First results on Deep Virtual Compton Scattering in Hall A

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For the DVCS/Hall A Collaboration

Jefferson Lab seminar
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From GPDs to DVCS, to GPDs back

Designing a DVCS experiment

Characteristics of E00-110 in Hall A

Analysis of cross-section difference and sum

Handbag dominance at Jefferson Lab energies

Results and discussion

Based on the work of the DVCS Hall A Ph.D. students: A. Camsonne
M. Mazouz
C. Munoz Camacho

The baby steps towards the full nucleon wave function

After understanding the basic properties of the nucleon, physicists tried to understand its structure:

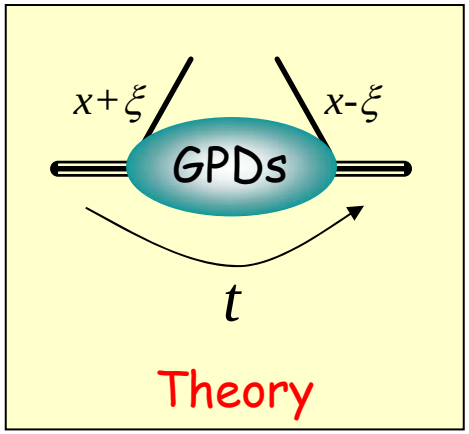
-By Elastic Scattering, we discovered the proton is not a point-like particle and we infered its charge and current distributions by measuring the Form Factors F_1 and F_2.

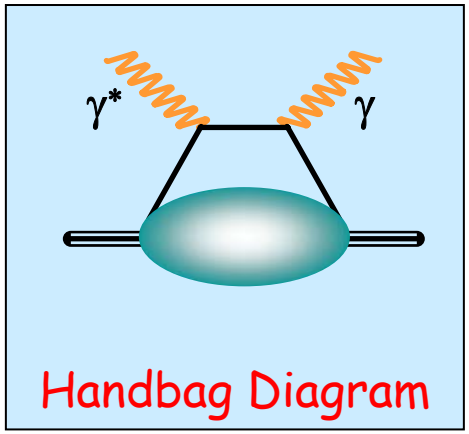
-By Deep Inelastic Scattering, we discovered quarks inside the nucleon and after 30 years of research, have a rather complete mapping of the Quark Momentum and Spin Distributions $q(x)$, $\Delta q(x)$.

Since the late 90's, a new tool was developed, linking these representations of current/charge and momentum/spin distributions inside the nucleon, offering correlation information between different states of the nucleon in terms of partons. The study of Generalized Parton Distributions through Deep Exclusive Scattering will allow for a more complete description of the nucleon than ever before.

Mueller, Radyushkin, Ji

GPDs from Theory to Experiment





2. The GPDs enter the DVCS amplitude as an integral over x:

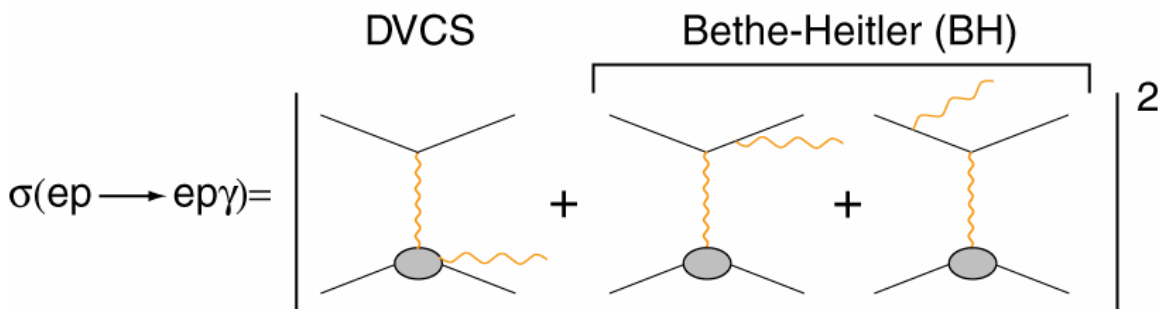
- GPDs appear in the real part through a PP integral over x
- GPDs appear in the imaginary part but at the line x=ξ

$$T^{DVCS} = \int_{-1}^{+1} \frac{GPD(x,\xi,t)}{x-\xi+i\varepsilon} dx \quad + \quad \cdots$$

$$= P\int_{-1}^{+1} \frac{GPD(x,\xi,t)}{x-\xi} dx \quad - \quad i\pi GPD(x=\xi,\xi,t) \quad + \quad \cdots$$

Experimental observables linked to GPDs

3. Experimentally, DVCS is undistinguishable with Bethe-Heitler



However, we know FF at low t and BH is fully calculable

Using a polarized beam on an unpolarized target, 2 observables can be measured:

$$\frac{d^4\sigma}{dx_B dQ^2 dt d\varphi} \approx \left|T^{BH}\right|^2 + 2T^{BH} \cdot \mathrm{Re}\left(T^{DVCS}\right) + \left|T^{DVCS}\right|^2$$

$$\frac{d^4\overrightarrow{\sigma} - d^4\overleftarrow{\sigma}}{dx_B dQ^2 dt d\varphi} \approx 2T^{BH} \cdot \mathrm{Im}\left(T^{DVCS}\right) + \left[\left|T^{DVCS\rightarrow}\right|^2 - \left|T^{DVCS\leftarrow}\right|^2\right]$$

At JLab energies, $|T^{DVCS}|^2$ is small

Kroll, Guichon, Diehl, Pire, …

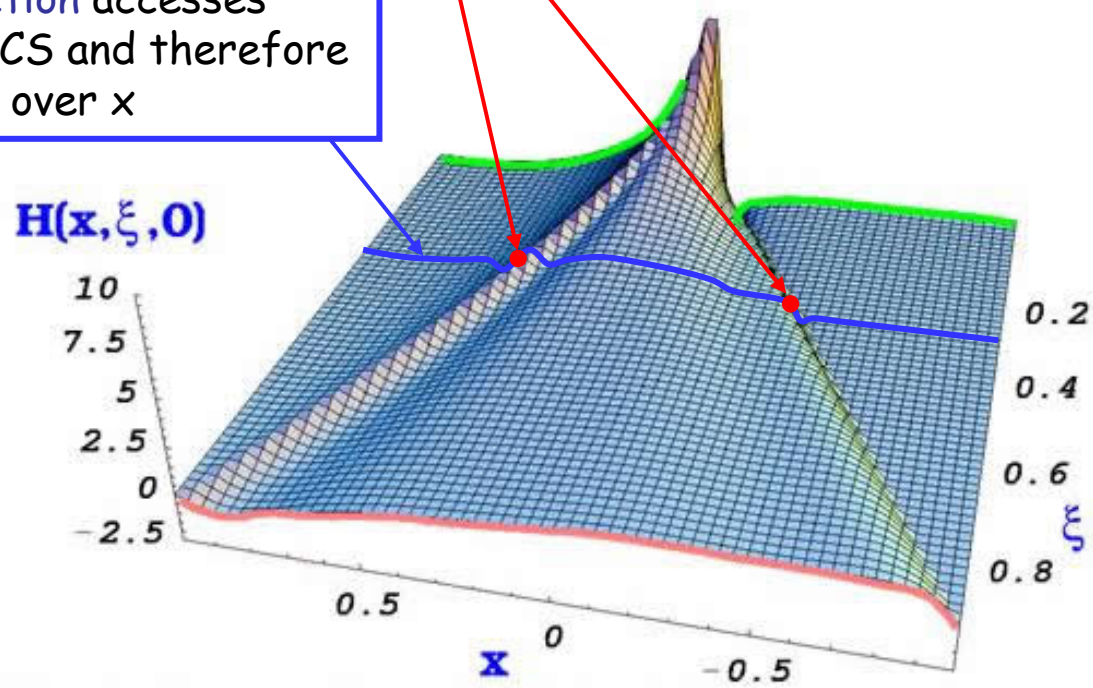
Observables and their relationship to GPDs

$$T^{DVCS} = \int_{-1}^{+1} \frac{GPD(x,\xi,t)}{x-\xi+i\varepsilon} dx \quad + \quad \cdots$$

The cross-section difference accesses the imaginary part of DVCS and therefore GPDs at $x = \xi$

$$= P\int_{-1}^{+1} \frac{GPD(x,\xi,t)}{x-\xi} dx \quad - \quad i\pi GPD(x=\xi,\xi,t) \quad + \quad \cdots$$

The total cross-section accesses the real part of DVCS and therefore an integral of GPDs over x



Into the harmonic structure of DVCS

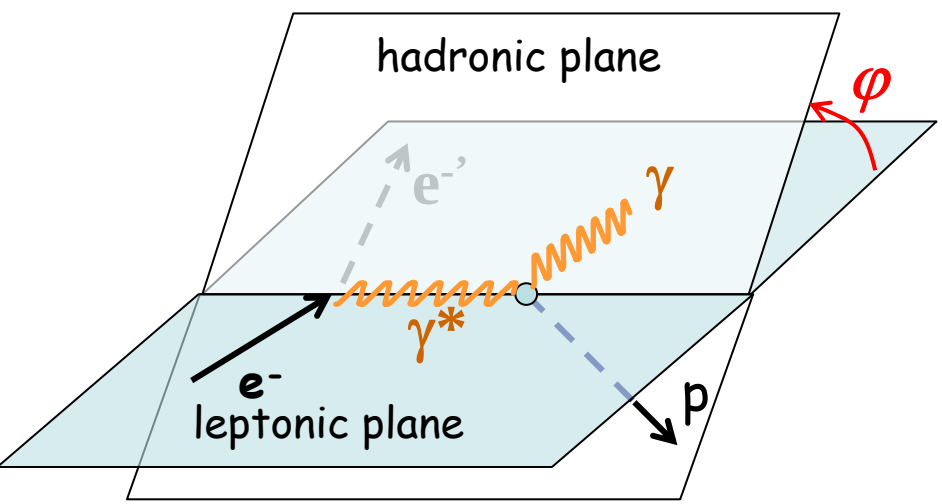
$$\frac{d^4\sigma}{dx_B dQ^2 dt d\varphi} = \frac{1}{P_1(\varphi)P_2(\varphi)}\Gamma_1(x_B,Q^2,t)\left\{c_0^{BH} + c_1^{BH}\cos\varphi + c_2^{BH}\cos 2\varphi\right\}$$

$|T^{BH}|^2$

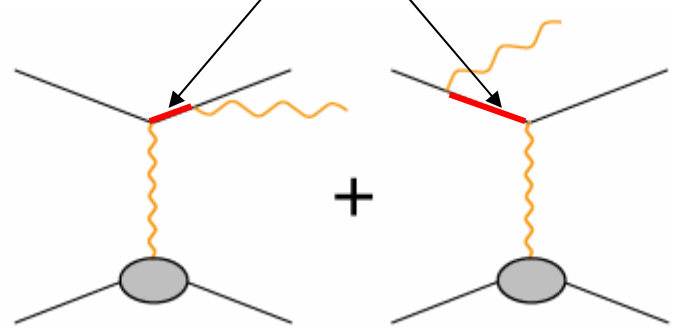
$$+\frac{1}{P_1(\varphi)P_2(\varphi)}\Gamma_2(x_B,Q^2,t)\left\{c_0^{I} + c_1^{I}\cos\varphi + c_2^{I}\cos 2\varphi + c_3^{I}\cos 3\varphi\right\}$$

$$\frac{d^4\vec{\sigma} - d^4\overleftarrow{\sigma}}{dx_B dQ^2 dt d\varphi} = \frac{\Gamma(x_B,Q^2,t)}{P_1(\varphi)P_2(\varphi)}\left\{s_1^{I}\sin\varphi + s_2^{I}\sin 2\varphi\right\}$$

Interference term



$$\frac{1}{P_1(\varphi)P_2(\varphi)}$$



BH propagators φ dependence

Belitsky, Mueller, Kirchner

Tests of the handbag dominance

$$\frac{d^4\sigma}{dx_B dQ^2 dt d\varphi} = \frac{1}{P_1(\varphi)P_2(\varphi)}\Gamma_1(x_B,Q^2,t)\left\{c_0^{BH} + c_1^{BH}\cos\varphi + c_2^{BH}\cos 2\varphi\right\}$$

$$+\frac{1}{P_1(\varphi)P_2(\varphi)}\Gamma_2(x_B,Q^2,t)\left\{\boxed{c_0^I + c_1^I\cos\varphi} + c_2^I\cos 2\varphi + c_3^I\cos 3\varphi\right\}$$

$$\frac{d^4\vec{\sigma} - d^4\overleftarrow{\sigma}}{dx_B dQ^2 dt d\varphi} = \frac{\Gamma(x_B,Q^2,t)}{P_1(\varphi)P_2(\varphi)}\left\{\boxed{s_1^I\sin\varphi} + s_2^I\sin 2\varphi\right\}$$

1. Twist-2 terms should dominate σ and $\Delta\sigma$
2. All coefficients have Q^2 dependence which can be tested!

Designing a DVCS experiment

Measuring cross-sections differential in 4 variables requires:

- **The high precision measurement of all 4 kinematical variables**

Q^2, x $\quad$ t, φ

Scattered electron
detected in the **Hall A HRS**:
High precision determination
of the γ^* 4-vector

Emitted photon
detected in a high resolution
Electromagnetic Calorimeter:
High precision determination
of the real photon direction $\frac{\vec{q}}{\|\vec{q}\|}$

Designing a DVCS experiment

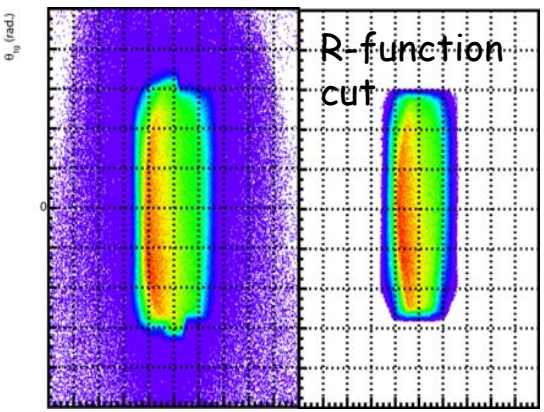
<u>Measuring cross-sections differential in 4 variables requires:</u>

- **A good knowledge of the acceptance**

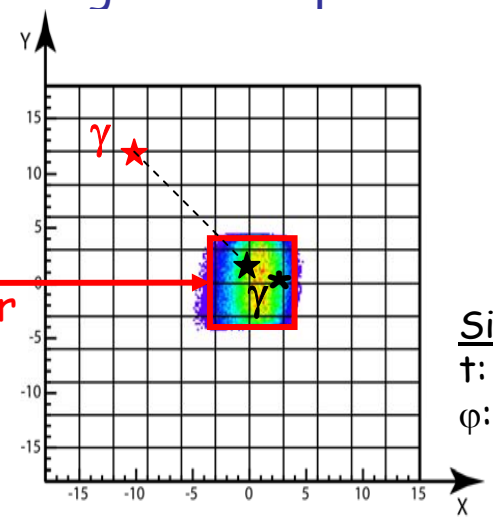
$$e\,p \rightarrow e\,(p)\,\gamma$$

Scattered electron
The HRS acceptance is well known

Emitted photon
The calorimeter has a simple rectangular acceptance



Perfect acceptance matching by design !
Virtual photon « acceptance » placed at center of calorimeter



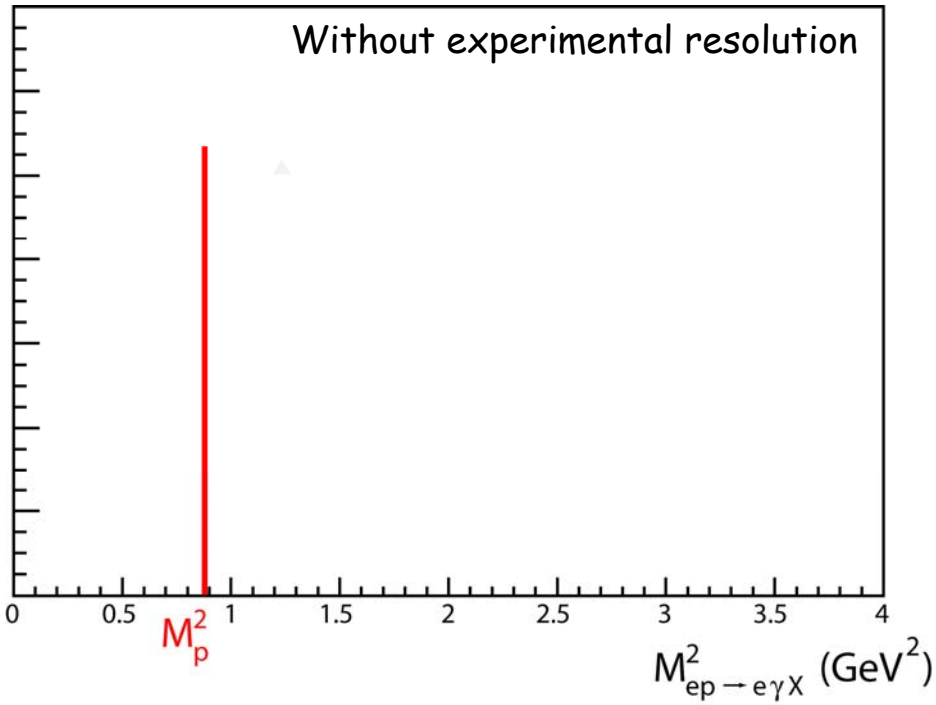
<u>Simply:</u>
t: radius
φ: phase

Designing a DVCS experiment

Measuring cross-sections differential in 4 variables requires:

- **Good identification of the experimental process, i.e. exclusivity**

$$ep \rightarrow ep\gamma$$



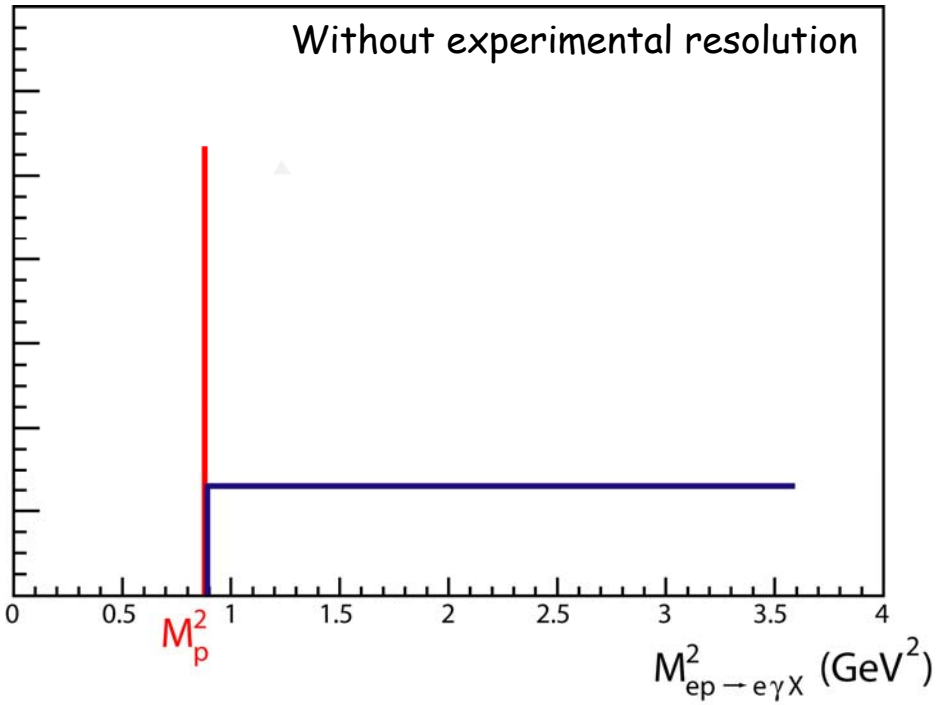
Designing a DVCS experiment

Measuring cross-sections differential in 4 variables requires:

- **Good identification of the experimental process, i.e. exclusivity**

$$ep \rightarrow ep\gamma$$

$$ep \rightarrow ep\pi^o$$
$$\hookrightarrow \gamma\gamma$$



Designing a DVCS experiment

<u>Measuring cross-sections differential in 4 variables requires:</u>

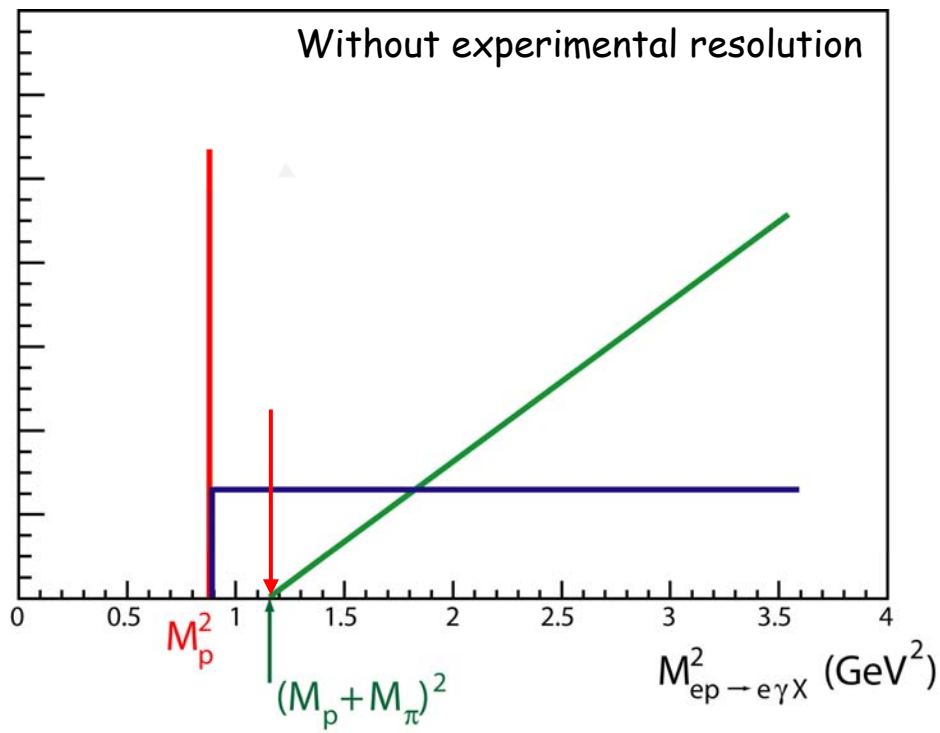
- **Good identification of the experimental process, i.e. exclusivity**

$ep \rightarrow ep\gamma$

$ep \rightarrow ep\pi^o$
$\hookrightarrow \gamma\gamma$

$ep \rightarrow eN\pi\gamma$ resonant or not

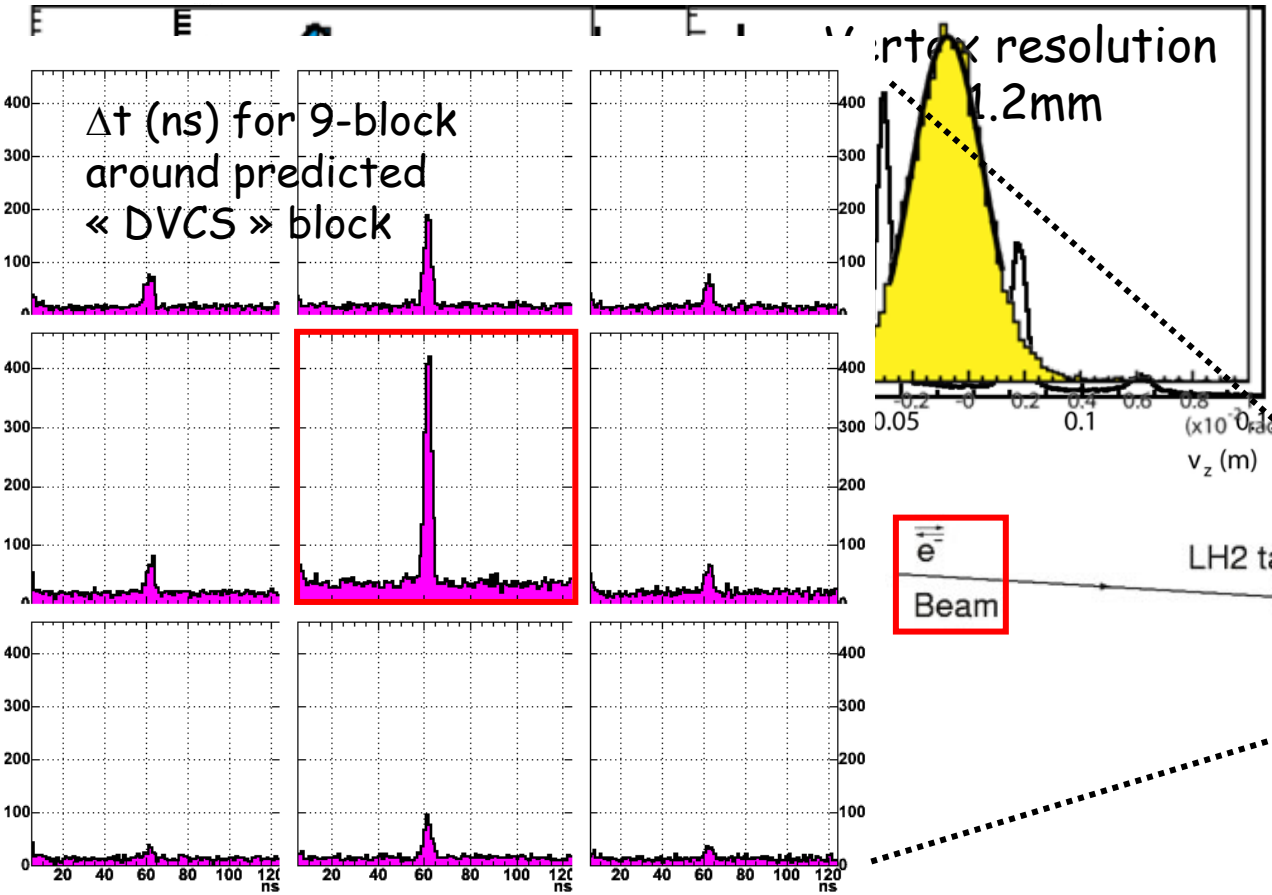
.....

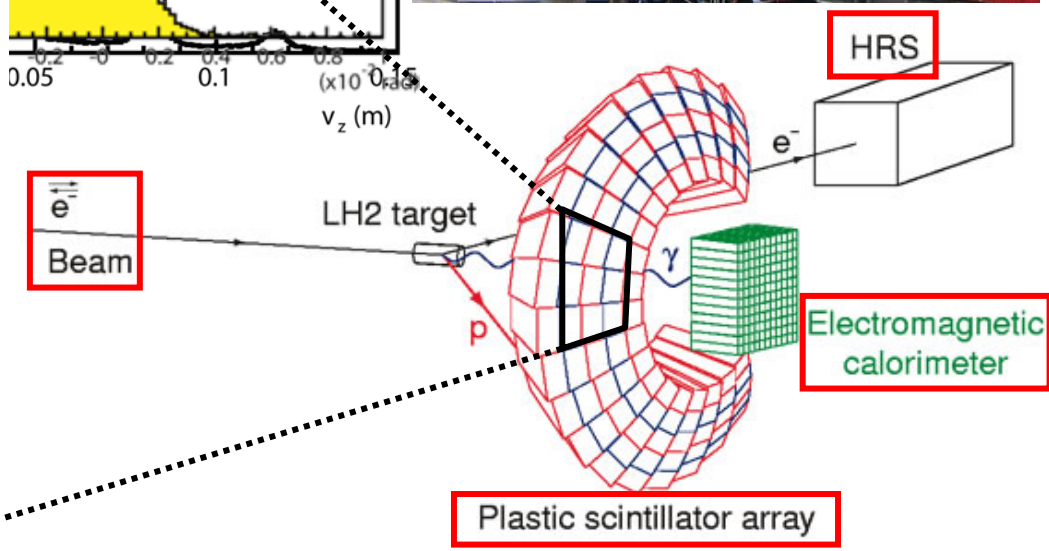


If the Missing Mass resolution is good enough, with a tight cut, one get rids of the associated pion channels, but π^o electroproduction needs to be subtracted no matter what.

E00-110 experimental setup and performances

- 75% polarized 2.5uA electron beam
- 15cm LH2 target
- Left Hall A HRS with electron package
- 11x12 block PbF2 electromagnetic calorimeter
- 5x20 block plastic scintillator array





E00-110 custom electronics and DAQ scheme

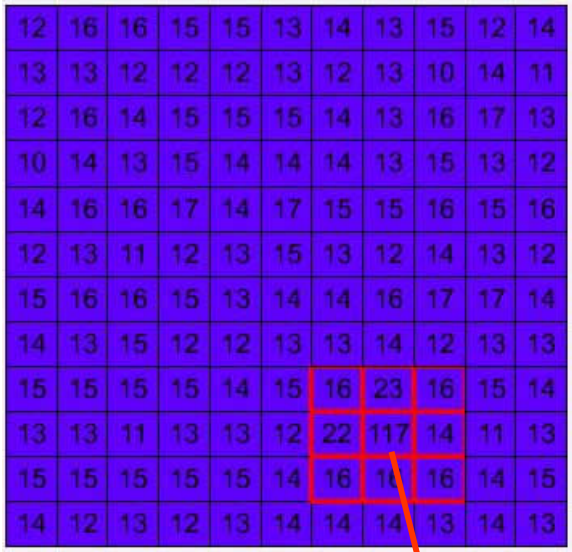
1. Electron trigger starts the game

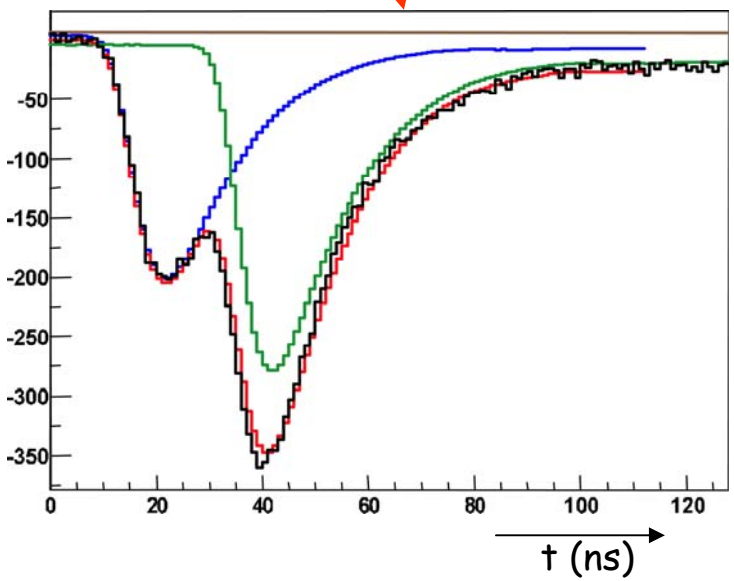
2. Calorimeter trigger (350ns):

- selects clusters
- does a fast energy reconstruction
- gives a read-out list of the modules which enter clusters over a certain threshold
- gives the signal to read-out and record all the experiment electronics channels

3. Each selected electronics channel is digitized on 128ns by ARS boards

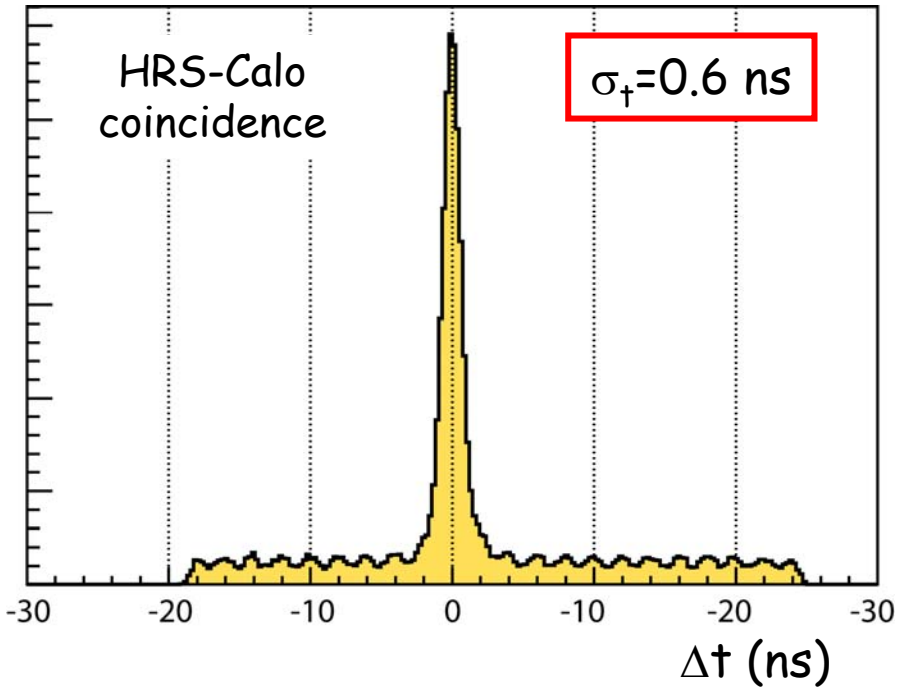
4. Offline, a waveform analysis allows to extract reliable information from pile-up events





ARS system in a high-rate environment

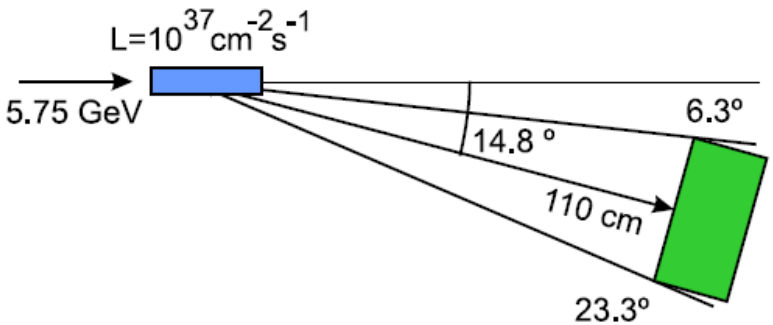
- 5-20% of events require a 2-pulse fit
- Energy resolution improved by a factor from 1.5 to 2.5 !
- Optimal timing resolution



E00-110 kinematics

Kin	Q^2 (GeV^2)	x_B	θ_{γ^*} (deg.)	W (GeV)
1	**1.5**	0.36	**22.3**	1.9
2	**1.9**	0.36	**18.3**	2.0
3	**2.3**	0.36	**14.8**	2.2

The calorimeter is centered on the virtual photon direction



50 days of beam time in the fall 2004, at 2.5μA intensity

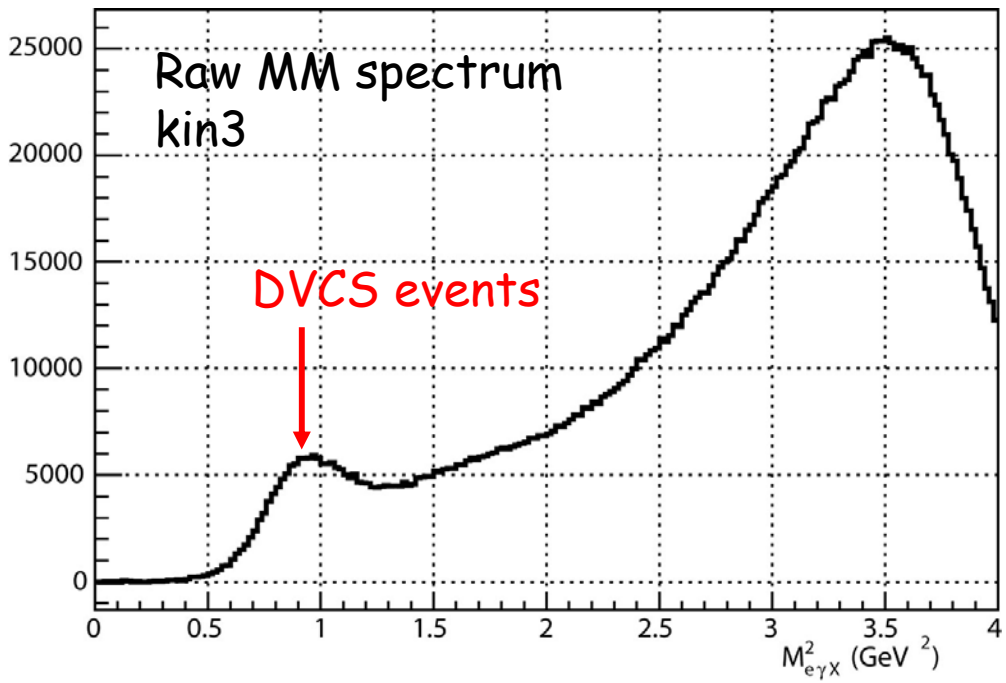
$$\int Lu \cdot dt = 13294 \text{ fb}^{-1}$$

Analysis – Looking for DVCS events

HRS: Cerenkov, vertex, flat-acceptance cut with R-functions)

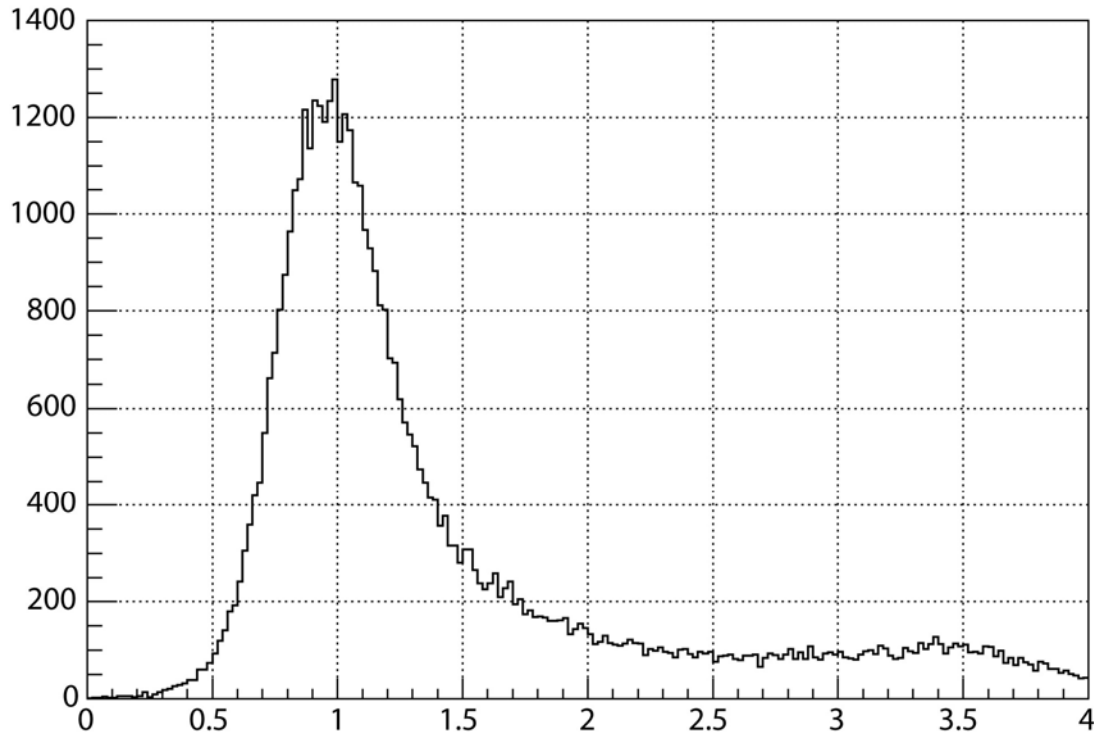
Calo: 1 cluster in coincidence in the calorimeter above 1.2GeV

With both: subtract accidentals, build missing mass of (e,γ) system



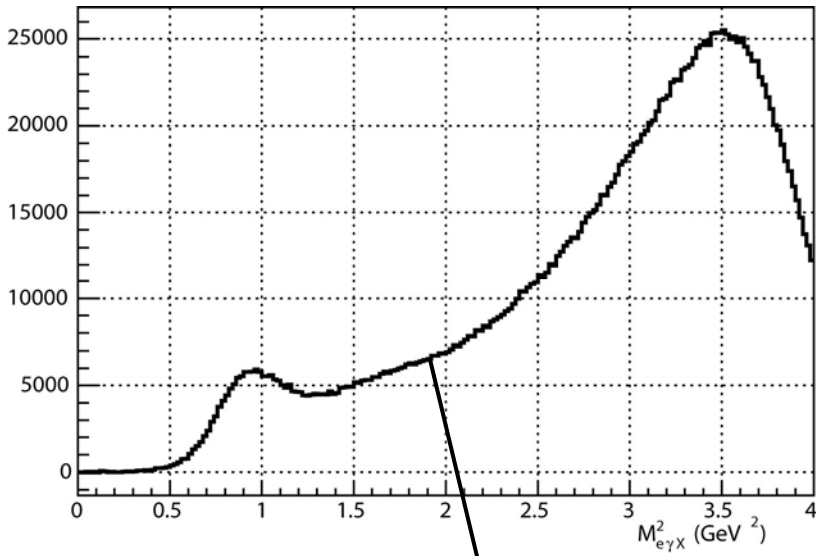
Analysis – Looking for DVCS events

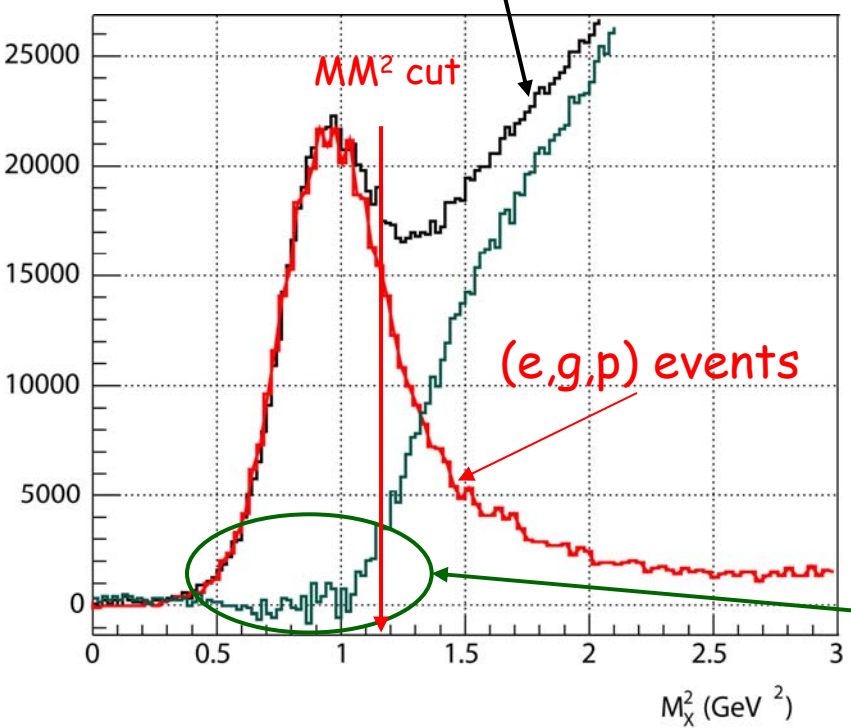
<u>Proton Array:</u> For all events, only select events with matching proton corresponding to DVCS



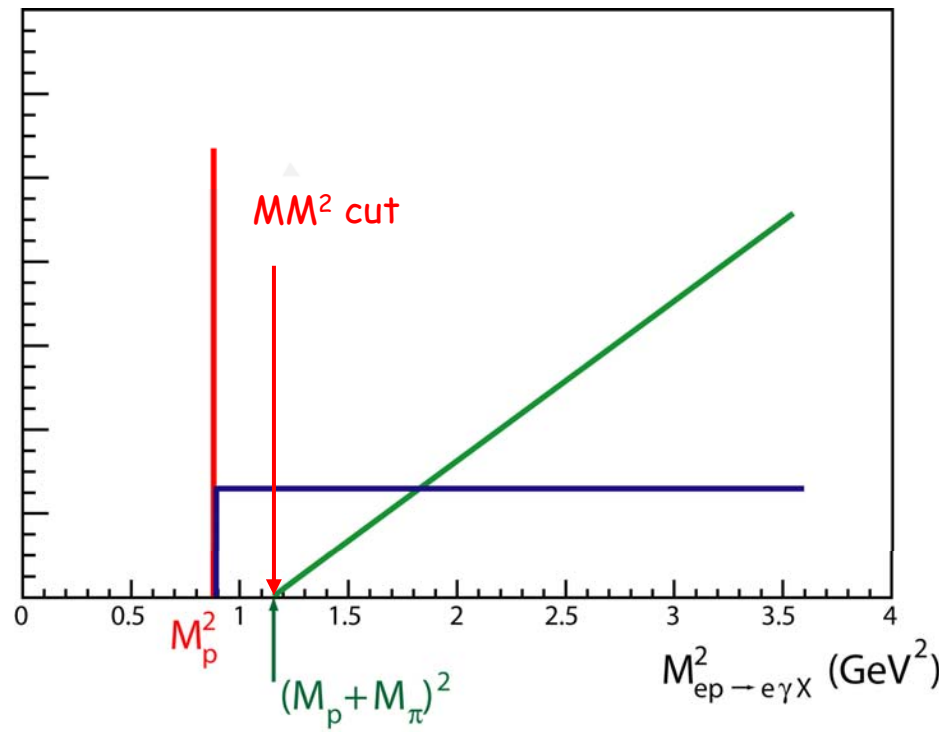
<u>But:</u> the PA cannot get rid of part of the π^0 events

Analysis – Looking for DVCS events



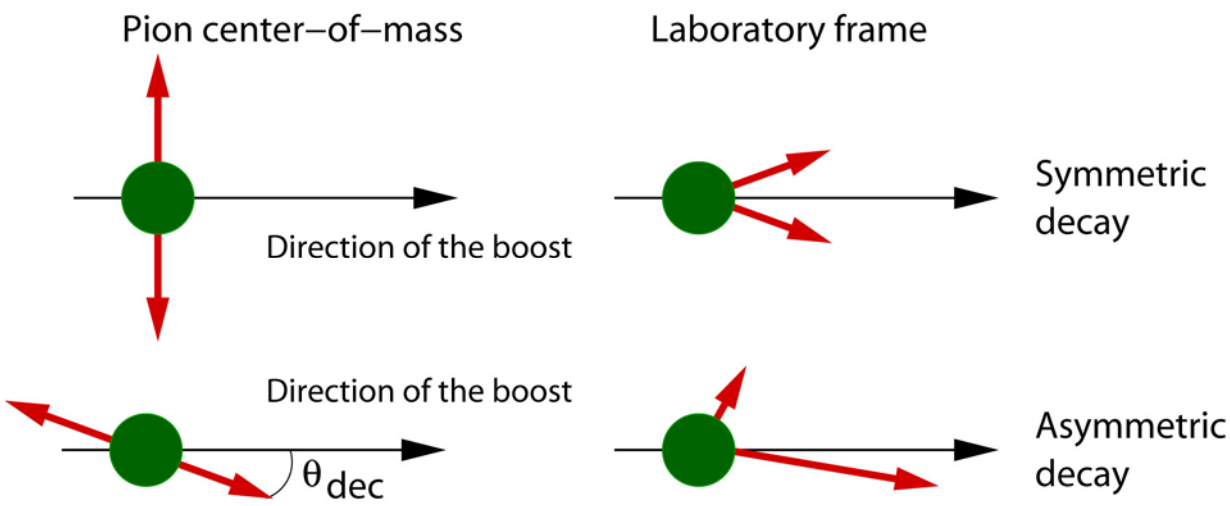


<u>However:</u> One needs to do a thorough π^o subtraction if the only (e,γ) system is used to select DVCS events !!!



Remaining contribution: ~1.7%
(all non-π^o electroproduction)

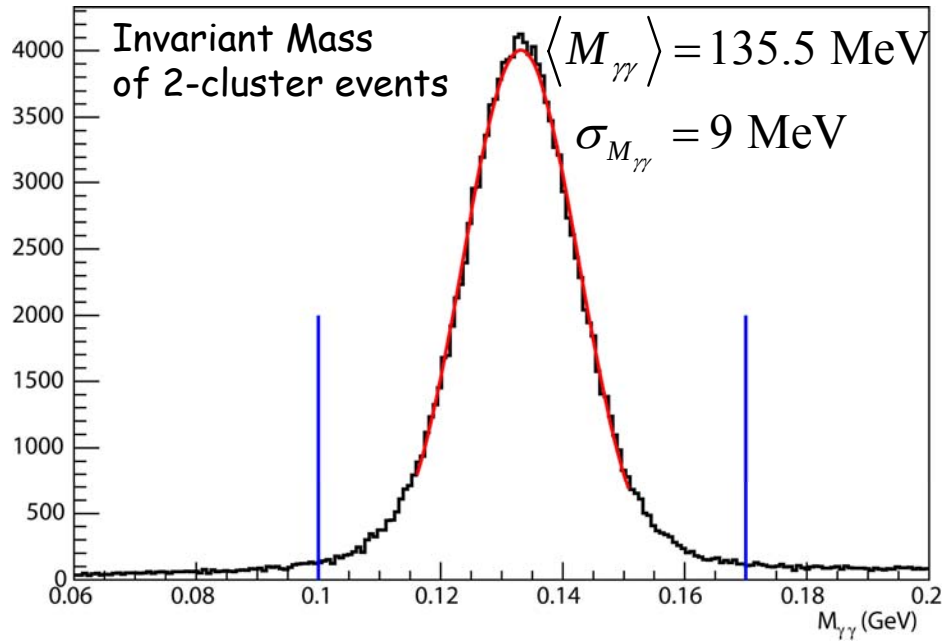
Analysis – π^0 contamination



- Symmetric decay: minimum angle in lab of 4.4° at max π^0 energy
- Asymmetric decay: sometimes one high energy cluster… mimicks DVCS!

Analysis – π^o subtraction using data

1. Select π^o events in the calorimeter using 2 clusters in the calorimeter



2. For each π^o event, randomize the decay in 2-photons and select events for which only one cluster is detected (by MC)
3. Using appropriate normalization, subtract this number to the total number of 1-cluster (e,γ) events

<u>Note:</u> this not only suppressed π^o from electroproduction but also part of the π^o from associated processes

Analysis – Extraction of observables

Re-stating the problem (difference of cross-section):

$$\frac{d^4\overrightarrow{\sigma} - d^4\overleftarrow{\sigma}}{dx_B dQ^2 dt d\varphi} = \frac{\Gamma(x_B, Q^2, t)}{\mathrm{P}_1(\varphi)\mathrm{P}_2(\varphi)}\left\{ s_1^I \sin\varphi + s_2^I \sin 2\varphi \right\}$$

$$s_1^I = 8Ky(2-y)\,\mathrm{Im}\,C^I(F)$$

$$C^I(F) = F_1\mathrm{H} + \frac{x_B}{2-x_B}(F_1+F_2)\tilde{\mathrm{H}} - \frac{t}{4M^2}F_2\mathrm{E}$$

$$\mathrm{Im}\,\mathrm{H} = \pi\sum_q e_q^2\left\{H^q(\xi,\xi,t) - H^q(-\xi,\xi,t)\right\}$$

GPD !!!

Analysis – Extraction of observables

$$\sigma^{\rightarrow} - \sigma^{\leftarrow} = \Gamma_{T2}(x_B, Q^2, t, \varphi)\; C_{T2}(\xi, t)\; \sin\varphi +$$

$$\Gamma_{T3}(x_B, Q^2, t, \varphi)\; C_{T3}(\xi, t)\; \sin 2\varphi$$

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

$C_{T2}(\xi, t)$ and $C_{T3}(\xi, t)$: linear combinations of GPDs

$$\Delta N^{\mathrm{Exp}}(\mathbf{i}_e) = N^{+}_{\mathbf{i}_e} - N^{-}_{\mathbf{i}_e}$$

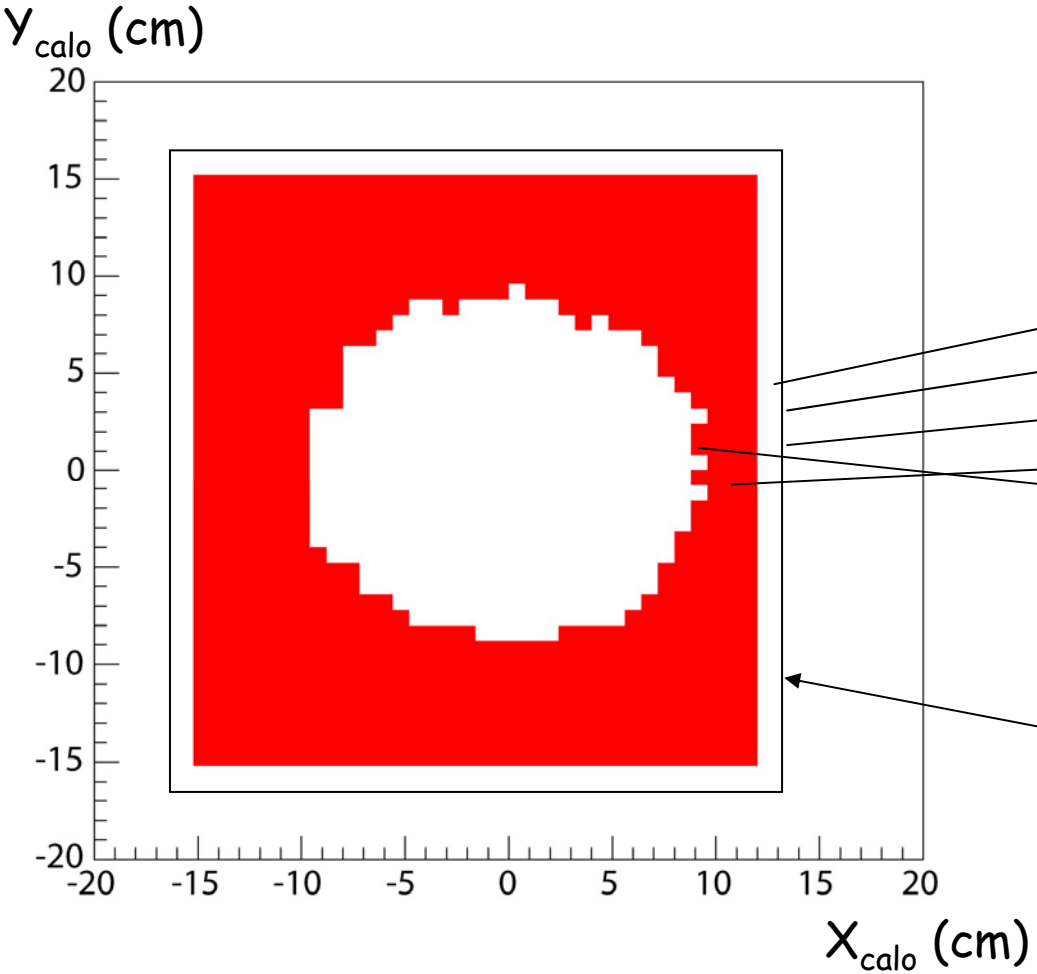
$$\Delta N^{\mathrm{MC}}(\mathbf{i}_e) = \mathcal{L}\left[C_{T2} \underbrace{\int_{x \in \mathbf{i}_e} \Gamma_{T2} \cdot \sin\varphi \otimes \text{Acc.}}_{\text{MC sampling}} + C_{T3} \underbrace{\int_{x \in \mathbf{i}_e} \Gamma_{T3} \cdot \sin 2\varphi \otimes \text{Acc.}}_{\text{MC sampling}} \right]$$

- MC includes real radiative corrections (both external and internal).

$$\chi^2 = \sum_{\mathbf{i}_e} \frac{\left[N^{\mathrm{Exp}}(\mathbf{i}_e) - N^{MC}(\mathbf{i}_e)\right]^2}{\left[\sigma^{\mathrm{Exp}}(\mathbf{i}_e)\right]^2} \Rightarrow \left\{ \begin{array}{l} C_{T2} \\ C_{T3} \end{array} \right.$$

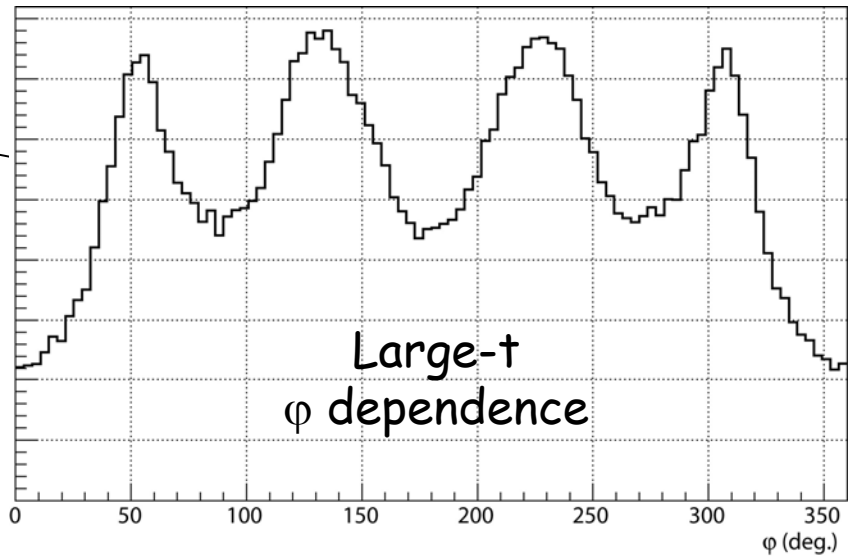
Analysis – Calorimeter acceptance

The t-acceptance of the calorimeter is complicated at high-t:



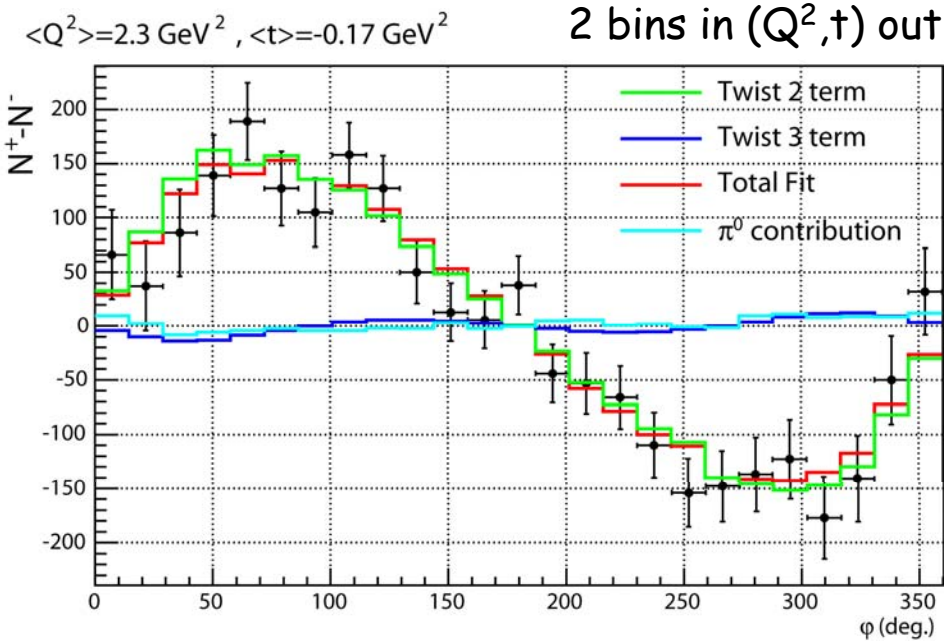
5 bins in t:

Min	Max	Avg
-0.40	-0.35	-0.37
-0.35	-0.30	-0.33
-0.30	-0.26	-0.28
-0.26	-0.21	-0.23
-0.21	-0.12	-0.17

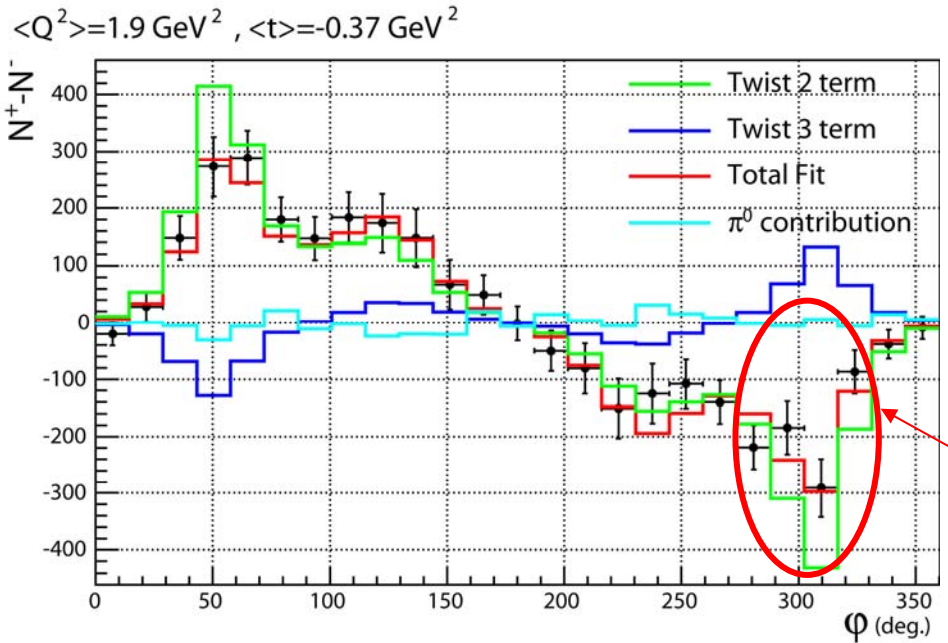


Analysis – Difference of counts

2 bins in (Q^2,t) out of 15, 25 bins in φ.



C_{T2} = 5.48 ± 0.41
C_{T3} = 6.46 ± 6.94



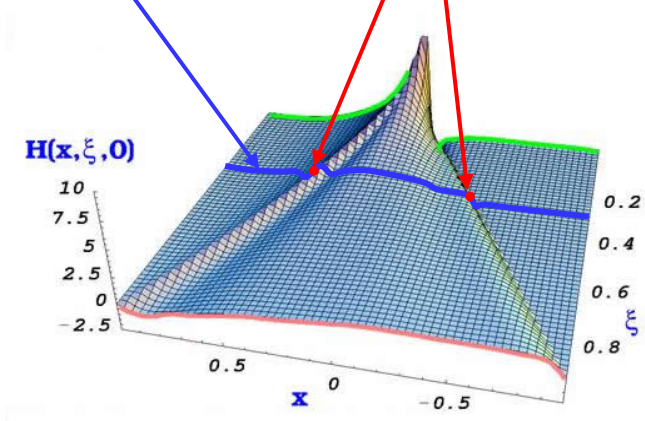
- Twist-3 contribution is small
- π^0 contribution is small

C_{T2} = 2.17 ± 0.16
C_{T3} = 3.13 ± 0.86

Acceptance effects included in fit

Total cross-section and GPDs

$$T^{DVCS} = P\int_{-1}^{+1} \frac{GPD(x,\xi,t)}{x-\xi}dx \quad - \quad i\pi GPD(x=\xi,\xi,t) \quad + \quad \cdots$$



Interesting !
Only depends on *H* and *E*

$$\frac{d^4\sigma}{dx_B dQ^2 dt d\varphi} = \frac{x_B}{2-x_B}\left(\frac{1}{P_1(\varphi)P_2(\varphi)}\right)\frac{t}{4M^2}\left(\frac{x_B}{2-x_B}\right)^2 \left(F_1+F_2\right)\tilde{H} - \Gamma_2(x_B,Q^2,t)\left\{c_0^I + c_1^I\cos\varphi + c_2^I\cos 2\varphi + c_3^I\cos 3\varphi\right\}$$

with

$$\Delta C^I(F) = -\frac{x_B}{2-x_B}(F_1+F_2)\left\{\frac{x_B}{2-x_B}(H+E)+\tilde{H}\right\}$$

$$c_0^I = -8\frac{(2-y)^3}{1-y}K^2\,\mathrm{Re}\left[C^I(F)\right] + \frac{t}{Q^2}(1-y)(2-y)(2-x_B)\,\mathrm{Re}\left[C^I(F)+\Delta C^I(F)\right]$$

$$c_1^I = -8K(2-y)^2\,\mathrm{Re}\left[C^I(F)\right]$$

$\ldots$

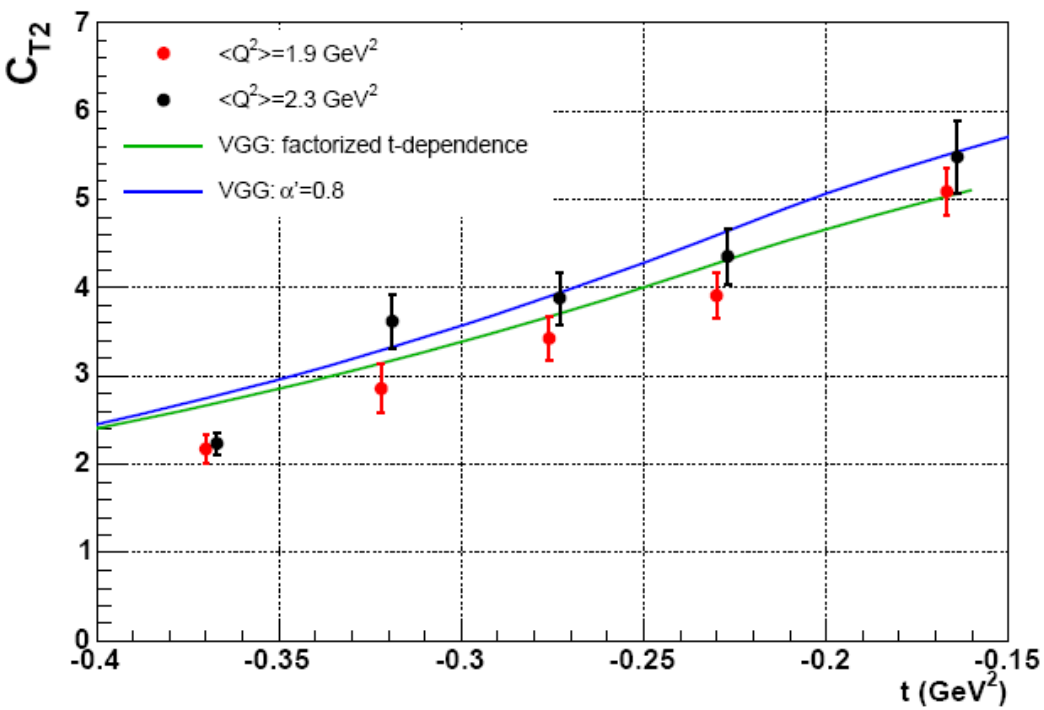
Conclusion so far

- High luminosity/high background rate experiments are doable using smart trigger + sampling system
- All tests of handbag dominance yield positive results
  - No Q^2 dependence of C_{T2} and C_{T3}
  - Twist-3 contributions in both $\Delta\sigma$ and σ are small
- In cross-section difference, accurate extraction of Twist-2 term
- High statistics extraction of total cross-section

Comparison with models - GPDs

$$C_{T2} = F_1(t)\mathcal{H} + \frac{x_B}{2-x_B}[F_1(t)+F_2(t)]\tilde{\mathcal{H}} - \frac{t}{4M^2}F_2(t)\mathcal{E}$$

Preliminary



$$H^q(x,0,t) = F_1(t)q(x)$$

$$H^q(x,0,t) = \frac{1}{x^{\alpha' t}}q(x)$$

If handbag dominates:

$$\mathcal{H} = \pi\sum_q e_q^2(H^q(\xi,\xi,t) - H^q(-\xi,\xi,t))$$

$$\mathcal{E} = \pi\sum_q e_q^2(E^q(\xi,\xi,t) - E^q(-\xi,\xi,t))$$

$$\tilde{\mathcal{H}} = \pi\sum_q e_q^2(\tilde{H}^q(\xi,\xi,t) + \tilde{H}^q(-\xi,\xi,t))$$

Conclusion

- First real test and constraints of DVCS models !
- Work needed on the virtual part of radiative corrections
- Large work needed with theorists to figure out the discrepancy (ies)

  Especially: definition of observables, etc
  (We have already checked all sources give the same BH)

- We now have accurate new data to be compared with models
- More data coming soon from Hall B (cross-sections needed !)
- In the near future, other kinematical domains need to be explored with a similar setup in Hall A