The fifth workshop on hadron physics in China and Opportunities in US
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Generalized Parton Distributions at Jefferson Laboratory

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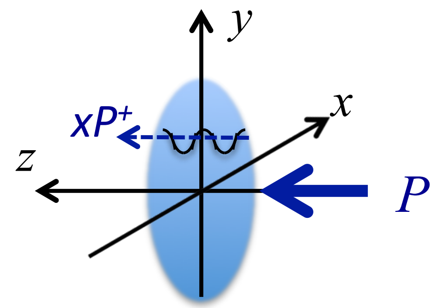
C. Hyde, M. Guidal, A. Radyushkin,
J. Phys. Conf. Ser. 299:012006, 2011,
arXiv:1101.2482

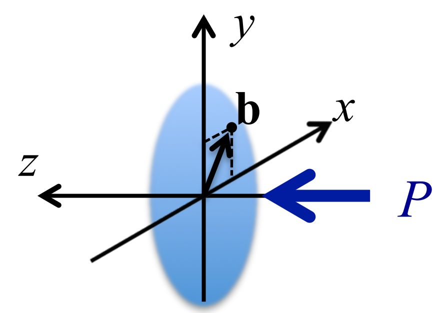
Partonic Structure of the Nucleon

Studying matter as it is illuminated by a light-front

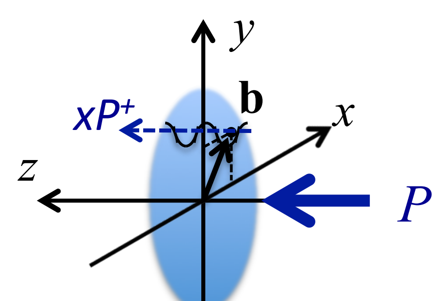
- DIS: H*(e,e')X*
  - Longitudinal (light-cone) Momentum distributions



- Elastic Electro-Weak Form Factors: H*(e,e')p*
  - Fourier Transform of spatial impact-parameter distributions
  - 2-D formalism fully compatible with Q.M. and Relativity

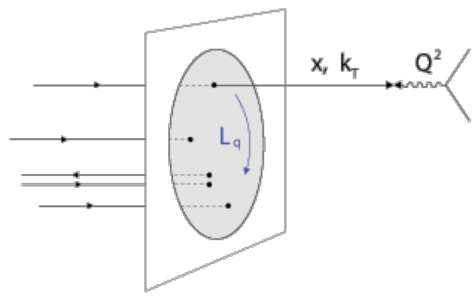


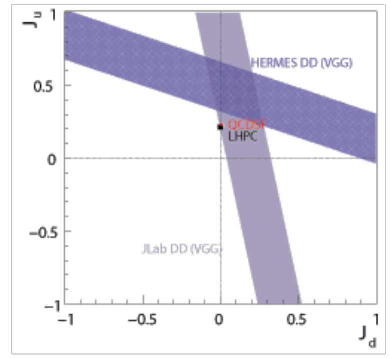
- Generalized Parton Distributions Deeply Virtual Exclusive Scattering
  - $eN \rightarrow eN\gamma$, $eN \rightarrow eN(\pi, \rho, \phi)$, etc
  - Correlations of longitudinal momentum fraction with transverse spatial position



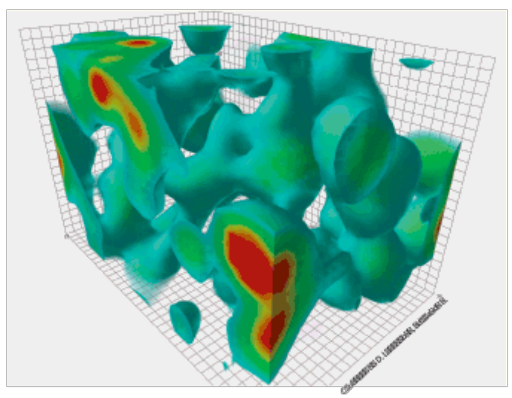
Spatial Structure and Spatial Correlations

$$\left|\Psi(xP^{+},\vec{b})\right|^{2}$$

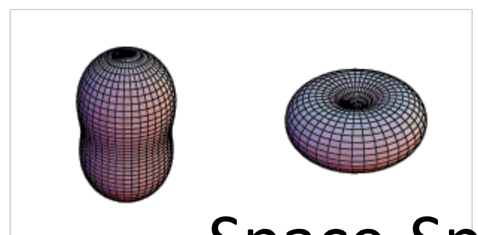




Angular Momentum



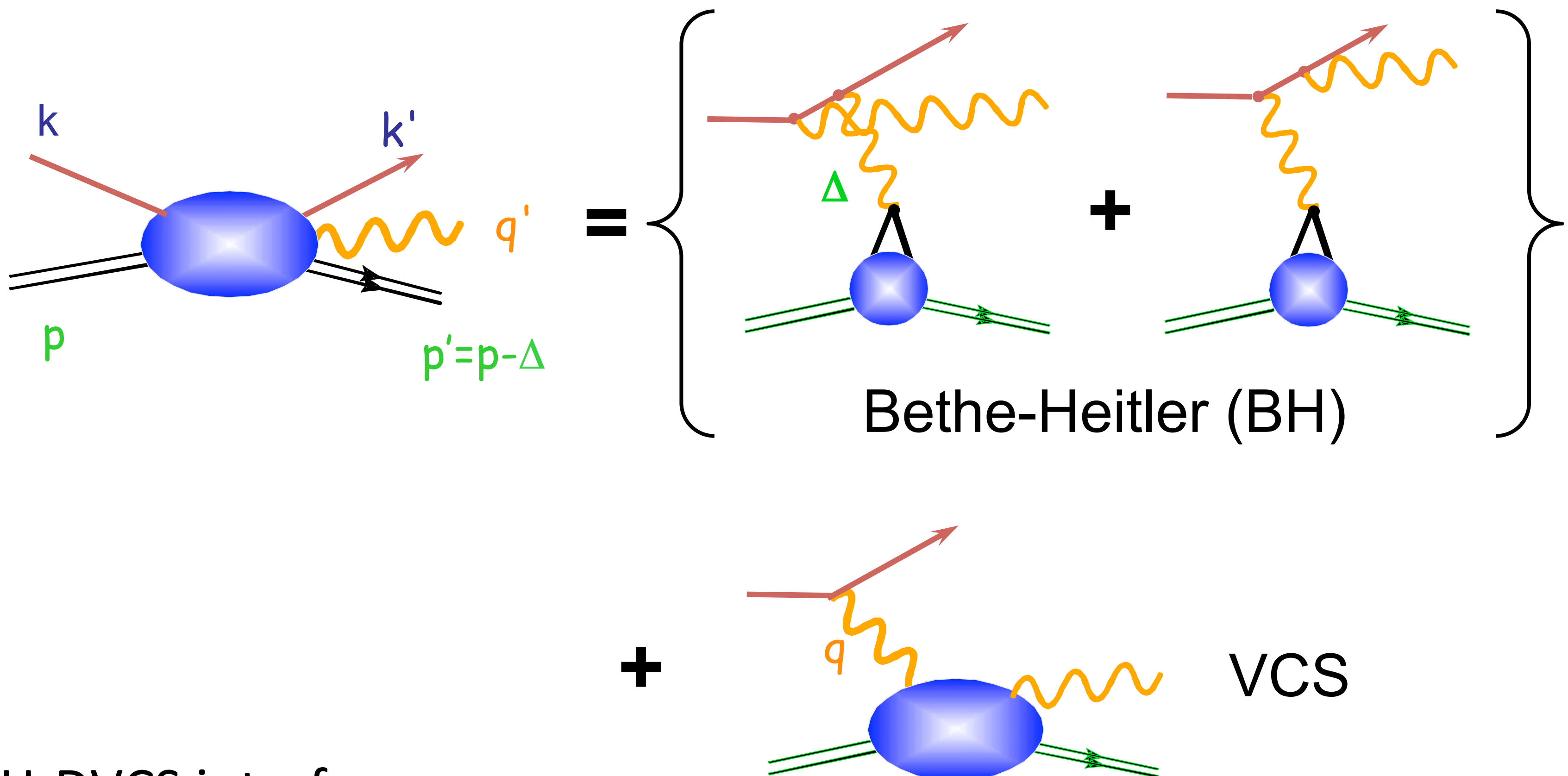
Spatial Correlations in the Vacuum



Space-Spin, Momentum-Spin, or Space-Space Correlations in the Proton

Bethe-Heitler (BH) and Virtual Compton Scattering (VCS)

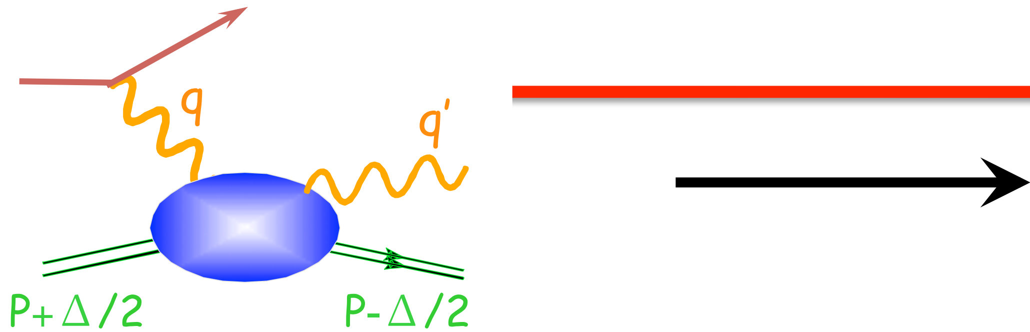
$ep \rightarrow ep\gamma$

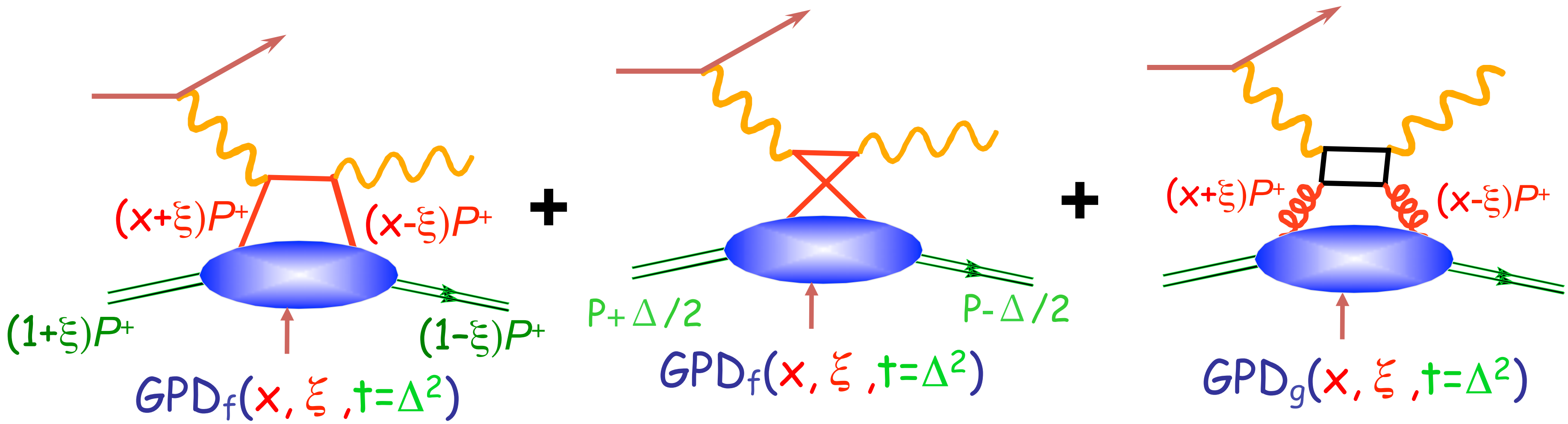


- BH-DVCS interference
  - Access to DVCS amplitude, linear in GPDs

QCD Factorization of DVCS (Co-Linear)

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

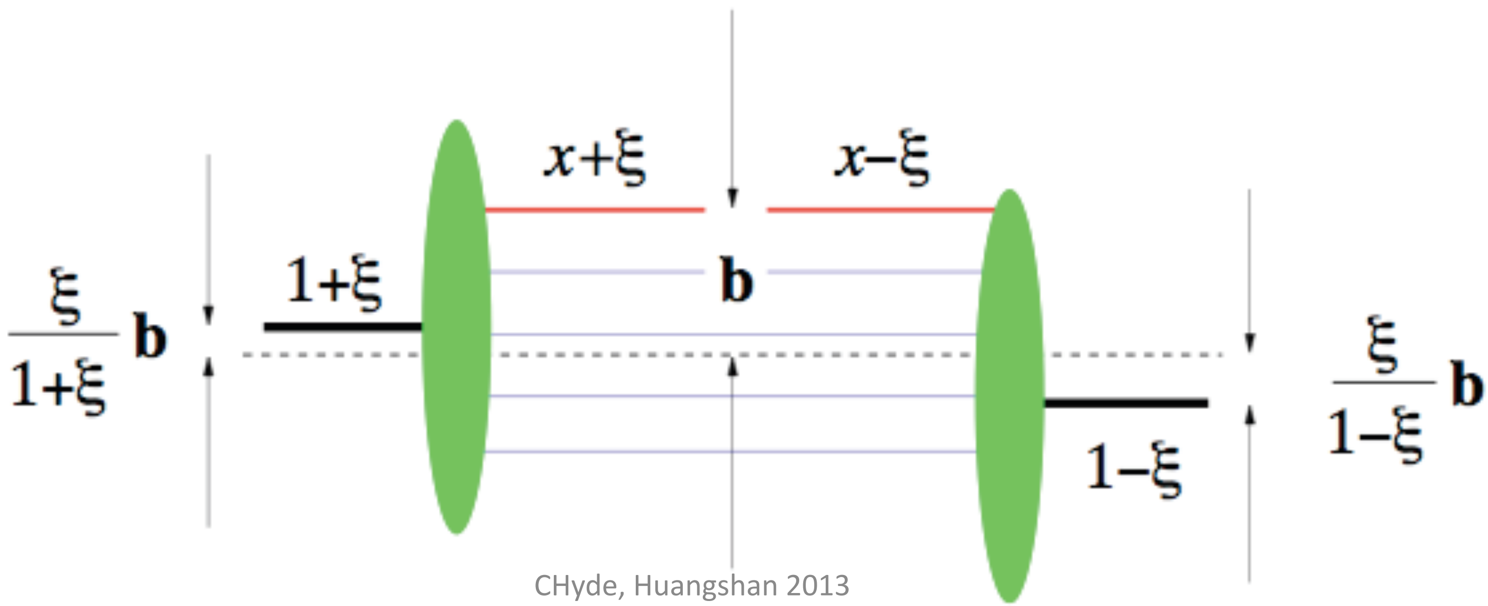




- Symmetrized Bjorken variable: $\xi = \frac{-(q+q')^2}{2(q+q')\cdot P} \xrightarrow[\Delta^2 << Q^2]{} \frac{x_B}{2-x_B}$
- SCHC
  - Tranversely polarized virtual photons dominate to $O(1/Q)$

GPDs: Correlations of Transverse Spatial and Longitudinal Momentum. M. Diehl, M. Burkardt…

- Non-Local, Off-Diagonal one-body quark and gluon currents of the Nucleon
- $P = (p+p')/2$ $p^+ = (1+\xi)P^+$ $p'^+ = (1-\xi)P^+$
  - Remove a parton of momentum fraction $x+\xi$ at impact parameter $\mathbf{b}/(1+\xi)$ relative to initial proton center-of-momentum.
  - Replace it at $\mathbf{b}/(1-\xi)$ with momentum fraction $x-\xi$
  - Integrate over x.
- Fourier Transform $\mathbf{b} \leftarrow\rightarrow \Delta_\perp$ $\Delta_\perp^2 = -(1-\xi)^2\Delta^2 - 4\xi^2 M^2$



Physical Interpretation of GPDs: Two Limits

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

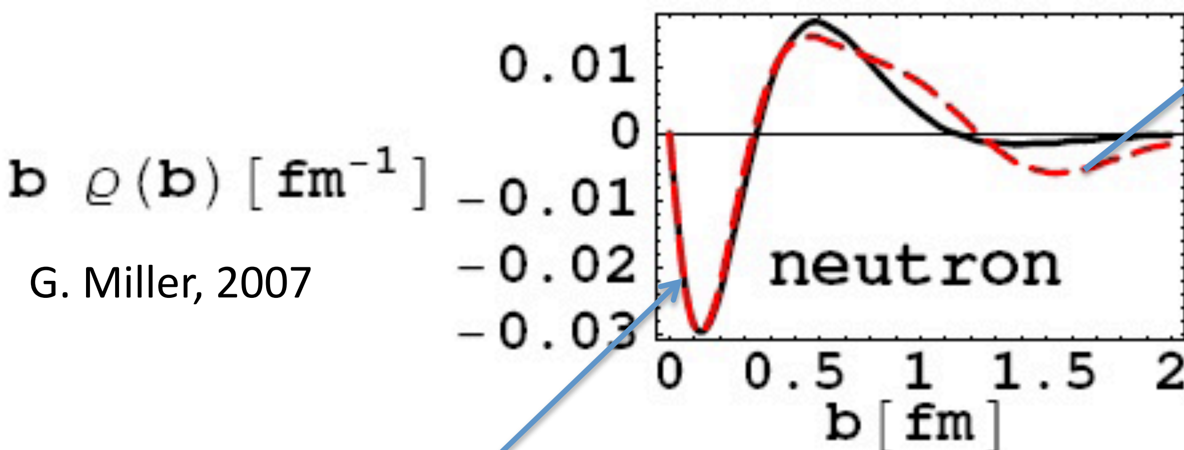
$$H(x,0,\Delta^2) \Leftrightarrow q(x,\vec{b})$$

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

- x=ξ: $H(\xi, \xi,\Delta^2)$, *etc*
  - 2-d Fourier-transform $\Delta_\perp$←→**r**
  - Transition amplitude for longitudinal momentum transfer *2*ξ at fixed impact parameter **r** relative to CM of *spectators*.
    - Not a positive definite density
  - Directly measurable

GPDs and the Nucleon Form Factors

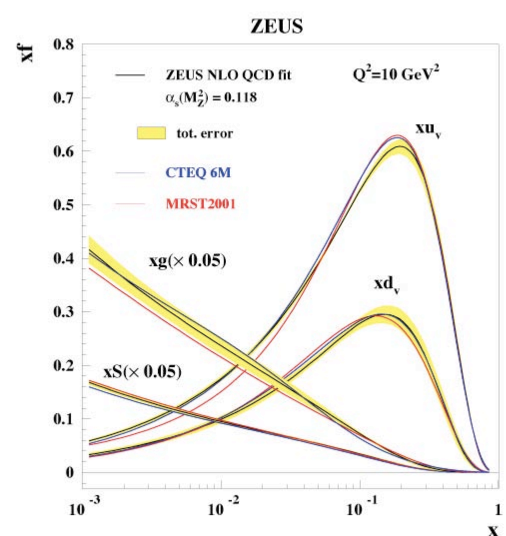
- $F_{1f}(-t) = \int dx\, H_f(x,0,t) = \int d^2\mathbf{b}\; e^{i\mathbf{b}\bullet\Delta_\perp} \int dx\, q_f(x,\mathbf{b})$
- $F_1(-\Delta^2) = \int d^2\mathbf{b}\; e^{i\mathbf{b}\bullet\Delta_\perp}\, \rho(\mathbf{b})$



G. Miller, 2007

$n \rightarrow p\pi^-$

GPD models link negative charge at center of neutron to excess of down-quarks at large-*x*
(excess of up-quarks in proton at large-*x*).
$u_p(x) \sim (1\text{-}x)^3 \quad d_p(x) \sim (1\text{-}x)^5$

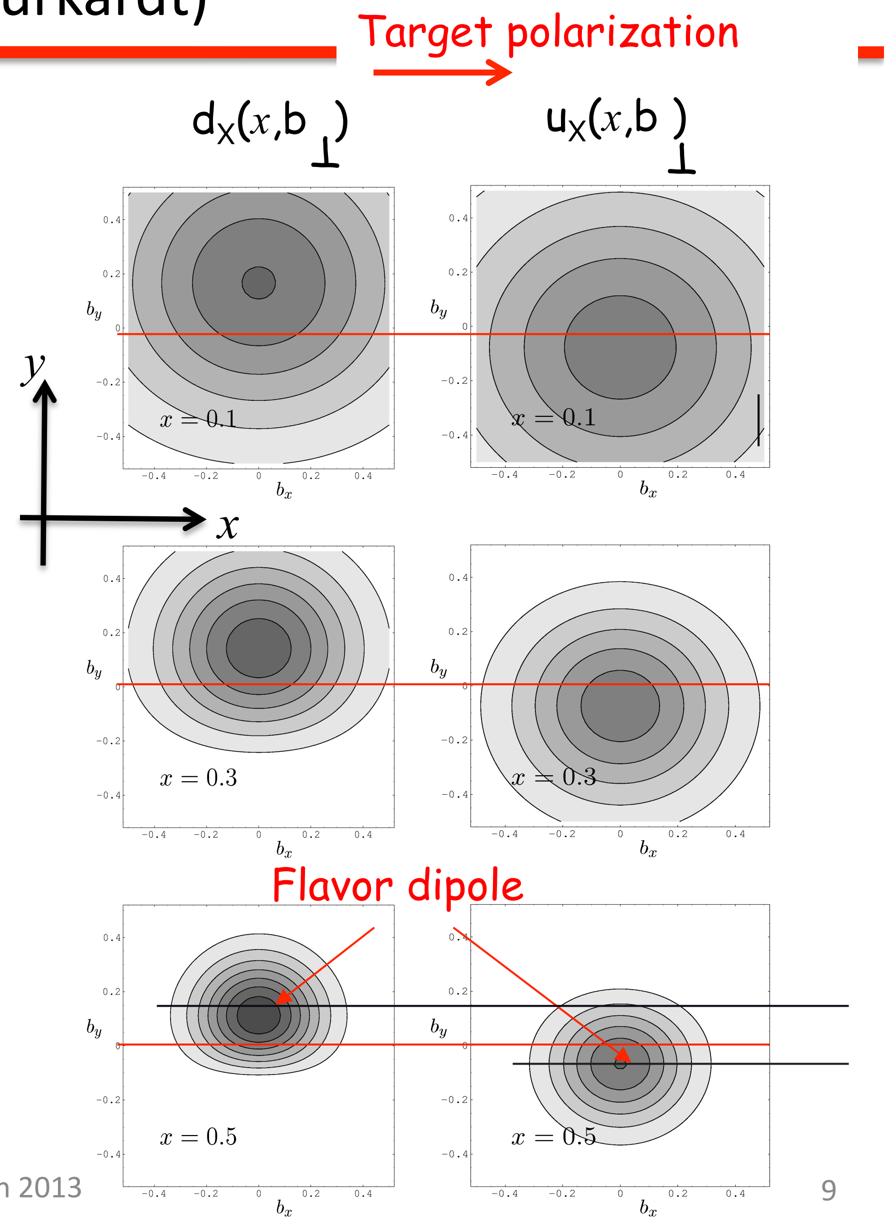


Tomography with Generalized Parton Distributions (M. Burkardt)

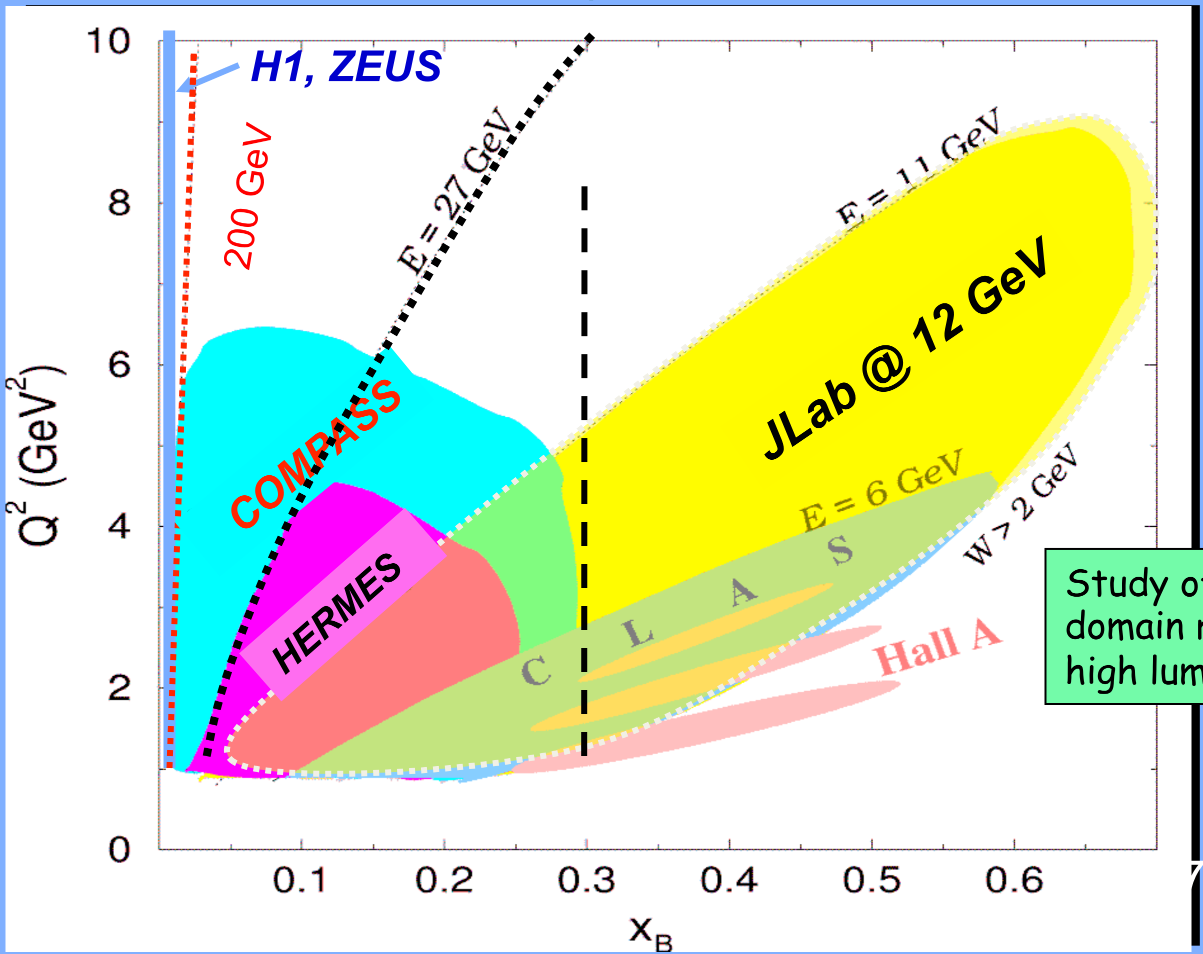
- $H(x,t)\gamma^{\mu} + E(x,t)\sigma^{\mu\nu}\Delta_{\nu}$
  - Proton size shrinks as x→ 1.
  - Spatial separation of up- and down-quarks in a transversely polarized proton
- Spin-Flavor dependence to Proton size & profile.
  - M. Burkardt
  - up and down quarks separate in transversely polarized proton

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

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



Deeply Virtual Exclusive Processes - Kinematic Coverage



Study of high x_B domain requires high luminosity

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):

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

$$\Re e\left[CFF(\xi,\Delta^2)\right] = \wp\int dx \frac{GPD(x,\xi,\Delta^2)}{x \pm \xi} \xrightarrow[D.R.]{} \wp\int d\xi' \frac{GPD(\xi',\xi',\Delta^2)}{\xi' \pm \xi} + D(\Delta^2)$$

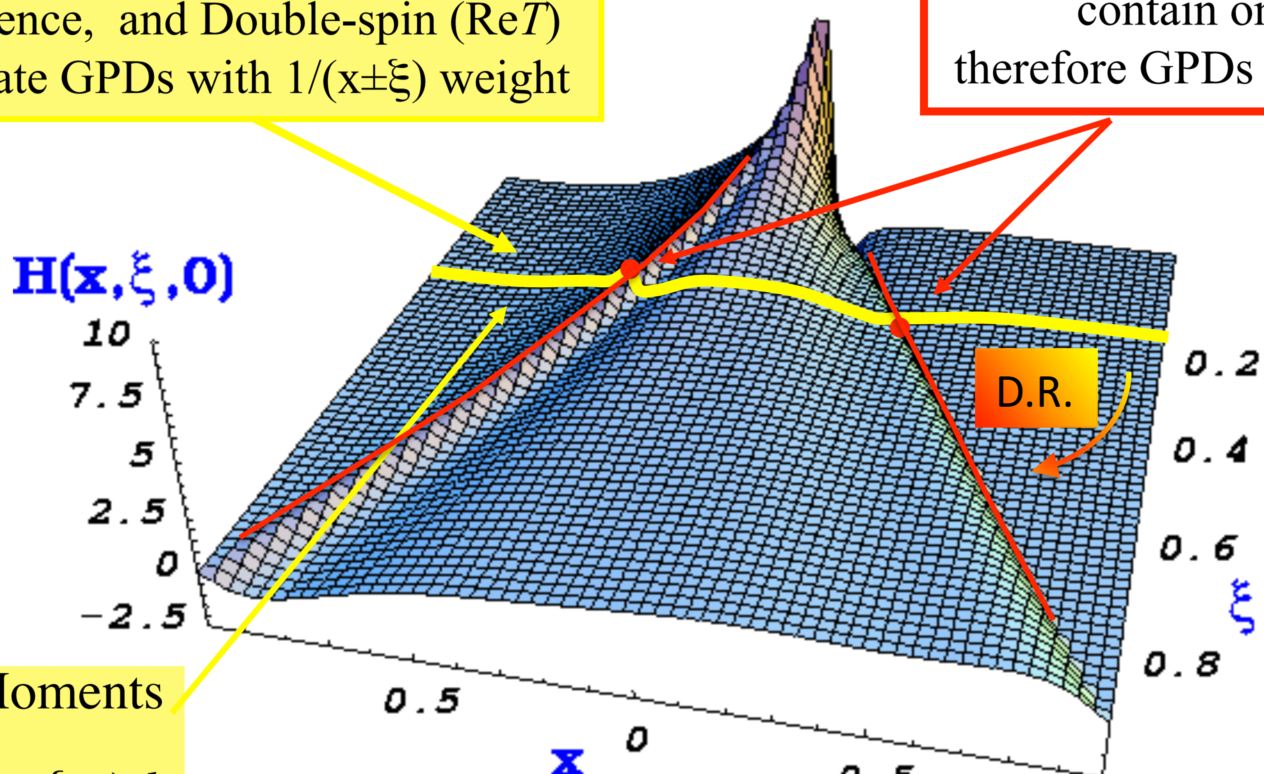
DVCS, GPDs, Compton Form Factors(CFF), and Lattice QCD

(at leading order:)

$$T^{DVCS} \sim \int_{-1}^{+1} \frac{H(x,\xi,t)}{x \pm \xi + i\varepsilon} dx + \ldots \sim \quad P\int_{-1}^{+1} \frac{H(x,\xi,t)}{x \pm \xi} dx - i\pi H(\pm\xi,\xi,t) + \ldots$$

Cross-section (σ), Beam-charge-difference, and Double-spin (Re*T*) integrate GPDs with 1/(x±ξ) weight

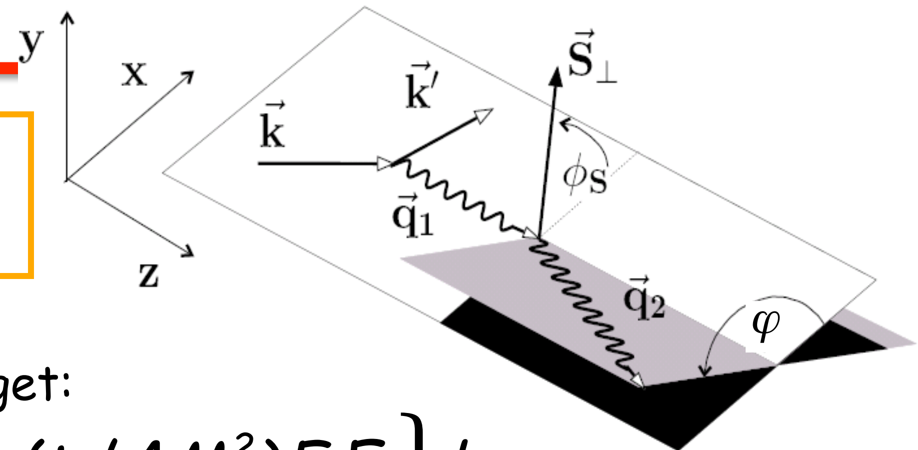
Beam or target spin Δσ contain only Im*T*, therefore GPDs at $x = \xi$ and $-\xi$



Lattice Moments

$= \int x^n H(x,\xi,t) dx$

Exploiting the harmonic structure of DVCS with polarization



The spin-dependence of cross-sections are key observables 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:

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

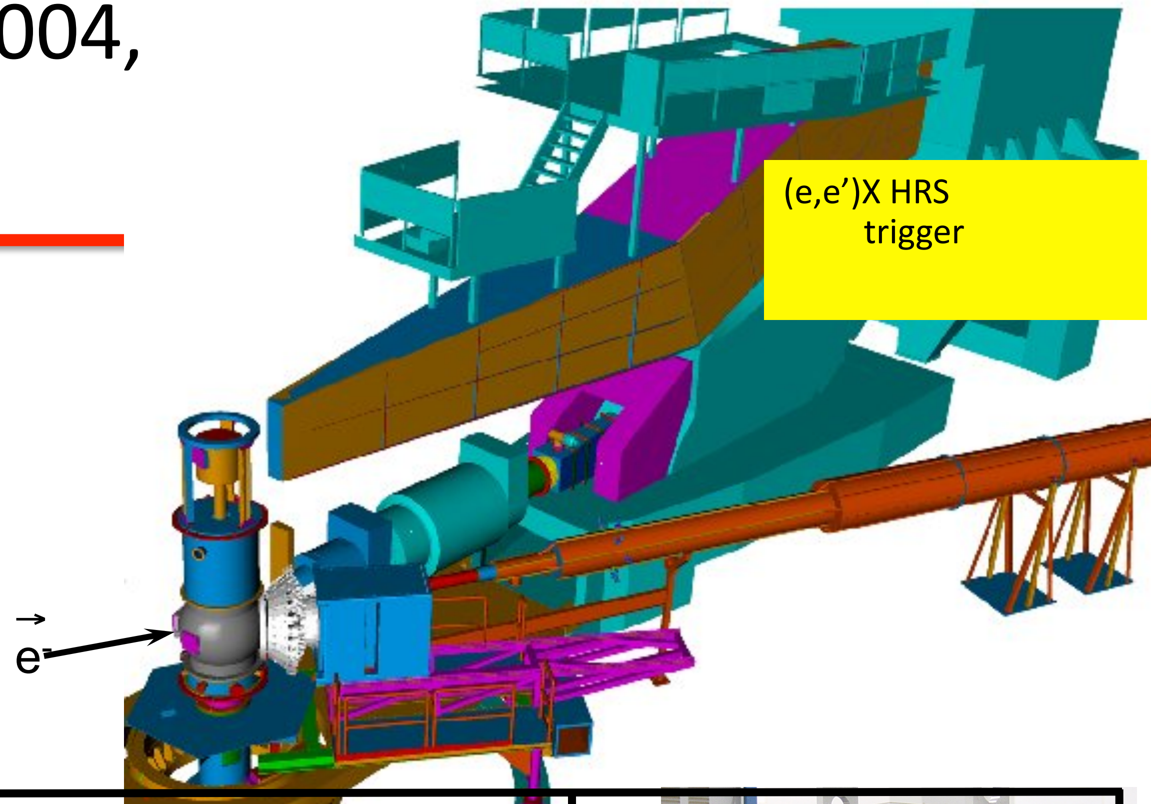
Separations of CFFs $H(\pm\xi,\xi,t)$, $E(\pm\xi,\xi,t)$,…

DVCS: JLab Hall A 2004, 2010

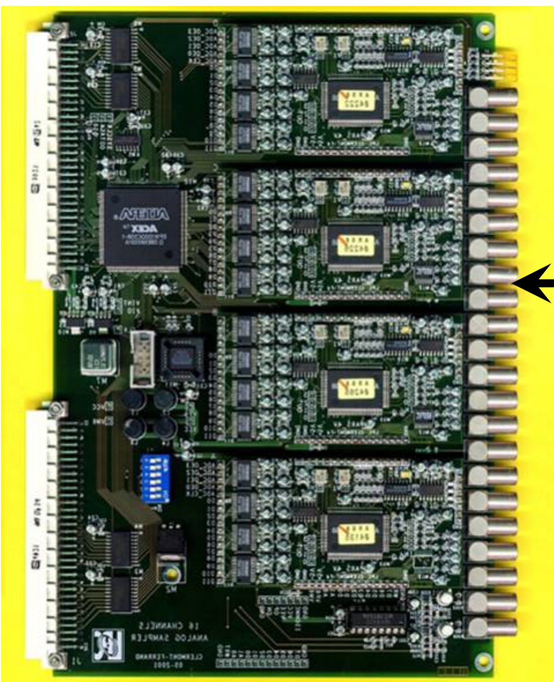
L ≥ 10^{37} cm^2/s

Precision cross sections

- Test factorization
- Calibrate Asymmetries

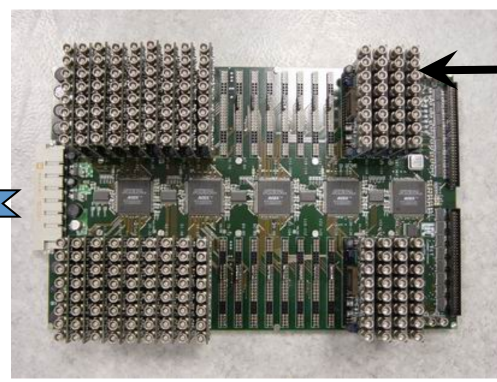


(e,e')X HRS trigger

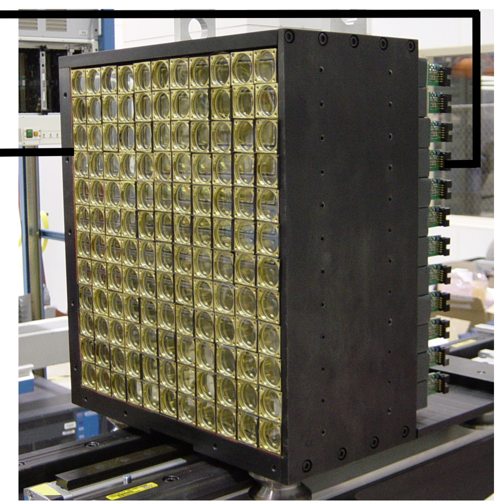


16chan VME6U: ARS

128 samples@1GHz



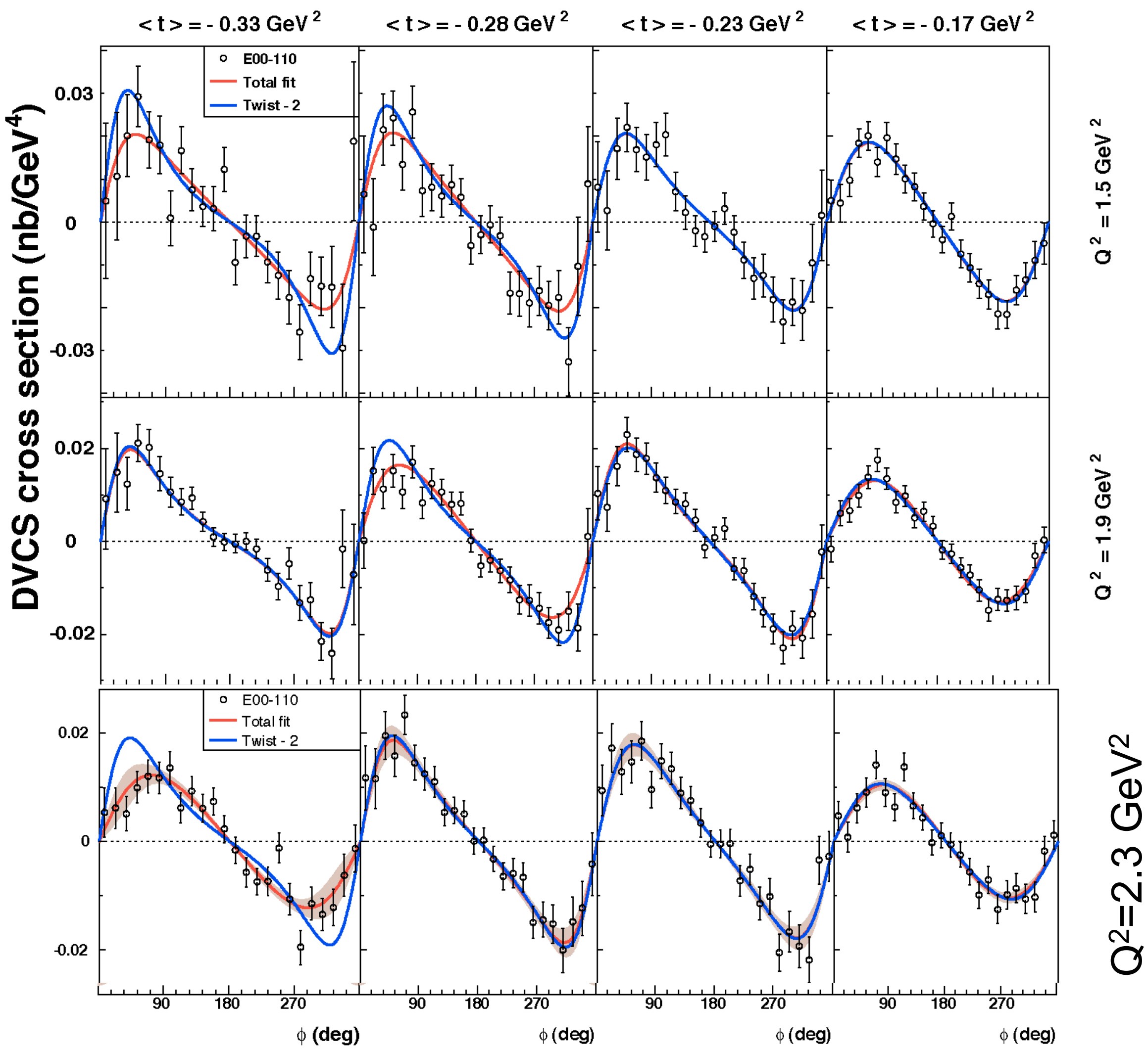
Digital Trigger Validation



132 PbF_2

Hall A Helicity Dependent Cross Sections E00-110

PRL**97**:262002 (2006)
C. MUNOZ CAMACHO, et al.,



Twist-2(GPD)+…

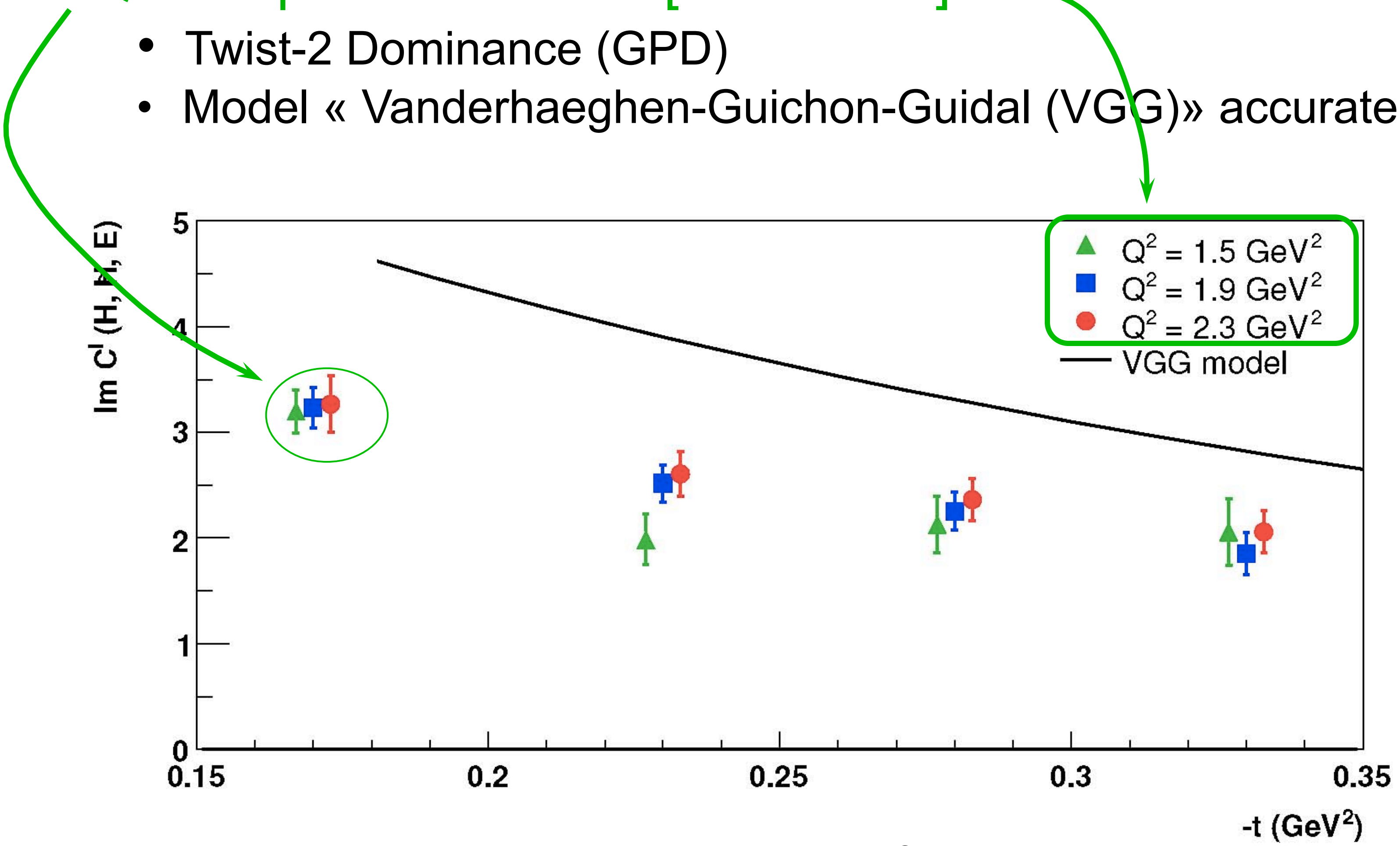
Twist-3(qGq)+…

$$\sum h d\sigma(h) = \frac{s_1 \sin(\phi_{\gamma\gamma})\Gamma_{s1} + s_2 \sin(2\phi_{\gamma\gamma})\Gamma_{s2}}{P_1(\phi_{\gamma\gamma})P_1(\phi_{\gamma\gamma})}$$

$\Gamma_{s1,2}$ = kinematic factors

GPD results from JLab Hall A (E00-110) (C.MUNOZ CAMACHO et al *PRL* **97**:262002)

- Q^2-independance of Im[DVCS*BH]
  - Twist-2 Dominance (GPD)
  - Model « Vanderhaeghen-Guichon-Guidal (VGG)» accurate to≈30%

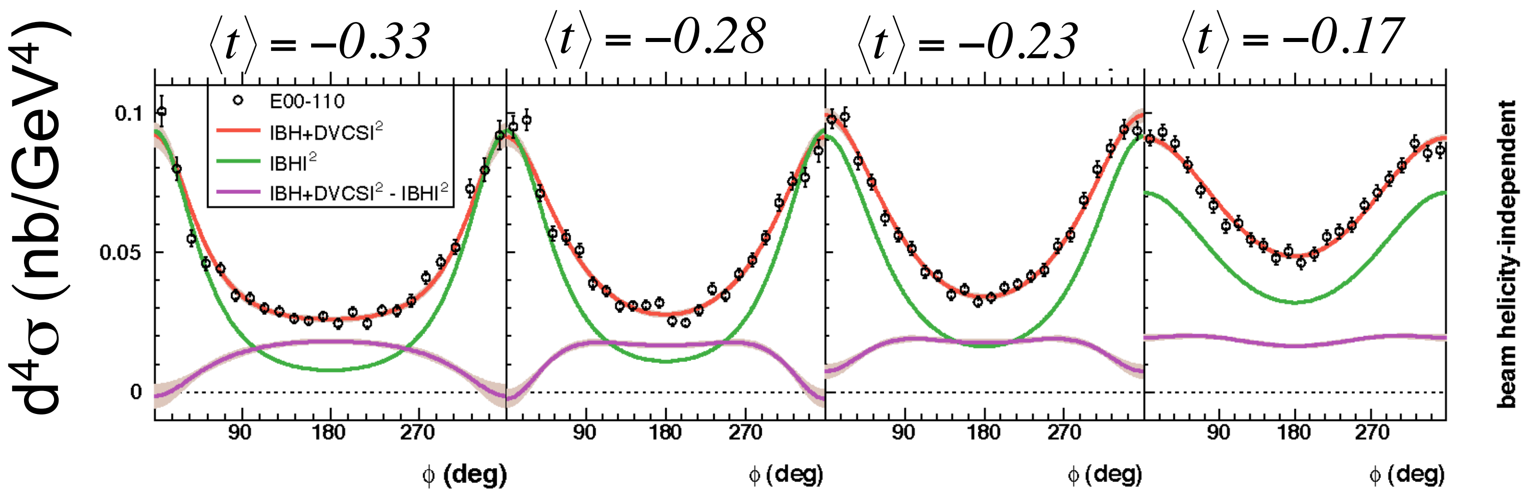


Compensate the small lever-arm in Q^2 with precision in $d\sigma$.

Beam helicity-independent cross sections at Q^2=2.3 GeV^2, x_B=0.36

•Contribution of Re[DVCS*BH] + |DVCS|^2 large.
•Positron beam or measurements at multiple incident energies to separate these two terms and isolate Twist 2 from Twist-3 contributions

PRL**97**:262002 (2006) C. MUNOZ CAMACHO, *et al.*,



$$d\sigma = d\sigma(|BH|^2) + 2\,\mathrm{Re}[DVCS^* BH] + |DVCS|^2$$

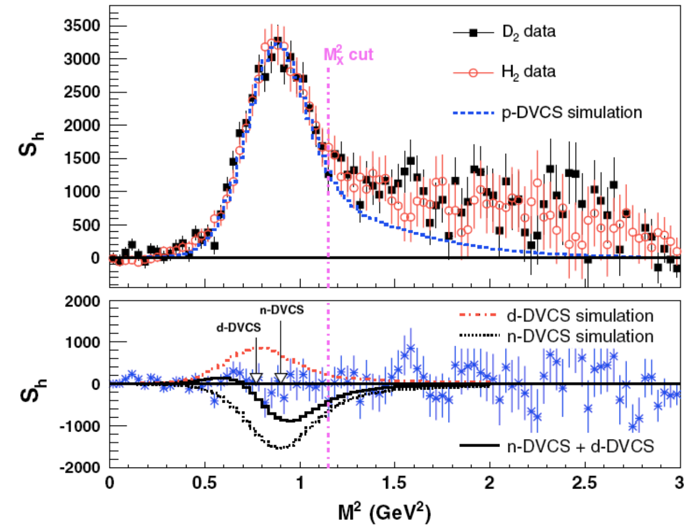
$$= d\sigma(|BH|^2) + \frac{c_0\Gamma_0 + c_1\cos(\phi_{\gamma\gamma})\Gamma_1 + c_2\cos(2\phi_{\gamma\gamma})\Gamma_2 + \ldots}{P_1(\phi_{\gamma\gamma})P_1(\phi_{\gamma\gamma})}$$

$$c_{0,1}(t) \approx \mathrm{Re}[C^I(GPD)] \pm C^{DVCS}\left(GPD^2\right)\ldots + \mathrm{Re}\left[\Delta C^I(GPD)\right]$$

$$c_2(t) = \mathrm{Twist}-3 = (qGq)$$

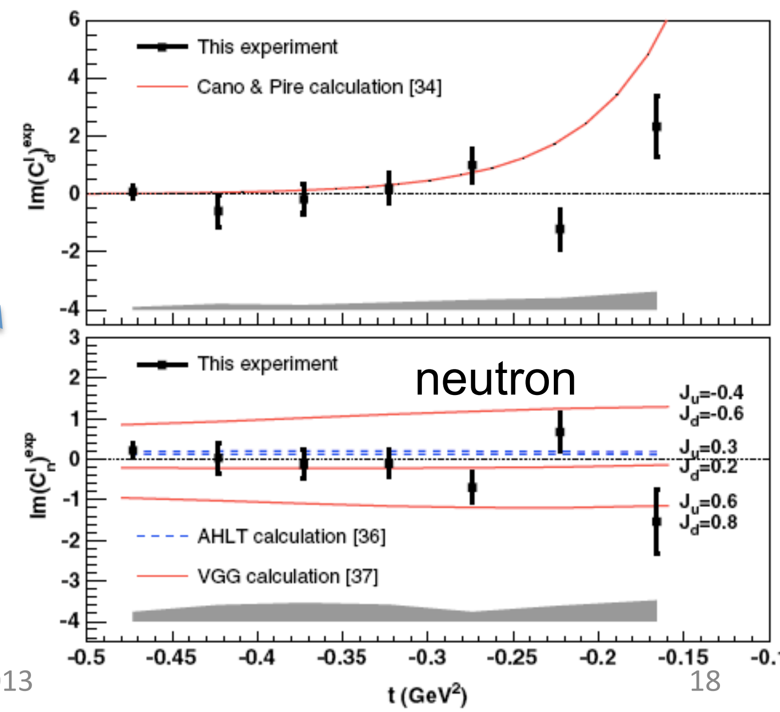
DVCS-Deuteron, Hall A

- E03-106:
  - D(e,e'γ)X ≈ *d(e,e'γ)d+n(e,e'γ)n+p(e,e'γ)p*
  - Sensitivity to $E_n(\xi,\xi,t)$ *in Im[DVCS*BH]*



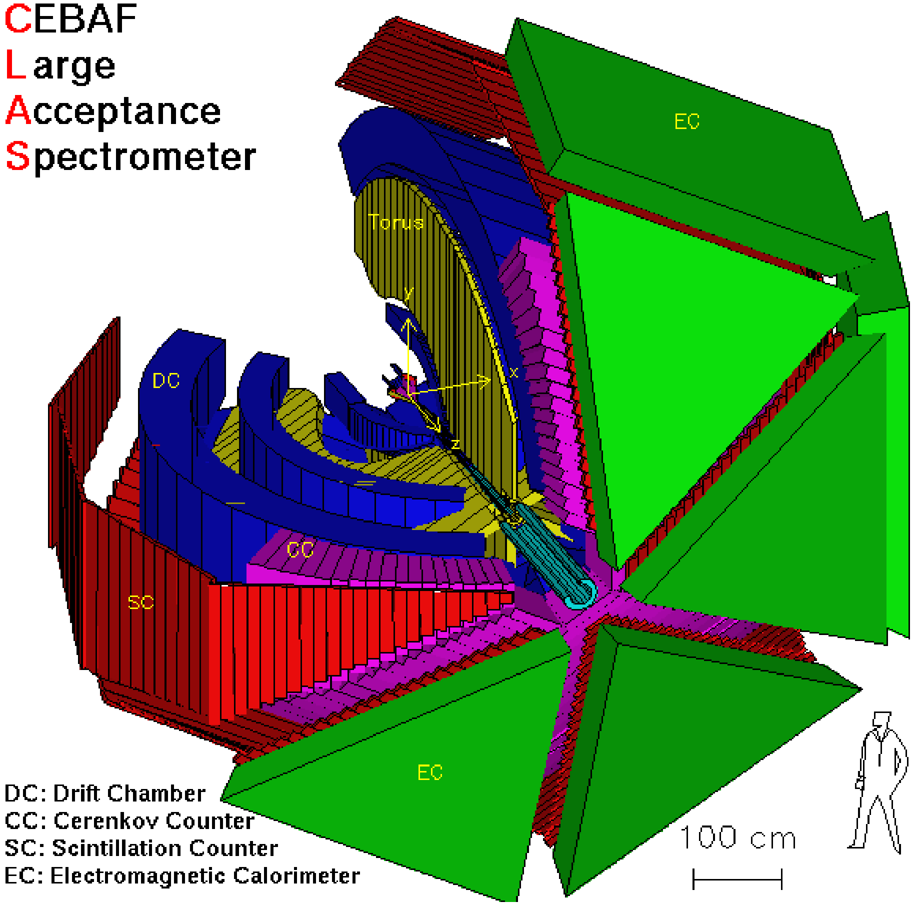
Q^2=2.3 GeV^2, x_B=0.36

- E08-025 (5.5 GeV- 2010)
  - Reduce the systematic errors
    - Expanded PbF_2 calorimeter for π^0 subtraction
  - Separate the *Re[DVCS*BH]* and $|DVCS|^2$ terms on the neutron via two beam energies.



The CLAS detector

CEBAF
Large
Acceptance
Spectrometer



- Toroidal magnetic field
- (6 supercondicting coils)
- Drift chambers (argon/CO2
- Gas, 35000 cells)
- Time-of-flight scintillators
- Electromagnetic calorimeters
- Cherenkov counters
  (e/π separation)

- Performances:
- Nearly 4π acceptance
- Large kinematical coverage
- Detection of charged
- and neutral particles

CLAS: Longitudinally Polarized Protons A_{UL}

JLab/Hall B – Eg1 Non-dedicated experiment(no inner calorimeter), but H(e,e'γp) fully exclusive.

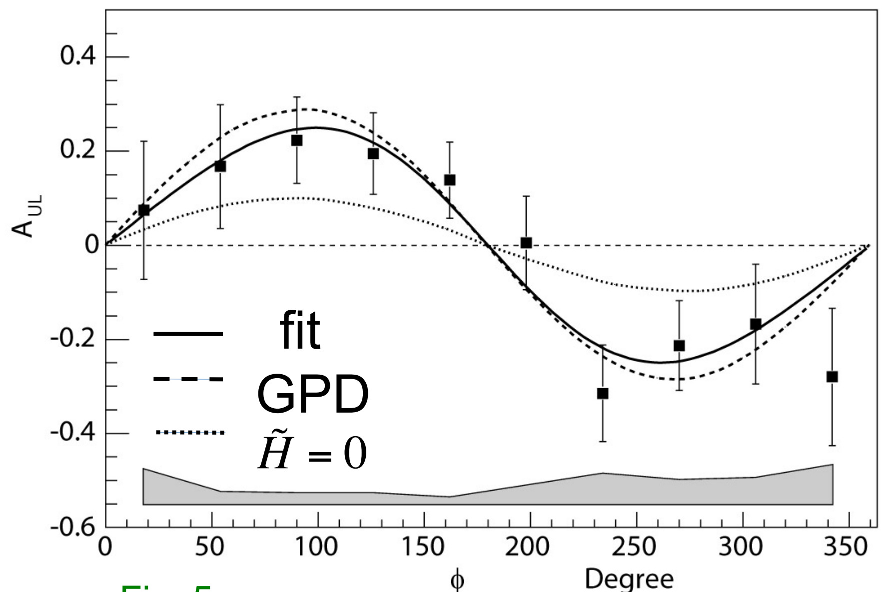


Fig. 5.

S.Chen, *et al*, PRL 97, 072002 (2006)

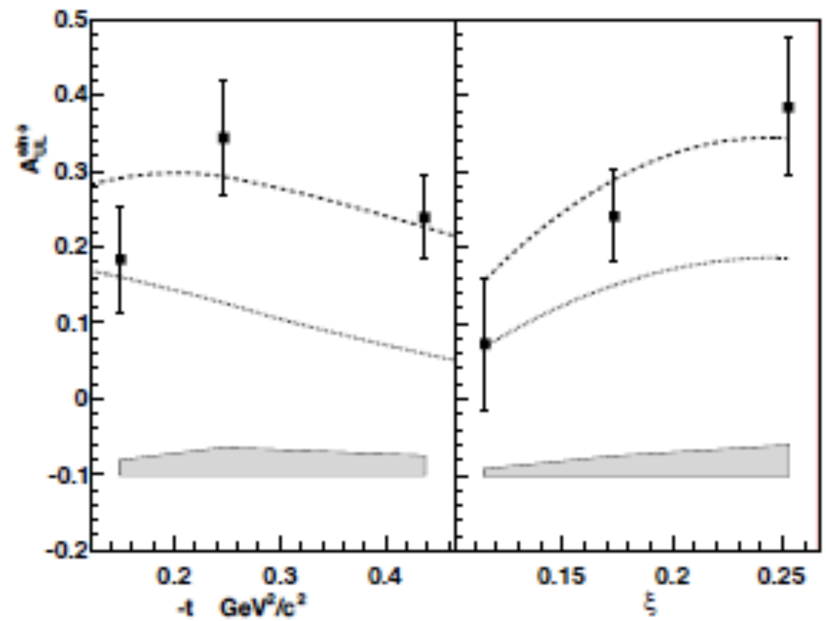
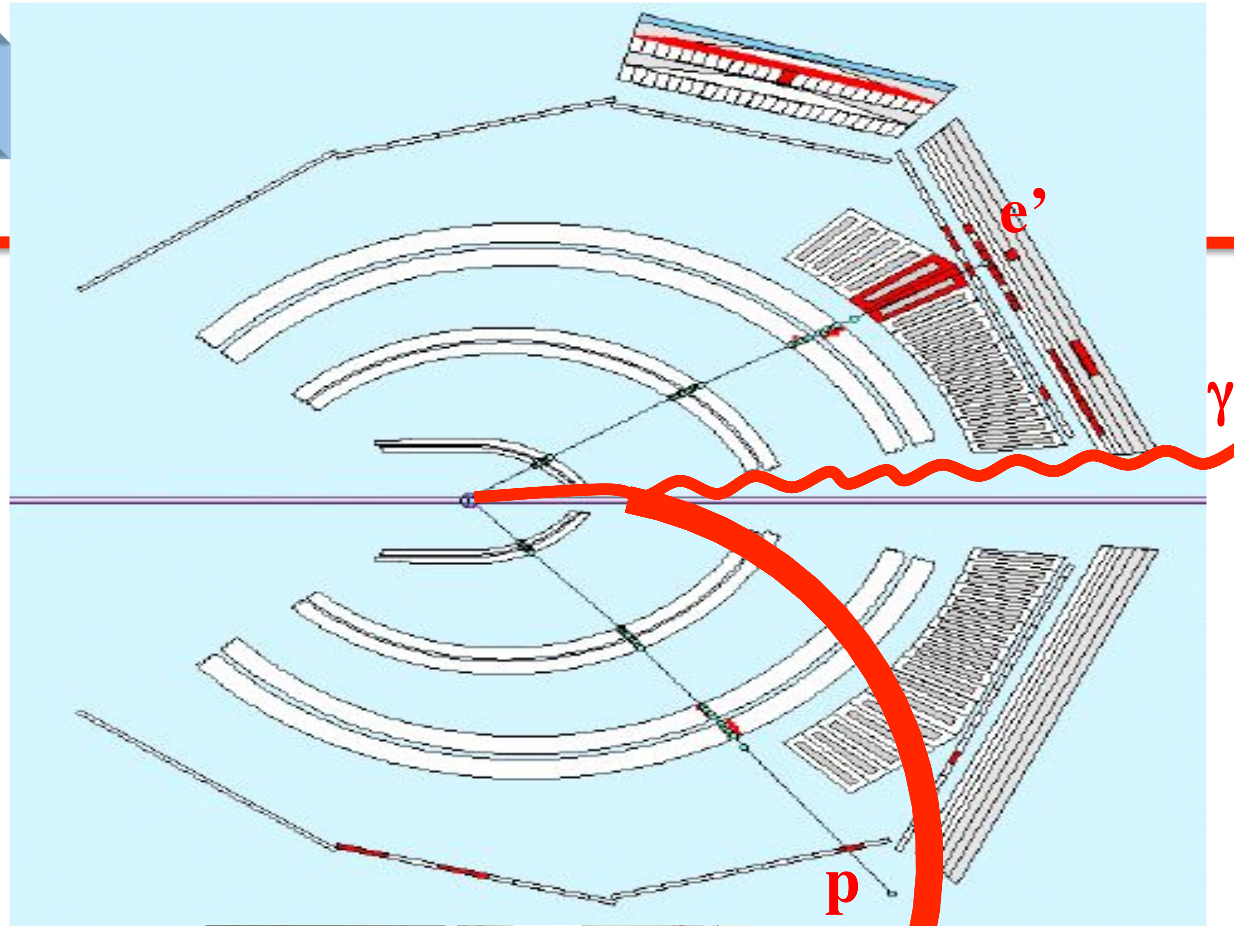


FIG. 6: The left panel shows the $-t$ dependence of the $\sin\phi$-moment of A_{UL} for exclusive electroproduction of photons, while the right shows the ξ dependence. Curves as in Fig. 5.

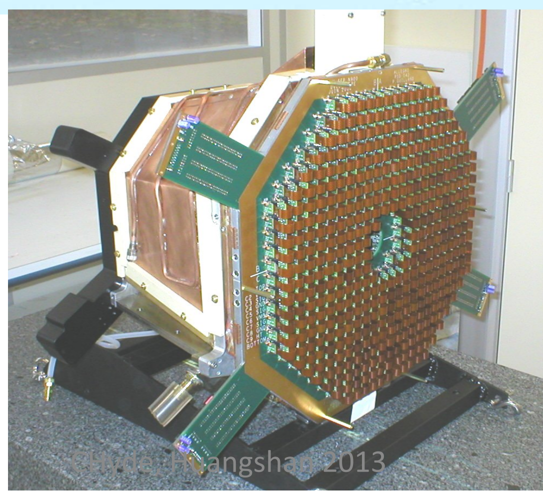
Higher statistics and larger acceptance (Inner Calorimeter) run Feb-Sept. 2009

DVCS@Hall B



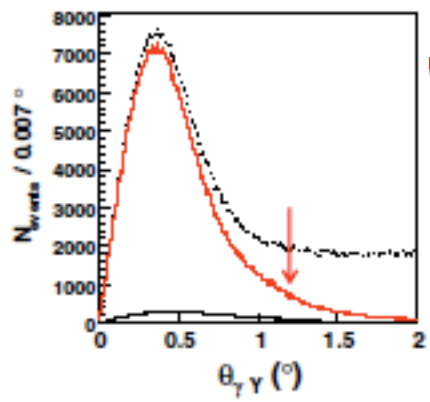
ep⇨ epγ

5 Tesla Solenoid
420 $PbWO_4$ crystals :
~10x10x160 mm^3
APD+preamp readout
Orsay / Saclay / ITEP / Jlab

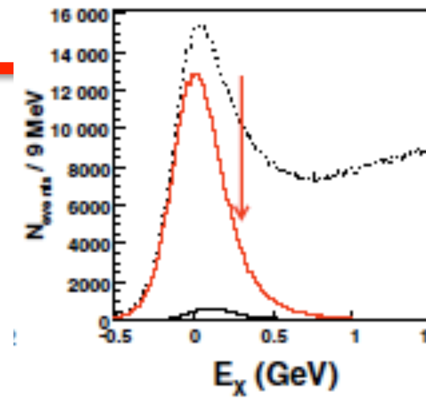


CLAS 6 GeV: Exclusivity and Kinematics

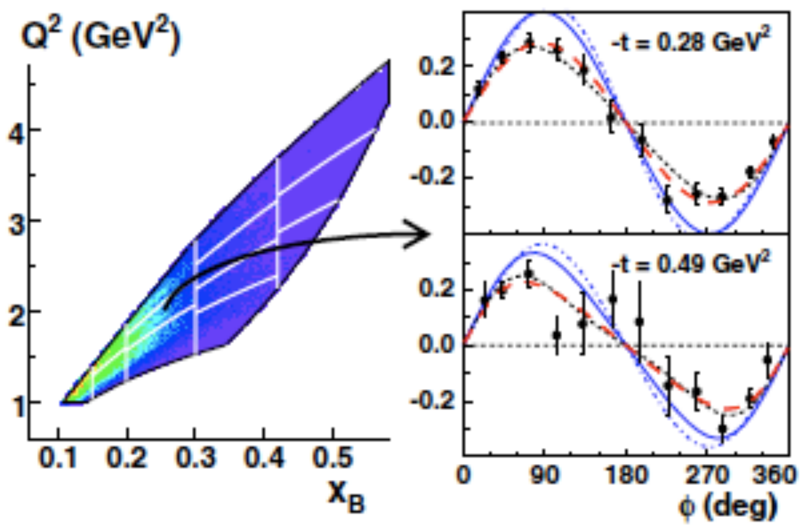
- H*(e,e'γp')x*
  - Overcomplete triple coincidence



Co-linearity of γ with *q-p'*



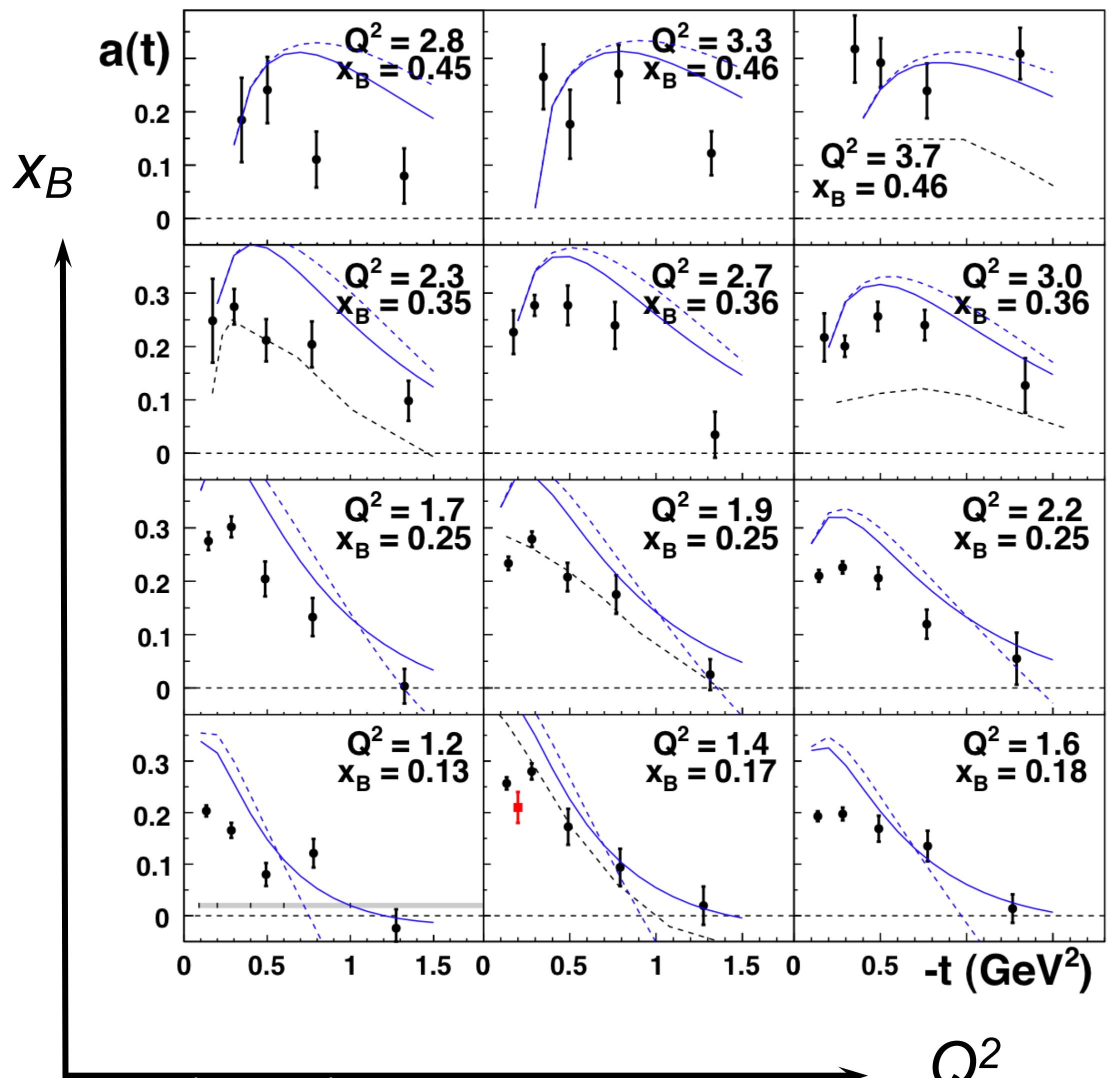
Missing Energy E_x



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

CLAS, 6 GeV Beam Helicity Asymmetry

- F.X. Girod et al, Phys.Rev.Lett.**100,** 162002, 2008
- sinϕ moments of A_{LU}
  - Solid blue curves: VGG GPD model
- Data set doubled by Fall/Winter 2008/2009 run



CLAS DVCS Longitudinally Polarized Target

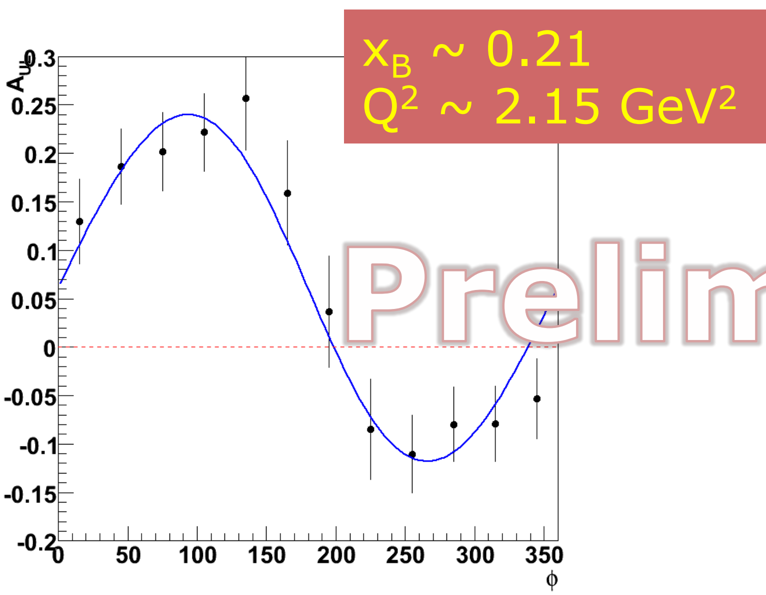
DVCS Target Spin Asymmetry

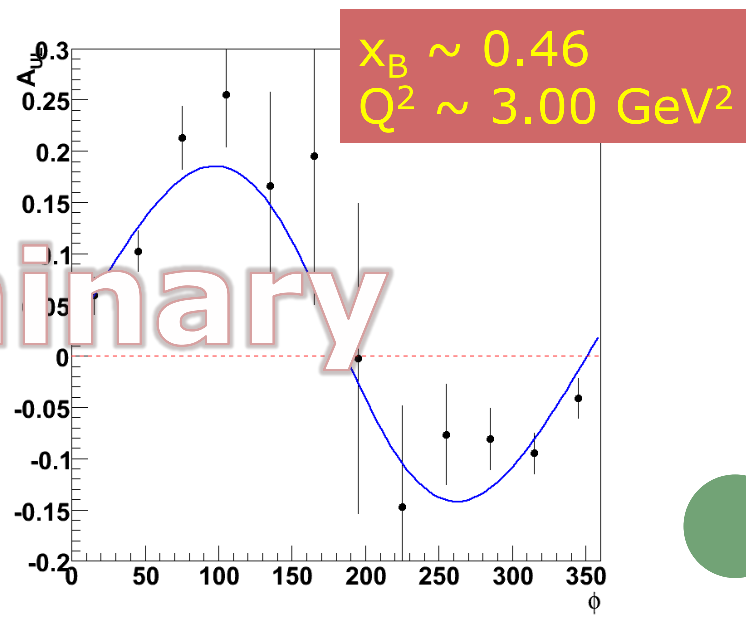
$$A_{UL} = \frac{N^+ - N^-}{f(P^- N^+ + P^+ N^-)}$$

- $N^{+(-)}$: number of DVCS events with a positive (negative) target polarization
- $P^{+(-)}$: target polarization
- F: dilution factor

Fitting function:

$$A_{UL} \sim \alpha \sin \Phi + \beta \sin 2\Phi$$

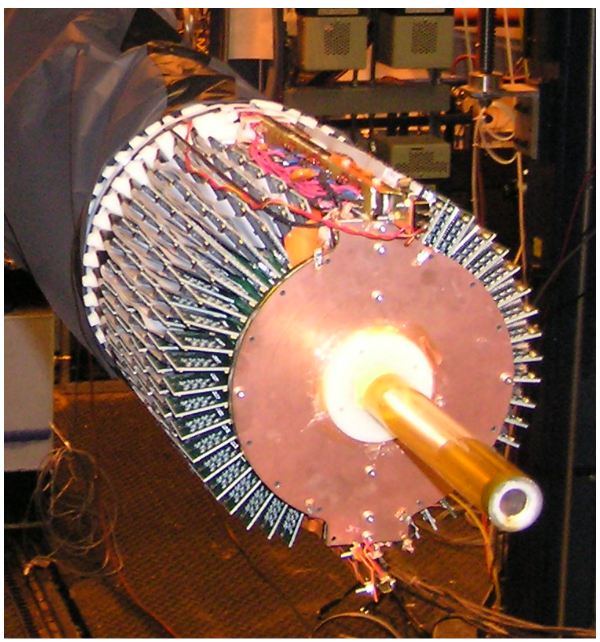




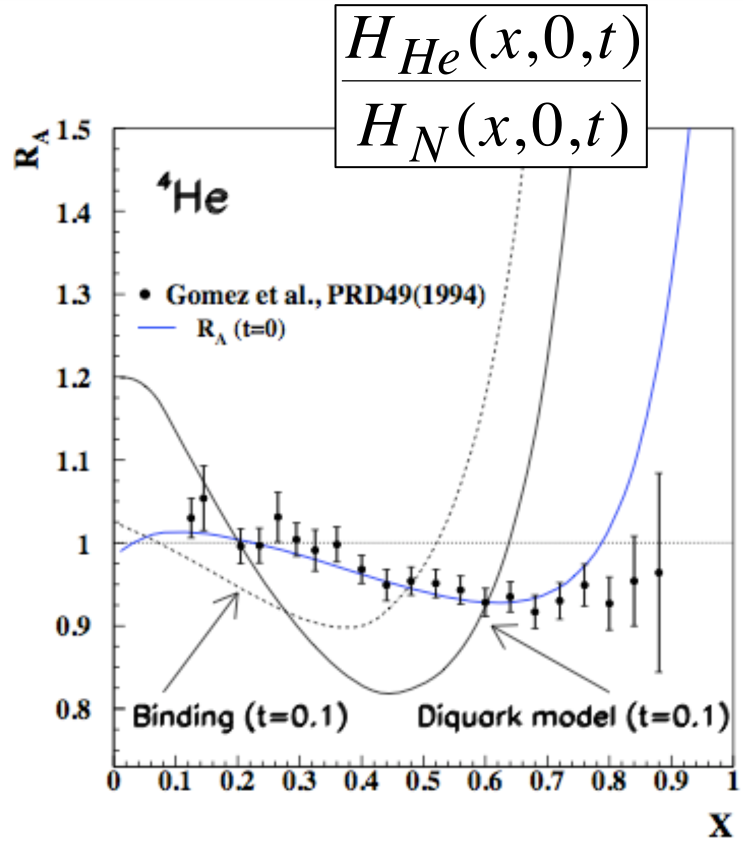
Plots and analysis done by Erin Seder

CLAS: Coherent $^4He(e,e'\gamma\alpha)$

- A single GPD ($H_u=H_d$)
  - $H(\xi,\xi,t)=(4/9)H_u+(1/9)\ H_u$.
  - $G_E=\int dx[(2/3)H_u-(1/3)H_u]$.
- E08-024, Autumn 2009
  - BoNuS GEM radial TPC

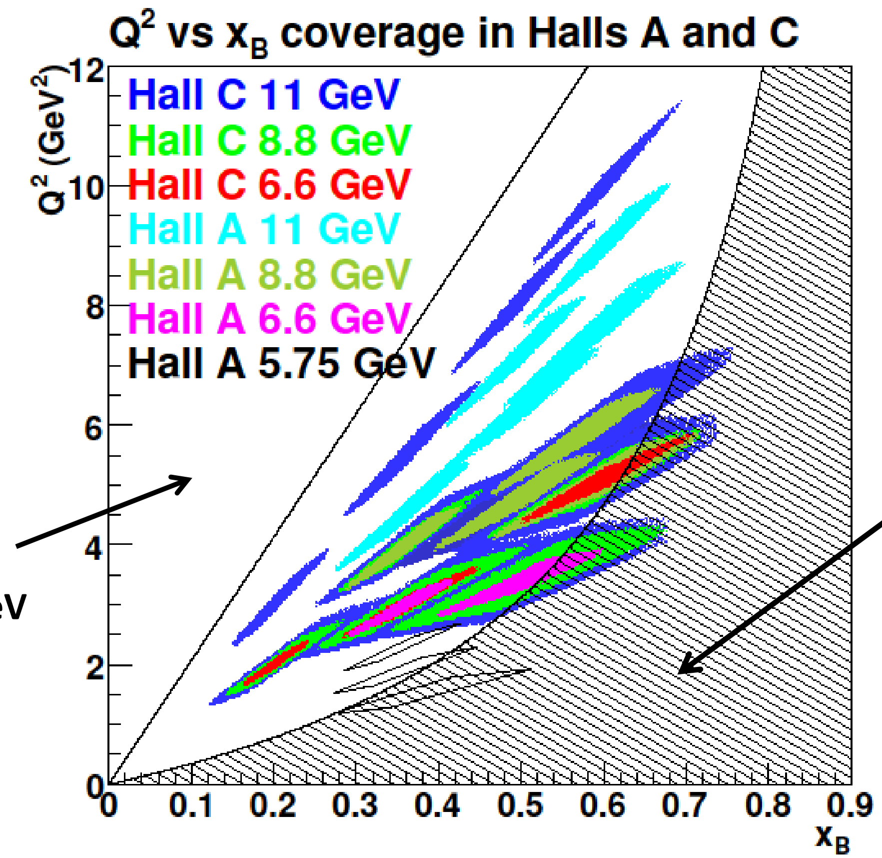


Upgrade planned for 12 GeV



[t=0.0] →EMC effect,
[t=-0.1]→ GPD
(Liuti & Taneja, Guzey & Strickman)

DVCS at 12 GeV in Halls A & C: (Spectrometer)x(Calorimeter)

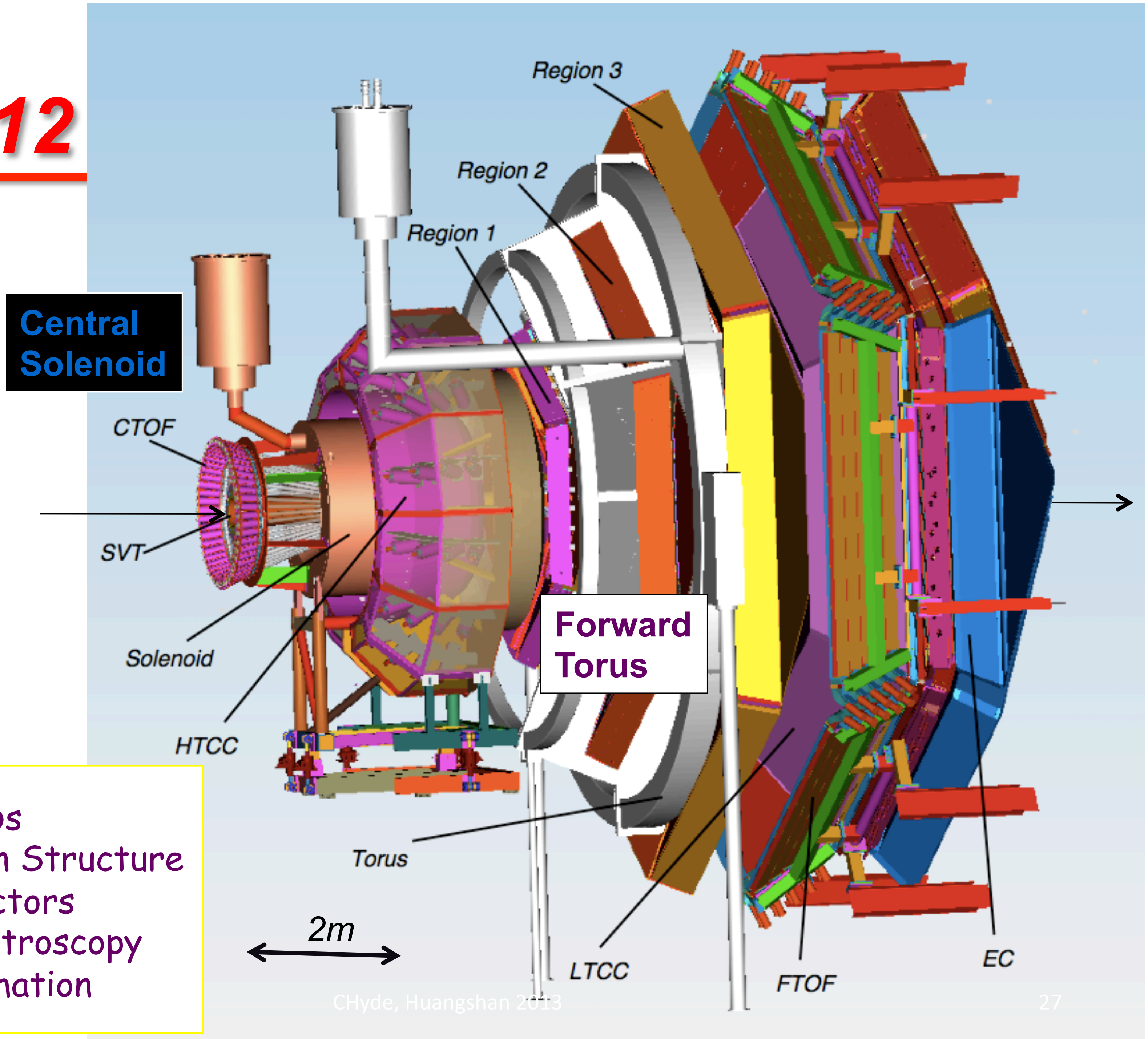


Hall A: 100 days approved
HRS ×(208 PbF_2)
crystals purchased from SICCAS
Ready for first beam 2014

Hall C:
53 days approved (PAC40)
HMS ×(new $PbWO_4$ calorimeter)

Systematic errors on absolute cross sections < 4%
Statistics equilibrated in all (Q^2,x_B) bins

CLAS12



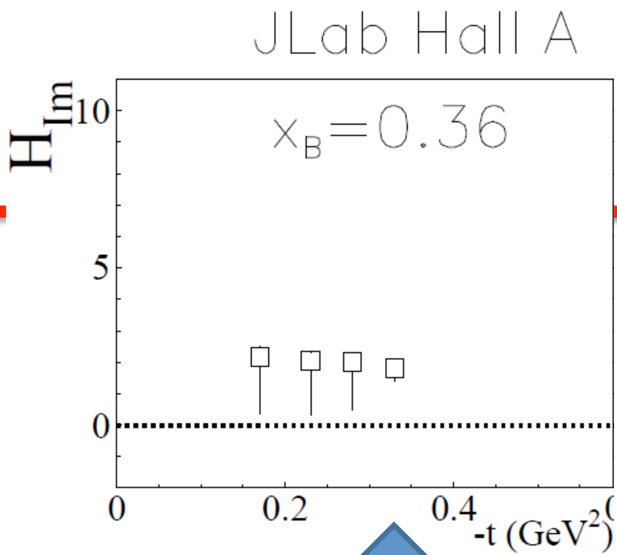
- GPDs & TMDs
- Nucleon Spin Structure
- N* Form Factors
- Baryon Spectroscopy
- Hadron Formation

DVCS with CLAS at 12 GeV

- 80 days on H_2 target at ~10^{35} /cm^2/s
- 120 days on Longitudinally Polarized NH_3 target
  - Total Luminosity 10^{35} /cm^2/s, dilution factor ~1/10
- $D(e,e'\gamma n)p_S$
- $^4He(e,e'\ \gamma\alpha)$ with upgraded BoNUS detector
  - GEM based radial TPC for recoil α-detection
- Ambitions/options for Transversely polarized targets
  - NH_3 target has 5 T transverse field
    - need to shield detectors from "sheet of flame"
    - Reduce (Luminosity)•(Acceptance) by factor of 10 (my guess)
  - HD-ice target (weak holding field, less dilution)
    - Development in progress for transversely polarized H
    - Luminosity•(polarization)^2 not yet known
  - Polarized ^3He also possible

Global analyses of GPD data

- K. Kumericki, D. Mueller, M. Murray,
  - arXiv:1301.1230 hep-ph, arXiv:1302.7308 hep-ph
- M. Guidal, H.Moutarde, EPJA **42** (2009) 71.
- M. Guidal,
  - PLB **689** (2010) 159, PLB **693** (2010) 17.
- LO, or NLO implemented
  - Kinematic twist-3 contributions known
    - (V. Braun, 2013).
- Dynamic twist-3 formalism known, not implemented in global analysis yet.



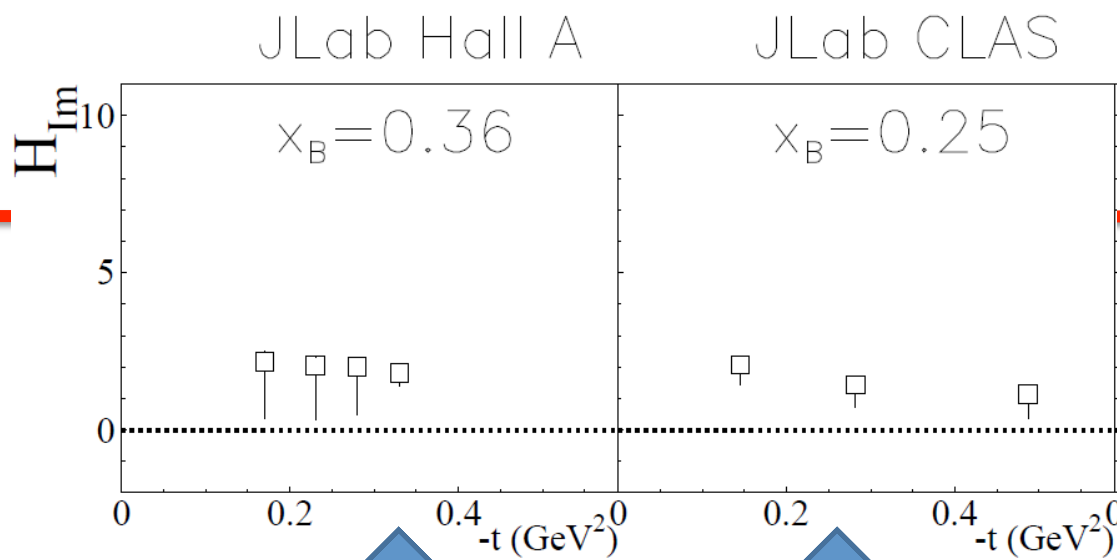
unpol. cross section

+

helicity-dependent cross section

- **χ^2 minimization**

$$\Delta\sigma_{LU} \sim \sin\phi \; \mathrm{Im}\{F_1\mathcal{H} + \xi(F_1+F_2)\widetilde{\mathcal{H}} - kF_2\mathcal{E}\}d\phi$$



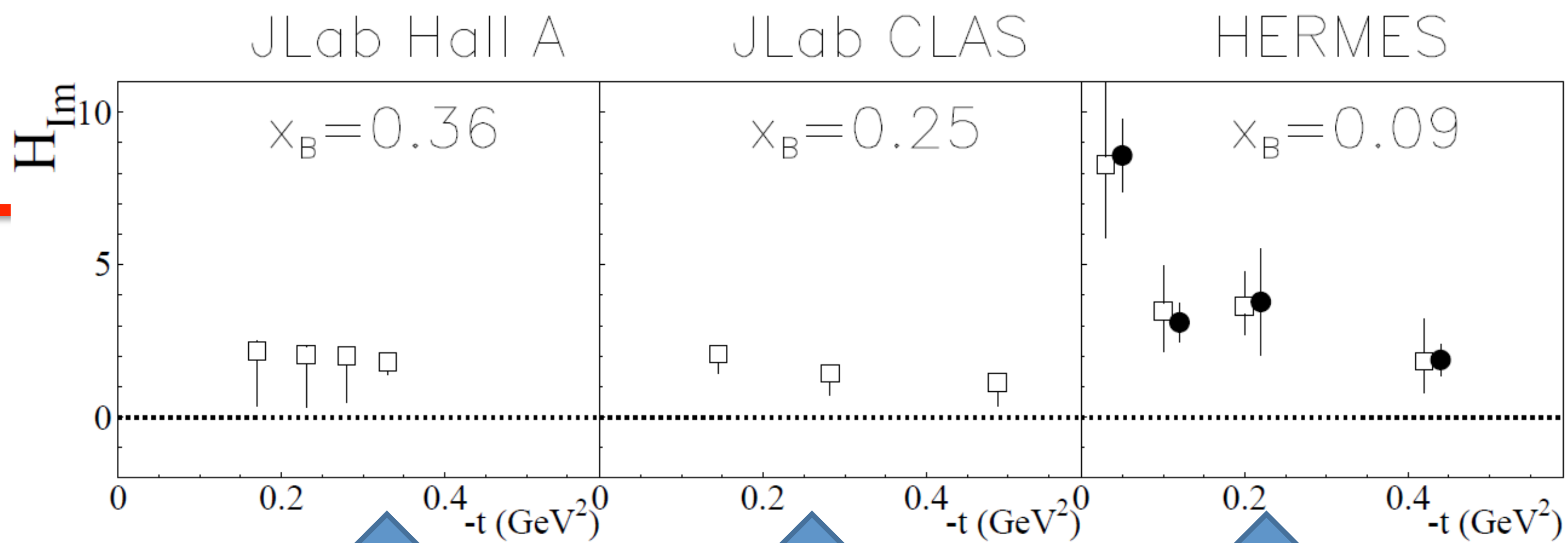
unpol. cross section
+
helicity-dependent cross section

beam spin asym.
+
long. pol. tar. asym

- **χ^2 minimization**

$$\Delta\sigma_{LU} \sim \sin\phi \; \mathrm{Im}\{F_1\mathcal{H} + \xi(F_1+F_2)\widetilde{\mathcal{H}} - kF_2\mathcal{E}\}d\phi$$

$$\Delta\sigma_{UL} \sim \sin\phi \mathrm{Im}\{F_1\widetilde{\mathcal{H}} + \xi(F_1+F_2)(\mathcal{H} + x_B/2\mathcal{E}) - \xi kF_2 \widetilde{\mathcal{E}} + \ldots\}d\phi$$



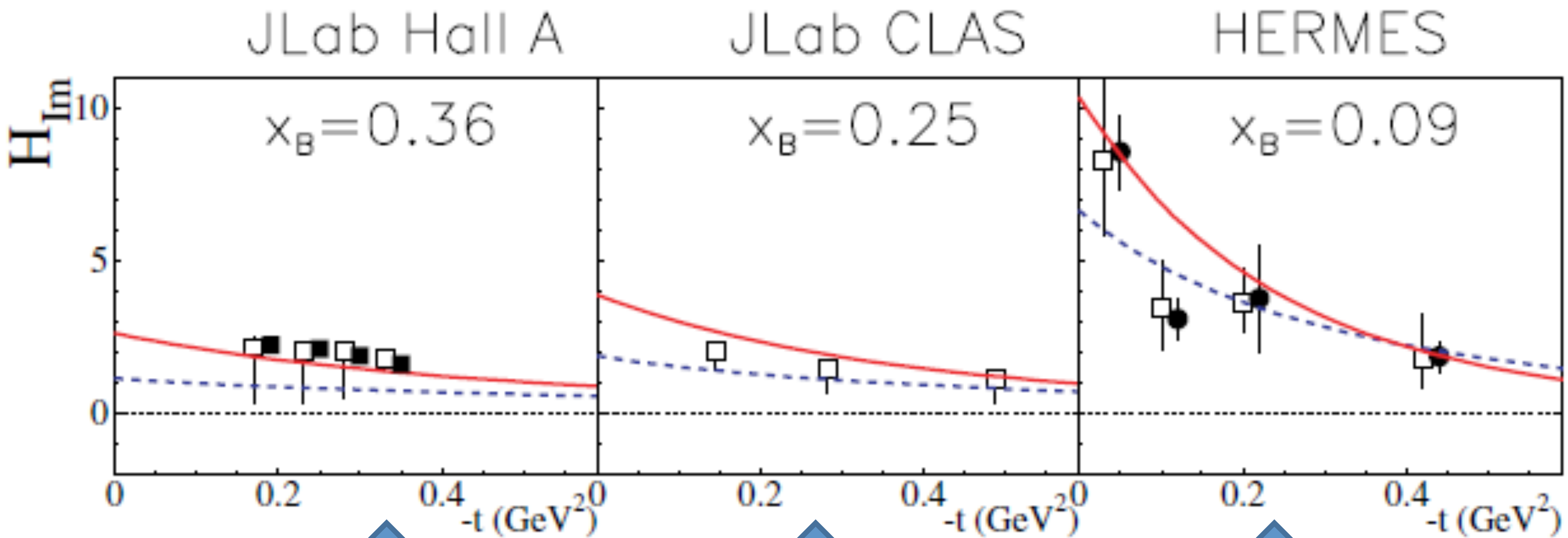
unpol. cross section + helicity-dependent cross section	beam spin asym. + long. pol. tar. asym	beam charge asym. + beam spin asym + …

□ χ^2 **minimization**

● **linearization**

$$\Delta\sigma_{LU} \sim \sin\phi \; \mathrm{Im}\{F_1\mathcal{H} + \xi(F_1+F_2)\widetilde{\mathcal{H}} - kF_2\mathcal{E}\}d\phi$$

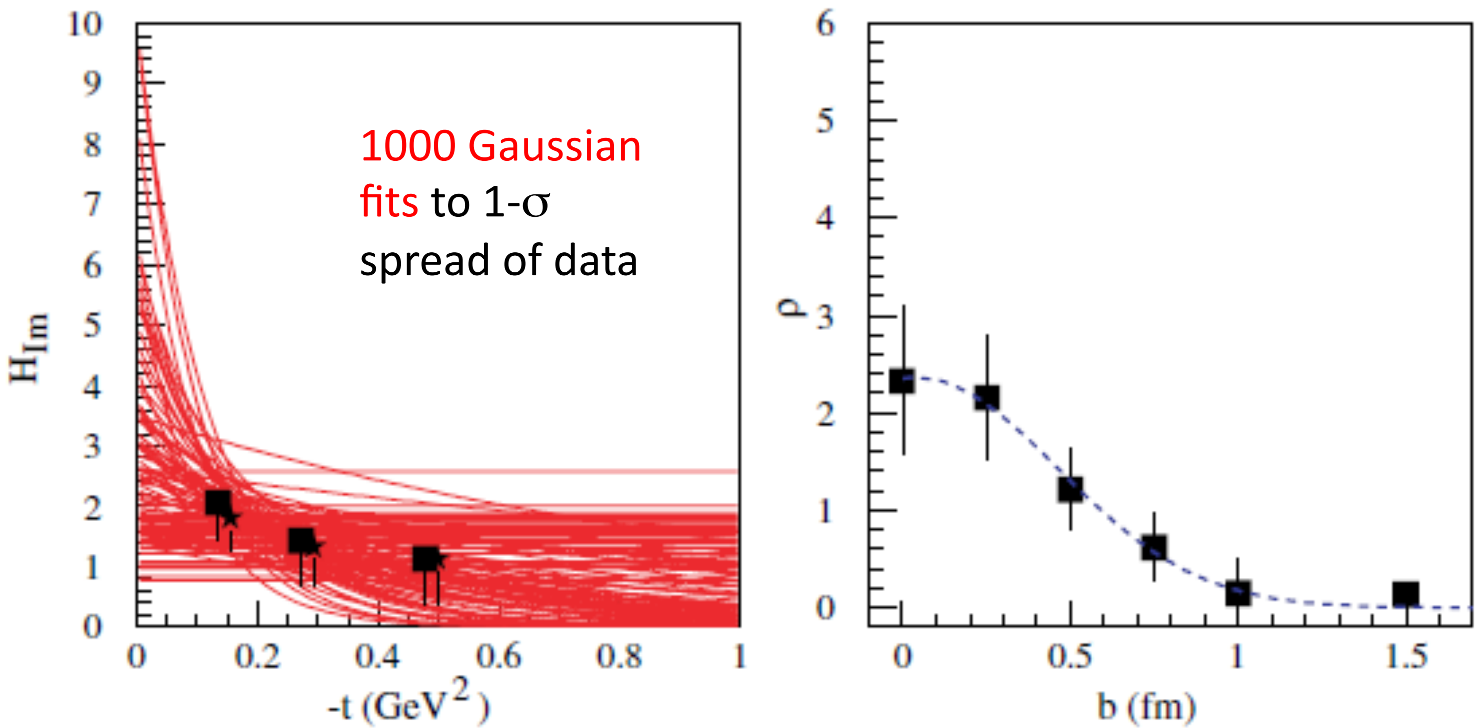
$$\Delta\sigma_{UL} \sim \sin\phi \mathrm{Im}\{F_1\widetilde{\mathcal{H}}+\xi(F_1+F_2)(\mathcal{H} + x_B/2\mathcal{E}) - \xi kF_2\,\widetilde{\mathcal{E}}+\ldots\}d\phi$$



unpol.sec.eff.	beam spin asym.	beam charge asym.
+	+	+
beam pol.sec.eff.	long. pol. tar. asym	beam spin asym
		+
		…

- □ χ^2 minimization
- ● linearization
- ■ Moutarde 10 model/fit
- red solid line: VGG model
- blue dashed line: KM10 model/fit

From GPDs to spatial images
Sample exercise with CLAS data (x_B=0.25)



"skewed" H_{Im}

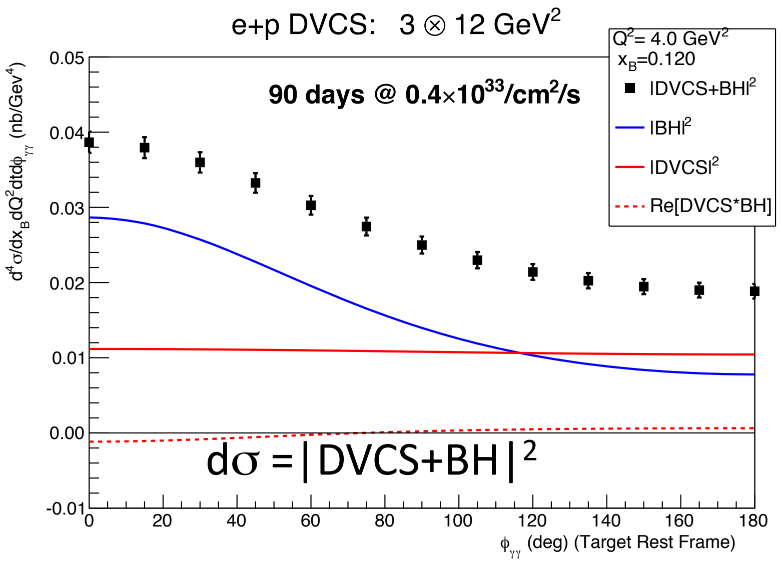
"unskewed" H_{Im}

(fits applied to « unskewed » data)

Highlights of Generalized Parton Distributions

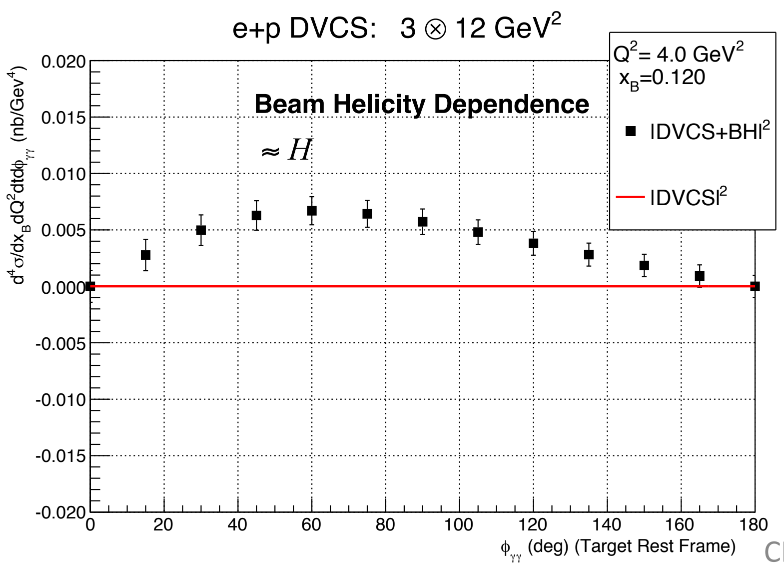
- Spatial imaging of quarks and gluons
  - Consistent with Q.M. and Relativity.
- Integrals of GPDs are measurable
  - DVCS, DVES ➔ GPD(ξ,ξ,Δ^2) for $Q^2 >> \Lambda^2_{QCD}$
  - Extensive program in preparation at JLab
- (Positive) Moments are calculable in Lattice QCD
- Models are improving in sophistication.
  - Data precision already exceeds predictive power of models and flexibility of parameterizations.
- DVCS (and related deep exclusive meson production) will be a multi-decade effort
  - Each stage can teach us something new and interesting about how QCD generates force, mass, spin, *etc*.

EIC@HIAF: DVCS

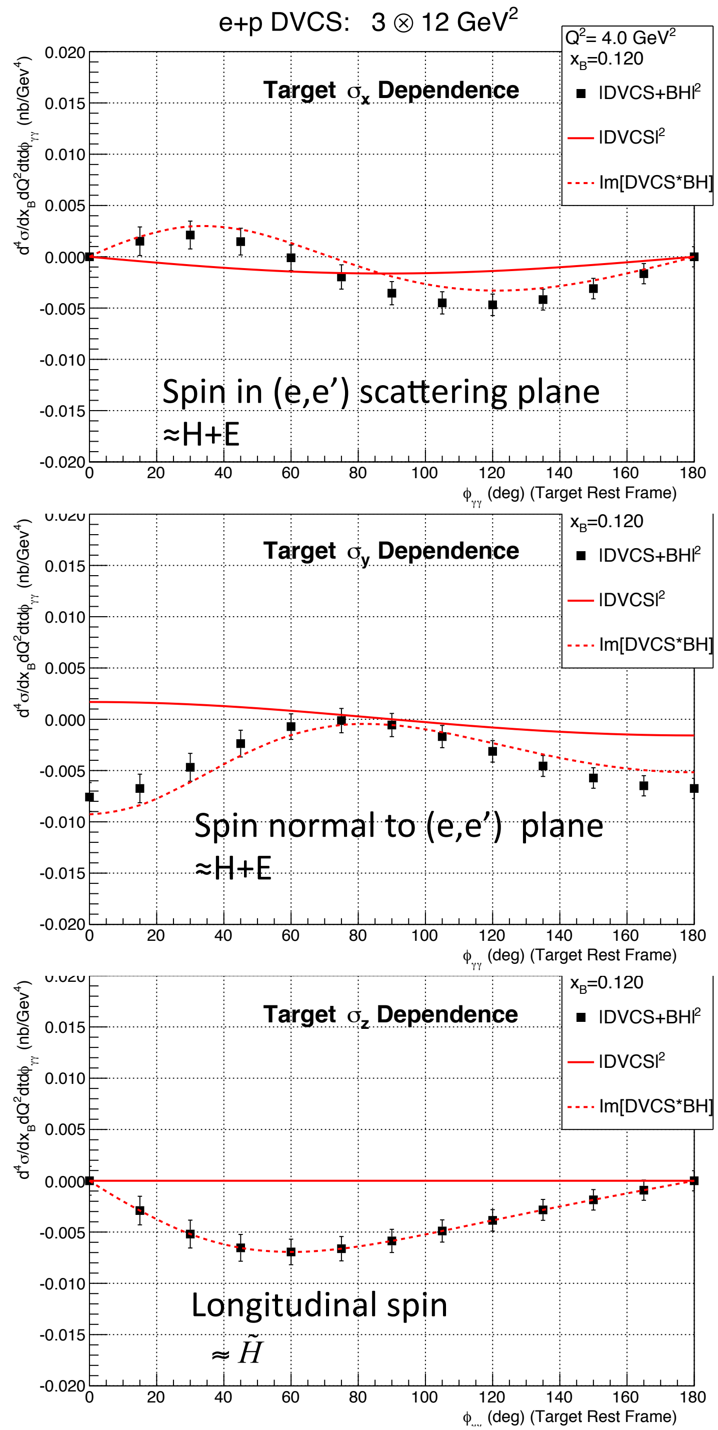


Acceptance

$$\Delta Q^2 \Delta x_b \Delta t = \frac{Q^2}{\sqrt{2}} \frac{x_b}{\sqrt{2}} \left(0.1\ \mathrm{GeV}^2\right)$$



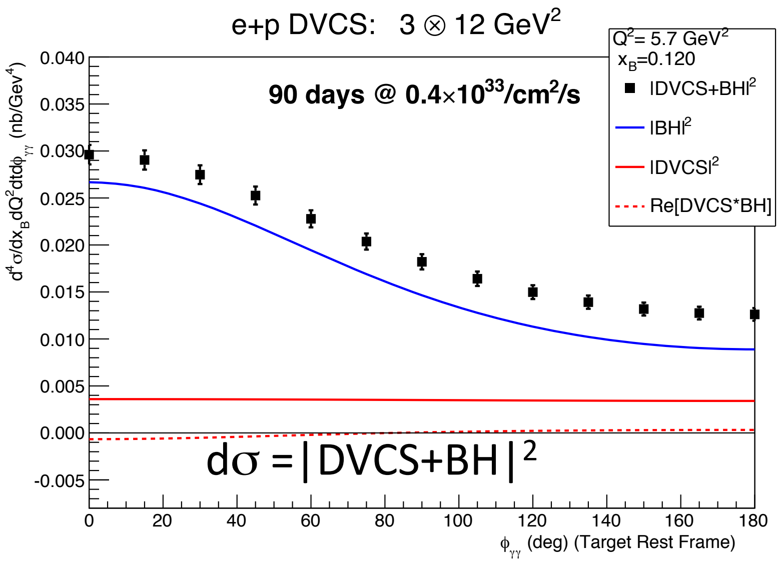
Single Spin Observables: $\mathrm{Im}[\mathrm{DVCS}^{\dagger}\mathrm{BH}]$



CHyde, Huangshan 2013

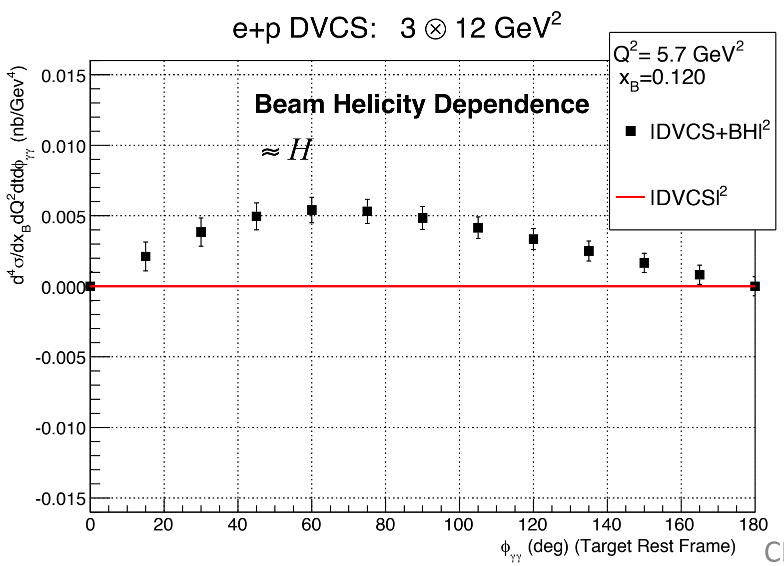
EIC@HIAF: DVCS

Higher Q^2

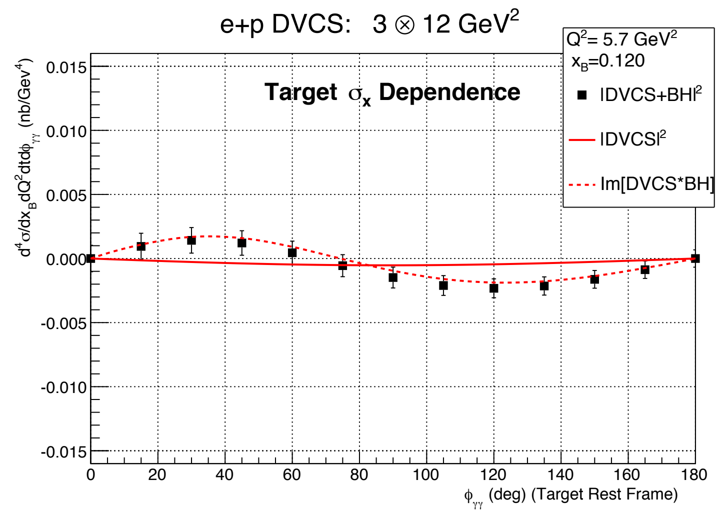


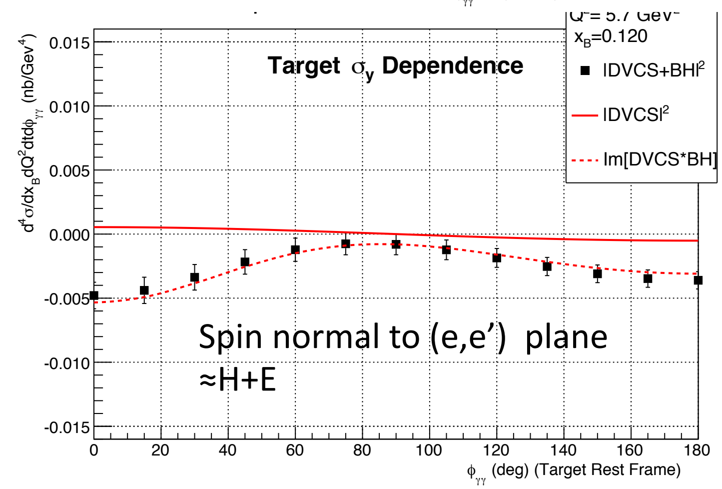
Acceptance

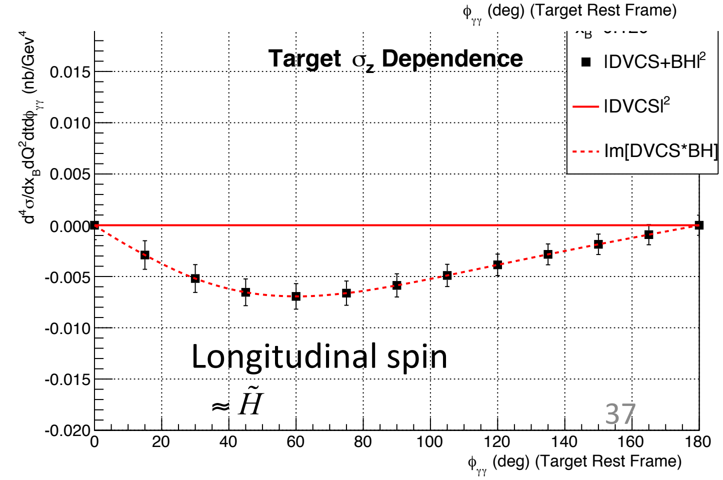
$$\Delta Q^2 \Delta x_b \Delta t = \frac{Q^2}{\sqrt{2}} \frac{x_b}{\sqrt{2}} \left(0.1\ \mathrm{GeV}^2\right)$$



Single Spin Observables: Im[DVCS†BH]

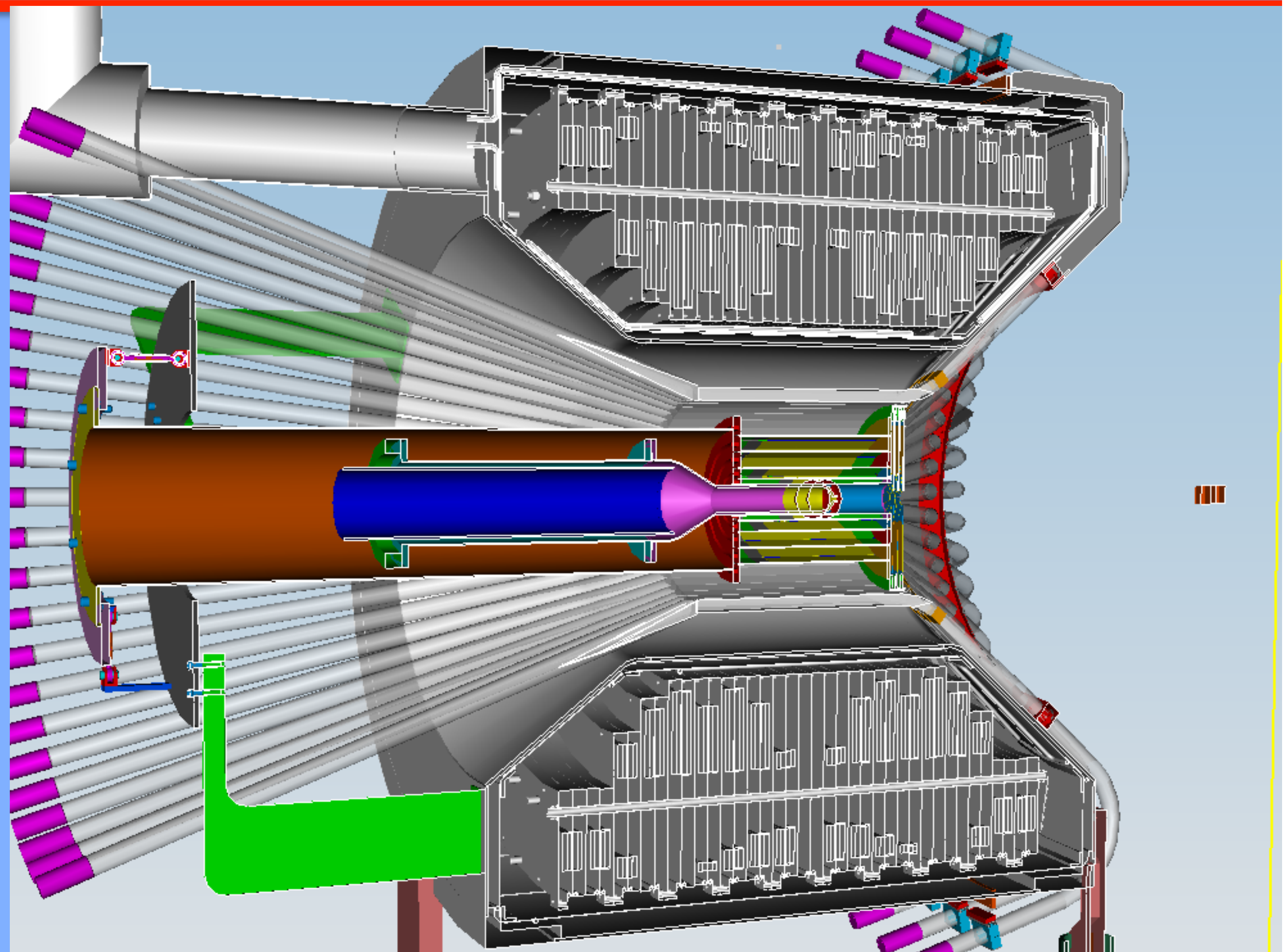




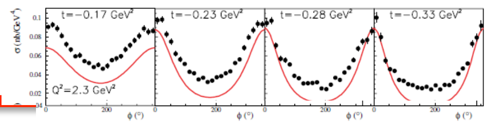


CLAS12 – Central Detector SVT, CTOF

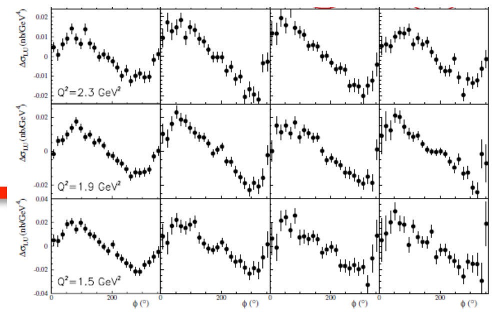
- Charged particle tracking in 5T field
- ΔT < 60psec in for particle id
- Moller electron shield
- Polarized target operation $\Delta B/B<10^{-4}$



JLab
Hall A

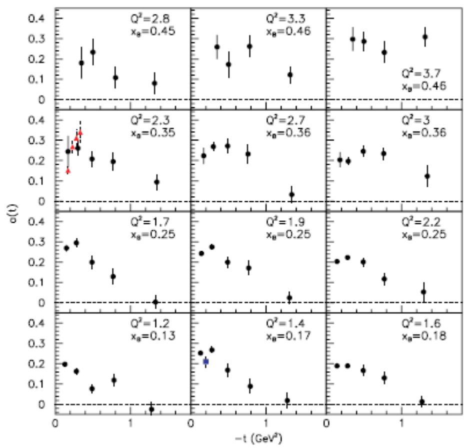


DVCS
unpol. X-section

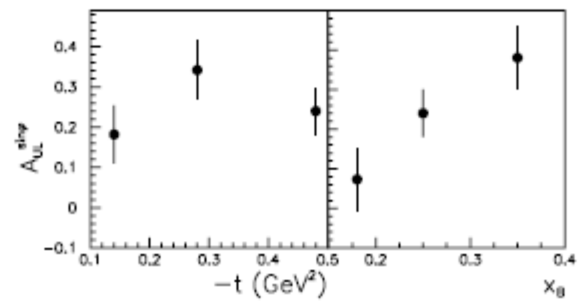


DVCS
B-pol. X-section

JLab
CLAS

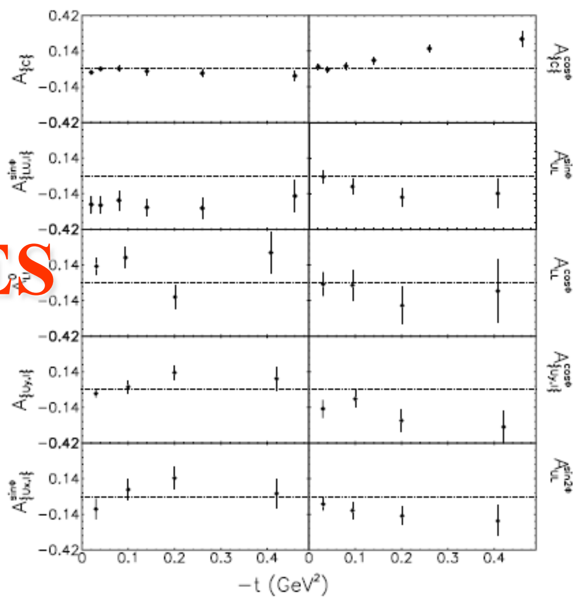


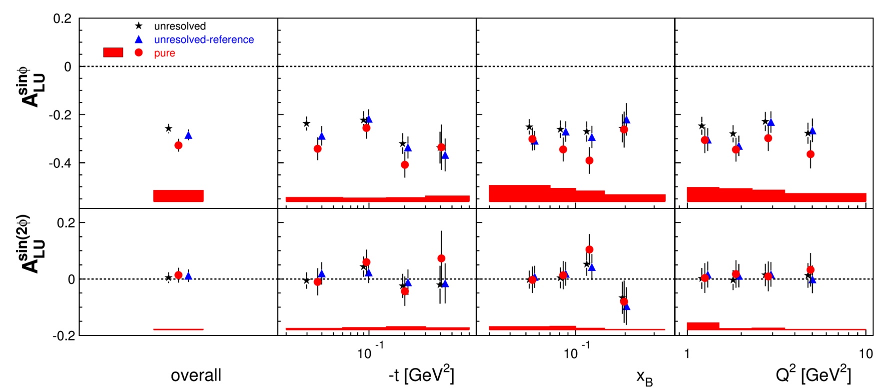
DVCS
BSA



DVCS
lTSA

HERMES



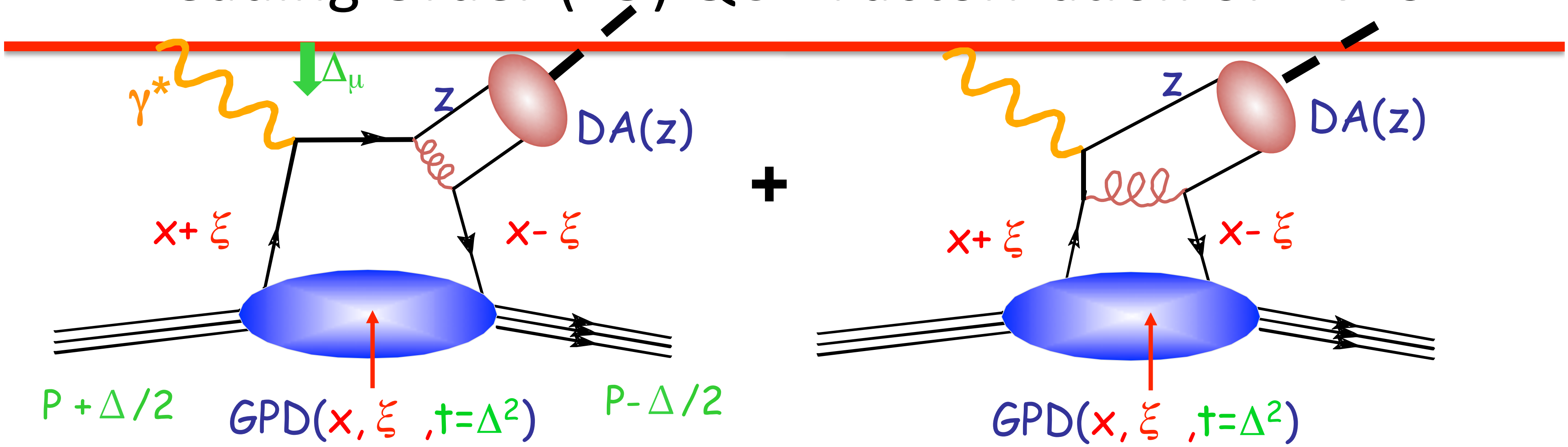


DVCS
BSA,lTSA,tTSA,BCA

Deep Virtual Meson Production

- Spin-flavor sensistivity
- Gluons
  - Gluons are still important at large-x

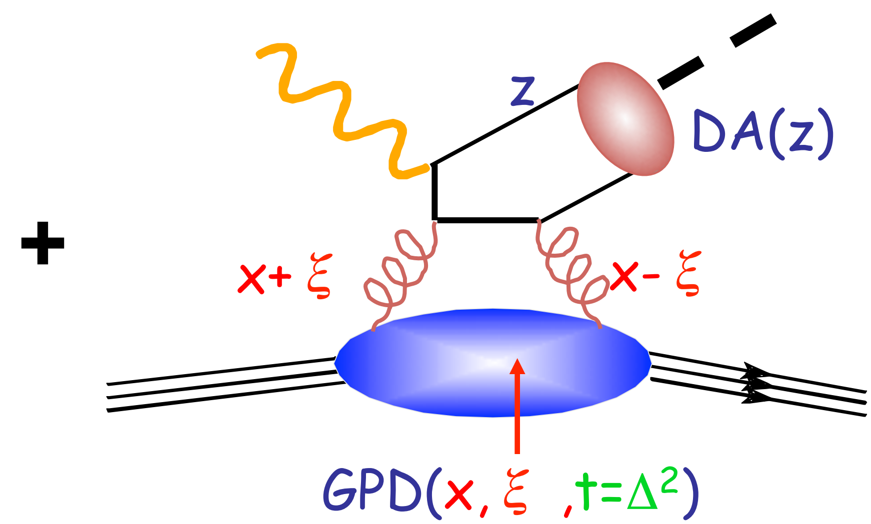
Leading Order (LO) QCD Factorization of DVES



Gluon and quark GPDs enter to same order in α_S.

SCHC: $\sigma_L \sim [Q^2]^{-3}$ $\sigma_T \sim [Q^2]^{-4}$

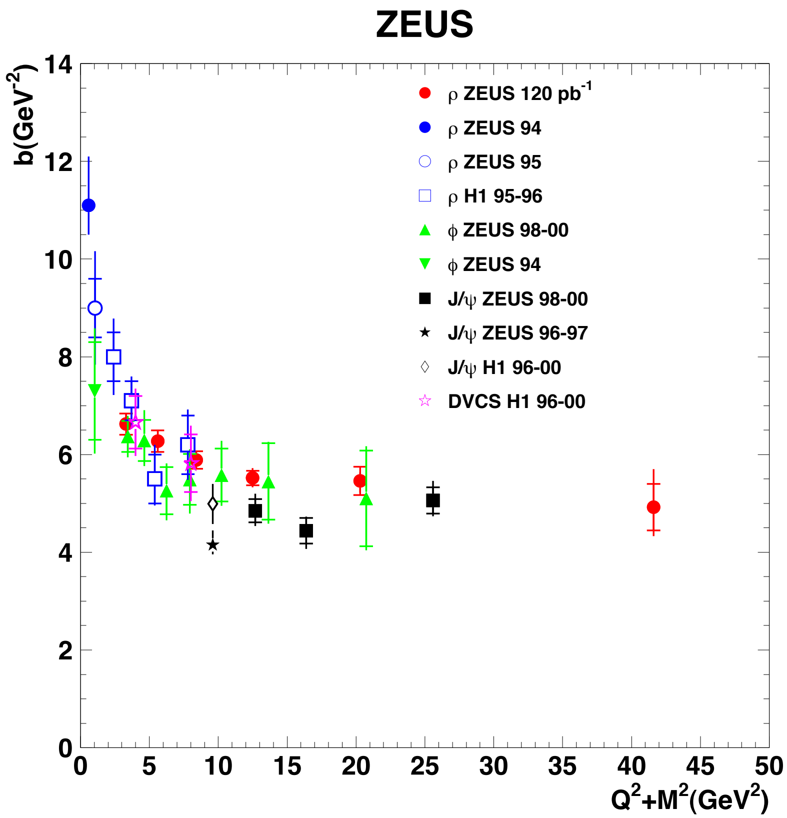
Spin/Flavor selectivity



[Diffractive channels only]

Semi Universal behavior of exclusive reactions at high W^2

- Two views:
  - Extracting leading twist information is hopeless for $Q^2+q'^2<10$ GeV^2
  - Perturbative *t*-channel exchange even for modest Q^2, but convolution of finite size of nucleon and probe.
- Fitting data (cf C.Weiss) requires setting scale of gluon pdf $\mu^2 << Q^2$
  - Finite transverse spatial size $b \approx 1/\mu$ of $\gamma \rightarrow V$ amplitude



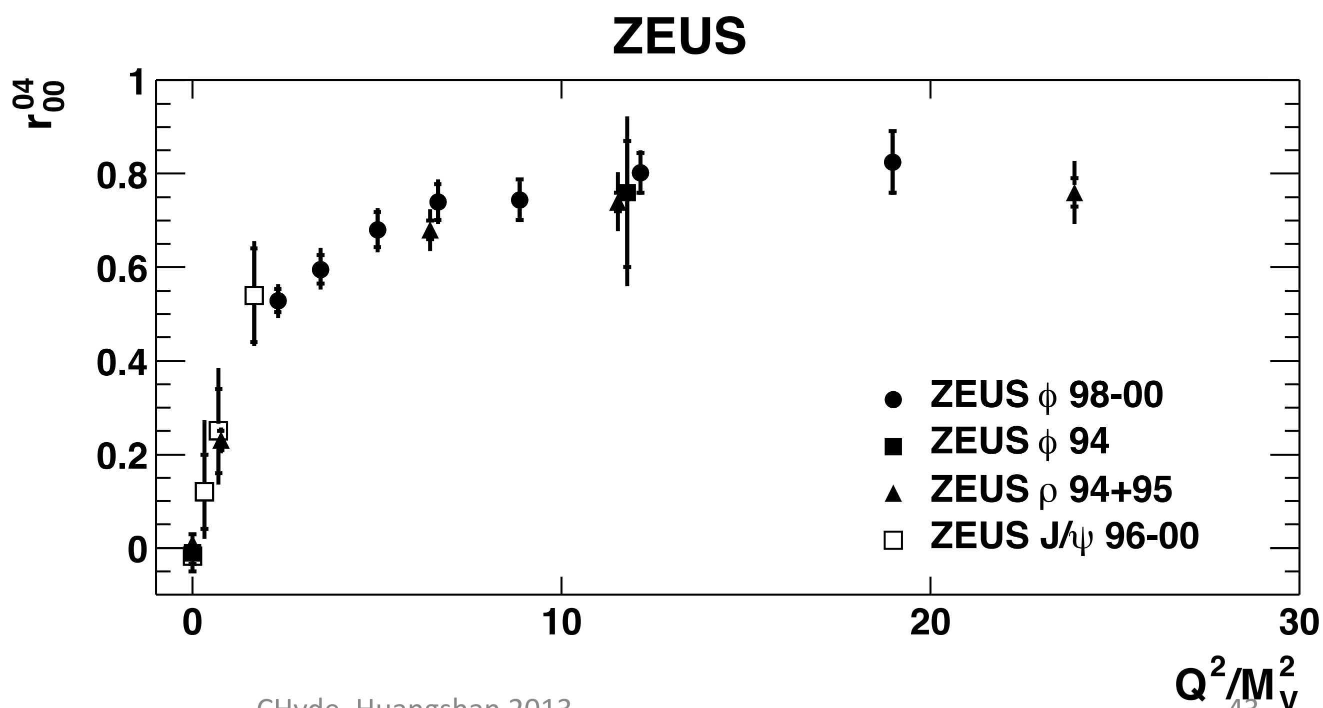
GWolf 0907.1217

σ_L/σ_T in vector meson production at HERA

- SCHC: $\rho \rightarrow \pi\pi$, $\omega \rightarrow \pi\pi\pi$, $\phi \rightarrow KK$
  - Validate SCHC from decay angular distribution (Schilling & Wolf)
  - Extract $d\sigma_L$ from

$$r_{00}^{04} = \frac{\varepsilon R}{1+\varepsilon R} = \frac{\varepsilon d\sigma_L}{d\sigma_T + \varepsilon d\sigma_L}$$

- Rapid rise in r^{04} *vs* Q^2:
  - Validation of perturbative exchange in *t*-channel.
- Sub-asymptotic saturation of $d\sigma_L/d\sigma_T$
  - Extra mechanism for $d\sigma_T$?

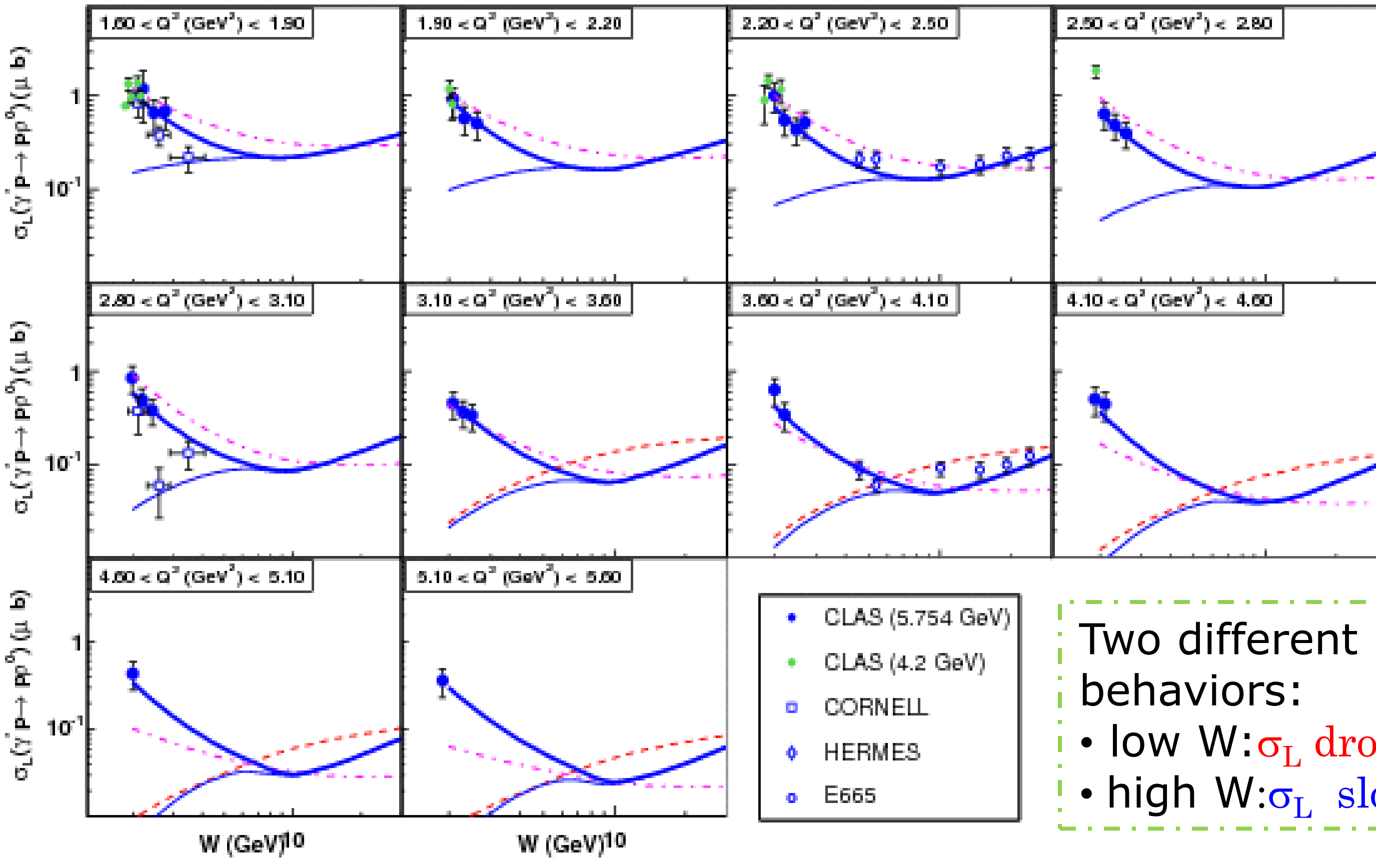


Vector Mesons at JLab

- Deep ρ
  - SCHC observed at 20% level
  - Anomalous rise in $d\sigma_L$ at low W
- Deep ω
  - SCHC strongly violated in CLAS data
  - No (??) SCHC tests from HERMES or HERA.
- Deep ϕ
  - SHCH validated
  - Model of P.Kroll & S.Goloskokov
    - (Eur.Phys.J. C53 (2008) 367-384) Consistent with world data set
    - Perturbative *t*-channel exchange (2*gluons*), but factor of 10 suppression relative to co-linear factorization from finite size (Sudakov) effects in $\gamma \rightarrow \phi$ transition amplitude

LONGITUDINAL CROSS SECTION σ_L ($\gamma^*_L P \rightarrow P\rho_L^0$)

S. Morrow et al., Eur. Phys. J. A 39 (2009) 5.



Two different behaviors:

- low W: σ_L drops
- high W: σ_L slowly rises

- --- GK [*]
- \- thin blue VGG [*]
- \- thick blue VGG + strong D-term [*]
- -.-.- dash-dotted JLM calculation *à la* Regge [*]

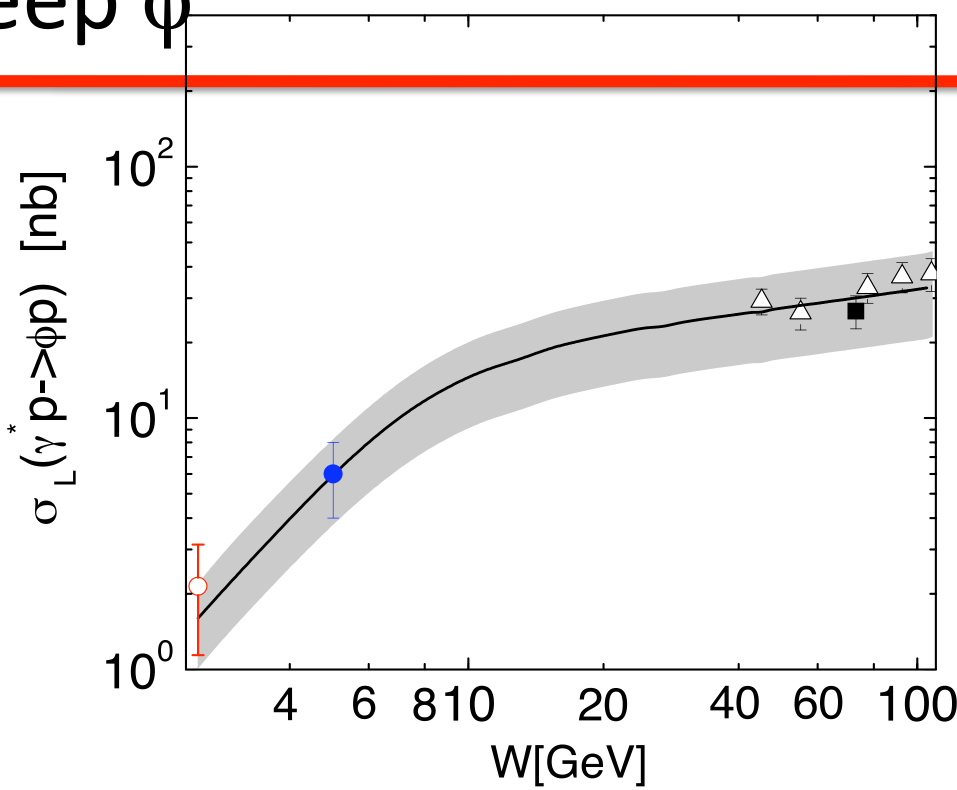
} GPD approaches based on Double-Distributions

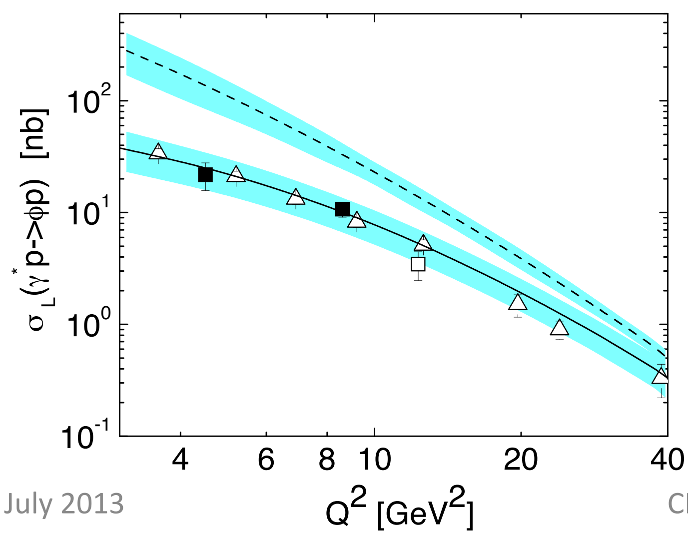
} Hadronic approach

* K. Goeke *et al.*, Prog. Part. Nucl. Phys. 47 (2001) 401.
* M. Guidal, M.V. Polyakov, A.V. Radyushkin and M. Vanderhaeghen, Phys. Rev. D72 (2005) 054013.
* F. Cano and J.-M. Laget, Phys. Rev. D 65 (2002) 074022

Deep ϕ

- $Q^2 \approx 2\ GeV^2$
  - CLAS, HERMES, HERA
- Model of S.Goloskokov and P. Kroll





Proposals/LOI in Hall B and Hall A

LOI for J/Ψ in Halls B and C.

The next 20 years of DVCS experiments

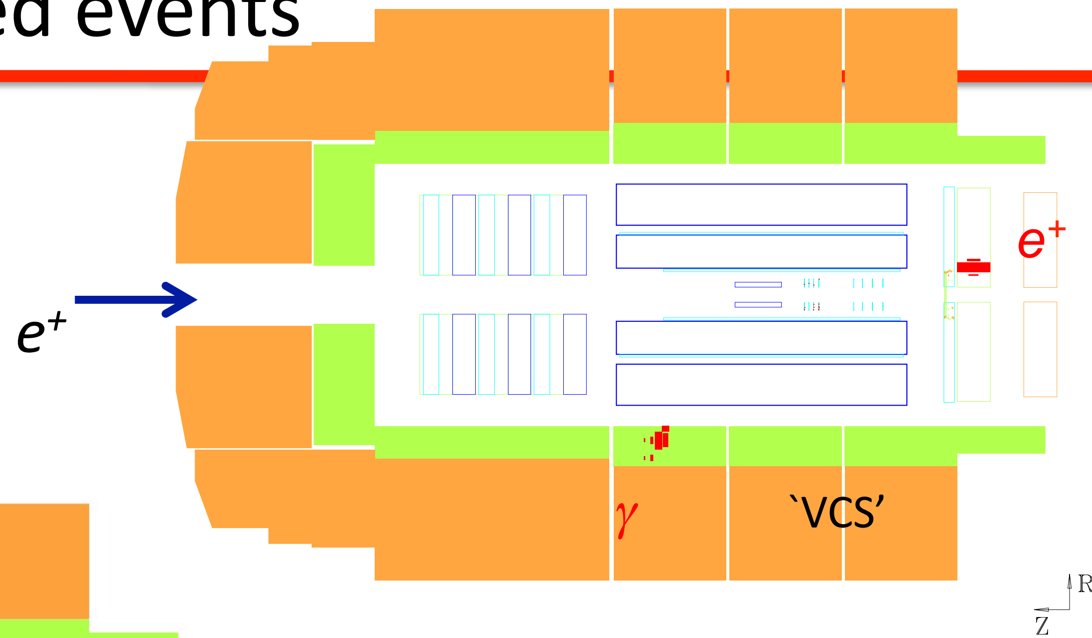
- 5 years
  - Precision tests of factorization with Q^2 range ≥ 2:1 for
    - $x_B \in [0.25,0.6]$. $t_{min}-t < 1$ GeV^2 + COMPASS : $x_B \in [0.01,0.1]$
    - Proton unpolarized target observables
    - Im[DVCS*BH], Re [DVCS*BH], $|DVCS|^2$.
  - Longitudinal, target spin observables
    - Primary sensitivity to H, ˜H, at $x = \pm\xi = \pm x_B/(2-x_B)$ point.
  - Partial *u,d* flavor separations from quasi-free neutron.
  - Coherent Nuclear DVCS on D, He
- 5-10 years
  - Transversely Polarized H, D, ^{3}He in JLab Halls A,B,C
    - Optimize targets
    - Improved recoil/spectator detection?
  - Polarized targets at COMPASS?
- 10-15 years: Build electron ion collider with s≥1000 GeV^2 and L > $2 \bullet 10^{34}$ /cm^2/s.

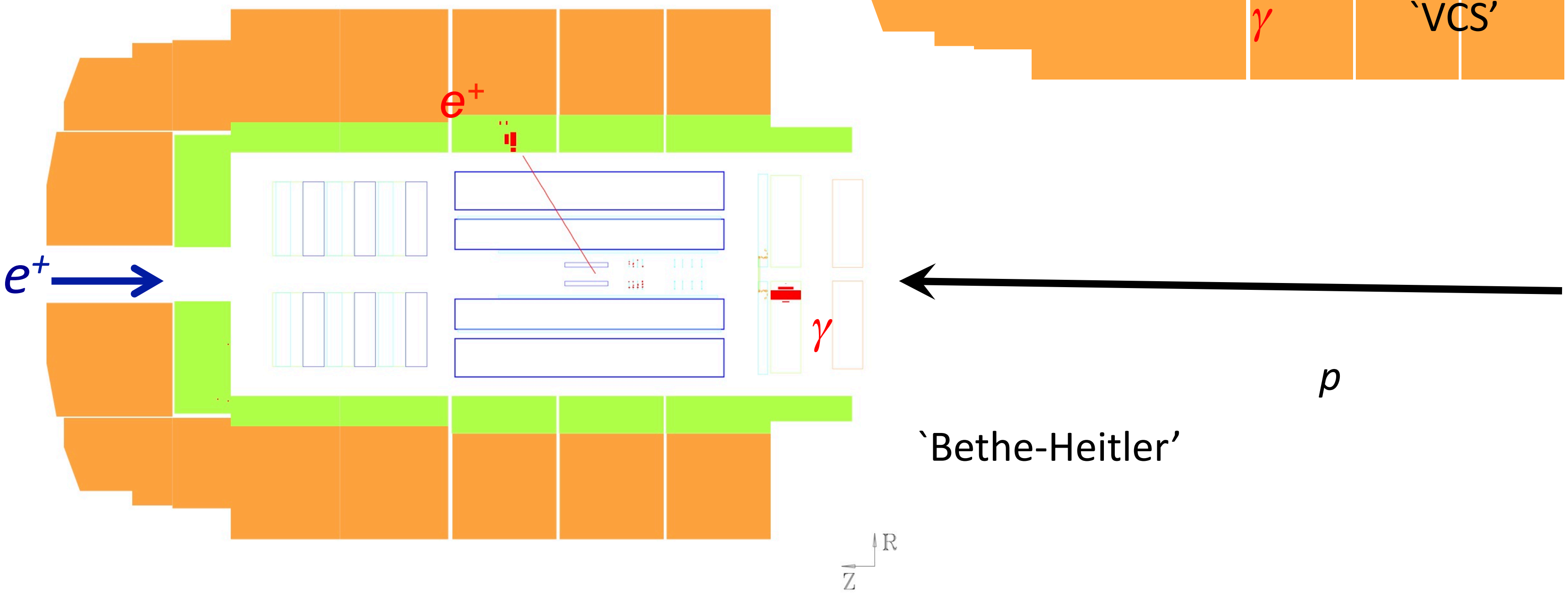
Back-up Slides

HERA and HERMES

HERA-H1: Sample VCS-dominated; and BH-dominated events

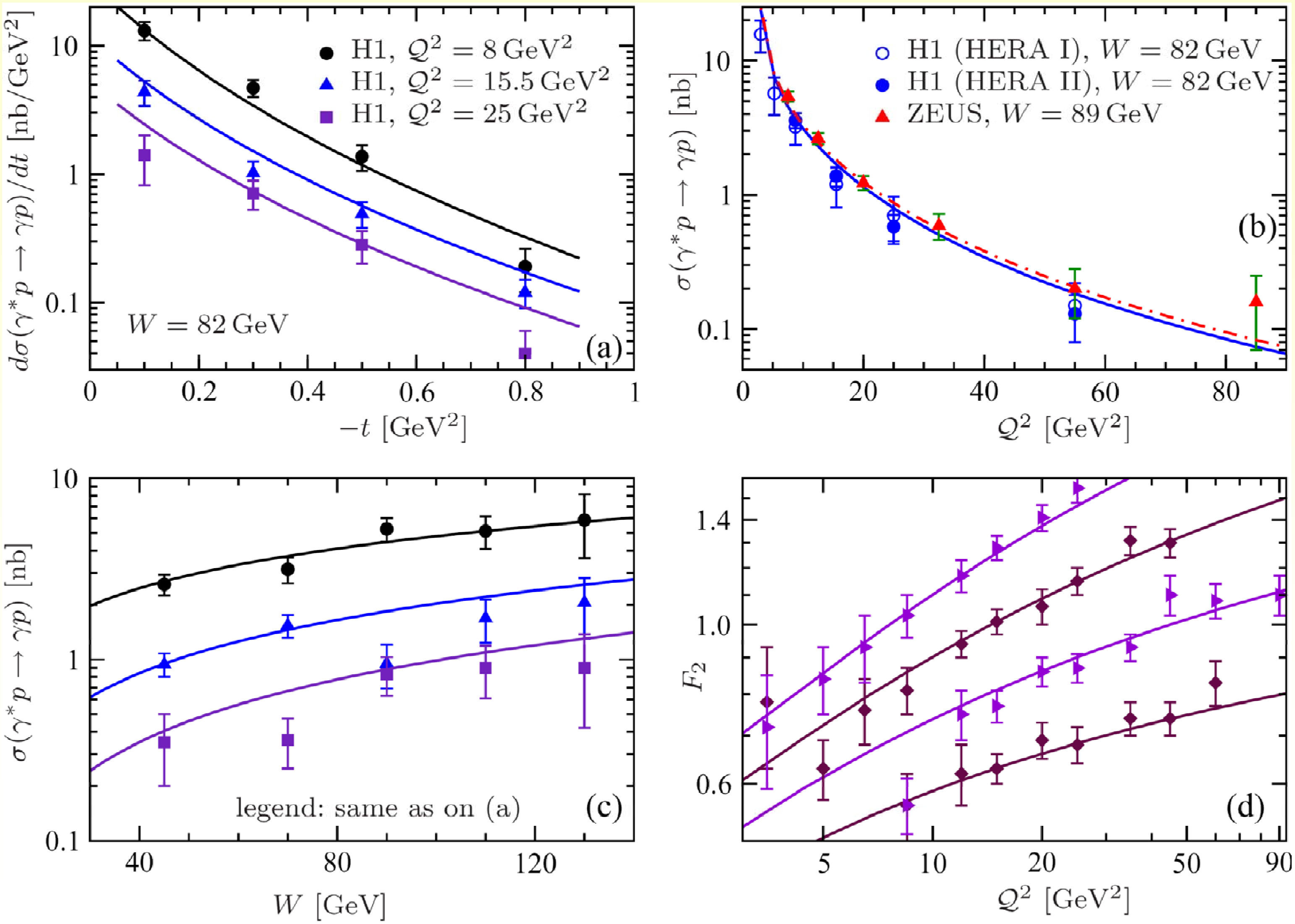
ep→eγX
X is ultra-forward (left)→
no visible energy →
dominated by exclusive





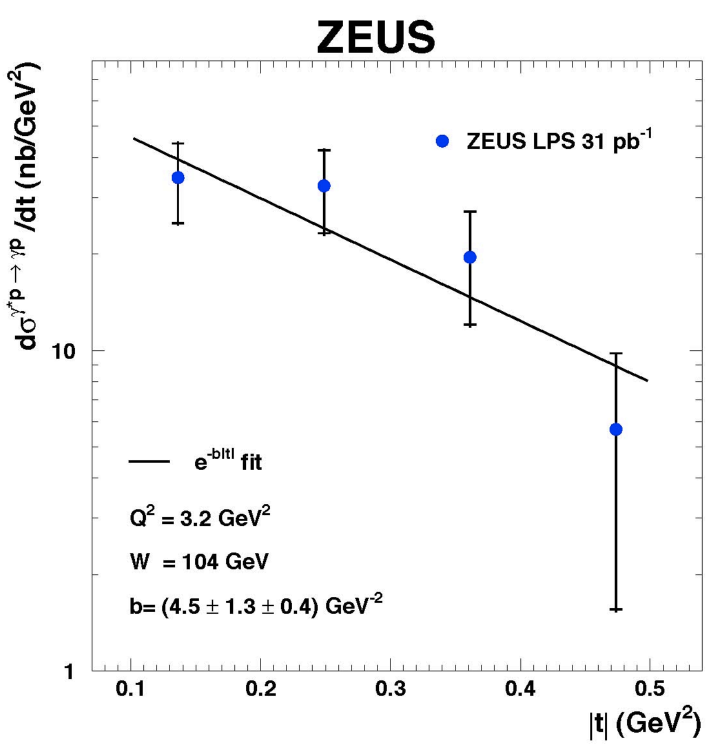
HERA DVCS, fits by D.Muller *et al., 2012* for EIC whitepaper

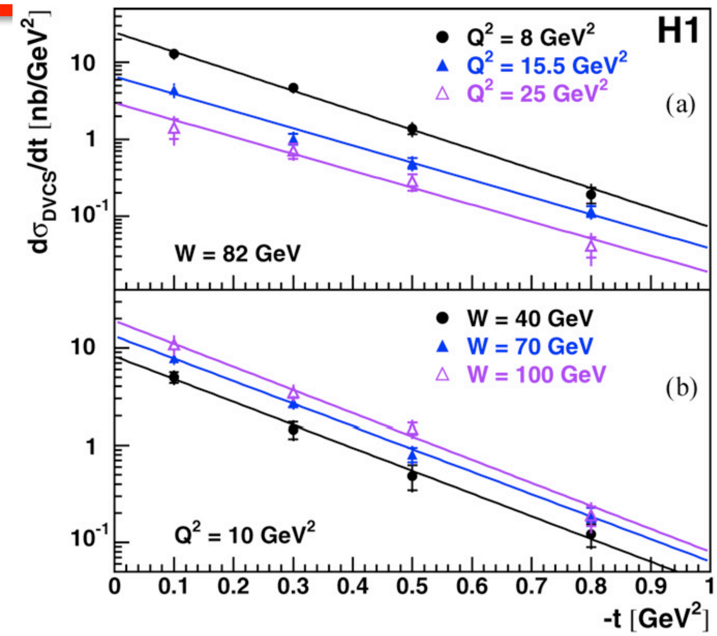
good DVCS fits at LO, NLO, and NNLO with flexible GPD ansatz

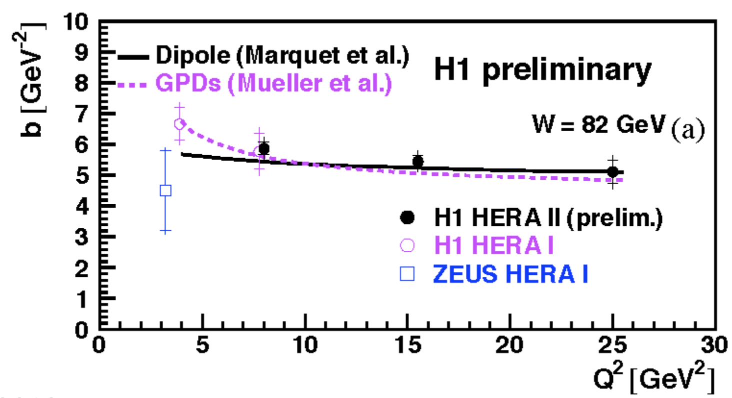


HERA DVCS

- Spatial imaging of gluons at small x_B

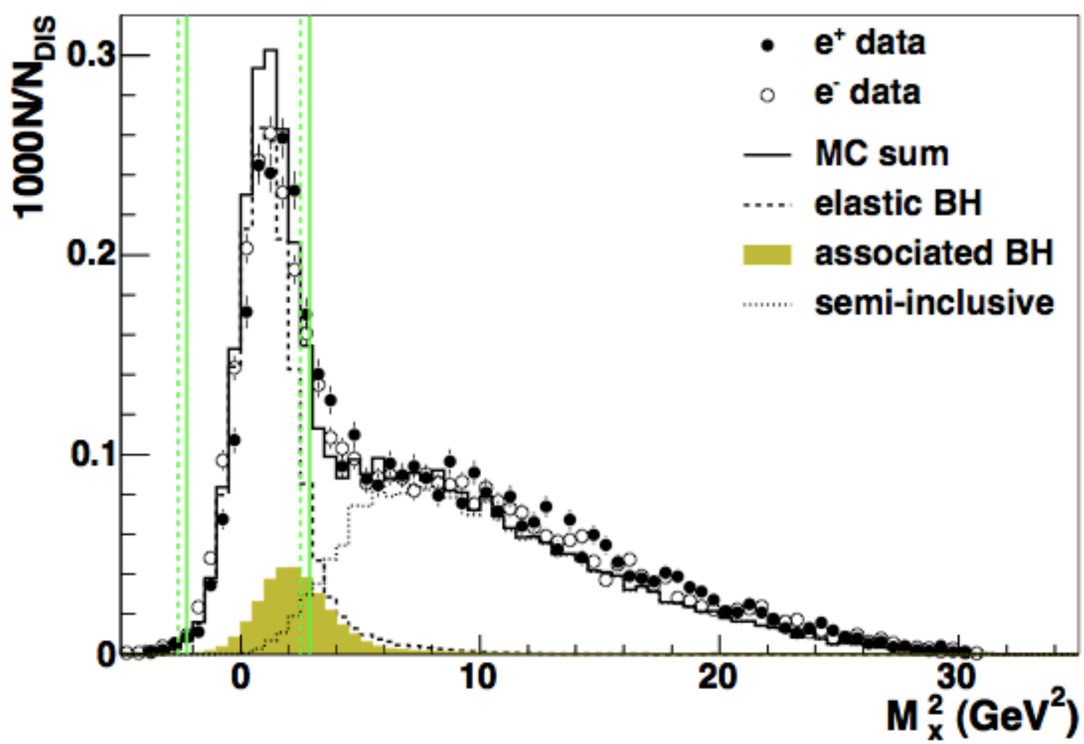




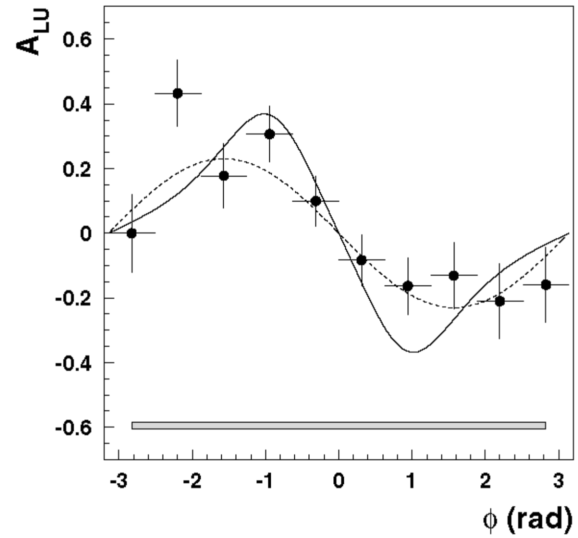


HERMES DVCS p(e,e'γ)X

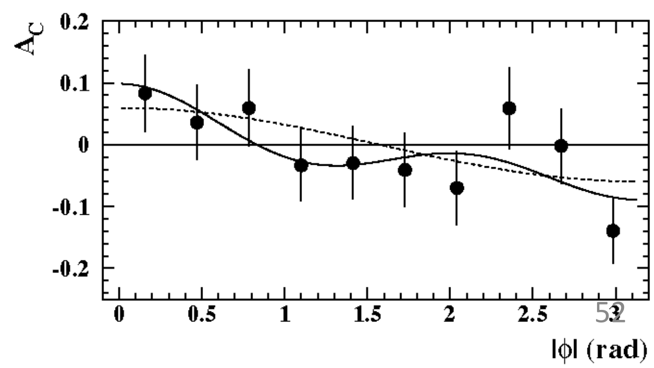
27 GeV polarized $e^{\pm}$ on
Internal Gas Jet
/ Atomic Beam Source targets



2001 BSA



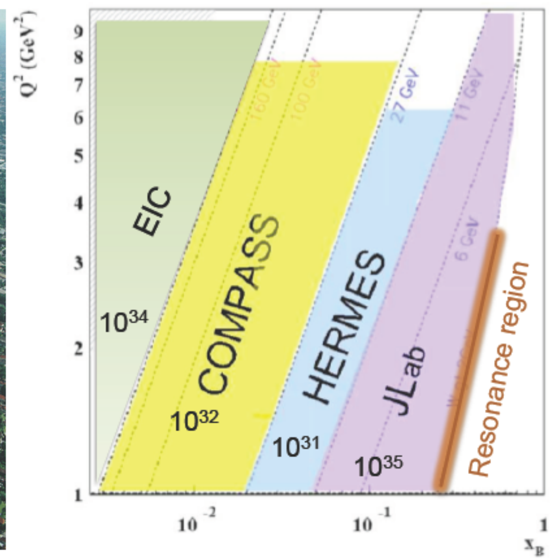
2006 BCA



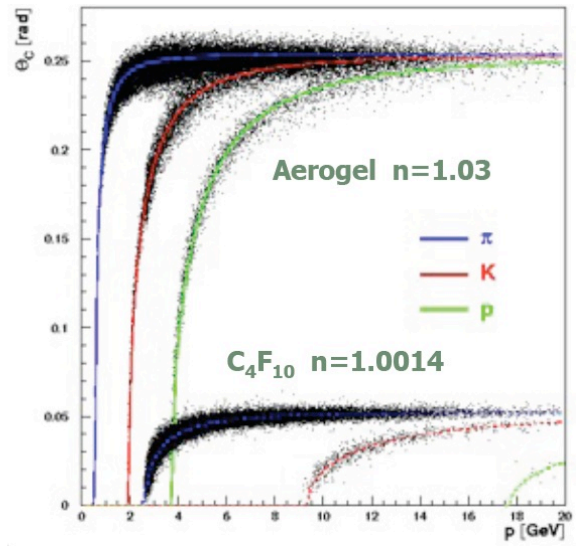
HERMES overview

27.6 GeV e+/e- HERA beam

Access to valence and sea



Electron and Hadron ID

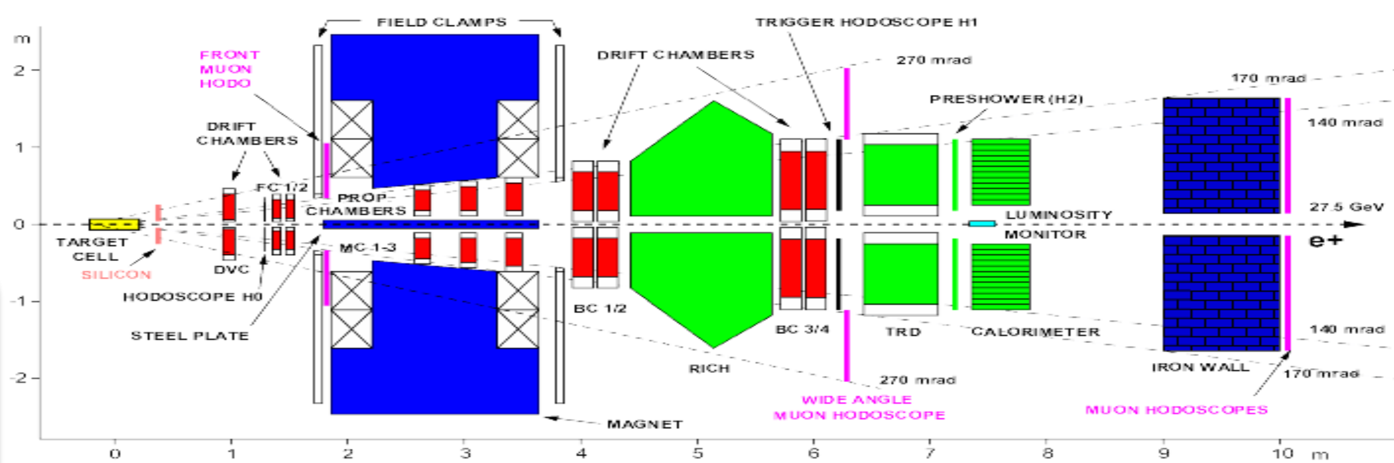


hermes

Data taking: 95-07

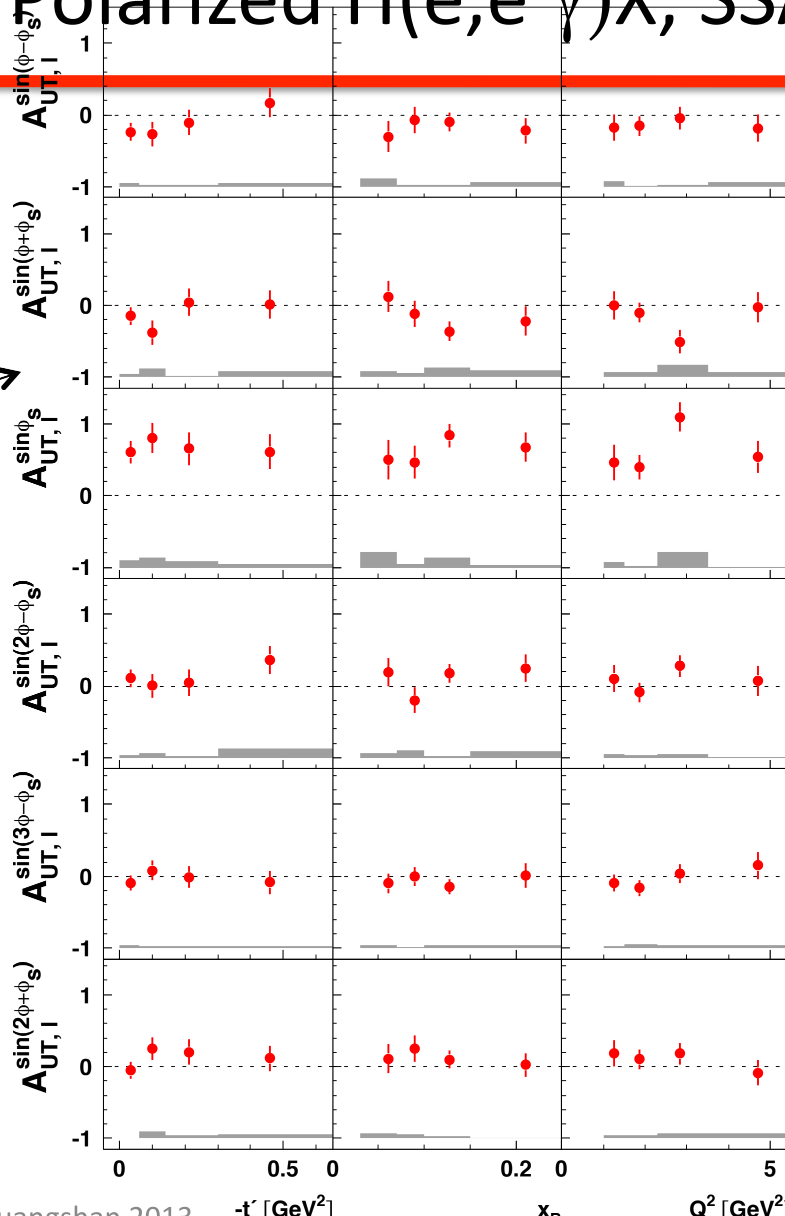
Internal gaseous target (no nuclear effects)

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



HERMES-Transversely Polarized H(e,e'γ)X, SSA

- Azimuthal moments
- Differential in x_{Bj}, Q^2, **or** t, integrated over other 2 variables.
- sinϕ moments
  - Sensitive to $E(\xi,\xi,t)$
- sin2ϕ moments ≈ 0
  - ≈ Twist 3
- sin3ϕ moments
  - ≈Gluon Transversity

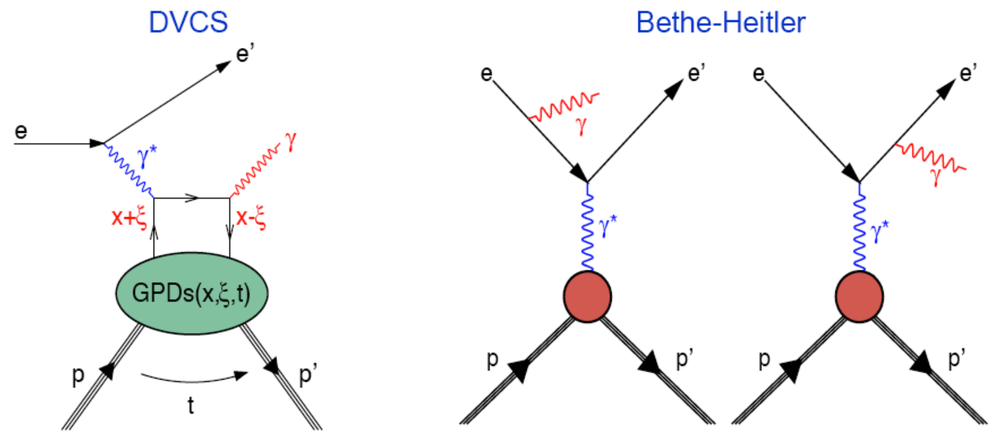


Deeply virtual Compton scattering

Theoretically cleanest
way to access GPDs

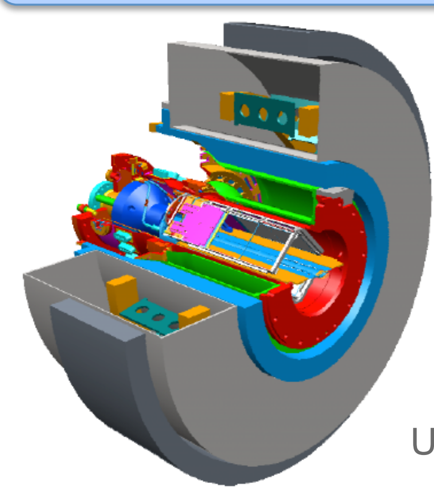
@ HERMES:

Large BH amplitude enhances
DVCS signal via interference



Complete set of beam helicity, beam charge, target polarization asymmetries

Recoil detector to tag exclusivity



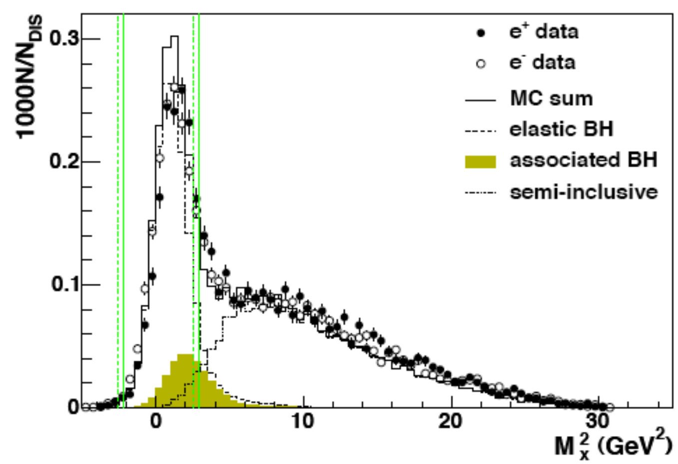
1T SC Solenoid

Photon Detector

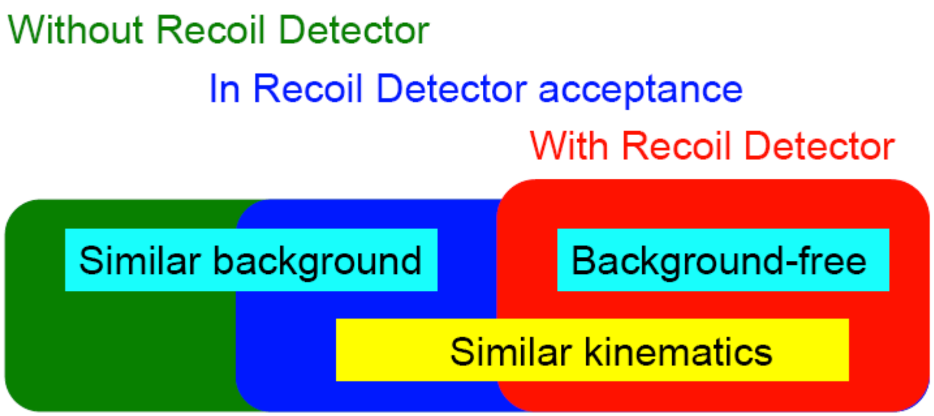
Scintillating Fiber Tracker

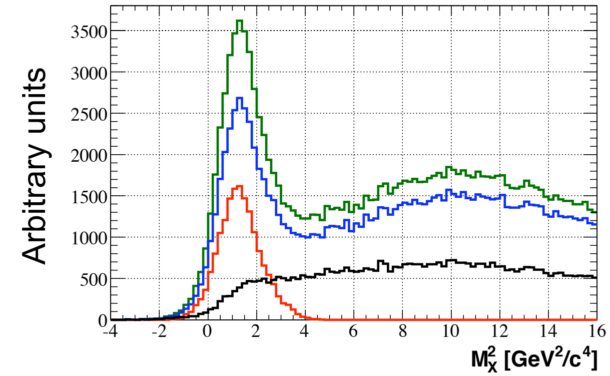
Silicon Strip Detector

Unpolarized H and D targets

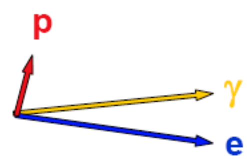


The recoil detector

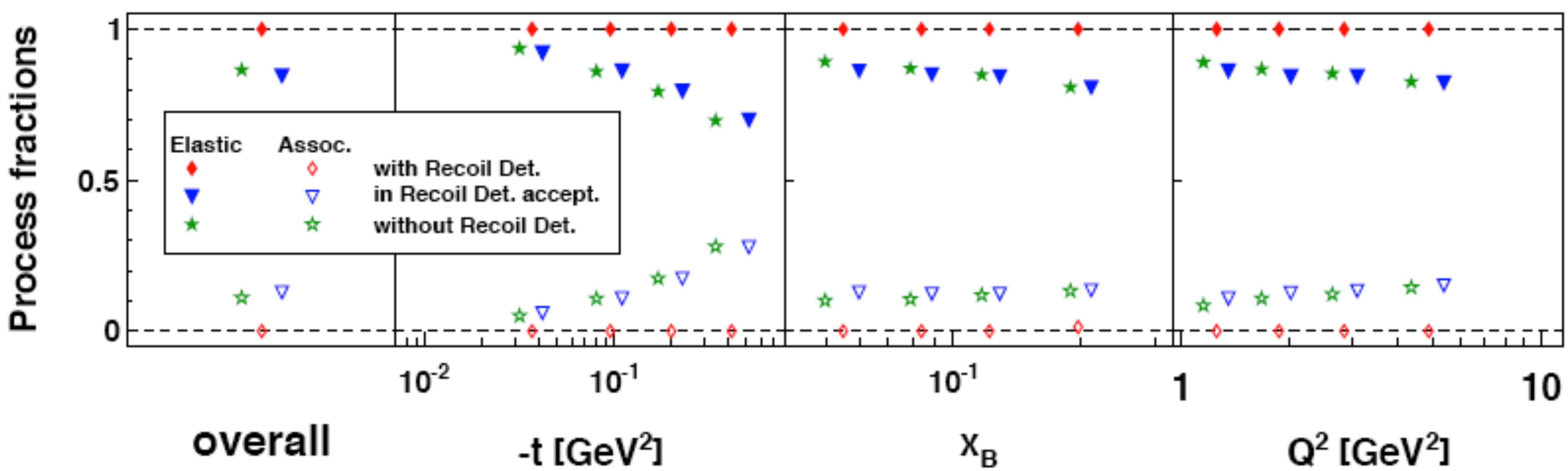




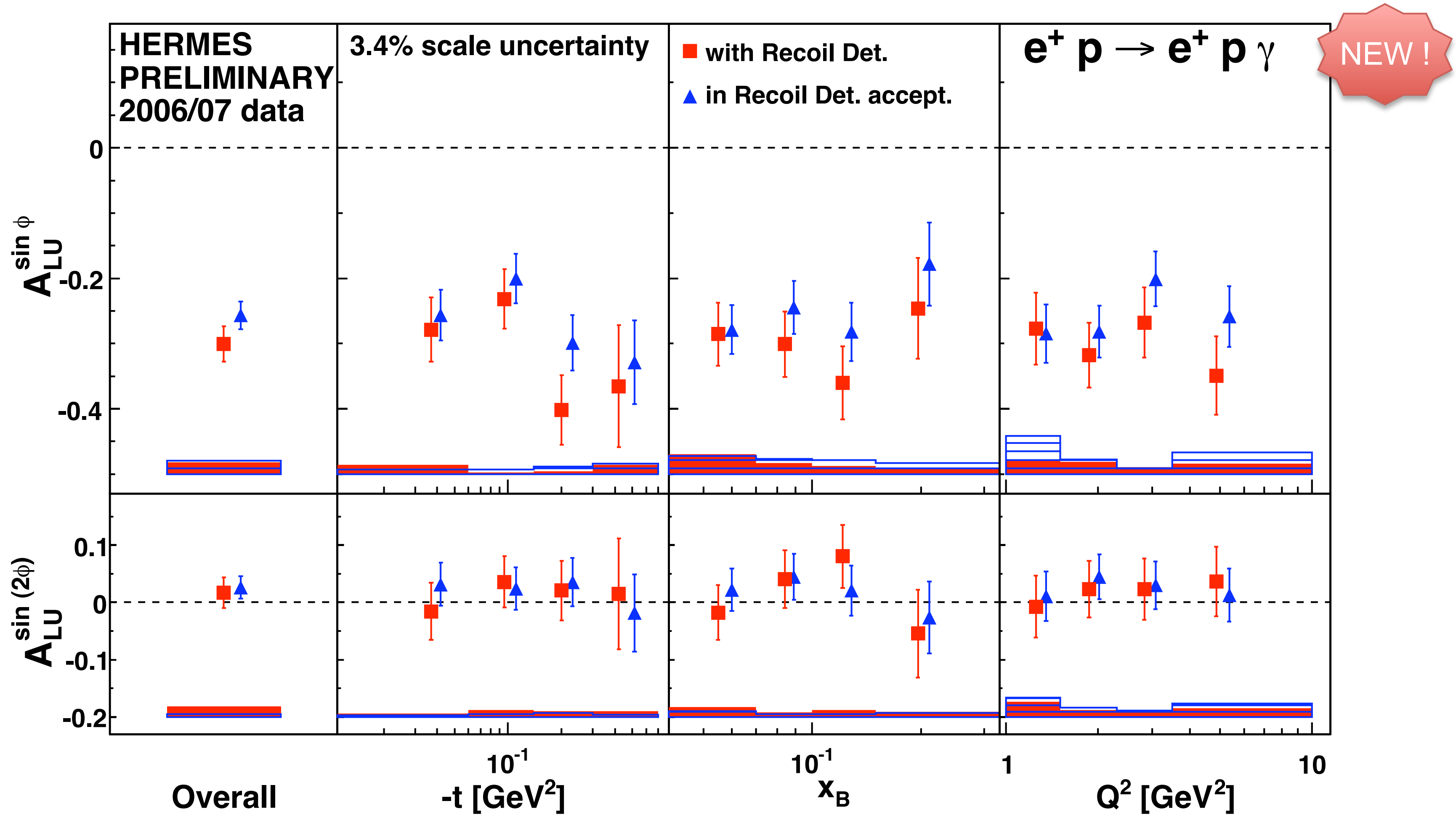
Kinematic event fitting technique: all 3 particles in the final state detected should satisfy 4-constraints on energy-momentum conservation



- No requirement for Recoil
- Charged recoil track in acceptance
- Kinematic fit probability > 1 %
- Kinematic fit probability < 1 %



Pure elastic DVCS

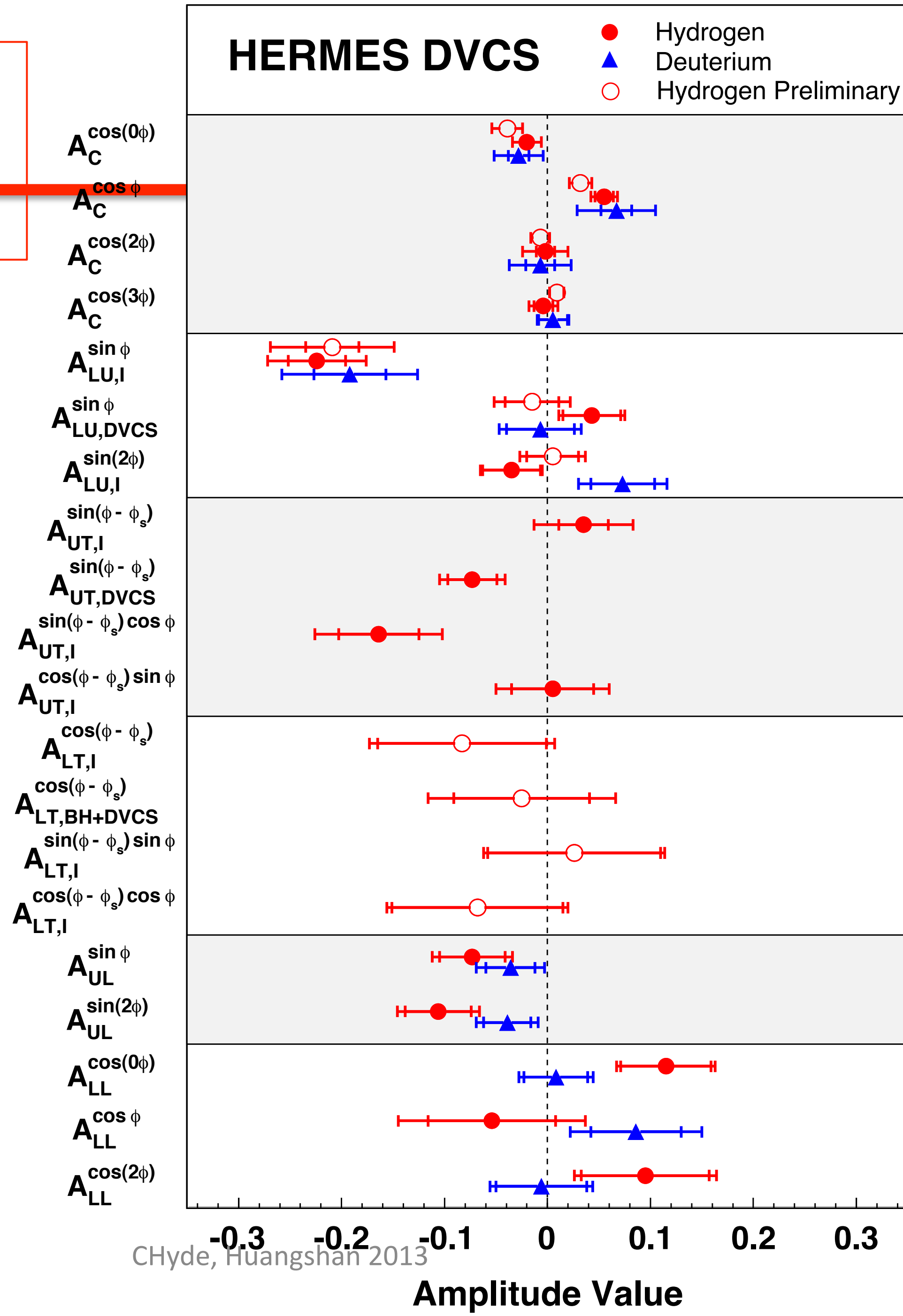


Within the present level of precision, the signal is stable with respect background subtraction

Indication that the leading amplitude for pure elastic process (background < 0.1%)
is slightly larger in magnitude than the one for not-resolved elastic+associated processes

HERMES summary 2011

- next to final
- averaged over Q^2 and t
- Transversely polarized H-target → sensitivity to $E(\xi,\xi,\Delta^2)$, $\xi\approx0.1$



DVCS Asymmetries

e^+e^-

Beam Spin Asymmetry

Transverse target Single Spin

Beam & Transverse Target Double Spin

Longitudinal Target