CEBAF Users Group Annual Meeting
4–6 June 2012, Jefferson Lab

Results and Insights on Generalized Parton Distributions in the 6 GeV Era

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INT-12-49W:
Orbital Angular Momentum in QCD
February 6 - 17, 2012

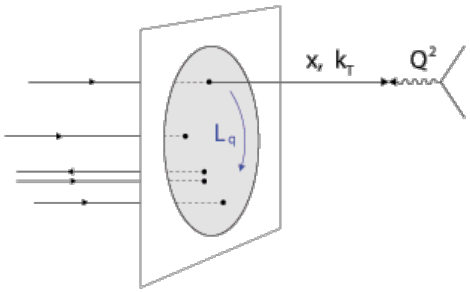
C. Hyde, M. Guidal, A. Radyushkin,
J. Phys. Conf. Ser. 299:012006, 2011,
arXiv:1101.2482

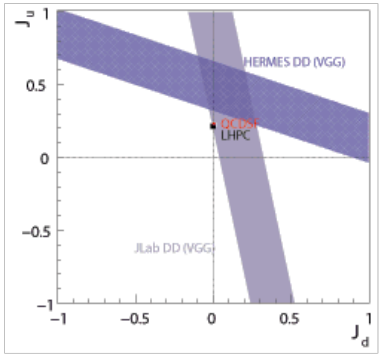
SPACE, The FINAL FRONTIER!

The Enterprise GPD

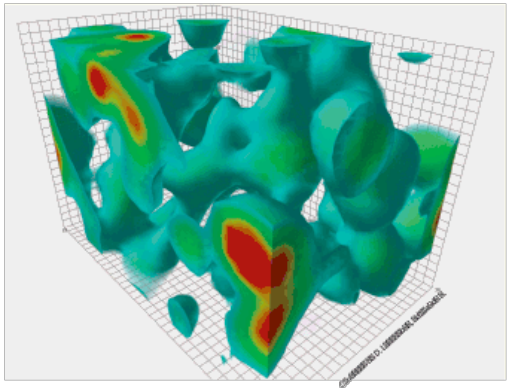
Spatial Structure and Spatial Correlations

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

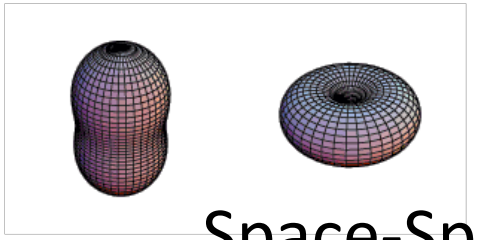




Angular Momentum



Spatial Correlations in the Vacuum

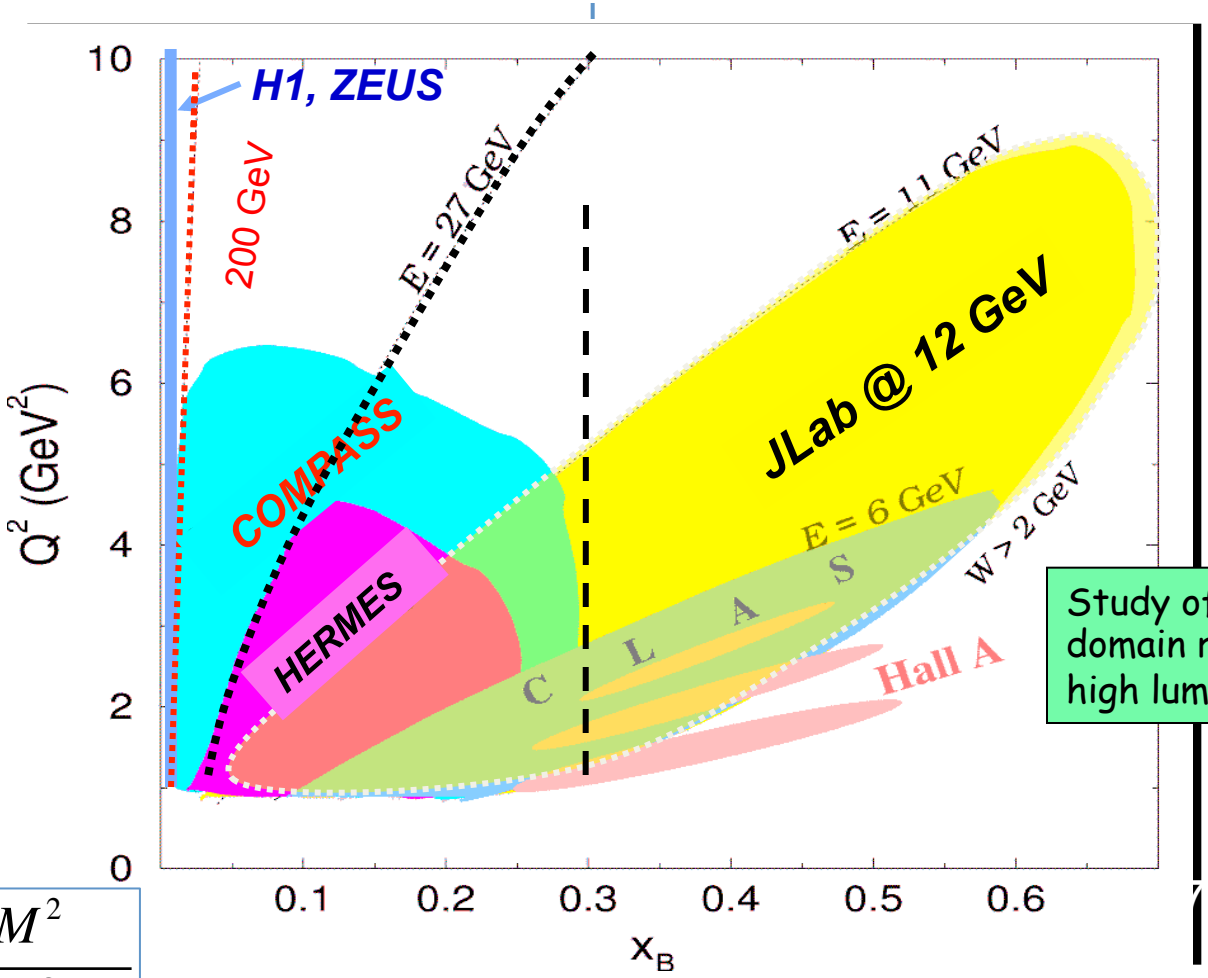


Space-Spin, Momentum-Spin, or Space-Space Correlations in the Proton

Highlights of Generalized Parton Distributions

- GPDs exist
  - D. Mueller, X-D. Ji, A. Raduyshkin
  - Spatial imaging consistent with Q.M. and Relativity.
- Integrals of GPDs are measurable
  - DVCS, DVES ➔ GPD(ξ,ξ,Δ^2) for $Q^2 >> \Lambda^2_{QCD}$
- (Positive) Moments are calculable in Lattice QCD
- Models are crude, but improving in sophistication.
  - Data precision already exceeds predictive power of models and flexibility of parameterizations.
- DVES will be a multi-decade effort
  - Each stage can teach us something new and interesting about how QCD generates force, mass, spin, *etc*.

Deeply Virtual Exclusive Processes - Kinematic Coverages

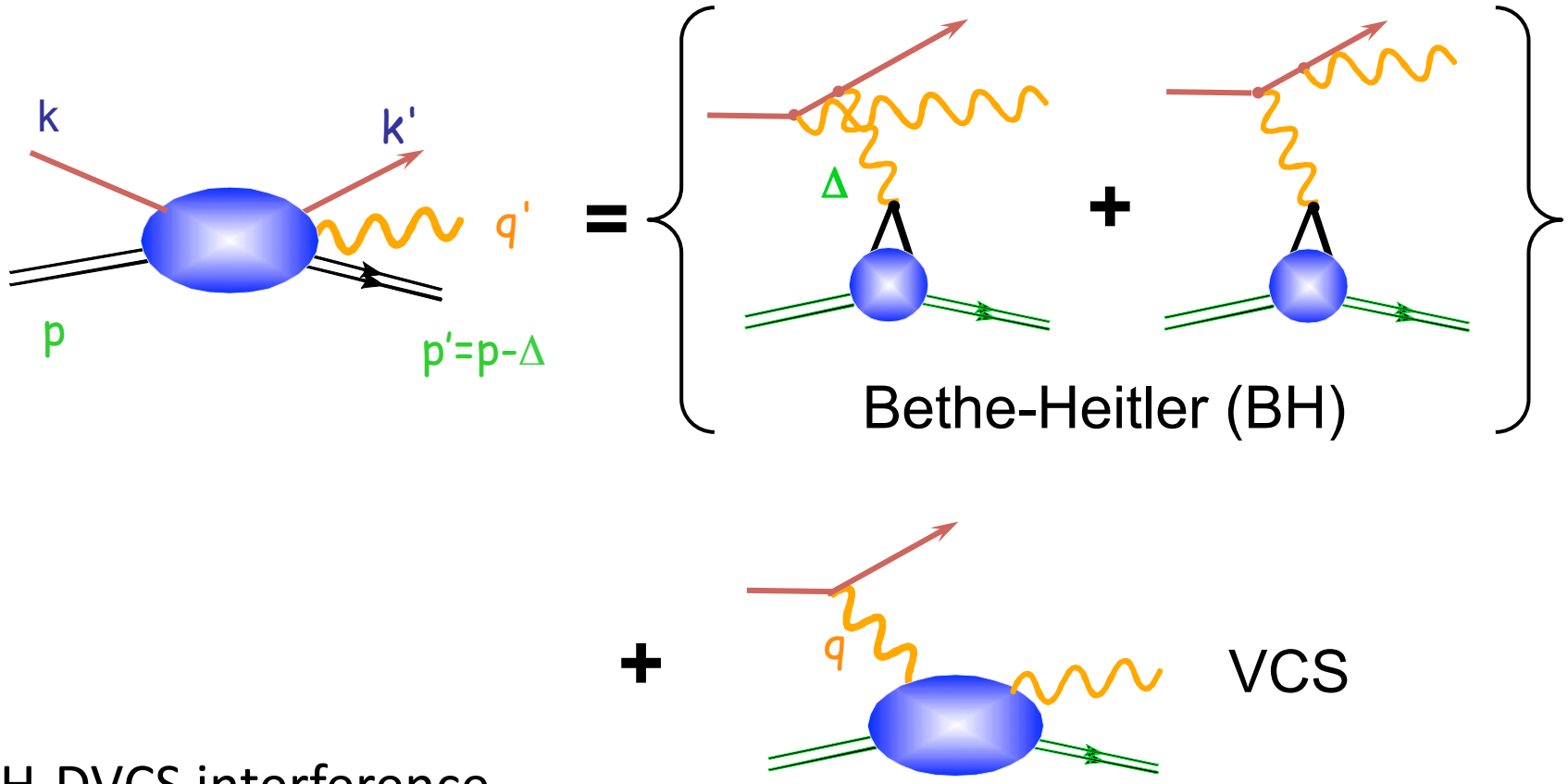


Study of high x_B domain requires high luminosity

$$\Delta^2 < -\frac{x_{Bj}^2 M^2}{1 - x_{Bj}\dfrac{2\nu}{\nu + |\vec{q}|}}$$

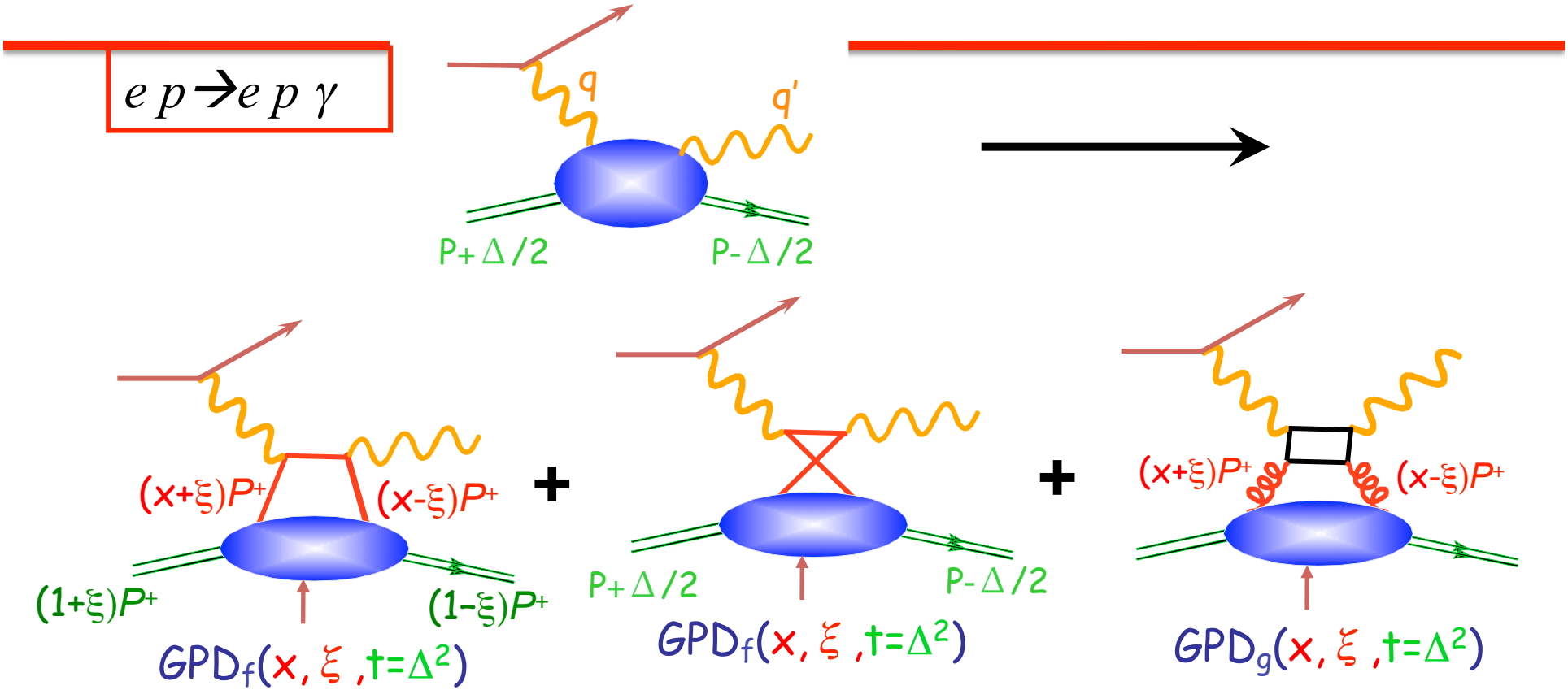
Bethe-Heitler (BH) and Virtual Compton Scattering (VCS)

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



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

QCD Factorization of DVCS (Co-Linear)



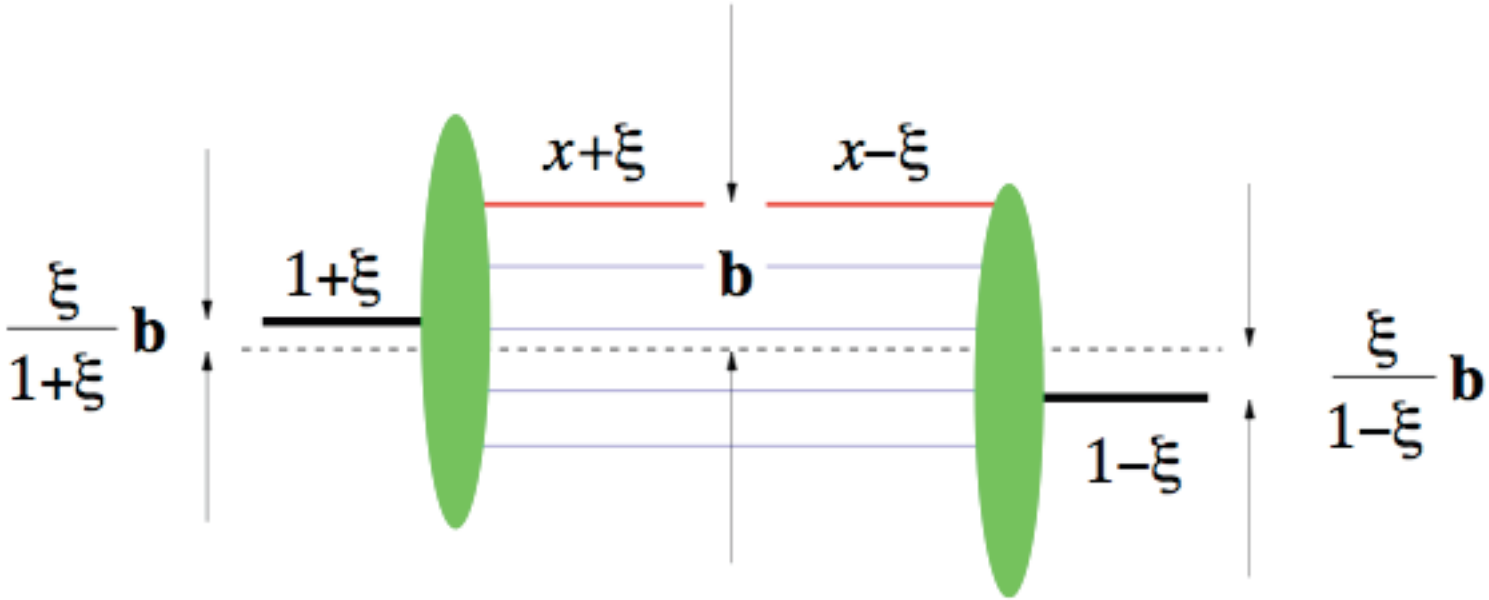
- Symmetrized Bjorken variable:

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

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

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

- $P = (p+p')/2$ $\quad p^+ = (1+\xi)P^+$ $\quad p'^+ = (1-\xi)P^+$
- $\Delta^2 = -(4\xi^2M^2+\Delta_\perp^2)/(1-\xi)^2$
- Remove a parton of momentum fraction $x+\xi$ at impact parameter $\mathbf{b}/(1+\xi)$ relative to initial proton center-of-momentum.
- Replace it with momentum fraction $x-\xi$ at $\mathbf{b}/(1-\xi)$
- Fourier Transform $\mathbf{b} \leftrightarrow \Delta_\perp$ $\quad \Delta_\perp^2 = -(1-\xi)^2\Delta^2 - 4\xi^2M^2$



Two Limits

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

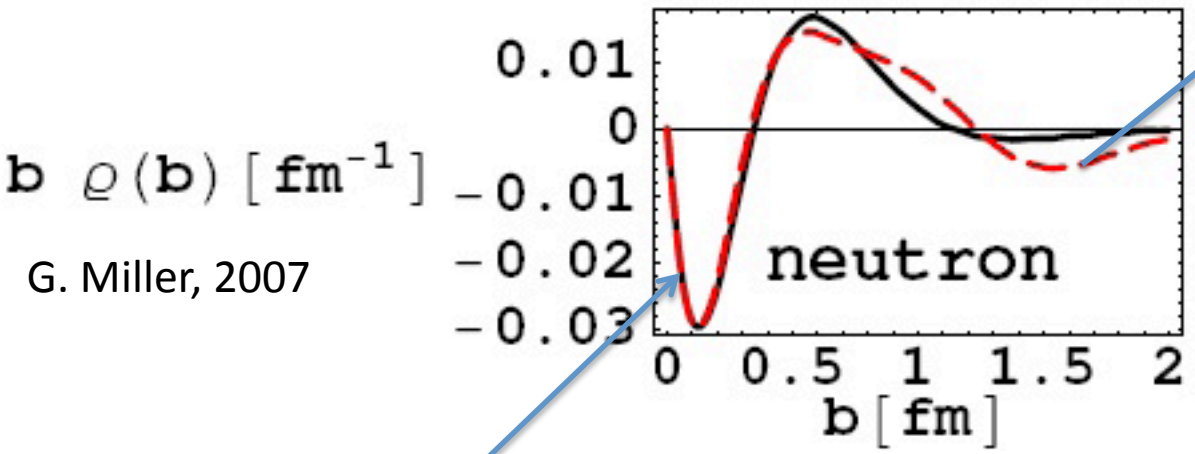
$$H(x,0,\Delta^2) \Leftrightarrow q(x,\vec{b})$$

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

- x=ξ: $\Delta_\perp \leftrightarrow$ **r**
  - Transition amplitude for longitudinal momentum transfer 2ξ at fixed impact parameter **r** relative to CM of *spectators*.
  - Not a positive definite density

GPDs and the Nucleon Form Factors

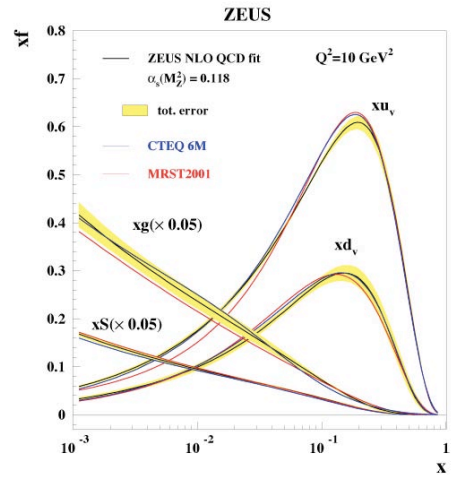
- $F_{1f}(-t) = \int dx\, H_f(x,0,t) = \int d^2\mathbf{b}\, e^{i\mathbf{b}\cdot\Delta_\perp} \int dx\, q_f(x,\mathbf{b})$
- $F_1(-\Delta^2) = \int d^2\mathbf{b}\, e^{i\mathbf{b}\cdot\Delta_\perp} \rho(\mathbf{b})$



G. Miller, 2007

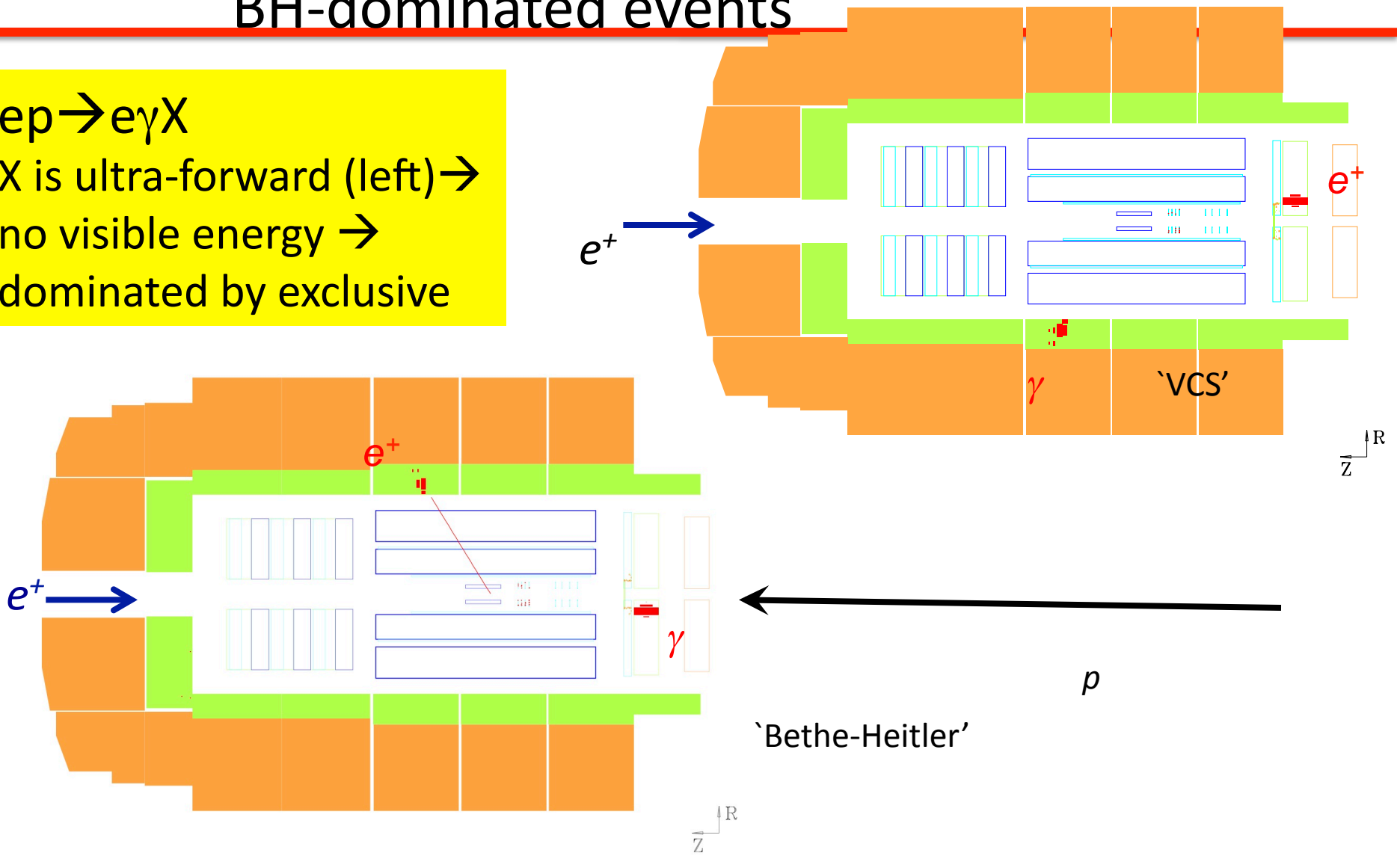
n→pπ⁻

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*).
$u_p(x) \sim (1-x)^3 \quad d_p(x) \sim (1-x)^4$



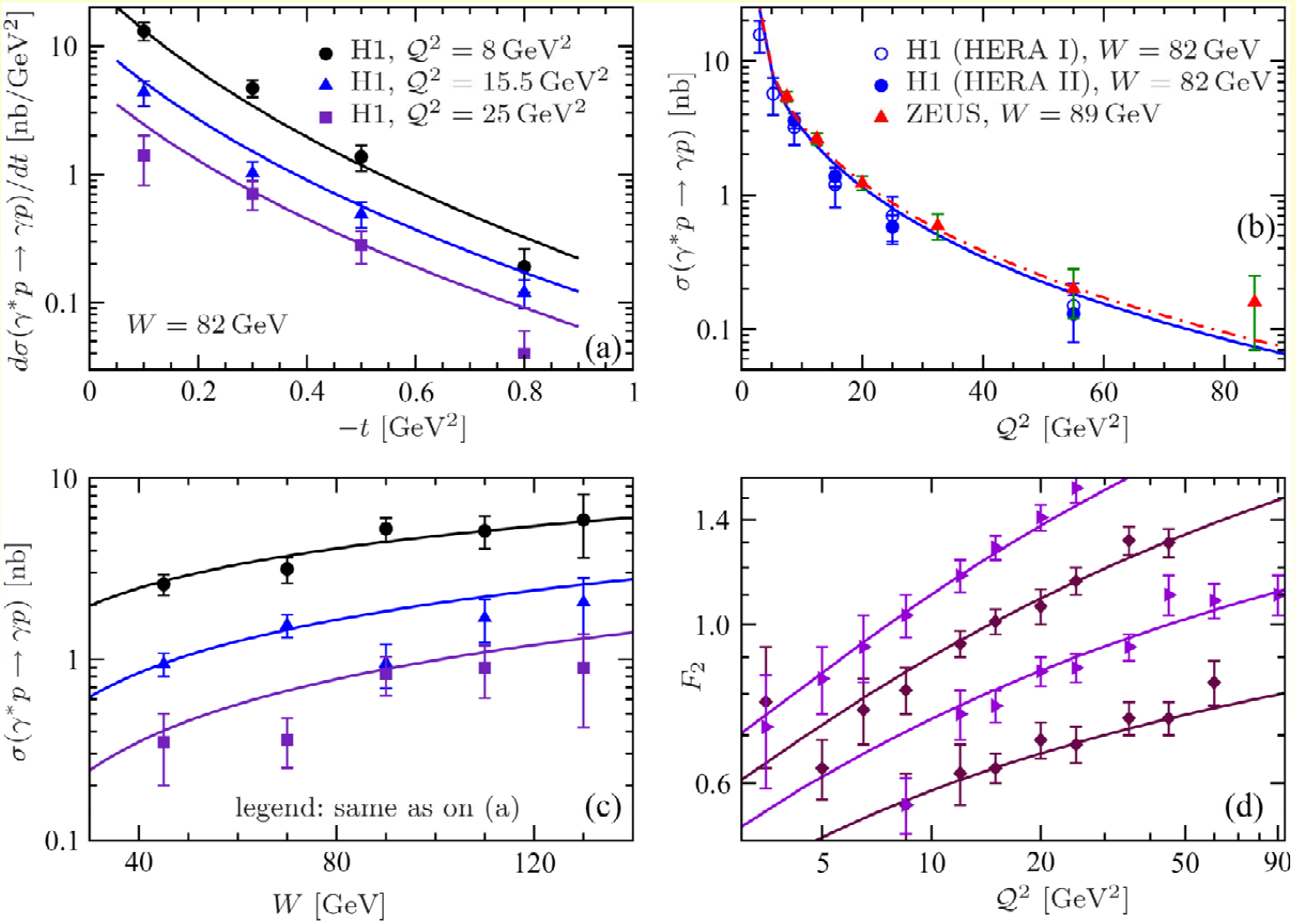
HERA-H1: Sample VCS-dominated; and BH-dominated events

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



HERA DVCS, fits by D.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); *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):

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

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

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

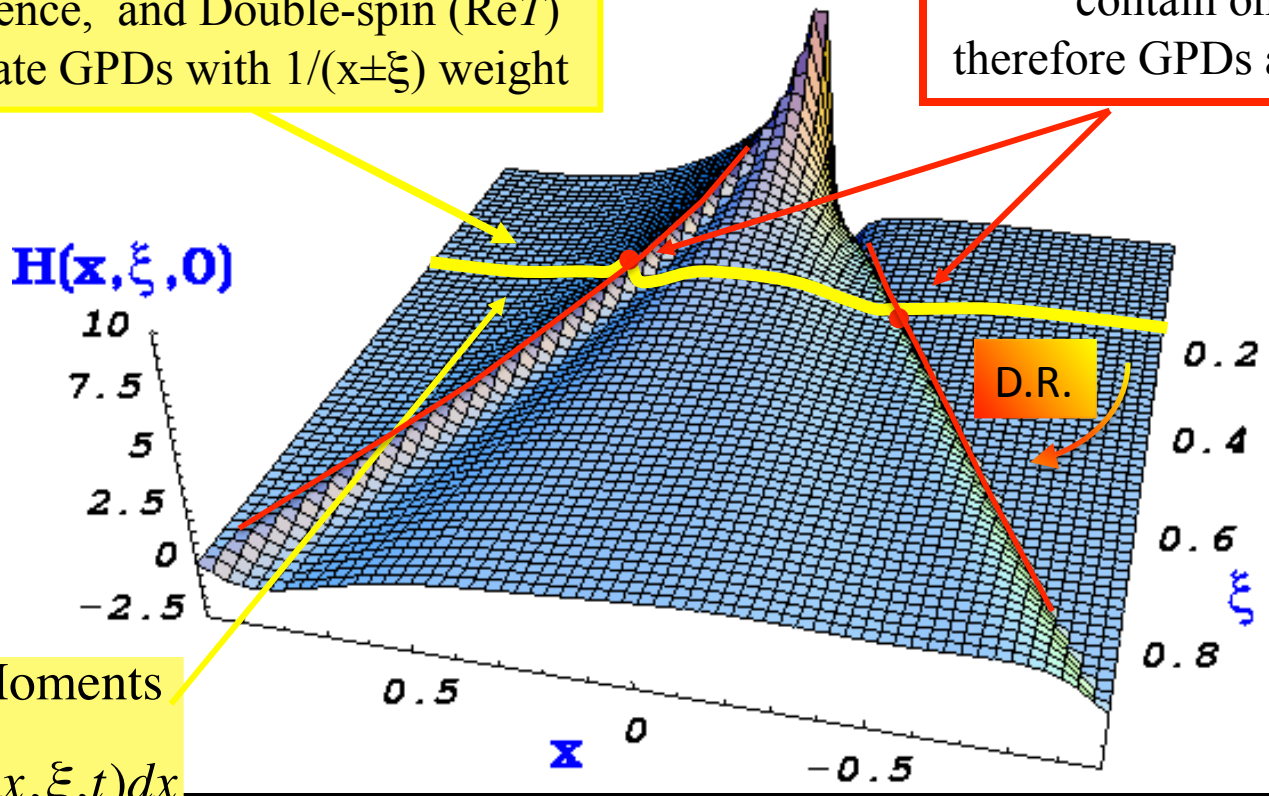
DVCS, GPDs, Compton Form Factors(CFF), and Lattice QCD

(at leading order:)

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

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 $-\xi$

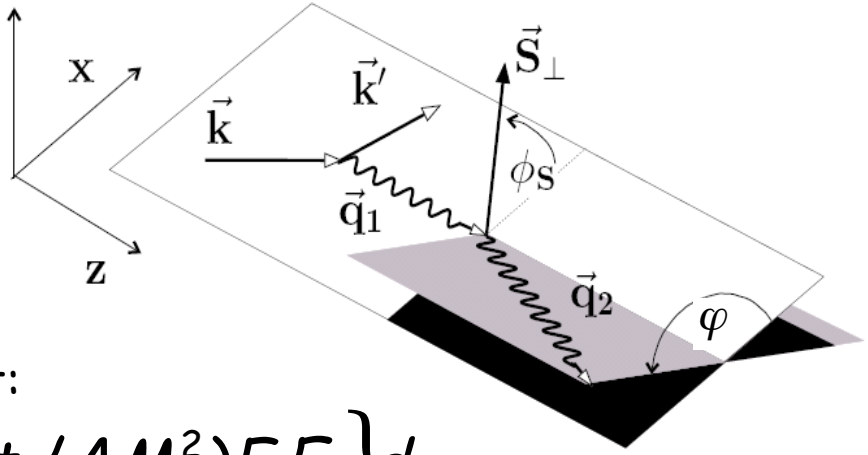


Lattice Moments

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

Exploiting the harmonic structure of DVCS with polarization

The 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:

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

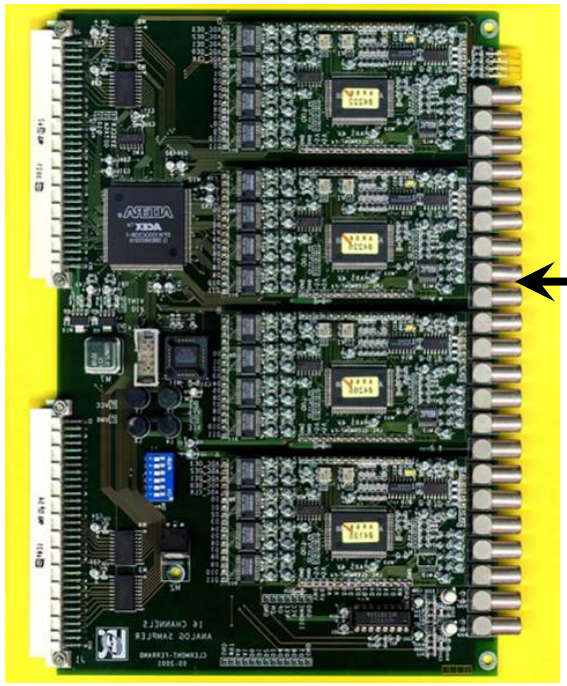
With unpolarized beam and Transversely polarized target:

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

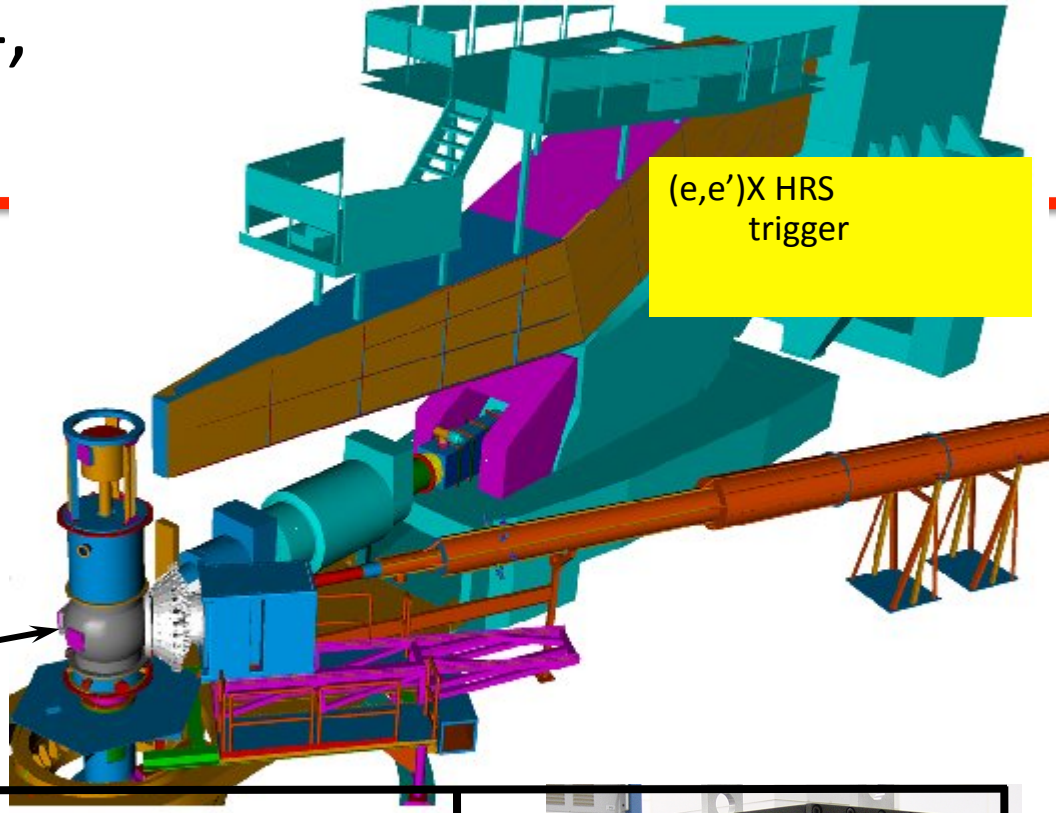
Separations of CFFs $H(\pm\xi,\xi,t)$, $E(\pm\xi,\xi,t)$,…

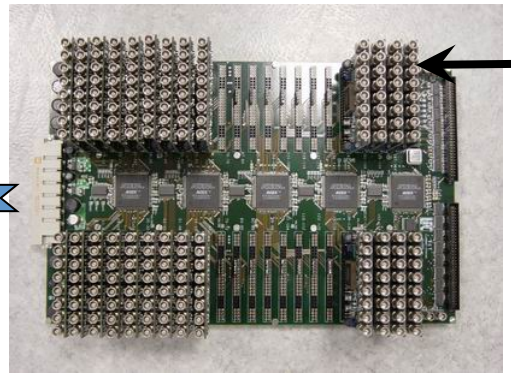
DVCS: JLab Hall A 2004, 2010

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

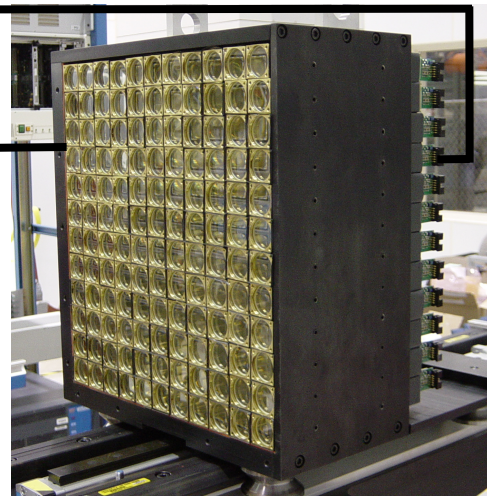


16chan VME6U: ARS
128 samples@1GHz

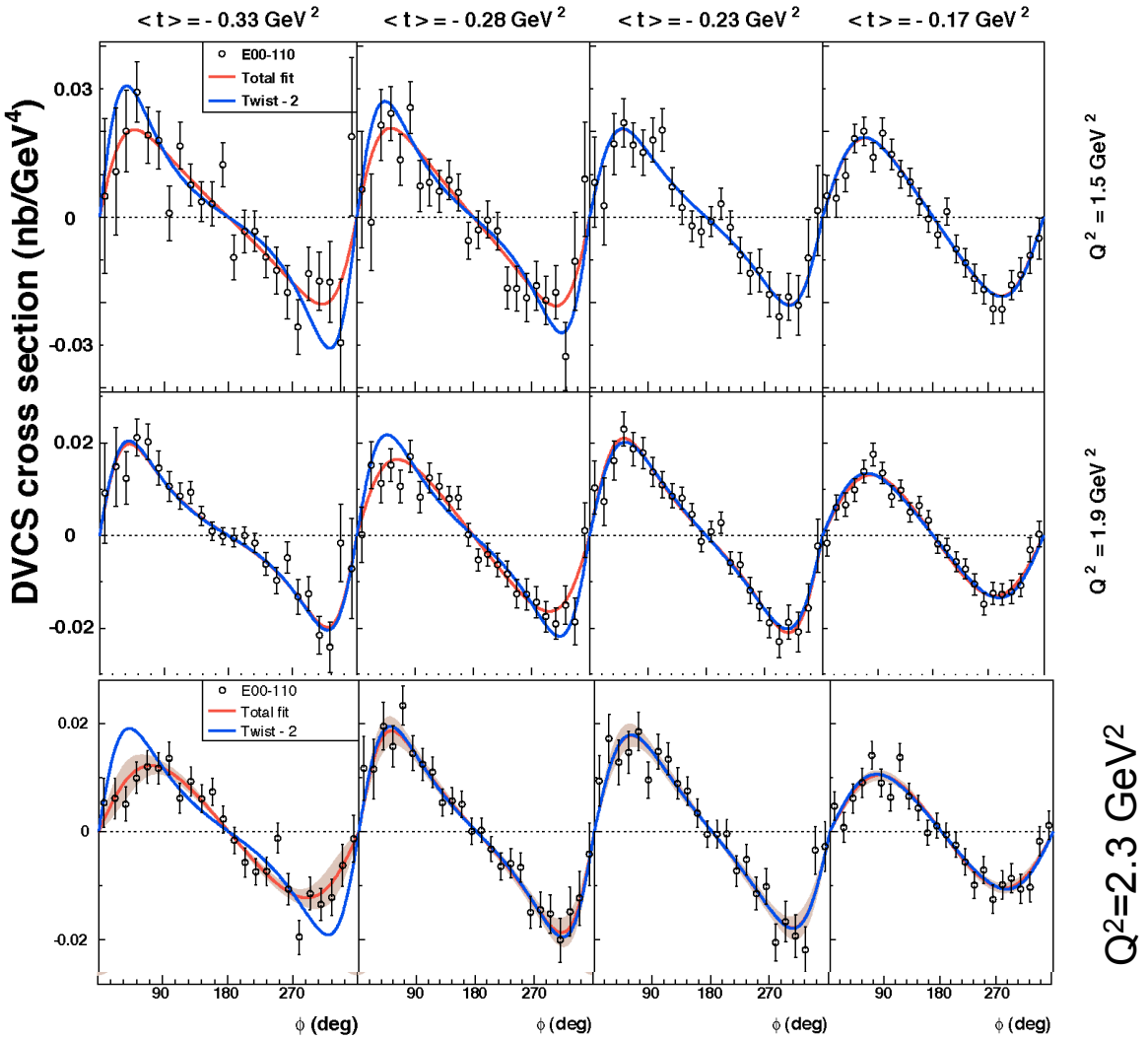




Digital Trigger Validation



132 PbF_2



Hall A Helicity Dependent Cross Sections E00-110

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

Twist-2(GPD)+…

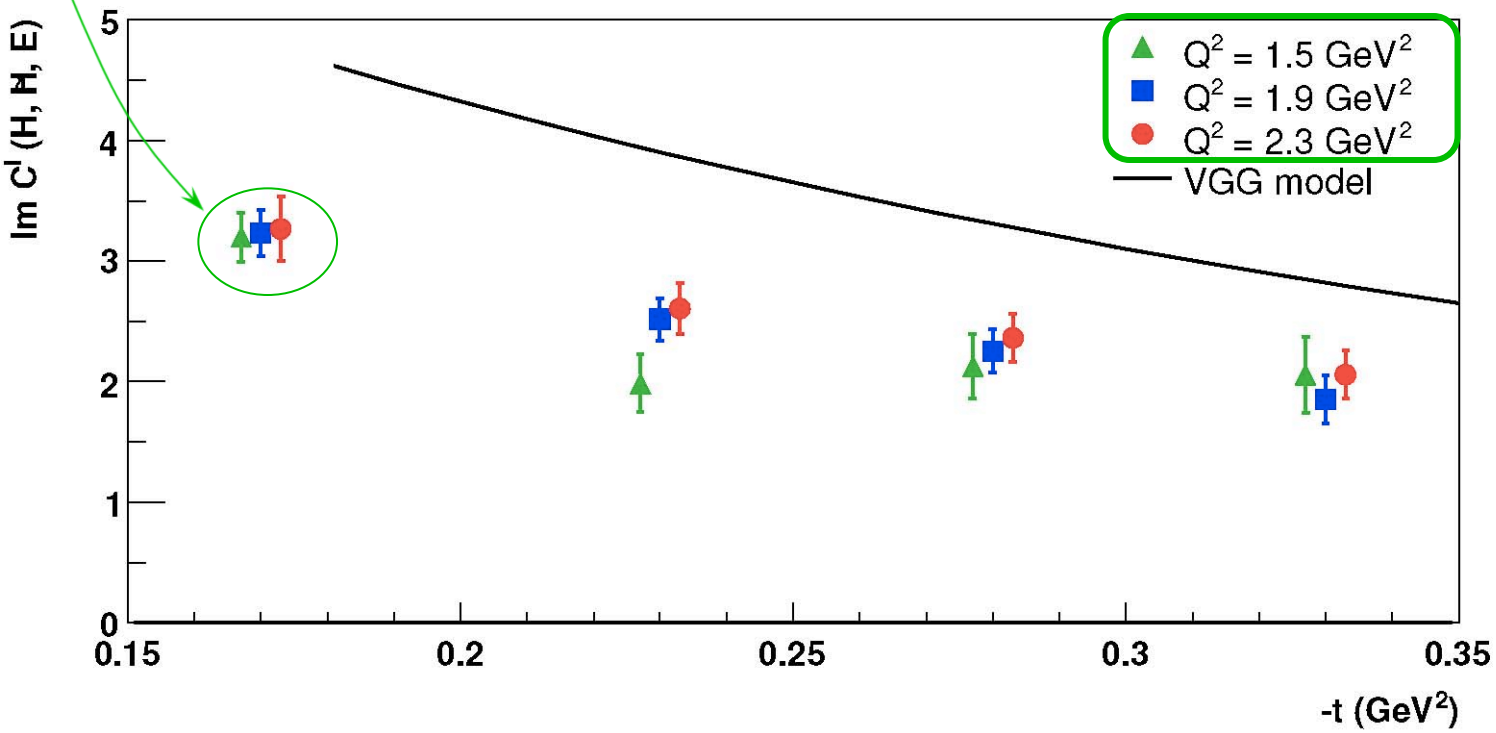
Twist-3(qGq)+…

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

$\Gamma_{s1,2}$ = 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) » (based on Double Dist. of A.Radyushkin) accurate to ≈30%



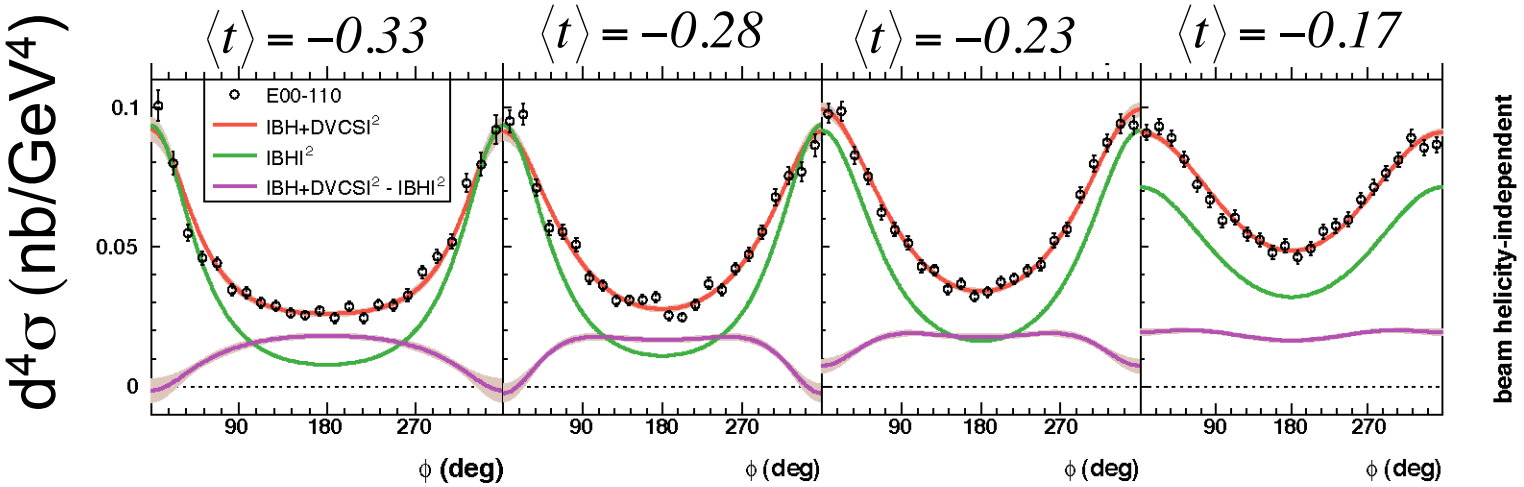
Extend to $Q^2 = 4.5$ GeV^2 @11GeV

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.*,



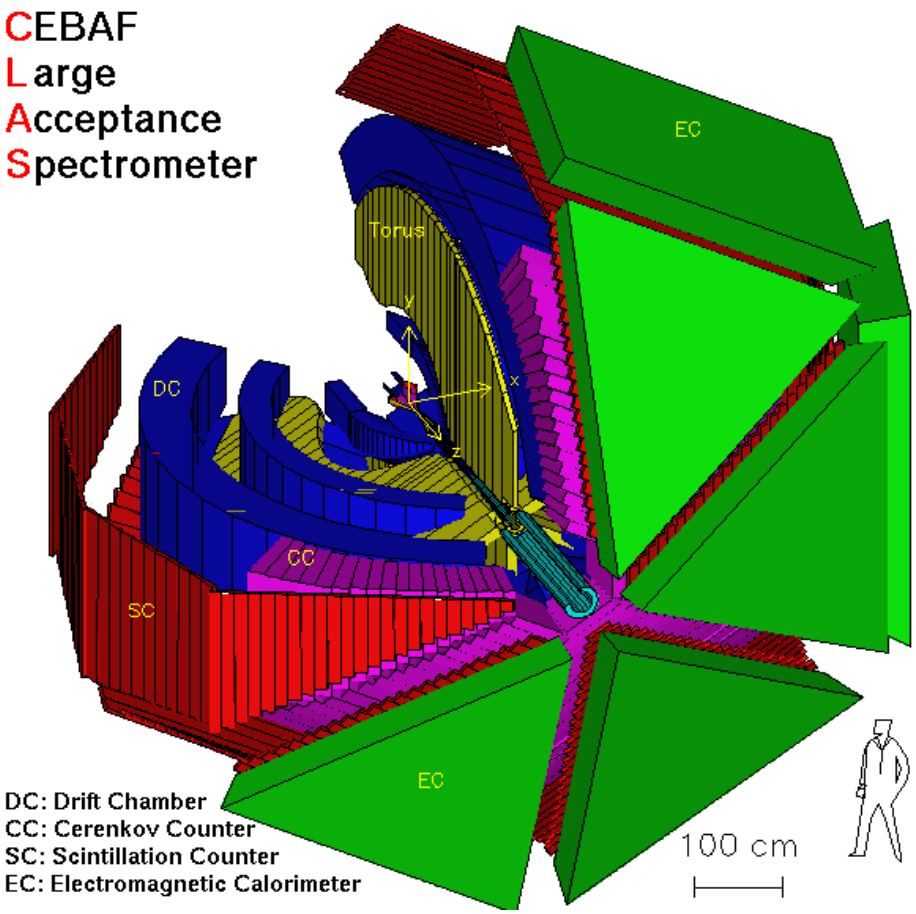
$$d\sigma = d\sigma(|BH|^2) + 2\,\mathrm{Re}[DVCS^{*}BH] + |DVCS|^2$$

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

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

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

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.

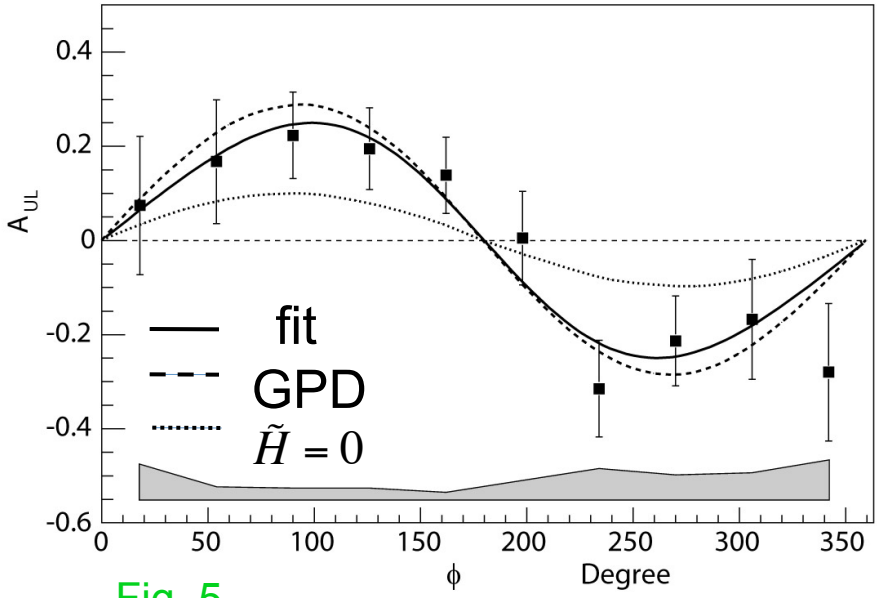


Fig. 5.

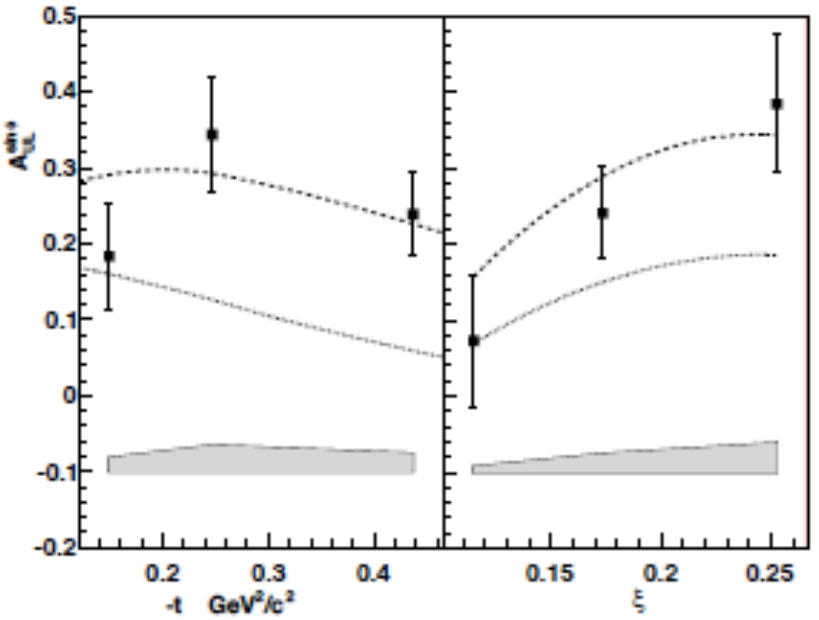


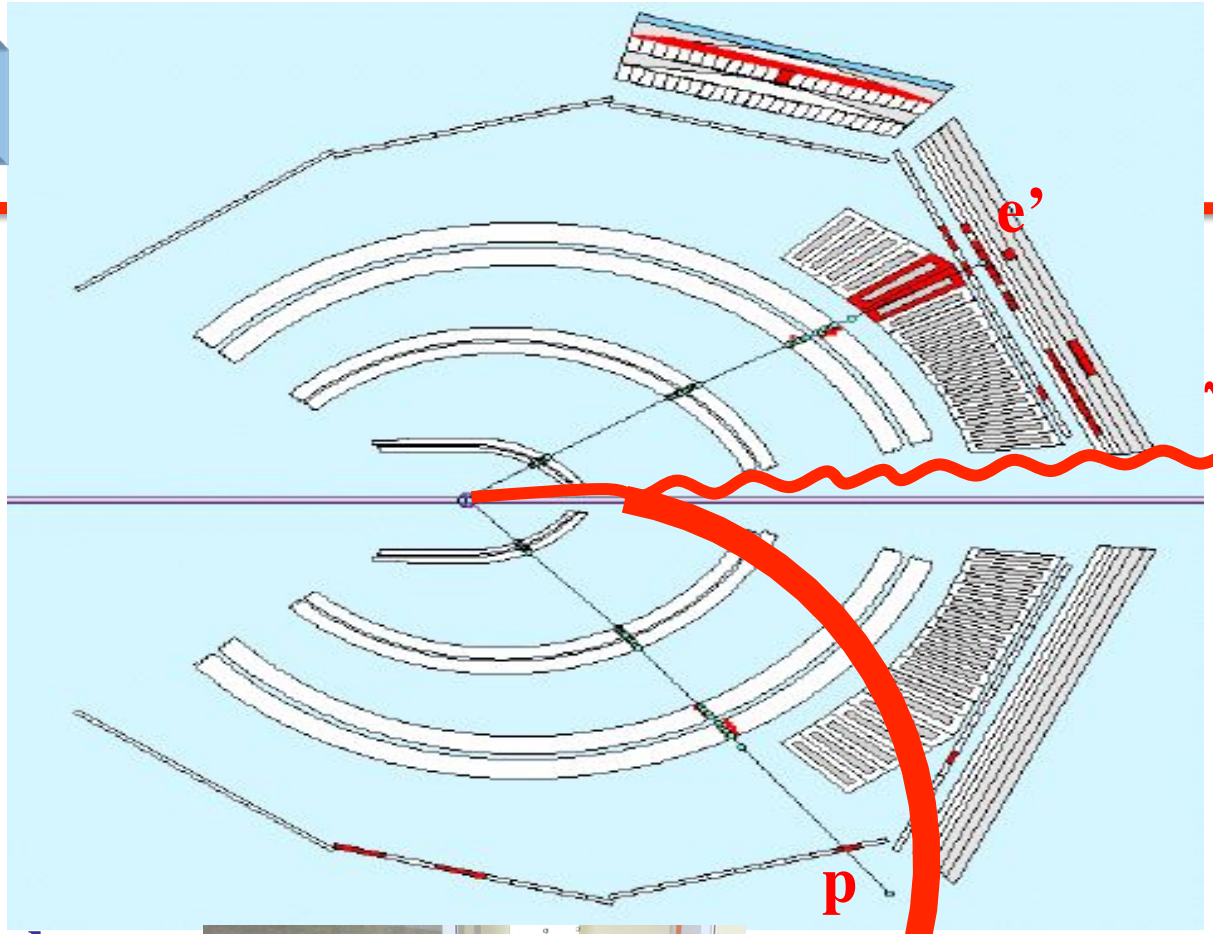
FIG. 6: The left panel shows the $-t$ dependence of the $\sin\phi$-moment of A_{UL} for exclusive electroproduction of photons, while the right shows the ξ dependence. Curves as in Fig. 5.

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

$\langle Q^2 \rangle$ = 1.8 GeV^2, $\langle -t \rangle$ =0.3 GeV^2, $\langle \xi \rangle$ = 0.16

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

DVCS@Hall B



ep⇨ epγ

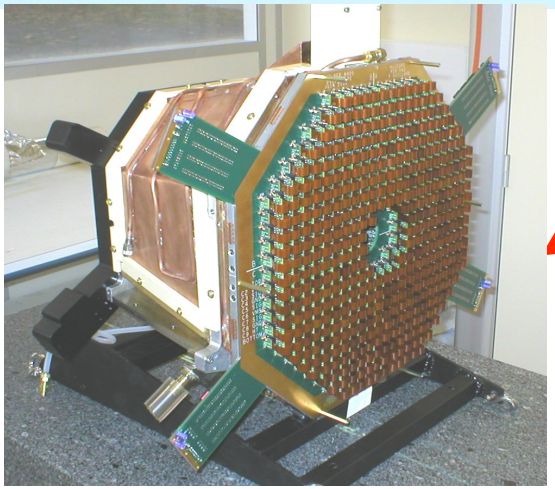
5 Tesla Solenoid

420 $PbWO_4$ crystals :

~10x10x160 mm^3

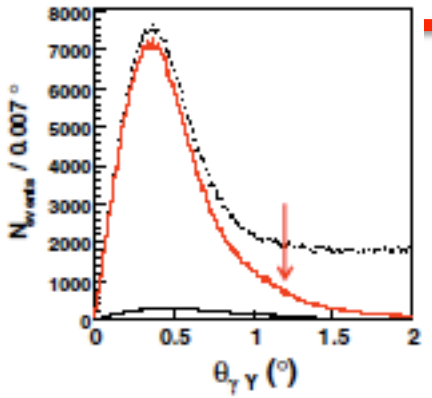
APD+preamp readout

Orsay / Saclay / ITEP / Jlab

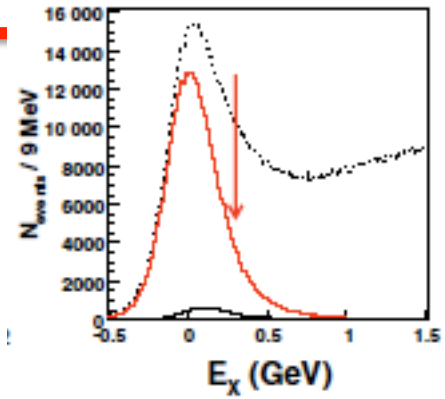


CLAS 6 GeV: Exclusivity and Kinematics

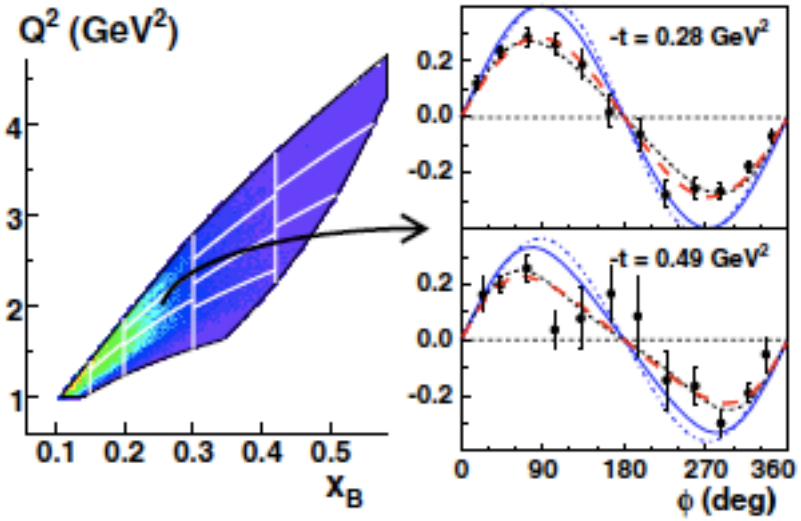
- H(*e,e'γp'*)*x*
- Overcomplete triple coincidence



Co-linearity of γ with *q-p'*



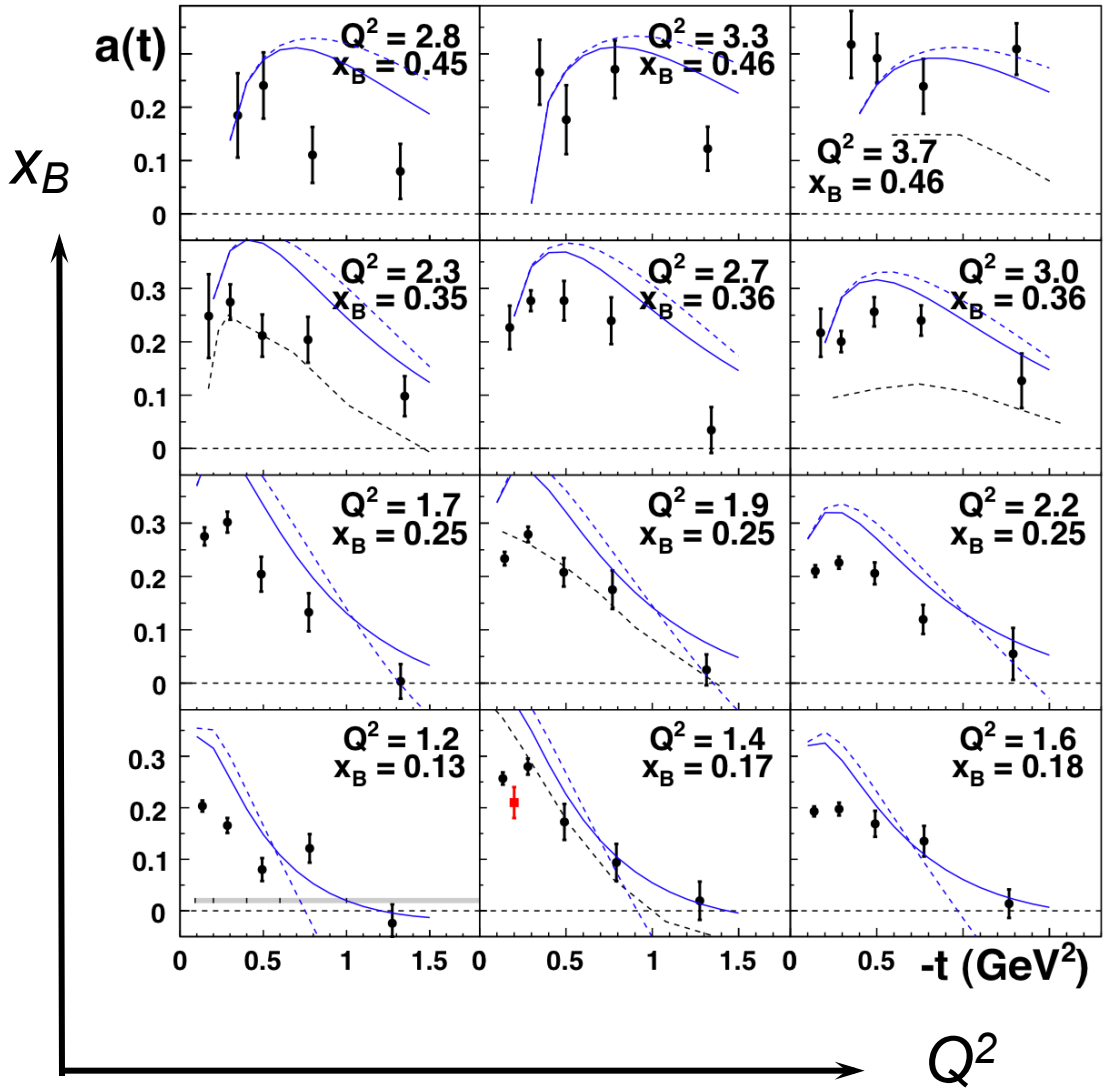
Missing Energy E_x



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

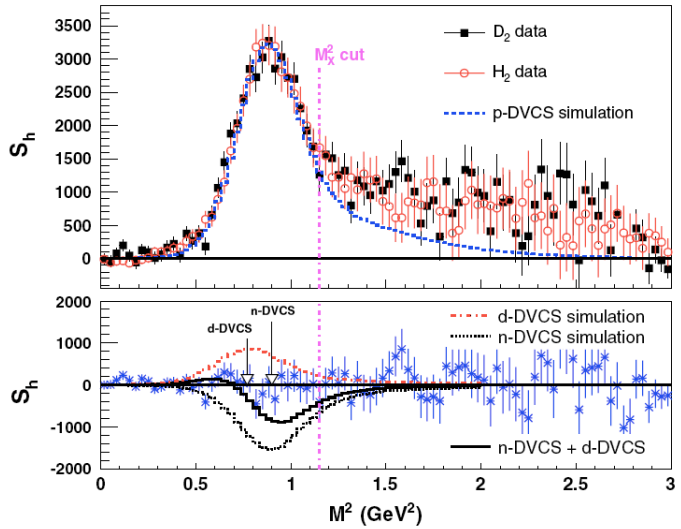
CLAS, 6 GeV Beam Helicity Asymmetry

- 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



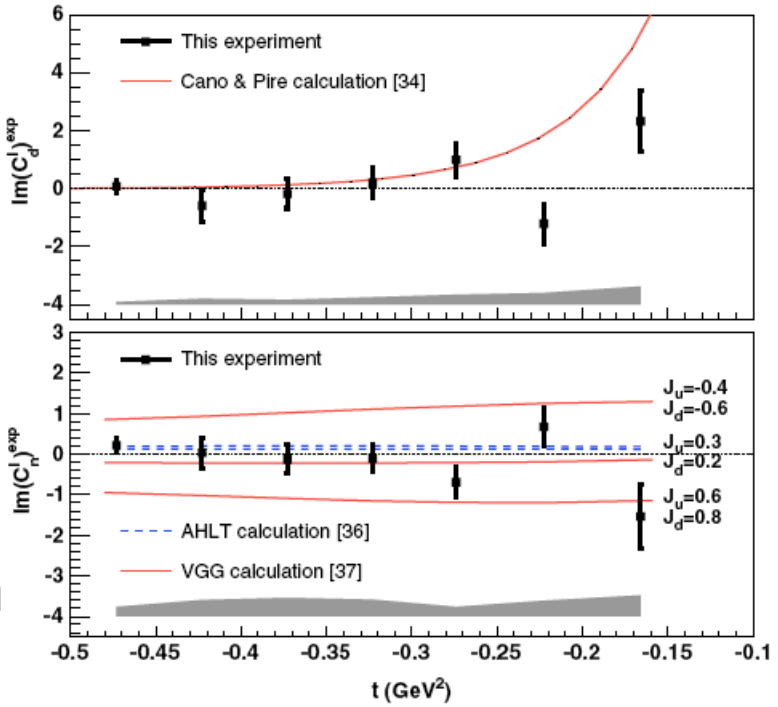
DVCS-Deuteron, Hall A

- 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]*



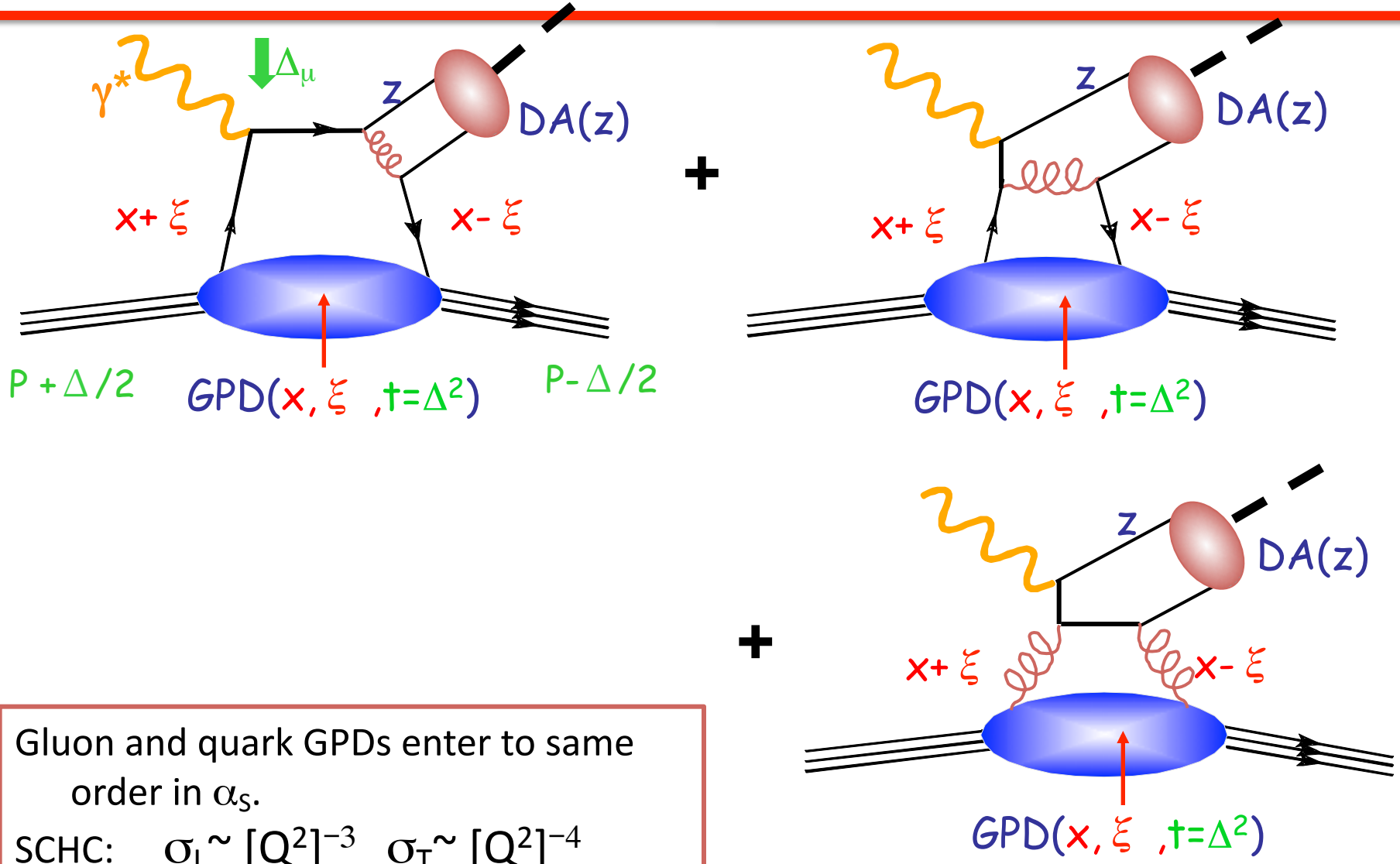
Q^2=2.3 GeV^2, x_B=0.36

- 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.



neutron

Leading Order (LO) QCD Factorization of DVES



Gluon and quark GPDs enter to same order in α_S.

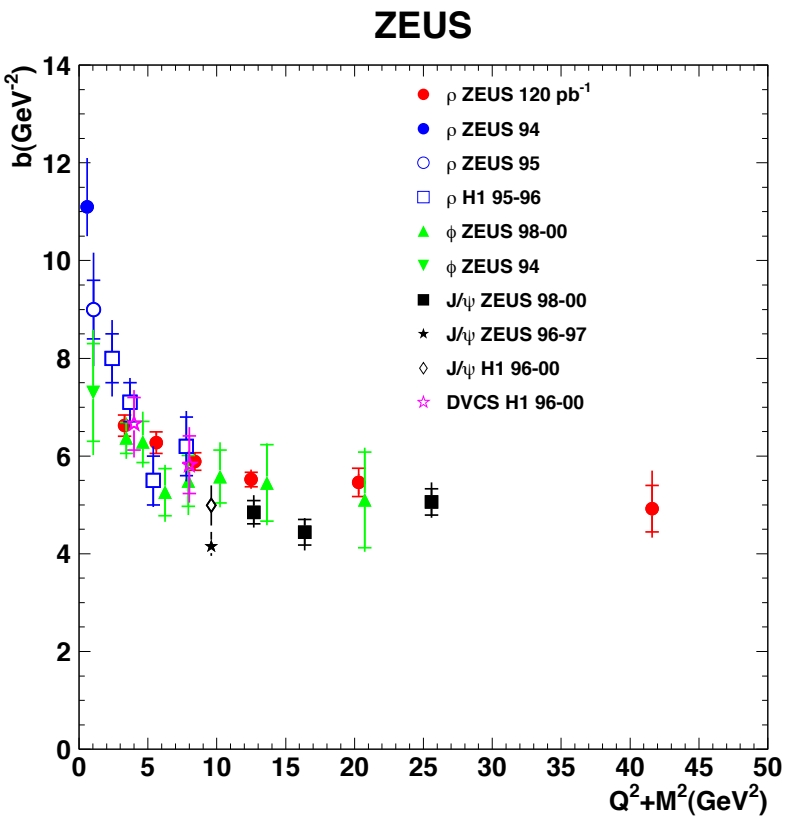
SCHC: $\sigma_L \sim [Q^2]^{-3}$ $\sigma_T \sim [Q^2]^{-4}$

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 requires setting scale of gluon pdf $\mu^2 << Q^2$
  - Finite transverse spatial size $b \approx 1/\mu$ of $\gamma \rightarrow V$ amplitude



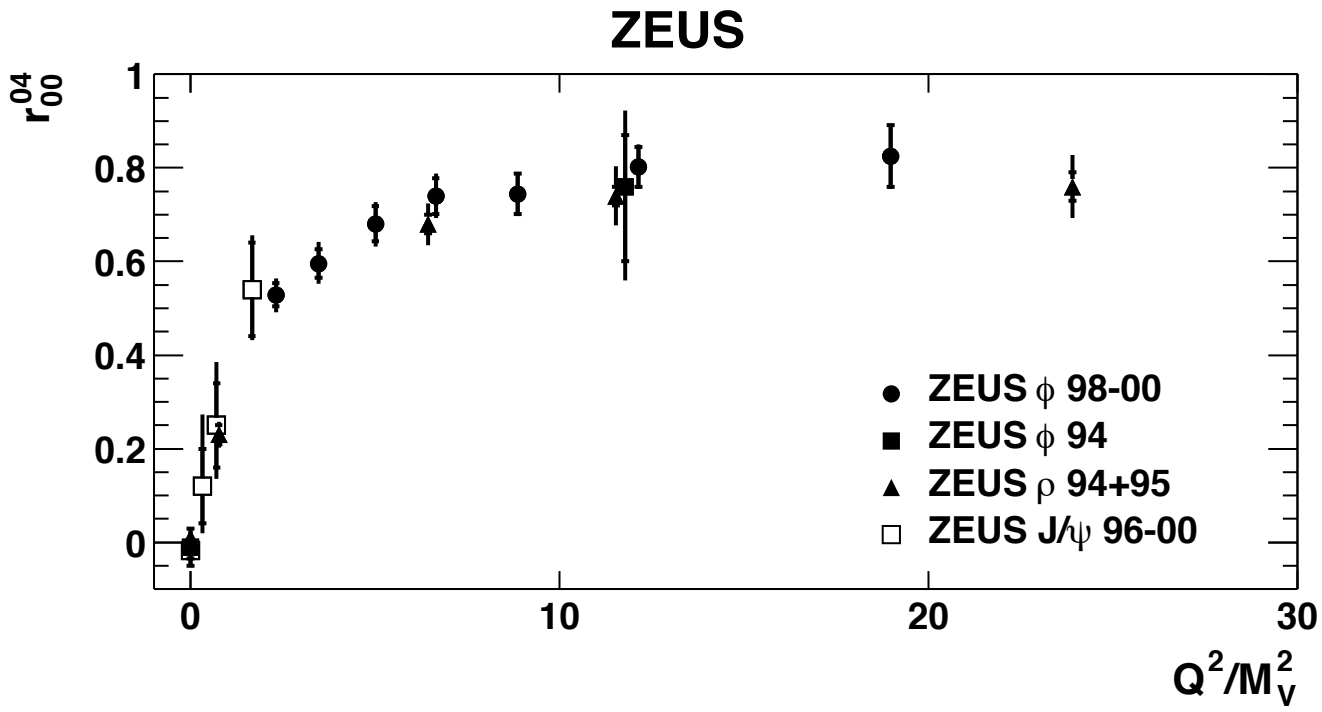
GWolf 0907.1217

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 $d\sigma_T$?

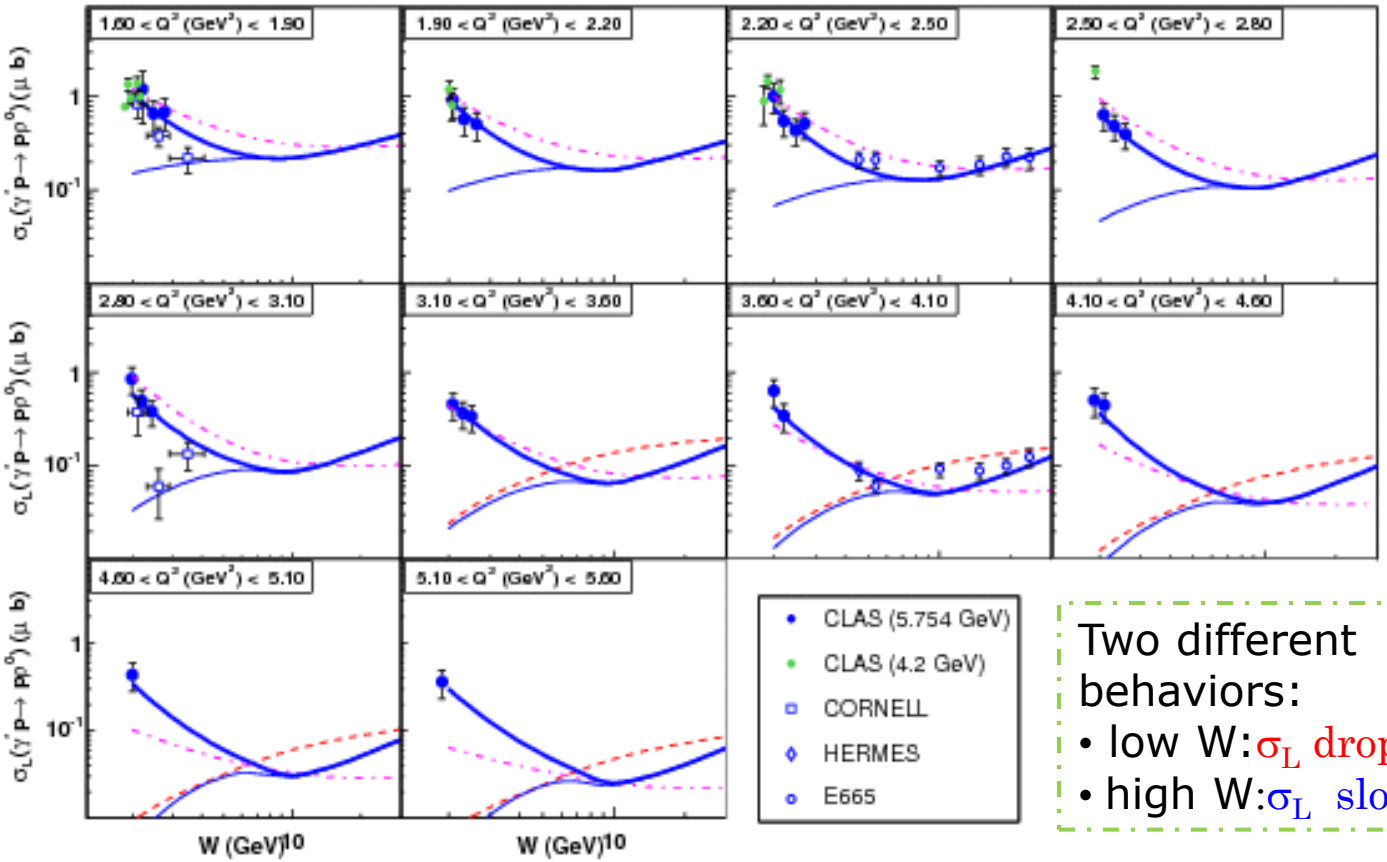


Vector Mesons at JLab

- 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 Kroll & Goloskokov consistent with world data
    - Perturbative *t*-channel exchange (two gluons), but factor of 10 suppression relative to co-linear 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 [*]
- -.-.- dash-dotted JLM calculation *à la* Regge [*]

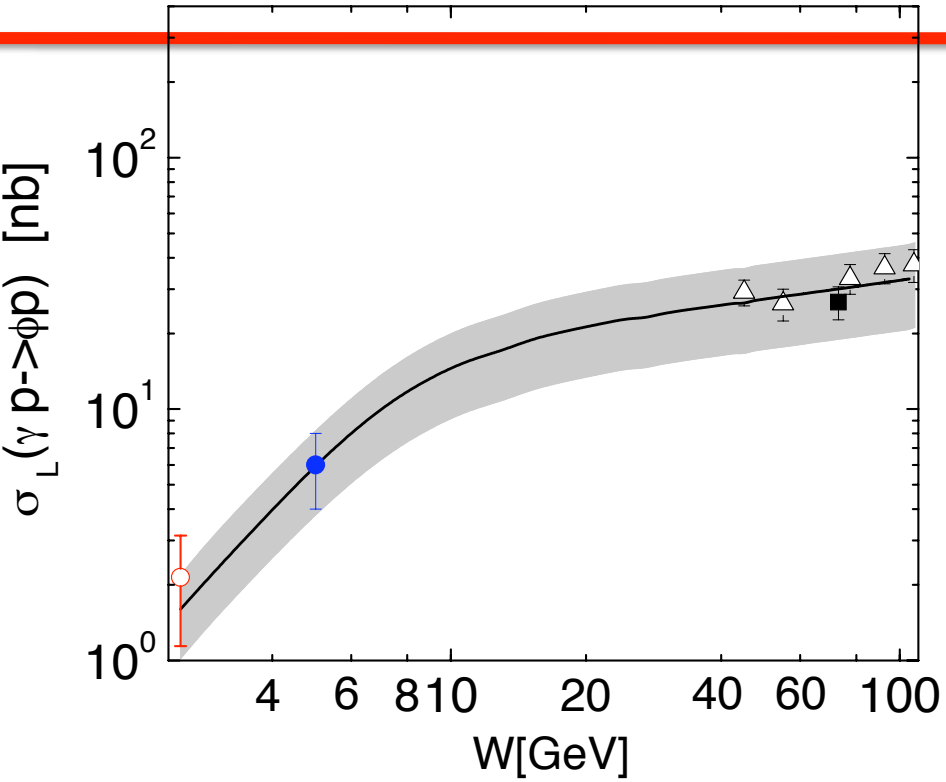
} GPD approaches based on Double-Distributions

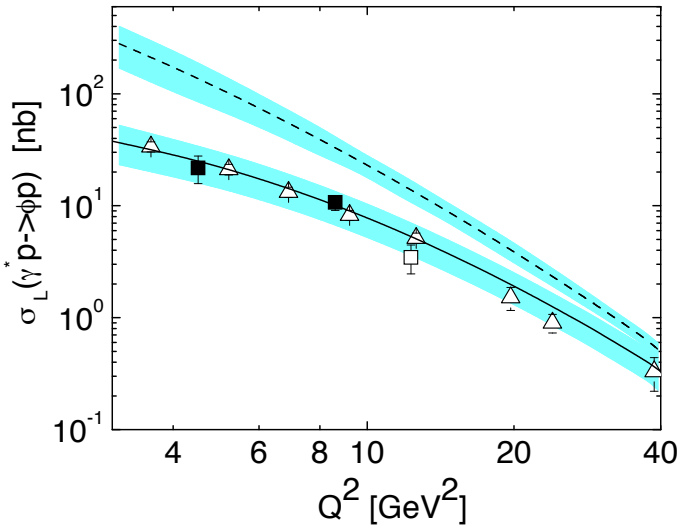
} Hadronic approach

* 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

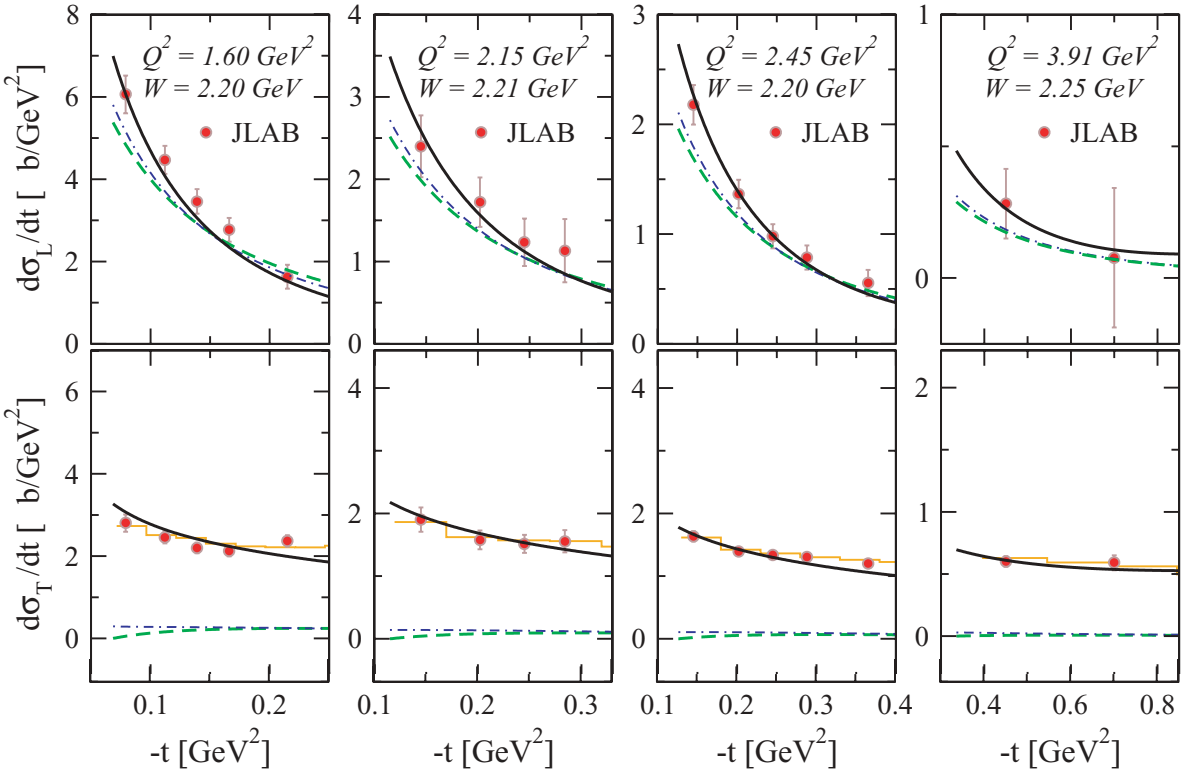




12 GeV
Proposals/LOI in Hall B and Hall A
Proposals for J/Ψ in Halls A and B.

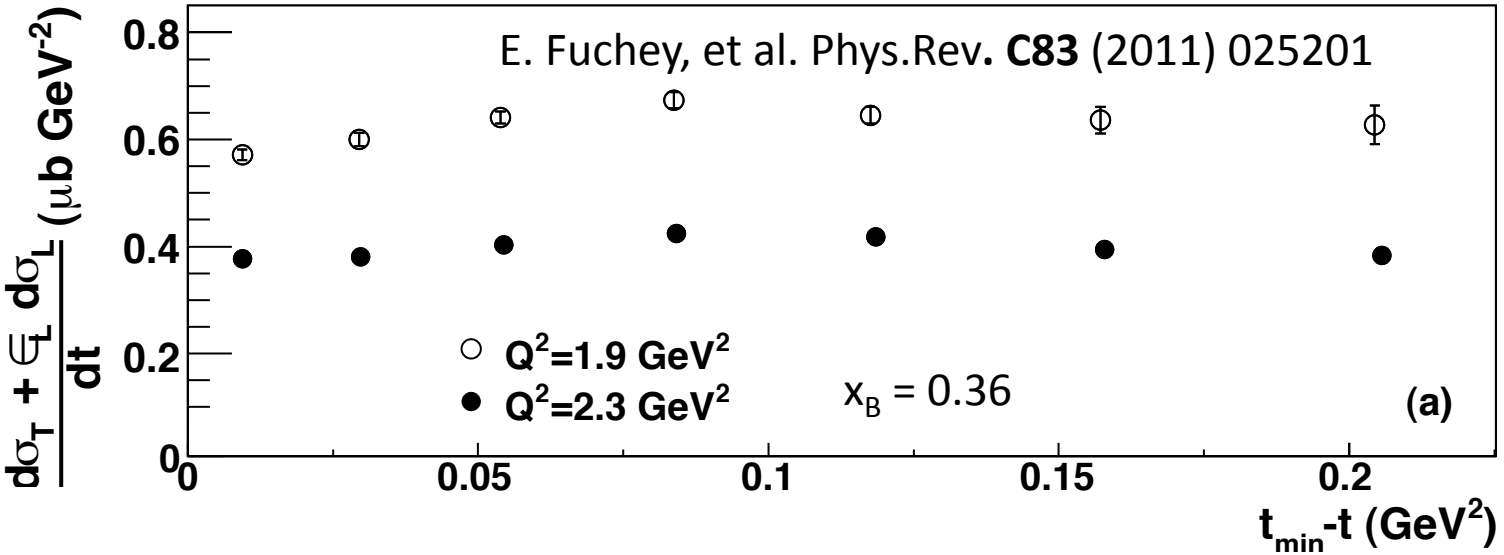
Pseudo Scalar Meson Production

- H(e,e'π^+)n: Strong pion pole in σ_L as $\Delta^2 \rightarrow 0$
  - T. Horn et al., Phys. Rev. Lett. 97, 192001 (2006).
  - $F_\pi(Q^2)g_{\pi NN}(t) \rightarrow$ GPD $\tilde{E}$
  - Fragmentation Model for σ_T
    M.Kaskulov U. Mosel, Phys Rev **C81** (2010)

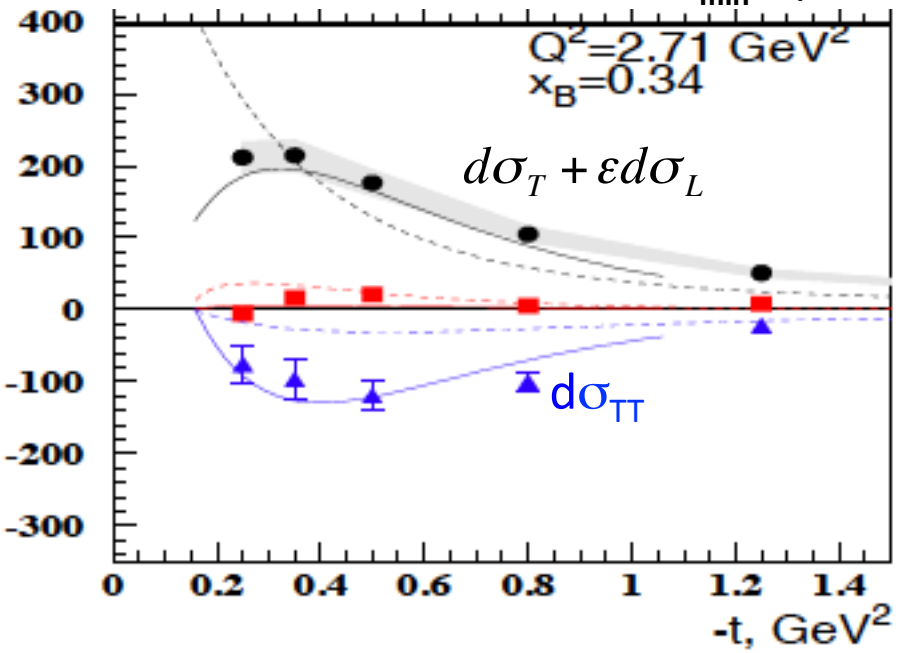


Deep Virtual π^0 Production: H(e,e'π^0)p

- Hall A,
- $d\sigma \sim Q^{-5}$, not Q^{-8}
- GPDs 10% of $d\sigma$

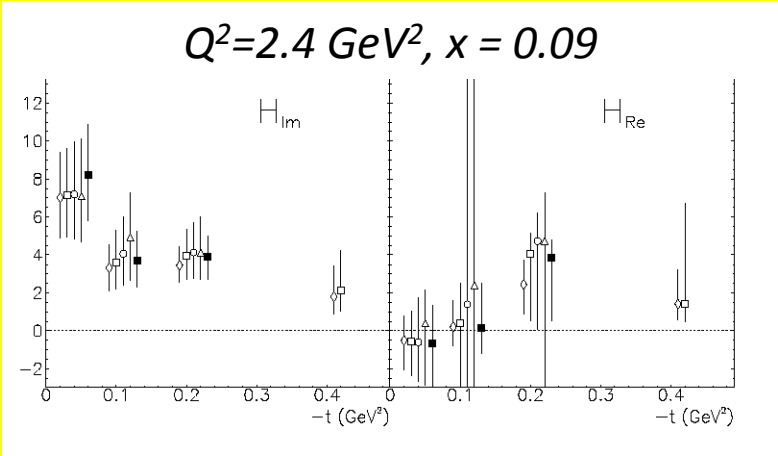


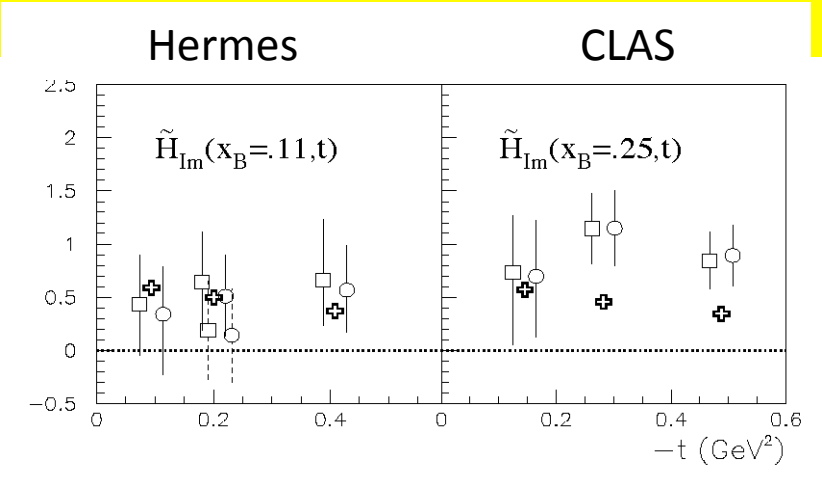
- CLAS, to be submitted
- Transversity GPDs and $k_\perp$ effects in pion DA
- Goldstein, Gonzalez Hernandez and Liuti, PRD**84**, 034007(2011)
- P.Kroll and S.Goloskokov Eur. Phys. J. **A47**, 112 (2011).



Constraining GPDs from Data: $\Re e[H], \Im m[H], \Im m[\tilde{H}]$

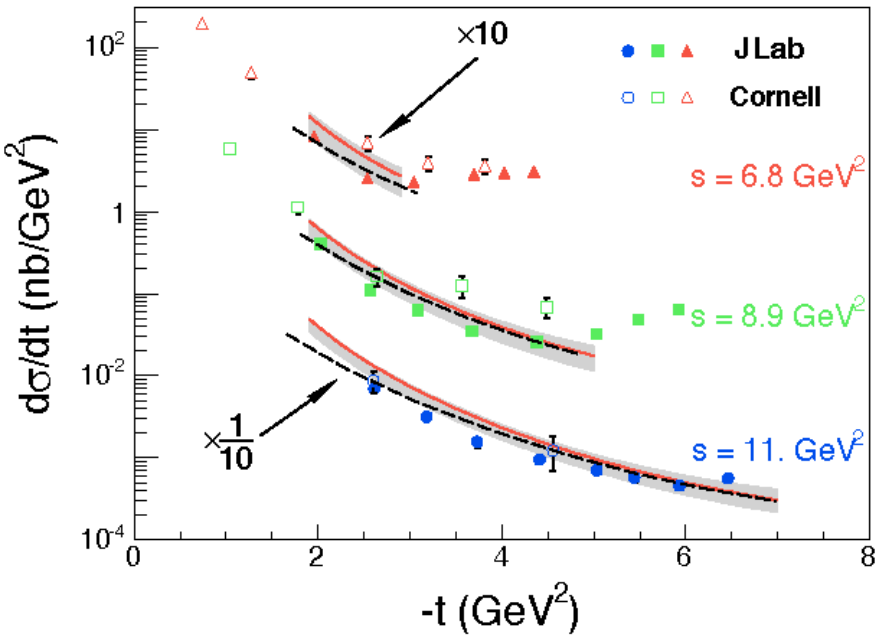
- M. Guidal, H. Moutarde
  - *Eur.Phys.J.* **A42** (2009) 71-78 arXiv:0905.1220 [hep-ph]
  - Twist-2 analysis of 17 HERMES observables
- M. Guidal
  - *Phys.Lett.* **B693** (2010) 17-23 arXiv:1005.4922 [hep-ph]
  - Longitudinally polarized target analyses
- also, K.Kumericki, D. Mueller, & K.Passek-Kumericki V. Guzey...



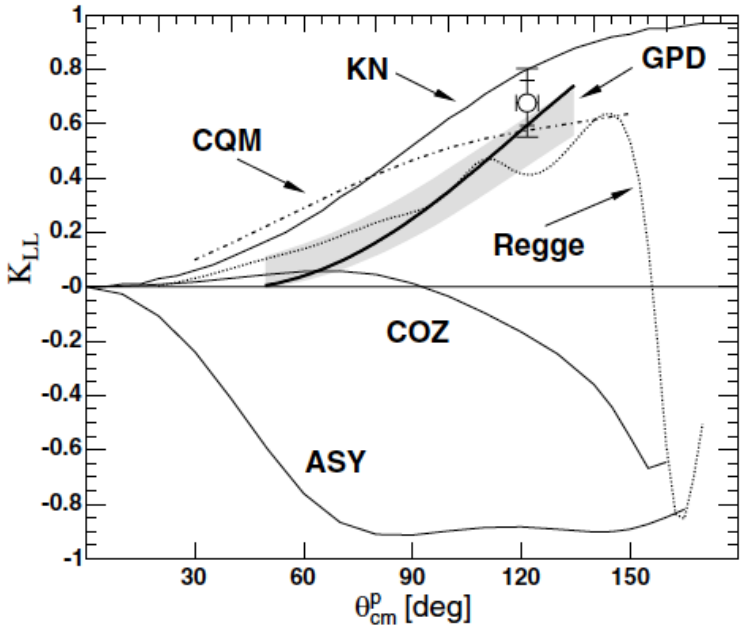


Real Compton Scattering: ∫H dx/x (Hall A)

Factorization described by A. Radyushkin



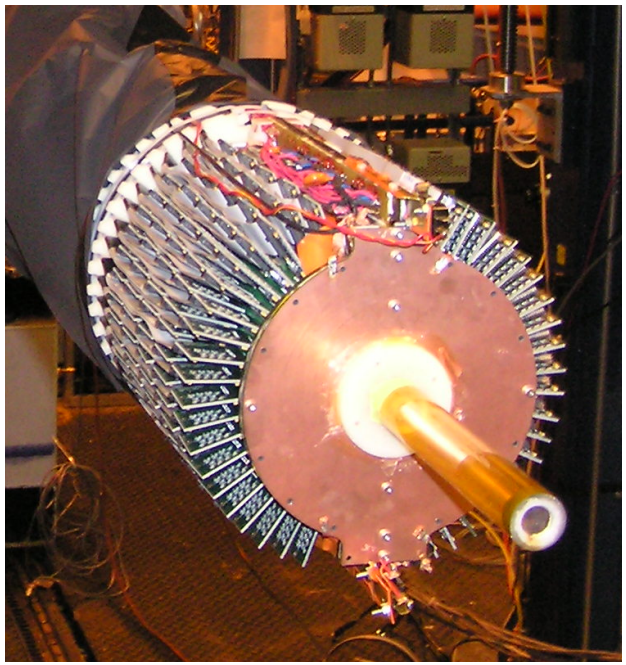
- A. Danagoulian *et al*, PRL **98** (2007) 152001
- Theory curves
  - P. Kroll (solid)
  - G.A.Miller (dashed)



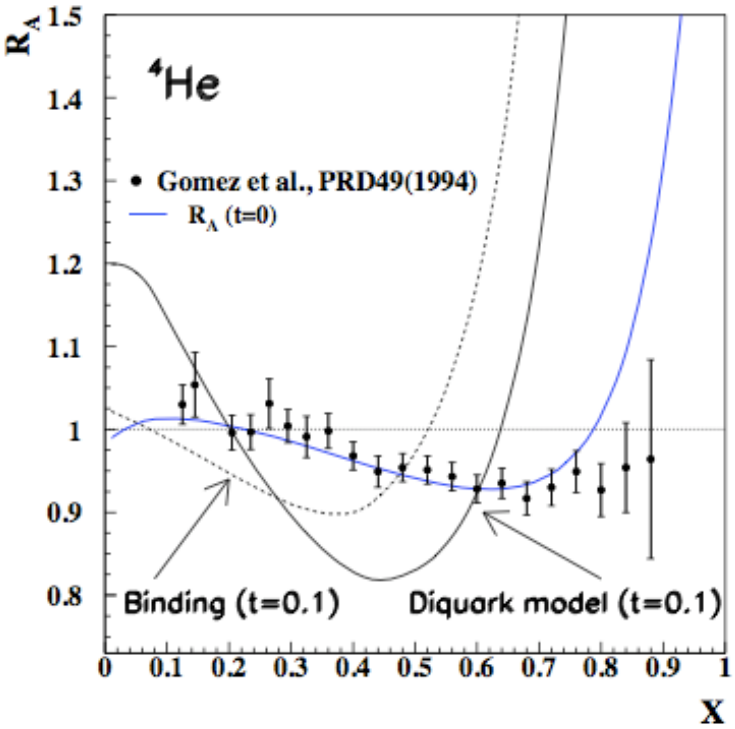
- D. Hamilton *et al.* PRL **94** (2005)242001

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)

The next 20 years of GPD experiments

- First 5 years
  - Precision tests of factorization with Q^2 range ≥ 2:1 for
    - $x_B \in [0.25,0.6]$. $Q^2 \geq 2$ GeV^2 t_{min}-t < 1 GeV^2 + COMPASS : $x_B \in [0.01,0.1]$
    - Proton unpolarized target observables (Hall A and B)
    - Im[DVCS*BH], Re [DVCS*BH], $|DVCS|^2$.
  - Longitudinal, target spin observables: CLAS12
    - 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 > $2 \cdot 10^{34}$ /cm^2/s (also LHeC)

Back-up Slides

CLAS Longitudinal Target w/ Inner Calorimeter

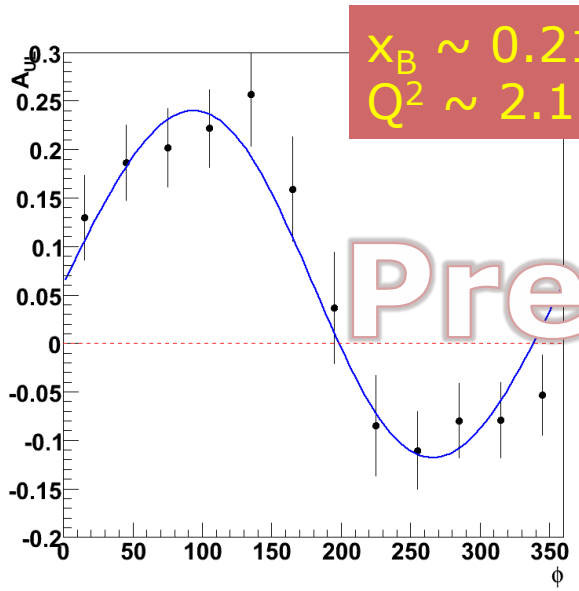
DVCS Target Spin Asymmetry

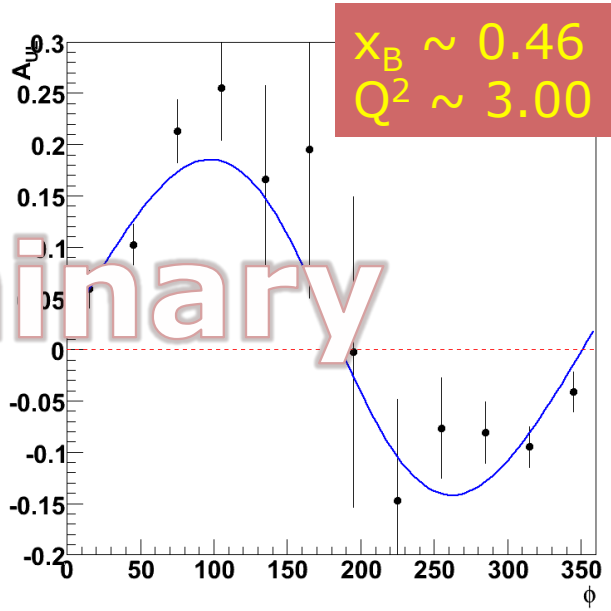
$$A_{UL} = \frac{N^+ - N^-}{f(P^- N^+ + P^+ N^-)}$$

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

Fitting function:

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



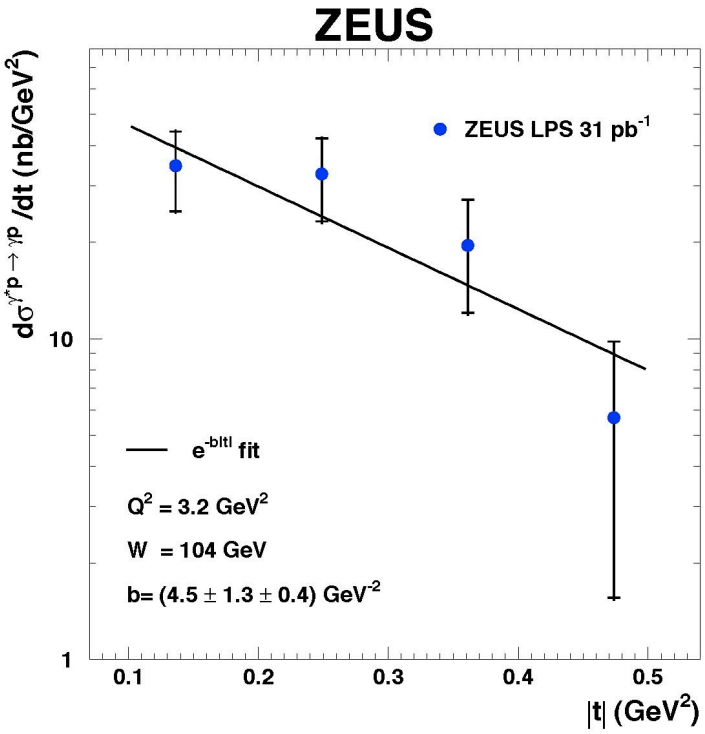


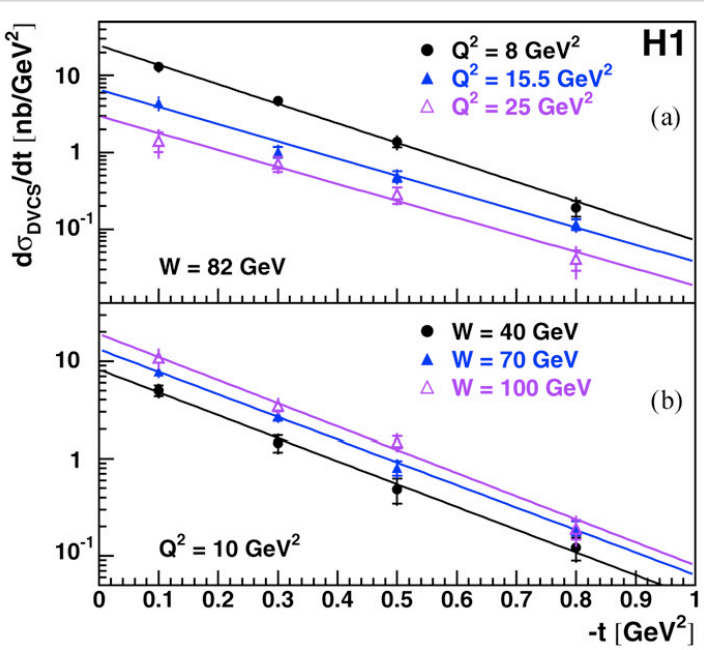
Preliminary

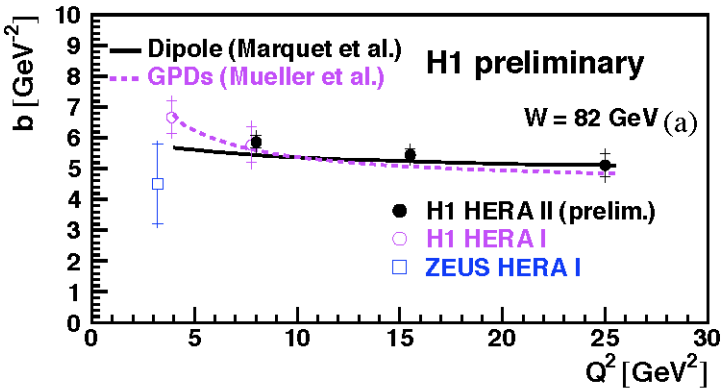
Plots and analysis done by Erin Seder

HERA DVCS

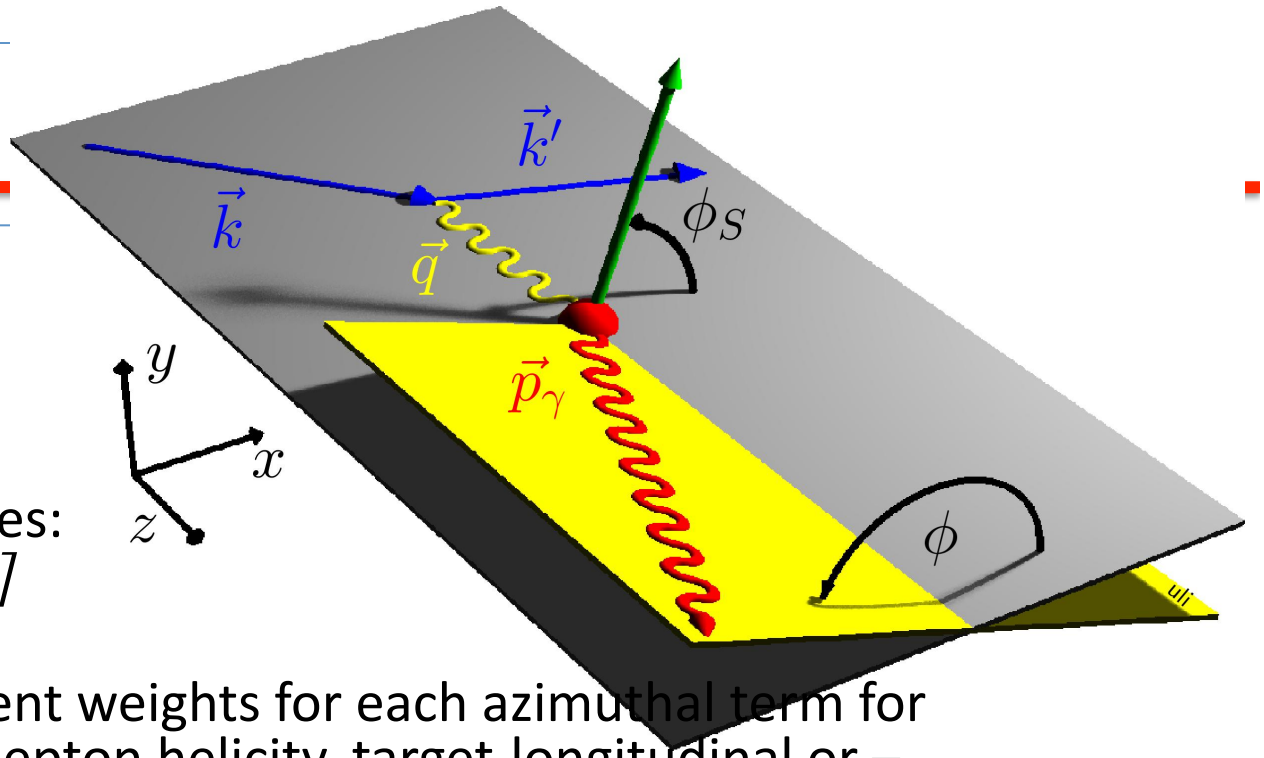
- Spatial imaging of gluons at small x_B







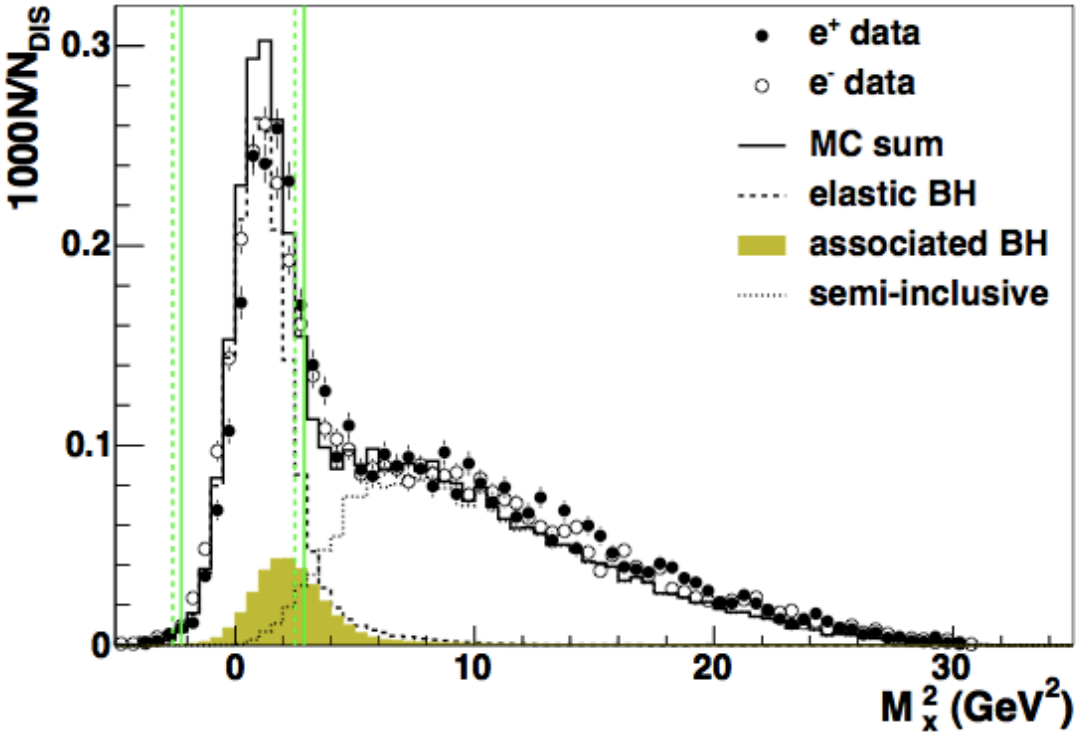
Unraveling DVCS observables



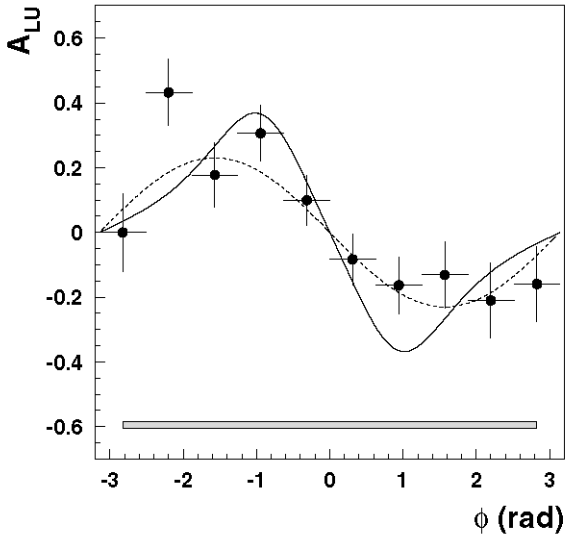
- Twist-2 terms ≈ 1, cosϕ, sinϕ
- Twist-2 terms ≈ sin2ϕ
- Not a pure Fourier series: $1/[A + B\cos\phi + C\cos2\phi]$ from *BH* propagators.
- GPDs enter with different weights for each azimuthal term for different polarization (lepton helicity, target-longitudinal or –transverse) observables
  - Single 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

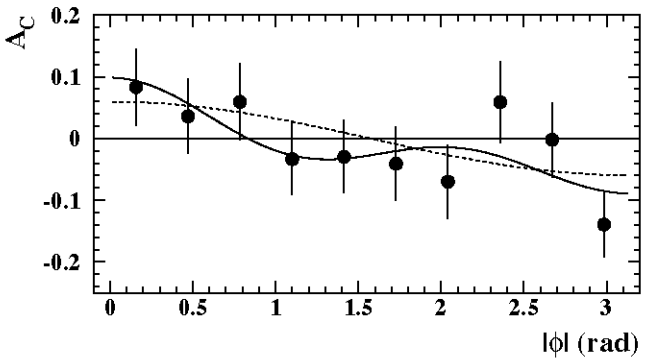
27 GeV polarized $e^{\pm}$ on
Internal Gas Jet
/ Atomic Beam Source targets



2001 BSA

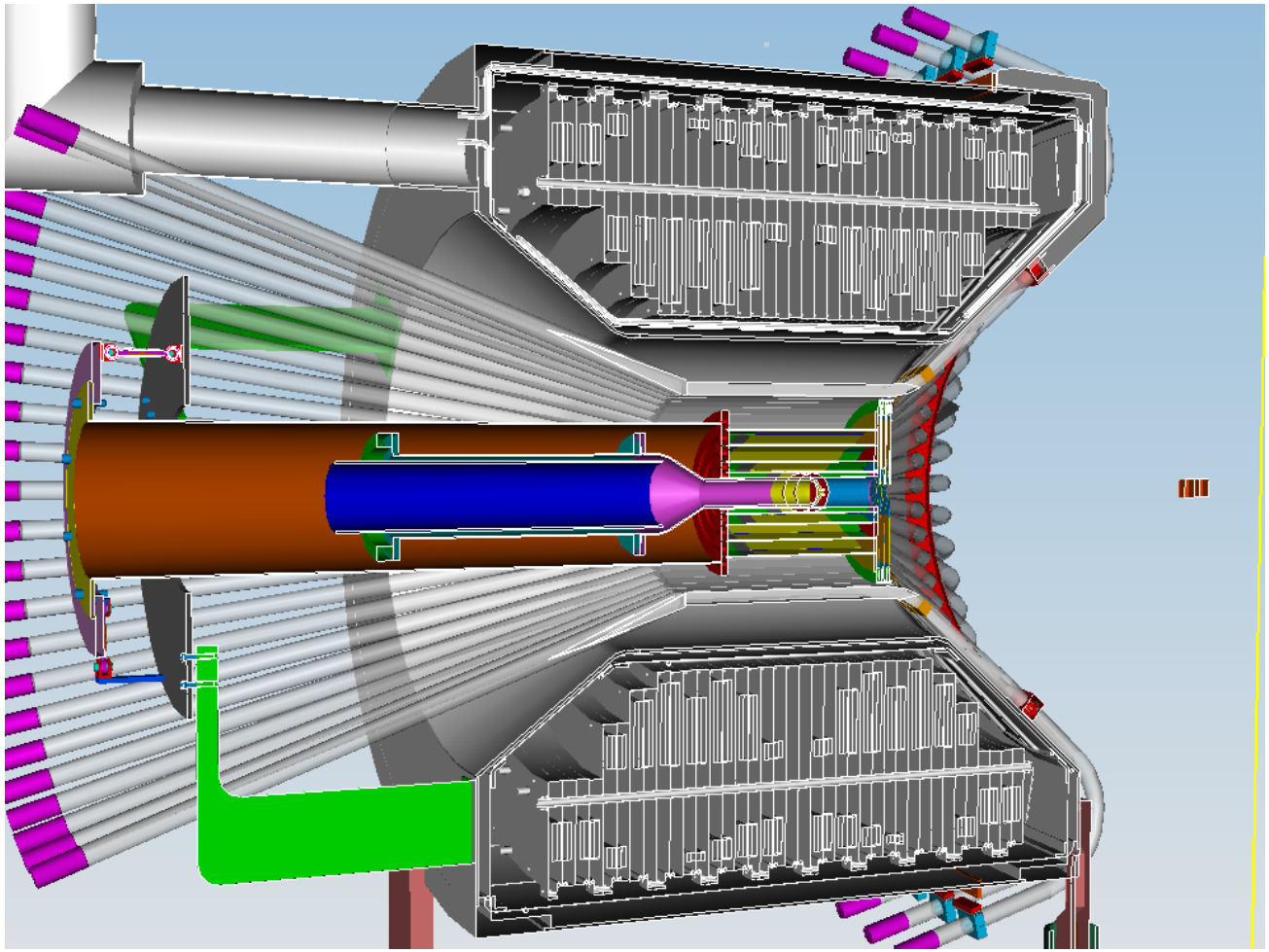


2006 BCA



CLAS12 – Central Detector SVT, CTOF

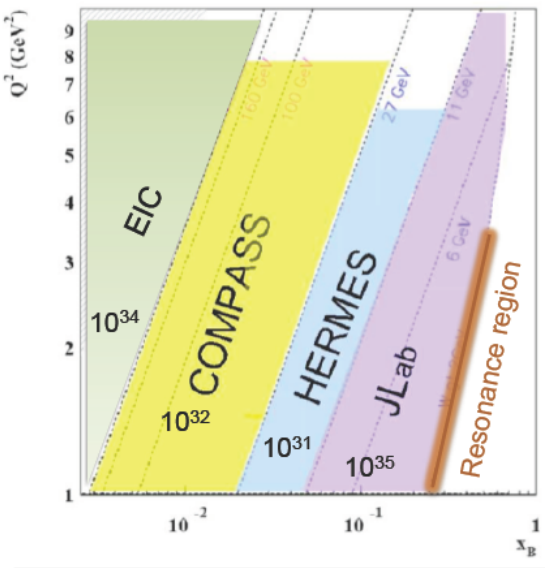
-
-
-
-



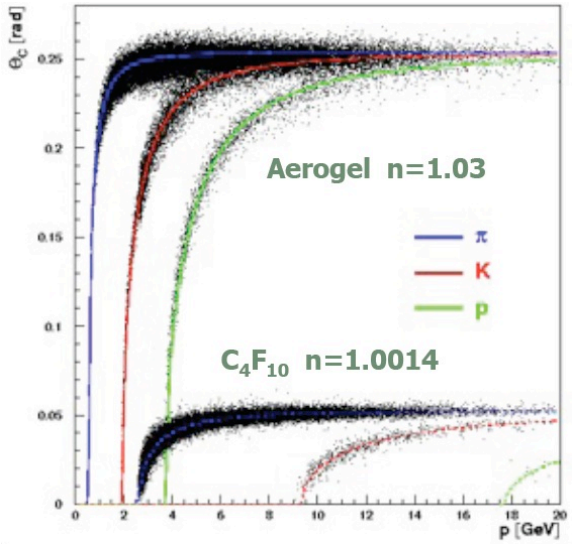
HERMES overview

27.6 GeV e+/e- HERA beam

Access to valence and sea



Electron and Hadron ID

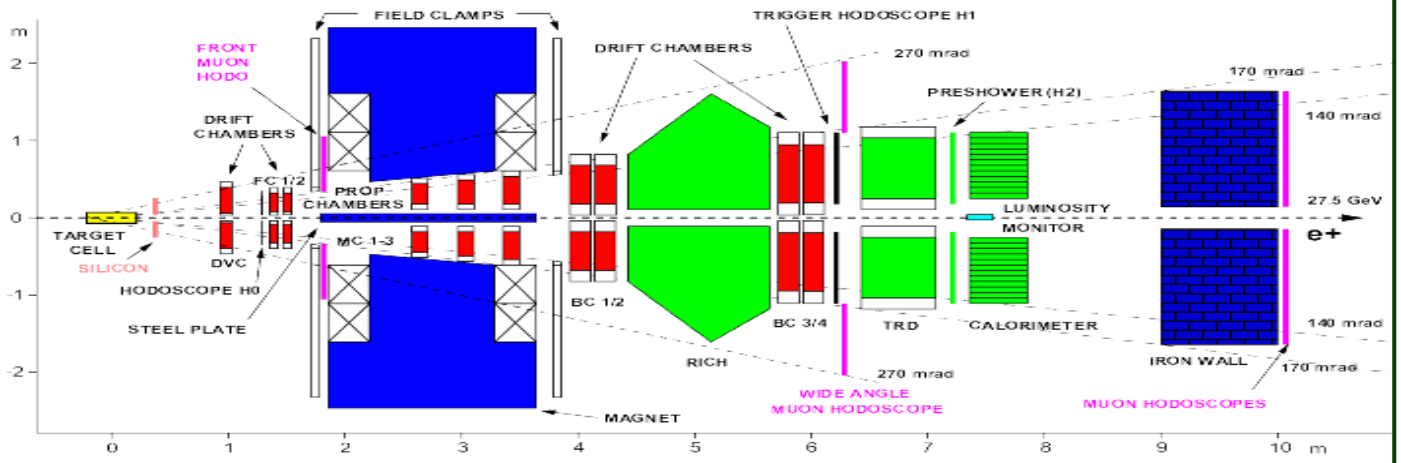


hermes

Data taking: 95-07

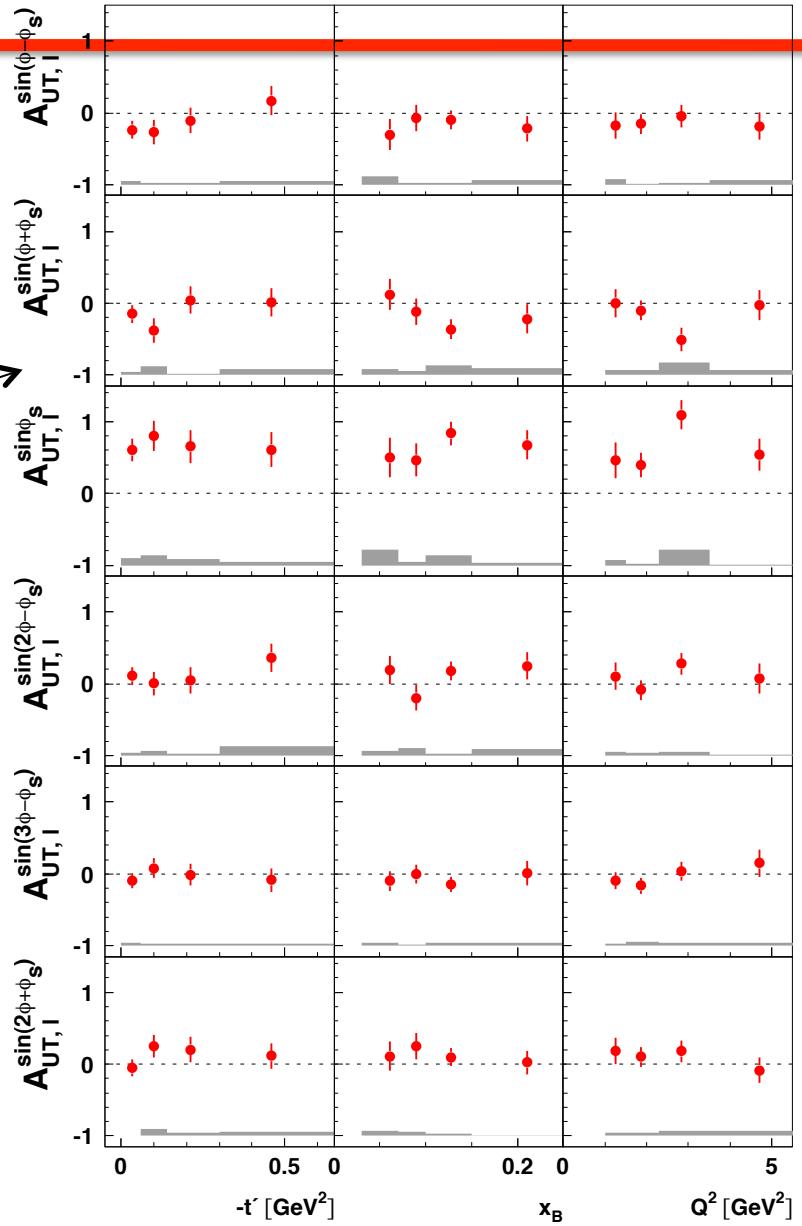
Internal gaseous target
(no nuclear effects)

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

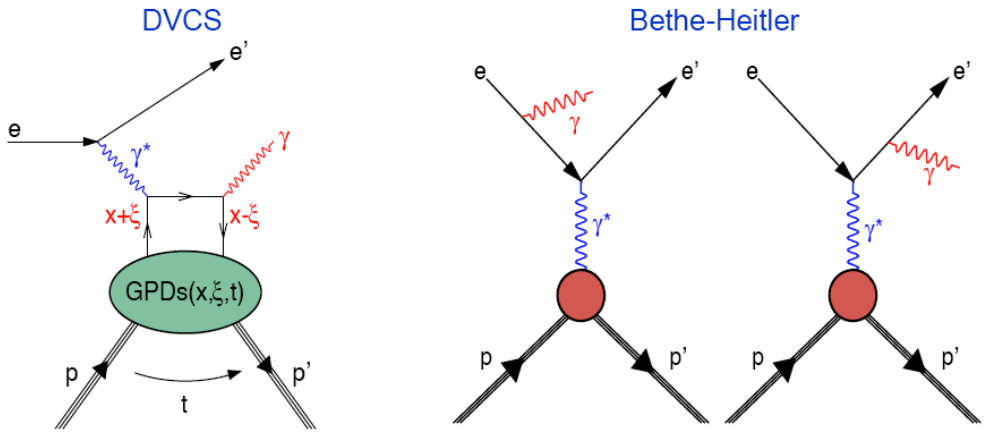


Deeply virtual Compton scattering

Theoretically cleanest way to access GPDs

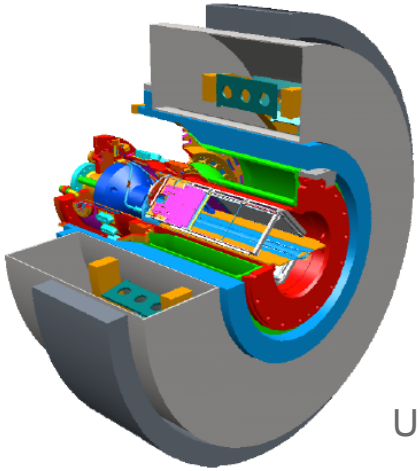
@ HERMES:

Large BH amplitude enhances DVCS signal via interference



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

Recoil detector to tag exclusivity



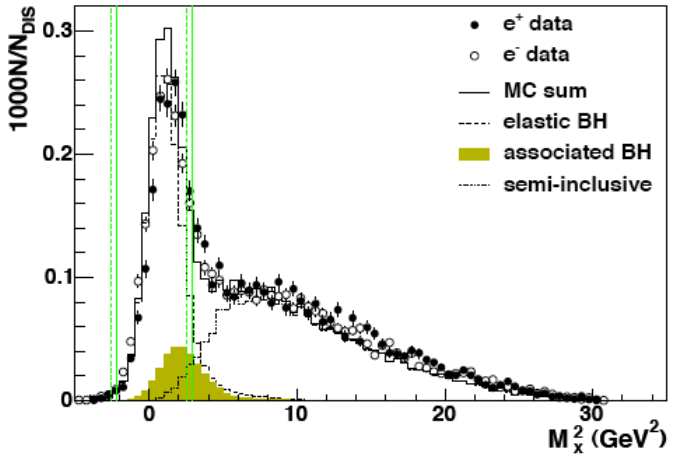
1T SC Solenoid

Photon Detector

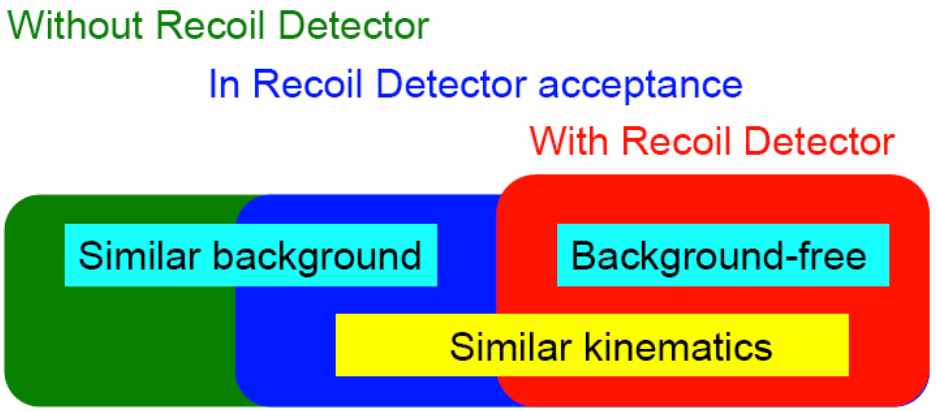
Scintillating Fiber Tracker

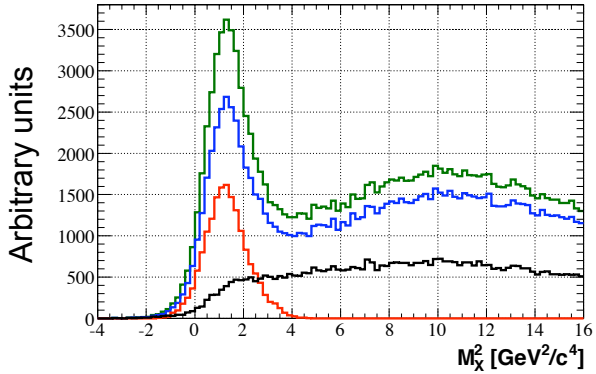
Silicon Strip Detector

Unpolarized H and D targets

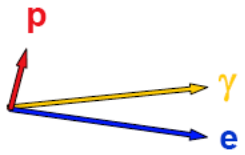


The recoil detector

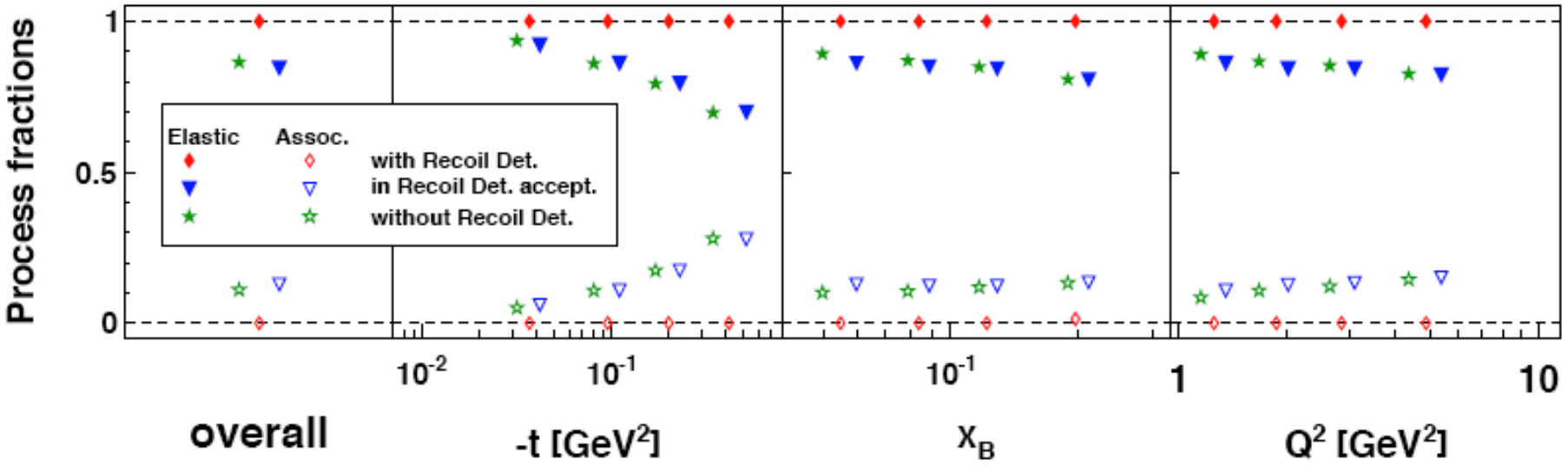




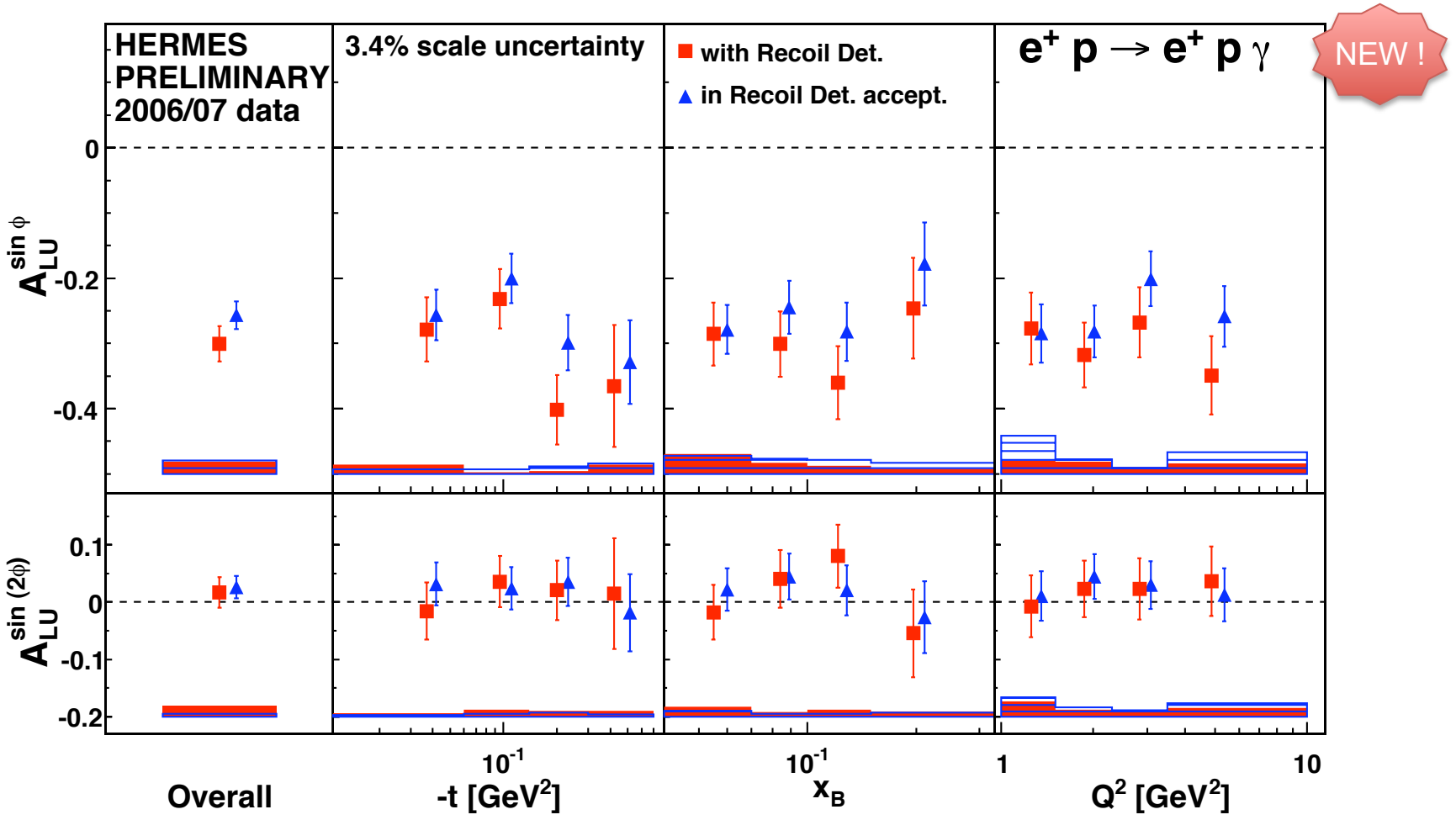
Kinematic event fitting technique: all 3 particles in the final state detected should satisfy 4-constraints on energy-momentum conservation



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



Pure elastic DVCS

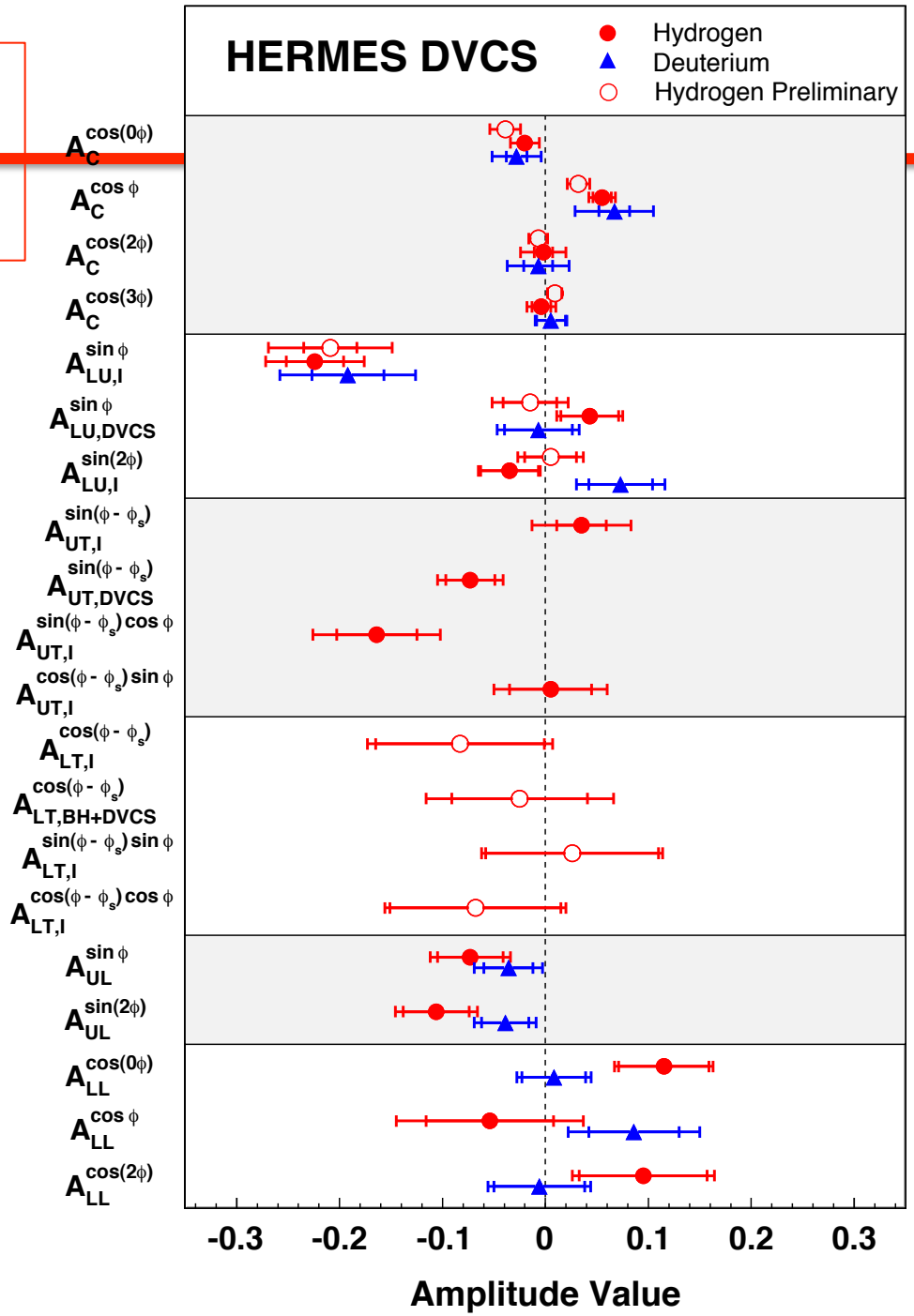


Within the present level of precision, the signal is stable with respect background subtraction

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

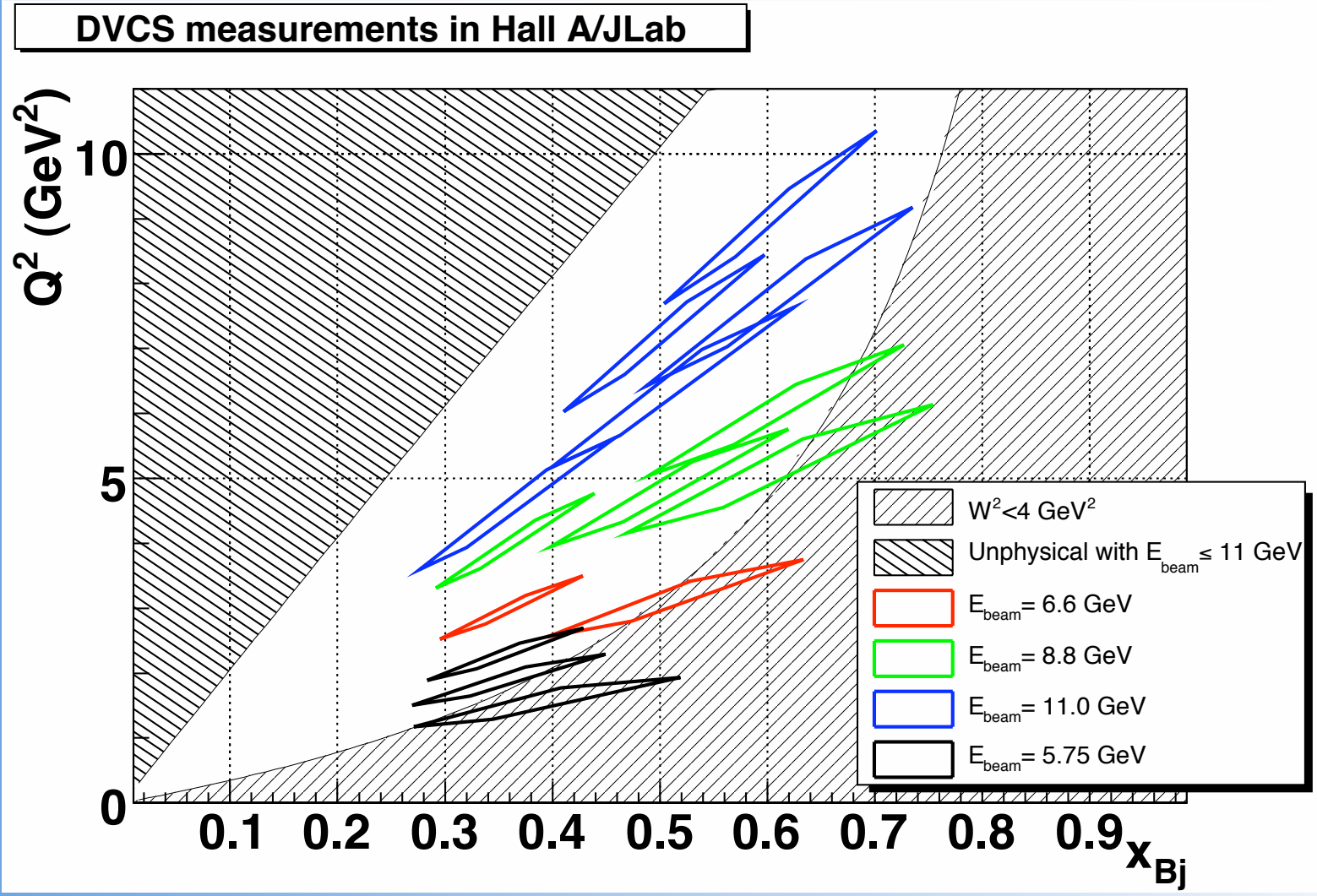
Transverse target Single Spin

Beam & Transverse Target Double Spin

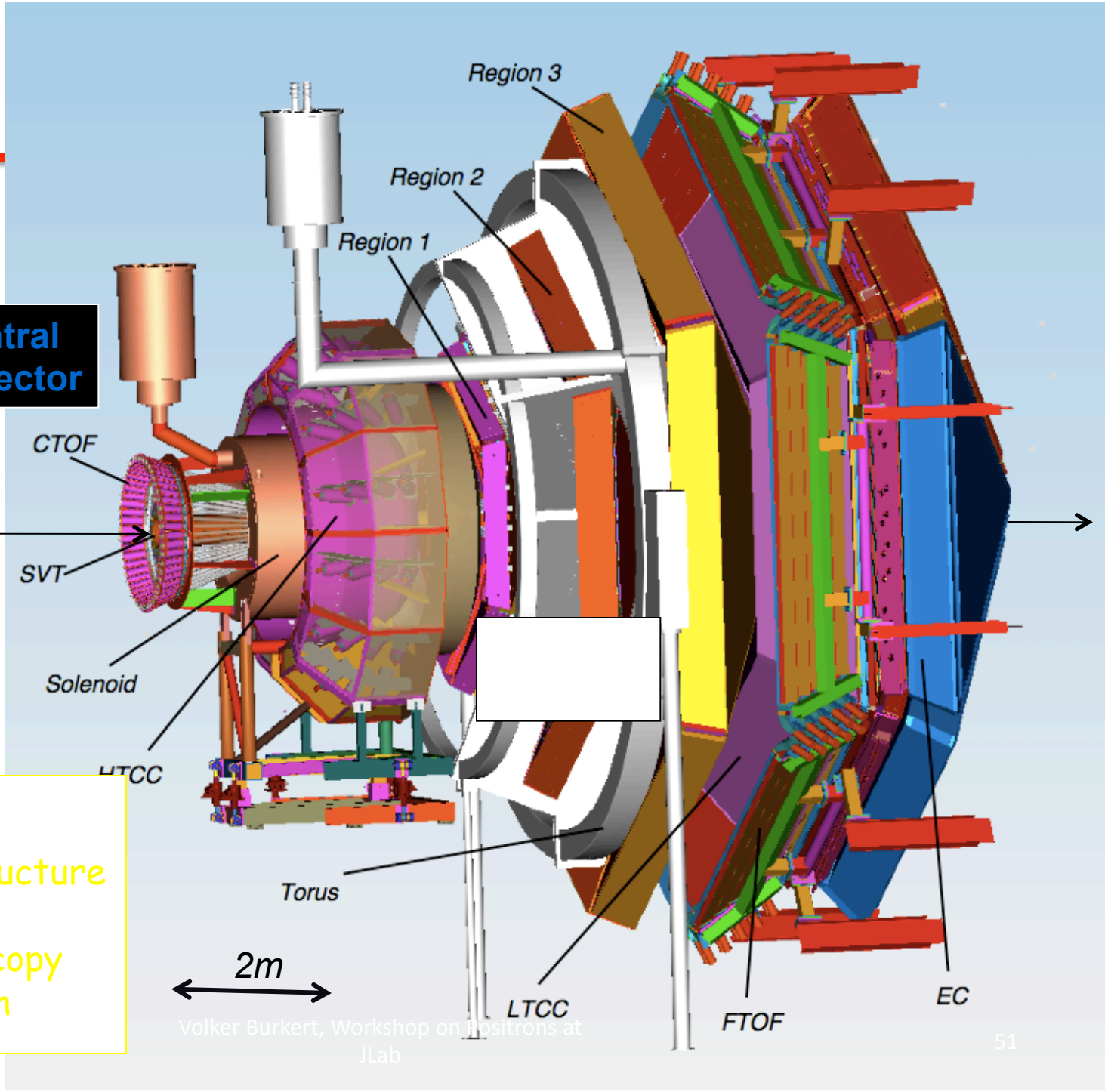
Longitudinal Target

DVCS at 12 GeV in Hall A: 100 days HRS ×PbF_2

All equipment in-hand.
Ready for beam !



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.

COMPASS 2014+ DVCS & DVES

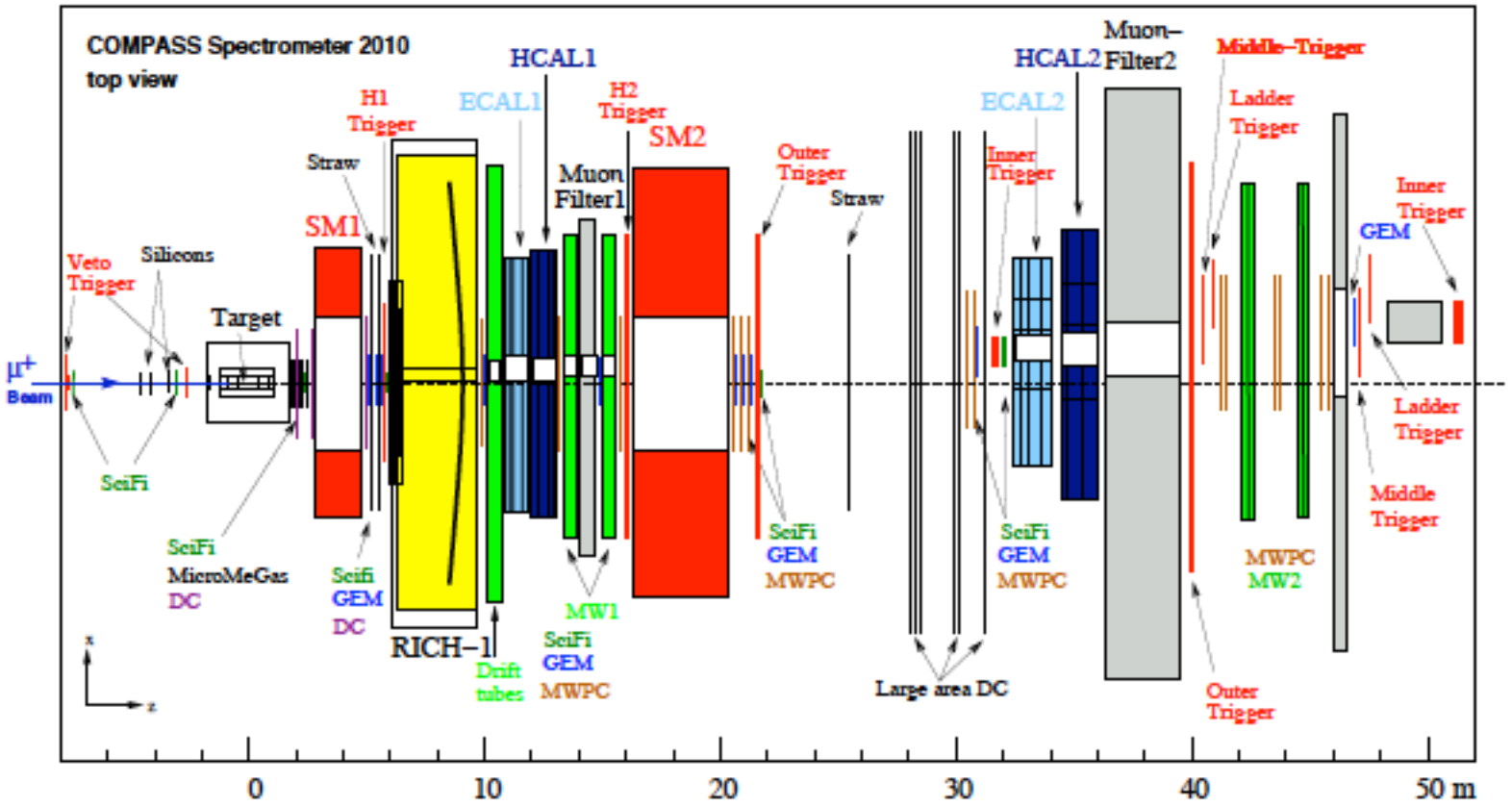
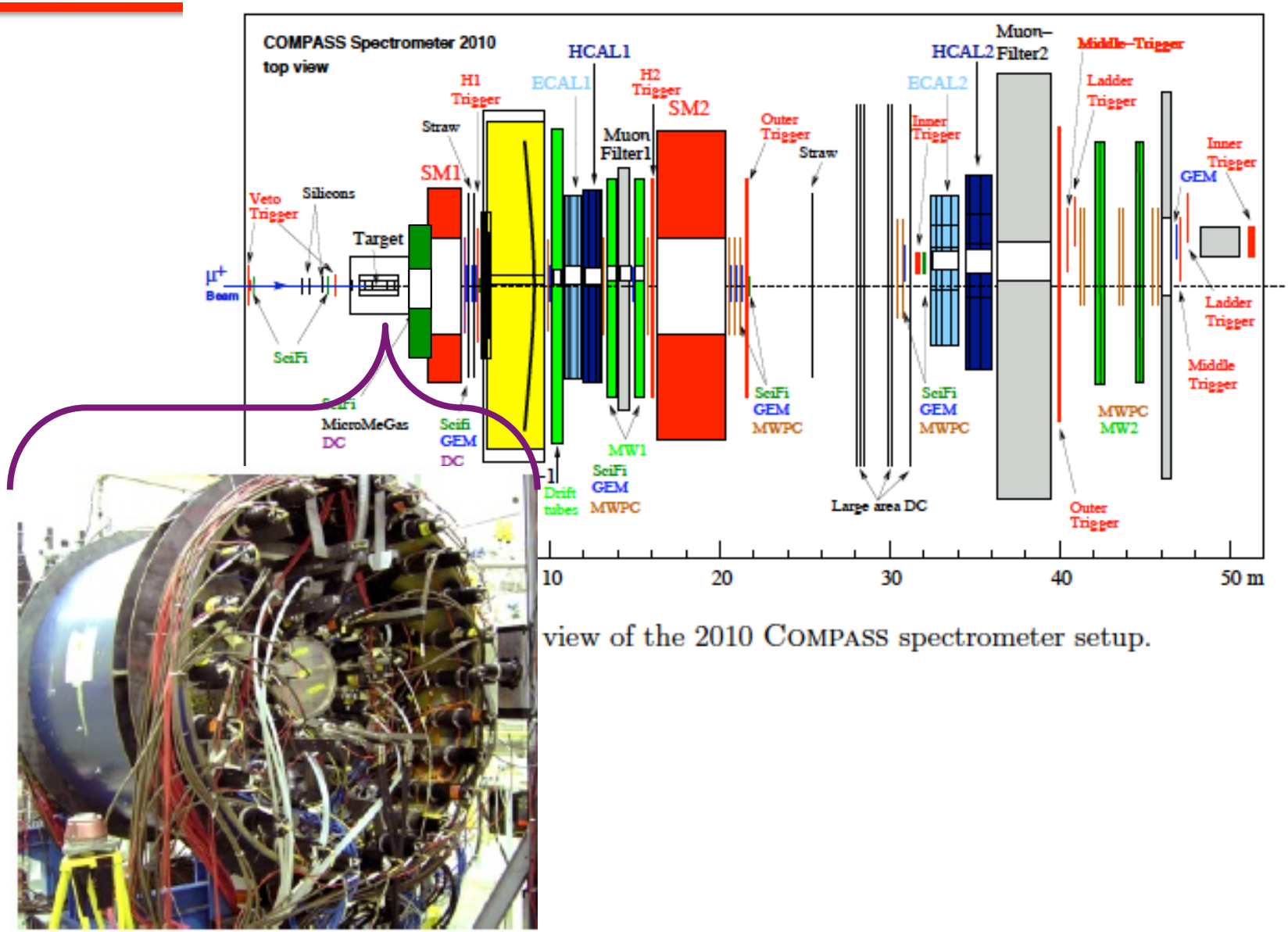


Figure 50: Top view of the 2010 COMPASS spectrometer setup.

COMPASS Recoil Proton Detector + ECAL0



view of the 2010 COMPASS spectrometer setup.

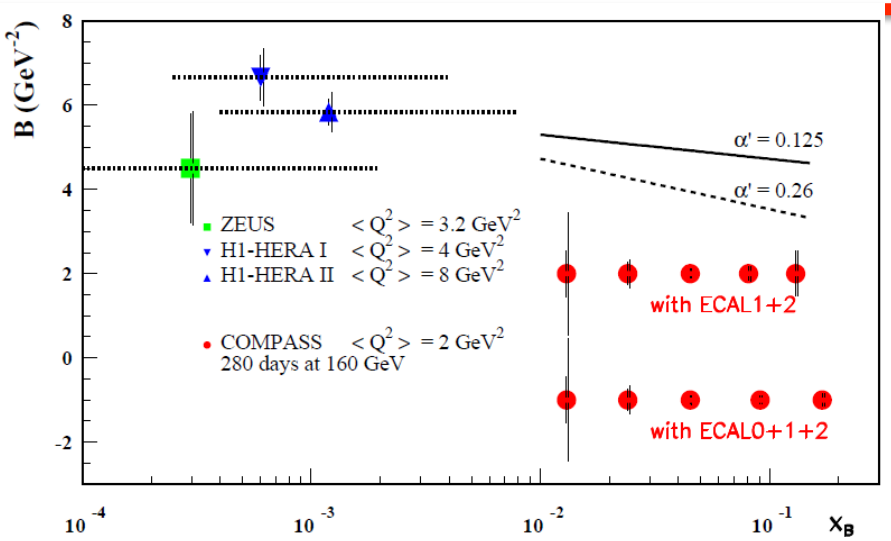
COMPASS DVCS Projections

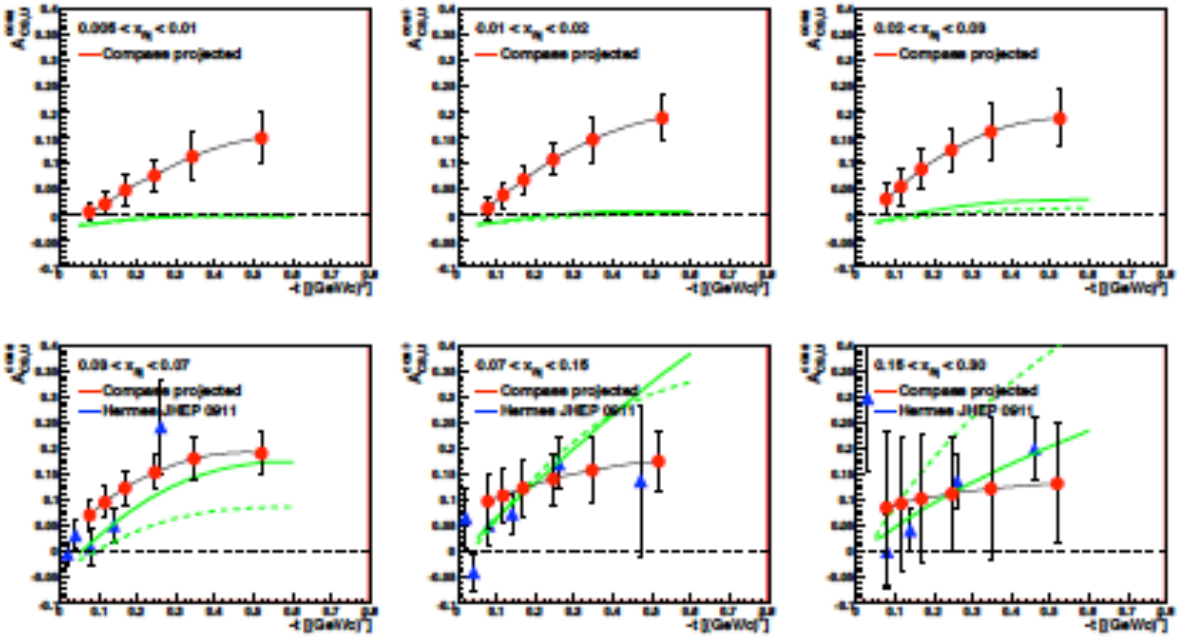
- 160 GeV

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

- Spin×Charge averaged

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





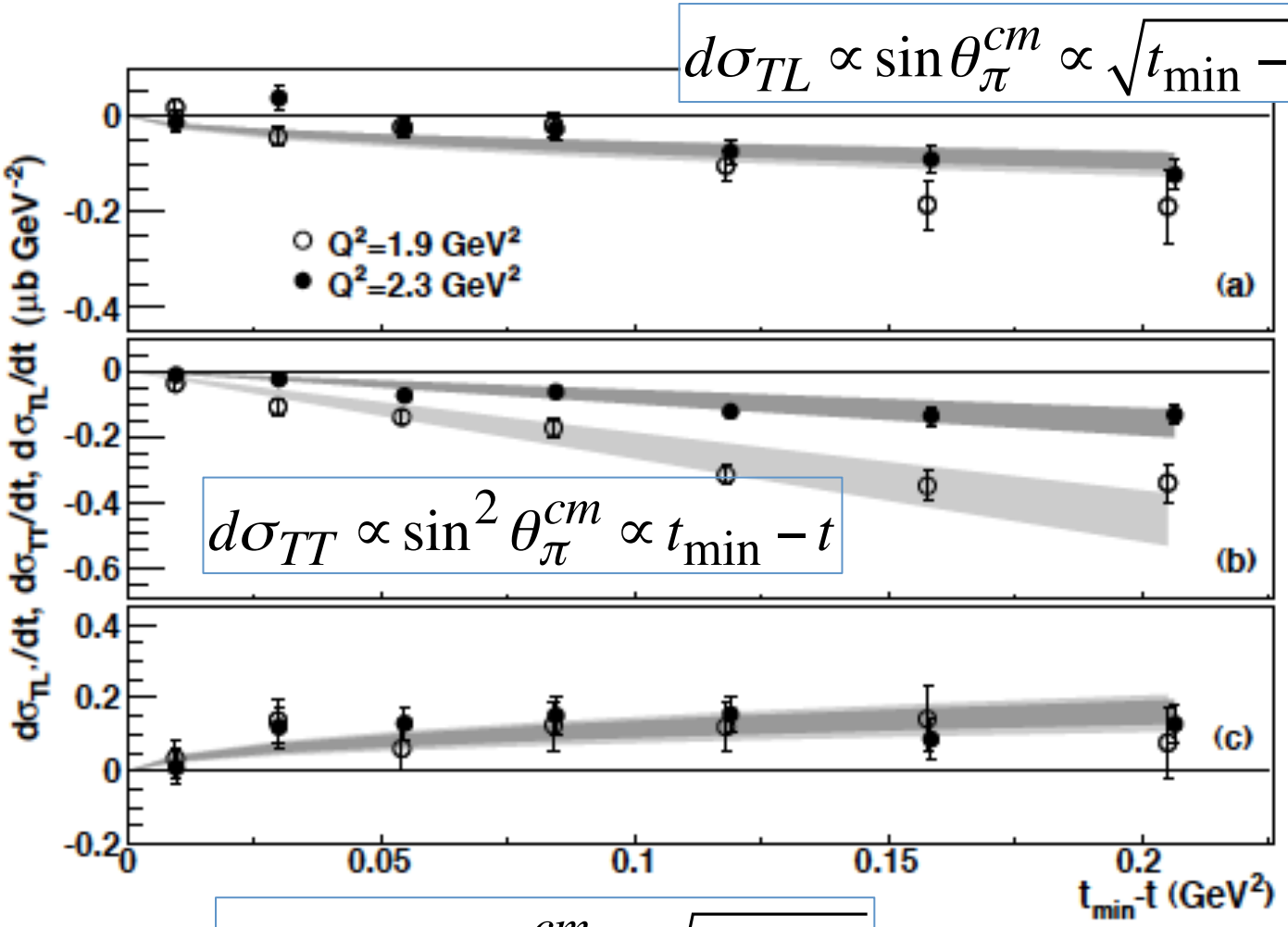
- Spin×Charge difference

$$\Delta\sigma \approx$$

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

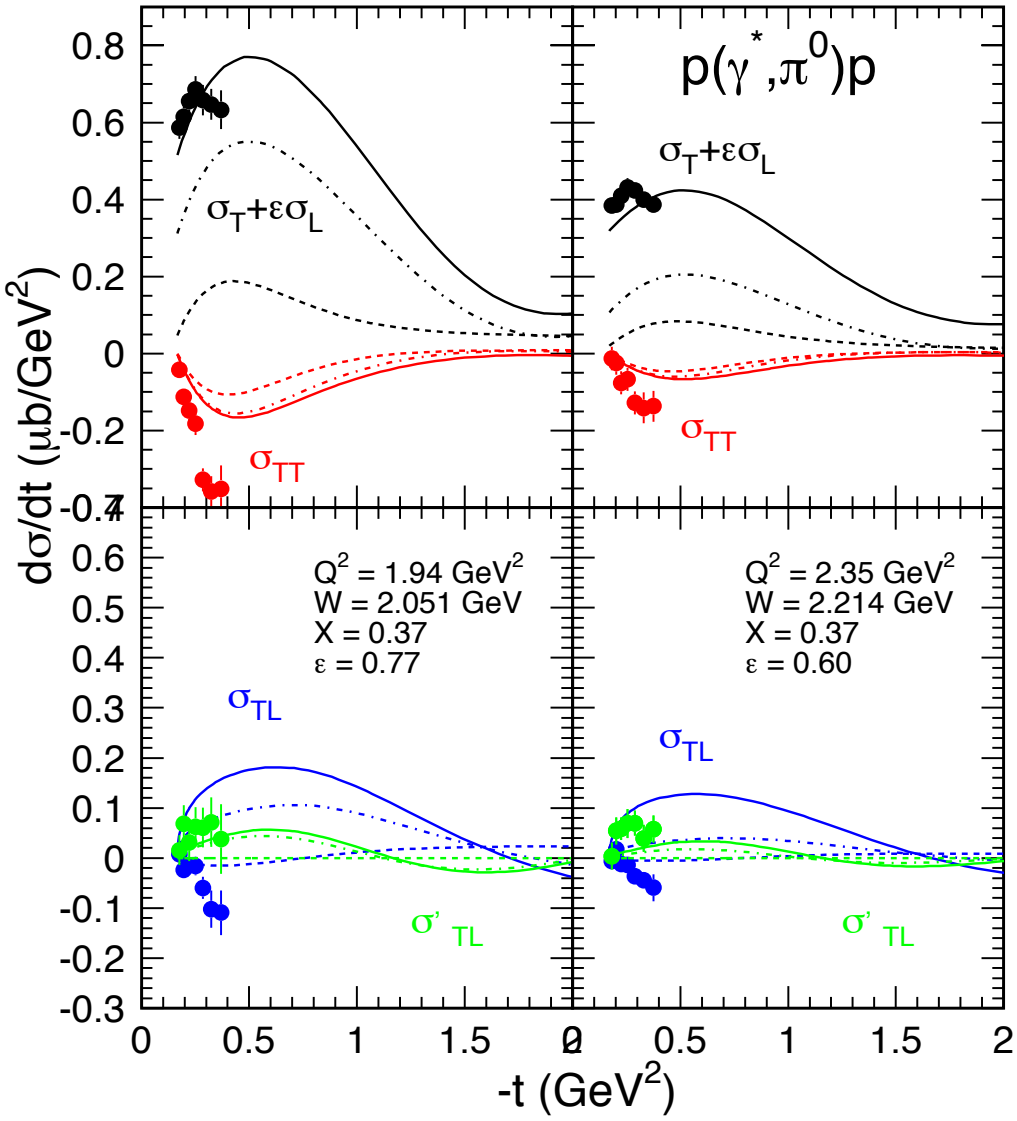
Separated Cross Sections

- Bands are fits:
  - $\sin\theta_\pi$
  - $\sin 2\theta_\pi$
  - $\sin\theta_\pi$



Regge inspired model of J.-M. Laget

- Magnitude ~OK
- σ_{TT} too small
- Wrong sign to σ_{TL}



Generalized Parton Distributions

- Non-Local, Off-Diagonal one-body quark and gluon currents of the Nucleon
  - Non-Local operators are common in Q.M.
    - Hartree-Fock Exchange potential
    - Momentum **p** is a zero-range non-local operator.
- Remove a parton of momentum fraction $x+\xi$ at impact parameter b