Deeply Virtual Compton Scattering at Jefferson Lab

May 30, 2017

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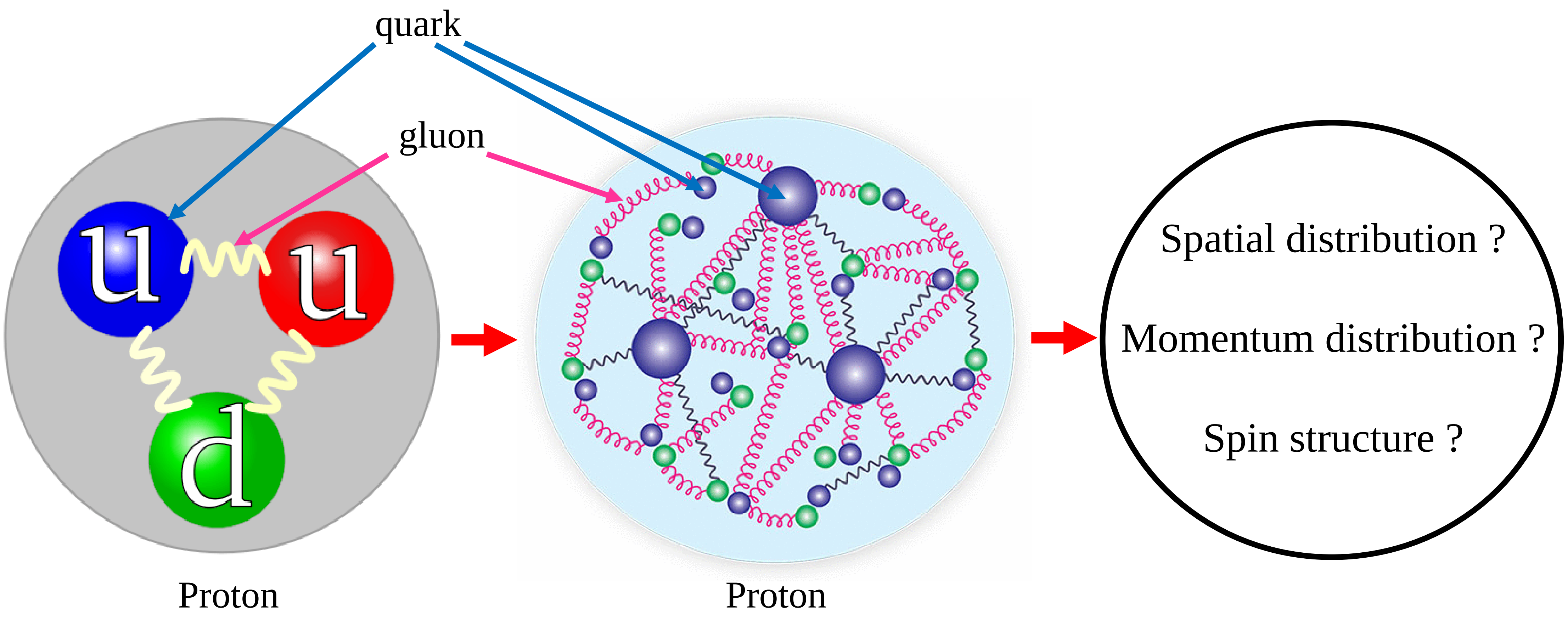
Outline

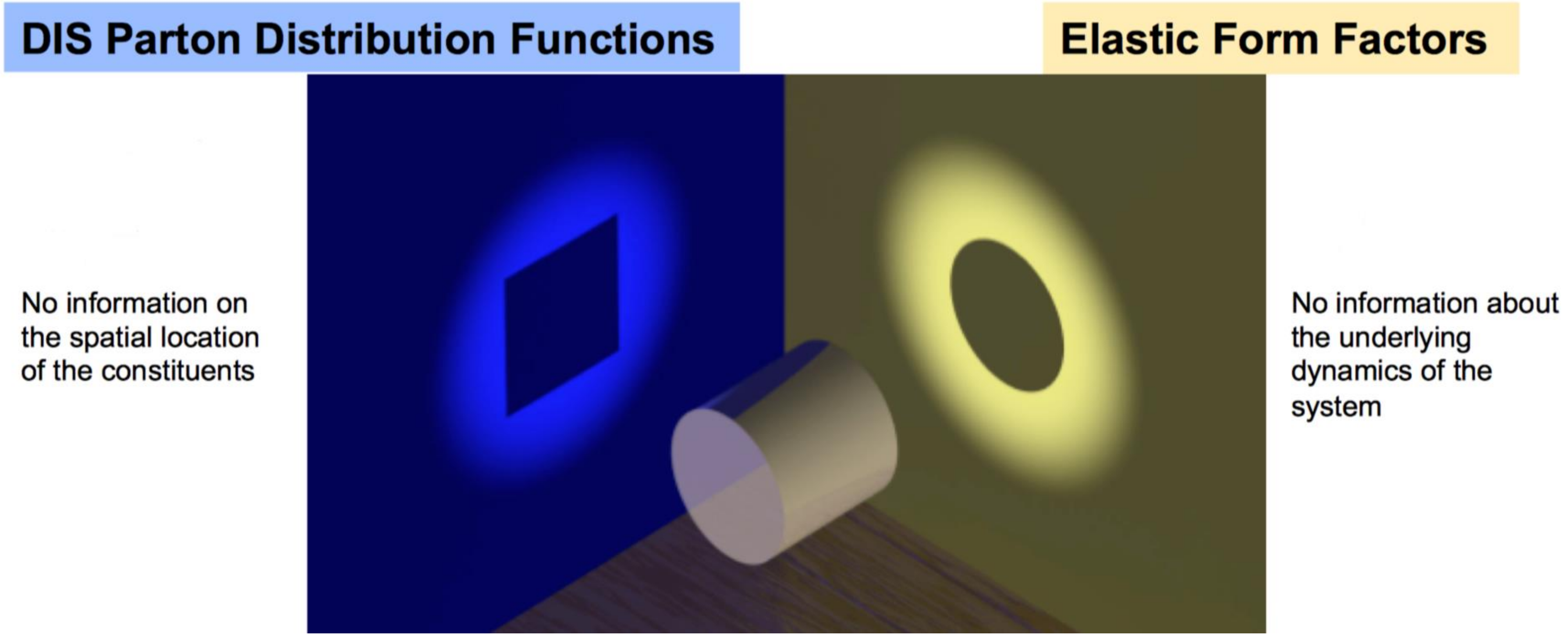
- Introduction – physics motivations
- Experimental setup
- High Resolution Spectrometer optics calibration
- Calorimeter π^0 calibration

Internal structure of the proton



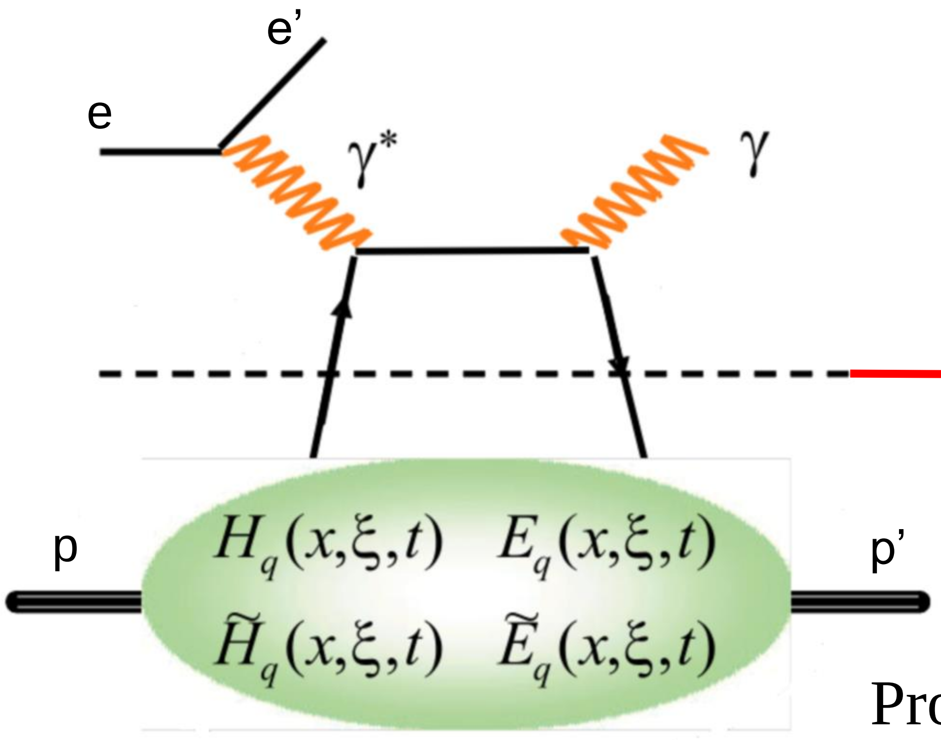
electron – proton collisions allow to probe the internal structure of the proton

Generalized Parton Distributions (GPDs)



- Elastic Scattering (ep → e'p') ➔ Elastic Form Factors ➔ Spatial distribution
- Inelastic Scattering (ep → e'X) ➔ Parton Distribution Functions ➔ Momentum distribution
- DVCS (ep → e'p'γ) ➔ Generalized Parton Distributions ➔ Spatial-Momentum correlations & Spin structure

Deeply Virtual Compton Scattering (DVCS)



DVCS : ep → e'p'γ

Hard part
(QED, can be computed)

Factorization

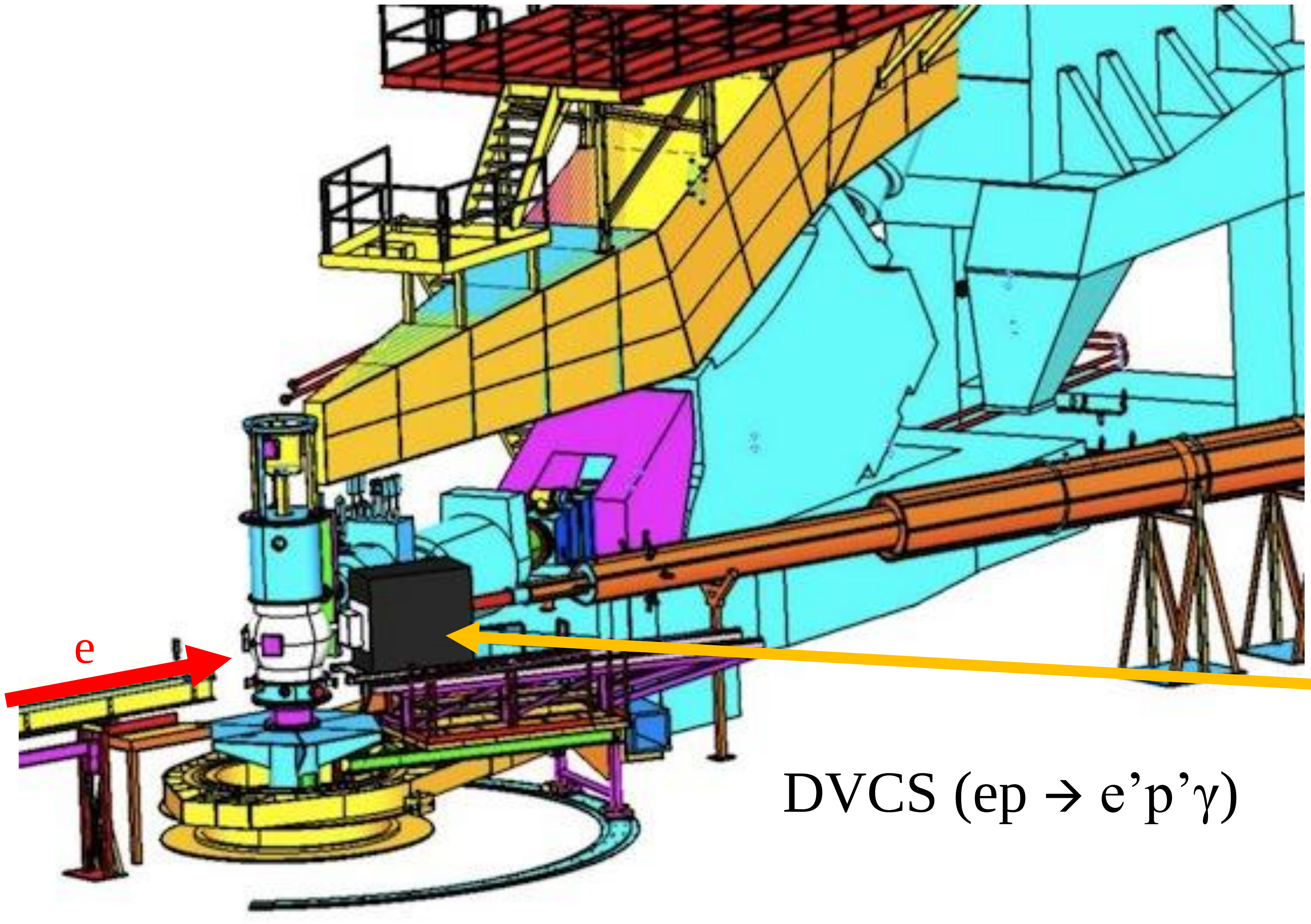
Soft part
Parametrized by GPDs

Proton structure described by 4 quark GPDs:
H, E, $\tilde{H}$ $\tilde{E}$

DVCS cross section (~occurrence probability) measurement → access GPDs
→ Description of the proton internal structure

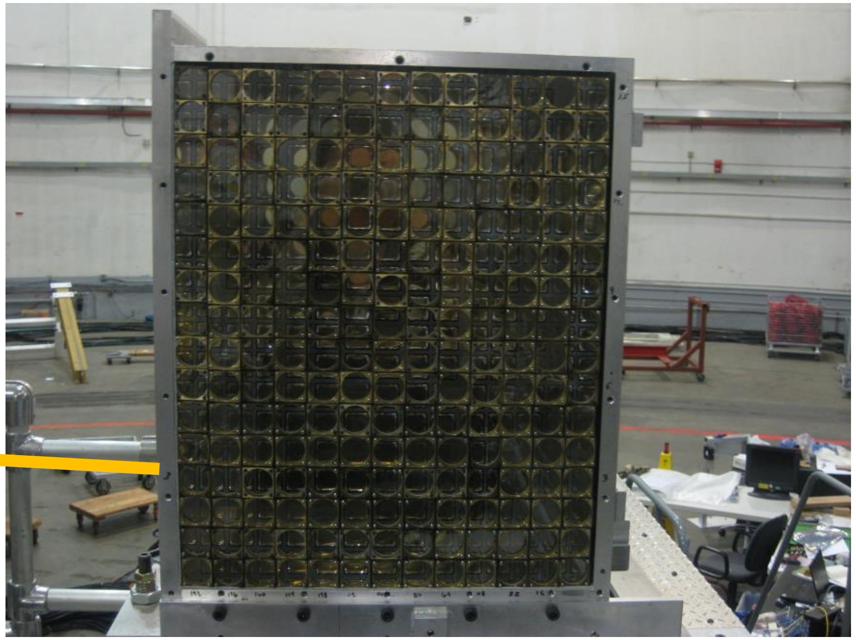
DVCS at Jefferson Lab, Hall A (2014-2016)

- Jlab : 12 GeV electron accelerator facility + 4 experimental Halls (A, B, C, D)



DVCS ($ep \rightarrow e'p'\gamma$)

- Electron beam : e
- Liquid Hydrogen target : p
- Spectrometer : detect e’
- Calorimeter : detect γ
- p’ not detected

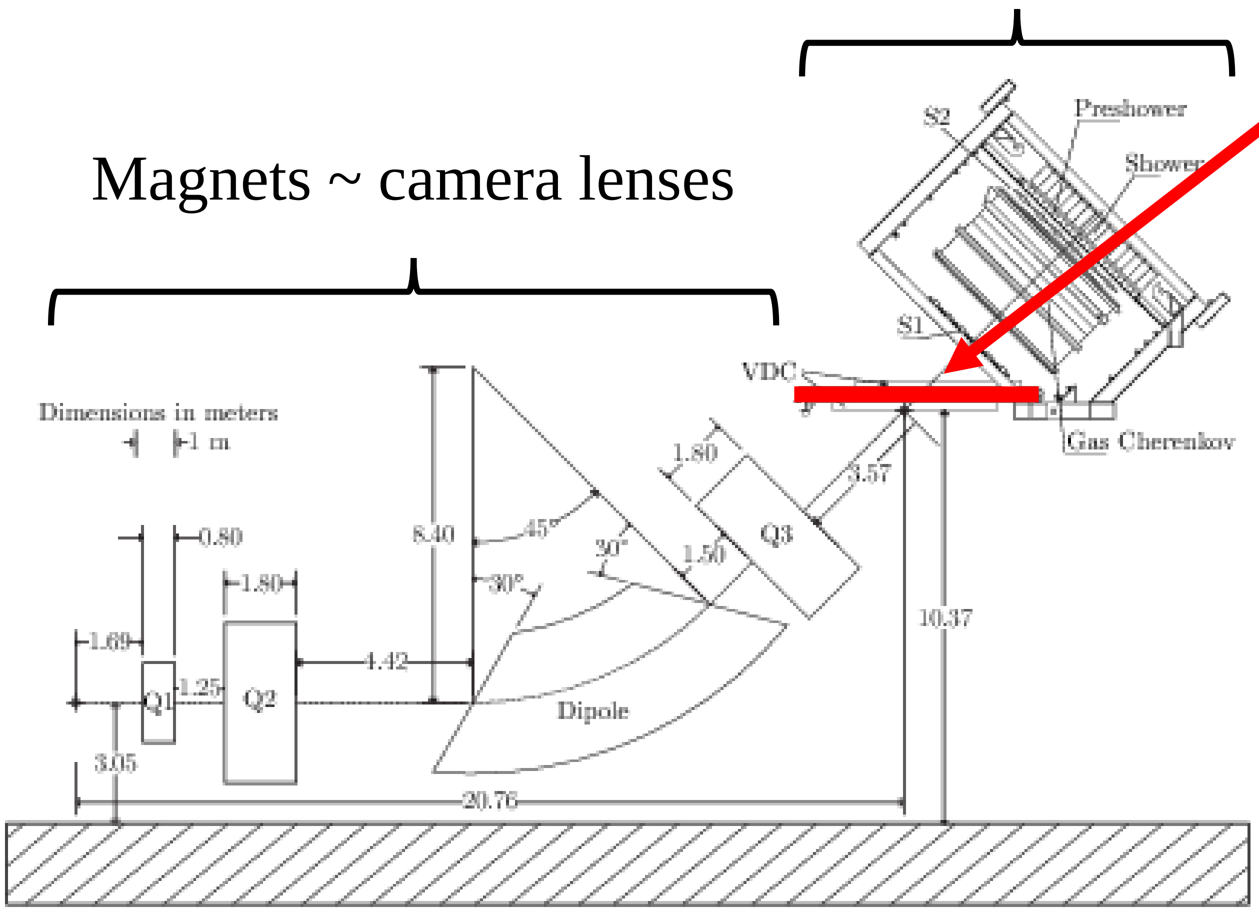


High Resolution Spectrometer (HRS) optics calibration

The HRS focal plan

Detector package ~ camera film

Magnets ~ camera lenses



HRS ~ camera

Focal plan : "picture" of events happening at the target.

Detected electrons at the focal plan, measured :

- Position (x_{fp} , y_{fp})
- Direction (dx_{fp}/dz_{fp} , dy_{fp}/dz_{fp}) = (θ_{fp} , ϕ_{fp})

At the target, to be reconstructed :

- Event vertex (= position) y_{tg}
- Electron scattering angles (θ_{tg} , ϕ_{tg})
- Electron momentum δ_{tg}

4 variables in focal plan coordinate system

$\downarrow$?

4 variables in target coordinate system

The optics matrix

1st order approximation :

$$\begin{bmatrix} \delta \\ \theta \\ y \\ \phi \end{bmatrix}_{tg} = \begin{bmatrix} \langle\delta|x\rangle & \langle\delta|\theta\rangle & 0 & 0 \\ \langle\theta|x\rangle & \langle\theta|\theta\rangle & 0 & 0 \\ 0 & 0 & \langle y|y\rangle & \langle y|\phi\rangle \\ 0 & 0 & \langle\phi|y\rangle & \langle\phi|\phi\rangle \end{bmatrix} \begin{bmatrix} x \\ \theta \\ y \\ \phi \end{bmatrix}_{fp}$$

Full polynomial expression, order 5:

$$y_{tg} = \sum_{j,k,l} \sum_{i=1}^{m} C_i^{Y_{jkl}} x_{fp}^i \theta_{fp}^j y_{fp}^k \phi_{fp}^l$$

$i + j + k + l \leq 5$

$C_i^{Y_{jkl}}$ "Optics matrix coefficients"

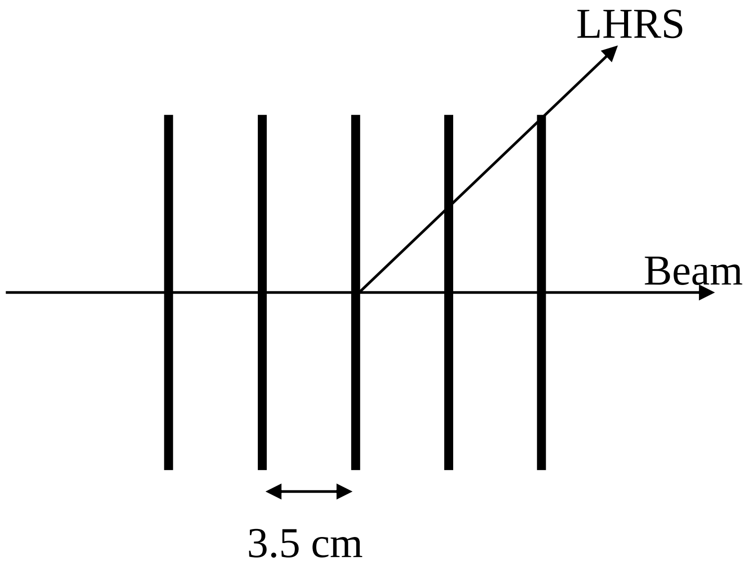
- Need calibration if magnets tuning is changed.
- Spring 2016 : magnet issue

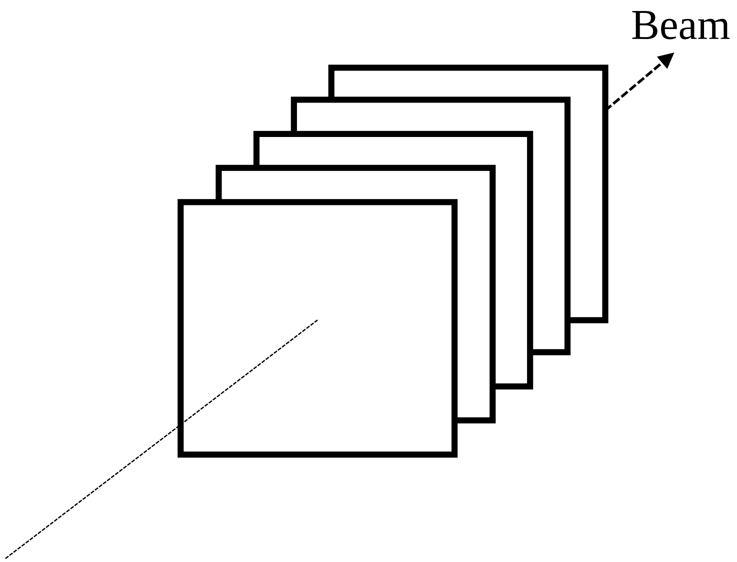
Step 1 : vertex reconstruction calibration

- Data taken on a 5 thin carbon foils target (1mm thick)

→ Expected vertex values y_{tg}^0 , correlated to precise areas of the focal plan

→ Computation of the new optics matrix coefficients $C_i^{Y_{jkl}}$ by minimizing the aberration function Δ(y)





$$\Delta(y) = \sum_s \left[\frac{\sum_{j,k,l} Y_{jkl}\theta_{fp}^j y_{fp}^k \phi_{fp}^l - y_{tg}^0}{\sigma_y^s}\right]^2$$

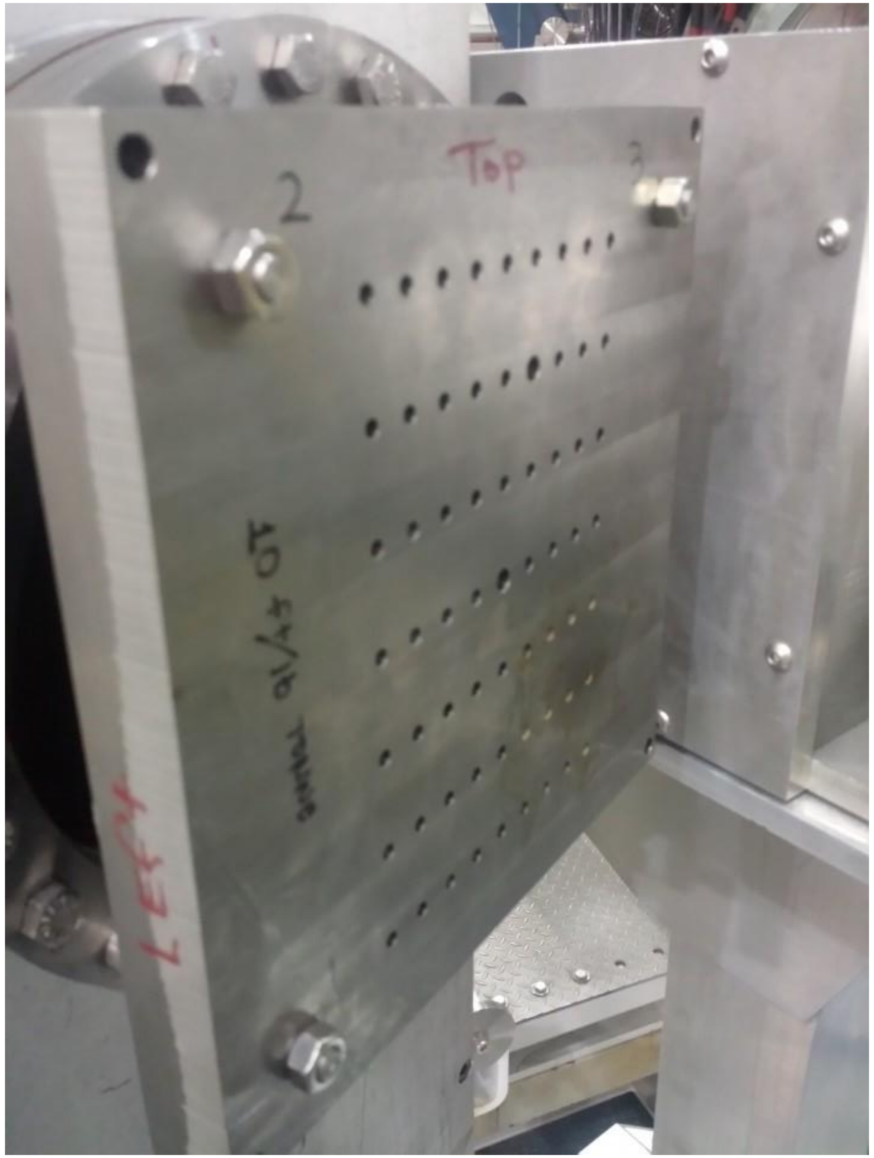
$$Y_{jkl} = \sum_{i=1}^{m} C_i^{Y_{jkl}} x_{fp}^i$$

Step 2 : angles reconstruction calibration

- Thick metal plate with holes inserted in front of the LHRS entrance (Sieve)

→ Holes = expected values for electron scattering angles θ_{tg} and ϕ_{tg} , correlated to precise areas of the focal plan

→ Computation of new optics matrix coefficients by minimization of aberration functions $\Delta(\theta)$ and $\Delta(\phi)$



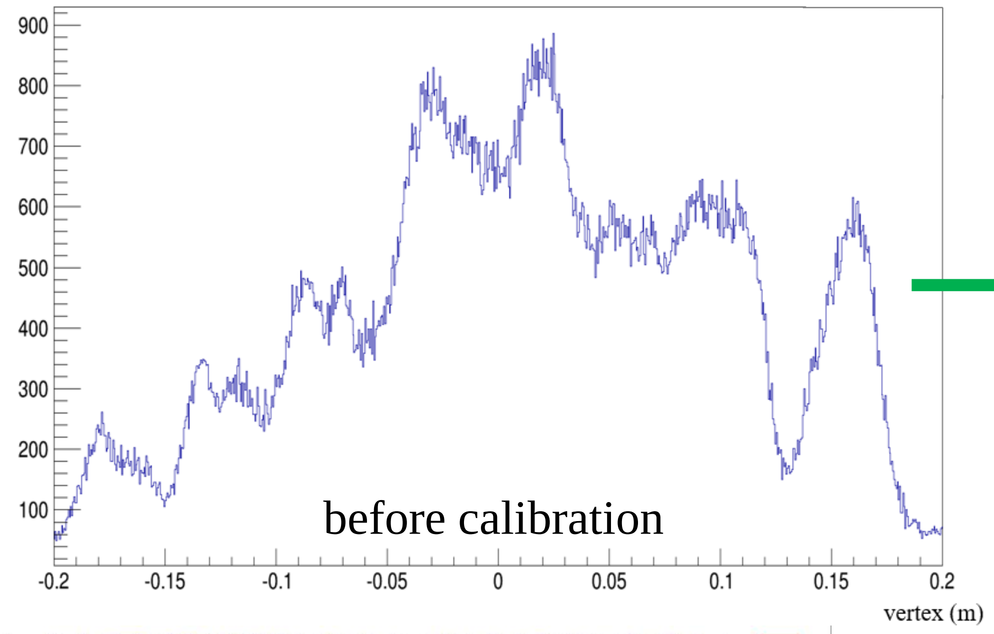
Step 3 : momentum reconstruction calibration

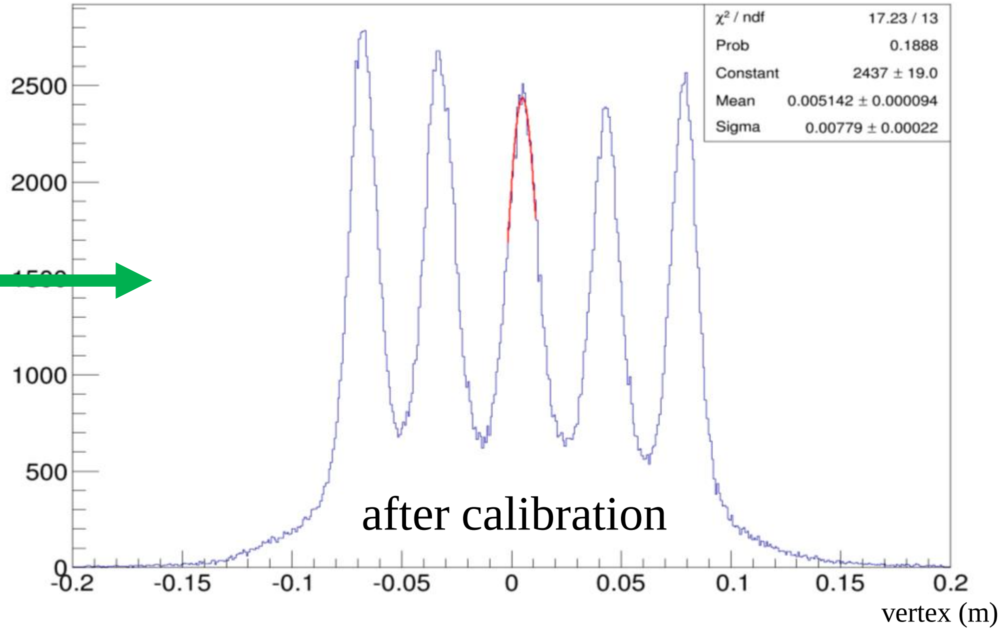
- Data taken on an LH_2 target, elastic scattering ep → ep setting
  - Constrained system: known scattering angle = known scattering momentum
- "Delta Scan"
  - LHRS angle fixed
  - 5 runs varying HRS central momentum setting (central momentum, ± 2%, ± 4%)
    - Elastic momentum-scattering angle correlation → each momentum value correlated to precise and different focal plan areas

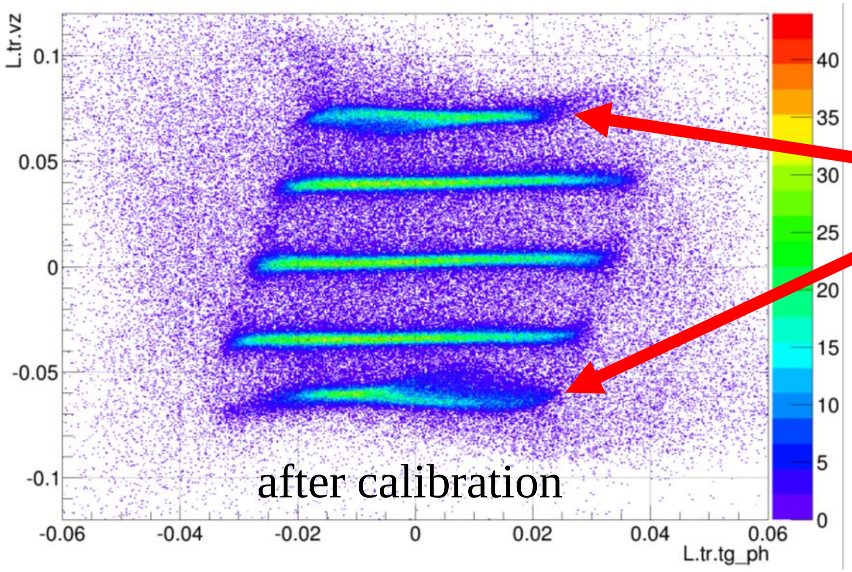
→ Expected values for momentum δ_{tg} , correlated to precise areas of the focal plan

→ Computation of new optics matrix coefficients by minimization of aberration function $\Delta(\delta)$.

HRS optics – Preliminary results



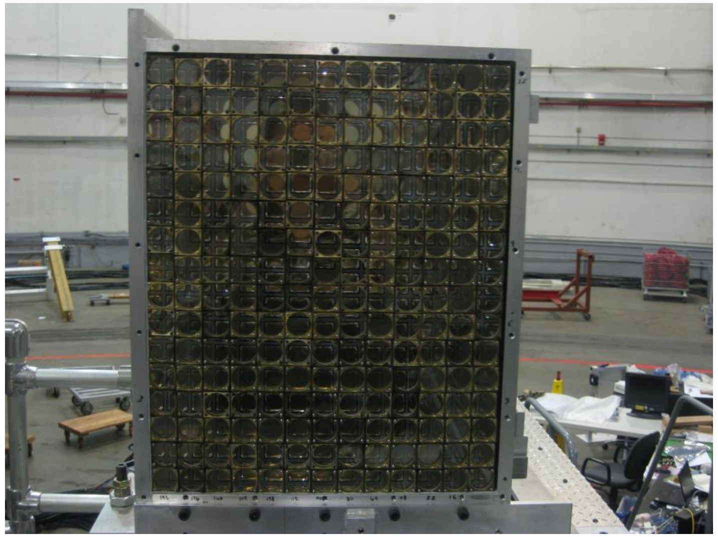




- Remaining issue with vertex reconstruction on target edges
- Corrections : work in progress

Calorimeter π^0 calibration

Calorimeter π^0 calibration



- 208 PbF_2 crystals
- Measure photons energy deposit in each crystal

- Radiation damages : PbF_2 crystals become darker

→Loss of gain

→Need to compute new correction coefficients often to compensate

→π^0 calibration, uses π^0 mass reconstruction

- $\pi^0 \rightarrow \gamma_1 + \gamma_2$
- $m^2_\pi = 2E_{\gamma1}E_{\gamma2}(1 - \cos\theta_{\gamma1\gamma2})$

Calorimeter π^0 calibration

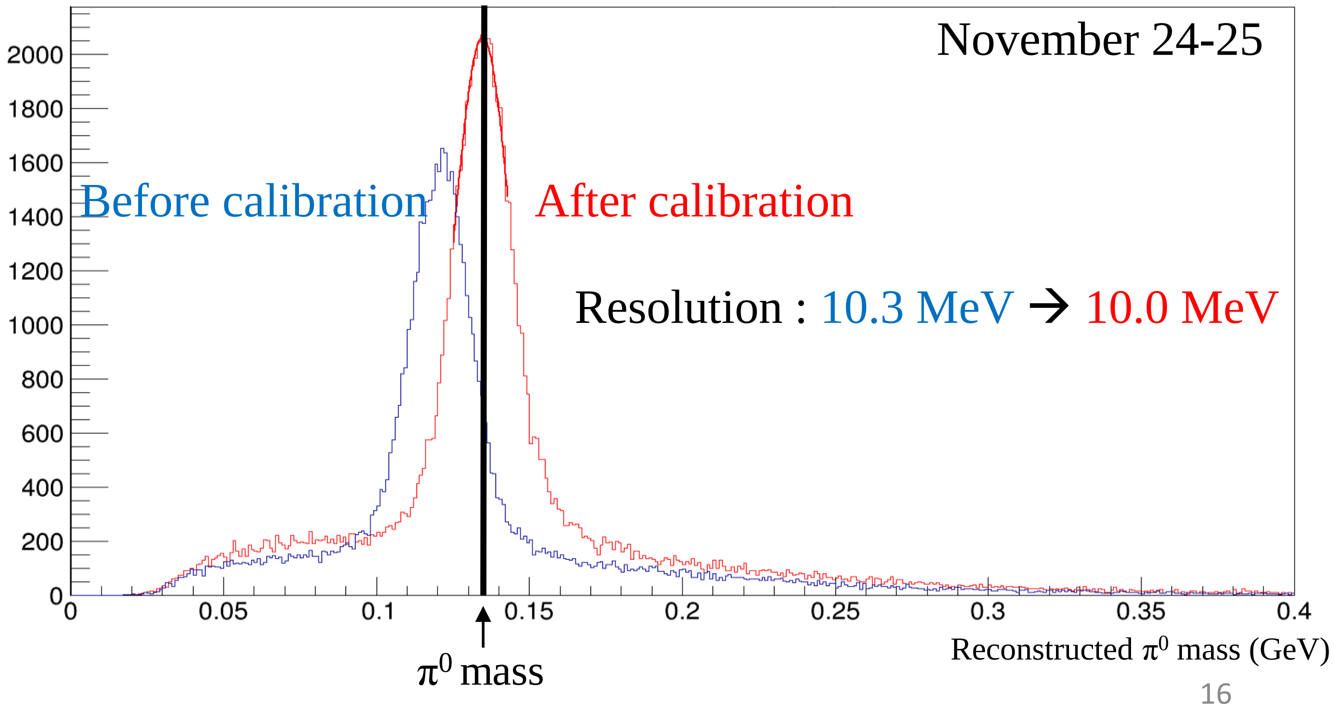
- Correction coefficients → optimize mean value + π^0 reconstructed mass resolution
- Minimize : $$F = \sum_{i=1}^{N} \left(m_i^2 - m_{\pi^0}^2\right)^2 + \lambda \sum_{i=1}^{N} \left(m_i^2 - m_{\pi^0}^2\right)$$

$$m_i^2 = 2 \overbrace{\left(\sum_{i=0}^{N_1} c_i E_i\right)}^{\text{Photon 1}} \overbrace{\left(\sum_{j=0}^{N_2} c_j E_j\right)}^{\text{Photon 2}} (1 - \cos\theta_{12})$$

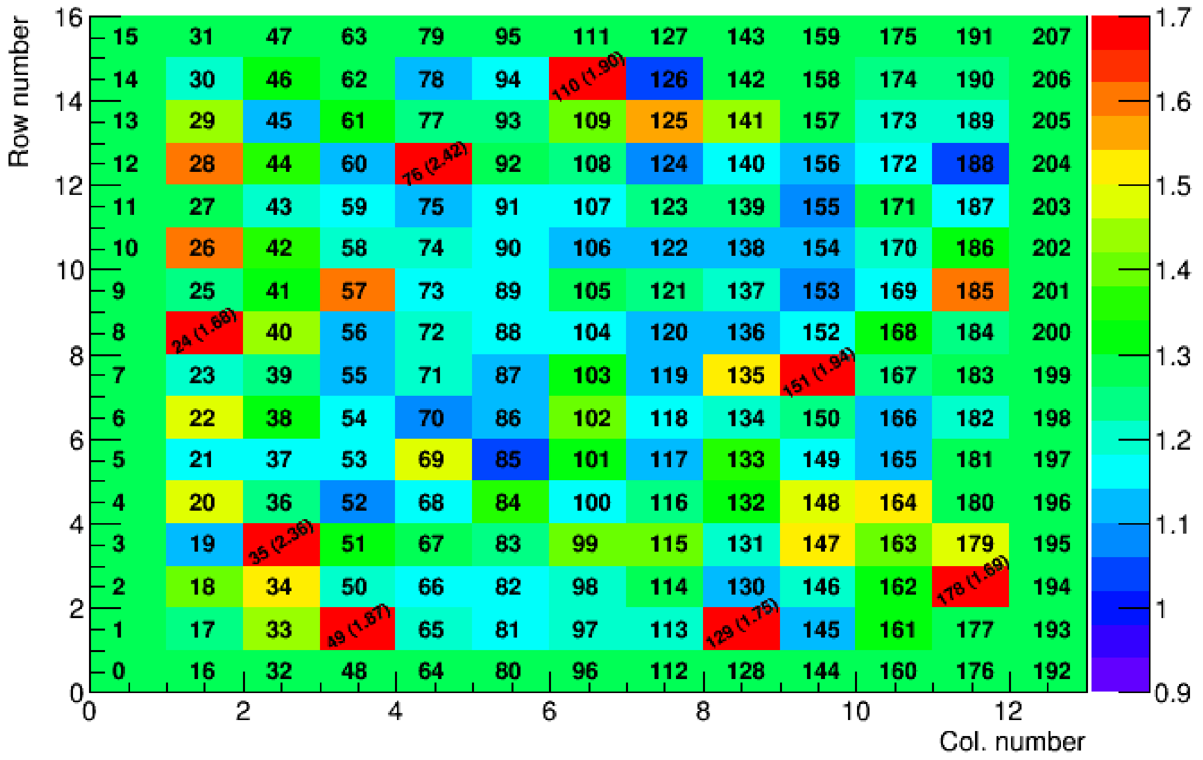
Correction coefficients

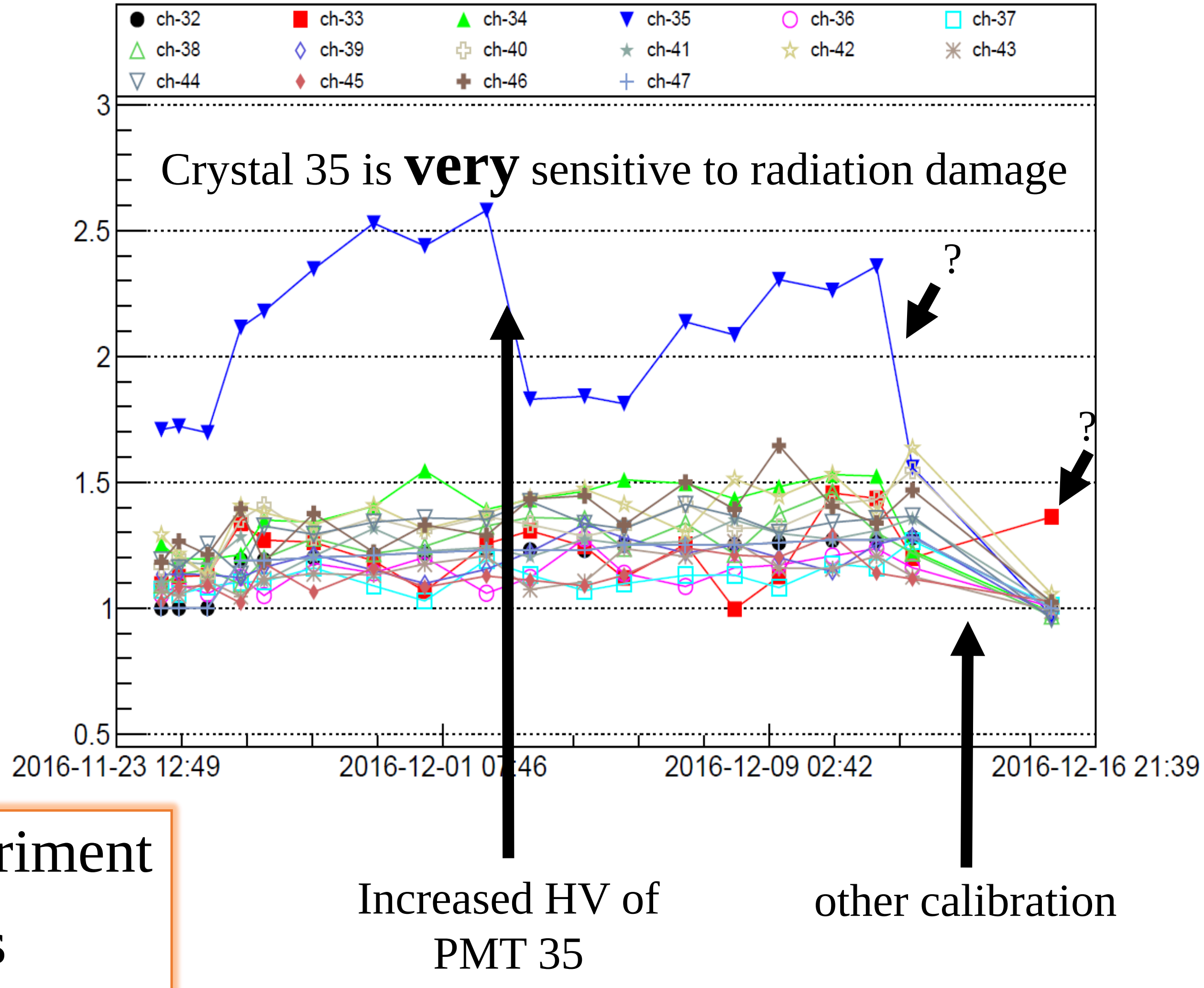
$$\left.\frac{\partial F}{\partial C_k}\right|_{\forall k \in [0;208]} = 0$$

Linear system : 208 equations and 208 variables



Calorimeter π^0 calibration – Preliminary results





- ~30% total gain loss at the end of the experiment
- Issues with edges and few peculiar crystals

Summary and Outlook

- Data acquisition ended Fall 2016
- Data analysis in progress
  - Many Calibrations/Corrections studies almost complete
    - HRS Optics
    - Calorimeter π^0 calibration
    - Wave form analysis (= how to identify and fit raw signals)
    - …
  - Then :
    - data decoding/analysis using completed calibrations/corrections
    - DVCS cross sections extraction
    - GPDs (long term)

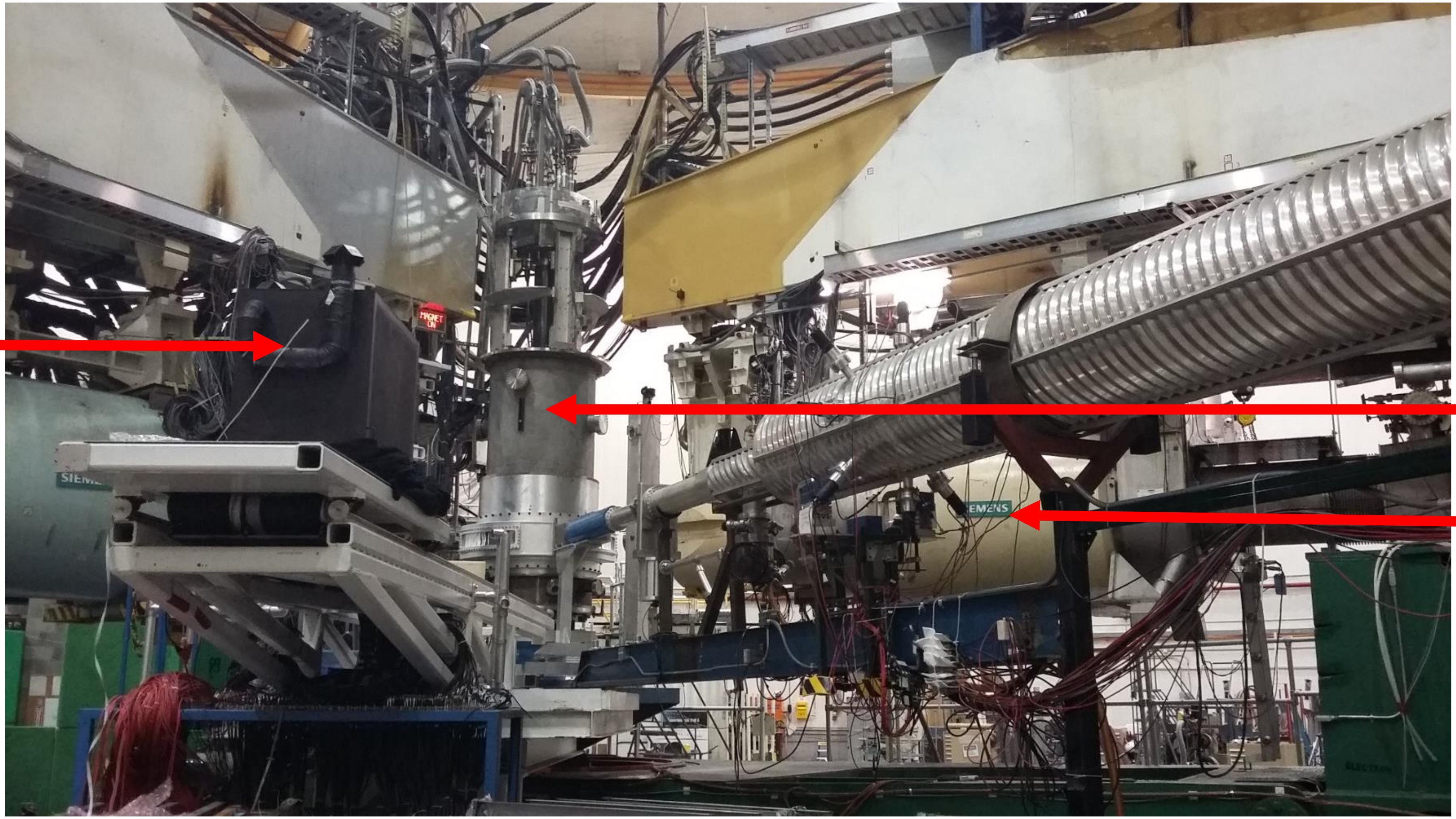
Thank You !

Questions ?

DVCS in Hall A - Apparatus

$ep \rightarrow e'p'\gamma$

Calorimeter
(γ)



Target

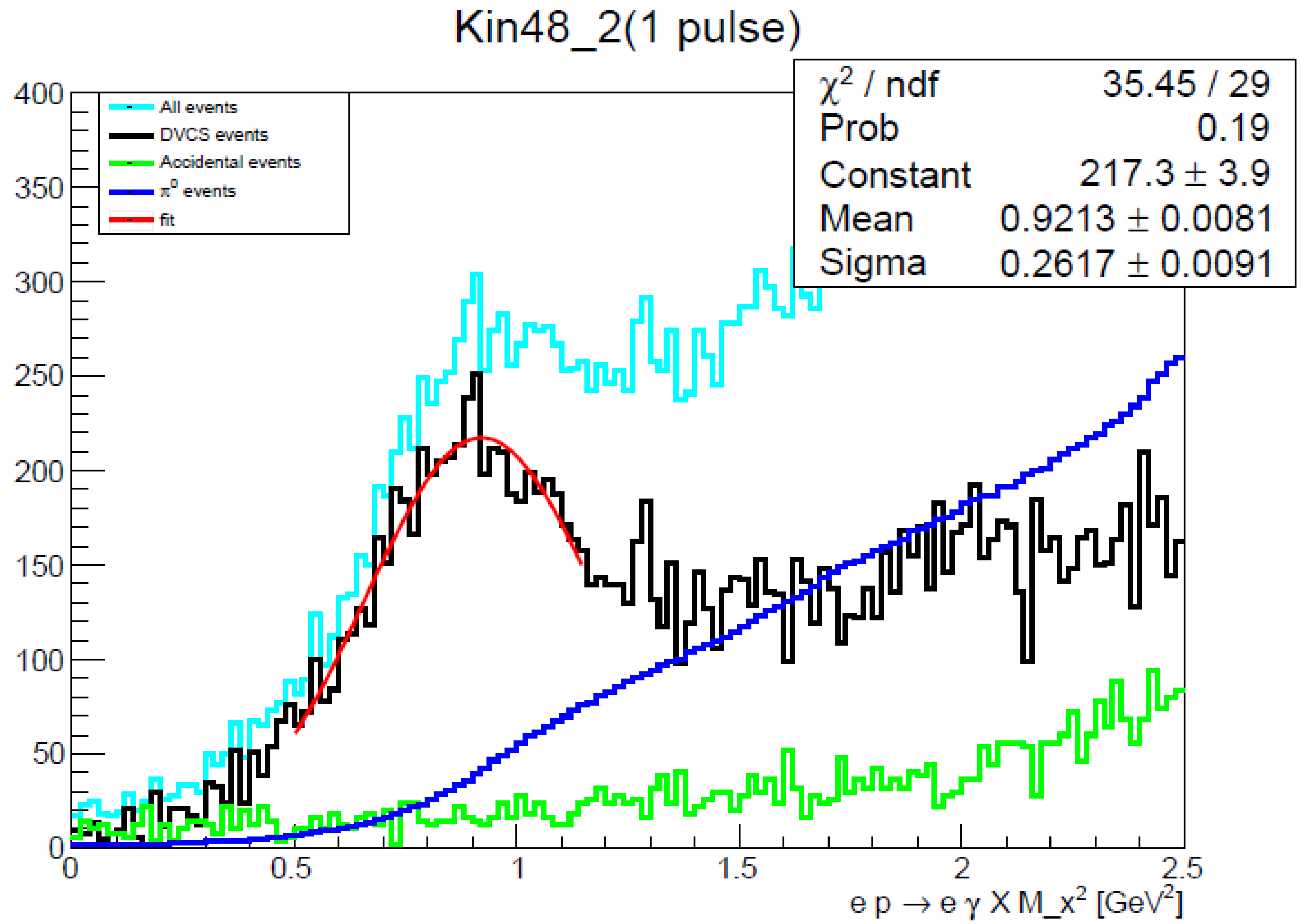
LHRS
(e')

DVCS missing mass and exclusivity

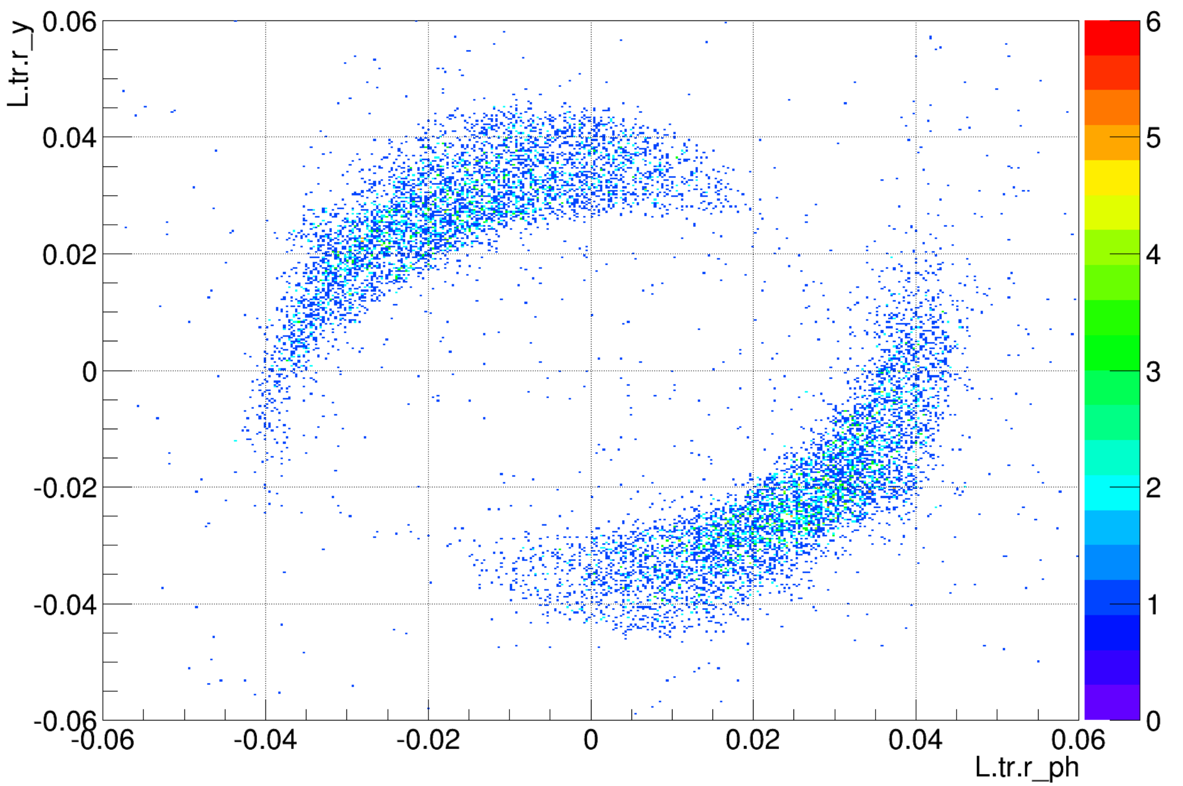
DVCS missing mass :
ep → e'Xγ

Missing mass² = (e + p - e' - γ)²

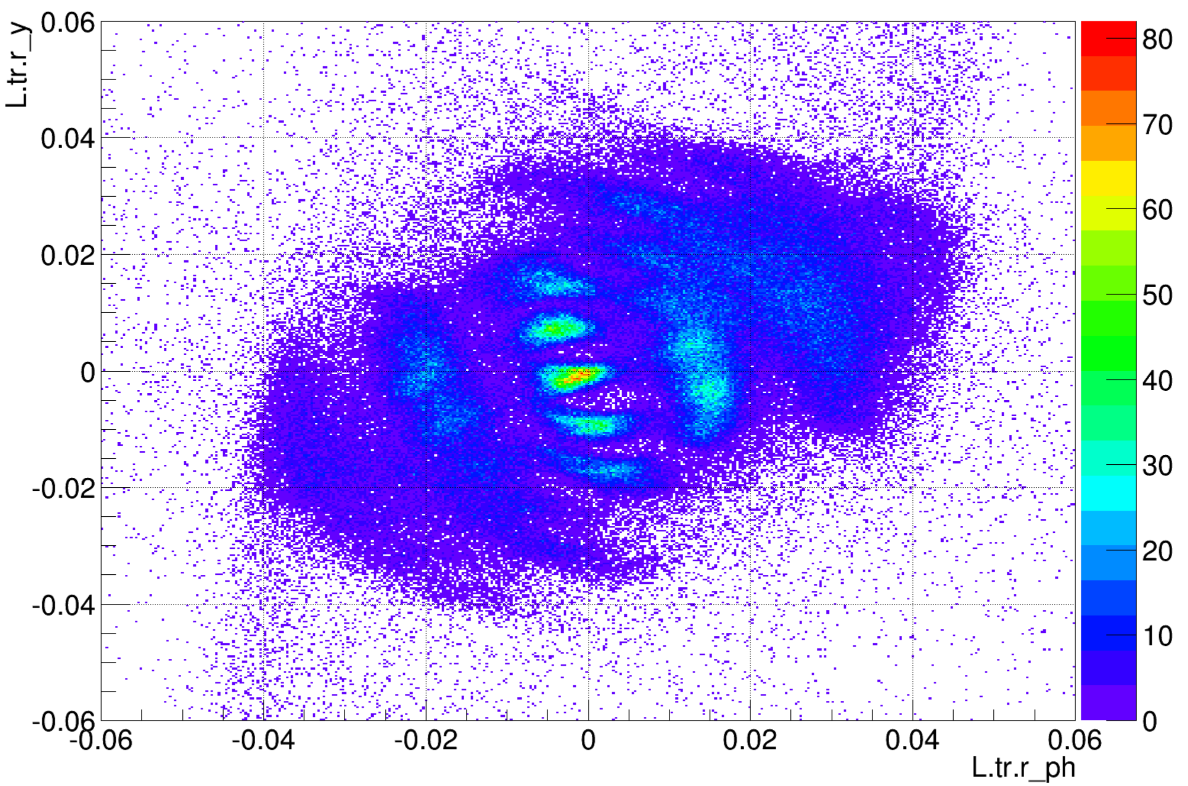
Exclusivity of the DVCS process is ensured by a cut on the missing mass.



HRS optics calibration – focal plan area issue



Production run setting - HRS angle : 37,1 deg



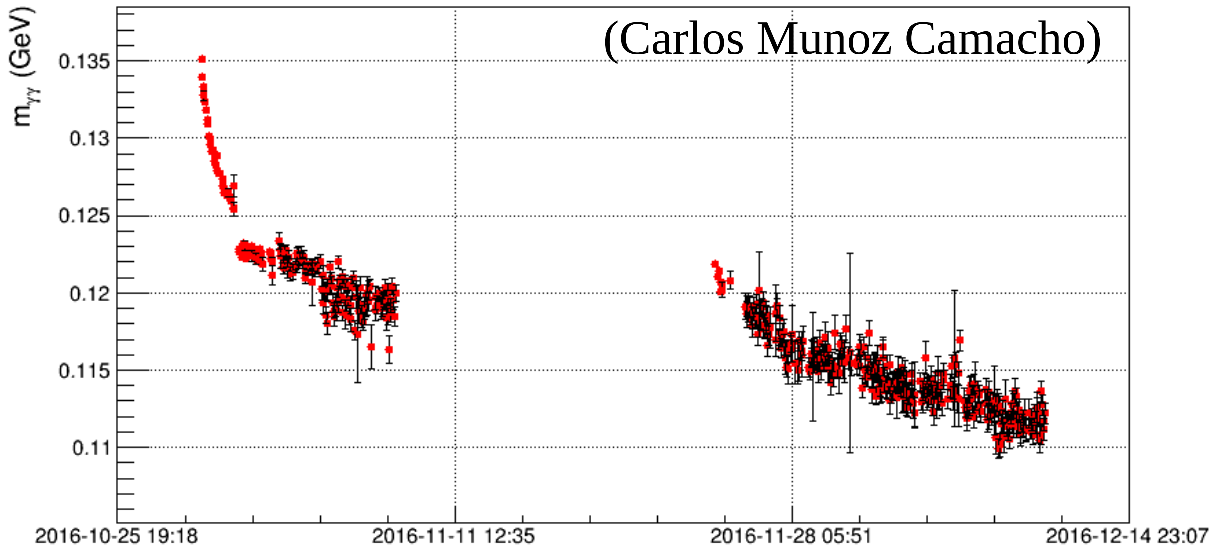
Optics calibration run - HRS angle : 16,6 deg

- Optics calibration run taken at small angle → areas of focal plan were not illuminated
  - →Poor calibration of the not illuminated area → Poor vertex reconstruction
  - →Poor vertex reconstruction on target edges for production runs → reconstructed target is too short

Calorimeter π^0 calibration

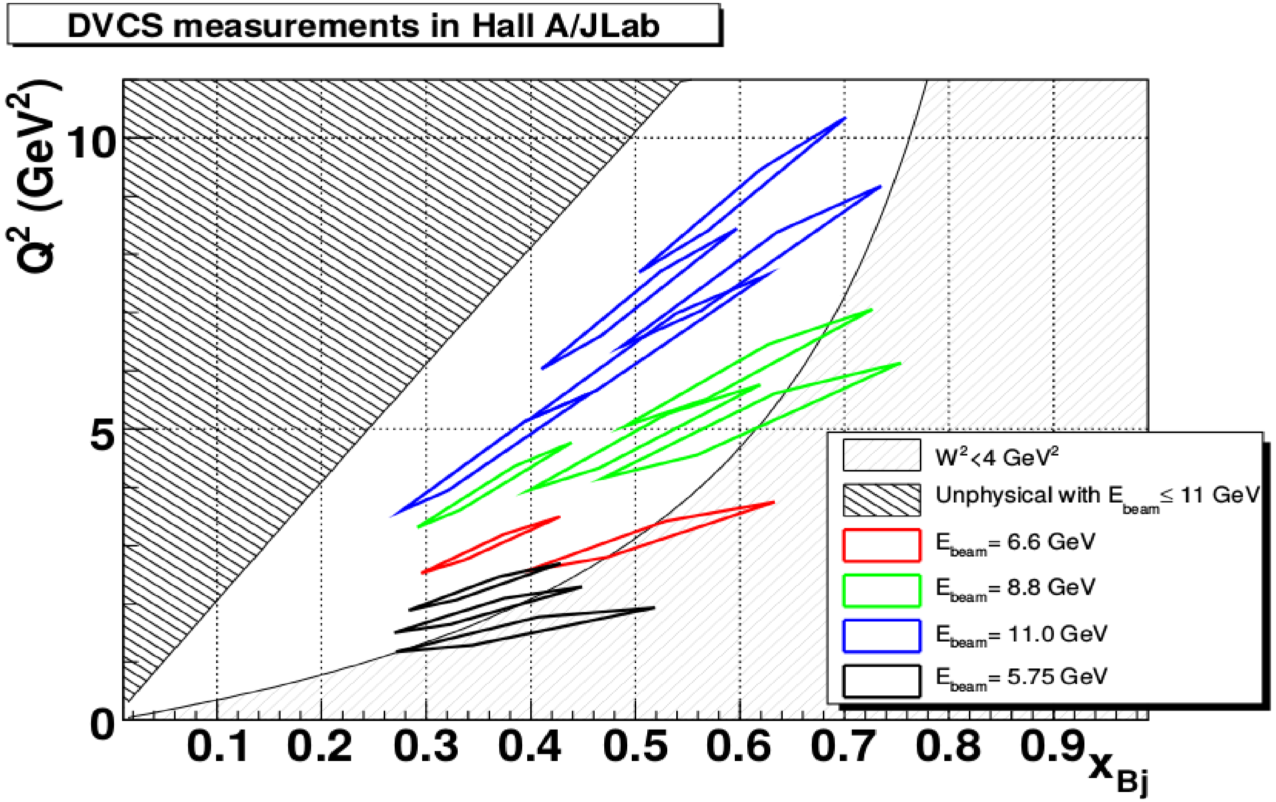
- Initial calibration (elastic calibration) :
  - Time consuming (~1 day)
  - Requires experimental setup changes
  - Cannot take DVCS data while calibrating
- π^0 calibration uses π^0 detected while taking DVCS data.
  - Can be done very often and after the actual data taking.
  - No beam time loss.

π^0 invariant mass (with no correction)



DVCS in Hall A - Goal

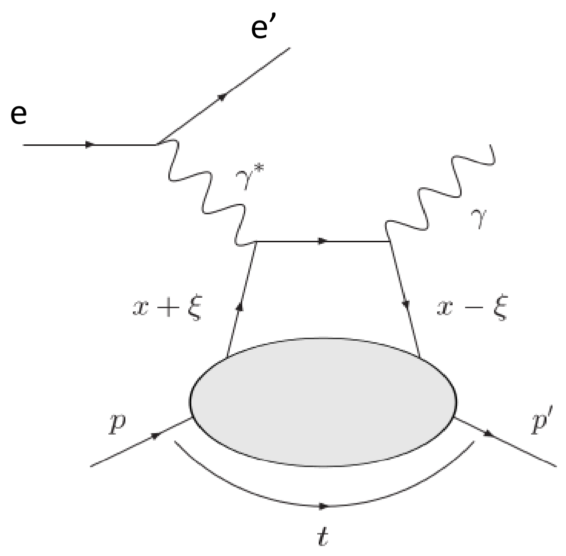
- Timeline:
  - E00-110/E03-106 (2004) : first round of dedicated experiments (Q^2 dependence study)
  - E07-007/E08-025 (2010) : second round of dedicated experiments (Q^2 dependence study + beam energy dependence)
  - E12-06-114 (2014 - 2016) : ~50% PAC days completed



- E12-06-114 goals :
  - Scaling test : Wider Q^2 scans at fixed x_B (larger Q^2 lever arm than in 2010 & several values of x_B)
  - Separation of Re and Im parts of DVCS cross-section amplitude

100 PAC days (88 + 12 calibration)

The DVCS + Bethe-Heitler interactions ep → e'p'γ



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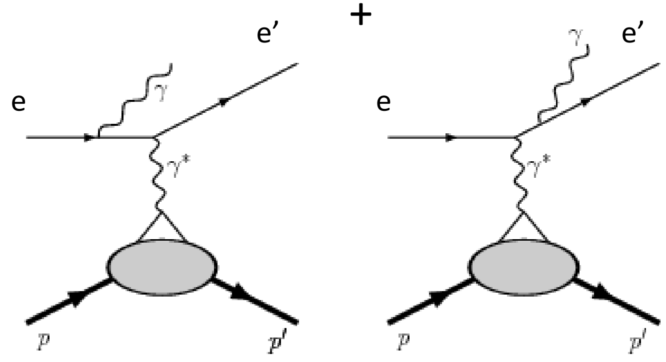


$Q^2 = -(e' - e)^2$: virtuality of γ^*

$\nu = E - E'$, energies of the electron before and after scattering

$x_B = \frac{Q^2}{2M\nu}$ (NB: $x_B \neq x$)

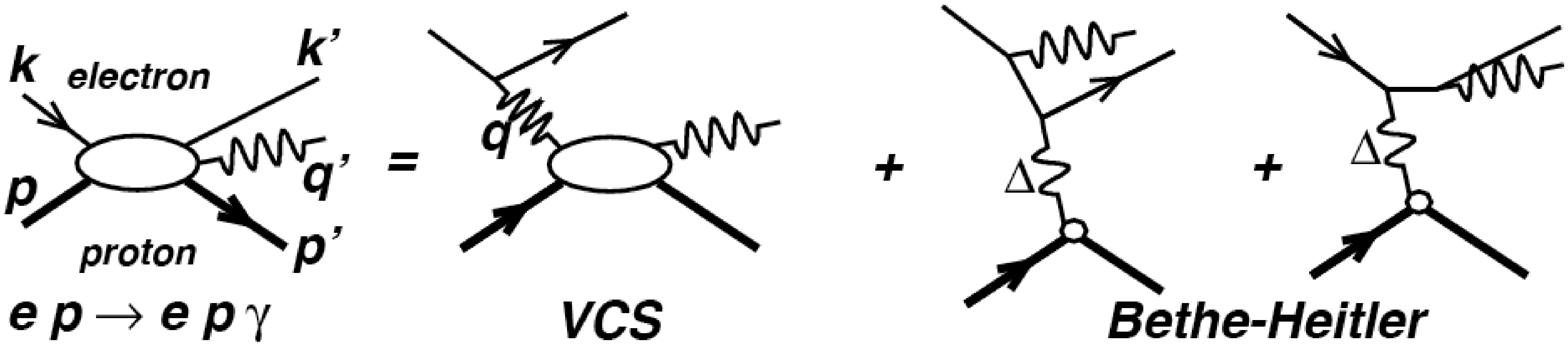
$\xi = \frac{x_B}{2-xB}$

-2ξ : longitudinal momentum transfer to the struck quark.

$t = (p - p')^2$: squared momentum transfer to the proton

In the limit $Q^2 \to \infty$ and $\nu \to \infty$ but fixed x_B (Bjorken limit), the virtual photon γ^* interacts with a single quark in the proton.

DVCS and Bethe-Heitler



At leading twist:

$$d^5\overrightarrow{\sigma} - d^5\overleftarrow{\sigma} = \Im m\,(T^{BH}\cdot T^{DVCS})$$

$$d^5\overrightarrow{\sigma} + d^5\overleftarrow{\sigma} = |BH|^2 + \Re e\,(T^{BH}\cdot T^{DVCS}) + |DVCS|^2$$

Known to 1%