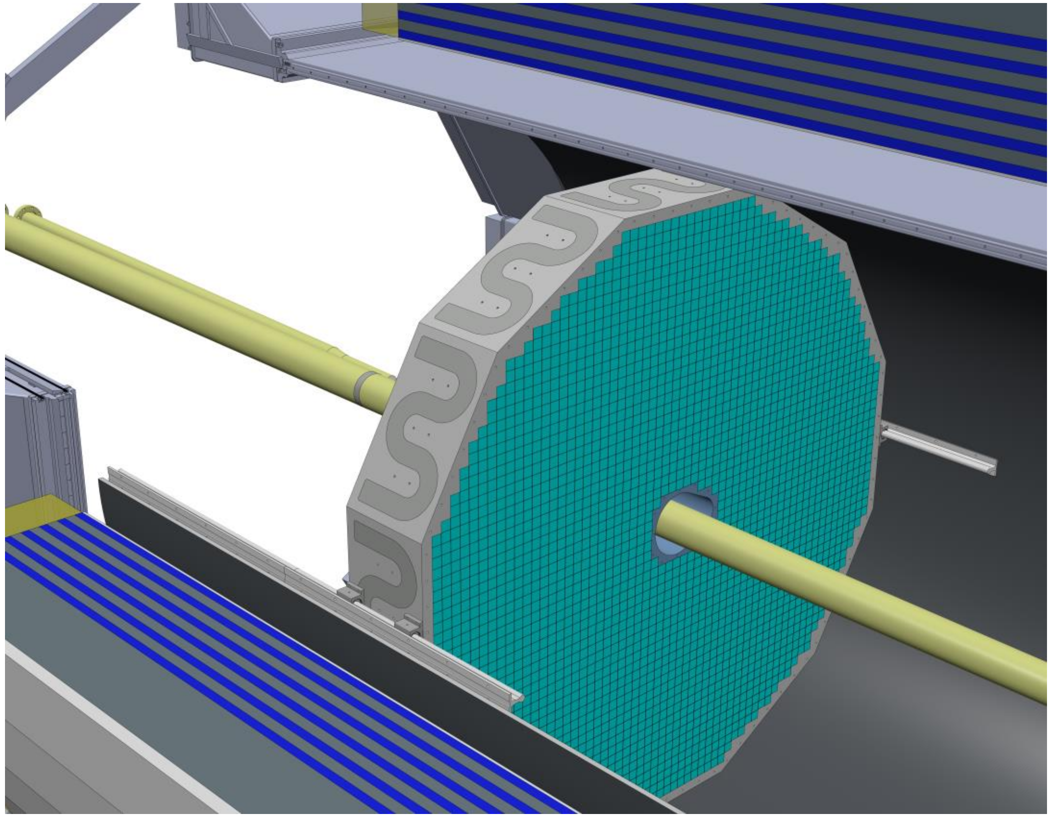


ePIC backward ECal

DESY beam test with H2GCROC3

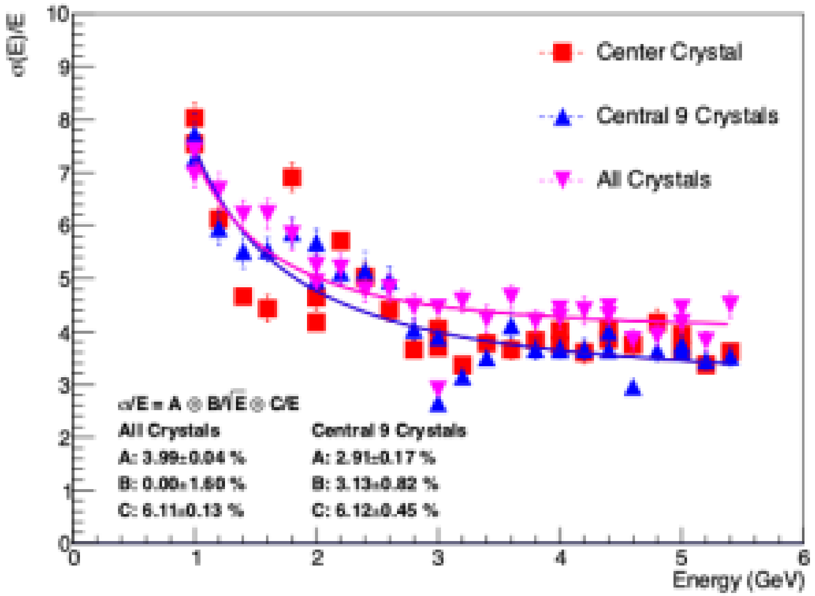
Carlos Muñoz Camacho

TIC Meeting – August 24, 2026

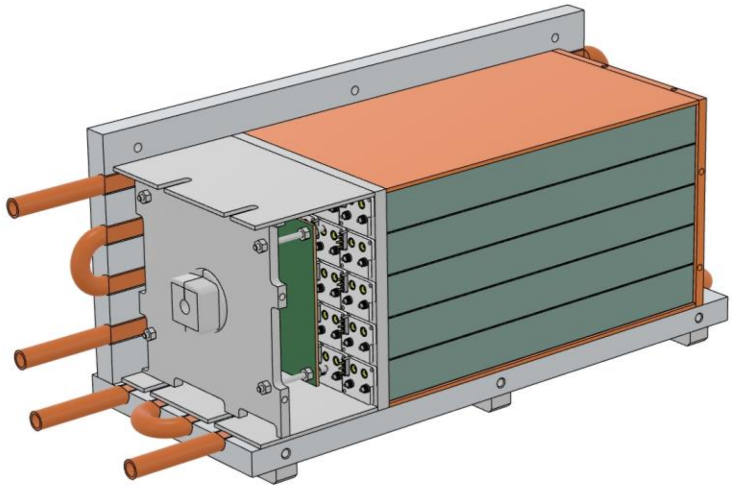
Introduction

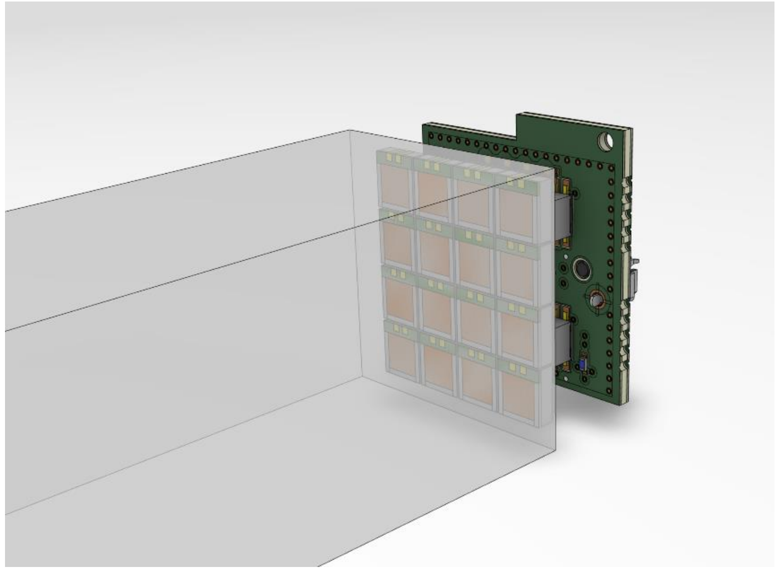
- Preliminary beam-test results showed poor energy resolution.
- Correlated & uncorrelated noise measured in pedestal runs could not account for the observed performance.
- Subsequent bench tests achieved percent-level single-channel resolution.
- This prompted a reanalysis of the beam-test data.

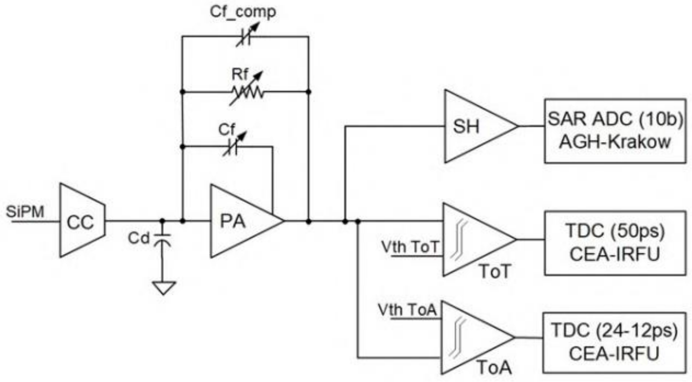
A bug was found in the code the aligns event fragments from different FPGAs



Preliminary data analysis of beam test data







ADC + ToT + ToA

25 PWO crystals

16 SiPMs per crystal

400 independent detector channels • 8 H2GCROC3 ASICs • 4 FPGA streams

Readout configuration

Crystal numbering and cluster

- beam center
- 3 × 3 cluster
- outer ring

4	9	14	19	24
3	8	13	18	23
2	7	12	17	22
1	6	11	16	21
0	5	10	15	20

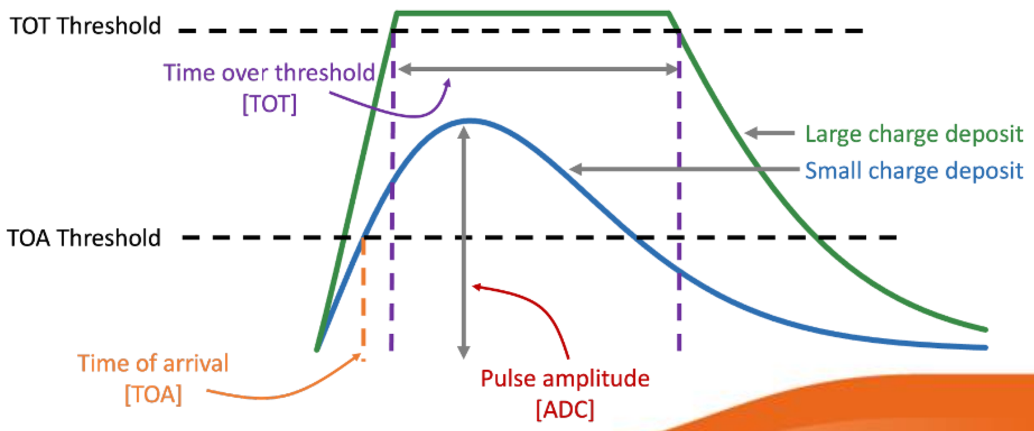
KCU–ASIC–SiPM matrix map

4 209:1:A	**9** 210:0:A	**14** 209:0:D	**19** 210:1:B	**24** 210:1:D
3 211:1:A	**8** 211:1:D	**13** 209:1:B	**18** 208:1:C	**23** 209:0:A
2 209:0:C	**7** 210:1:A	**12** 210:0:D	**17** 211:0:B	**22** 208:0:A
1 211:0:A	**6** 208:1:D	**11** 210:0:C	**16** 208:0:C	**21** 208:1:B
0 210:1:C	**5** 209:0:B	**10** 209:1:D	**15** 210:0:B	**20** 209:1:C

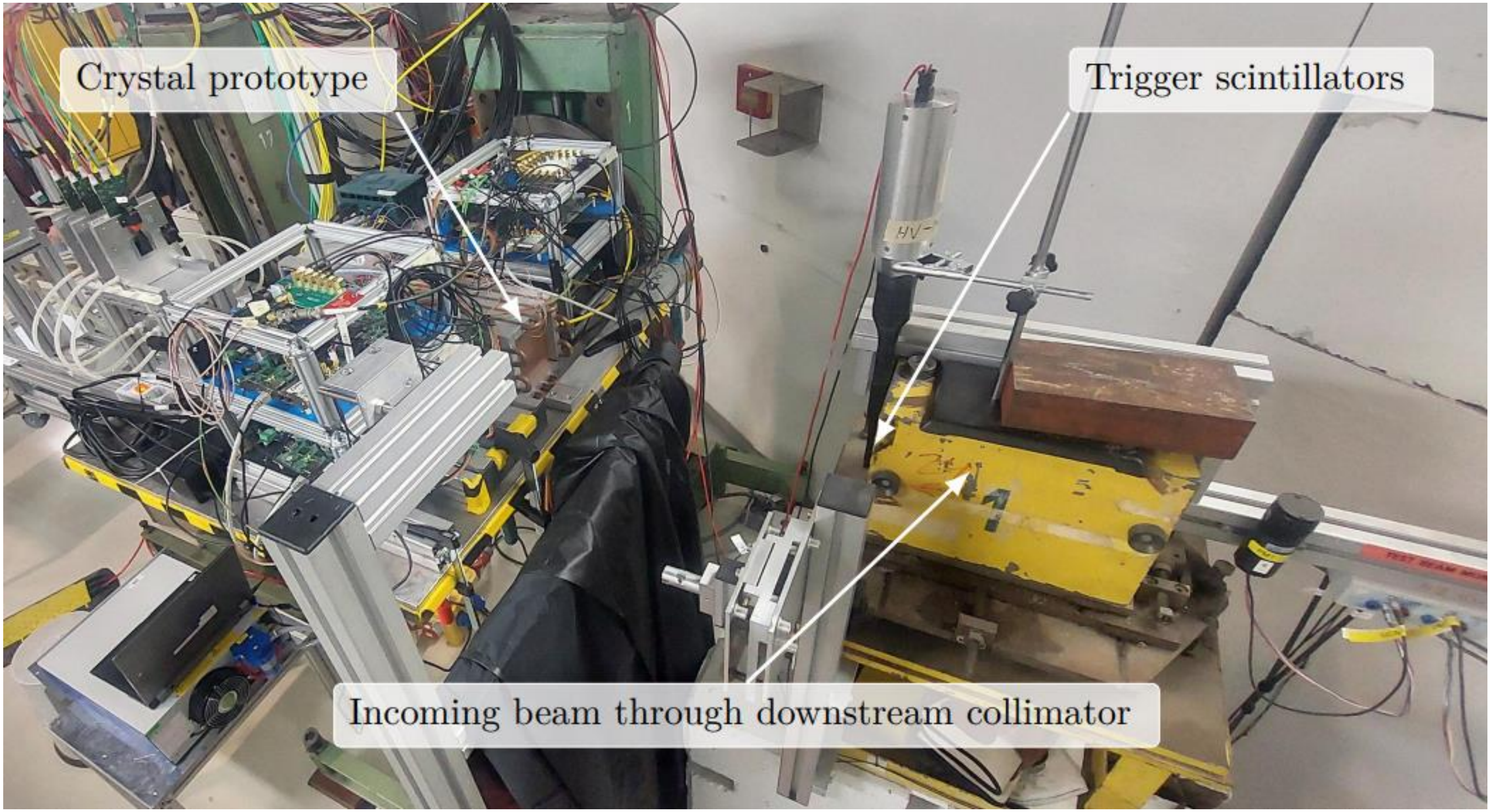
Cell contents

Crystal number
KCU:Asic:SiPM matrix

Analogue pulse shapes



Setup at T24 in DESY test beam facility

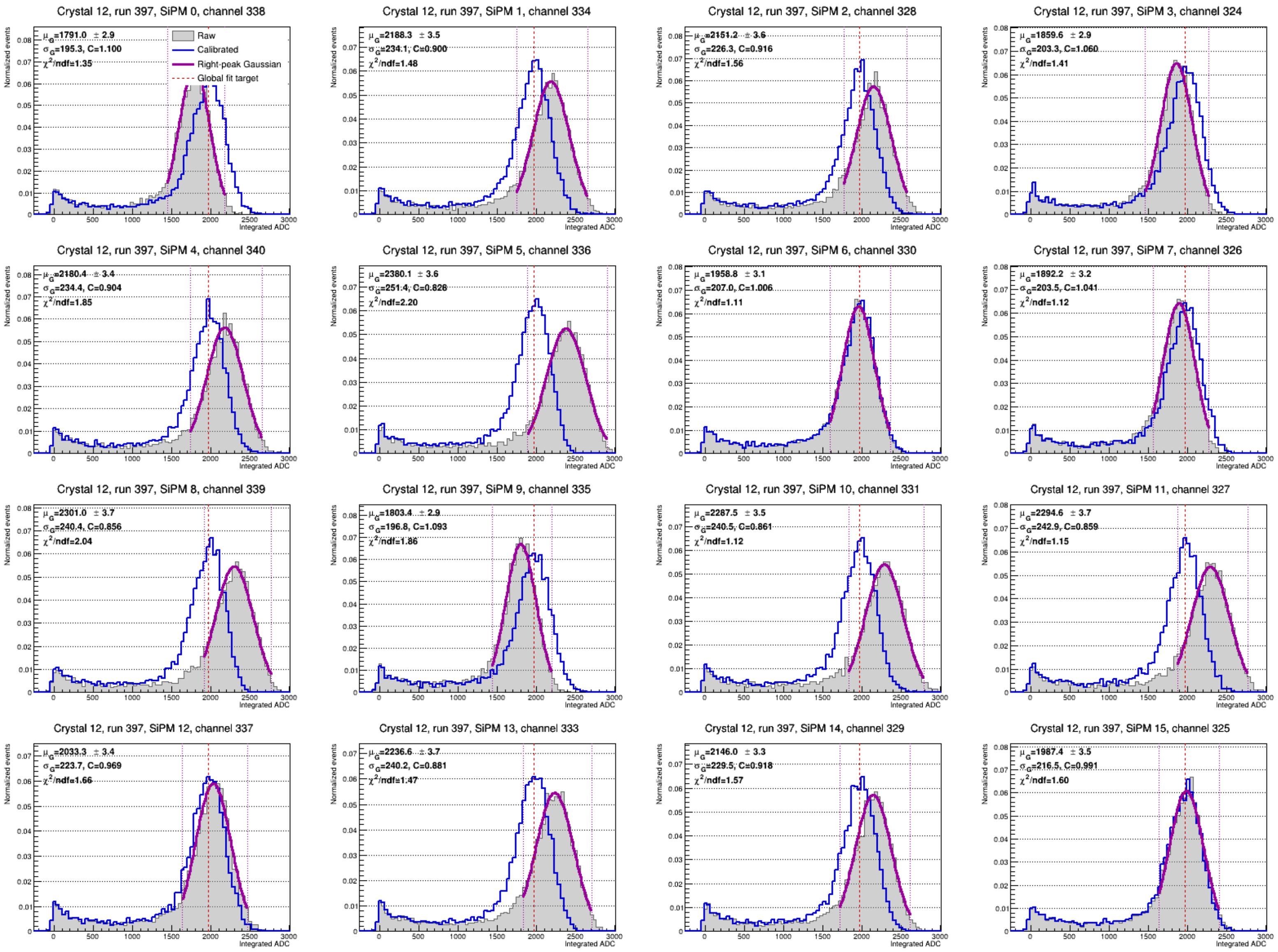


Test dates: Dec 8-21 (2025)

- 1 – 5 GeV electron beam through a 10x10 mm^2 collimator downstream (9x9 mm^2 upstream)
- Triggered by 2 scintillators
- Rate limited to ~100 Hz by introducing a 10 ms veto period after each trigger with NIM logic
- Prototype on a X-Y table with 0.1 mm position accuracy

Channel ADC gain-match at 1 GeV

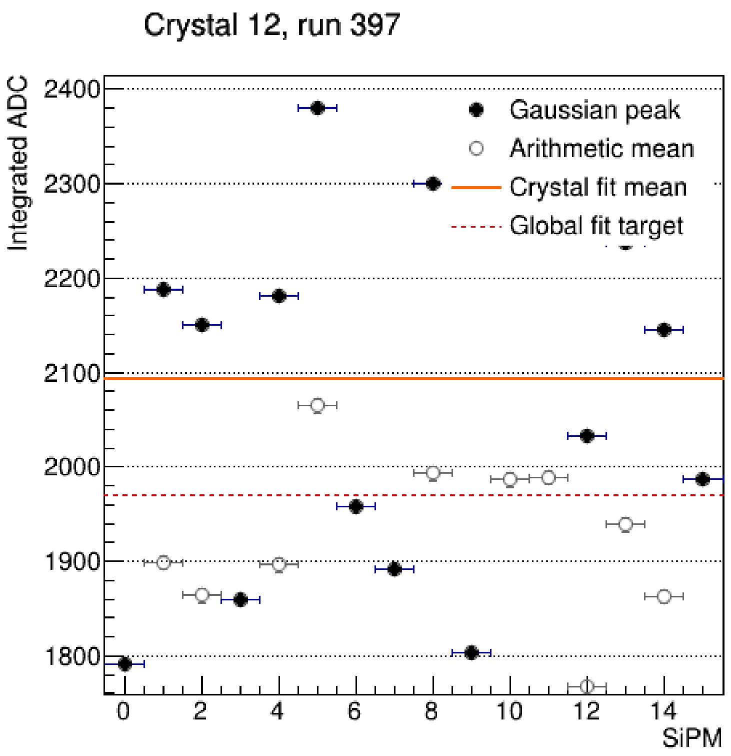
- First step of the analysis
- 25 1-GeV runs shooting at the center of each crystal
- All channels are in the ADC region
- We compute a relative gain coefficient to align their signal at the same (arbitrary) value

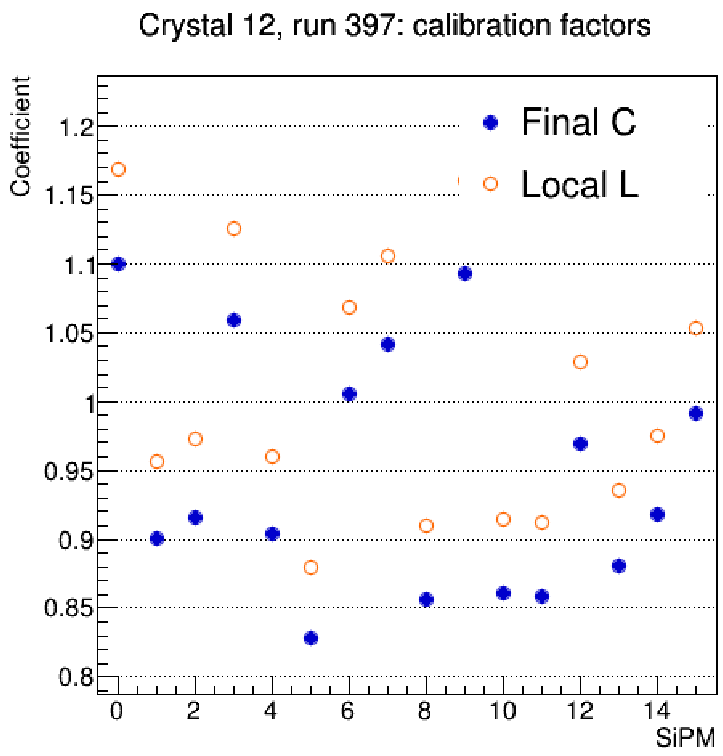


Calibration coefficients: crystal 12

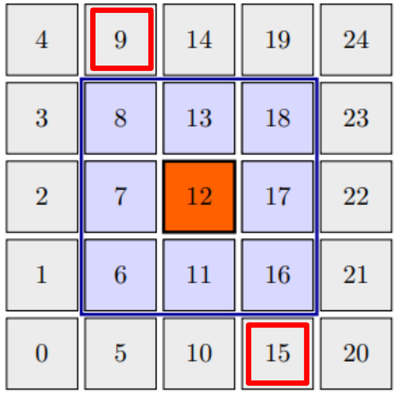
2-step correction:

- Each 16 SiPM of the crystal is aligned to the average signal of its channels
- Then each crystal get an additional globa coefficient to align all crystals at the same value





Channel QA overview



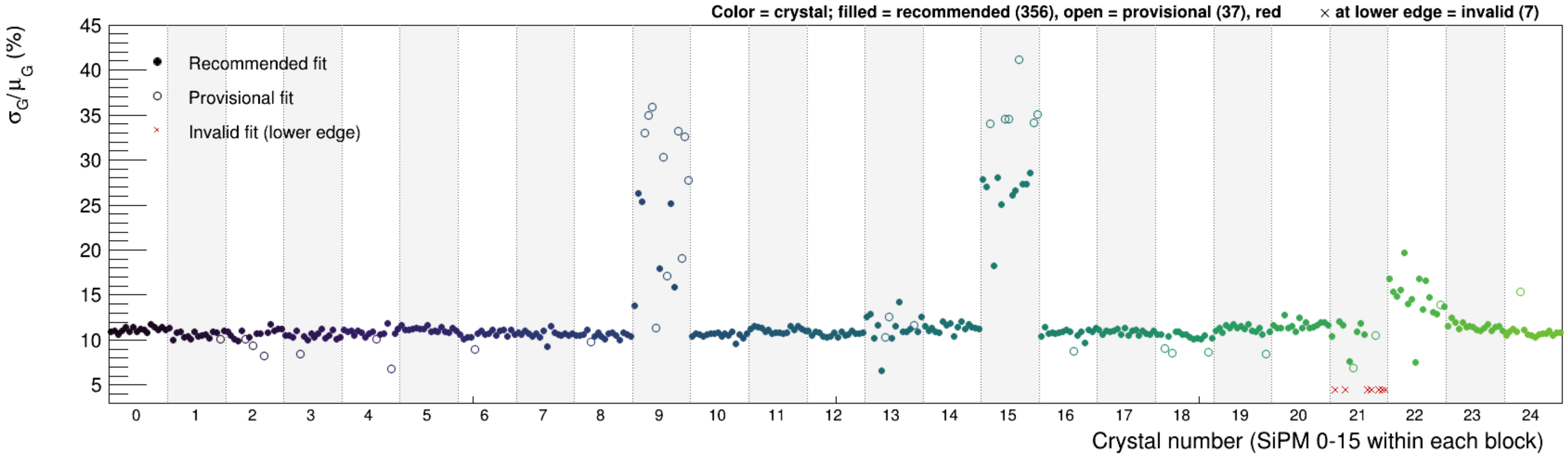
392 / 400

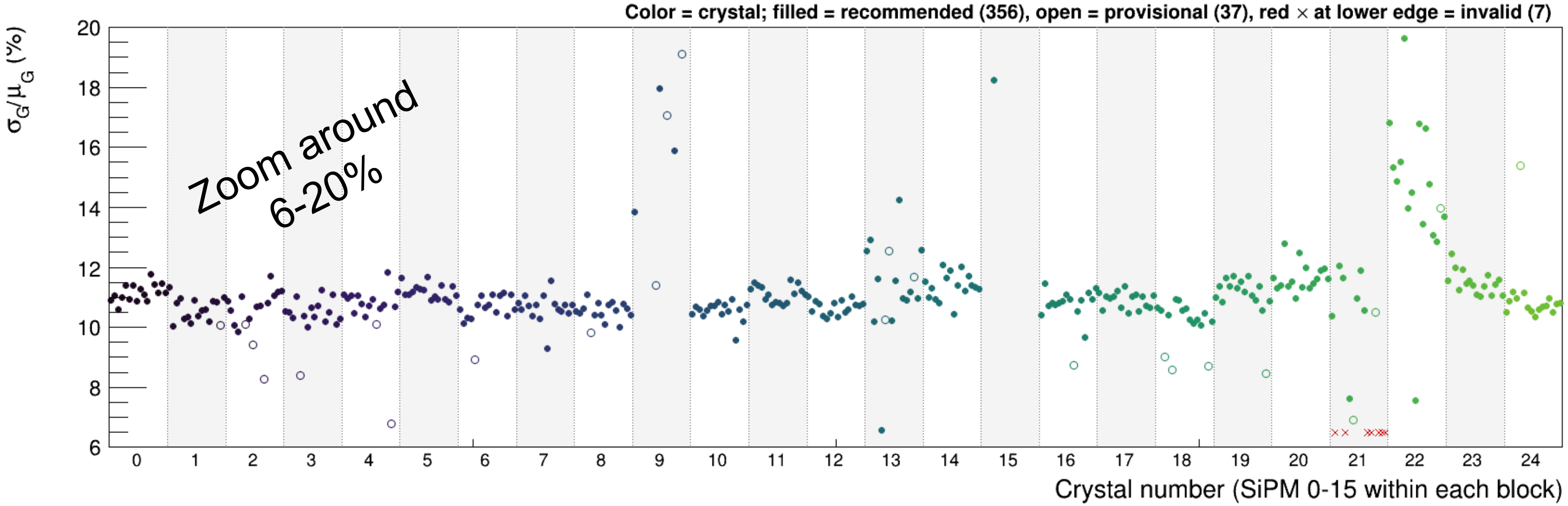
finite positive coefficients

364

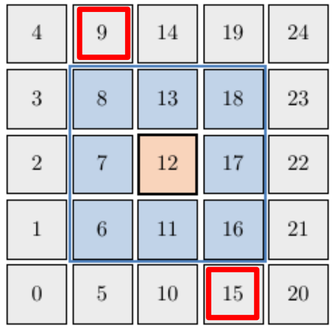
good fits

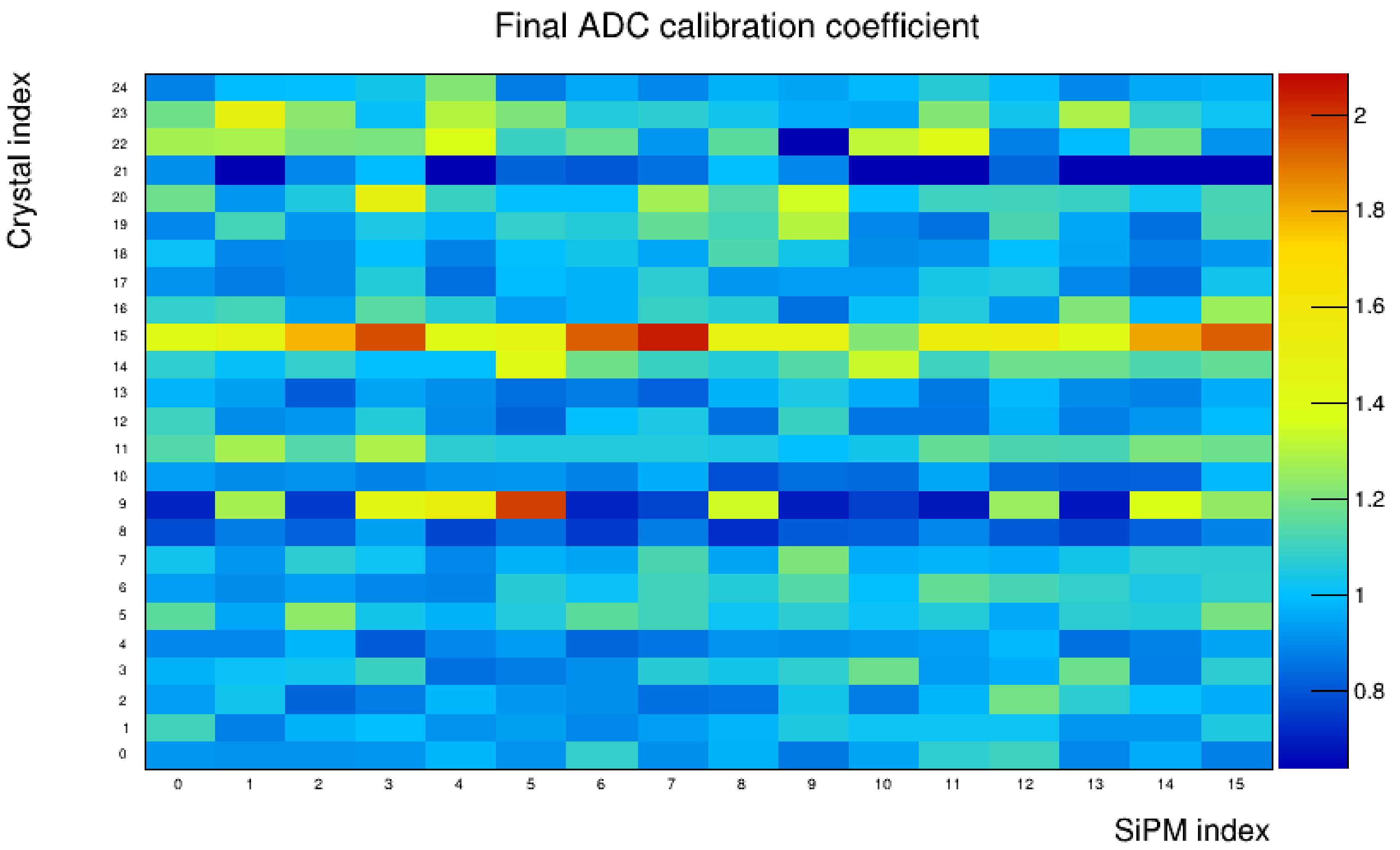
Common target: 1970.50 integrated-ADC units

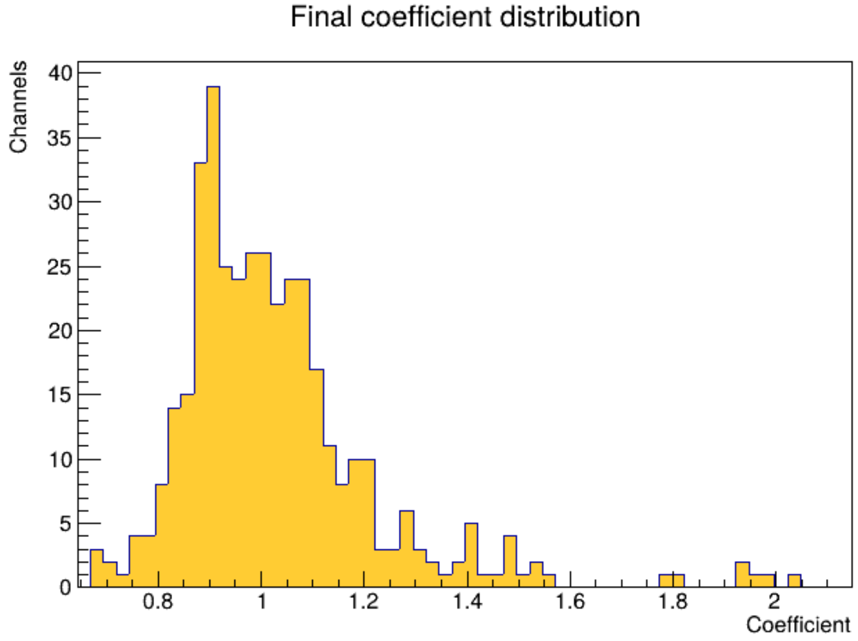




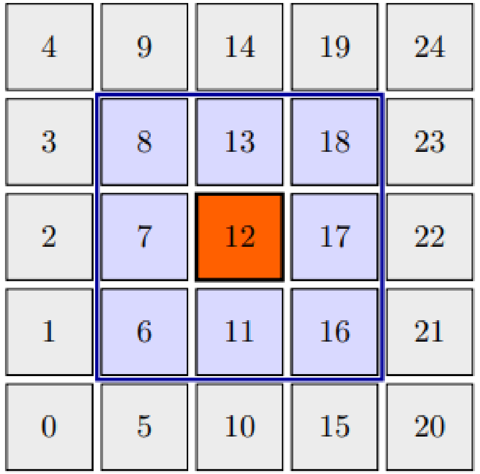
ADC calibration coefficients: all channels



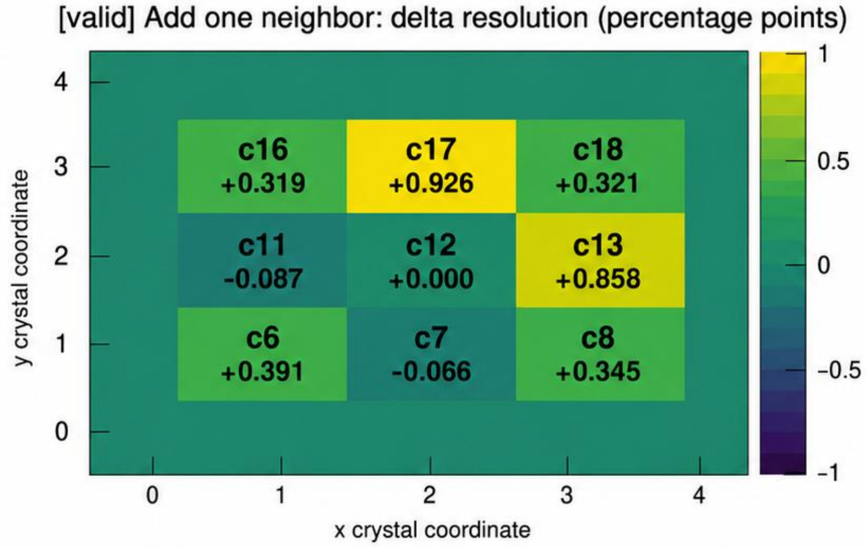




The bug: smoking gun



Region	Crystals	σ/μ
Central	$\{12\}$	7.1%
Same-FPGA triplet	$\{12, 7, 11\}$	6.0%
Full 3×3	$\{6, 7, 8, 11, 12, 13, 16, 17, 18\}$	8.0%
All crystals	$0 \ldots 24$	10.4%



KCU−ASIC−SiPM matrix map

4 209:1:A	9 210:0:A	14 209:0:D	19 210:1:B	24 210:1:D
3 211:1:A	8 211:1:D	13 209:1:B	18 208:1:C	23 209:0:A
2 209:0:C	7 210:1:A	12 210:0:D	17 211:0:B	22 208:0:A
1 211:0:A	6 208:1:D	11 210:0:C	16 208:0:C	21 208:1:B
0 210:1:C	5 209:0:B	10 209:1:D	15 210:0:B	20 209:1:C

The decoder/realigner bug

Trigger # misalignment

Current: 147 147 147 147
Next: 148 148 148 149

→

Faulty recovery

Advance FPGA 0, 1 and 2 because the look-ahead rows differ

→

Mixed output row

148 148 148 147

Implemented checks didn't catch the problem

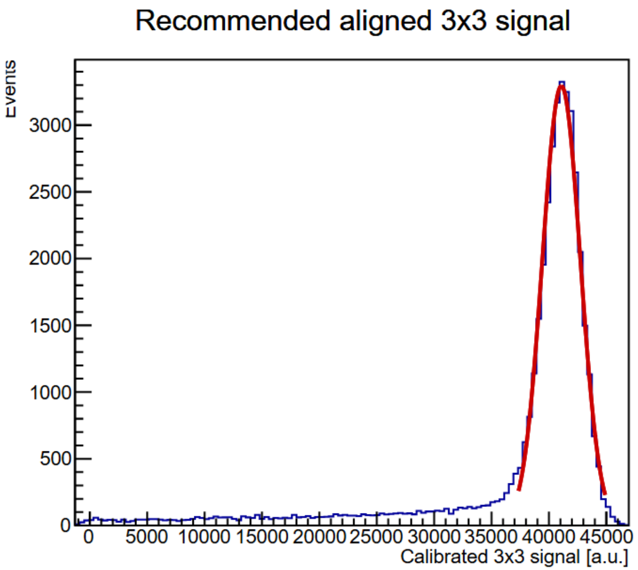
- The checks suffered from the same wrong logic
- Counters remain ordered within each stream
- The next fragments appear synchronized again

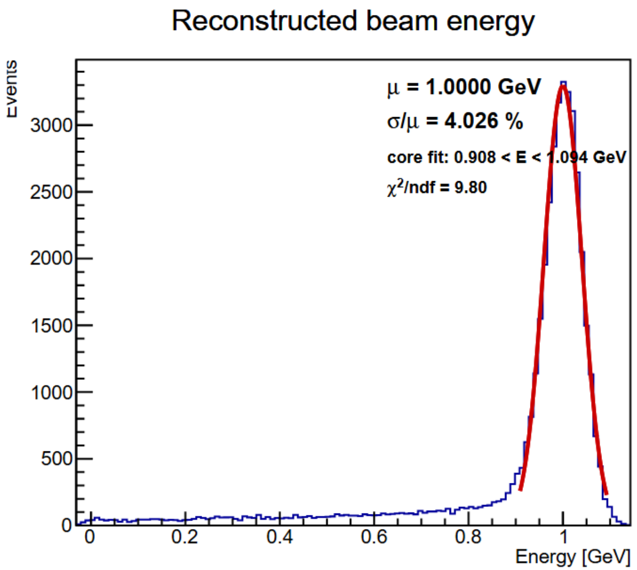
Correct behavior

Write trigger 147
Drop incomplete trigger 148
Resume with trigger 149

After events are properly realigned…

Region	Raw	Realigned	Relative change
Crystal 12	7.3%	7.3%	0.0%
Same-FPGA triplet	6.3%	6.3%	0.0%
Full 3 × 3	7.9%	4.0%	−49.4%
All 25 crystals	10.8%	7.2%	−33.2%





Broad fit (μ±2.0σ) : 4.026 ± 0.02% | Final μ±1.5σ core: 4.01 ± 0.03%

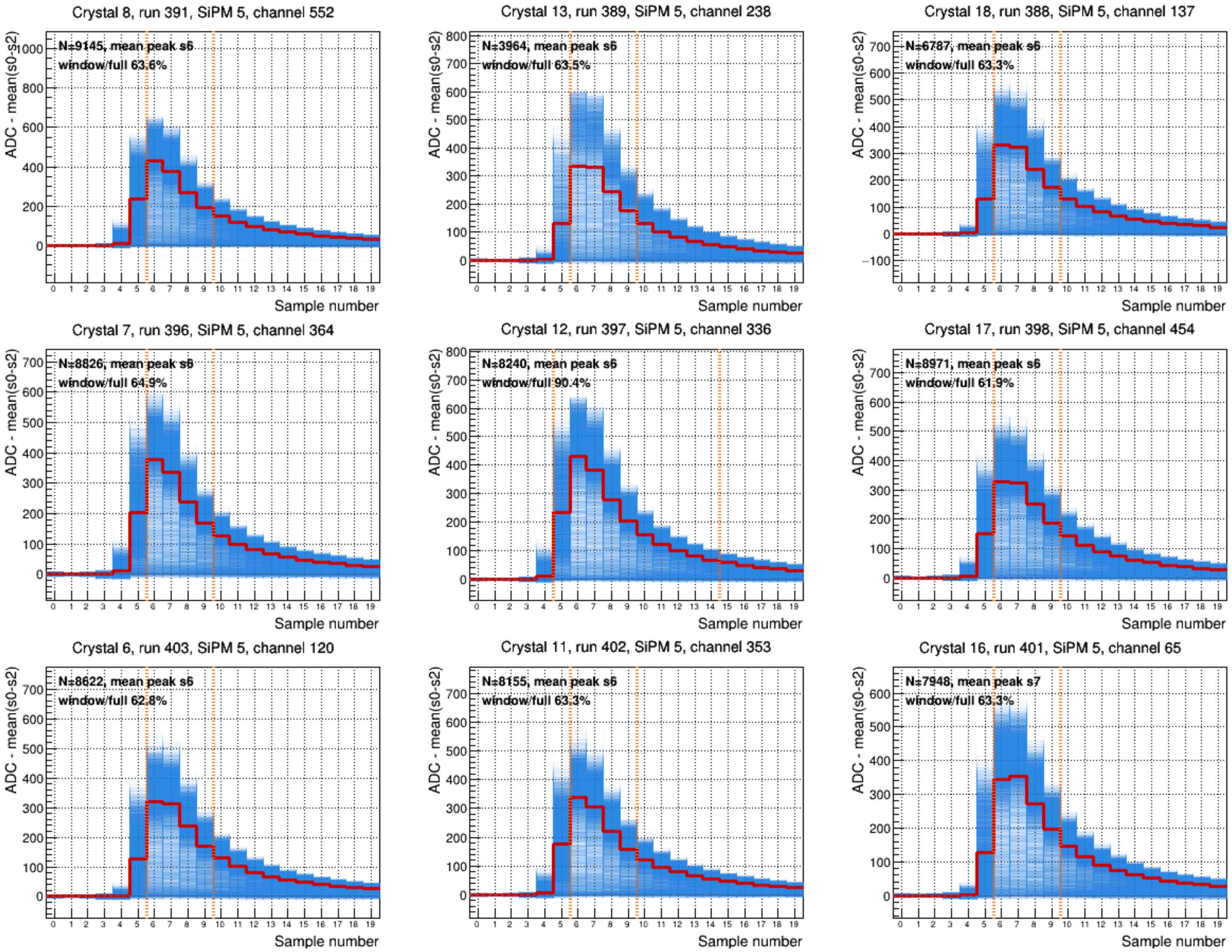
ADC integration window: optimization

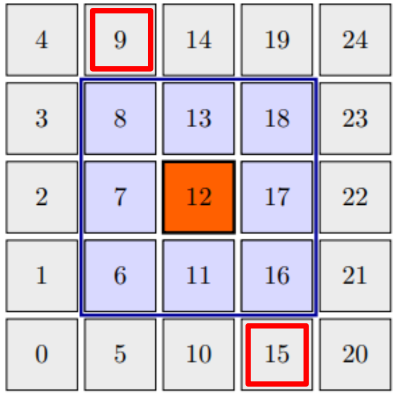
Central crystal 12

Inclusive [5,14]:
Captures the large centered pulse

Eight neighbors

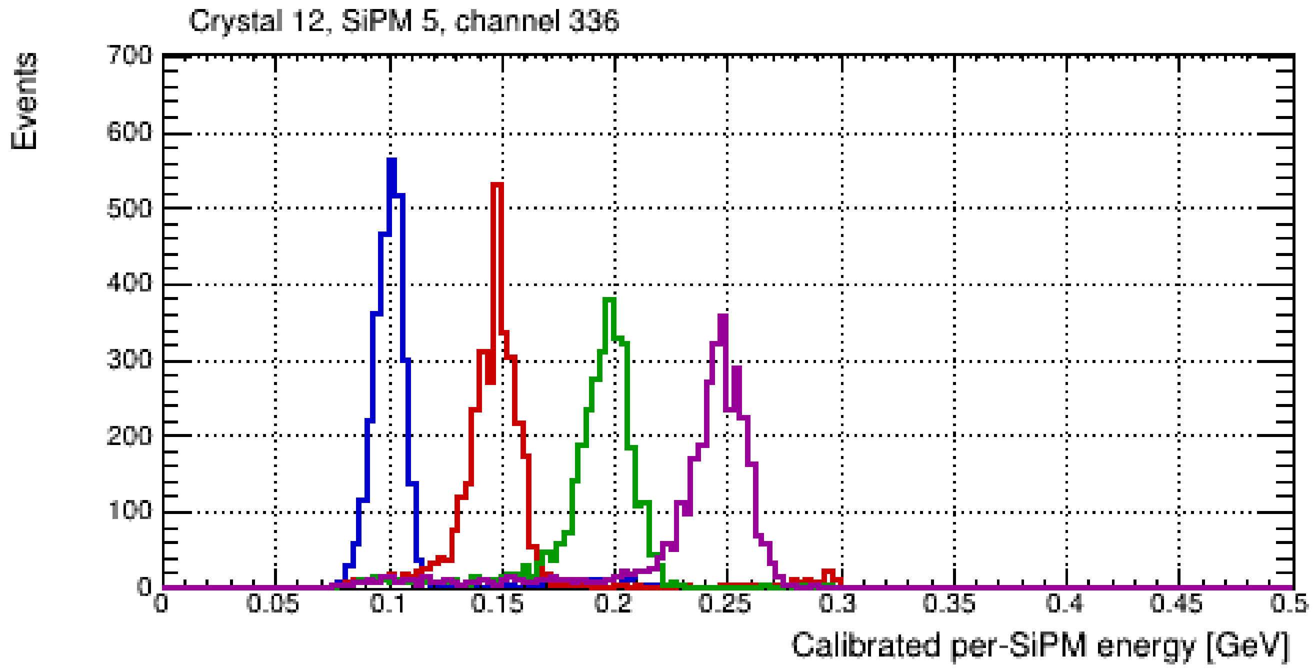
Inclusive [6,9]:
Reduces integrated pedestal noise in small signals





ToT region

At 2 GeV and above:



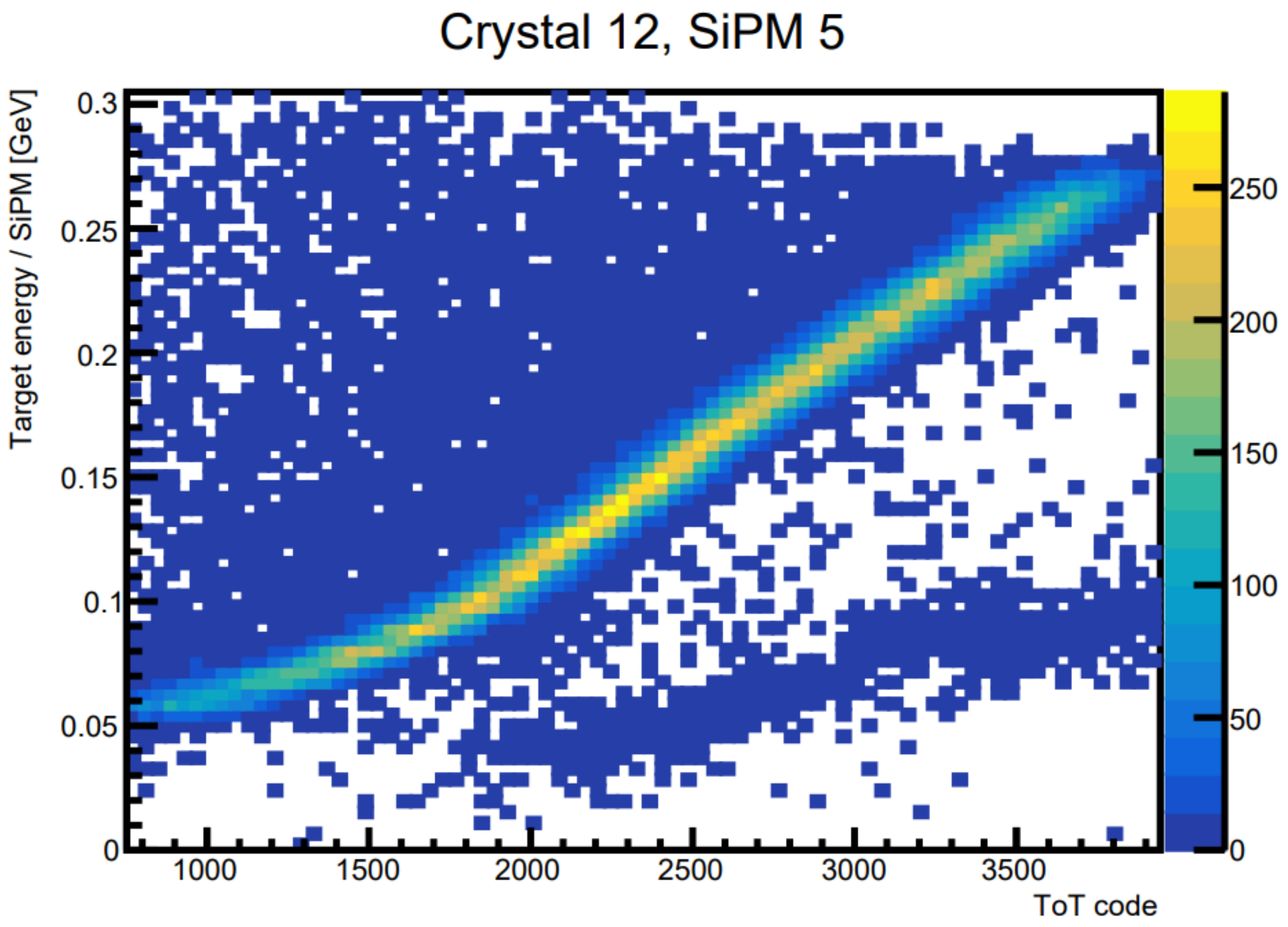
ToT distributions: 2, 3, 4 and 5 GeV runs

Eight ADC neighbors

ADC [6,9]	ADC [6,9]	ADC [6,9]
ADC [6,9]	Crystal 12 16 ToTs	ADC [6,9]
ADC [6,9]	ADC [6,9]	ADC [6,9]

Ereco = Σ16 EToT + E8 ADC

ToT calibration

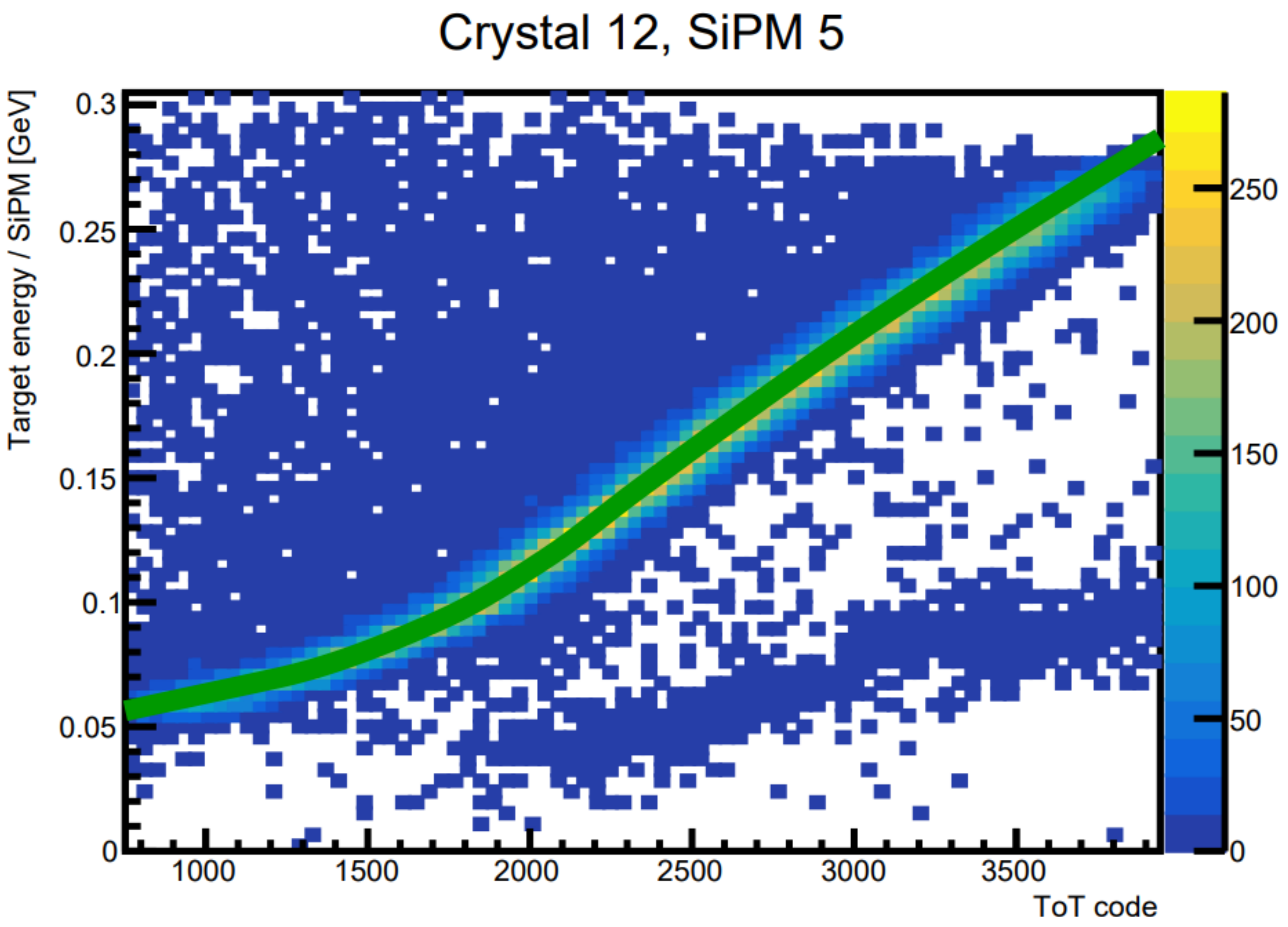


Calibration target

y = (Ebeam − E8 ADC) / 16

- Eight equal-statistics calibration nodes
- Monotonic PCHIP interpolation
- Small smooth energy-scale correction
- Independent calibration for each central SiPM

ToT calibration

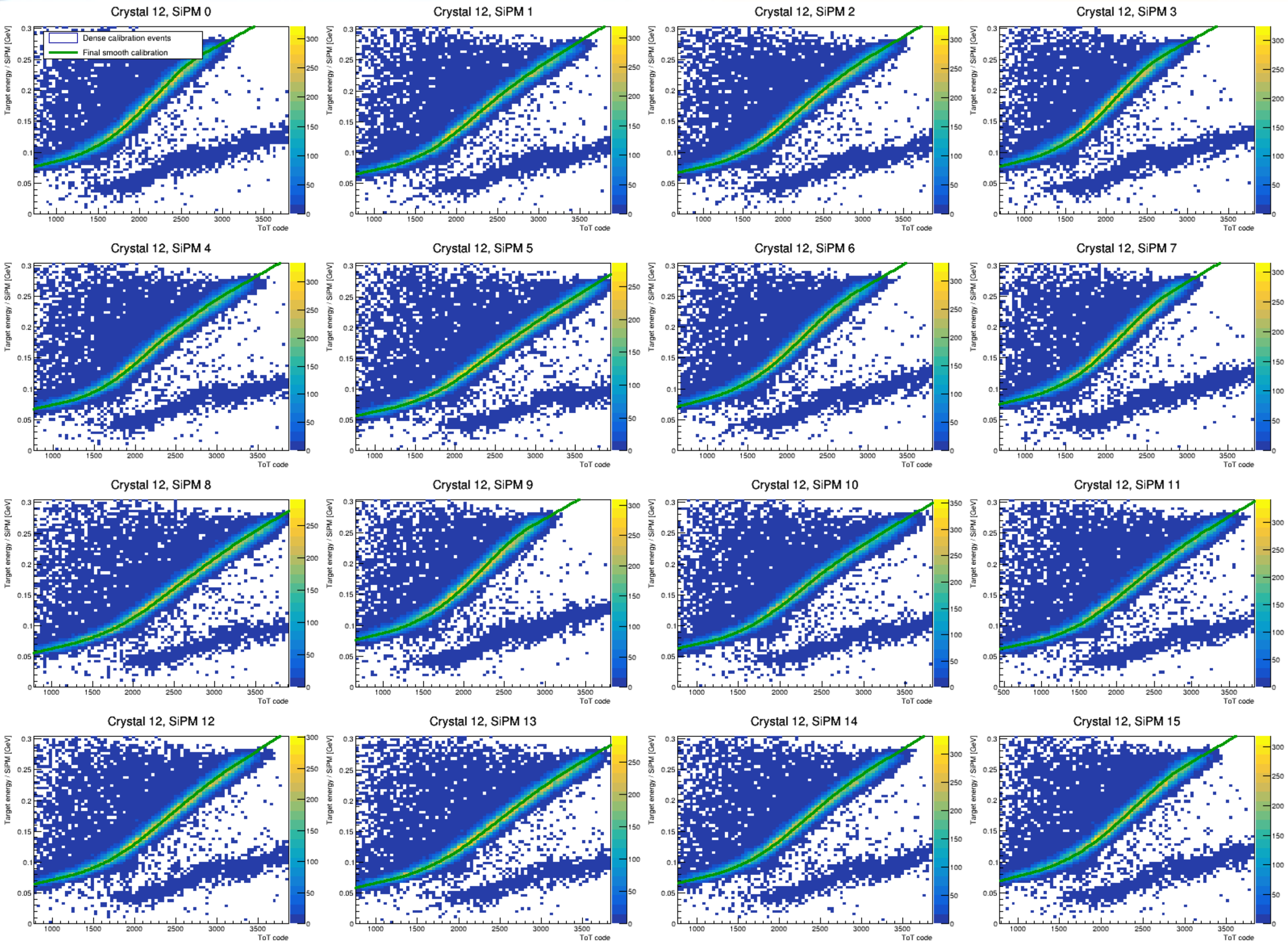


Calibration target

y = (Ebeam − E8 ADC) / 16

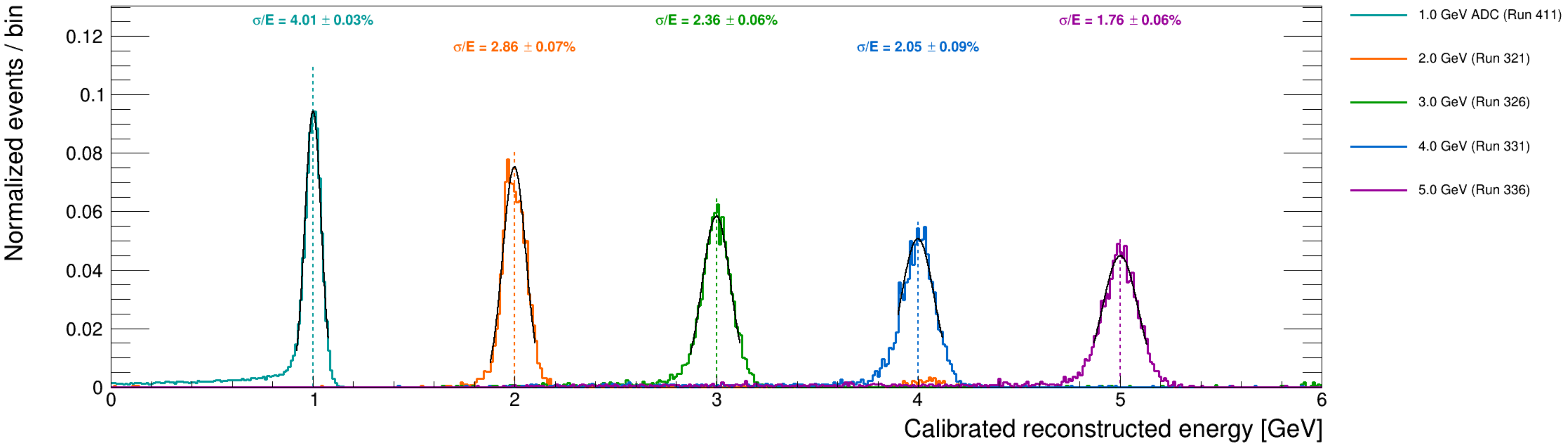
- Eight equal-statistics calibration nodes
- Monotonic PCHIP interpolation
- Small smooth energy-scale correction
- Independent calibration for each central SiPM

16 ToT channels of the central crystal



Energy resolution at the 5 calibration runs

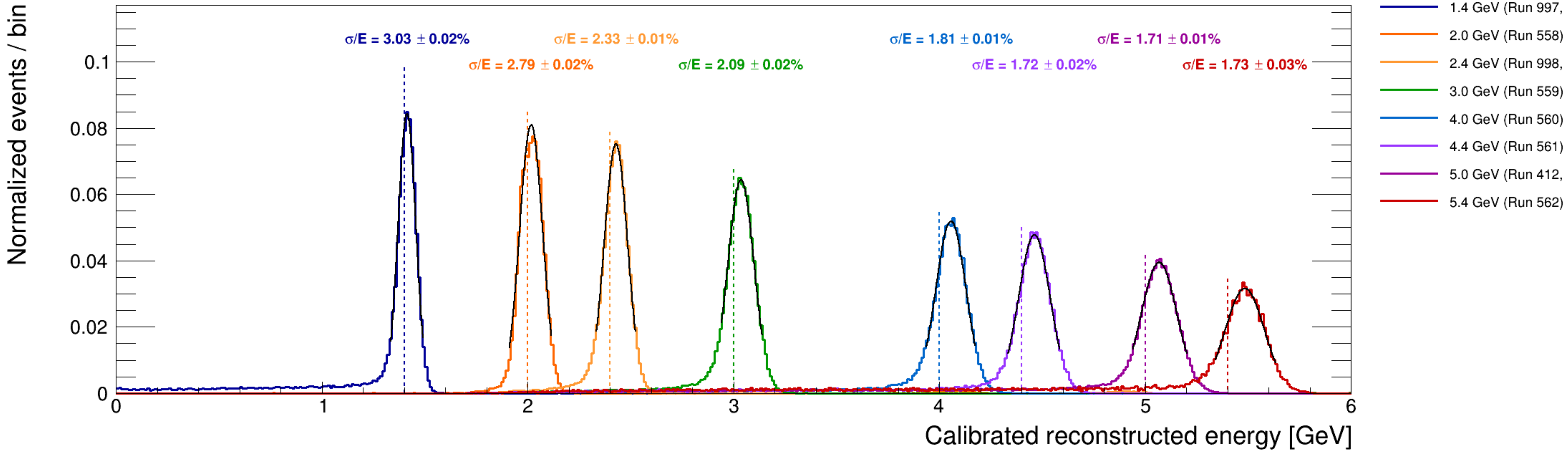
Final Gaussian-core fits over μ±1.5σ



1 GeV	2 GeV	3 GeV	4 GeV	5 GeV
4.01%	**2.86%**	**2.36%**	**2.05%**	**1.76%**

Independent runs with narrower collimator

Upstream collimator set to ±2 mm *horizontally* (± 4.5 mm in previous >1 GeV runs)

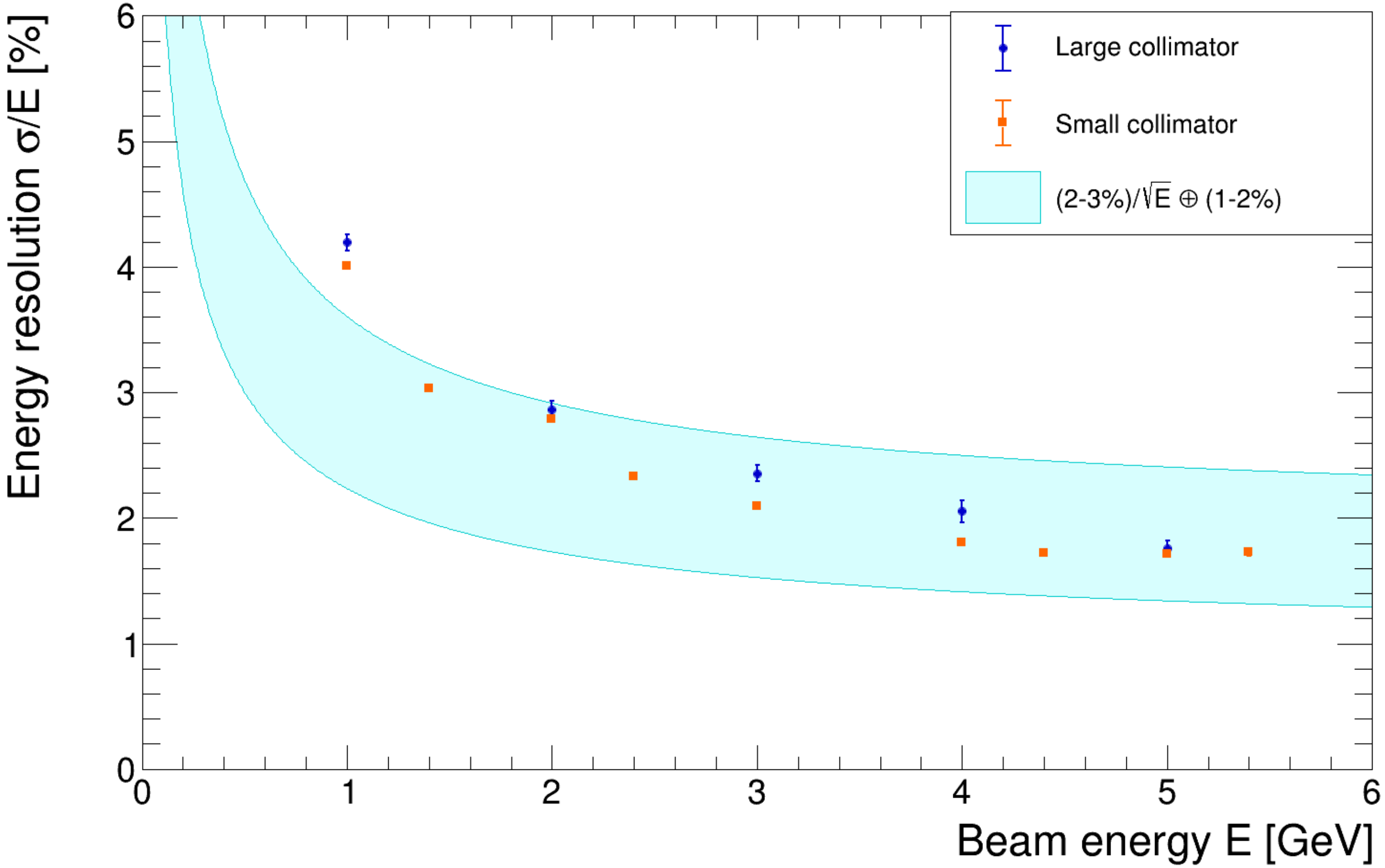


2 GeV 2.79% **3 GeV 2.09%** **4 GeV 1.81%** **4.4 GeV 1.72%** **5.4 GeV 1.73%**

Frozen ADC, ToT and cluster corrections applied without retuning

Narrower widths are consistent with reduced beam spread; means shifts up to +2.69%.

Resolution vs energy

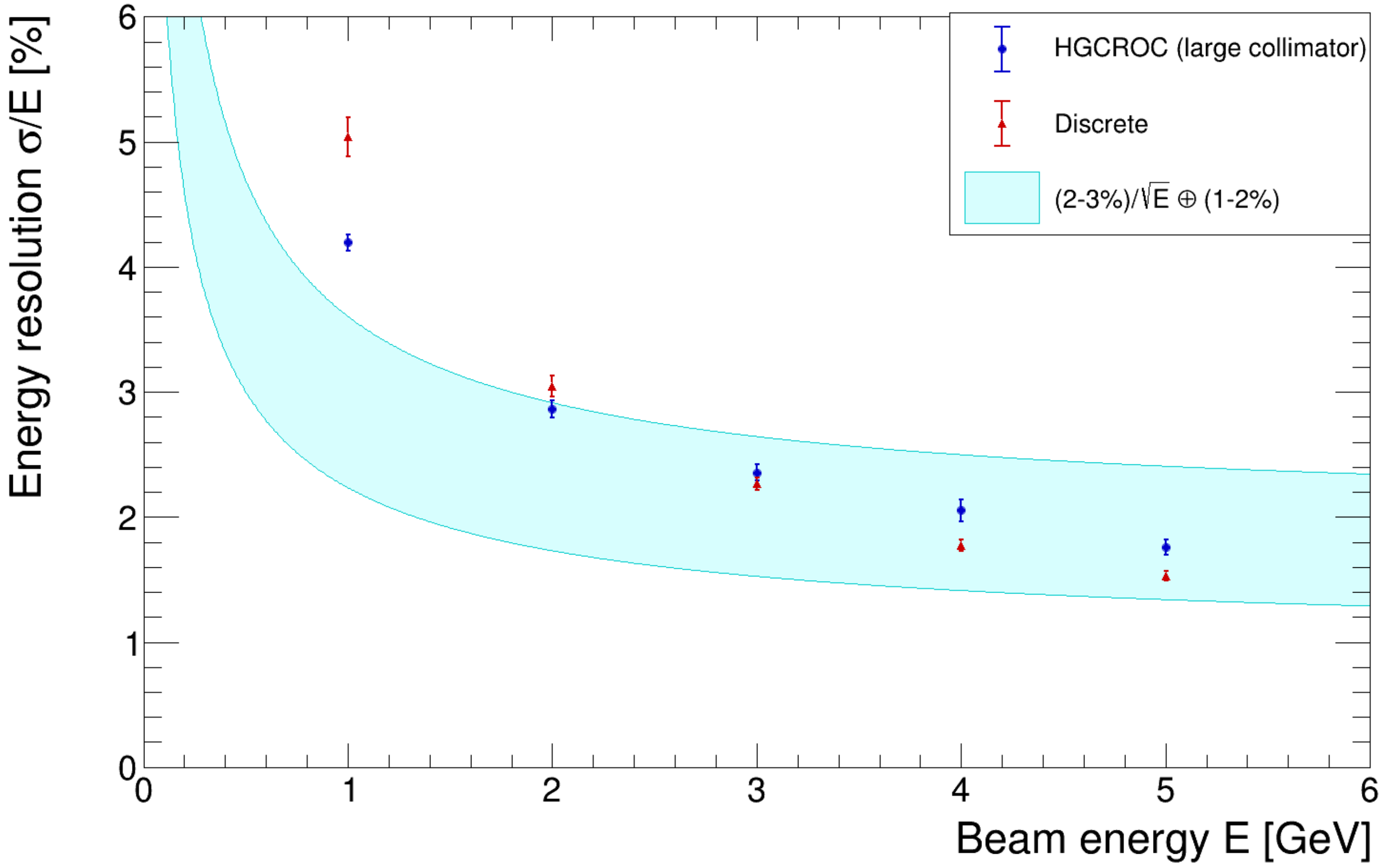


Requirement band:

$(2\text{-}3)\%/\sqrt{E} \oplus (1\text{-}2)\%$

- Resolution within requirements, except for the lowest energy point (1 GeV)
- Smaller-collimator improves the resolution slightly
- High-energy behavior approaches a ~1.7% constant value

H2GCROC versus discrete electronics

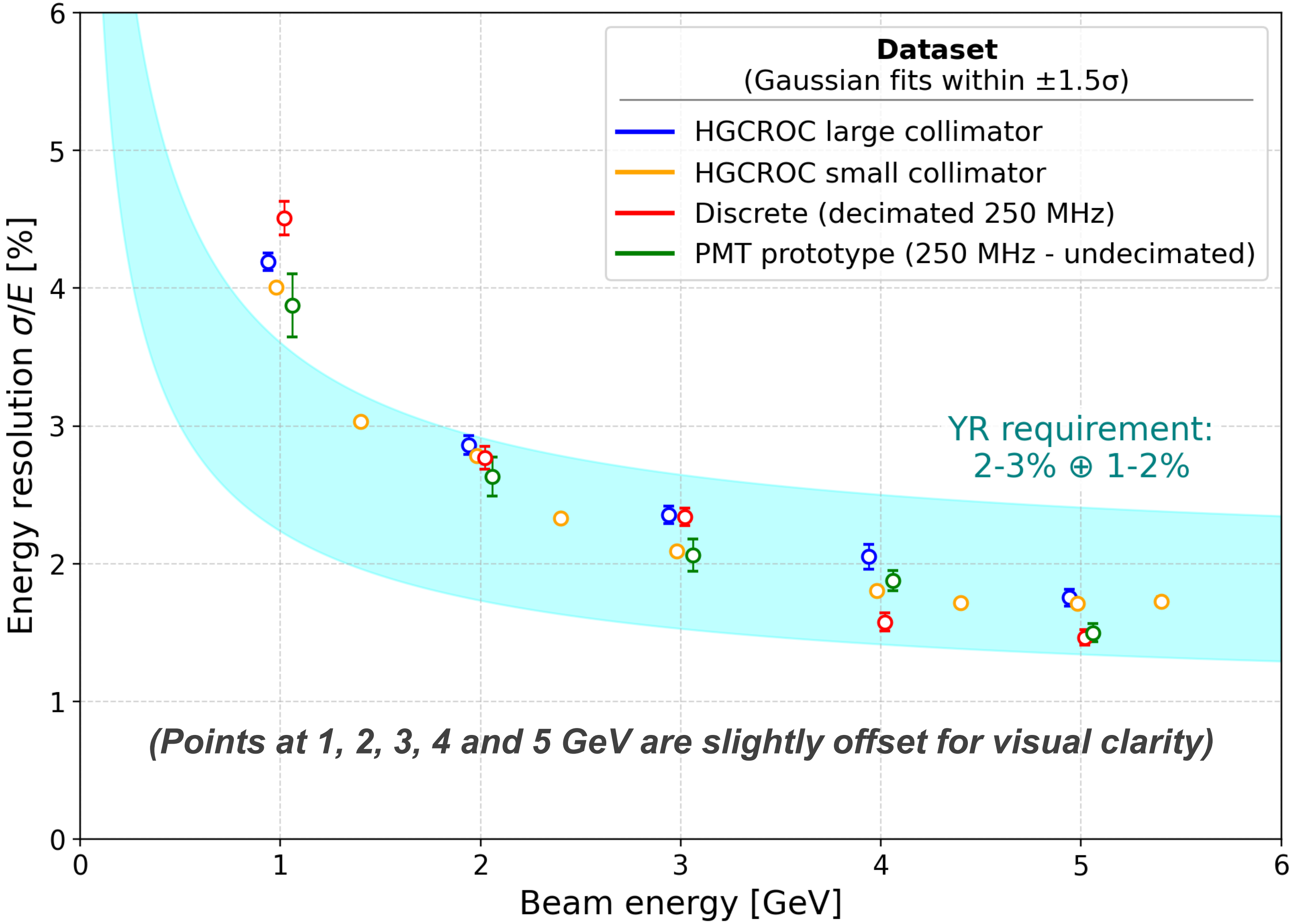


Same overall performance scale

- H2GCROC narrower at 1-2 GeV
- Similar near 3 GeV
- Discrete chain narrower at 4-5 GeV

Not a strict electronics comparison: beam conditions, reconstruction and data analyses differ

Same fit-method comparaison



Comparison of datasets with a Gaussian fit within ±1.5σ

- Discrete data acquired at 250 MHz and decimated by a factor 5
- PMT prototype used 250 MHz digitizers

Overall agreement within the datasets using different photosensors and/or electronics

Summary and conclusions

- ✓ A bug in the realignment script combined mismatched event fragments from different FPGA data streams.
- ✓ Correcting the alignment dramatically improved the energy resolution in the ADC regime.
- ✓ The ToT regime additionally required careful calibration of its nonlinear response.

> - ➢ The H2GCROC readout achieves performance comparable to the discrete electronics across the full energy range measured in the EEEMCal DESY beam test.
> - ➢ The modest resolution at low energy is likely dominated by the beam-energy spread and will be verified in a future beam test at a low-energy facility.

Documentation

epic-TN-TC-2026-007

ePIC backward ECal beam test

H2GCROC readout

J. Bettane[1], L. Bucuru Rodriguez[1], V. Chaumat[1], E. Cline[2,3], J. Crafts[4], M. Czeller[5], C. de La Taille[6], C. Delafosse[1], P. Dinaucourt[6], C. Domingues Goncalves[1], F. Dulucq[6], P. Dumas Ziehlmann[6], R.H. Fatemi[7], J. Frantz[8], B. Geoffroy[1], D.K. Hasell[2], A. Hoghmrtsyan[9], T. Horn[4,10], M. Imre[1], L.D. Isenhower[11], S. Jia[12], C.-T. Kuan[1], O. Le Dortz[13], Y. Le Roux[13], H. Marukyan[9], B. Mathon[1], A. Migayron[1], R.G. Milner[2], H. Mkrtchyan[9], C. Muñoz Camacho[1], G. Nagy[5], M. Nguyen[13], T. Nguyen Trung[1], N. Novitzky[14], S. Obraztsov[13], S. Olmo[1], T. Protzman[15], R. Reed[15], A. Shatat[13], V. Tadevosyan[9], D. Thienpont[6], and G. Visser[16]

Analysis note

zenodo.org/records/21909894

ePIC Technical Note epic-TN-TC-2026-007

Raw data

doi.org/10.5281/zenodo.21859699

DESY beam-test dataset on Zenodo

Analysis code

Reconstruction and analysis repository

github.com/carlosmunozcamacho/DESY_BeamTest_Dec2025

Version used for this work (v.1.0.0) archived at: doi.org/10.5281/zenodo.21859338

Outlook

RARiS beams momentum spread

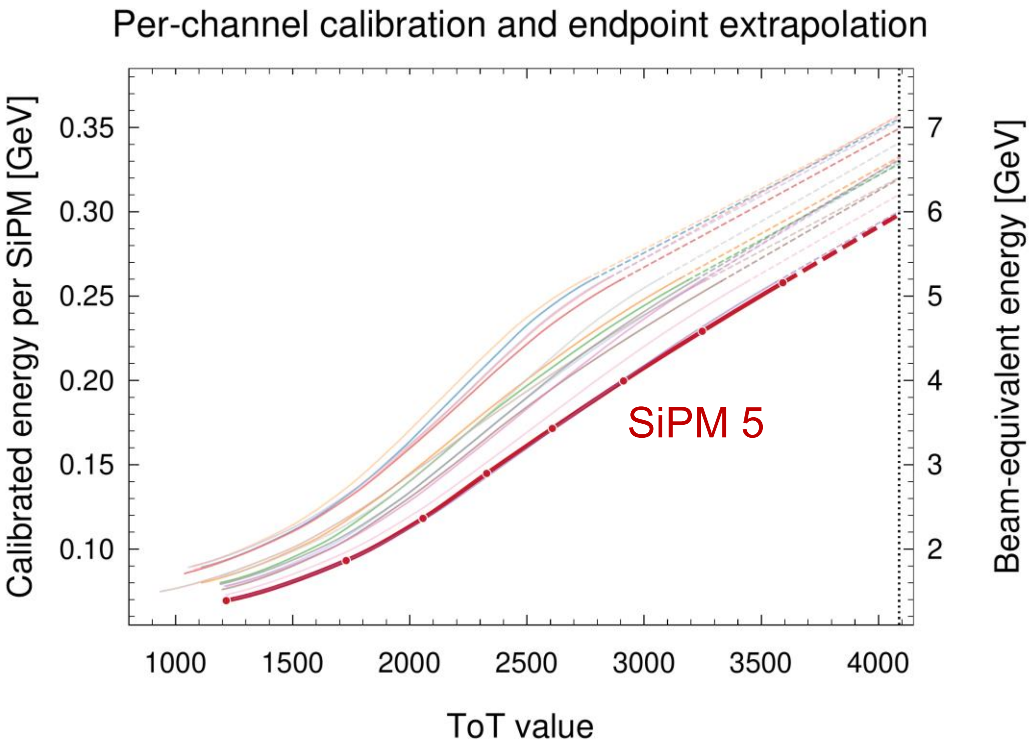
I (A)	x_{PS} 制限なし μ_P (MeV/c)	σ_P (MeV/c)	σ_P/μ_P (%)
025	47.18(2)	5.48(1)	11.63(3)
050	98.19(4)	4.92(3)	5.01(3)
075	148.22(4)	4.77(2)	3.22(2)
100	197.94(3)	4.91(2)	2.48(1)
125	247.79(3)	5.00(2)	2.02(0)
150	297.30(2)	5.29(2)	1.78(0)
175	346.81(2)	5.31(1)	1.53(0)
200	395.90(2)	5.55(1)	1.40(0)
225	444.56(2)	5.73(1)	1.29(0)
230	454.25(2)	5.74(1)	1.26(0)
250	492.50(2)	5.83(1)	1.18(0)
275	539.29(2)	6.00(1)	1.11(0)
300	584.59(2)	6.17(1)	1.06(0)
325	628.06(2)	6.32(1)	1.01(0)
350	669.20(2)	6.45(1)	0.96(0)
375	706.61(2)	6.58(1)	0.93(0)
400	739.16(2)	6.71(1)	0.91(0)
425	768.86(2)	6.87(1)	0.89(0)
450	796.60(2)	6.89(1)	0.87(0)
475	823.26(2)	7.01(1)	0.85(0)
500	849.10(2)	7.08(1)	0.83(0)

- Upcoming beam test at RARiS (Tōhoku, JP) , Dec 7-11 (2026) to check low energy performance
  - RARiS: 850 MeV e-/e+ beams with <1% momentum spread
- CALOROC chips + DAQ should be available by then
  - We should be able to test performance of CALOROC 1B and compare to H2GCROC (CALOROC 1A)
- Continue tests on the bench (with LEDs) to characterize CALOROC (1A & 1B)

Investigating also possibilities of low-energy beam test at Mainz (in 2027)

Back up

Dynamic range



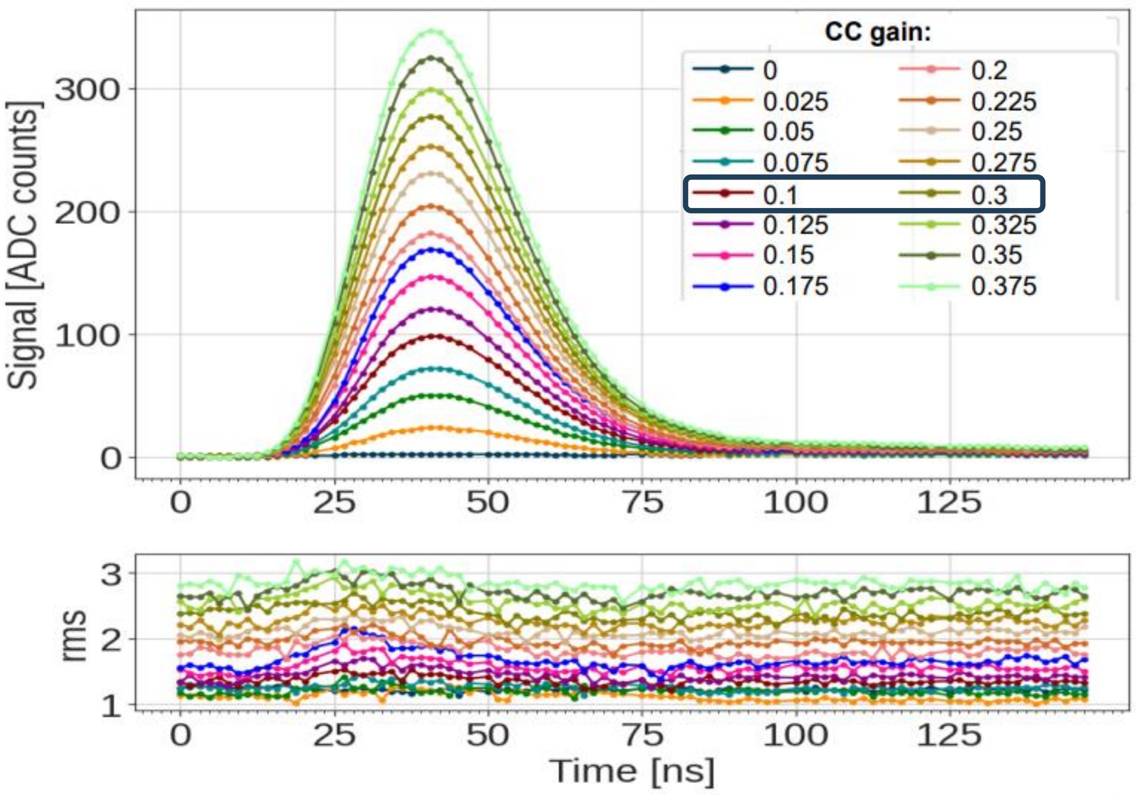
- **Full dynamic range of HGCROC tested at DESY**
- DESY setup adjusted for a 6-7 GeV dynamic range
- The additional factor of 3 needed for EIC can be adjusted by modifying the CC factor from 12 (DESY config) to 4 (and still room available for attenuation if needed).
- Resolution may worsen if dynamic range is extended

Several scenarios:

- Optimistic: noise is attenuated with the signal → resolution unchanged
- Pessimistic: noise stays the same while signal is attenuated
- Reality: S/N depends on the CC setting

Electronic noise: CC gain dependence

CC gain scan:



CdLT FCC-France 24 nov 23

- Bench scan shows that the noise itself does decrease when the current-conveyor attenuation is increased:

Noise from CC=12 to CC=4: 2.35 →1.33 ADC

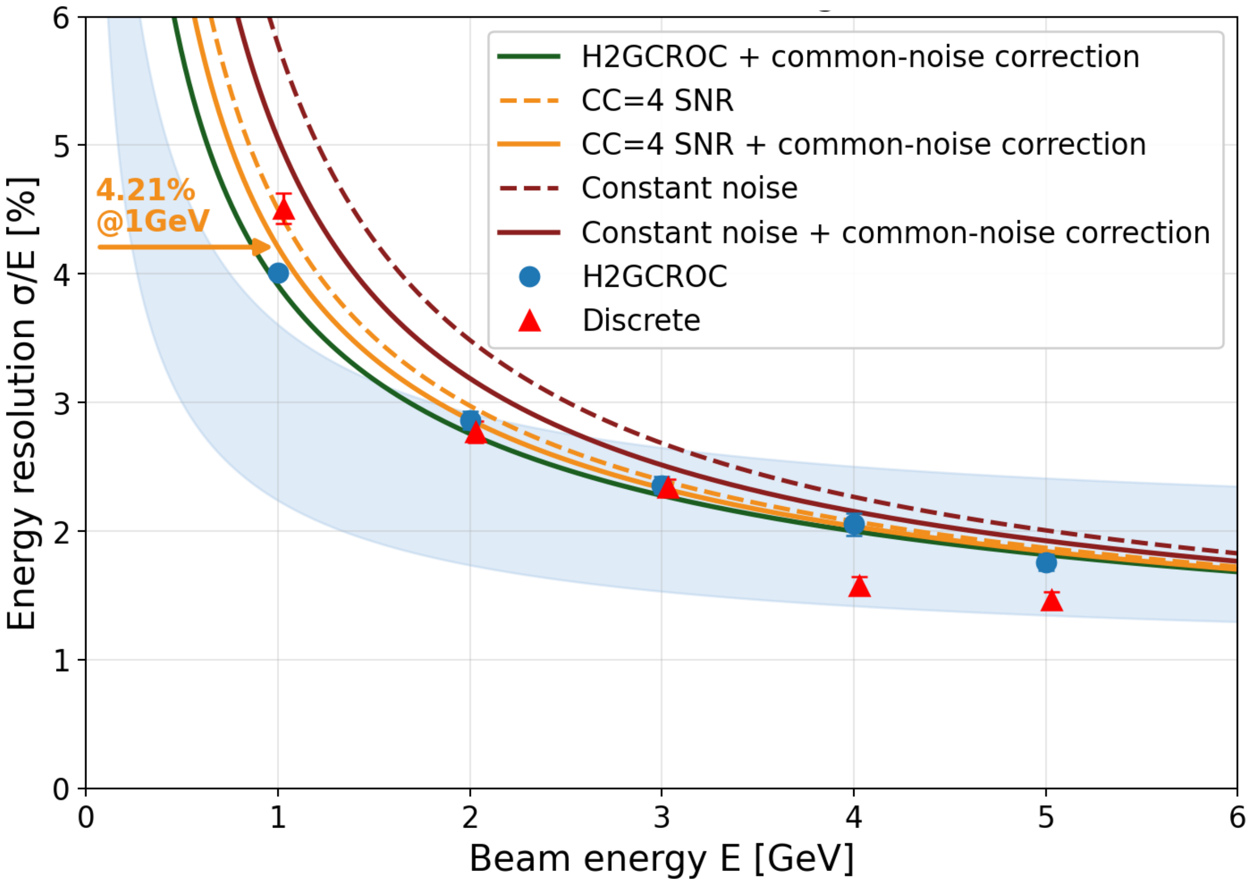
- The signal is reduced by a factor of ~3. So the noise reduction does not completely compensate for the signal loss:

SNR(CC=4) / SNR(CC=12) ≈ 0.6

Resolution projection model

$$\sigma/E = \sqrt{A^2 + B^2/E + (N/E)^2}$$

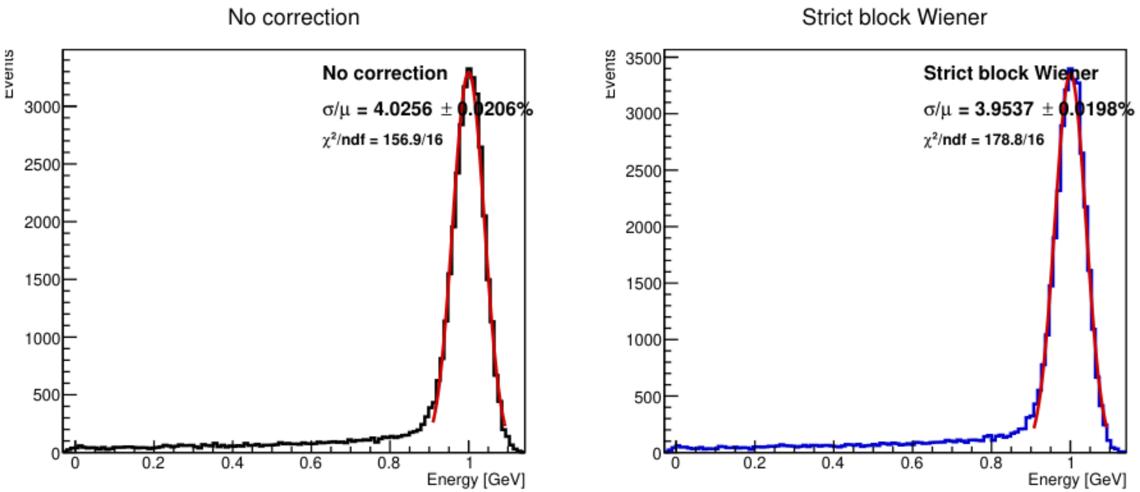
- A = 0.74% and B = 3.7% fitted to DESY test-beam data
- N = 14.7 MeV fixed using pedestal run
- Projection curves keep A and B fixed, then replace N with the scenario-dependent noise term
- Common-noise-corrected curves use N=11.3 MeV instead of 14.7 MeV before applying the SNR



Common-noise-corrected 1 GeV projection: 4.0 → 4.2%

Common-noise subtraction

- For each cluster crystal, average the 16 channels at samples 0, 1, and 2.
- Build three pulse-free features per crystal: level, slope, and curvature.
- Nine crystals × three features gives 27 predictors for the 3×3 cluster.
- Fit a ridge/Wiener estimator on pedestal data to predict the correlated electronics fluctuation.
- Subtract the predicted fluctuation once from the full calibrated cluster signal, not channel-by-channel.

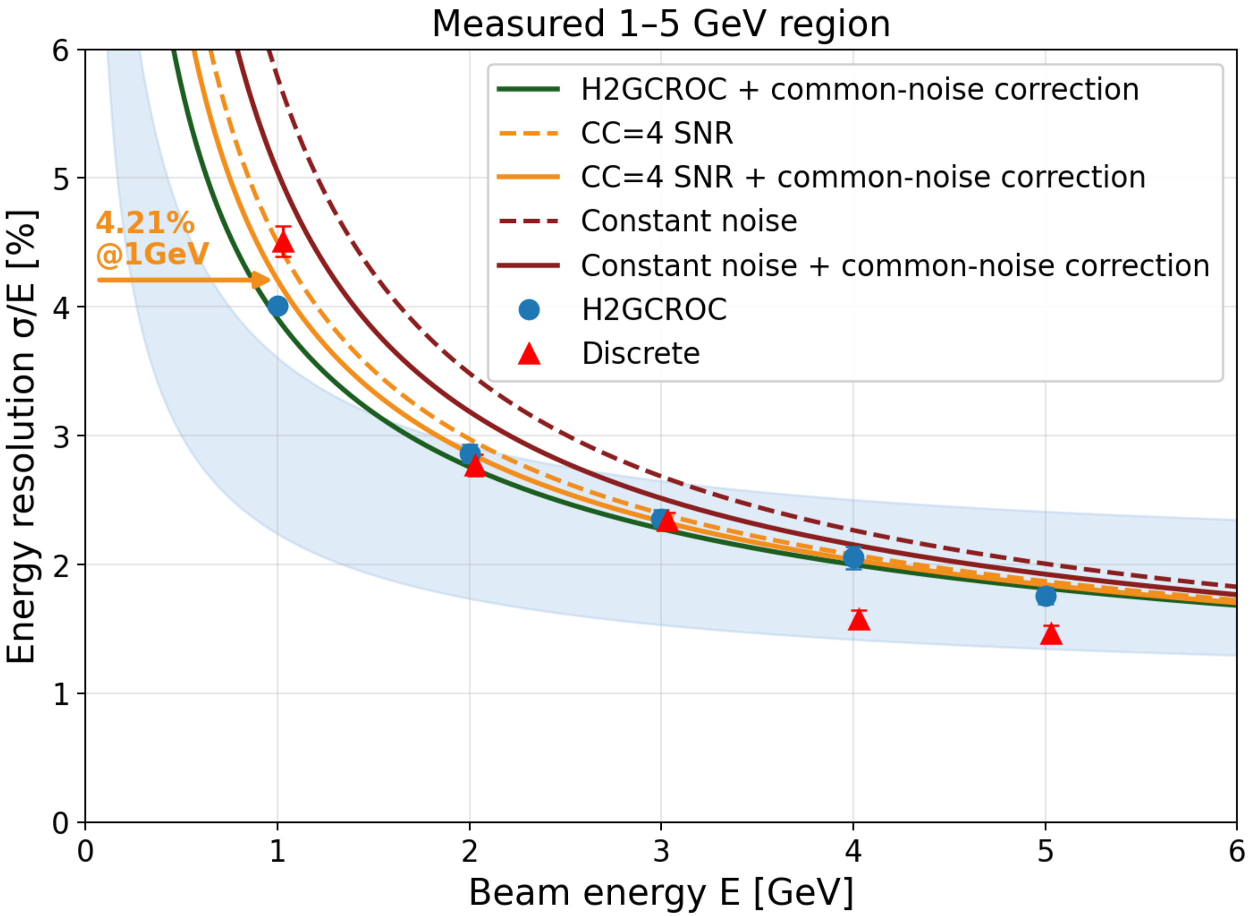


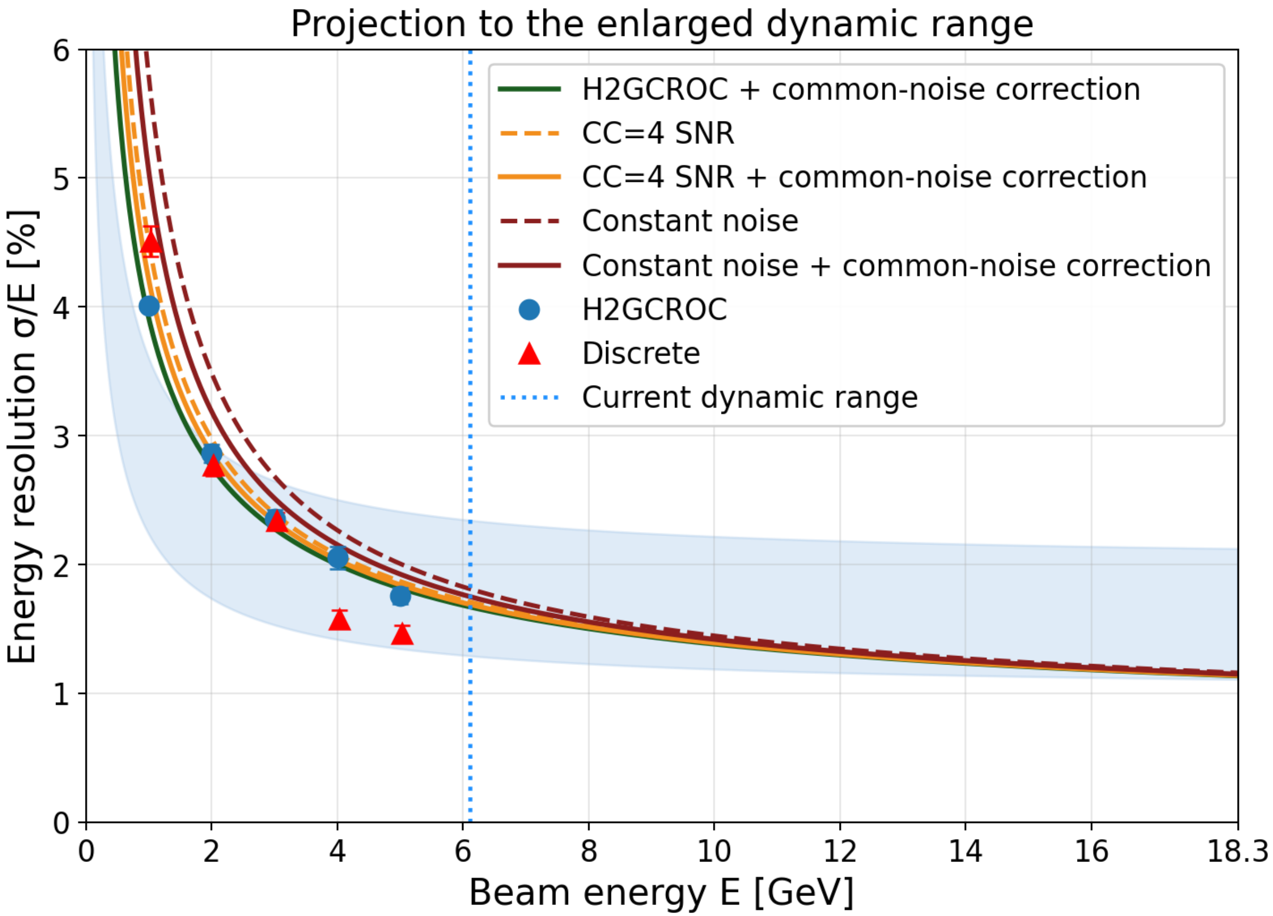
Measured pedestal effect

Full cluster noise: 14.7 MeV → 11.3 MeV

RMS reduction: 23.3%

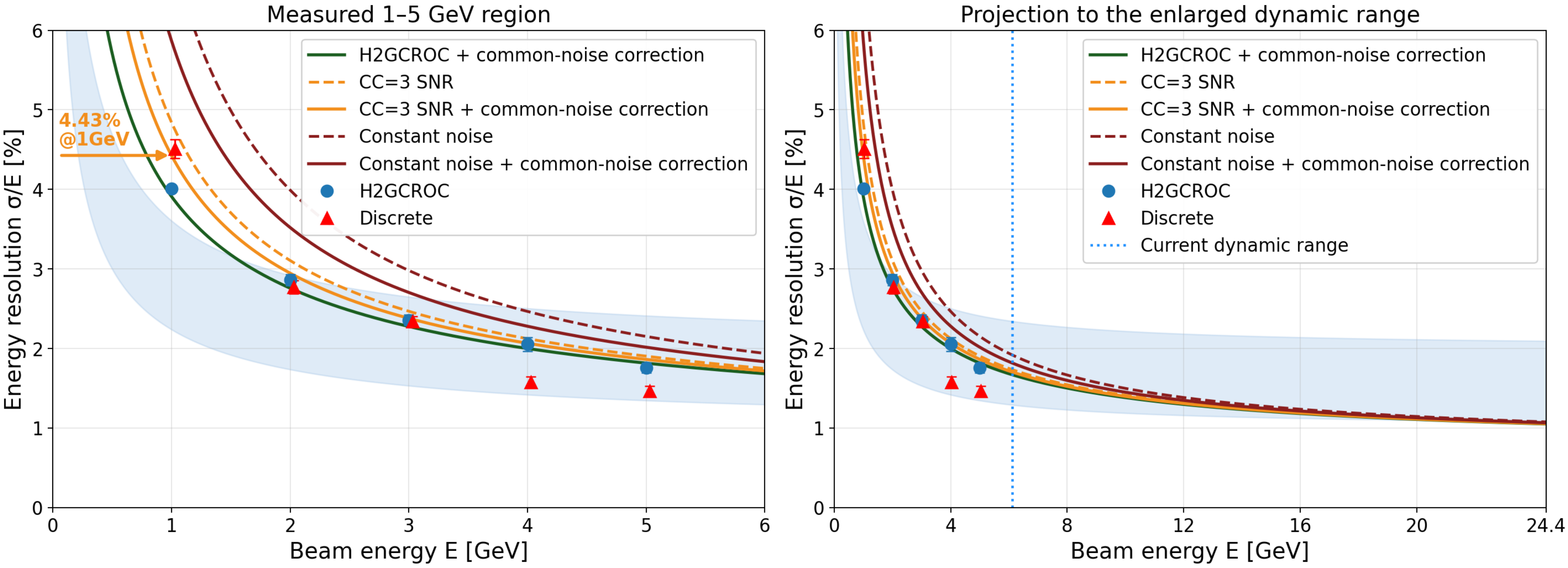
Projection for CC=4





Common-noise-corrected 1 GeV projection: 4.0 → 4.2%.

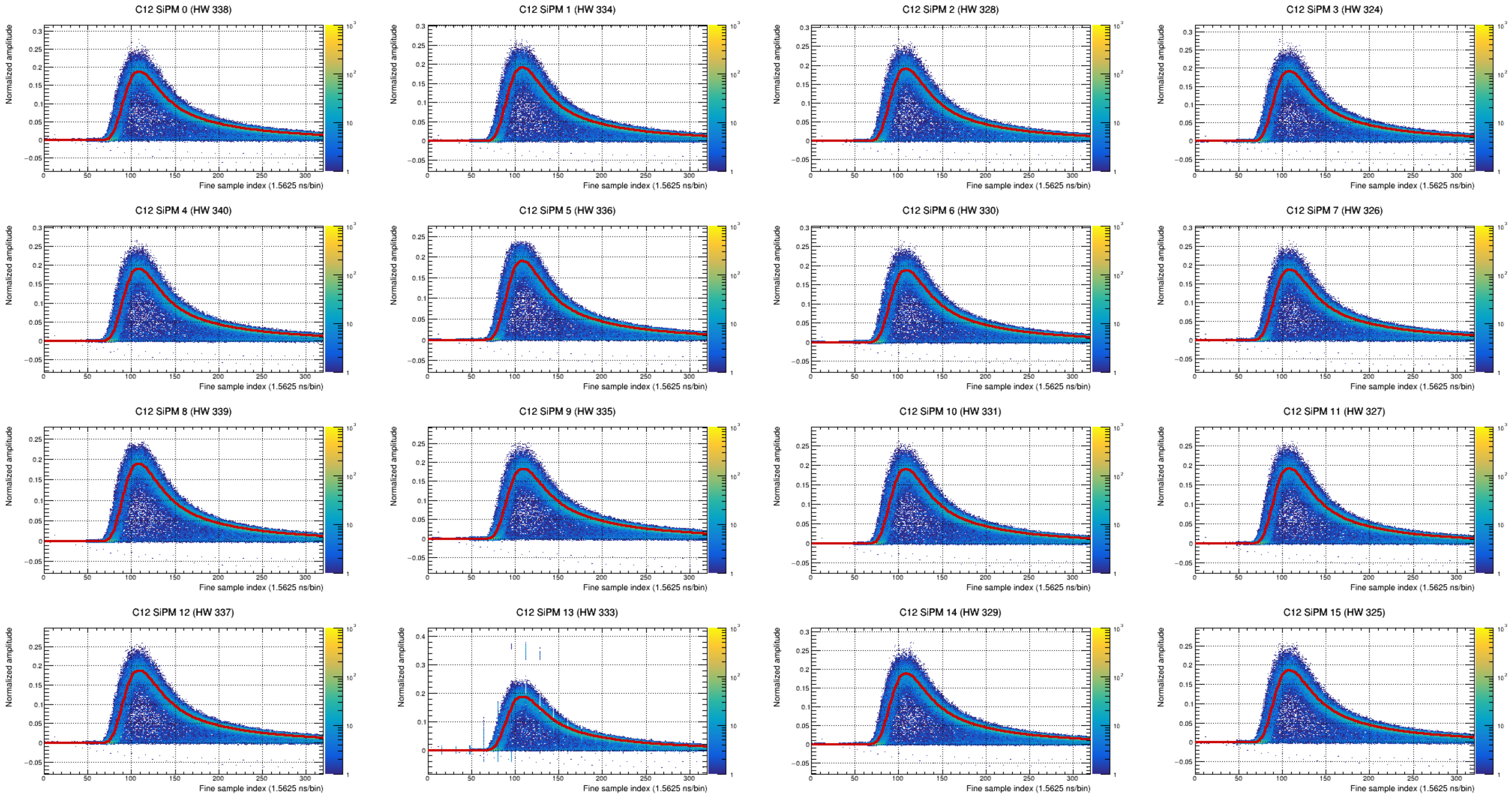
Projection for CC=3



Common-noise-corrected 1 GeV projection: 4.0 → 4.4%.

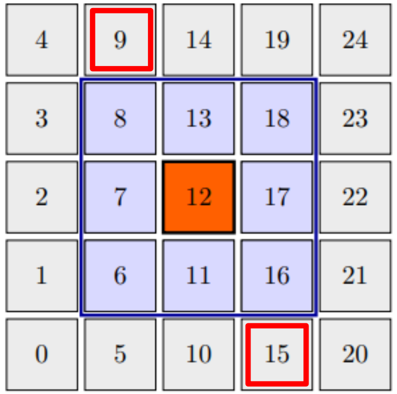
Phase scans

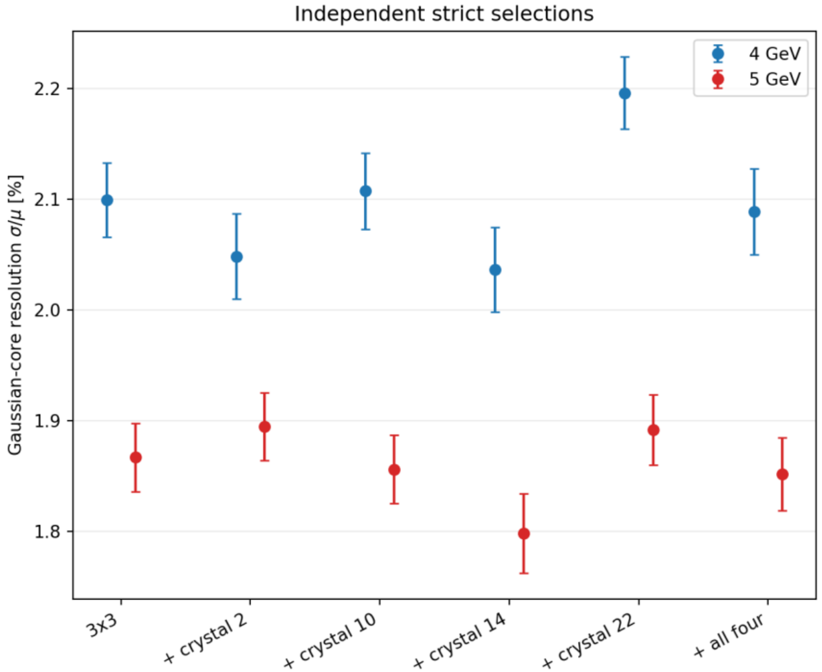
Normalized: pulse shape

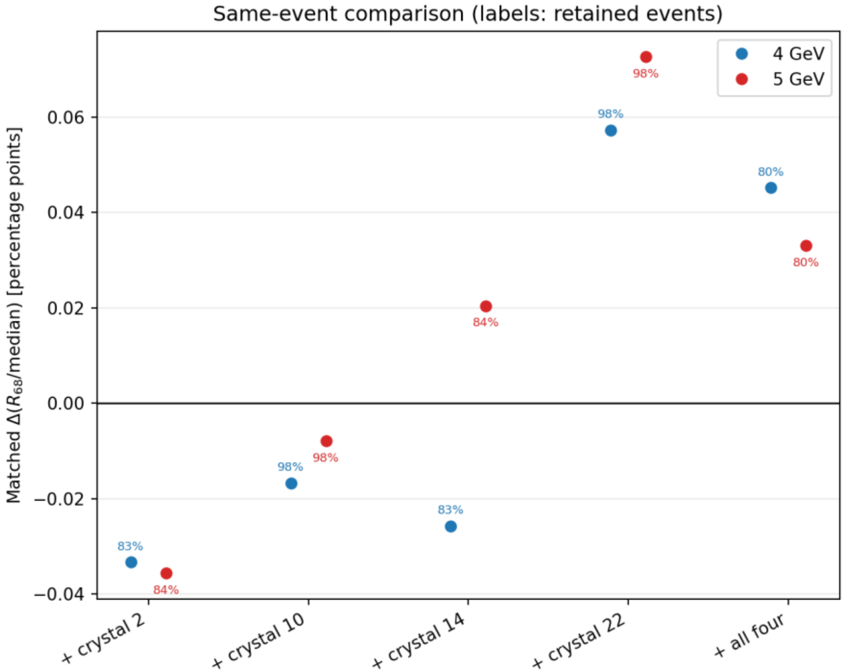


16 phases sample the 25 ns clock period in 1.6 ns steps

High-energy scans favor fixed 3×3







Why keep the baseline?

- Wider [5,14] or [3,16] neighbor windows worsen 2-3 GeV
- A safe 13-crystal sum gives no energy-independent gain
- Outer additions change the selected event population

Retain fixed 3×3 with [6,9] ADC neighbors.