UNIVERSITY OF LIVERPOOL

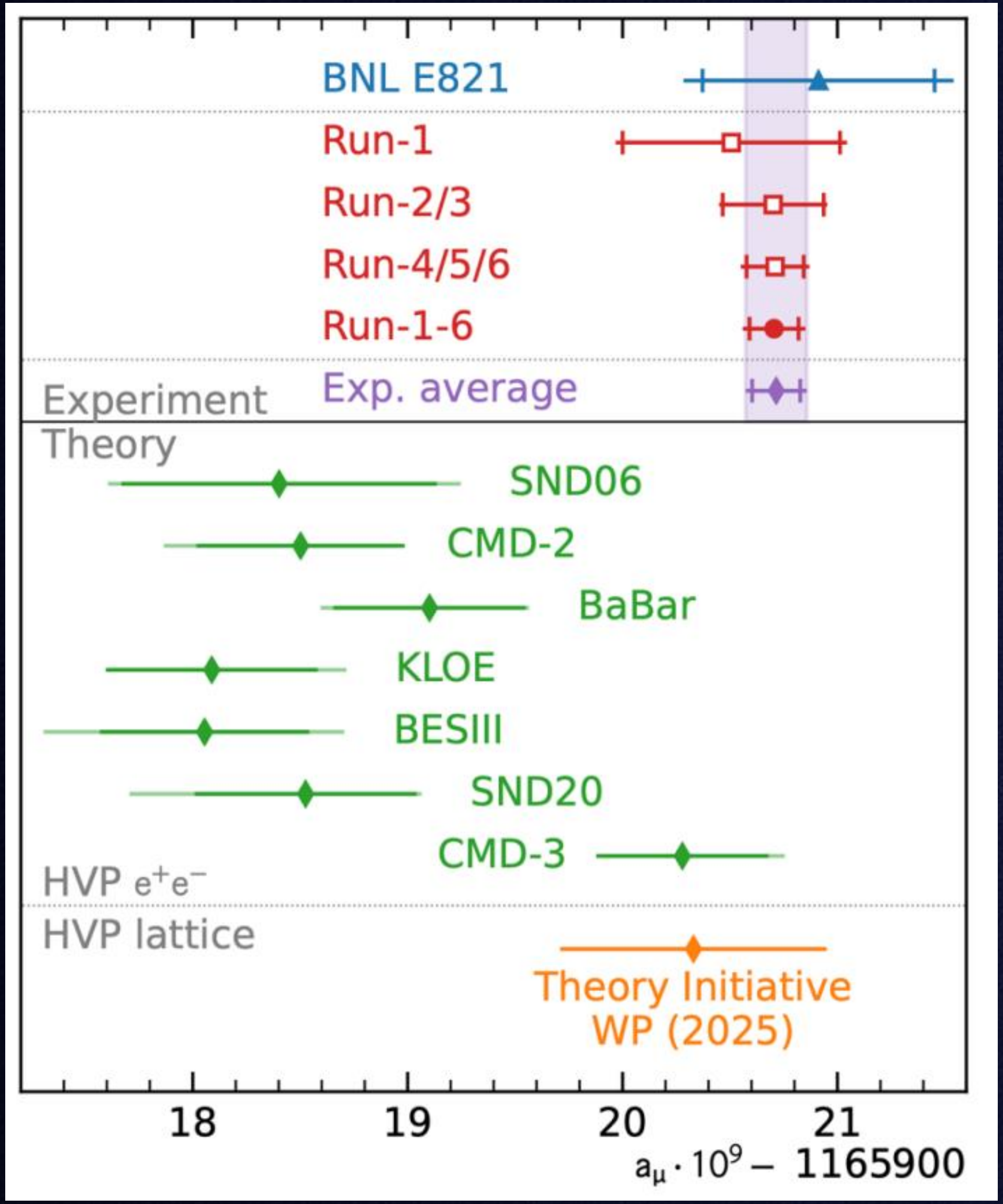
LEVERHULME TRUST

MUonE - 2025 run

Status of the experiment

Clément Devanne

a_μ^{HLO} : Status



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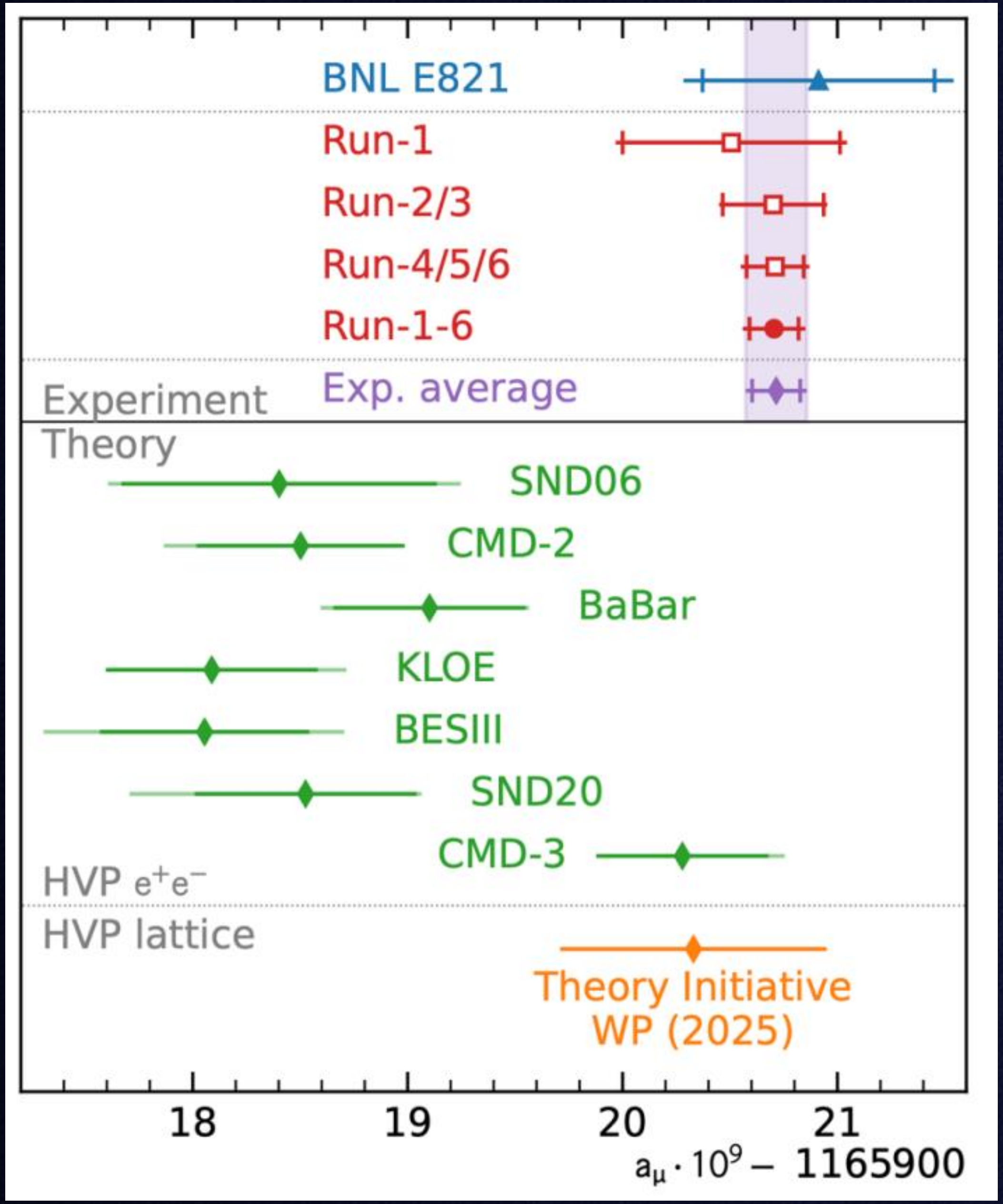
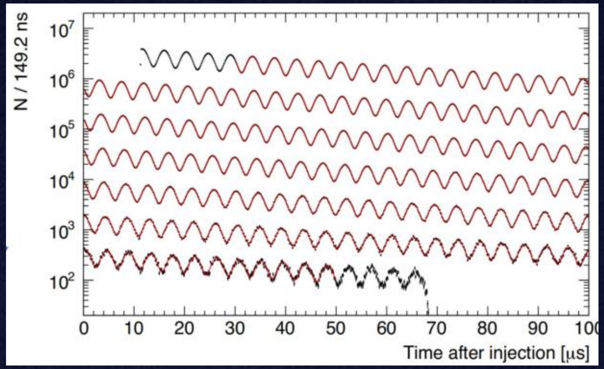


g-2 experiment



$$a_\mu \equiv \frac{g_\mu - 2}{2} \qquad a_\mu^{\rm SM} = a_\mu^{\rm QED} + a_\mu^{\rm EW} + a_\mu^{\rm had}$$

$$\vec{\omega}_a = \frac{e}{m}\left[a_\mu \vec{B} - \left(a_\mu - \frac{1}{\gamma^2 - 1}\right)(\vec{\beta} \times \vec{E})\right]$$

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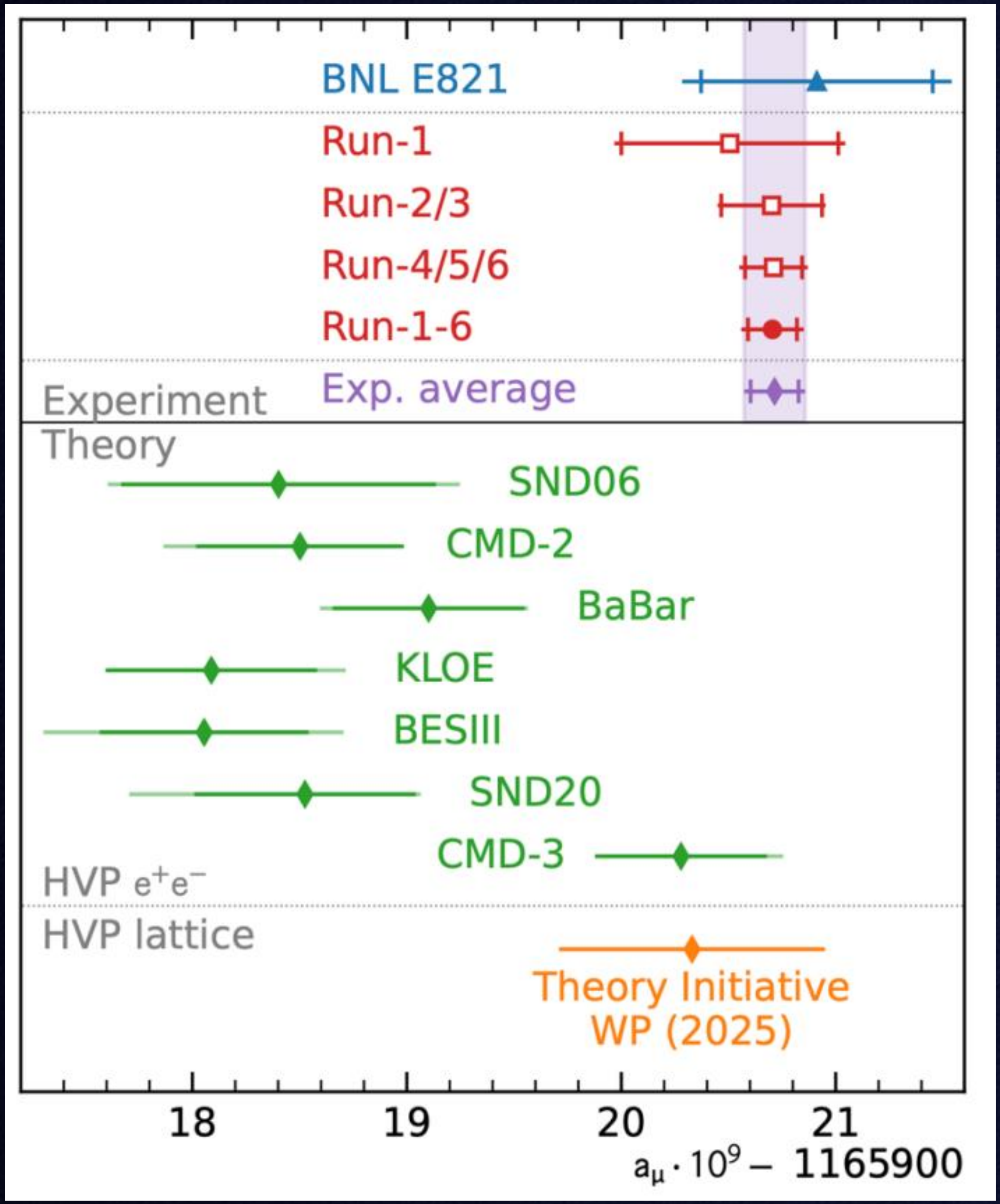

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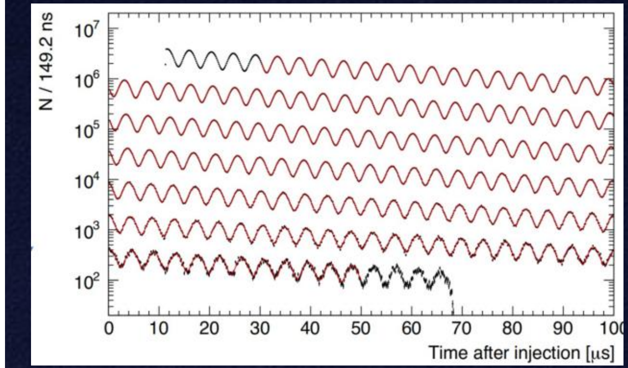

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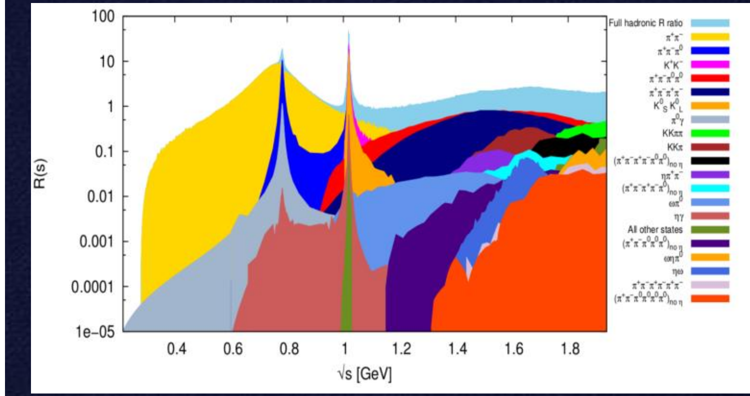
Dispersive approach

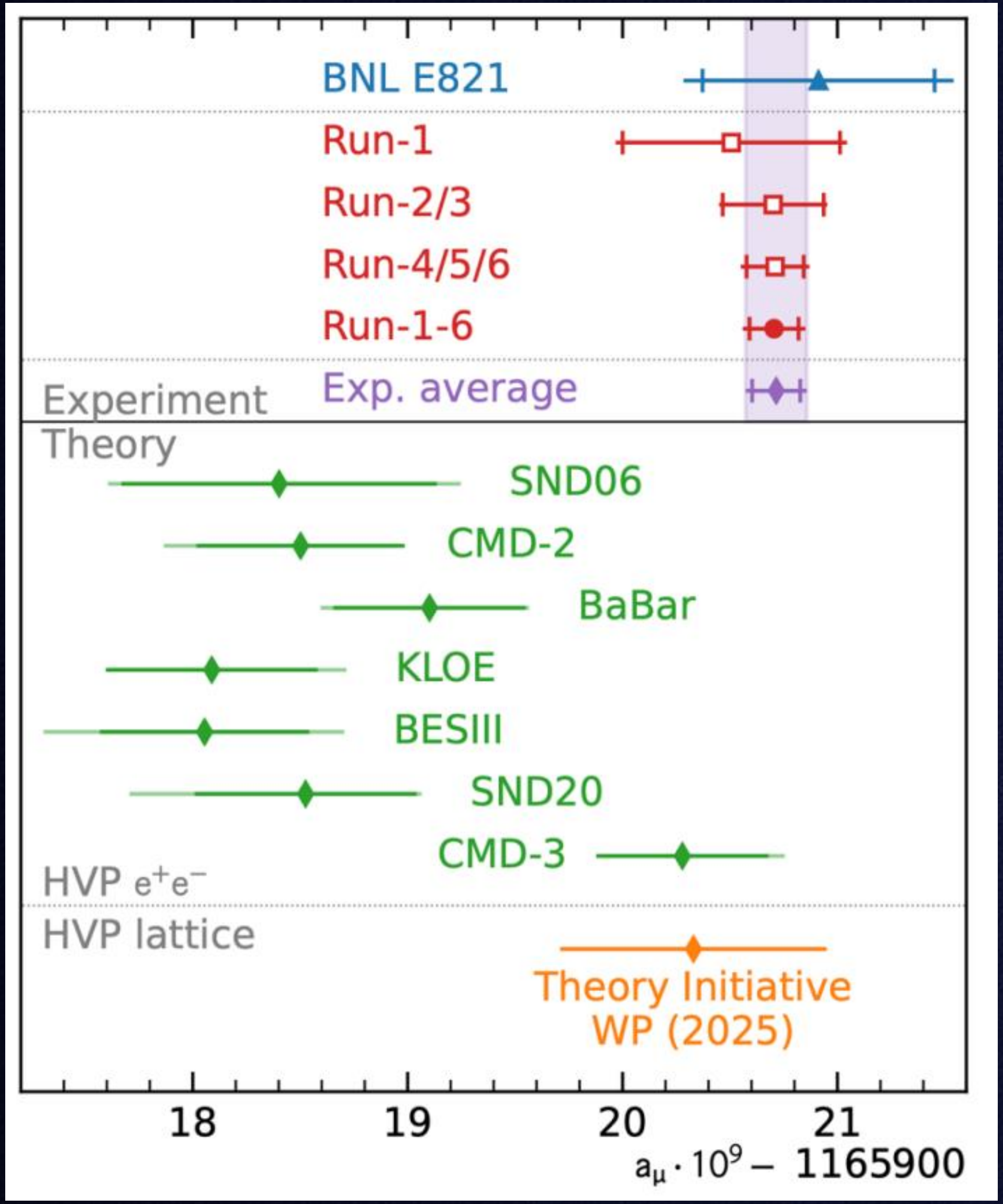


$$a_\mu^{\rm HLO} = \frac{\alpha^2}{3\pi^2} \int_{m_{\pi^0}^2}^{\infty} ds \, \frac{K(s)}{s} R(s)$$

$$R(s) = \frac{\sigma(e^+e^- \to {\rm hadrons})}{\sigma(e^+e^- \to \mu^+\mu^-)}$$

- *Merges different measurements*
- *Resonances*
- *Tension between CMD-3 and others*

a_μ^{HLO} : Status



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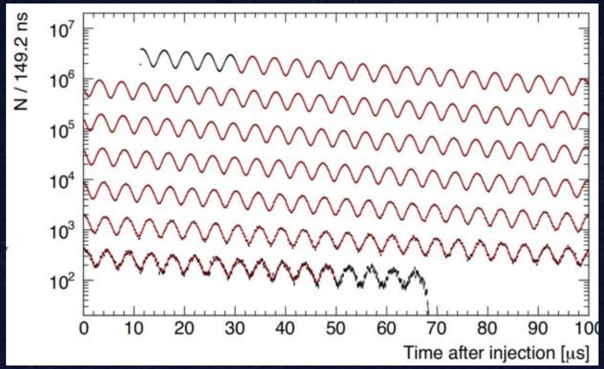

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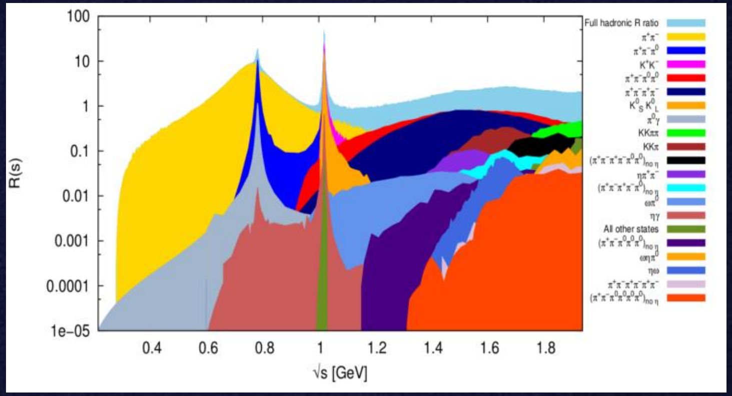

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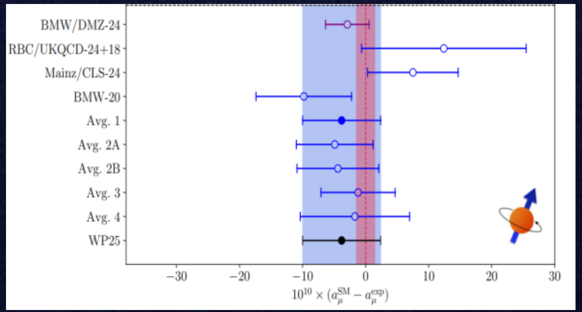
Lattice QCD



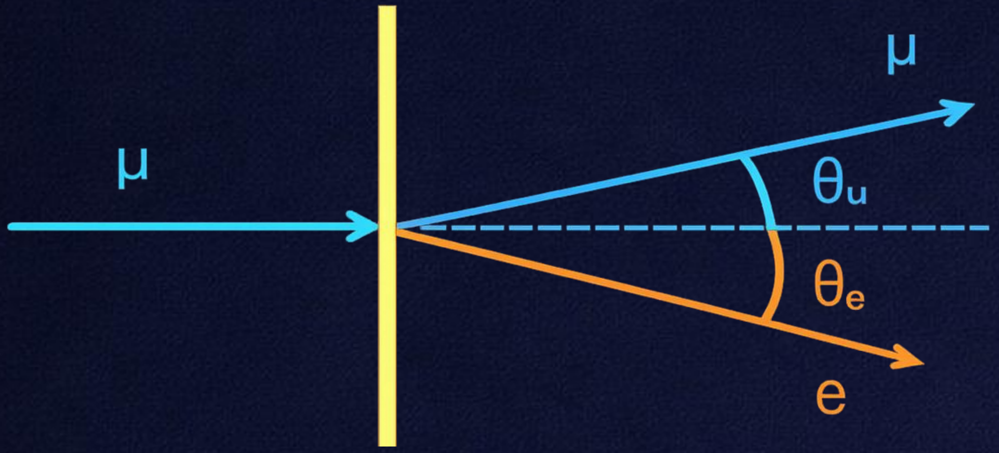
$$a_\mu^{HVP,LO} = 4\alpha_{em}^2 \int_0^\infty dQ^2 \, \frac{1}{Q^2} \, f\left(\frac{Q^2}{m_\mu^2}\right) \left[\Pi(Q^2) - \Pi(0)\right]$$

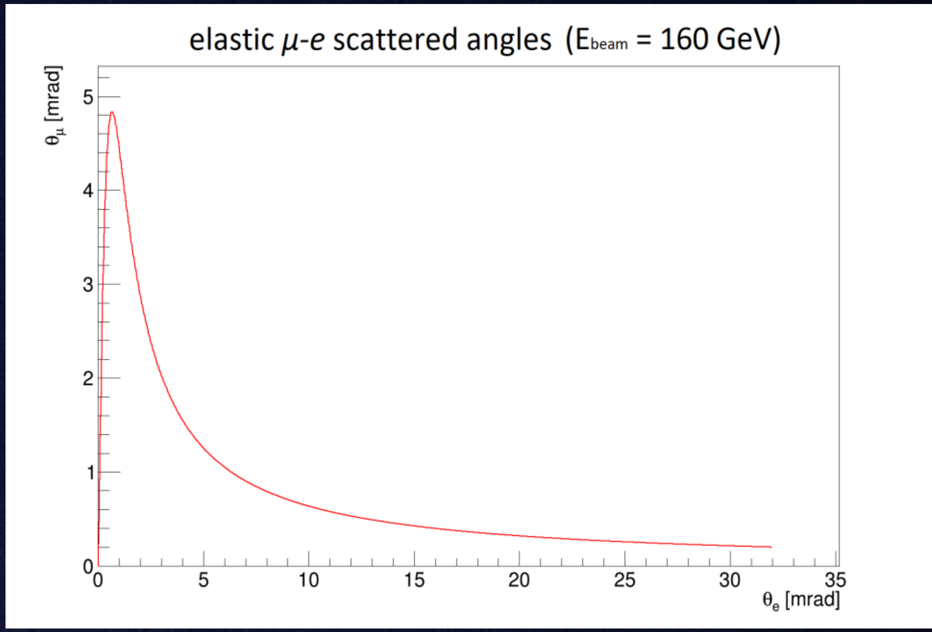
$$a_\mu^{HVP,LO} = 4\alpha_{em}^2 \int_0^\infty dt \, \tilde{f}(t) \, V(t)$$

- *Discretize spacetime*
- QCD path integral numerically

a_μ^{HLO} : MUonE

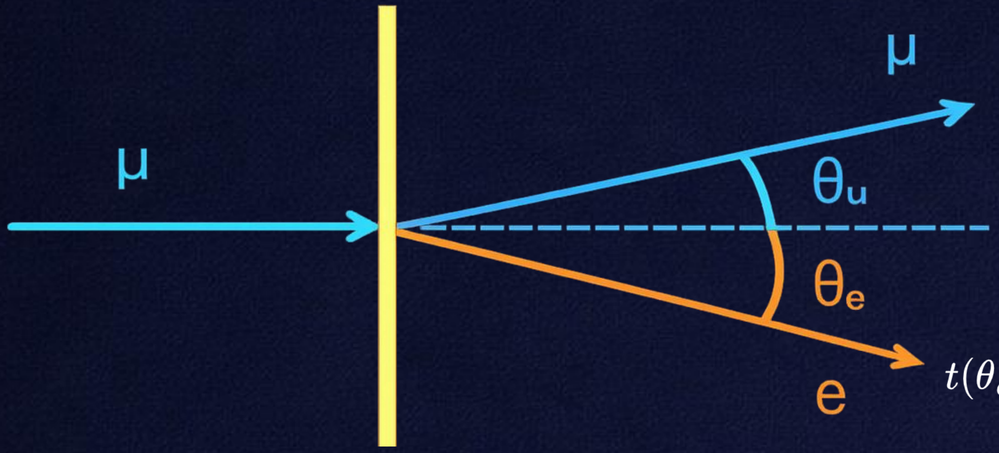
Measure the differential cross-section of the elastic process $\mu e \to \mu e$



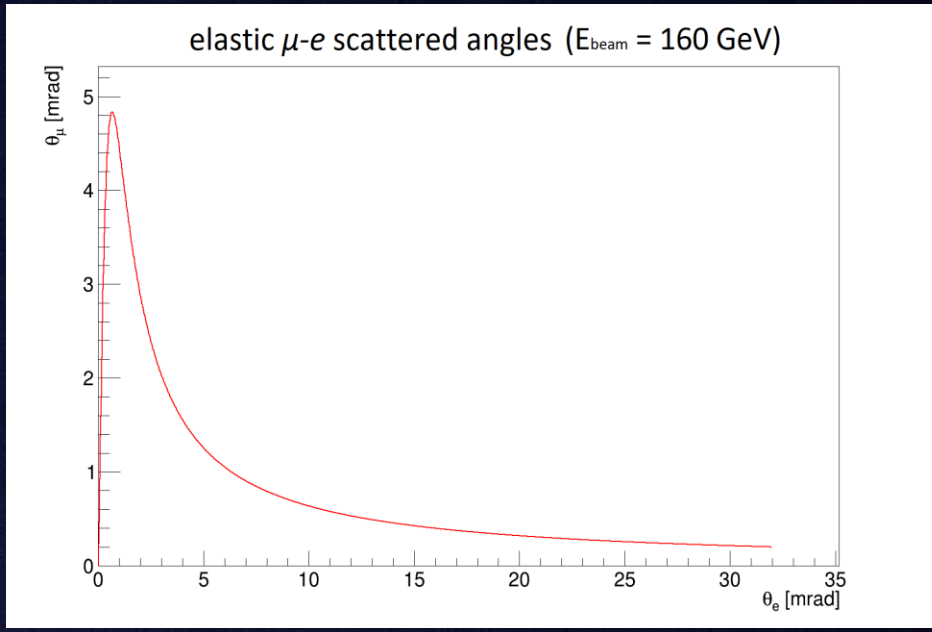


a_μ^{HLO} : MUonE

Measure the differential cross-section of the elastic process μe → μe

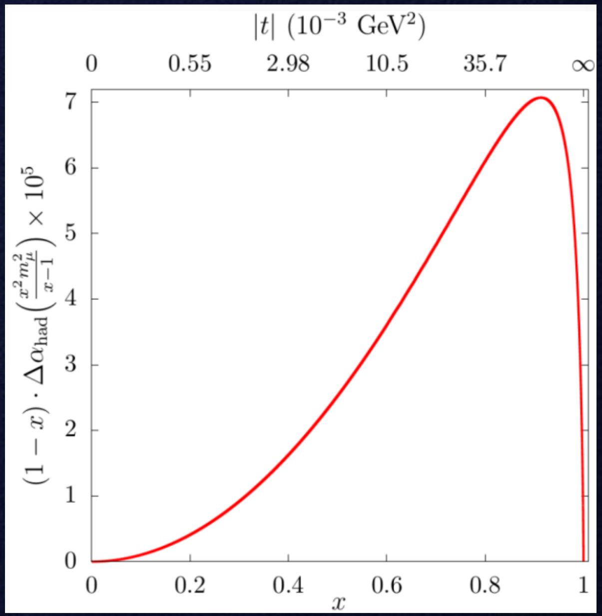


$$t(\theta_e) = \frac{4m_e^2 r^2 \cos^2\theta_e}{r^2\cos^2\theta_e - 1}$$



The experiment directly probes the hadronic contribution to the running of α

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



Δα is a smooth function free of resonances

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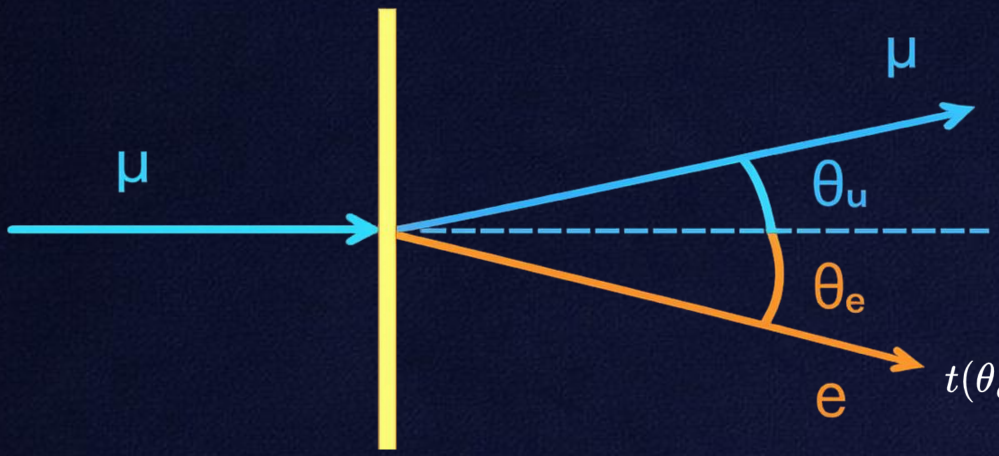

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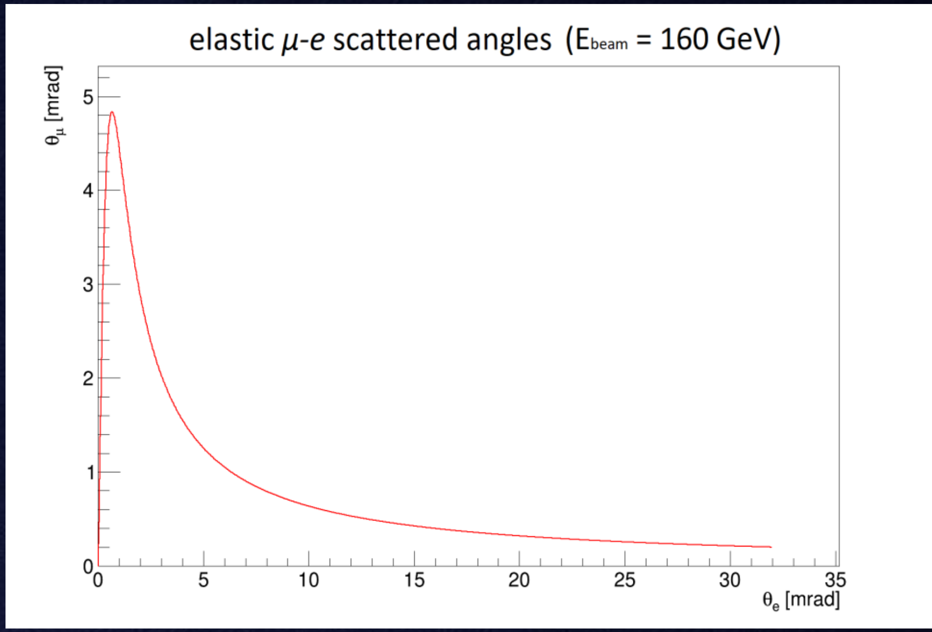

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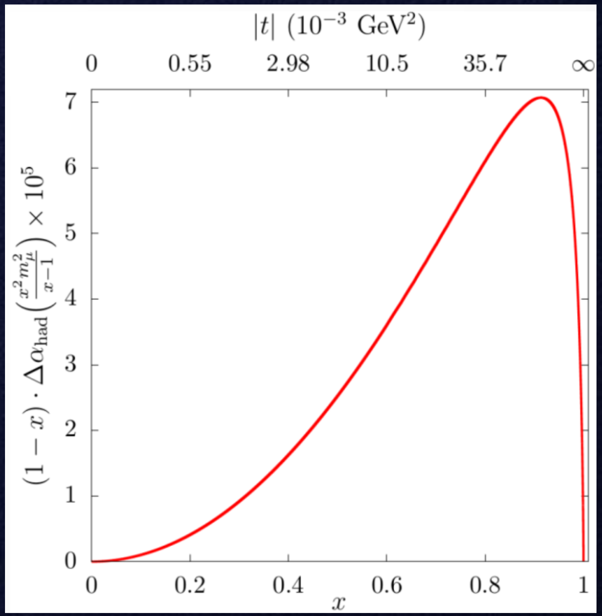
We can therefore extract

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



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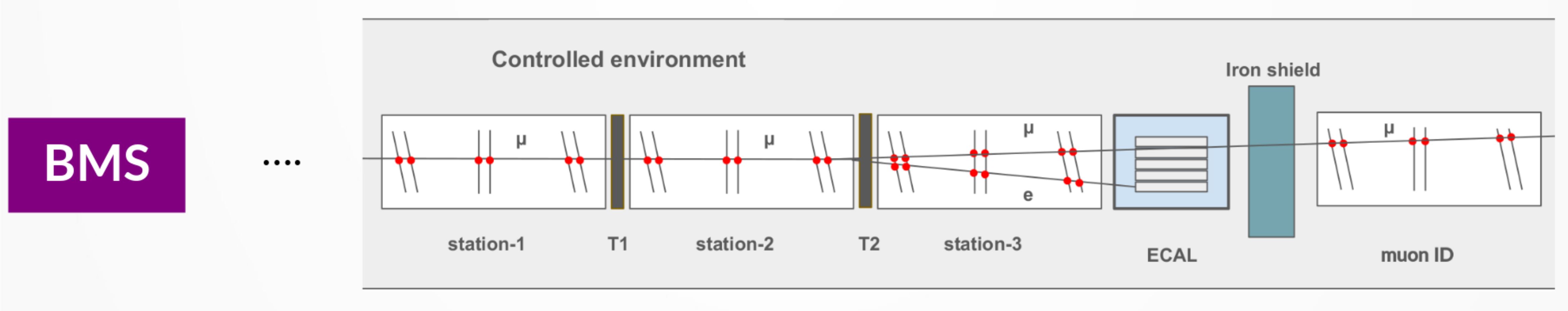
MUonE: Setup for 2025 testrun

We aim to measure the angular differential cross section, using the scattered muon and electron angles



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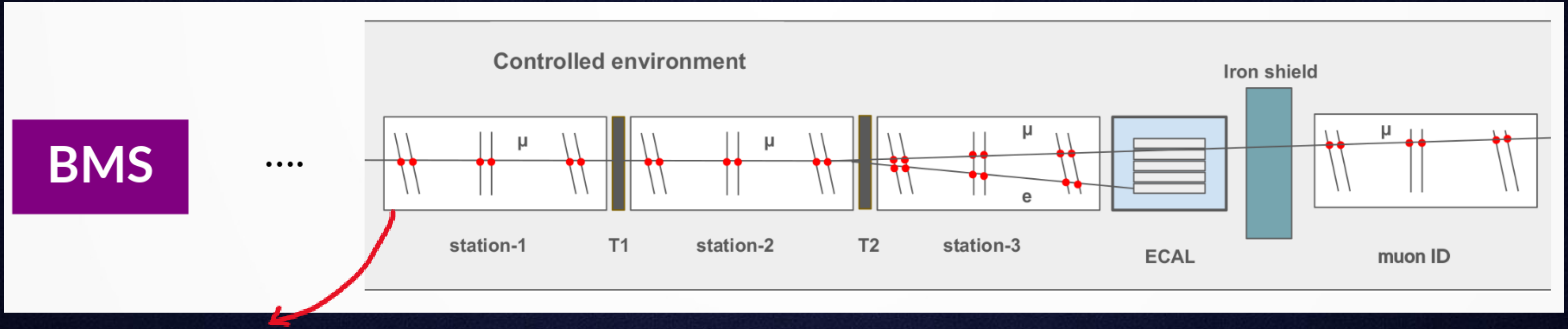
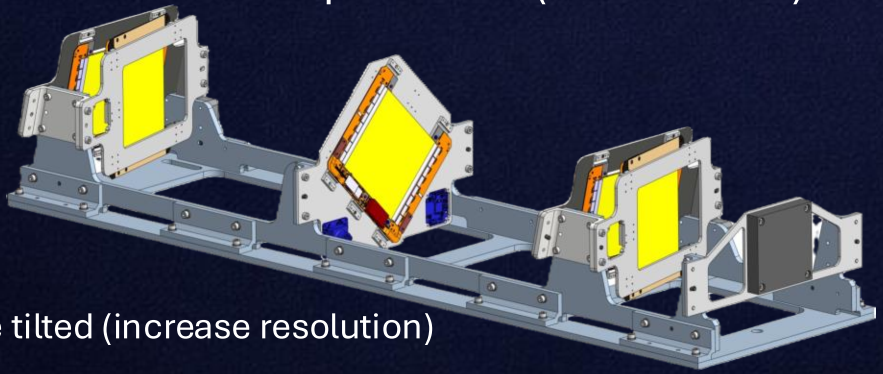


Tracking station:

- Telescope made of 6 silicon strip sensors (2S modules)
- X Y - U V - X Y
- X and Y modules are tilted (increase resolution)



Final experiment will have ~40 stations

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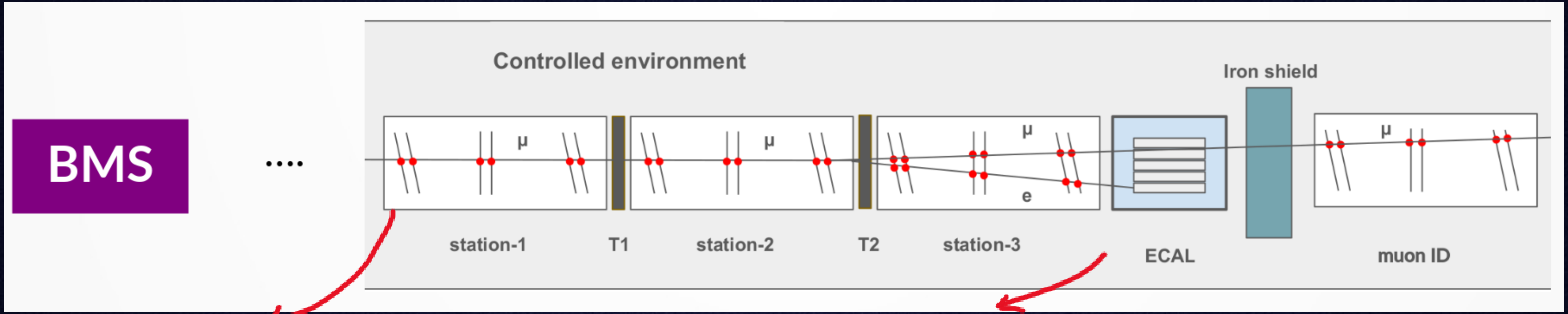

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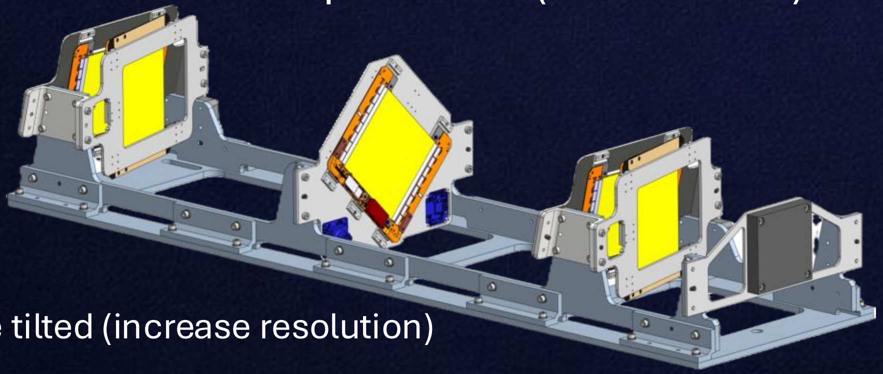

ECAL

- 5x5 array of $PbWO_4$ crystals
- improved PID
- Remove possible hadronic particle contamination
- Independent measurement of cross section ?

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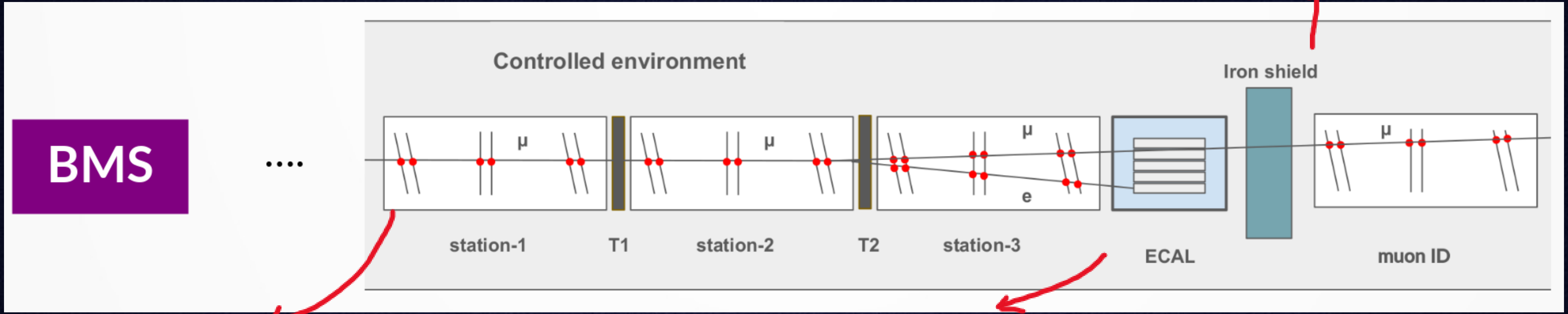
Muon filter:
- improved PID
- Consists of 1 tracking station*



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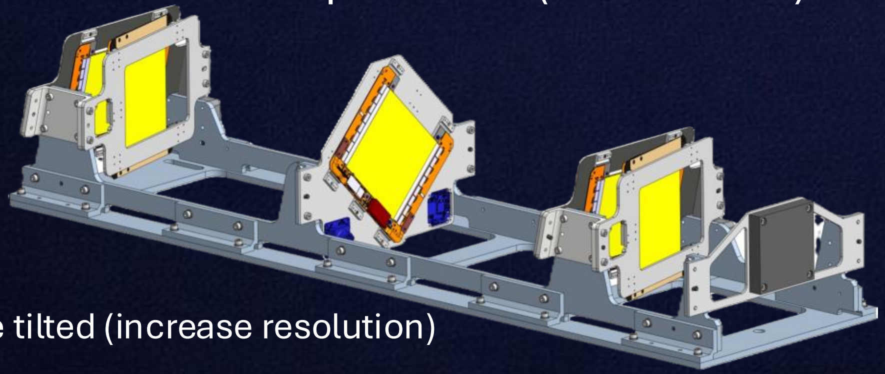

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MUonE: Setup for 2025 testrun

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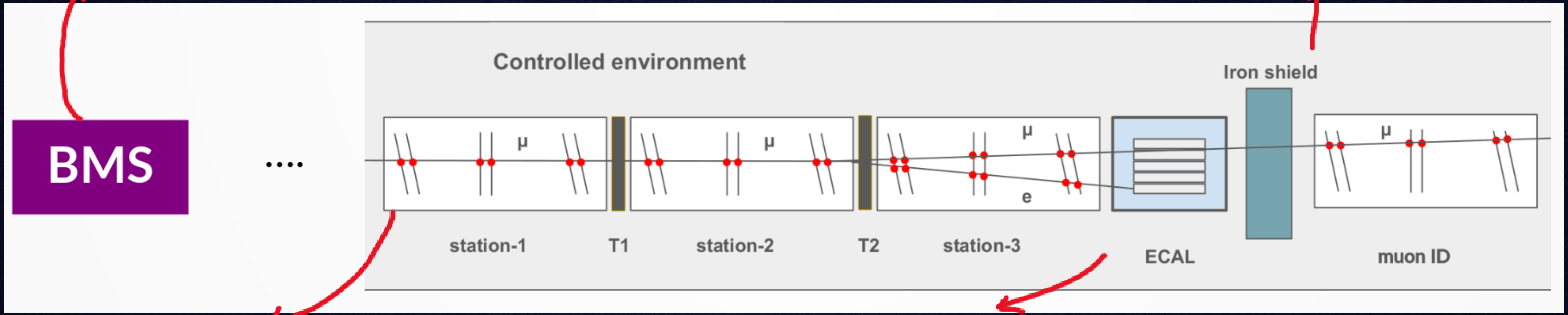
BMS:

- upstream measurement of beam energy scale
- Consists of 2 tracking station*

Muon filter:

- improved PID
- Consists of 1 tracking station*



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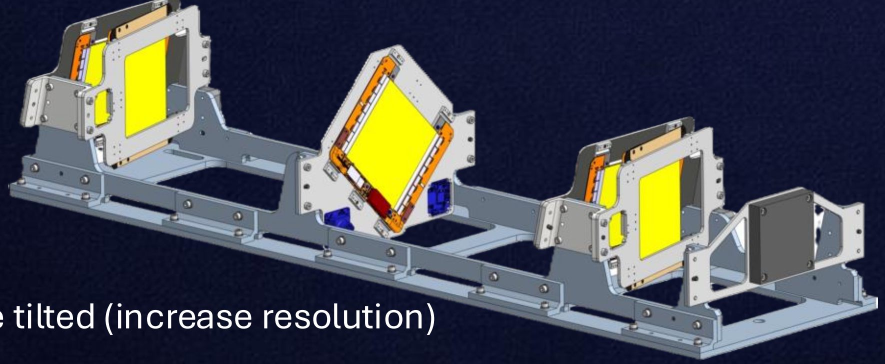

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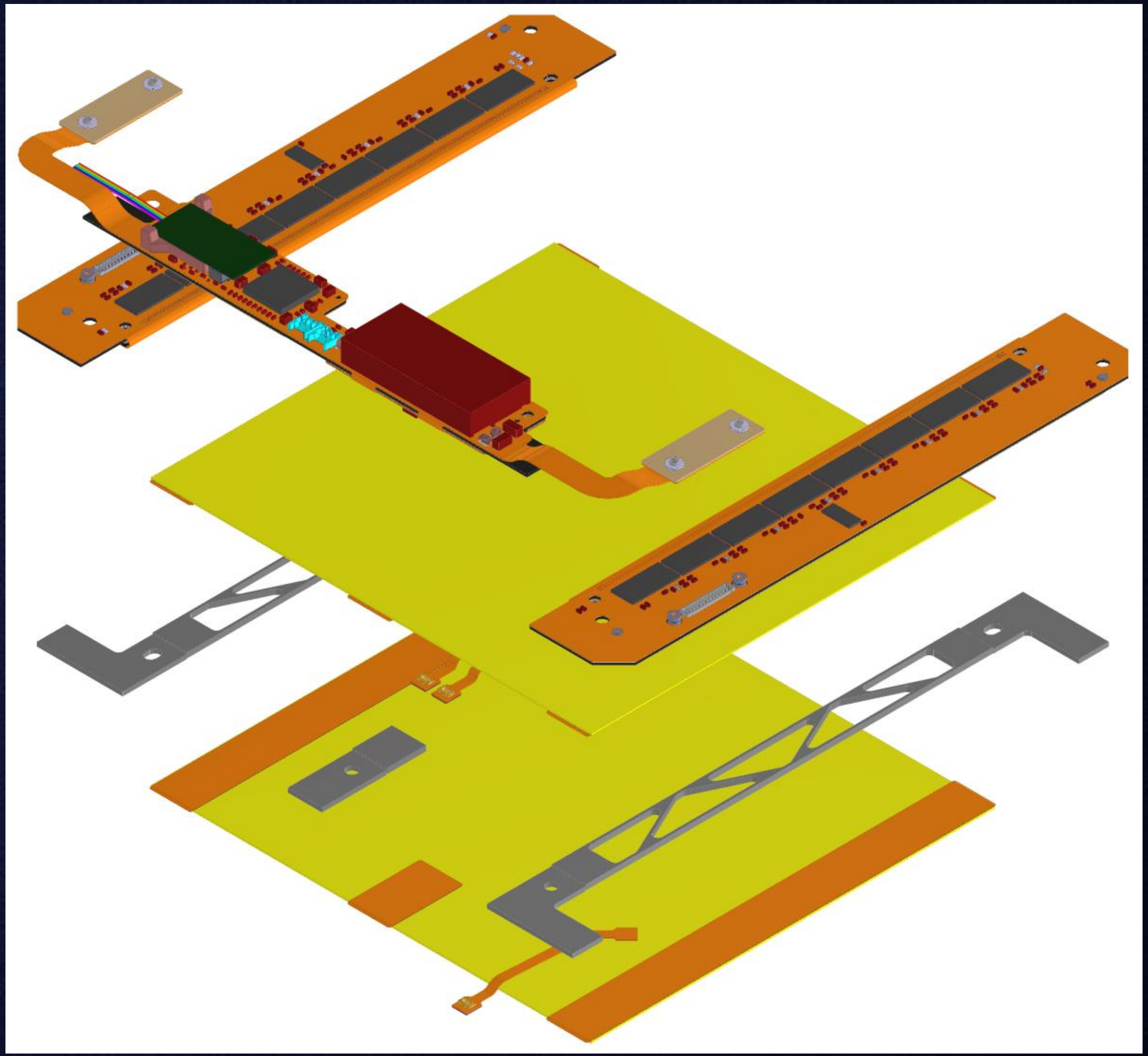
Key detector – 2S modules

The MUonE detector is based on 2S modules developed by CMS for the upgrade of its tracker

- Two close-by strip reading the same coordinate
  - Suppress background of single sensor hits
  - Reject large angle tracks
- 2 x 320μm
- Pitch 90μm
- Digital readout
- Readout rate at 40MHz
- 10x10cm^2



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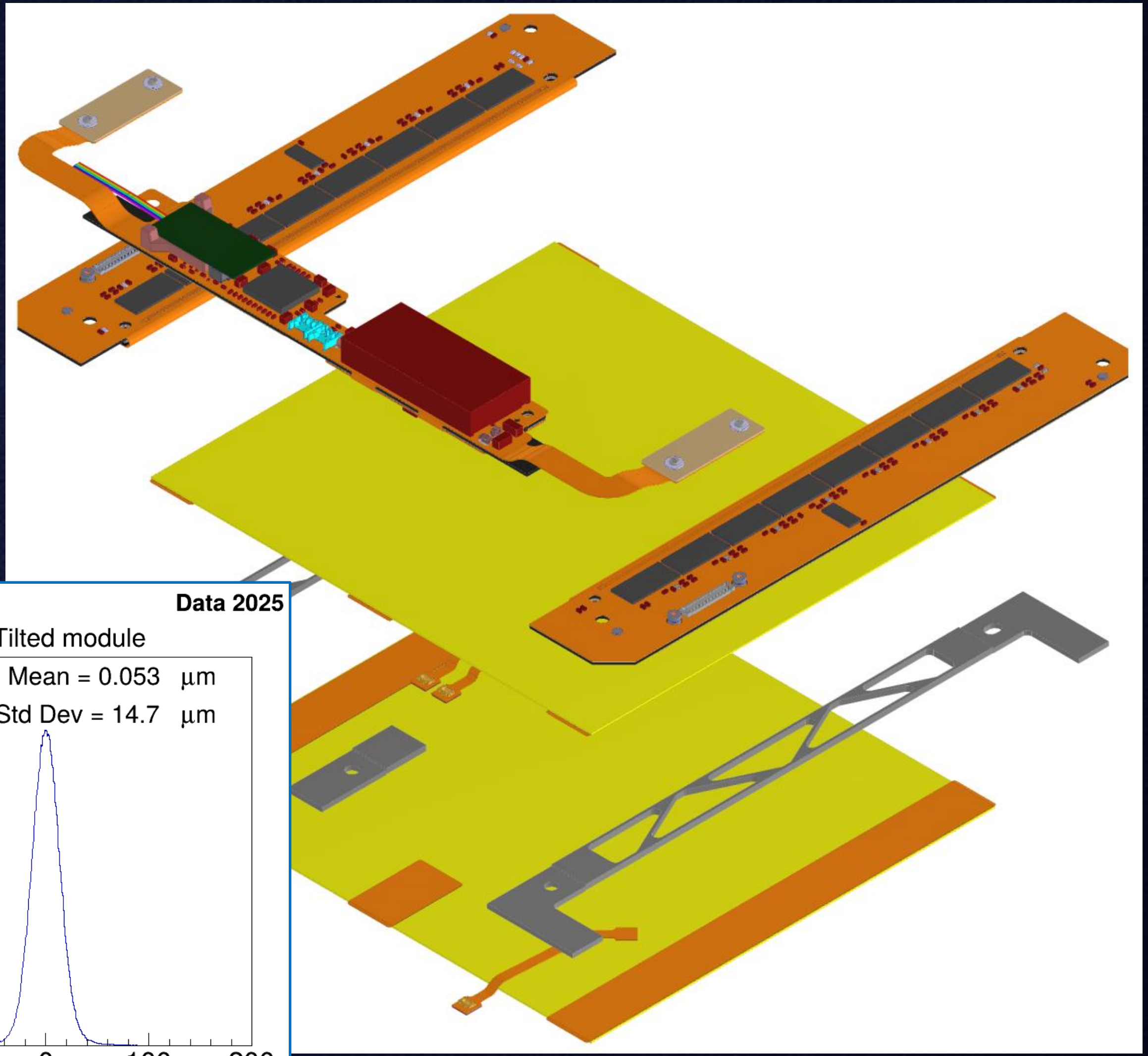
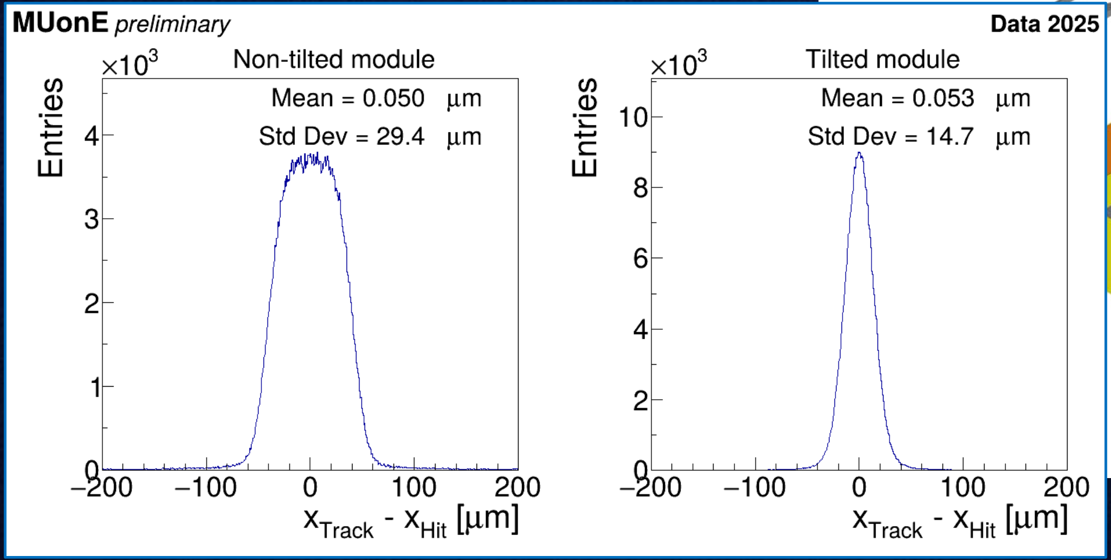
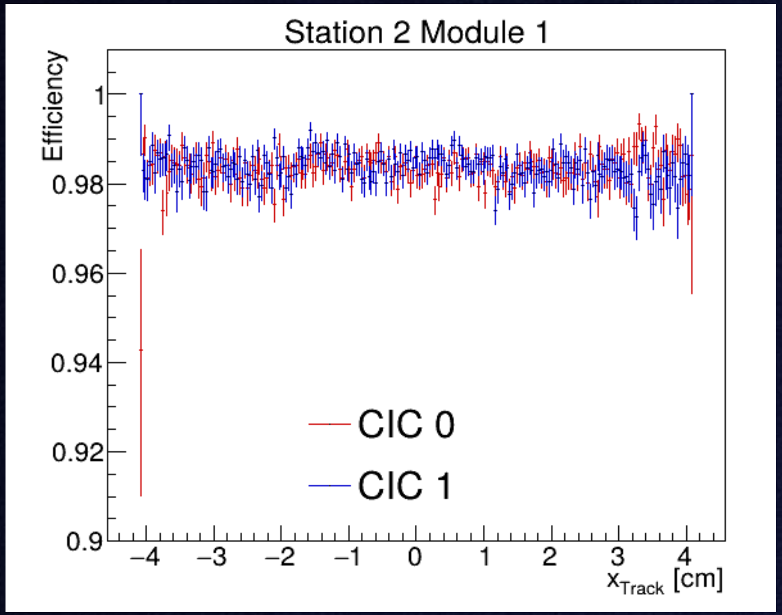
Some modules are *tilted* to improve the resolution





2S modules and tracking station - efficiency



Depending on the module, the efficiency is between 98-99%

Most of the modules show some non-uniformity across the module (RMS ~0.3%)

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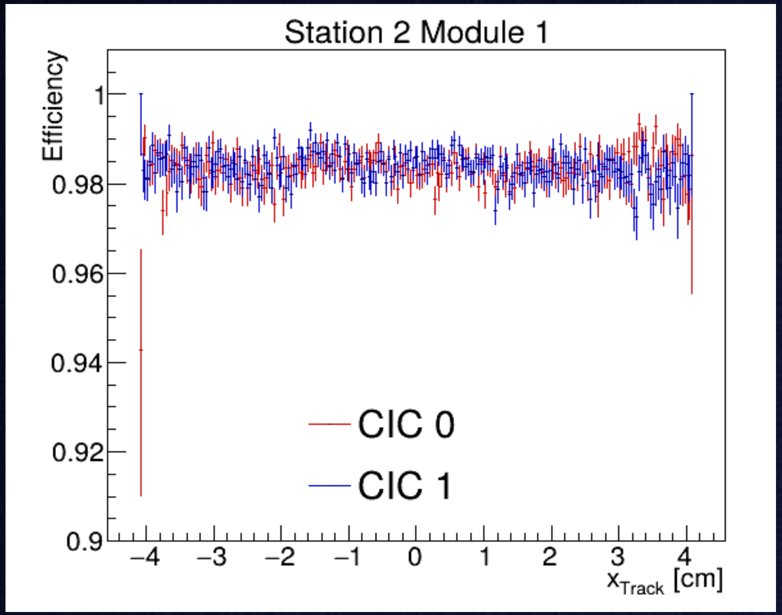

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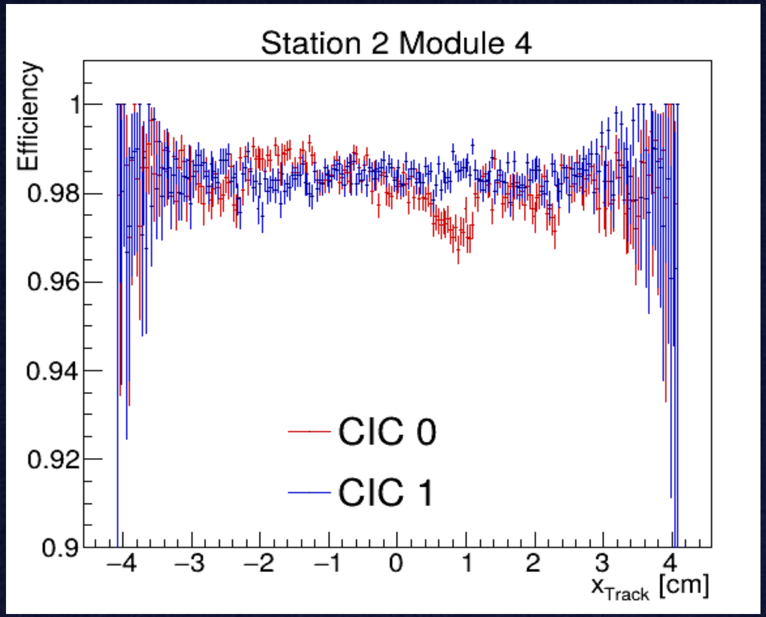

Some modules have clear area with a drop of efficiency

- We measure the cross section only with the scattered angles ⟶our physics is directly affected

  These non-uniformities on the efficiency for each module will be added to the simulation

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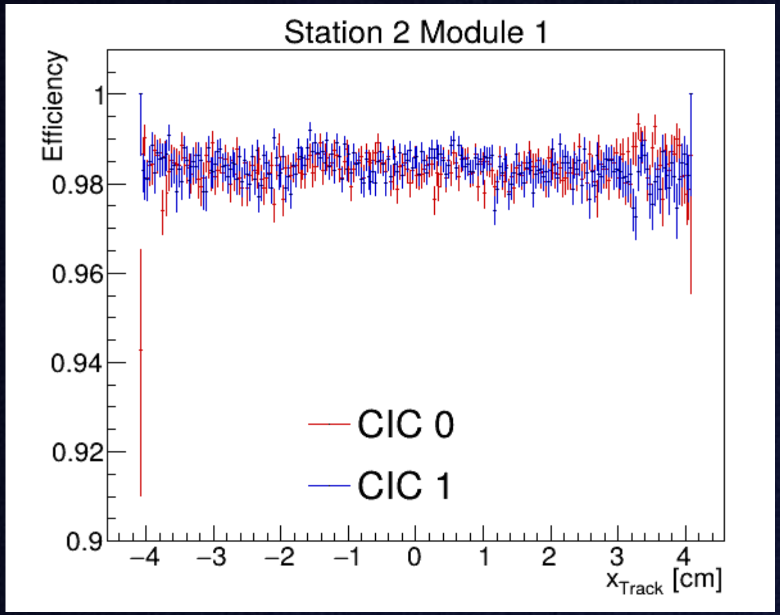

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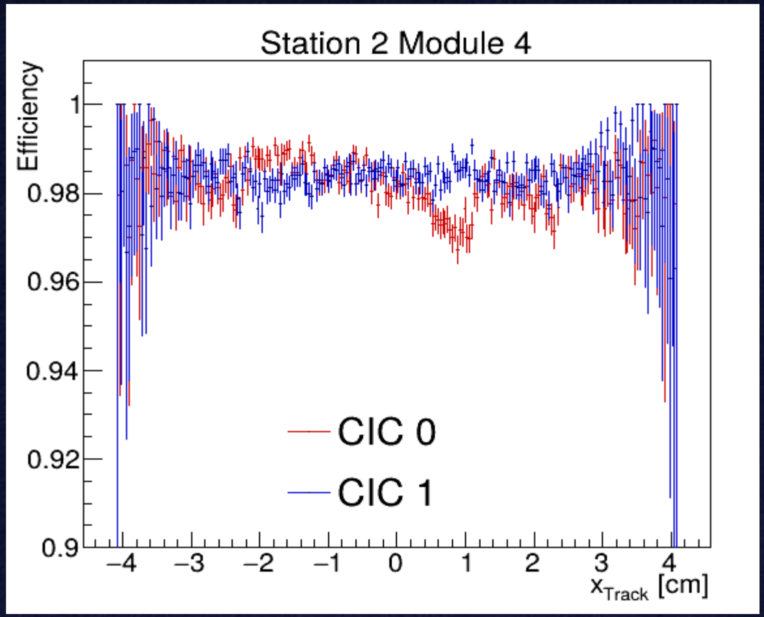

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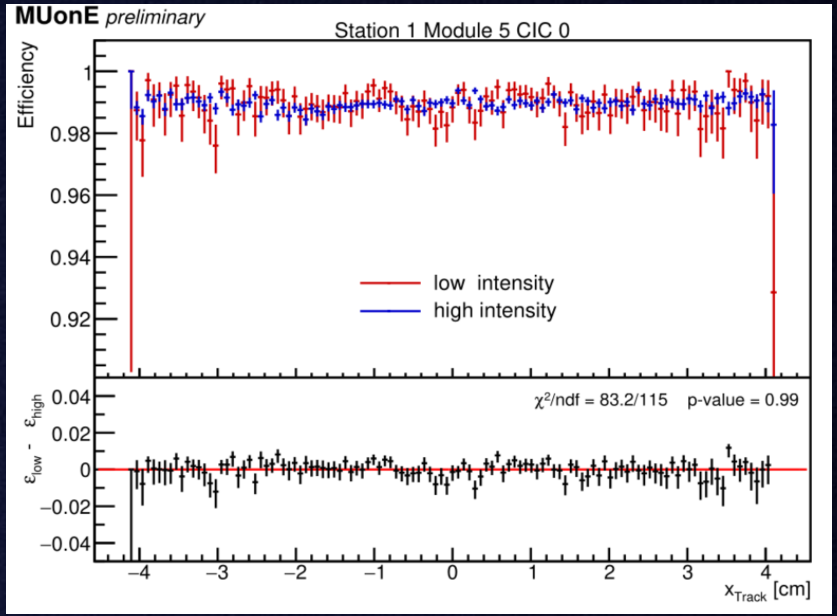


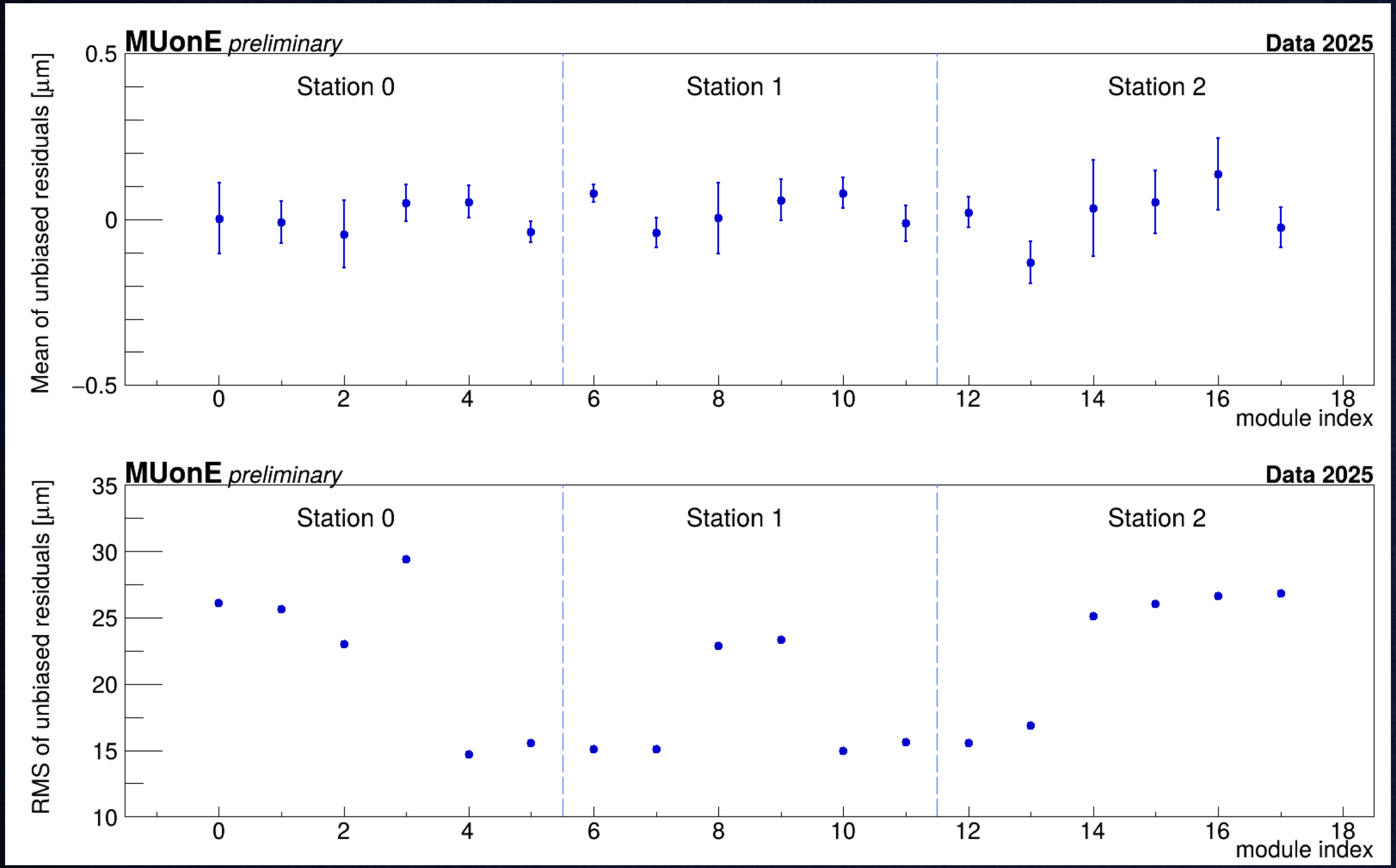
Module performances is stable at different beam intensity

- We measure the cross section only with the scattered angles ⟶our physics is directly affected
  These non-uniformities on the efficiency for each module will be added to the simulation
- Efficiency over time has been studied and is stable within a run <0.1% (limited by the available statistics)

2S modules and tracking station - resolution

Good control of the geometry:

- The alignment procedure shows good results (μ_{res} < 0.1µm)



Module resolution is computed subtracting the track error:

~12µm for tilted module

~26µm for non-tilted

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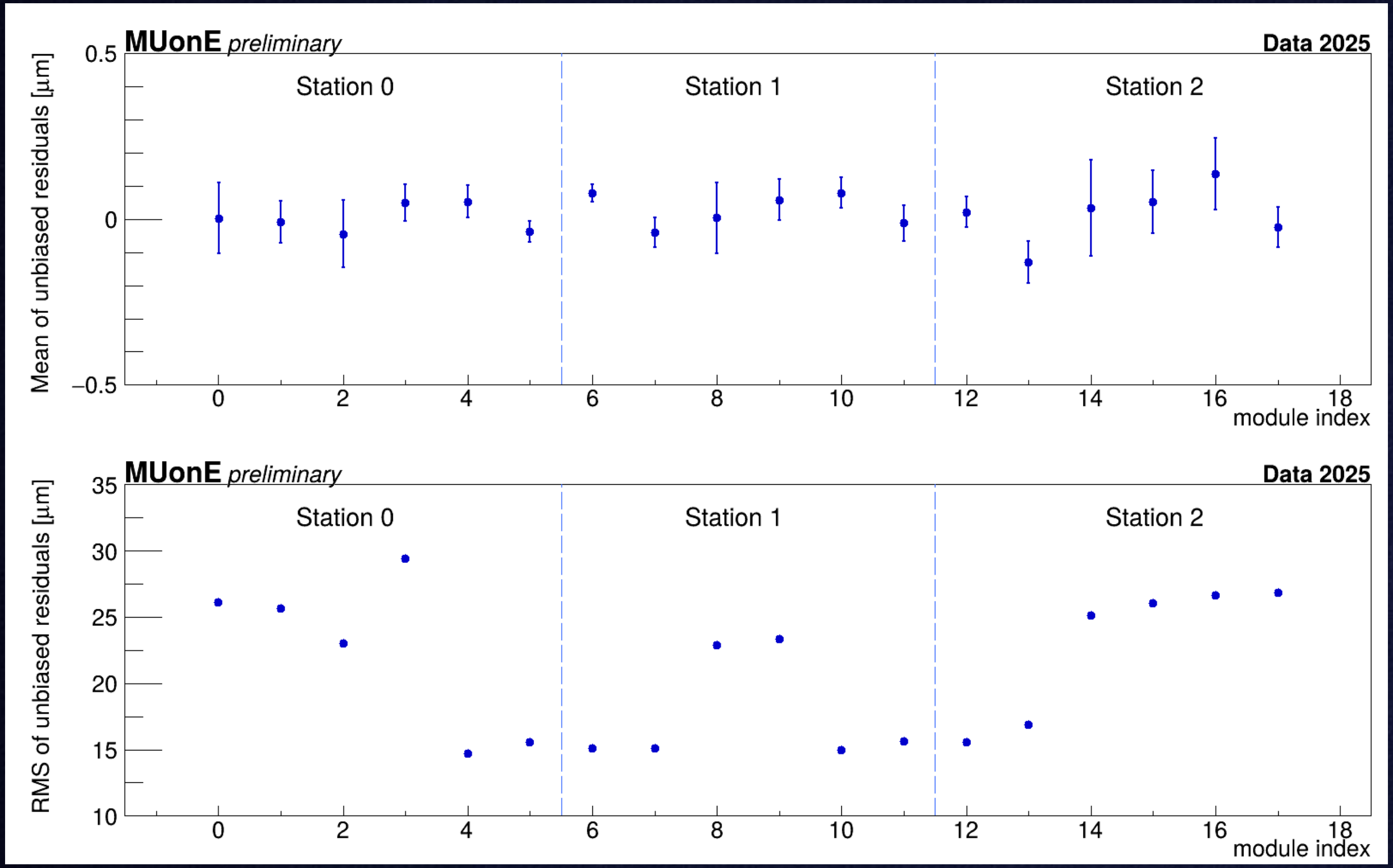

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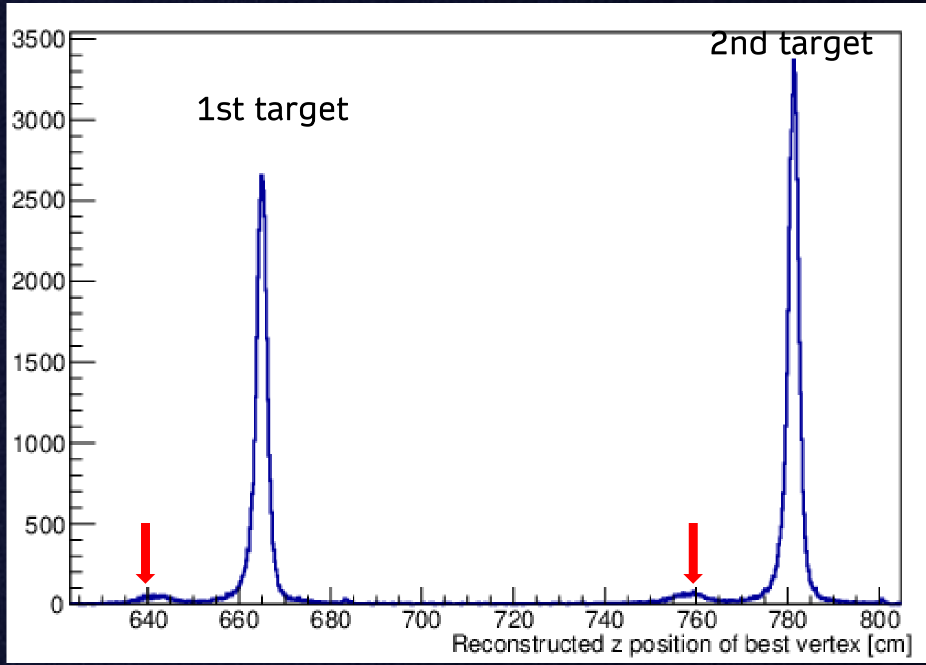
Vertex reconstruction successfully reconstruct event at the target position

Vertex resolution ~8mm



Small peak correspond to interaction happening in the last module of the previous station

Online event selection and statistics

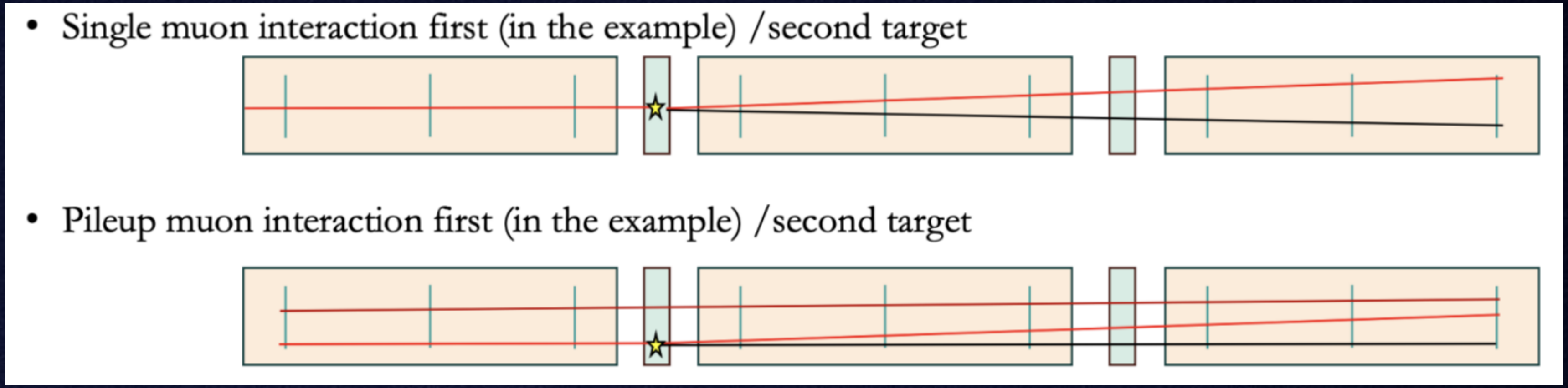
- We trigger on potential interaction events by counting the number of hits (stubs) in each station

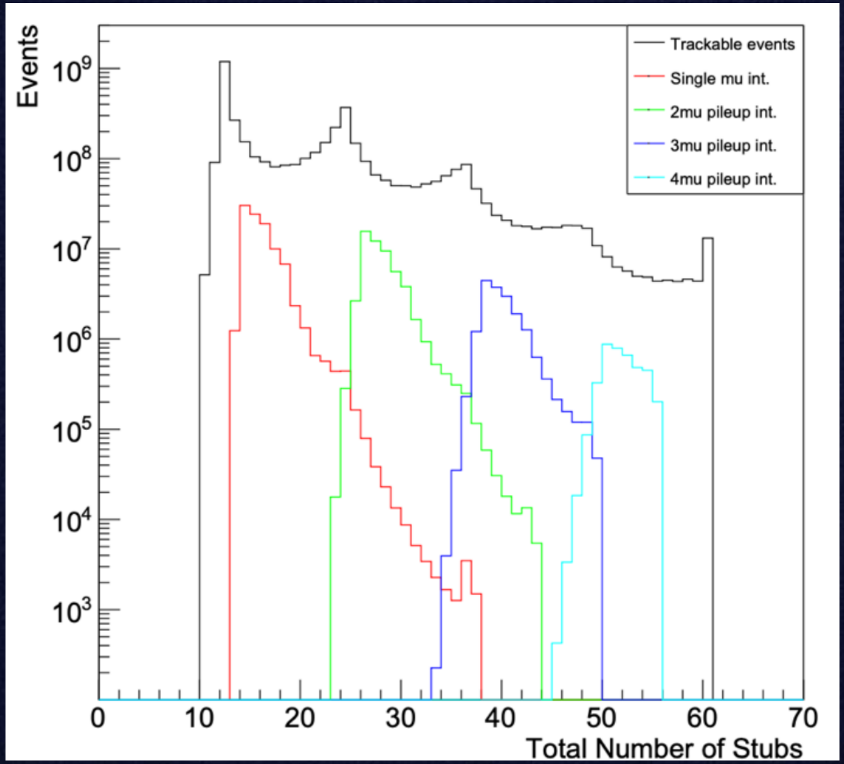
- We keep 1-2 % of recorded events

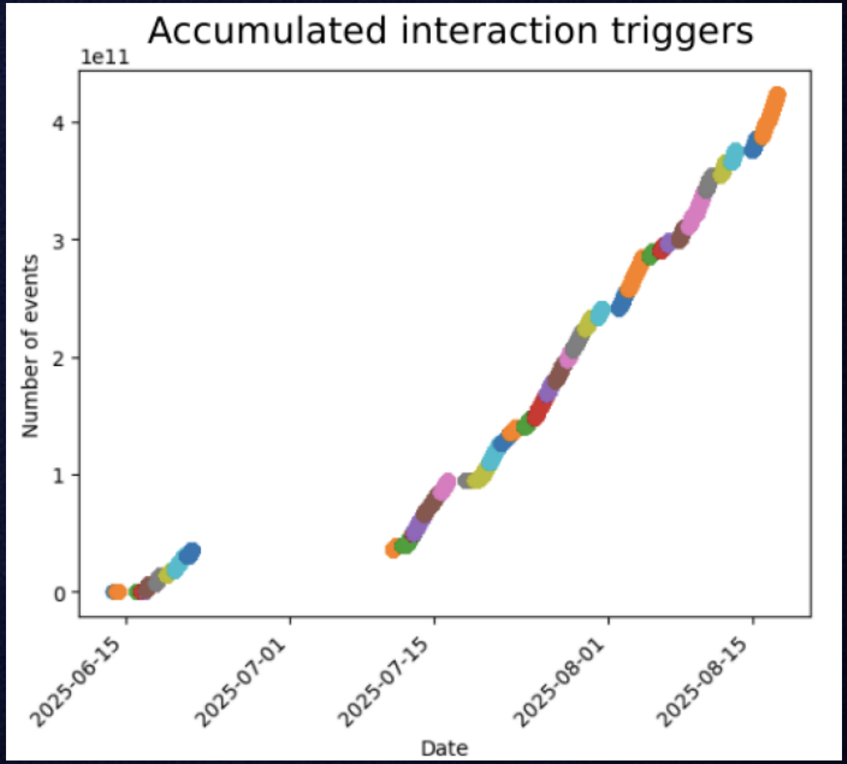
With 2025 statistics, we aim for the extraction of

- $\Delta\alpha_{lep}$ [~1%] (proof-of-principle)

- $\Delta\alpha_{had}$ [~20%]

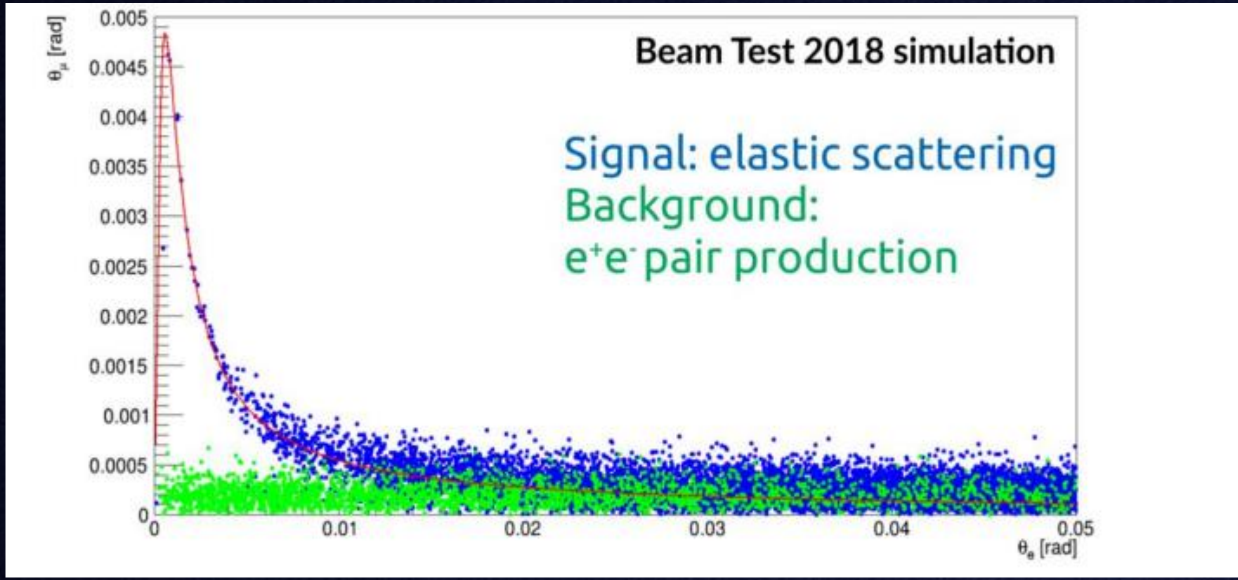


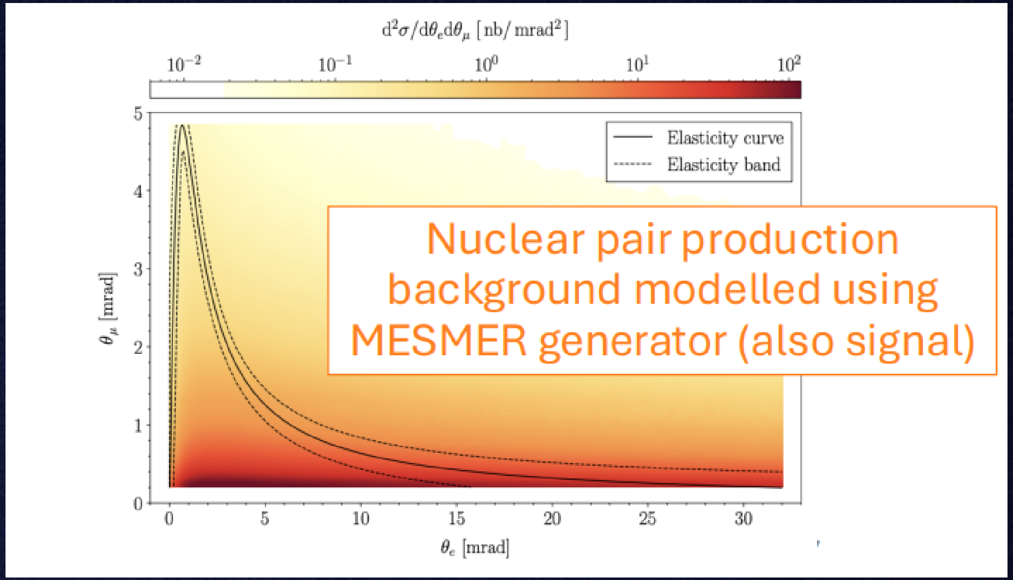




Offline selection and background

The main background comes from nuclear pair production



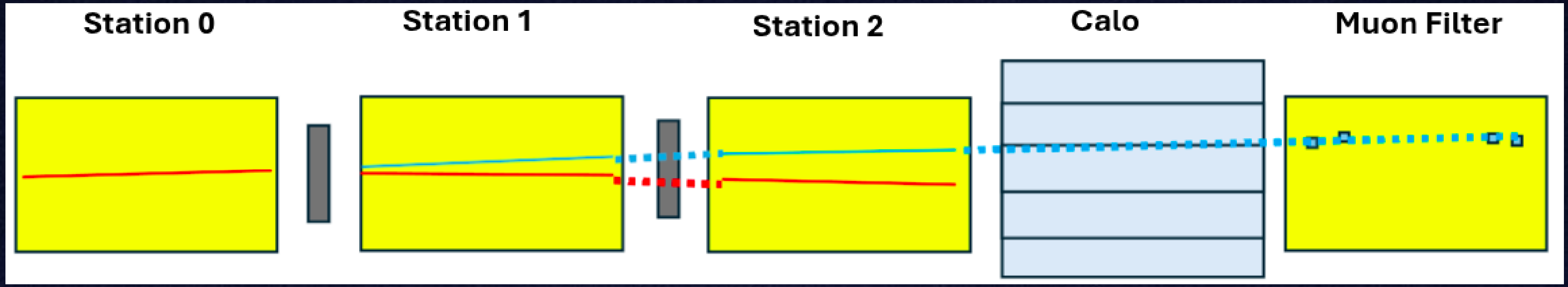


A combination of cut keep a large fraction of the signal event and remove most of the background

- Acoplanarity *(elastic events are coplanar)*
- Elastic cut *(they must be close the elastic curves)*

Muon filter

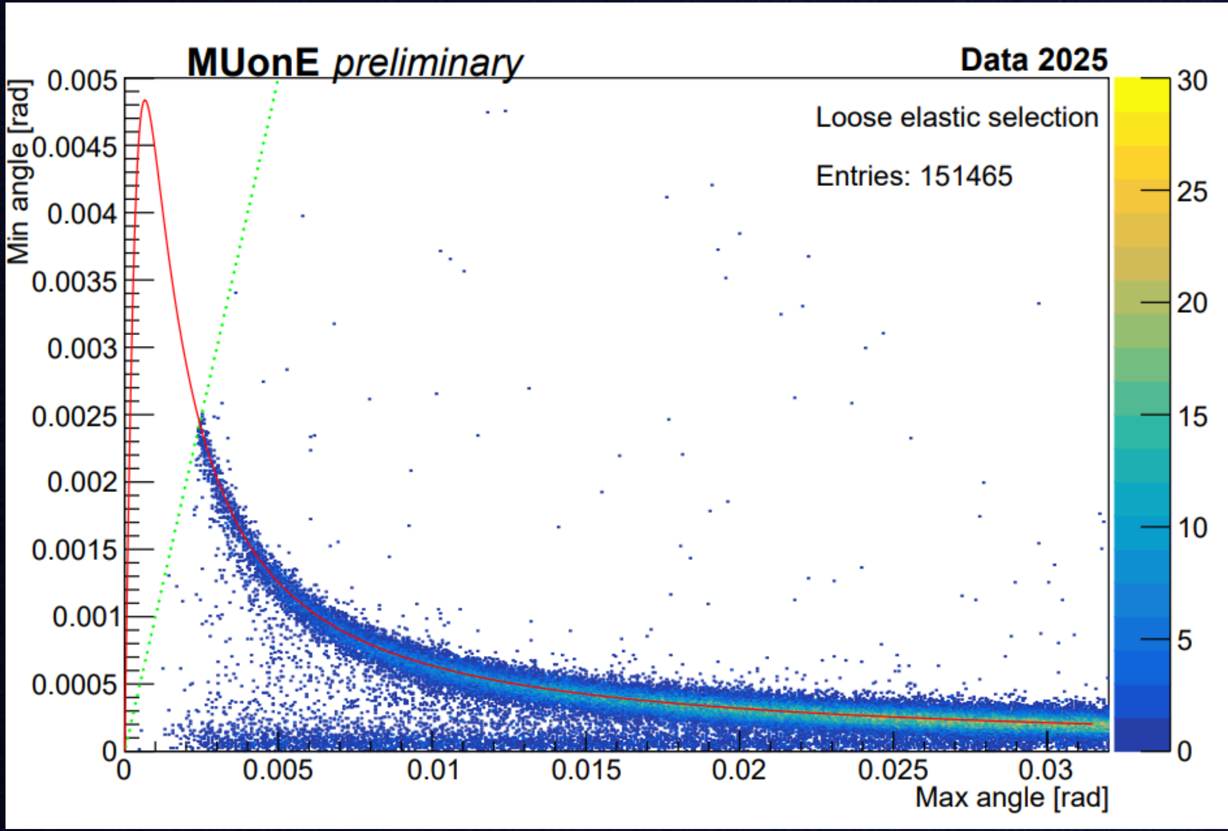
- The muon filter provides PID in the ambiguity region: angles < 5mrad

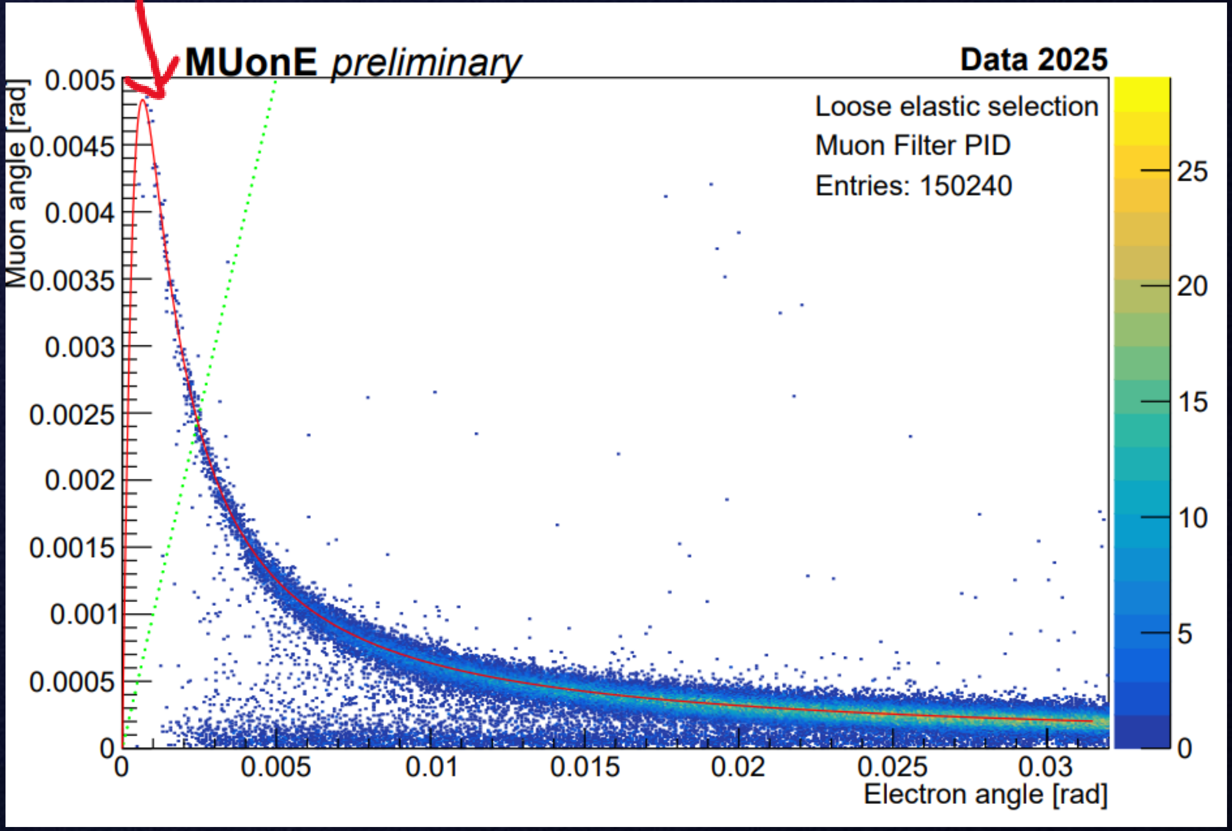


Without PID

Events identified in ambiguity region

With PID



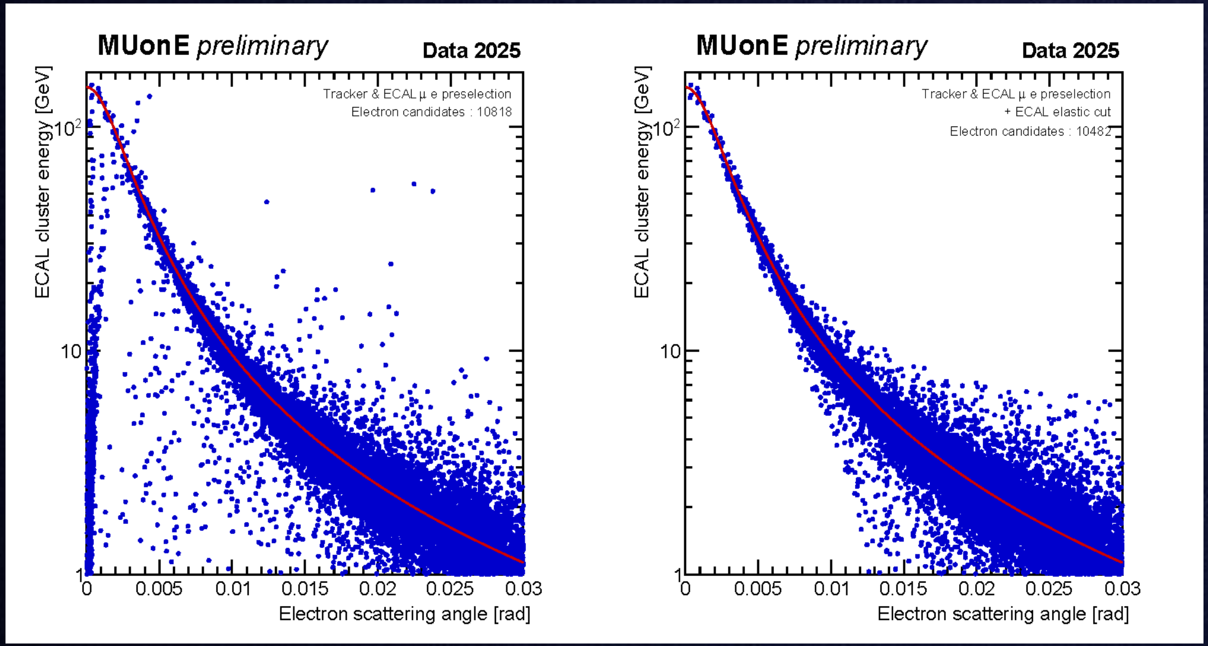


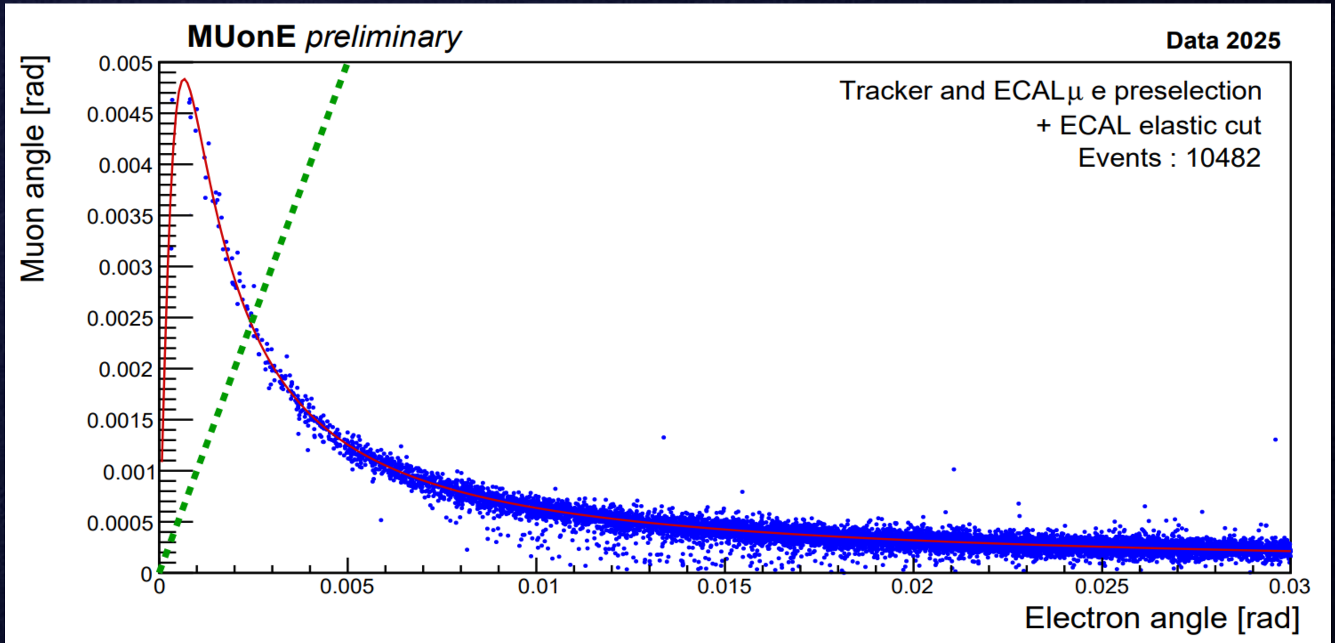
ECAL

ECAL can be used on last stations to study systematics and verify our control of the experiment

Cross-check/improve PID performances

- We extrapolate outgoing tracks and see if one matches the position of the cluster in the calorimeter
- Check that the event is on the elastic region





Monte Carlo: Procedure towards - $\Delta\alpha^{lep}$

[WiP]

Extracting $\Delta\alpha^{lep}$ with the 2025 test run aims to demonstrate that we control the experiment and can reliably works towards extraction of $\Delta\alpha^{had}$

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Procedure:

- We generate MC events samples with and without the running of alpha, and compute t

- From the scattered angles we can recover the squared four-momentum transfer **t**

$$t(\theta_e) = \frac{4m_e^2 r^2 \cos^2\theta_e}{r^2\cos^2\theta_e - 1}$$

- The ratio gives direct sensitivity to $\Delta\alpha_{Lep}(t)$

$$\frac{d\sigma/dt}{d\sigma_0/dt} = \frac{1}{|1-\Delta\alpha(t)|^2} \simeq 1 + 2\Delta\alpha(t)$$

Monte Carlo: Procedure towards - $\Delta\alpha^{lep}$

Extracting $\Delta\alpha^{lep}$ with the 2025 test run aims to demonstrate that we control the experiment and can reliably works towards extraction of $\Delta\alpha^{had}$

Procedure:

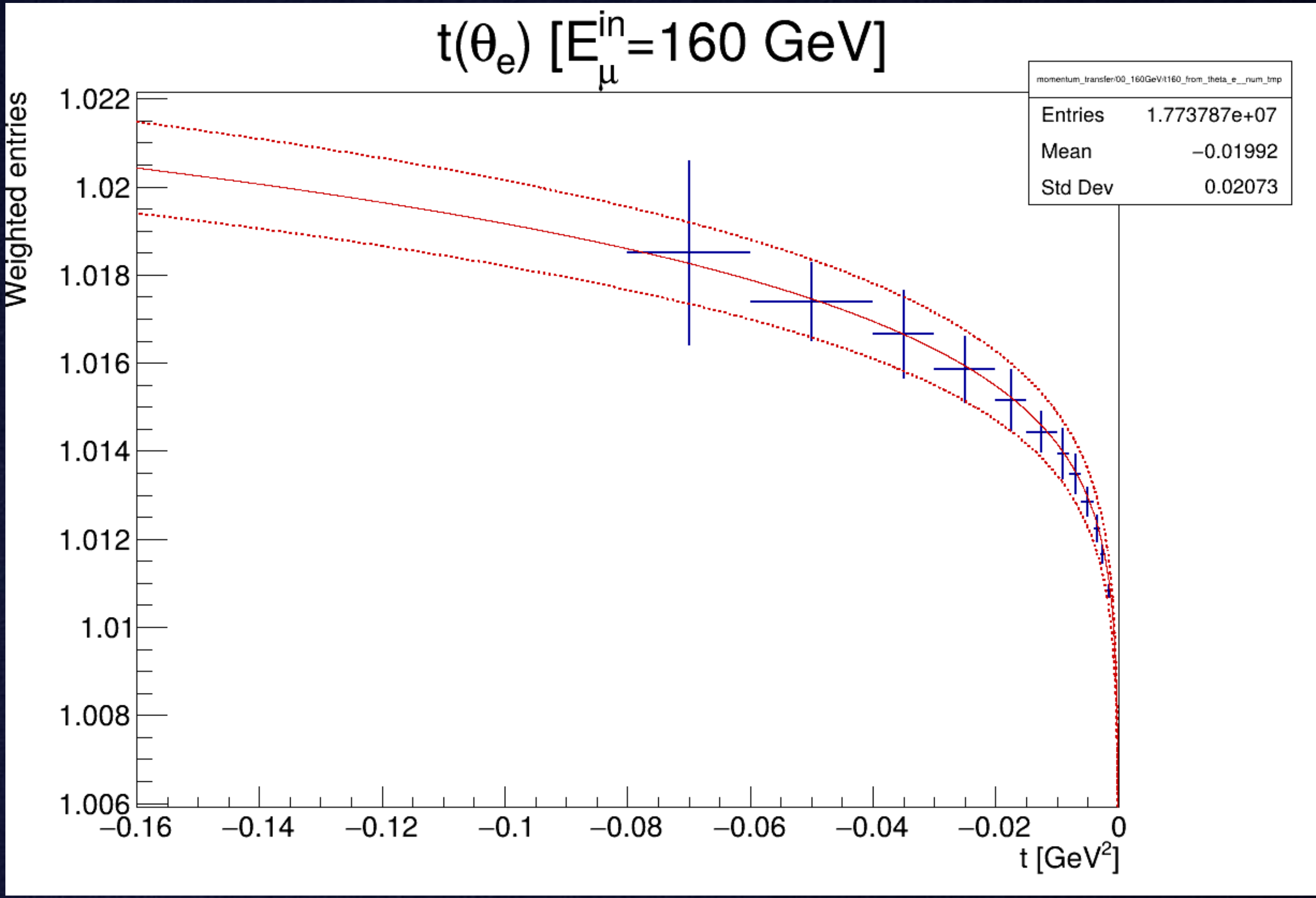
- We generate MC events samples with and without the running of alpha, and compute t

- From the scattered angles we can recover the squared four-momentum transfer **t**

$$t(\theta_e) = \frac{4m_e^2 r^2 \cos^2\theta_e}{r^2\cos^2\theta_e - 1}$$

- The ratio gives direct sensitivity to $\Delta\alpha_{Lep}(t)$

$$\frac{d\sigma/dt}{d\sigma_0/dt} = \frac{1}{|1-\Delta\alpha(t)|^2} \simeq 1 + 2\Delta\alpha(t)$$



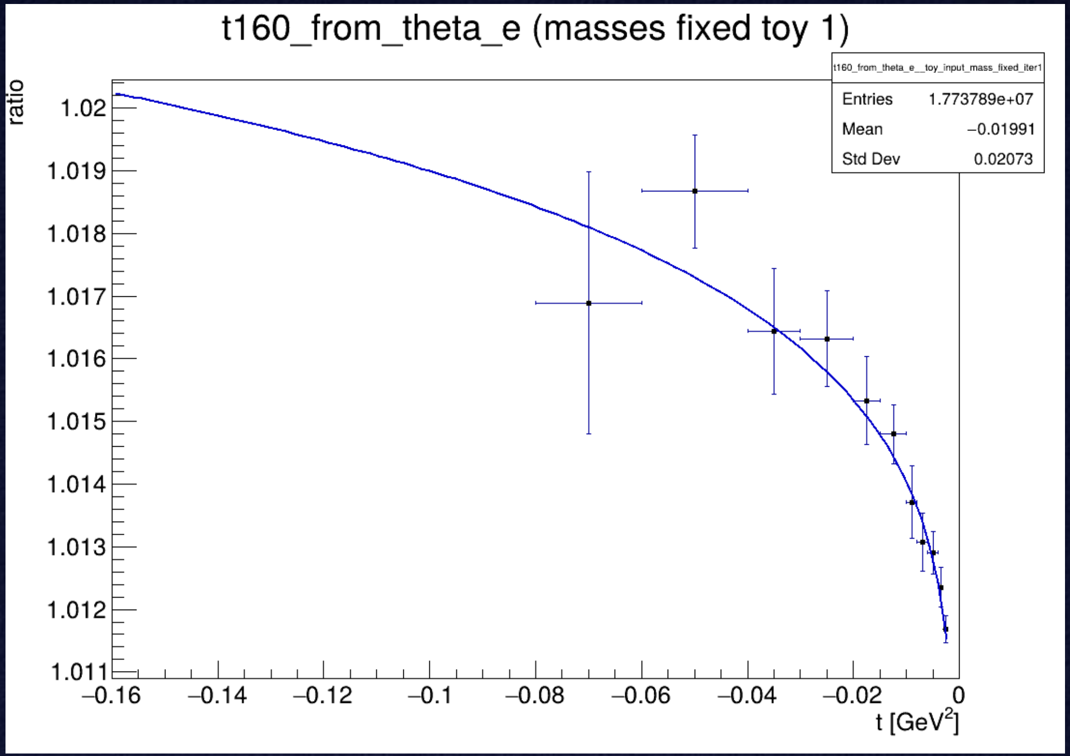
- *MC samples are fully correlated*
- *Statistics match the dataset **run32** (~30M elastic events)*
- *The red curves show the leptonic running of α from theory at ±5%*

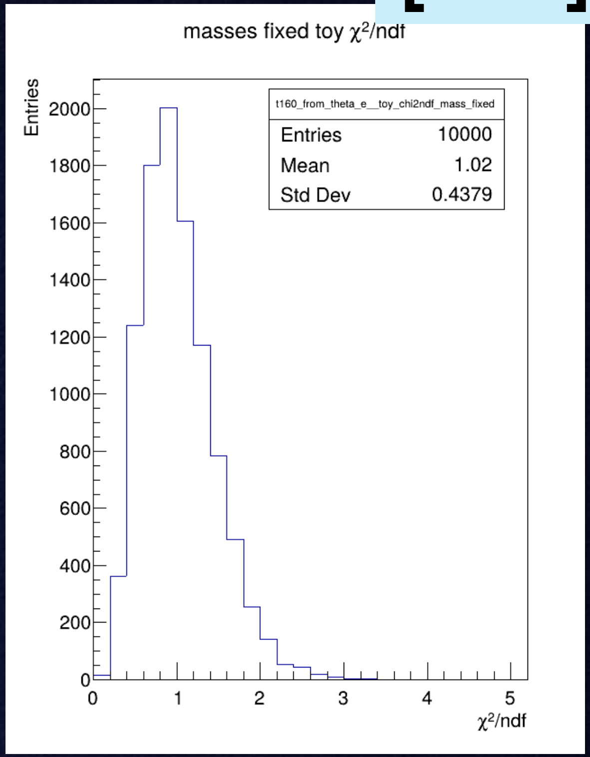
Monte Carlo: Procedure towards - $\Delta\alpha^{lep}$

[WiP]

Toy MC: we smear each point randomly according to its error bars

Perform a fit on the leptonic function (masses fixed, one free parameter k)





Monte Carlo: Procedure towards - $\Delta\alpha^{lep}$

[WiP]

Toy MC: we smear each point randomly according to its error bars

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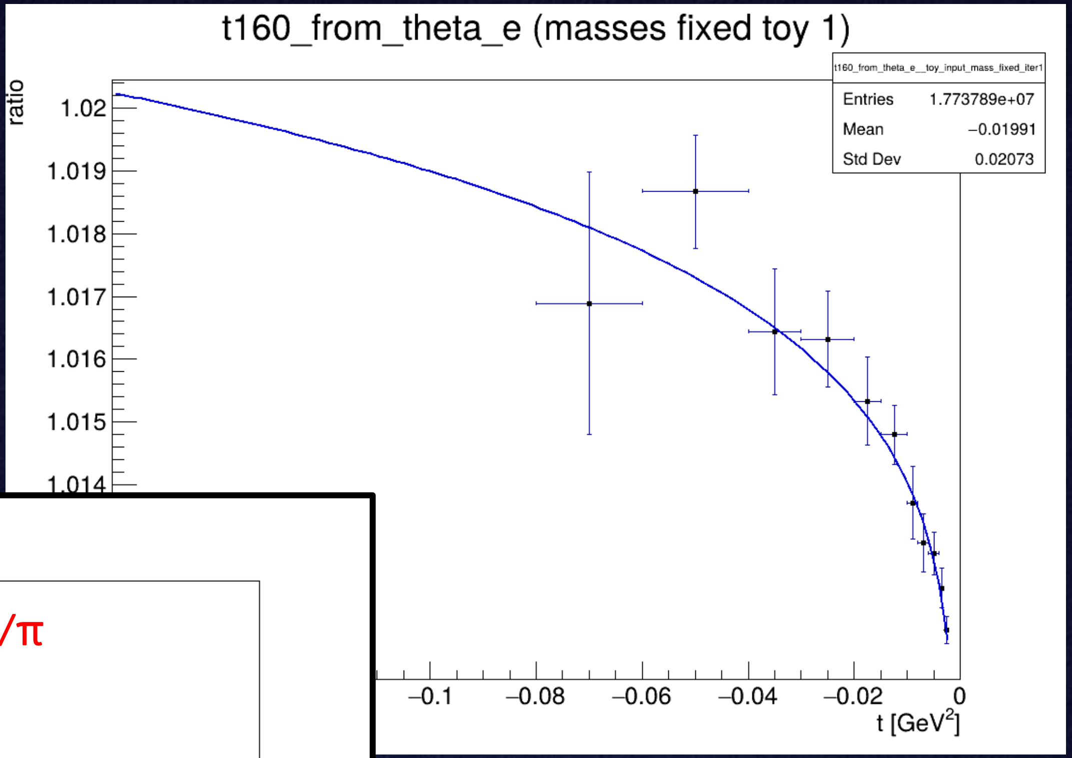
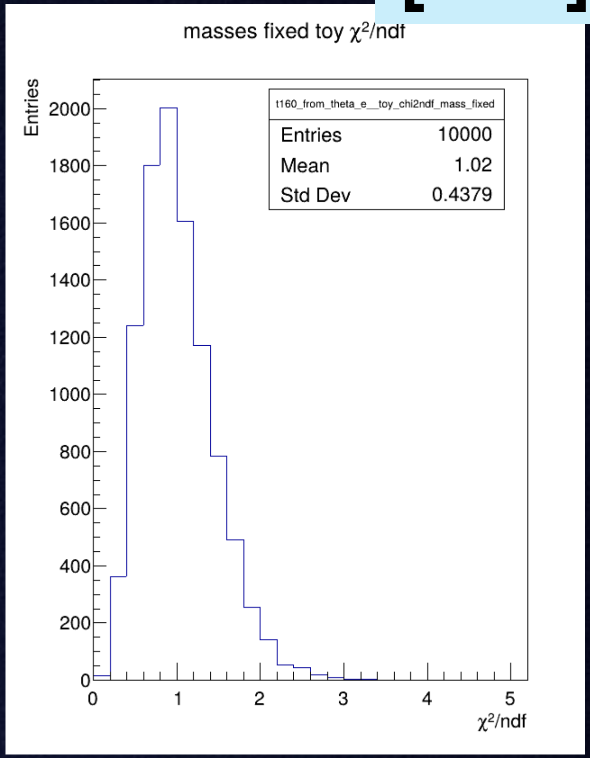
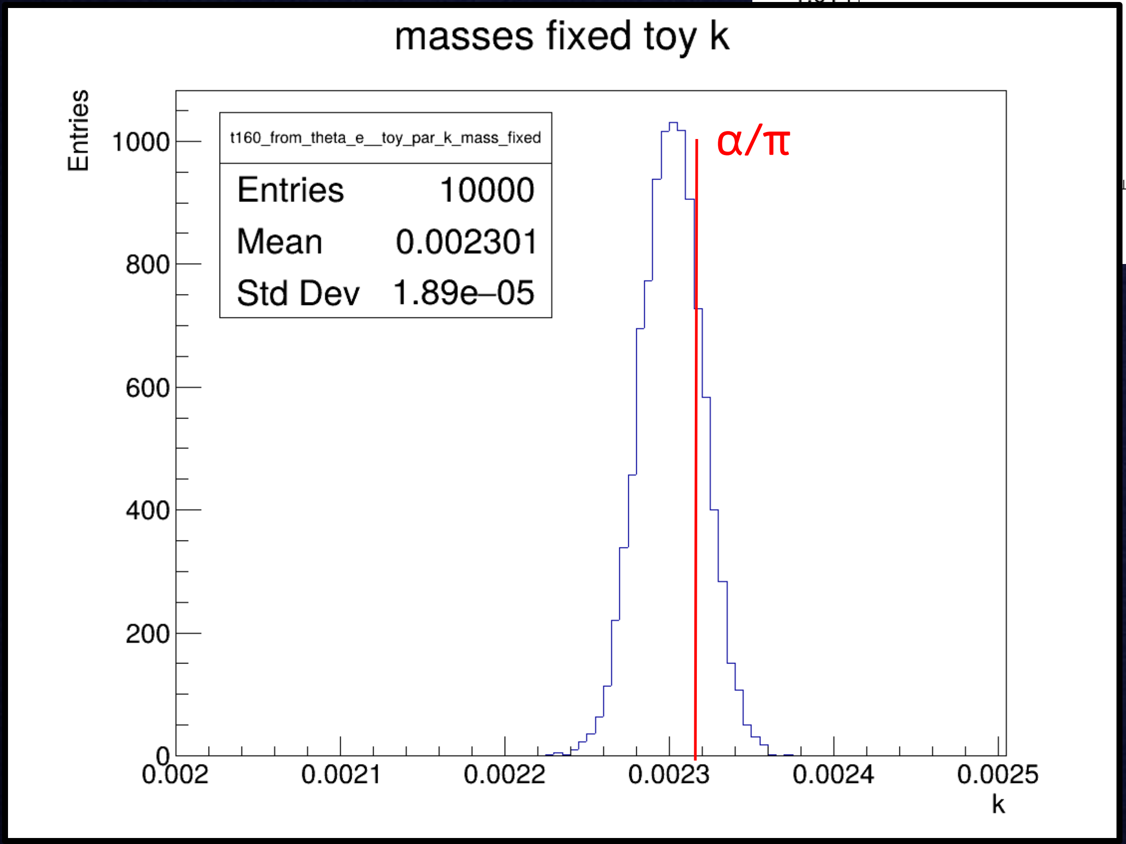






Precision at 1%

Real value k = α/π ~ 0.002323

Systematic bias to underestimate the parameter k ~1%

Could be effect from hadronic contribution not included in analysis but simulated

Conclusion

Successful 3 months running with full apparatus

- 3 stations (2 targets) + ECAL + BMS + Muon Filter
- Online DQM and Trigger tested
- Stable DAQ at 40 MHz

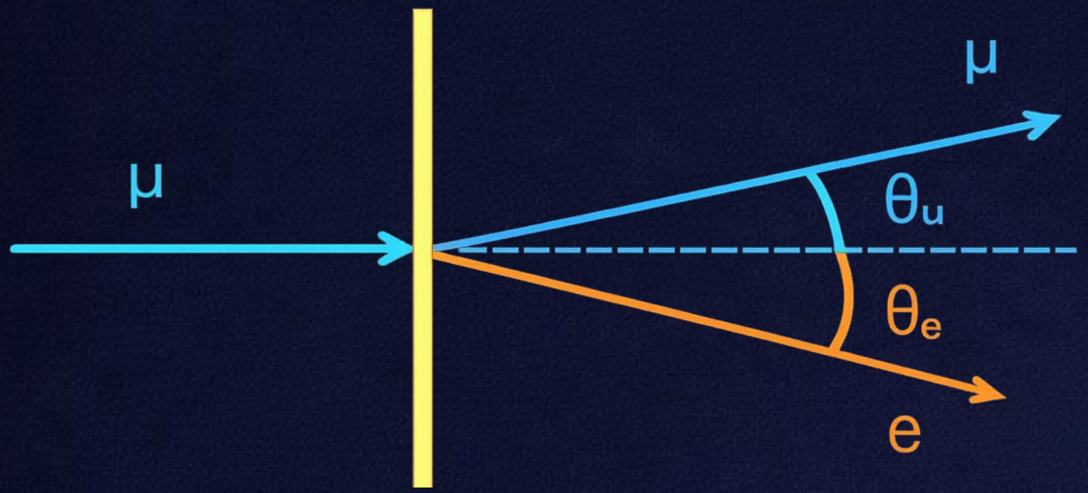
Analysis campaign underway

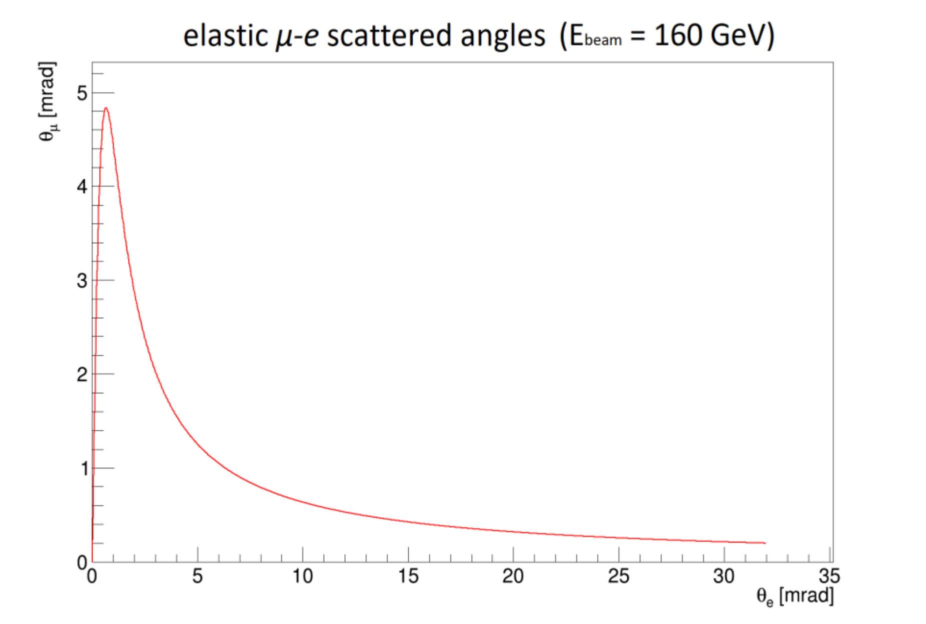
- Upgrading MC for good data/MC
- Measure $\Delta\alpha^{lep}$ for proof-of-principle
- Preliminary measurement of $\Delta\alpha^{had}$

Backup

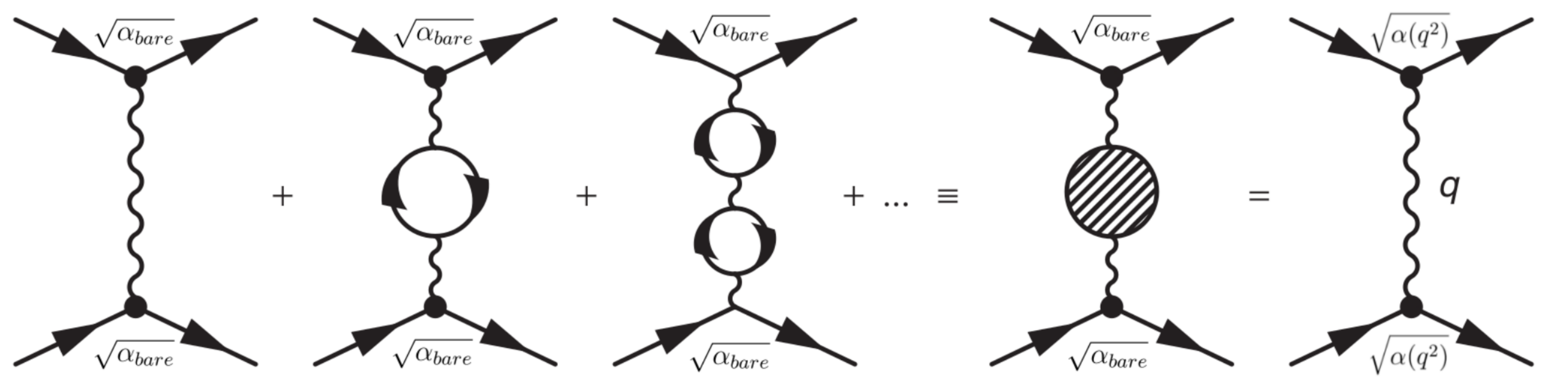
a_μ^{HLO} : MUonE

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





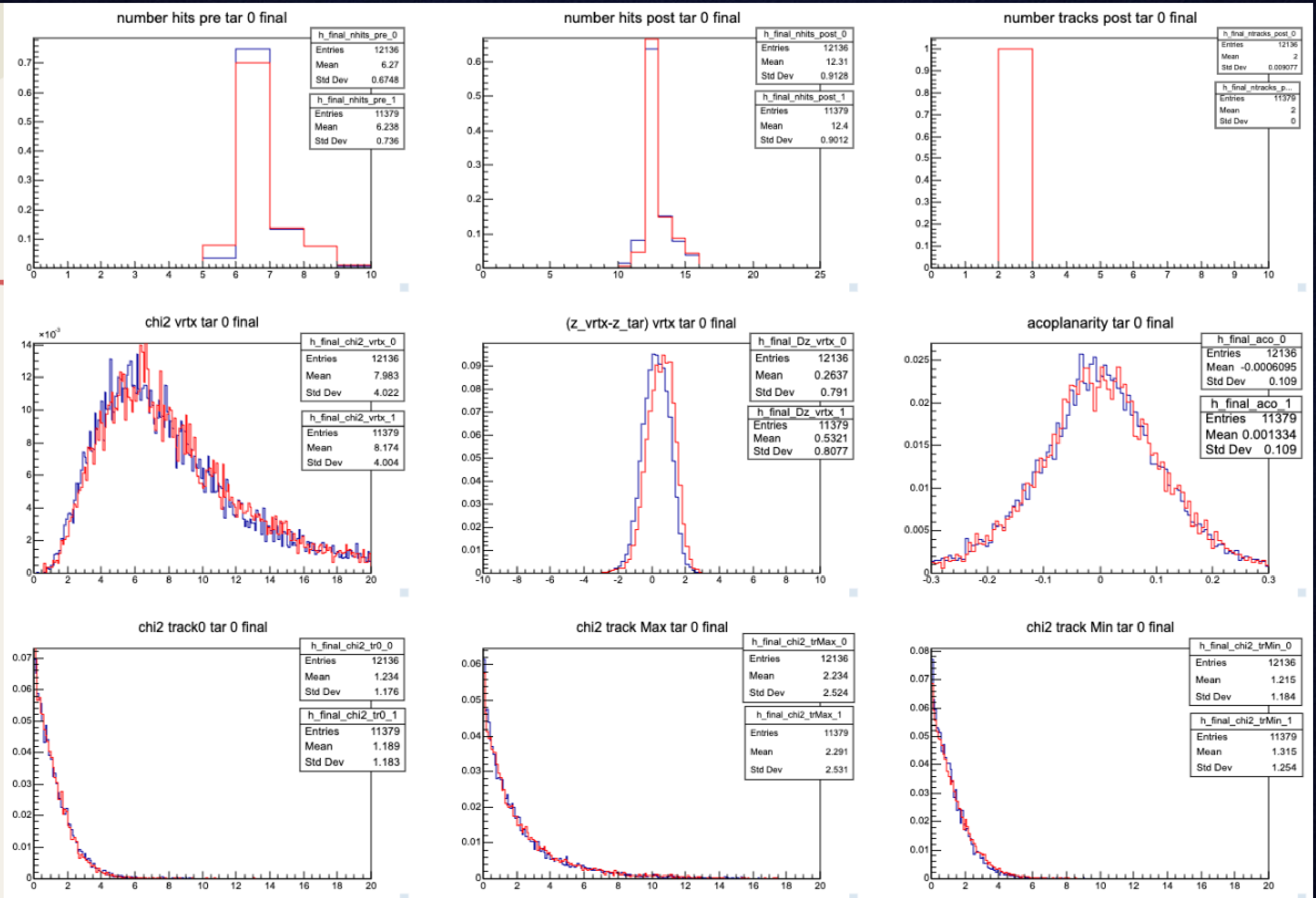
The result of the loop insertions can be absorbed in a redefinition of the coupling constant

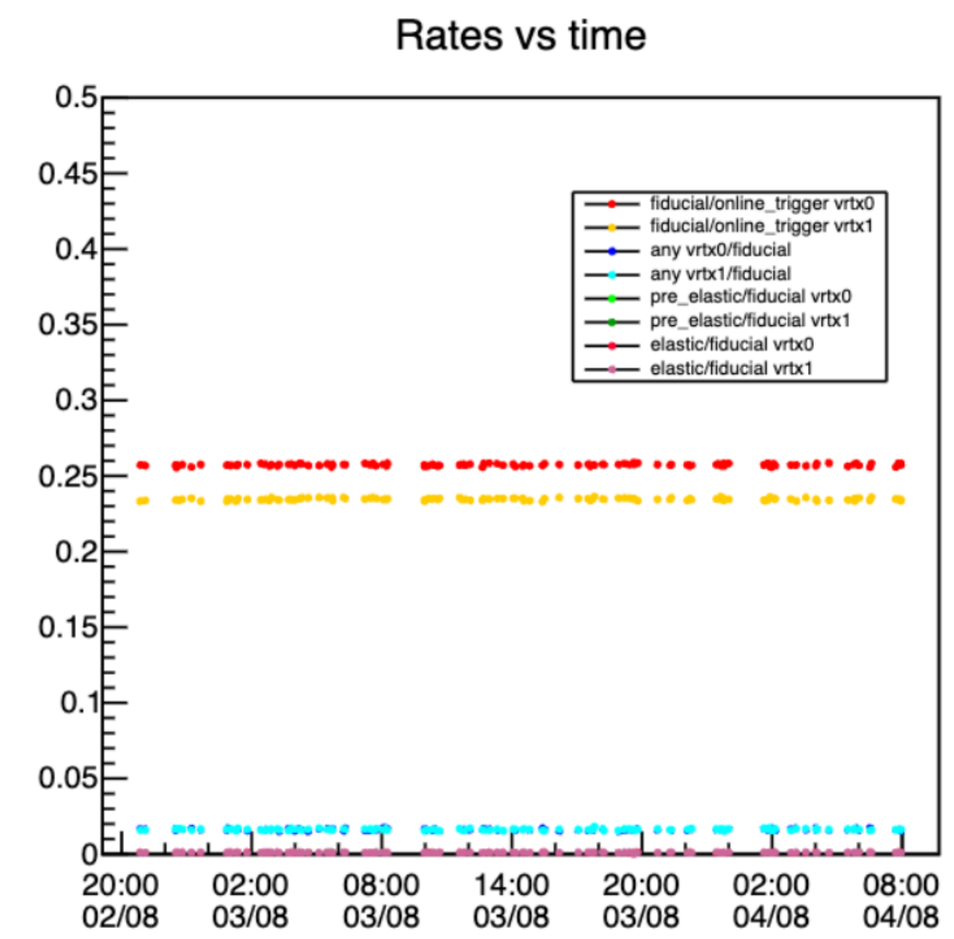


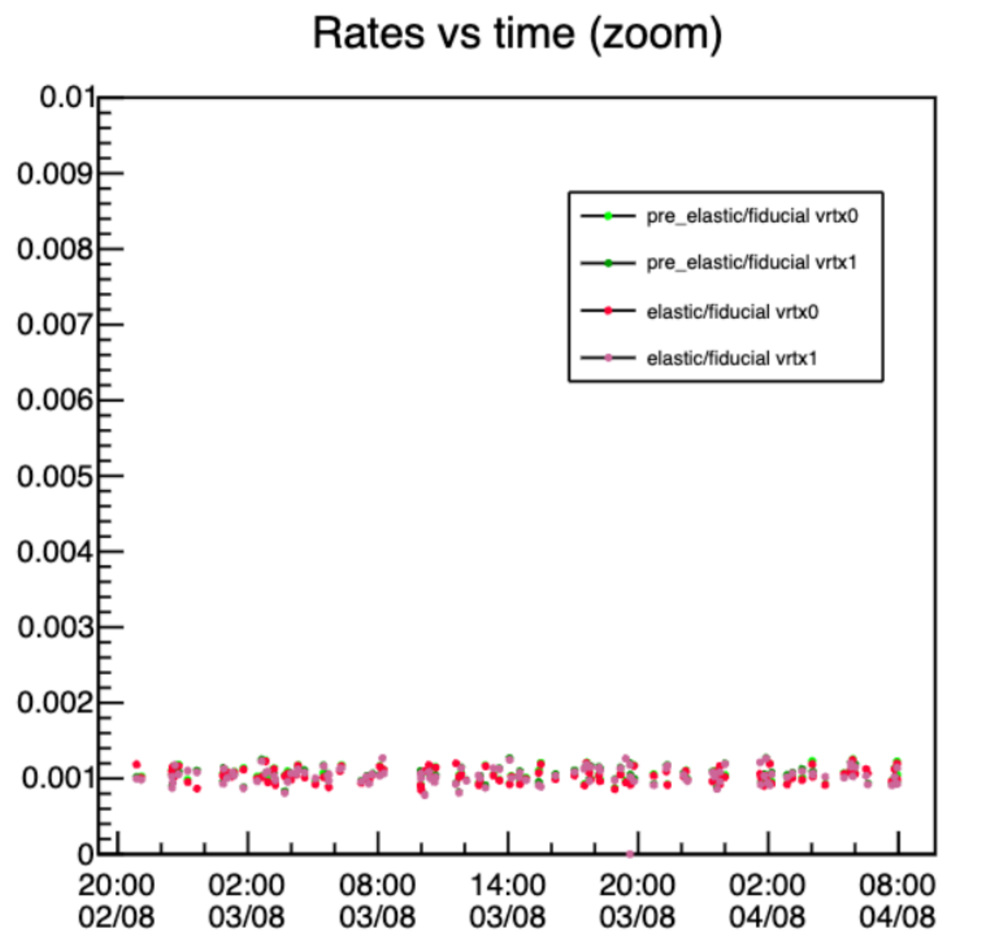
$$\alpha(t) = \frac{\alpha}{1 - \Delta\alpha(t)}$$

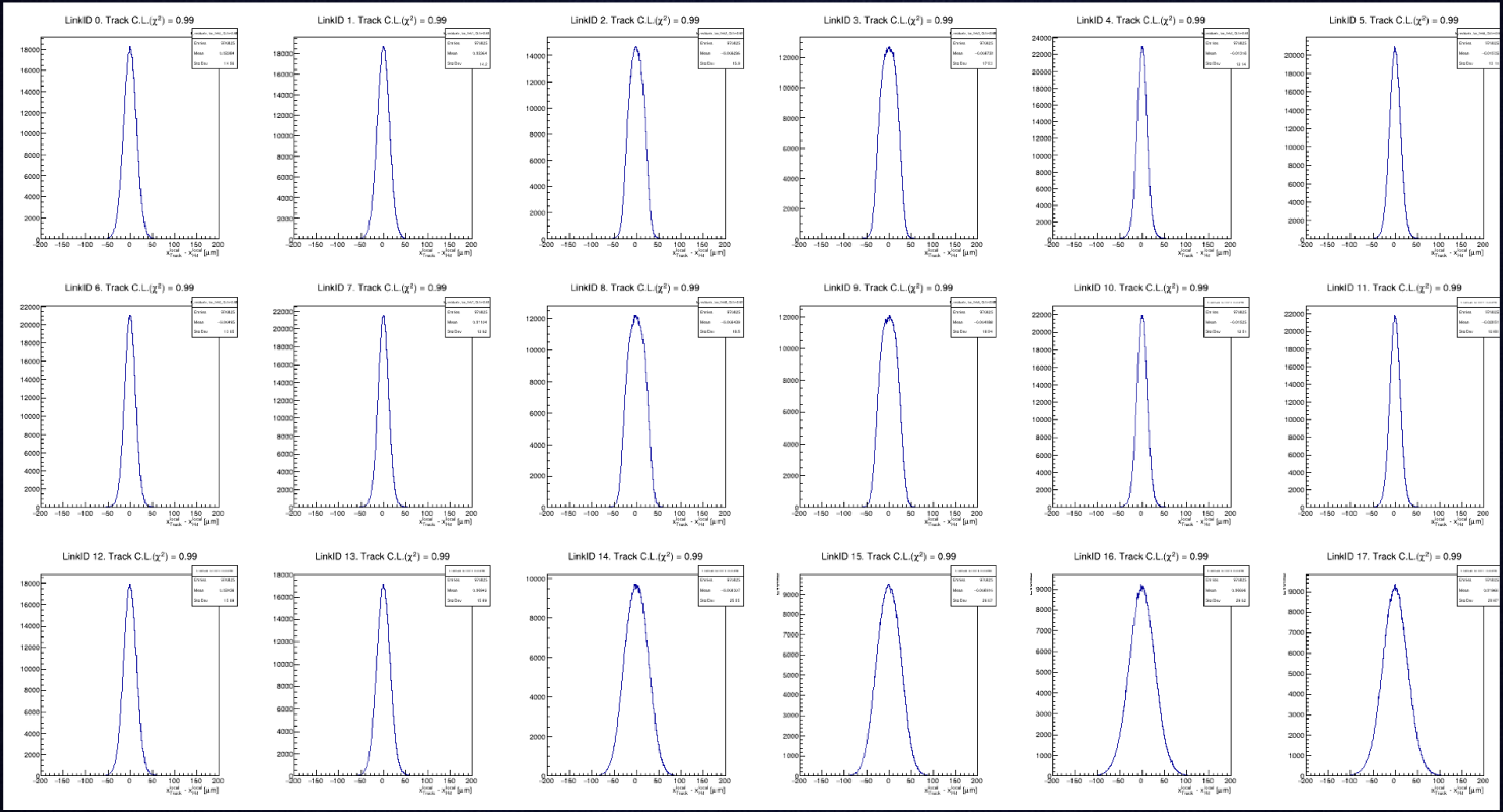
$\Delta\alpha(t) = \Delta\alpha_{\text{lep}}(t) + \boxed{\Delta\alpha_{\text{had}}(t)} + \Delta\alpha_{\text{top}}(t) + \Delta\alpha_{\text{weak}}(t)$; All terms except hadronic are well known

Tar0
Tar1


number hits pre tar 0 final
h_final_nhits_pre_0
Entries 12136
Mean 6.27
Std Dev 0.6748
h_final_nhits_pre_1
Entries 11379
Mean 6.238
Std Dev 0.736
number hits post tar 0 final
h_final_nhits_post_0
Entries 12136
Mean 12.31
Std Dev 0.9128
h_final_nhits_post_1
Entries 11379
Mean 12.4
Std Dev 0.9012
number tracks post tar 0 final
h_final_ntracks_post_0
Entries 12136
Mean 2
Std Dev 0.009077
h_final_ntracks_p...
Entries 11379
Mean 2
Std Dev 0
chi2 vrtx tar 0 final
h_final_chi2_vrtx_0
Entries 12136
Mean 7.983
Std Dev 4.022
h_final_chi2_vrtx_1
Entries 11379
Mean 8.174
Std Dev 4.004
(z_vrtx-z_tar) vrtx tar 0 final
h_final_Dz_vrtx_0
Entries 12136
Mean 0.2637
Std Dev 0.791
h_final_Dz_vrtx_1
Entries 11379
Mean 0.5321
Std Dev 0.8077
acoplanarity tar 0 final
h_final_aco_0
Entries 12136
Mean -0.0006095
Std Dev 0.109
h_final_aco_1
Entries 11379
Mean 0.001334
Std Dev 0.109
chi2 track0 tar 0 final
h_final_chi2_tr0_0
Entries 12136
Mean 1.234
Std Dev 1.176
h_final_chi2_tr0_1
Entries 11379
Mean 1.189
Std Dev 1.183
chi2 track Max tar 0 final
h_final_chi2_trMax_0
Entries 12136
Mean 2.234
Std Dev 2.524
h_final_chi2_trMax_1
Entries 11379
Mean 2.291
Std Dev 2.531
chi2 track Min tar 0 final
h_final_chi2_trMin_0
Entries 12136
Mean 1.215
Std Dev 1.184
h_final_chi2_trMin_1
Entries 11379
Mean 1.315
Std Dev 1.254


Rates vs time
0.5
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
fiducial/online_trigger vrtx0
fiducial/online_trigger vrtx1
any vrtx0/fiducial
any vrtx1/fiducial
pre_elastic/fiducial vrtx0
pre_elastic/fiducial vrtx1
elastic/fiducial vrtx0
elastic/fiducial vrtx1
20:00 02/08
02:00 03/08
08:00 03/08
14:00 03/08
20:00 03/08
02:00 04/08
08:00 04/08


Rates vs time (zoom)
0.01
0.009
0.008
0.007
0.006
0.005
0.004
0.003
0.002
0.001
0
pre_elastic/fiducial vrtx0
pre_elastic/fiducial vrtx1
elastic/fiducial vrtx0
elastic/fiducial vrtx1
20:00 02/08
02:00 03/08
08:00 03/08
14:00 03/08
20:00 03/08
02:00 04/08
08:00 04/08



LinkID 0. Track C.L.(χ²) = 0.99
LinkID 1. Track C.L.(χ²) = 0.99
LinkID 2. Track C.L.(χ²) = 0.99
LinkID 3. Track C.L.(χ²) = 0.99
LinkID 4. Track C.L.(χ²) = 0.99
LinkID 5. Track C.L.(χ²) = 0.99
LinkID 6. Track C.L.(χ²) = 0.99
LinkID 7. Track C.L.(χ²) = 0.99
LinkID 8. Track C.L.(χ²) = 0.99
LinkID 9. Track C.L.(χ²) = 0.99
LinkID 10. Track C.L.(χ²) = 0.99
LinkID 11. Track C.L.(χ²) = 0.99
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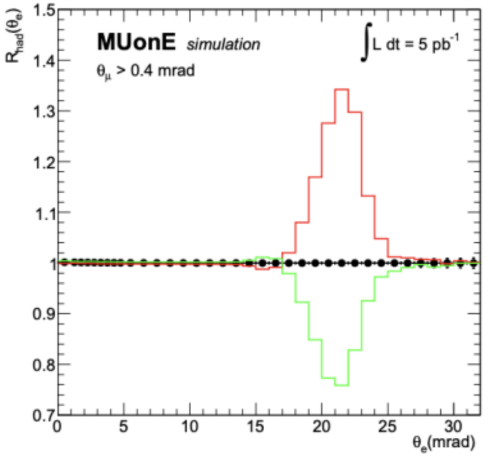
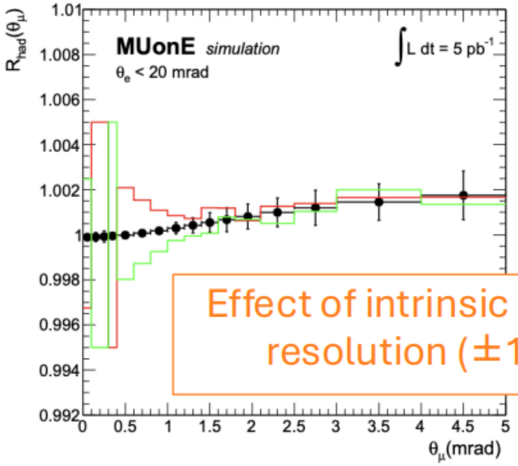
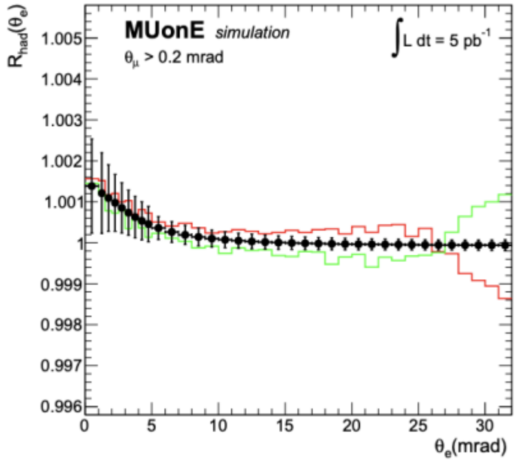
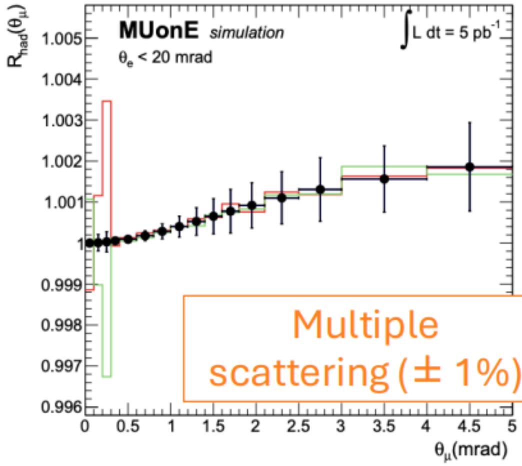
LinkID 13. Track C.L.(χ²) = 0.99
LinkID 14. Track C.L.(χ²) = 0.99
LinkID 15. Track C.L.(χ²) = 0.99
LinkID 16. Track C.L.(χ²) = 0.99
LinkID 17. Track C.L.(χ²) = 0.99
x local Track - x local Hit [μm]





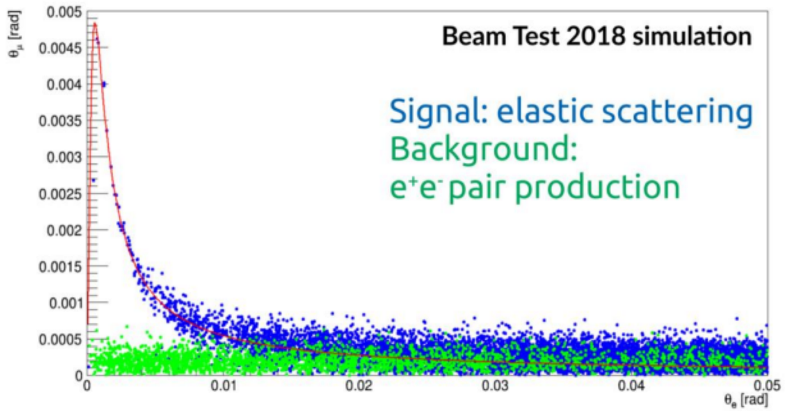
Effect of intrinsic angular resolution (±10%)

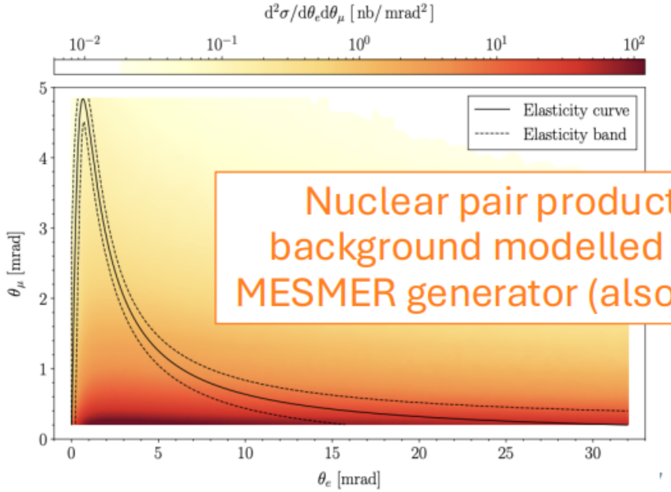




Multiple scattering (± 1%)

Dominant background: nuclear pair production





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