INT-12-49W:
February 6 - 17, 2012

Orbital Angular Momentum in QCD

Experimental Overview of Deeply Virtual Exclusive Reactions

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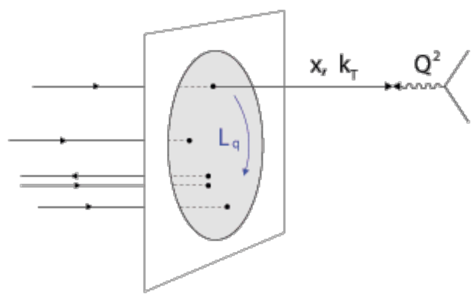
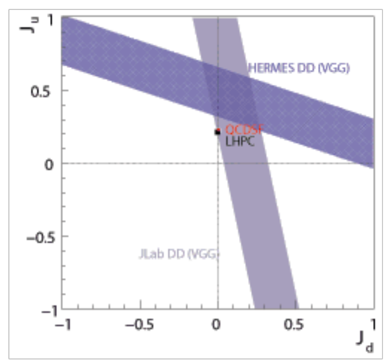
Norfolk VA

J. Phys. Conf. Ser. 299:012006, 2011,
arXiv:1101.2482

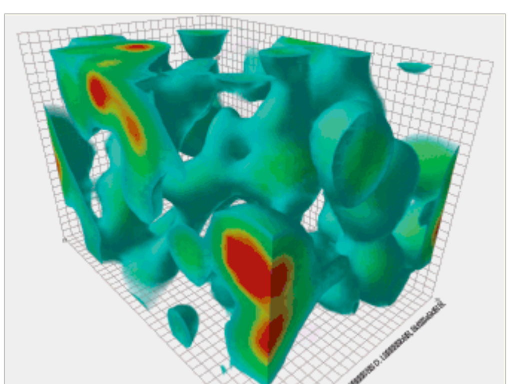


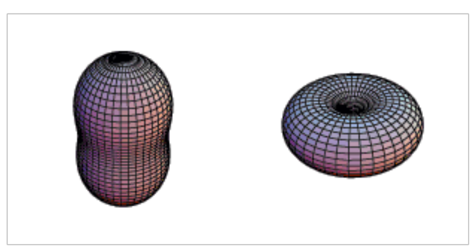


A universally correct statement for the nucleon spin

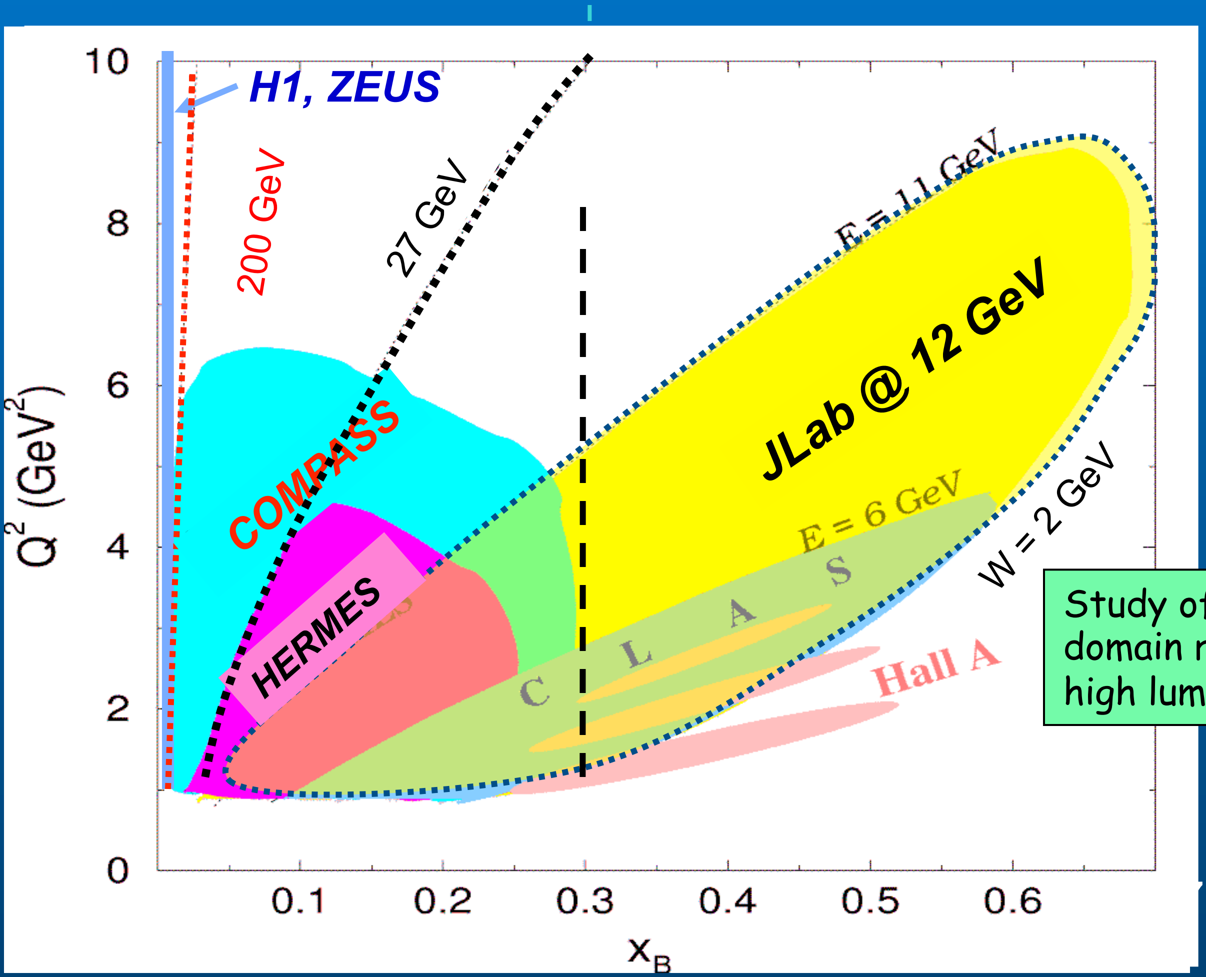
Nucleon spin comes from the spin and orbital motion of quarks and gluons

--- Chairman Mao



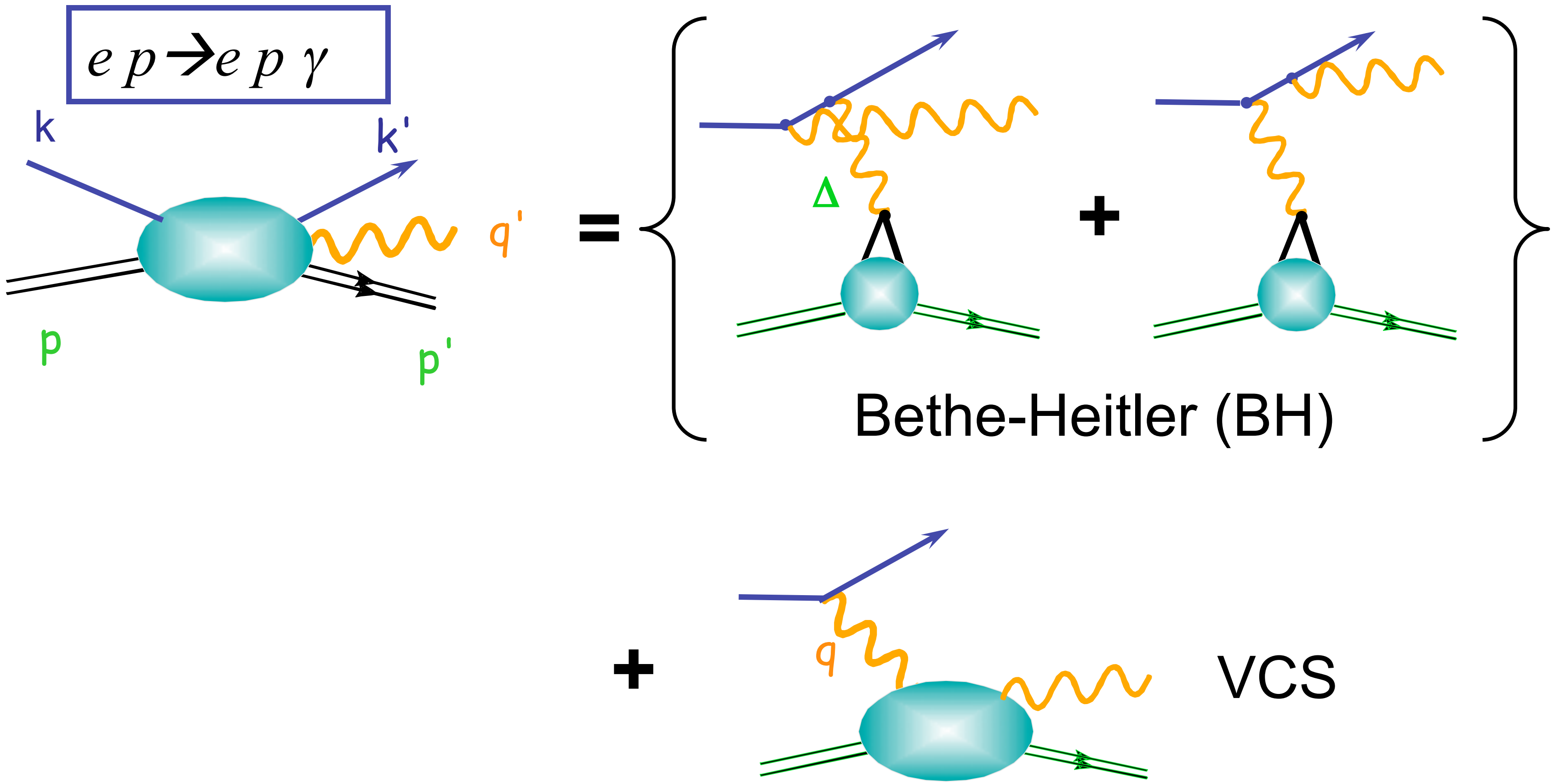


Deeply Virtual Exclusive Processes - Kinematic Coverages



Study of high x_B domain requires high luminosity

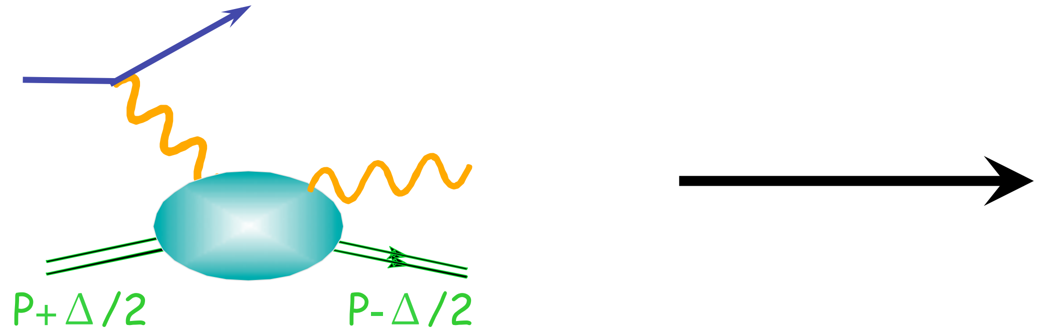
Bethe-Heitler and Virtual Compton Scattering (VCS)

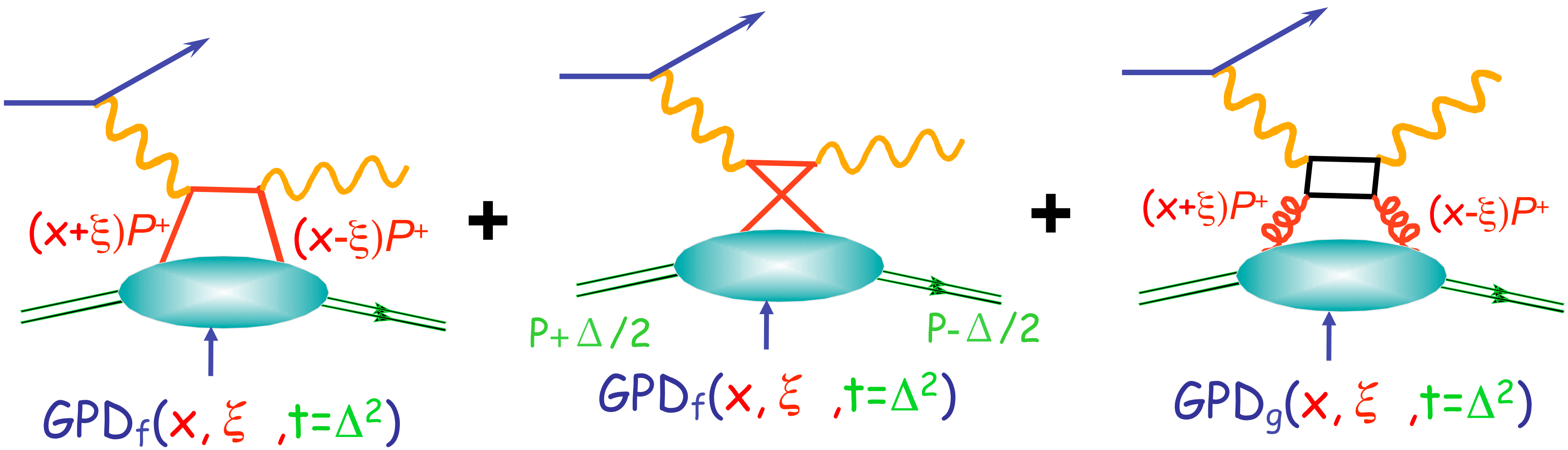


- BH-DVCS interference
  - Access to DVCS amplitude, linear in GPDs

Leading Order (LO) QCD Factorization of DVCS

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





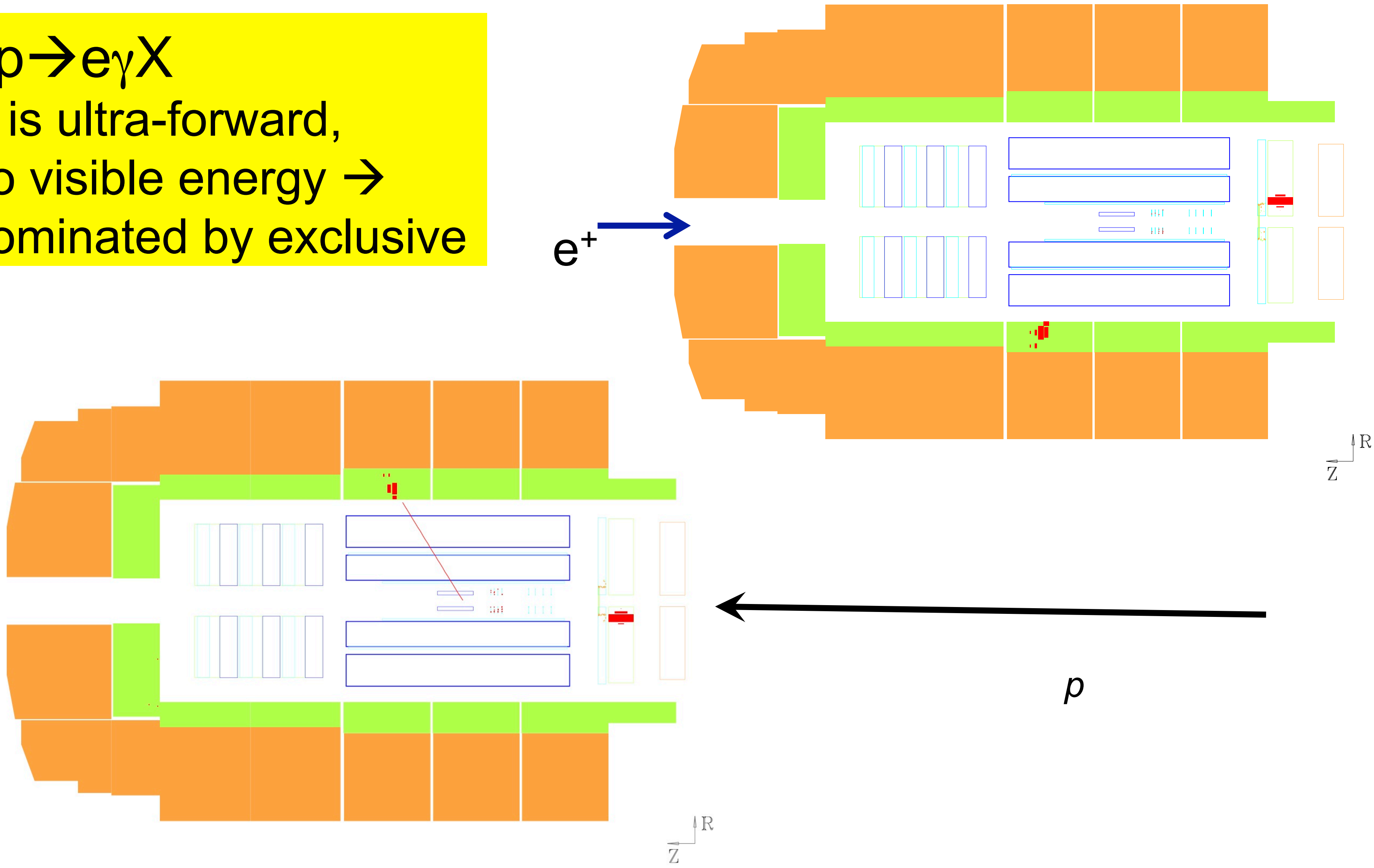
- Symmetrized Bjorken variable:

$$\xi = \frac{-(q+q')^2}{2(q+q')\cdot P} \xrightarrow[\Delta^2 << Q^2]{} \frac{x_B}{2-x_B}$$

- SCHC
  - Tranversely polarized virtual photons dominate to $O(1/Q)$

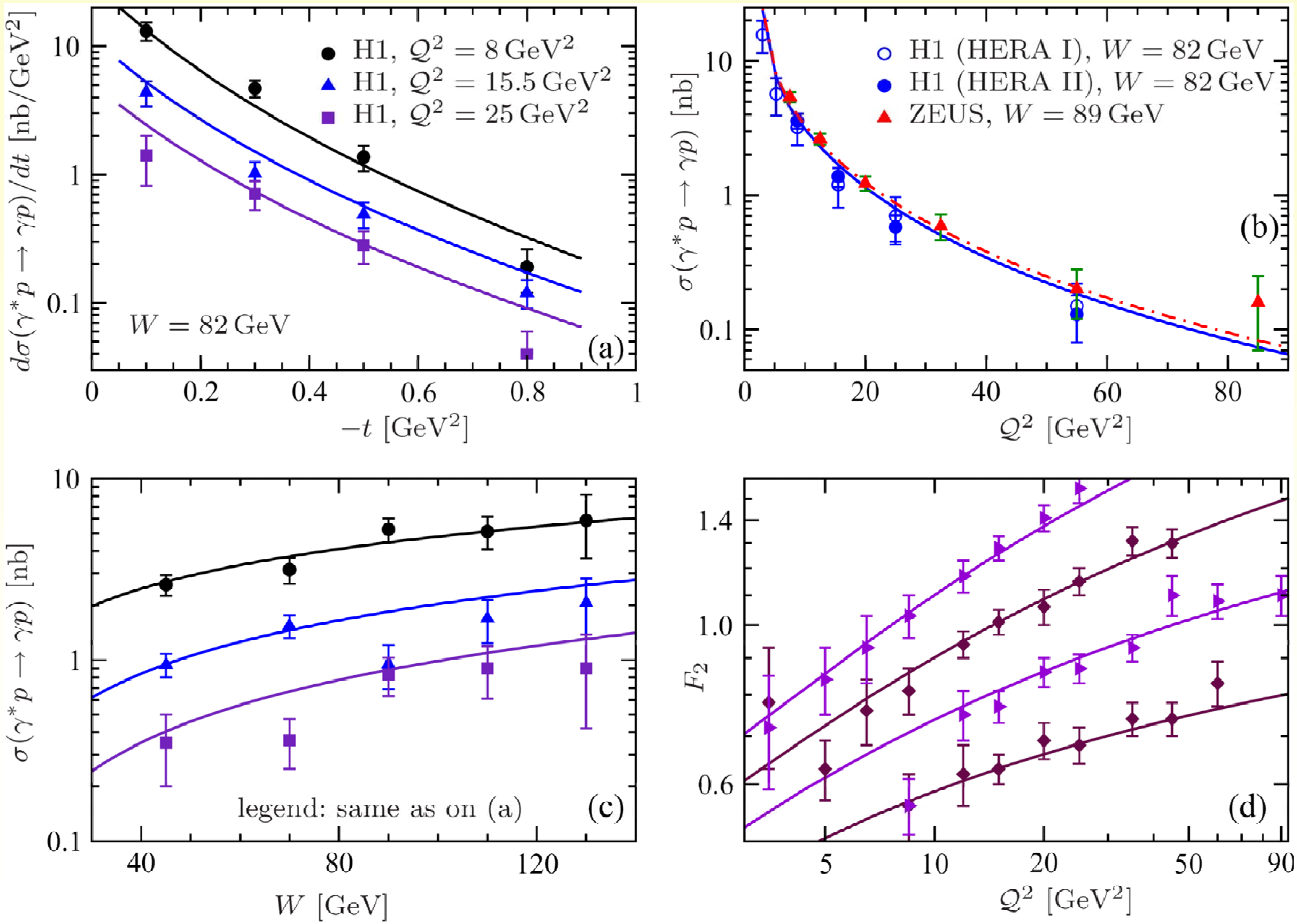
HERA-H1 DVCS-dominated and BH-dominated events

ep→eγX
X is ultra-forward,
no visible energy →
dominated by exclusive



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

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



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).
- *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):

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

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

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

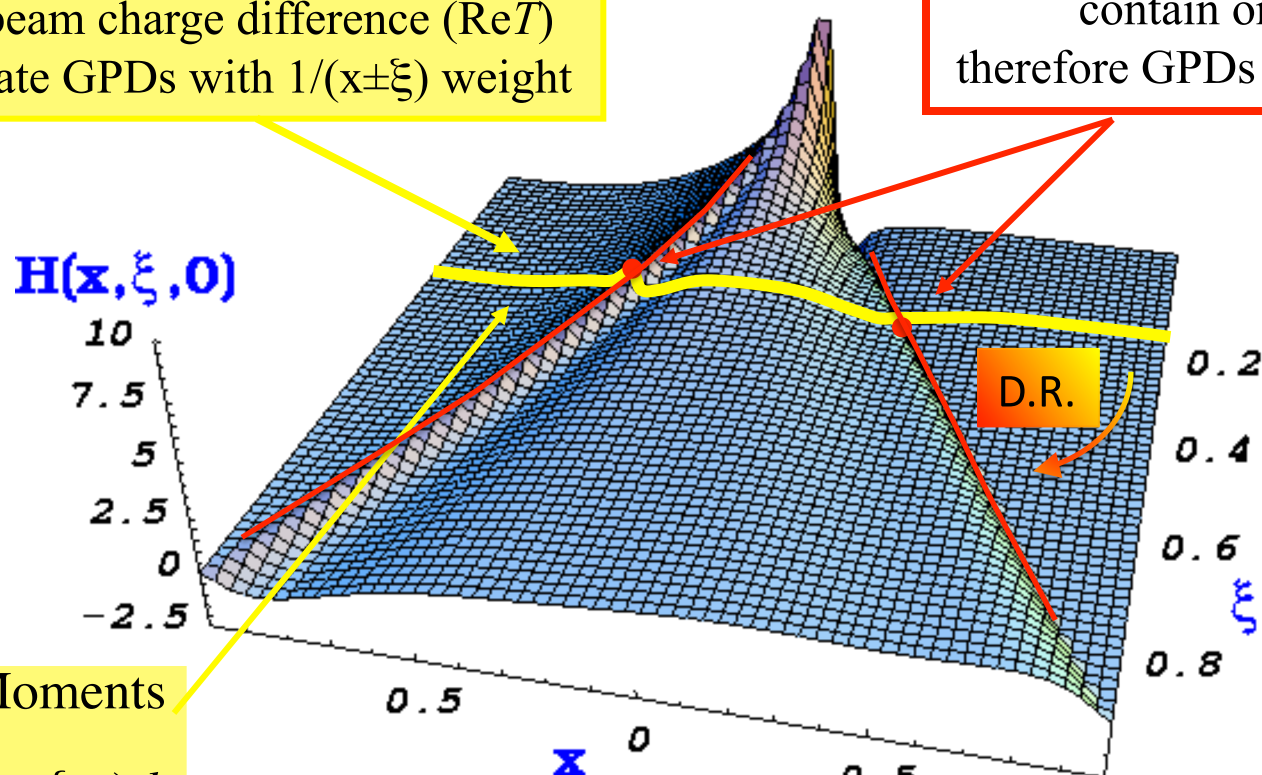
DVCS, GPDs, Compton Form Factors(CFF), and Lattice QCD

(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) measurement and beam charge difference (ReT) integrate GPDs with 1/(x±ξ) weight

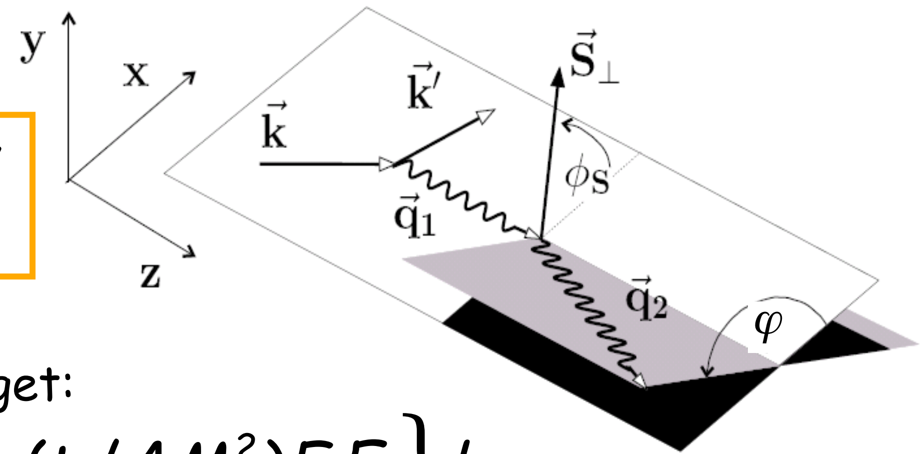
Beam or target spin Δσ contain only ImT, therefore GPDs at $x = \xi$ and $-\xi$



Lattice Moments

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

Exploiting the harmonic structure of DVCS with polarization



The 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:

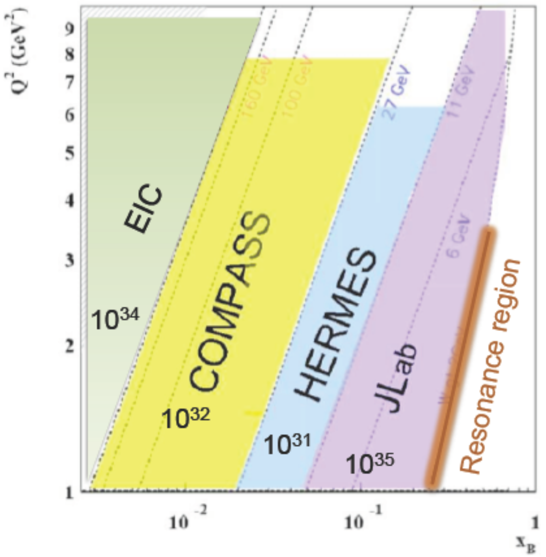
$$\Delta\sigma_{UT} \sim \cos\varphi \sin(\phi_S - \varphi) \left\{ (t/4M^2)F_2 H - (t/4M^2)F_1 E + \ldots \right\} d\varphi$$

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

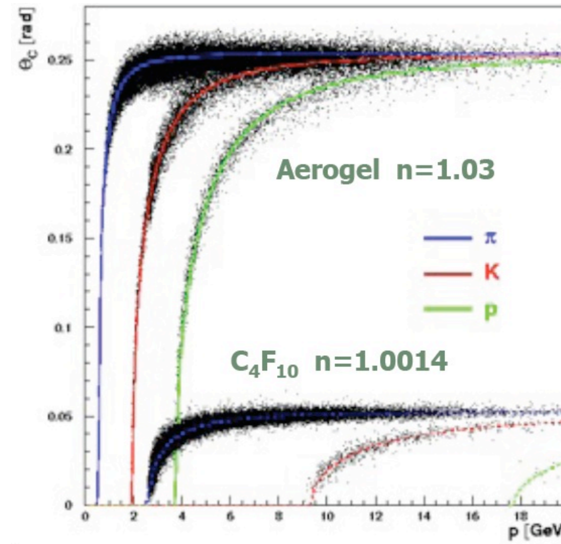
HERMES overview

27.6 GeV e+/e- HERA beam

Access to valence and sea



Electron and Hadron ID

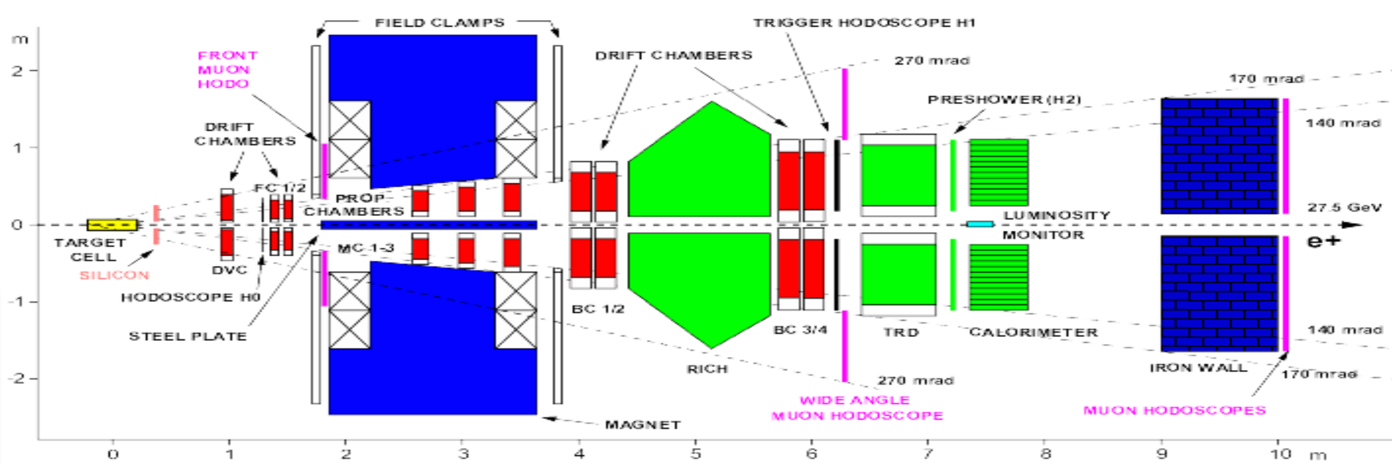


hermes

Data taking: 95-07

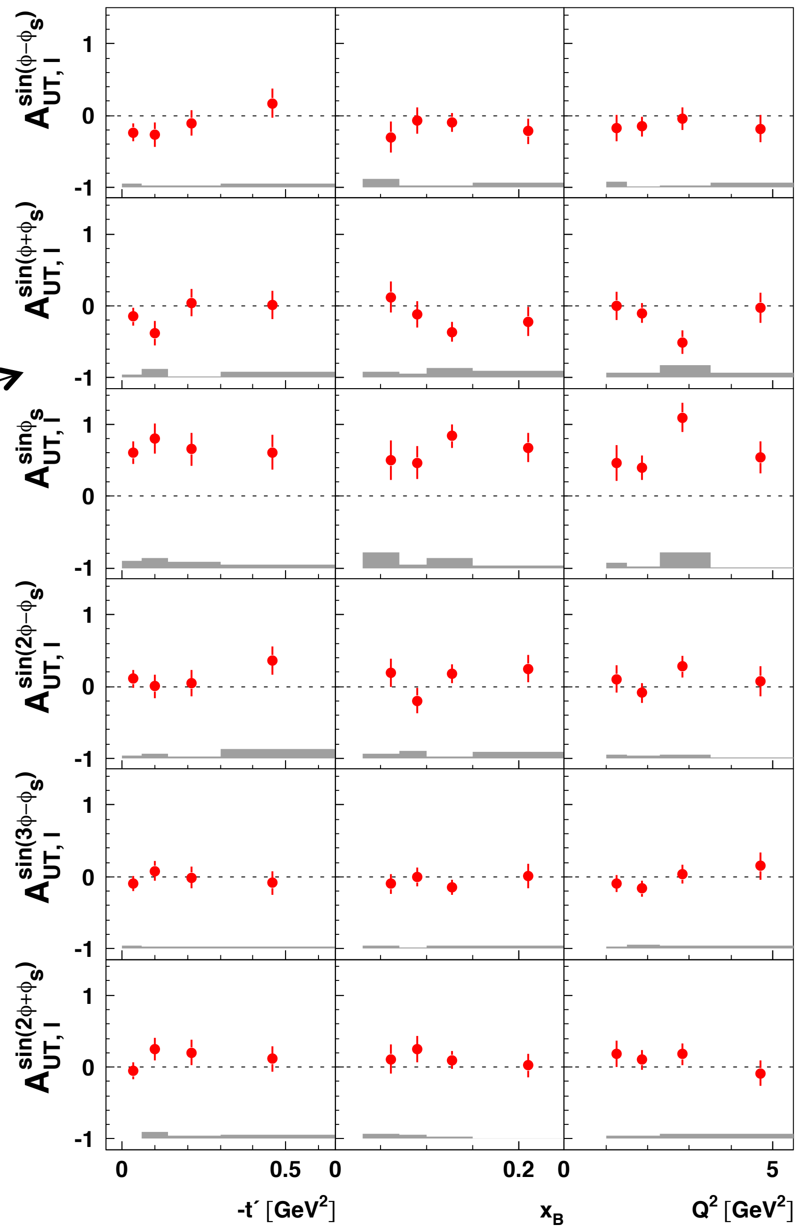
Internal gaseous target
(no nuclear effects)

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



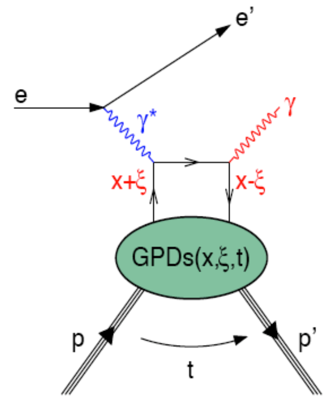
Deeply virtual Compton scattering

Theoretically cleanest
way to access GPDs

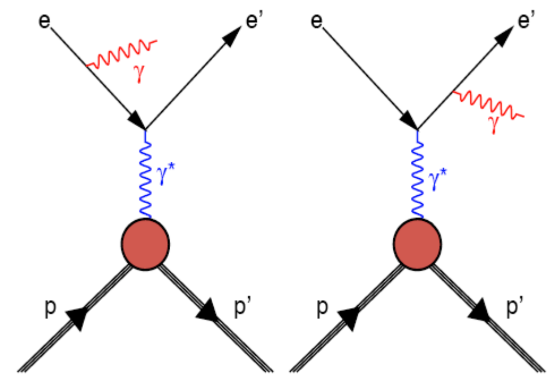
@ HERMES:

Large BH amplitude enhances
DVCS signal via interference

DVCS

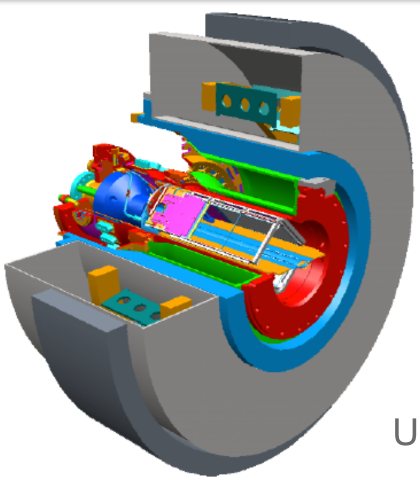


Bethe-Heitler



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

Recoil detector to tag exclusivity



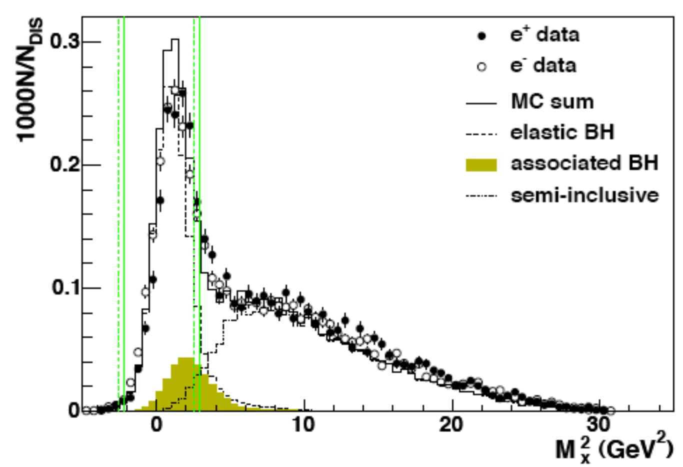
1T SC Solenoid

Photon Detector

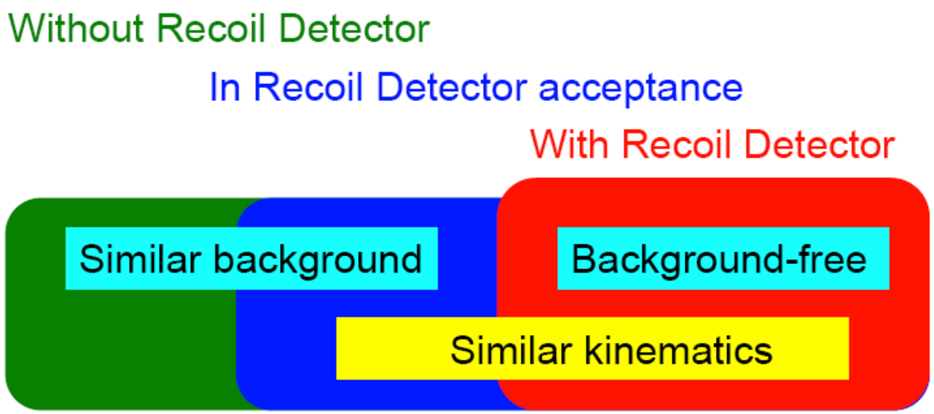
Scintillating Fiber Tracker

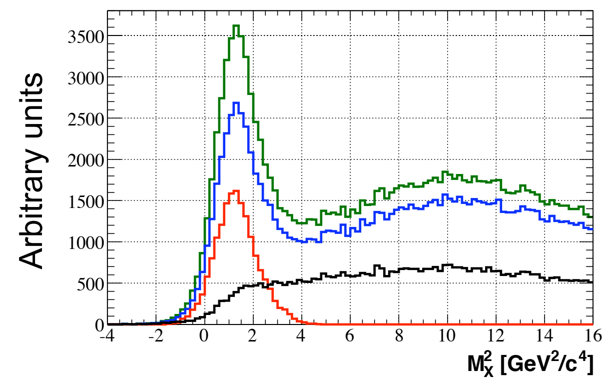
Silicon Strip Detector

Unpolarized H and D targets

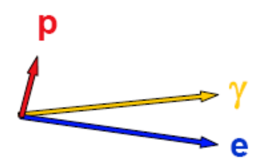


The recoil detector

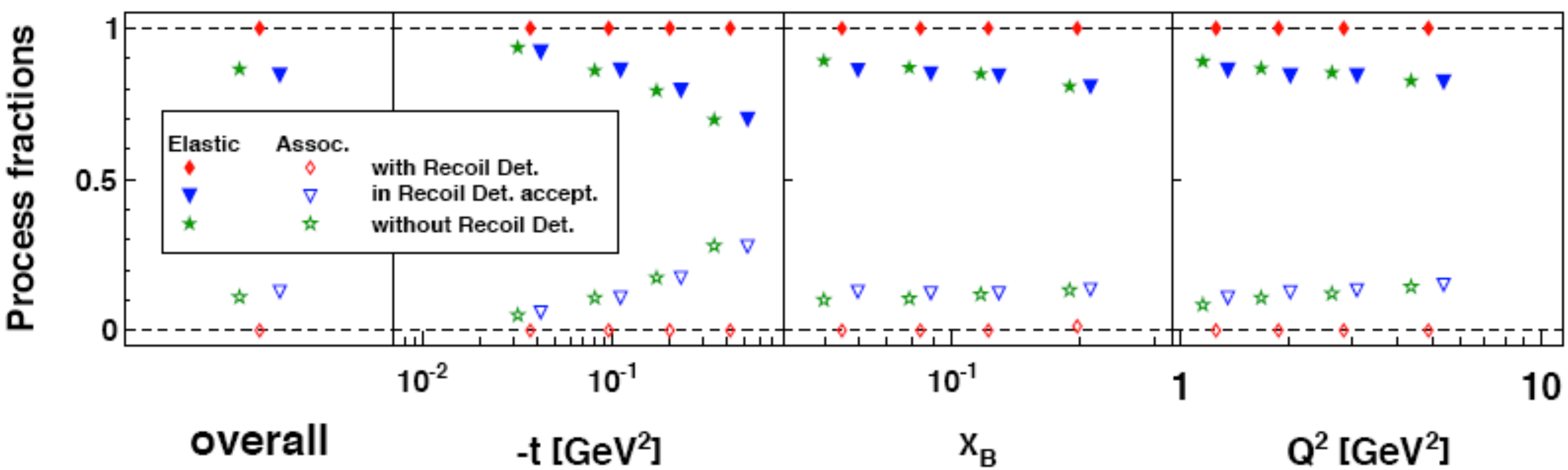




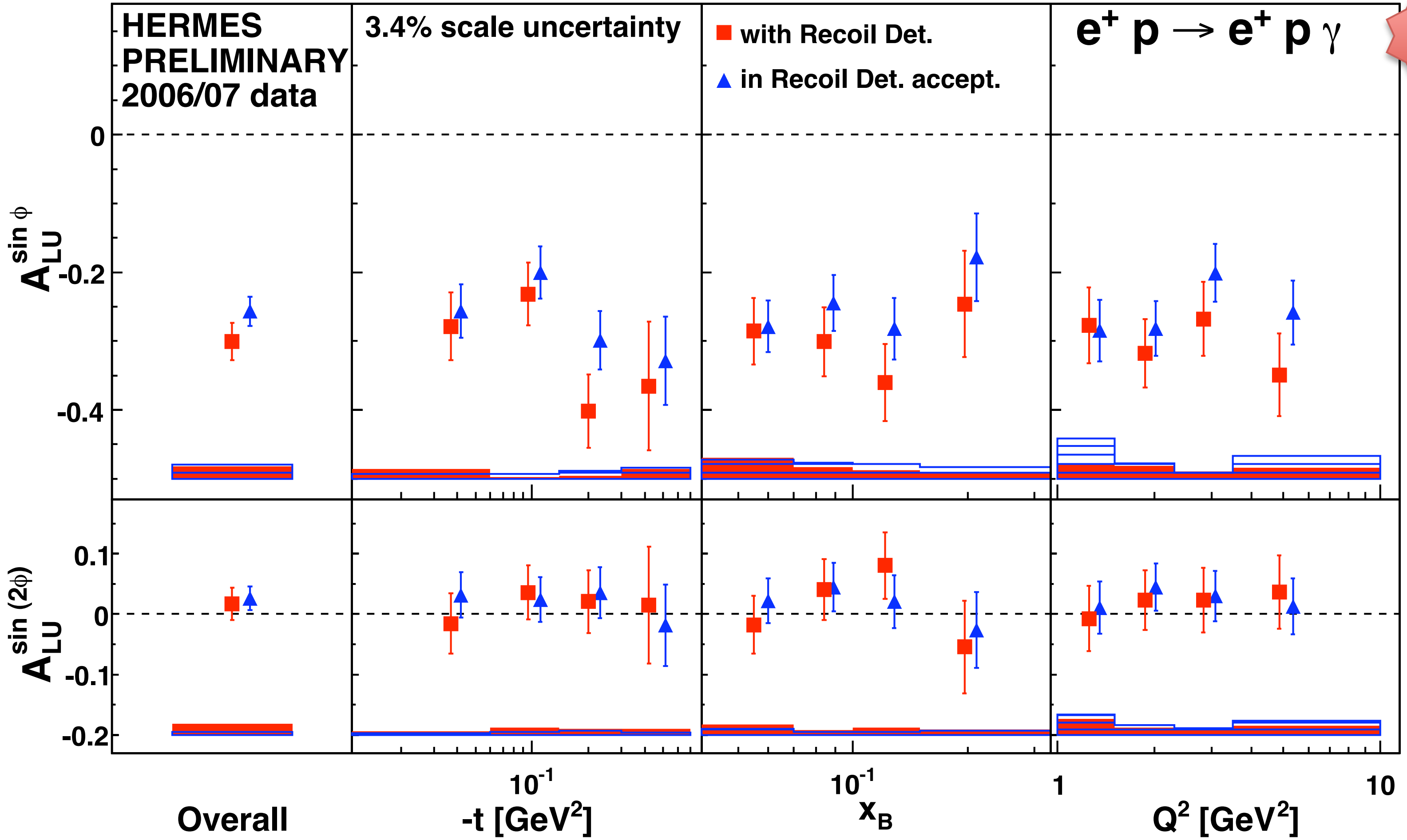
Kinematic event fitting technique: all 3 particles in the final state detected should satisfy 4-constraints on energy-momentum conservation



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



Pure elastic DVCS



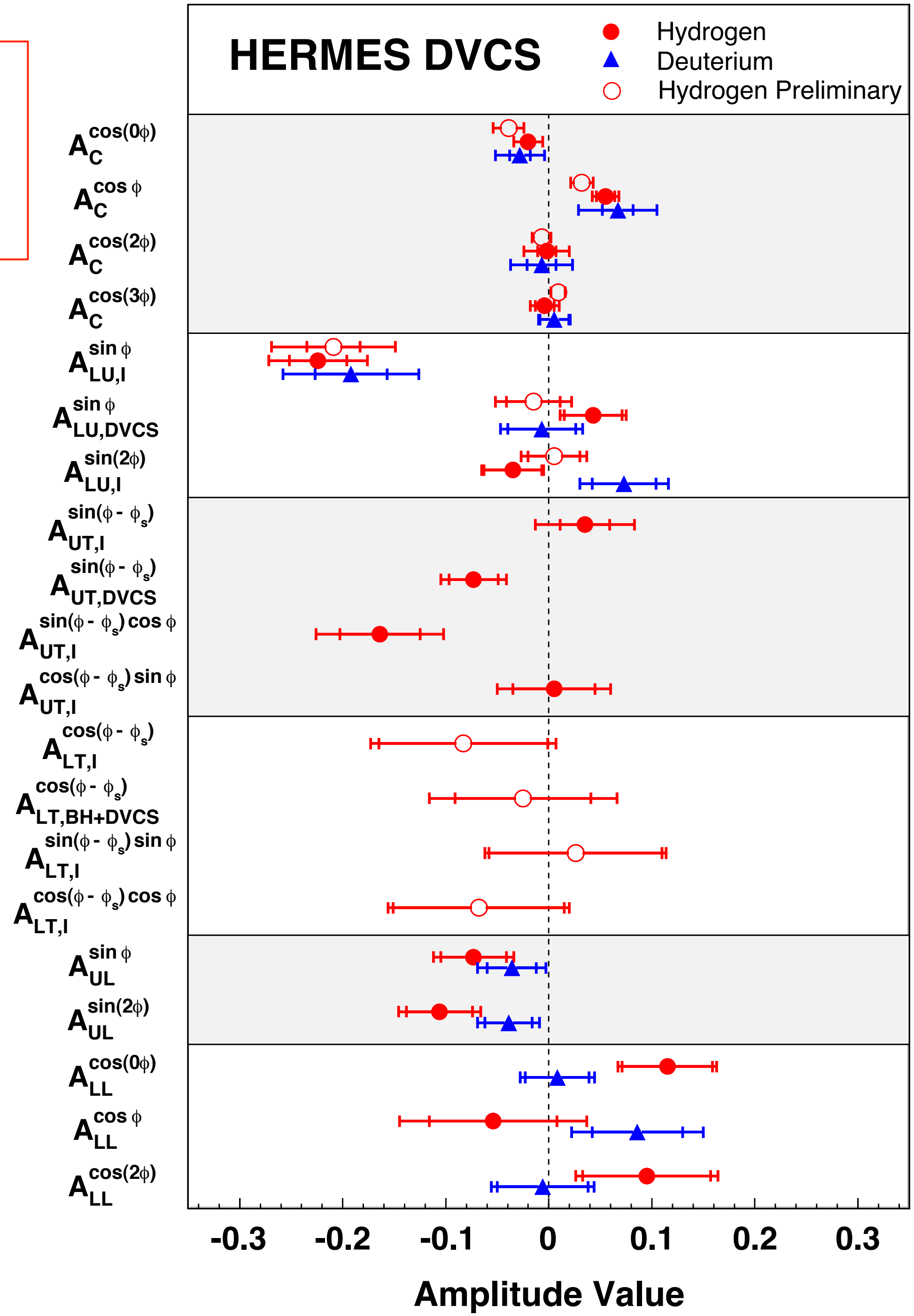
NEW !

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 $E(\xi,\xi,\Delta^2)$, $\xi \approx 0.1$



DVCS Asymmetries

e^+e^-

Beam Spin Asymmetry

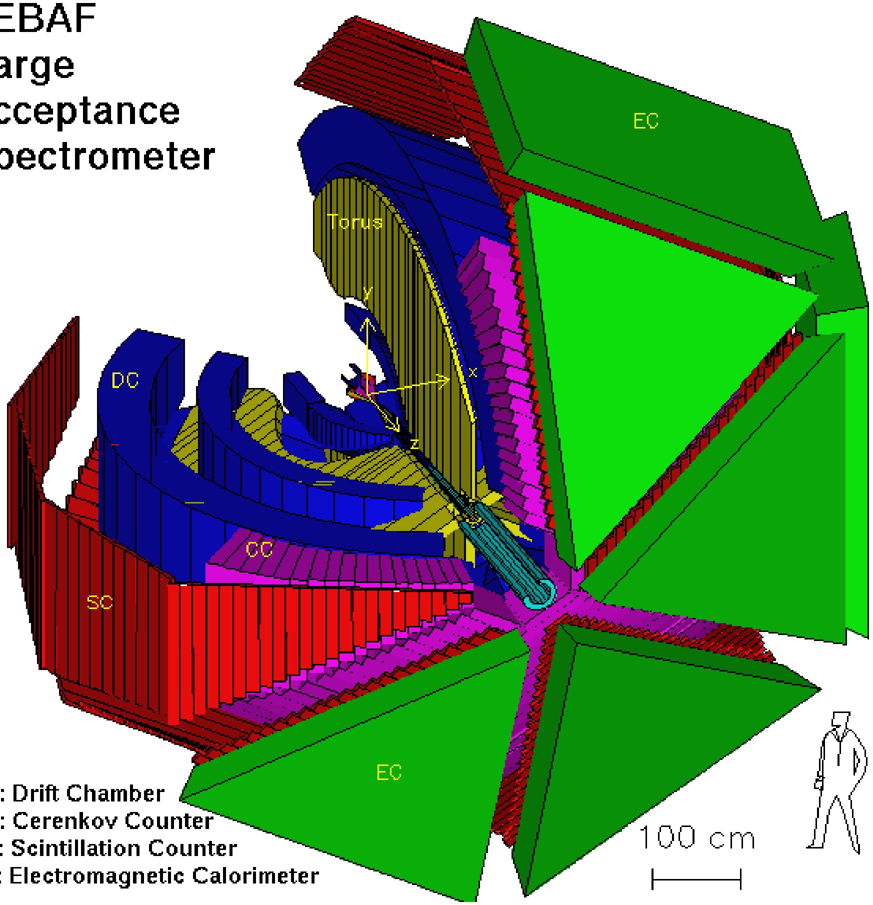
Transverse target Single Spin

Beam & Transverse Target Double Spin

Longitudinal Target

The CLAS detector

CEBAF
Large
Acceptance
Spectrometer



DC: Drift Chamber
CC: Cerenkov Counter
SC: Scintillation Counter
EC: Electromagnetic Calorimeter

- 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 $H(e,e'\gamma p)$ fully exclusive.

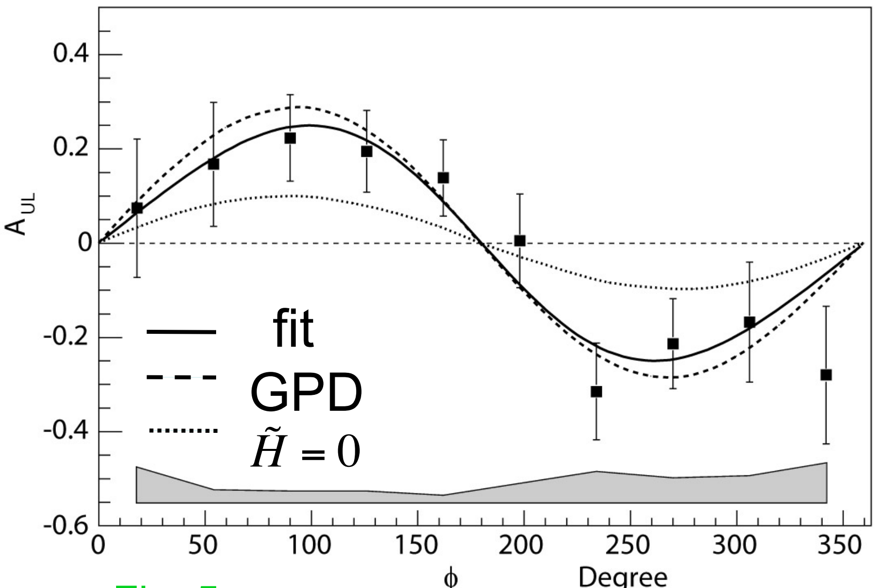


Fig. 5.

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

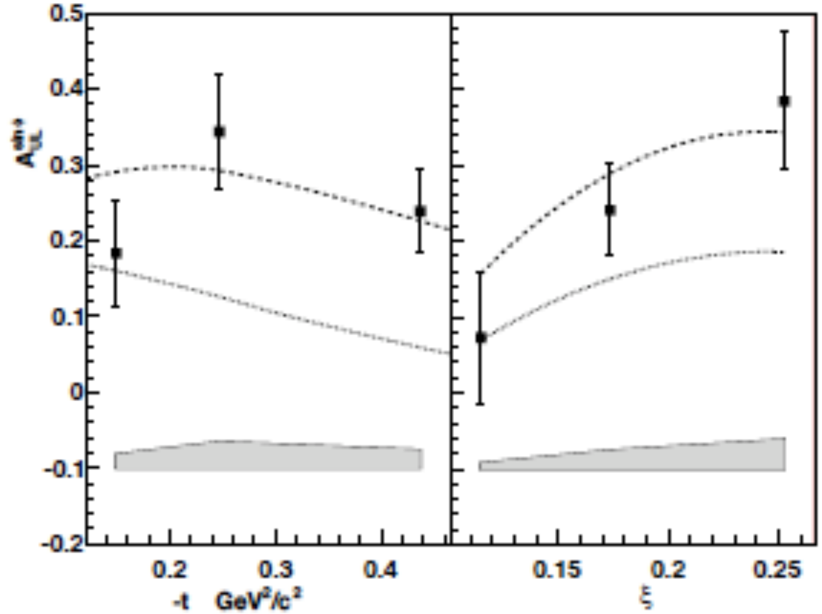
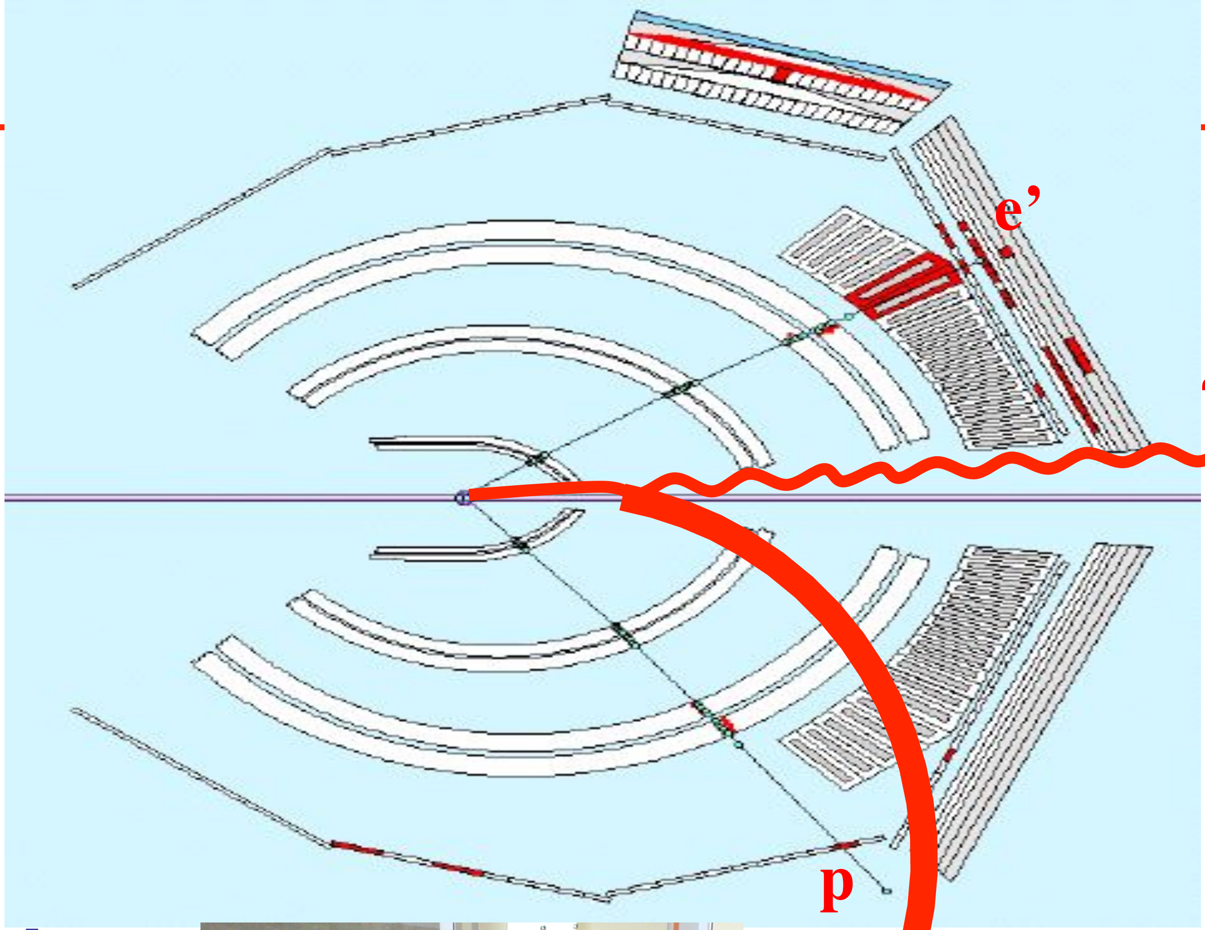


FIG. 6: The left panel shows the $-t$ dependence of the $\sin\phi$-moment of A_{UL} for exclusive electroproduction of photons, while the right shows the ξ dependence. Curves as in Fig. 5.

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

DVCS@Hall B



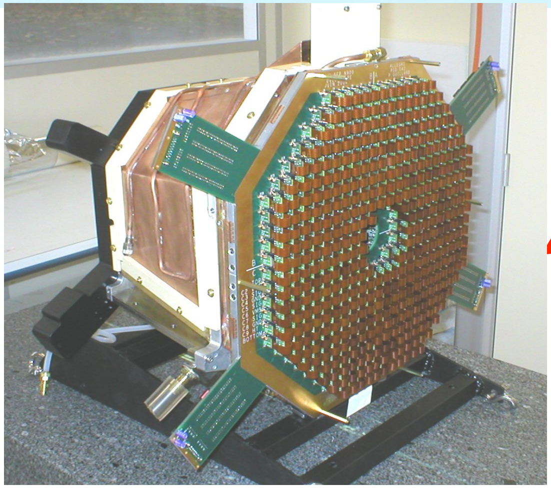
ep⇨ epγ

5 Tesla Solenoid

420 $PbWO_4$ crystals :

~10x10x160 mm^3

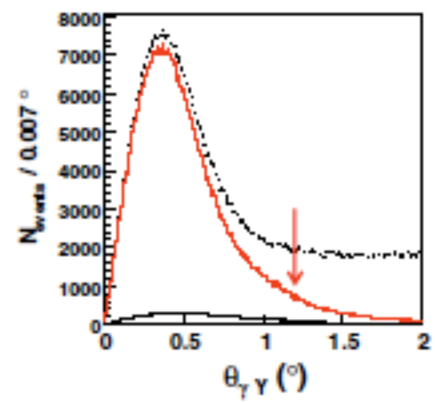
APD+preamp readout



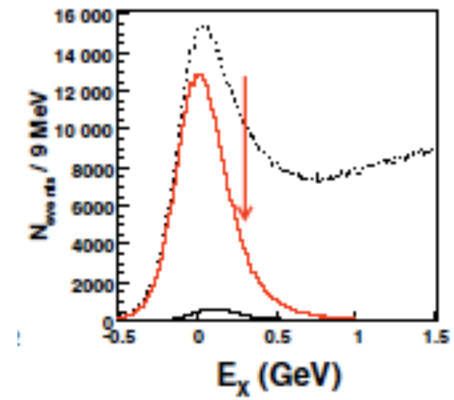
Orsay / Saclay / ITEP / Jlab

CLAS 6 GeV: Exclusivity and Kinematics

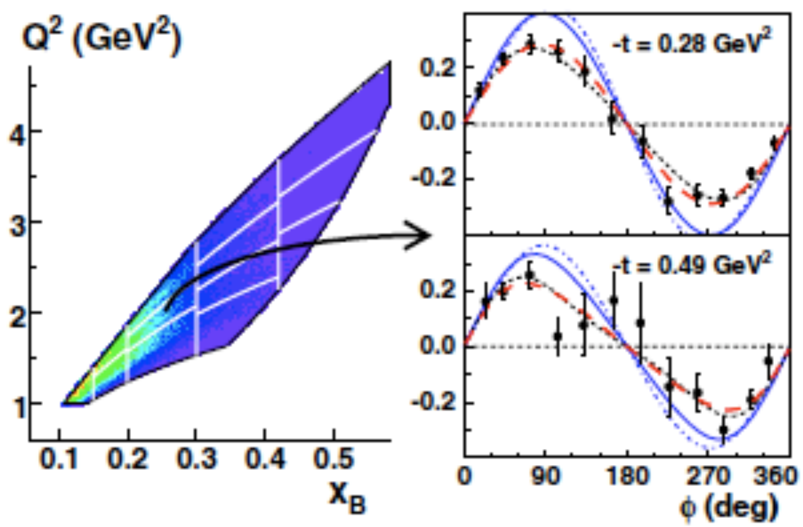
- H$(e,e'\gamma p')x$
- Overcomplete triple coincidence



Co-linearity of γ with q-p'



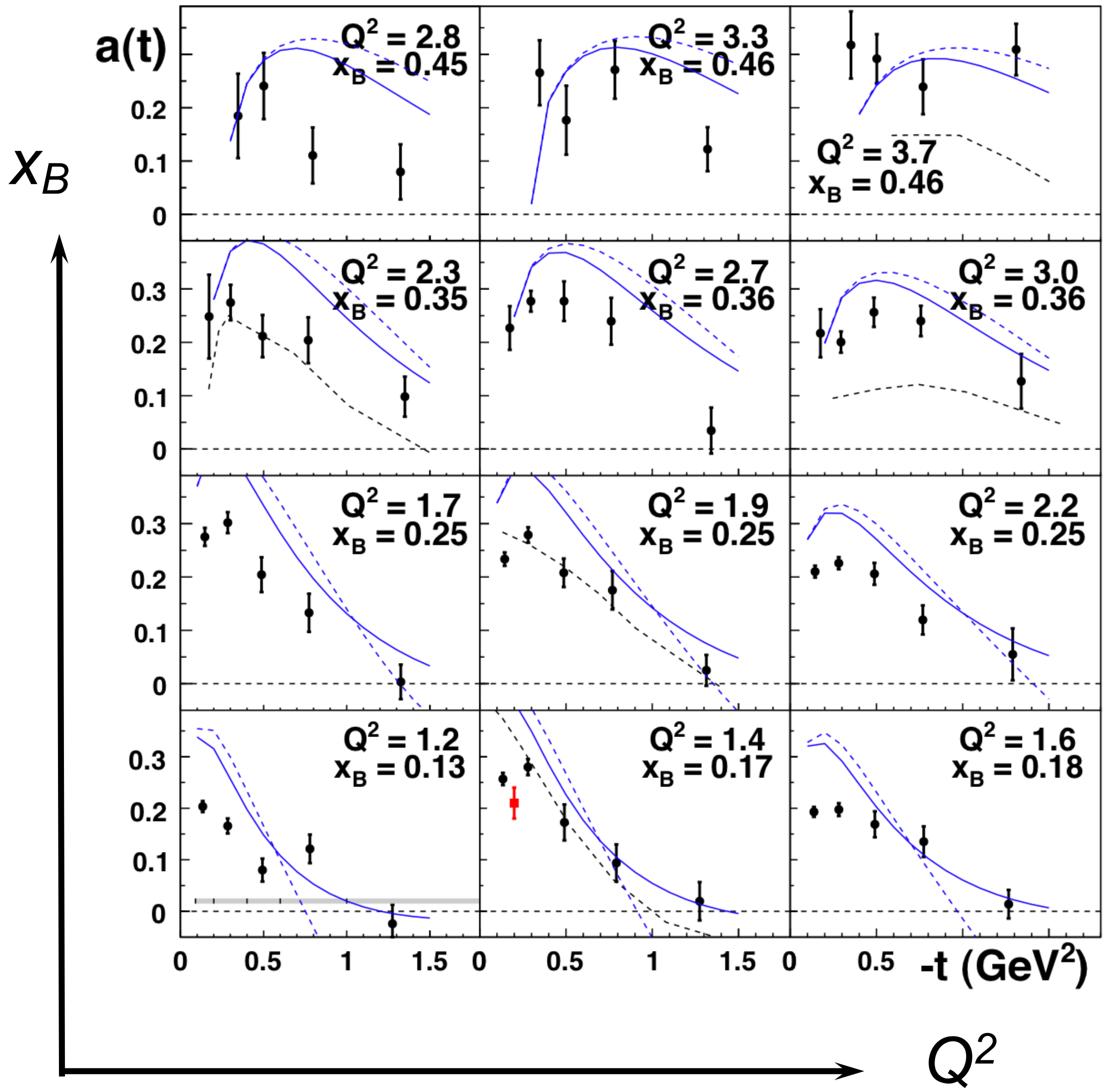
Missing Energy E_X



- 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 Longitudinal Target w/ Inner Calorimeter

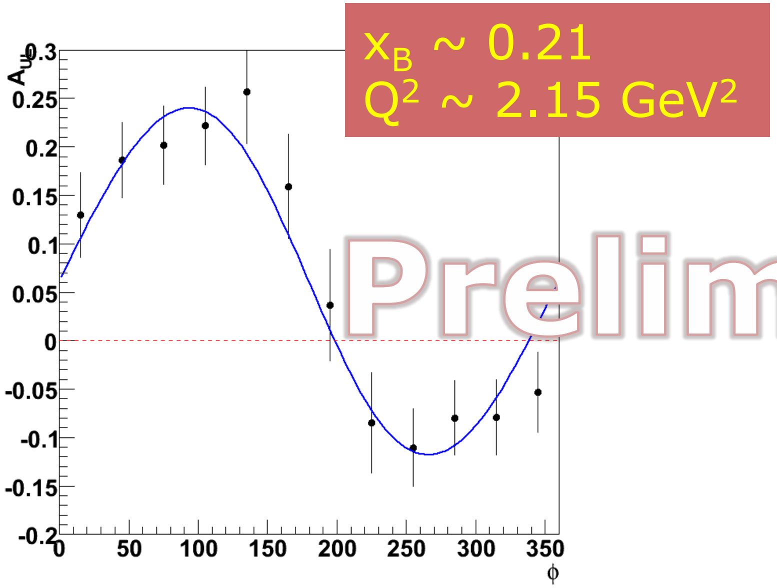
DVCS Target Spin Asymmetry

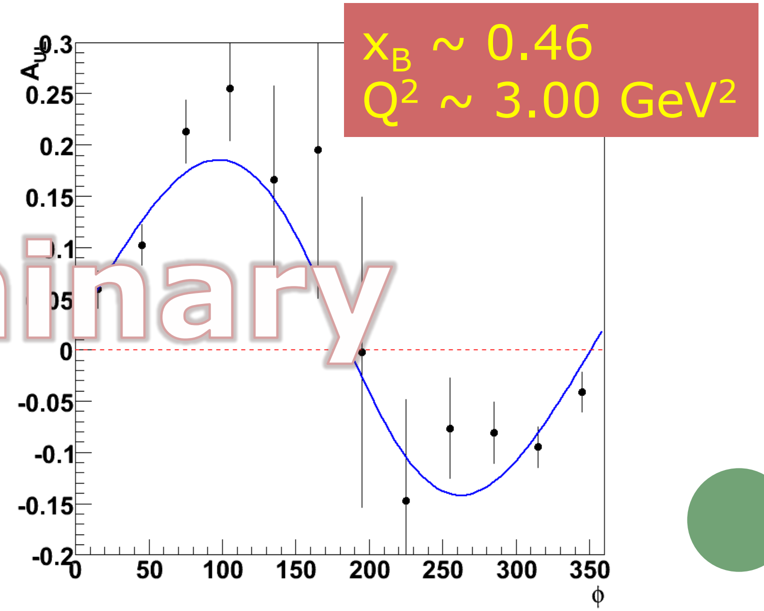
$$A_{UL} = \frac{N^{+} - N^{-}}{f\,(P^{-}N^{+} + P^{+}N^{-})}$$

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

Fitting function:

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





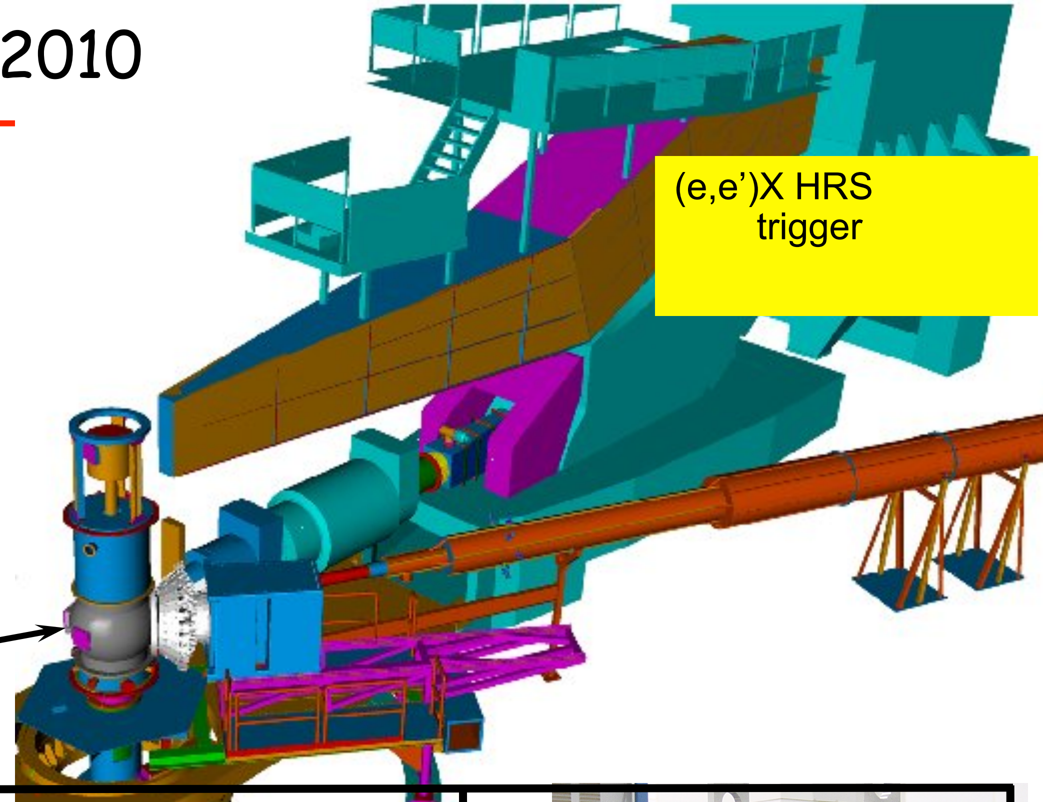
Plots and analysis done by Erin Seder

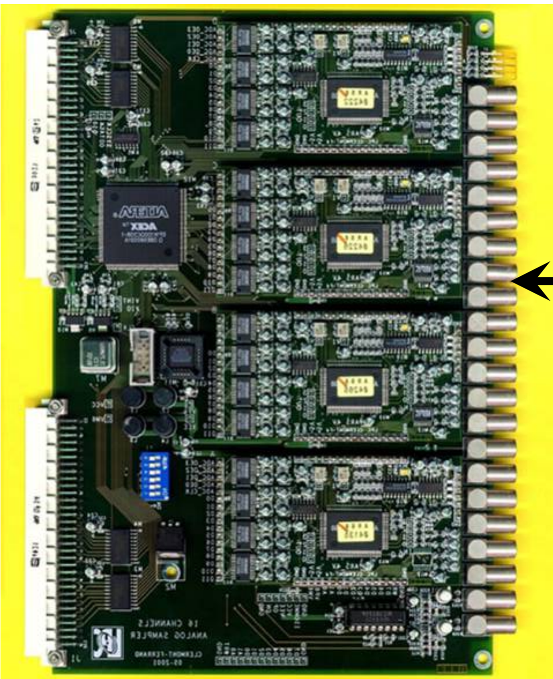
DVCS: JLab Hall A 2004, 2010

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

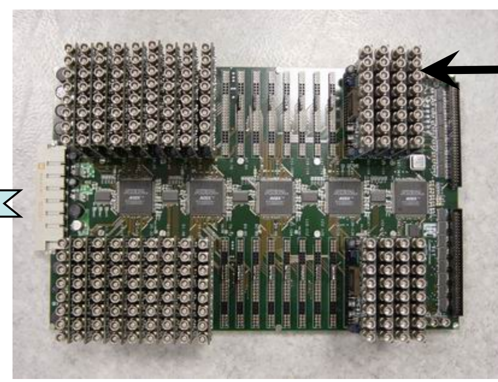
Precision cross sections

- Test factorization
- Calibrate Asymmetries

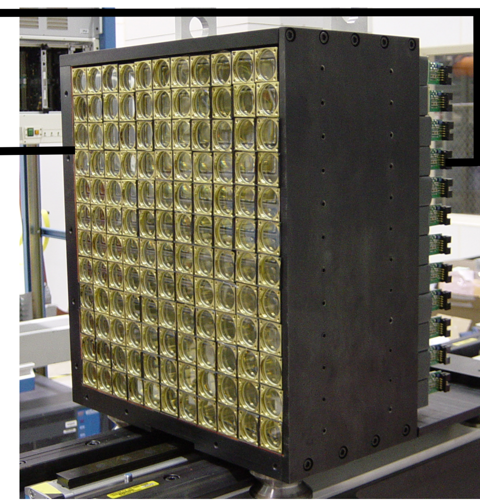




16chan VME6U: ARS
128 samples@1GHz



Digital Trigger Validation

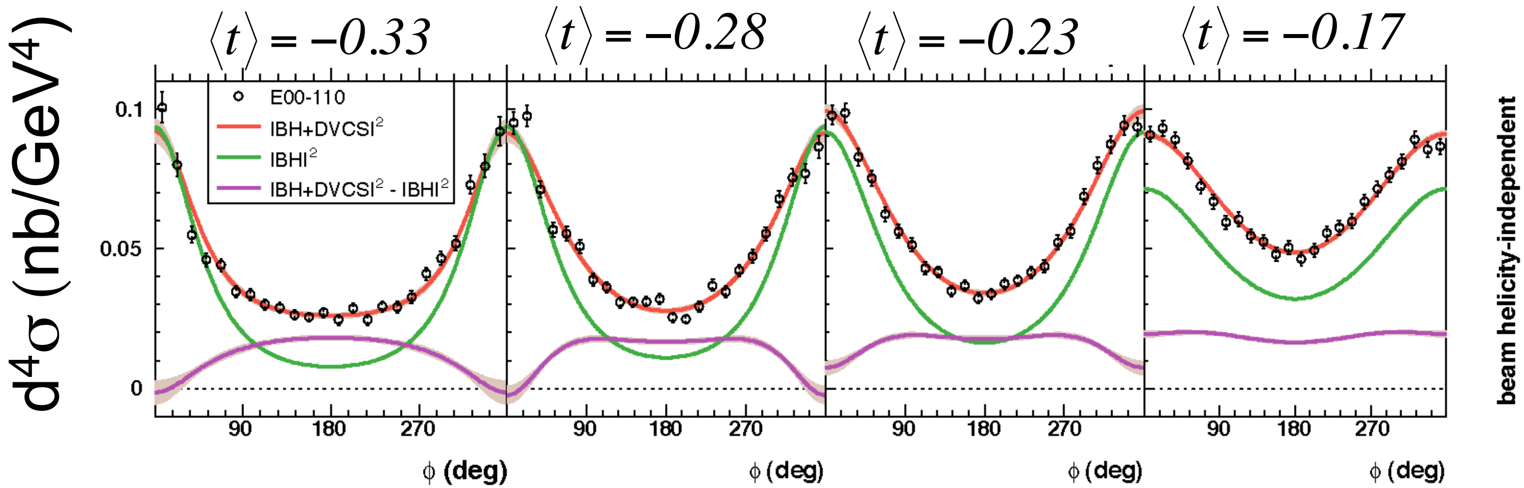


132 PbF_2

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.*,



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

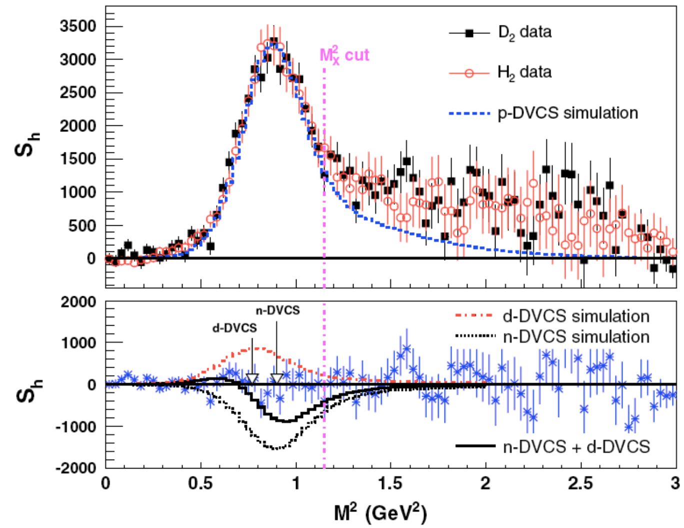
$$= d\sigma(|BH|^2) + \frac{c_0\Gamma_0 + c_1\cos(\phi_{\gamma\gamma})\Gamma_1 + c_2\cos(2\phi_{\gamma\gamma})\Gamma_2 + \ldots}{P_1(\phi_{\gamma\gamma})P_1(\phi_{\gamma\gamma})}$$

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

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

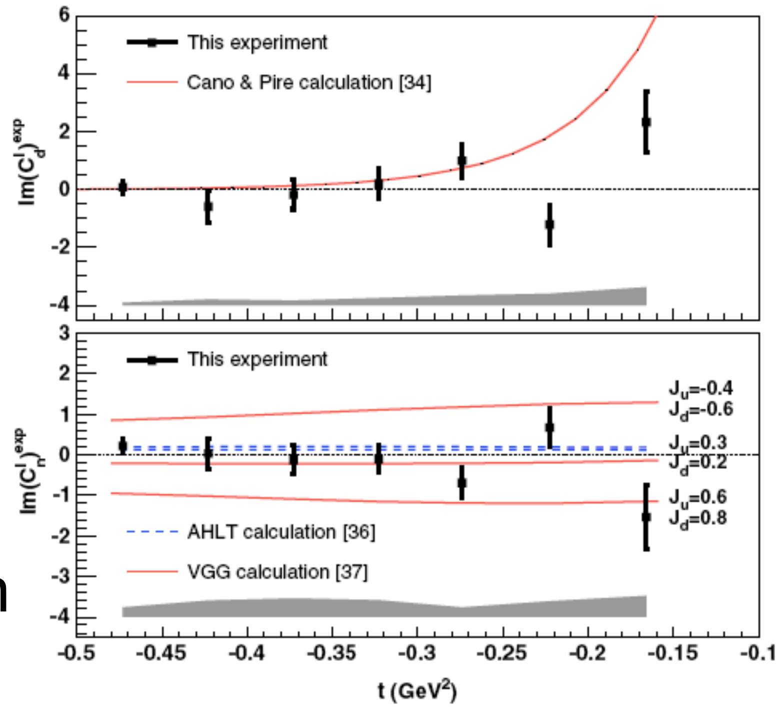
DVCS-Deuteron, Hall A

- 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]*



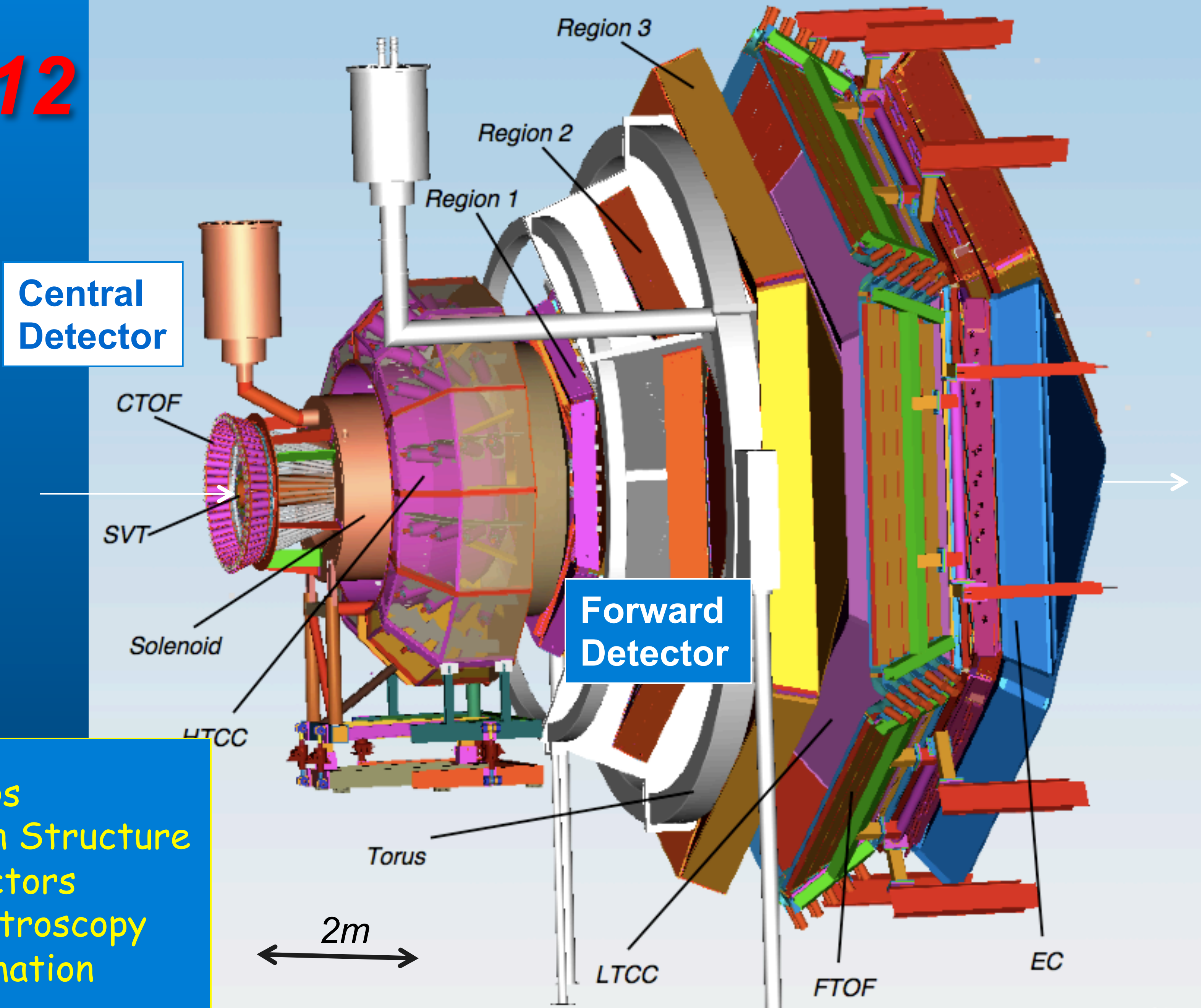
- E08-025 (5.5 GeV- 2010)
  - Reduce the systematic errors
    - Expanded PbF_2 calorimeter for π^0 subtraction
  - Separate the *Re[DVCS*BH]* and *|DVCS|^2* terms on the neutron via two beam energies.

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



neutron

CLAS12



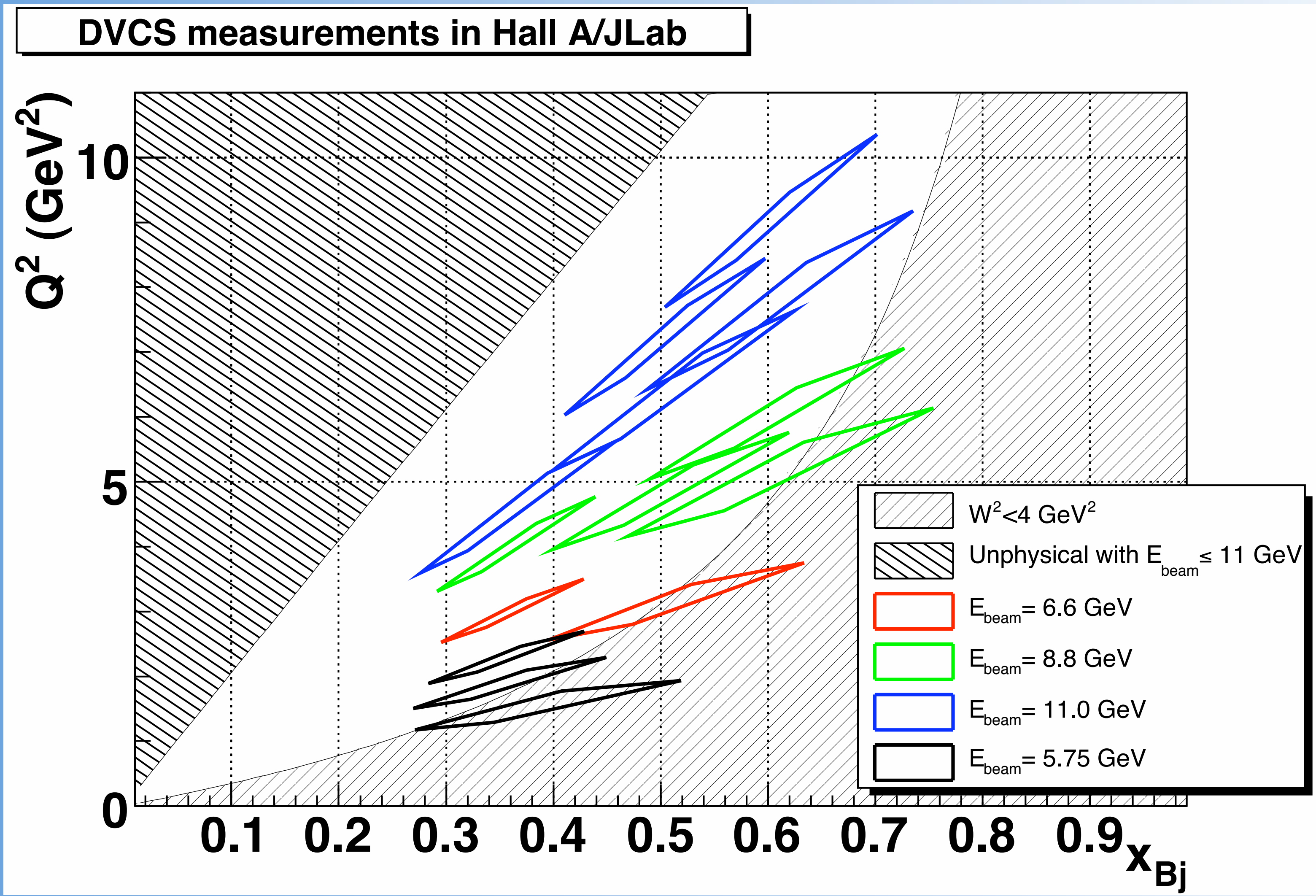
- GPDs & TMDs
- Nucleon Spin Structure
- N* Form Factors
- Baryon Spectroscopy
- Hadron Formation

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
- $D(e,e'\gamma n)p_S$
- 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)
    - Currently taking data with photon beam
    - Polarization measurements incomplete
    - Test with electron beam in 1-2 months.

DVCS at 12 GeV in Hall A: 100 days HRS $\times PbF_2$

All equipment in-hand. Ready for beam !



COMPASS 2014+ DVCS & DVES

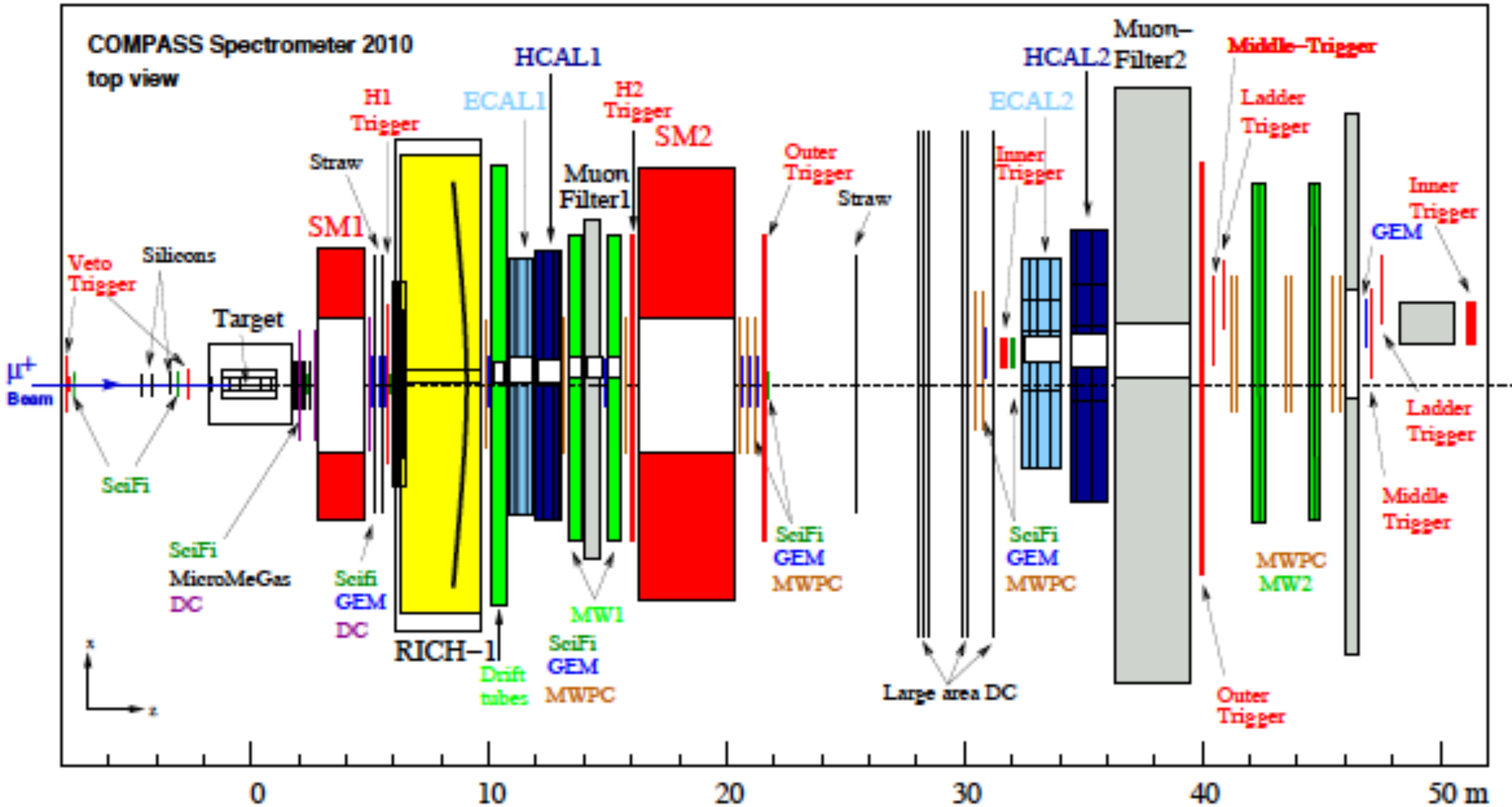
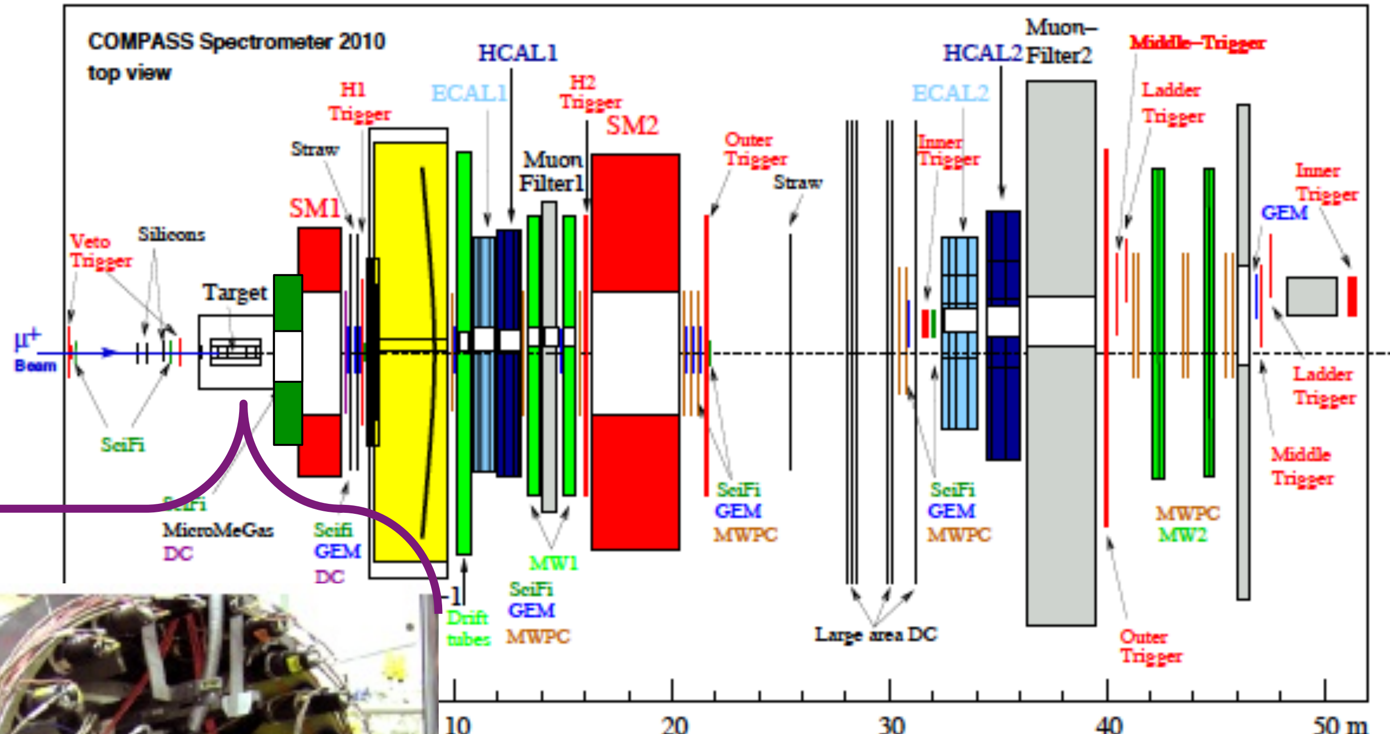
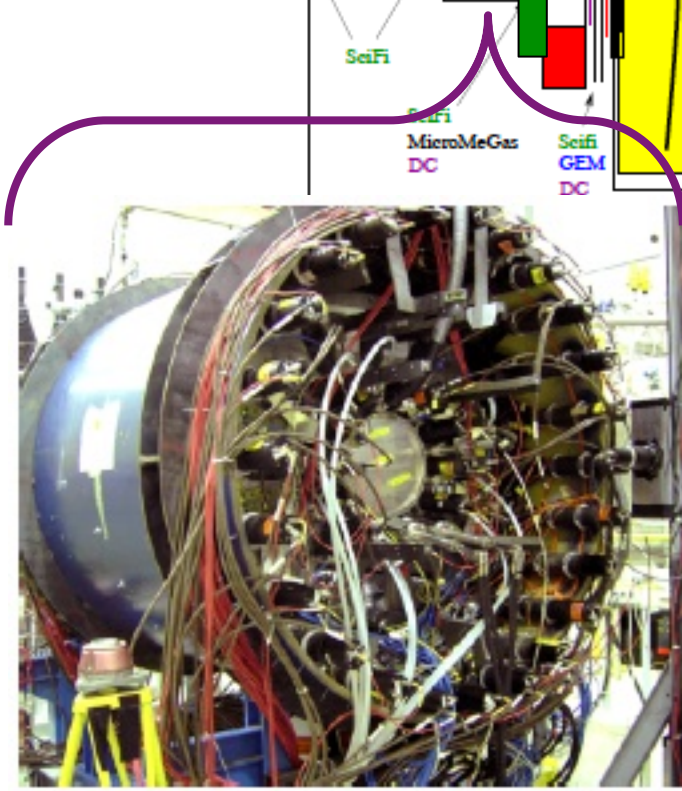


Figure 50: Top view of the 2010 COMPASS spectrometer setup.

COMPASS Recoil Proton Detector + ECAL0





view of the 2010 COMPASS spectrometer setup.

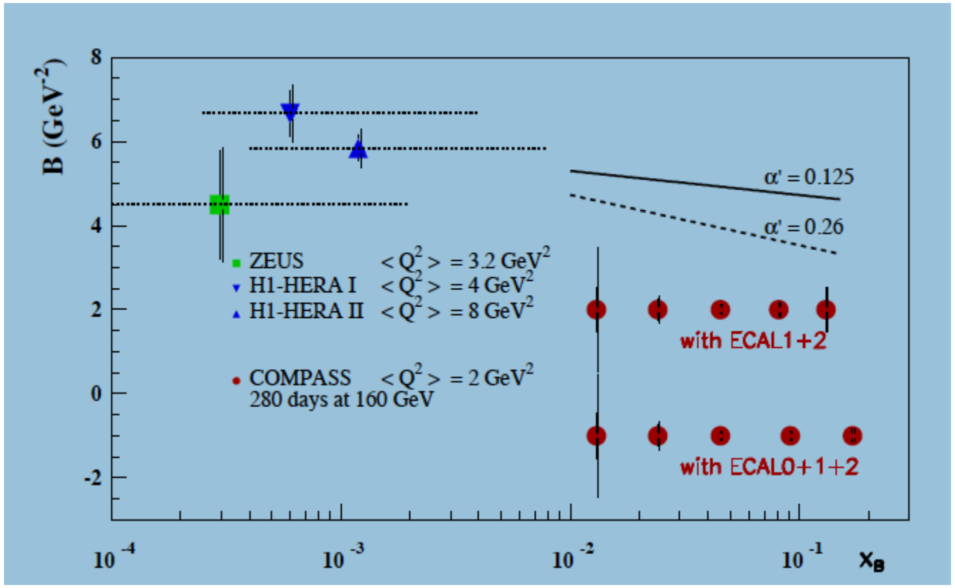
COMPASS DVCS Projections

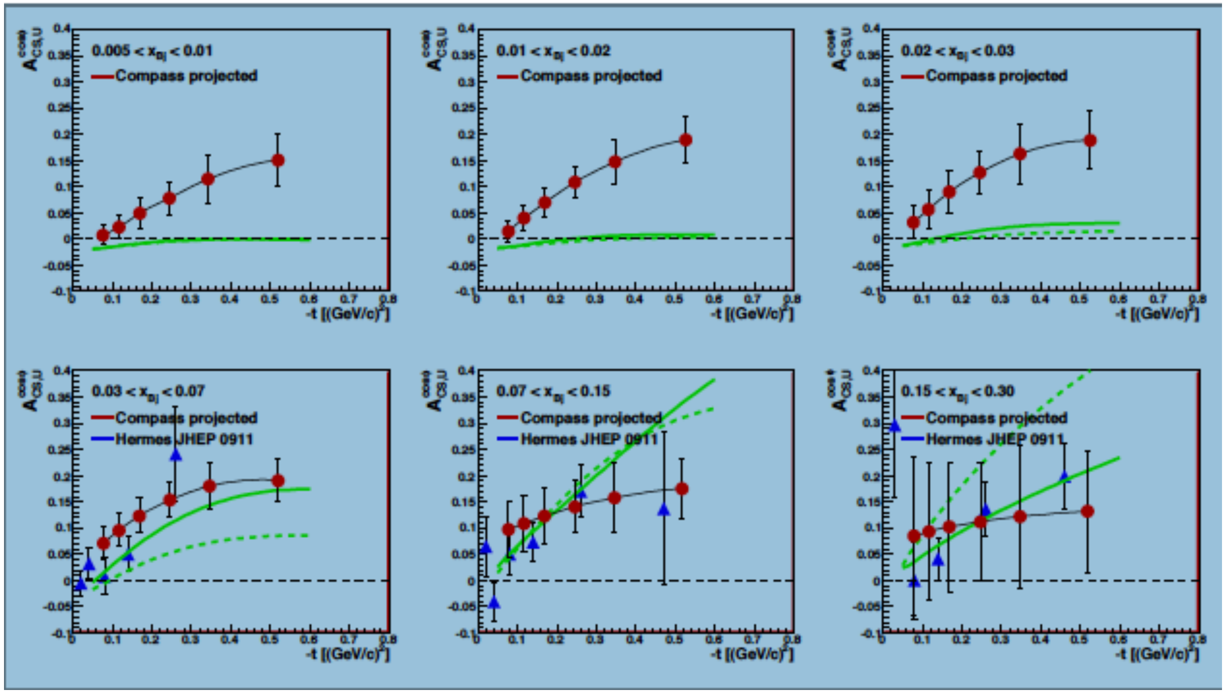
- 160 GeV

  $\overleftarrow{\mu}^{+}$ and $\vec{\mu}^{-}$

- Spin×Charge averaged

$$d\sigma \approx \left|\mathcal{H}(\xi,t)\right|^2$$

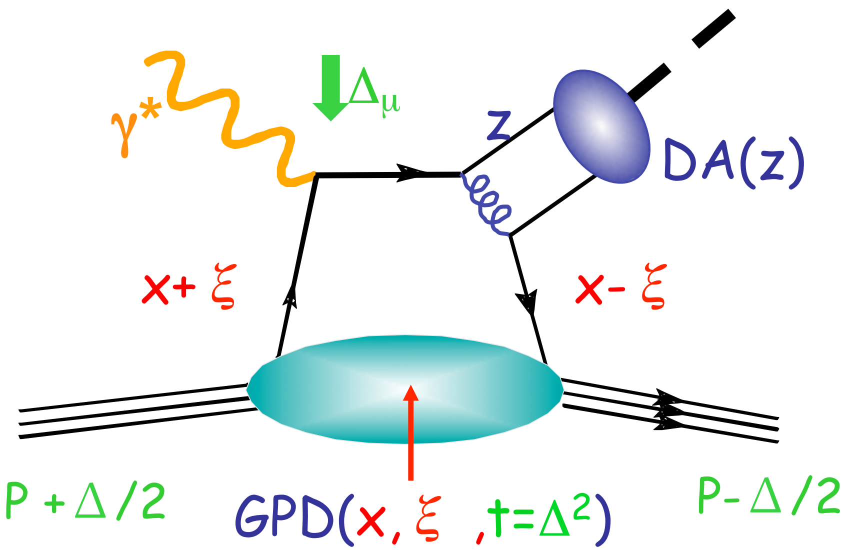




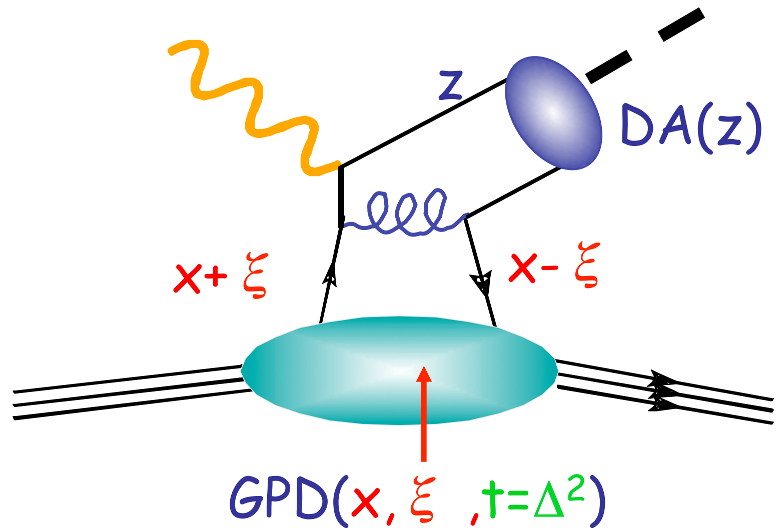
- Spin×Charge difference

$$\Delta\sigma \approx F_1(-t)\Re e\left[\mathcal{H}(\xi,t)\right]\cos\phi$$

Leading Order (LO) QCD Factorization of DVES



+



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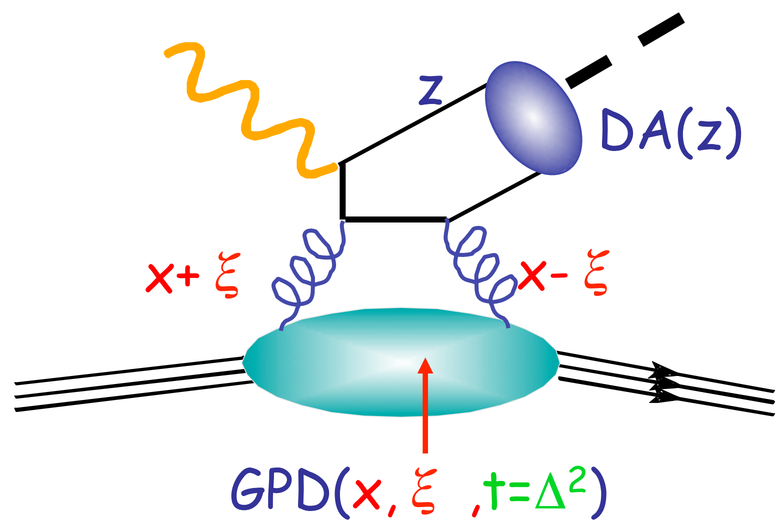


[Diffractive channels only]

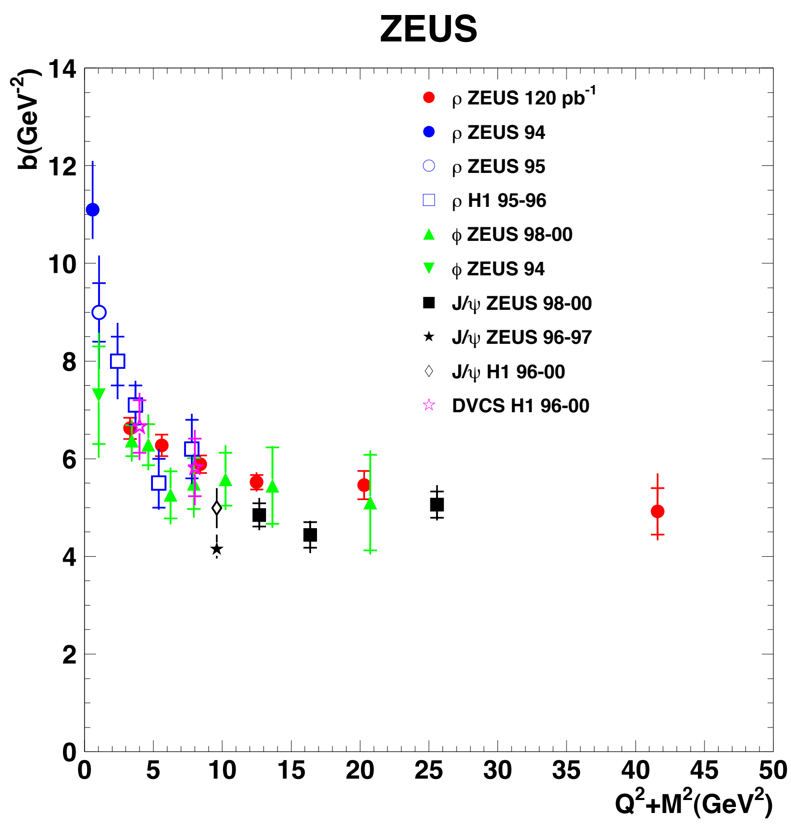
Gluon and quark GPDs enter to same order in α_S.

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

Spin/Flavor selectivity

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



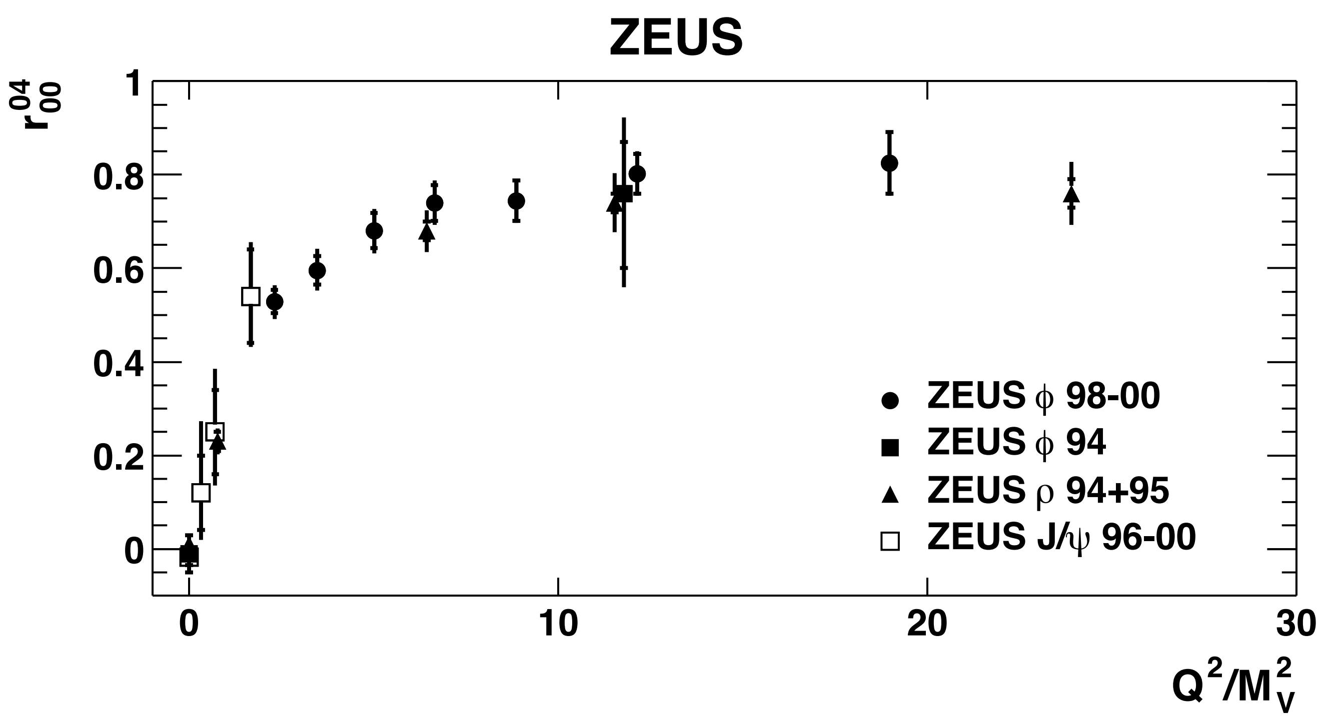
GWolf 0907.1217

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 $d\sigma_T$?

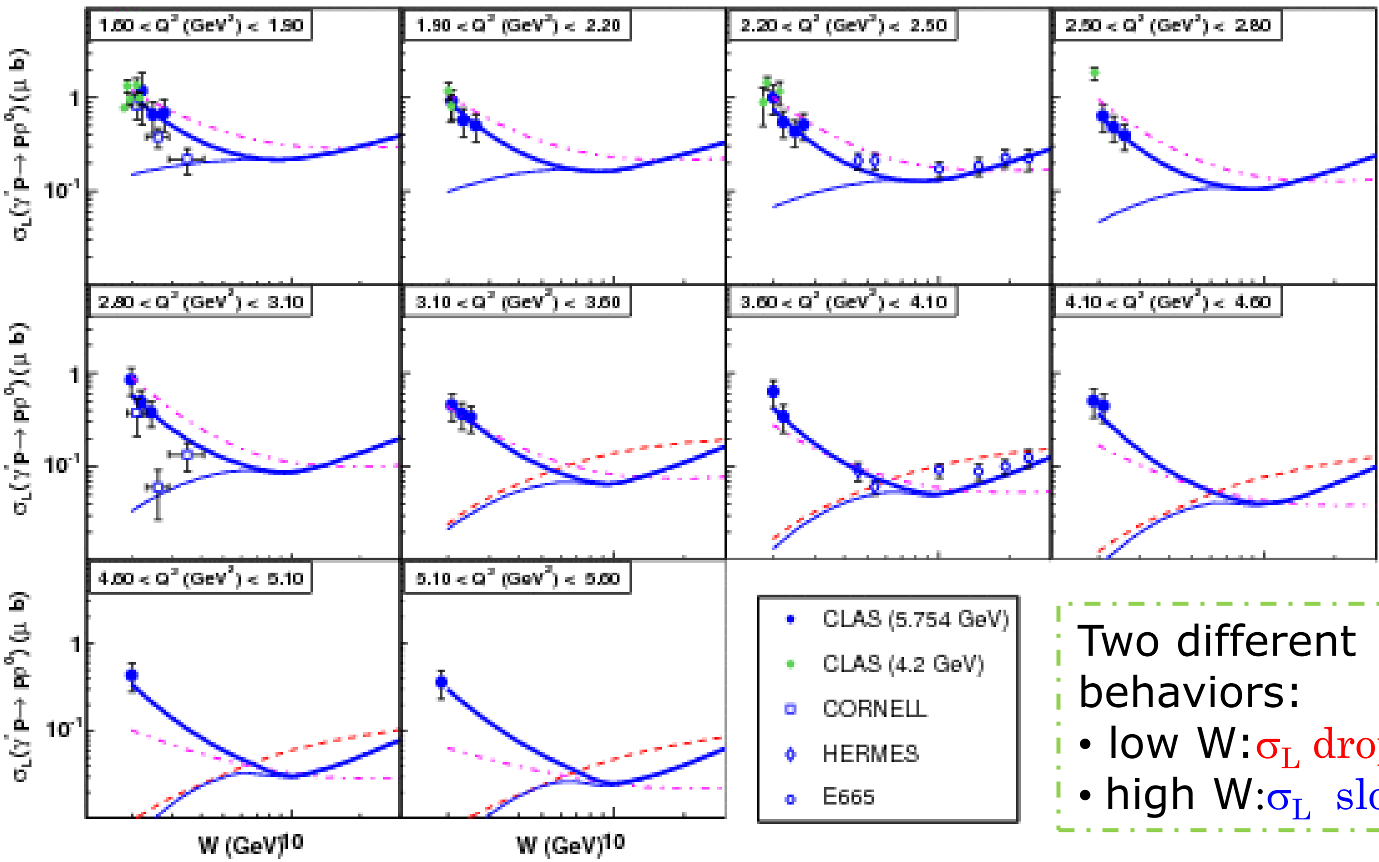


Vector Mesons at JLab

- 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 consistent with world data set
    - Perturbative *t*-channel exchange (2*g*), but factor of 10 suppression relative to colinear factorization from Sudakov effects in $\gamma \rightarrow \phi$

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 [*]

} GPD approaches based on Double-Distributions

- -.-.- dash-dotted JLM calculation *à la* Regge [*] } Hadronic approach

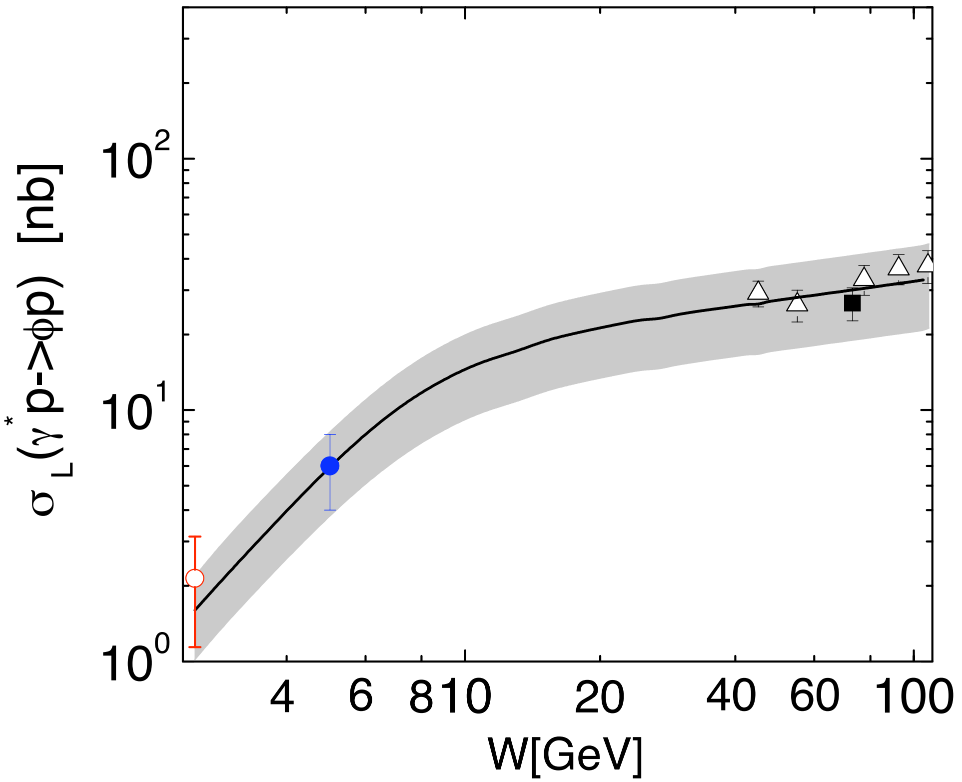
* K. Goeke *et al.*, Prog. Part. Nucl. Phys. 47 (2001) 401.

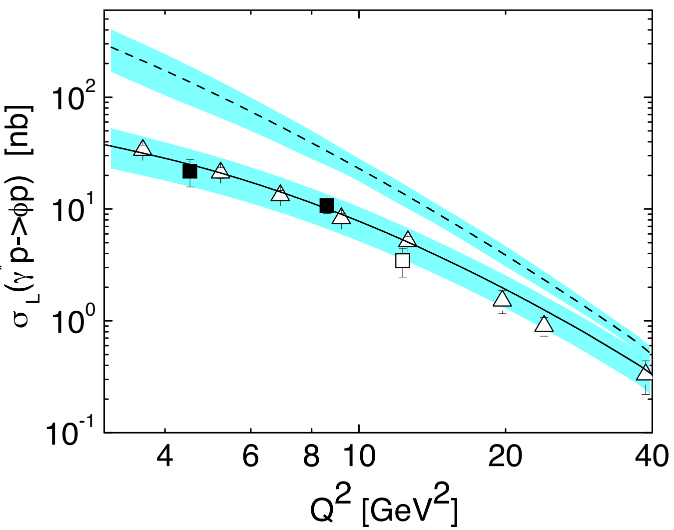
* M. Guidal, M.V. Polyakov, A.V. Radyushkin and M. Vanderhaeghen, Phys. Rev. D72 (2005) 054013.

* 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.

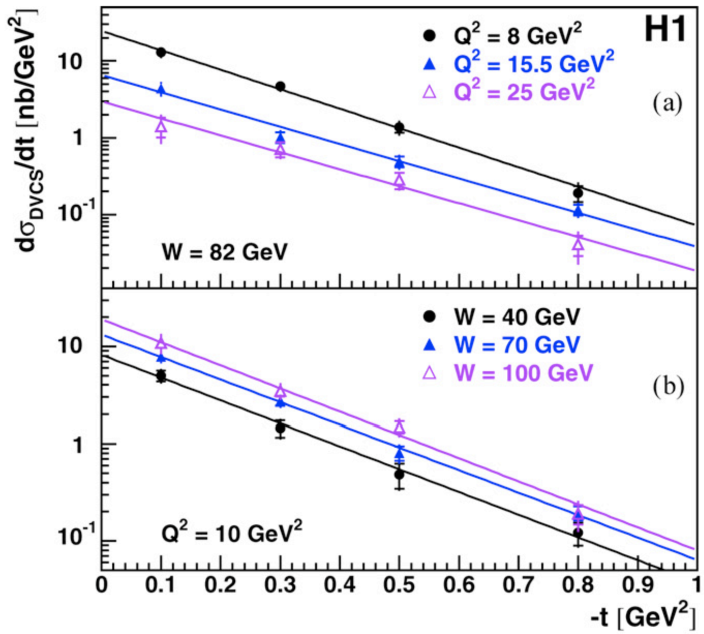
The next 20 years of DVCS experiments

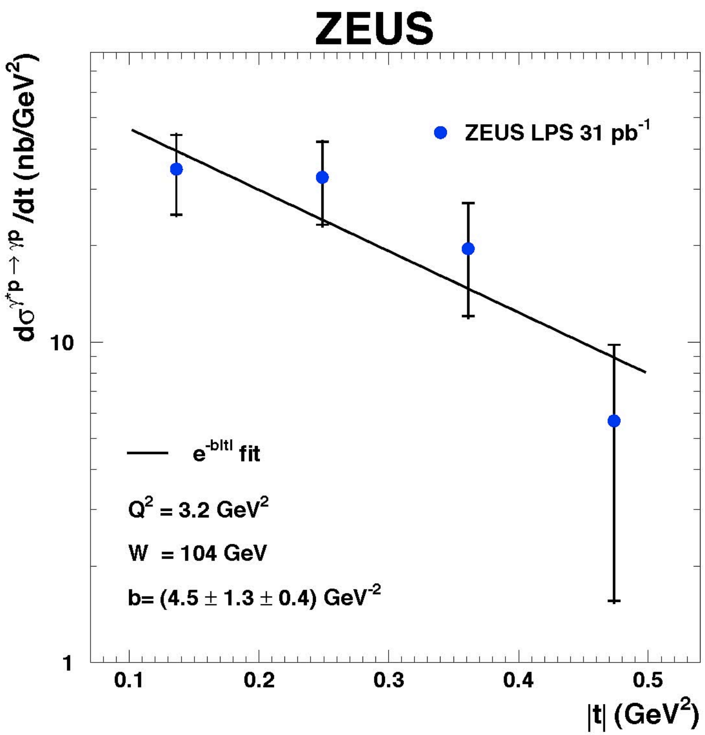
- First 5 years
  - Precision tests of factorization with Q^2 range ≥ 2:1 for
    - $x_B \in [0.25,0.6]$. $t_{min}-t < 1$ GeV^2 + COMPASS : $x_B \in [0.01,0.1]$
    - Proton unpolarized target observables
    - Im[DVCS*BH], Re [DVCS*BH], $|DVCS|^2$.
  - Longitudinal, target spin observables
    - Primary sensitivity to H, $\tilde{H}$, 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 $s \geq 1000$ GeV^2 and $\mathcal{L} > 2 \cdot 10^{34}$ $/cm^2/s$.

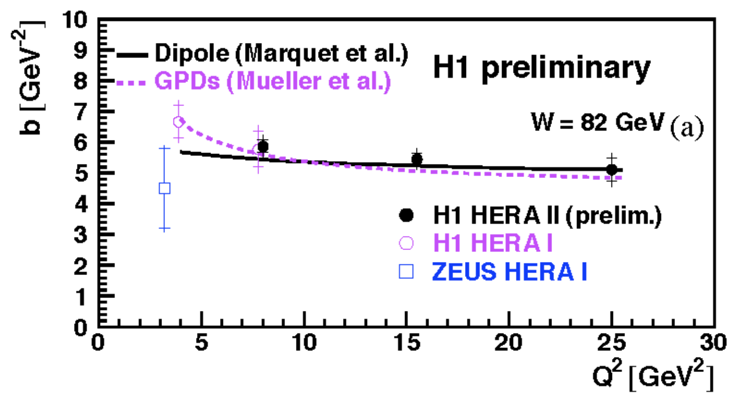
Back-up Slides

HERA DVCS

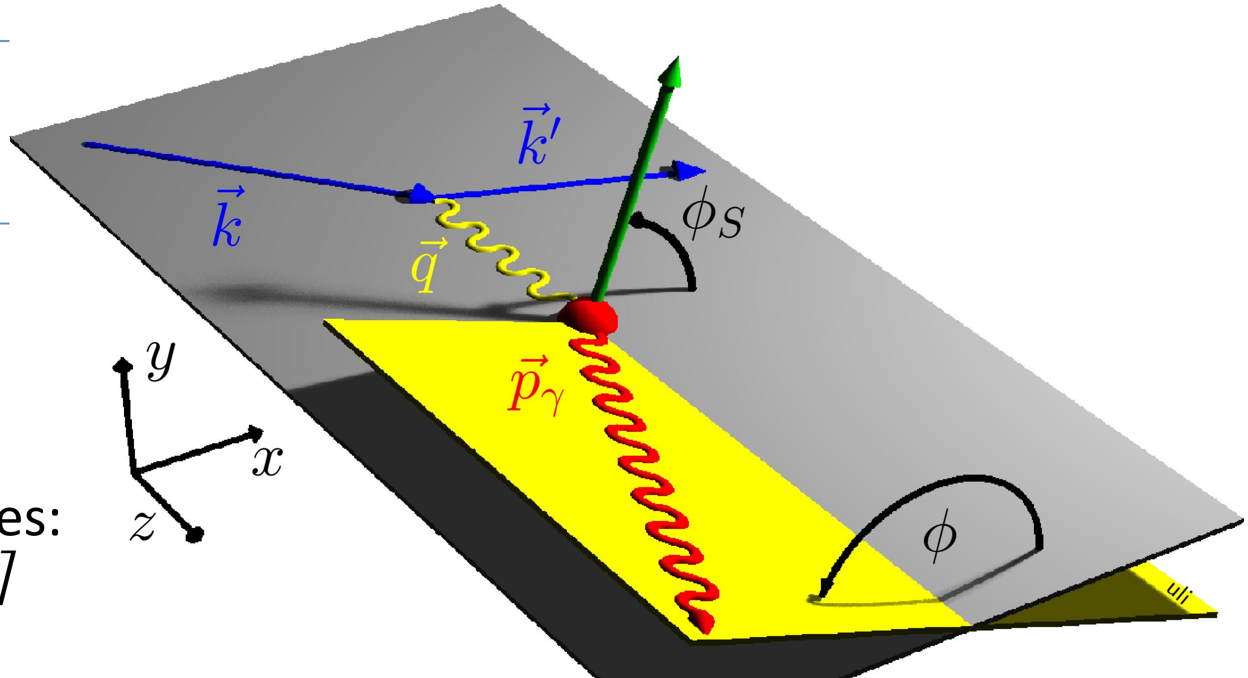
- Spatial imaging of gluons at small x_B







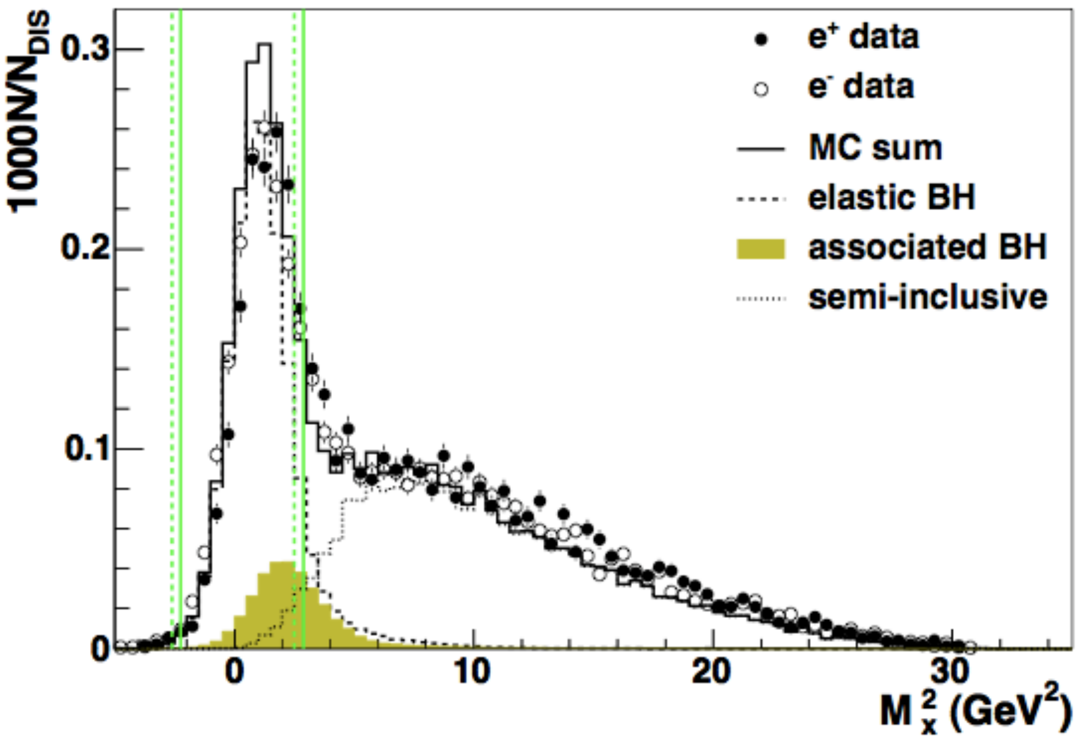
Unraveling DVCS observables



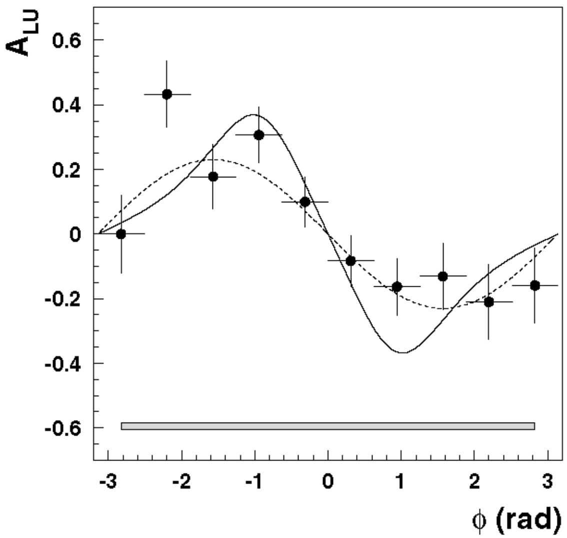
- Twist-2 terms ≈ 1, cosϕ, sinϕ
- Twist-2 terms ≈ sin2ϕ
- Not a pure Fourier series: 1/*[A + B*cosϕ + *C*cos2ϕ*]* from *BH* propagators.
- GPDs enter with different weights for each azimuthal term for different polarization (lepton helicity, target-longitudinal or –transverse) observables
  - Single and Double spin observables
  - Beam charge difference (e^+e^- HERMES, JLab$^{????}$; $\mu^+\mu^-$ COMPASS)
  - Energy dependence (JLab)
- Complete separation of *Re* and *Im* parts of CFF of E, H,… in-principle possible (D.Mueller, next)
- *u, d* flavor separations require neutron targets (or deep meson electroproduction)

HERMES DVCS p(e,e'γ)X

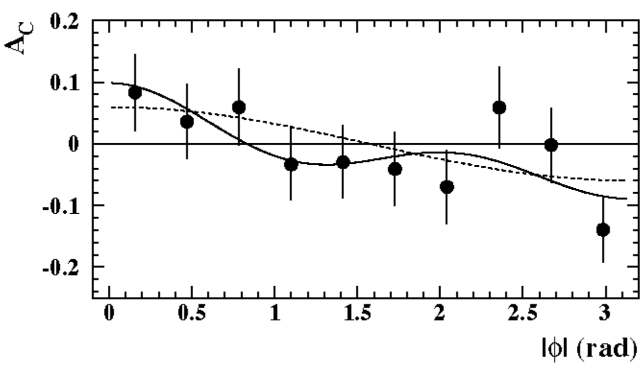
27 GeV polarized $e^{\pm}$ on
Internal Gas Jet
/ Atomic Beam Source targets

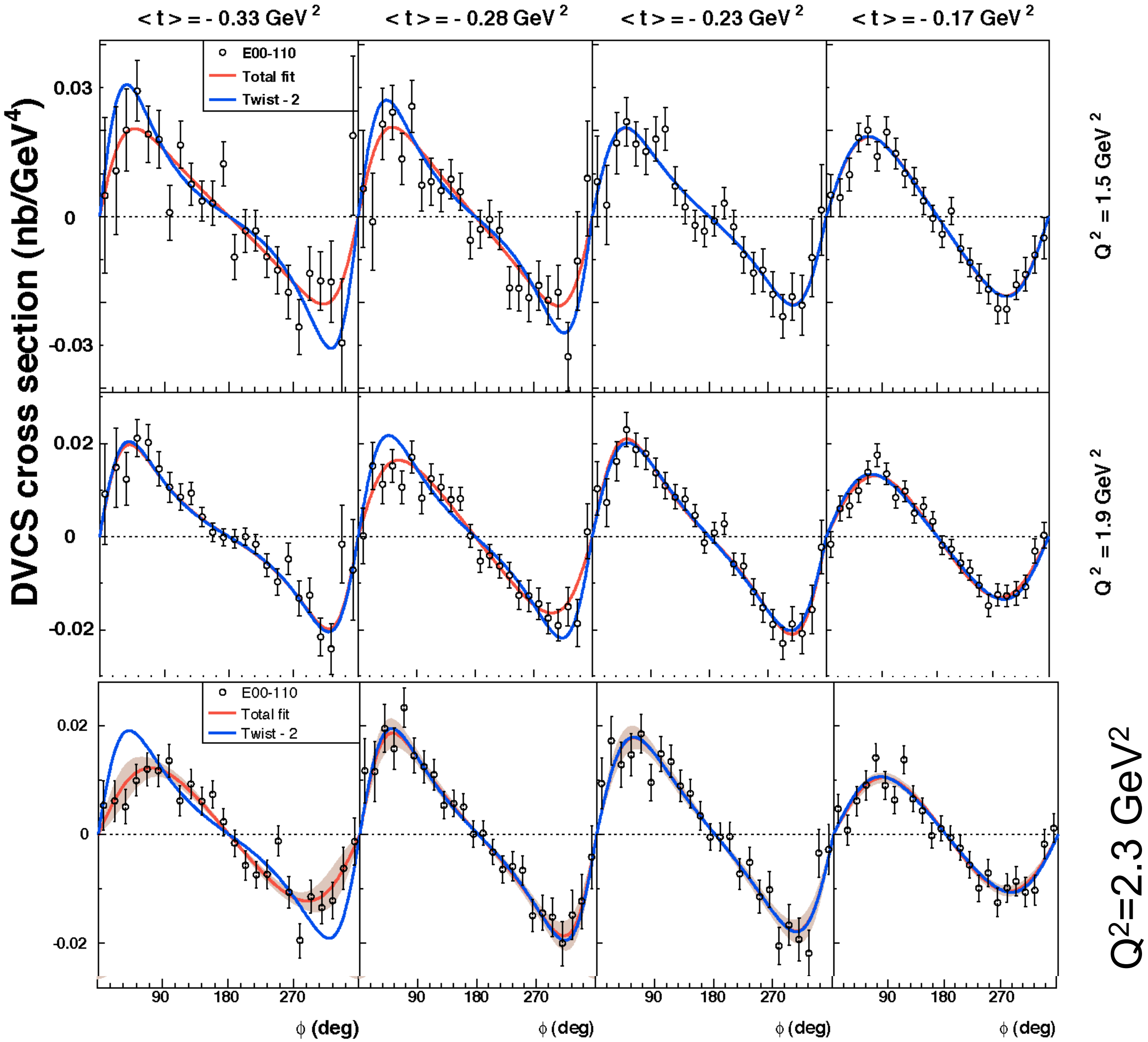


2001 BSA



2006 BCA





Hall A Helicity Dependent Cross Sections E00-110

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

Twist-2(GPD)+…

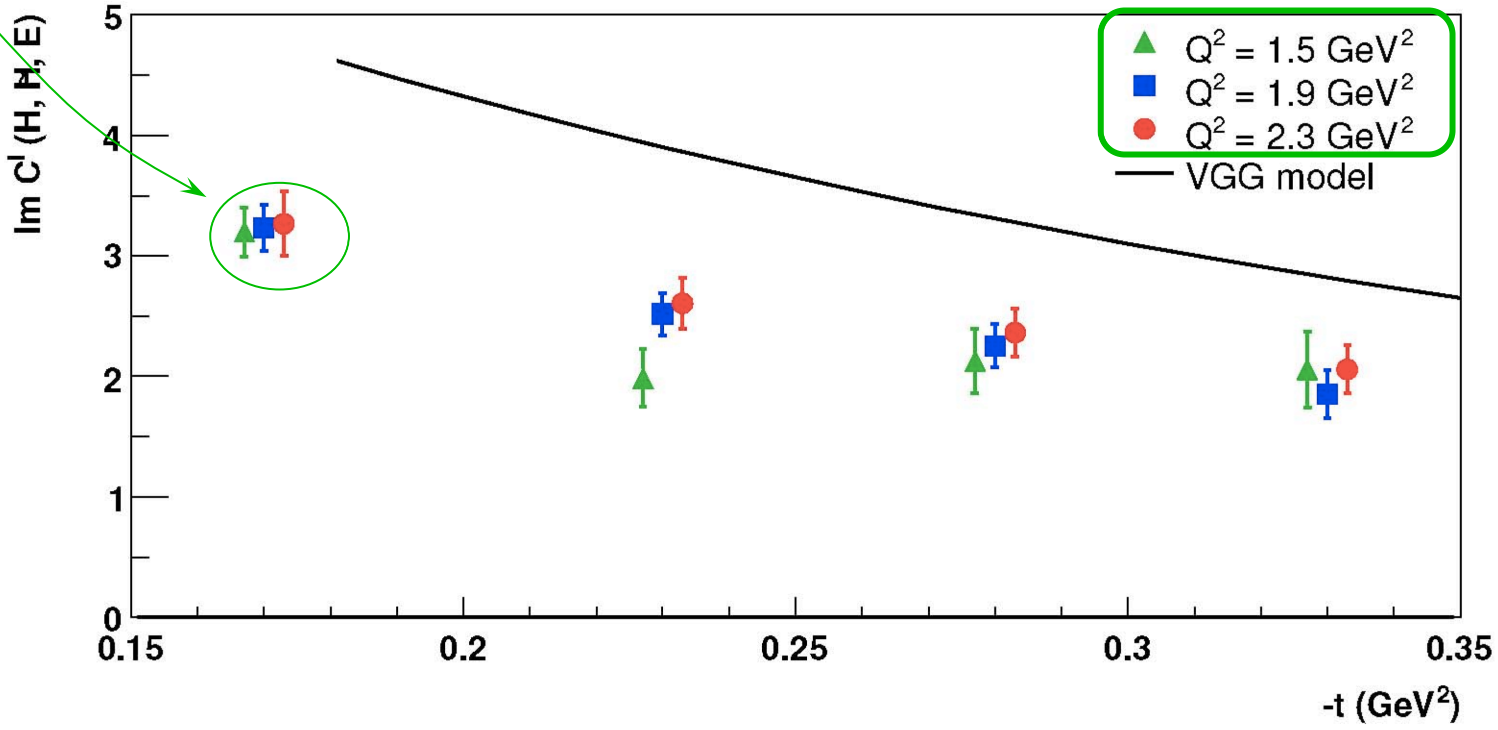
Twist-3(qGq)+…

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

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

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

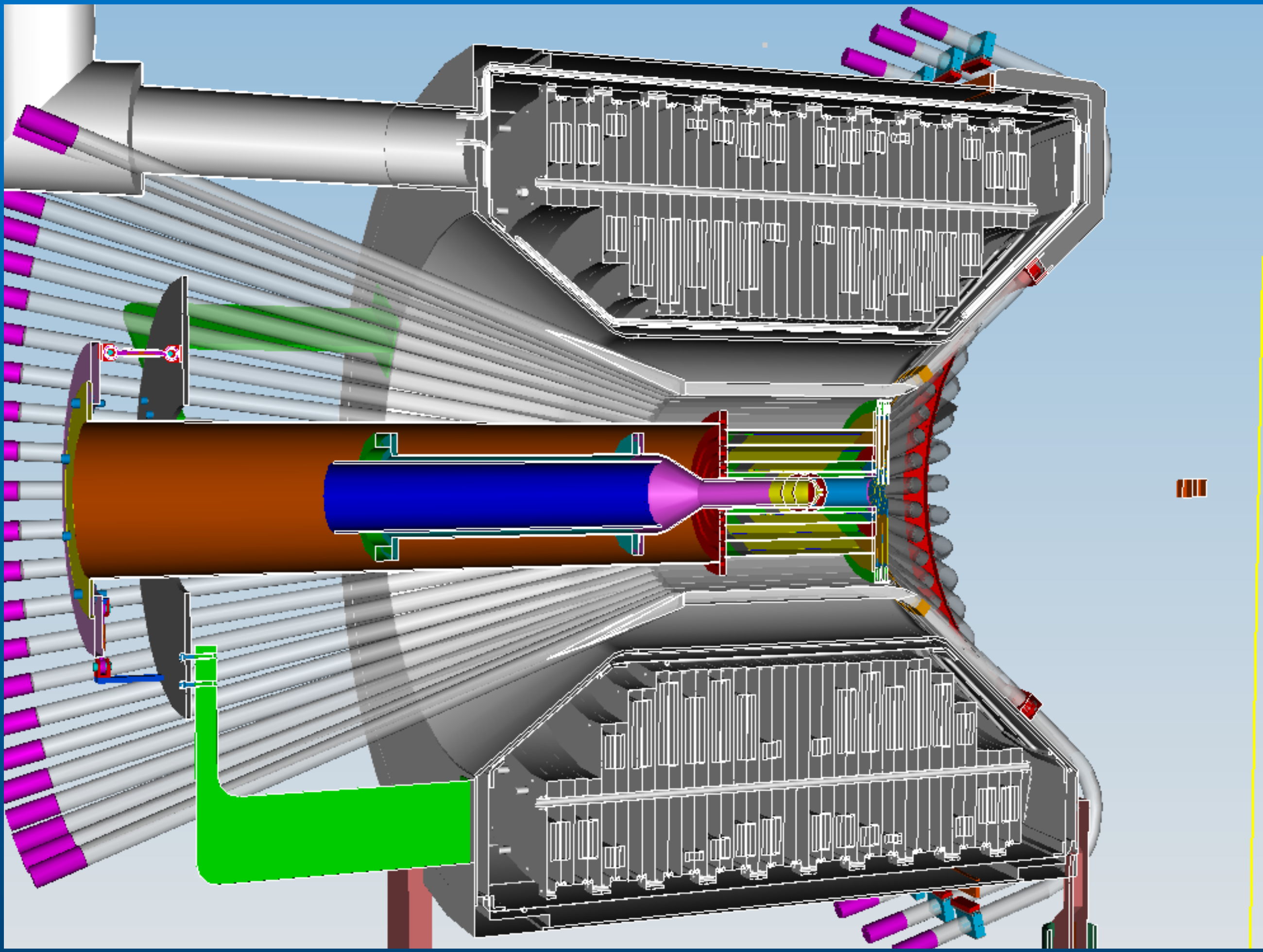
- Q^2-independance of Im[DVCS*BH]
  - Twist-2 Dominance (GPD)
  - Model « Vanderhaeghen-Guichon-Guidal (VGG) » accurate to ≈30%



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

CLAS12 – Central Detector SVT, CTOF

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



HD ice : a transversely polarized target for CLAS

Operates at **T~500-750mK**
•Long spin relaxation times (months)
•Weak transverse magnetic field

- 25+ years of development…
- Successful operation at LEGS photon beam
- Just in time for DVCS!!!!

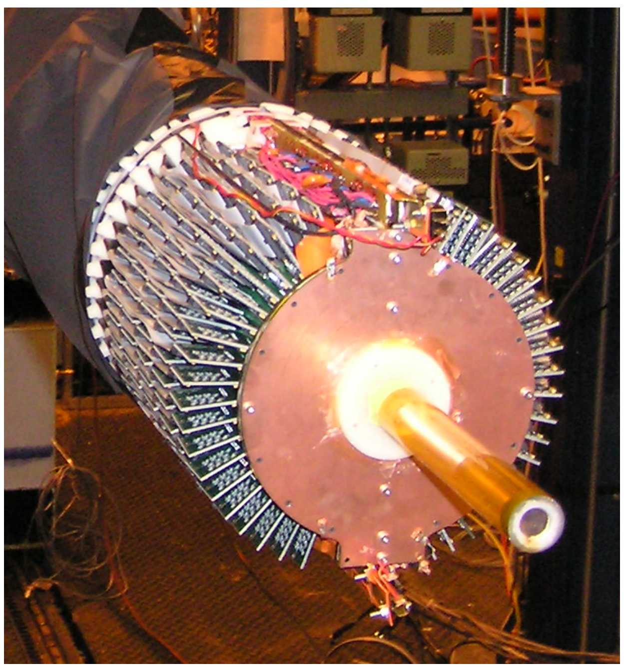
Material	gm/cm^2	mass fraction
HD	0.735	77%
Al	0.155	16%
CTFE (C_2ClF_3)	0.065	7 %

Test in 2010 with electron beam, Experiment conditionally scheduled in 2011

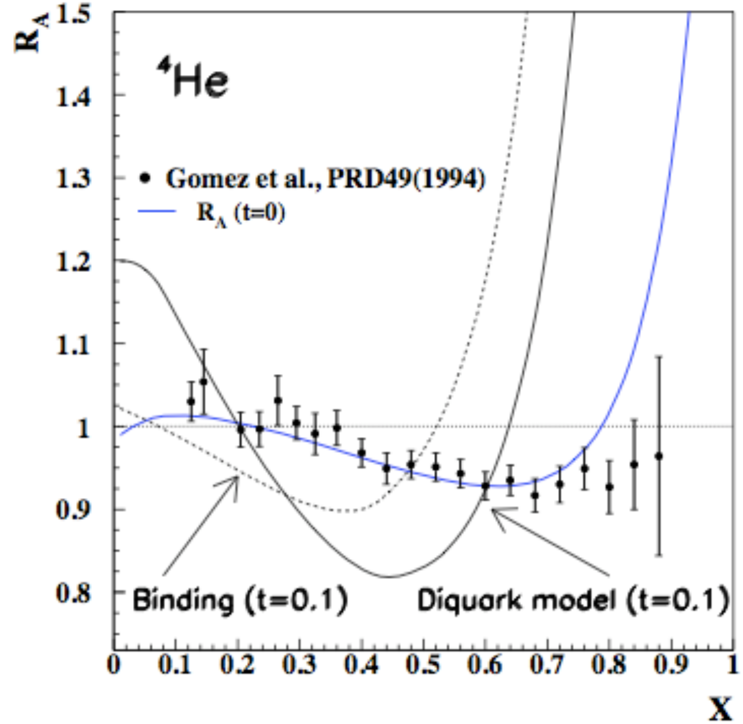
Heat extraction is accomplished with thin aluminum wires running through the target

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

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



$$\frac{H_{He}(x,0,t)}{H_N(x,0,t)}$$



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

DVCS in Hall A

- Elastic form factors, Real Compton Scattering: Correlated two-body final state,
  - Spectrometers have the advantage over large acceptance:
    - product of (Luminosity)(Acceptance)
    - Precision of absolute cross sections
- DVCS is a 3-body final state
  - For $-t/Q^2 << 1$, final photon close to **q**-direction.
  - Quasi two-body final state for limited *t* coverage