A prototype electromagnetic calorimeter for the MUonE experiment: status and first performance results

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Overview

- Subject of this talk is the MUonE experiment at CERN
  - focusing on its prototype Electromagnetic Calorimeter (ECAL)
  - more information on MUonE will be presented in:
    - David Monk, *25 August 2023 15:10, Hörsaal B:* ***The MUonE DAQ: Online Track-finding and Event Selection in Hardware at 40 MHz****.*
    - *Andrea Gurgone , 25 August 2023 16:00, Hörsaal M:* **Theory for the MUonE experiment**
    - Riccardo Pilato, *25 August 2023 16:15, Hörsaal M:* ***The MUonE experiment: mu-e elastic scattering as a key to understand the muon g-2 puzzle***
- Motivation: discrepancy on the theory vs experiments for muon anomalous magnetic moment
- Principles of measurement
- Apparatus and its current status
- ECAL
- Outlook

Lepton anomalous magnetic moment

- The lepton anomalous magnetic moment (produced by quantum fluctuations), is defined as $a_l = \frac{\boldsymbol{g}-2}{2}$, $(\vec{\mu} = \boldsymbol{g}\frac{e}{2m}\vec{S})$

Aoyama, Kinoshita & Nio, Atoms 7 (2019) 1.

Mohr et al., CODATA 2018, posted online 20 May 2019, to be published.

- Dirac's predicts a value of $g = 2$.
- The electron magnetic anomaly is predicted very well by the Standard Model:

$$a_e = \begin{cases} 0.001\,159\,652\,181\,61\,(23) & [\text{SM}, (\alpha/\pi)^5 \text{ order}] \\ 0.001\,159\,652\,181\,28\,(18) & [\text{experiment}, 0.16 \text{ ppb}] \end{cases}$$

- Because $(m_\mu/m_e)^2 \sim 4 \times 10^4$, the muon anomaly is more sensitive to BSM effects from heavy particles contributing to quantum loops.

Muon anomalous magnetic moment

- a_μ is a superb probe of the vacuum, i.e., of new physics if it exists.

a_μ term	Value($\times 10^{-11}$)	uncertainty
QED	116,584,718.931	0.104
El-weak	153.6	1.0
HVP	6,845	40
HLbL	92	18
Total SM	116,591,810	43

g-2 Theory Initiative Whitepaper :
Phys. Rep. 887 (2020) 1

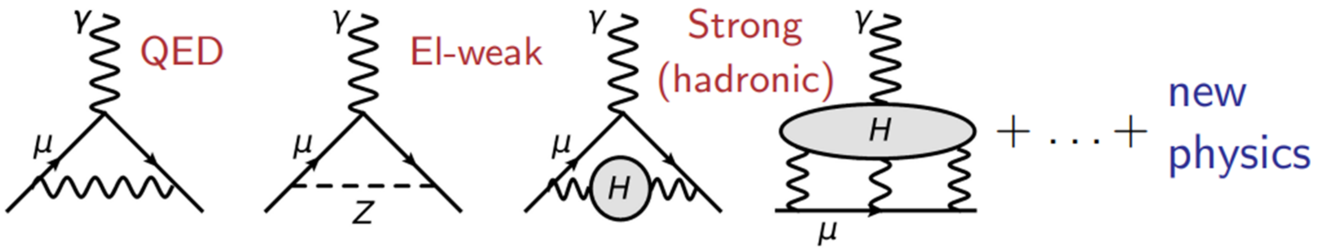
HVP-LO	6931(40)
HVP-NLO	-98.3(7)
HVP-NNLO	12.4(1)

- Cannot be calculated perturbatively
- Driven by LO hadronic vacuum polarization

Hadronic Vacuum Polarization leads the Standard Model uncertainty (cannot be calculated perturbatively).

$$a_\mu^{SM} = a_\mu^{QED} + a_\mu^{EW} + a_\mu^{HVP} + a_\mu^{HLbL}$$

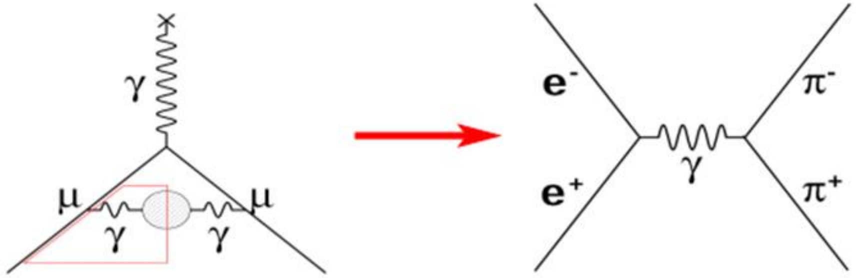
Leading order contributions to a_μ



a_μHVP

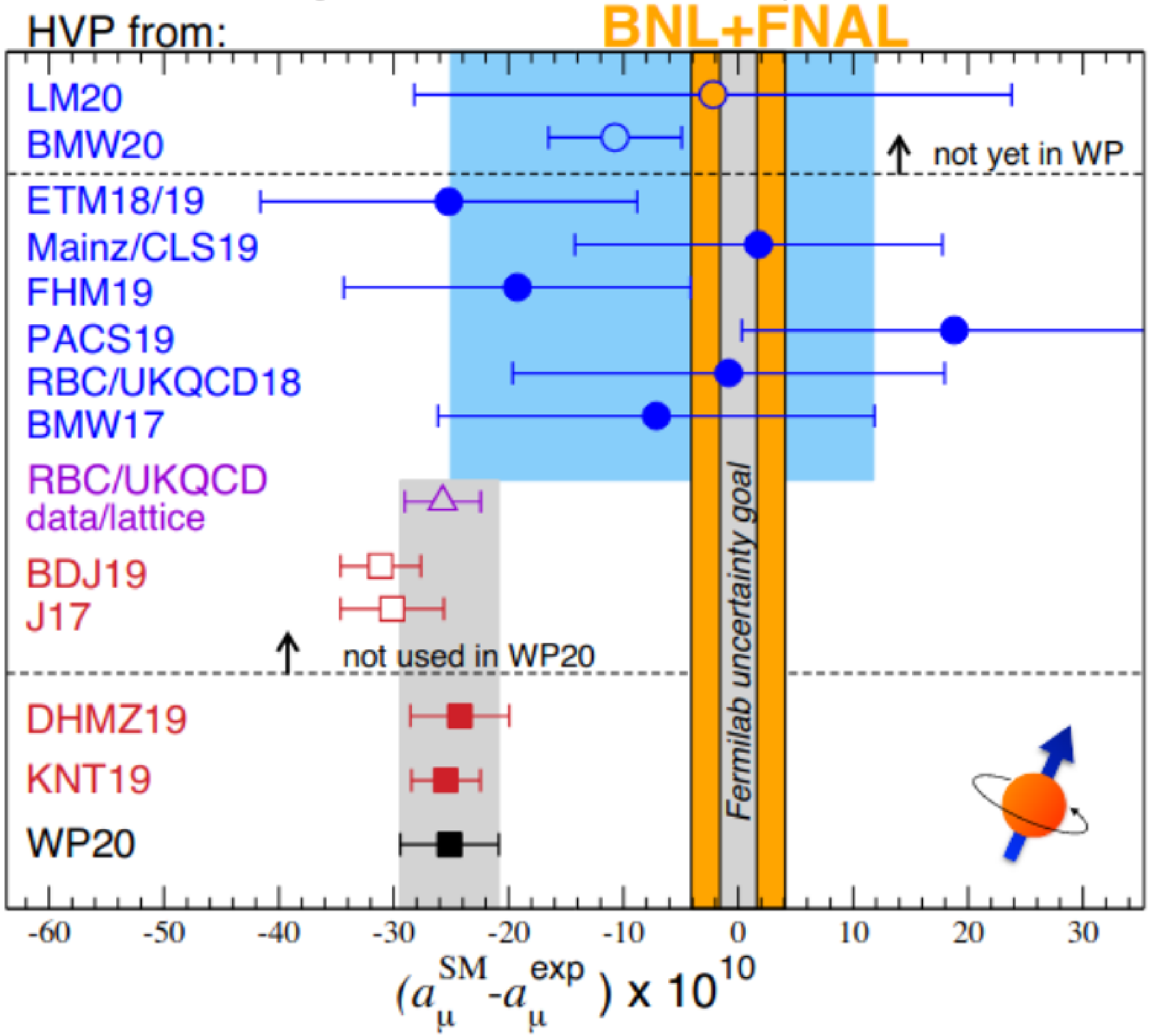
- A clear discrepancy in $a_\mu$between theory and experiment (mainly coming from HVP)
- Three possible ways to determine a_μHVP:
  - Theory (lattice QCD)
  - Data driven:
    1. Time-like
    2. Space-like (MUonE)

In time-like process we usually measure:



Most of the HVP is determined based on measurements of:
$e^- e^+ \to \pi^-\pi^+ \,/\, \pi^-\pi^+\pi^0 \,/\, \pi^0\gamma$

Muon g – 2: A review, Nuclear Physics B, 2022.



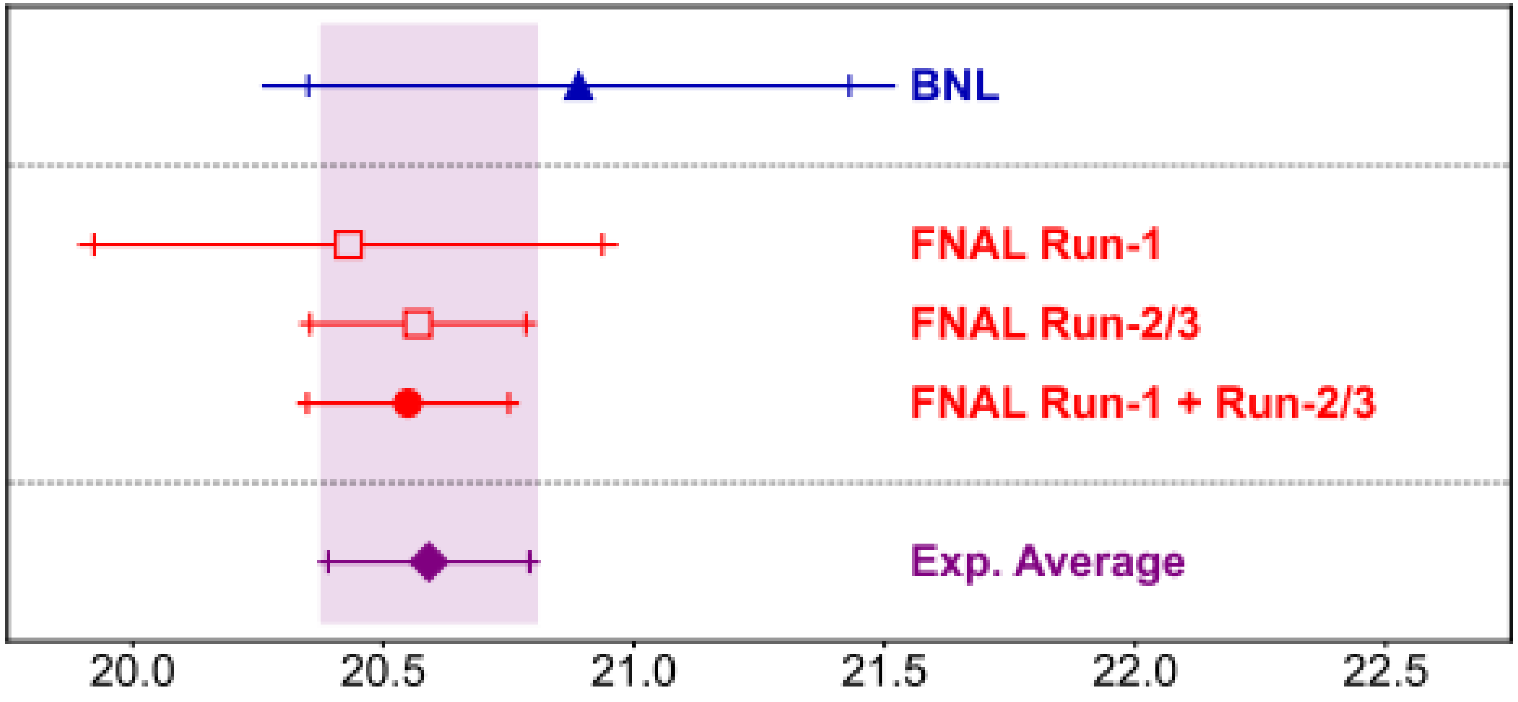
Circles—lattice, Squares—data driven

a_μ: $g - 2$ *new results*

- The new measurement of a_μ at Fermilab is consistent with earlier experimental values and is 5.1σ away from the old 2020 Theory Initiative White Paper value, which is now in question..

- Complementary and precise new experiments are needed to understand discrepancies from SM.

Measurement of the Positive Muon Anomalous Magnetic Moment to 0.20 ppm, arXiv:2308.06230



The combined (BNL and FNAL) experimental (Exp) average becomes:

$$a_\mu = 116592059(22) \times 10^{-11} (0.19\ ppm)$$

The MUonE experiment: a space like approach to HVP

- The novel approach, proposed by MUonE, bypass the challenging part of data driven calculation, i.e. integration of hadronic cross section.
- The task is reduced to a measurement of the change (running) of the effective fine structure constant
- in a single scattering process μ + e → μ + e:

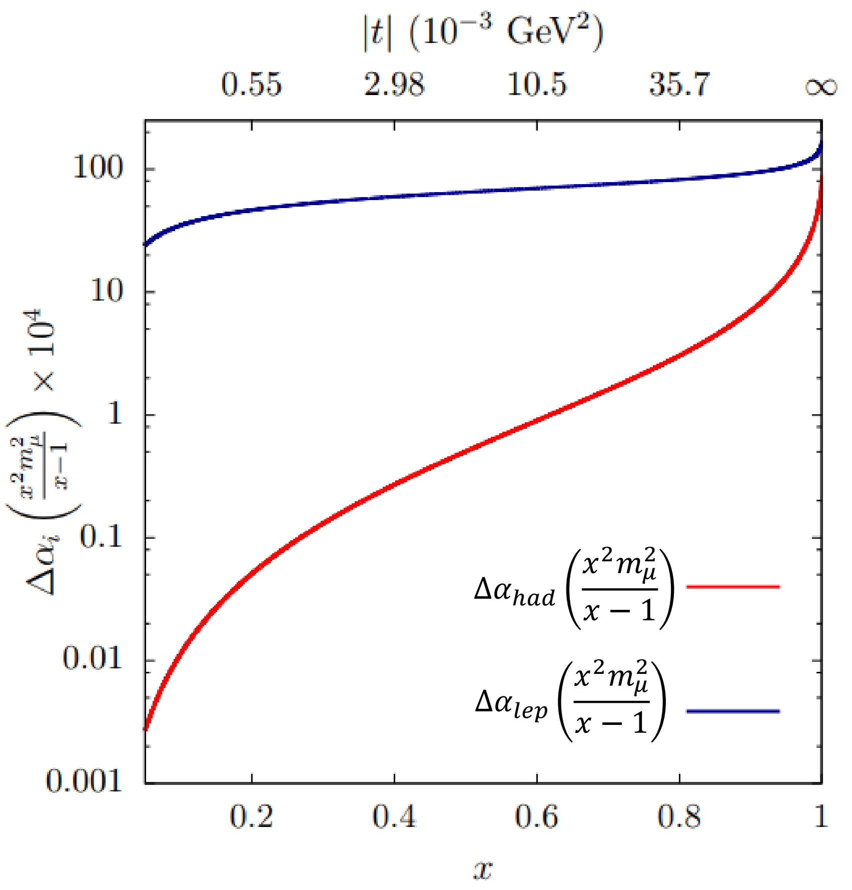
$$a_\mu^{HLO} = \frac{\alpha}{\pi}\int_0^1 dx(1-x)\Delta\alpha_{had}[t(x)]$$

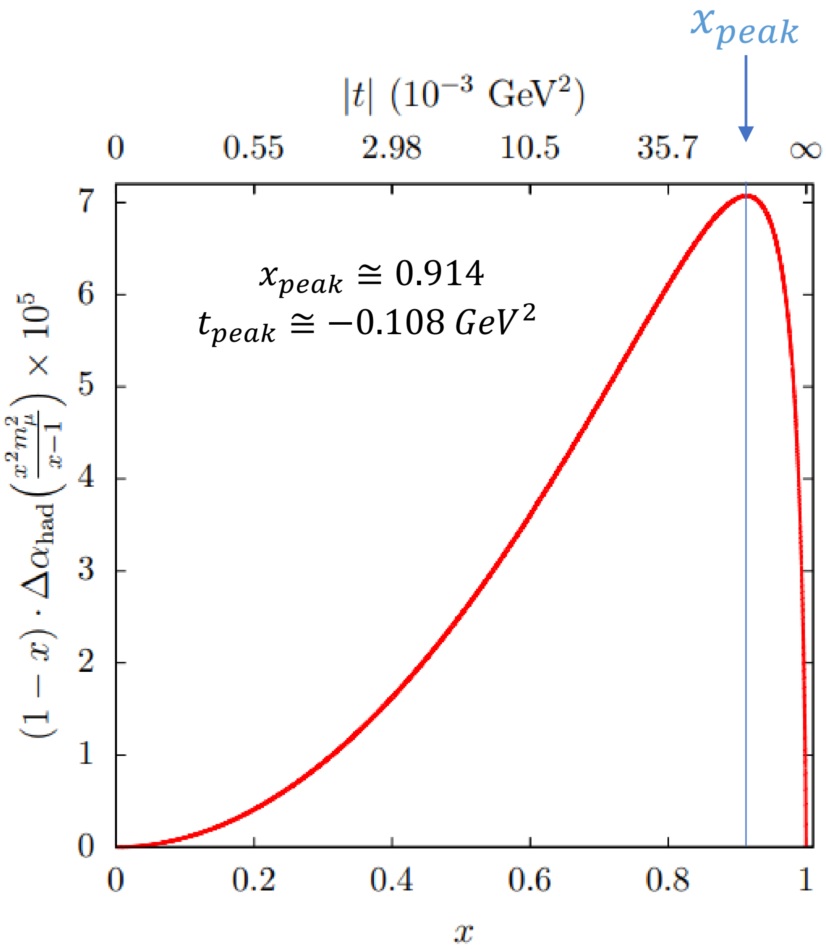
where $\Delta\alpha_{had}$ is the hadronic contribution to the running of α in the space-like region (t<0):

$$\alpha(t) = \frac{\alpha}{1-\Delta\alpha(t)}$$

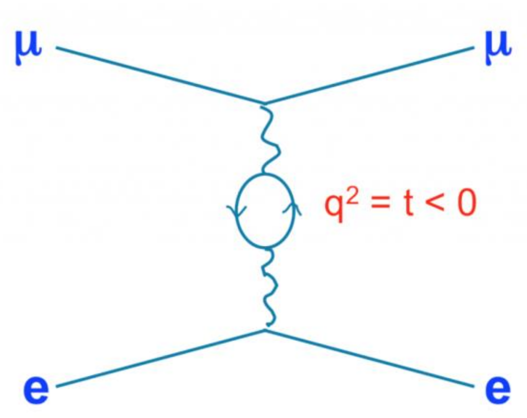
$$\Delta\alpha = \Delta\alpha_{lep} + \Delta\alpha_{had}$$

$$t = \frac{x^2 m_\mu^2}{x-1} < 0$$





$\mu - e$ scattering process



$$\mu + e \rightarrow \mu + e$$

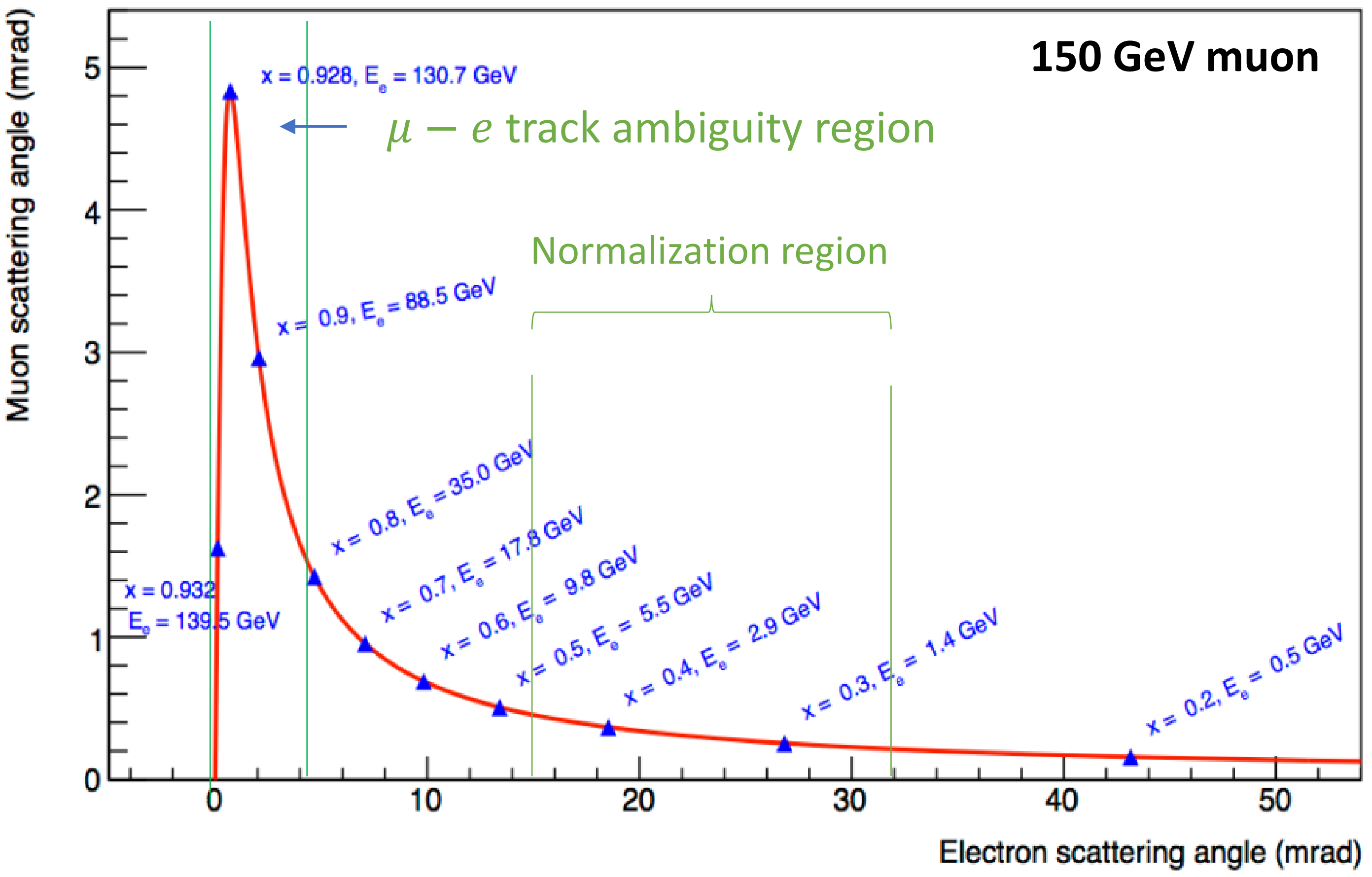
$$\frac{d\sigma_{data}/dt}{d\sigma_{MC}^{no\,VP}/dt} = \frac{1}{\left|1 - \Delta\alpha_{lep}(t) - \Delta\alpha_{had}(t)\right|^2}$$

Theory

To be measured by MUonE

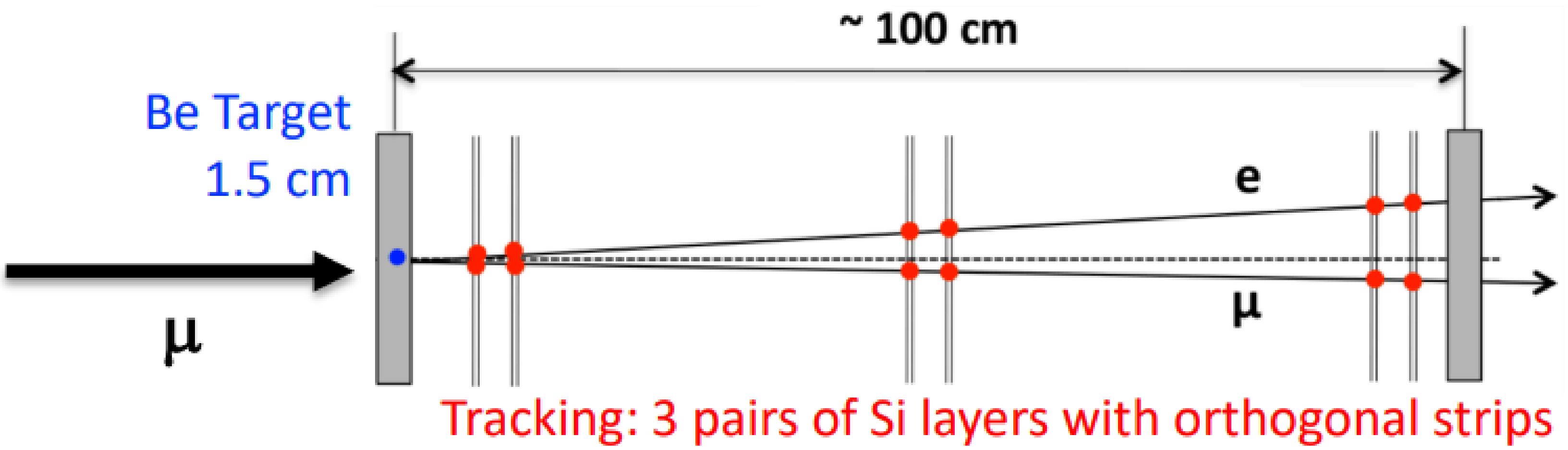
- System boosted;
  - Will cover entire area of: $\theta_e < 32\ mrad$ and $\theta_\mu < 5\ mrad$
- The integrand (x < 0.936) , will cover 88% for incoming μ ≃ 160 GeV (with the remaining being extrapolated)

Eur. Phys. J. C (2017) 77:139

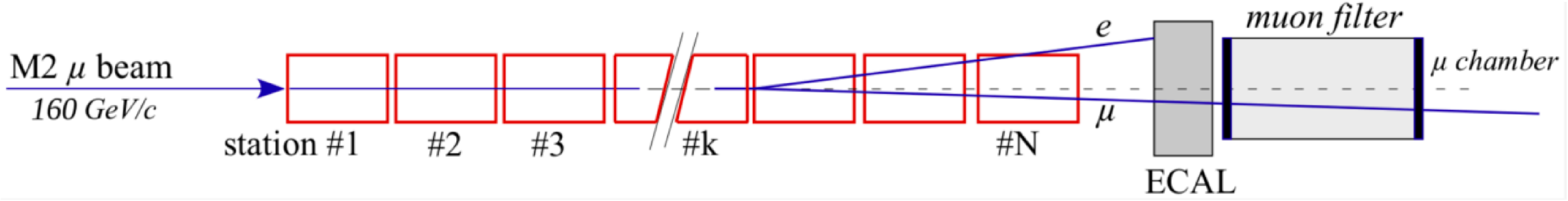


The relation between the muon and electron scattering angles for 150 GeV incident muon beam momentum. Blue triangles indicate reference values of the Feynman's x and electron energy

MUonE detector setup



The simplicity of the detector will keep the systematics low



MUonE final 40 tracking stations are planned in total (each w/ 1.5 cm Be target), but the modular design allows for flexibility and running in stages. MUonE will be utilizing the M2 line at CERN (160 GeV muons)

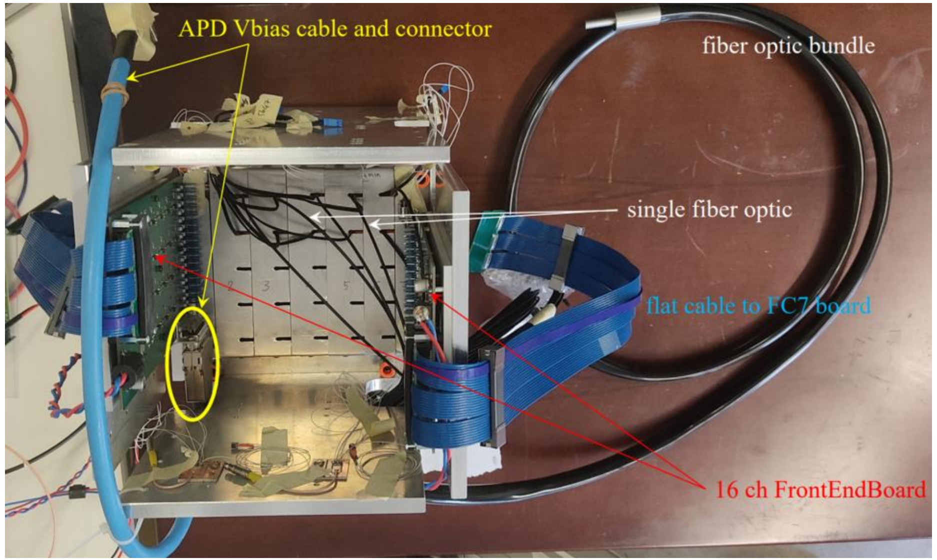
Electromagnetic calorimeter (ECAL)

- The ECAL (coming from CMS endcap calorimeters) consist of:
  - 5×5 $PbWO_4$ crystals (individual crystal cross section $2.85 \times 2.85\ cm^2$)
  - Total cross section $14.25\ cm^2$
  - APD readout sensors

- Currently testing a small prototype, depending on results we will fix the size of the final proposed ECAL

- Purpose of ECAL in MUonE:
  - Select elastic events by breaking the $\mu - e$ track ambiguity; check on E_{dep} inferred from track angles.
  - Background estimate and reduction
  - assess systematic errors

- PID necessary on regions of ambiguity (tracker can't distinguish between μ or e); can be solved by extrapolation of tracker + ECAL + muon detector.



ECAL expected energy resolution

- MUonE ECAL uses same APDs type as CMS (but different size ; 10mm x 10 mm).
  - affects the observed signal, i.e., the energy resolution.
  - C = 270 pF -> expect 9 pe/MeV

- rms noise $\approx 4.00\ ADC\ counts$ (single crystal).

- For 150 GeV electrons, 9 pe/MeV, and an APD gain of 50 (single crystal):

$$150{,}000 \times 9 \times 50\ e = 6.75\ 10^{8} e \approx 28{,}723\ ADC\ counts$$

- The system noise should be dominated by the MGPA.
  - This will determine the ability to identify beam muons whose signal value is only $\sim 700\ MeV$ at $150\ GeV$
  - estimates shown many times previously suggest an energy resolution of 5-7% at 700 MeV

CMS: MGPA specifications

Parameter	**Barrel**	**End-cap**
Full-scale signal	60 pC	16pC
Noise level	10,000 e, 1.6 fC	3,500 e, 0.56 fC
Input capacitance	~ 200 pF	~ 50 pF
Output signals (to match ADC)	Differential 1.8V, +/- 0.45 V around 1.25 V common mode voltage	
Gain ranges	1, 6, 12	
Gain tolerance (each range)	+/- 10%	
Linearity (each range)	+/- 0.1% full-scale	
Pulse shaping	40 ns CR-RC	
Pulse shape matching	< +/- 1%	

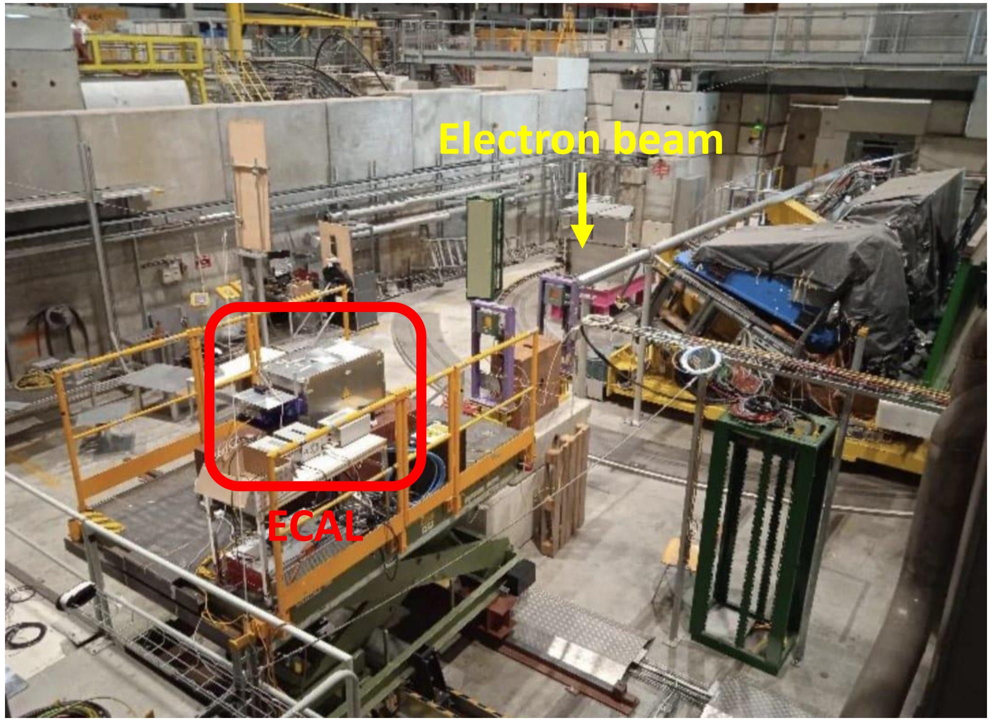
"The MGPA Electromagnetic Calorimeter Readout Chip for CMS"

MUonE test beam runs 2023

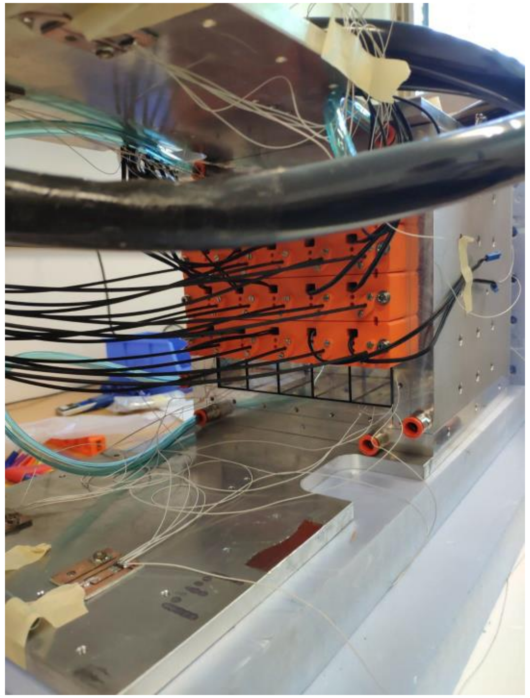
- A test in 2018 run with muons in the North Area at CERN, running parasitically downstream of the COMPASS spectrometer shown satisfactory agreement and demonstrated that measuring the angles of the outgoing particles, a clean sample of elastic interaction could be identified.
  - G. Abbiendi *et al* 2021 *JINST* **16** P06005
- calibration beam tests of the current prototype:
  - June 2023:
    1. ECAL test with electron energies ranging from 20-150 GeV, H2 beam line at CERN.
    2. ECAL test with electron energies ranging from 1-10 GeV, T9 beam line at CERN.

CERN T9

CERN H2



Back view of ECAL



June-2023 data: Preliminary analysis

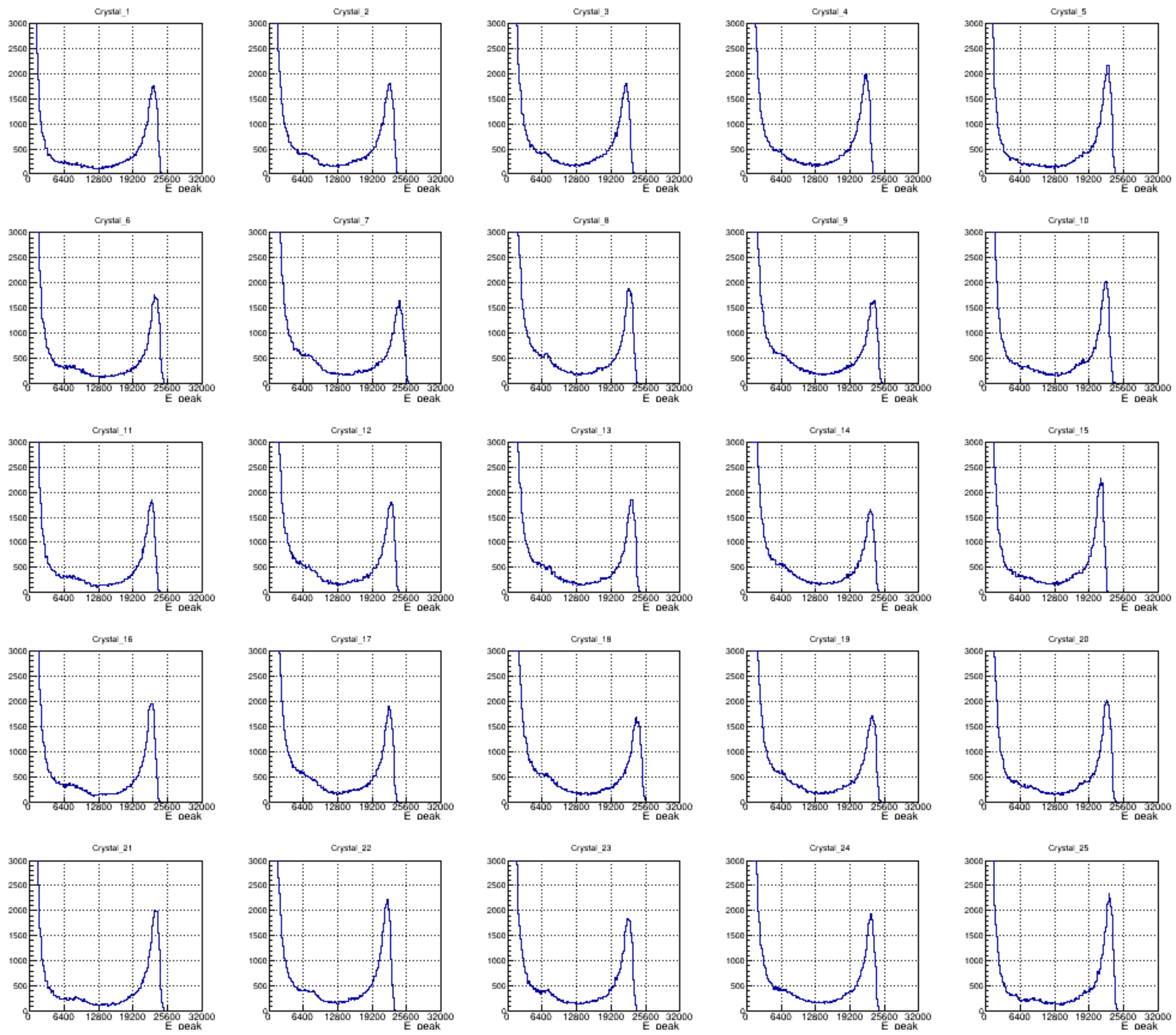
- APD voltages adjusted during June 2023 test beam to achieve individual gain match of 10% within the E_{mean}
- $27600\ ADC\ counts \cong 150\ GeV$
- Set up allows us to cover the necessary energy spectrum.

Back view of ECAL during test beam

Crystal no (bold) → | ← FEB channel no

1 2	**2** 1	**3** 30	**4** 31	**5** 32
6 4	**7** 3	**8** 27	**9** 28	**10** 29
11 7	**12** 6	**13** 5	**14** 25	**15** 26
16 10	**17** 9	**18** 8	**19** 23	**20** 24
21 13	**22** 12	**23** 11	**24** 21	**25** 22

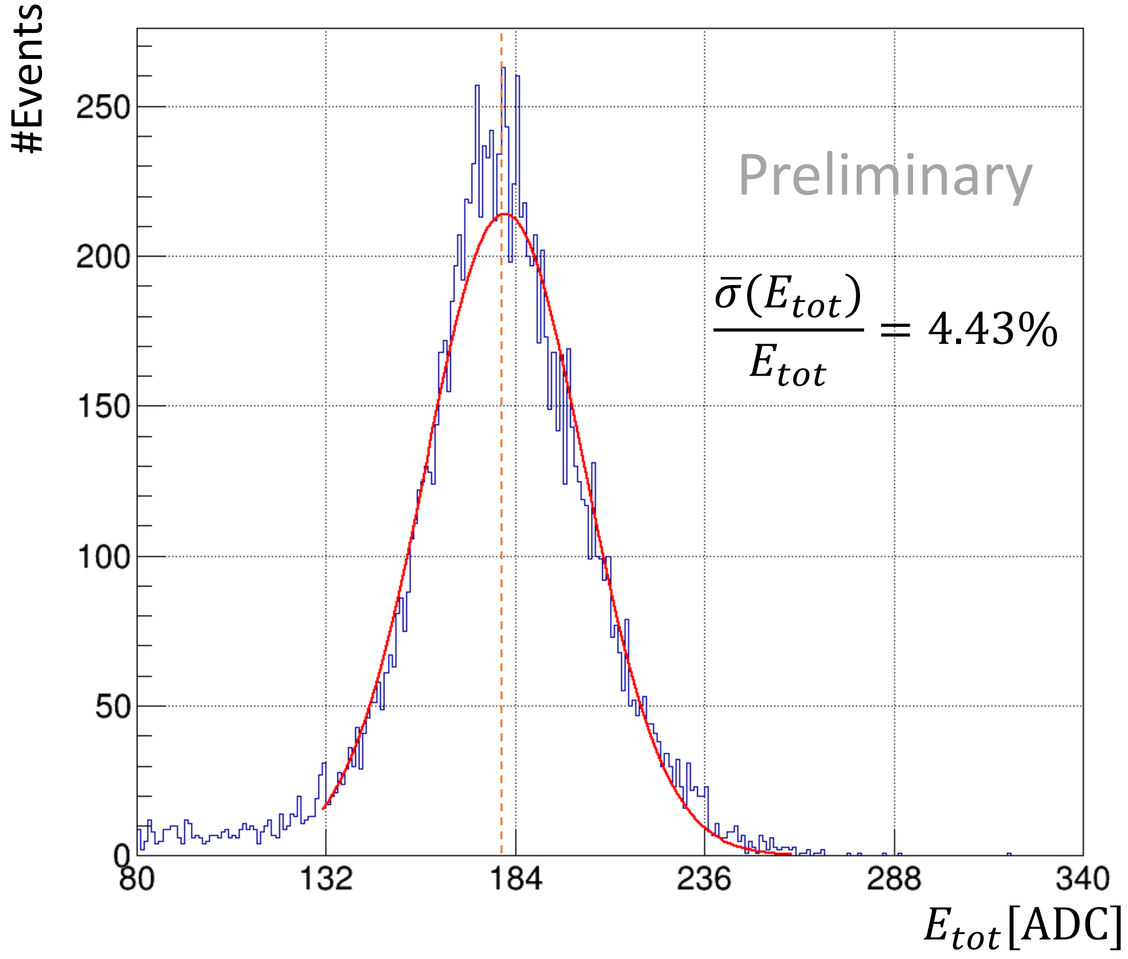
150 GeV electron (2500k events)



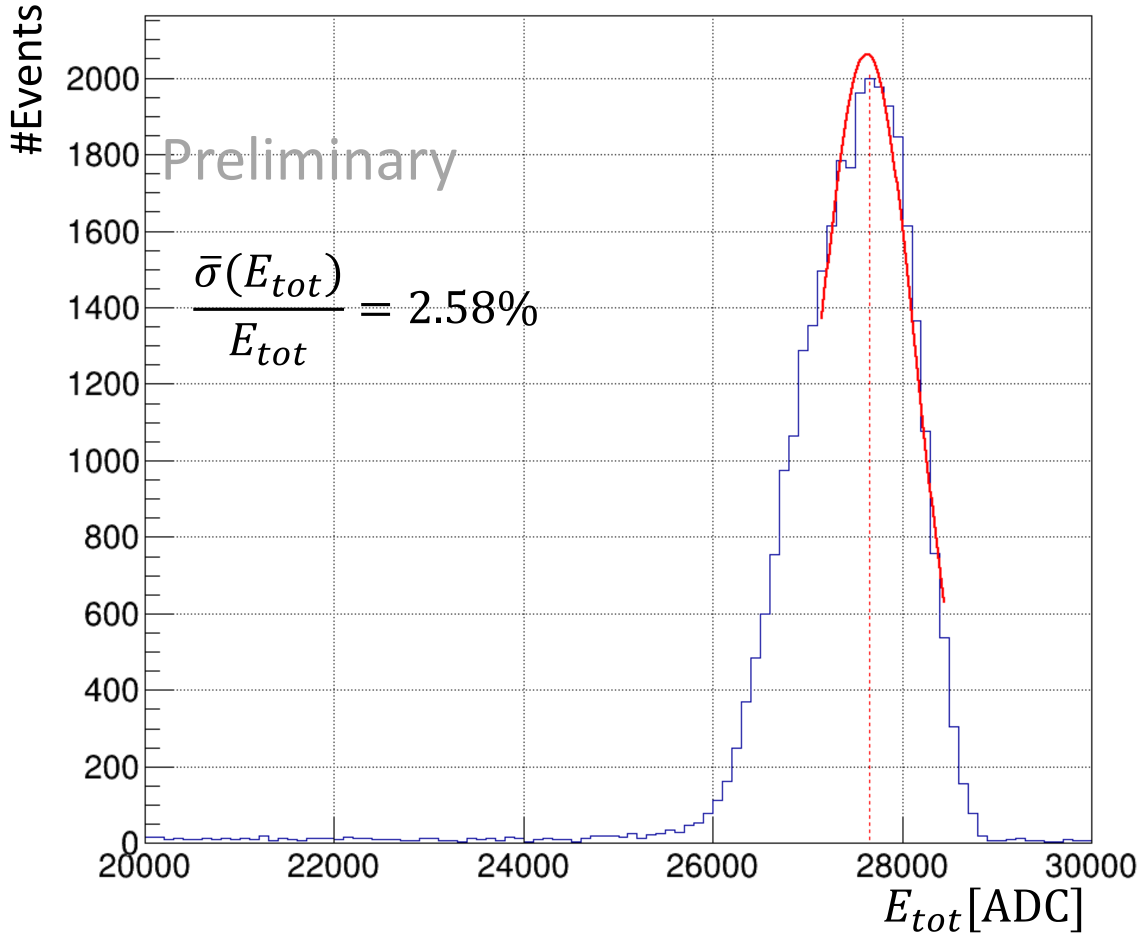
Individual energy distribution of all 25 crystals; x-axis is the energy deposit (0-32,000 ADCs), y-axis is the number of events.

June-2023 data: Preliminary analysis

FEB channel 5; 1 GeV electron



FEB channel 5; 150 GeV electron



- total energy distributions for single crystals in which the energy of a single crystal, i is at least $E_i > 0.70E_{tot}$
  - 1 GeV electron peaks $\sim 184\ ADC\ channels$
  - 150 GeV electron peaks $\sim 27600\ ADC\ channels$
- observed width is dominated by the beam momentum spread

Simulation ⟶ $\frac{\bar{\sigma}(E_{tot})}{E_{tot}} = \{0.9\%\ (1GeV), 0.32\%(150GeV)\}$

August/September 2023 test beam

- A Pilot Run is planned for the end of August beginning of September, this time with 2-3 fully instrumented stations.

    - Full integration of ECAL and tracker DAQ
    - Test a simplified on-line selection for data reduction in real time
    - Background study with final detector configuration
    - Test of global alignment
    - Study of beam energy calibration
    - Measurement of the leptonic running of α

Results will be used to prepare the full experiment proposal. Submission to the SPSC planned for 2024.

Conclusion and future

- The main source of error for anomalous magnetic moment of the muon comes from a_μ^{HLO}
- MUonE proposes a novel approach (space-like) independent from previous measurements.
- The addition of the ECAL can shine light to regions of ambiguity (between $\mu - e$), background estimate and reduction.
- The first preliminary results on ECAL data are helping us to understand its capabilities and increase its efficiency for upcoming new test beams
- A new test beam for the MUonE experiment is scheduled for August/September 2023 at CERN (2-3 tracking stations + ECAL).

Thank you!

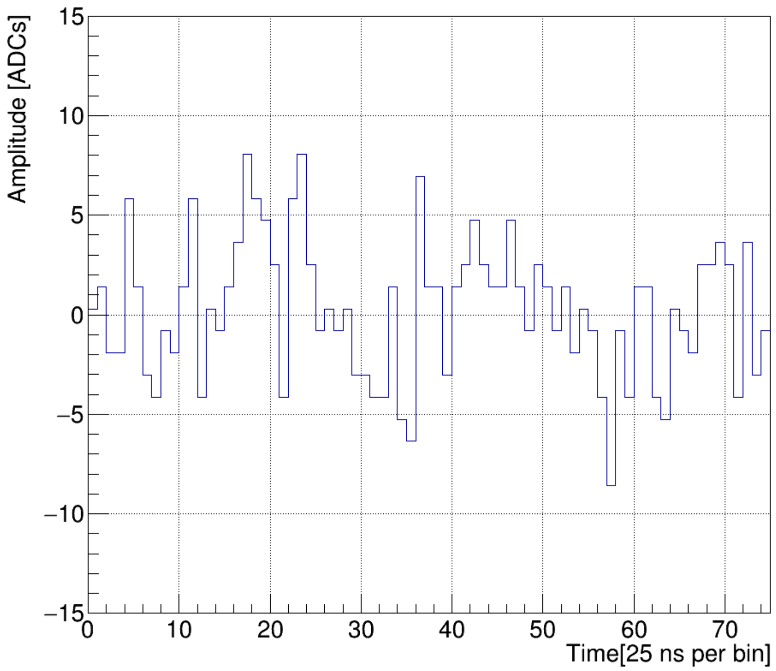

Being formed
still growing up
CERN
CERN
Exp-Th
INFN +Univ. (Bologna, Milano-Bicocca, Padova, Pavia, Perugia, Pisa, Trieste)
Exp-Th
Imperial College (London), Liverpool U. Durham U.
Exp-Th
Krakow IFJ Pan
Exp
Cornell U., Northwestern U., Regis U., Virginia U.
Exp
Shanghai Jiao Tong U.
Exp
The MUonE Collaboration
Demokritos INPP (Athens) Exp-Th
PSI (Villigen), U.Zürich, ETH Zürich
Th
Mainz U., Max-Planck Inst.
Exp-Th
+ other involved theorists from: New York City Tech (USA), Vienna U. (A)

Backup slides

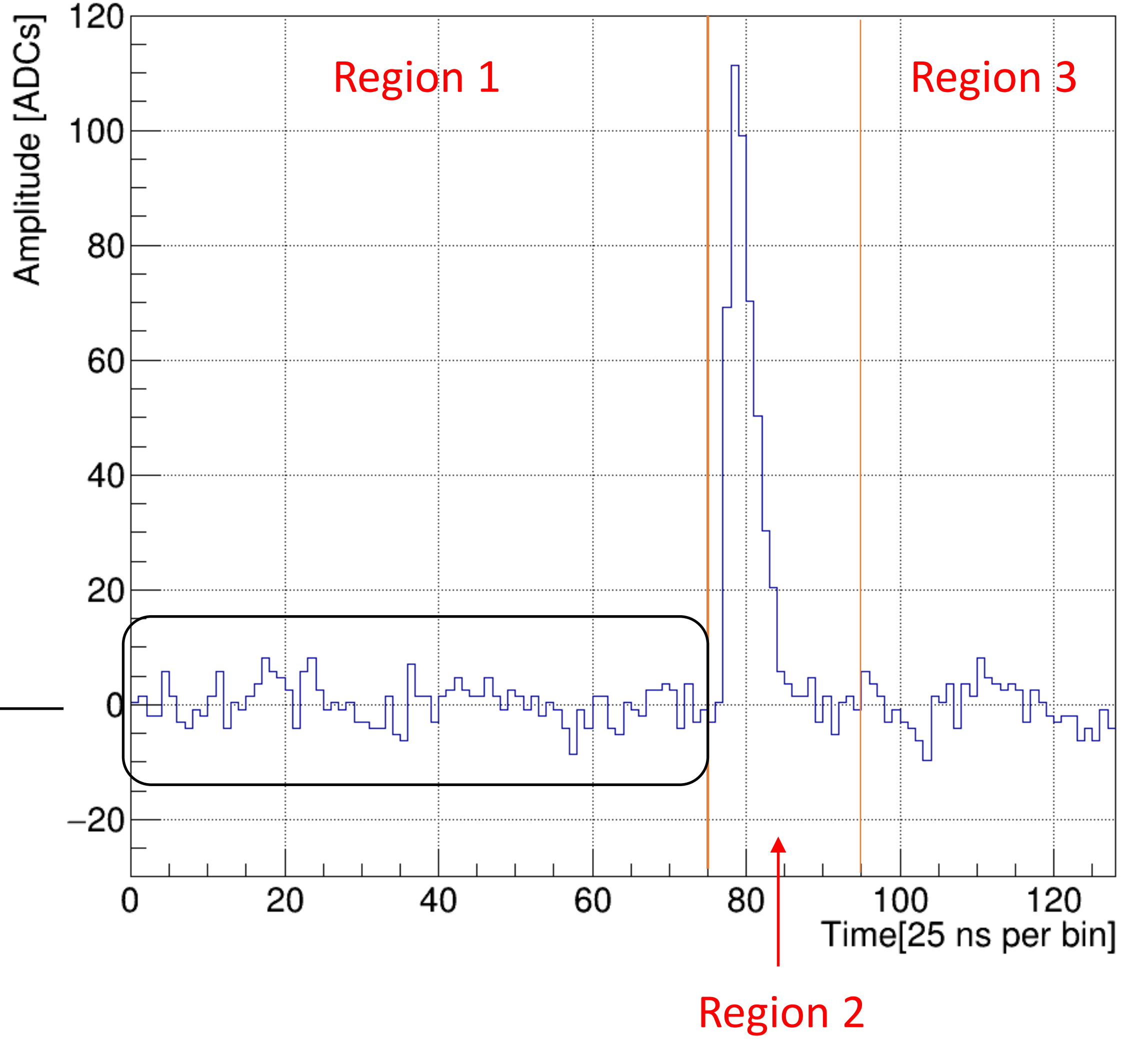
June-2023 data: Preliminary analysis

- Waveform of a single event and a single channel for a ***1 GeV electron beam***.
- DAQ currently separates data into three regions;
    1. Noise (before signal)
    2. Signal
    3. Noise (after signal)

FEB channel 5; signal minus pedestal



Zoom in



Data collected help us study both signal and noise

June-2023 data: Preliminary analysis

Due to the level of precision we need to achieve, noise reduction is under development

We can use correlation coefficient (C) between crystals to reduce their noise;

$$C_{k,l}^{j} = \frac{\frac{1}{75}\sum_{i=1}^{75} k_i l_i - \frac{1}{75}\sum_{i=1}^{75} k_i \sum_{i=1}^{75} l_i}{\sqrt{\sigma_k^j \sigma_l^j}}$$

- k … FEB channel amp
- l … FEB channel amp
- i … time bin
- j … event number

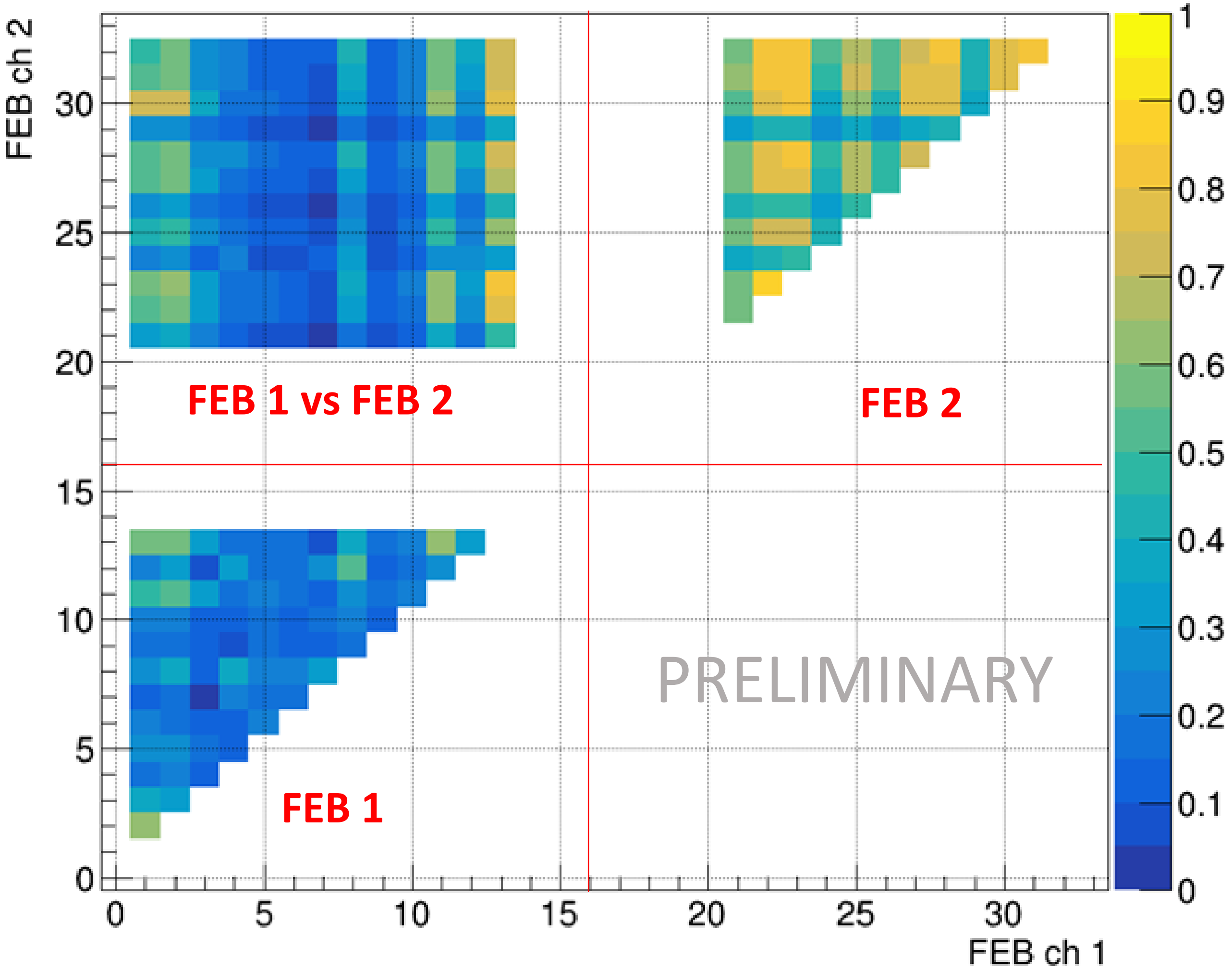
The average for N events:

$$\bar{C}_{k,l} = \frac{1}{N}\sum_{j=1}^{N} C_{k,j}^{j}$$

1 2	**2** 1	**3** 30	**4** 31	**5** 32
6 4	**7** 3	**8** 27	**9** 28	**10** 29
11 7	**12** 6	**13** 5	**14** 25	**15** 26
16 10	**17** 9	**18** 8	**19** 23	**20** 24
21 13	**22** 12	**23** 11	**24** 21	**25** 22

Back view of ECAL during test beam

1 GeV electrons; FEB pairs $\bar{C}_{k,l}$



FEB 2 has a bigger set of high correlated crystals, i.e. crystals with $\bar{C}_{k,l} > 0.80$.

June-2023 data: Preliminary analysis

- Let k be a channel that's highly correlated with a set of different crystals, l_{set}, such that:

$$\bar{C}_{k,l_{set}} > 0.80$$

- FEB channel 23 (no reduction)

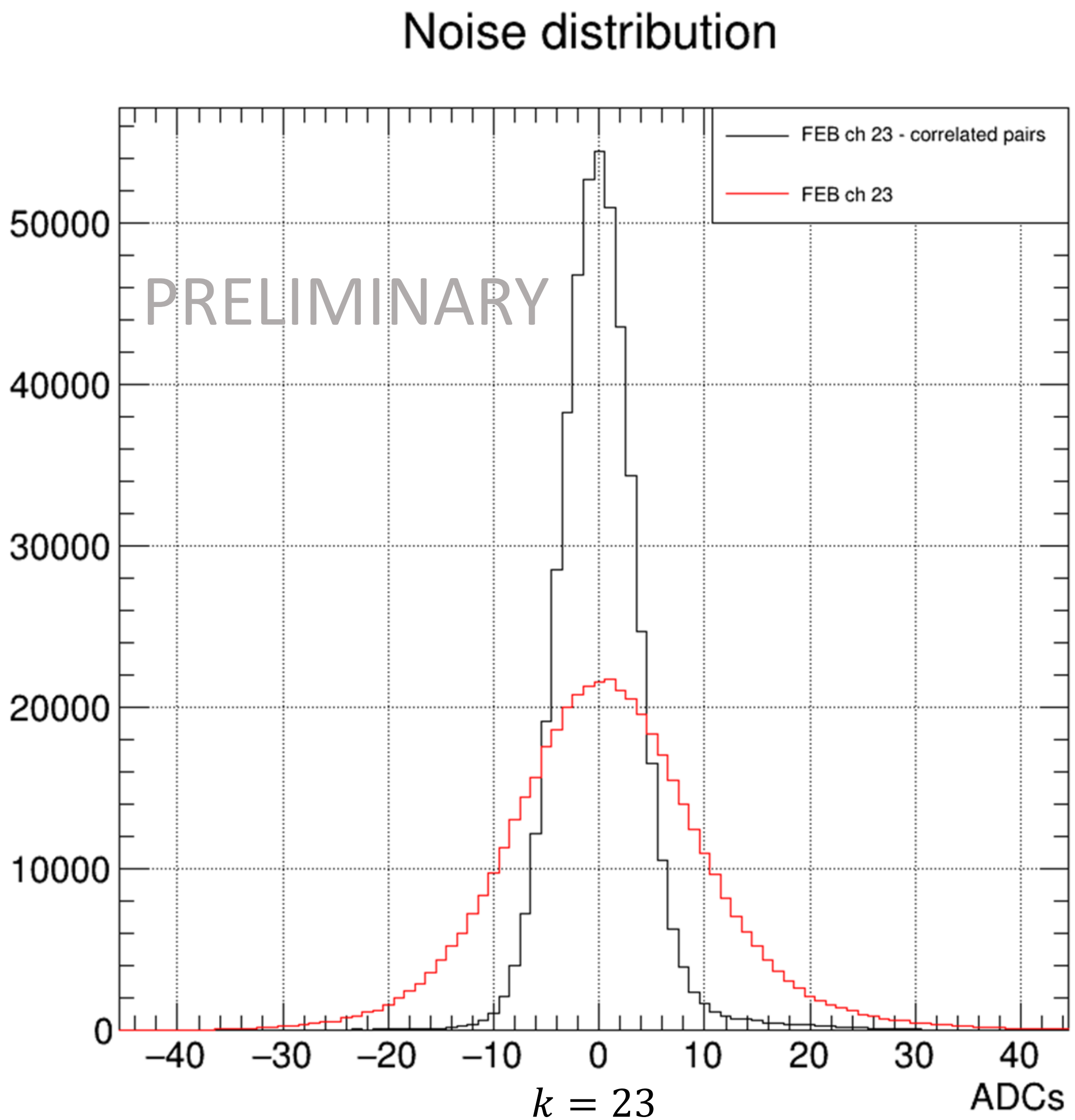
$$\sigma = 8.96\ ADC\ counts$$

- FEB ch 23 (noise reduced from l_{sel}):

$$\sigma = 3.5\ ADC\ counts$$

- Pros:
  - σ_{23} reduced by 61%
- Cons:
  - Only works with highly correlated crystal pairs

- Several studies techniques are being tested to deal with the noise (FFT, waveform averaging, etc).



$k = 23$

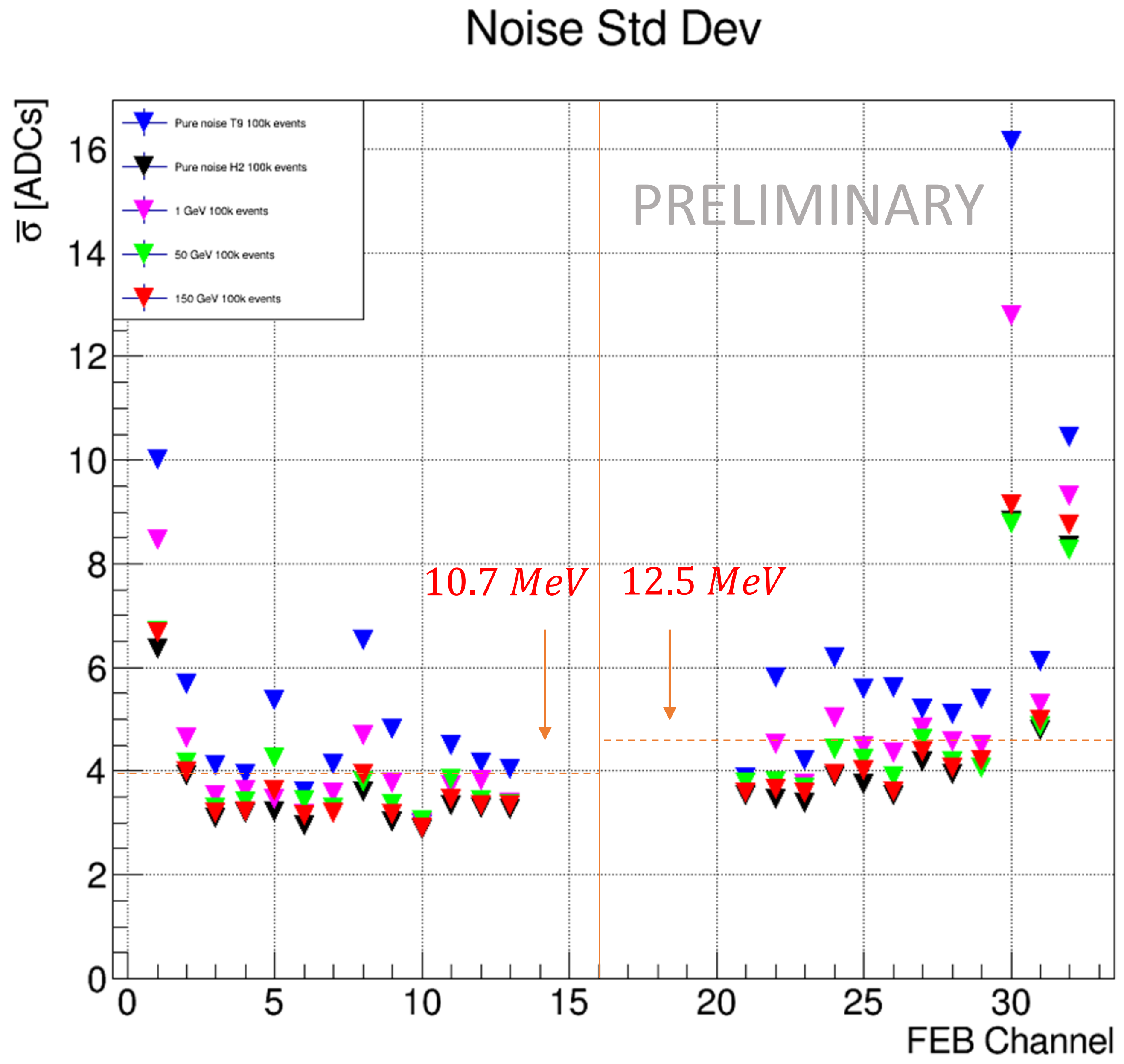
$l_{set} = \{13,21,24,27,28,30,31,31\}$

June-2023 data: Preliminary analysis

- Amplitude fluctuation sigma, $\bar{\sigma}_{noise}$, can happen during our tests due to, electronics, temperature, incident particle type, etc.

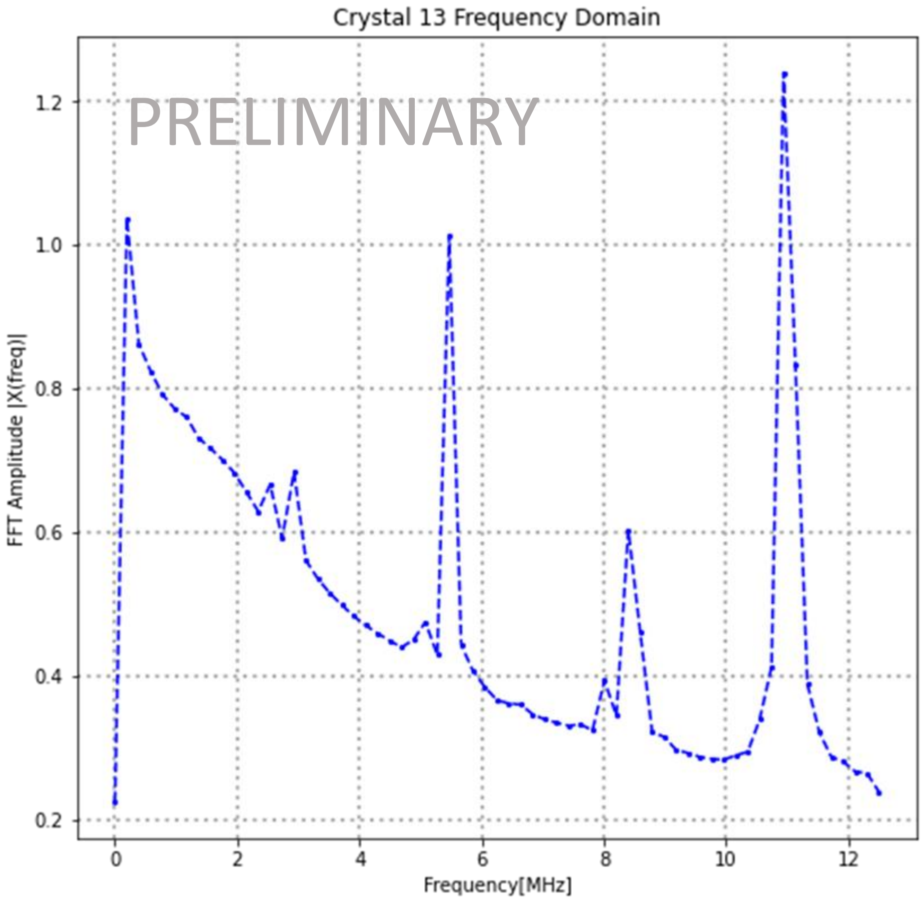
- Important to watch for consistency over different test runs.

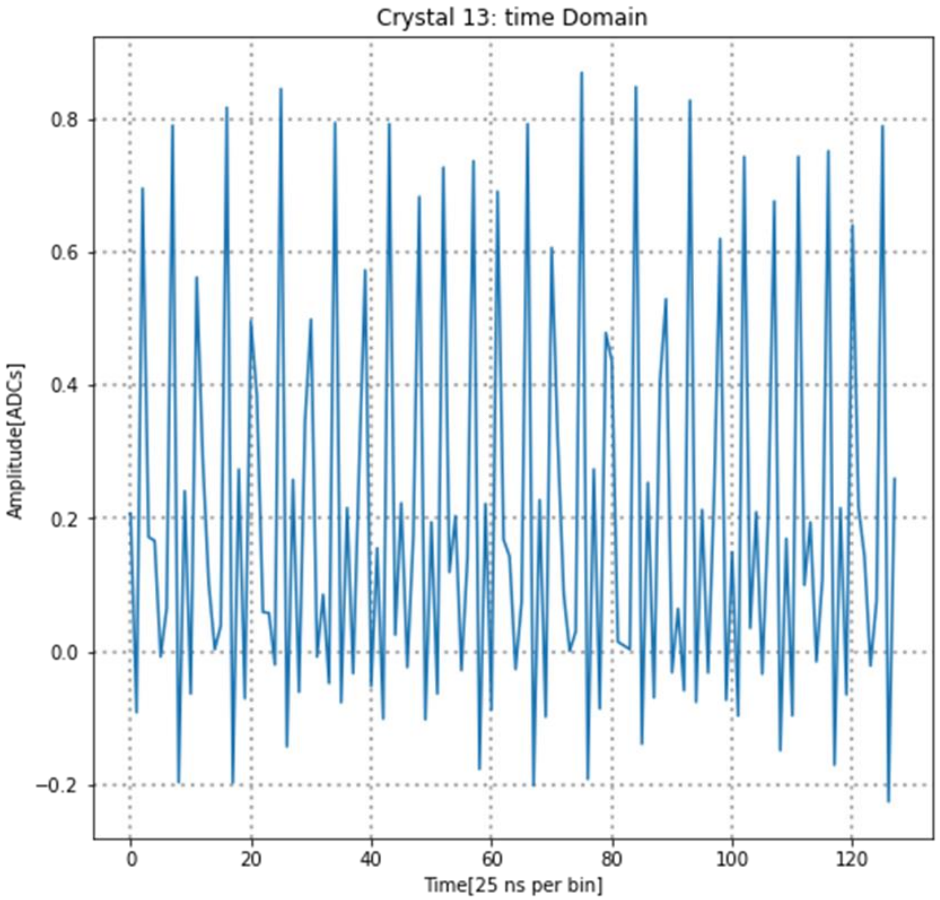
- $\bar{\sigma}$ is relatively stable over different runs:
- FEB 1 average (excl. ch 1) = 3.98 ADCs
- FEB 2 average (excl. ch 30, 32) = 4.63 ADCs
  - $1\ GeV \approx 184\ ADC$
  - $5.4\ MeV \approx 1\ ADC$



June-2023 data: Preliminary analysis

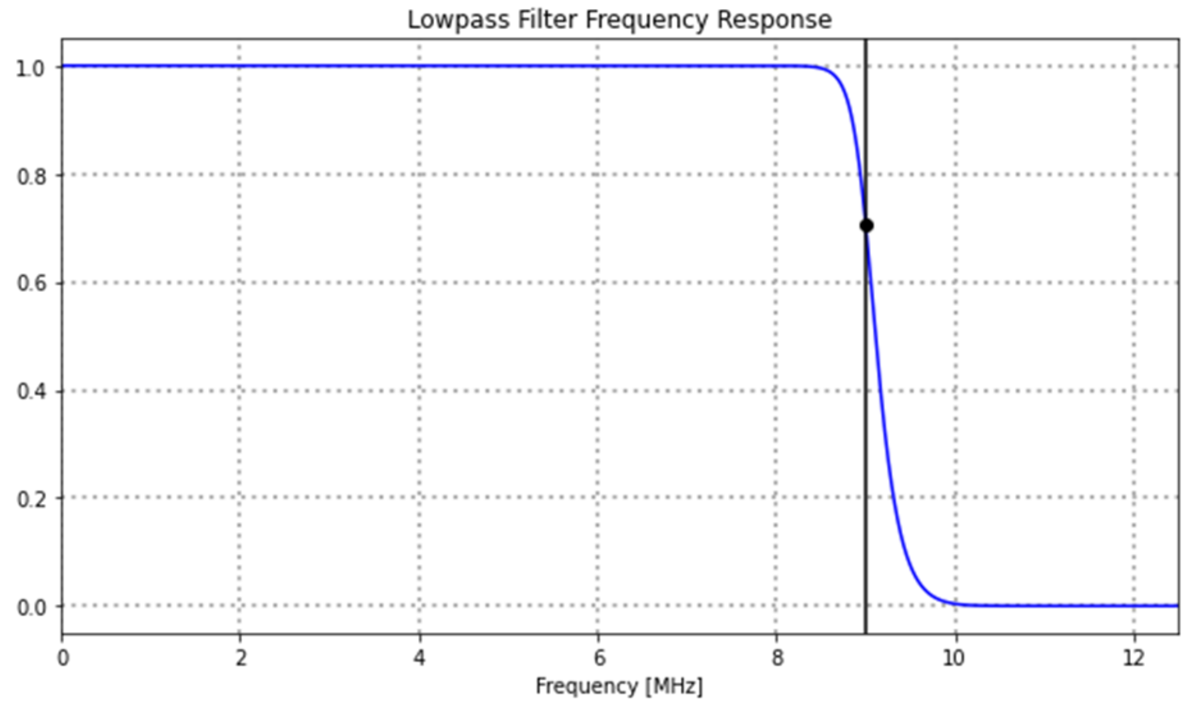
- Another issue with our crystals is high frequency noise
- It converts time domain to frequency domain.
- It can be used as a filtering algorithm to reduce high frequency noise.

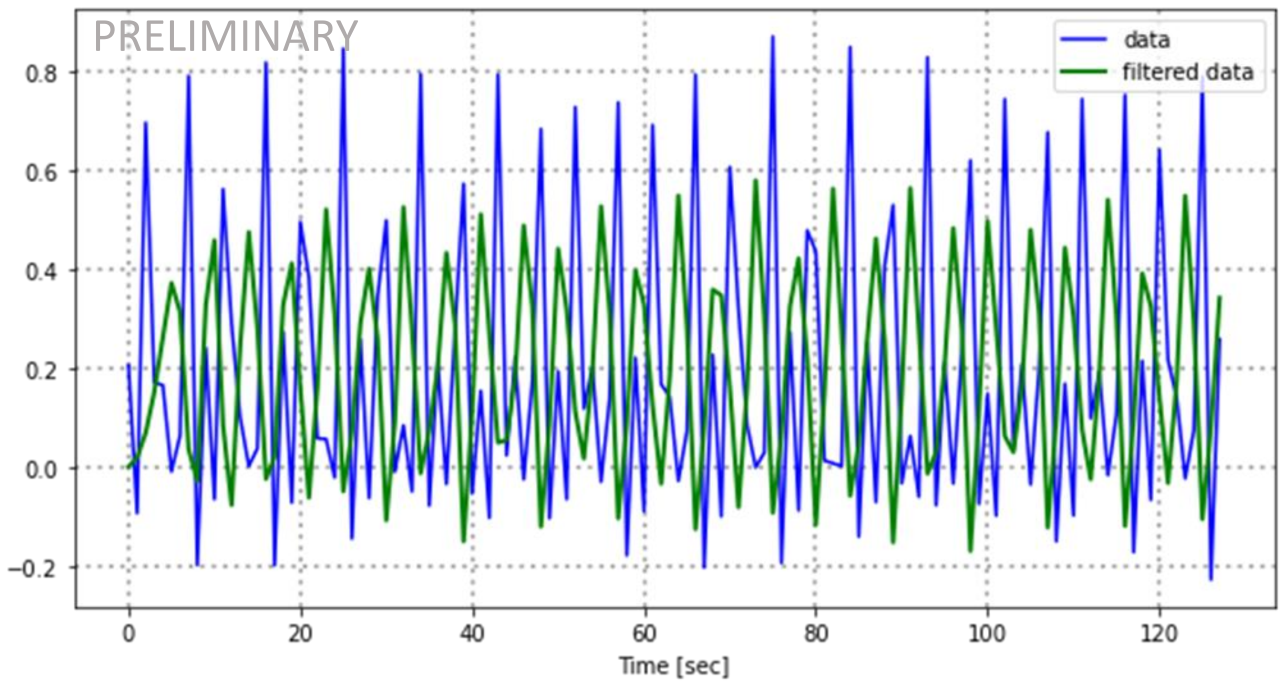




June-2023 data: Preliminary analysis

Applying a low pass filter on 9MHz frequencies reduces noise by 37.5%





June-2023 data: Preliminary analysis

- Log weighted centroid:

$$\vec{x}_{PoI} = \frac{\sum_i w_i \vec{x}_i}{\sum_i w_i},$$

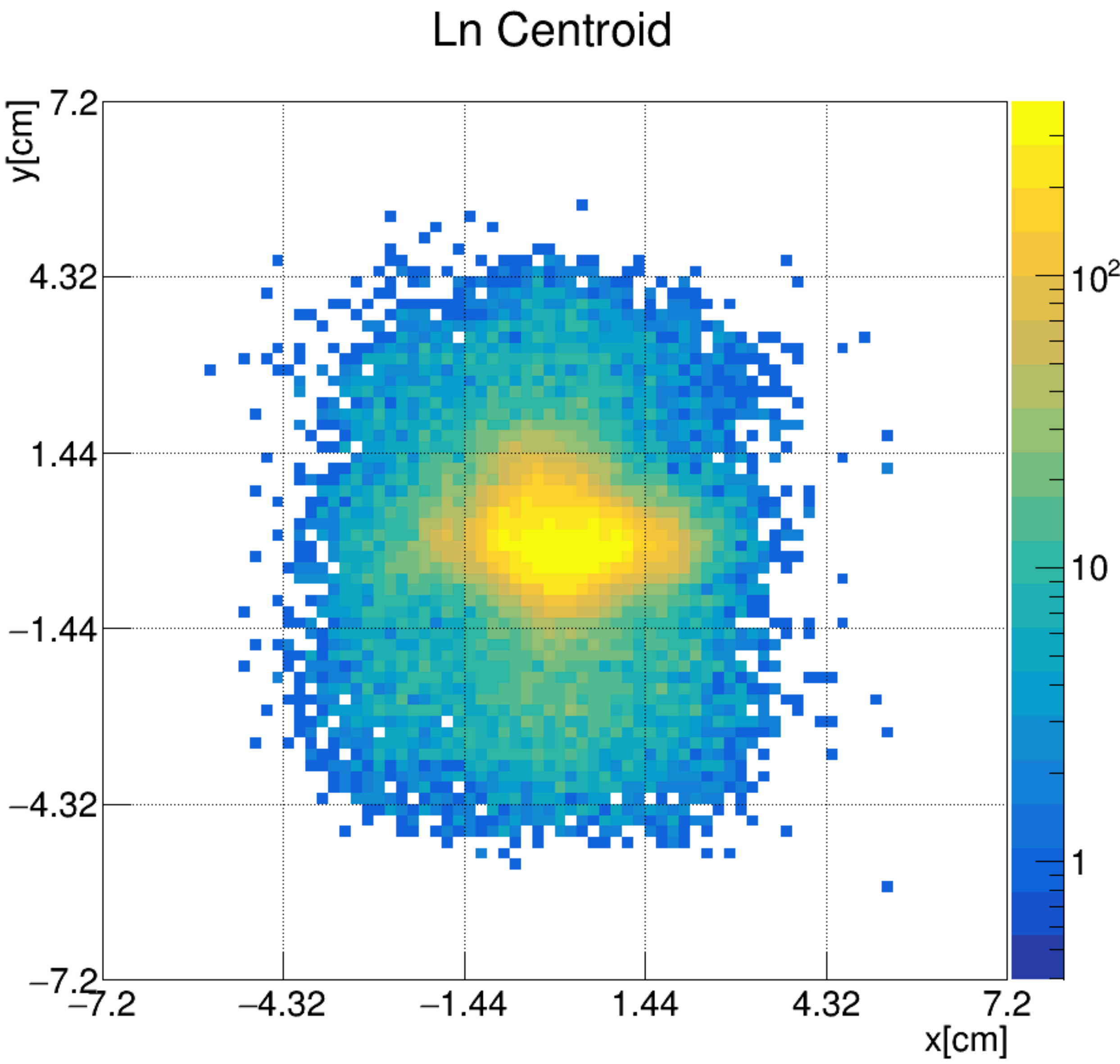
$$w_i = max\left\{0, w_o + \ln\left(\frac{E_i}{E_{tot}}\right)\right\},$$

$$w_o = 7$$

- $\sigma_x = 1.13\ cm$
- $\sigma_y = 1.22\ cm$

During the 2023 test beam in June we scan every single crystal, in between crystals and corners of the whole ECAL with energies ranges of {1,2,4,8,25,50,75,100,125,150 GeV}

150 GeV electron



The coordinate is set (0,0) at the center of FEB channel 5