E12-06-114: Deeply Virtual Compton Scattering at Jefferson Lab, Hall A

Salamanca Hadron 2017

September 27

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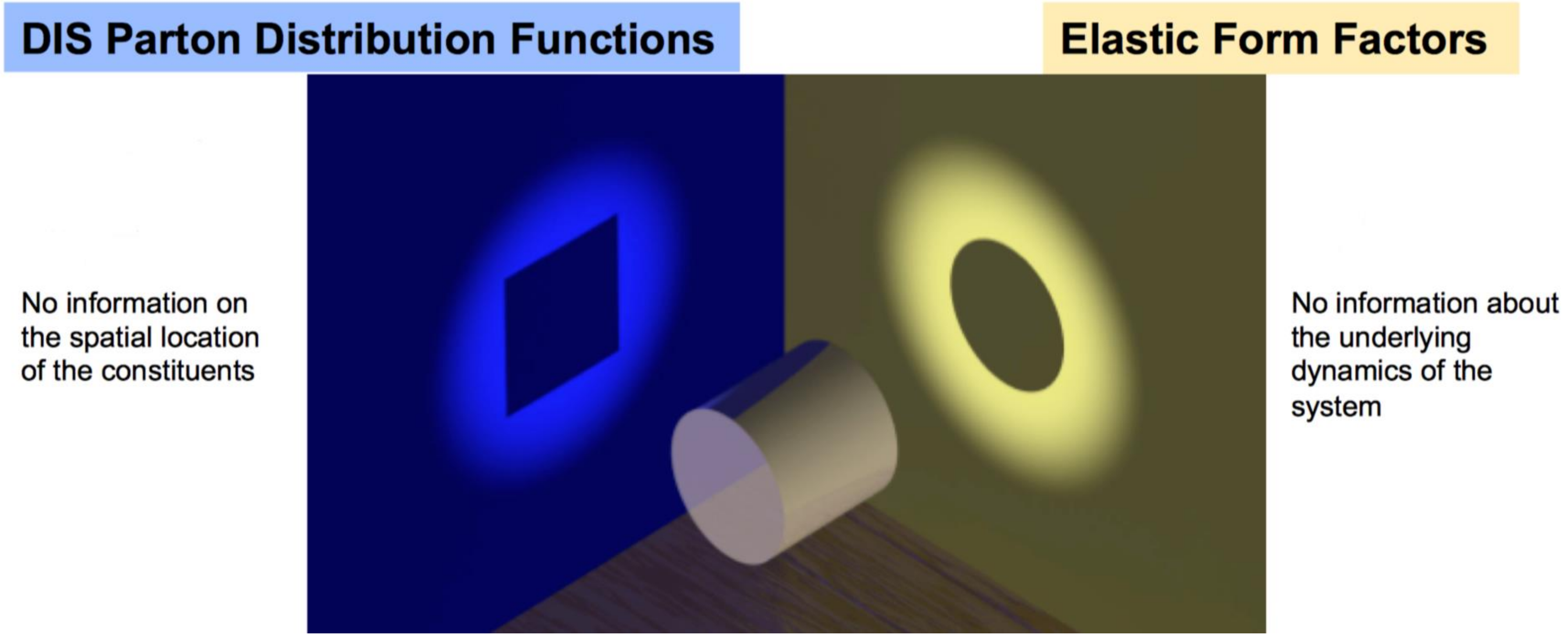
Jefferson Lab

Outline

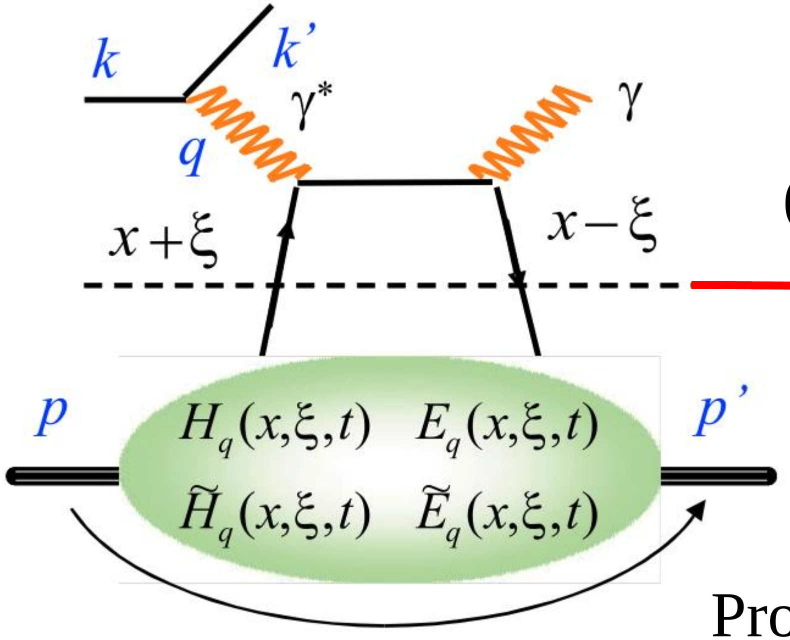
- Introduction – physics motivations
- DVCS at Jlab, Hall A – Goal
- Experimental setup
- Overview of the ongoing data analysis
- Summary and Outlook

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)



$$t = (p' - p)^2$$

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

In the Bjorken Limit : $\left.\begin{array}{l} Q^2 = -q^2 \to \infty \\ \nu \to \infty \end{array}\right\}$ $x_B = \frac{Q^2}{2M\nu}$ fixed

Hard part
(QED, can be computed)

Factorization

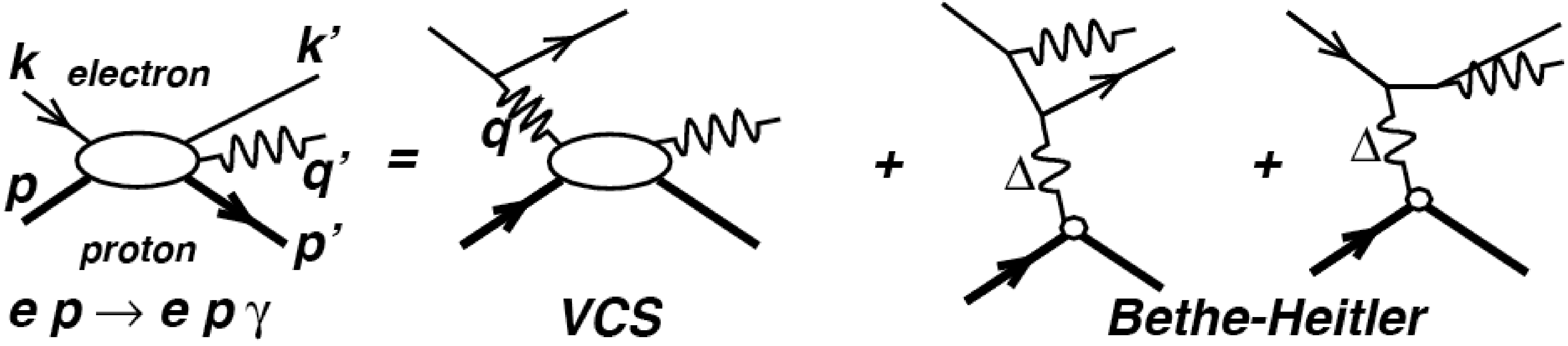
Soft part
Parametrized by GPDs

DVCS : ep → e'p'γ

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

DVCS cross section → GPDs → Description of the proton internal structure.

DVCS and Bethe-Heitler



At leading twist:

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

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

↓

Known to 1%

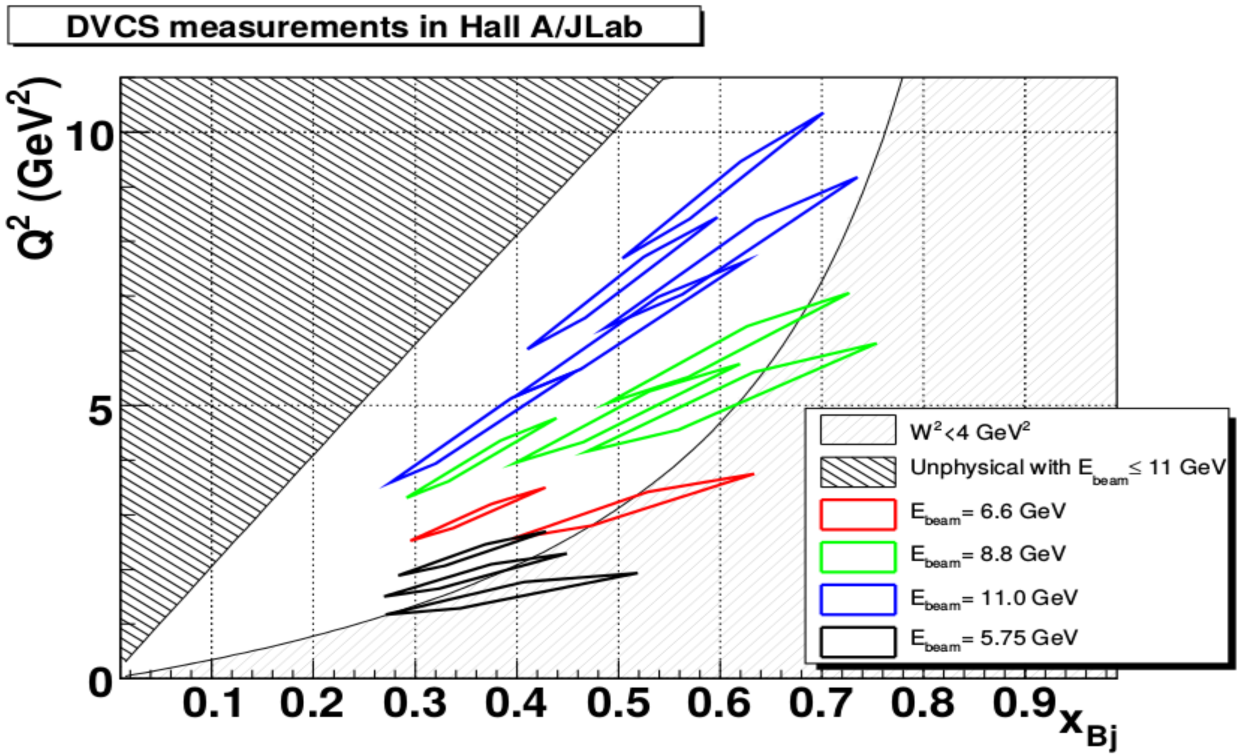
DVCS at Jefferson Lab, Hall A – Goal

- Data acquisition between Fall 2014 and Fall 2016

kinematic	Q^2 (GeV^2)	x_B
kin36_1	3.2	0.36
kin36_2	3.6	0.36
kin36_3	4.5	0.36
kin48_1	2.7	0.48
kin48_2	4.4	0.48
kin48_3	5.3	0.48
kin48_4	6.9	0.48
kin60_1	5.5	0.60
kin60_2	6.1	0.60
kin60_3	8.4	0.60
kin60_4	9.0	0.60

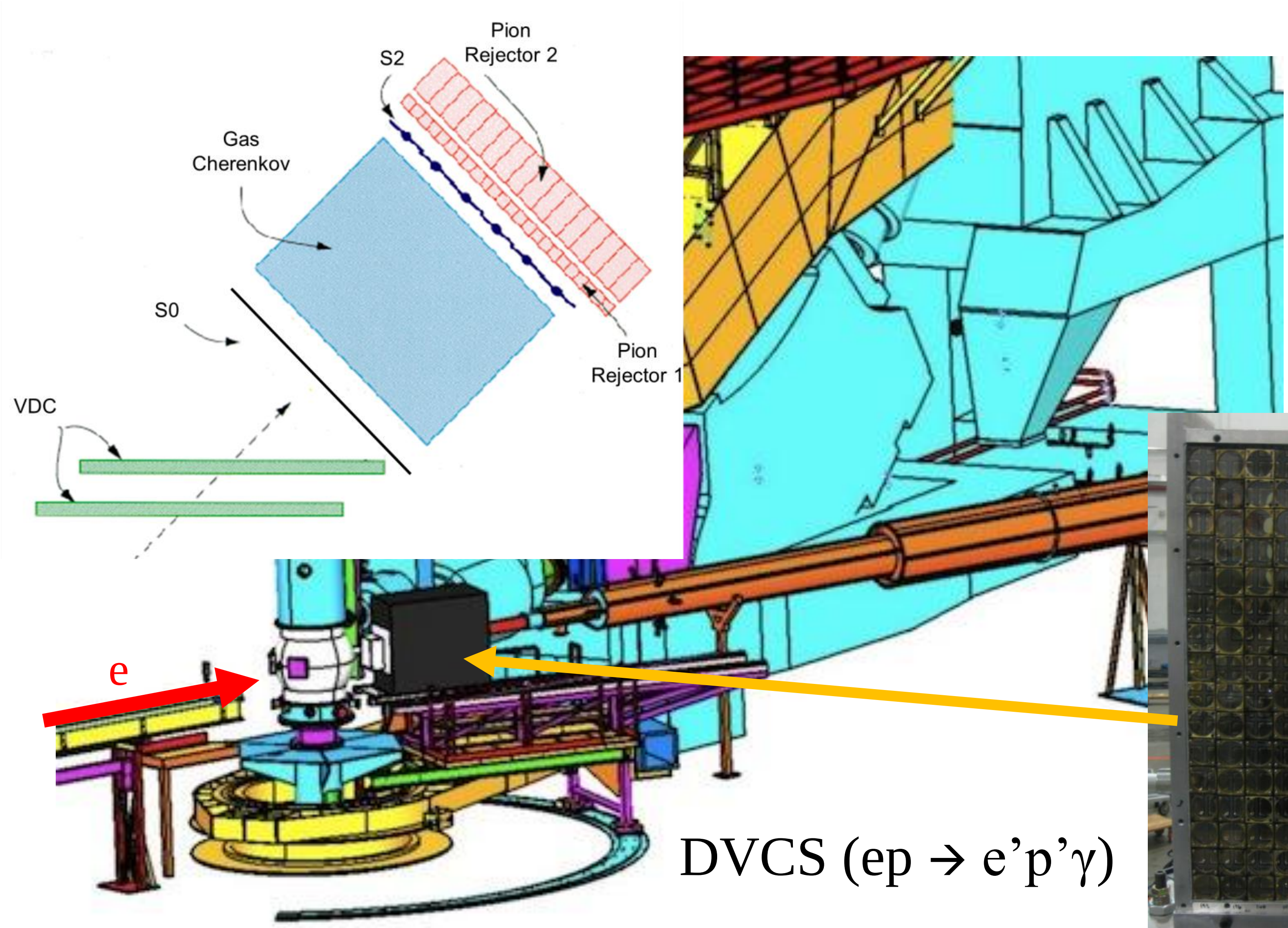
100 days of beam (88 + 12 calibration)

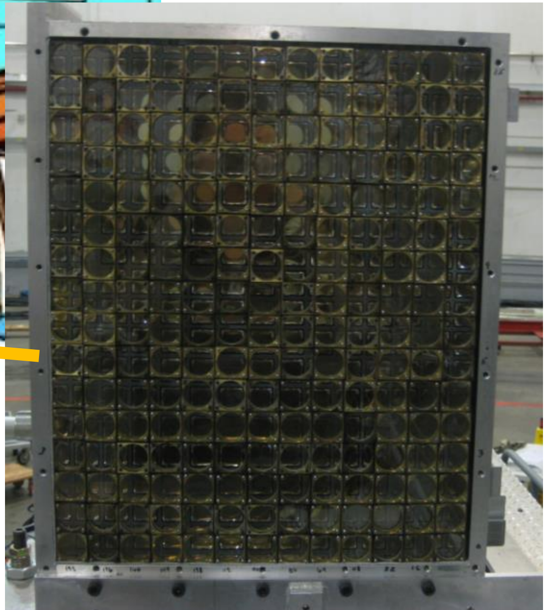
- E12-06-114 goals :
  - Scaling test : Wide Q^2 scans at fixed x_B (larger Q^2 lever arm than previously & several values of x_B)
  - Separation of Re and Im parts of DVCS cross-section amplitude



DVCS at Jefferson Lab, Hall A – Apparatus

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





DVCS (ep → e'p'γ)

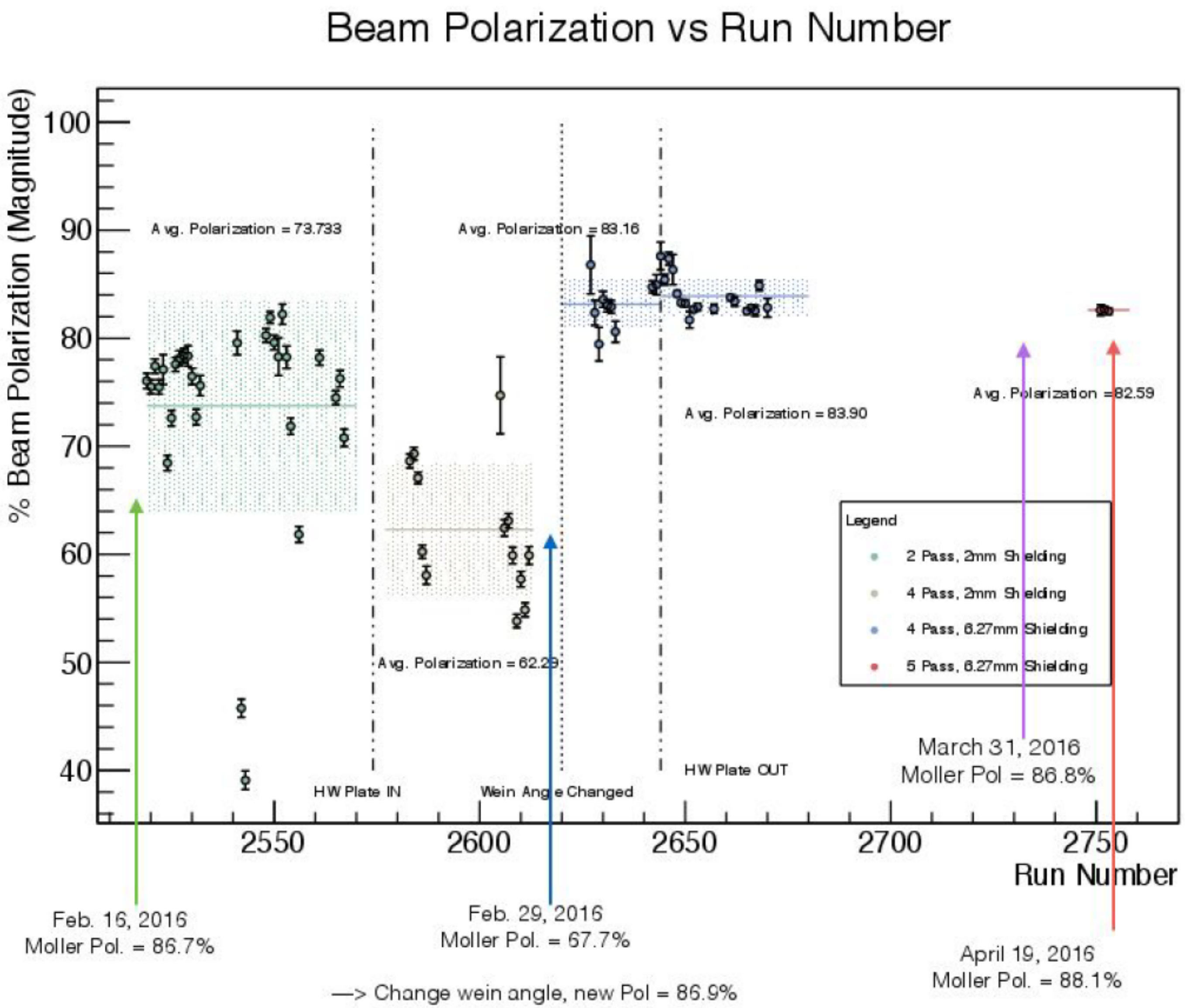
- Electron beam : e
- Liquid Hydrogen target : p
- Spectrometer : detect e'
- Calorimeter : detect γ
- p' not detected

DVCS missing mass :
ep → e'Xγ

Missing mass^2 = (e + p - e' - γ)^2

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

Beam polarization measurement

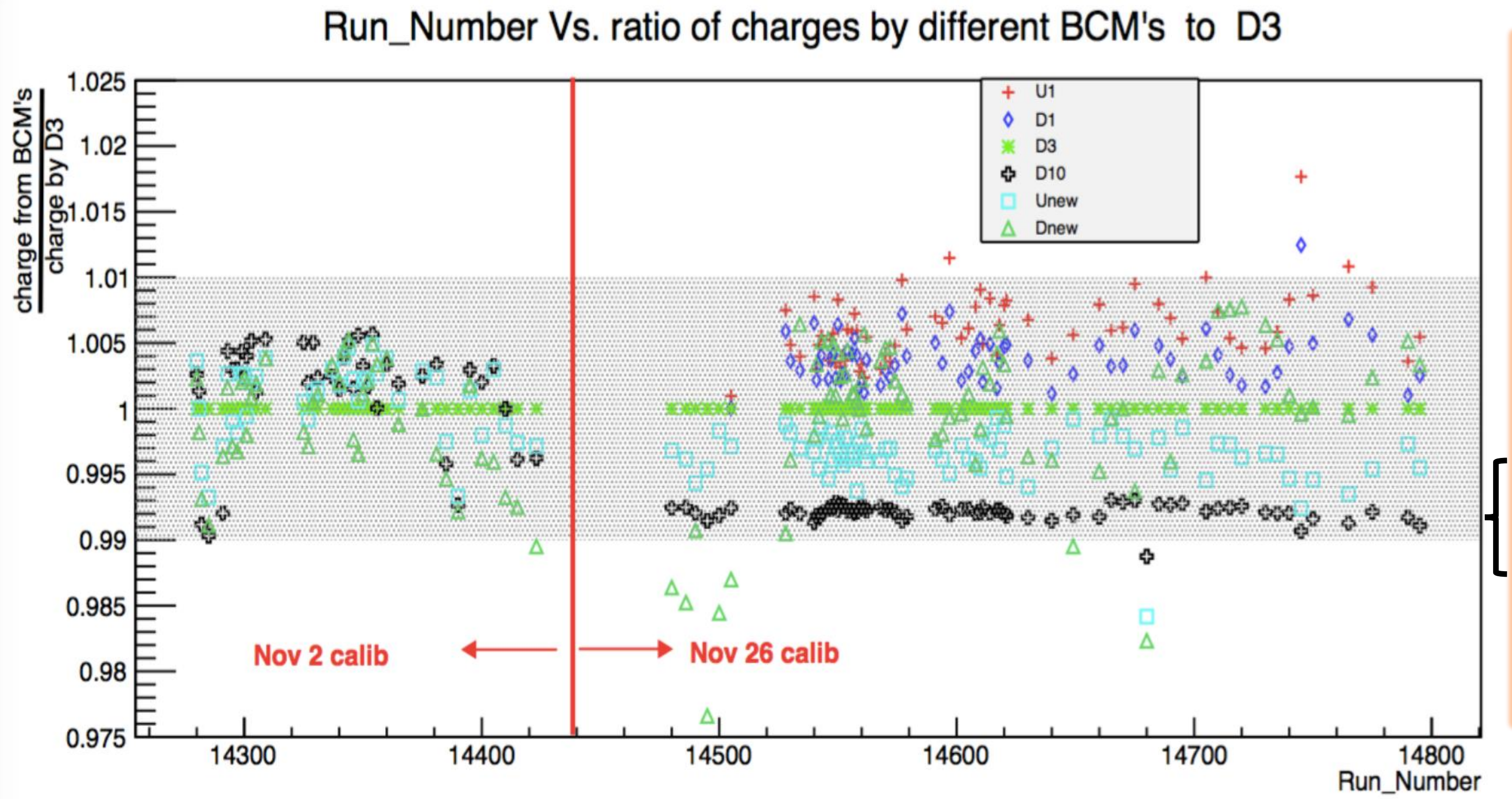


- Moller & Compton polarization measurements
- Moller : e^- - e^- scattering on dedicated Moller target (both e^- polarized), measure counting asymmetry.
- Compton : e^- – γ scattering (circularly polarized laser), measure counting asymmetry.

- Moller results finalized
- Compton analysis not finalized yet, discrepancies being investigated
- **Fall 2016 : beam polarization ~85%, and stable**

Beam current measurement

- Used Beam Current Monitors : RF cavity in which the electron beam induces a current
- BCM calibration : induced current in cavity ↔ beam current
- 2 BCMs : U (upstream) & D (downstream), connected to several amplification electronics : D → D1, D3, D10

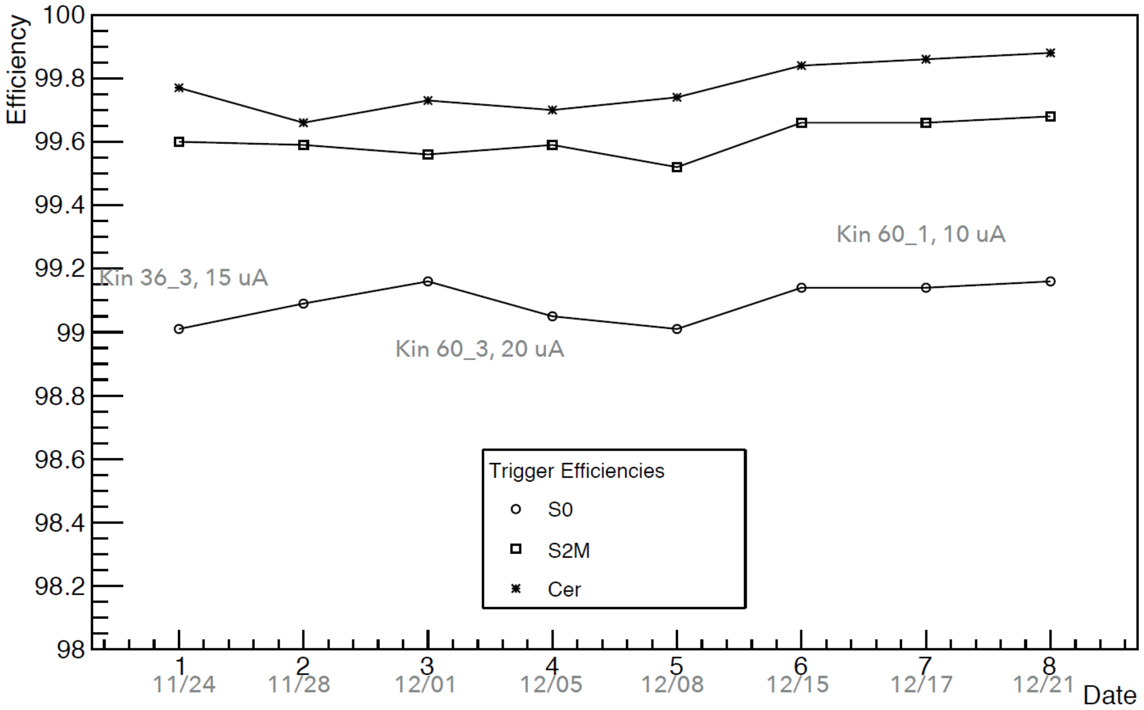


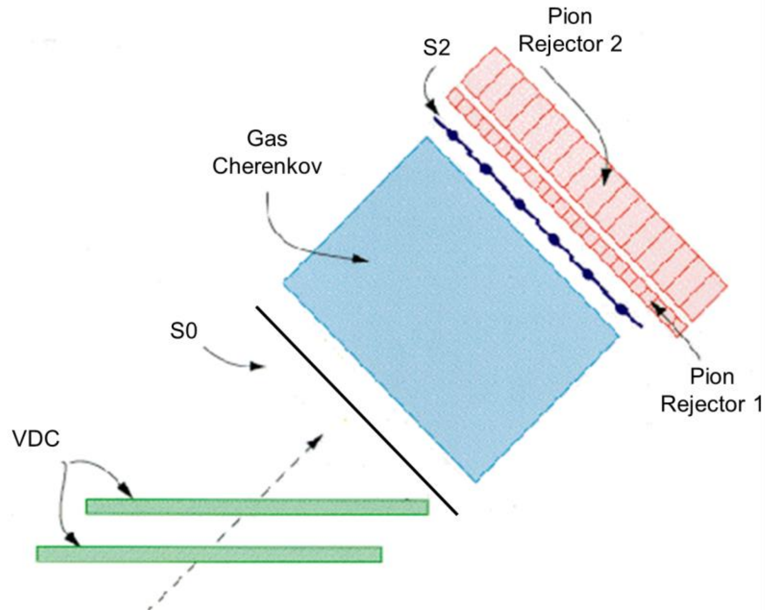
- Beam current used: 10 μA ≤ I ≤ 20 μA
- Unew & Dnew are noisier (electronics) → not used
- U1 & D1 are not linear ≤ 10 μA

  → not used
- D3 & D10 linear for 5 μA ≤ I ≤ 25 μA
- D3 & D10 agree within 1%
- D10 stable against D3
- **Conclusion: can rely on average of D3 & D10**

Trigger efficiency measurement

	11/24/16 (36_3, 15uA)	11/28/16 (60_3, 20uA)	12/01/16 (60_3, 20uA)	12/05/16 (60_3, 20uA)	12/08/16 (60_3, 20uA)	12/15/16 (60_1, 10uA)	12/17/16 (60_1, 10uA)	12/21/16 (60_1, 10uA)
S0	99.01	99.09	99.16	99.05	99.01	99.14	99.14	99.16
S2M	99.60	99.59	99.56	99.59	99.52	99.66	99.66	99.68
Cer	99.77	99.66	99.73	99.70	99.74	99.84	99.86	99.88



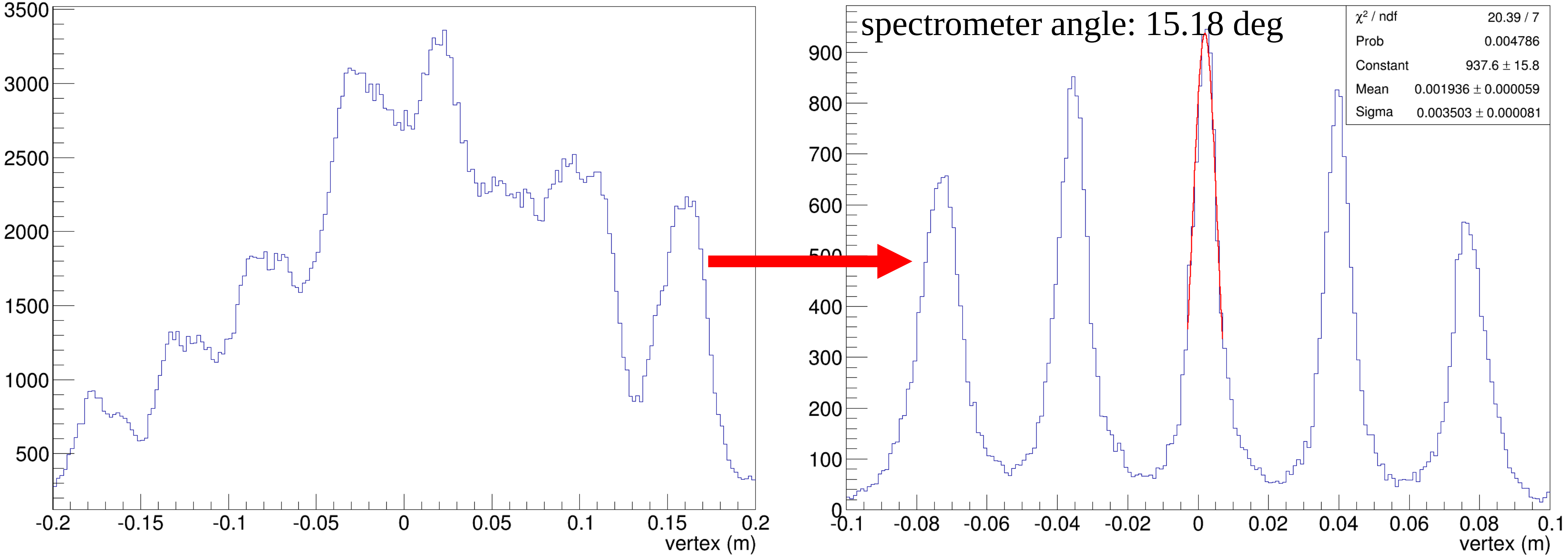


- Method :
  - Use 2 out of 3 detectors as trigger
  - Upon trigger detection, check if particle detected in 3rd (left out) detector

  → Measure efficiency of 3rd (left out) detector
- S0, S2 and Cerenkov **efficiency** > **99%**

Spectrometer optics calibration

Reconstructed vertex (not calibrated) Reconstructed vertex (calibrated)



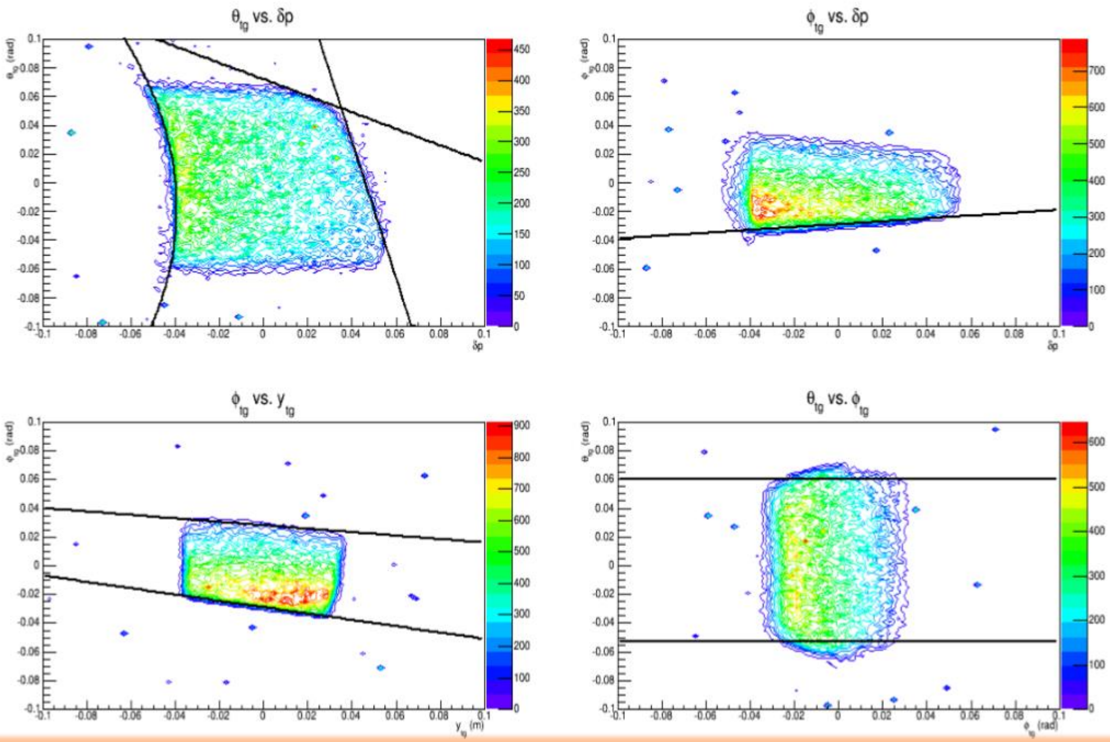
- Issue with one spectrometer magnet during Spring 2016, changed magnet during Fall 2016

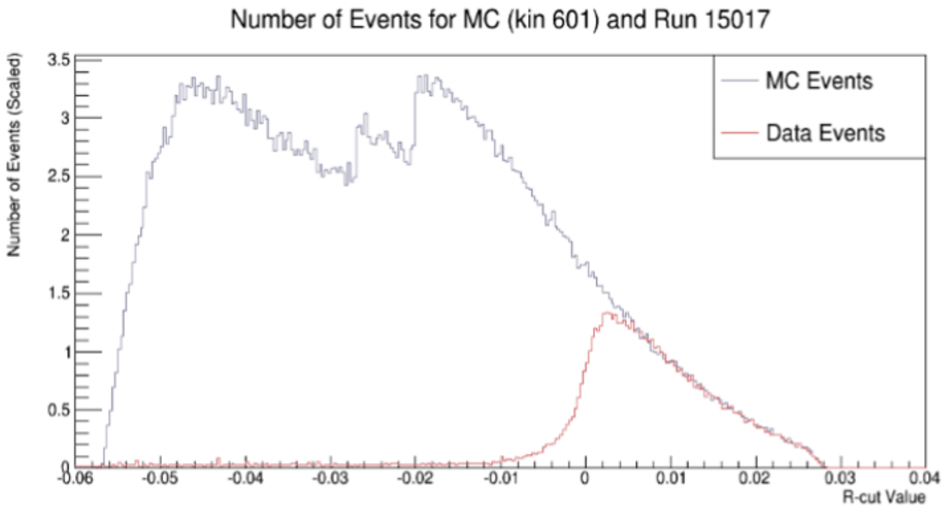
→ Optics calibrations

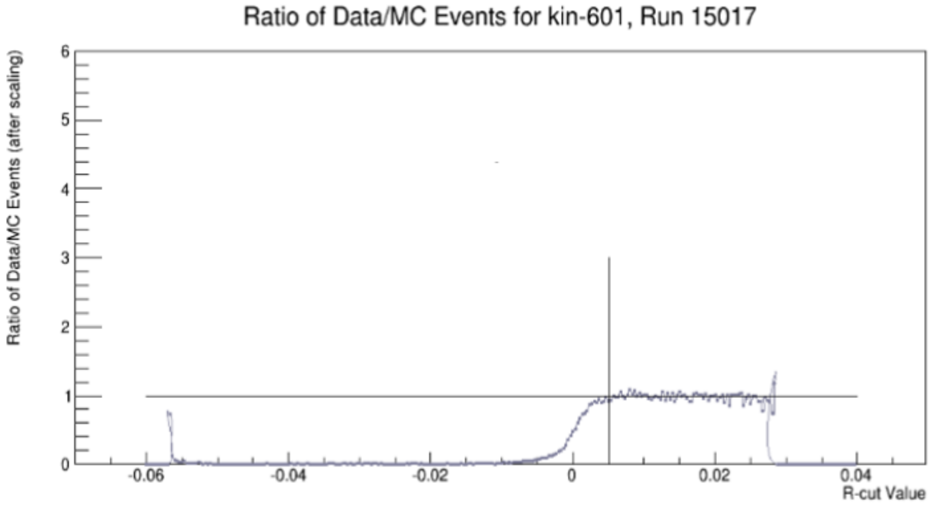
→ **Good vertex resolution** (σ = 3.5 mm with spectrometer at 15.18 deg)

→ **Good momentum resolution** ($\sigma_{dp/p} = 10^{-3}$)

Spectrometer acceptance study

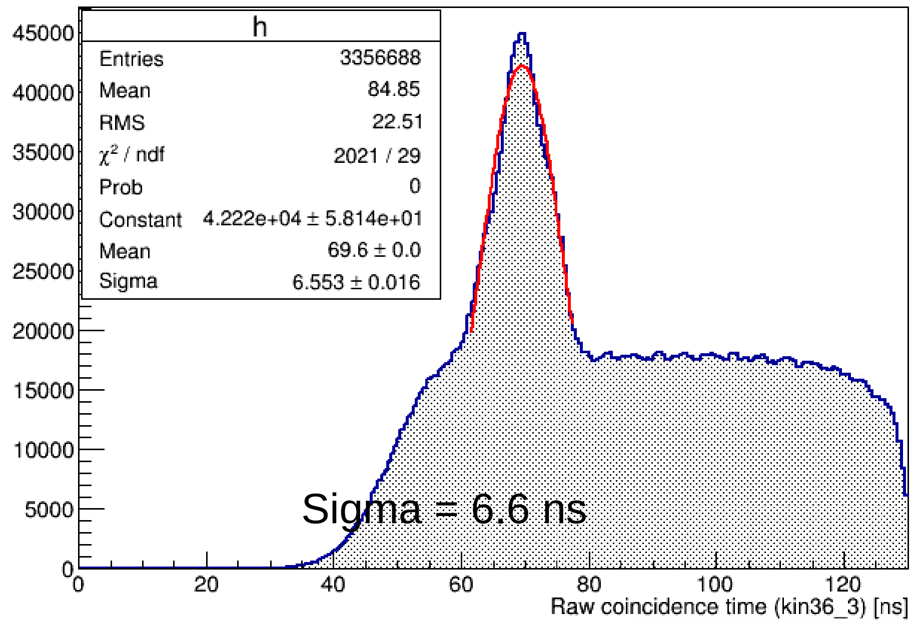


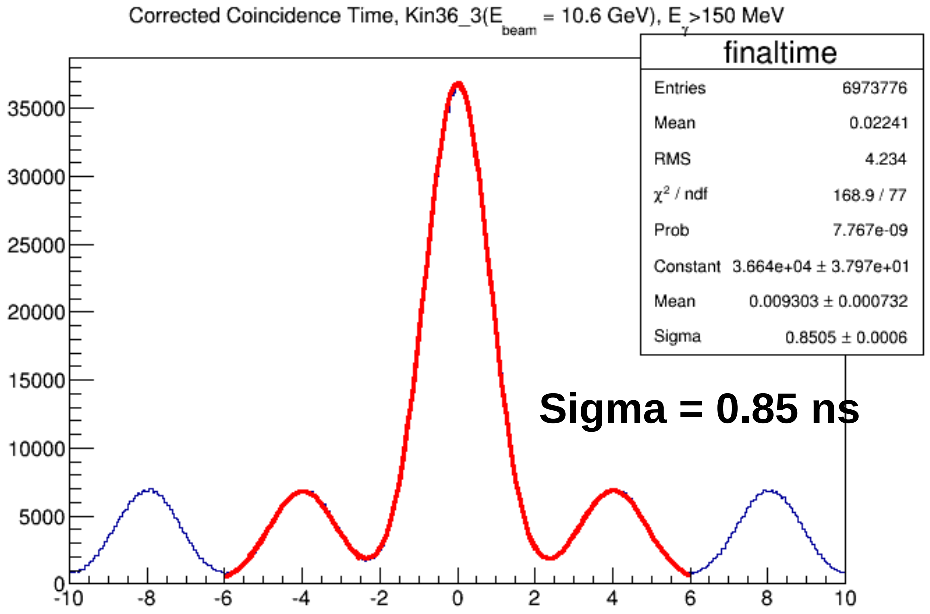


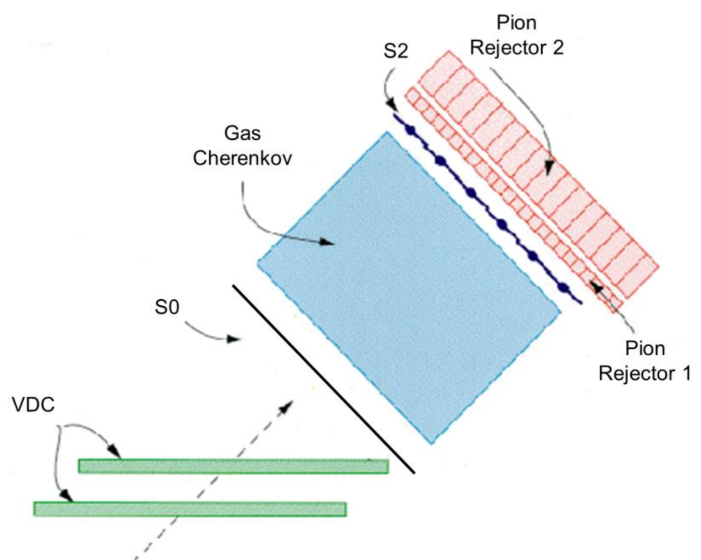


- R-function : computes distance (R-value) of an event to the edges of the spectrometer 4D-acceptance.
- **More efficient cut than four 1D-cuts (because of correlations).**
- Cut on R-value : R-cut. Data and Monte Carlo event distributions must agree for R-value > R-cut.
- MC simulation will use R-cut to compute spectrometer acceptance.

Coincidence time correction





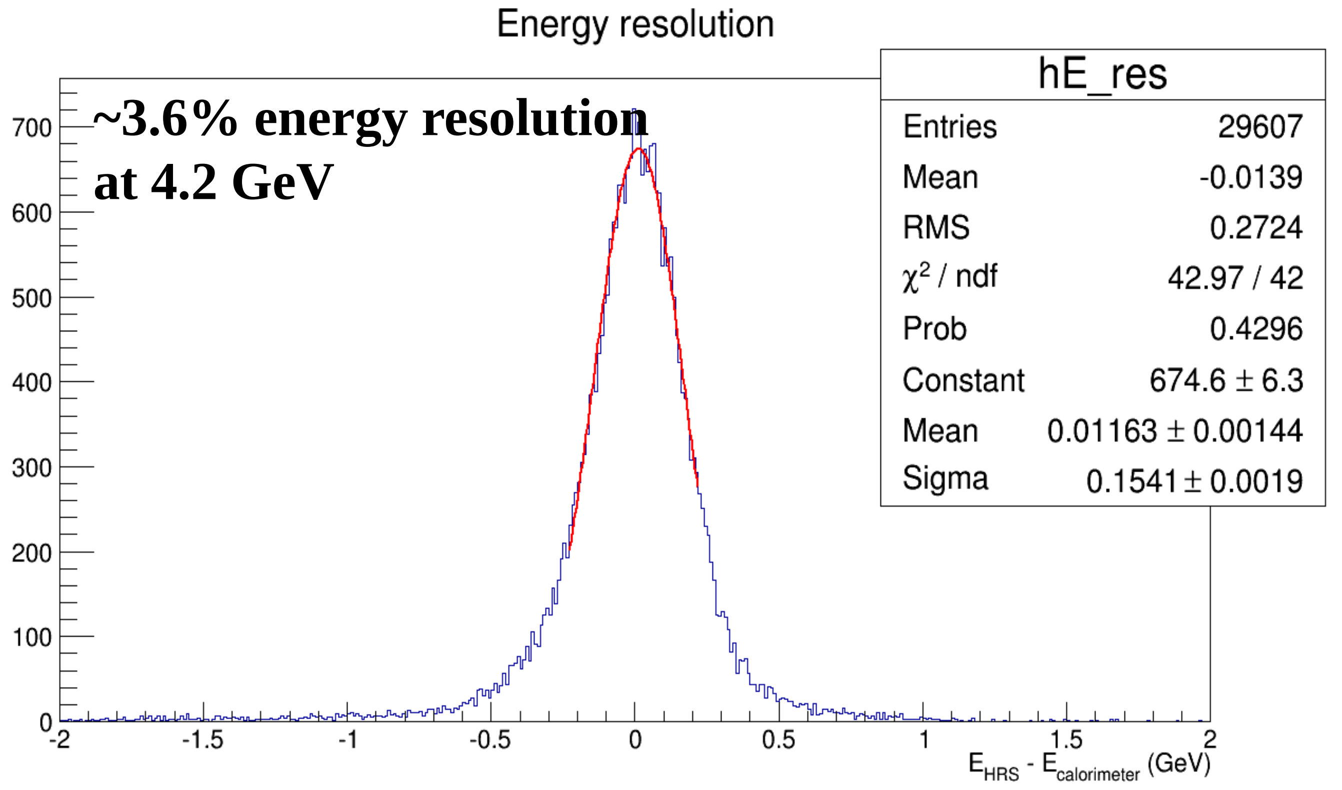


Corrected for:

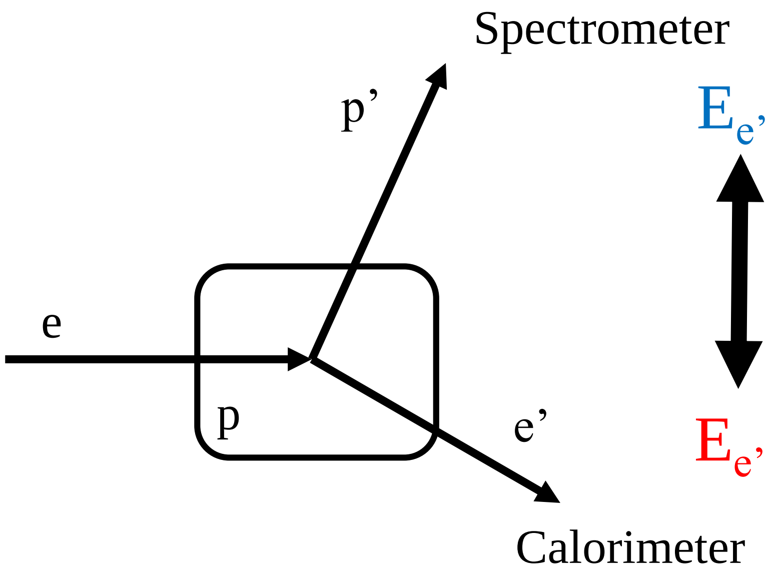
- Trigger jitter (relative time between calorimeter and spectrometer triggers)
- Calorimeter blocks relative time (cabling)
- S2m paddles relative time
- Photons travel time in S2m
- Electron travel time

Good identification of calorimeter - spectrometer coincidence allows to **remove accidentals**.

Calorimeter energy calibration

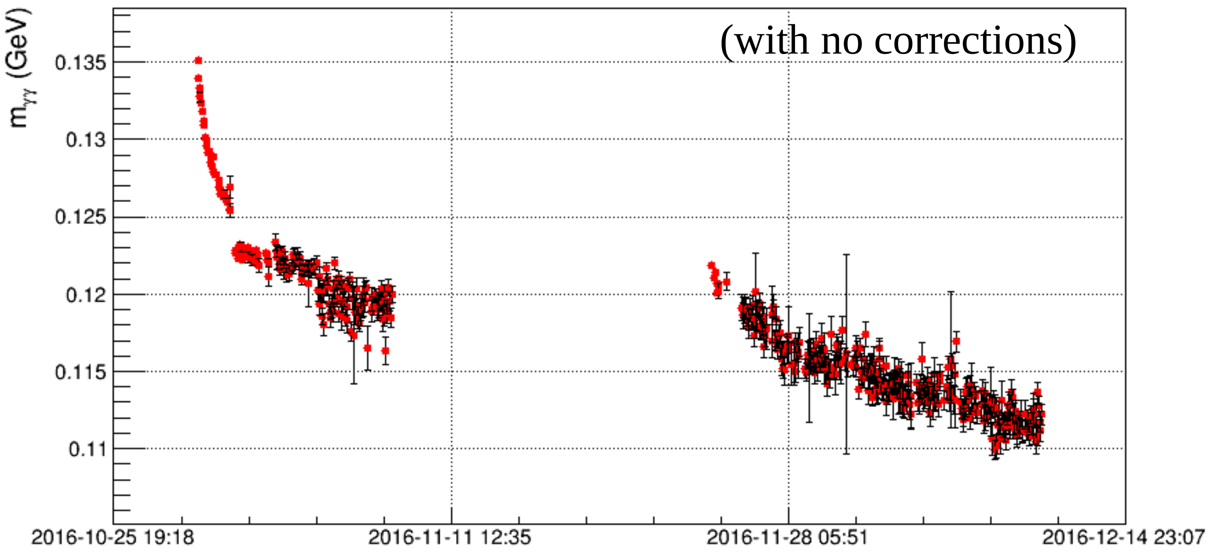


- Proton detected in spectrometer, electron detected in calorimeter.
- Compute expected electron energy using detected proton (elastic) : $E_{e'}$
- Reconstruct electron energy in calorimeter : $E_{e'}$
- Adjust calorimeter blocks calibration coefficients so that $E_{e'} = E_{e'}$

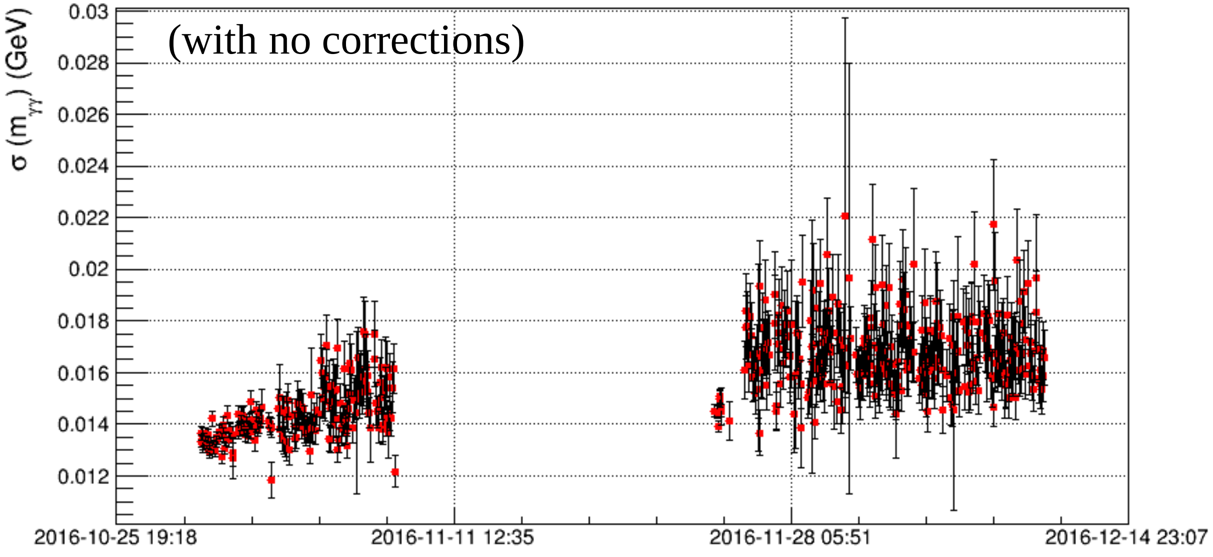


Calorimeter energy calibration

π^0 invariant mass



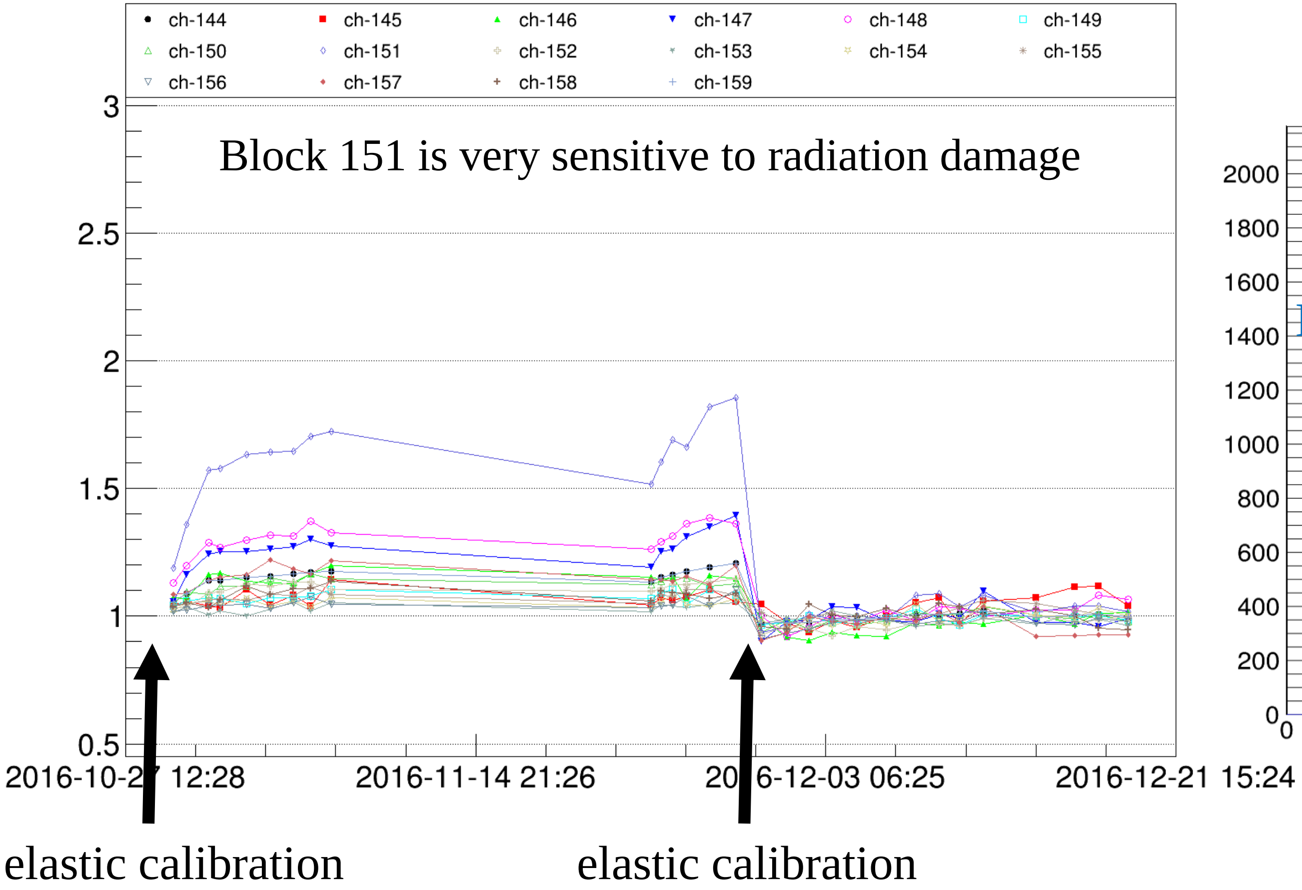
π^0 invariant mass resolution

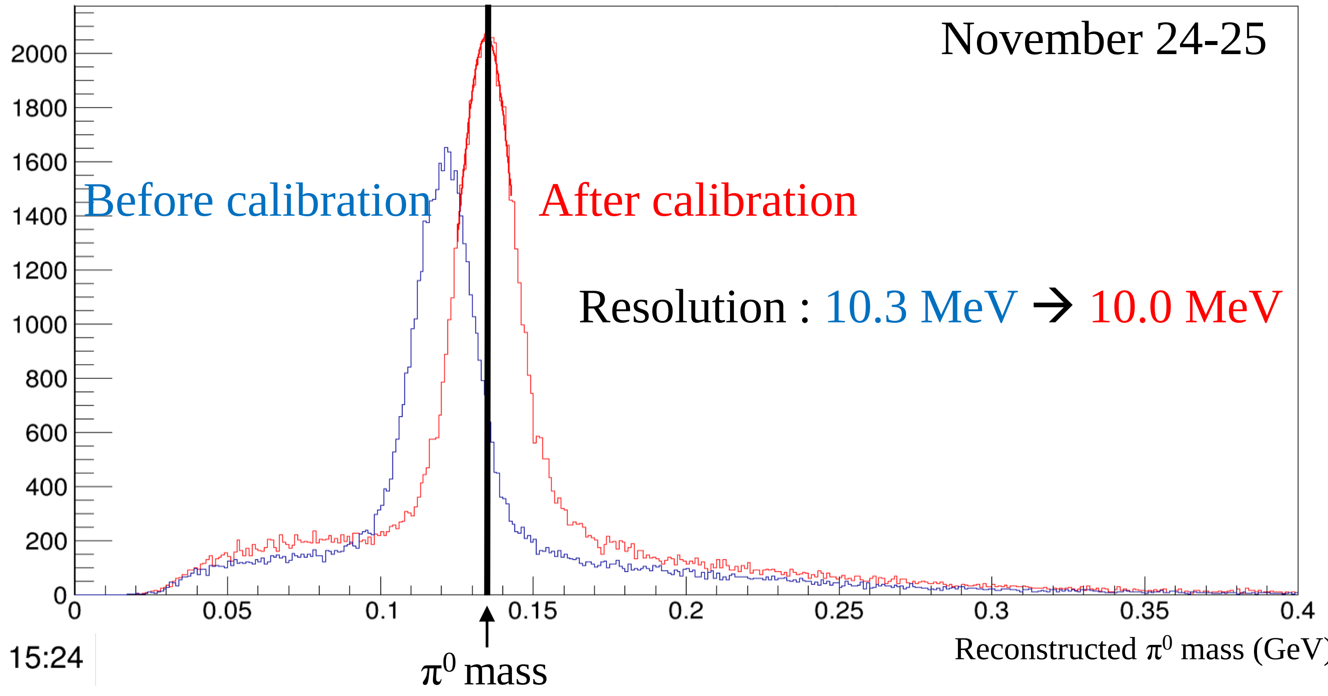


- Extremely fast initial loss of gain of the calorimeter blocks (radiation damage)
- Slower but **continuous loss of gain** afterward
- Small recovery after long down time

Calorimeter energy calibration

- Compute correction coefficients by reconstructing π^0 invariant mass.
- Optimize π^0 invariant mass mean value and resolution
- **Correct calorimeter calibration coefficients between elastic calibrations**





Dead time

- Use scalers to compute dead time.
- Took specific runs to check that our dead time correction is correct
- Normalized "spectrometer electron" rates corrected by dead time are independent from beam current
  - Study ongoing…

Dead time = 1 – live time

$$\text{Live time} = \frac{\text{live scaler rate}}{\text{raw scaler rate}}$$

I (μA)	Live Time	Normalized "spectrometer electron" rate / LT (Hz/μA)
10.61	0.985	3.422
15.32	0.976	3.450
20.53	0.965	3.449

Summary and Outlook

- Data acquisition ended in Fall 2016 with very good statistics

- Data analysis in progress
  - Calibrations complete
  - Lot of corrections/preliminary studies (almost) complete

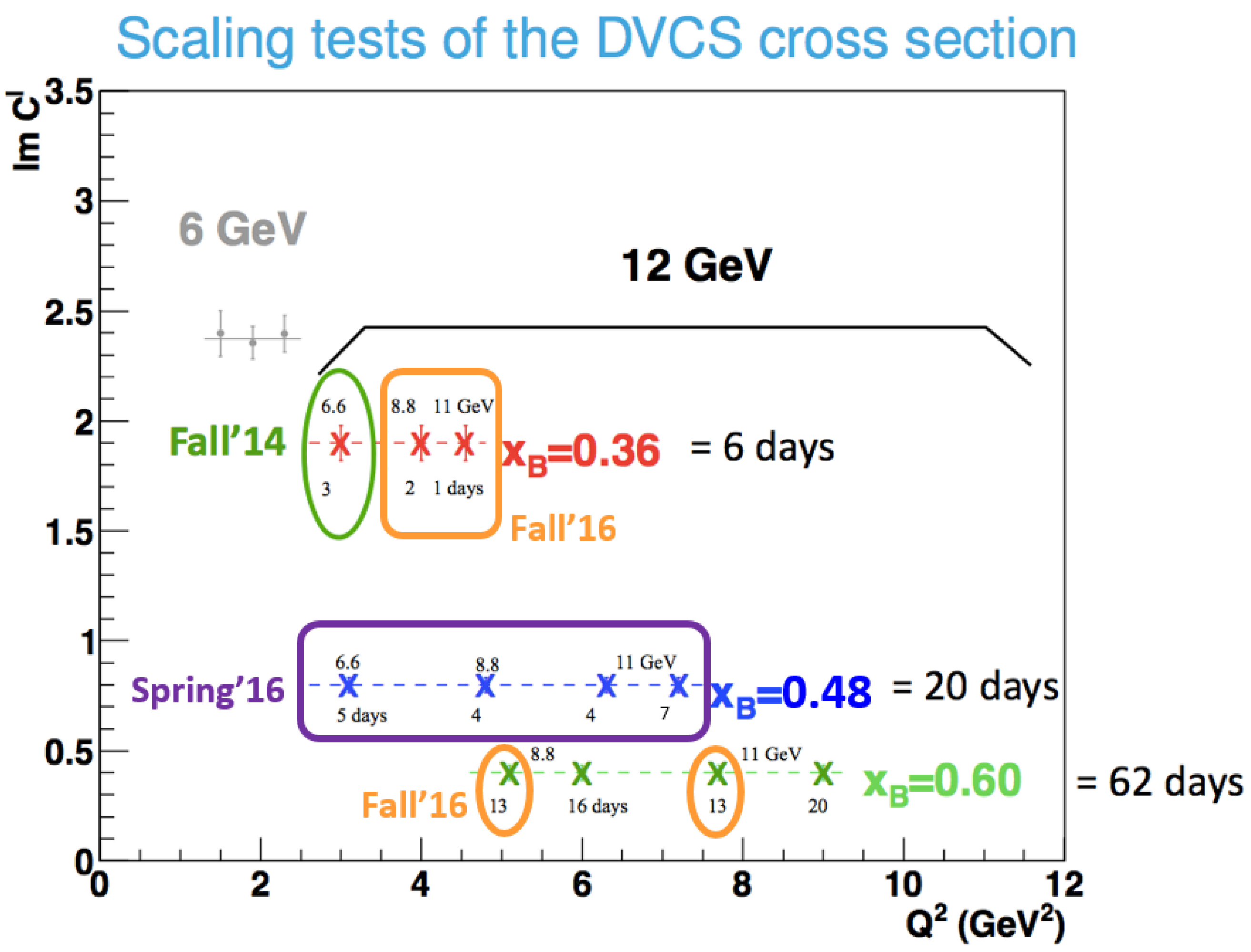
  - Next : DIS cross-section, MC simulation, π^0 substraction, DVCS cross-section extraction, systematic uncertainties
  - **2018 : Preliminary DVCS cross-sections extraction !**

Thank You !

Questions ?

Backup slides

DVCS cumulated statistics



kinematic	% of target charge	PAC days
kin36_1	100.0	3
kin36_2	100.0	2
kin36_3	100.0	1
kin48_1	100.0	5
kin48_2	56.6	4
kin48_3	76.4	4
kin48_4	53.0	7
kin60_1	100.0	13
kin60_2	0.0	16
kin60_3	100.0	13
kin60_4	0.0	20

Could not go back and complete kin48_[234] because of beam energy change over the summer 2016.

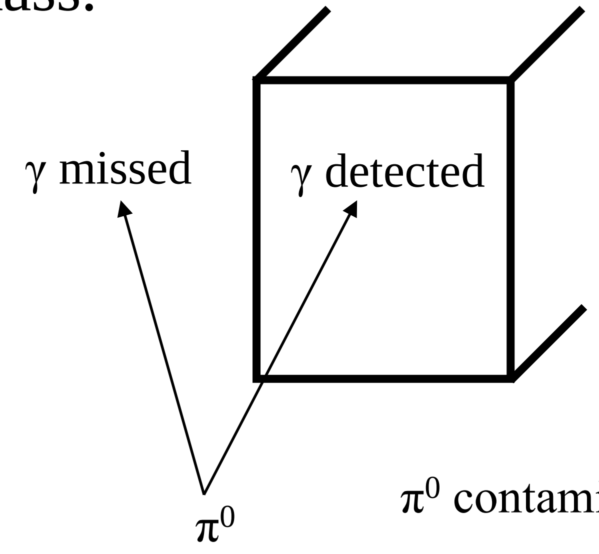
~50% of beam time allocation completed between 2014 and 2016.

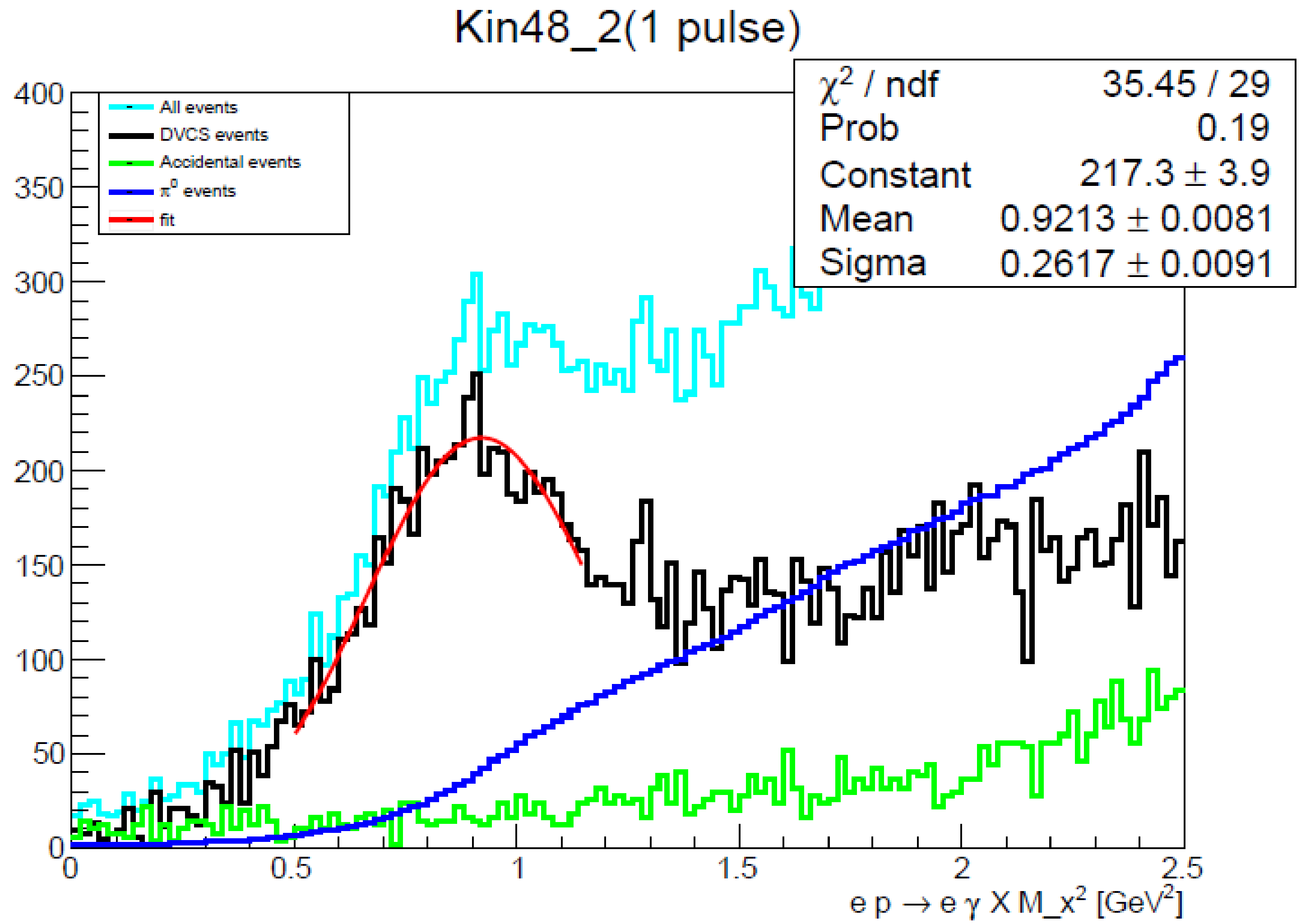
DVCS missing mass and exclusivity

DVCS missing mass :
ep → e'Xγ

Missing mass² = (e + p - e' - γ)²

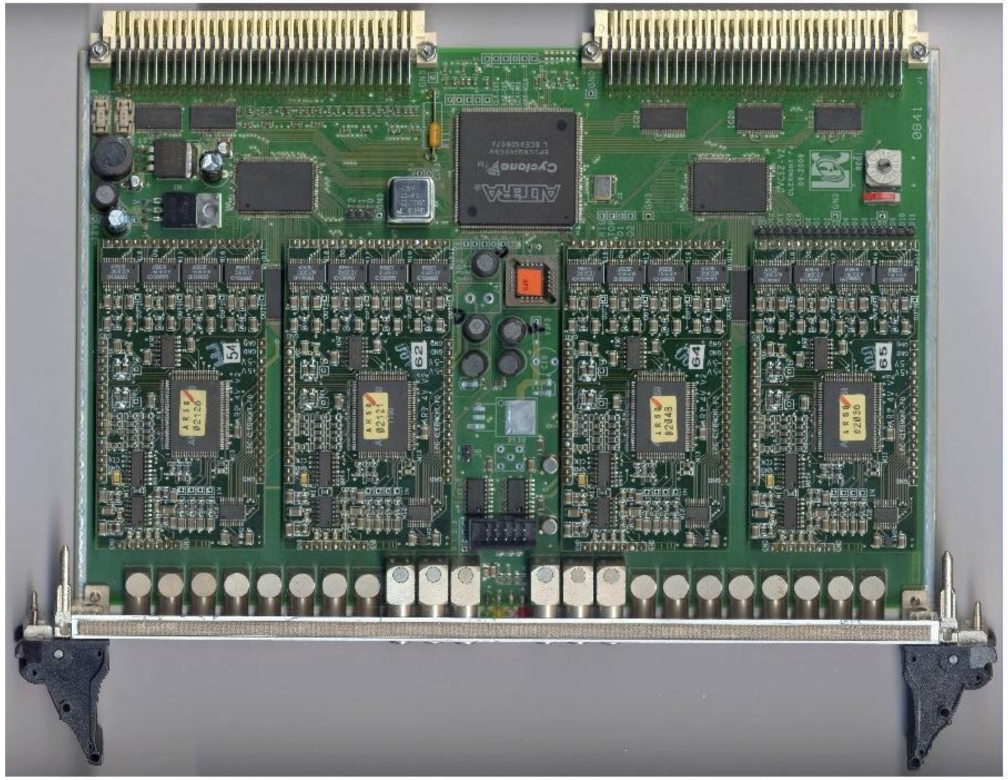
Exclusivity of the DVCS process is ensured by a cut on the missing mass.

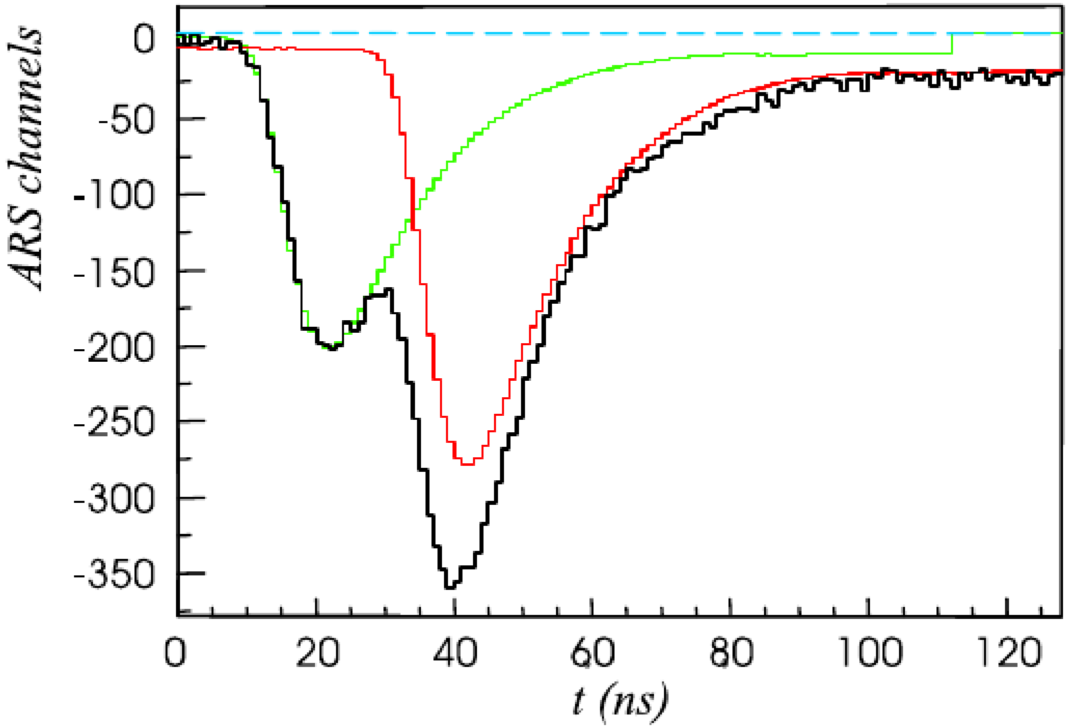




π^0 contamination, "looks like" a DVCS γ

DVCS Calorimeter DAQ





- Jlab : High Luminosity → Challenge : **Pile-up**.
- **Analog Ring Sampler boards** : 1GHz Digitizer electronics, 128 ns samples.

→Allows clear identification of DVCS photons and **pile-up resolution**.

→Challenge : Large amount of data to deal with, **need "smart" trigger**.

DVCS Trigger System

- **Level 1 – Electron Trigger in Spectrometer** :
  - Coincidence : Scintillator paddle + Gaz Cerenkov detector

- If Level 1 trigger fired → **Level 2 – Coincidence with Calorimeter** :
  - Calorimeter ARS boards freeze
  - Look for event in Calorimeter
  - Energy threshold

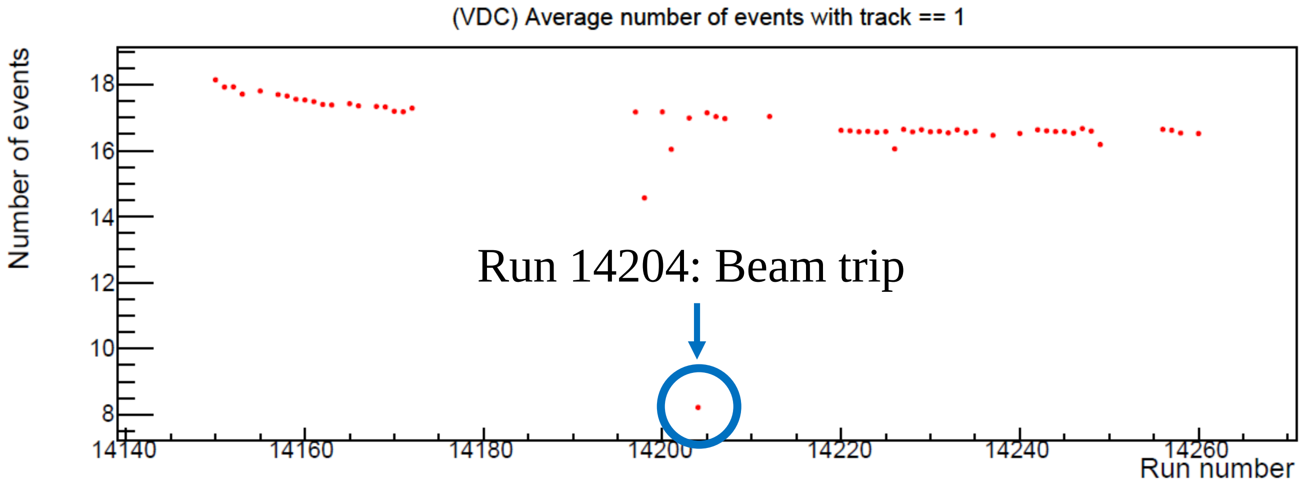
- If level 2 fired → Event recorded (**ARS encoding slow → dead time**)
- If level 2 NOT fired → Event NOT recorded (**no ARS encoding → fast**)
- Then, clear ARS boards and resume acquisition

Beam energy measurement

- Beam energy calculated from the settings of the accelerator. But calibration of the method is from the "6 GeV era" → Does not yield correct beam energy value for the "12 GeV era".
- **Accurate beam energy measurement : "Dispersive" method**, measures beam bending in a dipole with known magnetic field.
- But beam energy shifts against time → A few beam energy measurements is not enough for several weeks/months of running.
- Solution : Dispersive beam energy measurement provides **correction scale factor** to the value calculated from the accelerator settings.

- Conclusion: reliable beam energy using "**calculated value * scale factor**", run by run.
- $1 \leq$ scale factor ≤ 1.003

Quality analysis



Main rejection reasons:

- Very short runs / Very few “real” events recorded (beam trips)
- Abnormal trigger rates
- Abnormally high dead time

Fall 2016:

- Kin36_2: removed ~3.8% of total charge
- Kin36_3: removed ~5.3% of total charge
- Kin60_1: removed ~0.9% of total charge
- kin60_3: removed ~1% of total charge

Spring 2016:

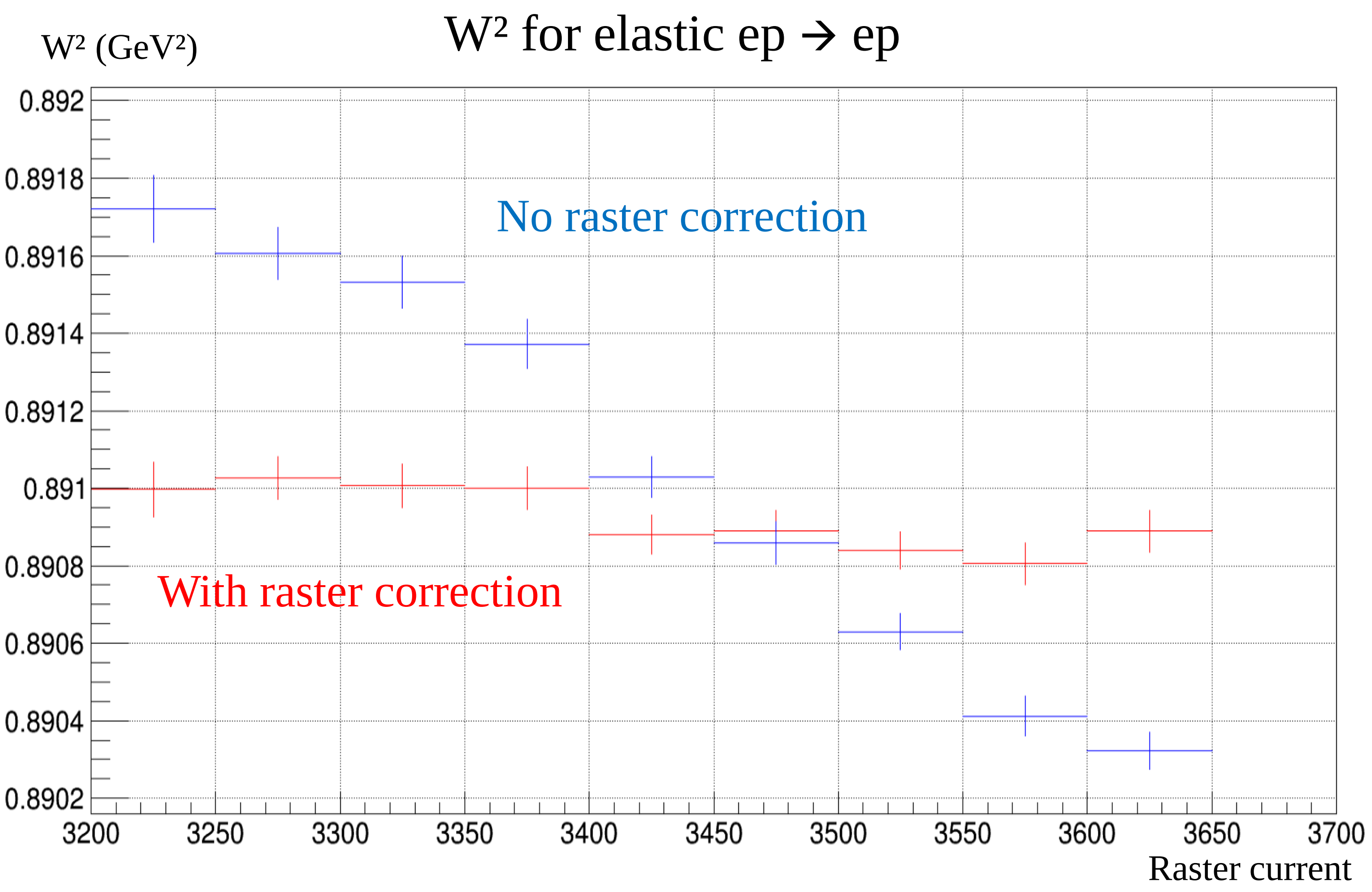
- Kin48_1: removed ~1.3% of total charge
- Kin48_2: removed ~0.5% of total charge
- Kin48_3: removed ~1% of total charge
- Kin48_4: removed ~3.9% of total charge

Fall 2014:

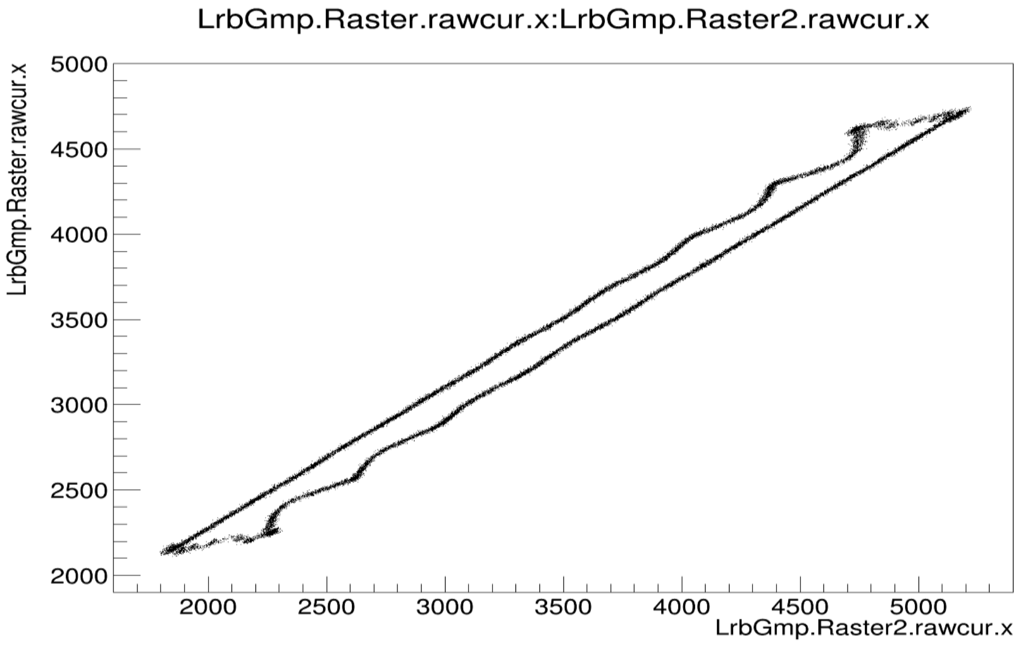
- Kin36_1: removed negligible percentage of total charge

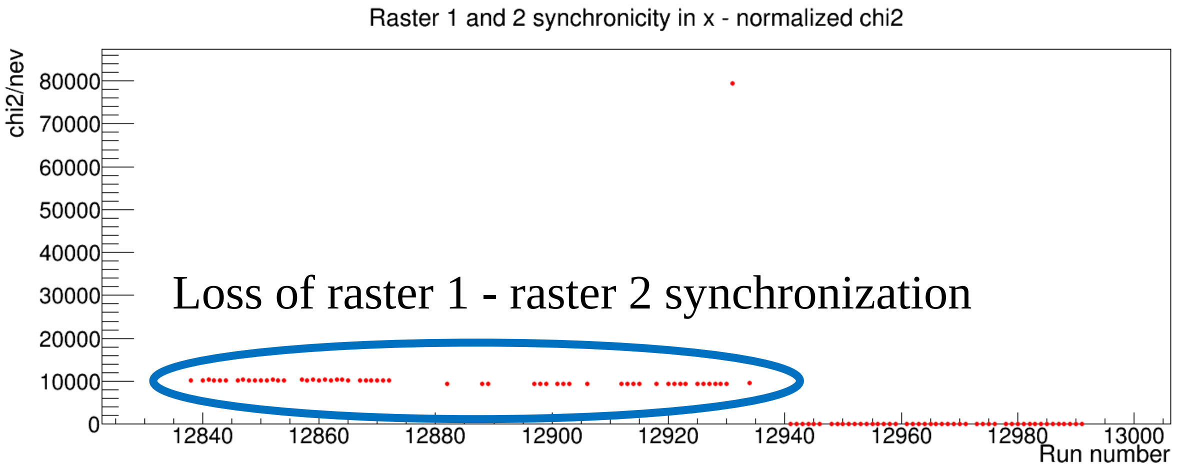
Raster calibration

- Raster calibration complete
- Raster size calibrated against BPM readings.



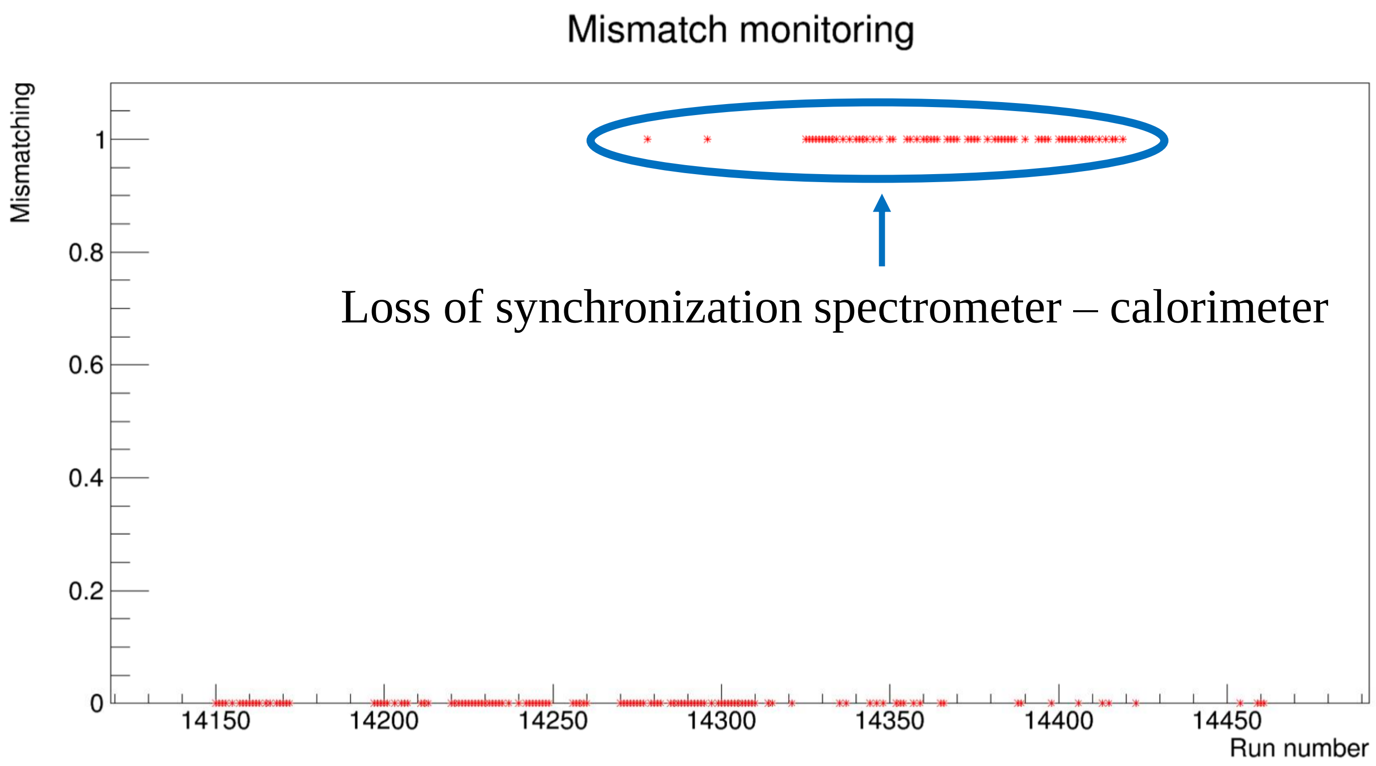
Raster calibration





- Failing raster power supply → loss of synchronization between raster 1 and 2.
- Calibration not possible (assumes raster 1 and 2 synchronized).
- > 50% of kin48_3 statistics affected.
- But simulation shows that error on variable reconstruction is smaller than experimental resolution.

Spectrometer – calorimeter synchronization



- Loss of synchronization between spectrometer and calorimeter during Fall 2016.
- 63 runs compromised (3.5 full days of production ~ 30% of kin60_1 statistics)
- Synchronization recovered using 6Hz clock signal sent to both spectrometer and calorimeter.
- **Negligible loss of statistics.**

Dead time

- Use scalers to compute dead time.
- Took specific runs to check that our dead time correction is correct
- Prescales effect : normalized DVCS rates well corrected by dead time (< 1%)
- Beam current effect : Normalized DVCS rates corrected by dead time are still dependent on beam current
  - **Suspicion : Accidental coincidences calorimeter-spectrometer**
  - Study in progress…

Dead time = 1 – live time

$$\text{Live time} = \frac{\text{live scaler rate}}{\text{raw scaler rate}}$$

Prescale	I (μA)	Live Time	DVCS rate (Hz)	(Prescale * DVCS rate) / (I * Live Time) (Hz/μA)
1	4.41	0.164	564.6	782
2	4.53	0.320	566.8	783
4	4.54	0.626	561.4	790
8	4.56	1.0	448.8	787.4
16	4.55	1.0	224.4	789.1
32	4.44	1.0	109.4	788.5

Prescale :

$\frac{1}{\text{Prescale}}$ events are recorded

(Recording is the main source of dead time)

I (μA)	Live Time	Normalized DIS rate / LT (Hz/μA)	Normalized DVCS rate / LT (Hz/μA)
10.61	0.985	3.422	5.212
15.32	0.976	3.450	5.615
20.53	0.965	3.449	5.936