E12-06-114:
Deeply Virtual Compton Scattering at 11 GeV in Jefferson Lab Hall A

Ferrara Spin 2018

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Frédéric Georges

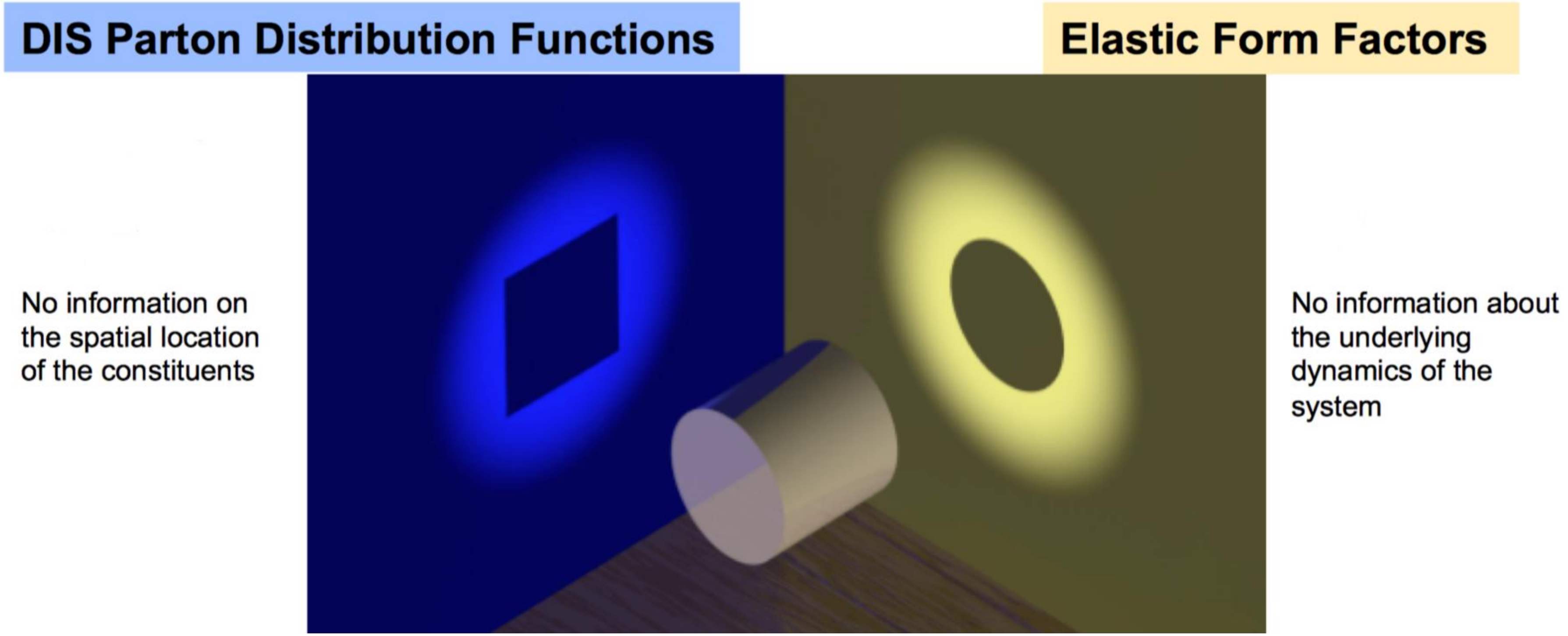
Institut de Physique Nucléaire d’Orsay, France

for the Hall A DVCS collaboration

Outline

- Introduction – physics motivations
- DVCS at Jlab, Hall A – Goal
- Experimental setup
- Analysis overview
- Preliminary results
- Summary and Outlook

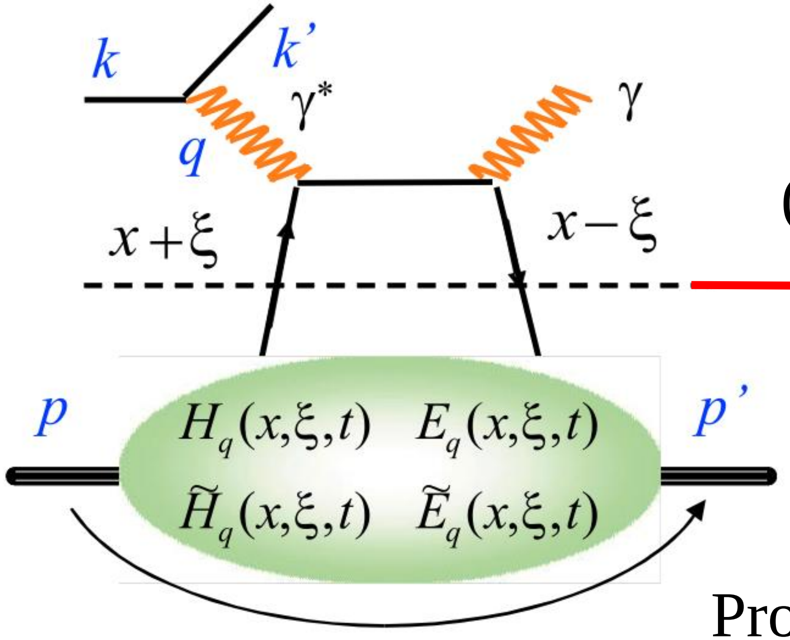
Generalized Parton Distributions (GPDs)



- 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)

In the Bjorken Limit: $\left.\begin{array}{rcl} Q^2 = -q^2 & \rightarrow & \infty \\ \nu & \rightarrow & \infty \end{array}\right\} \quad x_B = \frac{Q^2}{2M\nu} \quad \text{fixed}$



Hard part
(QCD, can be computed)

Factorization

DVCS: ep → e'p'γ

Soft part
Parametrized by GPDs

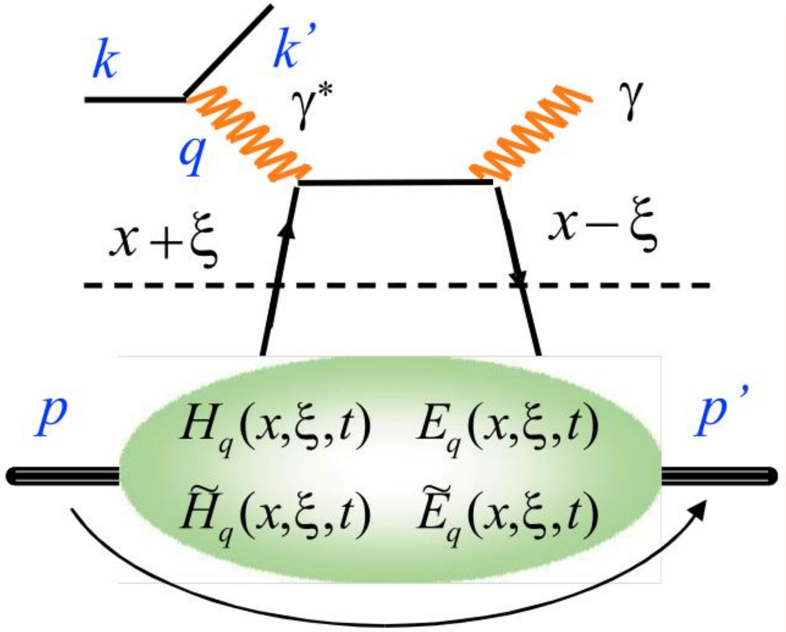
$t = (p' - p)^2$

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

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

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

GPDs and Compton Form Factors (CFFs)



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

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

The variable **x is not experimentally accessible** with DVCS.

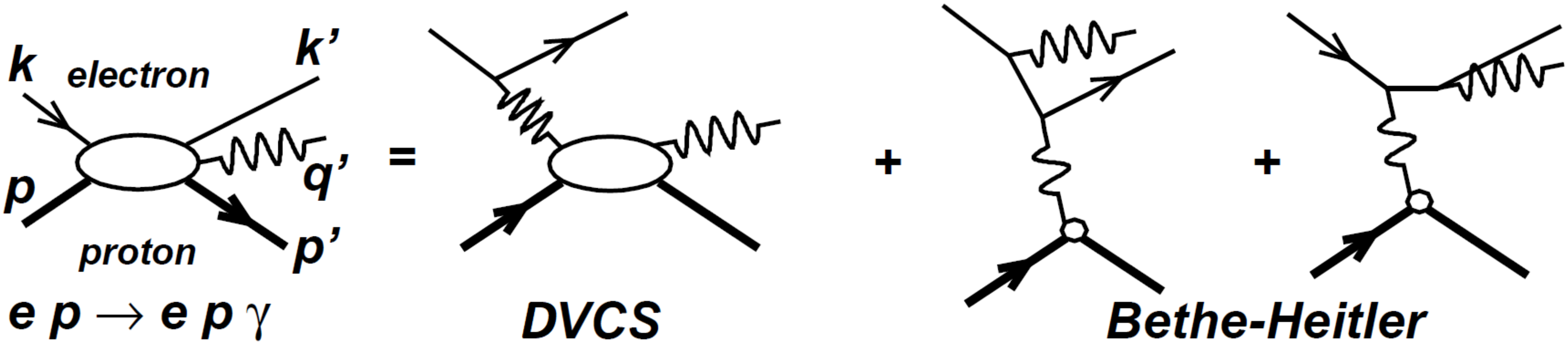
In the DVCS amplitude, GPDs are integrated over x or evaluated in x = ξ.

To study GPDs, one must extract **Compton Form Factors:**

$$Re\mathcal{H}_q\,(\xi, t) = P\ \int_0^1 [H_q(x, \xi, t) - H_q(-x, \xi, t)]\,\frac{2x}{x^2 - \xi^2}\,dx$$

$$Im\mathcal{H}_q\,(\xi, t) = H_q(\xi, \xi, t) - H_q(-\xi, \xi, t)$$

DVCS and Bethe-Heitler



At leading twist:

$$
\begin{aligned}
d^5 \overrightarrow{\sigma} - d^5 \overleftarrow{\sigma} &= \Im m \left(T^{BH} \cdot T^{DVCS}\right) \\
d^5 \overrightarrow{\sigma} + d^5 \overleftarrow{\sigma} &= |BH|^2 + \Re e \left(T^{BH} \cdot T^{DVCS}\right) + |DVCS|^2
\end{aligned}
$$

Known to 1% (J. J. Kelly. Simple parametrization of nucleon form factors. *Phys. Rev. C 70, 068202*, 2004.)

DVCS at Jefferson Lab, Hall A – Goal

- Data acquisition between Fall 2014 and Fall 2016.

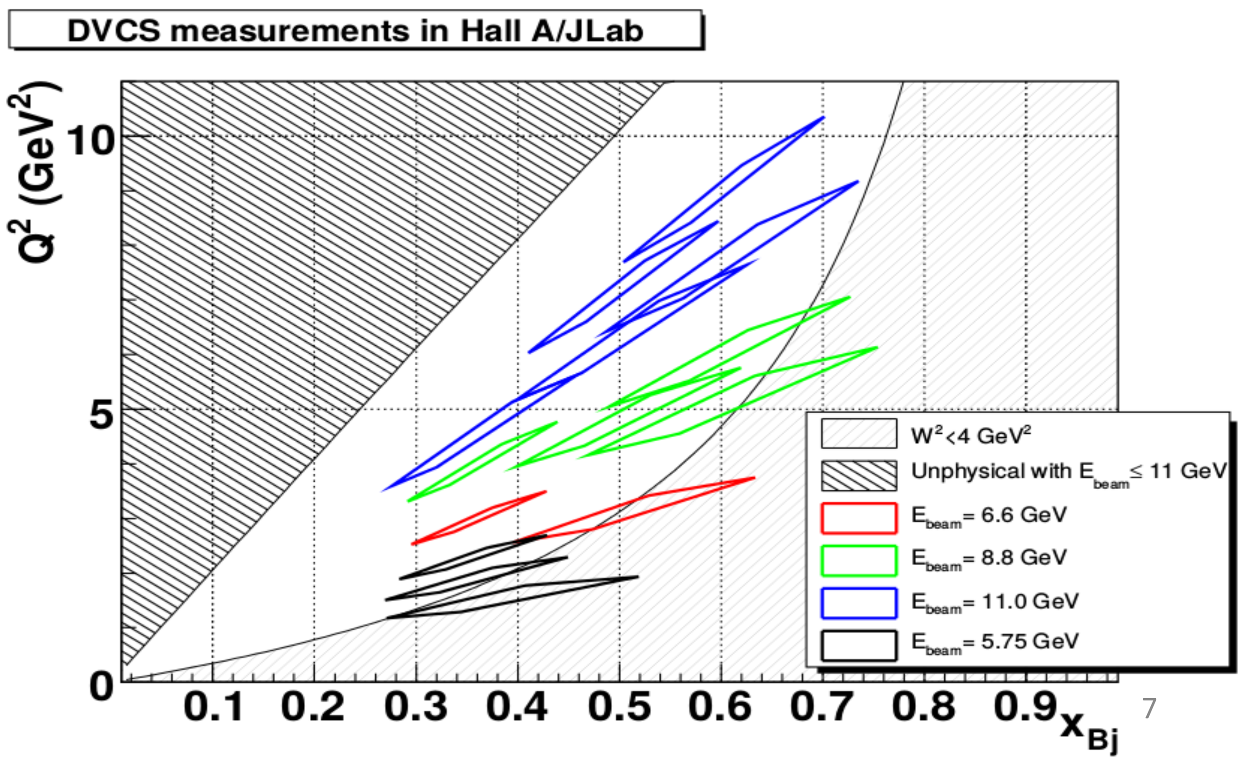
kinematic	Q^2 (GeV²)	x_B
kin36_1	3.2	0.36
kin36_2	3.6	0.36
kin36_3	4.5	0.36
kin48_1	2.7	0.48
kin48_2	4.4	0.48
kin48_3	5.3	0.48
kin48_4	6.9	0.48
kin60_1	5.5	0.60
kin60_2	6.1	0.60
kin60_3	8.4	0.60
kin60_4	9.0	0.60

← postponed (kin60_2)

← postponed (kin60_4)

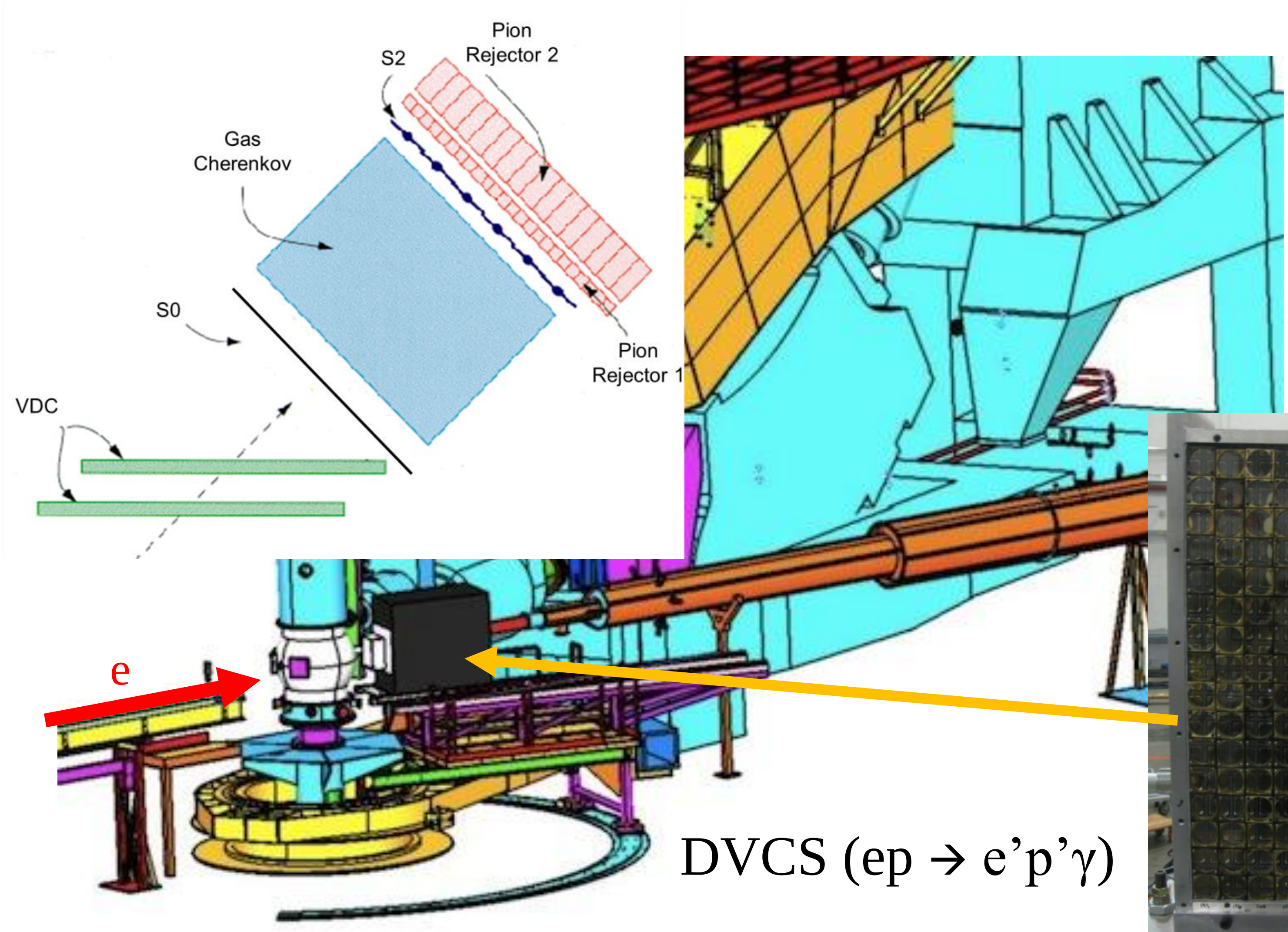
100 days of beam (88 + 12 calibration)

- 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.



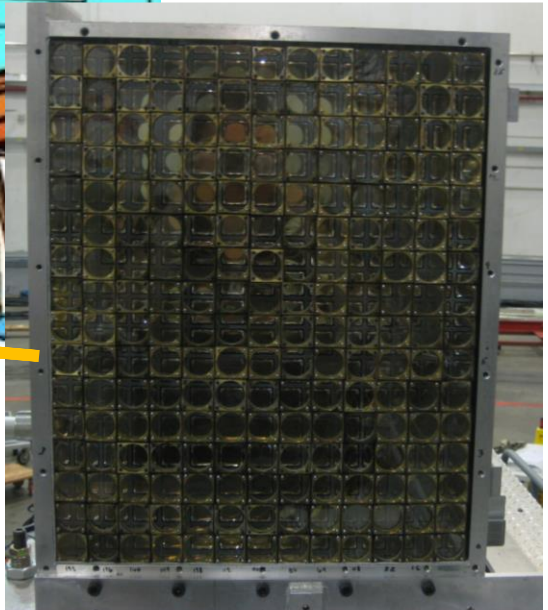
DVCS at Jefferson Lab, Hall A – Apparatus

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



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

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



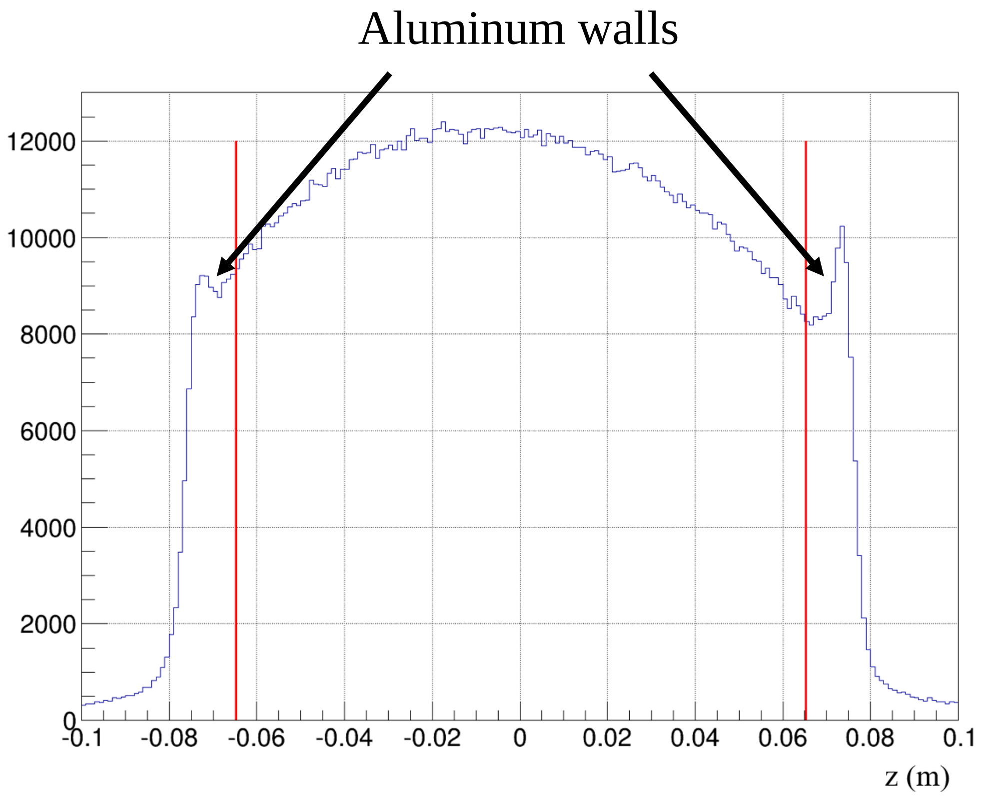
DVCS missing mass:
$ep \rightarrow e'X\gamma$

Missing mass^2 = $(e + p - e' - \gamma)^2$

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

Event selection and exclusivity

- Vertex: cut the target aluminum walls.
- Calorimeter:
  - Only 1 photon detected.
  - Minimum photon energy: cut low energy background.
  - Energy leaks on the edges: cut photons in edges blocks.
- Spectrometer:
  - Electron identification: Cherenkov & Pion Rejector cuts to eliminate π^-.
  - Single track: cut events with multiple tracks.
  - Acceptance cut: the R-Function.



Spectrometer acceptance: the R-function

Spectrometer acceptance: 5-dimensional.

- Naïve approach: five 1-dimensional cuts.

→ Inefficient (variables are correlated).

- Better approach: cut on the **distance of the electron to the acceptance edges**.

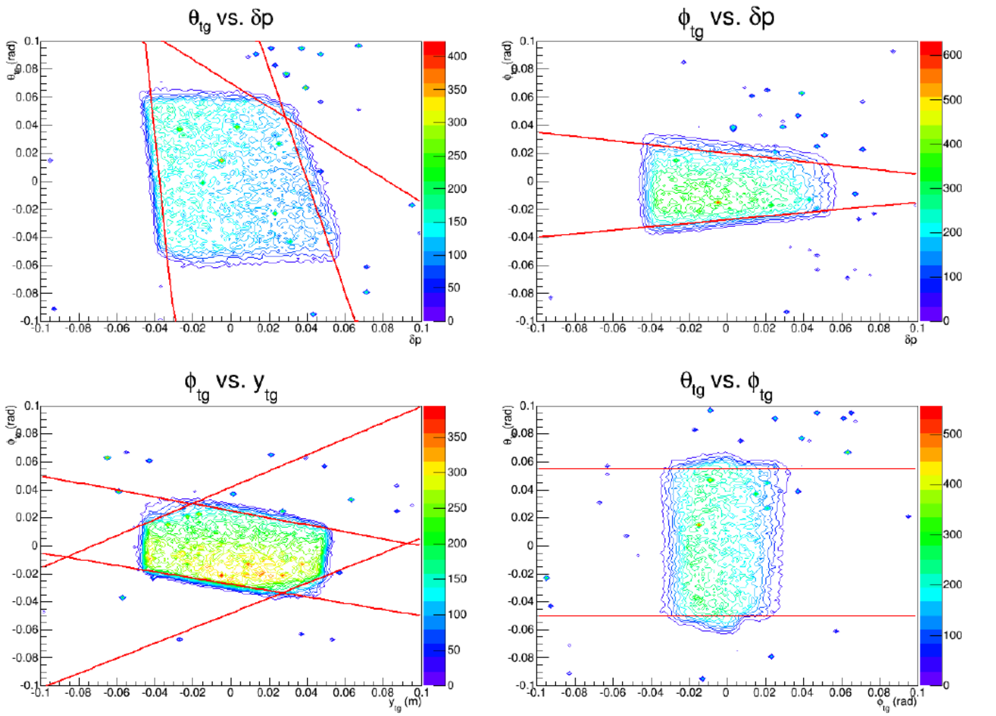
→ Efficiency multiplied by 2.

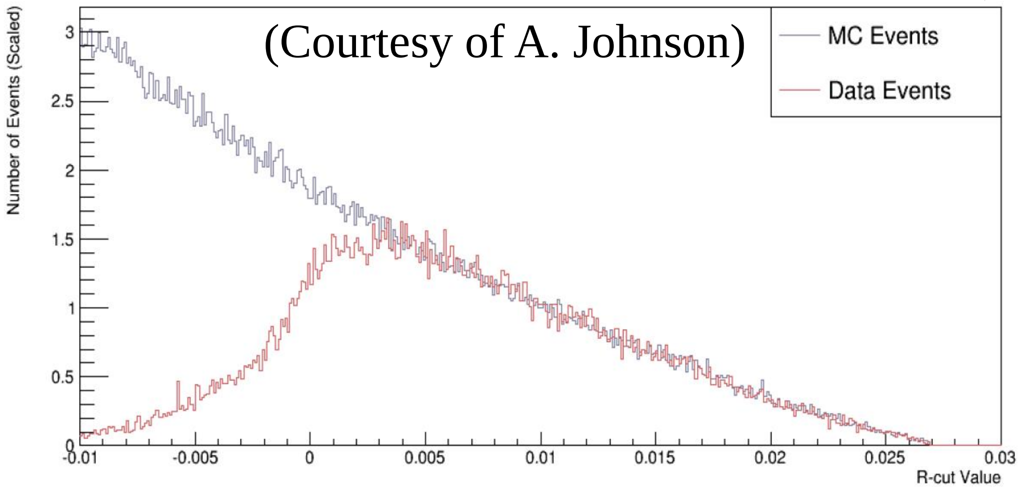
- The R-function computes this distance: the R-value.

→ If R-value > 0 the electron is inside of the acceptance.

- Cut on R-value: R-cut. **Data and Geant4 R-value distributions must agree for R-value > R-cut**.

Identical cuts will be applied to both data and simulation to compute the acceptance.

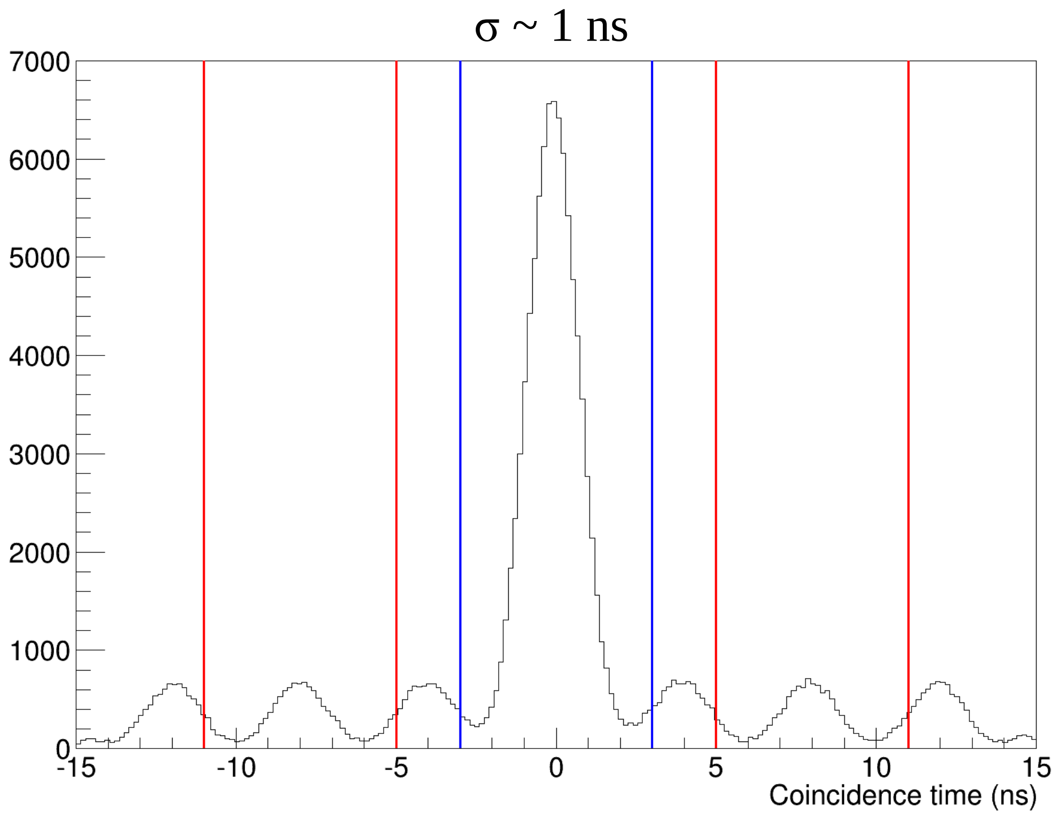




Background subtraction: accidental events

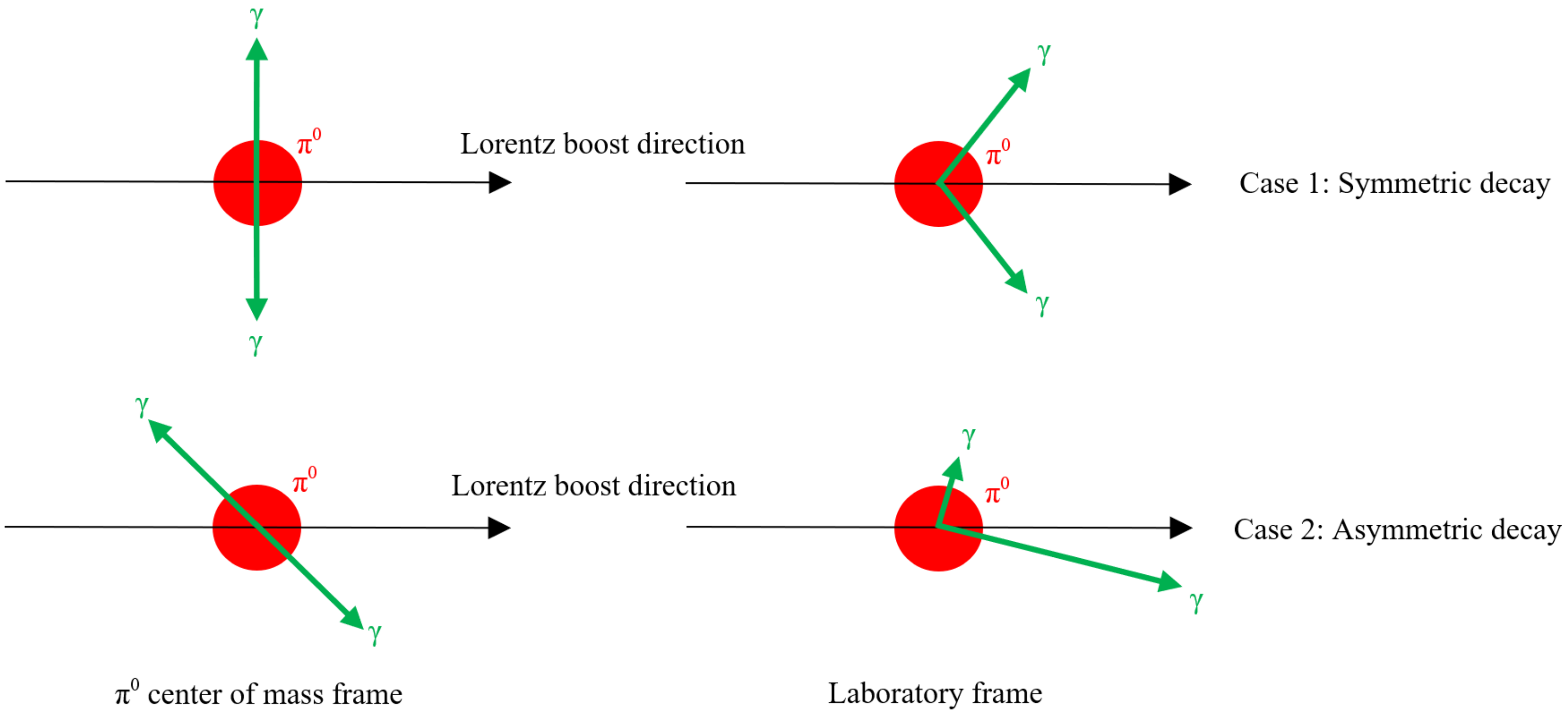
- DVCS event: photon & electron are detected in coincidence in [-3 ns , 3 ns].
- Photon & electron can come from different events and be in coincidence → **accidental events**.
- **Subtraction of accidental events**:
  - The probability for accidental events in [-3 ns , 3 ns] is the same as in [-3+n ns , 3+n ns].
  - Beam time structure: 4 ns.

→Subtract events detected in [-11 ns , -5 ns].



Background subtraction: π^0 contamination

- ep → e'p'γ and ep → e'p'π^0 can both occur.
- π^0 → γ γ : if asymmetric decay, low energy photon can be missed.
  - **ep → e'p'γ(γ) wrongfully identified as DVCS**.



π^0 contamination subtraction method

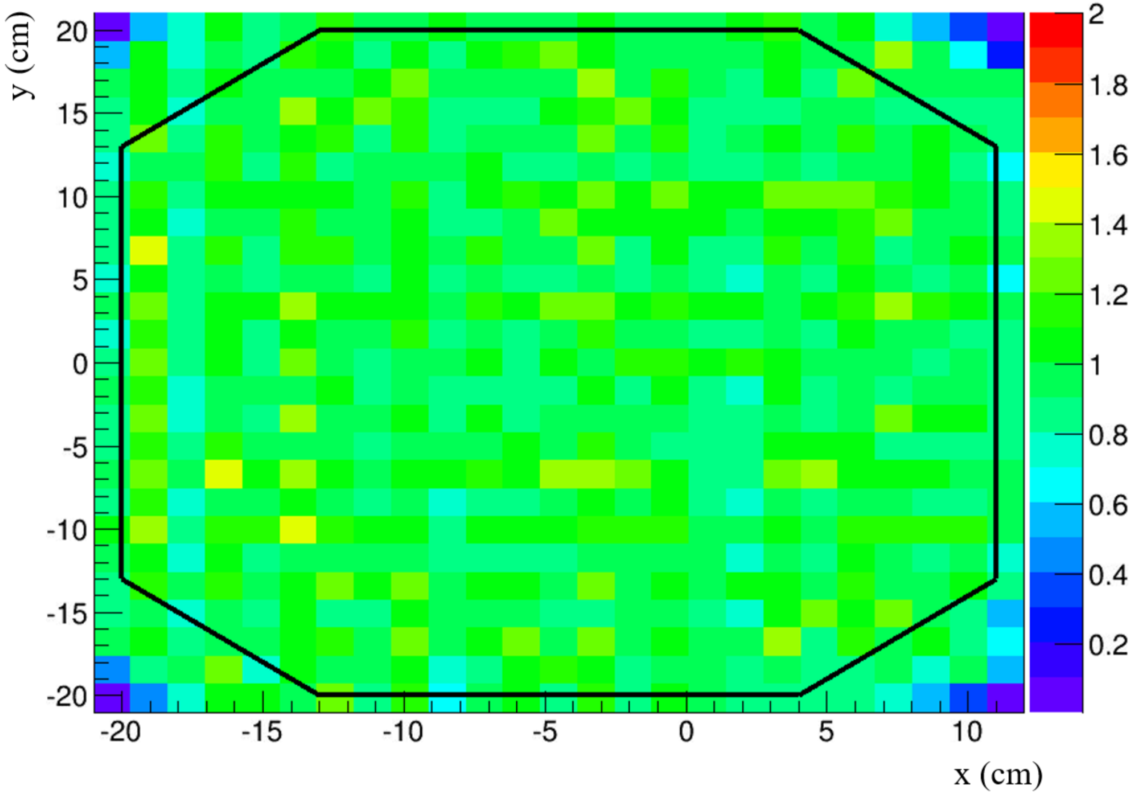
- **π^0 contamination** subtraction method:
  - Identify π^0 in data:
    - 2 photons.
    - Avoid calorimeter edges (energy leaks).
    - Invariant mass $m^2_\pi = 2E_{\gamma1}E_{\gamma2}(1 - \cos\theta_{\gamma1\gamma2})$ compatible with π^0.
  - For each π^0: MC simulation $\pi^0 \rightarrow \gamma\ \gamma$
  - **Subtract from DVCS data**:
    - Normalized MC events with only 1 photon detected.

→Advantage: **ep → e'p'π^0 cross section taken into account** by using π^0 data.

- Subtraction efficiency checked with Geant4

→ "Octagonal cut" (acceptance effect).

π^0 subtraction efficiency depending on the position in the calorimeter.



Recoil proton identification: the missing mass cut

- **DVCS missing mass**: ep → e'Xγ

$M_X^2 = (e + p - e' - \gamma)^2$

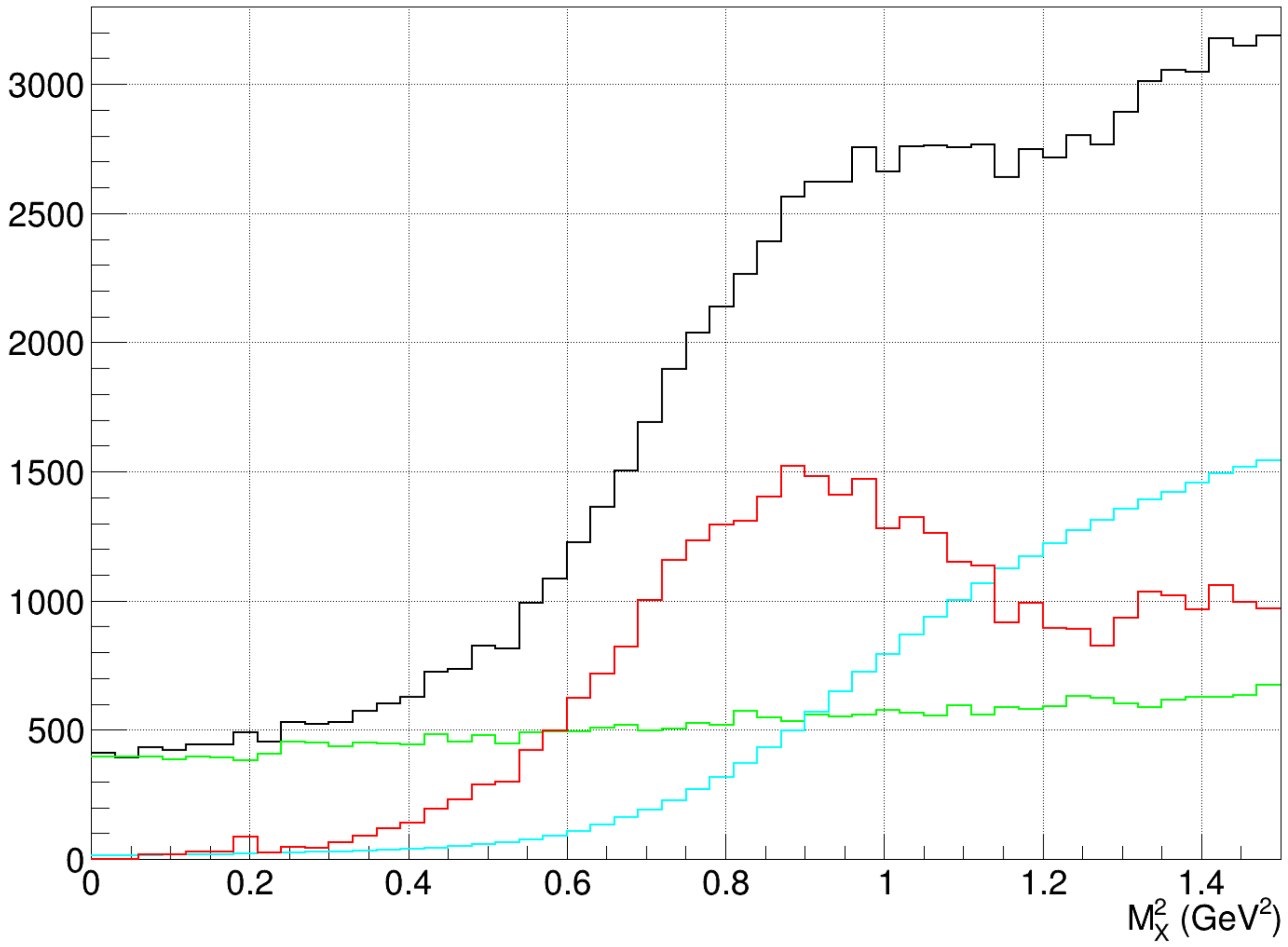
Exclusivity of the DVCS process is ensured by a cut on the missing mass.

- **Remaining contamination: SIDIS**

ep → e'p'γX

SIDIS process with lowest missing mass: ep → e'p'γπ⁰ ($M_X^2 \approx 1.15$ GeV²).

- $M_X^2 < 1.15$ GeV² eliminates (most of) SIDIS contamination.
- **Systematic uncertainty**.



Corrections

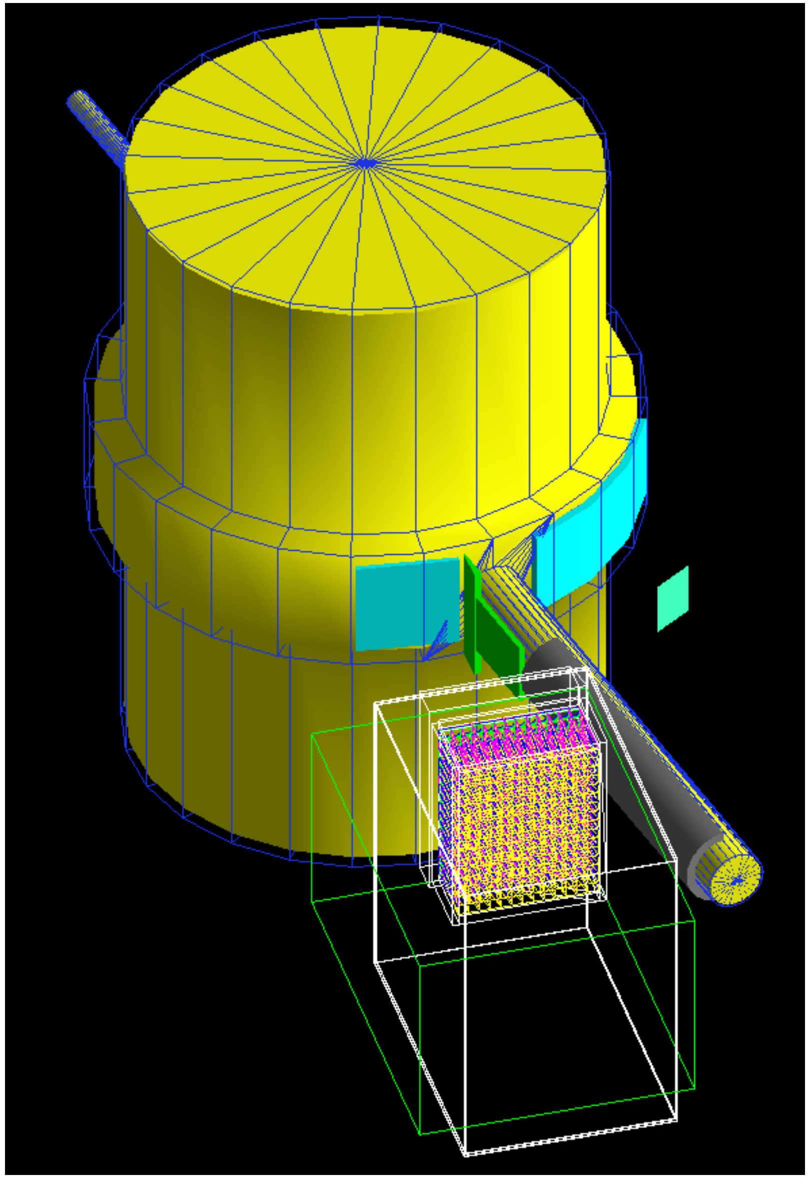
- Trigger efficiency: measured > 99%
- Beam polarization: measured 86%
- Dead time: 2% - 3% correction.
- Spectrometer multi-tracks: 4% - 7% correction.
- Calorimeter multi-clusters (1 DVCS γ + X) : 0.5% - 2% correction.
- …

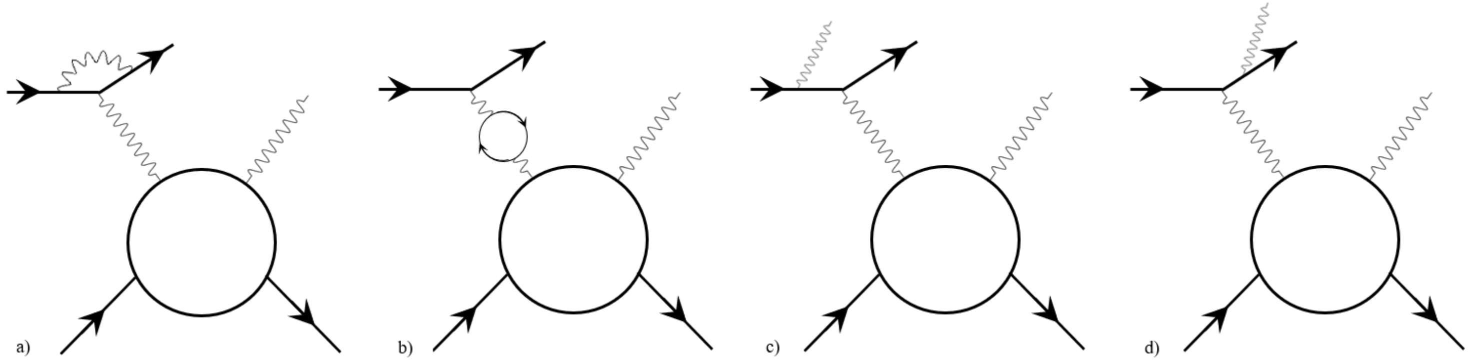
Geant4 simulation and radiative corrections

- **Acceptance computation** → Geant4 simulation:
  - Target + beam line + calorimeter fully implemented.
  - Spectrometer: only entrance window, then R-function.
- **Real radiative corrections** (event generator):
  - Bremsstrahlung for incoming electron (straggling effect)
  - Internal Bremsstrahlung
  - (Final state particles: handled by Geant4)

Advantage: **radiative tail taken into account in acceptance computation**.

- **Virtual radiative corrections** (preliminary):
  - Expected to be similar to previous experiment E00-110.
  - 3% correction to polarized cross sections, 6% to unpolarized cross sections.



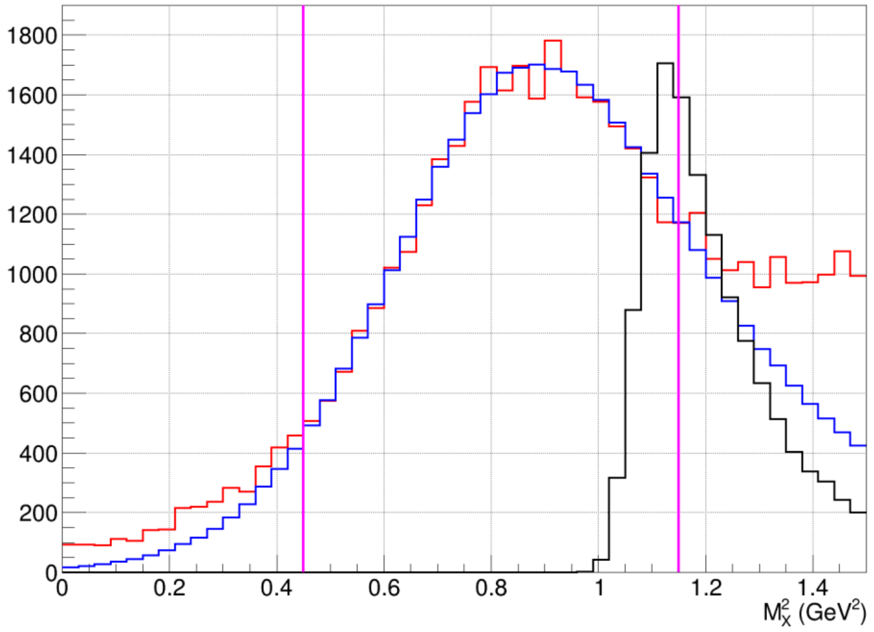


Simulation calibration and smearing

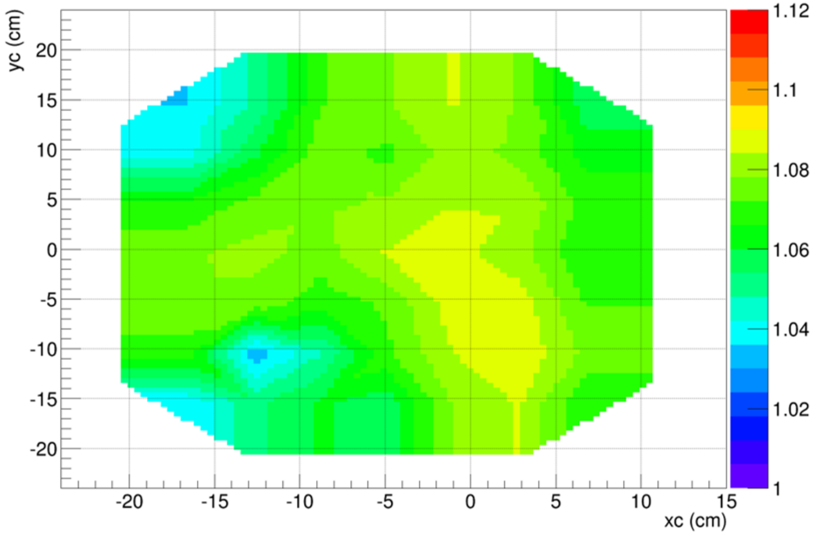
- Radiative tail + energy resolution → DVCS events lost due to missing mass cuts.
- Compensation: same cuts applied to simulation → need distributions to match.
  - Energy leaks + Cherenkov photon not simulated → **Calibration + Smearing**.
- Geant4 reconstructed photons energy **smeared by a Gaussian(μ,σ)**.
- (μ,σ) computed by χ^2 minimization:

$$\chi^2 = \sum \frac{data\_Mx^2 - geant4\_Mx^2}{\sigma^2(data\_Mx^2)}$$

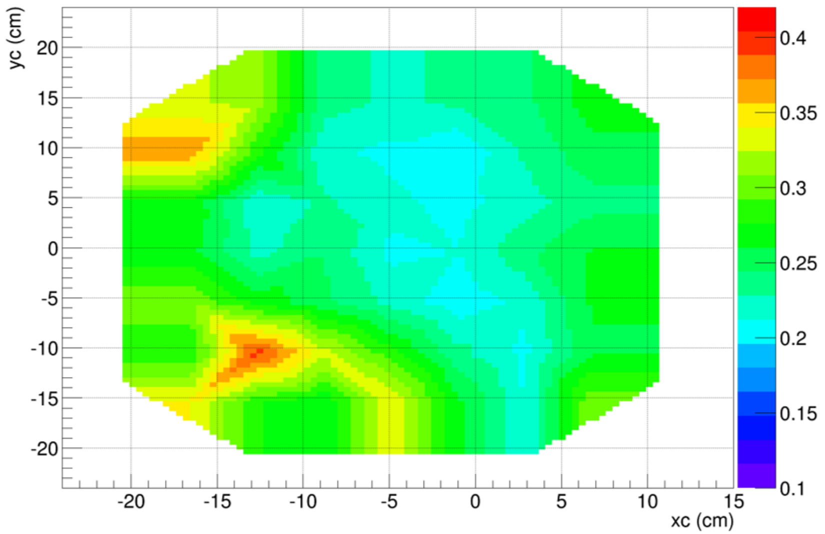
- **(μ,σ) dependence with respect to the position in the calorimeter.**



μ



σ (GeV)



Cross sections extraction

- **Four-fold cross section**: Q^2, x_B, t and ϕ.

(each kinematic setting: 1 Q^2 bin, 1 x_B bin, 5 $t\text{-}t_{min}$ bins, 24 ϕ bins)

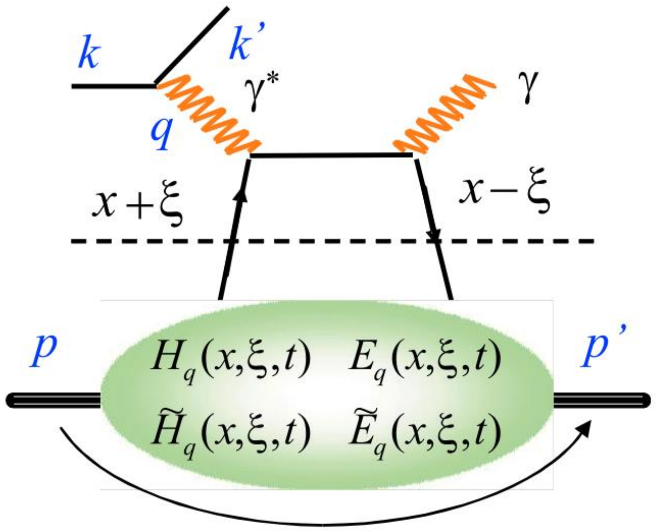
- One method:
  - $\frac{d\sigma}{d\Omega} = \frac{N_{exp}}{L\,\Delta\Omega}$ with $\Delta\Omega = \frac{N_{simu}}{N_{gene}} \Delta\Omega_{simu}$

  and L integrated luminosity.
  - Then fit cross sections, CFFs…

- Another method, that we use:
  - Fit number of events with **CFFs parametrization** of cross section.

  → **Correct bin migration**.

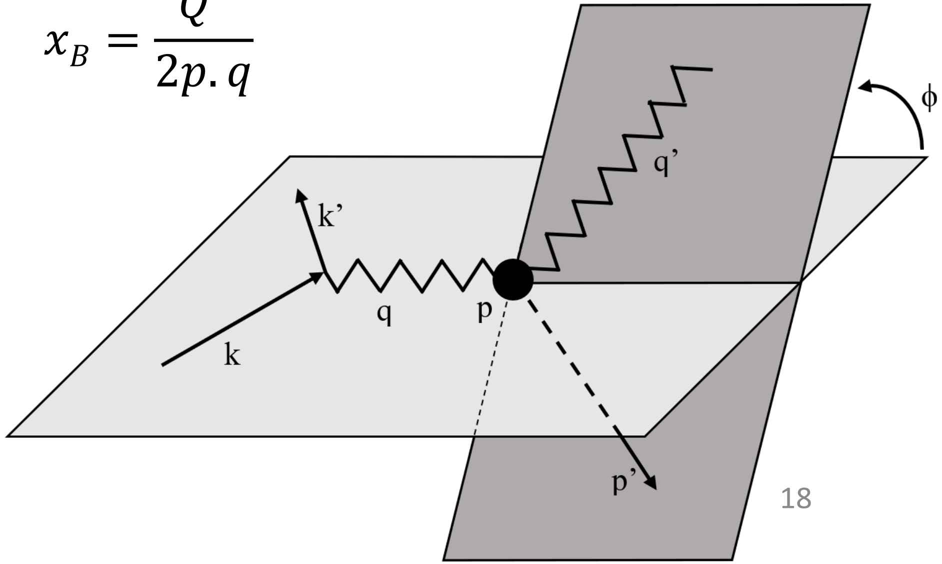
  → **Integrate kinematical dependences** over the experimental acceptance.



$Q^2 = -q^2$

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

$x_B = \frac{Q^2}{2p.q}$



The cross section fitting method

- $\chi^2 = \sum_{bins}\left(\frac{N_{exp} - N_{simu}}{\sigma_{exp}}\right)^2$ with $N_{simu} = L \int \frac{d\sigma}{d\Omega} d\Omega$

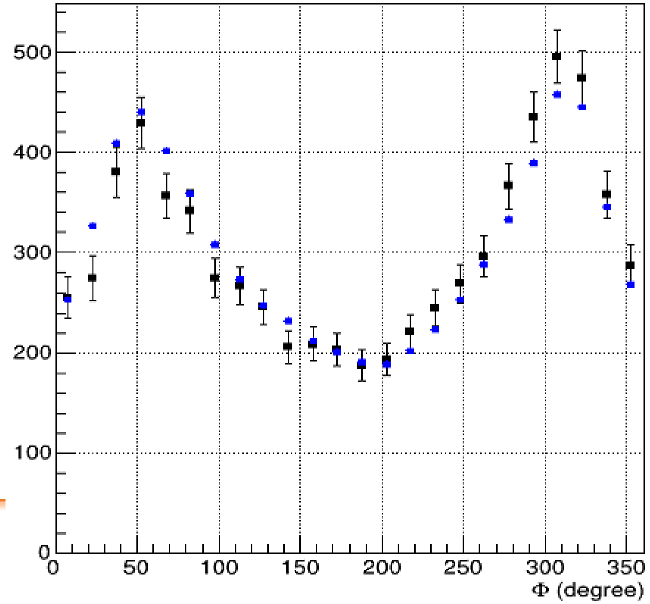
Parametrization $\sigma = \sum_n F_n X_n$ with $\mathbf{F_n}$ **kinematic prefactors** and $\mathbf{X_n}$ **CFF combinations** up to twist-3.

Example: $\sigma = K_0 CFF_0 + K_1 \cos(\phi)\, CFF_1 + K_2 \cos(2\phi)\, CFF_2$

(A.V. Belitsky and D. Müller. Compton scattering: from deeply virtual to quasi-real. *Nucl. Phys. B878, 214-268*, 2010. arXiv:1212.6674.)

Kinematic setting	χ^2_{unpol}/dof	χ^2_{pol}/dof
36_1	2.28	0.89
36_2	1.69	1.20
36_3	1.14	0.76
48_1	1.64	1.02
48_2	1.41	1.05
48_3	1.33	1.25
48_4	1.29	1.07
60_1	1.61	0.78
60_3	1.13	1.05

- **$\mathbf{F_n}$ integration & bin migration computed with the simulation.**
- χ^2 minimization with respect to X_n
  - → Fit X_n (3 for unpolarized, 2 for polarized)
  - → Compute $\sigma_{fit} = \sum_n F_n X_n$
  - → Compute $N_{simu} = L \int \frac{d\sigma_{fit}}{d\Omega} d\Omega$
  - → Reconstruct $\frac{d\sigma_{exp}}{d\Omega} = \frac{N_{exp}}{N_{simu}} \frac{d\sigma_{fit}}{d\Omega}$



- Experimental number of events
- Fitted number of events

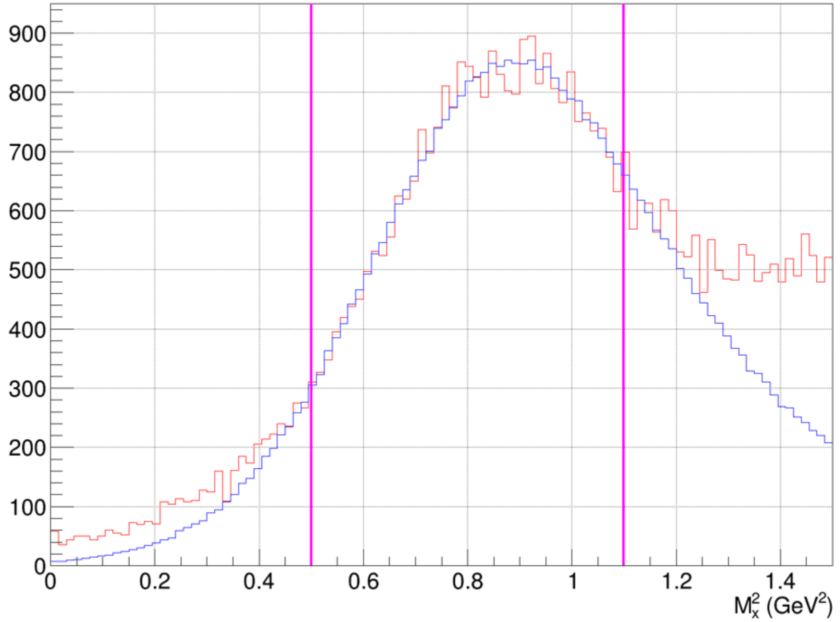
Preliminary systematic uncertainties

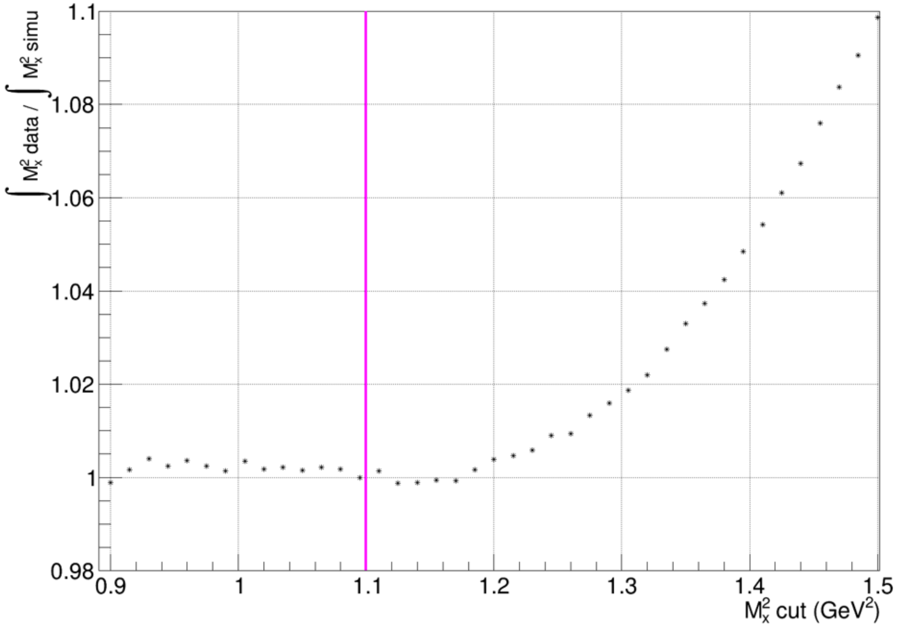
- Main **systematic uncertainty: missing mass cuts**.
  - Leftover **SIDIS contamination** below 1.15 GeV^2 (detector resolution).
  - Data and simulation missing mass distributions **imperfect matching** (smearing).

→ Define cuts where matching is still good.

→ Systematic uncertainty: cross section variations when the cut is changed.

→ **Point-to-point systematic uncertainty**: ~ 2% - 5%.





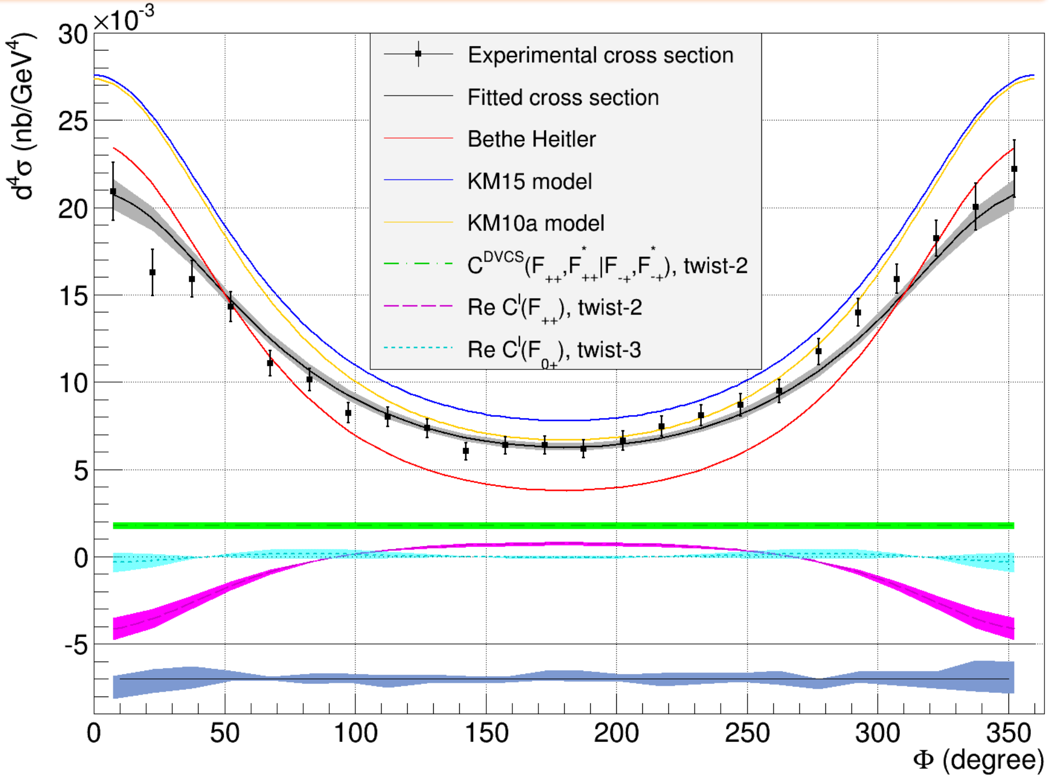
Systematic uncertainty	Value (%)
HRS electron identification *	0.5
HRS multi-track correction *	0.5
HRS acceptance (R-function) *	1.0
Luminosity and dead time *	1.0
Virtual radiative corrections *	2.0
Beam polarization	1.0 (2.2)
CFFs parametrization	1.5
Total (unpolarized)	3.0
Total (helicity-dependent)	3.1 (3.7)

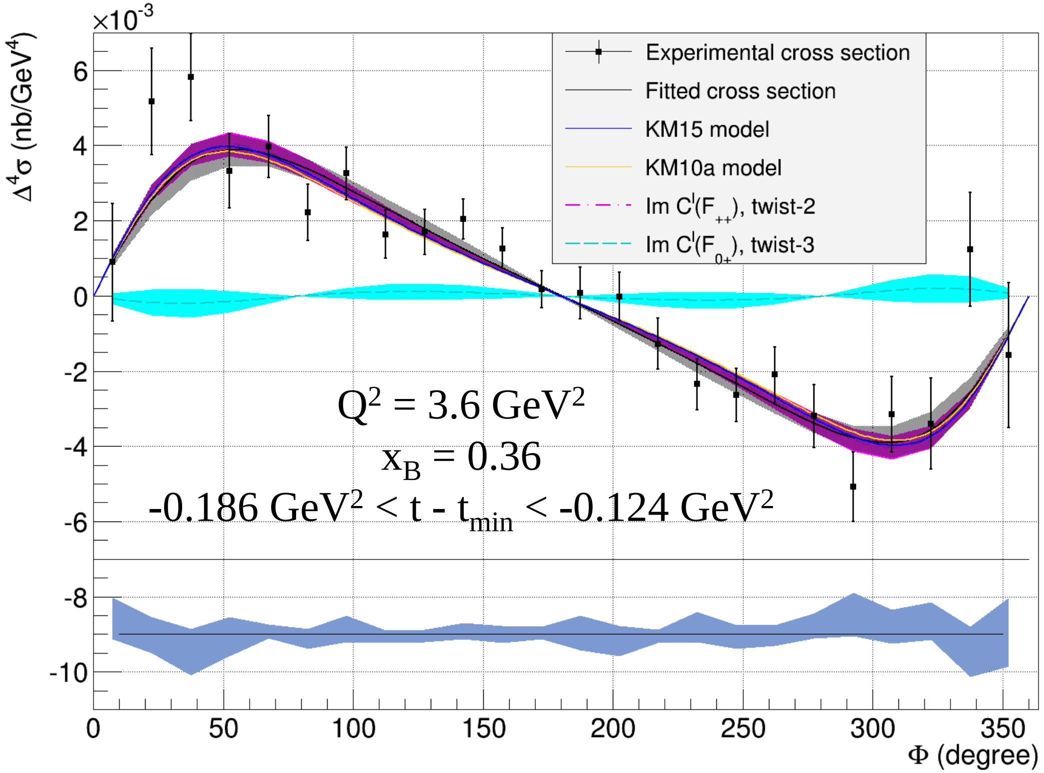
Preliminary

* Evaluated from experiment E00-110

Preliminary results

- Unpolarized: DVCS term dominant at $\phi = 180°$, interference increases at $\phi = 0°$ and $\phi = 360°$.
- Twist-2 dominant, Twist-3 compatible with 0.





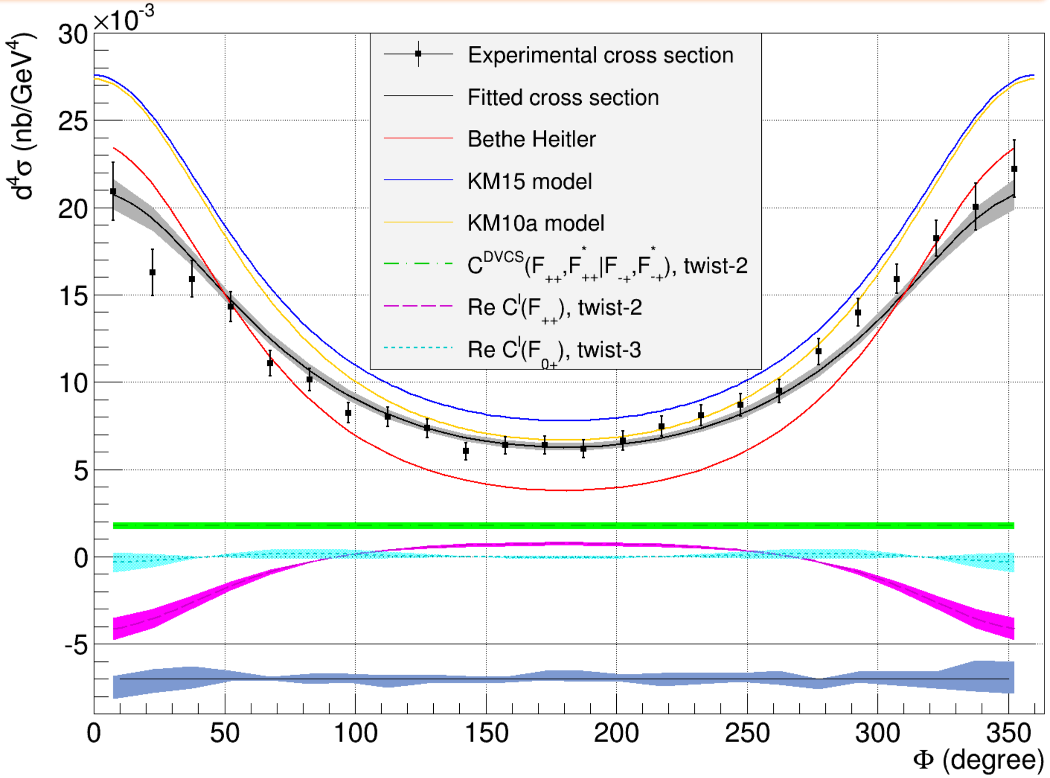
Preliminary results

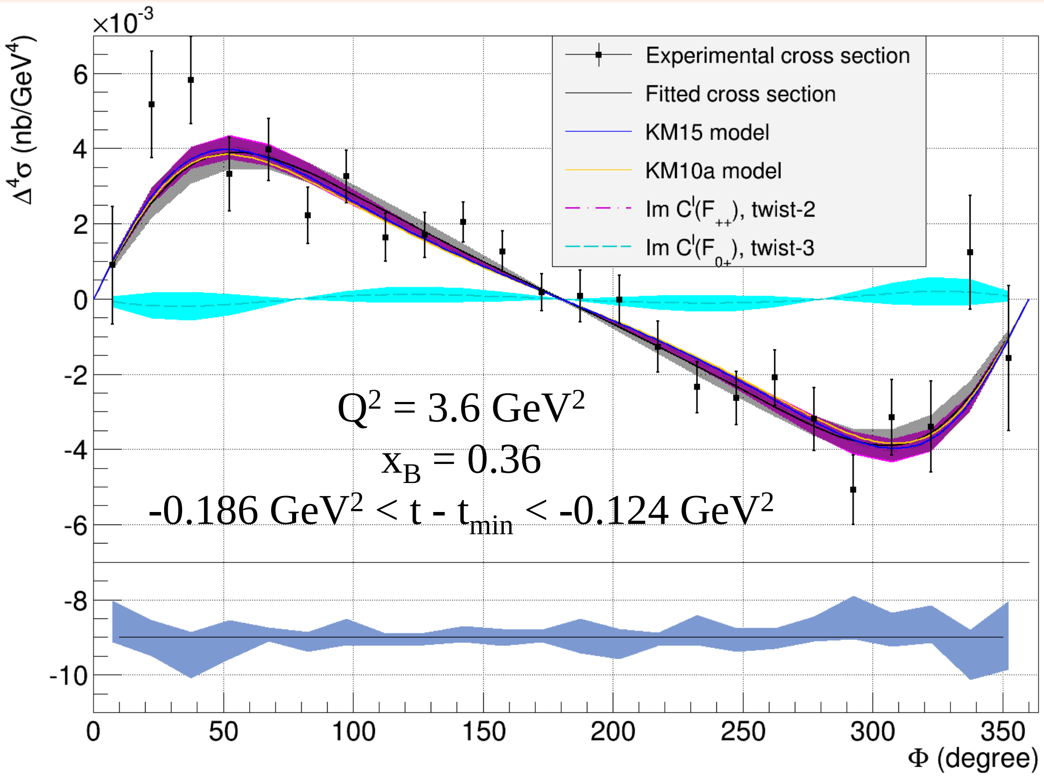
- Unpolarized: DVCS term dominant at ϕ = 180°, interference increases at ϕ = 0° and ϕ = 360°.
- Twist-2 dominant, Twist-3 compatible with 0.
- Unpolarized: models overshoot data, better agreement with model KM10a than KM15.
- Polarized: good agreement of both models with data.

- KM10a & KM15: global fits to DVCS data. http://calculon.phy.hr/gpd/
- KM10a: does not use Hall A data.
- KM15: use Hall A and CLAS data up to 2015.

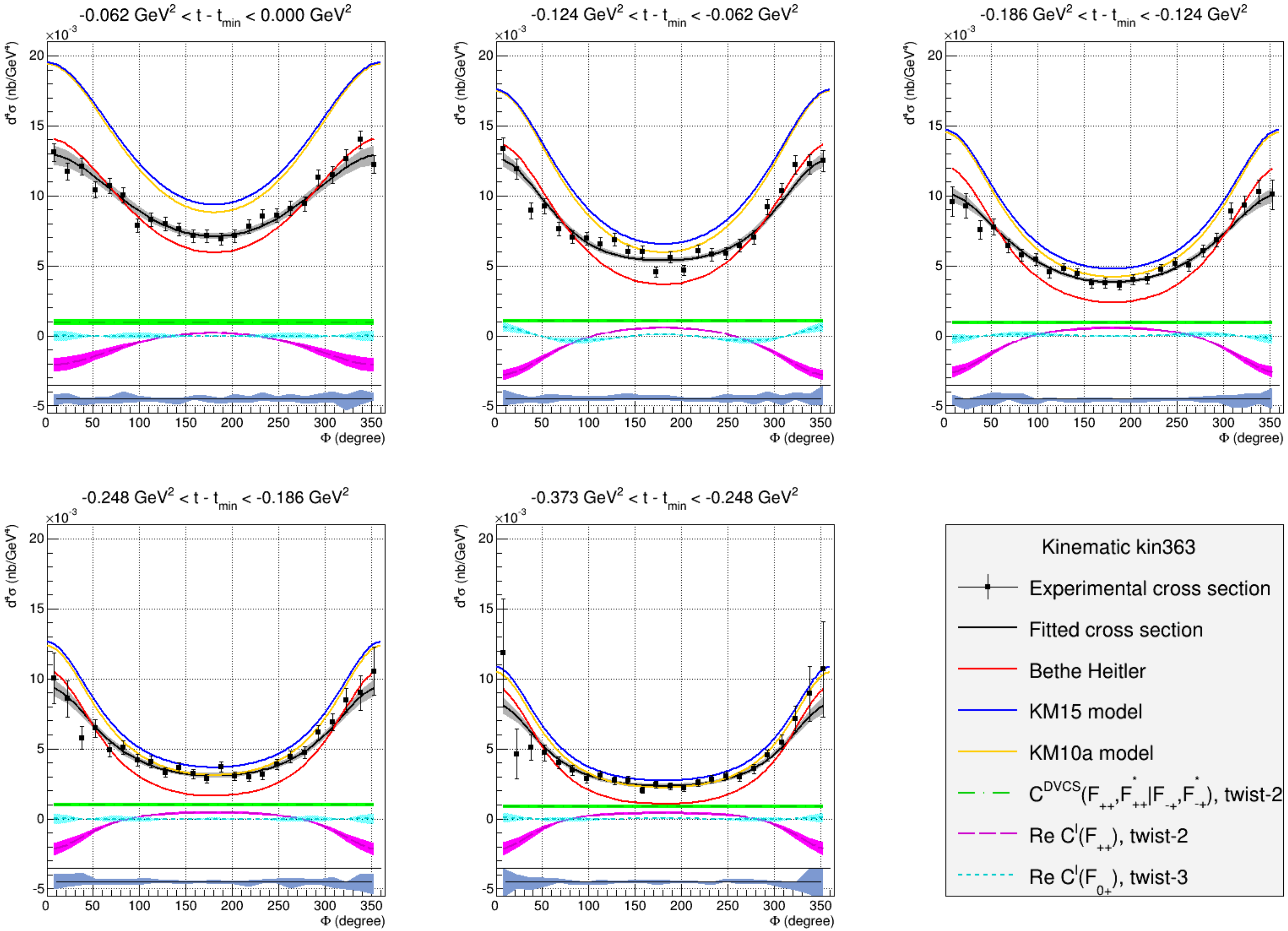
K. Kumerički, S. Liuti, and H. Moutarde. GPD phenomenology and DVCS fitting. *Eur. Phys. J. A. 52, 157*, 2016. arXiv:1602.02763.

K. Kumerički and D. Müller. Description and interpretation of DVCS measurements. *EPJ Web of Conferences 112, 01012*, 2015. arXiv:1512.09014.





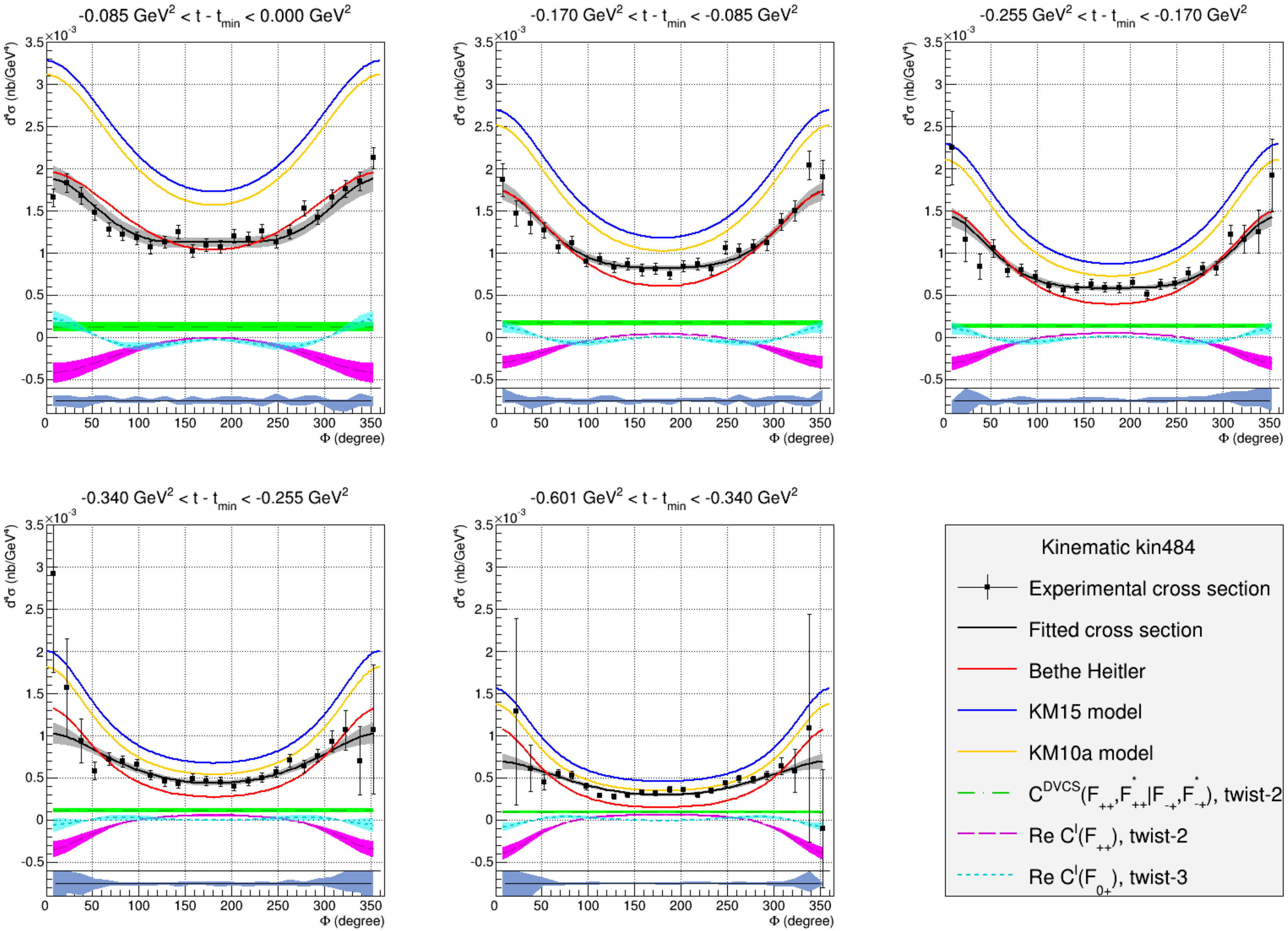
Preliminary results



$Q^2 = 4.4\ \mathrm{GeV}^2$

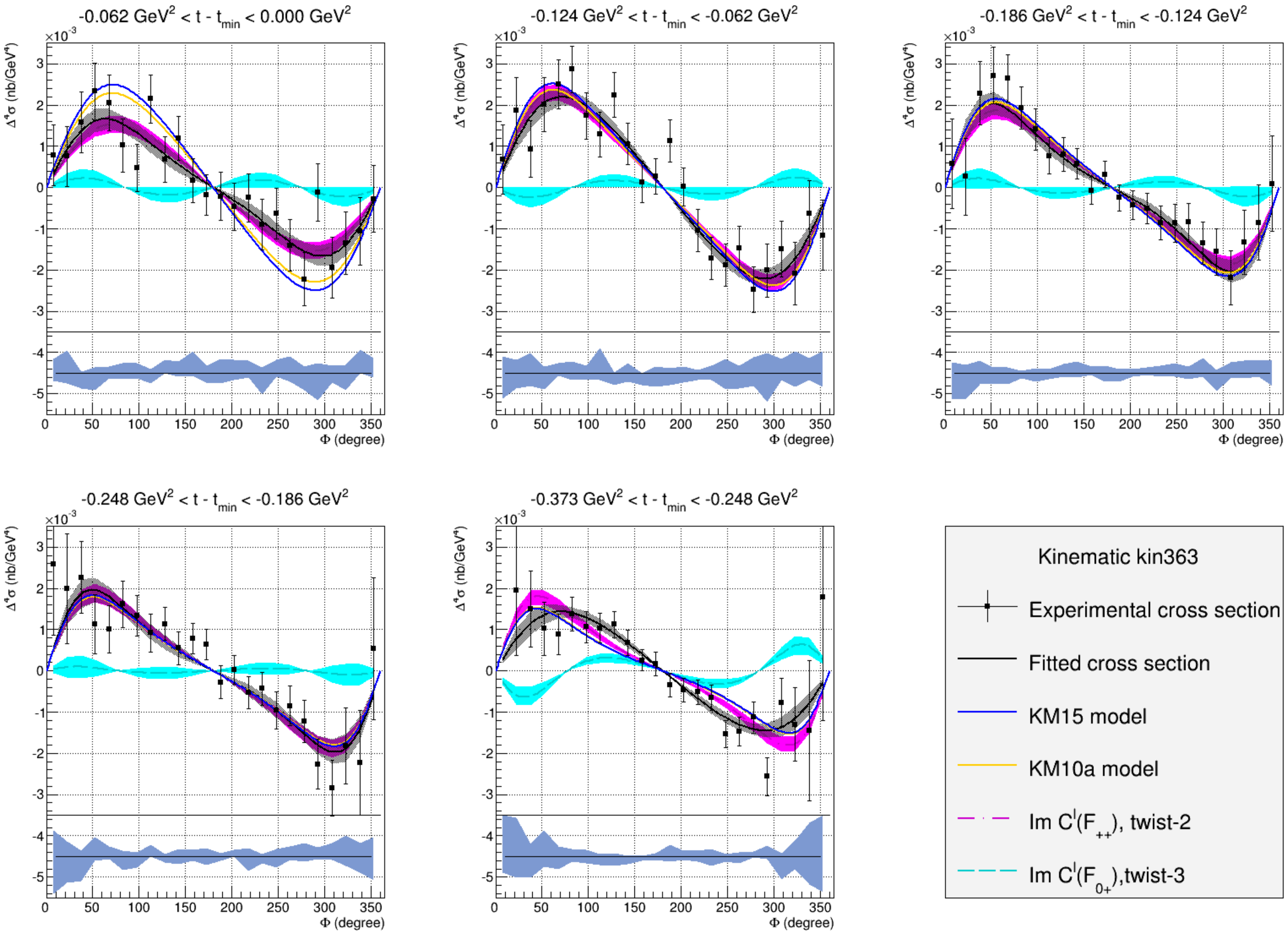
$x_B = 0.36$

Preliminary results



$Q^2 = 6.9\ \mathrm{GeV}^2$
$x_B = 0.48$

Preliminary results



Q^2 = 4.4 GeV^2
x_B = 0.36

Summary and Outlook

- First DVCS experiment at 11 GeV in Jefferson Lab Hall A.

- Measured unpolarized & polarized cross sections (preliminary results):
  - 9 kinematic settings.
  - 120 bins for each setting.
  - CFFs extracted.

  Total of 1080 new data points.

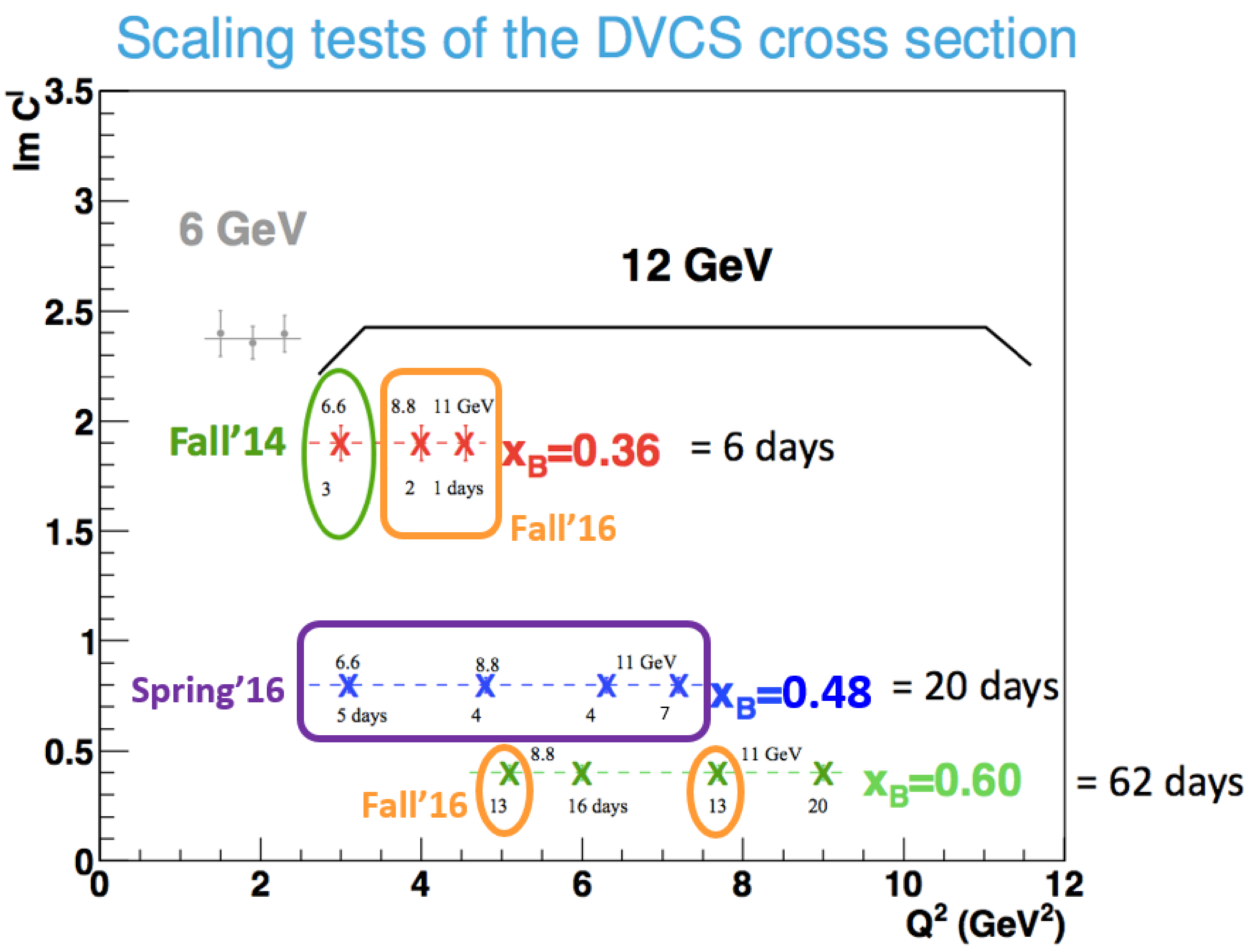
- Outlook:
  - Simulation smearing improvement (weighting with DVCS cross section).
  - Finalization of systematic uncertainties assessment.
  - Study of the Q^2 dependence of the CFFs (scaling test).

Thank You !

Questions ?

Backup

DVCS cumulated statistics

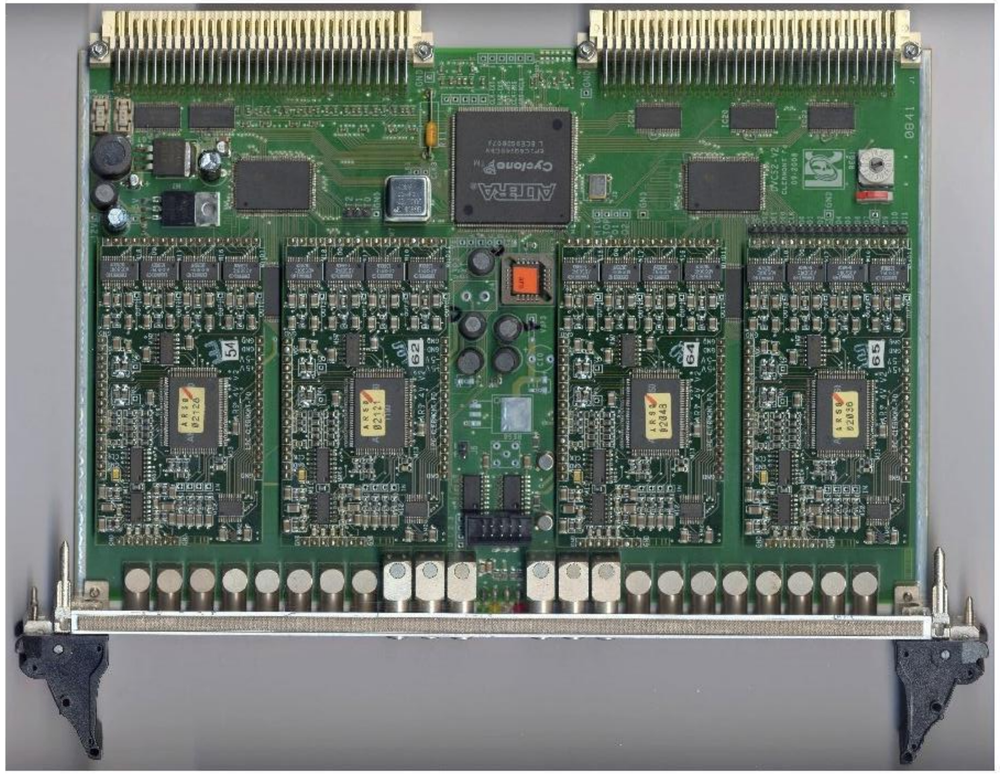


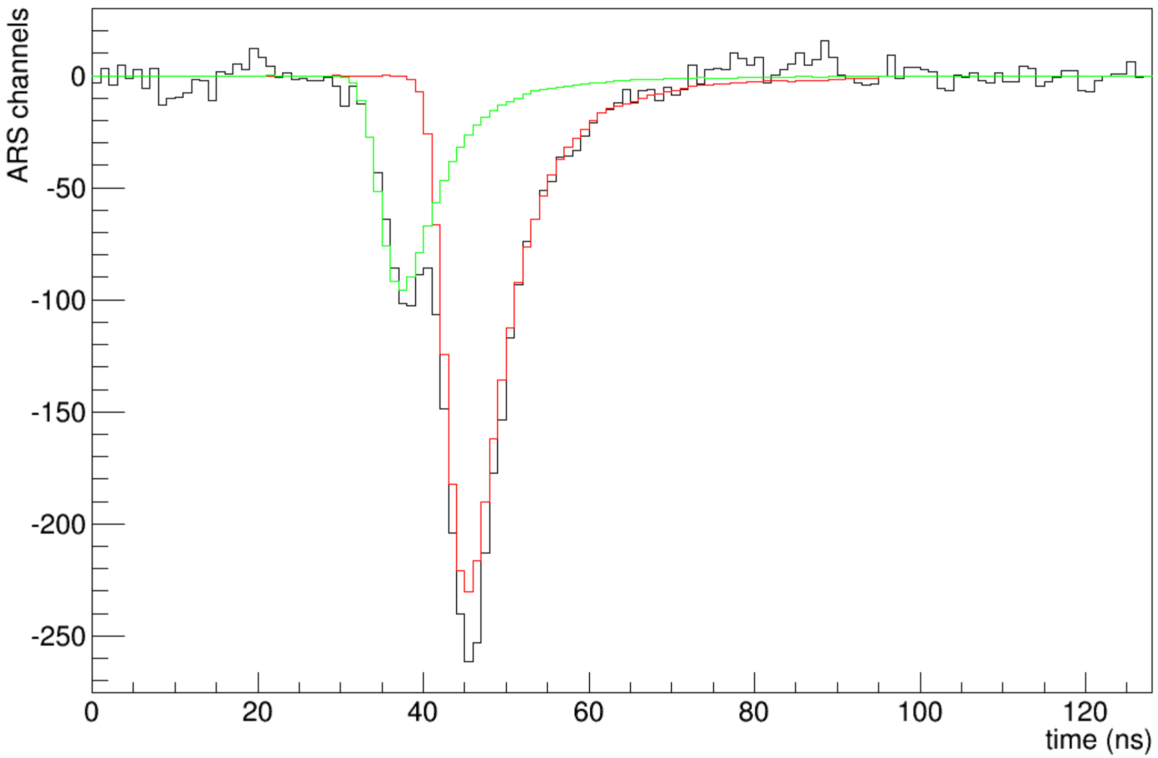
kinematic	% of target charge	PAC days
kin36_1	100.0	3
kin36_2	100.0	2
kin36_3	100.0	1
kin48_1	100.0	5
kin48_2	56.6	4
kin48_3	76.4	4
kin48_4	53.0	7
kin60_1	100.0	13
kin60_2	0.0	16
kin60_3	100.0	13
kin60_4	0.0	20

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 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.

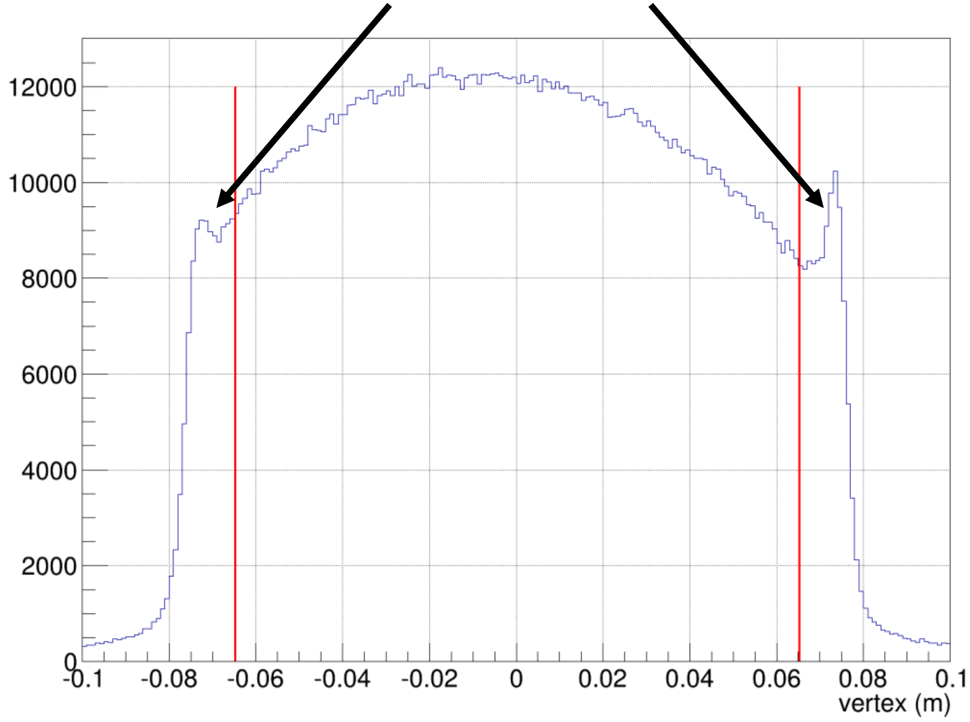
- If Level 1 trigger fired → **Level 2 – Coincidence with Calorimeter**:
  - Calorimeter ARS boards freeze.
  - Look for event in Calorimeter.
  - Energy threshold.

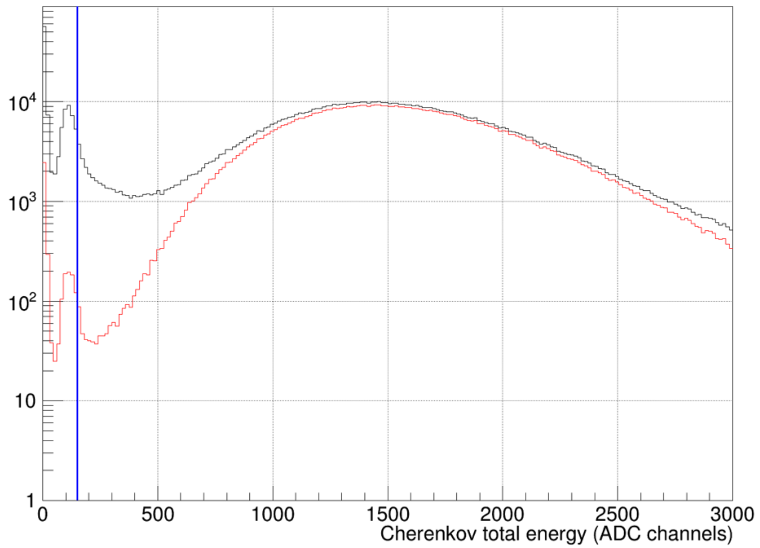
- If level 2 fired → Event recorded (**ARS encoding slow → dead time**).
- If level 2 NOT fired → Event NOT recorded (**no ARS encoding → fast**).
- Then, clear ARS boards and resume acquisition.

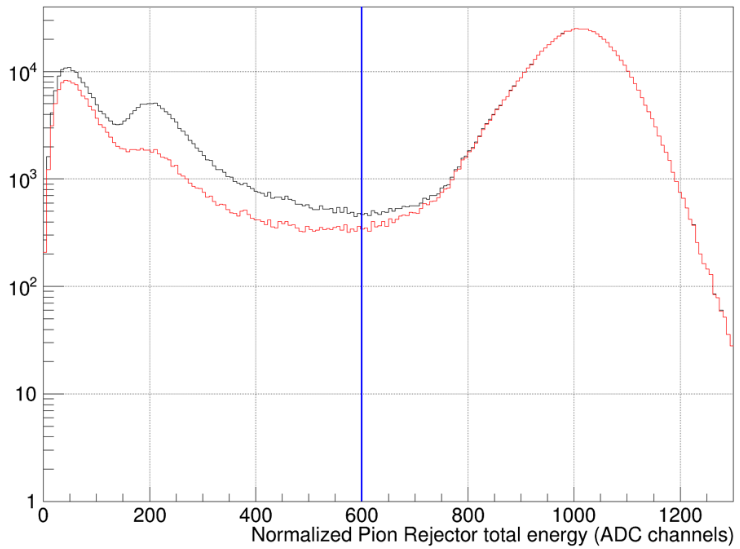
Event selection and exclusivity

- Vertex: cut the target aluminum walls.
- Calorimeter:
  - Only 1 photon detected.
  - Minimum photon energy: cut low energy background.
  - Energy leaks on the edges: cut photons in edges blocks.
- Spectrometer:
  - Electron identification: Cherenkov & Pion Rejector cuts to eliminate π^-.
  - Single track: cut events with multiple tracks.
  - Acceptance cut: the R-Function.

Aluminum walls

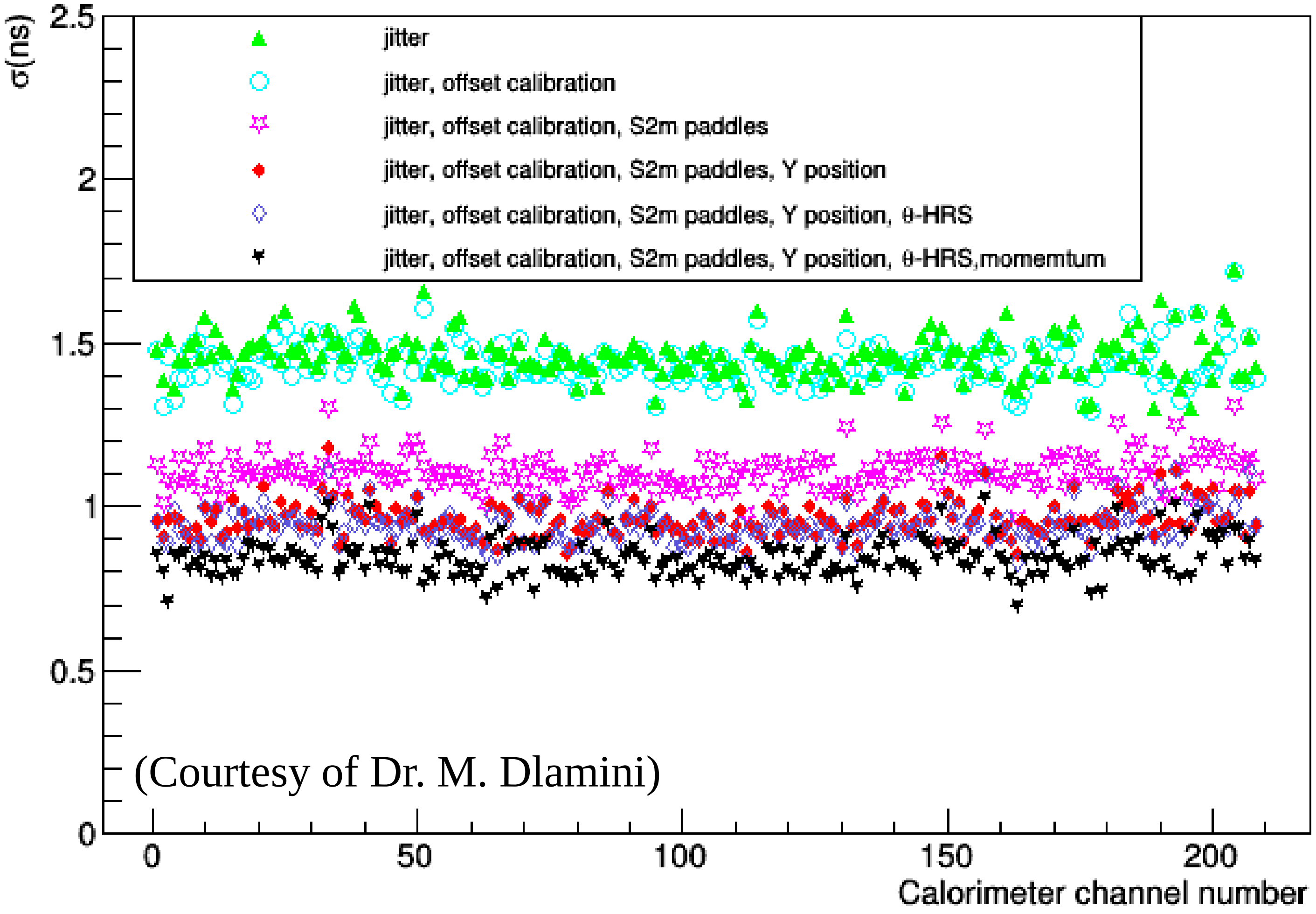






Coincidence time correction

- Trigger jitter correction.
- Scintillator S2 paddles relative time correction (cabling).
- Photon travel time in S2 correction.
- Electron travel time in the spectrometer correction (dispersive angle and momentum).



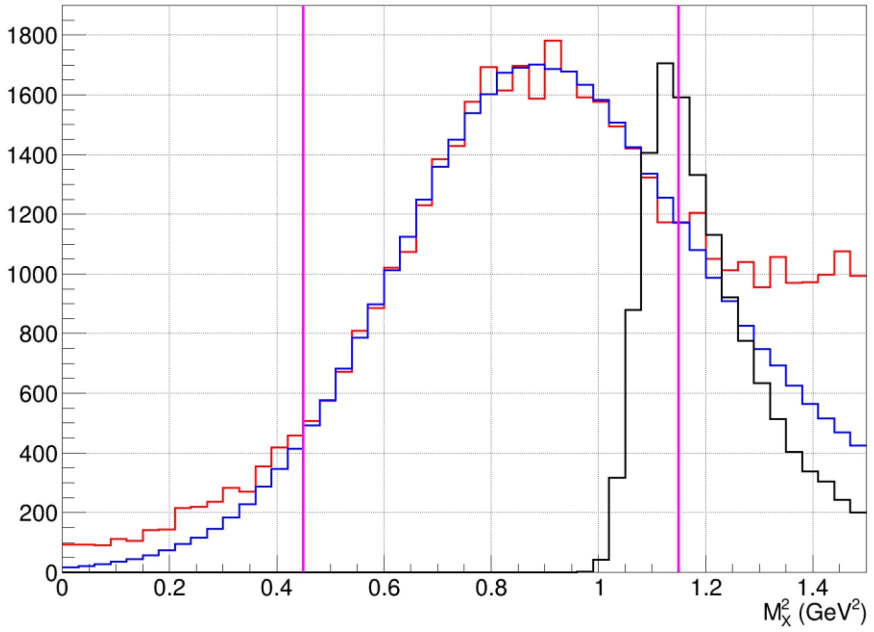
(Courtesy of Dr. M. Dlamini)

Simulation calibration and smearing

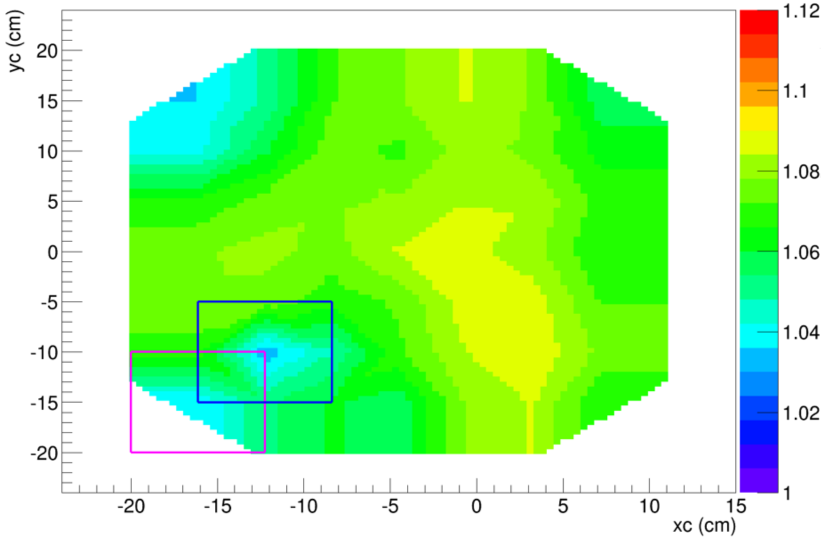
- Radiative tail + energy resolution → DVCS events lost due to missing mass cuts.
- Compensation: same cuts applied to simulation → need distributions to match.
  - Energy leaks + Cherenkov photon not simulated → **Calibration + Smearing**.
- Geant4 reconstructed photons energy **smeared by a Gaussian(μ,σ)**.
- (μ,σ) computed by χ^2 minimization:

$$\chi^2 = \sum \frac{data\_Mx^2 - geant4\_Mx^2}{\sigma^2(data\_Mx^2)}$$

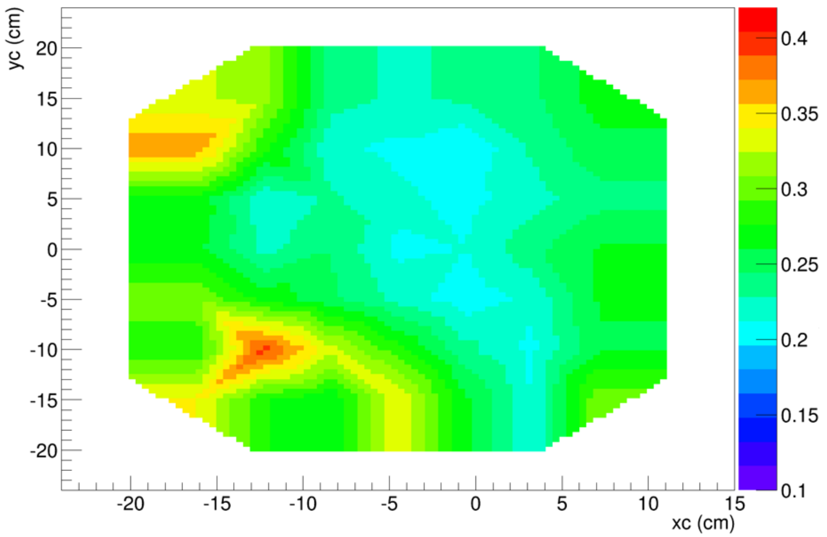
- **(μ,σ) dependence with respect to the position in the calorimeter.**



μ



σ (GeV)



Bin migration

- **bin migration**: (1) $N_r = \sum_v K_{rv} N'_v$

N_r = number of events in a bin r, reconstructed: **what we measure.**

N'_v = number of events in a bin v, at the vertex: **what we want.**

Ideally: $N_i = N'_i$ if same bins at vertex and reconstructed.

But **bin migration** (resolution effects, radiative effects, etc…).

K_{ij} = Probability event ϵ $\text{bin}_{j(\text{vertex})}$ → event ϵ $\text{bin}_{i(\text{reconstructed})}$: **what we need to compute with the simulation.**

- Cross section: (2) $N'_v = L \int_{\Omega_v} \frac{d\sigma}{d\Omega} d\Omega$

(2) in (1) → (3) $N_r = L \sum_v \int_{\Omega_v} K_{rv} \frac{d\sigma}{d\Omega} d\Omega$

Cross sections CFFs parametrization

- (3) $N_r = L \sum_v \int_{\Omega_v} K_{rv} \frac{d\sigma}{d\Omega} d\Omega$

- Cross section parametrization with CFFs: (4) $\frac{d\sigma}{d\Omega} = \sum_n F_n X_n$

with X_n CFFs combinations and F_n kinematic prefactors (known).

(4) in (3) → (5) $N_r = \mathrm{L} \sum_v \sum_n \int_{\Omega_v} K_{rv} F_n X_n d\Omega$

- Averaging X_n over Ω_v: $X_n \rightarrow X_{vn}$

(5) → (6) $N_r = L \sum_v \sum_n X_{vn} \int_{\Omega_v} K_{rv} F_n d\Omega$

Bin migration computation

- (6) $N_r = L \sum_v \sum_n X_{vn} \int_{\Omega_v} K_{rv} F_n d\Omega$
- Notation: $K_{rvn} = \int_{\Omega_v} K_{rv} F_n d\Omega$

(6) → (7) $N_r = L \sum_v \sum_n K_{rvn} X_{vn}$

- Compute K_{rvn} with simulation:

$$K_{rvn} = \sum_{i \in \{v \to r\}} F_n \frac{\Delta\Omega_{i\ simu}}{N_{gene}}$$

χ^2 minimization and CFFs fitting

- χ^2 minimization with respect to X_{vn} → fit CFF combinations X_{vn}

$$\chi^2 = \sum_r \left(\frac{N_{exp\,r} - N_{simu\,r}}{\sigma_{exp\,r}}\right)^2 \quad with \;\; N_{simu\,r} = L \sum_v \sum_n K_{rvn} X_{vn}$$

- From fitted CFFs X_{vn}:
  - Compute $N_{simu\ r}$
  - Compute $\frac{d\sigma_{fitted\,v}}{d\Omega} = \sum_n F_n X_{vn}$
  - Reconstruct $\frac{d\sigma_{exp\,r}}{d\Omega} = \frac{N_{exp\,r}}{N_{simu\,r}} \frac{d^4\sigma_{fitted\,r}}{d\Omega}$