Status of MUonE analysis and first results from the 2023 test run

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https://indico.mitp.uni-mainz.de/event/352

Outline

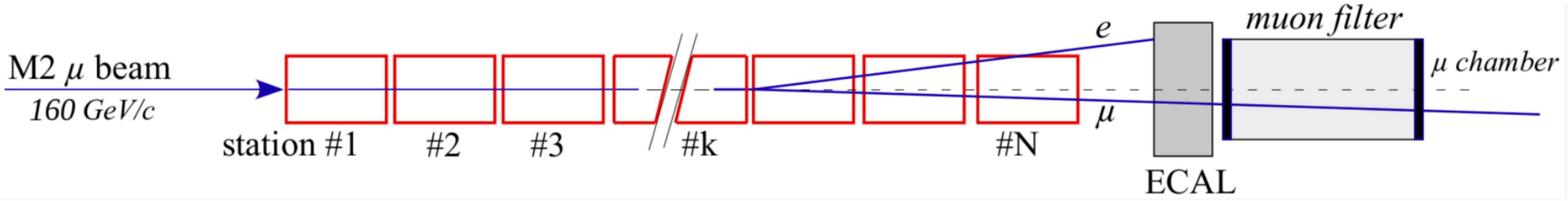
- 2023 Test Run: detector setup and commissioning
- Muon beam and Data processing
- Detector performance
- Selection of elastic scattering events and background studies
- MC physics performance
- Physics analysis workflow
- Conclusions

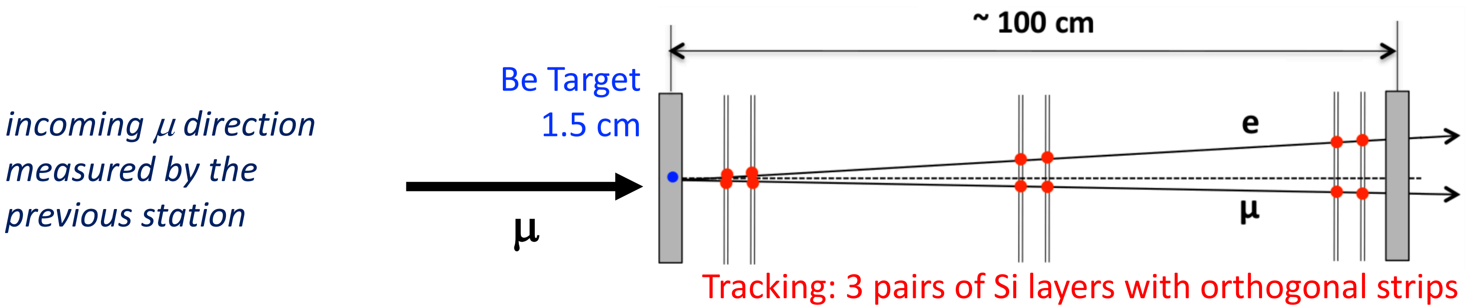
MUonE Detector Layout

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



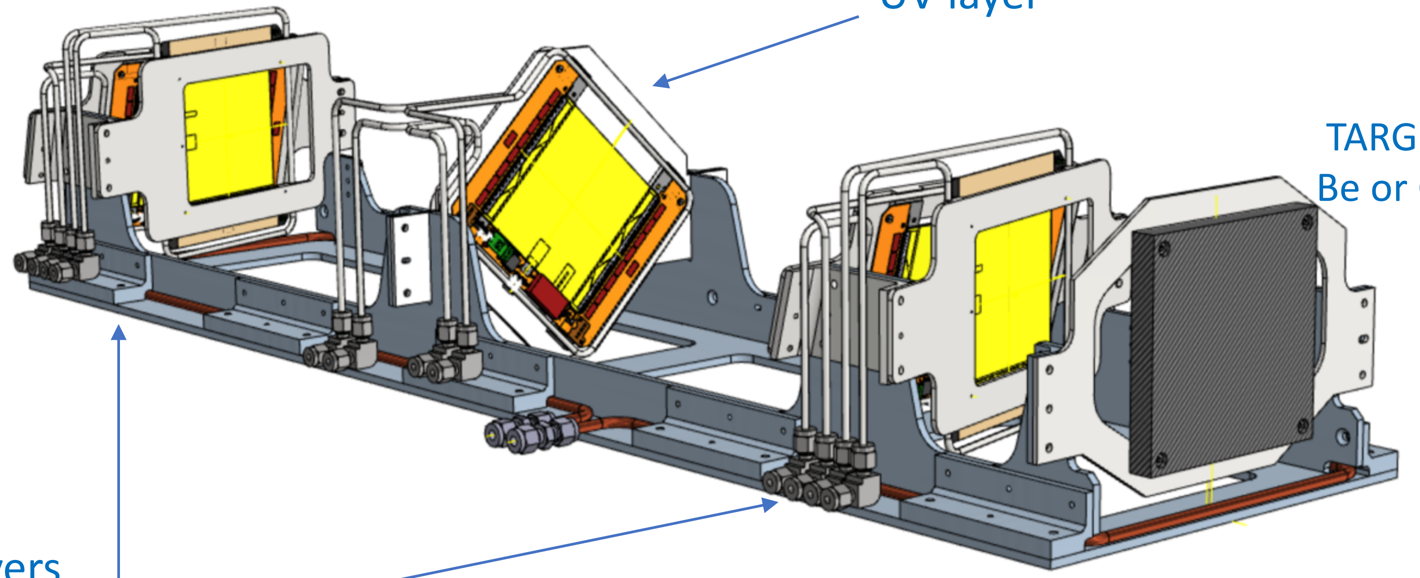


- Boosted kinematics: θ_e<32mrad (for E_e>1 GeV), θ_μ<5mrad:
  - the whole acceptance can be covered with a 10x10cm^2 silicon sensor at 1m distance from the target, reducing many systematic errors

MUonE tracking station

Length 1m
Transverse size 10cm

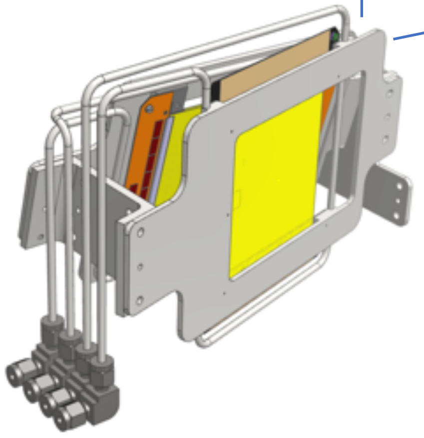
UV layer



TARGET
Be or C

Relative positions of modules must be stable within 10μm

Tilted XY layers



Tilted X and Y modules to improve the resolution

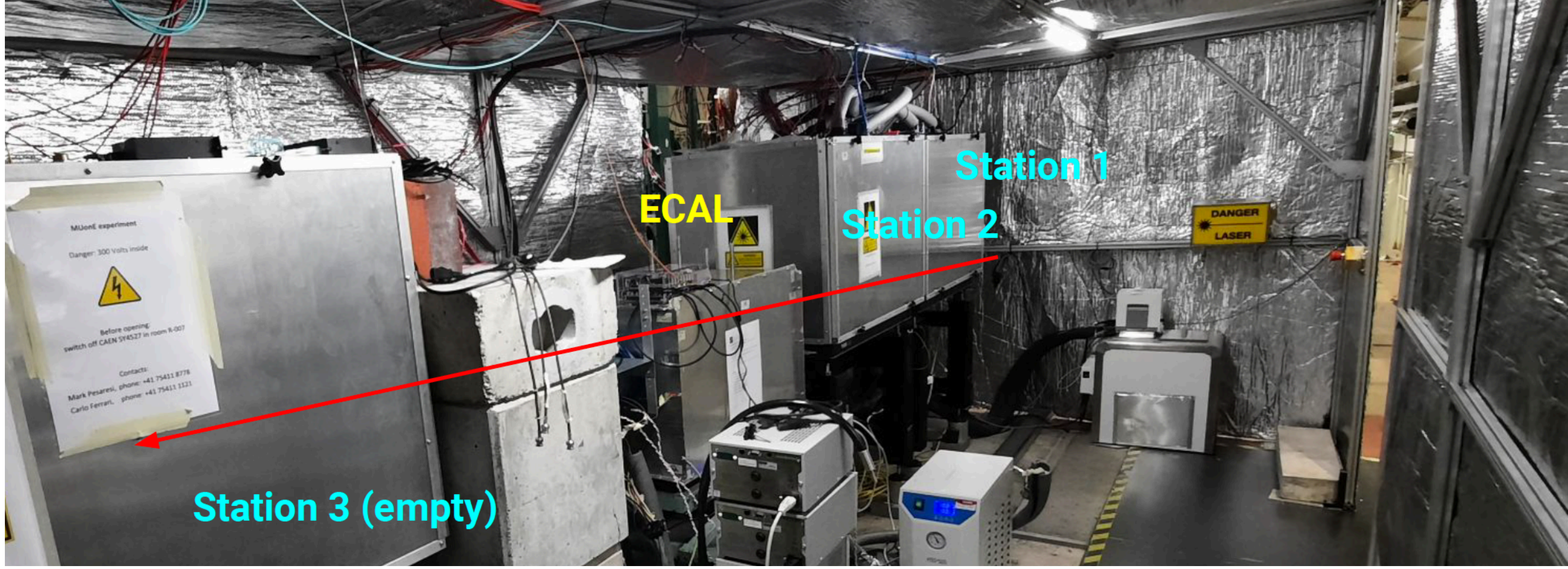
U, V modules to solve reconstruction ambiguities

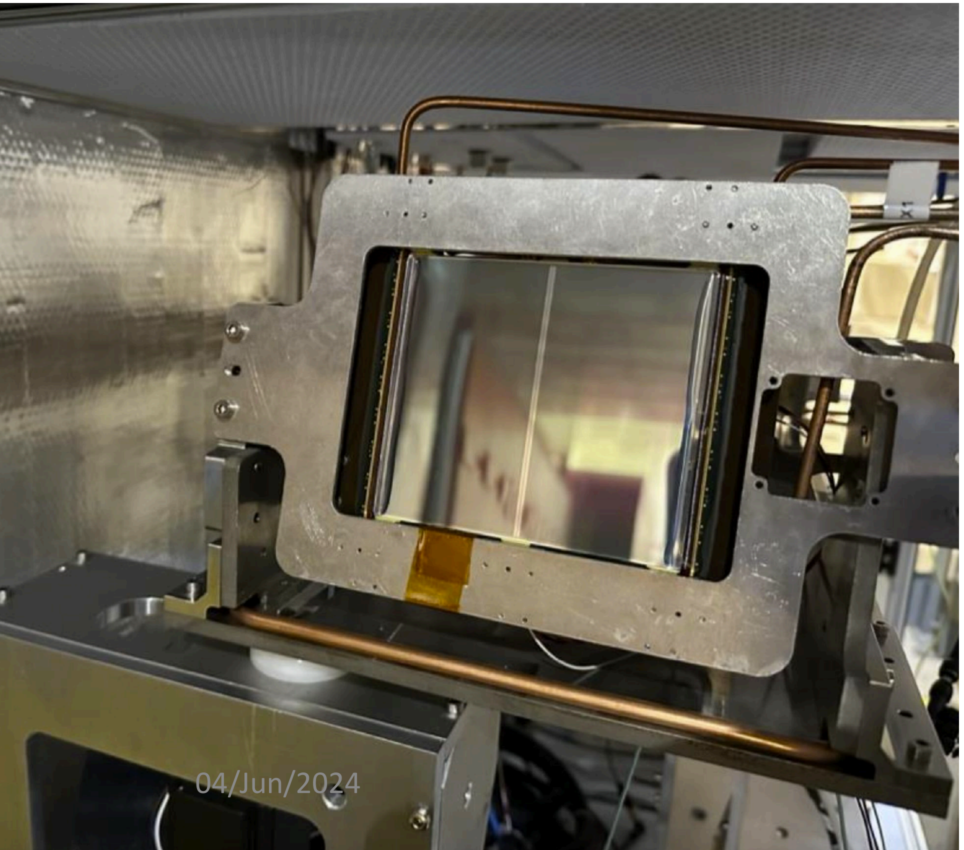
Low CTE support structure: INVAR (alloy of 65%Fe, 35%Ni)

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

Laser holographic system to monitor the stability

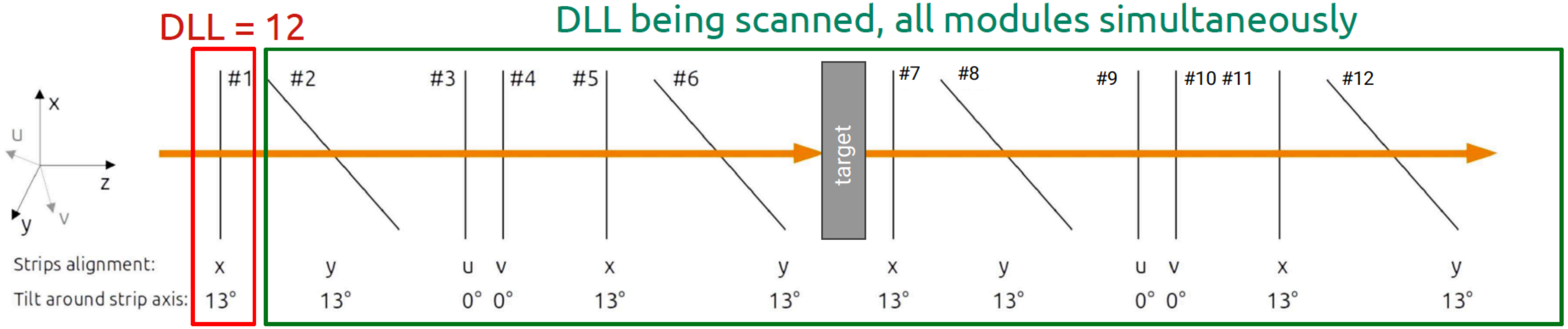
MUonE Test Run 2023



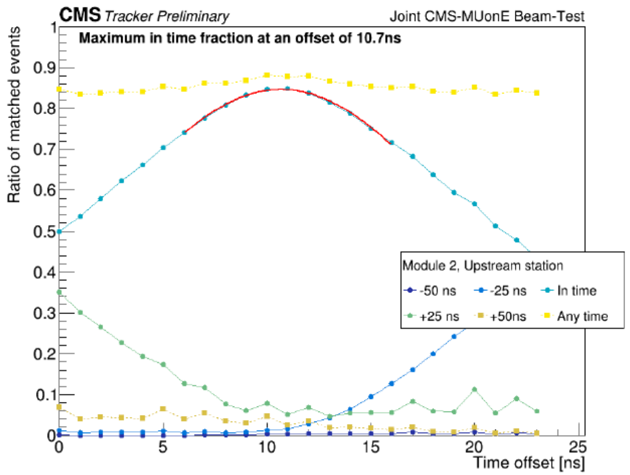


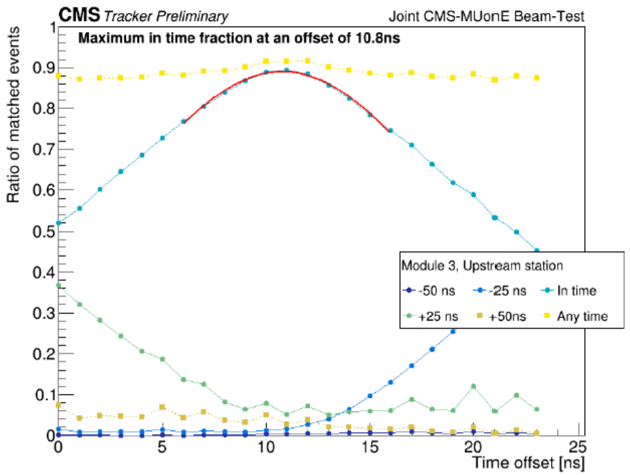
- MUonE Test Run at CERN North Area (M2 beam) (Aug/Sep)
- 160 GeV muons, max asynchronous rate of 50 MHz (2×10^8 muons per spill)
  - Hits (*stubs*) recorded to disk for every single 'BX' (40 MHz)
  - Low intensity runs for commissioning
- 2/3cm graphite target between the two tracking stations
  - also 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:
  - ~1×10^8 elastic events with 3 cm target, ~2×10^8 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



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

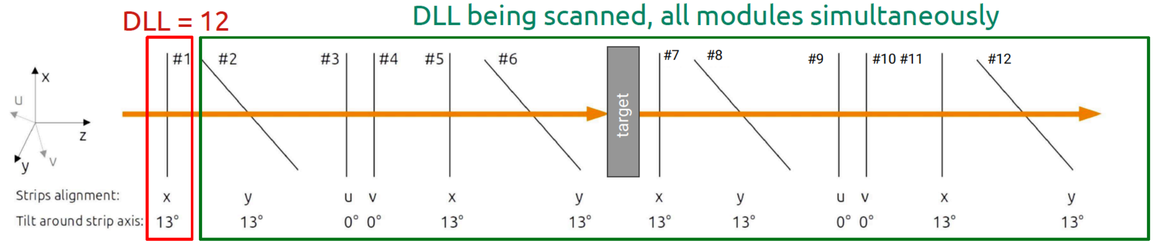




→ **Gives us the relative timing of modules (here, 0.1ns between module 2 & 3)**

Asynchronous beam muons

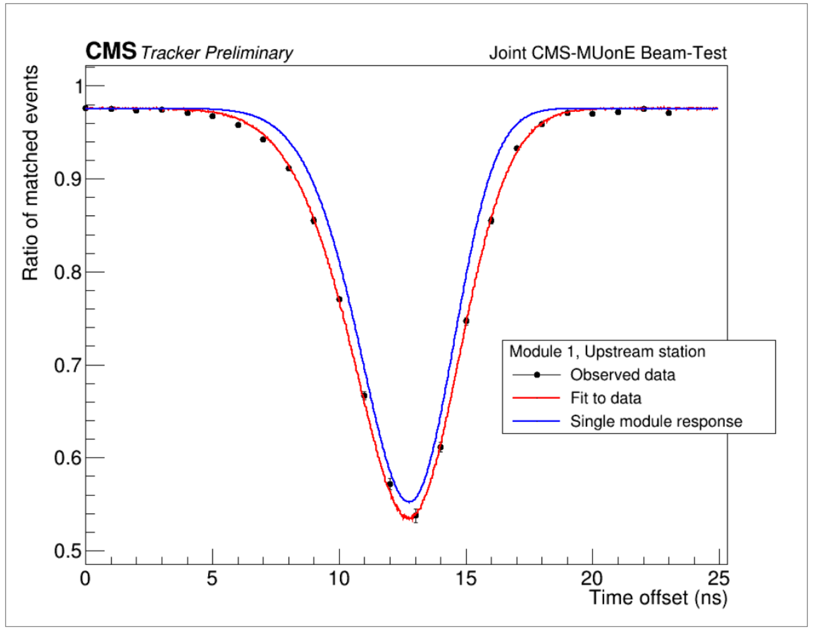
The DLL measurement



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.

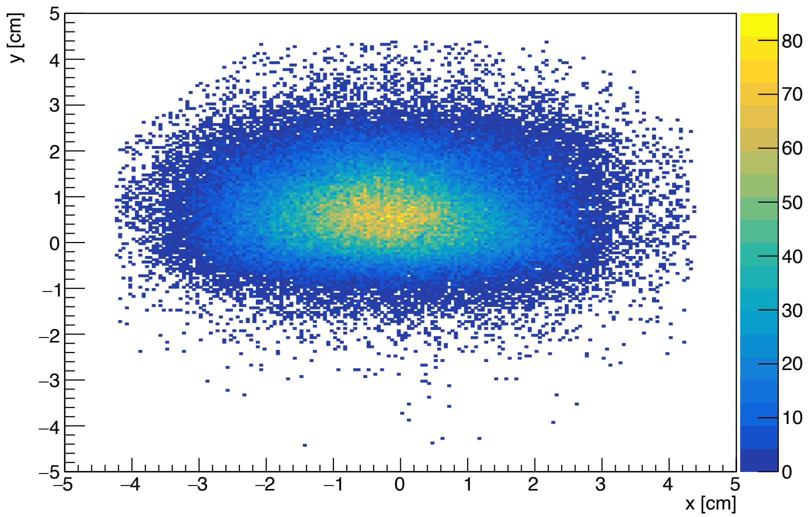
Martin Delcourt talk at BTTB12:

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

LINK

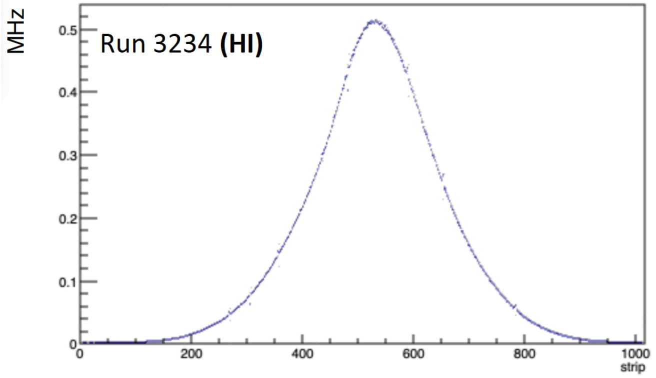
Muon beam profile and intensity

- 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
- Beam Intensity estimated independently from the Ratios of N-muon event multiplicities
  - Assuming Poisson distribution for the muon multiplicity
  - Estimated Poisson mean μ~0.85 → muon rate ~ 34 MHz

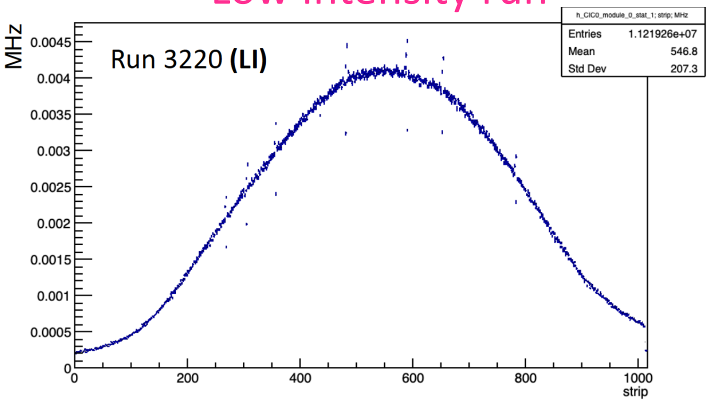


In agreement with the actual estimated rate from the SPS accelerator

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) $\simeq [\text{Eff(N)}]^{1/N}$	Golden Eff(N) | 1 hit	Estimated Eff(1) $\simeq [\text{Eff(N)}]^{1/N}$
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:

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

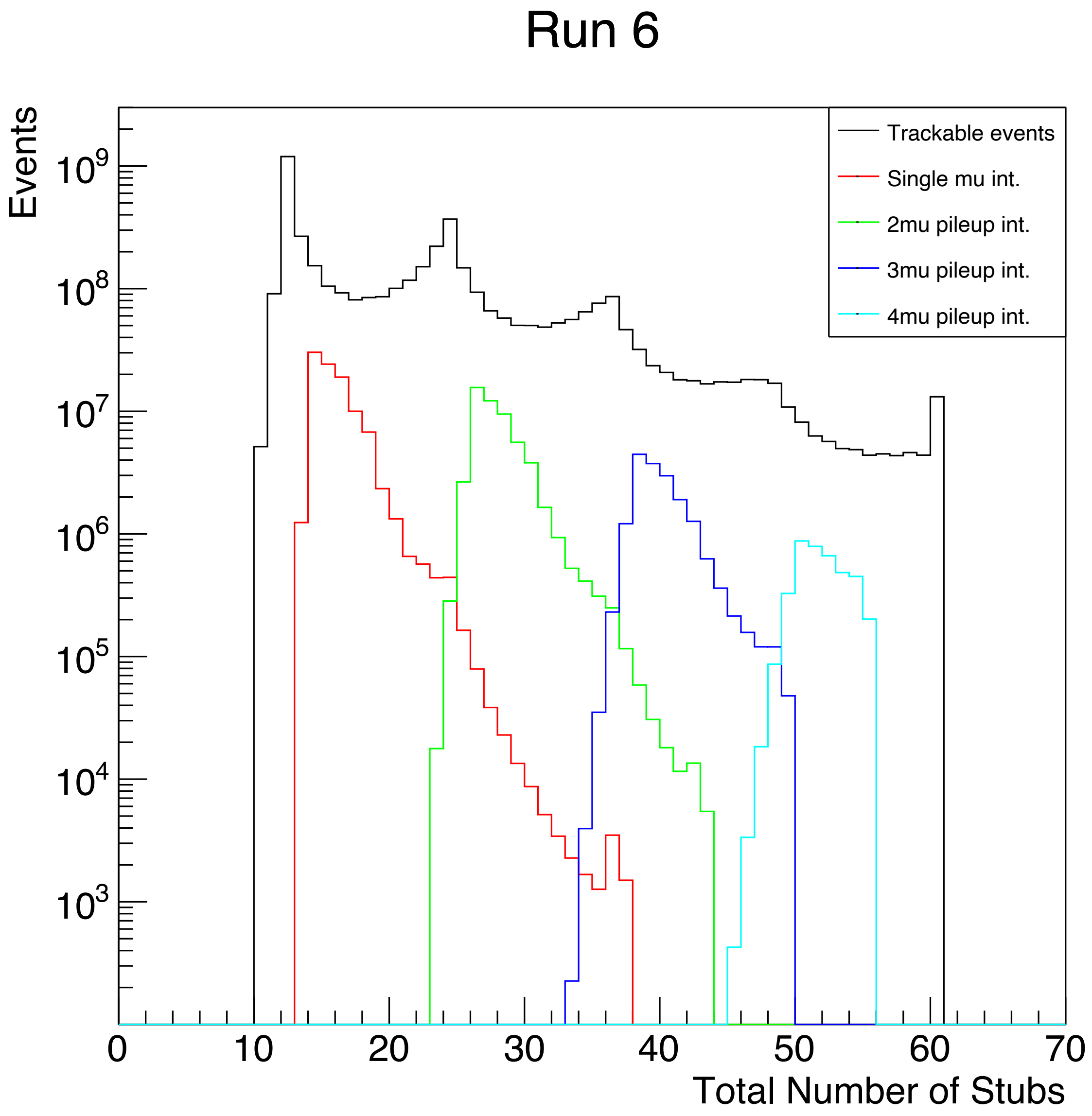
with ε=0.741 for S0, ε=0.749 for S1

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*)

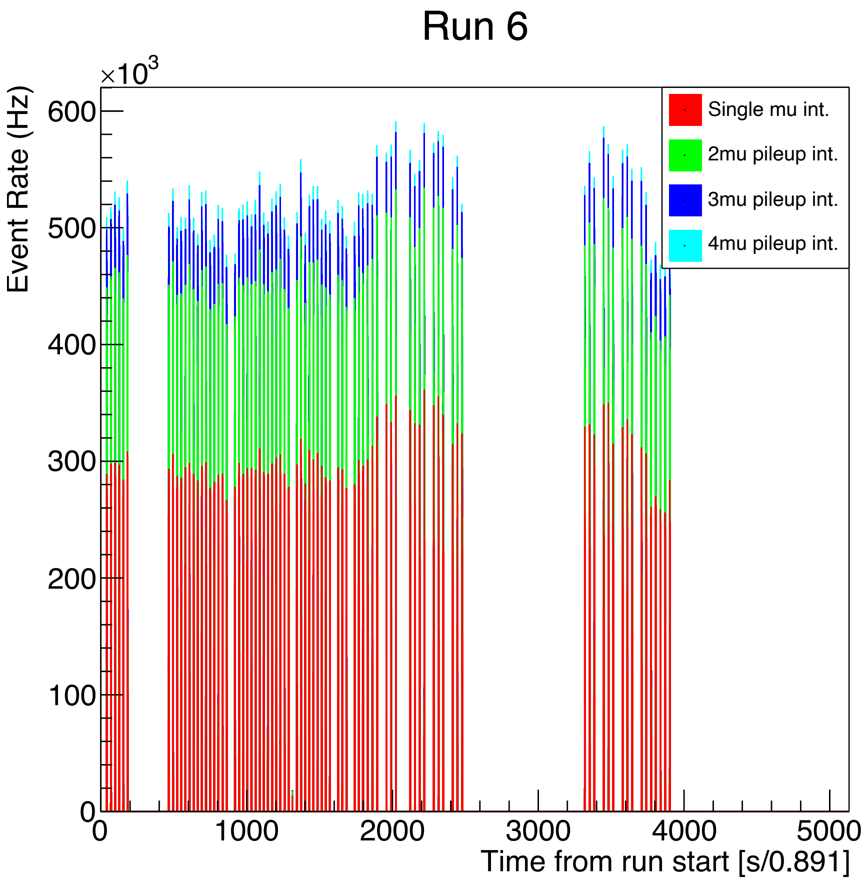


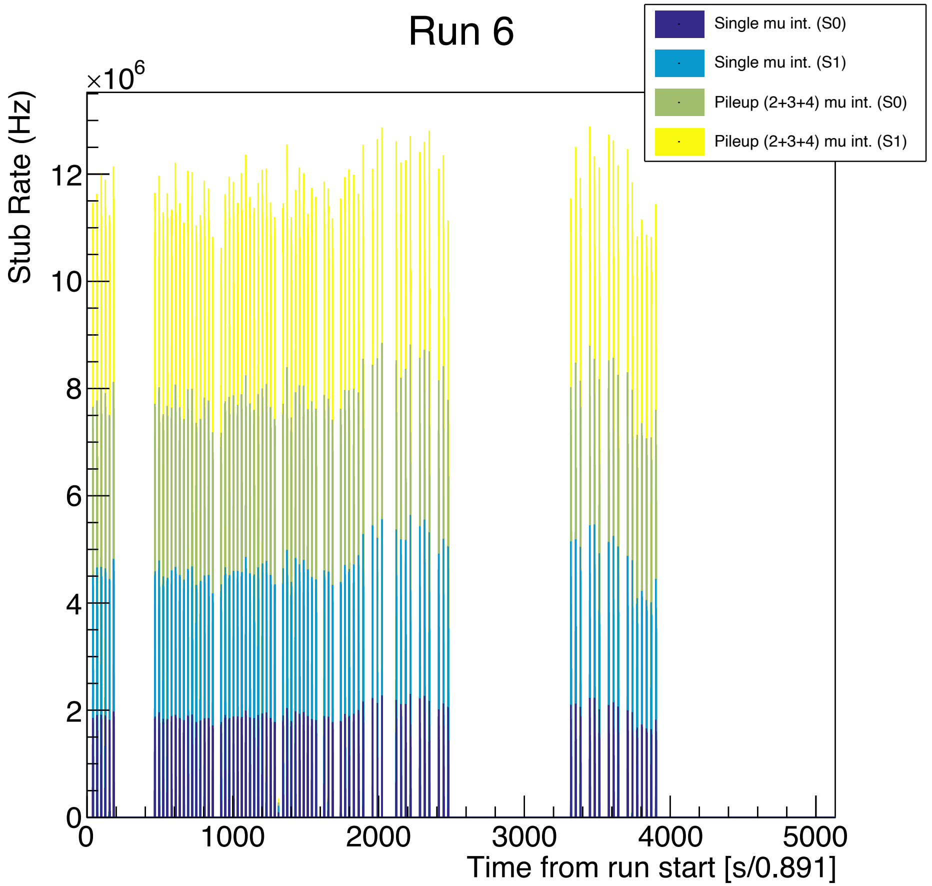
- 2023 Test Run operated with a Triggerless DAQ
  →Large Data volumes processed offline
- Skimming is aimed to preselect all the reconstructible events that can be associated to interactions in the target (from both signal and background processes)
- The algorithm is based simply on the hit patterns observed in the two 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

Event and Hit rates after Skimming Preselection





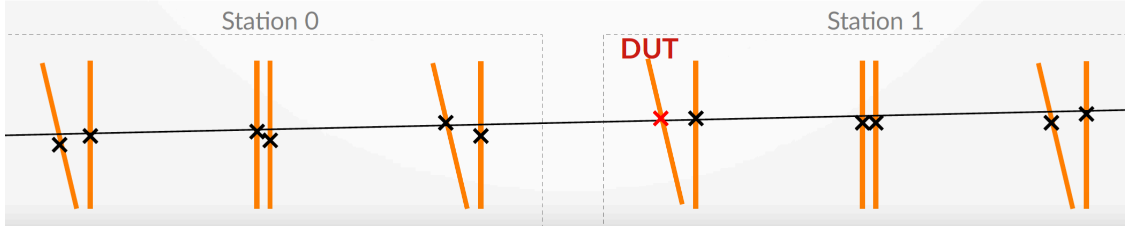
No beam in some time intervals: DAQ was carried on (nights)

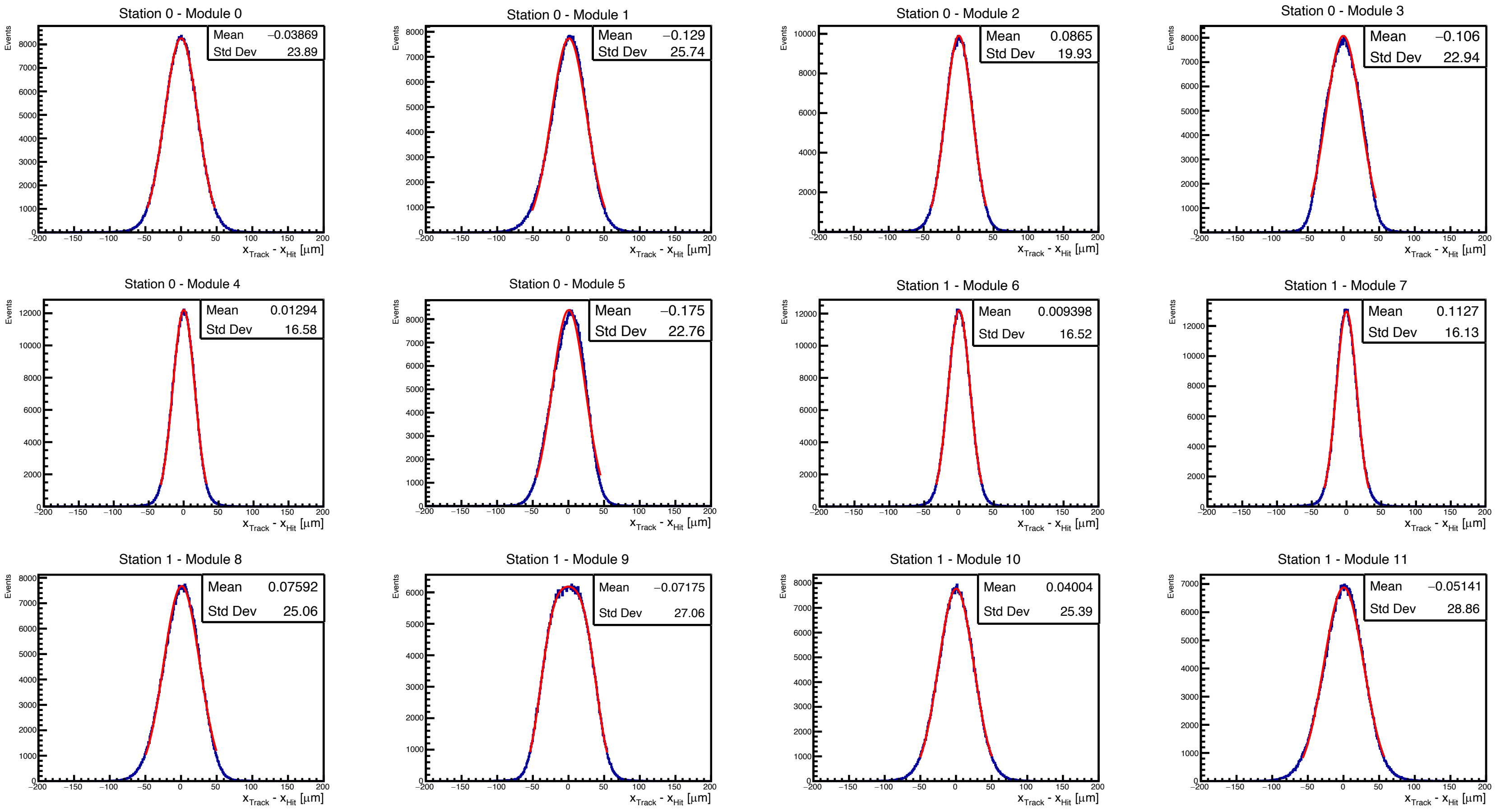
Rate ~500 KHz: algorithm can easily be implemented online on FPGA

OnLine Tracking on FPGA achieved in 2023 Run

→ Michael McGinnis at BTTB12 (LINK)

Detector Alignment - Resolution





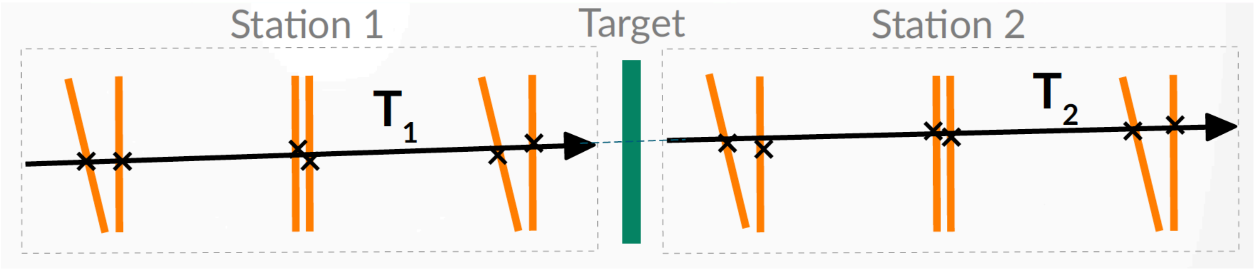
The tracker is aligned with passing beam muons leaving one hit in all the 12 detector modules

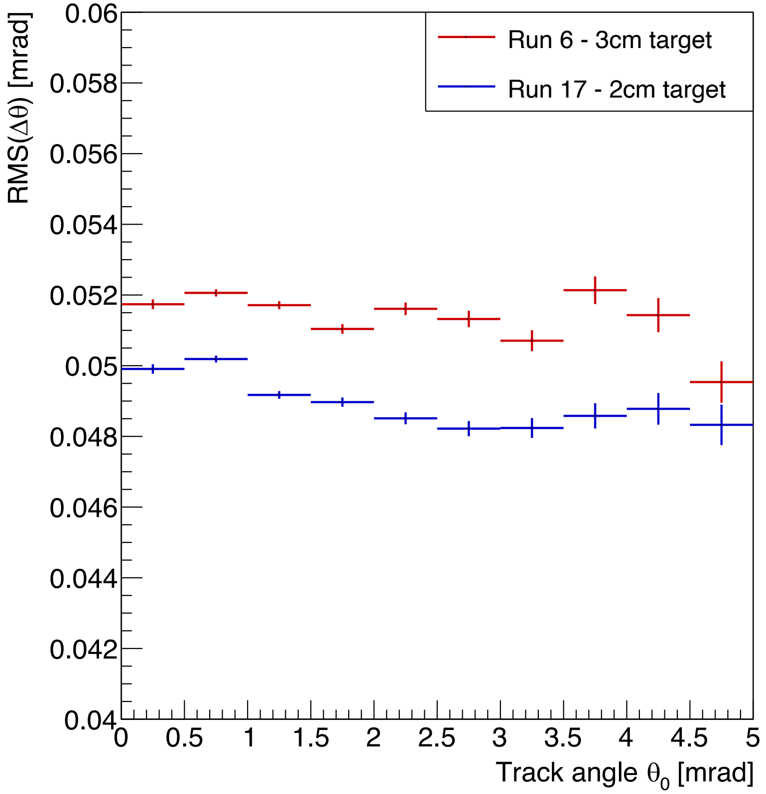
three coordinates aligned per each module:
Strip local position (local X)
Rotation angle around the Z axis
Orthogonal coordinate (local Y)

Unbiased residuals on the tracker modules after the alignment: resolution consistent with expected resolution

On-going development to include the metrology measurements as starting point

Angular resolution vs Track Position and Angle





Distribution of the angle difference measured for golden passing muons

$$D = \theta_1 - \theta_0$$

$$\sigma(D) = \sqrt{\sigma(\theta_1)^2 + \sigma(\theta_0)^2 + \sigma_T^2}$$

Sensitive to the intrinsic angular resolution of the tracking stations, the residual misalignment, the multiple scattering in the target

By subtracting quadratically the predicted multiple Coulomb scattering on the target we measure on real data an angular resolution of ~20 μrad consistent with design expectations

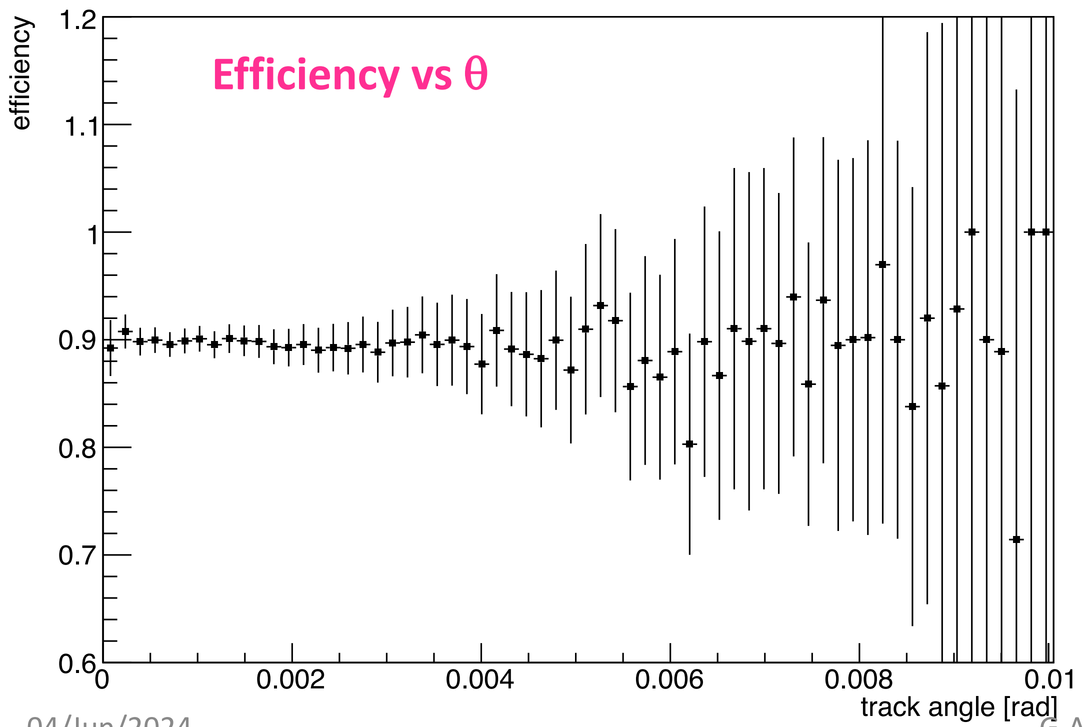
Tracker Efficiency (preliminary)

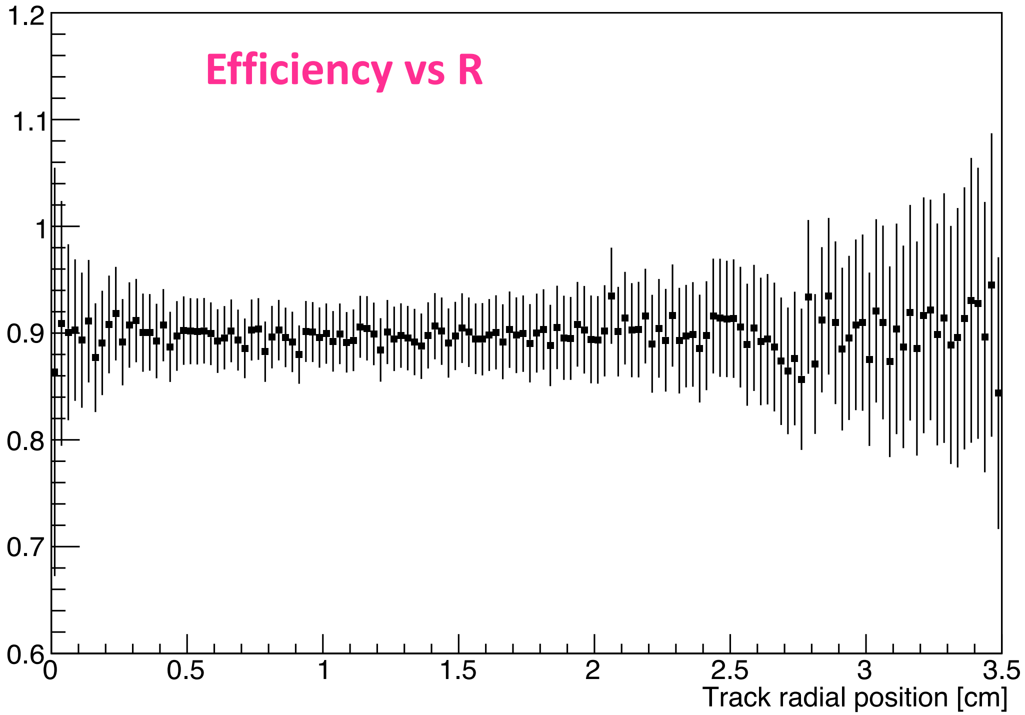
From selected golden muons: **average MODULE Efficiency** ~ 98%

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



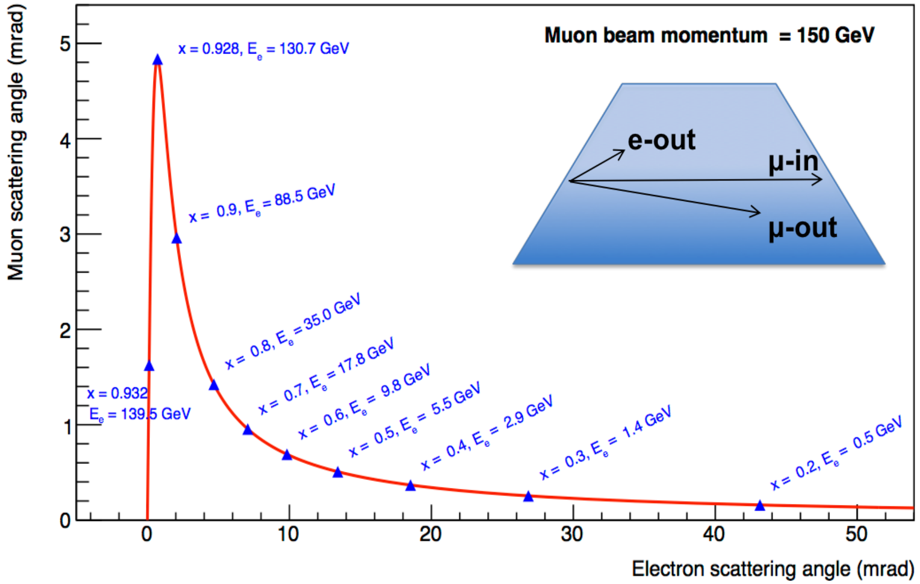


Event Selection

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

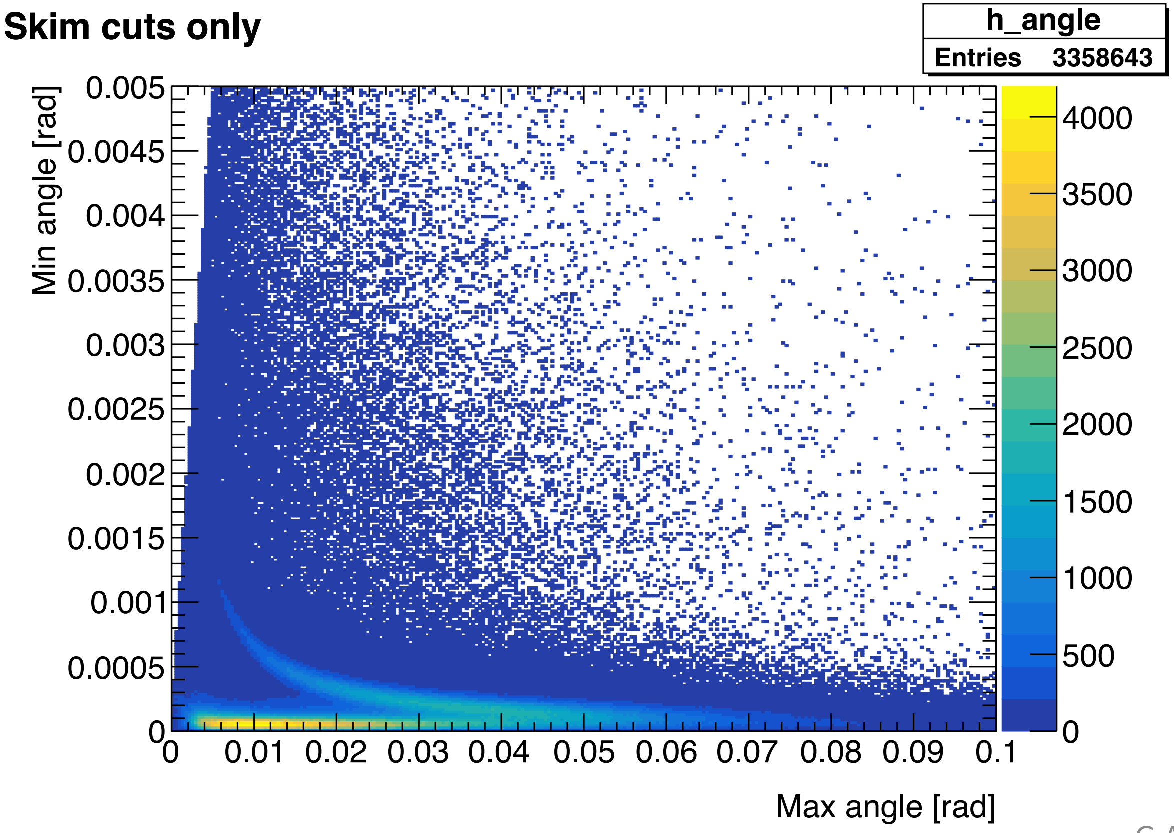


- Radiative events with real photon emission break these properties
  - but MESMER (N)NLO MC generator describes the effects very accurately
- Pileup of beam muons is easily controlled with the track impact parameters w.r.t. the candidate interaction vertex
- Events produced in interactions with the detector 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 (σ~Z^2) or an atomic electron (σ~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

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)

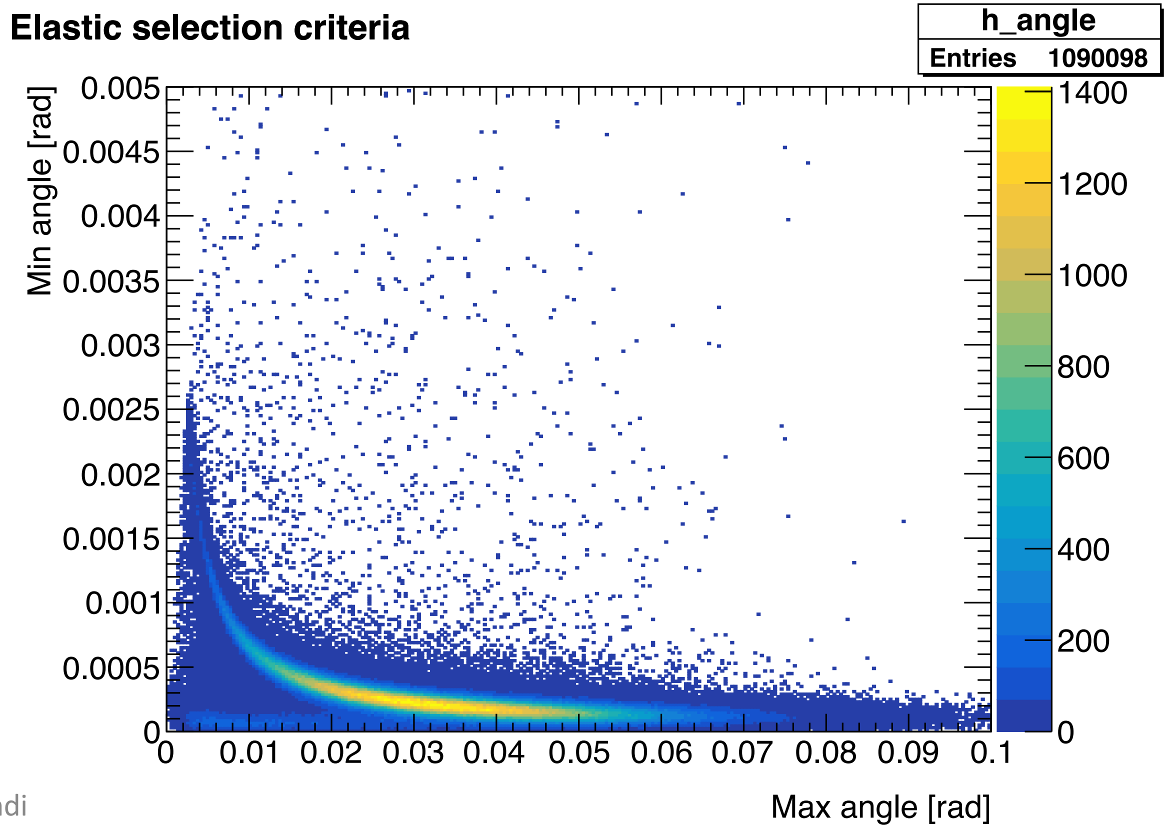


Initial selection:

2 outgoing tracks

Loose acoplanarity |A|<1;

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

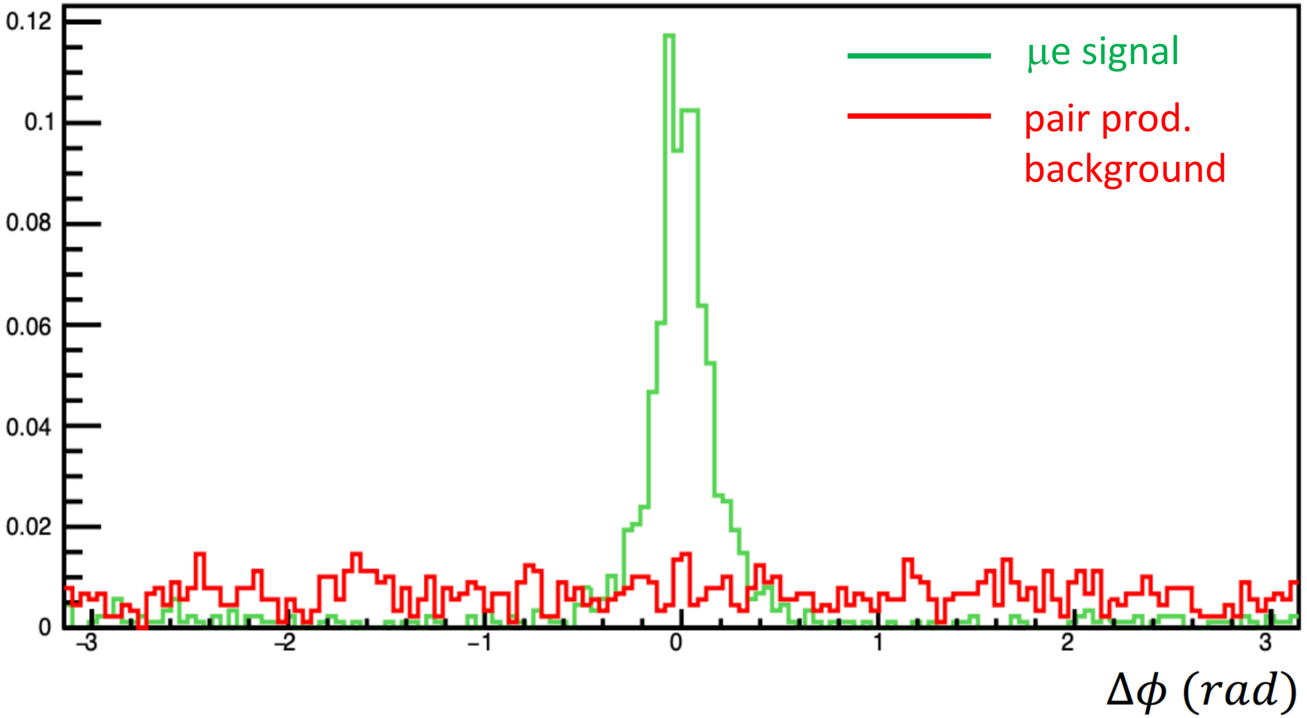


Minimum Bias simulation
(Signal and Background from GEANT4)

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

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

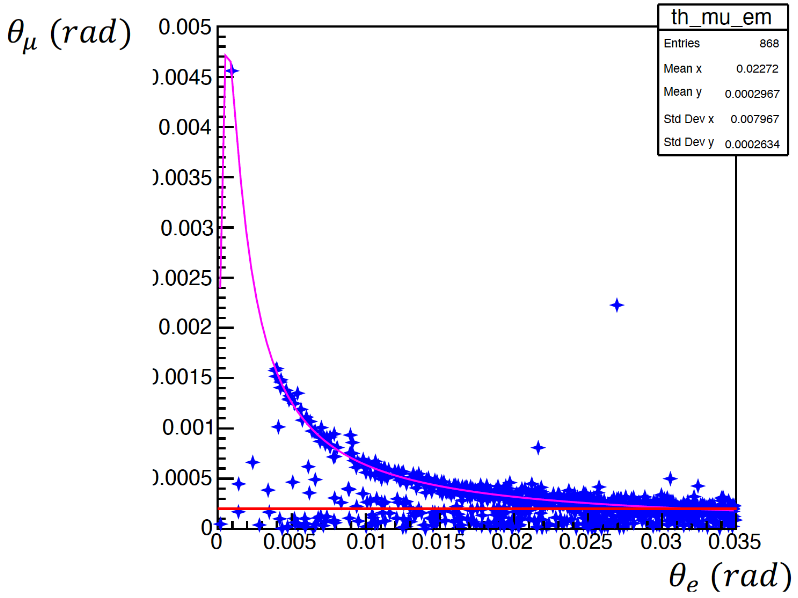


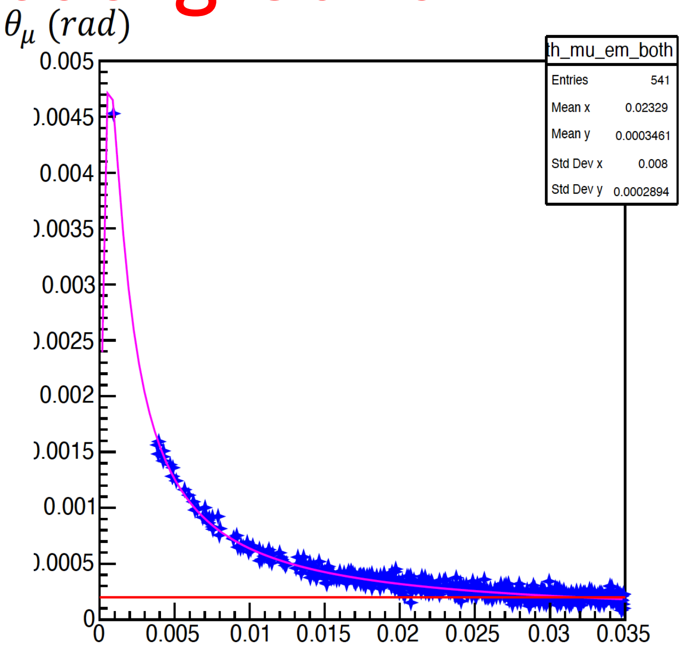
TRACK-BASED Observables
Track quality (Nr Hits; χ^2)
Vertex compatibility
Vertex position
Acoplanarity
Minimum scattering angle
Elasticity (from angular correlation)

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

Selection: MC signal and background

SIGNAL



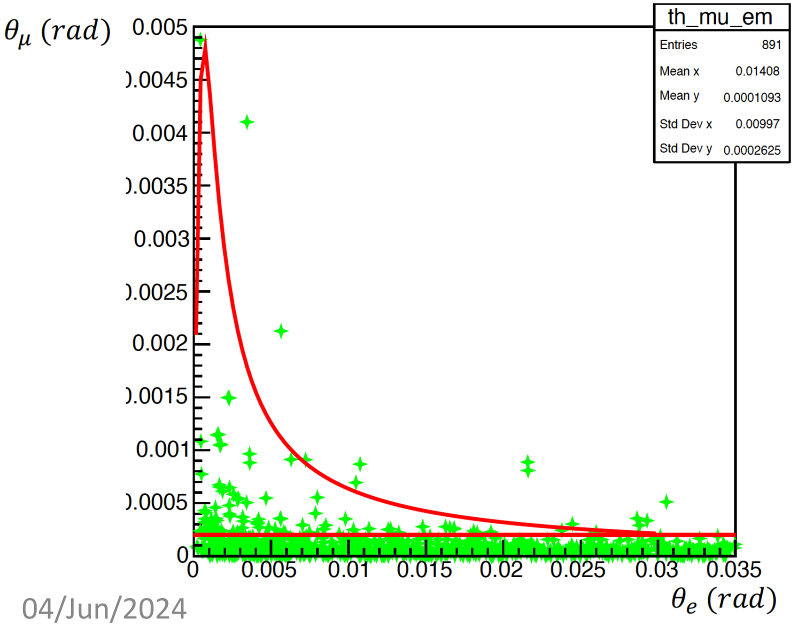


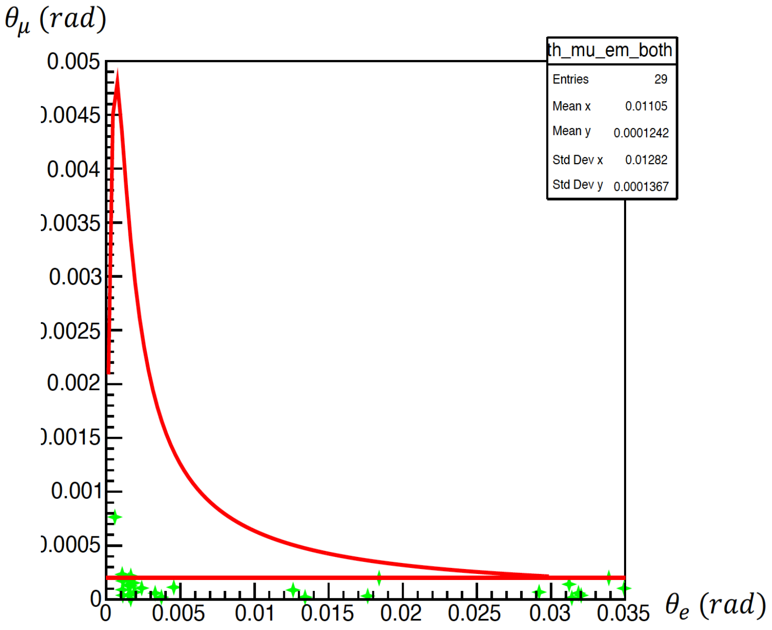
SIGNAL

Cuts on:

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

BACKGROUND

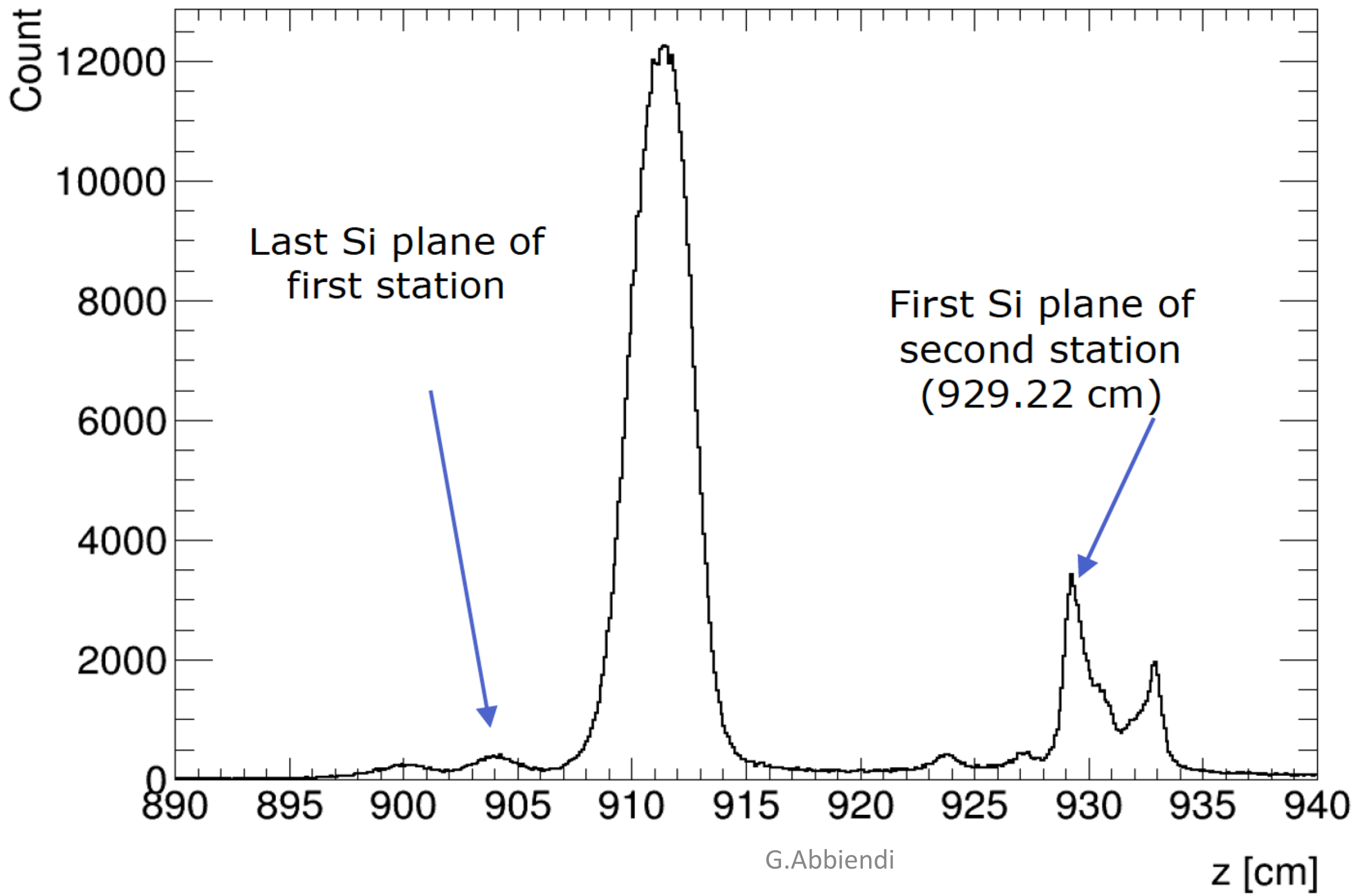




BACKGROUND

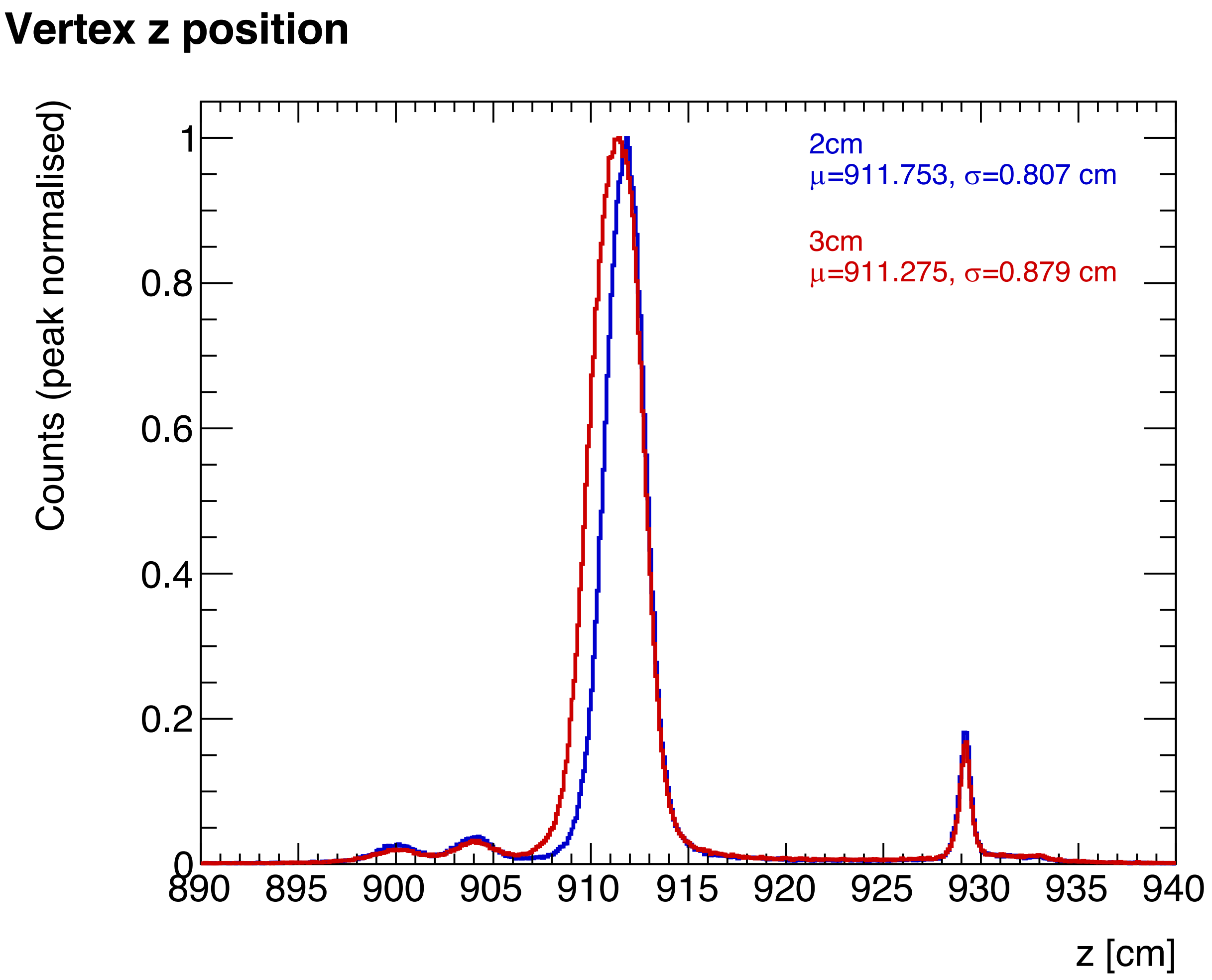
Vertexing

Skimming + 2 outgoing tracks + (min, max) angular cuts



We clearly distinguish events coming from the target and from the silicon planes

Vertexing



Two outgoing tracks within angular cuts (0.2 – 32 mrad)

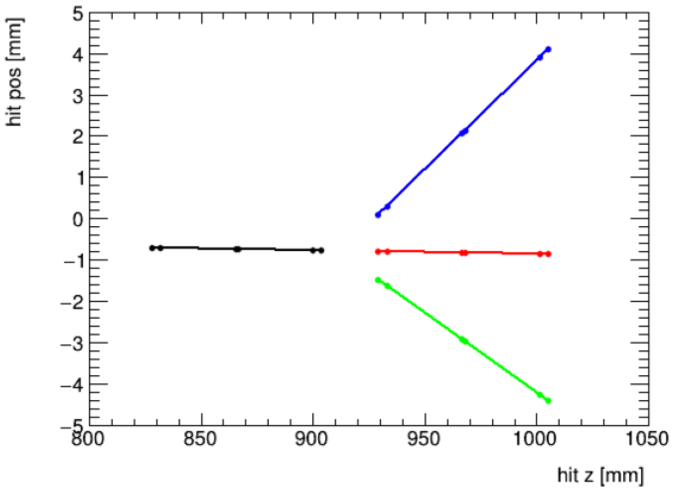
Vertex Z fitted to a box (2 or 3 cm, according to the target thickness) convoluted with a gaussian resolution

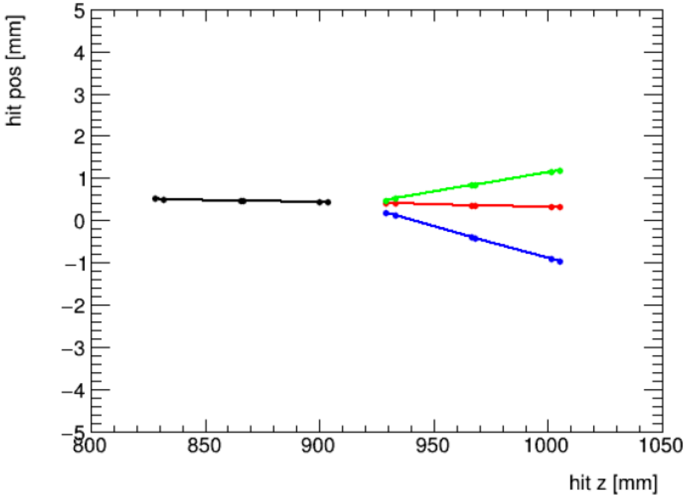
The target middle is shifted by 0.5 cm along Z changing between the thickness of 3cm and 2cm

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

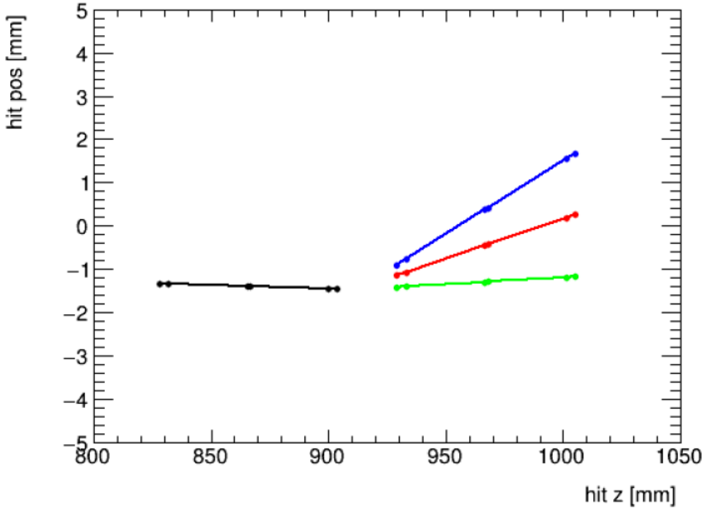
Background event displays

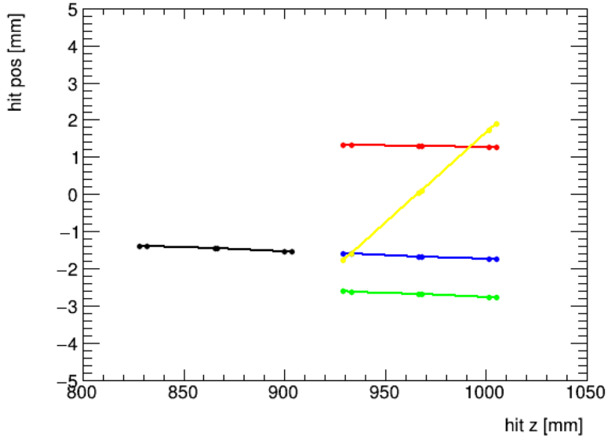
Studying: 3 or 4 track events, candidate background





Clear unbalanced event



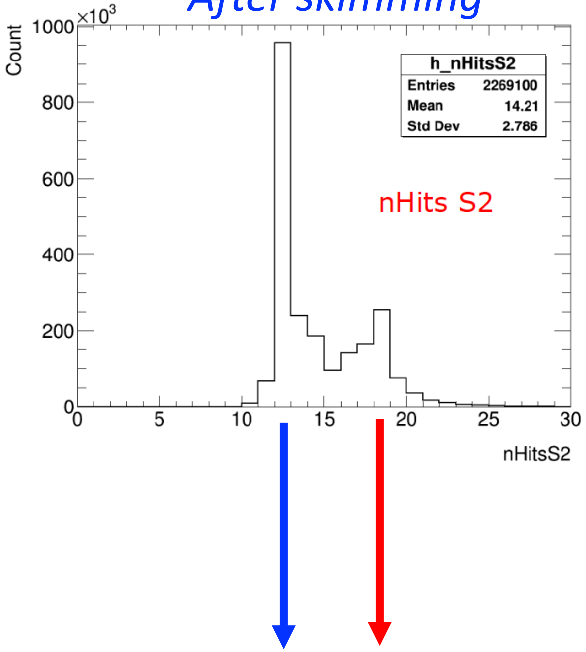


Weird background event
But easily rejected by the selection

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

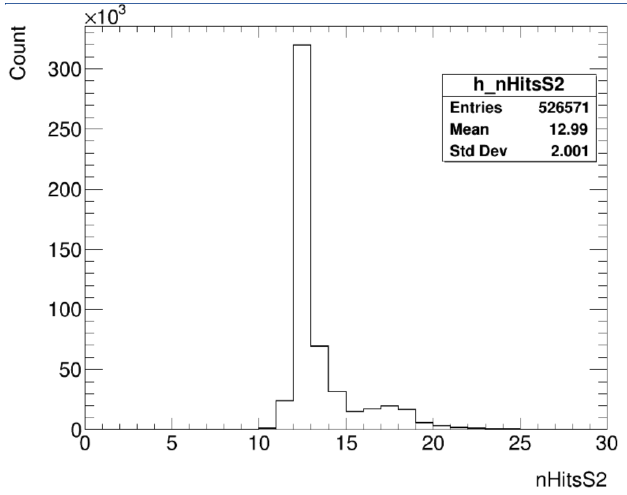
After skimming



2 tracks
(12 hits)

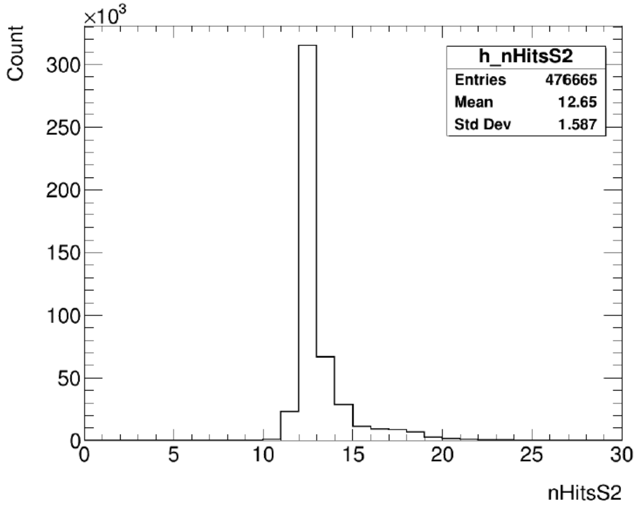
3 tracks
(18 hits)

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



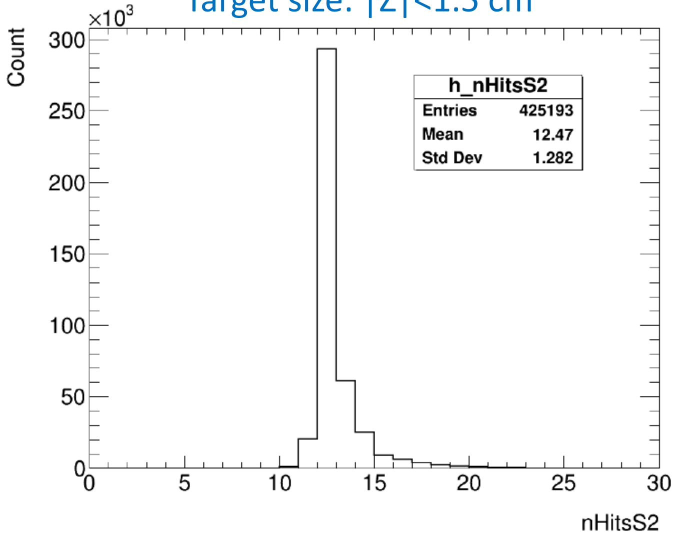
The third track may be not reconstructed

++ |Acoplanarity| < 1



++ |Zvtx| < 3cm

Target size: |Z|<1.5 cm



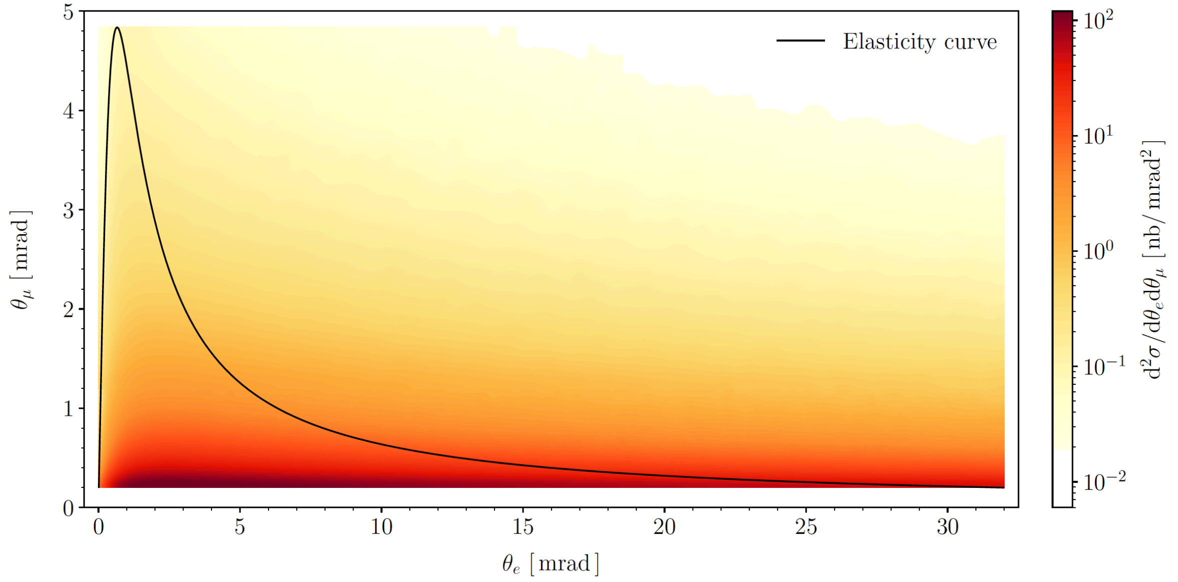
The residual background can be estimated by selecting background enriched events and using the MC to fit the data in the signal region

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 (analysis in progress)

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.

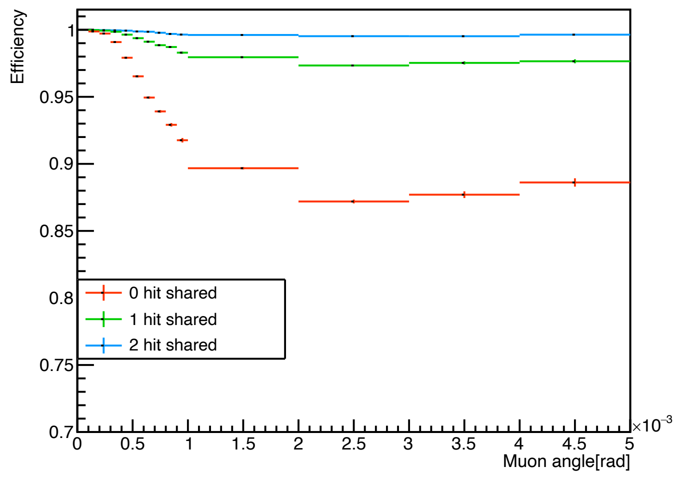
- 5D Bethe-Heitler process in Geant4

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

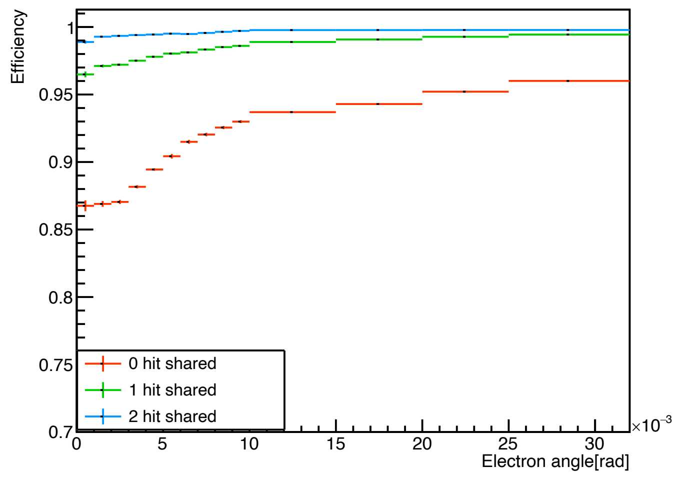
MC performance - Track reconstruction in μe elastic scattering events

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

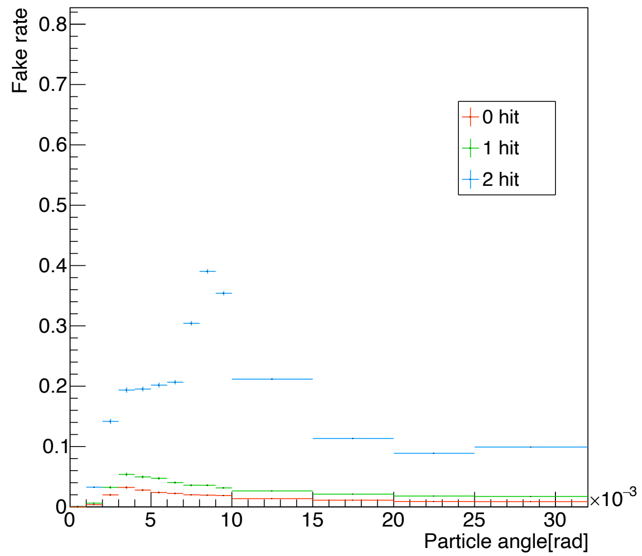
μ track efficiency



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)

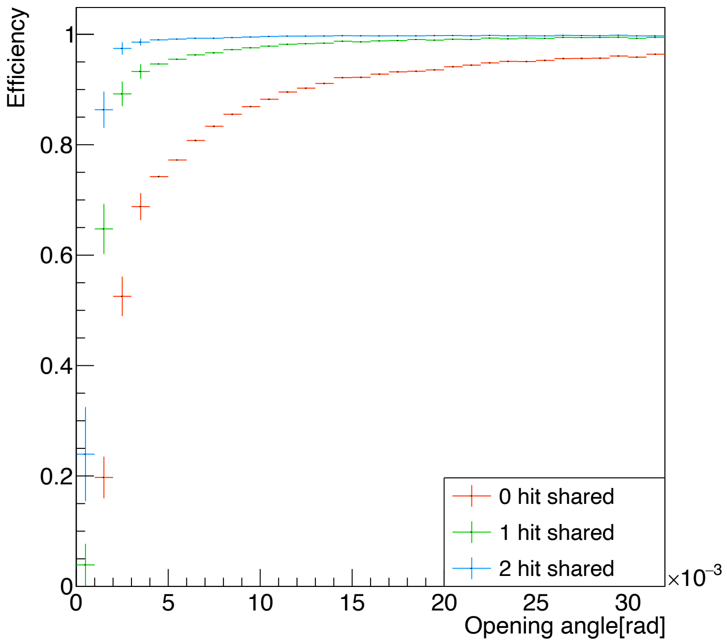
MC performance – μe elastic event reconstruction

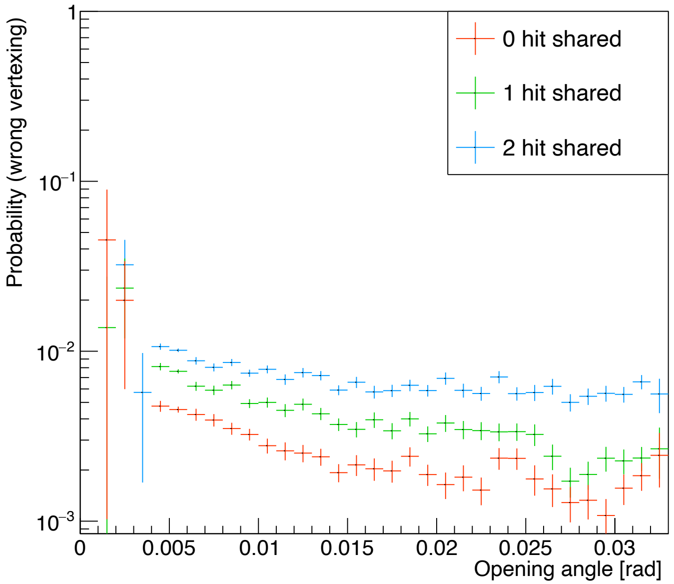
Algorithmic reconstruction performance for reconstructible events, with 3 cm Target,
for different setting of the reco configuration: maximum number of shared hits between two tracks = 0,1,2
The efficiency is defined by matching the MC truth with a Quality cut of Q>0.65,
i.e. at least 4/6 hits have to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

wrong vertex probability

μe event efficiency

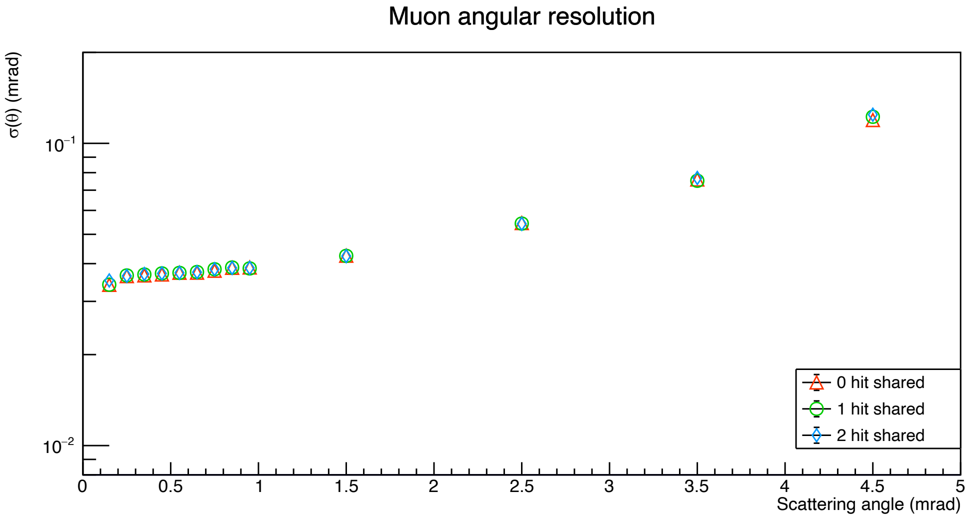
Flat efficiency
for 2 max shared hits
(close tracks in the first
pair of modules nearest
to the target)

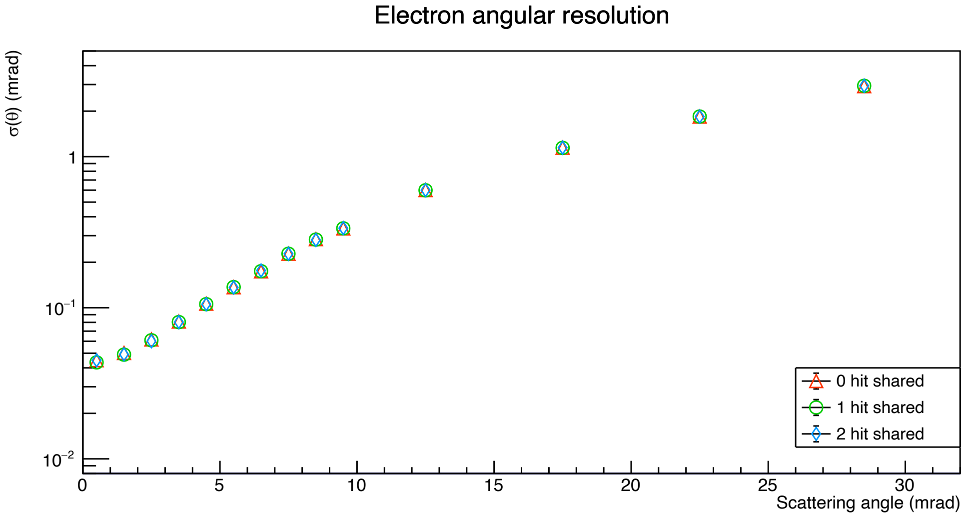


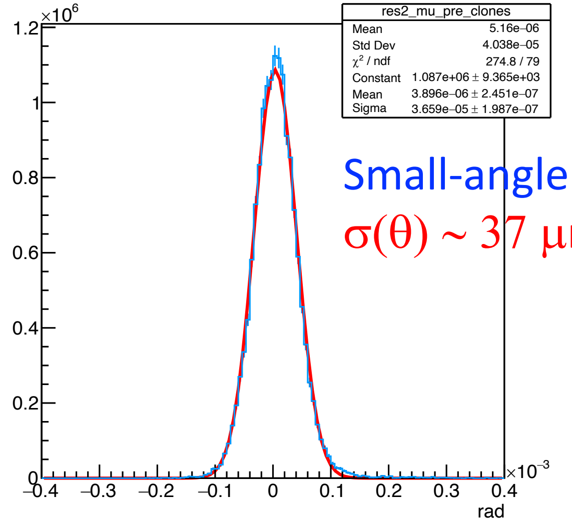


Very low probability
of wrong vertexing

MC performance – Angular Resolution vs Scattering Angle

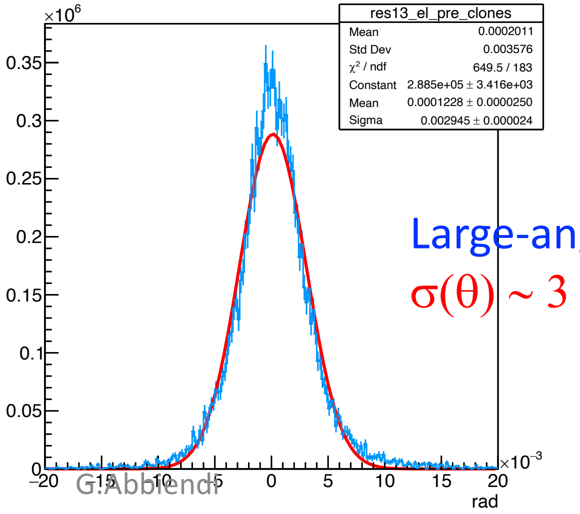






Small-angle μ (0.2-0.3 mrad)

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)

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:

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

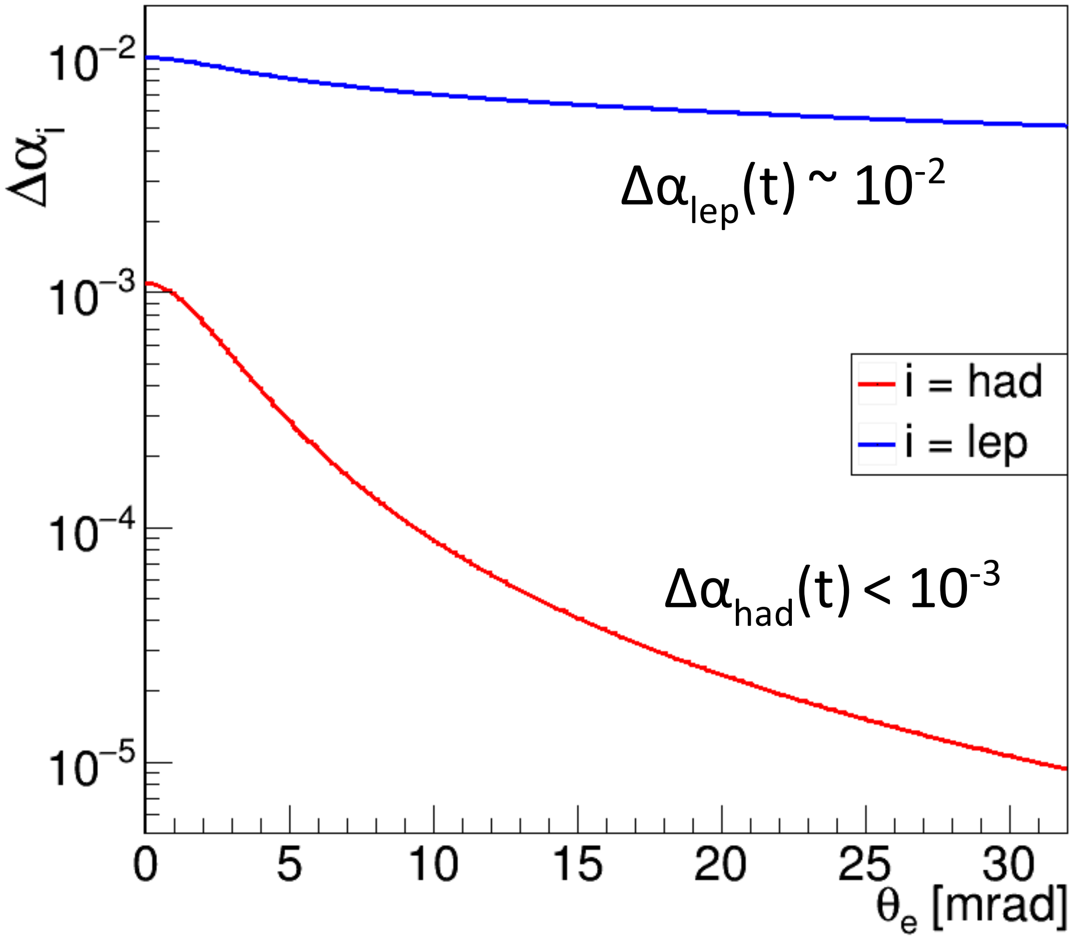
  σ : cross section for the considered process

  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 ~ $1 pb^{-1}$

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:

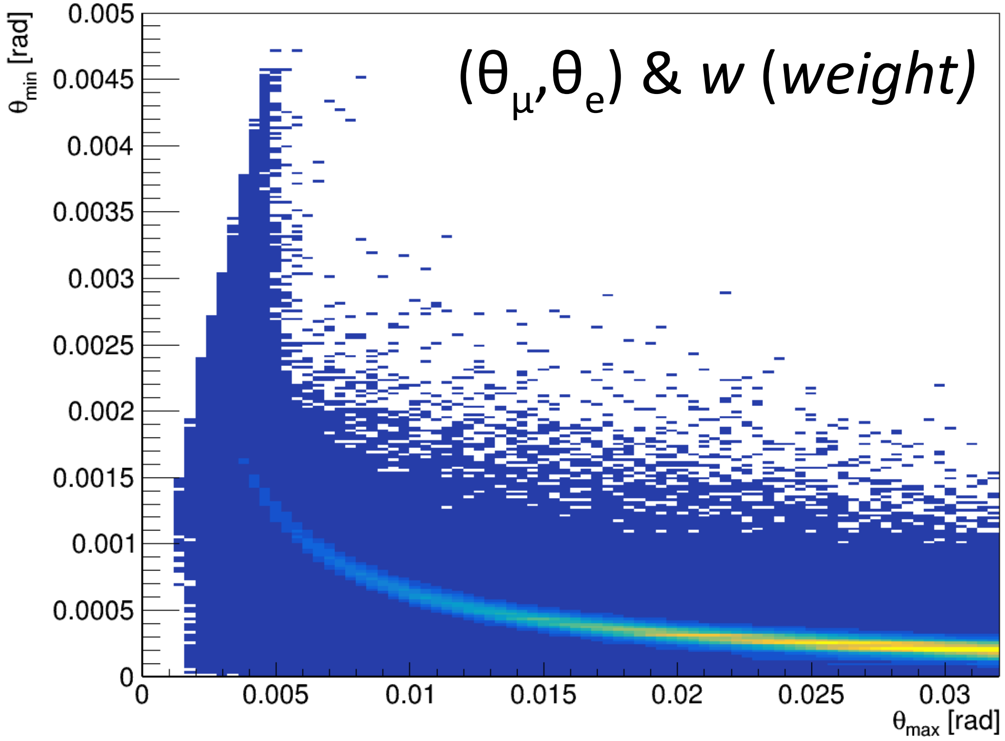
Fix lepton masses and fit k

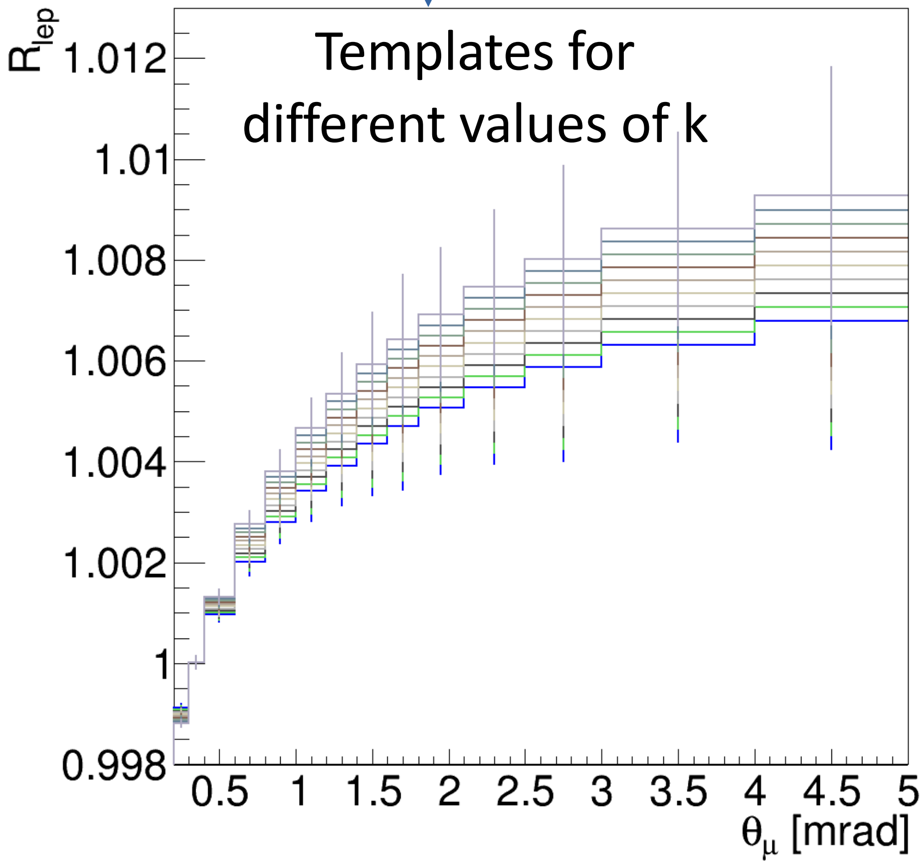
$$k = \frac{\alpha}{\pi}$$

Production of Monte Carlo templates

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

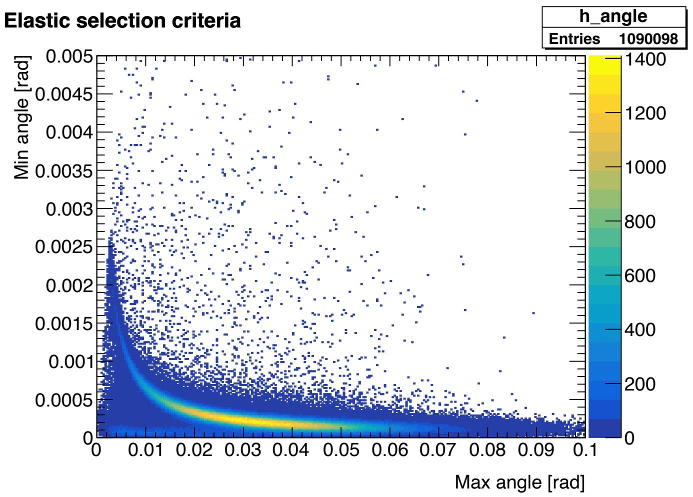
- Geant4 simulation
- Track reconstruction



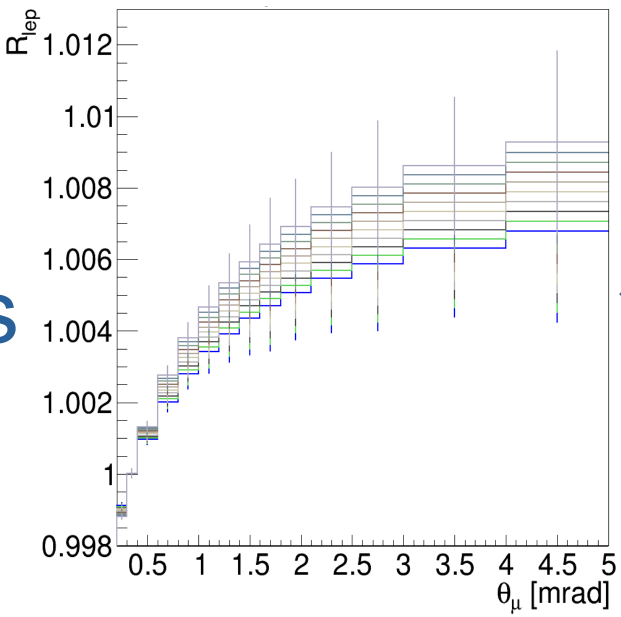


Analysis workflow

Data



Monte Carlo templates



combine

Take into account systematic effects

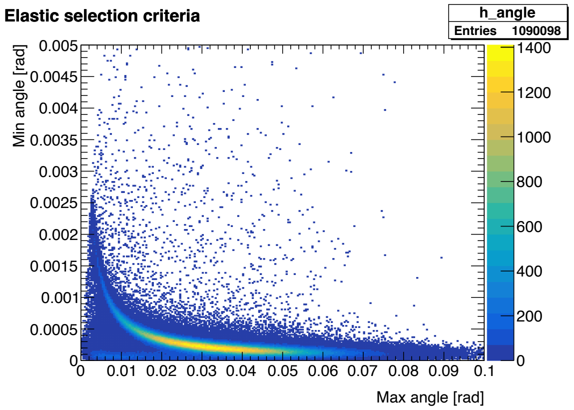
Likelihood/χ^2 fit

Data vs each template

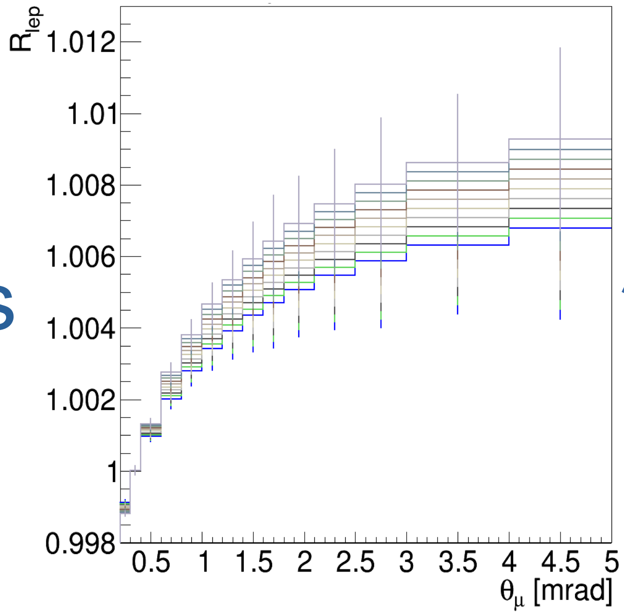
$k_{best} \pm \Delta k$

Test using pseudodata (Monte Carlo)

Pseudo data (MC)



Monte Carlo templates

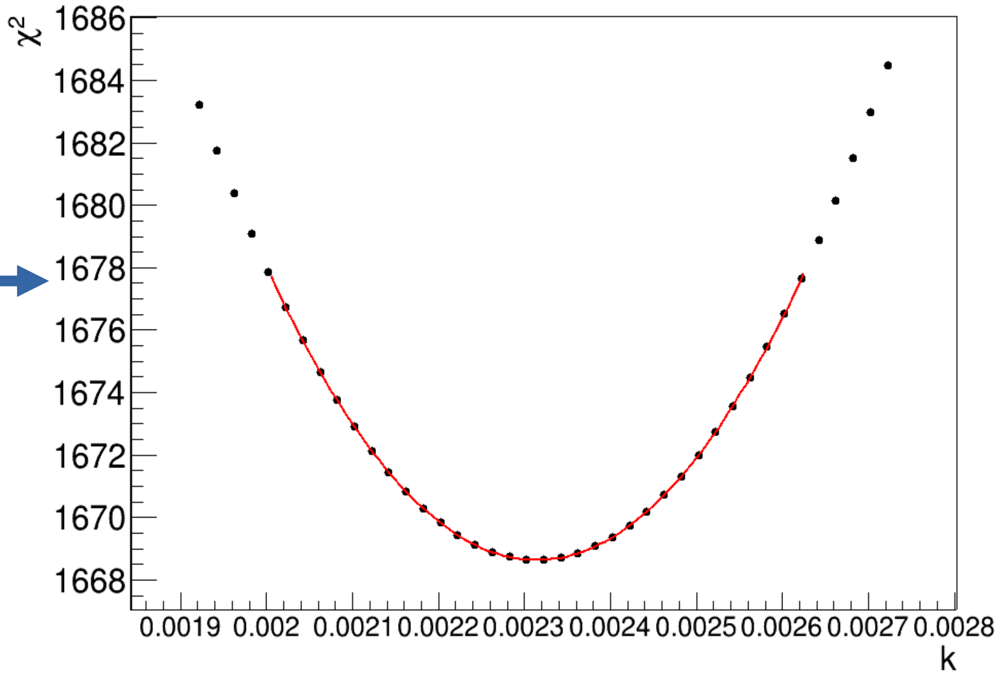


combine

Take into account systematic effects

Likelihood/χ^2 fit

Data vs each template



k_{best} = 0.00232(10) → ~5%

k_{input} = 0.00232

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, require further tests and investigations, to be done

- Tracking efficiency, vs the angle and the impact point, is uniform as expected
- Signal is clearly visible. It can be isolated by applying a selection procedure entirely based on the tracker information
- Vertexing is effective in selecting good tracks removing track clones
- Analysis workflow to measure the leptonic running defined
- Main sources of systematic effects established

- Work in progress:
  - Further improvements of the tracking and vertexing algorithm
  - Improvements in the alignment algorithm and Realistic MC misalignment model
  - Selection and Background studies
  - In view of the 2025 run: complete the foreseen setup with an additional tracking station, the ECAL and Muon filter, prototype new BMS spectrometer
    - ECAL and Muon filter would provide PID and the use of ECAL energy would allow independent checks of the background and also a completely independent physics measurement of the running alpha
    - The additional tracking station would allow testing our method for the calibration of the average beam energy
    - (with new BMS) Measurement of the incoming muon energy event-by-event would 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.

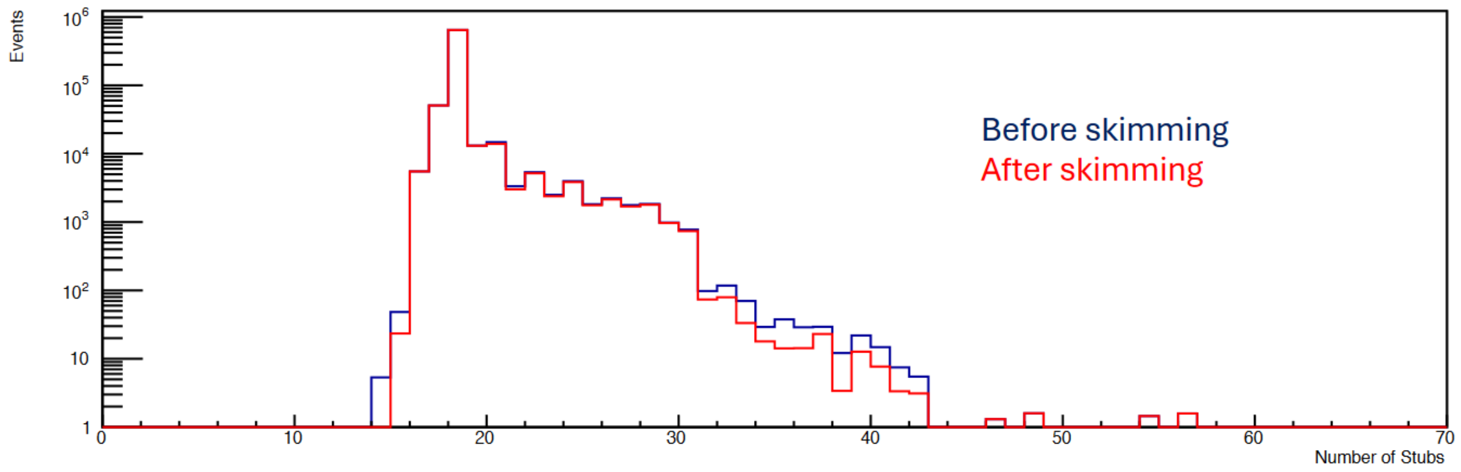
By selecting events that have a unique stub in two reference modules, with their stub being recorded in subsequent 25ns bins, the probability of seeing a stub in the DUT can be measured, when no other module recorded more than one stub within a time window of 250ns.

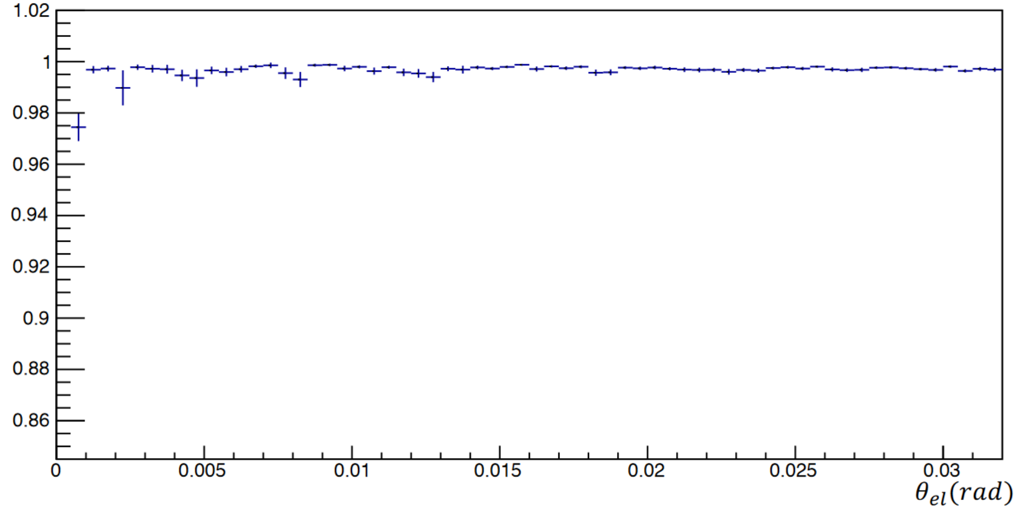
This allows to select particles that crosses the setup within a small window in time, and measure the relative efficiency as a function of time.

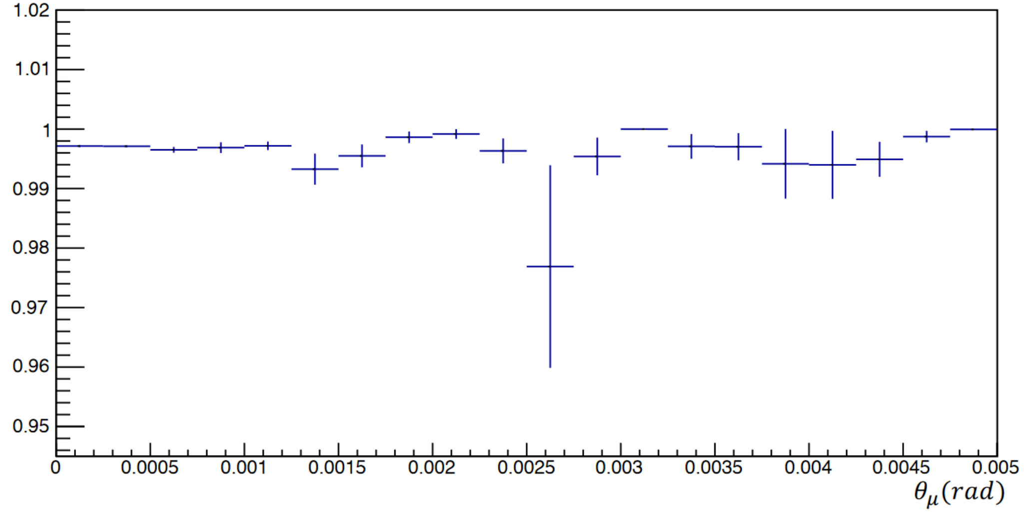
Assuming all three modules have the same timing profile, that it can be modelled by two error functions, and using the delays measured, the scan can be simulated and the parameters of the timing profile tuned so that the simulation fits the data.

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

Performance of the skimming algo on MC signal





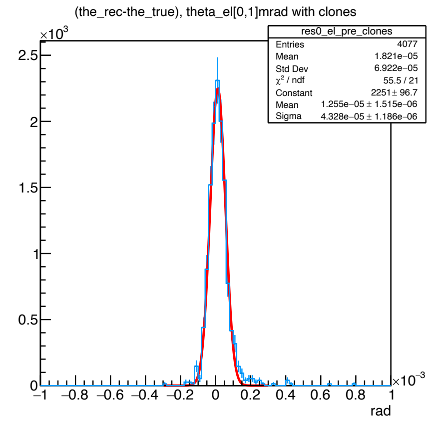


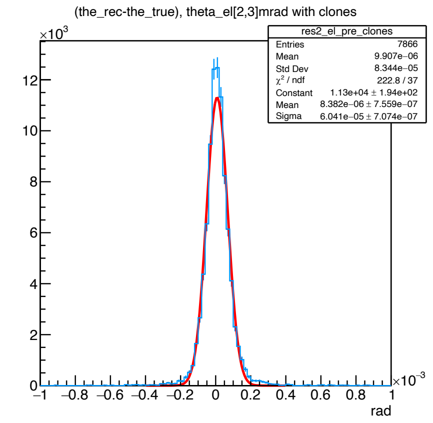
MC performance – Electron and Muon Angular Resolution

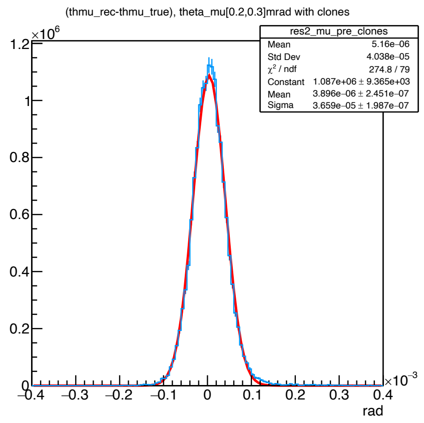
electron

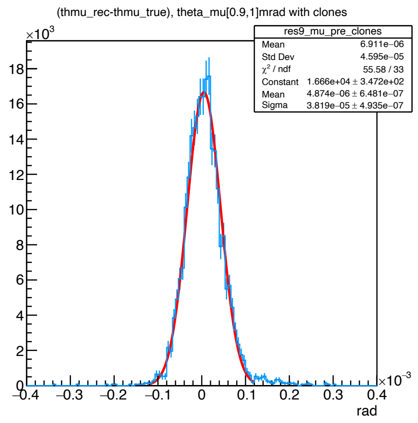
in different angular bins

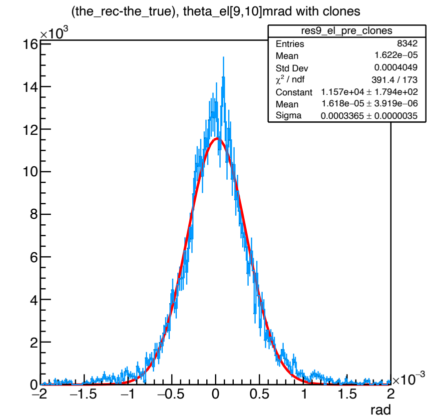
muon

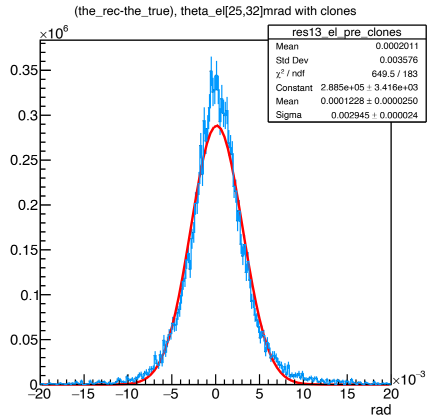


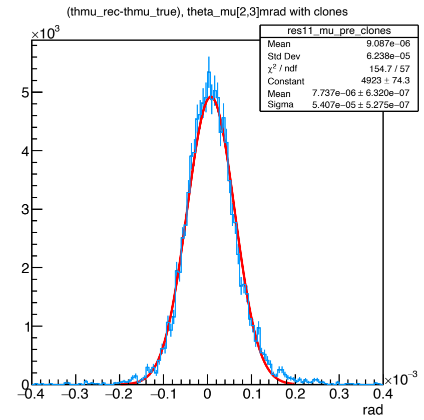


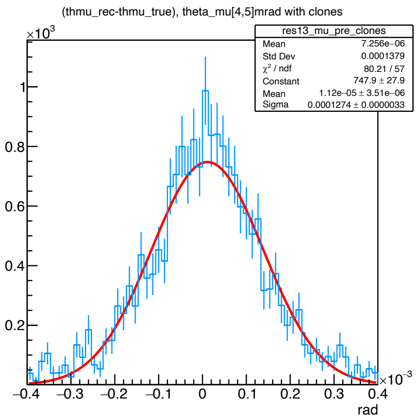










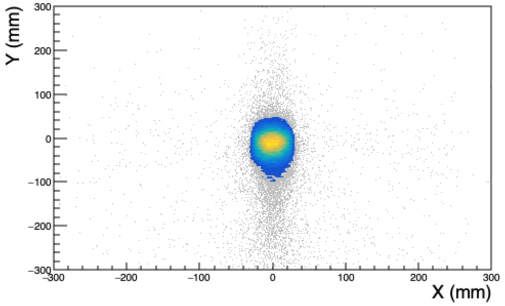


Beam Parameters – Simulation model

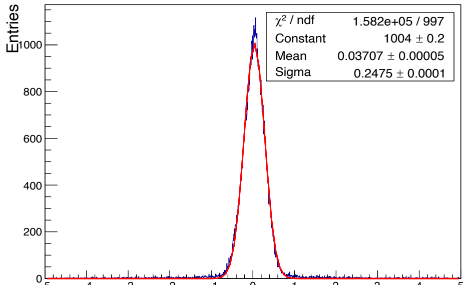
Parallel beam

σ_x = 13 mm

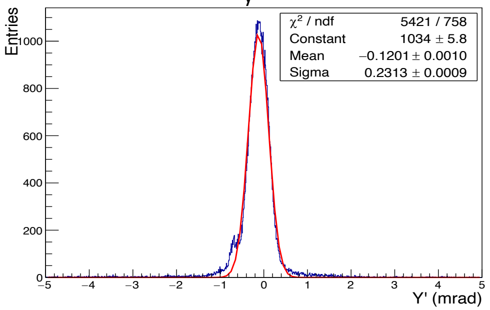
σ_y = 22 mm



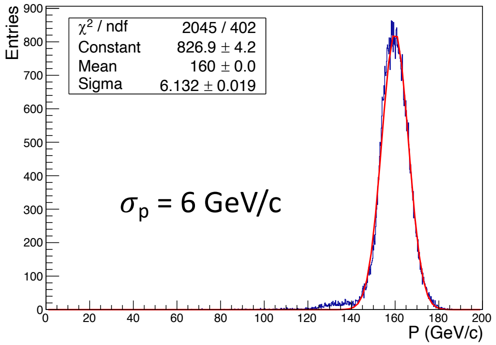
$\sigma_{x'}$ = 0.23 mrad



$\sigma_{y'}$ = 0.24 mrad



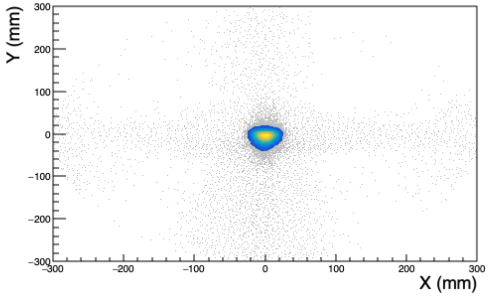
σ_p = 6 GeV/c



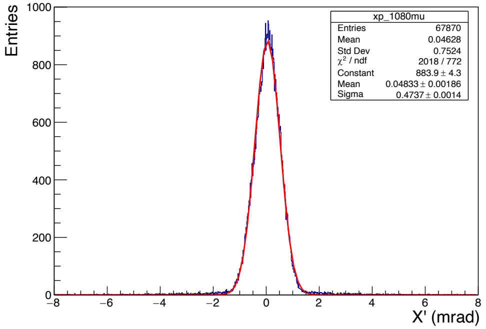
Focussed beam

σ_x = 9.99 mm

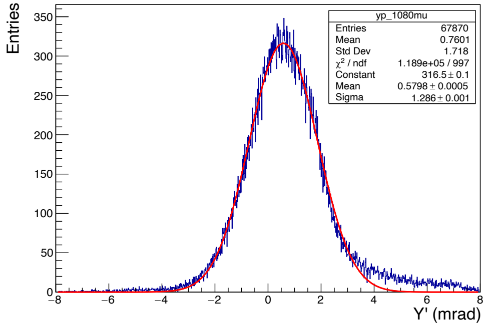
σ_y = 11.8 mm



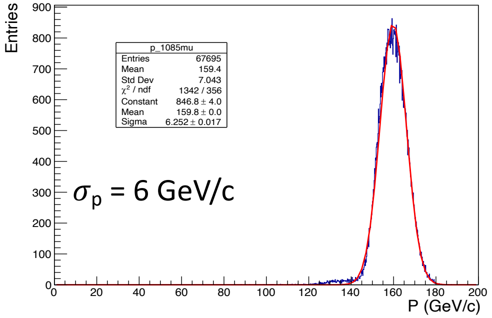
$\sigma_{x'}$ = 0.47 mrad



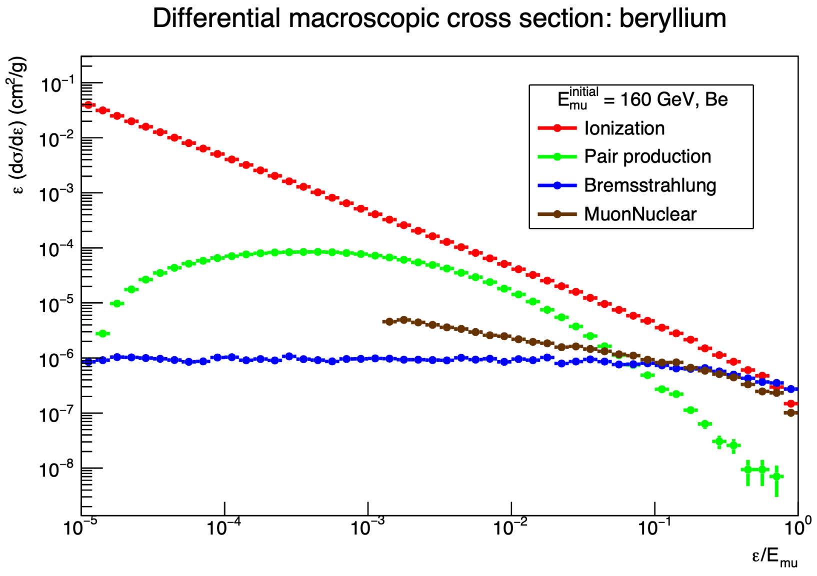
$\sigma_{y'}$ = 1.3 mrad

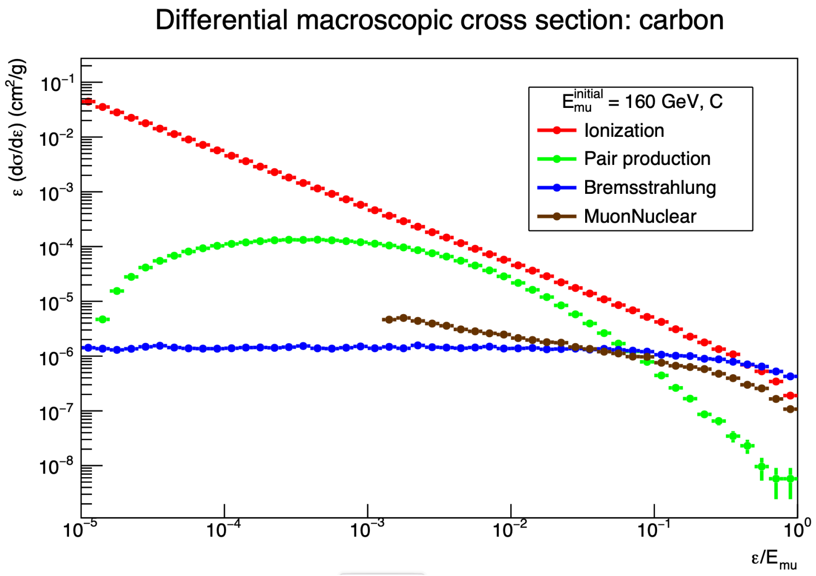


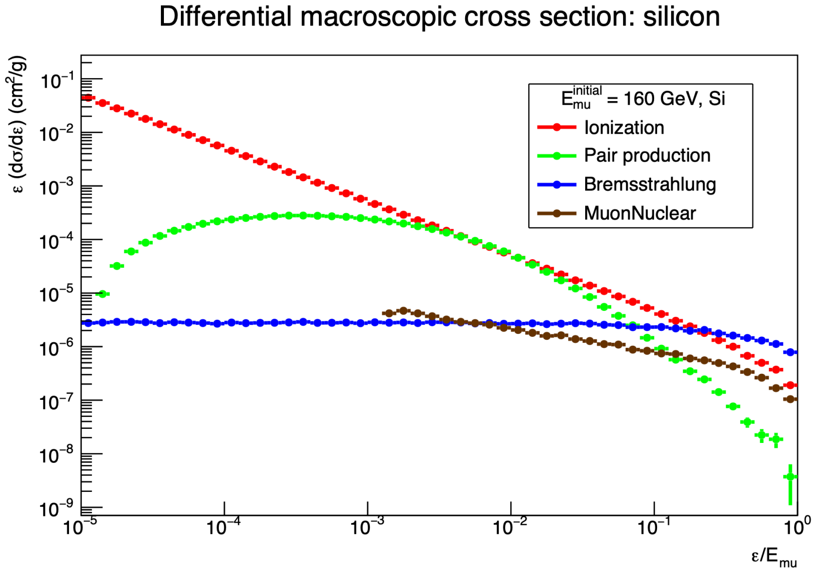
σ_p = 6 GeV/c



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/cm³