Deeply Virtual Exclusive Reactions at JLab

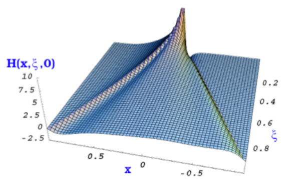
Valery Kubarovsky
Jlab and Uconn

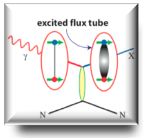
MIT-UConn workshop, September 6th, 2019

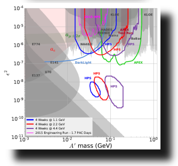
clas

The CLAS12 physics program

- Experiments at Jefferson Lab are generating the most comprehensive and the **most precise data ever** on the internal substructure of nucleons and nuclei.
- The 3D quark structure of the nucleon and N* states– from form factors and PDFs to GPDs and TMDs
- The quark/gluon orbital momentum contribution to the proton's spin
- Quark confinement and the role of the glue in meson and baryon spectroscopy
- Search for physics beyond the standard model of particle physics







CLAS12

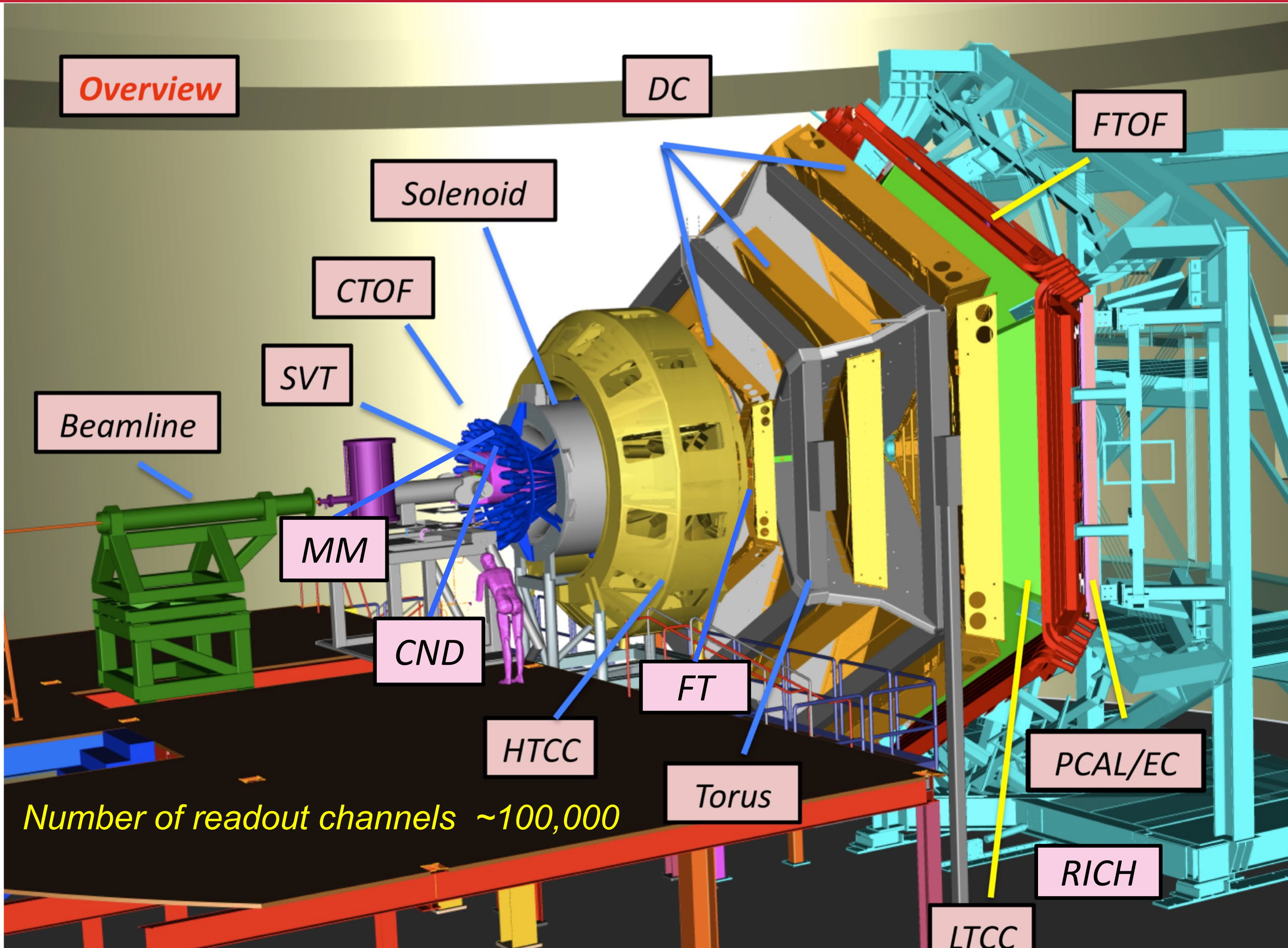
Central Detector:

- *SOLENOID magnet*
- *Barrel Silicon Tracker*
- *Micromegas*
- *Neutron detector*
- *Central Time-of-Flight*

Forward Detector:

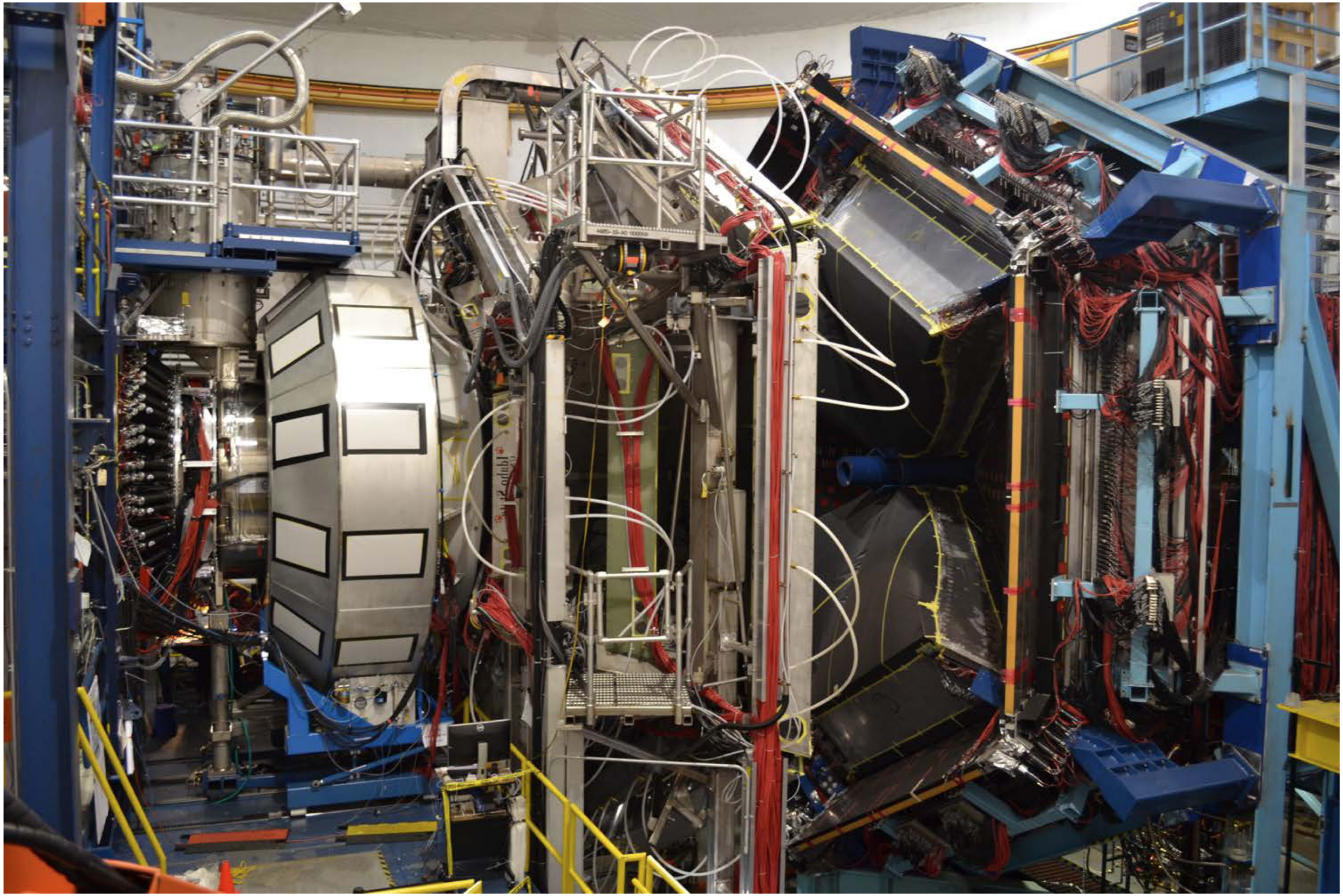
- *TORUS magnet*
- *HT Cherenkov Counter*
- *Drift chamber system*
- *LT Cherenkov Counter*
- *RICH detector*
- *Forward ToF System*
- *Preshower calorimeter*
- *E.M. calorimeter (EC)*

***Forward Tagger** (FD)*

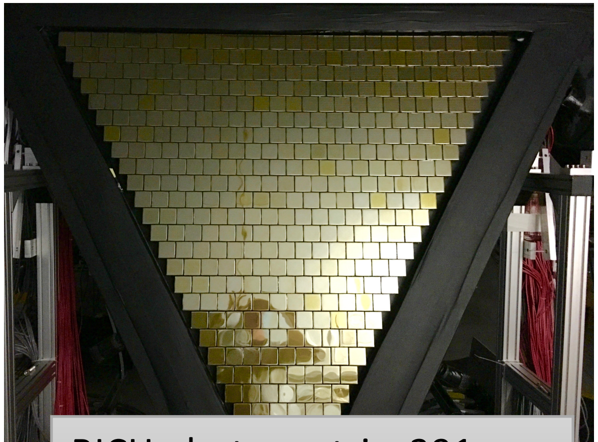


https://www.jlab.org/Hall-B/clas12-web/

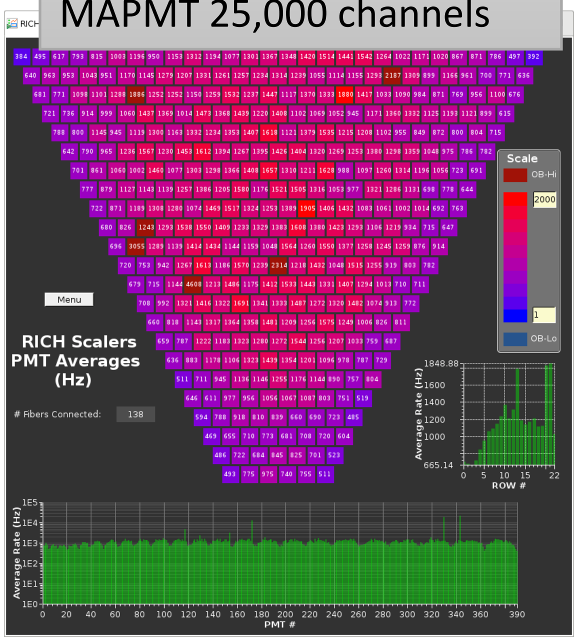
CLAS12 installation



Ring Imagine Cherenkov Counter

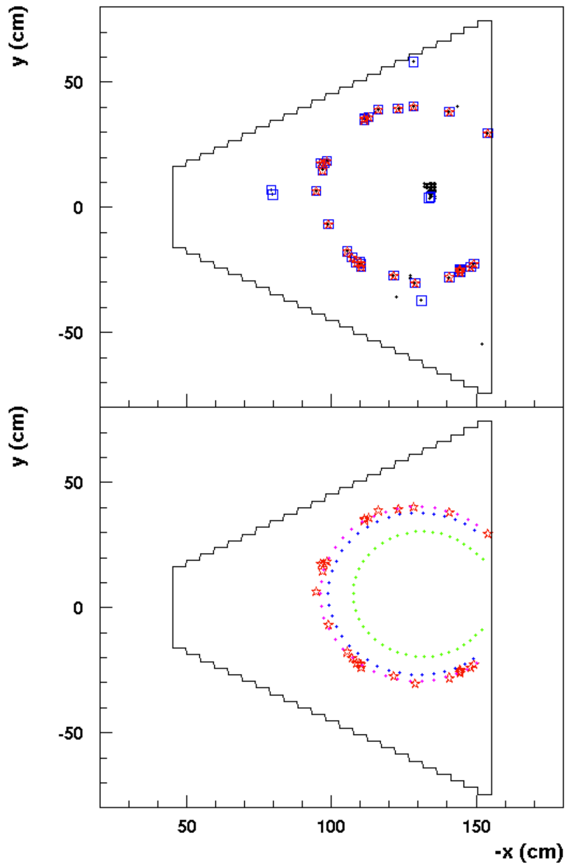


RICH photo matrix, 391 MAPMT 25,000 channels



Radiator: Aerogel tiles, Photon detectors: MAPMTs

- 391 HAMAMATSU 8x8 MAPMTs
- 25,000 channels were calibrated using laser stand
- RICH is using equalized gains for each pixel at 1000V

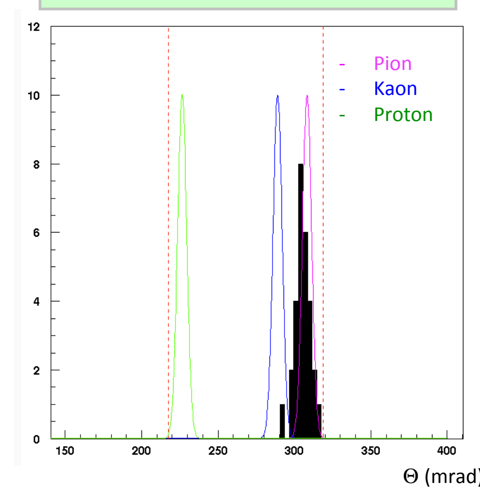


CLAS12 event

P=4.3 GeV/c

FTOF PID - π

RICH PID - π



CLAS12 trigger

- ***Inclusive electron scattering trigger***

High Threshold Cherenkov Counter

Drift Chambers track reconstruction

Electromagnetic calorimeter

- ***Photoproduction trigger (FT trigger)***

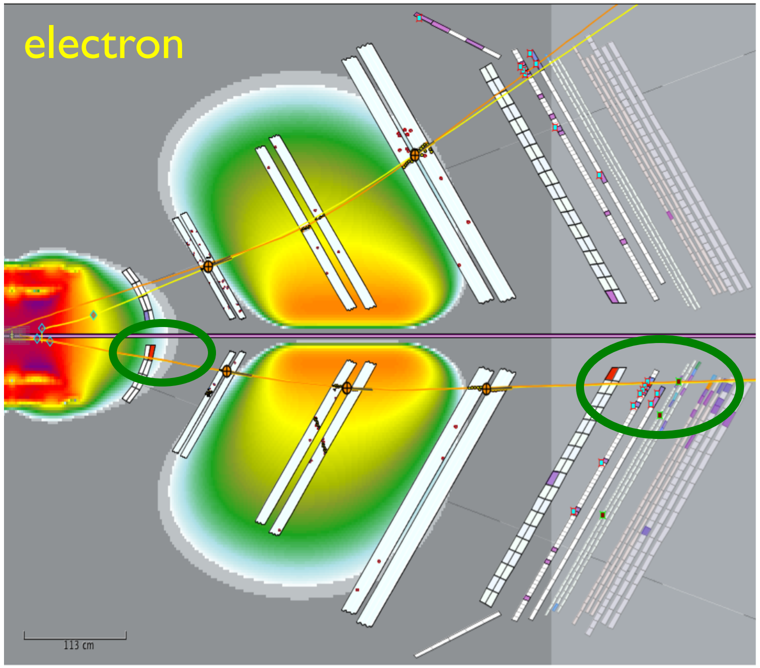
Forward Tagger (FT) and Hodoscope, cluster funding is used to determine the electron energy and coordinate

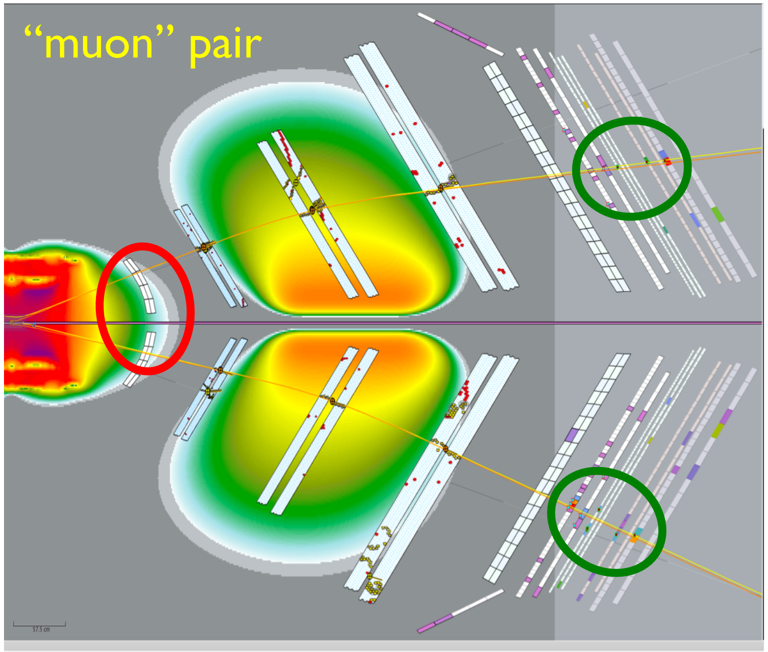
Charge particles in the Forward and Central Detectors.

- ***"Muon" trigger***

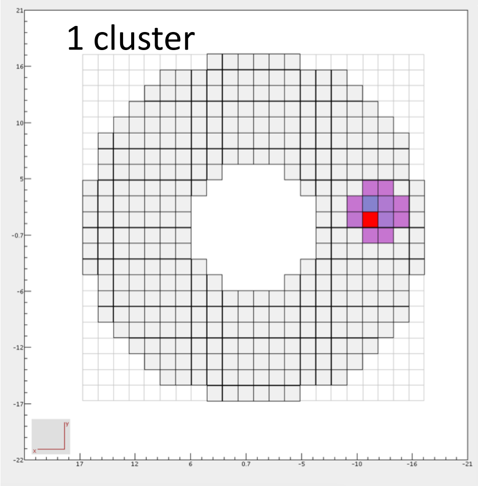
Select events with two muons detected in the Forward Detectors ONLY. This trigger does not require to detect scattered electron.

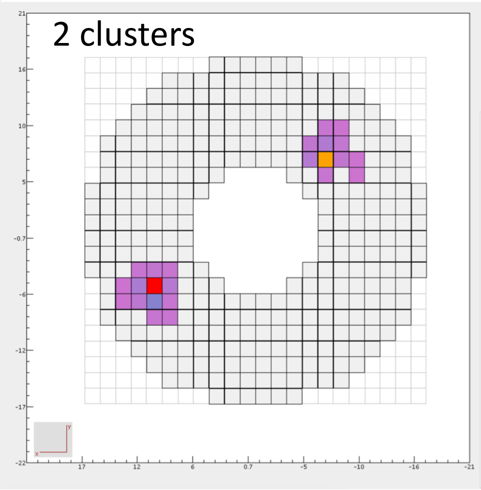
Event based triggers



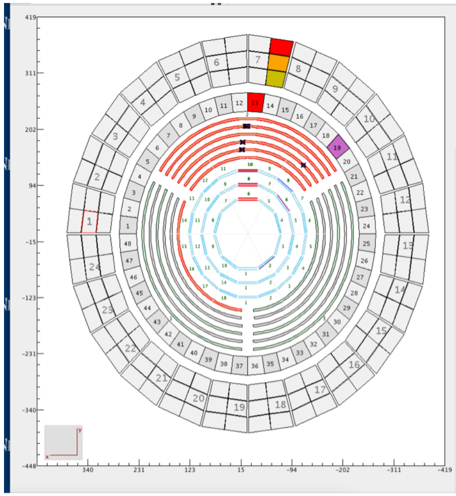


FT-CAL Trigger





CD - CTOF

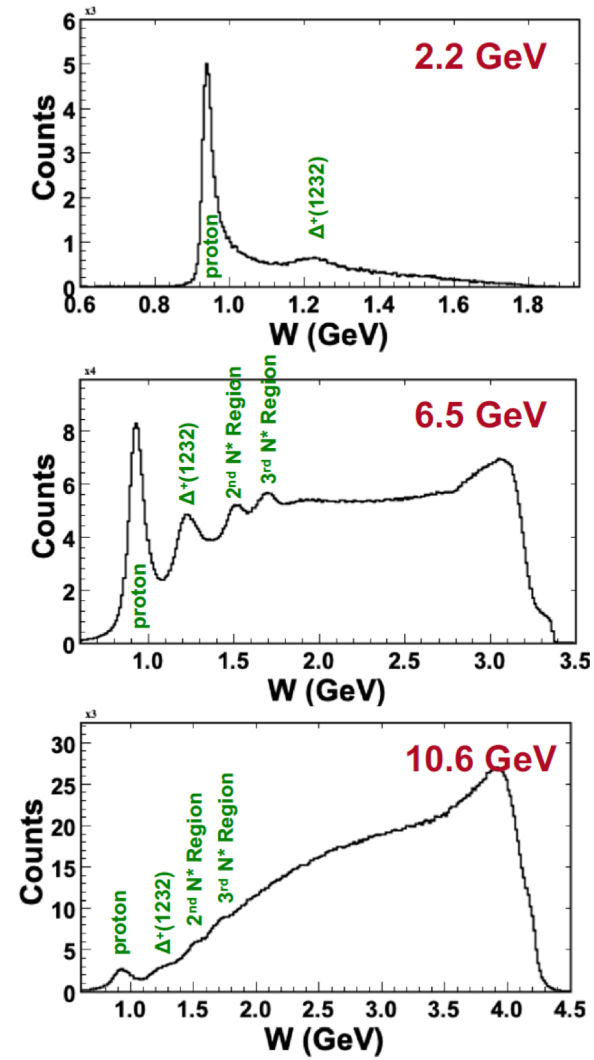


CLAS12

- **Collaboration**
  - More than 195 members
  - 43 Institutions
  - 9 countries
- **Experimental program**
  - 41 approved proposals
    - Targets
      - Proton, deuteron and nuclei
      - Unpolarized, longitudinally and transversally polarized
      - Solid, liquid and gas
    - beam:
      - highly polarized electron beam
      - linearly polarized quasi-real photons
    - final states: inclusive, semi-inclusive and exclusive
    - luminosity up to 10^{35} $cm^{-2}s^{-1}$
- **11 Run Groups**
- **10 years of approved data taking**

CLAS12 Data Taking

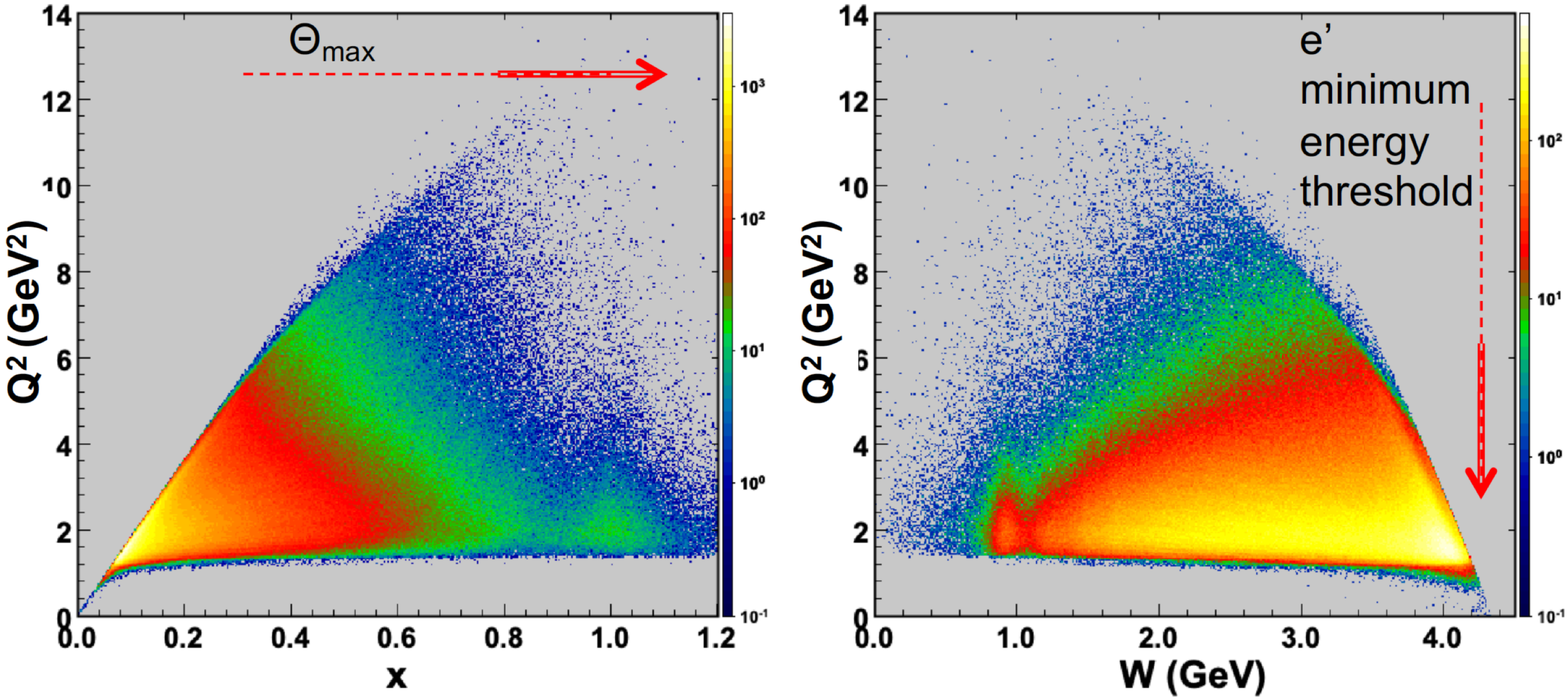
- **First commissioning run** (KPP) in February 2017
- **Engineering run** in December 2017-February 2018
- Physics data taking start in February 2018:
  - **Run Group A**:
    - 13 experiments
    - 10.2-10.6 GeV polarized electrons
    - Liquid-hydrogen target
    - ~300 mC, ~50% of approved beam time
  - **Run Group K**:
    - 3 experiments
    - 6.5, 7.5 GeV polarized electrons
    - Liquid-hydrogen target
    - ~45 mC, ~12% of approved beam time
  - **Run Group B**:
    - 7 experiments
    - 10.2-10.5 GeV polarized electrons
    - Liquid-deuterium target
    - ~84 mC, ~24% of approved beam time



CLAS12 Kinematics

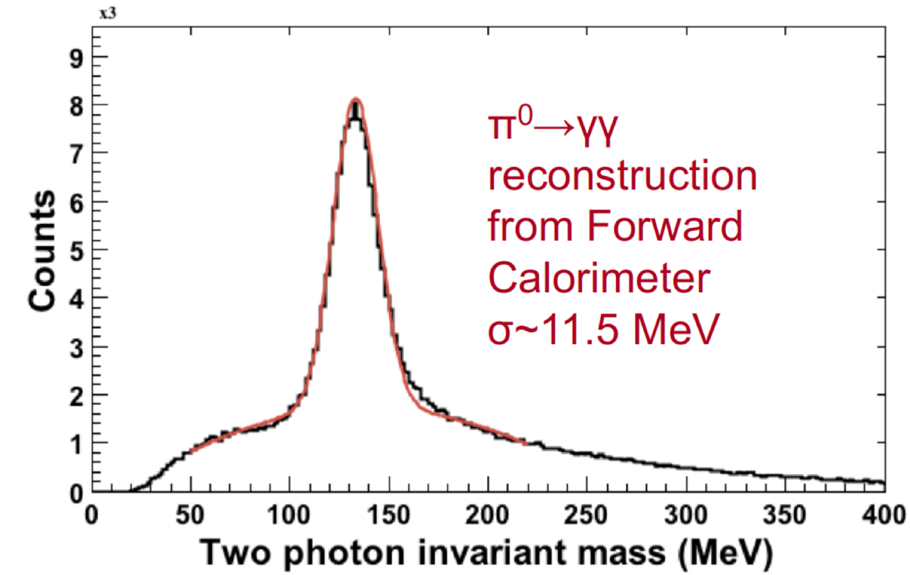
Beam energy at 10.6 GeV Torus current 3770 A, electrons in-bending, Solenoid magnet at 2416 A.

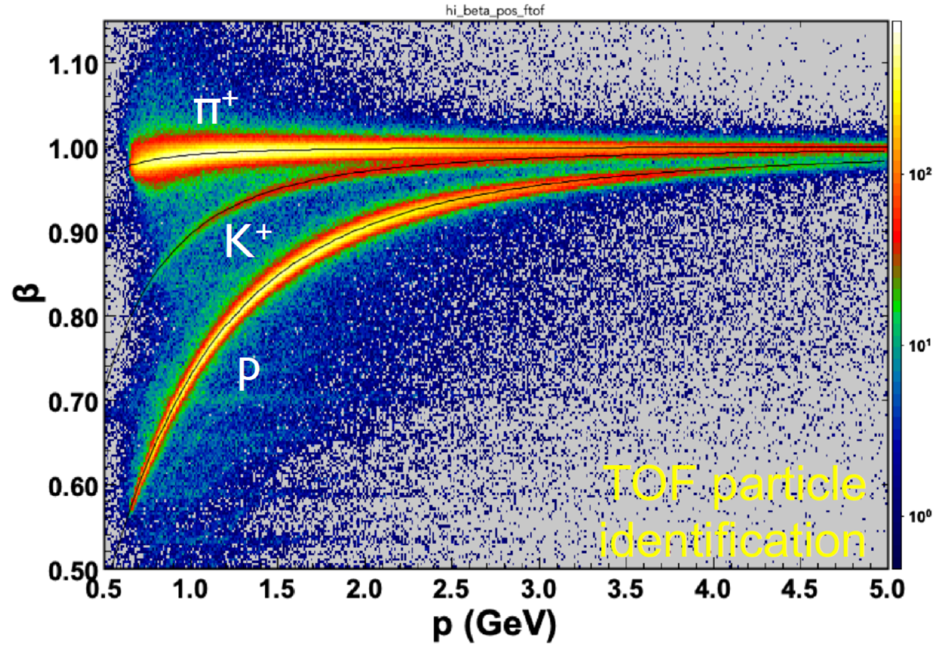
p(e,e')X

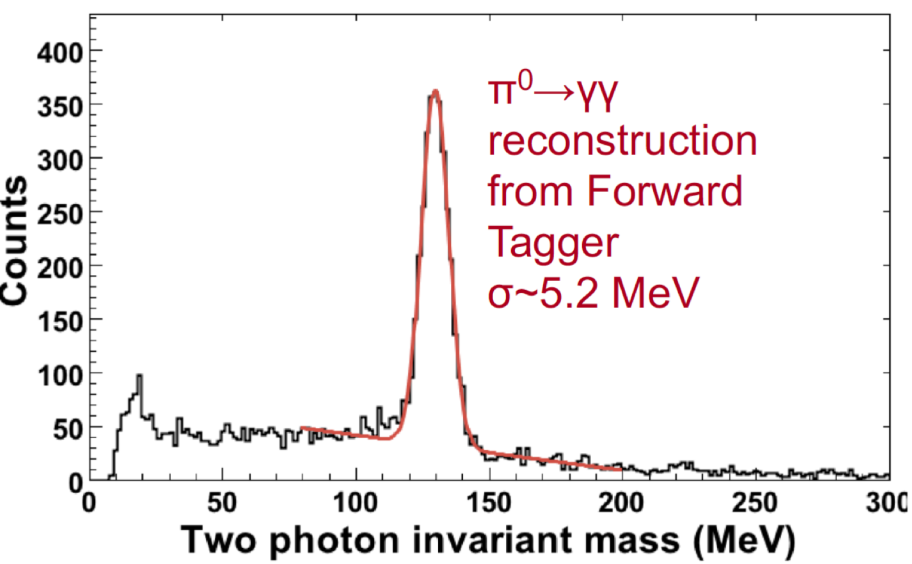


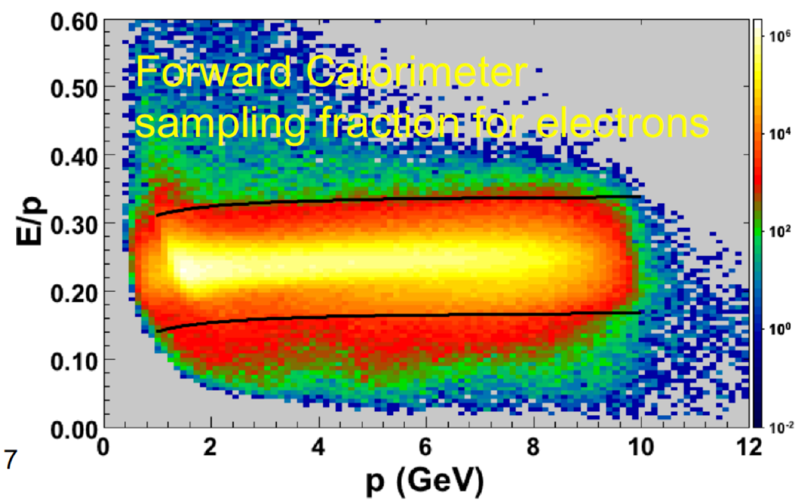
Plots based on 100 min. of data taking

Event Reconstruction and PID



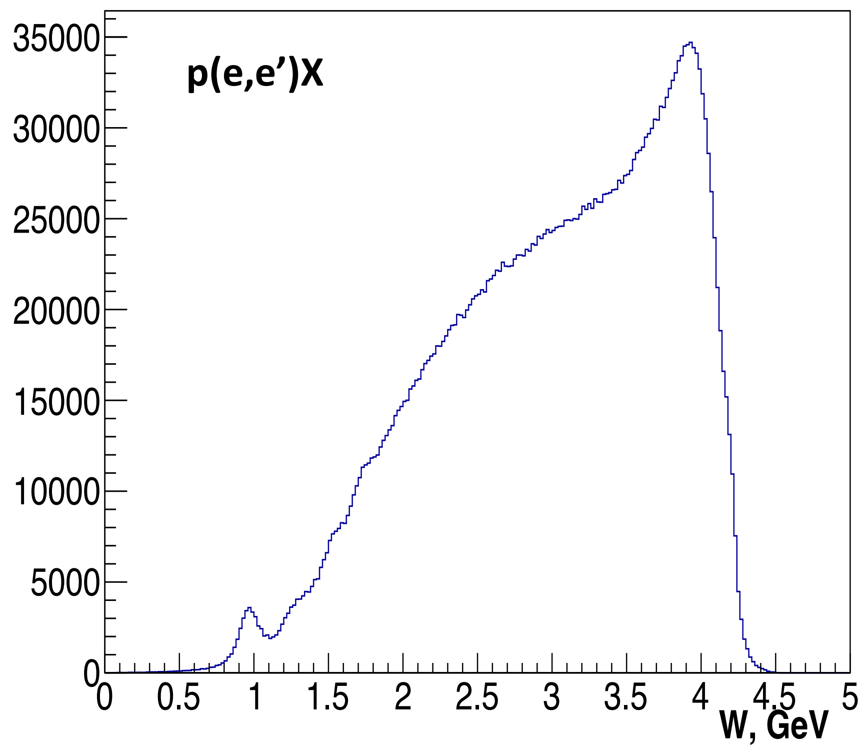




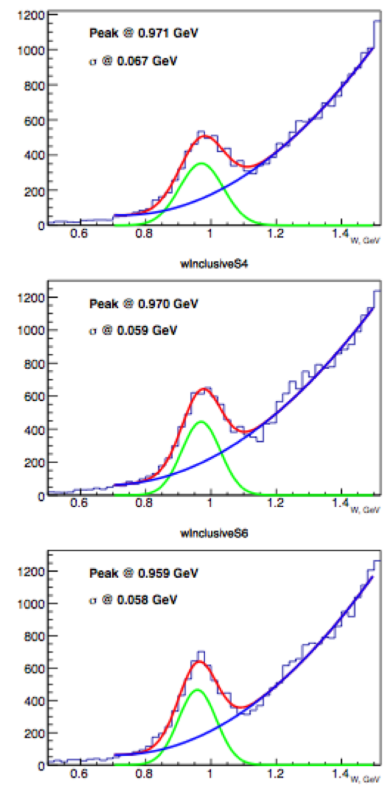


RGA – p(e,e')X, p(e,e'π^+)X

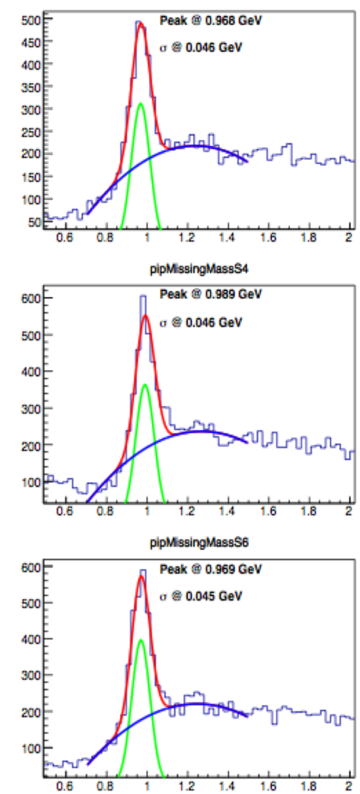
E = 10.6 GeV



p(e,e')X



p(e,e'π^+)X

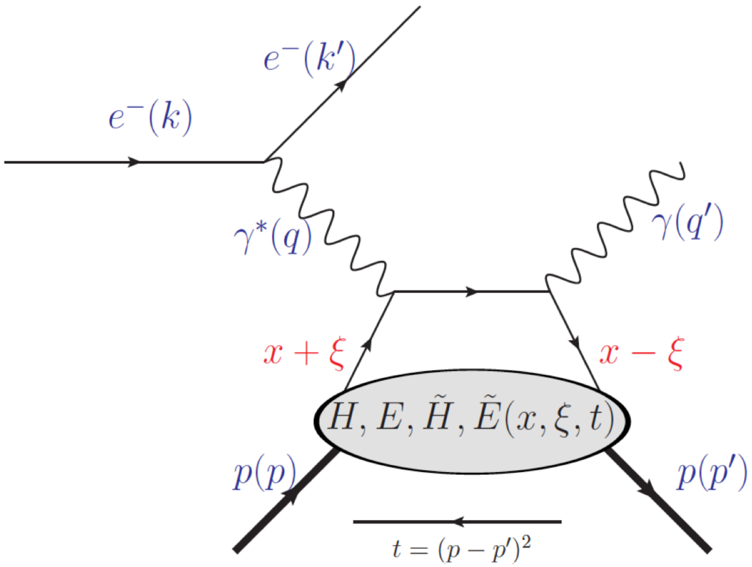


DVCS

Deeply Virtual Compton Scattering

- GPDs appear in the DVCS amplitude through Compton Form Factors (CFF) such as:

$$\mathcal{H} = \int_{-1}^{1} H(x,\xi,t)\Big(\frac{1}{\xi - x - i\epsilon} - \frac{1}{\xi + x - i\epsilon}\Big)dx$$



DVCS at leading order

Generalized Partons Distributions (GPDs)

- **Tomography** of the nucleon
- Contribution of quark orbital angular momentum to the **proton spin**

Exclusivity Cuts

Final state with:

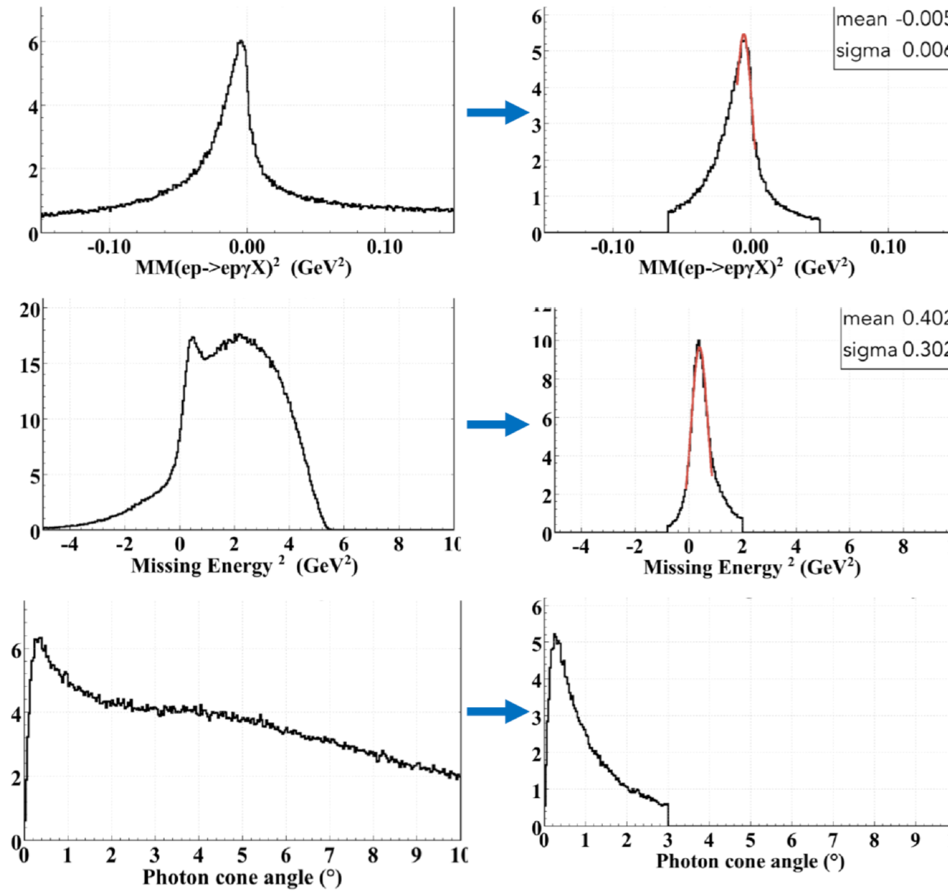
- High energy **electron**
- High energy **photon**
- **Proton**
- $Q^2 > 1$ GeV ^{2}
- $W^2 > 4$ GeV ^{2}

Selection of exclusive DVCS events:

- **Missing mass** $ep \rightarrow ep\gamma X$
- **Missing energy** $ep \rightarrow ep\gamma X$
- **Cone angle**: angle between measured and exclusive missing photon

π^0 **contamination** $ep \rightarrow ep\pi^0 \rightarrow ep\gamma\gamma$

- Different methods have been implemented



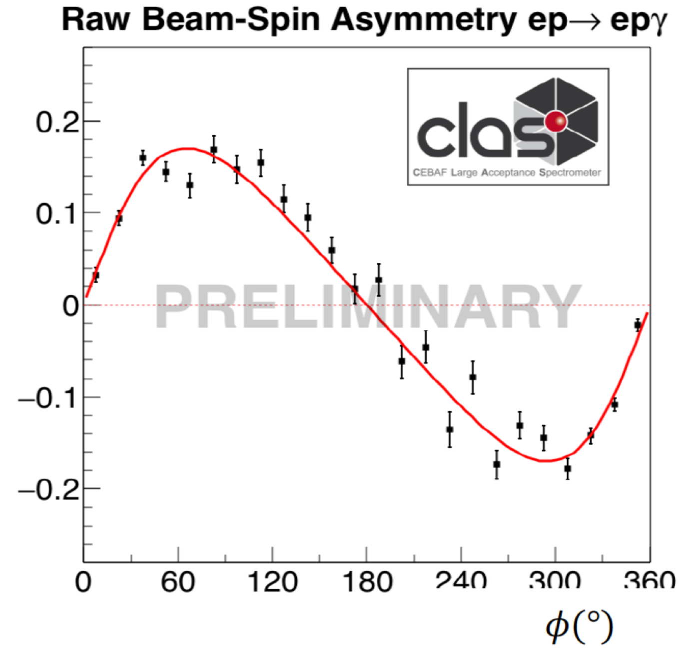
Before exclusivity cuts | After exclusivity cuts

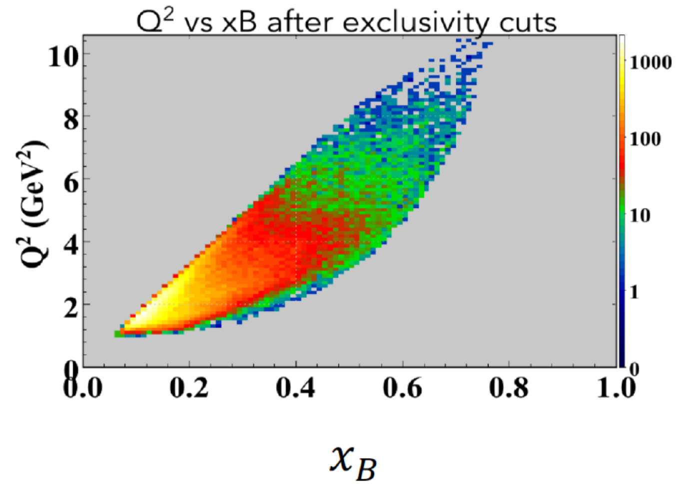
Beam-spin asymmetry

Preliminary asymmetry:

$$A_{LU} = \frac{1}{P}\frac{N^{+}(\phi)-N^{-}(\phi)}{N^{+}(\phi)+N^{-}(\phi)}$$

P	polarization
N^{+} / N^{-}	number of events with helicity + / -

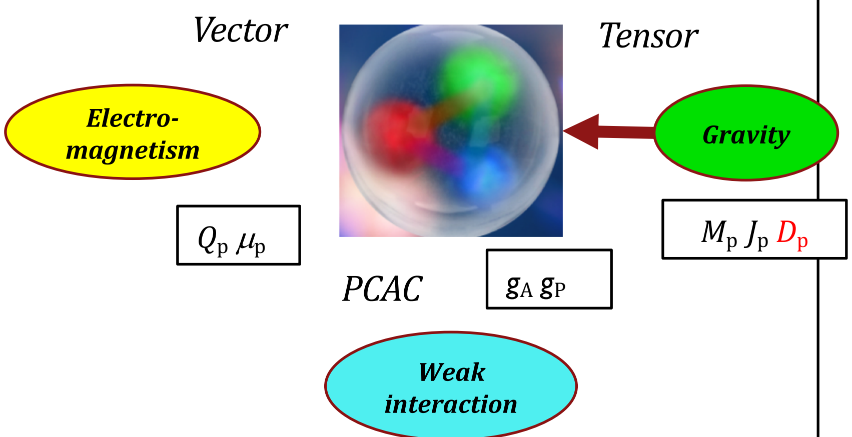




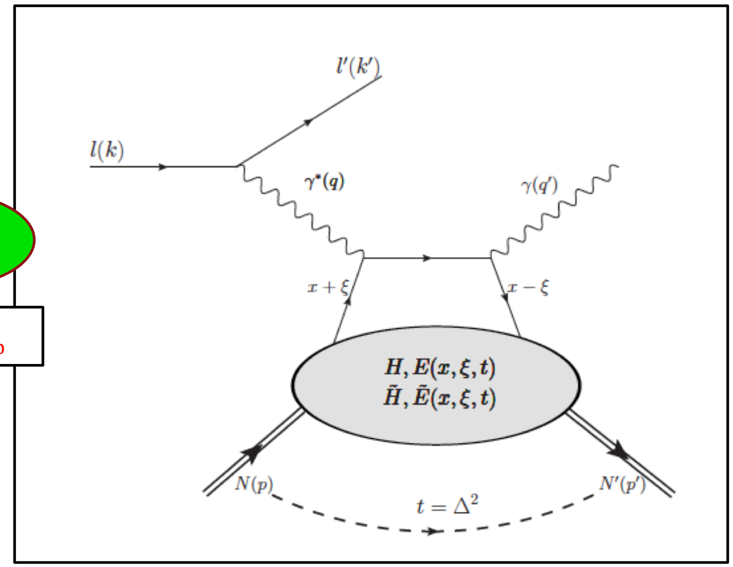
- Background not yet subtracted
- Integrated over all kinematic domain (average Q^2 = 2.5 GeV ^{2} , x_B = 0.22)

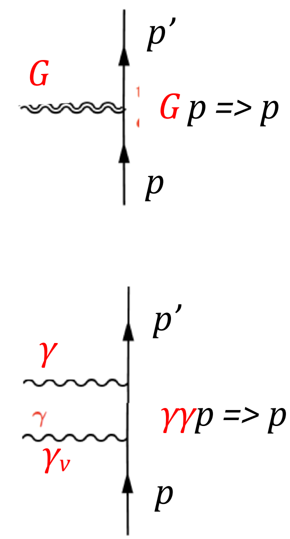
Gravity and Mechanical properties

Probing the proton



Deeply virtual Compton scattering





The DVCS process mimics graviton-proton coupling with many orders of magnitude higher rate that makes the experiments feasible.

Pressure Distribution inside the Proton

$$d_1(t) \propto \int \mathrm{d}^3\mathrm{r}\, \frac{j_0(r\sqrt{-t})}{2t}\, p(r)$$

Repulsive pressure near center

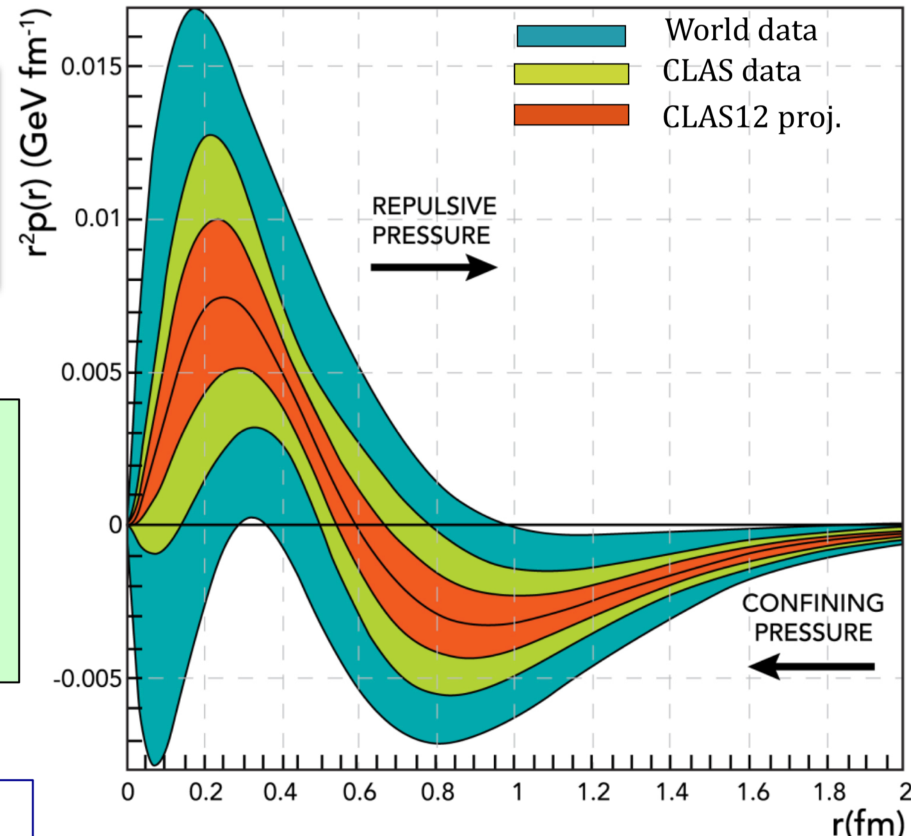
$p(r=0) = 10^{35}$ Pa

Confining pressure at r > 0.6 fm

(in χQSM due to the pion field)

Atmospheric pressure: 10^5 Pa

Pressure in the center of neutron stars ≤ 10^{34} Pa



V.B., L. Elouadrhiri, F.X. Girod

Nature 557 (2018) no.7705, 396-399

Run Group-K Questions to address

- The N* spectrum: what is the role of glue?

  → **Search for new baryon states**

  E12-16-010

- How do massless quarks acquire mass?

  → **Measure the Q^2 dependence of electrocoupling amplitudes**

  E12-16-010A

- How is color confinement realized in the force and pressure distributions and stabilize nucleons?

  → **Study GPDs and their moments from DVCS**

  E12-16-010B

Run Group-K: Data taking

Nov. – Dec. 2018

RG-K	Experiment
E12-16-010	A search for hybrid baryons in Hall B with CLAS12
E12-16-010A	Nucleon resonances in excl. KY electroproduction
E12-16-010B	DVCS with CLAS12 at 6.6 and 8.8 GeV

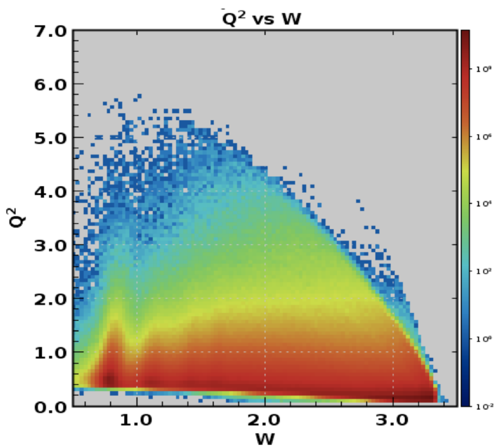
- 3 experiments
- Polarized electrons on Liquid-hydrogen target
- Torus setting: Negatives out-bending

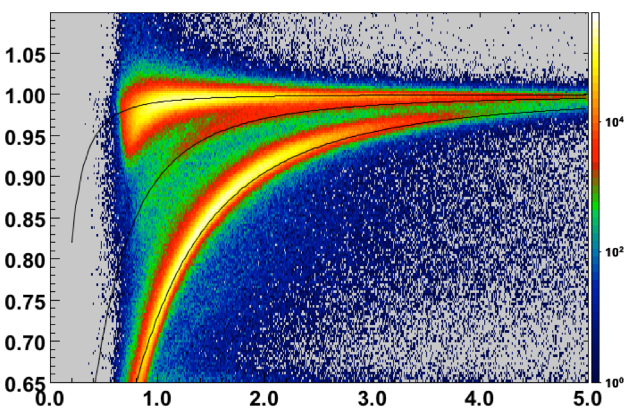
Beam Energy	Beam Current	Target	Trigger	Collected Events
7.5 GeV	35 nA	LH_2	e in CLAS or (e in FT + 1 Fwd Hadron)	3.5 G
7.5 GeV	45 nA	LH_2	e in CLAS – pre-scaled or (e in FT + 1 Fwd Hadron	4.3 G
6.5 GeV	60 nA	LH_2	e in CLAS	7.8 G

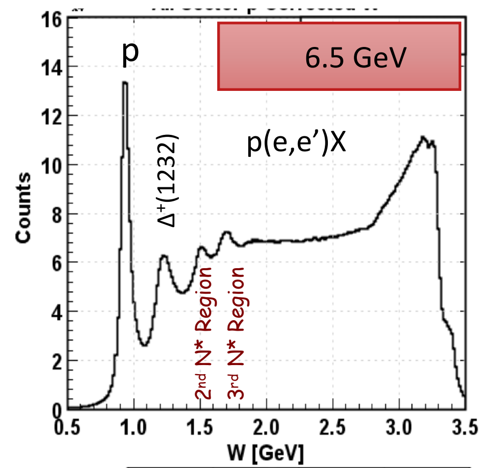
Q~45mC = 7% of Expected 648mC

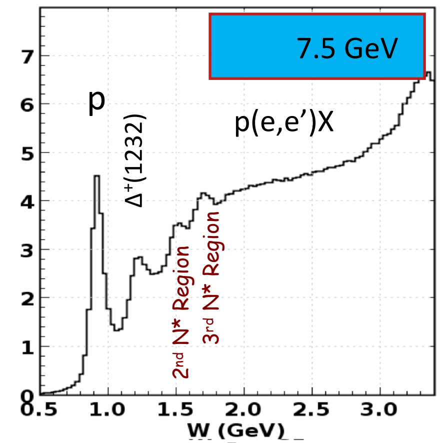
COLLECTED EVENTS
15.6×10^9

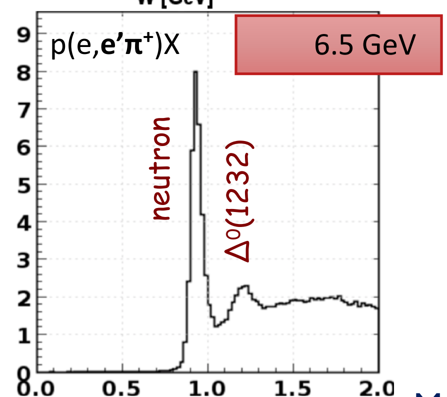
RGK: Electron Scattering & PID

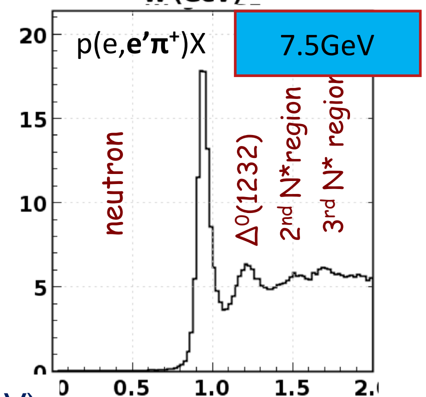












M_x (GeV)

Run Group B: Deuterium Target

Run schedule 6/02 – 25/03 (completed) 1/11 – 19/12 (upcoming)	50% of approved PAC days

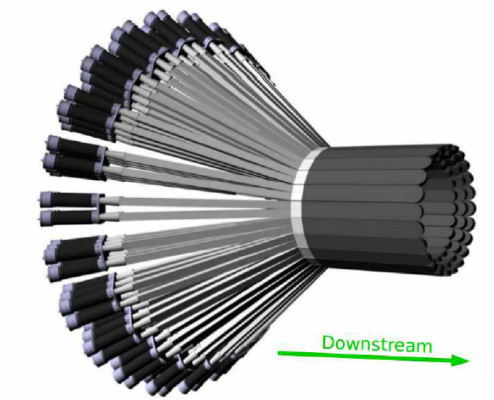
- 7 experiments:

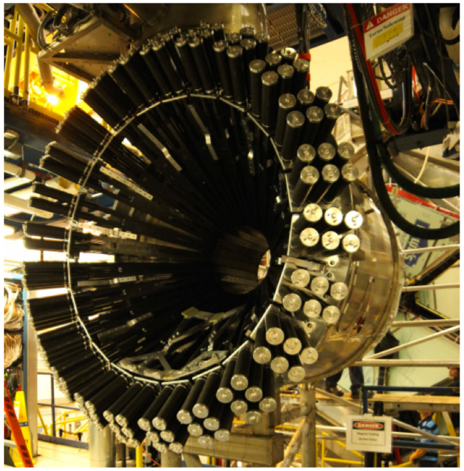
Experiment number	Title	Rating/approved days	Setup
E12-07-104	Neutron magnetic form factor	A-, 30 days	LD2 target
E12-09-007(a)	Study of partonic distributions in SIDIS kaon production	A-, 56 days	LD2 target, RICH
E12-09-008	Boer-Mulders asymmetry in K SIDIS	A-, 56 days	LD2 target, RICH, half time with reversed torus polarity
E12-11-003	Deeply Virtual Compton Scattering on the Neutron	A (high impact), 90 days	LD2 target, FT
E12-09-008(b)	Collinear nucleon structure at twist-3	RG experiment	LD2 target, RICH, half time with reversed torus polarity
E12-09-008(a)	In medium structure functions, SRC, and the EMC effect	RG experiment	LD2 target, BAND
E12-11-003(b)	Study of J/ψ photoproduction off deuteron	RG experiment	LD2 target, FT

- 7 PhD theses in progress:

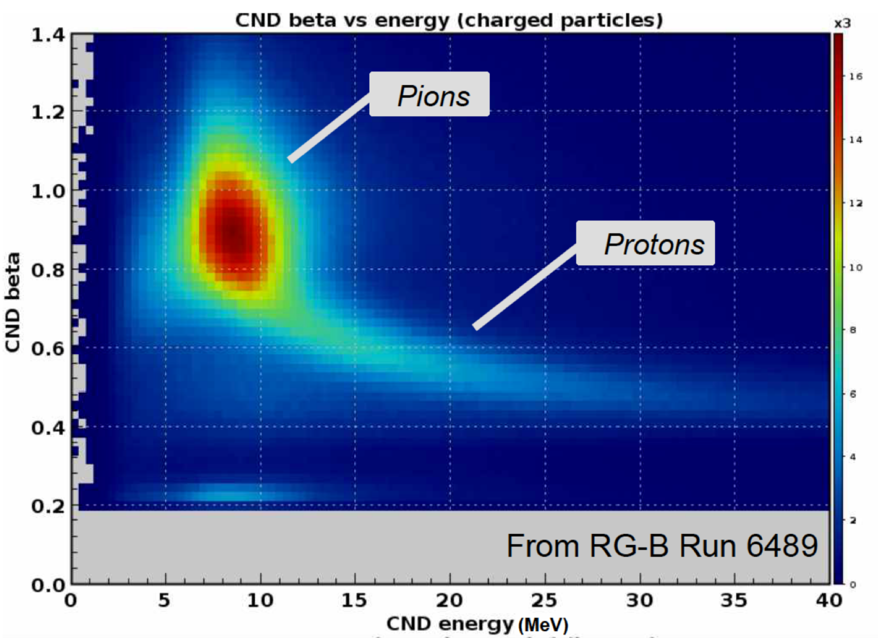
K. Price (IPN Orsay)	nDVCS
P. Naidoo (Glasgow)	Exclusive π^0 on neutron
Student from Yerevan	J/ψ
E. P. Segarra (MIT)	BAND experiment
R. C. Torres (MIT)	BAND experiment
C. Fogler (ODU)	BAND experiment
B. Tumeo (USC)	J/ψ
L. Basheen (FIU)	GMn

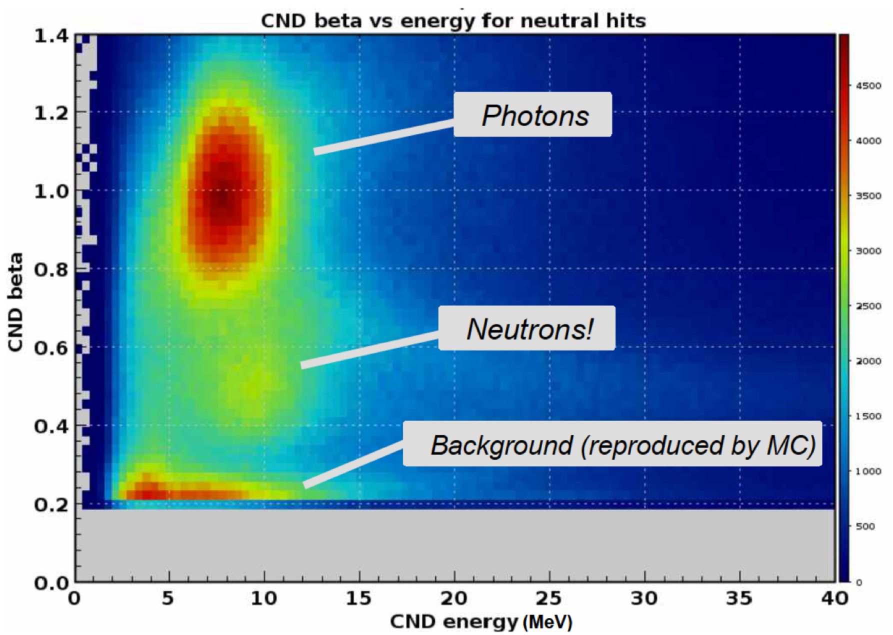
Central Neutron Detector



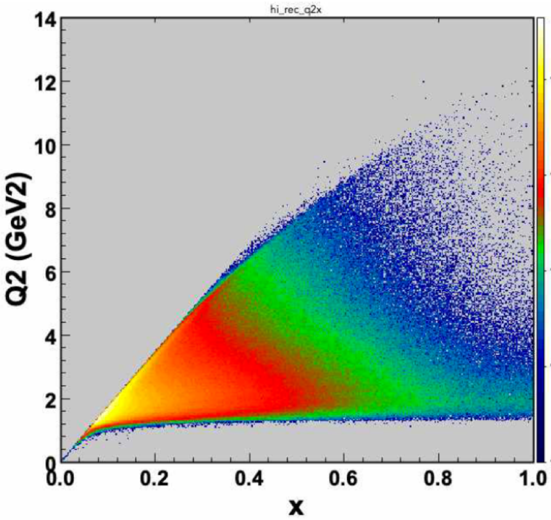


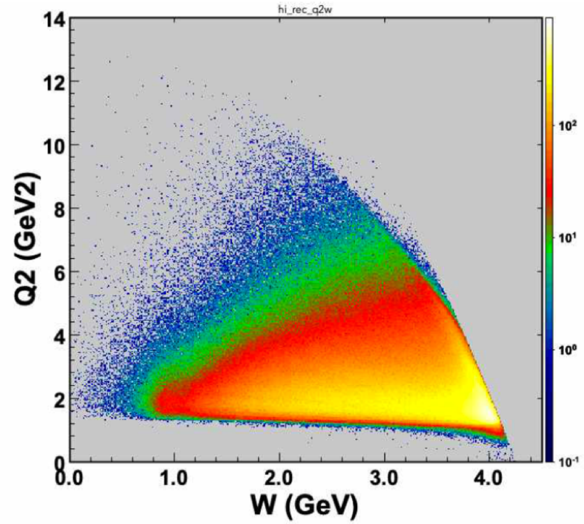
Specifications
Plastic scintillator
3 radial layers, total ~10 cm
Angular coverage 40° < θ <120°
Azimuthal coverage 2π
Neutron detection efficiency ~10%



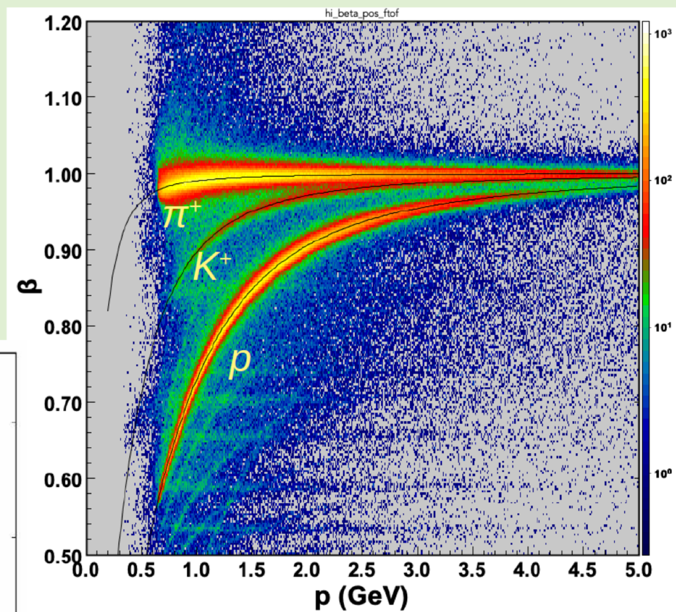


Kinematic Coverage & Calibration

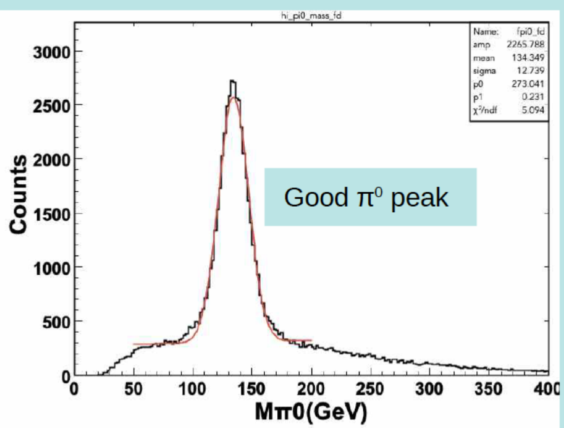




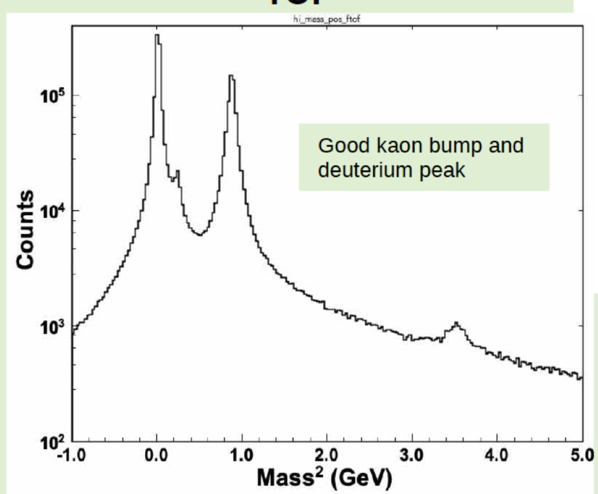
Monitoring plots from run 6489 (about 2 hours of data)



ECAL



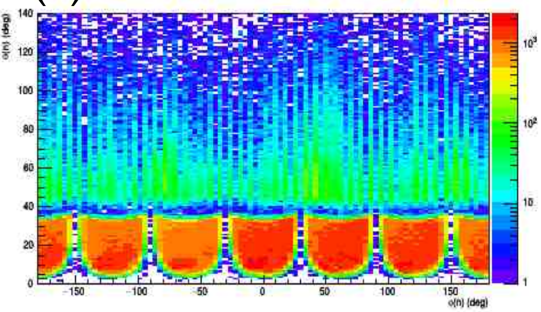
TOF



RGB: nDVCS Analysis

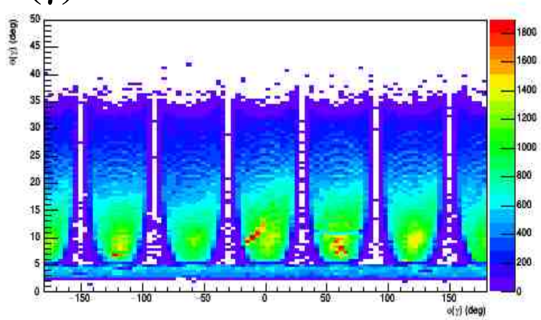
- Runs 6164, 6215, 6240, 6289, 6310, 6489, COATJAVA 5.9.0
- PID: electron neutron gamma detected (EB)
- Kinematic cuts: Q^2>1 GeV^2, p(e)>1 GeV, q(e)>5.5°, p(n)>0.35 GeV
- Preliminary « spectator » and « DVCS » cuts on MM^2(eng), missing energy, missing momentum, E_g>2 GeV
- nDVCS+BH simulation: GENEPI + GEMC 4.3.0 + COATJAVA 5.9.0

θ(n)



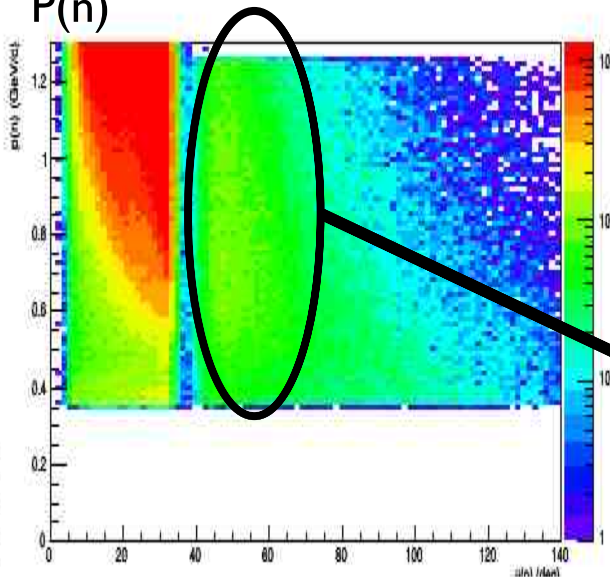
ϕ(n)

θ(γ)

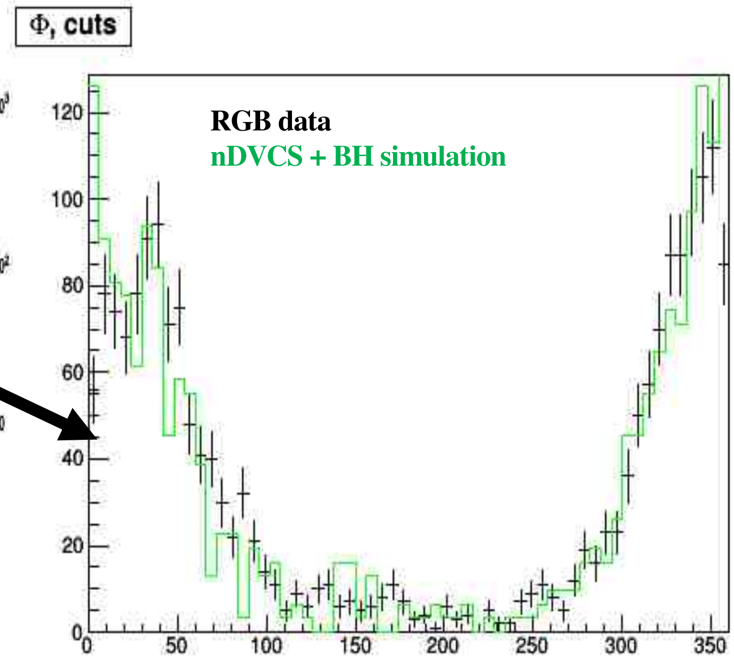


ϕ(γ)

P(n)



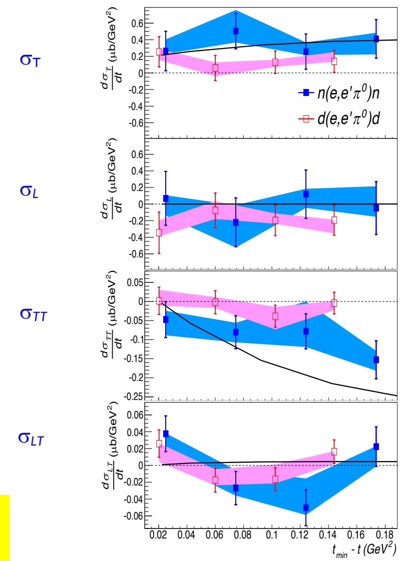
θ(n)



Experimental Studies on DVMP and Transversity GPDs

$$\gamma^* p \rightarrow p(\pi^0/\eta)$$

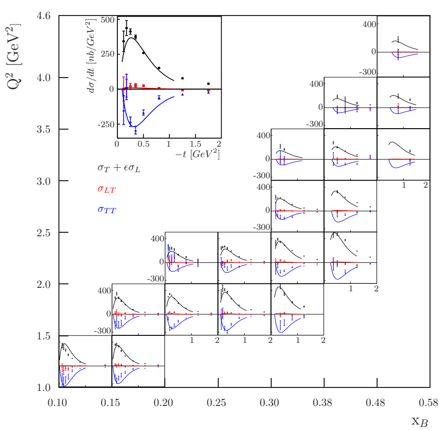
- CLAS6 π^0/η out of proton
- Hall-A π^0 , Rosenbluth σ_L/σ_T separation
- Hall-A π^0 out of neutron
- COMPASS π^0 with muon beam

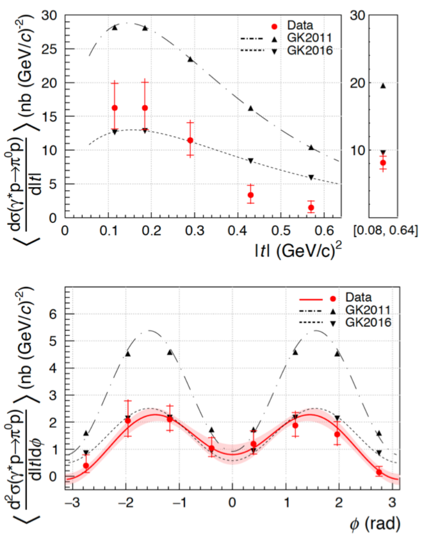


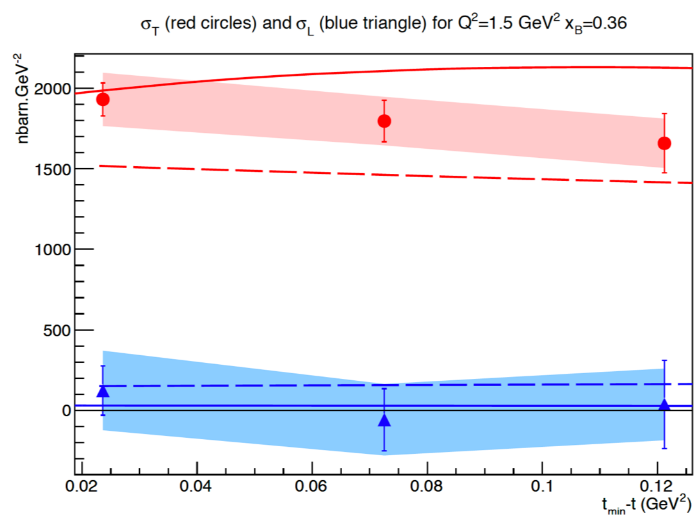
COMPASS

HALL-A

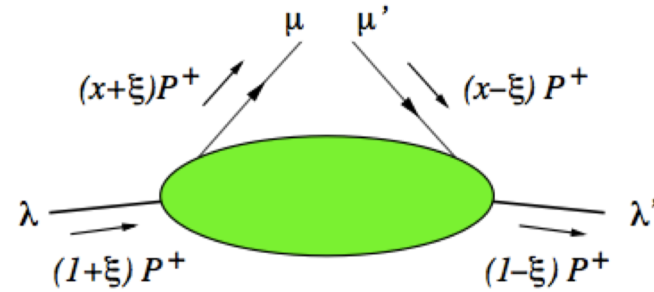
CLAS







Generalized Parton Distributions



- GPDs are the functions of three kinematic variables: x, ξ and t
- There are 4 chiral even GPDs where partons do not flip helicity $H, \tilde{H}, E, \tilde{E}$
- 4 chiral odd GPDs flip the parton helicity $\tilde{H}_T, H_T, \tilde{E}_T, E_T$
- The chiral-odd GPDs are difficult to access since subprocesses with quark helicity-flip are suppressed

Chiral-odd GPDs

- Very little known about the chiral-odd GPDs
- Anomalous tensor magnetic moment

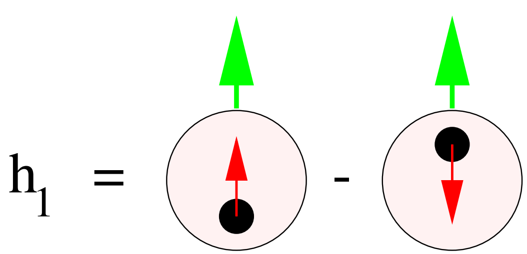
$$\kappa_T = \int_{-1}^{+1} dx\ \bar{E}_T(x, \xi, t = 0)$$

- (Compare with anomalous magnetic moment)

$$\kappa = \int_{-1}^{+1} dx\ E(x, \xi, t = 0) = F_2(t = 0)$$

- Transversity distribution

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



The transversity describes the distribution of transversely polarized quarks in a transversely polarized nucleon

PRL 109, 112001 (2012) PHYSICAL REVIEW LETTERS week ending 14 SEPTEMBER 2012

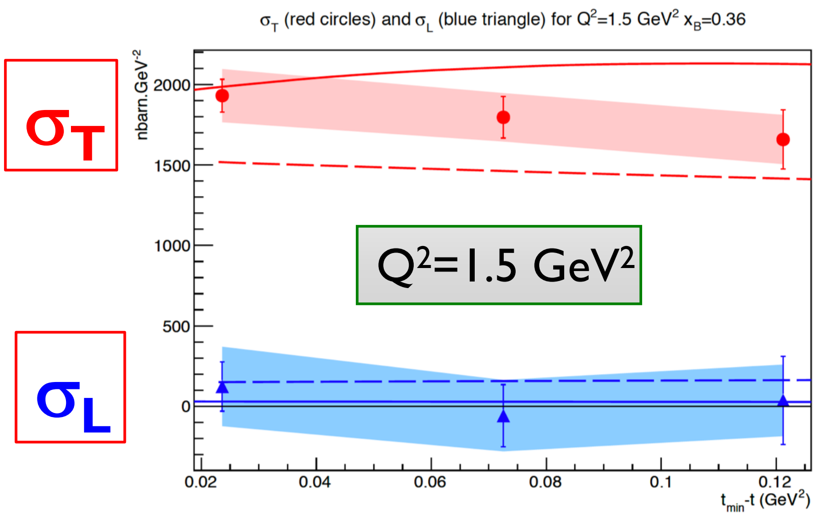
Measurement of Exclusive π^0 Electroproduction Structure Functions and their Relationship to Transverse Generalized Parton Distributions

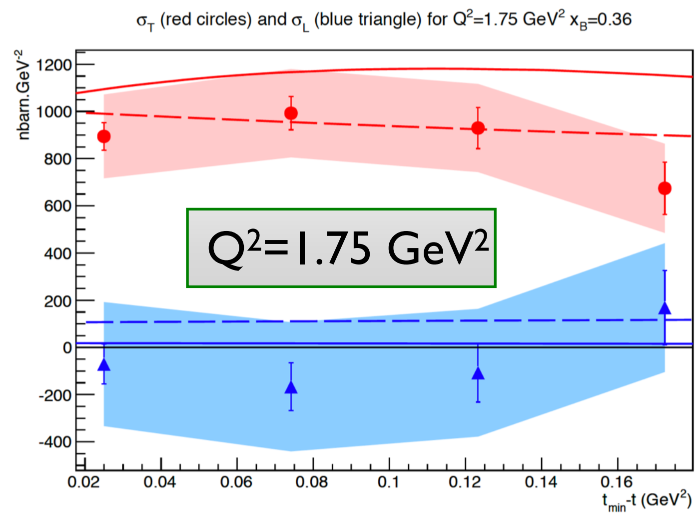
I. Bedlinskiy,[22] V. Kubarovsky,[35,30] S. Niccolai,[21] P. Stoler,[30] K. P. Adhikari,[29] M. Aghasyan,[18] M. J. Amaryan,[29]

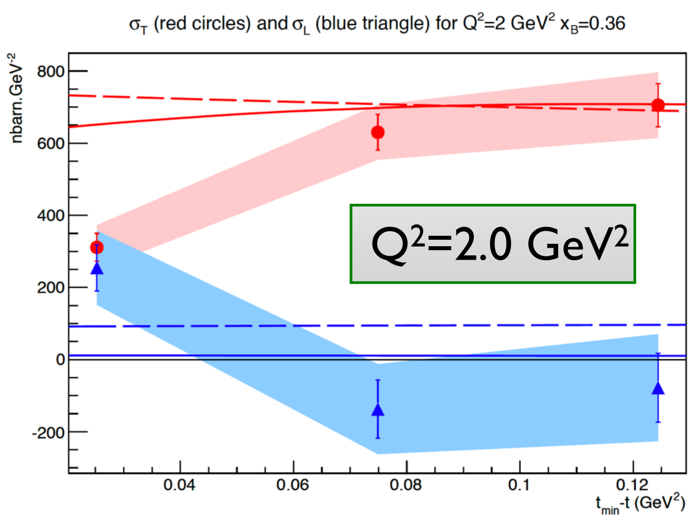
- The measured cross section of π^0 electroproduction is much larger than expected from leading-twist handbag calculation. This means that the contribution of the longitudinal cross section σ_L is small in comparison with σ_T. The same conclusion can be made in a almost model independent way from the comparison of the cross sections σ_U, σ_{TT} and σ_{LT}.

- The data appear to confirm the expectation that pseudoscalar and, in particular, π^0 electroproduction is a uniquely sensitive process to access the transversity GPDs $\bar{E}_T$ and H_T.

Rosenbluth separation σ_T and σ_L Hall-A Jefferson Lab





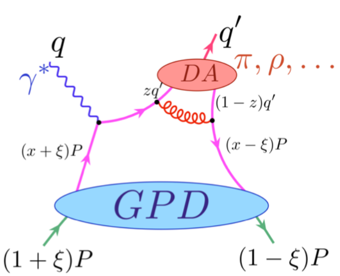


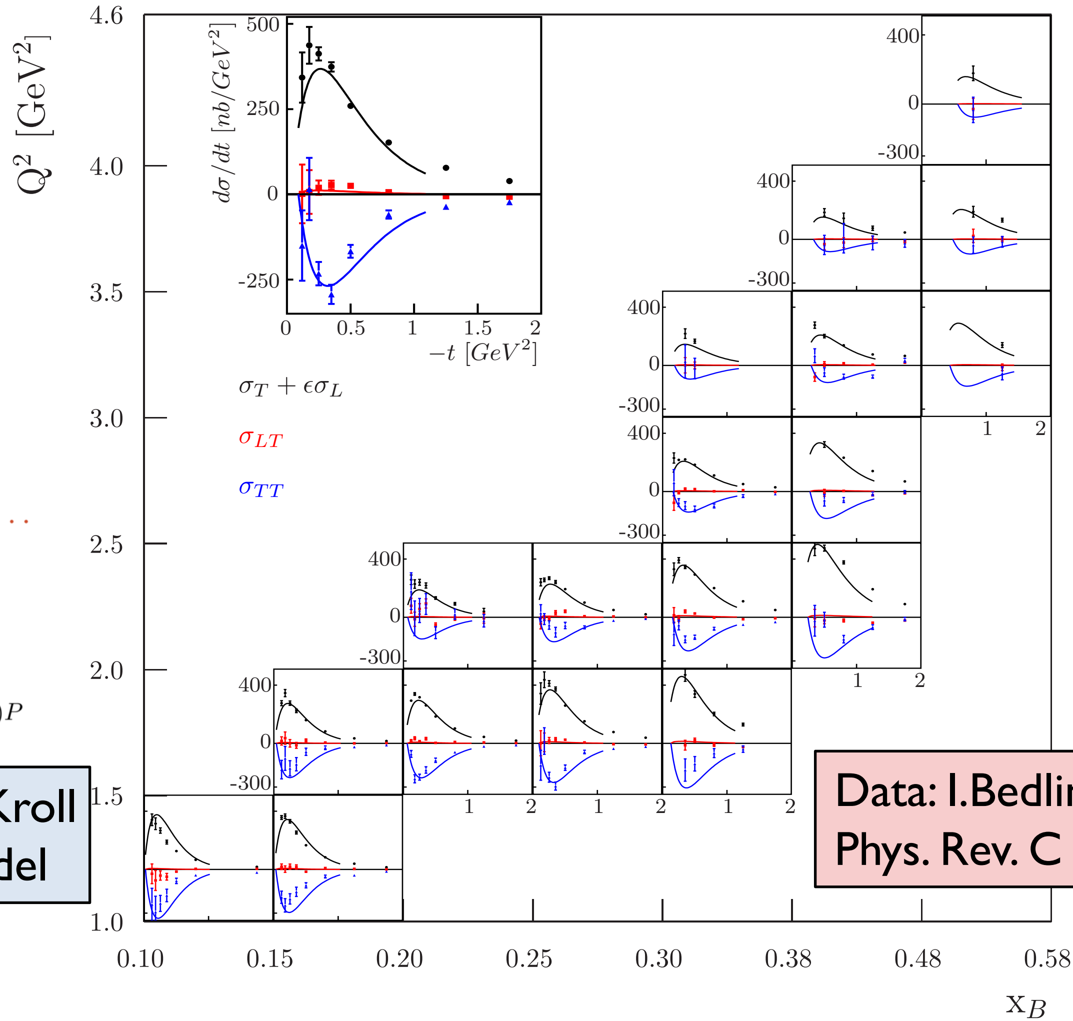
- Experimental **proof** that the transverse π^0 cross section is dominant!
- It opens the direct way to study the transversity GPDs in pseudoscalar exclusive production

Hall-A, Phys.Rev.Lett. **117**,262001(2016)

π^0 Structure Functions
$(\sigma_T + \varepsilon\sigma_L)$ σ_{TT} σ_{LT}

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



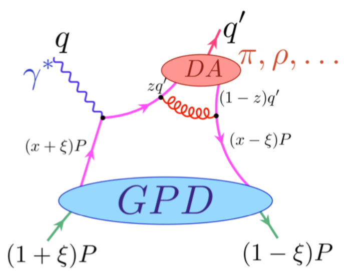


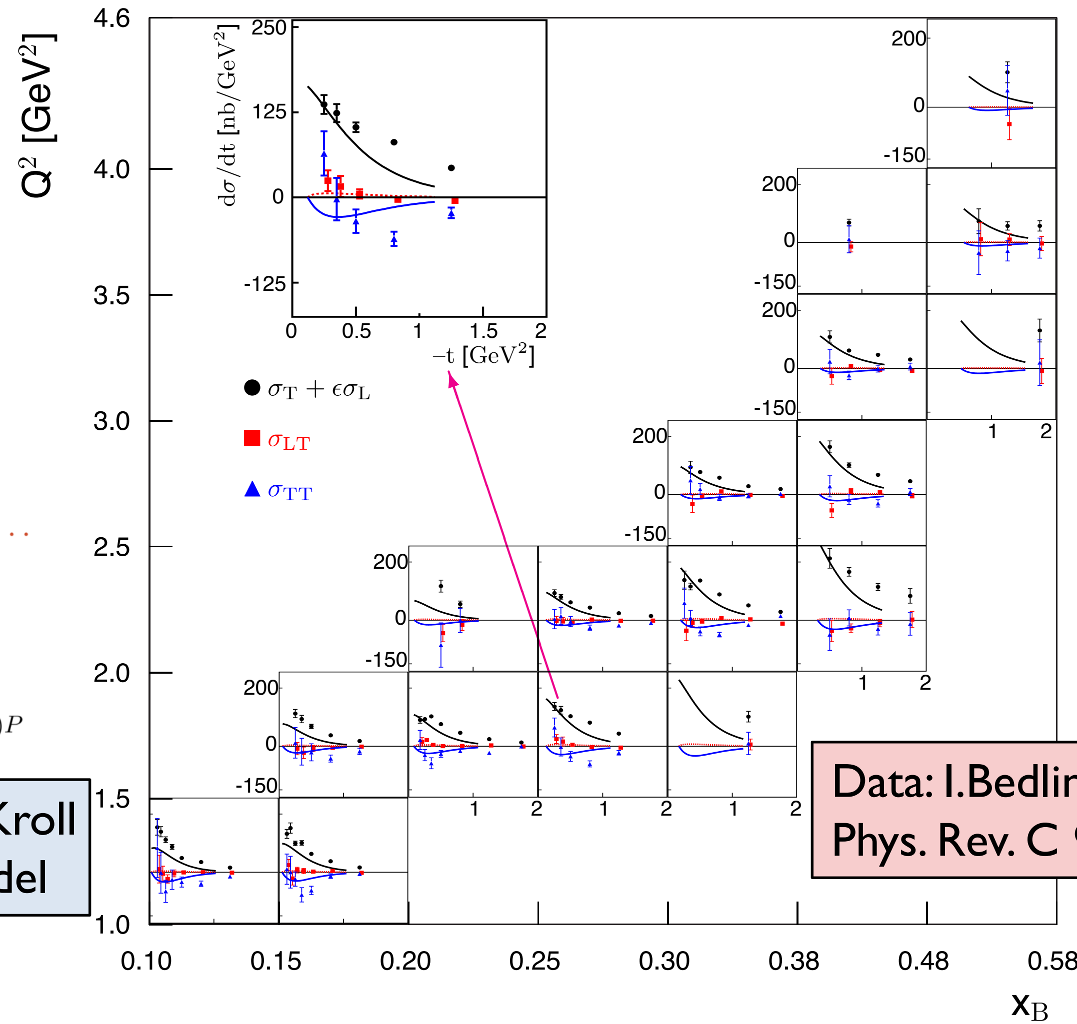
Curves: Goloskokov, Kroll
Transversity GPD model

Data: I.Bedlinskiy et al. (CLAS)
Phys. Rev. C 90, 039901 (2014)

η Structure Functions
$(\sigma_T + \epsilon\sigma_L)$ σ_{TT} σ_{LT}

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

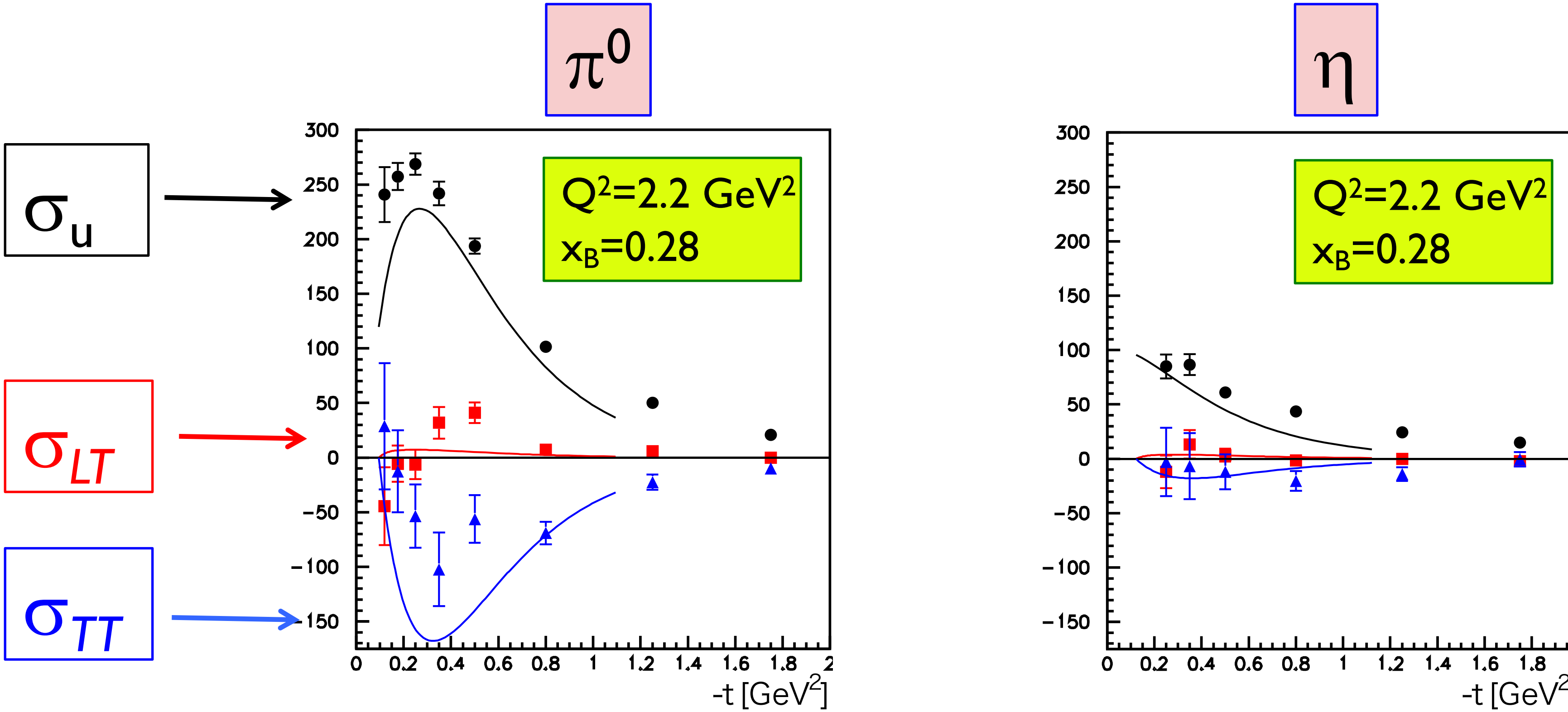




Curves: Goloskokov, Kroll
Transversity GPD model

Data: I.Bedlinskiy et al. (CLAS)
Phys. Rev. C **95**, 035202 (2017)

Comparison π^0/η



CLAS-Phys.Rev.C95(2017)

- $\sigma_U = \sigma_T + \varepsilon\sigma_L$ drops by a factor of 2.5 for η
- σ_{TT} drops by a factor of 10
- The GK GPD model (curves) follows the experimental data
- The statement about the ability of transversity GPD model to describe the pseudoscalar electroproduction becomes more solid with the inclusion of η data

Structure functions and GPDs

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

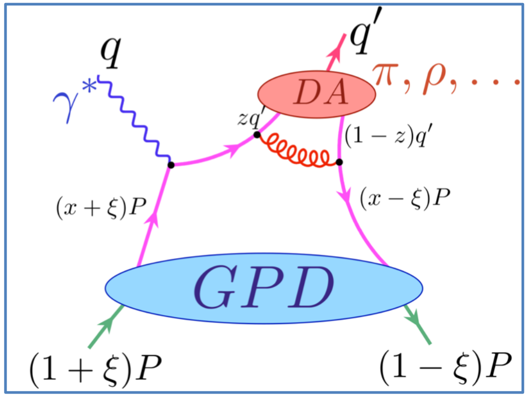
$$\frac{d\sigma_{TT}}{dt} = \frac{4\pi\alpha}{k'}\frac{\mu_P^2}{Q^8}\frac{t'}{16m^2}|\langle \bar{E}_T\rangle|^2$$

Goloskokov, Kroll
Transversity GPD model

$$|\langle \bar{E}_T\rangle^{\pi,\eta}|^2 = \frac{k'}{4\pi\alpha}\frac{Q^8}{\mu_P^2}\frac{16m^2}{t'}\frac{d\sigma_{TT}^{\pi,\eta}}{dt}$$

$$|\langle H_T\rangle^{\pi,\eta}|^2 = \frac{2k'}{4\pi\alpha}\frac{Q^8}{\mu_P^2}\frac{1}{1-\xi^2}\left[\frac{d\sigma_T^{\pi,\eta}}{dt} + \frac{d\sigma_{TT}^{\pi,\eta}}{dt}\right]$$

- *In the approximation* of the transversity GPDs dominance, that is supported by Jlab data, $\sigma_L \ll \sigma_T$, we have direct access to the generalized form factors for π and η production.



$$\langle H_T\rangle = \Sigma_\lambda \int_{-1}^{1} dx M(x,\xi,Q^2,\lambda) H_T(x,\xi,t)$$

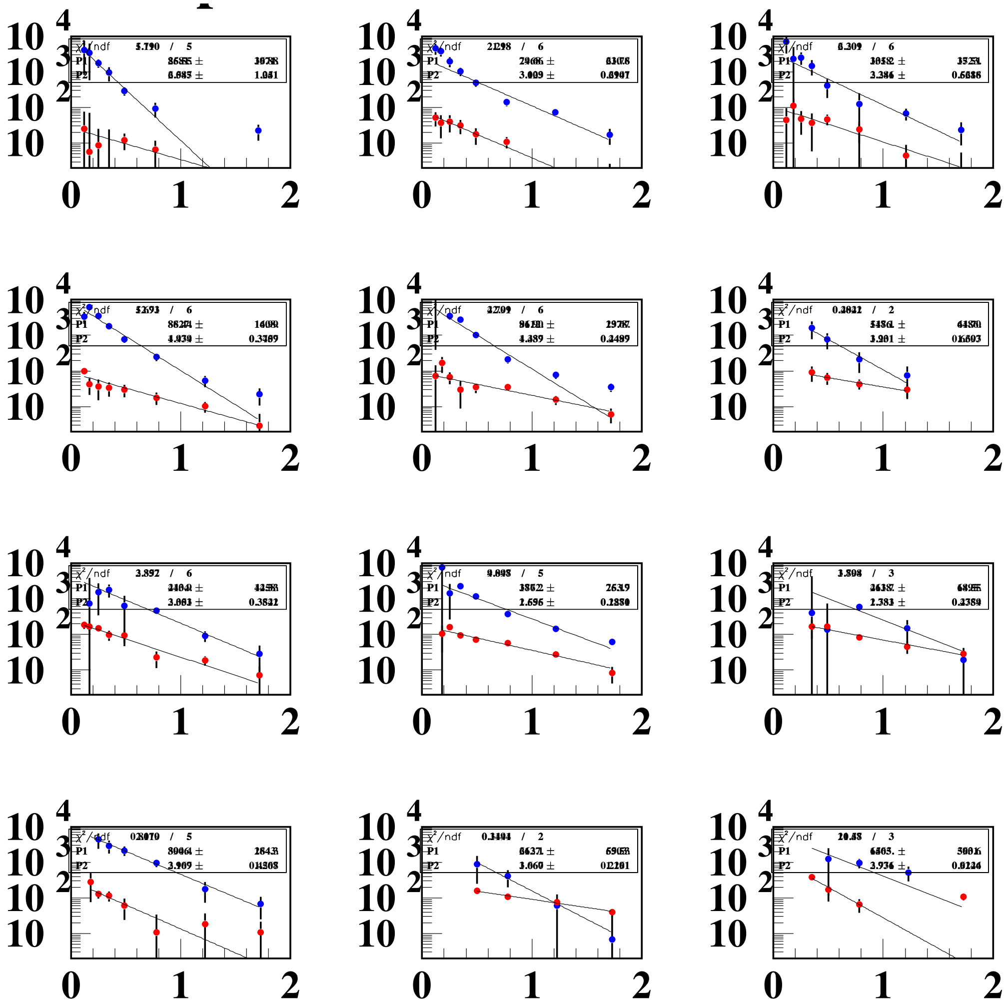
$$\langle \bar{E}_T\rangle = \Sigma_\lambda \int_{-1}^{1} dx M(x,\xi,Q^2,\lambda) \bar{E}_T(x,\xi,t)$$

The brackets <F> denote the convolution of the elementary process with the GPD F (generalized form factors)

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

$|\langle H_T \rangle|^2$ and $|\langle \bar{E}_T \rangle|^2$ t-distributions

π^0



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

Fit by exponential function looks reasonable

<H$_T$> and <E$_T$> parametrization

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

$$\sigma_T = \frac{4\pi\alpha_e}{2\kappa}\frac{\mu_\pi^2}{Q^4}[(1-\xi^2)|\langle H_T\rangle|^2 - \frac{t'}{8m^2}|\langle \bar{E}_T\rangle|^2]$$

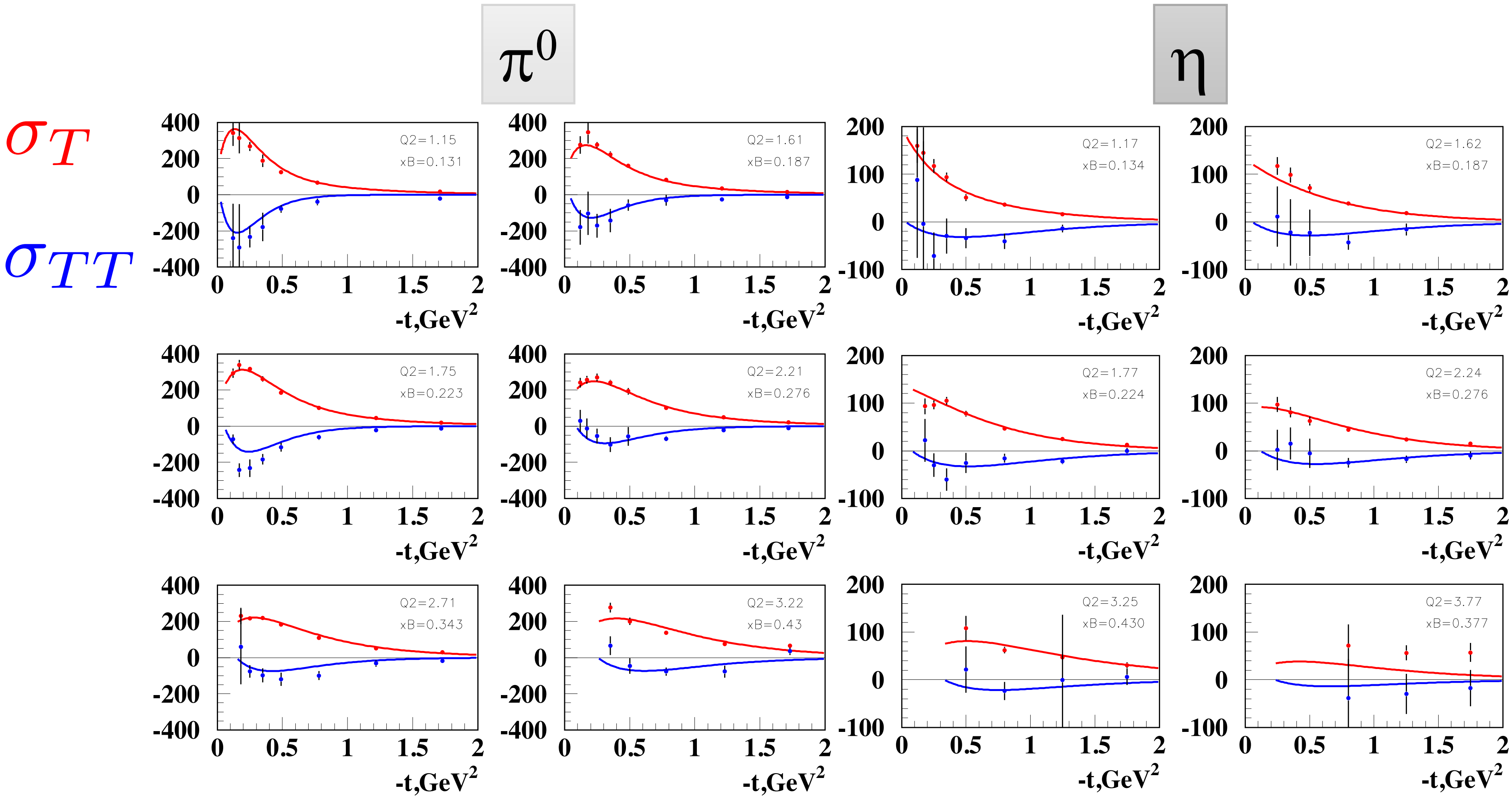
$$\sigma_{TT} = \frac{4\pi\alpha_e}{2\kappa}\frac{\mu_\pi^2}{Q^4}\frac{t'}{8m^2}|\langle \bar{E}_T\rangle|^2$$

$$\bar{E}_T(t, x_B, Q^2) = N_E \cdot e^{(\alpha_E + \beta_E \log(x_B))t} \cdot Q^{\gamma_E}$$

$$H_T(t, x_B, Q^2) = N_H \cdot e^{(\alpha_H + \beta_H \log(x_B))t} \cdot Q^{\gamma_H}$$

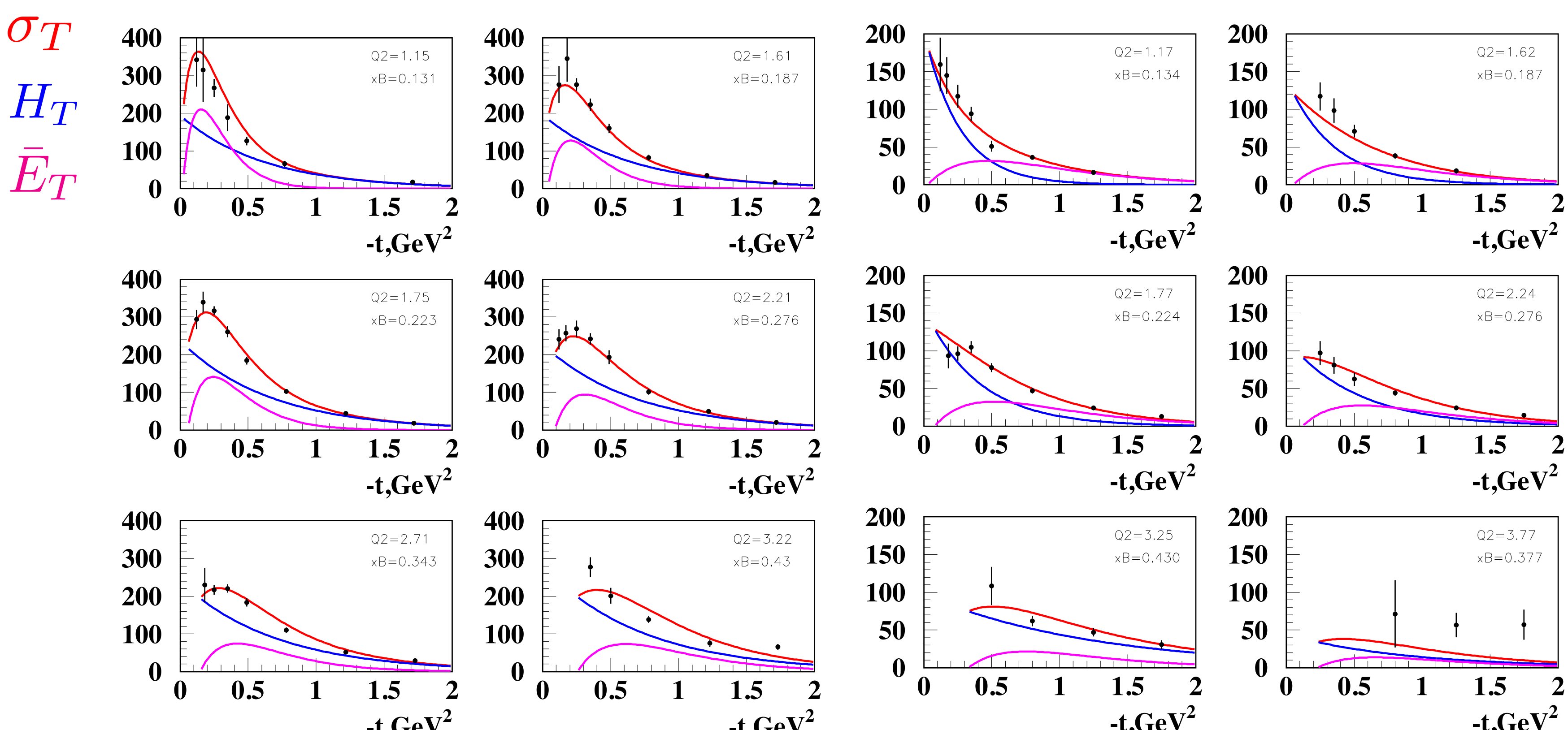
- t-slope parameter is a function of x_B
- Q^2 dependence reflects the dependence of the formfactors on Q^2
- The parameters were used in the fit of experimental observables – cross sections

Quality of the fit



Contributions of H_T and $\bar{E}_T$ to σ_T

π^0 η



$$\sigma_T = \frac{4\pi\alpha_e}{2\kappa}\frac{\mu_\pi^2}{Q^4}\left[(1-\xi^2)|\langle H_T\rangle|^2 - \frac{t'}{8m^2}|\langle \bar{E}_T\rangle|^2\right]$$

COMPASS arXiv:1903.12030, 28 Mar,2019

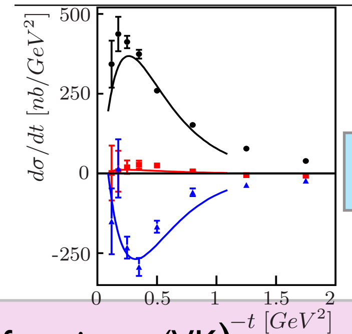
- 160 GeV/c polarized μ^+ and μ^- beams of the CERN SPS
- Data taken in 2012, within 4 weeks
- **<Q2>=2.0 GeV^2**
- **<xB>=0.093**
- <-t>=0.256 GeV^2

- 0.08 GeV^2 < |t| < 0.64 GeV^2
- 1 GeV^2 < Q2 < 5 GeV^2
- 8.5 GeV < ν < 28 GeV

COMPASS-Jlab comparison

- **<Q2>=2.0 GeV²**
- **<xB>=0.093**
- <-t>=0.256 GeV²
- **<ν>=12.8 GeV**

COMPASS data (5 points)

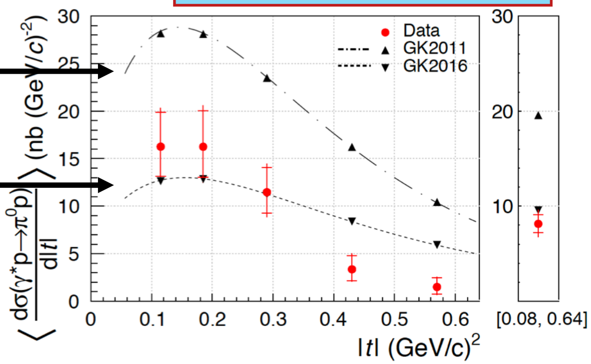


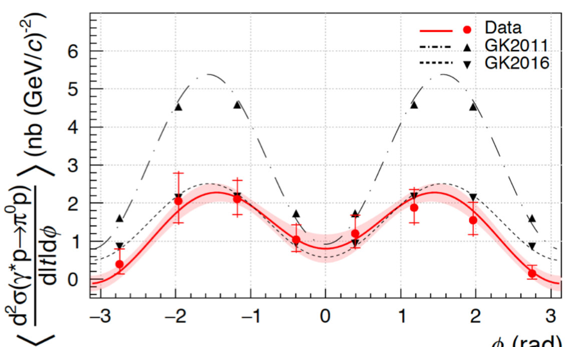
CLAS 2000 points

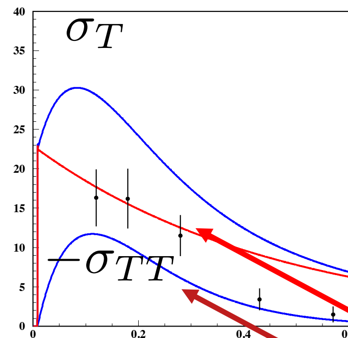
CLAS structure functions (VK)

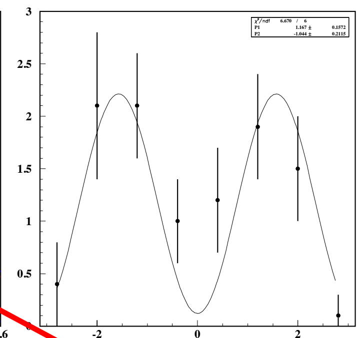
GK2011

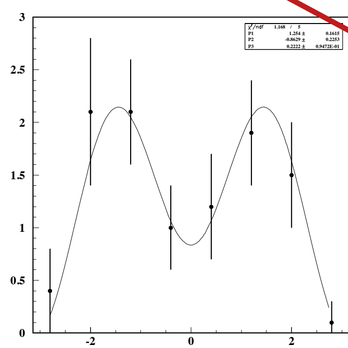
GK2016









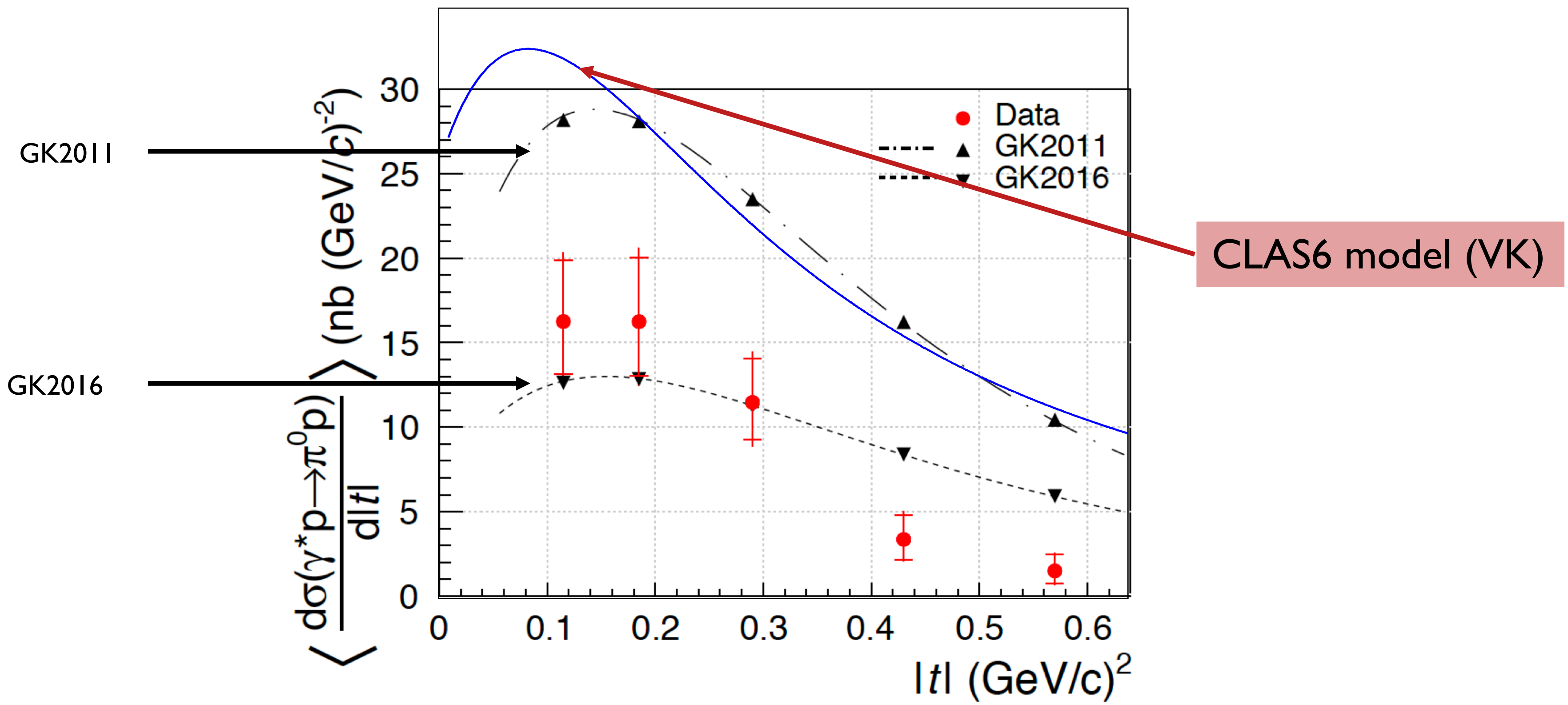


$\langle H_T \rangle$

$\langle \bar{E}_T \rangle$

- Factor of two difference between GK2011 and GK2016
- Factor of two difference between COMPAS and CLAS

GK2011 and CLAS6 model



Integrated cross section

- Compass has huge Q2(1-5 GeV[2)] bin and x_B bin
- It is not clear how this group calculated the kinematics in which they reported the differential cross section

$$\sigma = \int_{x_{min}}^{x_{max}} \frac{d\sigma}{dx} dx$$

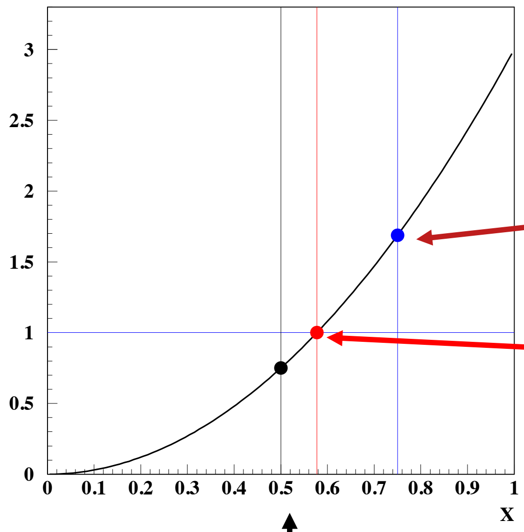
$$\frac{d\sigma}{dx}(\bar{x}) = \sigma/(x_{max} - x_{min})$$

$$\bar{x} = ???$$

There are different method how to estimate the point where you will report the cross section

- $\bar{x}_c = (x_{min} + x_{max})/2$
- $\bar{x}_a = \int_{x_{min}}^{x_{max}} x \cdot \frac{d\sigma}{dx} dx/\sigma$
- $\frac{d\sigma}{dx}(\bar{x}_1) = \sigma/(x_{max} - x_{min})$

Example



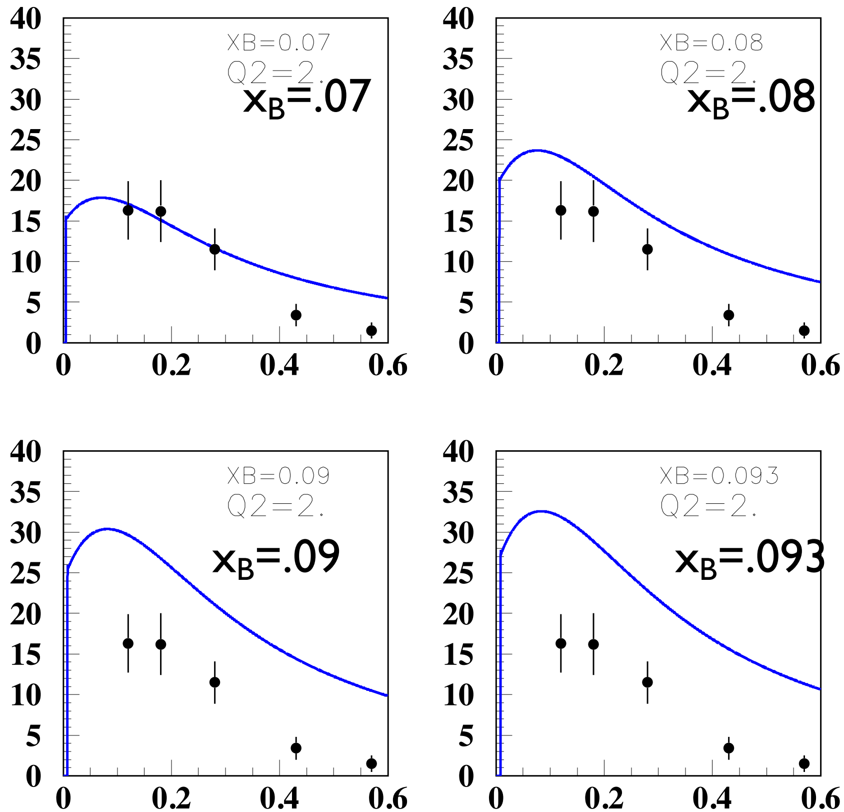
$\bar{x}_a = \int_{x_{min}}^{x_{max}} x \cdot \frac{d\sigma}{dx} dx / \sigma$

$\frac{d\sigma}{dx}(\bar{x}_1) = \sigma/(x_{max} - x_{min})$

$\bar{x}_c = (x_{min} + x_{max})/2$

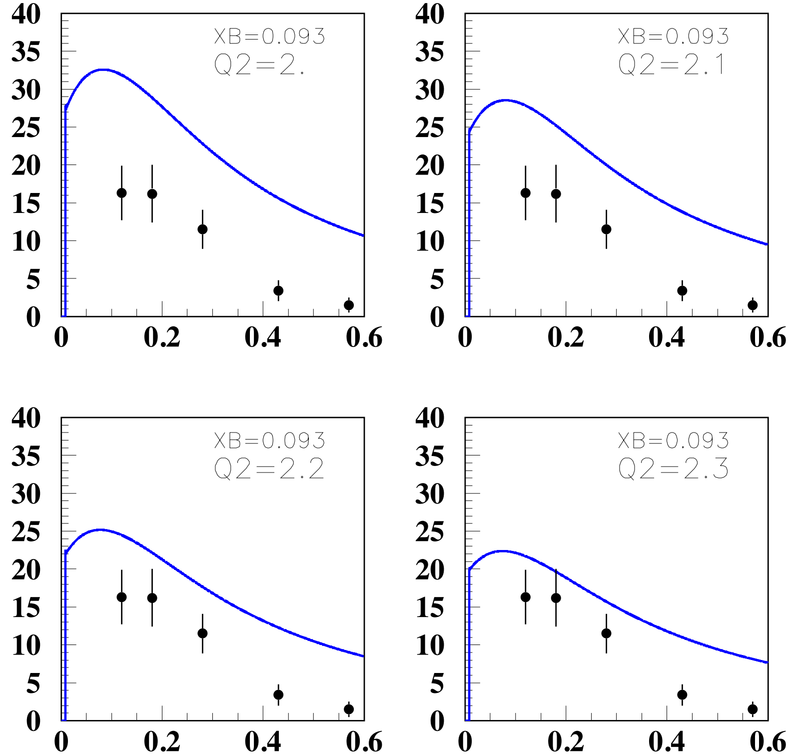
In this simple example the systematic error connected with the estimation of the kinematic point is as much as 25% and cross section 60%

x_B=(0.07 0.08 0.09 0.093) Q^2=2 GeV^2



Reported x_B =0.93 and Q2=2

Q2=(2.0 2.1 2.2 2.3) xB=0.093



Conclusion

- Compass released π^0 structure functions after 7 years of data analysis (data taken 2012)
- Compass published 5 experimental point for the structure function $d(\sigma_T+\varepsilon\sigma_\Lambda)/dt$ as a function of t in the kinematics closed to published CLAS data (2000 kinematic points).
- The comparison with the GPD model presented factor of two discrepancy with the extrapolated from the CLAS structure functions.
- However, the integrated bin sizes in Q^2 and x_B are so large that the kinematics in which COMPASS reported structure functions has to have significant systematic error. It is early to talk about this discrepancy

$\bar{E}_T(x,t,\xi)$ fit results

Data

- CLAS π^0/η
- Hall-A π^0
- $\bar{E}_T(x,t,\xi)$ parameters only

- Fit *ONLY* σ_{TT} data

$$\sigma_{TT} = \frac{4\pi\alpha_e}{2\kappa}\frac{\mu_\pi^2}{Q^4}\frac{t'}{8m^2}|\langle\bar{E}_T\rangle|^2$$

GPDs parameters

$$\bar{E}_T^u(x,t,\xi) = N^u \cdot e^{b^u t} \sum_{j=0}^{2} c_j^u \cdot \mathcal{D}(\frac{j}{2},x,\xi)$$

$$\bar{E}_T^d(x,t,\xi) = N^d \cdot e^{b^d t} \sum_{j=0}^{4} c_j^d \cdot \mathcal{D}(\frac{j}{2},x,\xi)$$

$$\mathcal{D}(i,x,\xi) = \frac{3}{2\xi^3(1+i-k)(2+i-k)(3+i-k)}\{(\xi^2-x)\left(\left(\frac{x+\xi}{1+\xi}\right)^{2+i-k} - \left(\frac{x-\xi}{1+-xi}\right)^{2+i-k}\right)$$
$$+\xi(1-x)(2+i-k)\left(\left(\frac{x+\xi}{1+\xi}\right)^{2+i-k} + \left(\frac{x-\xi}{1+-xi}\right)^{2+i-k}\right)\}$$

$$\mathcal{D}(i,x,\xi=0) = x^{i-k}(1-x)^3$$
$$k = \alpha_0 + \alpha' t$$

ξ=0 Limit

$$\bar{E}_T^u(x,t,\xi) = N^u \cdot e^{b^u t} \sum_{j=0}^{2} c_j^u \cdot \mathcal{D}(\frac{j}{2}, x, \xi)$$

$$\bar{E}_T^d(x,t,\xi) = N^d \cdot e^{b^d t} \sum_{j=0}^{4} c_j^d \cdot \mathcal{D}(\frac{j}{2}, x, \xi)$$

ξ–> 0

$$\bar{E}_T^u(x,t,\xi=0) = N^u \cdot x^{-\alpha_0^u}(1-x)^4 e^{(b^u - \alpha'^u \ln(x))t}$$

$$\bar{E}_T^d(x,t,\xi=0) = N^d \cdot x^{-\alpha_0^u}(1-x)^5 e^{(b^d - \alpha'^u \ln(x))t}$$

ξ=0 Limit

$$\bar{E}_T^u(x,t,\xi) = N^u \cdot e^{b^u t} \sum_{j=0}^{2} c_j^u \cdot \mathcal{D}(\frac{j}{2}, x, \xi)$$

$$\bar{E}_T^d(x,t,\xi) = N^d \cdot e^{b^d t} \sum_{j=0}^{4} c_j^d \cdot \mathcal{D}(\frac{j}{2}, x, \xi)$$

$$\bar{E}_T^u(x,t,\xi=0) = N^u \cdot x^{-\alpha_0^u}(1-x)^4 e^{(b^u - \alpha'^u \ln(x))t}$$

$$\bar{E}_T^d(x,t,\xi=0) = N^d \cdot x^{-\alpha_0^u}(1-x)^5 e^{(b^d - \alpha'^u \ln(x))t}$$

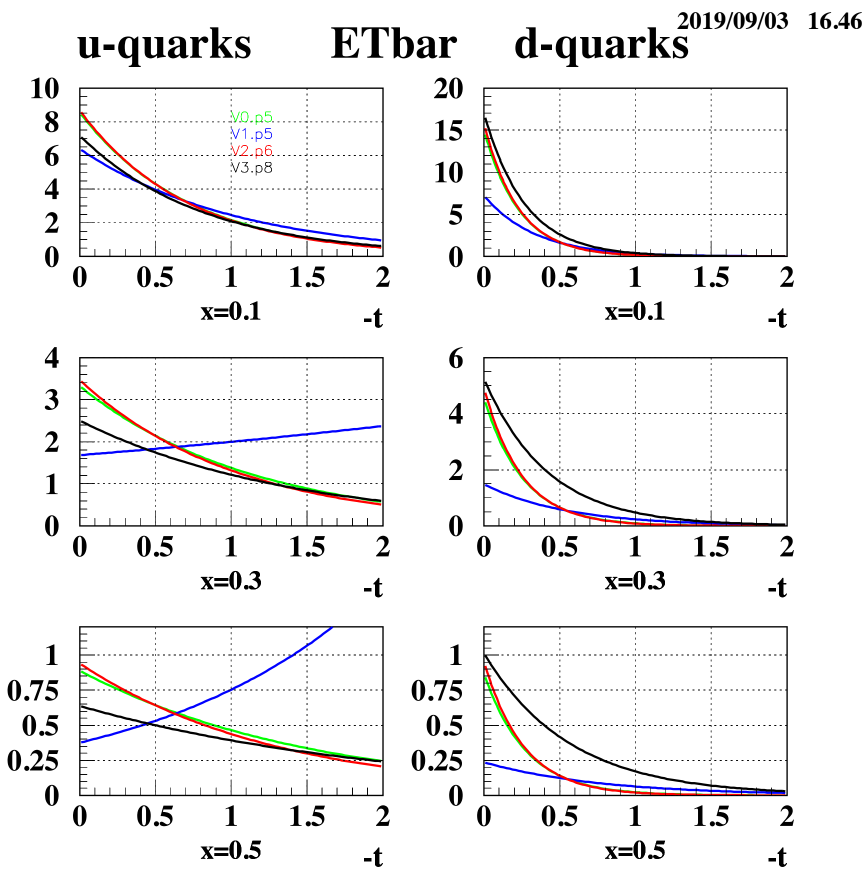
Fit Parameters

	V0.p5d	V1.p5d	V2.p6d	V3.p8d	+/-	GK Model
N^u	14.76	4.880	15.90	9.89	3.6	6.83
b^u	0.33	-1.40	0.49	0.16	0.48	0.5
α_0^u	-0.05	=0.3	-0.08	0.04	0.09	0.3
α'^u	=0.45	1.024	0.395	0.46	0.13	0.45
N^d	29.0	6.165	32.43	34.10	18.8	5.05
b^d	3.33	0.60	3.56	0.93	1.04	0.5
α_0^d	-0.05	=0.3	-0.08	-0.07	0.15	0.3
α'^d	=0.45	1.024	0.395	1.21	0.30	0.45

Suspicious fit

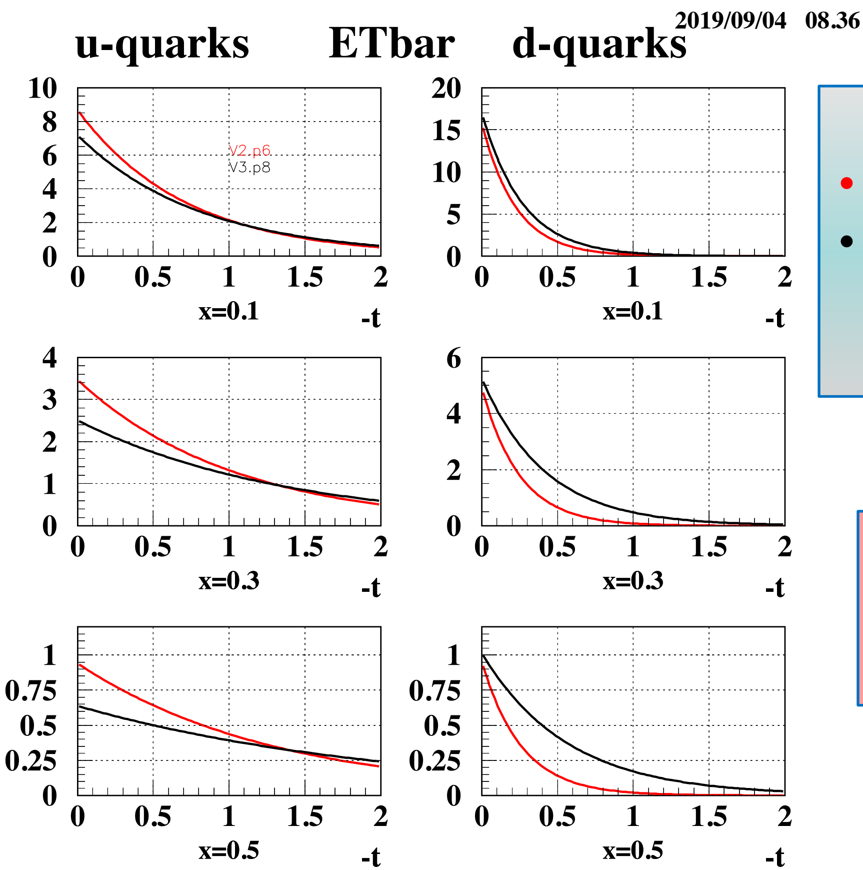
Best fit

$\bar{E}_T(x, t, \xi = 0)$ 4 versions



- v1.p5 has crazy t-behavior
- v0.p5 and v2.p6 almost identical
- We end up actually with **two versions** for v2.p6 and v3.p8

$\bar{E}_T(x, t, \xi = 0)$ t-distributions, x=0.1,0.3,0.5



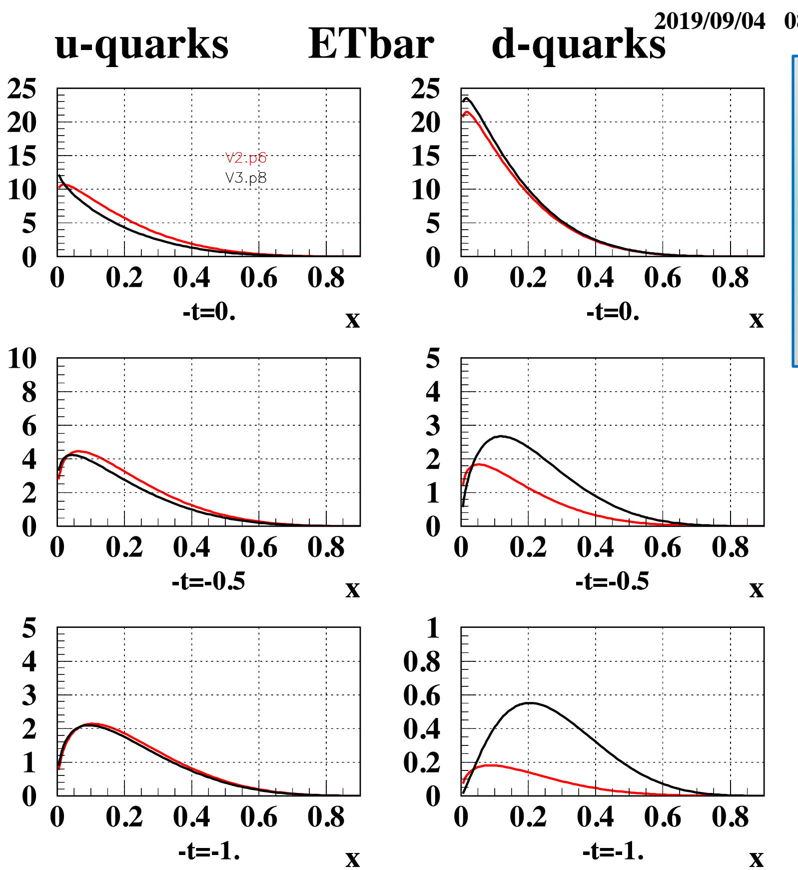
- α_0 and α' are the same for u and d quarks
- α_0 and α' for u and d quarks are free parameters

- We can conclude that that model with common α_0 and α' for u and d quarks doesn't work.

$$\bar{E}_T^u(x,t,\xi=0) = N^u \cdot x^{-\alpha_0^u}(1-x)^4 e^{(b^u - \alpha'^u \ln(x))t}$$

$$\bar{E}_T^d(x,t,\xi=0) = N^d \cdot x^{-\alpha_0^u}(1-x)^5 e^{(b^d - \alpha'^u \ln(x))t}$$

$\bar{E}_T(x, t, \xi = 0)$ x-distributions, -t=0,0.5,1 GeV²



- α_0 and α' are the same for u and d quarks
- α_0 and α' for u and d quarks are free parameters

Next steps

- Two sets of data were used for a moment: CLAS (π^0 and η) and Hall-A (π^0 only) out of proton
- Hall-A published π^0 structure functions for neutron
- COMPASS released π^0 muon electroproduction out of proton
- The problem with Hall-A neutron and COMPASS data is connected with the fact that there is only one kinematic point (Q^2,x_B) published
- Nevertheless, we will include these data for the combined global fit at the next step
- Neutron data will help for the flavor separation and COMPASS to fix energy dependence of GPDs

What $\bar{E}_T(x, t, \xi)$ will tell us about the nucleon structure?

The Fourier Transform of Generalized Parton Distribution

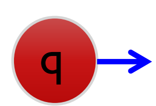
- The Fourier transforms of GPDs at $\xi = 0$ describe the distribution of partons in the transverse plane (M. Burkardt, 2002)
- It was shown that they satisfy positivity constraints which justify their physical interpretation as a probability density
- **H** is related to the impact parameter distribution of unpolarized quarks in an unpolarized nucleon
- $\tilde{\mathbf{H}}$ is related to the distribution of longitudinally polarized quarks in a longitudinally polarized nucleon
- **E** is related to the distortion of the unpolarized quark distribution in the transverse plane when the nucleon has transverse polarization.
- $\bar{\mathbf{E}}_{\mathbf{T}}$ is related to the distortion of the polarized quark distribution in the transverse plane for an unpolarized nucleon

$$\mathcal{K}(x,\vec{b}) = \int \frac{d^2\vec{\Delta}}{(2\pi)^2} \exp^{-i\vec{b}\cdot\vec{\Delta}} K(x,t=-\Delta^2)$$

The Density of Transversely Polarized Quarks in an Unpolarized Proton

$\bar{E}_T$ is related to the distortion of the polarized quark distribution in the transverse plane for an unpolarized nucleon

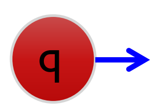
$$\delta(x,\vec{b}) = \frac{1}{2}[H(x,\vec{b}) - \frac{b_y}{m}\frac{\partial}{\partial b^2}\bar{E}_T(x,\vec{b})]$$



The Density of Transversely Polarized Quarks in an Unpolarized Proton

$\bar{E}$ is related to the distortion of the polarized quark distribution in the transverse plane for an unpolarized nucleon

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

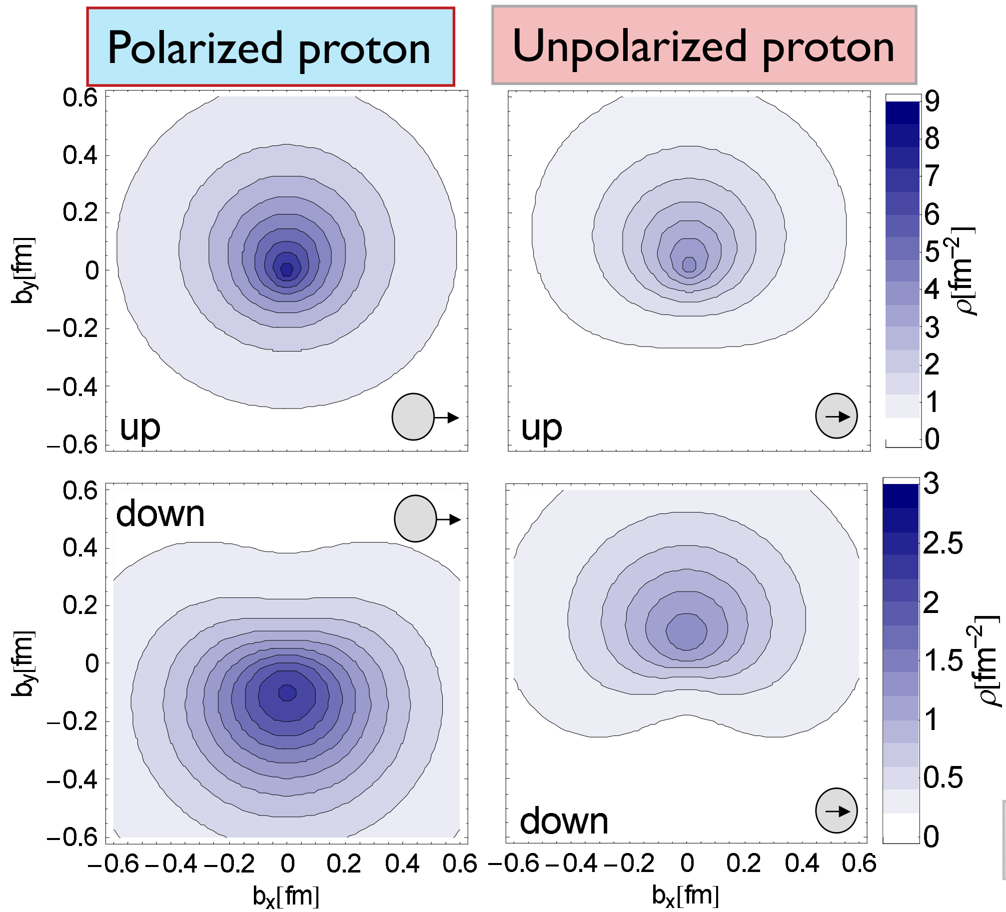


Integrated Over *x* Transverse Densities for u and d Quarks in the Proton

u quarks

Strong distortions for unpolarized quarks in transversely polarized proton

d quarks



Controlled by E

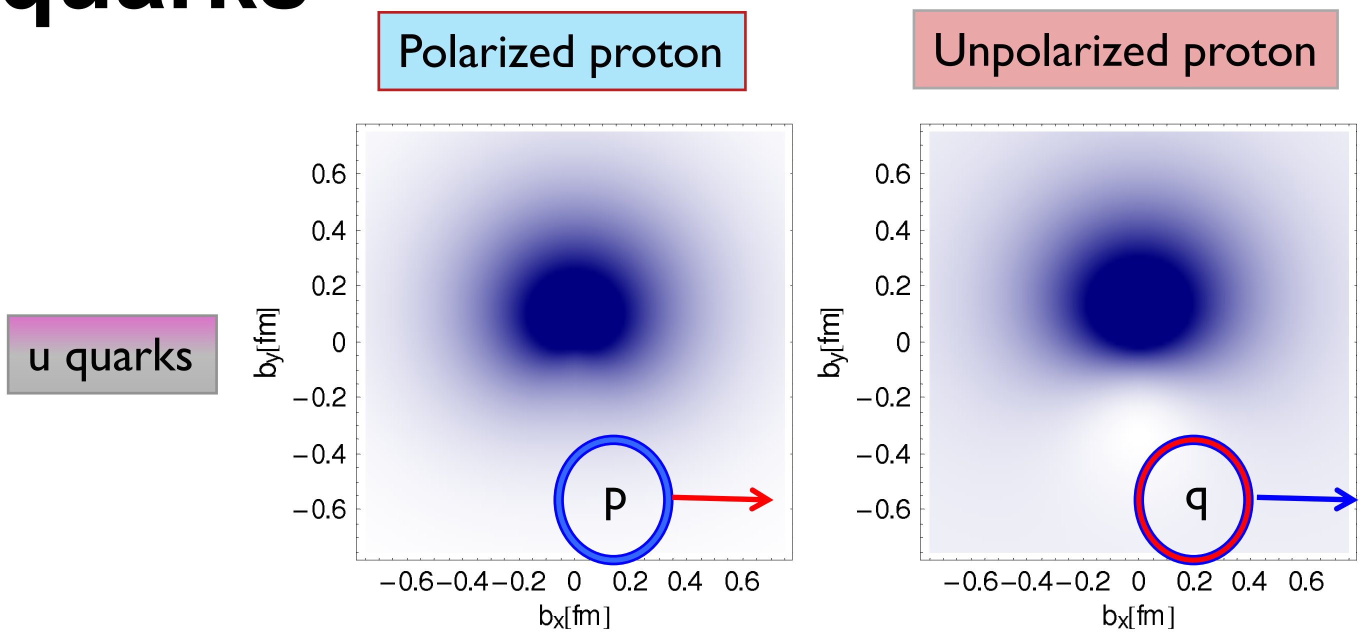
Controlled by $\bar{E}_T = 2\tilde{H}_T + E_T$

Strong distortions for transversely polarized quarks in an unpolarized proton

Lattice calculations

Gockeler et al, Phys. Rev. Lett. 98, 222001 (2007), lattice

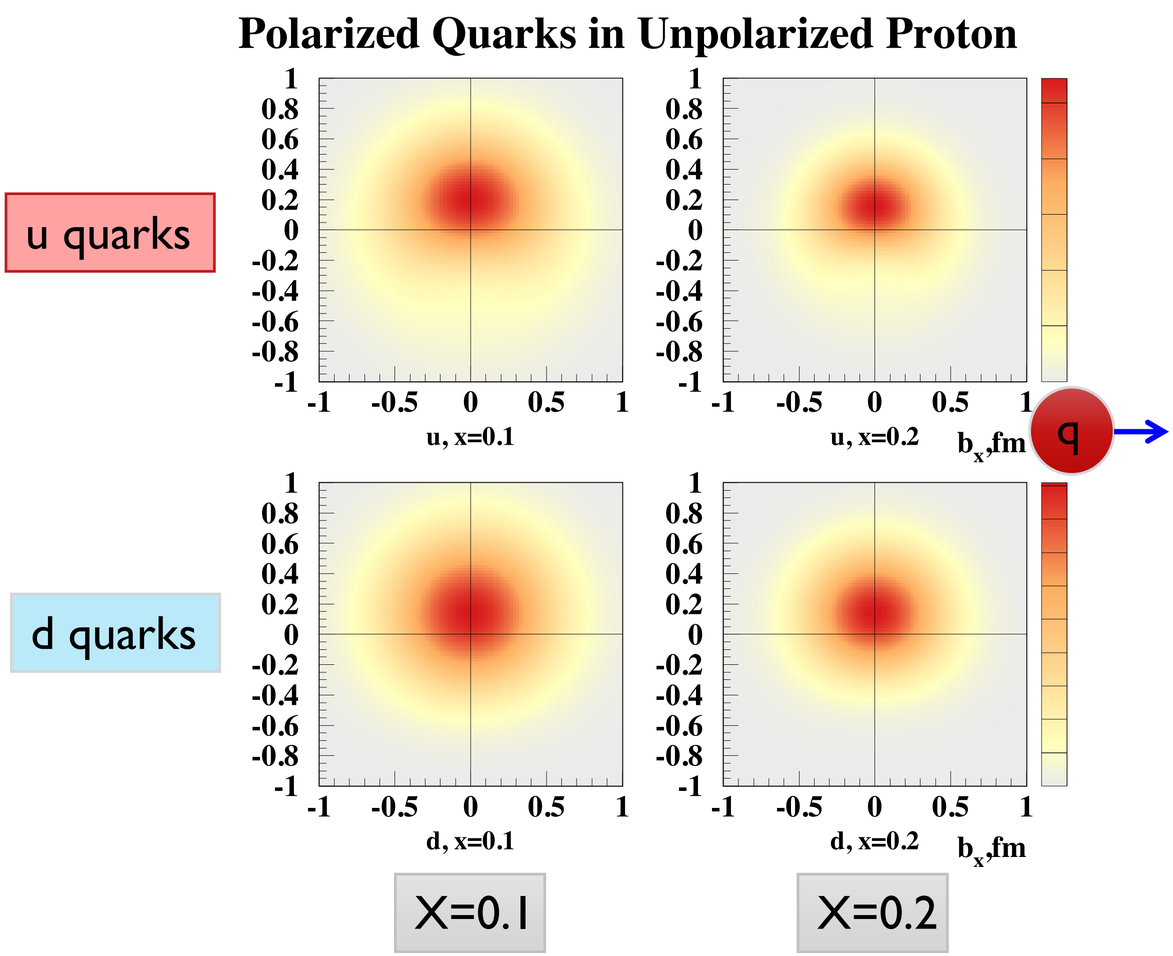
GPD model: integrated over *x* Impact Parameter Density for u-quarks



- **Left:** unpolarized u-q□uarks in a proton with transverse spin vector.
- **Right**: the distribution of u-quarks with transverse spin vector in an unpolarized proton.

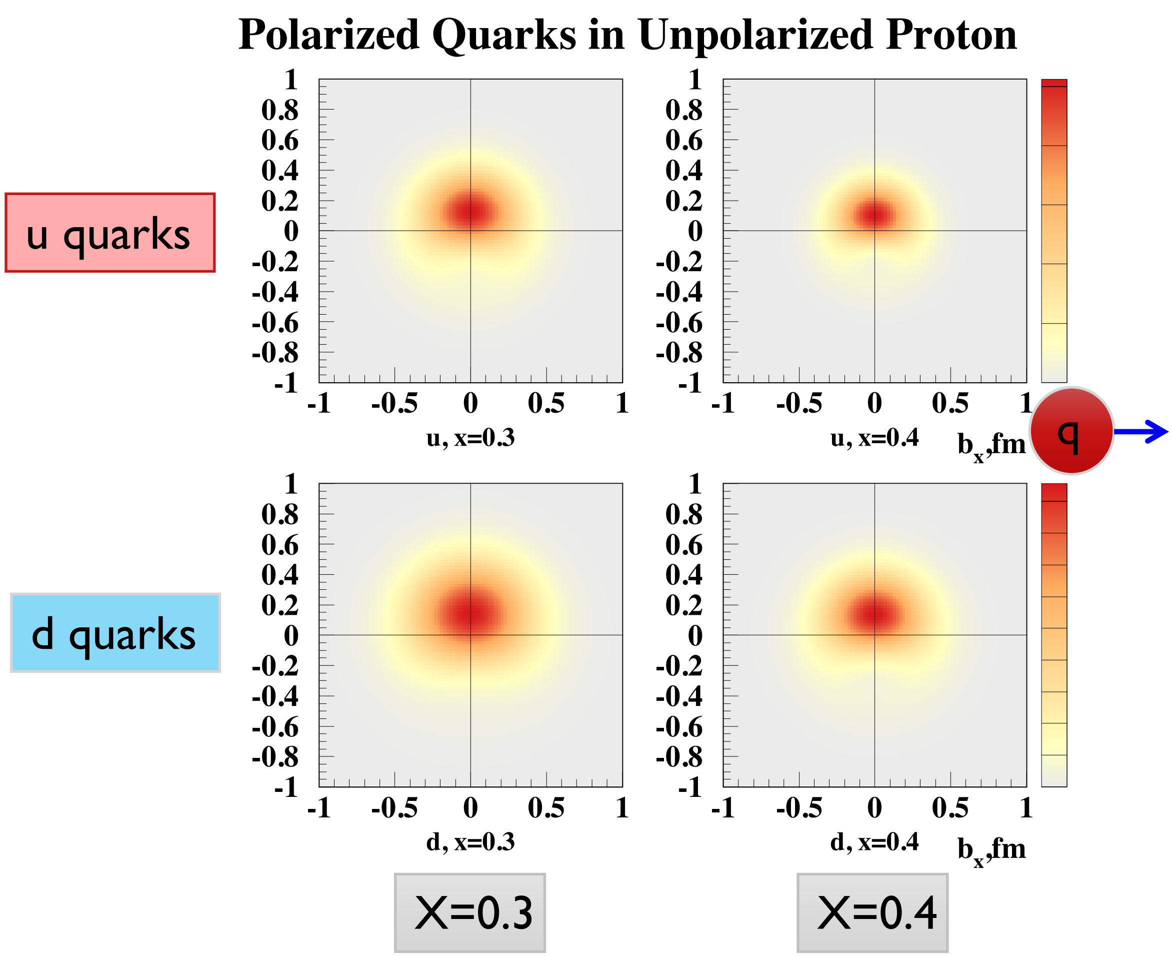
M. Diehl and Ph Hagler (2005) GPD model with "some reasonable " parameters.

Transverse Densities for u and d Quarks in the Proton

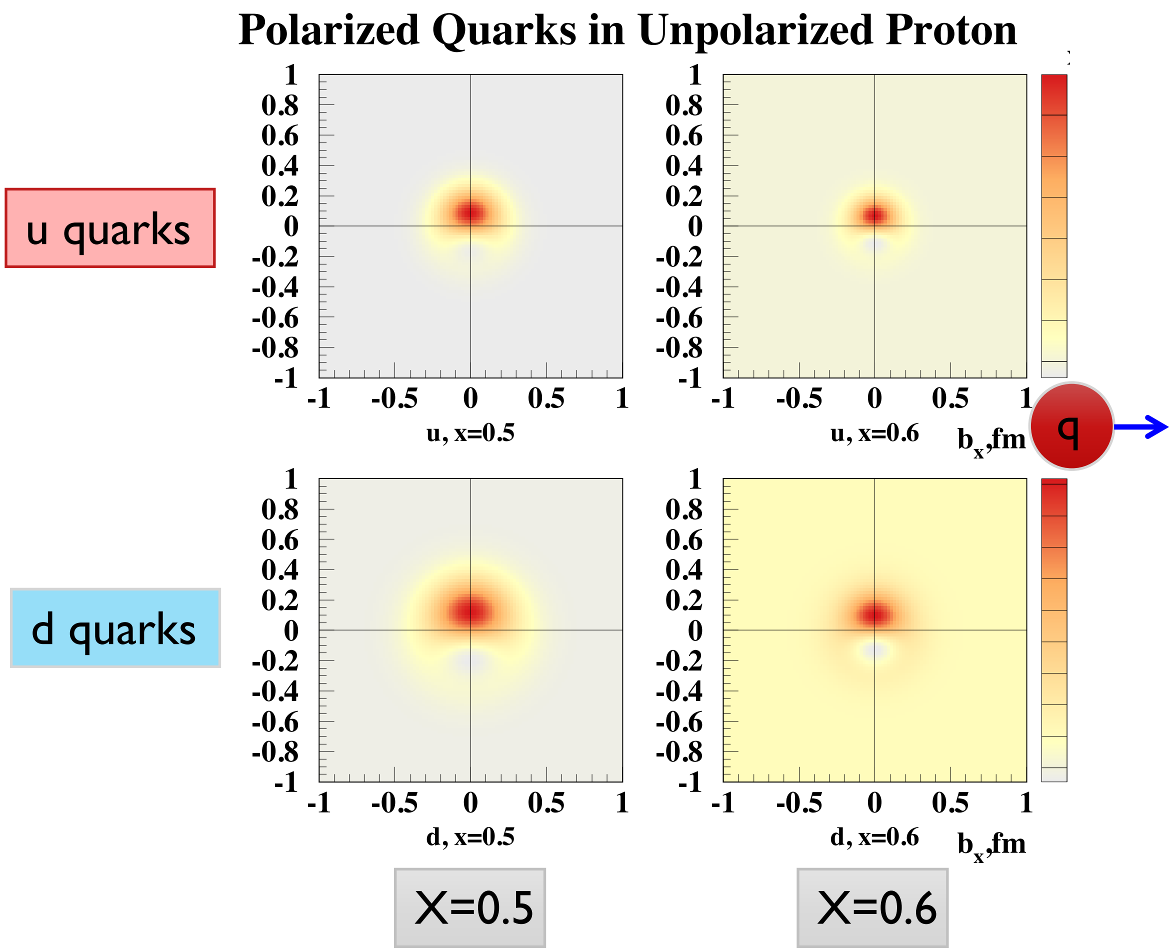


Note distortions for transversely polarized u and d quarks.

Transverse Densities for u and d Quarks in the Proton



Transverse Densities for u and d Quarks in the Proton



Summary

- The brand new CLAS12 detector successfully took data with proton and deuteron targets data with 10.6, 7.5 and 6.5 GeV electron beam
- Run Groups A, B and K are working on the calibration of the detectors and one step away from the start of the massive data processing
- The study of deeply virtual exclusive pseudoscalar meson production uniquely connected with the transversity GPDs, and has already begun to access their underlying polarization distributions of quarks in the nucleon.
- The combined π^0 and η, proton and neutron data analysis provide the way for the flavor decomposition of transversity GPD
- The full data set from CLAS, Hall-A and COMPASS detectors are used to get the transversity GPD parameters