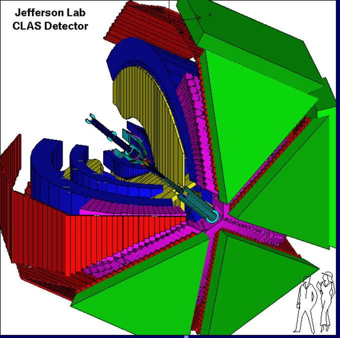
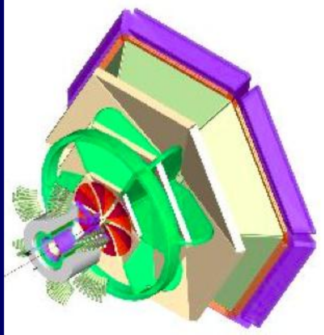




Deeply Virtual Exclusive Reactions with CLAS

Valery Kubarovsky
Jefferson Lab

Trento, Italy
October 14 , 2010

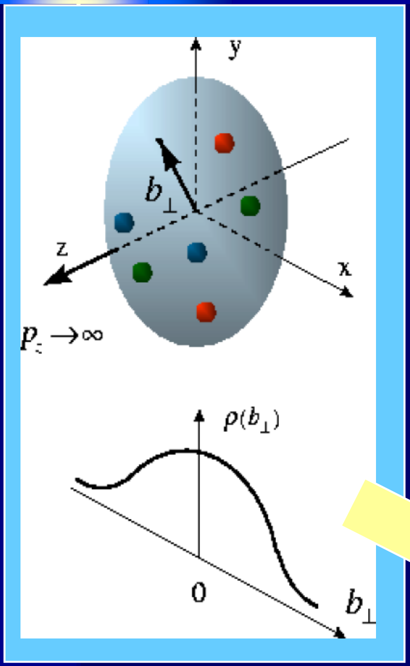
Jefferson Lab
Thomas Jefferson National Accelerator Facility

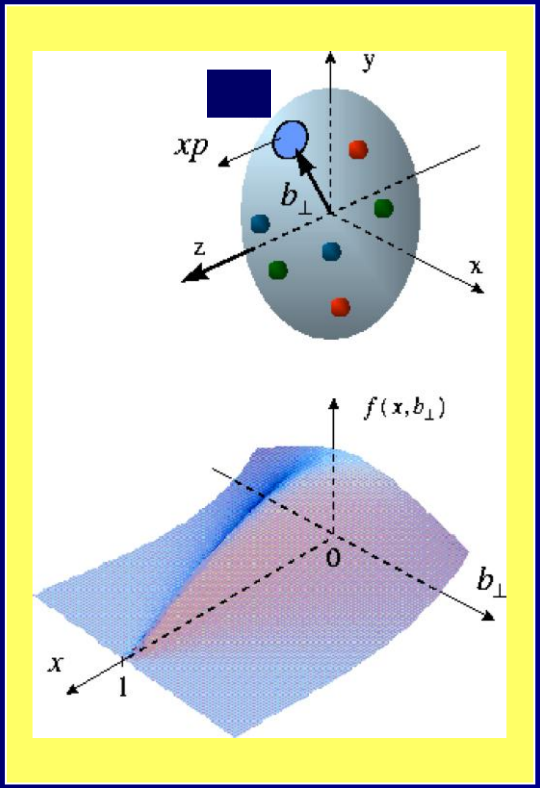
Outline

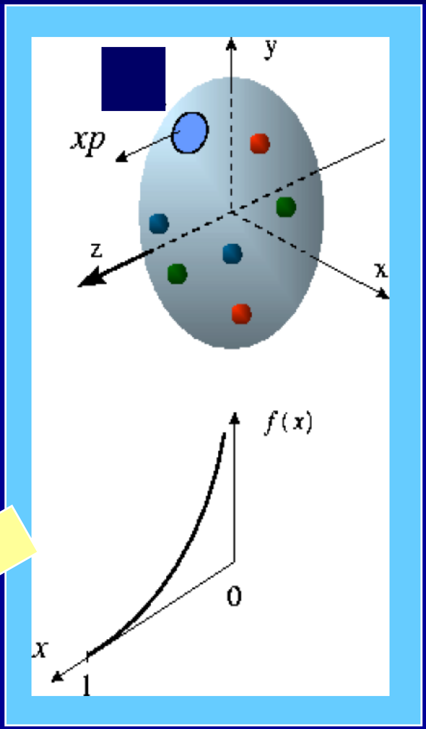
- Introduction
- DVMP theoretical models
- Brief update on DVCS
- π^0/η electroproduction
  - Cross sections
  - Structure functions
  - Beam spin asymmetry
  - Cross sections ratio
- Summary

How are the proton's charge densities related to its quark momentum distribution?

D. Mueller, X. Ji, A. Radyushkin, …1994 -1997
M. Burkardt, A. Belitsky… Interpretation in impact parameter space





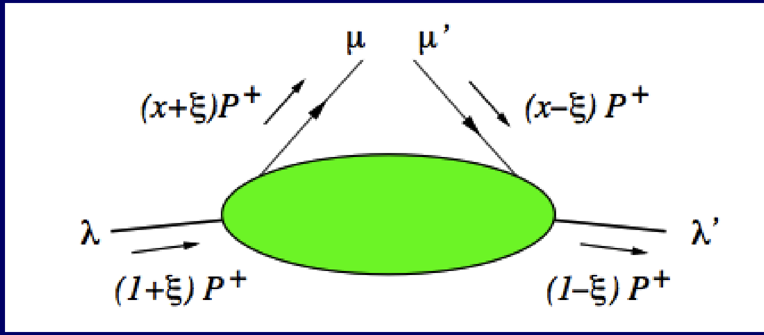


Proton form factors, transverse charge & current densities

Correlated quark momentum and helicity distributions in transverse space - GPDs

Structure functions, quark longitudinal momentum & spin distributions

Generalized Parton Distributions



- There are 4 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 GPDs flip the parton helicity
  $H_T, \tilde{H}_T, E_T, \tilde{E}_T$

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

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

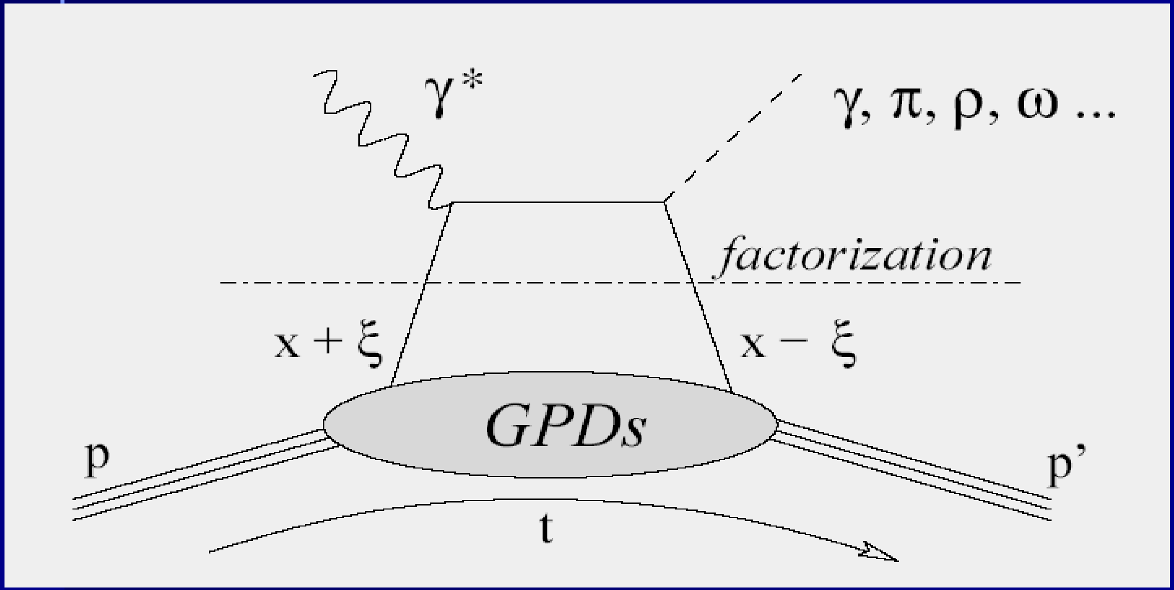
- Angular Momentum

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

(Ji's sum rule)

Basic Process – Handbag Mechanism

Deeply Virtual Compton Scattering (DVCS)
Deeply Virtual Meson Production (DVMP)



x – longitudinal quark momentum fraction

2ξ – longitudinal momentum transfer

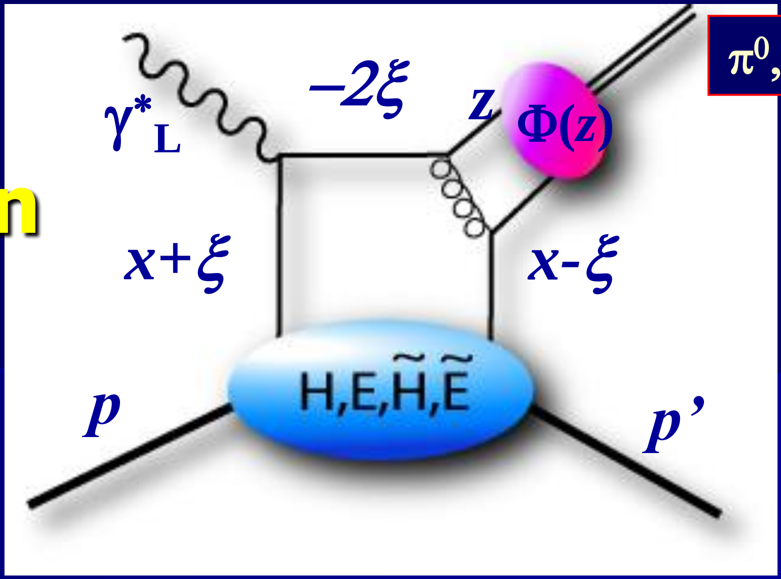
$\sqrt{-t}$ – Fourier conjugate to transverse impact parameter

GPDs depend on 3 variables, e.g. $H(x, \xi, t)$. They probe the quark structure at the amplitude level.

$$\xi = \frac{x_B}{2 - x_B}$$

High Q^2, Low t Region

Collins,Frankfurt,Strikman -1997



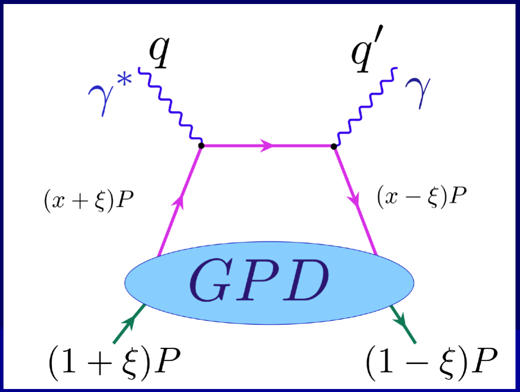
- Factorization theorem states that in the limit $Q^2 \rightarrow \infty$ exclusive electroproduction of mesons is described by hard rescattering amplitude, generalized parton distributions (GPDs), and the distribution amplitude $\Phi(z)$ of the outgoing meson.
- The prove applies only to the case when the virtual photon has longitudinal polarization
- $Q^2 \rightarrow \infty$ $\sigma_L \sim 1/Q^6$, $\sigma_T/\sigma_L \sim 1/Q^2$
- The full realization of this program is one of the major objectives of the 12 GeV upgrade

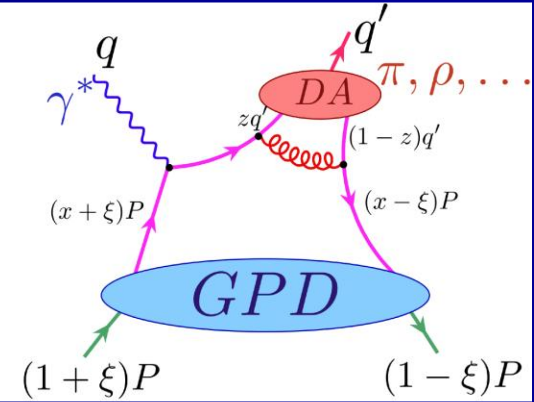
Deeply Virtual Meson production

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

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

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





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	$2u - d$

$$\tilde{H}, \tilde{E}$$

$$H, E$$

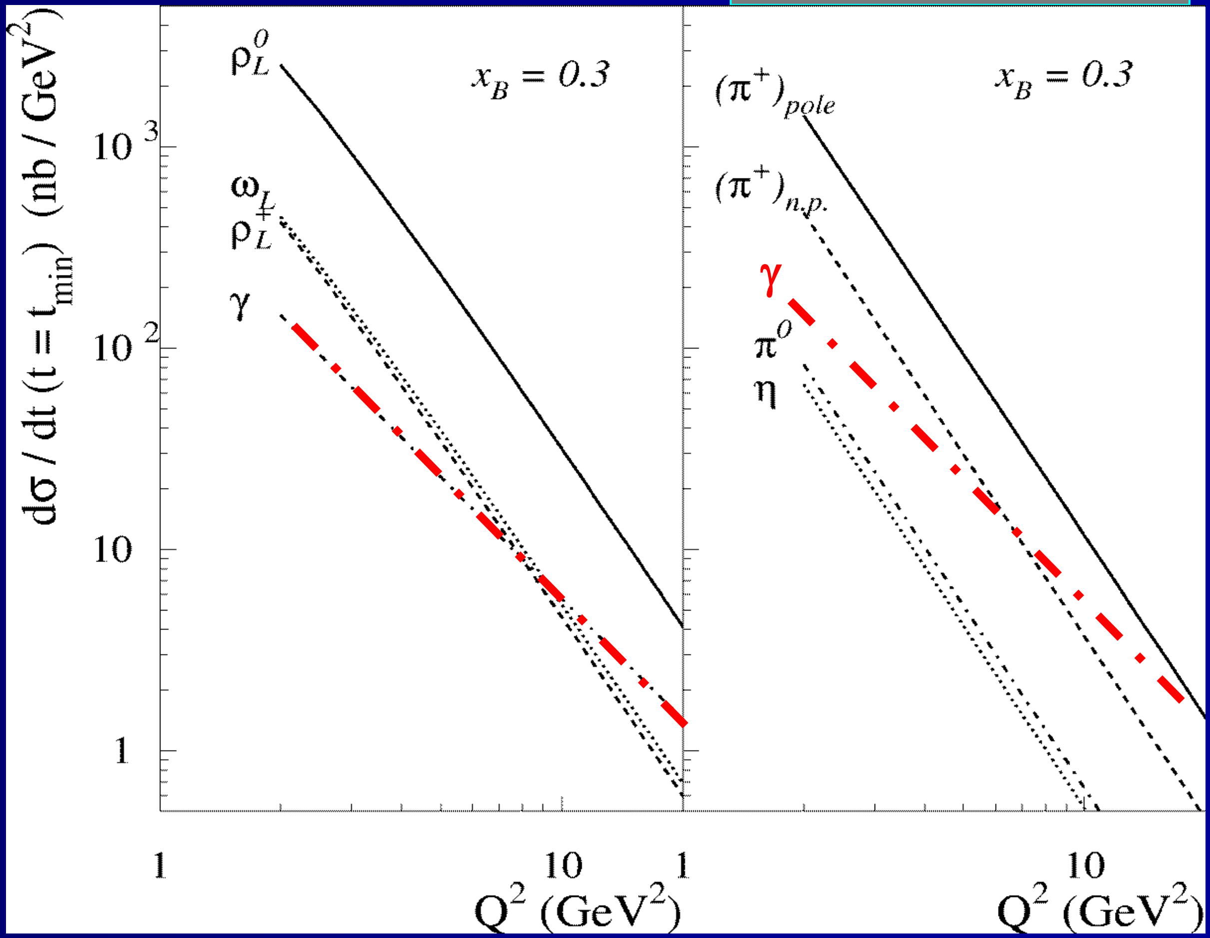
- DVCS is the cleanest way of accessing GPDs. However, it is difficult to perform a flavor separation.
- Vector and pseudoscalar meson production allows one to separate flavor and isolate the helicity-dependent GPDs.

GPD predictions (only σ_L)

Vanderhaeghen, Guichon, Guidal, 1999

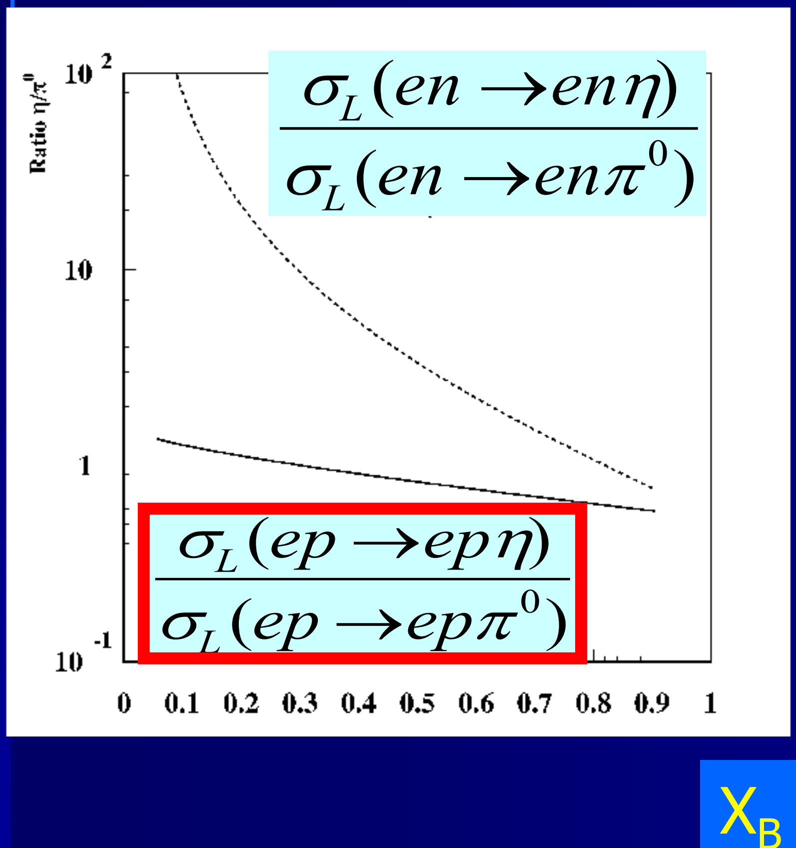
$$\frac{d\sigma_L}{dt}(t = t_{\min})$$

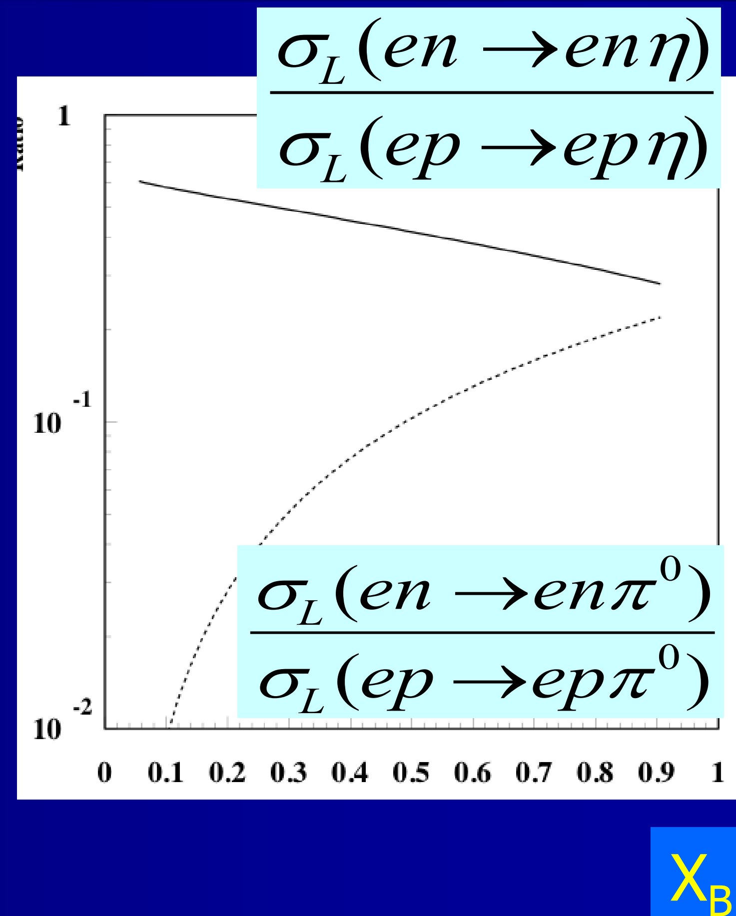
- $d\sigma_L/dt(t=t_{min})$ for vector mesons (left panel)
- Pseudoscalar mesons (right panel)
- Note the pion pole contribution to the π^+ electroproduction (shown separately)
- The scaling cross section for photons dominate at high Q^2 over meson production.



Cross Section Ratios as a function of x_B

Eides,Frankfurt,Strikman -1997



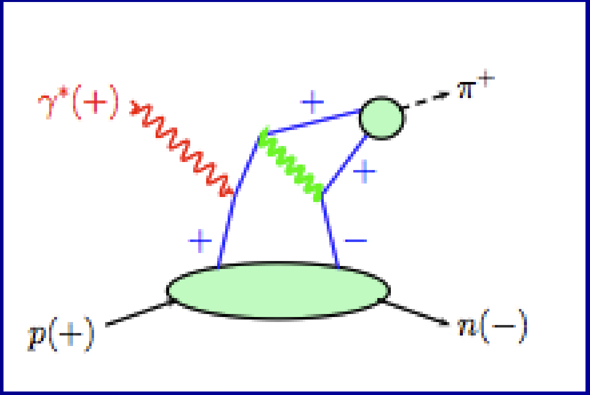


Transversity in DVMP

Kroll, Goloskokov
Goldstein, Luiti

- 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 distribution.

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



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

π^0 electroproduction Handbag predictions

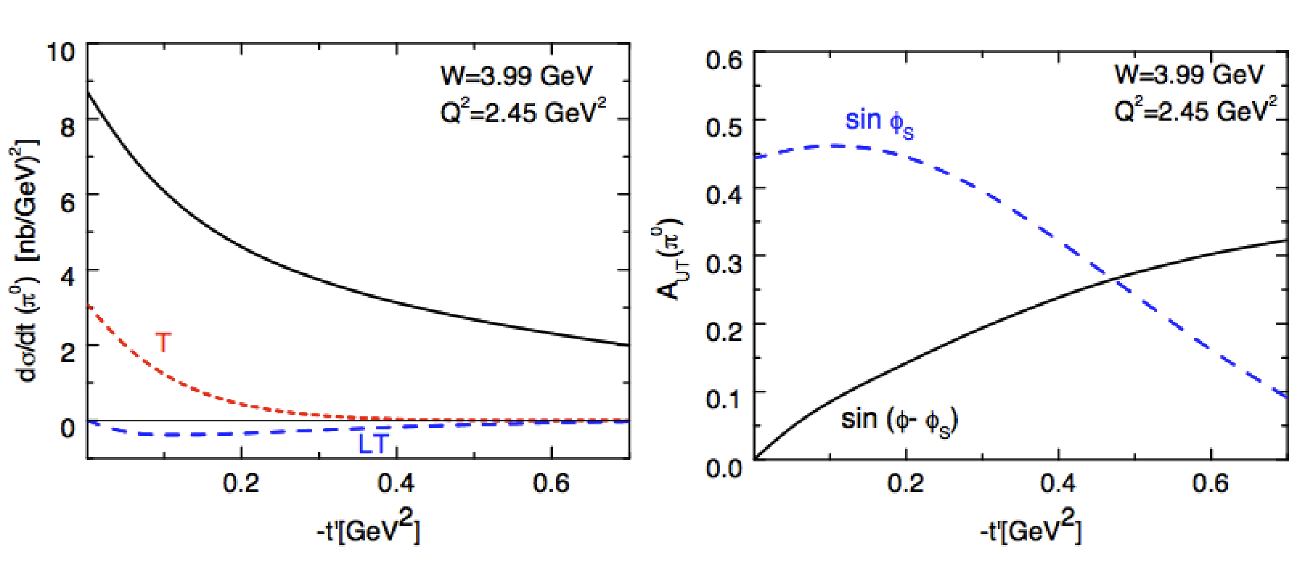
$$\gamma^* p \to p\pi^0$$

Kroll, Goloskokov, 2009.

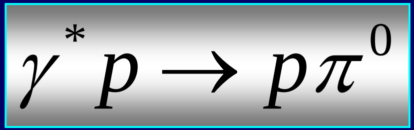
$\sigma_T + \varepsilon\sigma_L$

σ_T

σ_{LT}



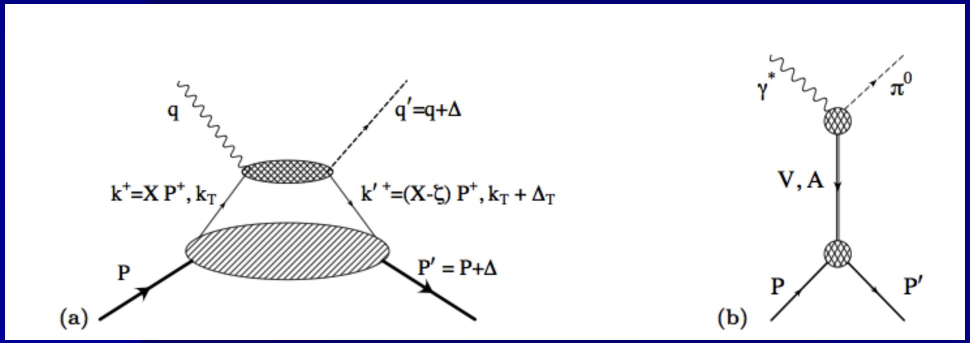
Predictions for the cross section (left) and A_{UT} (right) for the π^0 electroproduction versus –t. The unseparated(σ_L,σ_T) cross section was calculated as well as σ_T and σ_{LT}. At W=2.2 GeV the cross section will be a factor of 10 larger. We can check it at Jlab.



Nucleon Tensor Charge from Exclusive π^0 Elecrtroproduction

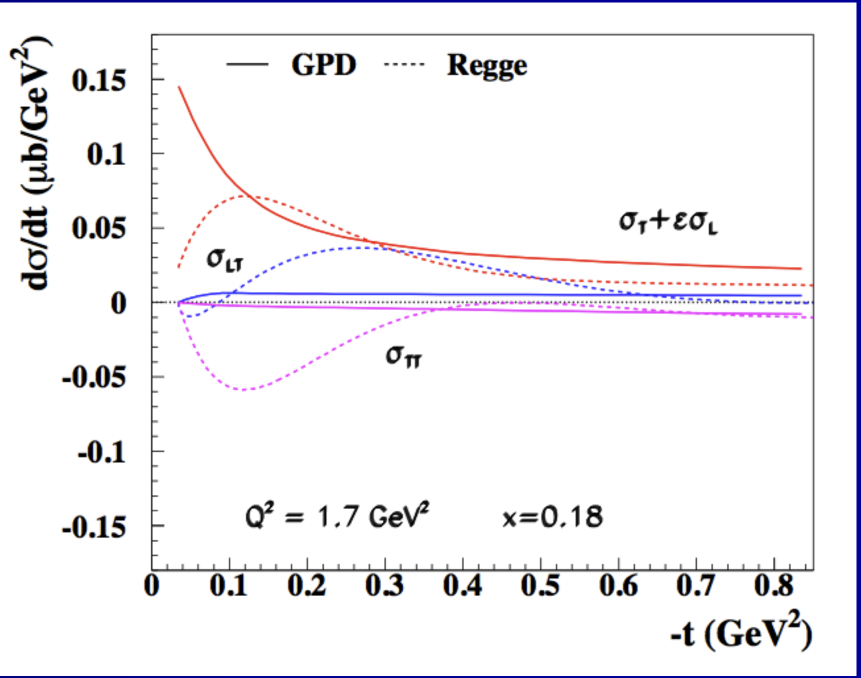
Ahmad, Goldstein, Luiti, 2009

- π^0 elecrtroproduction proceeds through C-parity odd and chiral odd combination of t-channel exchange quantum numbers. 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;

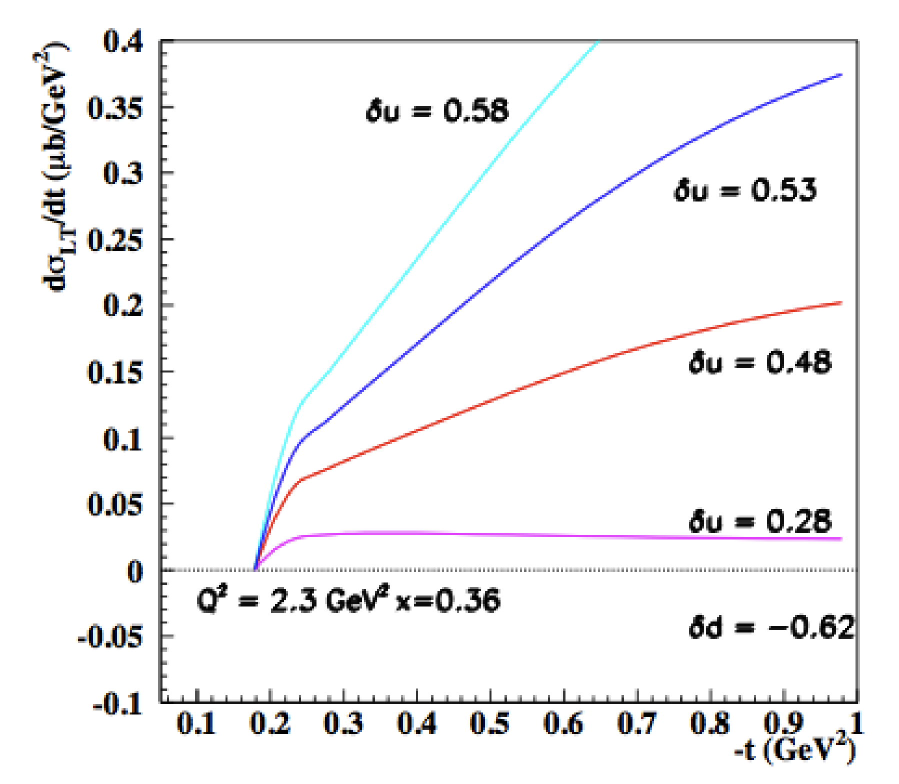
t-channel exchange diagram



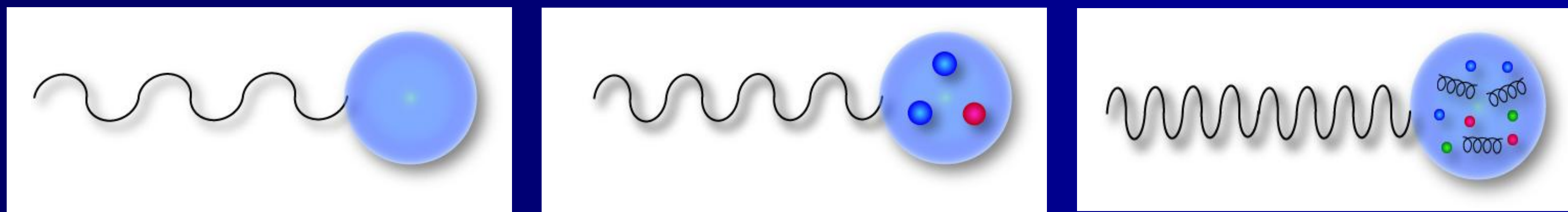
$$\gamma^* p \to p\pi^0$$

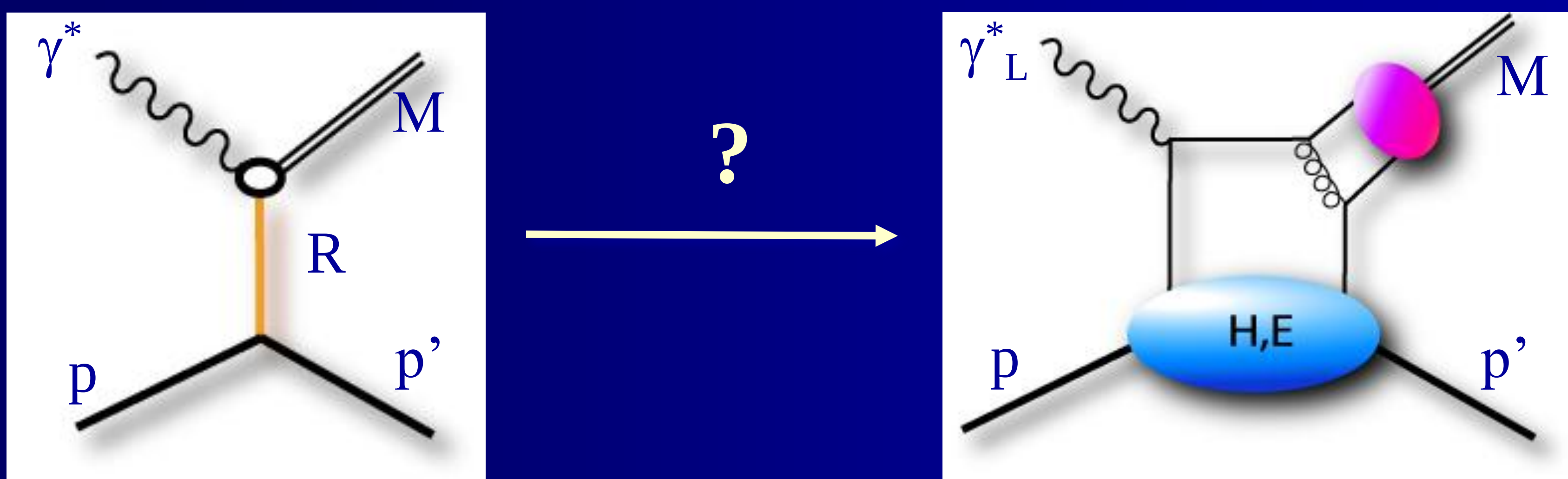
σ_{LT} for different values of the u quark tensor charge

Ahmad, Goldstein, Luiti, 2009



Transition from "hadronic" to the partonic degrees of freedom

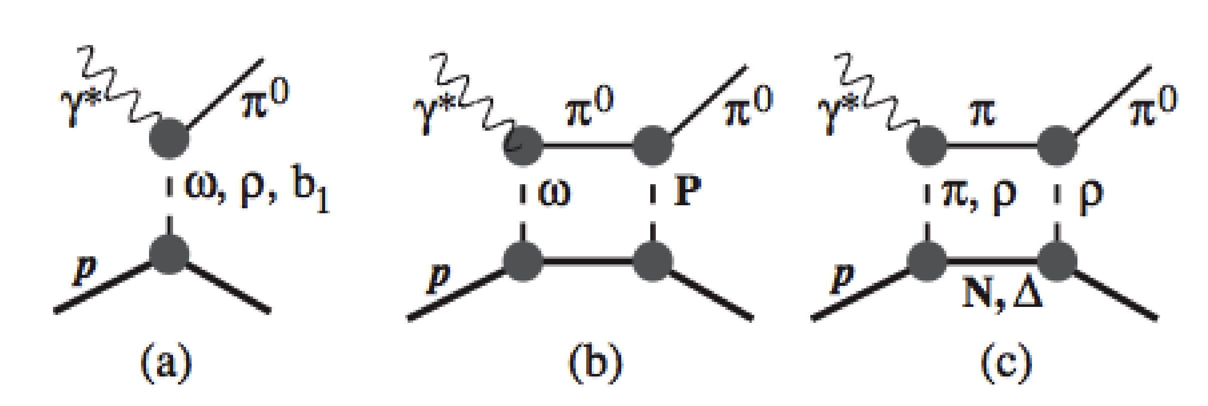


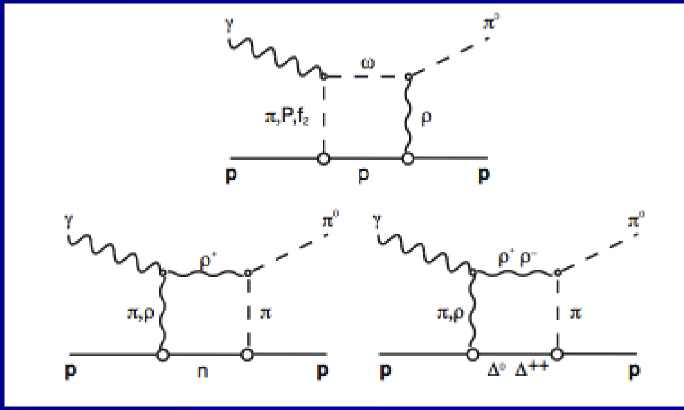


$$\gamma^* p \to p \pi^0$$

Regge Model

J.M. Laget 2010





(a) Regge poles (vector and axial vector mesons)
(b) and (c) pion cuts

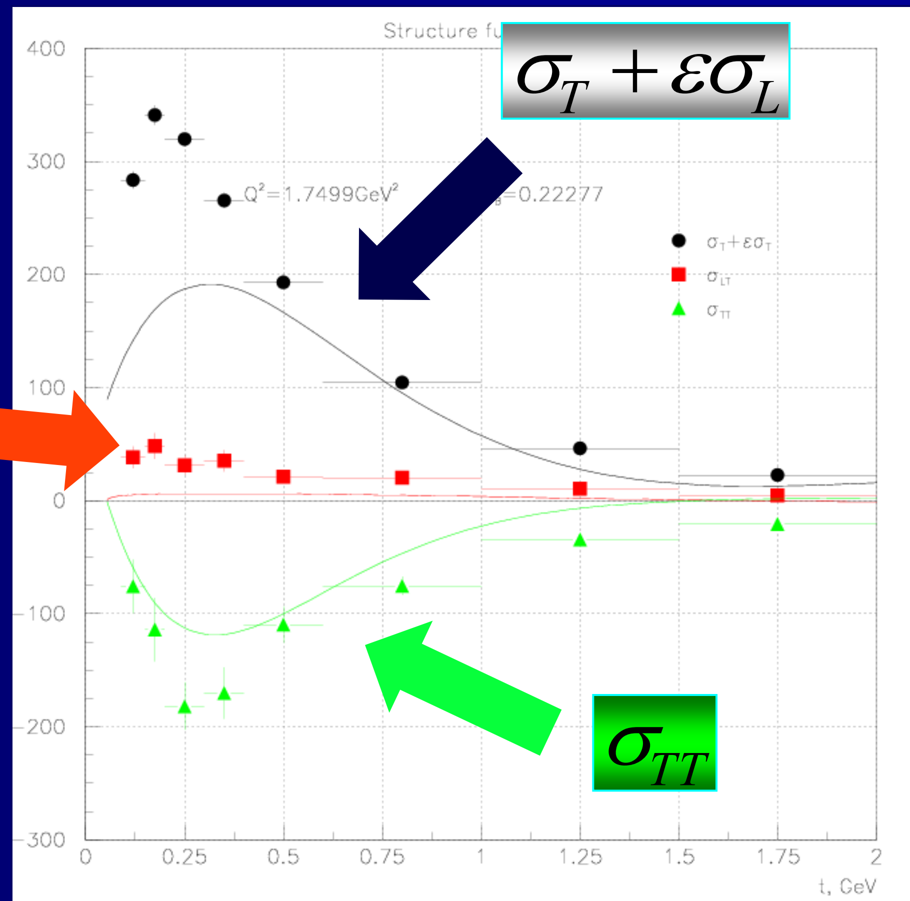
Vector meson cuts

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

Regge predictions

$Q^2=1.75$
$x^B=0.22$

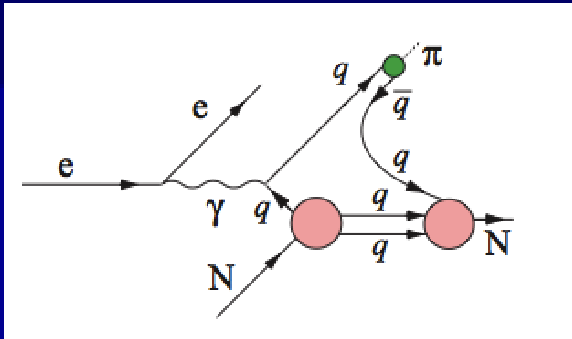
σ_{LT}



-t, GeV^2

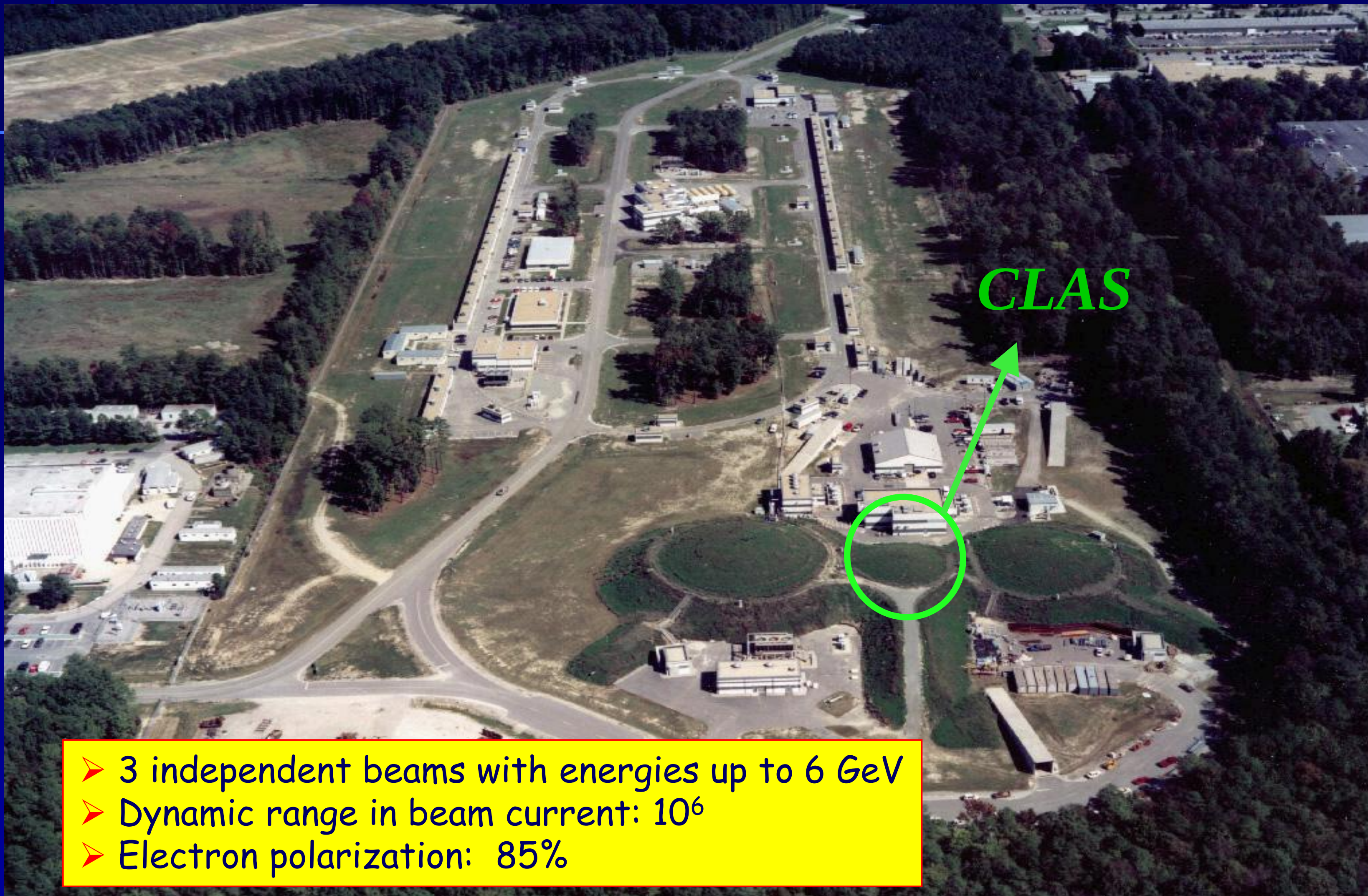
Combined Regge + DIS model

Kaskulov, Gallmeister, Mosel (2008-2010)



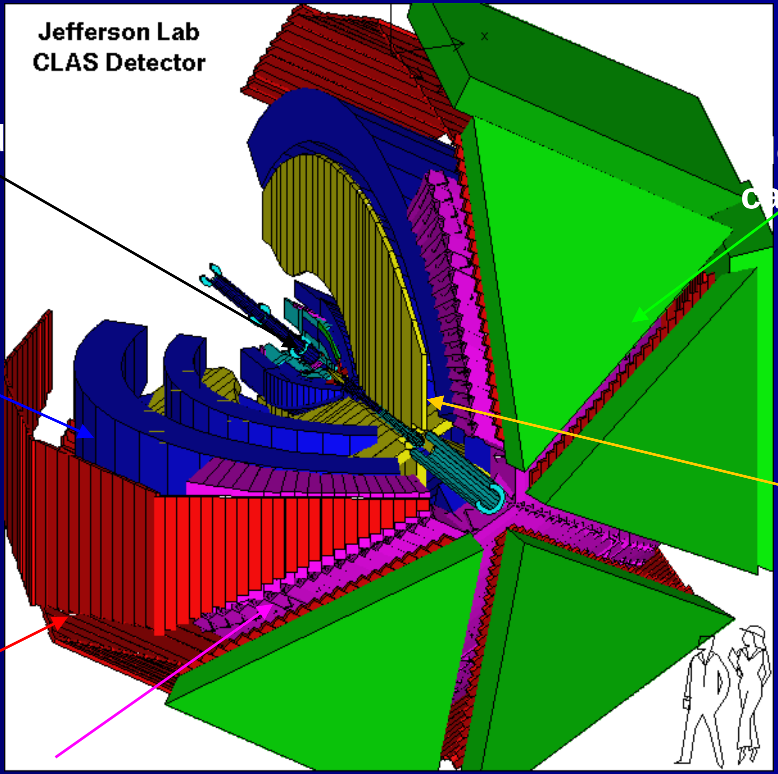
- σ_L is dominated by improved treatment of gauge Invariant Regge model.
- σ_T is described by direct hard interaction of virtual photons with partons followed by the hadronization process into πN channel.
- This explains the large transverse response at moderate and high photon virtualities.
- This process is sensitive to the intrinsic transverse momentum distribution of partons.

JLab Site: The 6 GeV Electron Accelerator

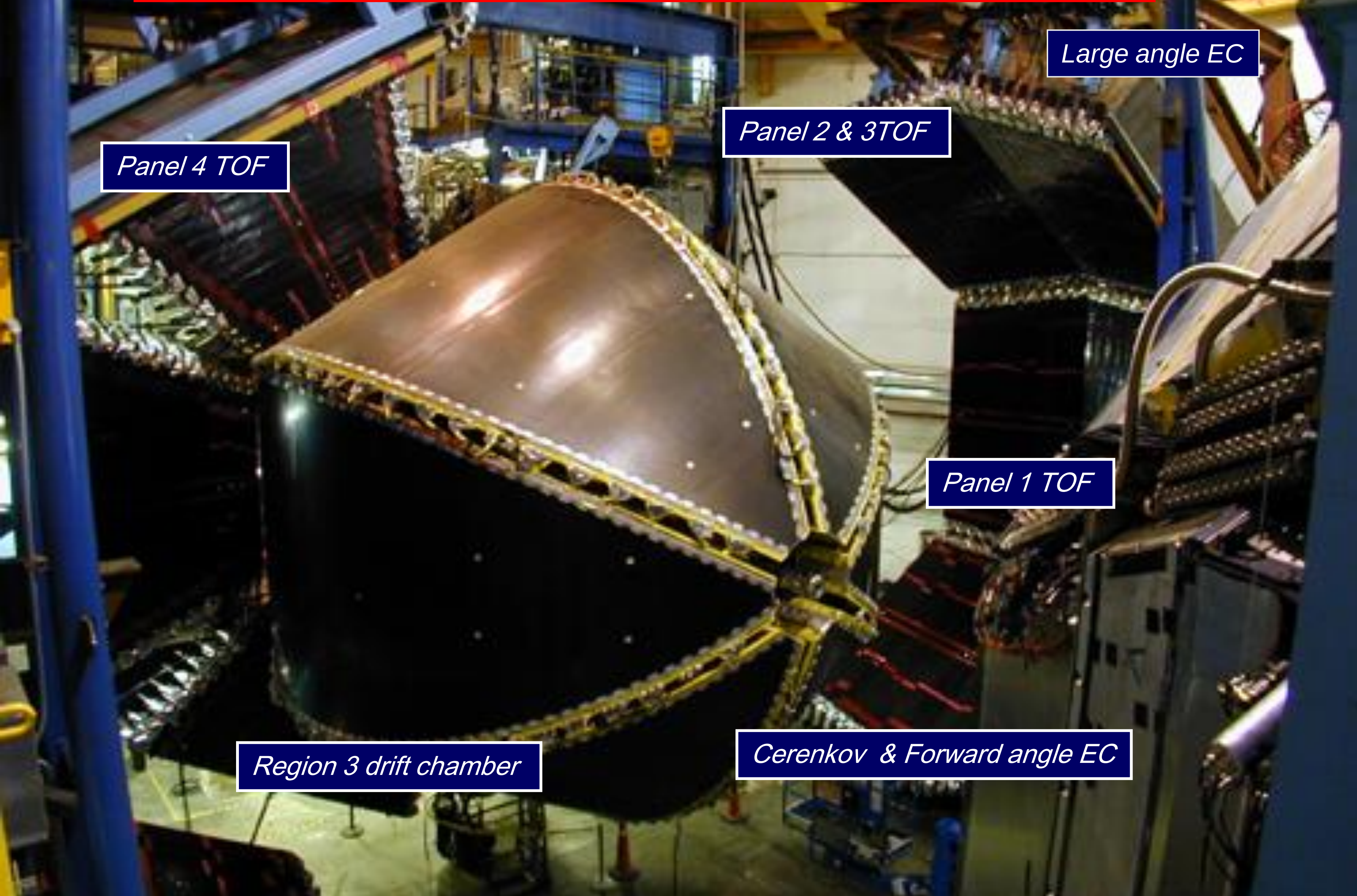


- 3 independent beams with energies up to 6 GeV
- Dynamic range in beam current: 10^6
- Electron polarization: 85%

CEBAF Large Acceptance Spectrometer CLAS

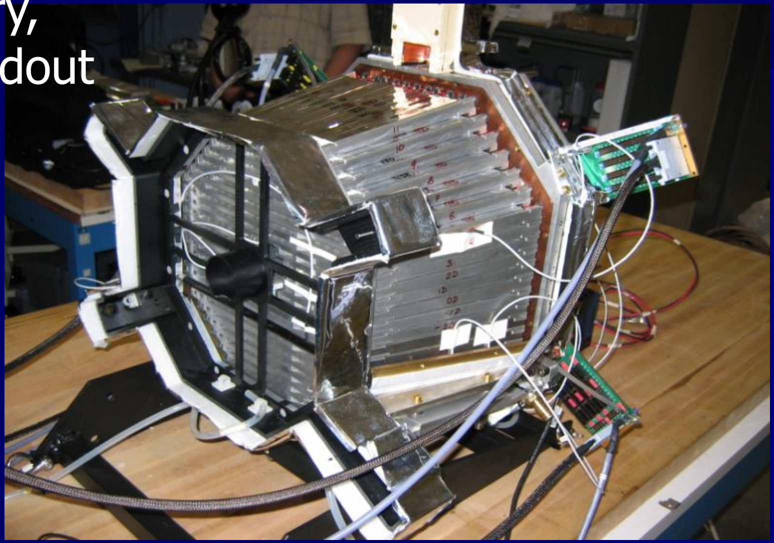


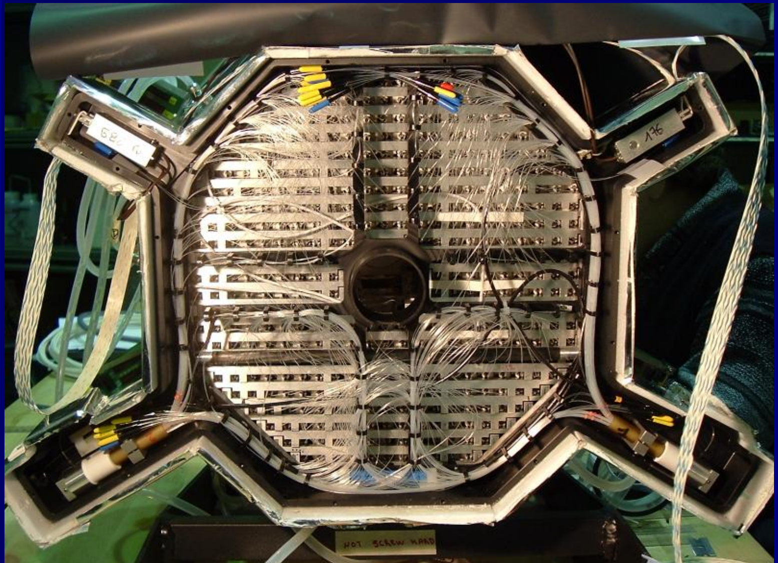
CLAS (forward carriage and side clamshells retracted)

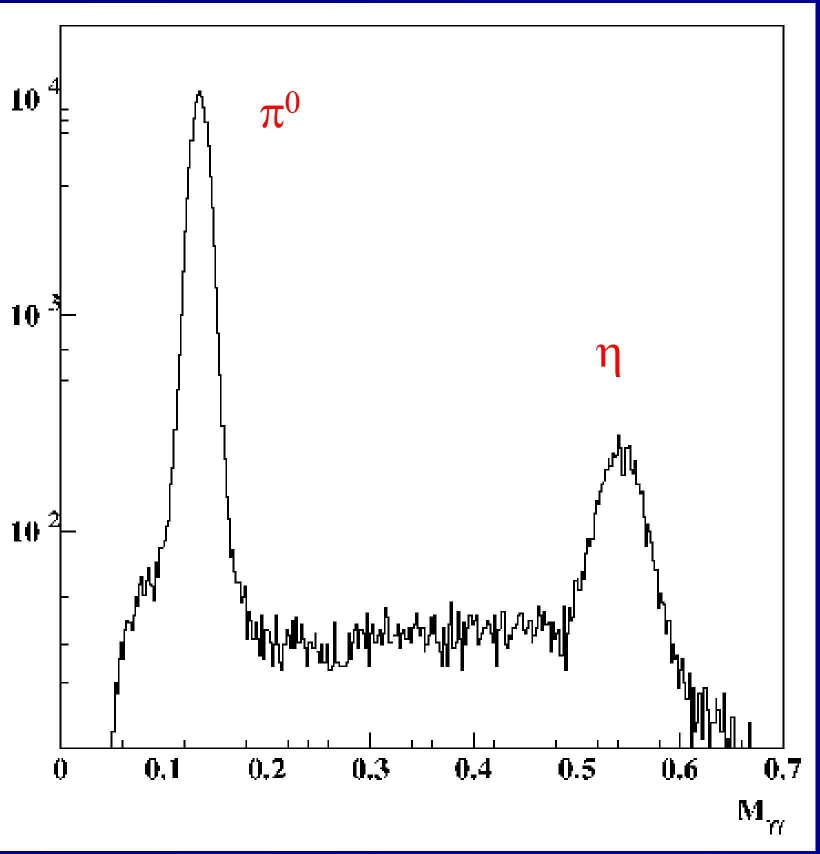


CLAS Lead Tungstate Electromagnetic Calorimeter

424 crystals,
18 RL,
pointing
geometry,
APD readout

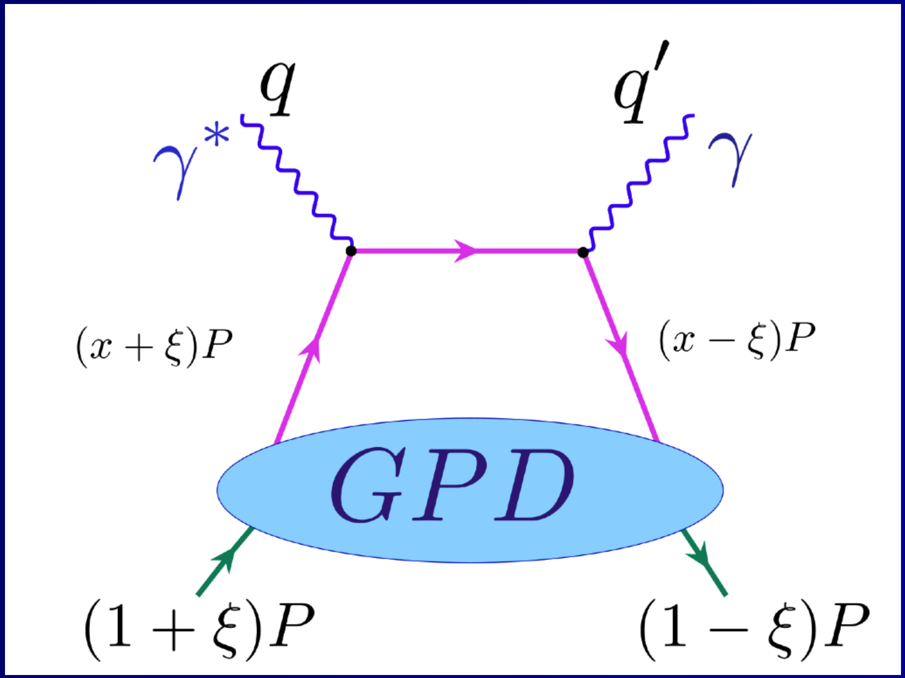






Deeply Virtual Compton Scattering

The cleanest process to access GPDs



DVCS BSA A_{LU}

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

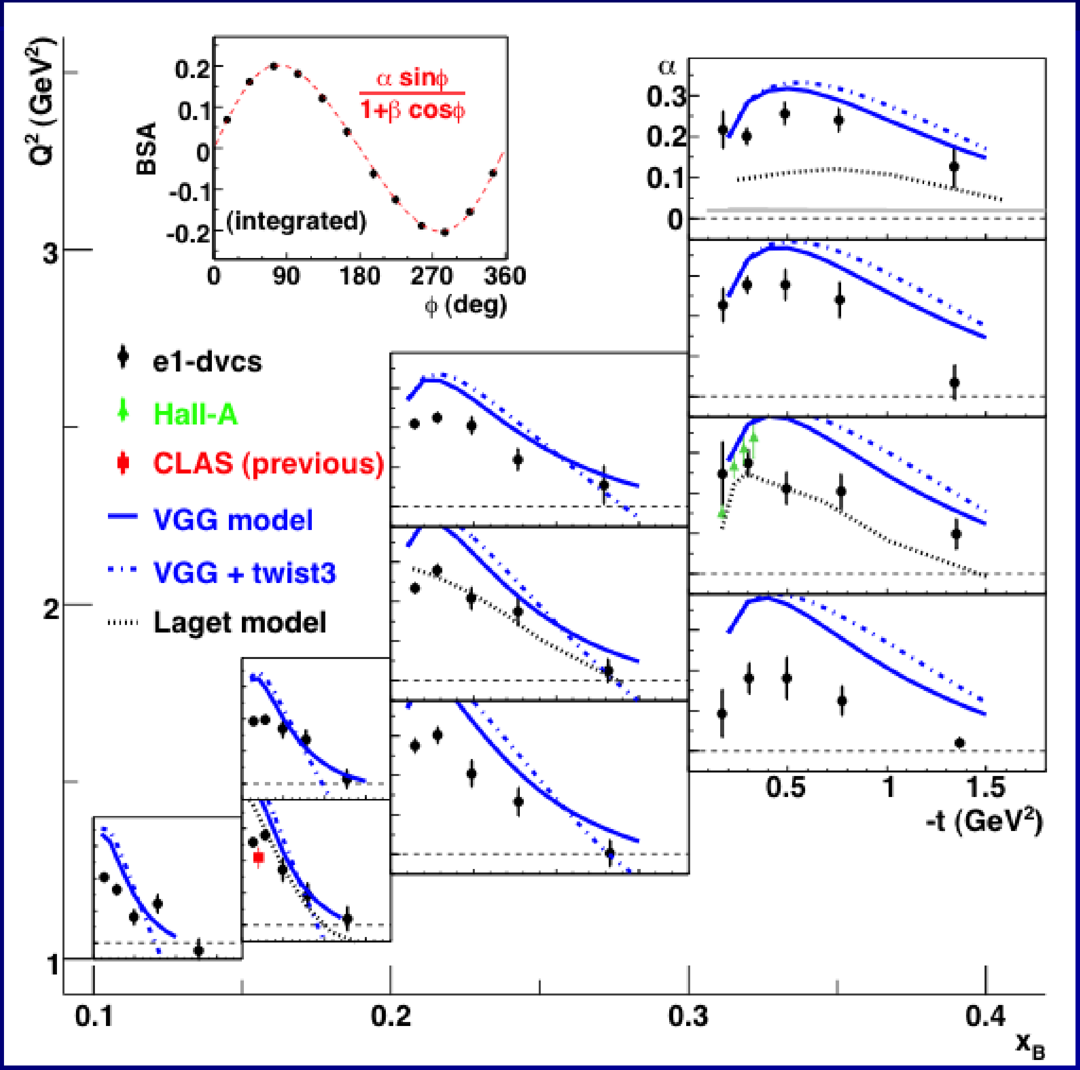
Fit: $A_{LU} = \alpha\sin\phi/(1 + \beta\cos\phi)$

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

VGG parameterization reproduces $-t > 0.5\,GeV^2$ behavior, and overshoots asymmetry at small t.

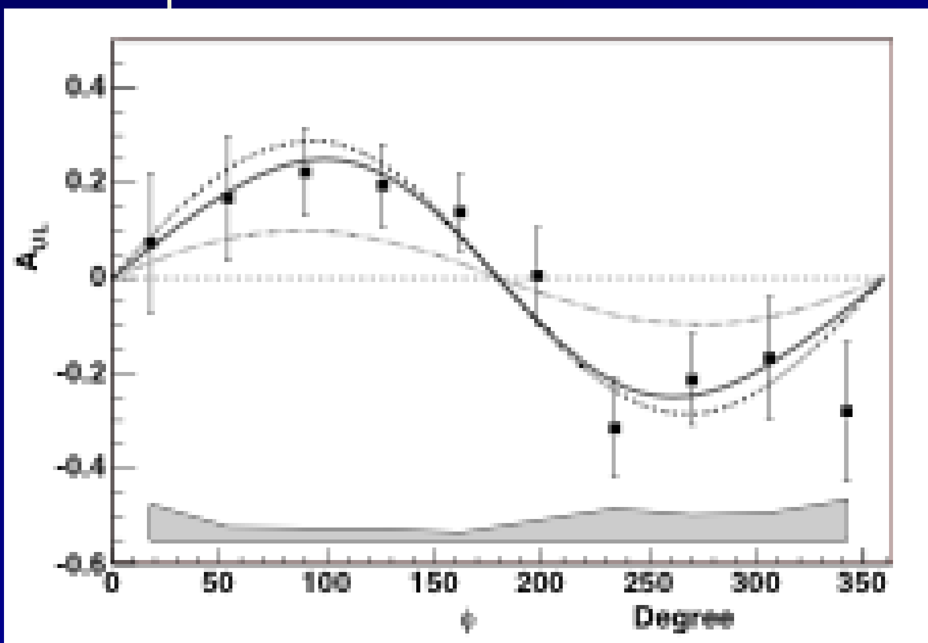
Regge model (J-M Laget) is in fair agreement in some kinematic bins with our results.

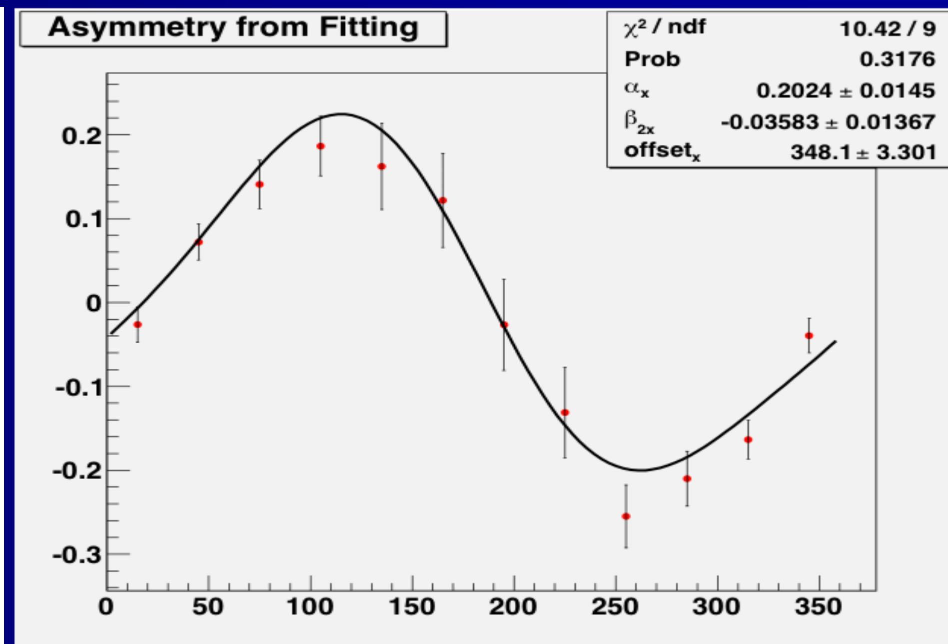
Phys.Rev.Lett 100:162002, 2008



Target Spin Asymmetry A_{UL}

(new data taken @2010)



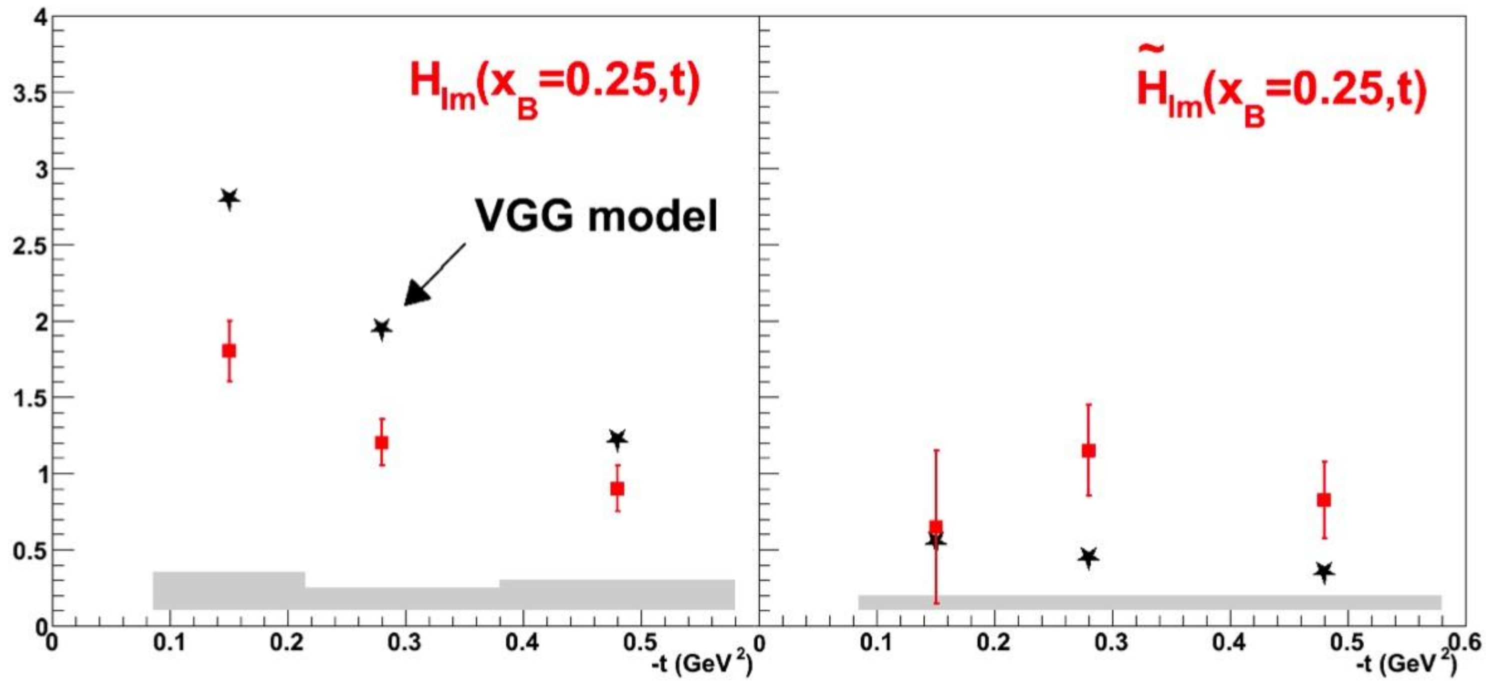


Phys.Rev.Lett 97:072002, 2006

eg1-dvcs (2010), not full statistics

Extraction of Compton Form Factors from CLAS DVCS data

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

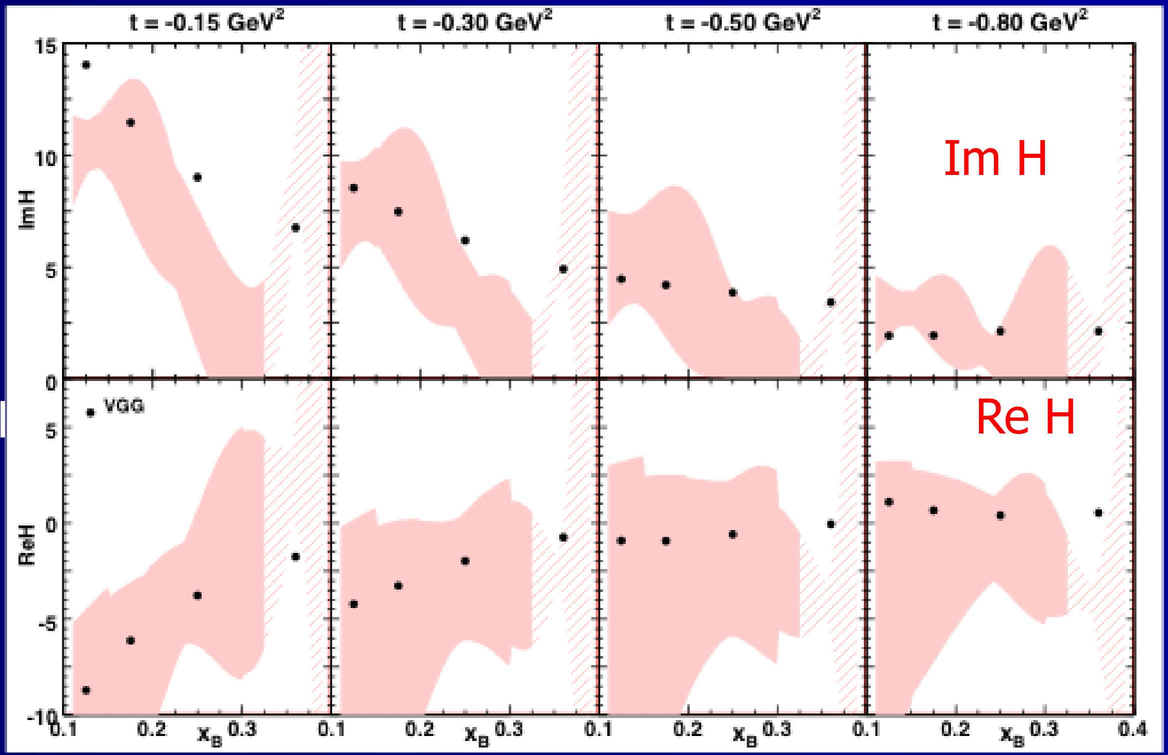


M. Guidal, arXiv:1003.0307

Global Analysis of the Compton FF (Jlab data)

$$CFF = \int_{-1}^{+1} F(x,\xi,t)\left(\frac{1}{\xi - x - i\varepsilon} \pm \frac{1}{\xi + x - i\varepsilon}\right)dx$$

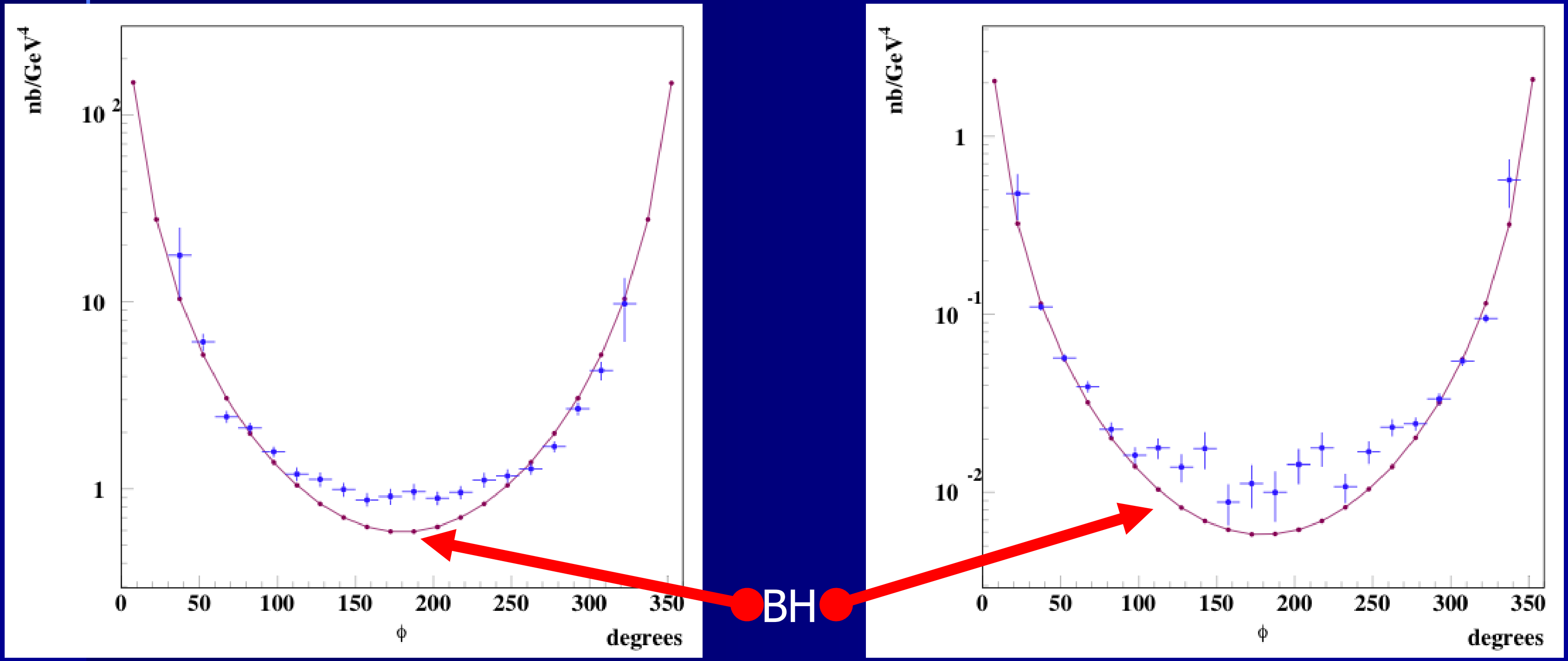
- The points are VGG model prediction
- The shadow is the Real and Imaginary parts of the CFF extracted from the experimental data



H. Moutarde, PR D79 (2009) 094021

DVCS cross section

preliminary



Q^2=1.2 GeV^2 x_B=0.13 t=0.12 GeV^2

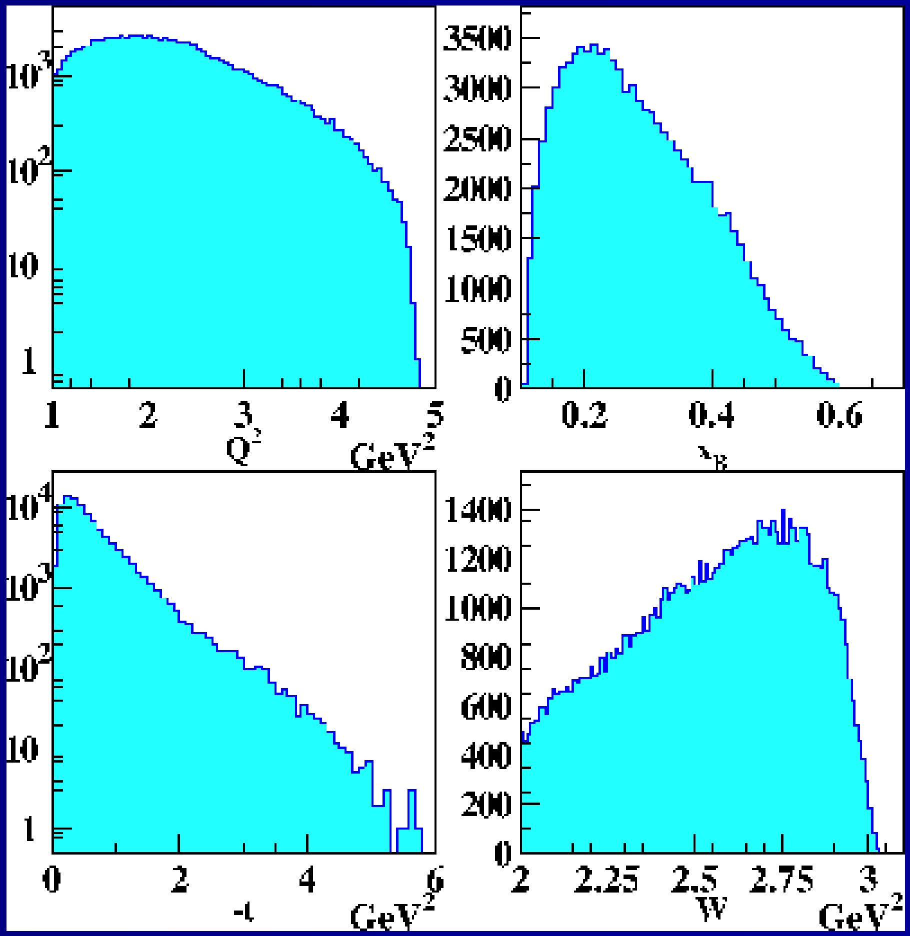
Q^2=2.2 GeV^2 x_B=0.25 t=0.45 GeV^2

DVMP: Kinematic Coverage

4 dimensional grid in Q^2, x_B, t, and ϕ

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

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

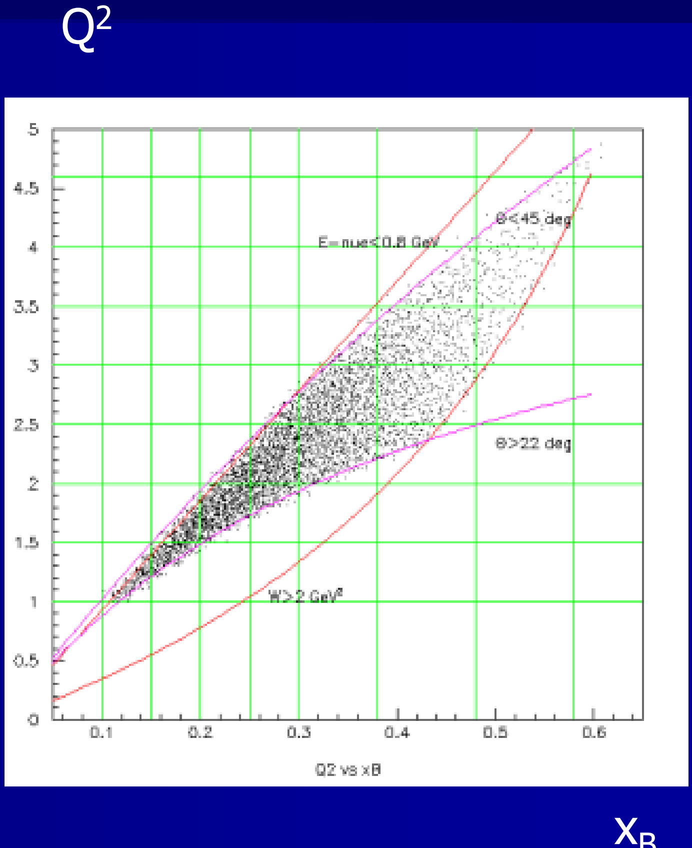


- Polarized Electron Beam
- E_0=5.776 GeV
- 75-80% polarization
- 2.5 cm Liquid Hydrogen target
- IC calorimeter
- Instant luminosity $2*10^{34}$ $cm^{-2}s^{-1}$
- Integrated luminosity: $3.27*10^7$ nb^{-1}

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



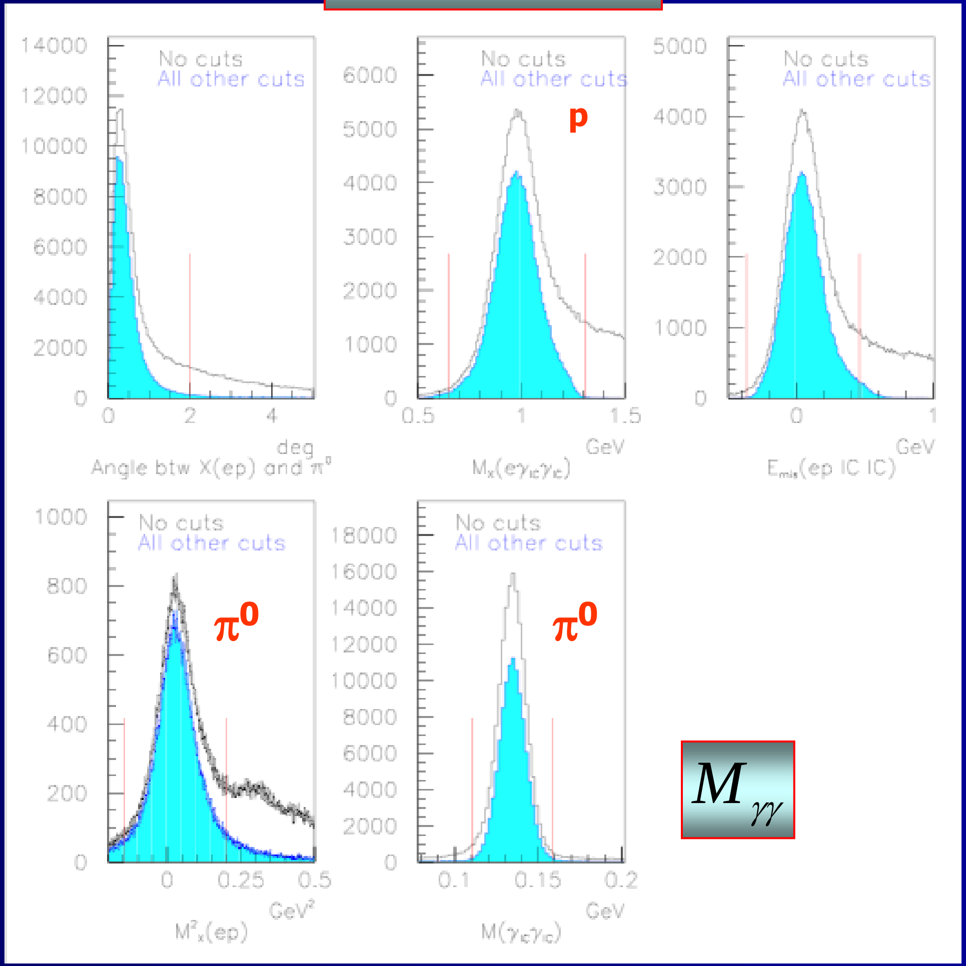
Exclusivity Cuts

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

$M_{missing}(e\gamma\gamma)$

$\theta(X^{ep}_{missing}, \gamma\gamma)$

$E_{missing}$



$M^2_{missing}(ep)$

$M_{\gamma\gamma}$

Monte Carlo

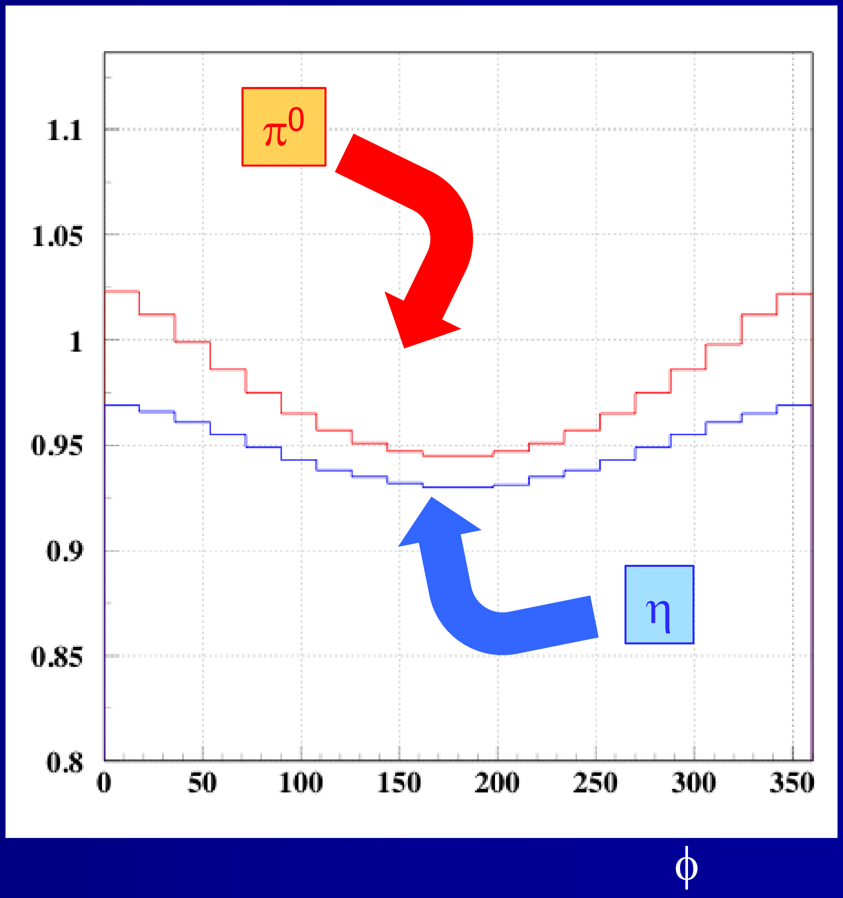
- Empirical model for the structure cross sections was used for the MC simulation and radiative corrections
- This model is based on CLAS data
- MC simulation included the radiative effects and used empirical model for the Born term.
- 100 M events were simulated with GSIM program.

Radiative Corrections

- Radiative Corrections were calculated using Exclurad package adapted by Kyungseon 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

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

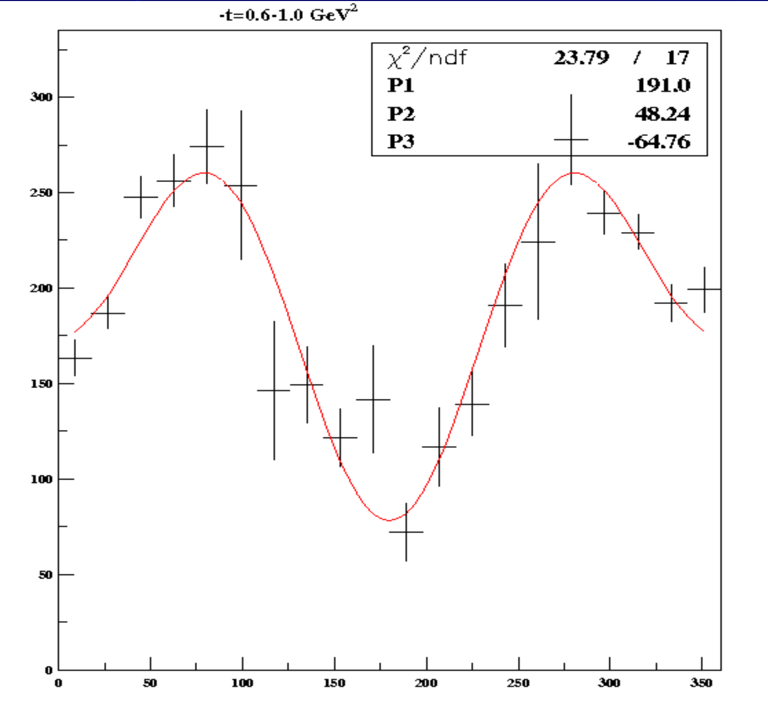


$$\gamma^* p \to p \pi^0$$

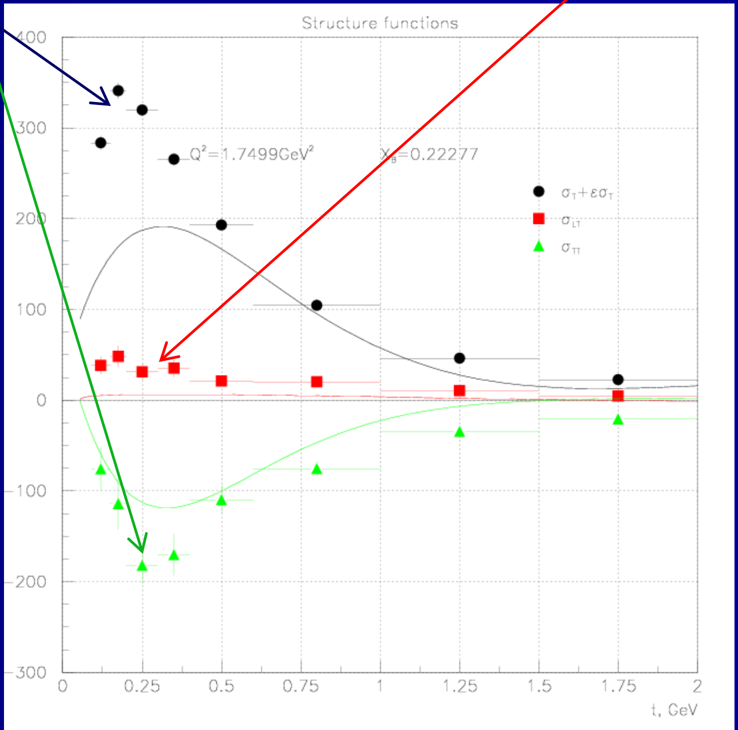
Structure Functions

$\sigma_T + \varepsilon\sigma_L$ σ_{TT} σ_{LT}

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



ϕ distribution



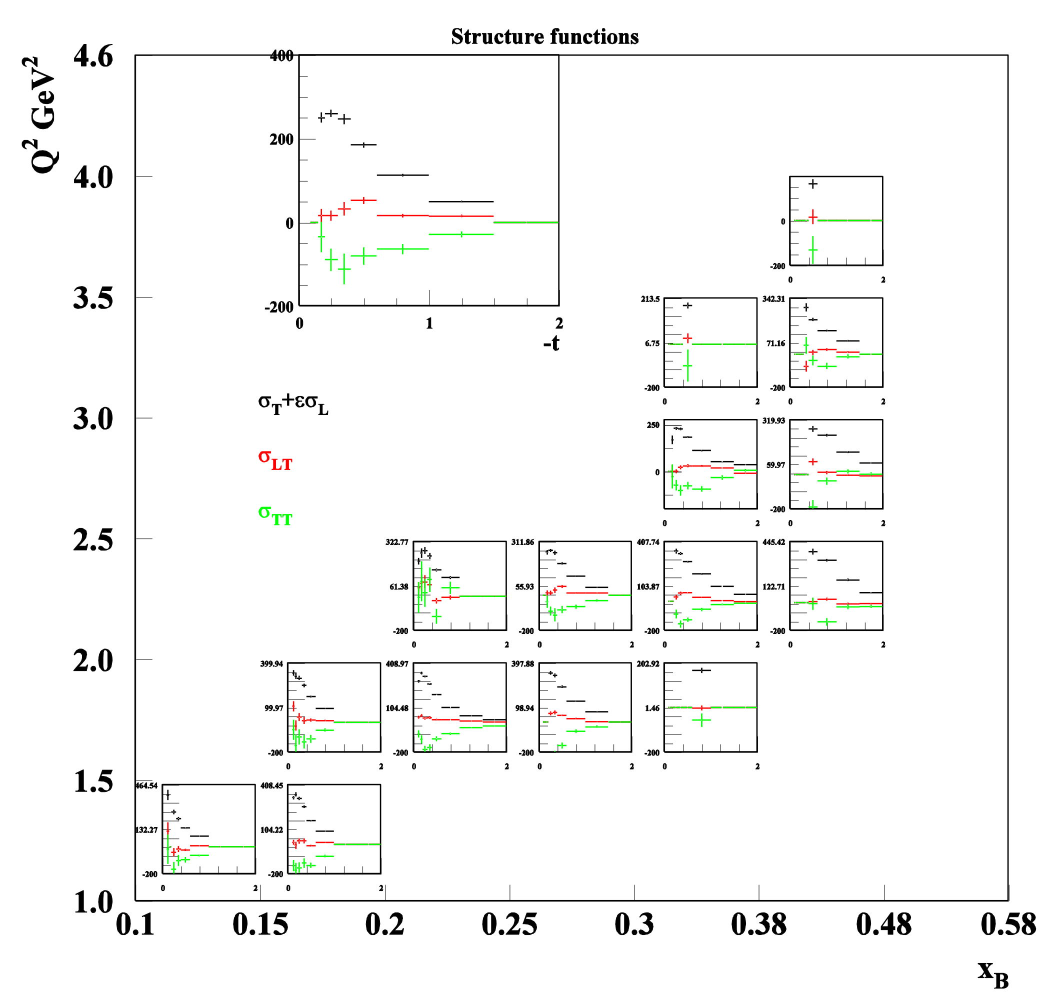
-t

GM Laget Regge model

Structure Functions

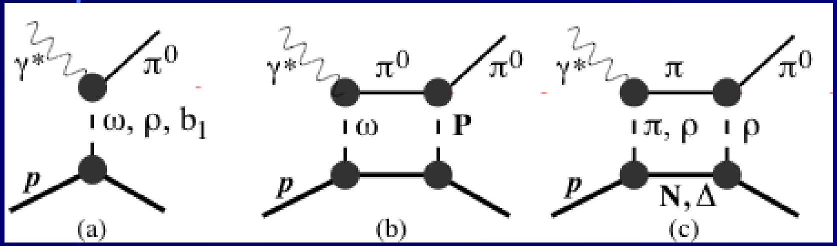
$(\sigma_T + \varepsilon\sigma_L)$ σ_{TT} σ_{LT}

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

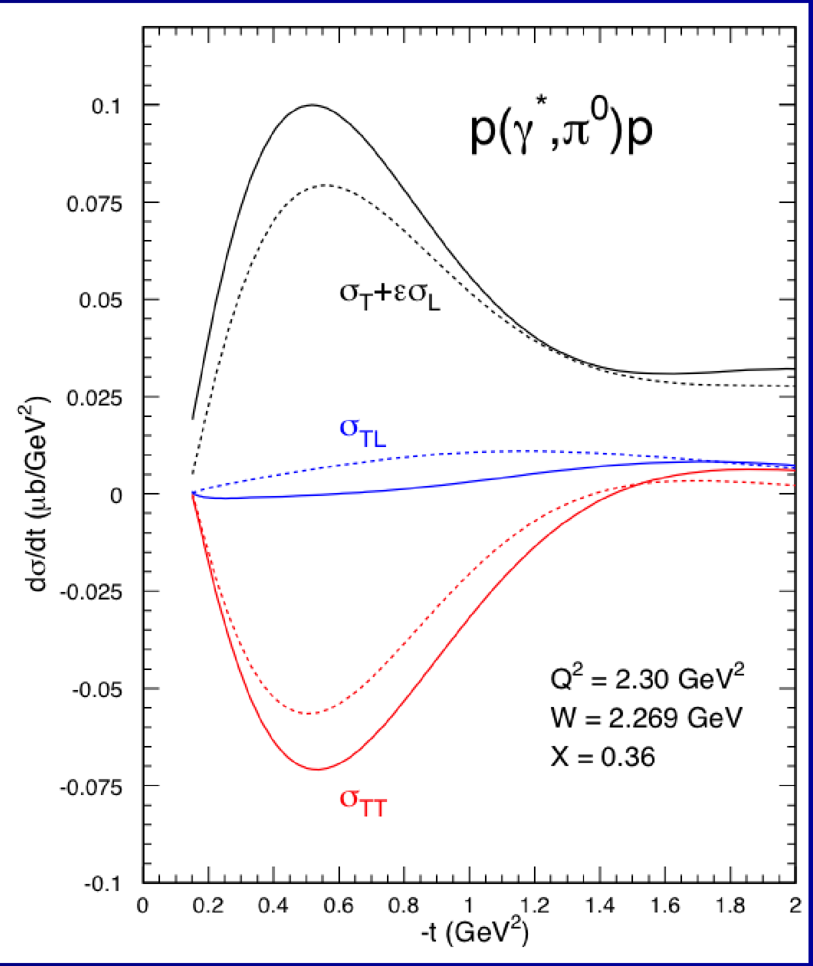


$\gamma^* p \to p\pi^0$

$(\sigma_T + \varepsilon\sigma_L)$ σ_{TT} σ_{LT} in Regge Model (J-M Laget)



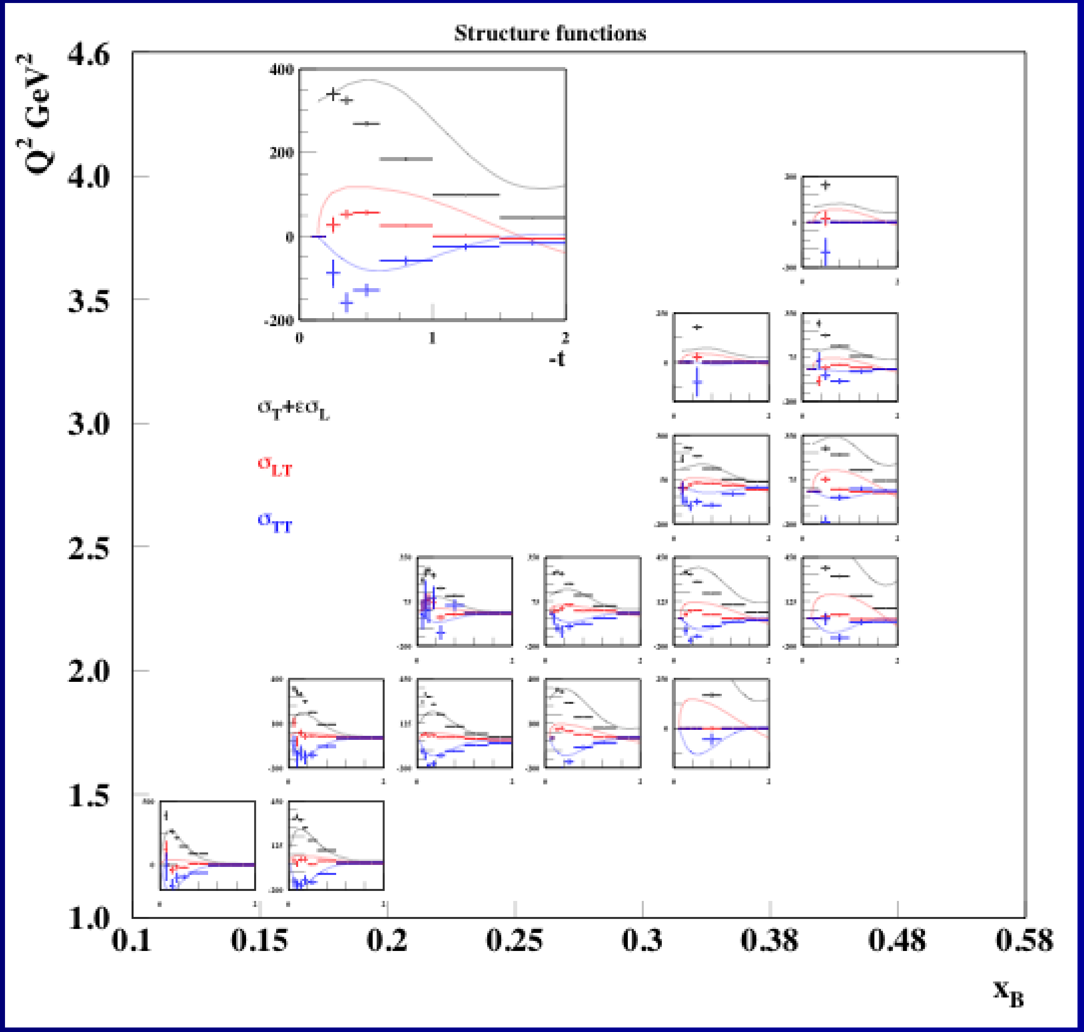
ω/ρ/b1 elastic rescat. charge pion

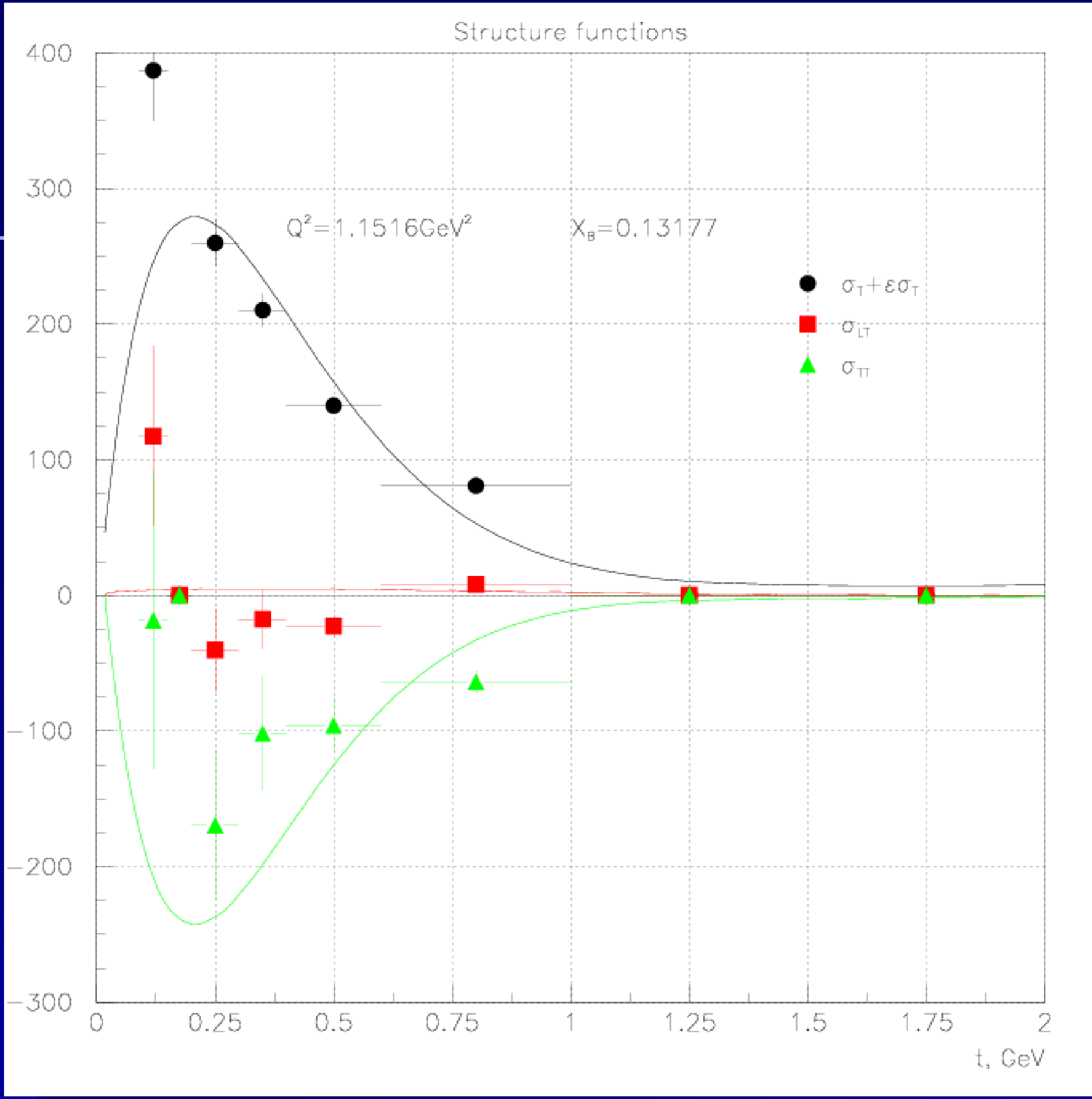


- The dashed lines correspond to the ω/ρ/b1 Regge poles and elastic rescattering
- The full lines include also charge pion nucleon and Delta intermediate states.
- Regge model qualitatively describes the experimental data

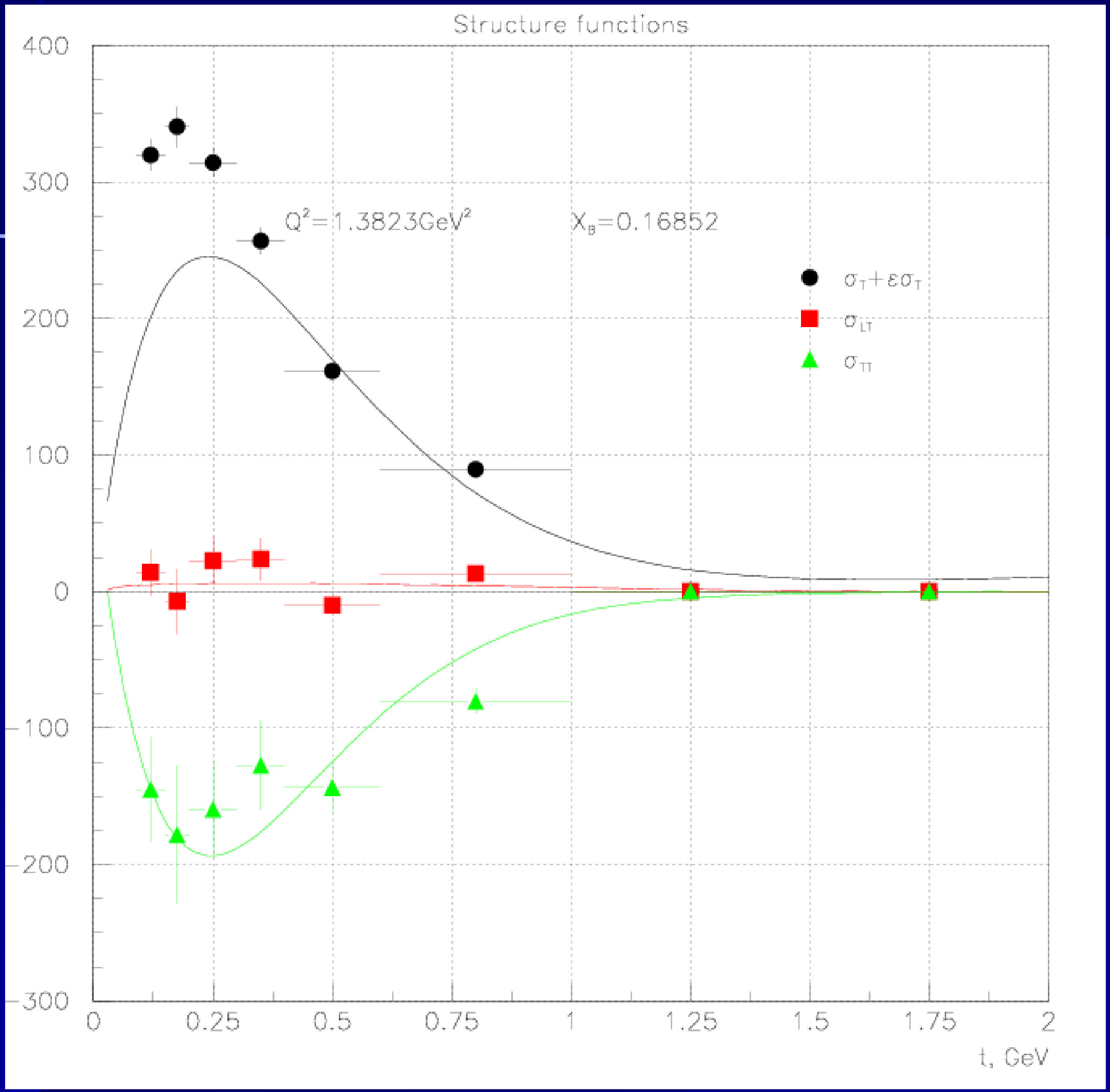
Comparison with J.M. Laget Regge model

- Extracted reduced cross sections were compared with predictions of J.M. Laget Regge Model



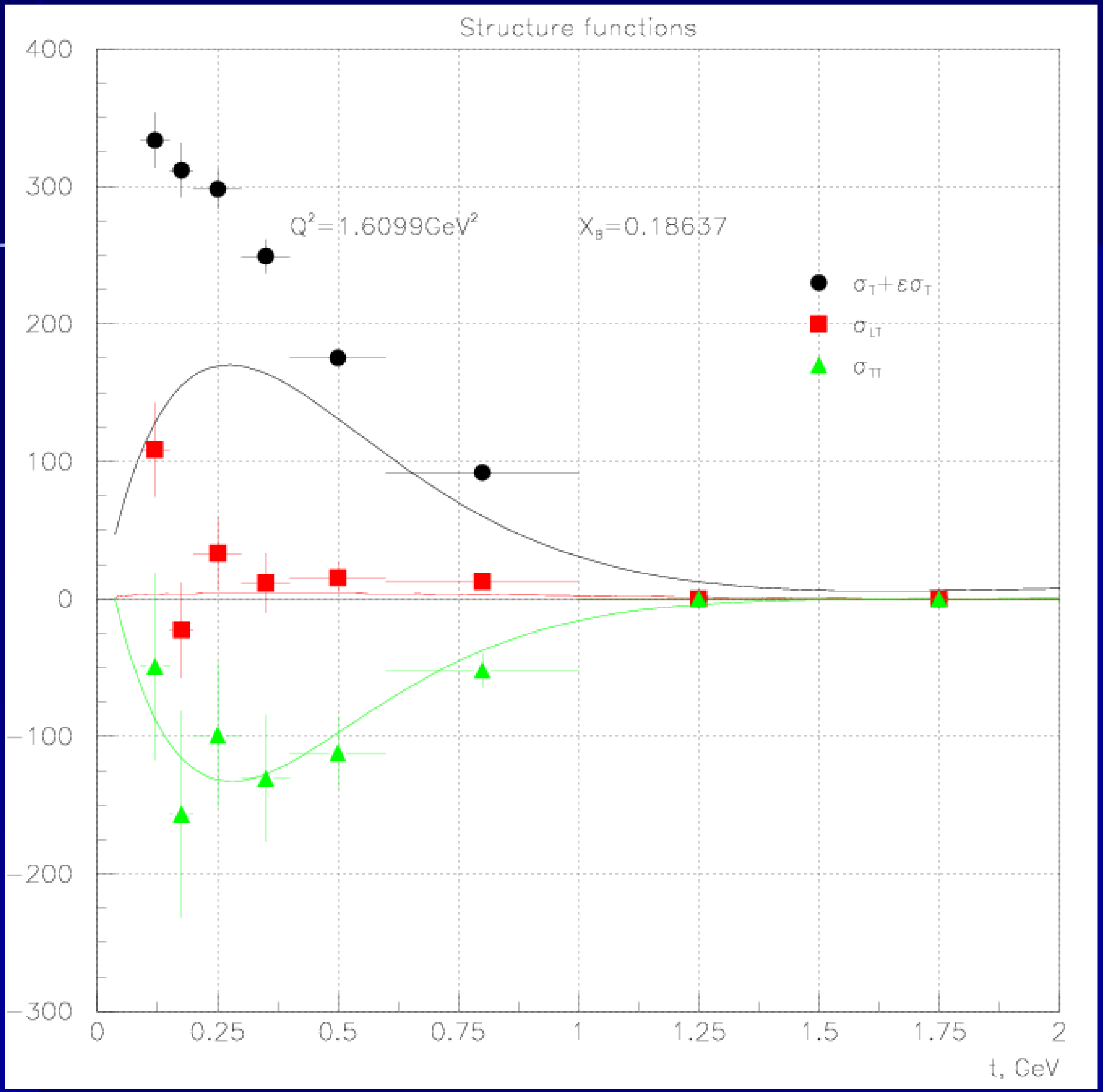


Q^2 = 1.15 GeV^2
x_B = 0.13

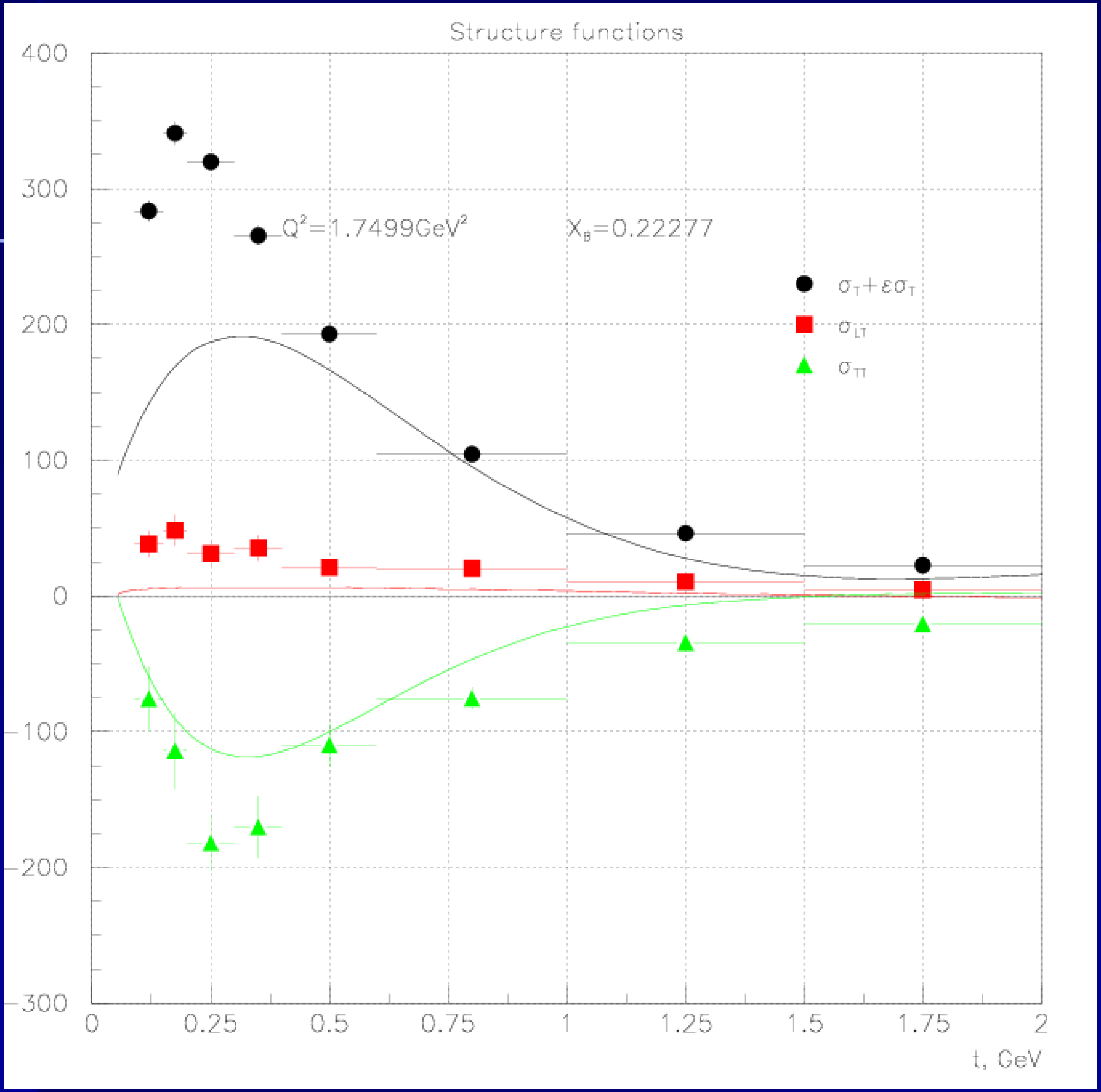


Q^2 = 1.38 GeV^2

x_B = 0.17

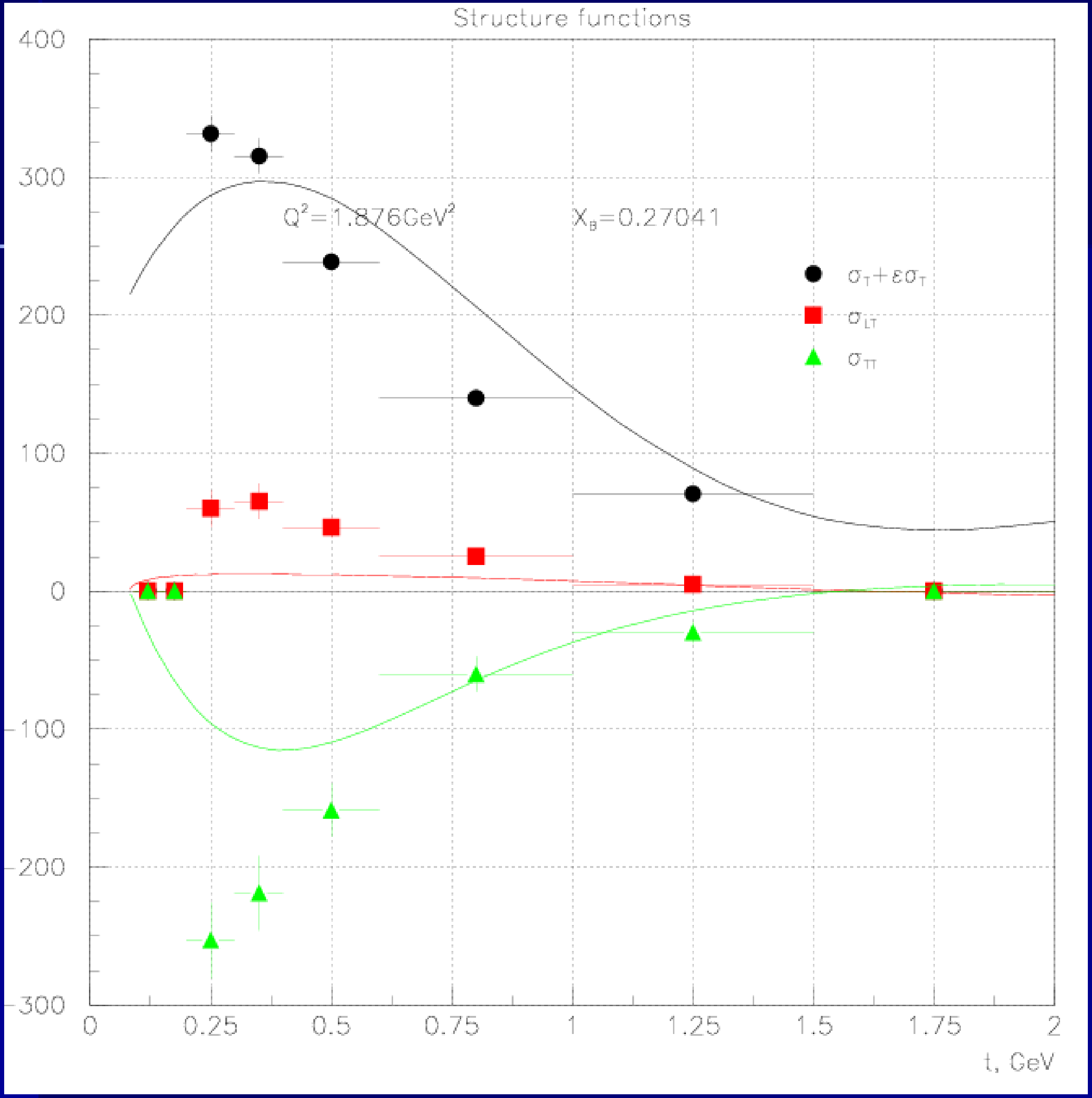


$Q^2 = 1.61\ \text{GeV}^2$
$x_B = 0.19$

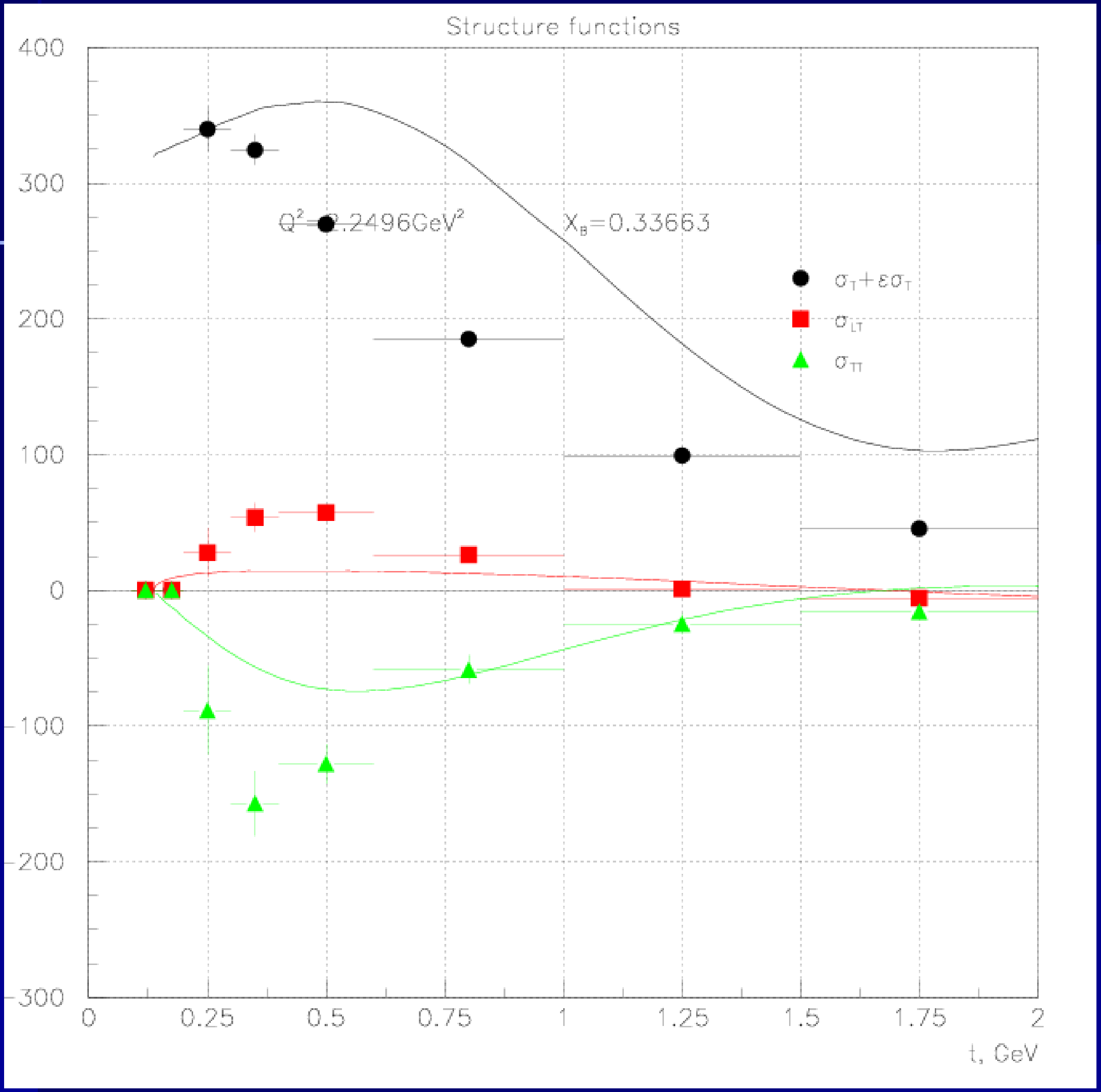


Q^2 = 1.74 GeV^2

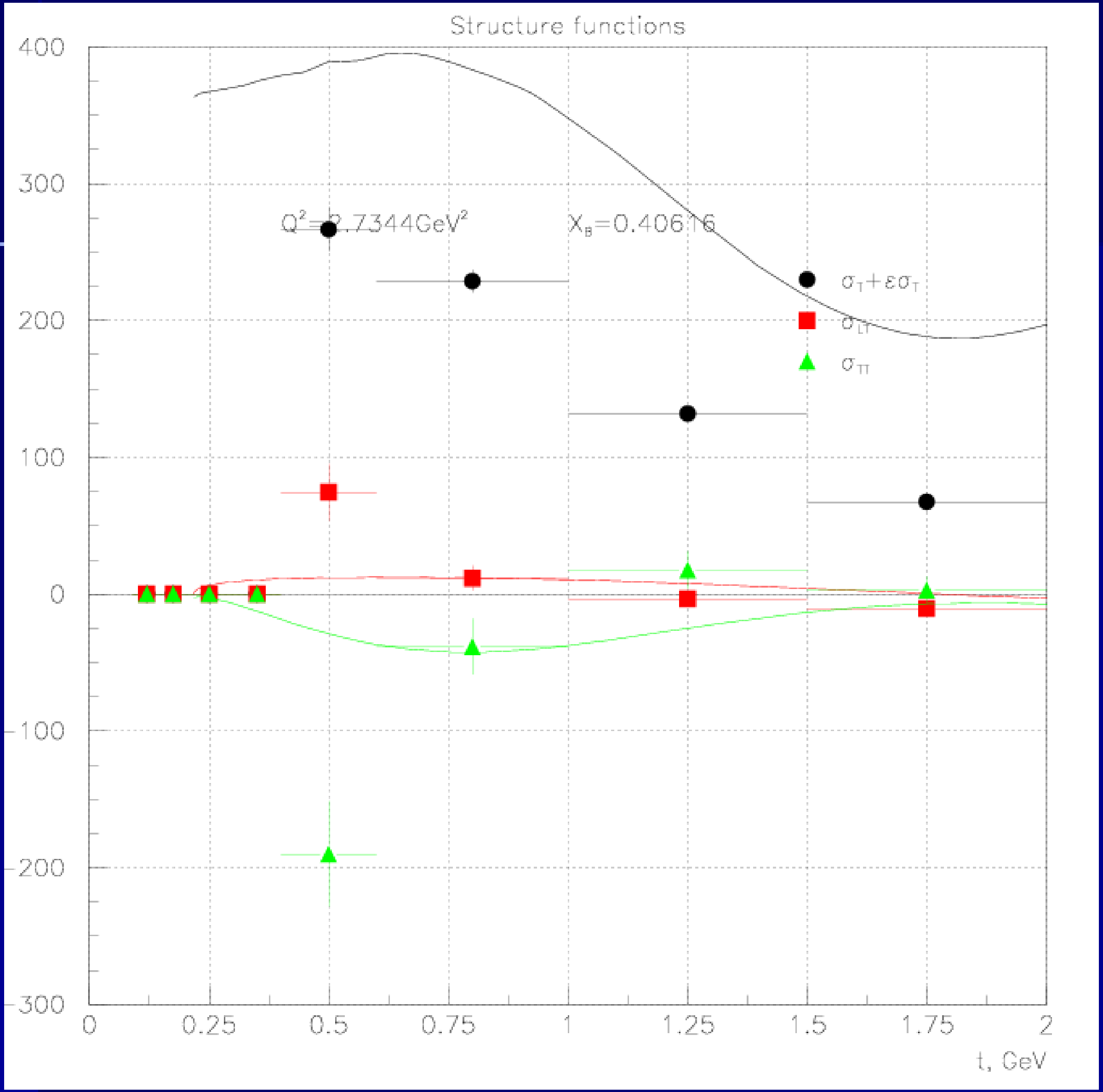
x_B = 0.22



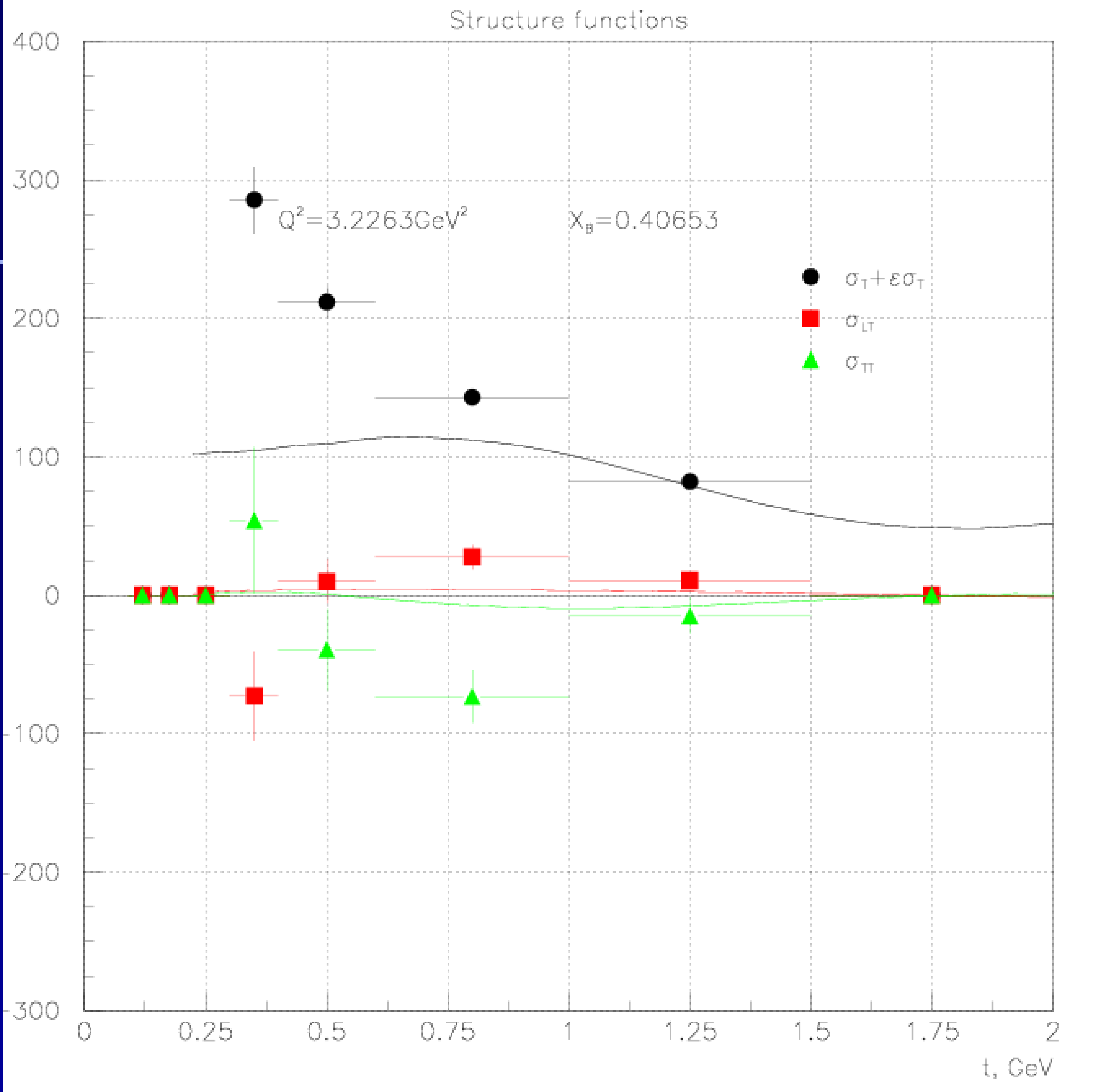
$Q^2 = 1.88\ GeV^2$
$x_B = 0.27$



Q^2 = 2.25 GeV^2
x_B = 0.34



Q^2 = 2.73 GeV^2
x_B = 0.41



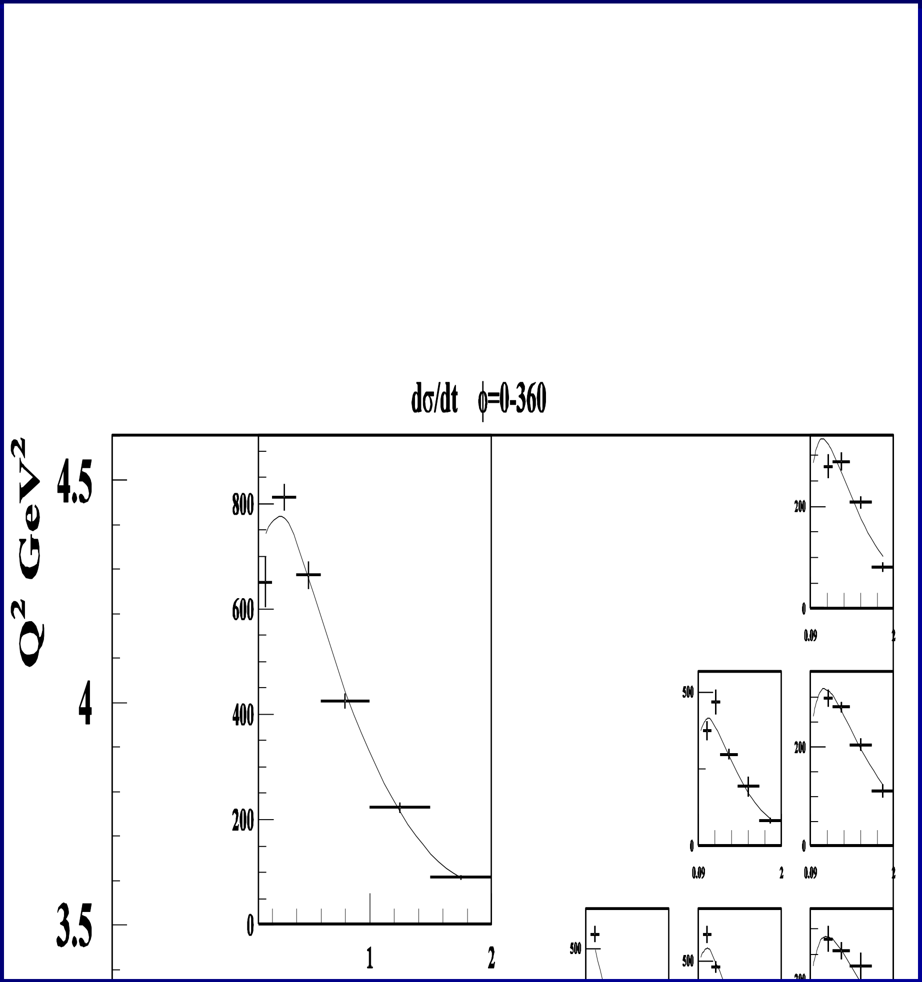
$Q^2 = 3.22\ GeV^2$

$x_B\ = 0.41$

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

t - distribution

$$\frac{d\sigma}{dt} \propto e^{B(x_B, Q^2)t}$$

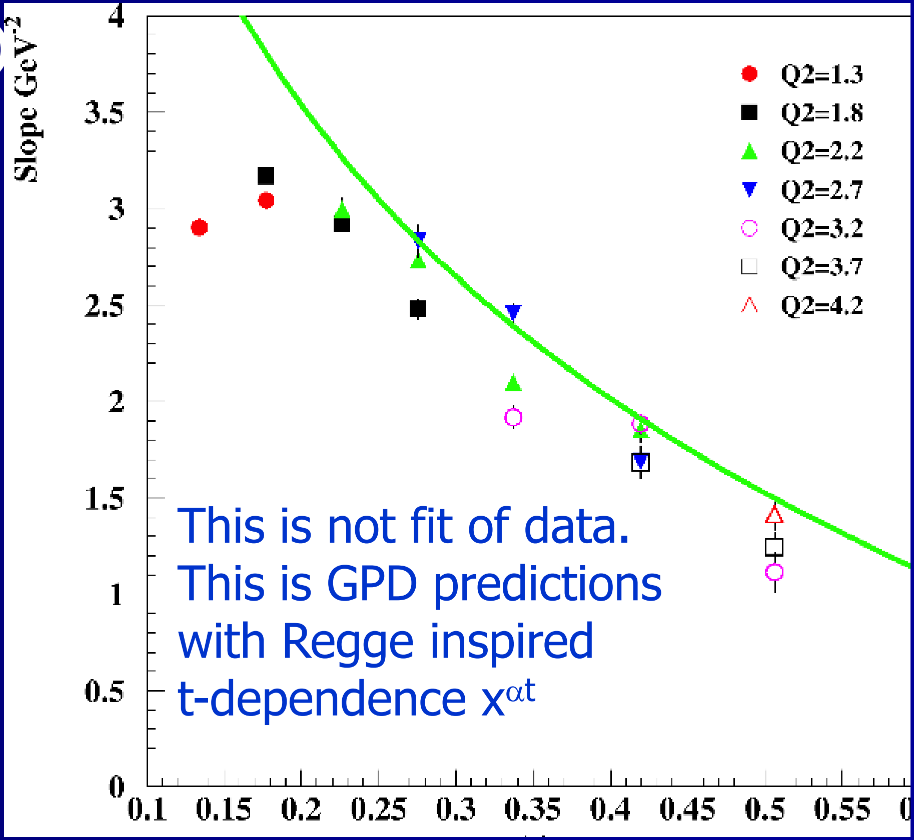


$$\gamma^* p \to p\pi^0$$

t-Slope Parameter as a Function of x_B and Q^2

$$\frac{d\sigma}{dt} \propto e^{B(x_B,Q^2)t}$$

$B(x_B, Q^2)$



x_B

$$f^q(x,t) \propto x^{\alpha_q(t)} \propto x^{\alpha' t}$$

$$\frac{d\sigma}{dt} \propto \left[x^{\alpha' t}\right]^2 = e^{2\alpha' \ln(1/x)t}$$

$$B(x) = 2\alpha' \ln(1/x)$$

$$\alpha' = 1.1$$

- **$B(x_B, Q^2)$ is almost independent of Q^2**
- **$B(x_B)$ is decreasing with increasing x_B**

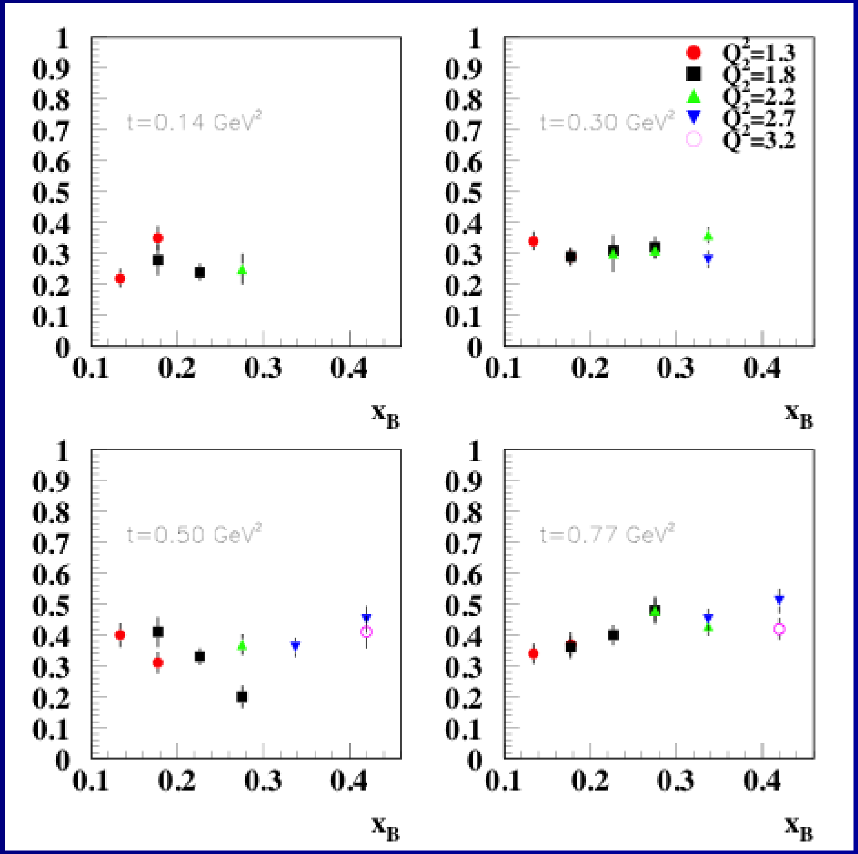
η/π^0 Ratio

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

Preliminary data on the ratio η/π^0 as a function of x_B for different bins in t.

The dependence on the x_B and Q^2 is very week.

Probably we have small positive slope.
The ratio in the photoproduction is near 0.2-0.3 (very close to what we have at our smallest Q^2).



π^0 and η Beam Spin Asymmetry

$$\frac{d\sigma}{dtd\phi}(Q^2,x,t,\phi)=\frac{1}{2\pi}\left(\frac{d\sigma_T}{dt}+\varepsilon\frac{d\sigma_L}{dt}+\varepsilon\frac{d\sigma_{TT}}{dt}\cos 2\phi+\sqrt{2\varepsilon(\varepsilon+1)}\frac{d\sigma_{LT}}{dt}\cos\phi\right.$$
$$\left.+h\sqrt{2\varepsilon(\varepsilon-1)}\sin\phi\frac{d\sigma_{L'T}}{dt}\right)$$

h is the beam helicity

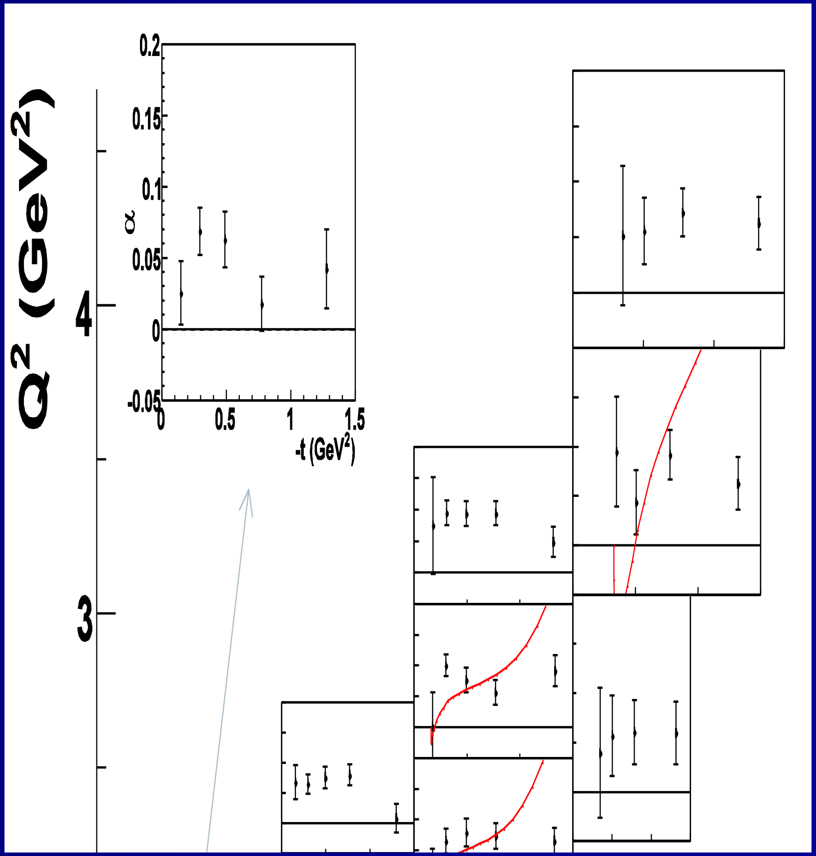
$$A=\frac{d^4\vec{\sigma}-d^4\overleftarrow{\sigma}}{d^4\vec{\sigma}+d^4\overleftarrow{\sigma}}\approx\alpha\sin\varphi$$

Any observation of a non-zero BSA
would be indicative of an L’T interference.
If σ_L dominates, σ_{LT}, σ_{TT}, and $\sigma_{L'T}$ go to zero

$\gamma^{*} p \to p \pi^{0}$

Beam Spin Asymmetry

- The red curves correspond to the Regge model (JML)
- BSA are systematically of the order of 0.03-0.09 over wide kinematical range in x_B and Q^2



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

Beam Spin Asymmetry

Ahmad, Goldstein, Luiti, 2009

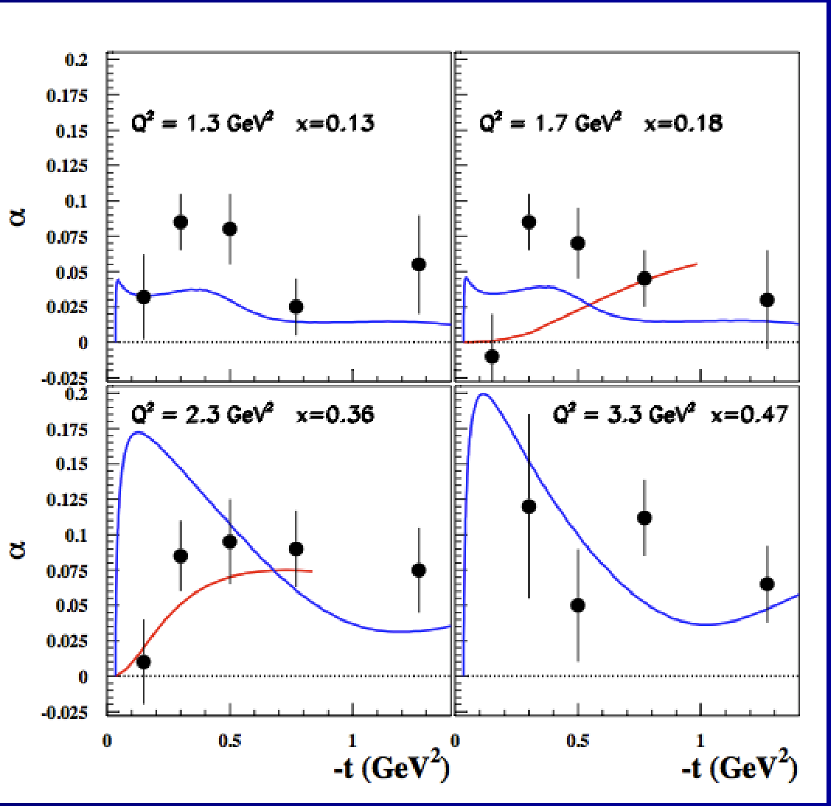
- Data CLAS
- Blue – Regge model
- Red – GPD predictions
- tensor charges

  $\delta u=0.48$,

  $\delta d = -0.62$
- transverse anomalous magnetic moments

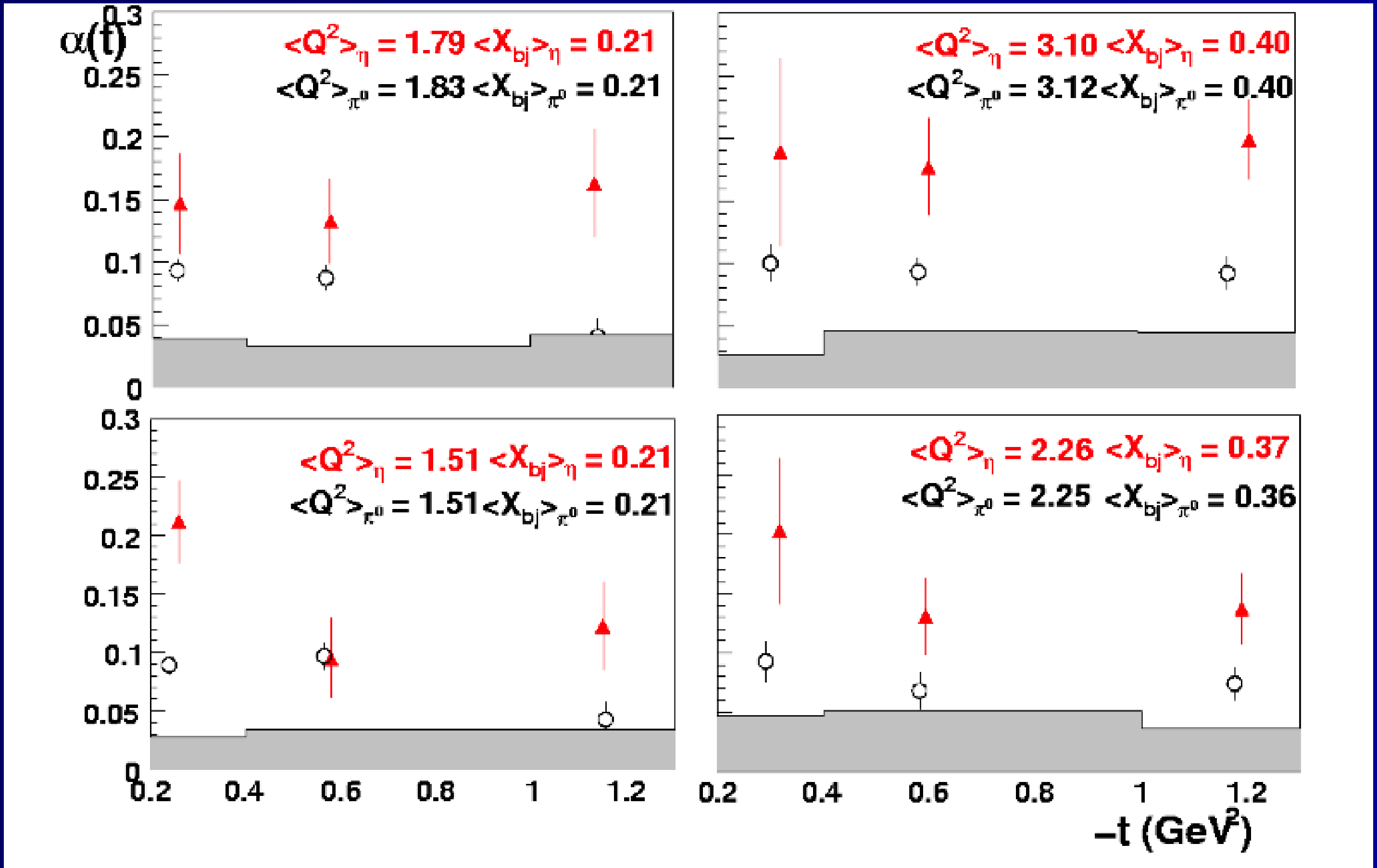
  $\kappa^u_T = 0.6$,

  $\kappa^d_T = 0.3$.



$\gamma^* p \rightarrow p\eta$

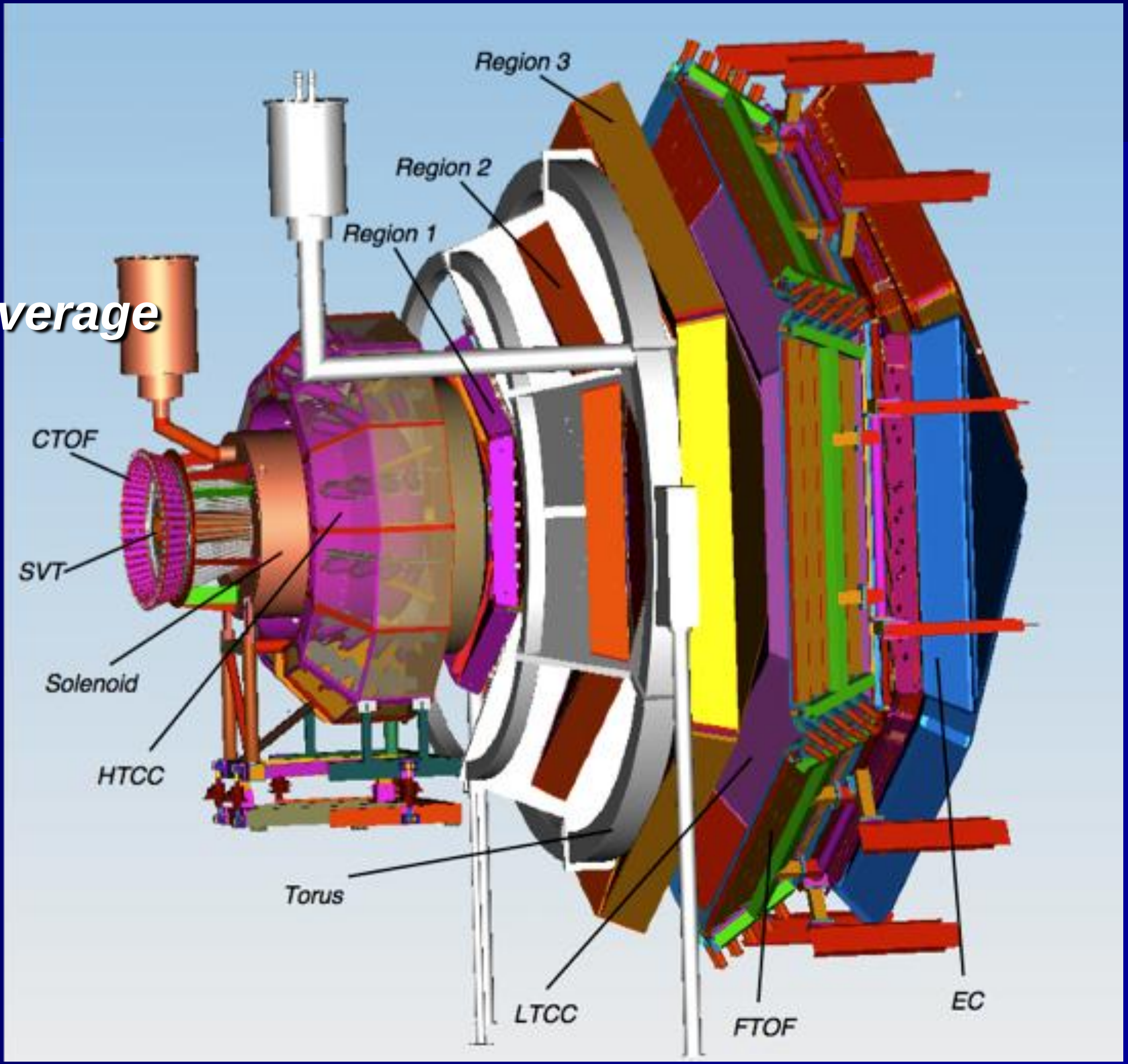
η Beam Spin Asymmetry



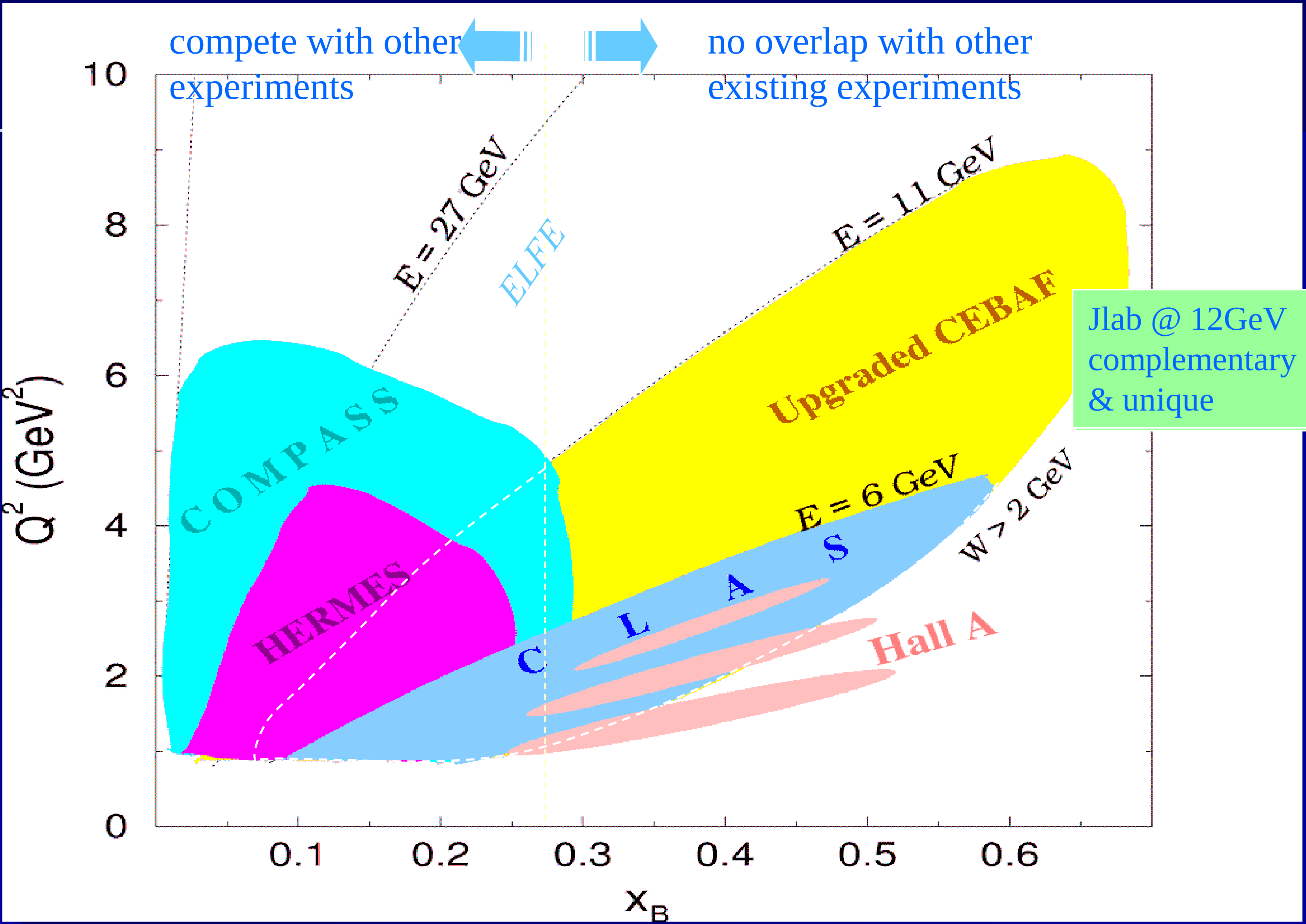
JLab 12 GeV Upgrade

CLAS12

- High luminosity
- Large acceptance
- Wide kinematic coverage
- High precision



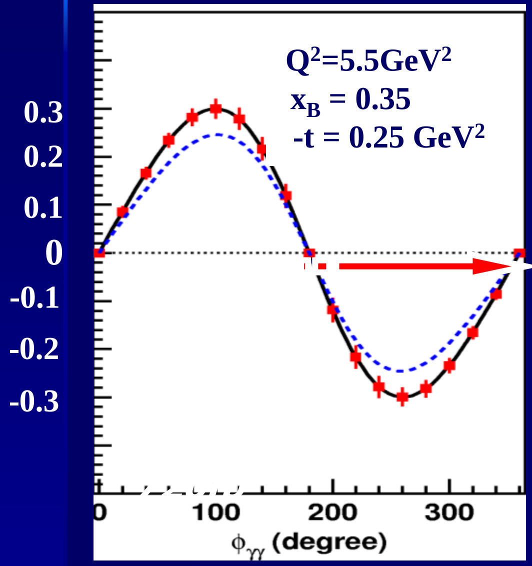
Kinematics coverage for deeply exclusive experiments



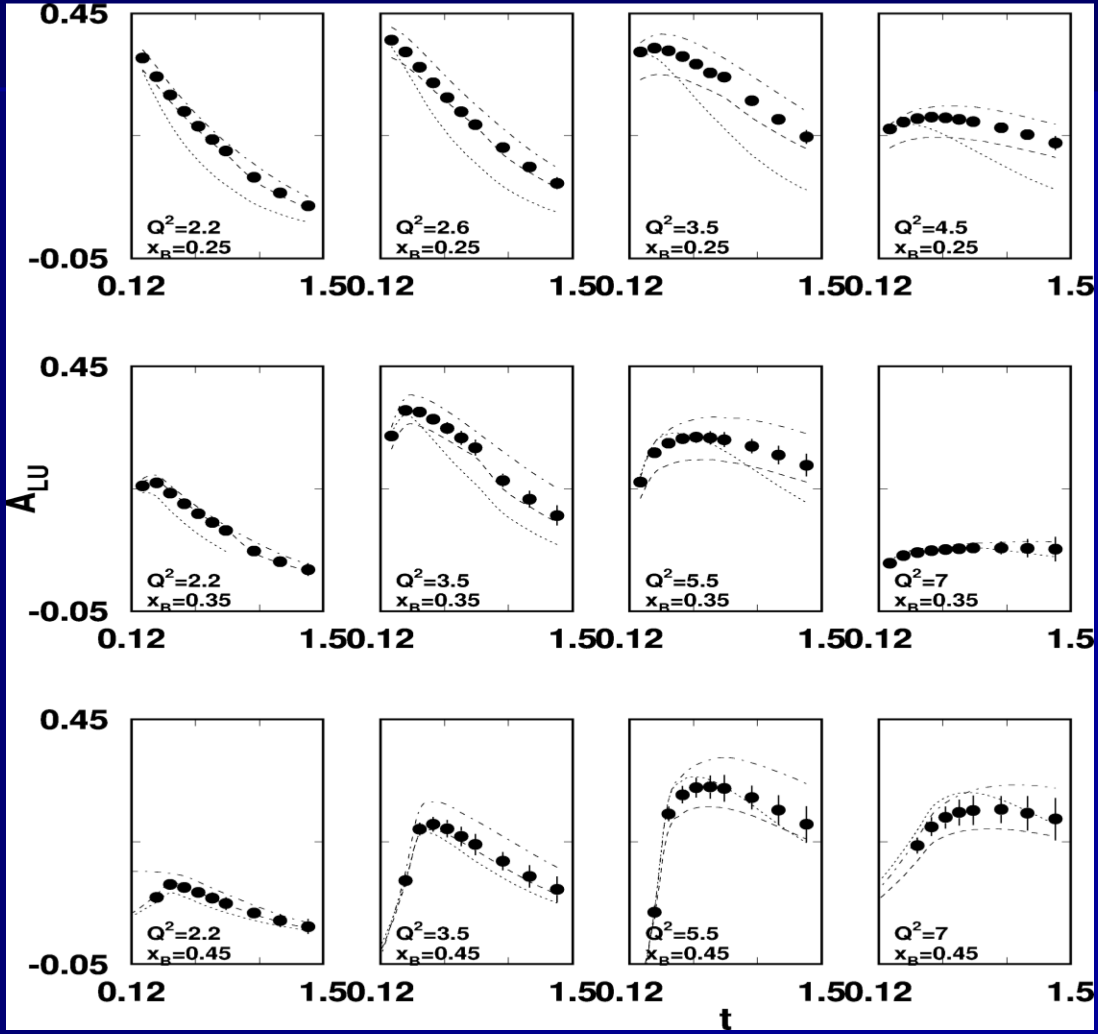
Jlab @ 12GeV
complementary
& unique

DVCS beam asymmetry at 12 GeV

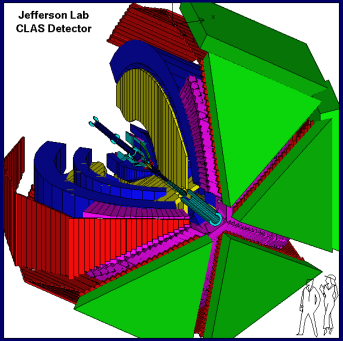
$$\vec{e}p \rightarrow ep\gamma$$



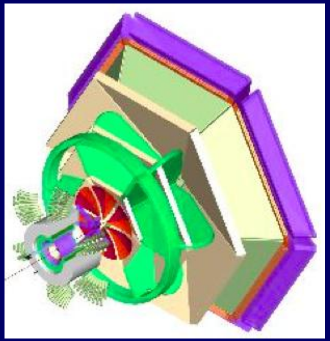
Kinematics coverage,
$Q^2 < 8$ GeV^2,
$x_B < 0.65$,
$t < 2.0$ GeV^2



Summary

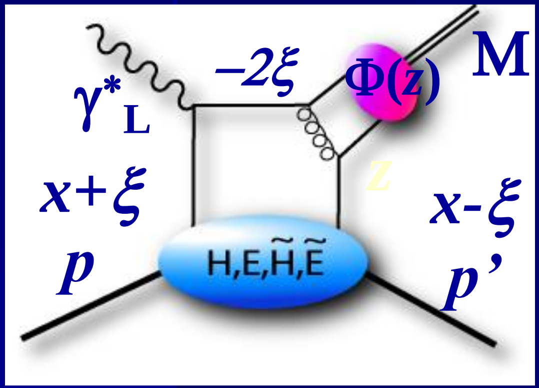


2015

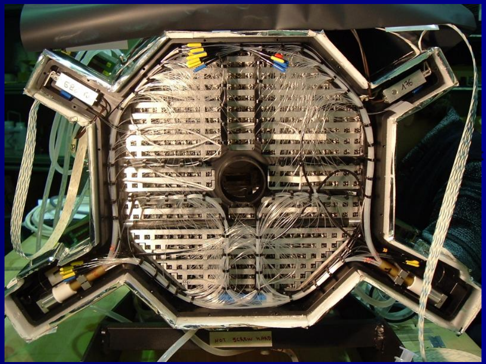


- Deeply Virtual Meson Production has the potential to probe the nucleon structure at the parton level, as described by Generalized Parton distributions (GPDs).
- The most extensive set of π^0, η, ρ^+,ρ^0,ω, and ϕ electroproduction to date has been obtained with the CLAS spectrometer.
- Structure functions, the π^0/η ratio of the cross sections and beam-spin asymmetries were extracted in the valence quark region.
- Sizable interference terms σ_{TT} and σ_{LT} and non-zero asymmetries imply that both transverse and longitudinal amplitudes participate in the process.
- The detailed comparison with the Regge model predictions was done. The model describes the data reasonably well.
- We are working with theorists who are doing the calculation of the DVMP cross sections within the handbag GPD based models. The comparison results are coming.
- CLAS12 will continue the GPD study with broader kinematics at 12 GeV machine.

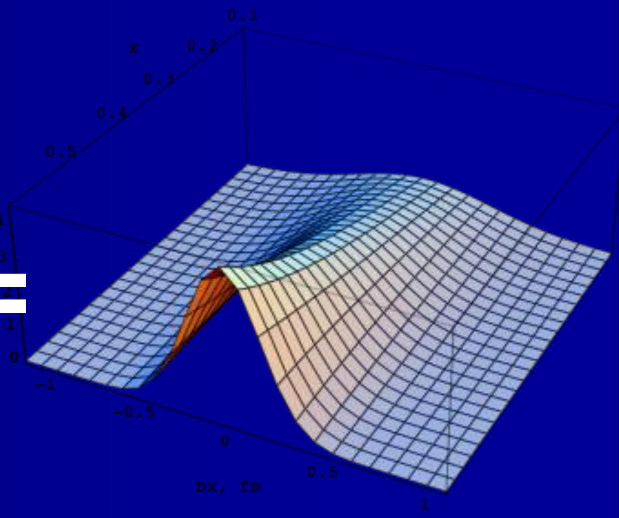
The End



+

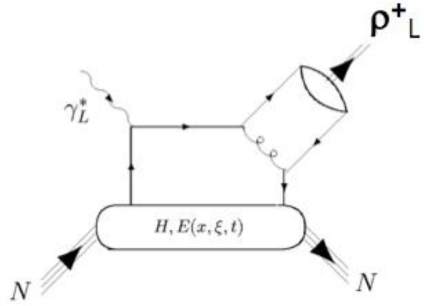


=



Vector mesons

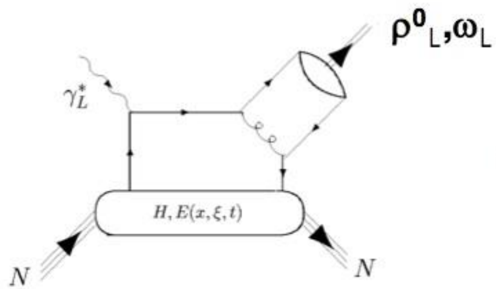
$\gamma^* p \to n\rho^+$



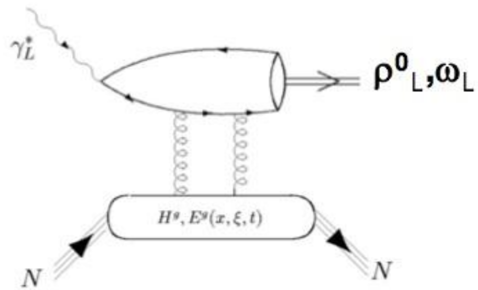
ρ^0	$e_u H^u - e_d H^d$ $e_u E^u - e_d E^d$
ω	$e_u H^u + e_d H^d$ $e_u E^u + e_d E^d$
ρ^+	$H^u - H^d$ $E^u - E^d$

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

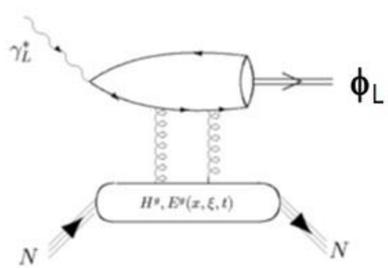
$\gamma^* p \to p\omega$



+

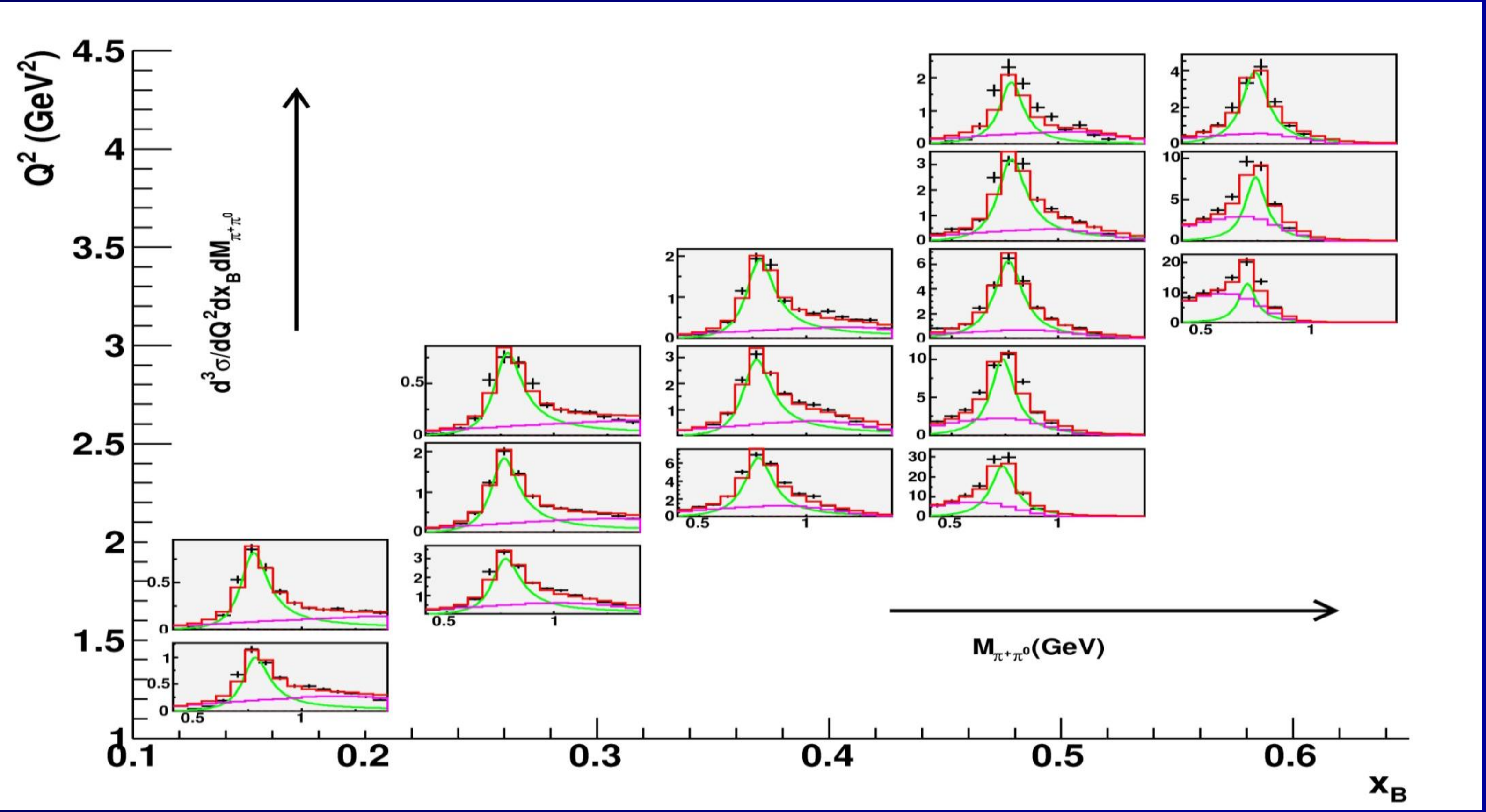


$\gamma^* p \to p\phi$



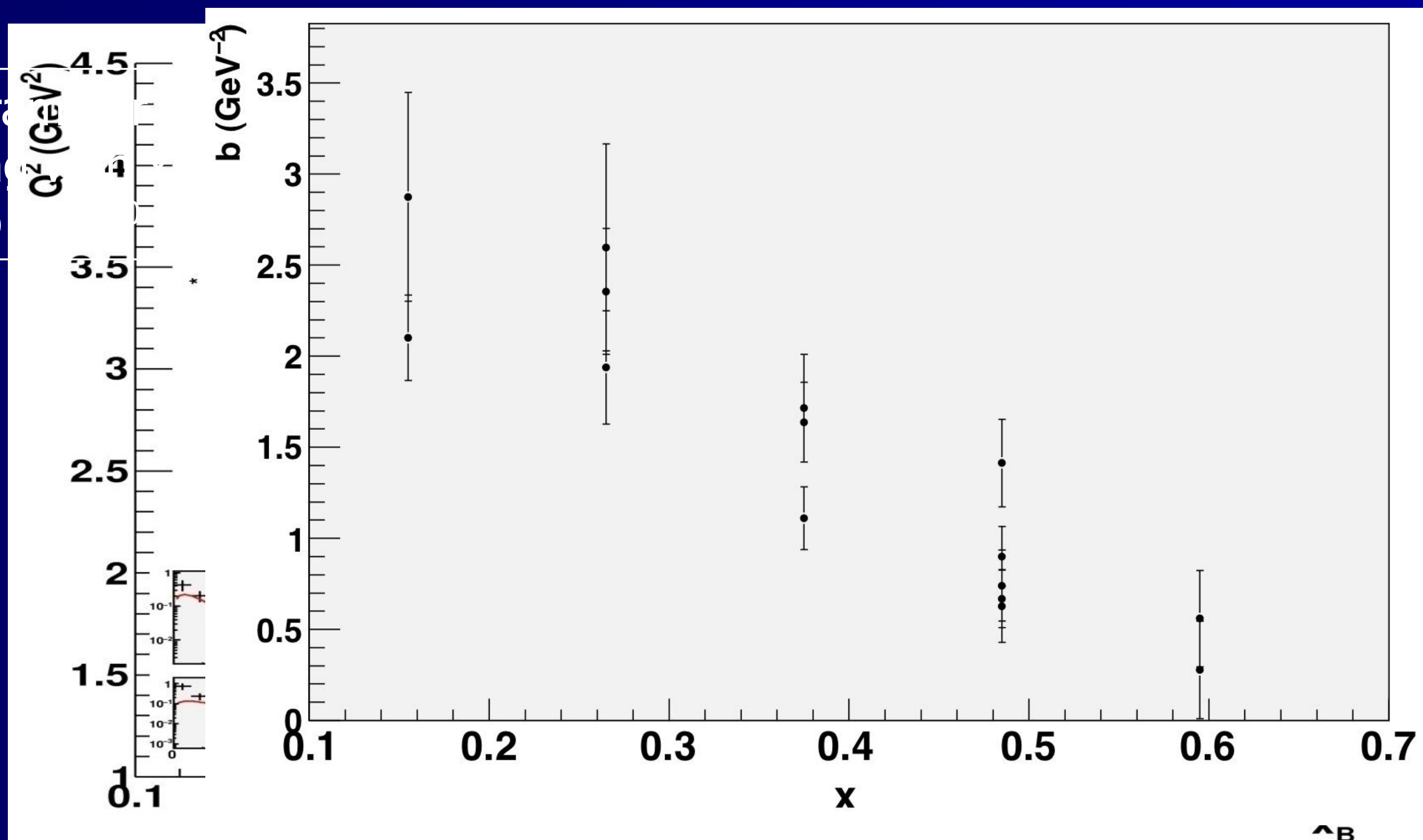
$$ep \rightarrow en\rho^{+}, \quad \rho^{+} \rightarrow \pi^{+}\pi^{0}, \quad \pi^{0} \rightarrow \gamma\gamma$$

World's first-ever measurement



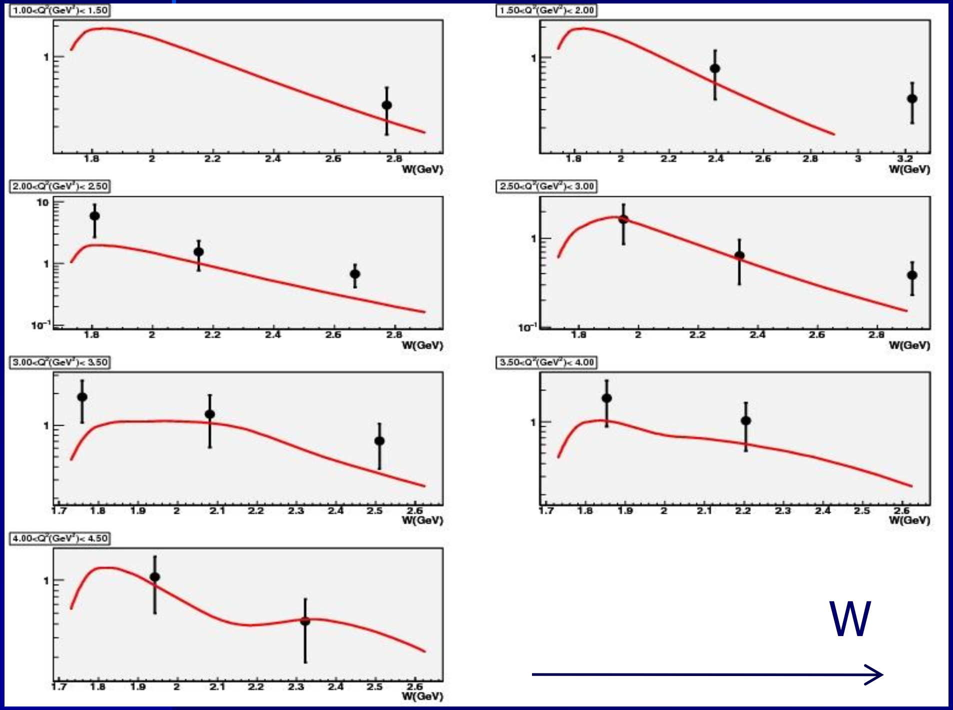
$$\frac{d\sigma}{dt}(\gamma^* p \rightarrow en\rho^+) \propto \sqrt{-t}e^{bt}$$

Slope para
decreasin
Similar to

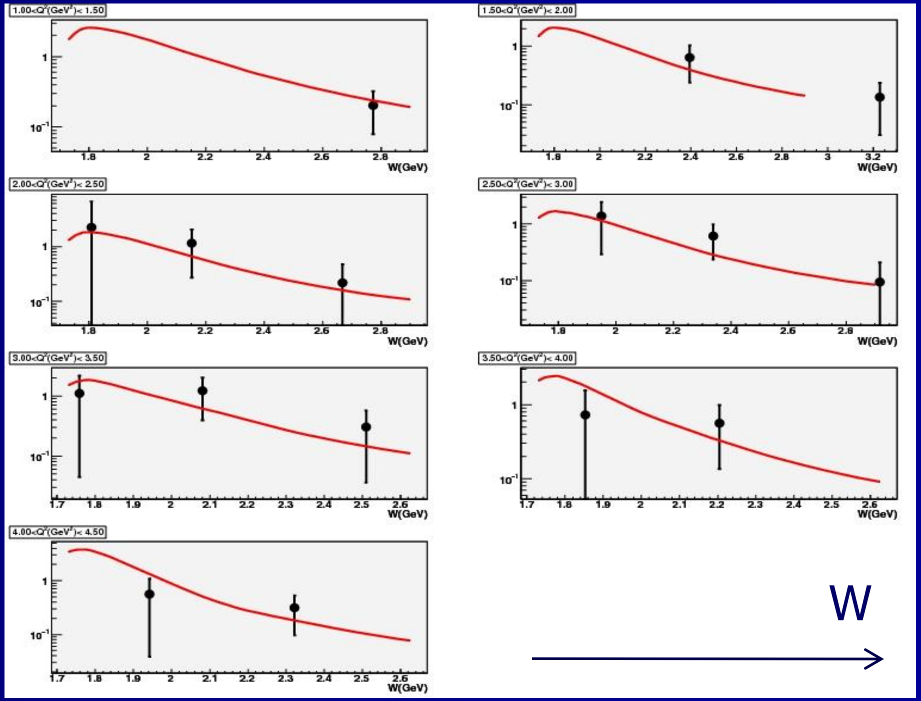


σ_L σ_T separation
SCHC S-channel helicity conservation

σ_L



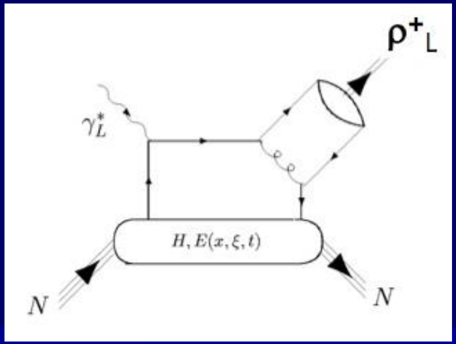
σ_T



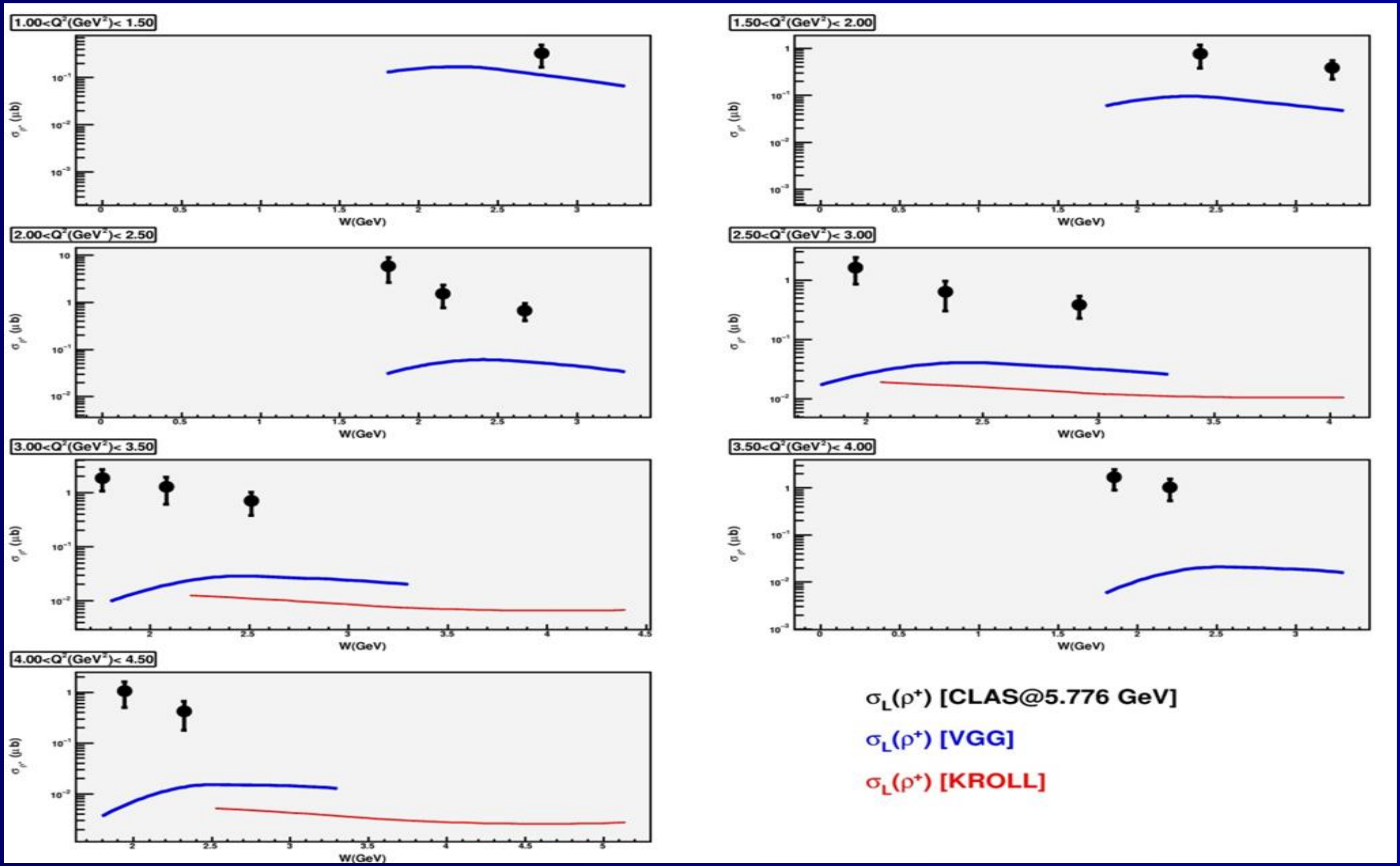
Red lines (Regge model) **:*Laget***, *Phys. Rev.* ***D 65***, *074022 (2002)*

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

CLAS data

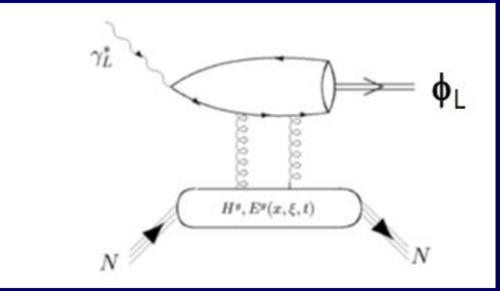


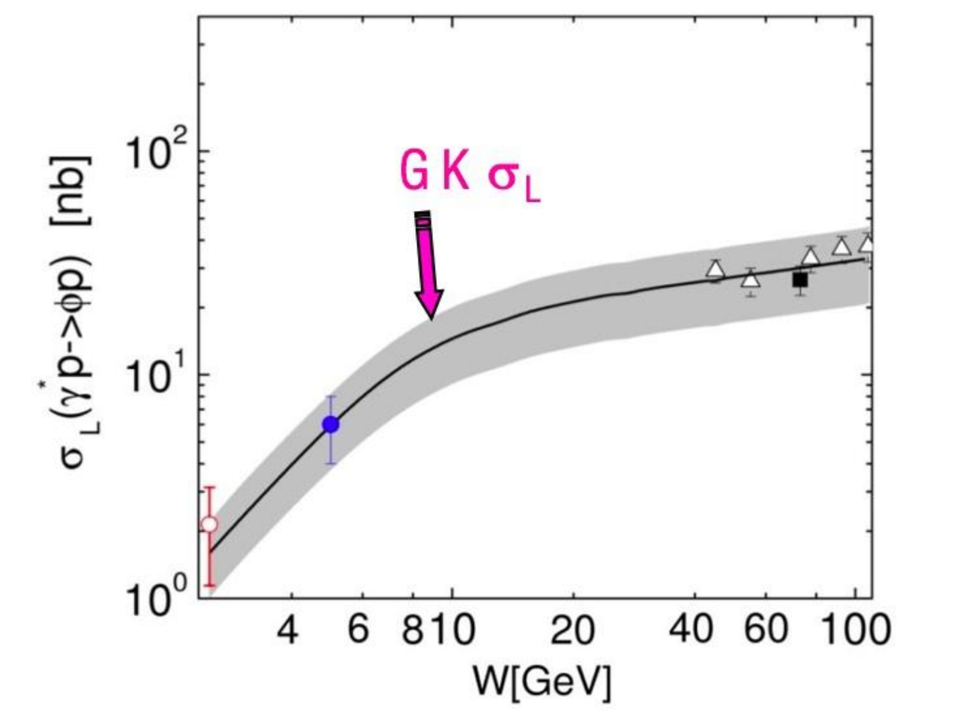
σ_L



GPD fails to describe data by more than order of magnitude

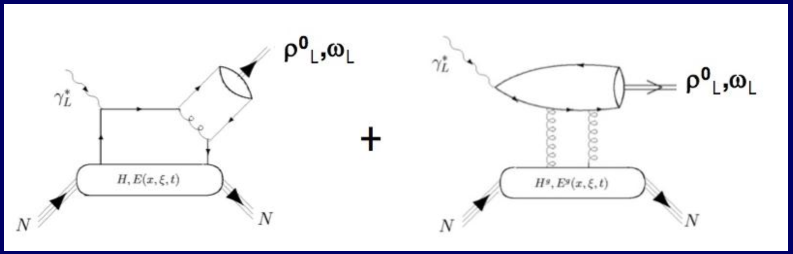
$$\gamma_L^* p \rightarrow p\phi$$





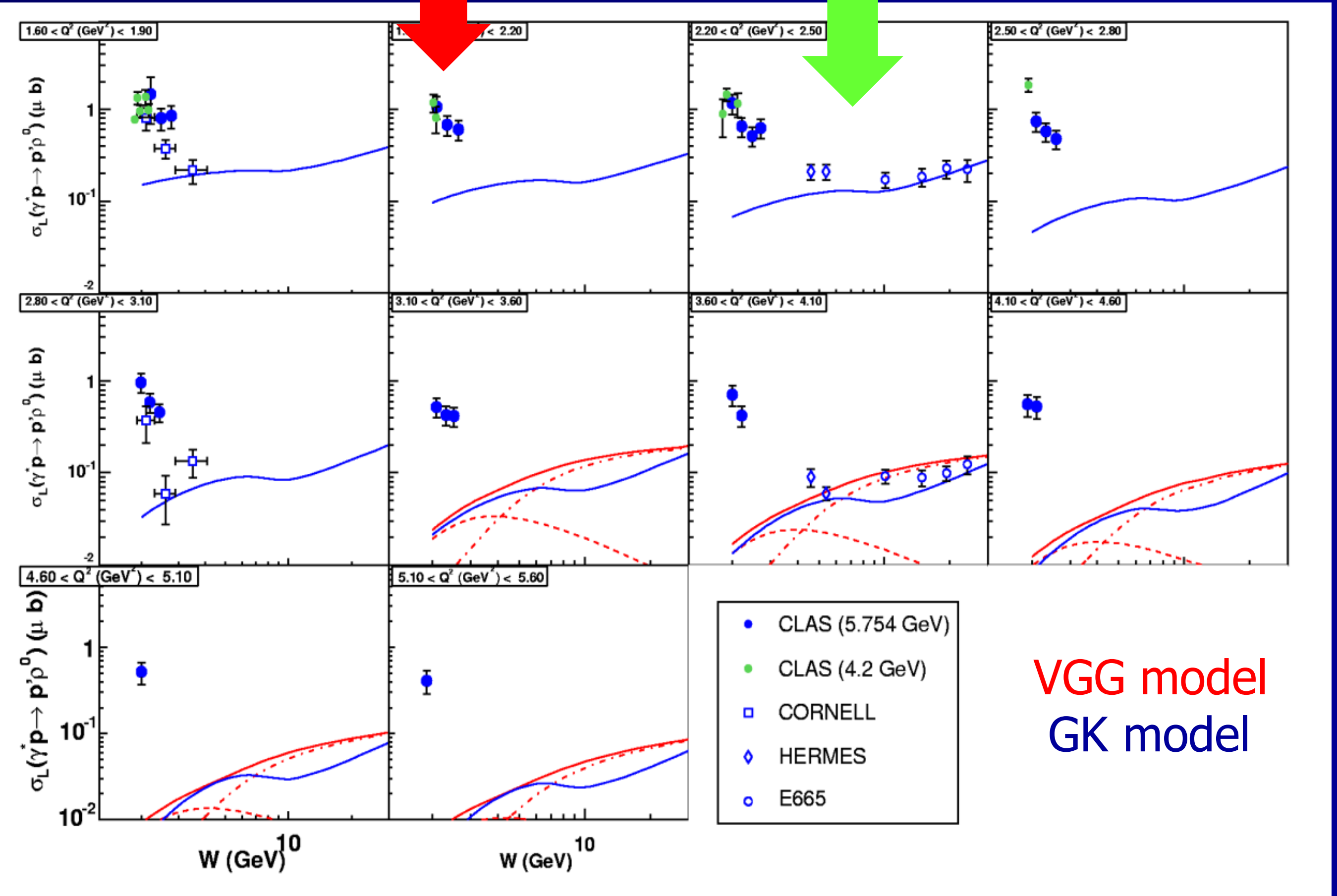
- Gluons GPD are dominant for ϕ mesons
- GPD approach describes well data for W>5 GeV
  for ρ^0 and ω channels: handbag for sea quarks and/or gluons is dominant.

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



Fails to describe data W<5 GeV

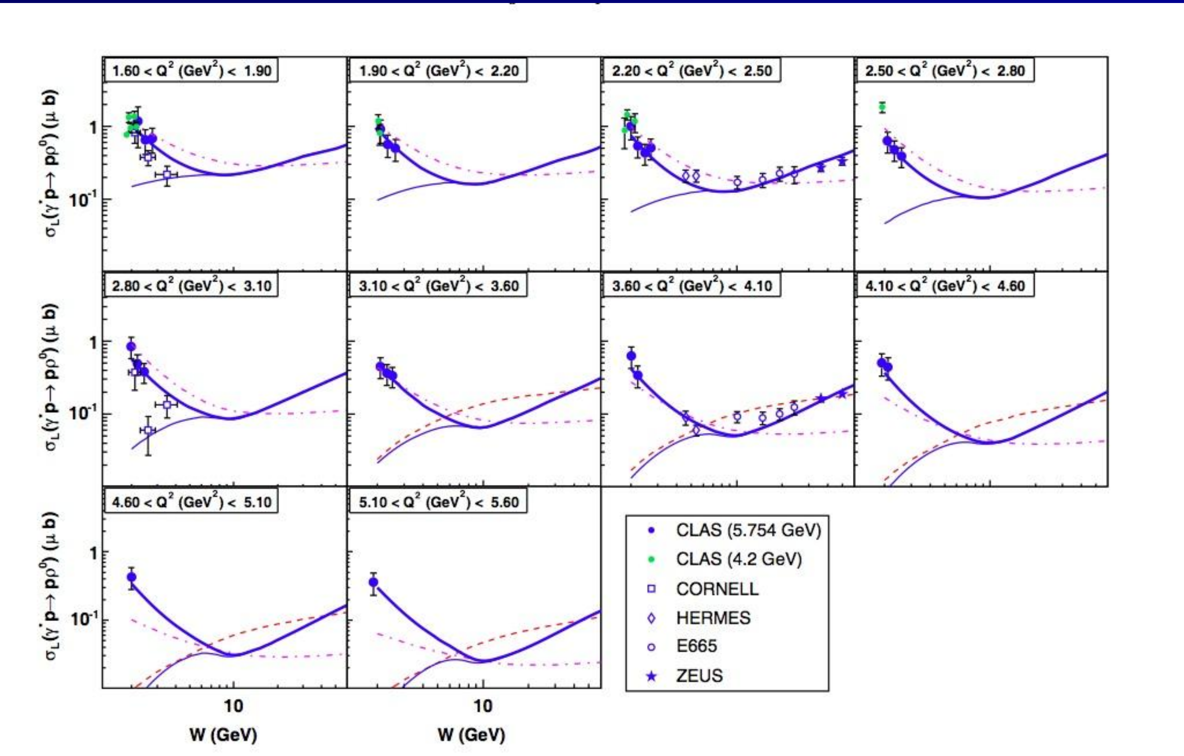
Describes well for W>5 GeV



VGG model

GK model

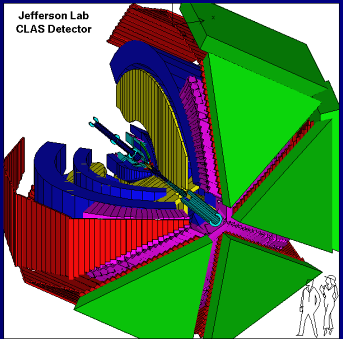
VGG "meson-like contribution"



•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, adding the so called generalized D-term together with standard VGG model successfully describes data

Summary

- CLAS DVCS results were used for the GPD extraction. This is the first step in 3-D imaging of the nucleon
- More data coming with H_2 and polarized targets.
- The most extensive data set of π^0, η, ρ^+,ρ^0,ω, and ϕ electroproduction to date has been obtained with the CLAS spectrometer
- Cross sections and beam-spin asymmetries were extracted in the valence quark region
- The detailed comparison with the Regge model predictions was done. The model describes the data reasonably well
- The popular GPD models fail to describe the experimentally measured meson cross sections. The present data provide important input to improve our understanding of these fundamental QCD issues
- CLAS12 will continue the GPD study with broader kinematics at 12 GeV machine



2015