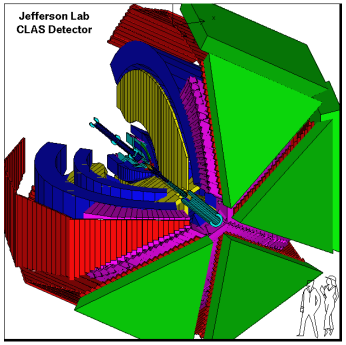
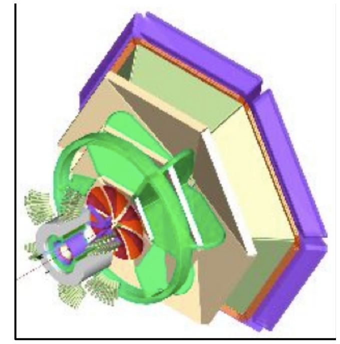


Jefferson Lab
Thomas Jefferson National Accelerator Facility



Hard exclusive π^0 and η production

Valery Kubarovsky

Jefferson Lab

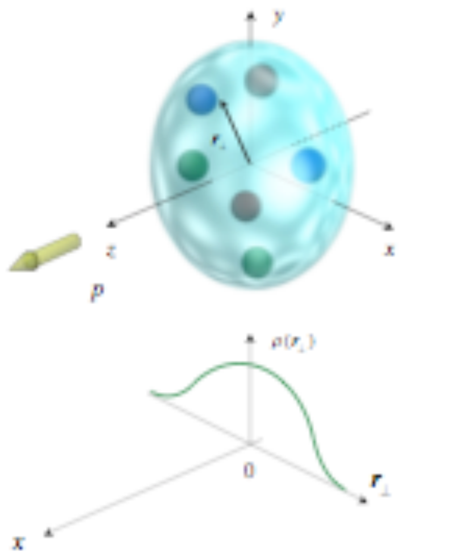
August 20, 2011

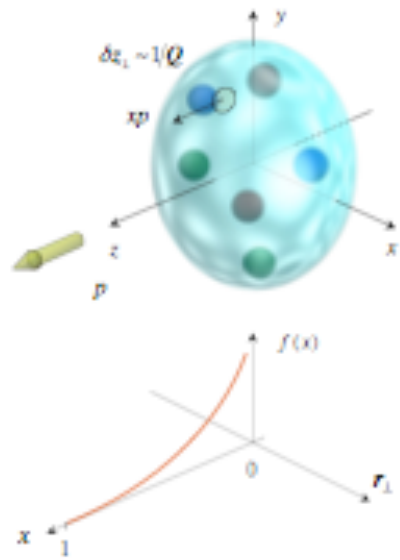
Hall-C Summer Workshop

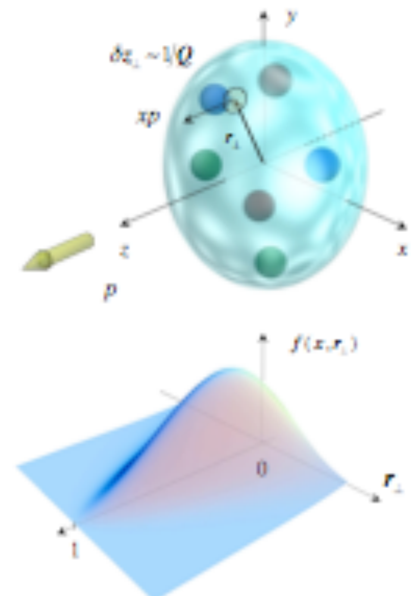
Outline

- Physics motivation
- CLAS6 data on pseudoscalar meson electroproduction
- E12-06-108 Hard exclusive electroproduction of π^0 and η with CLAS12
- Conclusion

Description of hadron structure in terms of GPDs

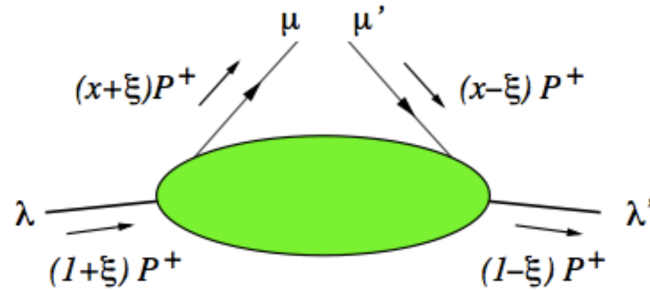






Nucleon form factors	Structure functions	GPDs
transverse charge & current densities Nobel prize 1961- R. Hofstadter	quark longitudinal momentum (polarized and unpolarized) distributions Nobel prize 1990 –J.Friedman, H. Kendall, R. Taylor	correlated quark momentum distributions (polarized and unpolarized)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

Generalized Parton Distributions



- There are 4 chiral even GPDs where partons do not transfer helicity H̃, H, E, E
- H and E are "unpolarized" and H̃ and Ẽ 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

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

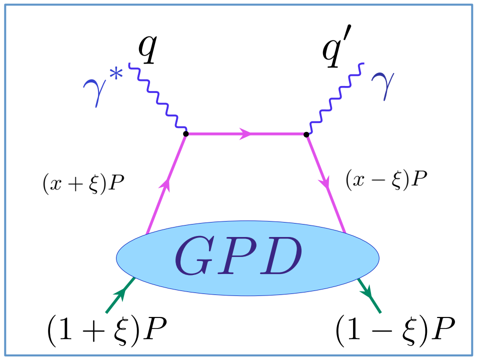
- Form factors

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

- Angular Momentum

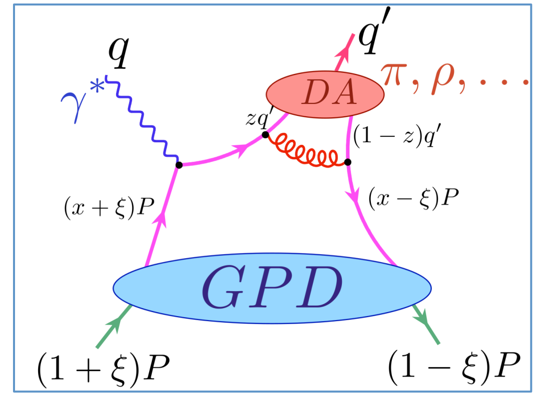
$$J^q(t) = \frac{1}{2}\int_{-1}^{1} \mathrm{d}x\, x\,[H^q(x,\xi,t) + E^q(x,\xi,t)]$$

(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.

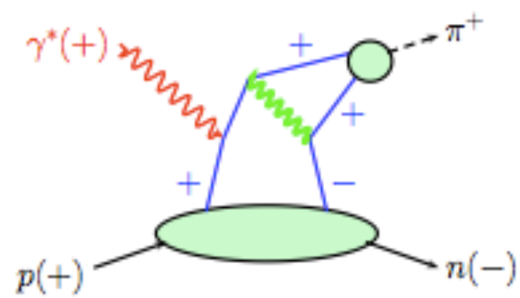
	Meson	GPD flavor composition
$\widetilde{H}, \widetilde{E}$	π^+	$\Delta u - \Delta d$
	π^0	$2\Delta u + \Delta d$
	η	$2\Delta u - \Delta d$
H, E	ρ^0	$2u + d$
	ρ^+	$u - d$
	ω	$2u - d$

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.

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



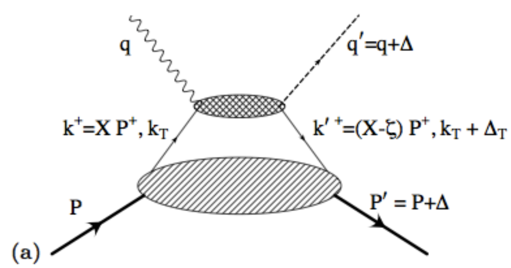
$$H_T^q(x,0,0) = h_1^q(x)$$

Nucleon Tensor Charge from Exclusive π^0 Electroproduction

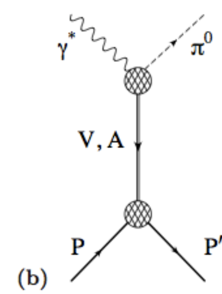
$$\gamma^* p \to p\pi^0$$

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.

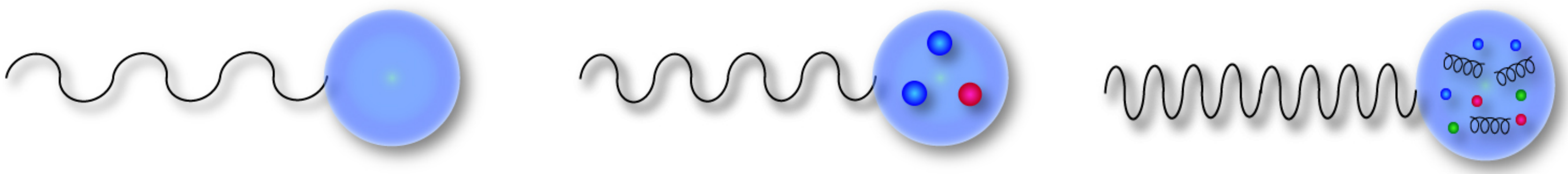


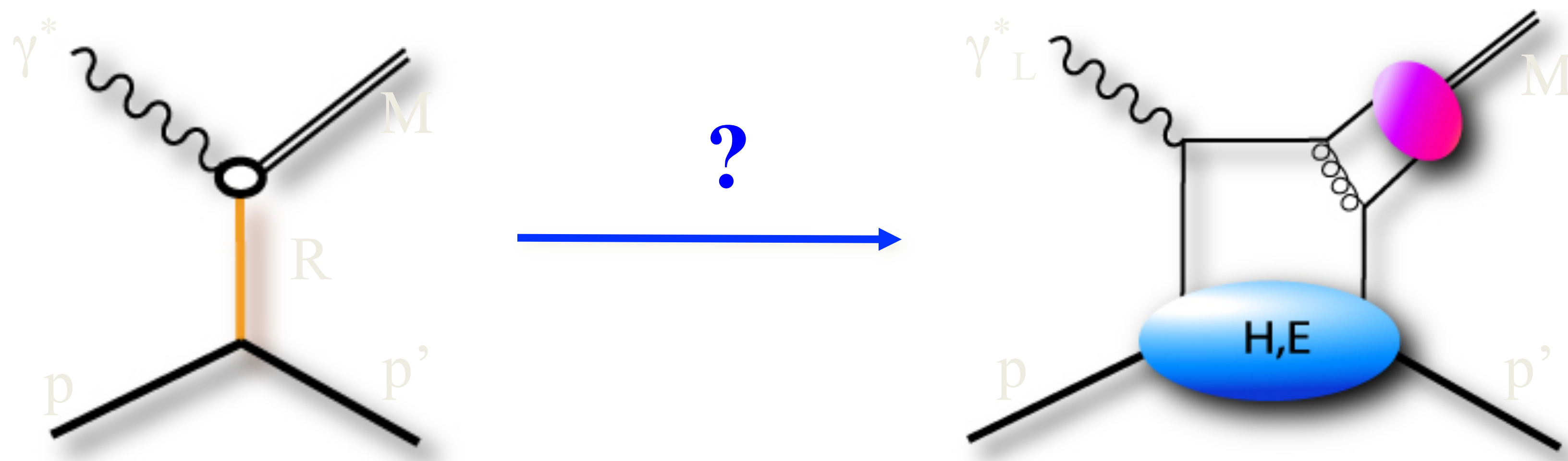
partonic degrees of freedom interpretation;



t-channel exchange diagram

Transition from "hadronic" to the partonic degrees of freedom

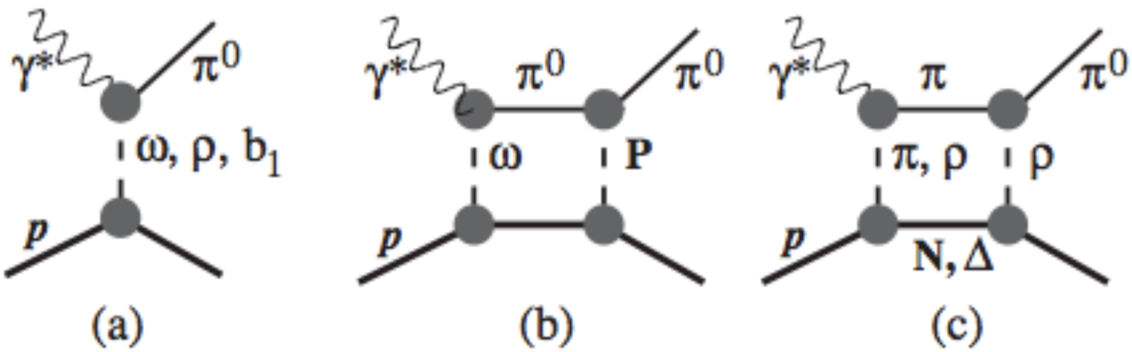


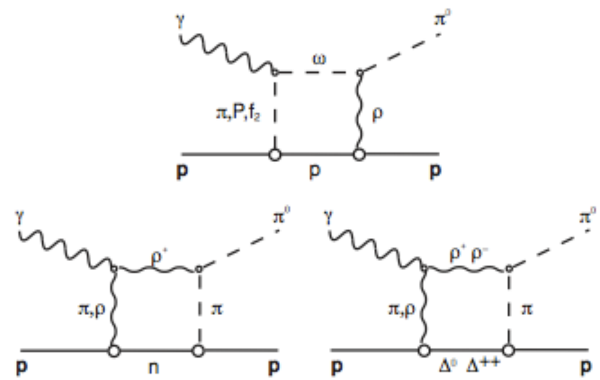


$$\gamma^* p \to p\pi^0$$

Regge Model

J.M. Laget 2010

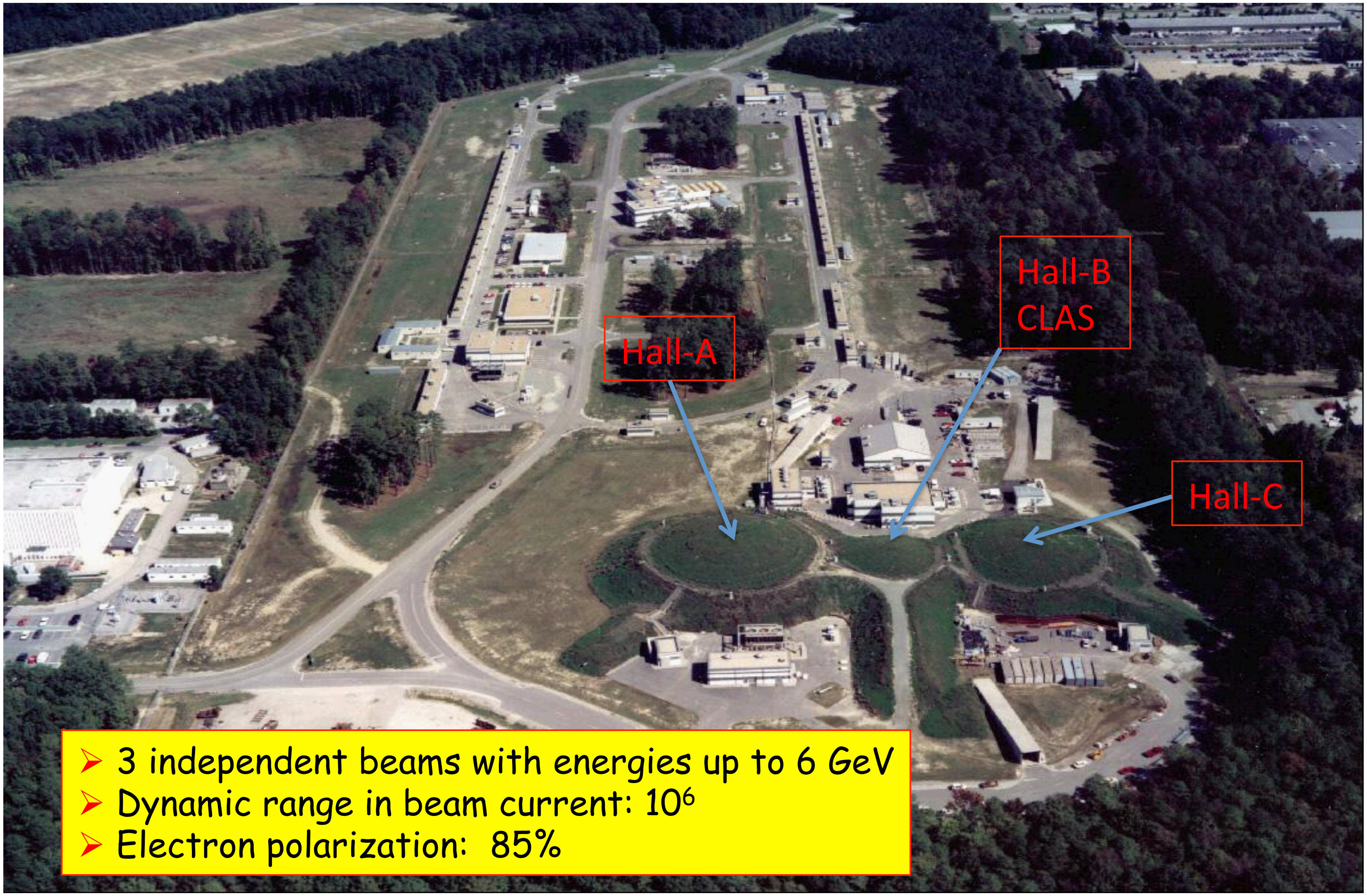




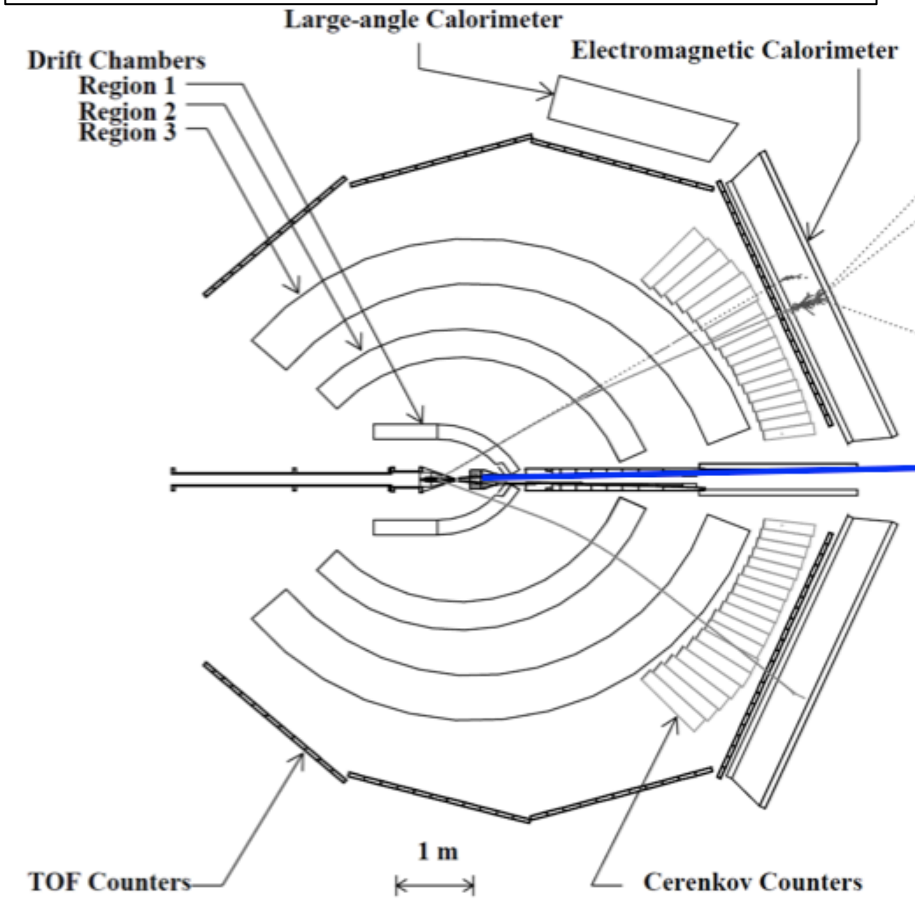
(a) Regge poles (vector and axial vector mesons)
(b) and (c) pion cuts

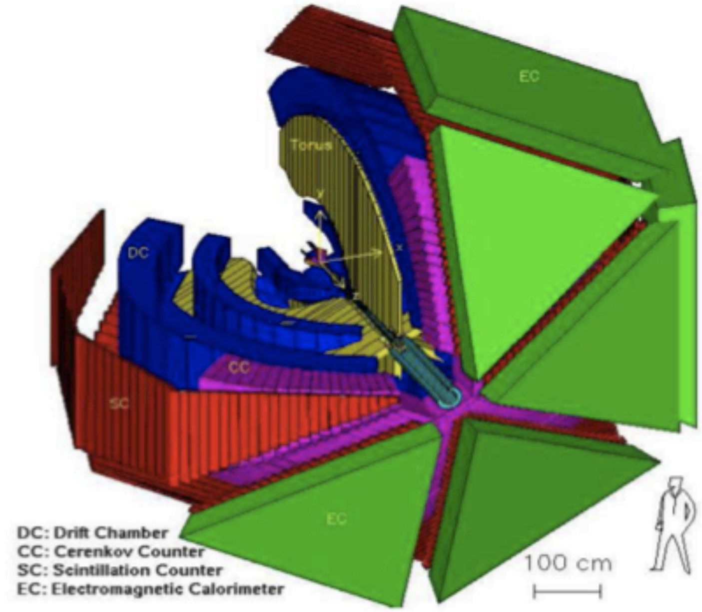
Vector meson cuts

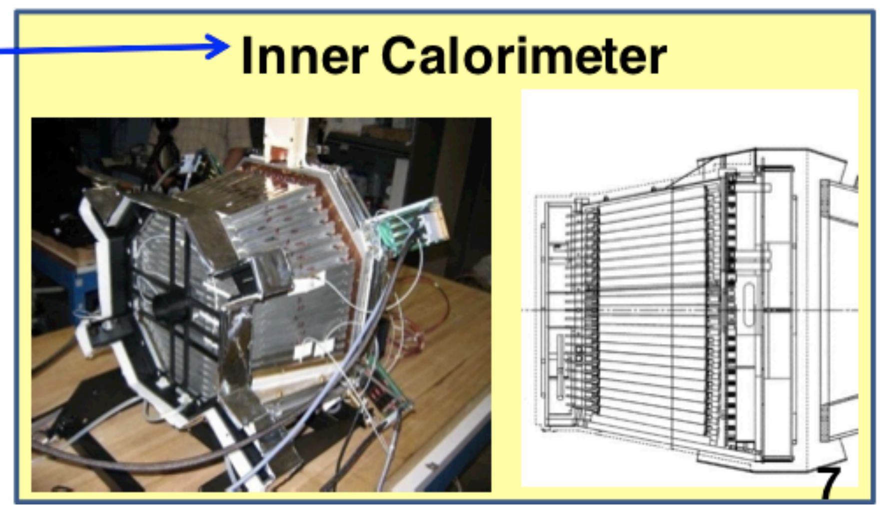
JLab Site: The 6 GeV Electron Accelerator



CEBAF Large Acceptance Spectrometer CLAS







CLAS Lead Tungstate Electromagnetic Calorimeter

424 crystals, 18 RL,
Pointing geometry,
APD readout

Pseudoscalar mesons

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

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

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

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

Vector mesons

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

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

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

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

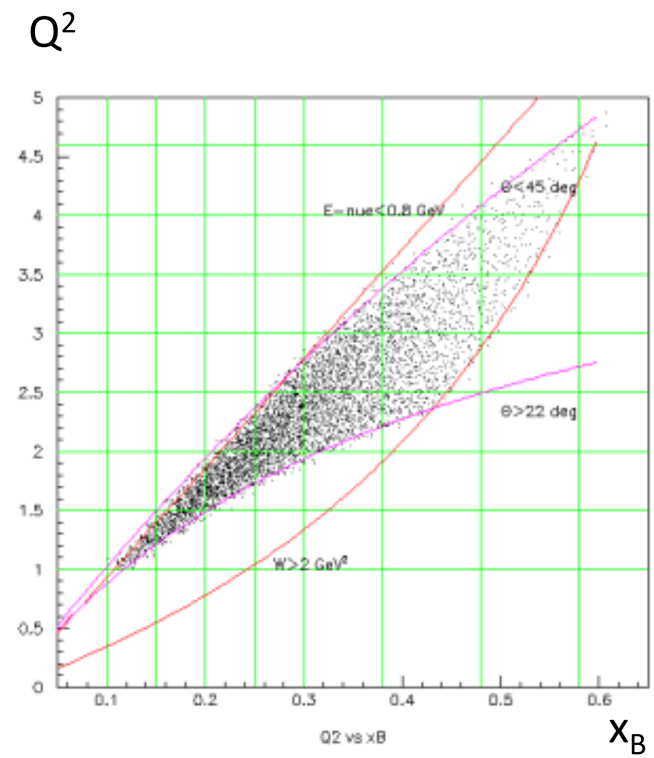
New proposal being prepared
for PAC 38

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

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

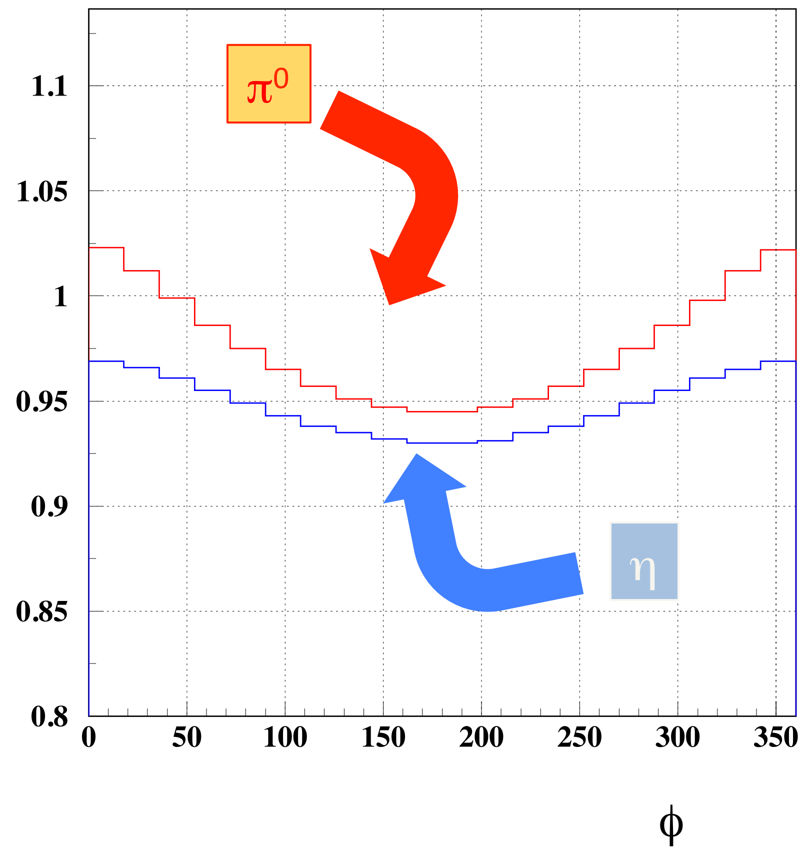
- Empirical model for the structure cross sections was used for the MC simulation and radiative corrections
- This model is based on CLAS data
- MC simulation included the radiative effects and used empirical model for the Born term.
- 100 M events were simulated with GSIM program.

Radiative Corrections

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

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

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

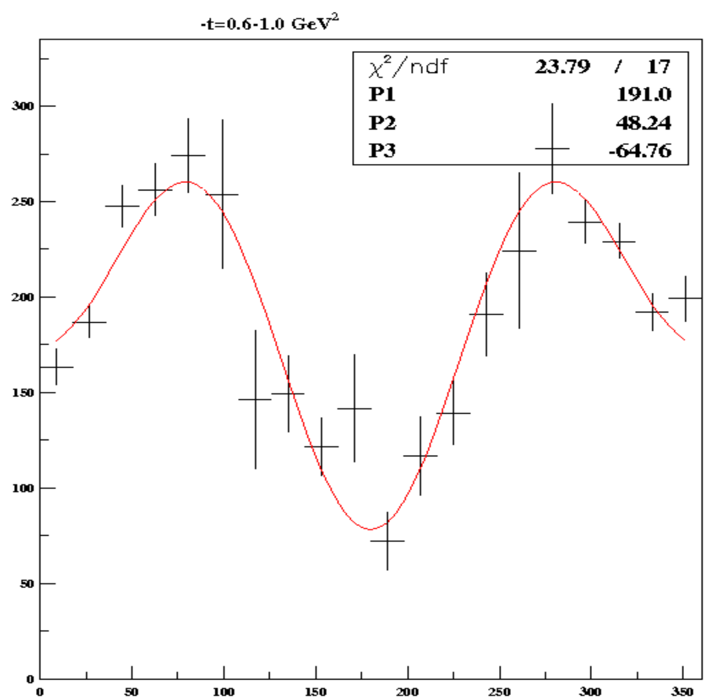


Structure Functions

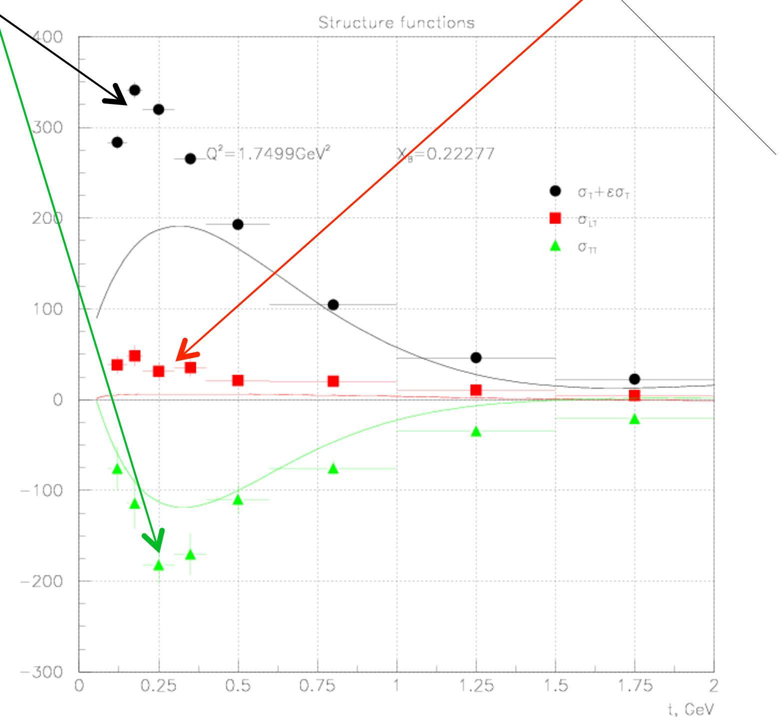
$\gamma^* p \rightarrow p\pi^0$

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

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



ϕ distribution

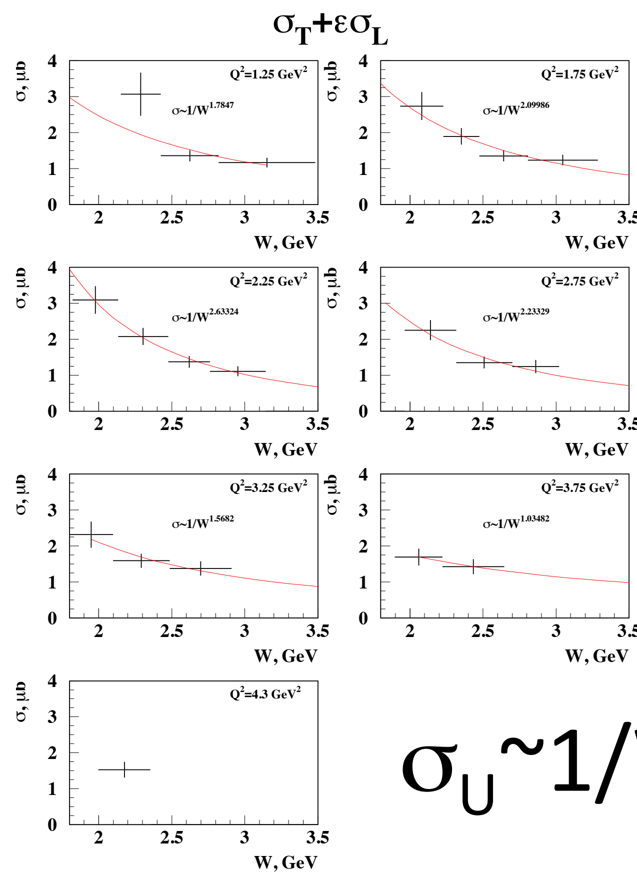


-t

GM Laget Regge model

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

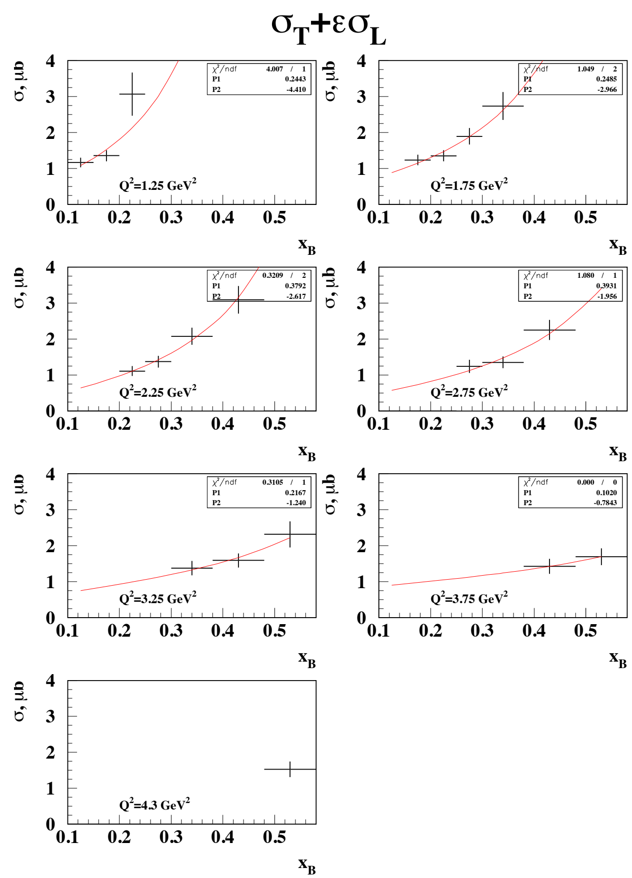
- σ_U decreases with W at Jlab kinematics
- This behavior is typical for Regge model
- Difficult to get such dependence with conventional GPD models



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

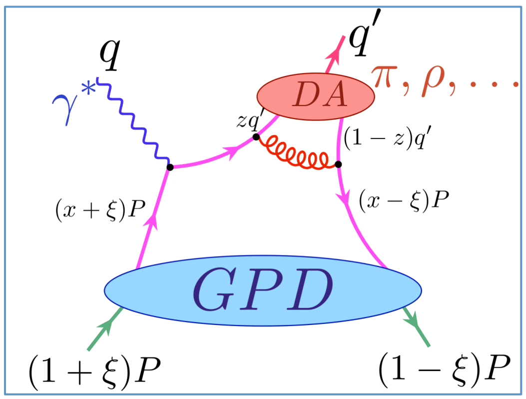
$\sigma_U=\sigma_T+\varepsilon\sigma_L$ x_B dependence

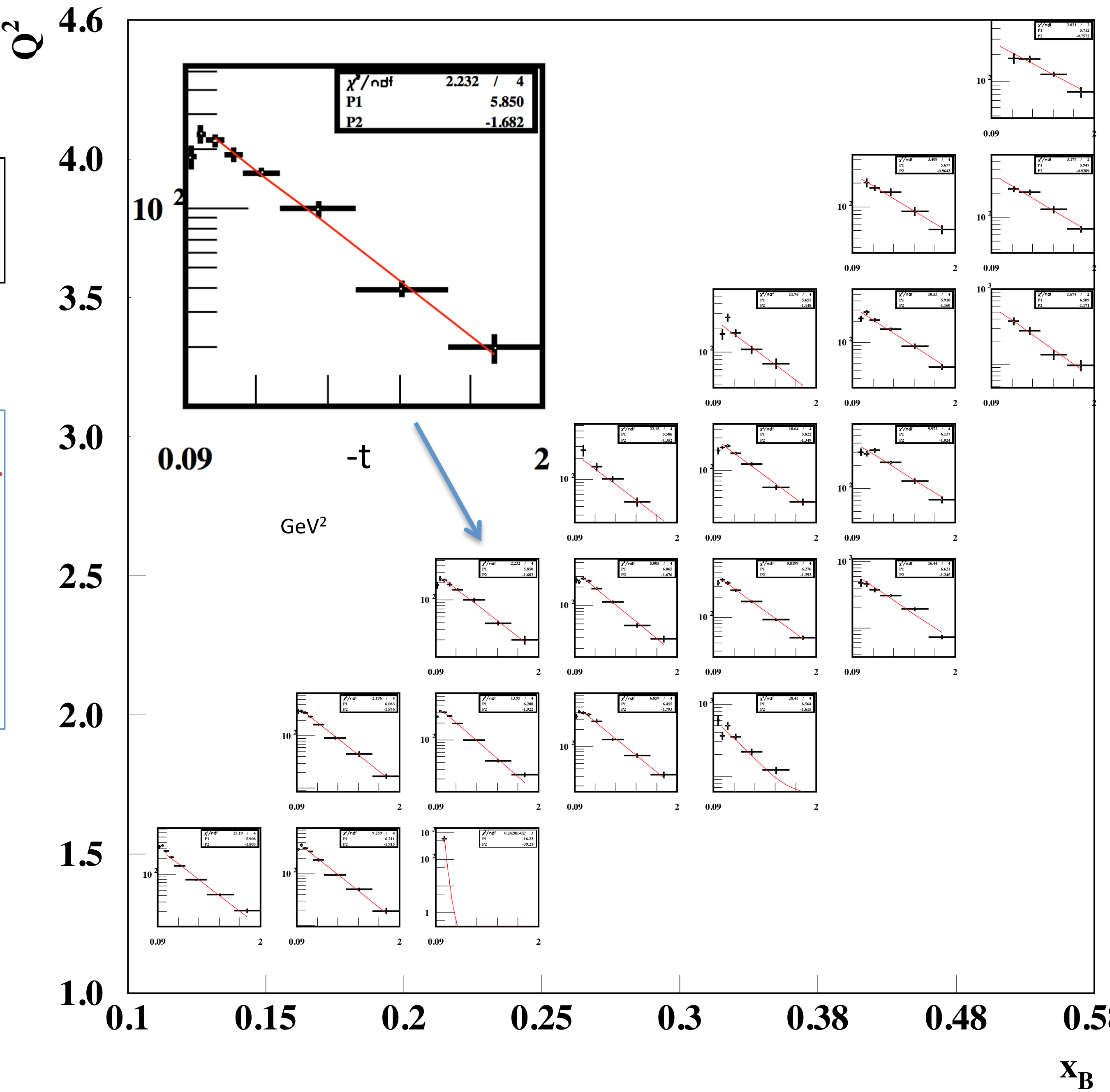
- Another way to view the cross section as a function of x_B
- σ_U increases with x_B
- $W=Q^2(1/x-1)$



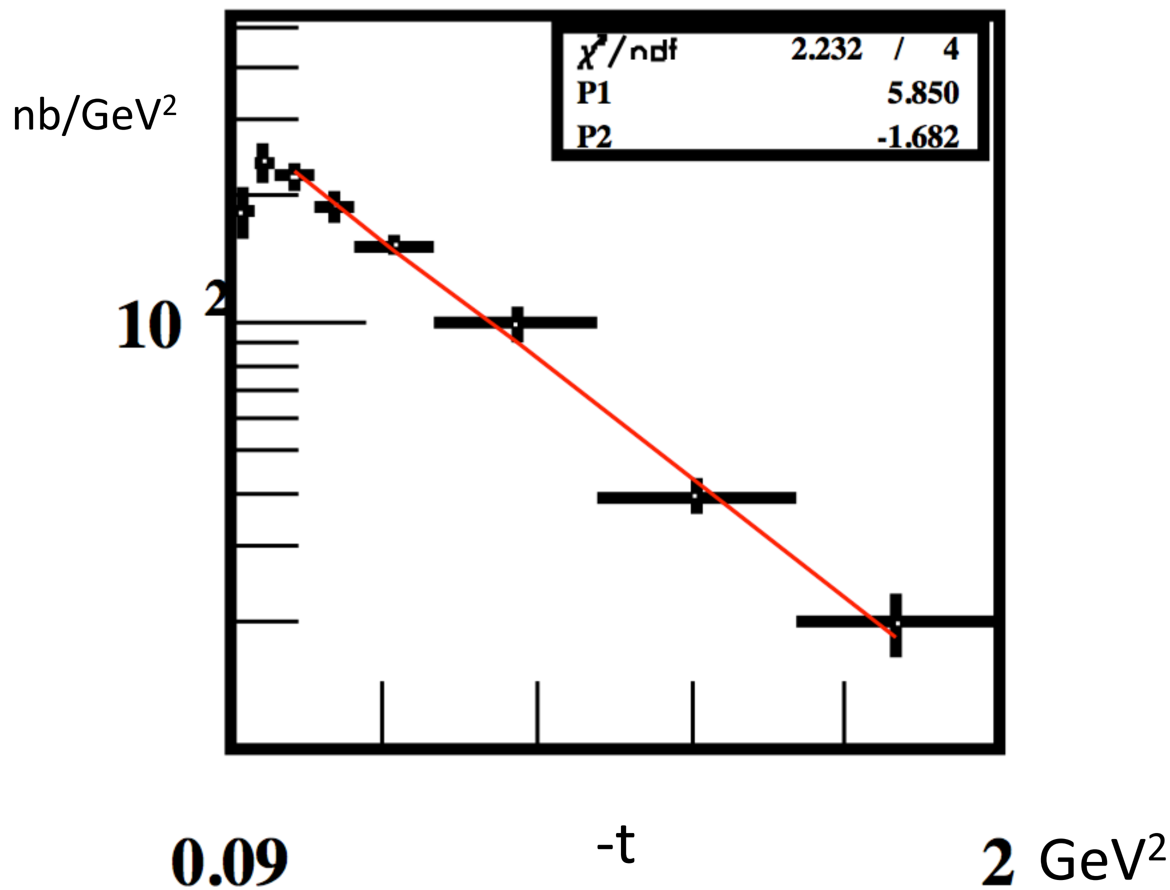
$d\sigma_U/dt$

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



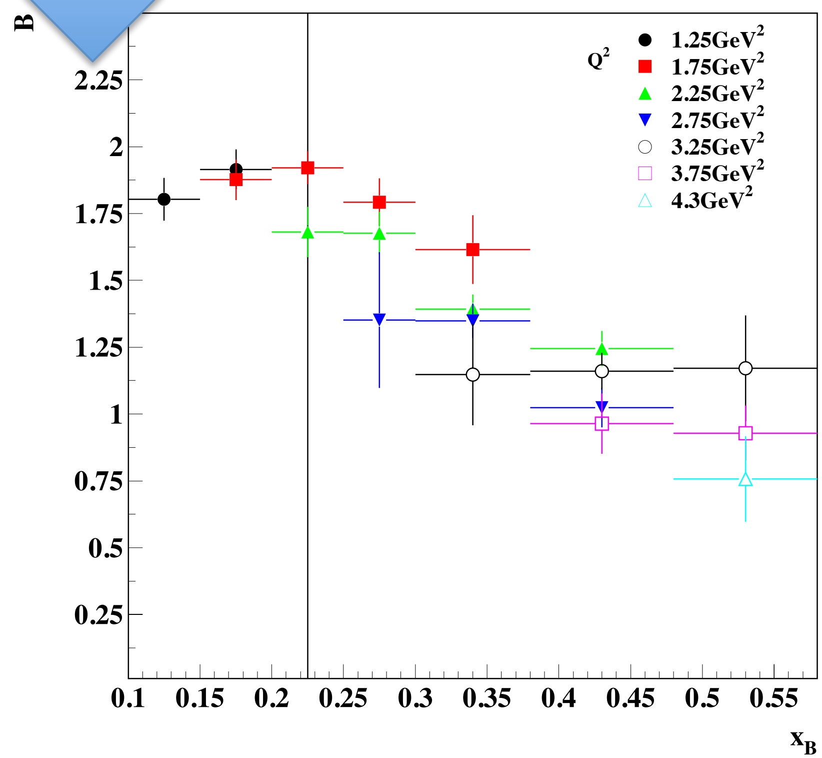


$d\sigma_U/dt$



t-slope parameter: x_B dependence

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

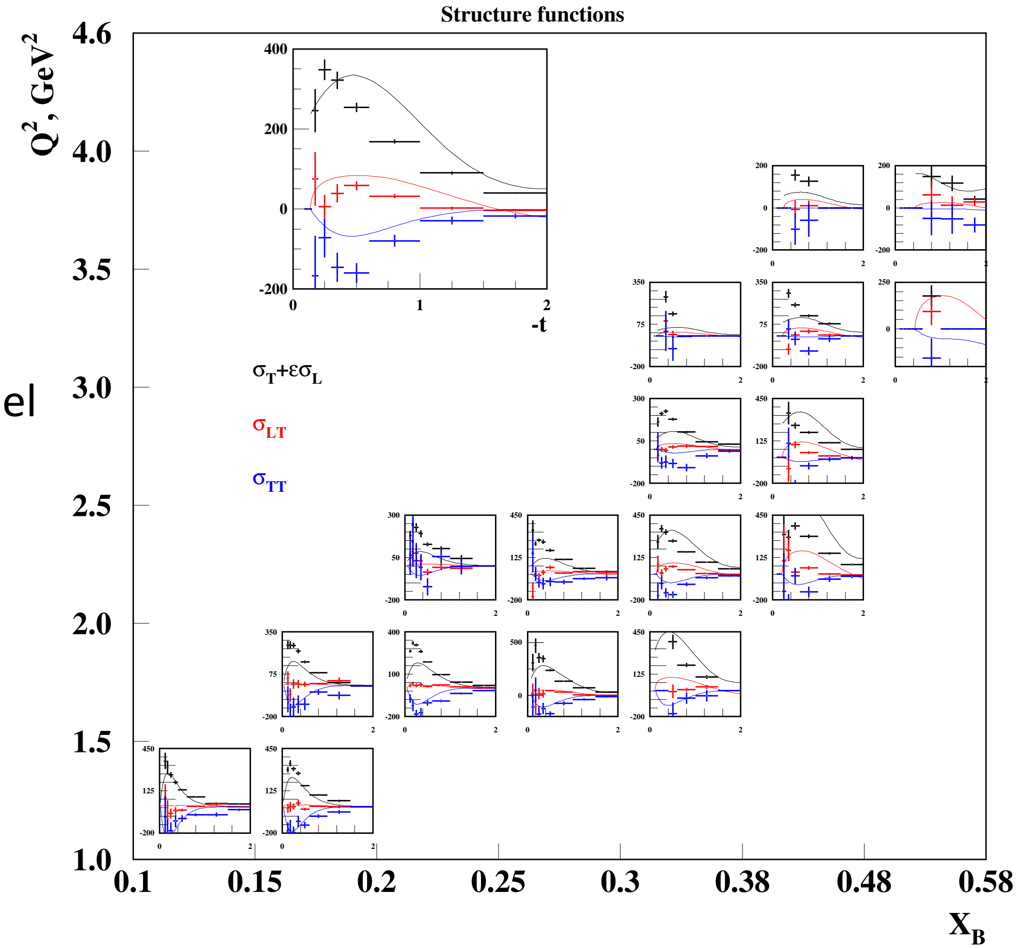


The dependence on Q2 is very week. The slope parameter is decreasing with increasing x_B. Looking to this picture we can say that the perp width of the partons with x→1 goes to zero.

Structure Functions

$$\sigma_U = \sigma_T + \varepsilon\sigma_L \qquad \sigma_{TT} \qquad \sigma_{LT}$$

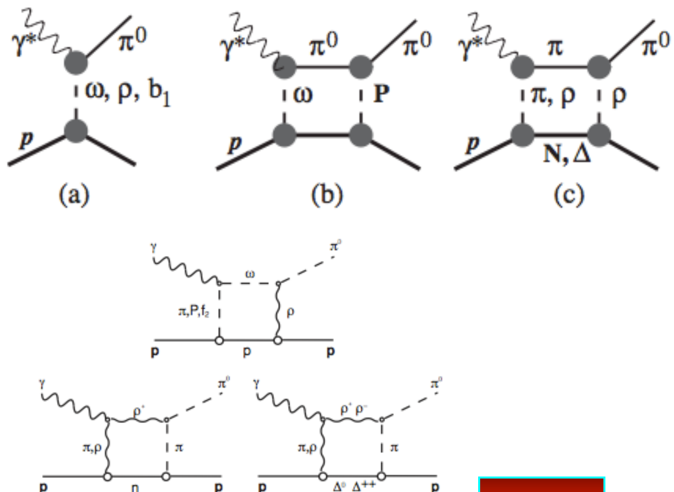
Lines – Regge model

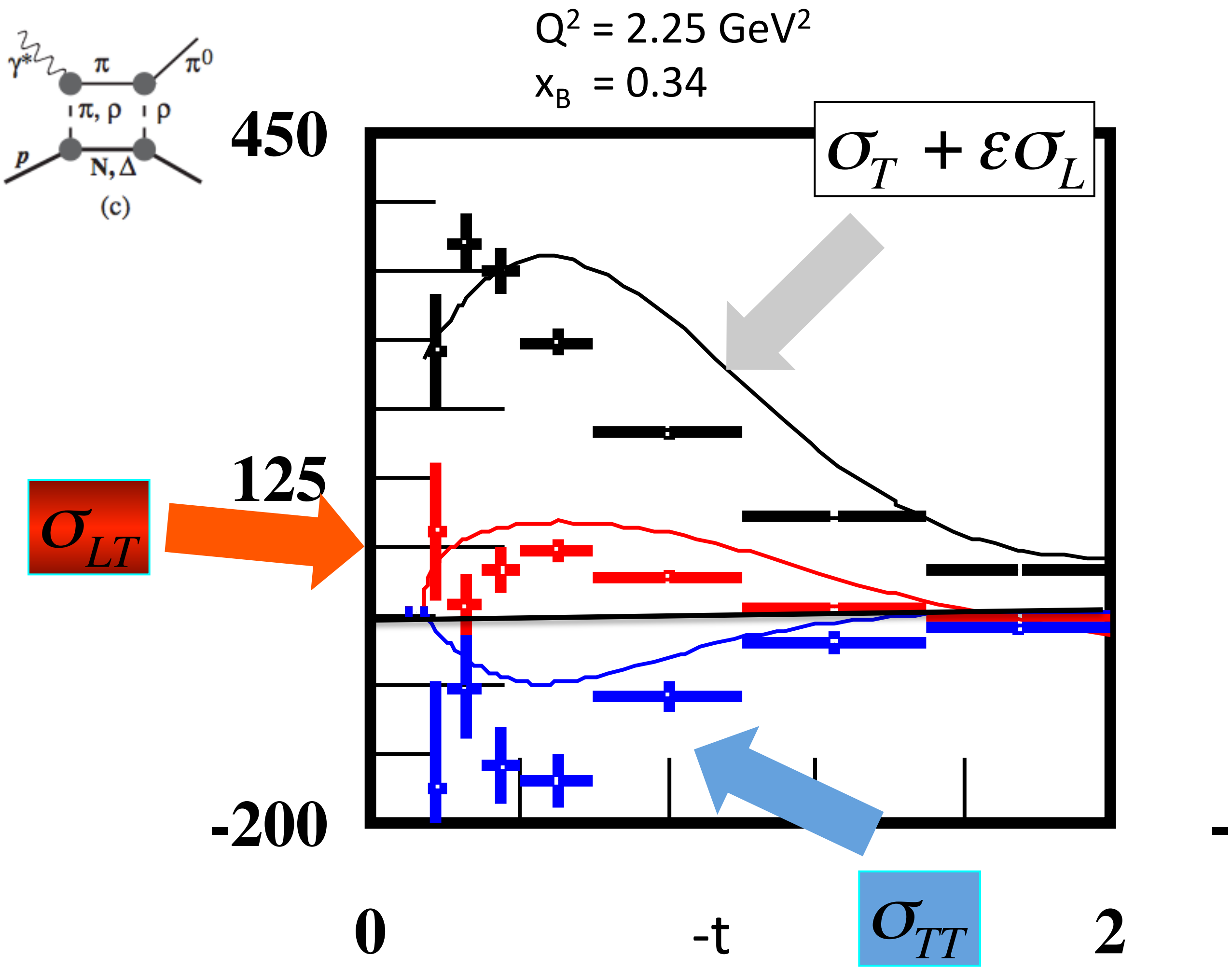


$$\gamma^* p \rightarrow p\pi^0$$

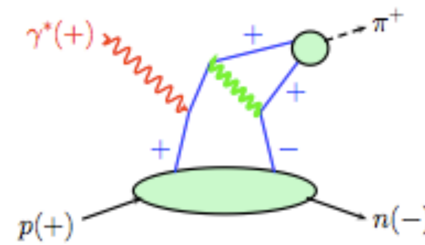
JML Regge model

$$\sigma_U = \sigma_T + \varepsilon\sigma_L \qquad \sigma_{TT} \qquad \sigma_{LT}$$

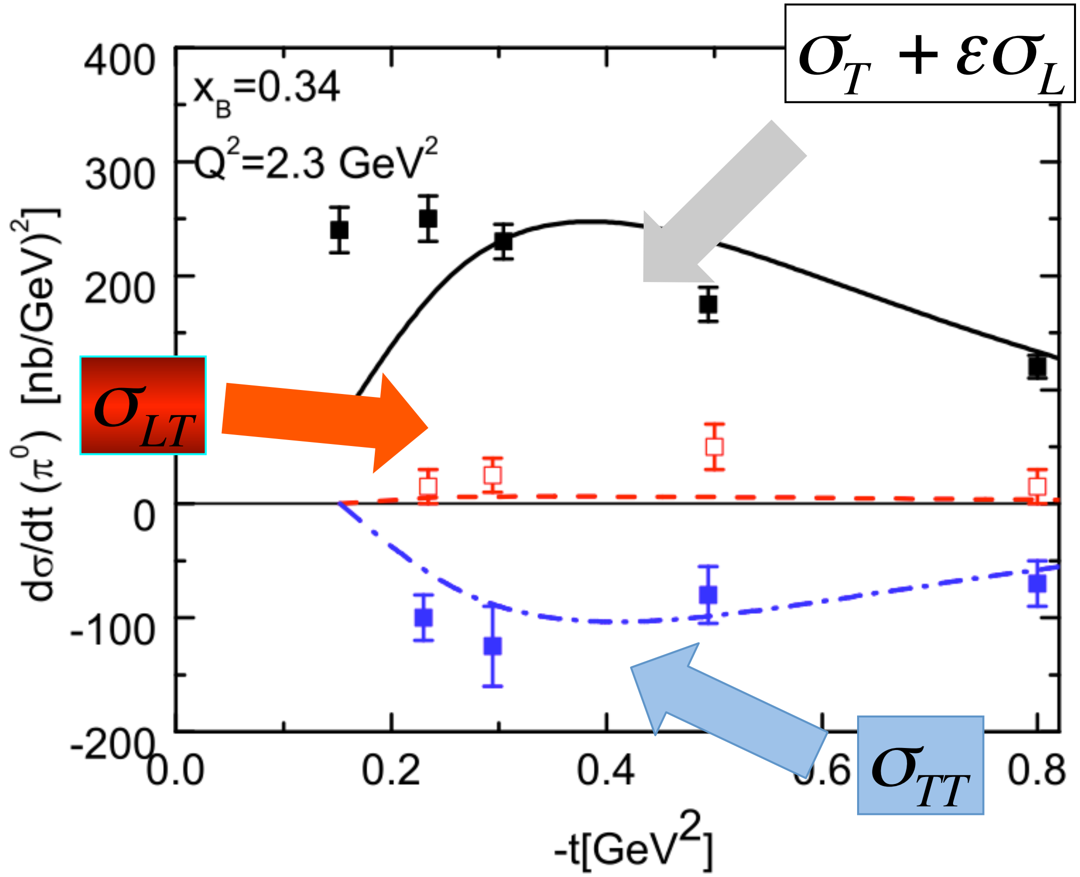




Goloskokov & Kroll GPD Model

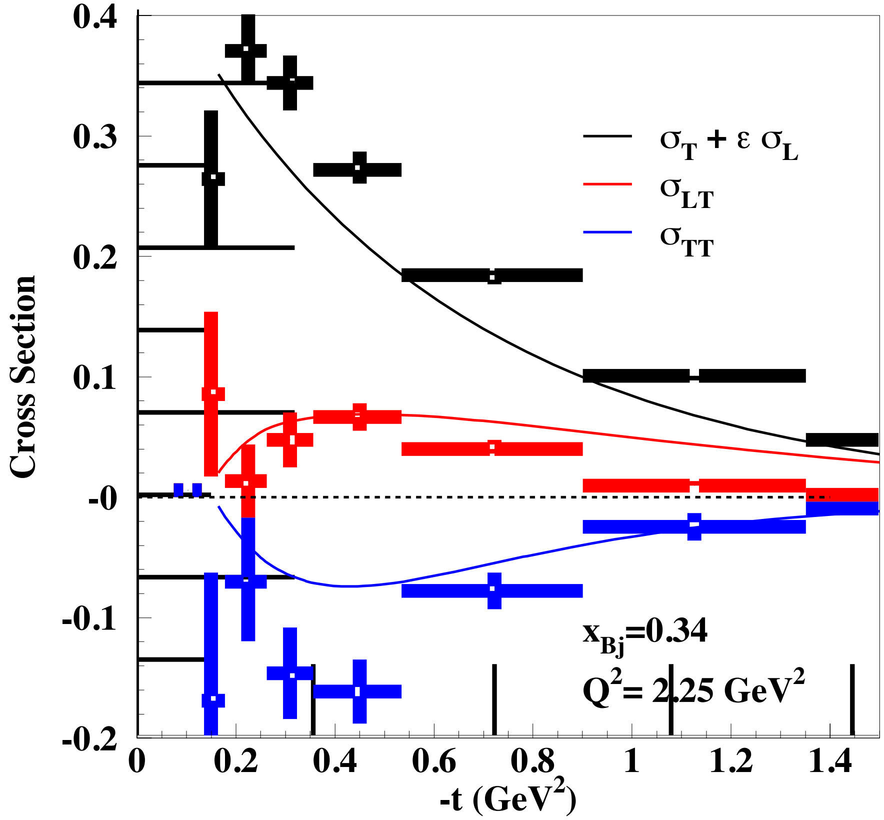


- Include ***transversity*** **GPDs** H_T and $\bar{E}_T = 2\tilde{H}_T + E_T$ Dominate in CLAS kinematics. Successfully described data.
- Pseudoscalar meson production provides unique possibility to access the transversity GPDs.



Goldstein and Liuti GPD_T model

Data – CLAS6

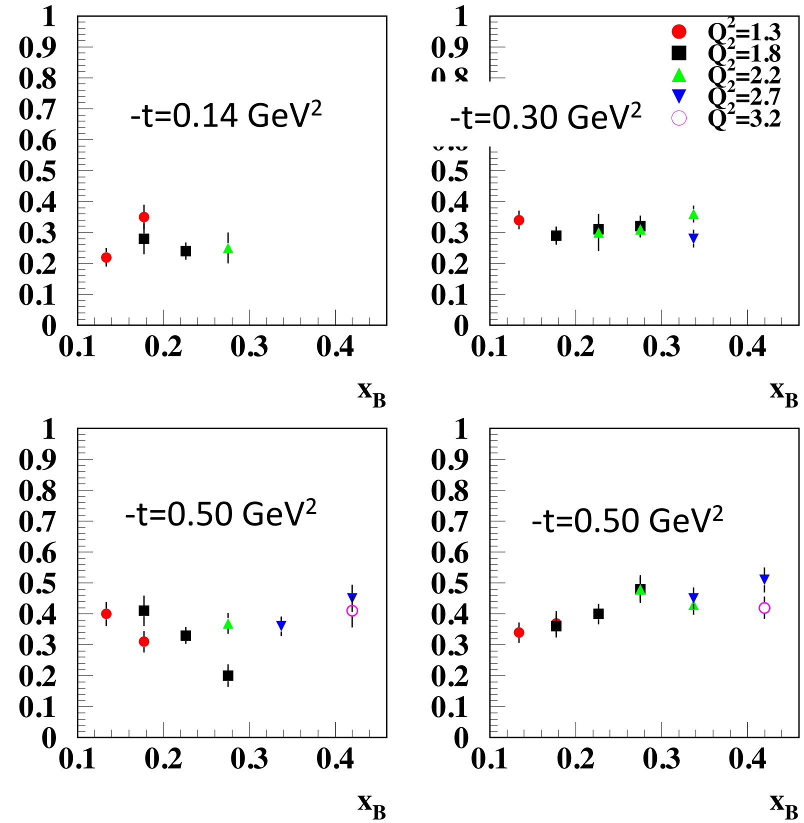


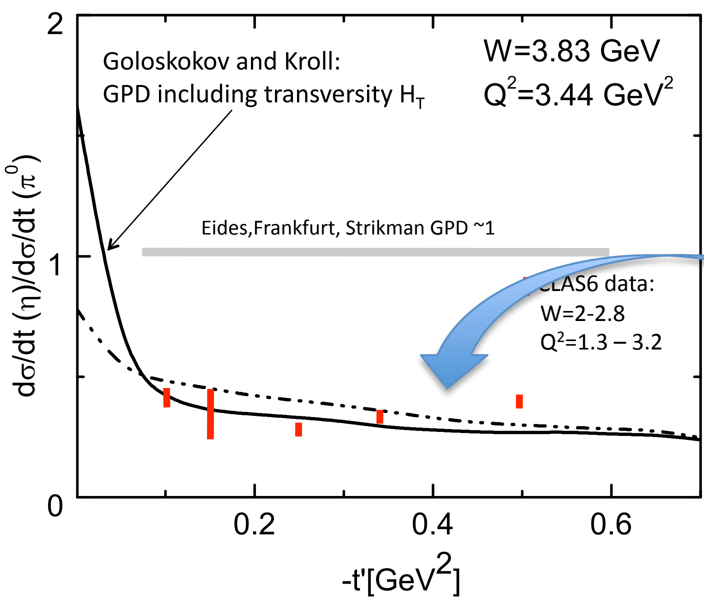
We are looking forward to extend the comparison with GPD-based model in the full kinematic domain of CLAS6

η/π^0 Ratio

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

- 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





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

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

CLAS12

Luminosity 10^{35} cm ^{2} s^{-1}

Forward Detector

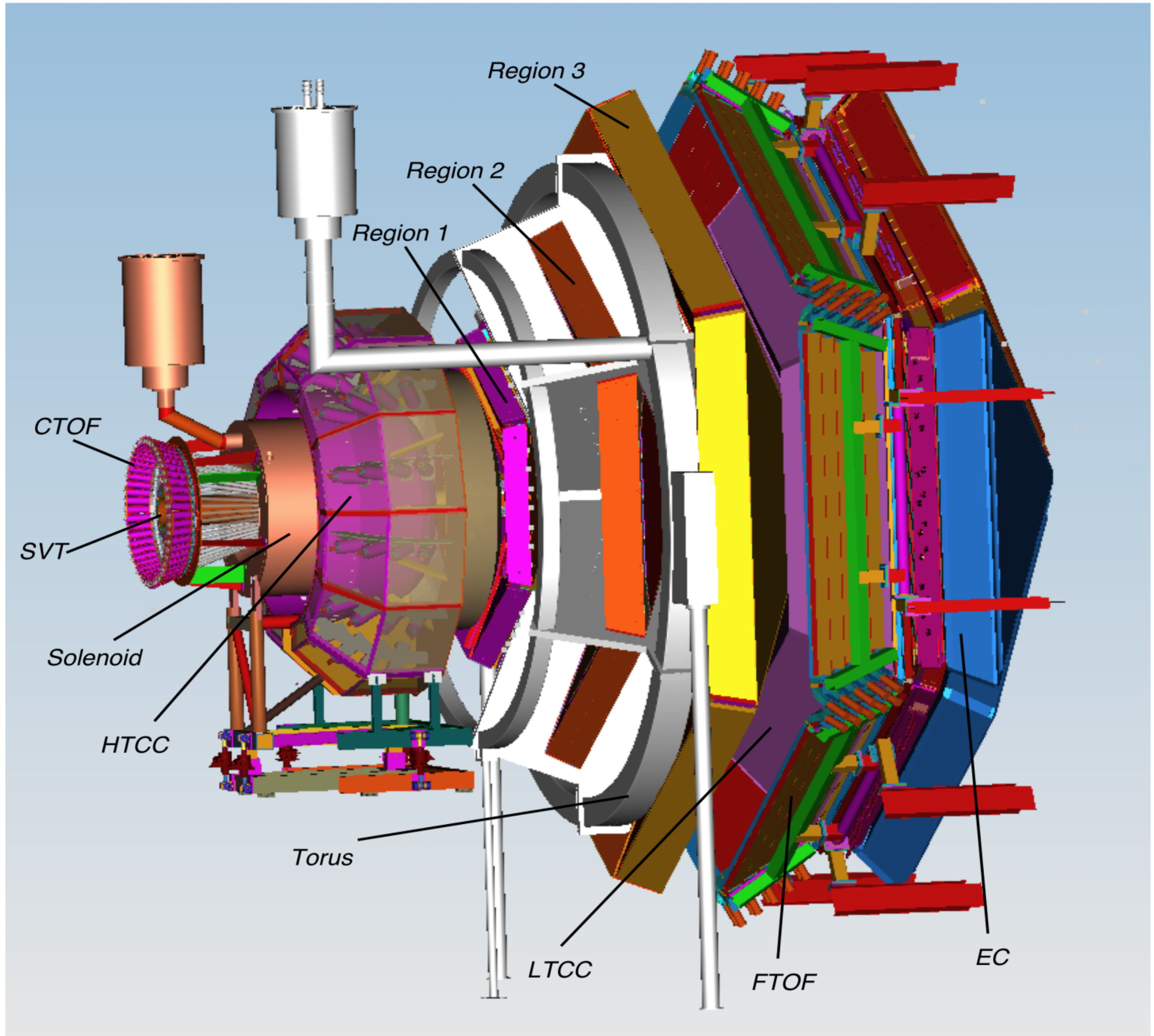
- TORUS magnet
- Forward SVT tracker
- HT Cherenkov Counter
- Drift chamber system
- LT Cherenkov Counter
- Forward ToF System
- Preshower calorimeter
- E.M. calorimeter

Central Detector

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

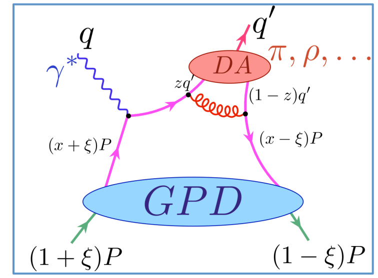
Proposed upgrades

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



$$ep \rightarrow ep\pi^0$$
$$ep \rightarrow ep\eta$$

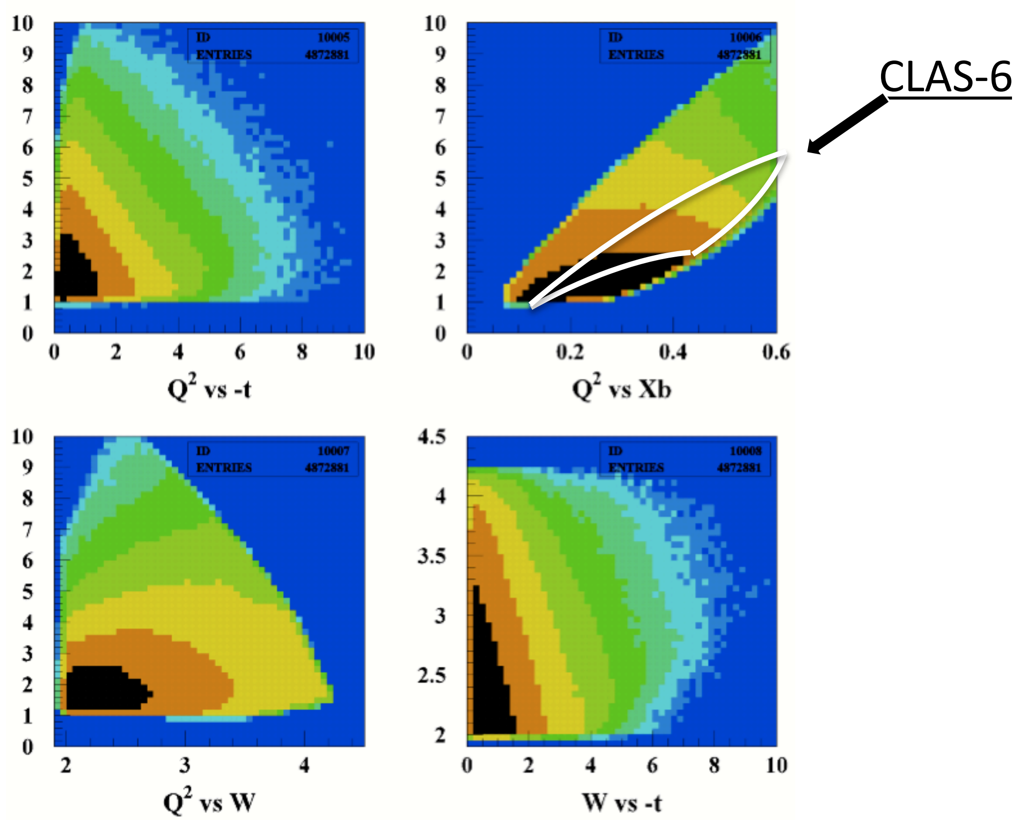
E12-06-108
Hard Exclusive Electroproduction of π^0 and η with CLAS12



- Cross sections of the reactions $ep \rightarrow ep\pi^0$, $ep \rightarrow ep\eta$
- Extract structure functions σ_T, σ_L, σ_{TT}, σ_{LT} $\sigma_{LT'}$ vs. Q^2, x_B, t
  - Fourier decomposition of the reduced cross section $\sigma_T+\varepsilon\sigma_L$, σ_{TT}, σ_{LT}
  - Beam-spin asymmetry $\sigma_{LT'}$
  - Rosenbluth separation σ_T, σ_L, at energies 11, 8.8 and 6.6 GeV
- Handbag - 3D nucleon tomography
  - ***transversity*** **GPDs** H_T and data.
  - Backward pion production ($\bar{E}_T = 2\tilde{H}_T + E_T$-u). Transition distribution amplitudes.
- Regge

CLAS6 data

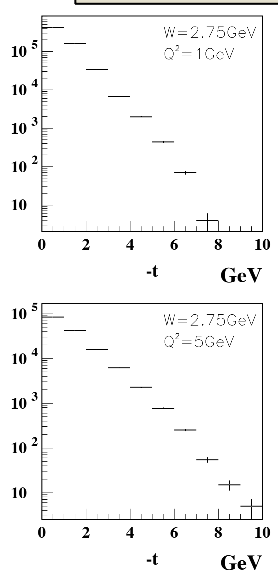
CLAS12 Kinematic Coverage



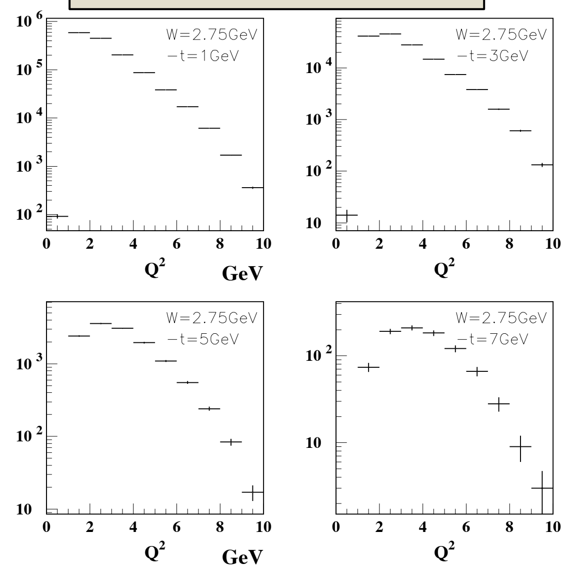
Statistics

W=2.75 +/- 0.75 GeV

t-distribution
ΔQ^2= 2 GeV^2



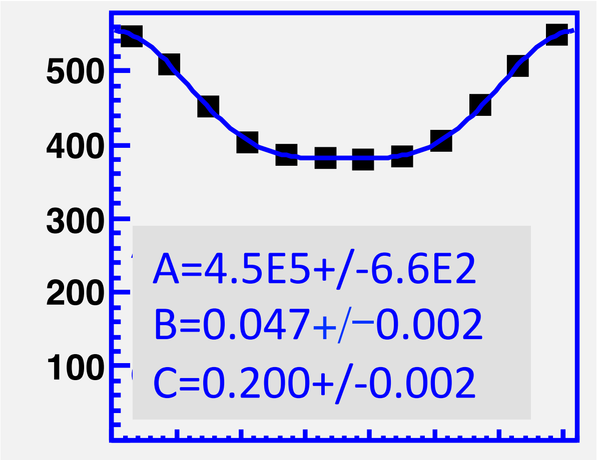
Q^2-distribution
Δt= 2 GeV^2



Example of the Simulated cross section and asymmetry

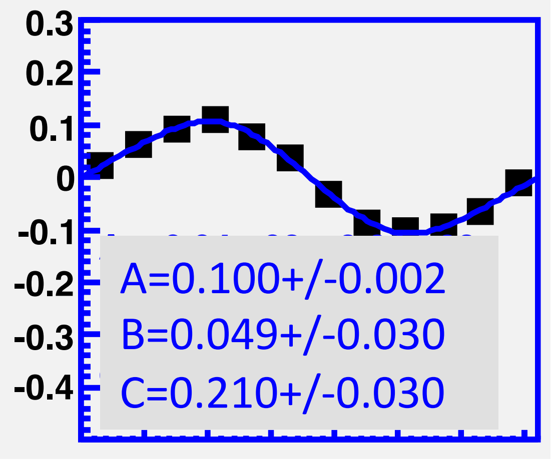
Simulated cross section

$$\sigma = A(1 + B\cos 2\varphi + C\cos\varphi)$$



Simulated beam-spin asymmetry

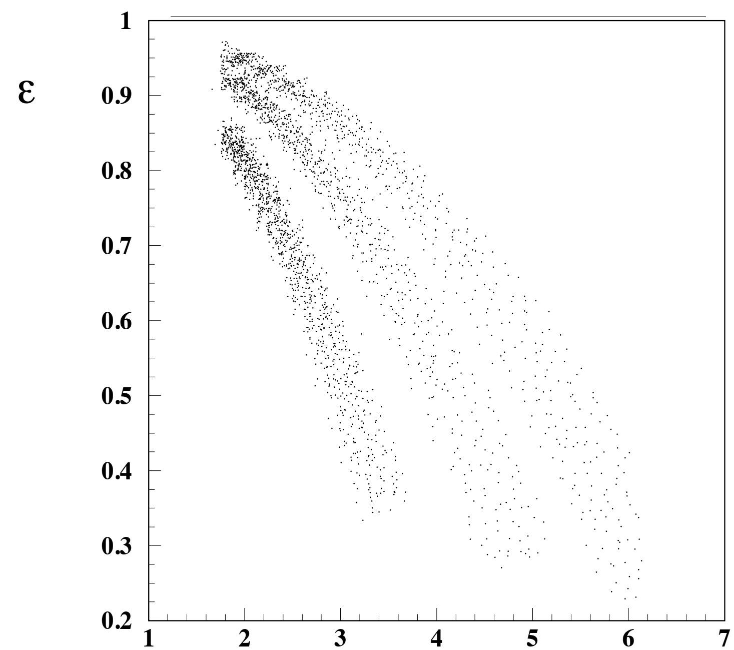
$$\alpha = A\sin\varphi / (1 + B\cos 2\varphi + C\cos\varphi)$$



Anticipated systematic errors

Source	Error
Acceptance	2.5 %
Beam Charge	0.2 %
Particle ID	1.0 %
Radiative Corrections	1.0 %
$\sigma_U = \sigma_T + \varepsilon s_L$	4.0 %
σ_L, σ_T	10-30 %

Rosenbluth Separation



Q^2 GeV^2

R=0.4
x_B=035+/-0.5

Q^2 GeV^2	3	3.5	4.5	5
$\Delta\sigma_T/\sigma_T$ %	33	16	28	18
$\Delta\sigma_L/\sigma_L$ %	20	13	23	19

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

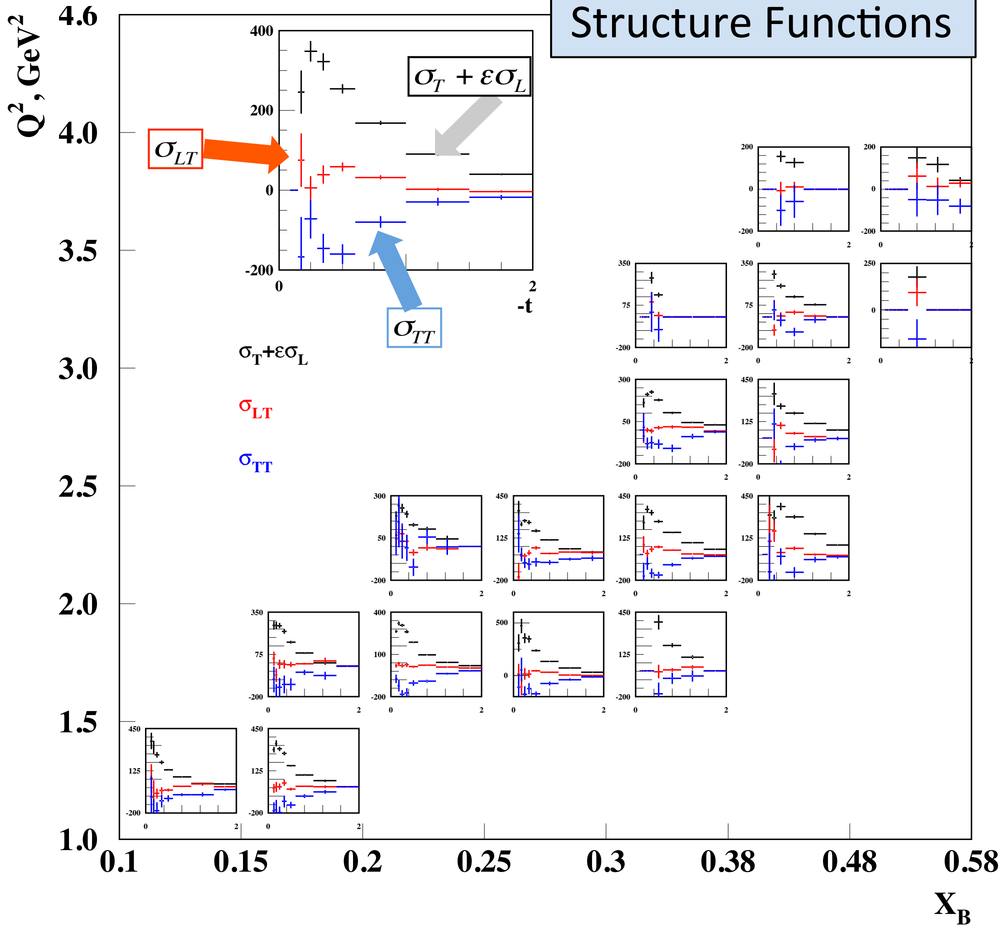
$\gamma^* p \to p\eta$

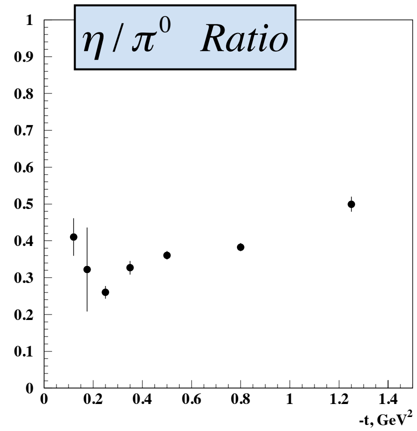
Going from 6 to 11 GeV

Reliable extraction of the structure functions for π^0 and η was demonstrated with CLAS6 experimental setup. These data and the new theoretical developments make the CLAS-12 experiment even more compelling

- Higher Q^2 – map the Q^2 evolution of structure functions
- Higher t range – backward pion production
- σ_T / σ_L separation

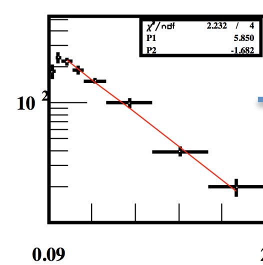
Structure Functions

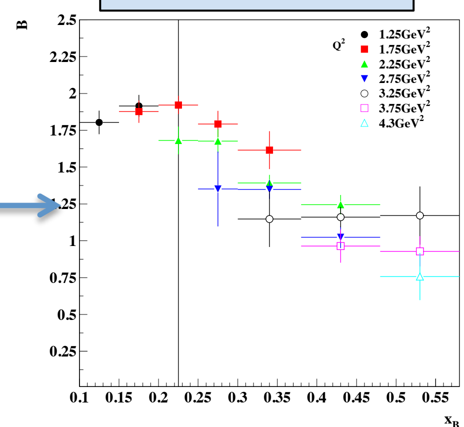




t slope parameter

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





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

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

$\sigma_U=\sigma_T+\varepsilon\sigma_L$: Q^2 dependence

$\sigma_U \sim 1/Q^3$

- 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*
- $Q^2 \rightarrow \infty$ $\sigma_L \sim 1/Q^6$, $\sigma_T/\sigma_L \sim 1/Q^2$
- We are not there yet!