Goldstein, Gonzalez-Hernandez, Liuti, Phys. Rev. **D84**, 034007 (2011)

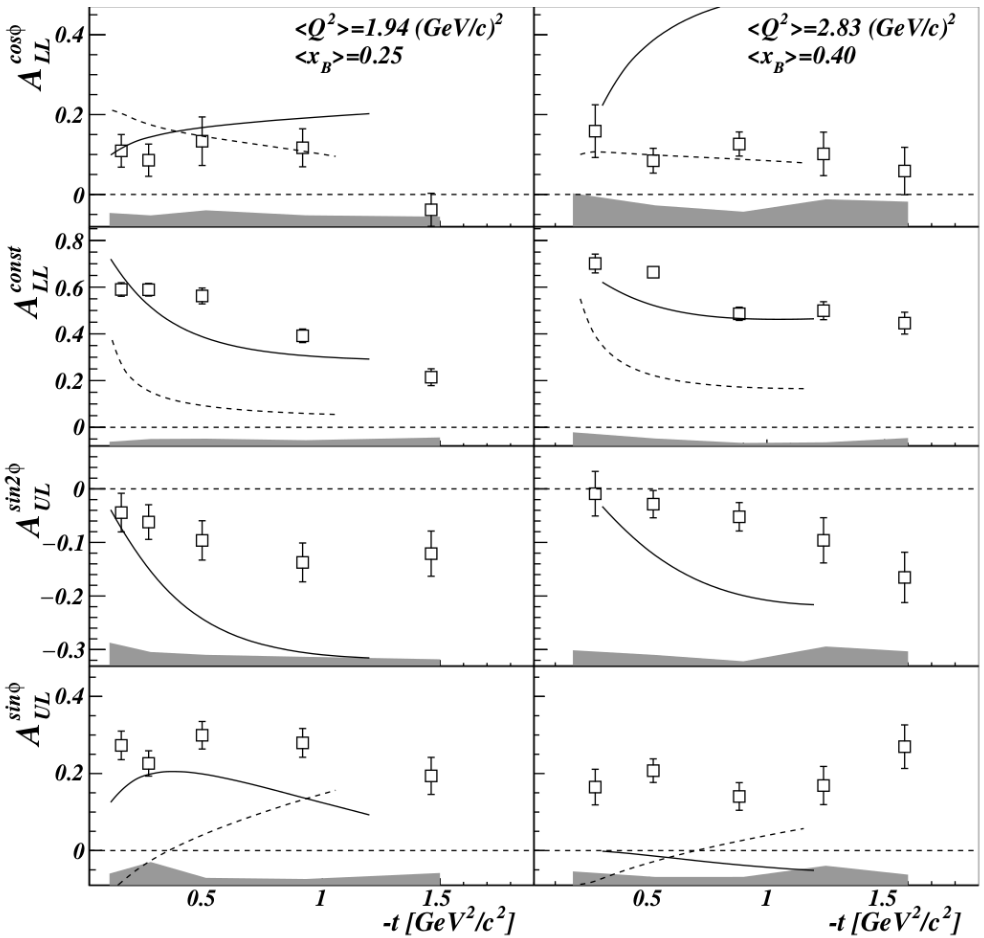
Fair agreement of these GPD models with data

6 GeV measurements

Highlights: $e\vec{p} \rightarrow ep\pi^0$ (longitudinally polarized proton)

CLAS

Target Spin Assymetry, Double Spin Asymmetry [Kim *et al.*: Phys.Lett. **B768** (2017) 168-173]



Curves: *calculations with chiral-odd GPDs =>* **mainly contribute to σ_T**

dashed: [S. Goloskokov and P. Kroll, Eur. Phys. J. **A 47**, (2011) 112]

solid: [Goldstein, Gonzalez-Hernandez, Liuti, Phys. Rev. **D84**, 034007 (2011)]

Overall agreement between GGL and data except for $A_{LL}^{\cos\phi}$.

More details in Andrey Kim's talk
(17:30 today, this session)

6 GeV measurements
Highlights / open questions: DVCS on ^{4}He

Coherent ^{4}He-DVCS

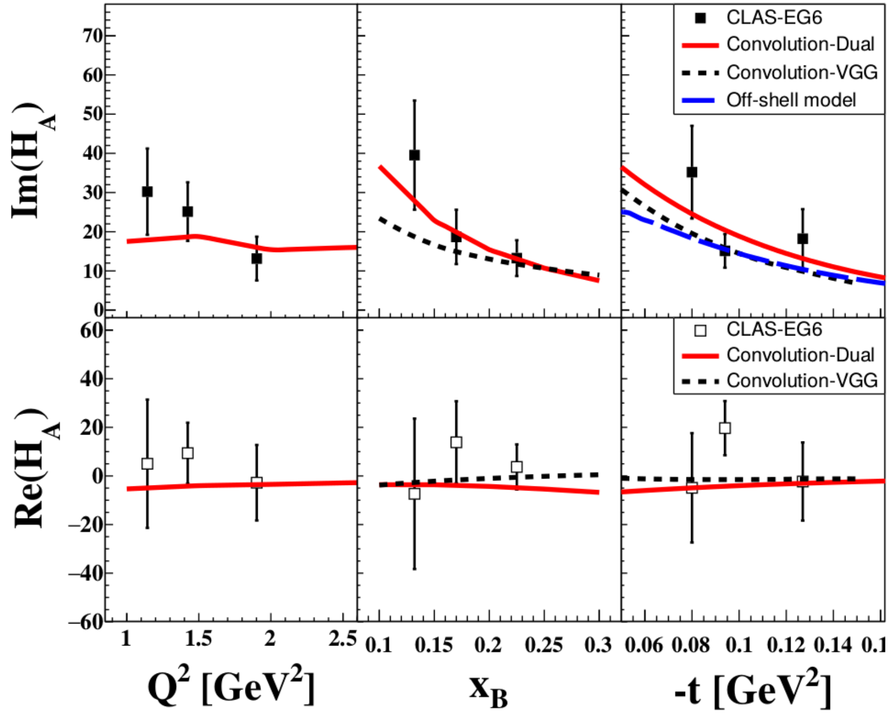
^{4}He: spin 0 => One GPD (H_A) to describe the system

=> *CFF extracted from BSA* (w/o model-dep assumptions)

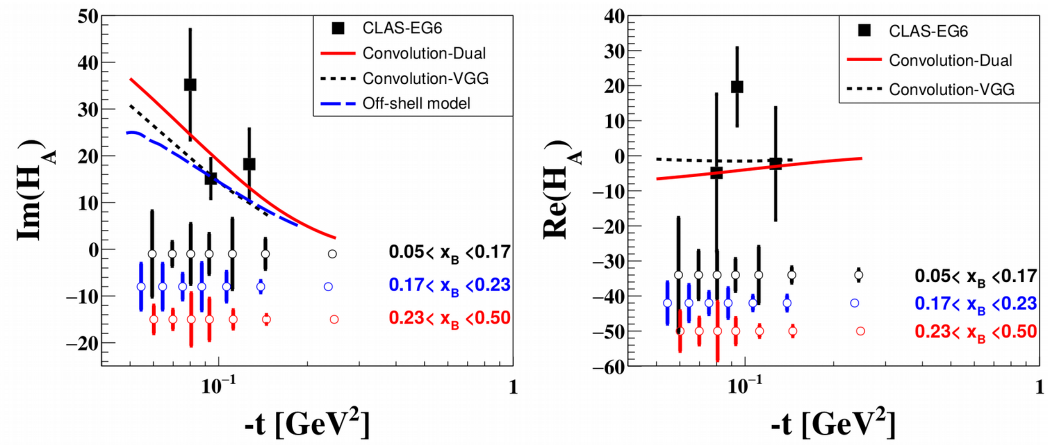
$$A_{LU}(\phi)=\frac{\alpha_0(\phi)\,\Im m(\mathcal{H})_A}{\alpha_1(\phi)+\alpha_2(\phi)\,\Re e(\mathcal{H})_A+\alpha_3(\phi)\left(\Re e(\mathcal{H})_A^2+\Im m(\mathcal{H})_A^2\right)}$$

valid at LO, LT

[Hattaway *et al.*, Phys. Rev. Lett. **119** (2017) no.20, 202004]



Coherent ^{4}He-DVCS 12 GeV projection with ALERT

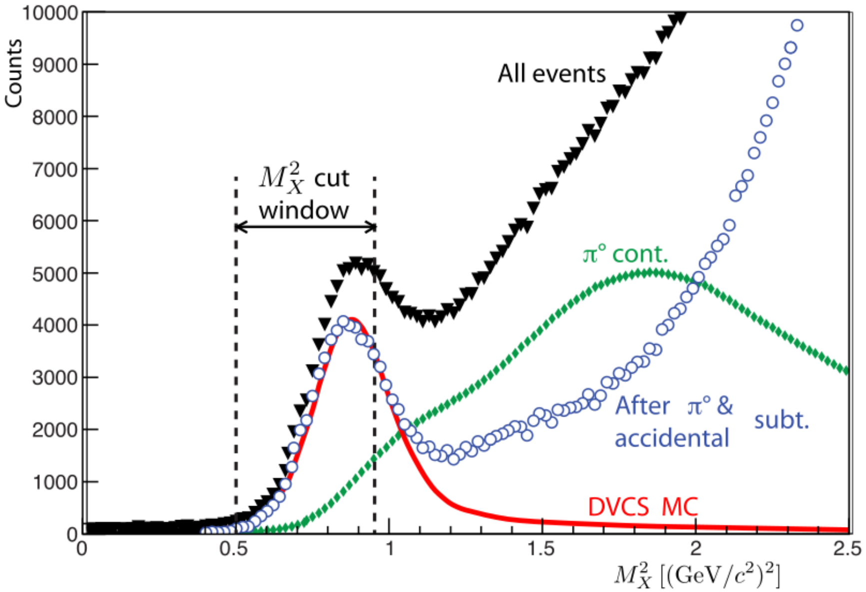


DVCS/π^0 measurements at 6 GeV: Hall A setup

Hall A: **valence** region
High Resolution Spectrometer+Calorimeter
Polarized e^- beam (≤ 6 GeV), fixed target:
Hydrogen, deuterium

- **High luminosity**: ($\mathcal{L}$ ~10^{37} cm^{-2} s^{-1})
- **High resolution equipements**

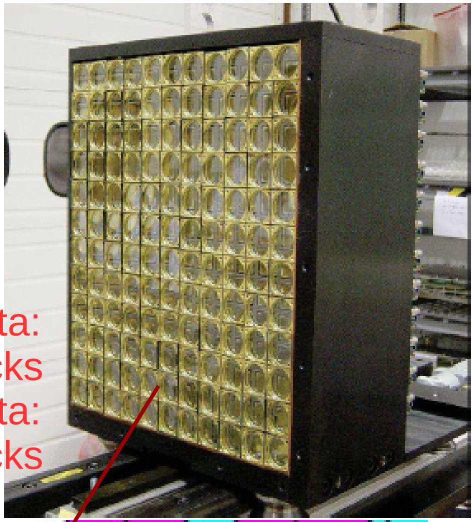
=> **High precision measurements**

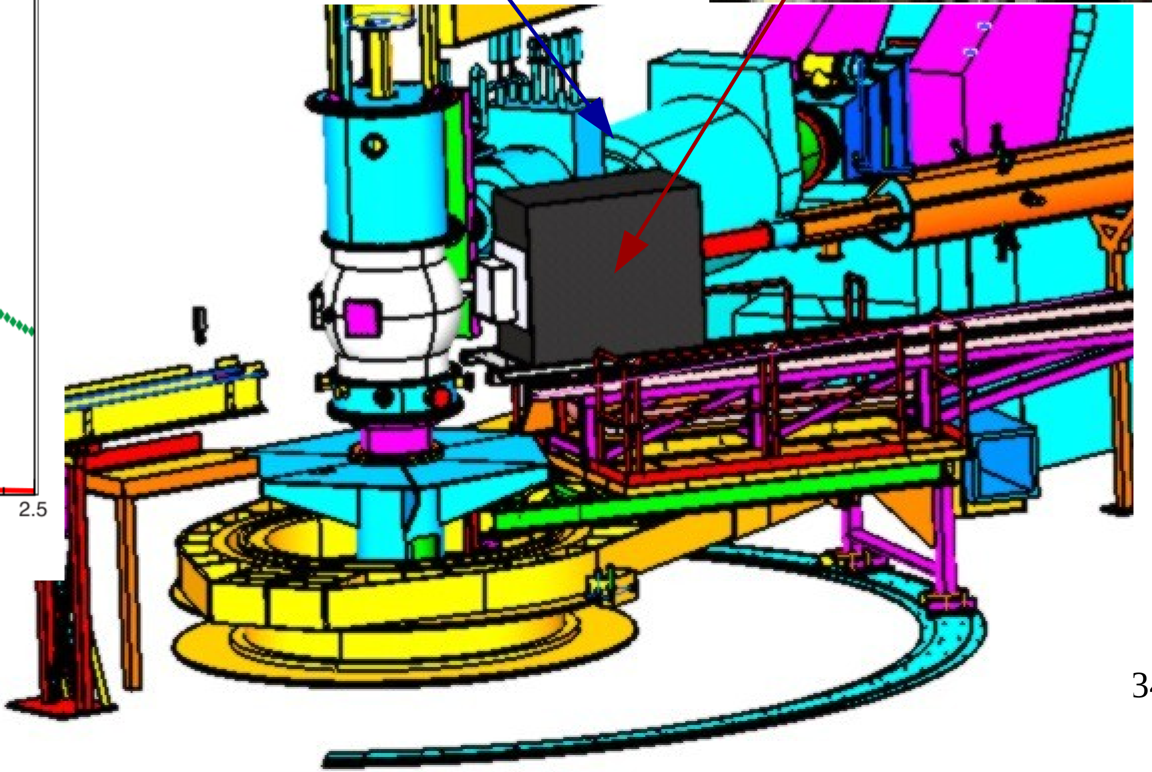


PbF$_2$ EM cal

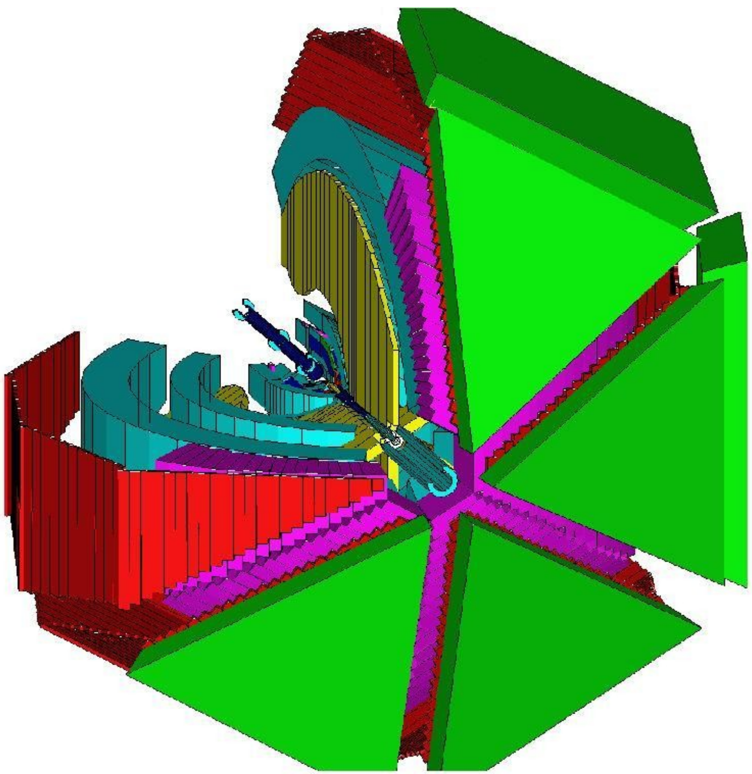
2004 data: 132 blocks
2010 data: 208 blocks

HRS





DVCS/π^0 measurements at 6 GeV: Hall B setup

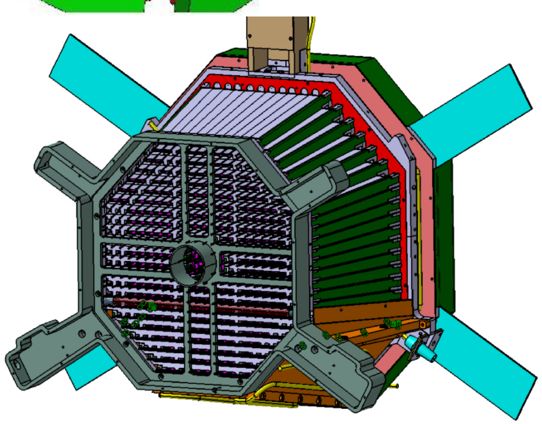


CLAS : valence region (**x_{Bj}>0.1**)

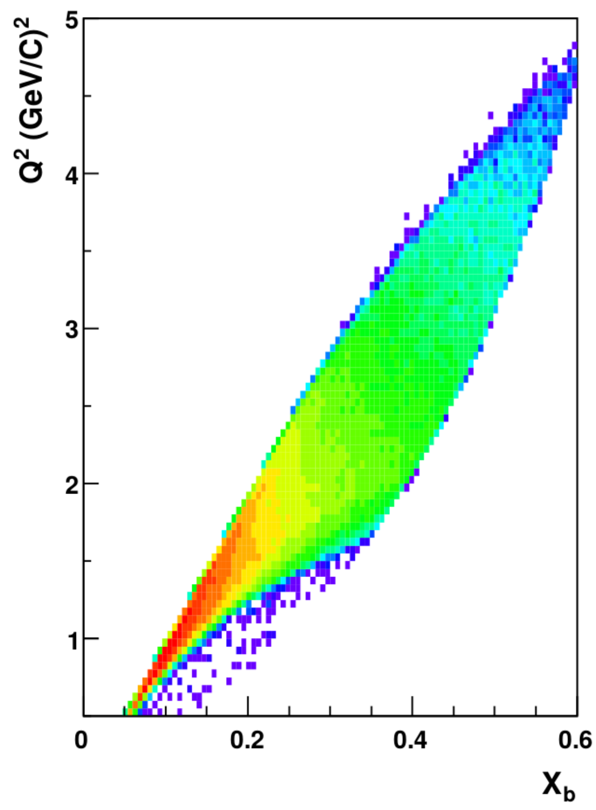
Large acceptance spectrometer

Polarized e^- beam (≤ 6 GeV), fixed target: hydrogen, L polarized proton

- **Kinematic coverage;**
- **multiple exclusive channels ($\pi,\rho,\omega,\ldots$)**



+ Inner Cal for DVCS



2 runs during 6 GeV era: e1-dvcs (proton); eg1-dvcs (L polarized proton)

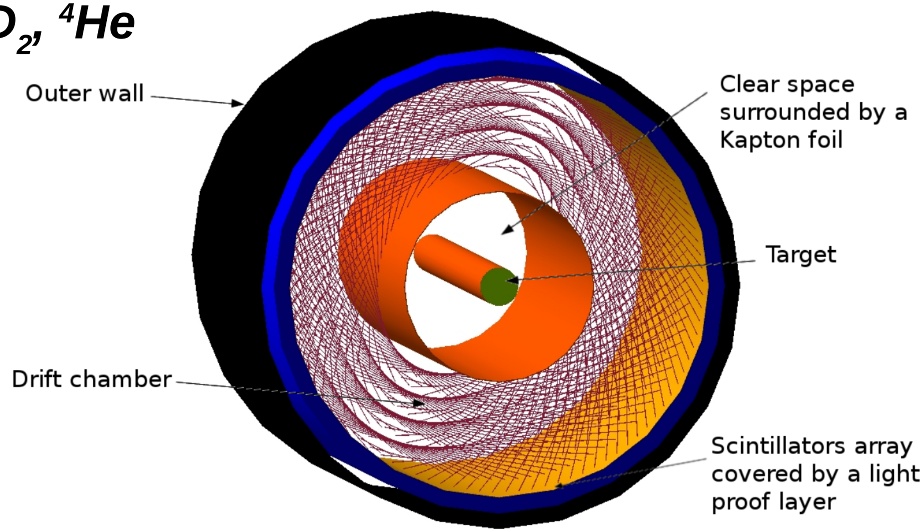
The ALERT detector
(just in case)

Applications:

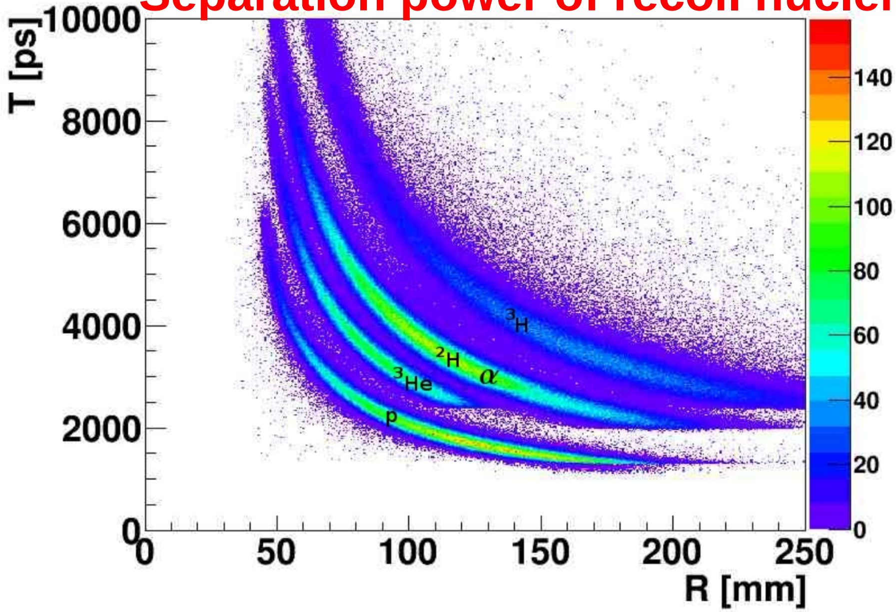
*** Tagged EMC (DIS) measurements,**

*** Tagged coherent/incoherent DVCS**

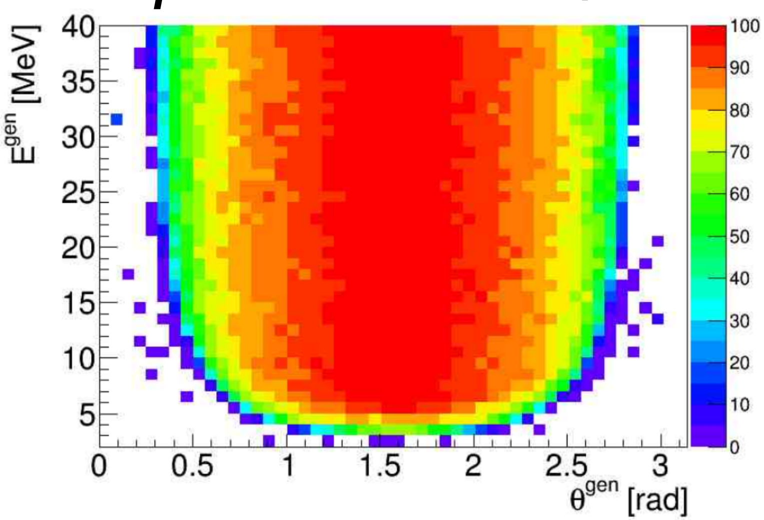
=> *off D_2, ^4He*



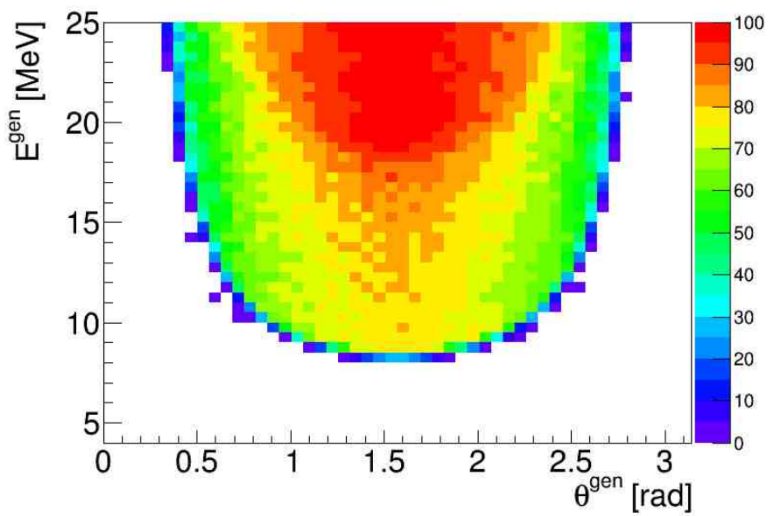
Separation power of recoil nuclei



***p*: det. thr.: 75 MeV/c**



^{4}He: det. thr.: 244 MeV/c

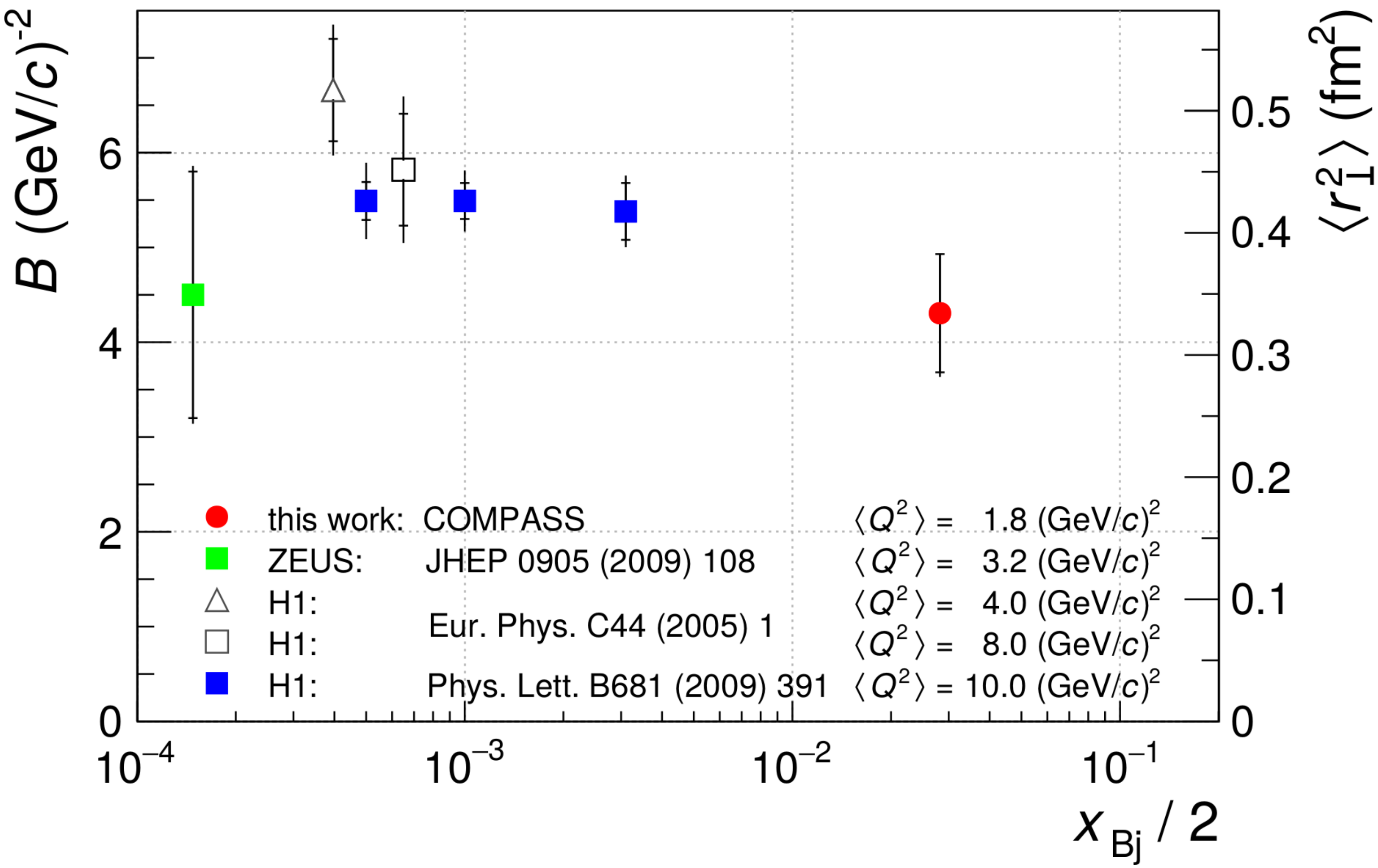


COMPASS (+HERA) proton tomography
(just in case...)

Spin and **charge** cross section **Sum**: **Proton size**

$$S_{CS,U} \equiv d\sigma(\overrightarrow{\mu}^{+}) + d\sigma(\overleftarrow{\mu}^{-}) \rightarrow d\sigma^{DVCS}/dt \sim \exp(-B|t|)$$

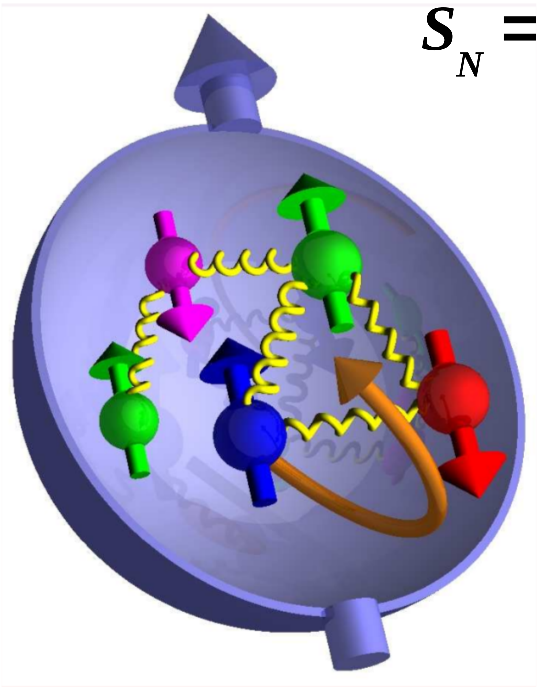
[R. Akhunzyanov *et al.*,arXiv:1802.02739 [hep-ex]]



$$b(x_{Bj}) = ½ \langle r_\perp^2 \rangle$$

Nucleon structure and QCD
Nucleon Spin Puzzle

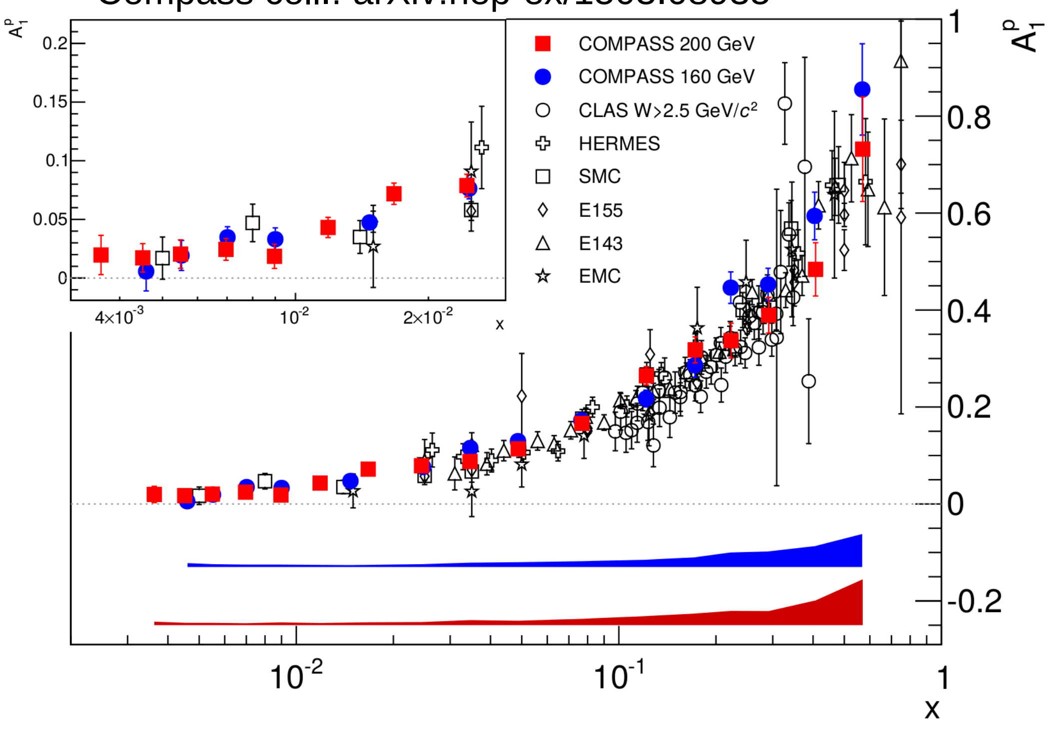
$$S_N = \tfrac{1}{2} = \tfrac{1}{2}\,\Delta\Sigma + \Delta G + L_q + L_g$$



Static quark model:
$\Delta\Sigma = 1$...

Experiments:
=> $\Delta\Sigma \sim 0.3$

Compass coll.: arXiv:hep-ex/1503.08935



ΔG ? (phenix, compass)

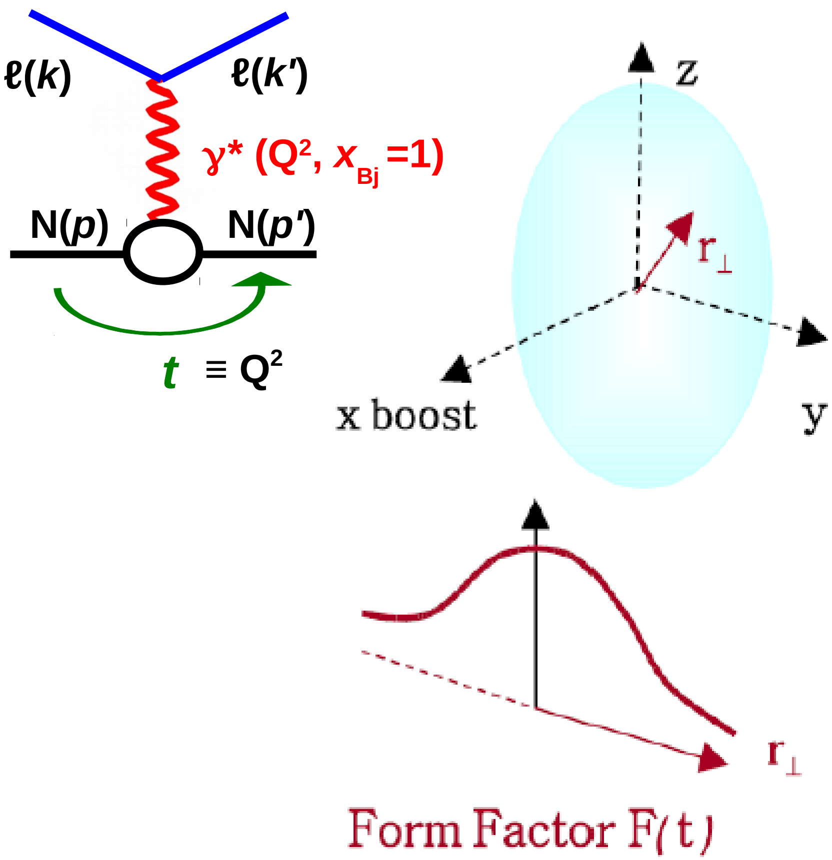
$\Delta g/g$=0.113±0.038(stat.)±0.036(syst.)
[Compass coll.: arXiv:hep-ex/1512.05053]

Nucleon spin is more than the sum of its constituents!

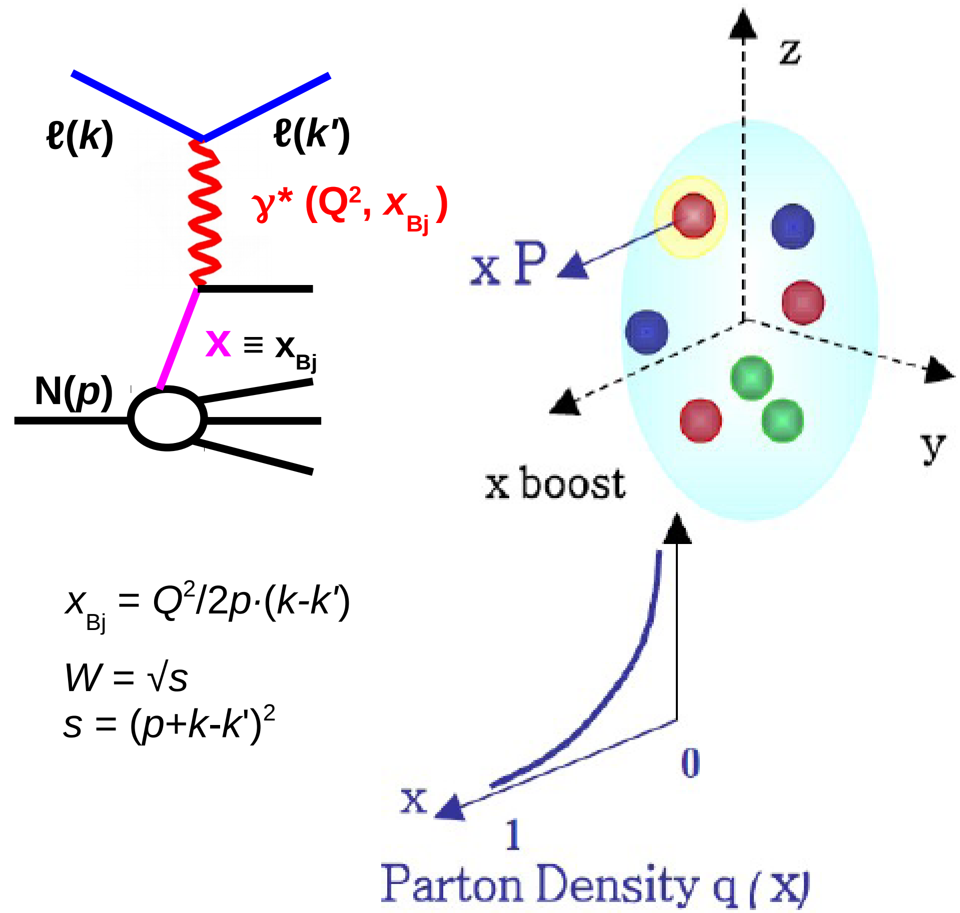
Orbital Angular Momentum $L_{q,g}$ => *missing piece of spin puzzle*
=> needs "3D" parameterization

Nucleon Structure : what we "know"

Form Factors



Parton Distribution Functions



$x_{Bj} = Q^2/2p\cdot(k\text{-}k')$

$W = \sqrt{s}$
$s = (p+k\text{-}k')^2$

"Polarized" PDFs: (spin structure functions):
polarization of quarks;
Obtained with *polarized* ℓ, *N*

Generalized Parton Distributions (GPDs) :
'3D' Structure of nucleon

In practice: GPDs encapsulated in Compton Form Factors (CFFs)

Factorization scale

$$\underbrace{\mathcal{F}(\xi, t, Q^2)}_{\text{CFF}} = \int_{-1}^{+1} dx\, \underbrace{C\left(x, \xi, \alpha_S(\mu_R), \frac{Q}{\mu_F}\right)}_{\text{Integration kernel}} \underbrace{F(x, \xi, t, \mu_F)}_{\text{GPD}}$$

CFF
(complex quantity)

Integration kernel
(calculated up to NLO)

GPD

Sometimes *effective* CFFs: combinations of CFFs with same kinematic dependence