Status of MUonE analysis of 2023 data and prospects for 2025 run

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III Muon Precision Physics Workshop (MPP2024)
https://indico.ph.liv.ac.uk/event/1666/

Outline

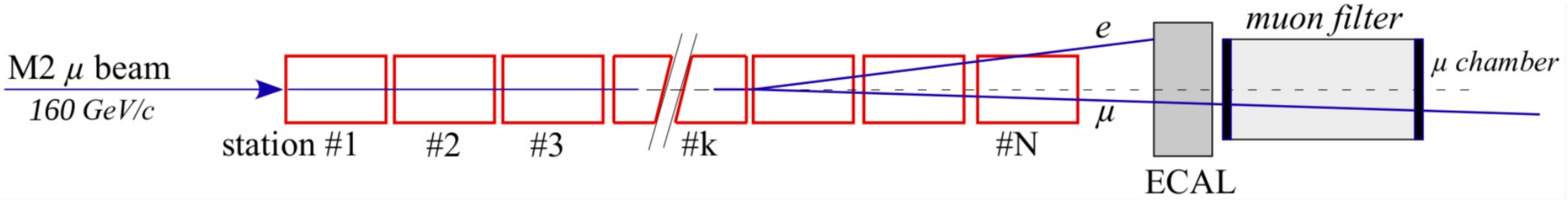
- 2023 Test Run: detector setup and commissioning
- Muon beam and Data processing
- Detector performance
- Selection of elastic scattering events and background studies
- MC physics performance
- Open points from 2023 run, prospects for 2025 run
- Conclusions

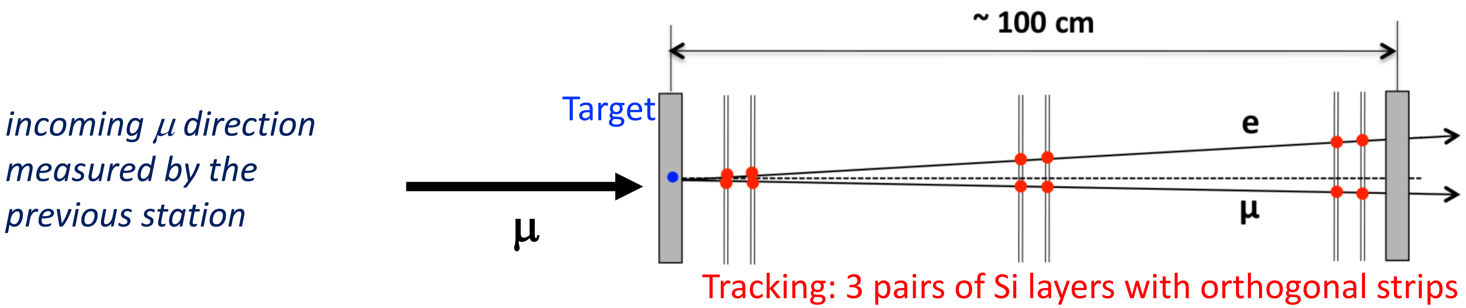
MUonE Detector Layout

Letter-Of-Intent SPSC-I-252
Proposal phase-1 SPSC-P-370

The detector concept is simple, the challenge is to keep the systematics at the same level as the statistical error .

- Modular structure of 40 independent and precise tracking stations, with split light targets equivalent to 60cm Be
- ECAL and Muon filter after the last station, to help the ID and background rejection





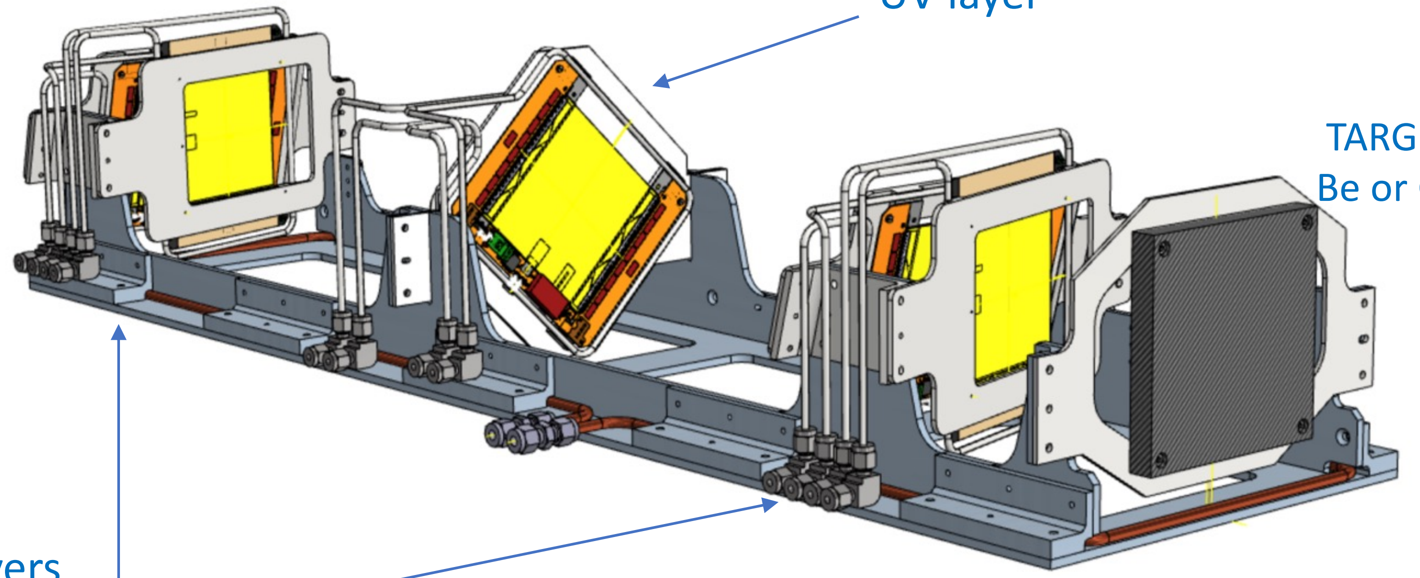
- Boosted kinematics: θ_e<32mrad (for E_e>1 GeV), θ_μ<5mrad:
  - the whole acceptance can be covered with a 10x10cm^2 silicon sensor at 1m distance from the target, reducing many systematic errors

MUonE tracking station

Length 1m
Transverse size 10cm

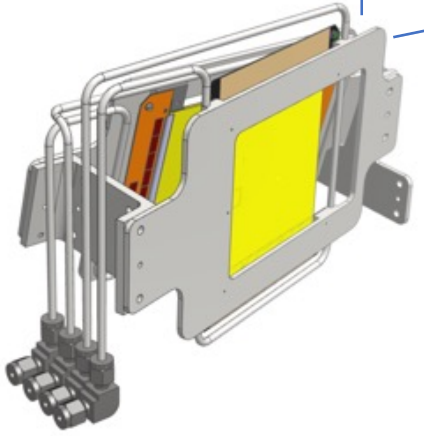
UV layer

TARGET
Be or C



Relative positions of modules must be stable within 10μm

Tilted XY layers



Low CTE support structure: INVAR (alloy of 65%Fe, 35%Ni)

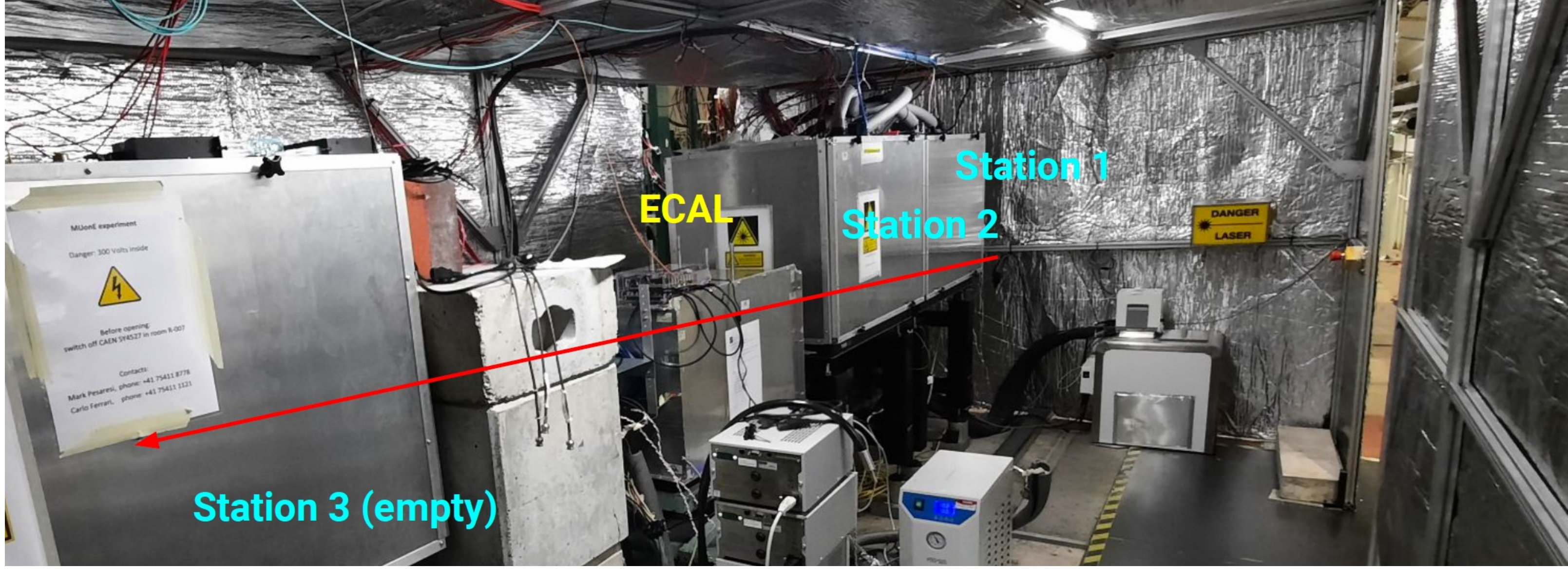
Cooling system, tracker enclosure,
Room temperature stabilized within 1-2 ^{o}C

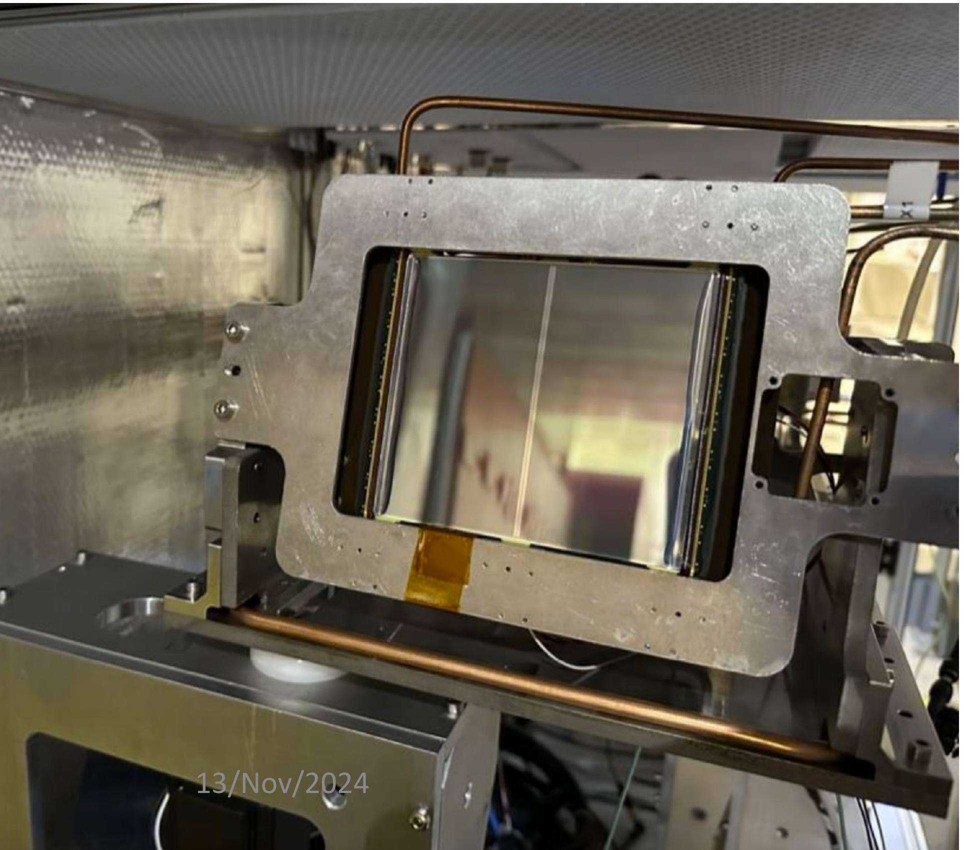
Laser holographic system to monitor the stability

Tilted X and Y modules to improve the resolution (by charge sharing between adjacent strips)

U, V modules to solve reconstruction ambiguities

MUonE Test Run 2023



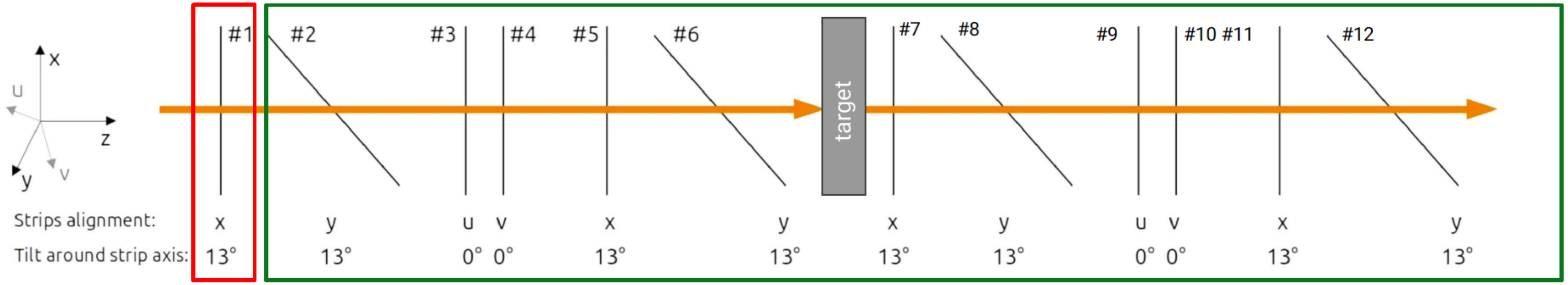


- MUonE Test Run at CERN North Area (M2 beam) (Aug/Sep 2023)
- 160 GeV muons, max rate of 50 MHz (2x10^8 asynchronous muons per 5s spill)
  - Hits (*stubs*) recorded to disk for every single ‘BX’ (40 MHz)
  - Low intensity runs for commissioning
- 2/3cm graphite target between the two tracking stations
  - also runs without target (for alignment purpose)
- Continuous readout of the two stations at 40 MHz for long runs
- 300 TB raw data recorded to disk:
  - ~1x10^8 elastic events with 3 cm target, ~2x10^8 with 2 cm target
- ECAL integrated in the DAQ at 40 MHz in the last part of the run
- Muon filter initially foreseen for 3rd station not setup (lack of hardware)

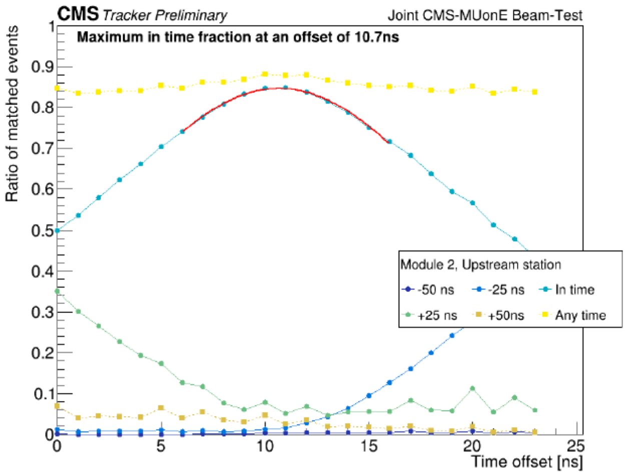
Tracker synchronisation

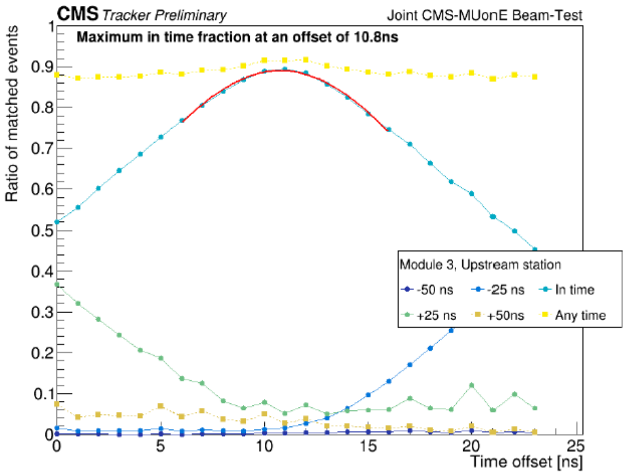
DLL = 12

DLL being scanned, all modules simultaneously



Computing fraction of events with a hit in module 1, if a hit ifs found in module X





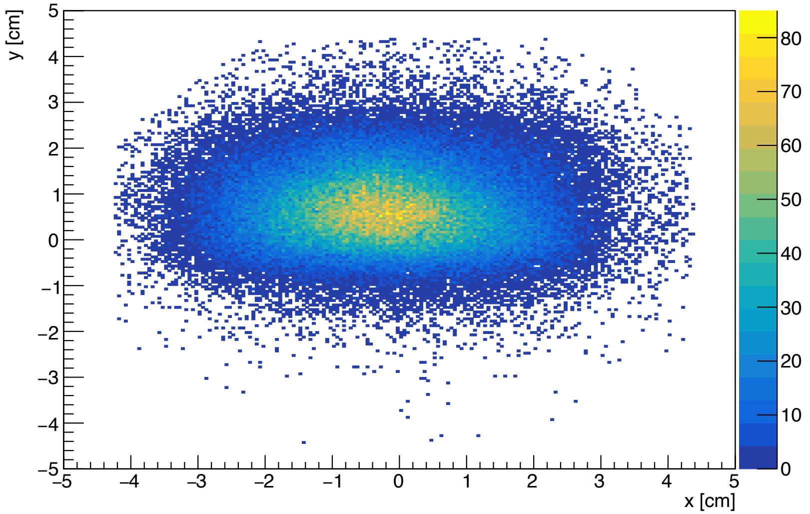
Also: performance with asynchronous readout of M2 beam muons in

Martin Delcourt talk at BTTB12:
Commissioning and study of a CMS 2S module with 40MHz readout
LINK

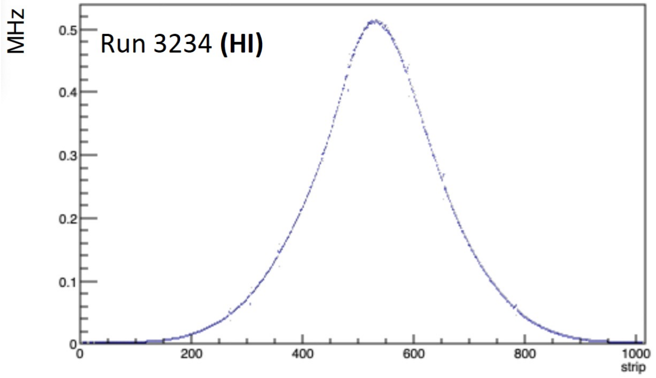
→ **Gives us the relative timing of modules (here, 0.1ns between module 2 & 3)**

Muon beam profile and intensity

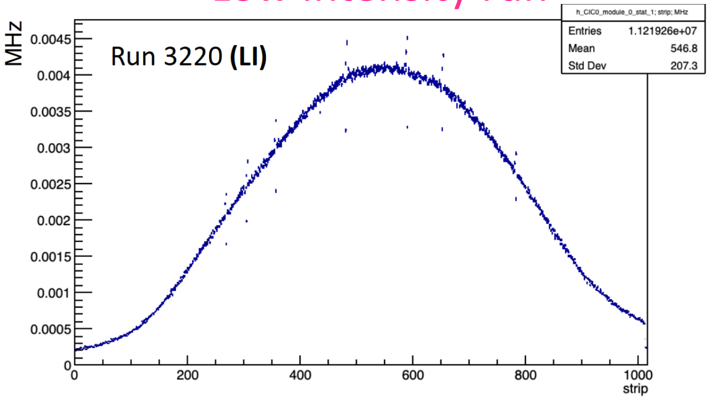
- M2 muon beam: spills of ~5 s every ~20 s
- Beam size fully contained in our detector for high intensity runs (1-2 x 10^8 μ/spill)
- Broader profile for low intensity (1 x 10^7 μ/spill), still almost fully contained



High Intensity run



Low Intensity run



Multi-Muon Efficiencies

- Having plenty of data we can select GOLDEN topologies like: 1,2,3,4 passing muons, leaving one hit on all the tracker modules.
- Define the efficiency for a N-golden muon pattern in the first (second) station from the events with N-golden muon pattern in the second (first) station. To exclude bad DAQ intervals add a preselection of at least one hit in the station under test.
- Is the N-muon efficiency factorisable from the 1-muon efficiency? It seems so:

Muon N	Station 0		Station 1	
	Golden Eff(N) | 1 hit	Estimated Eff(1) $\simeq [Eff(N)]^{1/N}$	Golden Eff(N) | 1 hit	Estimated Eff(1) $\simeq [Eff(N)]^{1/N}$
1	**0.741**		**0.749**	
2	0.569	**0.754**	0.572	**0.756**
3	0.422	**0.750**	0.426	**0.752**
4	0.297	**0.738**	0.304	**0.743**

Beam Muon Intensity

- Assuming the Poisson distribution for the multiplicity of incoming beam muons

$$P(N,\mu) = \frac{\mu^N}{N!} e^{-\mu}$$

- Assuming that muon efficiencies factorise:

$$\frac{N_2}{N_1} = \frac{\mu\,\varepsilon}{2} \qquad \frac{N_3}{N_1} = \frac{(\mu\,\varepsilon)^2}{6} \qquad \frac{N_4}{N_1} = \frac{(\mu\,\varepsilon)^3}{24}$$

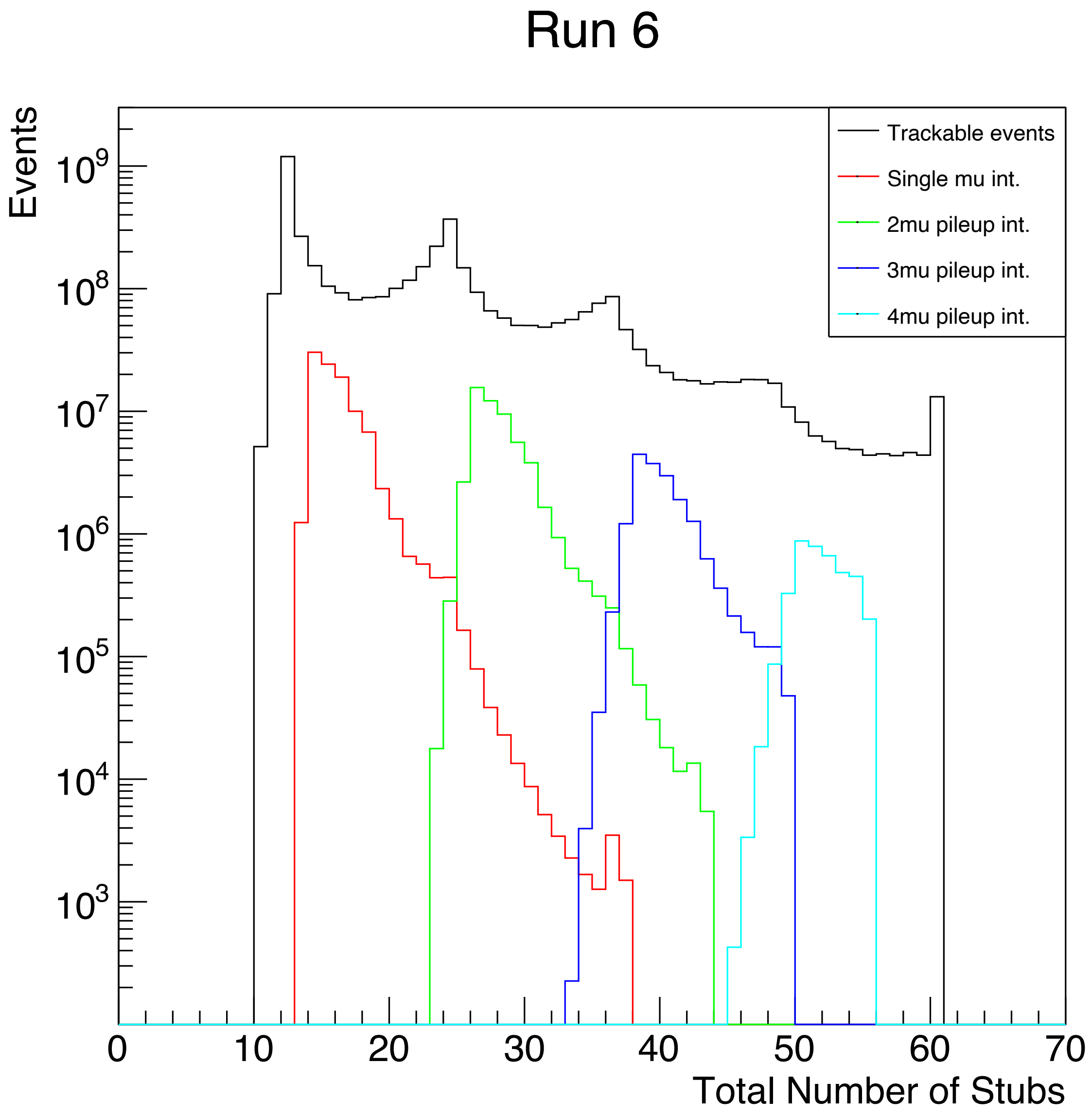
with ε=0.741 for S0, ε=0.749 for S1

Estimated μ	N2/N1	N3/N1	N4/N1
Station 0	0.854	0.882	0.891
Station 1	0.840	0.873	0.885

Estimated Poisson mean μ~0.85 → muon rate ~ 34 MHz

In agreement with the actual estimated rate from the SPS accelerator

Data preselection (*skimming*)



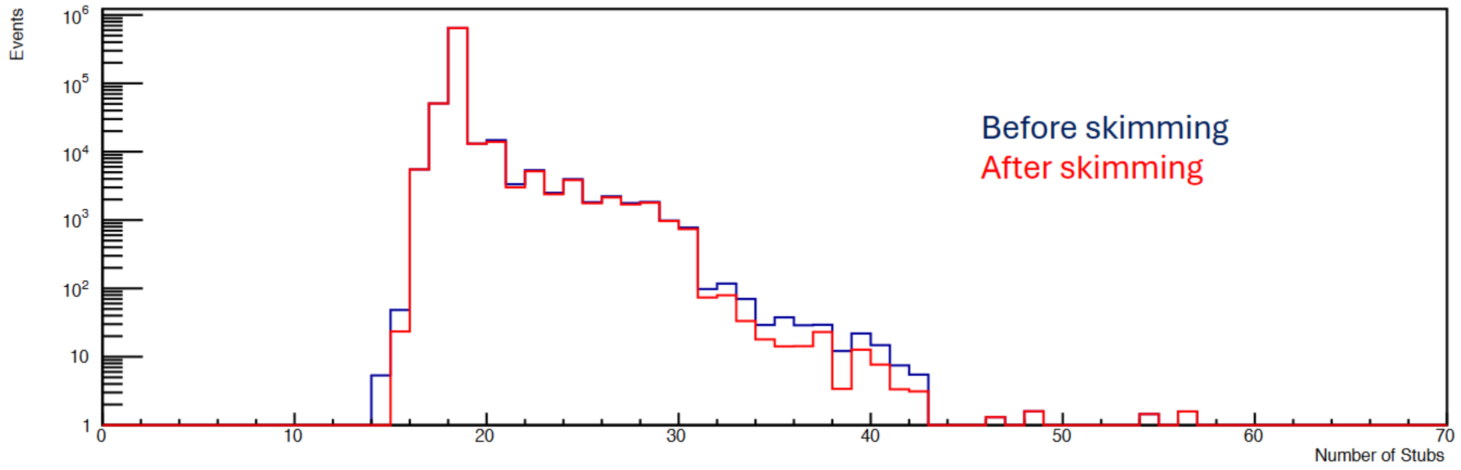
- 2023 Test Run operated with a Triggerless DAQ
  →Large Data volumes processed offline
- Skimming is aimed to preselect all the reconstructible events that can be associated to interactions in the target (from both signal and background processes)
- The algorithm is based simply on the **hit patterns observed in two consecutive stations**
- The loosest requirements are imposed, to avoid biases, still the event reduction is about a factor 100

On ~12 B merged events, the skimming selects:
0.8% ~97 M Single-Mu interaction candidates
0.6% ~75 M PU (2,3,4) Mu interaction candidates

The different classes are well separated:

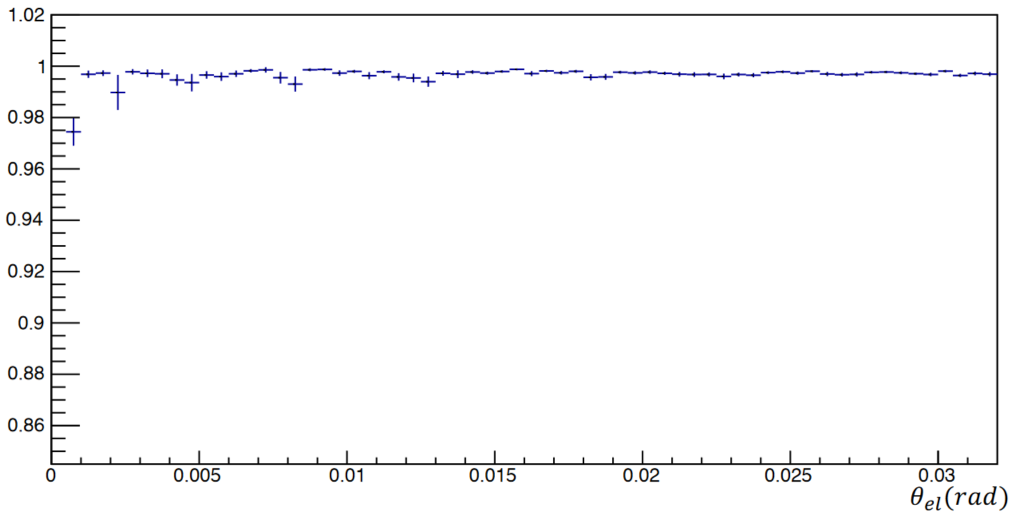
- Single muon interactions
- 2,3,4 pile-up muons with interactions

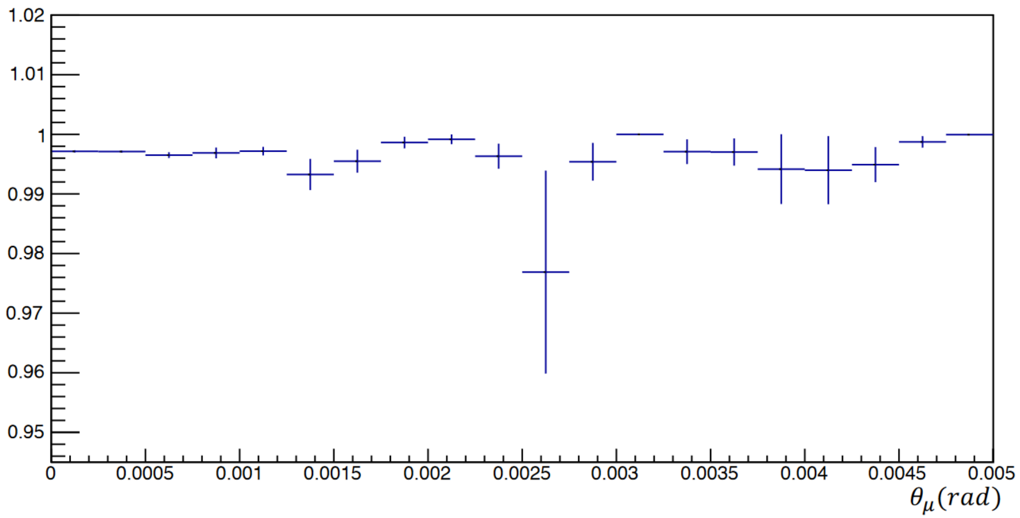
Performance of the skimming algo on MC signal



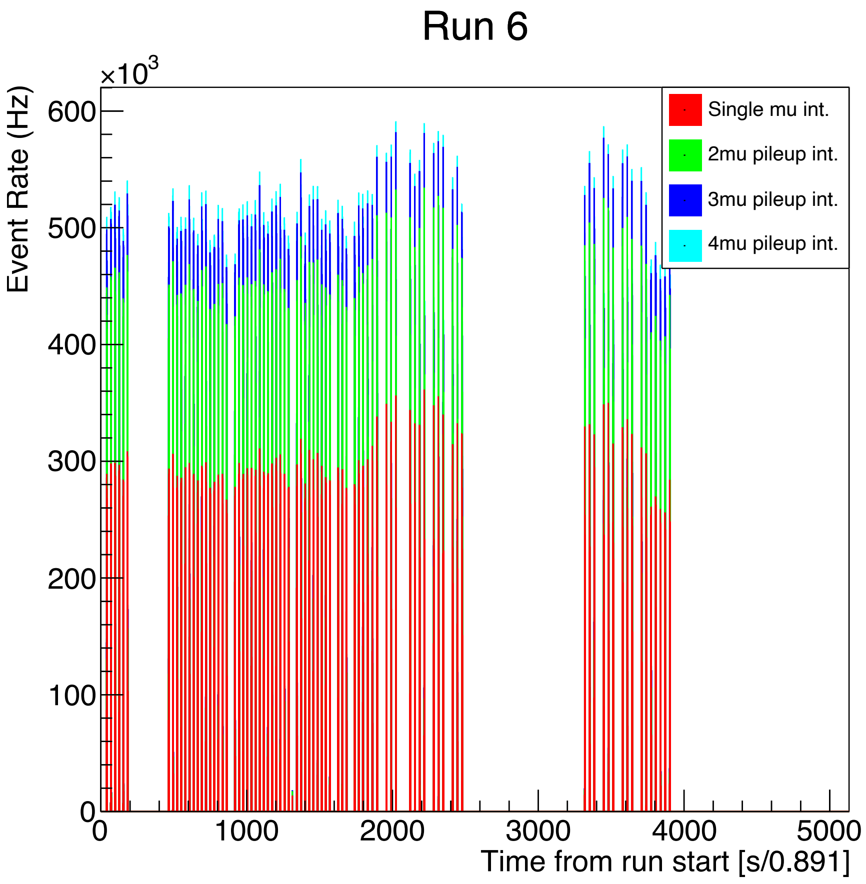
Selection based only on the hit pattern:

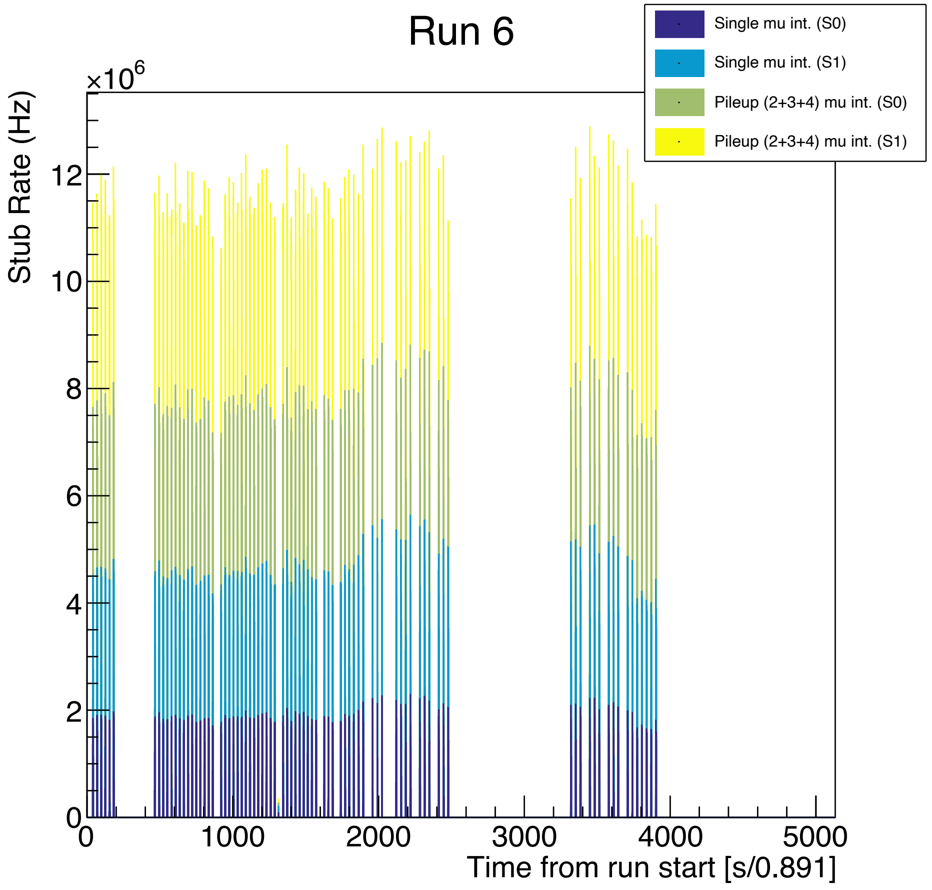
- **Full Efficiency**
- **No kinematic biases**





Event and Hit rates after Skimming Preselection





No beam in some time intervals: DAQ was carried on (nights)

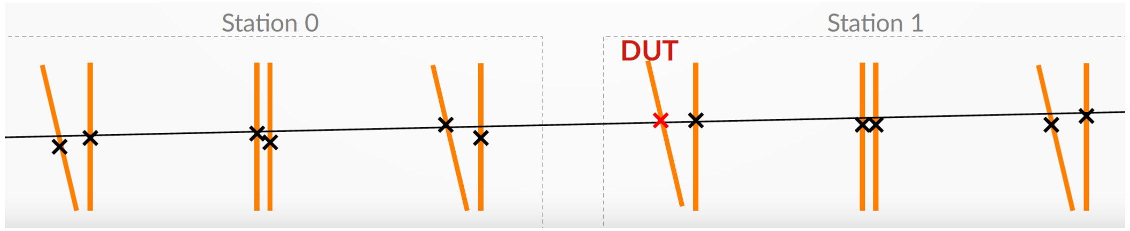
Rate ~500 KHz: algorithm can easily be implemented online on FPGA

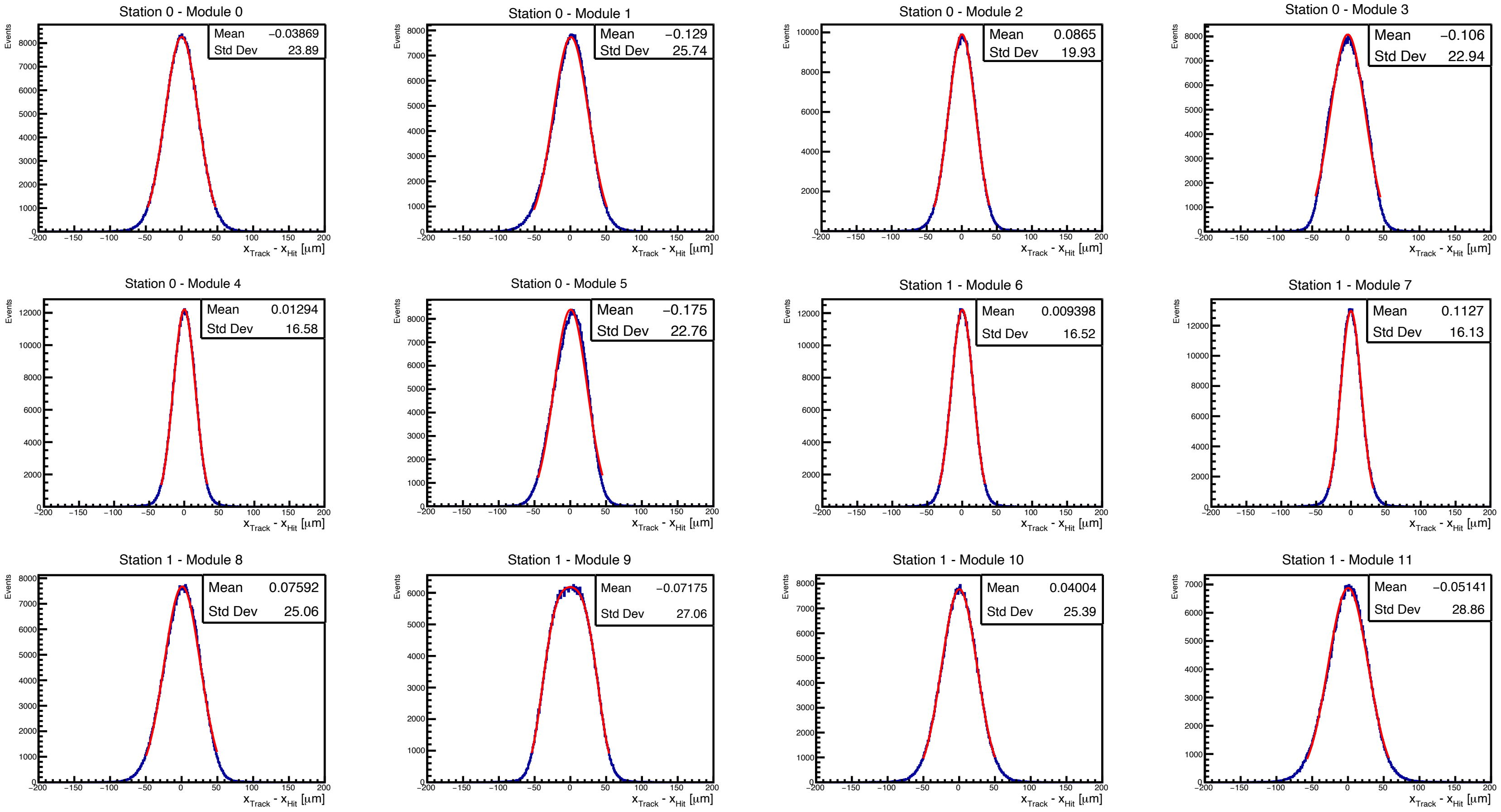
OnLine Tracking on FPGA achieved in 2023 Run

→ Michael McGinnis at BTTB12 (LINK)

Detector Alignment - Resolution

PROPOSAL
CERN-SPSC-P-370





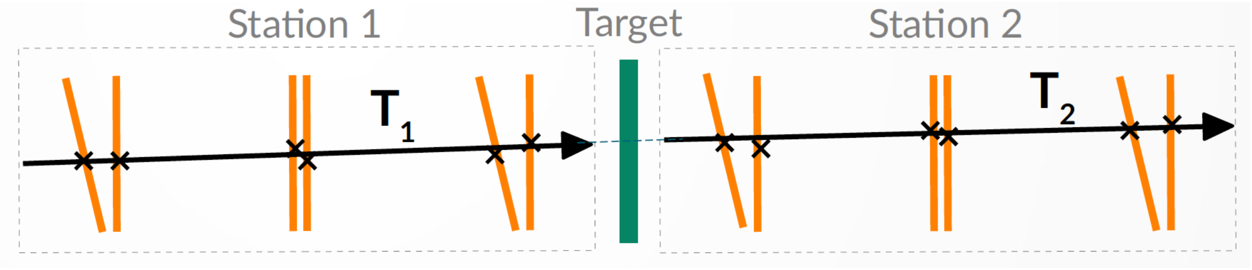
The tracker is aligned with passing beam muons leaving one hit in all the 12 detector modules

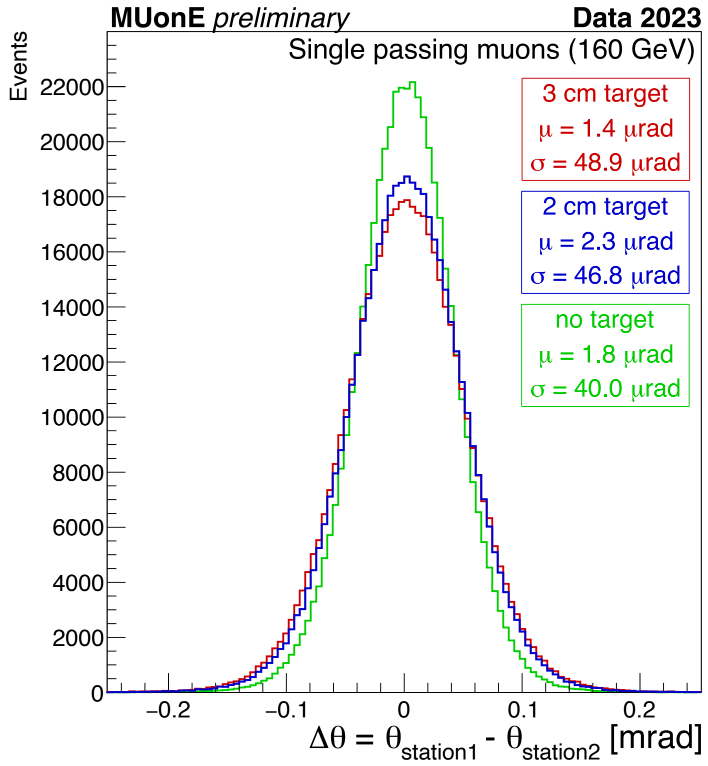
three coordinates aligned per each module:
Strip local position (local X)
Rotation angle around the Z axis
Orthogonal coordinate (local Y)
Transverse rotations fixed to ideal geometry (in part. X,Y modules' tilt)

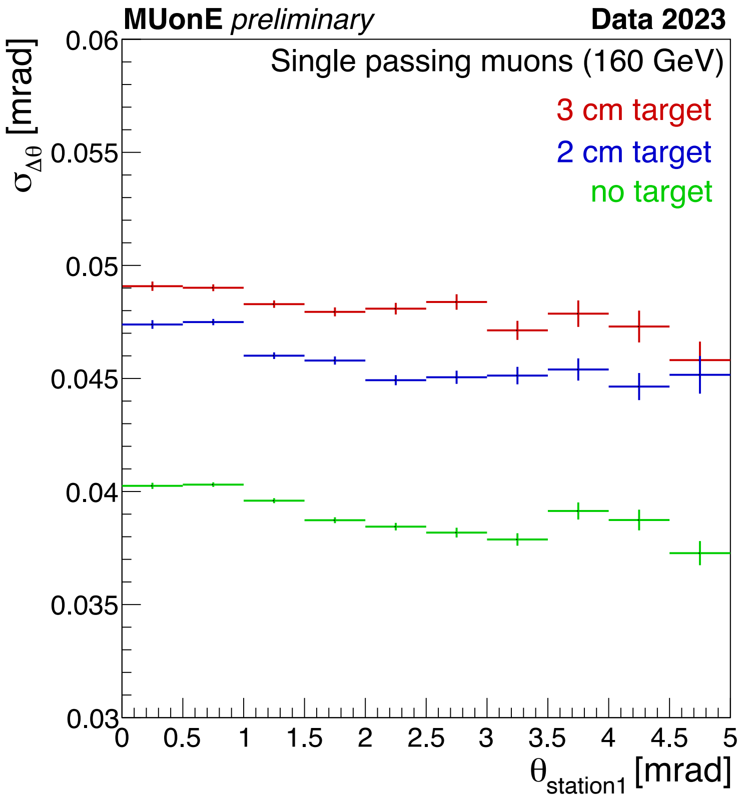
Unbiased residuals on the tracker modules after the alignment:

resolution consistent with expected resolution

Track Angular resolution







Measure the same beam muon track in the two stations:

Difference between the two measurements depends on the tracker resolution and the multiple Coulomb scattering

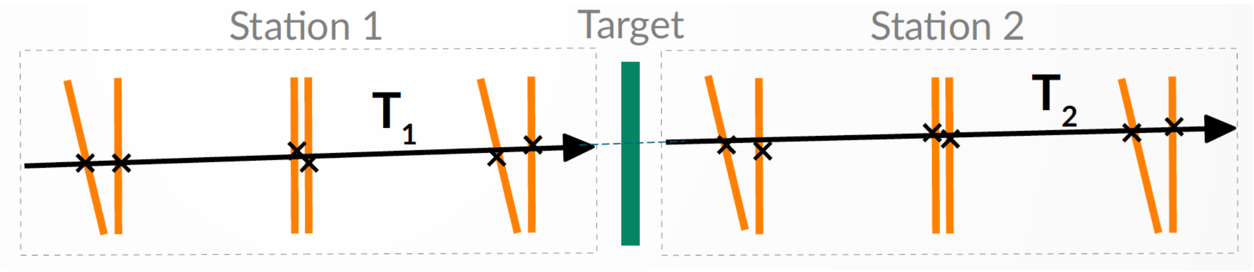
From the no-target case one gets:

$\sigma_\theta = (28.3 \pm 1.6)\ \mu\text{rad}$

as resolution for one station

MC simulation is still not satisfactory

Multiple Scattering in the Target



$$\sigma^2_{MS}(target) = \sigma^2_{\Delta\theta}(target) - \sigma^2_{\Delta\theta}(no\ target)$$

Target	$\sigma_{\Delta\theta}$ [μrad]	σ_{MS}(target) [μrad]	σ^{PDG}_{MS}(target) [μrad]
3 cm C	48.9 ± 2.1	28.1 ± 0.6	28.2
2 cm C	46.8 ± 2.1	24.3 ± 1.4	22.6
No Target	40.0 ± 2.2		

The main contribution to the uncertainties is due to residual misalignments

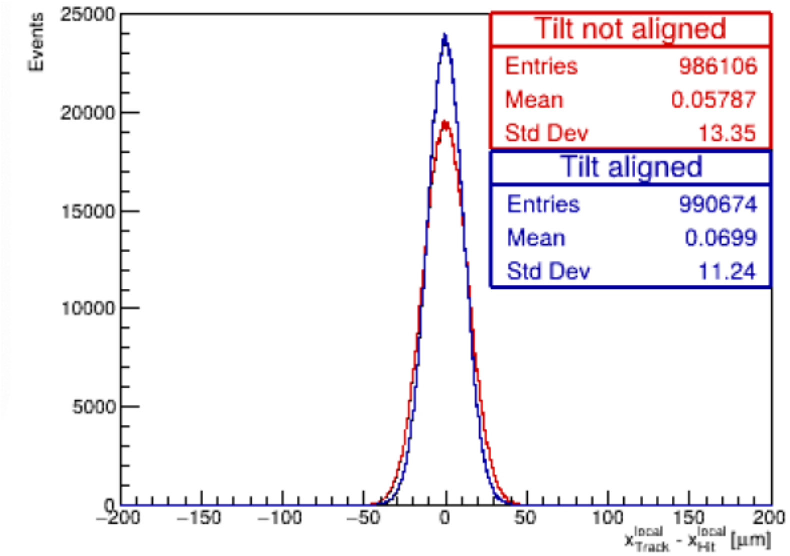
The muon deflection angle in the target is in good agreement with the expected multiple scattering for E=160 GeV

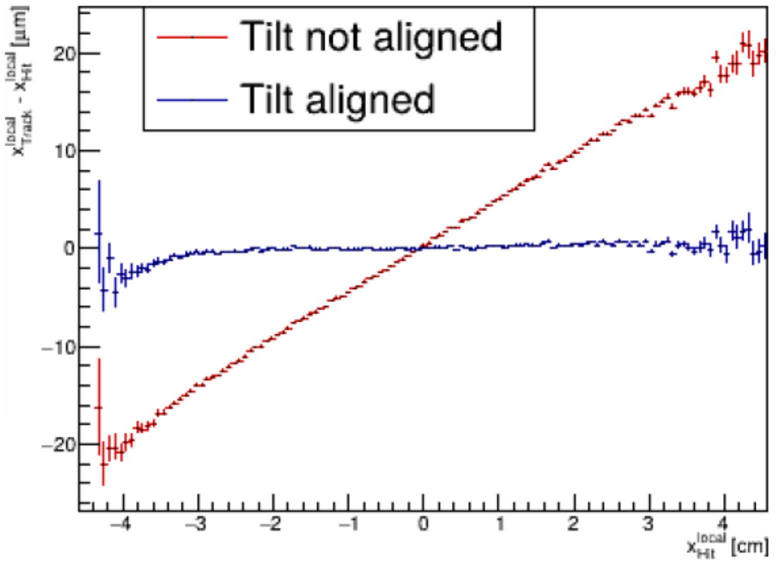
NEW: improved alignment

preliminary, R.Pilato

Full 3D geometry description with new tracking equations make possible to align the X,Y modules' tilt angle which with previous algorithm was a weak mode

- 233 mrad tilt around the strip axis to improve the resolution



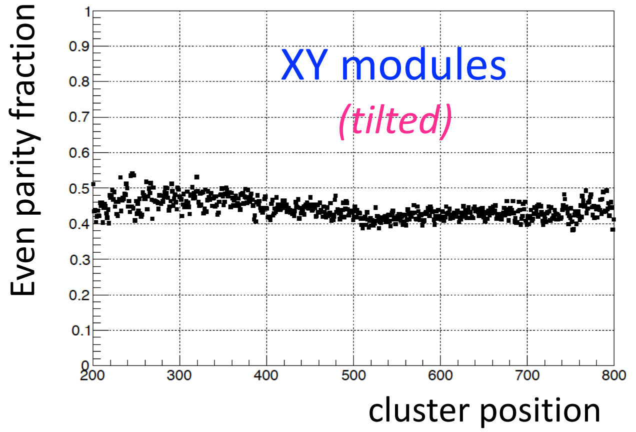


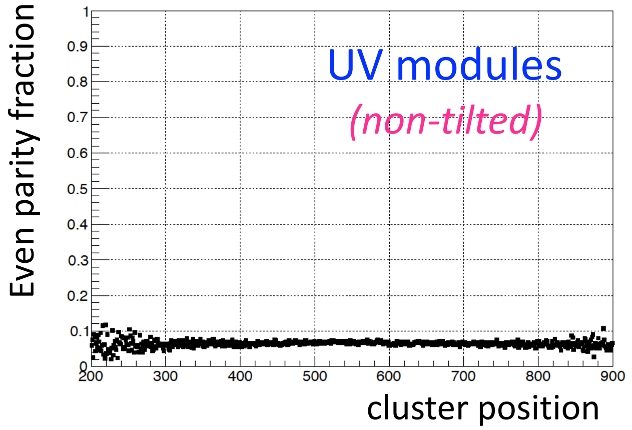
Clear improvement in the (biased) residual distributions and their profile as a function of the position

Preliminary results indicate an accuracy of ~0.5 mrad on the tilt angle, similar to that of the longitudinal rotation; ~1 μm on the measurement direction; ~10 μm on the transverse direction

Resolution for tilted and non-tilted sensors

consider just one silicon layer (there are 2 in the 2S modules)

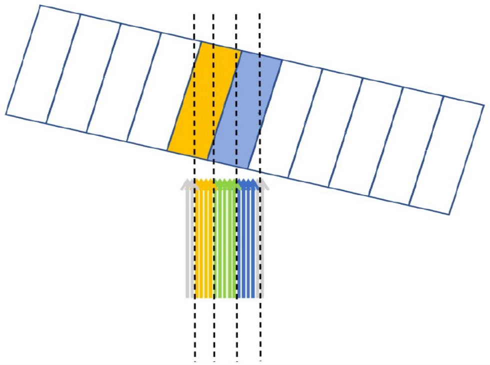




Cluster parity is odd for 1-strip clusters (or 2-)
Cluster parity is even for 2-strip clusters (or 4-)

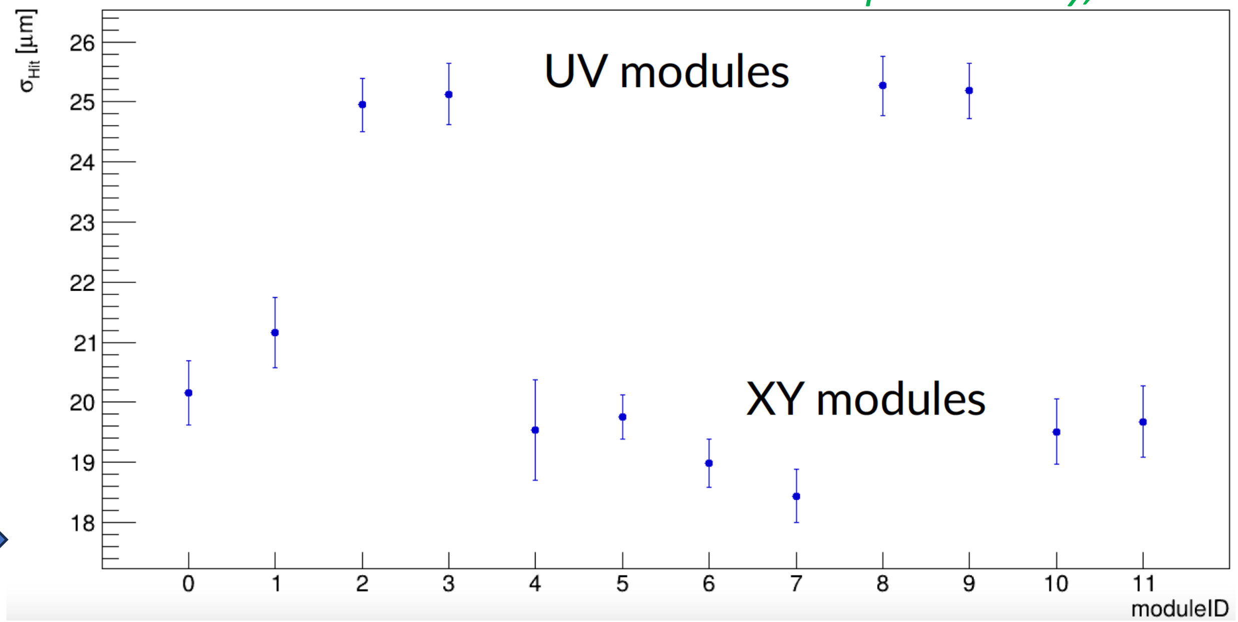
We have binary readout of strips
Non-tilted modules have mostly 1-strip clusters
Tilted modules ideally should have equal rate of 1- and 2-strip clusters, due to charge sharing, for a tilt angle of ~15 degrees

The position resolution is expected to improve with a tilt angle due to charge sharing



It does: (UV) σ ~ 25 μm
(XY) σ ~ 20 μm

preliminary, R.Pilato



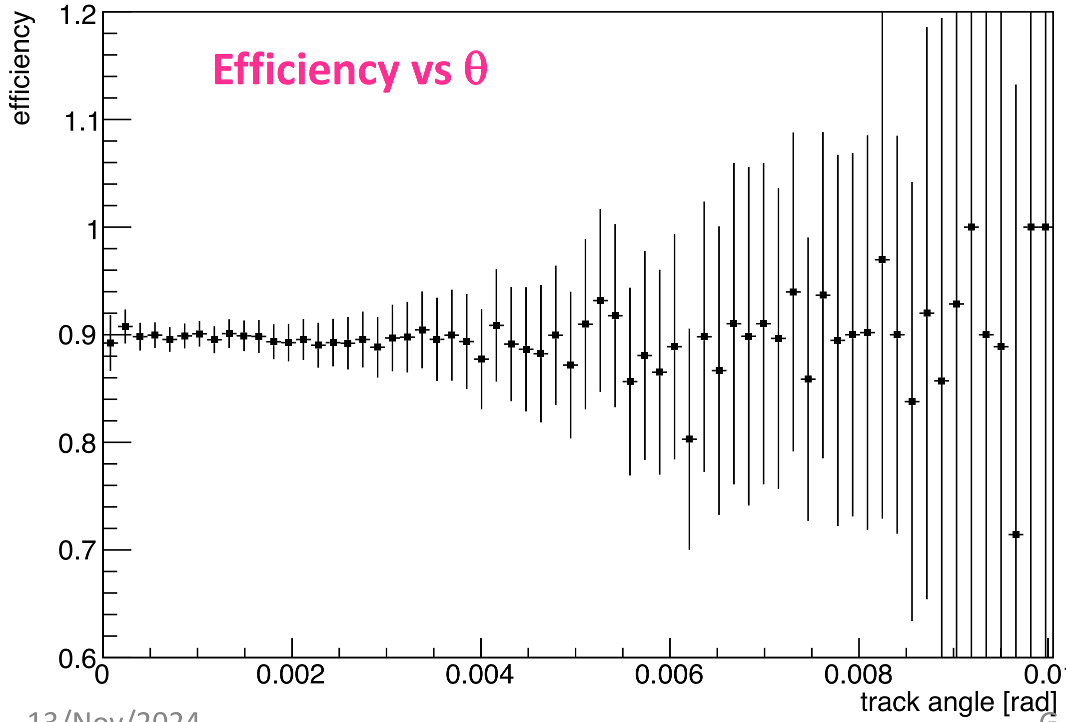
Tracker Efficiency (preliminary)

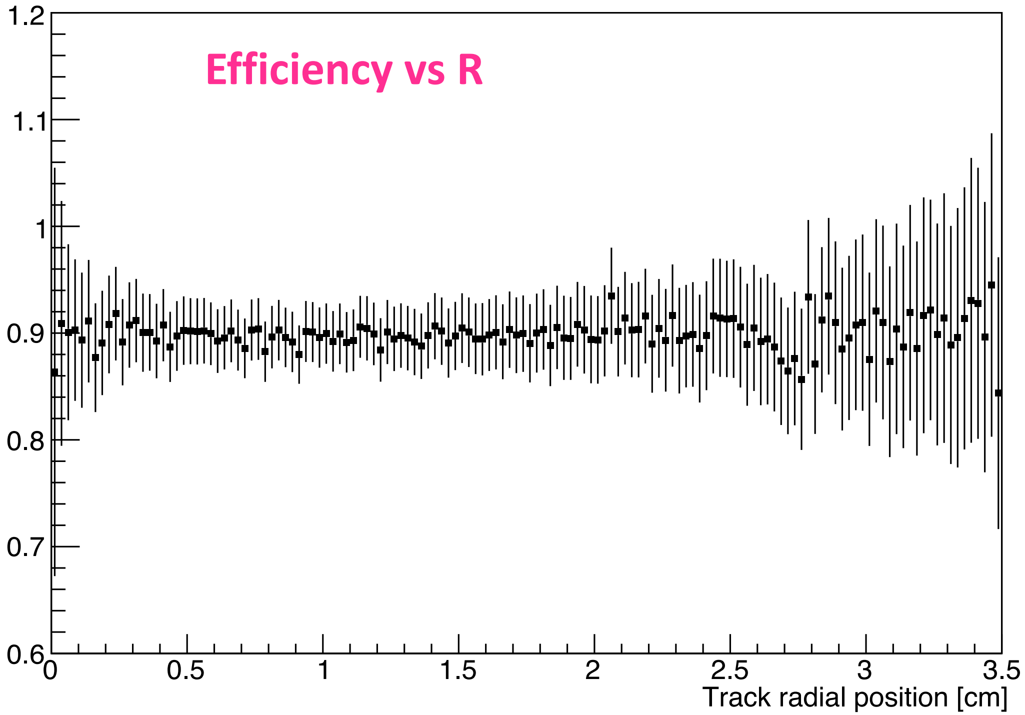
From selected golden muons: **average MODULE Efficiency** (98.0 ± 0.5)%

Tracking STATION Efficiency:
from events with only a passing golden muon in the First station (with 6 hits), looking for a reconstructed muon in the Second station

Muon Reconstruction Efficiency as a function of the Position and Angle at the target reference plane

Flat Efficiency at ~90% Consistent with the combinatorial result of the individual module efficiencies



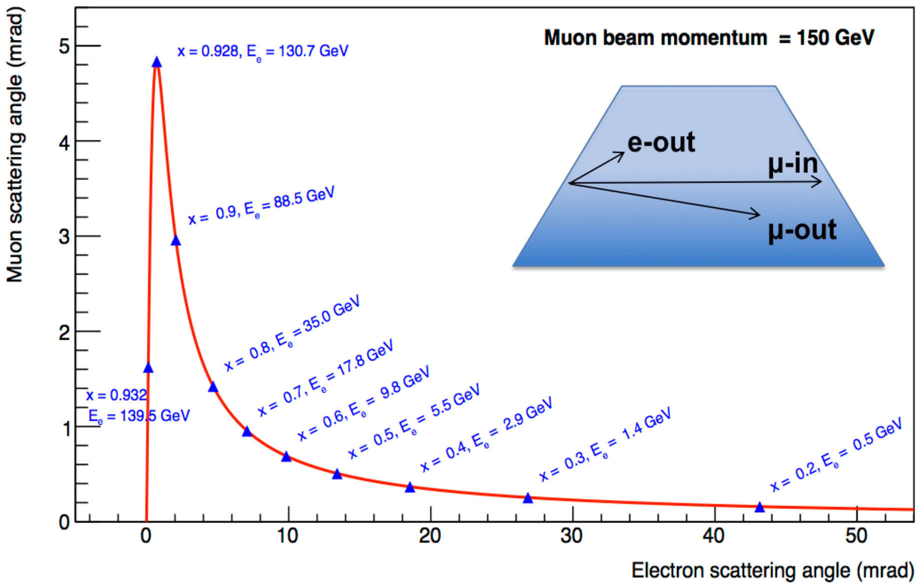


Event Selection

Basic signature of μe elastic scattering is:

- 1 incoming track (beam muon)
- 2 outgoing tracks
- interaction in the target

Elastic events are planar and the μ and e scattering angles are correlated



- Radiative events with real photon emission break these properties
  - but MESMER (N)NLO MC generator describes the effects very accurately

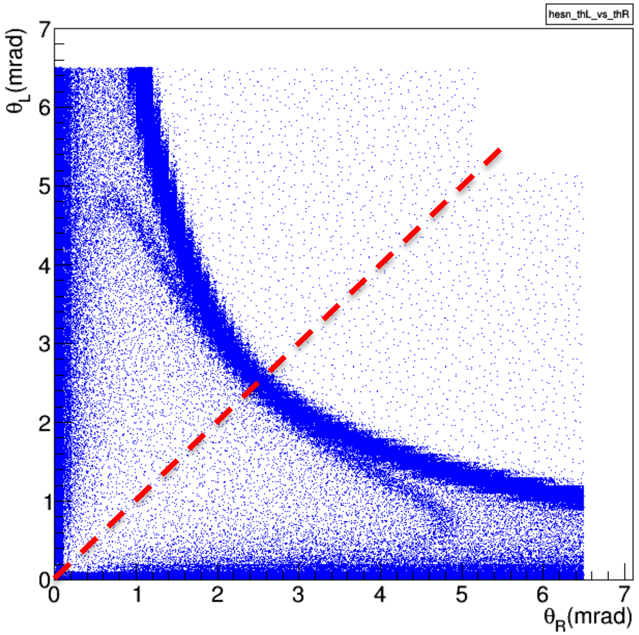
- Pileup of beam muons is easily controlled with the track impact parameters w.r.t. the candidate interaction vertex

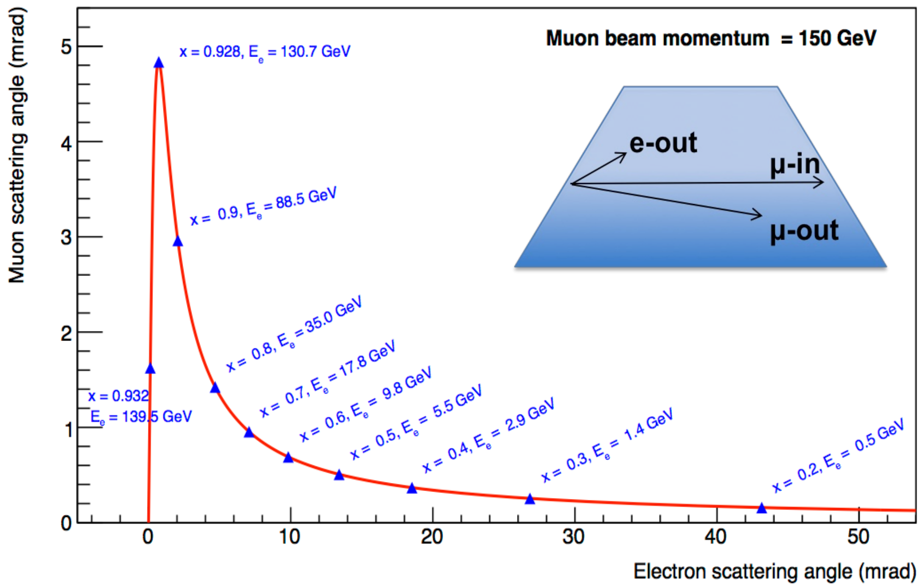
- Events produced in interactions with the detector's silicon layers can be removed by testing the compatibility with a vertex in the target

- Main physics background is the pair production μ X → μ e^+e^- X
  - X can be a nucleus ($\sigma \sim Z^2$) or an atomic electron ($\sigma \sim Z$)
  - These events produce 3 or 4 tracks in the final state: easily rejected when they are all reconstructed, they can mimic the signal when only 2 tracks are reconstructed

Particle Identification

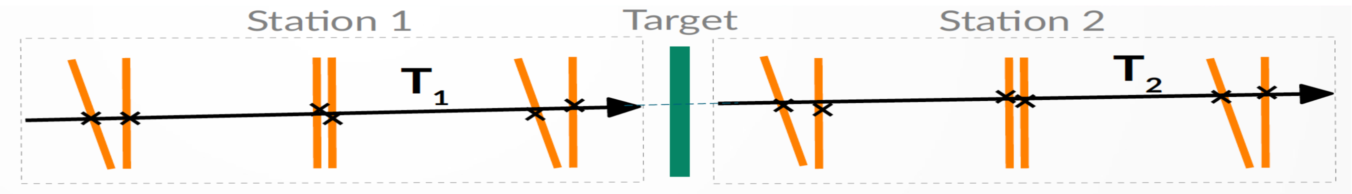
Tracking without magnetic field (no momentum measurement): the event interpretation has an ambiguity region at small angle

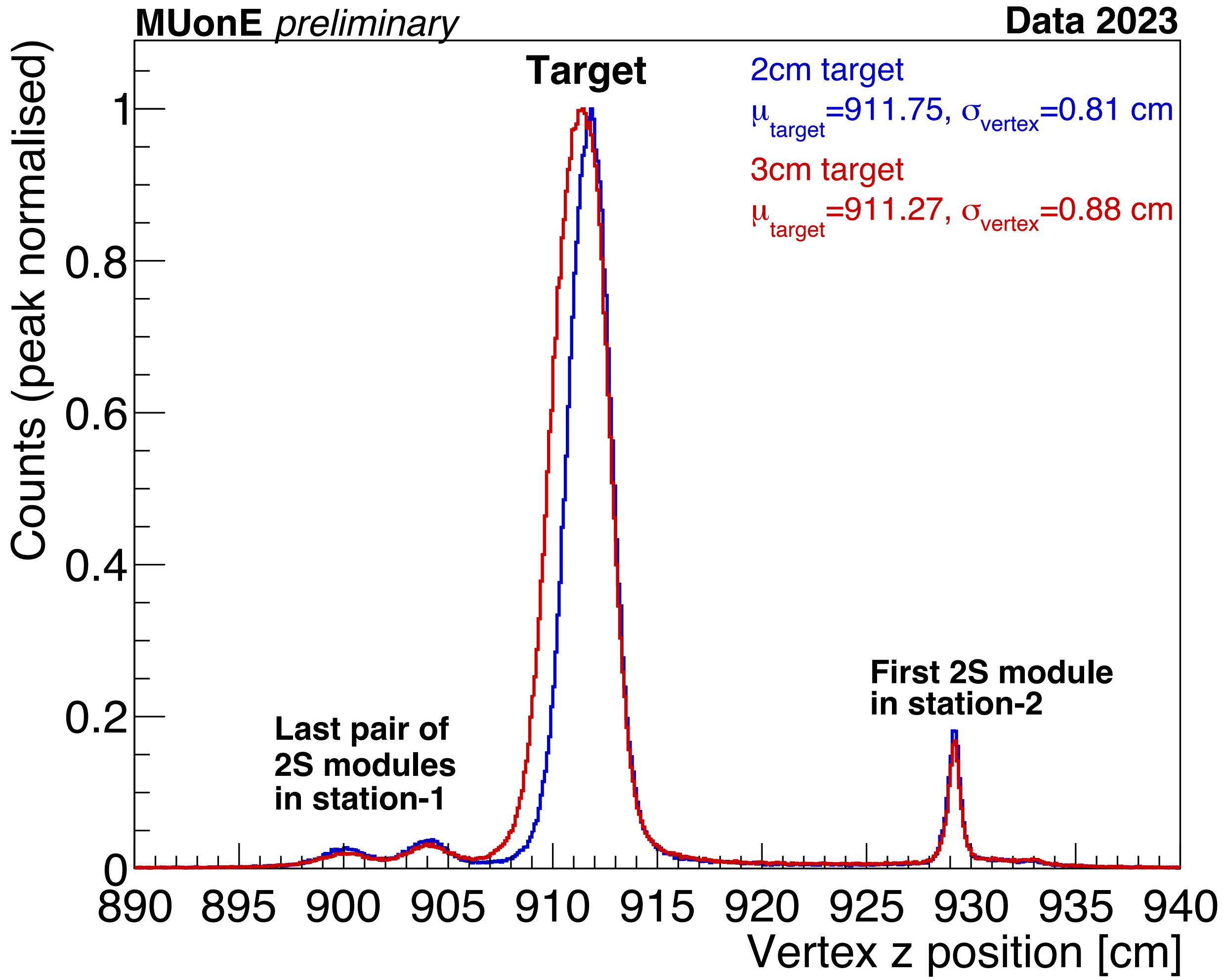




- In principle the analysis of μe elastic scattering events does not need the identification of the outgoing tracks
- However μ-e ID will be very useful to study systematics and determining detector performance
- ECAL measurement of electrons will be possible only for high-energy (low angle) electrons from events occurring at any station (although with reduced resolution for initial stations in the array)
- Instead muon identification will be possible with good performance for all interesting events from any station
- Nevertheless the last tracking station will be close to the ECAL, allowing to identify both μ and *e* in all events produced in the last station
  - ➢ It is important to study alternative event selections using the ECAL measurement of the electron energy which will be applicable at least to the last station.

Vertexing





VERTEX defined for:
1 incoming + 2 outgoing tracks

Two outgoing tracks within angular cuts (0.2 – 32 mrad)
reco setting allowing 1-shared-hit

Vertex Z fitted to a box (2 or 3 cm, according to the target thickness) convoluted with a gaussian resolution

The target middle is shifted by 0.5 cm along Z changing between the thickness of 3cm and 2cm

The vertez Z resolution is ~0.8 cm, slightly better with the thinner target, due to less MCS

Elastic Scattering Selection

2D distribution of the candidate μe scattering angles (θ_{min}, θ_{max}) (no Particle Identification)

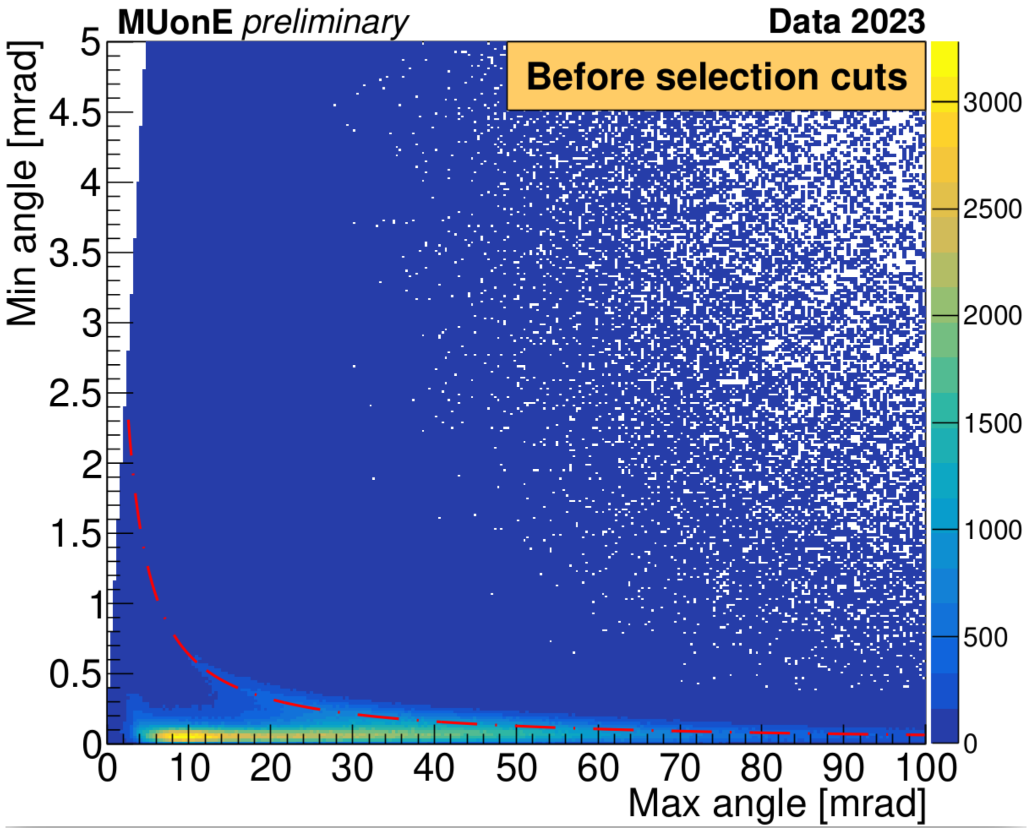
Skimming preselection of Single-Muon Interaction candidates with a candidate μe pair (loose vertex cut)

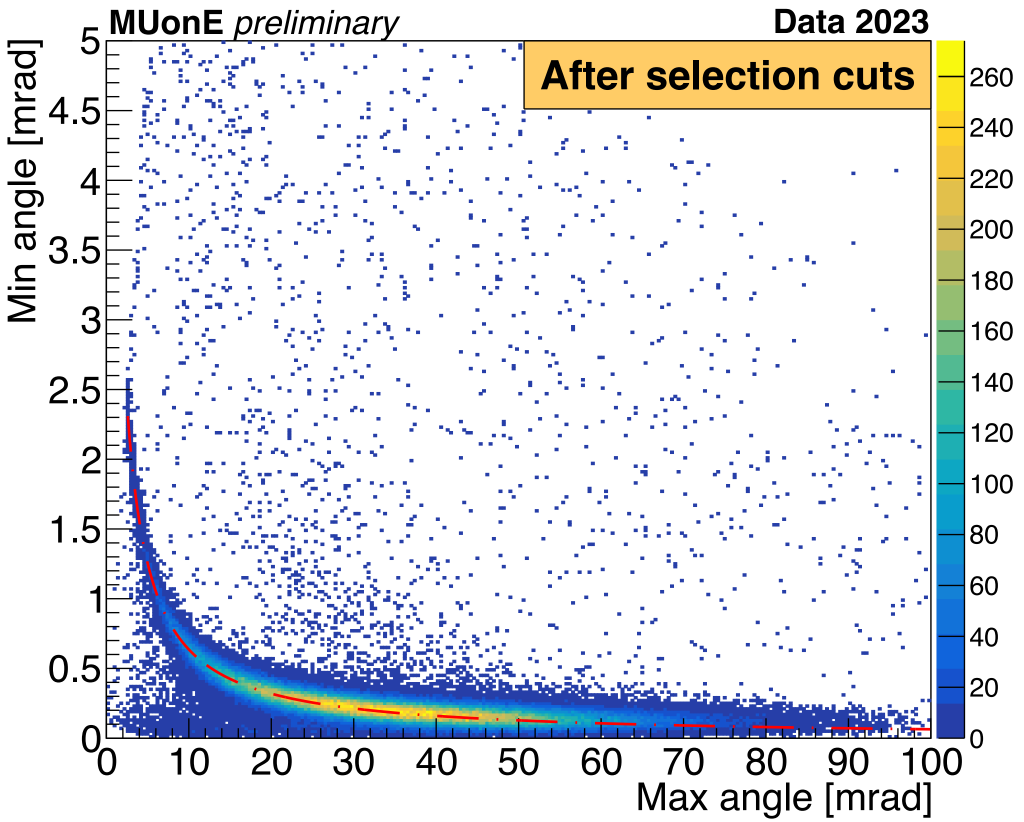
Initial selection:

$N_{hits}(S2) \leq 14$

Loose acoplanarity $|A| < 0.3$ rad;

vertex compatible with target position: $|Z_{vtx} - Z_{target}| < 3$cm





Minimum Bias simulation

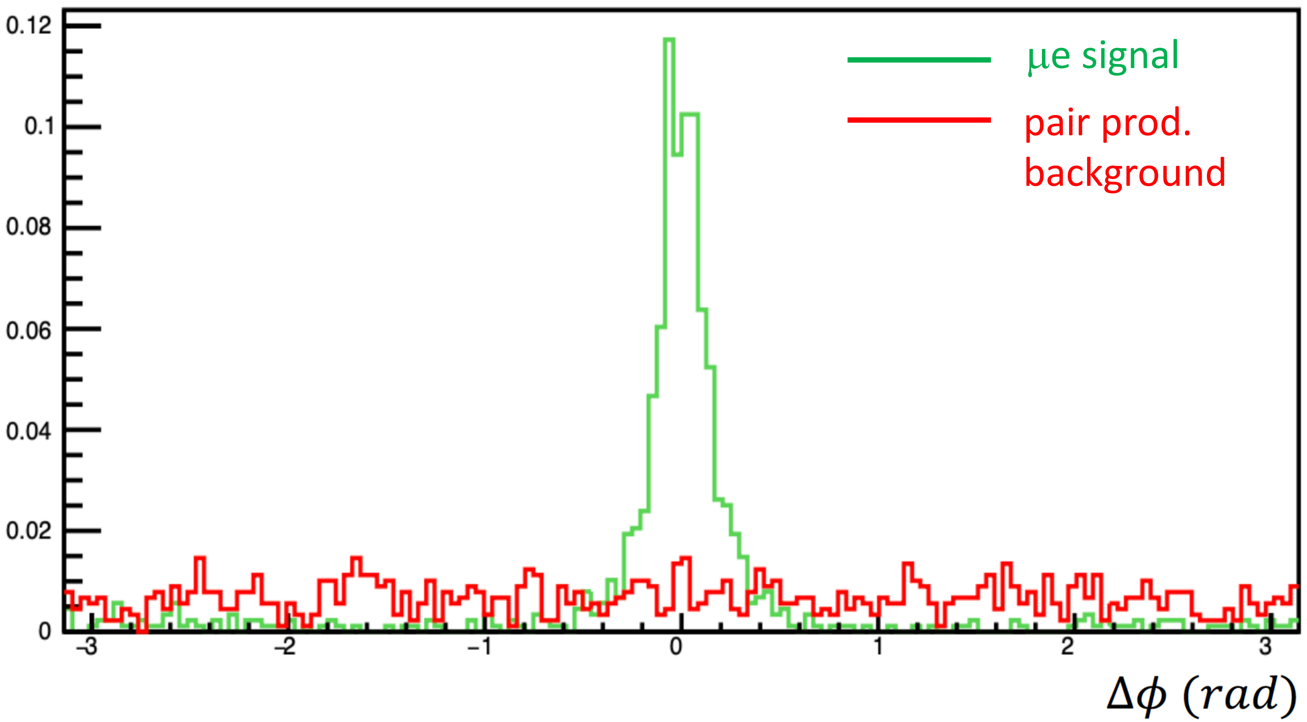
(Signal and Background from GEANT4)

Let **i** , **m** , **e** be unit vectors respectively along the directions of the incoming muon, the outgoing muon and the outgoing electron

Acoplanarity:

angle between the scattering planes formed by the outgoing particles with the incoming muon

$$\Delta\phi = \pm\left[\pi - \cos^{-1}\left(\frac{(\mathbf{i}\times\mathbf{m})\cdot(\mathbf{i}\times\mathbf{e})}{|\mathbf{i}\times\mathbf{m}|\,|\mathbf{i}\times\mathbf{e}|}\right)\right] \text{ for } \begin{bmatrix} T > 0 \\ T < 0 \end{bmatrix} \qquad T = \mathbf{i}\cdot\mathbf{m}\times\mathbf{e}$$



TRACK-BASED Observables

Track quality (Nr Hits; χ^2)

Vertex compatibility

Vertex position

Acoplanarity

Minimum scattering angle

Elasticity (from angular correlation)

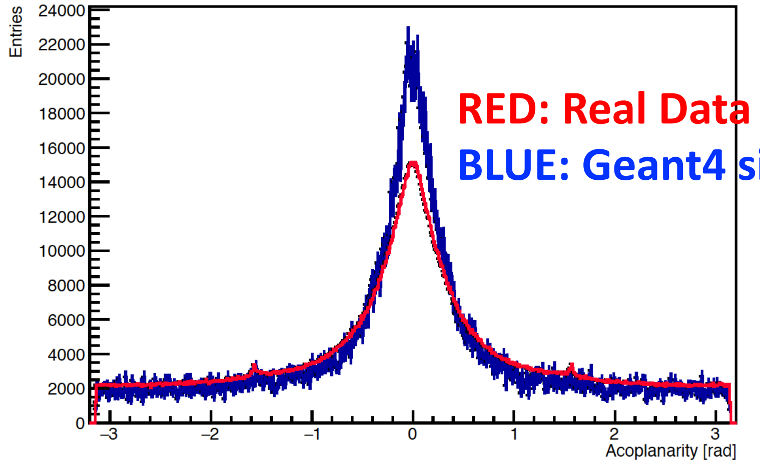
TRACK+CALO observables

Candidate electron (Calo cluster matching a track) and its Energy

Selection: acoplanarity

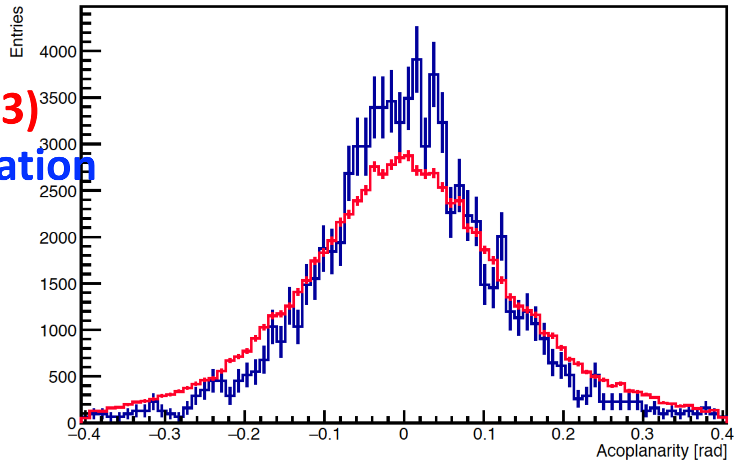
Preliminary,
from E.Spedicato's PhD thesis

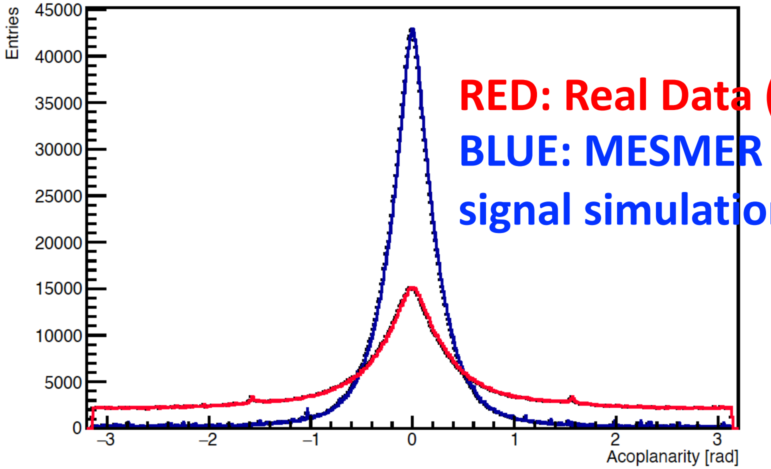
Preselection (skimming)



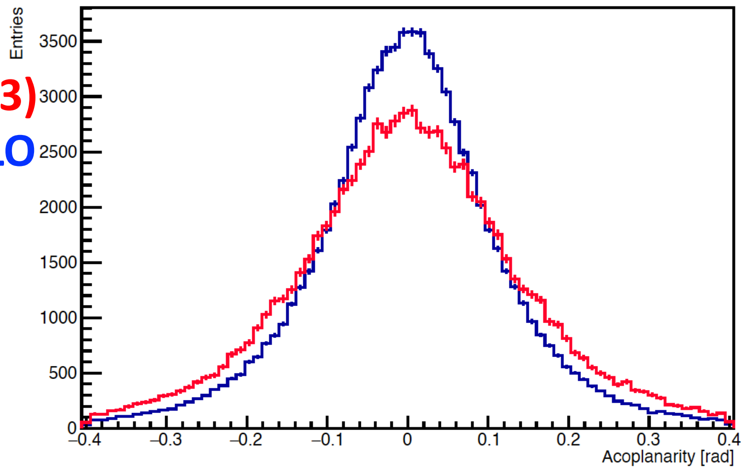
RED: Real Data (2023)
BLUE: Geant4 simulation

Elastic selection





RED: Real Data (2023)
BLUE: MESMER NNLO signal simulation



Data-MC comparisons with MC normalised to the data integral

Geant4 includes all sorts of backgrounds

We have also MESMER pair-production generators $\mu X \rightarrow \mu e^+e^- X$ which are more accurate, for both:
- nuclear production (~Z^2)
- production on atomic electrons (~Z)

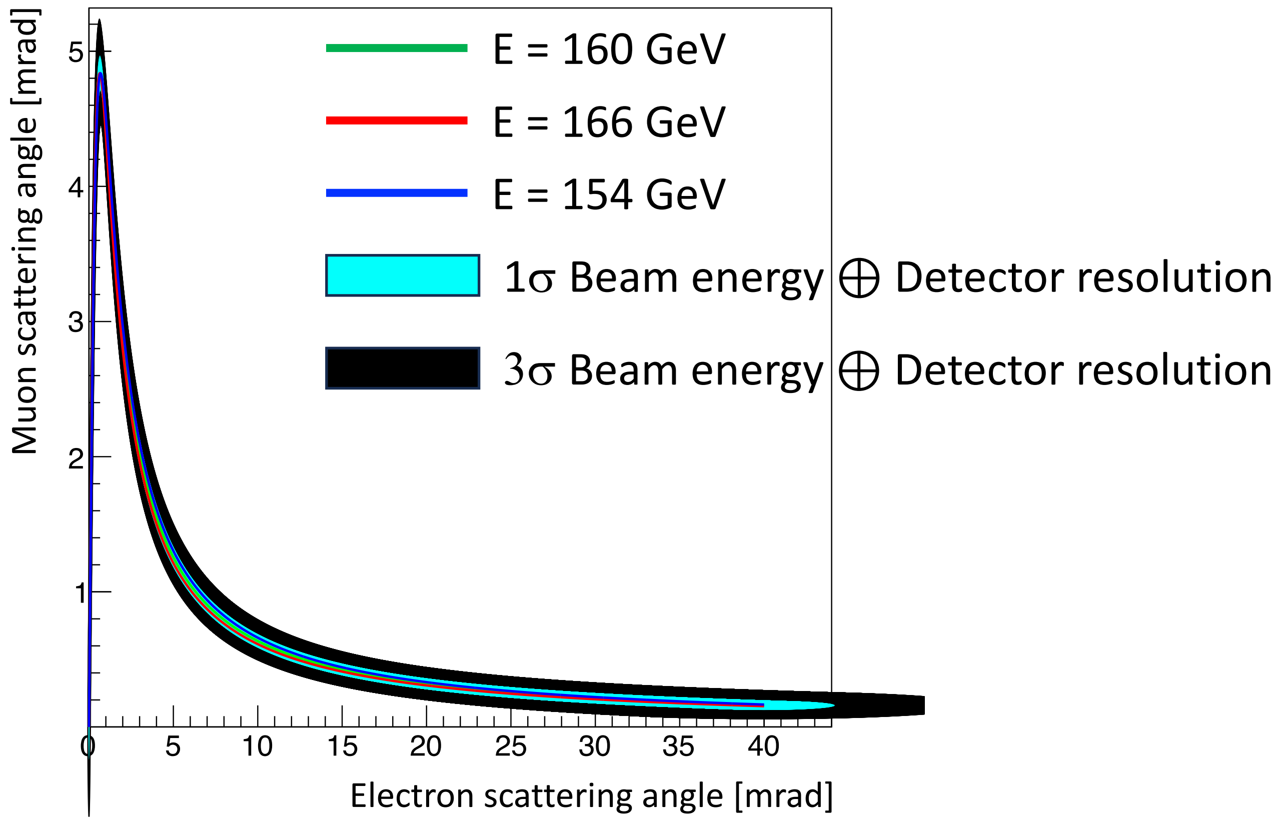
The width (after the selection) is not well described: impact of the resolution

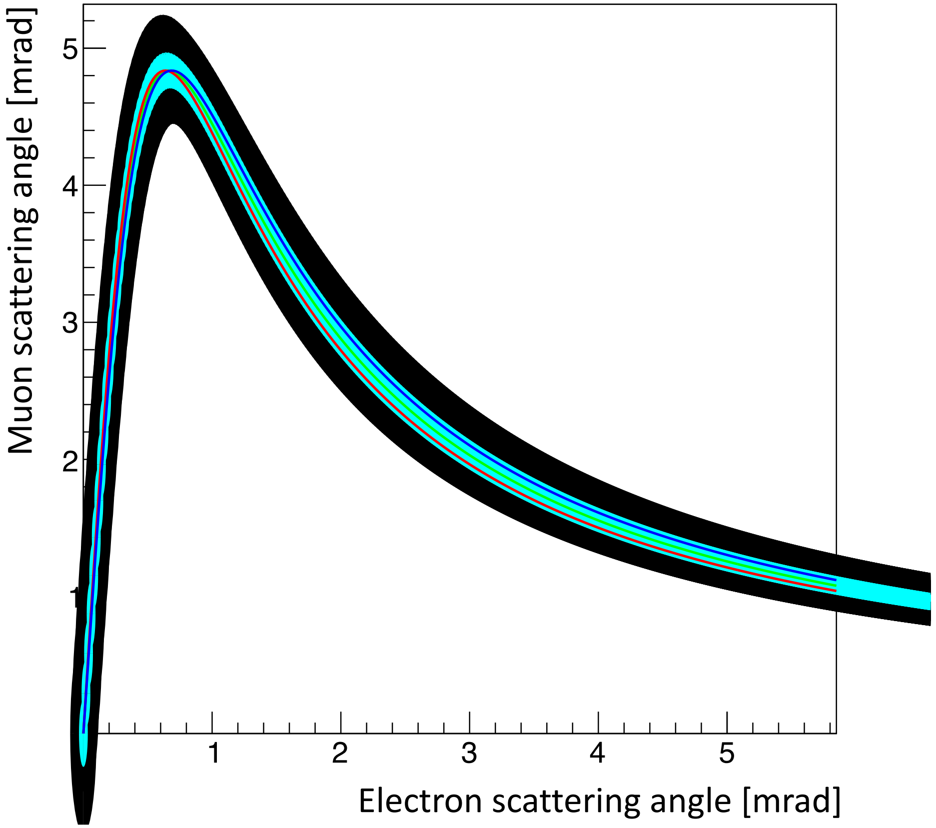
Elasticity

Distance from the predicted kinematic curve (θ_μ,θ_e) is the strongest elastic criterion

Depends on the beam energy resolution, as the curve moves with it (M2 beam has a natural width of 6 GeV at 160 GeV)
- *measuring the incoming muon momentum would improve the selection → new BMS spectrometer tested in 2025*

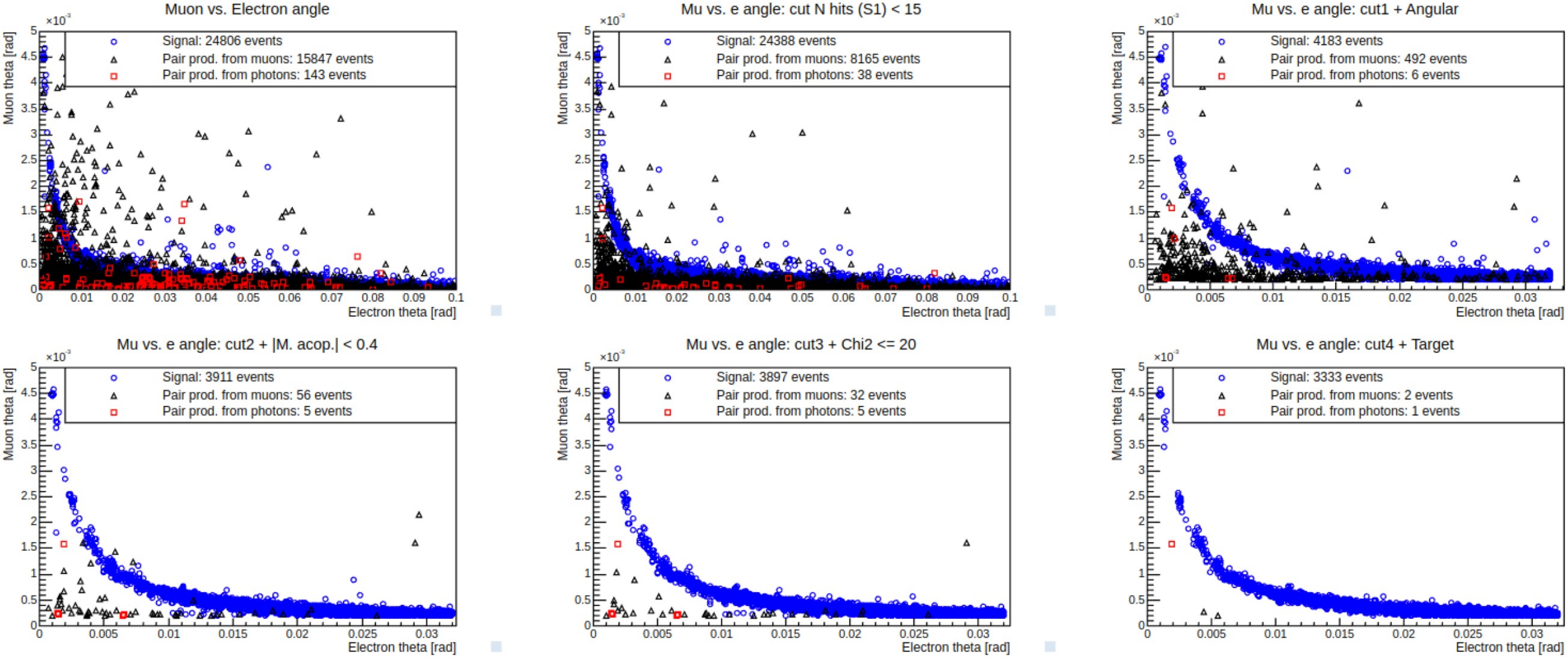
Depends on the experimental resolution (intrinsic + multiple scattering) for a given beam energy
- here assuming 2cm C target and 30μrad intrinsic angular resolution





Minimum Bias MC simulation (Geant4), from 10M events

preliminary, Emma Hess

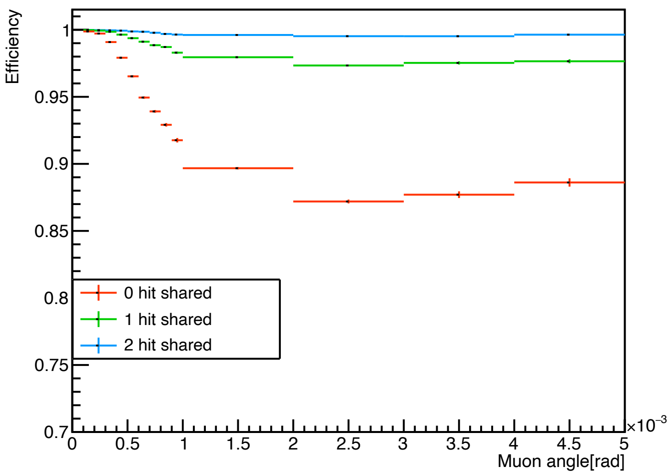


After elastic selection including vertex cuts the surviving background is ~0.1% (3 events)
No events would pass an elasticity cut. Statistics still low

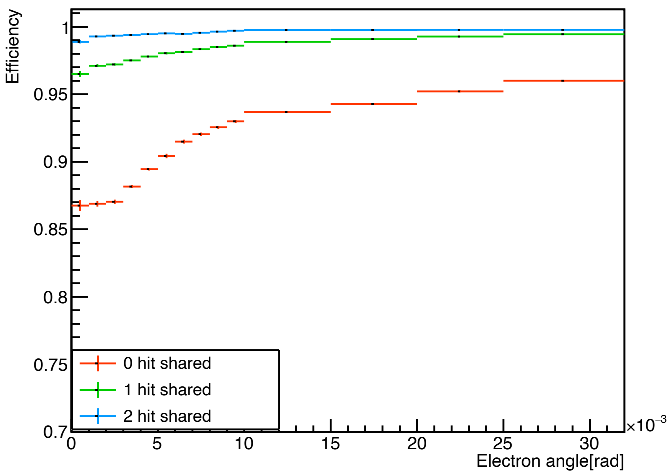
MC performance - Track reconstruction in μe elastic scattering events

Algorithmic reconstruction performance for reconstructible particles, with 3cm Target,
for different setting of the reco configuration: maximum number of shared hits between two tracks = 0,1,2
The efficiency is defined by matching the MC truth with a Quality cut of Q>0.65,
i.e. at least 4/6 hits have to be correctly taken in the reconstructed trajectory

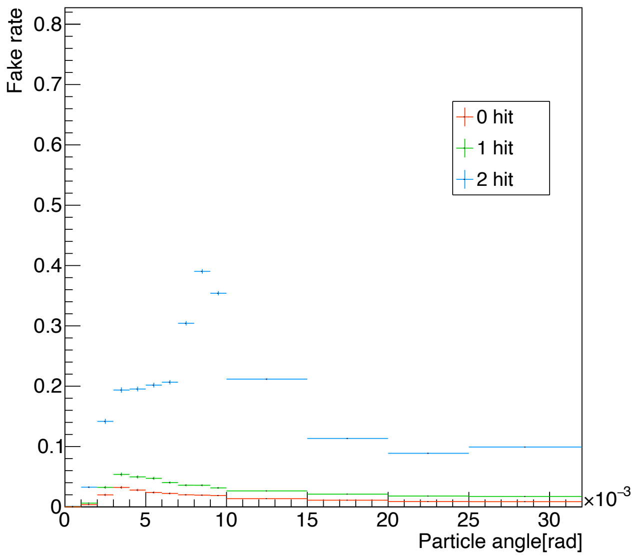
μ track efficiency



e track efficiency



fake track rate

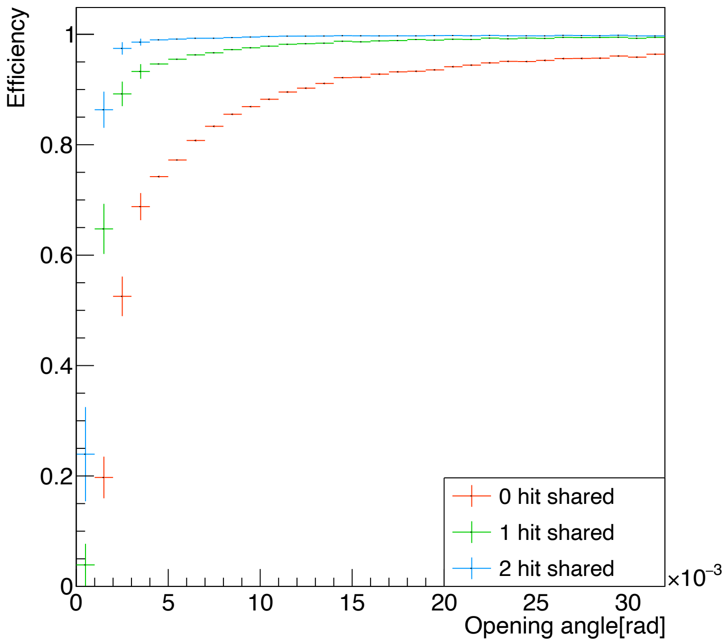


Flat and high efficiency for 2 max shared hits (close tracks in the first pair of modules nearest to the target)
Drawback: fake rate due to clone and background tracks, but can be easily rejected by later steps (vertexing)

MC performance –
μe elastic event reconstruction

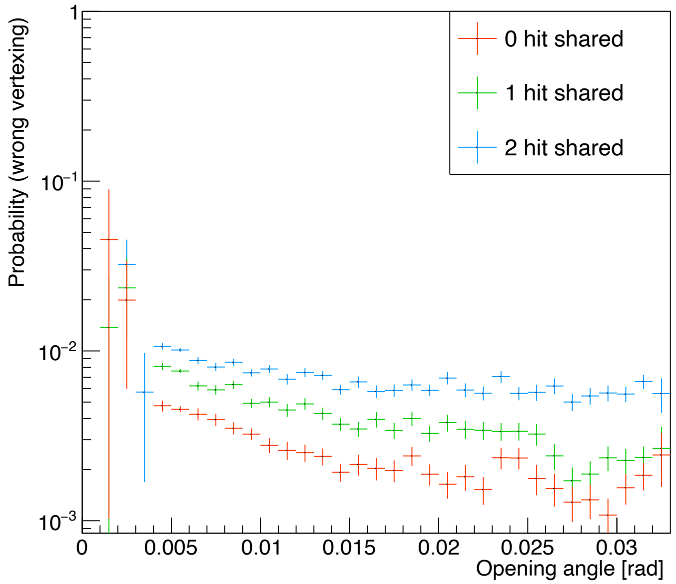
Algorithmic reconstruction performance for reconstructible events, with 3 cm Target,
for different setting of the reco configuration: maximum number of shared hits between two tracks = 0,1,2
The efficiency is defined by matching the MC truth with a Quality cut of Q>0.65,
i.e. at least 4/6 hits have to be correctly taken in the reconstructed trajectory

μe event efficiency



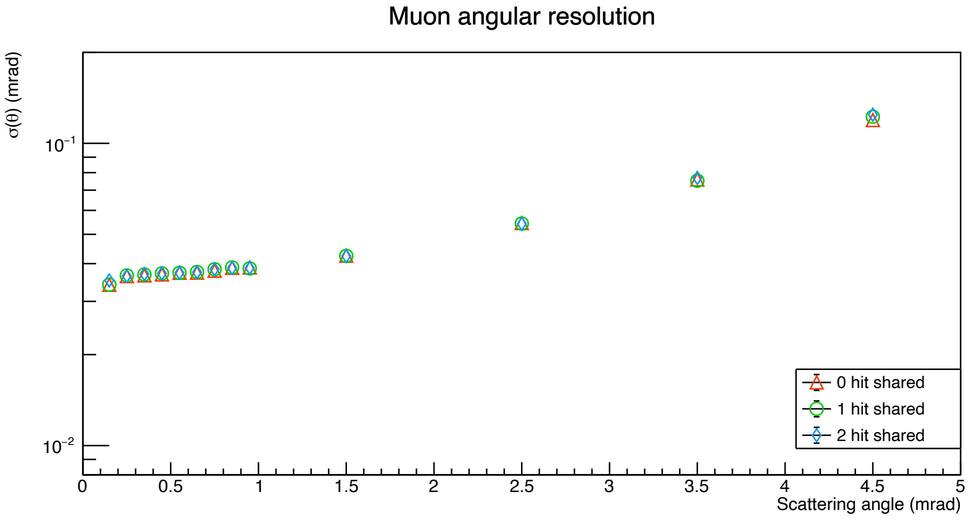
Flat efficiency
for 2 max shared hits
(close tracks in the first
pair of modules nearest
to the target)

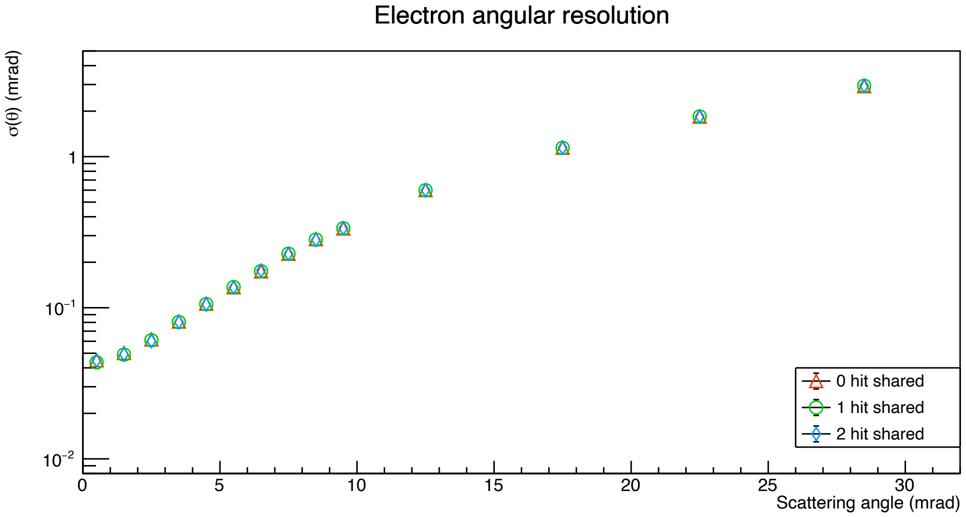
wrong vertex probability

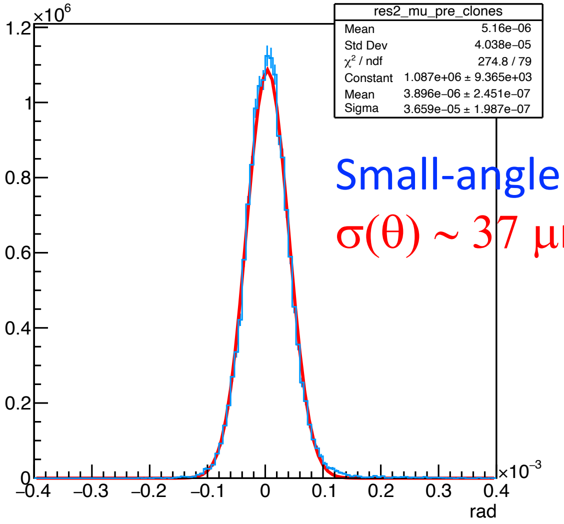


Very low probability
of wrong vertexing

MC performance – Angular Resolution vs Scattering Angle

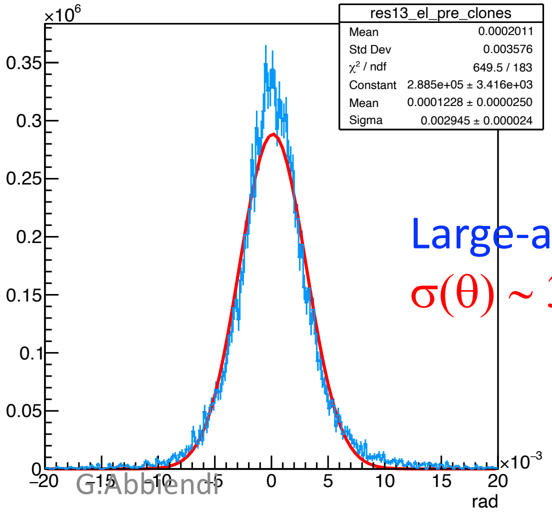






Small-angle μ (0.2-0.3 mrad)

σ(θ) ~ 37 μrad



Large-angle e (25-32 mrad)

σ(θ) ~ 3 mrad

Almost identical resolution for the different settings of the Max Number of Shared Hits: no degradation for the most tolerant setting (2)

Current problems

- Resolution not correctly modelled by detector simulation
  - ~30% difference in the angular resolution of beam muons (dominated by intrinsic resolution). This is a too distant starting point for physics analysis.

  →(ongoing developments in Simulation and in Alignment)

- Reconstruction not yet optimal in particular in the small-angle region (critical for the measurement of $\Delta\alpha(t)$)
  - Hit-sharing option not behaving as expected from simulation
    - Limitations related to lack of redundancy (just 3 planes per view)
  - Impact of residual misalignments in pattern recognition
  - Multiple scattering effects in track and vertex fit

  → (ongoing developments in Alignment, Reconstruction)

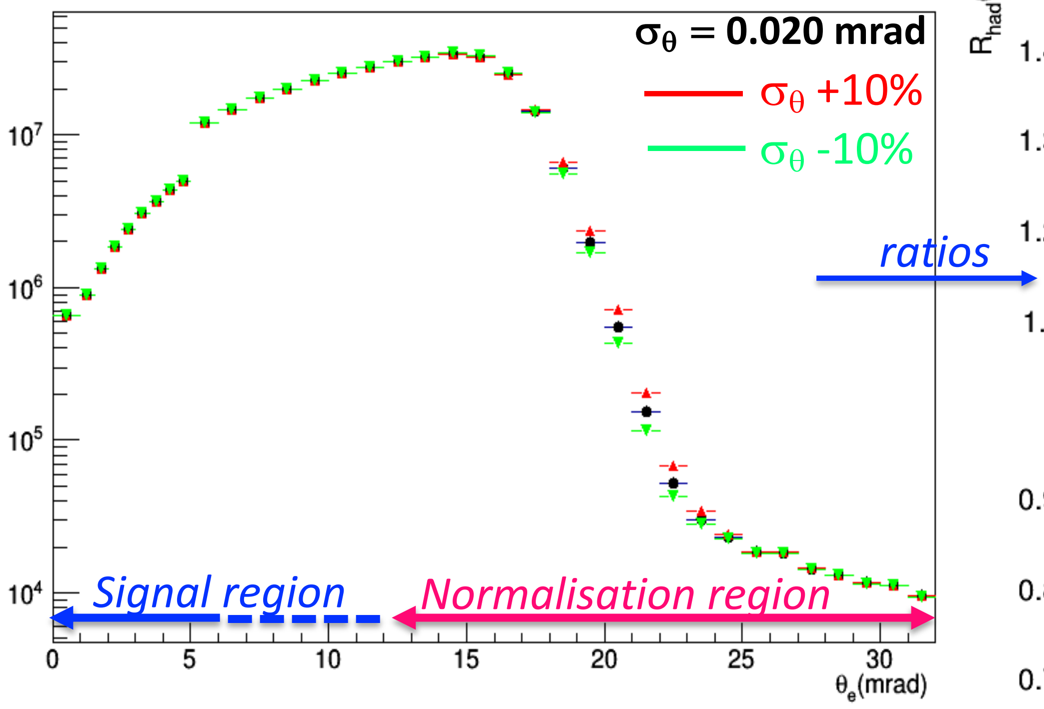
Probing systematics in the normalisation region

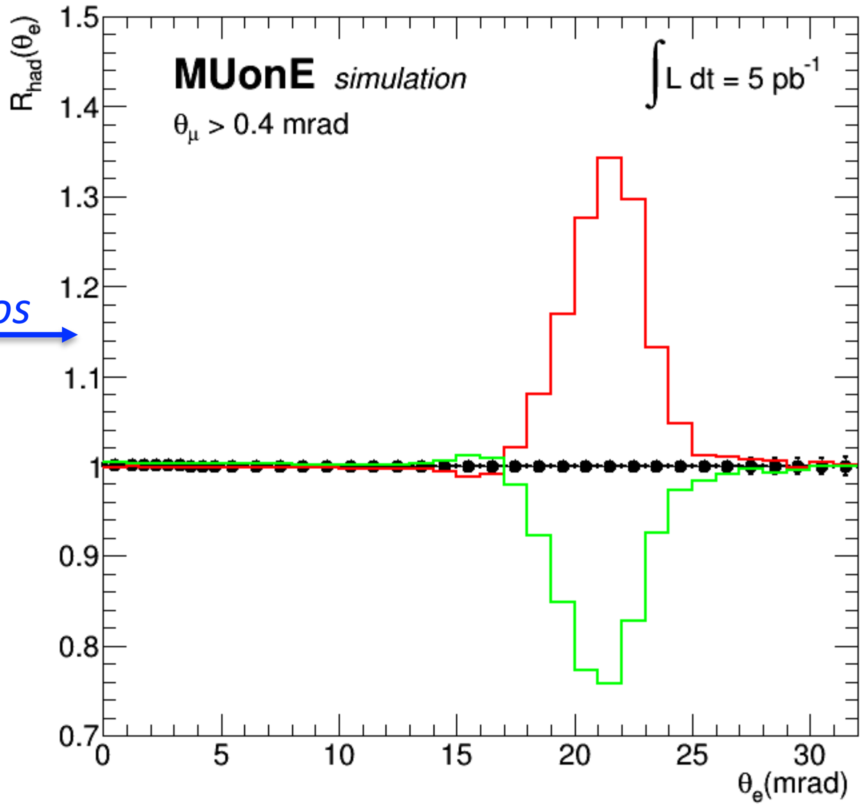
The **intrinsic angular resolution** can be probed by looking at the θ_e distribution after a cut on θ_μ distribution, e.g. cutting at $\theta_\mu > 0.4$ mrad

→ Effect of a ±10% error w.r.t. the nominal σ_θ = **0.020 mrad**

Huge distortion of 20-30% around electron angles of 20 mrad

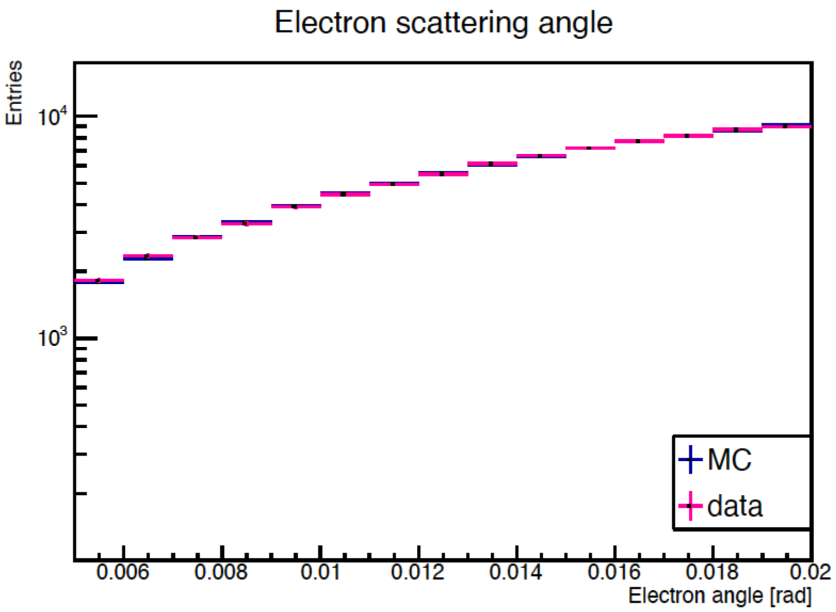
No effect in the signal region

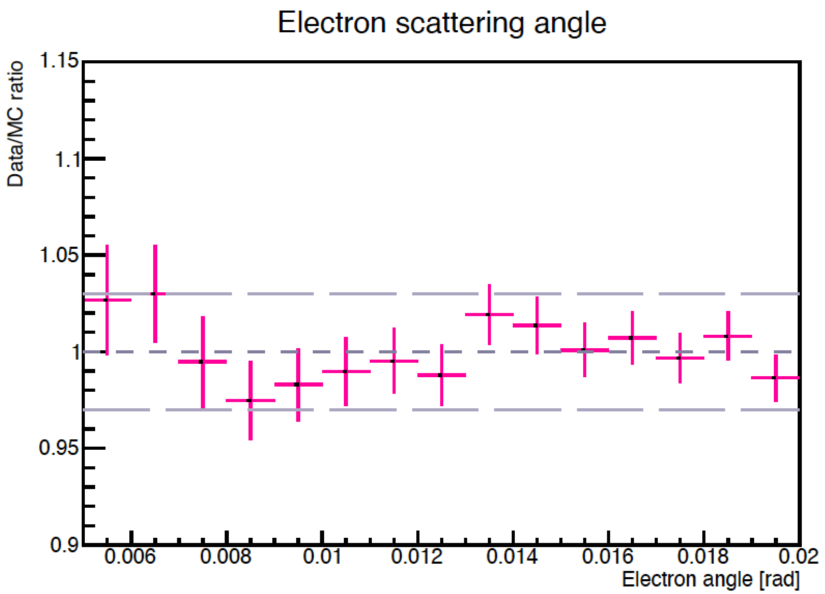




Preliminary Physics Analysis

Preliminary, from E.Spedicato's PhD thesis





Short run from 2023 Data (~1h data taking)
Track reconstruction with NO hit sharing
Elastic selection:

- single-muon in the first station within a fiducial region |X,Y|<1.5cm
- N(hits) in the second station ≤ 15 (suppress events with more than 2 tracks)
- vertex found with 1+2 tracks, with Z_{vtx} compatible with the target
- $\theta_{min} > 0.3$ mrad → muon
- $5 < \theta_{max} < 20$ mrad → electron
- Acoplanarity cut at $|A| < 0.4$ rad
- Elasticity cut as $|\theta_\mu^{rec} - \theta_\mu^{exp}(\theta_e^{rec})| < 0.2$ mrad

DATA-MC agreement in shape within 3%

Still large statistical uncertainty (small used sample)

Large impact of resolution effects, currently not well simulated

Analysis prospects for 2025

- Solve the open points from simulation and reconstruction (previous slide)
- Pending decisions on tracker geometry:
  - keep tilted modules or adopt a simpler setup with orthogonal layers
  - Add a pair of 2S modules in each station to have some redundancy ? (subject to availability of enough modules)
    - This would increase the material budget but would add measurement points
  - The pros/cons should be assessed soon
- Final improved alignment algorithm for 2025:
  - current iterative algorithm might be evolved to include more tracking stations
  - Or a global algorithm might be developed
  - The additional subdetectors have also to be aligned w.r.t. the tracking stations: Calorimeter, Muon Id, BMS Spectrometer
- 1 month data taking with 3 tracking stations
- Analysis in the full angular range should be carried out:
  - Without PID (just the two track scattering angles, with no tagging)
  - With PID defined by Calorimeter and Muon ID, to check the systematics

Conclusions

Link: MUonE web page

- Effects due to the timing of the muons, related to the asynchronous detection, are pretty well understood. Minor residual efficiency effects, likely caused by the high beam intensity and DAQ, will be further tested.
- Tracking efficiency, vs the angle and the impact point, is uniform as expected. Module efficiencies expected to further improve with final production quality detectors.
- Reconstruction significantly improved recently, also endowed with a powerful tool for automatised integration and validation of new developments
- Vertexing is effective in selecting good tracks removing track clones
- Signal is clearly visible. It can be isolated by applying a selection procedure entirely based on the tracker information
- Analysis workflow to measure the leptonic running defined
- Main sources of systematic effects established

- Work in progress on the 2023 Data analysis
  - Improvements in the detector simulation
  - Further improvements of the tracking and vertexing algorithm
  - Improvements in the alignment algorithm and Realistic MC misalignment model
  - Selection and Background studies

- For the 2025 run: complete the foreseen setup with an additional tracking station, the ECAL and Muon ID, and the new BMS spectrometer
  - ECAL and Muon filter would provide PID and allow independent checks of the background and systematics
  - The additional tracking station would allow testing our method for the calibration of the average beam energy
  - Event-by-event measurement of the incoming muon energy would improve the selection and reduce the systematic error

BACKUP

Method for timing studies

In order to operate in time with incoming particles coming from collisions at the LHC, the modules have an internal DLL delaying their reference clock that can be tuned with a precision of 1ns.

In this asynchronous beam-test, a run was performed where the first module (the DUT) was kept at a DLL of 12ns, while all other modules had their DLL simultaneously scanned, allowing to find their relative delays and operate them in sync during later runs.

By selecting events that have a unique stub in two reference modules, with their stub being recorded in subsequent 25ns bins, the probability of seeing a stub in the DUT can be measured, when no other module recorded more than one stub within a time window of 250ns.

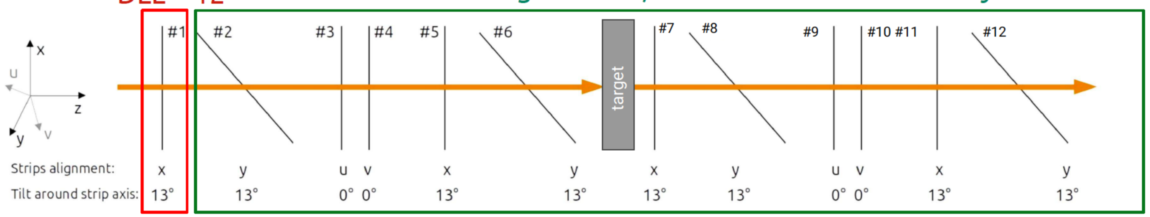
This allows to select particles that crosses the setup within a small window in time, and measure the relative efficiency as a function of time.

Assuming all three modules have the same timing profile, that it can be modelled by two error functions, and using the delays measured, the scan can be simulated and the parameters of the timing profile tuned so that the simulation fits the data.

The underlying timing profile can then be extracted to have an estimate of the relative module stub reconstruction efficiency as a function of time.

Asynchronous beam muons

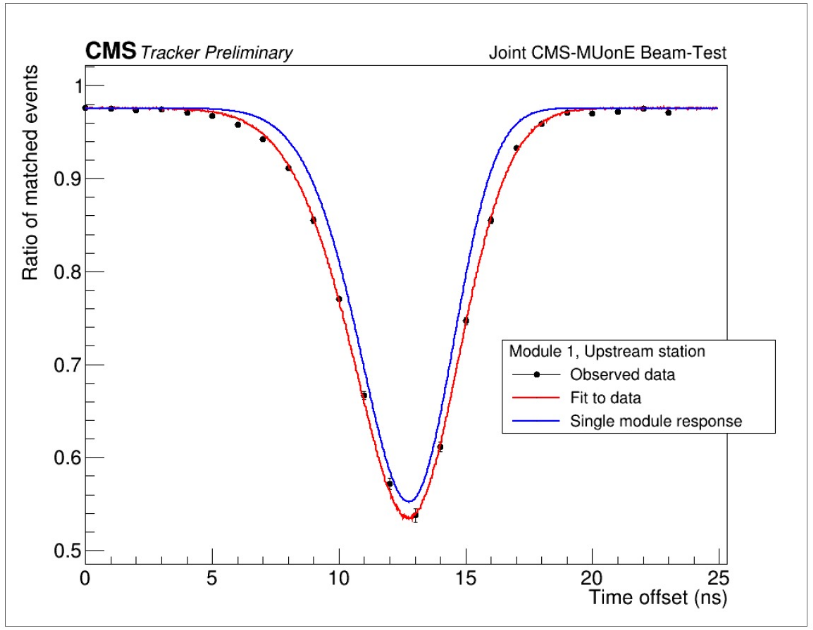
The DLL measurement



Selecting events with a single stub on module 2 & 3, and maximum 1 stub in all other

Requiring stubs in 2 & 3 to have $\Delta \mathrm{BX} = \pm 1$ ⟶ **Selecting clock edges**

Looking at fraction of events with a hit in module 1



Probability of observing a stub if two reference modules observe a stub in subsequent 25ns bins, as a function of delay between the device tested and the two reference modules. The data is fitted to a simulation assuming the in-time detection efficiency of all modules is modelled by two error functions, and is overlaid with the corresponding single module detection efficiency.

Martin Delcourt talk at BTTB12:

Commissioning and study of a CMS 2S module with 40MHz readout

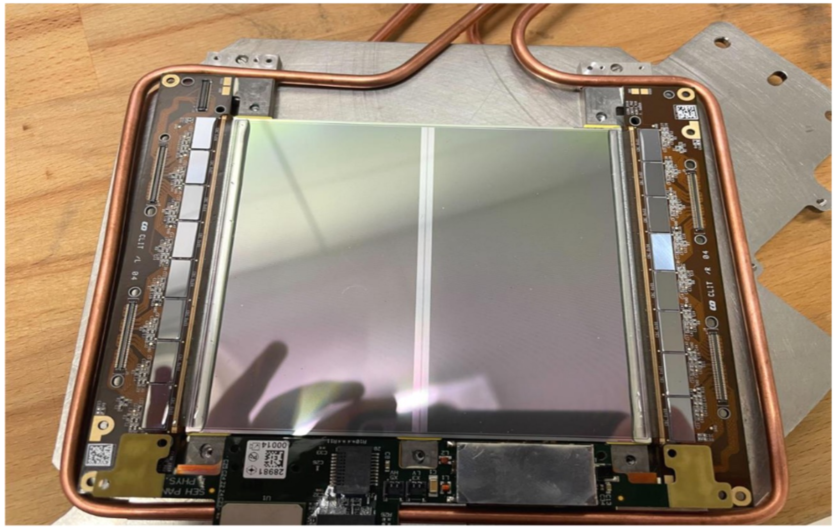
LINK

Digitisation

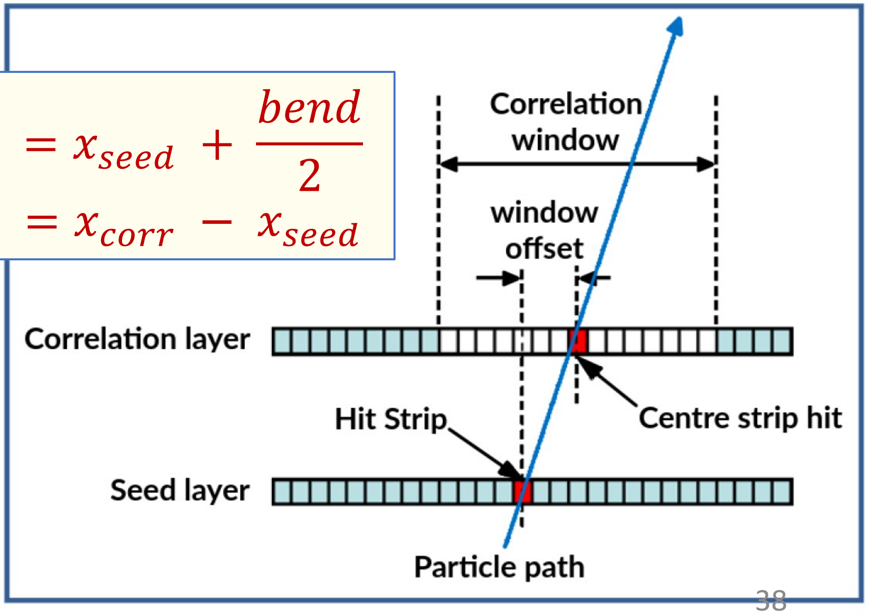
- **Tracker Digitisation** inspired by the CMS simulation of the 2S tracking module

  Input: particle hits in the Si sensors from Geant4

  Output: stubs reproducing the 2S FE electronics
- Algorithm includes: primary ionization, charge drift, signal induction, electronic noise, digis formation, stub finding logic and stub creation
- *To be implemented*: timing effects (module synchronisation, asynchronous arrival of signals w.r.t. DAQ clock, signal pulse shape)
  - Currently ideal simulation
- **Calorimeter Digitisation:** initial version implemented, to be improved with results from the ECAL beam tests

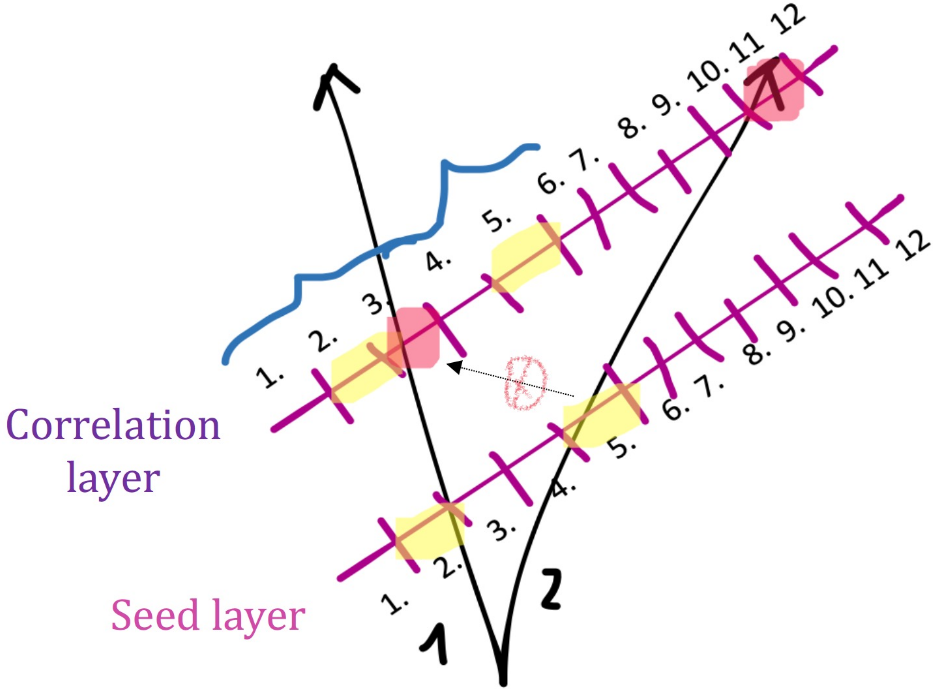


$$x_{stub} = x_{seed} + \frac{bend}{2}$$
$$bend = x_{corr} - x_{seed}$$



Digitiser logic: 2S limitations

- 2S modules with their trigger electronics were thought for CMS (@LHC):
  - The two sensor layers reduce the uncorrelated noise
  - Stub's bend thought to measure the track pT:
    low bend = high-pT
- With two close-by particles, it can happen that the stub with higher bend can be wrongly defined, taking the hit in the correlation layer that belongs to the other particle (corresponding to a lower bend, which is preferred by the CMS logic)
  - This can bias the reconstructed track direction and the reconstructed vertex
- **Seed position** (from one layer only) is unbiased although it has generally a slightly worse resolution

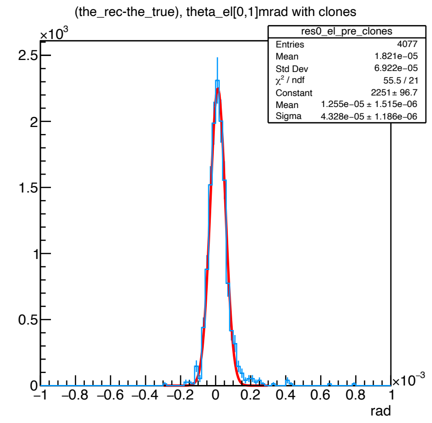


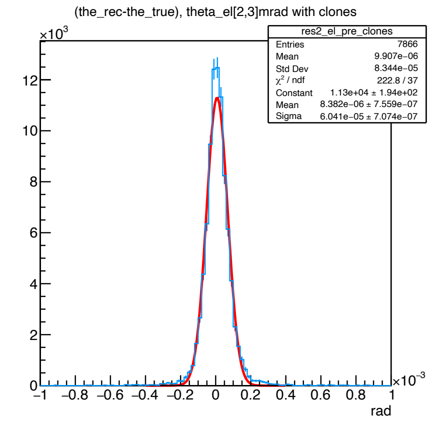
MC performance –
Electron and Muon Angular Resolution

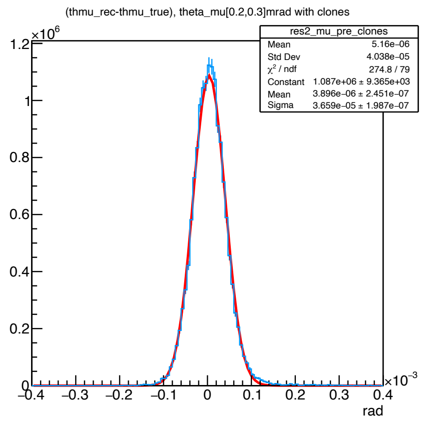
electron

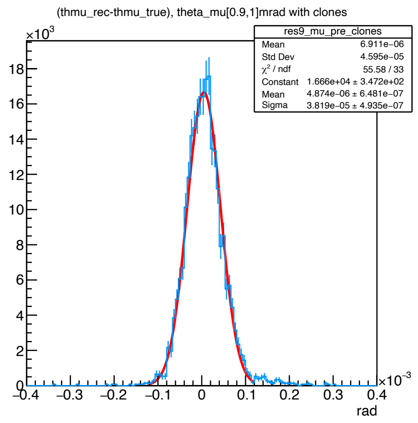
in different angular bins

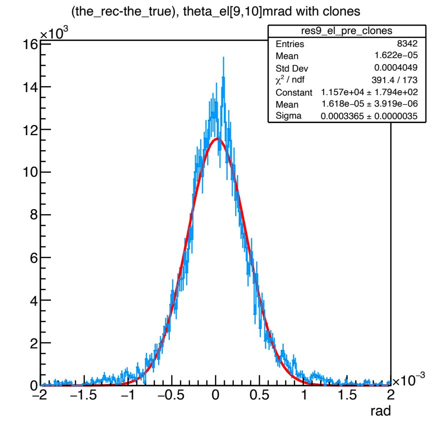
muon

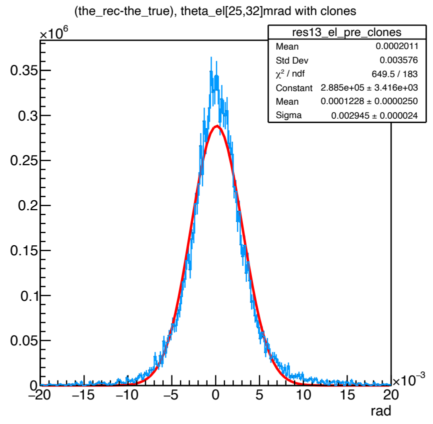


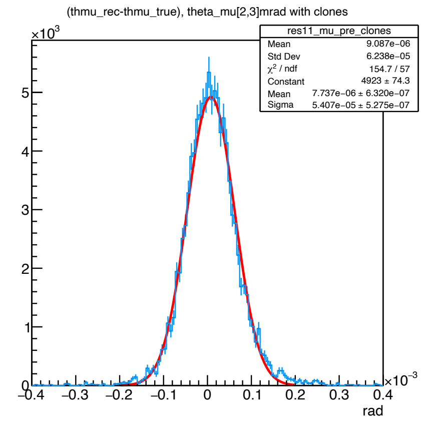


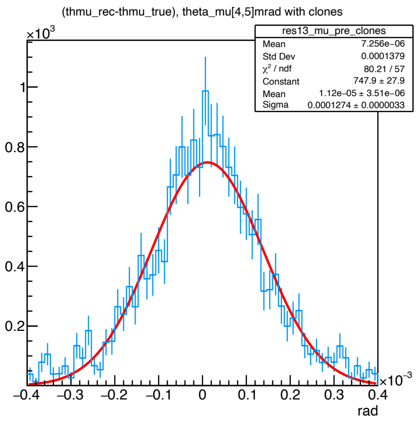










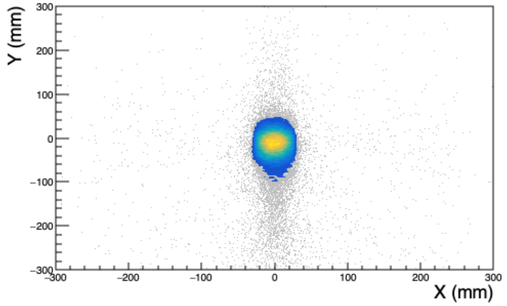


Beam Parameters – Simulation model

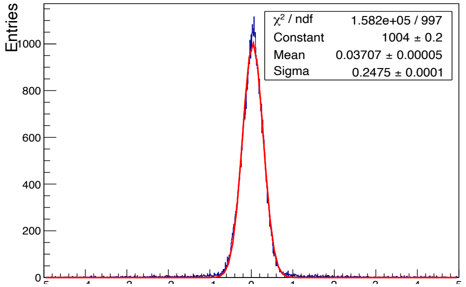
Parallel beam

σ_x = 13 mm

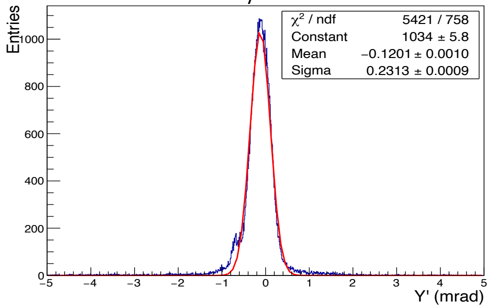
σ_y = 22 mm

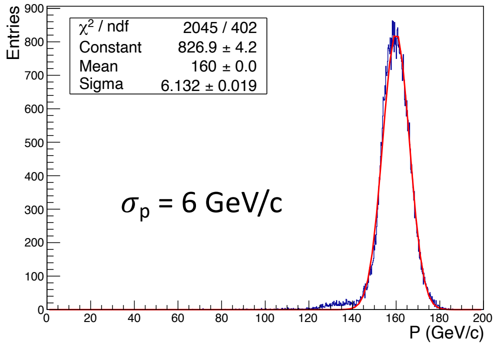


$\sigma_{x'}$ = 0.23 mrad



$\sigma_{y'}$ = 0.24 mrad



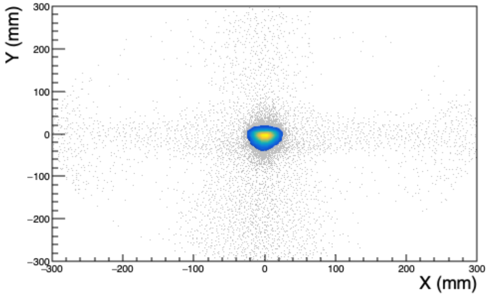


σ_p = 6 GeV/c

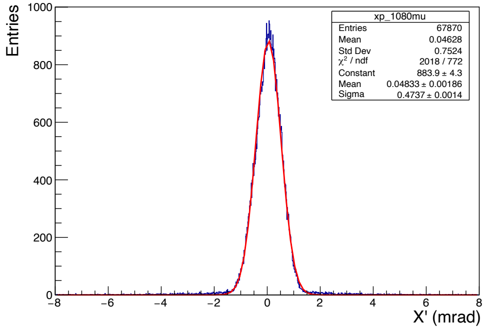
Focussed beam

σ_x = 9.99 mm

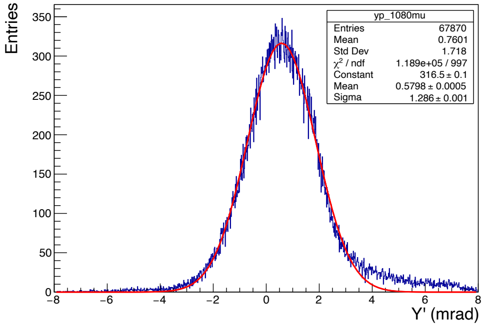
σ_y = 11.8 mm

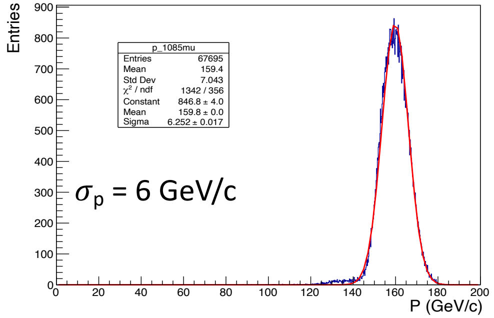


$\sigma_{x'}$ = 0.47 mrad



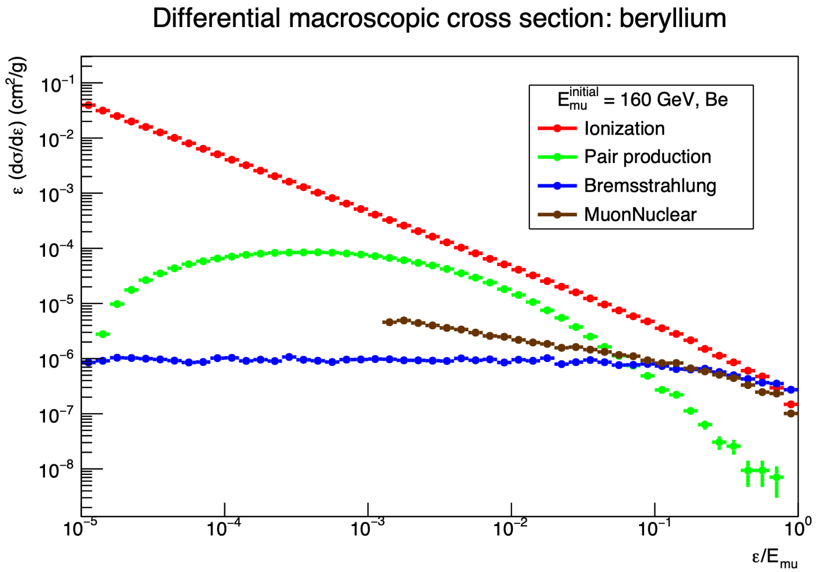
$\sigma_{y'}$ = 1.3 mrad

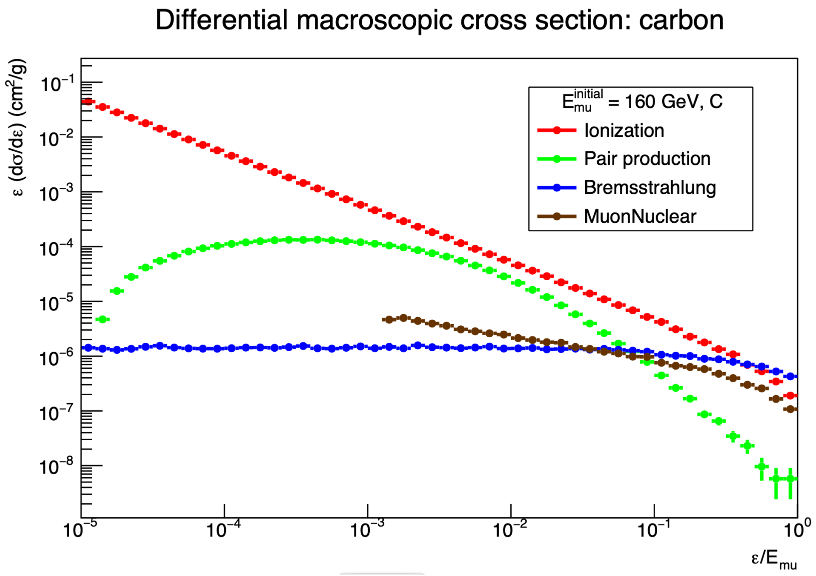


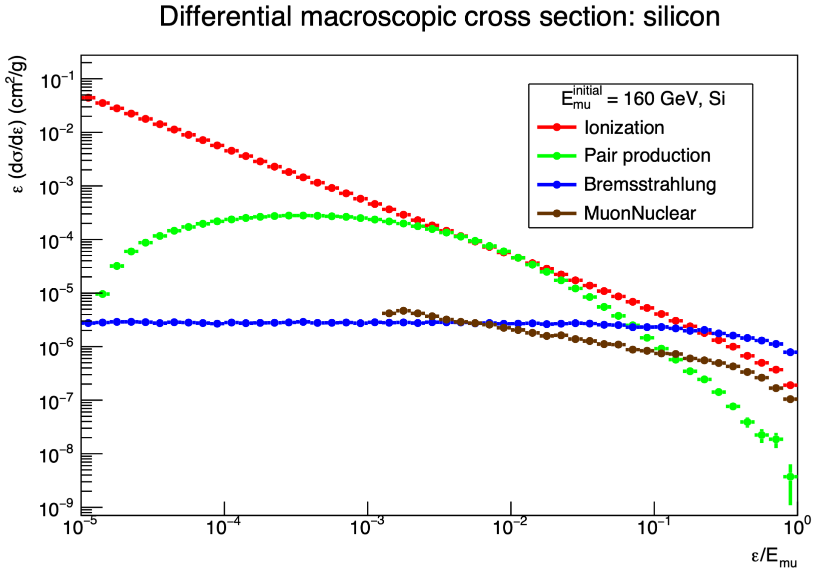


σ_p = 6 GeV/c

GEANT4: μ interaction cross sections







GEANT4 simulation

ε Muon Energy loss fraction

σ Macroscopic cross section

$\sigma = \sigma_A \, n_A / \rho_A$

σ_A Atomic cross section

n_A density of atoms per unit volume

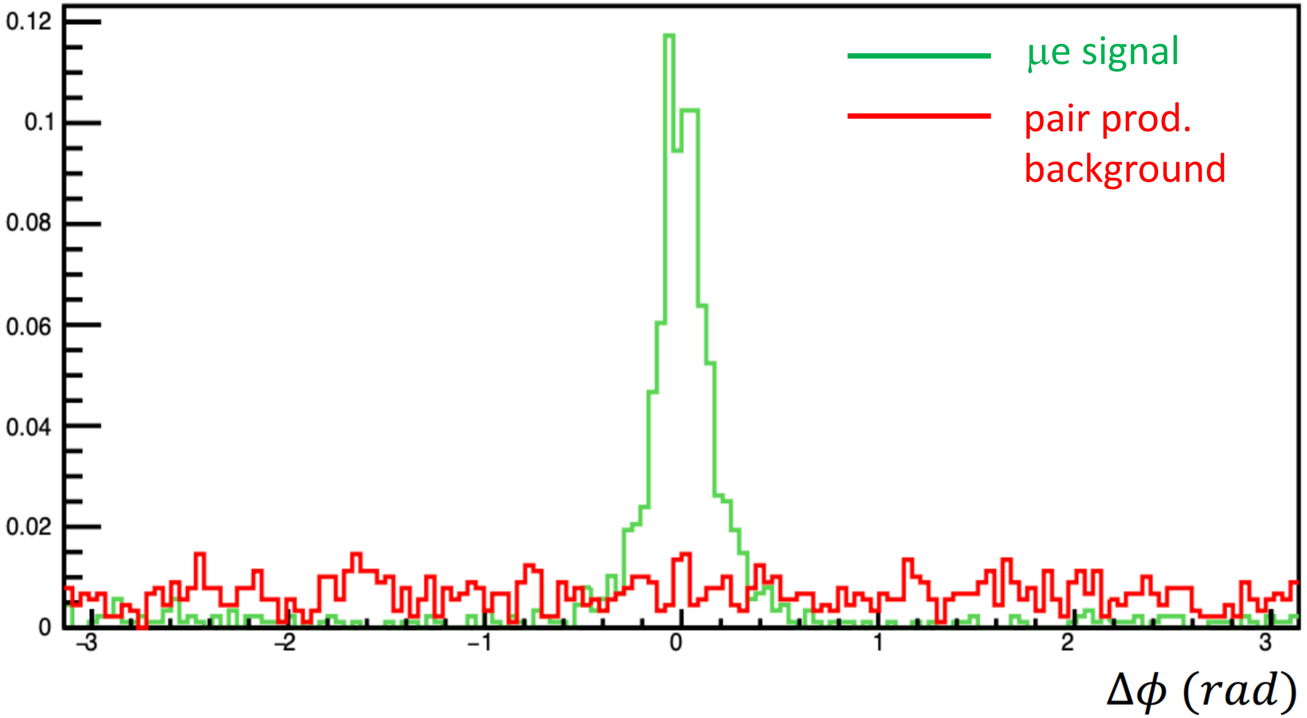
ρ_A material density in g/cm^3

Minimum Bias simulation
(Signal and Background from GEANT4)

Let $\mathbf{i}$, $\mathbf{m}$, $\mathbf{e}$ be unit vectors respectively along the directions of the incoming muon, the outgoing muon and the outgoing electron

Acoplanarity:
angle between the scattering planes formed by the outgoing particles with the incoming muon

$$\Delta\phi = \pm\left[\pi - \cos^{-1}\left(\frac{(\mathbf{i}\times\mathbf{m})\cdot(\mathbf{i}\times\mathbf{e})}{|\mathbf{i}\times\mathbf{m}|\,|\mathbf{i}\times\mathbf{e}|}\right)\right] \text{ for } \begin{bmatrix} T>0 \\ T<0 \end{bmatrix}$$

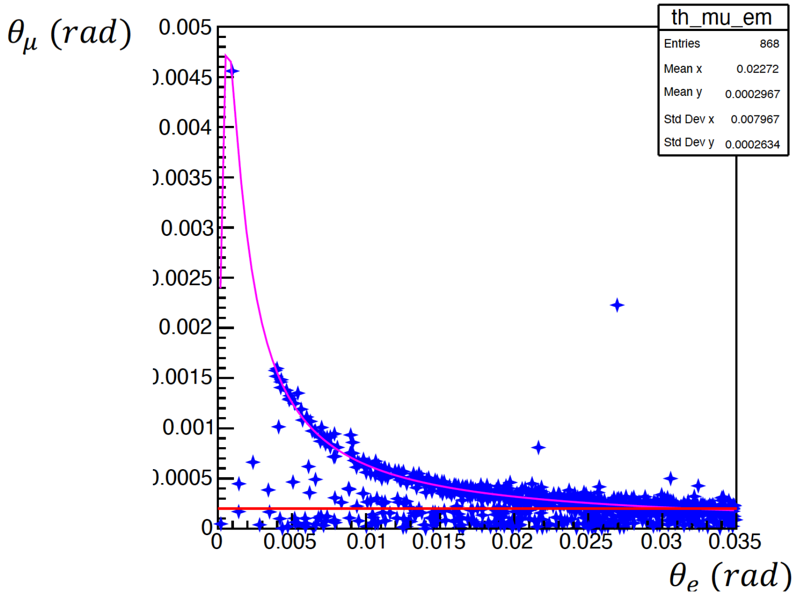


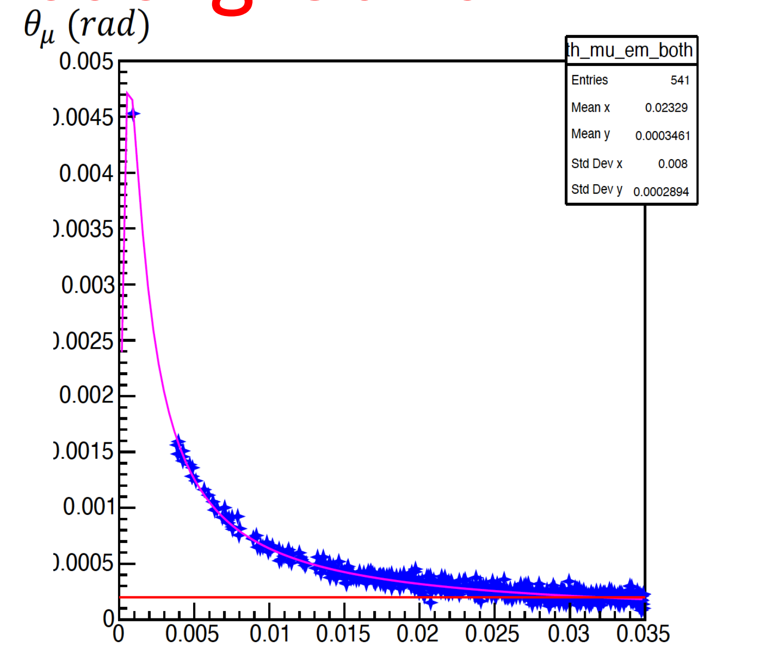
TRACK-BASED Observables
Track quality (Nr Hits; χ^2)
Vertex compatibility
Vertex position
Acoplanarity
Minimum scattering angle
Elasticity (from angular correlation)

TRACK+CALO observables
Candidate electron (Calo cluster matching a track)
and its Energy

Selection: MC signal and background

SIGNAL



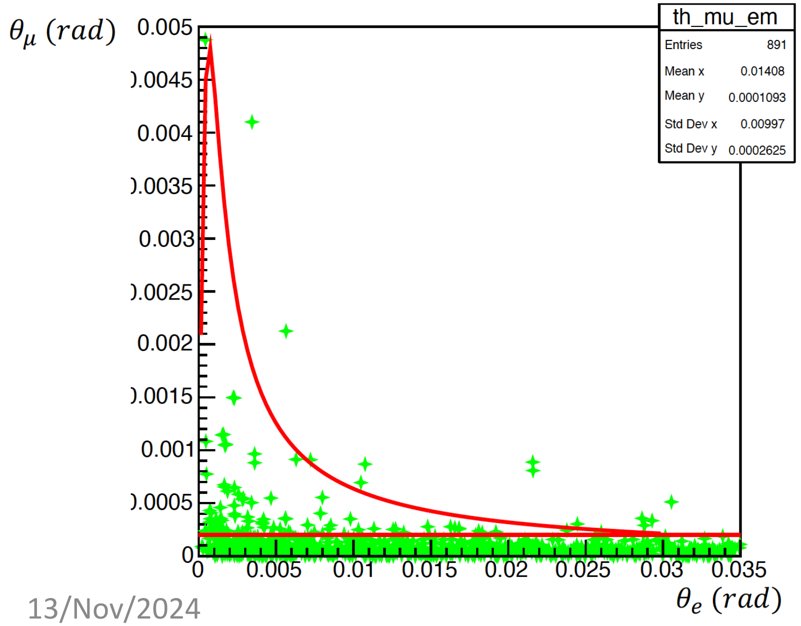


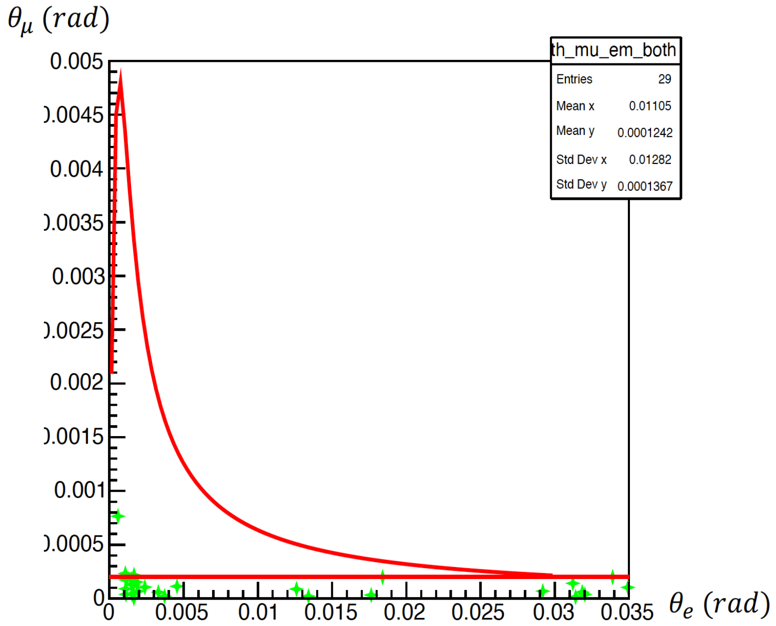
SIGNAL

Cuts on:

- Acoplanarity ($|\Delta\phi|<1$)
- Vertex compatibility ($\chi^2<100$)

BACKGROUND

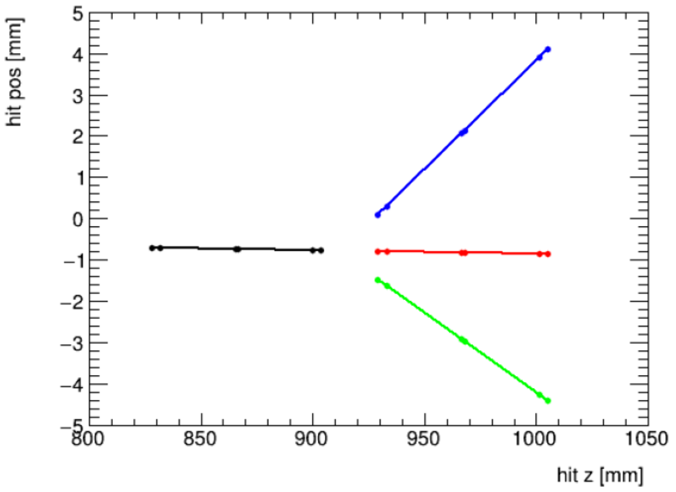


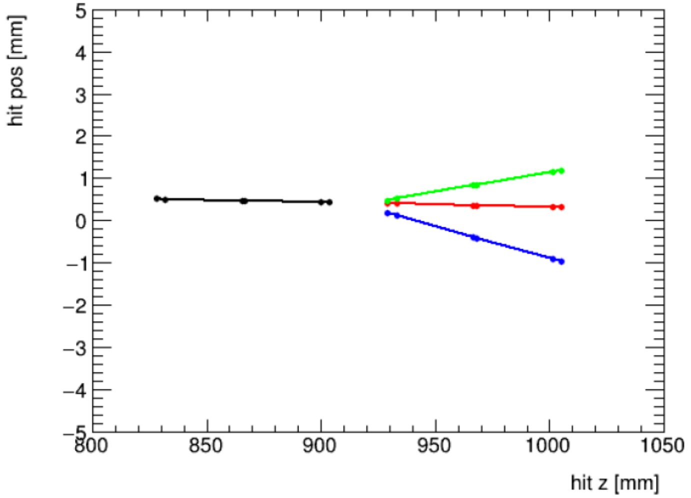


BACKGROUND

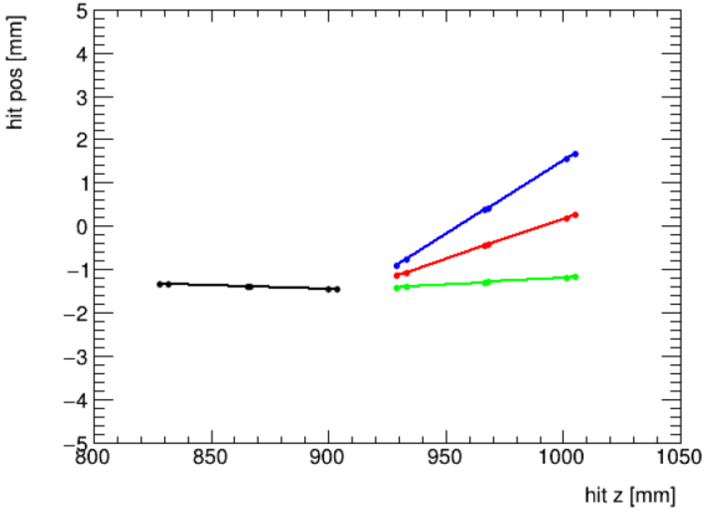
Background event displays

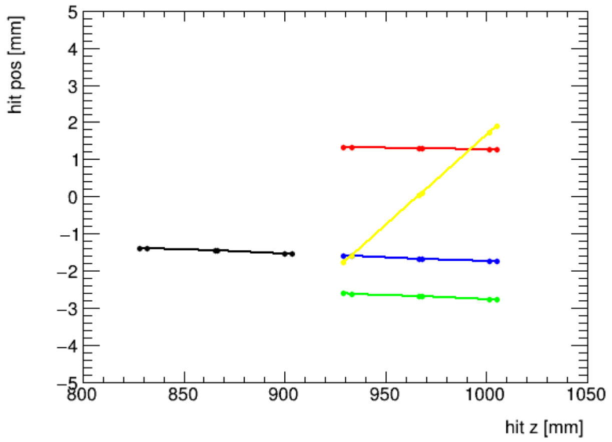
Studying: 3 or 4 track events, candidate background





Clear unbalanced event



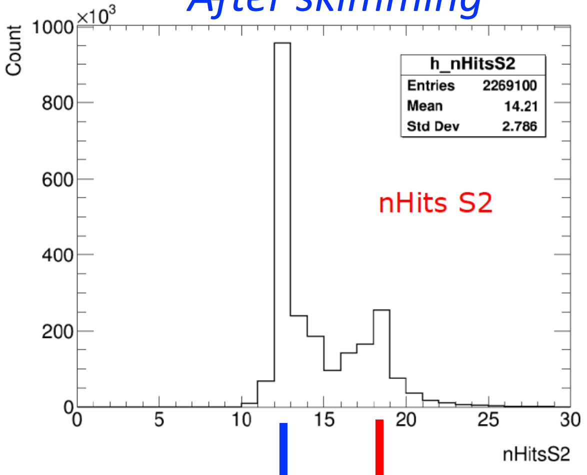


Weird background event
But easily rejected by the selection

Background reduction

The dominant background is expected to be the e+e- pair production, which leads to a 3-prong final state for μ scattering on nuclei

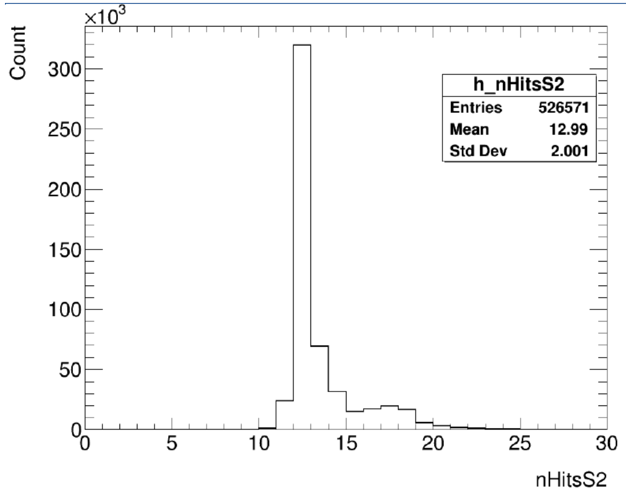
After skimming



2 tracks (12 hits)

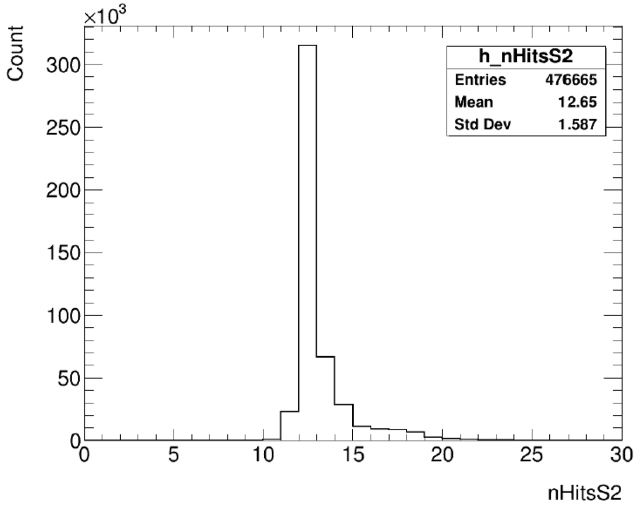
3 tracks (18 hits)

++ Ntracks=2, θ_e<32 mrad, θ_μ>0.2 mrad



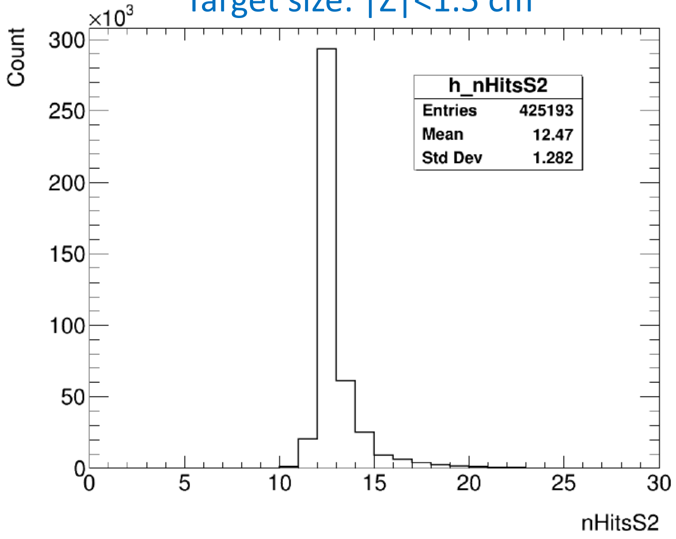
The third track may be not reconstructed

++ |Acoplanarity| < 1



++ |Zvtx| < 3cm

Target size: |Z|<1.5 cm

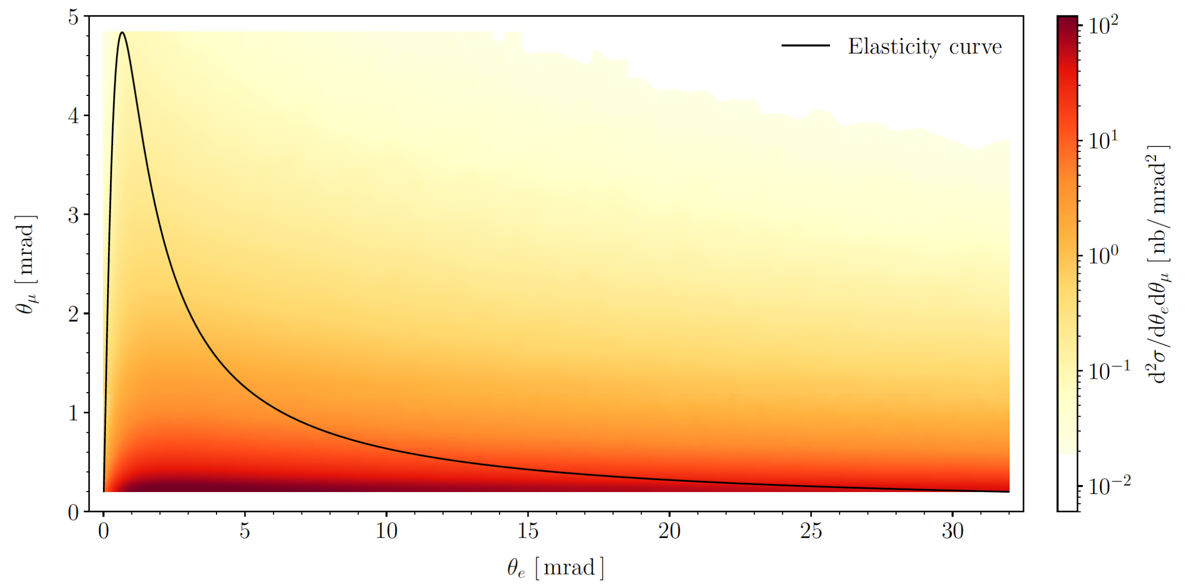


The residual background can be estimated by selecting background enriched events and using the MC to fit the data in the signal region

Background MC generator

Main background: lepton pair production
Implemented in MESMER *Phys.Lett.B* 854 (2024) 138720

Numerical results for $\mu^+ C \to \mu^+ C\, e^+ e^-$ (3)



interfaced with the MUonE detector simulation

In addition to the (prompt) production of a lepton pair it is interesting to study the real photon bremsstrahlung $\mu N \to \mu N \gamma$

The conversion of a real photon to an e+e- pair is a frequent event that produces other background events

Having a standalone generator for the primary bremsstrahlung event we could then interface it with the GEANT4-based detector simulation for simulating the photon conversion to e+e- pairs.

- 5D Bethe-Heitler process in Geant4

This would provide a convenient tool to study this other background with high statistics.

MC realistic misalignment scenario

In addition to the IDEAL geometry of the detector we have built a realistic model which represents the Geometry description after the alignment procedure in real data.

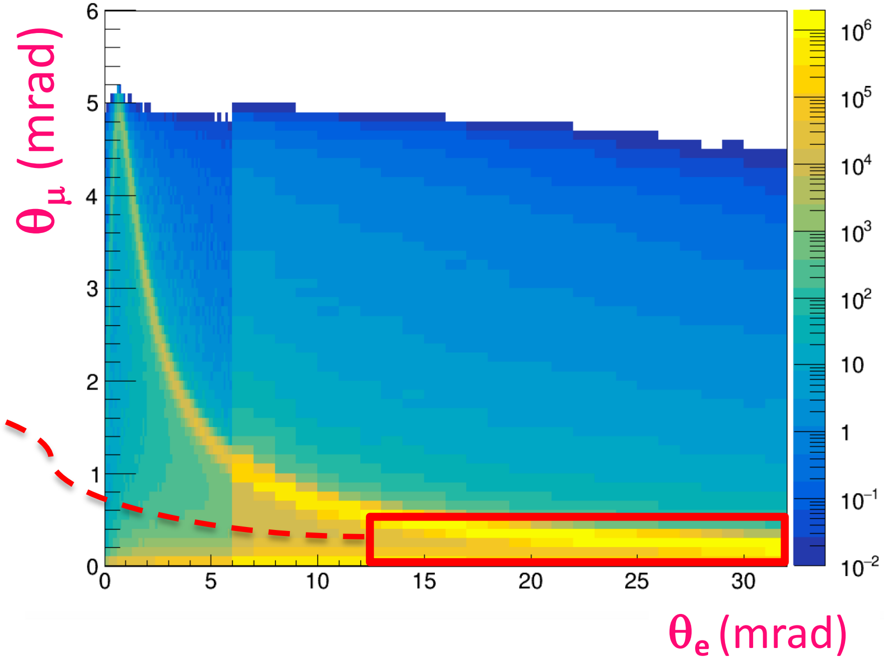
Initial positions and orientations of the two tracking stations have been defined from HW metrology measurements carried out by an in-situ laser survey with nominal precision of 100 μm

More precise metrology in CERN Laboratory was carried out on the entire tracking stations after the Test Run, determining the internal alignment to few tens of μm, including distortions of the sensors from perfect planarity

From these HW measurements we have defined the initial geometry of the tracker in the Lab frame.
Then the same track-based alignment algorithm used in real data has been run on MC simulated events of passing muons. The final geometry after alignment corrections has been used to define our Realistic Misalignment Scenario.

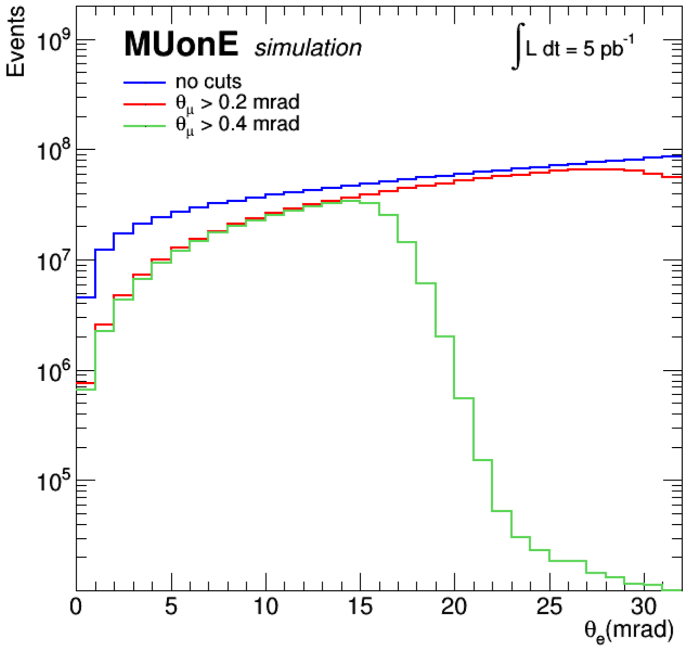
Physics analysis have been using this MC model

Probing systematics in the normalisation region

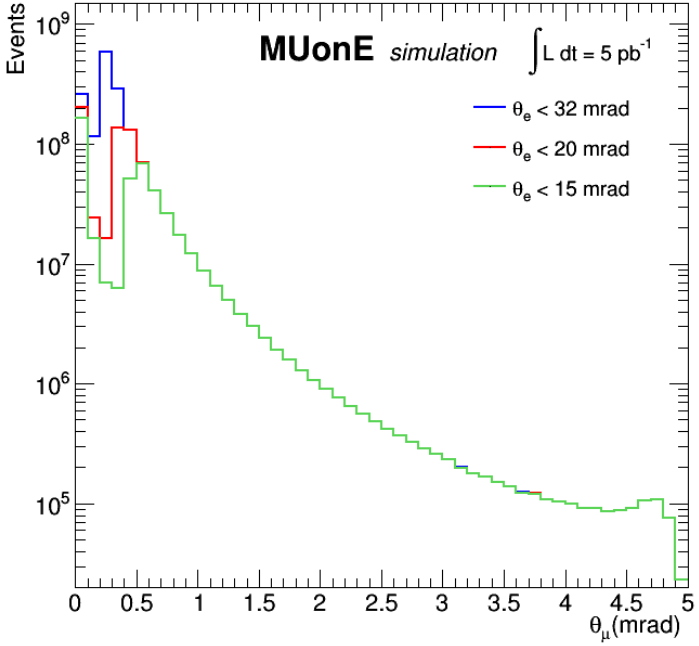


Normalisation region
huge statistics
vanishing signal ($\Delta\alpha_{had}$)
convenient for studies of systematics

θ_e



θ_μ



Absolute Data – MC comparisons

- We could have a quite precise estimate of the integrated luminosity of any real data sample by counting the number of muons on target selected *within a fiducial region*:

  $L = N_{\mu ot}\,\rho_A\,D$

  $\rho_A = \rho\mathcal{N}_{Av}/A$: atom density in the target [atoms / cm^3]

  D : target thickness [cm]

  - This is possible for the 2023 Test Run as we ran in triggerless mode: all the incoming muons were in principle recorded, independently of whether they produced interesting interactions in the target or not
- Then the expected number of events from a given process is:

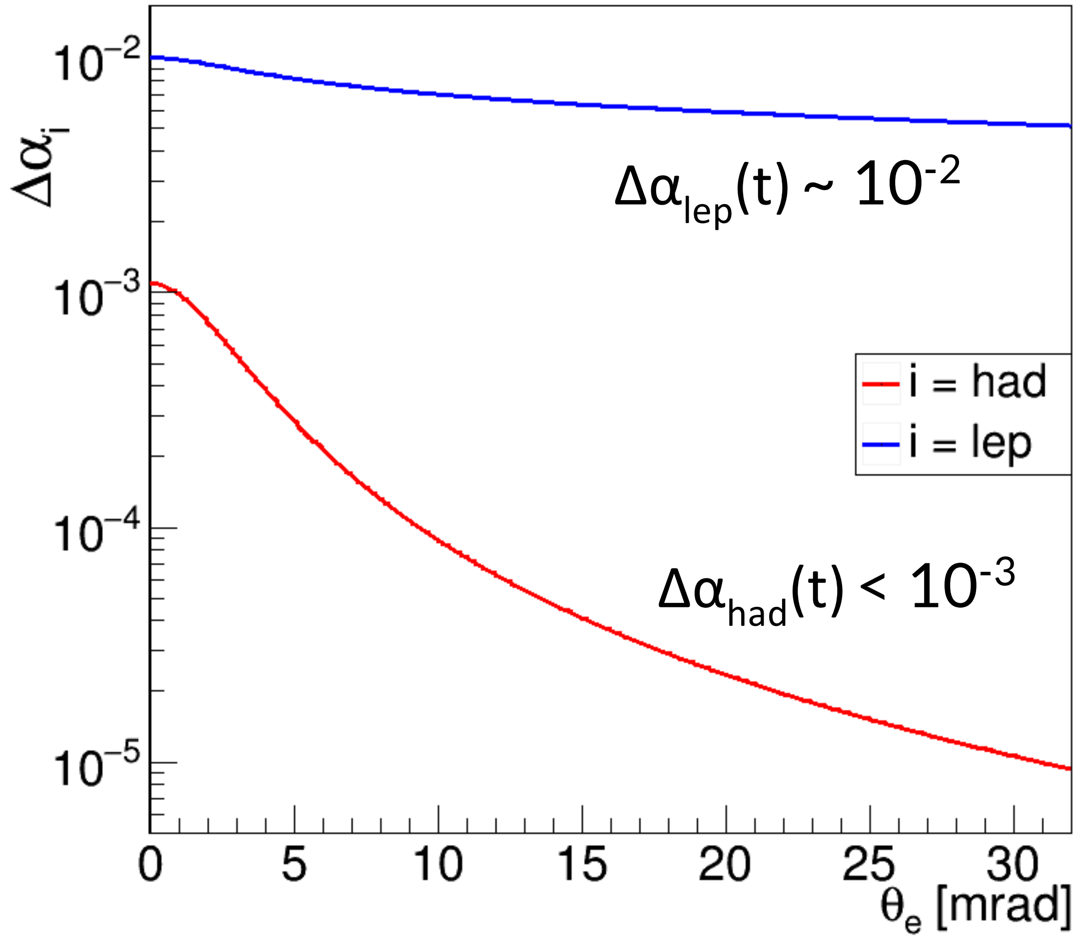
  $N_{ev} = L\,\sigma\,\varepsilon$

  σ : cross section for the considered process

  ε : selection efficiency
- The absolute predictions could provide further tests of the selection efficiency of signal and backgrounds
- Their use in the fit for the running alpha must be studied
  - for the leptonic running there is no “normalization region” as for the hadronic one, the $\Delta\alpha_{lep}$ is always significant

Test Run 2023 goal: extraction of $\Delta\alpha_{lep}(t)$

~10^{12} μ on target, Integrated Luminosity ~ $1pb^{-1}$
expected ~2.5×10^{8} elastic events E_e>1 GeV



Fit function:
1 loop QED contribution of lepton pairs

$$\Delta\alpha_{lep}(t) = k\left[f(m_e) + f(m_\mu) + f(m_\tau)\right]$$

$$f(m) = -\frac{5}{9} - \frac{4}{3}\frac{m^2}{t} + \left(\frac{4}{3}\frac{m^4}{t^2} + \frac{m^2}{3t} - \frac{1}{6}\right)\frac{2}{\sqrt{1-\frac{4m^2}{t}}}\ln\left|\frac{1-\sqrt{1-\frac{4m^2}{t}}}{1+\sqrt{1-\frac{4m^2}{t}}}\right|$$

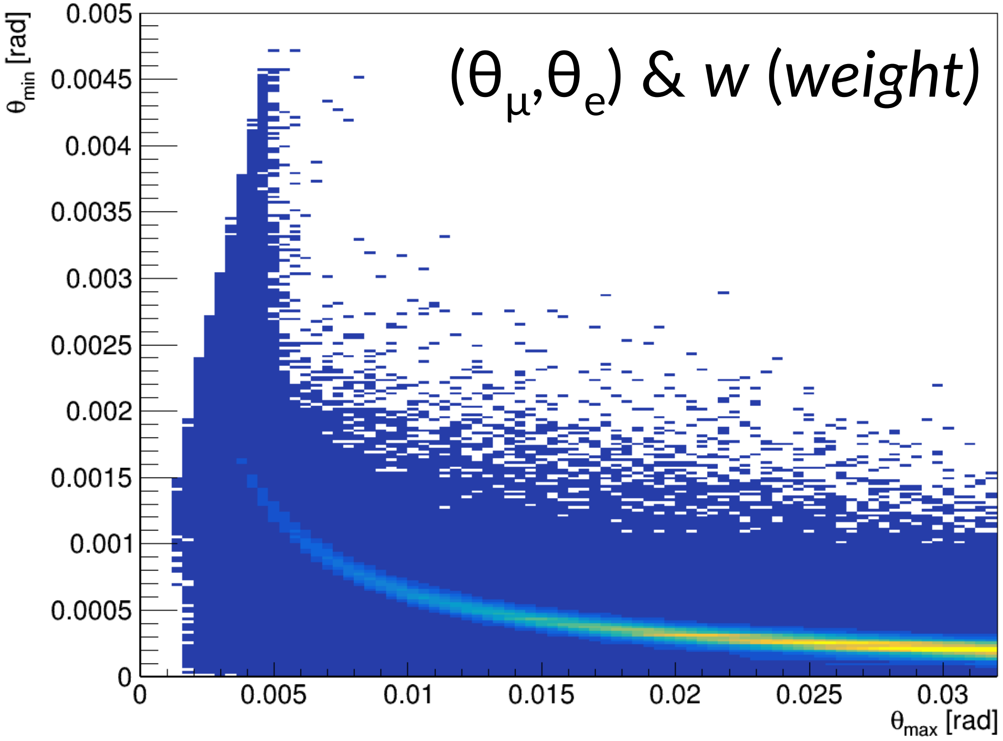
1 parameter template fit:
Fix lepton masses and fit k

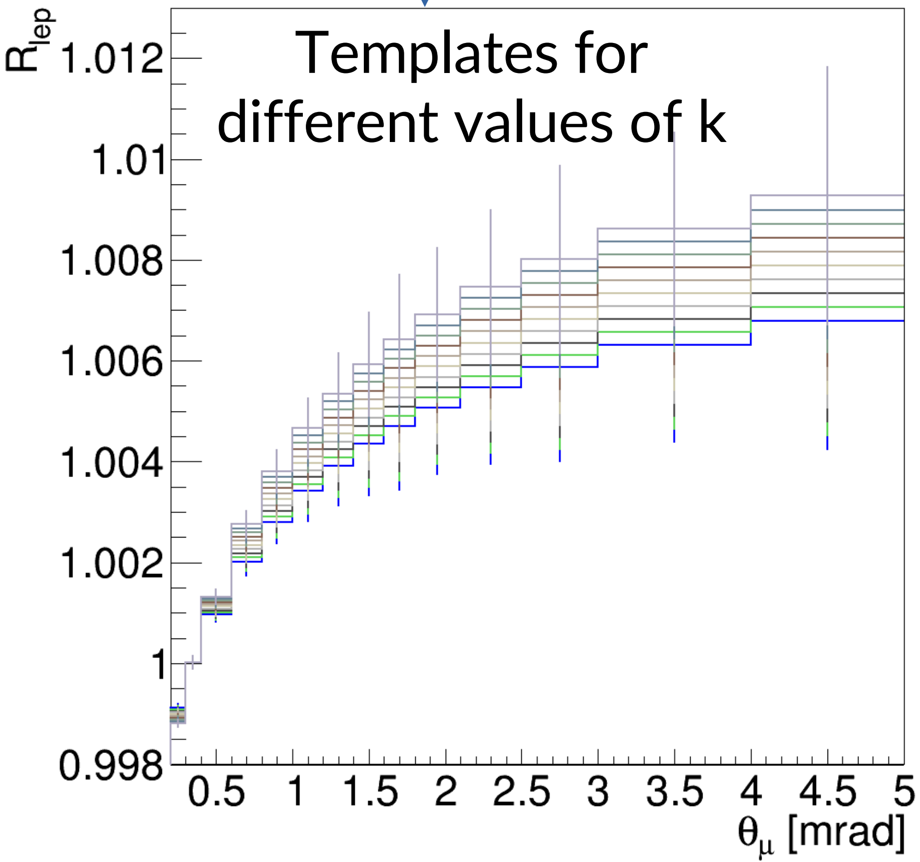
$$k = \frac{\alpha}{\pi}$$

Production of Monte Carlo templates

FairMUonE → **Reweighting** (θ_μ,θ_e) & $w \rightarrow w(k_i)$

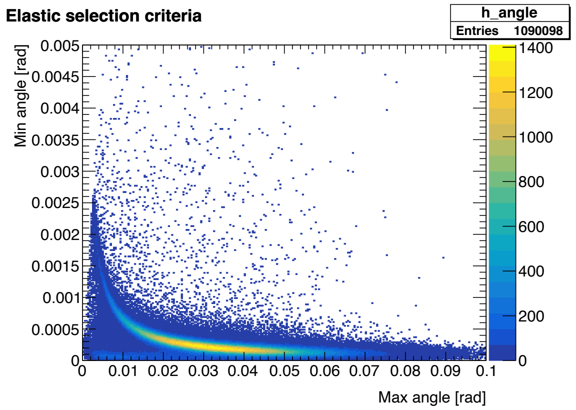
- Geant4 simulation
- Track reconstruction



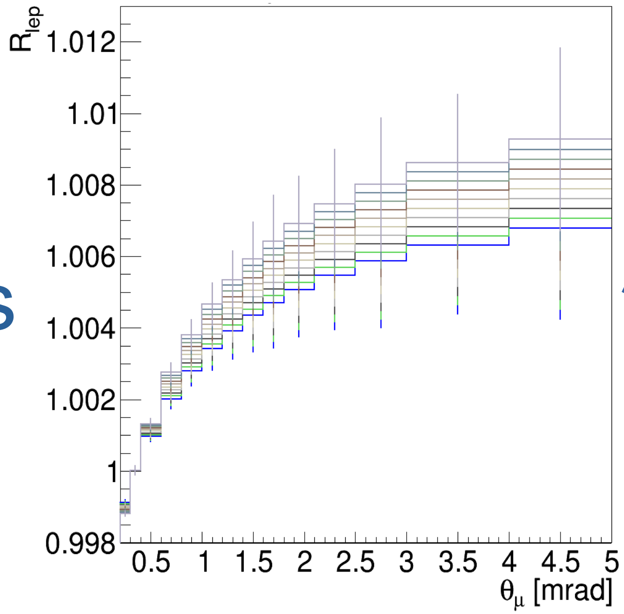


Test using pseudodata (Monte Carlo)

Pseudo data (MC)



Monte Carlo templates

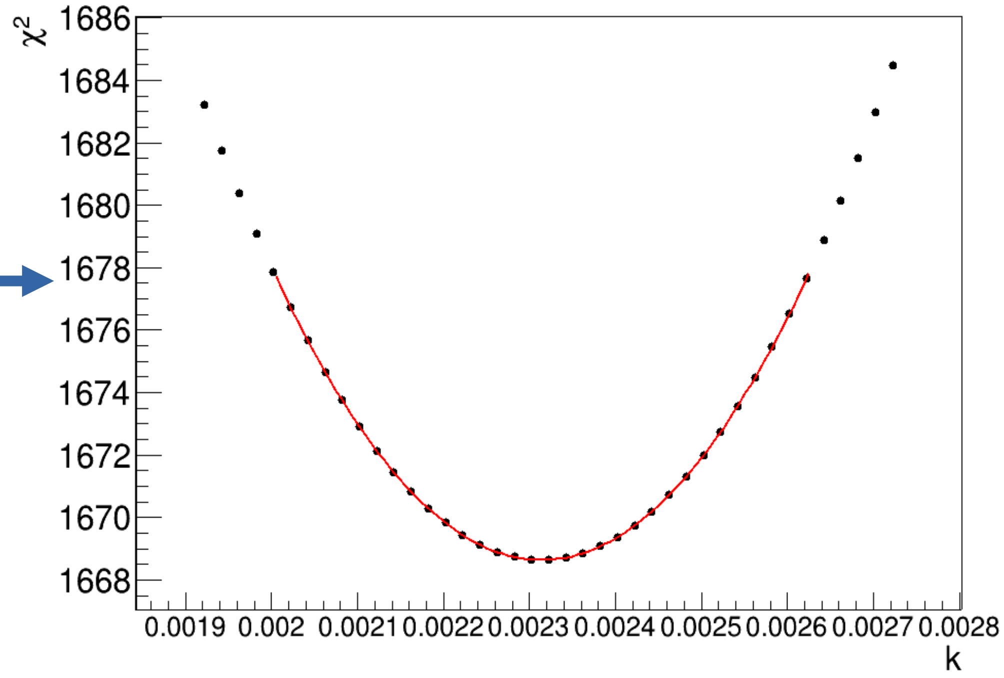


combine

Take into account systematic effects

Likelihood/χ^2 fit

Data vs each template



$k_{best} = 0.00232(10) \rightarrow \sim 5\%$

$k_{input} = 0.00232$