XIV WORKSHOP ON HIGH ENERGY SPIN PHYSICS

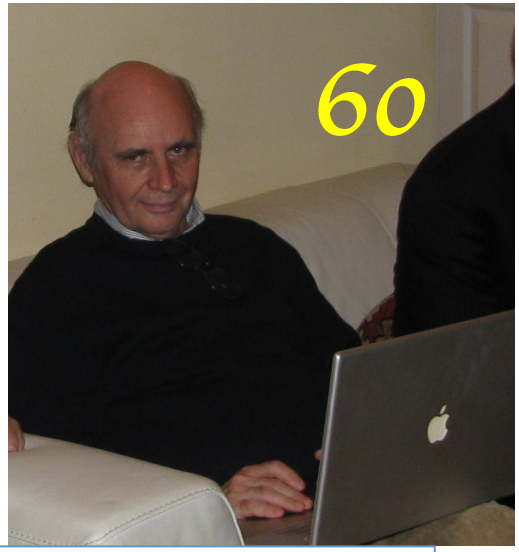
DSPIN-11

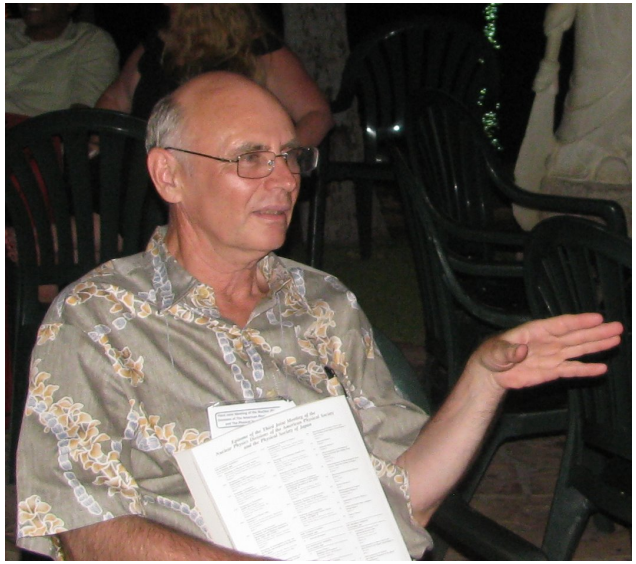
Dubna, Russia, September 20 - 24, 2011

Valery Kubarovsky

Jefferson Lab

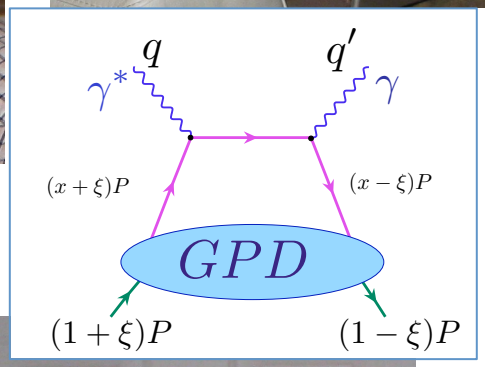
Virginia Outstanding Scientist

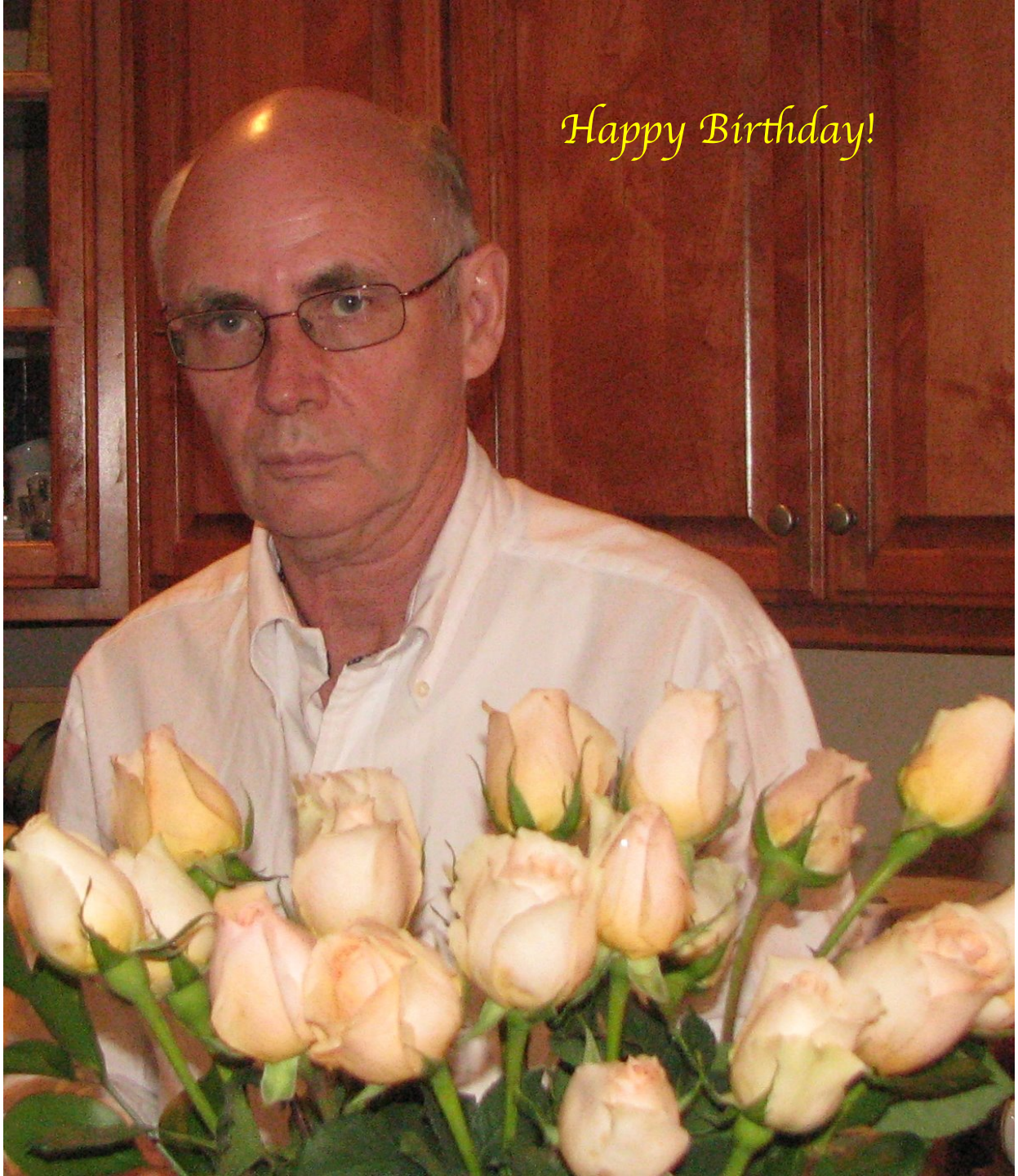


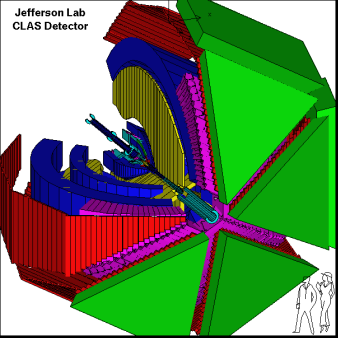


- Staff of the Laboratory of Theoretical Physics in Dubna
- Jlab senior scientist
- Physics Professor at Old Dominion University

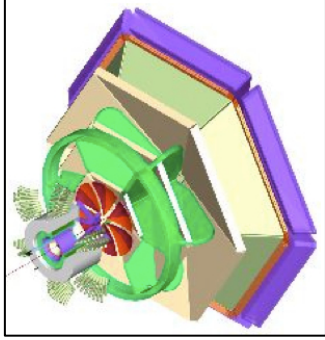
Published papers	106
Total number of citations	8 159
Average citations per published paper	**74**
Renowned papers (500+)	3
Famous papers (250-499)	7
Very well-known papers (100-249	12




Happy Birthday!



Jefferson Lab
Thomas Jefferson National Accelerator Facility



Hard Exclusive Reactions at Jlab

Valery Kubarovsky
Jefferson Lab

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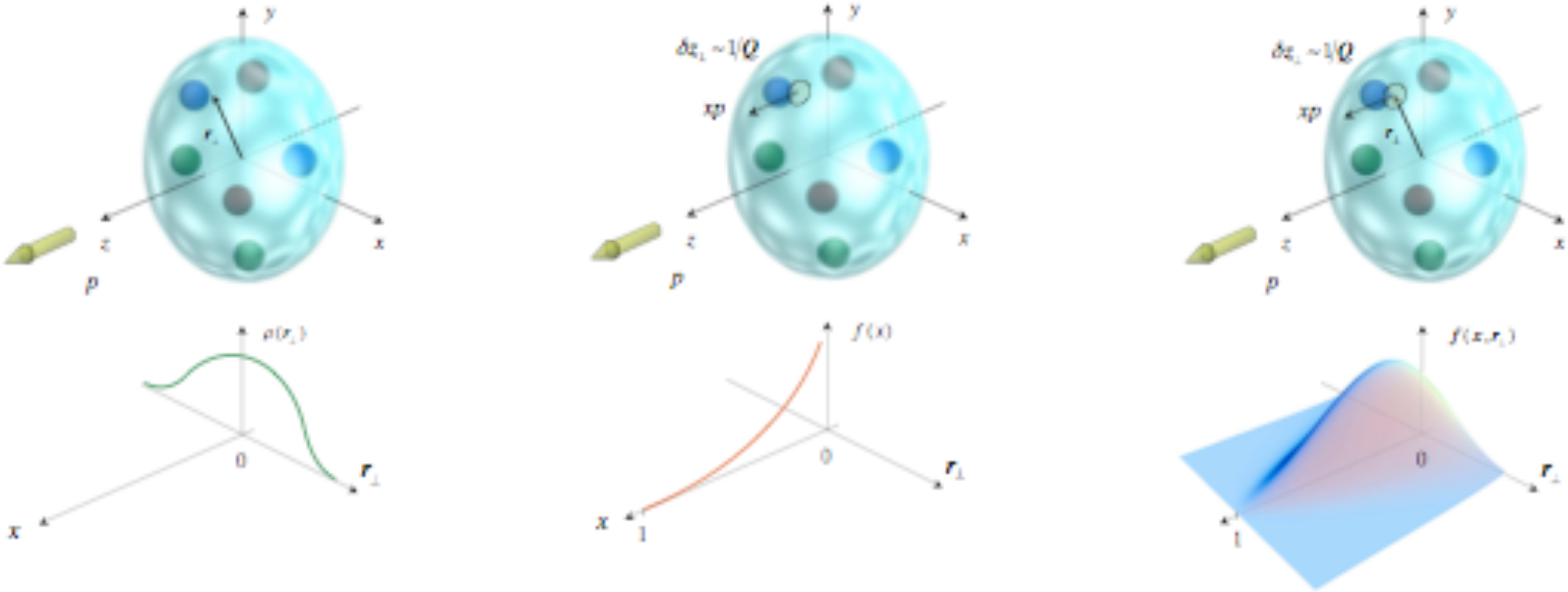
Outline

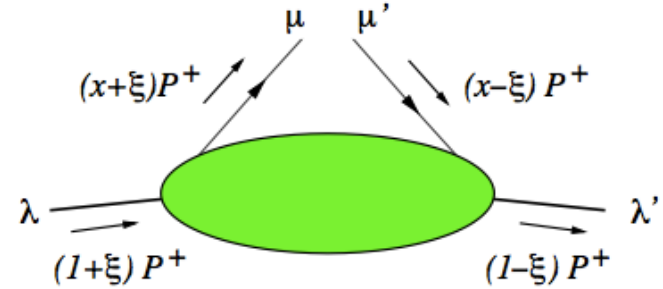
- Introduction
- Deeply Virtual Compton Scattering
- Pseudoscalar meson electroproduction
- Vector meson electroproduction
- JLAB 12 upgrade
- Conclusion

Description of hadron structure in terms of GPDs



Nucleon form factors transverse charge & current densities Nobel prize 1961- R. Hofstadter	*Structure functions* quark longitudinal momentum (polarized and unpolarized) distributions Nobel prize 1990 –J.Friedman, H. Kendall, R. Taylor	*GPDs* correlated quark momentum distributions (polarized and unpolarized) in transverse space

Generalized Parton Distributions



- There are 4 chiral even GPDs where partons do not transfer helicity H, $\tilde{H}$, E, $\tilde{E}$
- H and E are "unpolarized" and $\tilde{H}$ and $\tilde{E}$ are "polarized" GPD. This refers to the parton spins.
- 4 chiral odd GPDs flip the parton helicity

H_T, $\tilde{H}_T$, E_T, $\tilde{E}_T$. H_T is connected with transversity

$$H_T^q(x,0,0) = h_1^q(x)$$

Basic GPD properties

- Forward limit

$$H^q(x,0,0) = q(x)$$
$$\tilde{H}^q(x,0,0) = \Delta q(x)$$
$$H_T^q(x,0,0) = h_1^q(x)$$

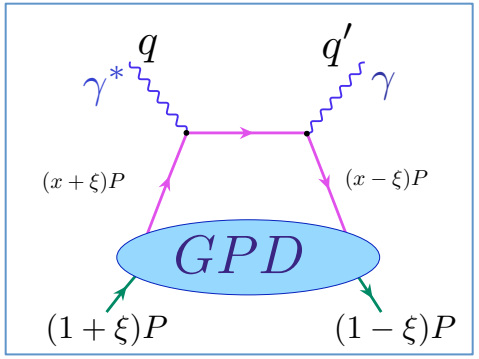
- Form factors

$$\int_{-1}^{1} \mathrm{d}x\, H^q(x,\xi,t) = F_1^q(t), \quad \int_{-1}^{1} \mathrm{d}x\, E^q(x,\xi,t) = F_2^q(t)$$
$$\int_{-1}^{1} \mathrm{d}x\, \tilde{H}^q(x,\xi,t) = g_A^q(t), \quad \int_{-1}^{1} \mathrm{d}x\, \tilde{E}^q(x,\xi,t) = g_P^q(t)\ ,$$

- Angular Momentum

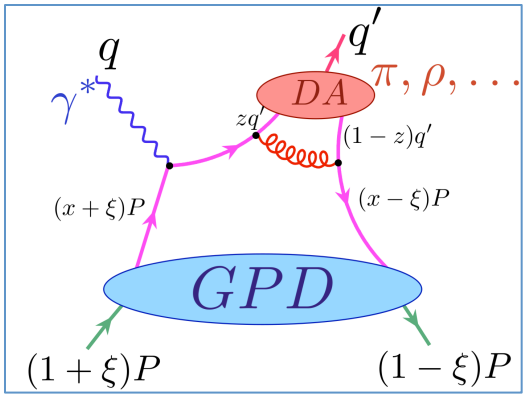
$$J^q(t) = \frac{1}{2}\int_{-1}^{1} \mathrm{d}x\, x\, [H^q(x,\xi,t) + E^q(x,\xi,t)]$$

(Ji's sum rule)



DVCS and DVMP

- Factorization theorem
- Access to fundamental degrees of freedom



DVCS:

- the clearest way to access the GPDs
- Only γ_T photons participate in DVCS
- Interference with BH process

DVMP:

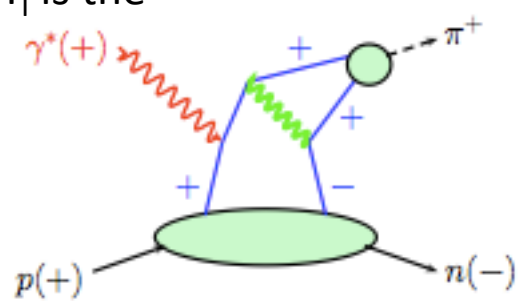
- Factorization proven only for σ_L
  $\sigma_L \sim 1/Q^6$, $\sigma_T/\sigma_L \sim 1/Q^2$
- Meson distribution amplitude
- Gluon exchange required
- Vector and pseudoscalar meson production allows to separate flavor and separate the helicity-dependent and helicity independent GPDs.

Transversity in hard exclusive electroproduction of pseudoscalar mesons

S. Goloskokov, P. Kroll, 2011, **arXiv:1106.4897v1**

- The data clearly show that a leading-twist calculation of DVMP within the handbag is insufficient. They demand higher-twist and/or power corrections
- There is a large contribution from the helicity amplitude $M_{0-,++}$. Such contribution is generated by the the helicity-flip or transversity GPDs in combination with a twist-3 pion wave function
- This explanation established an interesting connection to transversity parton distributions. The forward limit of H_T is the transversity

$$M_{0-,++} \sim H_T$$



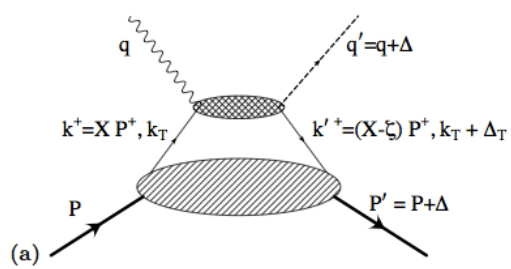
$$H_T^q(x,0,0) = h_1^q(x)$$

Nucleon Tensor Charge from Exclusive π^0 Electroproduction

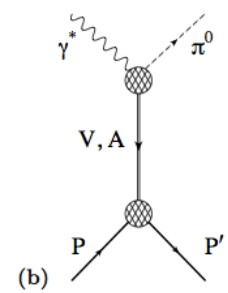
$$\gamma^* p \rightarrow p\pi^0$$

Ahmad, Goldstein, Luiti, Phys. Rev. D 79, 054014 (2009), arXiv:1104.5682v1

- The quantum numbers and Dirac structure of π^0 electroproduction restrict the possible contributions to the 4 chiral odd GPDs, one of which, H_T , is related to the transversity distribution and the tensor charge.
- This differs from DVCS and both vector and charge $\pi^{+/-}$ electroproduction, where the axial charge can enter the amplitudes.
- Contrary the tensor charge enters the π^0 process.

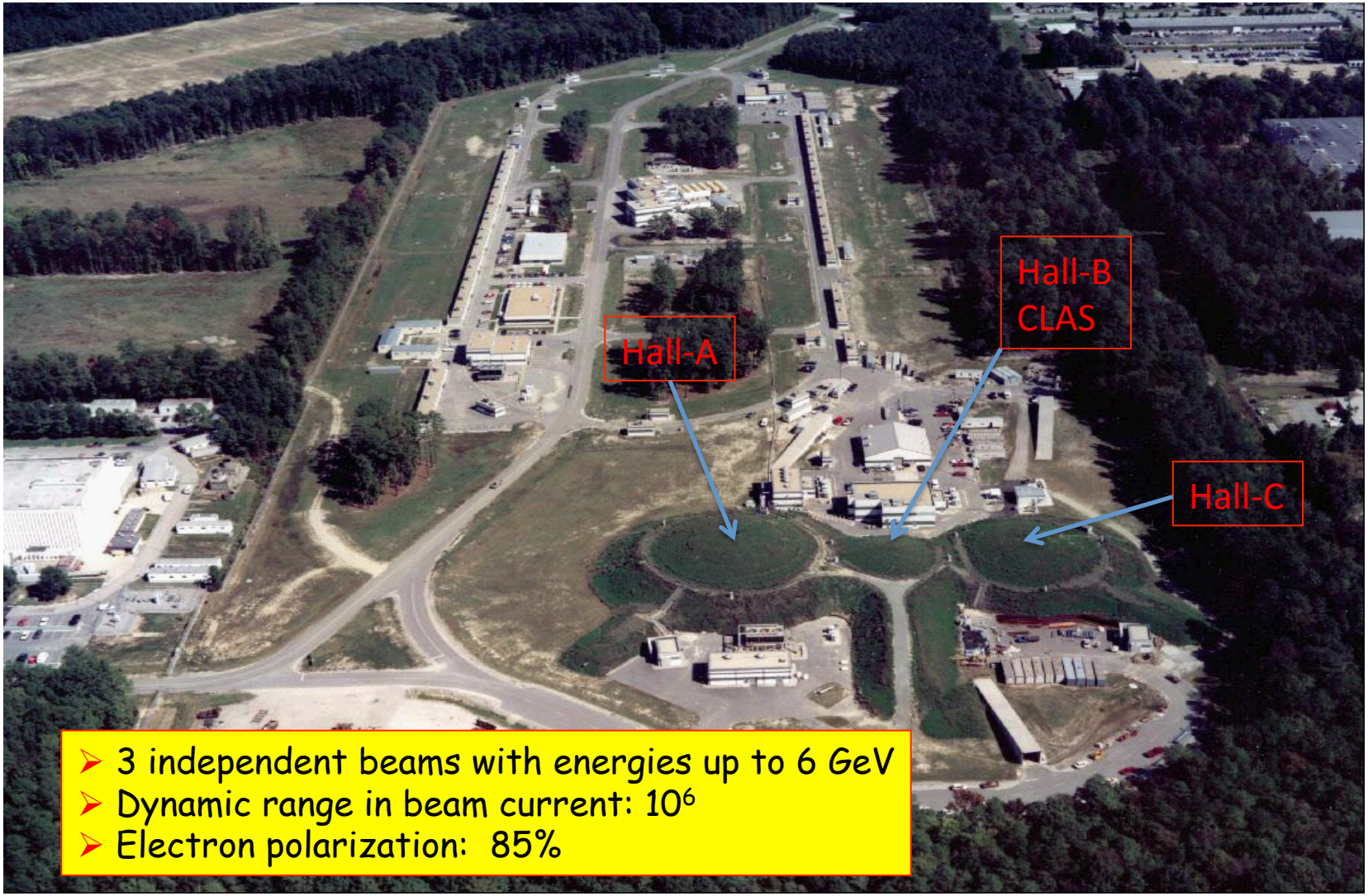


partonic degrees of freedom interpretation;



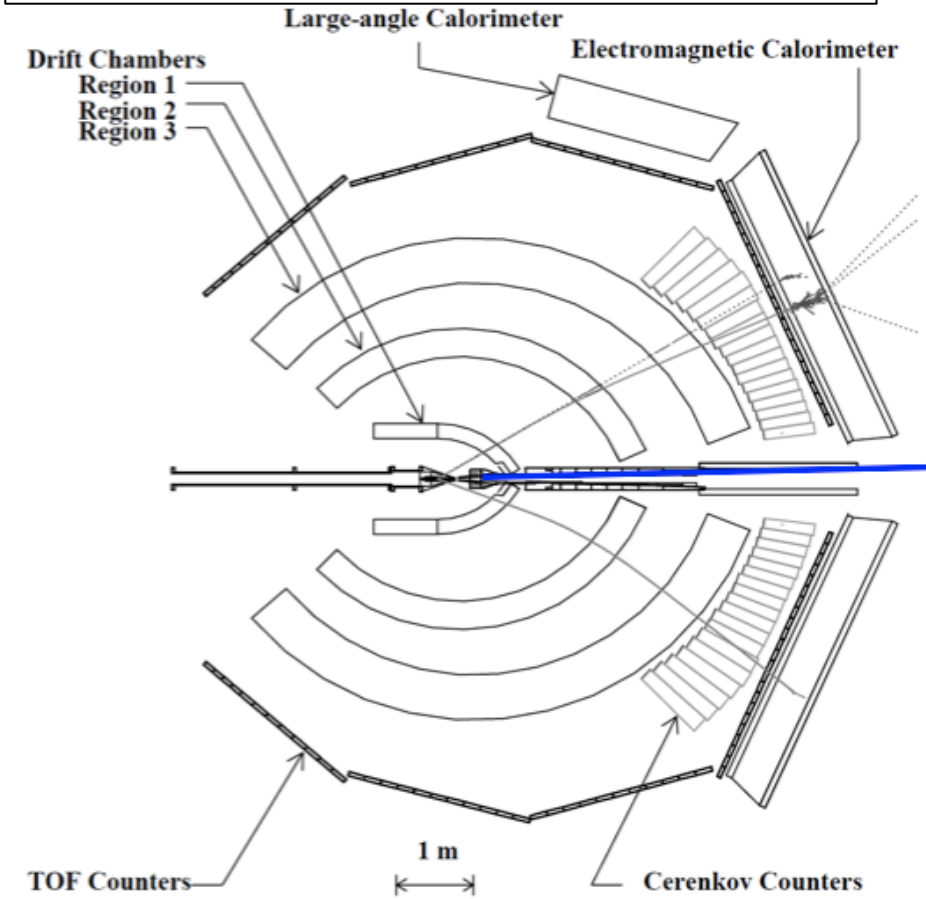
t-channel exchange diagram

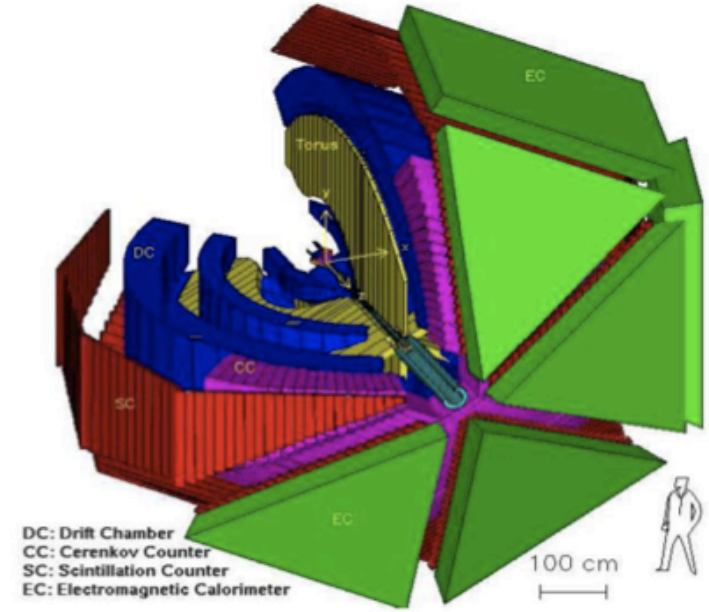
JLab Site: The 6 GeV Electron Accelerator



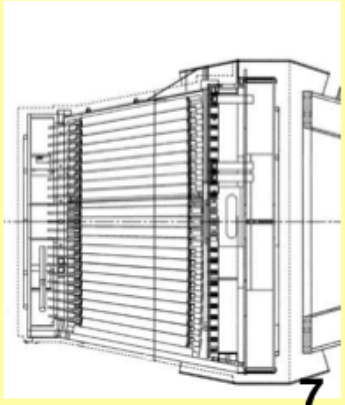
- 3 independent beams with energies up to 6 GeV
- Dynamic range in beam current: 10^6
- Electron polarization: 85%

CEBAF Large Acceptance Spectrometer CLAS





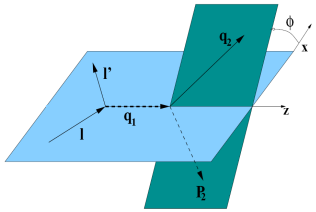
Inner Calorimeter



CLAS Lead Tungstate Electromagnetic Calorimeter

424 crystals, 18 RL,
Pointing geometry,
APD readout

Accessing GPDs through polarization



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

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

$k = t/4M^2$

Polarized beam, unpolarized proton target:

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

Kinematically suppressed

$\mathcal{H}(\xi,t)$

Unpolarized beam, longitudinal proton target:

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

Kinematically suppressed

$\mathcal{H}(\xi,t)$, $\tilde{\mathcal{H}}(\xi,t)$

Unpolarized beam, transverse proton target:

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

Kinematically suppressed

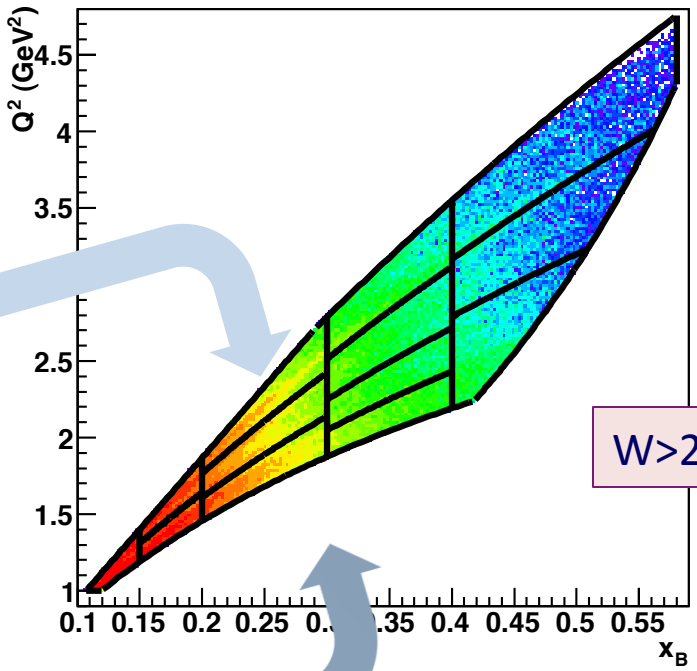
$\mathcal{H}(\xi,t)$, $\mathcal{E}(\xi,t)$

$\mathcal{H}(\xi,t)$, $\mathcal{E}(\xi,t)$… are CFF

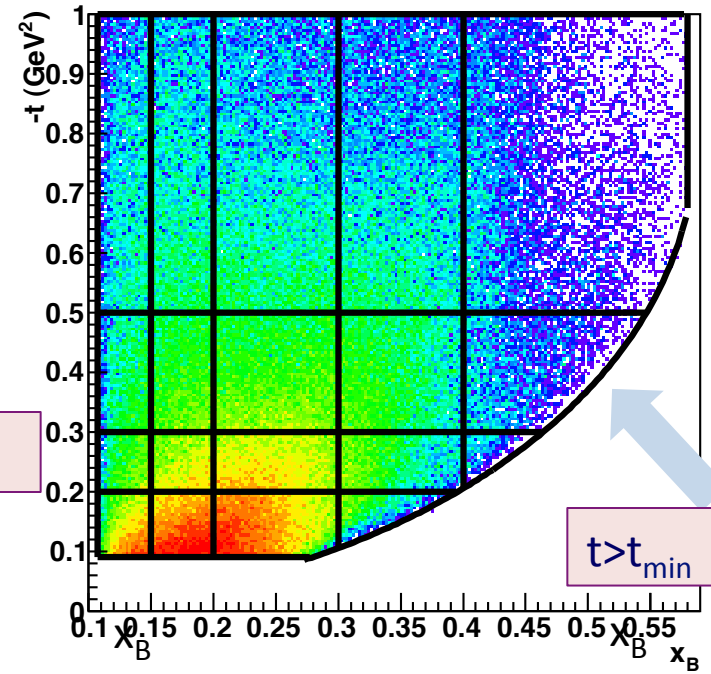
DVCS kinematics

$\Theta_e<45^0$

$\theta_e>22^0$



W>2GeV



$t>t_{min}$

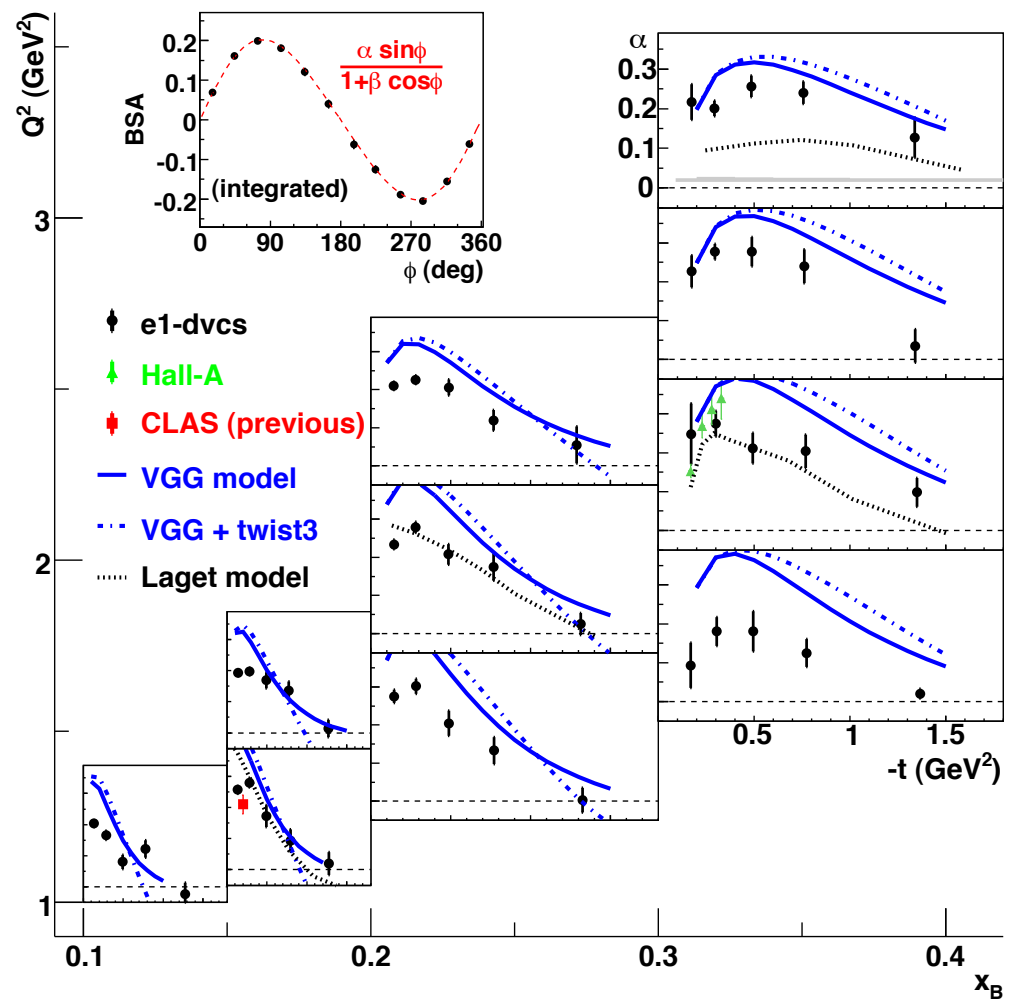
	Min	Max
Q^2	1 GeV^2	5 GeV^2
xB	0.1	0.6
-t	tmin	1 GeV^2
W	2 GeV	3 GeV

DVCS Beam Spin Asymmetry A_{LU}

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

- VGG parameterization reproduces $-t > 0.5\,\mathrm{GeV}^2$ behavior, and overshoots asymmetry at small t.
- The latter could indicate that VGG misses some important contributions to the DVCS cross section.
- Regge model (J-M Laget) is in fair agreement in some kinematic bins with our results.
- The Regge mode seems to be working at low Q^2 while the GDP approach gets better at larger Q^2. This is expected

CLAS data

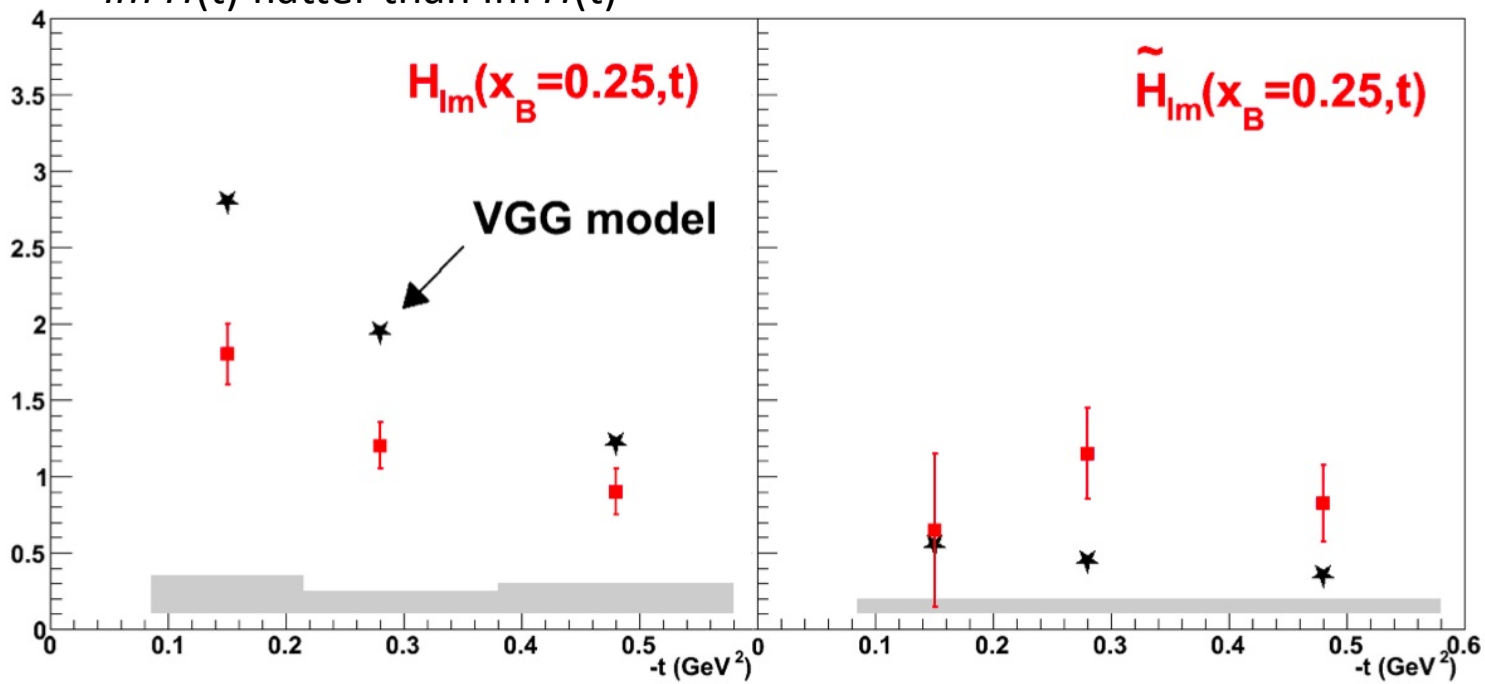


F.-X. Girod et al., PRL 100 (2008) 162002

Extraction of Compton Form Factors from CLAS DVCS data

- A_{LU} and A_{UL} CLAS results only
- *Im H*(t) Im $\tilde{H}$(t) are extracted
- *Im* $\tilde{H}$(t) flatter than Im *H*(t)

M. Guidal, Phys.Lett.B689:156-162,2010

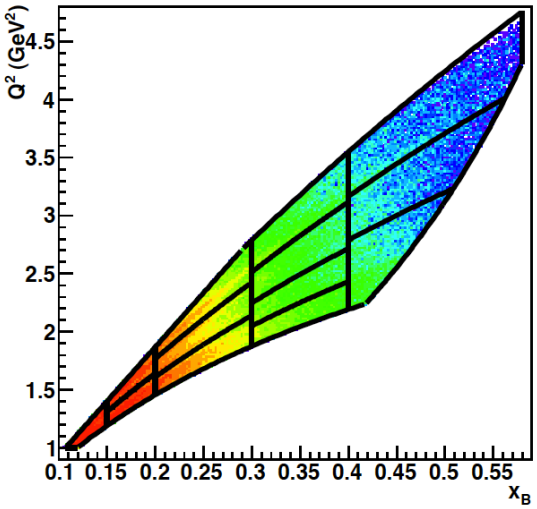


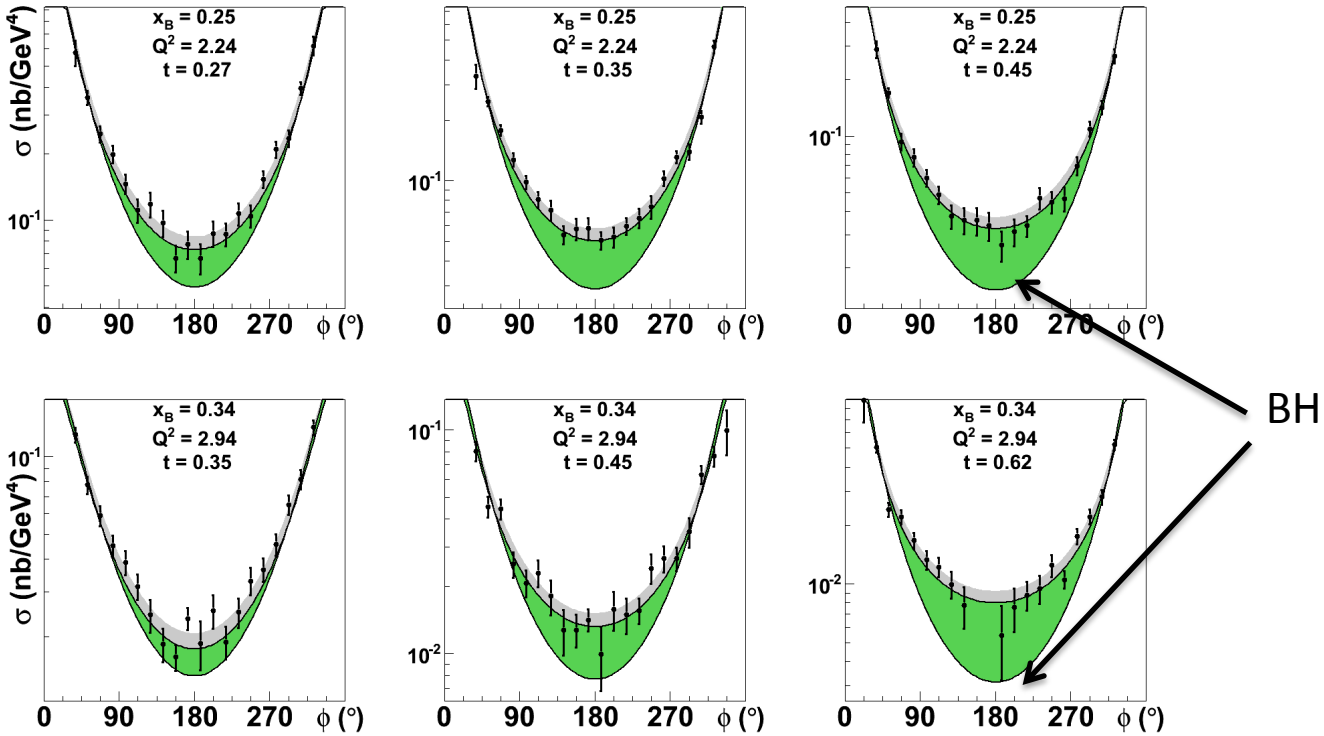
The fact that $\tilde{H}$ is "flatter" in t than H, hints that the axial charge of the nucleon is more concentrated than the electromagnetic charge. This is related to the fact that the axial form factor is also flatter than the EM form factors. We see that via different formalism (GDPS vs FFs) and reaction (DVCS vs elastic), one reaches the same conclusions.

$\sigma(ep \rightarrow ep\gamma)$

DVCS x-sections from CLAS

F.X. Girod





Four dimensional grid
Q^2, x_B, t, ϕ

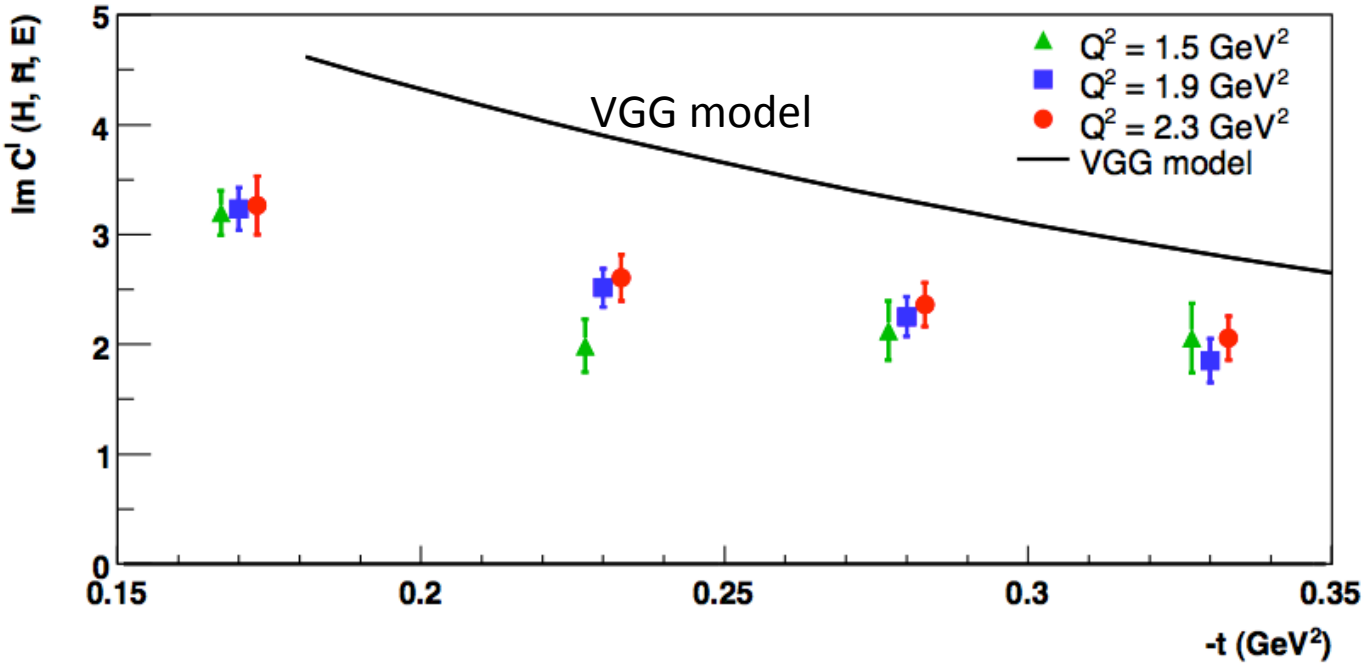
CLAS PRELIMINARY

Radiative corrections and π^0 contamination accounted

Hall A

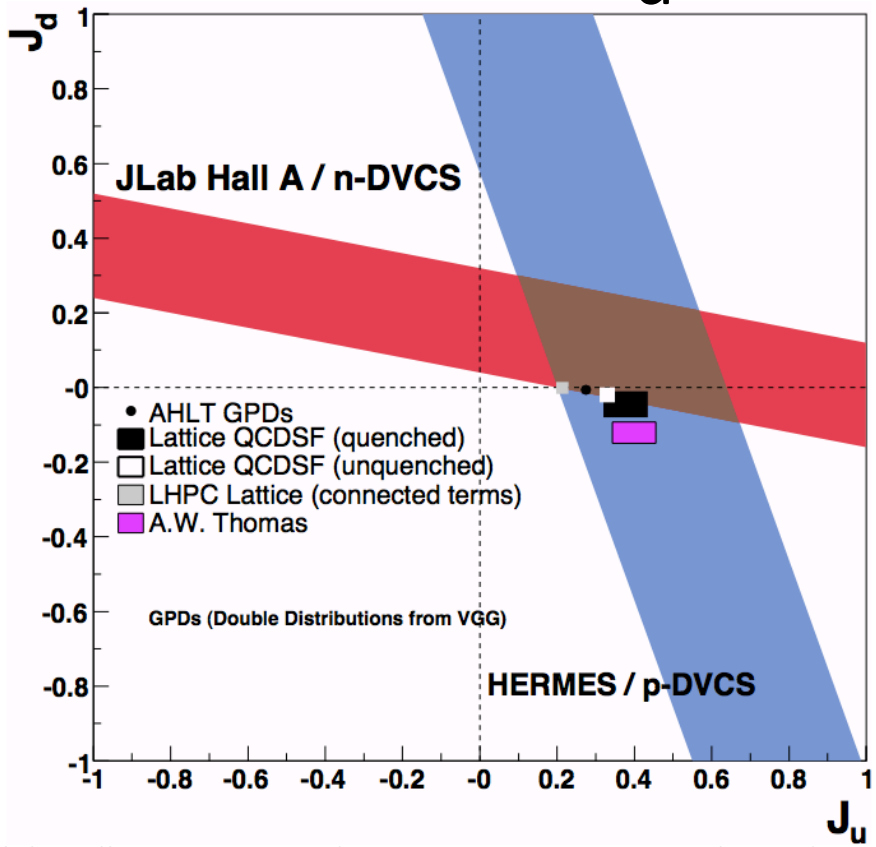
- Proton DVCS, helicity dependent and independent cross sections were measured at
  - Q^2=(1.5, 1.9, 2.3) GeV^2
  - -t=(0.17, 0.23, 0.28, 0.33) GeV^2
  - x_B=0.36
- Neutron DVCS, helicity dependent cross section on deuterium. Sensitive to $E(\xi,t)$
  - Q^2=1.9 GeV^2
  - x_B=0.36
- Completed data taking at 2010, which included measurements of DVCS on proton and deuterium at two different energies with the aim to separate Re [DVCS*BH] and $|DVCS|^2$ terms.

Imaginary Part of the Interference Term



- VGG model agrees in slope with the data but lies 30% above
- Q^2 independent in all t bins
- Provide support for the factorization at Q^2>2 GeV^2

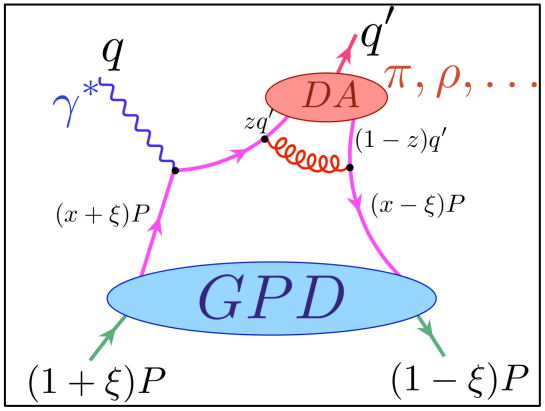
Constraint on J_d and J_u



Helicity-dependent Jlab Hall-A neutron and HERMES transversity polarized proton data constrain in ***a model dependent way*** on the total up and down quark contributions to the proton spin.

$$J_q = \frac{1}{2}\Delta\Sigma_q + L_q = \frac{1}{2}\int_{-1}^{1} x[H_q(x,\xi,t=0) + E_q(x,\xi,t=0)]dx$$

Exclusive Meson Production



Pseudoscalar mesons

$$ep \to en\pi^+$$

$$ep \to ep\pi^0, \quad \pi^0 \to \gamma\gamma$$

$$ep \to ep\eta, \quad \eta \to \gamma\gamma$$

Vector mesons

$$ep \to en\rho^+, \quad \rho^+ \to \pi^+\pi^0$$

$$ep \to ep\rho^0, \quad \rho^0 \to \pi^+\pi^-$$

$$ep \to ep\omega, \quad \omega \to \pi^+\pi^-\pi^0$$

$$ep \to ep\phi, \quad \phi \to K^+K^-$$

CLAS6: lots of data.
CLAS12: Exp. # E12-06-108

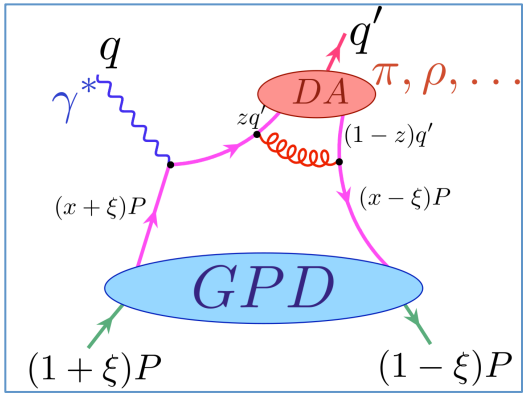
Deeply Virtual Meson Production

CLAS results

$$ep \rightarrow ep\pi^0, \quad \pi^0 \rightarrow \gamma\gamma$$

$$ep \rightarrow ep\eta, \quad \eta \rightarrow \gamma\gamma$$

$$ep \rightarrow en\rho^+, \quad \rho^+ \rightarrow \pi^+\pi^0$$



Meson	GPD flavor composition
π^+	$\Delta u - \Delta d$
π^0	$2\Delta u + \Delta d$
η	$2\Delta u - \Delta d$
ρ^0	$2u + d$
ρ^+	$u - d$
ω	$2u - d$

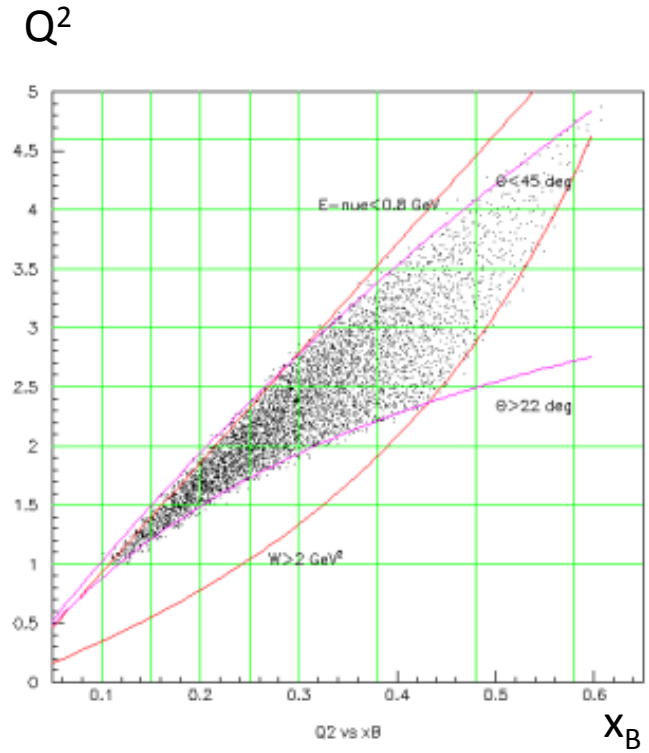
Flavor separation
Access to polarized GPDs
Access to transversity GPDs

$$\gamma^* p \rightarrow p\pi^0$$

4 Dimensional Grid

Rectangular bins are used.

- Q^2- 7 bins(1.-4.5GeV^2)
- x_B- 7 bins(0.1-0.58)
- t - 8 bins(0.09-2.0GeV)
- ϕ - 20 bins(0-360°)
- π^0 data ~2000 points
- η data ~1000 points



Monte Carlo

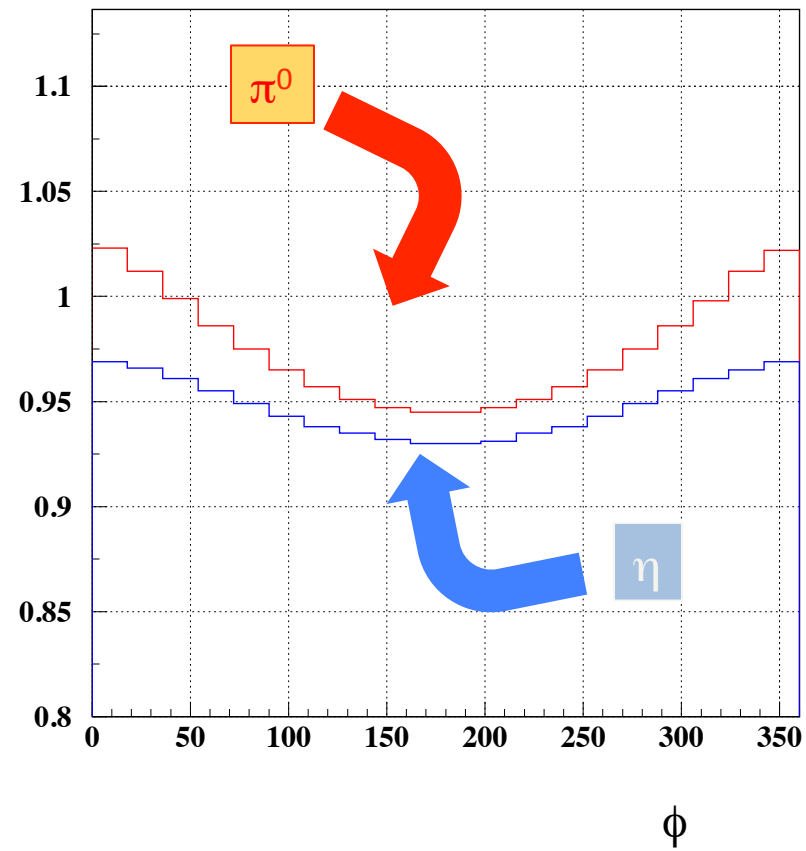
- Empirical model for the structure cross sections was used for the MC simulation and radiative corrections
- This model is based on CLAS data
- MC simulation included the radiative effects and used empirical model for the Born term.
- 100 M events were simulated with GSIM program.

Radiative Corrections

- Radiative Corrections were calculated using Exclurad package with structure cross sections described by our empirical cross section.

$Q^2 = 1.15\ GeV^2\ x_B = 0.13\ -t = 0.1\ GeV^2$

$$RadCor = \frac{\sigma_{Rad}}{\sigma_{Born}}$$

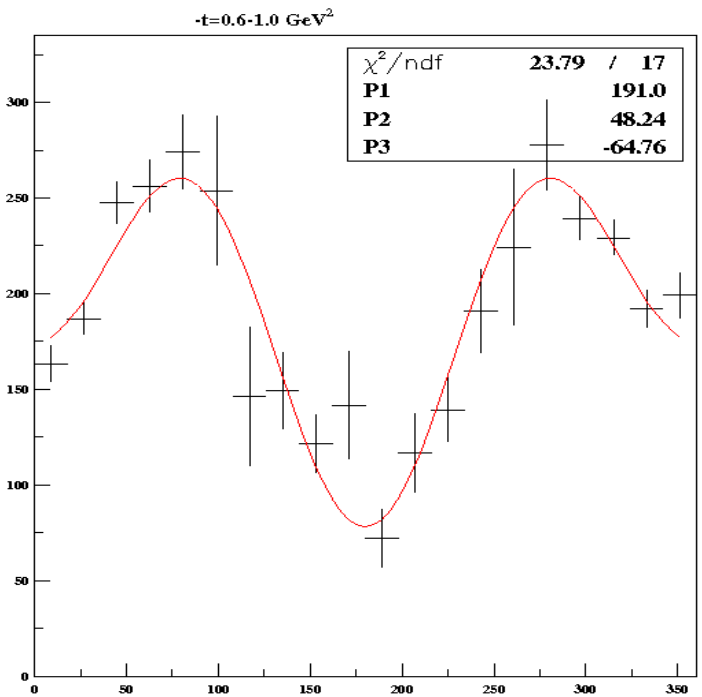


Structure Functions

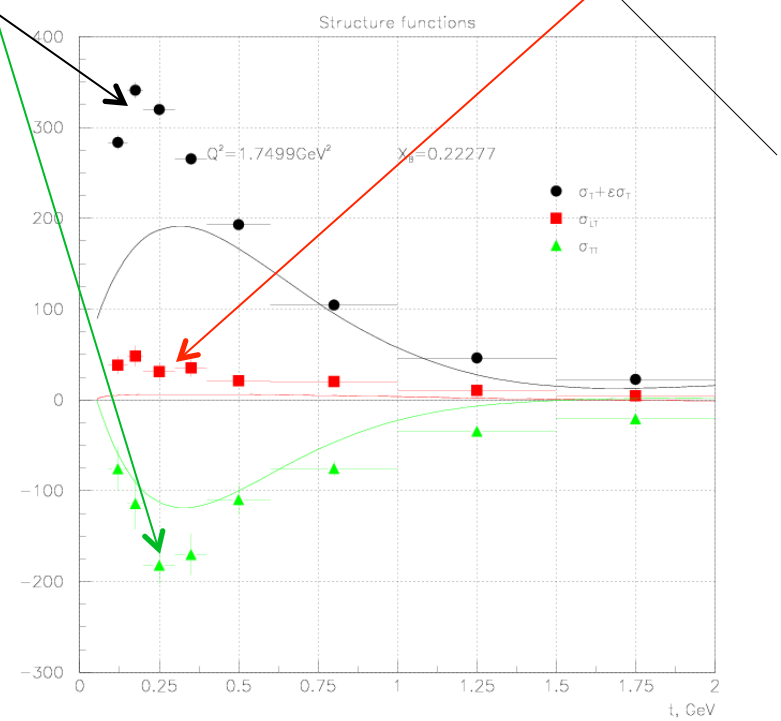
$\sigma_T+\varepsilon\sigma_L \quad \sigma_{TT} \quad \sigma_{LT}$

$$\gamma^* p \rightarrow p\pi^0$$

$$\frac{d\sigma}{dtd\phi}(Q^2,x,t,\phi) = \frac{1}{2\pi}\left(\frac{d\sigma_T}{dt} + \varepsilon\frac{d\sigma_L}{dt} + \varepsilon\frac{d\sigma_{TT}}{dt}\cos 2\phi + \sqrt{2\varepsilon(\varepsilon+1)}\frac{d\sigma_{LT}}{dt}\cos\phi\right)$$



ϕ distribution



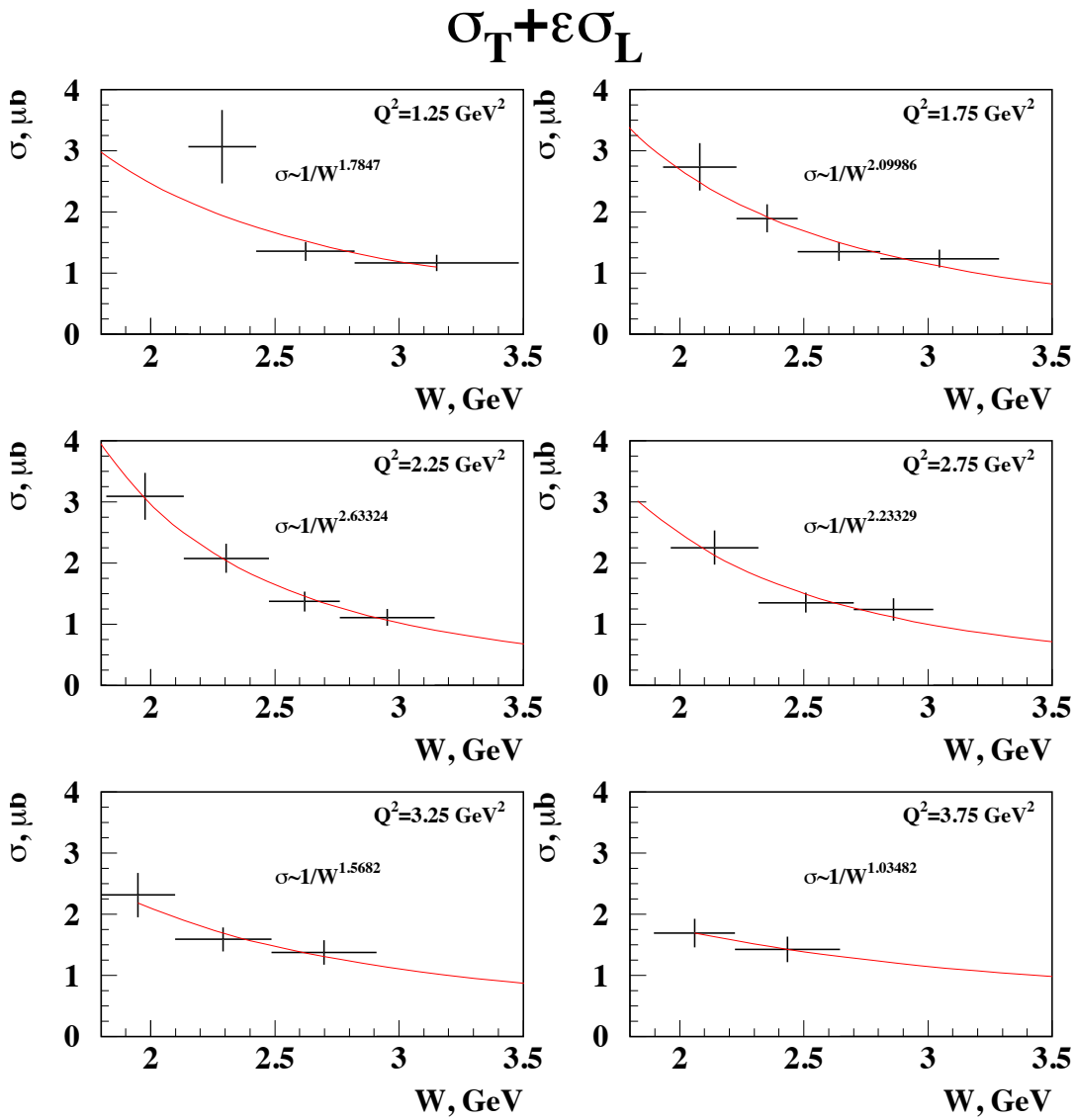
-t

GM Laget Regge model

$\sigma_U=\sigma_T+\varepsilon\sigma_L$ W dependence

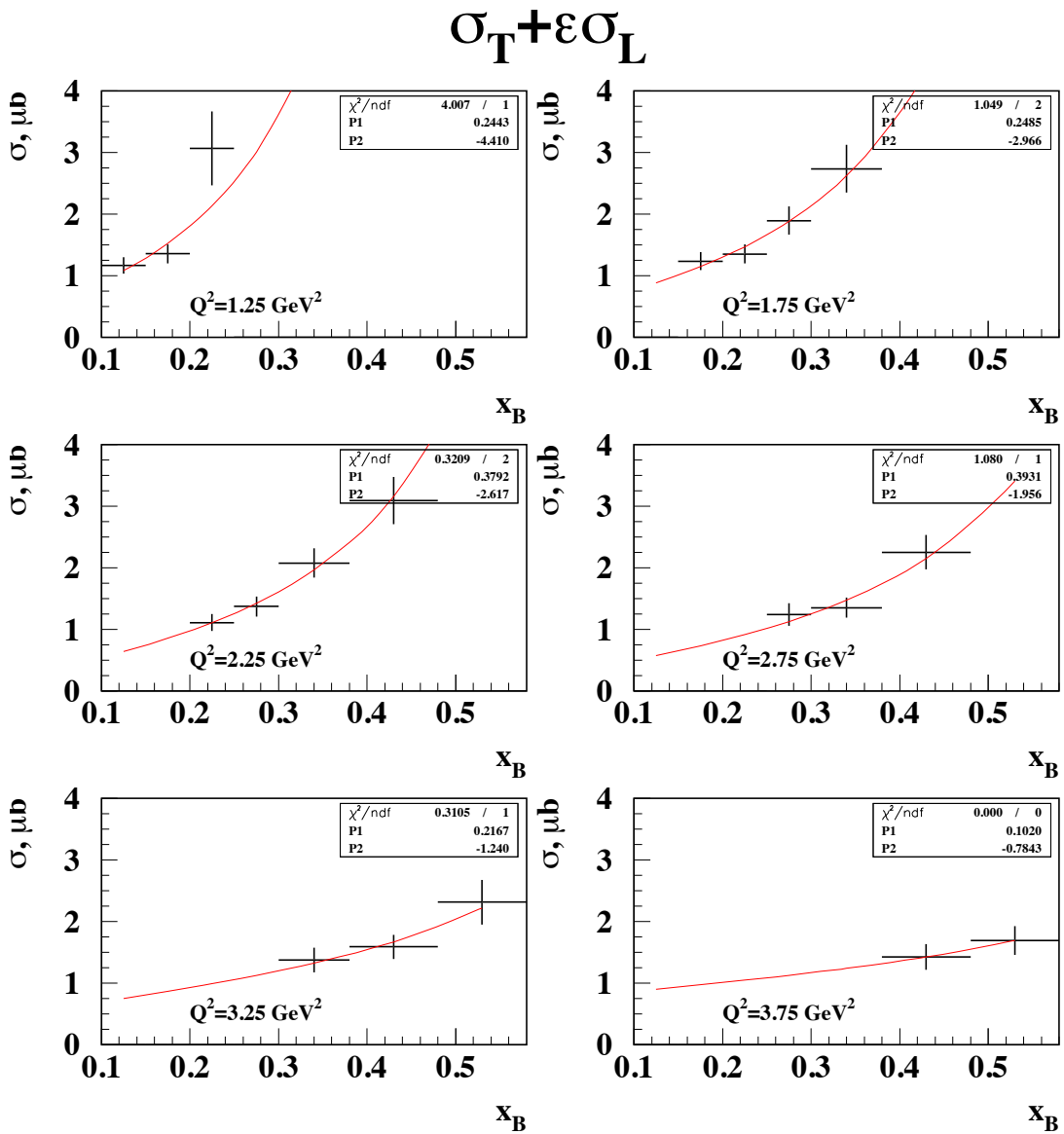
- σ_U decreases with W at Jlab kinematics
- This behavior is typical for Regge model
- Difficult to get such dependence with conventional GPD models

$$\sigma_U \sim 1/W^{1.5\text{-}2}$$



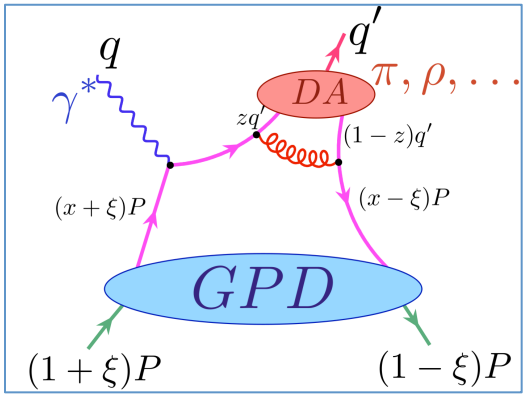
$\sigma_U=\sigma_T+\varepsilon\sigma_L$ x_B dependence

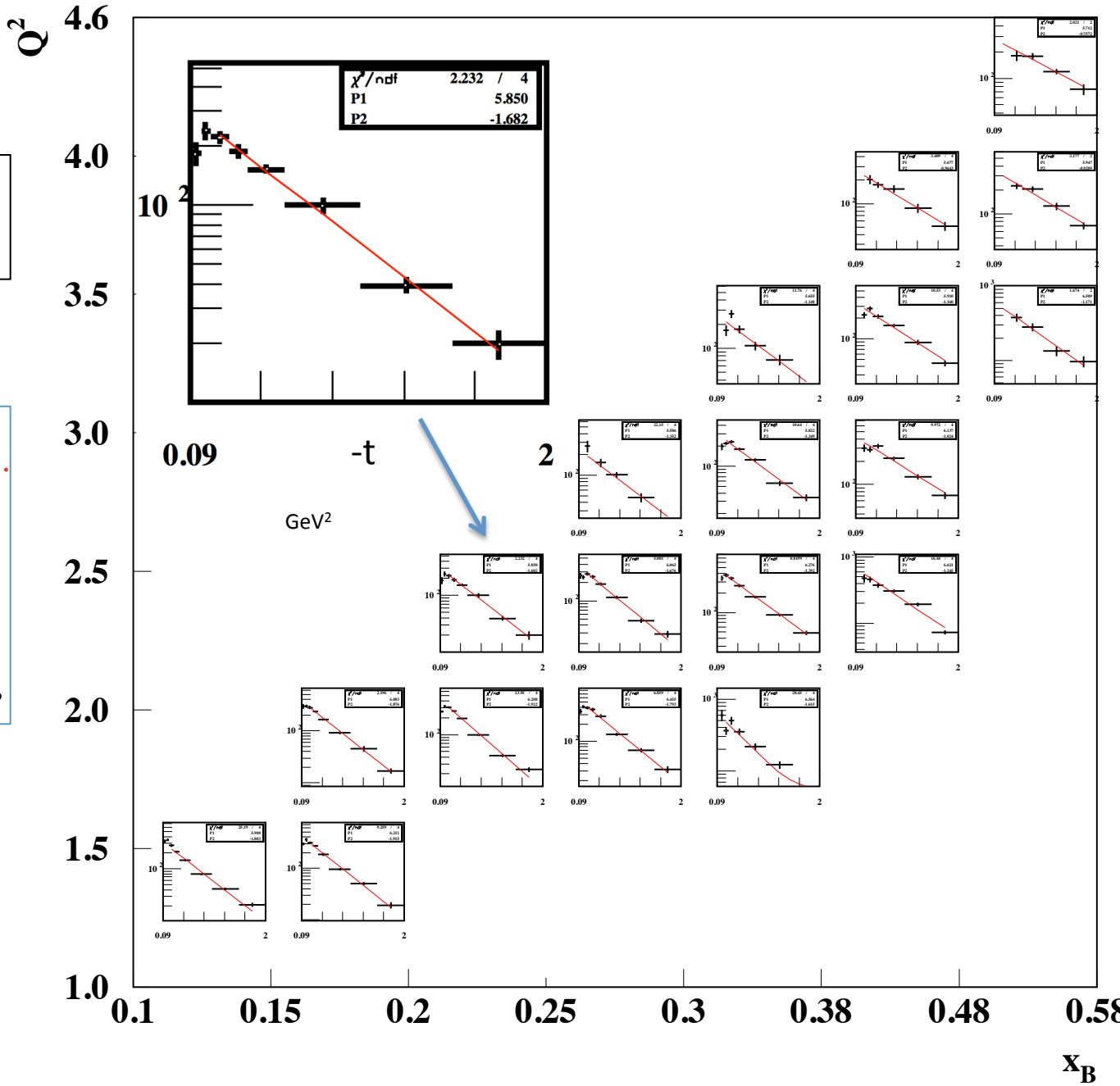
- Another way to view the cross section as a function of x_B
- σ_U increases with x_B
- $W=Q^2(1/x-1)$



$d\sigma_U/dt$

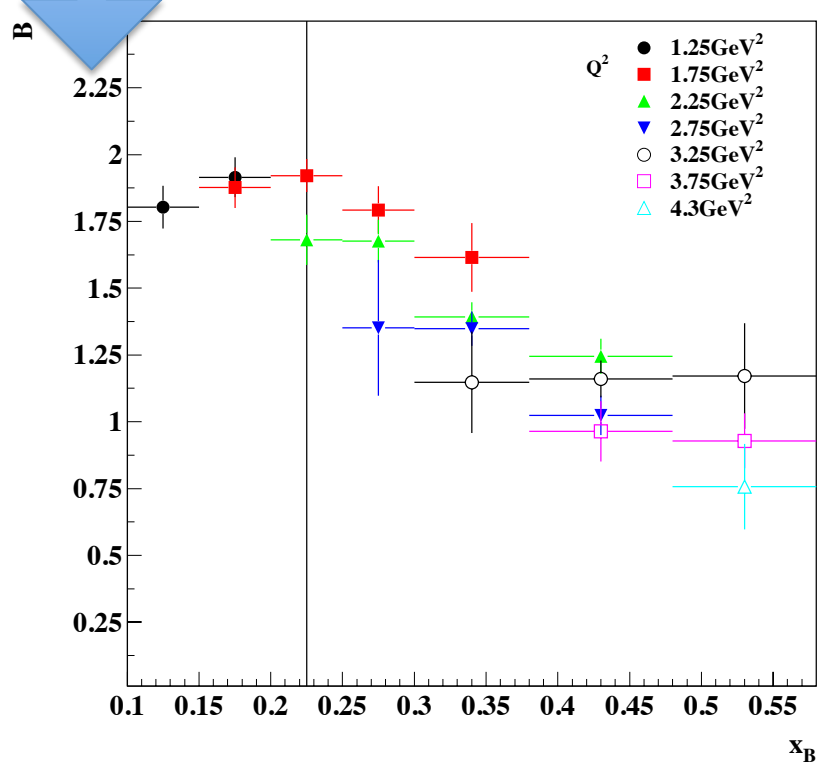
$$\frac{d\sigma}{dt}(\gamma^* p \to ep\pi^0) \propto e^{bt}$$





t-slope parameter: x_B dependence

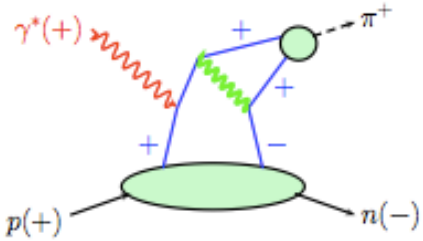
$$\frac{d\sigma}{dt} \propto e^{bt}$$



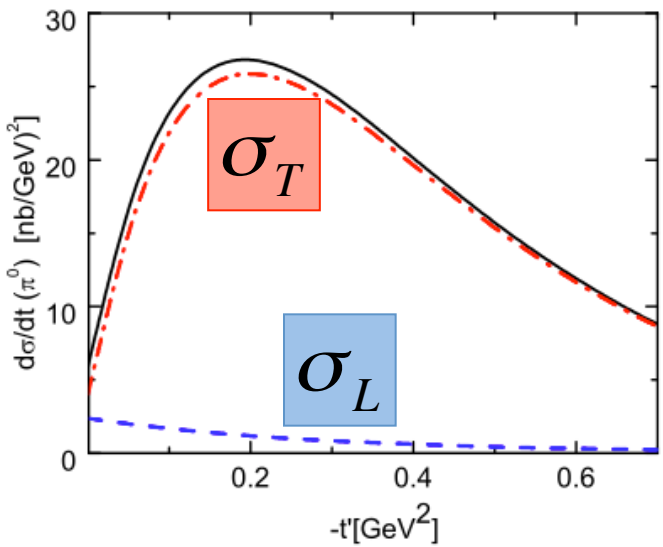
The slope parameter is decreasing with increasing x_B. Looking to this picture we can say that the perp width of the partons with $x \rightarrow 1$ goes to zero.

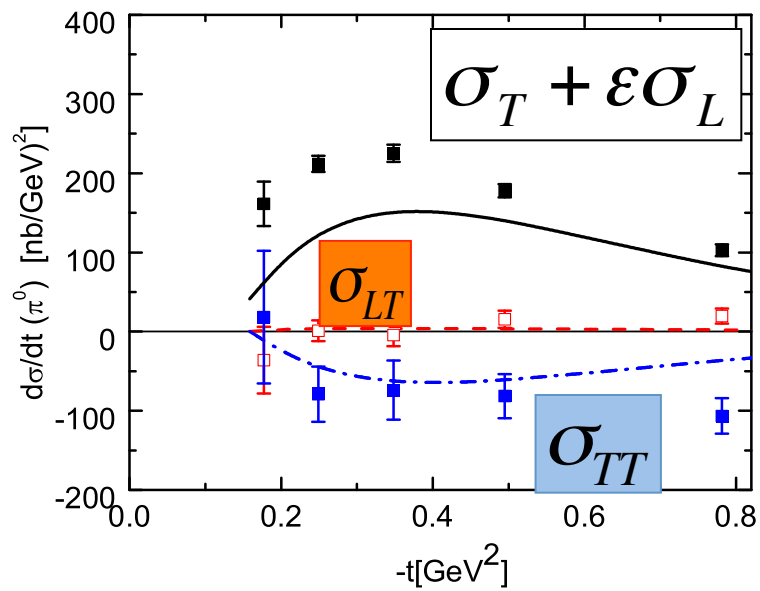
Transversity in π^0 electroproduction

S. Goloskokov, P. Kroll, 2011, **arXiv:1106.4897v1**



Q^2=2.71 GeV^2
x_B=0.34





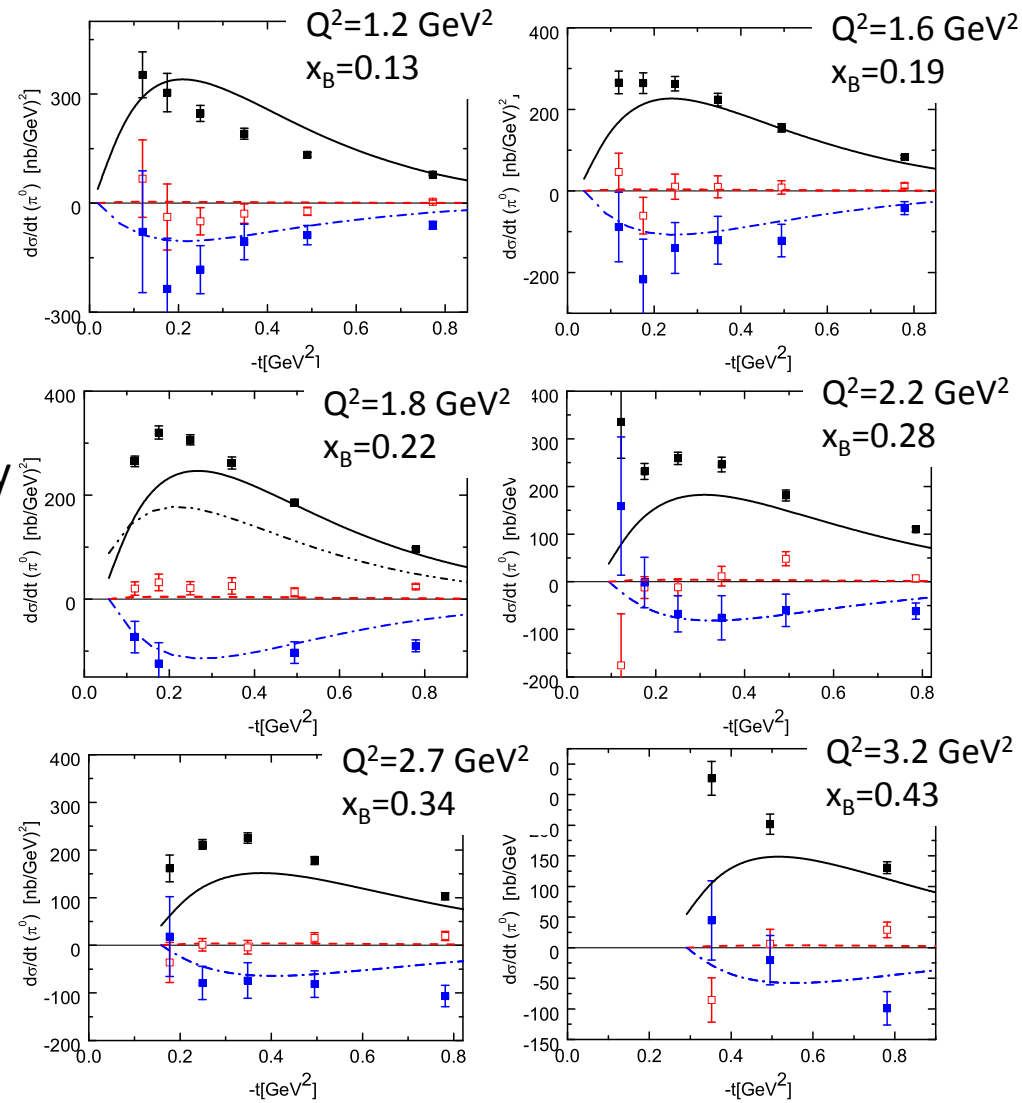
Transvers cross section dominates in this model

Theory: Goloskokov&Kroll
Data: CLAS (preliminary)

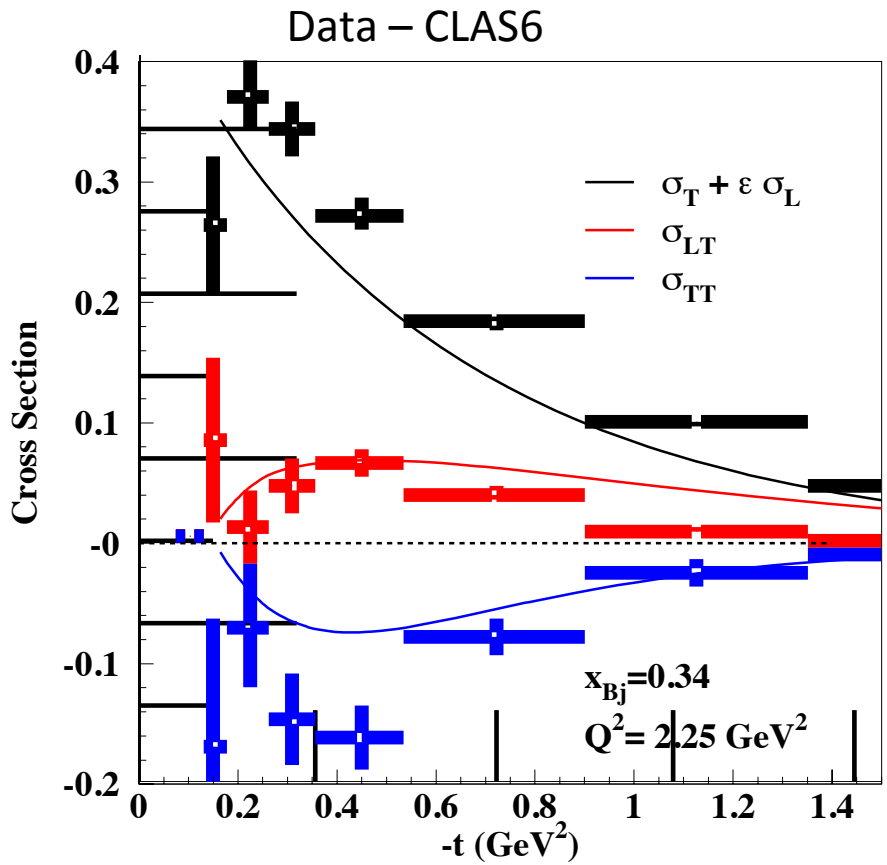
Transversity in π^0 electroproduction

S. Goloskokov, P. Kroll, 2011, **arXiv:1106.4897v1**

- Include ***transversity*** **GPDs** H_T and $\bar{E}_T = 2\tilde{H}_T + E_T$ Dominate in CLAS kinematics.
- The model was optimized for low x_B and high Q^2. The corrections t/Q^2 were omitted
- Nevertheless the model successfully described CLAS data even at low Q^2
- Pseudoscalar meson production <u>provides unique possibility to access the transversity GPDs.</u>



Goldstein and Liuti GPD_T model



We are looking forward to extend the comparison with GPD-based model in the full kinematic domain of CLAS

$$\gamma^* p \rightarrow p\pi^0$$

Beam Spin Asymmetry

Ahmad, Goldstein, Luiti, 2009

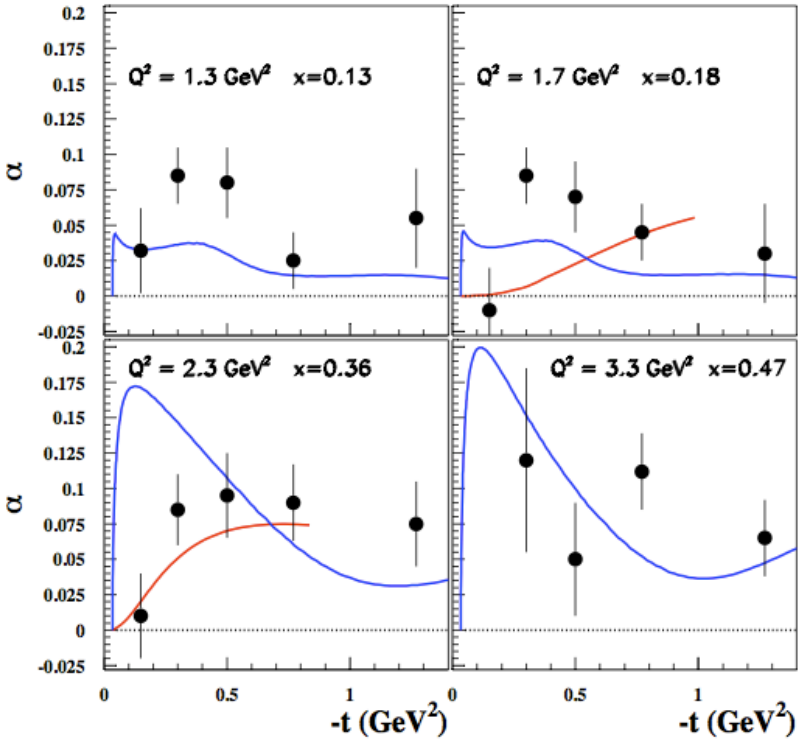
- Data CLAS
- Blue – Regge model
- Red – GPD predictions
- tensor charges

  δu=0.48,

  δd =-0.62
- transverse anomalous magnetic moments

  κ^u_T = 0.6,

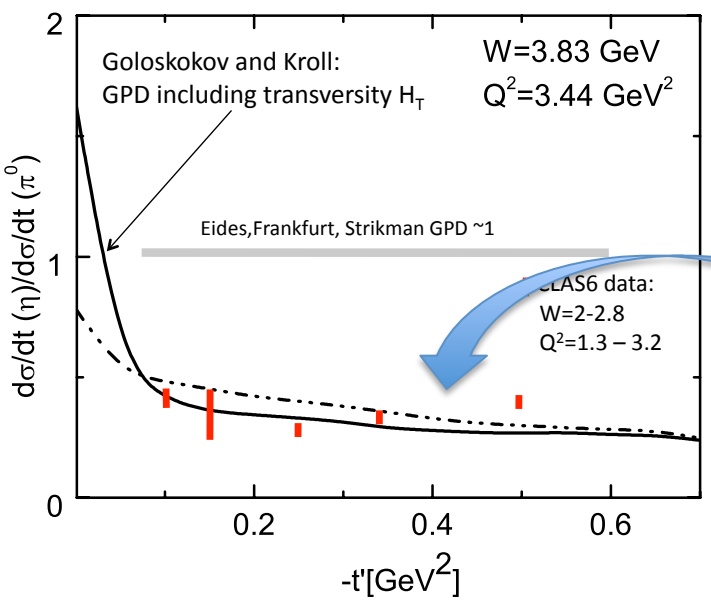
  κ^d_T = 0.3.

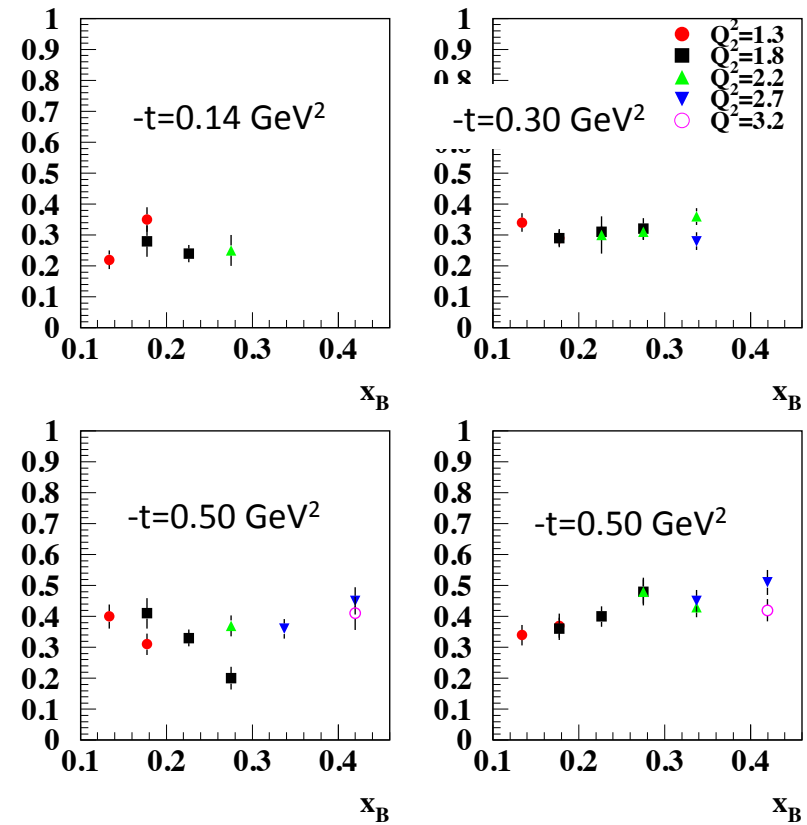


η/π^0 Ratio

$$\frac{\sigma(ep \to ep\eta)}{\sigma(ep \to ep\pi^0)}$$

- The dependence on the x_B and Q^2 is very week.
- The ratio in the photoproduction is near 0.2-0.3 (very close to what we have at our smallest Q^2).
- Conventional GPD models predict this ratio to be around 1 (at low –t).
- KG model predicts this ratio to be ~1/3 at CLAS values of t





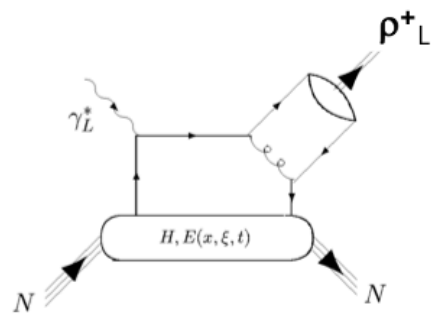
$$\bar{E}_T = 2\tilde{H}_T + E_T$$

Data: CLAS preliminary

Indication of large contributions from the GPD $\bar{E}_T$ with the same sign for u and d-quark parts

Vector Mesons
Quark and Gluon GPDs

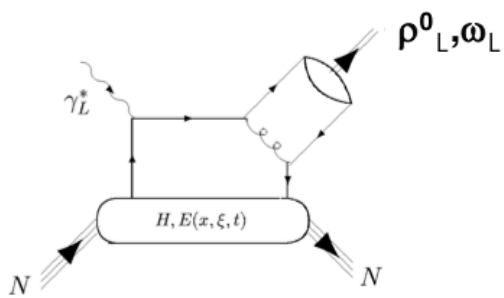
$\gamma^* p \rightarrow n\rho^+$



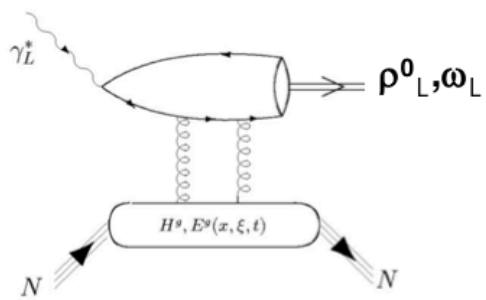
ρ^0	$e_u H^u - e_d H^d$ $e_u E^u - e_d E^d$
ω	$e_u H^u + e_d H^d$ $e_u E^u + e_d E^d$
ρ^+	$H^u - H^d$ $E^u - E^d$

$\gamma^* p \rightarrow p\rho^0$

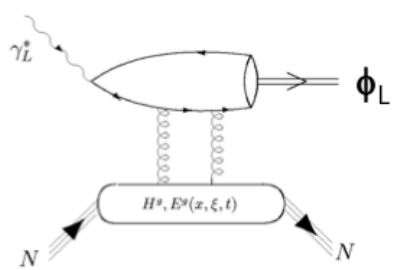
$\gamma^* p \rightarrow p\omega$



+

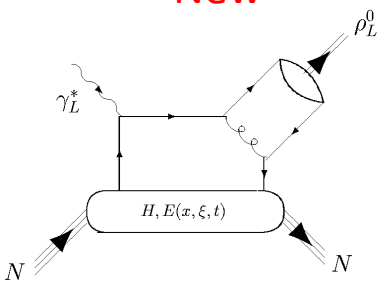


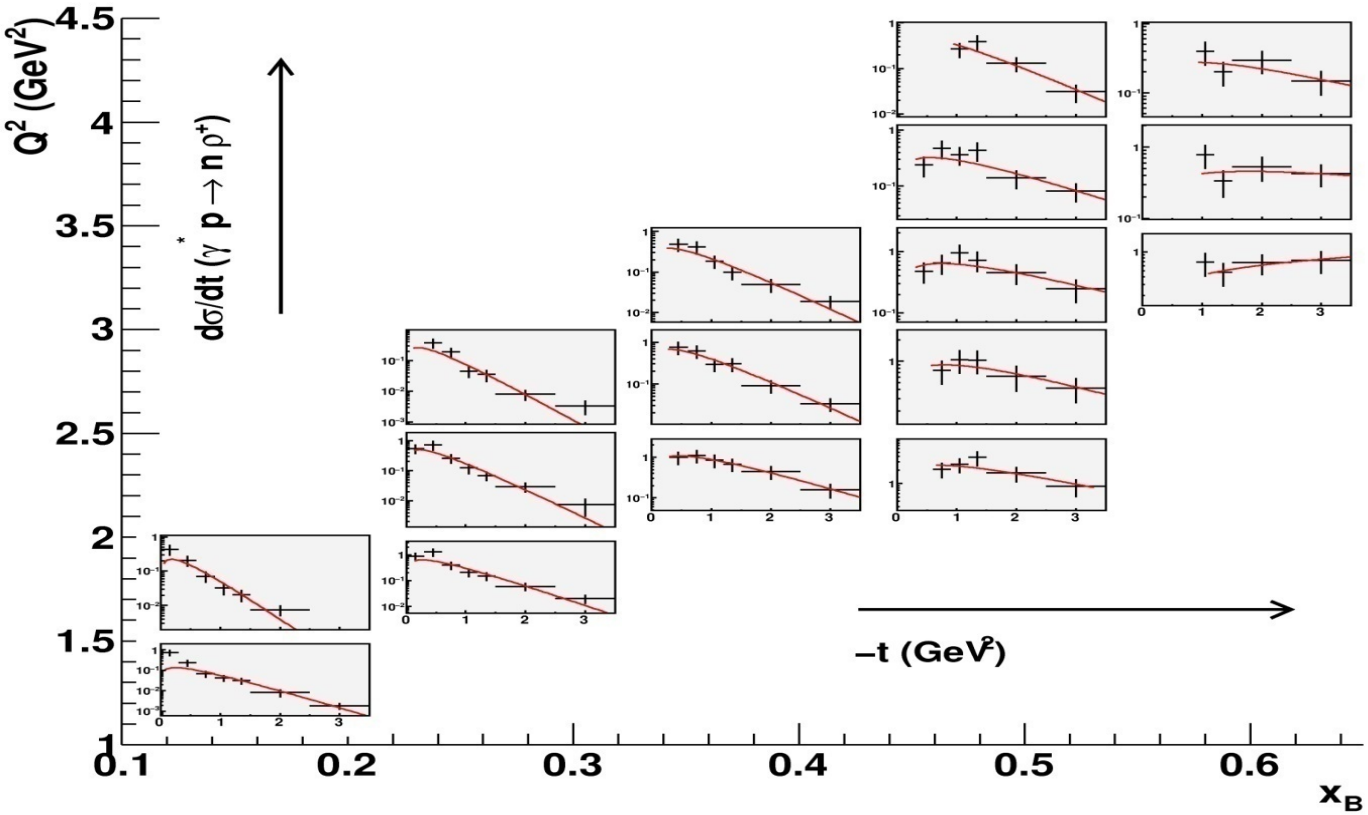
$\gamma^* p \rightarrow p\phi$



$$\frac{d\sigma}{dt}(\gamma^* p \rightarrow en\rho^+) \propto \sqrt{-t}e^{bt}$$

New



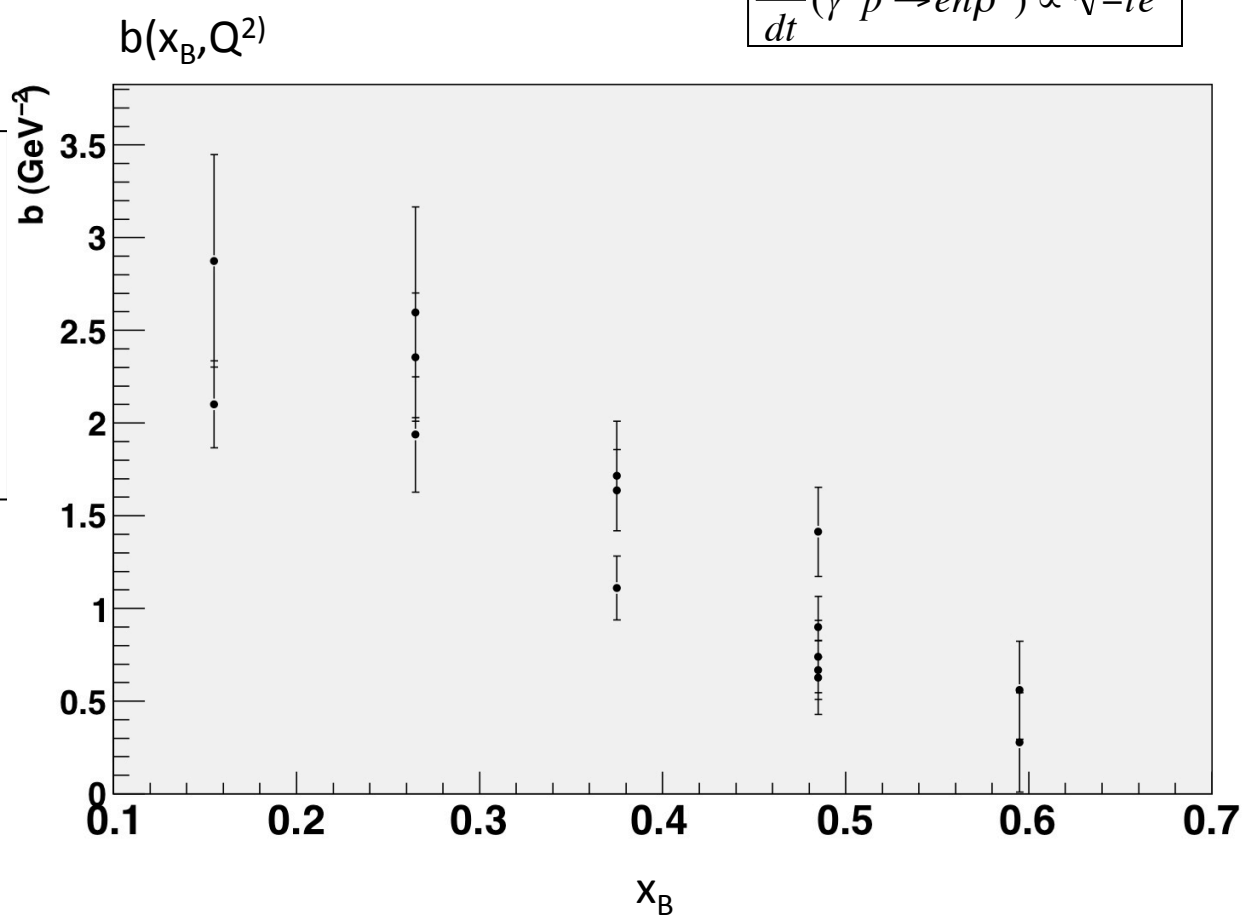


CLAS data. The first measurement of the ρ^+ exclusive electroproduction

ρ^+ t-slope parameter

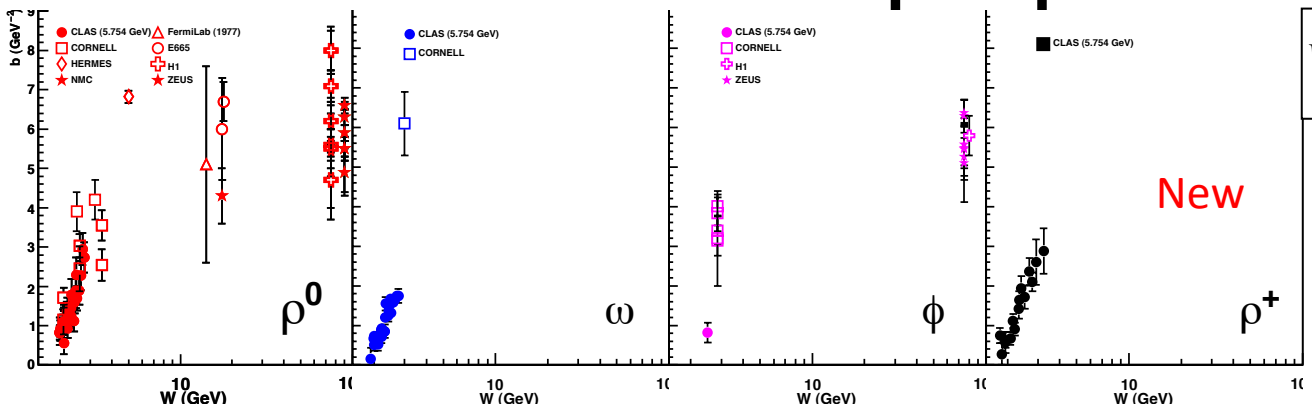
$$\frac{d\sigma}{dt}(\gamma^* p \rightarrow en\rho^+) \propto \sqrt{-t}e^{bt}$$

Slope parameter is decreasing with x_B. This indicates that the size of the interaction region decreases as $x_B \rightarrow 1$

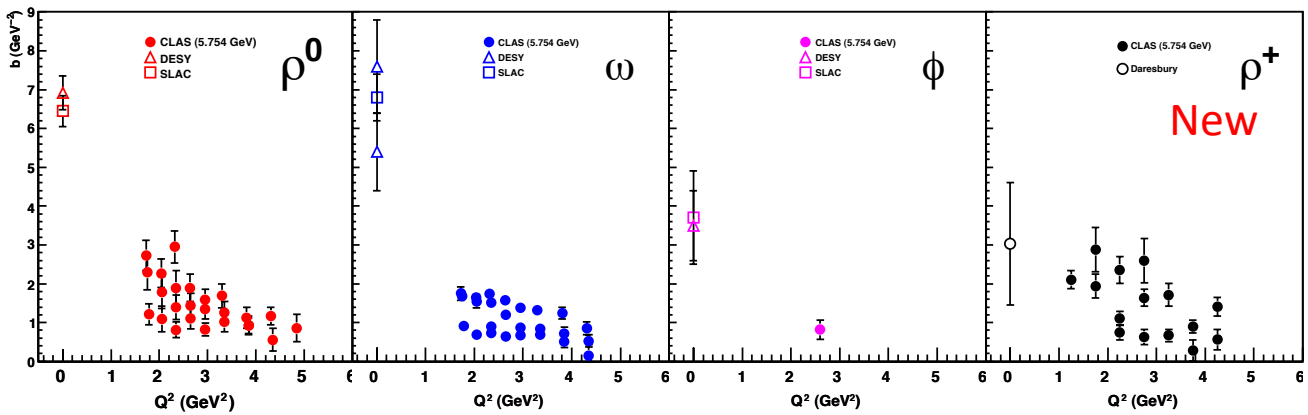


Vector mesons t-slope parameter

$$W^2 = Q^2\left(\frac{1}{x_B} - 1\right) + m_N^2$$



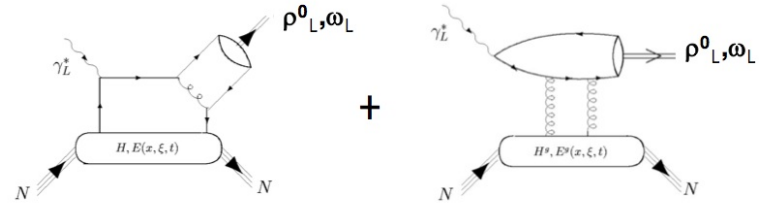
W



Q^2

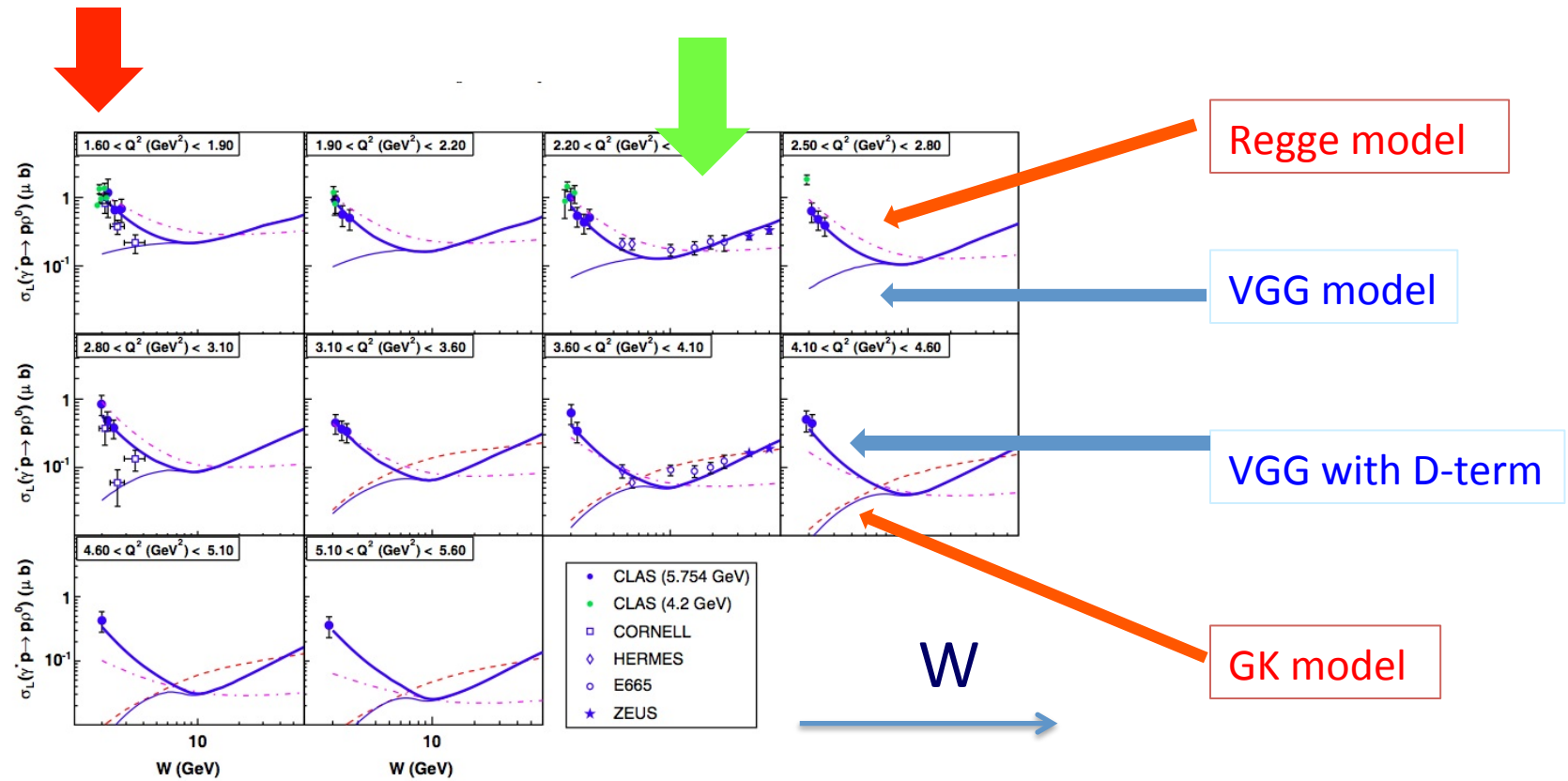
- b increases with W : the size of the nucleon increases as one probes the high W values (i.e. the sea quarks). Sea quarks tend to extend to the periphery of the nucleon.

$$\gamma_L^* p \rightarrow p\rho^0$$



Fails to describe data W<5 GeV

Describes well for W>5 GeV



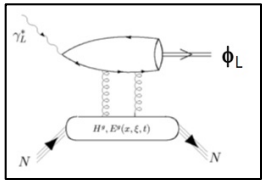
- Popular GK and VGG models can not provide the right W-dependence of the cross-section
- This does not mean that we can't access GPD in vector meson electroproduction
- For example, model with the addition of q-qbar exchange (M.Guidal) together with standard VGG model successfully describes data

$$\gamma_L^* p \to p\phi$$

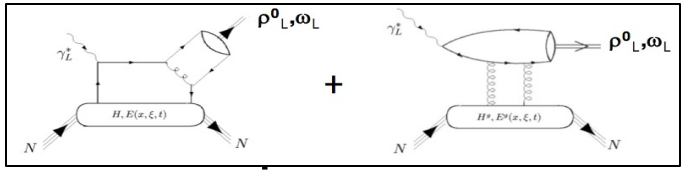
ϕ and ρ^0

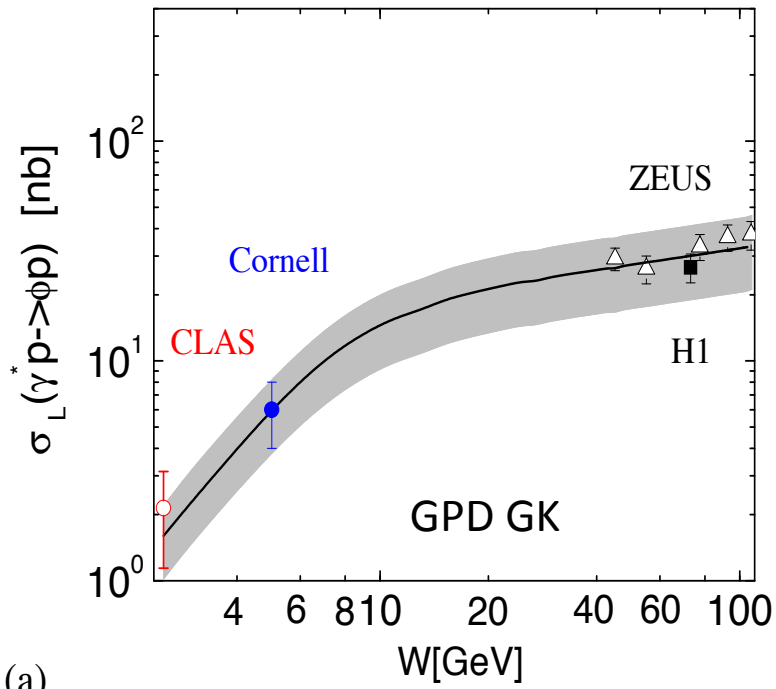
Goloskokov, Kroll

$$\gamma_L^* p \to p\rho^0$$

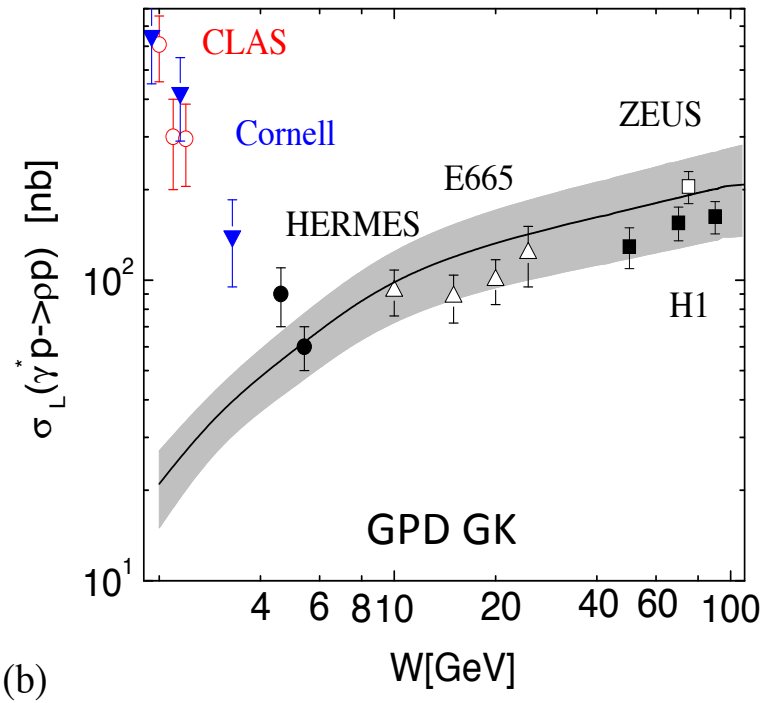


ϕ





(a)



(b)

- ϕ mesons - gluon GPD are dominant
- ρ^0 and ω – sea quarks and/or gluons dominant.

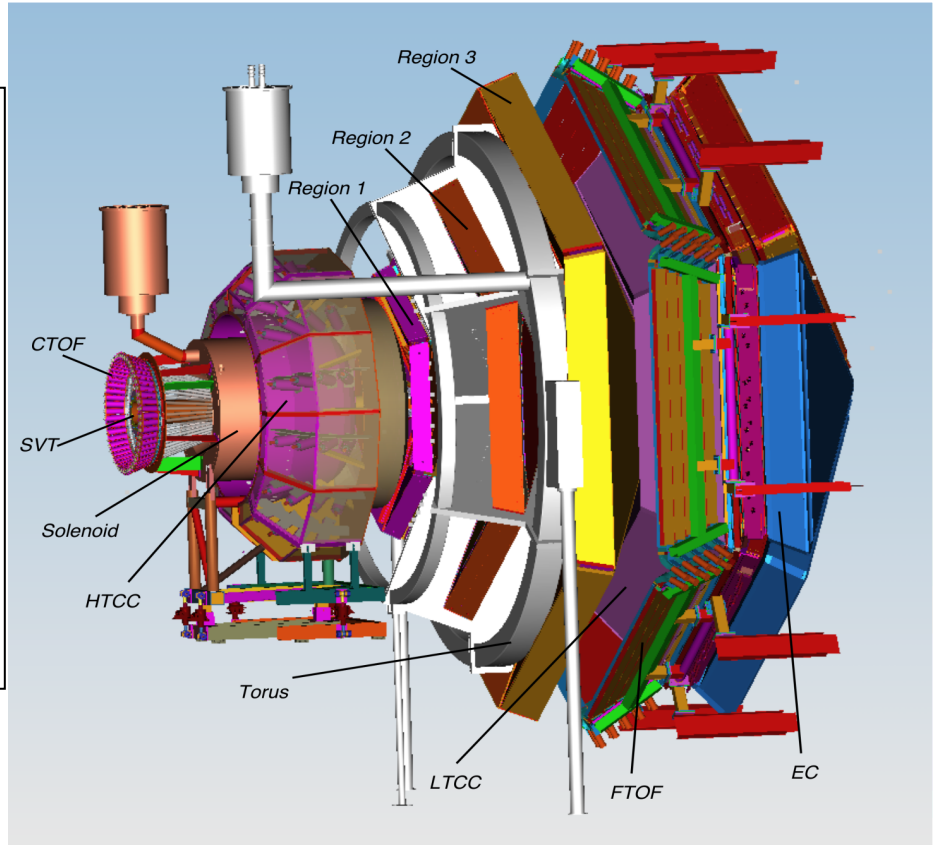
GPD approach describes well data for W>5 GeV

Hall B 12GeV upgrade overview from *CLAS* to *CLAS12*

CLAS will be replaced with *CLAS12*

CLAS12 is designed to operate with order of magnitude higher luminosity.

CLAS12 designed to accommodate polarized solid state targets NH_3, ND_3 and HD.



Jlab Upgrade Program

Deeply Virtual Exclusive Meson Electroproduction

$ep \rightarrow ep\pi^0$	$ep \rightarrow ep\eta$
$ep \rightarrow ep\phi$	$ep \rightarrow ep\rho^0$
$ep \rightarrow ep\omega$	$ep \rightarrow en\rho^+$

Deeply Virtual Compton Scattering

$ep \rightarrow ep\gamma$	$en \rightarrow en\gamma$

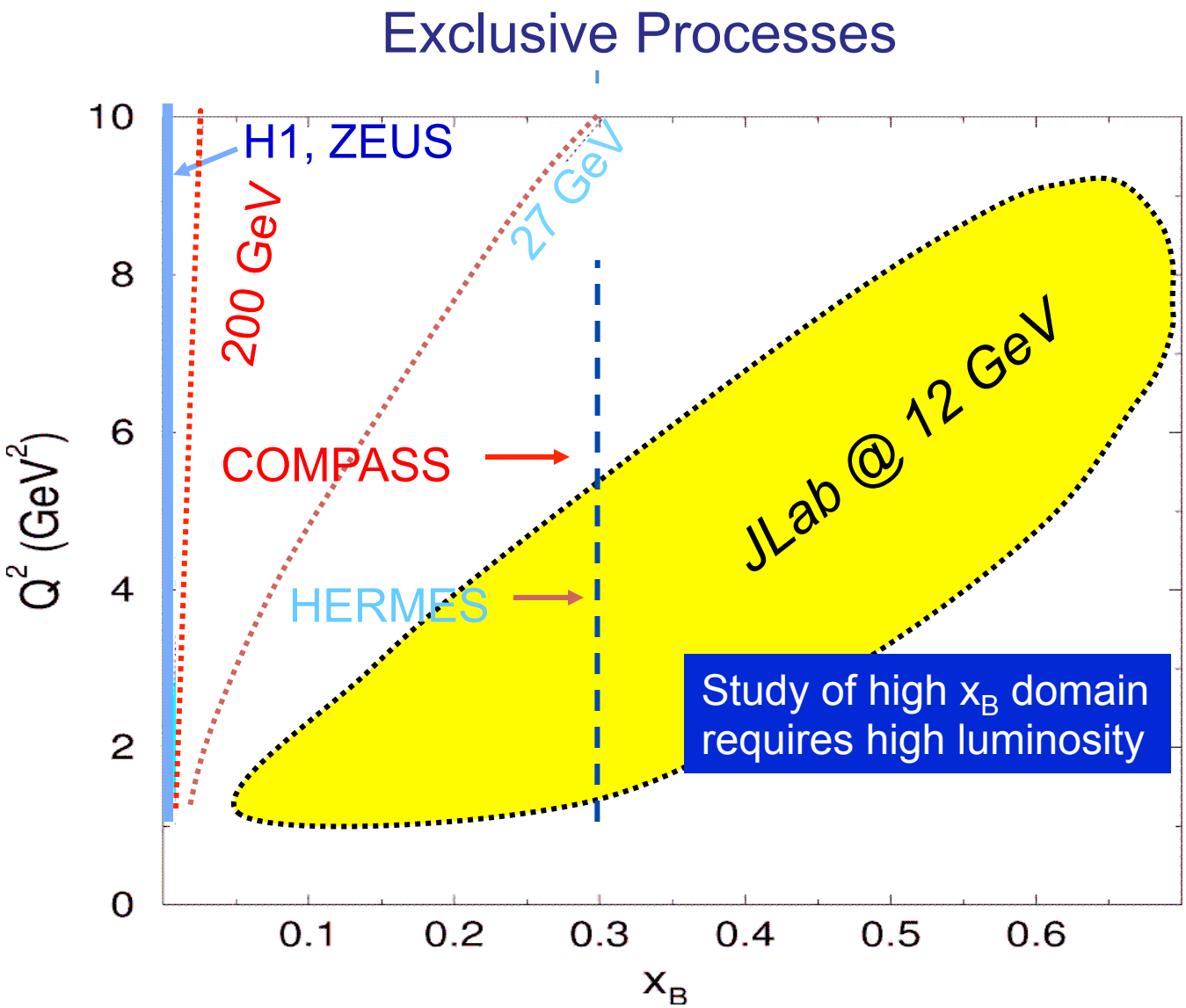
- Kinematics:

  Q^2 from 3 – 10 GeV^2

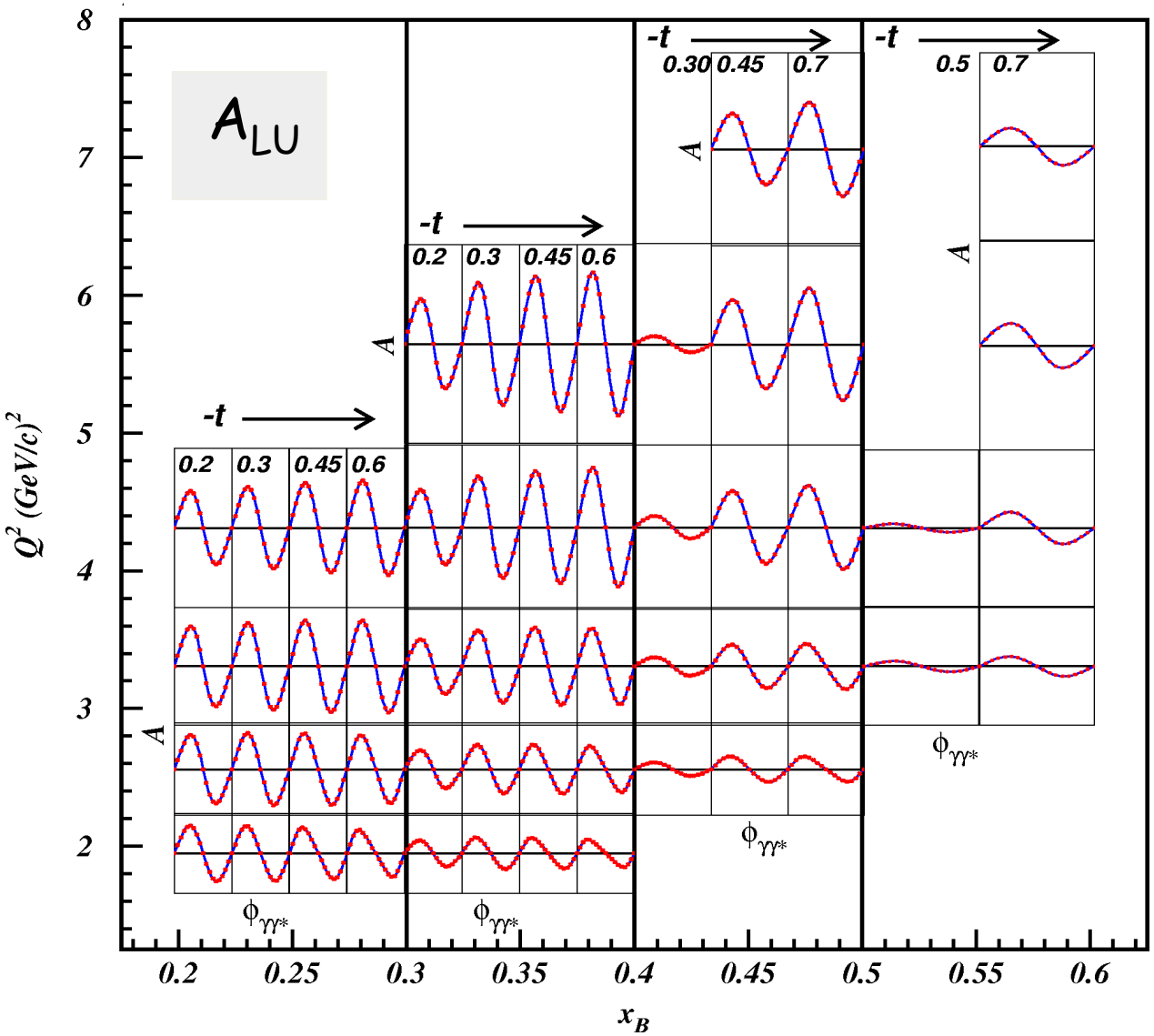
  -*t* from .5 to 10 Gev^2

  W from 2-4 GeV

Kinematic reach of the 12 GeV Upgrade



CLAS12 DVCS/BH- Beam Asymmetry at 12 GeV

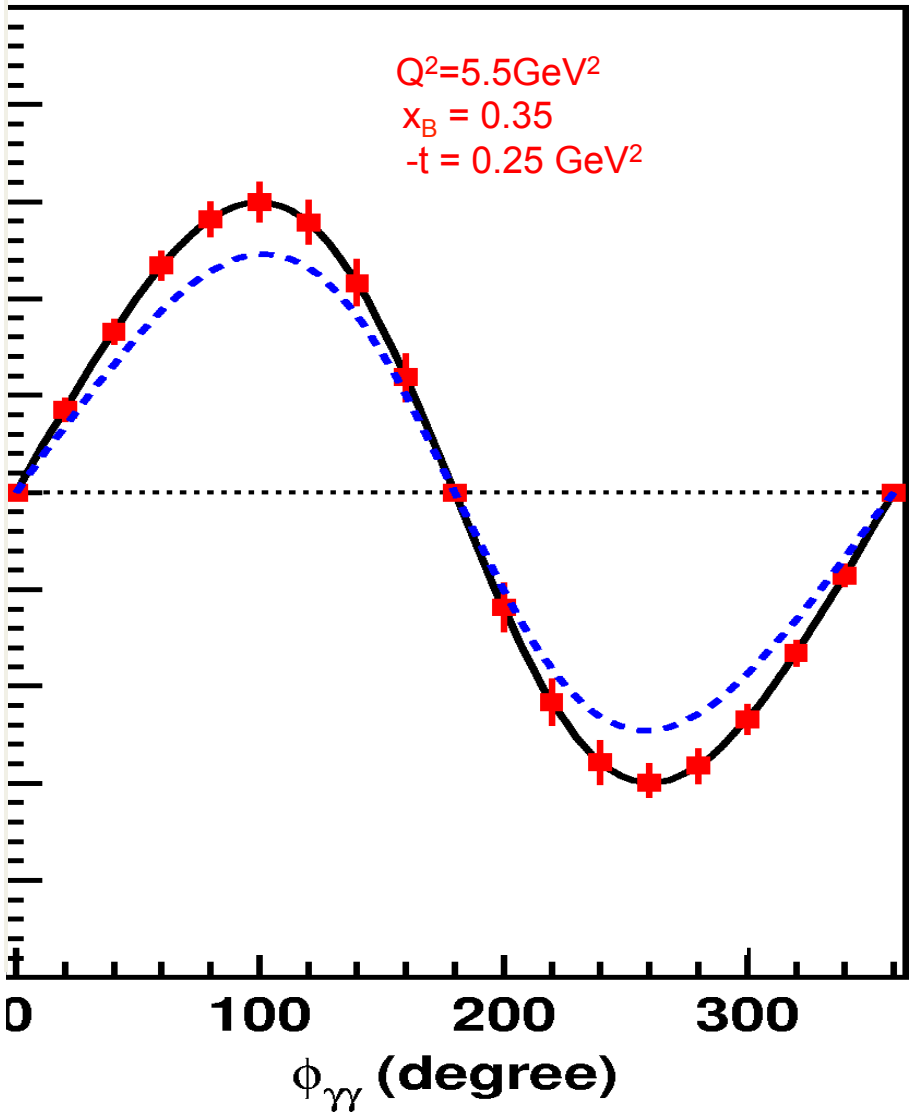


With large acceptance, measure large Q^2, x_B, t ranges simultaneously.

$A(Q^2,x_B,t)$
$\Delta\sigma(Q^2,x_B,t)$
$\sigma(Q^2,x_B,t)$

CLAS12 - DVCS/BH- Beam Asymmetry

Luminosity = 720fb^{-1}



CLAS12 - DVCS/BH Beam Asymmetry

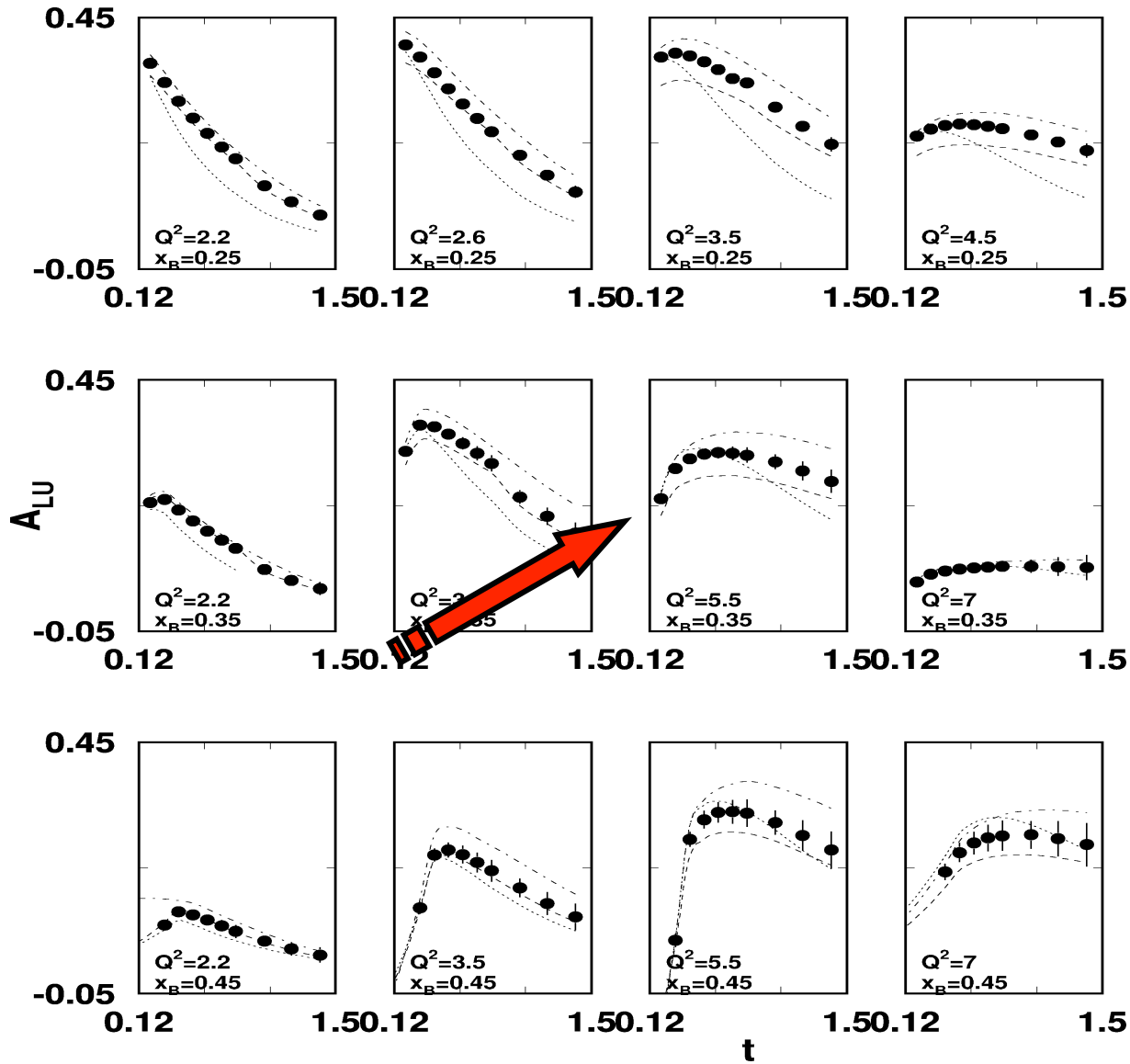
$\vec{e}\,p \longrightarrow ep\gamma$

E = 11 GeV

$\Delta\sigma_{LU} \sim \sin\phi\, \mathrm{Im}\{F_1 H + .\}d\phi$

Selected Kinematics

$L = 1\times10^{35}$
$T = 2000$ hrs
$\Delta Q^2 = 1\ \mathrm{GeV}^2$
$\Delta x = 0.05$



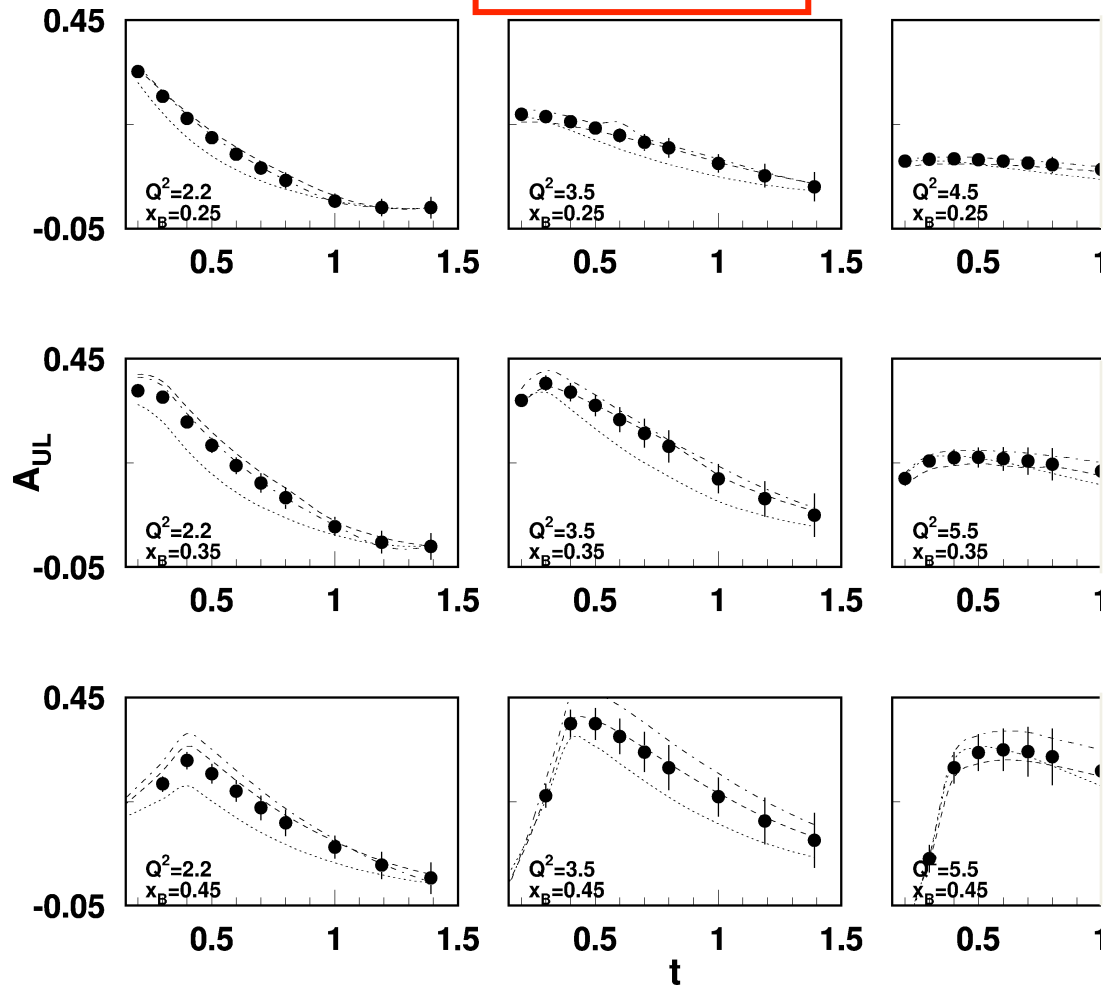
CLAS12 - DVCS/BH Longitudinal Target Asymmetry

E = 11 GeV

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

$$\Delta\sigma \sim \sin\phi\, \mathrm{Im}\{F_1 \tilde{H} + \xi(F_1+F_2)H \ldots\} d\phi$$

$L = 2\times10^{35}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$
$T = 1000$ hrs
$\Delta Q^2 = 1\mathrm{GeV}^2$
$\Delta x = 0.05$



CLAS12 - DVCS/BH Transverse Target Asymmetry

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

E = 11 GeV

Sample kinematics

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

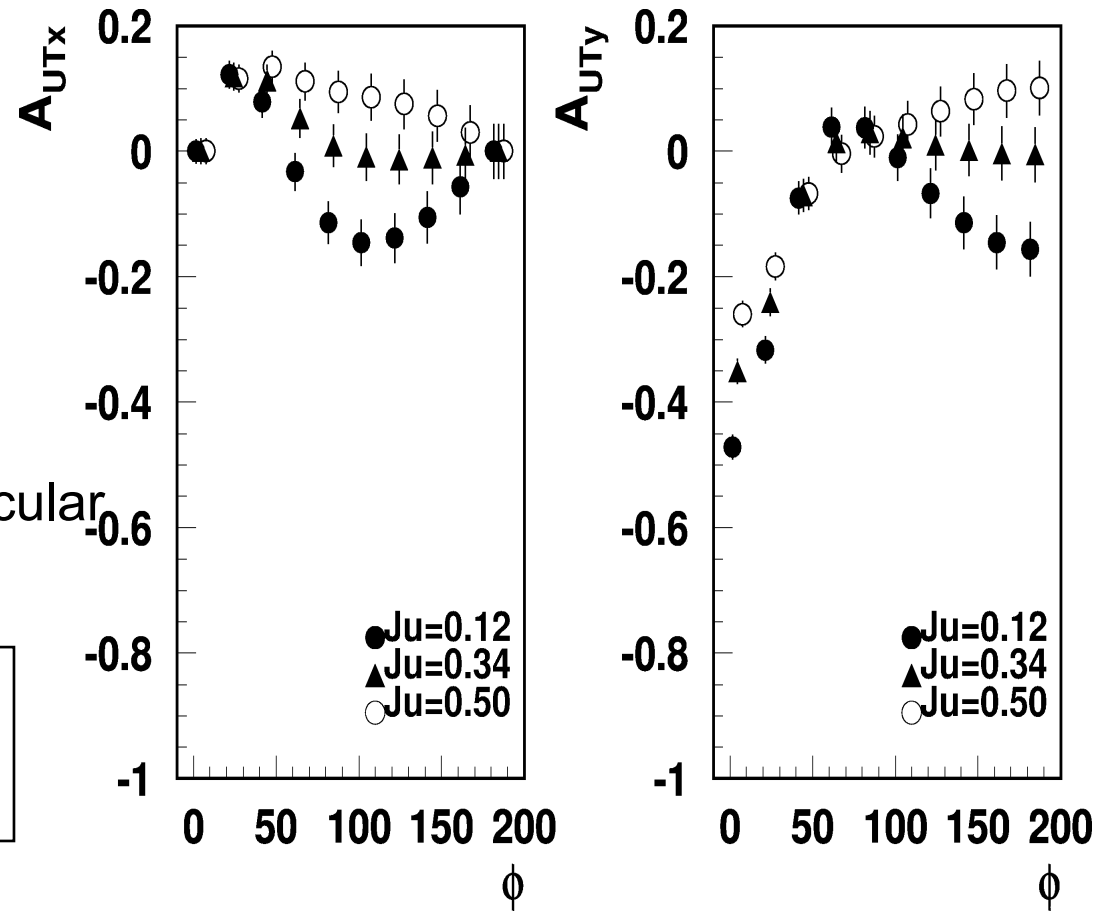
Transverse polarized target

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

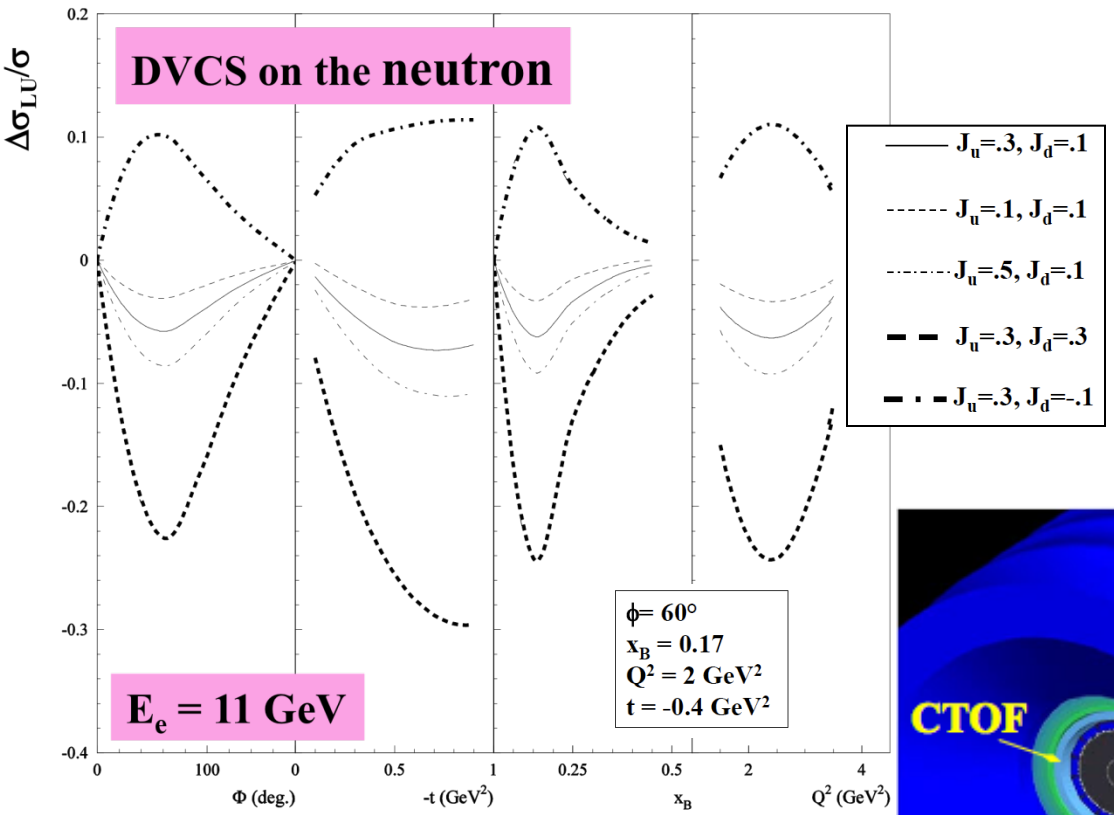
A_{UTx} Target polarization in the scattering plane

A_{UTy} Target polarization perpendicular to the scattering plane

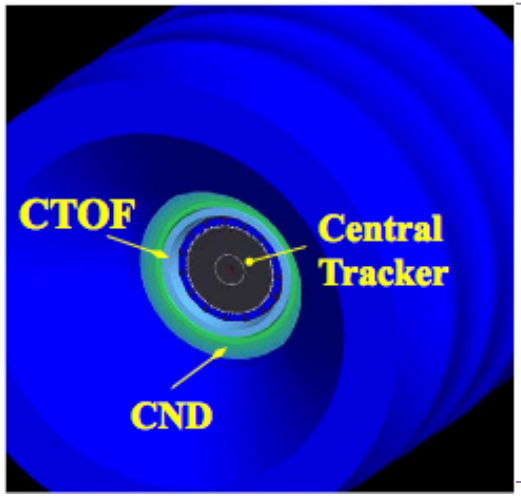
Asymmetries highly sensitive to the u-quark contributions to the proton spin.

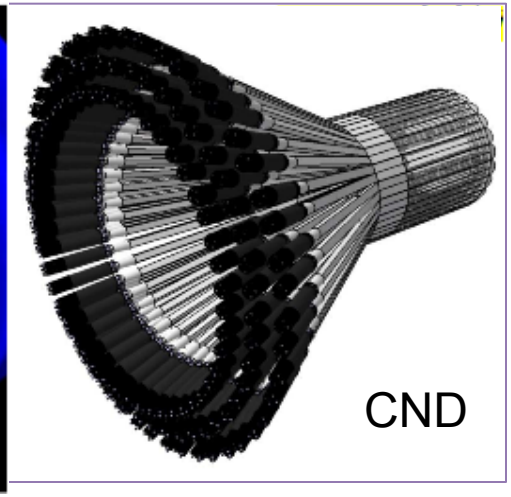


CLAS12 – DVCS/BH beam spin asymmetry on neutrons



This program requires adding a Central Neutron Detector (CDN) to the CLAS12 base equipment.





DVCS on neutrons is sensitive to GPD E^n and the d-quark content of the nucleon spin.

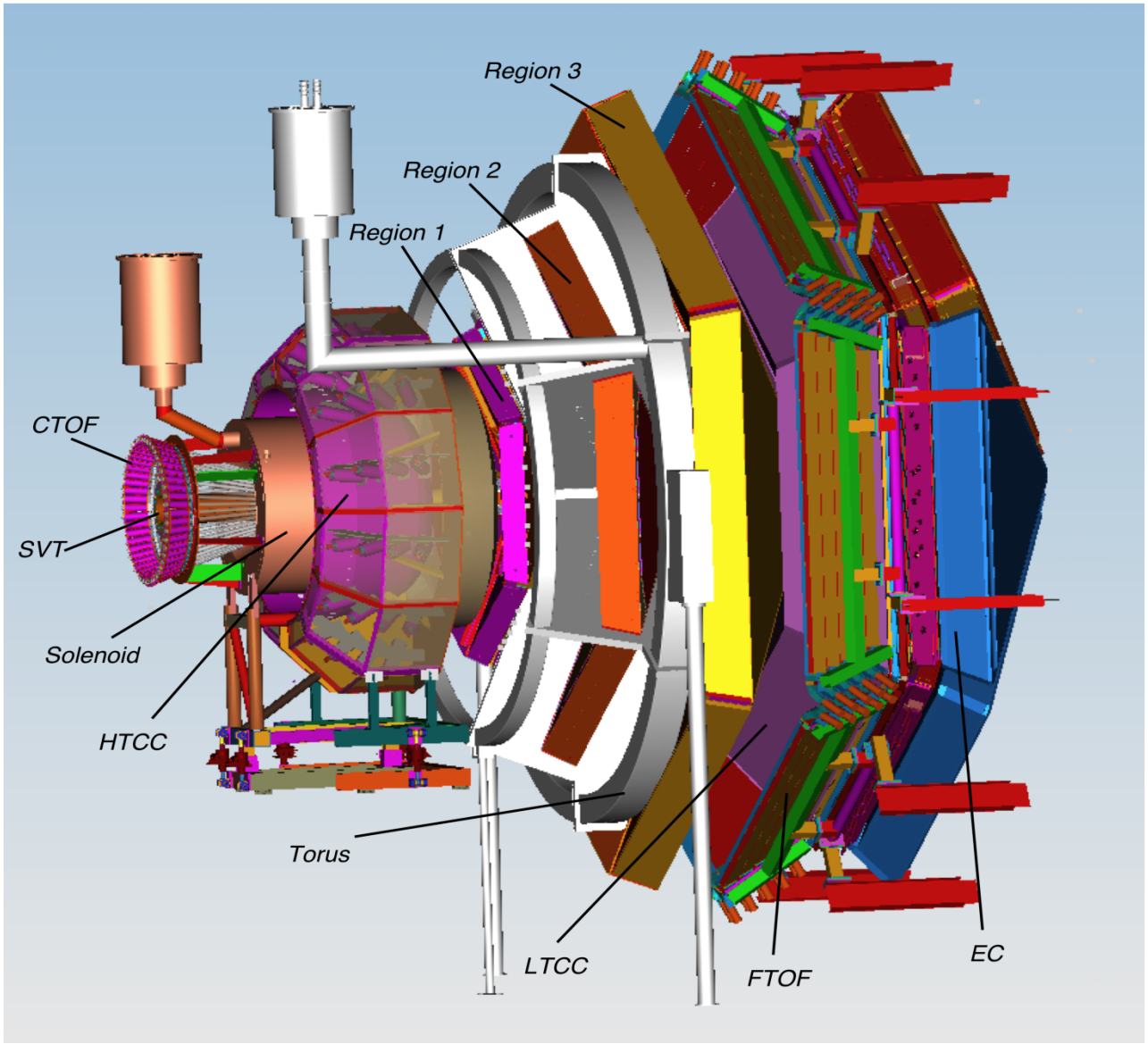
European Initiative led by: Orsay University

CLAS12

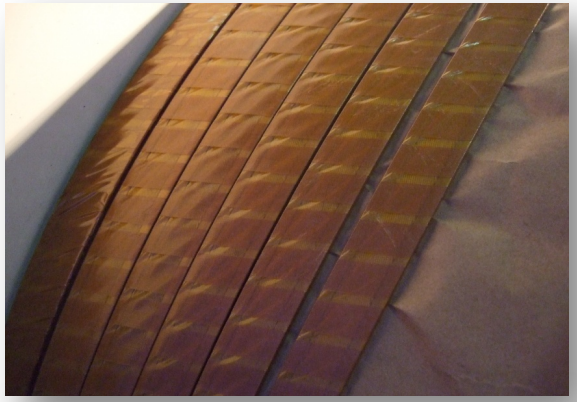
Forward Detector:
- TORUS magnet
- Forward SVT tracker
- HT Cherenkov Counter
- Drift chamber system
- LT Cherenkov Counter
- Forward ToF System
- Preshower calorimeter
- E.M. calorimeter

Central Detector:
- SOLENOID magnet
- Barrel Silicon Tracker
- Central Time-of-Flight
-Polarized target (NSF)

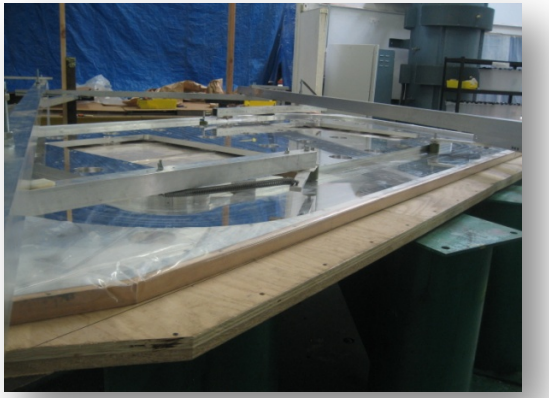
Proposed upgrades:
- Micromegas (CD)
- Neutron detector (CD)
- RICH detector (FD)
- Forward Tagger (FD)



CLAS12 in construction - examples



1. Super Conducting Magnets
   - Conductor ready
   - Torus Coil case being prepared for coil winding



2. Silicon Vertex Tracker
   - Testing of the readout chip
   - Sensor testing

3. Forward Time of Flight
   - PMT testing at USC
   - Scintillator testing at USC

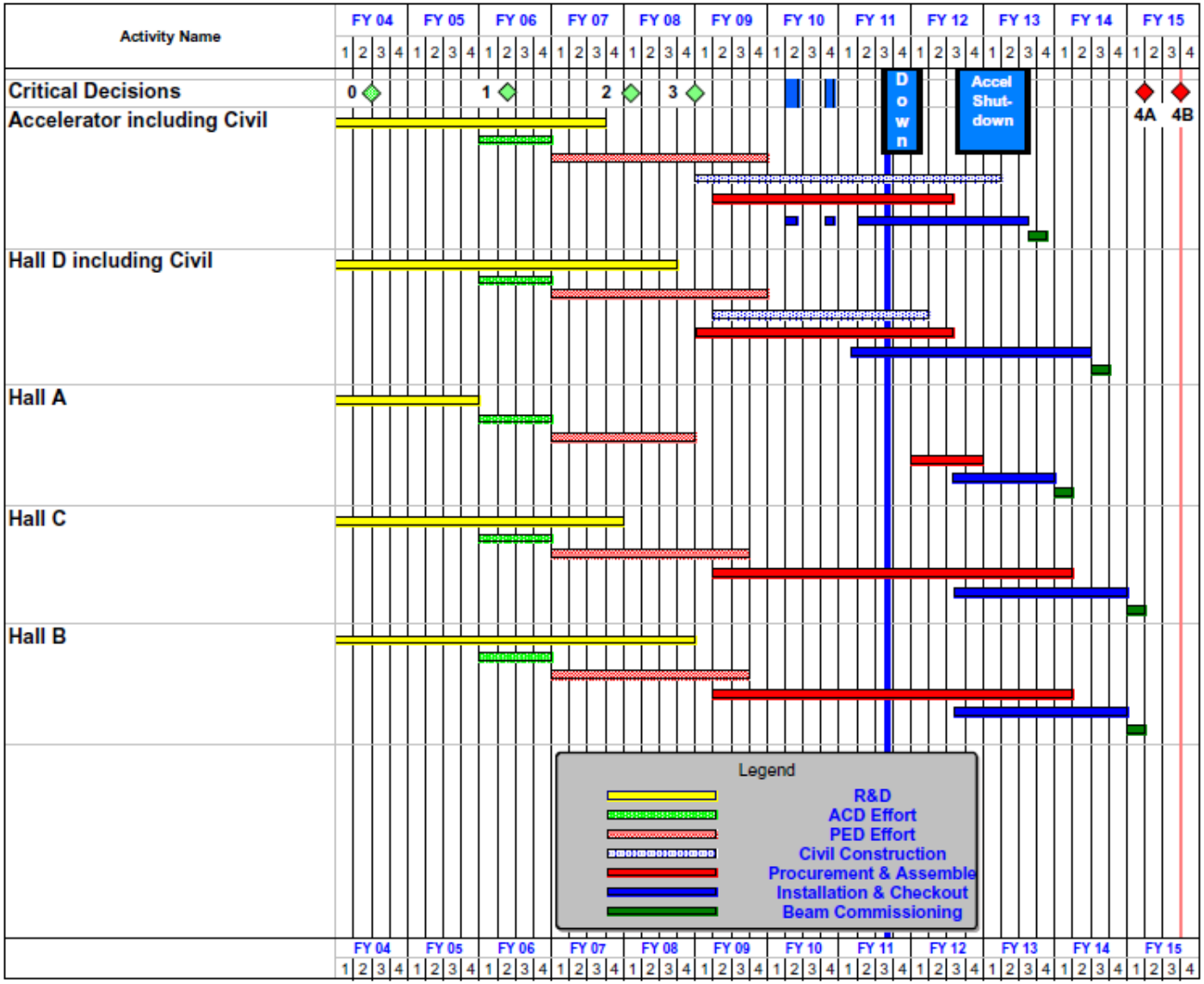
CLAS12 Under Construction - Examples

1. Drift Chambers
   - Wire stringing of RI at JLab
   - Wire stringing of RII at ODU

2. High Threshold Cerenkov
   - Mirror fabrication in the JLab Clean room
   - Mirror trimming at JLab Machine shop

3. Pre-Shower Calorimeter (MRI/NSF)
   - Module assembly
   - Fibers QA

12 GeV Upgrade Project Schedule



Two short parasitic installation periods in FY10

6-month installation May-Oct 2011

12-month installation May 2012-May 2013

Hall A commissioning start October 2013

Hall D commissioning start April 2014

Halls B & C commissioning start October 2014

Project Completion June 2015

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

— The discovery of Generalized Parton Distributions has opened up a new and exciting avenue of hadron physics that needs exploration in dedicated experiments.

— Moderate to high energy, high luminosity, and large acceptance spectrometers are needed to measure GPDs in deeply virtual exclusive processes.

— The JLab 12 GeV Upgrade provides the tools to do this well and explore the nucleon at a much deeper level.

The Fin