

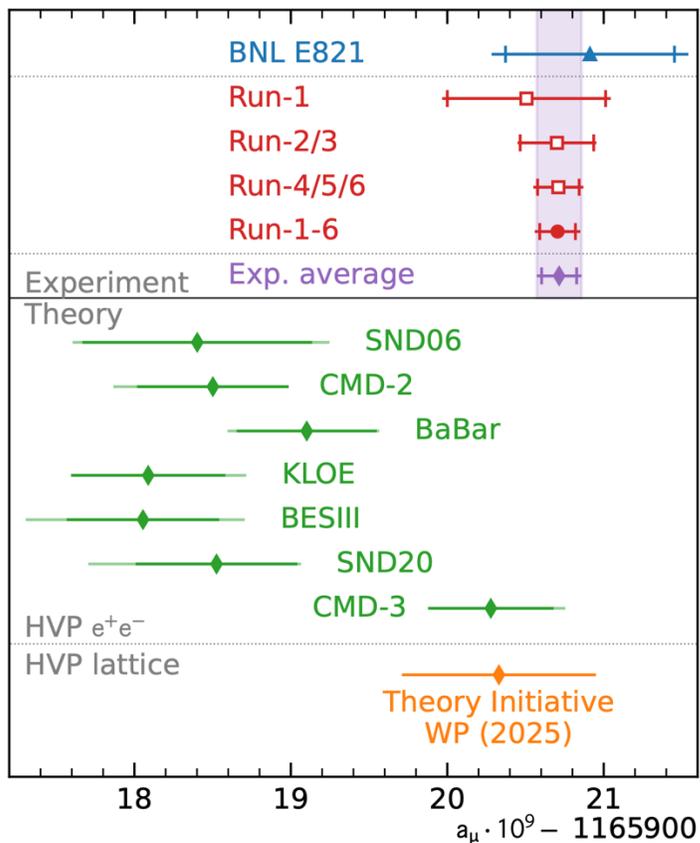
Status of the MUonE Experiment at CERN

Saskia Charity for the MUonE Collaboration

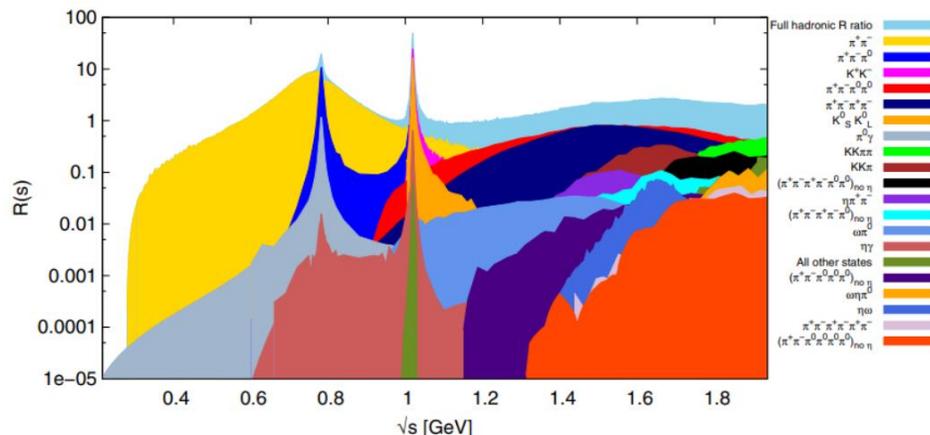
NuFACT 2025, Liverpool

2nd September 2025

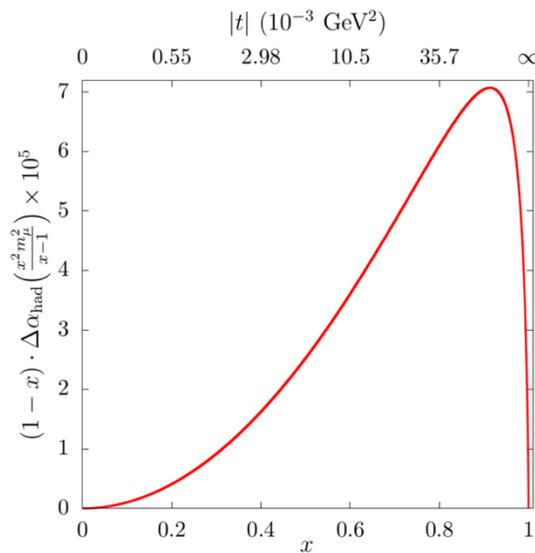
Why MUonE?



- Tension between data-driven and lattice determinations of SM prediction of a_μ
- Uncertainty dominated by non-perturbative hadronic vacuum polarisation (HVP) term



Dispersive approach:
many different
measurements,
resonances

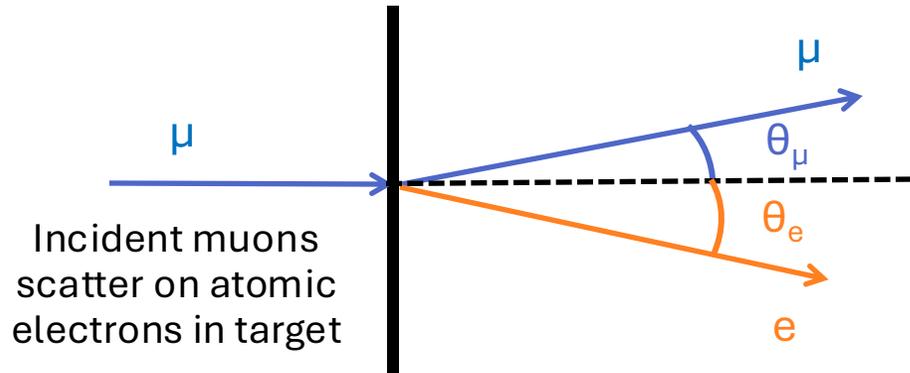


MUonE: single
measurement in the
spacelike domain →
smooth function

$$a_\mu^{HLO} = \frac{\alpha_0}{\pi} \frac{1}{2\pi} \int_0^1 dx (1-x) \Delta\alpha_{had}[t(x)]$$

Muon-electron elastic scattering $\mu e \rightarrow \mu e$

Measure the differential cross-section of the elastic process $\mu e \rightarrow \mu e$



Measure shape of differential cross-section

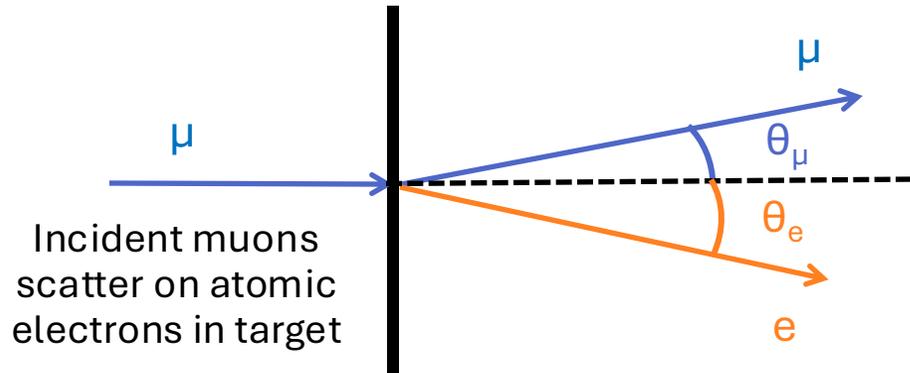
$$\frac{d\sigma}{dt} = \frac{d\sigma_0}{dt} \left| \frac{\alpha(t)}{\alpha(0)} \right|^2$$

t = four-momentum transfer

α = electromagnetic coupling constant

Muon-electron elastic scattering $\mu e \rightarrow \mu e$

Measure the differential cross-section of the elastic process $\mu e \rightarrow \mu e$



Measure shape of differential cross-section

$$\frac{d\sigma}{dt} = \frac{d\sigma_0}{dt} \left| \frac{\alpha(t)}{\alpha(0)} \right|^2$$

t = four-momentum transfer
 α = electromagnetic coupling constant

All terms except **hadronic** known extremely well

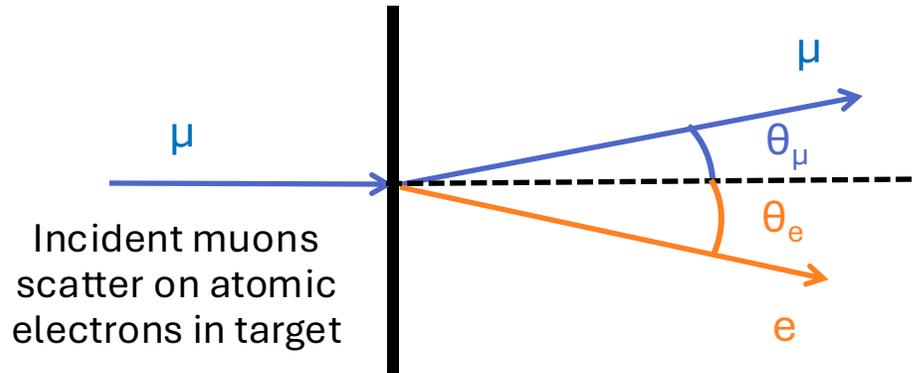
$$\alpha(t) = \frac{\alpha}{1 - \Delta\alpha(t)}$$

“Running” of α

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

Muon-electron elastic scattering $\mu e \rightarrow \mu e$

Measure the differential cross-section of the elastic process $\mu e \rightarrow \mu e$



Measure shape of differential cross-section

$$\frac{d\sigma}{dt} = \frac{d\sigma_0}{dt} \left| \frac{\alpha(t)}{\alpha(0)} \right|^2$$

t = four-momentum transfer
 α = electromagnetic coupling constant

All terms except hadronic known extremely well

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

“Running” of α

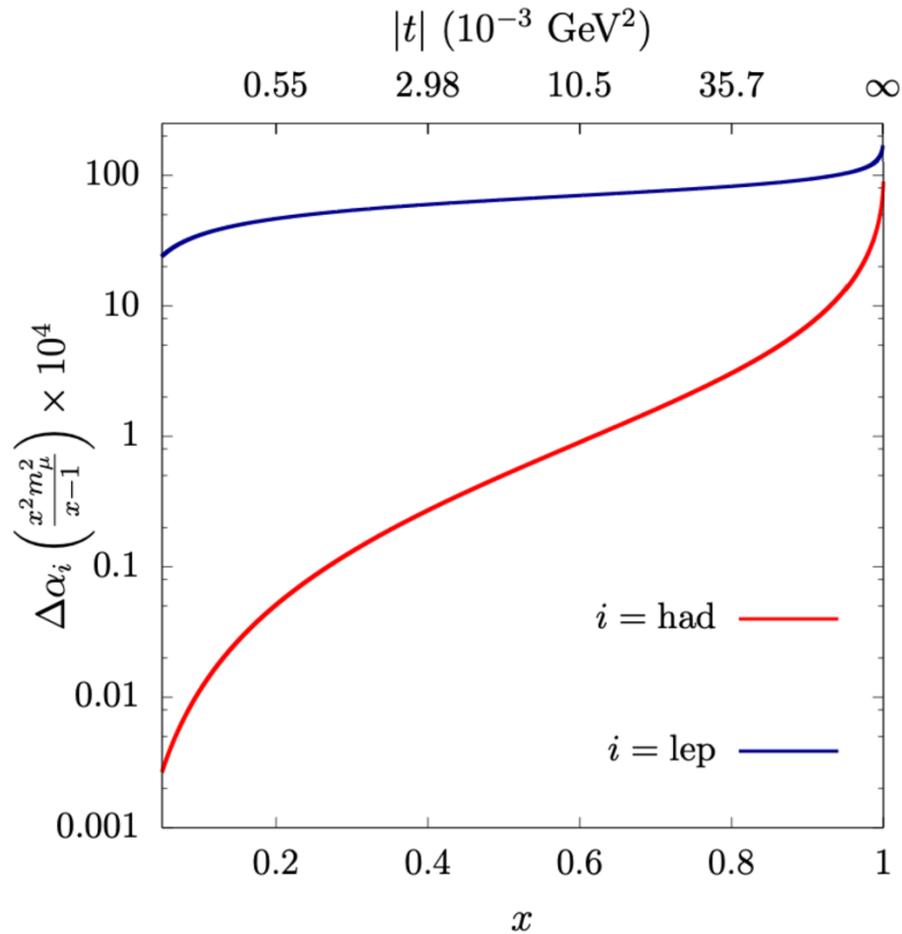
$$\Delta\alpha = \Delta\alpha_{lep} + \Delta\alpha_{had} + \Delta\alpha_{top} + \Delta\alpha_{weak}$$

$$R_{had}(t) = \frac{\text{measurement } d\sigma_{data}(\Delta\alpha_{had} \neq 0)}{\text{simulation } d\sigma_{MC}(\Delta\alpha_{had} = 0)} \approx 1 + 2\Delta\alpha_{had}(t)$$

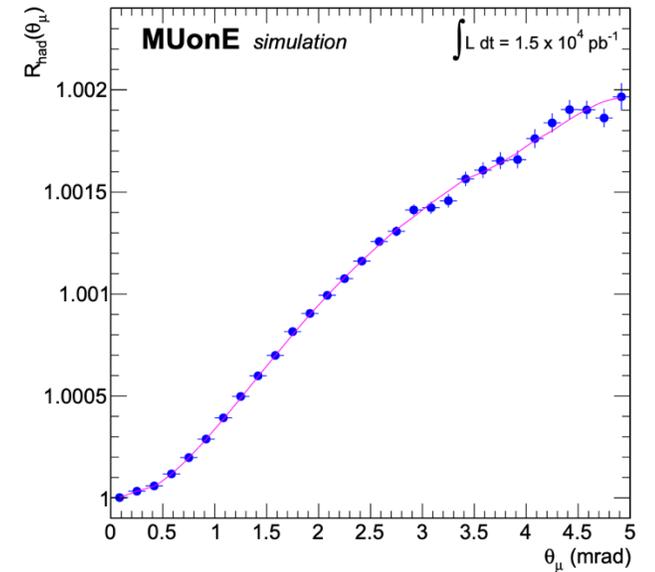
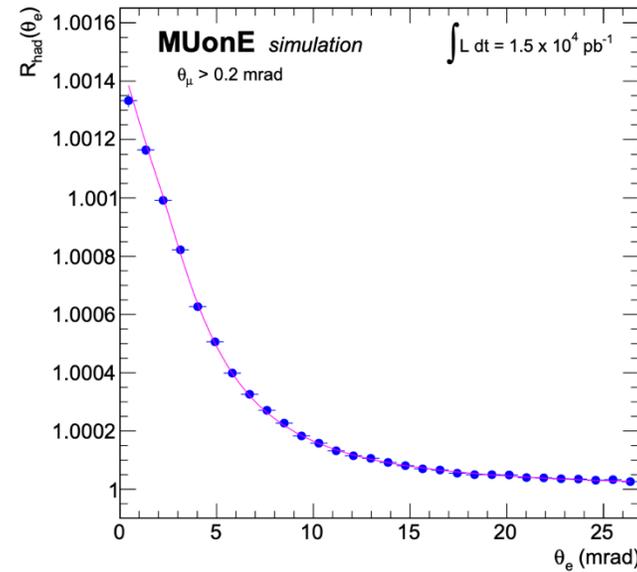
$$a_{\mu}^{HLO} = \frac{\alpha_0}{\pi} \frac{1}{2\pi} \int_0^1 dx (1-x) \Delta\alpha_{had}[t(x)]$$

a_{μ}^{HLO} depends directly on $\Delta\alpha_{had}$

Extraction of hadronic and leptonic running



Extract R_{had} via template fit to muon and electron angles



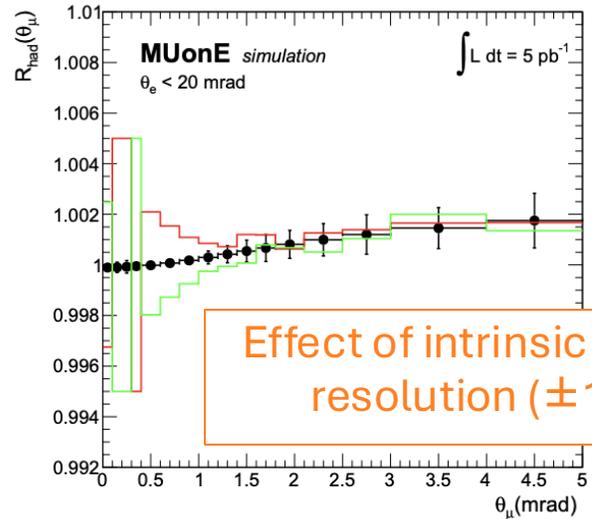
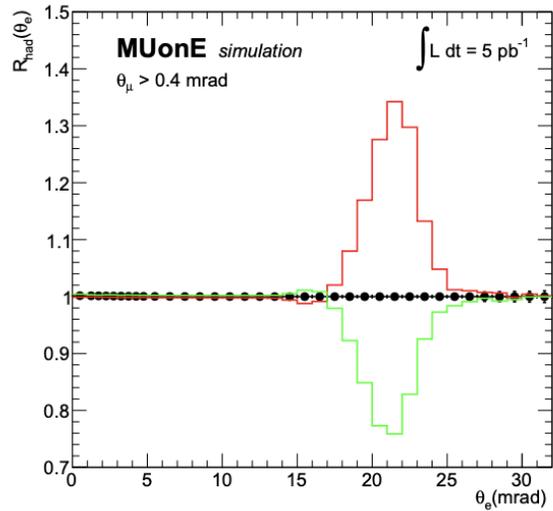
- Test measurement technique with $\Delta\alpha^{lep}$ measurement (well-known theoretically)

$$R_{had}(t) = \frac{d\sigma_{\text{data}}(\Delta\alpha_{had} \neq 0)}{d\sigma_{\text{MC}}(\Delta\alpha_{had} = 0)} \approx 1 + 2\Delta\alpha_{had}(t)$$

measurement

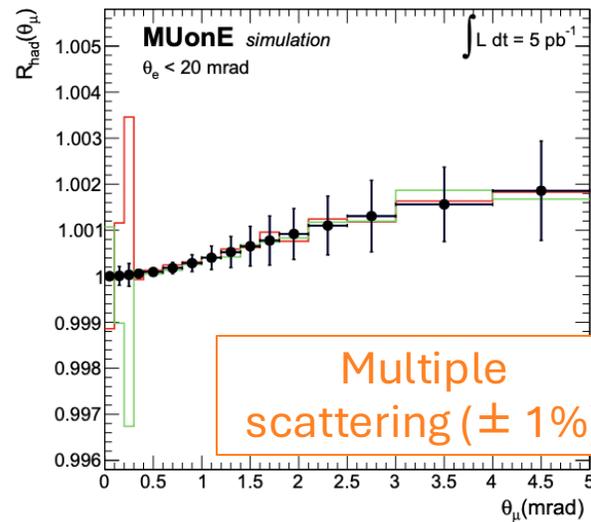
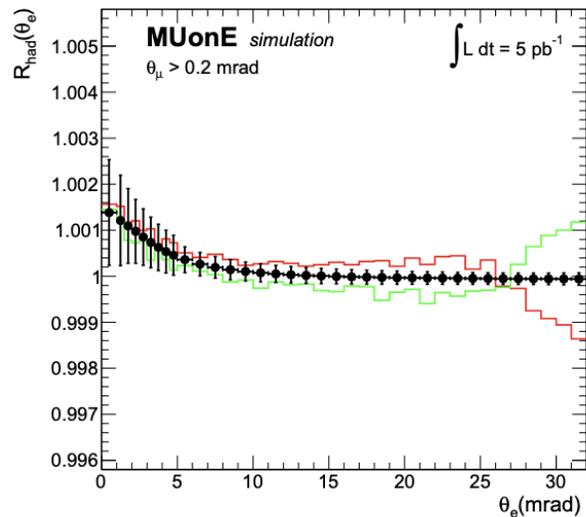
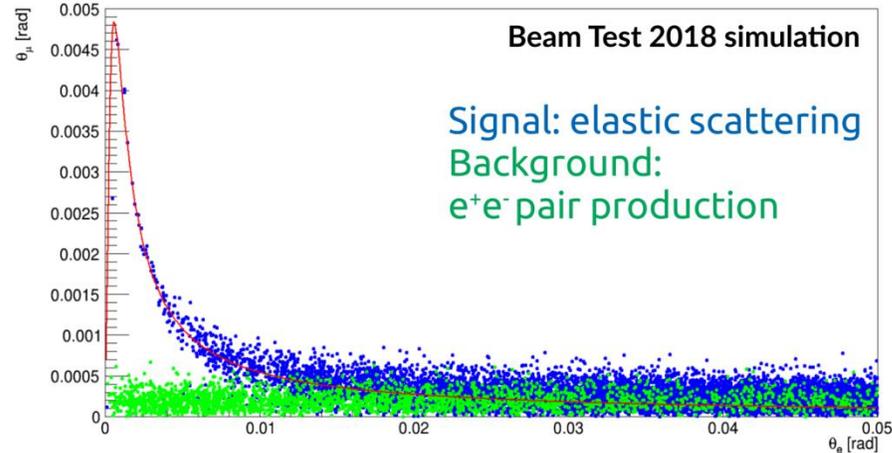
simulation

Backgrounds and systematic uncertainties

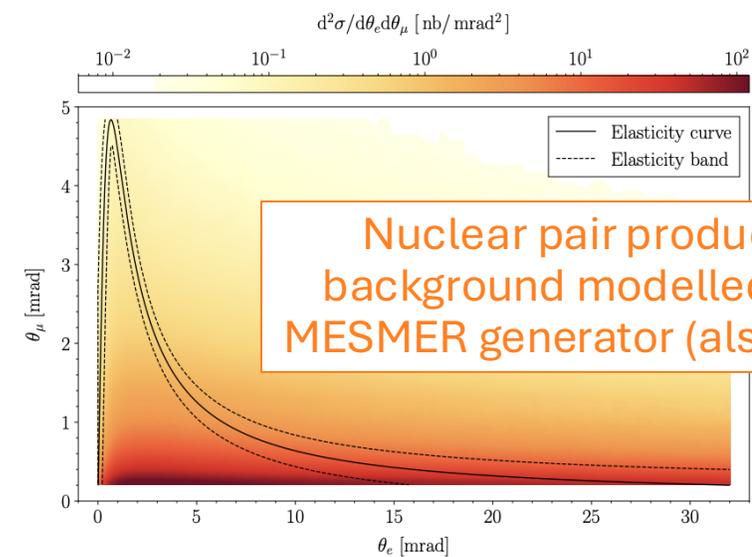


Effect of intrinsic angular resolution ($\pm 10\%$)

Dominant background: nuclear pair production



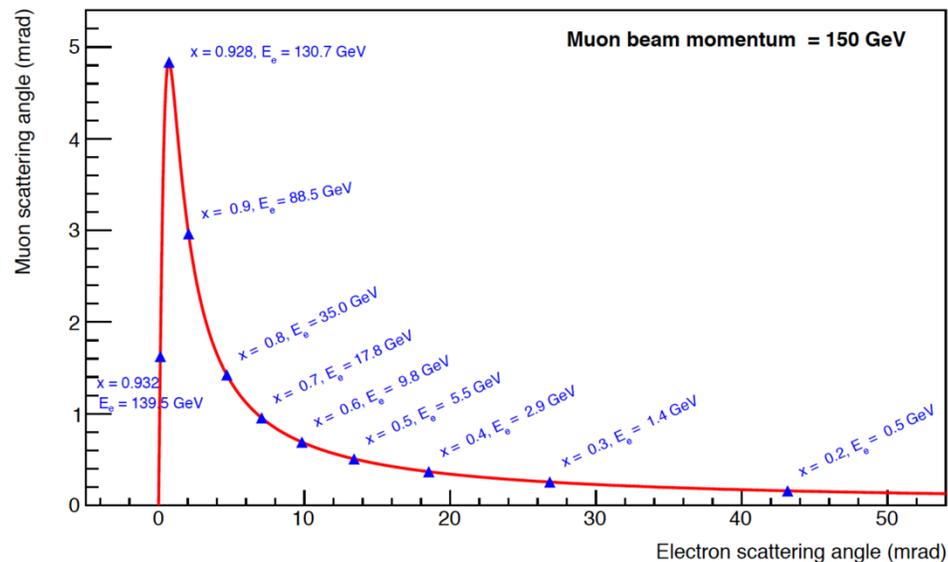
Multiple scattering ($\pm 1\%$)



Nuclear pair production background modelled using MESMER generator (also signal)

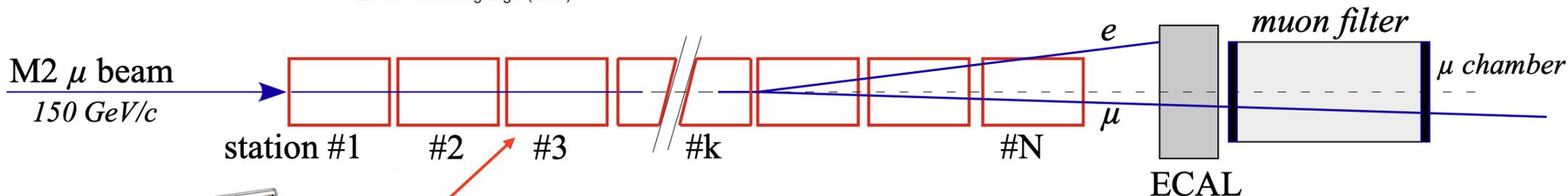
The MUnE Experiment at CERN

Elastic scattering: extract $\Delta\alpha^{\text{had}}$ from correlation between outgoing muon and electron angles

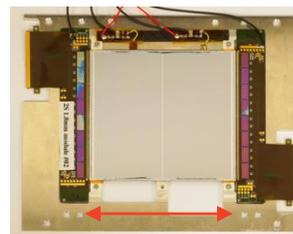
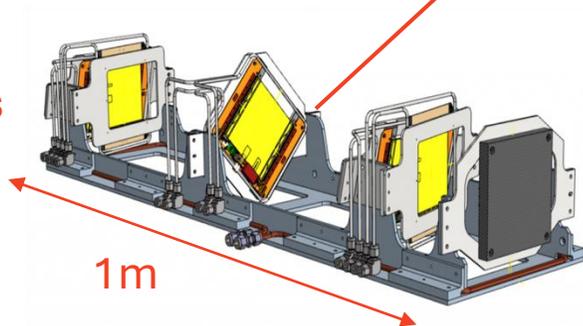


MUnE Goals & Timeline

- Post-LS3 (~2030): 40 stations, 3 years
 - Integrated luminosity $1.5 \times 10^7 \text{ nb}^{-1}$
 - Total target thickness 60 cm
 - Measure $\Delta\alpha^{\text{had}}$ to $<0.5\%$
- 10 ppm systematic uncertainty budget
 - 10 μm longitudinal alignment
 - Multiple Scattering 1%
 - Uniform efficiency over full energy range
 - Beam energy measured to $\sim\text{few MeV}$



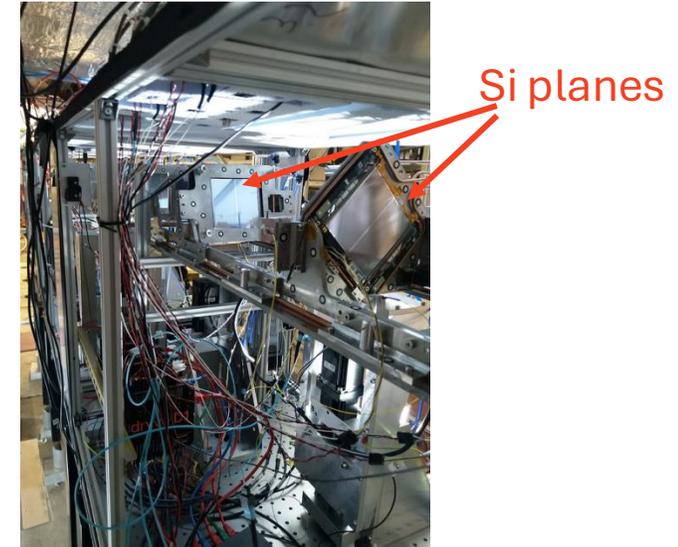
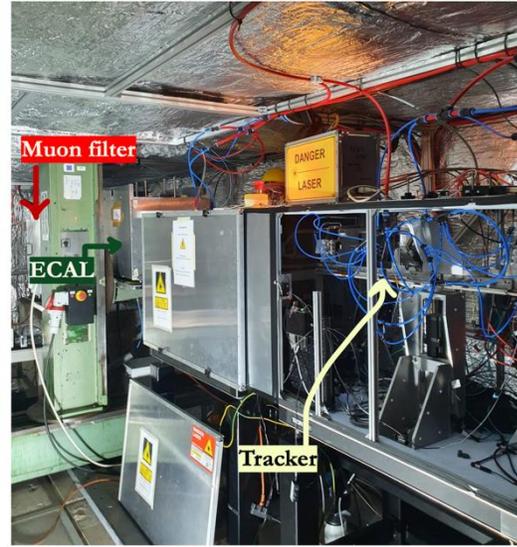
Single station: 6 Si planes



CMS 2S Silicon detectors

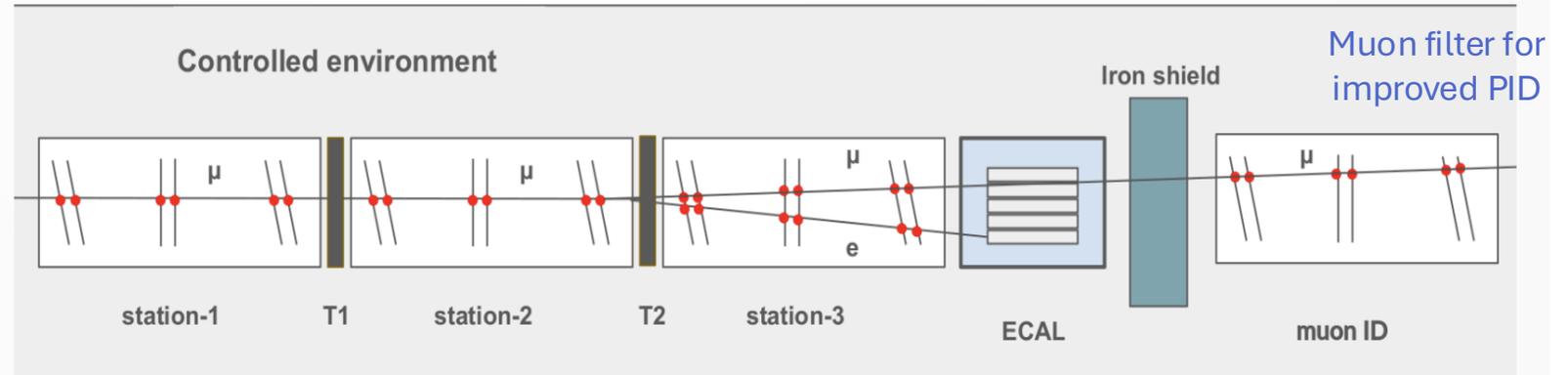
The 2025 MUonE Run

- 2025: 3 stations, 3 months (Jun – Aug)
 - All detector systems included
 - Full DAQ with all systems and full rate (40 MHz)
 - Online trigger to handle high rate
 - Proof-of-principle $\Delta\alpha^{\text{lep}}$ measurement to test full analysis chain
 - Aim preliminary measurement $\Delta\alpha^{\text{had}}$ to 20%



June-July 2025 Phase-I: 3 stations

BMS: upstream measurement of beam energy scale

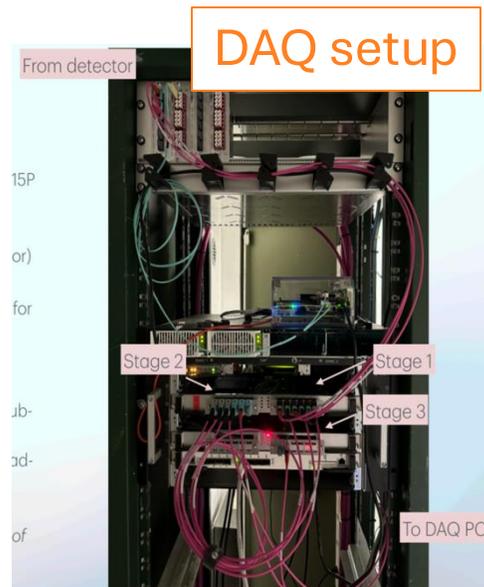


ECAL: PID, remove possible hadronic particle contamination

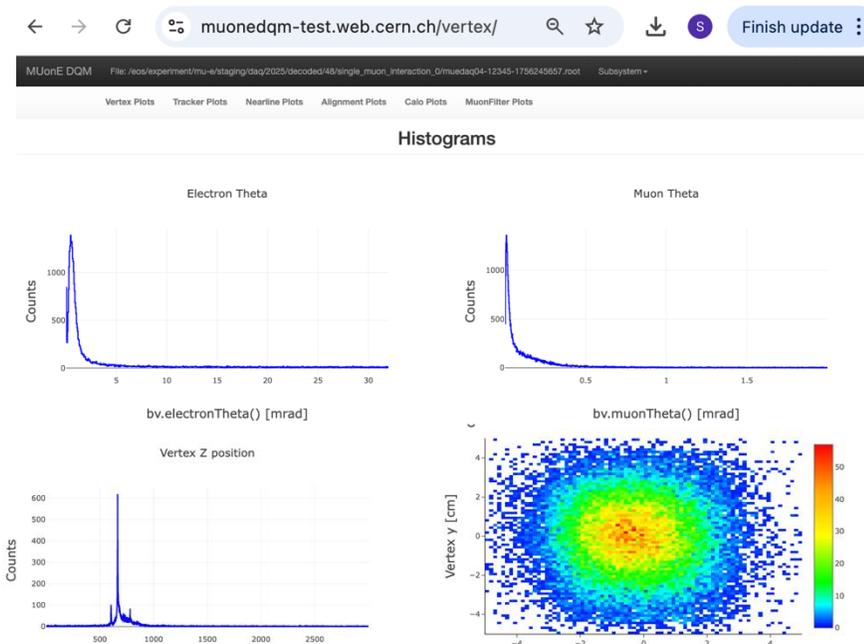
DAQ and DQM

DAQ rates and design

- Triggerless readout of all data at 40 MHz
- 36 LPGBT input links (30x 2S modules, 4x ECAL, 2x timing detector)
- Total throughput 180 Gb/s
- Stage 2: event building (4x 10 Gb/s ethernet links to DAQ PCs)
- Online DQM hosted on CERN's Platform-as-a-Service (based on plotly/JavaScript/HTML)



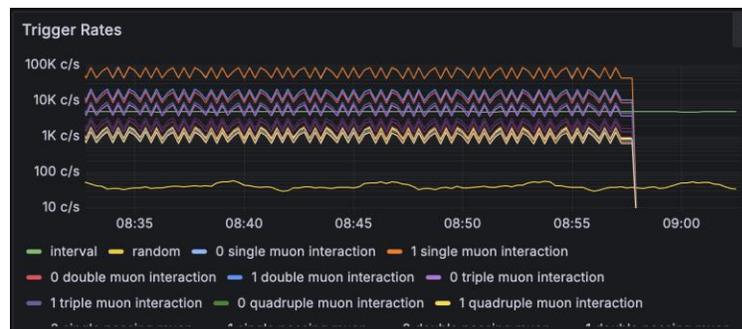
DAQ setup



Online DQM

2025 Test Run DAQ

- 2025 Run: first test of all systems included in DAQ with final design configuration and rate
- First test of online event selection based on event topologies (selecting scattering events)

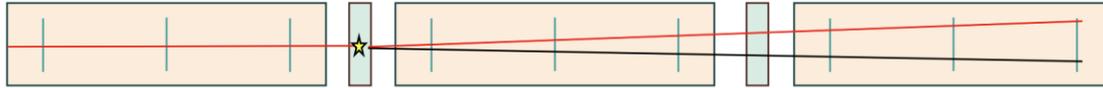


DAQ monitoring

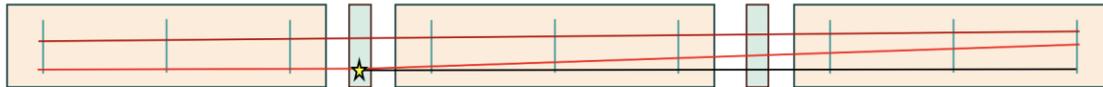
Online event selection (topology-based trigger)

Event topologies for 2025 run online trigger

- Single muon interaction first (in the example) /second target



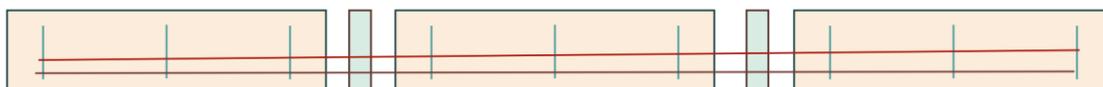
- Pileup muon interaction first (in the example) /second target



- Single passing muon station 1 && 2 / 2 &&3

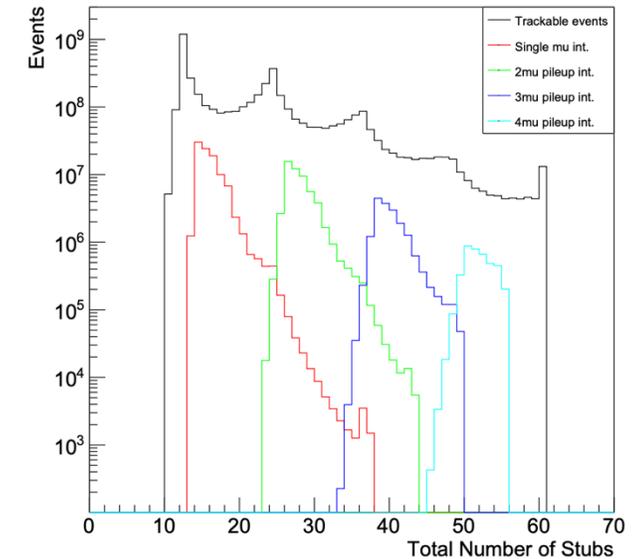


- Pileup passing muon station 1 && 2 / 2 &&3



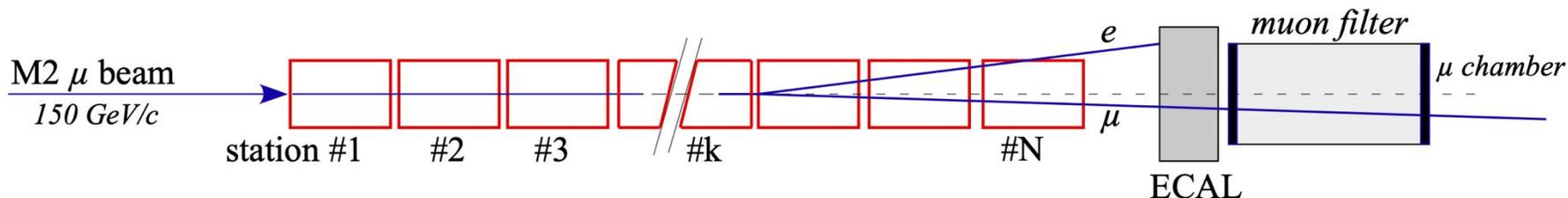
- In 2023 test run: triggerless DAQ, all events recorded
- Skim selections: keep 1-2 % of recorded events
- In 2025: apply these selections **online** (FPGA)

Skimming rates from 2023 test run data

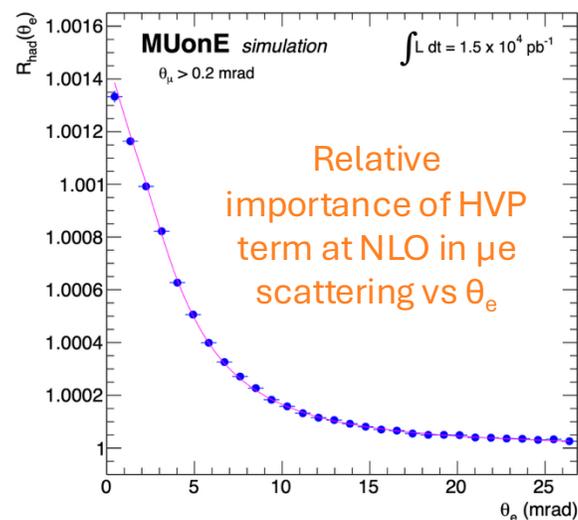
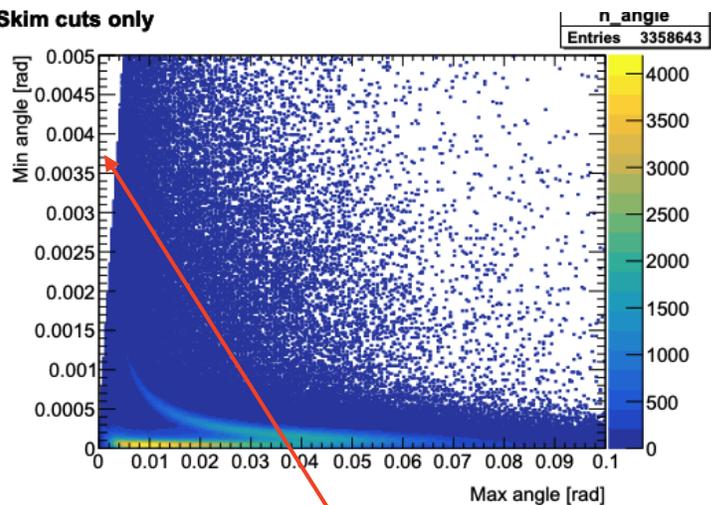


multiplicity	selected fraction	expected output rate (MHz)
1	0.023	0.3
2	0.012	0.1
3	0.004	0.02
4	0.0009	0.001
≥ 4	0.008	0.012

Particle Identification (PID)



Skim cuts only

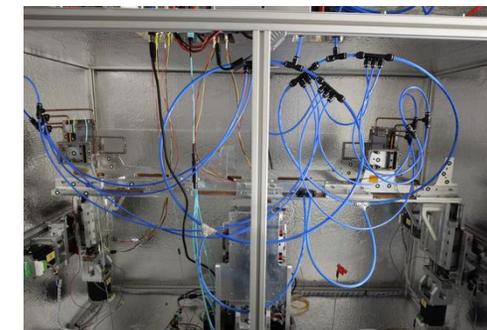


ECAL



25 PbWO_2 crystals, $\sim 25 X_0$

Muon Filter



4 planes (2 XY) of Si (same as tracker)

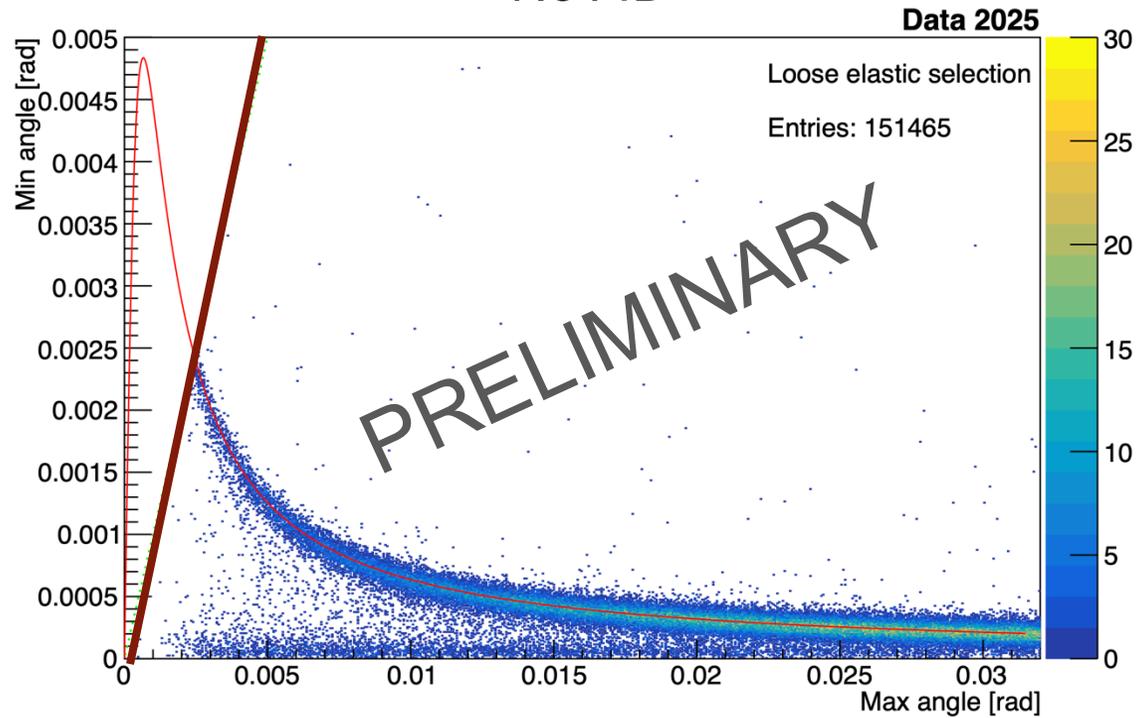
- Without PID, can misidentify events where $\theta_e < \theta_\mu$
- Important part of signal curve
- Two detectors for PID: **ECAL** and **muon filter**

ECAL also provides:

- Independent measurement of electron energy
- Direct identification of radiative events (+ photon)
- Background and systematics studies

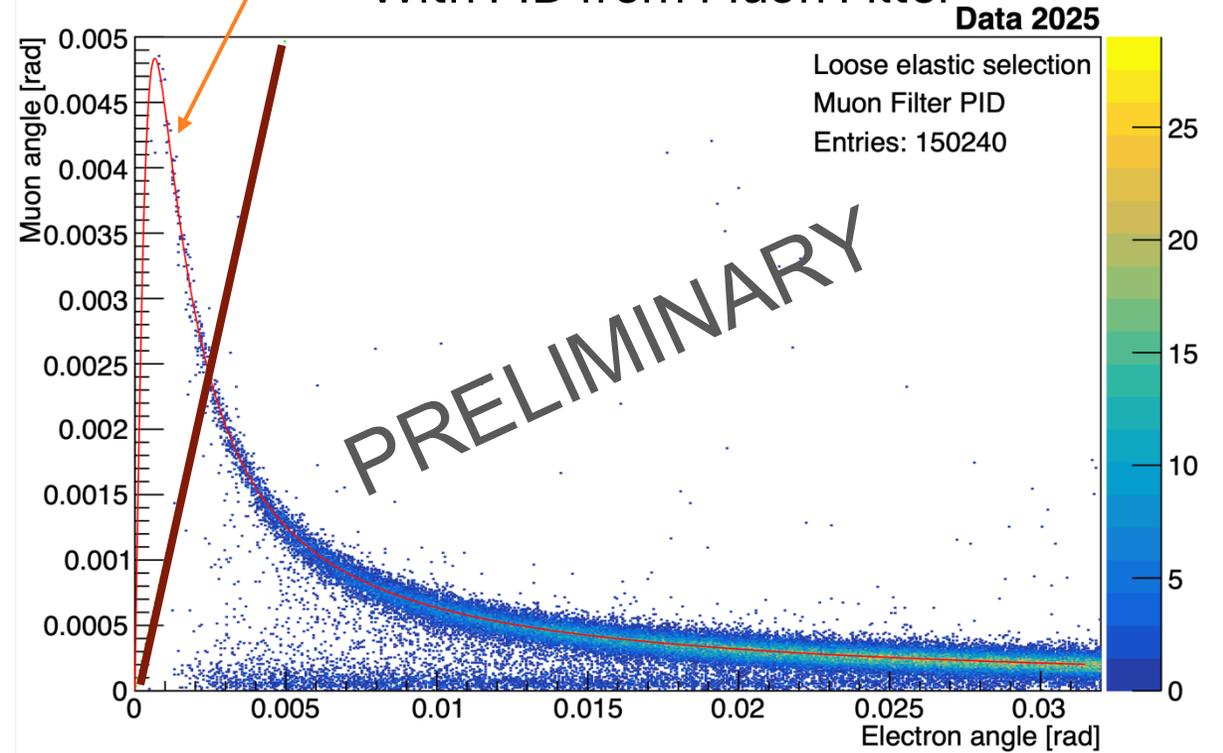
Test Run 2025: (Very) Preliminary Analysis

No PID



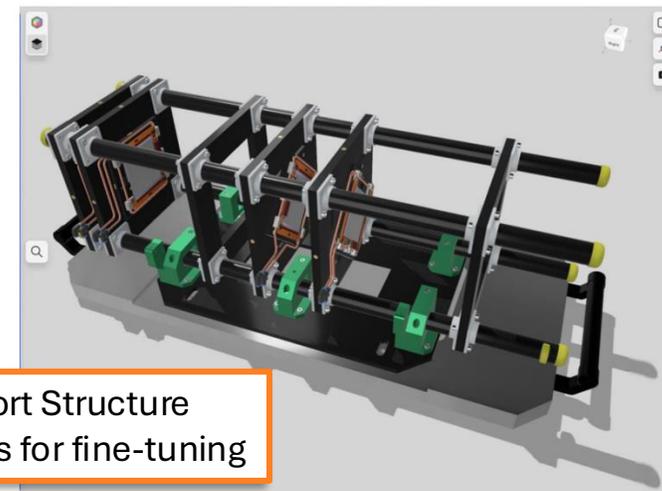
Events in
ambiguity region
thanks to PID

With PID from Muon Filter

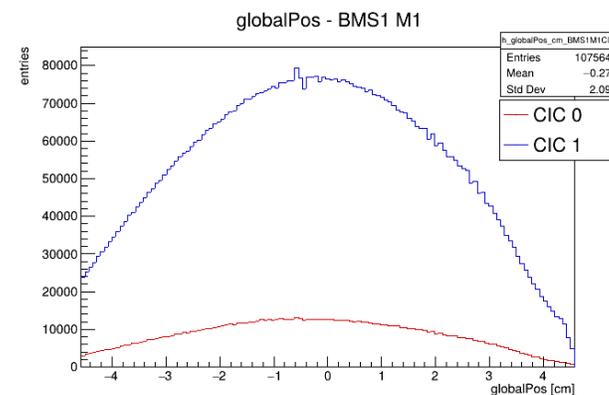
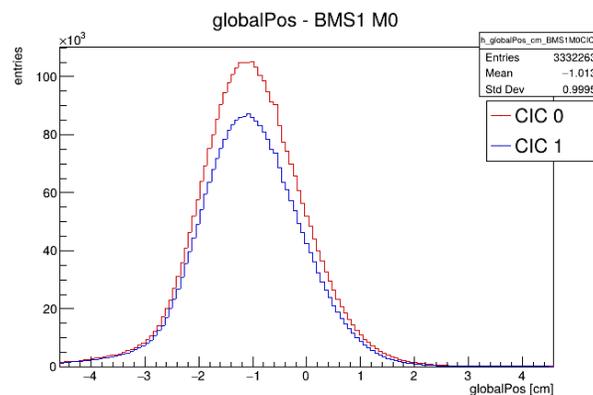


Beam Momentum Spectrometer (BMS)

- Event-by-event measurement of incoming beam momentum
- **Two locations** (before/after M2 bending magnets)
- For 2025, same sensors & readout as main tracker (CMS 2S)
- **Modular design** – different number of layers, different orientations,
- **Removable plate** accurate to \sim few μm , mount on fixed plate
- Sliding **CF plate** for fine-tuning yaw adjustment, CTE stability



Installing the BMS at CERN



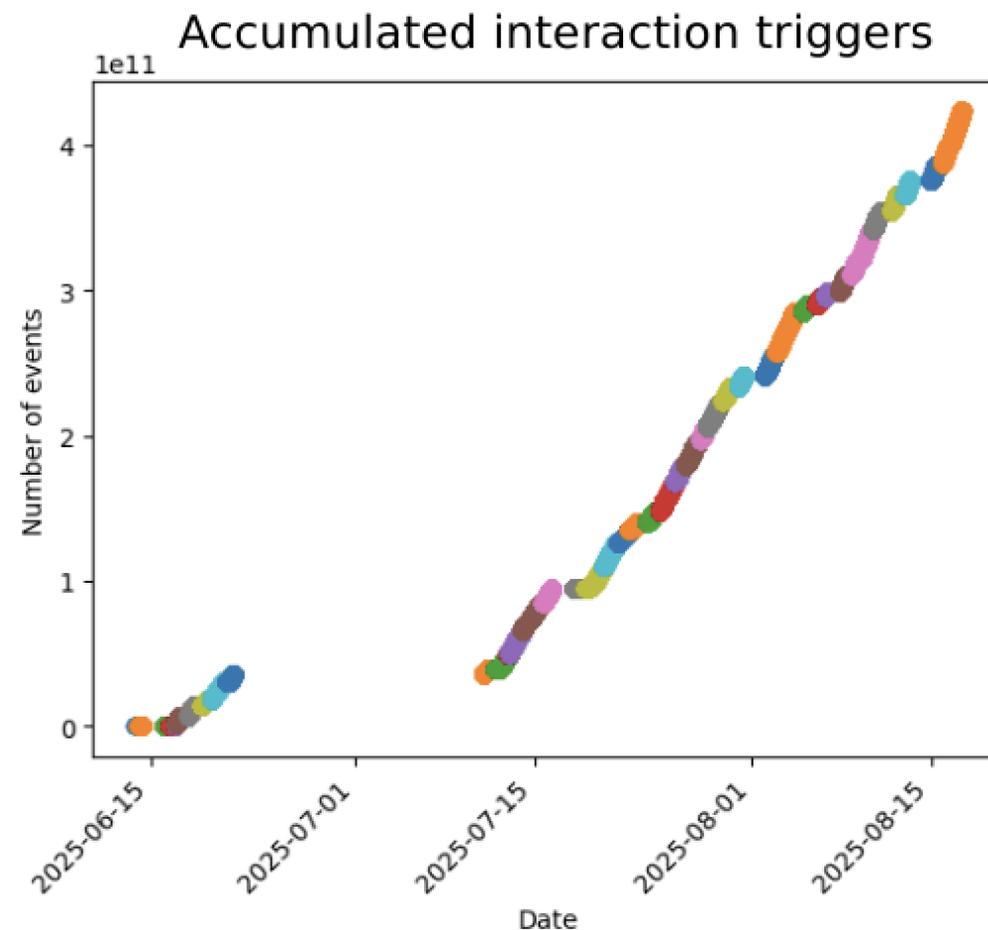
BMS beam profiles



Mounting a 2S module in the BMS CF structure

Summary and Next Steps

- MUonE 2025 Test Run coming to an end
- Successful 3 months running with 3 stations (2 targets)
 - Apparatus still in place – running opportunistically
- $\sim 4 \times 10^{11}$ scattering events (passing interaction trigger) recorded
- Stable DAQ at 40 MHz for the full test run
- Full machinery tested
 - All subdetectors included
 - Online FPGA trigger for scattering events
 - Online DQM
 - Central reconstruction for efficient data production
- Analysis campaign underway
 - First goal: measure $\Delta\alpha^{\text{lep}}$ for proof-of-principle
 - Preliminary measurement of $\Delta\alpha^{\text{had}}$



Phase-I proposal

<https://cds.cern.ch/record/2896293/files/SPSC-P-370.pdf>

Publications & documentation

<https://web.infn.it/MUonE/documents/>

Thank You

