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

Orbital Angular Momentum in QCD

Experimental Overview of Deeply Virtual Exclusive Reactions

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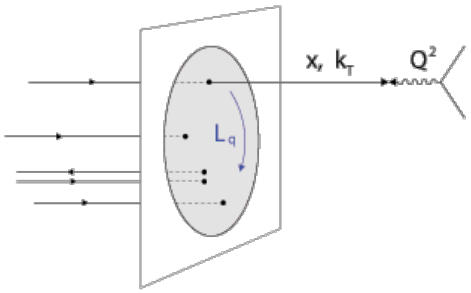
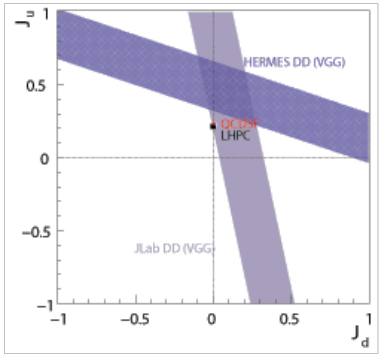
Norfolk VA

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

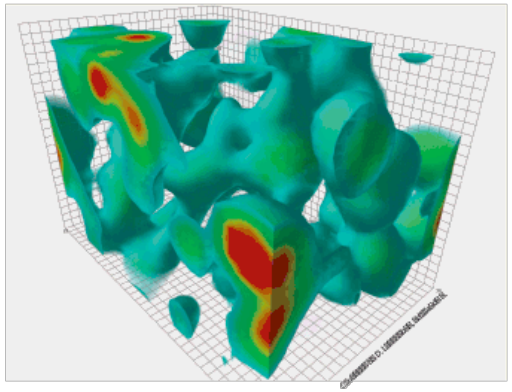


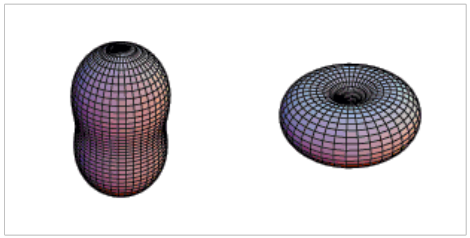


A universally correct statement for the nucleon spin

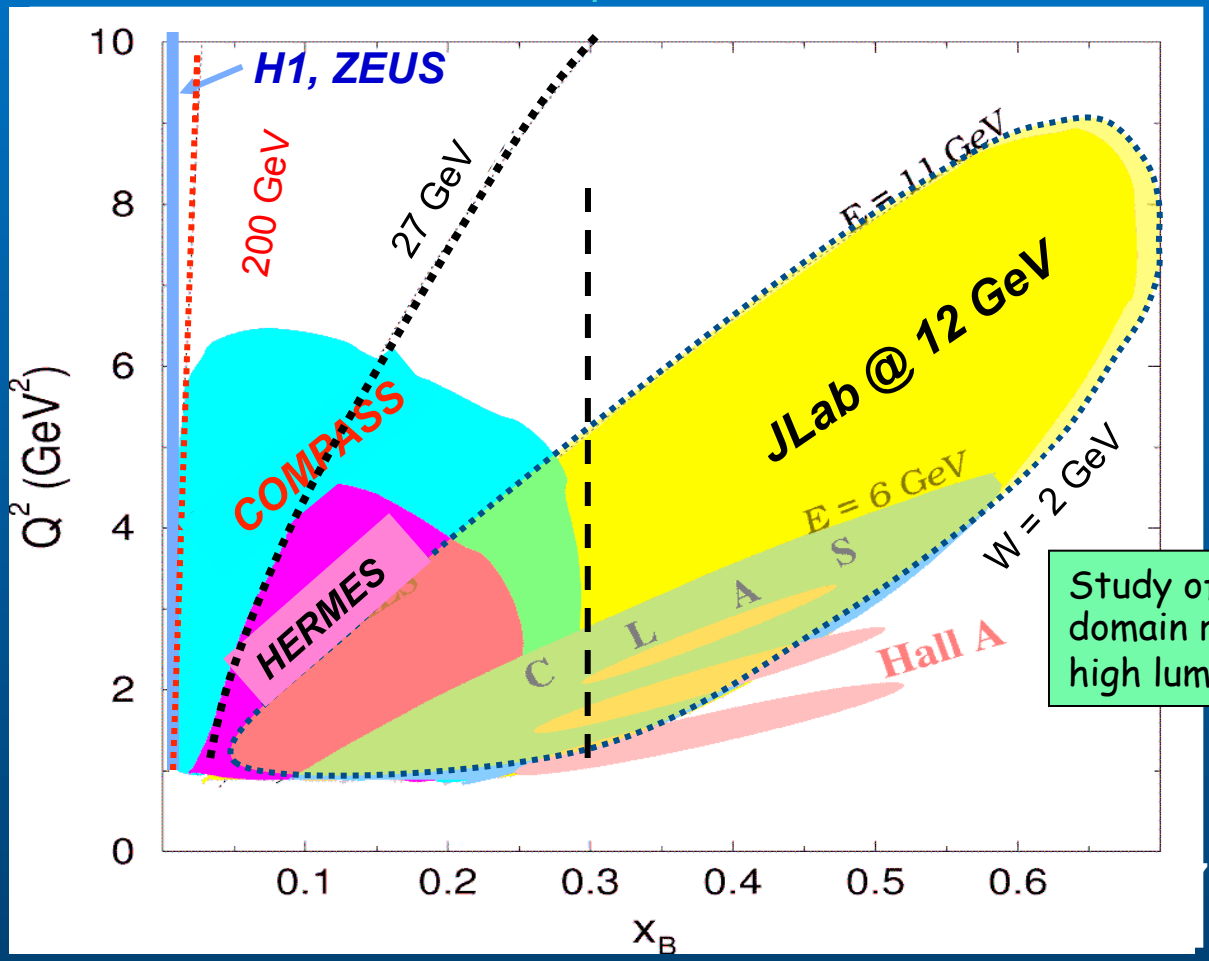
Nucleon spin comes from the spin and orbital motion of quarks and gluons

--- Chairman Mao



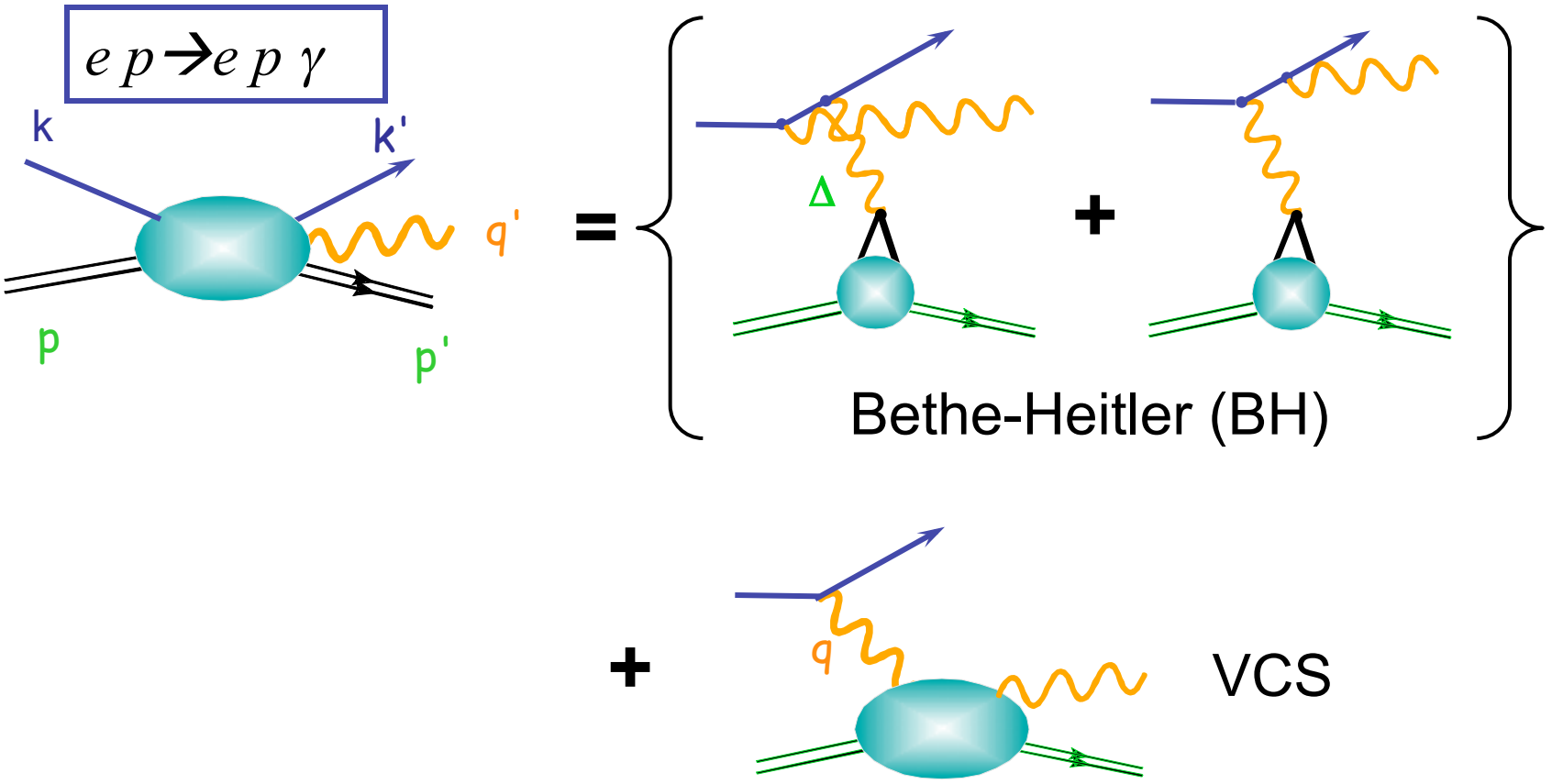


Deeply Virtual Exclusive Processes - Kinematic Coverages



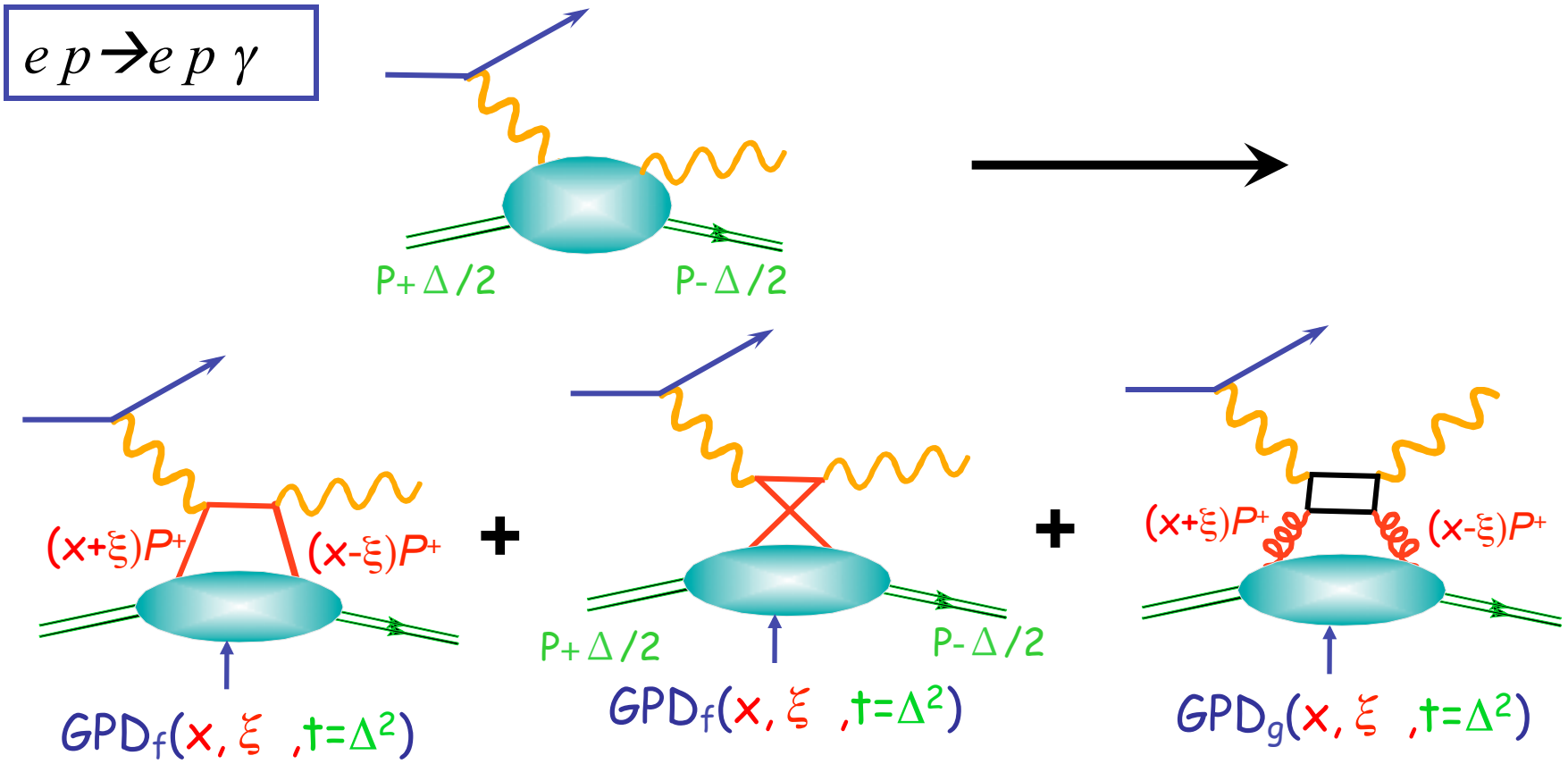
Study of high x_B domain requires high luminosity

Bethe-Heitler and Virtual Compton Scattering (VCS)



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

Leading Order (LO) QCD Factorization of DVCS



- Symmetrized Bjorken variable:

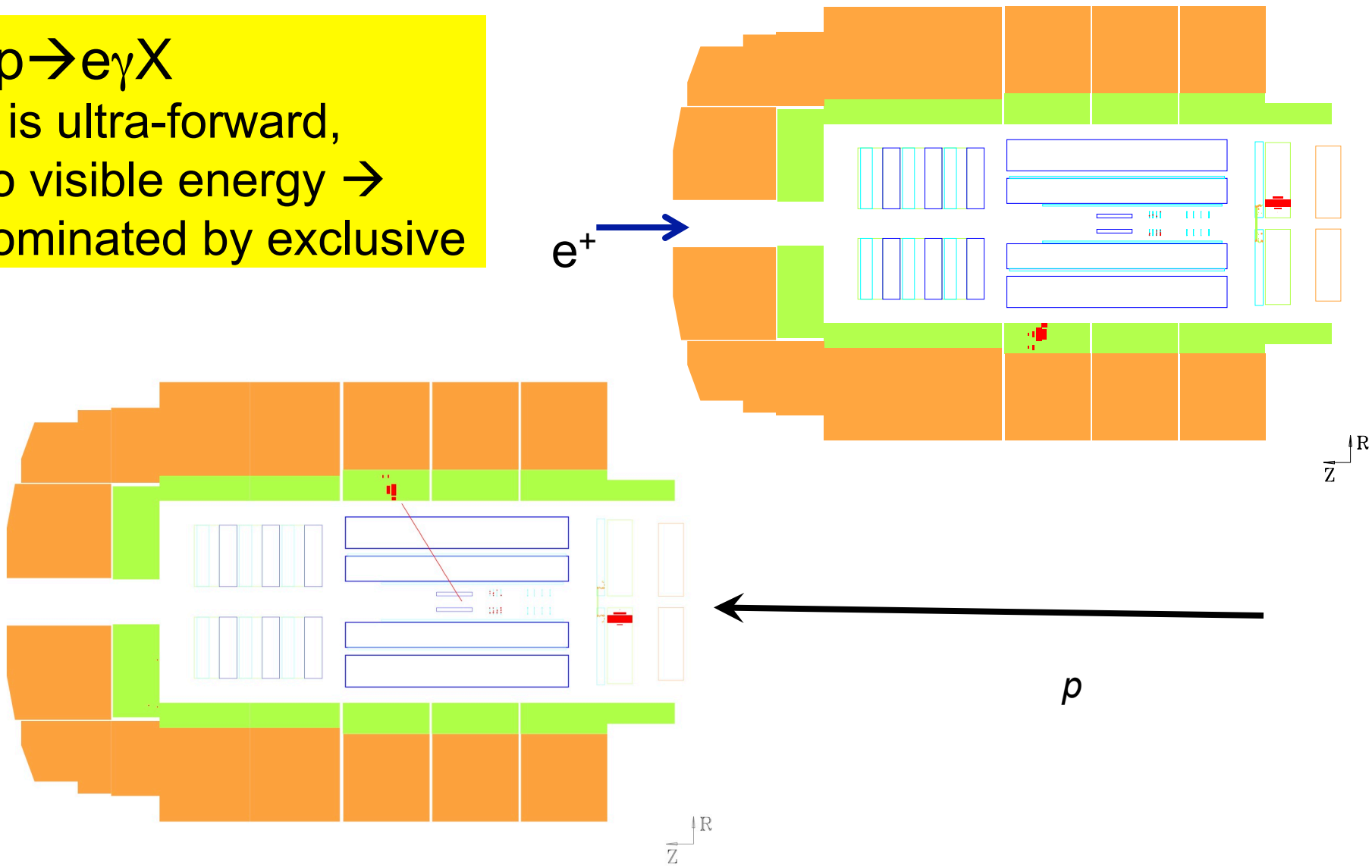
$$\xi = \frac{-(q+q')^2}{2(q+q')\cdot P} \xrightarrow[\Delta^2 << Q^2]{} \frac{x_B}{2-x_B}$$

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

HERA-H1 DVCS-dominated and BH-dominated events

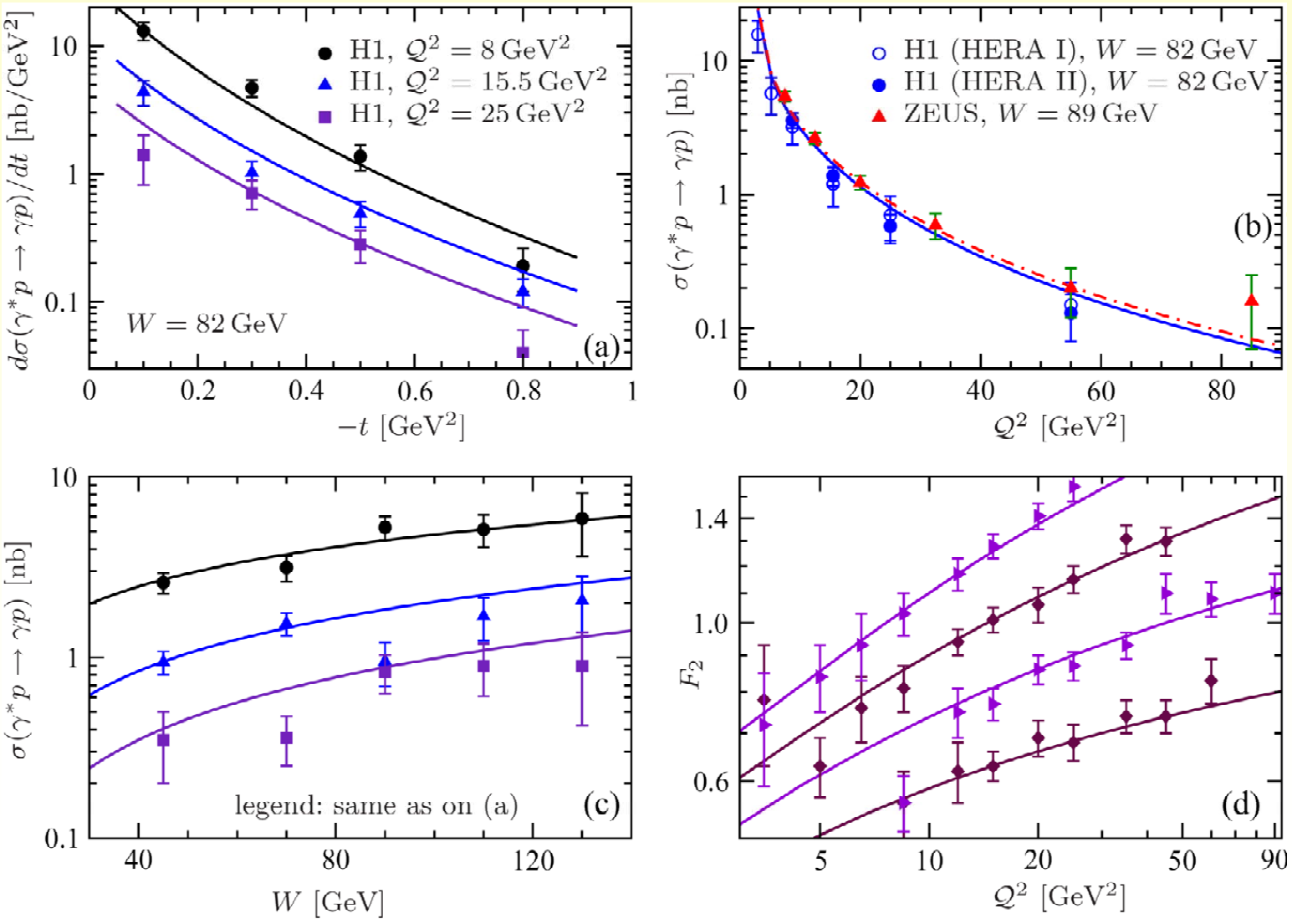
$ep \rightarrow e\gamma X$

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→epγ) = 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):

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

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

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

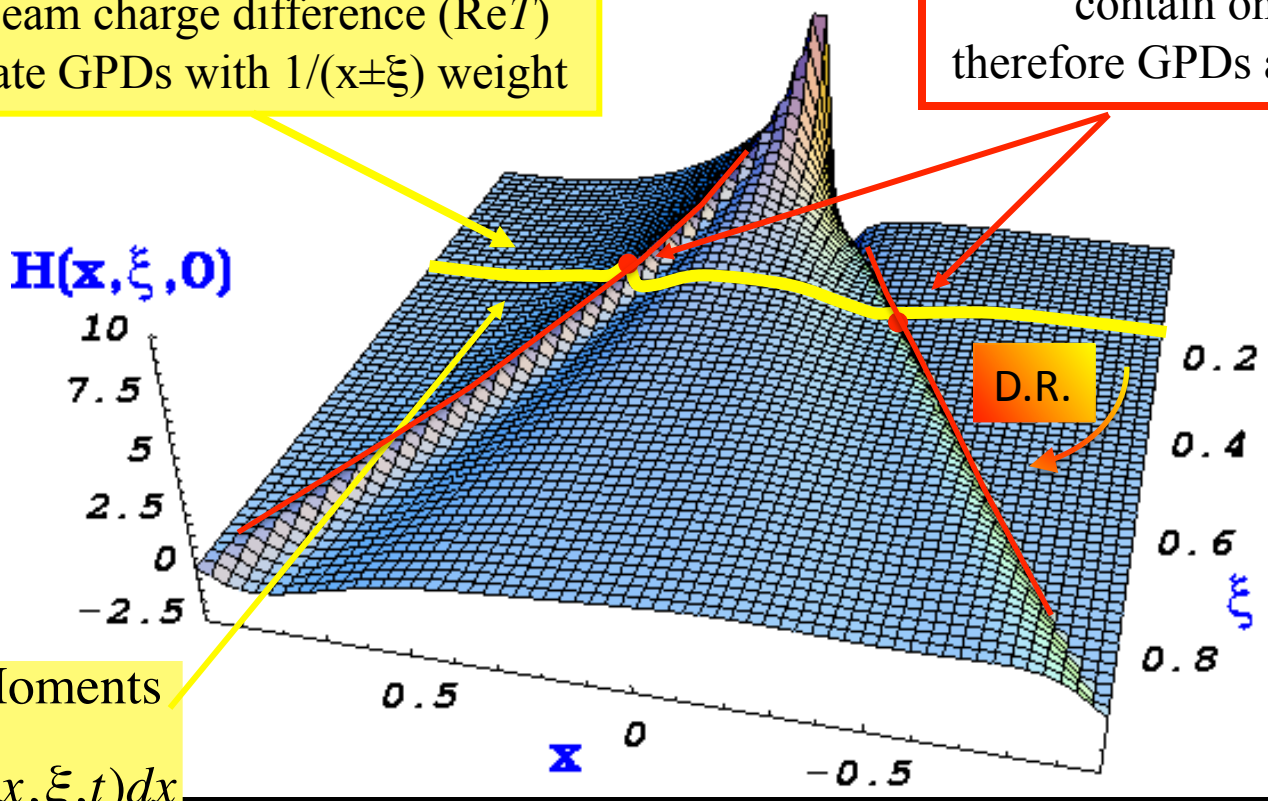
DVCS, GPDs, Compton Form Factors(CFF), and Lattice QCD

(at leading order:)

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

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 $-\xi$

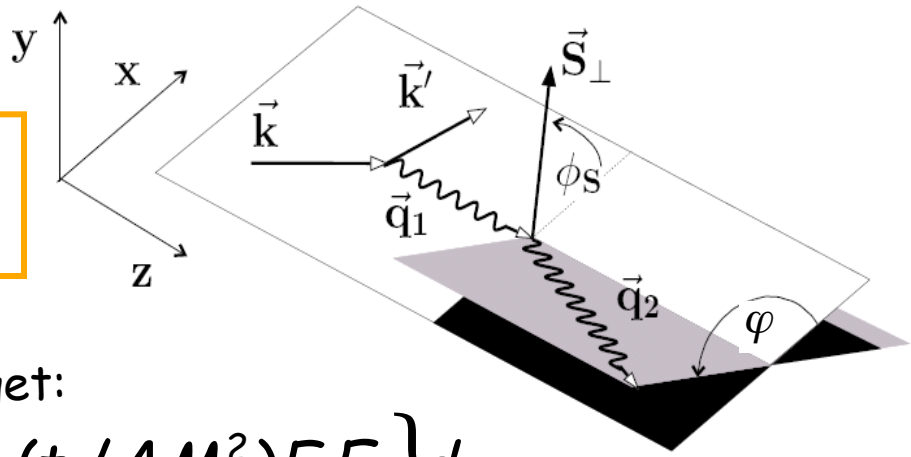


Lattice Moments

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

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:

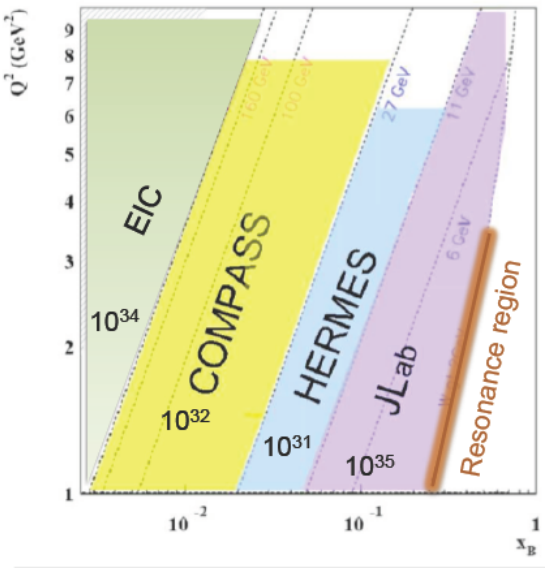
$$\Delta\sigma_{UT} \sim \cos\varphi \sin(\phi_S - \varphi) \left\{ (t/4M^2)F_2 H - (t/4M^2)F_1 E + \ldots \right\} d\varphi$$

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

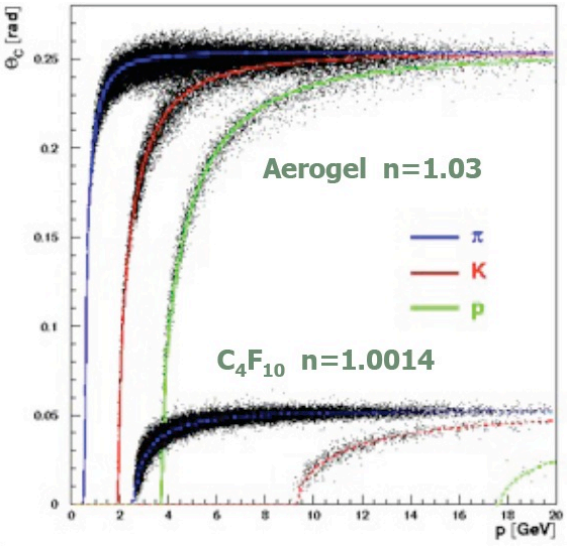
HERMES overview

27.6 GeV e+/e- HERA beam

Access to valence and sea



Electron and Hadron ID

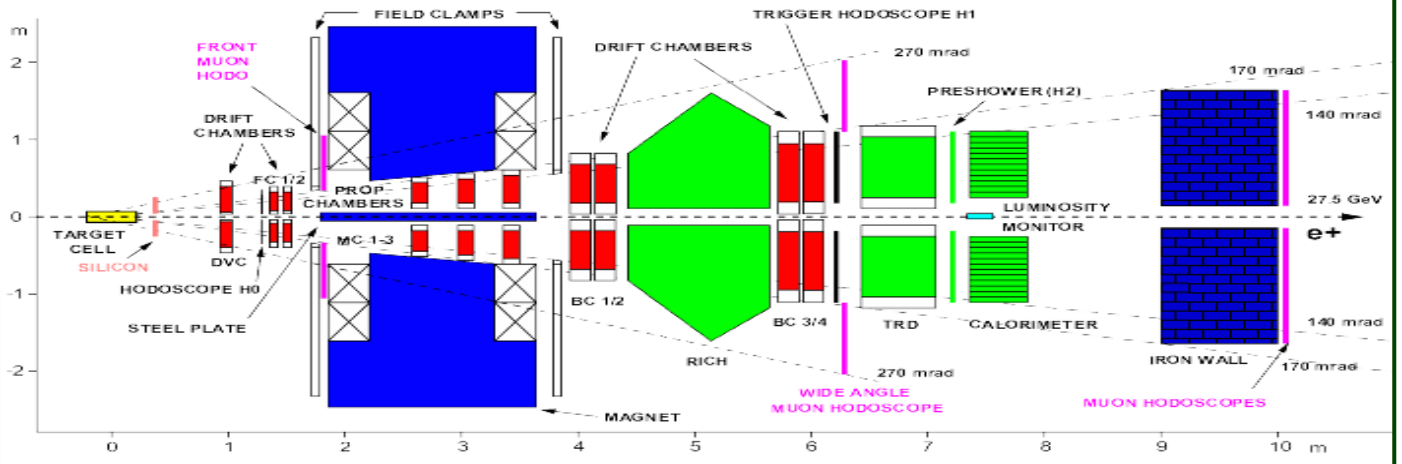


hermes

Data taking: 95-07

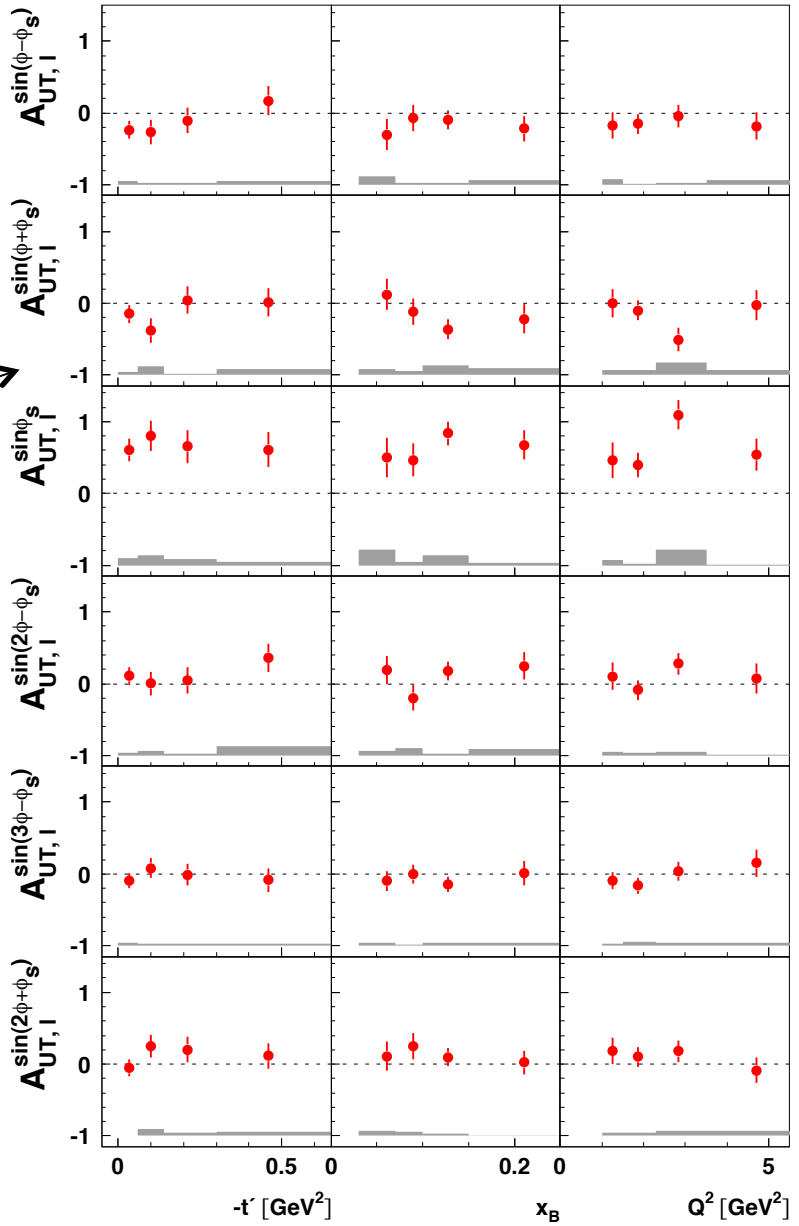
Internal gaseous target (no nuclear effects)

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

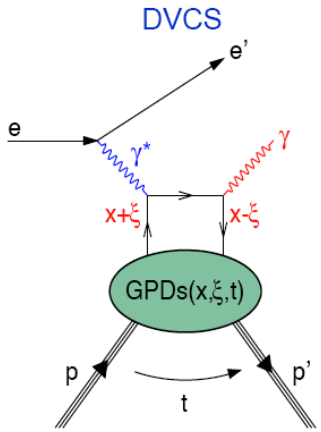


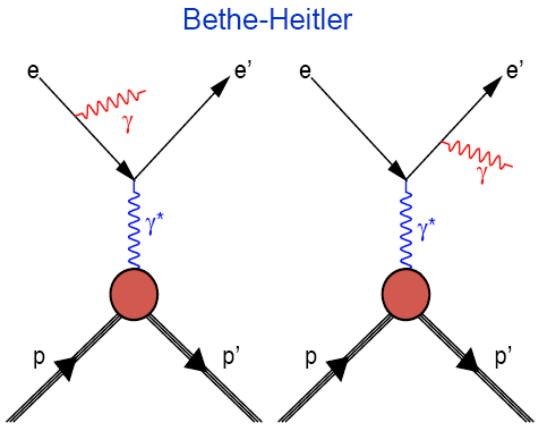
Deeply virtual Compton scattering

Theoretically cleanest way to access GPDs

@ HERMES:

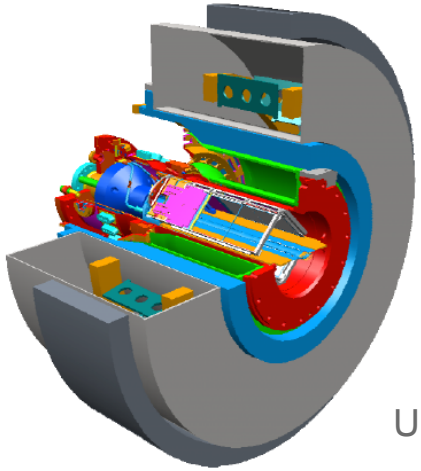
Large BH amplitude enhances DVCS signal via interference





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

Recoil detector to tag exclusivity



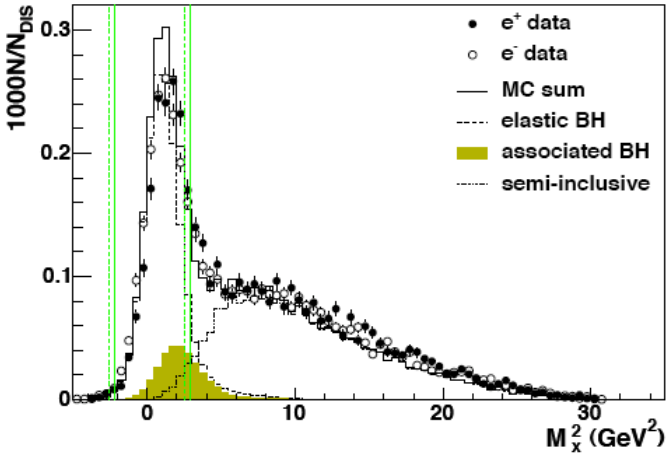
1T SC Solenoid

Photon Detector

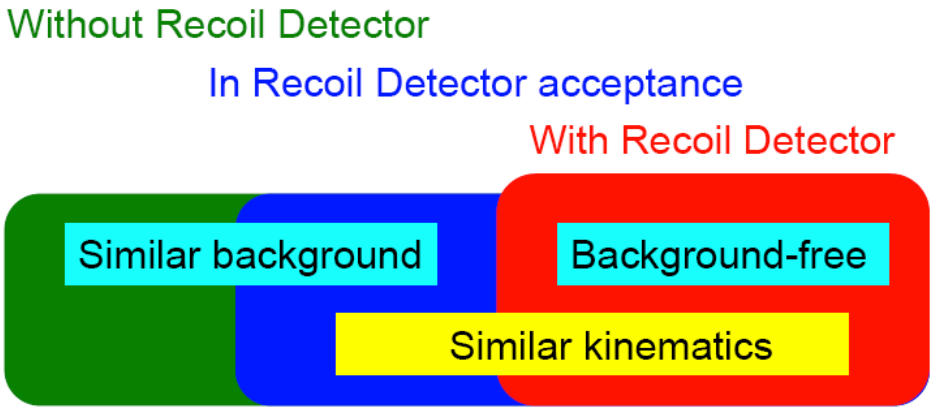
Scintillating Fiber Tracker

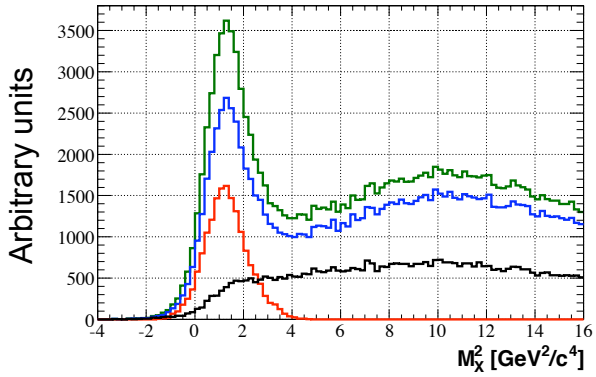
Silicon Strip Detector

Unpolarized H and D targets

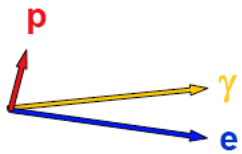


The recoil detector

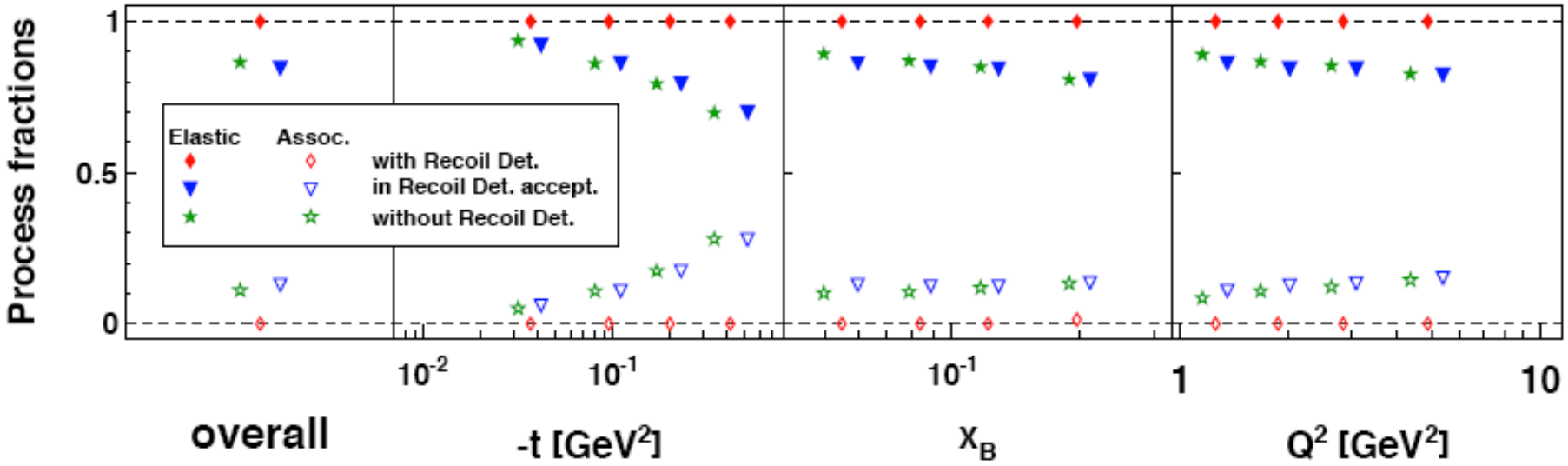




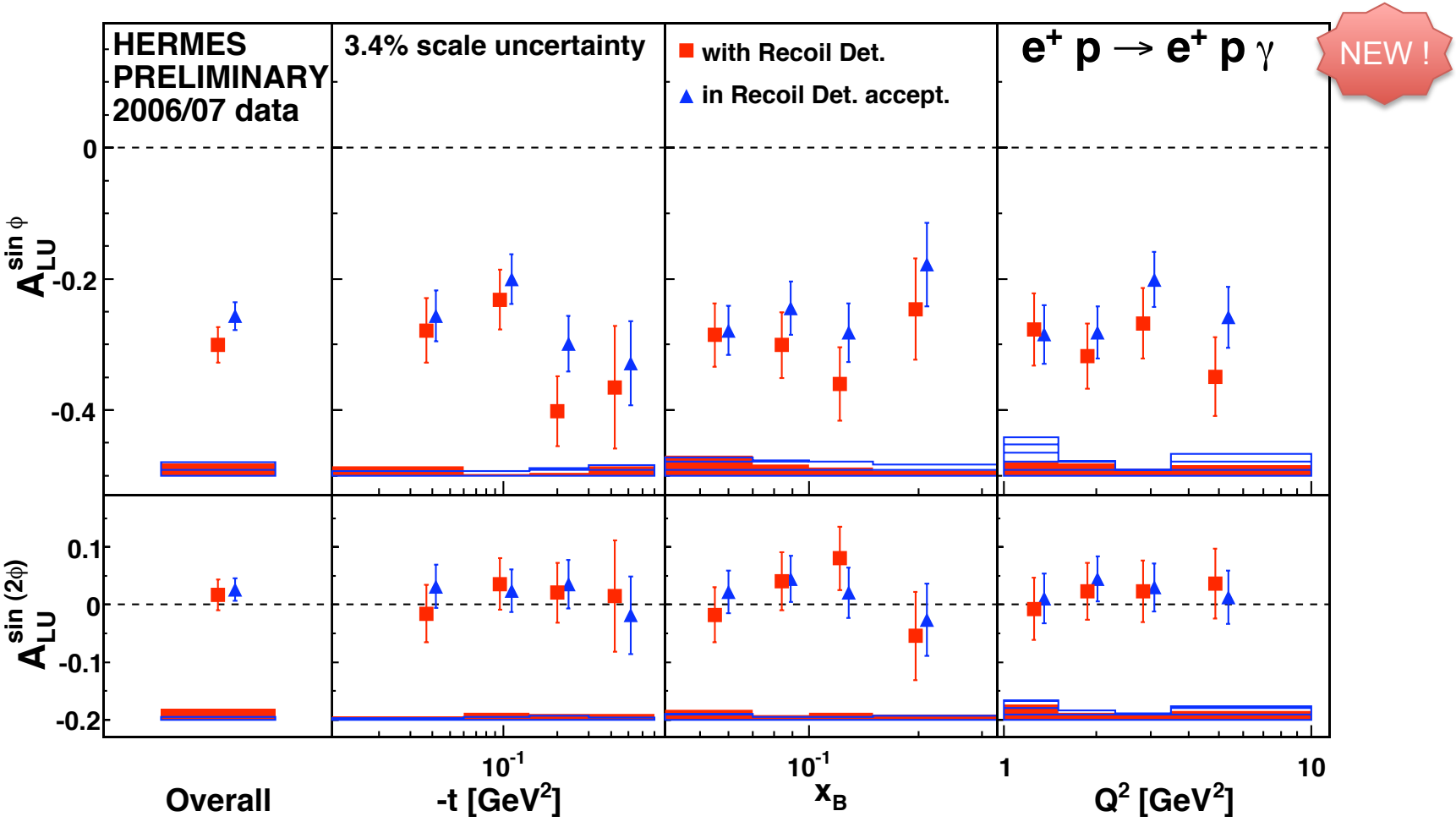
Kinematic event fitting technique: all 3 particles in the final state detected should satisfy 4-constraints on energy-momentum conservation



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



Pure elastic DVCS

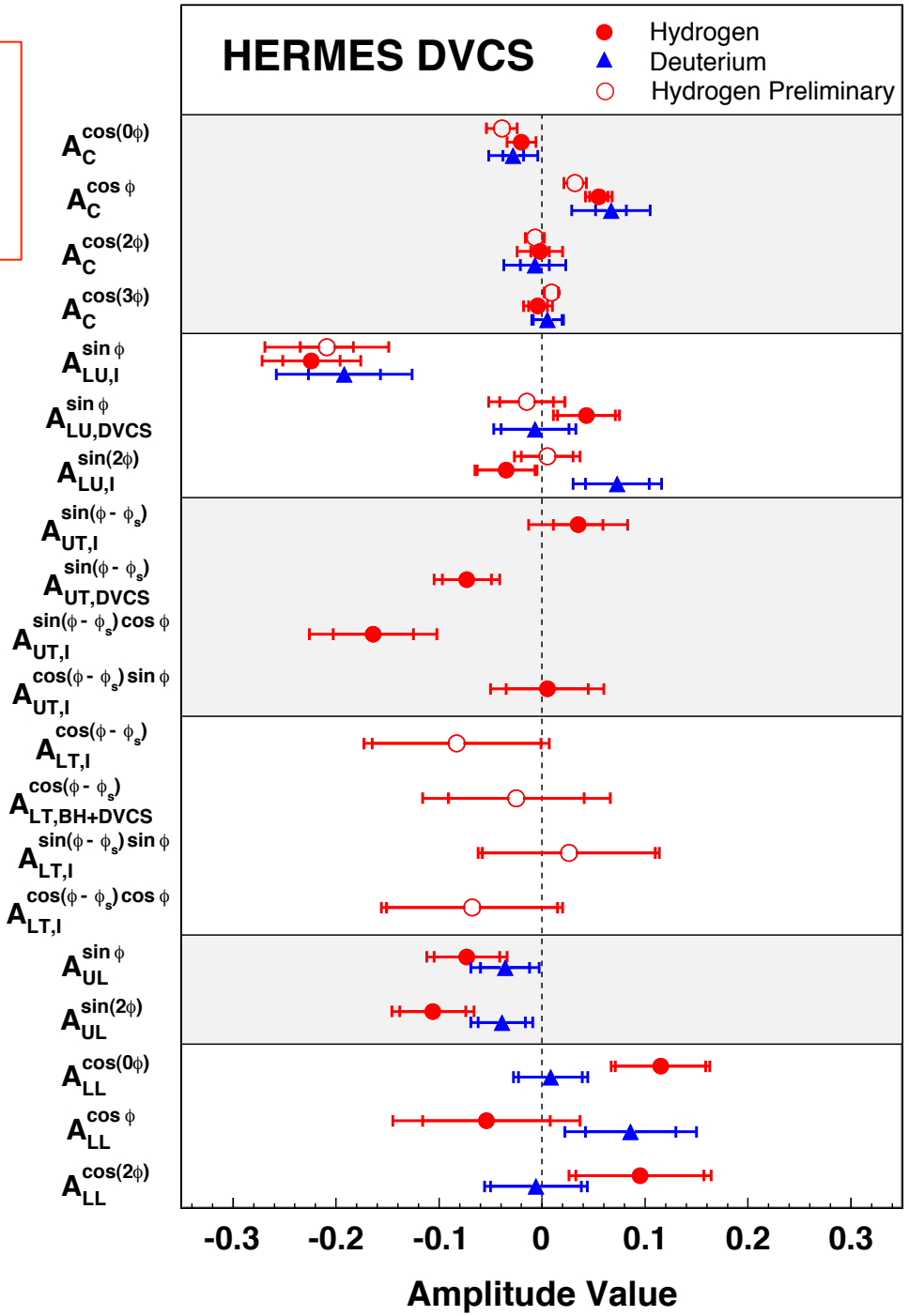


Within the present level of precision, the signal is stable with respect background subtraction

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



DVCS Asymmetries

e^+e^-

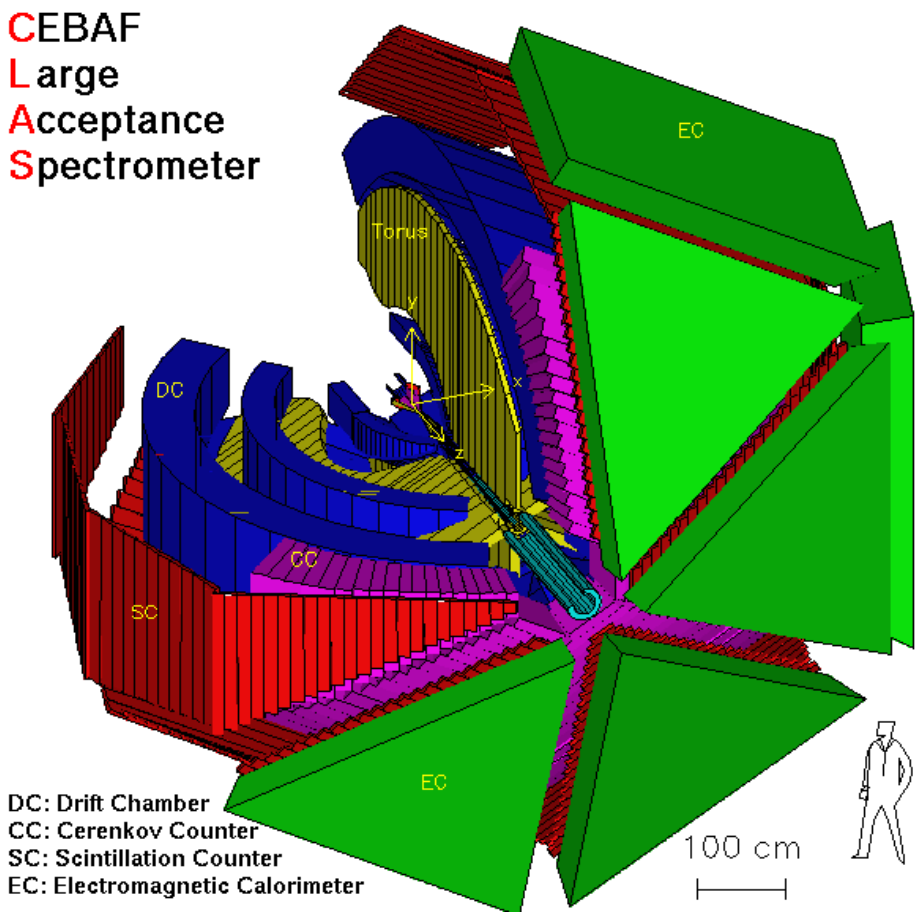
Beam Spin Asymmetry

Transverse target Single Spin

Beam & Transverse Target Double Spin

Longitudinal Target

The CLAS detector



- 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.

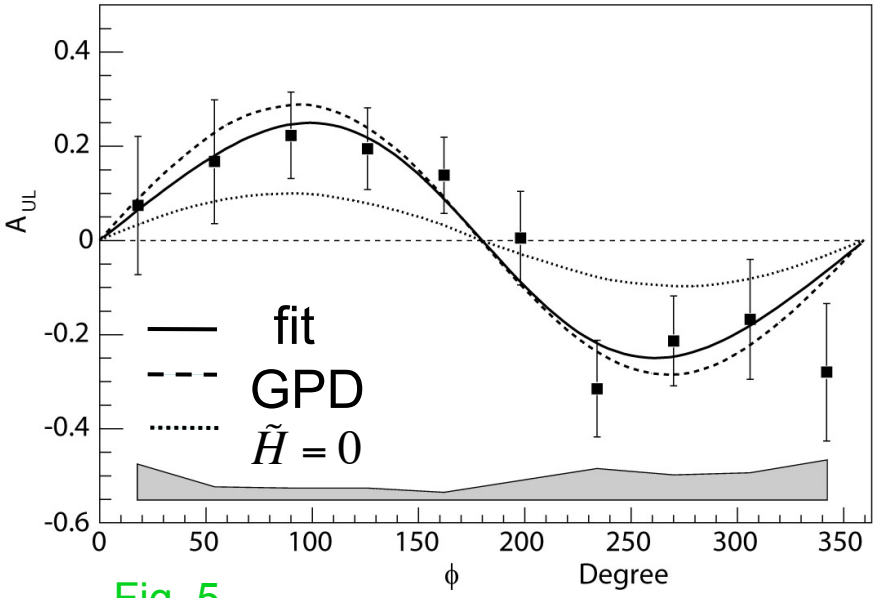


Fig. 5.

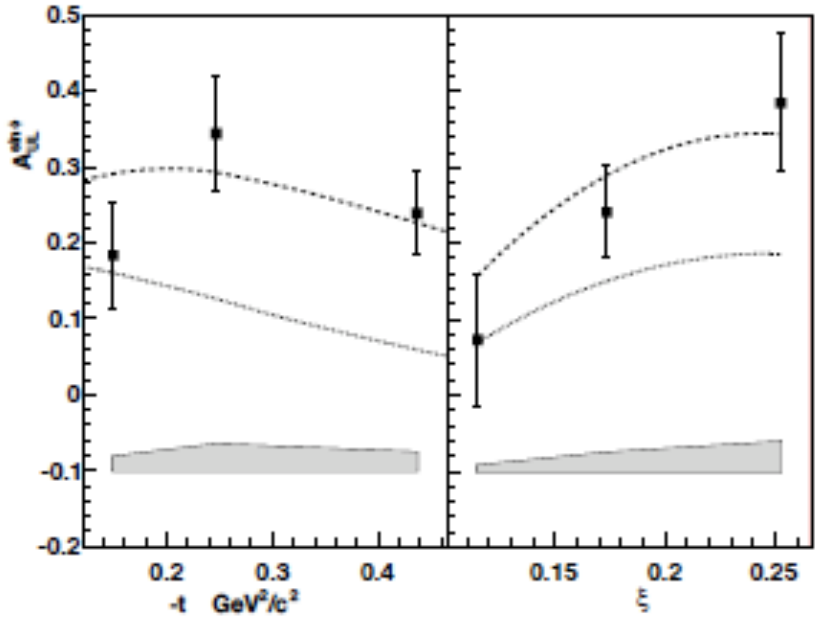
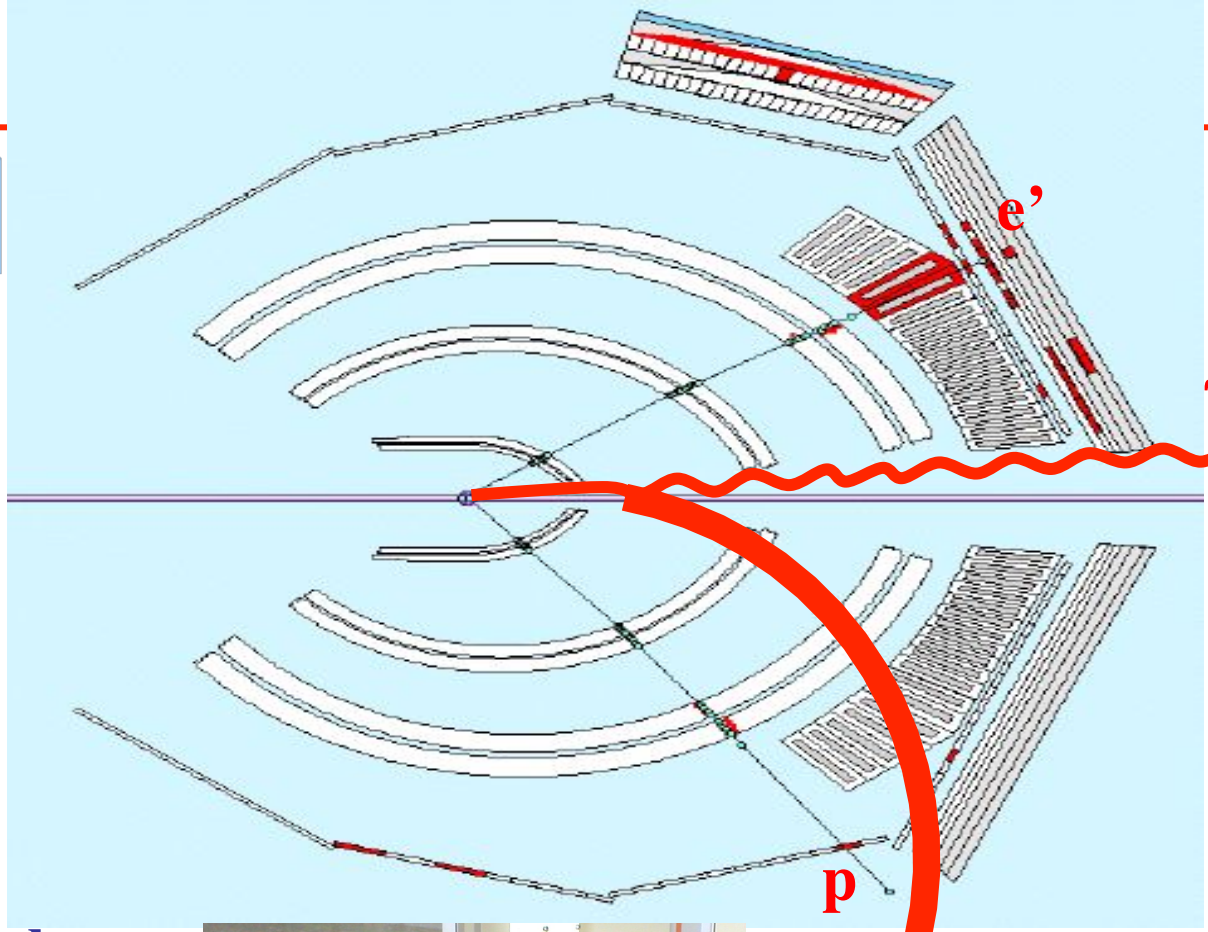


FIG. 6: The left panel shows the $-t$ dependence of the $\sin\phi$-moment of A_{UL} for exclusive electroproduction of photons, while the right shows the ξ dependence. Curves as in Fig. 5.

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

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

DVCS@Hall B



ep⇨ epγ

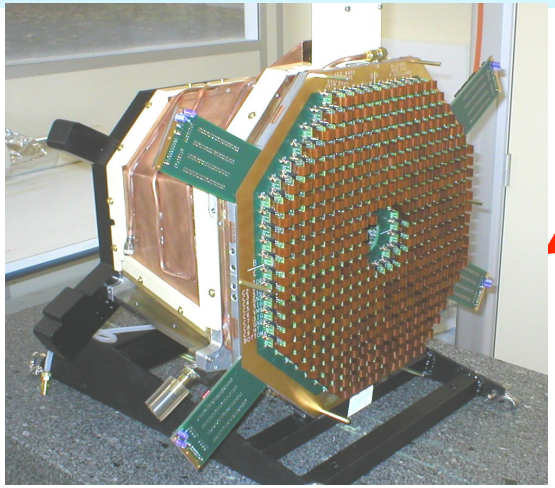
5 Tesla Solenoid

420 $PbWO_4$ crystals :

~10x10x160 mm^3

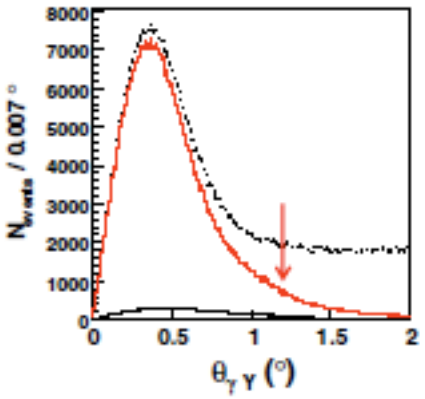
APD+preamp readout

Orsay / Saclay / ITEP / Jlab

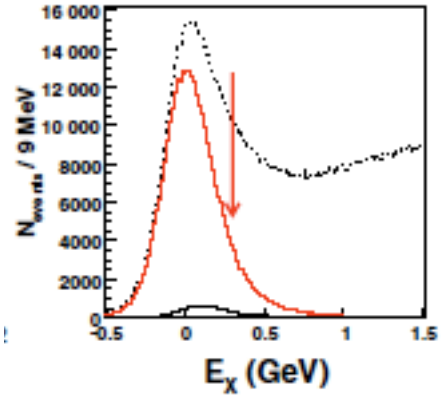


CLAS 6 GeV: Exclusivity and Kinematics

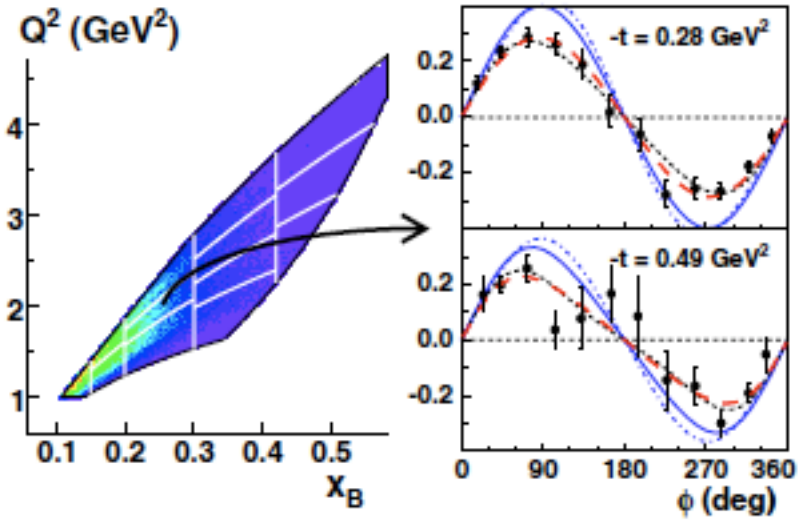
- H(*e,e'γp'*)*x*
- Overcomplete triple coincidence



Co-linearity of γ with *q-p'*



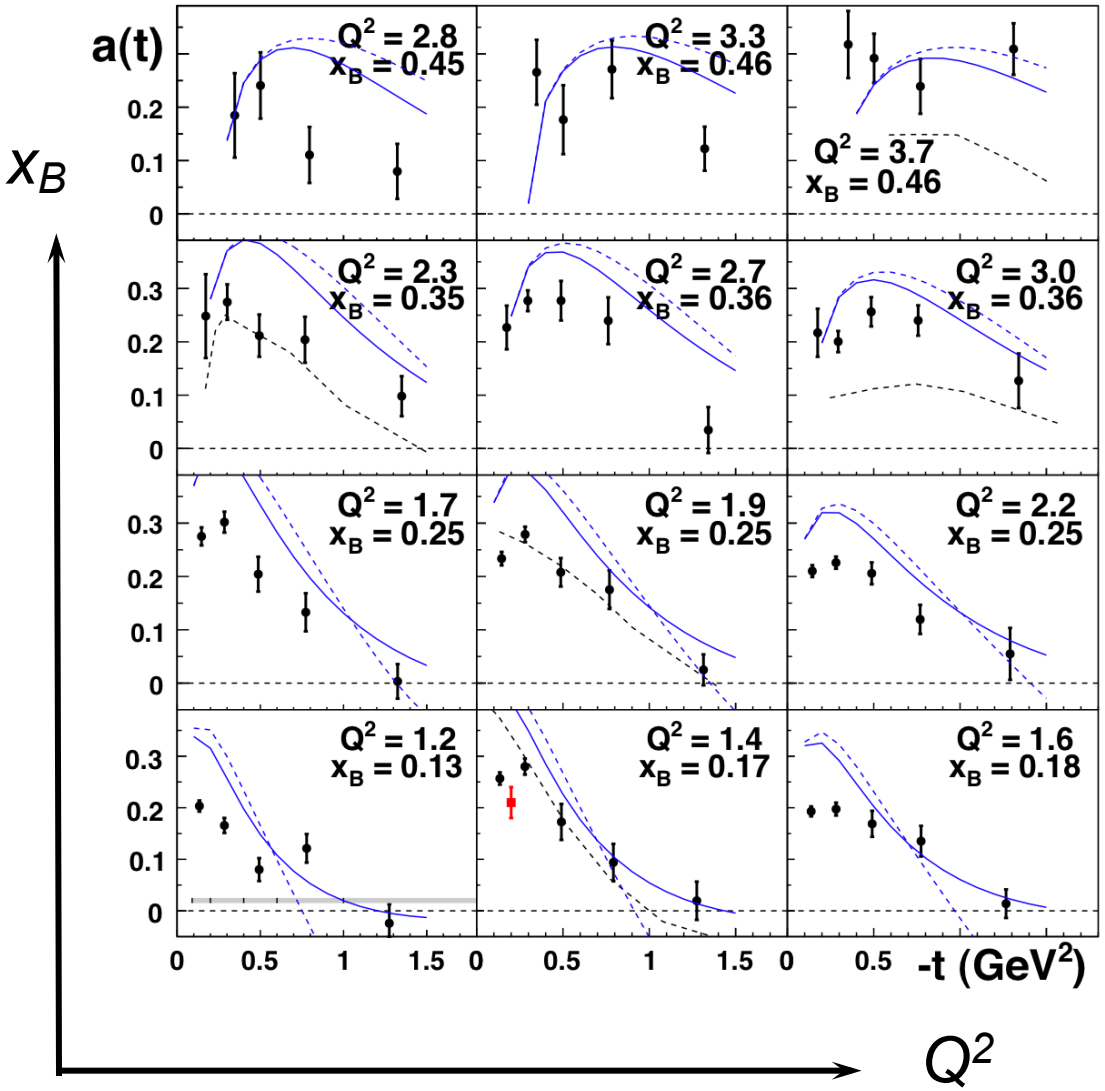
Missing Energy E_x



- 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 Longitudinal Target w/ Inner Calorimeter

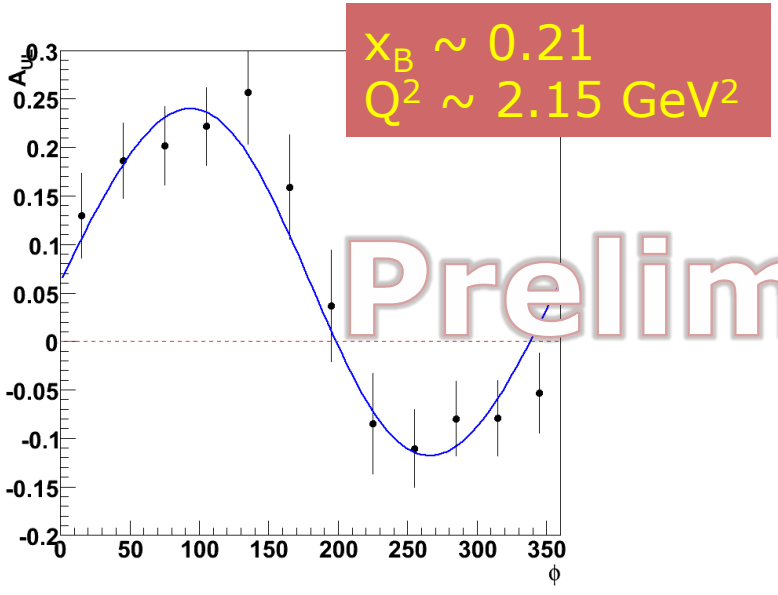
DVCS Target Spin Asymmetry

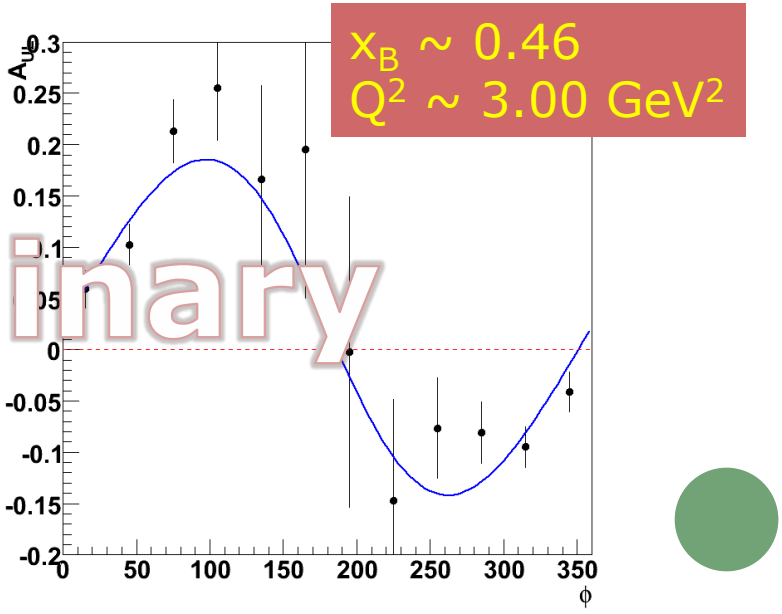
$$A_{UL} = \frac{N^+ - N^-}{f(P^-N^+ + P^+N^-)}$$

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

Fitting function:

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



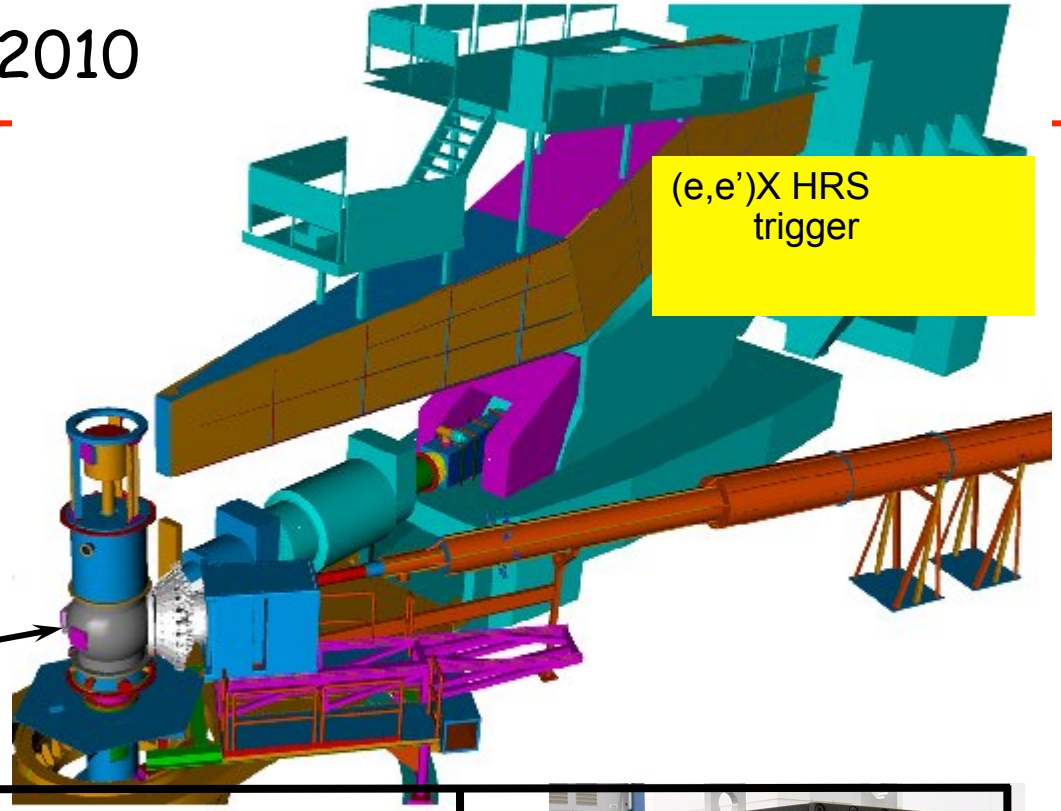


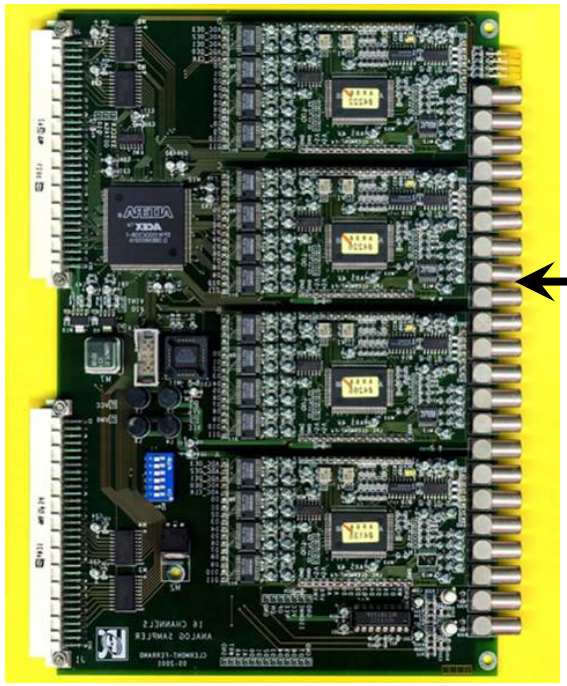
Preliminary

Plots and analysis done by Erin Seder

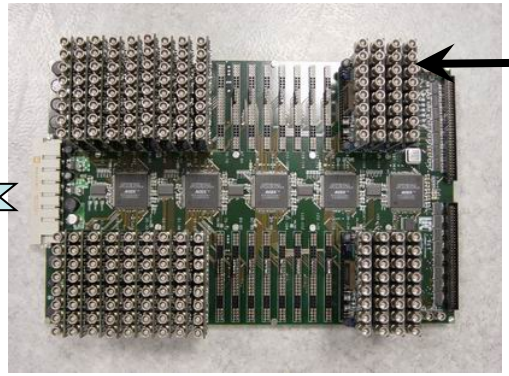
DVCS: JLab Hall A 2004, 2010

$L \geq 10^{37}$ cm^2/s
Precision cross sections
- Test factorization
- Calibrate Asymmetries

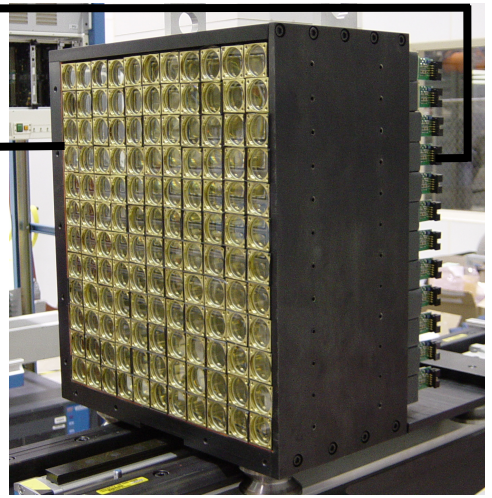




16chan VME6U: ARS
128 samples@1GHz



Digital Trigger
Validation

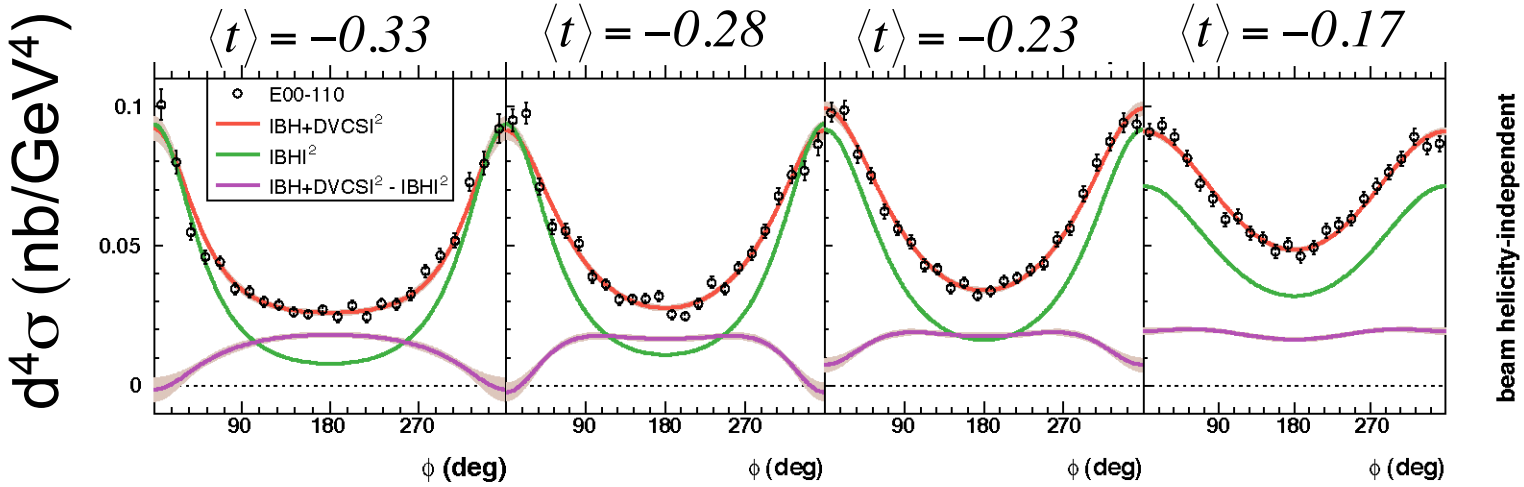


132 PbF_2

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.*,



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

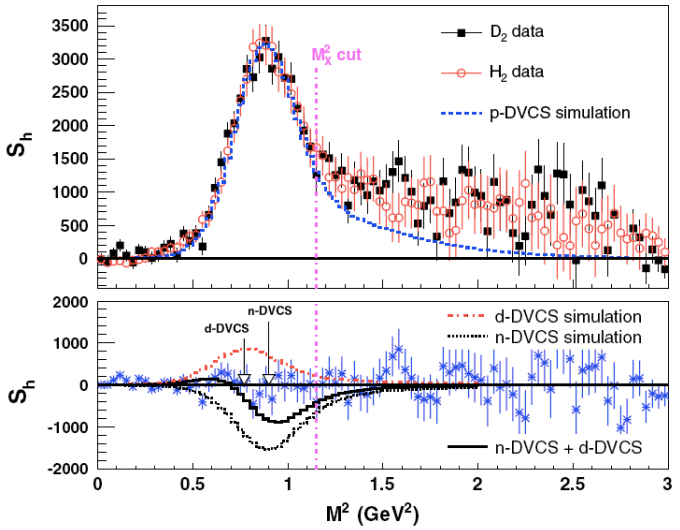
$$= d\sigma(|BH|^2) + \frac{c_0\Gamma_0 + c_1\cos(\phi_{\gamma\gamma})\Gamma_1 + c_2\cos(2\phi_{\gamma\gamma})\Gamma_2 + \ldots}{P_1(\phi_{\gamma\gamma})P_1(\phi_{\gamma\gamma})}$$

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

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

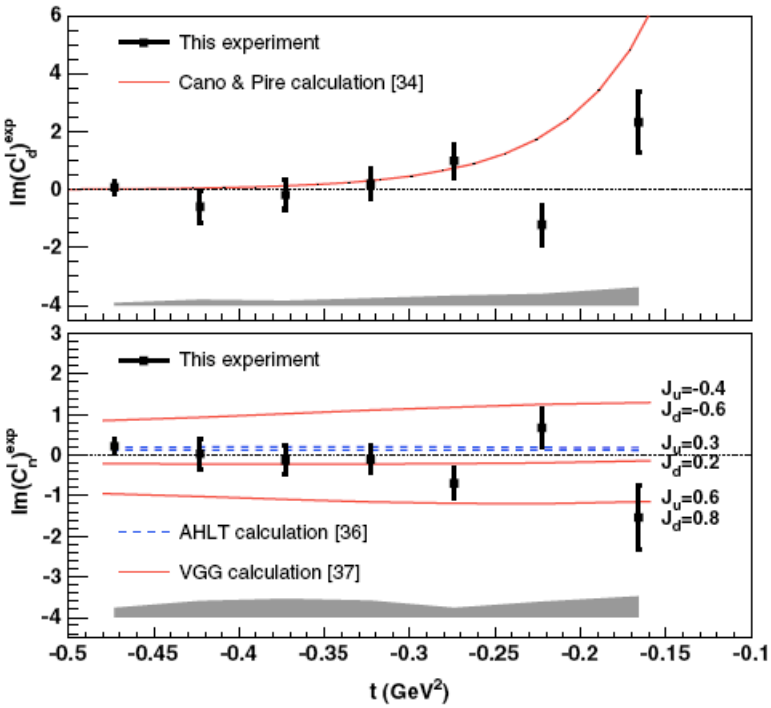
DVCS-Deuteron, Hall A

- 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]*



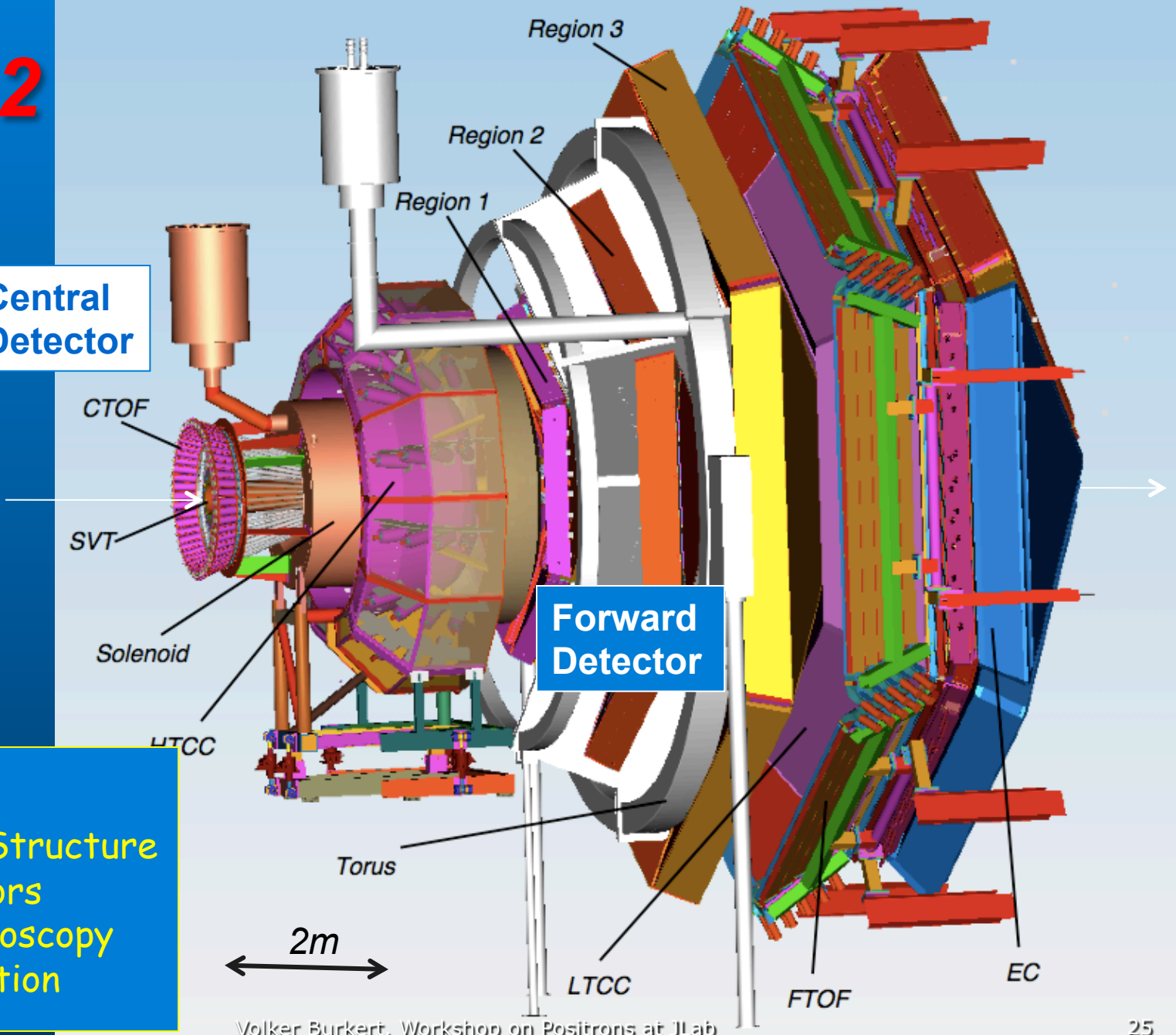
- E08-025 (5.5 GeV- 2010)
  - Reduce the systematic errors
    - Expanded PbF_2 calorimeter for π^0 subtraction
  - Separate the *Re[DVCS*BH]* and $|DVCS|^2$ terms on the neutron via two beam energies.

Q^2=2.3 GeV², x_B=0.36



neutron

CLAS12



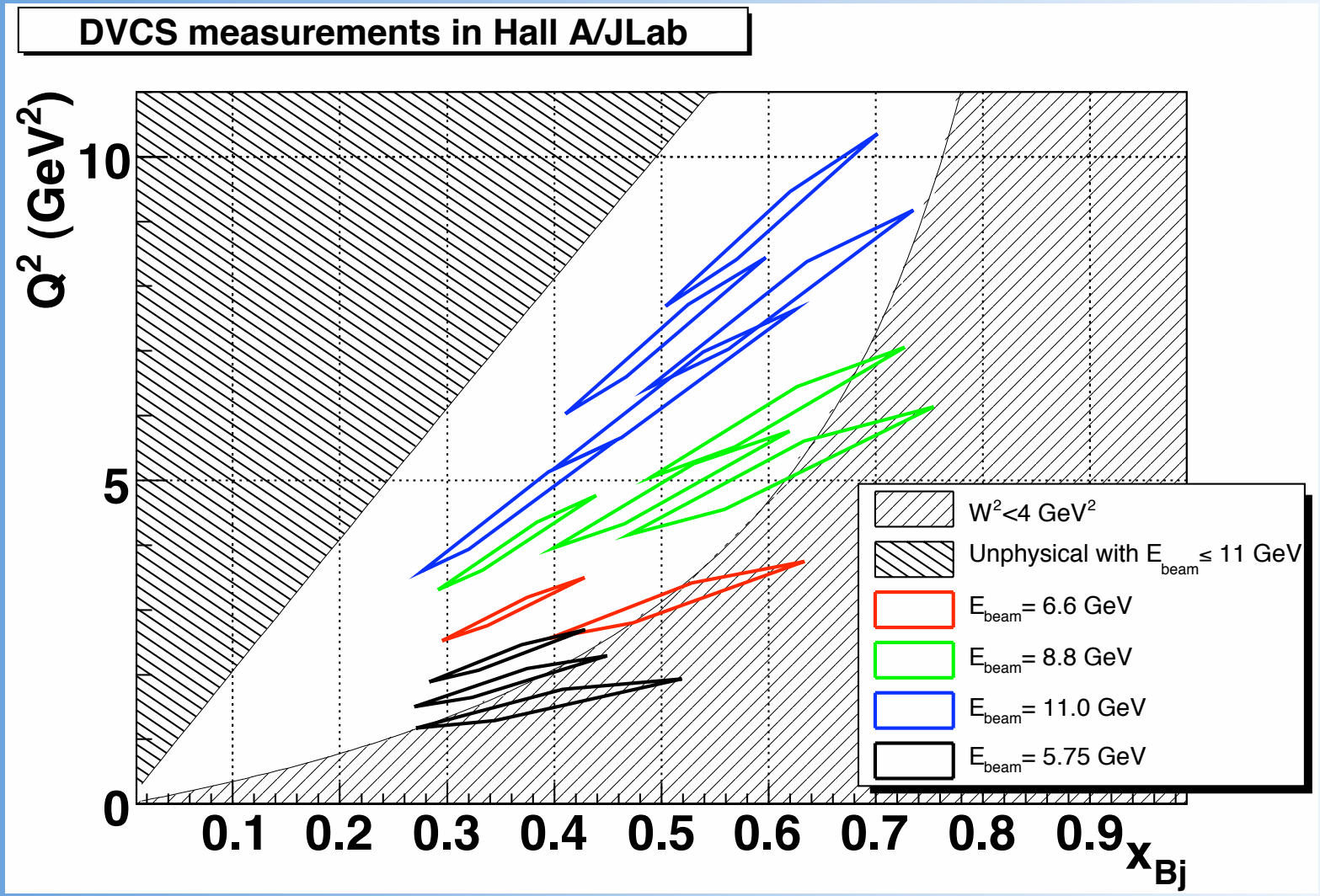
- GPDs & TMDs
- Nucleon Spin Structure
- N* Form Factors
- Baryon Spectroscopy
- Hadron Formation

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'γn)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 ×PbF_2

All equipment in-hand.
Ready for beam !



COMPASS 2014+ DVCS & DVES

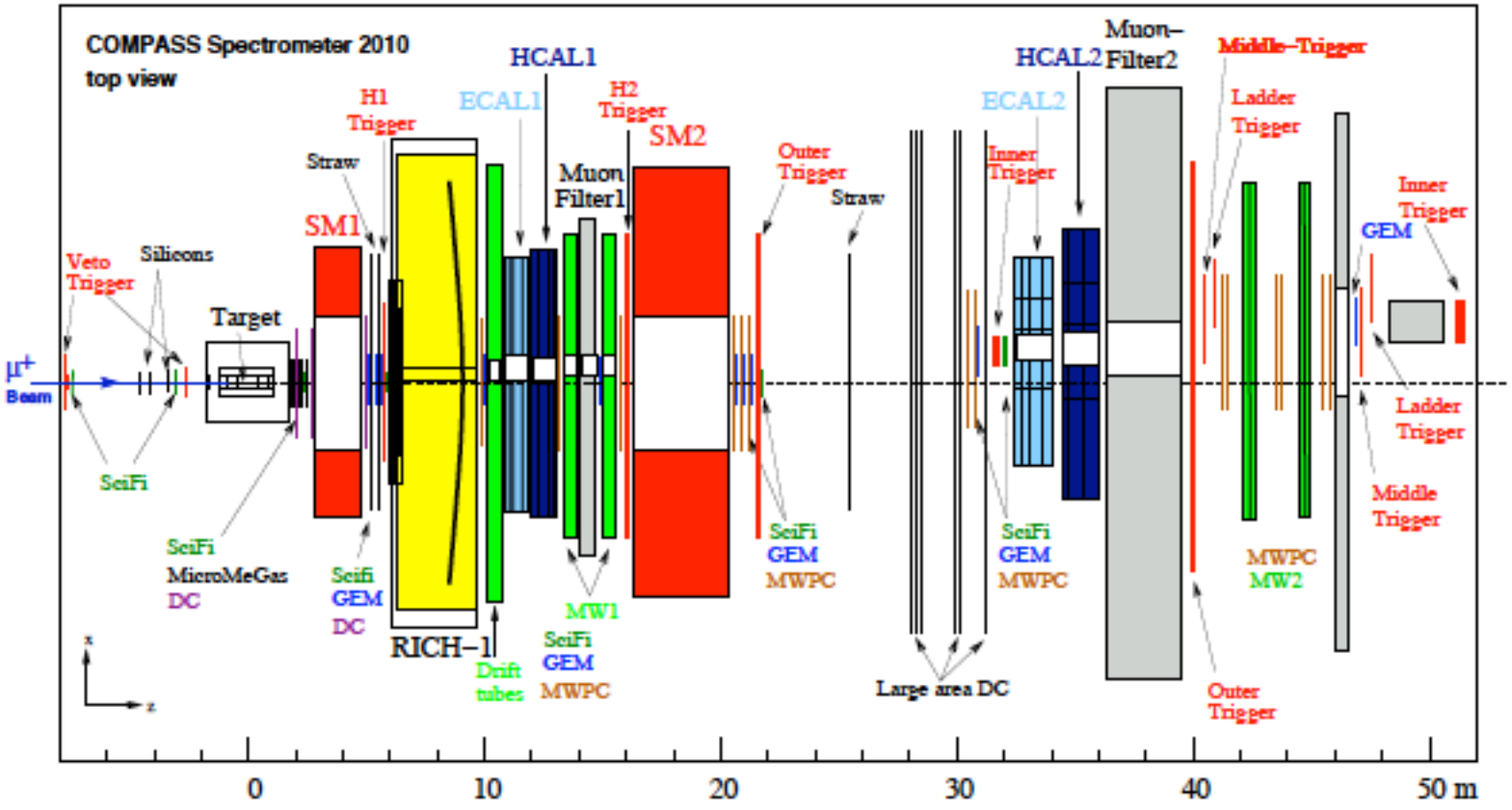
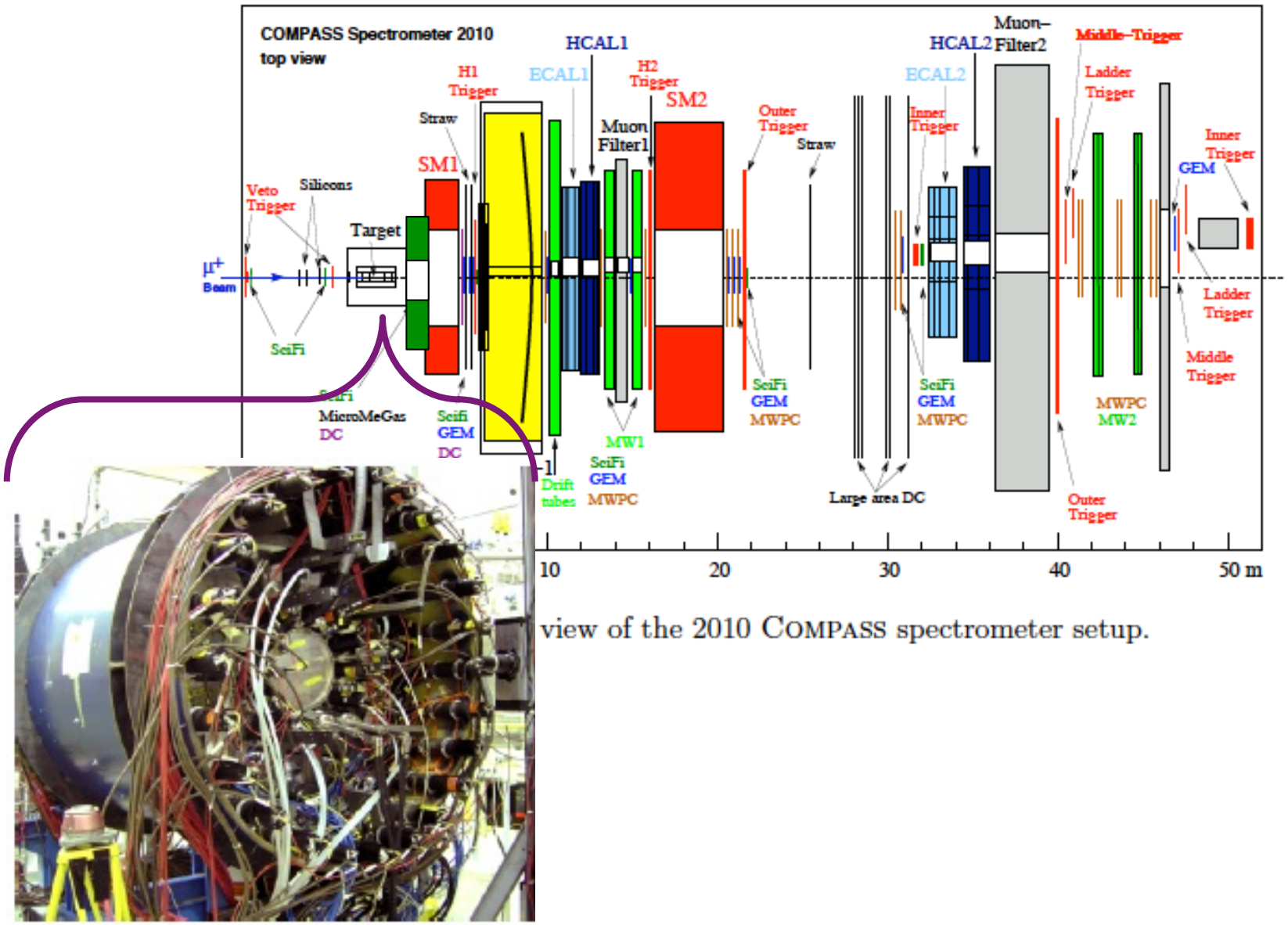


Figure 50: Top view of the 2010 COMPASS spectrometer setup.

COMPASS Recoil Proton Detector + ECAL0



view of the 2010 COMPASS spectrometer setup.

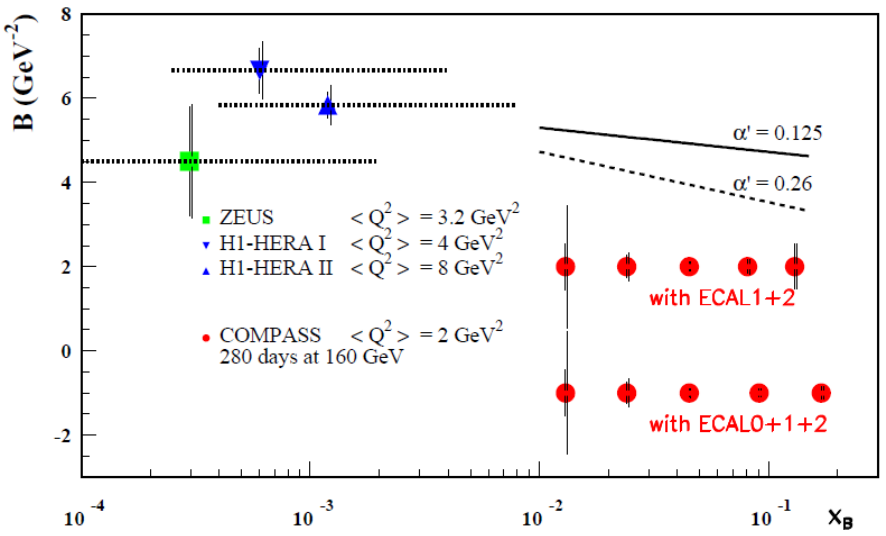
COMPASS DVCS Projections

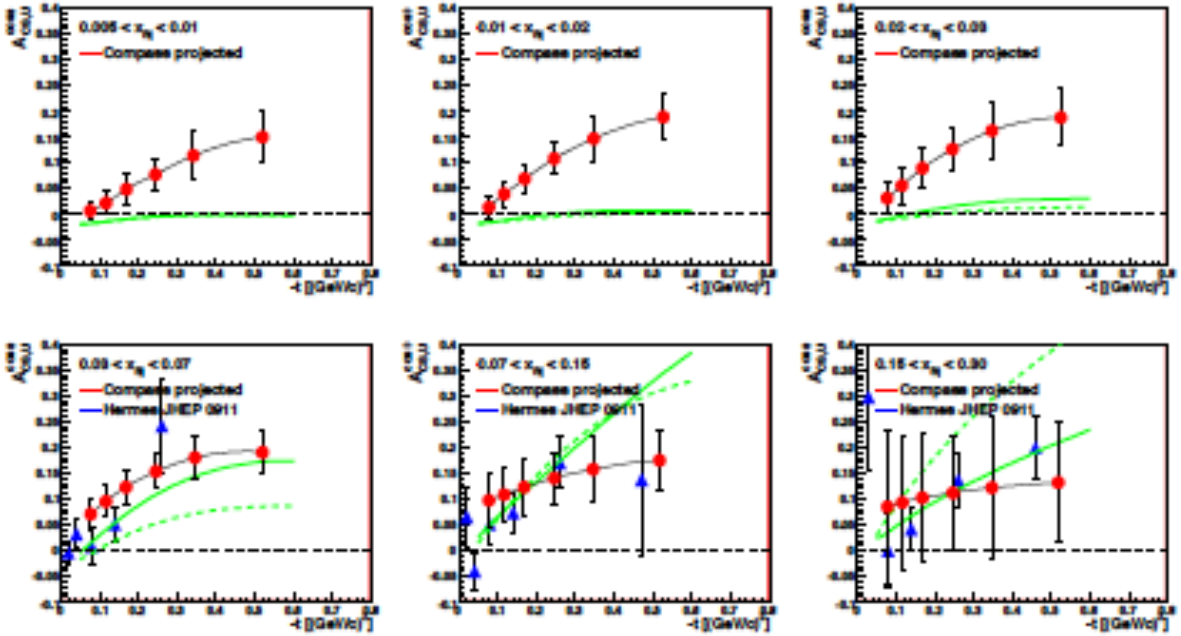
- 160 GeV

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

- Spin×Charge averaged

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



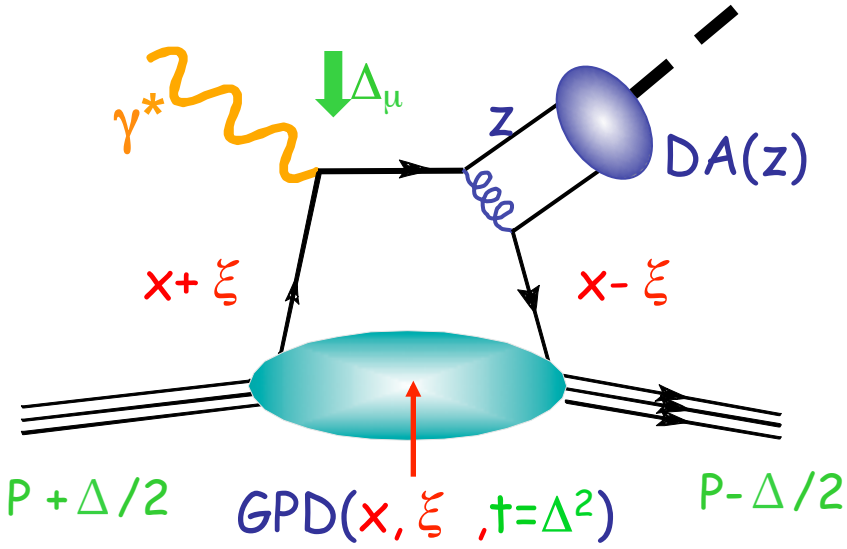


- Spin×Charge difference

$$\Delta\sigma \approx$$

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

Leading Order (LO) QCD Factorization of DVES



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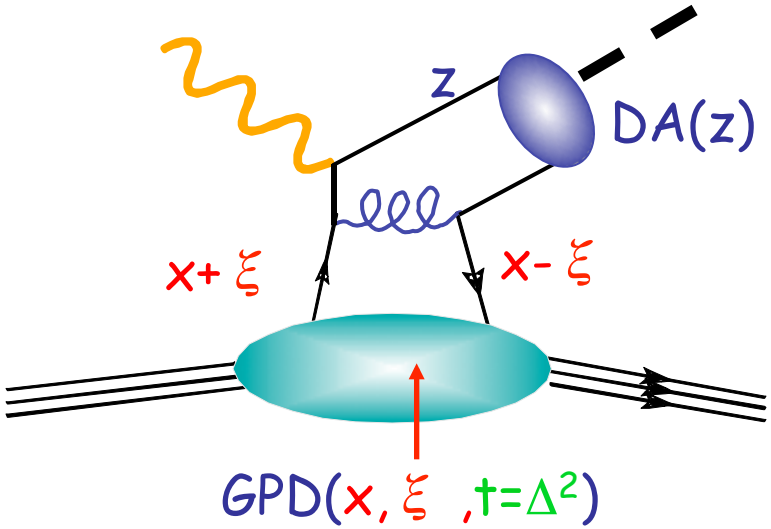

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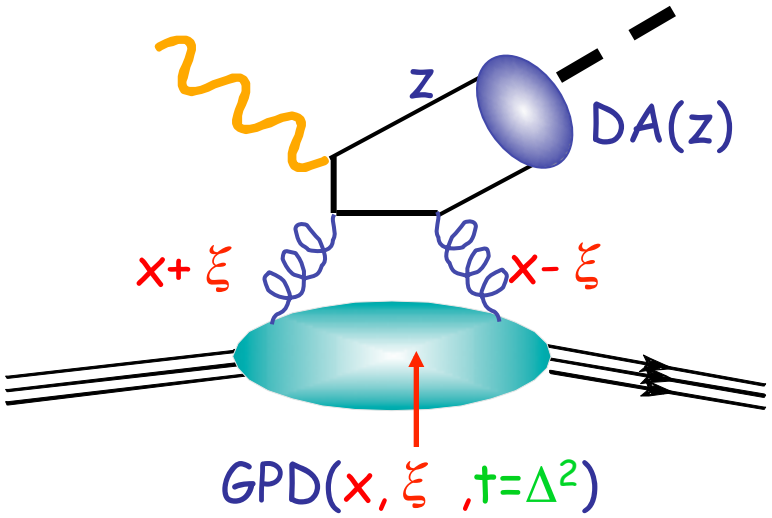


Gluon and quark GPDs enter to same order in α_S.

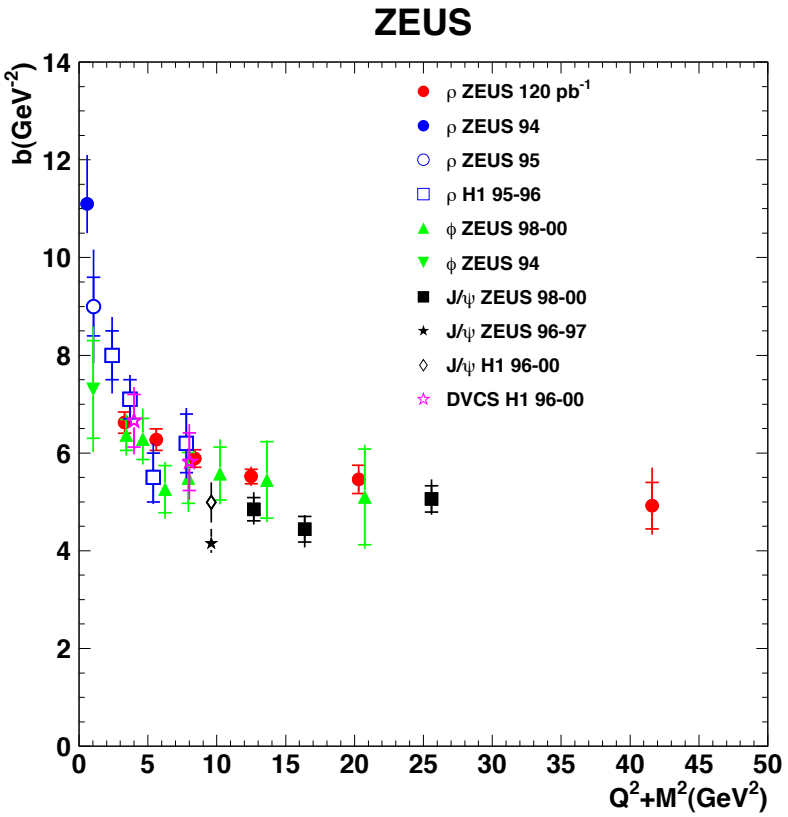
SCHC: $\sigma_L \sim [Q^2]^{-3}$ $\sigma_T \sim [Q^2]^{-4}$

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

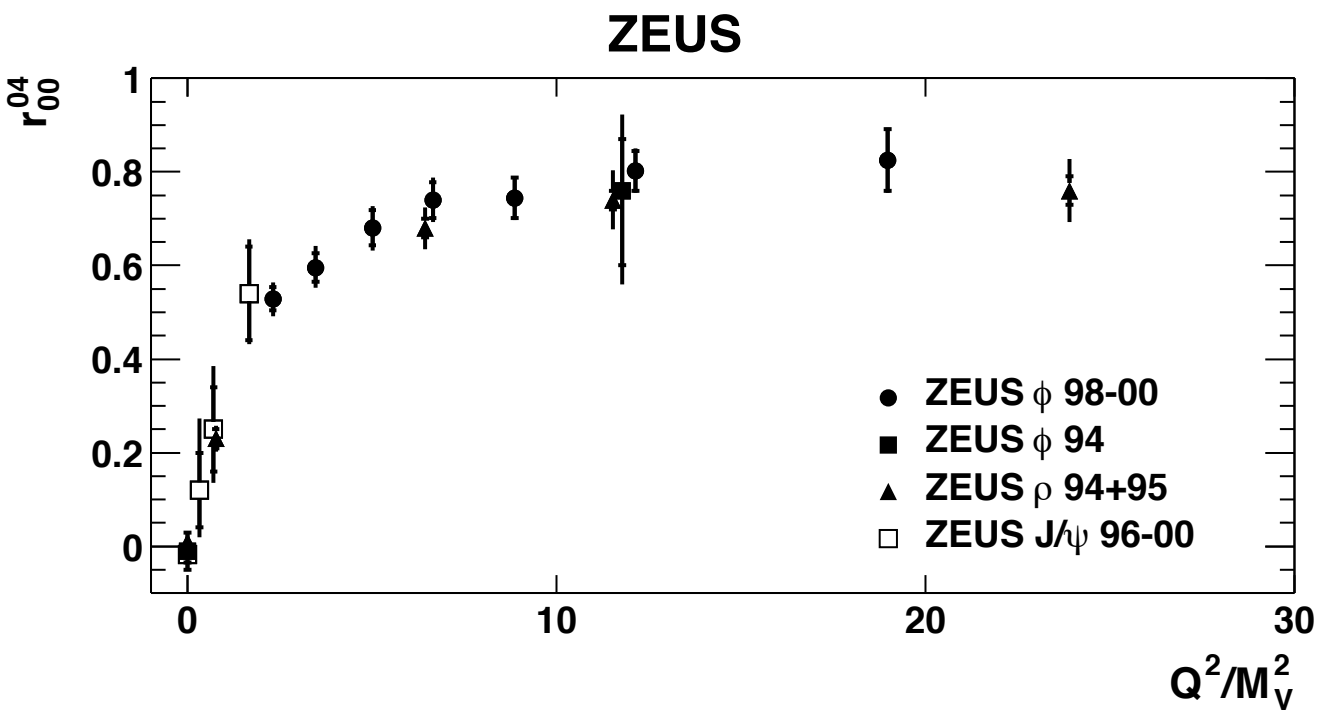


GWolf 0907.1217

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
- 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 $d\sigma_T$?

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

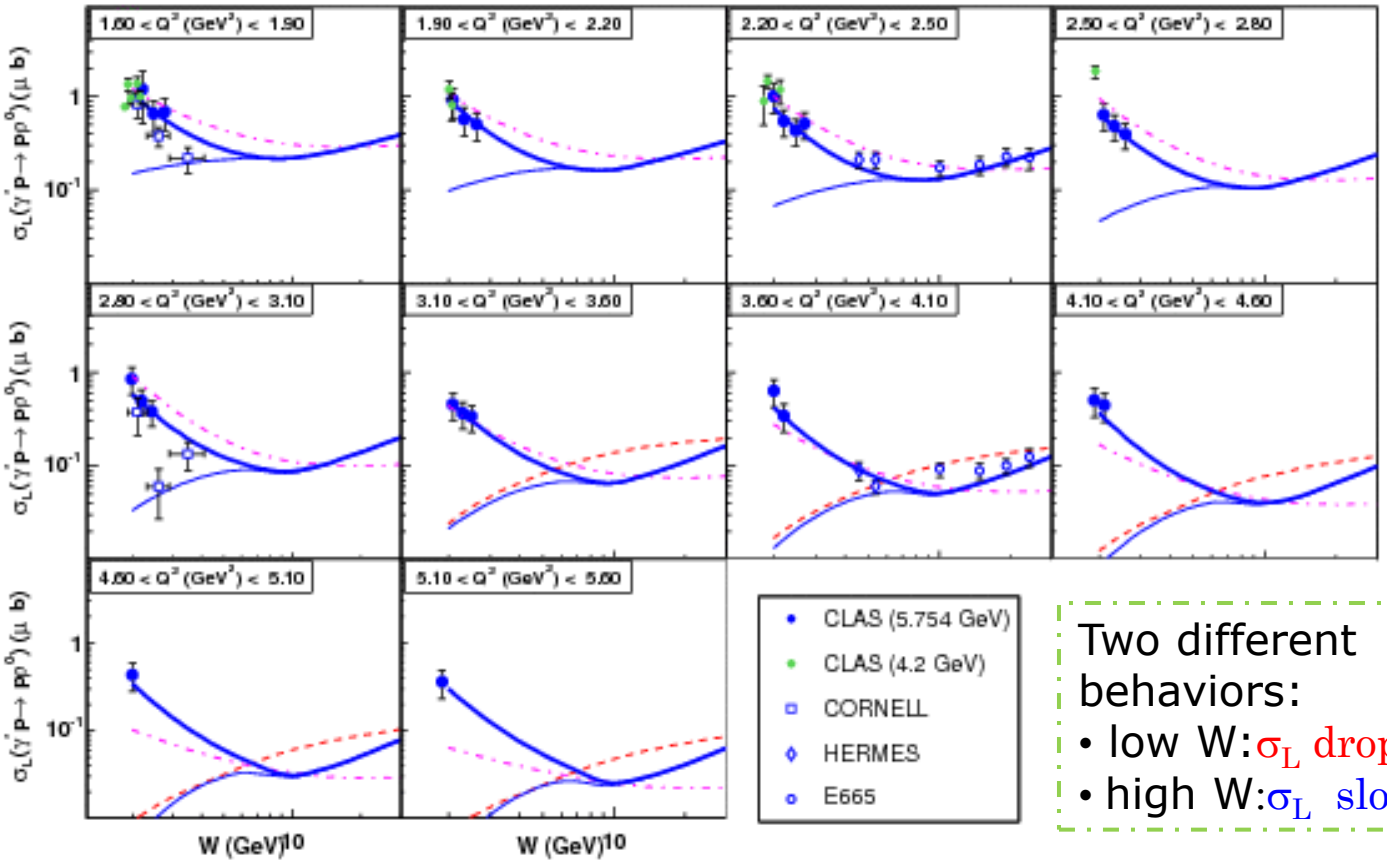


Vector Mesons at JLab

- 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 ($\gamma^*_L P \to P\rho_L^0$)

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 [*]

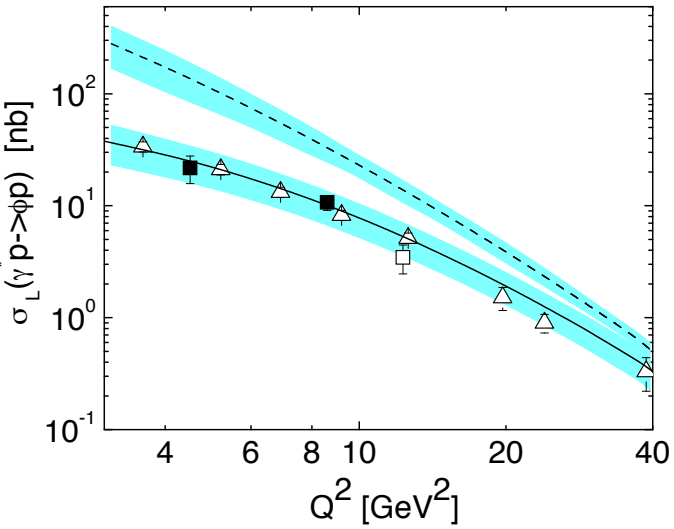
} GPD approaches based on Double-Distributions

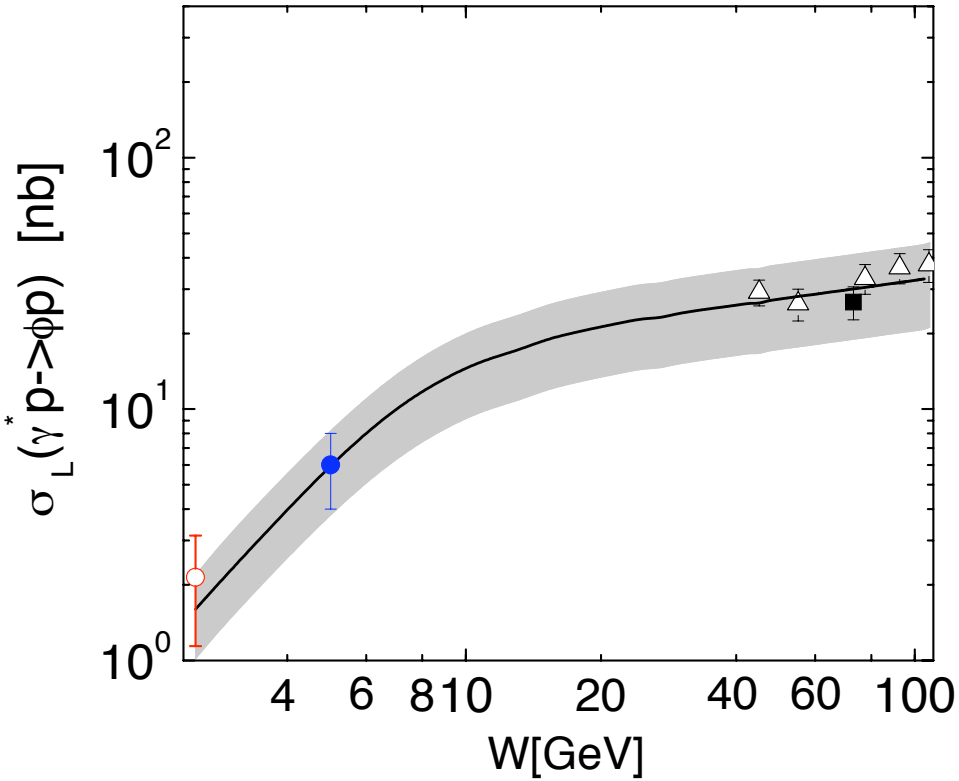
- -.-.- dash-dotted JLM calculation *à la* Regge [*] } Hadronic approach

* 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.

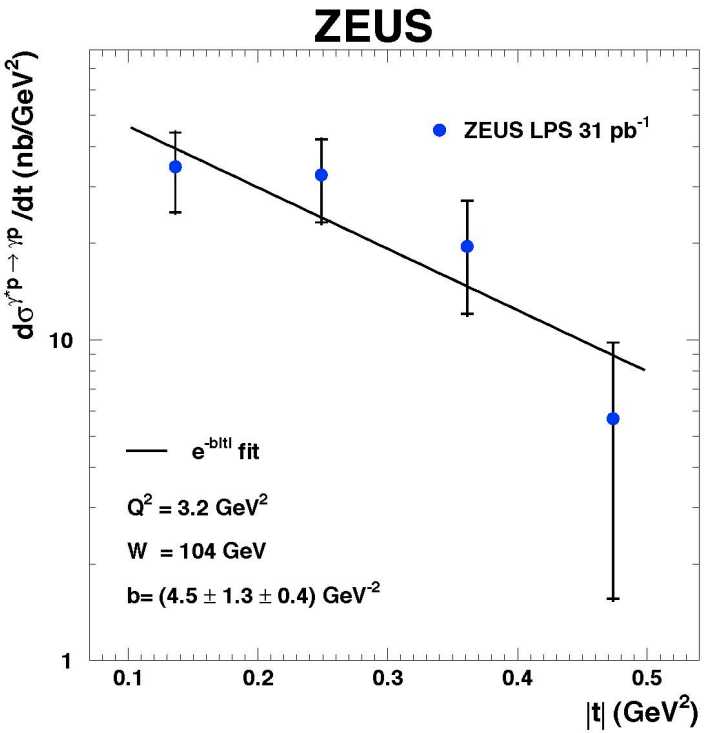
The next 20 years of DVCS experiments

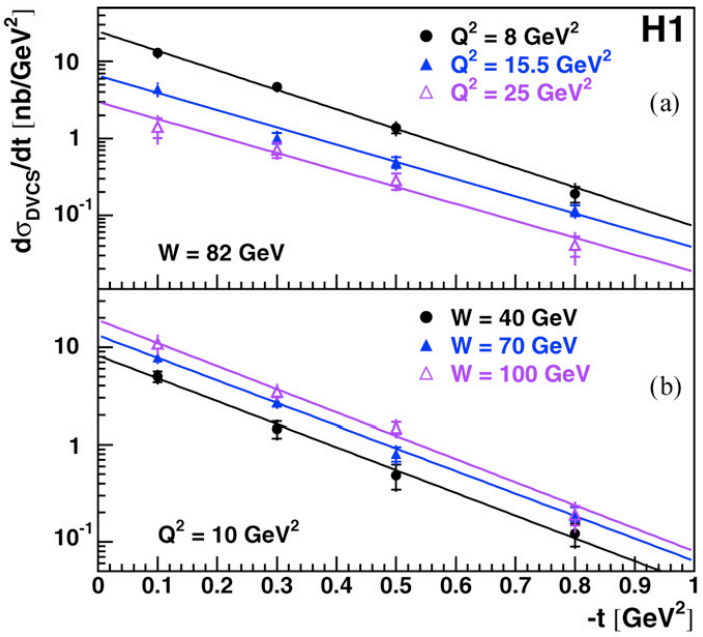
- First 5 years
  - Precision tests of factorization with Q^2 range ≥ 2:1 for
    - $x_B \in [0.25,0.6]$. $t_{min}-t < 1$ GeV^2 + COMPASS : $x_B \in [0.01,0.1]$
    - Proton unpolarized target observables
    - Im[DVCS*BH], Re [DVCS*BH], $|DVCS|^2$.
  - Longitudinal, target spin observables
    - Primary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

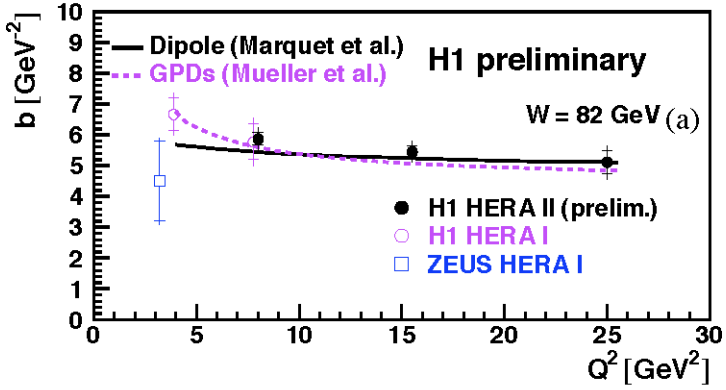
Back-up Slides

HERA DVCS

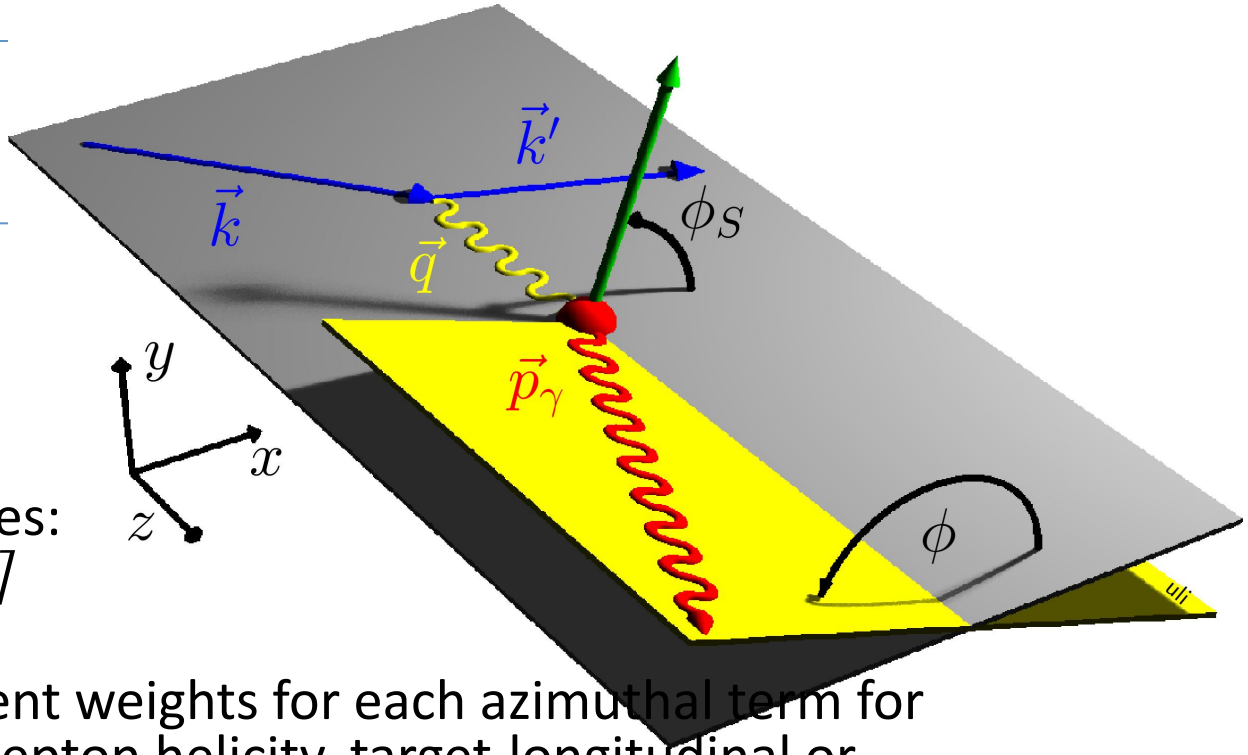
- Spatial imaging of gluons at small x_B







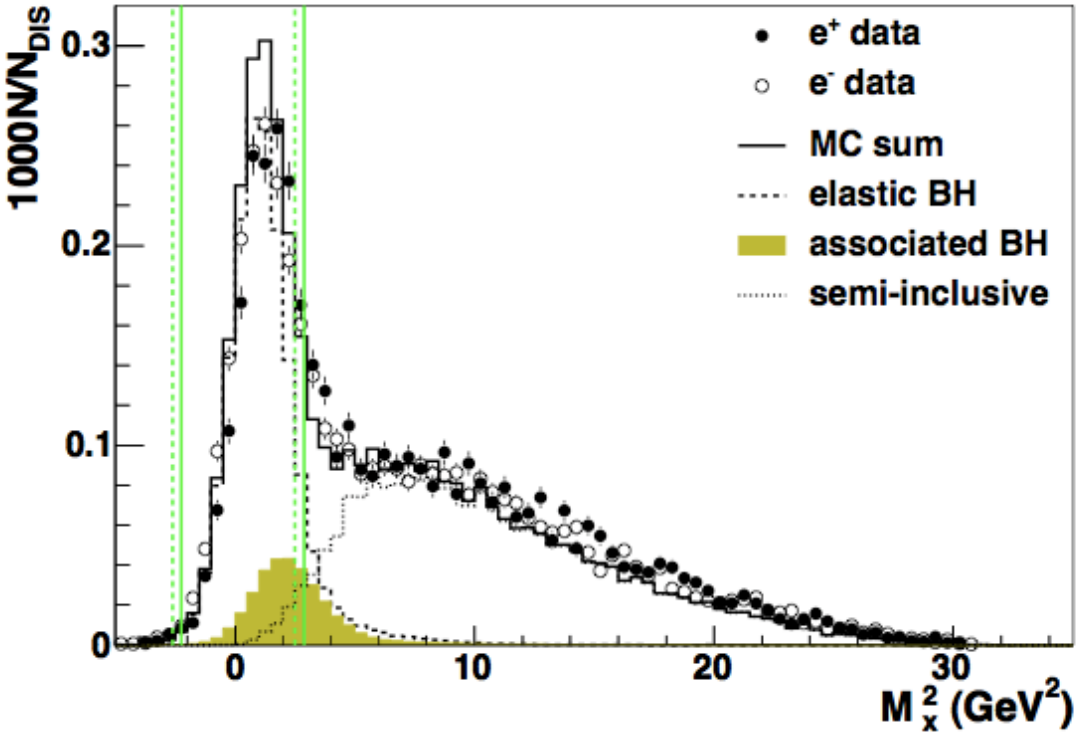
Unraveling DVCS observables



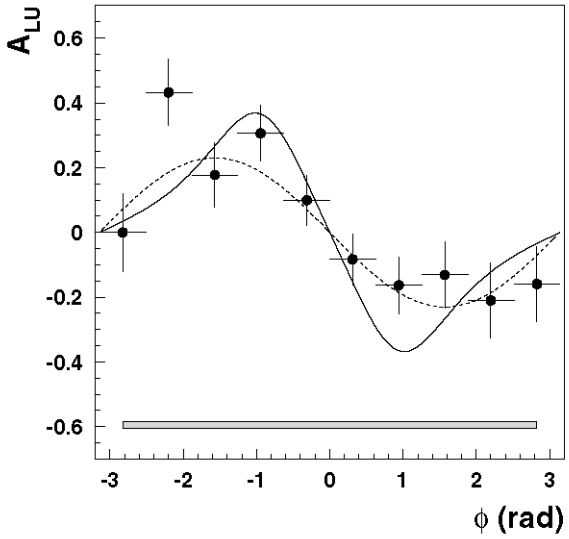
- Twist-2 terms ≈ 1, cosϕ, sinϕ
- Twist-2 terms ≈ sin2ϕ
- Not a pure Fourier series: $1/[A + B\cos\phi + C\cos 2\phi]$ from *BH* propagators.
- GPDs enter with different weights for each azimuthal term for different polarization (lepton helicity, target-longitudinal or –transverse) observables
  - Single 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

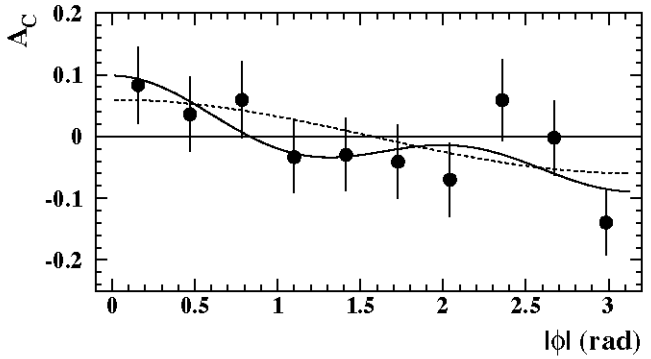
27 GeV polarized e± on
Internal Gas Jet
/ Atomic Beam Source targets

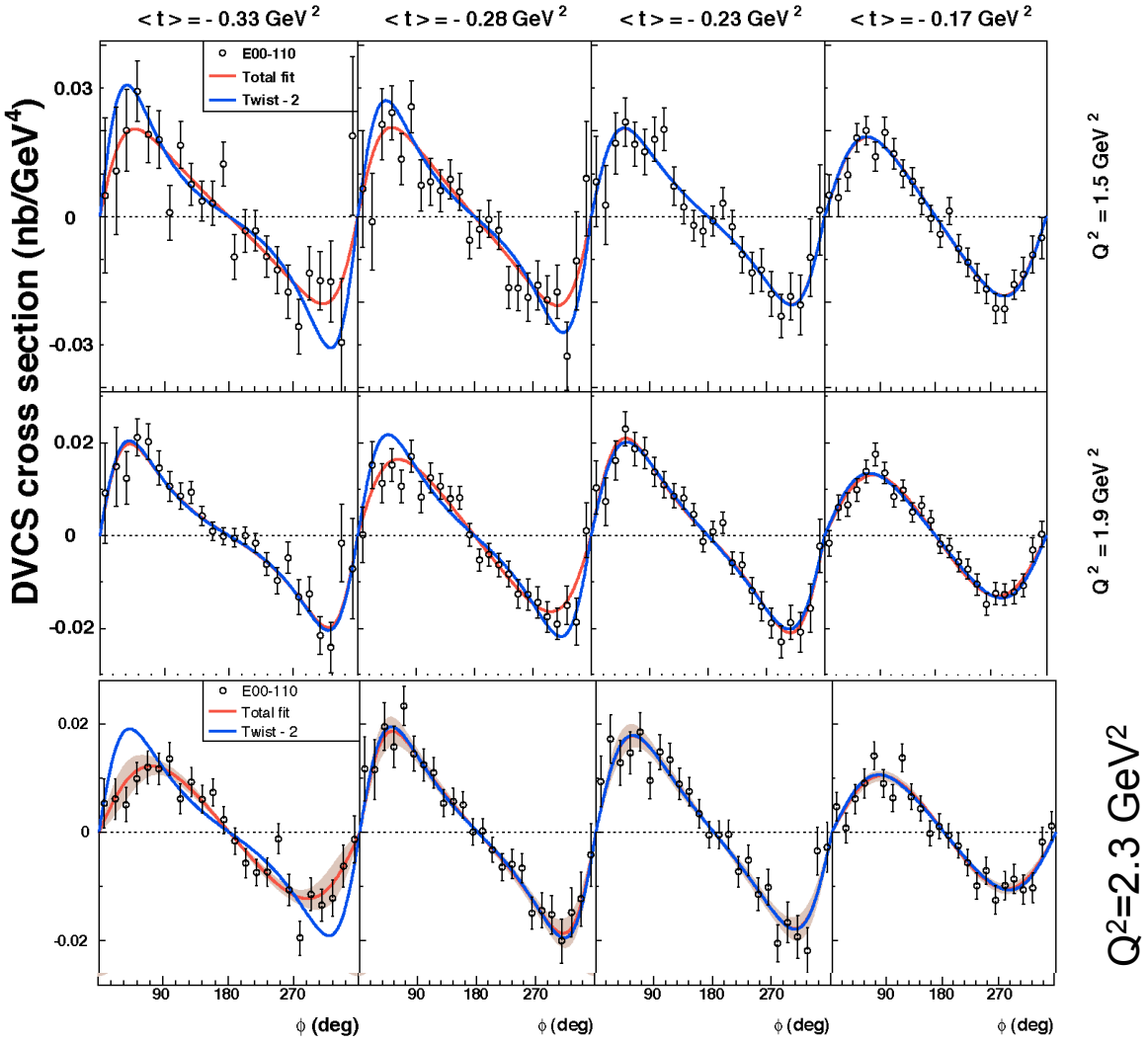


2001 BSA



2006 BCA





Hall A Helicity Dependent Cross Sections E00-110

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

Twist-2(GPD)+…

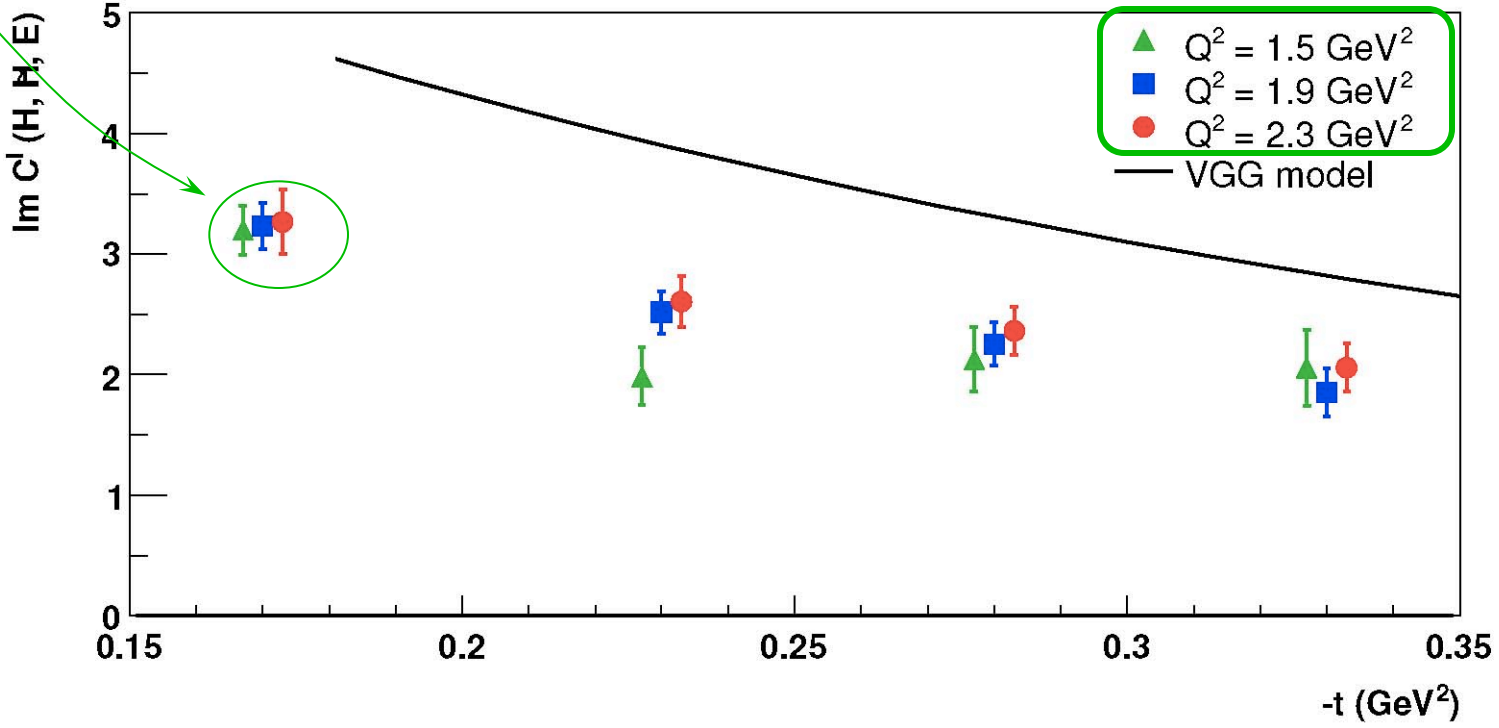
Twist-3(qGq)+…

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

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

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

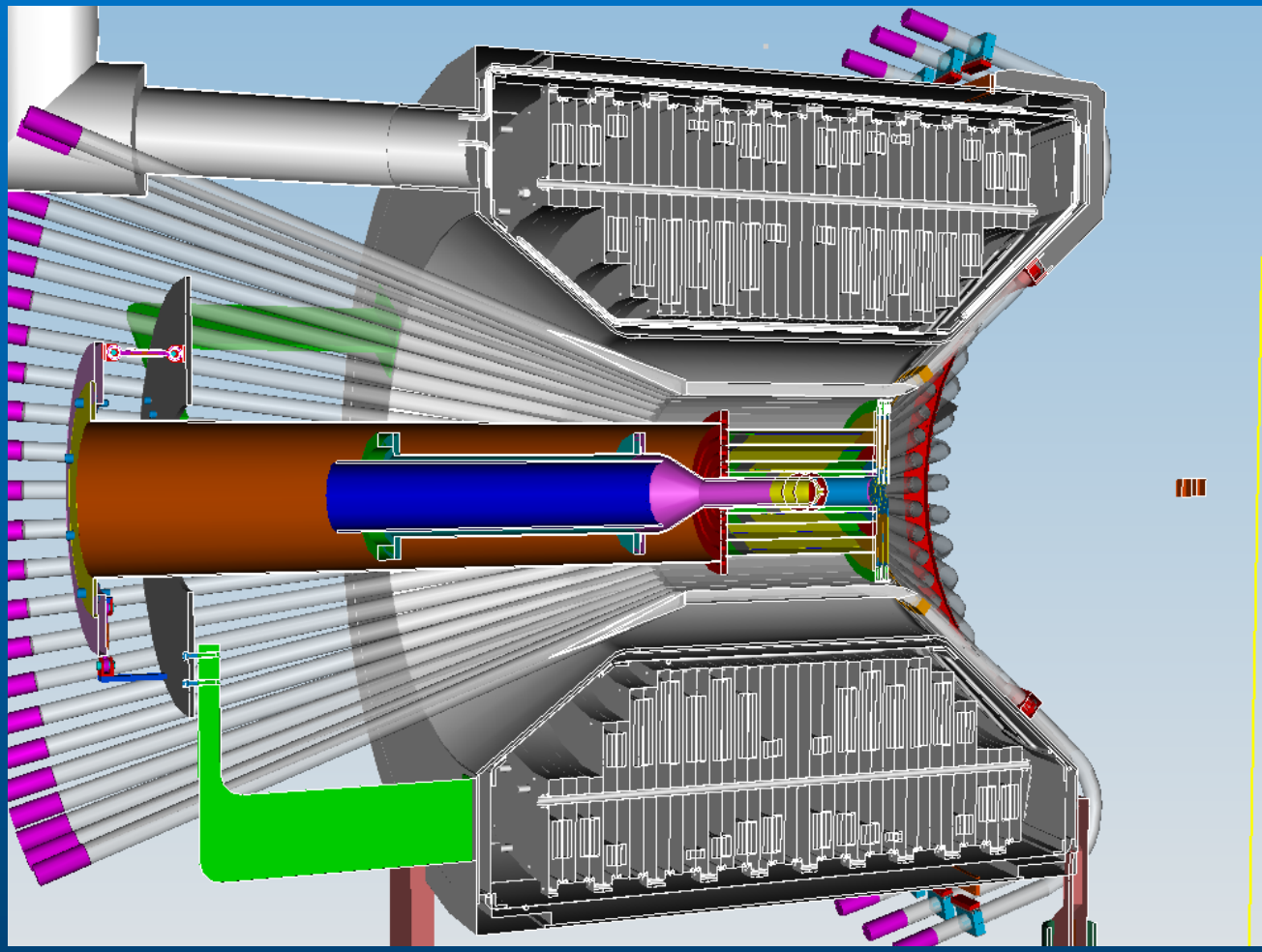
- Q^2-independance of Im[DVCS*BH]
  - Twist-2 Dominance (GPD)
  - Model « Vanderhaeghen-Guichon-Guidal (VGG) » accurate to ≈30%



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

CLAS12 – Central Detector SVT, CTOF

- Charged particle tracking in 5T field
- $\Delta T < 60$psec 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!!!!

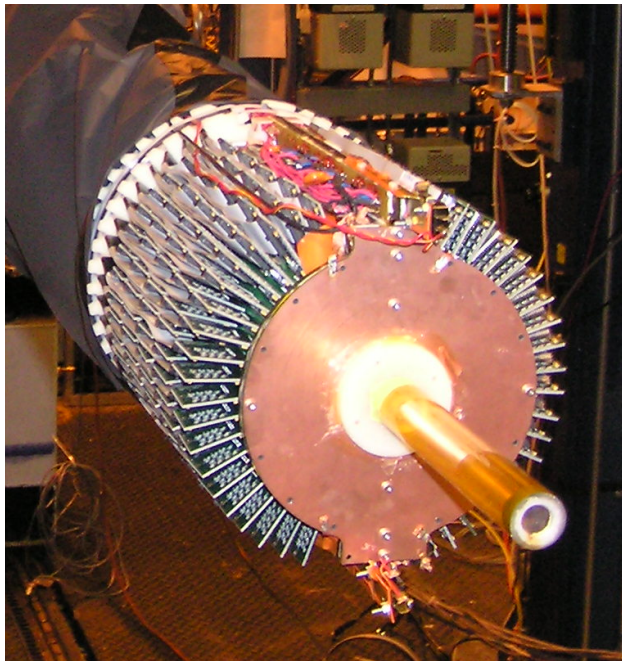
Material	gm/cm^2	mass fraction
HD	0.735	77%
Al	0.155	16%
CTFE (C_2ClF_3)	0.065	7 %

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

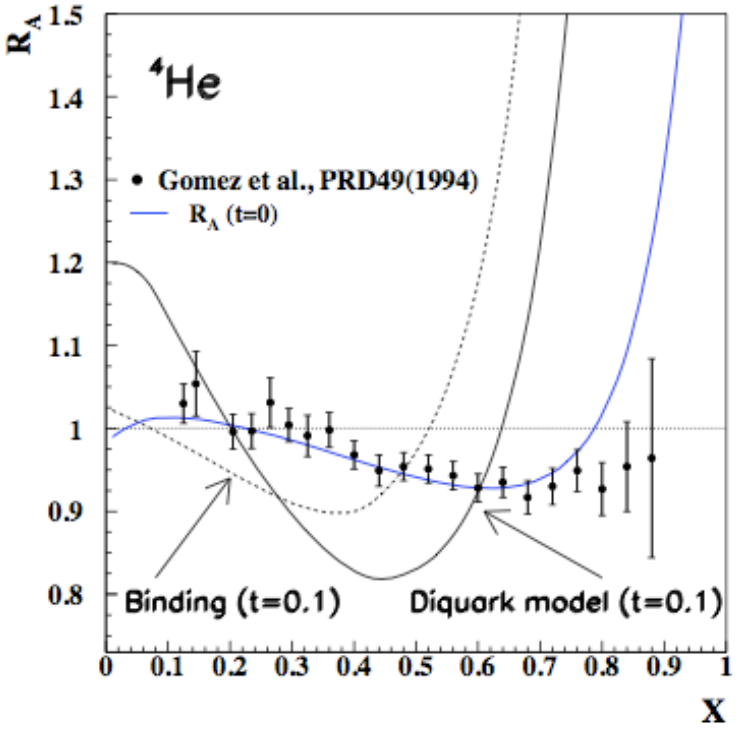
Heat extraction is accomplished with thin aluminum wires running through the target

CLAS: Coherent ^{4}He(e,e'γα)

- 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