Deeply Virtual Compton Scattering on the neutron in Jefferson Lab Hall A.

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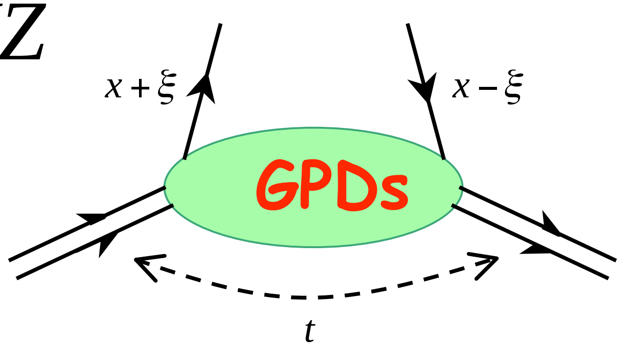
Ph.D. Defense, Grenoble

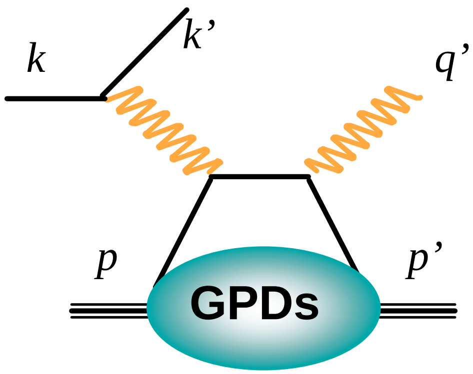
8 December 2006



C. Hyde-Wright, Hall A Collaboration Meeting

- Physics case
- n-DVCS experimental setup
- Analysis method
- Results and conclusions

How to access GPDs: DVCS



Handbag diagram

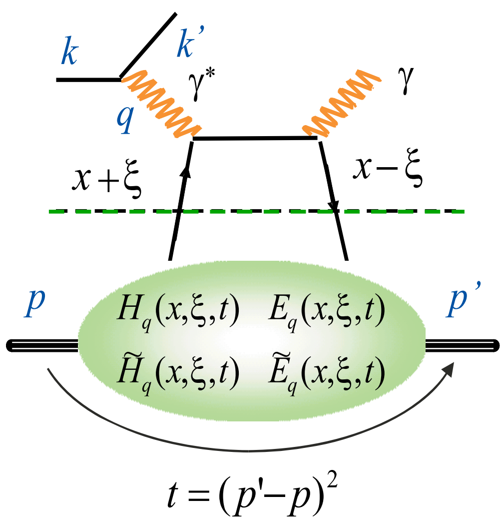
Deeply Virtual Compton Scattering is the simplest hard exclusive process involving GPDs

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 Q^2 virtual photon)

Non perturbative description by

Generalized Parton Distributions

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

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

$\xi \pm x =$ fraction of longitudinal momentum

Deeply Virtual Compton Scattering

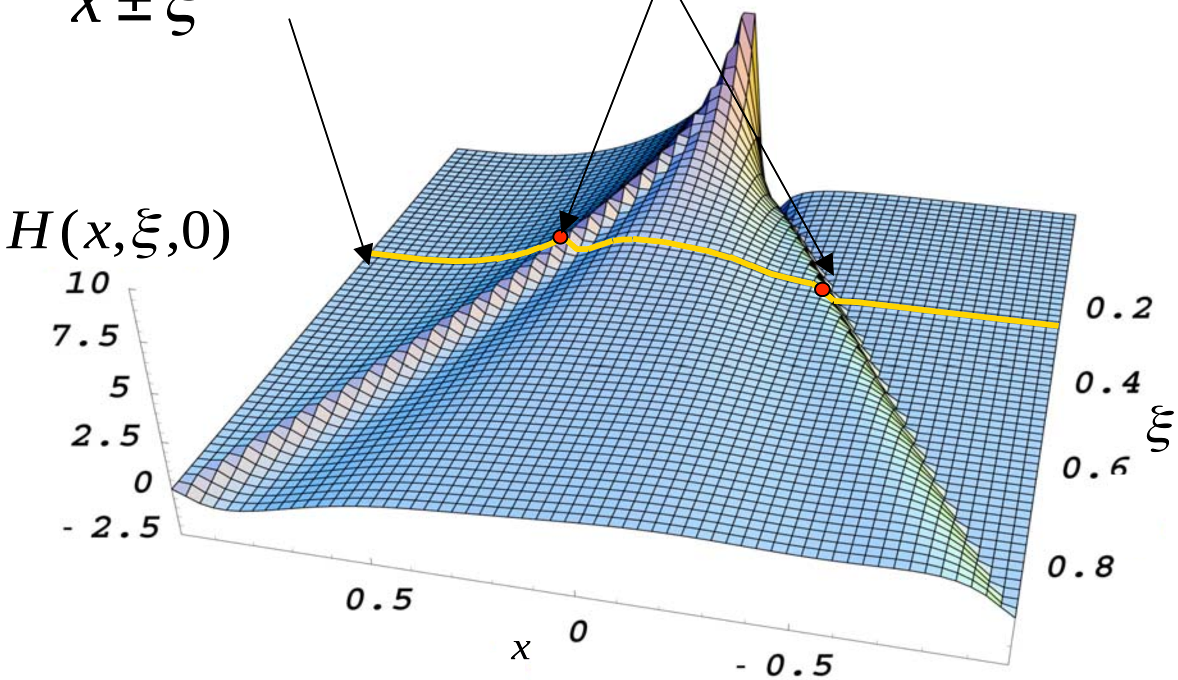
The GPDs enter the DVCS amplitude as an integral over x :

DVCS amplitude

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

Real part

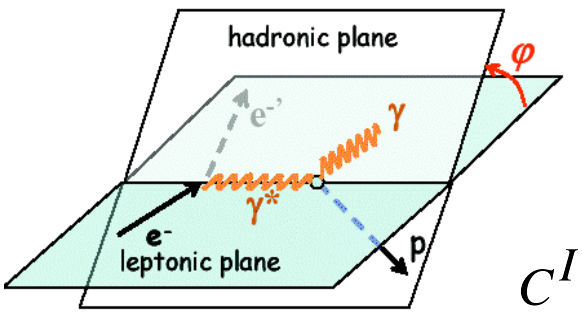
Imaginary part



Expression of the cross-section difference

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

$$\frac{1}{2}\left[\frac{d^5\vec{\sigma}}{dQ^2 dx_B dt d\phi_e d\varphi} - \frac{d^5\overleftarrow{\sigma}}{dQ^2 dx_B dt d\phi_e d\varphi}\right] = \frac{\Gamma_3(x_B,Q^2,t)}{P_1(\varphi)P_2(\varphi)}\left\{s_1^I \sin(\varphi) + s_2^I \sin(2\varphi)\right\} + \Gamma_2(x_B,Q^2,t)s_1^{DVCS}\sin(\varphi)$$



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

$$C^I(H,\tilde{H},E) = F_1(t)\mathbf{H}(\xi,t) + \xi G_M(t)\tilde{\mathbf{H}}(\xi,t) + \frac{-t}{4M^2}F_1(t)\mathbf{E}(\xi,t)$$

If handbag dominance

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

GPDs

Neutron Target

Model:

(Goeke, Polyakov and Vanderhaeghen)

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

$Q^2 = 2\ \text{GeV}^2$

$x_B = 0.3$

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

$$C^I(H,\tilde{H},E) = F_1(t)\mathbf{H}(\xi,t) + \xi G_M(t)\tilde{\mathbf{H}}(\xi,t) + \frac{-t}{4M^2}F_1(t)\mathbf{E}(\xi,t)$$

$-t$	$F_2^n(t)$	$F_1^n(t)$	$\left(F_1^n(t)+F_2^n(t)\right)\cdot x_B/(2-x_B)$	$(-t/4M^2)\cdot F_2^n(t)$
0.3	-0.91	-0.04	-0.17	-0.07

$$\Im m\left(C^I\right) = F_1(t)\cdot \text{H} - \frac{x_B}{2-x_B}\cdot\left(F_1(t)+F_2(t)\right)\cdot \tilde{\text{H}} - \frac{t}{4M^2}F_2(t)\cdot \text{E}$$

$$\Im m\left(C^I\right) = -0.03 \quad + \quad 0.01 \quad - \quad 0.13$$

n-DVCS experiment

An **exploratory** experiment was performed at JLab Hall A on hydrogen target and deuterium target with high luminosity (4.10^{37} cm^{-2} s^{-1}) and exclusivity.

Small cross-sections

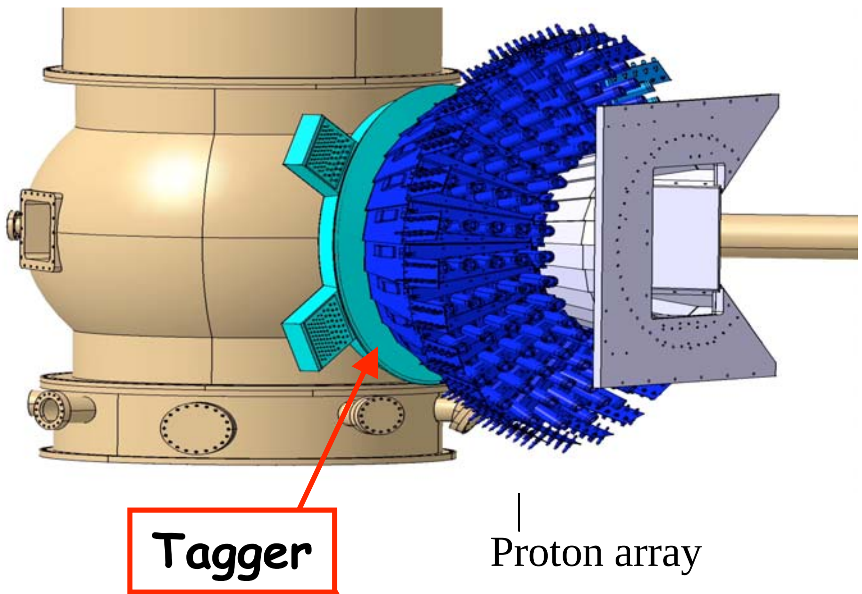
Requires good experimental resolution

Goal : Measure the n-DVCS polarized cross-section difference which is mostly sensitive to GPD E (less constrained!)

E03-106 (n-DVCS) followed directly the p-DVCS experiment and was finished in December 2004 (started in November).

x_{Bj}=0.364	s (GeV²)	Q² (GeV²)	P_e (Gev/c)	Θ_e (deg)	$-\Theta_{\gamma^*}$ (deg)	$\int Ldt$ (fb^{-1})
Hydrogen	4.22	1.91	2.95	19.32	18.25	4365
Deuterium	4.22	1.91	2.95	19.32	18.25	24000

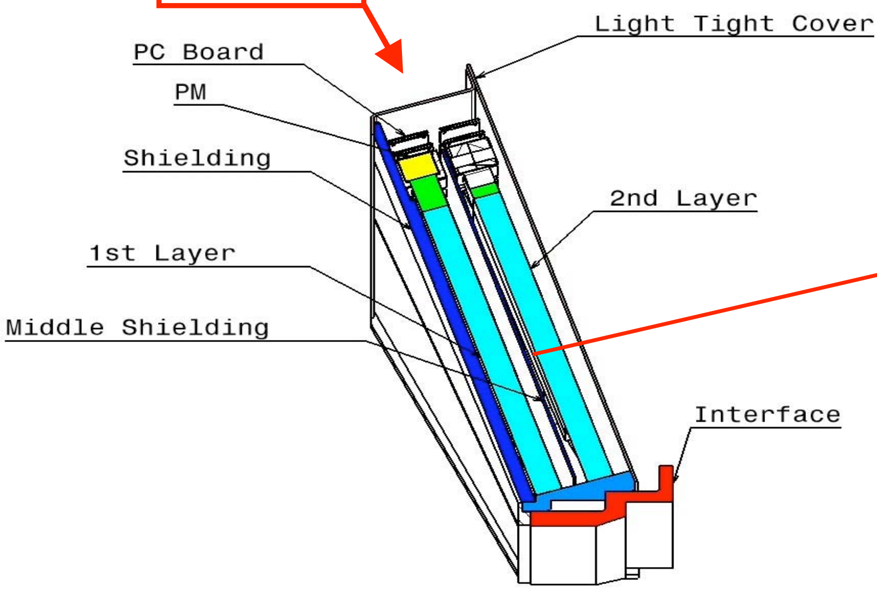
Proton tagger : neutron-proton discrimination

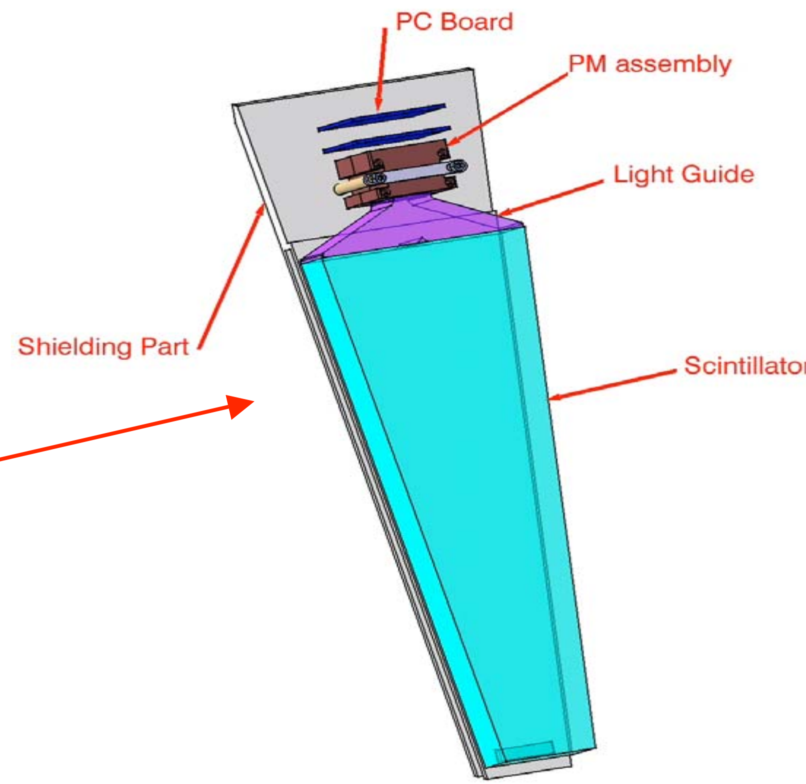


Two scintillator layers:

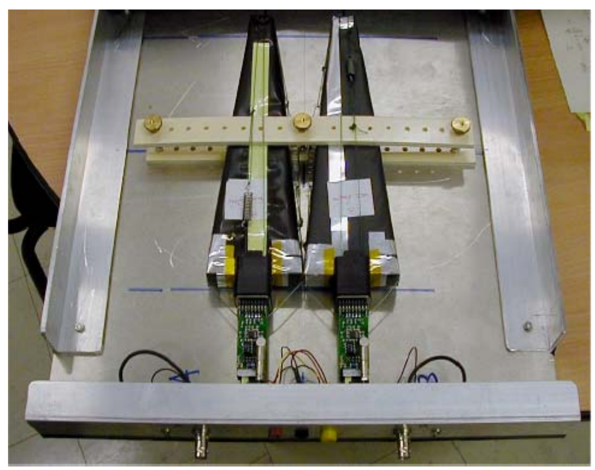
-1st layer: 28 scintillators, 9 different shapes

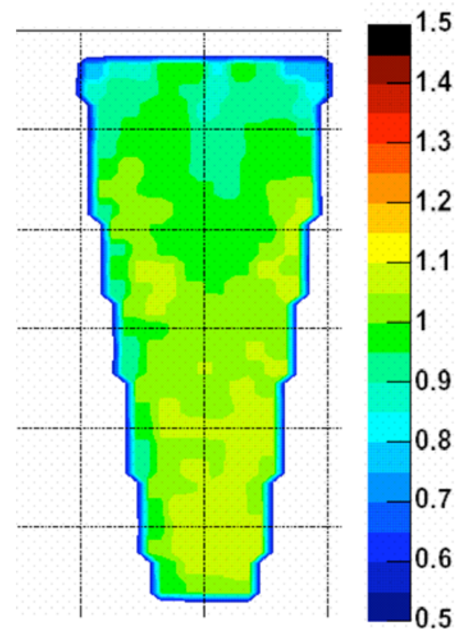
-2nd layer: 29 scintillators, 10 different shapes

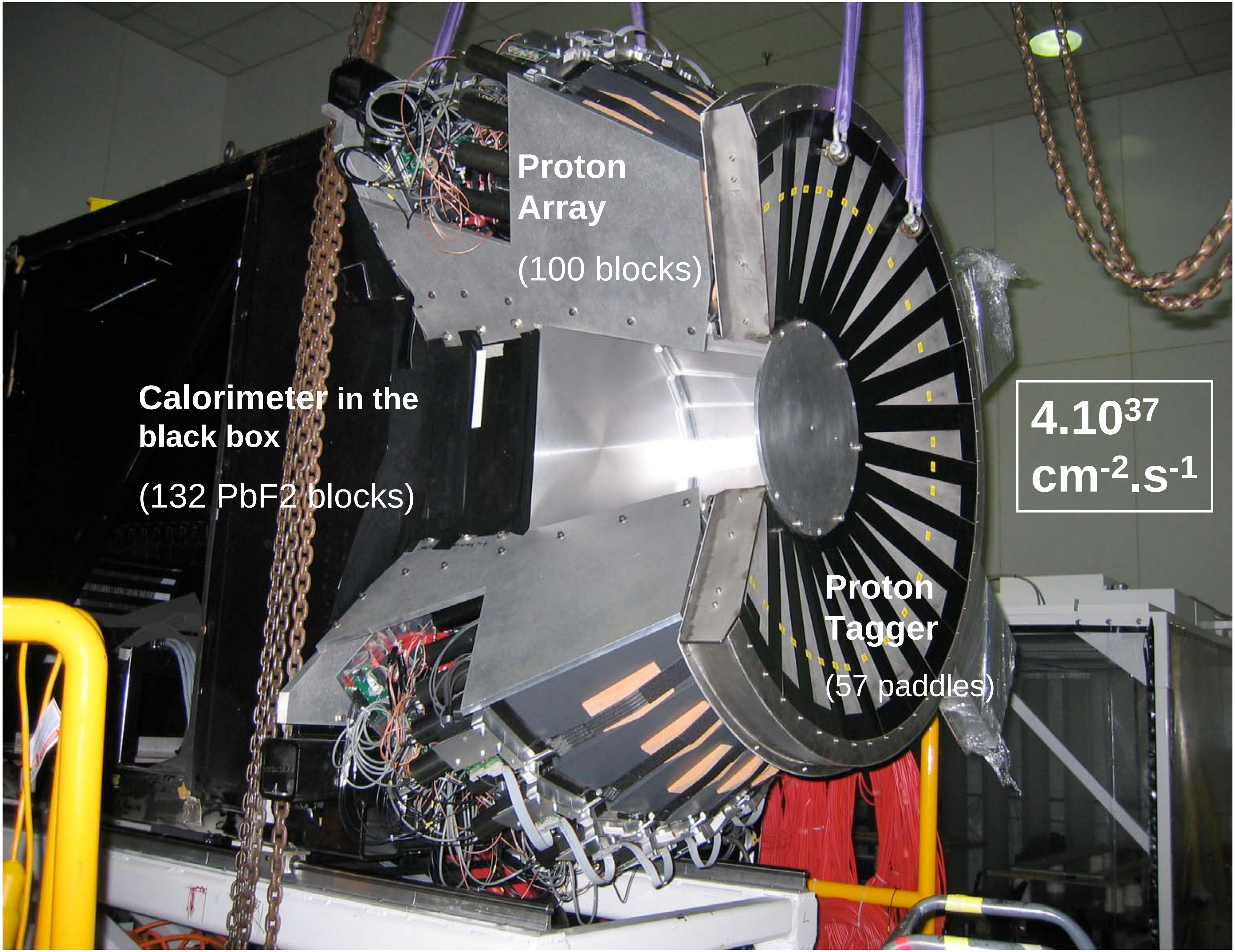




Proton tagger





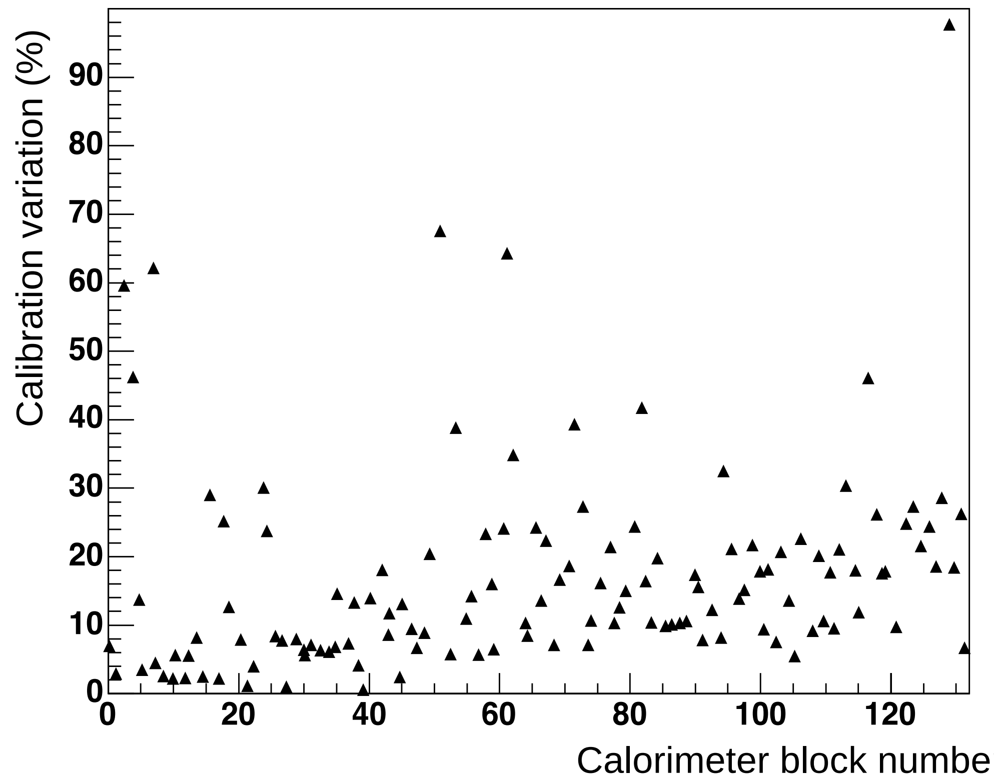

Proton
Array
(100 blocks)
Calorimeter in the
black box
(132 PbF2 blocks)
Proton
Tagger
(57 paddles)
4.10^37
cm^-2.s^-1

Calorimeter energy calibration

2 elastic runs H(e,e'p) to calibrate the calorimeter

Achieved resolution : $\frac{\sigma(E)}{E} = 2.4\%$ at 4.2 GeV ; $\delta x = 2$ mm

Variation of calibration coefficients during the experiment due to radiation damage.



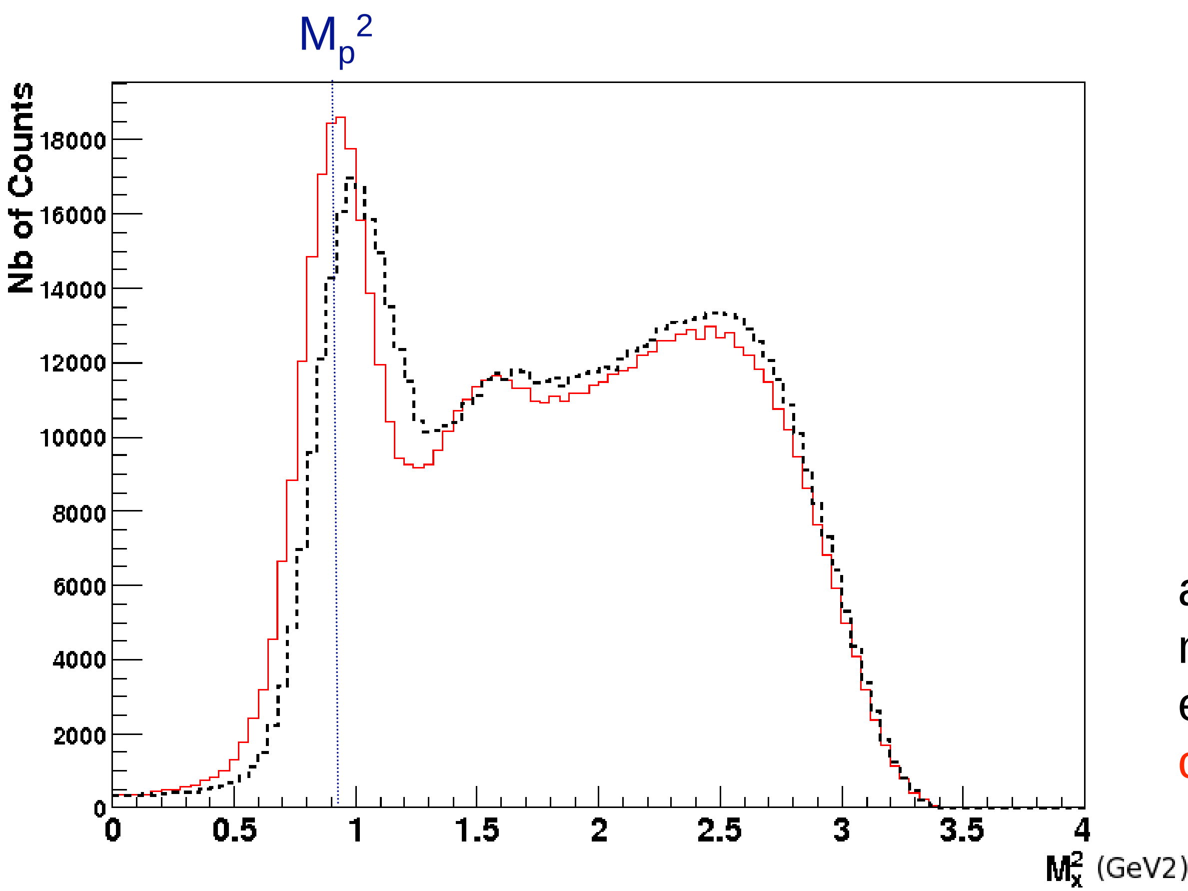
Solution : extrapolation of elastic coefficients assuming a linearity between the received radiation dose and the gain variation

H(e,e'γ)p and D(e,e'γ)X data measured "before" and "after"

Calorimeter energy calibration

We have 2 independent methods to check and correct the calorimeter calibration

1st method : missing mass of $D(e,e'\pi^-)X$ reaction

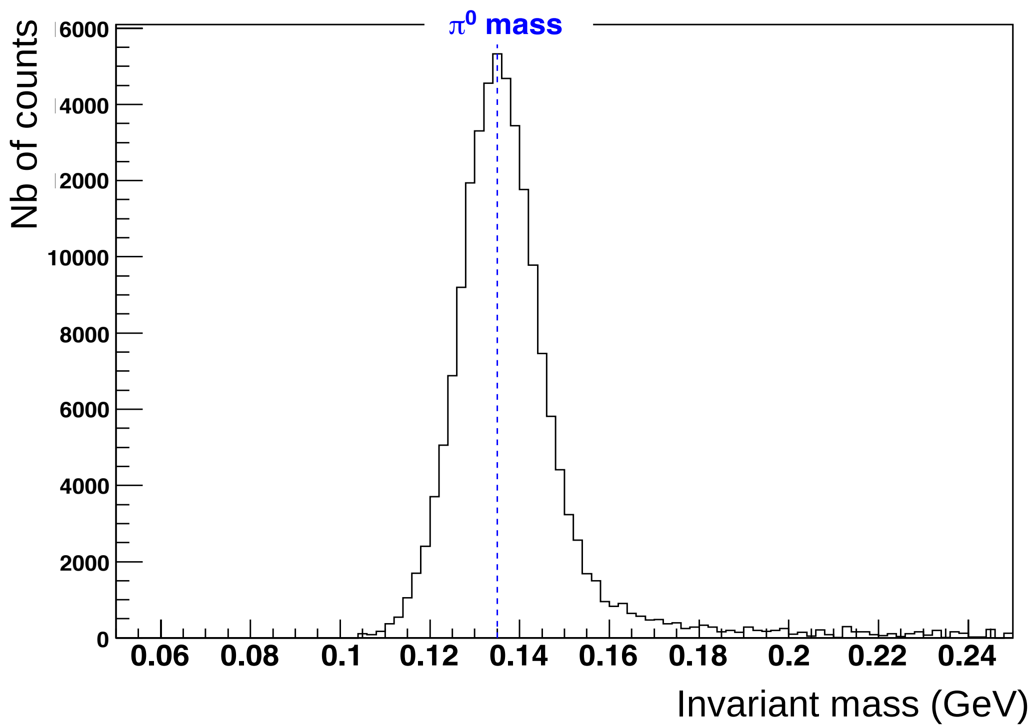


By selecting $n(e,e'\pi^-)p$ events, one can predict the energy deposit in the calorimeter using only the cluster position.

a χ^2 minimisation between the measured and the predicted energy gives a better calibration.

Calorimeter energy calibration

2nd method : Invariant mass of 2 detected photons in the calorimeter (π^0)



π^0 invariant mass position check the quality of the previous calibration for each calorimeter region.

Corrections of the previous calibration are possible.

Differences between the results of the 2 methods introduce a systematic error of **1%** on the calorimeter calibration.

Triple coincidence analysis

Proton Array and Tagger (hardware) work properly during the experiment, but :

Identification of n-DVCS events with the recoil detectors is impossible because of the high background rate.

→ Many Proton Array blocks contain signals on time for each event .

→ Accidental subtraction is made for p-DVCS events and gives stable beam spin asymmetry results. The same subtraction method gives incoherent results for neutrons.

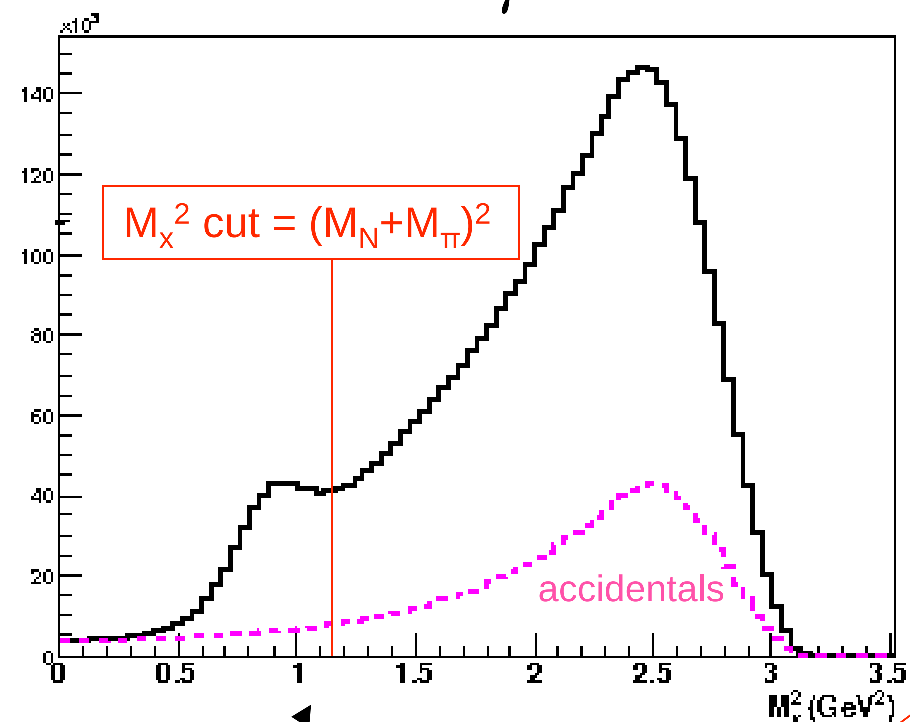
Other major difficulties of this analysis:

→ proton-neutron conversion in the tagger shielding.
Not enough statistics to subtract this contamination correctly

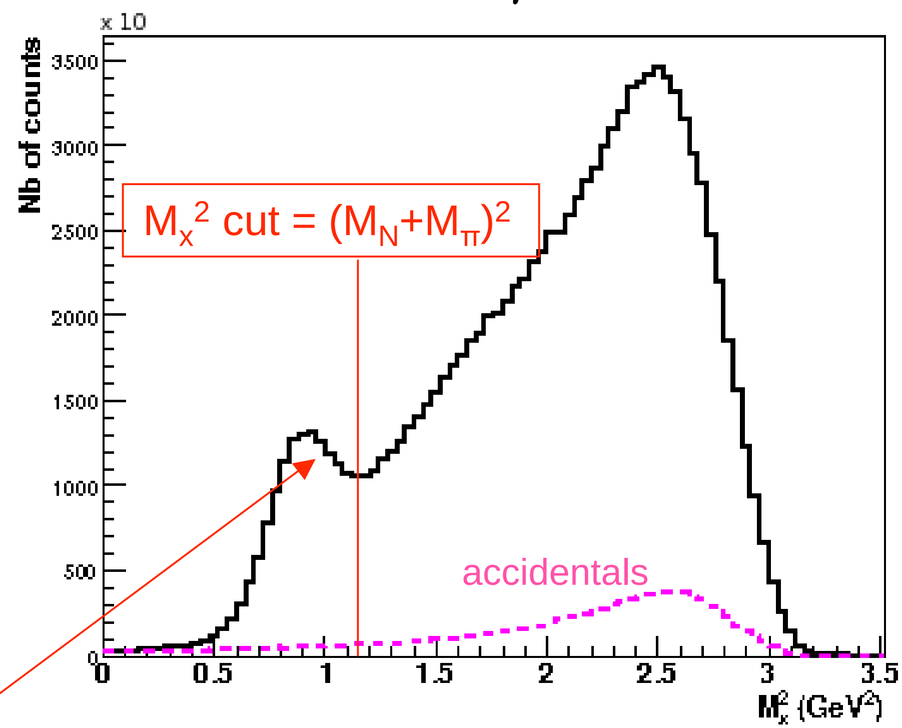
→ The triple coincidence statistics of n-DVCS is at least a factor 20 lower than the available statistics in the double coincidence analysis.

Double coincidence analysis

$eD \rightarrow e\gamma\, X$



$eH \rightarrow e\gamma\, X$



$$D(e,e'\gamma)X = p(e,e'\gamma)p + n(e,e'\gamma)n + d(e,e'\gamma)d + \dots$$

p-DVCS events

n-DVCS events

d-DVCS events

Mesons production

Double coincidence analysis

1) Normalize Hydrogen and Deuterium data to the same luminosity

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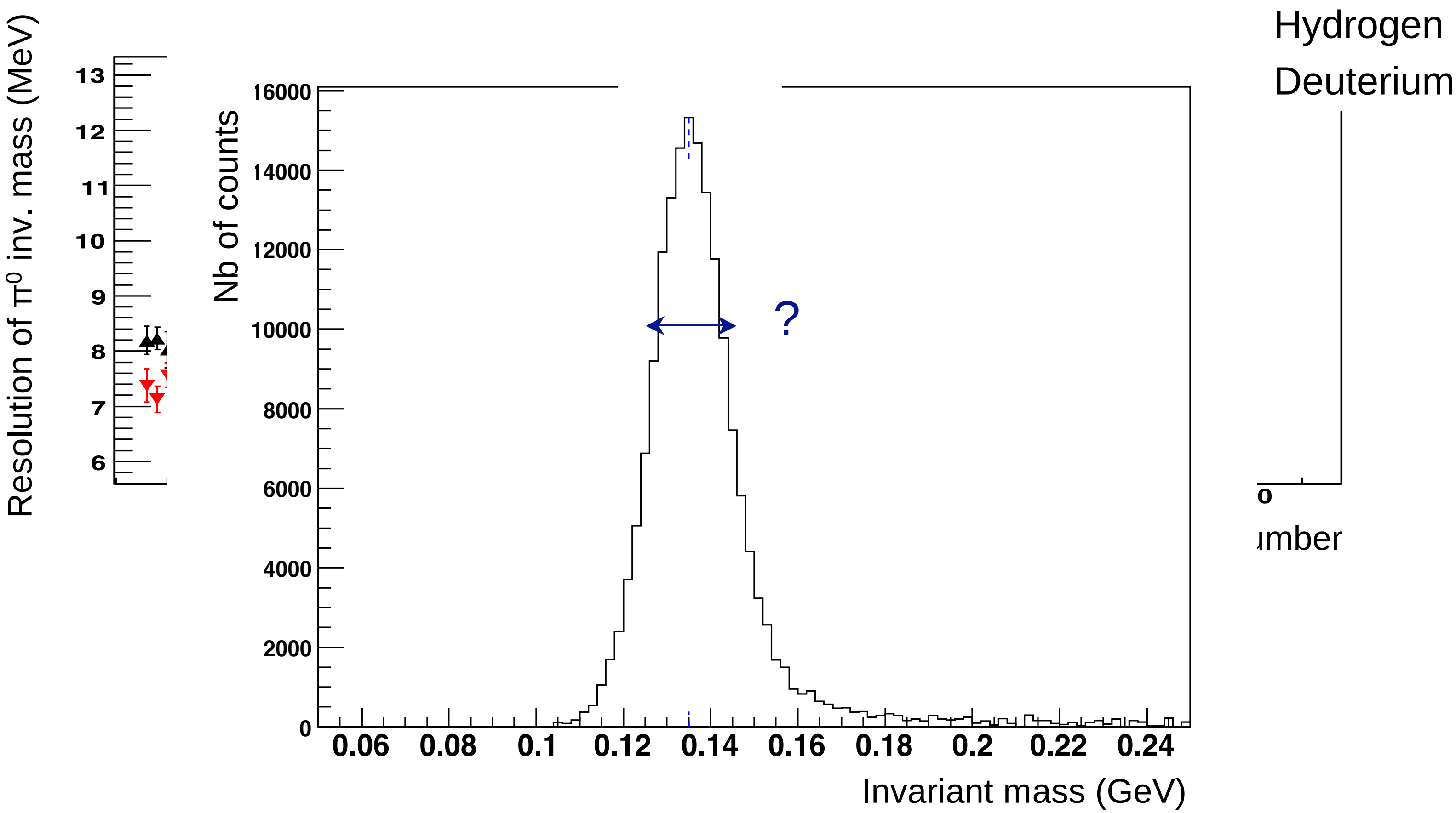
2) The missing mass cut must be applied identically in both cases

- Hydrogen data and Deuterium data must have the same calibration
- Hydrogen data and Deuterium data must have the same resolution

Double coincidence analysis



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- Add nucleon Fermi momentum in deuteron to Hydrogen events

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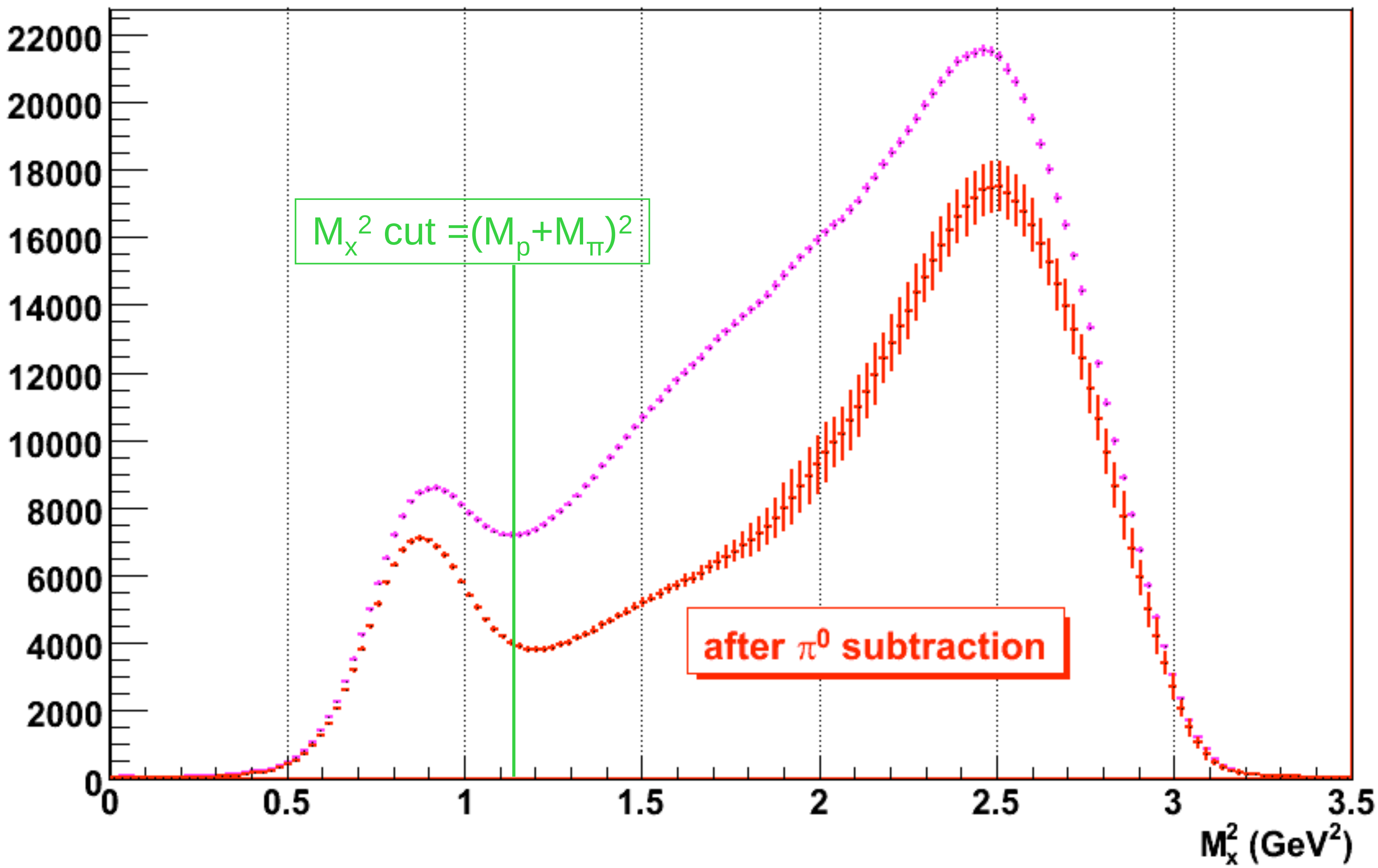
3) Remove the contamination of π^0 electroproduction under the missing mass cut.

π^0 contamination subtraction



Hydrogen data

Double coincidence analysis

1) Normalize Hydrogen and Deuterium data to the same luminosity

2) The missing mass cut must be applied identically in both cases

- Hydrogen data and Deuterium data must have the same calibration
- Hydrogen data and Deuterium data must have the same resolution
- Add nucleon Fermi momentum in deuteron to Hydrogen events

3) Remove the contamination of π^0 electroproduction under the missing mass cut.

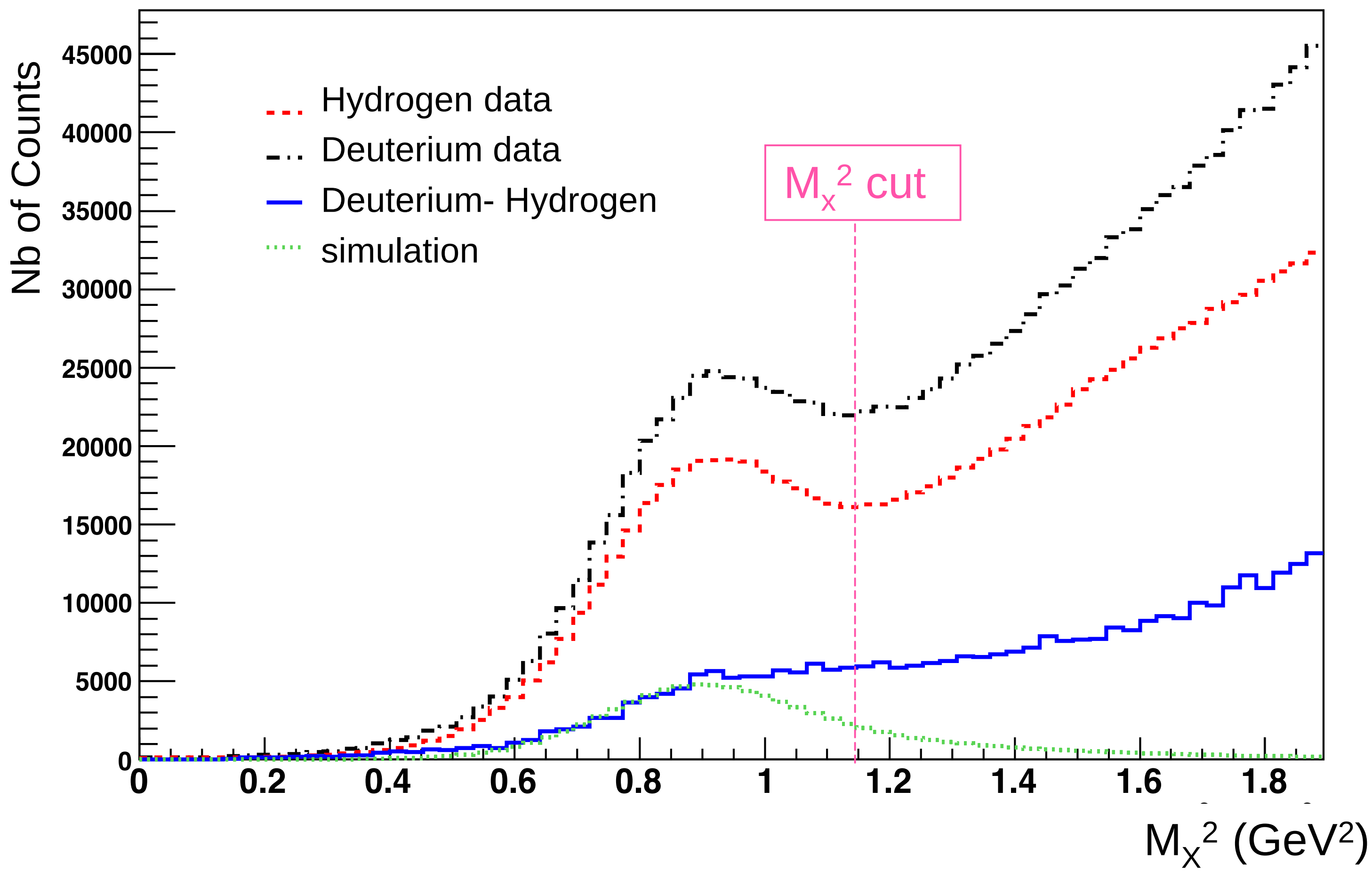
Unfortunately, the high trigger threshold during Deuterium runs did not allow to record enough π^0 events.

But : $$\frac{\sigma(ed \to e\pi^0 X)}{\sigma(ep \to e\pi^0 X)} = 0.95 \pm 0.06 \pm sys$$

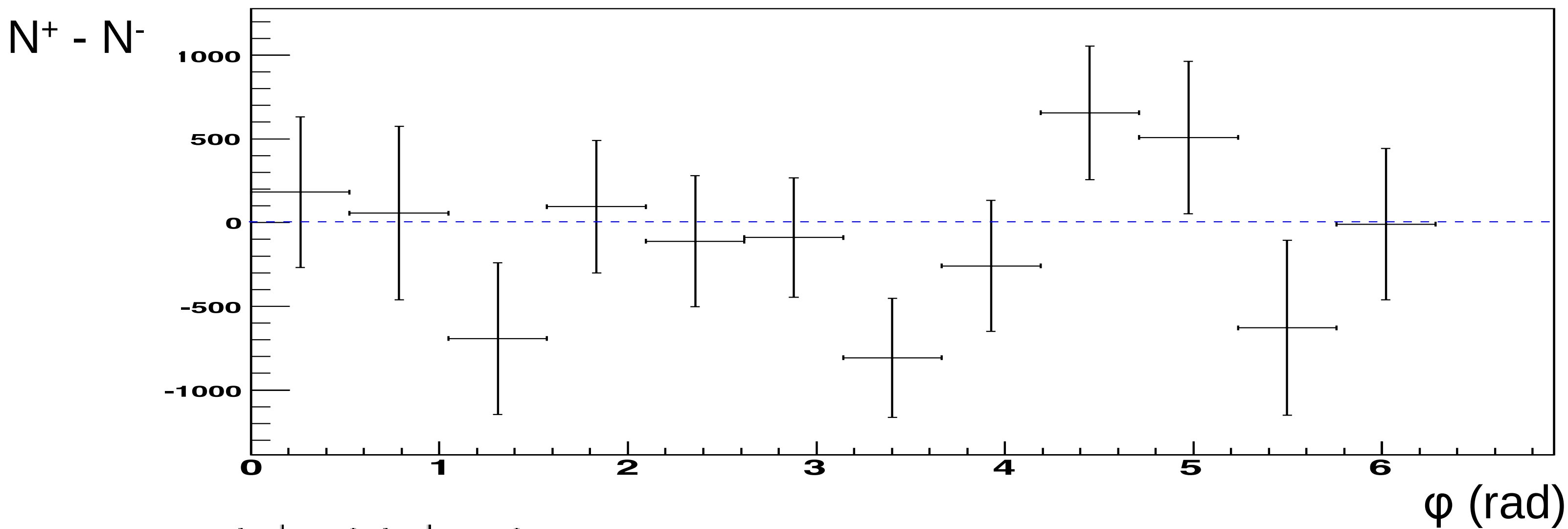
⇨ In our kinematics π^0 come essentially from proton in the deuterium

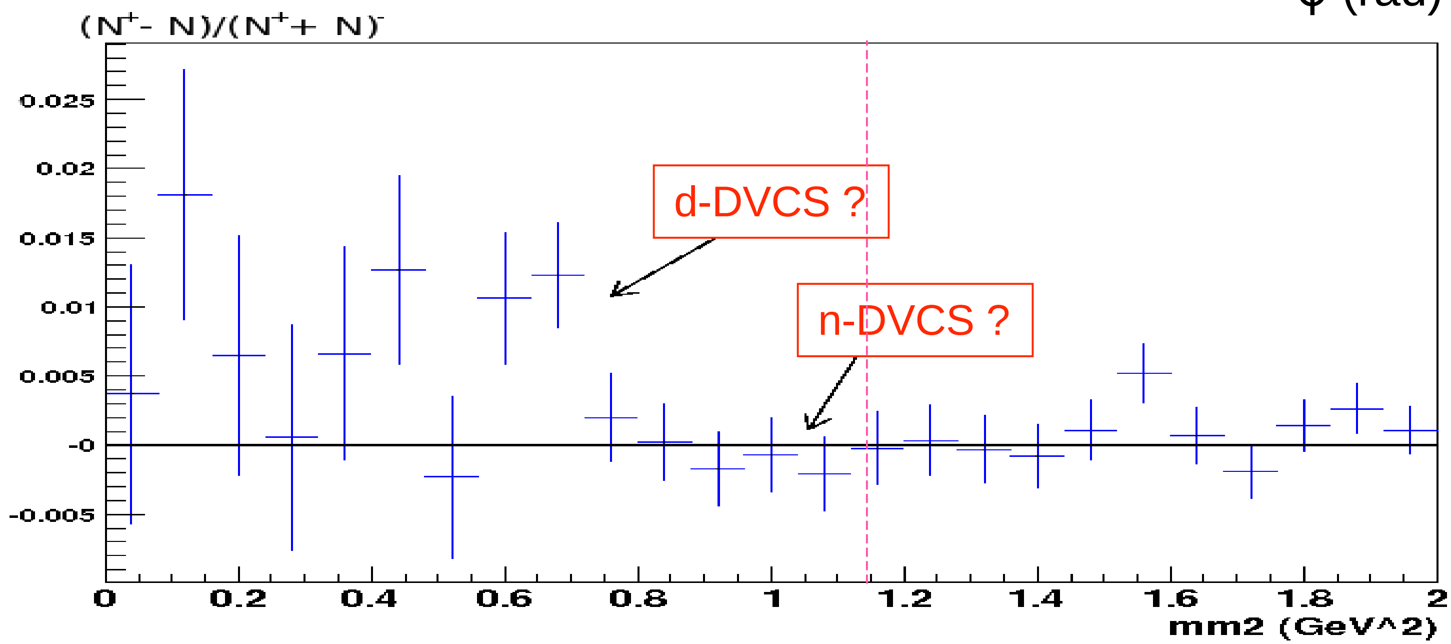
⇨ No π^0 subtraction needed for neutron and coherent deuteron

Double coincidence analysis

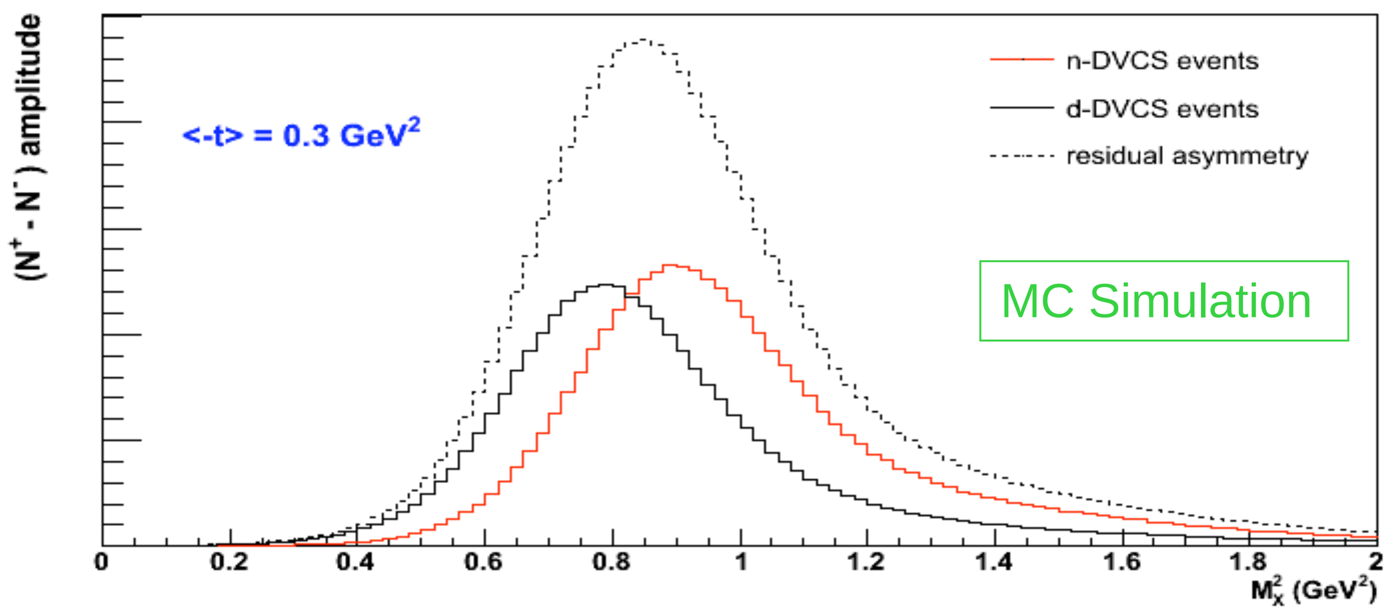


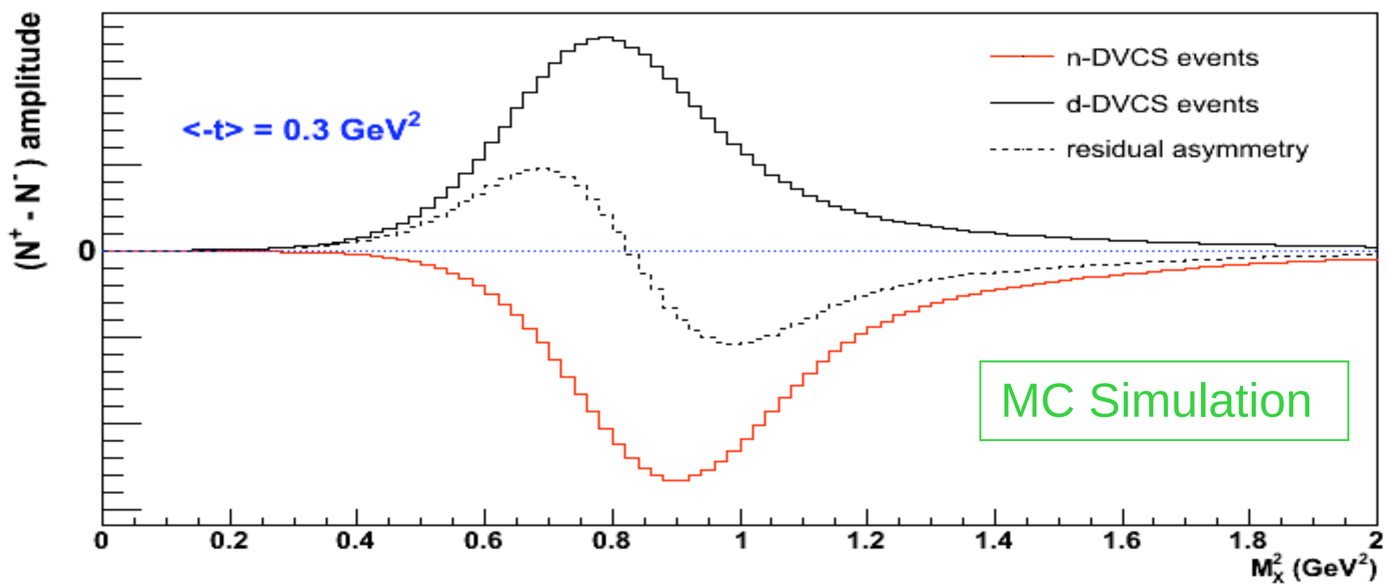
Double coincidence analysis





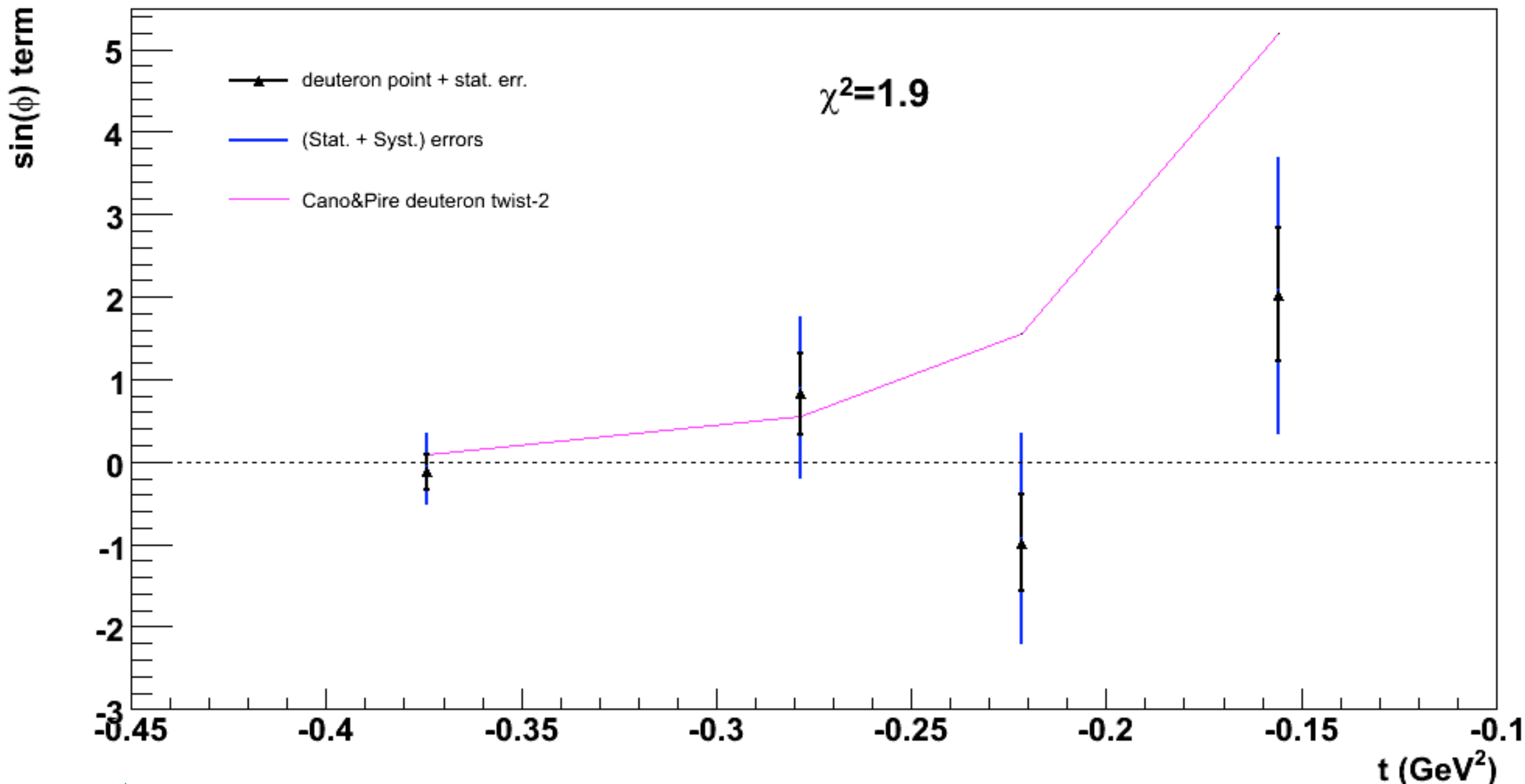
Double coincidence analysis





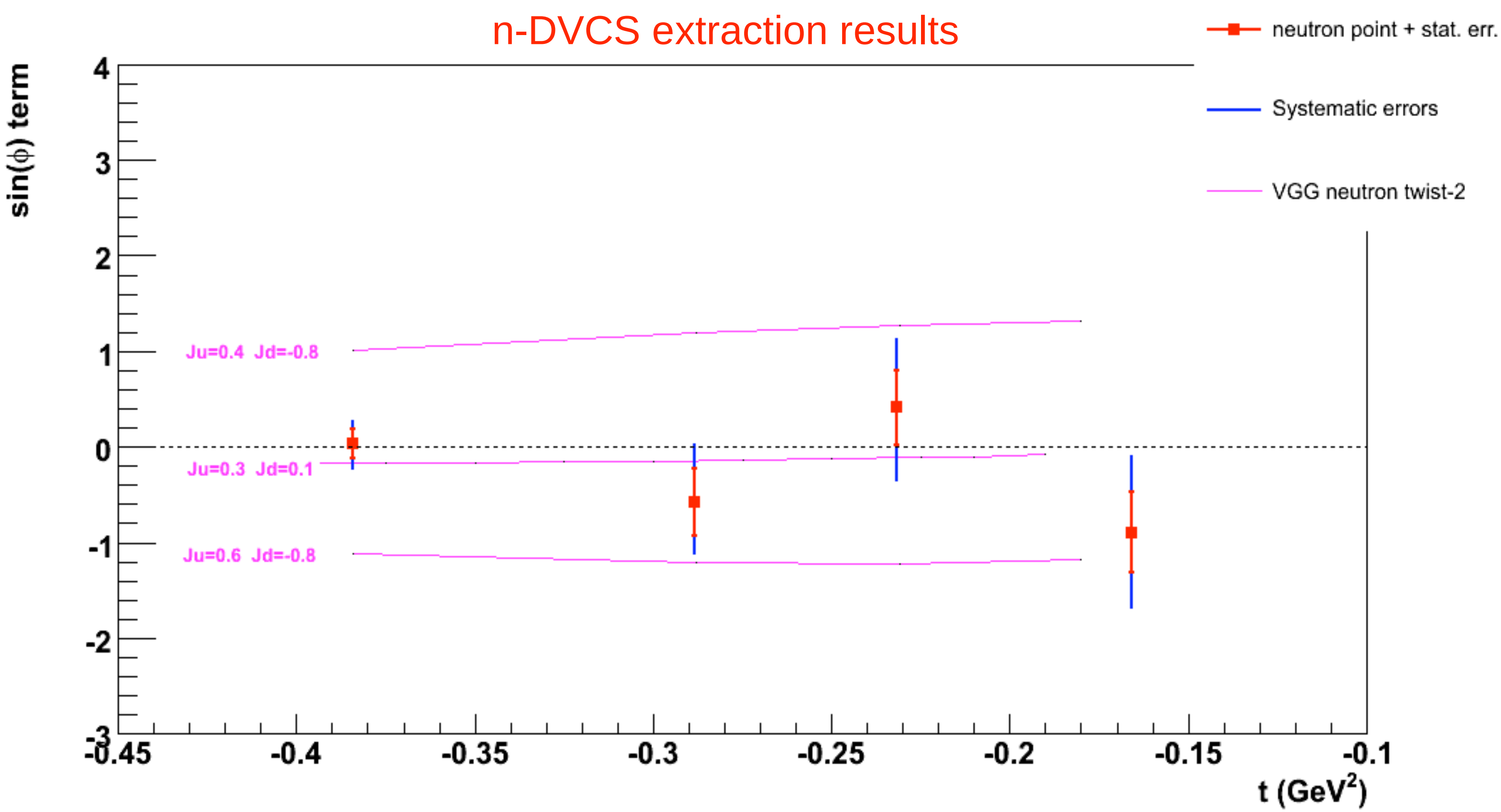
Extraction results

d-DVCS extraction results



- Large error bars (statistics + systematics)
- Exploration of small –t regions in future experiments might be interesting

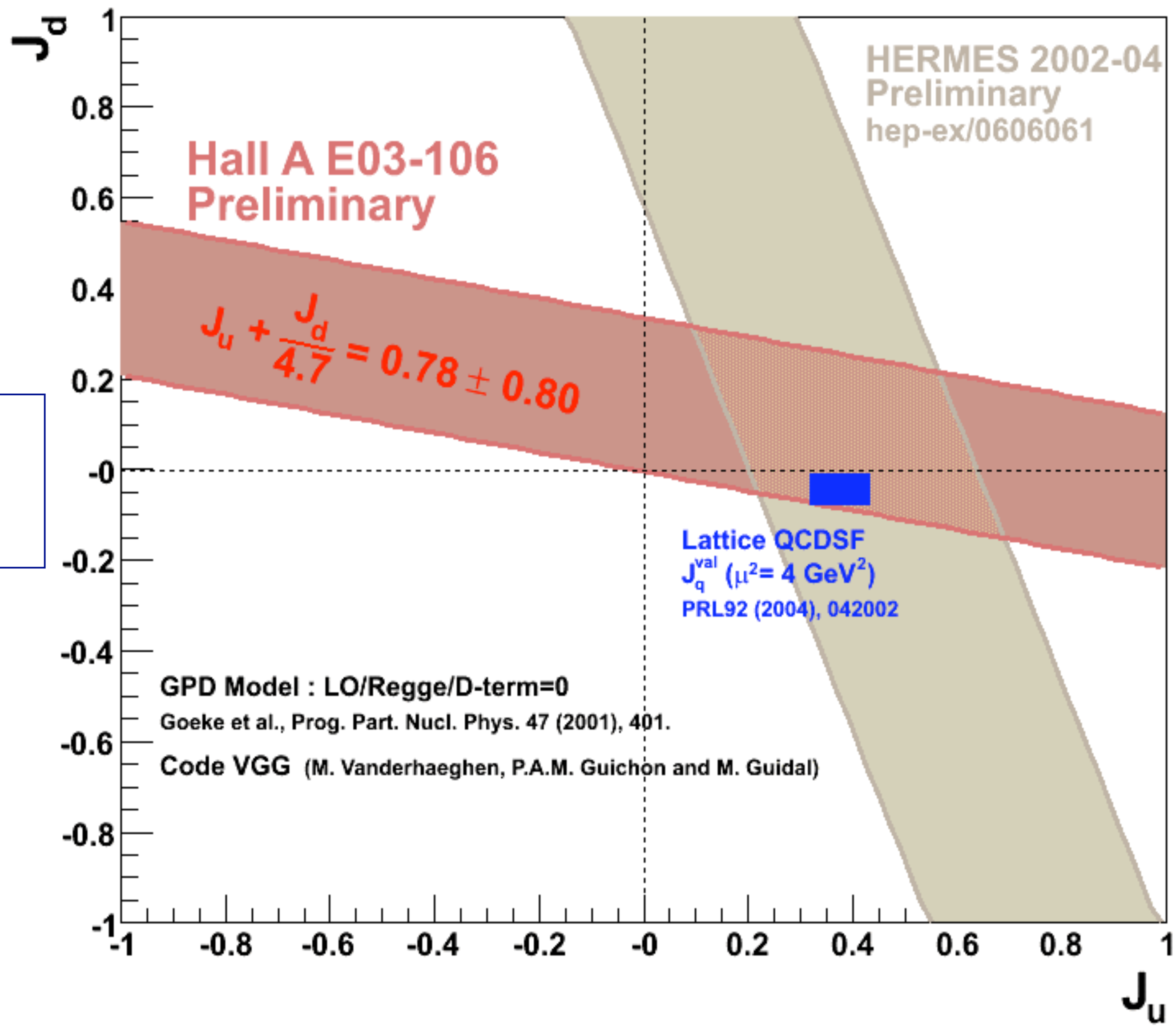
Extraction results



- Neutron contribution is small and close to zero
- Results can constrain GPD models (and therefore GPD E)

n-DVCS experiment results

Systematic errors of models are not shown



Summary

- - n-DVCS is mostly sensitive to GPD E : the least constrained GPD and which is important to access quarks orbital momentum via Ji's sum rule.

- Our experiment is exploratory and is dedicated to n-DVCS.

- n-DVCS and d-DVCS contributions are obtained after a subtraction of Hydrogen data from Deuterium data.

- The experimental separation between n-DVCS and d-DVCS is plausible due to the different kinematics. The missing mass method is used for this purpose.

- To minimize systematic errors, we must have the same calorimeter properties (calibration, resolution) between Hydrogen and Deuterium data.

Outlook

- Future experiments in Hall A (6 GeV) to study p-DVCS and n-DVCS
  - For n-DVCS : Alternate Hydrogen and Deuterium data taking to minimize systematic errors.
  - Modify the acquisition system (trigger) to record enough π^0s for accurate subtraction of the contamination.
- Future experiments in CLAS (6 GeV) and JLab (12 GeV) to study DVCS and mesons production and many reactions involving GPDs.

VGG parametrisation of GPDs

Vanderhaeghen, Guichon, Guidal,
Goeke, Polyakov, Radyushkin, Weiss …

Non-factorized *t* dependence

$$H^q(x,\xi,t) = \int_{-1}^{1} d\beta \int_{-1+|\beta|}^{1-|\beta|} d\alpha\ \delta(x-\beta-\alpha\xi) F^q(\beta,\alpha,t) + \theta(\xi-|x|) D^q\left(\frac{x}{\xi}\right)$$

D-term

Double distribution :

$\alpha' = 0.8\ \mathrm{GeV}^{-2}$ for quarks

$$F^q(\beta,\alpha,t) = \frac{1}{|\beta|^{\alpha' t}} h(\beta,\alpha) q(\beta)$$

Parton distribution

Profile function :

$$h(\beta,\alpha) = \frac{\Gamma(2b+2)}{2^{2b+1}\Gamma^2(b+1)} \frac{\left[(1-|\beta|)^2-\alpha^2\right]^b}{(1-|\beta|)^{2b+1}}$$

for GPD E, the spin-flip parton densities is used : $e_q(\beta)$

Modelled using J_u and J_d as free parameters

π^0 electroproduction on the neutron

Pierre Guichon, private communication (2006)

Amplitude of pion electroproduction :

$$T(N,\alpha) = \delta(\alpha,3)T^+ + \tau_N^\alpha T^0 + i\varepsilon_{3\alpha\beta}\tau^\beta T^-$$

α is the pion isospin

nucleon isospin matrix

π^0 electroproduction amplitude (α=3) is given by :

$$T(p,3) = T^+ + T^0 \propto \frac{2}{3}\Delta u + \frac{1}{3}\Delta d$$

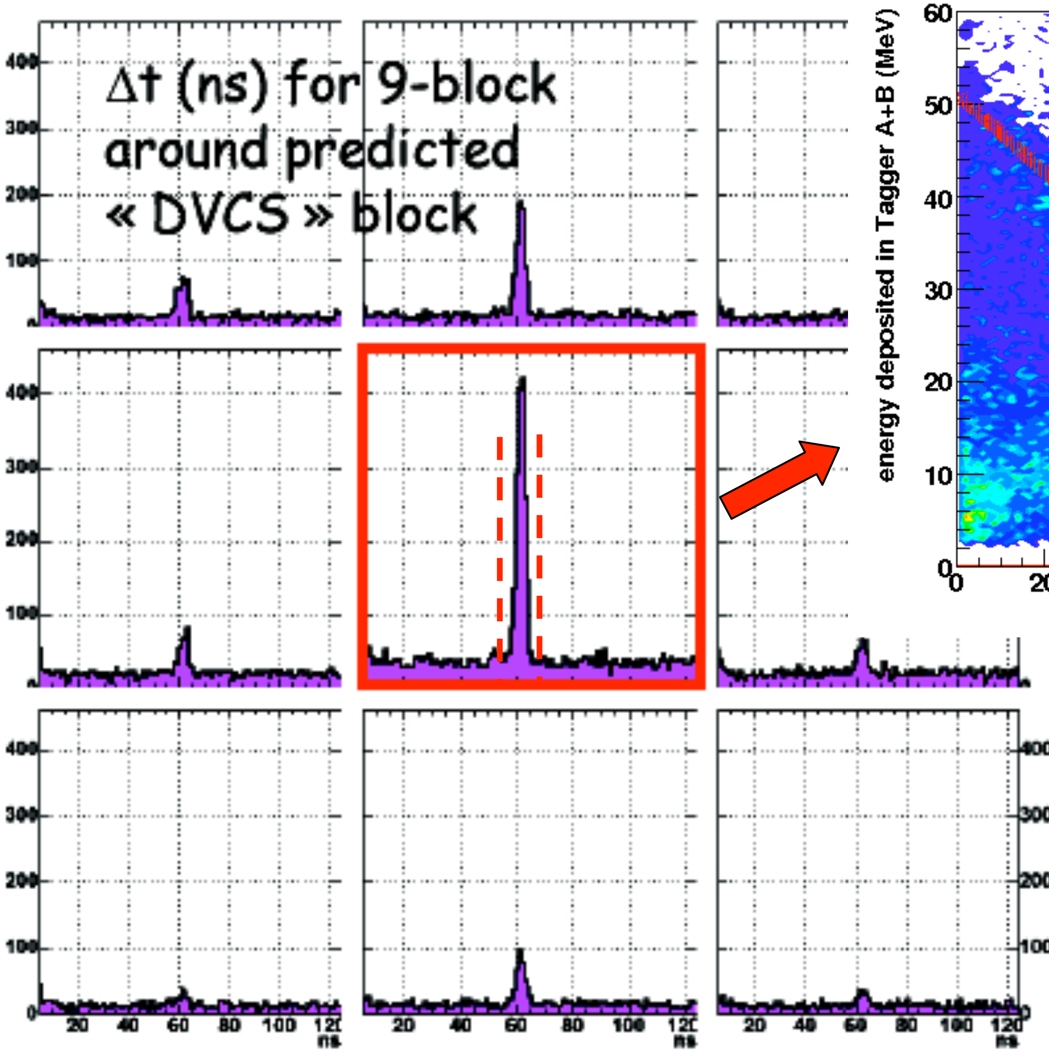
$$T(n,3) = T^+ - T^0 \propto \frac{1}{3}\Delta u + \frac{2}{3}\Delta d$$

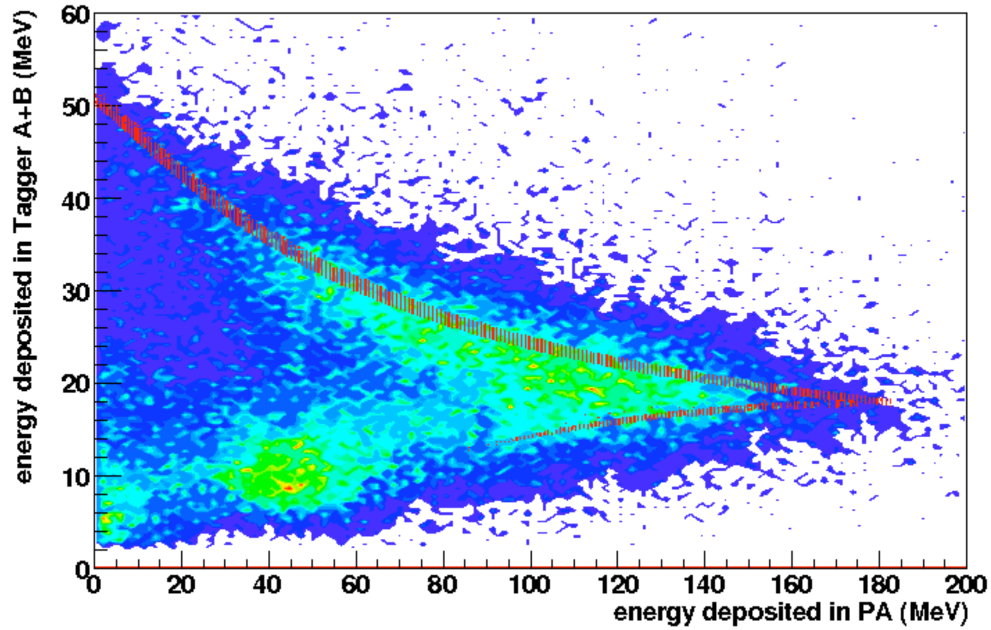
$$\frac{T(p,3)+T(n,3)}{T(p,3)} \approx \frac{3+3\Delta d/\Delta u}{2+\Delta d/\Delta u} \approx 1.15$$

Polarized parton distributions in the proton

Triple coincidence analysis

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



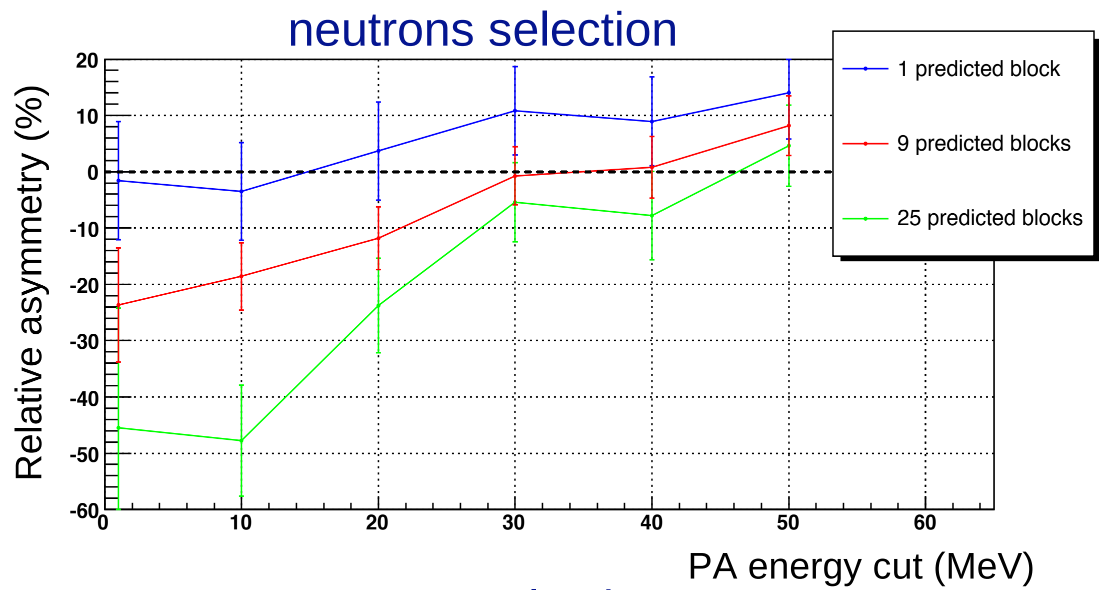


Triple coincidence analysis

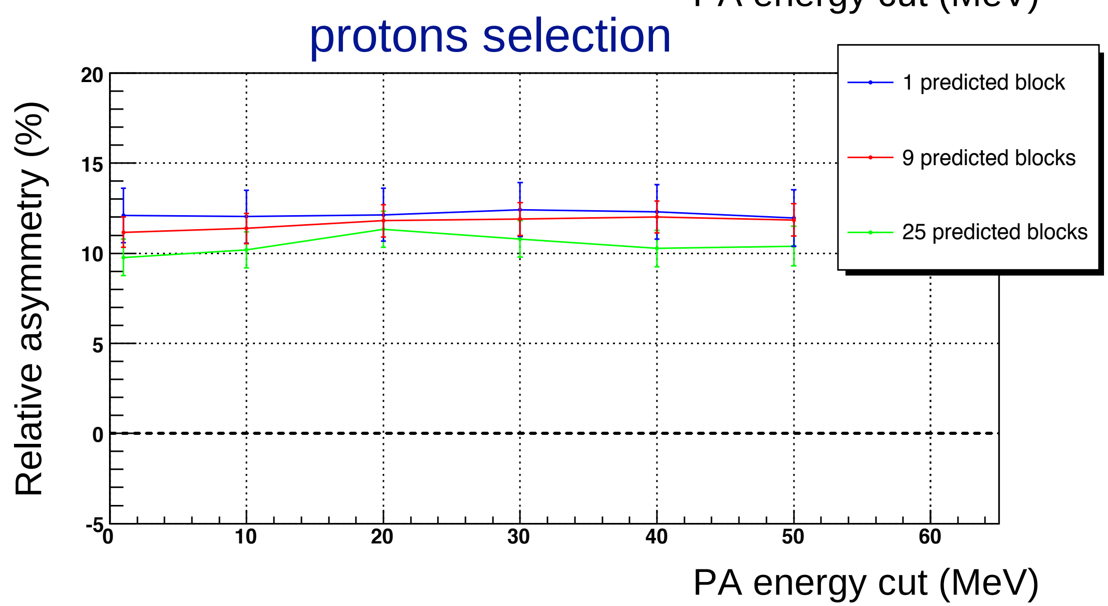
After accidentals subtraction

-proton-neutron conversion in the tagger shielding

- accidentals subtraction problem for neutrons

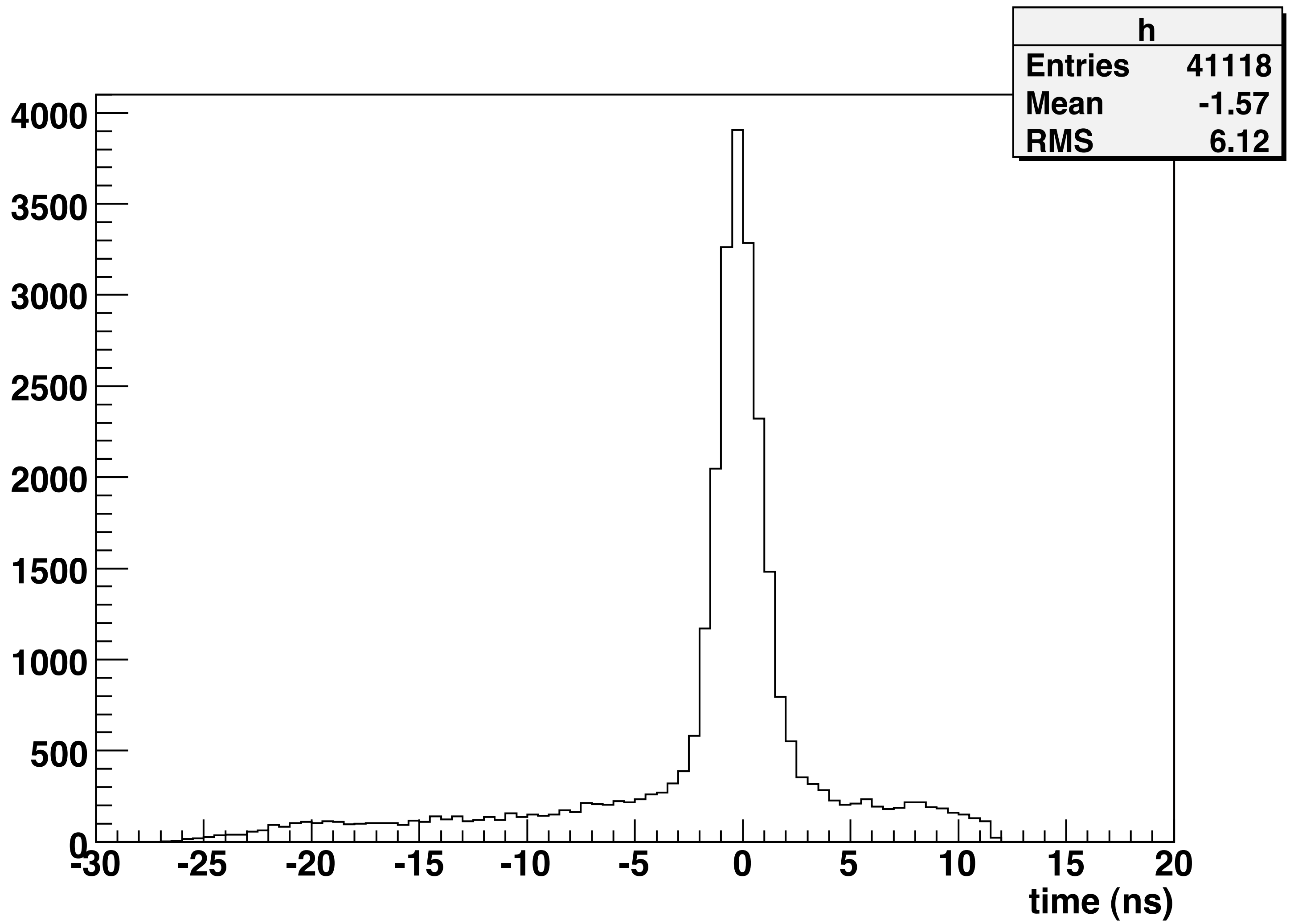


p-DVCS events (from LD2 target) asymmetry is stable



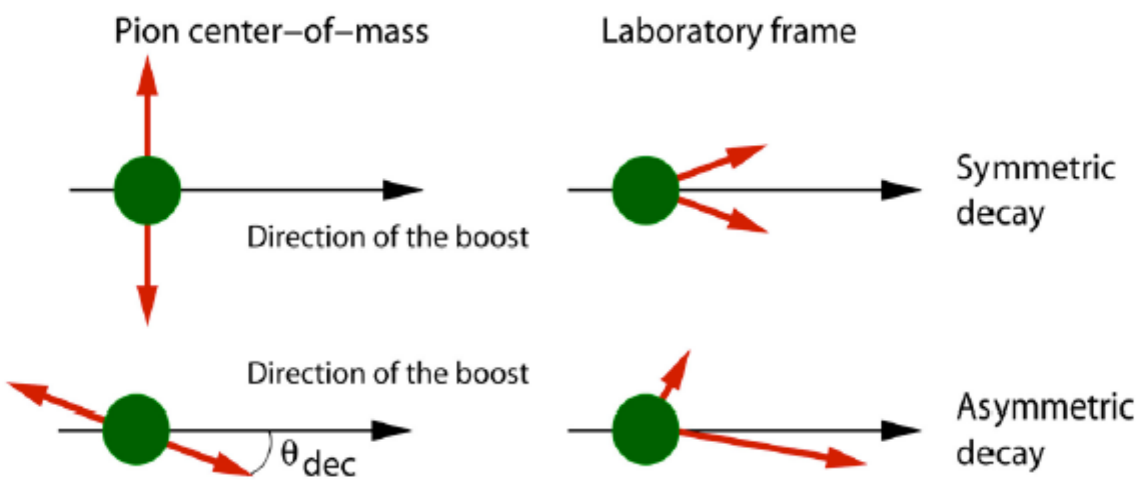
Time spectrum in the tagger

(no Proton Array cuts)



π^0 contamination subtraction

One needs to do a π^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.

Proton Target

$$A = F_1(t)\cdot \mathrm{HHE}\frac{x_B}{2-x_B}\cdot\left(F_1(t)+F_2(t)\right)\cdot \;\tilde{}\; -\frac{t}{4M^2}F_2(t)\cdot$$

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

<u>Model</u>:

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

Target	H	H̃	E
Proton	1.13	0.70	0.98

Goeke, Polyakov and Vanderhaeghen

t=-0.3

$$A = F_1(t)\cdot \mathrm{HHE}\frac{x_B}{2-x_B}\cdot\left(F_1(t)+F_2(t)\right)\cdot \;\tilde{}\; -\frac{t}{4M^2}F_2(t)\cdot$$

$$A = 0.34 + 0.17 + 0.06$$

DVCS polarized cross-sections

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

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

$|T^{BH}|^2$

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

Interference term

Calorimeter energy calibration

We have 2 independent methods to check and correct the calorimeter calibration

1st method : missing mass of $D(e,e'\pi^-)X$ reaction

By selecting $n(e,e'\pi^-)p$ events, one can predict the energy deposit in the calorimeter using only the cluster position.

→ a χ^2 minimisation between the measured and the predicted energy gives a better calibration.

2nd method : Invariant mass of 2 detected photons in the calorimeter (π^0)

π^0 invariant mass position check the quality of the previous calibration for each calorimeter region.

→ Corrections of the previous calibration are possible.

Differences between the results of the 2 methods introduce a systematic error of **1%** on the calorimeter calibration.

Analysis method

$$eD \to e\gamma\, X$$