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

EUGENIA SPEDICATO FOR **MUONE**

UNIVERSITY OF BOLOGNA, INFN

Topical Seminar on Innovative Particle and Radiation Detectors, Siena 2023

Anomalous magnetic moment of the muon

$\overrightarrow{M_l} = g_l \frac{e}{2m_l}\vec{S}$ → Dirac prediction $g_l = 2$ → Quantum corrections give the anomaly: $a_l = \frac{g_l - 2}{2}$

Are those **discrepancies** still real? Hint of **new physics?**

Experimental average **FERMILAB-BNL**
P. B. Aguillard et al., (2023) arXiv:2308.06230

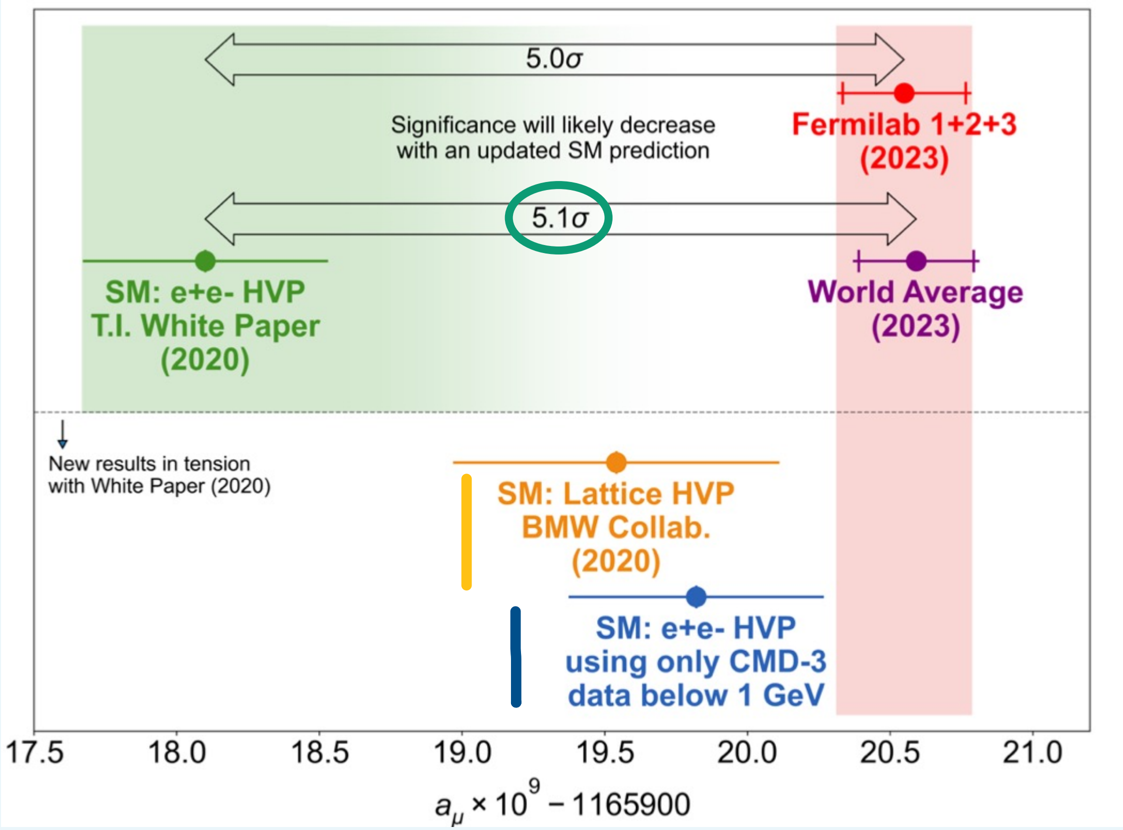
VS

Theoretical **reference value (WP)**
T. Aoyama et al., (2020) arXiv:2006.04822

but...

Most precise LQCD result
T. Borsanyi et al., (2021) arXiv:2002.12347v3

New result from $e^+ - e^- \to$ **had** cross section with CMD-3 data
F. V. Ignatov et al., (2023) arXiv:2302.08834



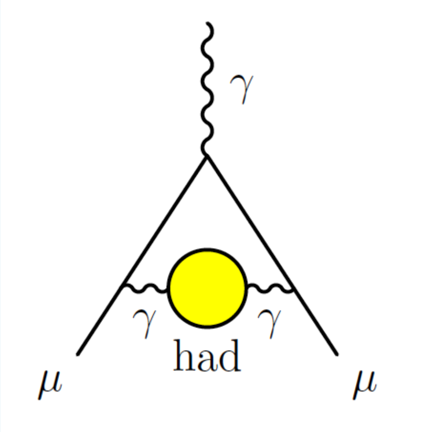
1. Reduce the **experimental** error → Fermilab g-2 goal (0.54 ppm (BNL) → 0.20 ppm $\xrightarrow{goal}$ 0.14 ppm)
2. Improve **theoretical** precision → Dominant contribution: LO hadronic vacuum polarization term $< a_\mu^{HLO} \to 0.6\%$

Anomalous magnetic moment of the muon

$$a_\mu^{SM} = \underbrace{a_\mu^{QED} + a_\mu^{EWK}}_{} + a_\mu^{had}$$

Precise estimates from perturbation theory

$a_\mu^{had} \rightarrow a_\mu^{HLO} + \textit{higher order terms}$



Hadronic contribution to the LO vacuum polarization term a_μ^{HLO} is not calculable through pQCD

Dominates theoretical **uncertainty** → $\mathbf{0.6\%}$

Reference approach (WP before BMW) is **data-driven**:

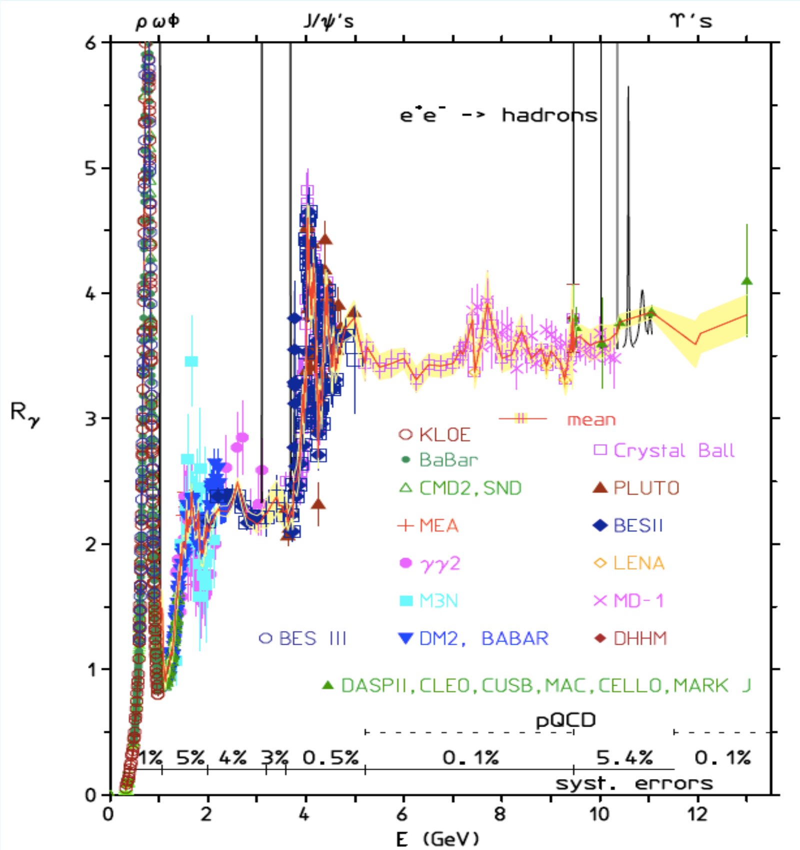
$$a_\mu^{HLO} = \left(\frac{\alpha m_\mu}{3\pi}\right)^2 \int_{4m_\pi^2}^{\infty} ds\, \frac{\hat{K}(s) R_{had}(s)}{s^2} \longrightarrow R_{had}(s) \propto \sigma(e^- e^+ \rightarrow had)$$

measurements

Main contribution: region of *low energies*, highly *fluctuating* because of hadronic resonances and threshold effects

Alternative methods are needed

New a_μ^{HLO} with data from CMD-3 $\sigma(e^- e^+ \rightarrow had)$ and with LQCD (BMW) **weaken** $\Delta a_\mu(th - exp)$ discrepancy, introducing some **tensions** with the reference theoretical estimate.



F.Jegerlehner, EPJ Web Conf. 118 (2016) 01016

MUonE proposal

Independent estimate of a_μ^{HLO} through innovative method:
C.M. Carloni Calame, et al. Phys.Lett.B746(2015)325

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

Space-like

Smooth function →

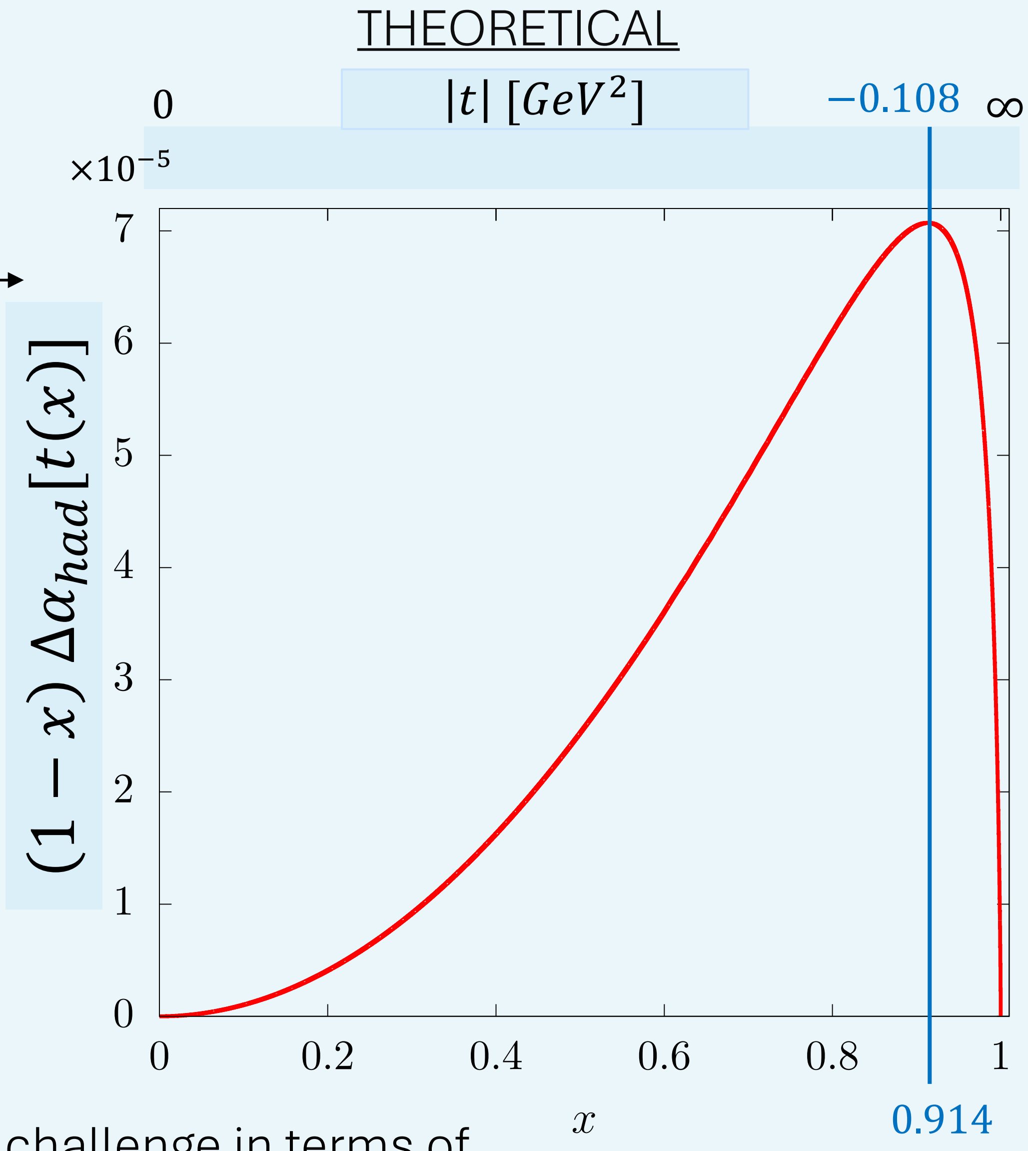
Proposed process to measure $\Delta\alpha_{had}$: **elastic scattering**
G.Abbiendi et al., Eur.Phys.J.C77(2017)139 ; B. E. Lautrup et al., Phys. Rept. 3 (1972) 193

$$\mu\,(160GeV) + e^-(rest) \rightarrow \mu + e^-$$

↓ M2 muon beam at CERN SPS

$$\frac{d\sigma}{dt} = \frac{d\sigma_0}{dt}\left|\frac{1}{1-\Delta\alpha(t)}\right|^2 \xrightarrow{\text{Template fit}} \Delta\alpha_{had}(t) \xrightarrow{\text{Master integral}} a_\mu^{HLO}$$

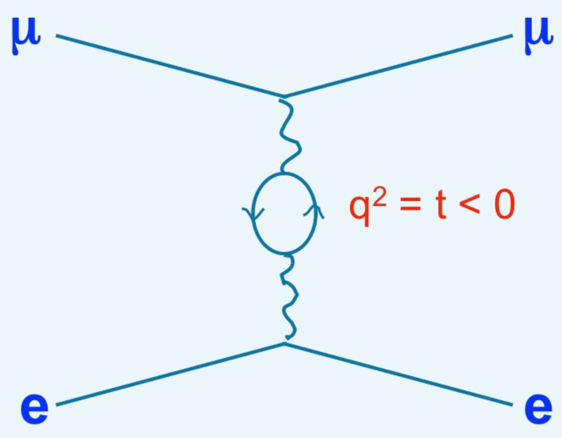
$$\Delta\alpha(t) = \Delta\alpha_{lep}(t) + \Delta\alpha_{had}(t)$$



Required precision on $a_\mu^{HLO} < 1\%$ implies a relative precision of $\sim\mathbf{10^{-5}}$ on the shape of the elastic differential cross section

Great challenge in terms of required precision!

$\mu - e$ elastic scattering



$$\frac{d\sigma_{el}}{dt} \xleftrightarrow{\text{Simple kinematics relations } (t \leftrightarrow \theta_l)} \frac{d\sigma_{el}}{d\theta_l}$$

Measuring the **leptons scattering angles**

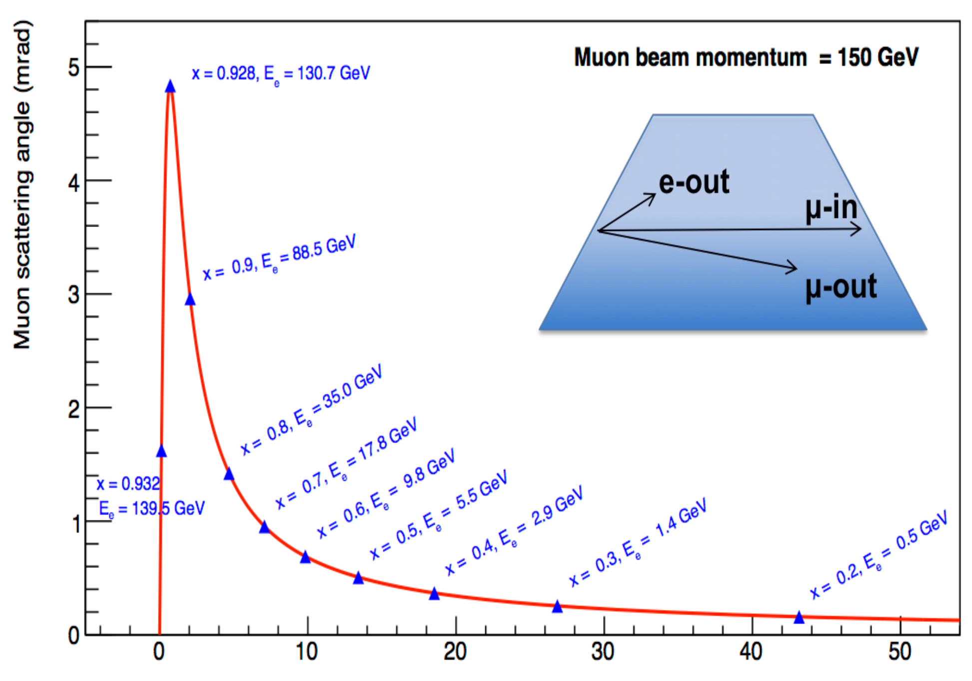
↓

Precise correlation

$0 < \theta_\mu < 5\ mrad$

$0 < \theta_e \lesssim 50\ mrad$

ELASTIC CURVE

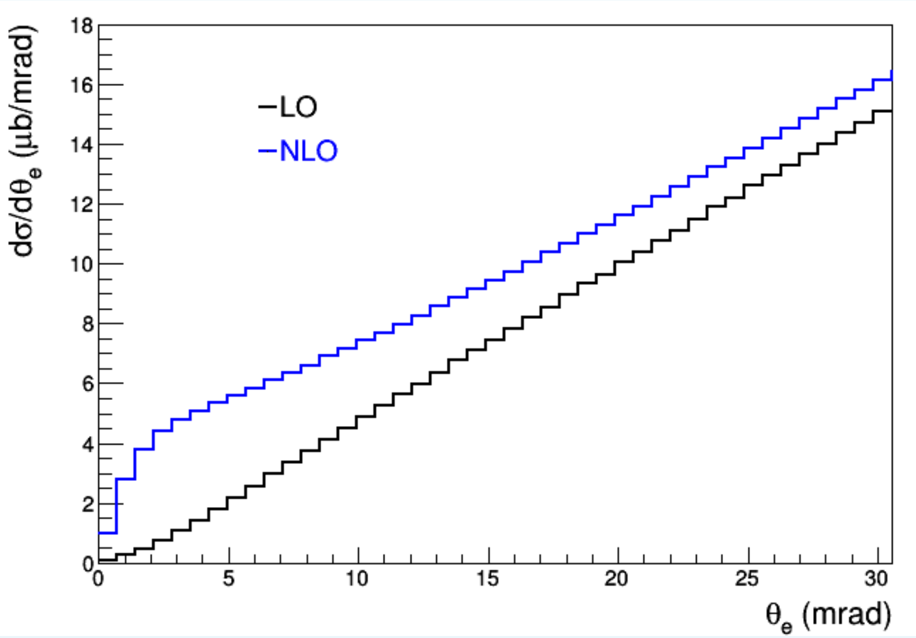


Abbiendi et al, Eur. Phys. J. C 77.3 (2017), 139

Helps in the selection of **purely elastic events**

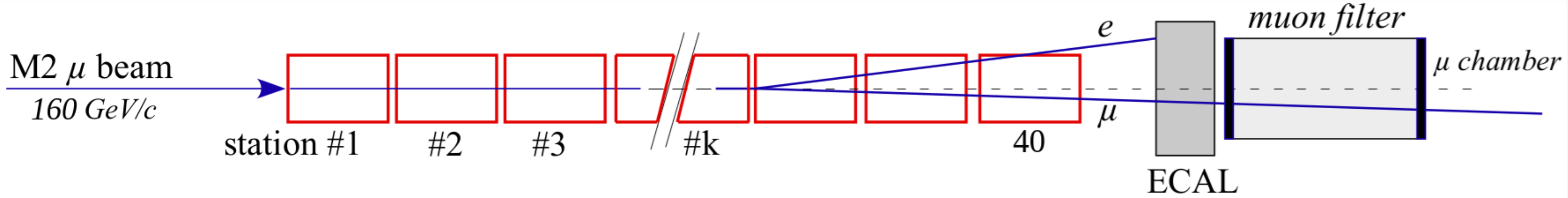
Radiative events with real photons are expected

DIFFERENTIAL CROSS SECTION



Experimental apparatus

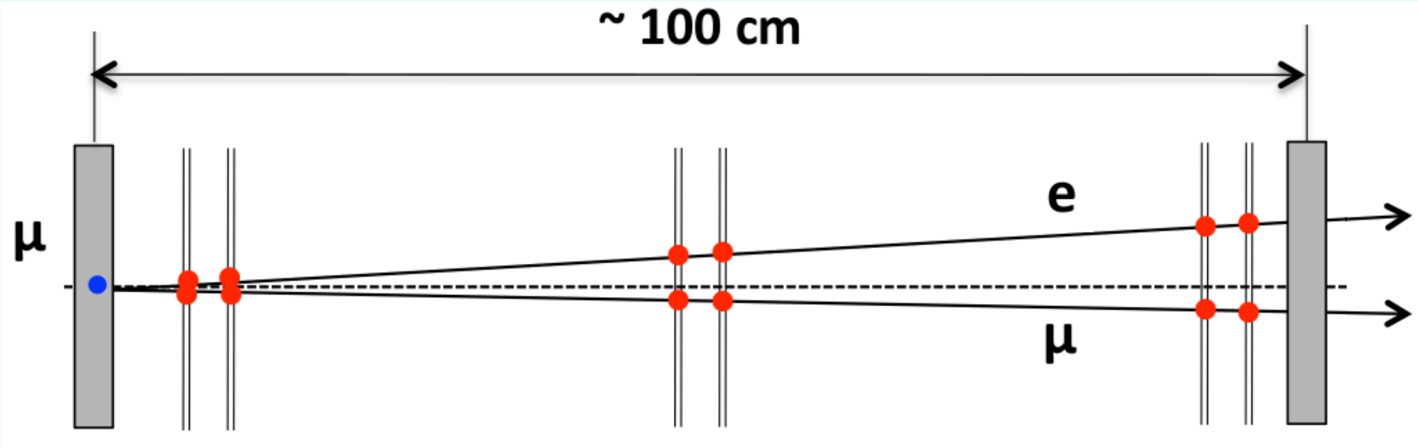
40 tracking stations ➕ Electromagnetic calorimeter ➕ Muon chambers



Each tracking station behaves as an independent *detector*

- 1 beryllium or carbon target ($1.5\ cm$)
- 6 silicon strip modules (CMS 2S modules)

CMS Collaboration, Technical design report (2017)



Letter of Intent: The MUonE Project, SPSC-I-252

Electromagnetic calorimeter

Reduced format for **Test Run** aimed at the validation of the experimental proposal

- **25** cells in $PbWO_4$ ($22\ X_0$) (from CMS endcaps calorimeter)
- Surface ~ $14\times14\ cm^2$
- Readout: APDs read out by two **FEBs** connected to a **FC7 board**

Larger size w.r.t. CMS ones: $10\times10\ mm^2$ → Affects **observed signal size** and **energy resolution**

$expected\ 9\ pe/MeV$

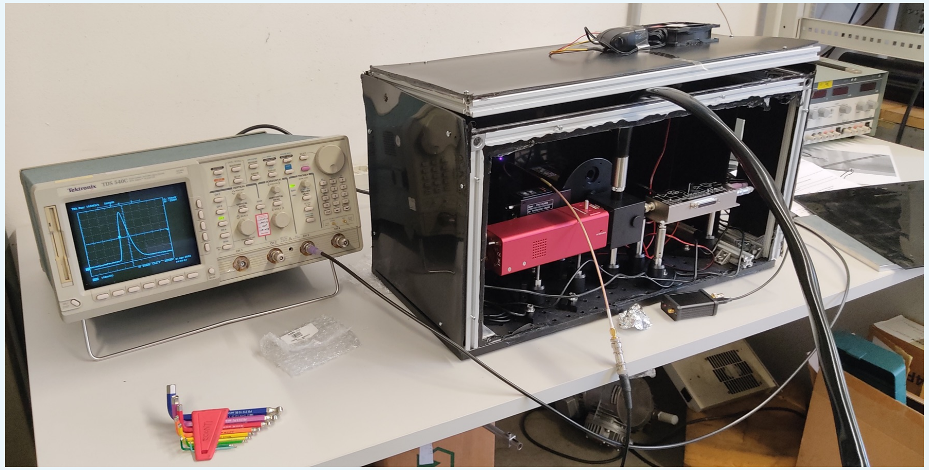
Rms noise: $4\ ADC\ counts$ (single crystal)

According to hardware specifics:

$$150000\ MeV\times9\frac{pe}{MeV}\times50=6.75\times10^7\ e\approx28723\ ADC\ count$$

$150\ GeV\ e^-$ (150000 MeV) ; $APD\ gain$ (×50)

Laser pulse system (at $\mathbf{450\ nm}$) for APD calibration



System noise: dominated by MGPA (CMS one)

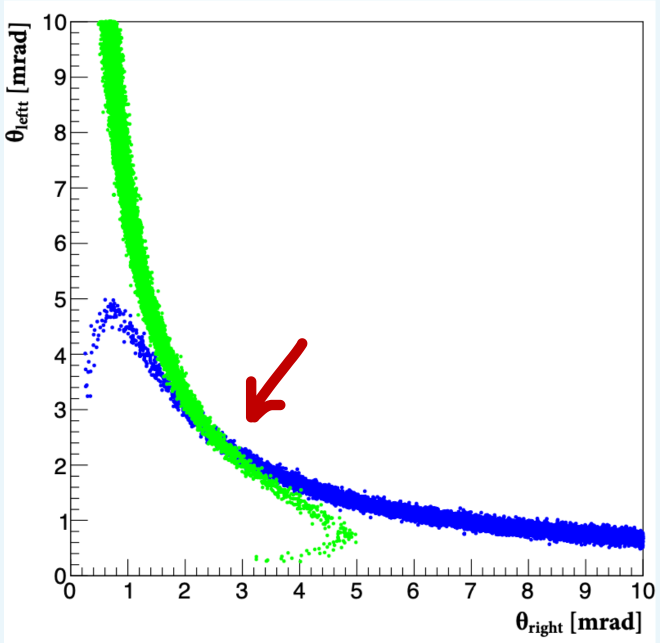
1. Determining the ability to identify beam muons ($160\ GeV\rightarrow$ 700 MeV signal)
2. Expected **energy resolution**: ~ $5-7\%$ at 700 MeV

MGPA specifics: M.Raymond et al., 10.1109/TNS.2005.850979 (2005)

What is the purpose of the ECAL in MUonE?

Use it as a control system for the tracker→ assess systematic effects:

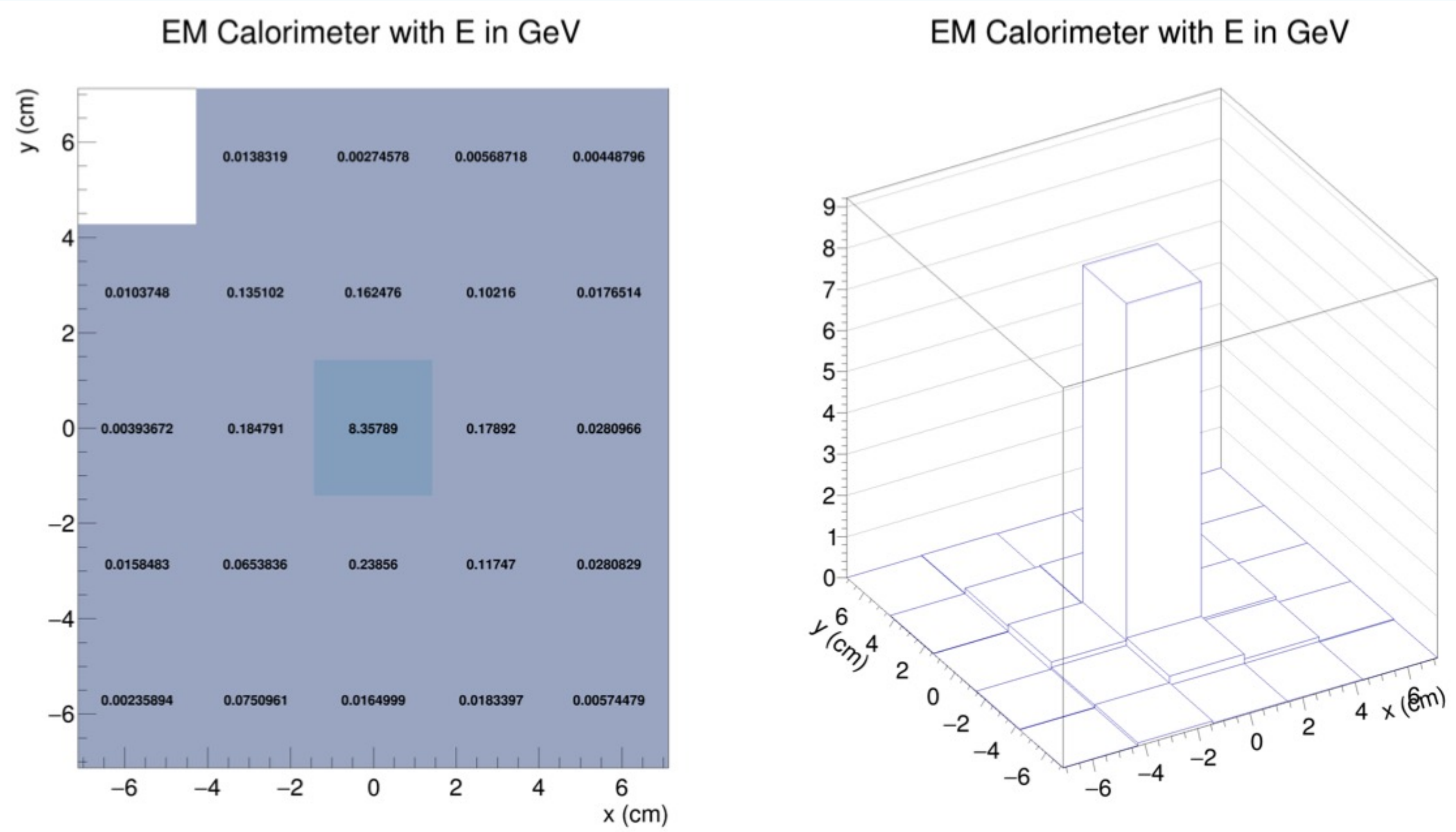
- Possibility to control tracker's signal selection at least in the *last* stations and small scattering angles events;
- Helping in describing and recognizing background and radiative events;
- Resolving the PID ambiguity in the region of similar angles ($2-3\ mrad$): tracker is not enough when electron and muon have *similar scattering angle* → check ECAL E_{dep} and associate ECAL cluster to track



Selection of simulated elastic events with ECAL: GFLASH Fast Simulation

- Fast simulation of the *entire homogeneous ECAL* based on **GFLASH** parametrization used by CMS (Grindhammer et al., arXiv:hep-ex/0001020);
- Used to study its **response** and its **capability of selecting signal events.**

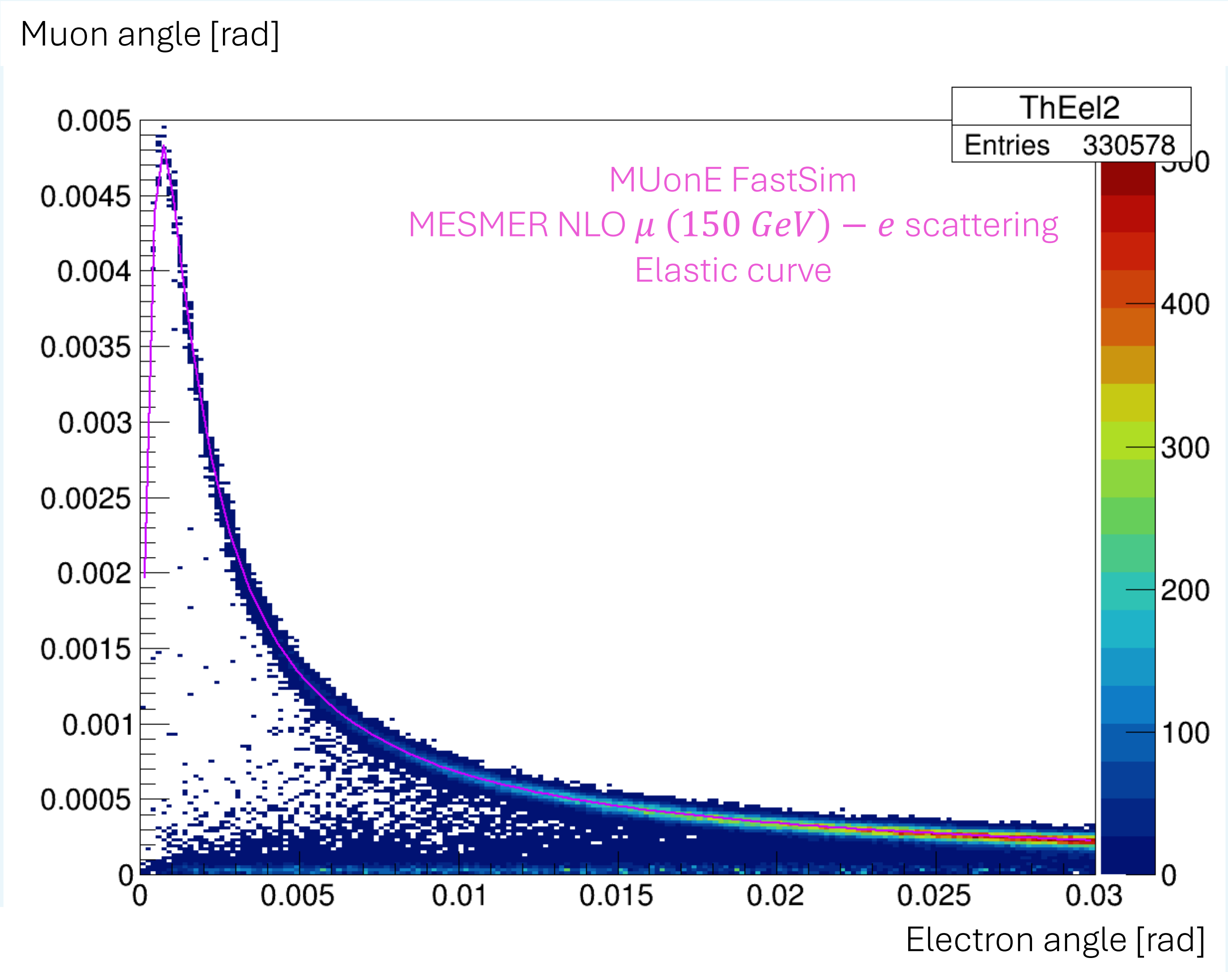
Simulated event of a **10 GeV electron** impinging on the *central* cell of the ECAL

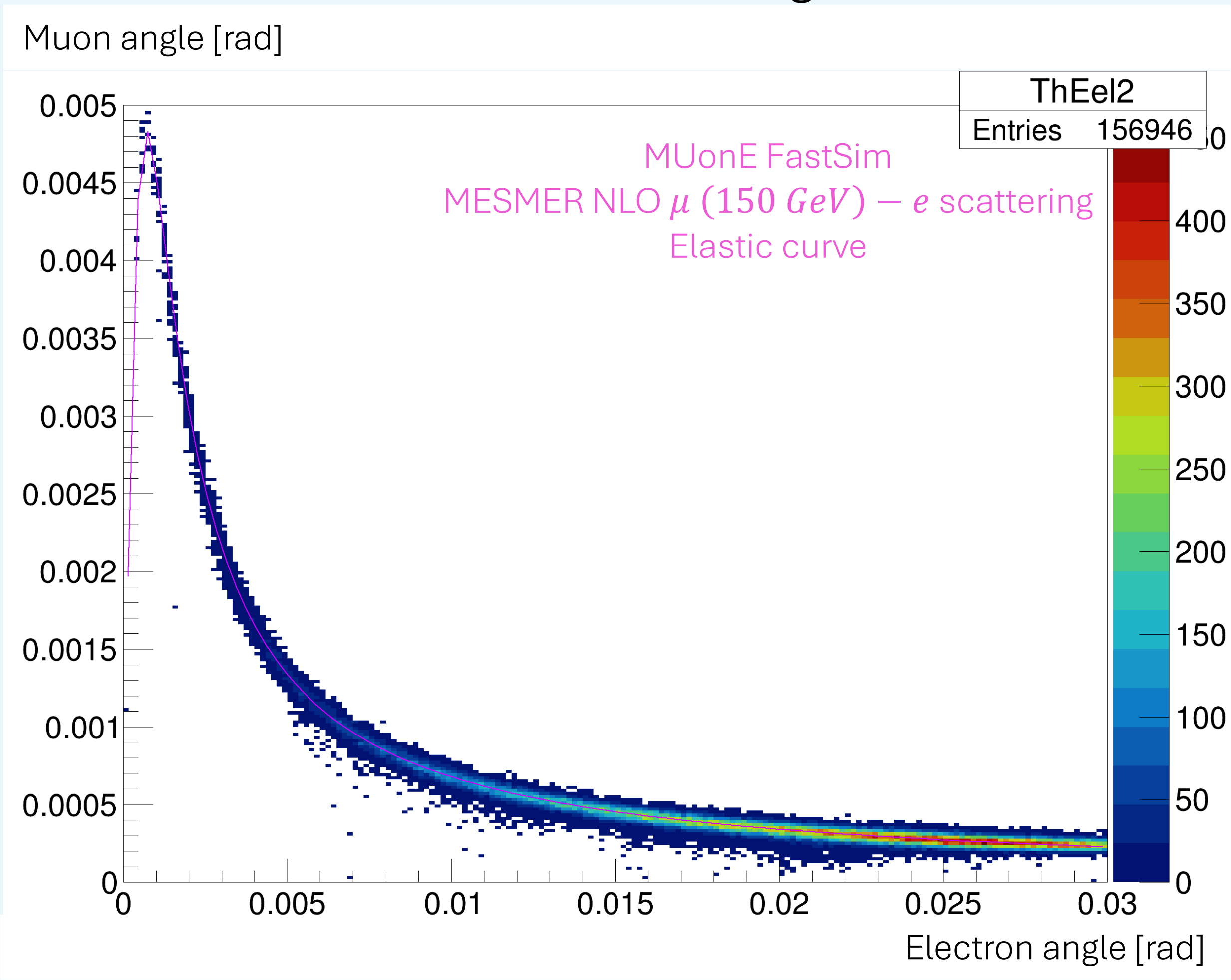


Selection of simulated elastic events with ECAL

NLO $\boldsymbol{\mu - e}$ scattering events <u>without</u> any selection: presence of **radiative** and **background** events

NLO $\boldsymbol{\mu - e}$ scattering events <u>with</u> ECAL selection (based on $\boldsymbol{E_{dep}^{3x3}}$, $\boldsymbol{\sigma(E)}$, centroid coordinates): Clear **elastic** signal



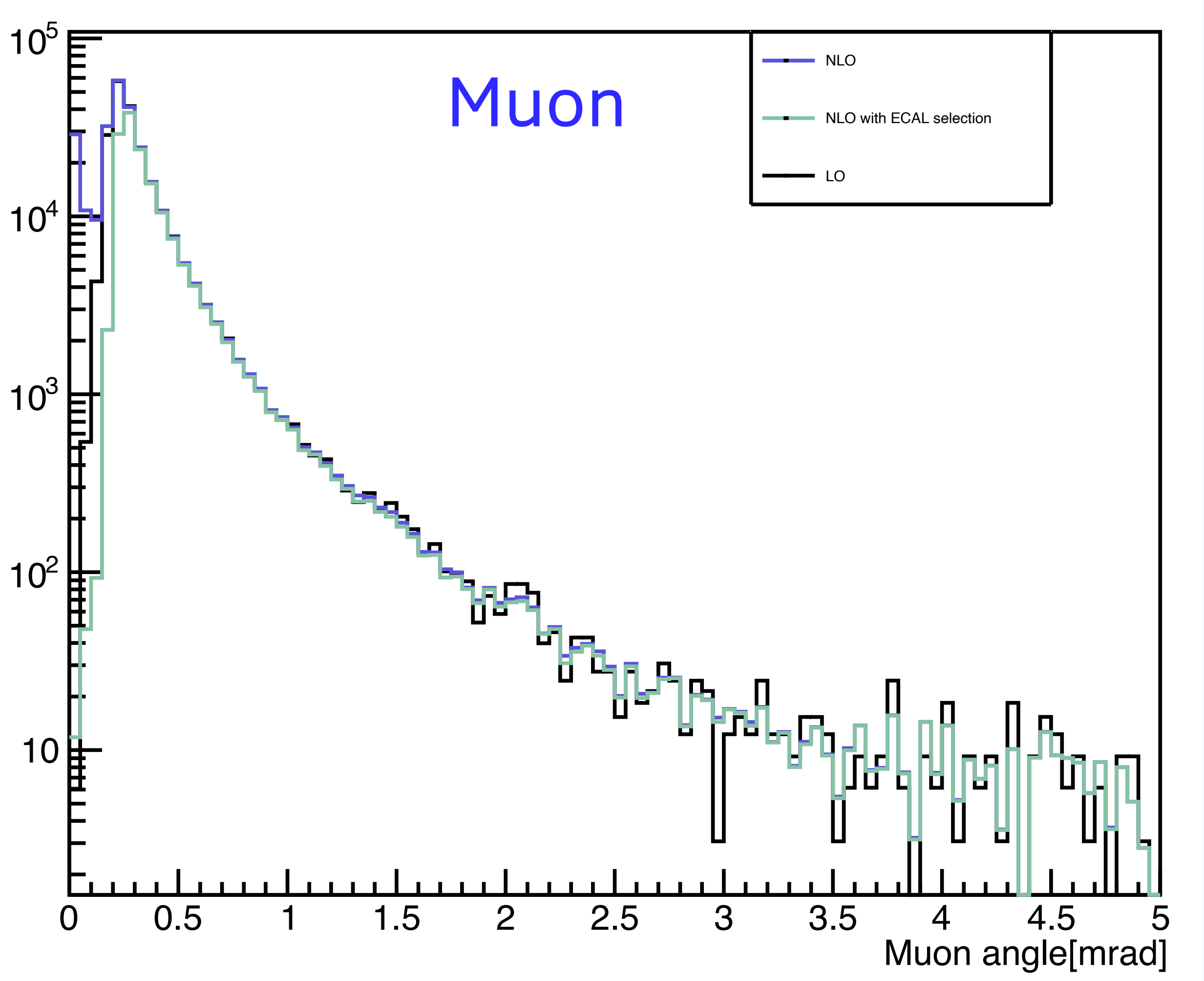


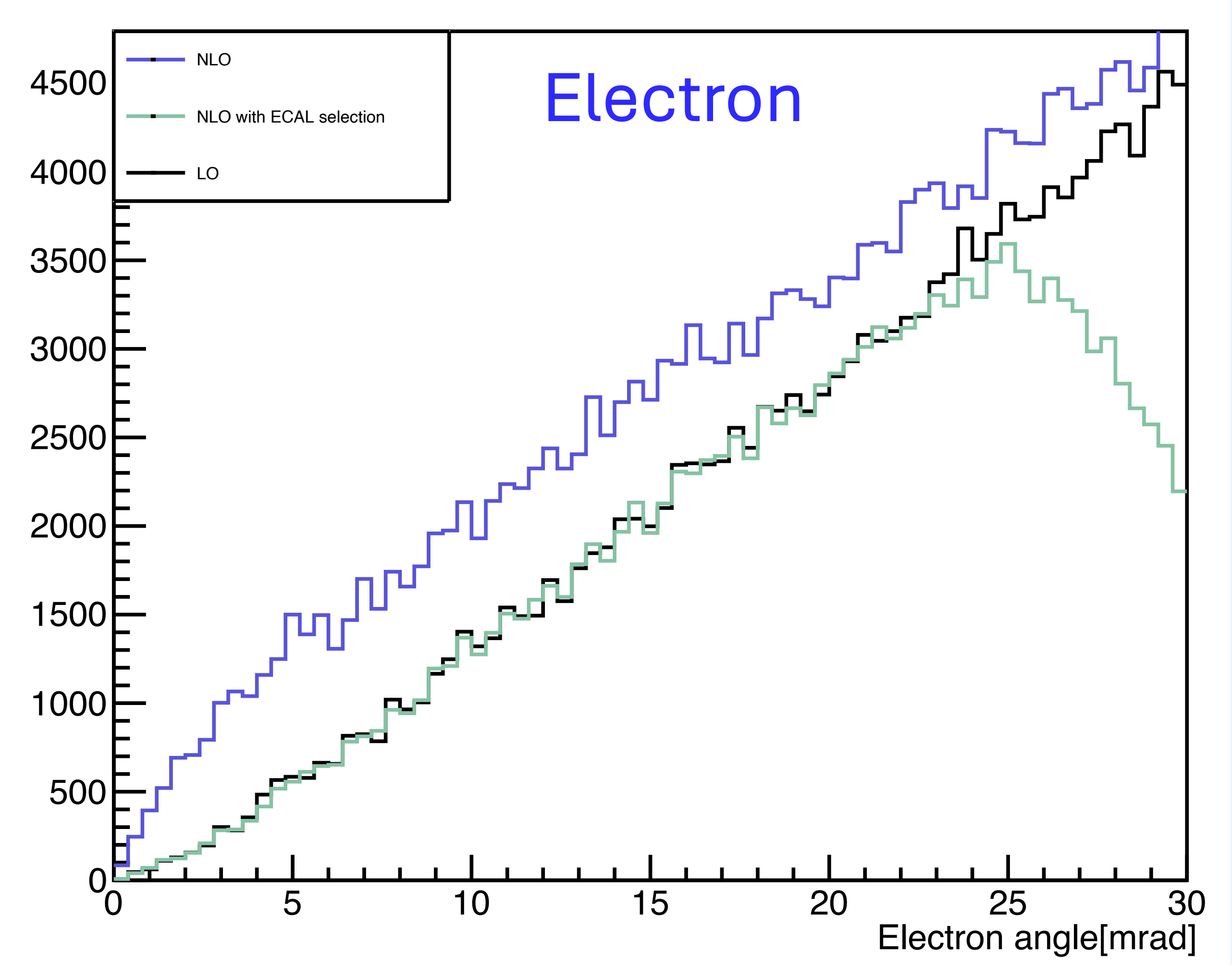
E. Spedicato, <u>Master thesis</u> (2021)

Cross-check in the last stations the **tracker-based** selection with the **calorimetric** selection

Angular distributions of the electron and muon

MESMER MC + MUonE Fast Simulation





Muon cross section is **robust** against radiative effects

With **calorimetric** selection, the LO elastic cross section of the electron is well recovered

ECAL tests beam 2023

Calibration tests have been performed with the current prototype:

1. CERN H2 *electron* line: energy range $\rightarrow 20 - 150\ GeV$

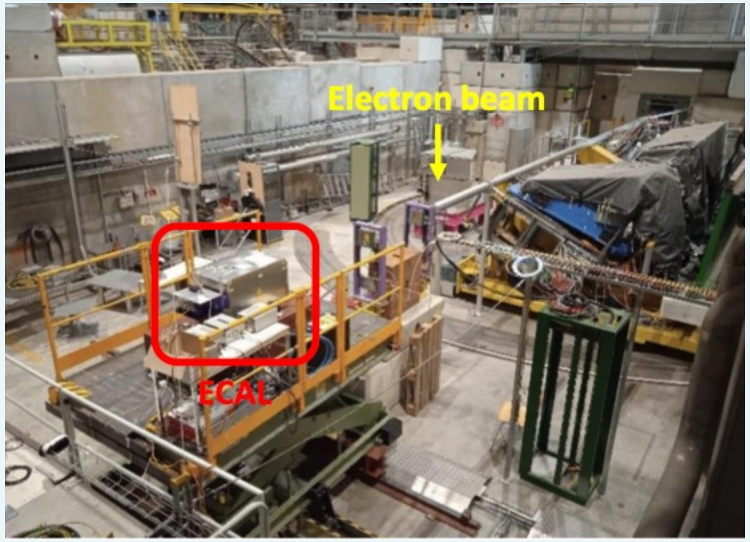
2. CERN T9 *electron* line: energy range $\rightarrow 1 - 10\ GeV$

Main purpose:

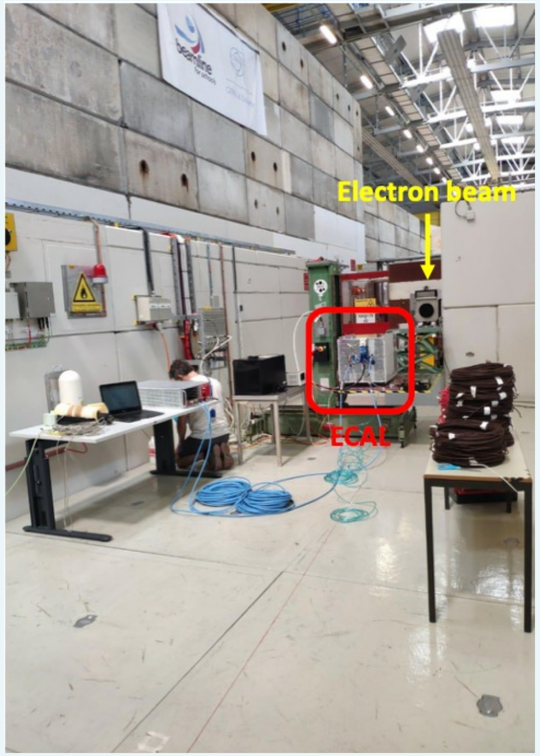
- Set APD voltages to *better equalize* the signal within 10% in all the APDs. Calibration done with laser signal.

Some preliminary results..

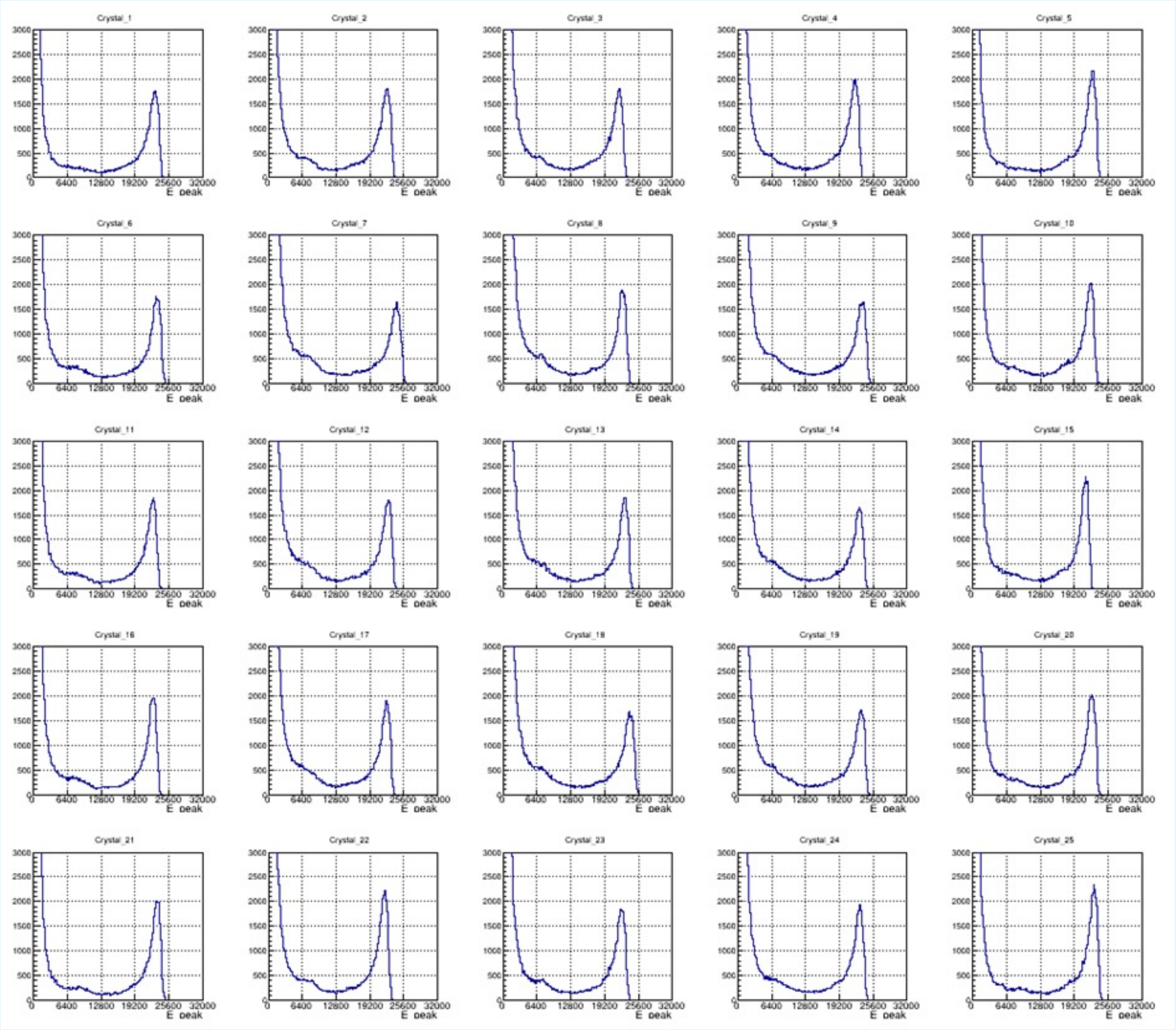
CERN H2



CERN T9



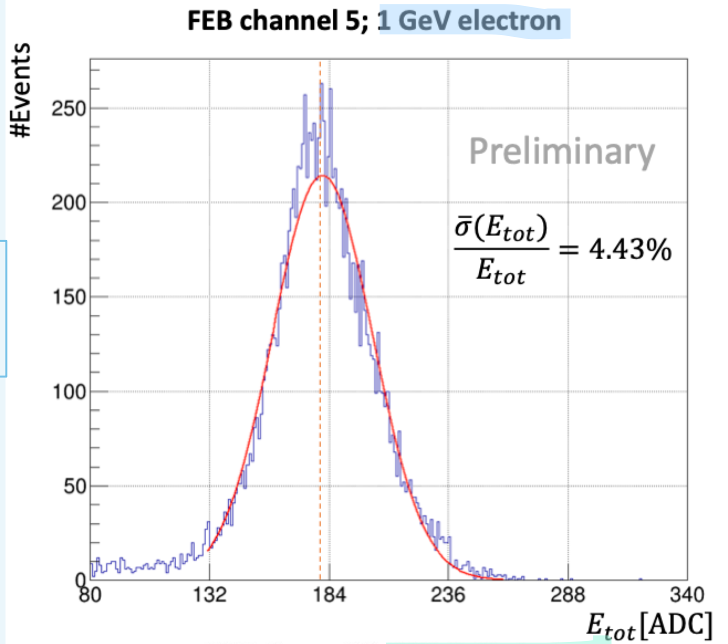
Calibrated energy distribution of the signal, for all crystals with $\forall E_{dep}$



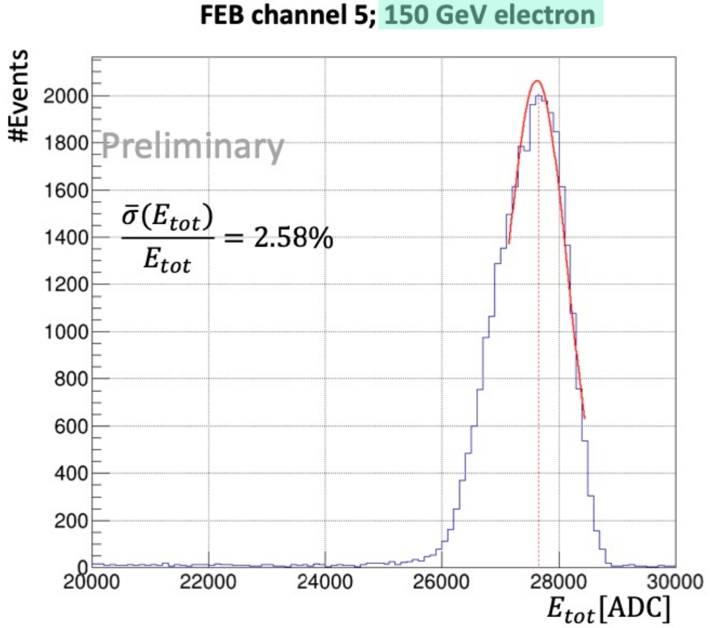
X axis: energy deposit per crystal ($0 - 32000\ ADCs$) for a 150 GeV $\boldsymbol{e}$ beam
Y axis: number of events

Calibrated energy distribution of the signal for crystal $\mathbf{5}$ with $\mathbf{E_{dep}} > \mathbf{70\%}\ \boldsymbol{E_{tot}}$

$1\ GeV$ peak: $\sim 184\ ADC$



$150\ GeV$ peak: $\sim 27600\ ADC$



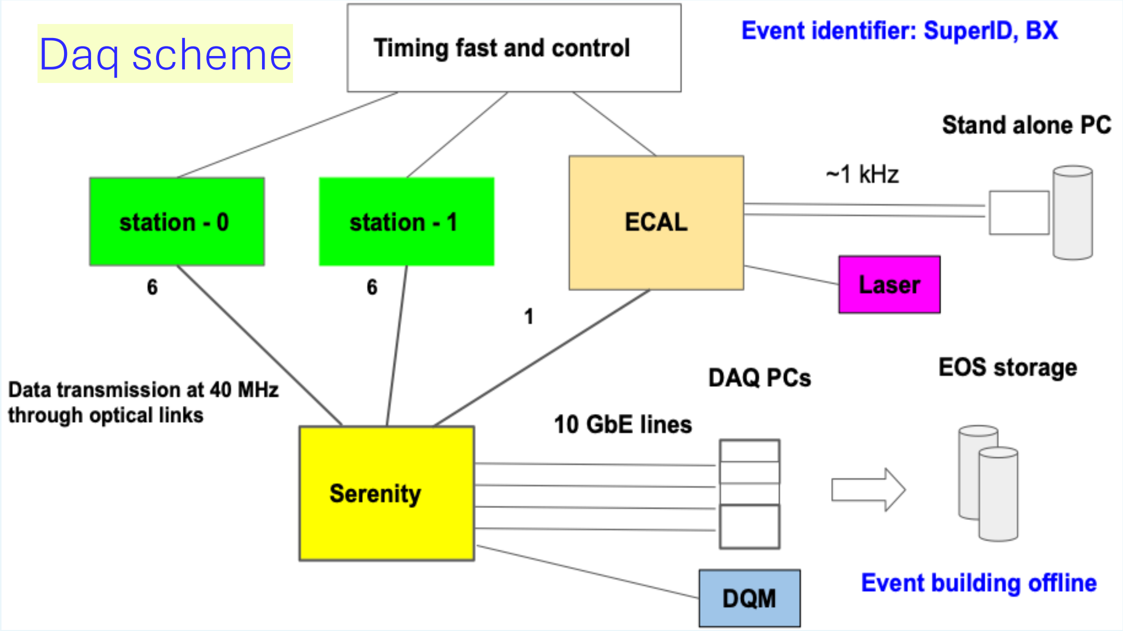
Pilot Run August-September 2023

- M2 beam line at cern (muons $160\ GeV$);
- First time with **2 full-equipped stations** (12 modules);
- **ECAL** set after the second station.

Main Purposes:

1. Scale the DAQ from **1 to 2** tracking stations;
2. **Integrate** and **synchronize** tracker and ECAL DAQ;
3. Test the **software and hardware alignment** procedure;
4. Collect enough statistics to provide the **measurement of the leptonic running of α.**

→ We managed to read out the calorimeter at **$40\ MHz$,** tuning the rate to fit in the available **$10\ GbE$** data link.



Results will be used to write the **technical proposal**. Submission to the SPSC planned in 2024!

Web site

Conclusions

- **MUonE** proposes an **innovative and independent method** for the evaluation of the hadronic vacuum polarization term at LO a_μ^{HLO} which is alternative with the *previous ones*. Great possibility to *shade some light* on this intriguing **puzzle**!
- We are analysing the new Test Run data to determine the performance of the ECAL and understand its role for future tests and final experiment;
- *Test beams* and *data analysis* are carried out together with the **CMS Tracker group**. Results will be published in a *joint paper*;
- Next important step is **write** the technical proposal in 2024, with the full experiment setup and goals;
- An intermediate step before the final configuration → **10 tracking stations** before *LS3 (2026)*.

Thank you for the attention!

BACKUP

2018 MUONE TEST BEAM

G. Abbiendi et al., arXiv:2102.11111