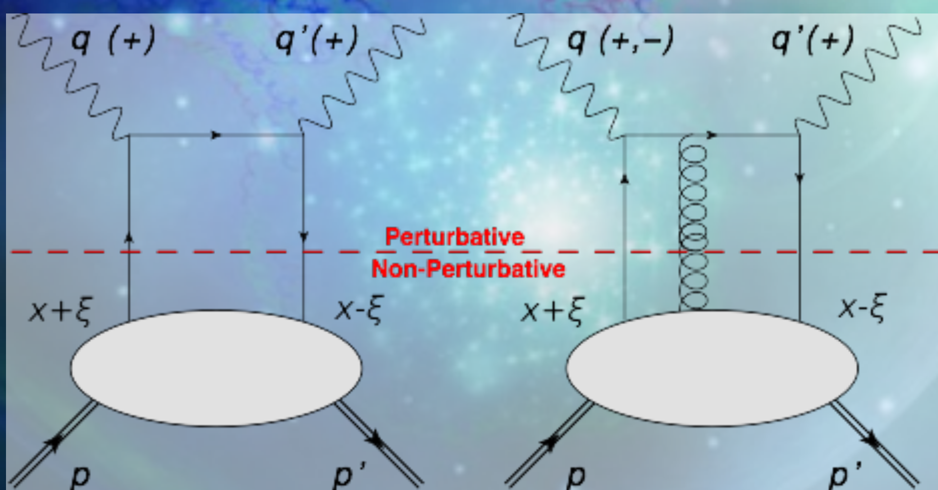
DVCS Factorization

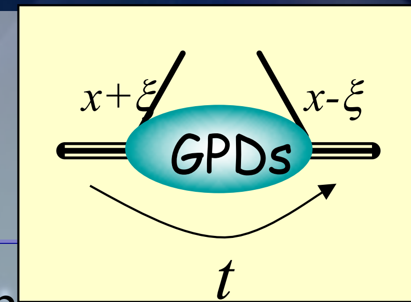
- Works great for $Q^2 \geq 20$ GeV^2! (HERA)
  - COMPASS (muons), HERMES(fixed target at HERA), Jlab $Q^2 < 10$ GeV^2
  - Even if vector meson content of photon is suppressed, what about higher order perturbative QCD effects.
    - Enter Amplitude with powers $[\Lambda^2/Q^2]^{n/2}$
    - Coefficients not known *a priori.* Can be large from Chiral symmetry breaking effects.

Higher Order *qqg* Correlations, as corrections to DVCS

- GPD ~ $1/Q^2$
    - *qqg* Correlation ~ $1/[Q^2]^{3/2}$
        - *qqqq* “Cat’s Ears” ~$1/Q^4$



GPDs: Correlations of Spatial, Momentum, and Spin coords.



$$\text{Vector}: H_f(x,\xi,t), E_f(x,\xi,t) \Leftarrow \int e^{iP^+z^-} dz^- \langle P+\Delta/2 | \overline{\Psi}(+z^-)\gamma^+\Psi(-z^-) | P-\Delta/2 \rangle$$

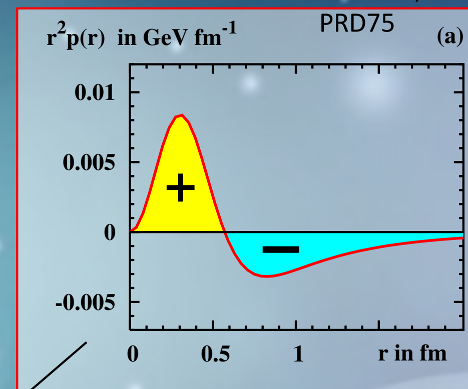
$$\text{Axial}: \tilde{H}_f(x,\xi,t), \tilde{E}_f(x,\xi,t) \Leftarrow \int e^{iP^+z^-} dz^- \langle P+\Delta/2 | \overline{\Psi}(+z^-)\gamma^+\gamma_5\Psi(-z^-) | P-\Delta/2 \rangle$$

Forward limits:
DIS

$$H_f(x,0,0) = q_f(x)$$

$$\tilde{H}_f(x,0,0) = \Delta q_f(x)$$

K.Goeke, et al
PRD75



First Moments:
Elastic FFs

$$\int_{-1}^{1} dx [H, E]_f(x,\xi,\Delta^2) = [F_1, F_2]_f(-\Delta^2)$$

Second Moments:
Energy-Momentum tensor

Pressure

$$\int x dx H_f(x,\xi,t) = +M_{2f}(t) + \frac{4}{5}\xi^2 d_{1f}(t)$$

$$\int x dx E_f(x,\xi,t) = -M_{2f}(t) + \frac{4}{5}\xi^2 d_{1f}(t) + 2J_f(t)$$

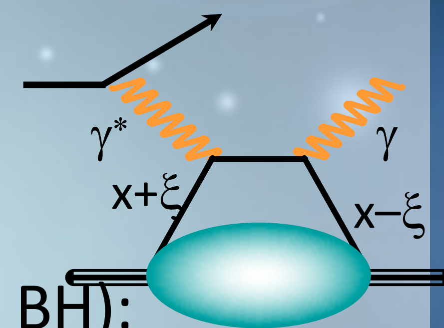
Proton Spin

X. Ji: Origin of Spin

$$\int_{-1}^{1} x dx \left[H_f(x,\xi,0) + E_f(x,\xi,0) \right] = 2J_f$$

What do DVCS experiments measure?

- $d\sigma(ep \rightarrow ep\gamma)$ = twist-2 (GPD) terms + Σ_n [twist-n]/Q^{n-2}
  - Isolate twist-2 terms → cross sections *vs* Q^2 at fixed (x_{Bj}, t); *or*
  - → Multiple beam energies at fixed (Q^2, x_{Bj}, t)
- *GPD* terms are `Compton Form Factors'



$$CFF(\xi,\Delta^2) = \int_{-1}^{1} dx \frac{GPD(x,\xi,\Delta^2;Q^2)}{x \pm \xi \mp i\varepsilon}$$

  - *Re* and *Im* parts (accessible via interference with BH):

$$\Im m\left[CFF(\xi,\Delta^2)\right] = \pi\left[GPD(\xi,\xi,\Delta^2) \pm GPD(-\xi,\xi,\Delta^2)\right]$$

$$\Re e\left[CFF(\xi,\Delta^2)\right] = \wp\int dx \frac{GPD(x,\xi,\Delta^2)}{x \pm \xi}$$

$$\xrightarrow[D.R.]{} \wp\int d\xi' \frac{GPD(\xi',\xi',\Delta^2)}{\xi' \pm \xi} + D(\Delta^2)$$

Physical Interpretation of GPDs:

- ξ=0: Probability densities of impact parameter **b** relative to Center-of-Momentum of proton:

$$H(x,0,\Delta^2) \Leftrightarrow q(x,\vec{b})$$

$$\tilde{H}(x,0,\Delta^2) \Leftrightarrow \Delta q(x,\vec{b})$$

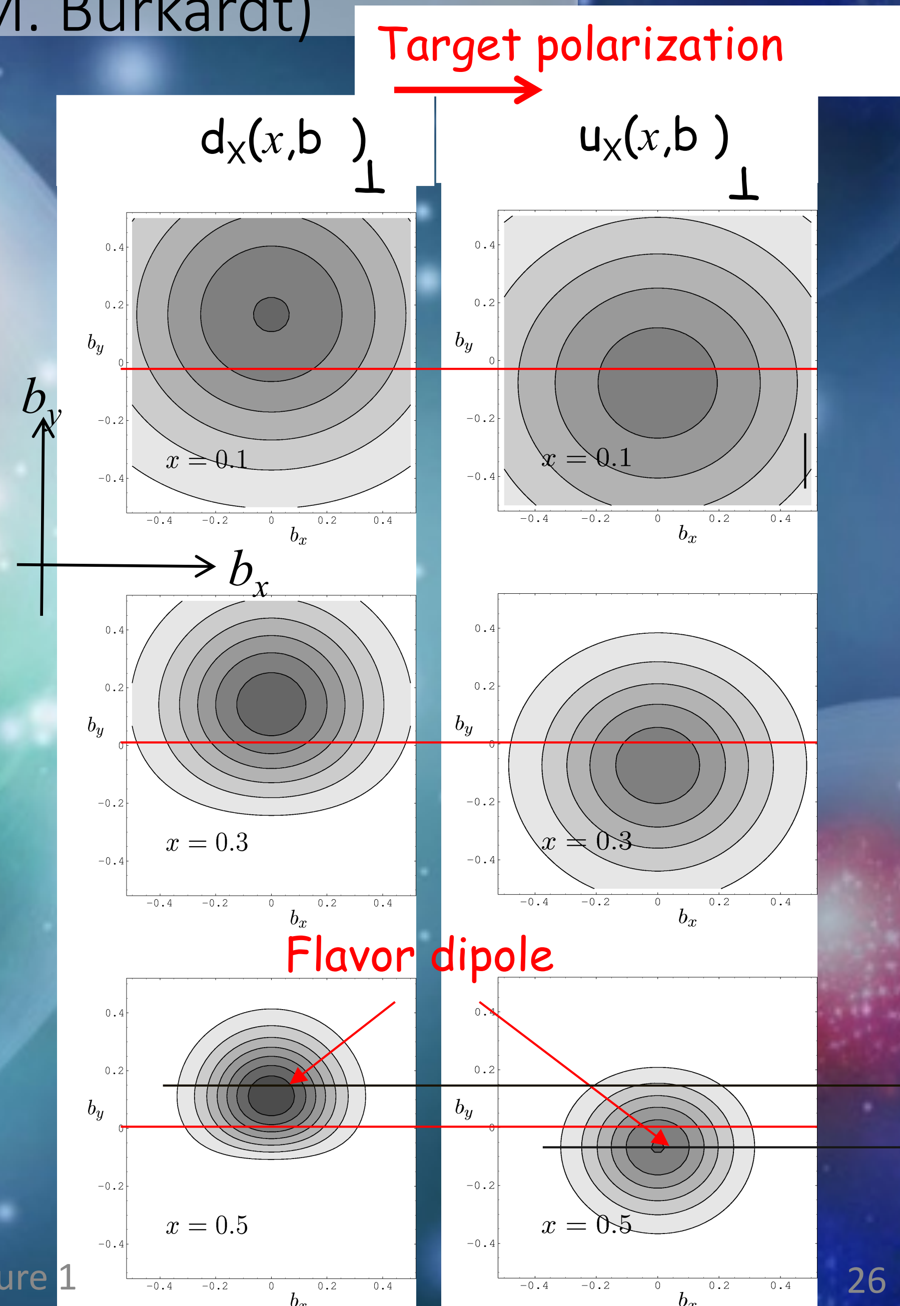
- x=ξ: $H(\xi, \xi,\Delta^2) - H(-\xi,\xi,\Delta^2)$, E, *etc.*
  - 2-d Fourier-transform $\Delta_\perp$ ⟷ **r**
  - Transition amplitude from longitudinal momentum 0 to $2\xi/(1+\xi)$ at fixed impact parameter **r** relative to CM of *spectators*.
    - Not a positive definite density, but still an image.
  - Directly measurable
  - Expect size shrinks as ξ ➔1
  - Different profiles for *u, d, glue,…*

Tomography with Generalized Parton Distributions (M. Burkardt)

- H(x,t)γ^μ + E(x,t)$\sigma^{\mu\nu}\Delta_\nu$
  - Proton size shrinks as x→ 1.
  - Spatial separation of up- and down-quarks in a transversely polarized proton
- Spin-Flavor dependence to Proton size & profile.
  - up and down quarks separate in transversely polarized proton

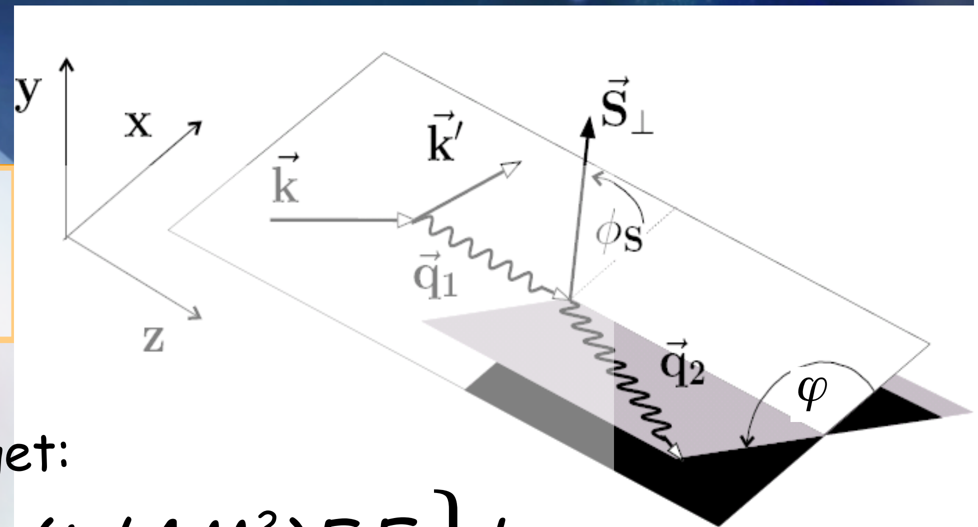
$$\varepsilon_f(x,b_\perp) = \int \frac{d^2\Delta_\perp}{(2\pi)^2} e^{i\Delta_\perp \cdot b_\perp} E_f(x,\Delta_\perp)$$

$$q_X(x,b_\perp) = h_q(x,b_\perp) + \frac{1}{2M}\frac{\partial}{\partial y}\varepsilon_q(x,b_\perp)$$



Exploiting the harmonic structure of DVCS with polarization

The difference of cross-sections is a key observable to extract GPDs



With polarized beam and unpolarized target:

$$\Delta\sigma_{LU} \sim \sin\varphi \left\{ F_1 H + \xi (F_1 + F_2) \tilde{H} + (t/4M^2) F_2 E \right\} d\varphi$$

With unpolarized beam and Long. polarized target:

$$\Delta\sigma_{UL} \sim \sin\varphi \left\{ F_1 \tilde{H} + \xi (F_1 + F_2) H + (t/4M^2) F_2 E \right\} d\varphi$$

With unpolarized beam and Transversely polarized target:

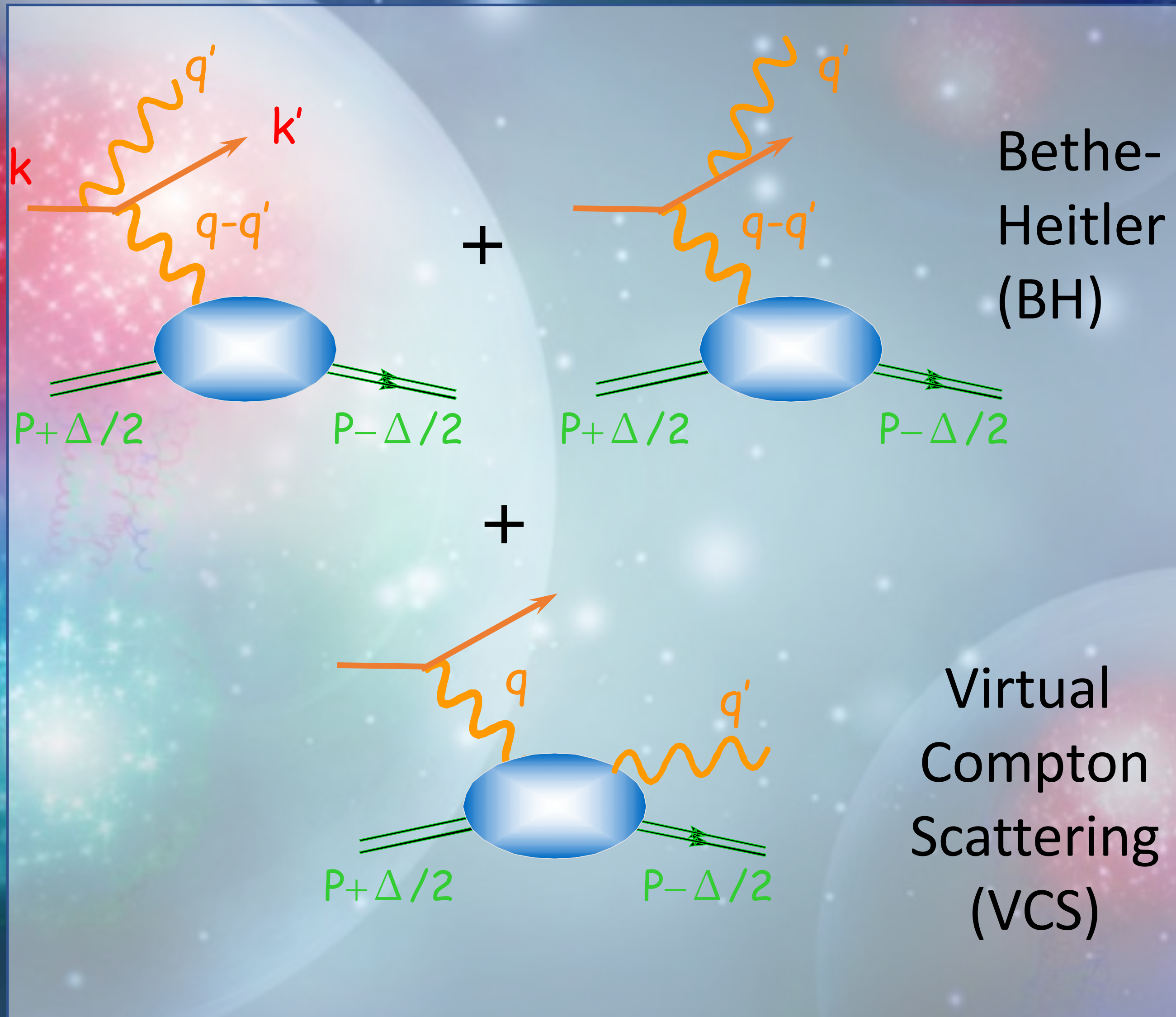
$$\Delta\sigma_{UT} \sim \cos\varphi \sin(\phi_S - \varphi) \left\{ (t/4M^2) F_2 H - (t/4M^2) F_1 E + \ldots \right\} d\varphi$$

Separations of CFFs $H(\pm\xi,\xi,t)$, $\tilde{H}(\pm\xi,\xi,t)$, $E(\pm\xi,\xi,t)$,…

Measuring GPDs

$e\,p \rightarrow e\,p\,\gamma$

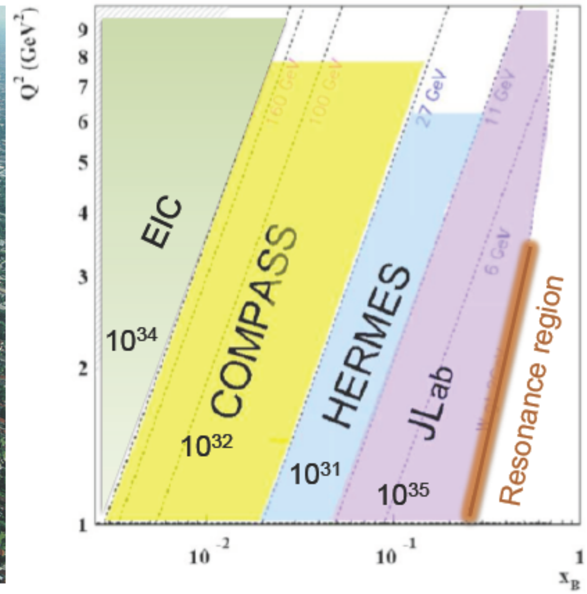
- HERA (2001 – 2007)
- HERMES (2001 – 2007)
- JLab 6 GeV (2001 – 2012)
- JLab 12 GeV (2014 –
- COMPASS (2016 –
- EIC (2025+?



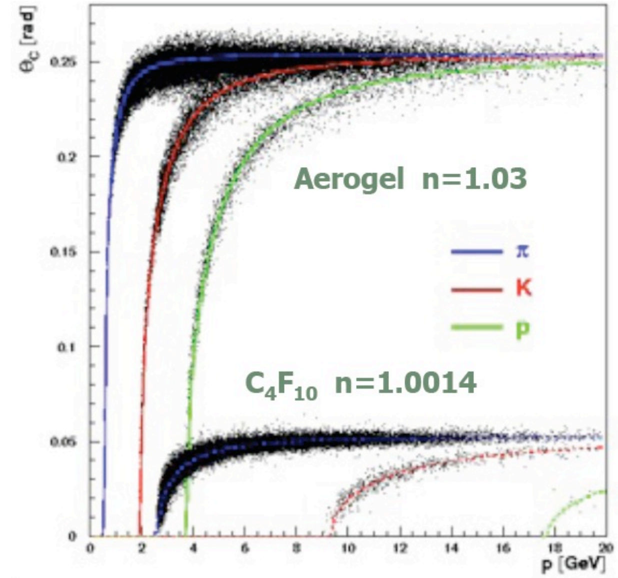
HERMES overview

27.6 GeV e+/e- HERA beam

Access to valence and sea



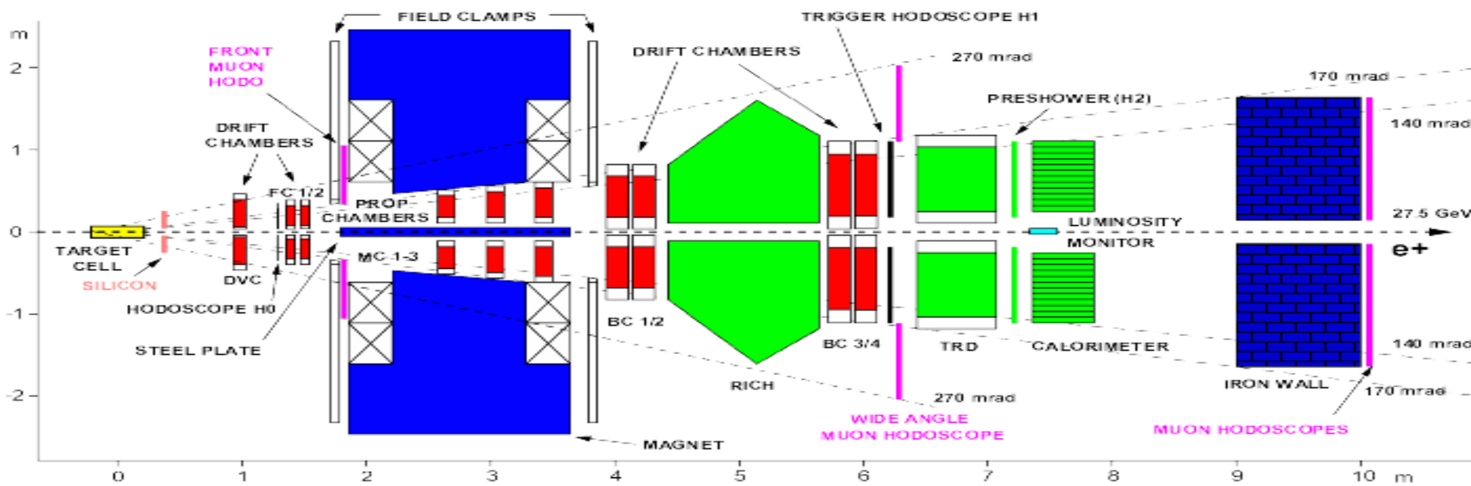
Electron and Hadron ID



Data taking: 95-07

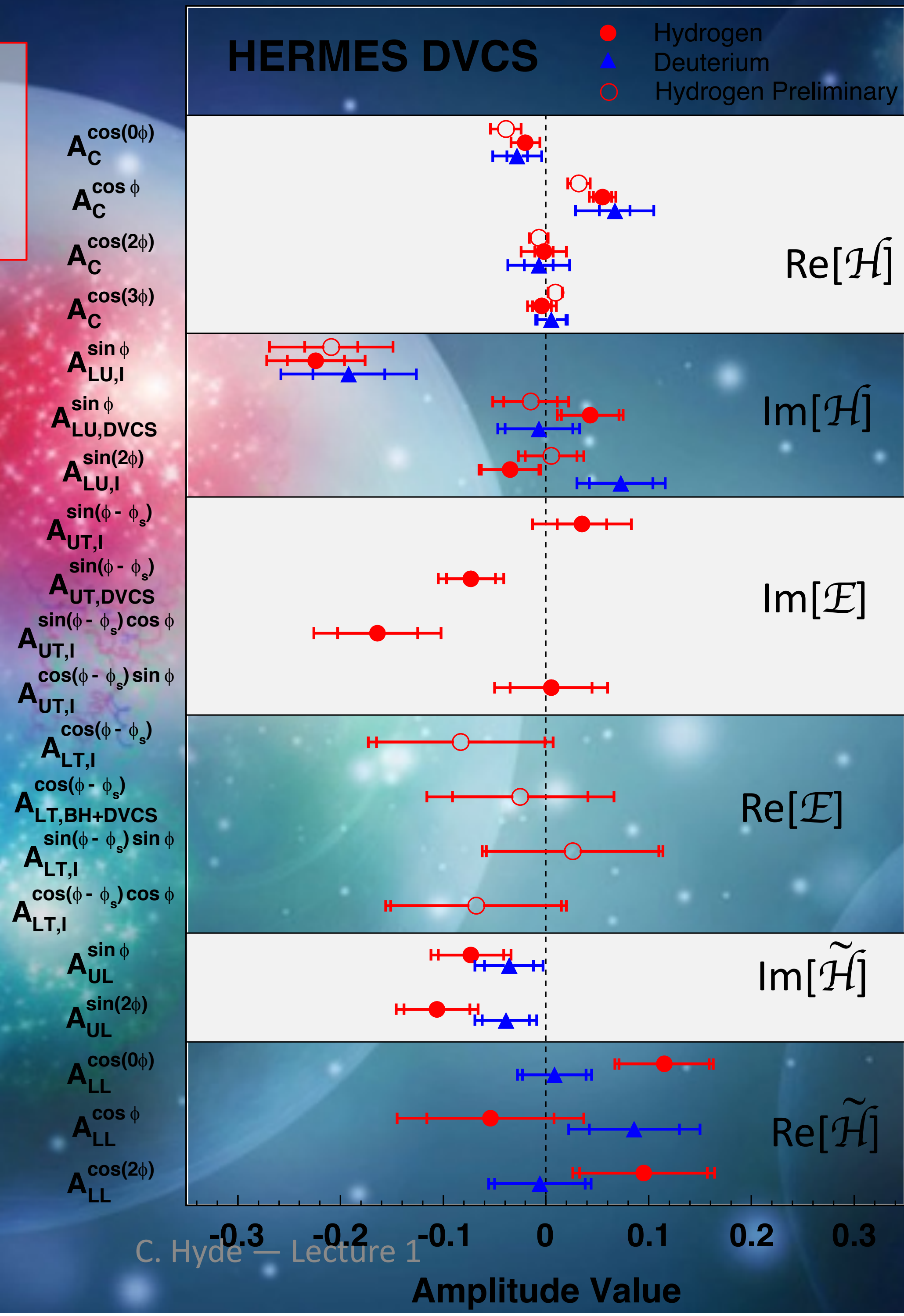
Internal gaseous target
(no nuclear effects)

96-00 (H/D) Lpol + Upol
02-05 (H) Tpol + Upol
06-07 (H/D) Upol+Recoil



HERMES summary

- averaged over Q^2 and t
- Transversely polarized H$^-$ target → sensitivity to $E(\xi,\xi,\Delta^2)$, $\xi \approx 0.1$



DVCS Asymmetries

e^+e^-

Beam Spin Asymmetry

Transverse target Single Spin

Beam & Transverse Target Double Spin

Longitudinal Target

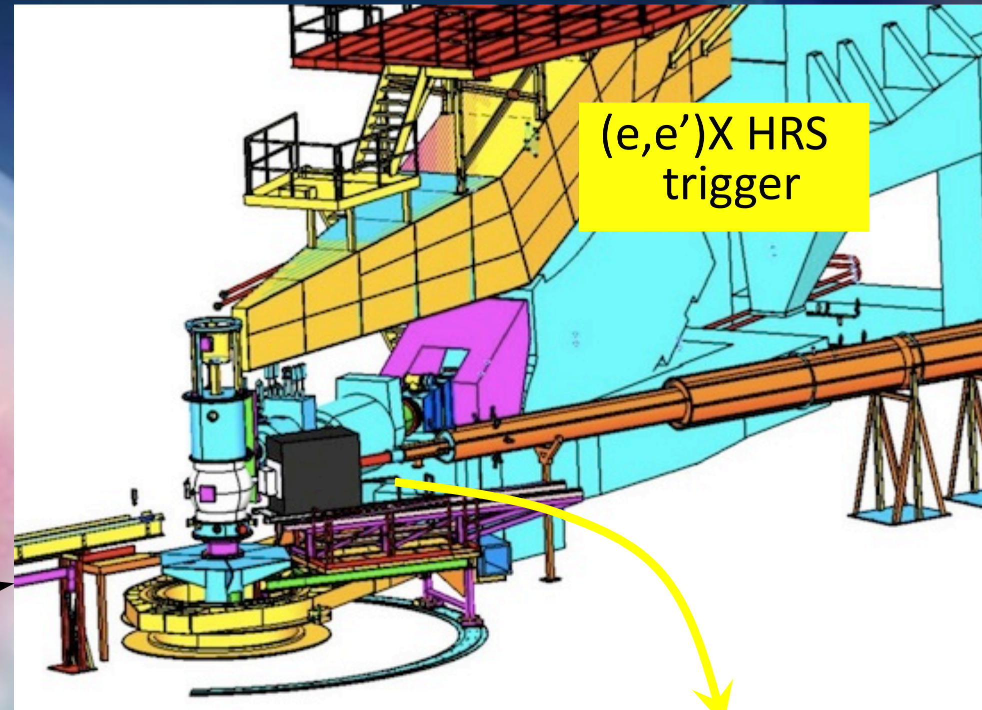
DVCS: JLab Hall A

2004, 2010, 2014-2016

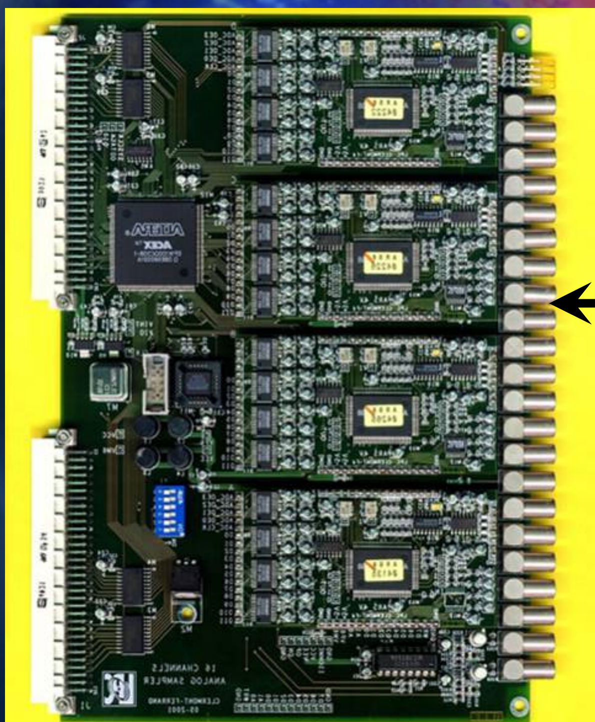
$L \geq 10^{37}$ cm^2/s

Precision cross sections

- Test factorization
- Calibrate Asymmetries



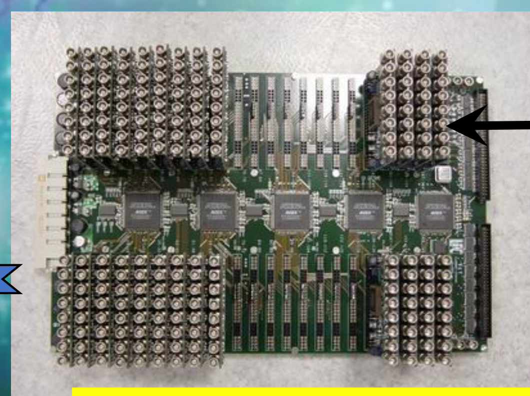
$\vec{e}^-$



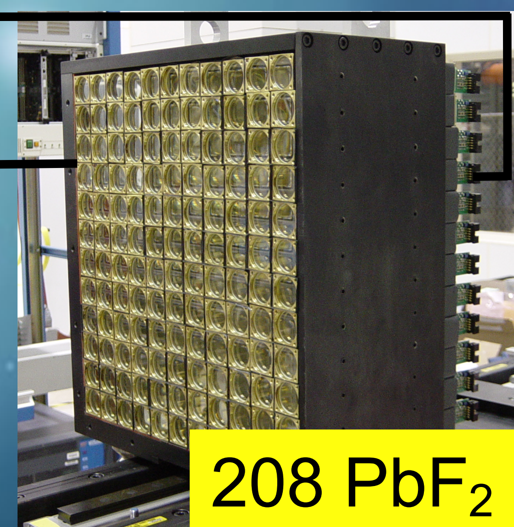
16chan VME6U: ARS

128

samples@1GHz



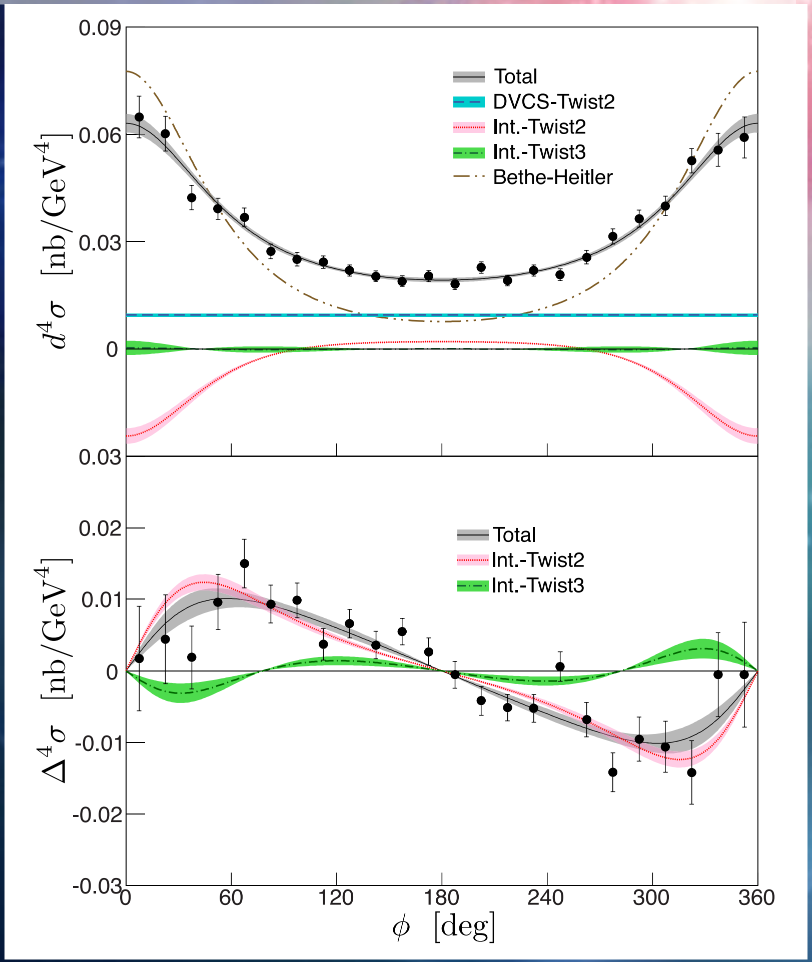
Digital Trigger Validation



208 PbF_2

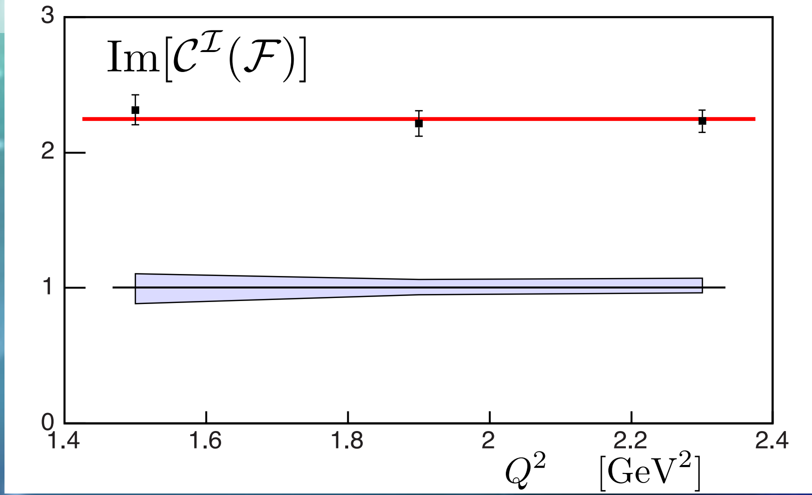
Hall A Results: Scaling Tests

- *Q^2=2.3 GeV^2, x_{Bj}=0.36, t=–0.23 GeV^2*



PRL**97**:262002 (2006)
C. Muñoz Camacho, et al.,
PRC **92**, 055202 (2015)
M.Defurne, *et al.*,

- Empirical extraction
  - Leading-twist (GPD);
  - Higher-twist terms
- Test Q^2-independence of GPD terms

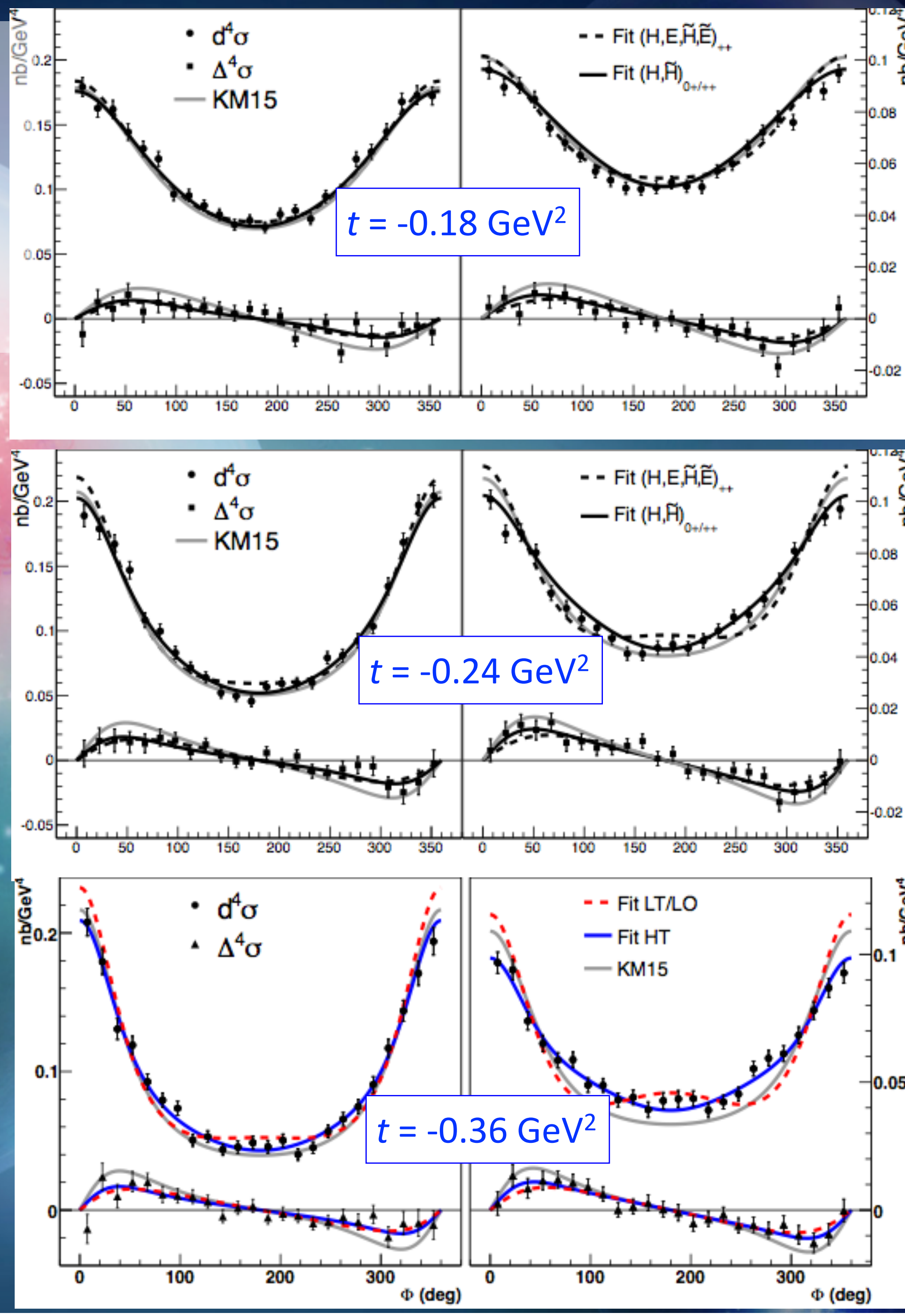


Hall A: H(e,e'γ)

x_B = 0.36, Q^2=1.5, 1.75, 2.0 GeV^2

M.Defurne *et al.*, *"A Glimpse of Gluons"*, Nat. Comm.**8** (2017)

- Q^2 = 1.75
  - E_e = 4.455 (left), 5.55 (right) GeV
- $d^4\sigma/[dQ^2 dx_B dt d\phi_{\gamma\gamma}]$
  $\Delta^4\sigma = d^4\sigma(h=+) - d^4\sigma(-)$
- Solid Grey Line = KM2015
- Dashed: Leading Twist / Leading Order (LT/LO) fit with V. Braun Kinematic Twist-4 (t/Q^2) constrained by LO/LT:
  - Global fit at each $-t$: *3⊗Q^2 & 2⊗E_e*
  - Poor χ^2

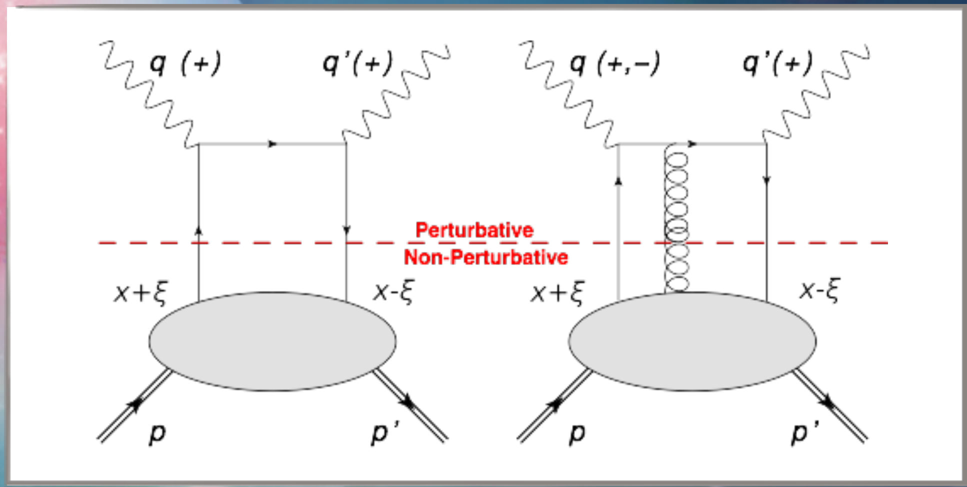


Two Fit-Scenarios

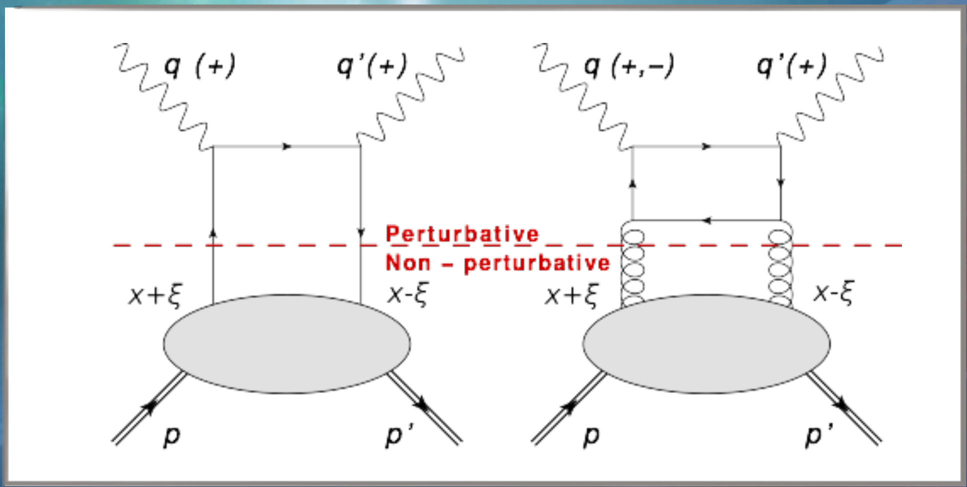
[Using V. Braun et al, PRD **89**, 074022 (2014)]

$\mathbb{H}(x,\xi,t), \quad \widetilde{\mathbb{H}}(x,\xi,t)$

- LO/LT + Twist-3 + Kinematic Twist-4

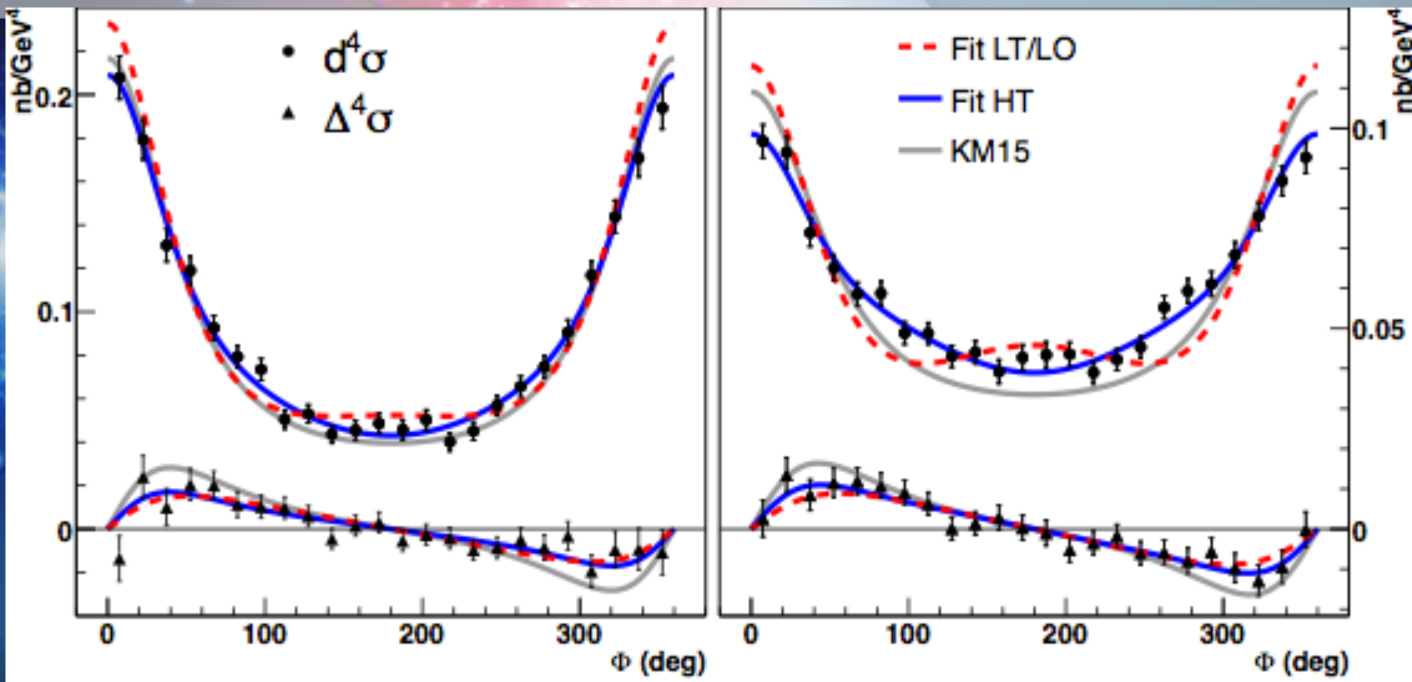


- LO+ NLO (gluon transversity) + Kinematic Twist-4



`Global' Fit:
Q^2=1.5, 1.75, 2.0 GeV^2 & E_e = 4.45, 5.55 GeV

Displayed at Q^2 = 1.75 for $-t$ = 0.030 GeV^2

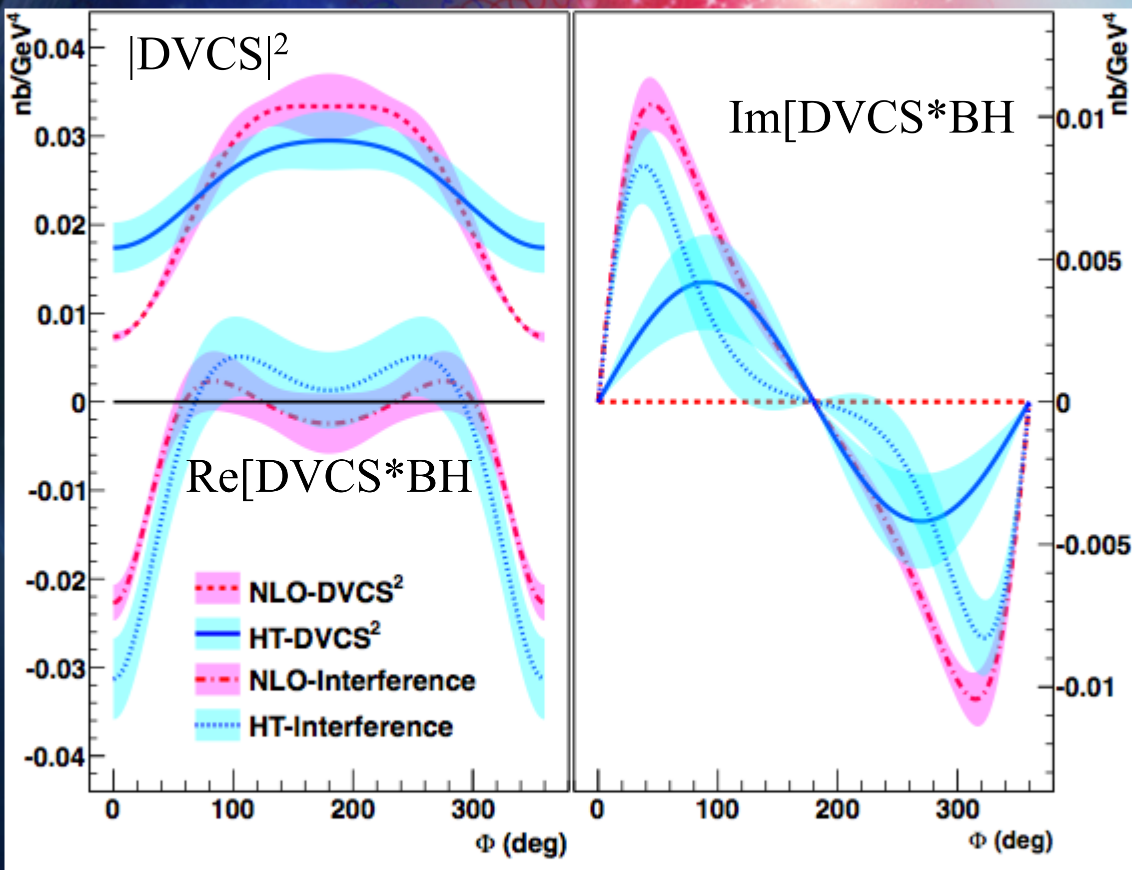


Identical fit (blue⬆) for either: Twist-3 or NLO (gluon) scenarios.
Both fits have Kinematic Twist-4 contribution constrained from Twist-2 component of fit

E07-007 `Global' Fit

Separations of Re,Im[DVCS†BH], |DVCS|^2

$-t$ = 0.030 GeV^2 (of three t-bins): Displayed at Q^2 = 1.75



Total Fit (previous slide blue)

⇐ Sum of Pink (LO+NLO)

OR

⇐ Sum of Cyan (LO+HT)

Model dependence, but full measurement of interference: amplitude & phase

36

DVCS in CLAS @ 6 GeV

- H(e,e'γp)
- Longitudinally polarized NH_3 target.
- Add:

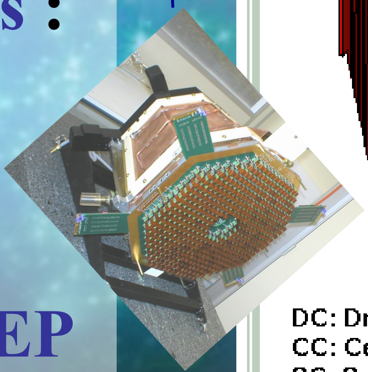
5 Tesla Solenoid

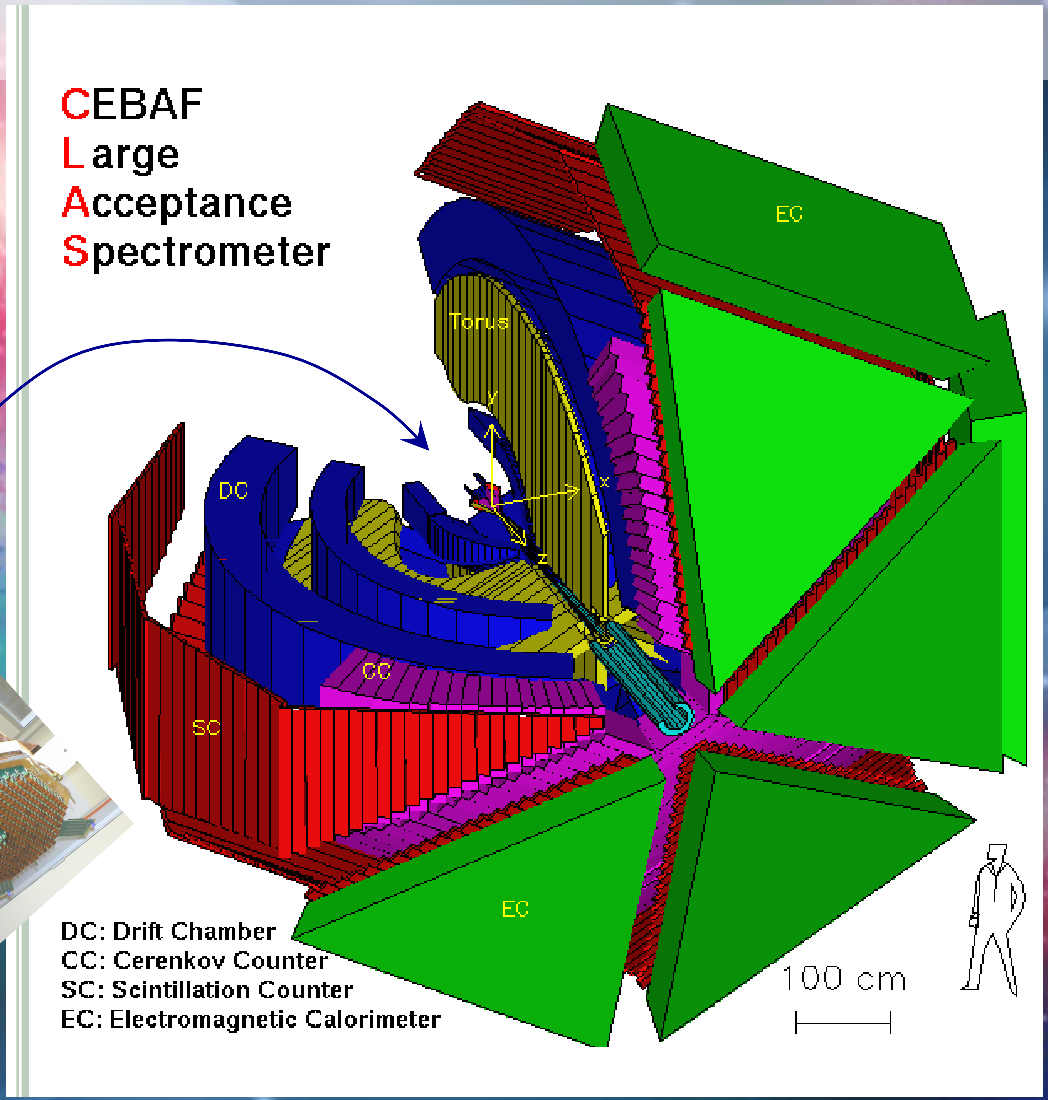
420 $PbWO_4$ crystals :

~10x10x160 mm^3

APD+preamp readout

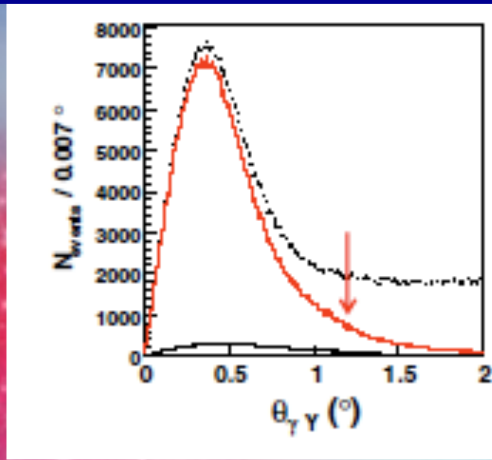
Orsay / Saclay / ITEP / Jlab



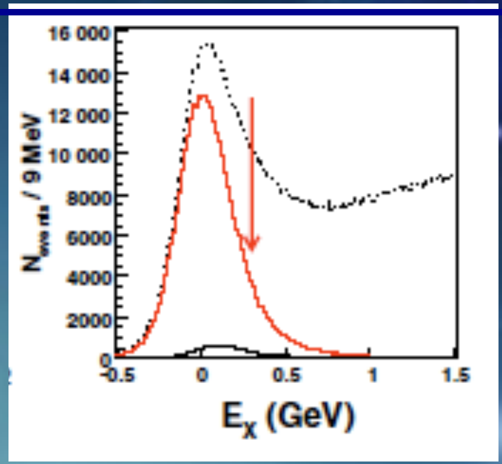


CLAS 6 GeV: Exclusivity and Kinematics

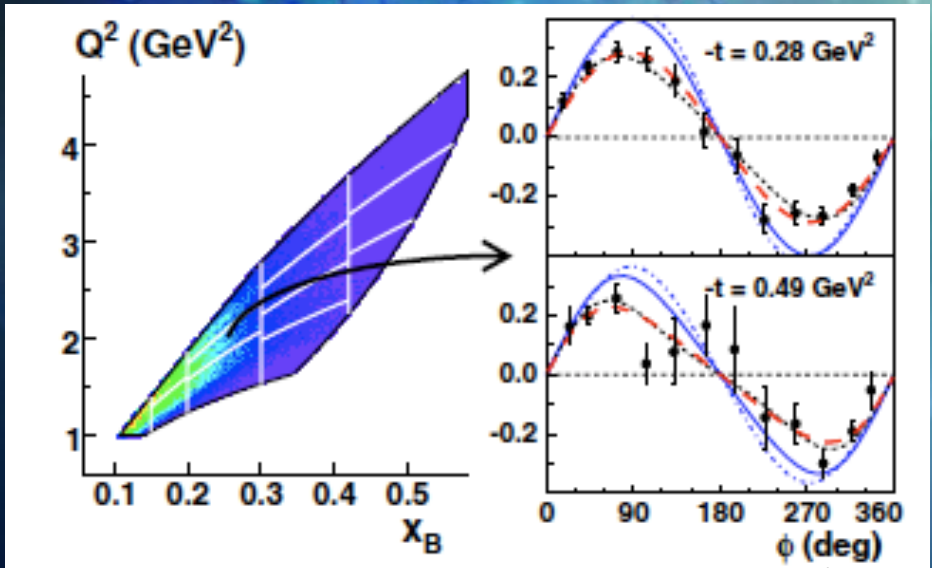
- H*(e,e'γp')x*
- Overcomplete triple coincidence



Co-linearity of γ with *q-p'*



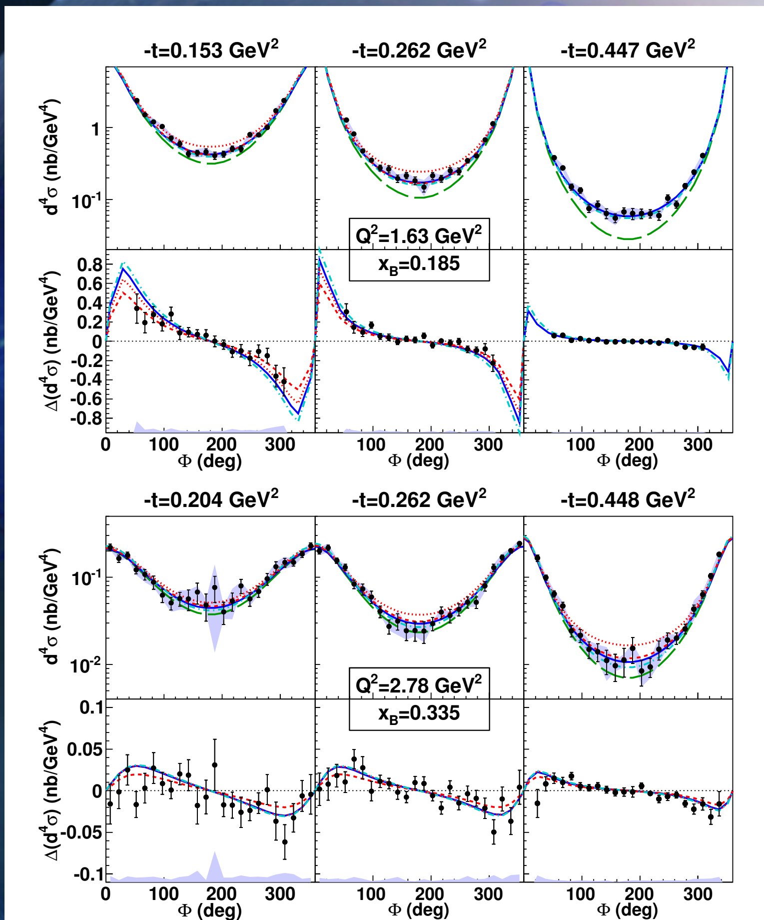
Missing Energy E_x



- Example angular distribution of Beam Spin Asymmetry
  - •One (Q^2,x_B) bin
  - •Two *t*-bins.

CLAS DVCS (unpolarized Target)

K.S. Jo, F.-X Girod, *et al.*, Phys.Rev.Lett. 115 (2015) 21, 212003



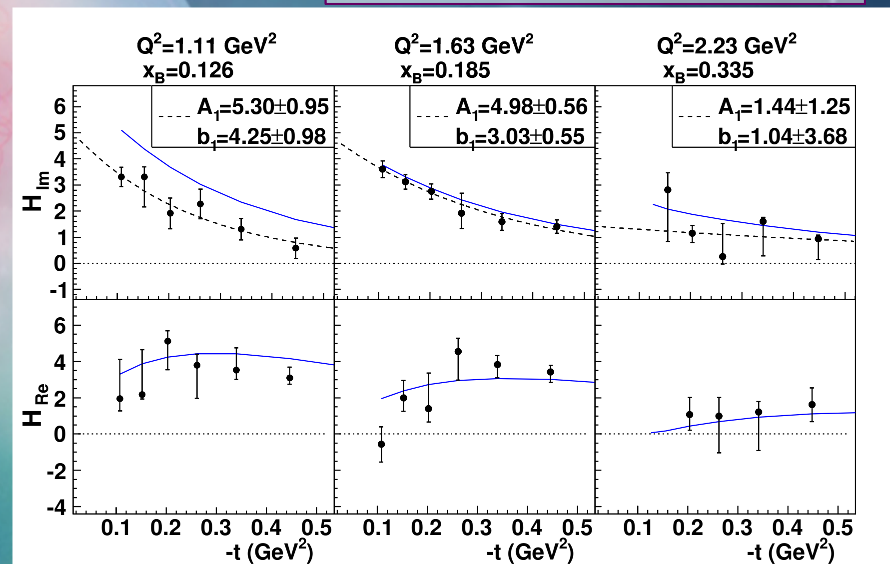
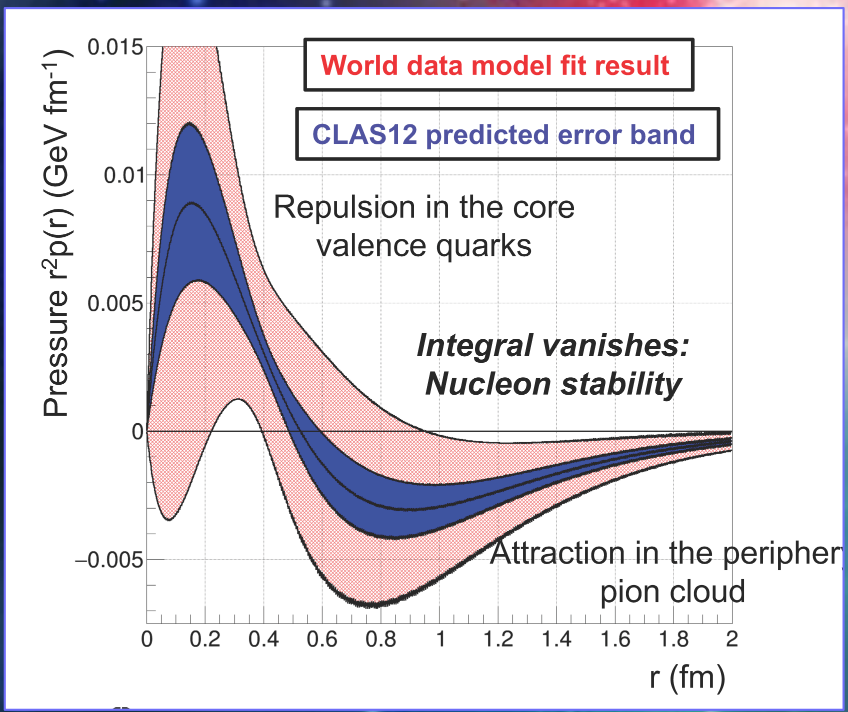


FIG. 5. (Color online) Results of the CFF fit of our data

Model-dependent extraction of Re and Im parts of the *H(ξ,ξ,t)* Compton form Factor (unpolarized GPD)

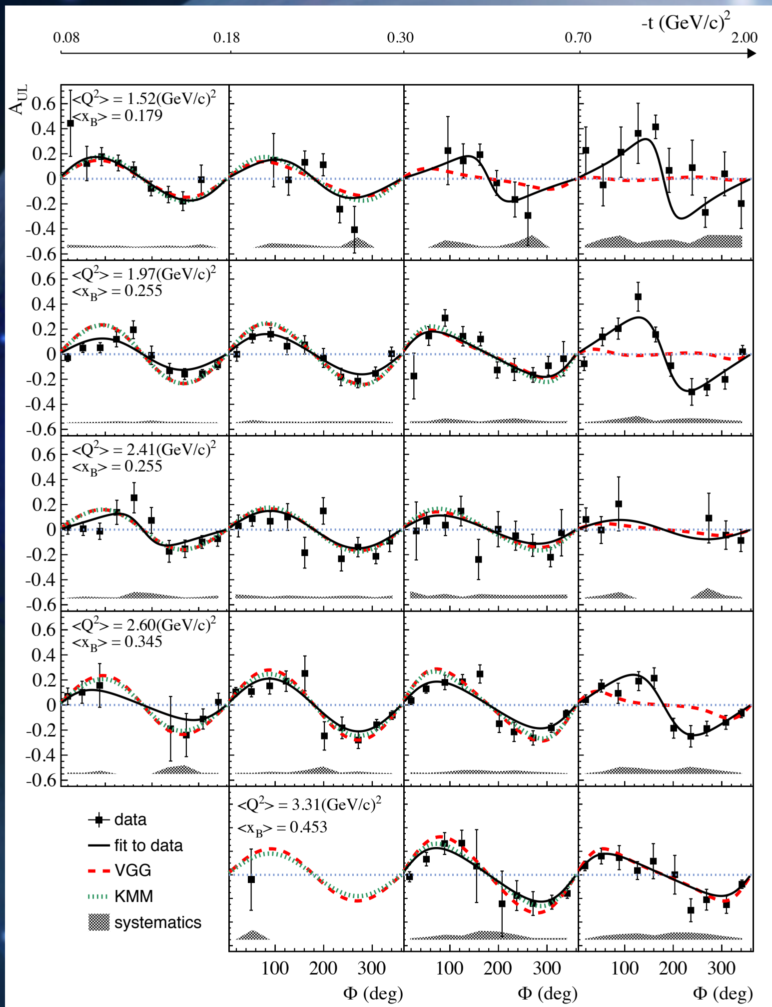
The pressure distribution acting on quarks in the proton

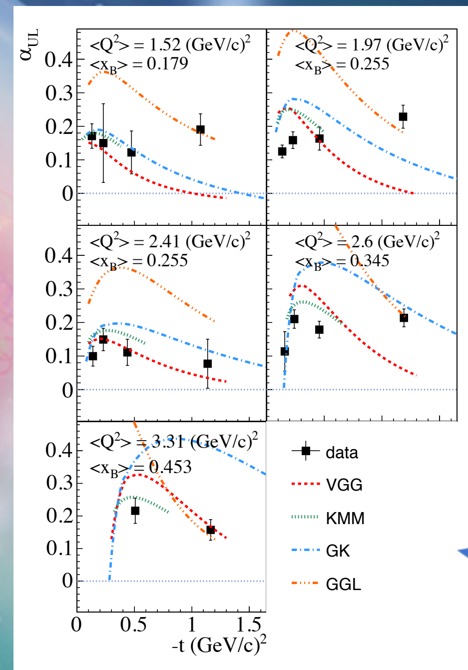


$$\int x\left[H(x,\xi,t) - H(x,0,t)\right] dx = \frac{4}{5}\xi^2 d_1(t)$$

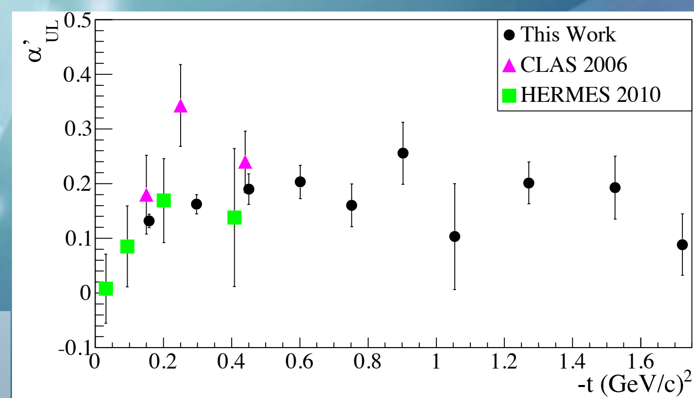
V.Burkert, L.Elourdrhiri, F.X.Girod, Nature **557** (2018) 396

CLAS: Longitudinally Polarized Protons Target-Spin Asymmetries A_{UL}



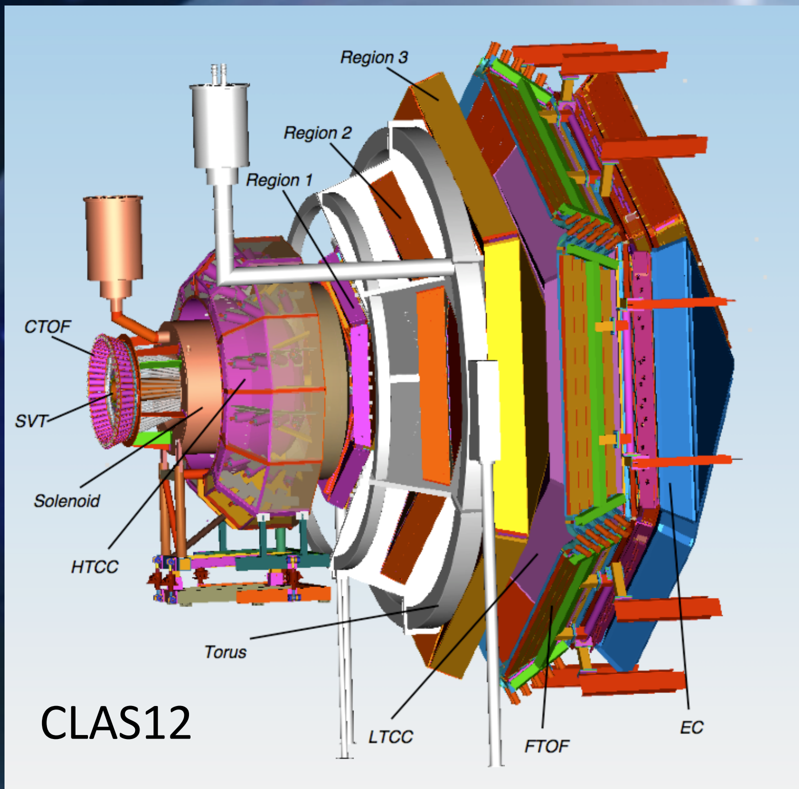


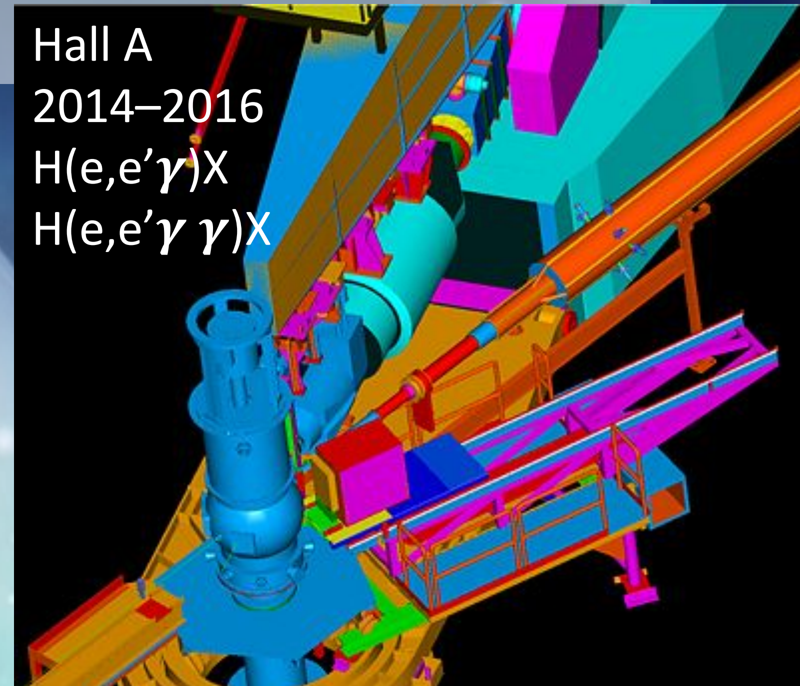
S. Pisano, *et al.*, Phys.Rev. **D91** (2015) 5, 052014



- Spatial distribution of quark helicity
- On to to 11 GeV!

On to ~~12~~ ~~(11)~~ 10.6 GeV!





Hall C:NPS
NSF MRI + JLab
PbWO4 + Sweep magnet