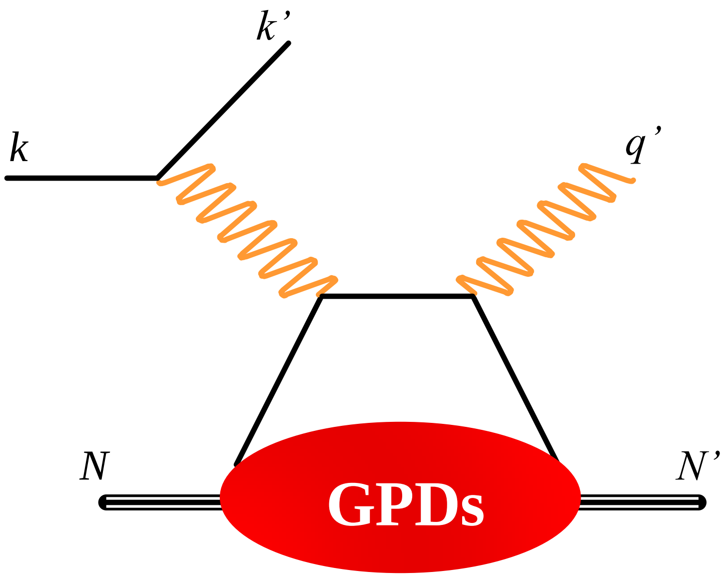
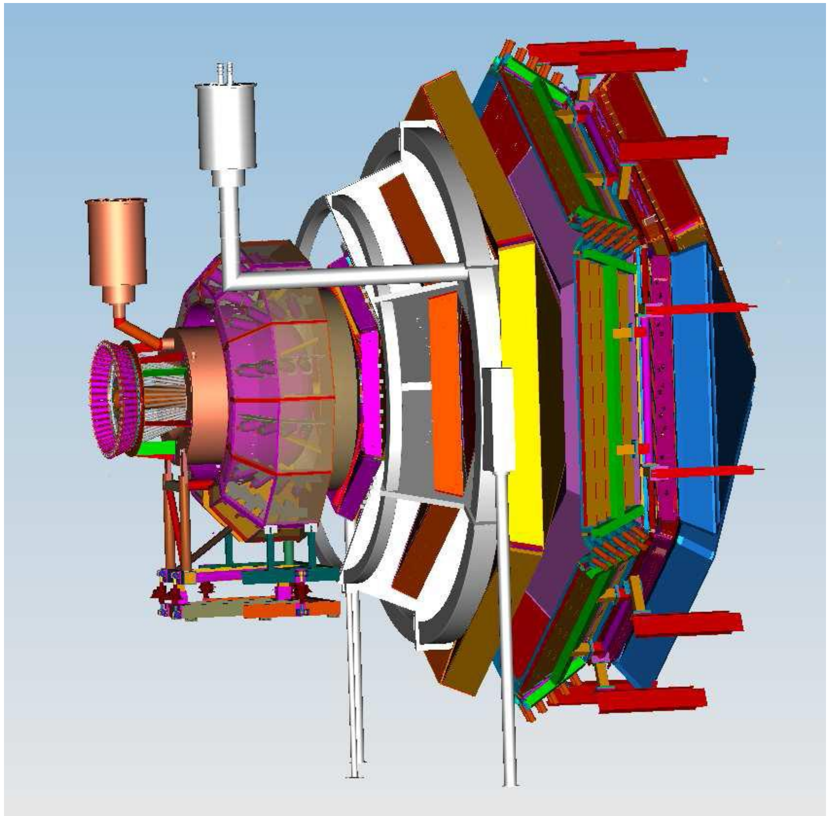
Generalized Parton Distributions with CLAS and CLAS12





Silvia Niccolai IPN ORSAY **for the CLAS Collaboration**

From Quarks and Gluons to Hadrons and Nuclei

Erice (Italia) – September 22nd 2011

Generalized Parton Distributions with CLAS and CLAS12

- **Interest of GPDs**
- **GPDs and Deeply Virtual Compton Scattering**
- **The CLAS detector**
- **DVCS results with CLAS**
- **GPDs and Deeply Virtual Meson Production**
- **DVMP results with CLAS**
- **The JLab 12 GeV upgrade and CLAS12**
- **Future experiments on GPDs with CLAS12**

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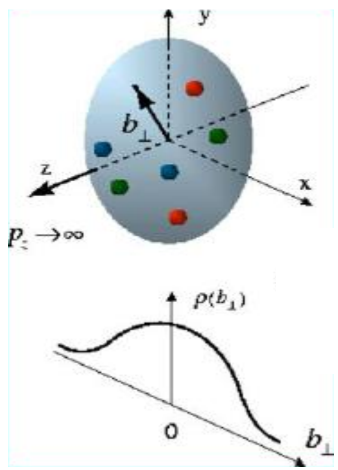
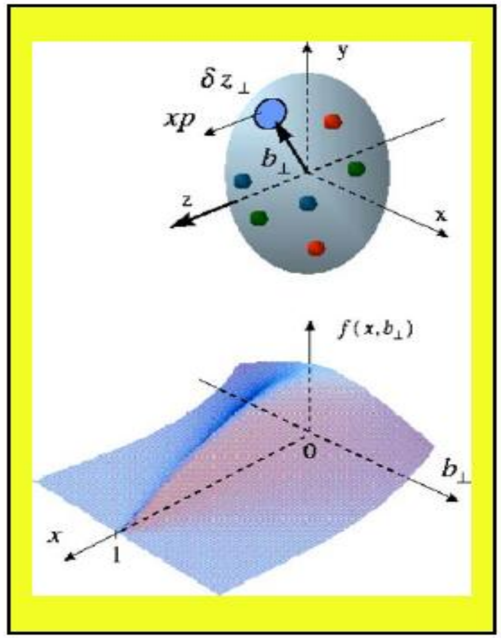
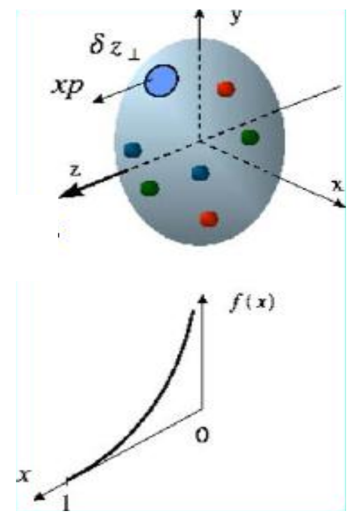
Generalized Parton Distributions

GPDs: H, E, $\tilde{H}$, $\tilde{E}$
Fully correlated quark distributions in both coordinate and momentum space

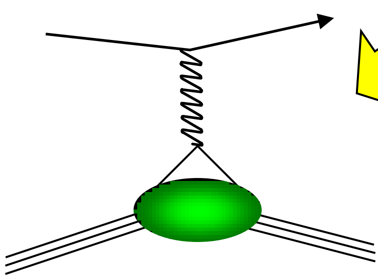


Form factors: **transverse quark distribution** **in coordinate space**



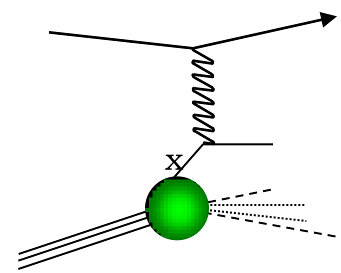


Parton distributions: **longitudinal quark distribution** **in momentum space**



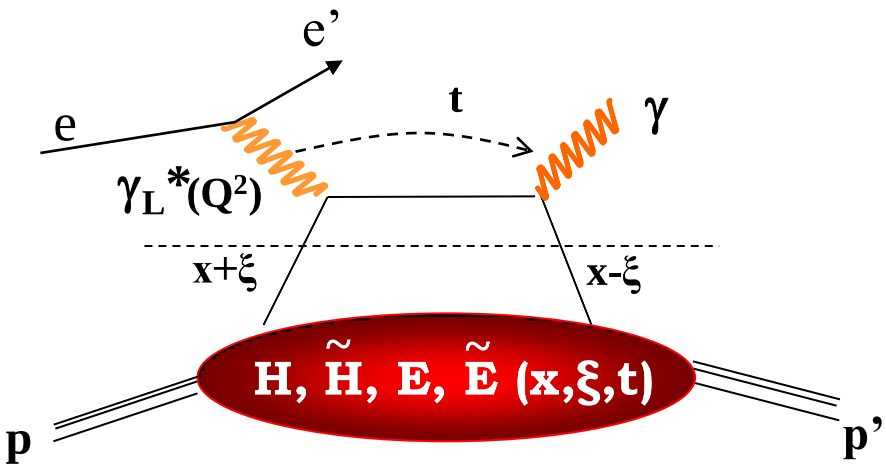
$$\int H(x,\xi,t)dx = F_1(t) \quad (\forall\ \xi)$$
$$\int E(x,\xi,t)dx = F_2(t) \quad (\forall\ \xi)$$

Accessible in hard exclusive processes



$$H(x,0,0) = q(x),$$
$$\tilde{H}(x,0,0) = \Delta q(x)$$

Deeply Virtual Compton Scattering and GPDs



- $Q^2 = -(e-e')^2$
- $x_B = Q^2/2M\nu \quad \nu = E_e - E_{e'}$

- $x+\xi$, $x-\xi$ longitudinal momentum fractions
- $t = (p-p')^2$
- $\xi \cong x_B/(2-x_B)$

4 GPDs for each quark flavor

conserve nucleon helicity

Vector: $H\ (x,\xi,t)$ **Axial-Vector: $\tilde{H}\ (x,\xi,t)$**

Tensor: $E\ (x,\xi,t)$ **Pseudoscalar: $\tilde{E}\ (x,\xi,t)$**

flip nucleon helicity

« Handbag » factorization valid in the Bjorken regime: high Q^2 , ν (fixed x_B), $t \ll Q^2$

Quark angular momentum (Ji's sum rule)

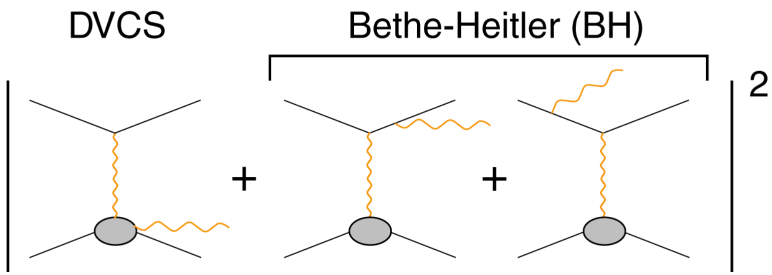
$$J^q = \frac{1}{2} - J^G = \frac{1}{2}\int_{-1}^{1} x\,dx \left[H^q(x,\xi,0) + E^q(x,\xi,0)\right]$$

X. Ji, Phy.Rev.Lett.78,610(1997)

«3D» quark/gluon image of the nucleon

Accessing GPDs through DVCS

$\sigma(eN \longrightarrow eN\gamma) =$

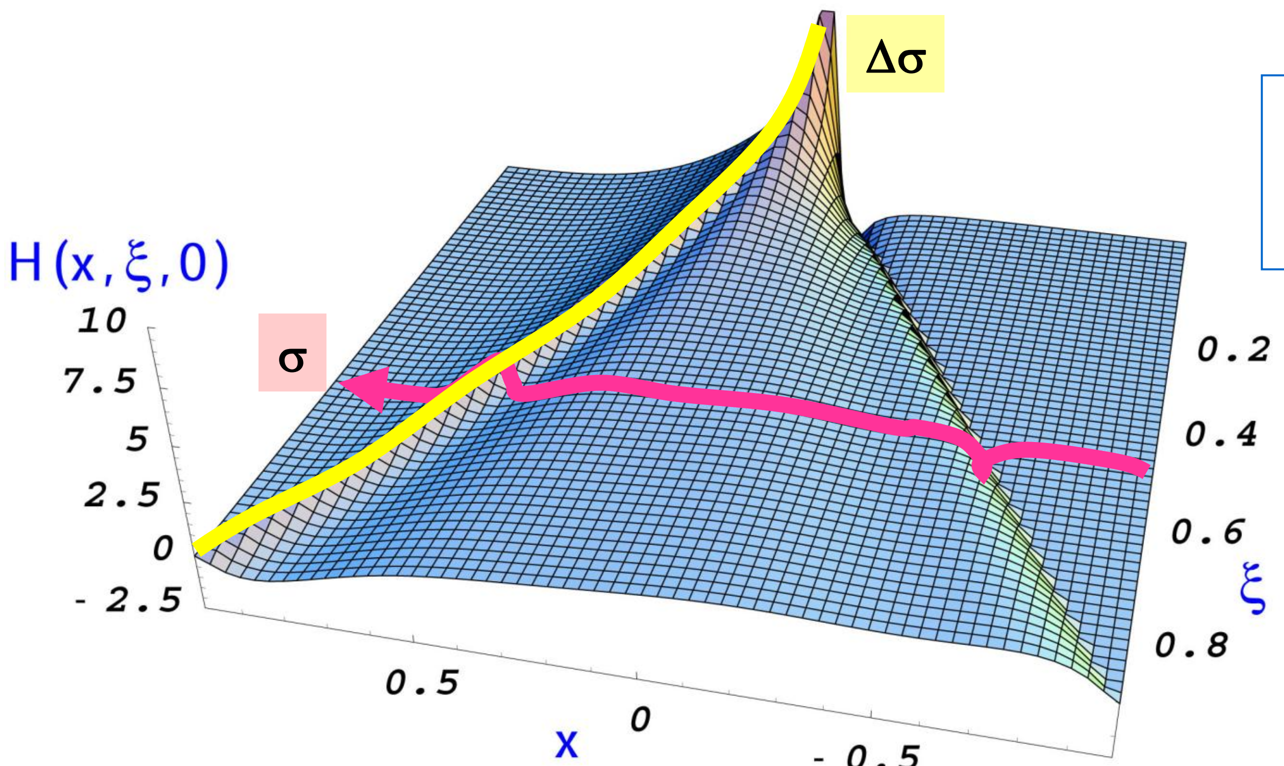


$$\sigma \sim |T^{DVCS} + T^{BH}|^2$$

$$\Delta\sigma = \sigma^+ - \sigma^- \propto I(DVCS \cdot BH)$$

$$A = \frac{\Delta\sigma}{2\sigma} \propto \frac{I(DVCS \cdot BH)}{|BH|^2 + |DVCS|^2 + I}$$

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

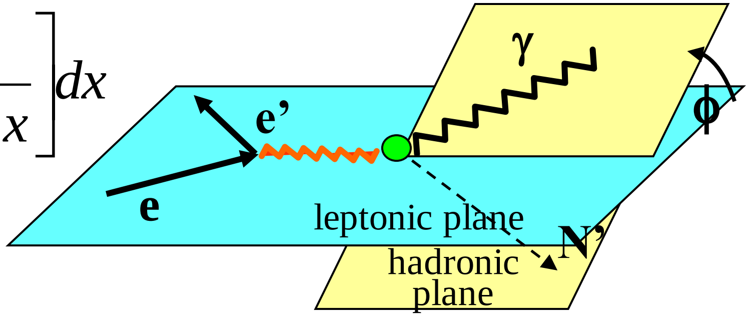


Only ξ and t are accessible experimentally

Sensitivity to GPDs of DVCS spin observables

$$Re\mathcal{H}_q = e_q^2 P\int_0^{+1}\left(H^q(x,\xi,t)-H^q(-x,\xi,t)\right)\left[\frac{1}{\xi-x}+\frac{1}{\xi+x}\right]dx$$

$$Im\mathcal{H}_q = \pi e_q^2\left[H^q(\xi,\xi,t)-H^q(-\xi,\xi,t)\right]$$



$\xi = x_B/(2-x_B)$ $k=-t/4M^2$

Proton **Neutron**

Polarized **beam**, unpolarized target:

$\Delta\sigma_{LU} \sim \sin\phi\ \mathbf{Im}\{F_1\mathcal{H} + \xi(F_1+F_2)\tilde{\mathcal{H}} - kF_2\mathcal{E}\}d\phi$ ⇒ $Im\{\mathcal{H}_p, \tilde{\mathcal{H}}_p, \mathcal{E}_p\}$, $Im\{\mathcal{H}_n, \tilde{\mathcal{H}}_n, \mathcal{E}_n\}$

Unpolarized beam, **longitudinal** target:

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

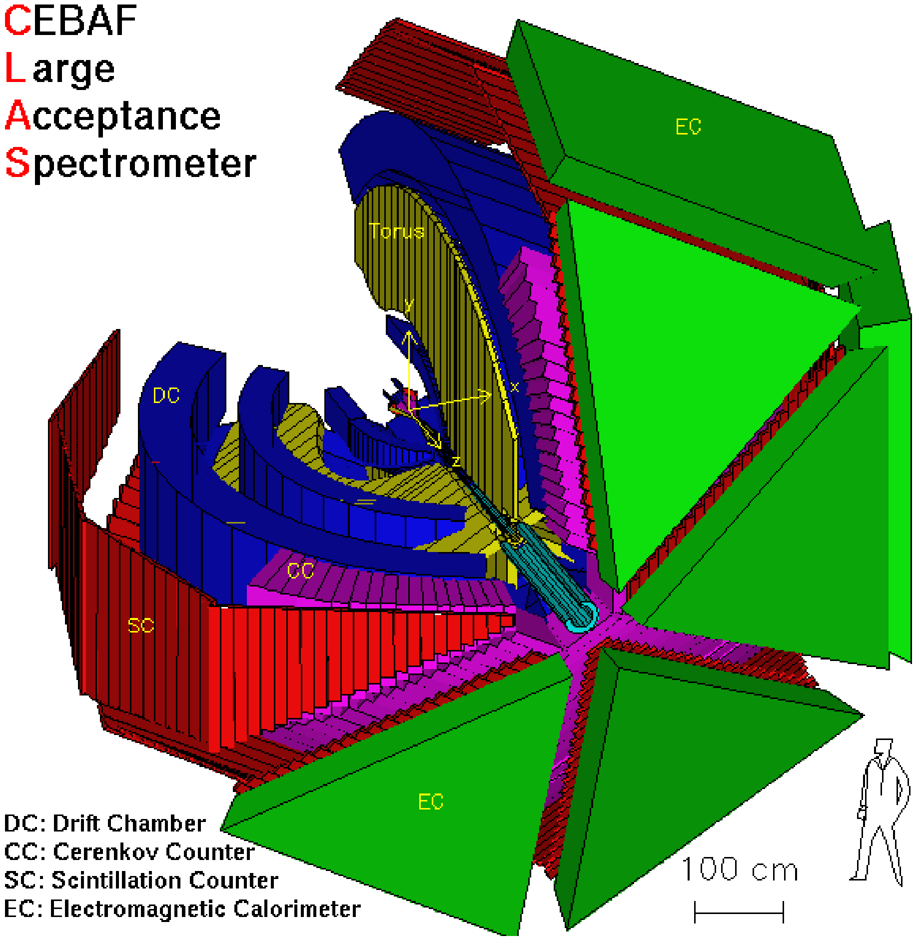
Polarized **beam**, **longitudinal** target:

$\Delta\sigma_{LL} \sim (A+B\cos\phi)\mathbf{Re}\{F_1\tilde{\mathcal{H}} + \xi(F_1+F_2)(\mathcal{H} + x_B/2\,\mathcal{E})\ldots\}d\phi$ ⇒ $Re\{\mathcal{H}_p, \tilde{\mathcal{H}}_p\}$, $Re\{\mathcal{H}_n, \mathcal{E}_n, \tilde{\mathcal{E}}_n\}$

Unpolarized beam, **transverse** target:

$\Delta\sigma_{UT} \sim \sin\phi\,\mathbf{Im}\{k(F_2\mathcal{H} - F_1\mathcal{E}) + \ldots\}d\phi$ ⇒ $Im\{\mathcal{H}_p, \mathcal{E}_p\}$, $Im\{\mathcal{H}_n\}$

The CLAS detector (Jefferson Lab, Hall B)



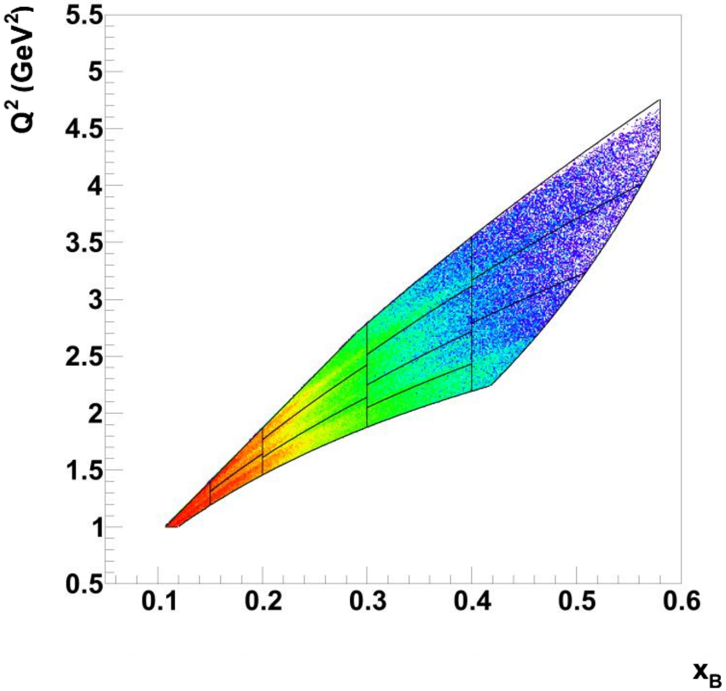
- Toroidal magnetic field (6 supercond. coils)
- Drift chambers (argon/CO_2 gas, 35000 cells)
- Time-of-flight scintillators
- Electromagnetic calorimeters
- Cherenkov Counters (e/π separation)

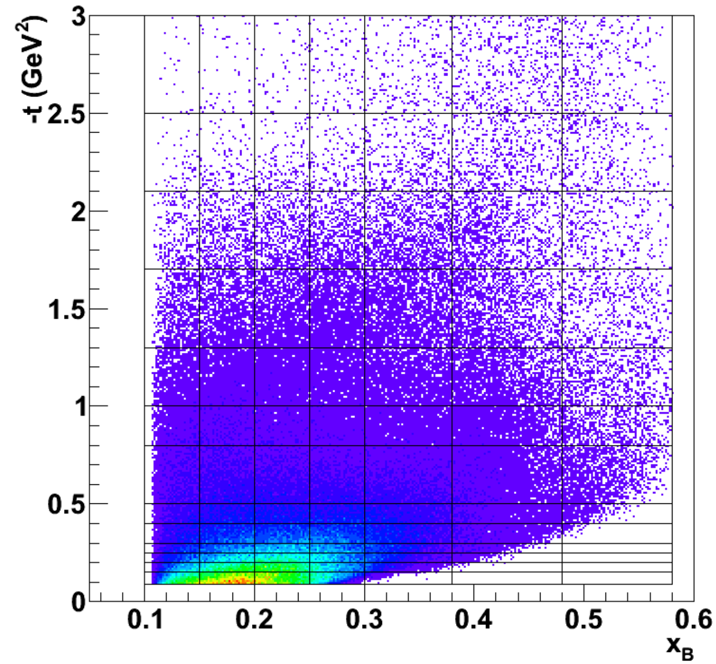
Performances:

- **large acceptance** for charged particles
  $8° < \theta < 142°$, $p_p > 0.3$ GeV/c, $p_\pi > 0.1$GeV/c
- **good momentum and angular resolution**
  $\Delta p/p \leq 0.5\%$- 1.5%, $\Delta\theta$, $\Delta\phi \leq 1$ mrad

Optimal for measurements of exclusive reactions with multi-particle final states

The e1-DVCS experiment



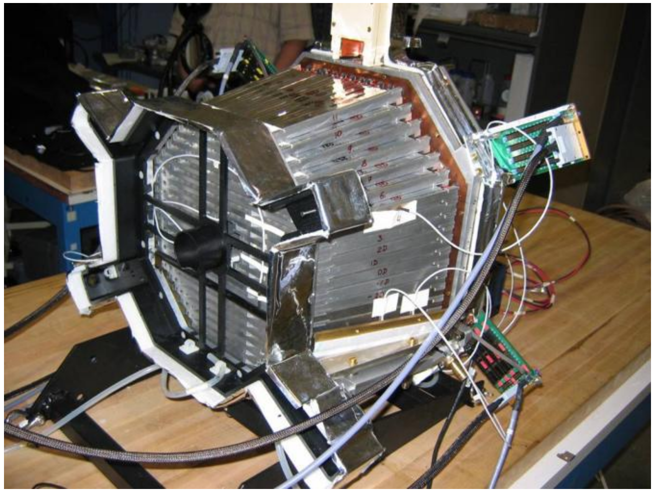


Part 1 of the e1-DVCS experiment:

- Data taken from March 11 until May 27, 2005
- Beam energy ~ 5.766 GeV
- Beam current = 20-25 nA
- Beam polarization ~ 80%
- Integrated luminosity ~ 3.33×10^{7} nb^{-1}
- Target LH_2

CLAS + Solenoid (Moeller shield) + IC

More data taken in fall 2008, under analysis

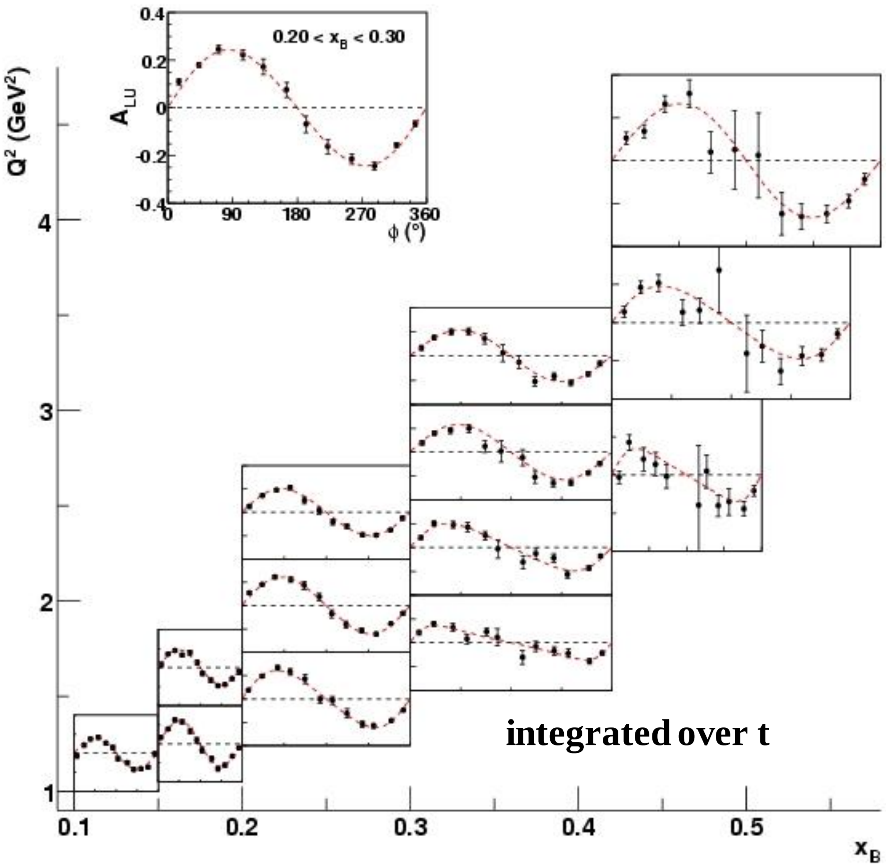


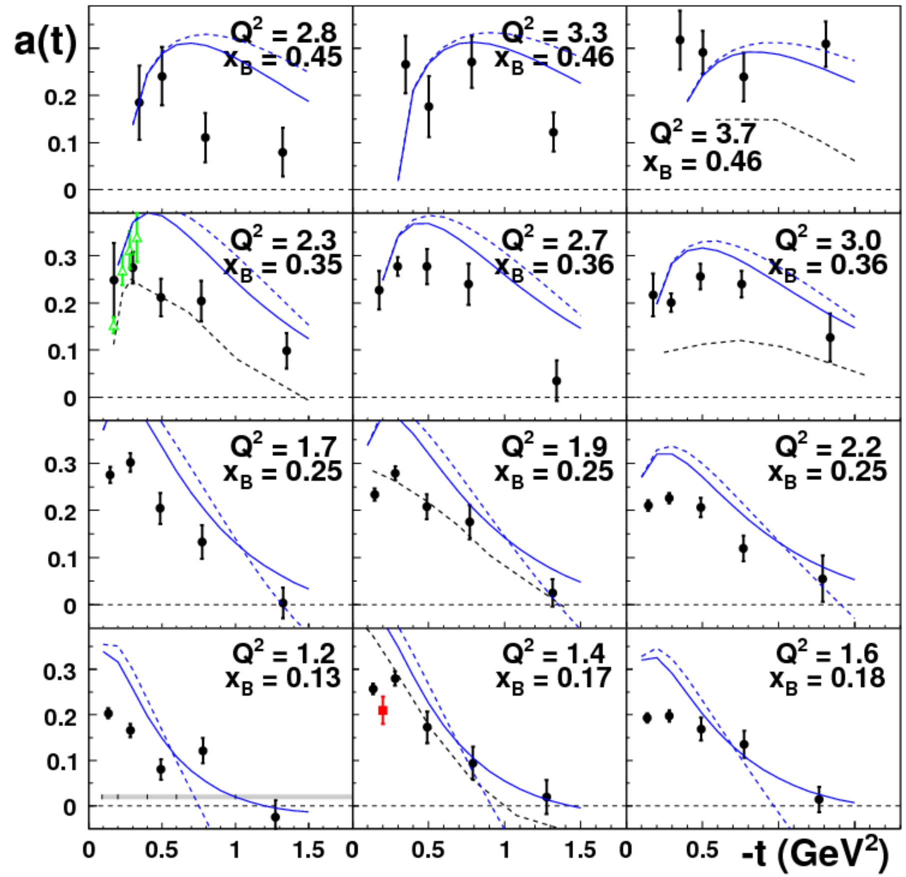
IC (inner calorimeter)
424 lead tungstate crystals + APD readout

DVCS Beam Spin Asymmetries

ep→epγ

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





- CLAS e1-dvcs
- Hall A
- CLAS @ 4.3 GeV^2
- VGG(*) twist-2 (DD)
- VGG(*) twist-2 and 3
- Regge model (**)

Fit = a sinϕ/(1+b cosϕ)

F.X. Girod et al. (CLAS Collaboration), Phys. Rev. Lett. 100, 162002 (2008)

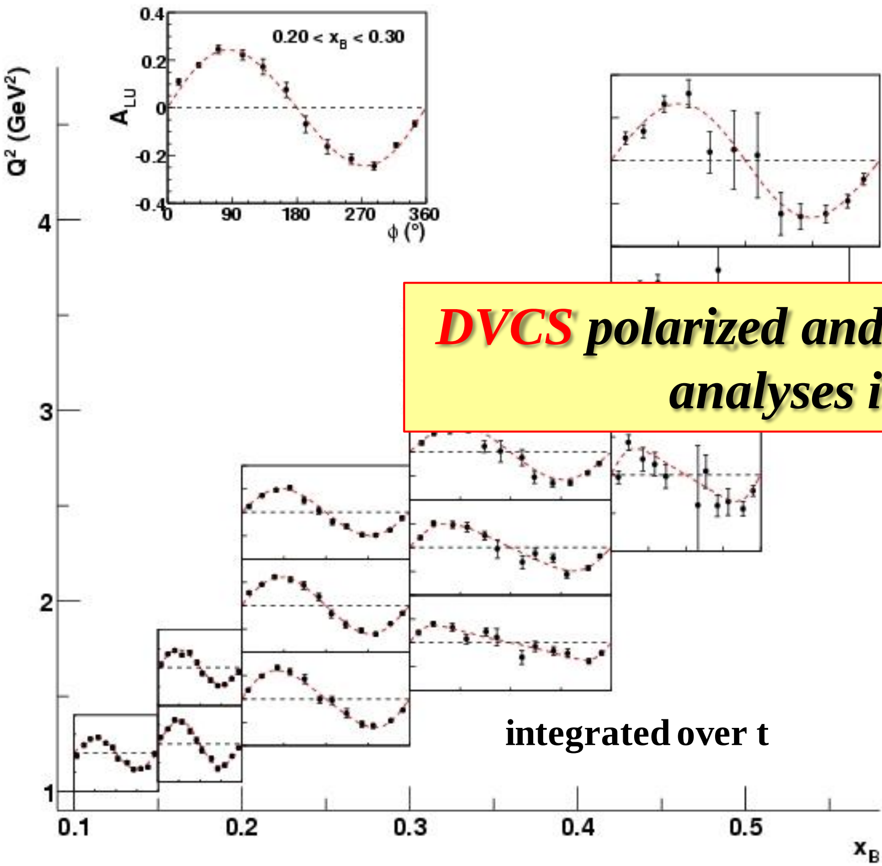
(*) Guidal, Polyakov, Radyushkin, Vanderhaegen, PRD 72 (2005)

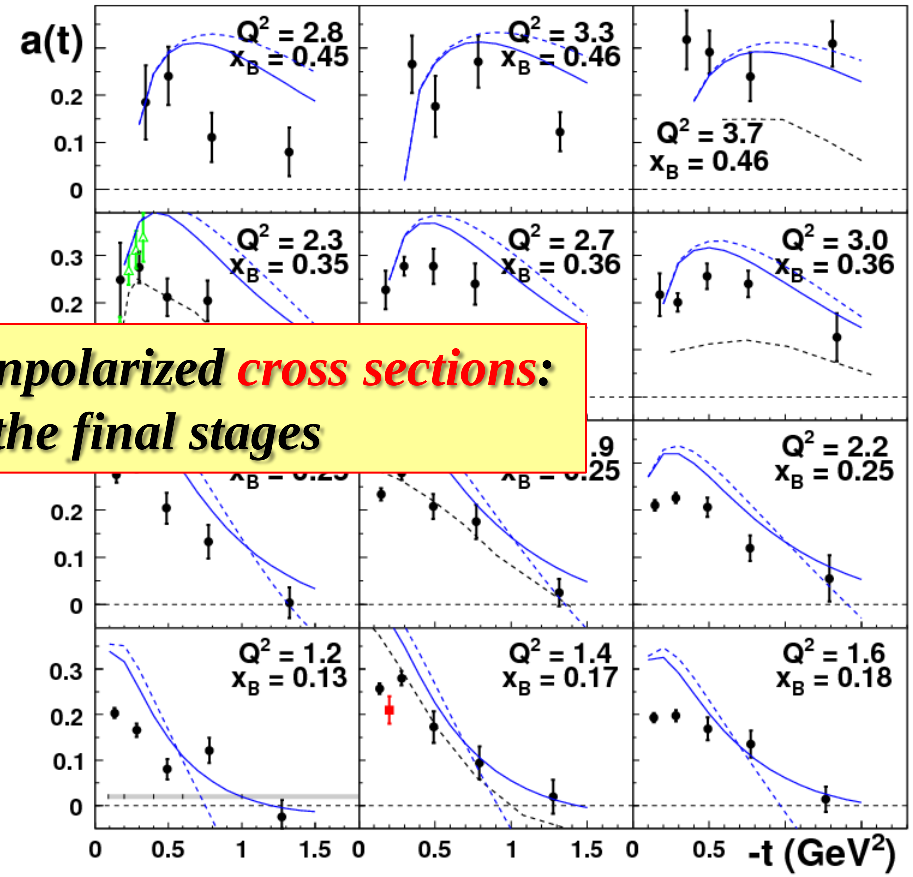
(**) Cano and Laget, PL B551 (2003)

DVCS Beam Spin Asymmetries

ep→epγ

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





DVCS polarized and unpolarized cross sections: analyses in the final stages

- CLAS e1-dvcs
- Hall A
- CLAS @ 4.3 GeV²
- VGG(*) twist-2 (DD)
- VGG(*) twist-2 and 3
- Regge model (**)

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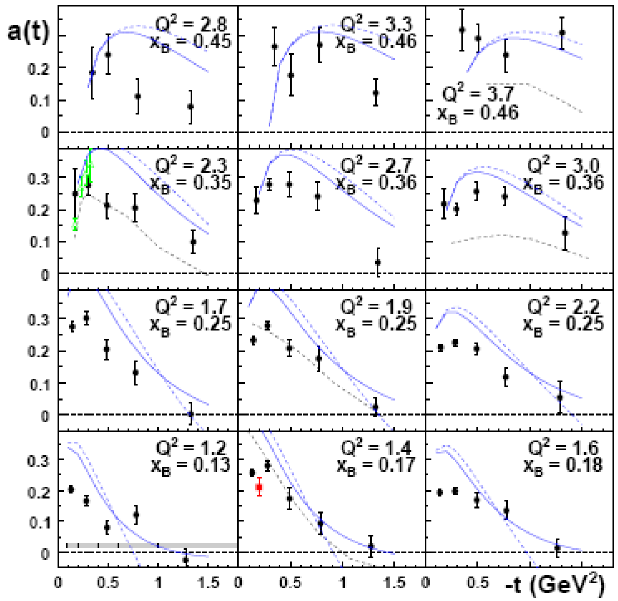
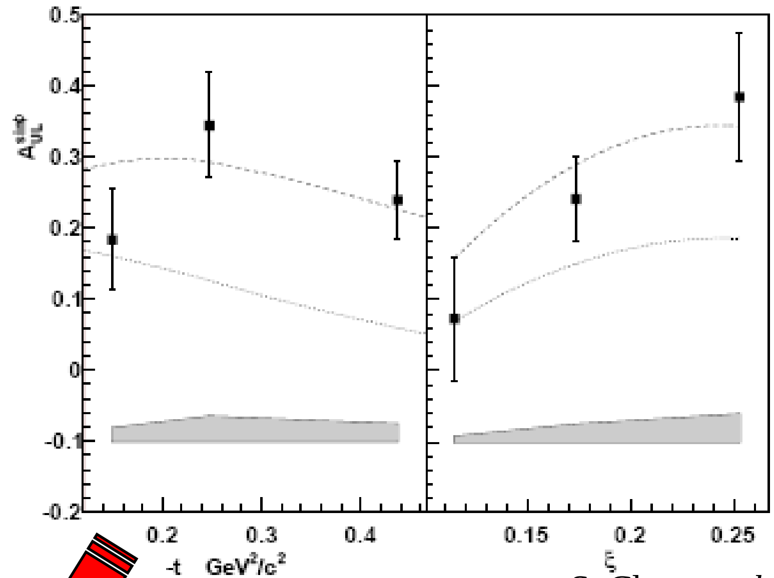
What we learn from the published CLAS asymmetries

CLAS
pDVCS
BSAs



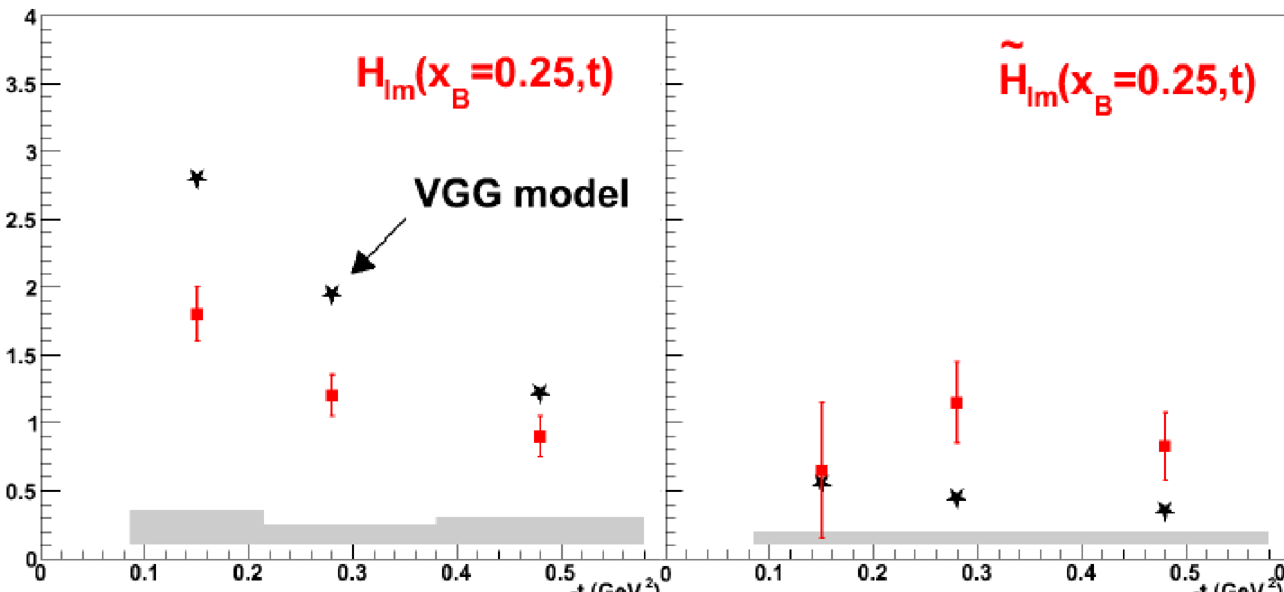


CLAS
pDVCS
TSAs

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

Model-independent fit
at fixed x_B, t, Q^2
of DVCS observables

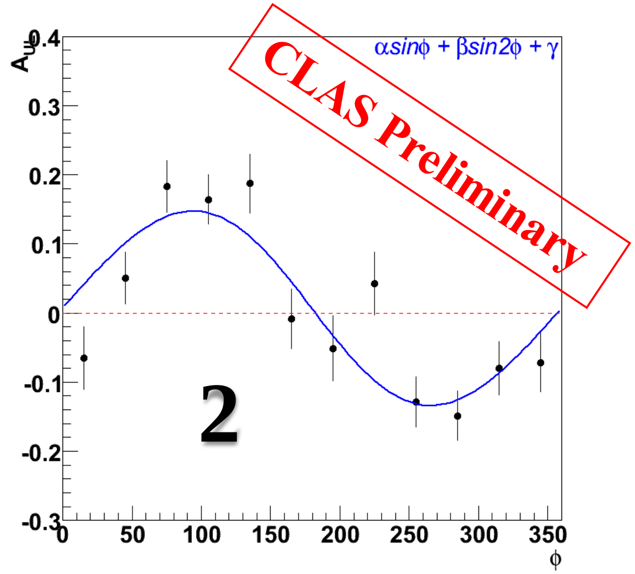
ImH has steeper t-slope than Im$\tilde{H}$: is axial charge more concentrated than the electromagnetic charge?

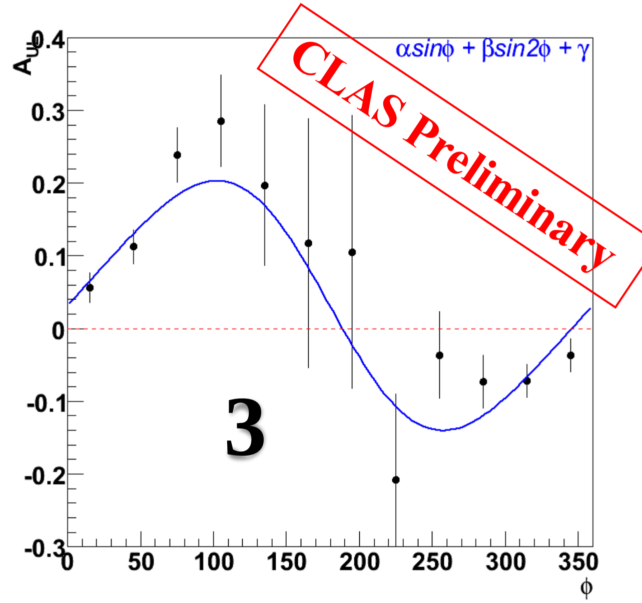


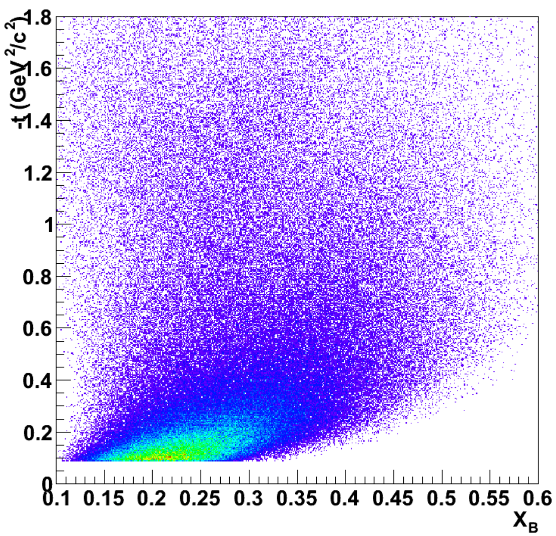
M. Guidal, Phys. Lett. B 689, 156-162 (2010)

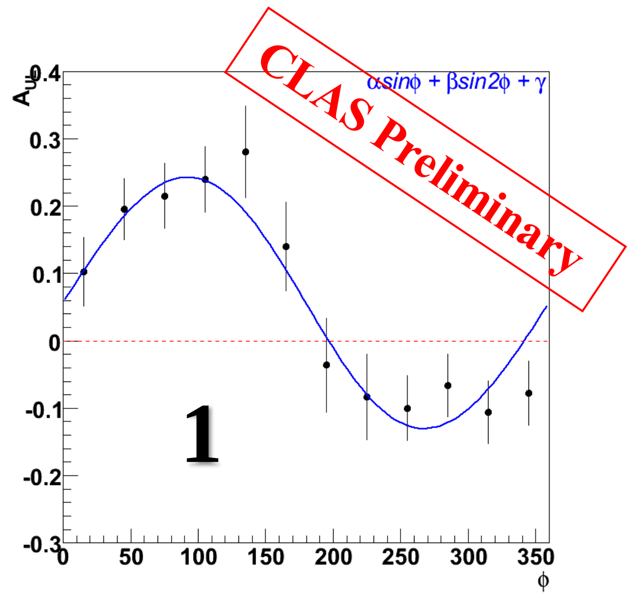
The eg1-DVCS experiment: TSA

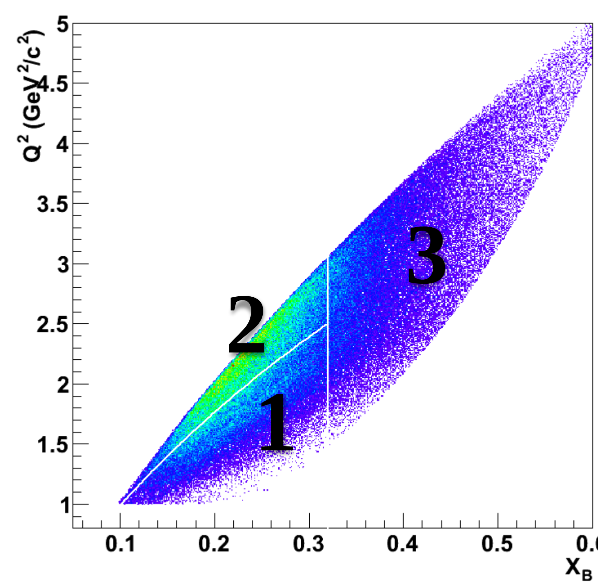
- Data taken from February 4 to September 21 2009
- Beam energy = 4.735, 5.764, 5.892, 5.967 GeV
- Target: longitudinally polarized NH_3 (~80%) and ND_3 (~30%)
- IC to detect forward photons











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

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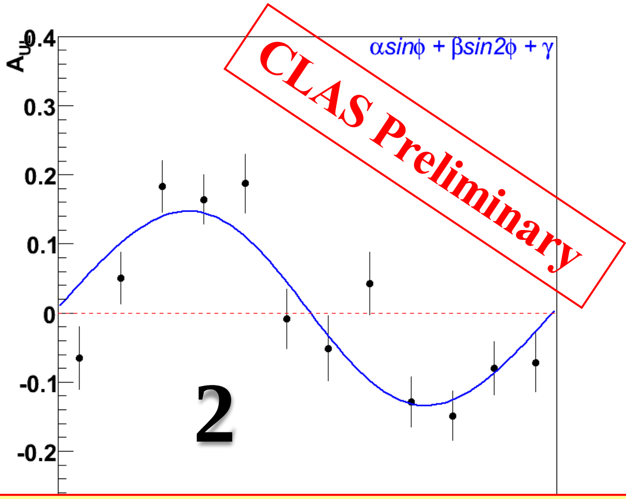
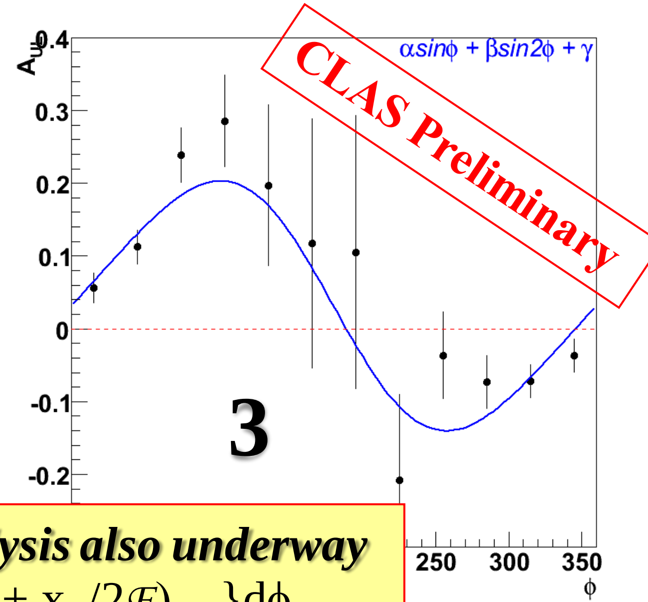
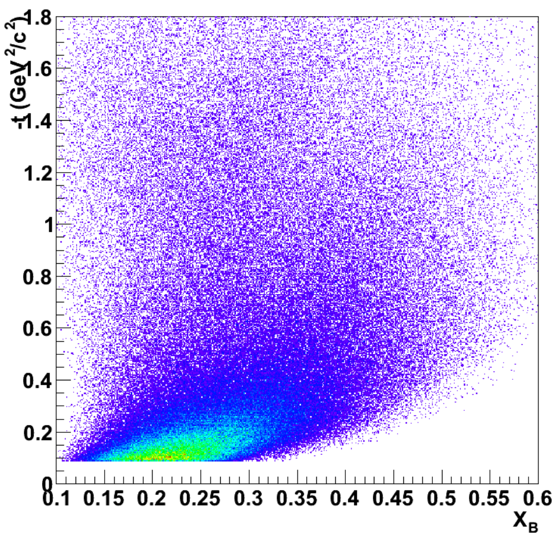
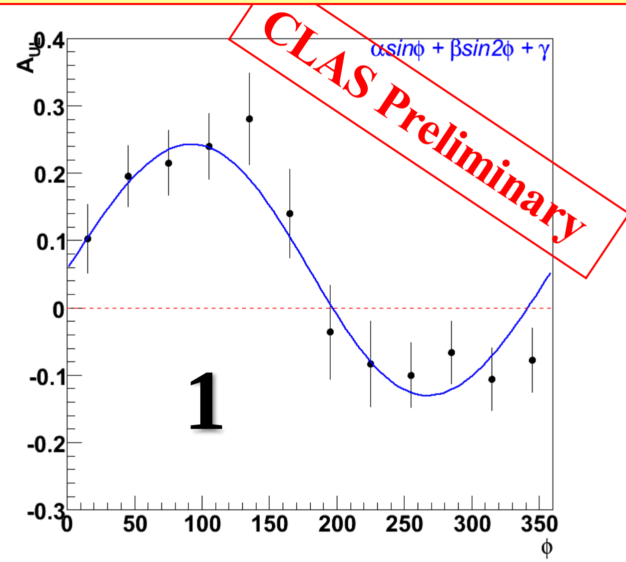


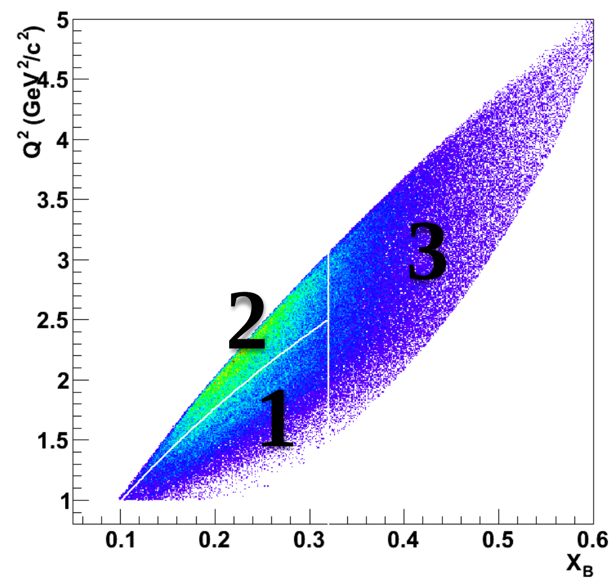


***Double-spin* (beam-target) asymmetry analysis also underway**

$$\Delta\sigma_{LL} \sim (A+B\cos\phi)\mathbf{Re}\{F_1\tilde{\mathcal{H}}+\xi(F_1+F_2)(\mathcal{H}+x_B/2\mathcal{E})\ldots\}d\phi$$

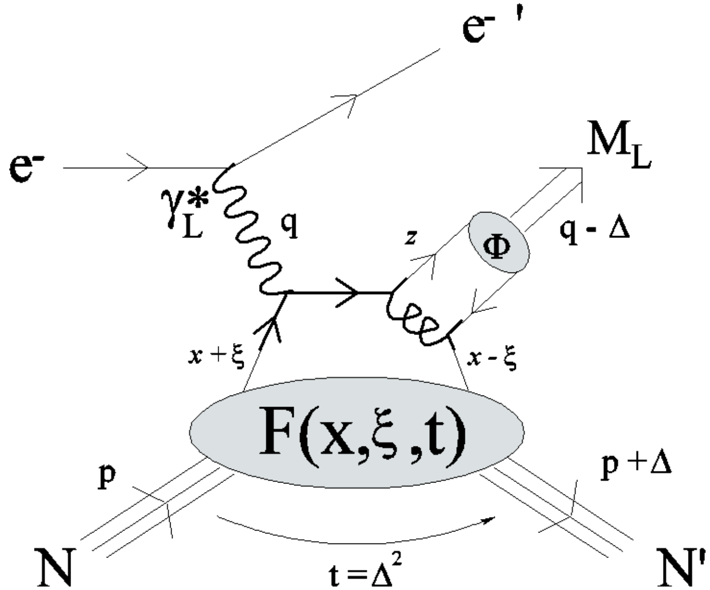






$$\Delta\sigma_{UL} \sim \sin\phi\mathbf{Im}\{F_1\tilde{\mathcal{H}}+\xi(F_1+F_2)(\mathcal{H}+x_B/2\mathcal{E})-\xi kF_2\,\mathcal{E}+\ldots\}d\phi$$

Deeply virtual meson production and GPDs



Different mesons → different sensitivity to GPDs

H	$\tilde{\mathbf{H}}$
E	$\tilde{\mathbf{E}}$
Vector mesons (ρ, ω, ϕ)	**Pseudoscalar** mesons (π, η)

π^0	2Δu+Δd
η	2Δu-Δd

ρ^0	2u+d
ω	2u-d
ρ^+	u-d

Factorization proven only for **longitudinally polarized** virtual photons and valid at **high Q^2** and **small t**

quark flavor decomposition accessible via meson production

$$\mathcal{A}_L = -\frac{2ie}{9}\left(\int_0^1 dz \frac{\Phi(z)}{z}\right) \frac{4\pi\alpha_S(Q^2)}{Q} \int_{-1}^{+1} dx \left\{\left[\frac{1}{x-\xi+i\epsilon} + \frac{1}{x+\xi-i\epsilon}\right] F(x,\xi,t)\right\}$$

Complications: effective scale in the hard scattering process, meson distribution amplitude

Deeply virtual meson production at CLAS

Vector mesons: exclusive ρ^0, ω, ϕ and ρ^+ electroproduction on the proton with CLAS:

K. Lukashin *et al.*, Phys. Rev. C 63, 065205, 2001 **(ϕ@4.2 GeV)** C. Hadjidakis *et al.*, Phys. Lett. B 605, 256-264, 2005 **(ρ^0@4.2 GeV)**	e1-b (1999)
L. Morand *et al.*, Eur. Phys. J. A 24, 445-458, 2005 **(ω@5.75GeV)** J. Santoro *et al.*, Phys. Rev. C 78, 025210, 2008 **(ϕ@5.75 GeV)** S. Morrow *et al.*, Eur. Phys. J. A 39, 5-31, 2009 **(ρ^0@5.75GeV)**	e1-6 (2001-2002)
A. Fradi, Orsay Univ. PhD thesis **(ρ^+@5.75 GeV)**	e1-DVCS (2005)

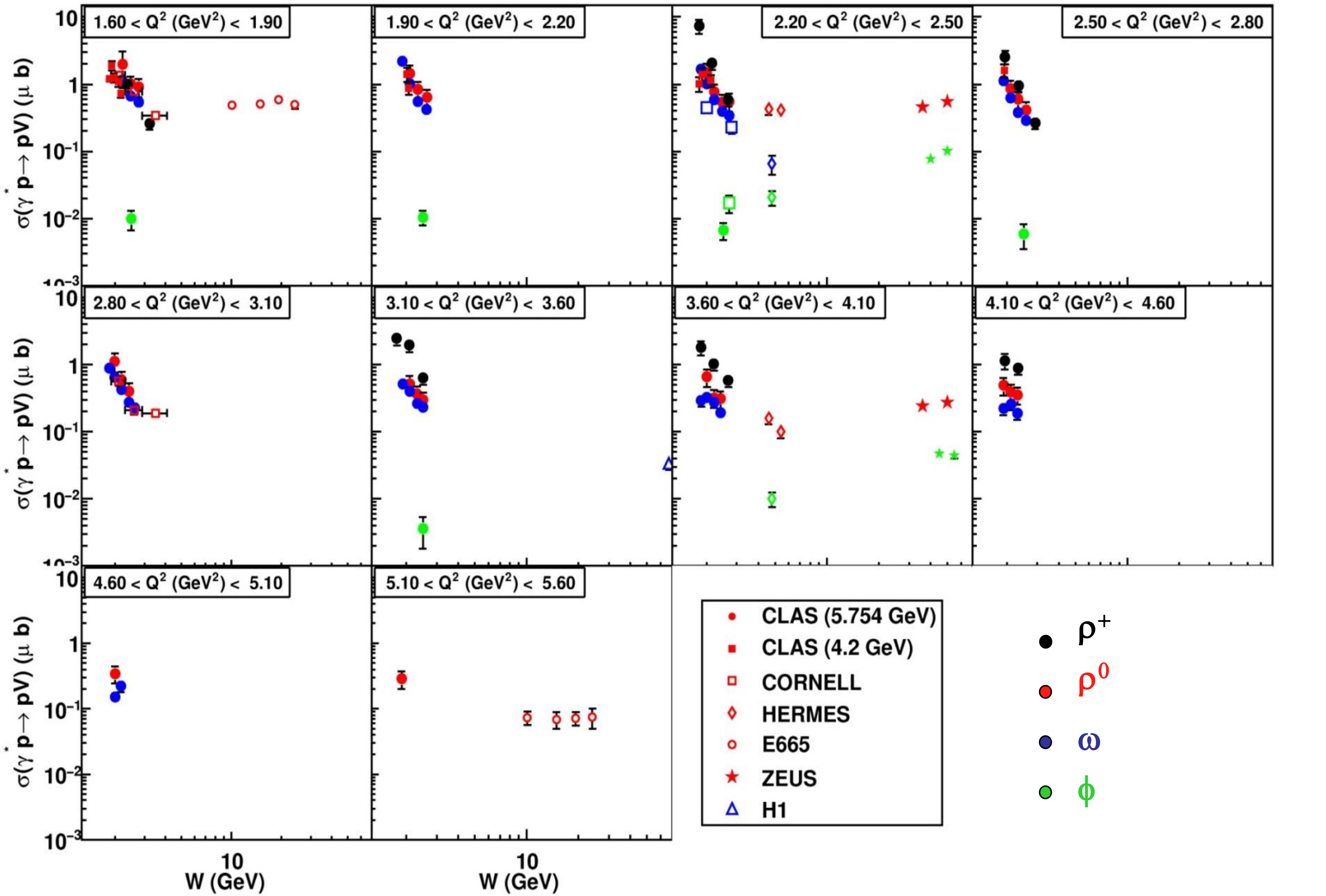
There are also results on **exclusive pseudoscalar meson electroproduction** on the proton with CLAS:

R. De Masi *et al.*, Phys. Rev. C 77, 042201(R), 2008 **(π^0@5.75GeV)**

K. Park *et al.*, Phys. Rev. C 77, 015208, 2008 **(π^+@5.75 GeV)**

I. Bedlinskiy *et al.*, paper in preparation **(π^0@5.75GeV)**

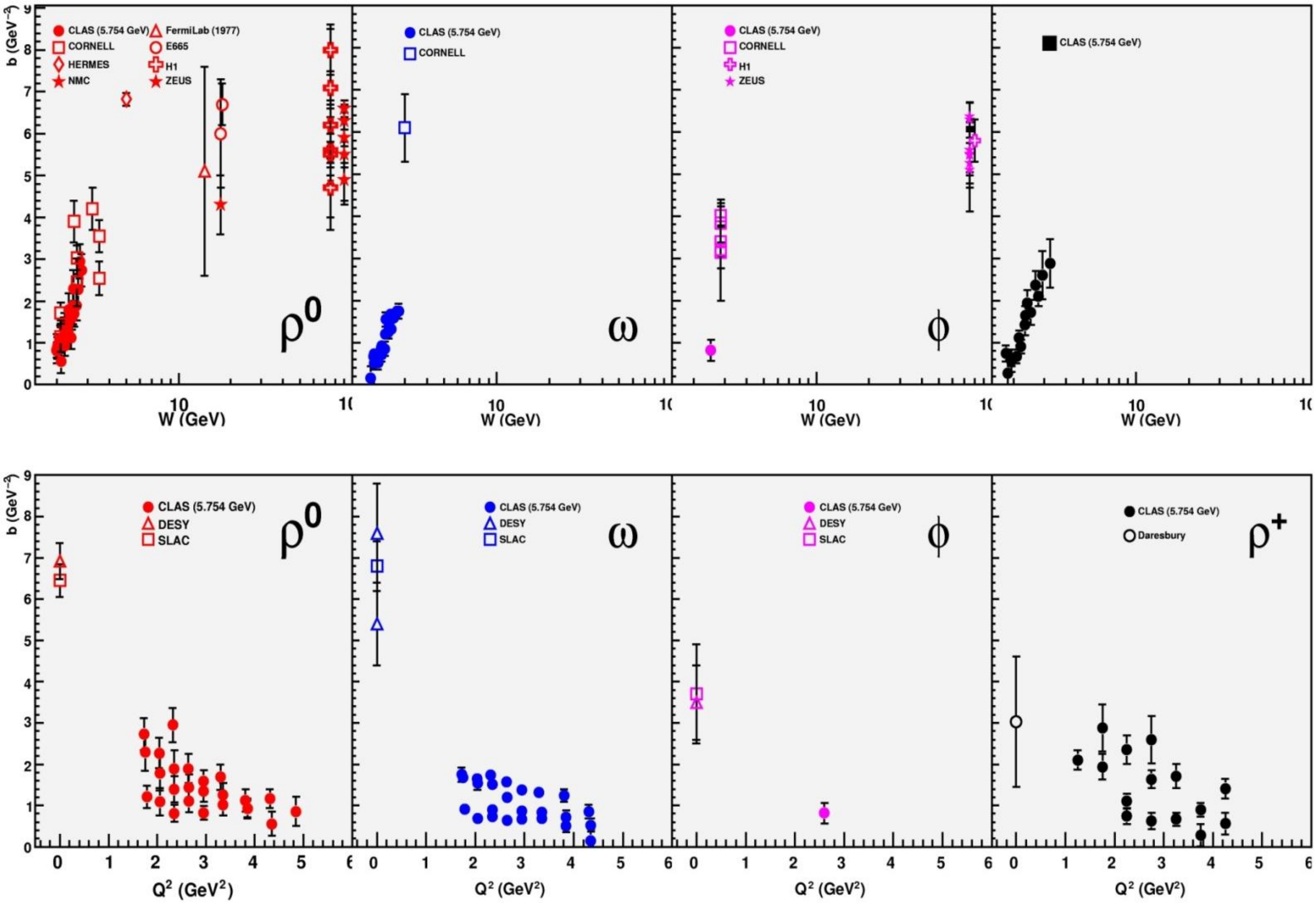
Comparison between vector mesons (σ)



Comparison between vector mesons

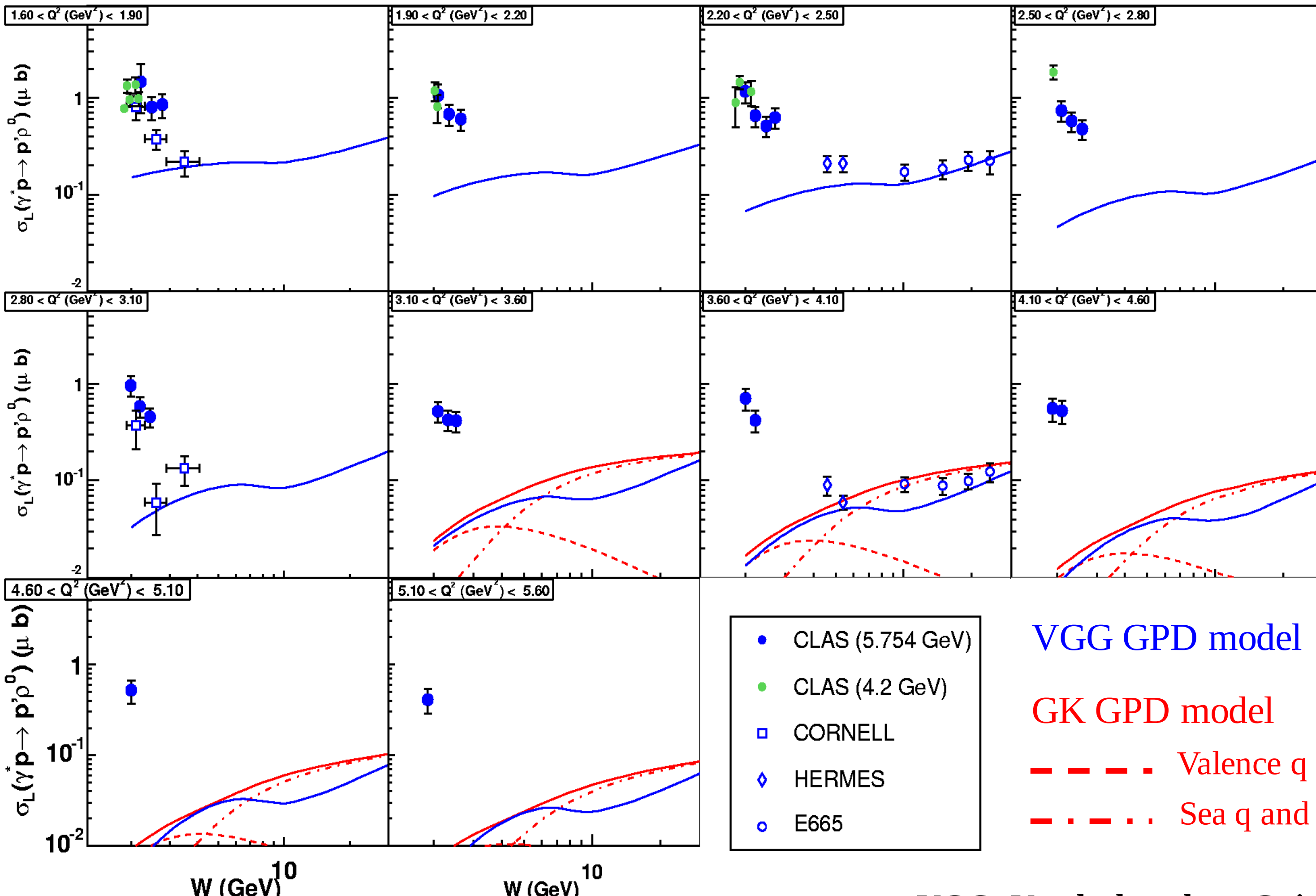
b increases with W (~1/x): valence (fast) quarks in the center and sea (slow) quarks at the periphery of the nucleon

$d\sigma/dt \sim e^{bt}$



b decreases with Q²: by increasing the resolution of the probe, smaller objects in the nucleon can be seen

Longitudinal cross section $\sigma_L(\gamma^*_L p \rightarrow p\, \rho^0_L)$



The GPD models fail to reproduce the behavior at **low W** (W < 5 GeV)

VGG GPD model

GK GPD model

Valence q

Sea q and gluons

S. Morrow *et al.*, Eur. Phys. J. A 39, 5-31, 2009

VGG: Vanderhaeghen, Guichon, Guidal

GK: Goloskokov, Kroll

GPDs: where we stand, where we are going

- Pioneering dedicated experiments on **DVCS** (Hall A, CLAS), show evidence for **handbag (twist-2) dominance** (asymmetry ~sinϕ) and **unexpected scaling** at **Q^2~ 2 GeV^2** (Hall A)
- **DVMP** experiments at CLAS (ρ, ω, π^0) and Hall A (π^0) hint that either **scaling cannot be reached** for Q^2 as low as for DVCS or **something is missing** in GPDs parameterizations
- Model-independent fits need to combine **several observables** to constrain GPDs
- Hall A's first attempt to measure **nDVCS** showed the importance of this channel for **Ji's sum rule** and the extraction of **J_q**

More data needed on DVCS and DVMP:

- **High Q^2 to verify scaling for DVCS on a wider Q^2 range, and to approach GPD validity regime for DVMP**
- **Wide x_B coverage**
- **High accuracy on measured observables to test models (high luminosity required)**
- **Measurements of spin-asymmetries and cross sections on proton and neutron**

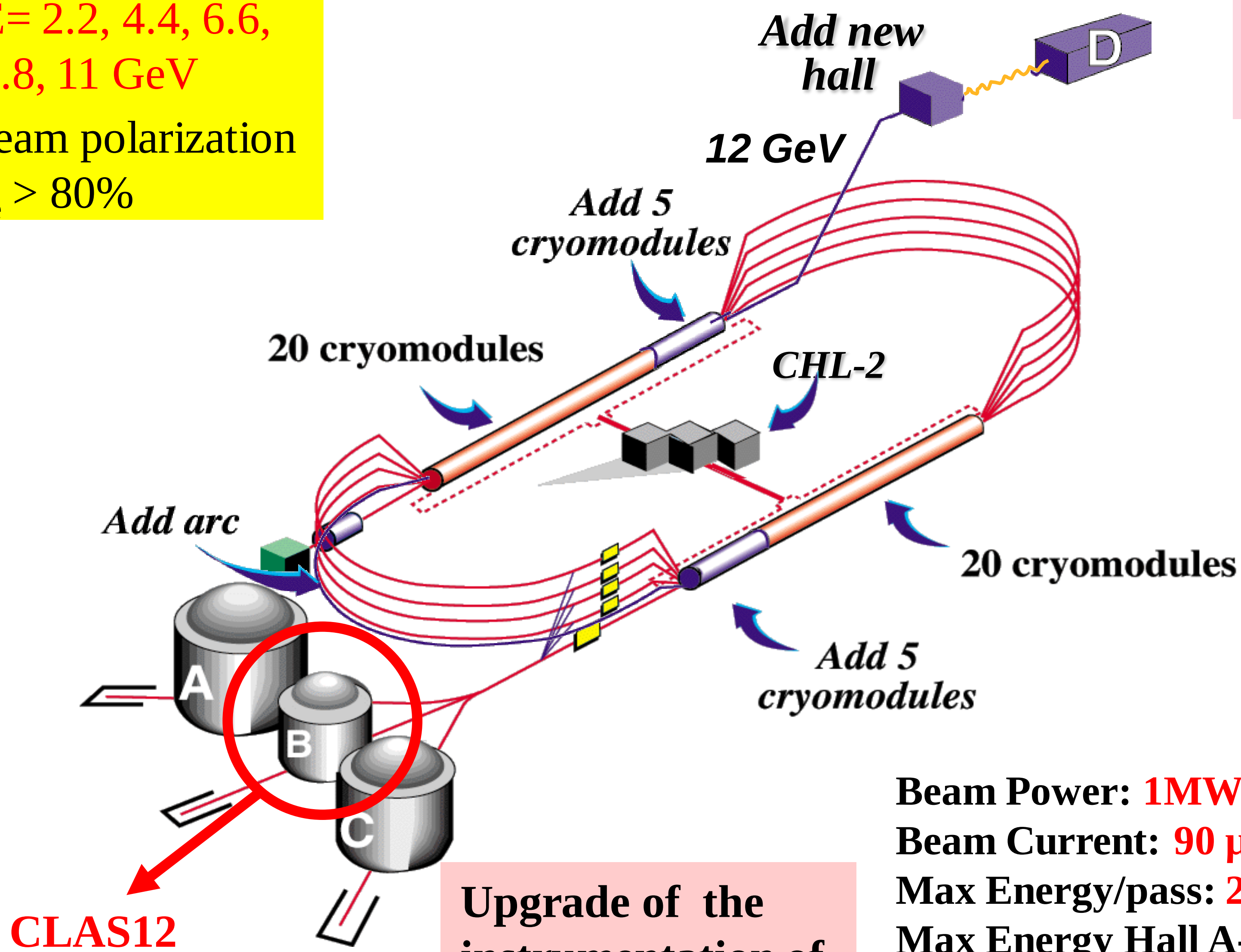
CLAS12 will be the optimal facility for these goals

JLab upgrade to 12 GeV

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

Beam polarization $P_e > 80\%$

Continuous
Electron
Beam
Accelerator
Facility



Upgrade of the instrumentation of the existing Halls

Beam Power: 1MW
Beam Current: 90 μA
Max Energy/pass: 2.2 GeV
Max Energy Hall A-C: 11 GeV
Max Energy Hall D: 12 GeV

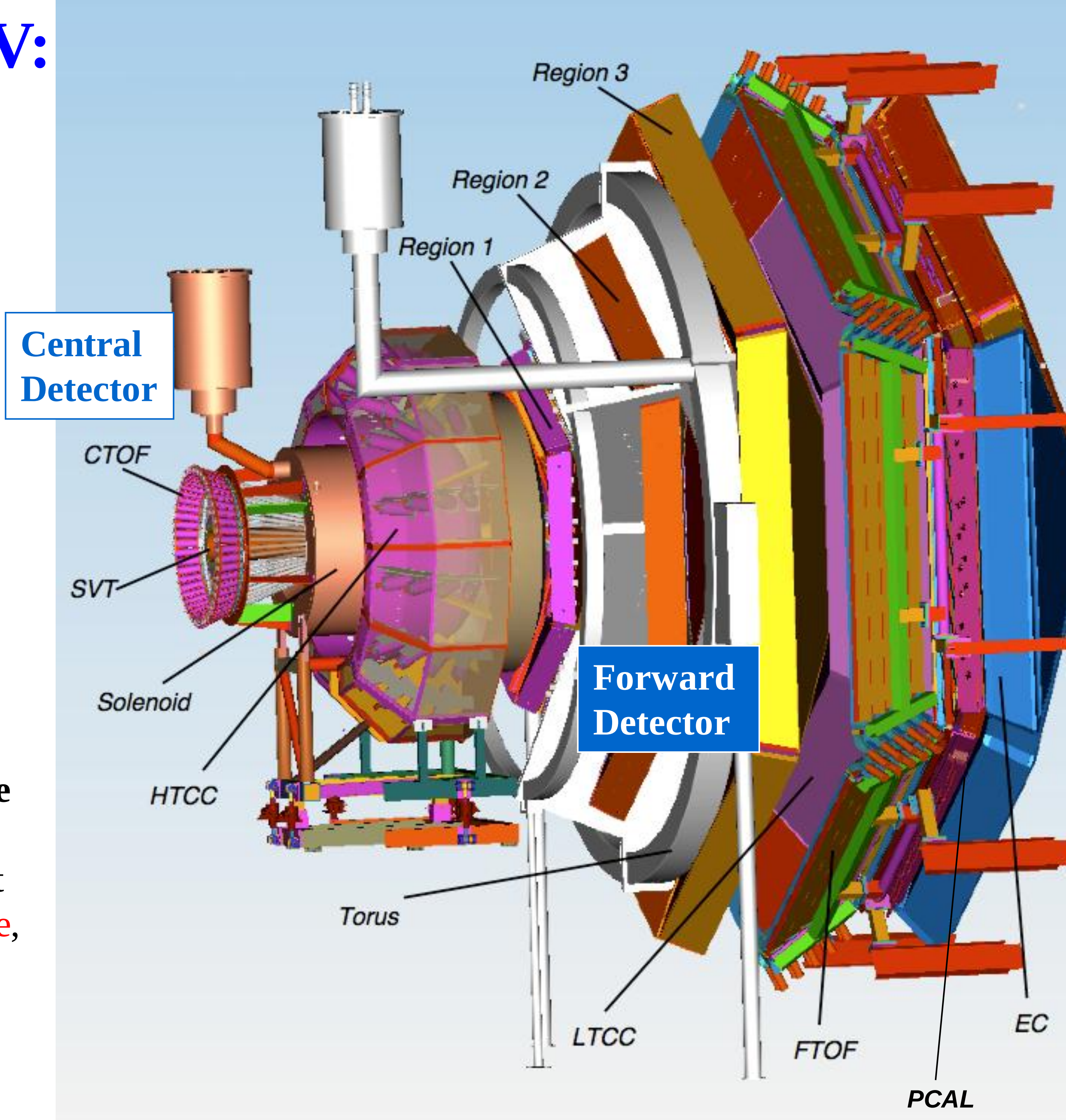
Hall B@12 GeV: CLAS12

Design luminosity
L ~ 10^{35} cm^{-2}s^{-1}

Acceptance for charged particles:
- **Central (CD), 40º<θ<135º**
- **Forward (FD), 5º<θ<40º**

Acceptance for photons:
- **IC 2º<θ<5º**
- **EC, 5º<θ<40º**

High luminosity & large acceptance:
Concurrent measurement of deeply virtual exclusive, semi-inclusive, and inclusive processes



Hall B@12 GeV: CLAS12

Forward Detector:

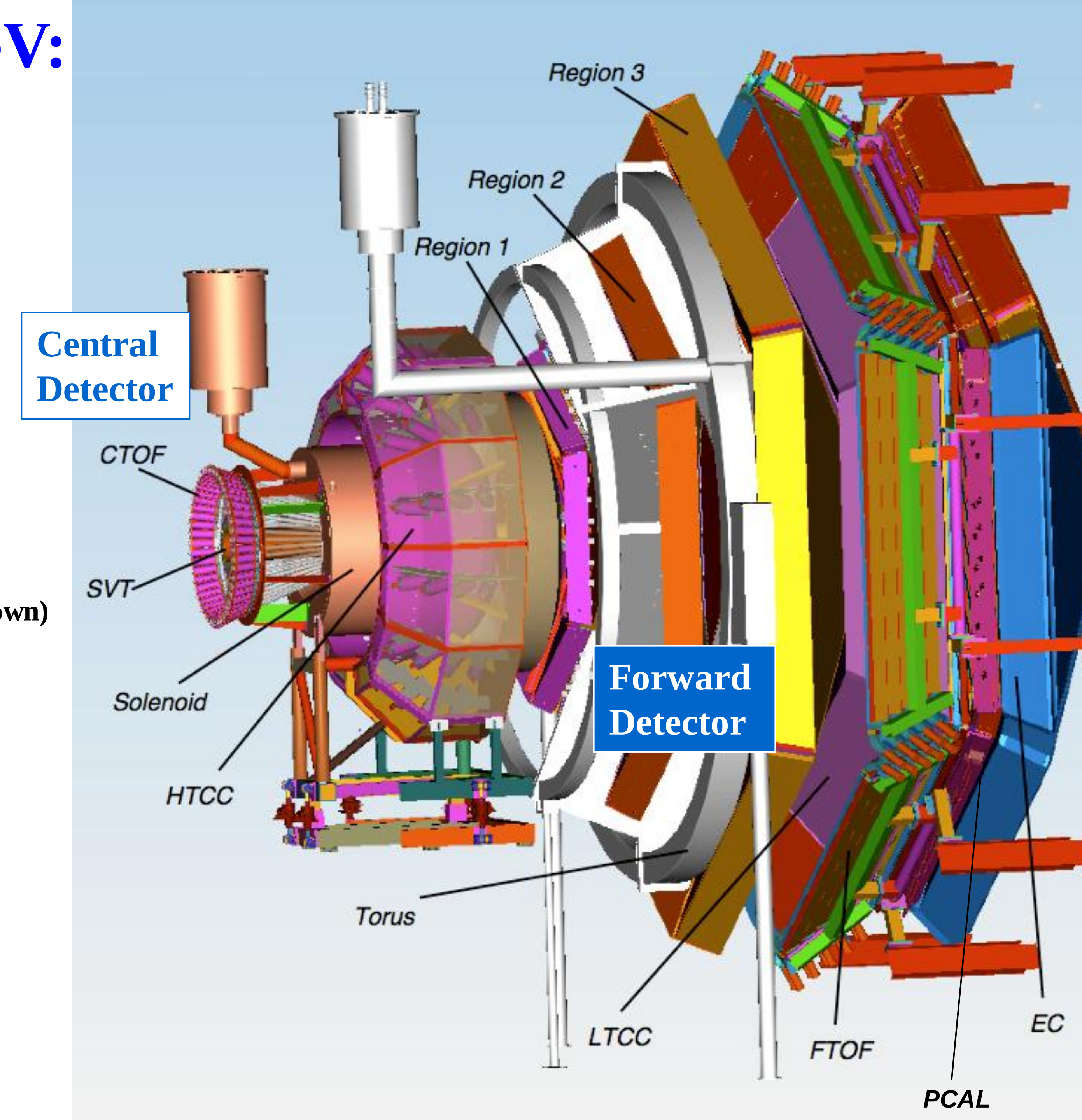
TORUS magnet
Forward tracker
HT Cherenkov Counter
Drift chambers (3 regions)
LT Cherenkov Counter
Forward ToF System
Preshower calorimeter
E.M. calorimeter (EC)
Inner Calorimeter (IC, not shown)

Central Detector:

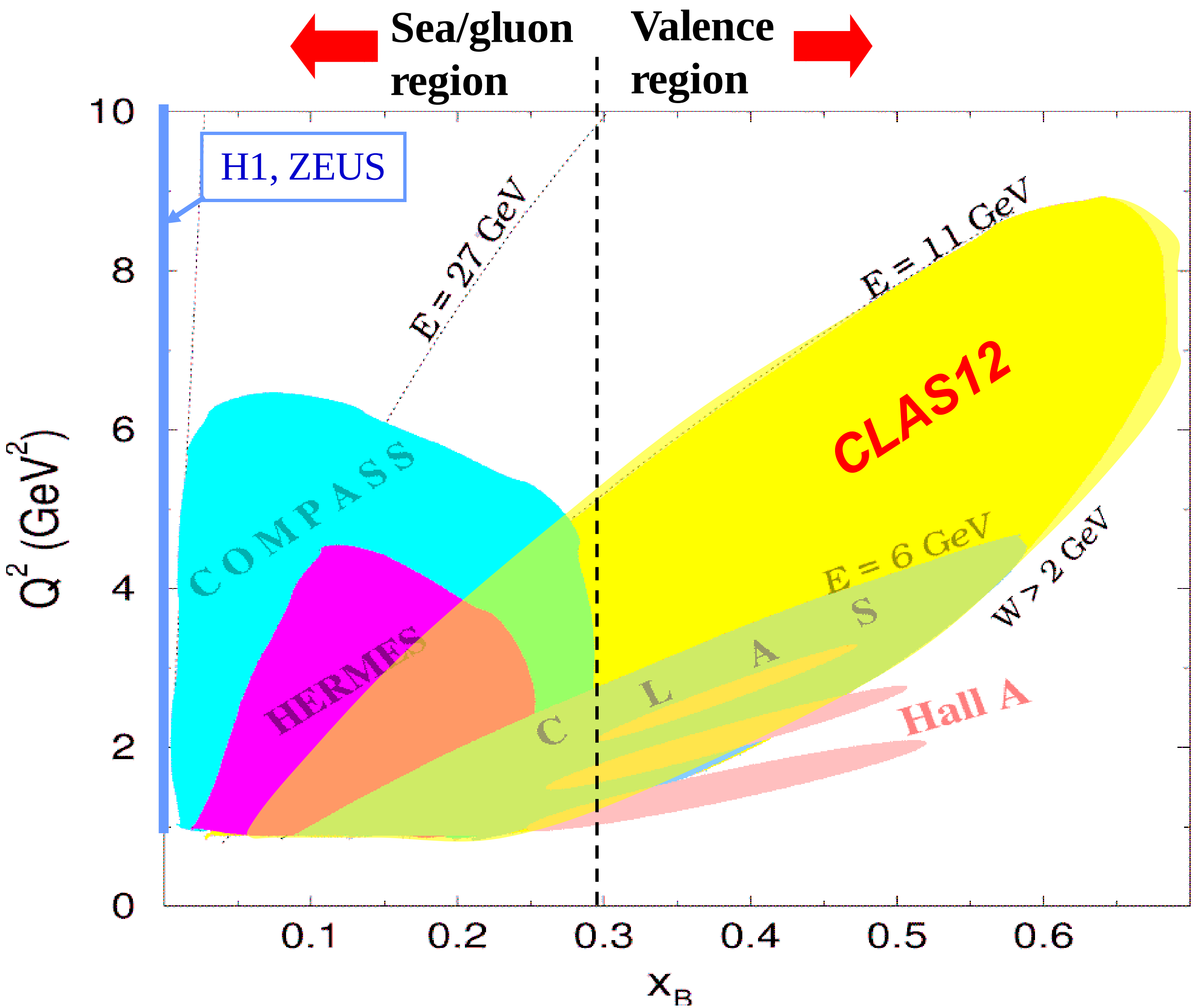
SOLENOID magnet
Barrel Silicon Tracker
Central Time-of-Flight

Proposed upgrades:

Micromegas (CD)
Neutron detector (CD)
RICH detector (FD)
Forward Tagger (FD)

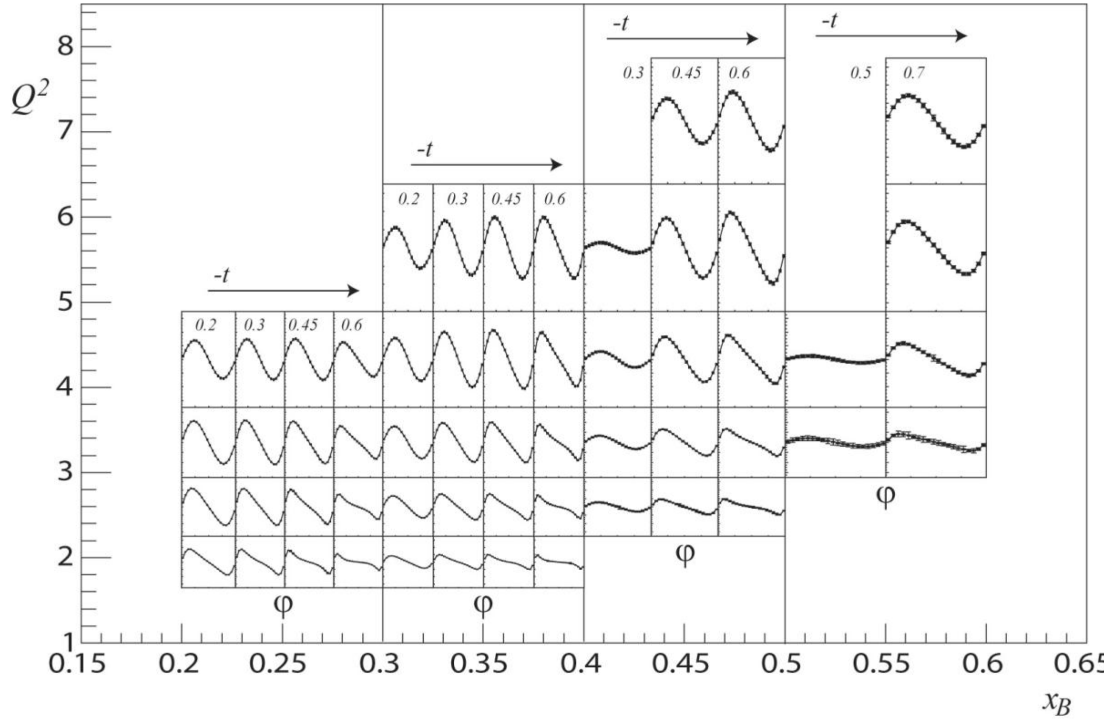


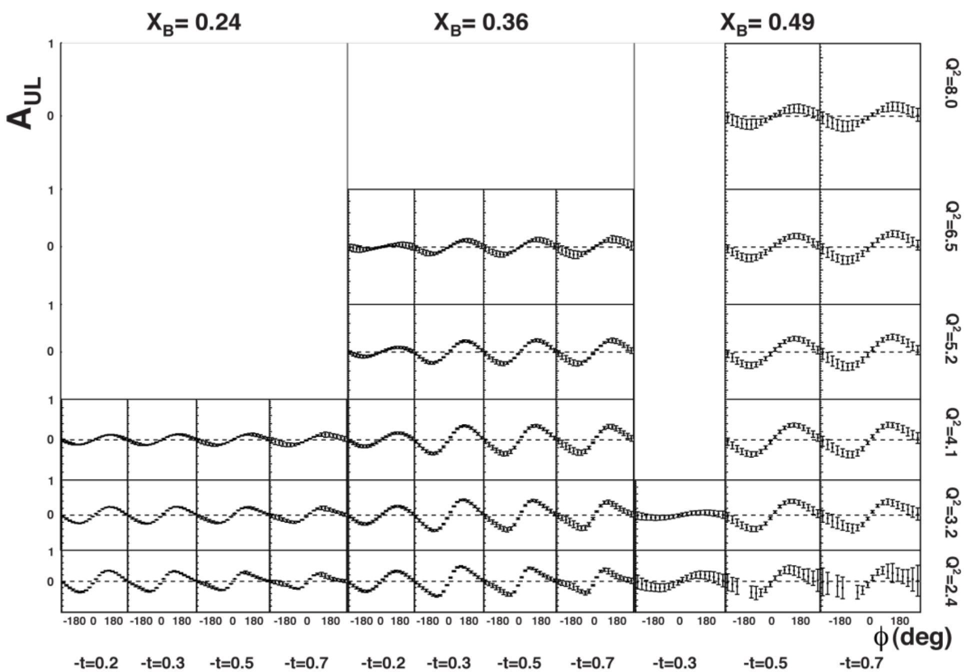
Large phase space (ξ,t,Q^2) and high luminosity



DVCS BSA and TSA with CLAS12 & 11 GeV beam

85 days of beam time
P_{beam} = 85%
L = 10^{35} $cm^{-2}s^{-1}$
1< Q^2 < 10 GeV^2
0.1 < x_B < 0.65
$-t_{min}$ < -t < 2.5 GeV^2
Statistical error: 1% to 10%
on sinϕ moments
Systematic uncertainties: ~6-8%

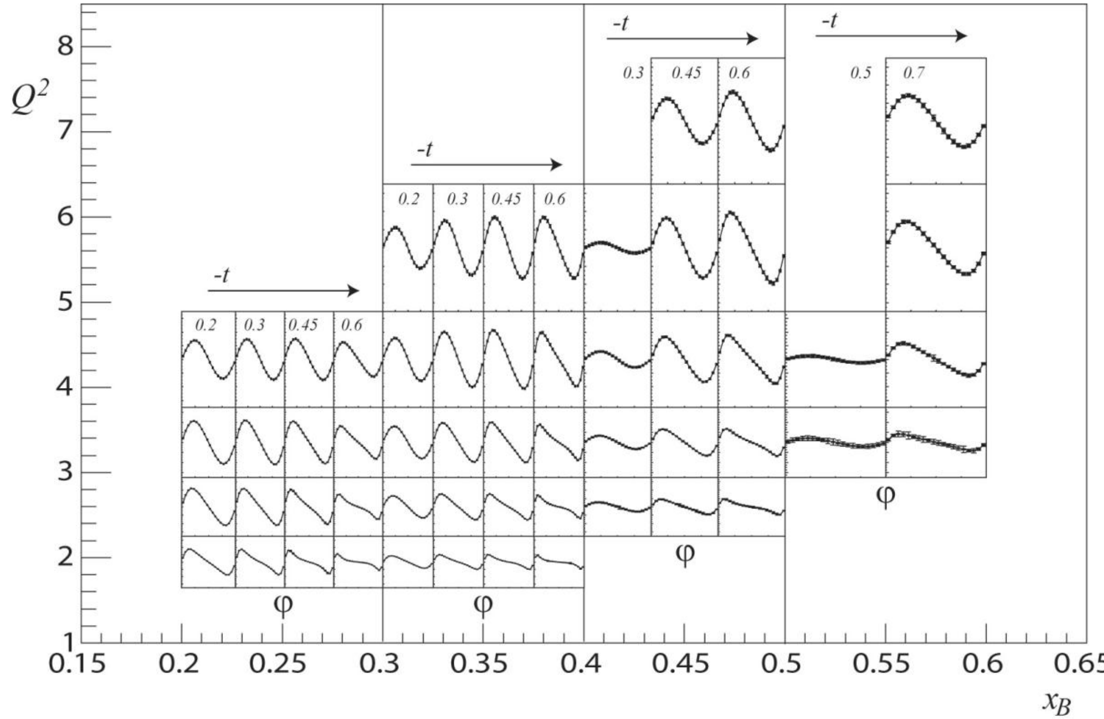


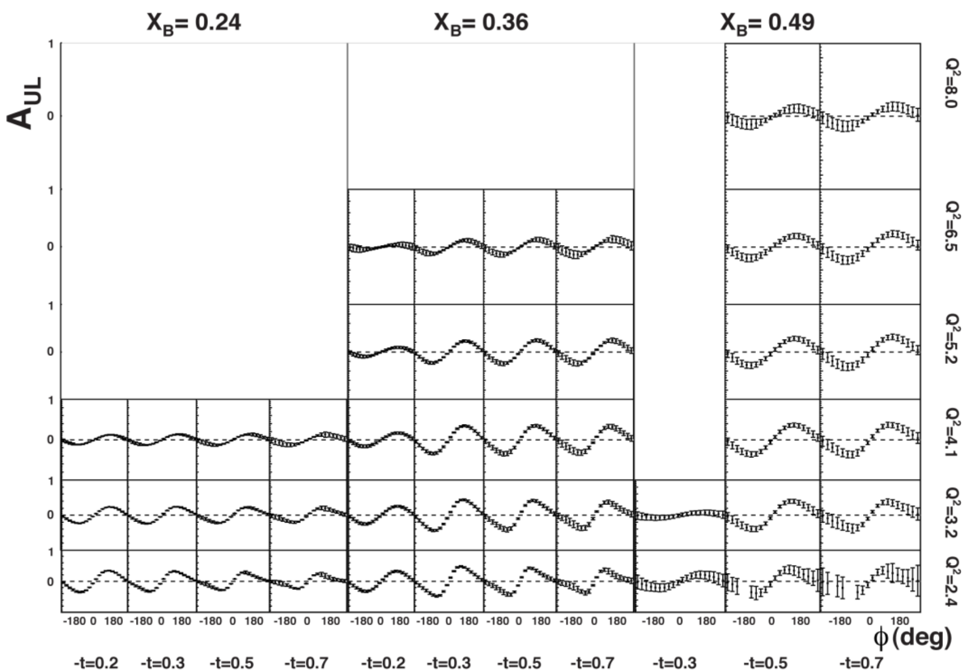


120 days of beam time
P_{beam} = 85%, P_{target} = 80%
L = 2.10^{35} $cm^{-2}s^{-1}$
1< Q^2 < 10 GeV^2
0.1 < x_B < 0.65
$-t_{min}$ < -t < 2.5 GeV^2
Statistical error: 2% to 15%
on sinϕ moments
Systematic uncertaintiess: ~6-8%

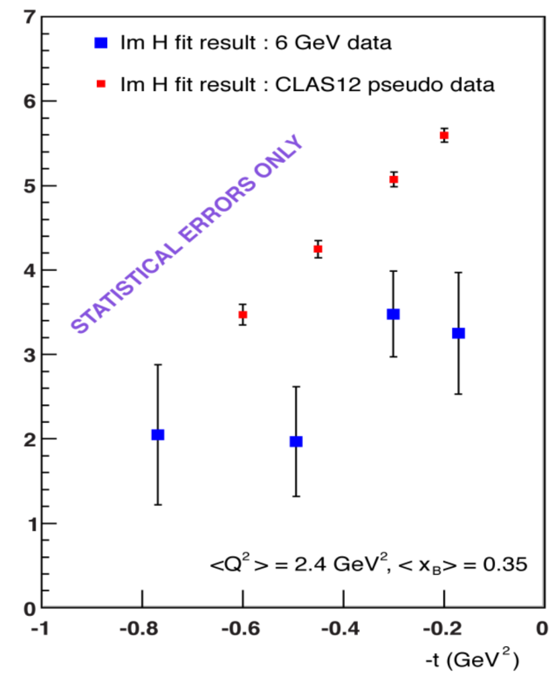
DVCS BSA and TSA with CLAS12 & 11 GeV beam

85 days of beam time
$P_{beam} = 85\%$
$L = 10^{35}\ cm^{-2}s^{-1}$
$1 < Q^2 < 10\ GeV^2$
$0.1 < x_B < 0.65$
$-t_{min} < -t < 2.5\ GeV^2$
Statistical error: 1% to 10%
on $\sin\phi$ moments
Systematic uncertainties: ~6-8%





Impact of CLAS12 DVCS-BSA data on model-independent fit to extract Im(H)



BSA for DVCS *on the neutron* with CLAS12

$$(H,E)_u(\xi,\xi,t) = \tfrac{9}{15}\left[4(H,E)_p(\xi,\xi,t) - (H,E)_n(\xi,\xi,t)\right]$$

$$(H,E)_d(\xi,\xi,t) = \tfrac{9}{15}\left[4(H,E)_n(\xi,\xi,t) - (H,E)_p(\xi,\xi,t)\right]$$

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

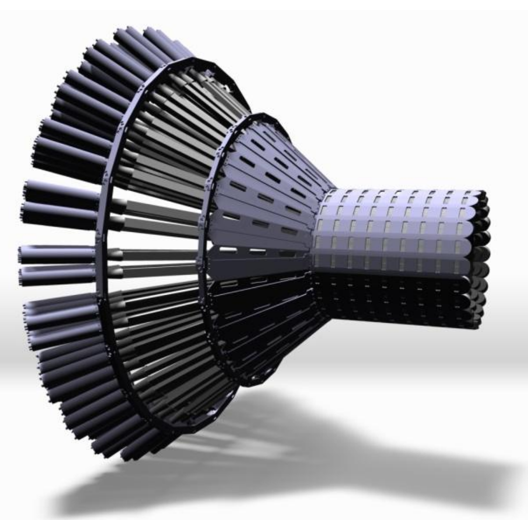
The most sensitive observable to the GPD E

First-time measurement

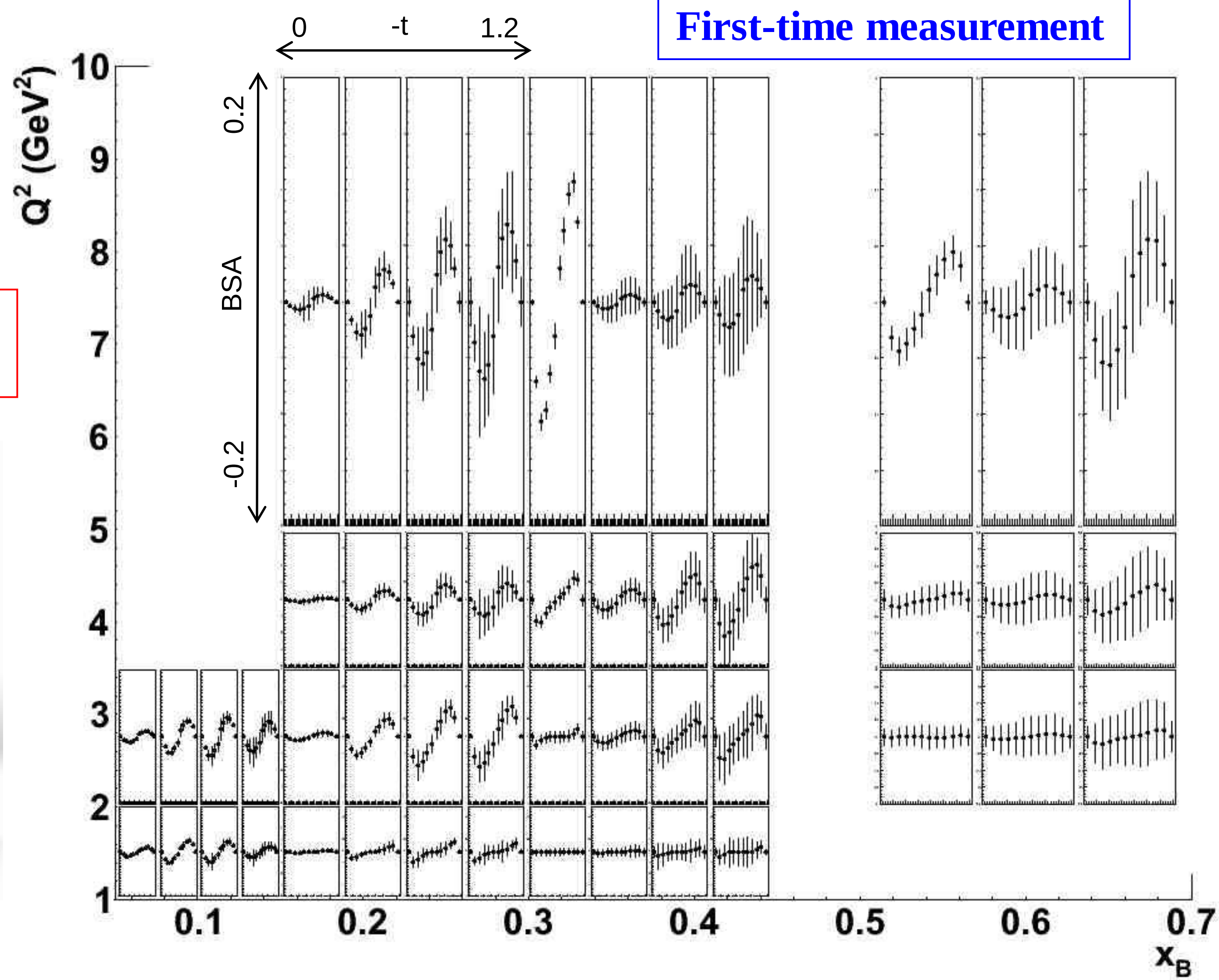
$ed \rightarrow e(p)n\gamma$

CLAS12 +
Forward Calorimeter +
Neutron Detector

80 days of data taking
L = 10^{35} cm^{-2}s^{-1}/nucleon



Under construction at IPN Orsay



BSA for DVCS *on the neutron* with CLAS12

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The most sensitive observable to the GPD E

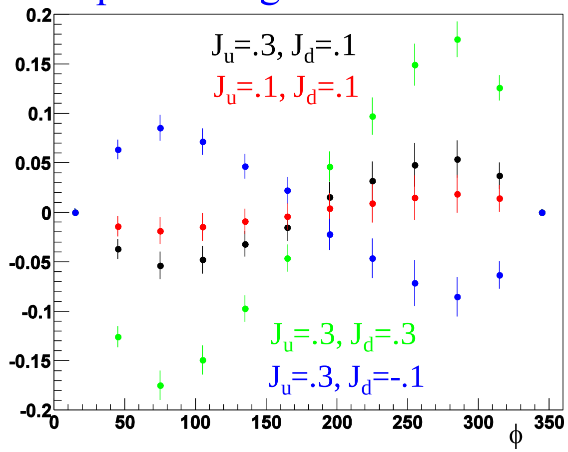
First-time measurement

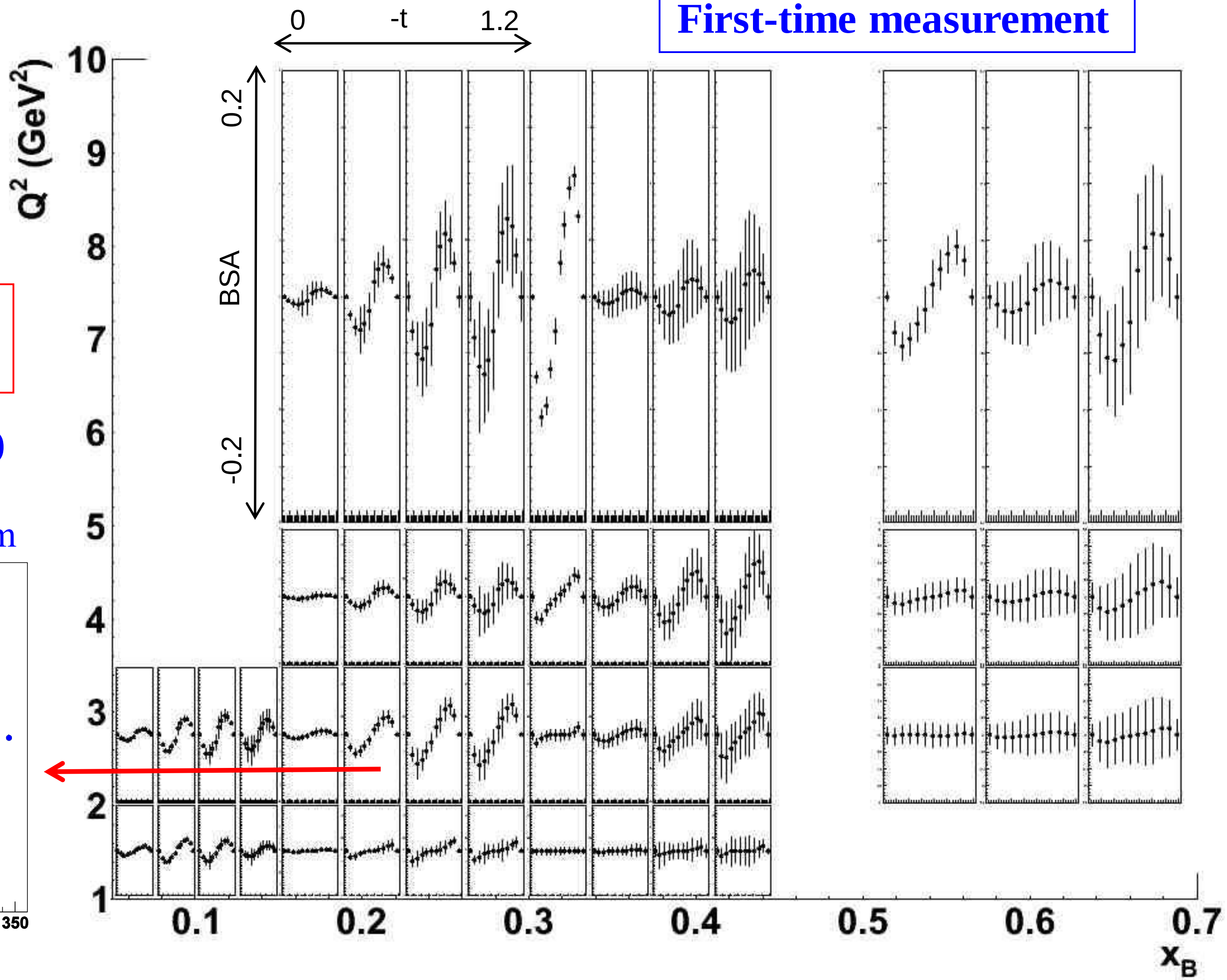
ed→ e(p)nγ

CLAS12 +
Forward Calorimeter +
Neutron Detector

80 days of data taking
L = 10^{35} cm^{-2}s^{-1}/nucleon

Model predictions (VGG)
for different values of
quarks' angular momentum





CLAS12: DVCS *transverse* target-spin asymmetry

E = 11 GeV

e p↑ ⟶ epγ

Transversely polarized target

$\Delta\sigma \sim \sin\phi \, \mathrm{Im}\{k_1(F_2\mathcal{H} - F_1\mathcal{E}) + \ldots\}d\phi$

A_{UTx} Target polarization in scattering plane

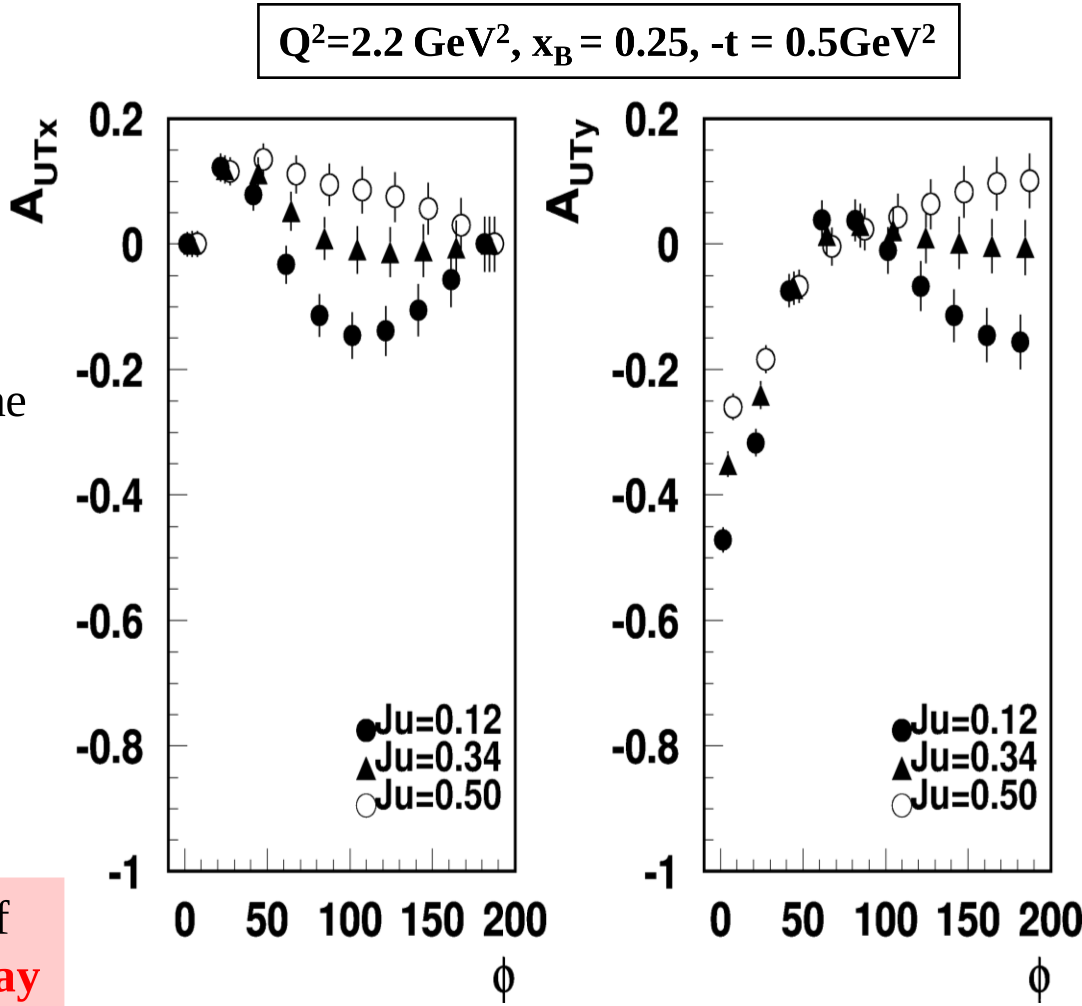
A_{UTy} Target polarization perpendicular to scattering plane

Transverse-target spin asymmetry is **highly sensitive** to the **u-quark contributions** to proton spin.

Transversely polarized target not part of CLAS12 base equipment. **R&D underway**

LOI approved by PAC38

Projected results



CLAS12: DVCS *transverse* target-spin asymmetry

$e\, p^{\uparrow} \longrightarrow e p \gamma$

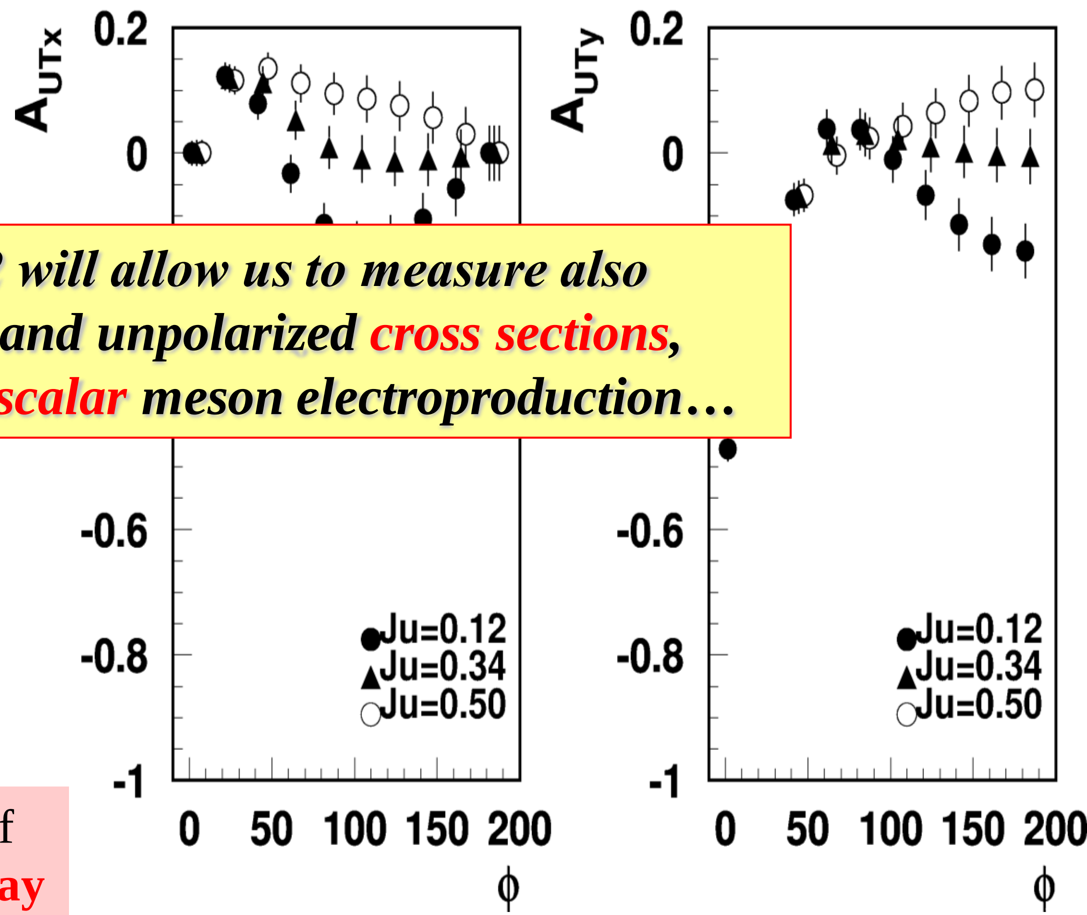
E = 11 GeV

Projected results

Transversely polarized target

Q^2=2.2 GeV^2, x_B = 0.25, -t = 0.5GeV^2

$\Delta\sigma \sim \sin\phi \,\mathrm{Im}\{k_1(F_2\mathcal{H} - F_1\mathcal{E}) + \ldots\}d\phi$



A_{UTx} Target polar

A_{UTy} Target polar
scattering plane

…and CLAS12 will allow us to measure also DVCS polarized and unpolarized cross sections, vector and pseudo-scalar meson electroproduction…

Transverse-target spin asymmetry is **highly sensitive** to the **u-quark contributions** to proton spin.

Transversely polarized target not part of CLAS12 base equipment. **R&D underway**

LOI approved by PAC38

Summary

- GPDs are a unique tool to explore the **internal landscape of the nucleon**:
  - **3D** quark/gluon **imaging** of the nucleon
  - **orbital angular** momentum carried by quarks

- Their extraction from experimental data is **very difficult**:
  - they depend on **3 variables**, only two (ξ, t) experimentally accessible
  - they appear as **integrals** in cross sections

- We need to measure **several exclusive channels and observables** over a **wide phase space** to constrain the parametrizations of GPDs

- Very promising **experimental results** on DVCS and DVMP are coming from **CLAS:**
  - first **constraints on GPD models**
  - first **model-independent GPD fits**

- The JLab 12 GeV upgrade is essential for the study of **3-D nucleon structure** in the **valence region** with high precision, allowing the measurement of **deeply virtual exclusive processes** (to access GPDs) with polarized beam and polarized targets

- **CLAS12** will be world wide **the only full acceptance**, general purpose detector for **high luminosity** electron scattering experiments, and it will be perfectly suited for the **GPD program**

- The first 11 GeV electron beam will hit the CLAS12 target at the **end of 2014**