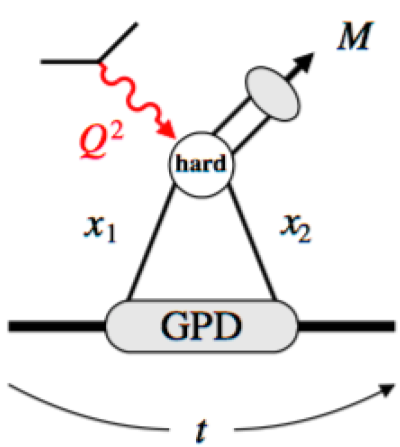
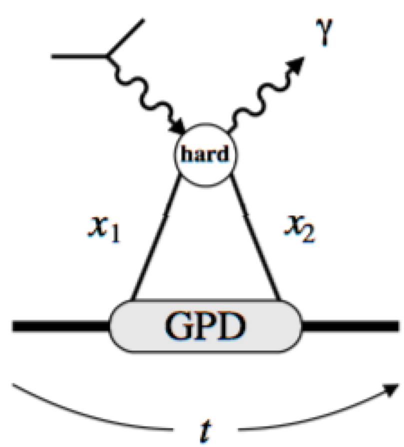
# $\pi$ and $\eta$ production at JLab with 6 and 12 GeV

J. Roche (Ohio U.)

JLab 12 meson production experiments:

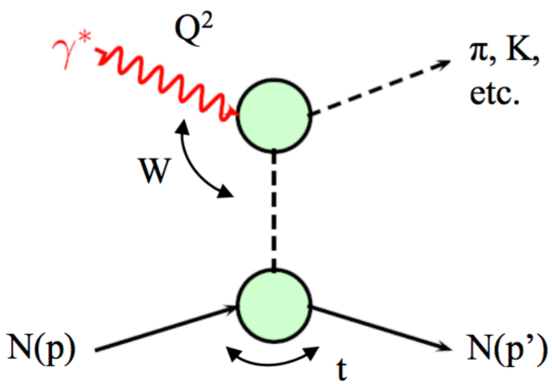
- $\phi$: nucleon gluonic radius : CLAS 12
- $\pi^0$ and $\eta$: helicity flip GPDs: CLAS12, Hall A
- $\pi^+$ and $K^+$: factorization tests: Hall C
- J/$\psi$ near threshold: high-t gluonic FF: Gluex, CLAS12, SOLID




Award #1614479

# QCD factorization in Deep Meson Electroproduction?



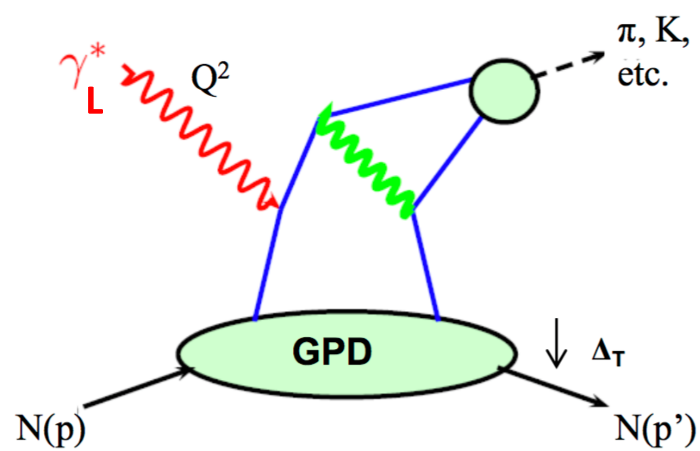

**t-channel process**

In the limit of small $-t$ meson production can be described by the t-channel meson production.

→ Spatial distribution described by form factor.

At sufficient high $Q^2$, meson production should be understandable in terms of the "handbag" diagram.

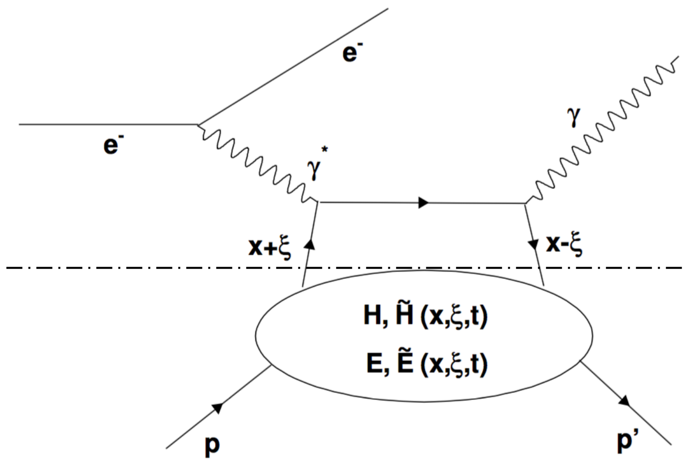
- the non-perturbative physics represented by GPDs
- the factorization is only exact for longitudinal photons (Collins, Frankfurt, Strikman, 1997)

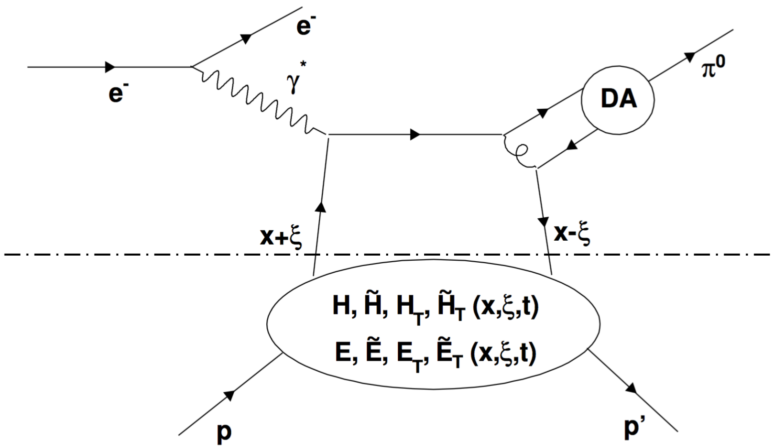



**Handbag diagram**

When the handbag diagram applies $\sigma_L/\sigma_T \rightarrow 1/Q^2$

# DVCS/DVMP : same GPDs??



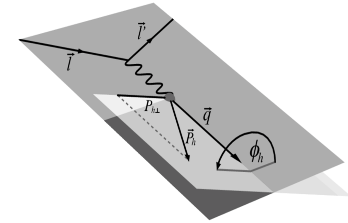

**Chiral even GPDs:**
(helicity of the parton is conserved)

| | Nucleon Helicity | |
|---|---|---|
| | conserving | non-conserving |
| unpolarized GPD | H | E |
| polarized GPD | $\tilde{H}$ | $\tilde{E}$ |

Chiral even GPDs
+
**Chiral-odd GPDs:**
(helicity of the parton can flip)

| | Meson | Flavor |
|---|---|---|
| $\mathcal{H}_T, \mathcal{E}_T$ | $\pi^+$ | $\Delta u - \Delta d$ |
| | $\pi^0$ | $2\Delta u + \Delta d$ |
| | $\eta$ | $2\Delta u - \Delta d + 2\Delta s$ |

# Structure function and GPDs



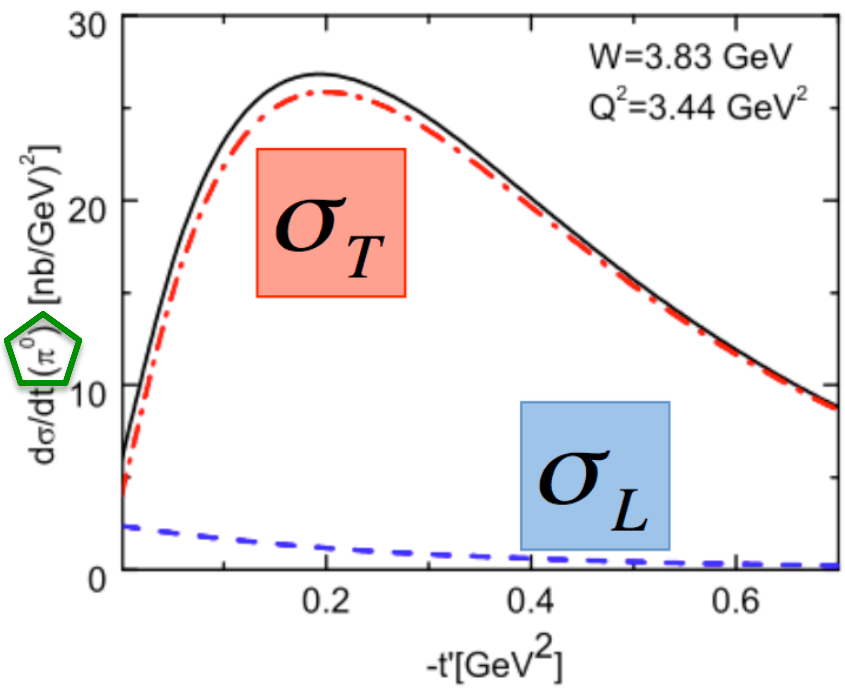
$$\frac{d^4\sigma}{dt\,d\phi\,dQ^2\,dx_B} = \frac{1}{2\pi}\Gamma_{\gamma^*}(Q^2, x_B, E_e)\left[\frac{d\sigma_T}{dt} + \epsilon\frac{d\sigma_L}{dt} + \sqrt{2\epsilon(1+\epsilon)}\frac{d\sigma_{TL}}{dt}cos(\phi) + \epsilon\frac{d\sigma_{TT}}{dt}cos(2\phi)\right]$$

Assuming factorization for transversely polarized photons:

$$\sigma_T = \frac{4\pi\alpha}{2\kappa}\frac{\mu_\pi^2}{Q^4}\left((1-\xi^2) < H_T >^2 - \frac{t'}{8m^2} < \bar{E}_T >^2\right)$$

$$\sigma_{TT} = \frac{4\pi\alpha}{2\kappa}\frac{\mu_\pi^2}{Q^4}\frac{t'}{8m^2} < \bar{E}_T >^2$$

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

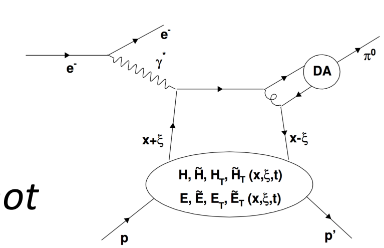



**Transversity GPD models**

S. Goloskokov and P. Kroll (Eur.Phys.J A47, 112(2011))
S. Liuti and G. Golstein (Phys.Rev.D79, 054014 (2009))

Twist 3 DA couple with transversity GPDs.
Twist 3 DA are associated to a kinematical factor:

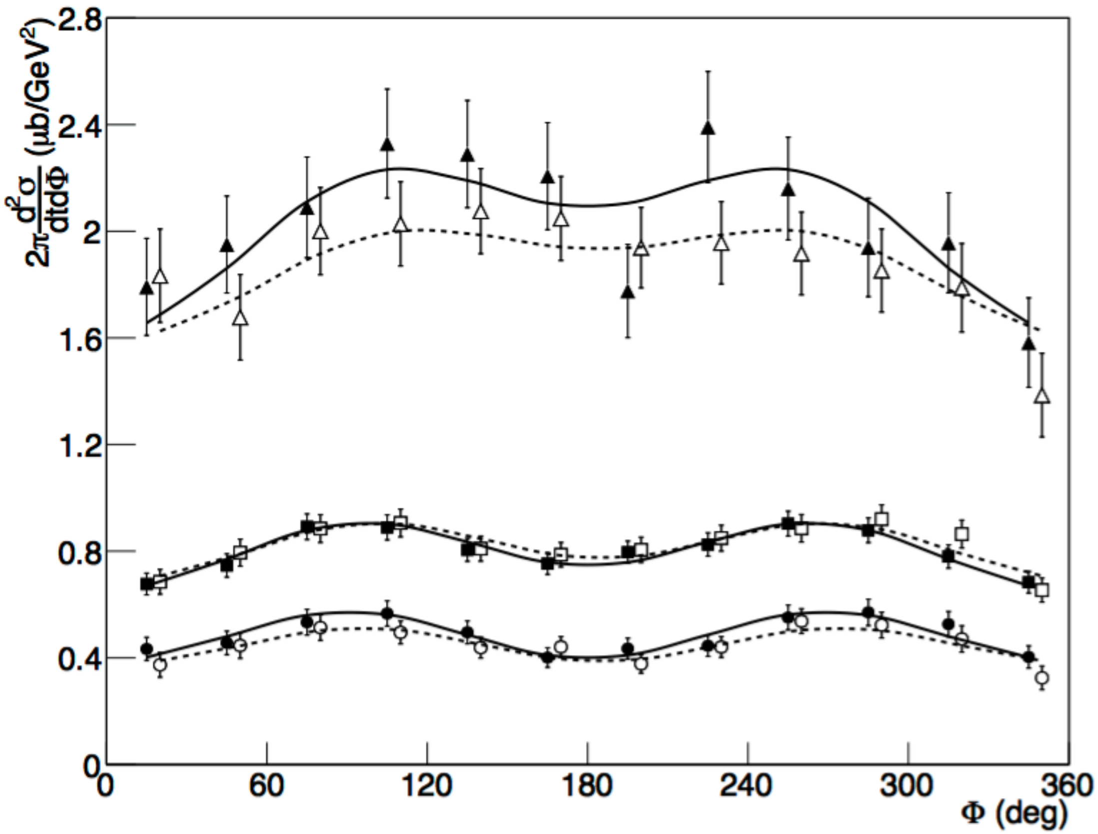
$$\mu_\pi = \frac{m_\pi^2}{m_u + m_d} \simeq 2.5 \text{ GeV}$$




*The dominant contribution is not the leading twist contribution.*

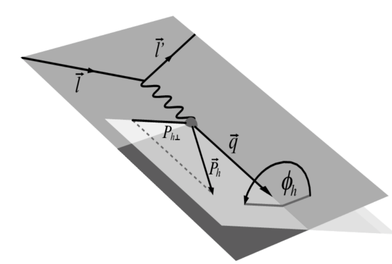
$$\frac{d^4\sigma}{dt\,d\phi\,dQ^2\,dx_B} = \frac{1}{2\pi}\Gamma_{\gamma^*}(Q^2, x_B, E_e)\Big[\frac{d\sigma_T}{dt} + \epsilon\frac{d\sigma_L}{dt} + \sqrt{2\epsilon(1+\epsilon)}\frac{d\sigma_{TL}}{dt}\cos(\phi) + \epsilon\frac{d\sigma_{TT}}{dt}\cos(2\phi)\Big]$$

| Setting | $E$ (GeV) | $Q^2$ (GeV$^2$) | $x_B$ | $\epsilon$ | | |
|---|---|---|---|---|---|---|
| 2010-Kin1 | (3.355 ; 5.55) | 1.5 | 0.36 | (0.52 ; 0.84) | △ | ▲ |
| 2010-Kin2 | (4.455 ; 5.55) | 1.75 | 0.36 | (0.65 ; 0.79) | □ | ■ |
| 2010-Kin3 | (4.455 ; 5.55) | 2 | 0.36 | (0.53 ; 0.72) | ○ | ● |

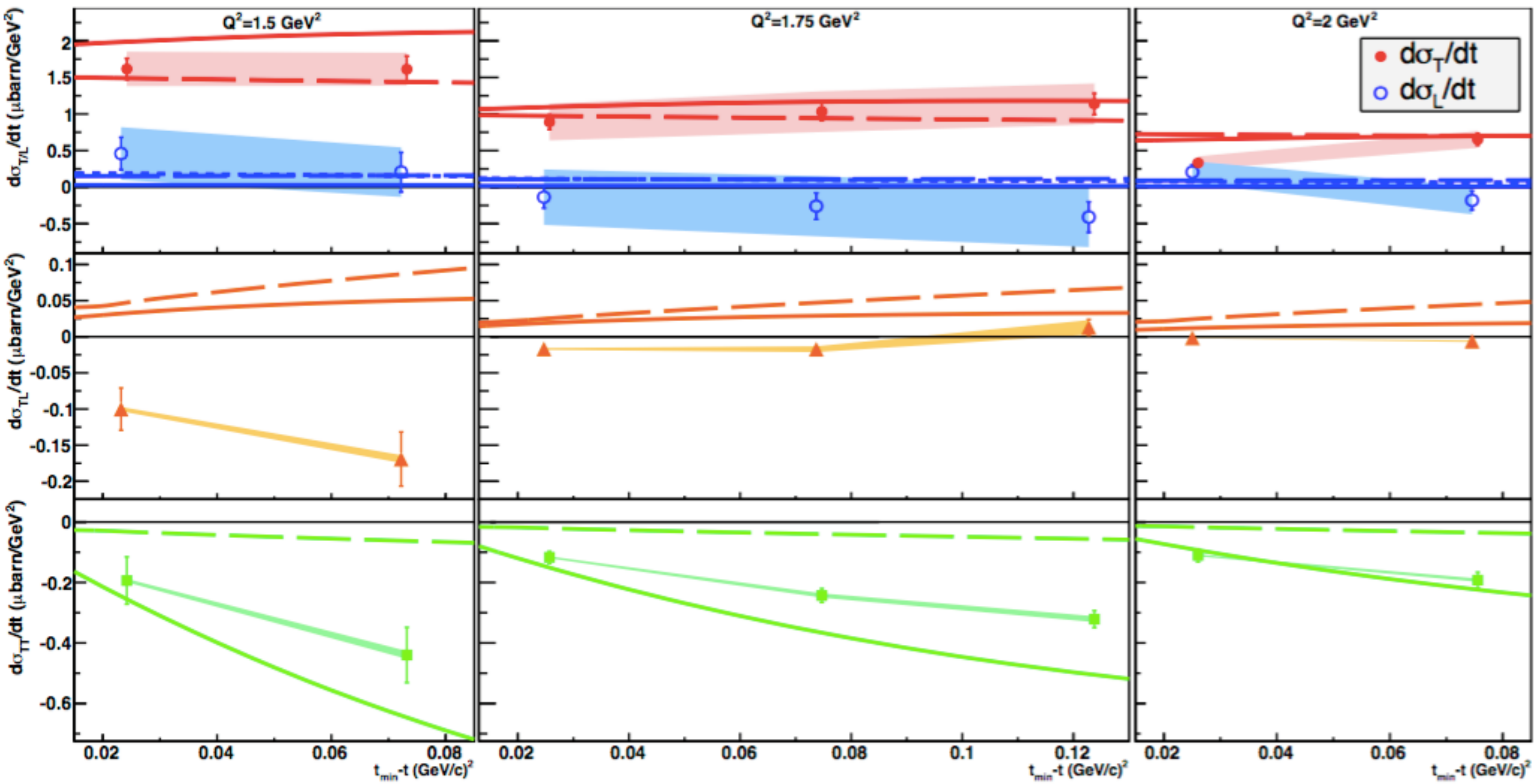



**DVCS2 @ Hall A**
**$\pi^0$ production**
M. Defurne et al.
PRL 117, 26 (2015)

$x_B$=0.36
$t-t_{min}$=0.025 GeV$^2$



# DVCS2@Hall A results: fully separated contributions




G-H-L ('11)

G-K

Dramatic effect of 3% normalization uncertainty on the results

Small $d\sigma_L$, large $d\sigma_T$: models ok on these

Wrong sign on $d\sigma_{TL}$

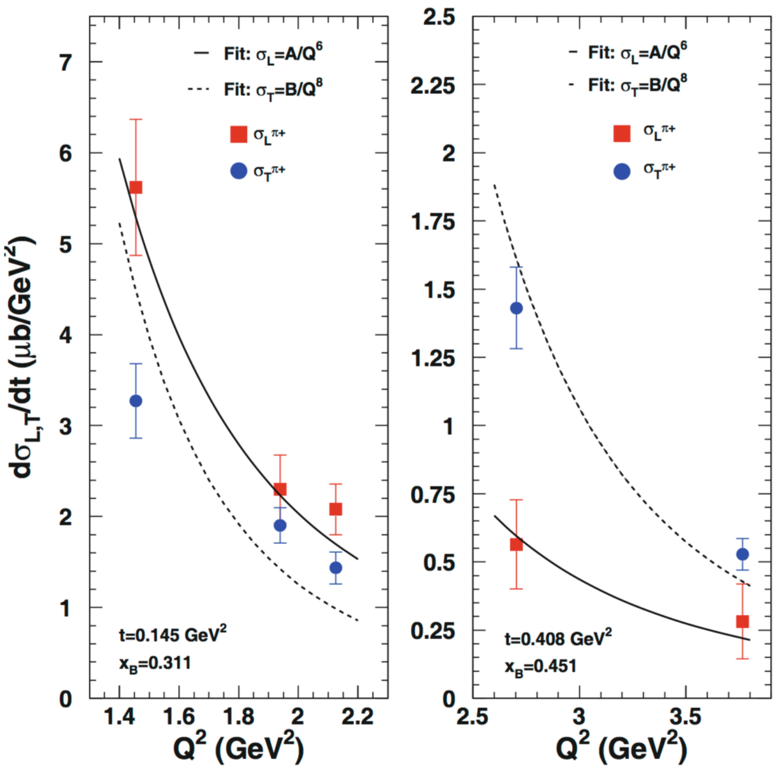
$d\sigma_{TL}$ sizeable => $d\sigma_L$ is small but not null

The measured Q dependence is 9+/-2 for $\sigma_T$, 4+/-2 for $\sigma_{TT}$ and 26+/- 5 for $\sigma_{TL}$.

# More on L/T separations in meson electroproduction

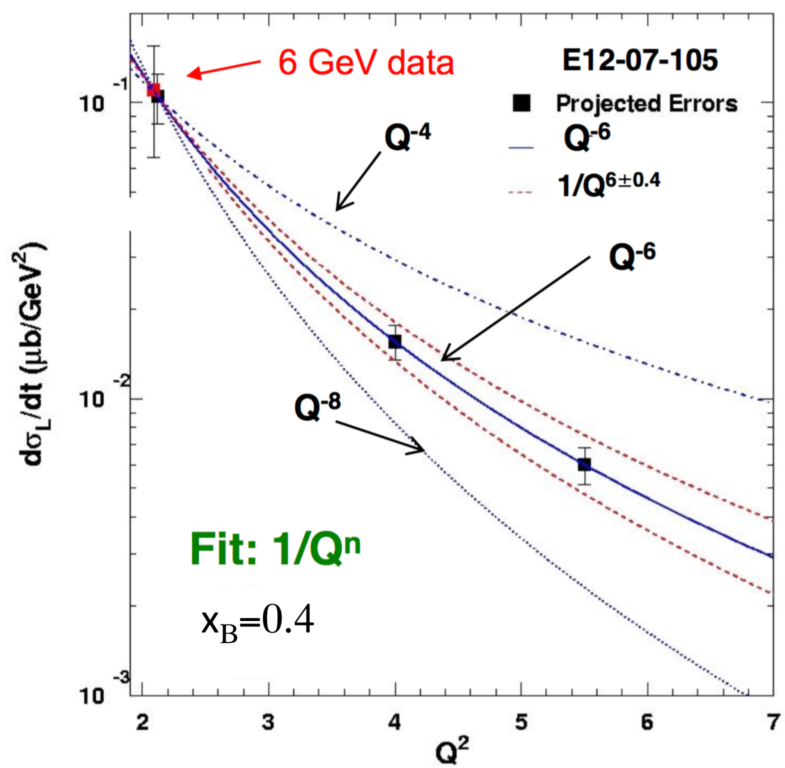
$\pi^+$ 6 GeV Hall C data

Favart, Guidal, Horn, Kroll, EPJA (2016)




$\pi^+$ 12 GeV Hall C proposal

*E12-07-105 spokespersons: T. Horn, G. Huber*




Not following the leading twist prediction:

$\sigma_L$~$1/Q^6$ *(ok)* , $\sigma_T$~$1/Q^8$ *(not quite right)*

$\sigma_L>\sigma_T$ *(not on the right panel)*

Contribution from the pole production?

also data at $x_B$=0.32 and 0.54

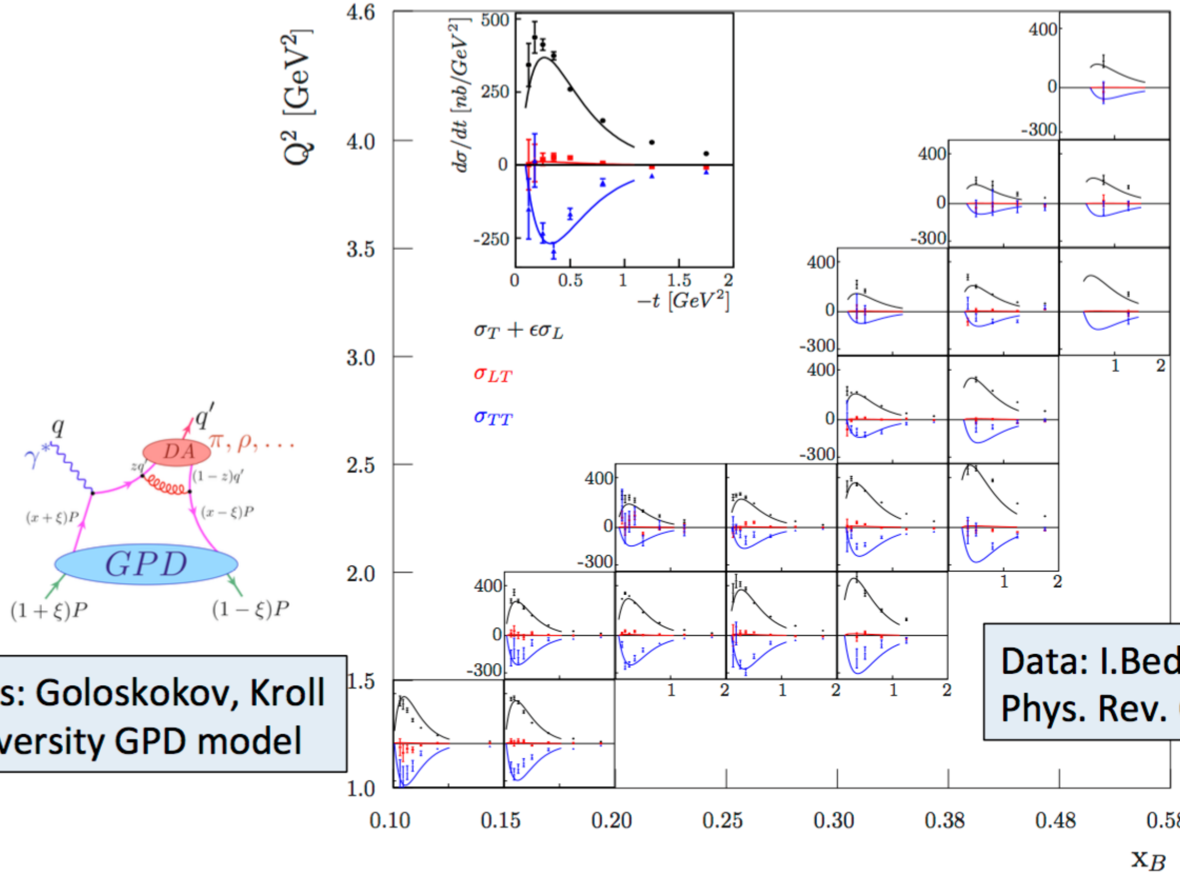
$\pi^0$ data:
E12-13-010 (Horn, Hyde, Munoz, Paremuzyan, JR)

Kaon data:
E12-09-011 (Horn, Huber, Markowitz)

# $\pi^0$ Structure Functions

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

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




Curves: Goloskokov, Kroll
Transversity GPD model

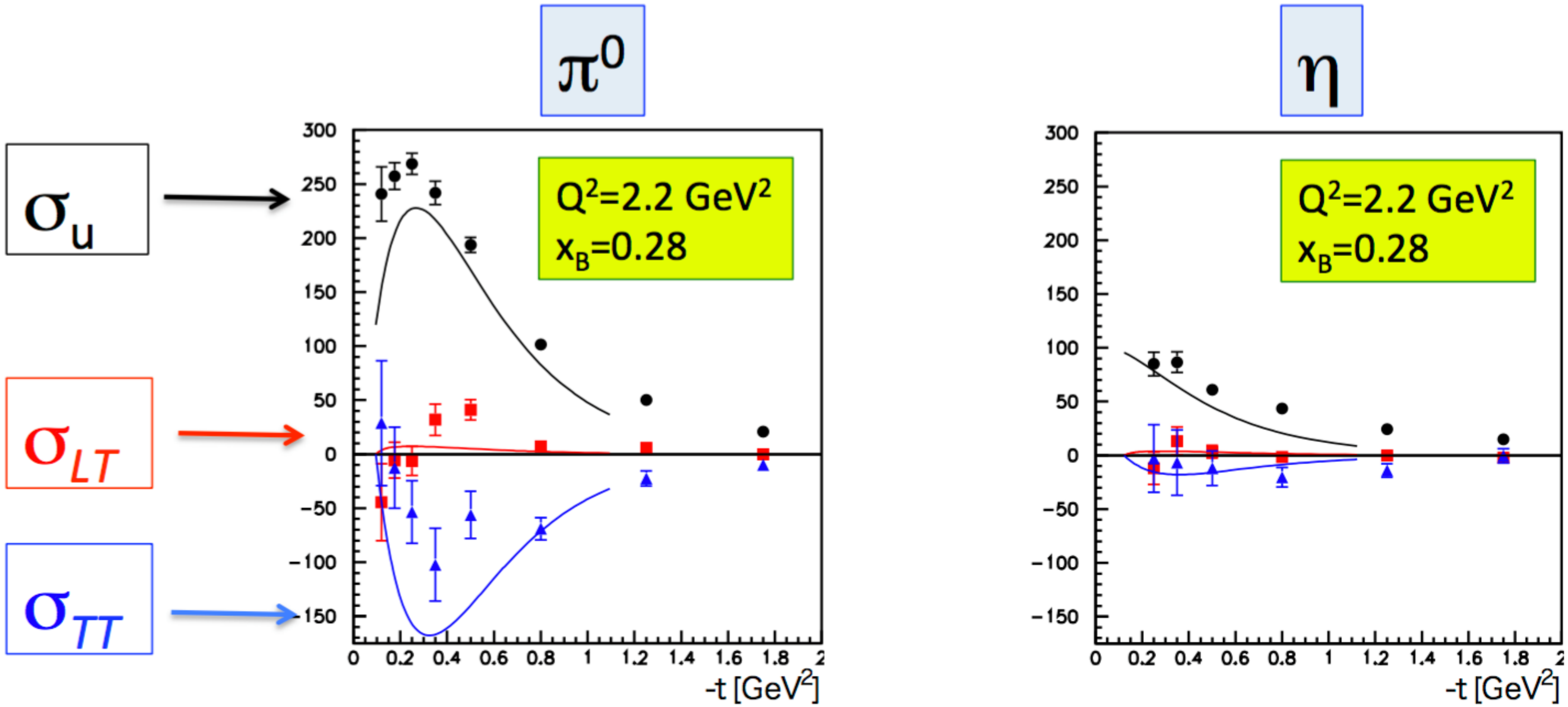
Data: I.Bedlinskiy et al. (CLAS)
Phys. Rev. C 95, 039901 (2014)



Slide from V. Kubarosky, 3D nucleon structure, March 2017

Experiment E12-06-118 : $\pi^0$ and $\eta$ production at 11 GeV
Data taking started, Kyungseon Joo can provide more info.

# Comparison $\pi^0/\eta$



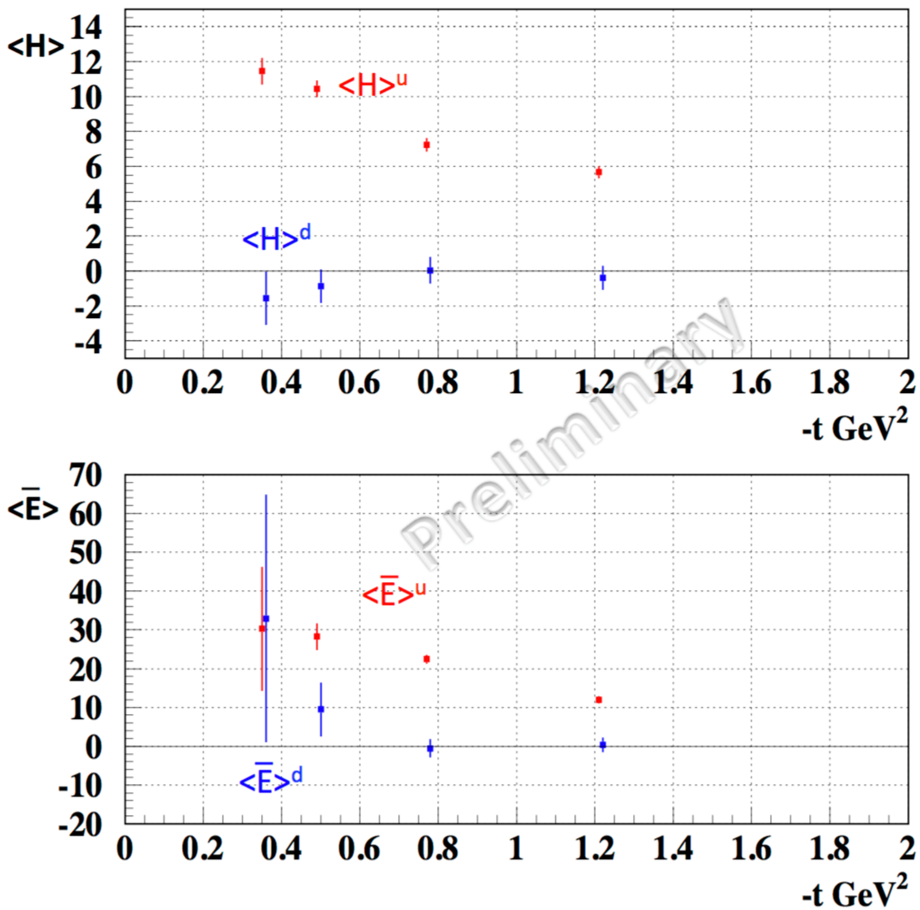

- $\sigma_U=\sigma_T+\varepsilon\sigma_L$ drops by a factor of 2.5 for $\eta$
- $\sigma_{TT}$ drops by a factor of 10
- The GK GPD model (curves) follows the experimental data
- The statement about the transversity GPD dominance in the pseudoscalar electroproduction becomes more solid with the inclusion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



Slide from V. Kubarosky, 3D nucleon structure, March 2017

# From structure functions to flavor decomposed GPDs

Consider $\pi^0$ and $\eta$ data simultaneously
- assume transversity GPDs dominance,
- assume no phase between the u and d quarks amplitudes.




$$\frac{d\sigma_T}{dt} = \Lambda \left[ (1-\xi^2)\left|\langle H_T\rangle\right|^2 - \frac{t'}{8M^2}\left|\langle \bar{E}_T\rangle\right|^2 \right]$$

$$\frac{d\sigma_{TT}}{dt} = \Lambda \, \frac{t'}{8M^2}\left|\langle \bar{E}_T\rangle\right|^2 .$$

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

V. Kubarosky, arXiv:1601.04367

$Q^2$=1.8 GeV$^2$, $x_B$=0.22

# DVCS2 results neutron data

M. Mazouz PRL 118 (2017) 22, 222002

At $Q^2$=1.75 $GeV^2$ and $x_B$=0.36 , half of the data taken on a LD2 target.

From LH2,
add Fermi smearing

Below the two pions threshold:

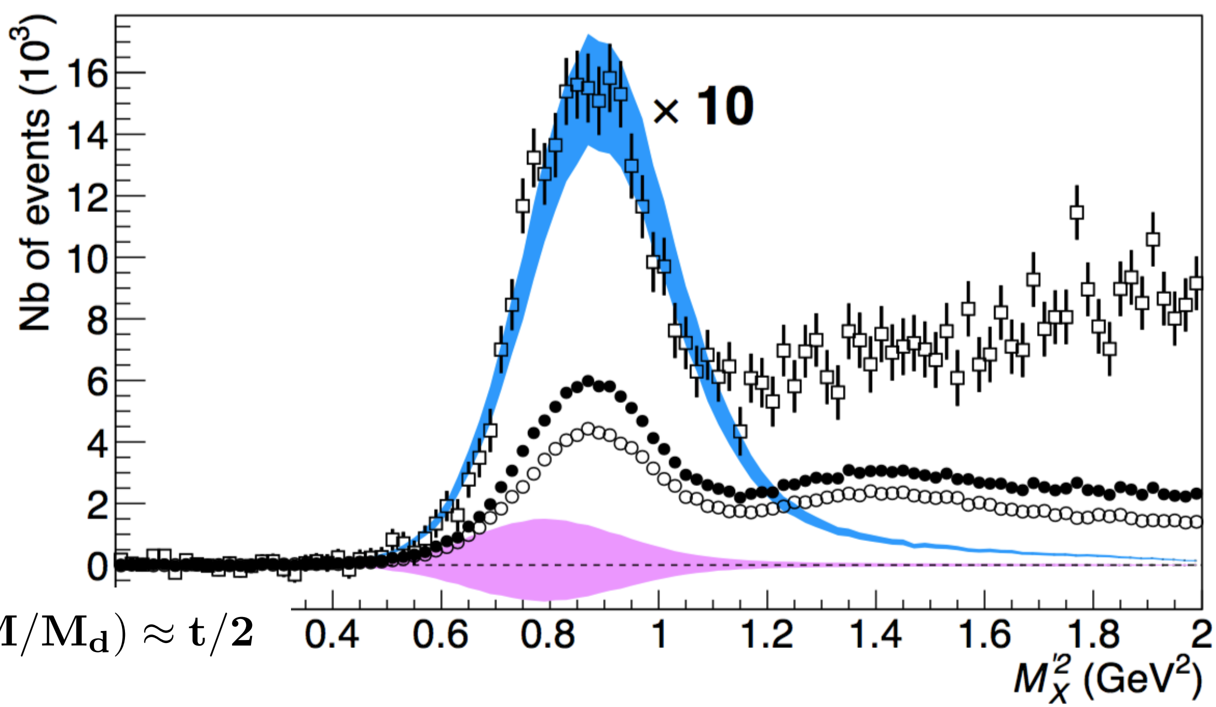
$$D(e,e'\pi^0)X = d(e,e'\pi^0)d + n(e,e'\pi^0)n + p(e,e'\pi^0)p.$$

- ● LD2
- ○ LH2
- □ LD2-LH2

- $d(e,e'\pi^0)d$
- $n(e,e'\pi^0)n$

separated by

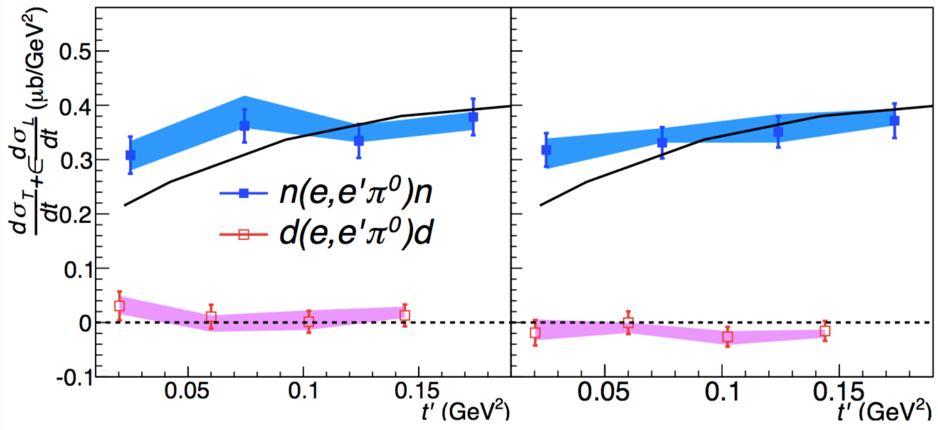
$$\Delta M_X^2 = t(1 - M/M_d) \approx t/2$$

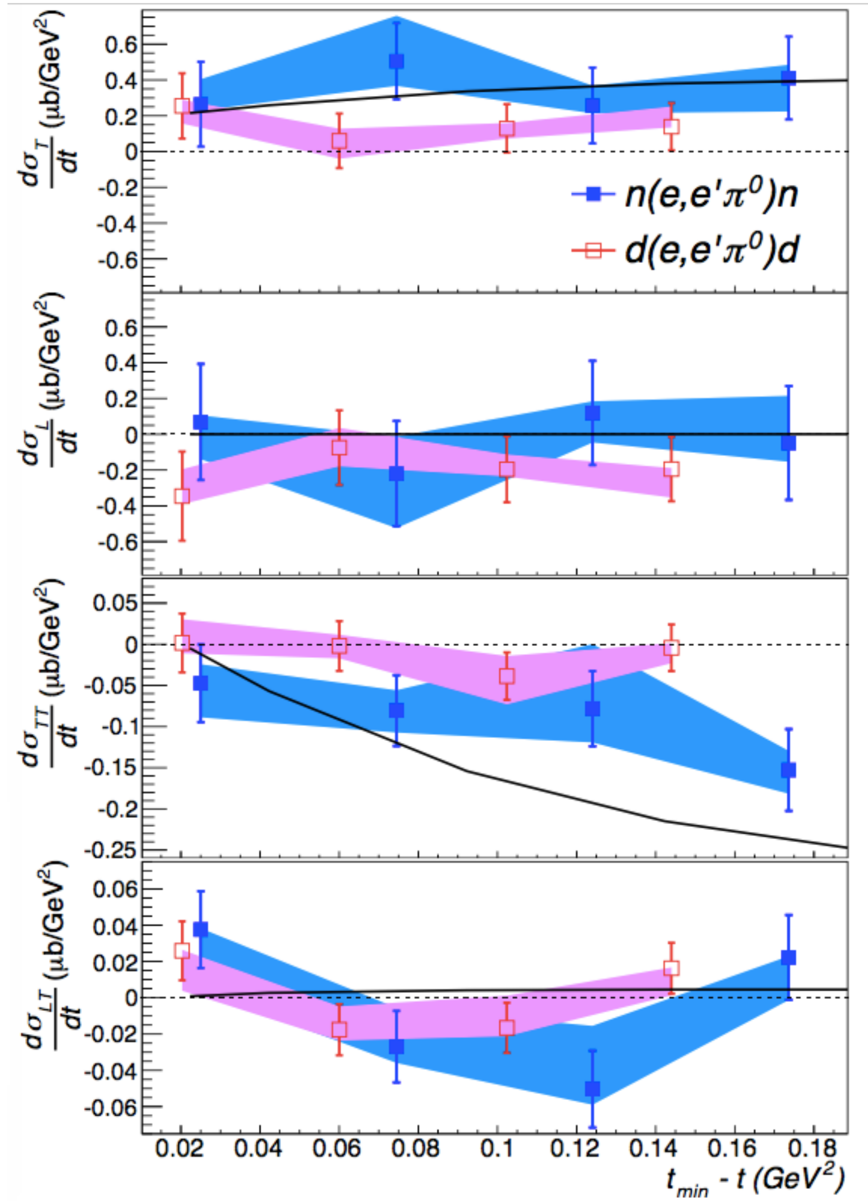



Computed for $n(e,e'\pi^0)X$

# DVCS2n results: fully separated contributions

$Q^2$=1.75 GeV$^2$ and $x_B$=0.36




— Goloskokov and Kroll
Eur Phys J A47 (2012)

$$\frac{d\sigma_T}{dt} = \Lambda \left[ \left(1-\xi^2\right) \left|\langle H_T \rangle\right|^2 - \frac{t'}{8M^2} \left|\langle \bar{E}_T \rangle\right|^2 \right]$$

$$\frac{d\sigma_{TT}}{dt} = \Lambda \frac{t'}{8M^2} \left|\langle \bar{E}_T \rangle\right|^2 .$$

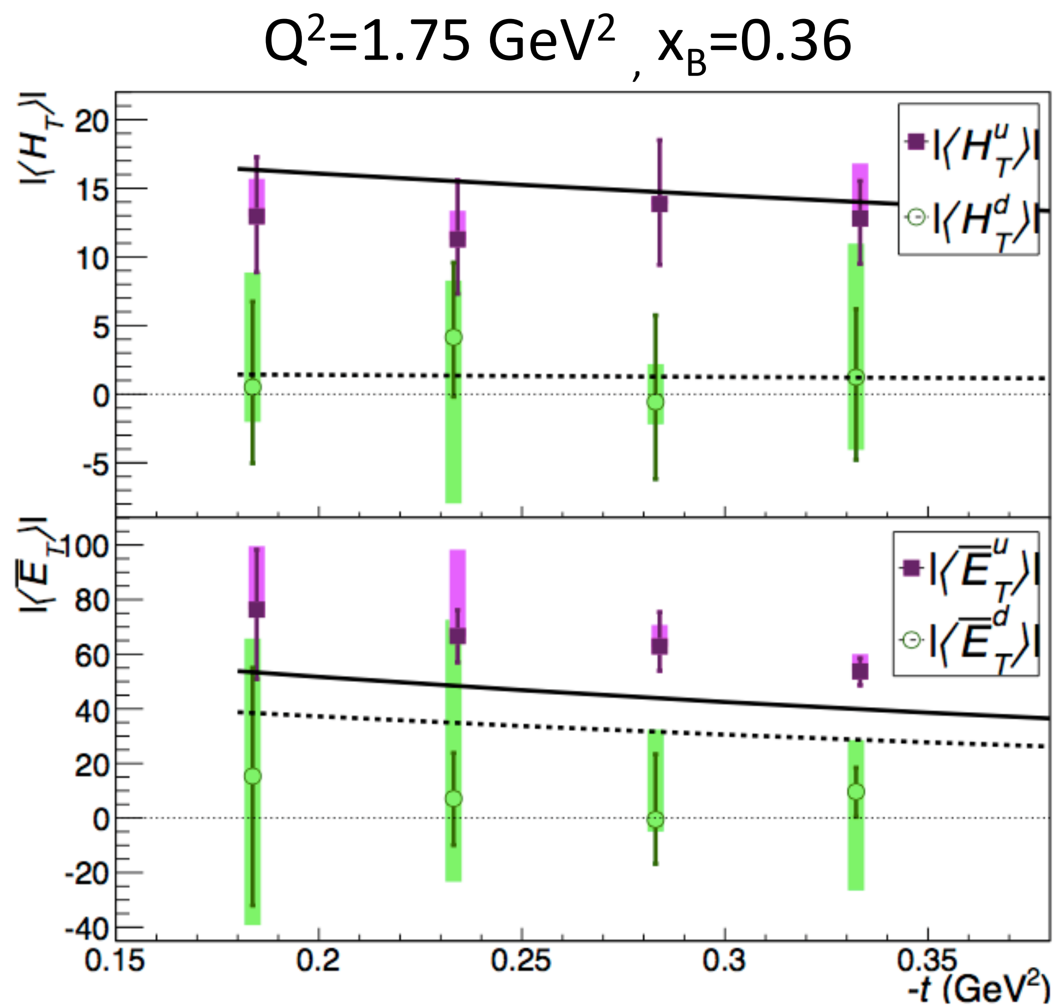
$$\bar{E}_T = 2\tilde{H}_T + E_T$$

# DVCS2n results: flavor separation

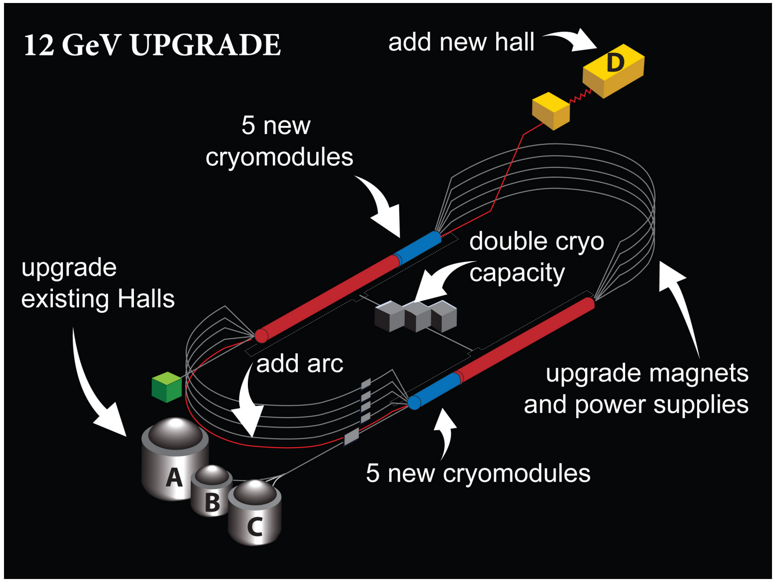
$$|\langle H_T^{p,n} \rangle|^2 = \frac{1}{2} \left| \frac{2}{3} \left\langle H_T^{u,d} \right\rangle + \frac{1}{3} \left\langle H_T^{d,u} \right\rangle \right|^2$$

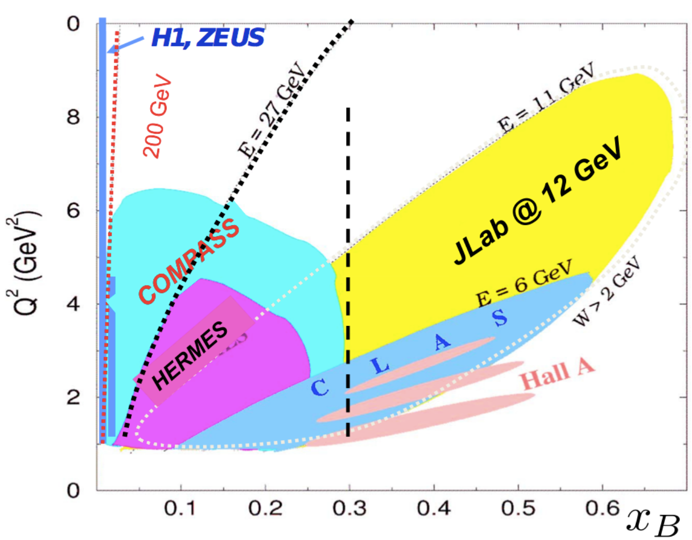
account for the unknown phase variation between u and the d amplitude $\gamma^* q \to q' \pi^0$ convoluted with $(H,E)_T$

Goloskokov and Kroll
Eur Phys J A47 (2012)



# Some 12 GeV outlook

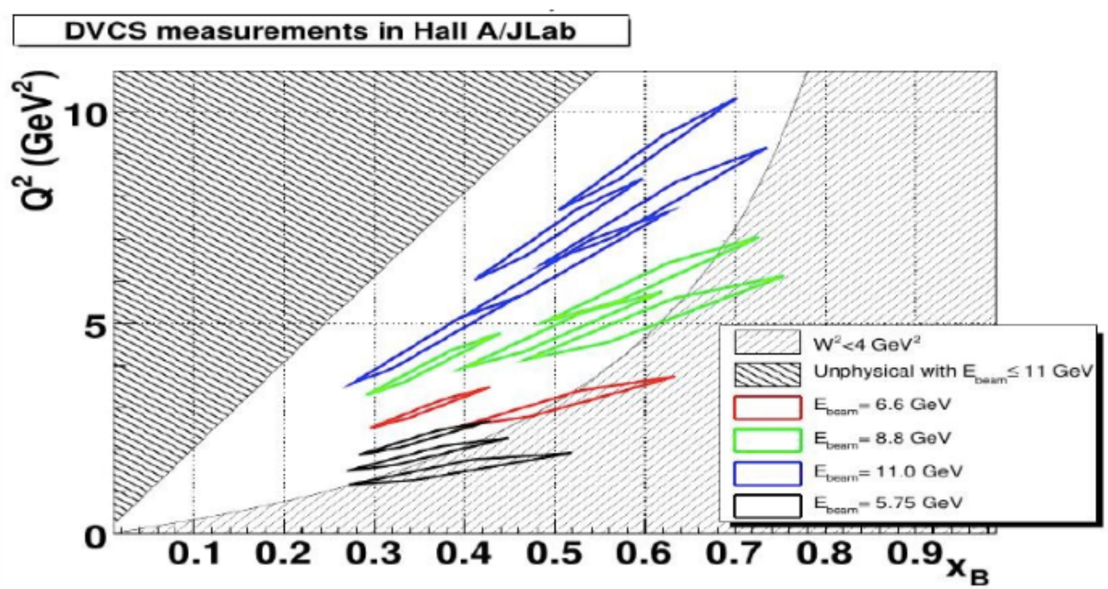


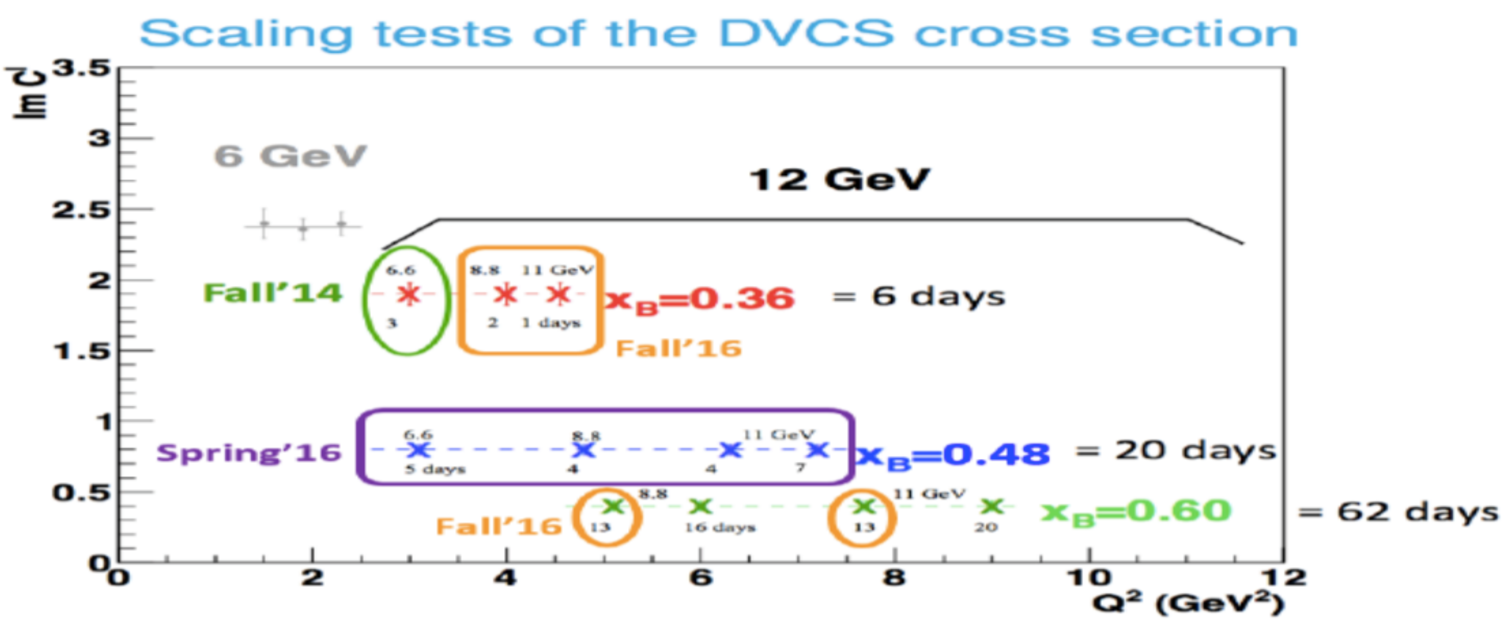




| Proposal | Title | Spokespersons | Hall | Rating |
|---|---|---|---|---|
| E12-06-114 | Measurement of Electron-Helicity Dependent Cross-Sections of Deeply Virtual Compton Scattering with CEBAF at 12 GeV | C. Hyde<br>B. Michel<br>C. Munoz-Camacho<br>J. Roche | A | A |
| E12-06-108 | Hard Exclusive Electroproduction of $\pi^0$ and $\eta$ with CLAS12 | P. Stoler<br>K. Joo<br>V. Kubarovsky<br>M. Ungaro<br>C. Weiss | B | B |
| E12-06-119 | Deeply Virtual Compton Scattering with CLAS at 11 GeV | F. Sabatié<br>A. Biselli<br>H. Egiyan<br>L. Elouadrhiri<br>M. Holtrop<br>D. Ireland<br>W. Kim | B | A |
| E12-11-003 | Deeply Virtual Compton Scattering on the Neutron with CLAS12 at 11 GeV | S. Niccolai<br>V. Kubarovsky<br>A. El Alaoui<br>M. Mirazita | B | A |
| E12-12-001 | Timelike Compton Scattering and $J/\psi$ photoproduction on the proton in $e^+e^-$ pair production with CLAS12 at 11 GeV | P. Nadel-Turonski<br>M. Guidal<br>T. Horn<br>R. Paremuzyan<br>S. Stepanyan | B | A- |
| E12-12-007 | Exclusive $\phi$ Meson Electroproduction with CLAS12 | P. Stoler<br>C. Weiss<br>F.-X. Girod<br>M. Guidal<br>V. Kubarovsky | B | B+ |
| E12-12-010 | Deeply Virtual Compton Scattering at 11 GeV with a transversely polarized target using the CLAS12 detector | L. Elouadrhiri<br>V. D. Burkert<br>M. Lowry<br>M. Guidal<br>S. Procureur | B | A |
| E12-07-105 | Scaling Study of the L-T Separated $\pi$ Electroproduction Cross-Section at 11 GeV | T. Horn<br>G. Huber | C | A- |
| E12-07-105 | Studies of the L-T Separated Kaon Electroproduction Cross-Section from 5 to 11 GeV | T. Horn<br>G. Huber<br>P. Markowitz | C | B+ |

E12-13-010: Exclusive Deeply Virtual Compton and Neutral Pion Cross-Section Measurements in Hall C, Horn, Munoz, Paremuzyan, Roche

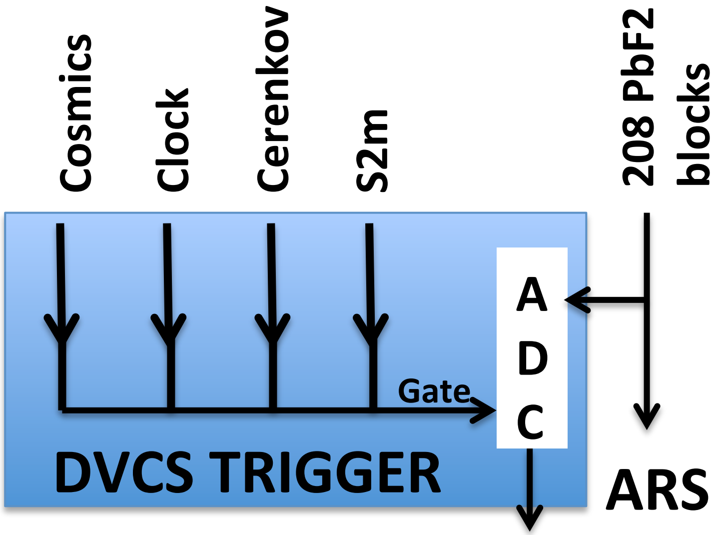
# Hall A E12-06-114: early 12 GeV experiment




50 % of PAC allocation taken in between 2014 and 2016

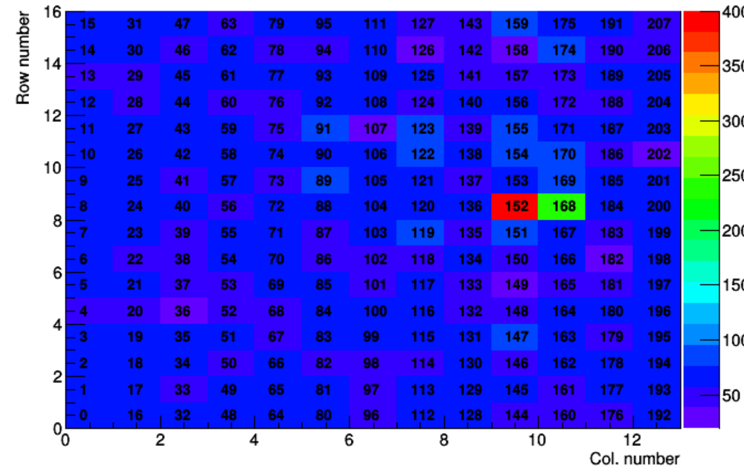
# Hall A : Trigger with *at least one* cluster in the calo.

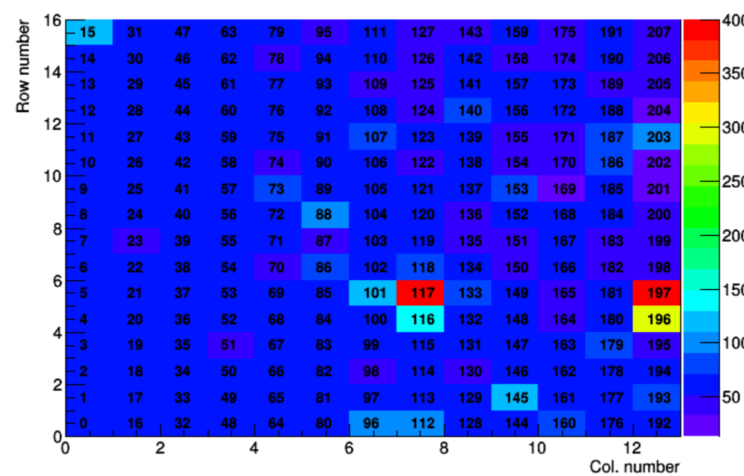



**Triggers if a group of 2*2 blocks is above threshold**

| DVCS3- kin | 1 cluster | 2 clusters |
|---|---|---|
| 36_1 | 100 | 23 |
| 36_2 | 100 | 27 |
| 36_3 | 100 | 26 |

In some case, this trigger is by-passed

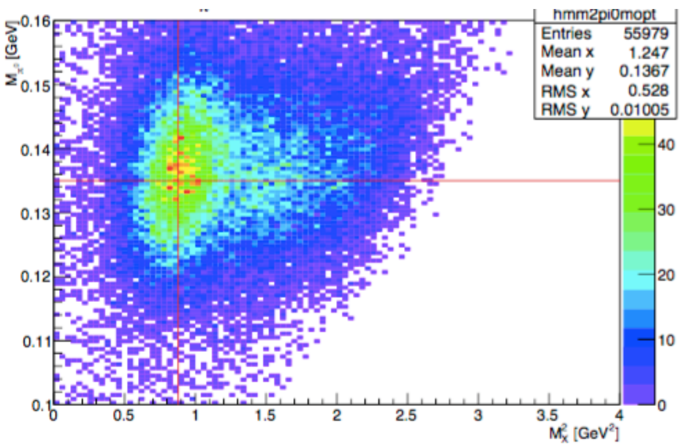


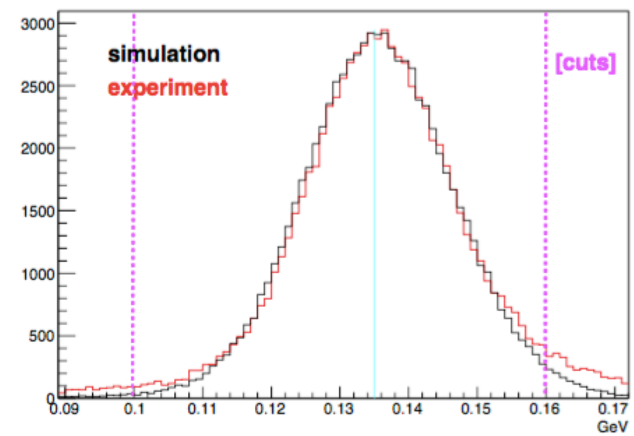



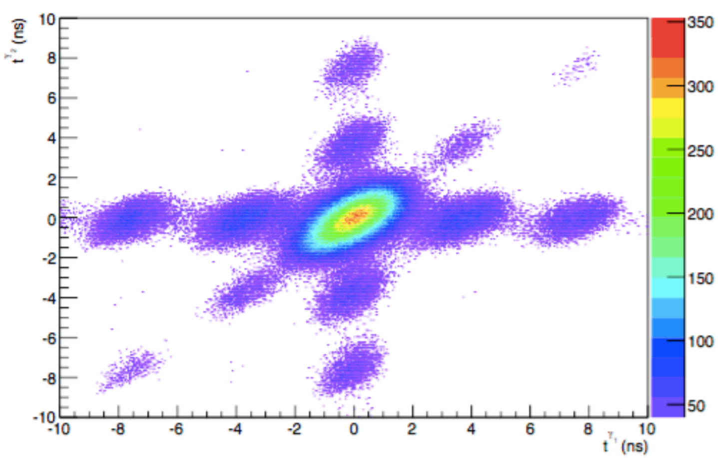

**Target-Calorimeter distance such that $2\gamma$ from $\pi^0$ are separated by 3 blocks**

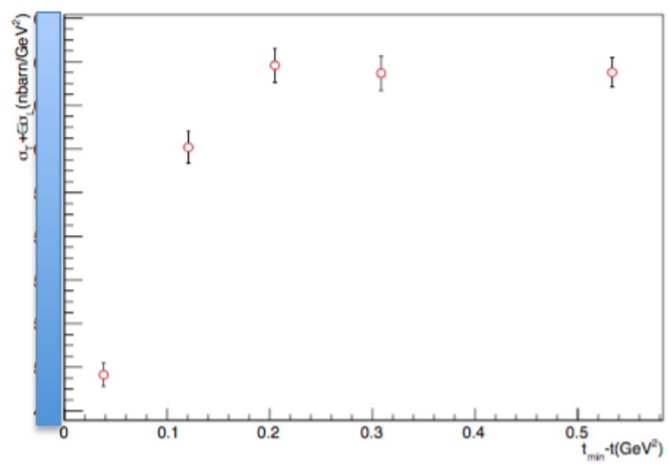
# E12-06-114: $\pi^0$ VERY preliminary results

$$\frac{d^4\sigma}{dt\,d\phi\,dQ^2\,dx_B} = \frac{1}{2\pi}\Gamma_{\gamma^*}(Q^2, x_B, E_e)\left[\frac{d\sigma_T}{dt} + \epsilon\frac{d\sigma_L}{dt} + \sqrt{2\epsilon(1+\epsilon)}\frac{d\sigma_{TL}}{dt}cos(\phi) + \epsilon\frac{d\sigma_{TT}}{dt}cos(2\phi)\right]$$



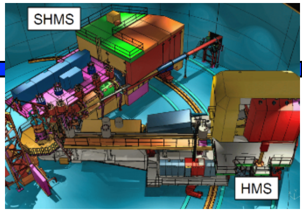




Mongi Dlamini (Ohio U)

# JLab12: kaon production    Slide from T. Horn




❑ **E12-09-011**: Separated L/T/LT/TT cross section over a wide range of $Q^2$ and t

*spokespersons: T. Horn, G. Huber, P. Markowitz*

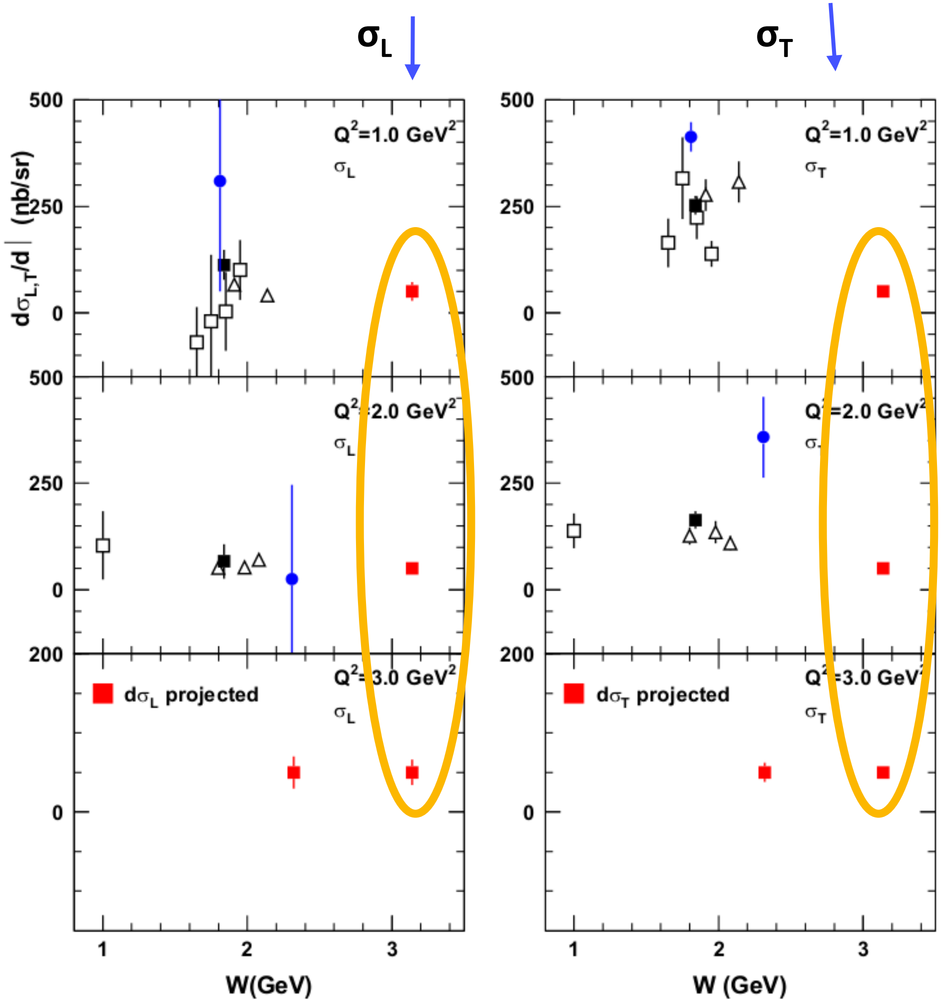
## JLab 12 GeV Kaon Program features:

- First cross section data for $Q^2$ scaling tests with kaons
- Highest $Q^2$ for L/T separated kaon electroproduction cross section
- First separated kaon cross section measurement above W=2.2 GeV

approved for 40 PAC days and

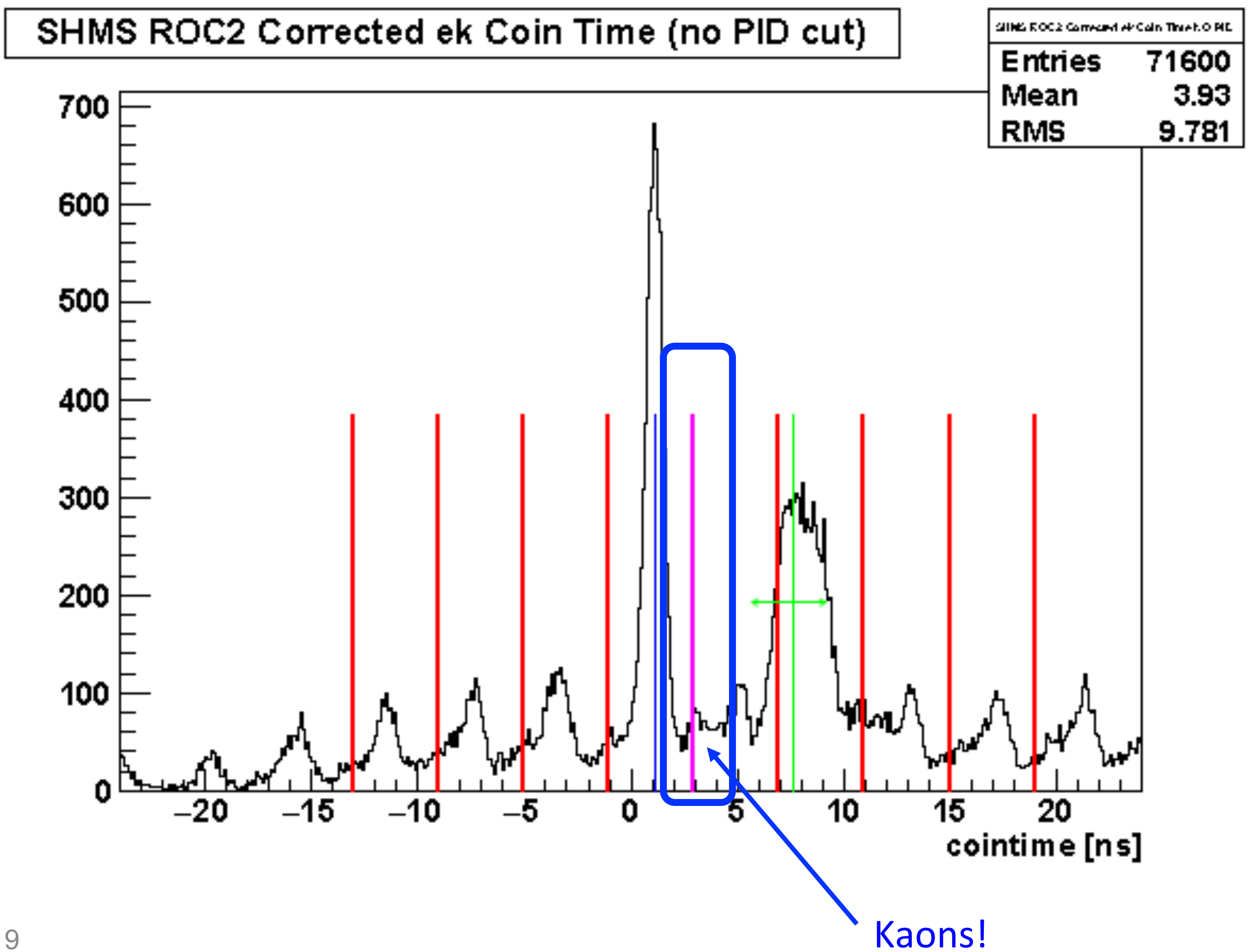
**scheduled to run in 2018/19**

| x | $Q^2$ ($GeV^2$) | W (GeV) | -t $(GeV/c)^2$ |
|---|---|---|---|
| 0.1-0.2 | 0.4-3.0 | 2.5-3.1 | 0.06-0.2 |
| 0.25 | 1.7-3.5 | 2.5-3.4 | 0.2 |
| 0.40 | 3.0-5.5 | 2.3-3.0 | 0.5 |



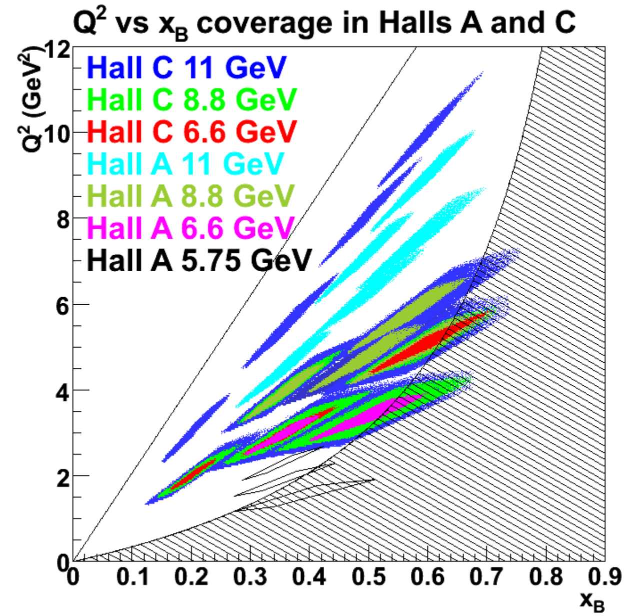

*[blue points from M. Carmignotto, PhD thesis **(2017)**]*

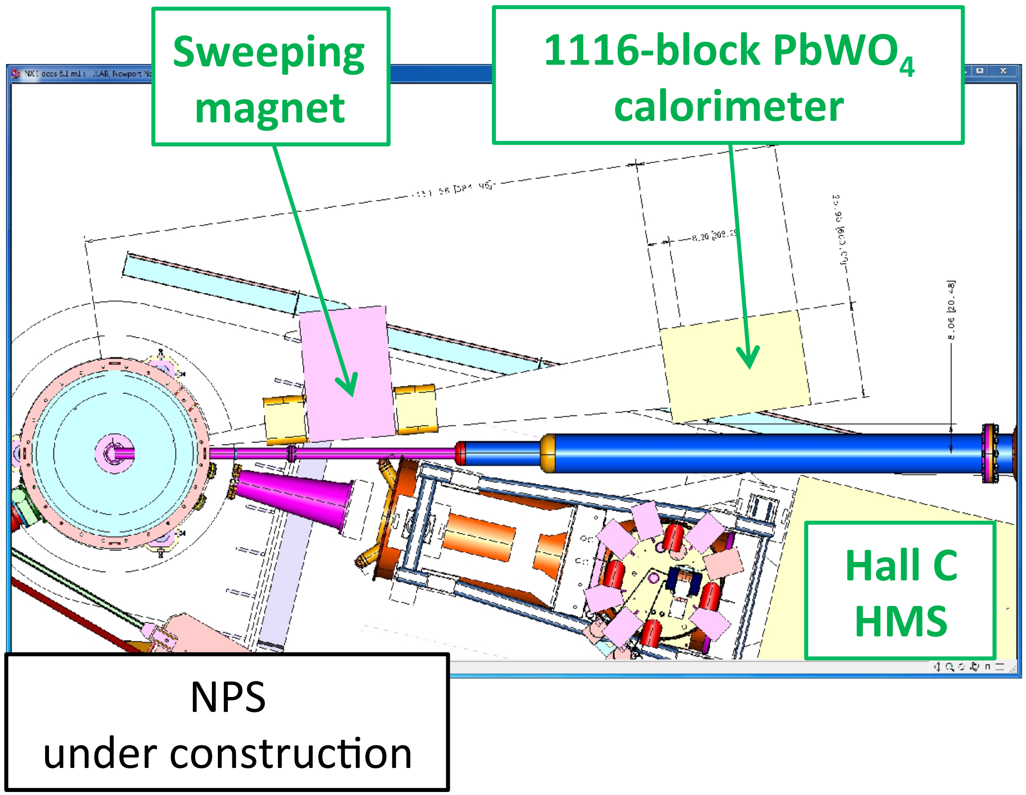
# First Exclusive Kaons from 2018 Data! Slide from T, Horn

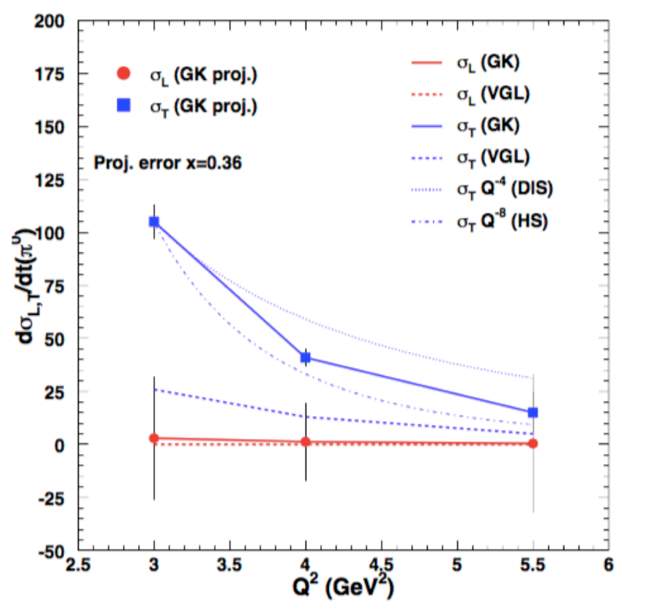


# E12-13-010 GeV in Hall C: $\pi^0$ production

- Charged particle spectrometer with large momentum reach and rigid connection to the pivot
- Electromagnetic calorimeter with active bases (high luminosity compatible)
- Sweeping magnet allowing high luminosity and low angle placement



# Outlook

- Detailed inspection of $\pi^0$ and $\eta$ electro-production data at 6 GeV reveals that the hand-bag approach is a serious candidate to describe them.
- The dominance of the contribution of transverse photon opens new and unique opportunities for accessing the transversity GPDs.
- The simultaneous consideration of different meson allow for a flavor decomposition of the GPDs. Using a neutron target also helps (but it's tought)
- 12 GeV experiments have started taking data.

Photonuclear Reactions

*Gordon Research Conference*

## From Quarks to Nuclei in Photonuclear Reactions

August 5 - 10, 2018

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Holderness, NH, US

https://www.grc.org/photonuclear-reactions-conference/2018/

Photo-nuclear Reactions is a forum for the presentation and discussion of the most recent and exciting results in a wide range of subatomic physics topics. Since 1959, the Photo-nuclear Gordon Research Conference has been a preeminent meeting for the discussion of new ideas and results, even at the preliminary stage, providing ample and unique opportunities for young scientists and leading researchers to interact in the most scientifically stimulating environment. Participation from students and junior researchers is particularly encouraged.

Topics for the 2018 conference are: **Nucleons in Nuclei, QCD for Neutrino Physics, Movement of Partons in the proton, Innovative Tools for the Study of Hadrons, Hadron Spectrum and QCD, Imaging the Proton in 3D, Long Range Structure of Hadrons, and Origin of the Proton Mass.** The full program is posted on the conference webpage.

**A unique format**: The conference is structured around invited morning and evening talks, and poster sessions. The afternoons are left free on purpose to promote discussions, exchange of new ideas, and connections among colleagues, while enjoying the many outdoor activities offered by the area.

**Poster competition:** A two-day poster competition will be organized at the beginning of the conference, and the best theory poster and experimental poster presenters will be rewarded with the chance to present their research in a short talk during the conference.

**Financial Support:** Limited but substantial support is available to help defray the registration or travel costs. Inquire with the conference Chairs about this opportunity.

Registration is on-going. **The deadline for application is July 8th, 2018**.

Conference Chairs: J. Roche (rochej@ohio.edu), N. d'Hose (nicole.dhose@cea.fr ) and H-W. Lin (hwlin@pa.msu.edu).

*We strongly encourage our junior attendees to also consider participating in the "Frontiers & Careers" workshop that is organized immediately before the Photo-nuclear Reactions GRC in Boston. http://frontiers.mit.edu/.*

## Movement of Partons in the Proton

Discussion Leader: **Elke Aschenauer**

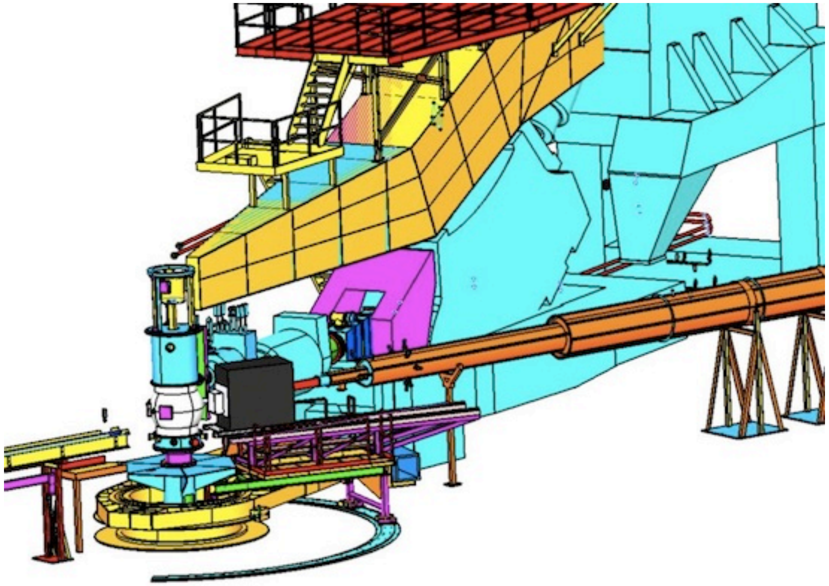
- **Emanuele Nocera** "Unpolarised an Polarised PDFs Today: Needs, Issues and Challenges"
- **Andrea Bressan** "The SIDIS Path to TMDs"
- **Jaroslav Adam** "Ultra-Peripheral Collisions in the STAR Experiment"
- **Marcia Quaresma** "Measurement of Transverse-Spin-Dependent Asymmetries in the Drell-Yan Process by COMPASS"
- **Jiunn-Wei Chen** "Towards the Determination of Nucleon Parton Distributions from Lattice QCD"
- **Nobuo Sato** "Universal QCD Analysis of Parton Densities and Fragmentation Functions"

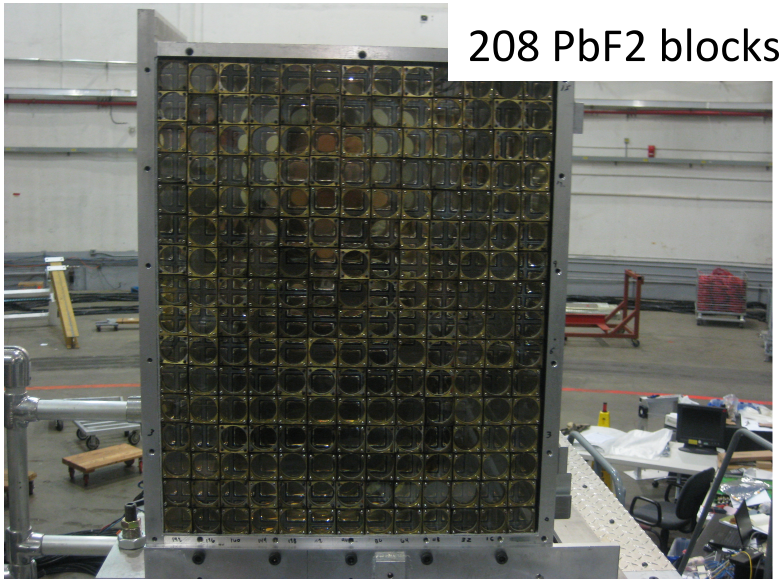
## Imaging the Proton in 3D

Discussion Leader: **Cédric Lorcé**

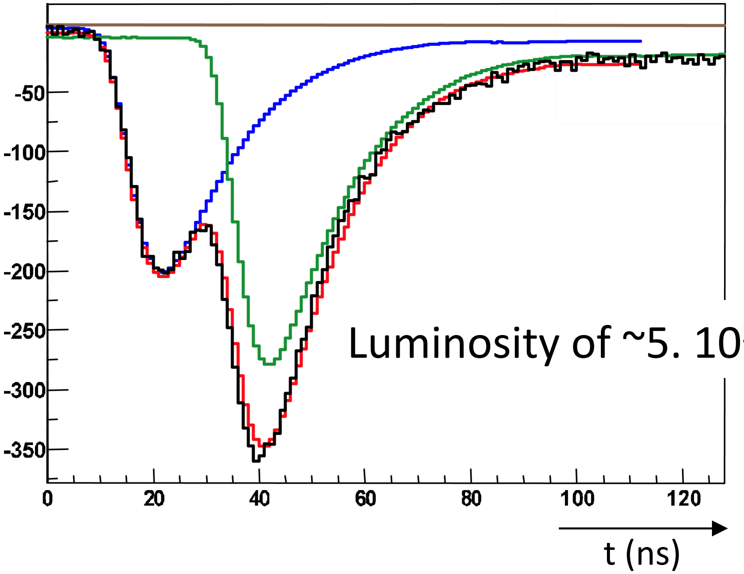
- **Barbara Pasquini** "Wigner Distributions"
- **Silvia Niccolai** "Exploring Nucleon Structure with Generalized Parton Distributions"
- **Marc Vanderhaeghen** "Spatial Tomography of the Proton from Present Data"
- **Yi-Bo Yang** "A Glimpse of the Proton Spin and GPD from Lattice QCD"

# The Hall A detector scheme

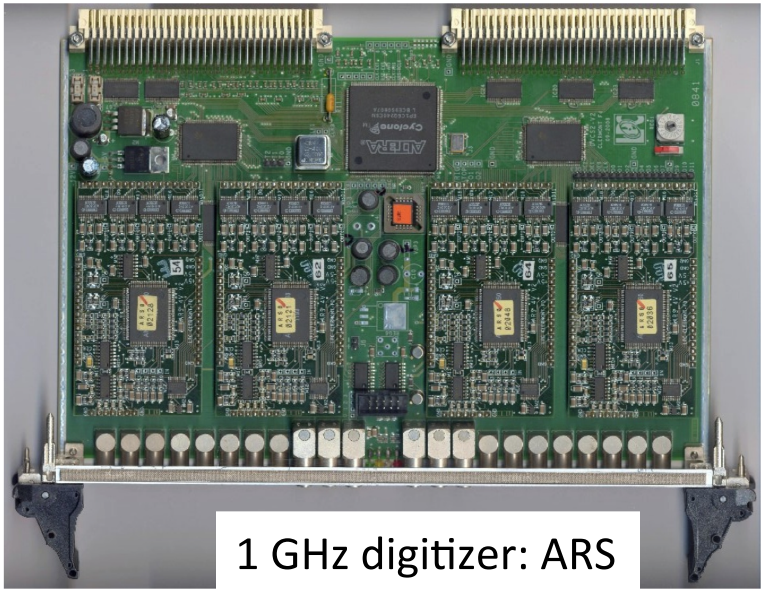




208 PbF2 blocks

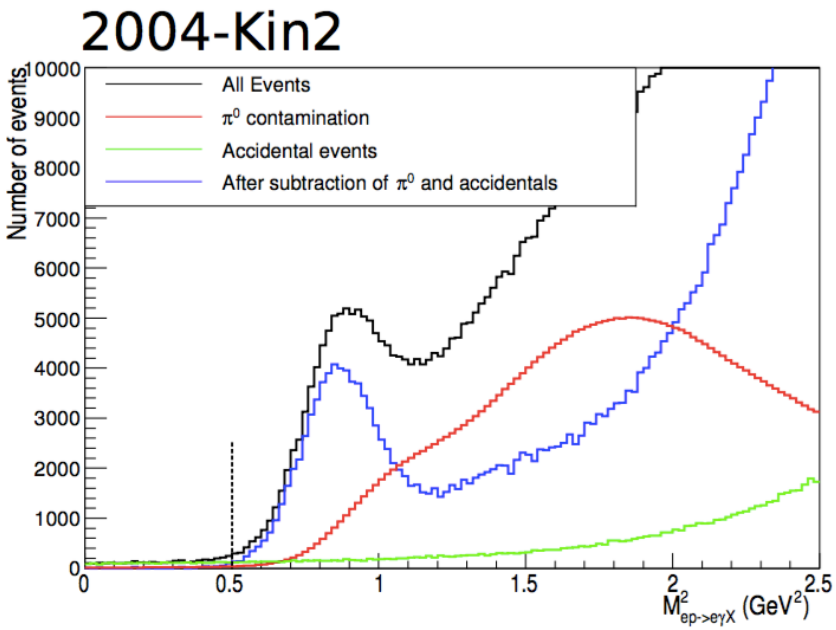



Luminosity of ~5. $10^{37}$ Hz/$cm^2$

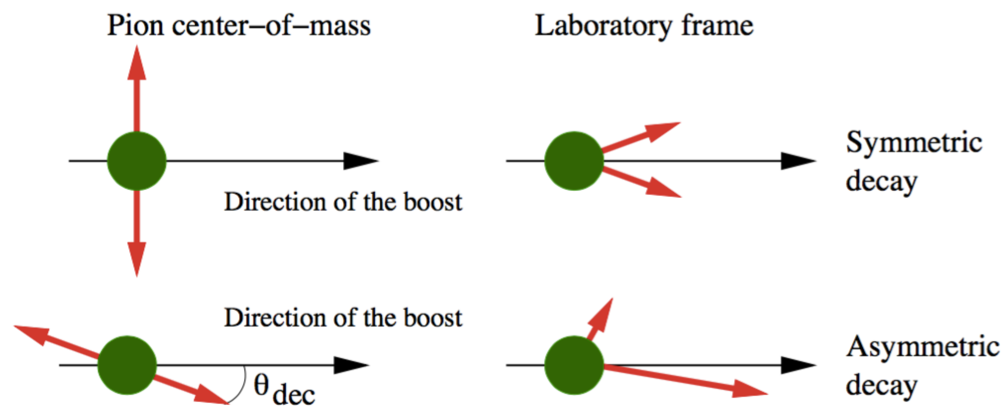


1 GHz digitizer: ARS

# 2-clusters events used for DVCS analysis

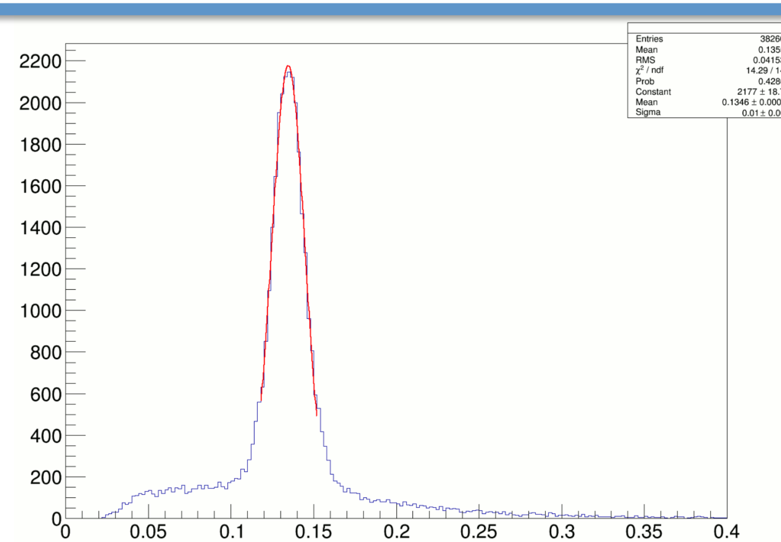



## Evaluation of $\pi^0$ contamination to DVCS signal




## Monitoring and fine adjusting of energy calibration

- First pass: elastic calibration p(e,e'p'): invasive about every 4 weeks
- Second pass: $\pi^0$ calibration with about 1 day of data parasitic to DVCS data taking

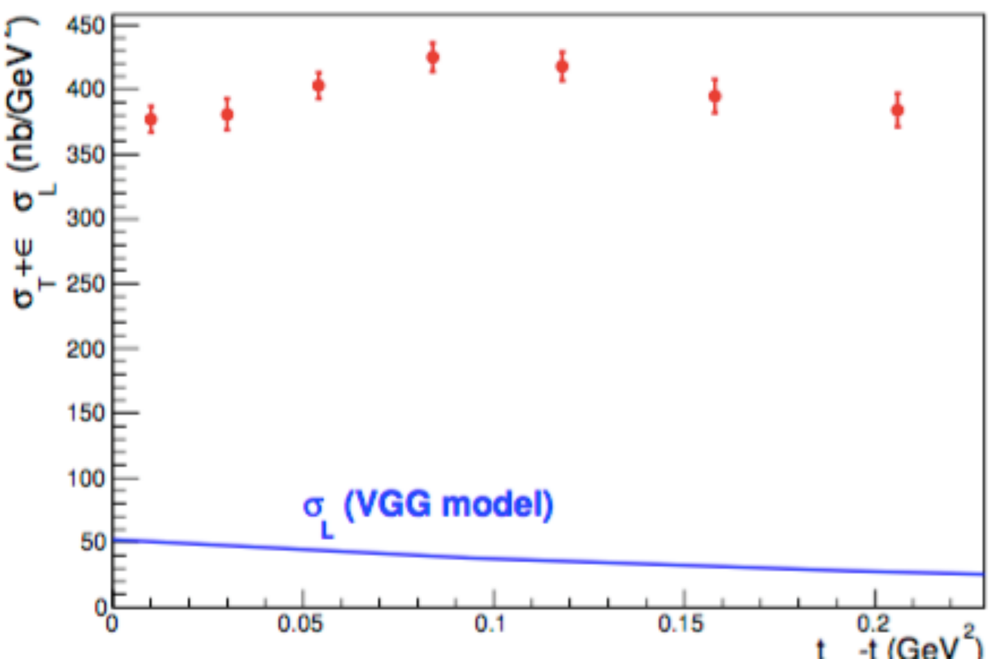


# Hard Exclusive Meson cross-section

$$\frac{d^4\sigma}{dt\,d\phi\,dQ^2\,dx_B} = \frac{1}{2\pi}\Gamma_{\gamma^*}(Q^2, x_B, E_e)\left[\frac{d\sigma_T}{dt} + \epsilon\frac{d\sigma_L}{dt} + \sqrt{2\epsilon(1+\epsilon)}\frac{d\sigma_{TL}}{dt}\cos(\phi) + \epsilon\frac{d\sigma_{TT}}{dt}\cos(2\phi)\right]$$

At first thought, if QCD factorization applies:
$\sigma_L$ expected to dominate with $\sigma_T$ suppressed by 1/Q.

But:




**DVCS1 results**

Fuchey et al. Phys Rev C 83.025201 (2011)

$Q^2$= 2.3 $GeV^2$

$x_B$=0.36

$\varepsilon$=0.61

Similar results at:

- CLAS with $\pi^0$
- HERMES & Hall C with $\pi^+$

Events with missing mass squared below 0.95 $GeV^2$:

- are divided in 12 x 2 x 5 x 30 bins in $\phi$, E, t and $M_x^2$

  $\phi$, E allow for L, T, LT and TT separation

  $M_x^2$ allows for the n/d separation

- fitted with eight cross-section function structure

$$\mathbf{d}\sigma_{\mathbf{\Lambda}}^{\mathbf{n,d}}(\mathbf{t}) \qquad \mathbf{\Lambda} = \mathrm{T, L, LT, TT}$$

$Q^2$=1.75 $GeV^2$ and $x_B$=0.36

E=4.45 GeV
<t'>= 0.025 $GeV^2$

E=5.55 GeV
<t'>=0.021 $GeV^2$