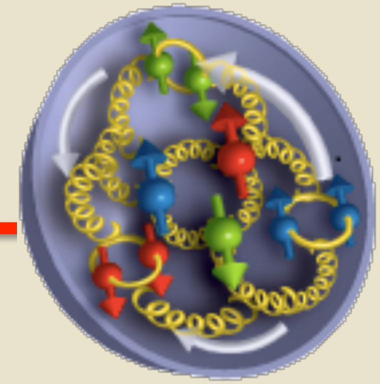


Experimental Study of Generalized Parton Distributions at Jefferson Lab

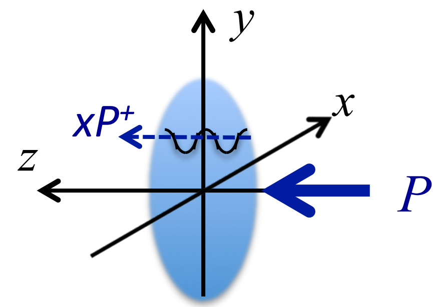
Charles E. Hyde
Old Dominion University
Norfolk VA

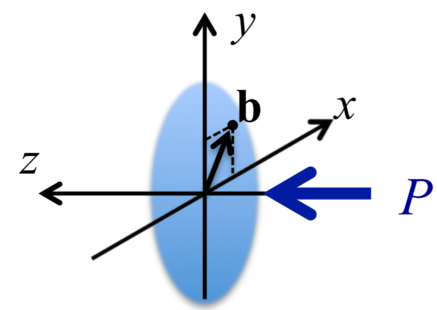
C. Hyde, M. Guidal, A. Radyushkin,
J. Phys. Conf. Ser. 299:012006, 2011,
arXiv:1101.2482

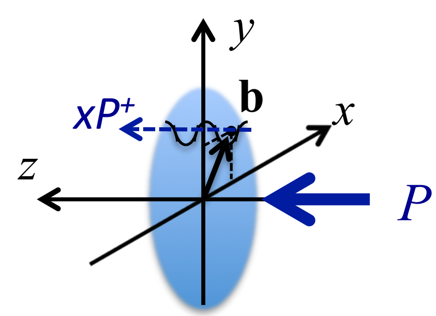
Partonic Structure of the Nucleon

Studying matter as it is illuminated by a light-front

- DIS: H*(e,e')X*
  - Longitudinal (light-cone) Momentum distributions
- Elastic Electro-Weak Form Factors: H*(e,e')p*
  - Fourier Transform of spatial impact-parameter distributions
  - 2-D formalism fully compatible with Q.M. and Relativity
- Generalized Parton Distributions Deeply Virtual Exclusive Scattering
  - $eN \rightarrow eN\gamma$, $eN \rightarrow eN(\pi, \rho, \phi)$, etc
  - Correlations of longitudinal momentum fraction with transverse spatial position

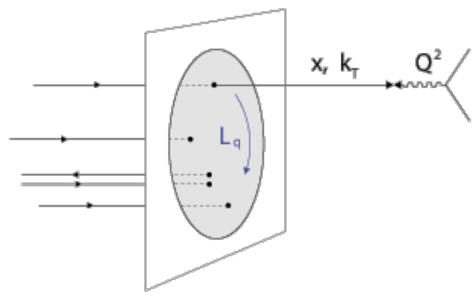


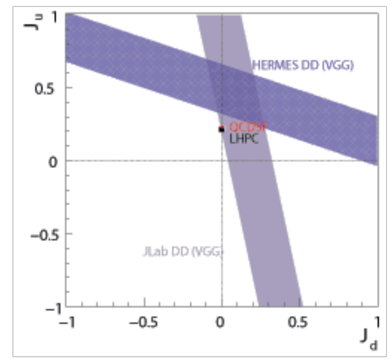




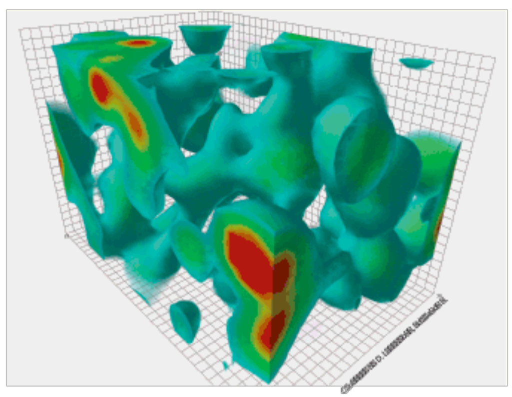
Spatial Structure and Spatial Correlations

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

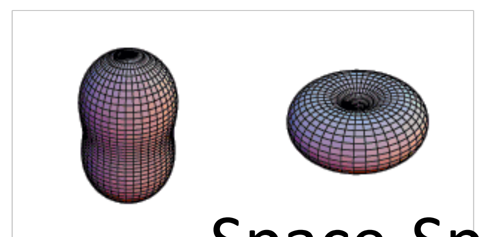




Angular Momentum



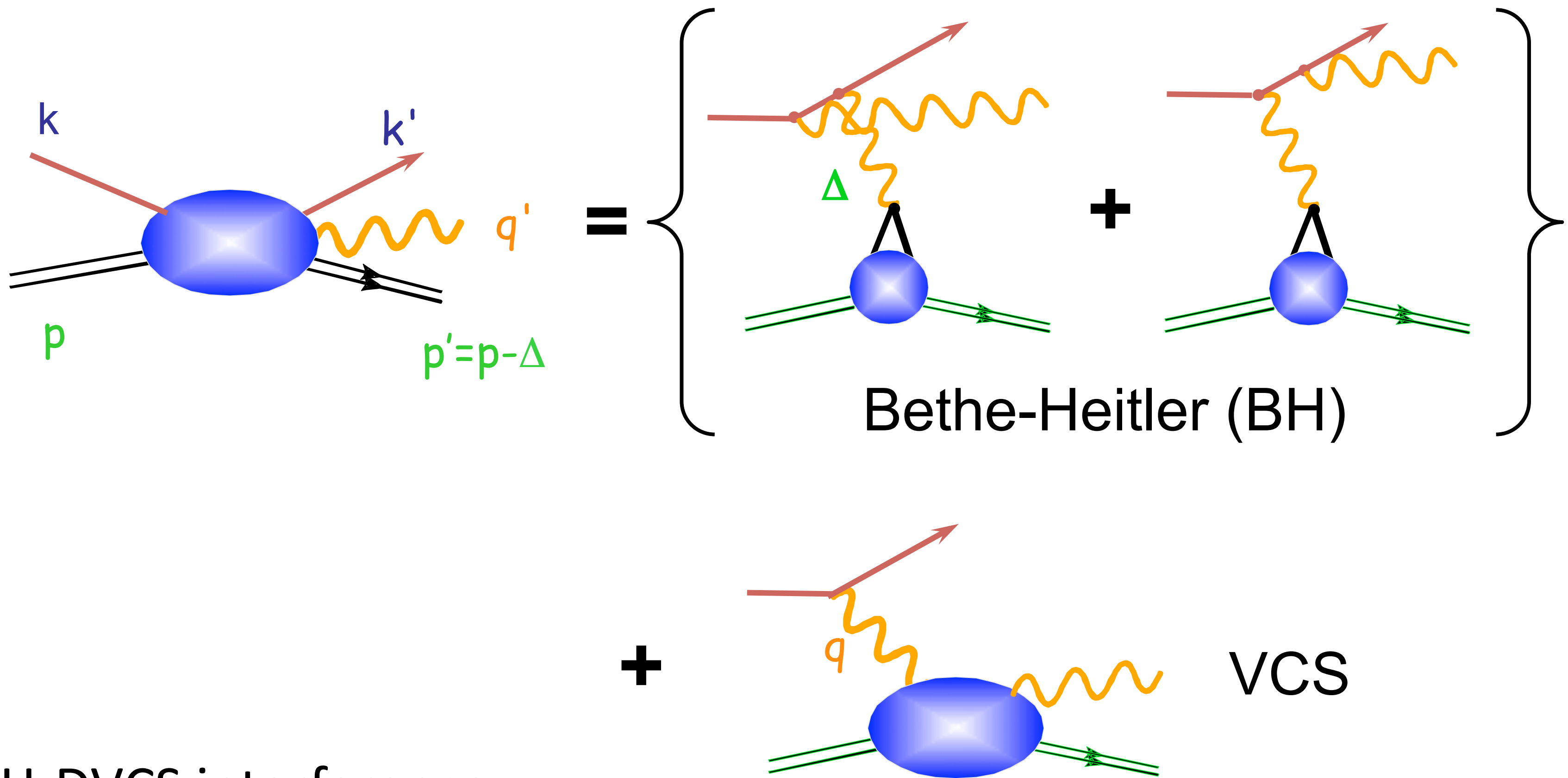
Spatial Correlations in the Vacuum



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

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

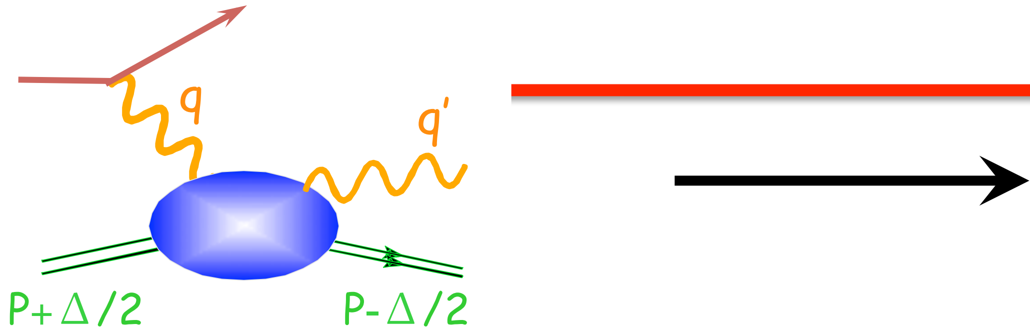
$e\,p \rightarrow e\,p\,\gamma$

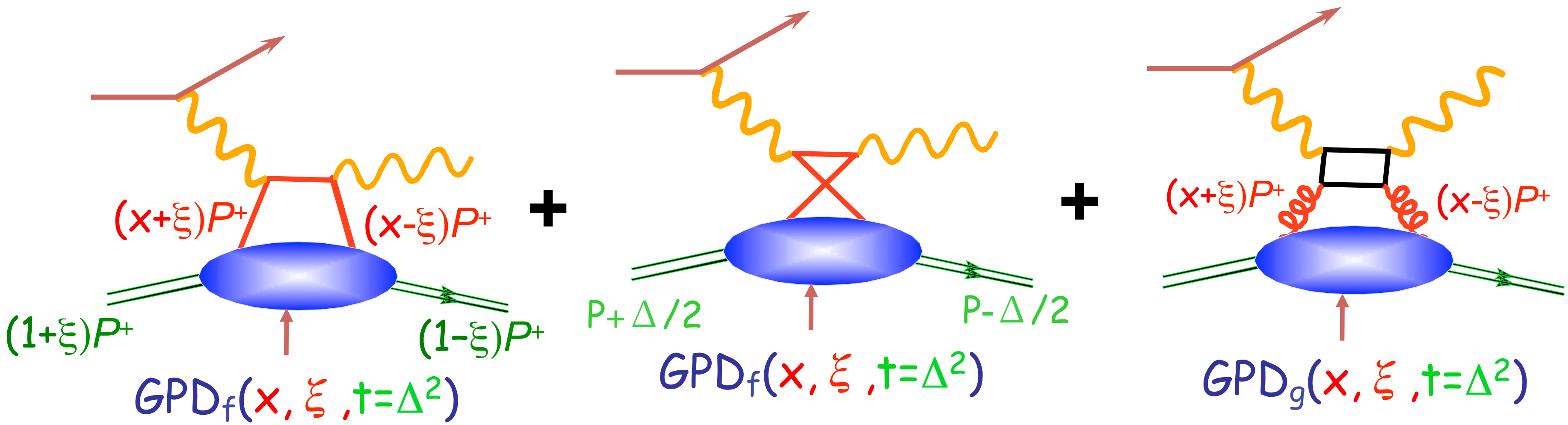


- BH-DVCS interference
  - Access to DVCS amplitude, linear in GPDs

QCD Factorization of DVCS (Co-Linear)

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



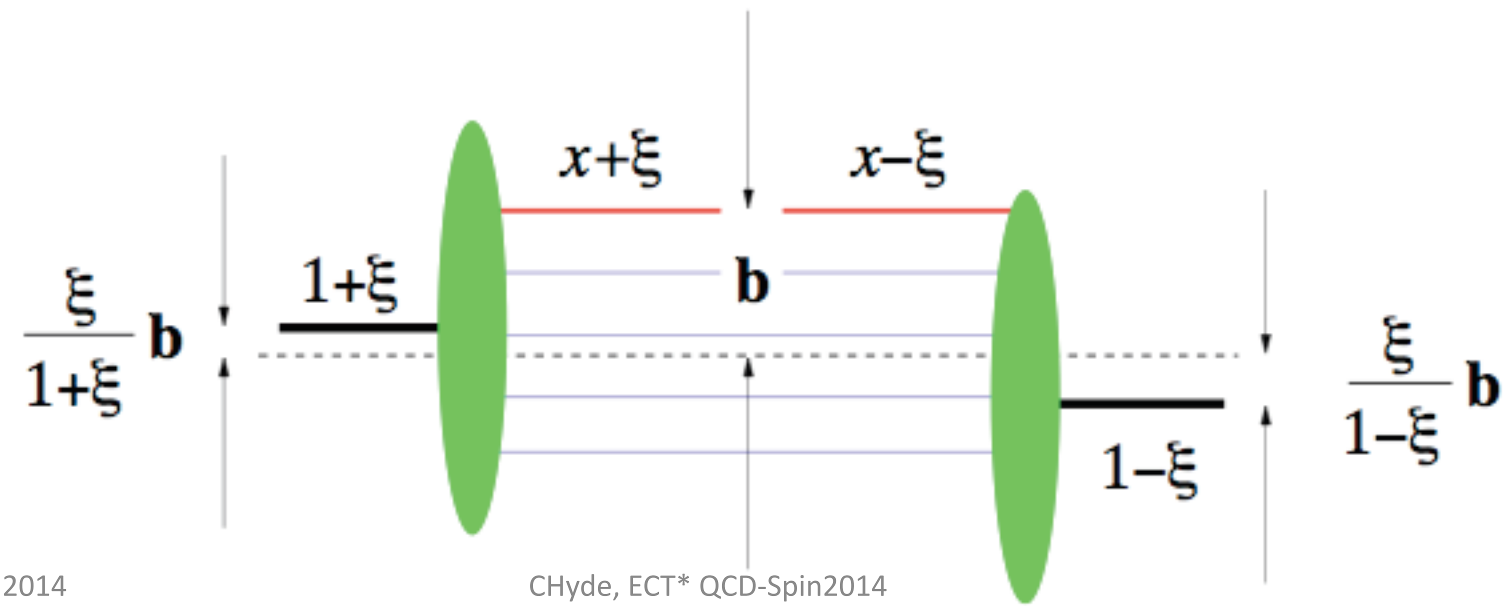


- Symmetrized Bjorken variable: $\xi = \frac{-(q+q')^2}{2(q+q')\cdot P} \xrightarrow[\Delta^2 << Q^2]{} \frac{x_B}{2-x_B}$
- SCHC
  - Transversely polarized virtual photons dominate to $O(1/Q)$

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

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

$$\Delta_\perp^{\,2} = -(1-\xi)^2\Delta^2 - 4\xi^2 M^2$$



Physical Interpretation of GPDs: Two Limits

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

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

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

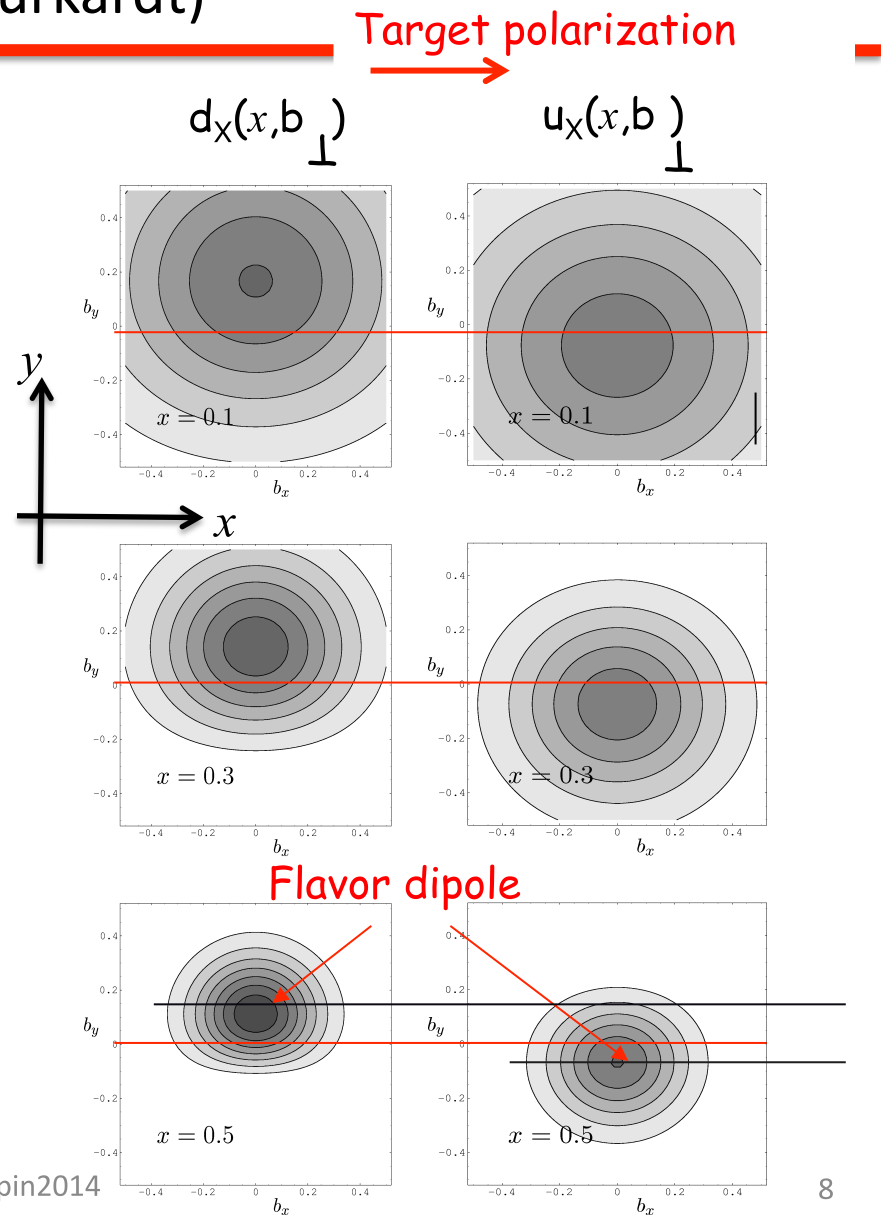
- x=ξ: $H(\xi, \xi, \Delta^2)+H(-\xi,\xi,\Delta^2)$, *E, etcetera*
  - 2-d Fourier-transform $\Delta_\perp$ ←→ **r**
  - Transition amplitude from longitudinal momentum 0 to $2\xi/(1+\xi)$ at fixed impact parameter **r** relative to CM of *spectators*.
    - Not a positive definite density, but still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

Tomography with Generalized Parton Distributions (M. Burkardt)

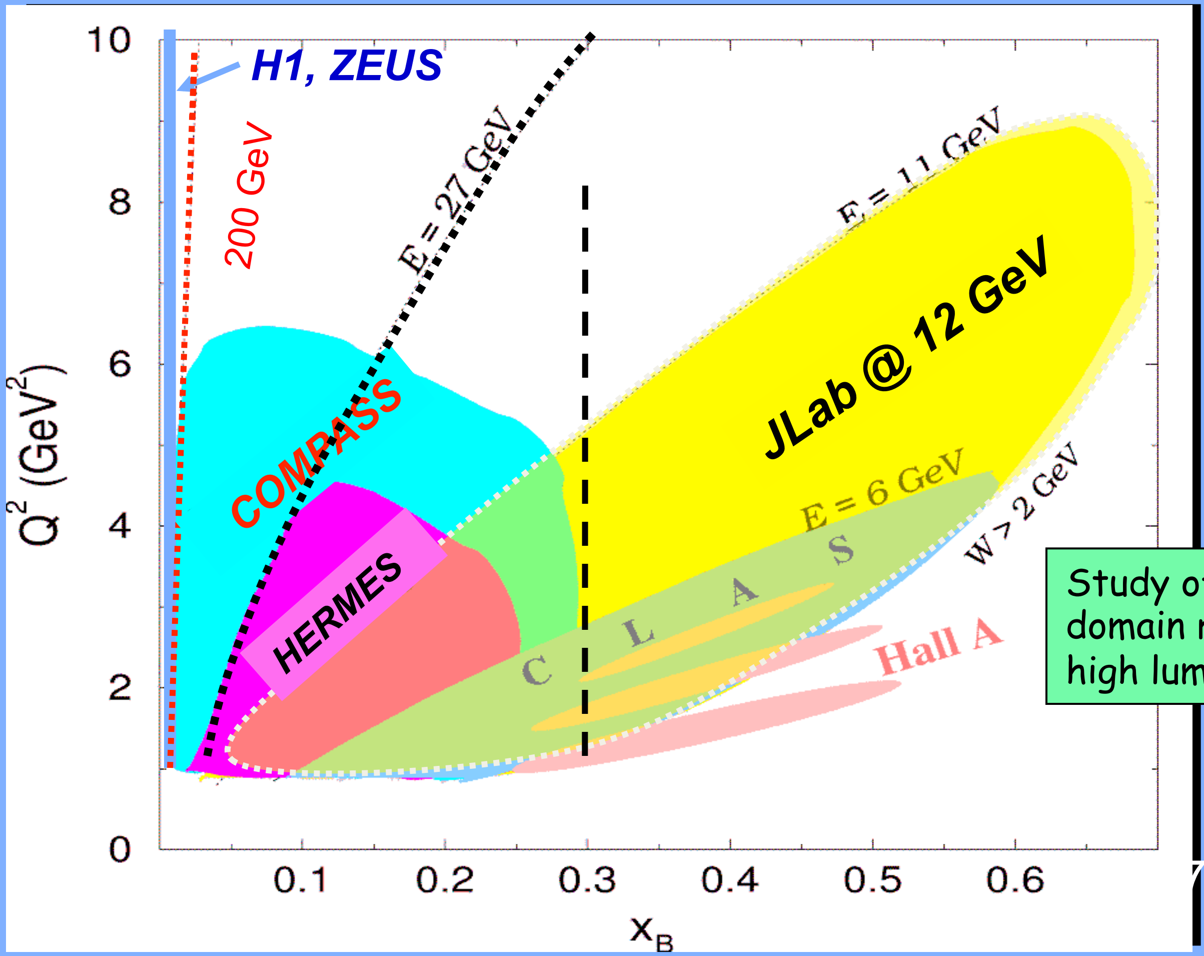
- $H(x,t)\gamma^{\mu} + E(x,t)\sigma^{\mu\nu}\Delta_{\nu}$
  - Proton size shrinks as x→ 1.
  - Spatial separation of up- and down-quarks in a transversely polarized proton
- Spin-Flavor dependence to Proton size & profile.
  - M. Burkardt
  - up and down quarks separate in transversely polarized proton

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

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



Deeply Virtual Exclusive Processes - Kinematic Coverage



Study of high x_B domain requires high luminosity

What do DVCS experiments measure?

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

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

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

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

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

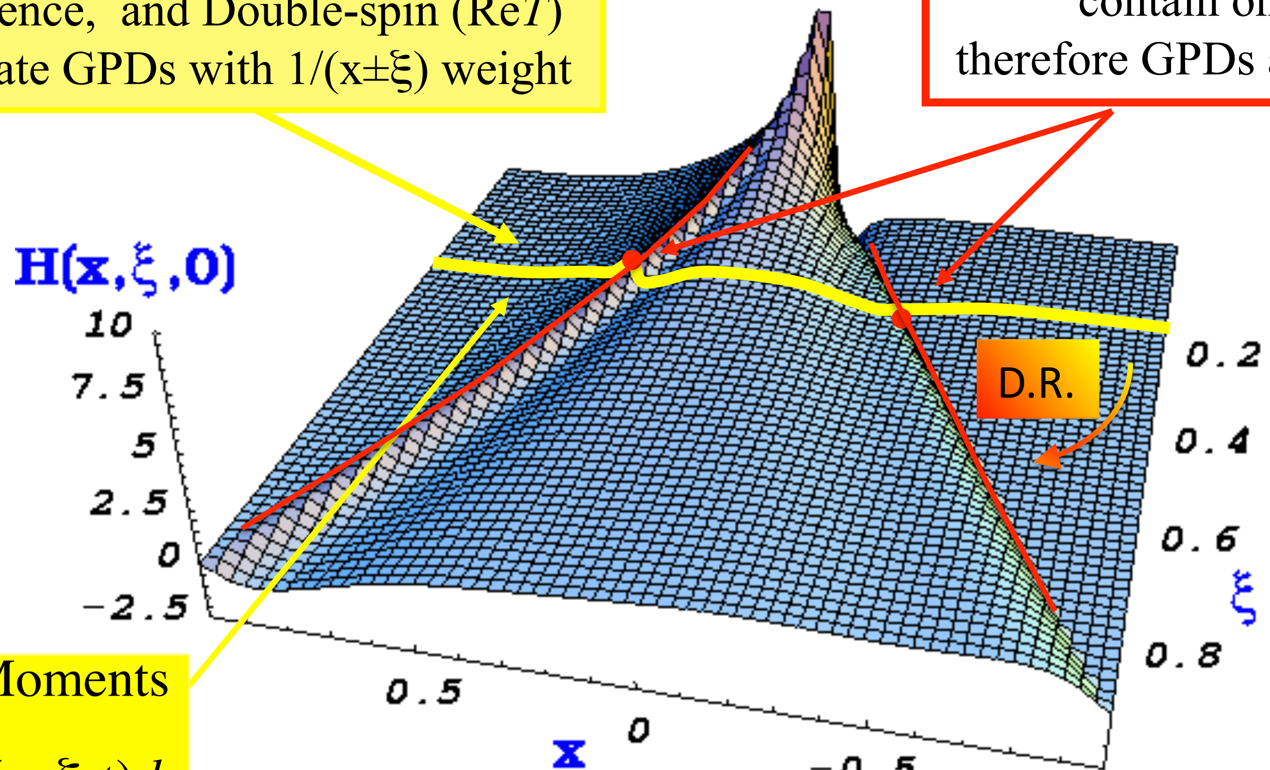
DVCS, GPDs, Compton Form Factors(CFF), and Lattice QCD

(at leading order:)

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

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

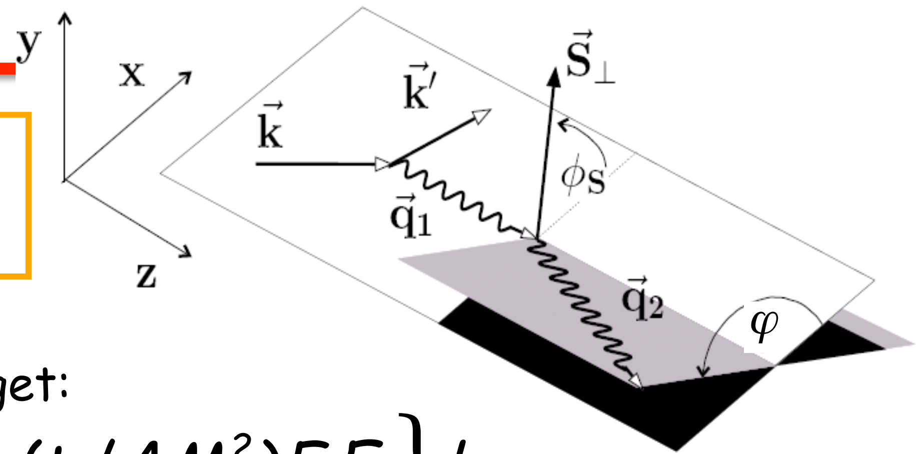
Beam or target spin Δσ contain only ImT, therefore GPDs at $x = \xi$ and $-\xi$



Lattice Moments

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

Exploiting the harmonic structure of DVCS with polarization



The spin-dependence of cross-sections are key observables to extract GPDs

With polarized beam and unpolarized target:

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

With unpolarized beam and Long. polarized target:

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

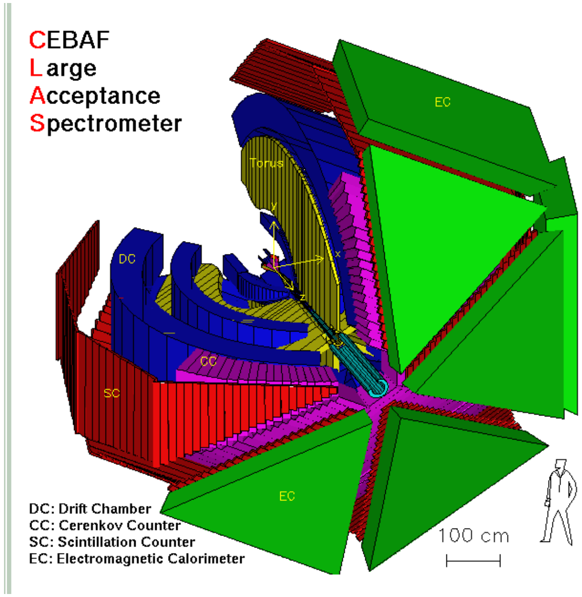
With unpolarized beam and Transversely polarized target:

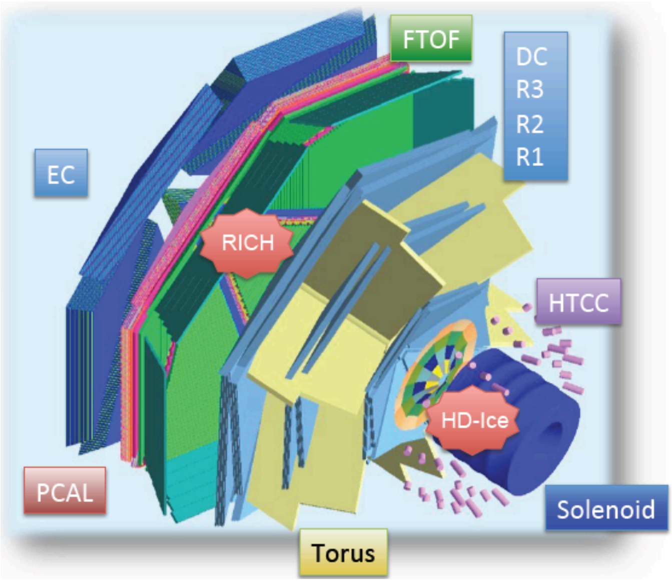
$$\Delta\sigma_{UT} \sim \cos\varphi \sin(\phi_S - \varphi) \left\{ (t/4M^2)F_2 H - (t/4M^2)F_1 E + \ldots \right\} d\varphi$$

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

GPDs at JLab: Hall B

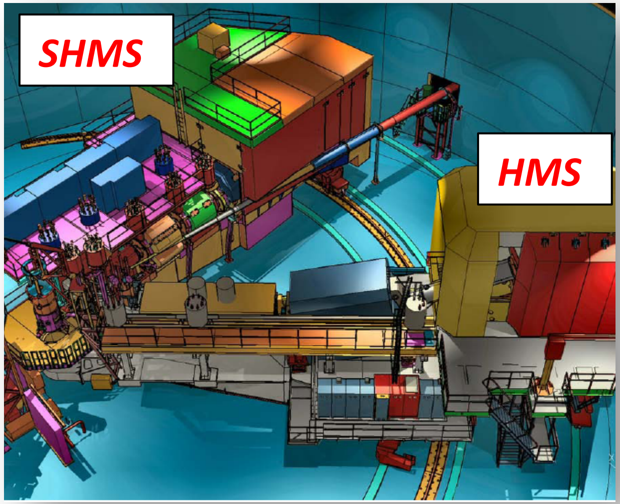
- CLAS, CLAS12
  - Wide kinematic coverage
  - Over-complete exclusivity
  - High multiplicity mesonic final states
    - $\rho \to \pi\pi$, $\omega \to \pi\pi\pi$, $\phi \to KK$
  - Timelike Compton Scattering (TCS)
    - $\gamma\, p \to p\, e^+ e^-$, (Quasi-real Photons)
    - $\gamma\, p \to p\, J/\Psi$
  - Cross section systematic errors 5-10%
  - Longitudinally polarized NH_3, ND_3
  - Transversely polarized HD target in development

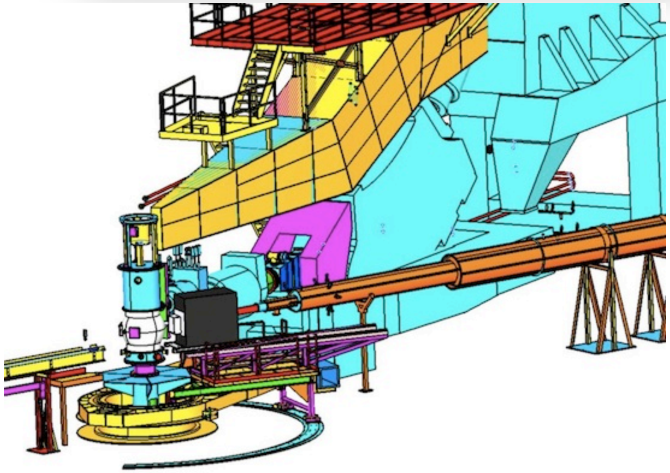




GPDs at JLab: Halls A & C

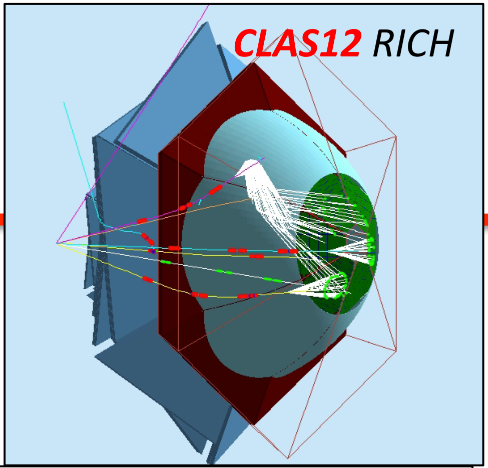
- Hall C: 12 GeV: HMS x SHMS
  - L/T separations:
    H$(e,e'\pi^+)n$, H$(e,e'K^+)\Lambda$
- Halls A & C:
  Spectrometer × Calorimeter
  - DVCS & Exclusive π^0.
  - H$(e,e'\gamma)p$ H$(e,e'\gamma\gamma)p$
    - Exclusivity by missing mass
  - $d\sigma$ systematic errors ≤ 4%
  - Polarized ^{3}He (L & T) possible



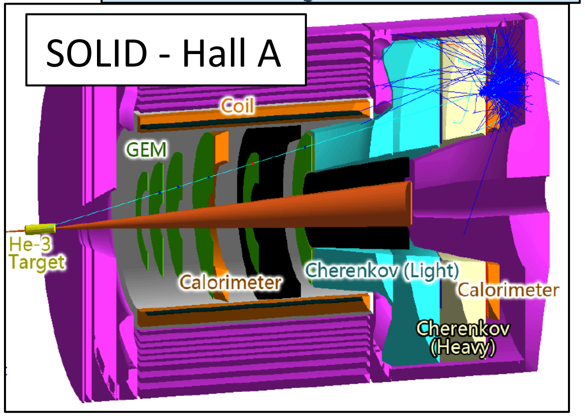


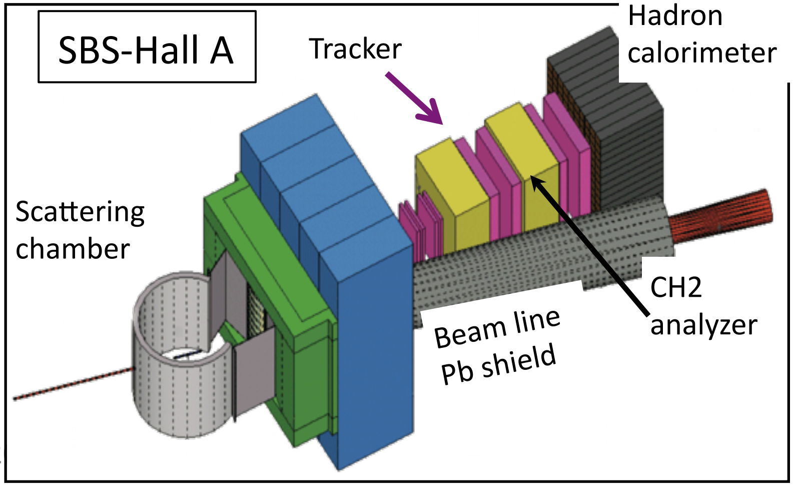
GPDs at JLab: Future Upgrades

(Mostly motivated by non-GPD topics)



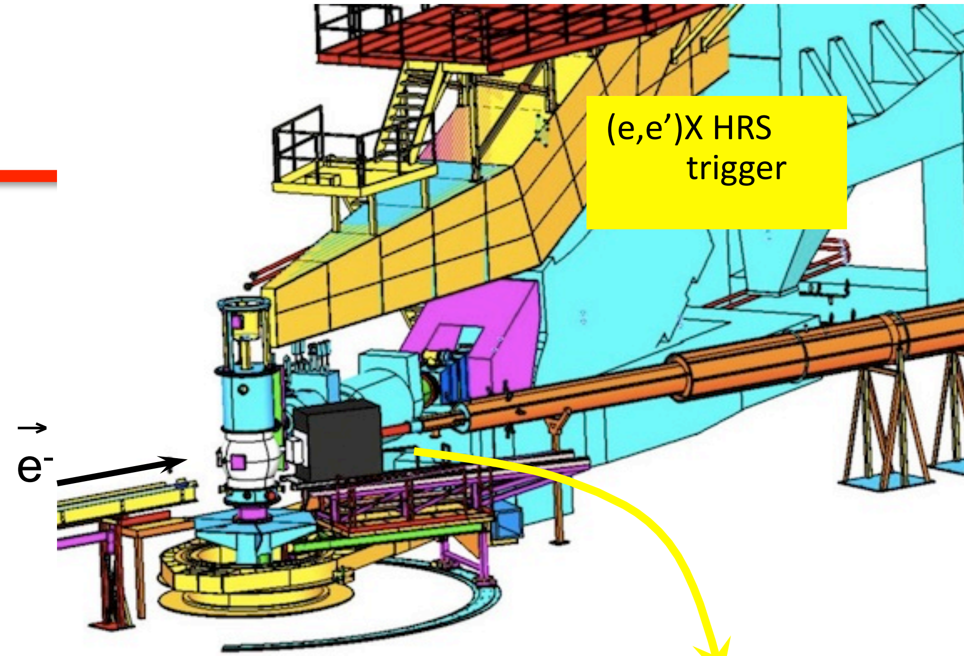
- RICH Detector (partial) in CLAS 12: π/K id
  - INFN participation
- **So**lenoidal **L**arge **I**ntensity **D**etector (SoLID) in Hall A (CLEO Solenoid)
  - TCS, J/Ψ
  - Chinese participation
- **S**uper **B**igBite **S**pectrometer
  - Dipole from BNL
  - Funded, under construction
  - GEM trackers for high rates

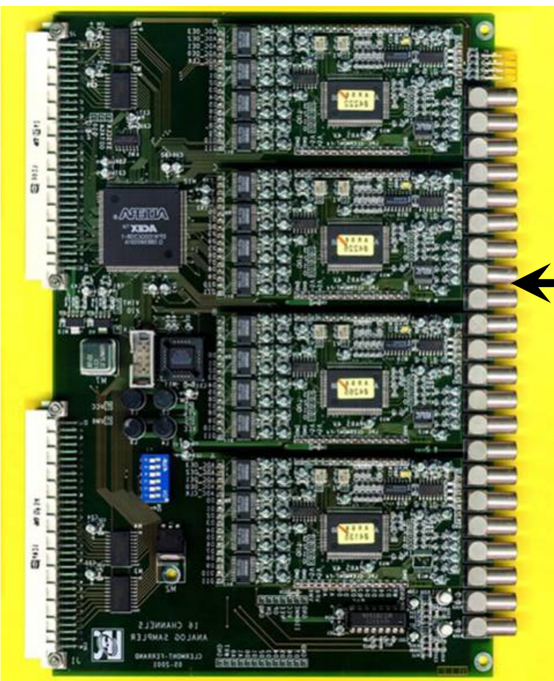




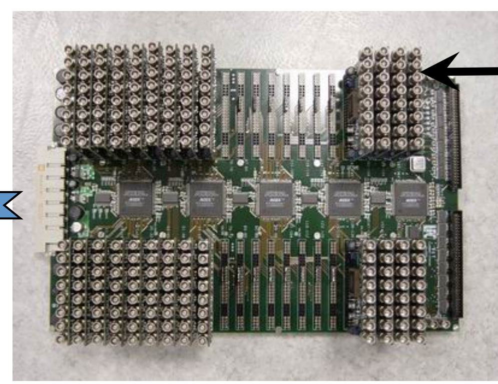
DVCS: JLab Hall A 2004, 2010, 2014-2015

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

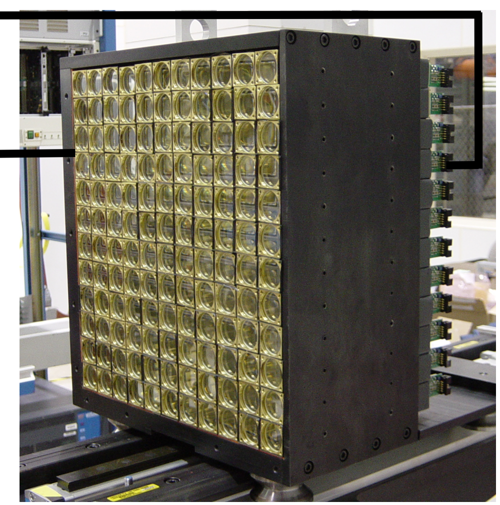




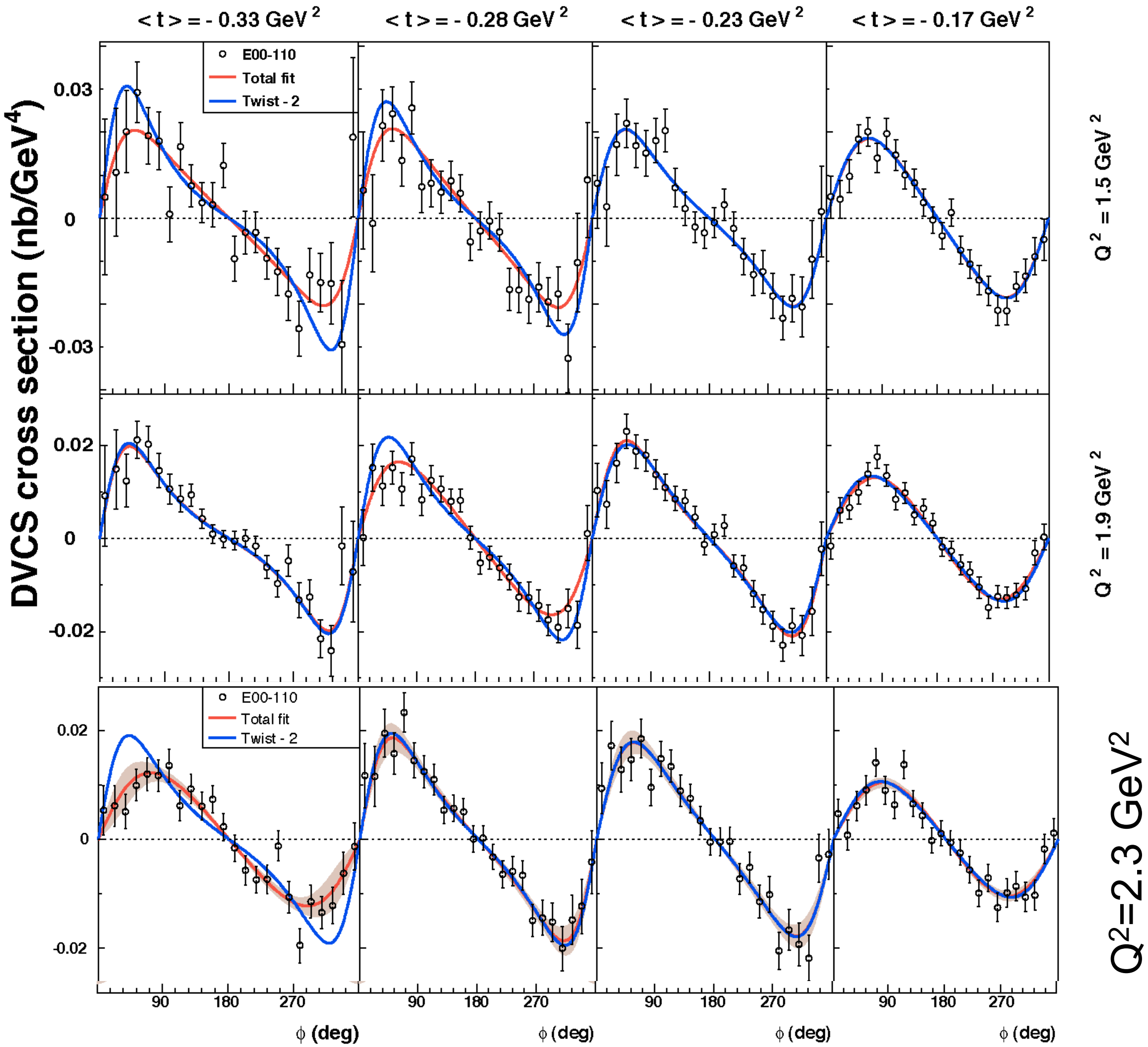
16chan VME6U: ARS
128 samples@1GHz



Digital Trigger Validation



208 PbF_2



Hall A Helicity Dependent Cross Sections E00-110

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

Twist-2(GPD)+…

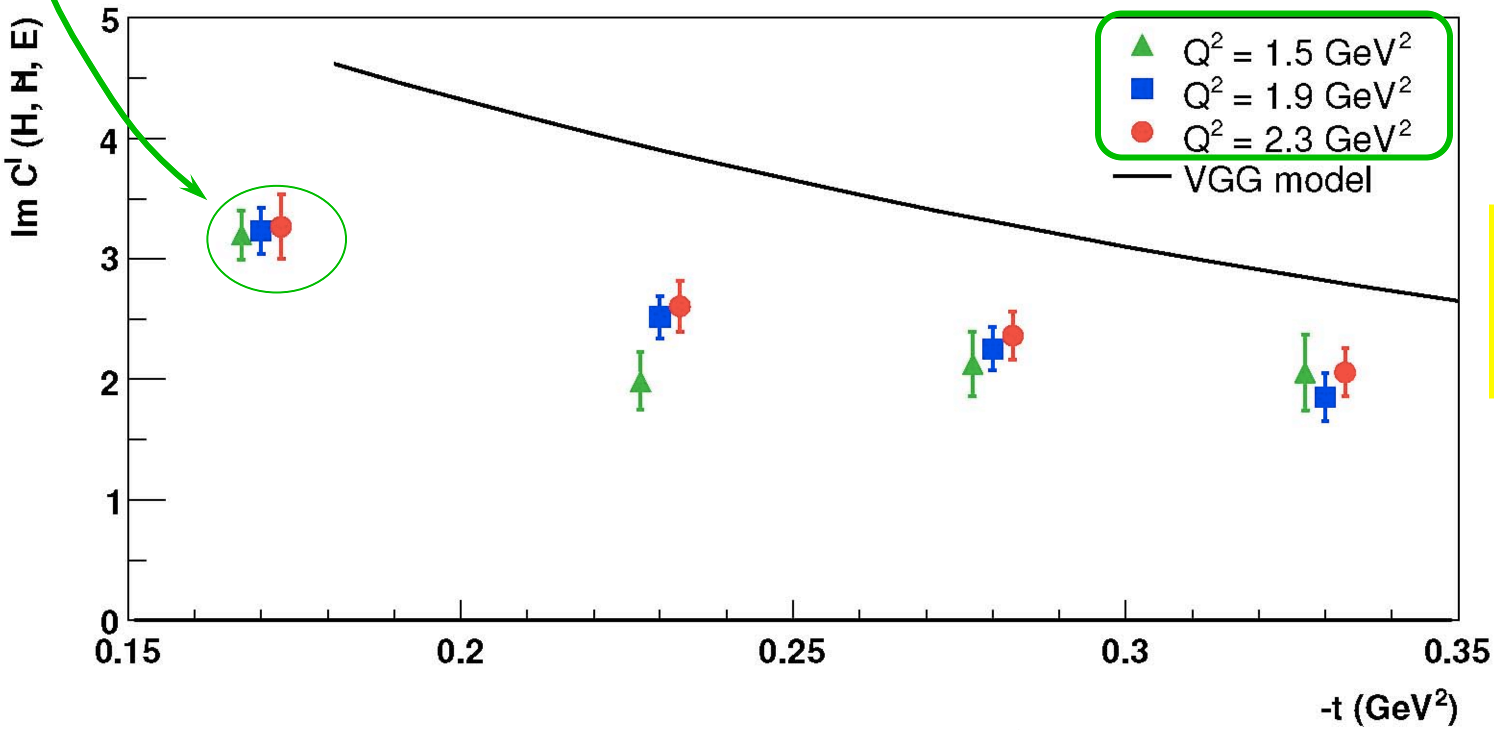
Twist-3(qGq)+…

$\Gamma_{s1,2}$ = 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)

- Q²-independance of Im[DVCS*BH]
  - Twist-2 Dominance (GPD)
  - Model « Vanderhaeghen-Guichon-Guidal (VGG)» accurate to≈30%



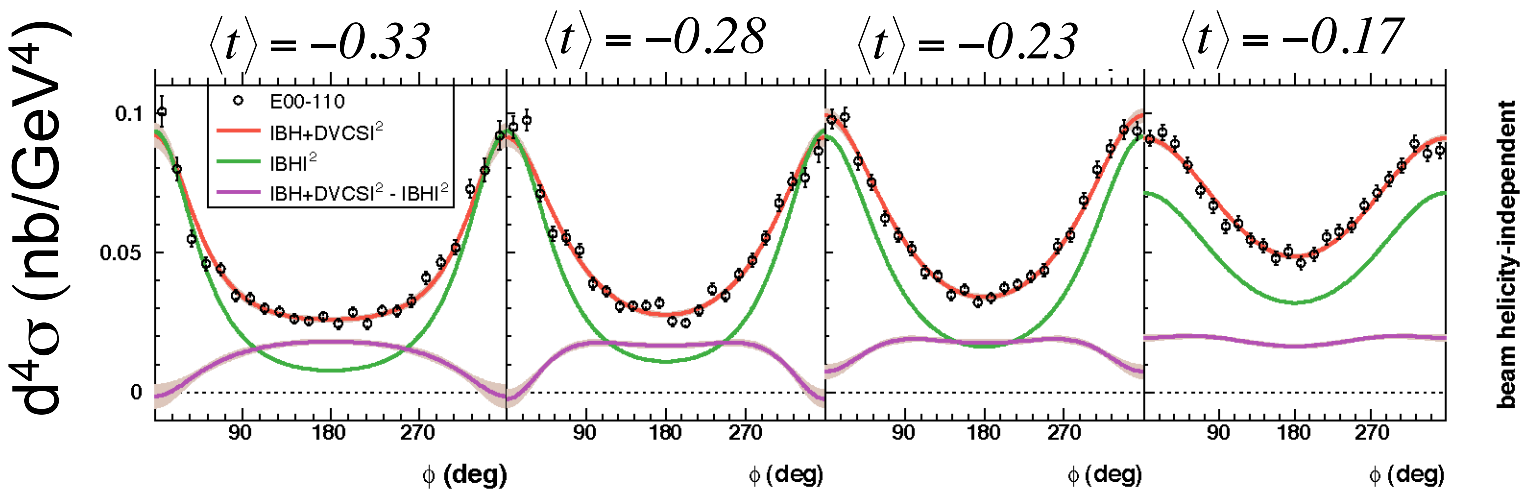
2015 run:
Extend to
Q^2=4.0 GeV²

Compensate the small lever-arm in Q^2 with precision in dσ.

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

- Contribution of Re[DVCS*BH] + |DVCS|^2 large.
- 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.*,



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

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

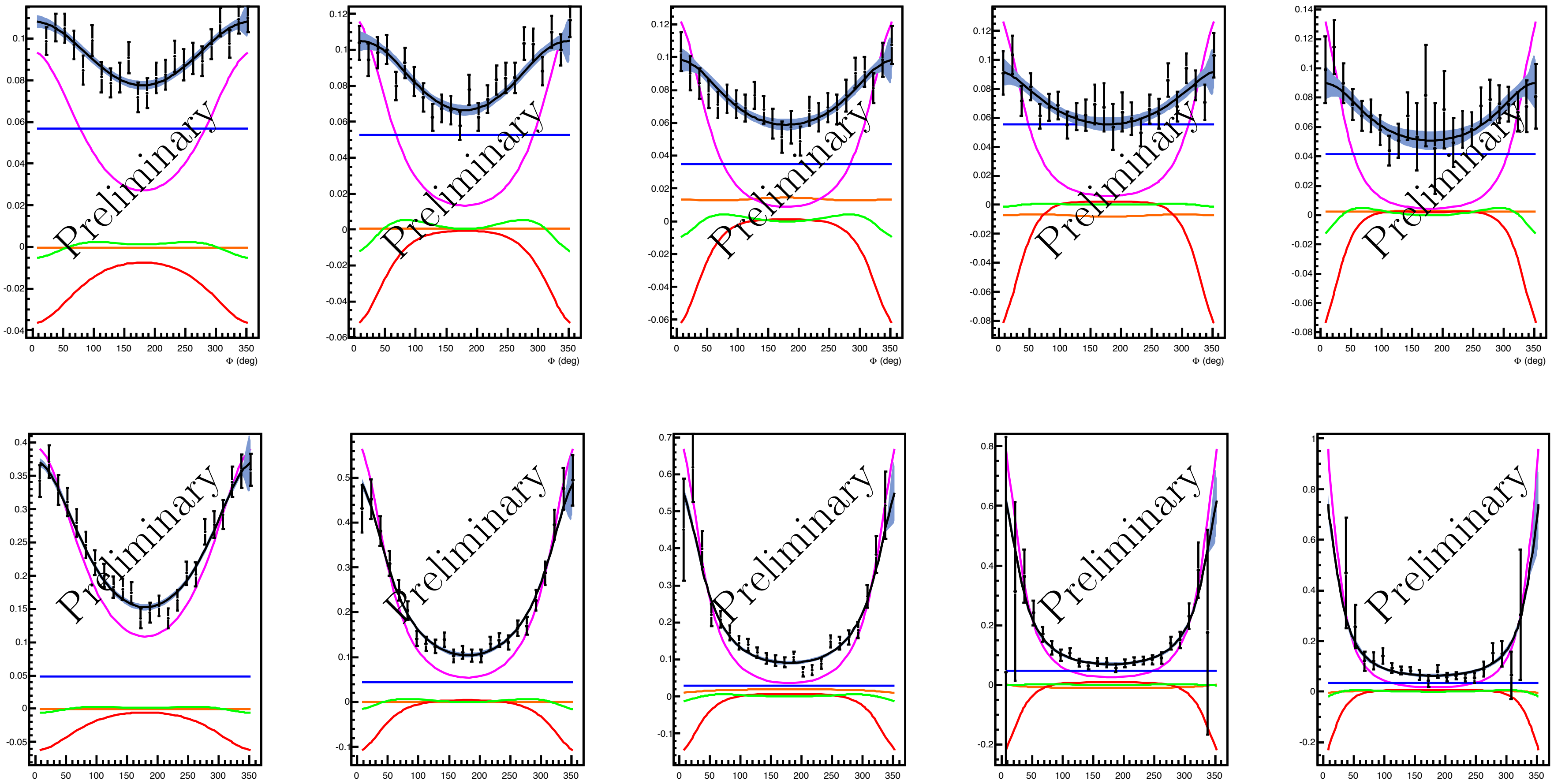
$$c_{0,1}(t) \approx \mathrm{Re}[C^I(GPD)] \pm C^{DVCS}\left(GPD^2\right) \ldots + \mathrm{Re}\left[\Delta C^I(GPD)\right]$$

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

E07-007/E08-025 results

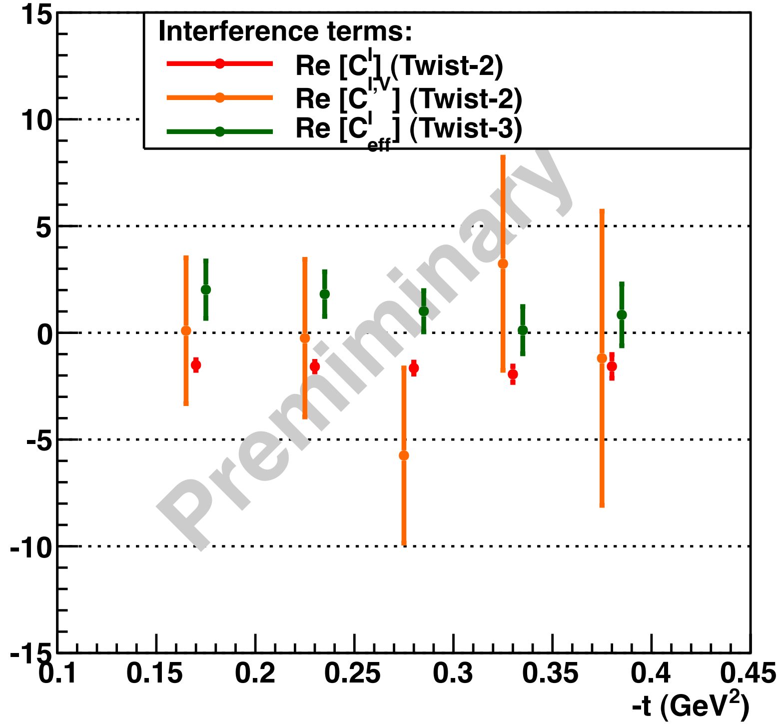
Hall A 2010 run

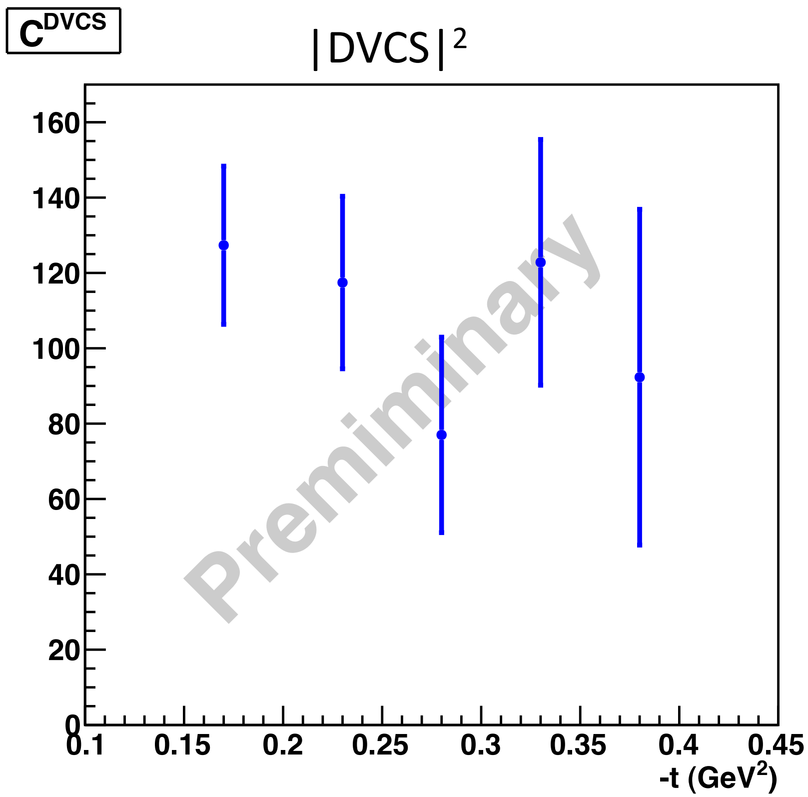
- $Q^2 = 1.5$ GeV^2, $x_B = 0.36$, $-t = 0.17, 0.23, 0.28, 0.33, 0.37$ GeV^2
- $E_b - 5.6$ GeV (top) & $E_b = 3.6$ GeV (bottom)



M. Defurne

E07-007: $\mathcal{I}/DVCS^2$ separation





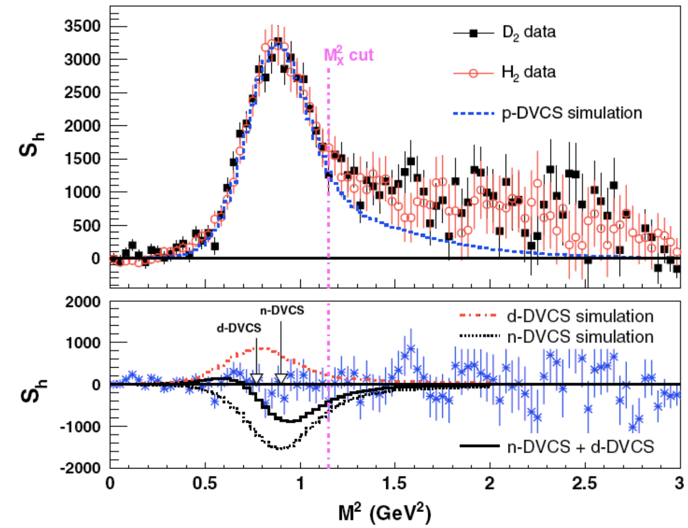
M. Defurne

Conclusions (preliminary)

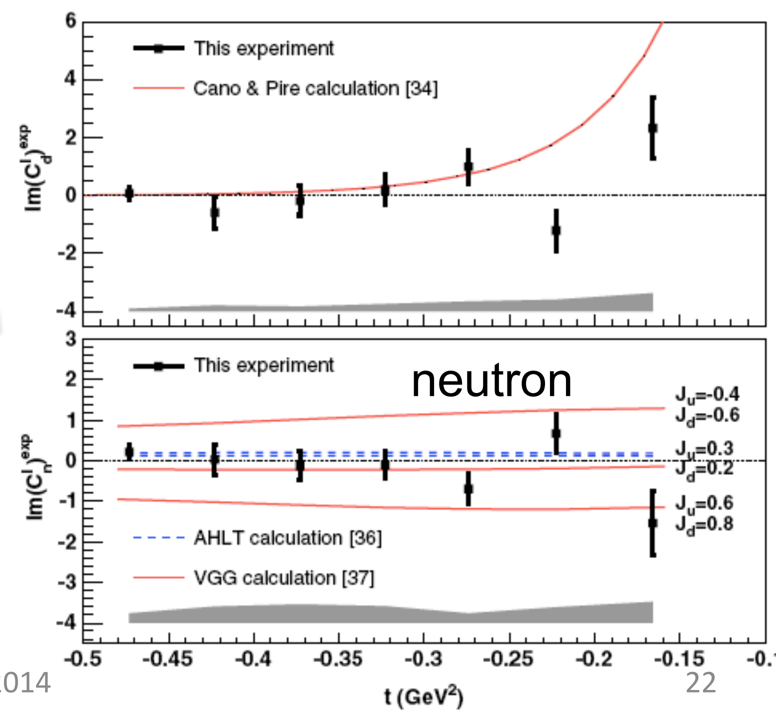
- DVCS^2 main contribution of the cross section around $\phi \sim 180°$
- Twist-3 (interference) contribution is small

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



DVCS in CLAS @ 6 GeV

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

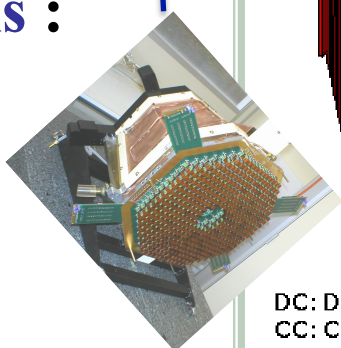
5 Tesla Solenoid

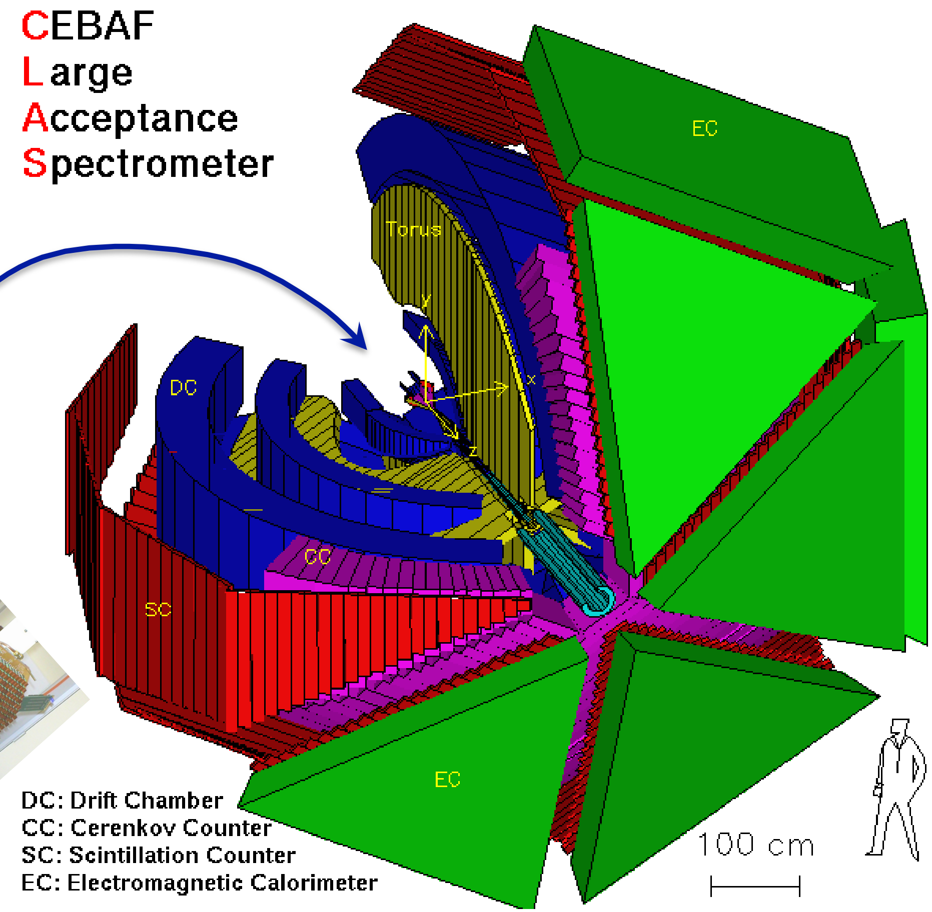
420 $PbWO_4$ crystals :

~10x10x160 mm^3

APD+preamp readout

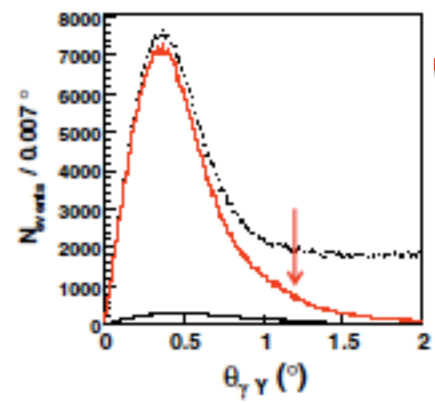
Orsay / Saclay / ITEP / Jlab



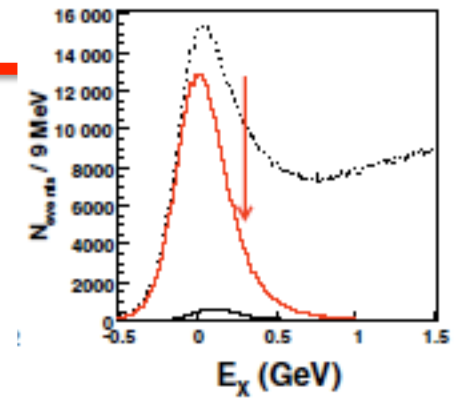


CLAS 6 GeV: Exclusivity and Kinematics

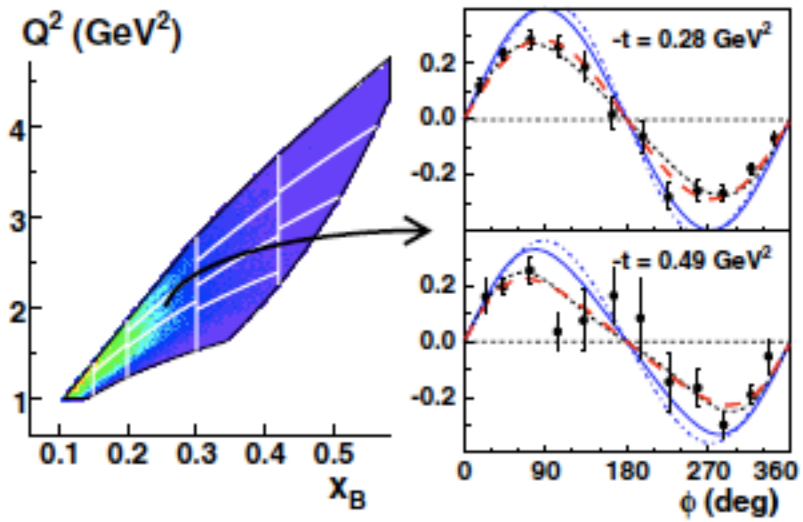
- $H(e,e'\gamma p')x$
  - Overcomplete triple coincidence



Co-linearity of γ with *q-p'*



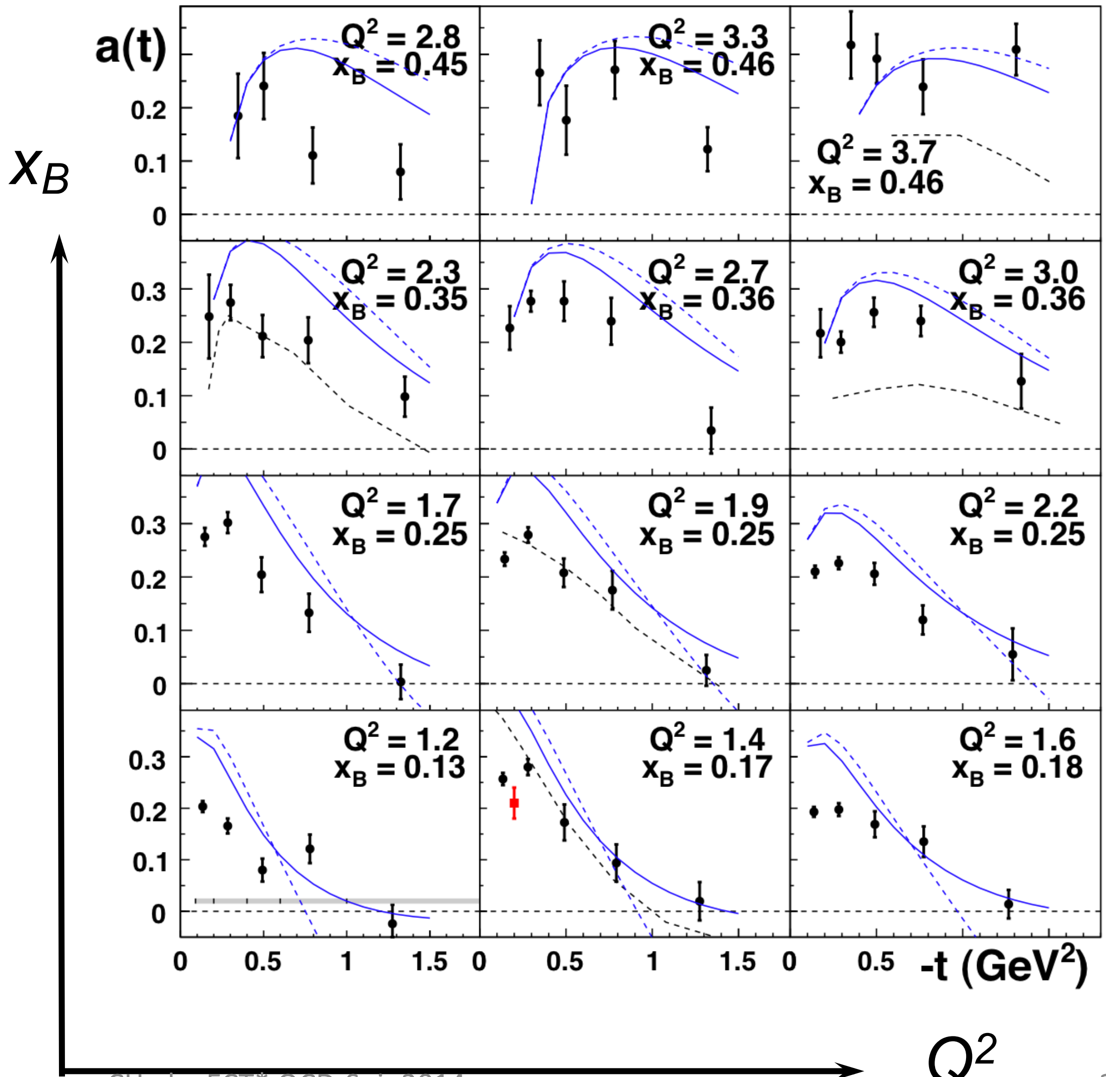
Missing Energy E_x



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

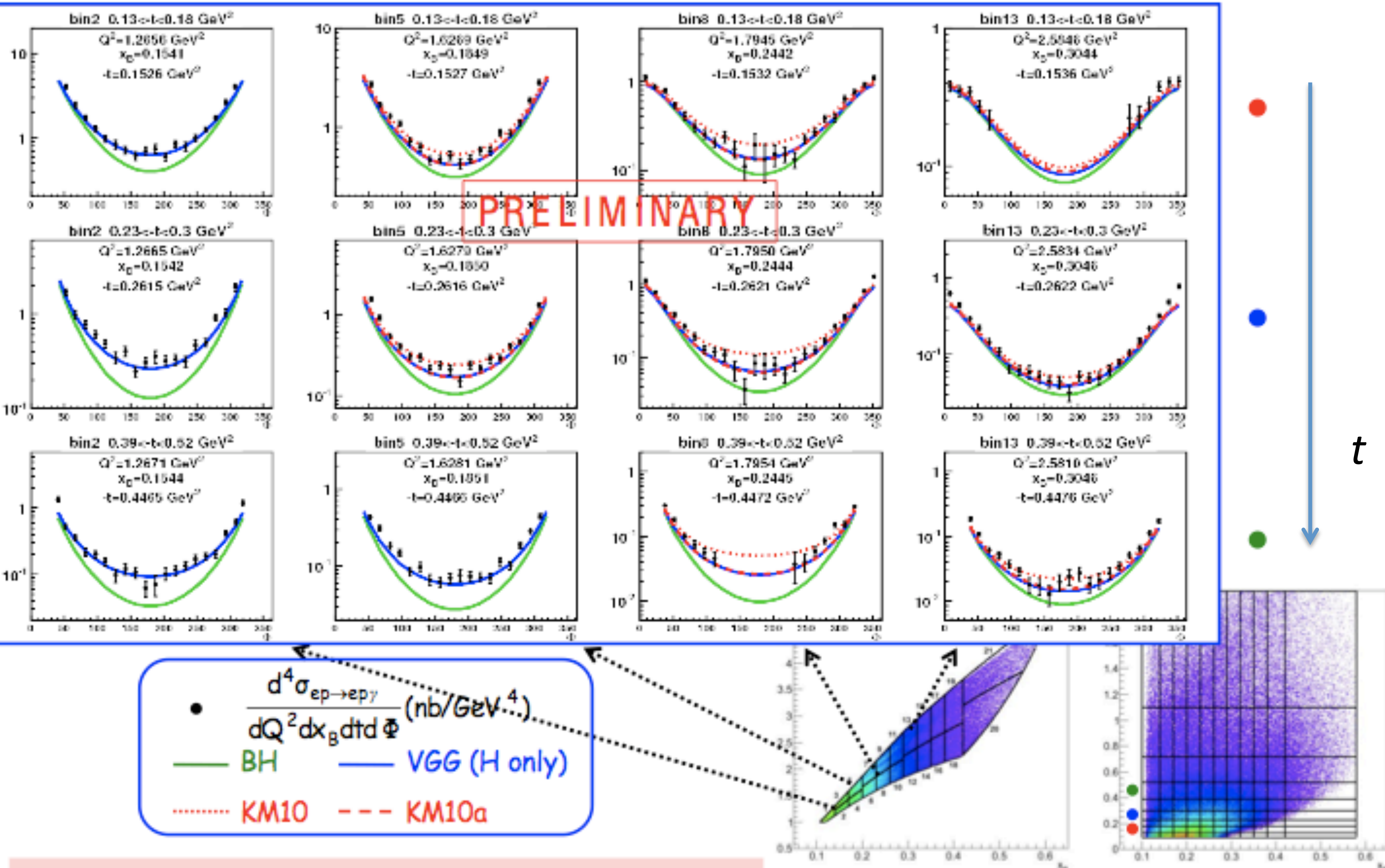
CLAS, 6 GeV Beam Helicity Asymmetry

- F.X. Girod et al, Phys.Rev.Lett.**100,** 162002, 2008
- sinϕ moments of A_{LU}
  - Solid blue curves: VGG GPD model
  - Primarily sensitive to *H*



CLAS e1-dvcs: DVCS cross sections

Publication in CLAS review



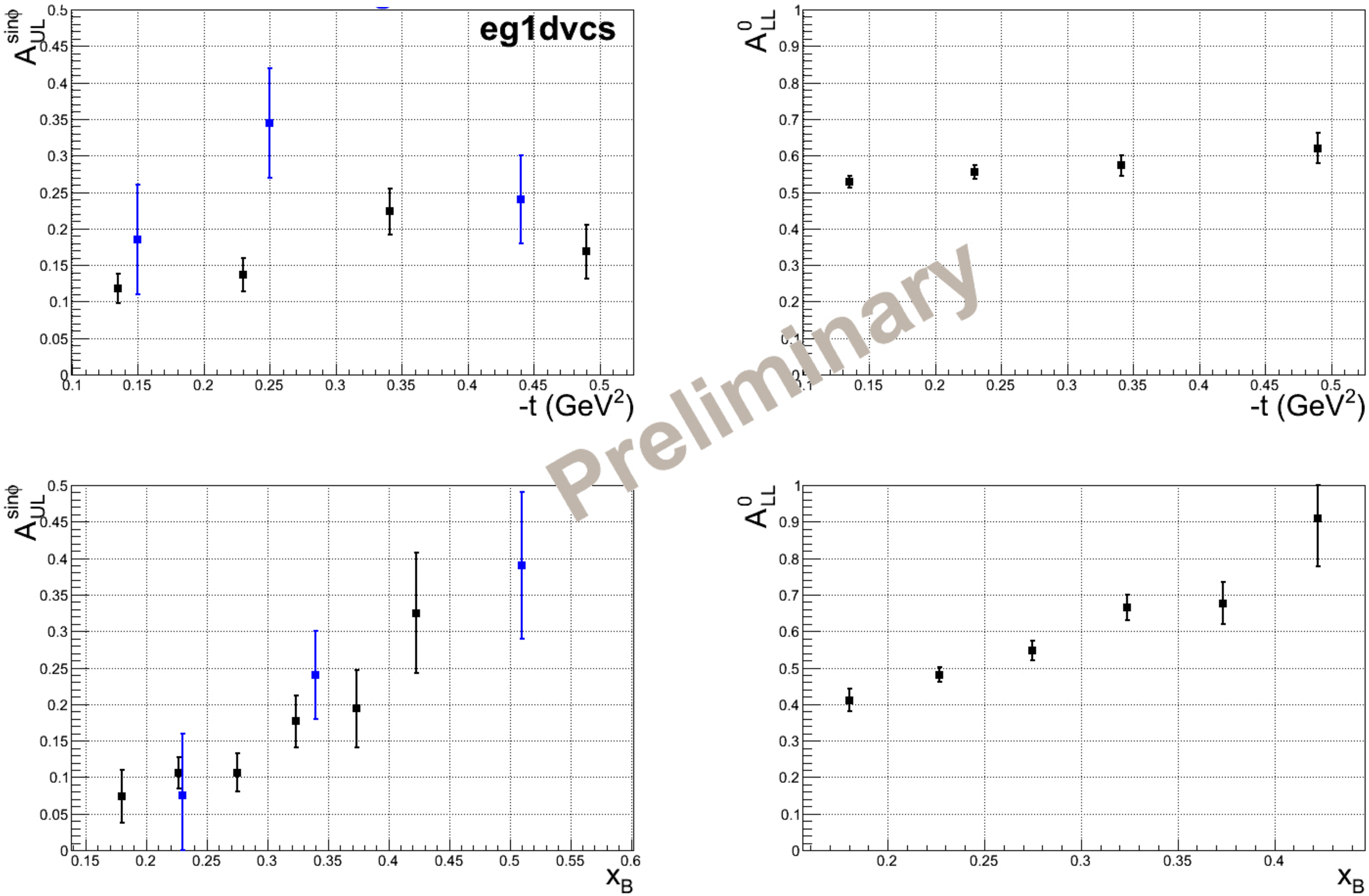
Same amount of statistics will come from e1-dvcs2

21 Q^2-x_B bins, 9 t bins, 24 φ bins

CLAS – Proton Target Spin Asymmetry

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

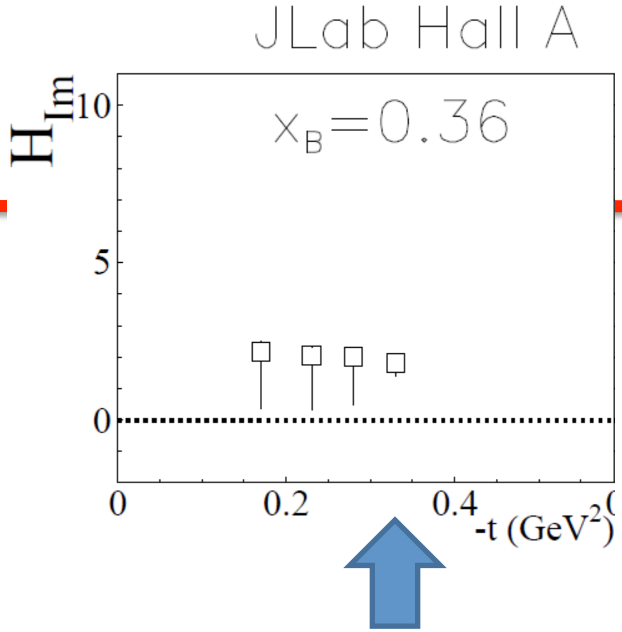
Erin Seder, Ph.D U.Conn, (2013)



Primarily sensitive to *H*-tilde

Global analyses of GPD data

- K. Kumericki, D. Mueller, M. Murray,
  - arXiv:1301.1230 hep-ph, arXiv:1302.7308 hep-ph
- M. Guidal, H.Moutarde,
  - EPJA **42** (2009) 71.
- M. Guidal,
  - PLB **689** (2010) 159, PLB **693** (2010) 17.
- S. Liutti, G. Goldstein,
  - Phys.Rev. D84 (2011) 034007
- LO, or NLO implemented
  - Finite $-t/Q^2$, M^2/Q^2 corrections up to kinematic twist-4.
  - V. Braun, *et al*, Phys.Rev. D89 (2014) 074022.
- Dynamic twist-3 formalism known, not implemented in global analysis yet.



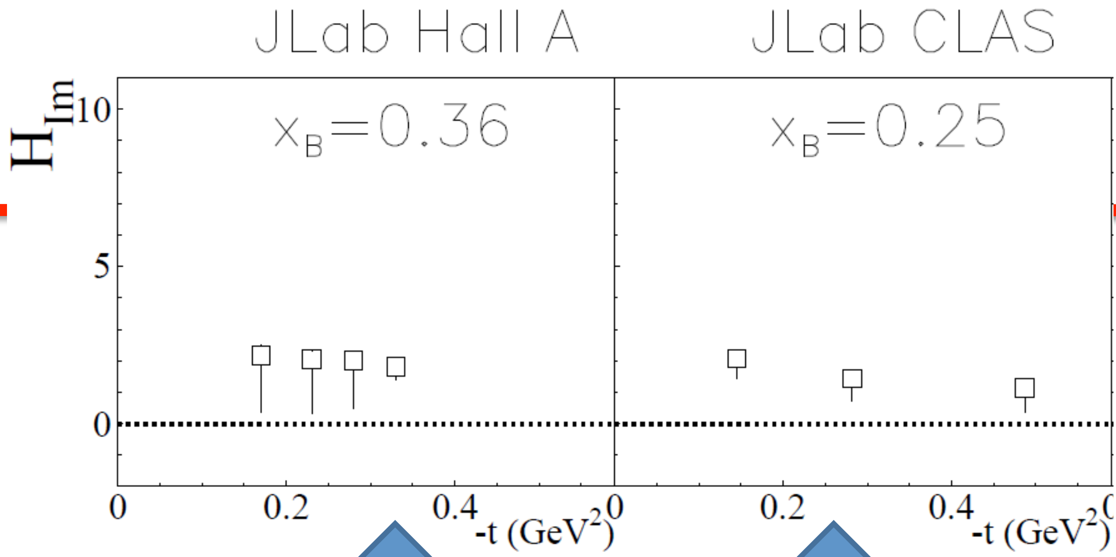
unpol. cross section

+

helicity-dependent cross section

□ χ^2 **minimization**

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



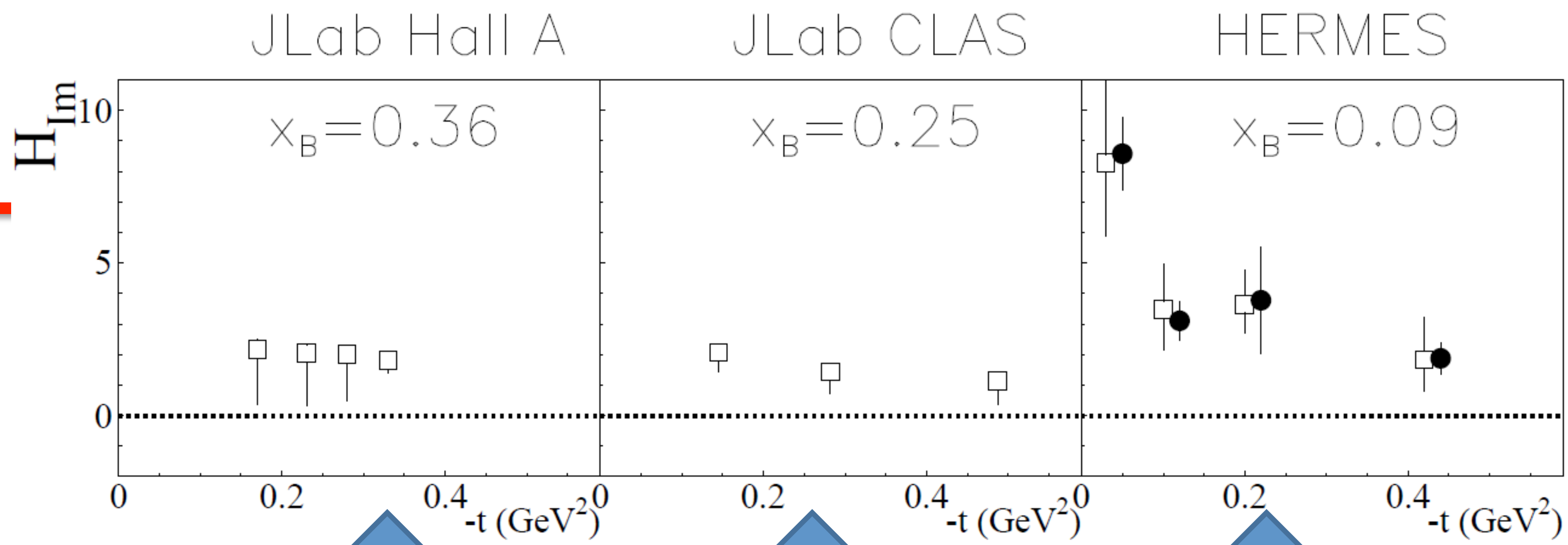
unpol. cross section
+
helicity-dependent cross section

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

□ χ^2 **minimization**

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

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



unpol. cross section + helicity-dependent cross section

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

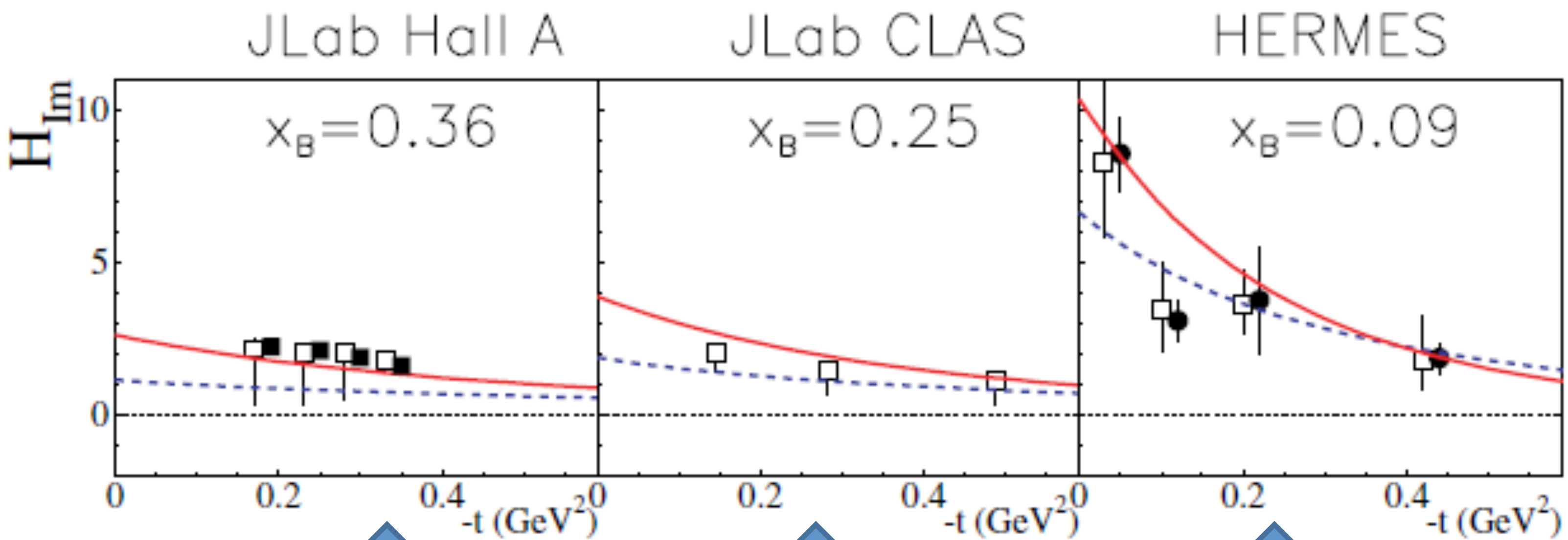
beam charge asym. + beam spin asym + …

□ χ^2 **minimization**

● **linearization**

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

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



unpol.sec.eff. + beam pol.sec.eff.

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

beam charge asym. + beam spin asym + …

□ χ^2 minimization

● linearization

■ Moutarde10 model/fit

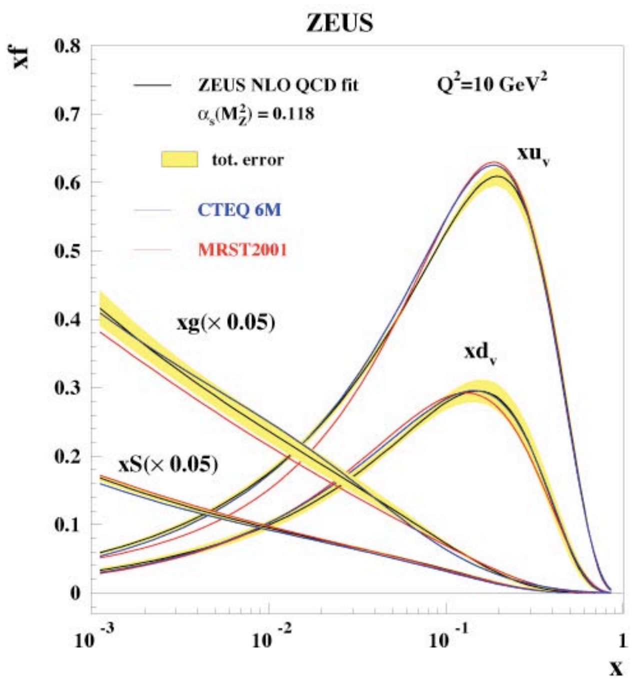
VGG model (solid red line)

KM10 model/fit (dashed blue line)

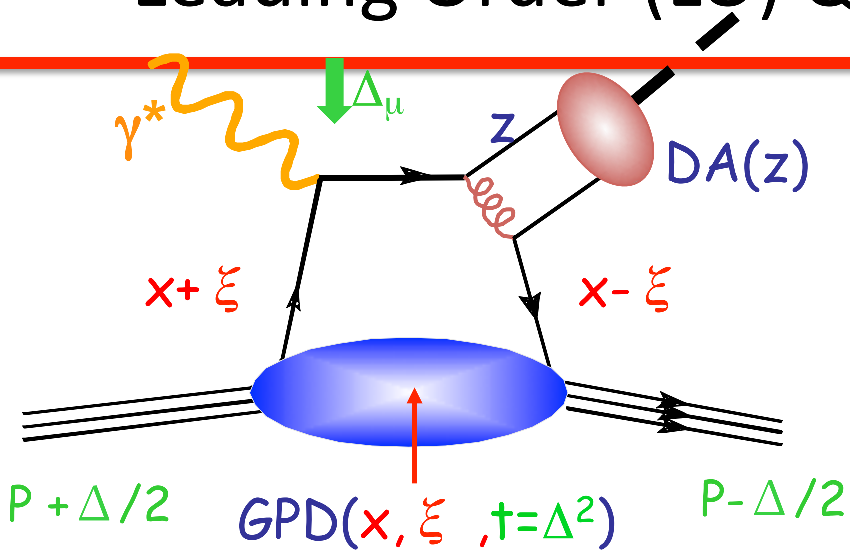
As x_B = *0.09* → *0.25* → *0.36*
t-slope flattens
Proton shrinks!

Deep Virtual Meson Production

- Spin-flavor sensitivity
- Gluons
  - Gluons are still important at large-x
  - Deep ϕ-production
  - J/Ψ photo-production



Leading Order (LO) QCD Factorization of DVES



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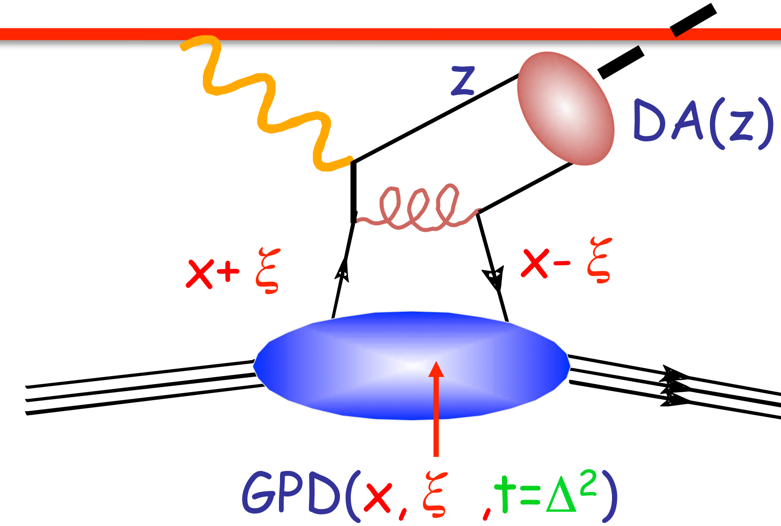

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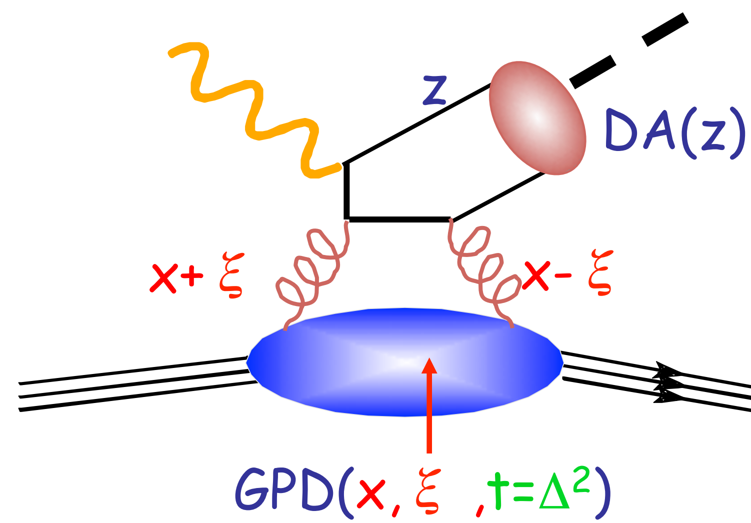


Gluon and quark GPDs enter to same order in α_S.

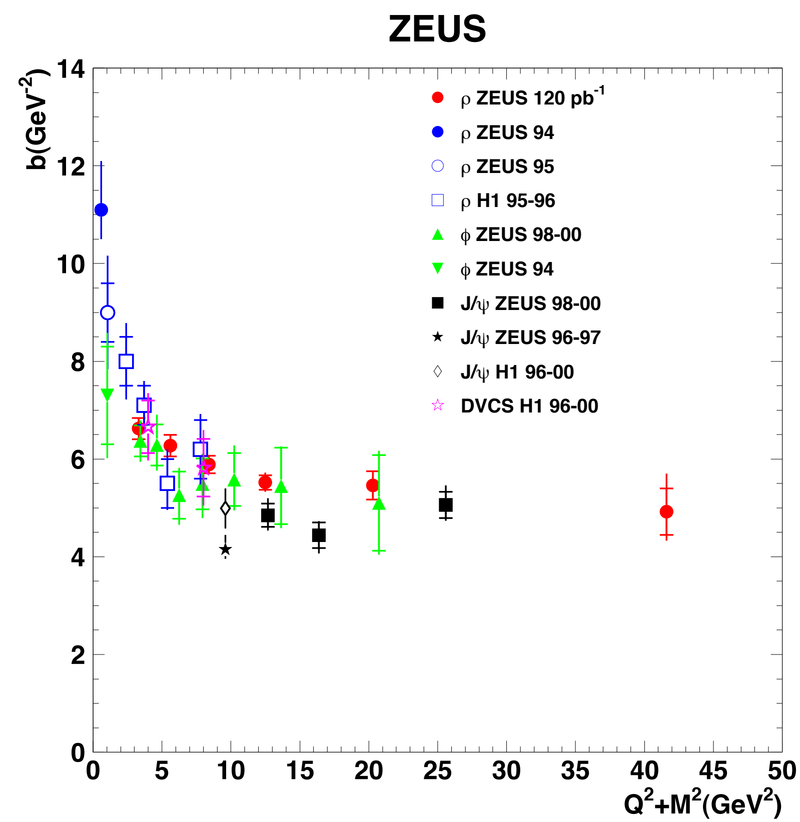
SCHC: $\sigma_L \sim [Q^2]^{-3}$ $\sigma_T \sim [Q^2]^{-4}$

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.
- HERA data: fitted from gluon pdf at scale $\mu^2 << Q^2$
  - Finite transverse spatial size $b \approx 1/\mu$ of $\gamma \rightarrow V$ amplitude



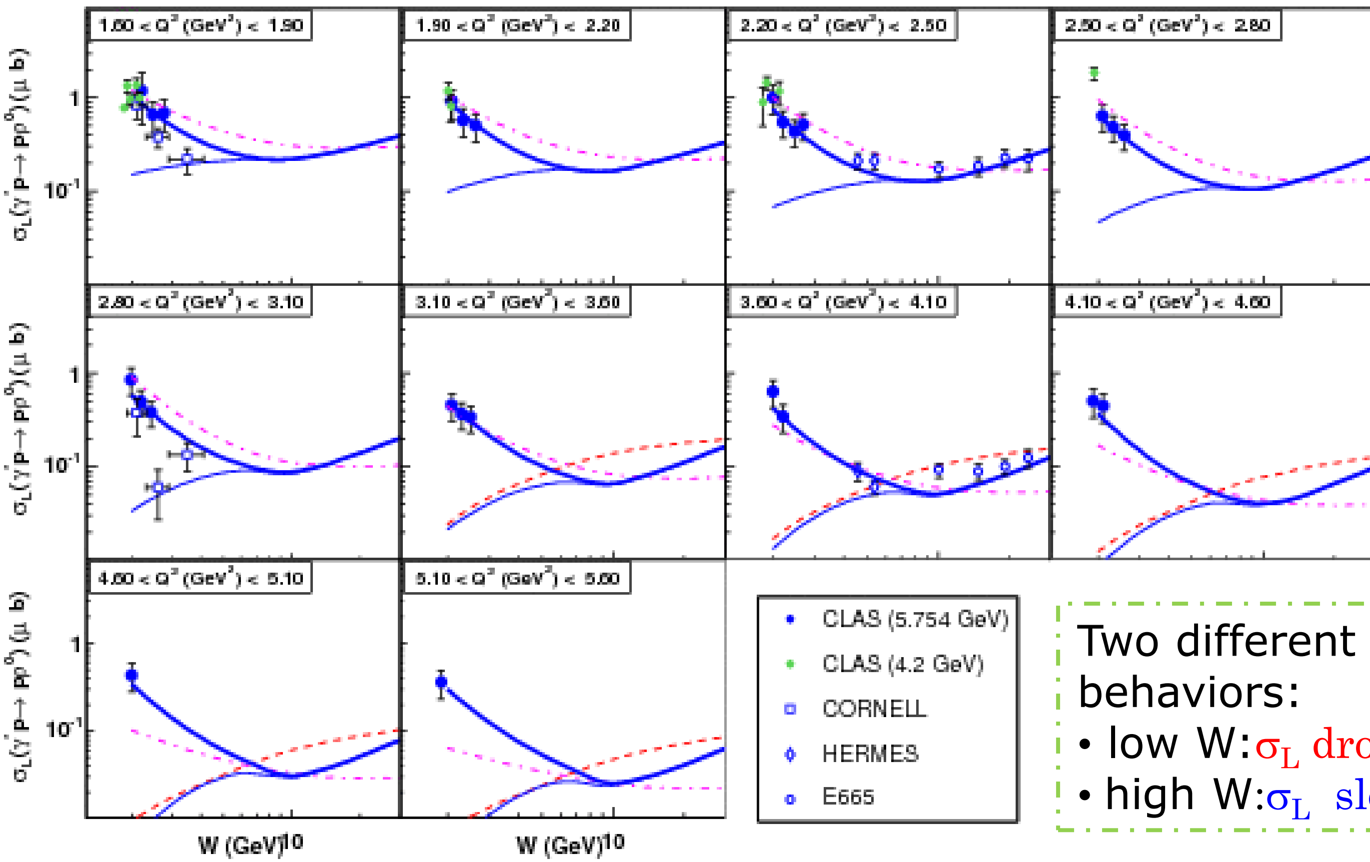
GWolf, 0907.1217

Vector Mesons at JLab

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

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 (GK, thin blue VGG, thick blue VGG + strong D-term)

} Hadronic approach (JLM calculation)

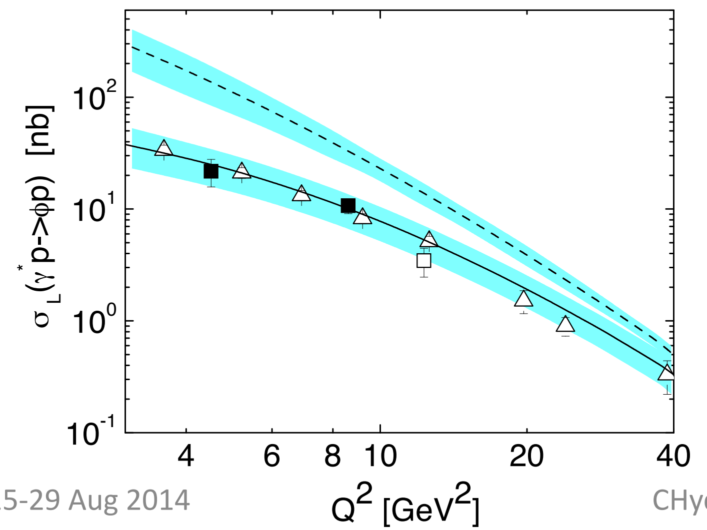
* K. Goeke *et al.*, Prog. Part. Nucl. Phys. 47 (2001) 401.

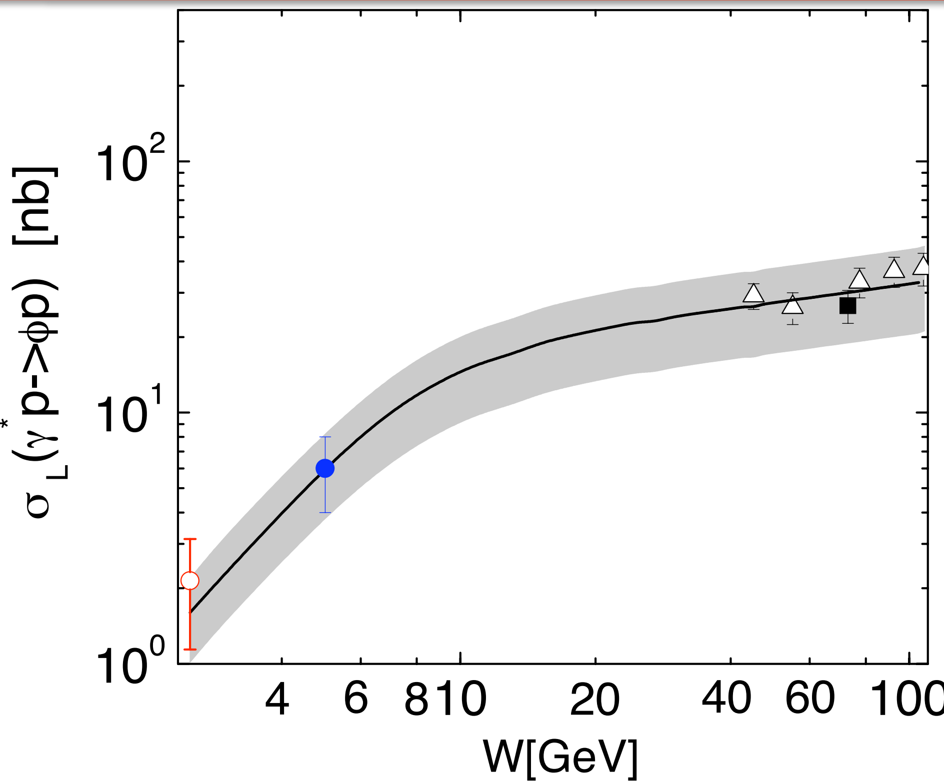
* M. Guidal, M.V. Polyakov, A.V. Radyushkin and M. Vanderhaeghen, Phys. Rev. D72 (2005) 054013.

* 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
  - Finite size effects at $\gamma^* \rightarrow \phi$ vertex





12 GeV Experiment in Hall B

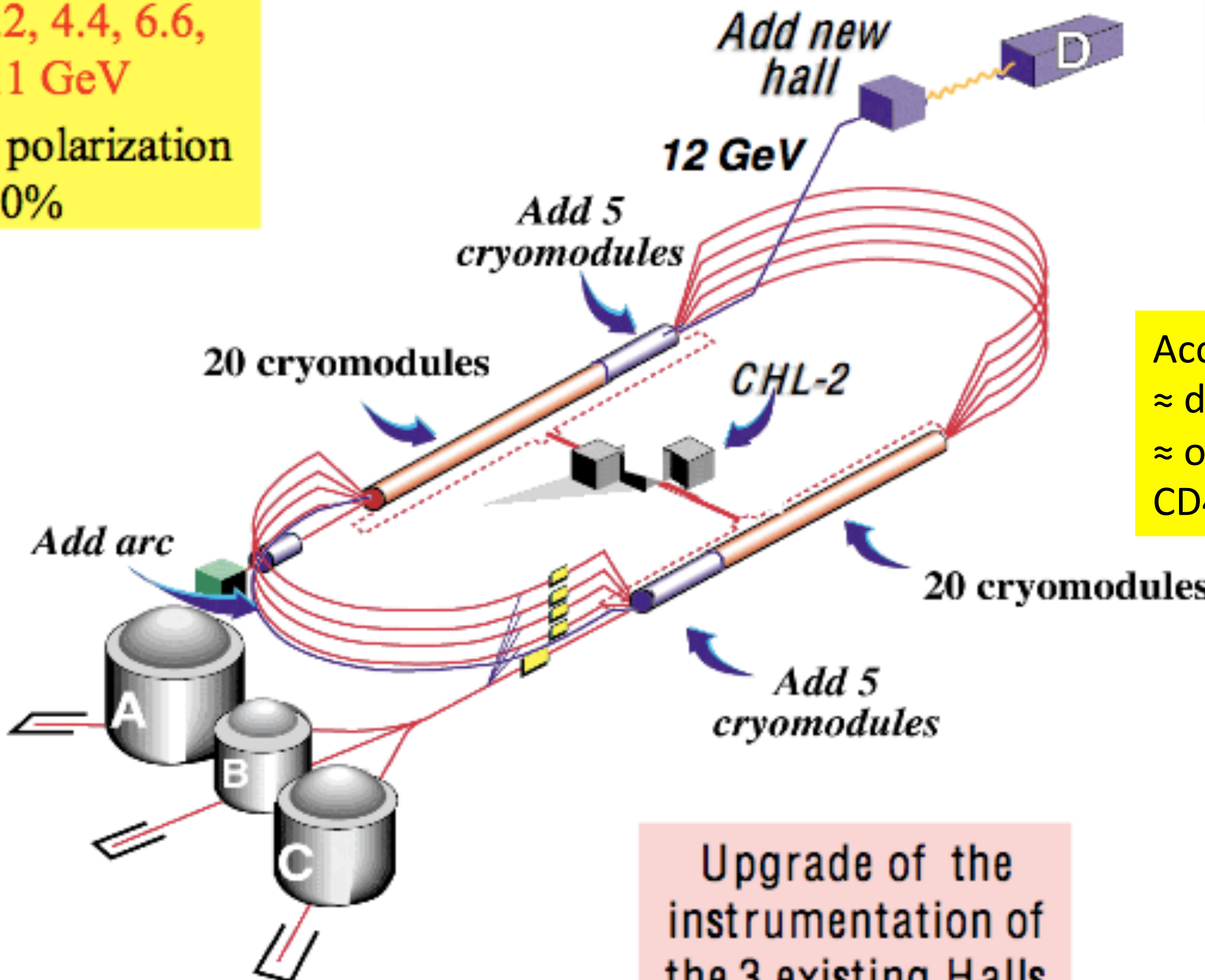
J/Ψ in Halls B and A.

JLab upgrade to 12 GeV

Continuous
Electron
Beam
Accelerator
Facility

E= 2.2, 4.4, 6.6, 8.8, 11 GeV

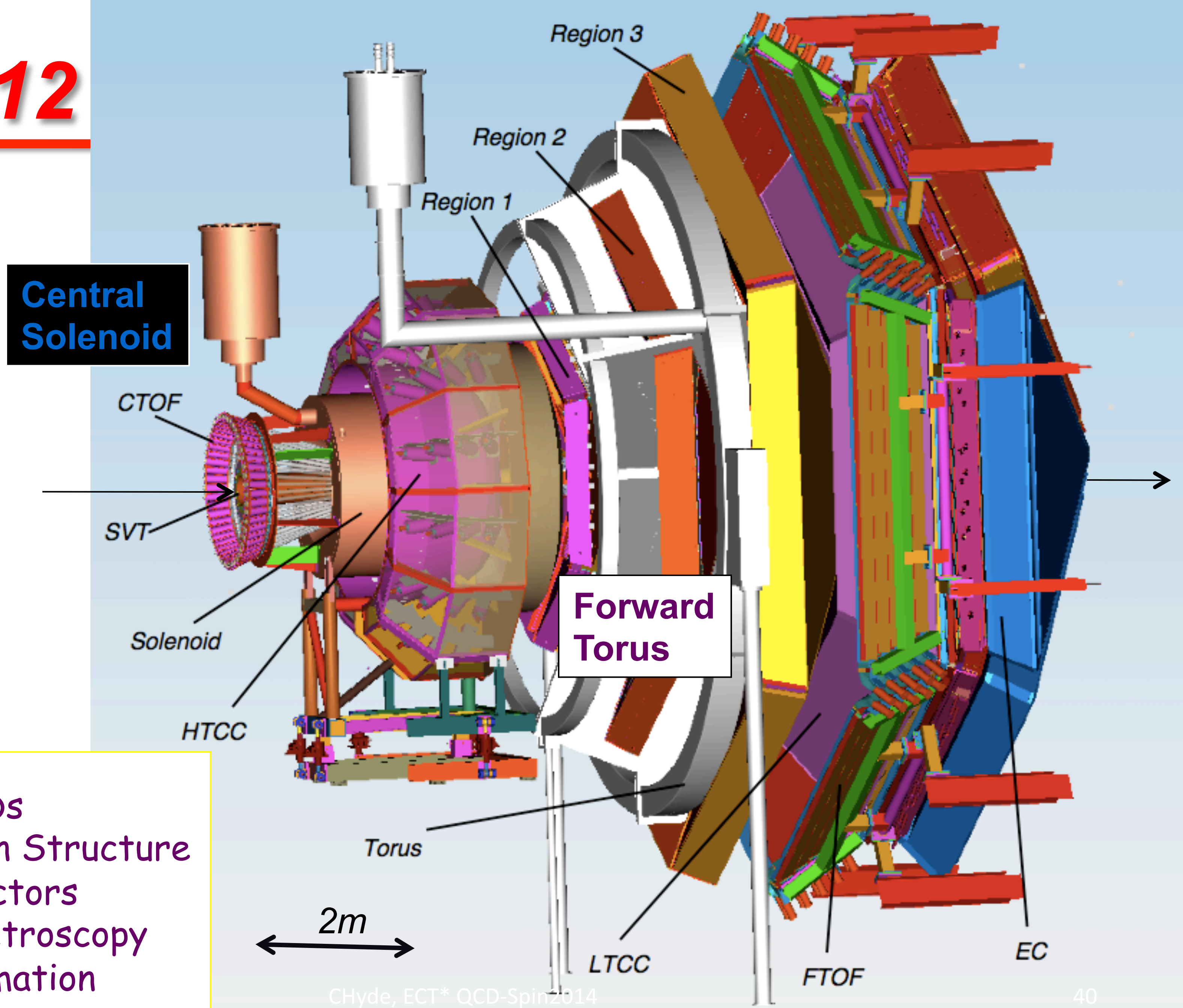
Beam polarization $P_e > 80\%$



Accelerator
≈ done
≈ operational
CD4A Spring 2014

Upgrade of the instrumentation of the 3 existing Halls

CLAS12



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

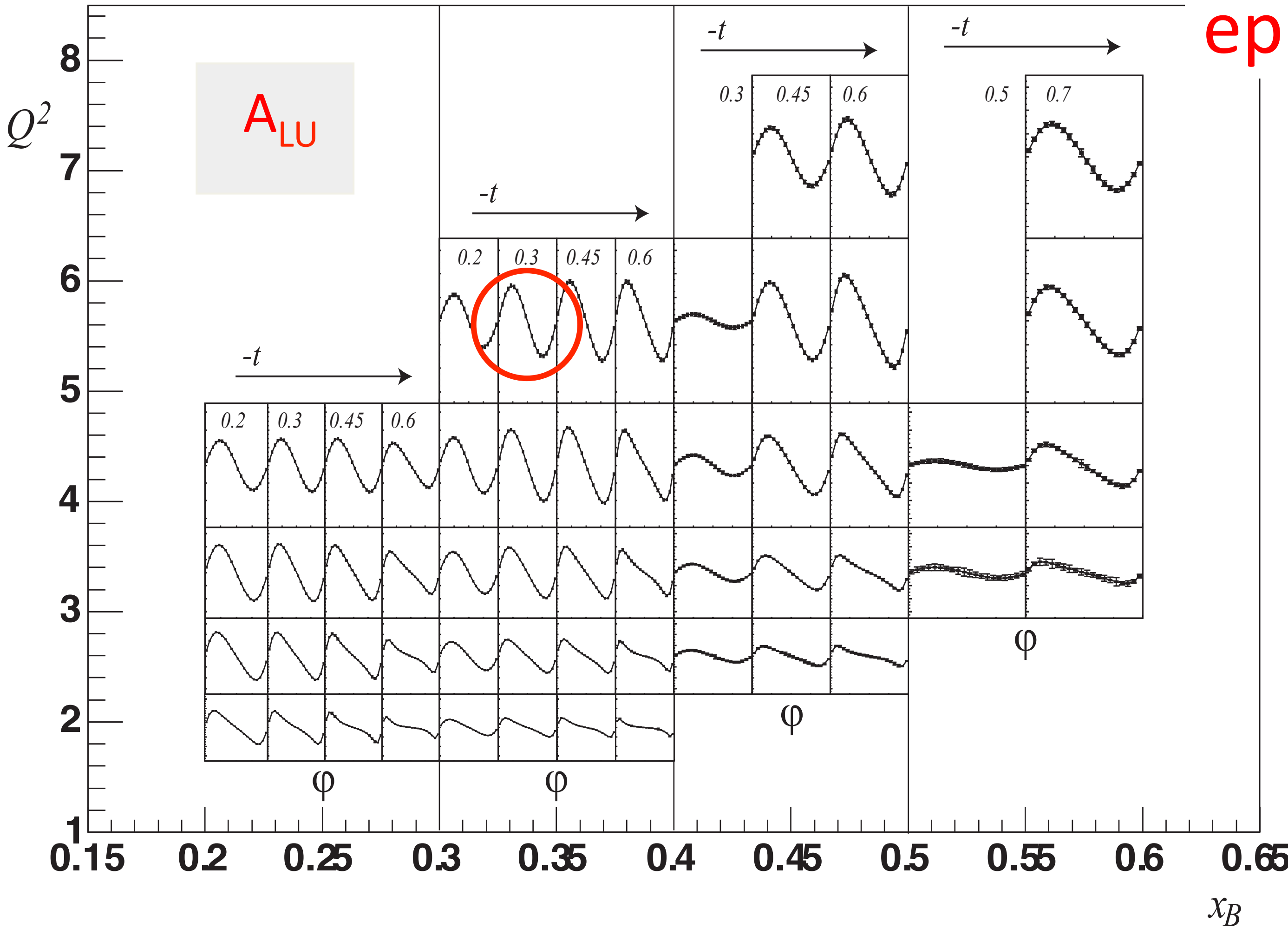
DVCS/DVMP with CLAS at 12 GeV

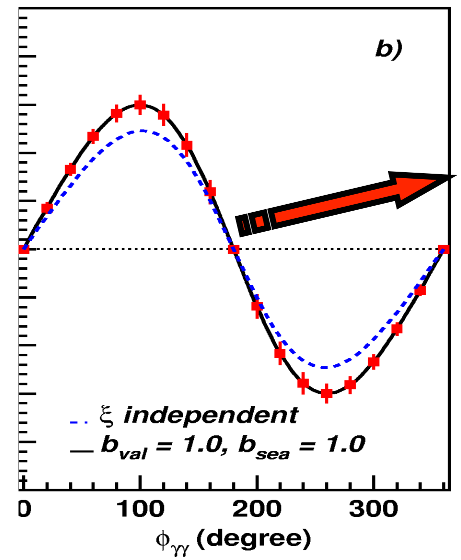
- 80 days on H_2 target at ~10^{35} /cm^2/s
  - DVCS/Vector Meson production/ TCS with low-Q^2 tagger concurrent
- 120 days on Longitudinally Polarized NH_3 target
  - Total Luminosity 10^{35} /cm^2/s, dilution factor ~1/10
- 90 days: D(e,e'γn)p_S
- ^{4}He(e,e' $\gamma\alpha$) with upgraded BoNUS detector
  - GEM based radial TPC for recoil α-detection
- Ambitions/options for Transversely polarized targets
  - NH_3 target has 5 T transverse field
    - need to shield detectors from "sheet of flame"
    - Reduce (Luminosity)•(Acceptance) by factor of 10 (my guess)
  - HD-ice target: Transversely polarized H
    - 110 Days approved
    - Luminosity•(polarization)^2 not yet known

A_{LU} projections for JLab@12GeV

$\Delta\sigma_{LU} \sim \sin\phi \, \{F_1 \mathcal{H} + \xi(F_1+F_2)\tilde{\mathcal{H}} + kF_2\mathcal{E}\}d\phi$

$\vec{e}p \rightarrow ep\gamma$





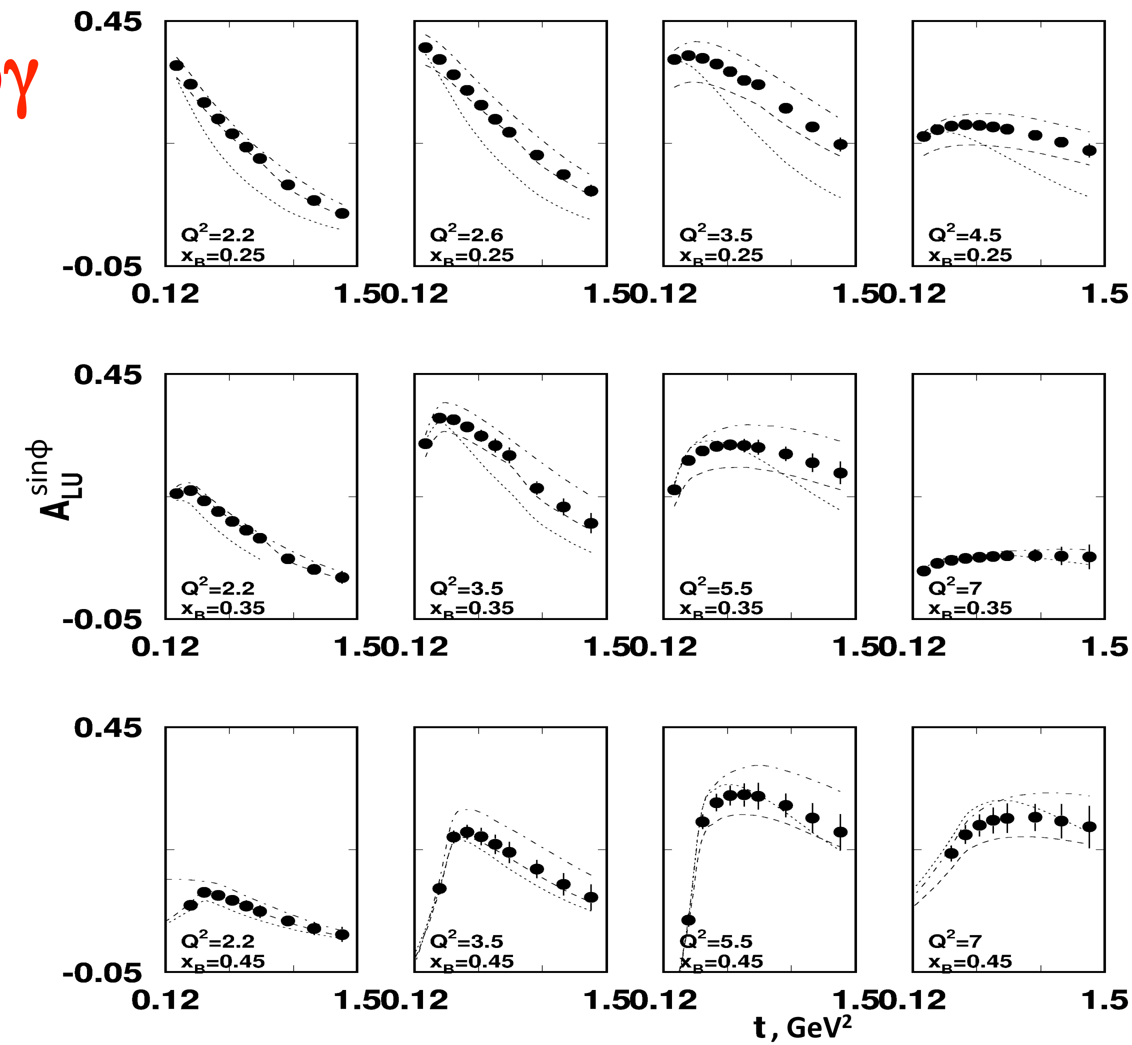
E12-06-114
E12-06-119

A_{LU} projections for protons

$$\Delta\sigma_{LU} \sim \sin\phi \, \{F_1 H + \xi(F_1+F_2)\widetilde{H} + kF_2 E\} d\phi$$

$\vec{e}\,p \longrightarrow ep\gamma$

E_e=11GeV

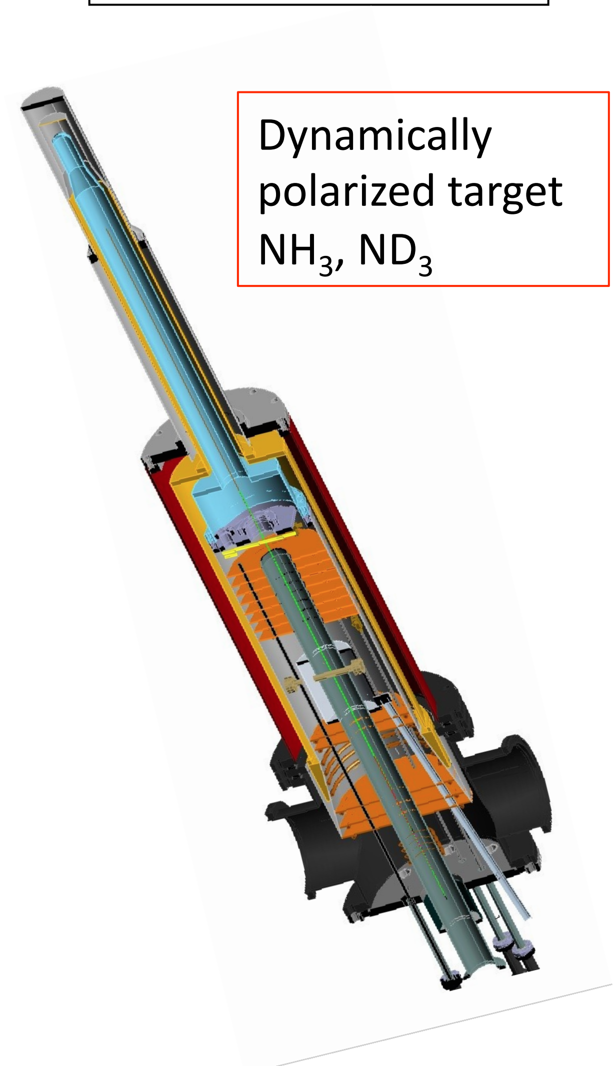


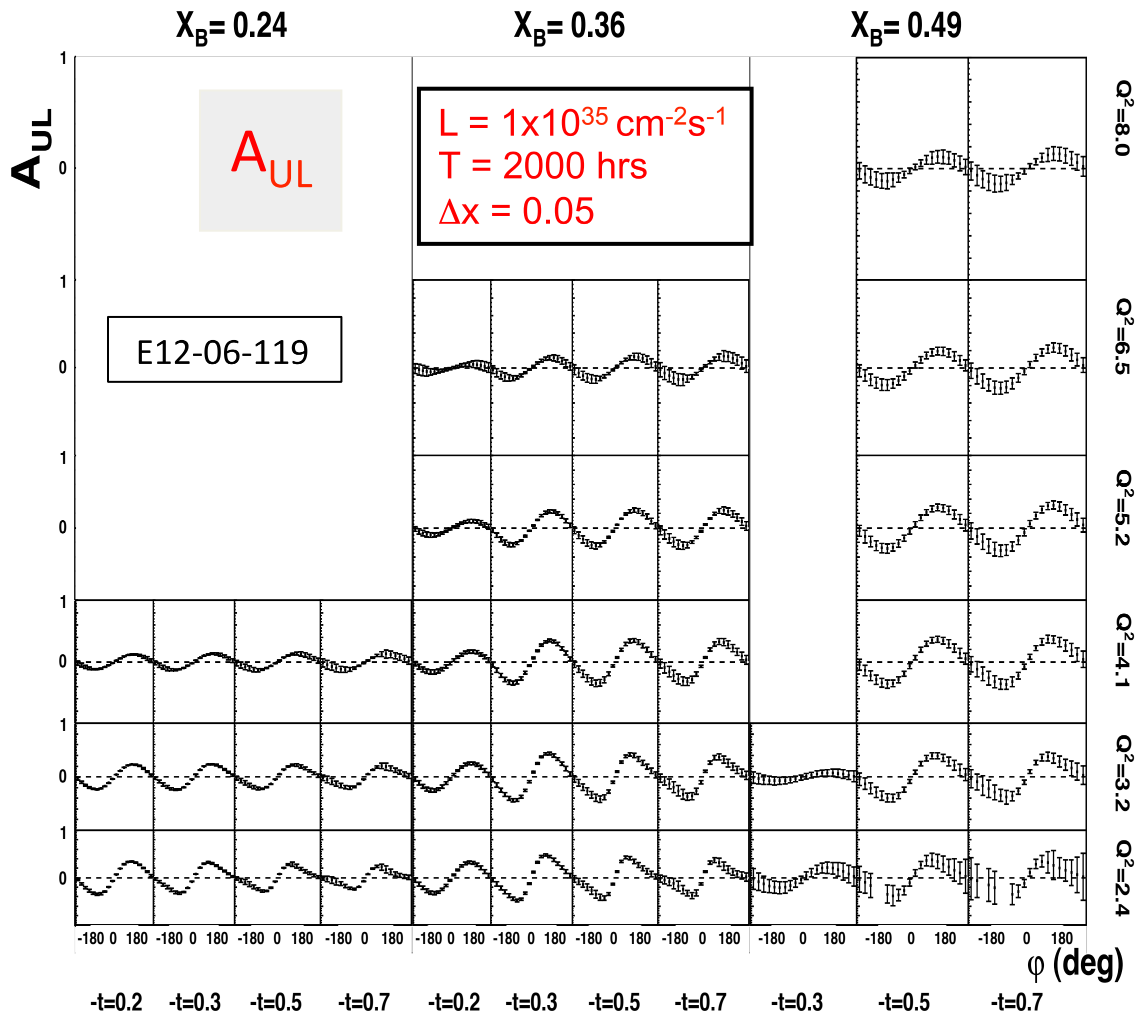
A_{UL} projections for protons

$e\,\vec{p} \rightarrow e p \gamma$

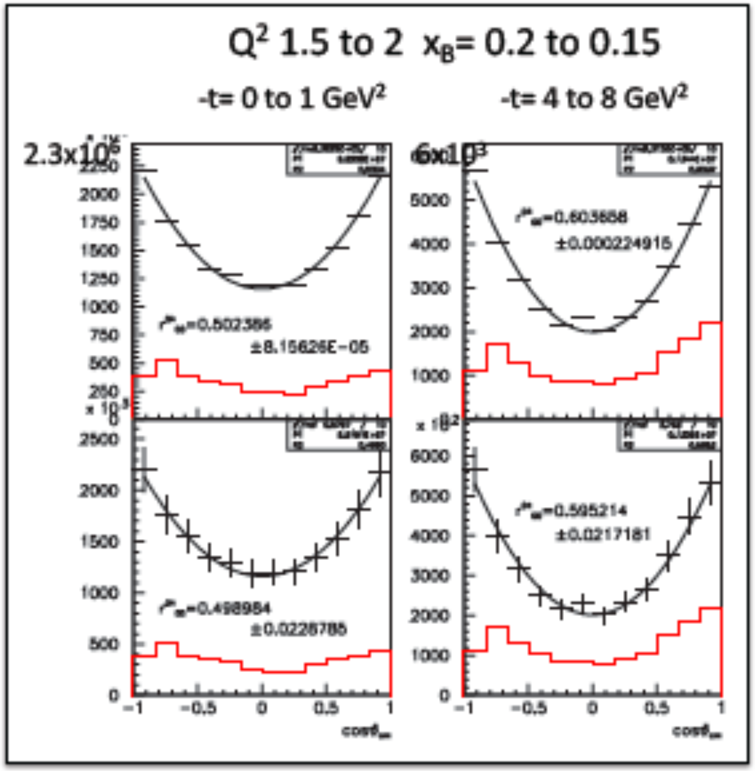
$\Delta\sigma_{UL} \sim \sin\phi \, \{F_1\widetilde{H} + \xi(F_1+F_2)(H + \xi/(1+\xi)E)\}d\phi$

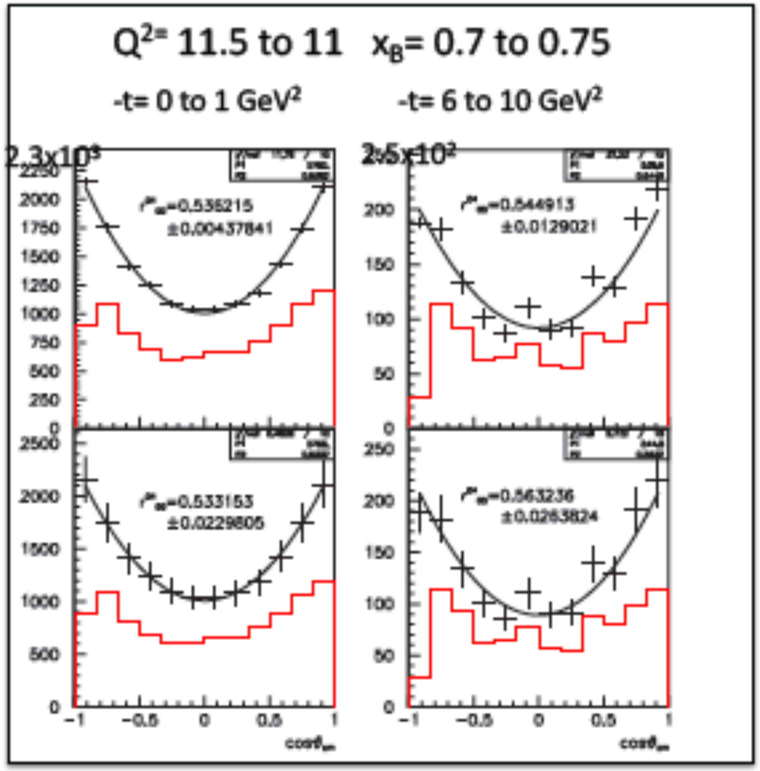
Dynamically polarized target
NH_3, ND_3



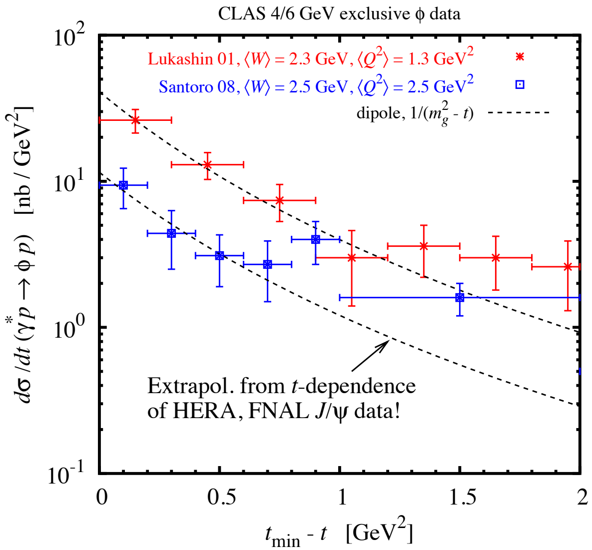


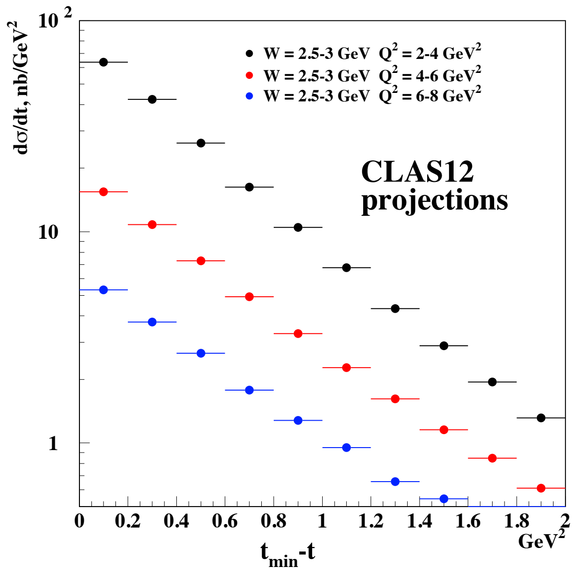
Exclusive $\rho^0 \rightarrow \pi\pi$ L/T separation from SCHC





Exclusive ϕ: CLAS12 experiment





- t–dependence of 6 GeV ϕ data consistent with gluonic radius measured at high energies

  Extrapolation of HERA, FNAL J/ψ results

- CLAS12: Test reaction mechanism and harden GPD–based description

  When does t–slope become independent of Q^2?

  How does W–dependence change with Q^2?

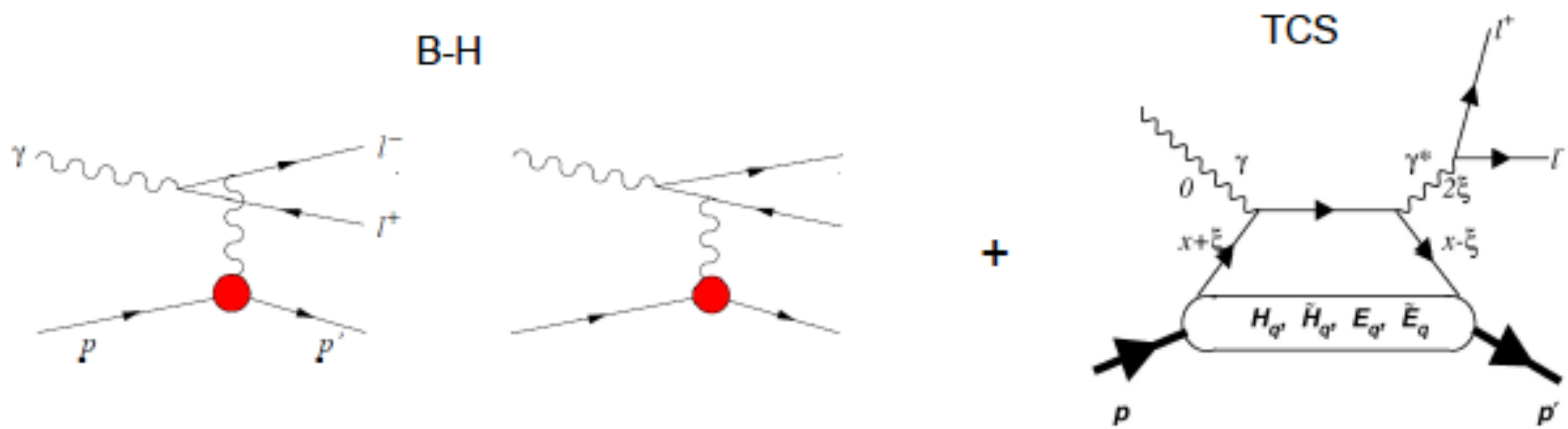
  L/T ratio from vector meson decay and s–channel helicity conservation

- CLAS12: Extract t–dependence of gluon GPD at $x = 0.2 - 0.5$

  Obtained from relative t–dependence of $d\sigma_L/dt$

First accurate gluonic image of nucleon at large x!

Time-Like Compton Scattering

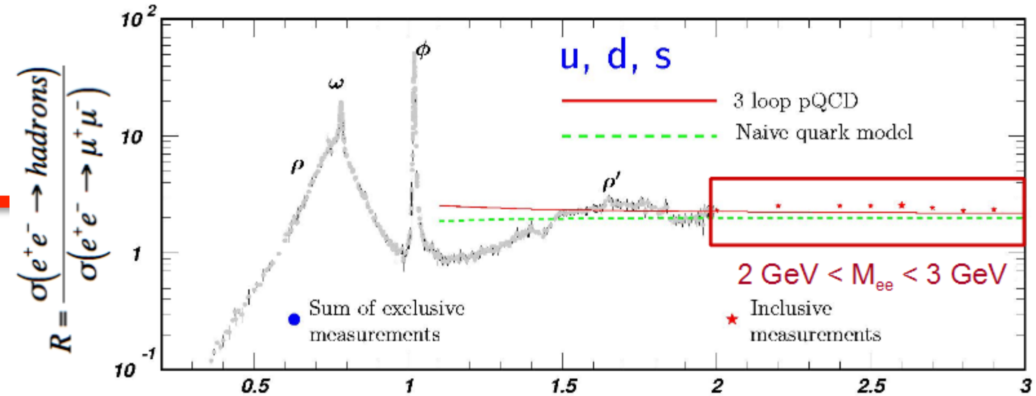


$$\frac{d\sigma^4}{dQ'^2\,dt\,d(\cos\theta)\,d\varphi} = |BH|^2 + I(BH\cdot TCS) + |TCS|^2$$

- Lepton Charge Conjugation:
  - $|TCS|^2$, $|BH|^2$ even
  - Interference term is odd:
  - e^+e^- decay distribution measures Re[TCS*BH]

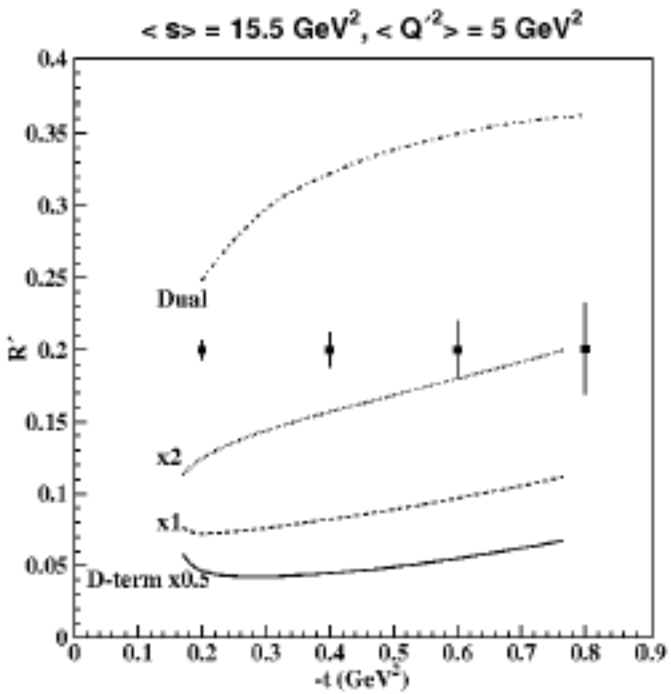
CLAS 12 TCS

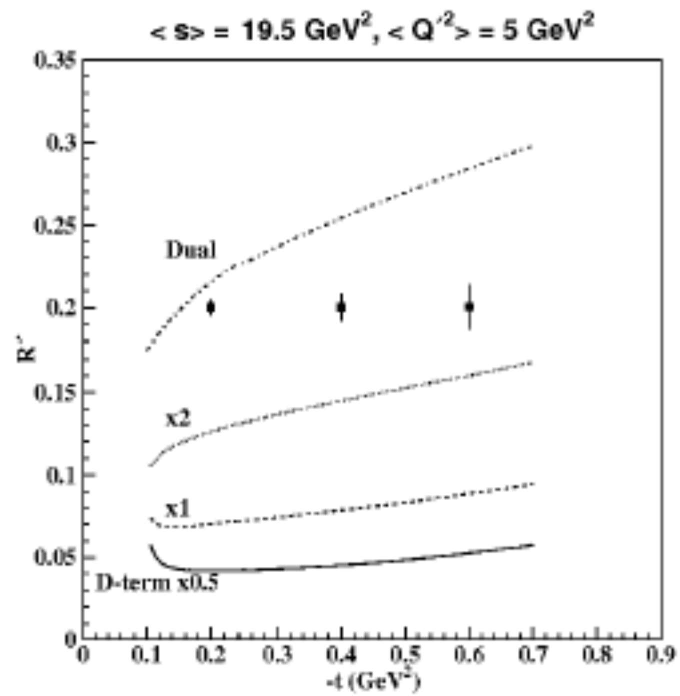
- Ratio of $e^+e^- \rightarrow$ *Hadrons / di-muons* versus e^+e^- mass



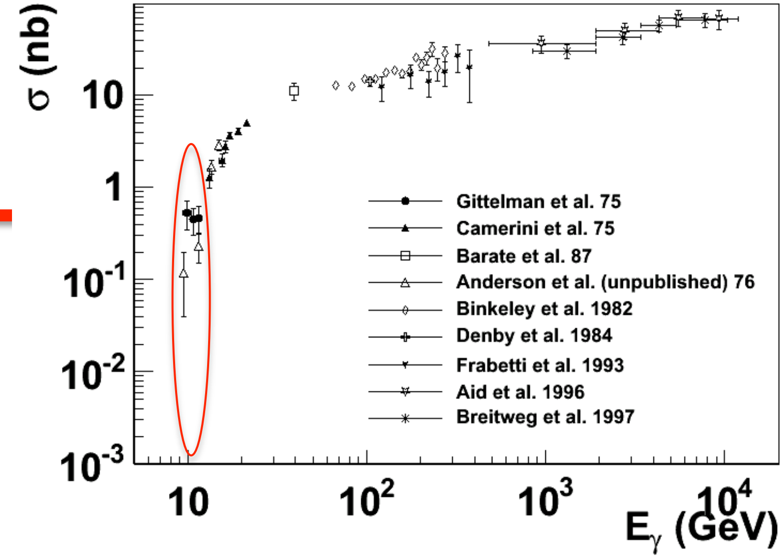
- Two bins in s
- Lowest bin in Q'^2
- *t*-dependence of Interference observable
- Illustrative GPD models

Statistical uncertainties for 100 days at a luminosity of 10^{35} cm^{-2}s^{-1}



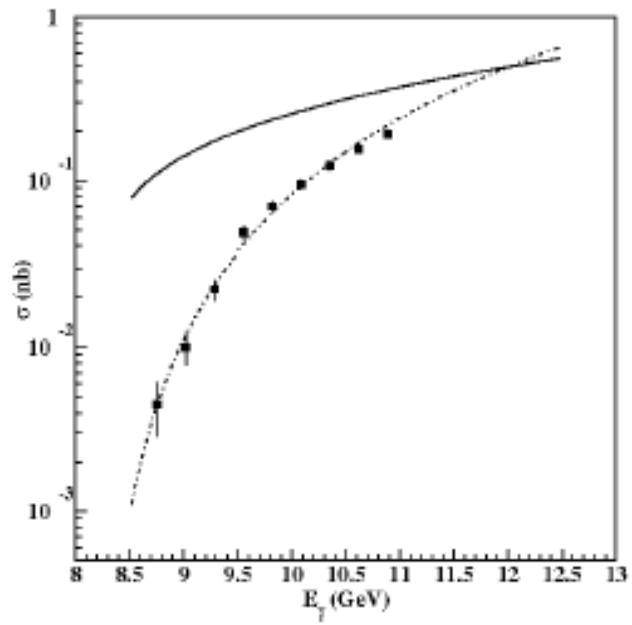


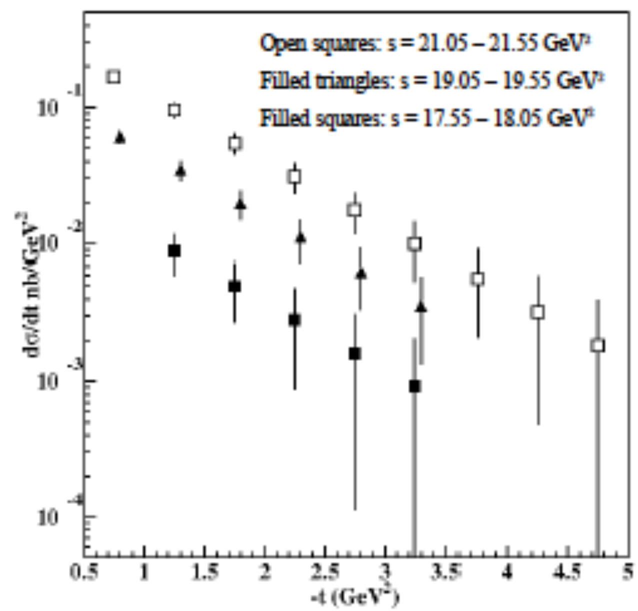
CLAS 12 Exclusive J/Ψ



- Threshold region poorly measured
- CLAS 12:
  - Full *t*-distrbution
  - fine bins in *s* at threshold
- SoLID,
  - Electro-production
  - Polarized Target

Statistical uncertainties for 100 days at a luminosity of 10^{35} cm^{-2}s^{-1}





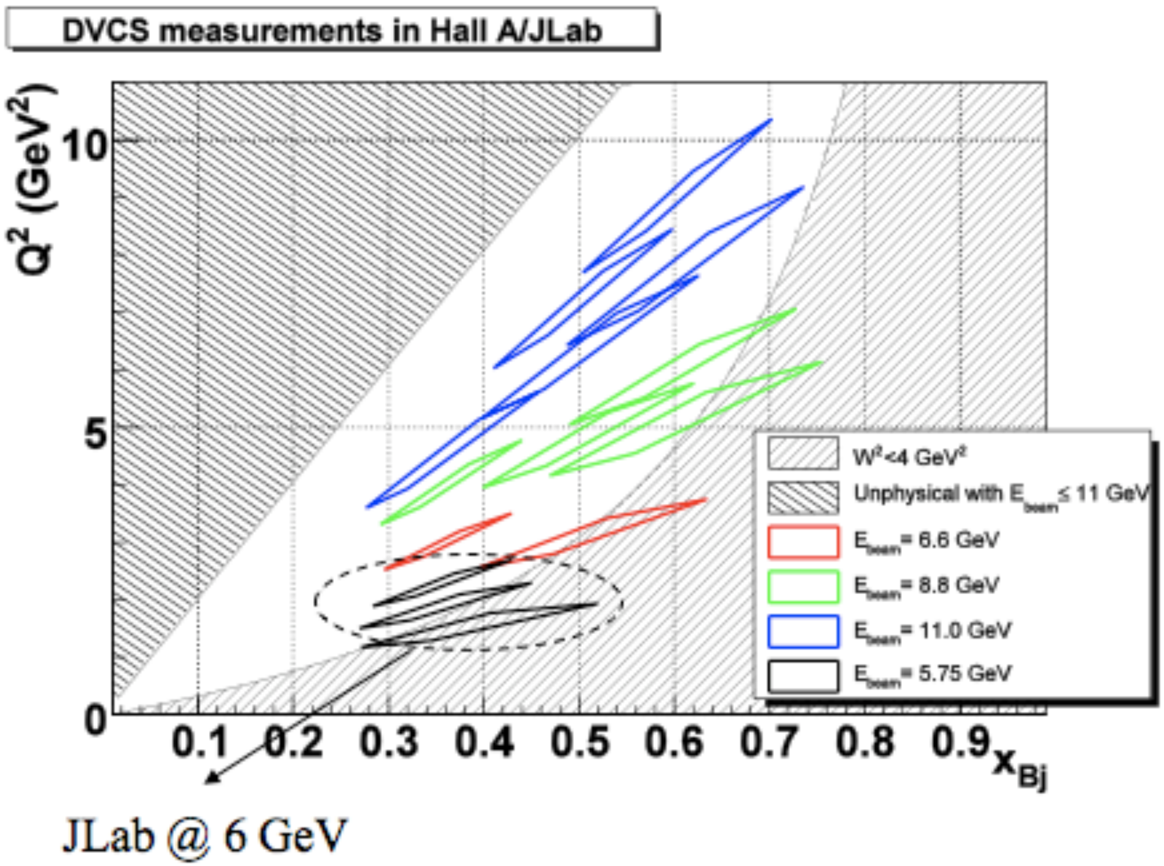
GPDs in Halls A & C at 11 GeV

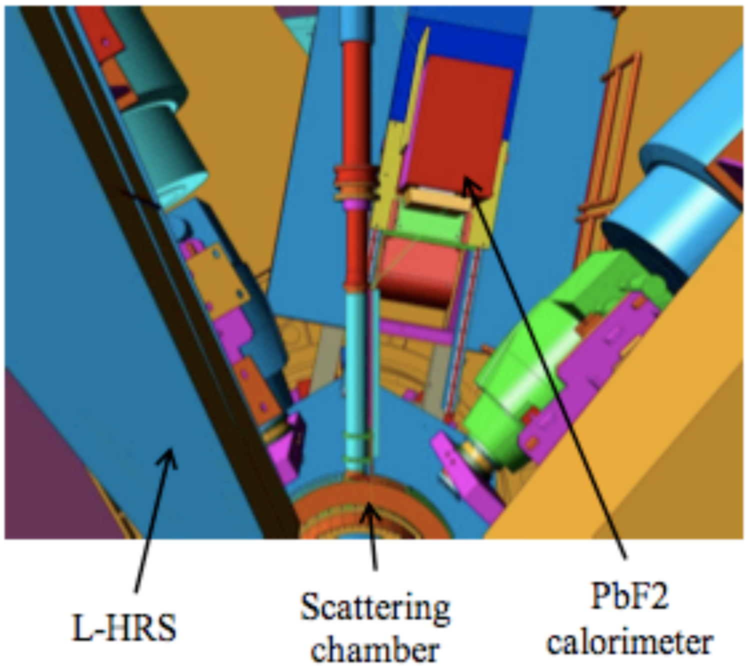
- Hall C: HMS + SHMS
  - $H(e,e'\pi^+)n$: L/T Separation (E12-06-101)
    - Approved for 52 days
    - Measurement of the Charged Pion Form Factor to High Q^2
    - Pion Form Factor ←→ GPD *E*-tilde
- Hall A 2014-2015
  - $H(e,e'\gamma)p$ and $H(e,e'\pi^0)p$
  - Subset of 100 days approved
- Hall C (53 days approved):
  - $H(e,e'\gamma)p$ and $H(e,e'\pi^0)p$
  - Beam energy dependence
  - Expanded x_B, Q^2 range
- Hall C Real Compton Scattering (large $-t$) approved by PAC 42

E12-06-114: DVCS at 11 GeV in Hall A

- Absolute cross-section measurements
- Test of scaling: Q^2 dependence of $d\sigma$ at fixed x_{Bj}
- Increased kinematical coverage

JLab12 with 3, 4, 5 pass beam (6.6, 8.8, 11.0 GeV)



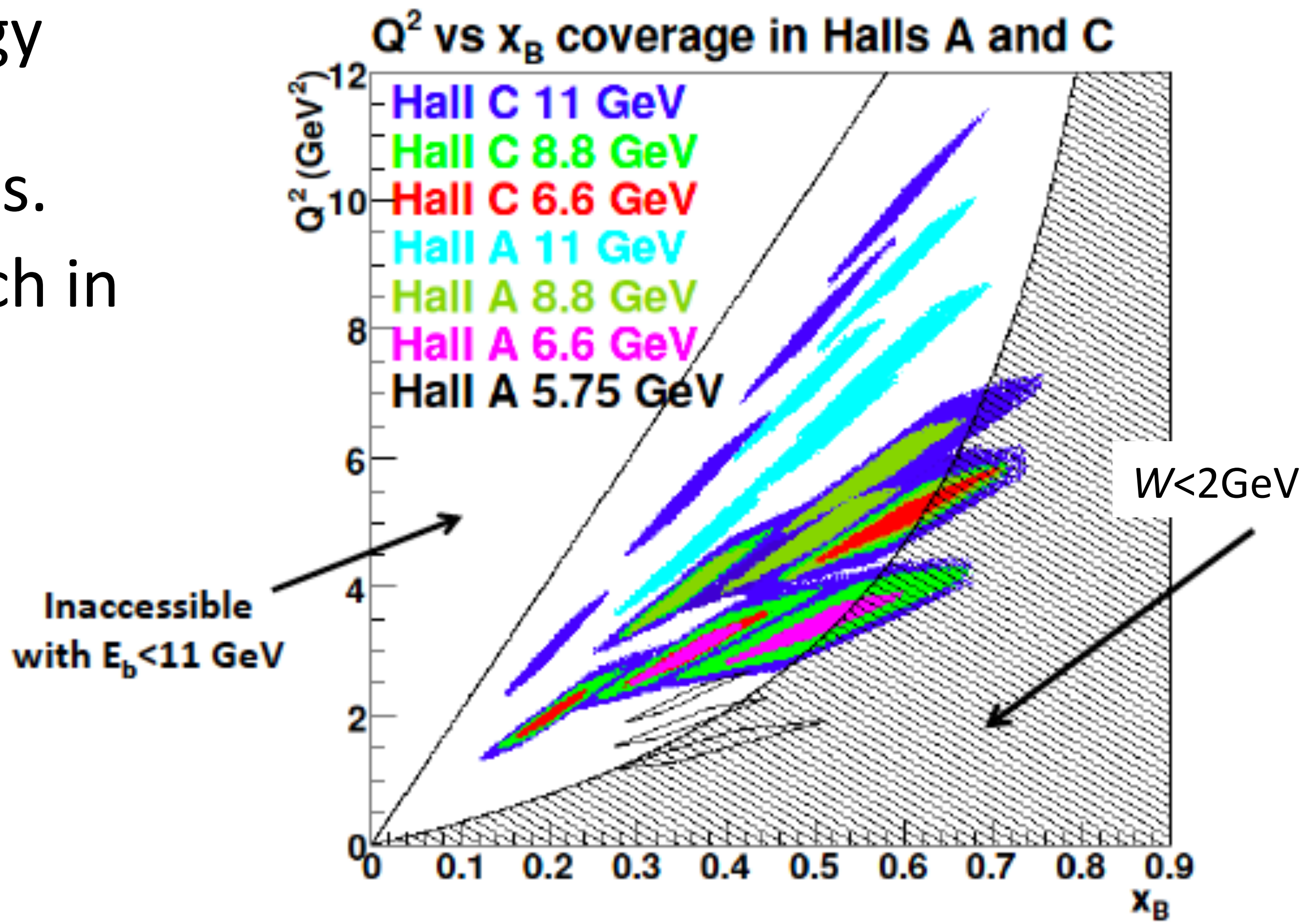


1st experiment to run after the 12-GeV upgrade

Start in 2014
for 1 year of data taking

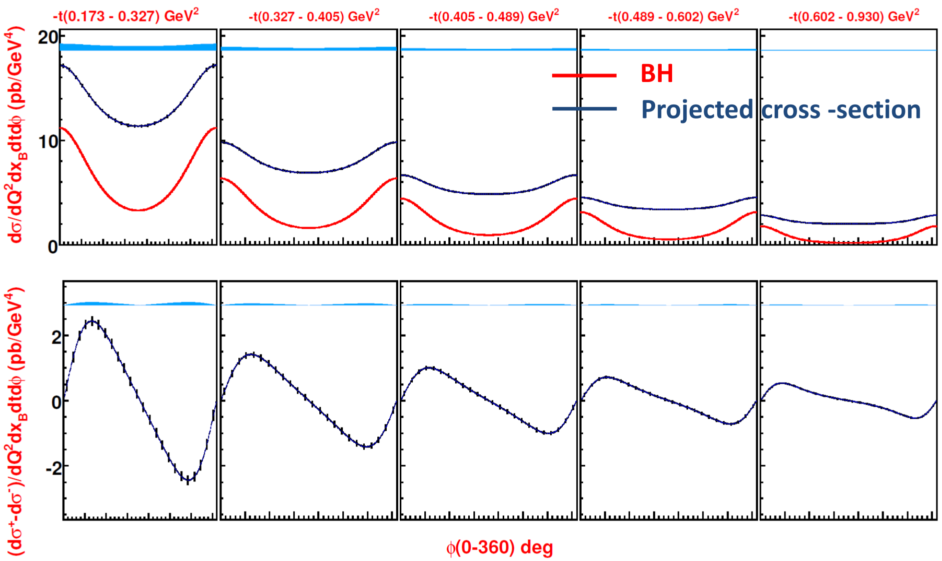
Impact of Hall A+C DVCS Kinematicss

- Multiple Energy settings at key *(x_B, Q^2)* settings.
- Expanded reach in x_B and Q^2.
- Beam time adjusted for ≈equal statistics in each bin

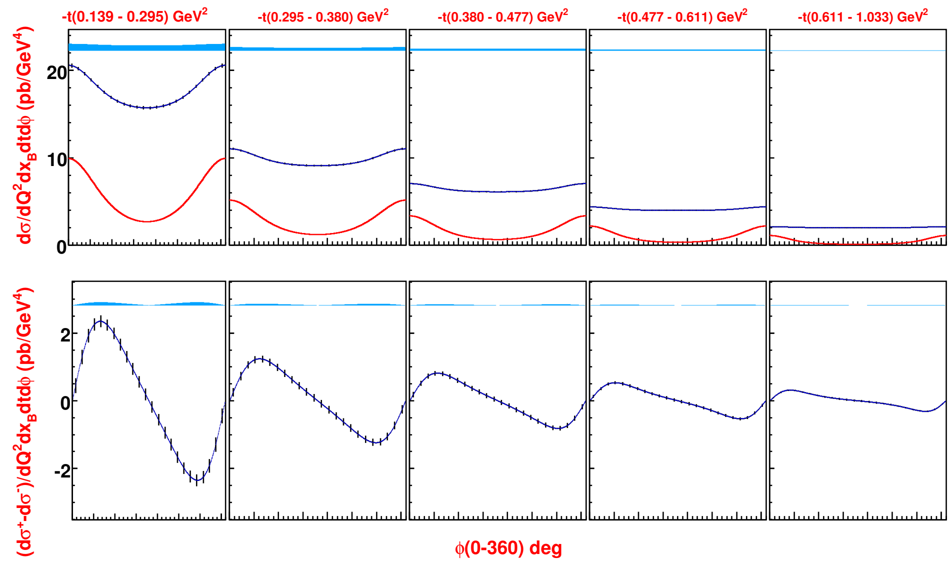


DVCS: Energy separation setting ($Q^2 = 3.4$ GeV^2, $x_B = 0.5$)

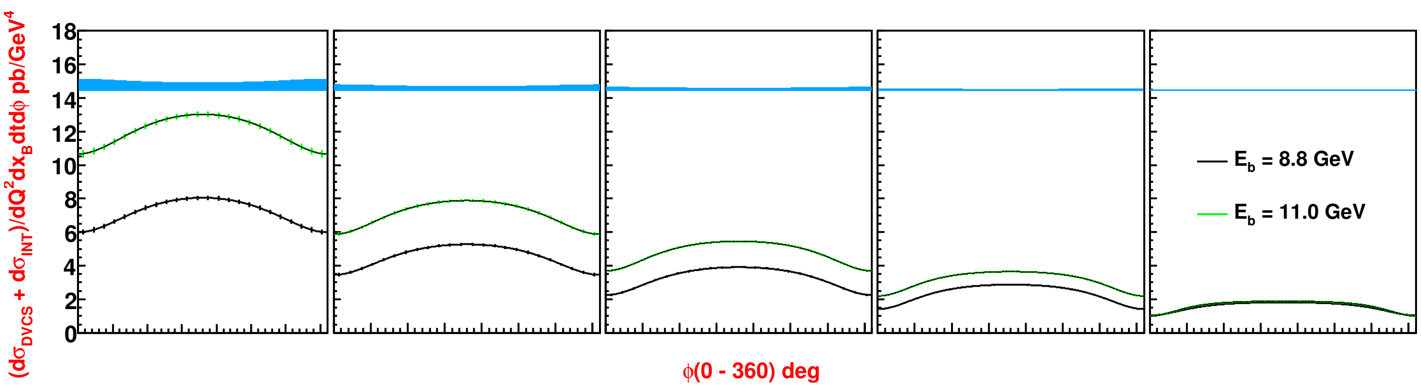
$E_b = 8.8$ GeV



$E_b = 11$ GeV



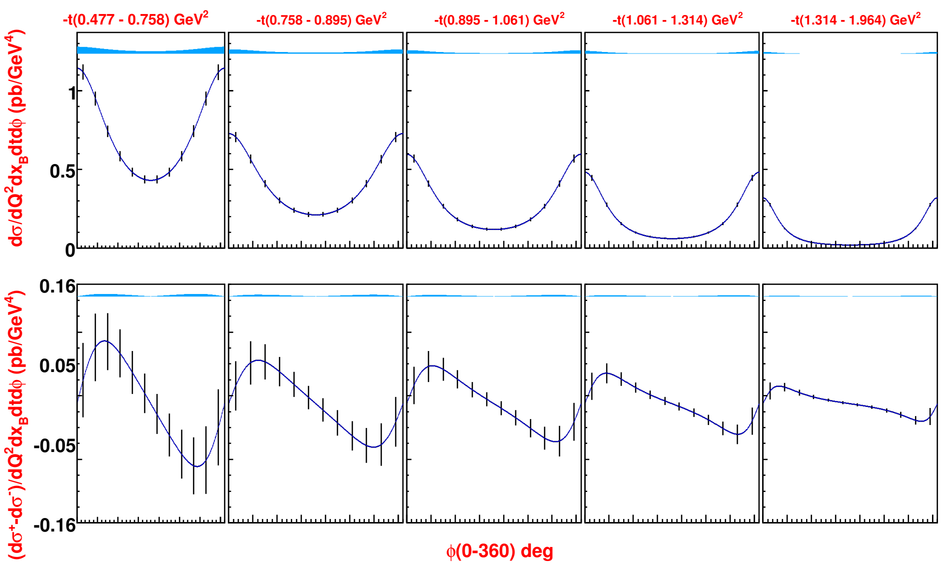
Cross section as a function of ϕ for different bins in t



Cross section after BH subtraction: large variation with E_b

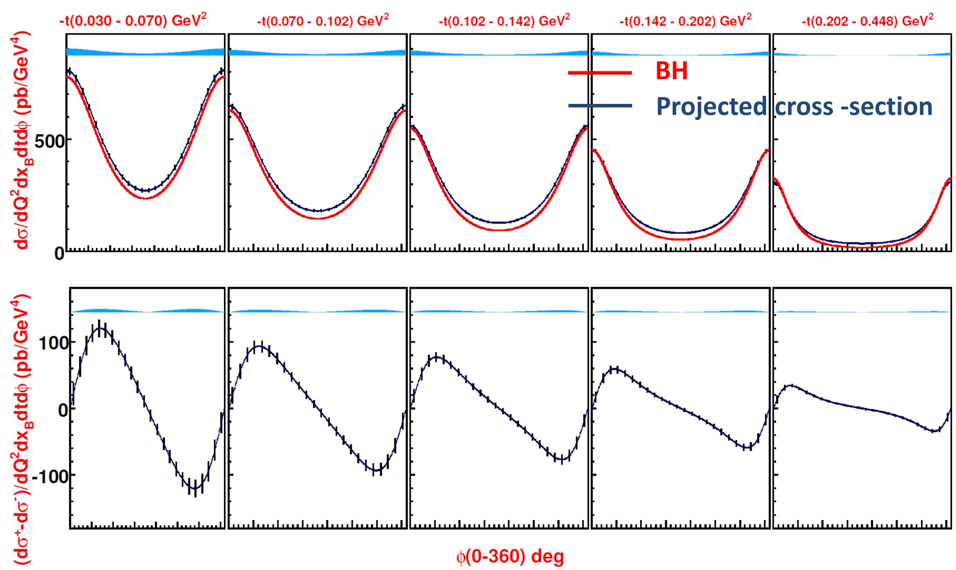
DVCS: high-Q^2 and low-x_B extension

$Q^2 = 10$ GeV^2, $x_B = 0.6$



12 days

$Q^2 = 3$ GeV^2, $x_B = 0.2$



1 day

The next 20 years of DVCS/DVMP experiments

- 5 years
  - Precision tests of factorization with Q^2 range ≥ 2:1 for
    - $x_B \in [0.25, 0.6]$. $t_{min}-t < 1$ GeV^2 + **COMPASS : $x_B \in [0.01, 0.1]$**
    - Proton unpolarized target observables
    - Im[DVCS*BH], Re [DVCS*BH], $|DVCS|^2$.
  - Longitudinal, target spin observables
    - Primary sensitivity to H, $\tilde{H}$, 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, recoil/spectator detection?
  - Polarized targets at COMPASS?
- 10-15 years:
  - Start physics with electron ion collider with $s \geq 1000$ GeV^2 and high Luminosity!

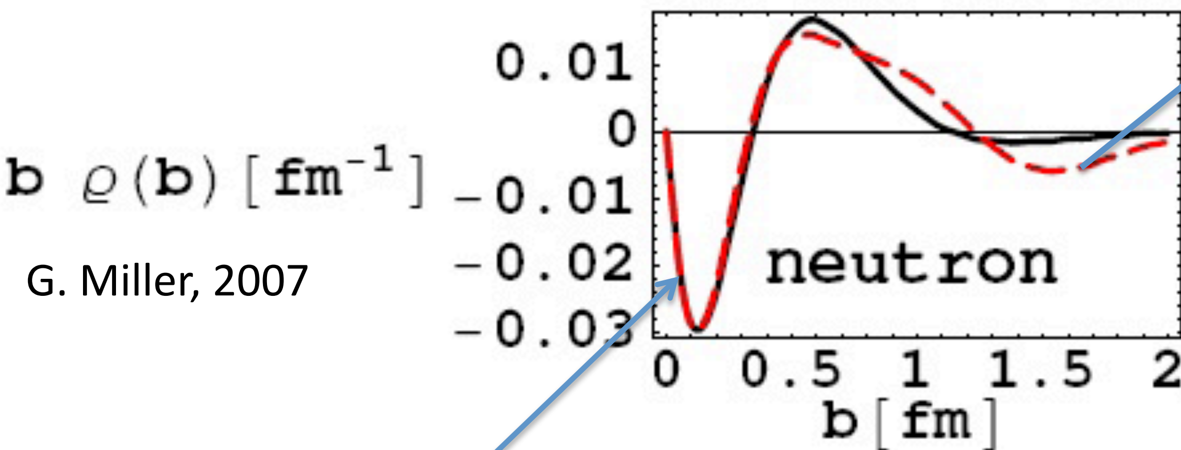
Back-up Slides

Highlights of Generalized Parton Distributions

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

GPDs and the Nucleon Form Factors

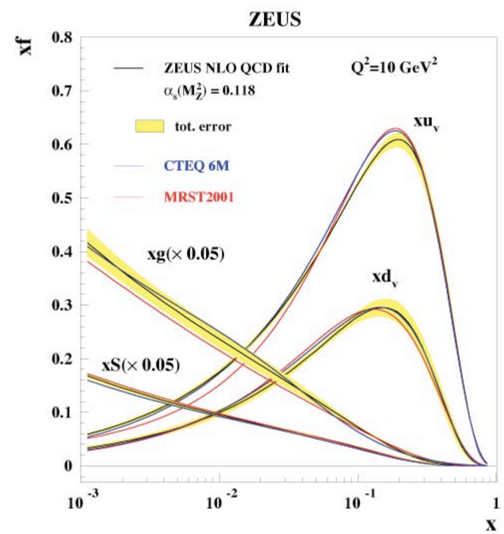
- $F_{1f}(-t) = \int dx\, H_f(x,0,t) = \int d^2\mathbf{b}\; e^{i\mathbf{b}\bullet\Delta_\perp} \int dx\; q_f(x,\mathbf{b})$
- $F_1(-\Delta^2) = \int d^2\mathbf{b}\; e^{i\mathbf{b}\bullet\Delta_\perp}\, \rho(\mathbf{b})$



G. Miller, 2007

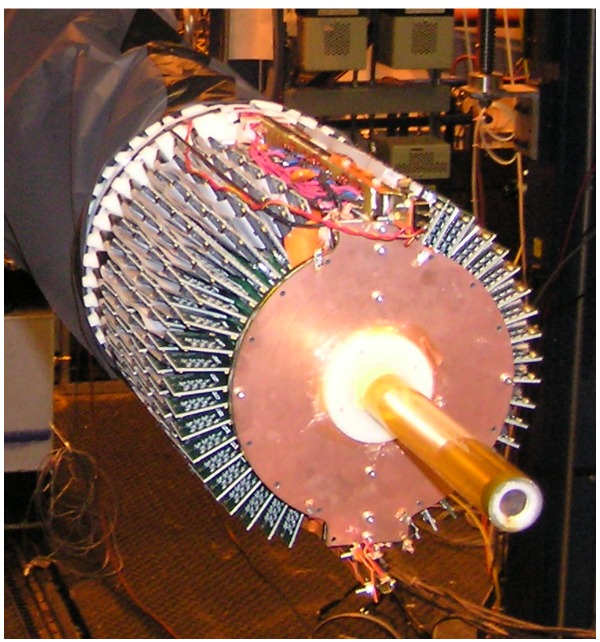
$n \rightarrow p\pi^-$

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

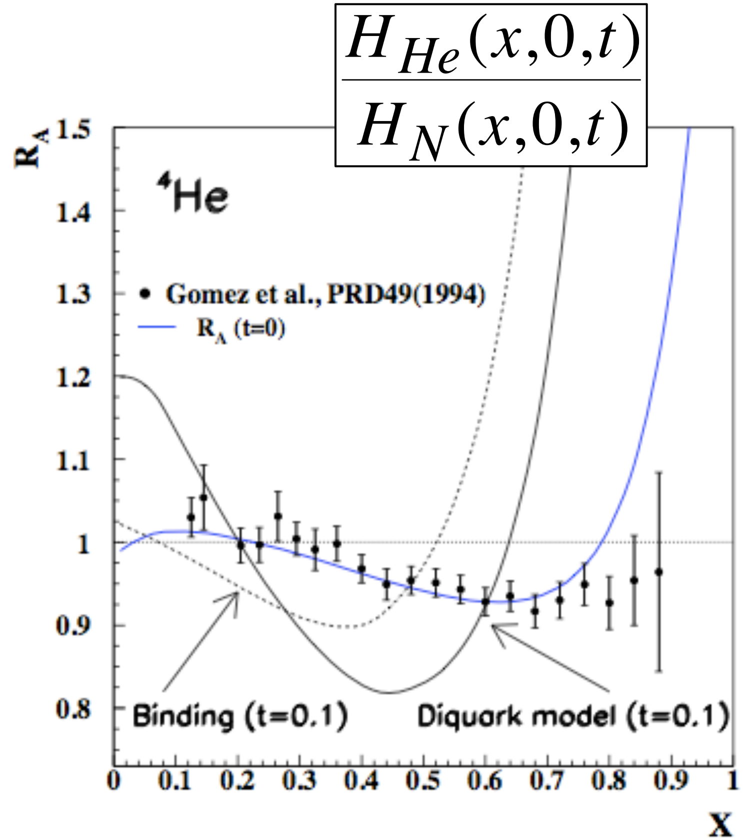


CLAS: Coherent ^{4}He(e,e'γα)

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



Upgrade planned for 12 GeV



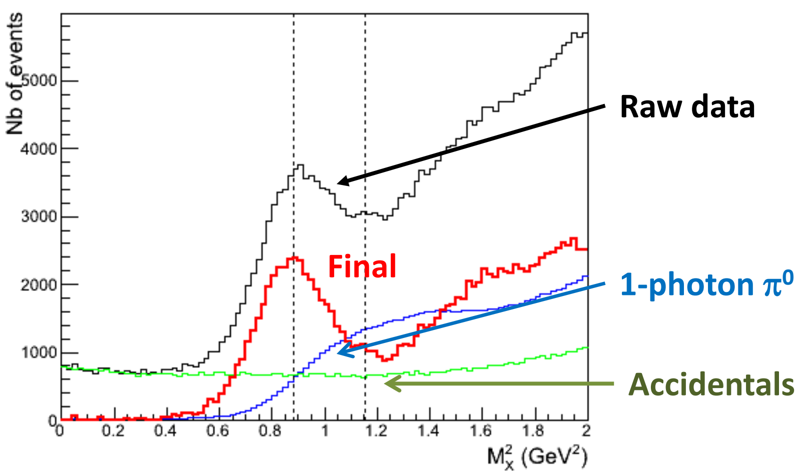
[t=0.0] →EMC effect,
[t=-0.1]→ GPD
(Liuti & Taneja, Guzey & Strickman)

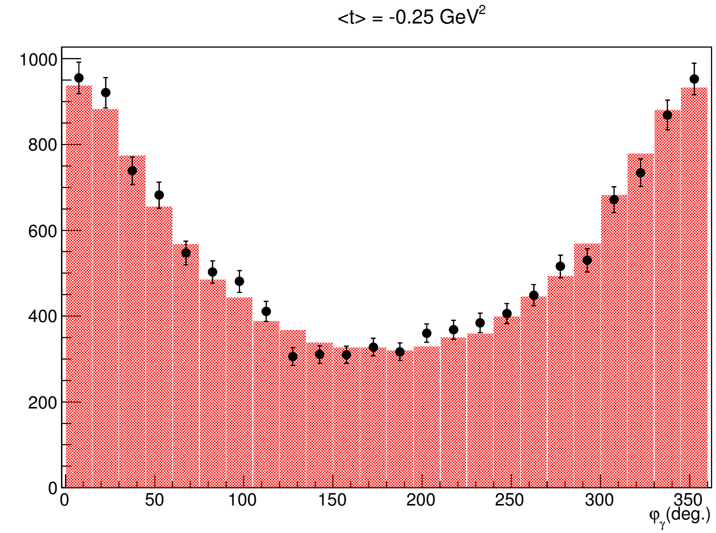
E07-007/E08-025 analysis

$$\sigma = \Gamma_{T2}^{DVCS} C_{T2}^{DVCS} + \Gamma_{T2}^{I} C_{T2}^{I} + \Gamma_{T2}^{\prime I} C_{T2}^{\prime I} \cos\varphi + \Gamma_{T3} C_{T3}^{I} \cos 2\varphi$$

$$N^{\mathrm{MC}}(\mathbf{i}_e) = \mathcal{L}\Big[C_{T2}^{DVCS} \underbrace{\int_{x\in\mathbf{i}_e} \Gamma_{T2}^{DVCS} \otimes \text{Acc.}}_{\text{MC sampling}} + \dots\Big]$$

$ep \to e\gamma X$ missing mass squared





$$\chi^2 = \sum_{\mathbf{i}_e} \frac{\left[N^{\mathrm{Exp}}(\mathbf{i}_e) - N^{MC}(\mathbf{i}_e)\right]^2}{\left[\sigma^{\mathrm{Exp}}(\mathbf{i}_e)\right]^2} \Rightarrow C_{T2}^{DVCS}, C_{T2}^{I}, C_{T2}^{\prime I}, C_{T3}^{I}$$

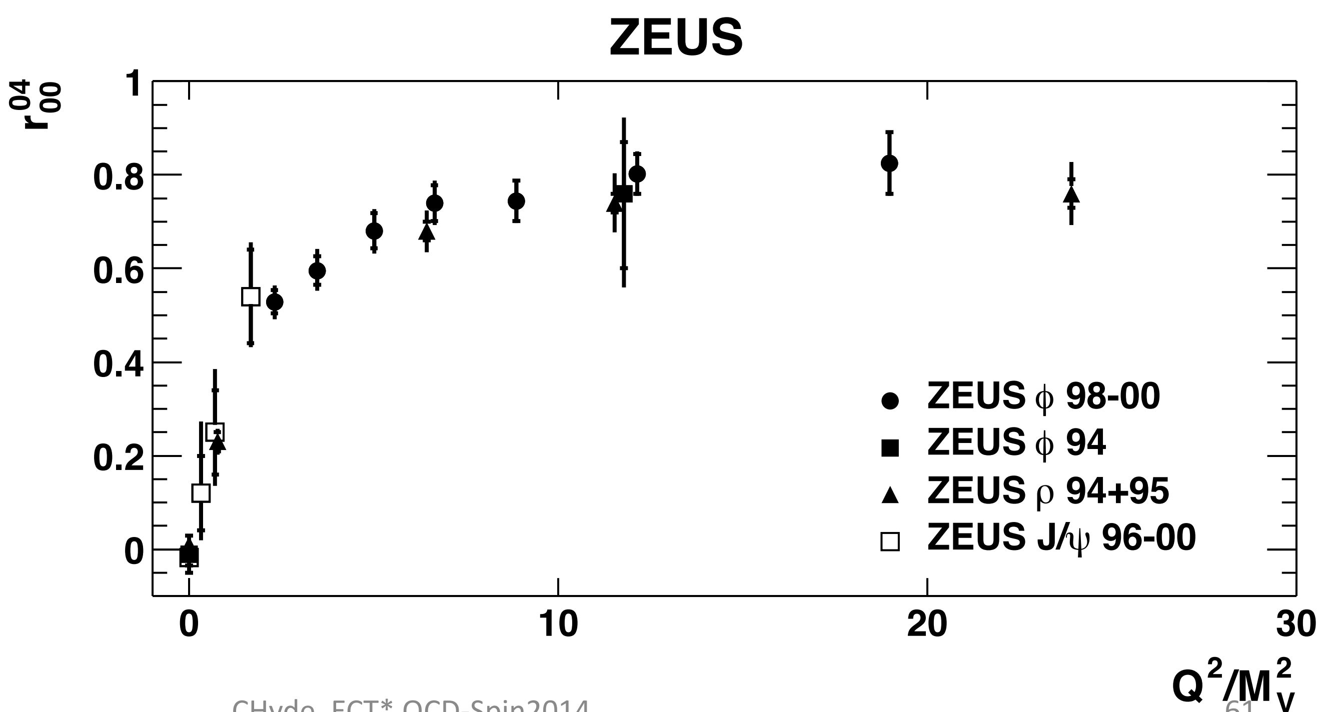
A. Martí

σ_L/σ_T in vector meson production at HERA

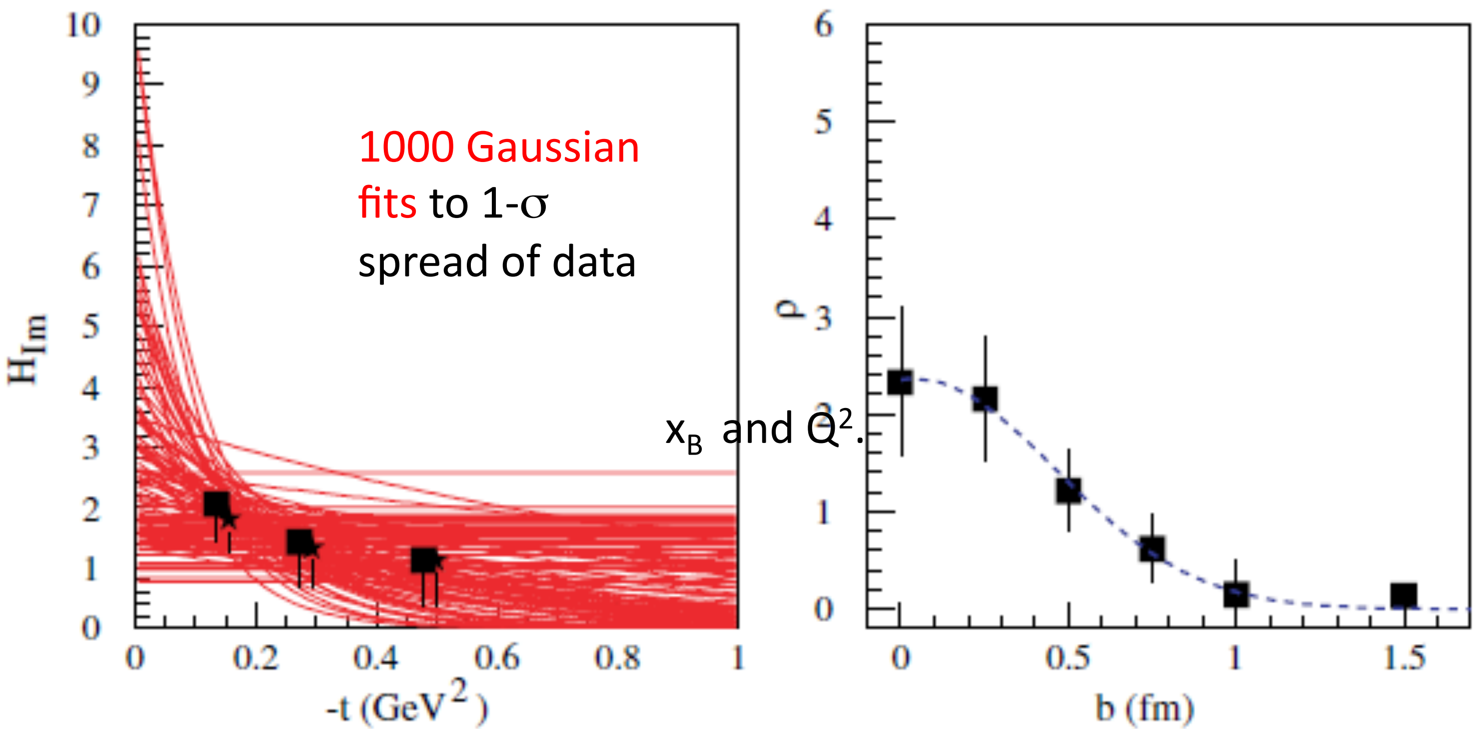
- SCHC: $\rho \to \pi\pi$, $\omega \to \pi\pi\pi$, $\phi \to KK$
  - Validate SCHC from decay angular distribution (Schilling & Wolf)
  - Extract $d\sigma_L$ from

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

- 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 $d\sigma_T$?



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



"skewed" H_{Im}

"unskewed" H_{Im}

(fits applied to « unskewed » data)

Spatial Imaging at $\xi = 0$ and at $x = \xi$

Charles Hyde

Informal Pre-Town Meeting at JLab

August 13 - 15, 2014

Regge-Inspired Model

✦M.Diehl, P. Kroll, *Eur.Phys.J. C***73** (2013) 2397.

- $H_f(x,0,\Delta^2) = q_f(x) exp[\Delta^2 B_{1f}(x)]$
  $E_f(x,0,\Delta^2) = e_f(x) exp[\Delta^2 B_{2f}(x)]$

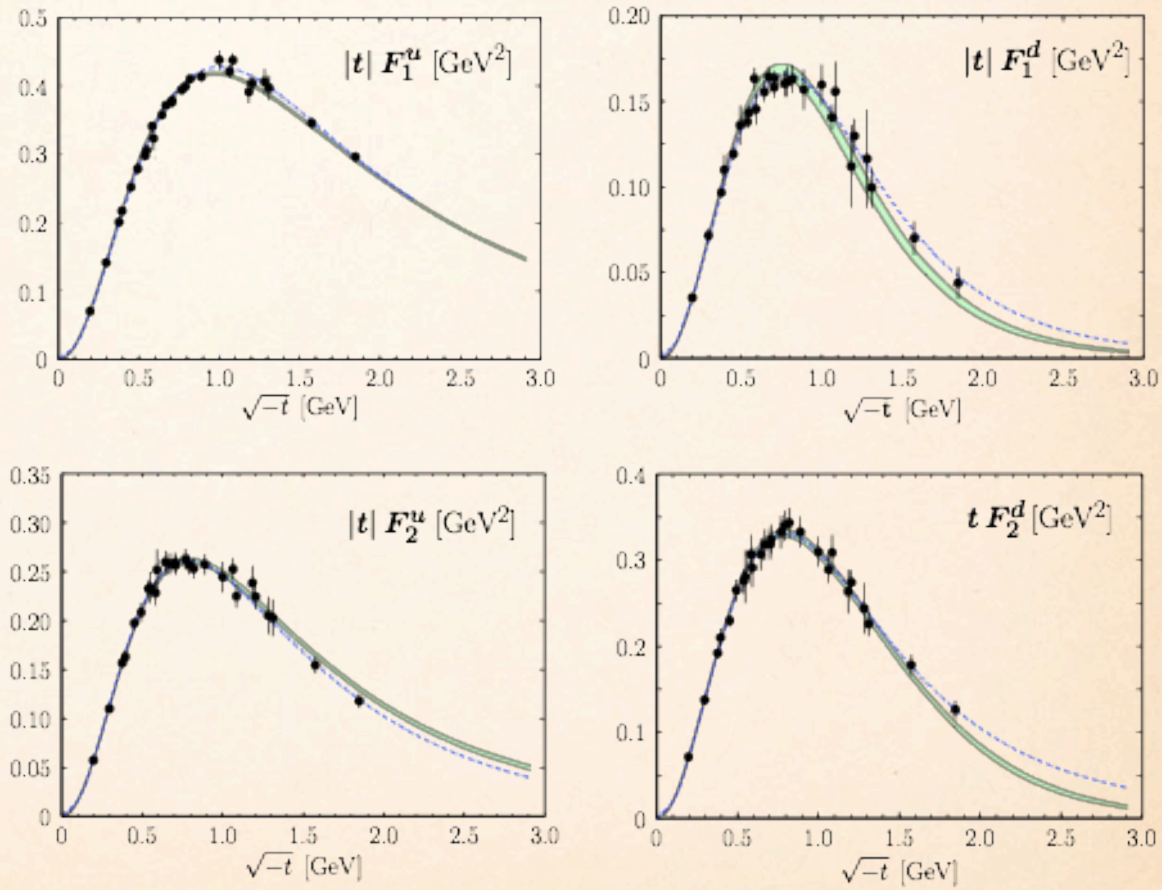
  - $q_f(x)$: *ABM2011*
    $e_f(x) = \kappa_f N_f\, x^{-\alpha f} (1\text{-}x)^{-\beta f} (1\text{-}\gamma_f\, x^{1/2})$

  - $B_{nf}(x) = \alpha_f' (1\text{-}x)^3 log(1/x) + A_{nf}\, x(1\text{-}x)^2 + B_{nf} (1\text{-}x)^3$

- Fit:
  $\int dx\, H_f(x,0,\Delta^2) = F_{1f}(-\Delta^2)$
  $\int dx\, E_f(x,0,\Delta^2) = F_{2f}(-\Delta^2)$

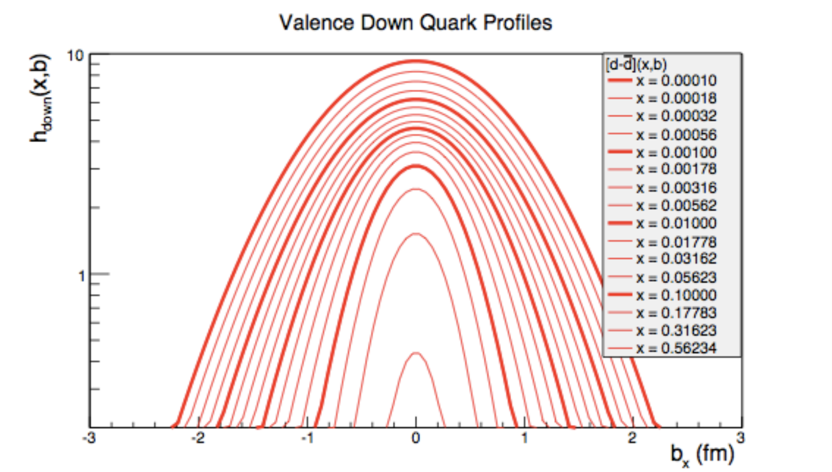
Form Factor Fits

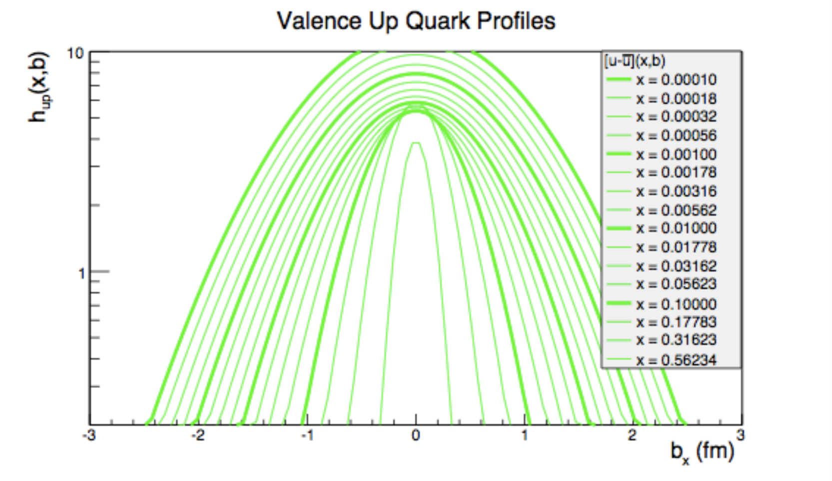
- Non-trivial t-dependence from x-dependent simple Regge slopes
- All the funny little wiggles in $G_{E,M}(-t)$ are resolved into a smooth behavior of the flavor separated $F_{1,2}$



Spatial Densities at $\xi = 0$

- *x*-dependent *t*-slope *B(x)*
  - Simple Gaussians in impact parameter space (b_x, b_y)
- Gaussian width strongly *x*-dependent
  - Negative charge density at center of neutron
- Scale: $\mu^2 = 2\ \text{GeV}^2$.



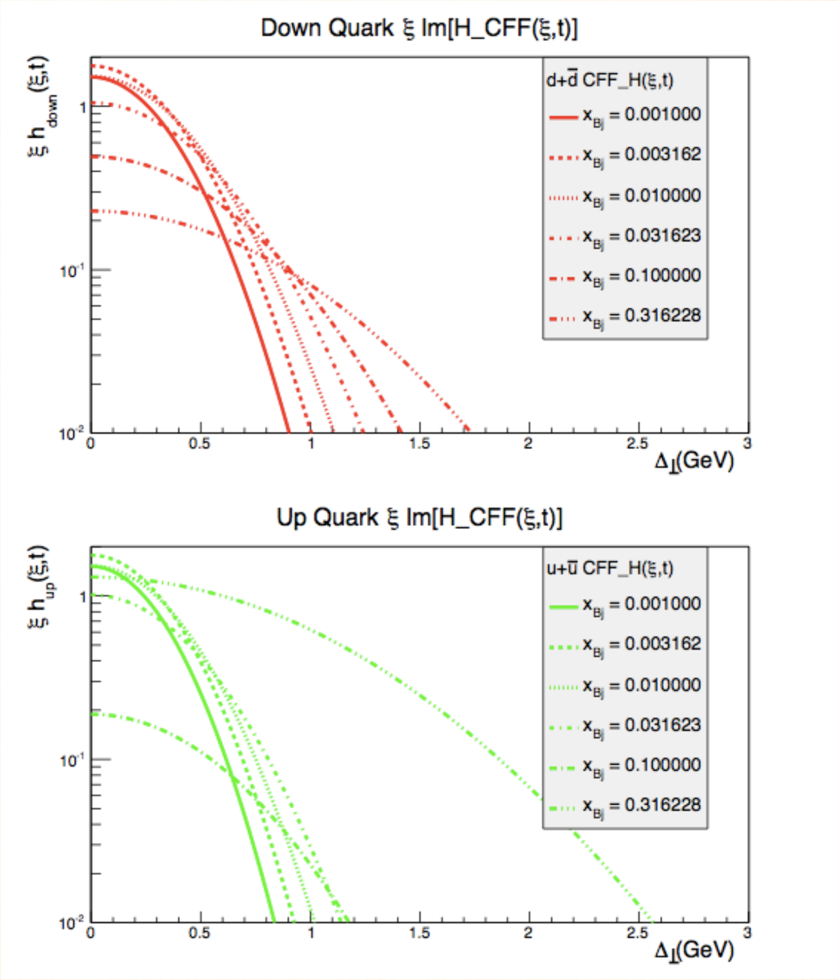


Double-Distribution GPDs at $x=\pm\xi$

- Compton Form Factor: $\xi = x_{Bj}/(2-x_{Bj})$
  $Im[\mathcal{H}_f(\xi, \Delta^2)] = \pi[H_f(\xi, \xi, \Delta^2) - H_f(-\xi, \xi, \Delta^2)]$
- $$\xi \, \mathrm{Im}\left[H_f\left(\xi,\Delta^2\right)\right] = \pi \int_0^{x_{Bj}} d\beta \left[q_f(\beta) + \bar{q}_f(\beta)\right]\left[h_f(\alpha,\beta)\right]_{\alpha=1-\beta/\xi} e^{\Delta^2 B_{1f}(\beta)}$$
- Profile functions $h(\alpha,\beta)$ arbitrary:
  - Use: $$h(\alpha,\beta) = N_1 \frac{\left[\left(1-|\beta|\right)^2 - \alpha^2\right]}{\left(1-|\beta|\right)^3}$$
- M. Burkardt, arXiv:0711.1881 $$\Delta^2 = -\frac{4\xi^2 M^2 + \Delta_\perp^2}{1-\xi^2}$$
  $\Delta_\perp$: Fourier Conjugate to $\mathbf{r}_\perp$, the transverse spatial separation between the active parton and the transverse spatial Center-of-Momentum of ***the spectator system***.

Compton Form Factors on the $x=\pm\xi$ line

- Compton Form Factors:
  $x = \pm\xi$ profiles of GPDs:
- Radial size:
  strongly ξ-dependent
- Flavor, gluon variation is measureable
  - Intriguing insight into dynamics without sum-rules or extrapolation to $\xi=0$



IMAGING

- In the Photoshop era, you don’t have to be a Philosopher or a Surrealist to understand that the image of an object is **not** the object.

- $[H_f(\xi, \xi, \Delta^2) - H_f(-\xi, \xi, \Delta^2)]$ **is** an image of the proton.
  - It is a non positive-definite quantum transition density, but it still can be interpreted physically.