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Particle-Nucleus and Nucleus-Nucleus Scattering at Relativistic Energies

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# Deeply Virtual Compton Scattering in JLAB Hall A

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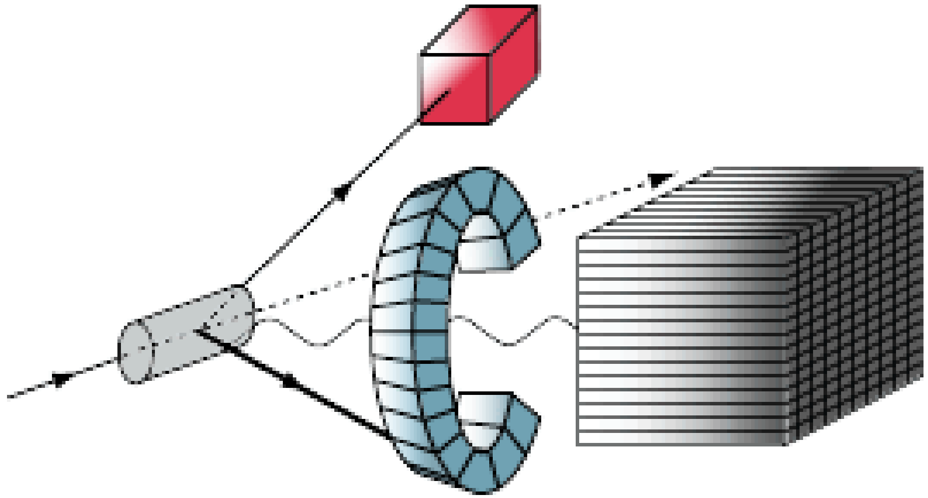
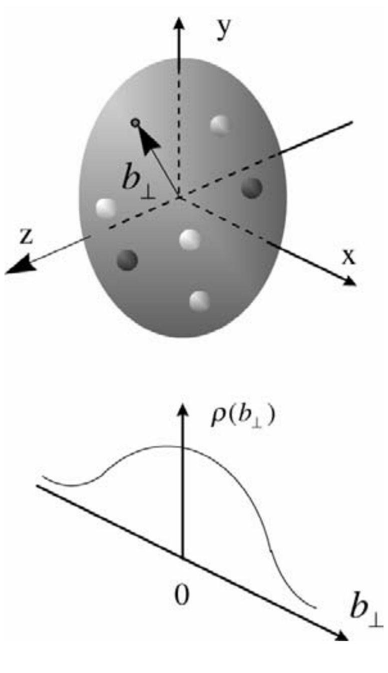
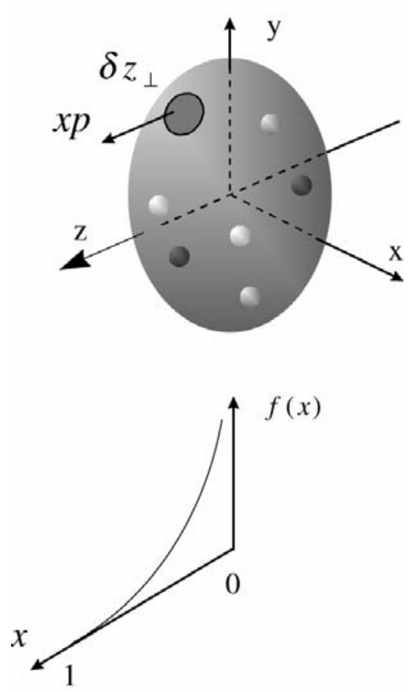
# Deeply Virtual Compton Scattering in JLAB Hall A

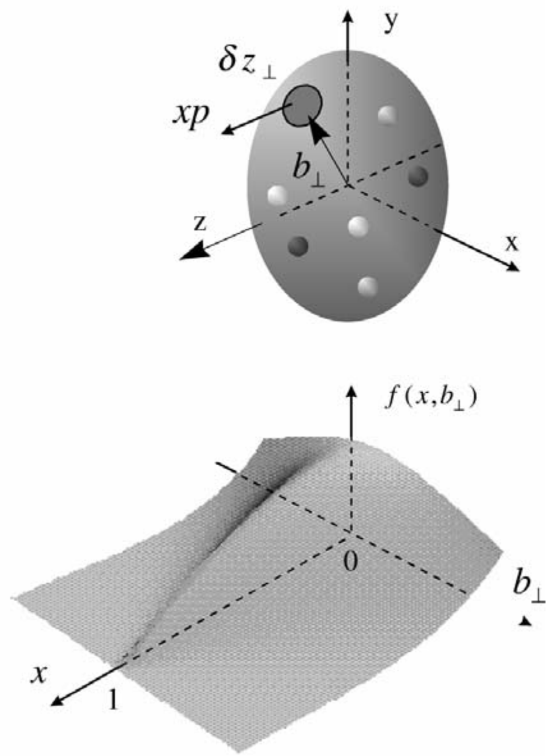
Malek MAZOUZ
*For JLab Hall A & DVCS collaborations*



# Generalized parton distributions: GPDs




Form Factors via
Elastic scaterring

Parton distribution via
Deep inelastic scatering

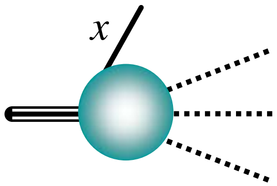
Generalized parton distribution
via Deep exclusive scaterring

Two independent informations
about the nucleon structure

**Link**

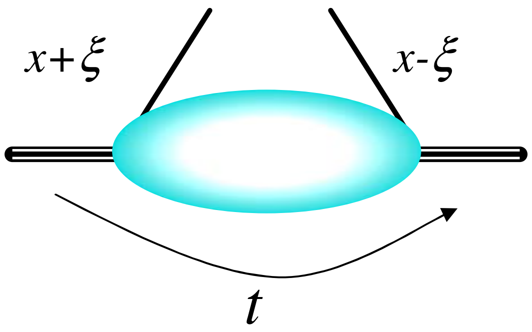
**Mueller, Radyushkin, Ji**

# Generalized parton distributions: GPDs




**Probability** $|\Psi(x)|^2$ that a quark carries a fraction x of the nucleon momentum

→ Parton distributions $q(x)$, $\Delta q(x)$ measured in inclusive reactions (D.I.S.)




**GPDs** measure the **Coherence** $\Psi^*(x+\xi)\ \Psi(x-\xi)$ between a initial state with a quark carrying a fraction *x+ξ* of the nucleon momentum and a final state with a quark carrying a fraction *x-ξ*

→ 4 GPDs : $H, \tilde{H}, E, \tilde{E}(x,\xi,t)$

For each quark flavor

→ Dependence in t : new wealth of physics to explore

**Mueller, Radyushkin, Ji**

# GPDs properties, link to DIS and elastic form factors

**Generalized Parton distributions**

$$H^q, E^q, \tilde{H}^q, \tilde{E}^q(x,\xi,t)$$

**Link to DIS at $\xi=t=0$**

$$H^q(x,0,0) = q(x) = -\overline{q}(-x)$$

$$\tilde{H}^q(x,0,0) = \Delta q(x) = -\Delta\overline{q}(-x)$$

**Link to form factors (sum rules)**

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

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

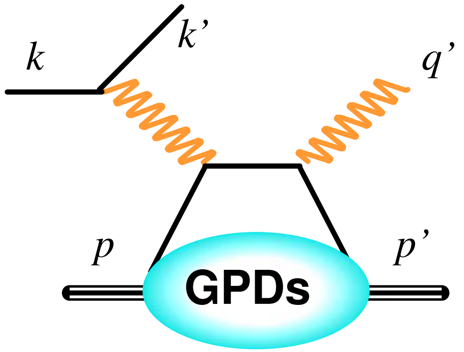
$$\int_{-1}^{1} dx\ \tilde{H}^q(x,\xi,t) = g_A^q(t)\ , \quad \int_{-1}^{1} dx\ \tilde{E}^q(x,\xi,t) = h_A^q(t)$$

**Access to quark angular momentum (Ji's sum rule)**

$$J_q = \frac{1}{2}\Delta\Sigma_q + L_q = \frac{1}{2}\int_{-1}^{1} x dx \left[ H^q(x,\xi,0) + E^q(x,\xi,0) \right]$$

# How to access GPDs: DVCS

Collins, Freund, Strikman

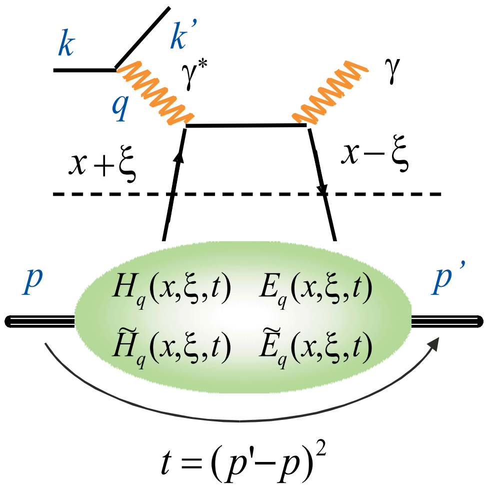



Simplest hard exclusive process involving GPDs

**pQCD factorization theorem**

$$Q^2 = -q^2 = -(k-k')^2 >> M^2$$
$$t = (p-p')^2 = \Delta^2 << Q^2$$

Bjorken regime




Perturbative description

(High Q² virtual photon)

Non perturbative description by

Generalized Parton Distributions

$$x_B = \frac{Q^2}{2pq} = \frac{Q^2}{2M\upsilon}$$

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

$\xi + x =$ fraction of longitudinal momentum

# Deeply Virtual Compton Scattering

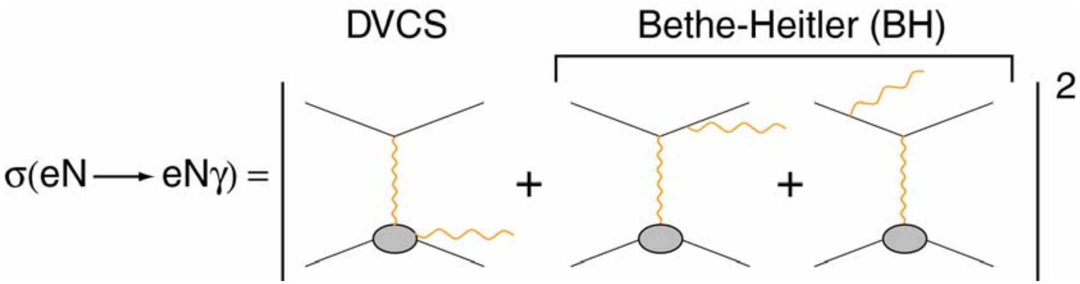
$$T^{DVCS} = \int_{-1}^{+1} \frac{GPD(x,\xi,t)}{x-\xi+i\varepsilon}dx + \cdots$$

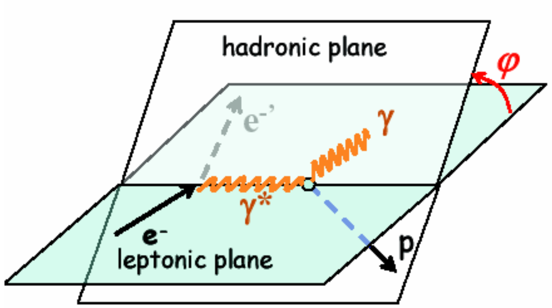
$$= P\int_{-1}^{+1} \frac{GPD(x,\xi,t)}{x-\xi}dx \quad - \quad i\pi GPD(x=\xi,\xi,t) \quad + \ldots$$

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

# What is done at JLab Hall A




But using a polarized electron beam: **Asymmetry appears in Φ**

$$d^5\vec{\sigma} - d^5\overleftarrow{\sigma} \approx 2\,\mathrm{Im}(T^{BH}.T^{DVCS}) + \left[ \left|\vec{T}^{DVCS}\right|^2 - \left|\overleftarrow{T}^{DVCS}\right|^2 \right]$$

The **cross-section difference** accesses the Imaginary part of DVCS and therefore **GPDs at x=ξ**

**Purely real** and **fully calculable**

**Small** at Jlab enegies

$$d^5\sigma \approx \left|T^{BH}\right|^2 + 2T^{BH}.\mathrm{Re}(T^{DVCS}) + \left|T^{DVCS}\right|^2$$

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

**Kroll, Guichon, Diehl, Pire …**

# cross-section difference in the handbag dominance

Pire, Diehl, Ralston, Belitsky, Kirchner, Mueller

$$\frac{d\vec{\sigma}}{dQ^2 dx_B d\Delta^2 d\varphi_e d\varphi_{\gamma\gamma}} - \frac{d\overleftarrow{\sigma}}{dQ^2 dx_B d\Delta^2 d\varphi_e d\varphi_{\gamma\gamma}} = \Gamma_A(x_B, \varphi_e, \Delta^2, \varphi).A\sin\varphi + \Gamma_B(x_B, \varphi_e, \Delta^2, \varphi).B\sin 2\varphi$$

with $x_B = Q^2 / 2p \cdot q$ and $\Delta = p' - p$ ,

and $\varphi_{\gamma\gamma}$ the angle between the leptonic and photonic planes

- Γ contains BH propagators and some kinematics

- A contains twist 2 terms and is a *linear* combination of three GPD imaginary part evaluated at *x=ξ*

$$A = F_1(t) \cdot \mathcal{H} + \frac{x_B}{2 - x_B} \cdot \left(F_1(t) + F_2(t)\right) \cdot \tilde{\mathcal{H}} - \frac{t}{4M^2} F_2(t) \cdot \mathcal{E}$$

- B contains twist 3 terms

# Test of the handbag dominance

-Twist-2 contribution(Γ.A.sinφ) dominate the total cross-section and cross-section difference.

-Twist-2 term (A) and twist-3 term (B) have only log($Q^2$) dependence.

} Test of the handbag dominance

To achieve this goal, an experiment was initiated at JLab Hall A on hydrogen target with high luminosity ($10^{37}$ $cm^{-2}$ $s^{-1}$) and exclusivity.

Another experiment on a deuterium target was initiated to measure DVCS on the neutron. The neutron contribution is very interesting since it will provide a direct measure of GPD E (less constrained!)

# Neutron Target

$$A = F_1(t)\cdot\mathcal{H} + \frac{x_B}{2-x_B}\cdot\left(F_1(t)+F_2(t)\right)\cdot\tilde{\mathcal{H}} - \frac{t}{4M^2}F_2(t)\cdot\mathcal{E}$$

Neutron

| $-t$ | $F_2^p(t)$ | $F_1^p(t)$ | $\left(F_1^p(t)+F_2^p(t)\right)\cdot x_B/(2-x_B)$ | $(-t/4M^2)\cdot F_2^p(t)$ |
|---|---|---|---|---|
| 0.1 | -1.46 | -0.01 | -0.26 | -0.04 |
| 0.3 | -0.91 | -0.04 | -0.17 | -0.06 |
| 0.5 | -0.6 | -0.05 | -0.12 | -0.08 |
| 0.7 | -0.43 | -0.06 | -0.09 | -0.08 |

$F_1^n(t) << F_2^n(t)$ !!!

Model:

$Q^2 = 2\ \mathrm{GeV}^2$
$x_B = 0.3$
$-t = 0.3$

| Target | $\mathcal{H}$ | $\tilde{\mathcal{H}}$ | $\mathcal{E}$ |
|---|---|---|---|
| neutron | 0.81 | -0.07 | 1.73 |

Goeke, Polyakov and Vanderhaeghen

*t=-0.3*

$$A = F_1(t)\cdot\mathcal{H} + \frac{x_B}{2-x_B}\cdot\left(F_1(t)+F_2(t)\right)\cdot\tilde{\mathcal{H}} - \frac{t}{4M^2}F_2(t)\cdot\mathcal{E}$$

$$A = -0.03 \quad + \quad 0.01 \quad - \quad 0.12$$

# Experiment kinematics

- E00-110 (p-DVCS) was finished in November 2004 (started in September)
- E03-106 (n-DVCS) was finished in December 2004 (started in November)

$x_{Bj}$=0.364

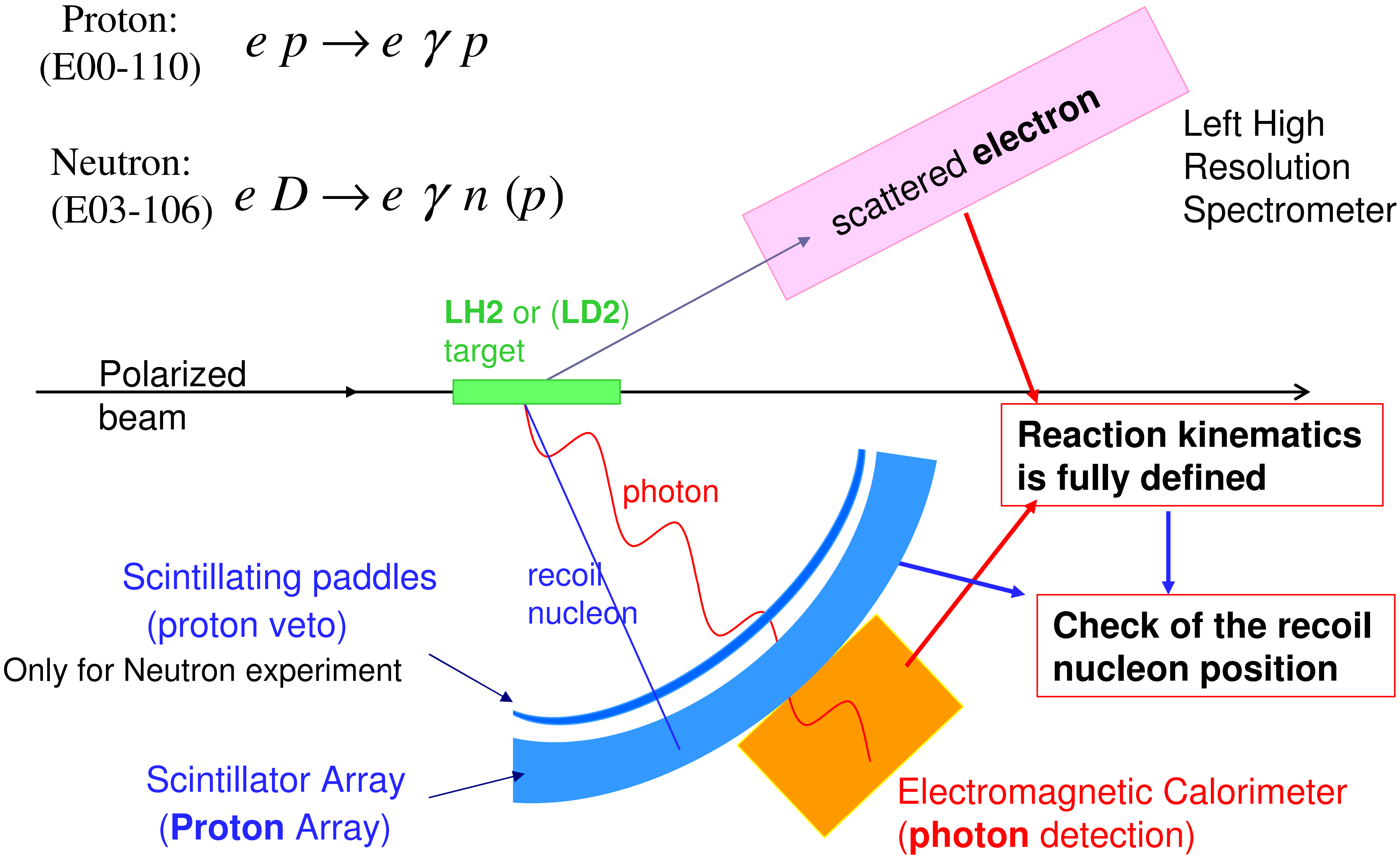
| | s (GeV²) | Q² (GeV²) | $P_e$ (Gev/c) | $\Theta_e$ (deg) | $-\Theta_{\gamma^*}$ (deg) | $\int Ldt$ (fb⁻¹) |
|---|---|---|---|---|---|---|
| proton | 4.94 | 2.32 | 2.35 | 23.91 | 14.80 | 5832 |
| proton | 4.22 | 1.91 | 2.95 | 19.32 | 18.25 | 4365 |
| proton | 3.5 | 1.5 | 3.55 | 15.58 | 22.29 | 3097 |
| neutron | 4.22 | 1.91 | 2.95 | 19.32 | 18.25 | 24000 |

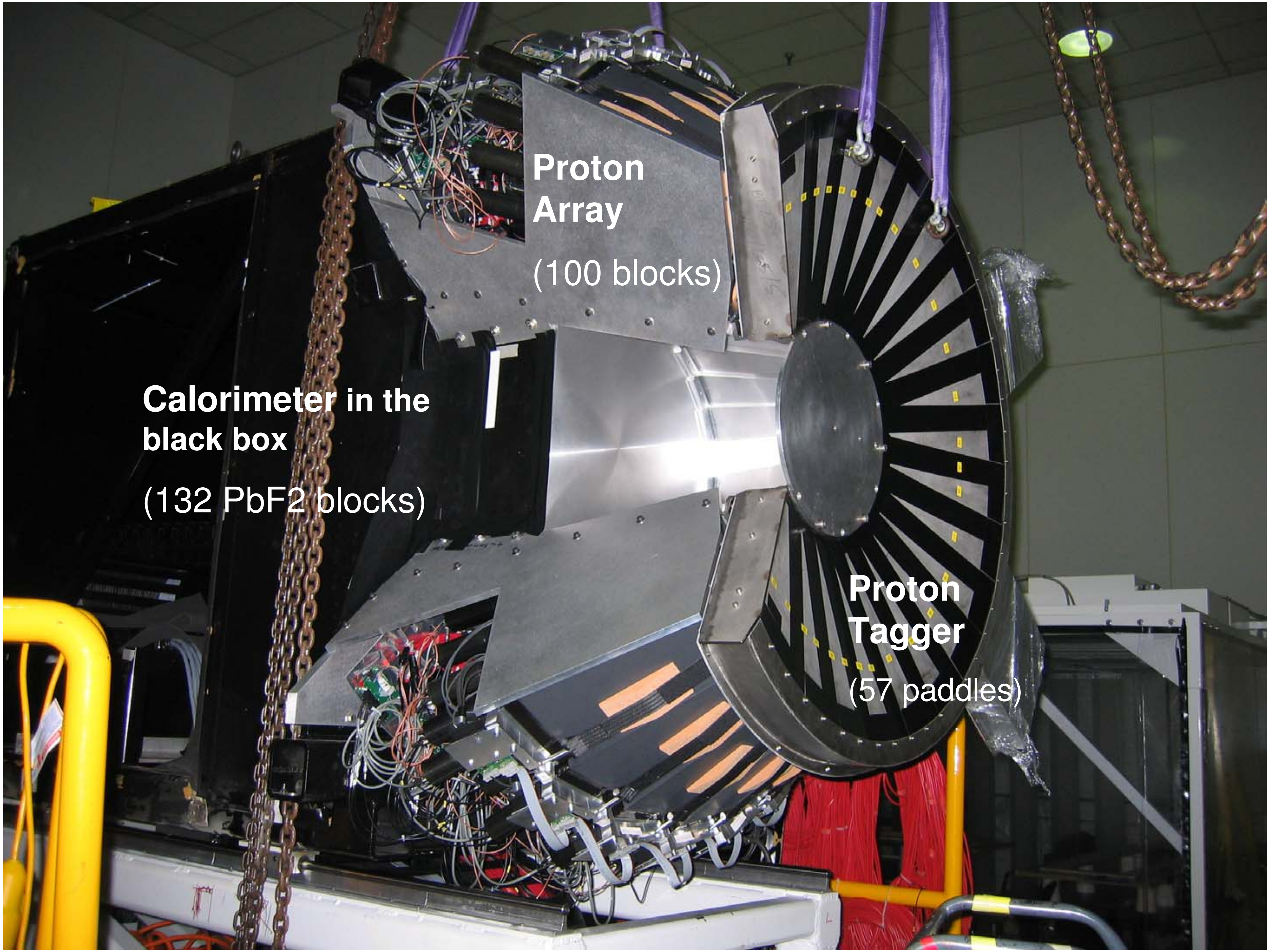
- Beam polarization was about 75.3% during the experiment

# Experimental method

Proton: $e\ p \rightarrow e\ \gamma\ p$
(E00-110)

Neutron: $e\ D \rightarrow e\ \gamma\ n\ (p)$
(E03-106)

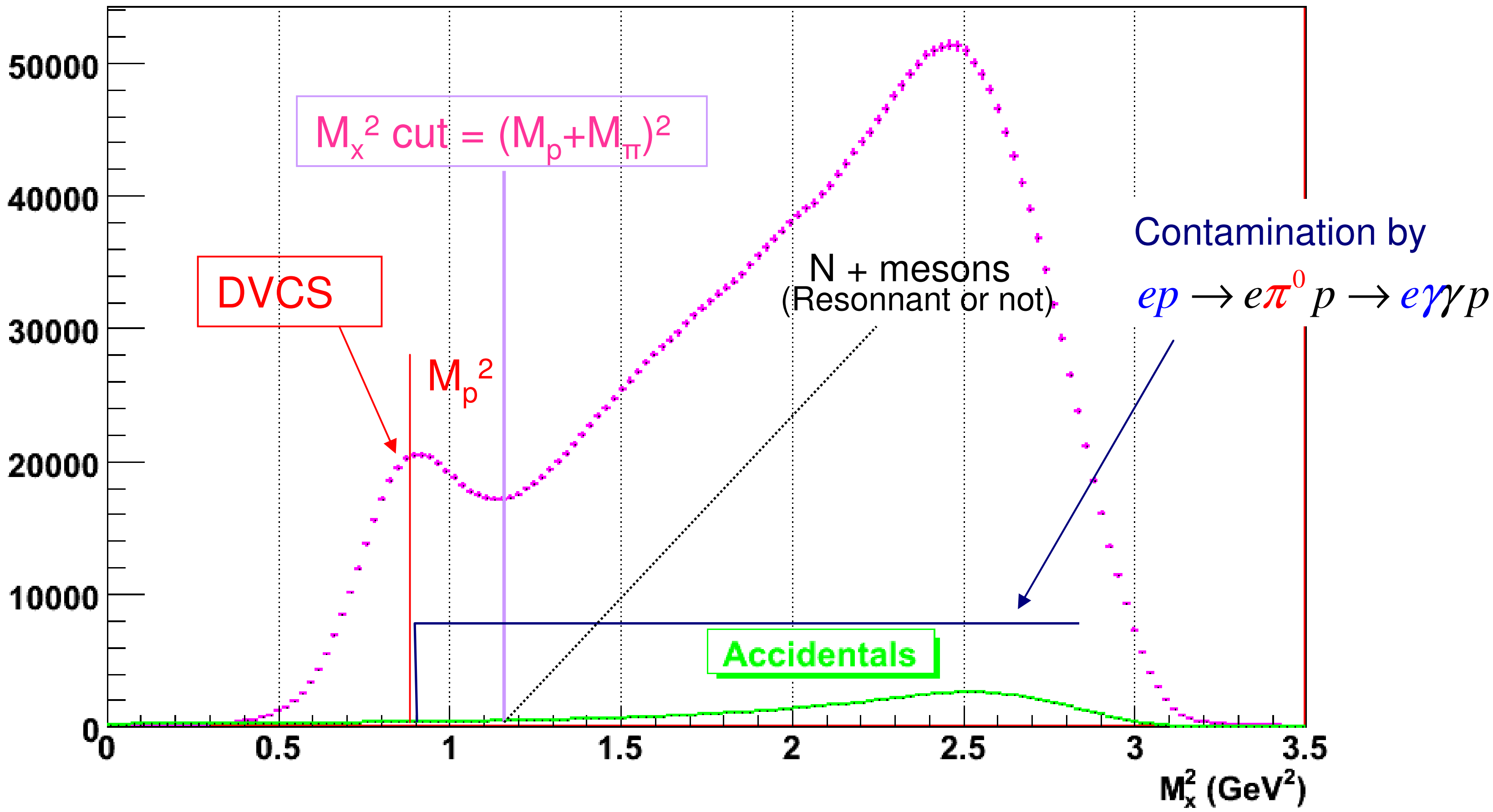




Proton
Array
(100 blocks)
Calorimeter in the
black box
(132 PbF2 blocks)
Proton
Tagger
(57 paddles)

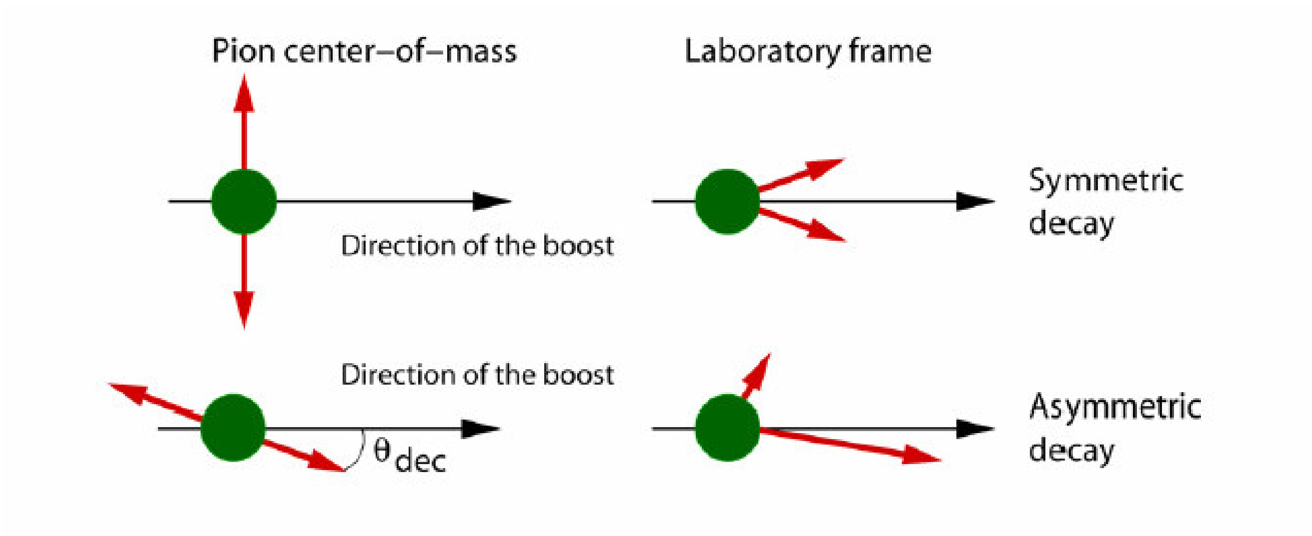
# Analysis - Selection of DVCS events

$$ep \rightarrow e\gamma X$$



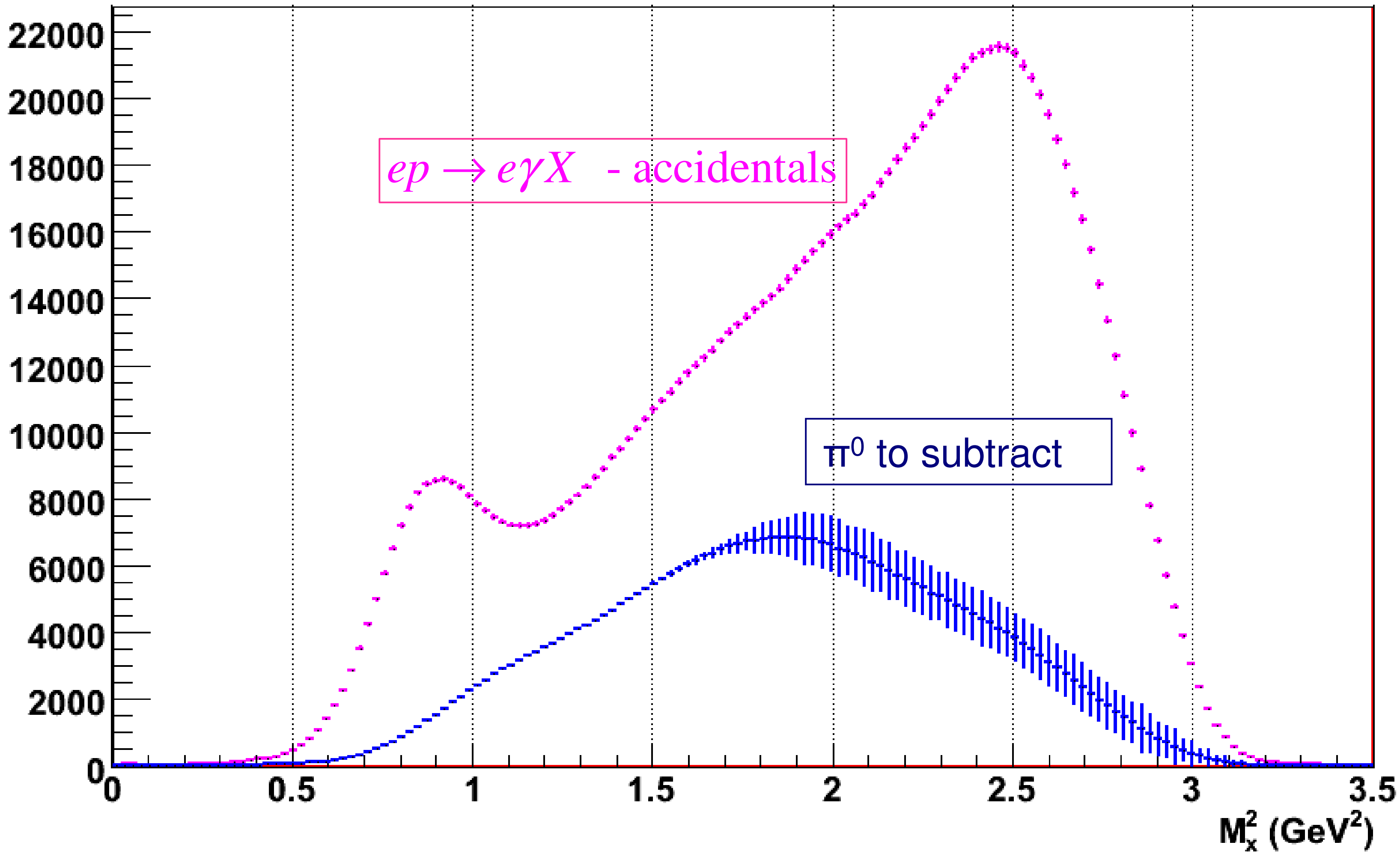
# $\pi^0$ contamination subtraction

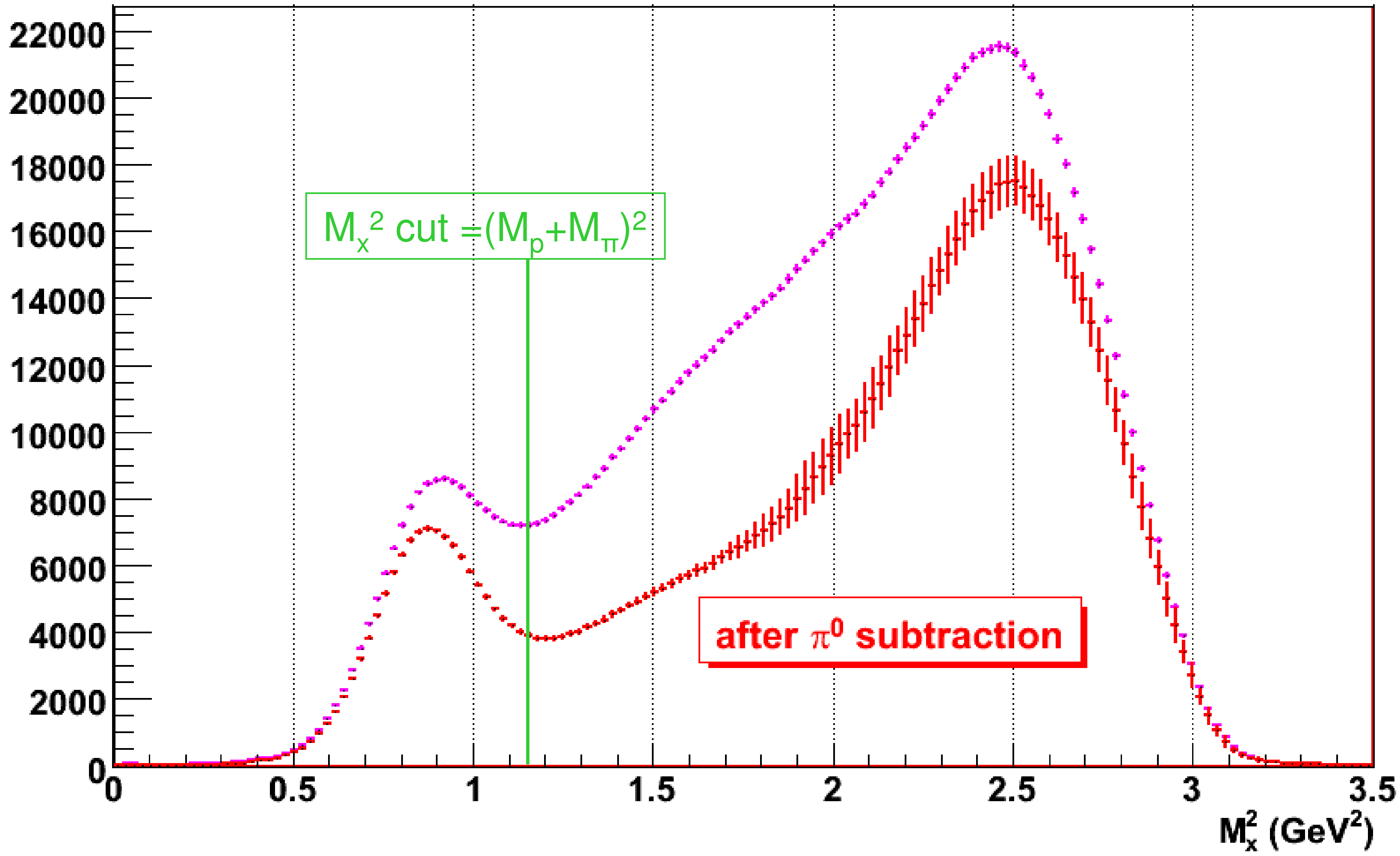
One needs to do a $\pi^0$ subtraction if the only (e,γ) system is used to select DVCS events.




- Symmetric decay: two distinct photons are detected in the calorimeter → No contamination
- Asymmetric decay: 1 photon carries most of the π0 energy → contamination because DVCS-like event.

# $\pi^0$ contamination subtraction

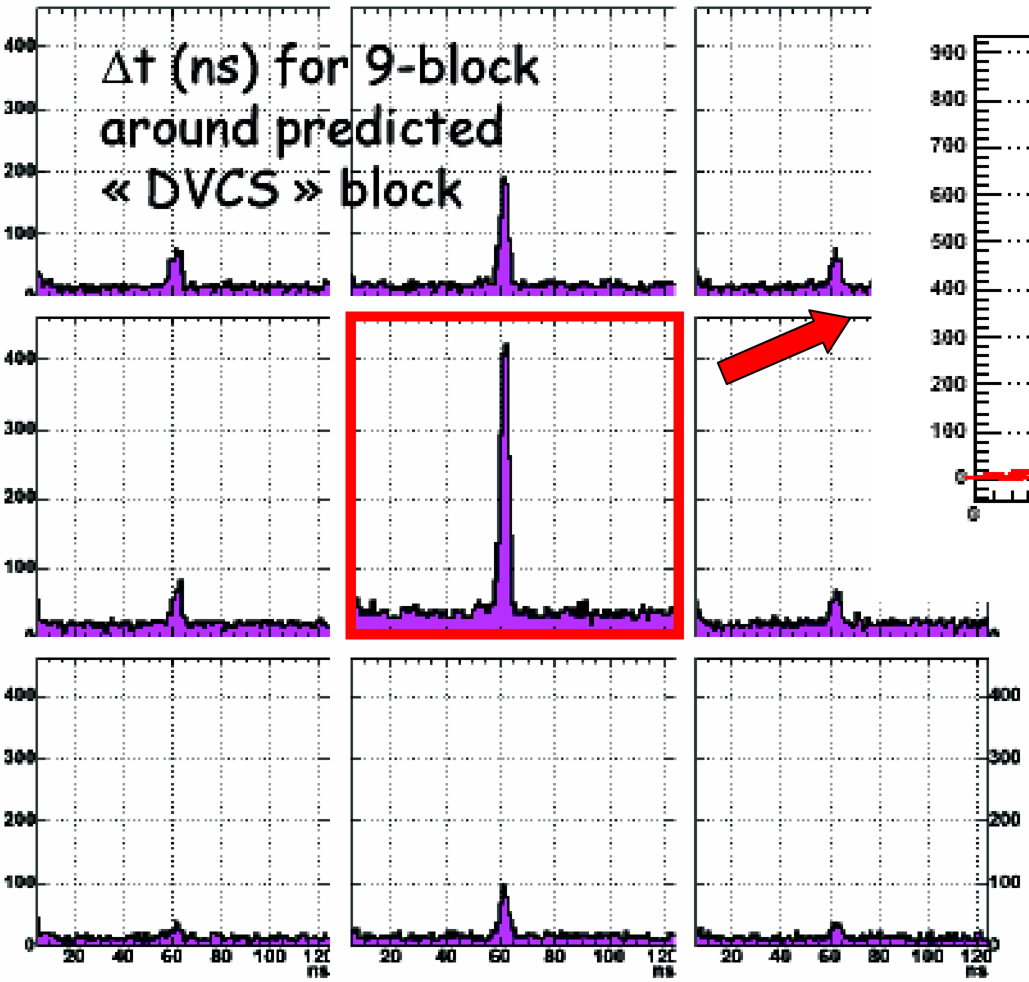


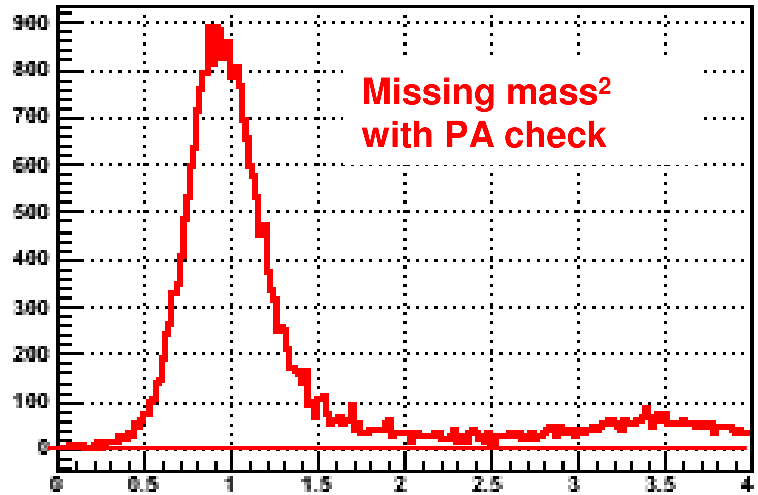


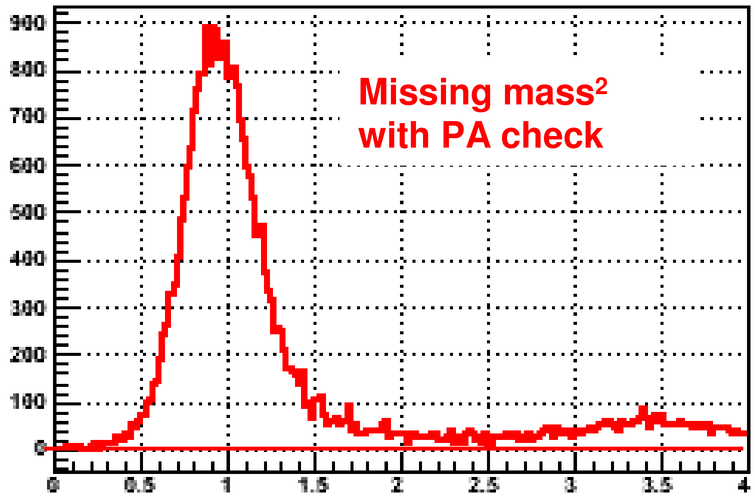

**Still to check the exclusivity under the missing mass cut !**

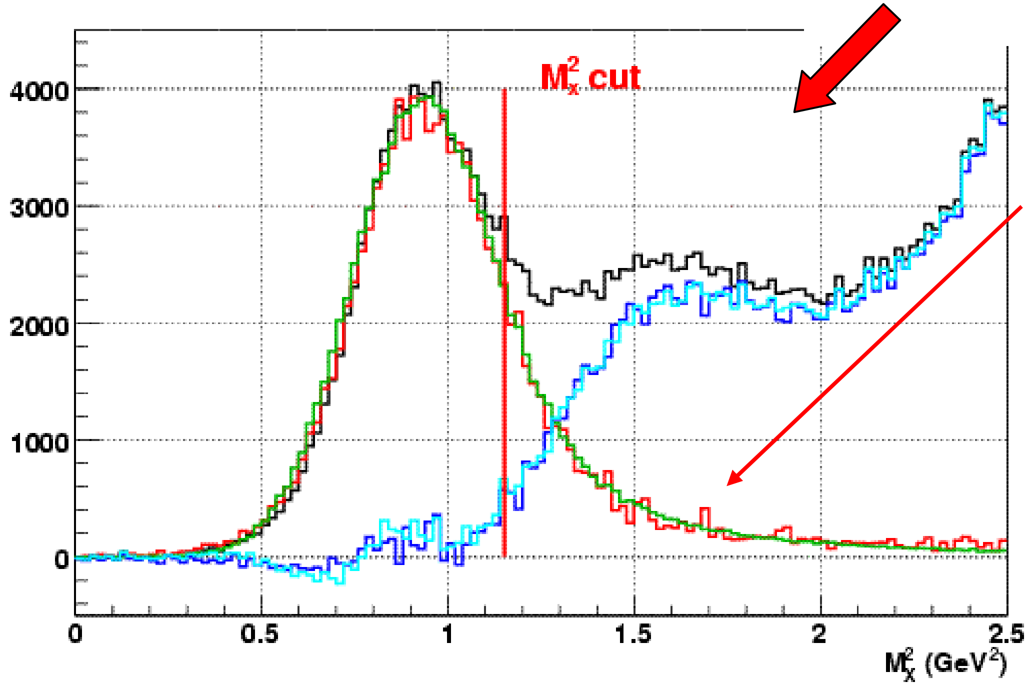
# Check of the exclusivity

One can **predict** for each (e,γ) event the Proton Array block where the missing proton is supposed to be (assuming DVCS event).






Contamination < 3%

# Extraction of observables

$$\frac{d\vec{\sigma}}{dQ^2 dx_B d\Delta^2 d\varphi_e d\varphi_{\gamma\gamma}} - \frac{d\overleftarrow{\sigma}}{dQ^2 dx_B d\Delta^2 d\varphi_e d\varphi_{\gamma\gamma}} = \Gamma_A(x_B, \varphi_e, \Delta^2, \varphi) \cdot A \sin\varphi + \Gamma_B(x_B, \varphi_e, \Delta^2, \varphi) B \sin 2\varphi$$

Q2 independent (A and B)

$$\Delta N^{Exp}(i_e) = N_{i_e}^{+} - N_{i_e}^{-}$$

$$\Delta N^{MC}(i_e) = L\left[ A \underbrace{\int_{x\in i_e} \Gamma_A . \sin\varphi \otimes Acc}_{\text{MC sampling}} + B \underbrace{\int_{x\in i_e} \Gamma_B . \sin 2\varphi \otimes Acc}_{\text{MC sampling}} \right]$$

MC includes real radiative corrections (external+internal)

$$\chi^2 = \sum_{i_e} \frac{\left[ N^{Exp}(i_e) - N^{MC}(i_e) \right]^2}{\left[ \sigma^{Exp}(i_e) \right]^2} \Rightarrow \begin{cases} \mathbf{A} \\ \mathbf{B} \end{cases}$$

# DVCS on the **neutron** and the **deuteron**

- Same exclusivity check as before
- The number of detected $\pi^0$ with hydrogen and deuterium target (same kinematics) shows that:

$$\frac{\sigma(ed \rightarrow e\pi^0 X)}{\sigma(ep \rightarrow e\pi^0 X)} \approx 1.0$$

→ In our kinematics $\pi^0$ come essentially from proton in the deuterium

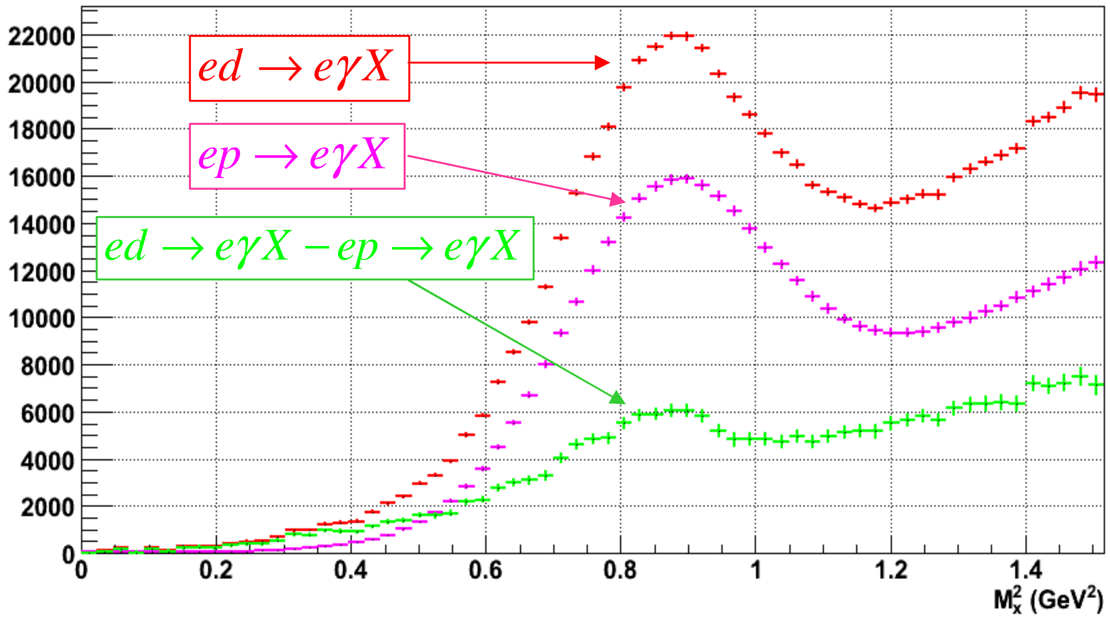
→ $\pi^0$ asymmetry is small

→ No $\pi^0$ subtraction needed for neutron and coherent deuteron

By subtracting proton contribution from deuterium, one should access to the neutron and coherent deuteron contributions.

$Q^2$= 1.9 GeV$^2$

<t>= -0.3 GeV$^2$



# Conclusion

- With High Resolution spectrometer and a good calorimeter, we are able to measure the Helicity dependence of **the nucleon**.
  - Work at precisely defined kinematics: $Q^2$ , *s and* $x_{Bj}$
  - Work at a high luminosity
- All tests of Handbag dominance give positive results :
  - No $Q^2$ dependence of twist-2 and twist-3 terms.
  - Twist-3 contribution is small.
- Accurate extraction of a linear combination of GPDS (twist-2 terms)
- High statistics extraction of the total cross-section (another linear combination of GPD!)
- Analysis in progress to extract the **neutron** and **deuteron** contribution

# Proton Target

$$A = F_1(t)\cdot\mathcal{H} + \frac{x_B}{2-x_B}\cdot\left(F_1(t)+F_2(t)\right)\cdot\tilde{\mathcal{H}} - \frac{t}{4M^2}F_2(t)\cdot\mathcal{E}$$

Proton

| $-t$ | $F_2^p(t)$ | $F_1^p(t)$ | $\left(F_1^p(t)+F_2^p(t)\right)\cdot x_B/(2-x_B)$ | $(-t/4M^2)\cdot F_2^p(t)$ |
|---|---|---|---|---|
| 0.1 | 1.34 | 0.81 | 0.38 | 0.04 |
| 0.3 | 0.82 | 0.56 | 0.24 | 0.06 |
| 0.5 | 0.54 | 0.42 | 0.17 | 0.07 |
| 0.7 | 0.38 | 0.33 | 0.13 | 0.07 |

Model:

$Q^2 = 2\ \text{GeV}^2$
$x_B = 0.3$
$-t = 0.3$

| Target | $\mathcal{H}$ | $\tilde{\mathcal{H}}$ | $\mathcal{E}$ |
|---|---|---|---|
| Proton | 1.13 | 0.70 | 0.98 |

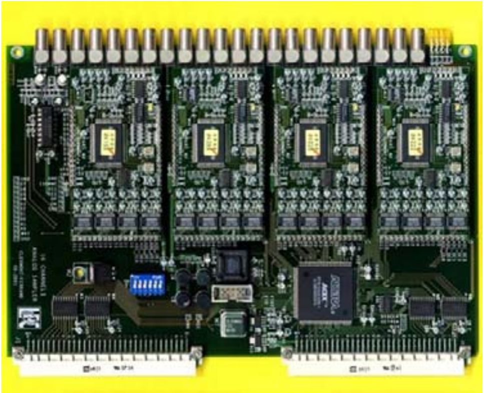
Goeke, Polyakov and Vanderhaeghen

*t=-0.3*

$$A = \underbrace{F_1(t)\cdot\mathcal{H}} + \underbrace{\frac{x_B}{2-x_B}\cdot\left(F_1(t)+F_2(t)\right)\cdot\tilde{\mathcal{H}}} - \underbrace{\frac{t}{4M^2}F_2(t)\cdot\mathcal{E}}$$

$$A = 0.34 + 0.17 + 0.06$$

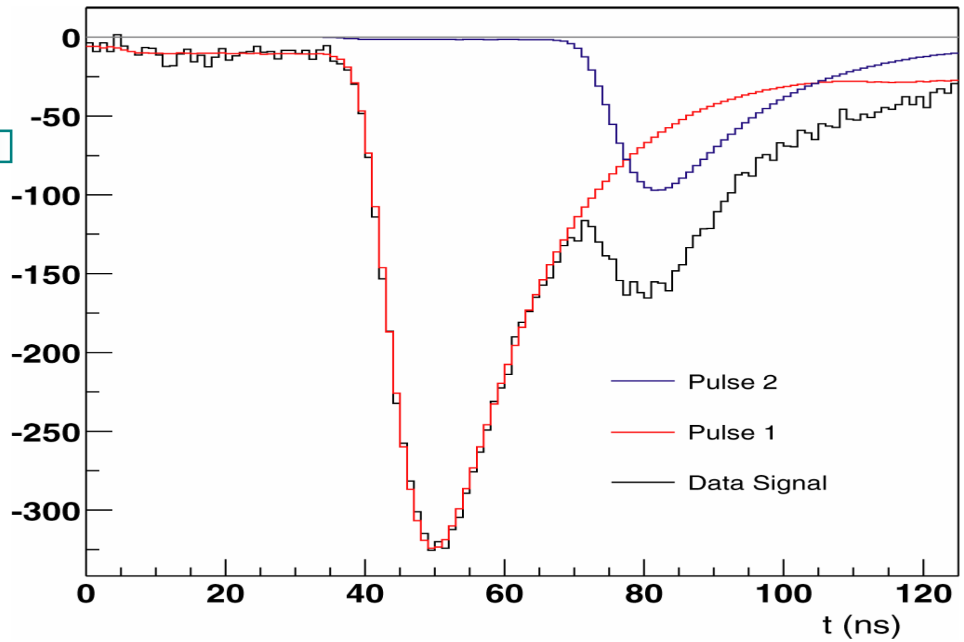
# Electronics



**1 GHz Analog Ring Sampler (ARS)**

**x 128 samples x 289 detector channels**

Sample each PMT signal in 128 values (1 value/ns)




Extract signal properties (charge, time) with a wave form Analysis.

Allows to deal with pile-up events.

# Electronics

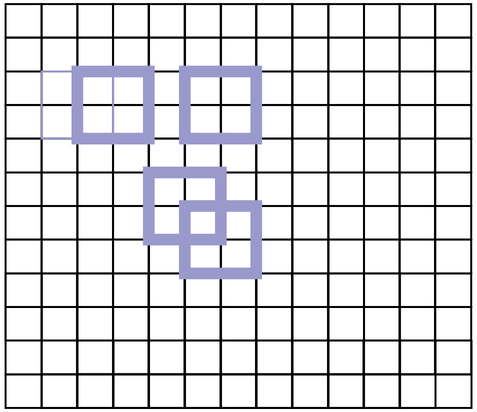
Not all the calorimeter channels are read for each event

Calorimeter trigger

Following HRS trigger, stop ARS.

30MHz trigger FADC digitizes all calorimeter signals in 85ns window.

- Compute all sums of 4 adjacent blocks.
- Look for at least 1 sum over threshold
- Validate or reject HRS trigger within 340 ns



Not all the Proton Array channels are read for each event

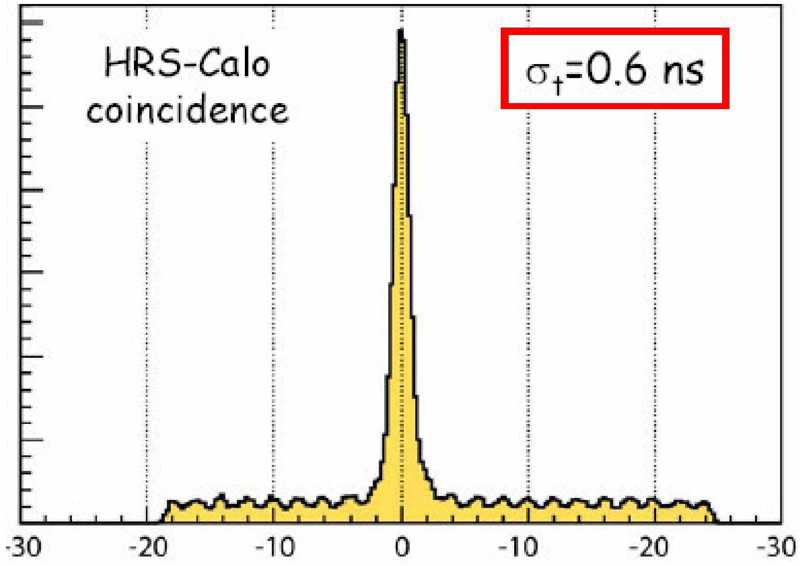
# Calorimeter resolution and calibration

-Time resolution < 1ns for all detectors

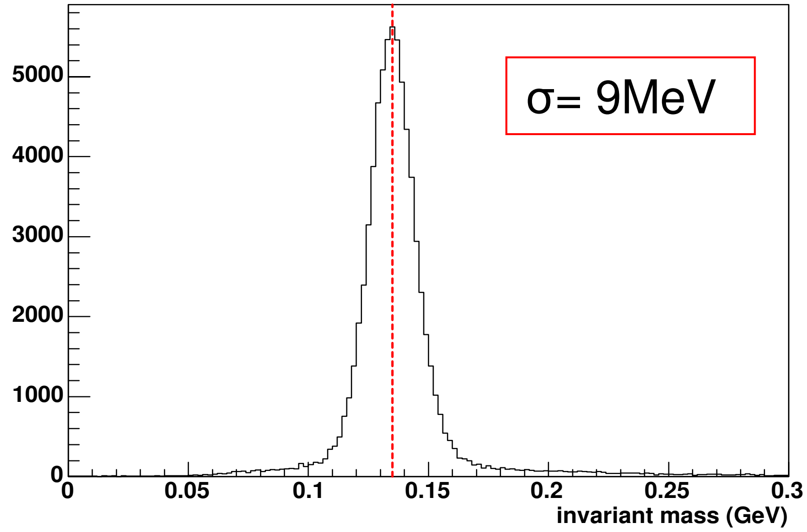
-Energy resolution of the calorimeter :

$$\frac{\delta E}{E} = 2.5\% \quad \text{at } 4.2GeV$$

- Photon position resolution in the calorimeter: **2mm**




Invariant mass of 2 photons in the calorimeter →




Detecting $\pi^0$ in the calorimeter checks its calibration

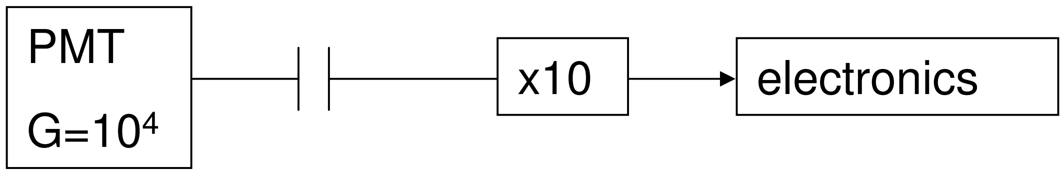
# High luminosity measurement

Up to

$$L_{nucleon} = 4.10^{37}\, cm^{-2} s^{-1}$$

At ~1 meter from target

($\Theta_{\gamma^*}$=18 degrees)

- Low energy electromagnetic background
- 

- Requires good electronics

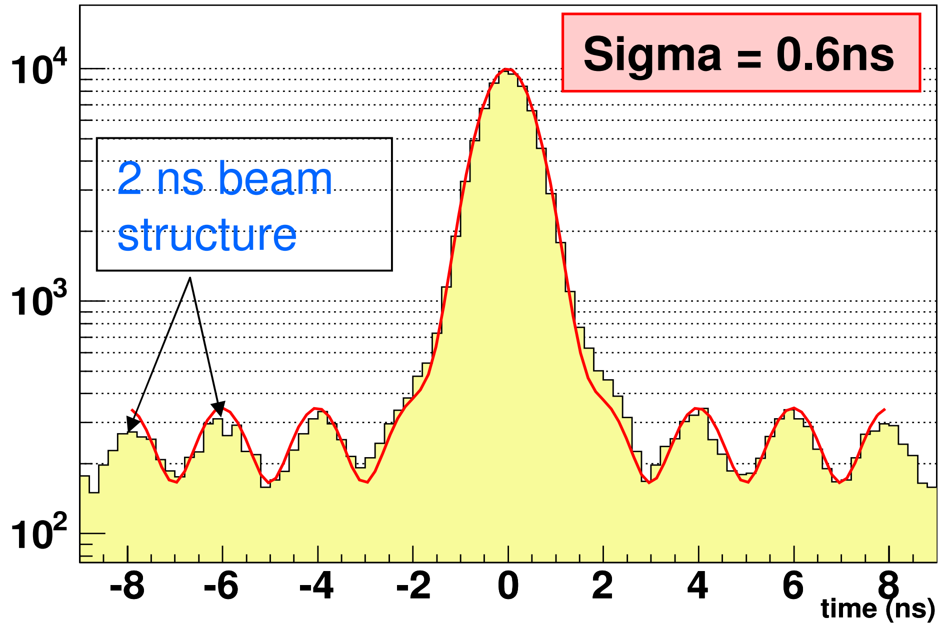
# Analysis status – preliminary

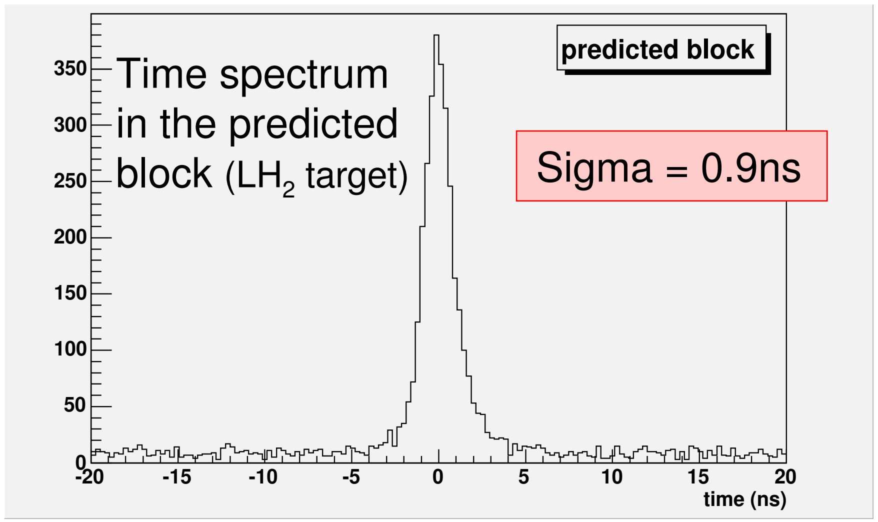
Time difference between the electron arm and the detected photon

Selection of events in the coincidence peak

Determination of the missing particle (assuming DVCS kinematics)

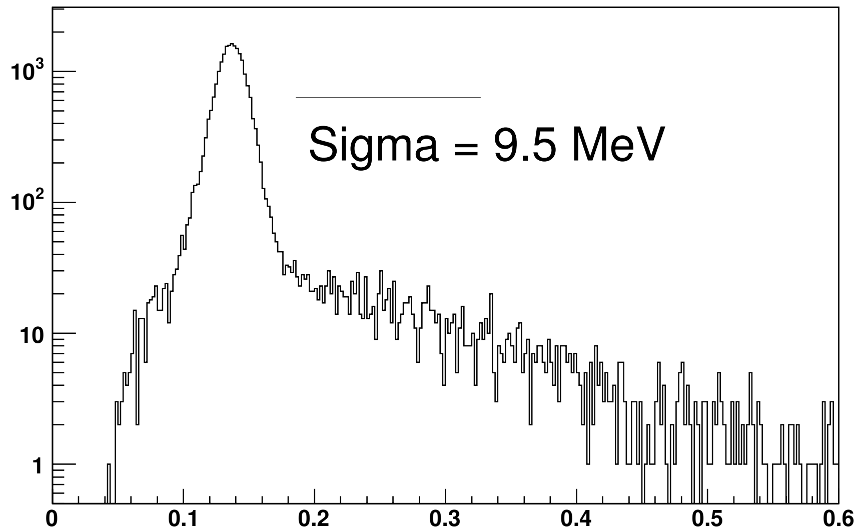
Check the presence of the missing particle in the predicted block (or region) of the Proton Array



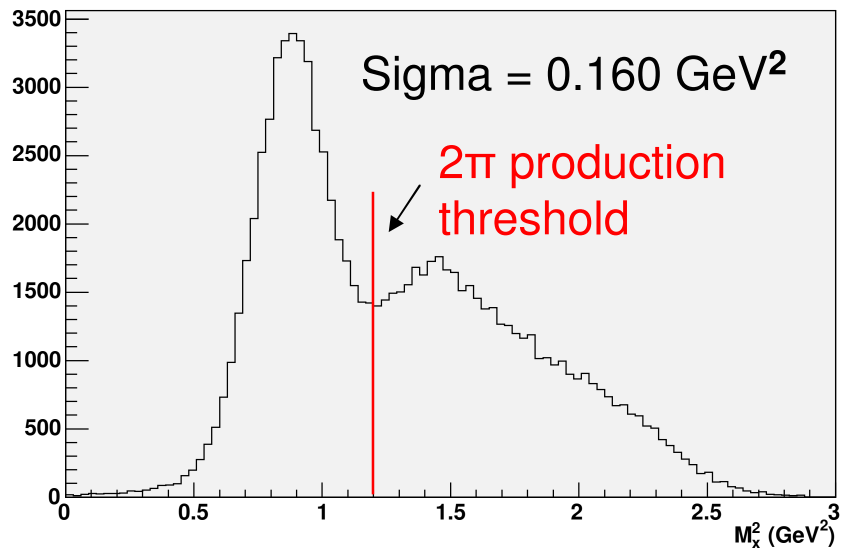
# $\pi^0$ electroproduction - preliminary

Invariant mass of 2 photons in the calorimeter




Good way to control calorimeter calibration

Missing mass² of ep→e$\pi^0$x

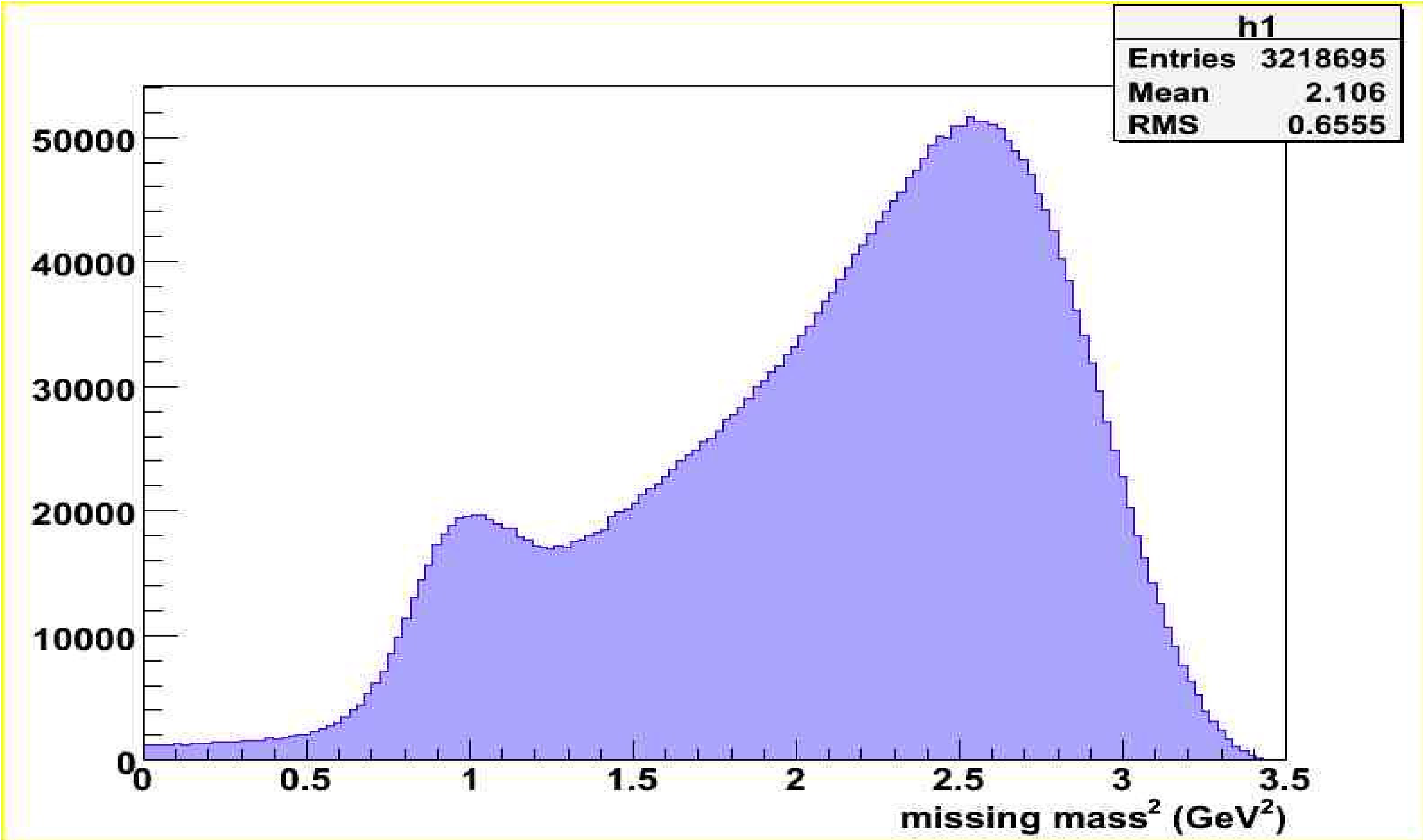



2 possible reactions:

ep→e$\pi^0$p

ep→en$\rho^+$ , $\rho^+$→ $\pi^0$ $\pi^+$

## Missing mass$^2$ with $LD_2$ target



# Time spectrum in the tagger

(no Proton Array cuts)