The Raymond and Beverly Sackler Faculty of Exact Sciences
Tel Aviv University

TEL AVIV UNIVERSITY
אוניברסיטת תל אביב

Deeply Virtual Neutral Pion Electroproduction at CLAS12

Igor Korover

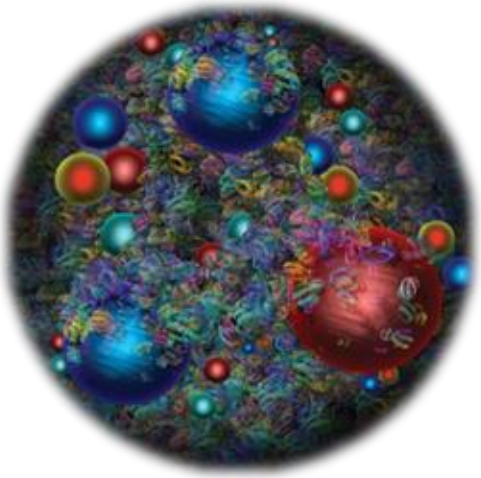
Tel Aviv University

DIS2026

May 5th, 2026

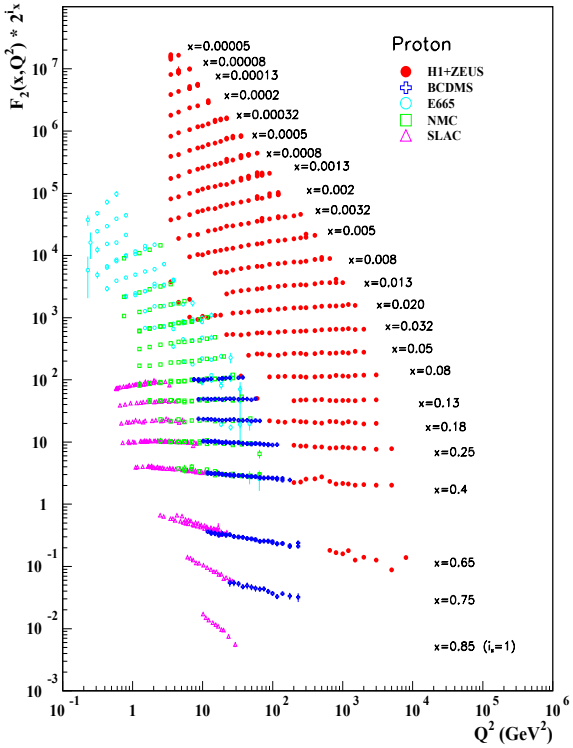
clas
CEBAF Large Acceptance Spectrometer

Proton: Simple Building Block of the Visible Universe



› 70 years of electron scattering provided insights to the structure of the proton

- ✓ Charge +1
- ✓ Mass 938 MeV/c^2
- ✓ Spin $\frac{1}{2}$
- ✓ Longitudinal structure, including flavor decomposition.
- ✓ Fundamental building block of nuclei



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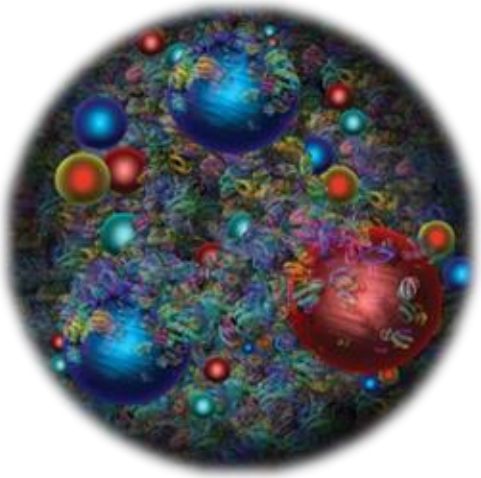
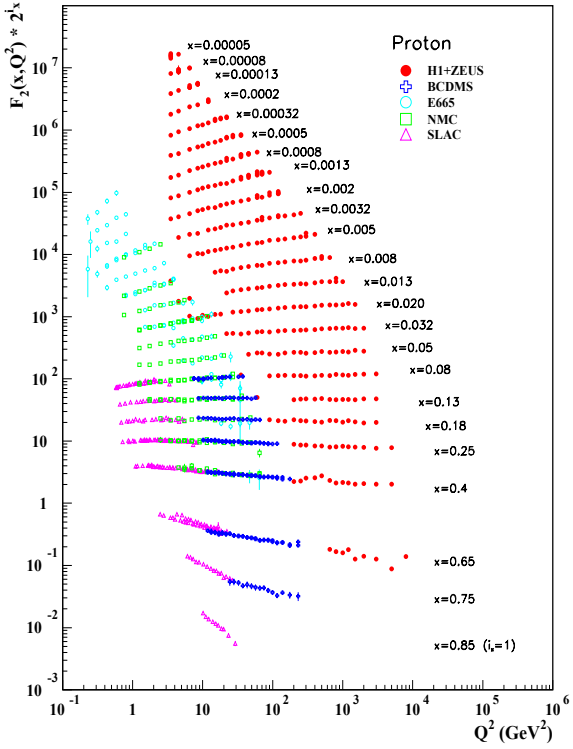


How well do we <u>understand</u> the <u>origin</u> of these properties?

- ✓ Charge +1
- ✓ Mass 938 MeV/c^2
  - **X Mass decomposition**
- ✓ Spin $\frac{1}{2}$
  - **X Spin decomposition**
- ✓ Longitudinal structure, including flavor decomposition.
  - **X Transverse structure**
- ✓ Fundamental building block of nuclei
  - **X Modification inside nuclei**



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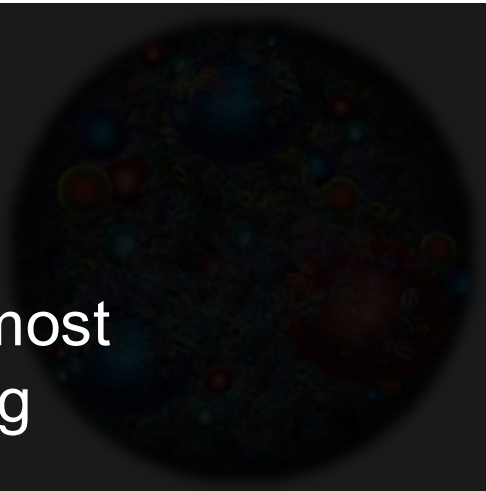

How well do we understand the origin of these properties?

The Proton is one of nature's most intriguing strongly-interacting many-body systems;

- ✓ Charge +1
- ✓ Mass 938 MeV/c^2
  - **X Mass decomposition**
- ✓ Spin $\frac{1}{2}$
  - **X Spin decomposition**
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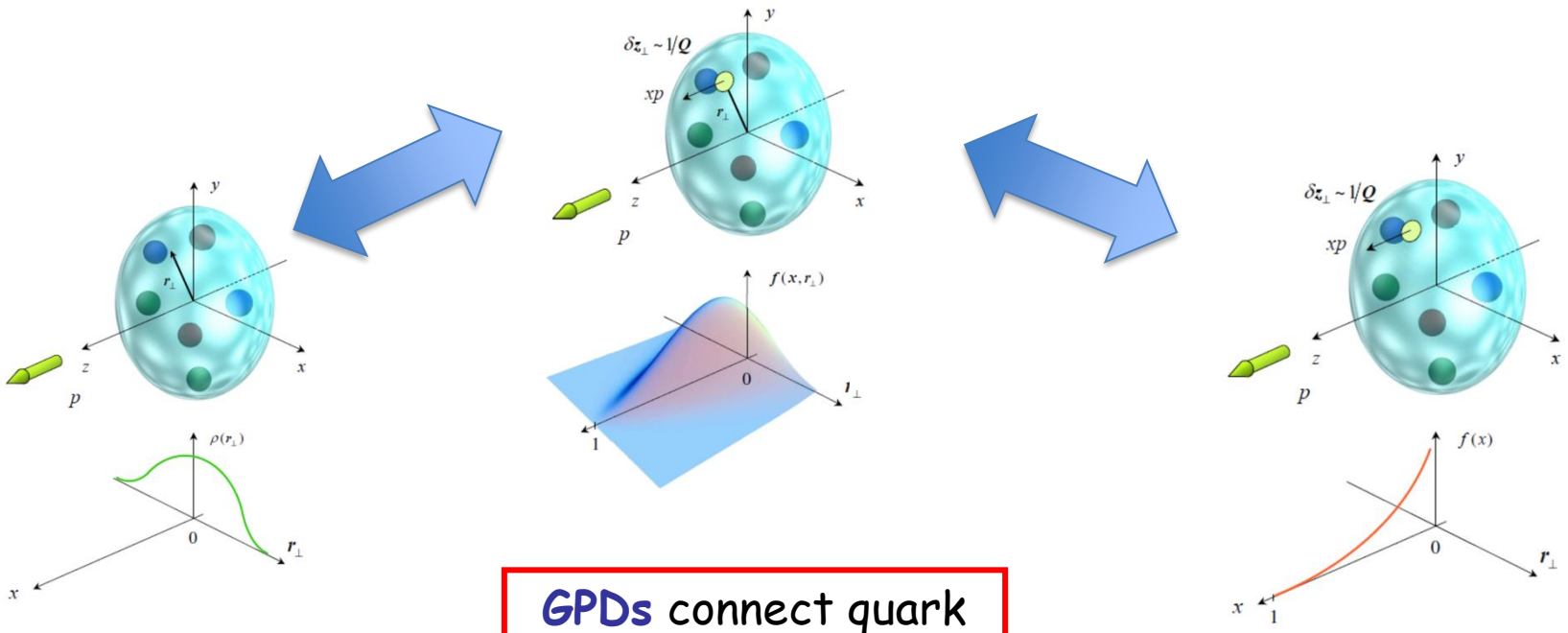
  - **X Transverse structure**
- ✓ Fundamental building block of nuclei
  - **X Modification inside nuclei**

➔ Experiment and theory advances required to provide novel insights!

3D Partonic Picture



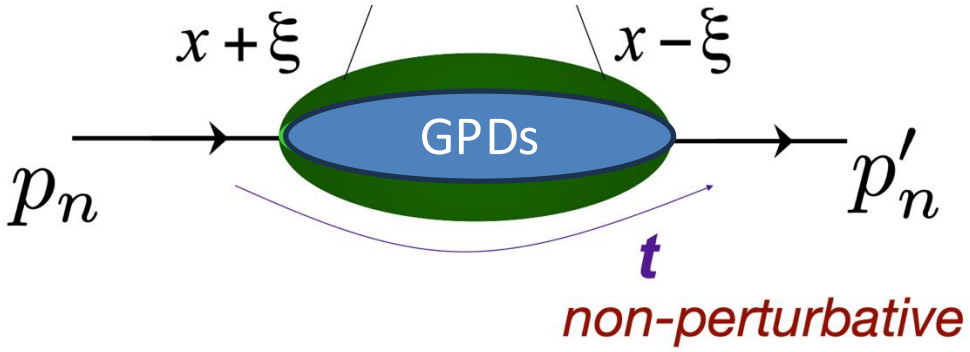
Proton size & structure.
Form factors,
transverse charge &
current distributions

Nobel prize 1961-
R. Hofstadter

GPDs connect quark distribution in transverse space & longitudinal momentum

Quark-gluon constituents.
longitudinal momentum
& helicity distributions
Nobel prize 1990 - J. Friedman,
H. Kendall, R. Taylor

Generalized parton distributions



Bjorken variable:

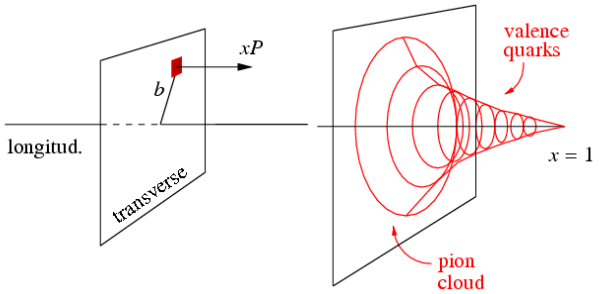
$$x_B = \frac{Q^2}{2p_n \cdot q}$$

Longitudinal momentum fractions of the struck parton: $x \pm \xi$

Skewness: $\xi \cong \frac{x_B}{2 - x_B}$

$t = (p'_n - p_n)^2$

- GPDs unify Form Factors and Parton Distribution Functions
- Generalized Parton Distributions (GPDs) are multi-dimensional structure functions
- GPDs can be interpreted as a transverse spatial distribution in the impact parameter space for each slice of longitudinal momentum fraction x



Generalized parton distributions

Dirac FF $\int_{-1}^{-1} dx H(x,\ \xi,\ |t|) = F_1(|t|)$

Pauli FF $\int_{-1}^{-1} dx E(x,\ \xi,\ |t|) = F_2(|t|)$

Axial-vector FF $\int_{-1}^{-1} dx \tilde{H}(x,\ \xi,\ |t|) = G_A(|t|)$

Pseudoscalar FF $\int_{-1}^{-1} dx \tilde{E}(x,\ \xi,\ |t|) = G_P(|t|)$

$H_q(x,\ 0,\ 0) = q(x)$

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

Proton anomalous tensor magnetic moment

$$\kappa_T^u = \int dx \bar{E}_T^u(x,\xi,t=0)$$
$$\kappa_T^d = \int dx \bar{E}_T^d(x,\xi,t=0)$$

Proton tensor charge

$$\delta_T^u = \int dx H_T^u(x,\xi,t=0)$$
$$\delta_T^d = \int dx H_T^d(x,\xi,t=0)$$

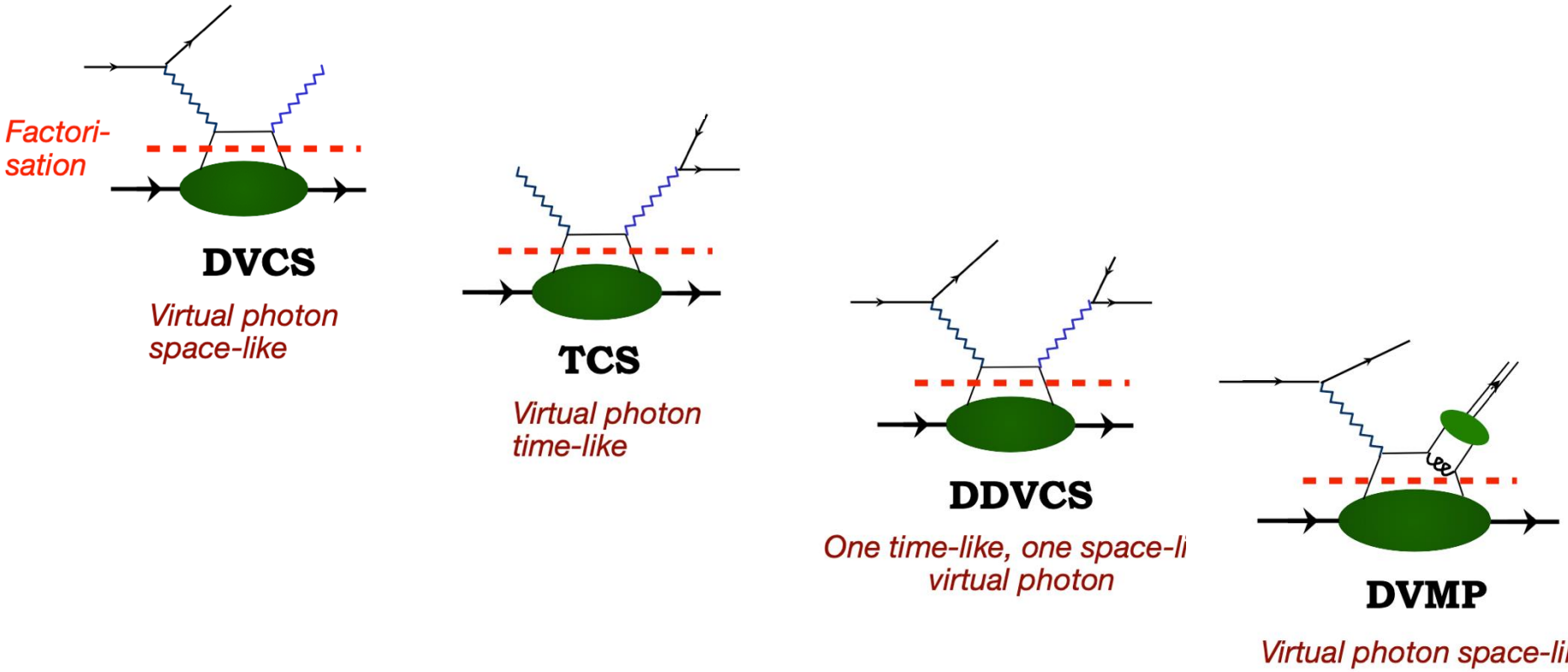
Density of transversity polarized quarks in an unpolarized proton in the transverse plane:

$$\delta(x,\vec{b}) = \frac{1}{2}[H(x,\vec{b}) - \frac{b_y}{m}\frac{\partial}{\partial b^2}\bar{E}_T(x,\vec{b})]$$

Deeply virtual exclusive processes

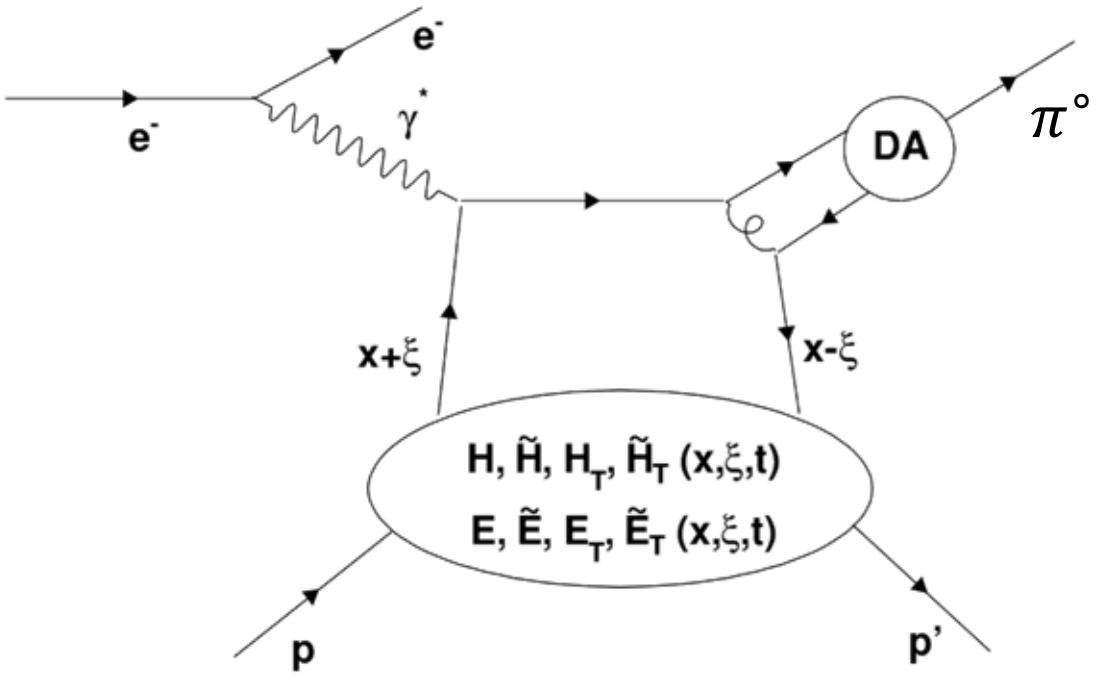
"The OFPD's depend on four independent variables ... It is unlikely that one can learn the entire parameter space of the distributions in one kind of experiments. "

Ji, Phys. Rev. D **55**, 7114



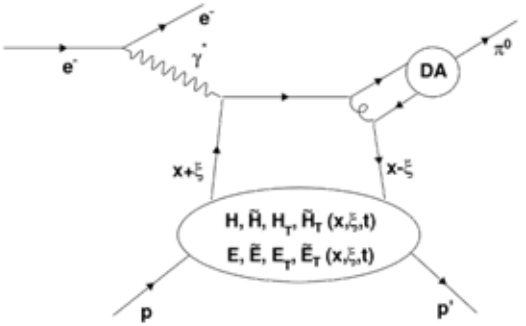
Deeply Virtual Meson Production

Neutral Pion Electroproduction $ep \rightarrow e'p\pi^\circ$



$$\frac{d^2\sigma}{dtd\phi_\pi} = \frac{1}{2\pi}\left[\left(\frac{d\sigma_T}{dt} + \epsilon\frac{d\sigma_L}{dt}\right) + \epsilon\cos 2\phi_\pi \frac{d\sigma_{TT}}{dt} + \sqrt{2\epsilon(1+\epsilon)}\cos\phi_\pi \frac{d\sigma_{LT}}{dt}\right]$$

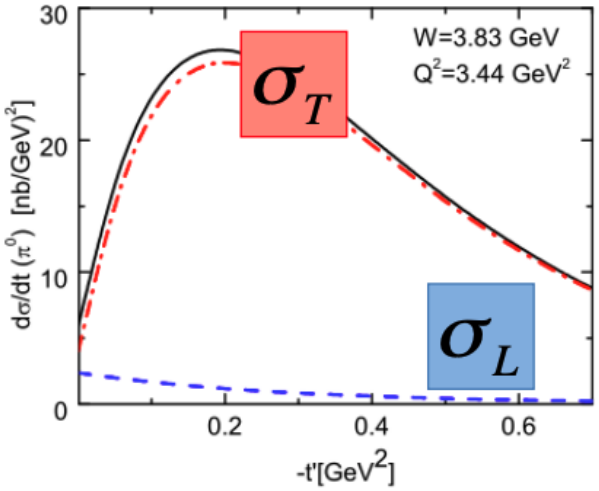
Structure functions and GPDs



Transversity GPD model:

- Goloskokov and Kroll
- Liuti and Goldstein

$\sigma_L \ll \sigma_T$



$$\frac{d^4\sigma}{dQ^2 dx_B dt d\phi_\pi} = \Gamma(Q^2, x_B, E)\frac{1}{2\pi}(\sigma_T + \epsilon\sigma_L + \epsilon\cos 2\phi_\pi \sigma_{TT} + \sqrt{2\epsilon(1+\epsilon)}\cos\phi_\pi \sigma_{LT})$$

$$\frac{d\sigma_L}{dt} = \frac{4\pi\alpha}{kQ^2}\left\{(1-\xi^2)\left|\langle\tilde{H}\rangle\right|^2 - 2\xi^2\Re\left[\langle\tilde{H}\rangle^*\langle\tilde{E}\rangle\right] - \frac{t'}{4m^2}\xi^2\left|\langle\tilde{E}\rangle\right|^2\right\}$$

$$\frac{d\sigma_T}{dt} = \frac{2\pi\alpha\mu_\pi^2}{kQ^4}\left\{(1-\xi^2)\left|\langle H_T\rangle\right|^2 - \frac{t'}{8m^2}\left|\langle\bar{E}_T\rangle\right|^2\right\}$$

$$\frac{d\sigma_{LT}}{dt} = \frac{4\pi\alpha\mu_\pi}{\sqrt{2}kQ^3}\xi\sqrt{1-\xi^2}\frac{\sqrt{-t'}}{2m}\Re\left\{\langle H_T\rangle^*\langle\tilde{E}\rangle\right\}$$

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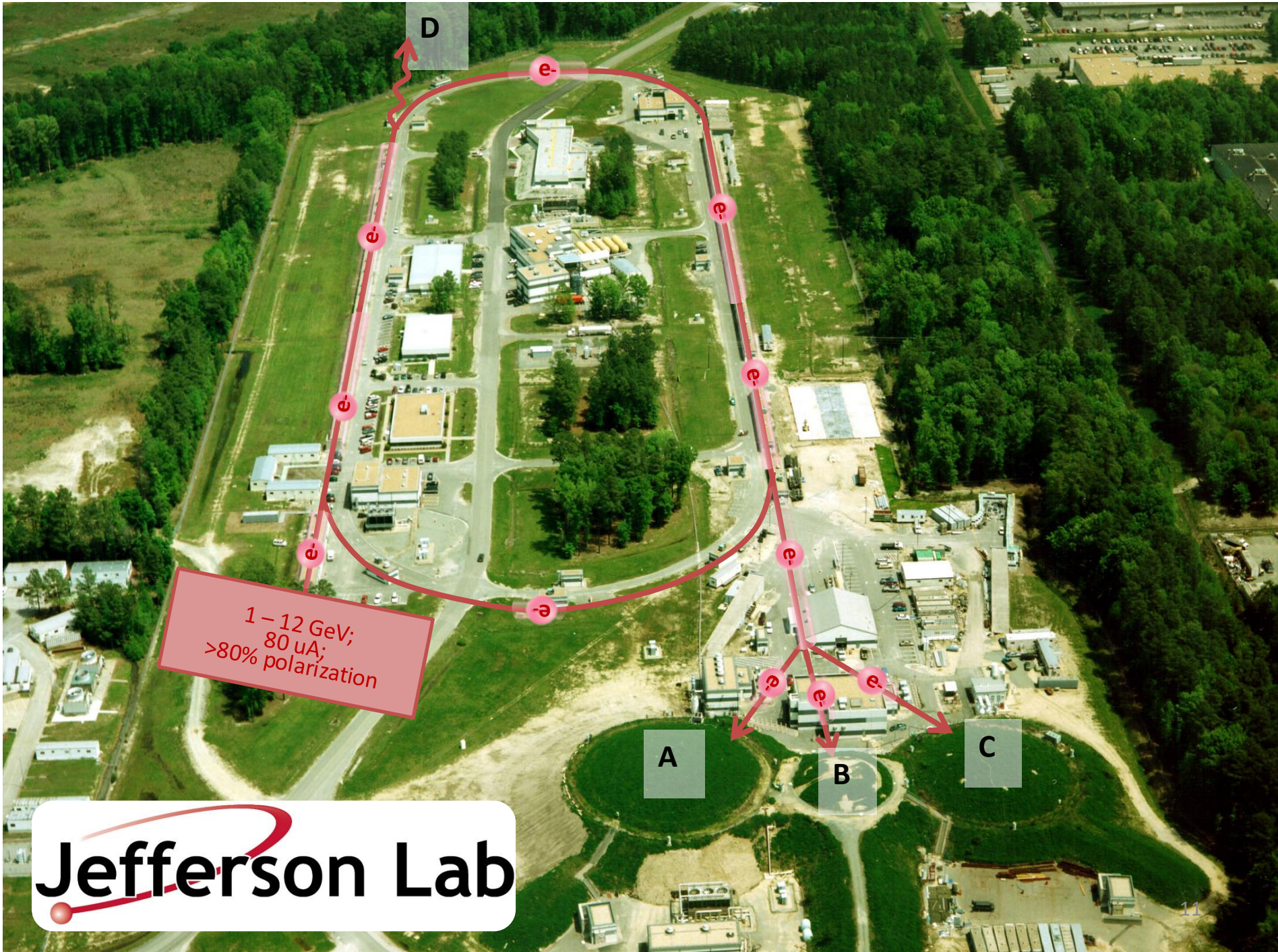
D
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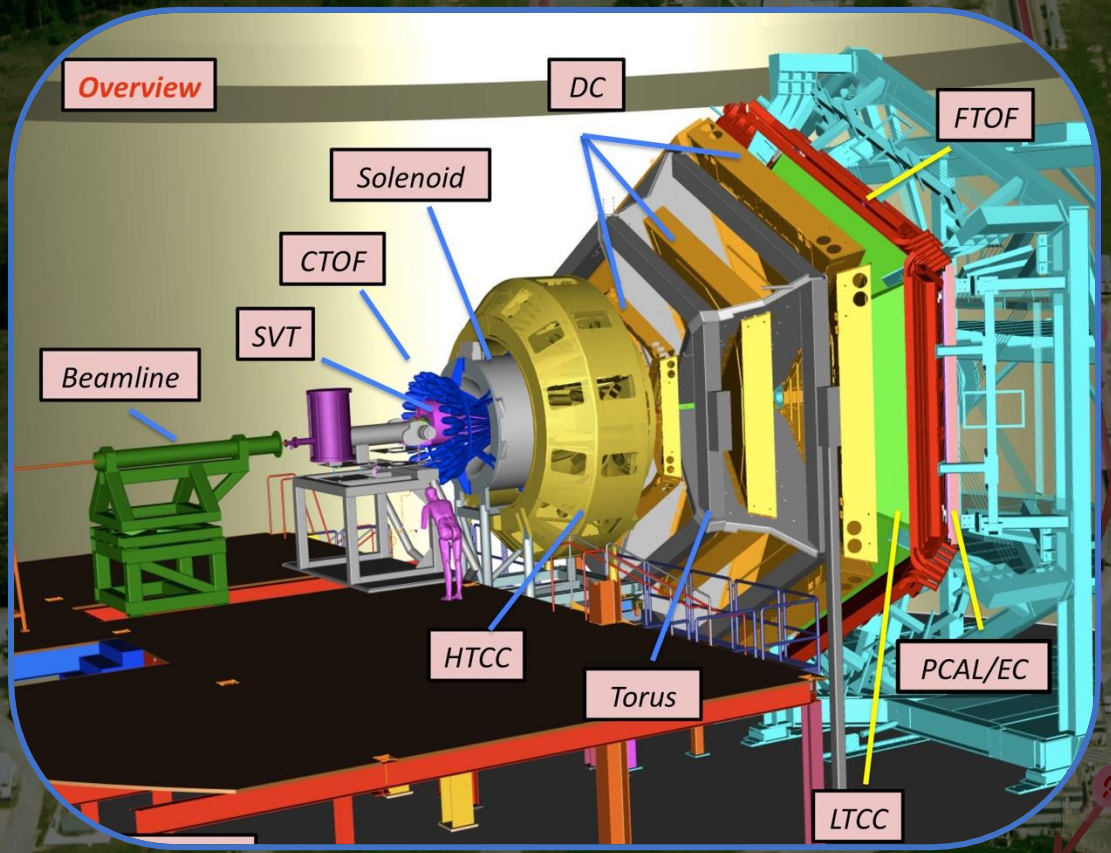
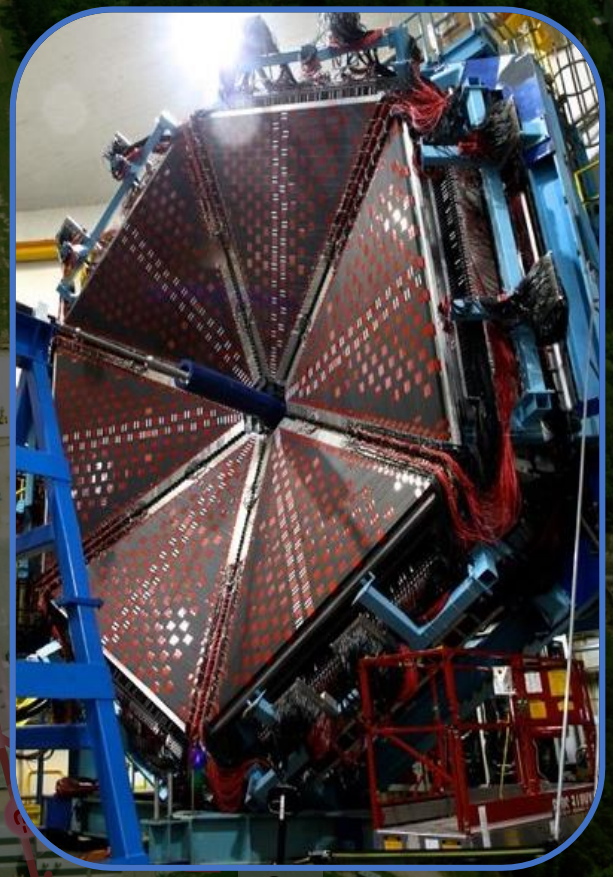
1 – 12 GeV;
80 uA;
>80% polarization
A
B
C
Jefferson Lab

Hall B – CLAS12 spectrometer





Jefferson Lab

Experimental Data (RG-A)

- 10.6 GeV electron beam
- LH_2 target (~10^{35} luminosity)
- ~80 fb^{-1} ~6 months running

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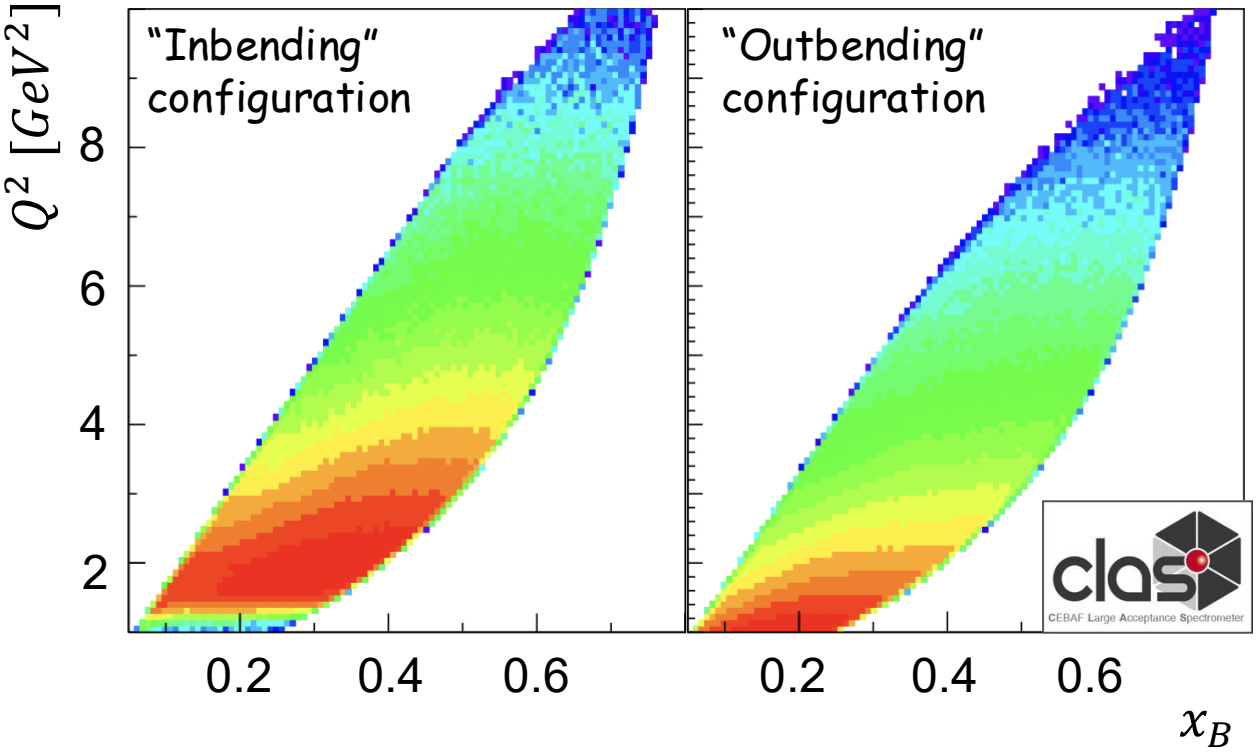
- Divided into bins of $(Q^2, x_B, -t)$: ~150 bins



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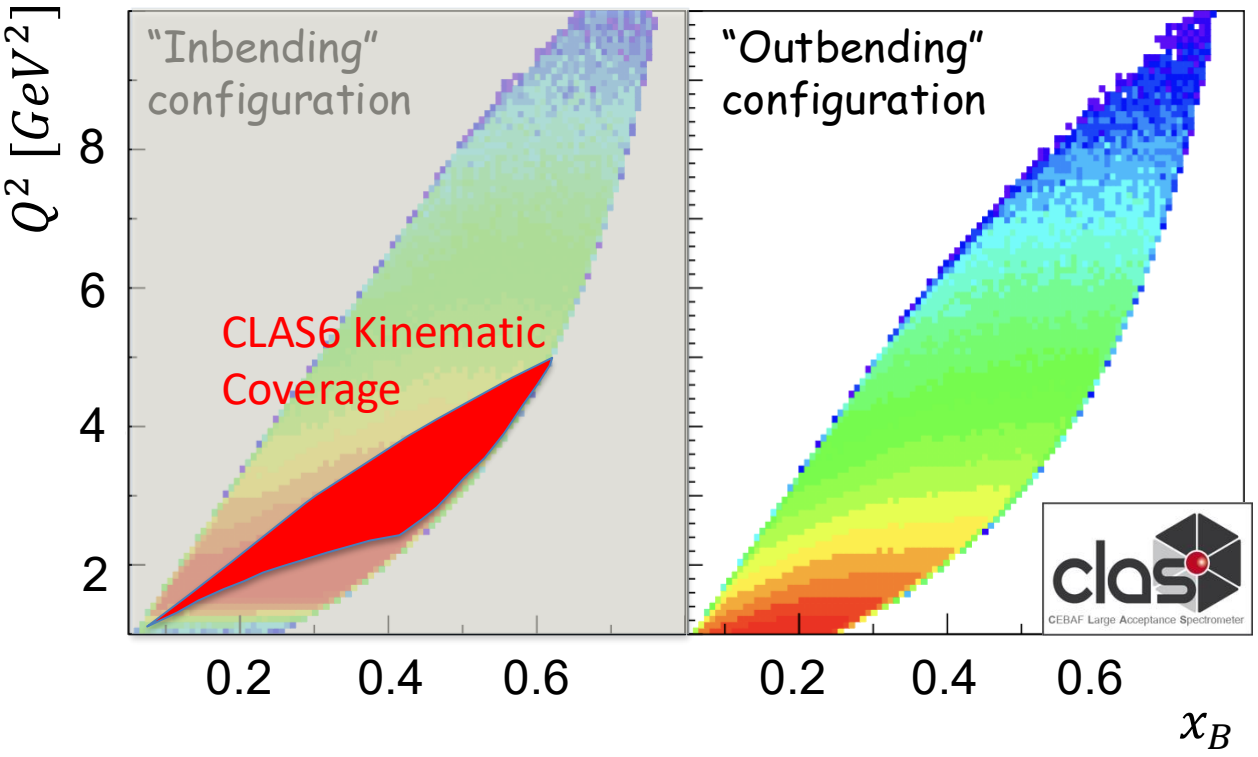
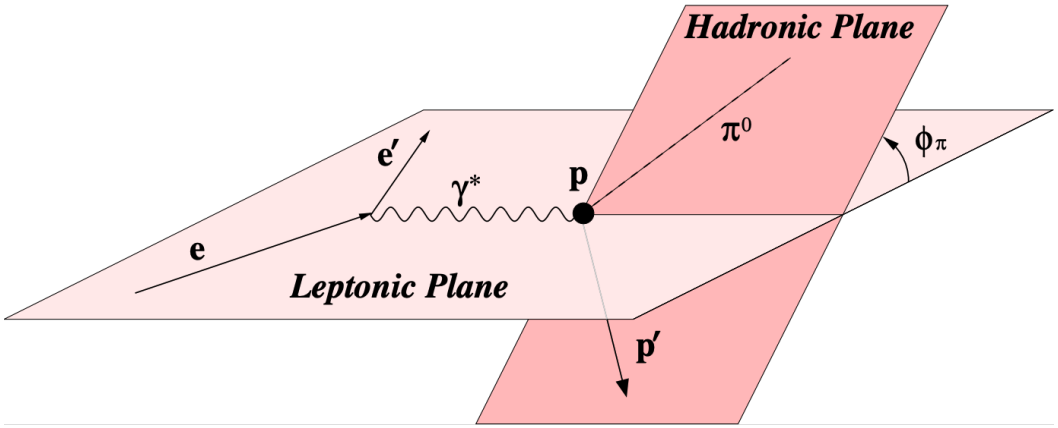


Cross-section measurement

$$\frac{d^4\sigma_{ep\to e'p'\pi^0}}{dQ^2 dx_B dt d\phi_\pi} = \frac{N(Q^2, x_B, t, \phi)}{\mathcal{L}_{int}(\Delta Q^2 \Delta x_B \Delta t \Delta\phi)} \times \frac{1}{\epsilon_{ACC}\delta_{RC}\delta_{Norm} Br(\pi^0 \to \gamma\gamma)}$$

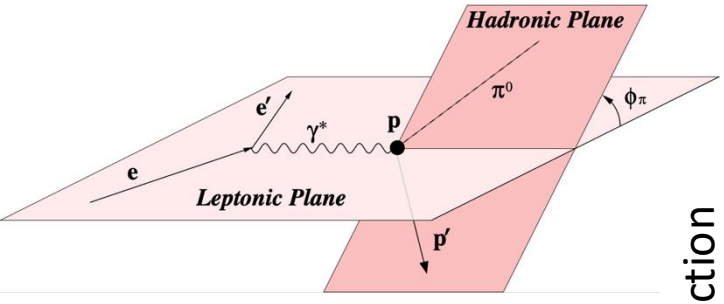
Reduced cross section $\frac{d^2\sigma_{\gamma^* p\to p'\pi^0}(Q^2, x_B, t, \phi_\pi, E)}{dt d\phi} = \frac{1}{\Gamma_V(Q^2, x_B, E)} \frac{d^4\sigma_{ep\to e'p'\pi^0}}{dQ^2 dx_B dt d\phi_\pi}$

$$\frac{d^2\sigma}{dt d\phi_\pi} = \frac{1}{2\pi}\left[\left(\frac{d\sigma_T}{dt} + \epsilon\frac{d\sigma_L}{dt}\right) + \epsilon\cos 2\phi_\pi \frac{d\sigma_{TT}}{dt} + \sqrt{2\epsilon(1+\epsilon)}\cos\phi_\pi \frac{d\sigma_{LT}}{dt}\right]$$

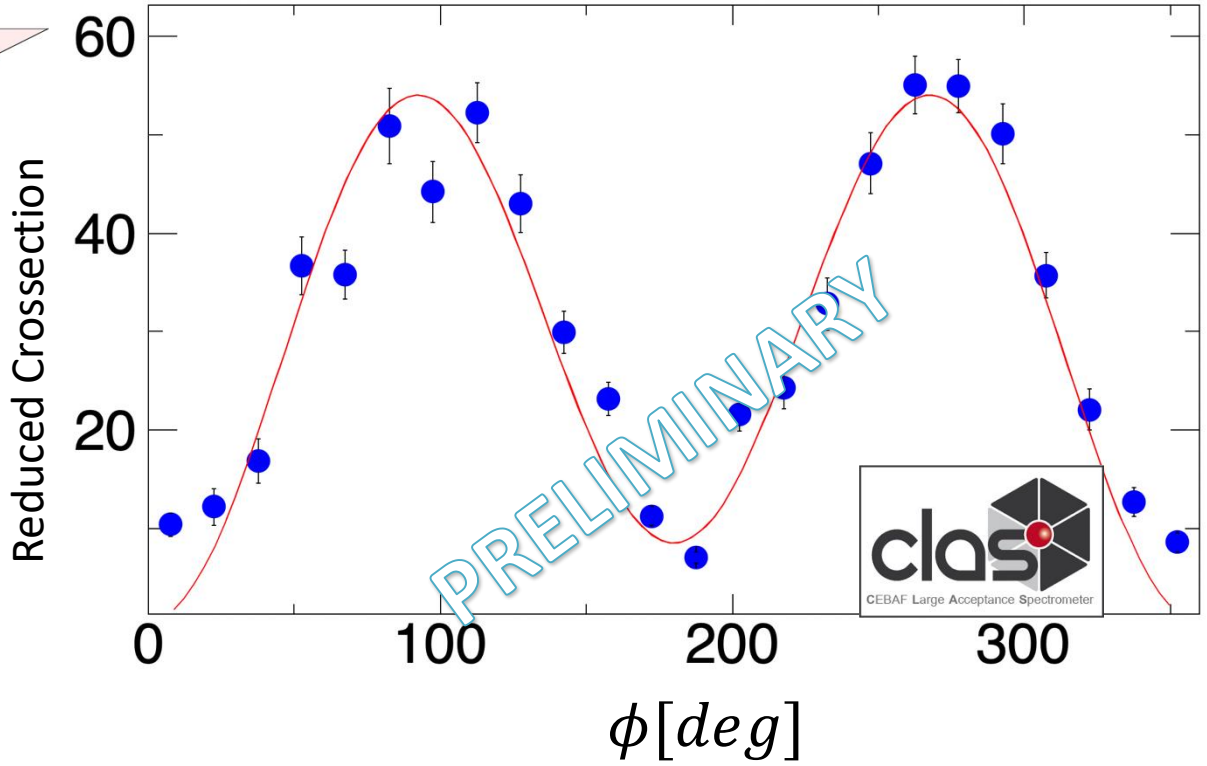


SF- extraction

Functional form: $f(\phi) = A + B \cdot cos(2\phi) + C \cdot cos(\phi)$



$1 < Q^2 < 1.5$
$0.15 < x_B < 0.2$
$0.4 < |t| < 0.6$



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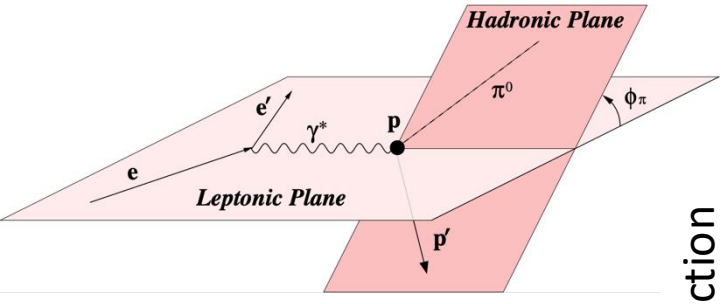

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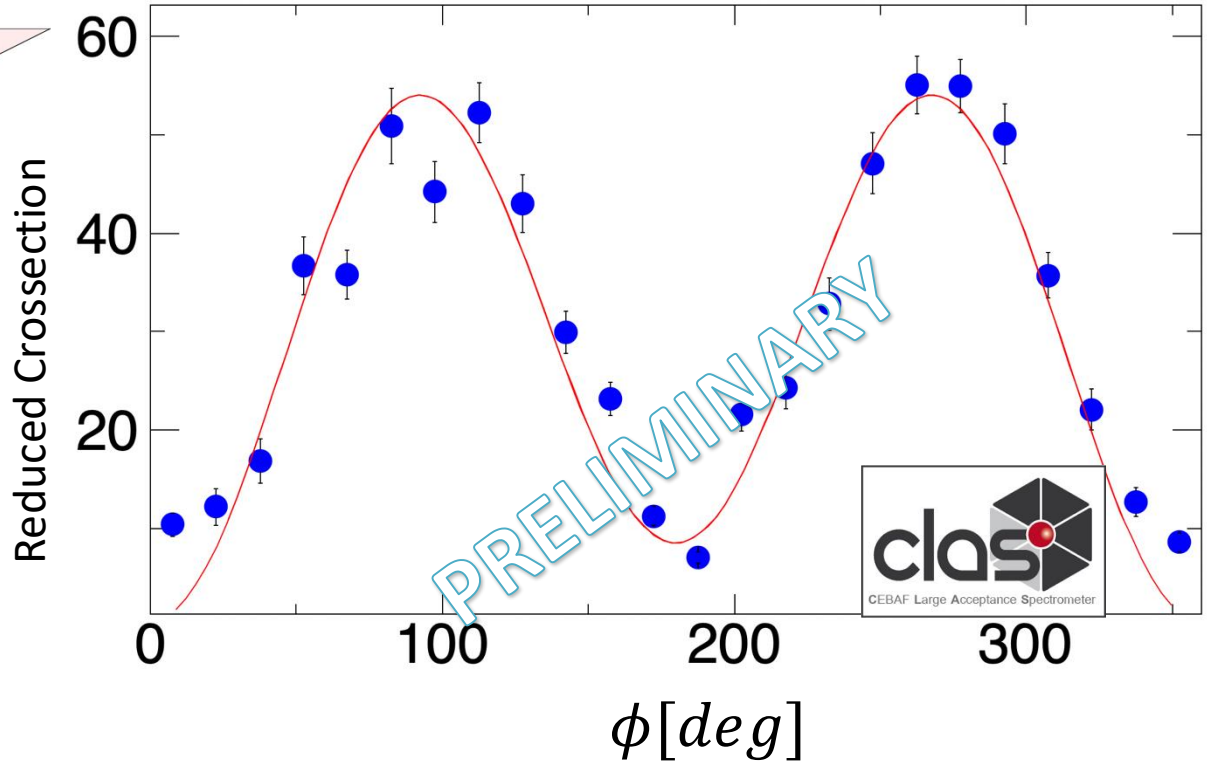

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Structure functions and GPDs

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$$\frac{d\sigma_T}{dt} = \frac{2\pi\alpha\mu_\pi^2}{kQ^4}\left\{(1-\xi^2)\left|\langle H_T\rangle\right|^2 - \frac{t'}{8m^2}\left|\langle\bar{E}_T\rangle\right|^2\right\}$$

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Structure functions and GPDs

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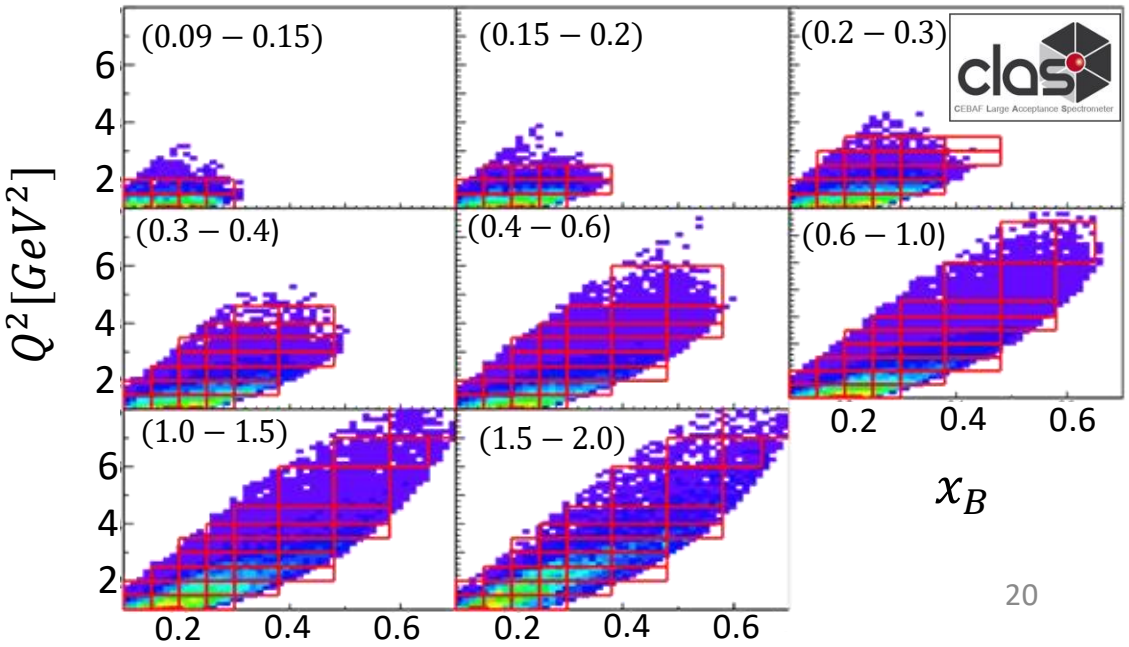
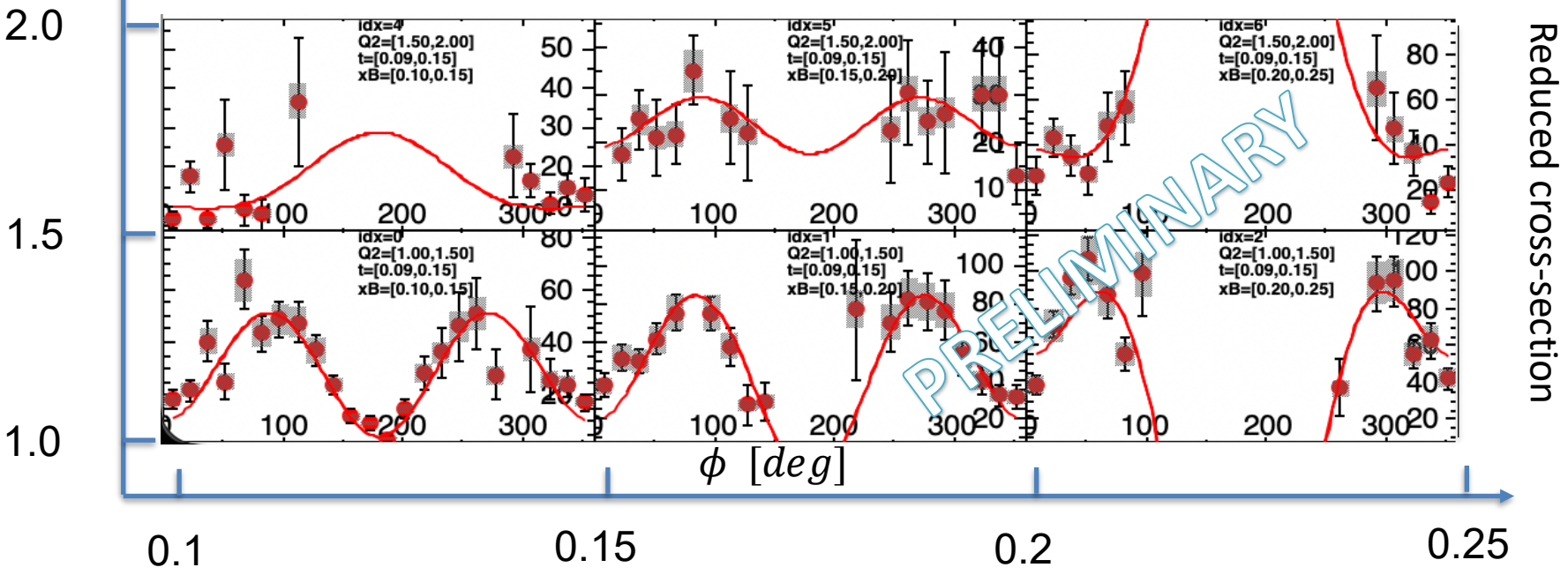


−t ranges are marked in brackets

$Q^2\ [GeV^2]$

$0.09 < |-t| < 0.15$



2.0

1.5

1.0

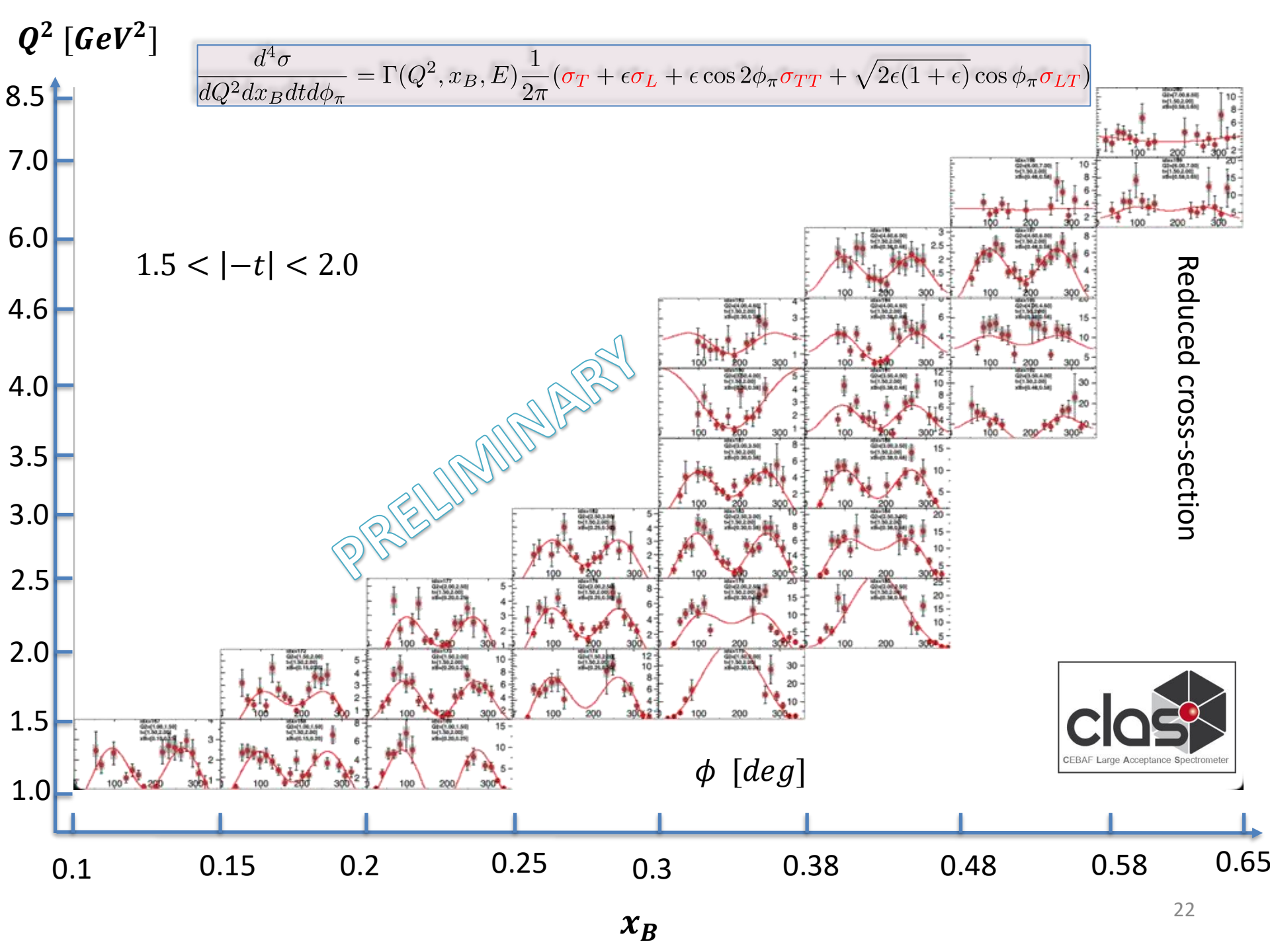
Reduced cross-section

$\phi\ [deg]$

0.1 0.15 0.2 0.25

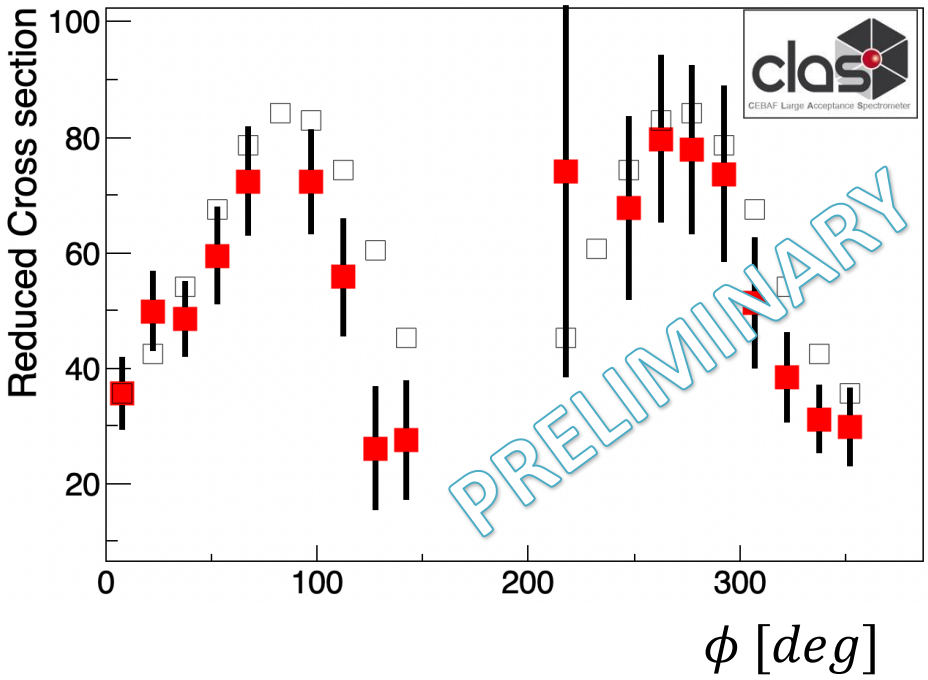
x_B

$$\frac{d^4\sigma}{dQ^2 dx_B dt d\phi_\pi} = \Gamma(Q^2, x_B, E)\frac{1}{2\pi}(\sigma_T + \epsilon\sigma_L + \epsilon\cos 2\phi_\pi \sigma_{TT} + \sqrt{2\epsilon(1+\epsilon)}\cos\phi_\pi \sigma_{LT})$$

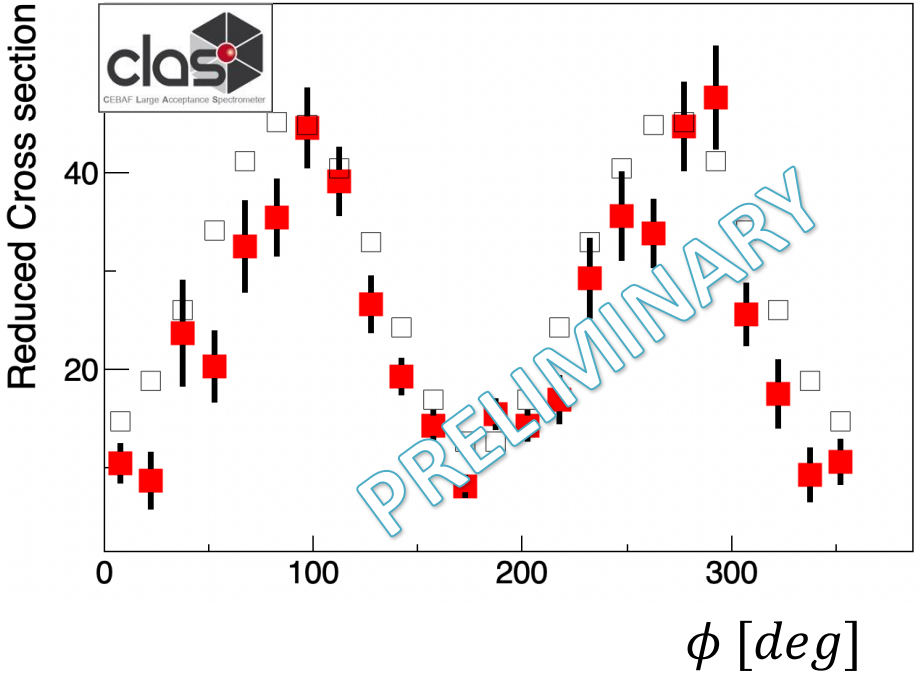

Q^2 [GeV^2]
$\frac{d^4\sigma}{dQ^2 dx_B dt d\phi_\pi} = \Gamma(Q^2, x_B, E)\frac{1}{2\pi}(\sigma_T + \epsilon\sigma_L + \epsilon\cos 2\phi_\pi \sigma_{TT} + \sqrt{2\epsilon(1+\epsilon)}\cos\phi_\pi \sigma_{LT})$
8.5
7.0
6.0
4.6
4.0
3.5
3.0
2.5
2.0
1.5
1.0
$1.5 < |-t| < 2.0$
PRELIMINARY
Reduced cross-section
ϕ [deg]
clas
CEBAF Large Acceptance Spectrometer
0.1
0.15
0.2
0.25
0.3
0.38
0.48
0.58
0.65
x_B

Comparison to CLAS6

$1 < Q^2 < 1.5$
$0.15 < x_B < 0.2$
$0.09 < |t| < 0.15$



$1.5 < Q^2 < 2.0$
$0.2 < x_B < 0.25$
$0.4 < |t| < 0.6$



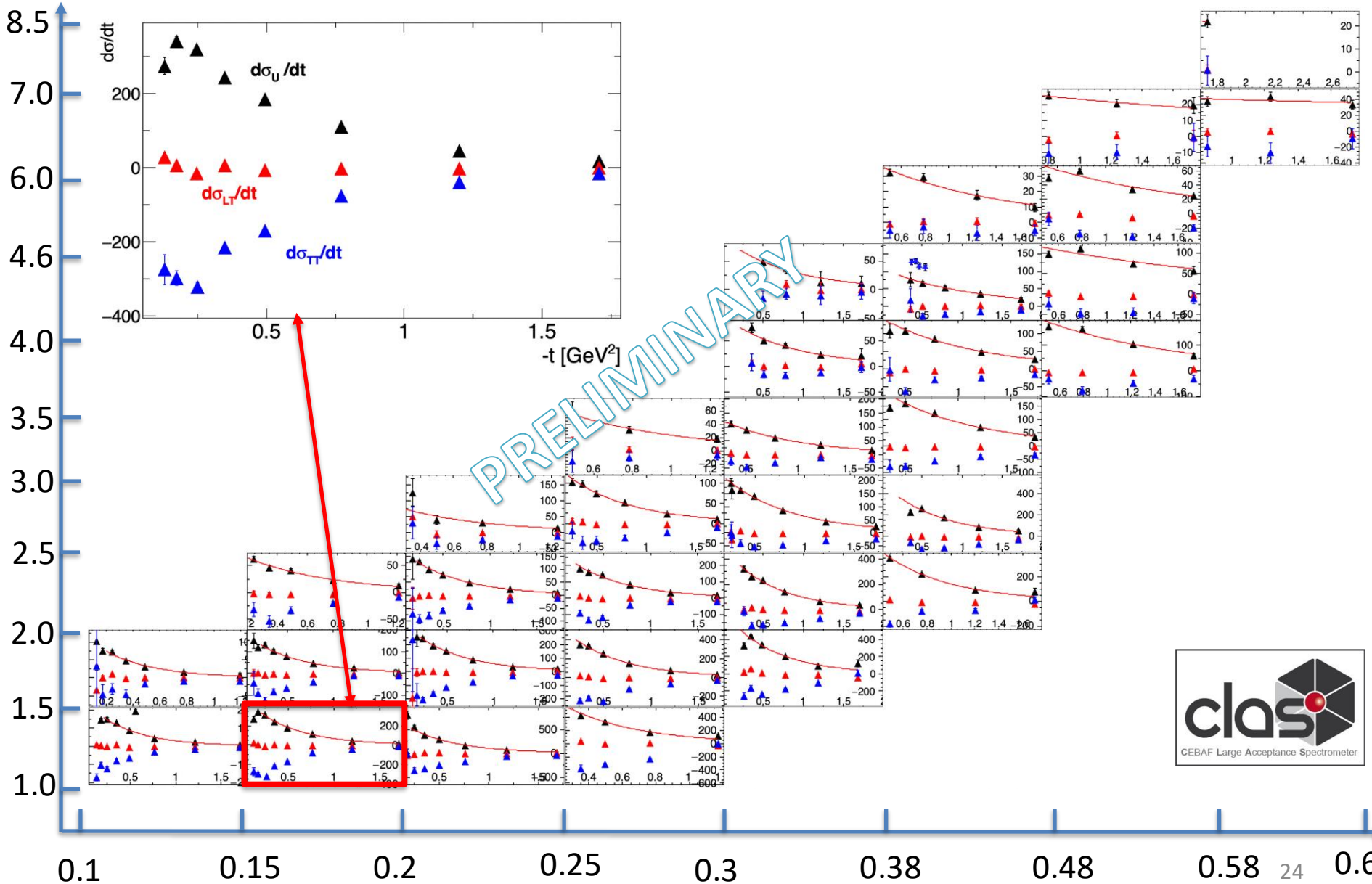
Red points – CLAS12

Open symbols – expected based on $\sigma_U, \sigma_{LT}, \sigma_{TT}$ from CLAS6 (Phys. Rev. C **90**, 025205)

$$\frac{d^2\sigma}{dtd\phi_\pi} = \frac{1}{2\pi}\left[\left(\frac{d\sigma_T}{dt} + \epsilon\frac{d\sigma_L}{dt}\right) + \epsilon\cos 2\phi_\pi \frac{d\sigma_{TT}}{dt} + \sqrt{2\epsilon(1+\epsilon)}\cos\phi_\pi \frac{d\sigma_{LT}}{dt}\right]$$

Structure Functions:

$$\sigma_U, \sigma_{TT}, \sigma_{LT}$$



clas
CEBAF Large Acceptance Spectrometer

t-Dependence and Impact Parameter

$$\frac{d^2\sigma}{dt\,d\phi_\pi} = \frac{1}{2\pi}\left[\left(\frac{d\sigma_T}{dt} + \epsilon\frac{d\sigma_L}{dt}\right) + \epsilon\cos 2\phi_\pi \frac{d\sigma_{TT}}{dt} + \sqrt{2\epsilon(1+\epsilon)}\cos\phi_\pi \frac{d\sigma_{LT}}{dt}\right]$$

Transvers + Longitudinal:

$$\frac{d\sigma_U}{dt} = \int_0^{2\pi} \frac{d^2\sigma}{dt\,d\phi_\pi}\,d\phi_\pi = \frac{d\sigma_T}{dt} + \epsilon\frac{d\sigma_L}{dt}$$

Can be parametrized: $\frac{d\sigma_U}{dt} = A\,e^{-B|t|}$

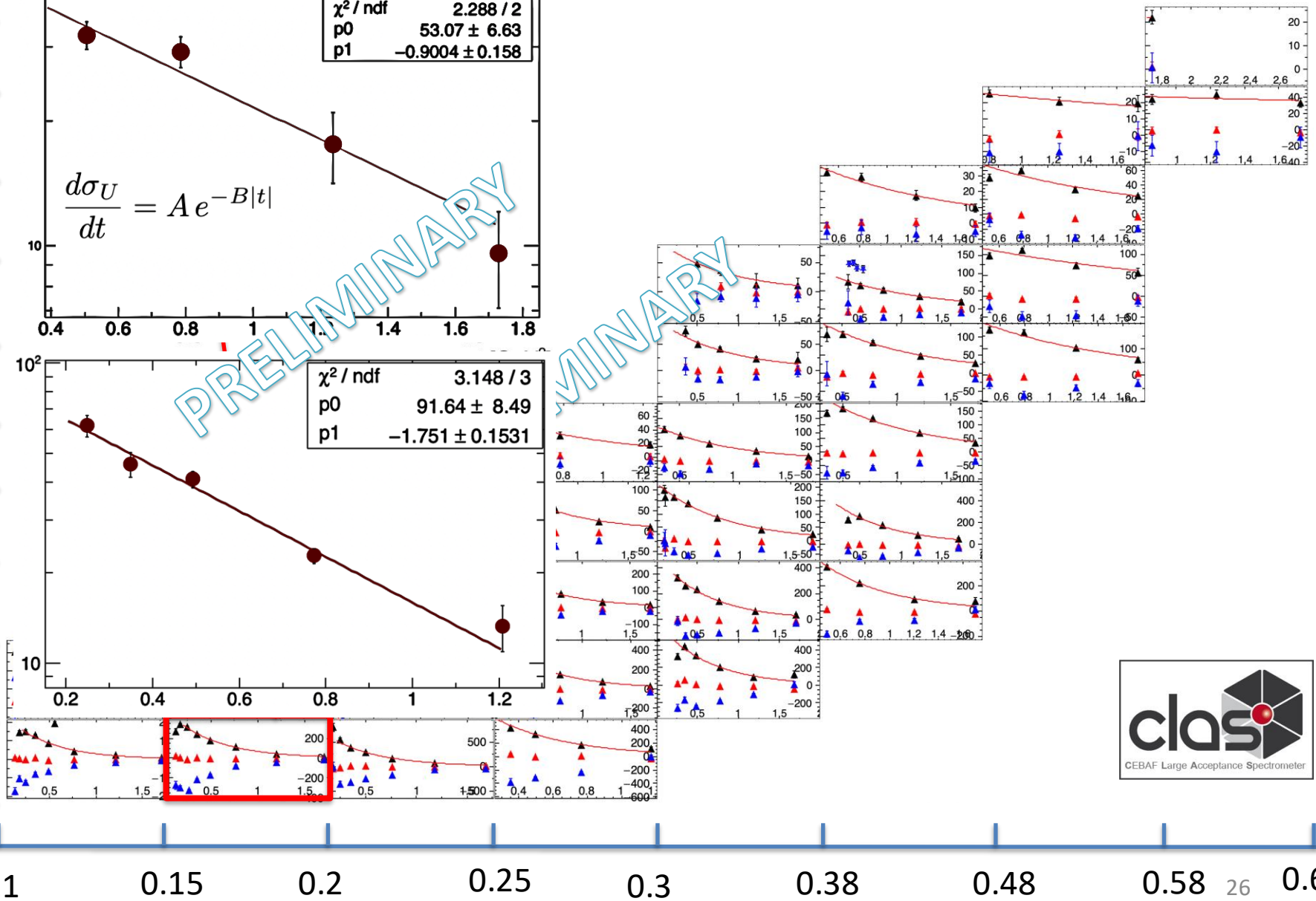
B is related to transverse radius of the interaction $< b_\perp^2 > \approx B$

Structure Functions:

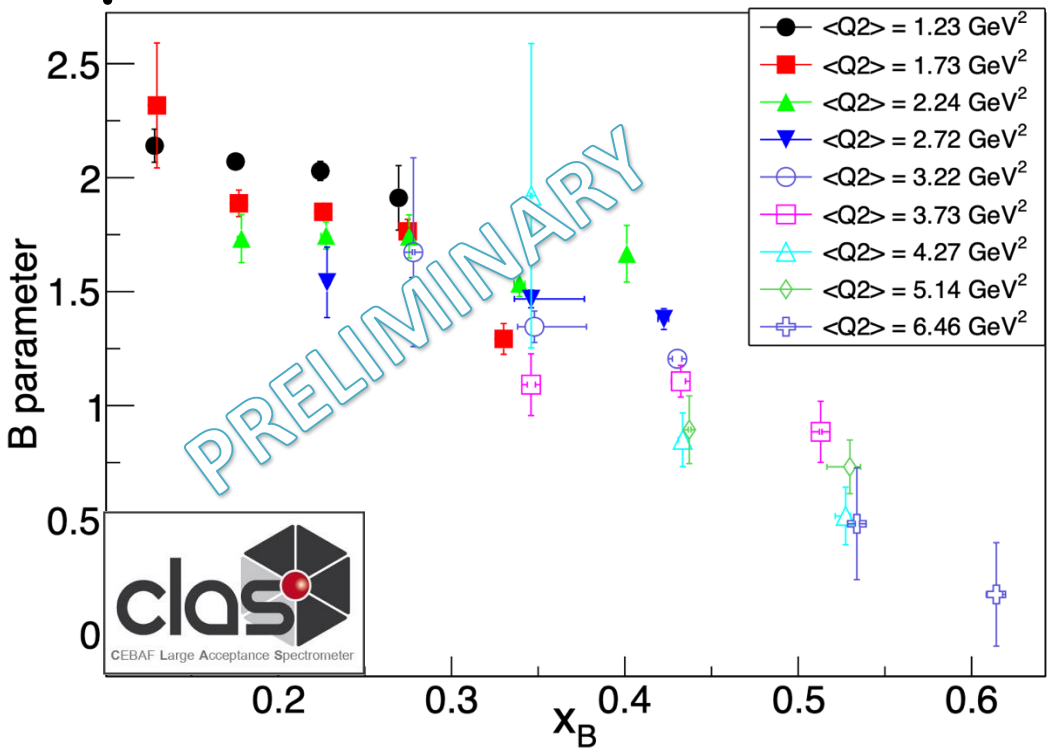
$\sigma_U, \sigma_{TT}, \sigma_{LT}$

PRELIMINARY

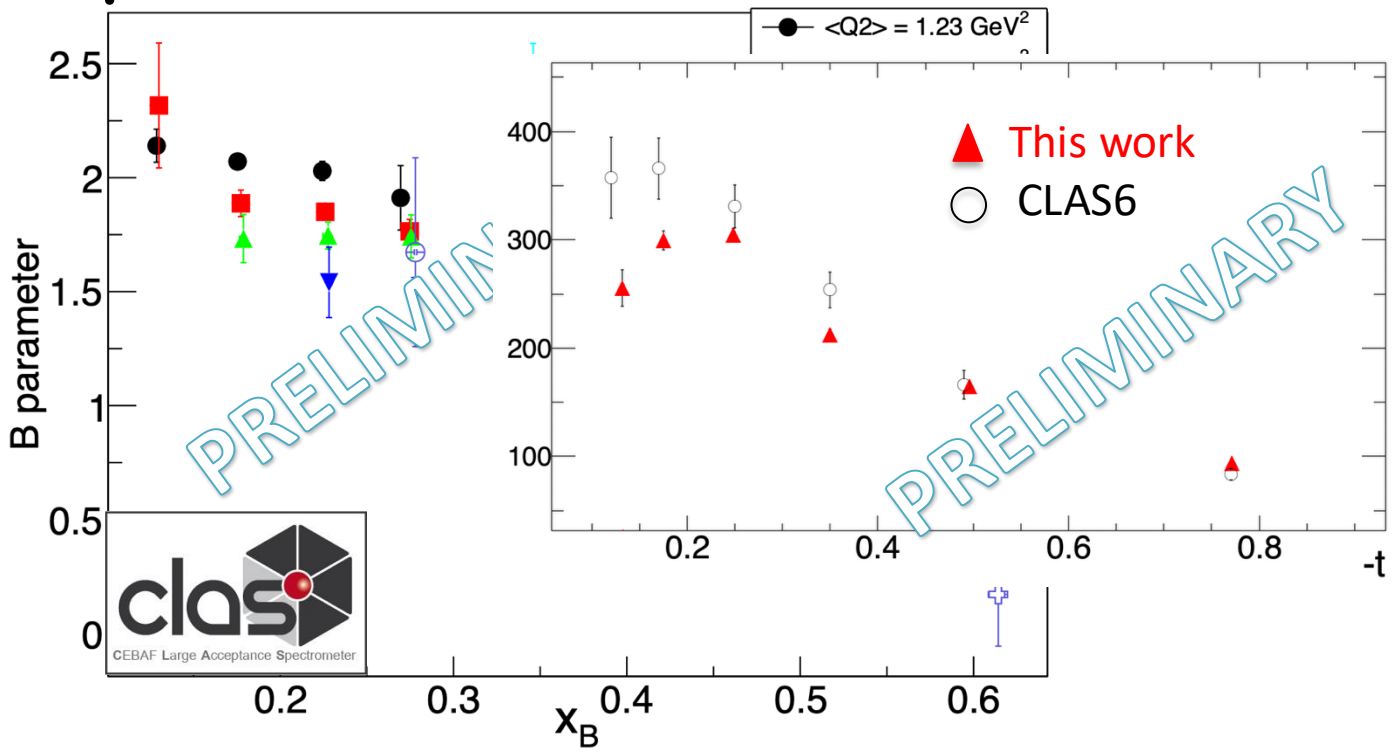
PRELIMINARY



Impact parameter



Impact parameter



- Limitation: the data is not well fitted at low t values.
- t-dependence of structure function σ_U depends on different GPDs

Need study the extraction of the indivitual GPDs.

Flavor Decomposition

- π^0 (out of proton/neutron)
- η (out of proton)

$$e + p \to e + \pi^0 + p$$
$$e + p \to e + \eta + p$$
$$e + n \to e + \pi^0 + n$$
$$\mu + p \to \mu + \pi^0 + p$$

$$\bar{E}_T^{\pi/proton} = \frac{1}{3\sqrt{2}}(2\bar{E}_T^u + \bar{E}_T^d)$$

$$\bar{E}_T^{\pi/neutron} = \frac{1}{3\sqrt{2}}(\bar{E}_T^u + 2\bar{E}_T^d)$$

$$\bar{E}_T^{\eta/proton} = \frac{1}{3\sqrt{6}}(2\bar{E}_T^u - \bar{E}_T^d - 2\bar{E}_T^s)$$

$$|\eta\rangle = \cos\theta_8 \left|\eta^8\right\rangle - \sin\theta_1 \left|\eta^1\right\rangle$$

For strange quarks $\bar{E}_T^s = \bar{E}_T^{\bar{s}}$, $e_s = -e_{\bar{s}}$

The contribution from sea quarks is cancelled out.

GPDs appear in the different flavor combinations

More to do…

CLAS12 Program

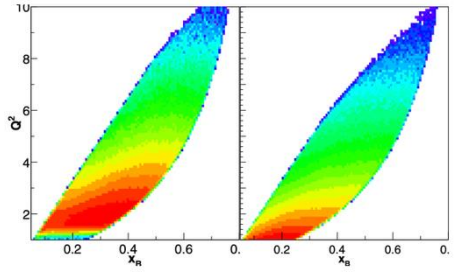
Asymmetries, Cross Sections at different energies:
10.6, 7.5 and 6.5 GeV (RGA, RGB, RGK)

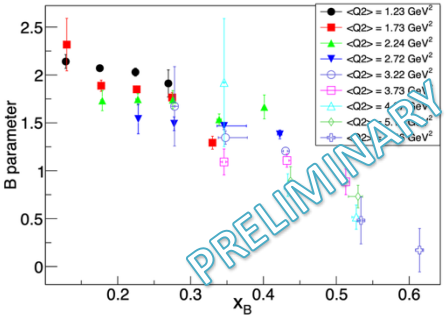
- Cross sections:
  - $ep \rightarrow ep(\pi^0, \eta)$
  - $en \rightarrow en(\pi^0, \eta)$
  - $ep \rightarrow e\pi^+ n$
  - $ep \rightarrow eK^+\Lambda$
- Asymmetries:
  - $\mathcal{A}_{LU}$ – beam spin
  - $\mathcal{A}_{UL}$ – target spin
  - $\mathcal{A}_{LL}$ – beam target

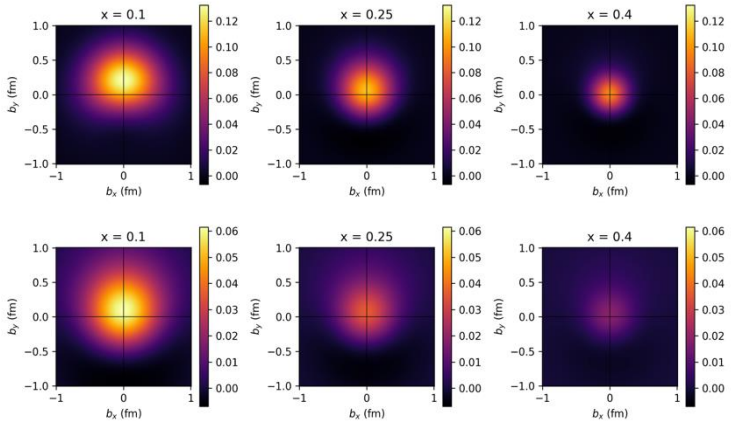
π^0 published

Summary

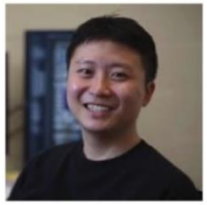
- DVπ° is an important tool for studying transversity GPDs.
- The CLAS12 detector enables to measurements over a wide kinematical range.
- Measurements of π°, η meson production from protons and neutrons enable a flavor decomposition of various GPDs.
- The t dependence provides access to the underlying distribution of transversely polarized quarks in impact-parameter space.





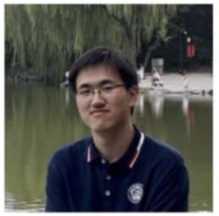


- Global analysis of full data set from all available data is underway with a goal to get the transversity GPD parameters with flavor decomposition.

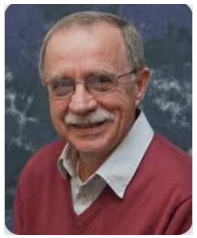


Dr. Sangbaek Lee
(ANL)

Dr. Timothy Hayward
(JLAB)



Yijie Wang
(MIT)



Dr. Valery Kubarovsky
(JLAB)

Dr. Latifa Elouadrhiri
(JLAB)

Dr. Igor Korover
(TAU)

Story Frantzen
(MIT)

Dr. Bhawani Singl
(JLAB)

Maggie Kerr
(MIT)

Dr. Richard Milner
(MIT)

Thank you for you attention

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