CLAS12 at Jefferson Lab

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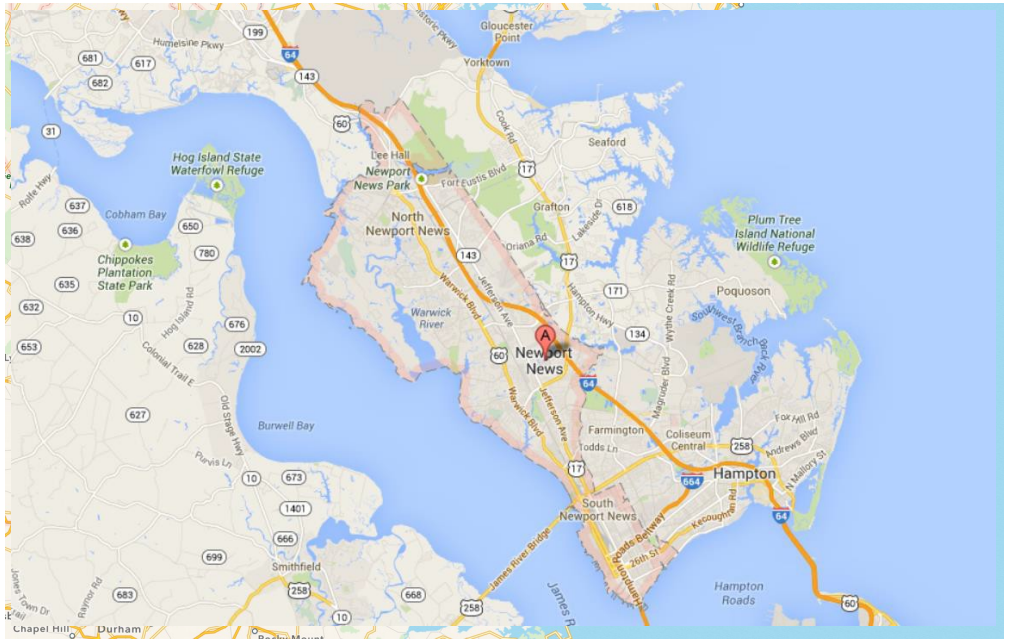
June 4, 2016

Jefferson Lab
Thomas Jefferson National Accelerator Facility

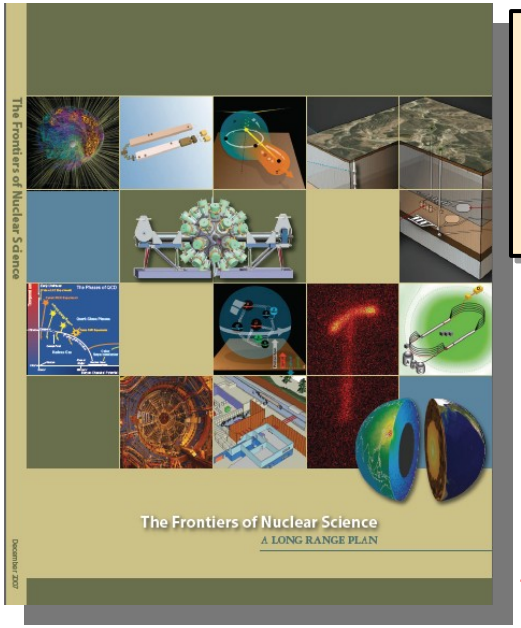
JLab Electron Accelerator Site

Continuous Electron Beam Accelerator:

- Continuous wave electron beam
- Simultaneous beam in all halls
- Beam energy up to 11 & 12 GeV
- Beam current I_B = 100pA – 100μA
- Electron beam polarization > 85%

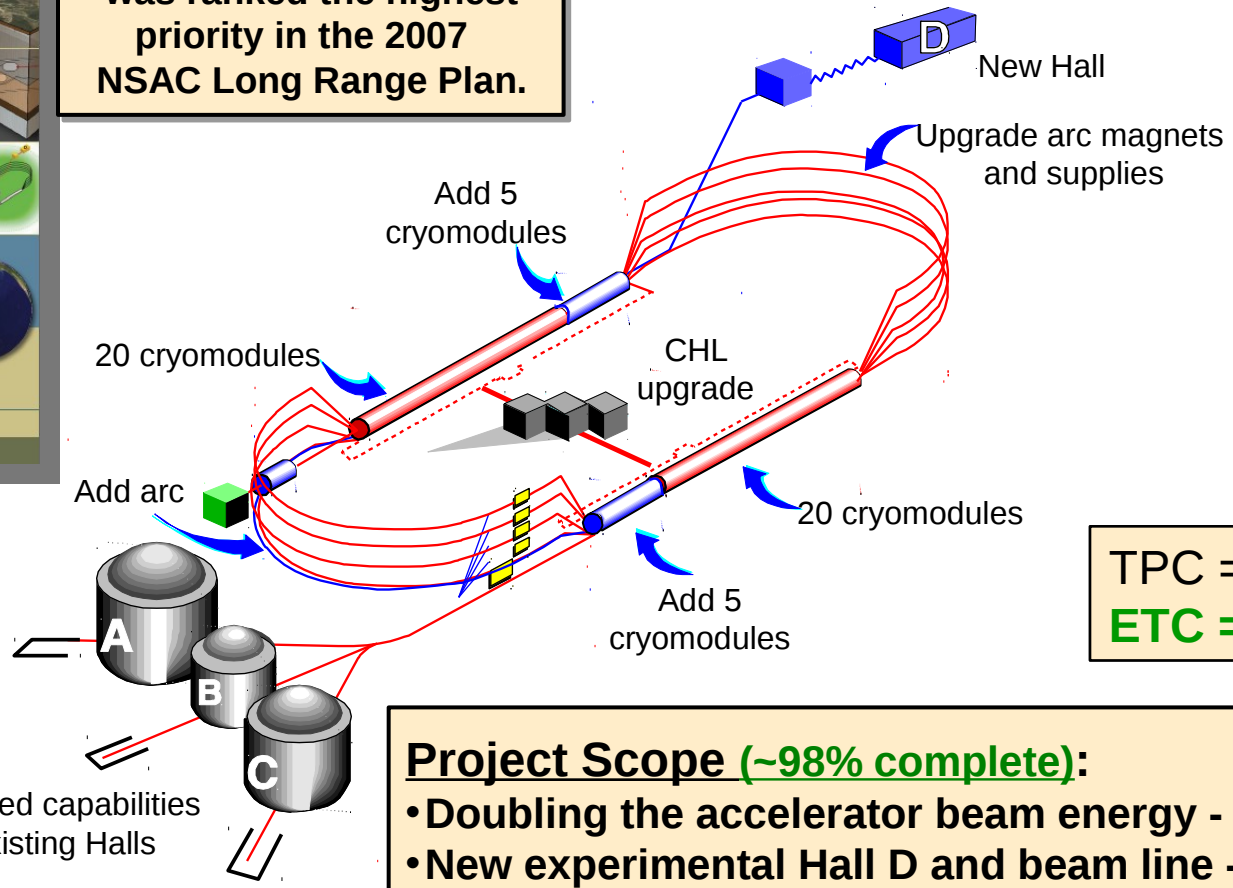


12 GeV Upgrade Project



Completion of the 12 GeV CEBAF Upgrade was ranked the highest priority in the 2007 NSAC Long Range Plan.

Upgrade is designed to build on existing facility: vast majority of accelerator and experimental equipment have continued use.



TPC = $338M
ETC = ~$8M

Maintain capability to deliver lower pass beam energies: 2.2, 4.4, 6.6….

Project Scope (~98% complete):

- **Doubling the accelerator beam energy - DONE**
- **New experimental Hall D and beam line - DONE**
- **Civil construction including Utilities - DONE**
- **Upgrades to Experimental Halls B & C - ~96%**

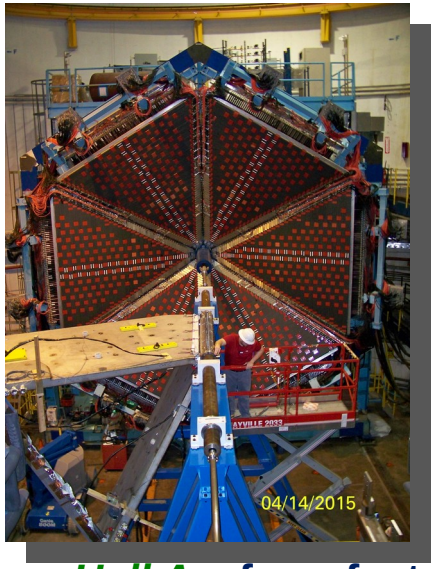
2015 NSAC Long Range Plan

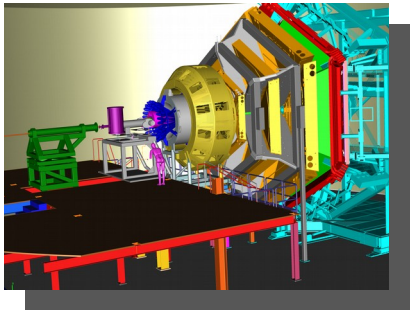
The 2015
LONG RANGE PLAN
for NUCLEAR SCIENCE

- NSAC = Nuclear Science Advisory Committee
- Advise DOE and NSF on future of Nuclear Physics program every 5-7 years
- Four recommendations
- Two initiatives
- Recommend modest budget growth at 4.5% per year

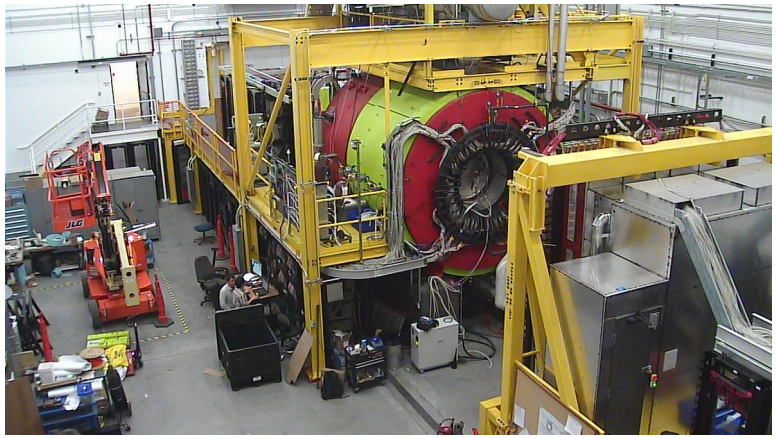
12 GeV Scientific Capabilities

Hall B **– understanding nucleon structure via generalized parton distributions**

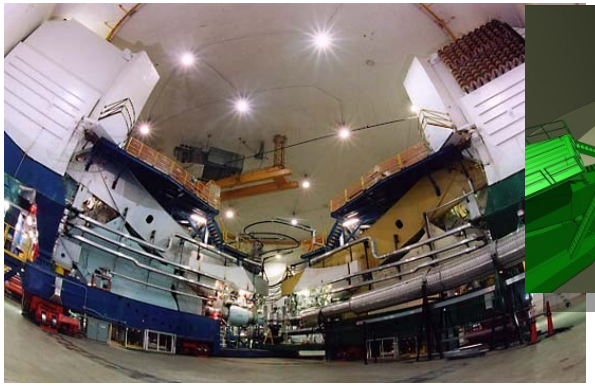


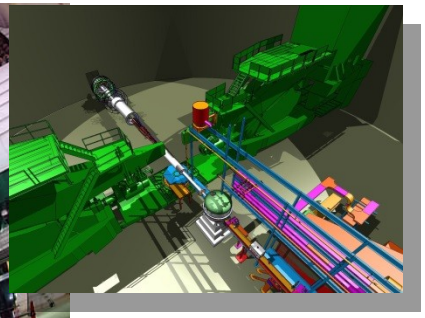


Hall D **– exploring origin of confinement by studying exotic mesons**

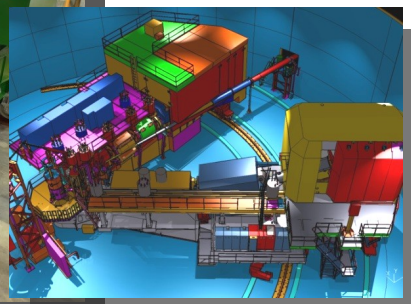


Hall A **– form factors, future new experiments (e.g., SoLID and MOLLER)**

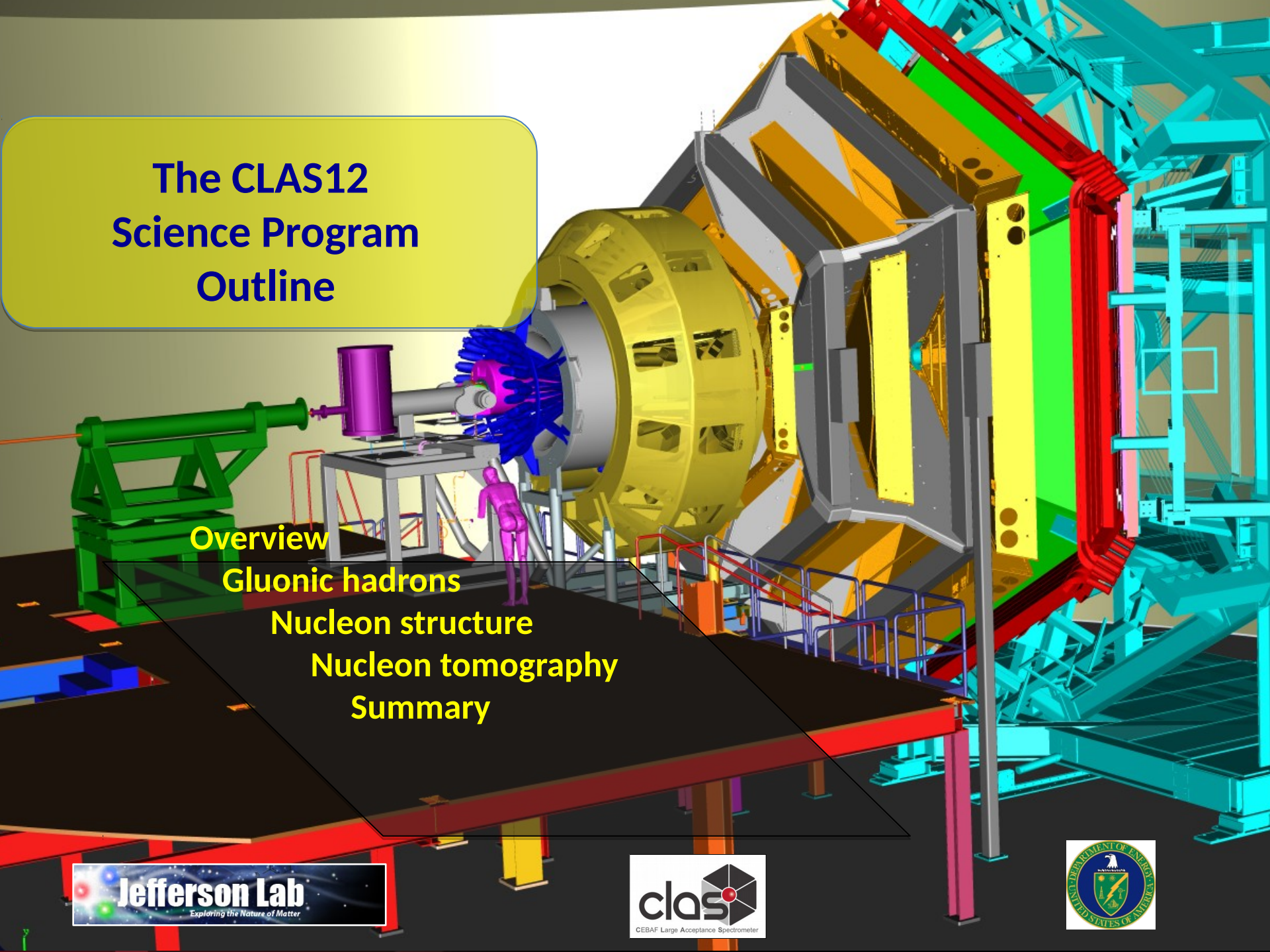




Hall C **– precision determination of valence quark properties in nucleons/nuclei**



The CLAS12 Science Program Outline



Overview
Gluonic hadrons
Nucleon structure
Nucleon tomography
Summary

Jefferson Lab
Exploring the Nature of Matter

clas
CEBAF Large Acceptance Spectrometer

CLAS12 Technical Scope

Forward Detector (FD)

- TORUS magnet (6 coils)
- HT Cherenkov Counter
- Drift Chamber System
- LT Cherenkov Counter
- Forward ToF System
- Pre-Shower Calorimeter
- E.M. Calorimeter

Central Detector (CD)

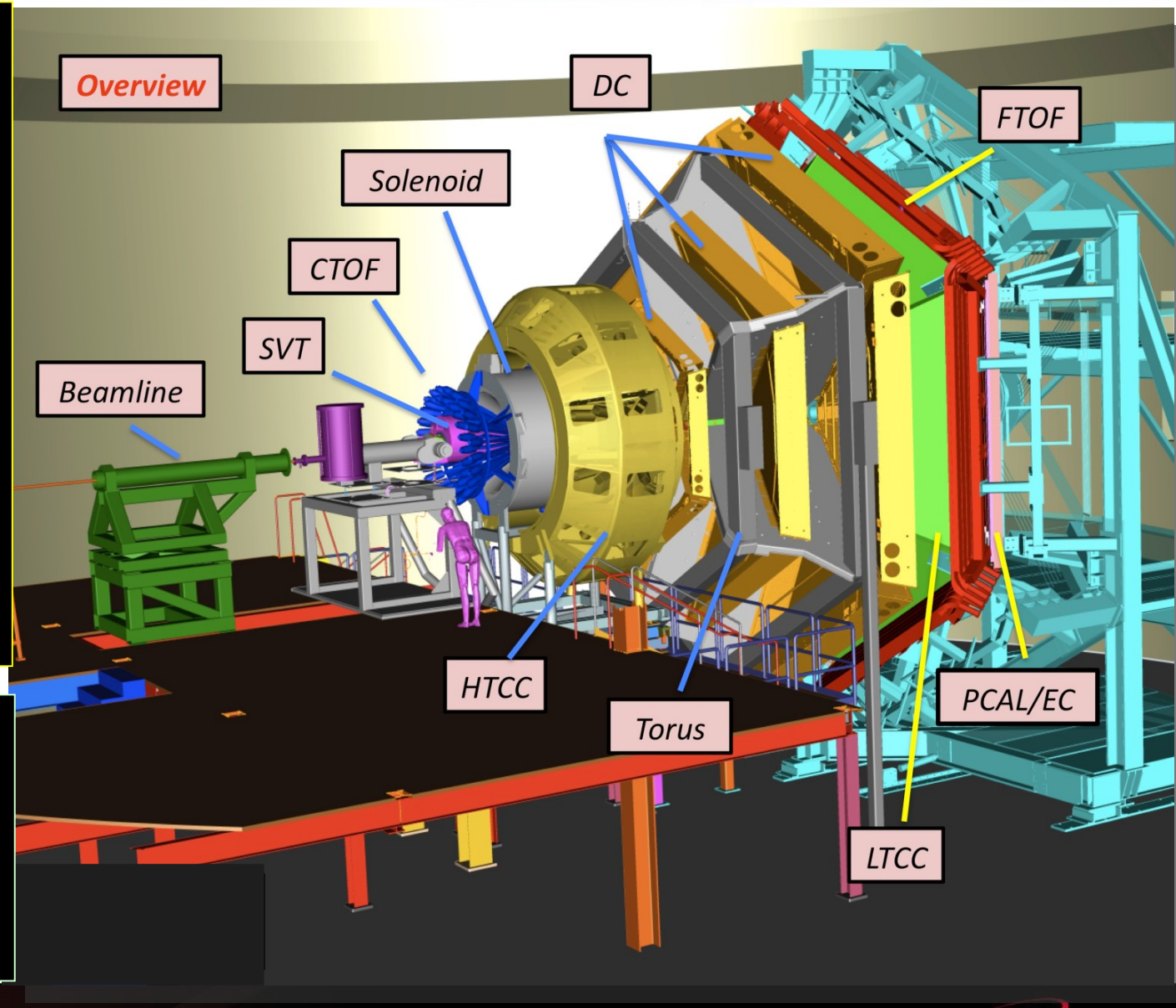
- SOLENOID Magnet
- Barrel Silicon Tracker
- Central Time-of-Flight

Beamline

- Targets
- Moller Polarimeter
- Photon Energy Tagger

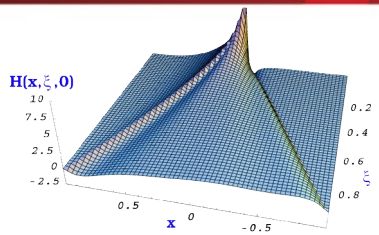
Upgrades to the baseline

- MicroMegas
- Central Neutron Detector
- Forward Tagger
- RICH Detector (2 sectors)
- Polarized Target (long.)

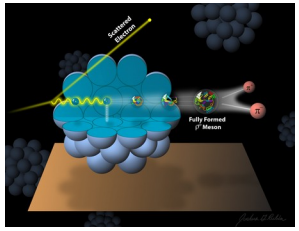


The science program with CLAS12

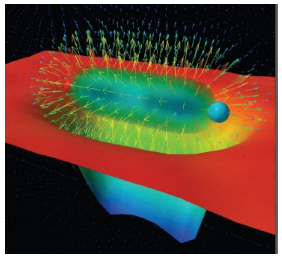
- The 3D structure of the nucleon – from form factors and PDFs to GPDs and TMDs



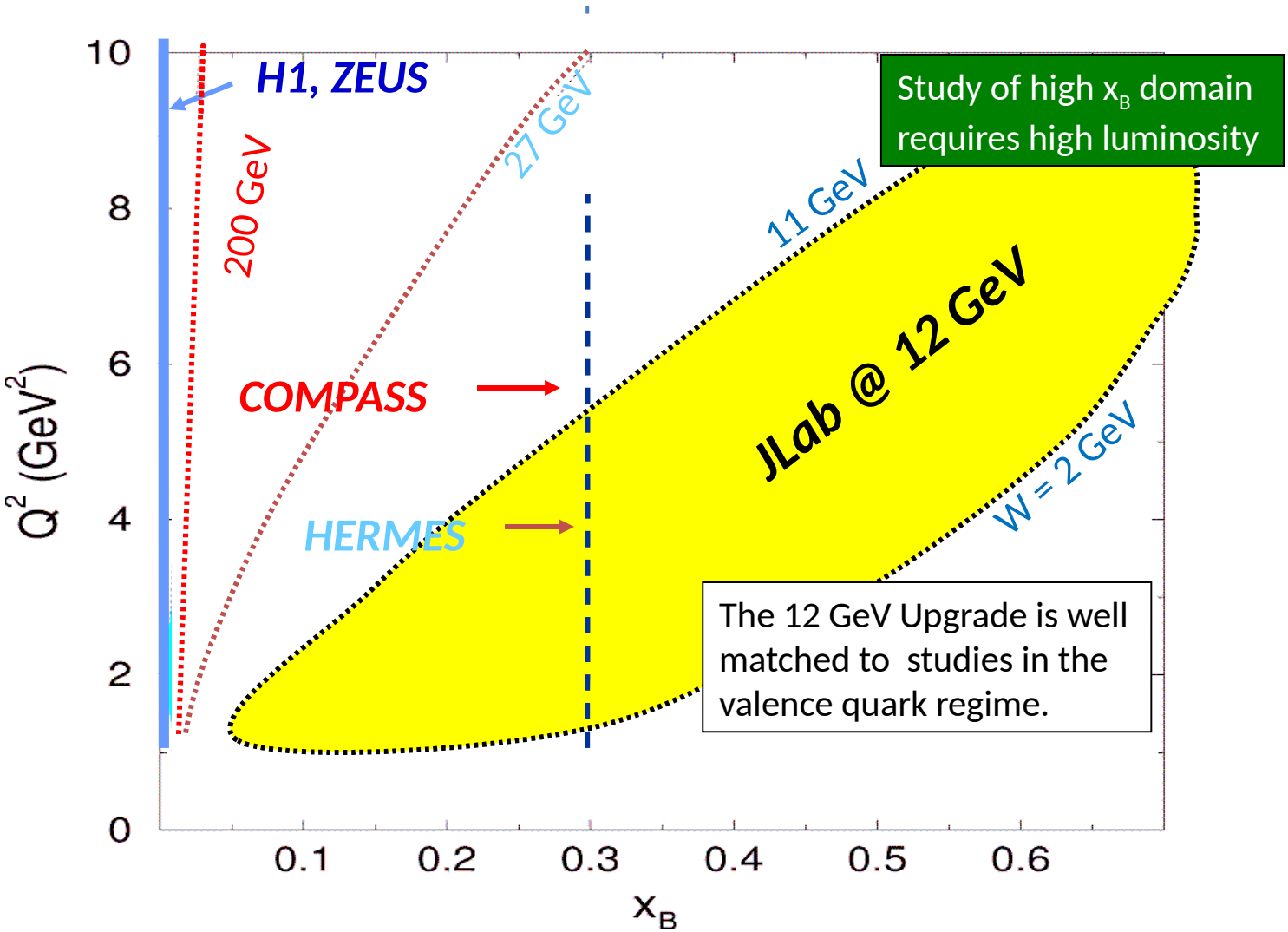
- The strong interaction in nuclei – evolution of quark hadronization, nuclear transparency of hadrons



- Quark confinement and the role of the glue in meson and baryon spectroscopy



Kinematic coverage of DVCS

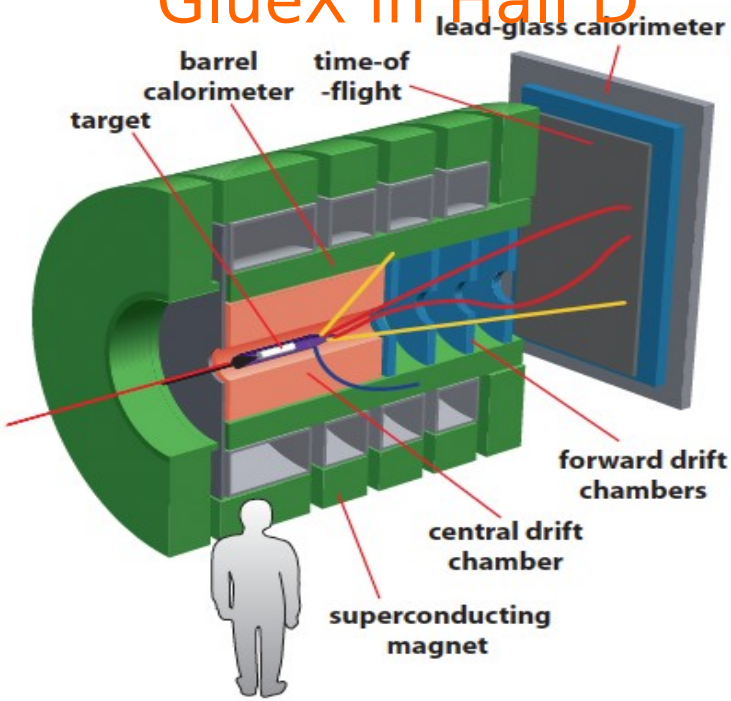


CLAS12 and GlueX

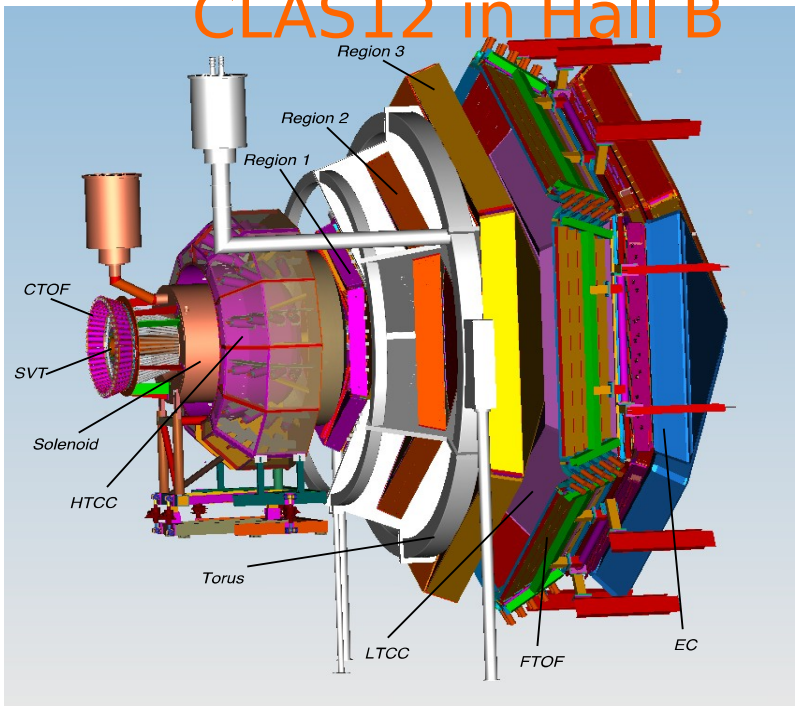
Meson spectroscopy is one of the main topics that will be studied with the Jlab 12 GeV upgrade. Key elements are:

- High intensity tagged photon beams
- Detectors with large acceptance and good particle identification capabilities

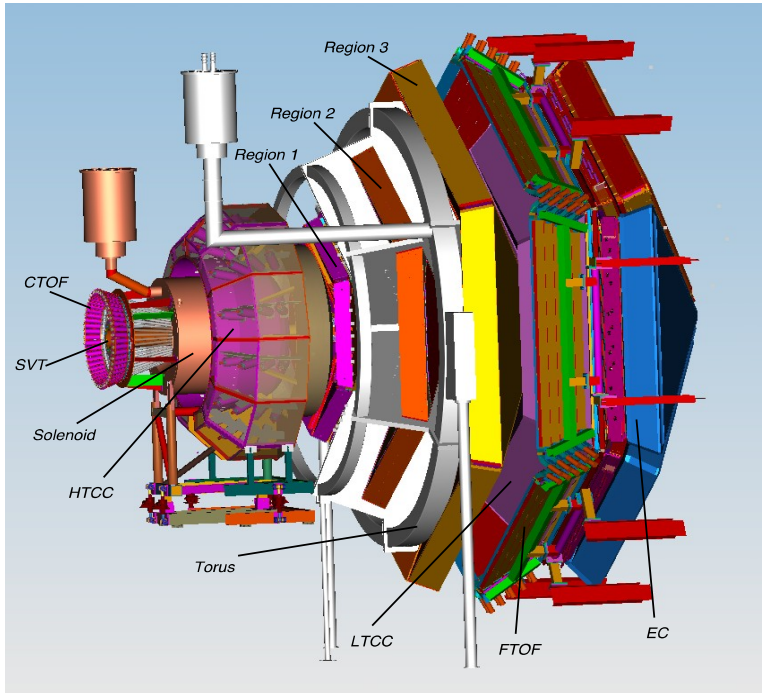
GlueX in Hall D



CLAS12 in Hall B



Meson Spectroscopy with CLAS12



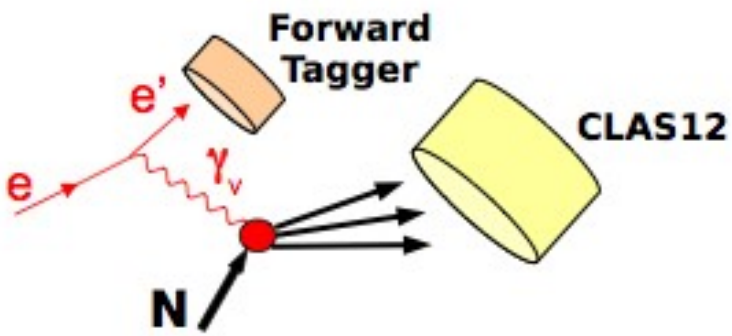
Quasi-real photoproduction on proton target:

- Detection of multiparticle final state from meson decay in the large acceptance spectrometer CLAS12
- Detection of the scattered electron for the tagging of the quasi-real photon in the novel Forward Tagger

Physics goals:

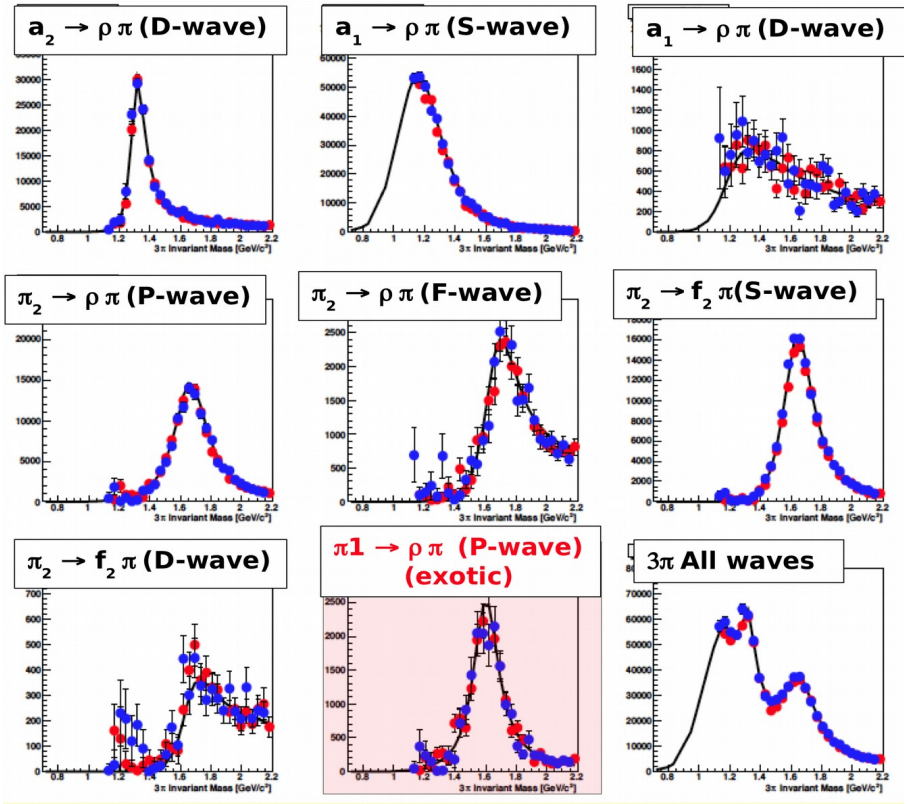
- Detailed mapping of the meson spectrum up to 2.5 GeV
- Search for exotics

Meson spectroscopy & Forward Photon Tagger



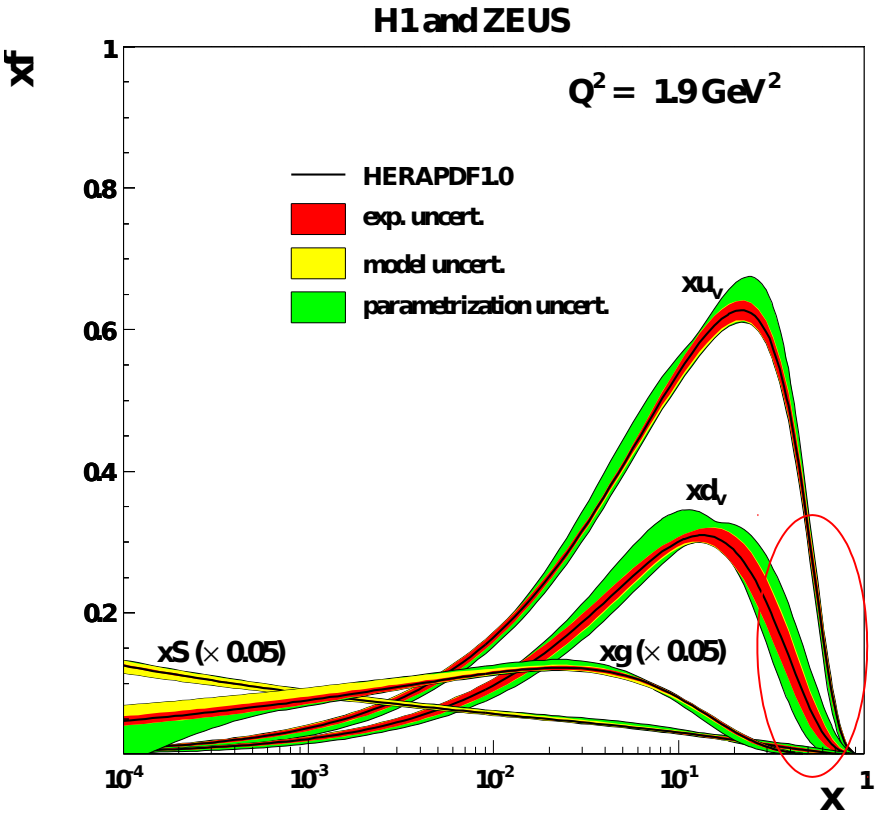
High luminosity – equivalent flux $N_\gamma \sim 5 * 10^8 s^{-1}$
on 5cm lH_2 target $L=10^{35} cm^{-2} s^{-1}$

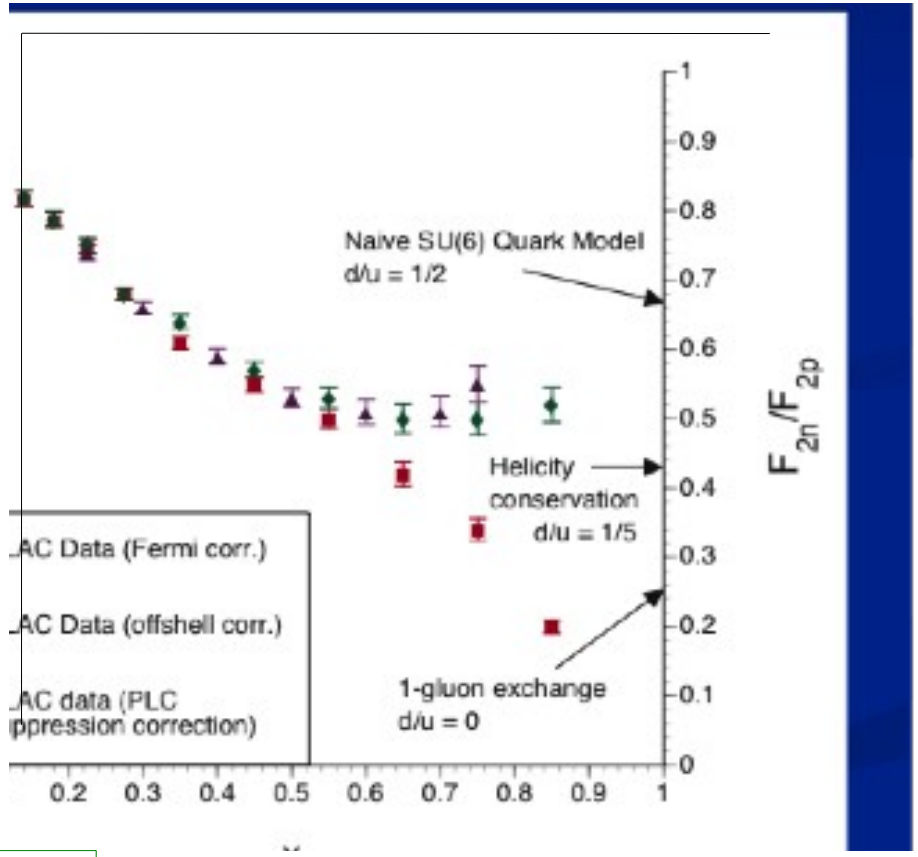
Generated/reconstructed waves



Events generated in specific partial waves, tracked through detector system and reconstructed, retain their initial partial wave contents..

DIS structure functions and $d_v(x)/u_v(x)$





d(x)/u(x) poorly constrained at x > 0.5 due to uncertainty in nuclear corrections

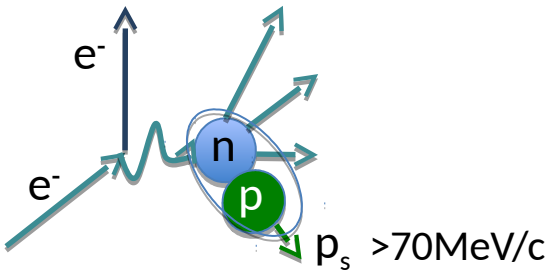
$$\frac{F_2^n}{F_2^p} \approx \frac{1+4d/u}{4+\ d/u}$$

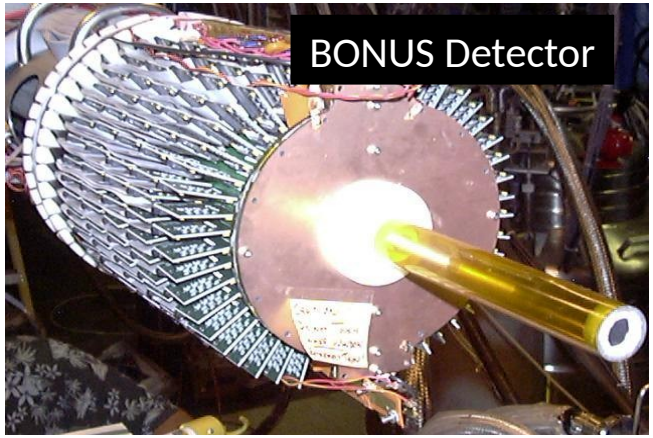
Neutron structure and quark distributions

F_2^n/F_2^p ratio by tagging almost unbound neutrons using detection of low momentum protons in a radial TPC.

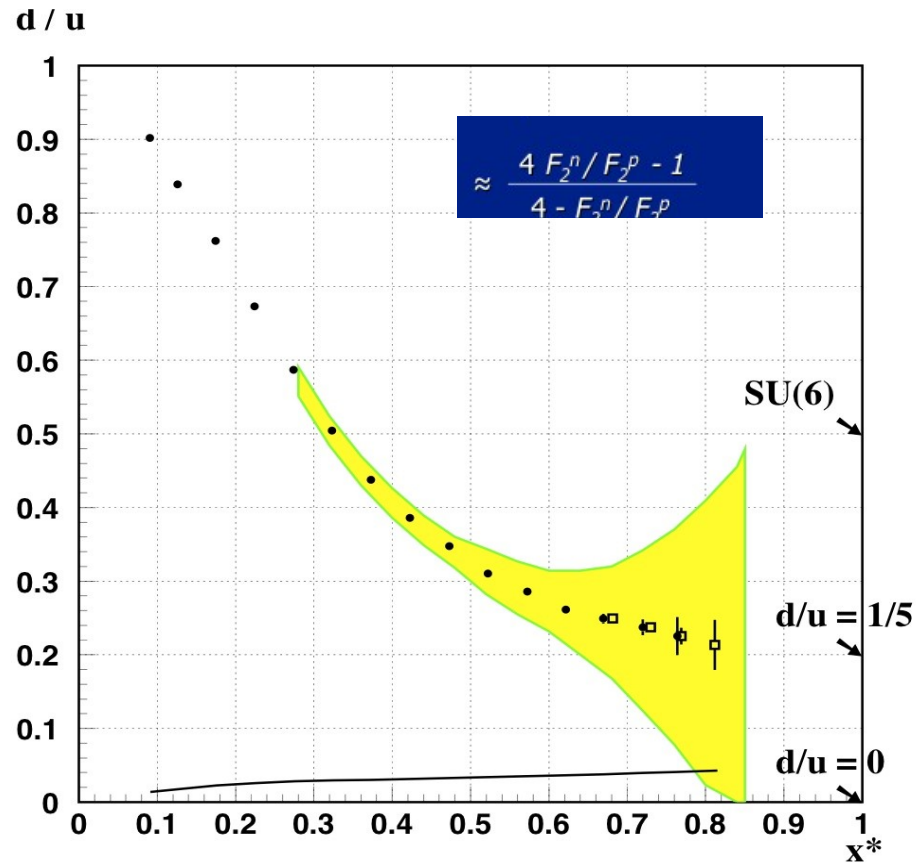
E12-10-102

$e^-D \rightarrow e^-p_sX$





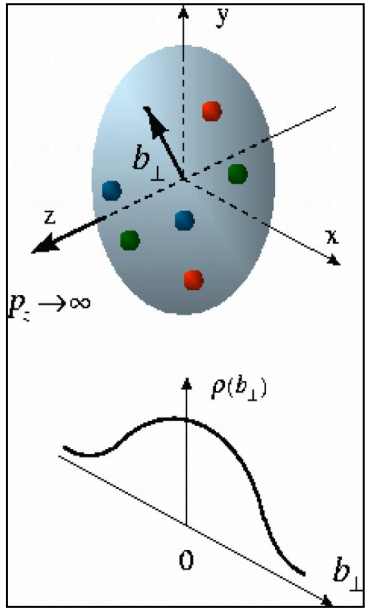
5 Tesla mag. field

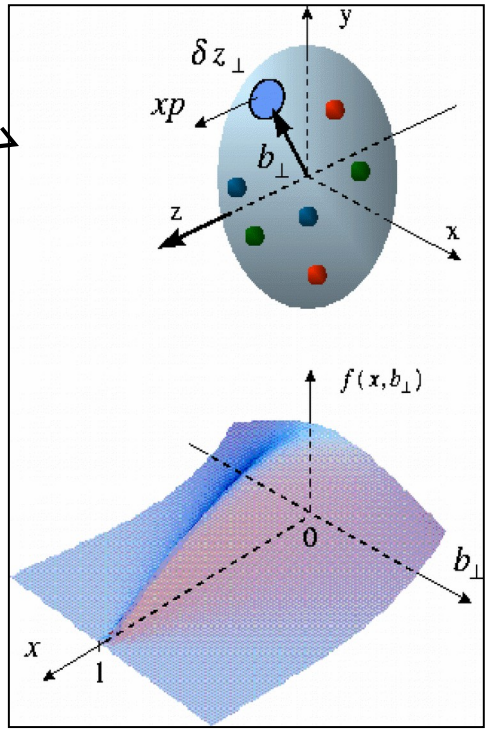


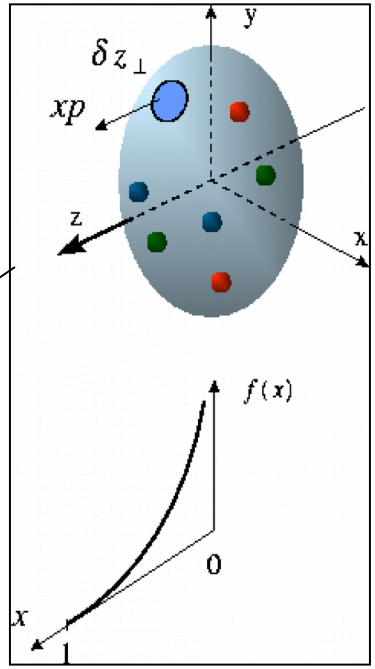
First model-independent measurement of F_2^n/F_2^p

Generalized Parton Distributions (GPDs)

D. Mueller, X. Ji, A. Radyushkin,(1994-1997),…
M. Burkardt, A. Belitsky (2000)…







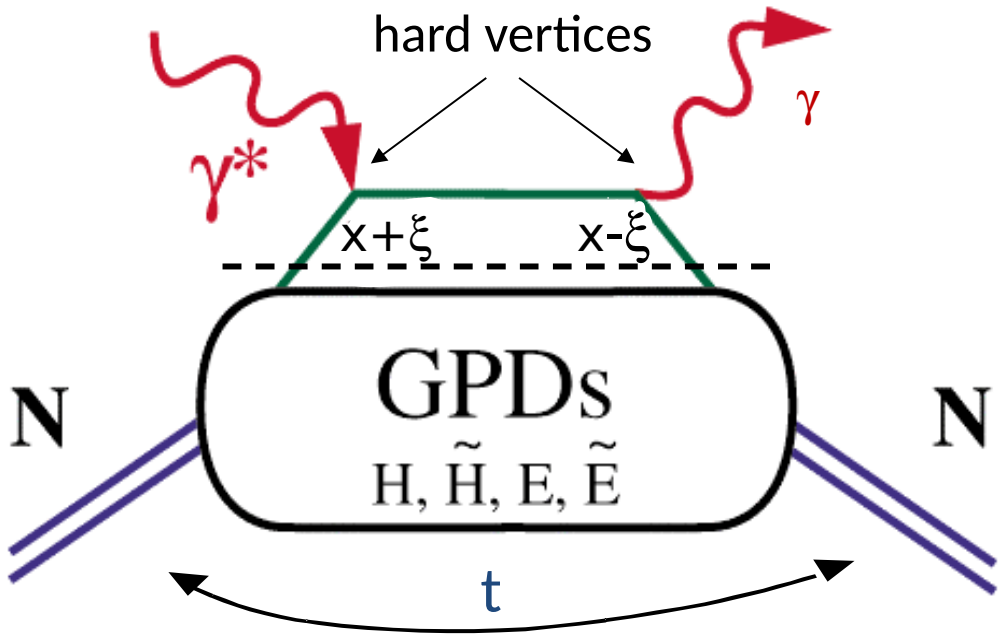
The size and structure of proton.
Proton form factors, transverse charge and current distributions
Nobel prize 1961- R. Hofstadter

Internal constituents of the nucleon
Quark longitudinal momentum and helicity distributions
Nobel prize 1990 - J. Friedman, H. Kendall, R. Taylor

GPDs connect the quark distribution in transverse space and longitudinal momentum

Deeply Virtual Compton Scattering & GPDs

Deeply Virtual Compton Scattering (DVCS)



x – longitudinal quark momentum fraction

2ξ – longitudinal momentum transfer

$\sqrt{-t}$ – Fourier conjugate to transverse impact parameter

GPDs depend on 3 variables, e.g. *H(x, ξ, t)*. They describe the internal nucleon dynamics.

Link to DIS and Elastic Form Factors

DIS at $\xi = t = 0$

$$H^q(x,0,0) = q(x)$$

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

Form factors (sum rules)

$$\int_{-1}^{1} dx \sum_q \left[H^q(x,\xi,t) \right] = F_1(t) \quad \text{Dirac f.f.}$$

$$\int_{-1}^{1} dx \sum_q \left[E^q(x,\xi,t) \right] = F_2(t) \quad \text{Pauli f.f.}$$

$$\int_{-1}^{1} dx\, \tilde{H}^q(x,\xi,t) = G_{A,q}(t), \quad \int_{-1}^{1} dx\, \tilde{E}^q(x,\xi,t) = G_{P,q}(t)$$

$$H^q, E^q, \tilde{H}^q, \tilde{E}^q(x,\xi,t)$$

Angular Momentum 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)

Generalized Parton Distributions

(Quantum phase-space quark distribution in the nucleon)

$$W_\Gamma(\mathbf{r},k) = \frac{1}{2M_N}\int \frac{d^3\mathbf{q}}{(2\pi)^3} e^{-i\mathbf{q}\cdot\mathbf{r}} \left\langle \mathbf{q}/2 \left| \hat{\mathcal{W}}_\Gamma(0,k) \right| -\mathbf{q}/2 \right\rangle ,$$

$$W_\Gamma(\mathbf{r},\mathbf{k}) = \int \frac{dk^-}{(2\pi)^2} W_\Gamma(\mathbf{r},k)$$

Integrate over ***momentum*** space

Polarized DVCS directly probes GPDs

Sensitivity to GPD

Nucleon polarization	Sensitivity to GPD
UP	H, $\tilde{H}$, E
LP	$\tilde{H}$, H, E
TP	E, H

Generalized Parton Distributions (GPD) $\tilde{H}$, H, $\tilde{E}$, E

3D nucleon imaging in transverse coordinate and longitudinal momentum space

Physical content of GPD *E* & *H*

Nucleon matrix element of the Energy-Momentum Tensor of QCD contains 3 scalar form factor:

$M_2(t)$: Mass distribution inside the nucleon
$J(t)$: Angular momentum distribution
$d_1(t)$: Forces and pressure distribution

Directly measured in elastic graviton-proton scattering!

GPDs are related to these form factors through 2nd moments

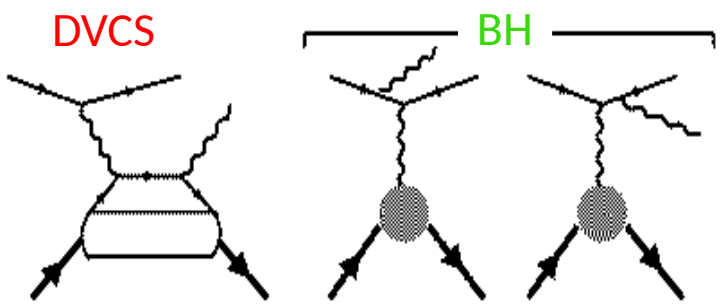
$$J^q(t) = \frac{1}{2}\int_{-1}^{1} dx\, x\,[H^q(x,\xi,t) + E^q(x,\xi,t)] \quad , \quad M_2^q(t) + \frac{4}{5}d_1(t)\xi^2 = \frac{1}{2}\int_{-1}^{1} dx\, x H^q(x,\xi,t)$$

(Ji's sum rule)

Accessing GPDs Through DVCS

- GPDs are universal, they can be determined in any suitable process

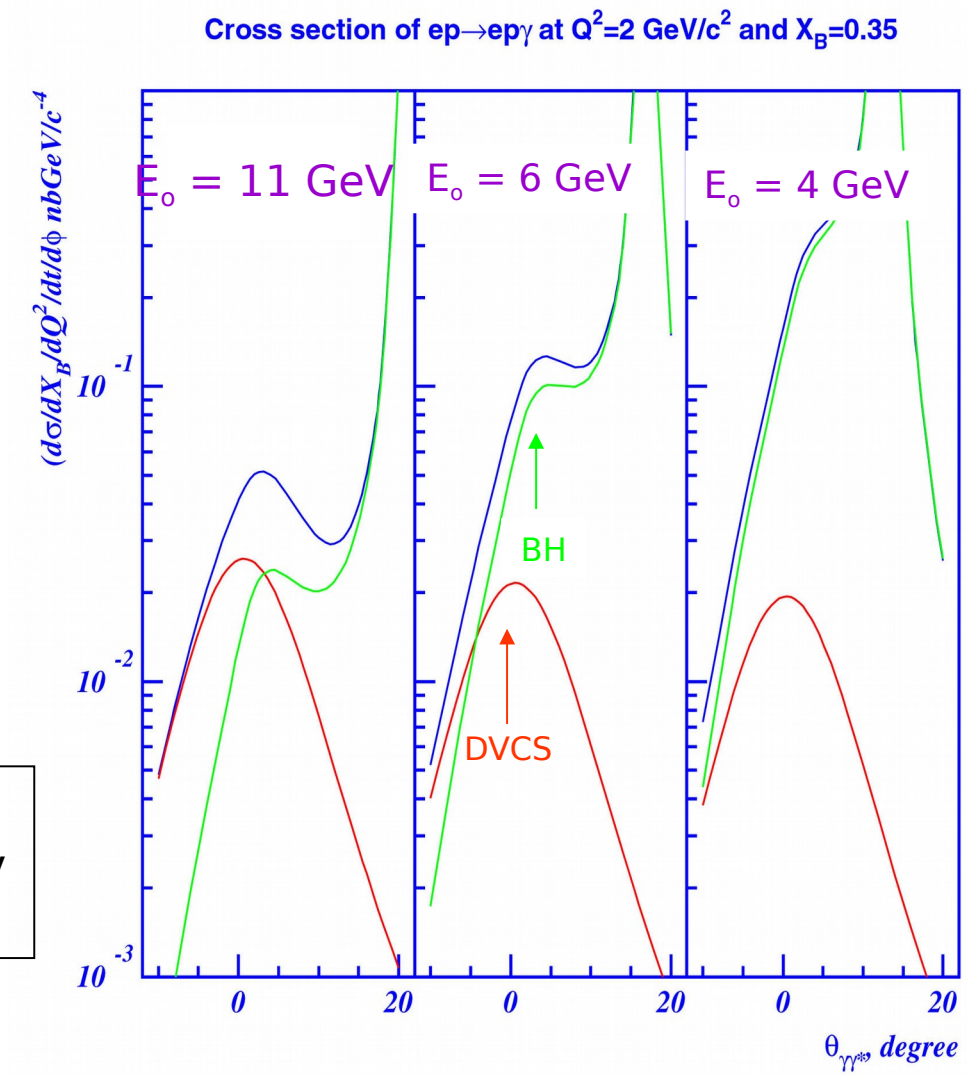
$$\frac{d^4\sigma}{dQ^2 dx_B dt d\phi} \sim |T^{DVCS} + T^{BH}|^2$$



T^{BH} : given by elastic form factors

T^{DVCS}: determined by GPDs

BH-DVCS interference generates beam and target asymmetries that carry the nucleon structure information.



Accessing GPDs through polarization

$$A = \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-} = \frac{\Delta\sigma}{2\sigma}$$

Polarized beam, unpolarized target:

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

Kinematically suppressed

$\Rightarrow$ H

$\xi = x_B/(2-x_B)$

$k = t/4M^2$

Unpolarized beam, longitudinal target:

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

Kinematically suppressed

$\Rightarrow$ $\tilde{H}$

Unpolarized beam, transverse target:

$$\Delta\sigma_{UT} \sim \cos\phi \, \mathrm{Im}\{k(F_2 H - F_1 E) + ... \} d\phi$$

Kinematically suppressed

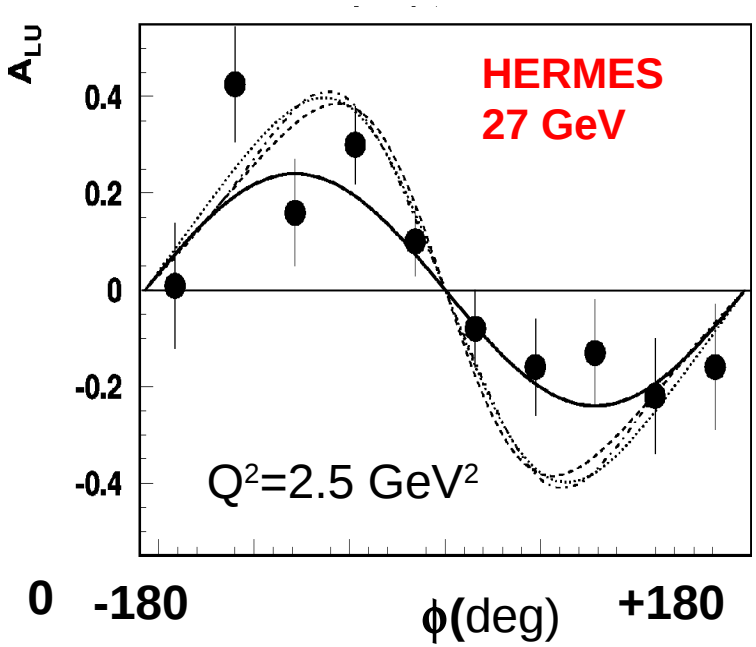
$\Rightarrow$ H, E

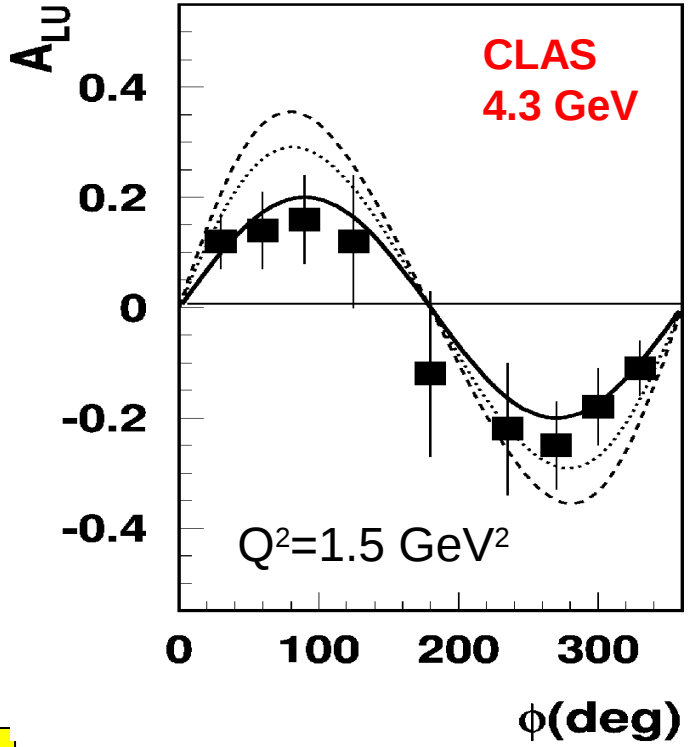
First observation of DVCS/BH beam asymmetry

$e^+p \rightarrow e^+\gamma X$

2001

$e^-p \rightarrow e^-pX$



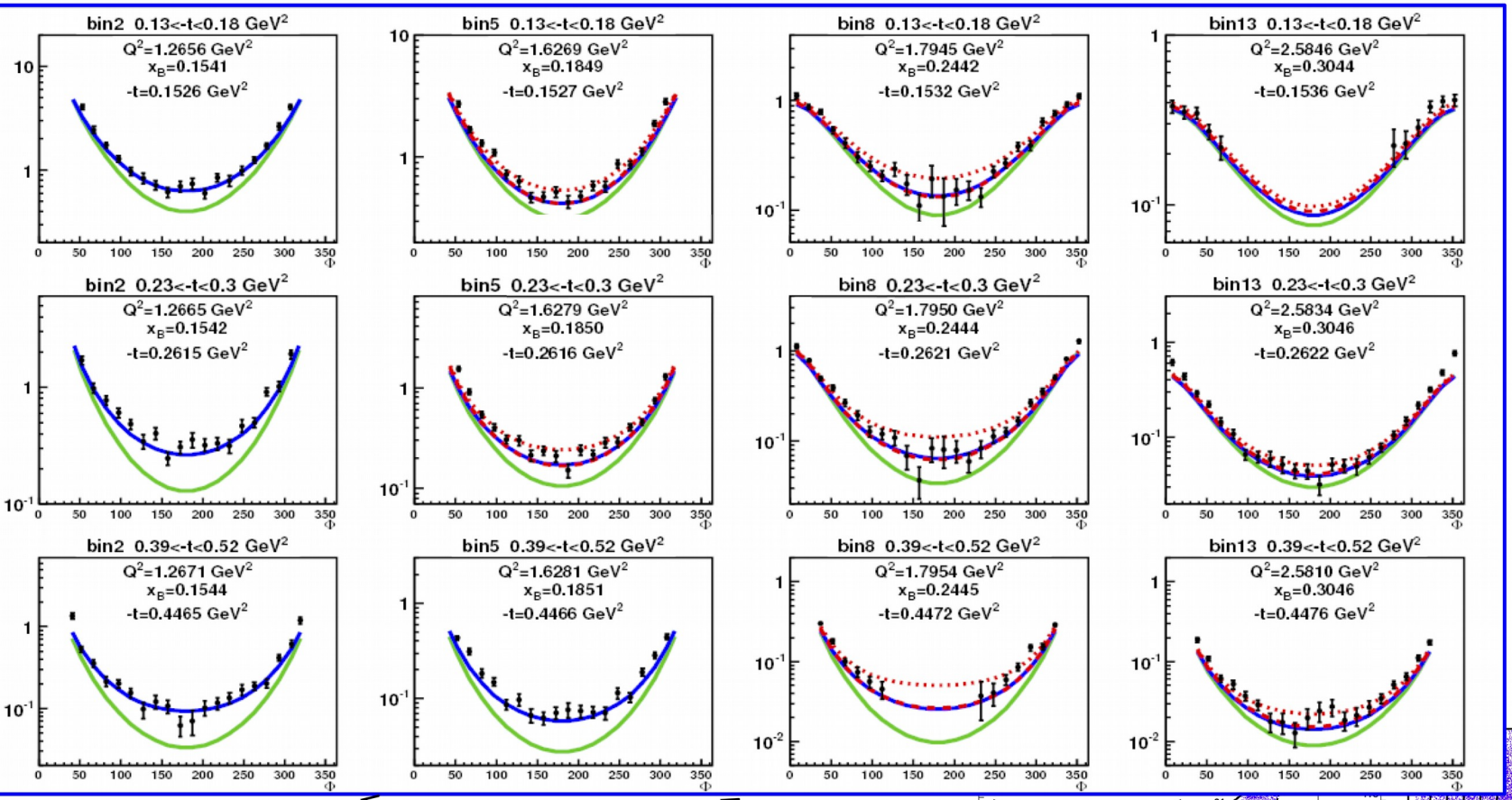


Early GPD analysis of CLAS/HERMES/HERA data in LO/NLO shows results consistent with handbag mechanism and lowest order pQCD. A. Freund (2003), A. Belitsky, et al. (2003)

$$A(\phi) = \alpha \sin\phi + \beta \sin 2\phi$$

$\beta/\alpha << 1 \longrightarrow$ twist-3 << twist-2

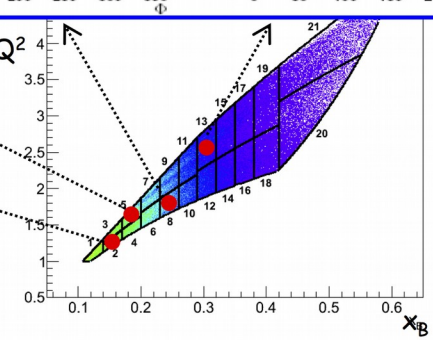
DVCS Unpolarized Cross-Sections (6GeV)

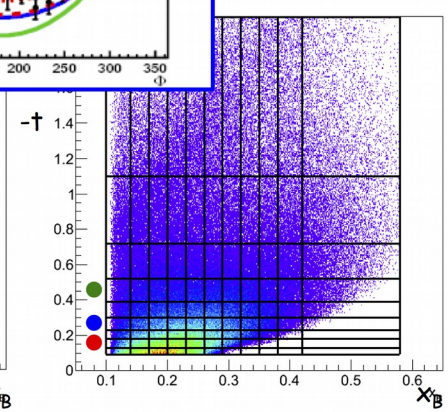


$$\bullet \quad \frac{d^4\sigma_{ep\to ep\gamma}}{dQ^2 dx_B dt d\Phi} (nb/GeV^4)$$

BH — VGG (H only)

KM10 - - - KM10a

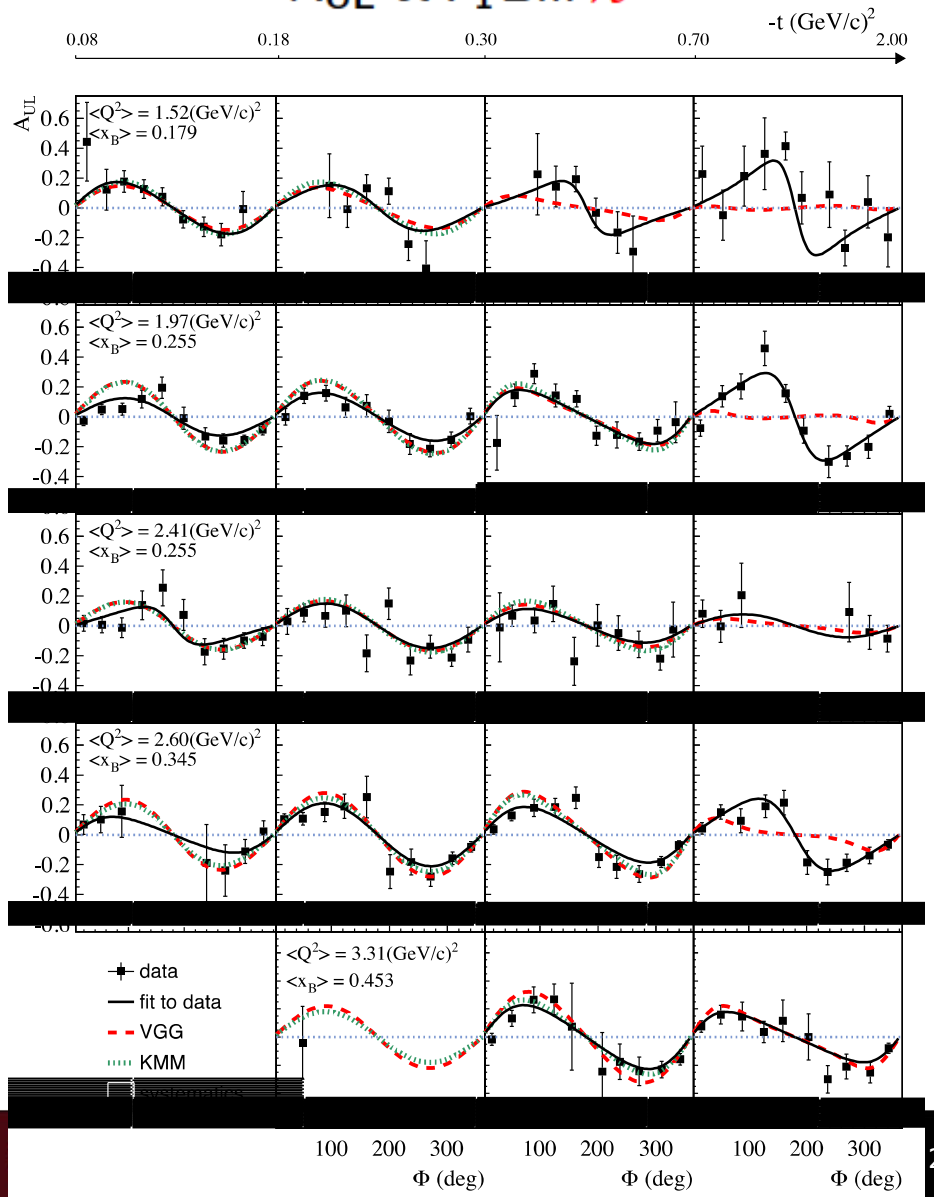




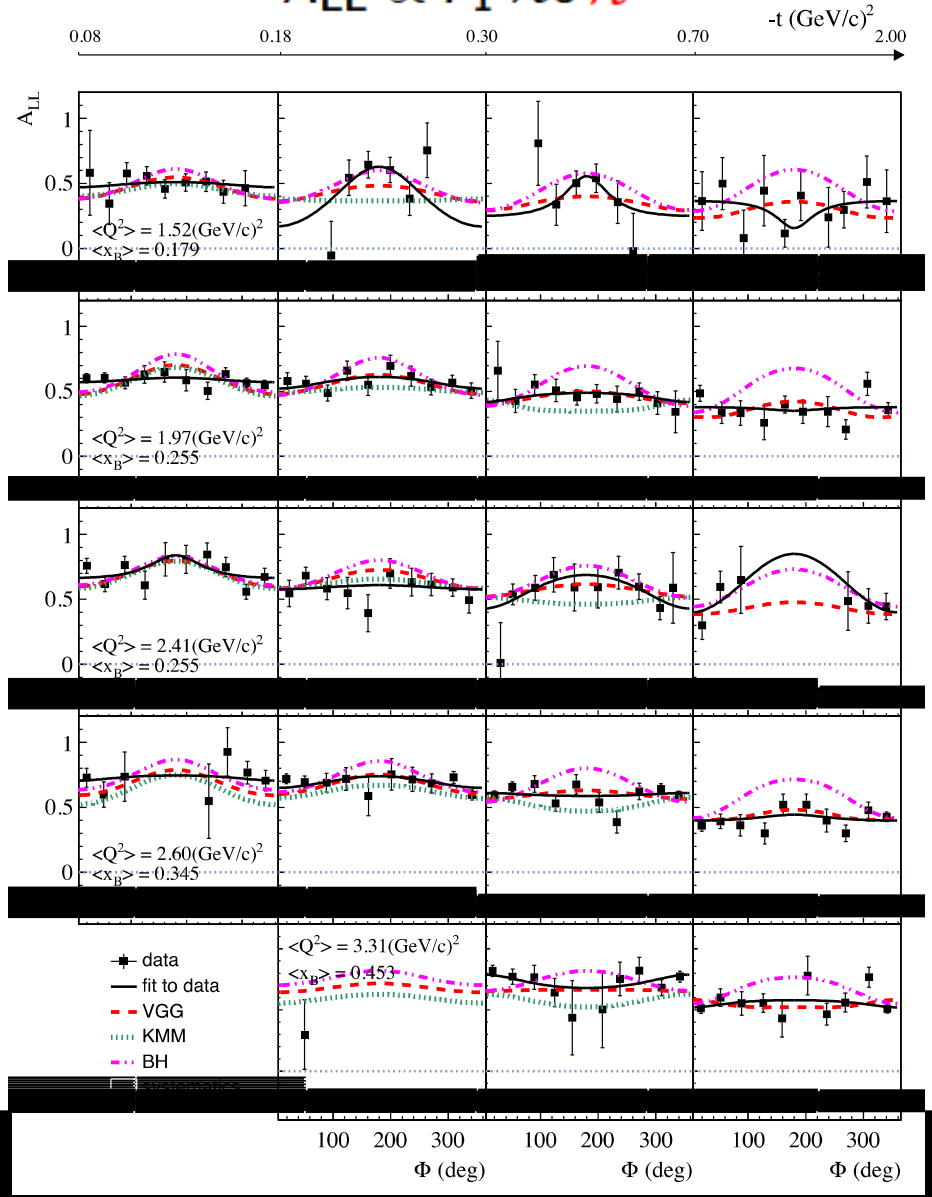
VGG : Vanderhaeghen, Guichon, Guidal *KM : Kumericki, Mueller*

DVCS Longitundinal Target (6GeV)

$A_{UL} \propto F_1 \mathcal{I}m \tilde{\mathcal{H}}$



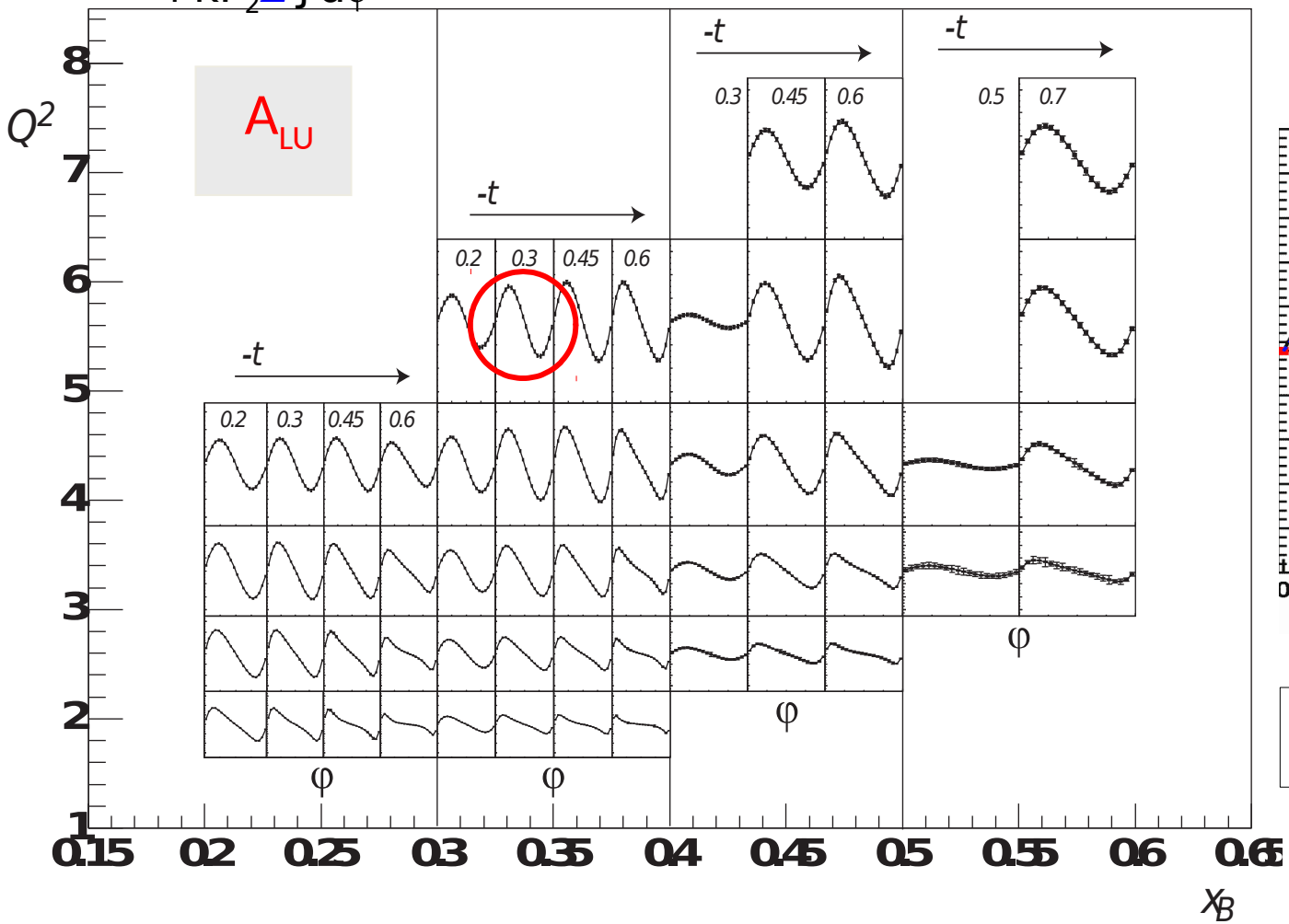
$A_{LL} \propto F_1 \mathcal{R}e \tilde{\mathcal{H}}$

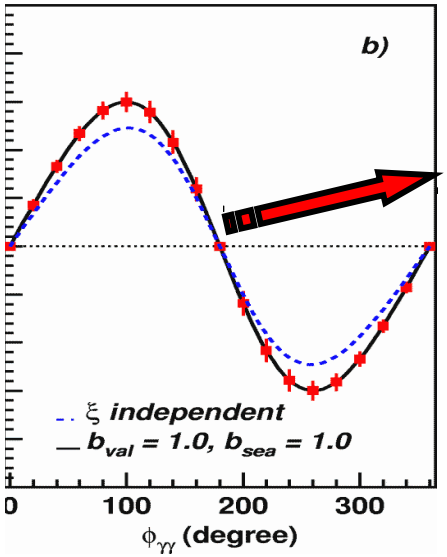


A_{LU} projections for JLab@12GeV

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

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





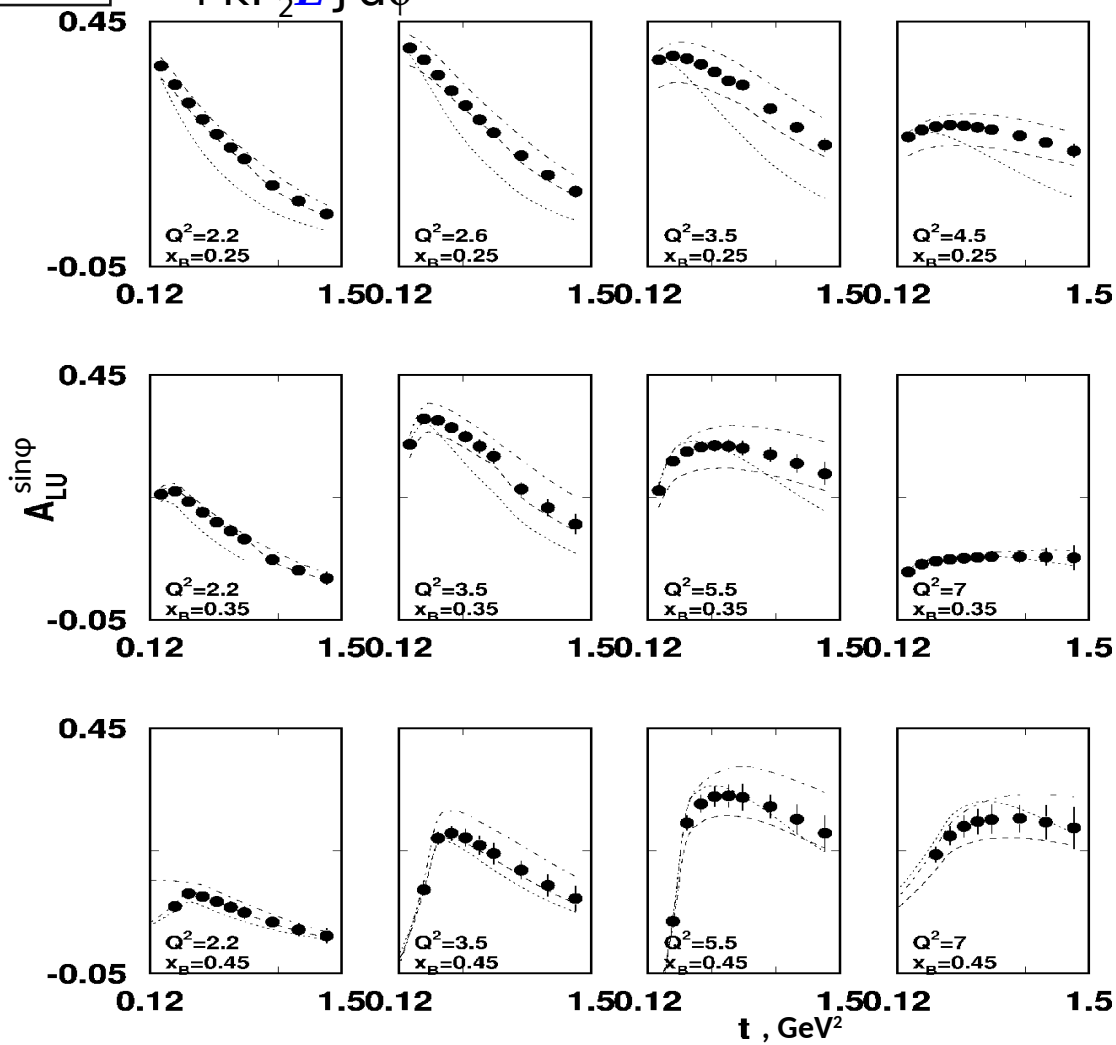
E12-06-114
E12-06-119

A_{LU} projections for protons

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

E_e=11GeV

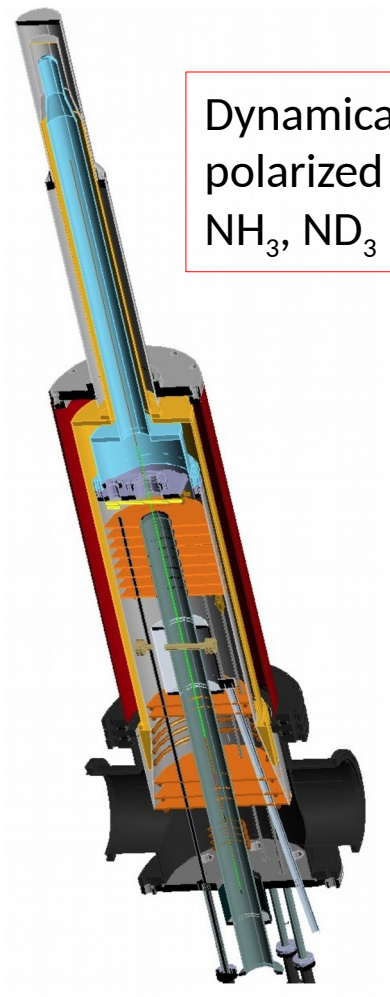
$\Delta\sigma_{LU} \sim \sin\phi\ \{F_1 H + \xi(F_1+F_2)\tilde{H} + kF_2 E\}d\phi$



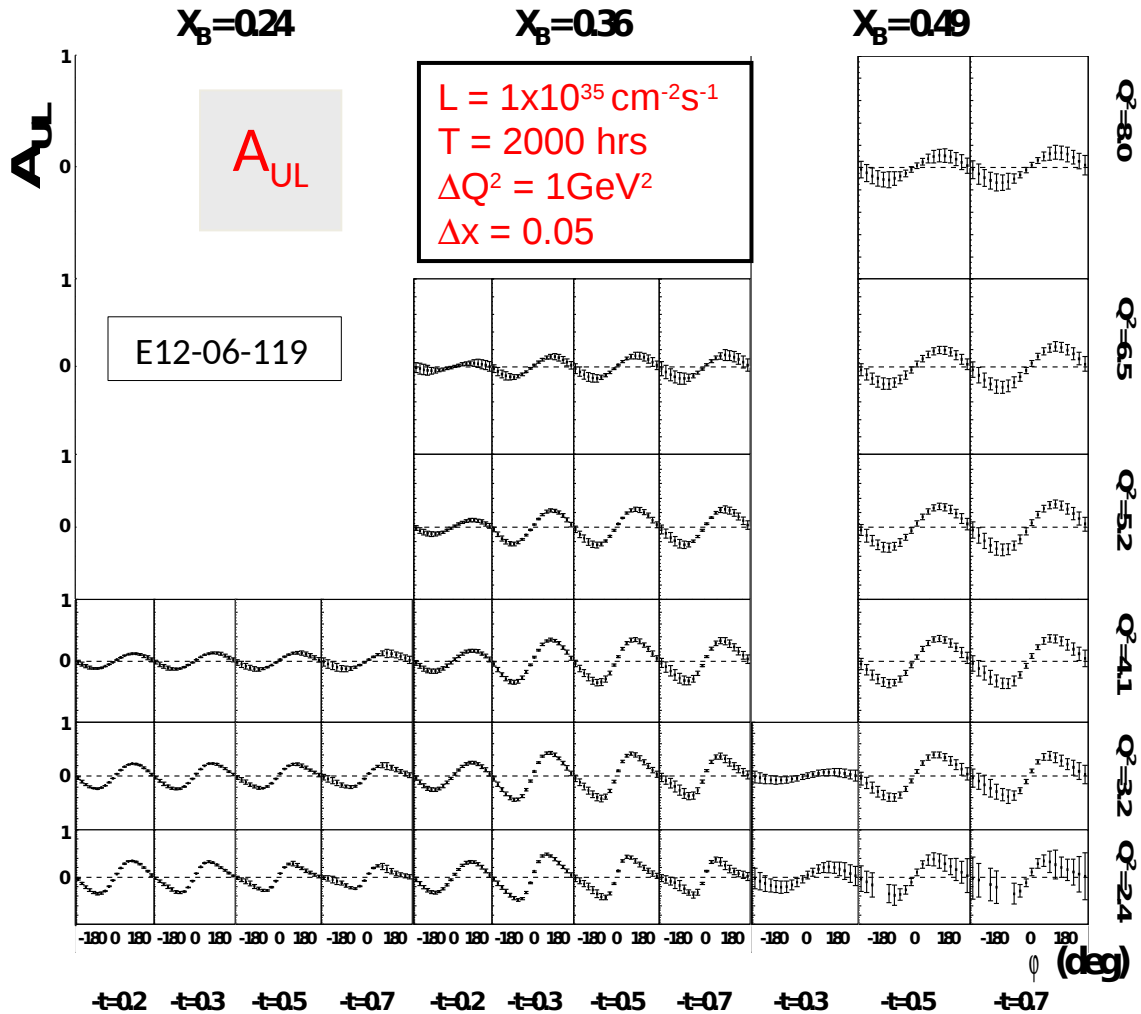
A_{UL} projections for protons

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

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



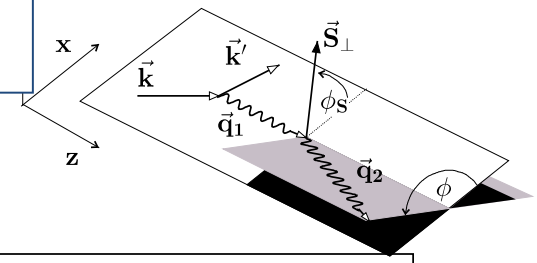
Dynamically polarized target NH_3, ND_3

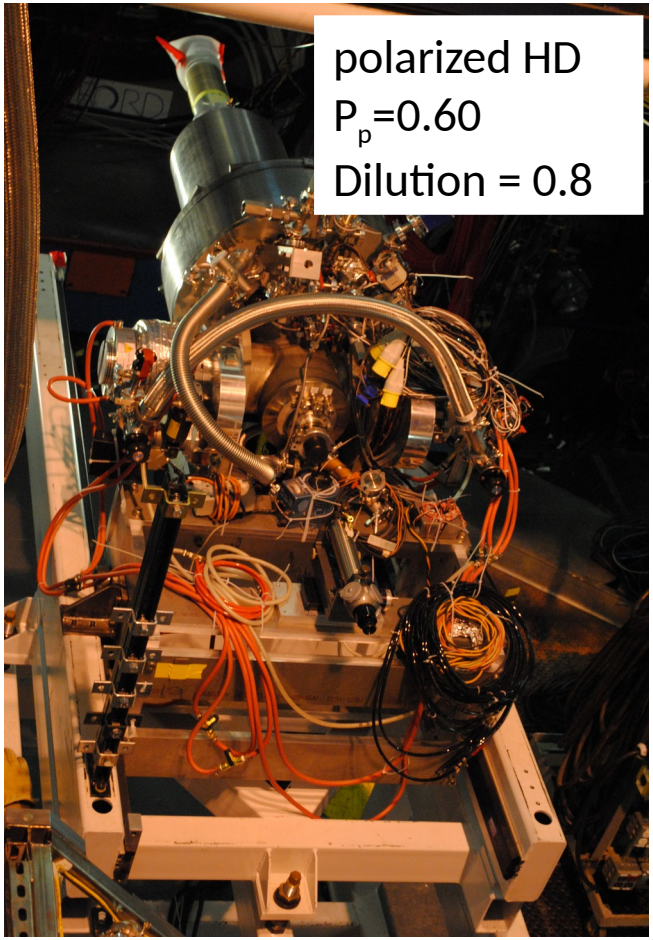


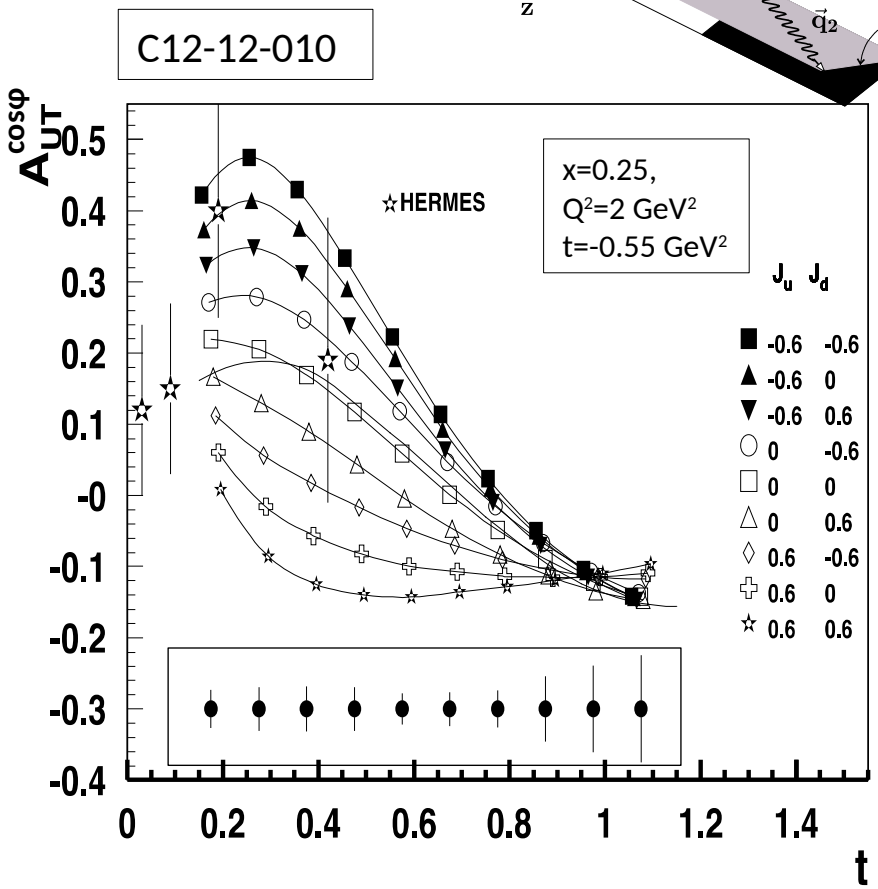
A_{UT} projections for 12GeV

$ep^{\uparrow} \longrightarrow ep\gamma$

$$\Delta\sigma_{UT} \sim \cos\phi \sin(\phi_s - \phi)\{k(F_2 H - F_1 E)\}d\phi$$





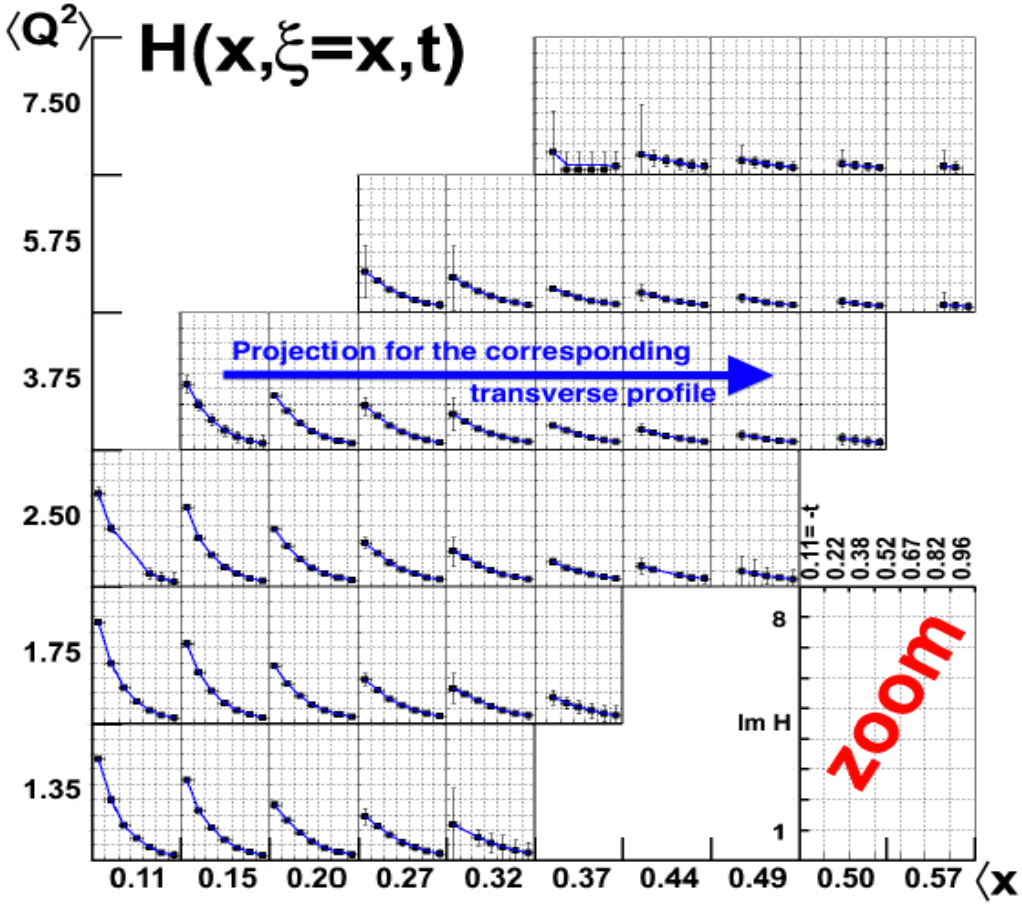


A_{UT} and A_{LT} are sensitive to the u and d-quark helicity content of the proton spin

GPD H from projected CLAS12 data

Review article: M. Guidal, H. Moutarde, M. Vanderhaeghen, Rept.Prog.Phys. 76 (2013) 066202

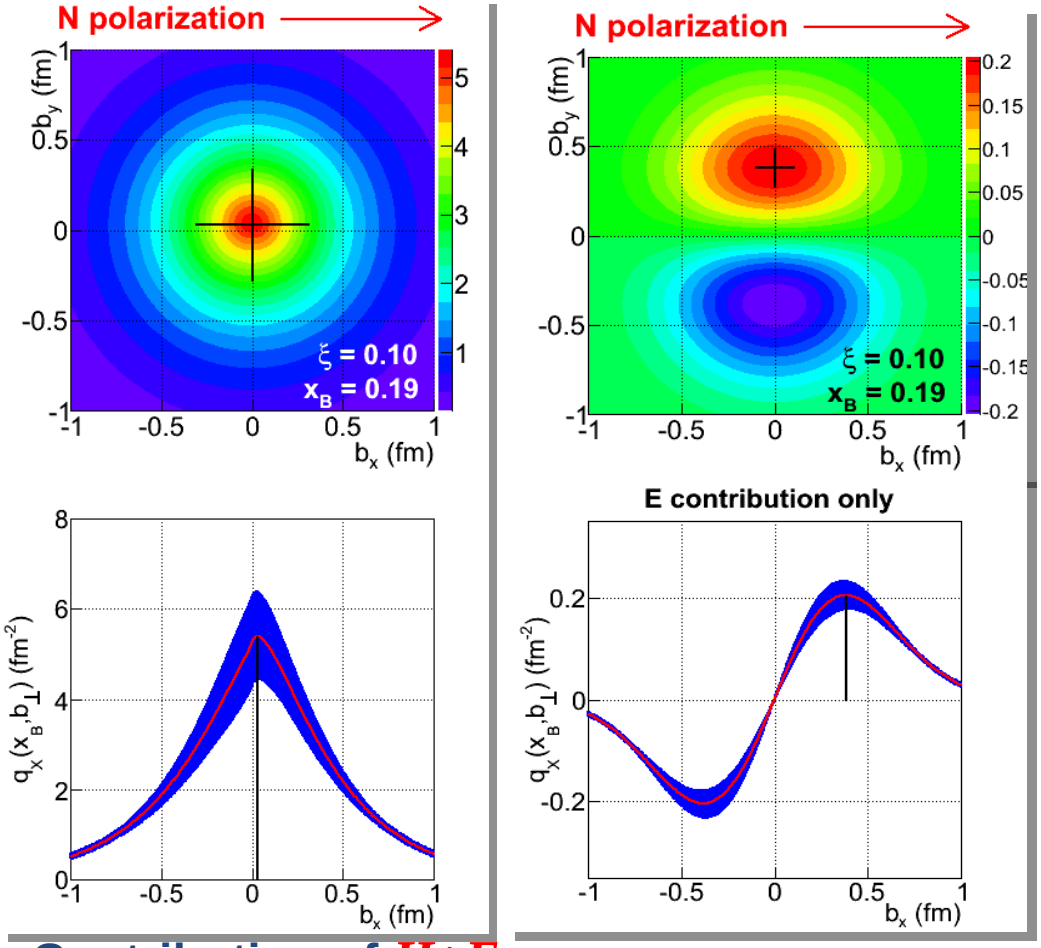
LO fit to all observables: σ, A_{LU}, A_{UL}, A_{LL}, A_{Ux}, A_{Uy}, A_{Lx}, A_{Ly}



For corrections see talk by H. Moutarde

Projected quark densities in impact parameter

$$\rho_X(x,\vec{b}_\perp) = \int \frac{d^2\vec{\Delta}_\perp}{(2\pi)^2}\left[H(x,0,t) - \frac{E(x,0,t)}{2M}\frac{\partial}{\partial b_y}\right] e^{-i\vec{\Delta}_\perp\cdot\vec{b}_\perp}$$



Contribution of $H+E$

Contribution of E

- Fourier transform of GPDs give access to the quark densities distribution in impact parameter space.

- GPD E probes the u- and d-quark separation in impact parameter space. Transversely polarized proton shows flavor dipole.

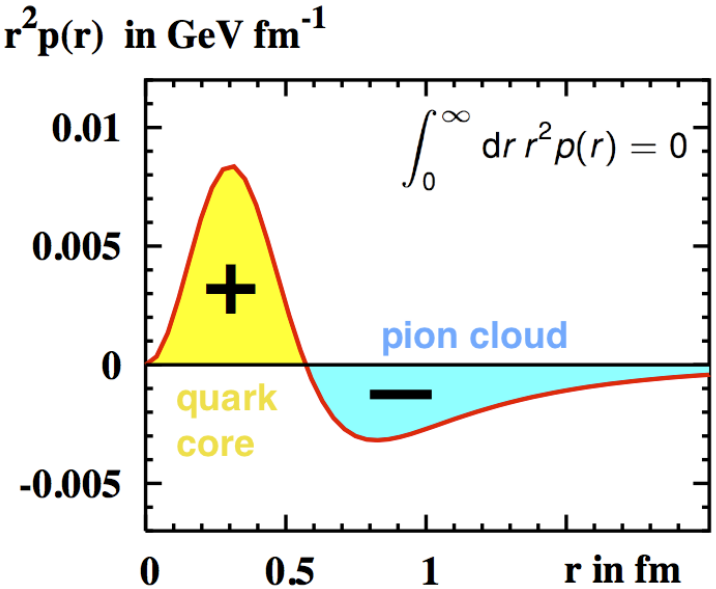
DVCS with CLAS12 at various beam energies

$$\mathcal{H}(\xi,t) = \sum_f \left[\frac{e_f}{e}\right]^2 \left\{ i\pi \left[H_f(\xi,\xi,t) - H_f(-\xi,\xi,t)\right] + \mathcal{P}\int_{-1}^{+1} dx \left[\frac{1}{\xi - x} - \frac{1}{\xi + x}\right] H_f(x,\xi,t) \right\}$$

Imaginary Part of CFF

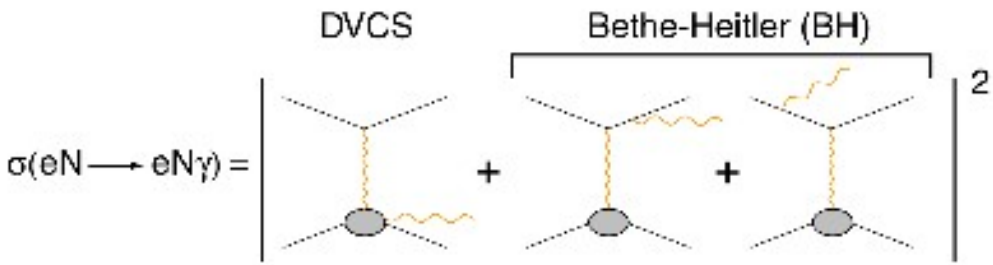
Real Part of CFF

$$\Re e[H(\xi,t)] = \int_{-1}^{1} dx \left\{ [H(x,x,t) + H(-x,x,t)] \left[\frac{1}{\xi - x} - \frac{1}{\xi + x}\right] + 2\frac{D(x,t)}{1-x} \right\}$$



- The D-term is the least known part of the conventional GPD H
- t-dependence of the D-term encodes the form factor associated with the distributions of forces on partons inside hadrons
- May shed light on the mechanism of confinement

Accessing GPDs through DVCS



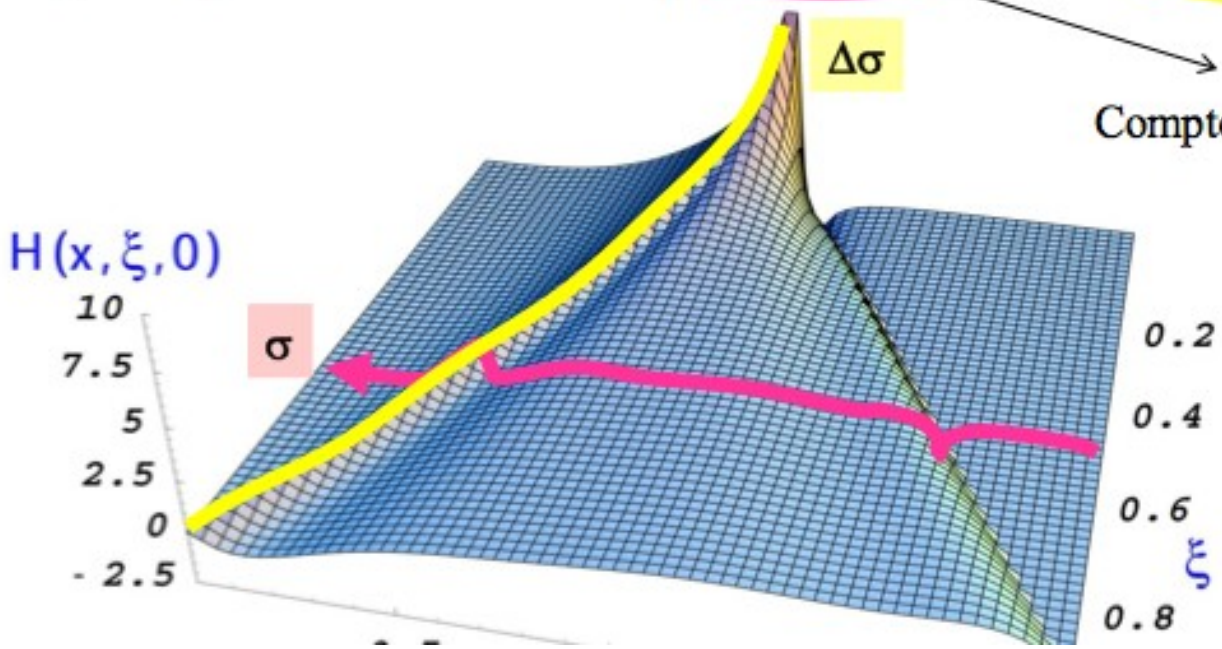
$$\sigma \sim |T^{DVCS} + T^{BH}|^2$$

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

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

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

Compton Form Factors



Only ξ and t are accessible experimentally

DDVCS with CLAS12 in Hall-B – LOI

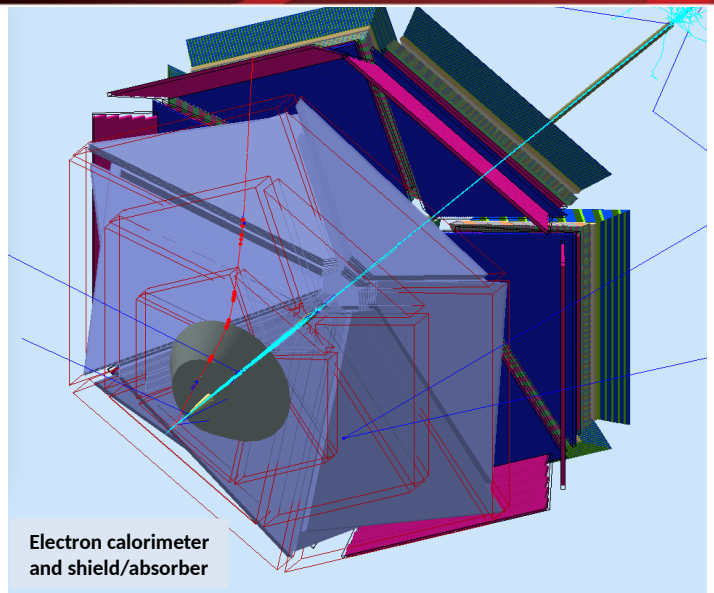
Two main challenges in DDVCS measurements:

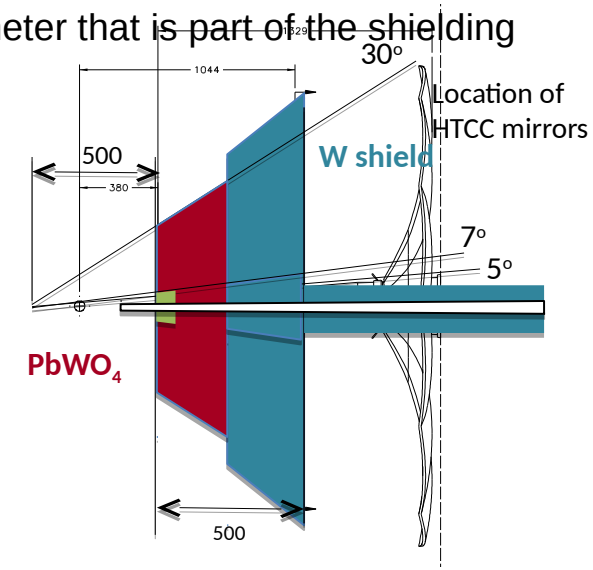
- cross section is two to three orders of magnitude smaller than the DVCS cross section
- decay leptons of the outgoing virtual photon must be distinguishable from the incoming-scattered lepton

Both challenges can be solved with by studying di-muon electroproduciton, $ep \rightarrow e'p'\mu^+\mu^-$

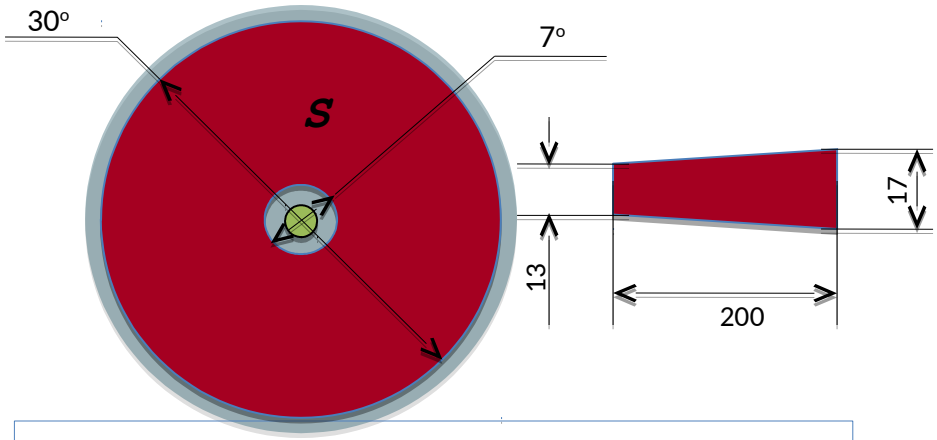
CLAS12 FD will be blocked with heavy shielding/absorber from electromagnetic and hadronic backgrounds to be able to run at luminosities ~10^{37} $cm^{-2}\,s^{-1}$, and will be used as muon detector

Scattered electrons will be detected in a compact $PbWO_4$ calorimeter that is part of the shielding





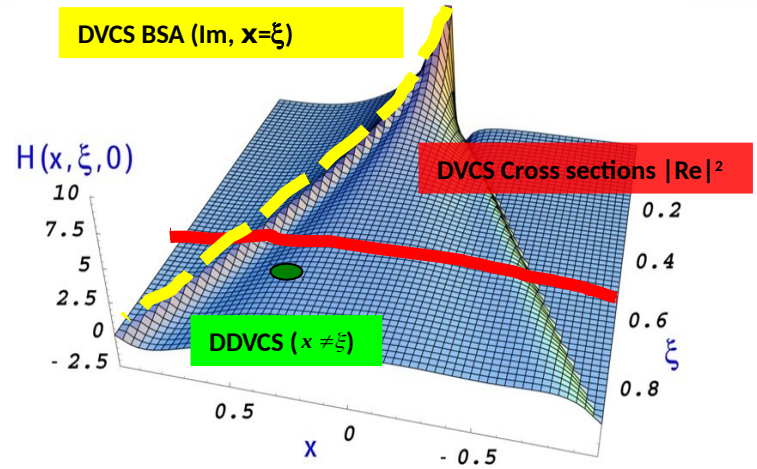
$$S = \pi l^2[(tg^2(30^o) - tg^2(7^o)] = 3600\,cm^2;\ l = 60\,cm$$



$PbWO_4$ modules with APD readout - ~ 1500 modules

Expected results on beam spin of DDVCS asymmetry

The beam spin asymmetry (BSA) in DDVCS is proportional to the imaginary part the, i.e. in a concise notation:



This allows the mapping of GPDs along each of the three axis (, ξ and *t*) independently

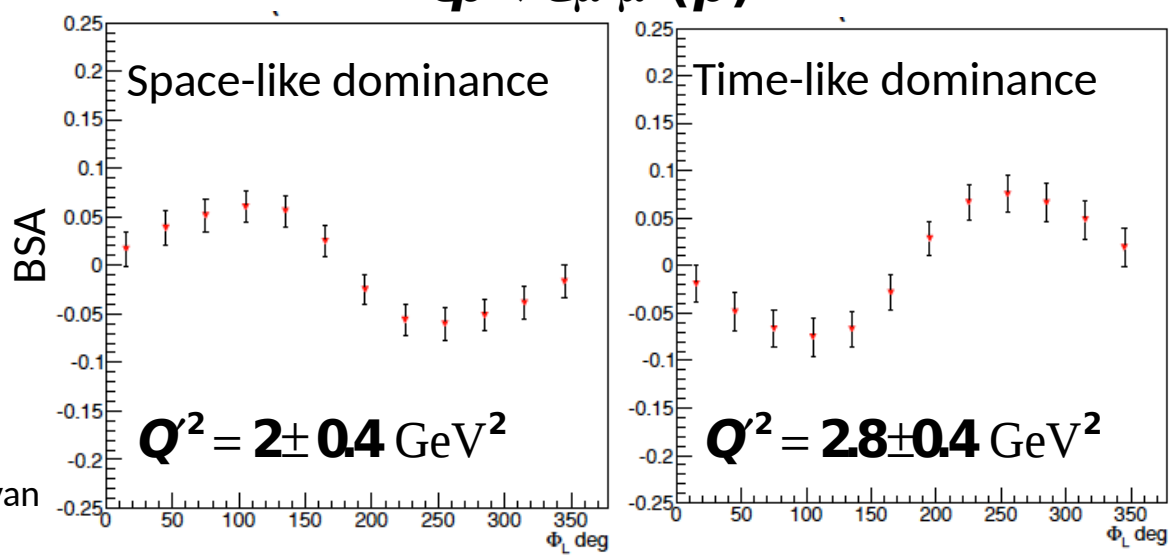
Prediction of the "handbag" formalism is the sign change of BSA in transitioning from "space-like dominated" to "time-like dominated" regime

BSA for 100 days of running with CLAS12 at luminosity of 10^{37} cm^{-2} s^{-1}

$$ep \to e'\mu^+\mu^-(p')$$

Electron kinematics:

Transferred momentum squared:



From Boer, Paremuzyan

Extraction and Validation Framework

- The main goal is to develop a framework for extraction and validation of 3 D PDFs from experimental measurements of hard exclusive and semi-inclusive production of photons and mesons through:
  - Developing multidimensional MC-simulation
  - Implementing self consistent QED radiative corrections in the cross sections for a complete set of structure functions needed for the extraction framework and MC simulations
  - Developing capabilities, within the extraction and validation framework, to provide persistence and data visualization tools
  - Robust strategy to propagate and control uncertainties to the extracted 3D PDFs
- The analysis framework to be used in 2 ways: from measured observables to 3D PDFs, and from models of 3D PDFs to predictions of observables.

CLAS Collaboration

Arizona State University, Tempe, AZ
University Bari, Bari, Italy
University of California, Los Angeles, CA
California State University, Dominguez Hills, CA
Carnegie Mellon University, Pittsburgh, PA
Catholic University of America
CEA-Saclay, Gif-sur-Yvette, France
Christopher Newport University, Newport News, VA
University of Connecticut, Storrs, CT
Edinburgh University, Edinburgh, UK
University Ferrara, Ferrara, Italy
Florida International University, Miami, FL
Florida State University, Tallahassee, FL
George Washington University, Washington, DC
University of Glasgow, Glasgow, UK

University of Grenoble, Grenoble, France
Idaho State University, Pocatello, Idaho
INFN, Laboratori Nazionali di Frascati, Frascati, Italy
INFN, Sezione di Genova, Genova, Italy
Institut de Physique Nucléaire, Orsay, France
ITEP, Moscow, Russia
James Madison University, Harrisonburg, VA
Kyungpook University, Daegu, South Korea
University of Massachusetts, Amherst, MA
Moscow State University, Moscow, Russia
University of New Hampshire, Durham, NH
Norfolk State University, Norfolk, VA
Ohio University, Athens, OH

Old Dominion University, Norfolk, VA
Rensselaer Polytechnic Institute, Troy, NY
Rice University, Houston, TX
University of Richmond, Richmond, VA
University of Rome Tor Vergata, Italy
University of South Carolina, Columbia, SC
Thomas Jefferson National Accelerator Facility, Newport News, VA
Union College, Schenectady, NY
University Santa Maria, Valparaiso, Chile
Virginia Polytechnic Institute, Blacksburg, VA
University of Virginia, Charlottesville, VA
College of William and Mary, Williamsburg, VA
Yerevan Institute of Physics, Yerevan, Armenia
Brazil, Germany, Morocco and Ukraine,
, have individuals or groups involved with CLAS,
but with no formal collaboration at this stage

Summary

- CLAS12 with JLab 12 GeV upgrade has a broad science program covering many facets of hadron physics.

- Extending knowledge of PDFs to high x in measurements of (un)polarized structure functions using tagging. Addresses part of the nucleon “spin-puzzle” and extend knowledge of quark density distribution at high x.

- Precision studies of DVCS in polarization measurements give access to GPDs and enable quark spatial imaging. They relate to the quark spin, mass and force distributions in the nucleon (confinement?).

- Precise measurements of SIDIS improve access to TMDs and quark momentum tomography, and relate to the quark orbital angular momentum.

- Many topics not discussed, hadron spectroscopy, nucleon e.m. form factors, dark matter searches, QCD and nuclei, ….

Electron Ion Collider