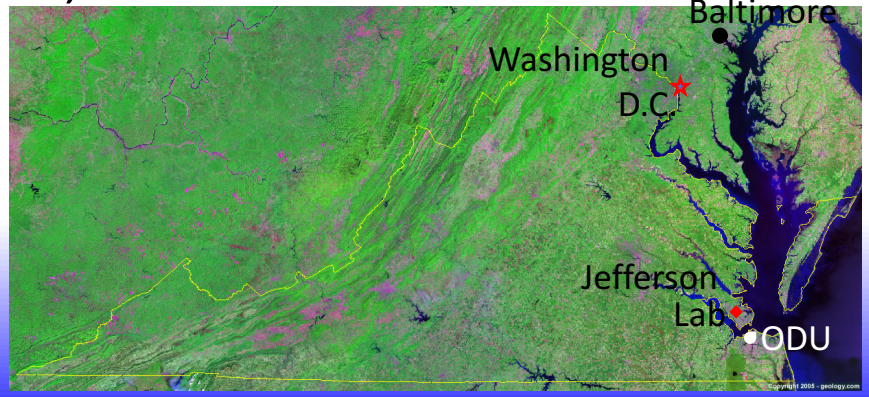
XXVI International Workshop on Deep Inelastic Scattering and Related Subjects

2018

Generalized Parton Distributions with Jefferson Lab @ 12 GeV

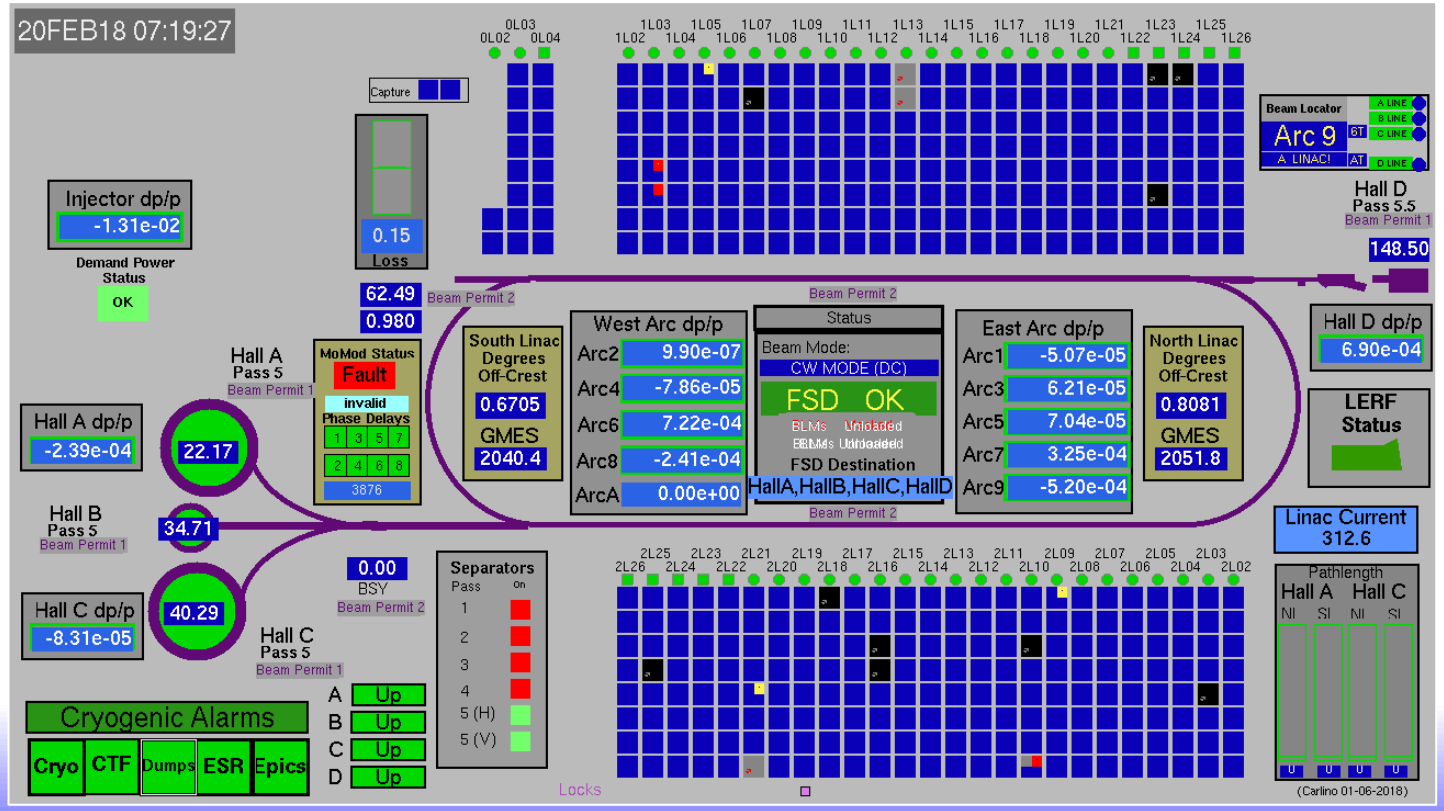
Charles Hyde
Old Dominion University
Norfolk Virginia, USA



OLD DOMINION UNIVERSITY

12 GeV Upgrade Complete!

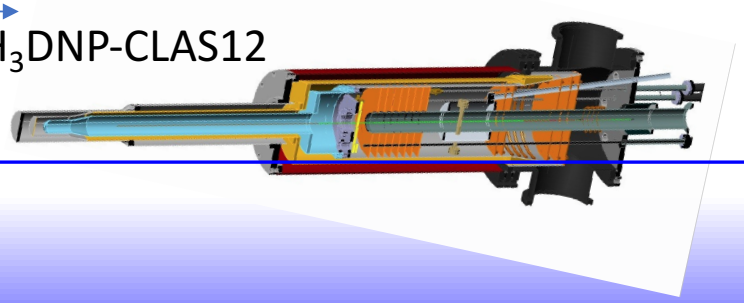
- Simultaneous 4-Hall Operation
- Full Linac design power = 300μA•2GV = 600 KWatt



Deep Virtual Exclusive Scattering

- Fully exclusive final states
  - e p → e p γ, ep → e N meson
  - e d→ e pn γ, etc.
- Nuclei
  - e d → e d γ
  - e^{4}He→e^{4}He γ
- Polarized electrons, longitudinally polarized p, d

$\vec{NH_3}$DNP-CLAS12

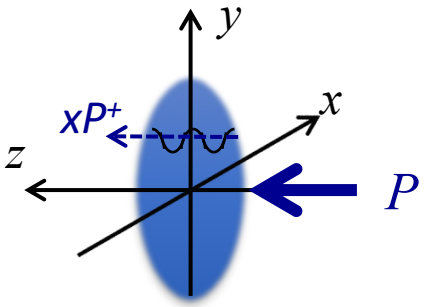


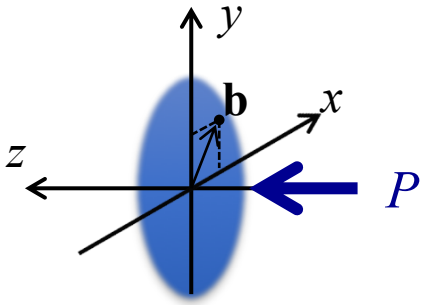
- Transverse polarized targets:
  - HD_{ice} in CLAS12
  - (test beam studies in preparation)
  - ^{3}He with SOLiD (Hall A),
  - NH_3, ND_3 with TCS (Hall C)
- Time-like Compton Scattering (TCS)
  - $\gamma p \rightarrow l^+ l^- p$

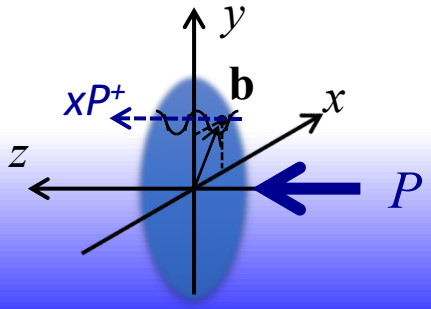
Partonic Structure of the Nucleon

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

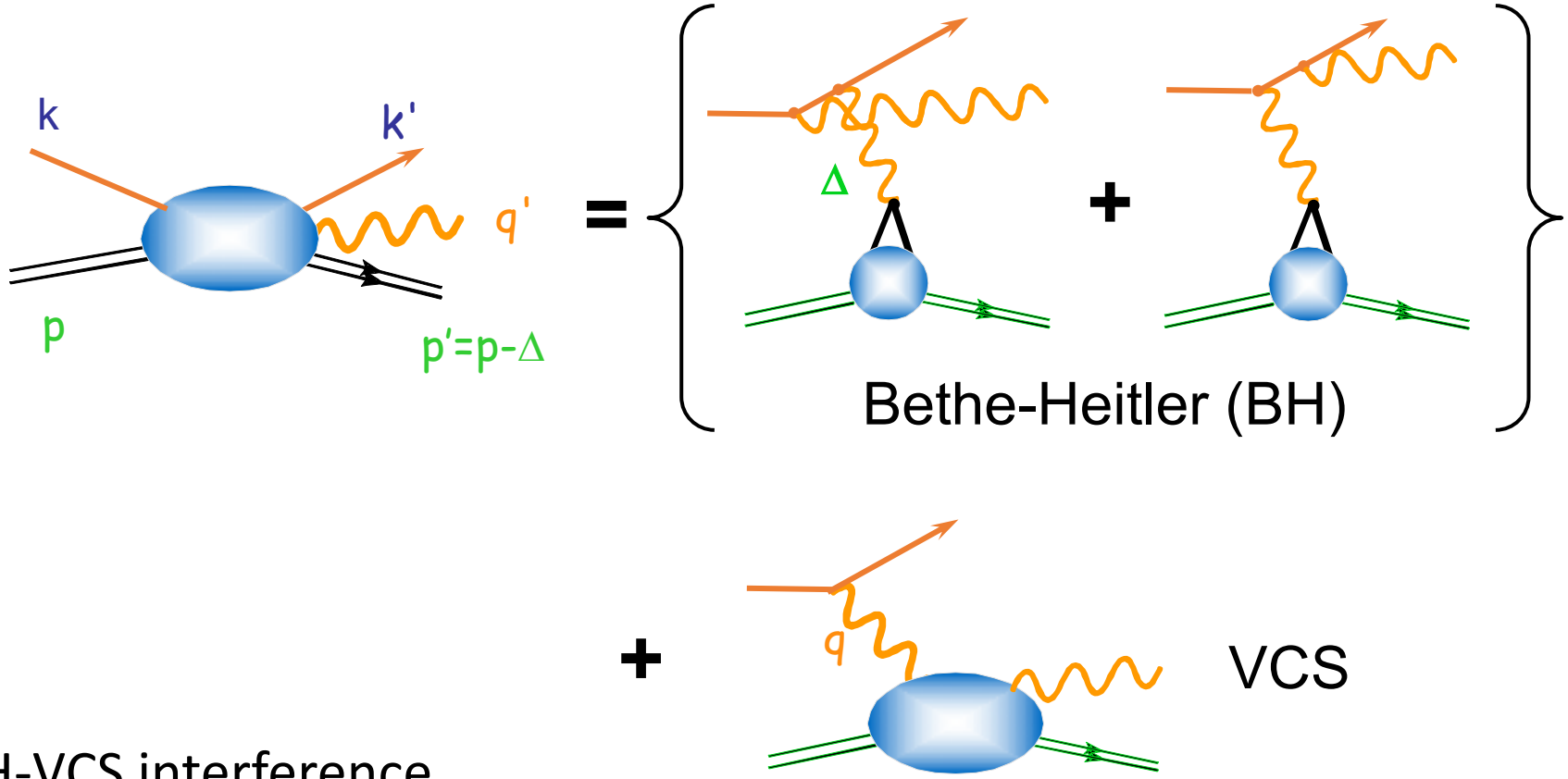






Bethe-Heitler (BH) and Virtual Compton Scattering (VCS)

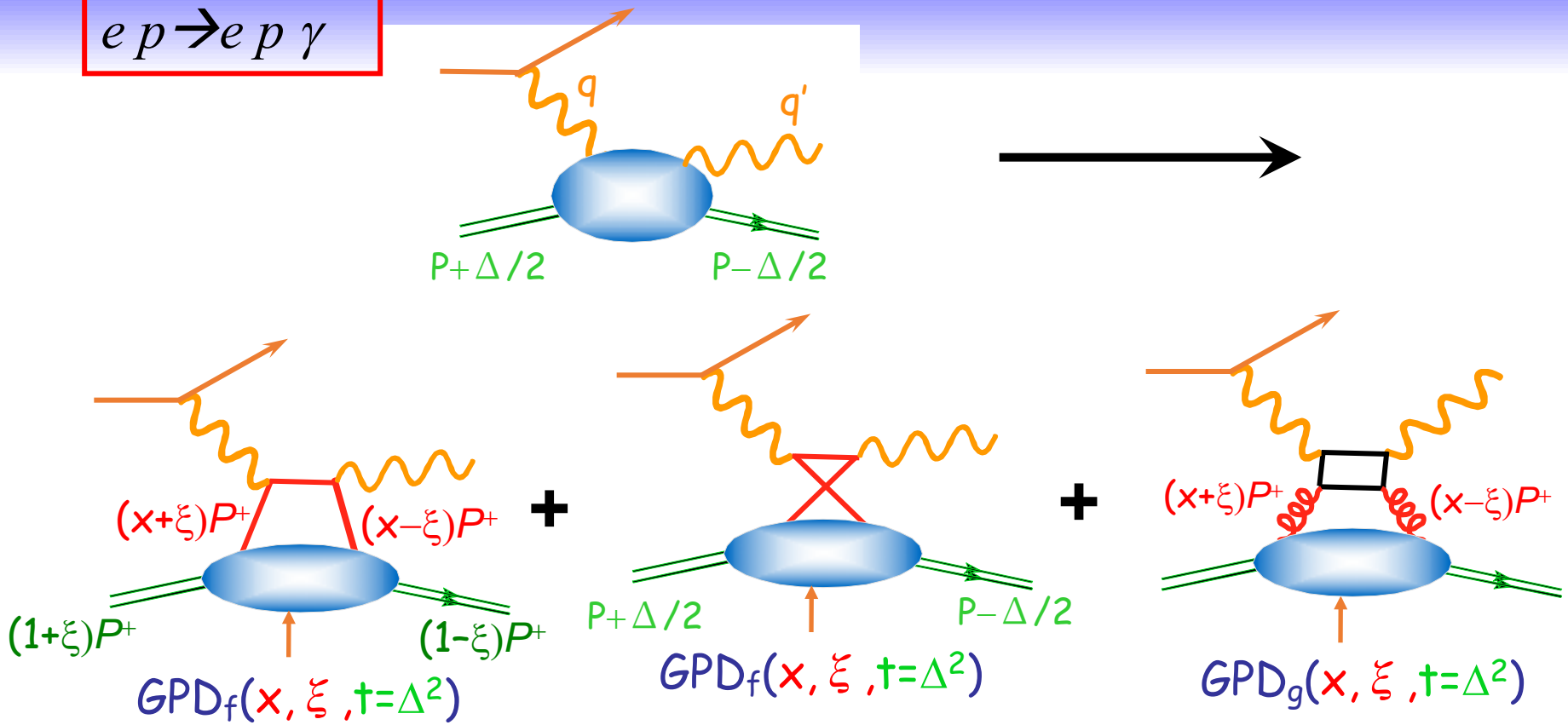
$e\,p \rightarrow e\,p\,\gamma$



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

QCD Factorization of DVCS (Co-Linear)

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

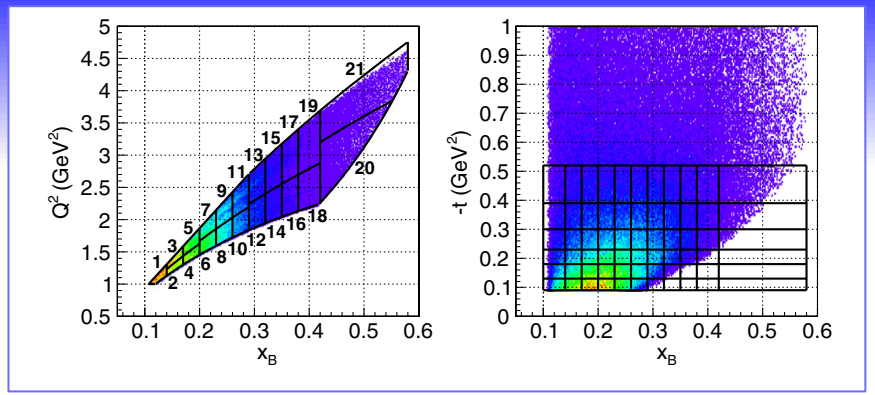


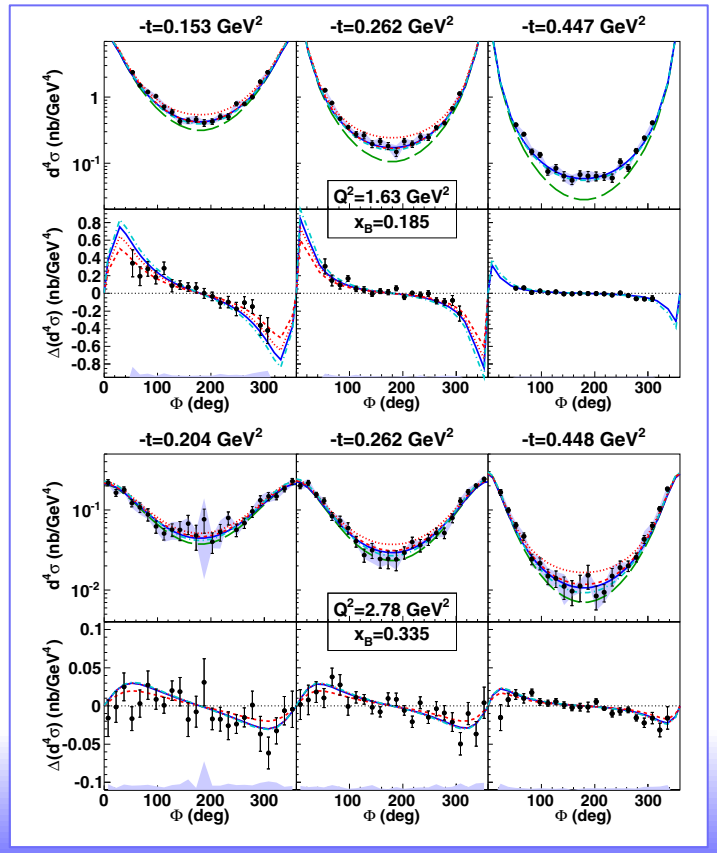
- Symmetrized Bjorken variable: $\xi = \dfrac{-(q+q')^2}{2(q+q')\cdot P} \xrightarrow[\Delta^2 << Q^2]{} \dfrac{x_B}{2-x_B}$

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

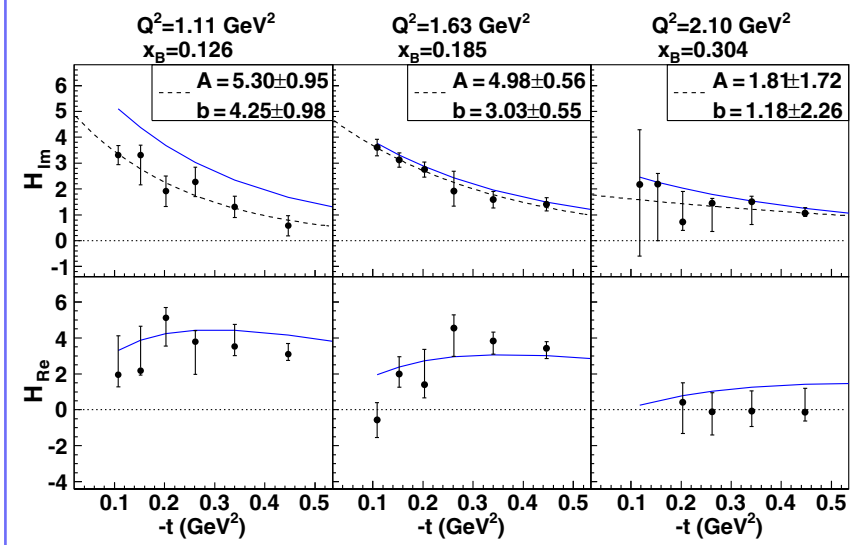
CLAS: H($\vec{e}$,e'pγ)

- K.Jo, *et al.* [CLAS], PRL **115** (2015)





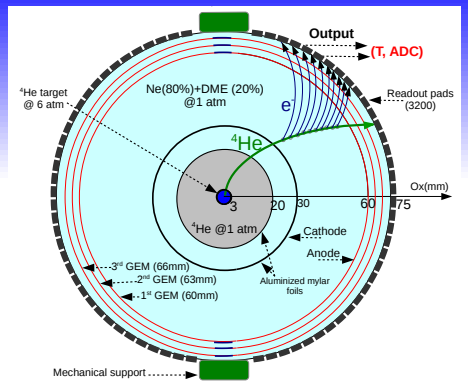
- Constrained Fits to Re, Im [H(x,t)]

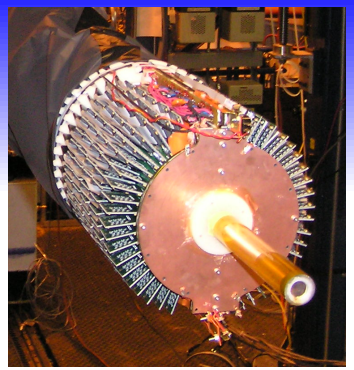


- Im[H(x,t)] ~ $e^{b(x)t}$
  - ➜ b decreases as x_B increases
  - ➜ Proton is shrinking!

CLAS: $^4He(\vec{e},e'\gamma\alpha)$

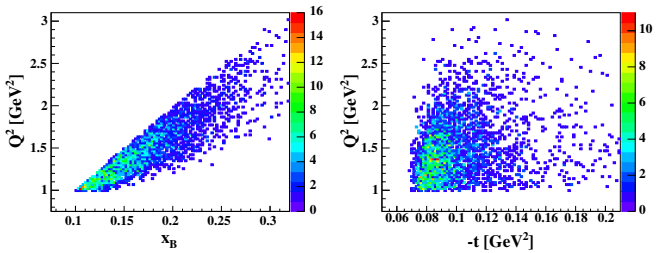
M.Hattawy *et al.*, PRL **119** (2017)

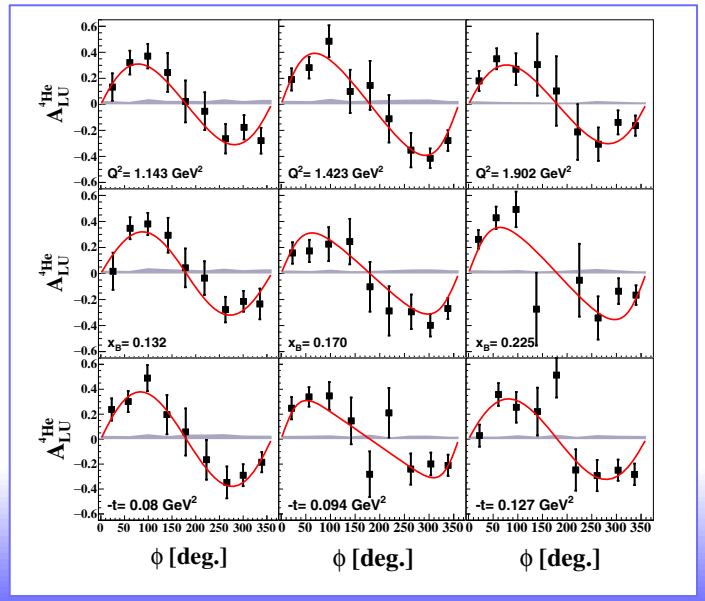


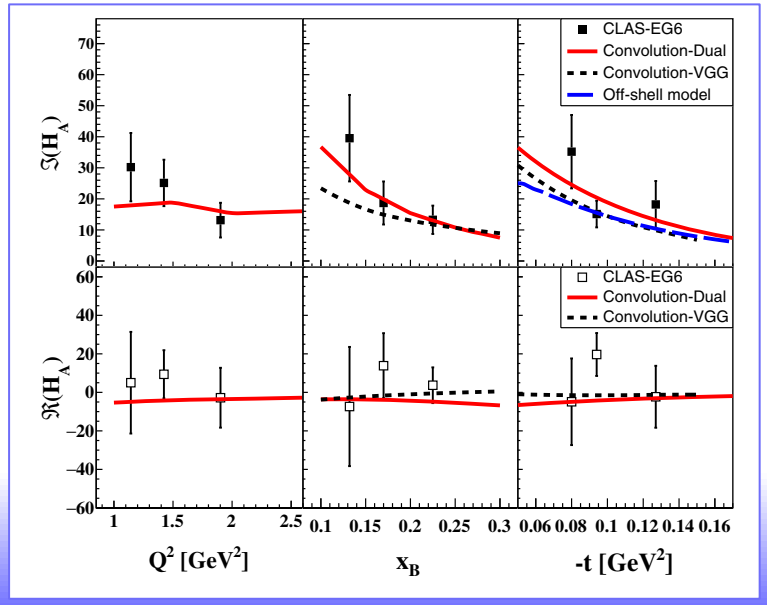


- Radial TPC for recoil α
  - 250mm z ⊗ 160 mm ϕ
- Only one GPD: $H(x,\xi,t)$
  - Compton Form Factor $\mathcal{H}(\xi,t)$

$$A_{LU}(\phi) = \frac{\alpha_0(\phi)\Im(\mathcal{H}_A)}{\alpha_1(\phi)+\alpha_2(\phi)\Re(\mathcal{H}_A)+\alpha_3(\phi)[\Re(\mathcal{H}_A)^2+\Im(\mathcal{H}_A)^2]}.$$



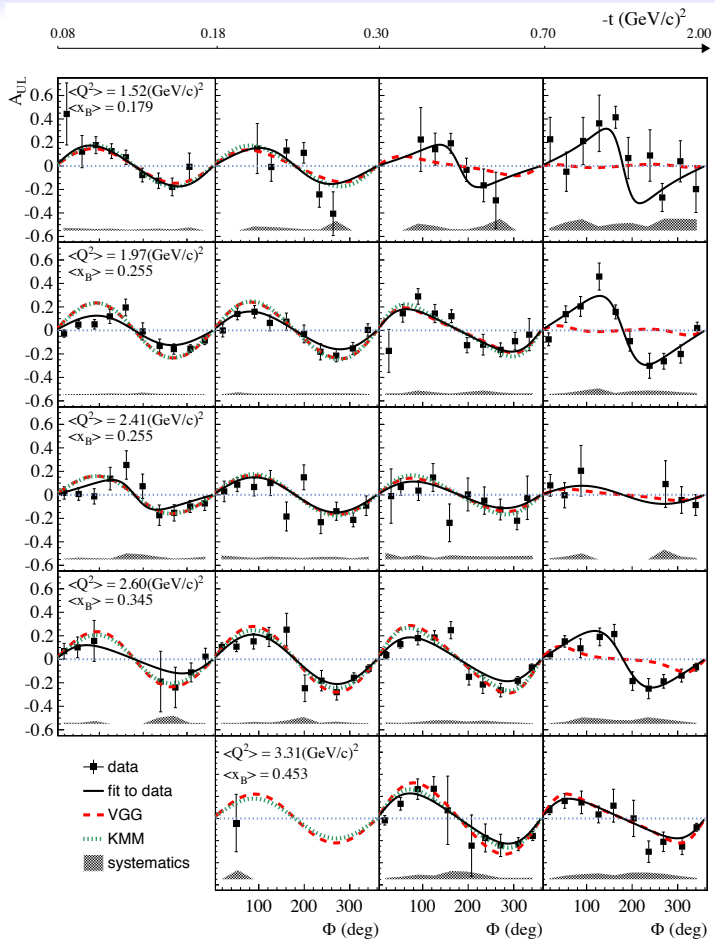


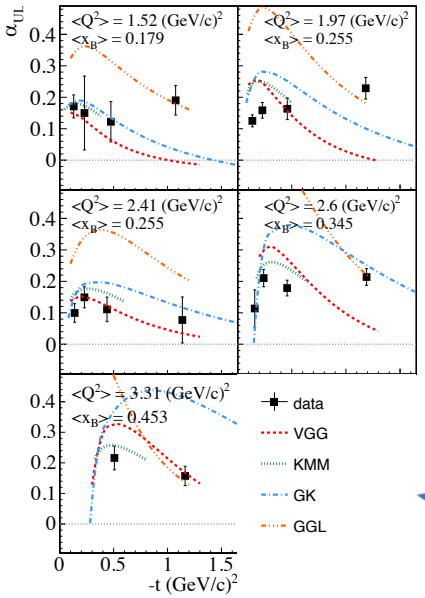


CLAS: Longitudinally Polarized Protons Target-Spin Asymmetries

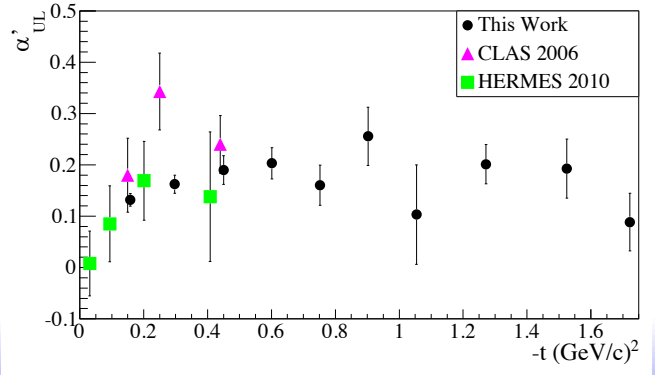
A_{UL}

Q^2, x_B



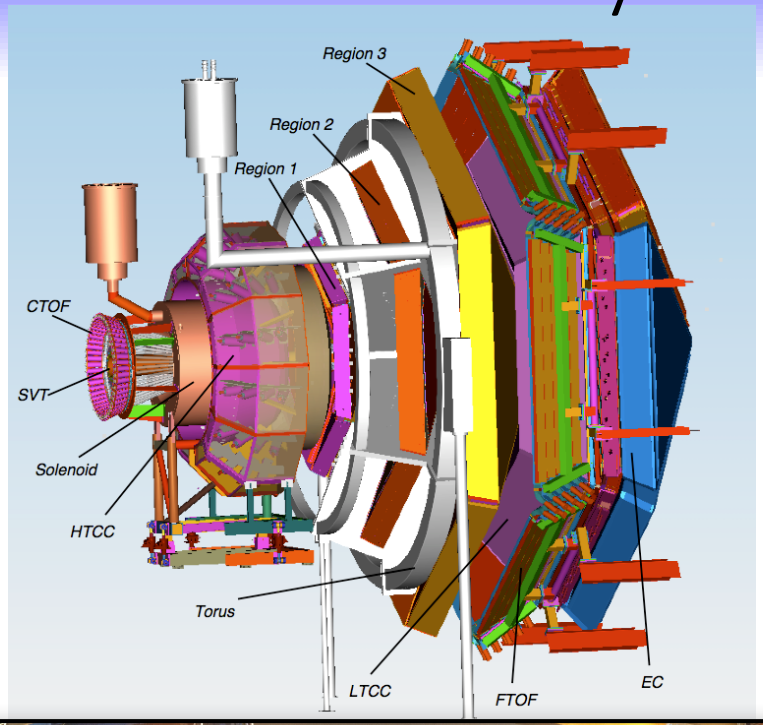


S. Pisano, *et al.*, Phys.Rev. **D91** (2015) 5, 052014

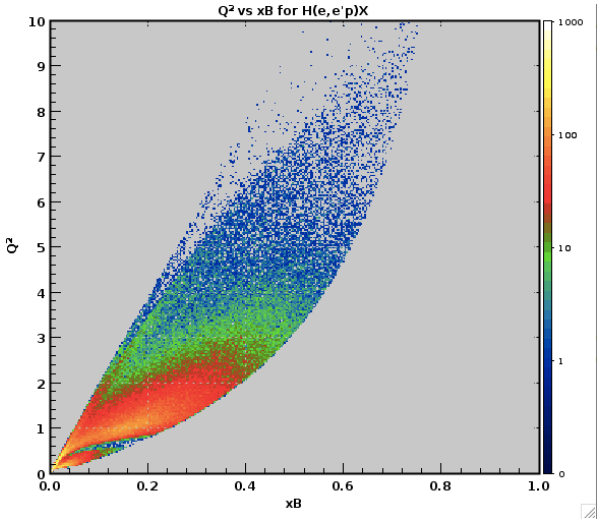


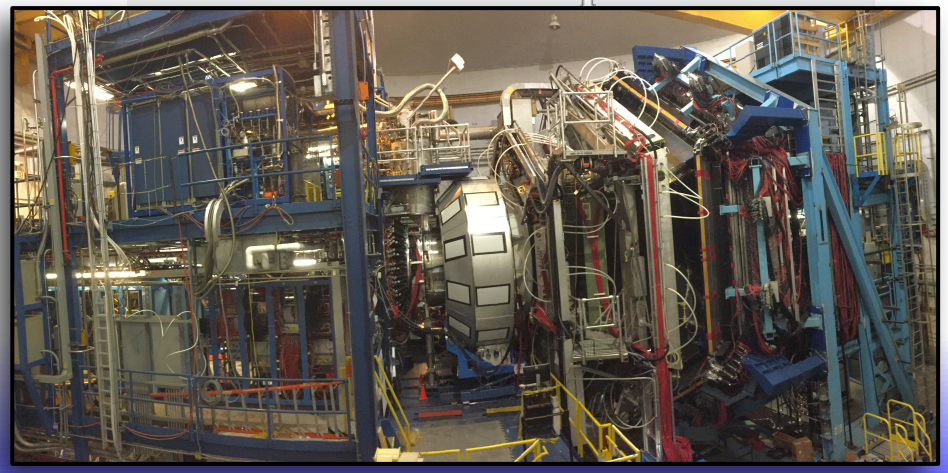
- Spatial distribution of quark helicity
- On to to 11 GeV!

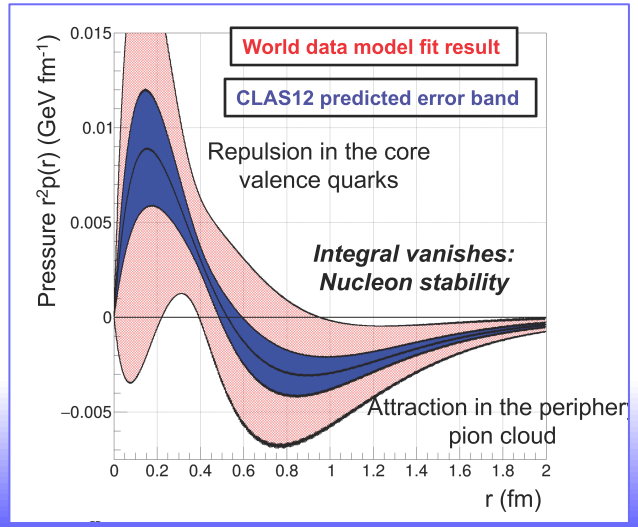
CLAS12 First Physics Run: Jan 11-May 7 2018



4 hours @ 10.6 GeV
Candidate Exclusive events H(e,e'p…)





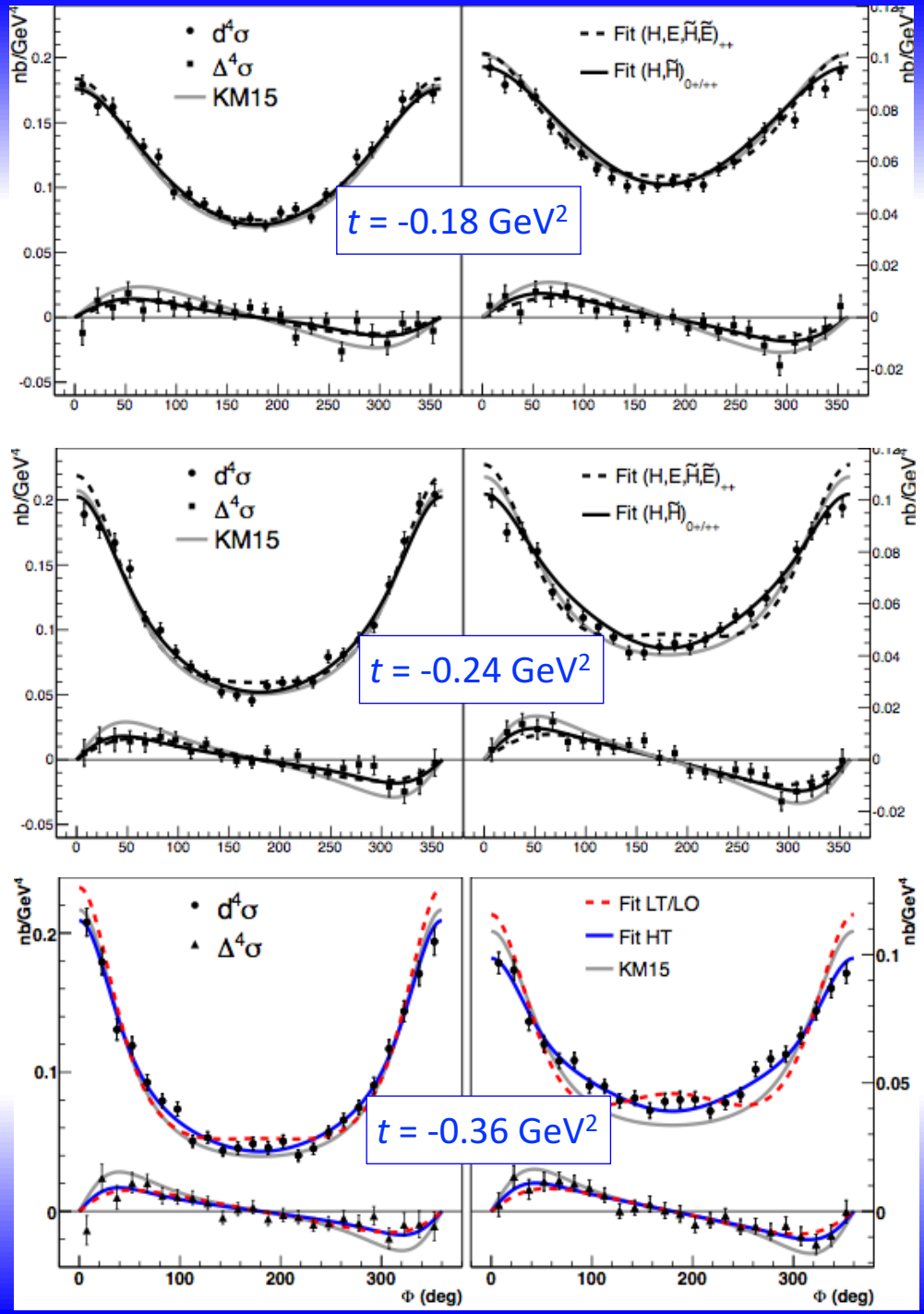


Hall A: H(e,e'γ)

x_B = 0.36, Q^2=1.5, 1.75, 2.0 GeV^2

M.Defurne *et al., "A Glimpse of Gluons"*, Nat. Comm.**8** (2017)

- Q^2 = 1.75
  - E_e = 4.455 (left), 5.55 (right) GeV
- $d^4\sigma/[dQ^2 dx_B dt d\phi_{\gamma\gamma}]$
  $\Delta^4\sigma = d^4\sigma(h=+) - d^4\sigma(-)$
- Solid Grey Line = KM2015
- Dashed: Leading Twist / Leading Order (LT/LO) fit with V. Braun Kinematic Twist-4 constrained by LO/LT:
  - Global fit at each $-t$: $3 \otimes Q^2$ & $2 \otimes E_e$
  - Poor χ^2

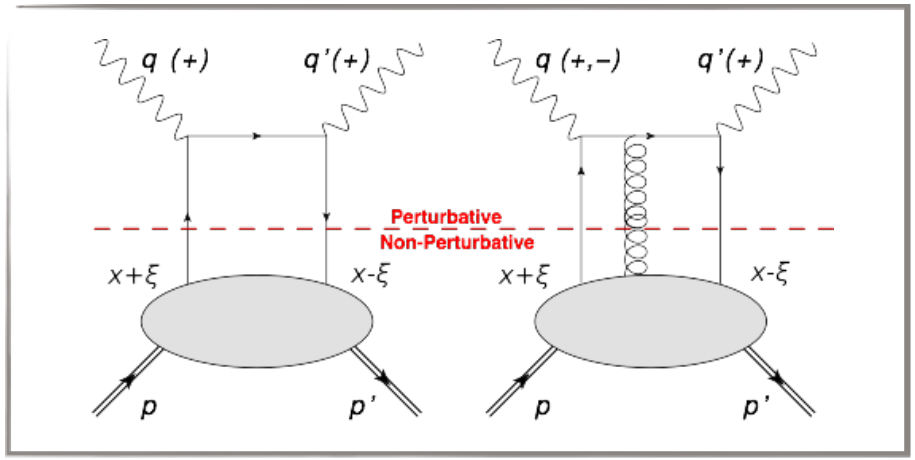


Two Fit-Scenarios

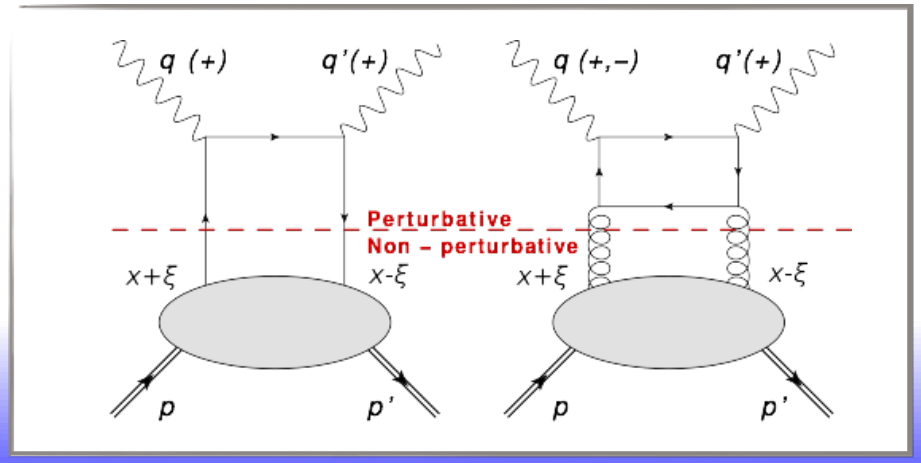
[Using V. Braun et al, PRD **89**, 074022 (2014)]

$$\mathbb{H}(x,\xi,t), \quad \widetilde{\mathbb{H}}(x,\xi,t)$$

- LO/LT + Twist-3 + Kinematic Twist-4

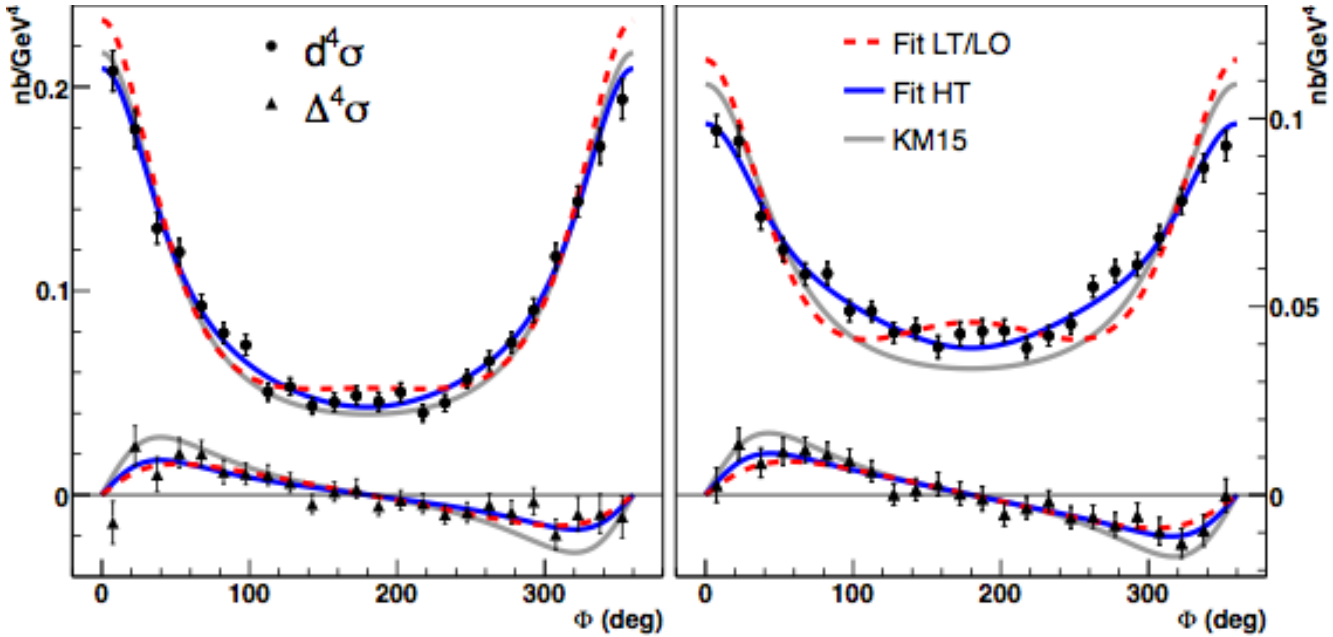


- LO+ NLO (gluon transversity) + Kinematic Twist-4



`Global' Fit:
Q^2=1.5, 1.75, 2.0 GeV^2 & E_e = 4.45, 5.55 GeV

Displayed at Q^2 = 1.75 for $-t$ = 0.030 GeV^2

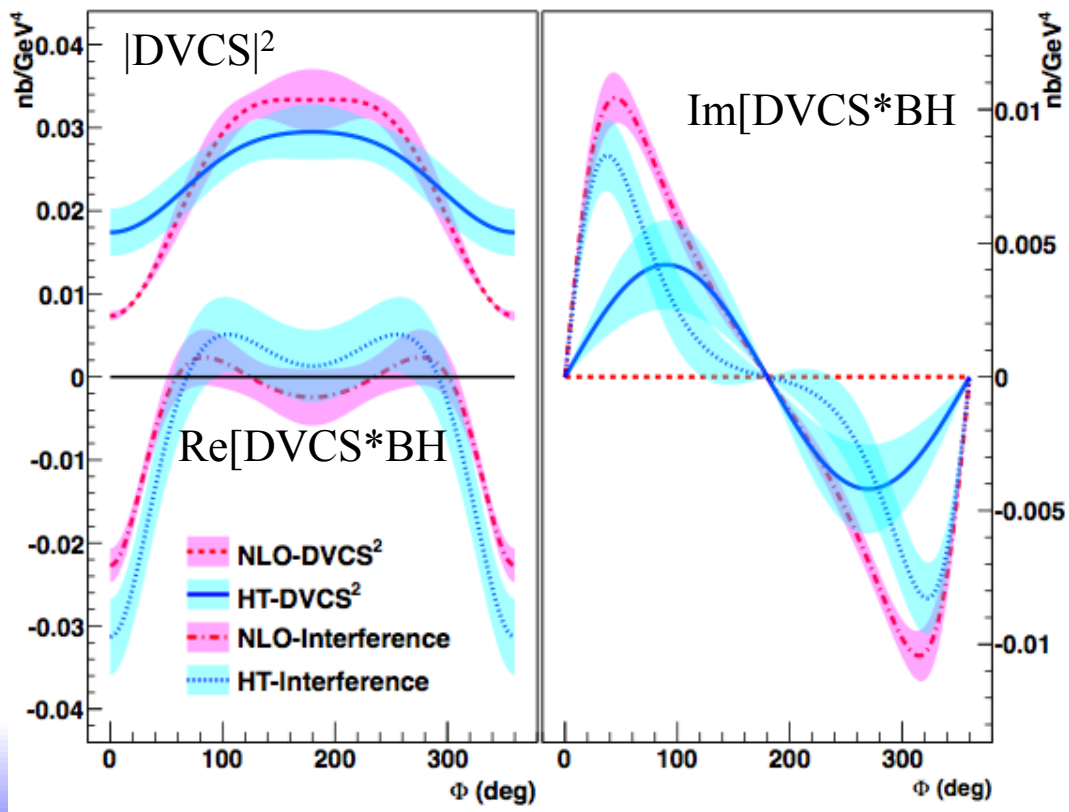


Identical fit (blue⬆) for either: Twist-3 or NLO (gluon) scenarios.
Both fits have Kinematic Twist-4 contribution constrained from Twist-2 component of fit

E07-007 `Global' Fit

Separations of Re,Im[DVCS†BH], |DVCS|^2

$-t$ = 0.030 GeV^2 (of three t-bins): Displayed at Q^2 = 1.75



Total Fit (previous slide blue)

⬅Sum of Pink (LO+NLO)

OR

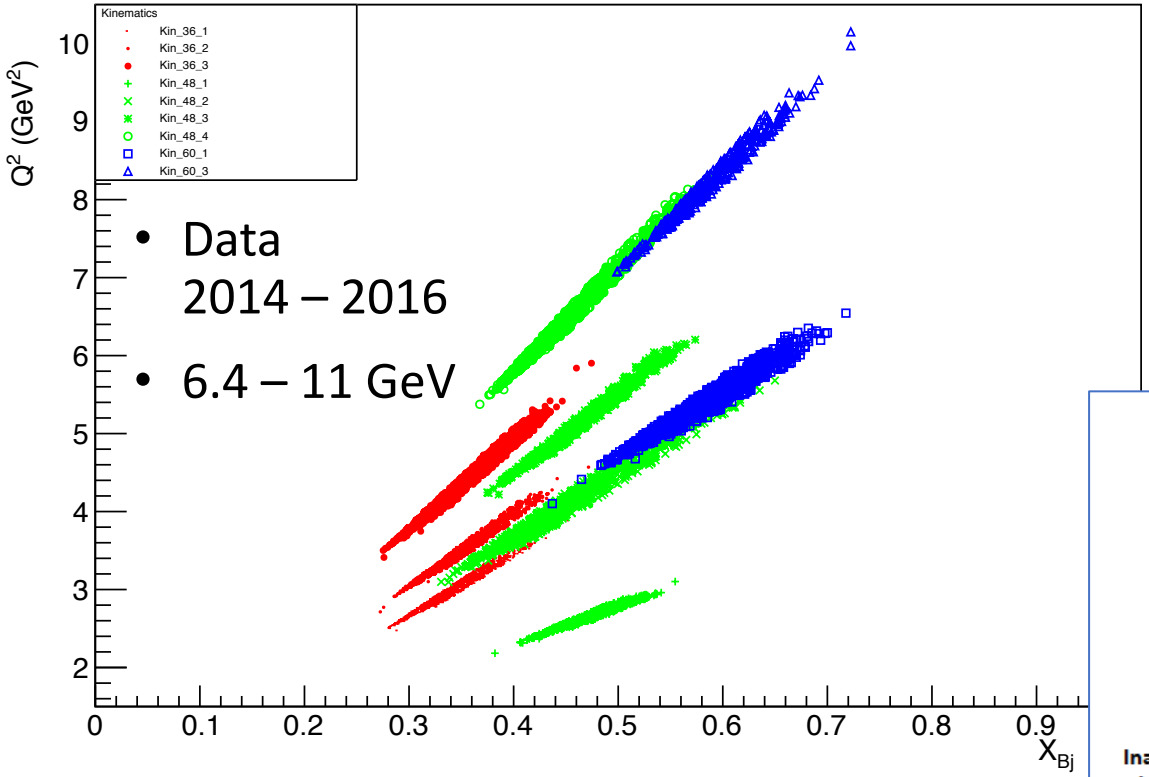
⬅Sum of Cyan (LO+HT)

Model dependence, but full measurement of interference: amplitude & phase

14

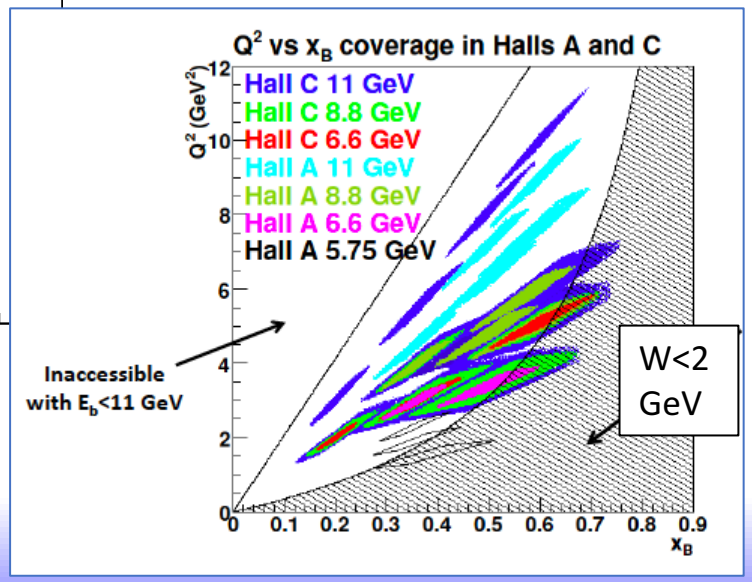
Hall A DVCS, Deep π^0

DVCS3 Kinematic_Coverage

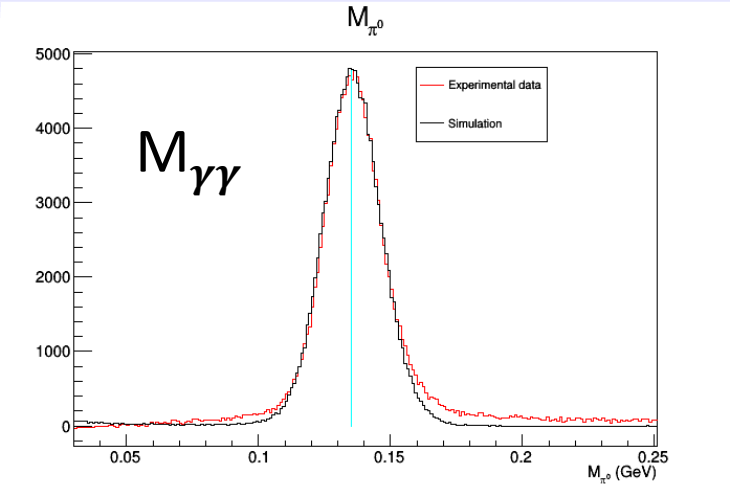


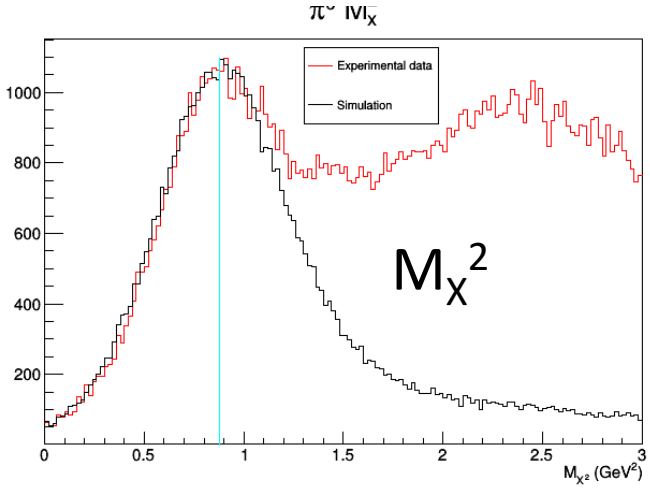
- Data 2014 – 2016
- 6.4 – 11 GeV

Previous, present, + approved



Hall A: Deep π^0, $E_e = 7.4$ GeV



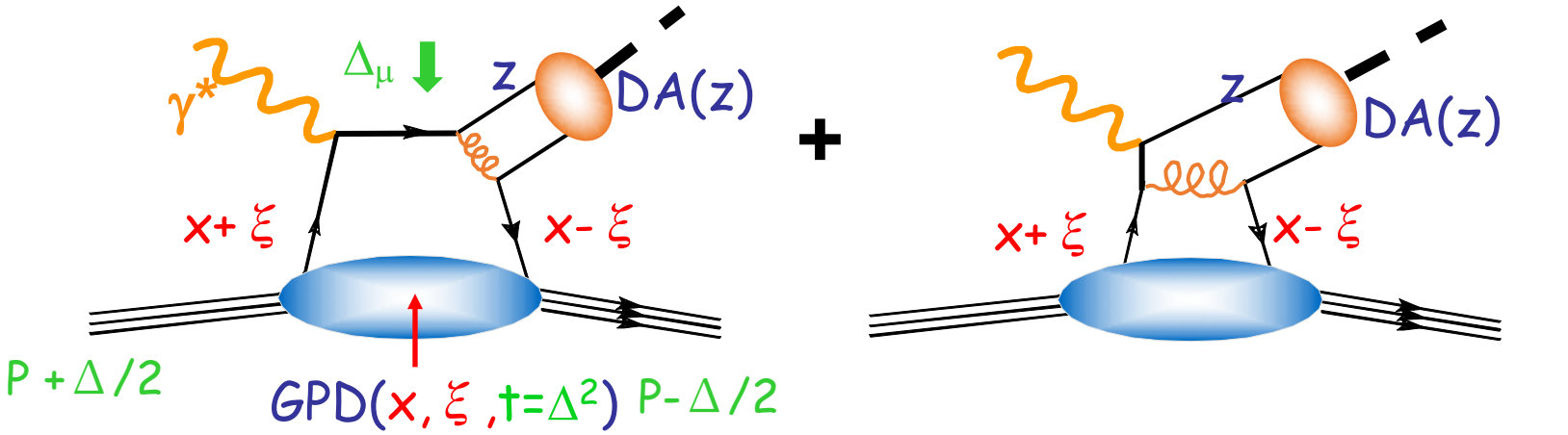


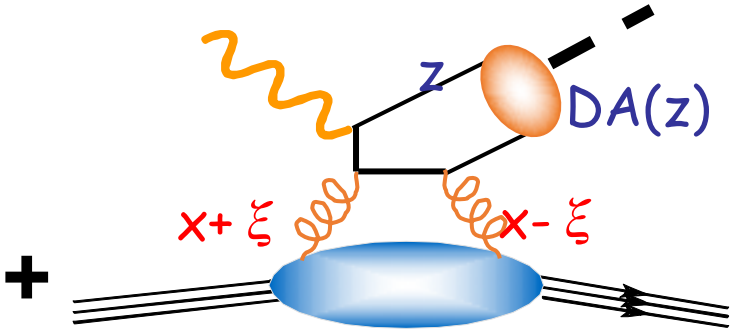
- H(e,e'$\gamma\gamma$)X

, $x_B = 0.36$

Preliminary results:
Mongi Dlamini (Ohio U.)

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

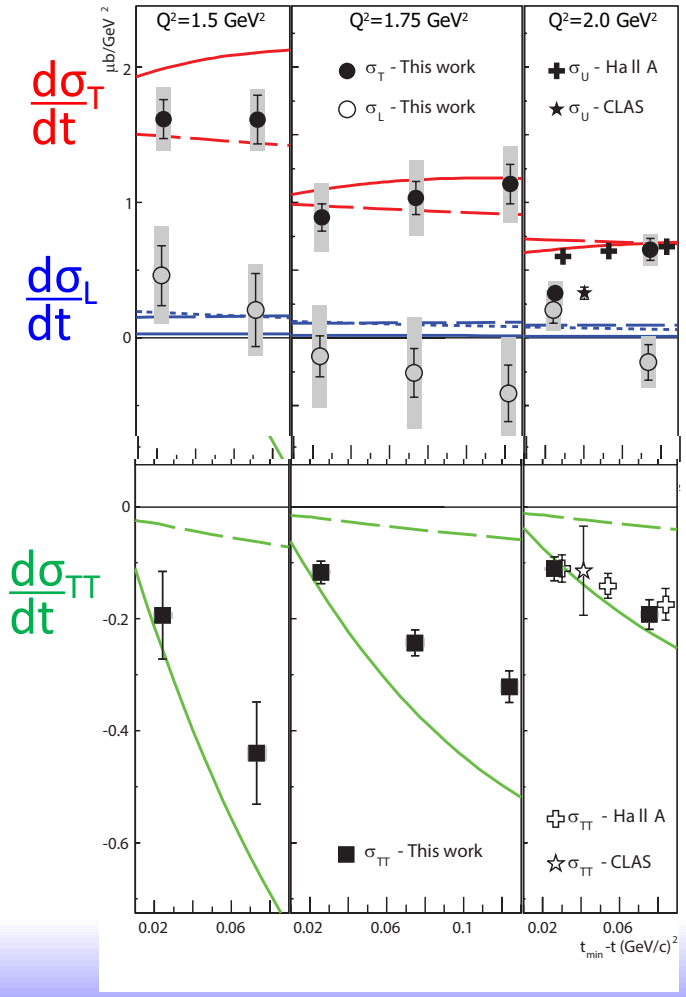
[Gluon GPDs in Diffractive channels only]

Pseudo-Scalars

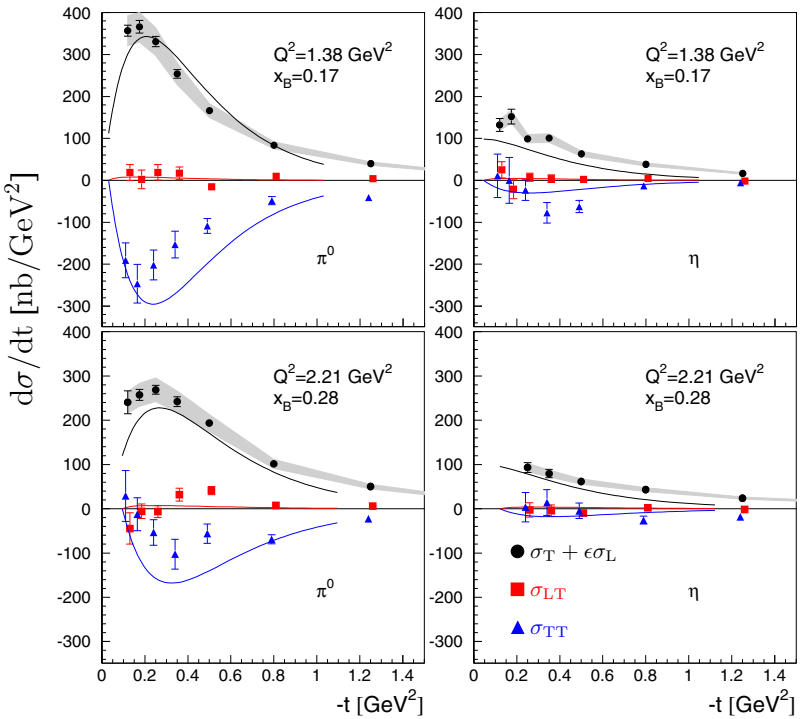
- JLab Hall A
  - L/T separation for H(e,e' π^0)p and D(e,e' π^0)pn
  - $\sigma_T >> \sigma_L$
- JLab CLAS
  - $\sigma_T + \epsilon\, \sigma_L$ for H*(e,e' p π^0)*, H*(e,e' p η)*
    - $\sigma_T + \epsilon\, \sigma_L$ >> naïve colinear factorization.
- Twist-3 helicity flip meson Distribution Amplitude enhanced by χSB ➔ coupling to nucleon transversity GPD: $\langle \pi(q') \left| \overline{\psi} \sigma^{+-} \psi \right| 0 \rangle \otimes \mathcal{H}_T$
  - S. Goloskokov, P. Kroll, Eur. Phys. J. A 47, 112 (2011).
  - S. Ahmad, G. R. Goldstein, and S. Liuti, Phys. Rev. D 79, 054014 (2009).

DVMP: π^0, η @ 6 GeV

M.Defurne *et al* [Hall A] PRL **117** (2016)



I.Bedlinskiy *et al* [CLAS] PRC **95** (2017)



Solid Curves: S. Goloskokov and P. Kroll, Eur. Phys. J. A **47**, 112 (2011).

Dashed: G. R. Goldstein, J. O. Hernandez, and S. Liuti, Phys. Rev. D **84**, 034007 (2011).

[Flavor ⊗ Spin]-Structure Separation

- Hall A: D$(e,e'\pi^0)pn$–H$(e,e'\pi^0)p$,
  - M.Mazouz *et al* PRL **118** (2017)
- CLAS: H$(e,e'\pi^0)p$ ± H$(e,e'\eta)p$
  - I. Bedlinskiy PRC **95** (2017)
  - V. Kubarovsky SPIN2014

$$\frac{d\sigma_T}{dt} = \Lambda\left[(1-\xi^2)|\langle H_T\rangle|^2 - \frac{t'}{8M^2}|\langle \bar{E}_T\rangle|^2\right],$$

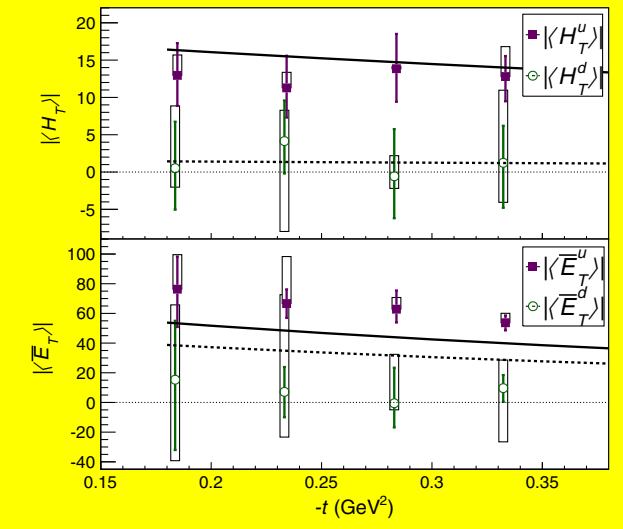
$$\frac{d\sigma_{TT}}{dt} = \Lambda\frac{t'}{8M^2}|\langle \bar{E}_T\rangle|^2.$$

π^0 $$|\langle H_T^{p,n}\rangle|^2 = \frac{1}{2}\left|\frac{2}{3}\langle H_T^{u,d}\rangle + \frac{1}{3}\langle H_T^{d,u}\rangle\right|^2,$$

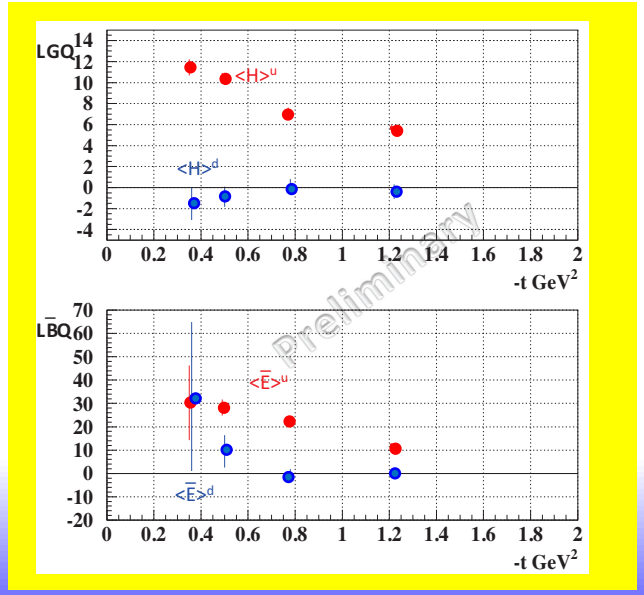
η $$|\langle H_T^{p,n}\rangle|^2 = \frac{1}{2}\left|\frac{2}{3}\langle H_T^{u,d}\rangle - \frac{1}{3}\langle H_T^{d,u}\rangle\right|^2,$$

Hall A
Q^2=1.75 GeV^2
x_{Bj} = 0.36

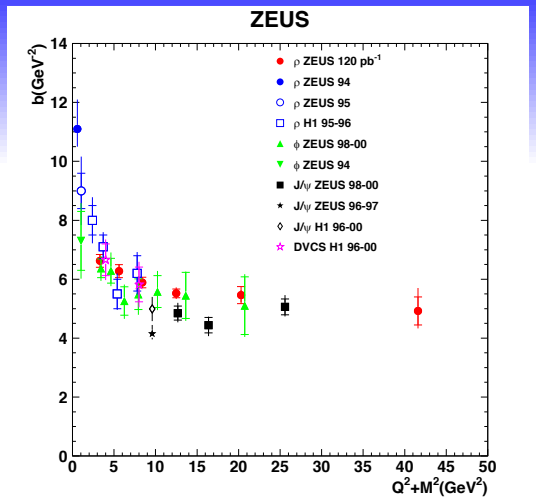
Error boxes are phase ambiguity, resolvable with η



CLAS
Q^2=2.2GeV^2
x_{Bj} = 0.27
Assume $\sigma_T \gg \sigma_L$

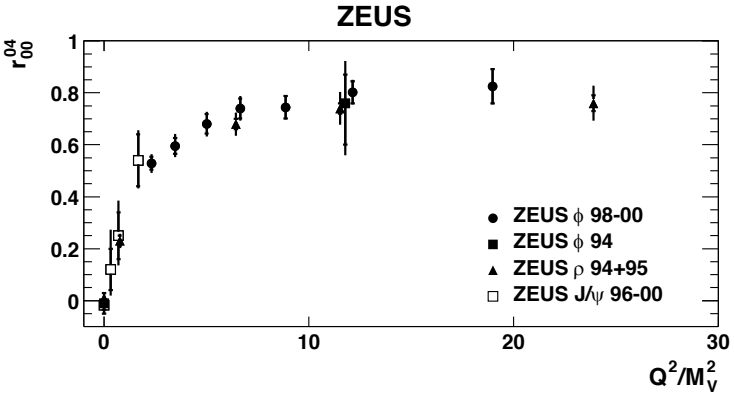


Vector mesons

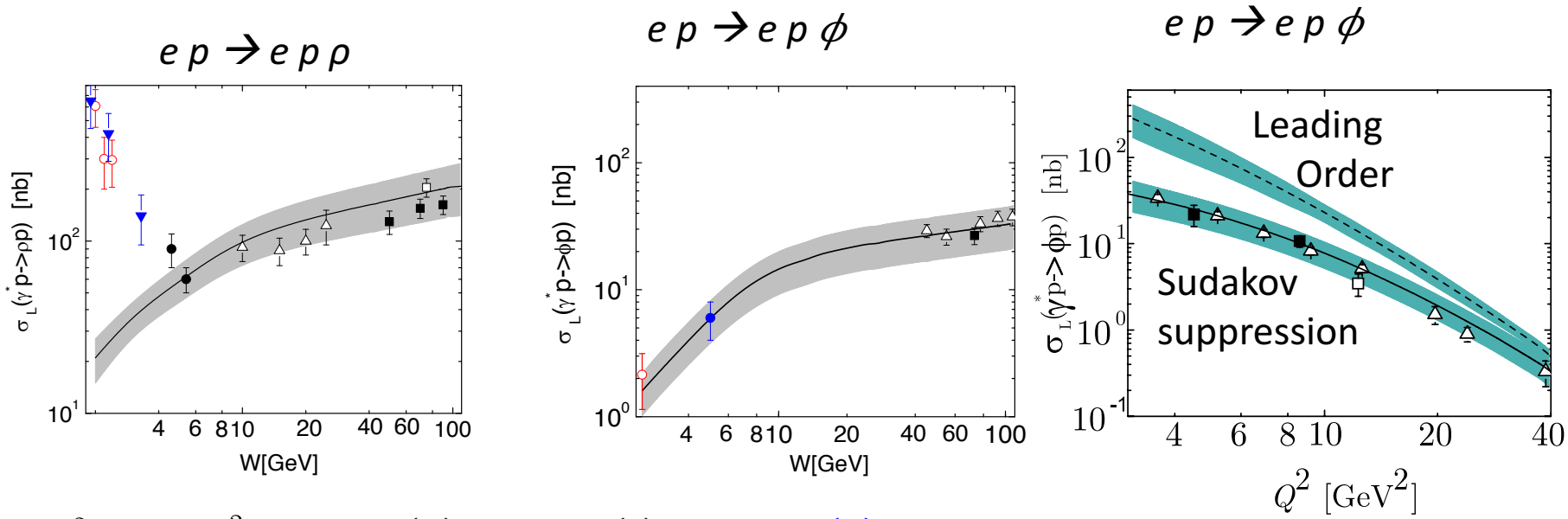


- ϕ: JLab12 kinematics:
  - Expect Gluon GPDs + ≤20% gluon⊗strange
- J/Psi: seen in Hall D.
  - Threshold production → large $-t_{min}$.
  - CLAS12 search for LHCb J/ψ⊗p resonances
- ρ, ω
  - Slow approach to longitudinal
  - dominance in HERA data
  - Unexplained enhancement in ρ-production at low W^2 in CLAS data.
    - Helicity violating amplitudes ➔ Transversity GPDs *à la* pseudo-scalars?
  - ω: strong violation of SCHC

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



Deep rho, Deep phi



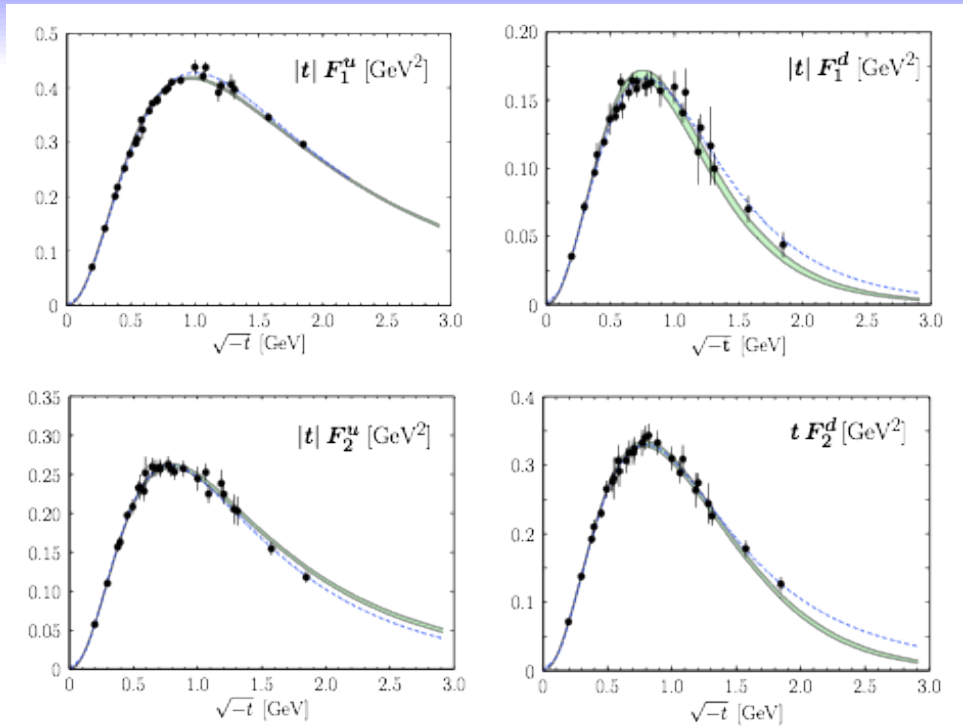
$Q^2 = 4\ \mathrm{GeV}^2$ E665 (△), HERMES (●), CORNELL (▲)
ZEUS (□), H1 (■), CLAS (○)

- Calculations of S. Goloskokov, P. Kroll EPJC **50** (2007) 829

What about the Ji Sum-Rule?

- $lim_{t\to 0} \int x dx[H_f(x,\xi,t)+E_f(x,\xi,t)] = 2\, J_f$
  - Skewing effects, Extracting *E* ?
  - *u,d* flavor separations from proton, neutron
  - $E^{(n)}$ dominates unpolarized n(e,e'γ)n
  - $E^{(p)}$ requires transversely polarized targets
    - HD_{ice} for CLAS12
    - NH_3, ^{3}He with SOLiD or TCS?

Example Regge-Inspired Model of GPDs



M.Diehl, … EPJ*C* **73** (2013)

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

- $q_f(x)$: ABM2011
  $e_f(x) = \kappa_f N_f\, x^{-\alpha_f}(1-x)^{-\beta_f}(1-\gamma_f x^{1/2})$
- $B_{nf}(x) = \alpha_f'(1-x)^3\log(1/x) + A_{nf}x(1-x)^2 + B_{nf}(1-x)^3$
- Fit:
  $\int dx\, H_f(x,0,\Delta^2) = F_{1f}(-\Delta^2)$
  $\int dx\, E_f(x,0,\Delta^2) = F_{2f}(-\Delta^2)$

- Compton Form Factors: $\xi = x_{Bj}/(2-x_{Bj})$
  $\mathrm{Im}[\mathcal{H}_f(\xi,\Delta^2)] = \pi[H_f(\xi,\xi,\Delta^2) - H_f(-\xi,\xi,\Delta^2)]$

$$\xi\,\mathrm{Im}\left[H_f\left(\xi,\Delta^2\right)\right] = \pi\int_0^{x_{Bj}} d\beta\left[q_f(\beta)+\bar{q}_f(\beta)\right]\left[h_f(\alpha,\beta)\right]_{\alpha=1-\beta/\xi} e^{\Delta^2 B_{1f}(\beta)}$$

- Profile functions $h(\alpha,\beta)$ arbitrary (symmetric in α,β):

$$h(\alpha,\beta) = N_1\frac{\left[\left(1-|\beta|\right)^2-\alpha^2\right]}{\left(1-|\beta|\right)^3}$$

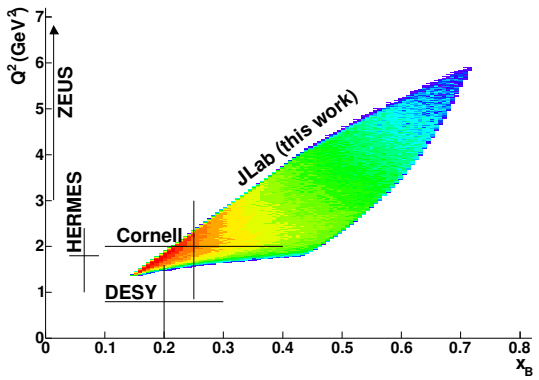
Constraints on Ji Sum Rule

- $H_f(x,0,t)$ essentially known from fits to $F_{1f}(-t) \otimes q_f(x)$
  - Measure $H_f(x,x,t)$ → Determines DD Profile function
  - JLab 12 → higher x, Q^2 range
- $E_f(x,0,t)$ constrained from $F_{2f}(-t)$ and *assumption* $e_f(x)$ does not change sign.
  - Test this assumption
    - x≈0.1 COMPASS 2020
    - x≈0.4 Jlab12
    - Lattice QCD
- My prediction: In 10 years, we will be confident in value of $J_{u,d}$

Backup Slides

Deep ω

- L. Morand [CLAS] EPJ A **24**, (2005) 445.
  - $r_{0,0}^{04} \approx 0.5 \rightarrow \sigma_T \sim \sigma_L$
  - $r_{1,-1}^{04} \approx -0.2 \rightarrow$ ~~SCHC~~
    - $\gamma^*_T \rightarrow \omega_L$
    - $\gamma^*_L \rightarrow \omega_T$
    - $\gamma^*(\pm) \rightarrow \omega(\mp)$



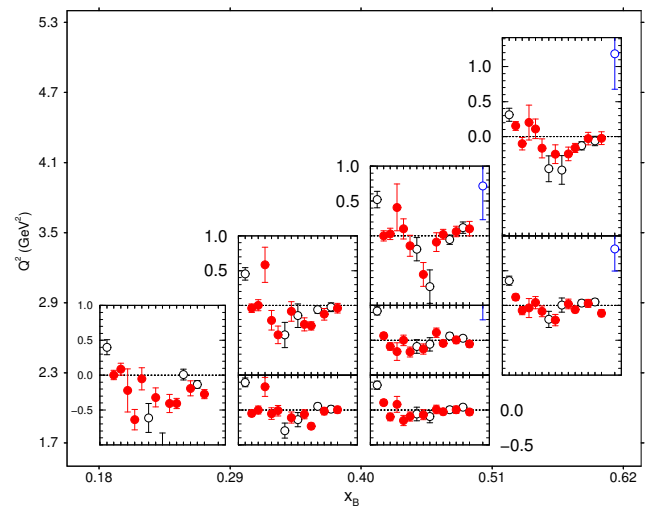


Fig. 18. (Color online) r^{α}_{ij} extracted with the method of moments for 8 bins in (Q^2, x_B) and for $t' < 0.5$ GeV^2. The location and size of each graph correspond to the (Q^2, x_B) range over which the data is integrated, but the scale is the same on all graphs. The abscissa on each graph corresponds to the following list of matrix elements: r^{04}_{00}, Rer^{04}_{10}, r^{04}_{1-1}, r^{1}_{00}, r^{1}_{11}, Rer^{1}_{10}, r^{1}_{1-1}, Imr^{2}_{10}, Imr^{2}_{1-1}, r^{5}_{00}, r^{5}_{11}, Rer^{5}_{10}, r^{5}_{1-1}, Imr^{6}_{10}, Imr^{6}_{1-1}. The filled symbols (red online) indicate those matrix elements which are zero if SCHC applies. The 16th entry (empty circle, blue online, in some cases off scale) is the combination of r^{α}_{ij} given by eq. (11). Error bars include systematic uncertainties added in quadrature.

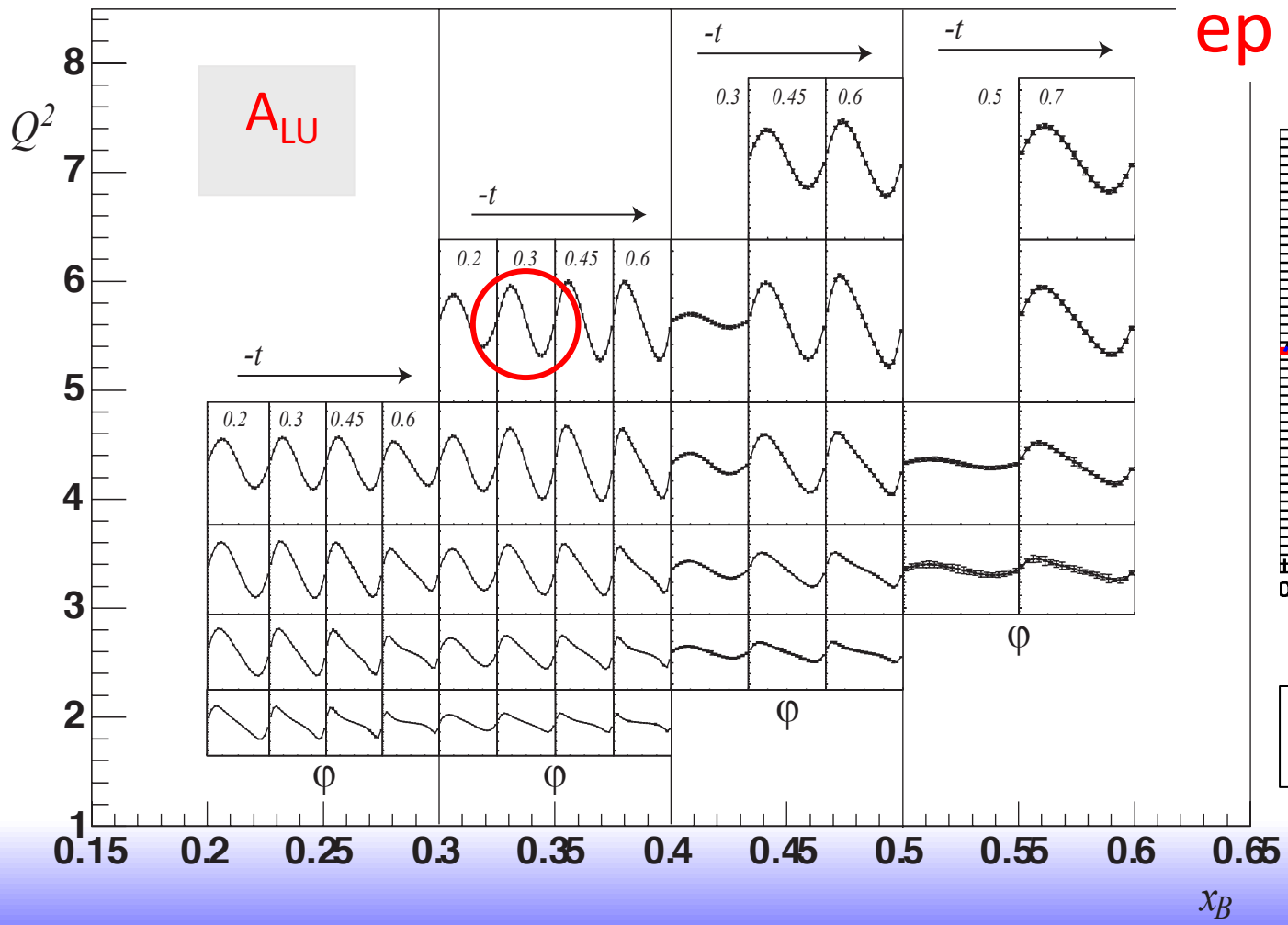
DVCS/DVMP with CLAS at 12 GeV

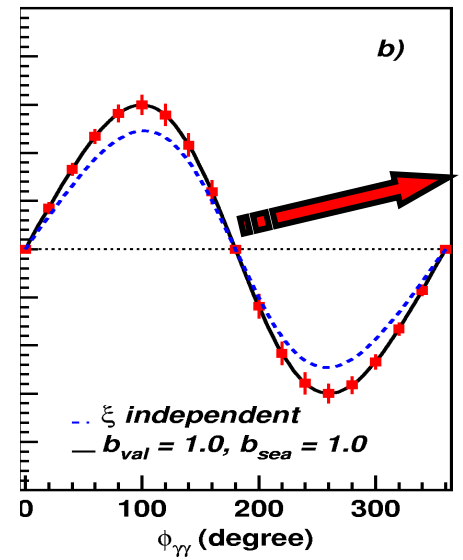
- 80 days on H_2 target at ~10^{35} /cm^2/s
  - DVCS/Vector Meson production/ TCS with low-Q^2 tagger concurrent
- 120 days on Longitudinally Polarized NH_3 target
  - Total Luminosity 10^{35} /cm^2/s, dilution factor ~1/10
- 90 days: $D(e,e'\gamma n)p_S$
- $^4He(e,e'\ \gamma\alpha)$ with upgraded BoNUS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

A_{LU} projections for JLab@12GeV

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

$\vec{\rightarrow}$ ep → epγ





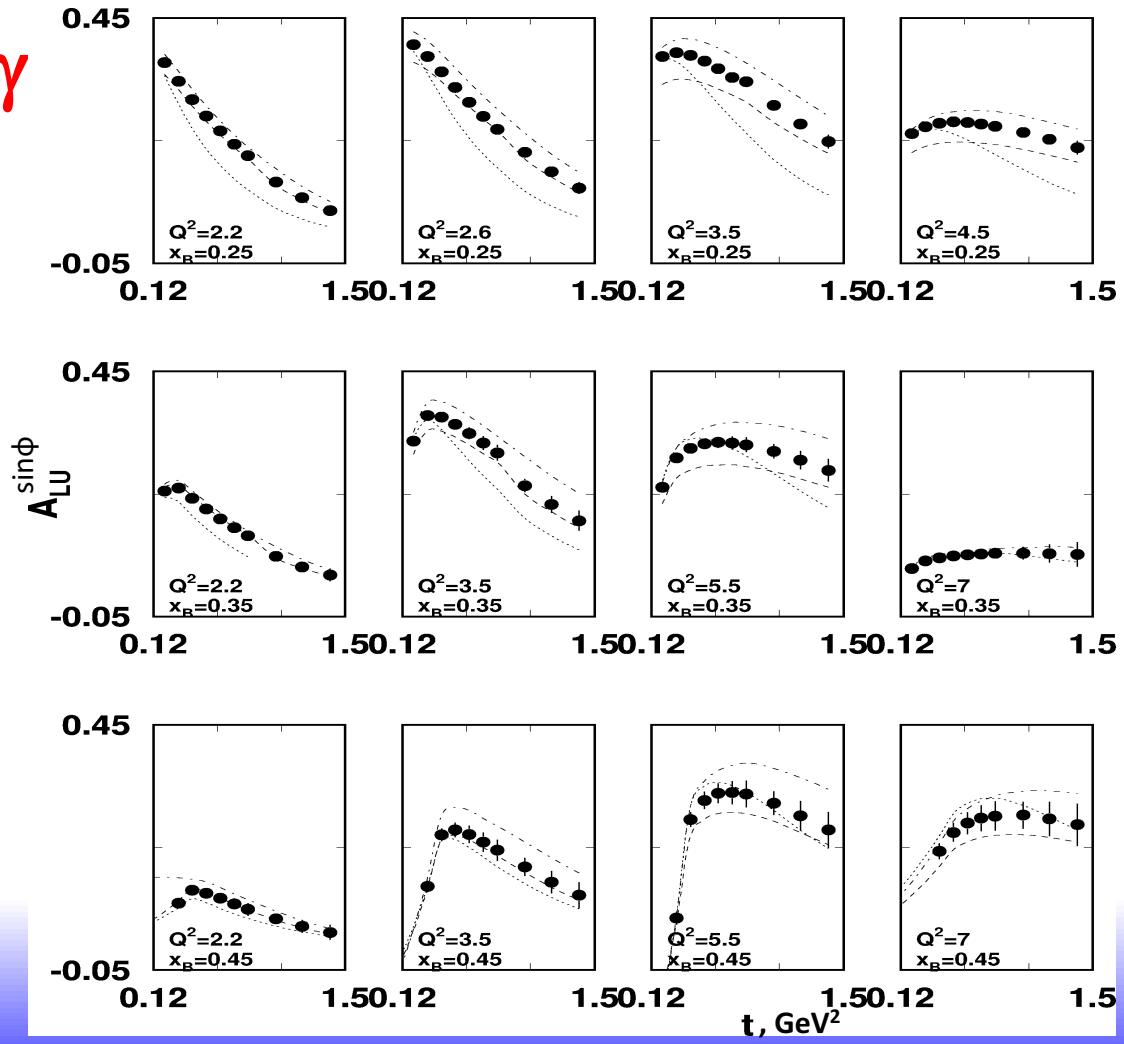
E12-06-114
E12-06-119

A_{LU} projections for protons

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

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

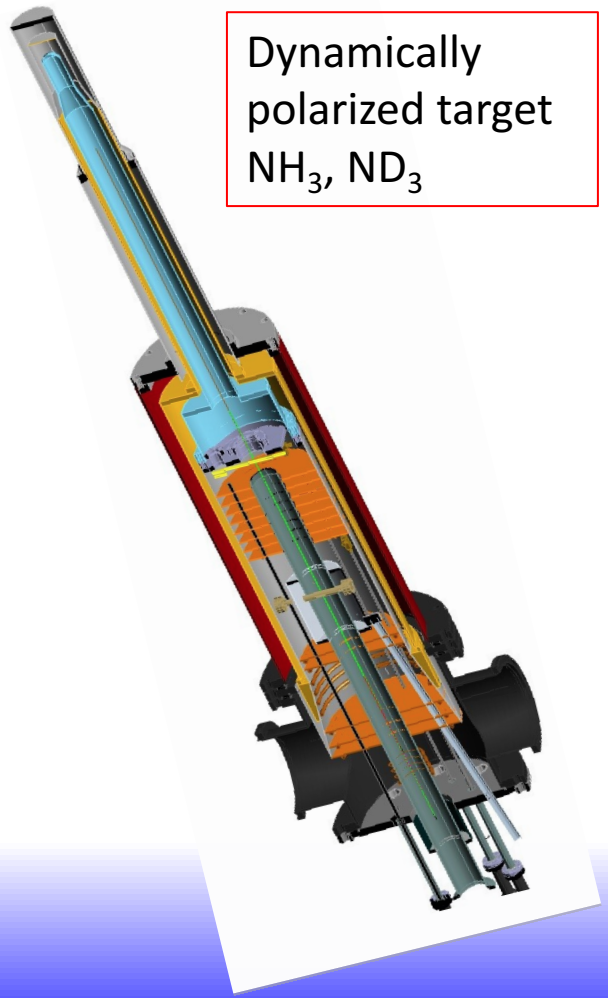
E_e=11GeV



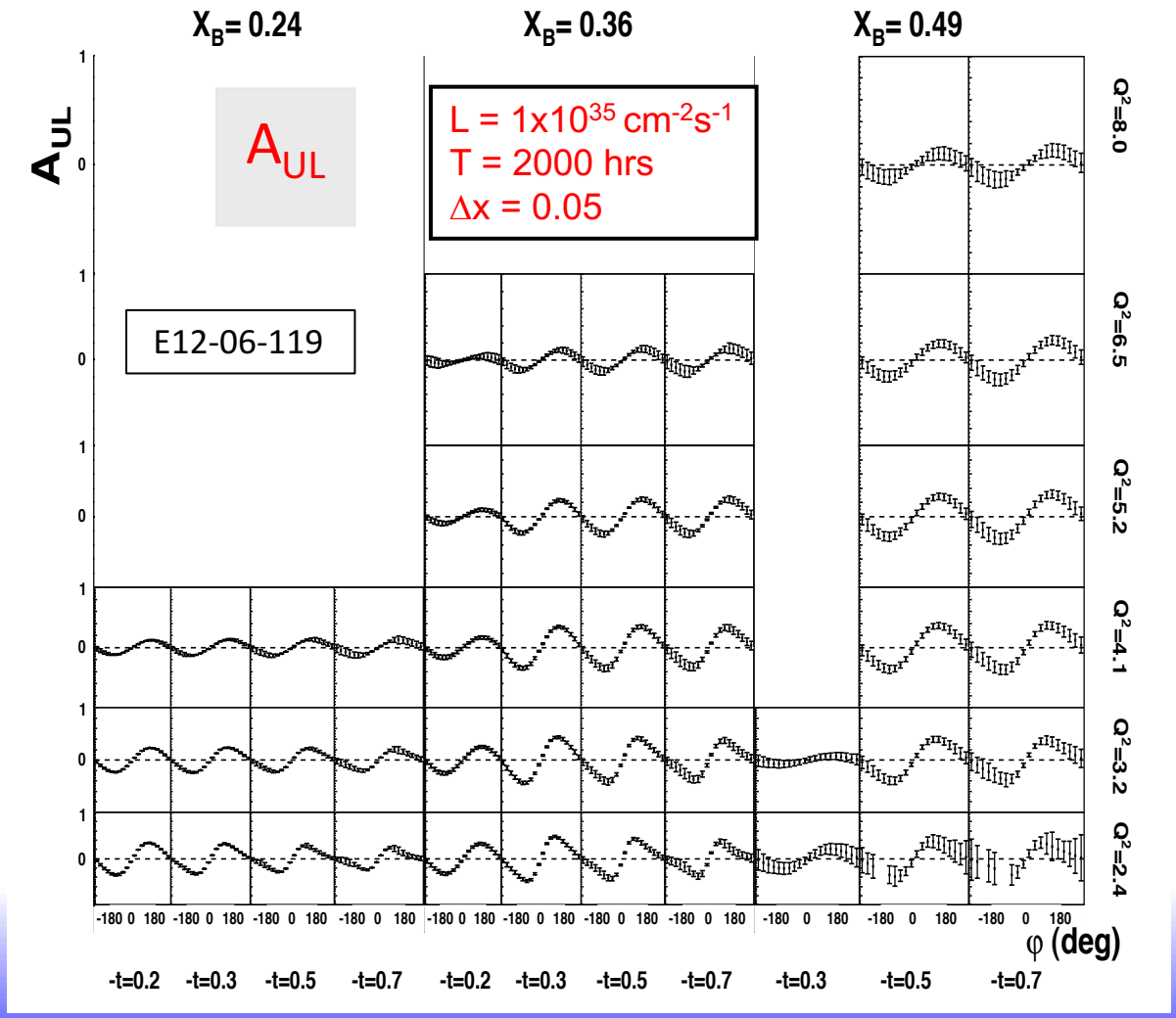
A_{UL} projections for protons

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

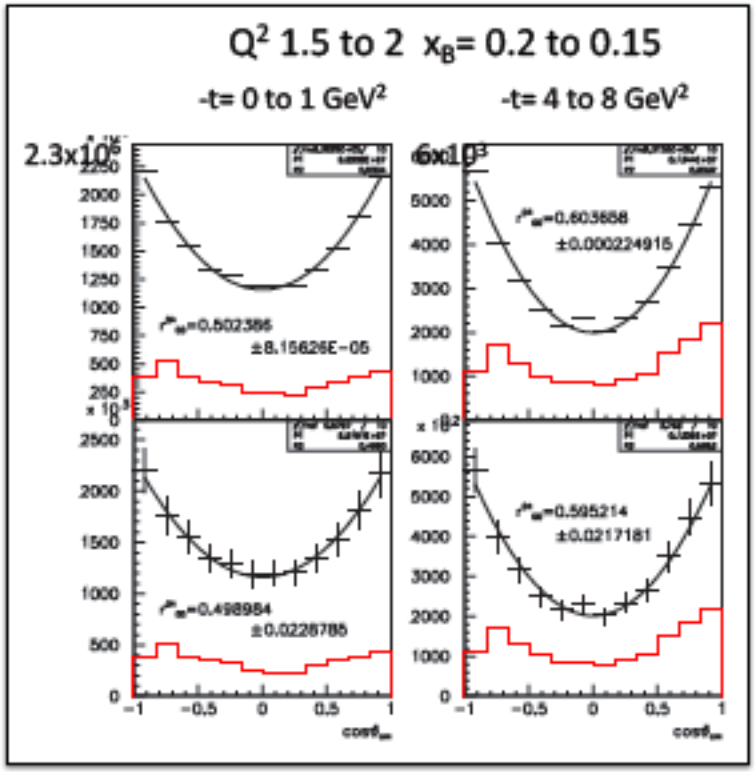
$$\Delta\sigma_{UL} \sim \sin\phi\,\{F_1\tilde{H}+\xi(F_1+F_2)(H+\xi/(1+\xi)E)\}d\phi$$

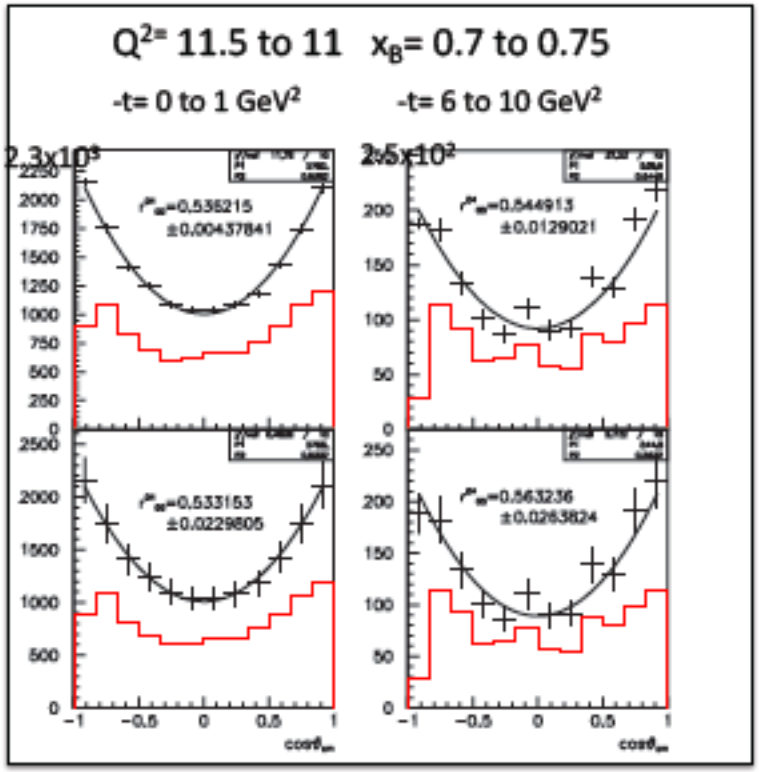


Dynamically polarized target NH_3, ND_3

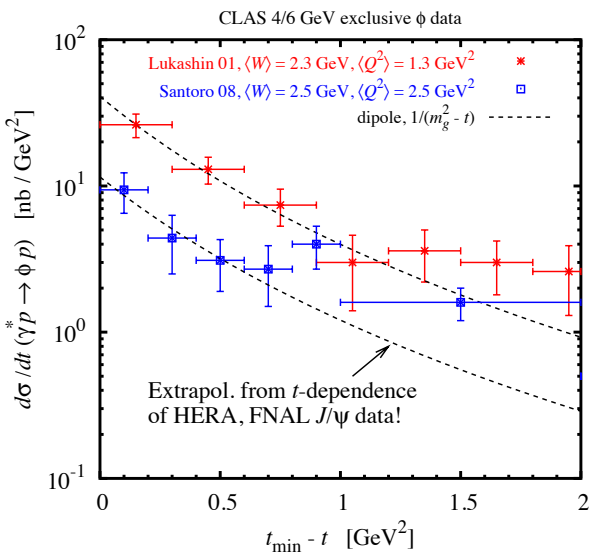


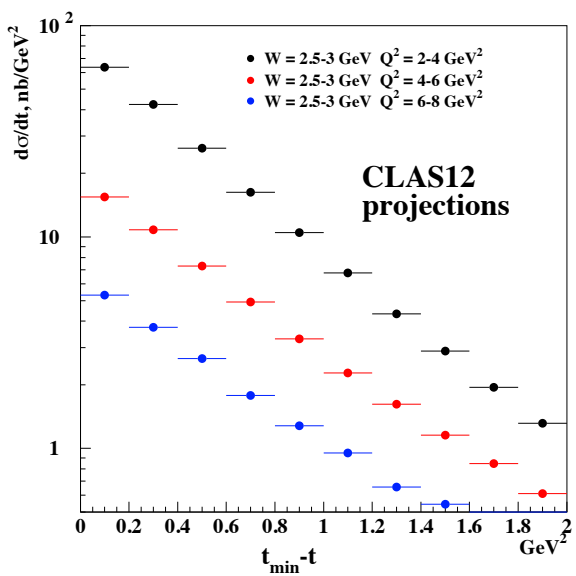
Exclusive $\rho^0 \rightarrow \pi\pi$ L/T separation from SCHC





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?

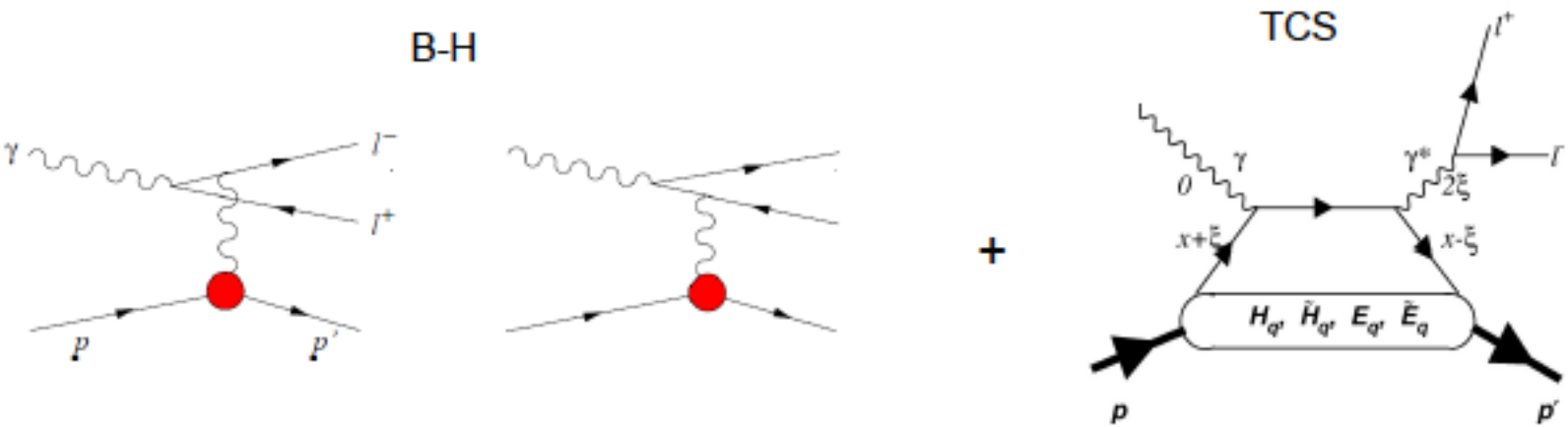
  L/T ratio from vector meson decay and s–channel helicity conservation

- 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

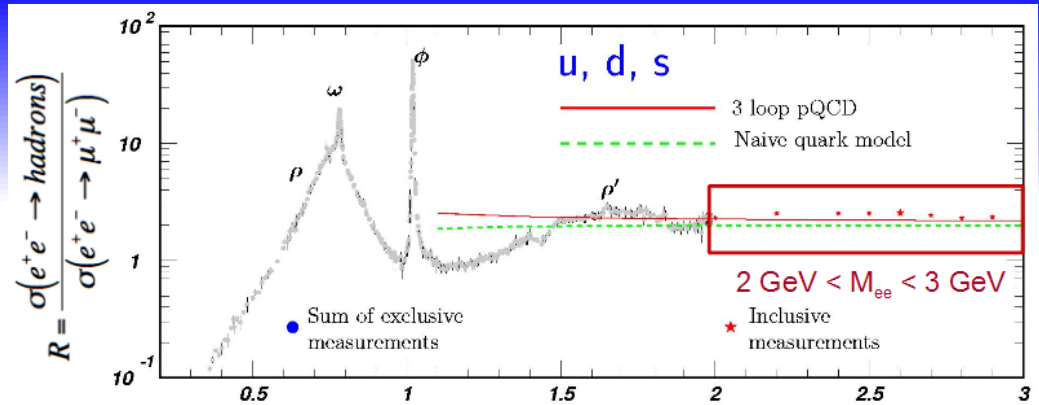


$$\frac{d\sigma^4}{dQ'^2\,dt\,d(\cos\theta)\,d\varphi} = |BH|^2 + I(BH\cdot TCS) + |TCS|^2$$

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

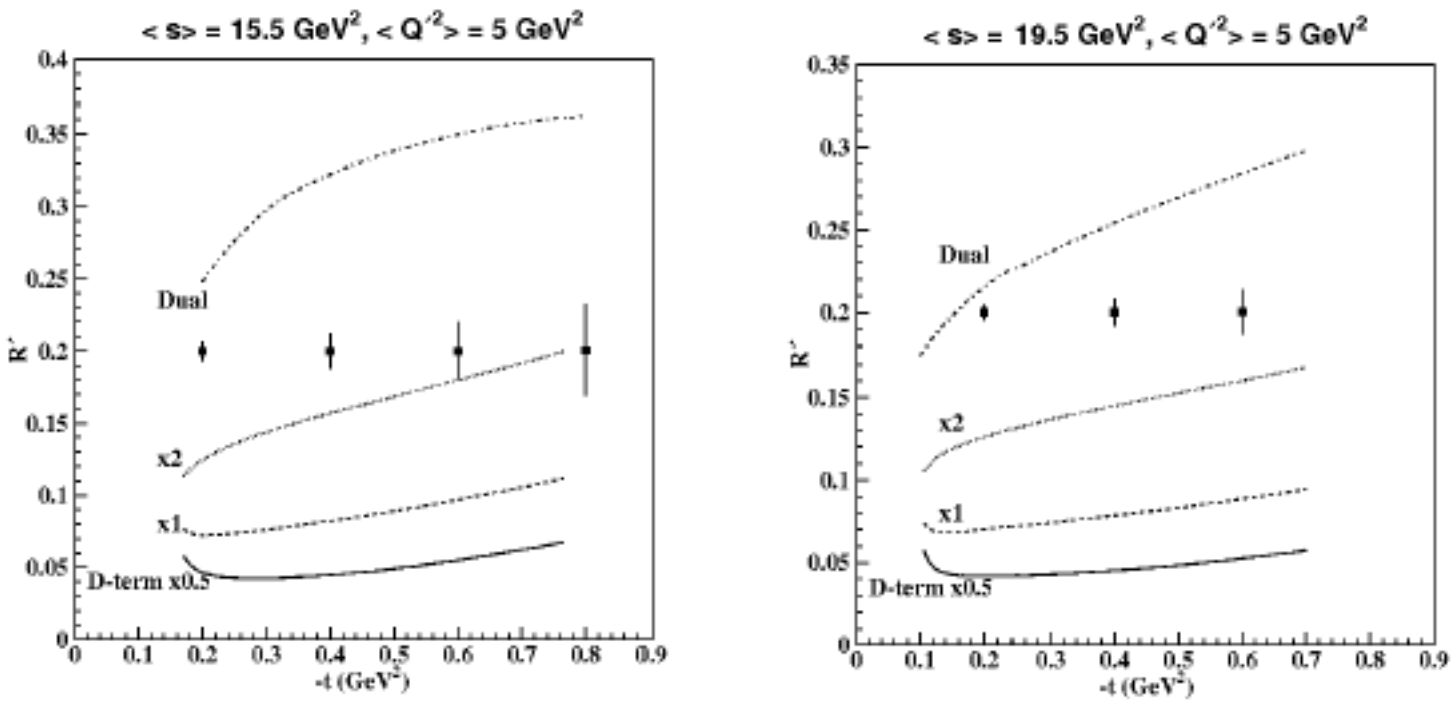
CLAS 12 TCS

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

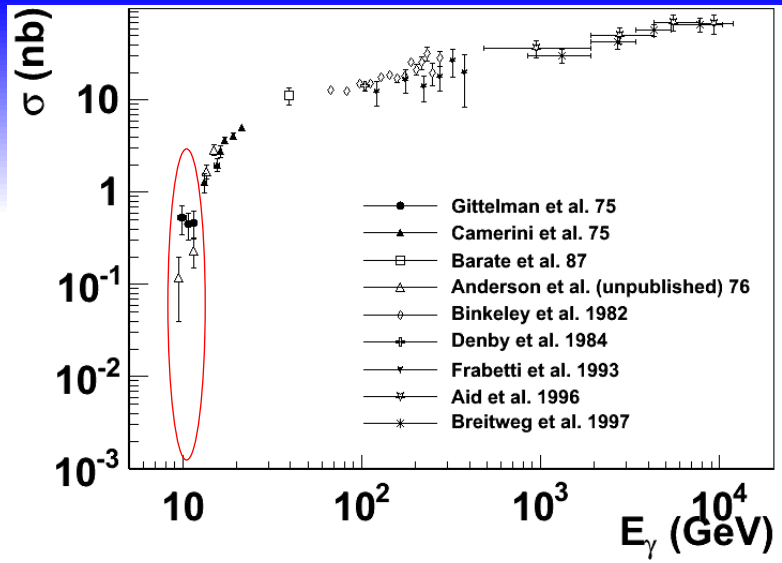


Statistical uncertainties for 100 days at a luminosity of 10^{35} $cm^{-2}s^{-1}$

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

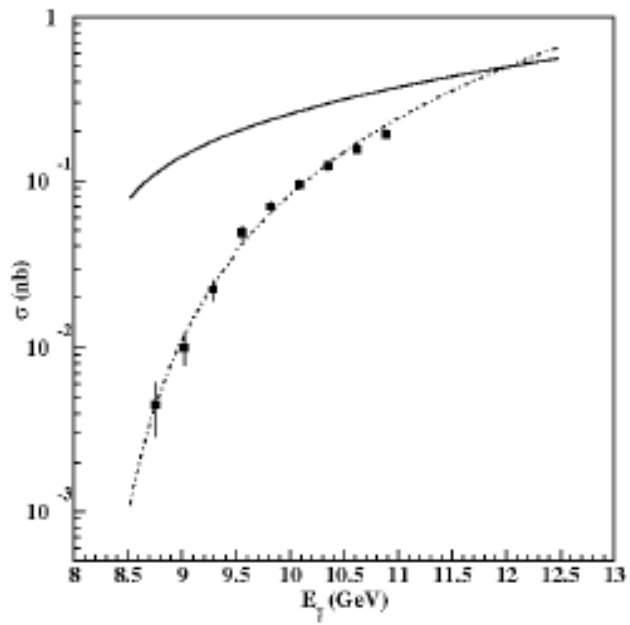


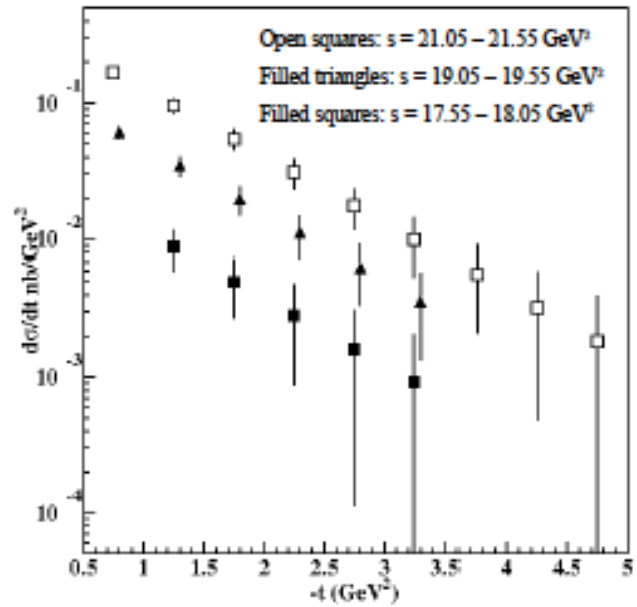
CLAS 12 Exclusive J/Ψ



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

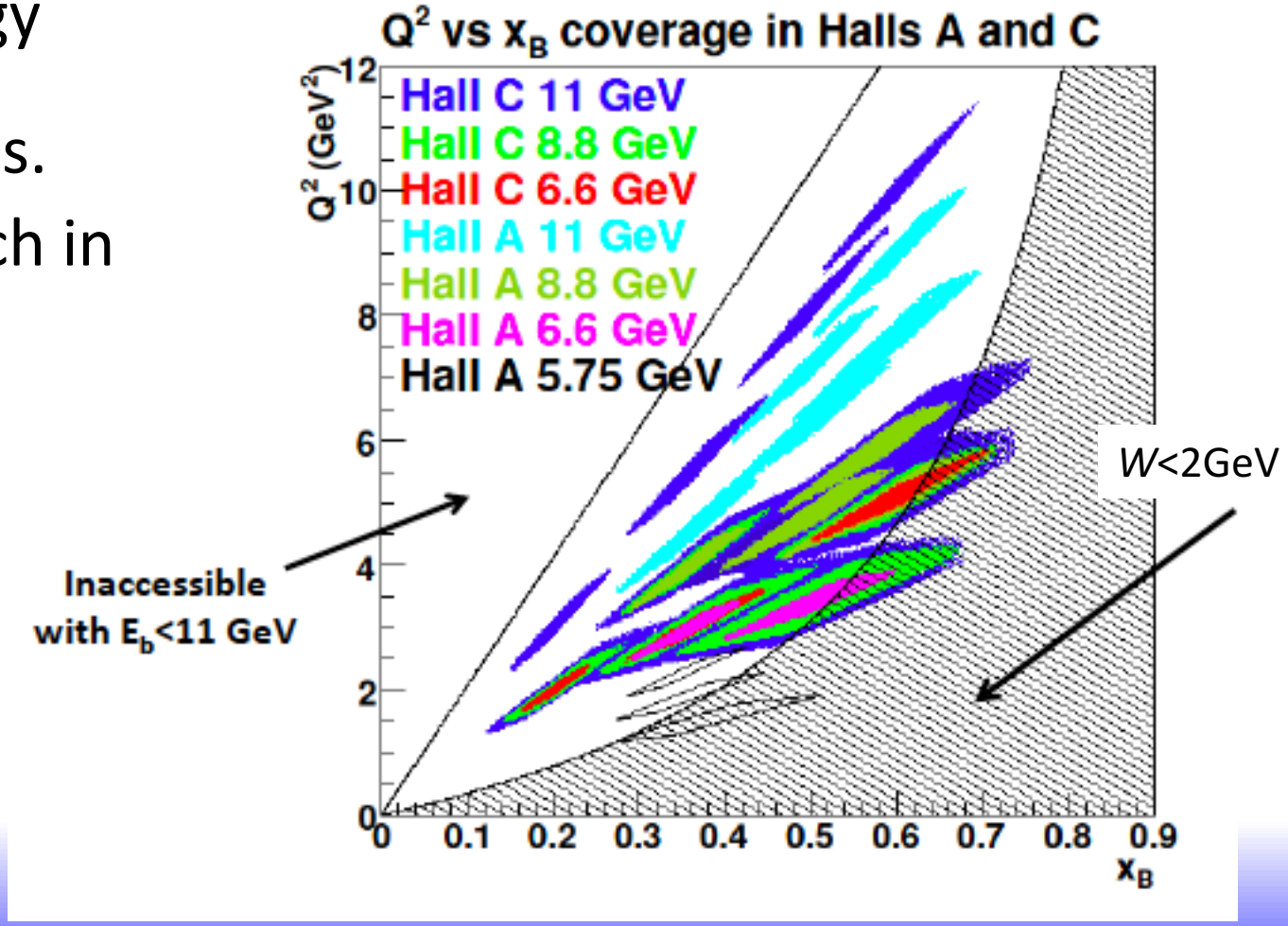
Statistical uncertainties for 100 days at a luminosity of 10^{35} $cm^{-2}s^{-1}$





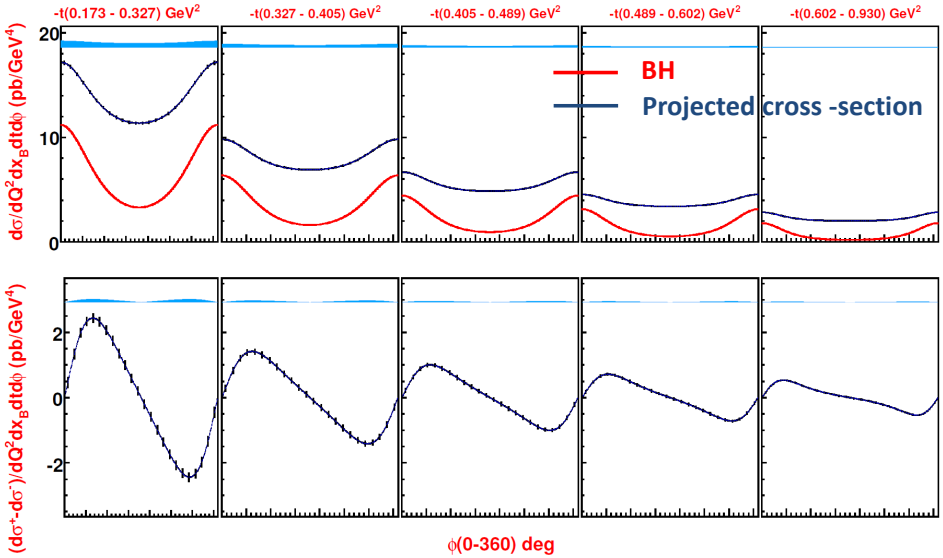
Impact of Hall A+C DVCS Kinematicss

- 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

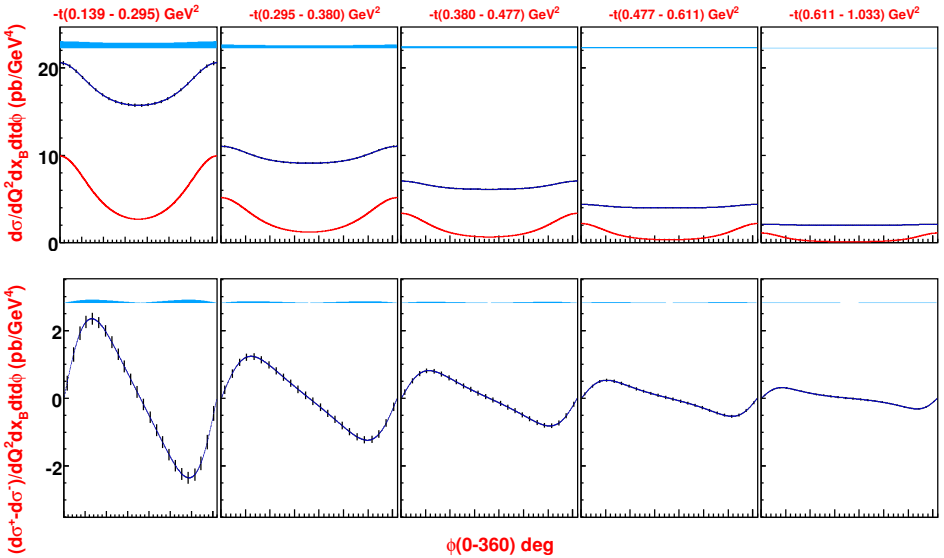


DVCS: Energy separation setting ($Q^2 = 3.4$ GeV^2, $x_B = 0.5$)

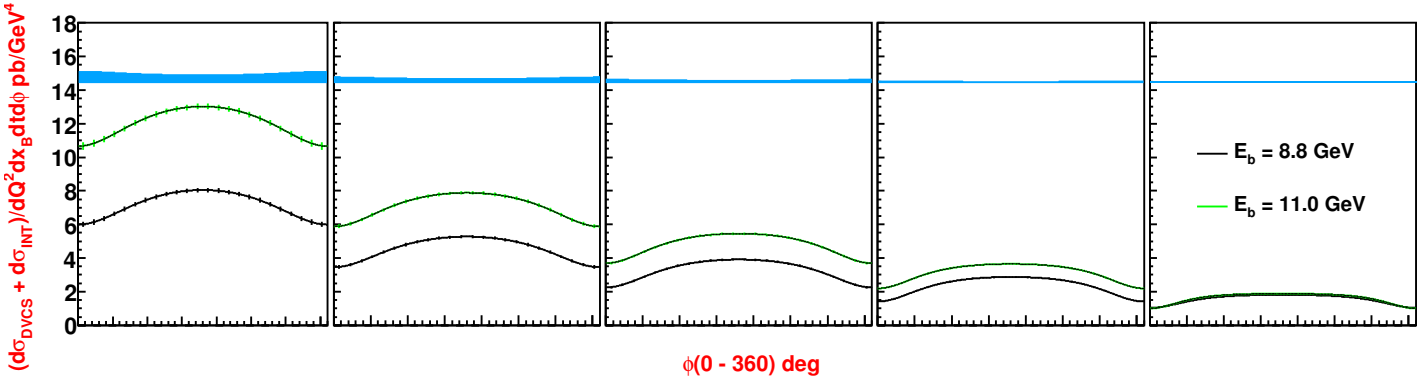
$E_b = 8.8$ GeV



$E_b = 11$ GeV



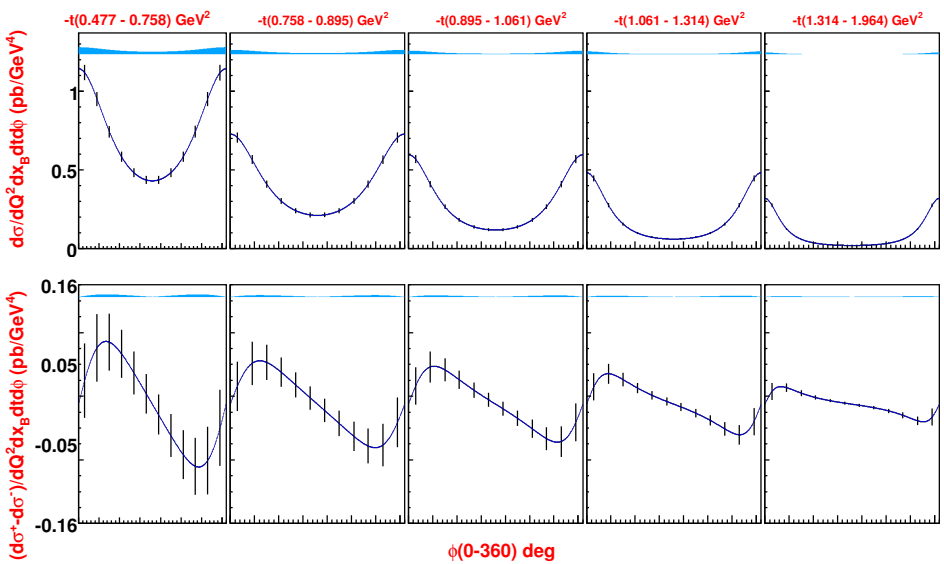
Cross section as a function of ϕ for different bins in t



Cross section after BH subtraction: large variation with E_b

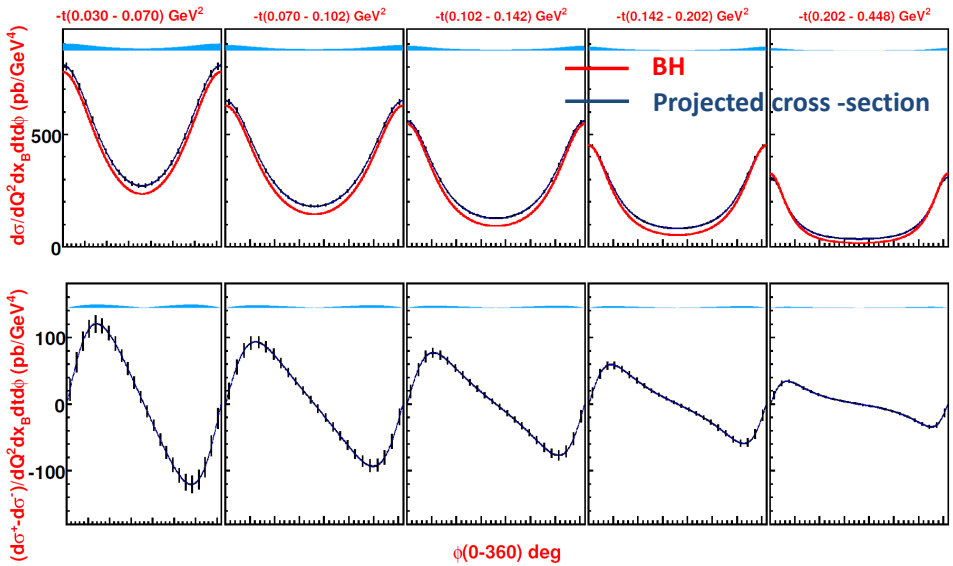
DVCS: high-Q^2 and low-x_B extension

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



12 days

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



1 day