Deeply Virtual Meson Production with CLAS

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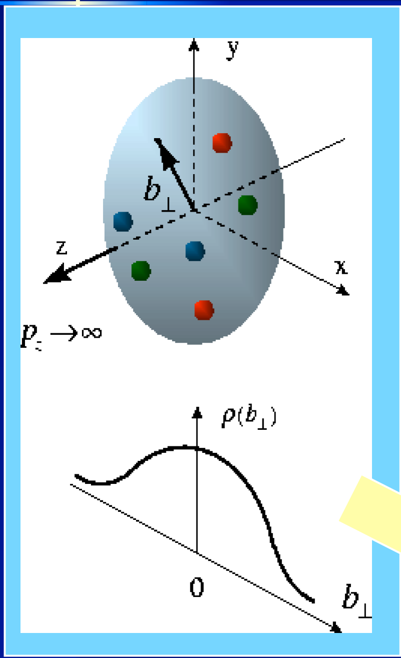
May 18-21, 2010
Thomas Jefferson National Accelerator Facility
Newport News, Virginia USA

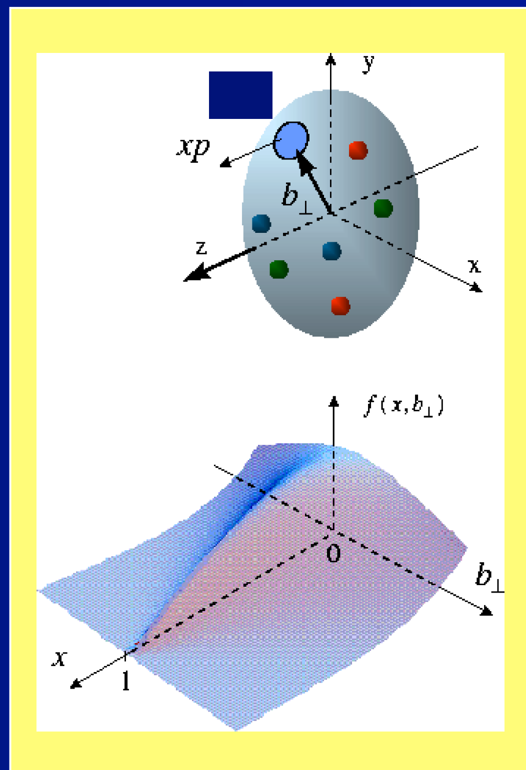
Outline

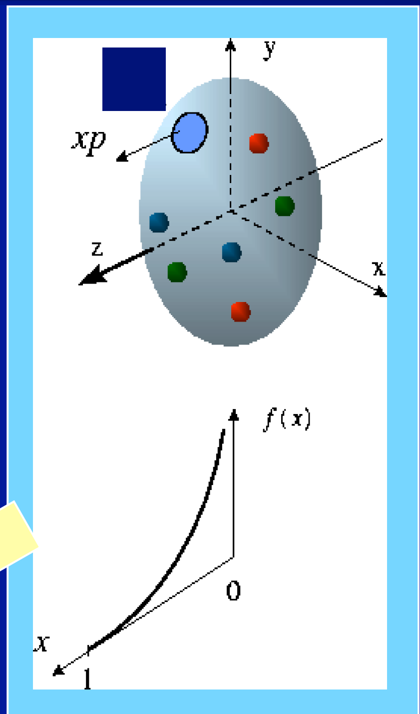
- Introduction
- DVMP theoretical models
- π^0/η electroproduction
  - Cross sections
  - Structure functions
  - Beam spin asymmetry
  - Cross sections ratio
- Summary

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







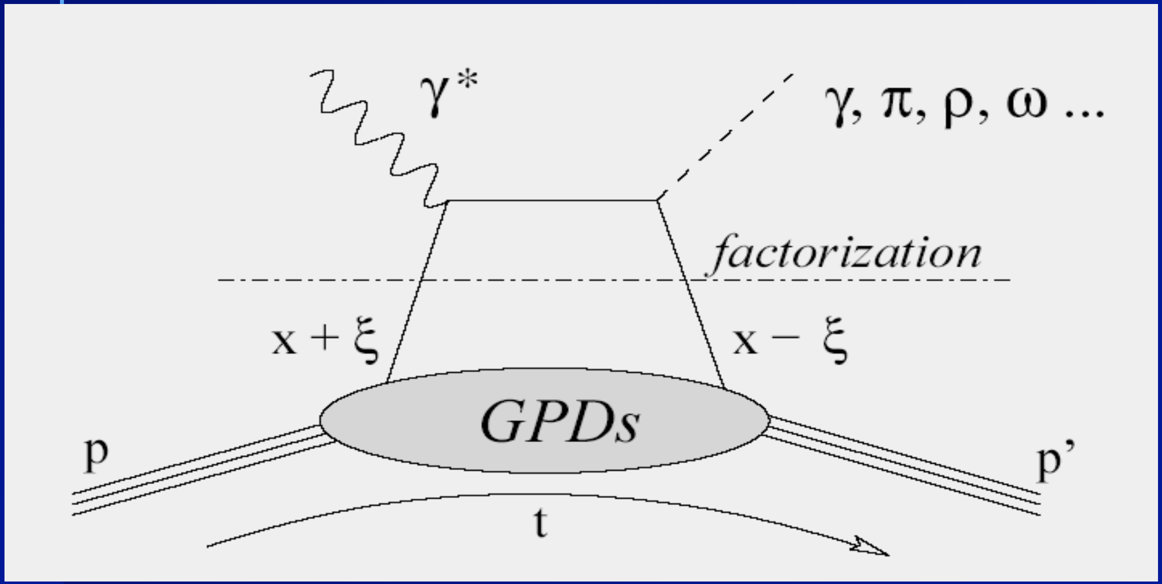
Proton form factors, transverse charge & current densities

Correlated quark momentum and helicity distributions in transverse space - GPDs

Structure functions, quark longitudinal momentum & spin distributions

Basic Process – Handbag Mechanism

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



x – longitudinal quark momentum fraction

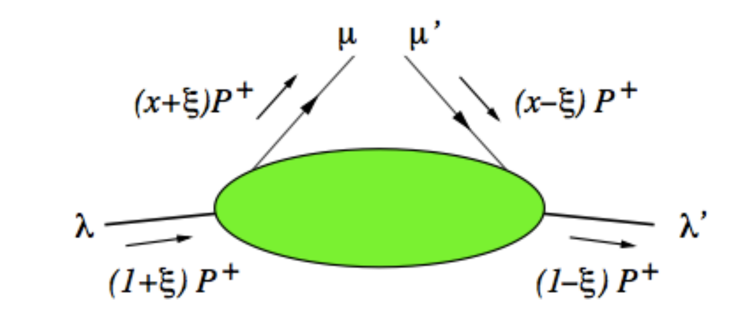
2ξ – longitudinal momentum transfer

$\sqrt{-t}$ – 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.

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

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

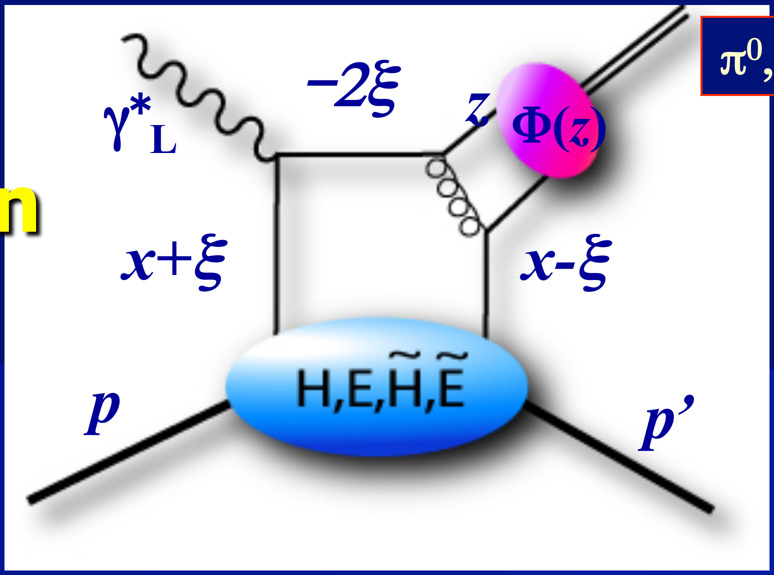
$$\int_{-1}^{1} \mathrm{d}x\, H^q(x,\xi,t) = F_1^q(t), \quad \int_{-1}^{1} \mathrm{d}x\, E^q(x,\xi,t) = F_2^q(t)$$
$$\int_{-1}^{1} \mathrm{d}x\, \tilde{H}^q(x,\xi,t) = g_A^q(t), \quad \int_{-1}^{1} \mathrm{d}x\, \tilde{E}^q(x,\xi,t) = g_P^q(t),$$

- 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)

High Q^2, Low t Region



$\pi^0, \eta, \rho^0, \omega, \phi$...

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 Φ (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

+ t.c.

Flavor Separation and Helicity-Dependent GPDs

- 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.

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	$2u - d$

$$\widetilde{H}, \widetilde{E}$$

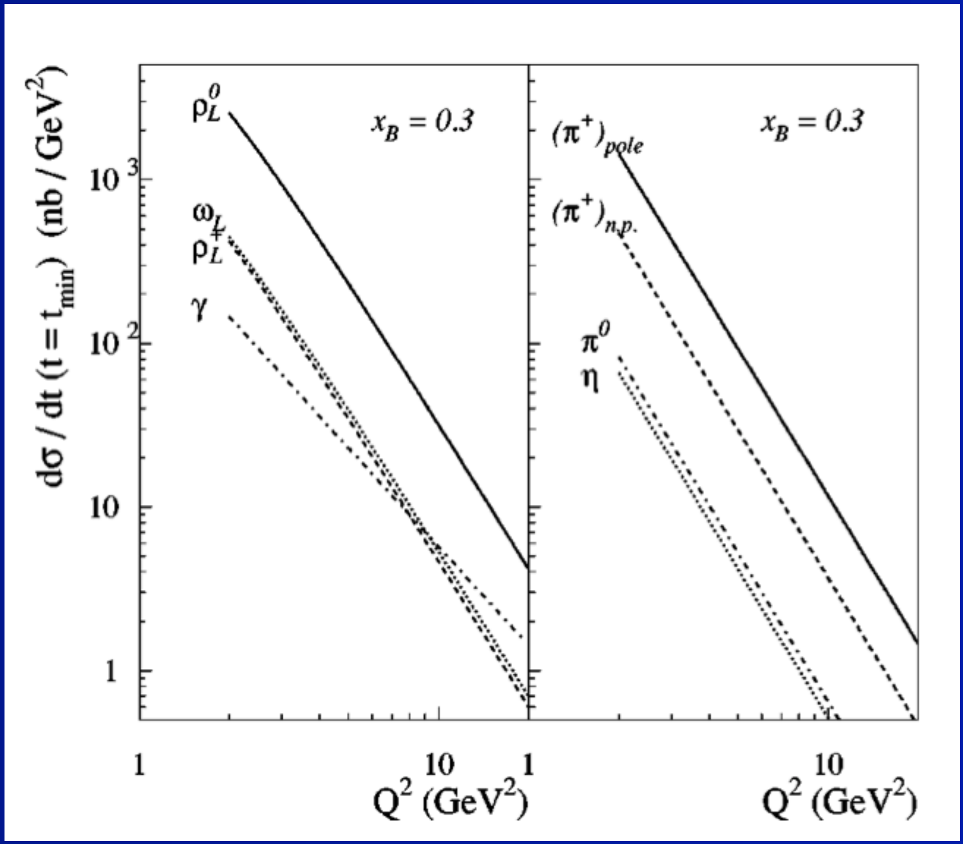
$$H, E$$

GPD predictions (only σ_L)

Vanderhaeghen, Guichon, Guidal, 1999

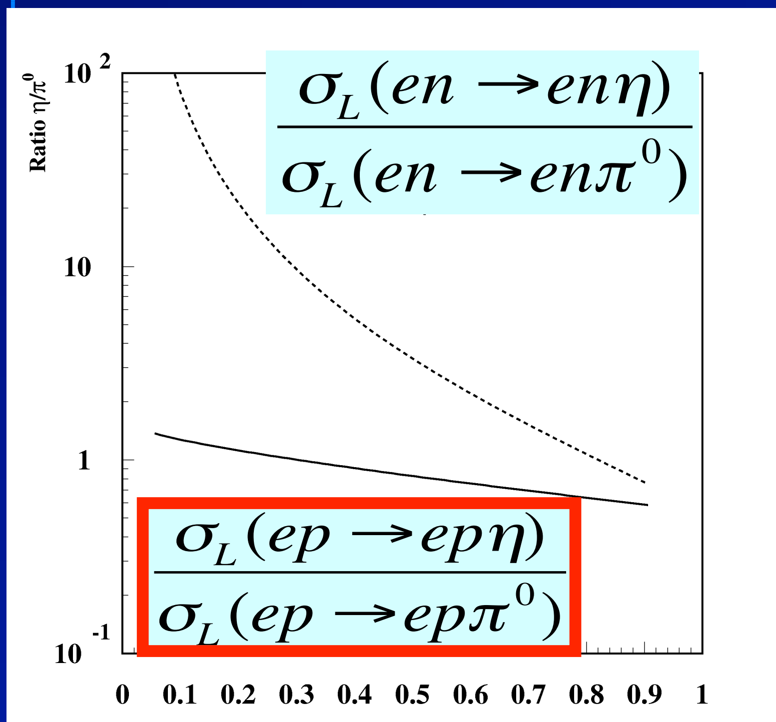
$$\frac{d\sigma_L}{dt}(t = t_{\min})$$

- $d\sigma_L/dt(t=t_{min})$ for vector mesons (left panel)
- Pseudoscalar mesons (right panel)
- Note the pion pole contributionton to the π^+ electroproduction (shown separately)

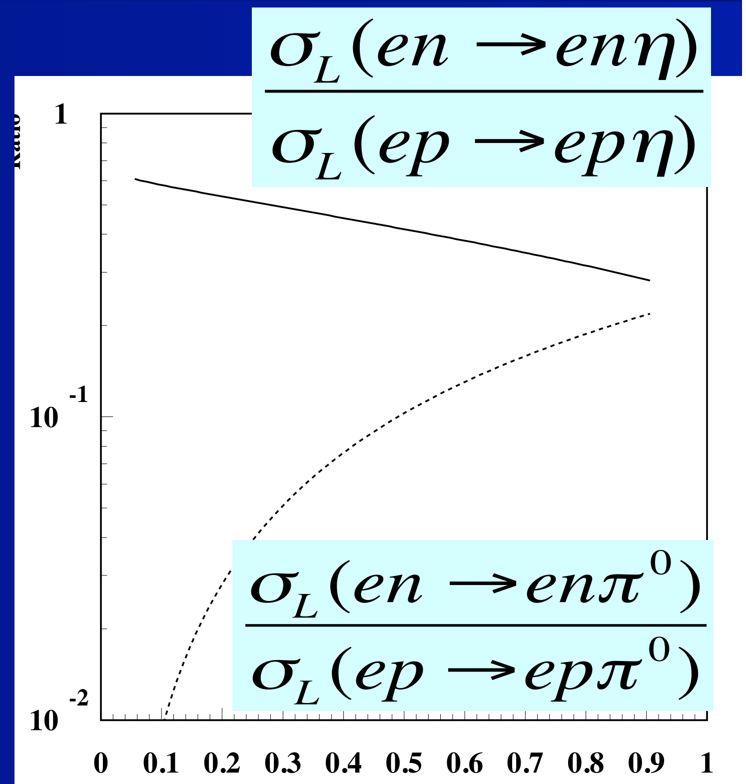


Cross Section Ratios as a function of x_B

Eides,Frankfurt,Strikman -1997



X_B



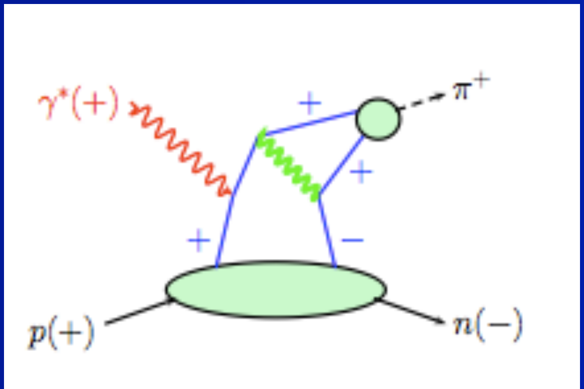
X_B

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

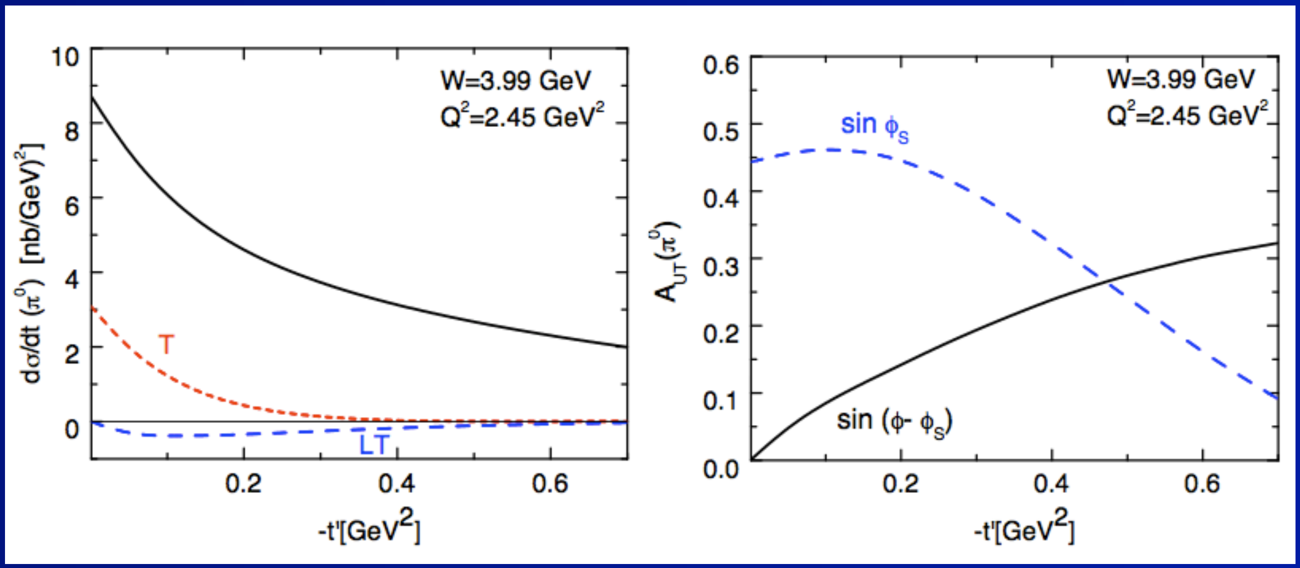
$\gamma^* p \to p\pi^0$

Kroll, Goloskokov, 2009.

$\sigma_T + \varepsilon\sigma_L$

σ_T

σ_{LT}



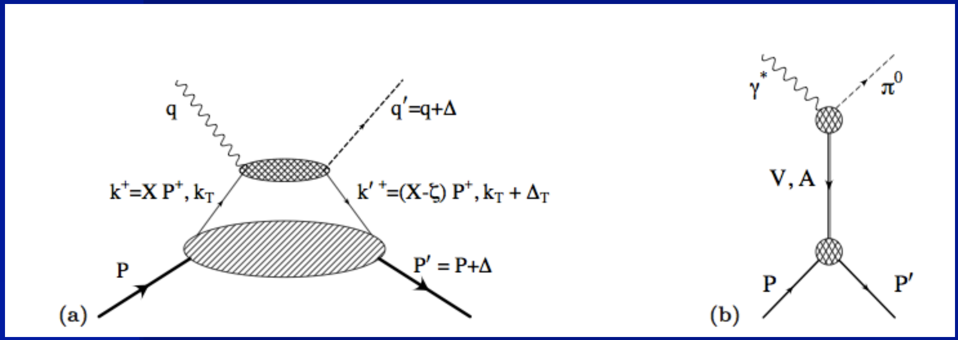
Predictions for the cross section (left) and A_{UT} (right) for the π^0 electroproduction versus –t. The unseparated(σ_L,σ_T) cross section was calculated as well as σ_T and σ_{LT}. At W=2.2 GeV the cross section will be a factor of 10 larger. We can check it at Jlab.

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

Nucleon Tensor Charge from Exclusive π^0 Electroproduction

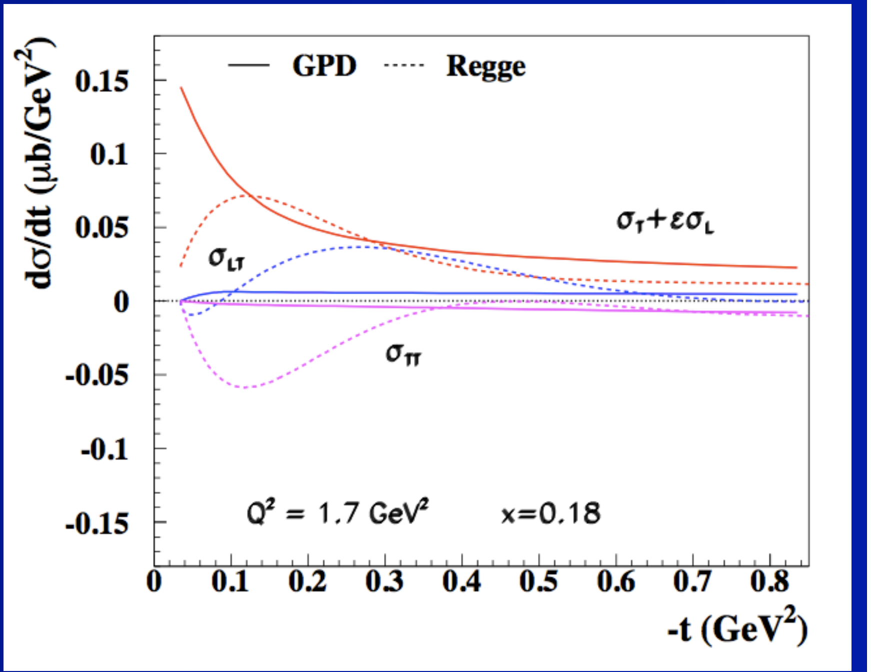
Ahmad, Goldstein, Luiti, 2009

- 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;

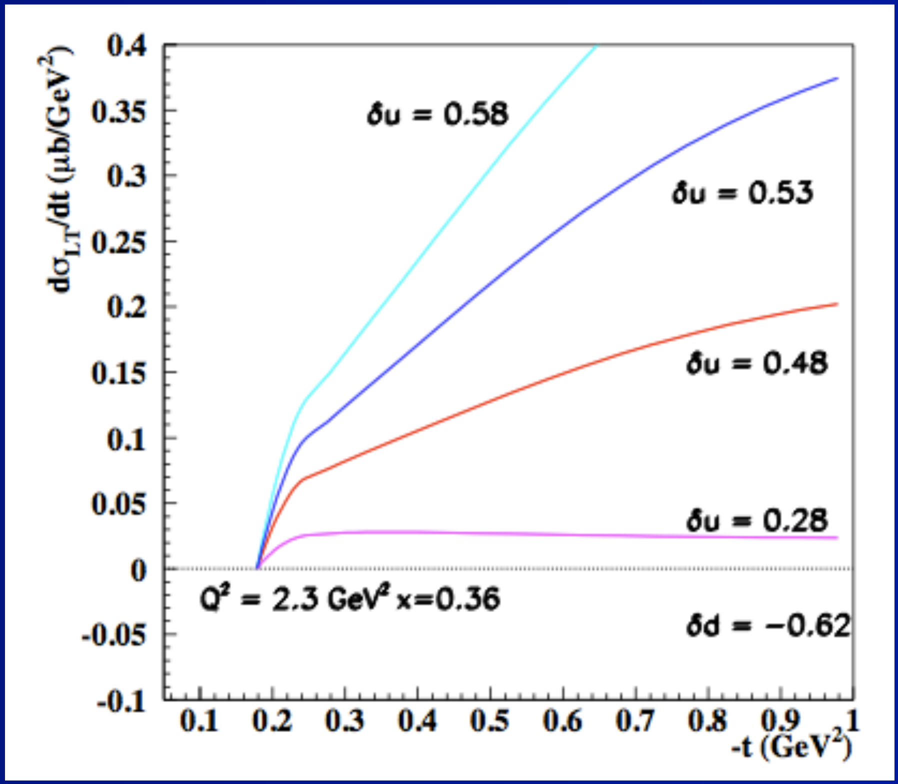
t-channel exchange diagram



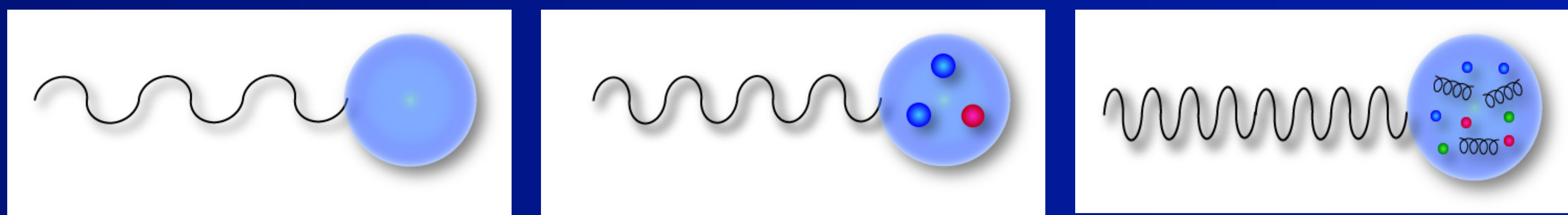
$$\gamma^* p \rightarrow p\pi^0$$

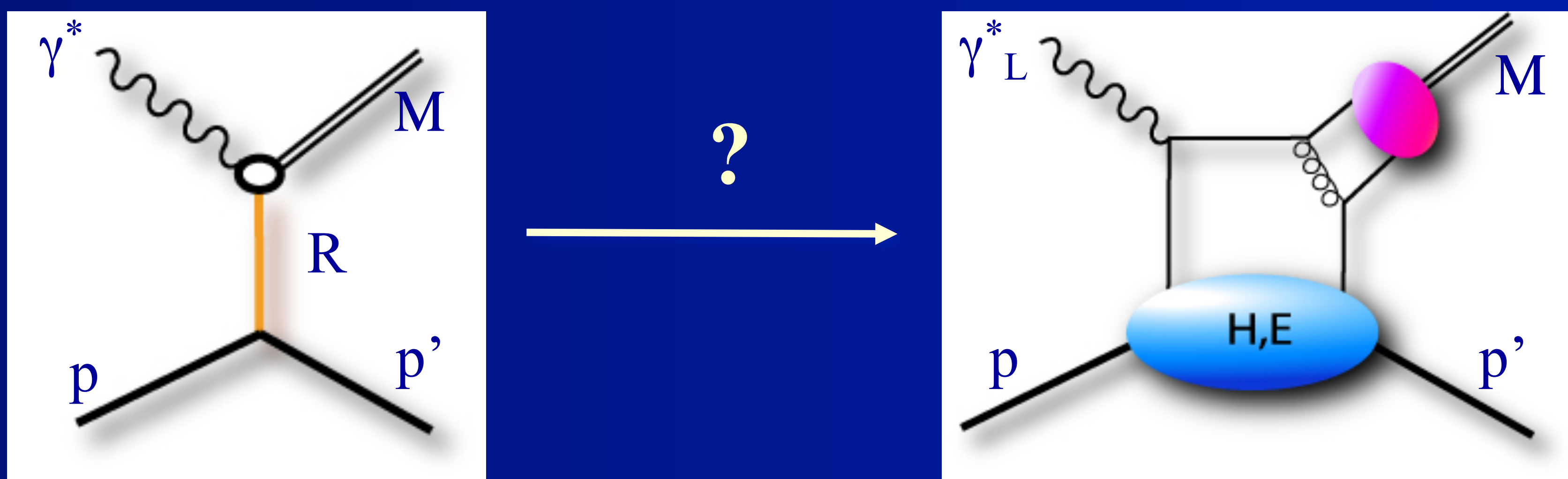
σ_{LT} for different values of the u quark tensor charge

Ahmad, Goldstein, Luiti, 2009



Transition from “hadronic” to the partonic degrees of freedom

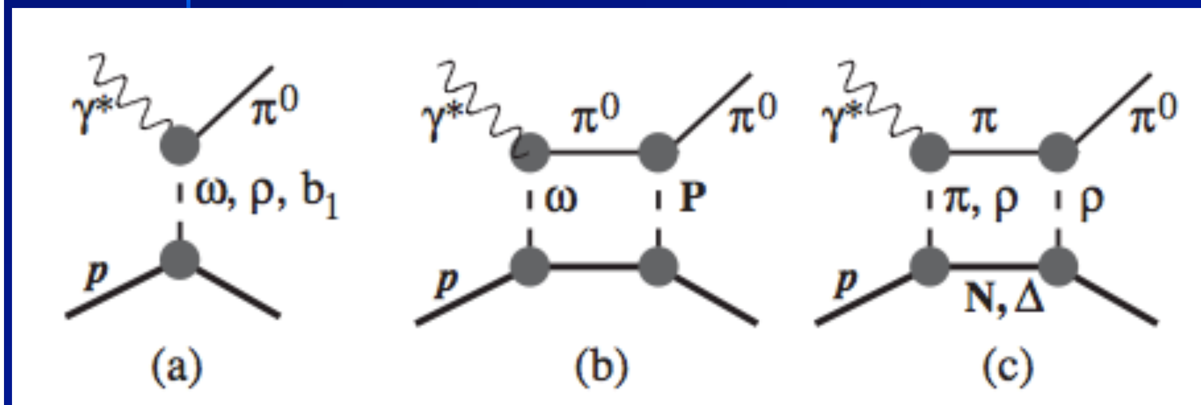


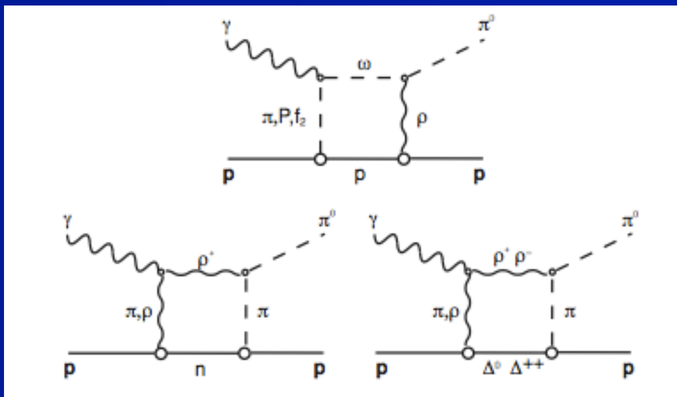


$$\gamma^* p \to p\pi^0$$

Regge Model

J.M. Laget 2010





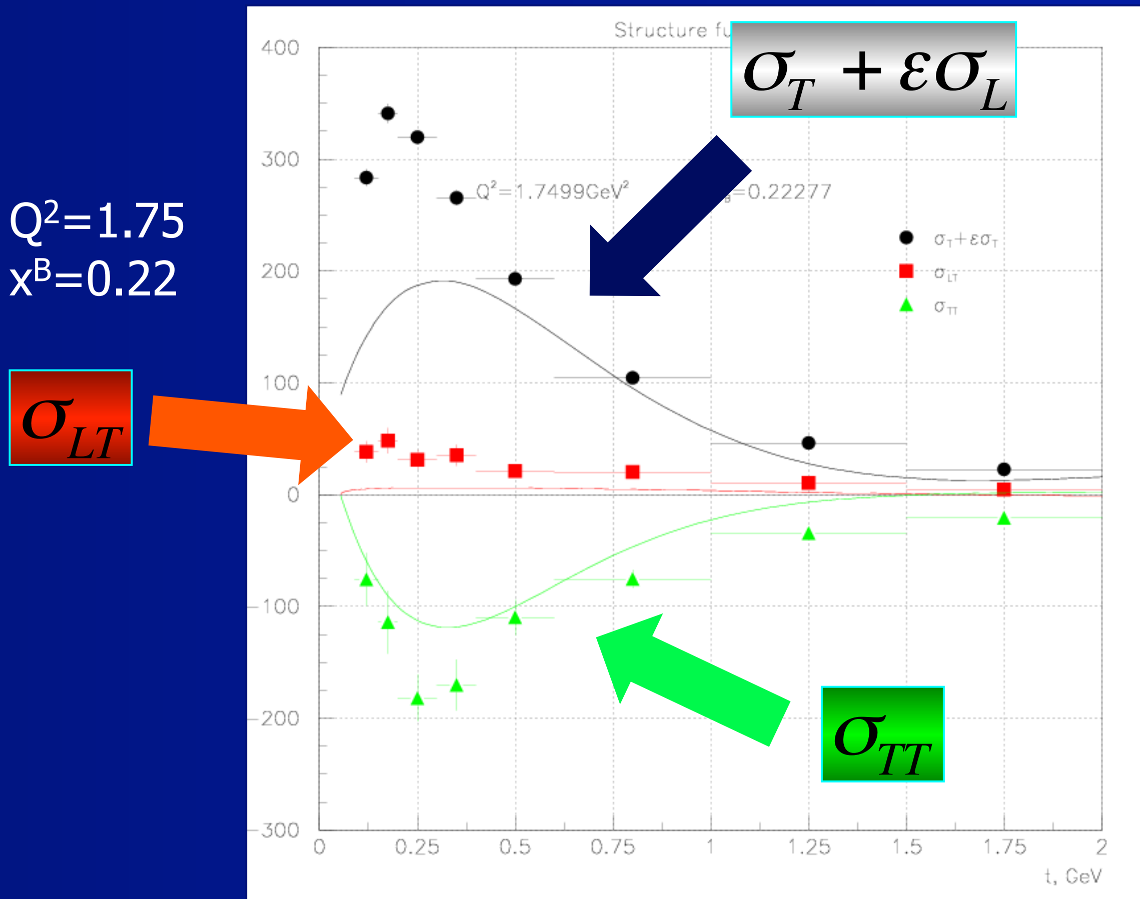
(a) Regge poles (vector and axial vector mesons)
(b) and (c) pion cuts

Vector meson cuts

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

Regge predictions

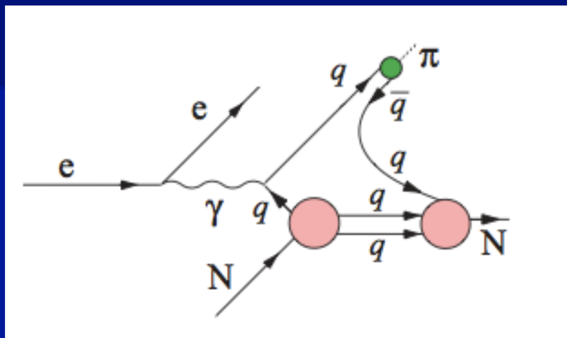
$Q^2=1.75$
$x^B=0.22$



-t, GeV²

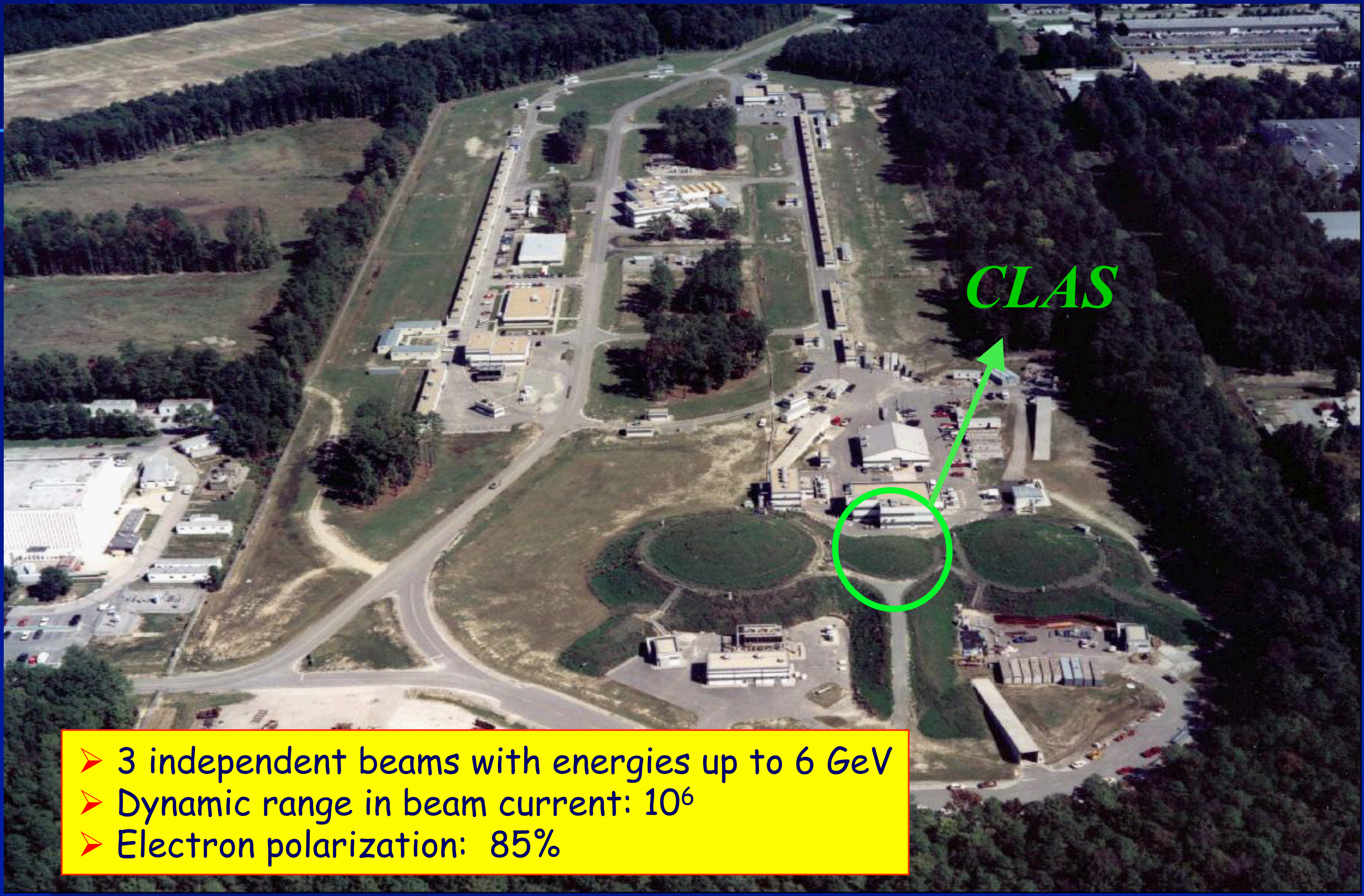
Combined Regge + DIS model

Kaskulov, Gallmeister, Mosel (2008-2010)



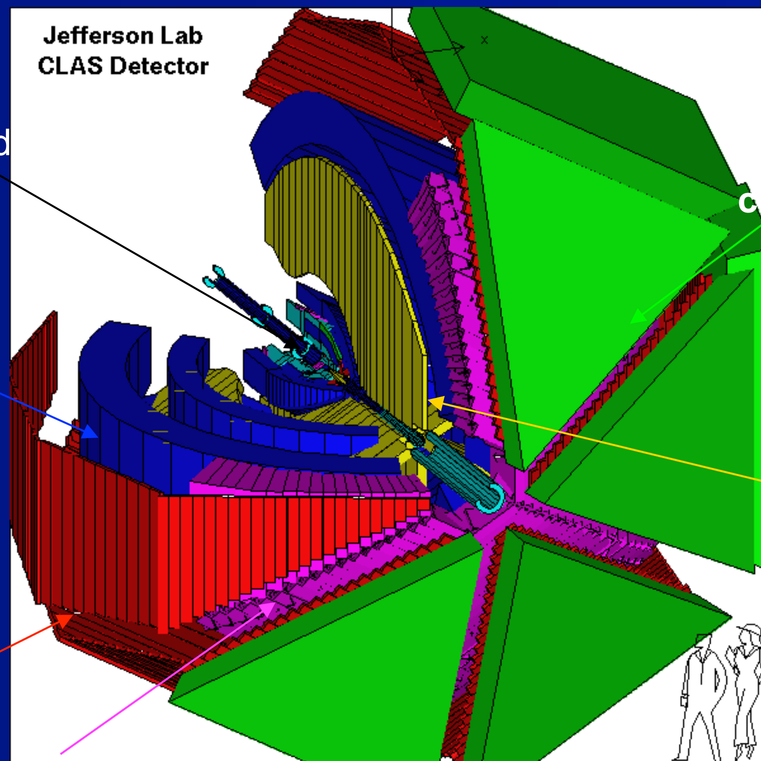
- σ_L is dominated by improved treatment of gauge Invariant Regge model.
- σ_T is described by direct hard interaction of virtual photons with partons followed by the hadronization process into πN channel.
- This explains the large transverse response at moderate and high photon virtualities.
- This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

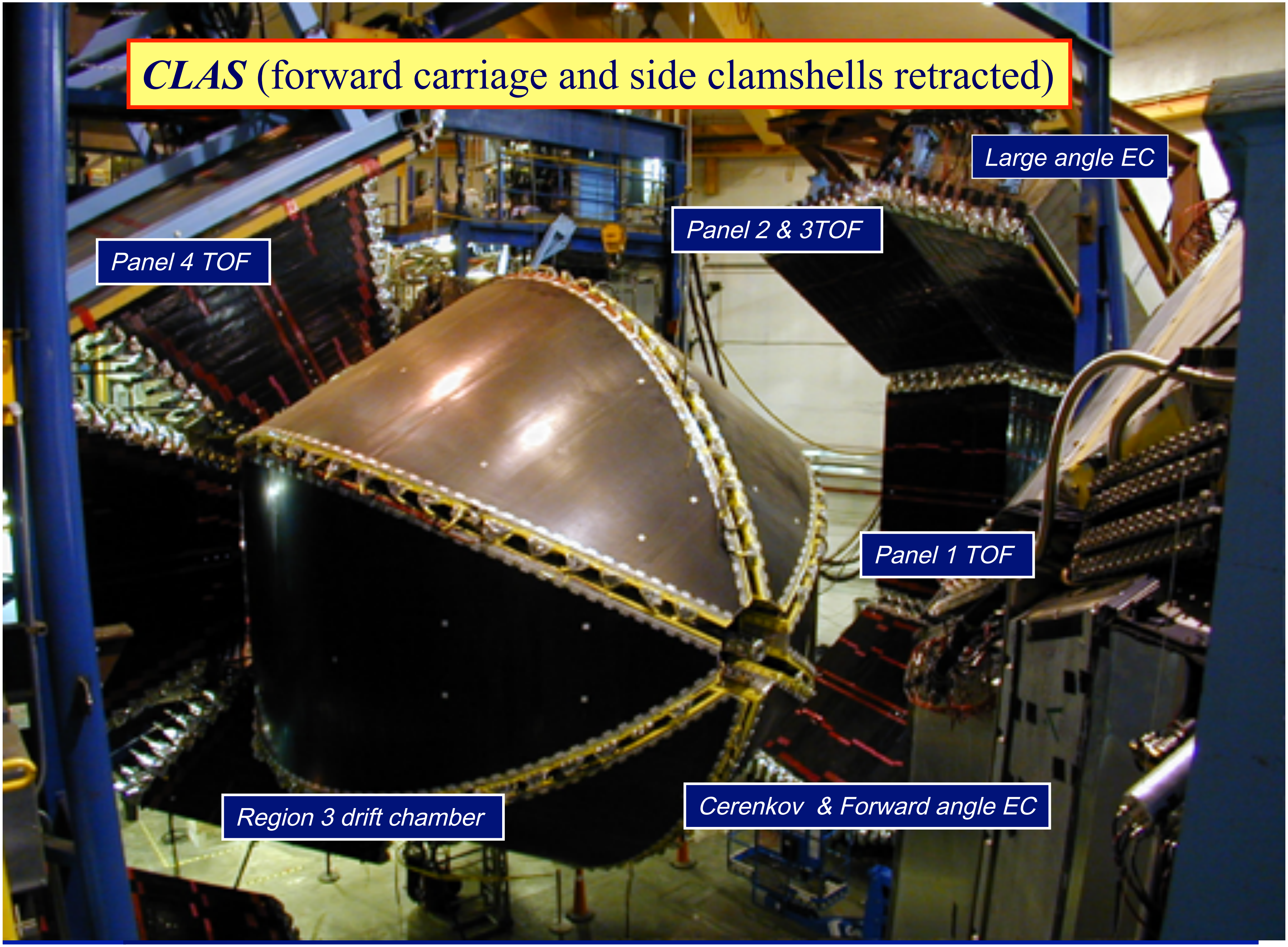
JLab Site: The 6 GeV Electron Accelerator



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

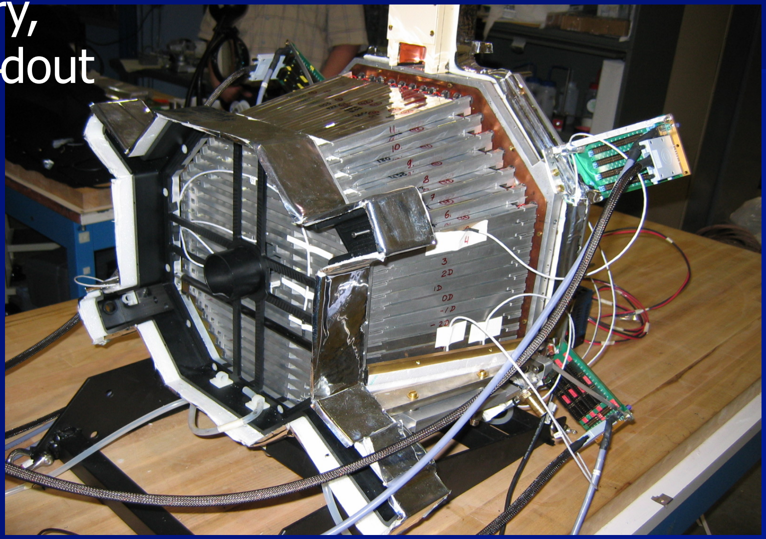
CEBAF Large Acceptance Spectrometer
CLAS

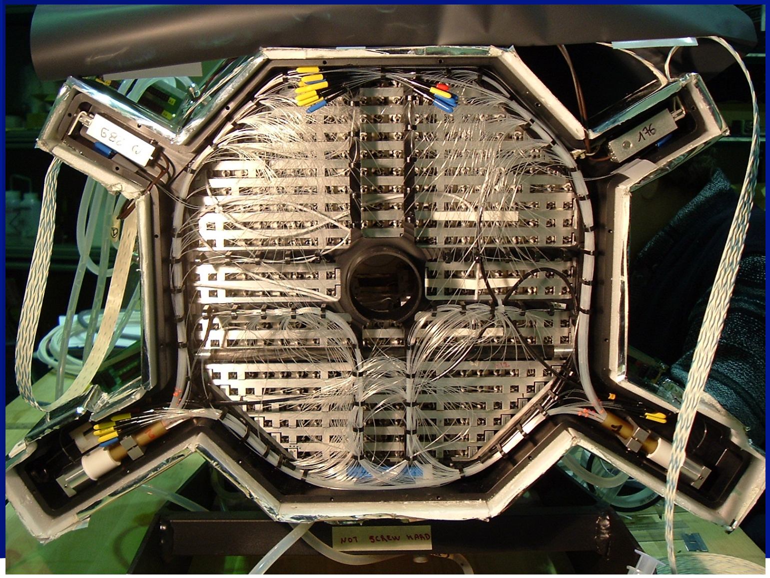


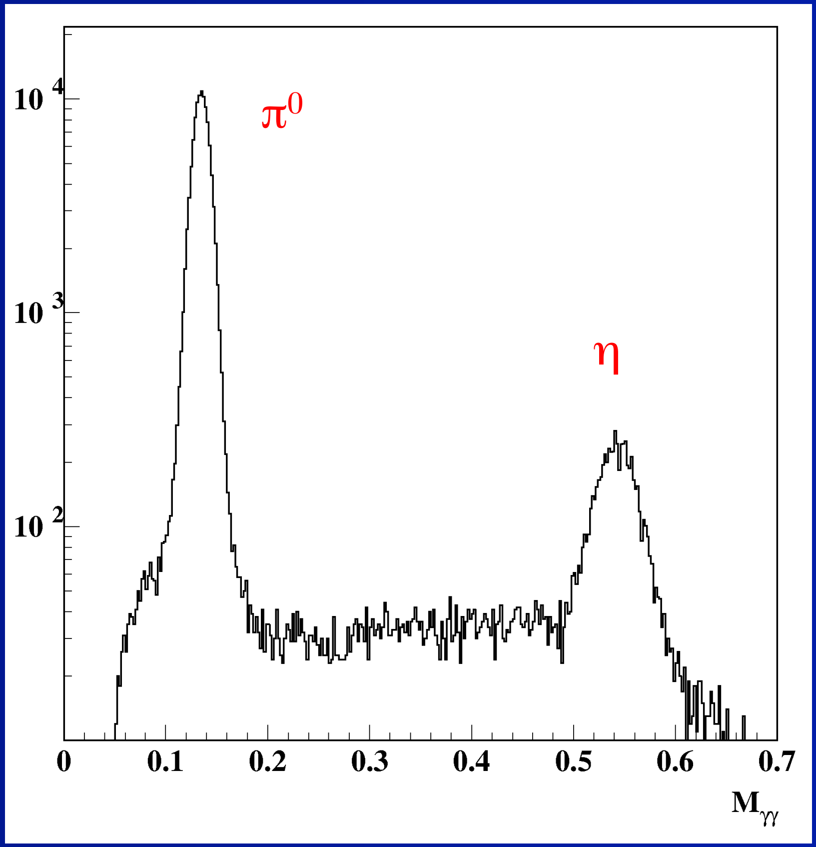

CLAS (forward carriage and side clamshells retracted)
Large angle EC
Panel 2 & 3TOF
Panel 4 TOF
Panel 1 TOF
Region 3 drift chamber
Cerenkov & Forward angle EC

CLAS Lead Tungstate Electromagnetic Calorimeter

424 crystals,
18 RL,
pointing geometry,
APD readout

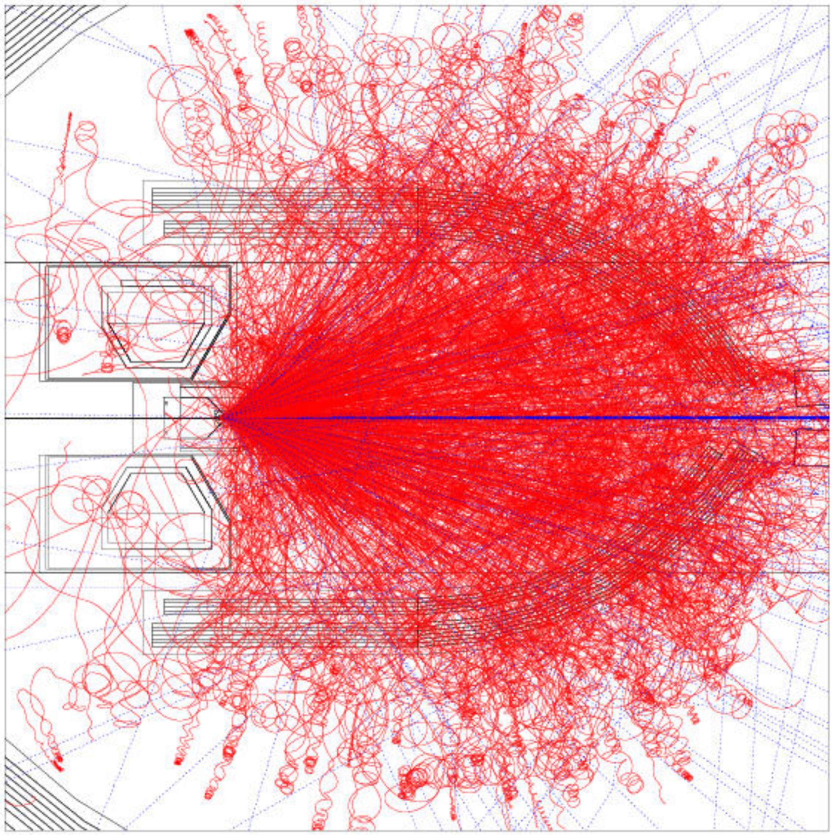




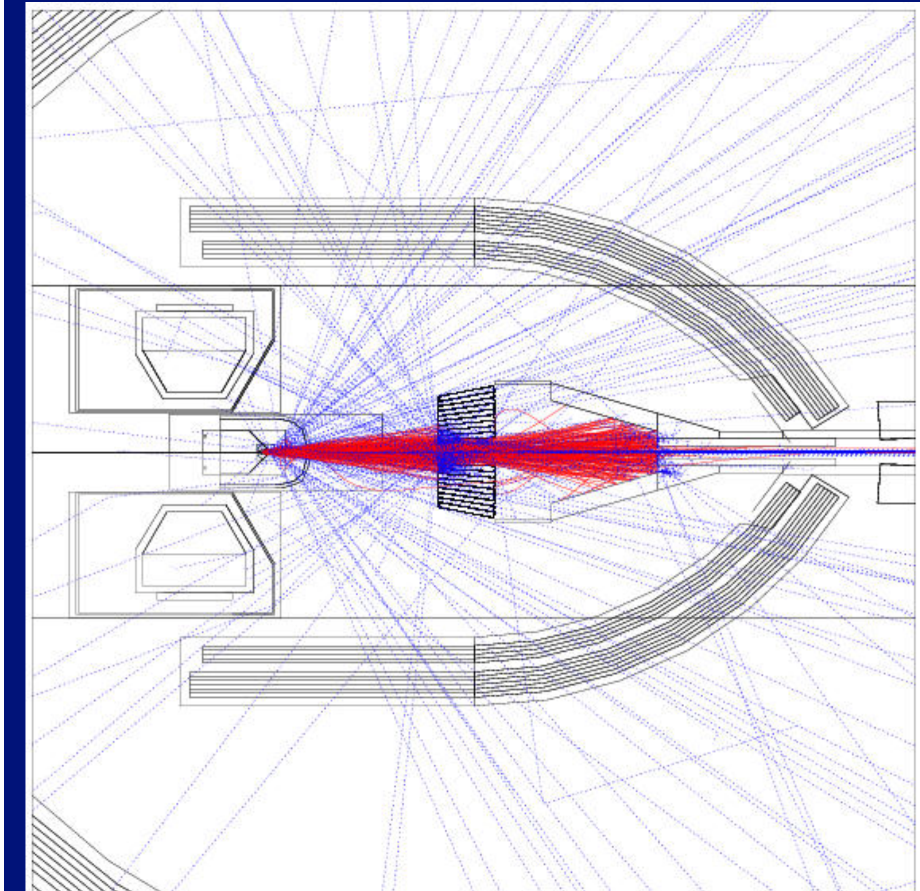


Møller electron shielding

Møller background without B field



Møller background with B field



Huge amounts of electrons drowning the tracking chambers in background.

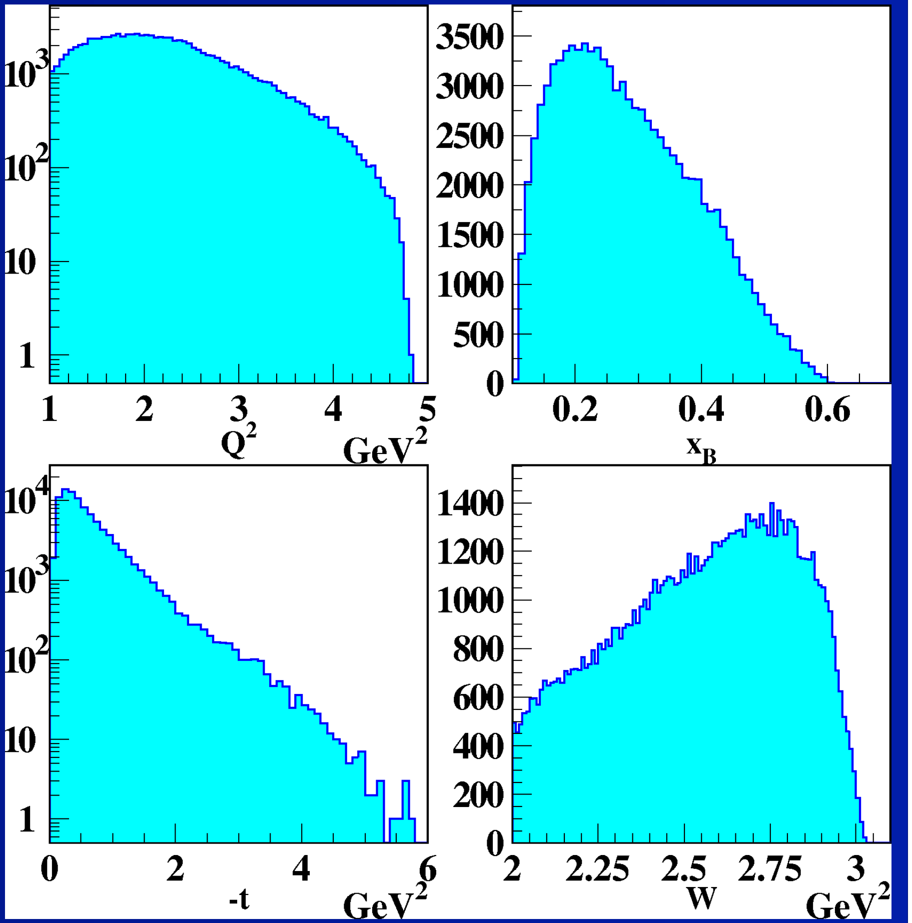
Background electrons hitting the tracking chambers are eliminated.

DVMP: Kinematic Coverage

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

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

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



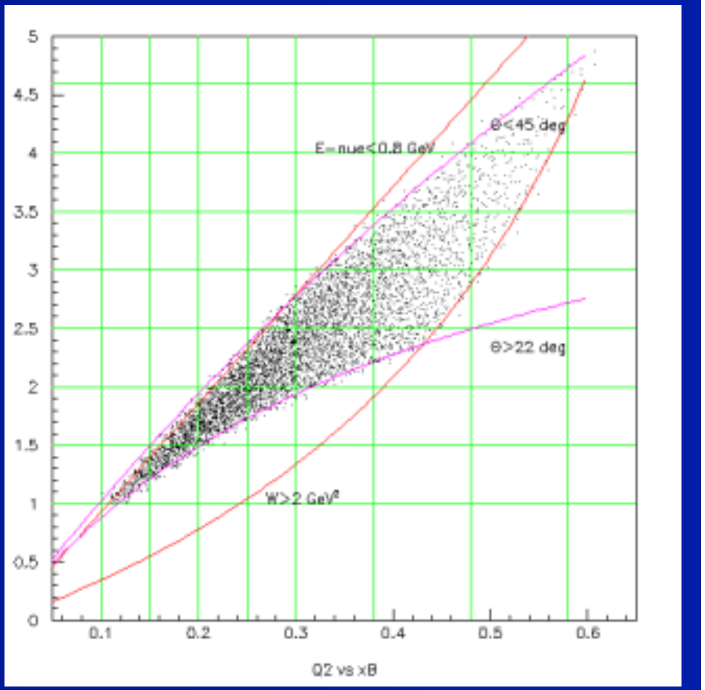
- Polarized Electron Beam
- E_0=5.776 GeV
- 75-80% polarization
- 2.5 cm Liquid Hydrogen target
- IC calorimeter
- Instant luminosity $2*10^{34}$ cm^2/s
- Integrated luminosity: $3.27*10^7$ nb^{-1}

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

Q^2



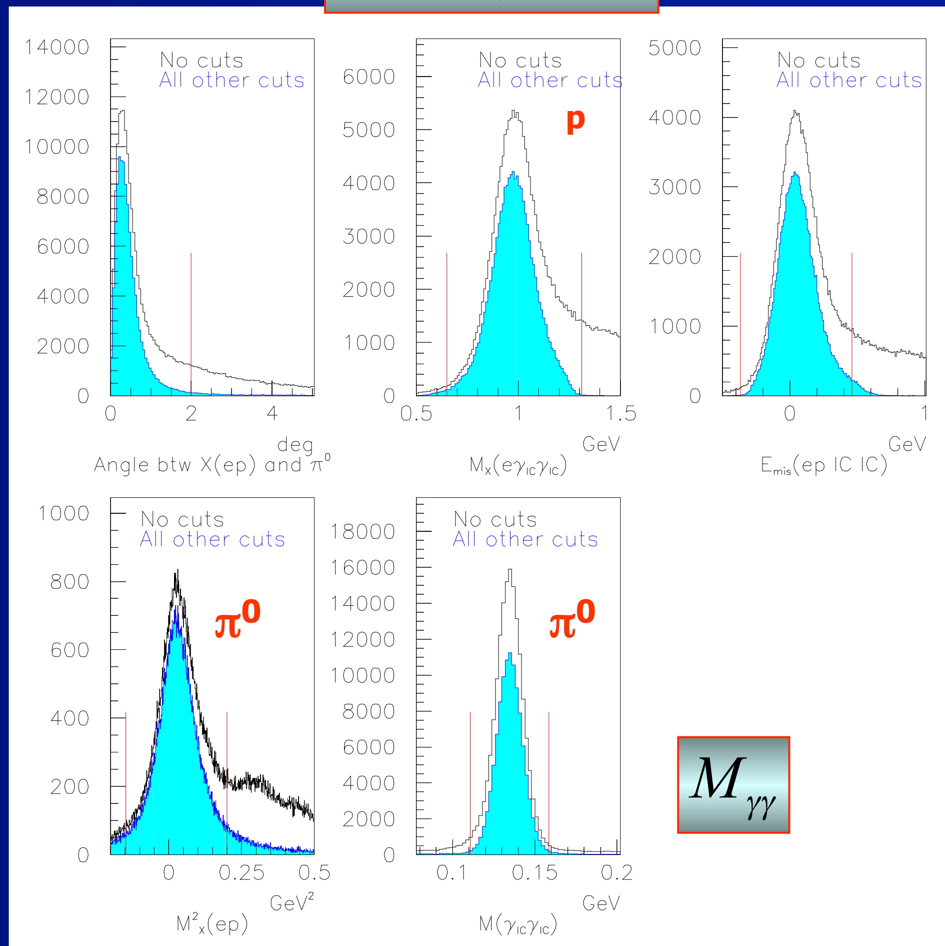
x_B

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

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

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

$E_{missing}$



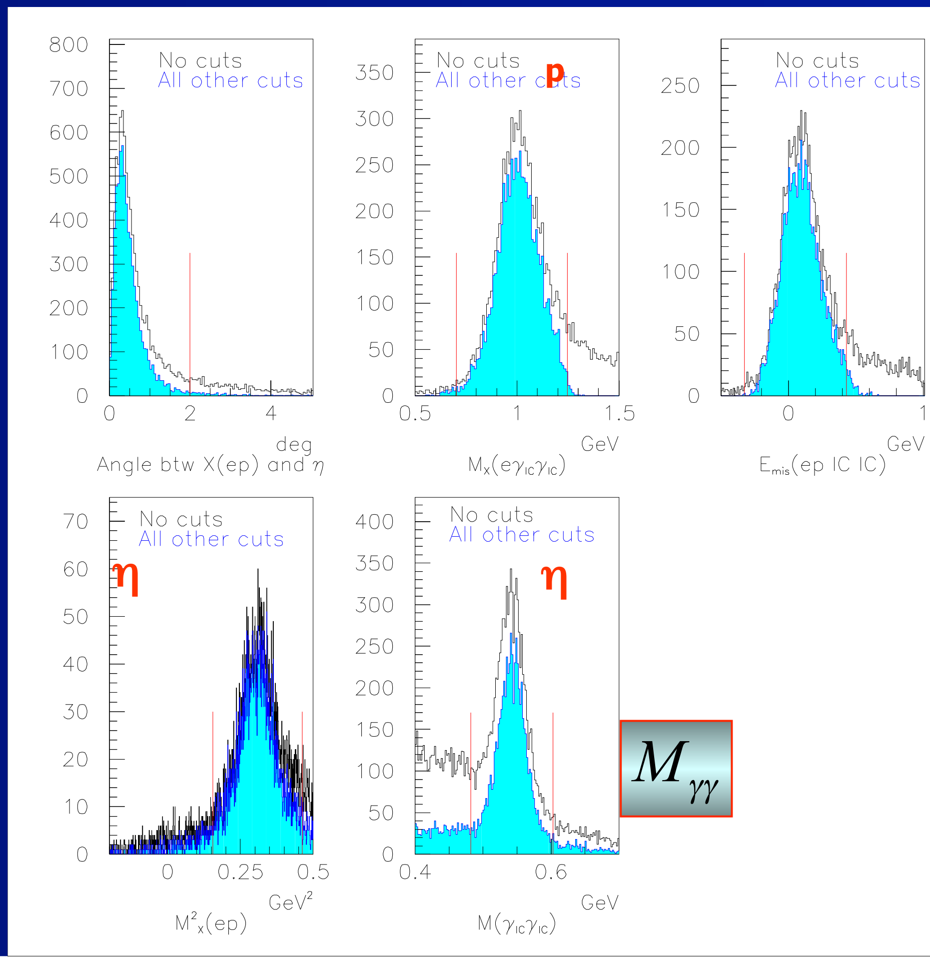
$M_{\gamma\gamma}$

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

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

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

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



$E_{missing}$

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

$M_{\gamma\gamma}$

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

Structure Functions

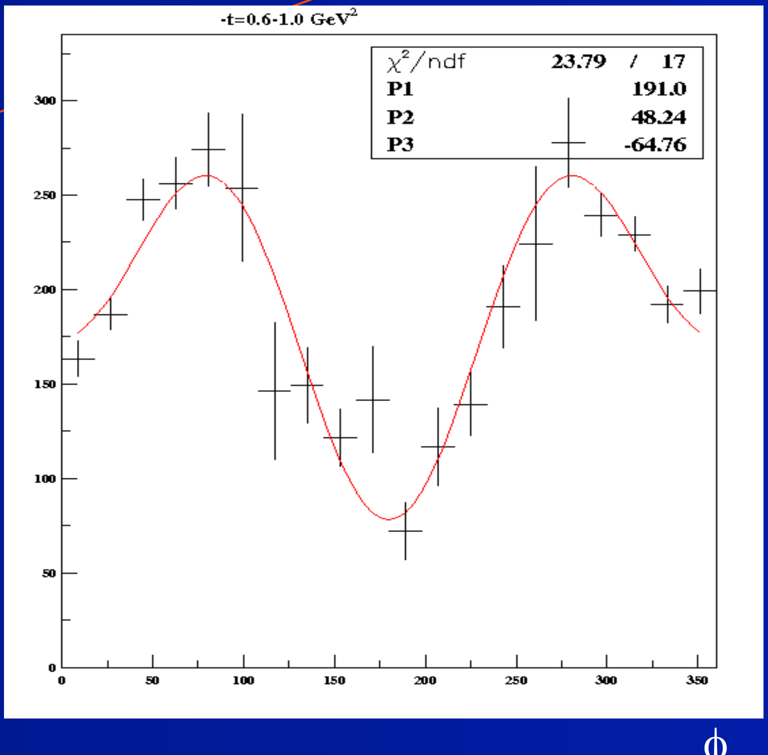
$$\frac{d\sigma}{dtd\phi}(Q^2,x,t,\phi) = \frac{1}{2\pi}\left(\frac{d\sigma_T}{dt} + \varepsilon\frac{d\sigma_L}{dt} + \varepsilon\frac{d\sigma_{TT}}{dt}\cos 2\phi + \sqrt{2\varepsilon(\varepsilon+1)}\frac{d\sigma_{LT}}{dt}\cos\phi\right)$$

Fit of the ϕ-distribution gives us three structure functions

$$\frac{d\sigma_T}{dt} + \varepsilon\frac{d\sigma_L}{dt}$$

$$\frac{d\sigma_{TT}}{dt}$$

$$\frac{d\sigma_{LT}}{dt}$$



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.

Cross section model

The package includes independent functions for the calculations of all structure functions: $\sigma_T, \sigma_L, \sigma_{TT}, \sigma_{LT}, \sigma_{LT'}$.

The model is as follows:

- $\sigma_T = \sigma^T e^{B_T(x_B)t}/(Q^2+M^2)^n$, $B_T(x_B) = \alpha^T * 2 * 1.1 * ln(x_B)$
- $\sigma_L = \sigma^L Q^2 e^{B_L(x_B)t}/(Q^2+M^2)^n$, $B_L(x_B) = \alpha^L * 2 * 1.1 * ln(x_B)$
- $\sigma_{TT} = \sigma^{TT}(t-t_{min}) e^{B_{TT}(x_B)t}/(Q^2+M^2)^n$, $B_{TT}(x_B) = \alpha^{TT} * 2 * 1.1 * ln(x_B)$
- $\sigma_{LT} = \sigma^{LT}\sqrt{t-t_{min}}\, e^{B_{LT}(x_B)t}/(Q^2+M^2)^n$, $B_{LT}(x_B) = \alpha^{LT} * 2 * 1.1 * ln(x_B)$
- $\sigma_{LT'} = 0$

where $\sigma^T, \sigma^L, \sigma^{TT}, \sigma^{LT}, \alpha^T, \alpha^L, \alpha^{TT}, \alpha^{LT}, M^2, n$ are free parameters. Note the different t-dependence for

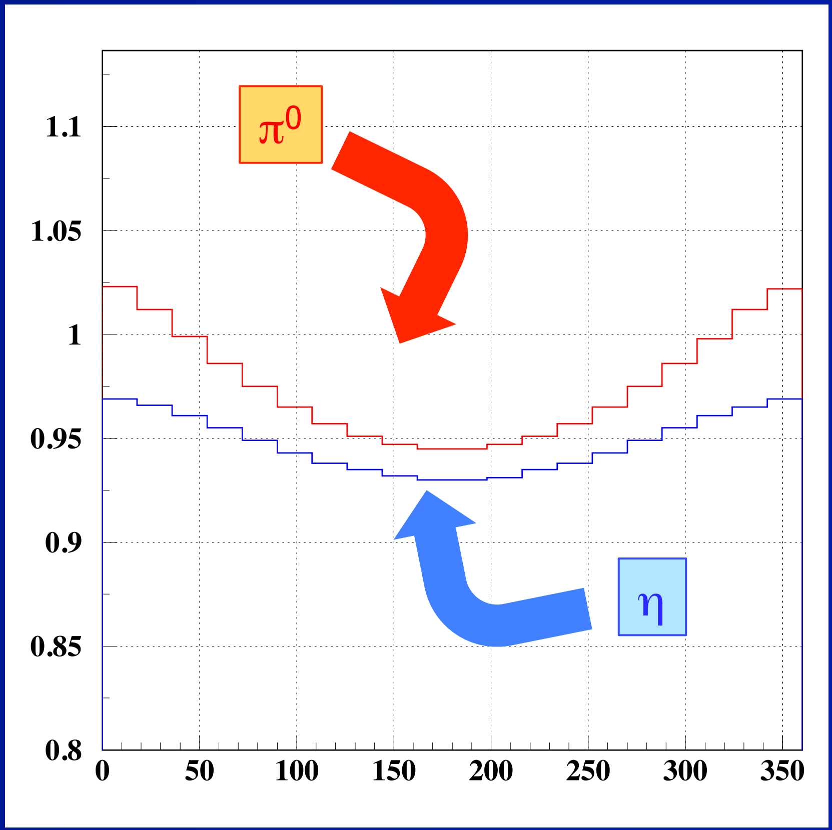
- $\sigma^{TT} \sim (t-t_{min})$ and
- $\sigma^{LT} \sim \sqrt{t-t_{min}}$.

Radiative Corrections

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

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

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



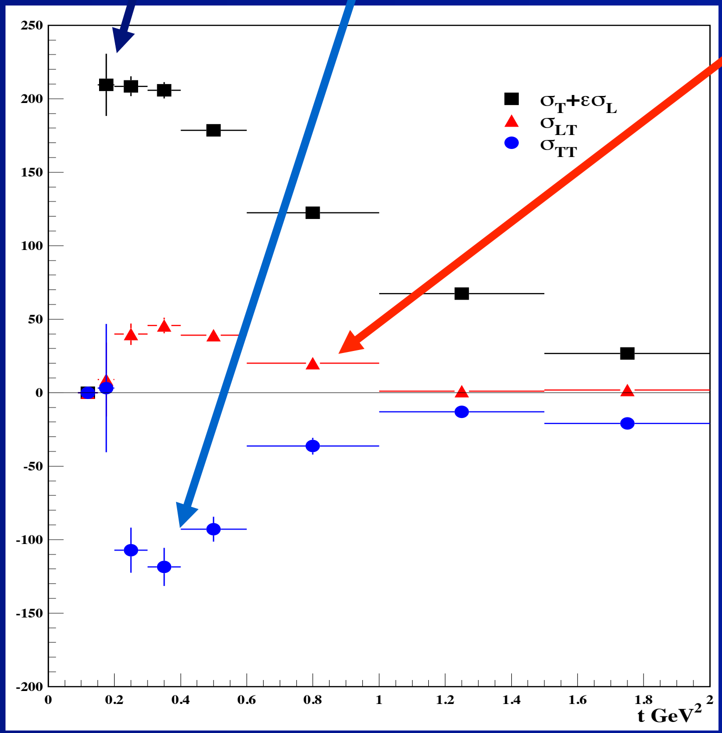
ϕ

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

$(\sigma_T + \varepsilon\sigma_L)$ σ_{TT} σ_{LT} as a function of t

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

Non-zero σ_{TT} and σ_{LT} imply that both transverse and longitudinal amplitudes participate in the process



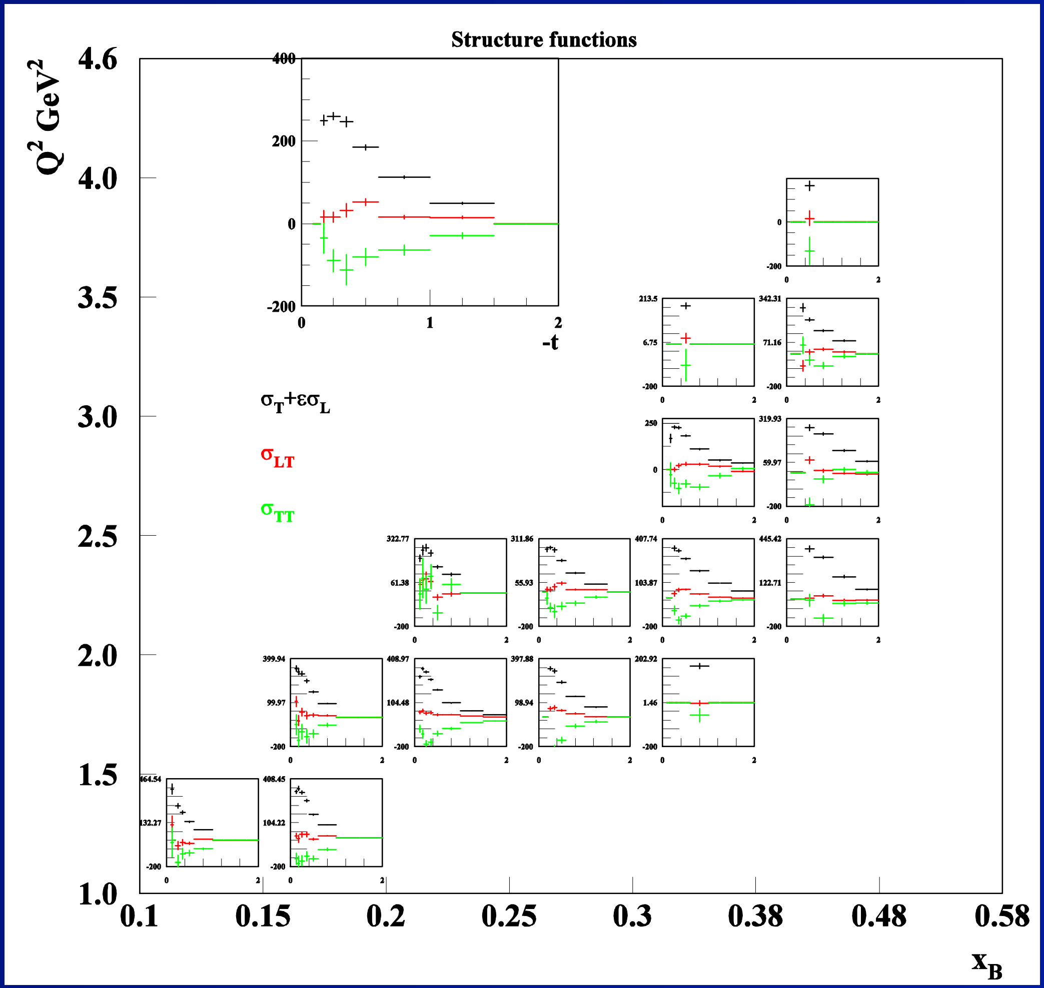
Q^2=2.3
x_B=0.4

t GeV^2

Structure Functions

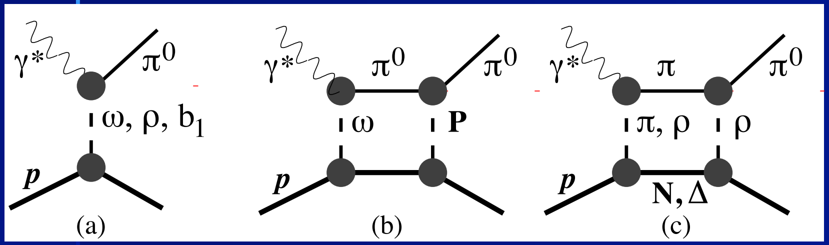
$(\sigma_T + \varepsilon\sigma_L)$ σ_{TT} σ_{LT}

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



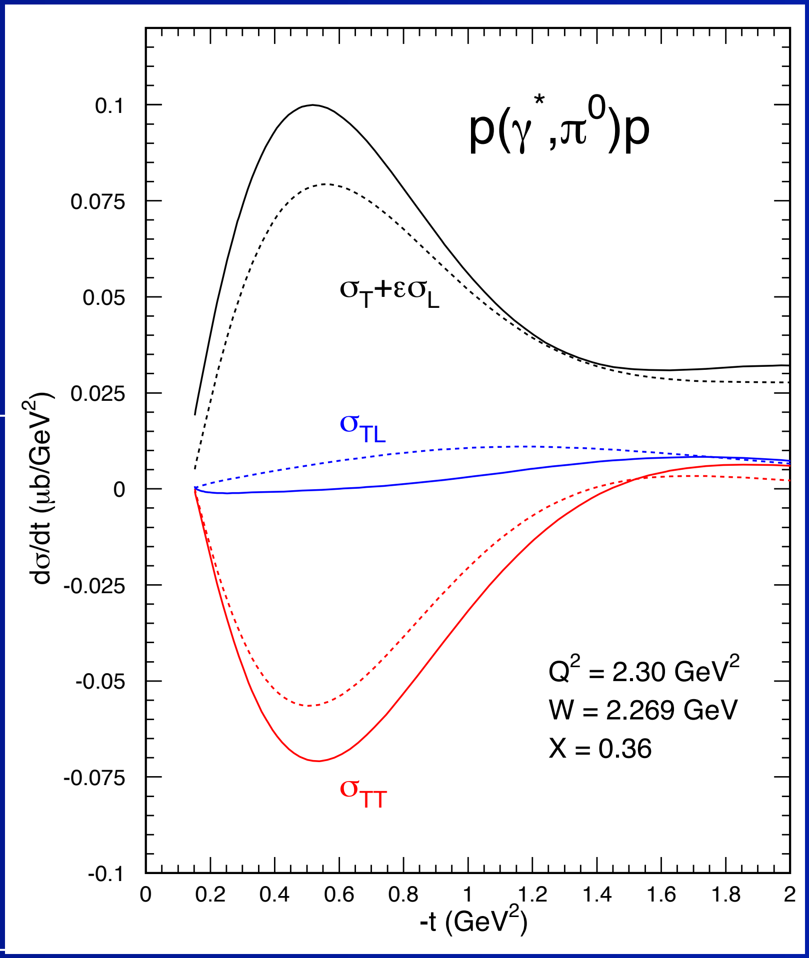
$\gamma^* p \to p\pi^0$

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



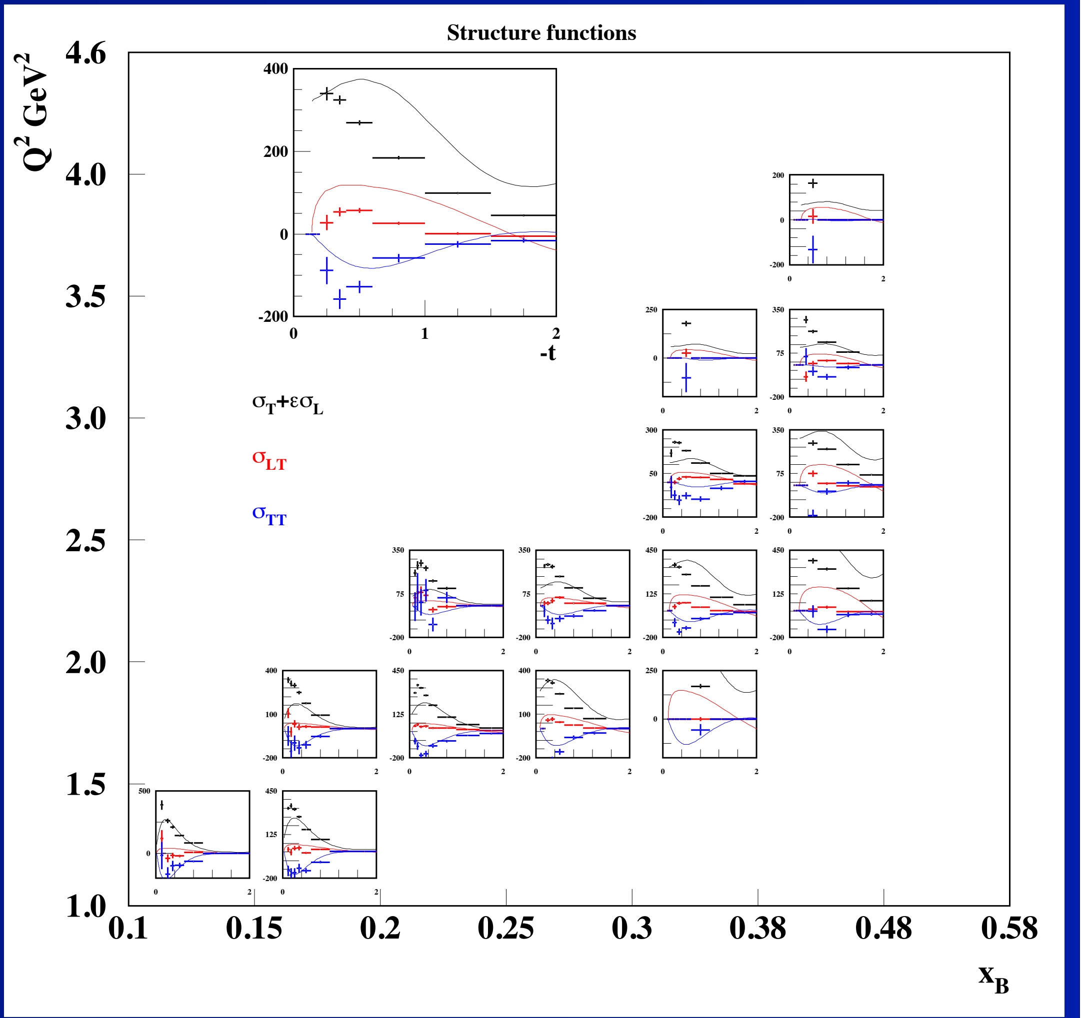
ω/ρ/b1 elastic rescat. charge pion

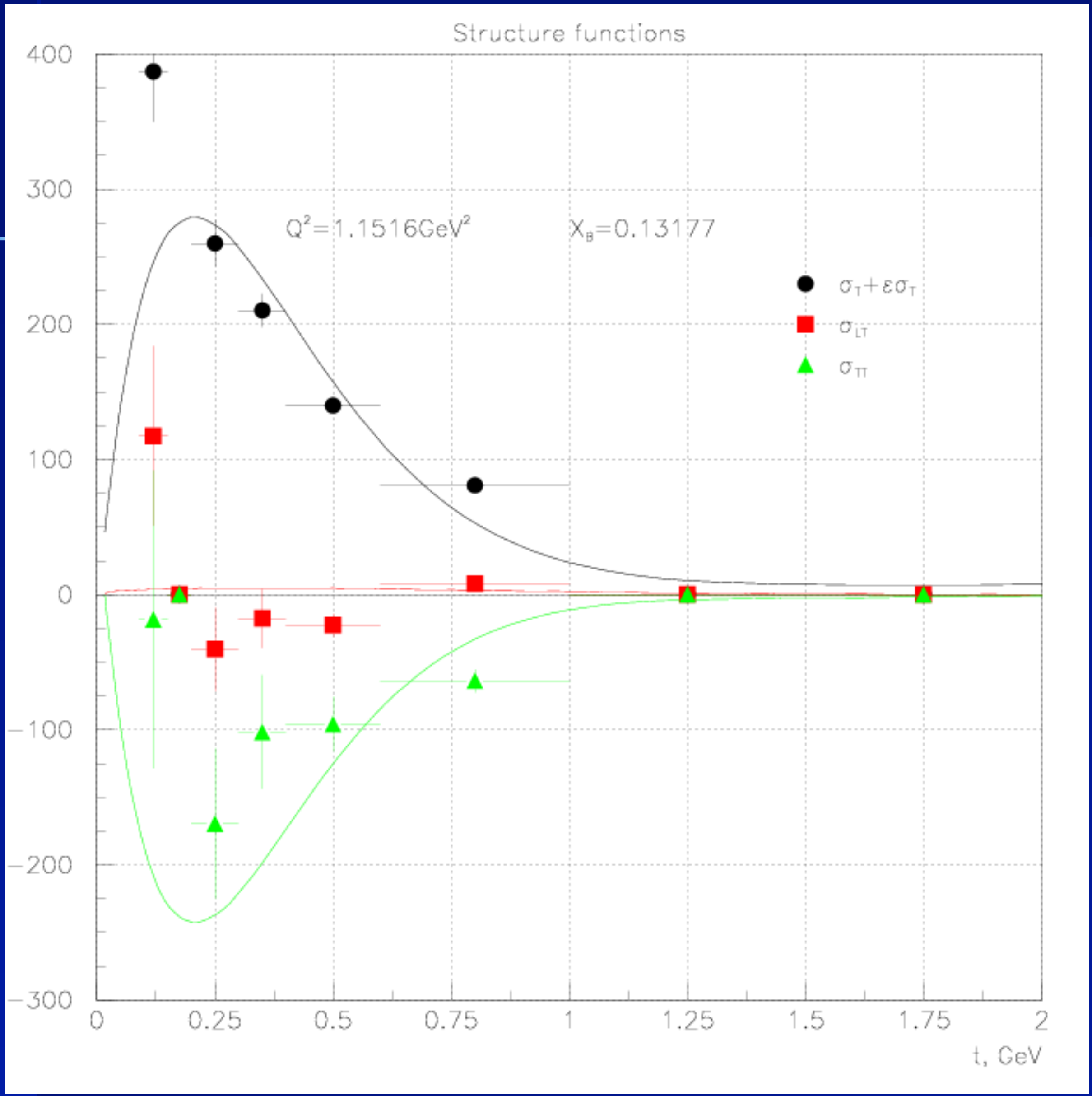
- The dashed lines correspond to the ω/ρ/b1 Regge poles and elastic rescattering
- The full lines include also charge pion nucleon and Delta intermediate states.
- Regge model qualitatively describes the experimental data



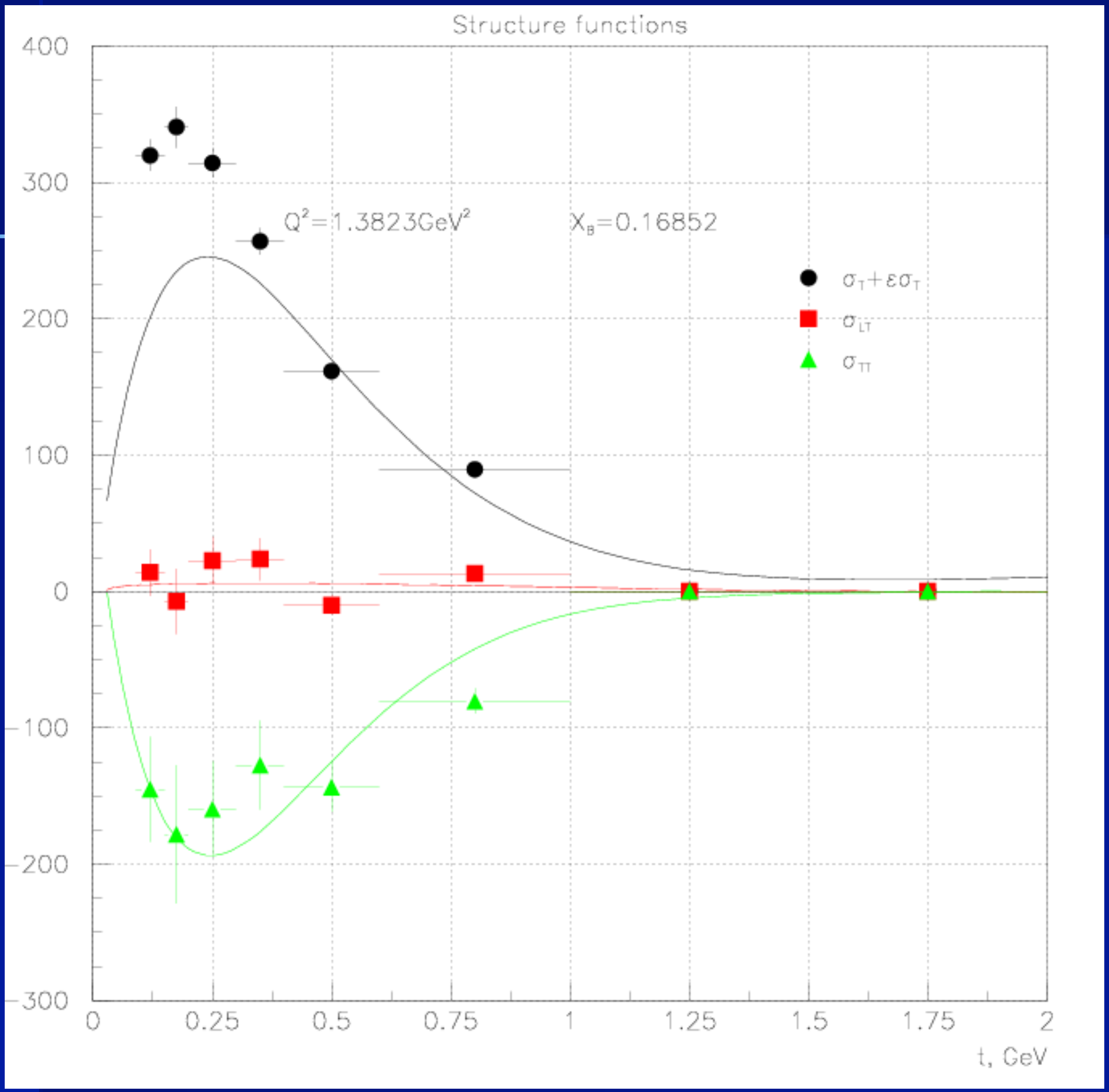
Comparison with J.M. Laget Regge model

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

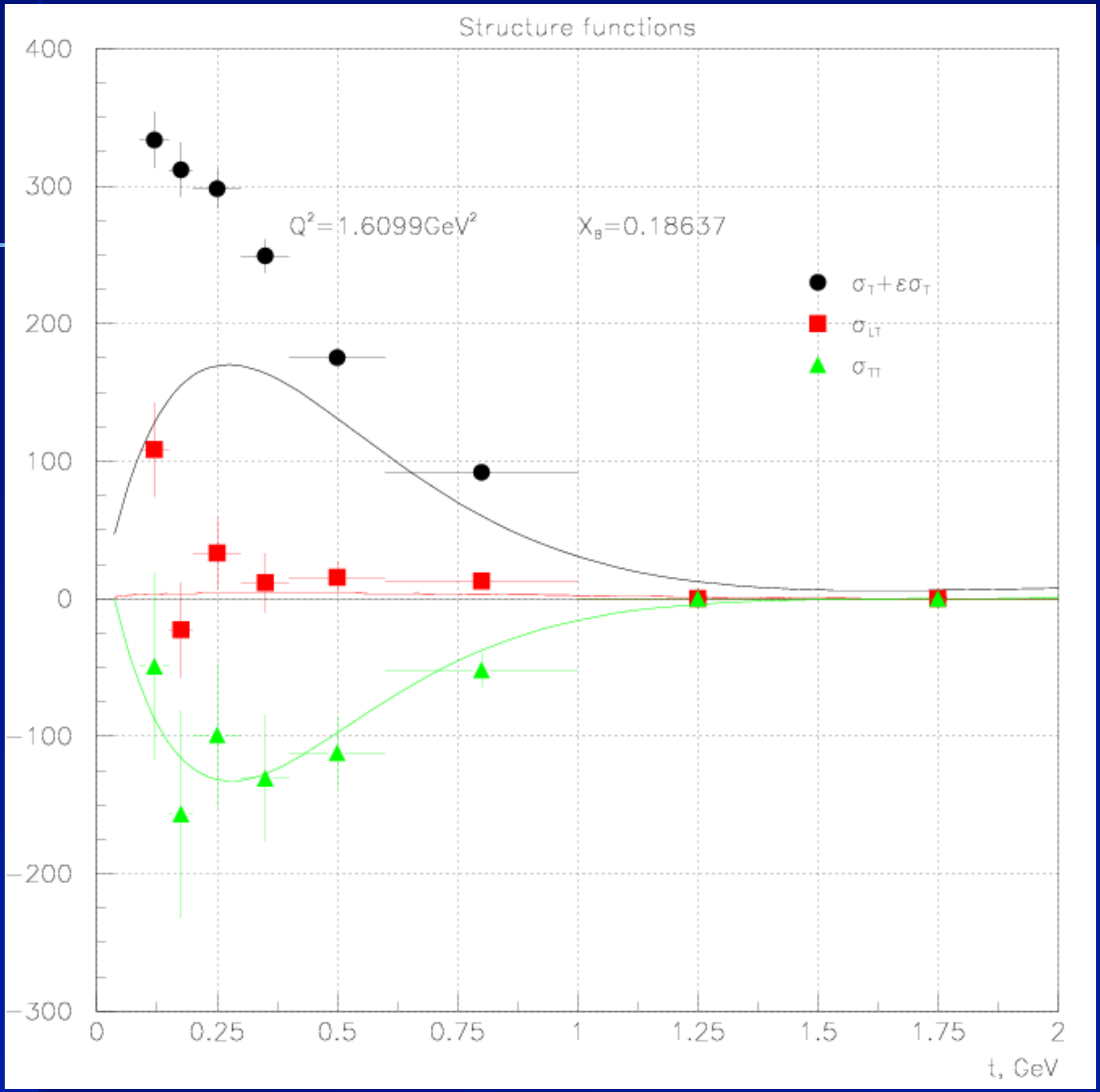




$Q^2 = 1.15\ GeV^2$
$x_B = 0.13$

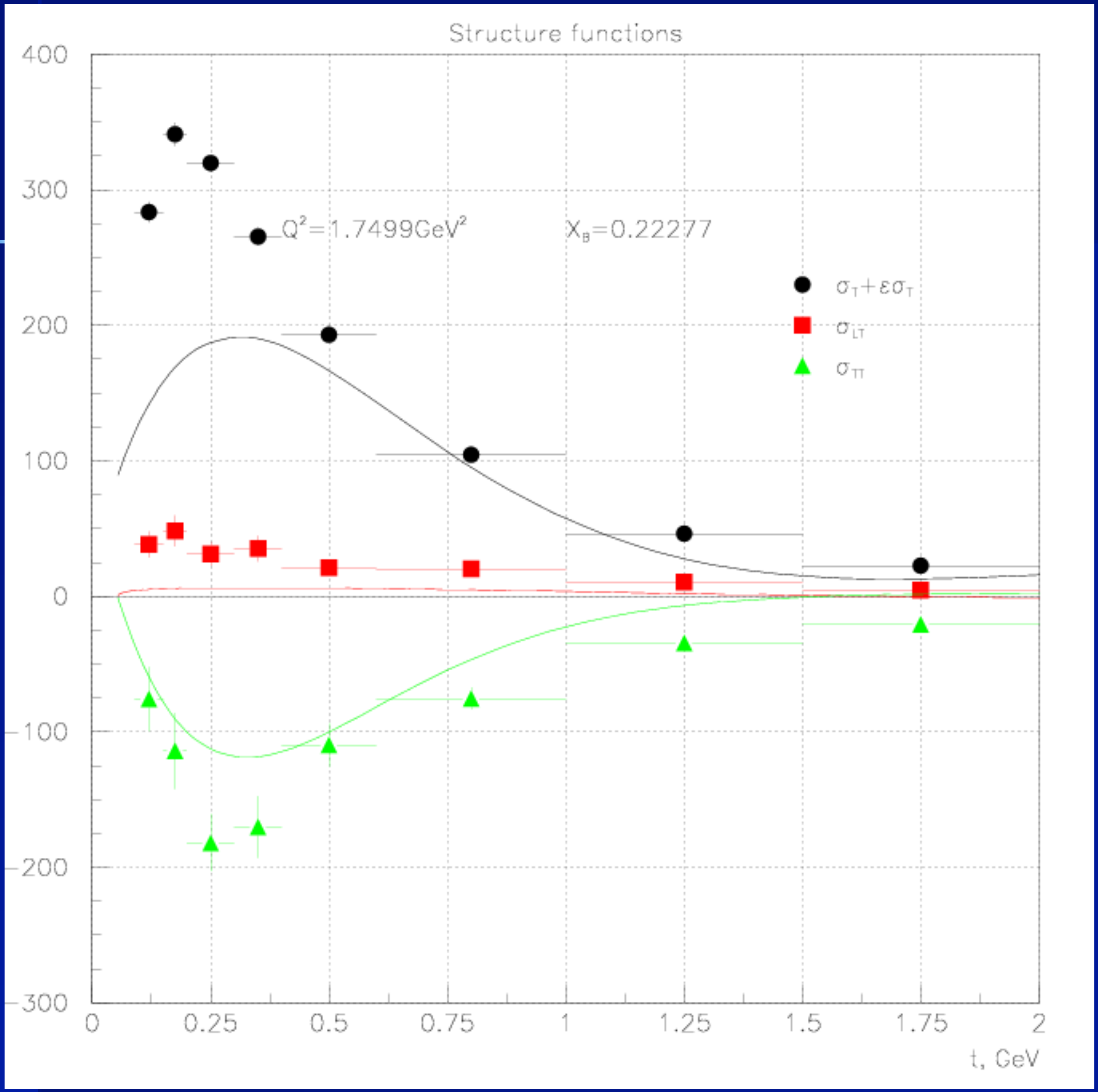


Q^2 = 1.38 GeV^2
x_B = 0.17



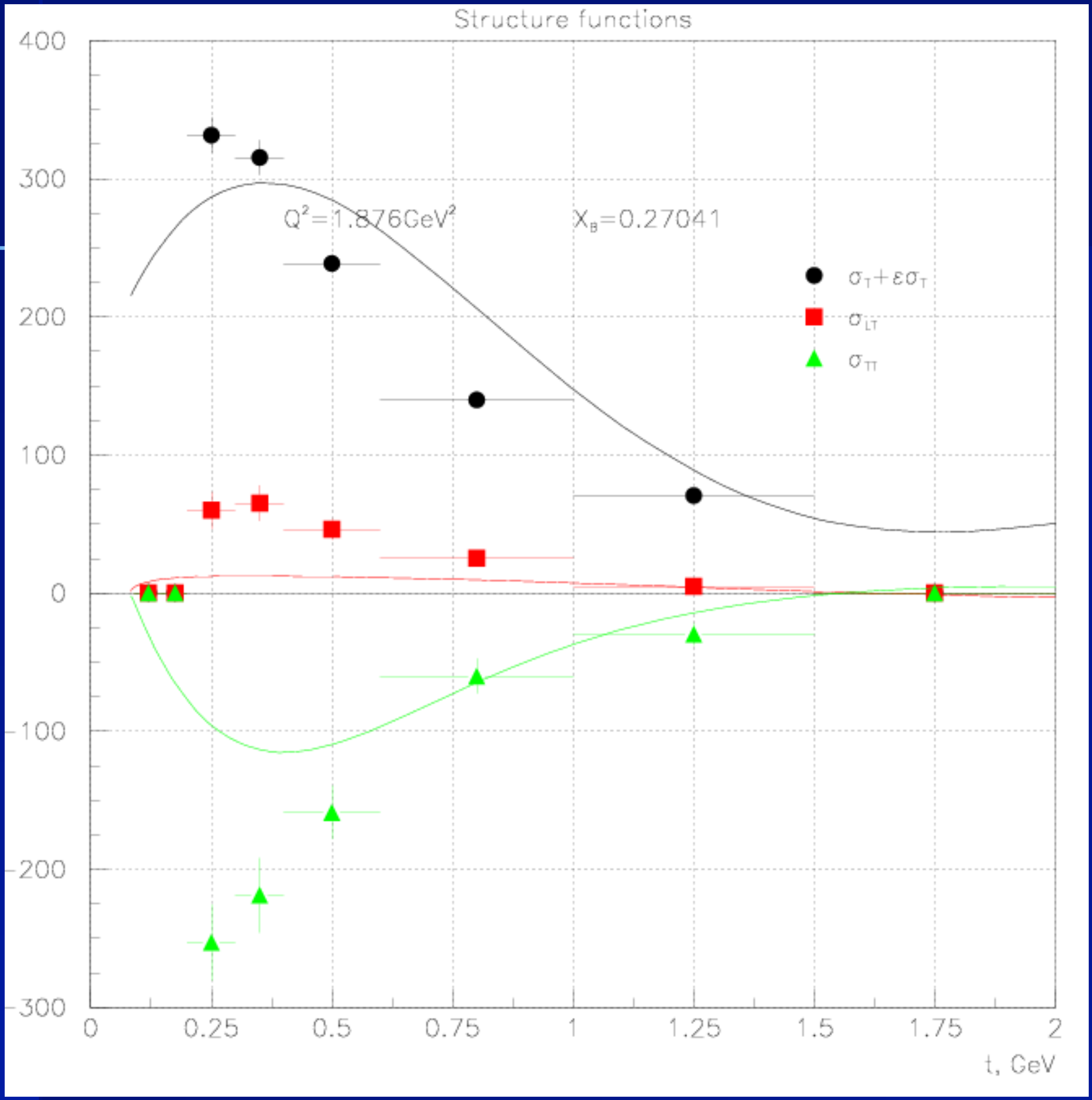
Q^2 = 1.61 GeV^2

x_B = 0.19

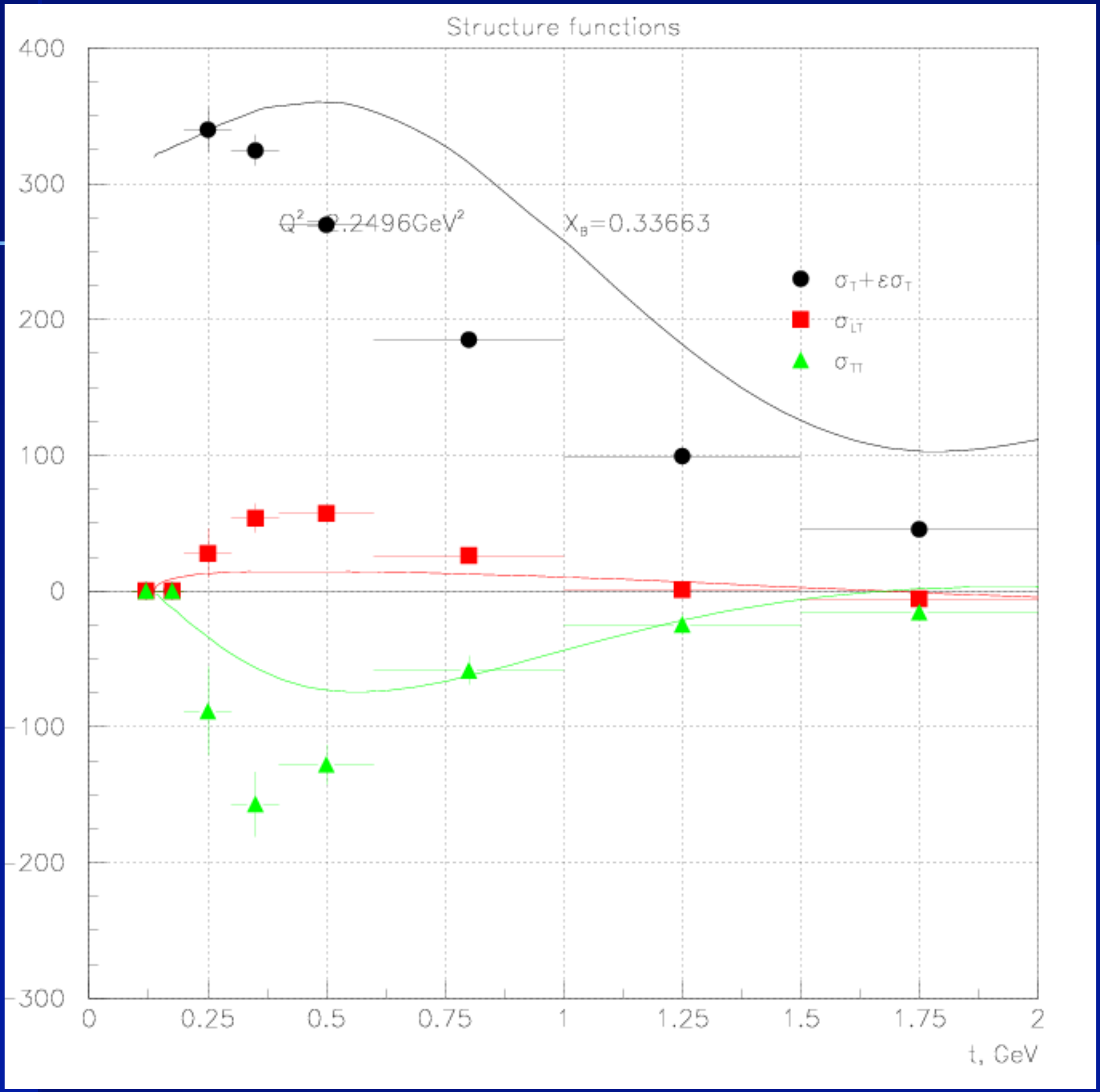


Q^2 = 1.74 GeV^2

x_B = 0.22

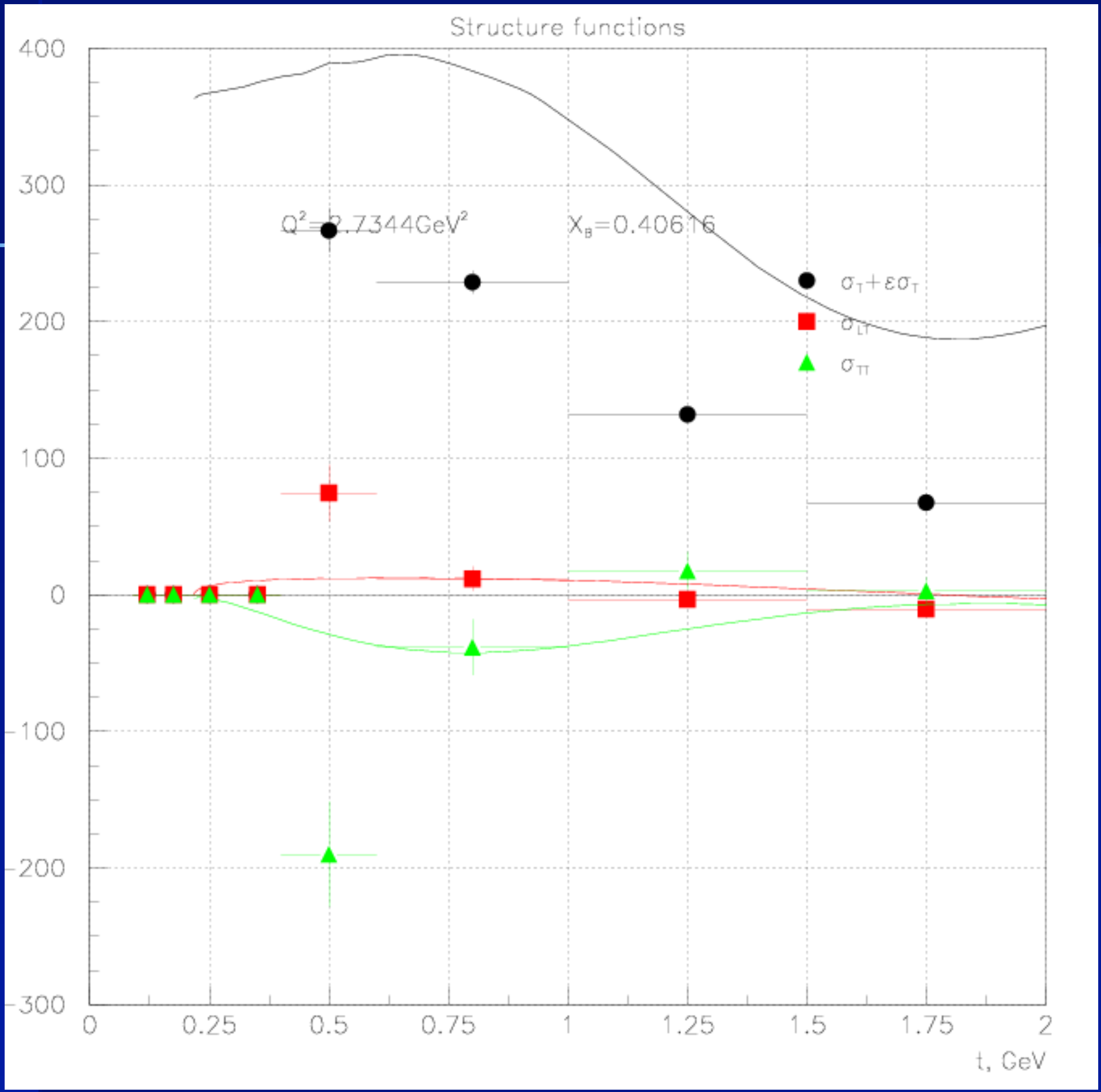


Q^2 = 1.88 GeV^2
x_B = 0.27

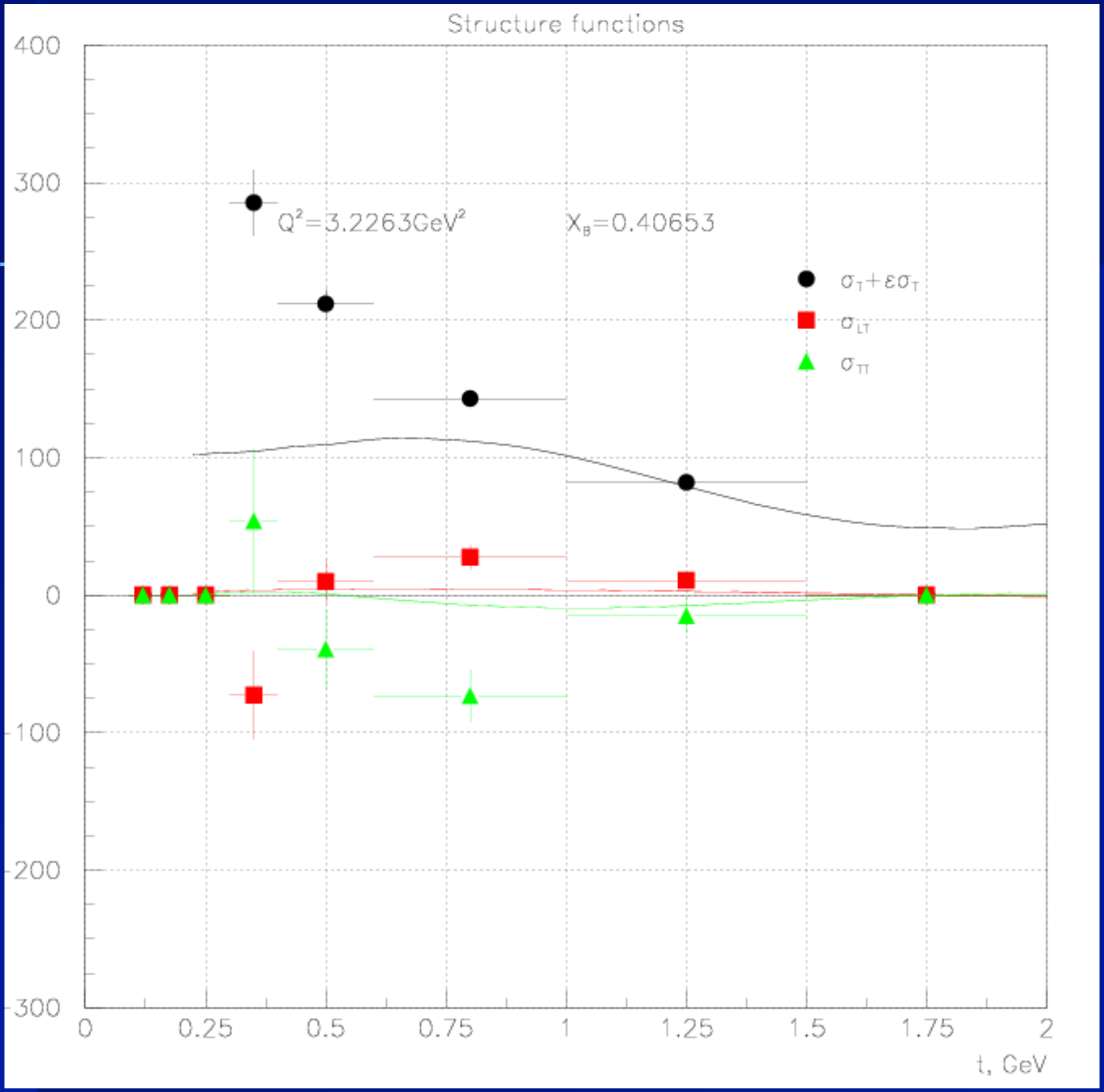


$Q^2 = 2.25\ GeV^2$

$x_B = 0.34$



Q^2 = 2.73 GeV^2
x_B = 0.41

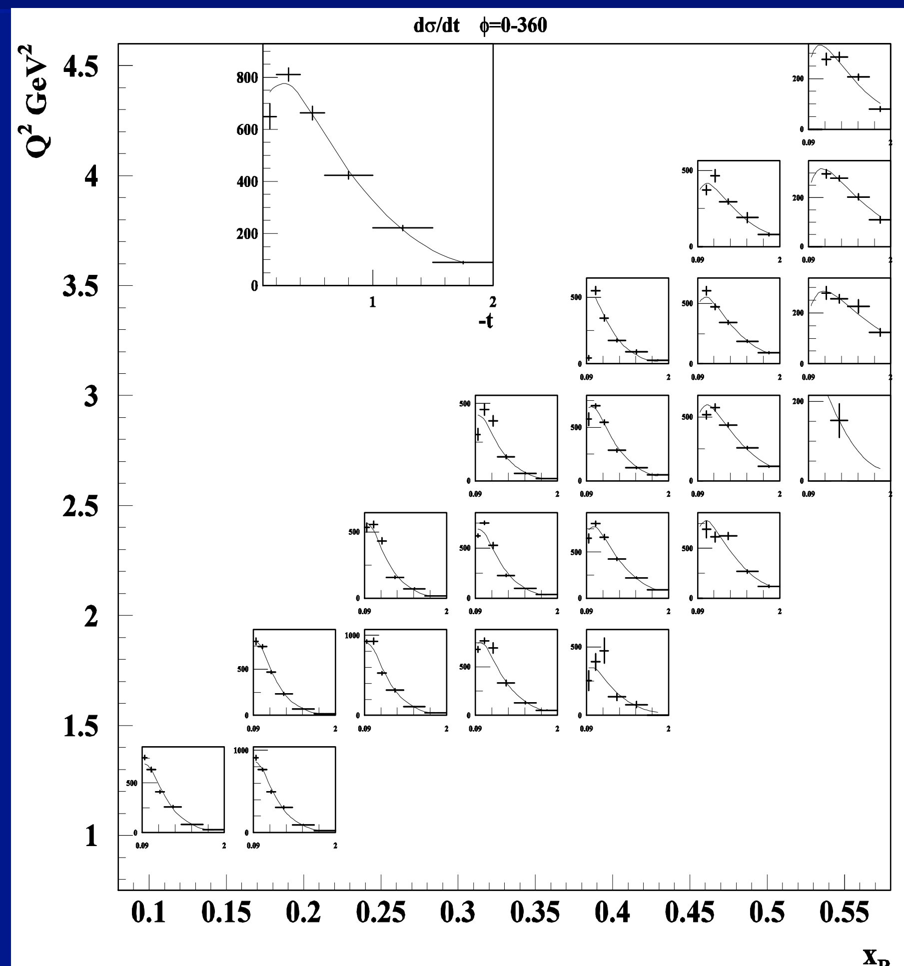


Q^2 = 3.22 GeV^2
x_B = 0.41

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

t - distribution

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



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

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

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

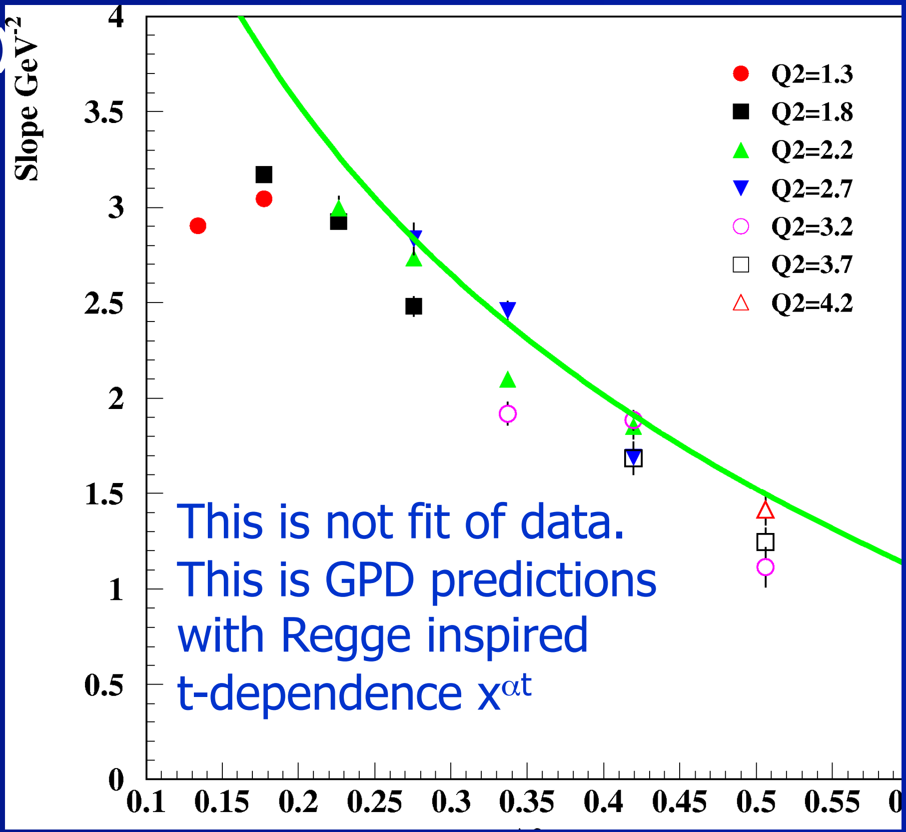
$$f^q(x,t) \propto x^{\alpha_q(t)} \propto x^{\alpha' t}$$

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

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

$$\alpha' = 1.1$$

$B(x_B, Q^2)$

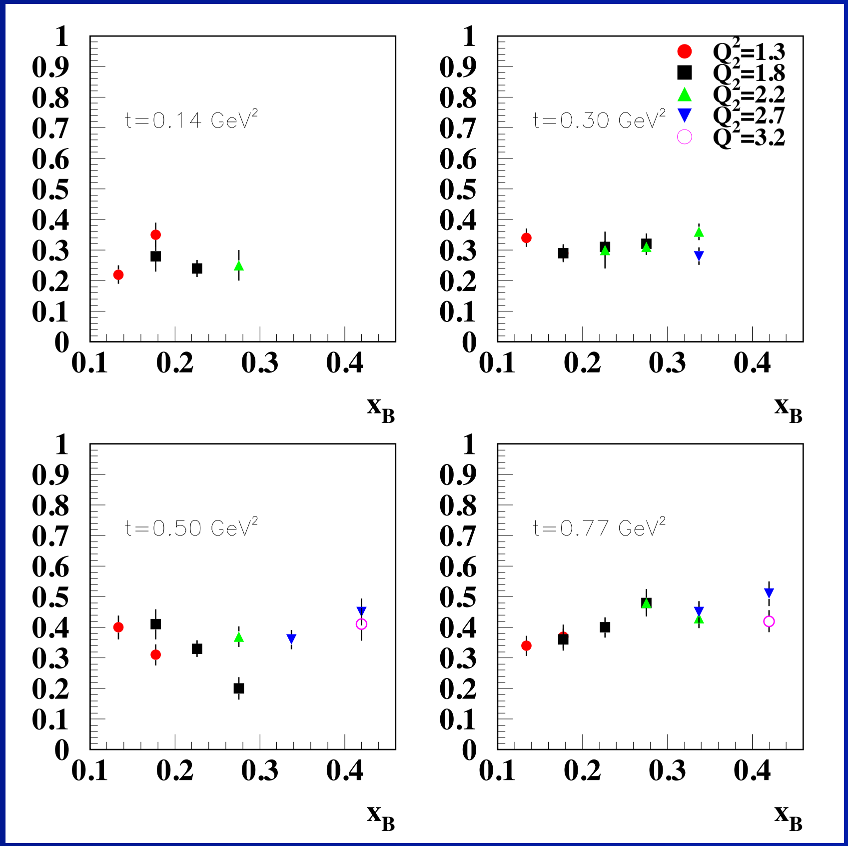


x_B

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

η/π^0 Ratio

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



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

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

h is the beam helicity

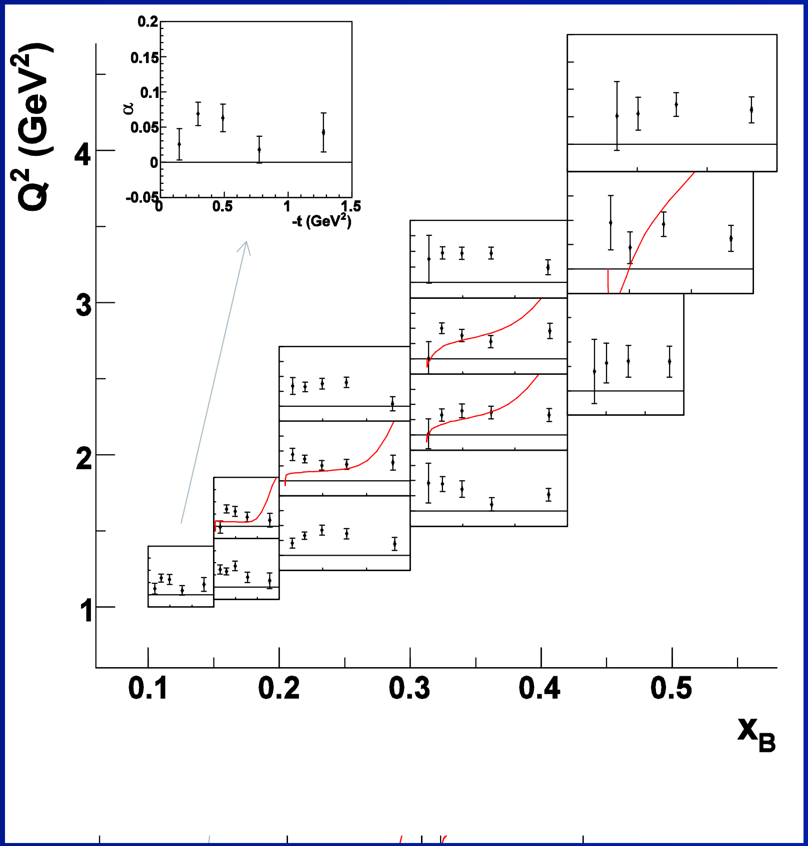
$$A=\frac{d^4\vec{\sigma}-d^4\overleftarrow{\sigma}}{d^4\vec{\sigma}+d^4\overleftarrow{\sigma}}\approx\alpha\sin\varphi$$

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

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

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



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

Beam Spin Asymmetry

Ahmad, Goldstein, Luiti, 2009

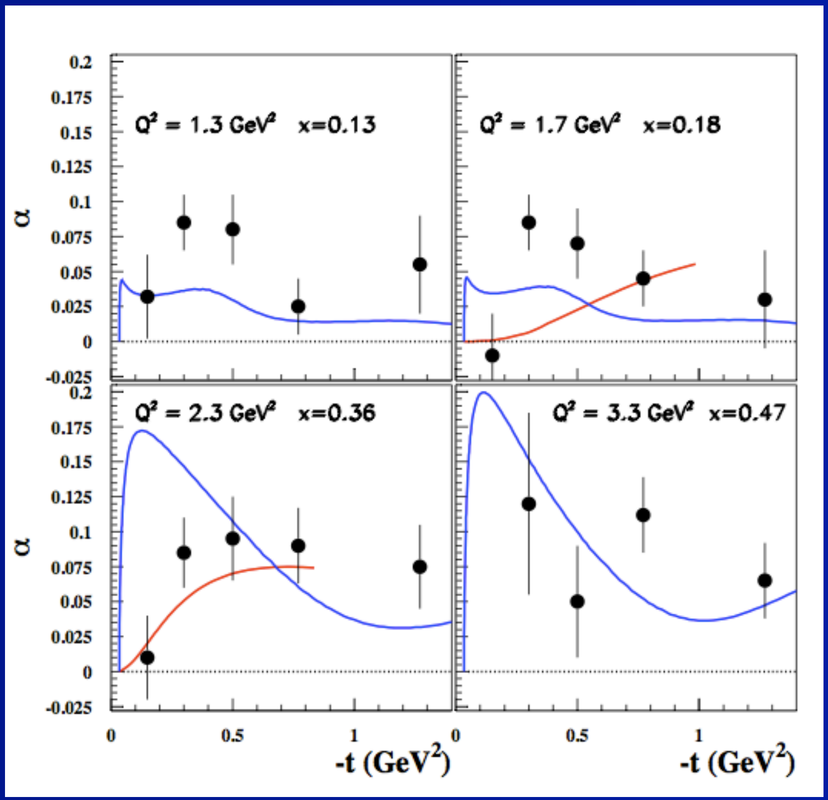
- Data CLAS
- Blue – Regge model
- Red – GPD predictions
- tensor charges

  δ u=0.48,

  δ d =-0.62
- transverse anomalous magnetic moments

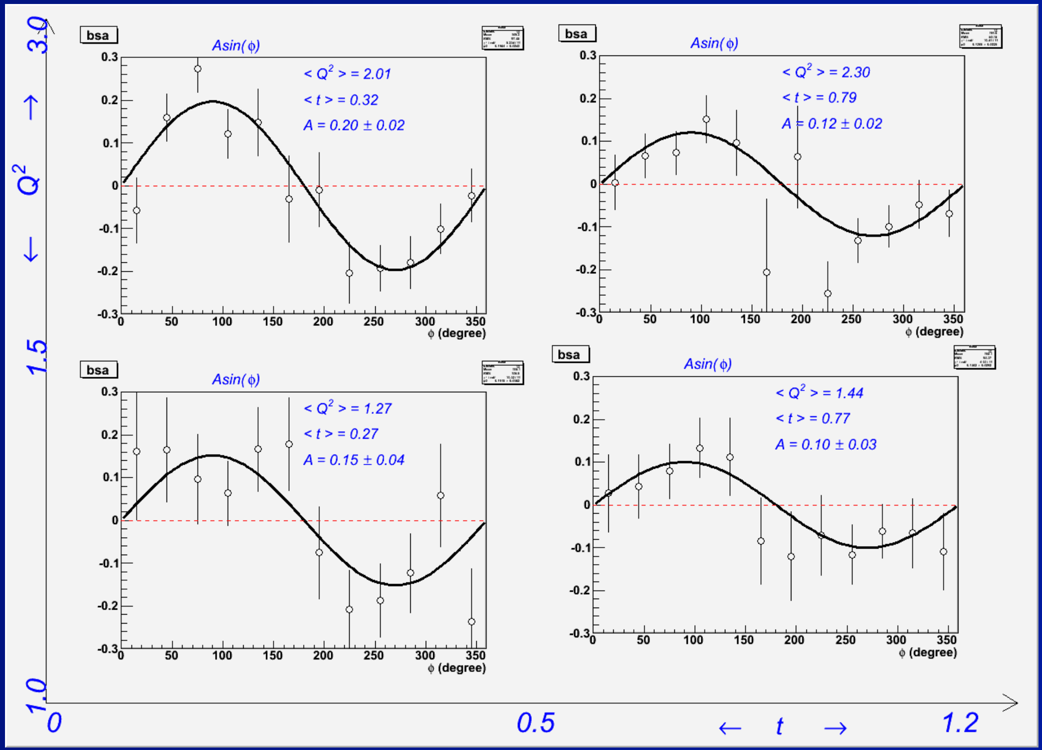
  $\kappa^u_T = 0.6$,

  $\kappa^d_T = 0.3$.

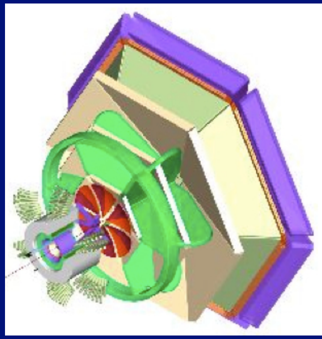


$\gamma^* p \rightarrow p\eta$

η Beam Spin Asymmetry

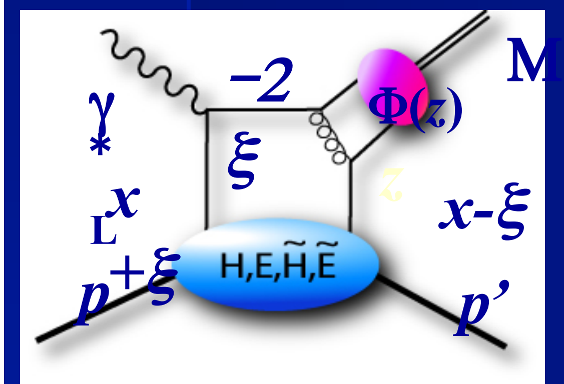


Summary



- 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 and η electroproduction data 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



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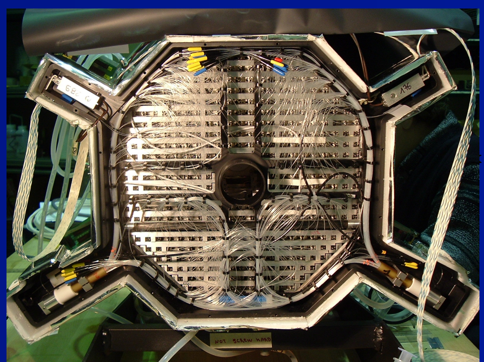

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