MUonE software and preliminary results of Test Run 2023

Giovanni Abbiendi

(INFN Bologna)

II Muon Precision Physics Workshop (MPP2023)
https://indico.ph.liv.ac.uk/event/1297/

Outline

- MUonE software (simulation, reconstruction)
- Analysis on fast MC simulation (particle ID, ECAL-based selection)
- Analysis on full MC simulation (event selection)
- Preliminary results from the Test Run 2023
- Conclusions / ToDos

FAIRMUONE SOFTWARE

FairMUonE

- FairMUonE is built on top of the FairRoot framework, which provides a lot of basic functionalities and automation
  - translation between ROOT and Geant4 geometry description
  - interplay of Geant4-based simulation and MUonE-specific code
  - user interface based on ROOT macros
- FairRoot has been successfully used by other experiments, e.g. ALICE and SHiP, and also by MUonE for beam tests in 2018 and 2022.
- Conveniently, all required external packages are combined and released as FairSoft with pre-compiled versions available on lxplus via cvmfs.

Event processing steps

- Data processing happens event-by-event and is defined by 3 files:
  - job configuration
  - detector configuration
  - Geant4 configuration (MC only)
- All steps:
  - Event generation
  - Simulation of interaction with the detector (Geant4)
  - Digitisation
  - Reconstruction
  - Event filter

are performed by dedicated algorithms, that can be enabled/disabled in separate optional sections in the configuration file

MC Generation

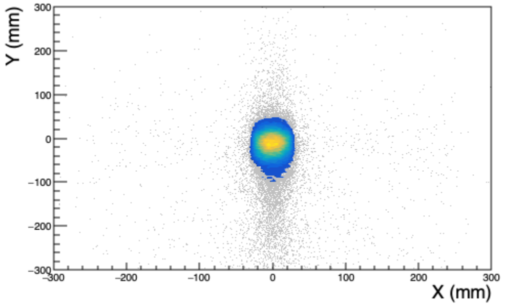
- MESMER MC has been integrated with FairMUonE and can be run calling it event-by-event from the MUonE standard processing job
  - All the MESMER inputs can be specified
  - The generated events can be saved in ROOT format
  - Both unweighted and weighted generation is possible
  - Multiple weights are calculated and can be saved to be used in reweighting a generated sample with different parameterisations of the hadronic contribution to the vacuum polarization
  - Physics processes: LO $\mu e \rightarrow \mu e$, NLO, NNLO (approximate) photonic corrections, NNLO real and virtual QED pair corrections
    - Pair production in nuclear interactions soon to be included
  - See more on Fulvio’s talk
- GEANT4 simulation of particle guns
  - Minimum bias simulation of muon interactions in the material
- Optional Pileup of beam muons with given input Poisson mean
- The beam profile is simulated according to the calculations of the CERN SPS accelerator division
  - See more on Dipanwita’s talk

Beam Parameters

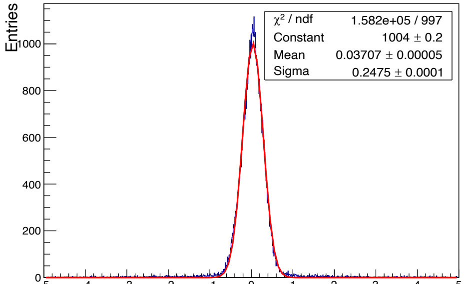
Parallel beam

σ_x = 13 mm

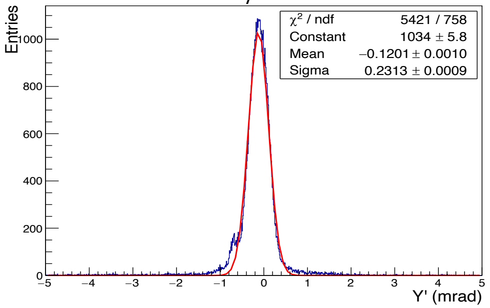
σ_y = 22 mm

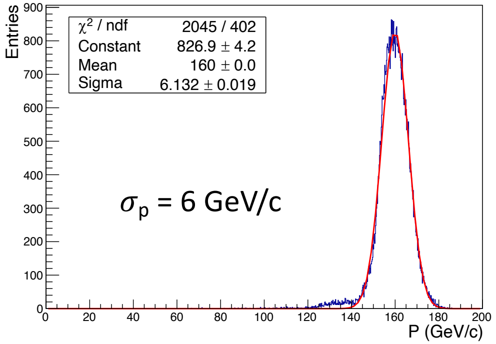


$\sigma_{x'}$ = 0.23 mrad



$\sigma_{y'}$ = 0.24 mrad



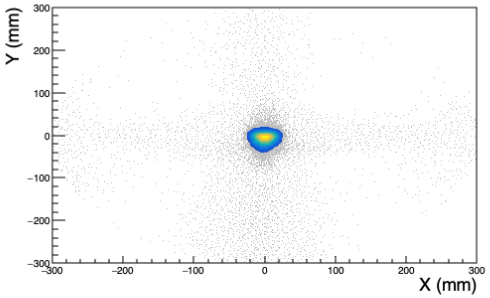


σ_p = 6 GeV/c

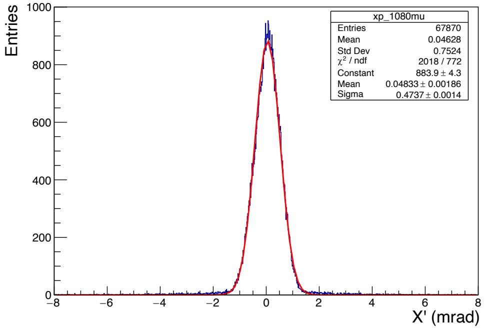
Focussed beam

σ_x = 9.99 mm

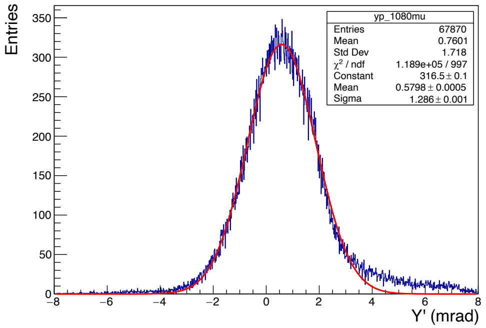
σ_y = 11.8 mm

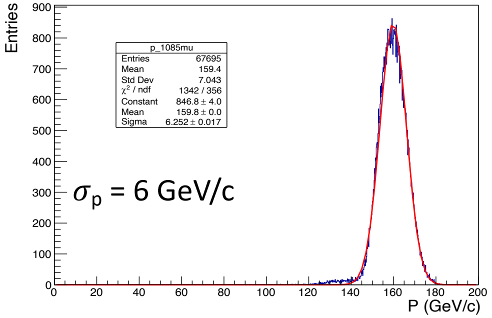


$\sigma_{x'}$ = 0.47 mrad



$\sigma_{y'}$ = 1.3 mrad





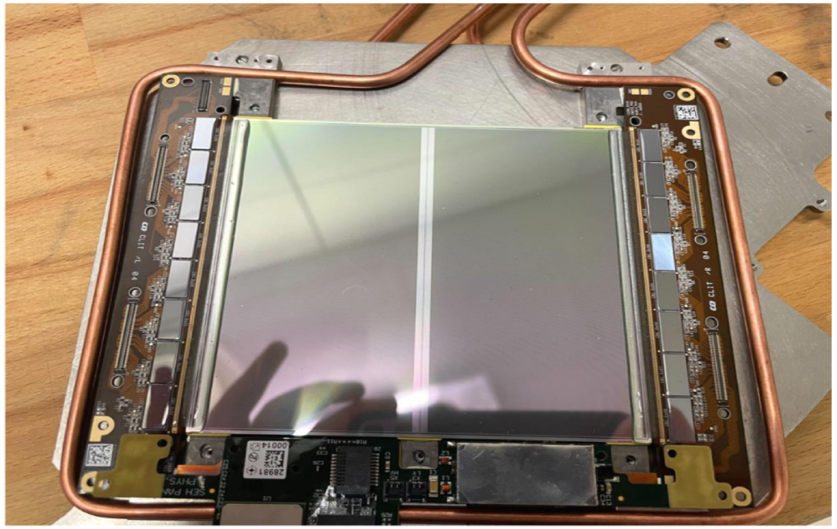
σ_p = 6 GeV/c

Digitisation

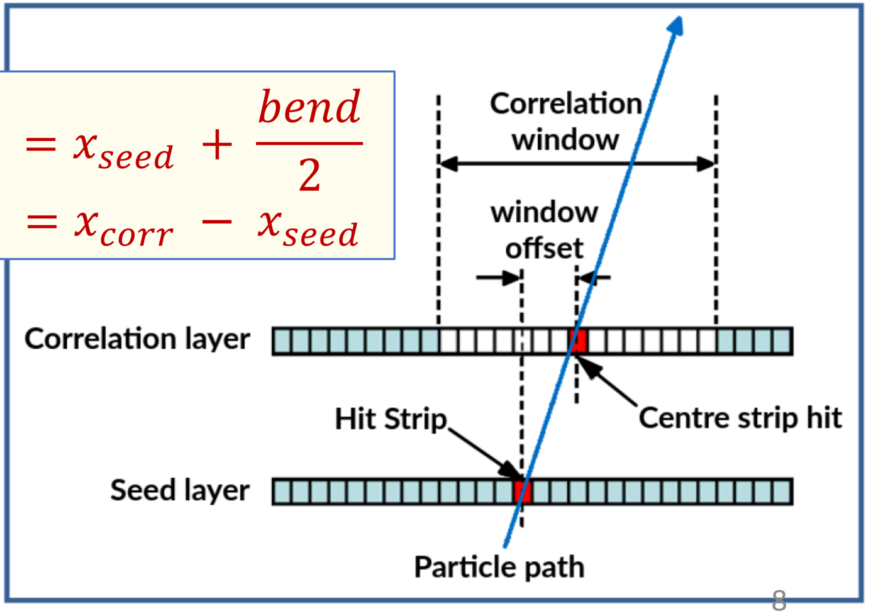
- **Tracker Digitisation** inspired by the CMS simulation of the 2S tracking module

  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



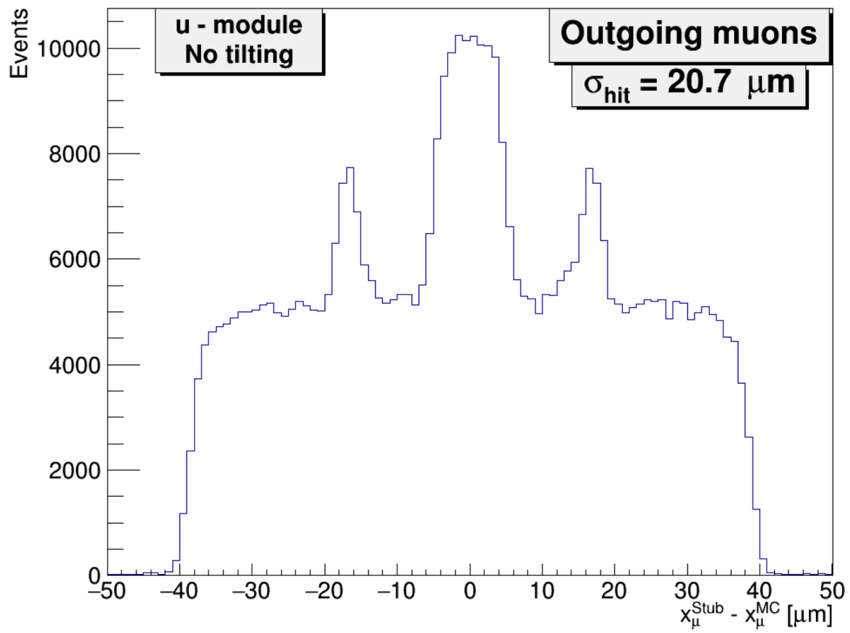
$$x_{stub} = x_{seed} + \frac{bend}{2}$$
$$bend = x_{corr} - x_{seed}$$

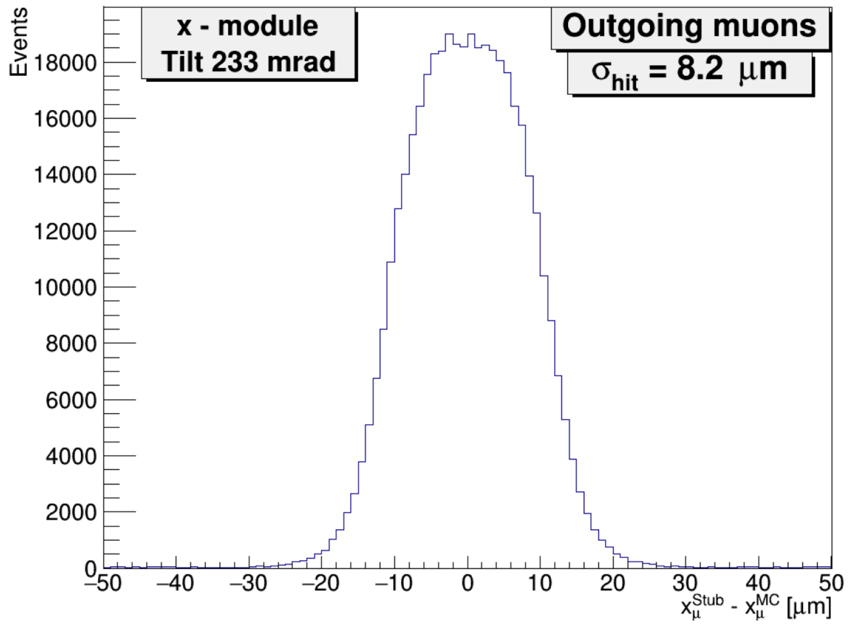


Resolution: tilted modules

- Strip digital readout: with 90μm pitch the expected resolution is 90/sqrt(12)≅26μm on a single sensor layer for single-strip clusters
- Tilting a sensor around an axis parallel to the strips
  → Charge sharing between adjacent strips,
  improving the resolution
- The best is obtained when <cluster width>~1.5 (same number of clusters made of 1 or 2 strips) for a tilt angle ~15 degrees
- Best estimate of position using info from both sensors

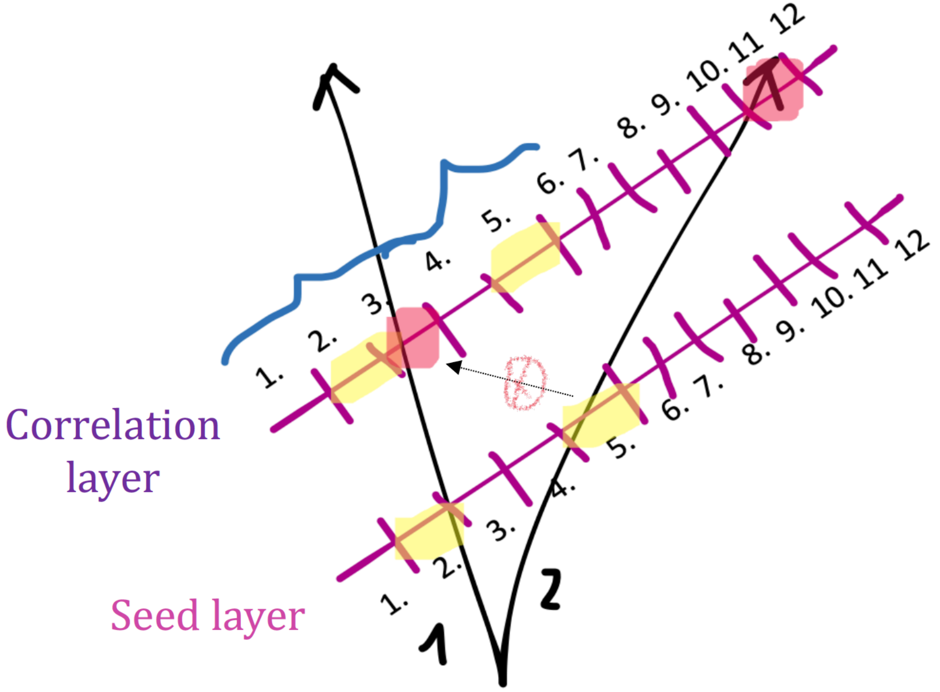
$$x_{stub} = x_{seed} + \frac{bend}{2}$$
$$bend = x_{corr} - x_{seed}$$





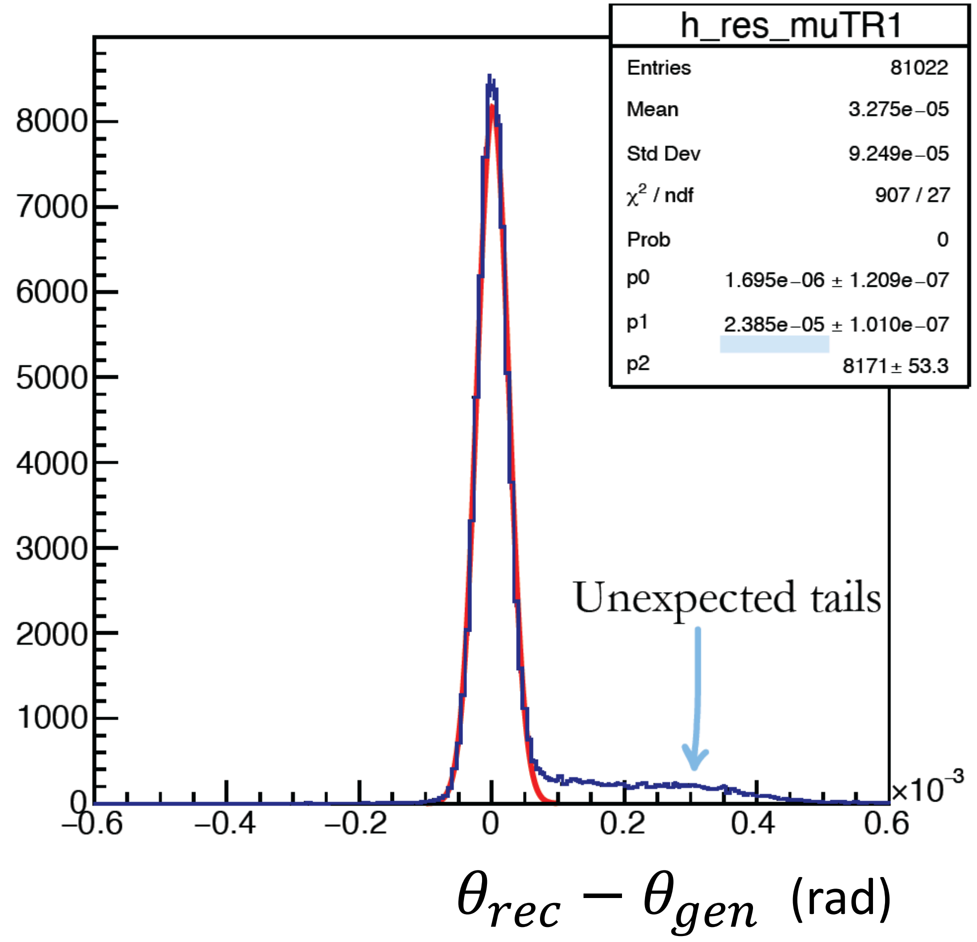
Digitiser logic: 2S limitations

- 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

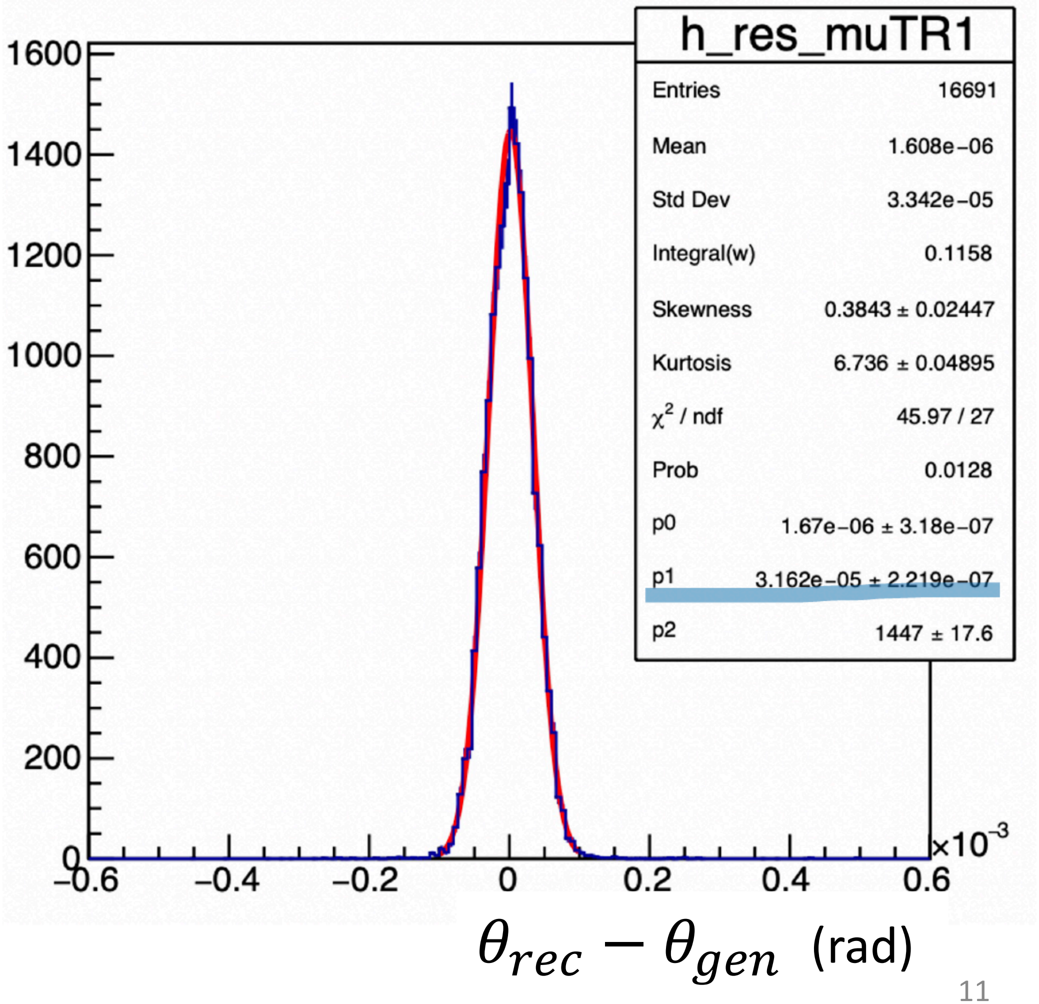


μe scattering events: outgoing muon angular resolution

stub positions including bend

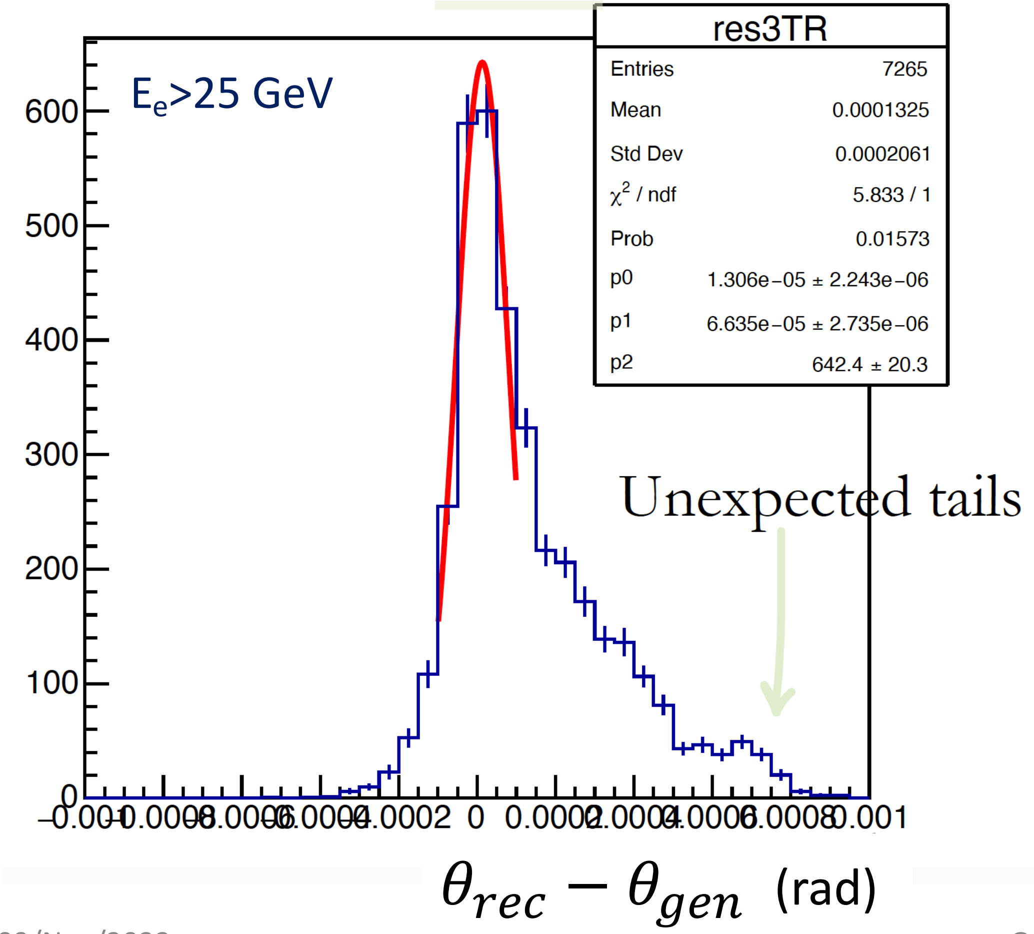


stub positions neglecting bend

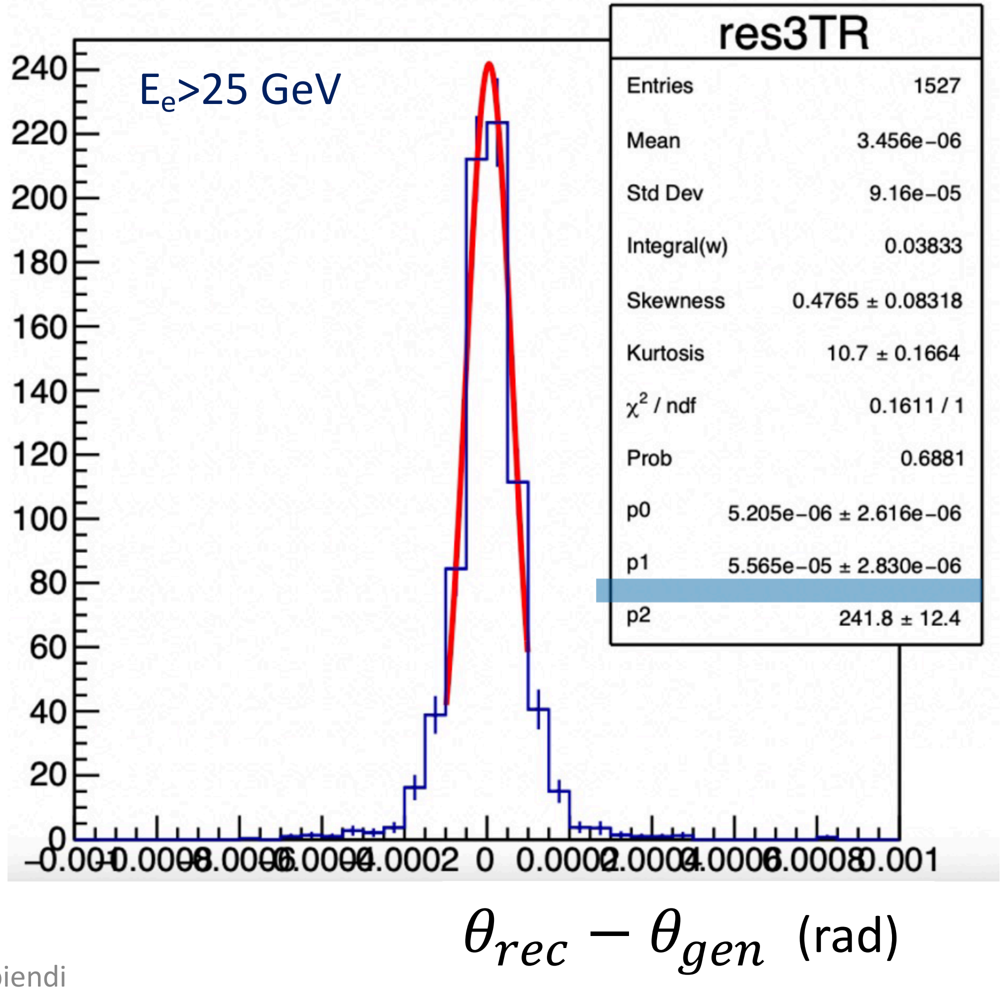


μe scattering events: electron angular resolution

stub positions including bend



stub positions neglecting bend



Reconstruction

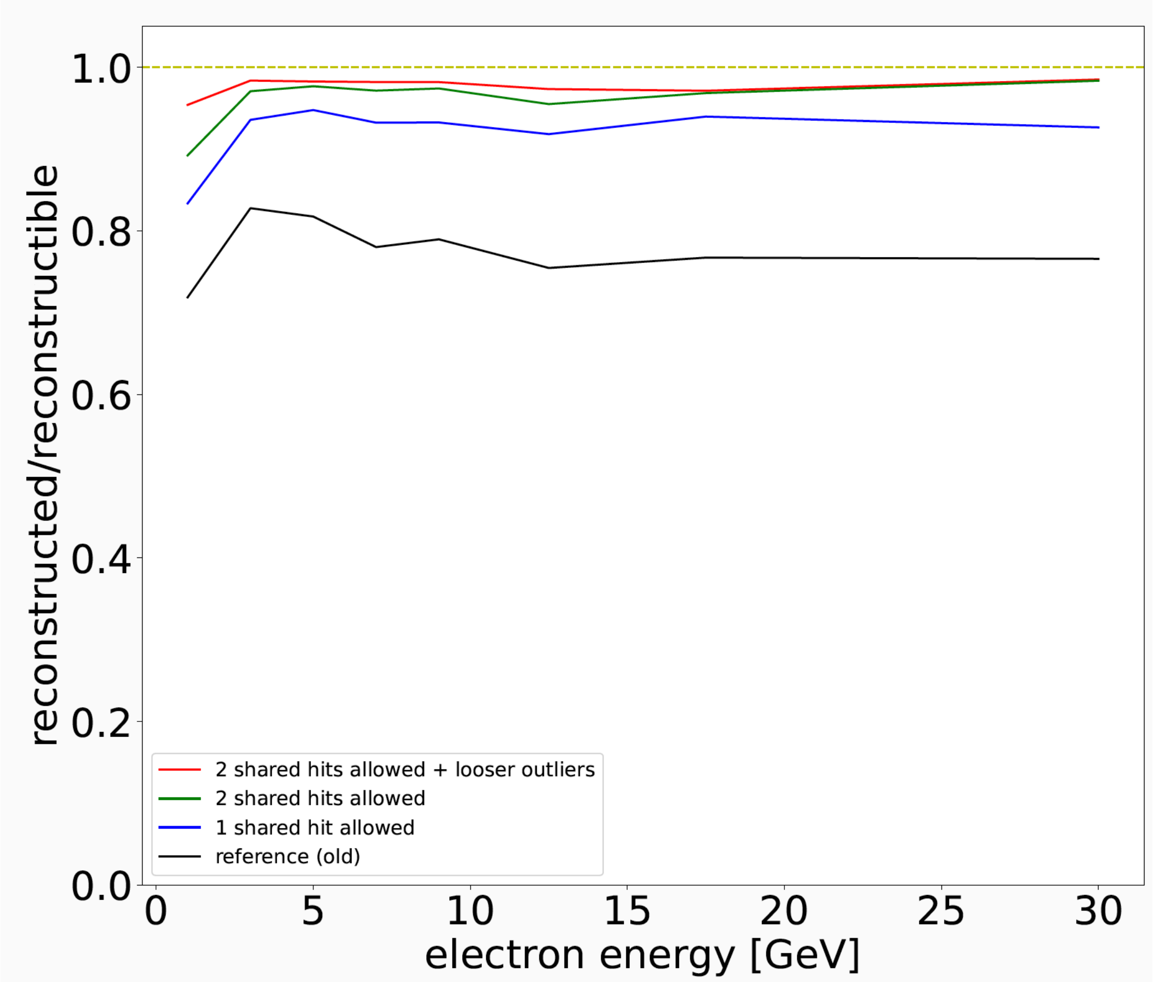
Reconstruction uses all stubs recorded in an event. Tracks are reconstructed in each station separately

1) Hit reconstruction
   - Both sensors can be used to reconstruct hits (2S, using bend info), or only the seed sensor (1S, neglecting bend info)
   - The z coordinate of hits is taken as constant in stereo modules (U,V), while it is corrected for the tilt angle in X and Y modules
2) 2D track reconstruction
   - The hits in X and Y modules are used to reconstruct 2D lines in both projections separately. As the occupancy is relatively low, all 2-hit combinations can be tested, resulting in high reconstruction efficiency
   - For each such pair: slope and intercept of a line are calculated
     - additional hits are assigned to the line within a configurable window. In case of multiple choices, the closest hit is selected
     - if new hits are assigned, the line is refitted
     - The steps are repeated until no new hits can be added. If the resulting set of hits is different from all previously found, a new 2D line is added.
3) 3D track reconstruction
   - In each station, track candidates are formed from all unique combinations of 2D lines in both projections
   - For each candidate, the closest stereo hits within an assignment window are added
   - The track is refitted and outlier hits are removed, then it is repeated until no more outliers found. The χ^2 threshold for outlier removal can be set as input parameter and has a significant impact on reconstructed tracks multiplicity.
4) Track filtering and sorting
   - track candidates with low hit multiplicity are removed, by requiring:
     - at least one stereo hit (with 2X and 2 Y hits)
     - or at least 3 X and 3 Y hits.
   - Given the current geometry used in the Test Run this means having tracks with either 6 or 5 hits.
   - Tracks are finally sorted first by number of hits and number of stereo hits, then by χ^2

Reconstruction - II

5) Clone removal

- The sorted list of track candidates is then checked starting from the bottom looking for shared hits. Depending on the parameter setting the criterium can be:
  - Strict: the hits shared with better candidates are removed
  - Loose: the candidate is removed if it shares more than a given amount of hits with any of the better ones
- The updated candidates are then again filtered (as above), refitted and sorted and become reconstructed tracks



Reconstruction efficiency depends on the ability to deal with close-by tracks and include multiple scattering for electrons

Vertexing

- Without measurements of the track momenta, multiple scattering is taken into account in an approximate way, before vertexing
  - The outgoing track with larger angle wrt the incoming one is assumed to be the scattered electron
    - this introduces a misidentification region, where the true angles are inverted
  - the contribution of multiple scattering to the hit uncertainties of the candidate electron track is estimated by assuming the track momentum determined from the LO θ-p relationship for the scattered electron in elastic events and added in quadrature
  - Included the expected effect of the target and the silicon planes
- Candidate vertices are formed from all (1+2) combinations of an incoming and two outgoing tracks
- A kinematic fit is carried out for each (1+2) combination testing the hypothesis of a common vertex at a coordinate Z_V corresponding to median plane of the target thickness
- The linear fit obtains the transverse position of the fitted vertex (X_V, Y_V) and the slopes X'=dX/dZ and Y'=dY/dZ of the three tracks
- The vertex χ^2 is obtained as the sum of the three individual track χ^2
  - It is an effective quantity to remove background and vertices from wrong combinations
- All the possible vertices are then sorted according to their normalised χ^2
- A similar vertexing algorithm is also available for events with many (3-10) outgoing tracks
- Optional Adaptive vertex fit (implemented starting from LHCb algorithm) useful to reject background
  - It can also be used to provide a vertex constraint to the kinematic fit, including the estimated vertex Z position

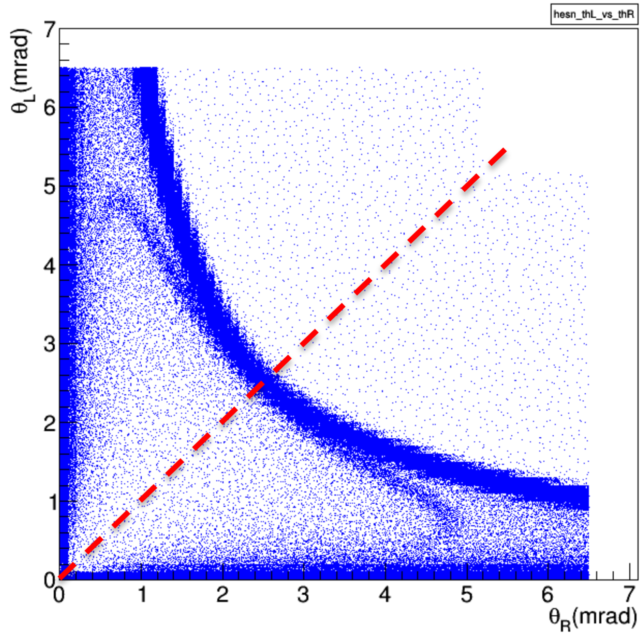
FASTSIM ANALYSIS

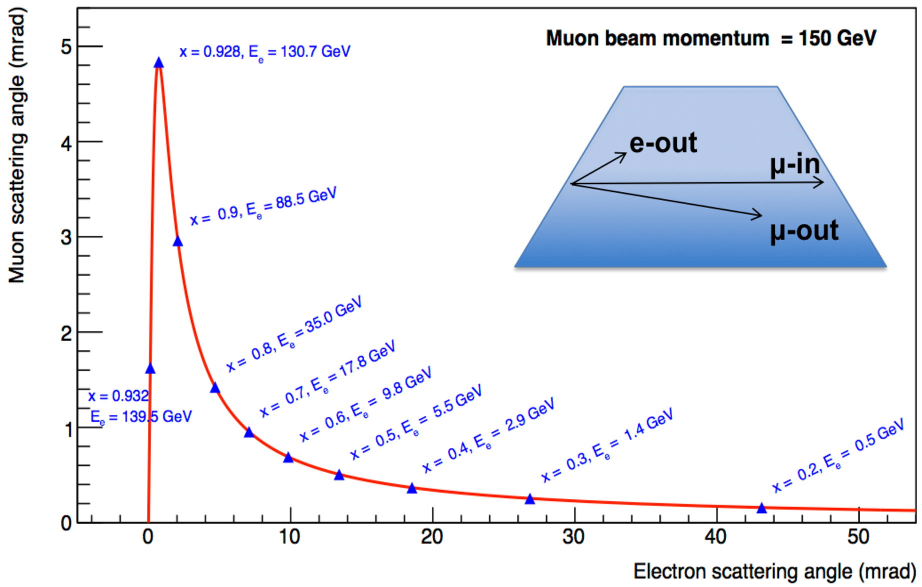
EVENT SELECTION: USE OF CALORIMETER

Methods for signal extraction, see Riccardo’s talk

Particle Identification

With only tracking without 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.

Fast Simulation of ECAL

Master thesis of Eugenia Spedicato (Bologna, 2021): https://amslaurea.unibo.it/23207/

- Development of a fast simulation of the TestRun geometry (Tracking stations and ECAL) including the beam profile.
- Calorimeter response parametrised with the GFLASH model as used in CMS for the ECAL FastSim.
- NLO MESMER MC used to simulate events with real photon radiation

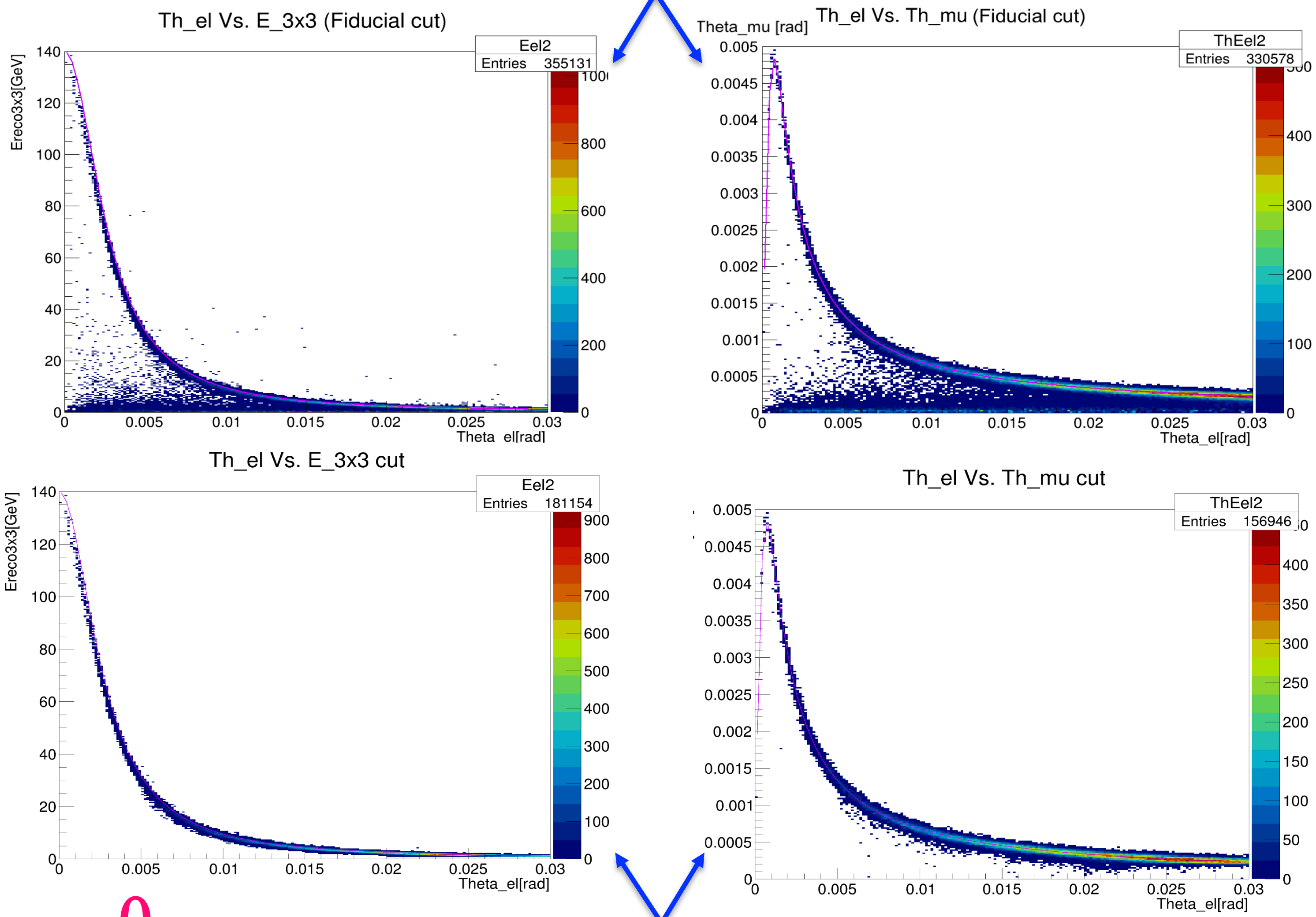
Definition of a clean calorimetric selection of Elastic events using:

- ECAL Cluster energy
- $\Delta E(\theta_e)$ Difference w.r.t. expected energy for the given electron angle
- Distance of ECAL cluster centroid from the extrapolated track

Fast Simulation of ECAL (2)

Before selection, only fiducial cuts

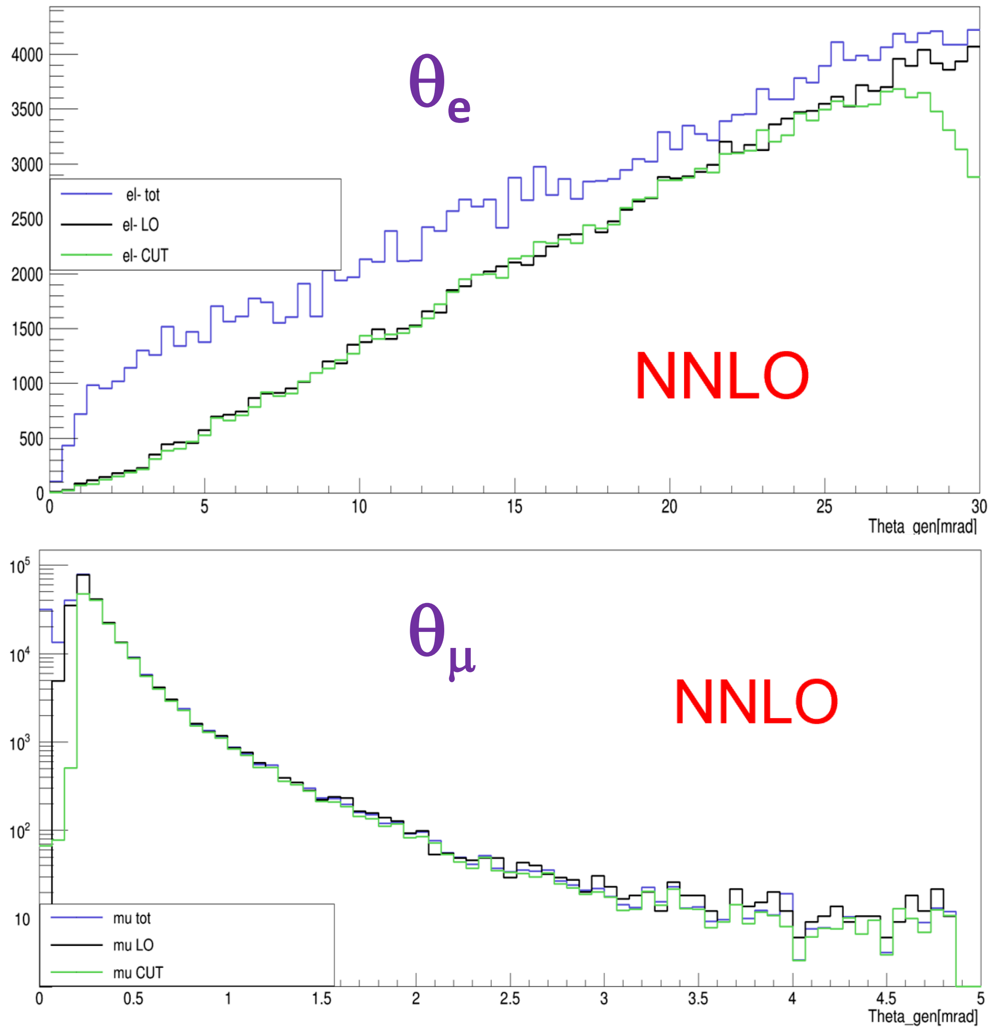
E_{3x3} θ_μ



θ_e θ_e

After full calorimetric selection

Fast Simulation of ECAL with NNLO MESMER



- Calorimetric selection is able to isolate a clean elastic sample
- Selected (N)NLO angular distributions are close to the LO
  - ➢ Electron distribution is substantially affected by radiative events
  - ➢ Muon distribution is robust

ECAL-based selection also tested with NNLO MESMER code
Sara Cesare, master thesis (Padova, 2022)
http://hdl.handle.net/20.500.12608/34647

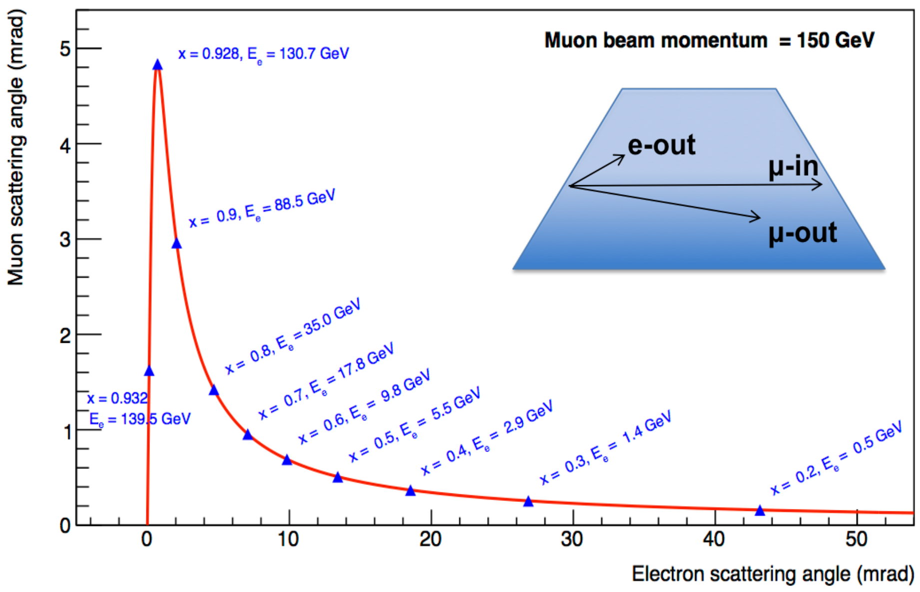
FULLSIM+RECO ANALYSIS

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
  - However the MESMER (N)NLO MC generator describes the effects very accurately, so they do not constitute a problem.
- 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 $\mu X \rightarrow \mu e^+e^- X$
  - 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

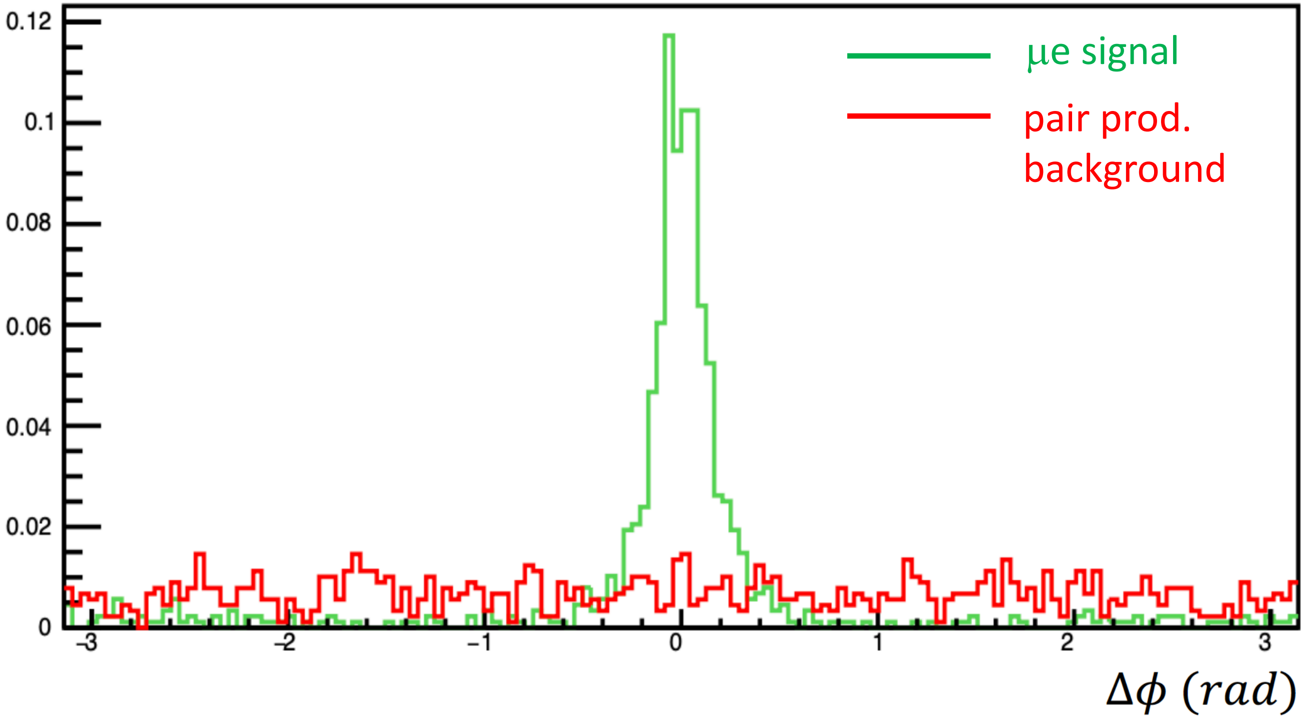
Minimum Bias simulation

(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

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

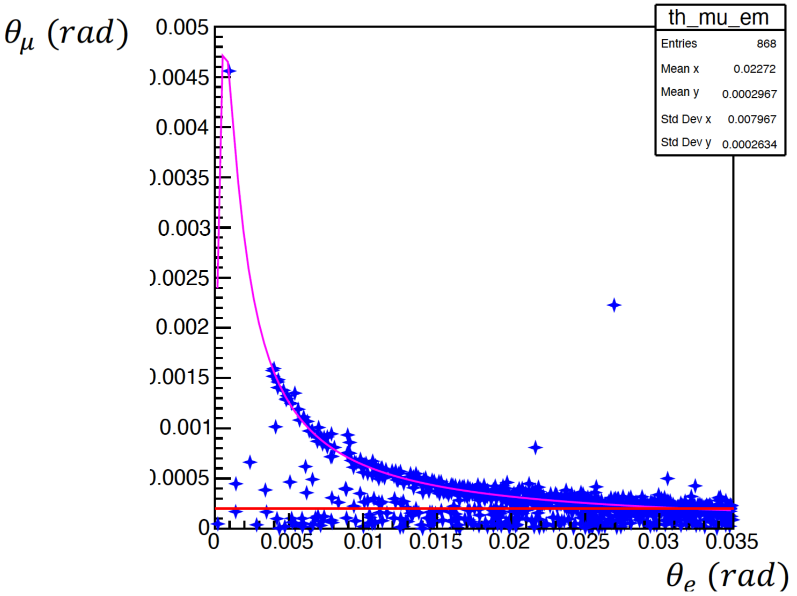


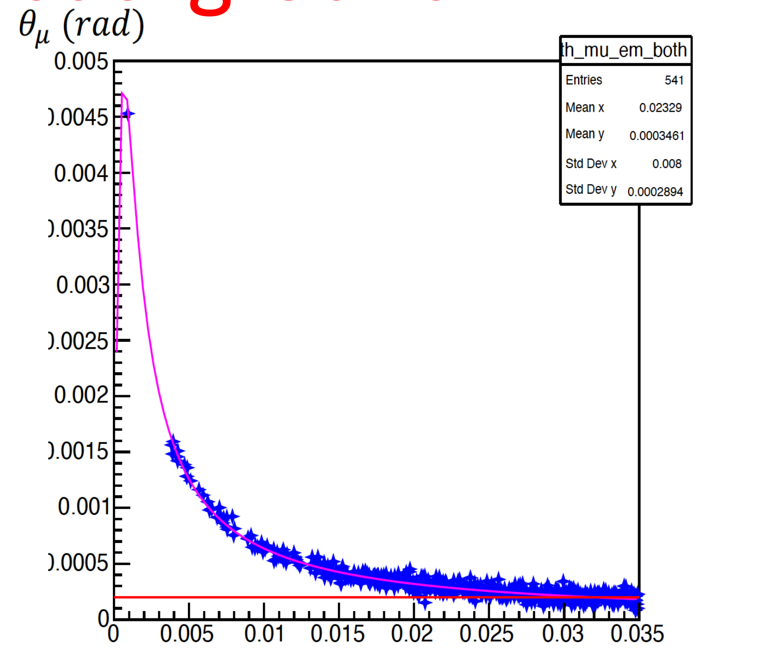
TRACK-BASED Observables
Track quality (Nr Hits; χ^2)
Vertex compatibility
Vertex position
Acoplanarity
Minimum scattering angle
Elasticity (from angular correlation)

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

Selection: MC signal and background

SIGNAL



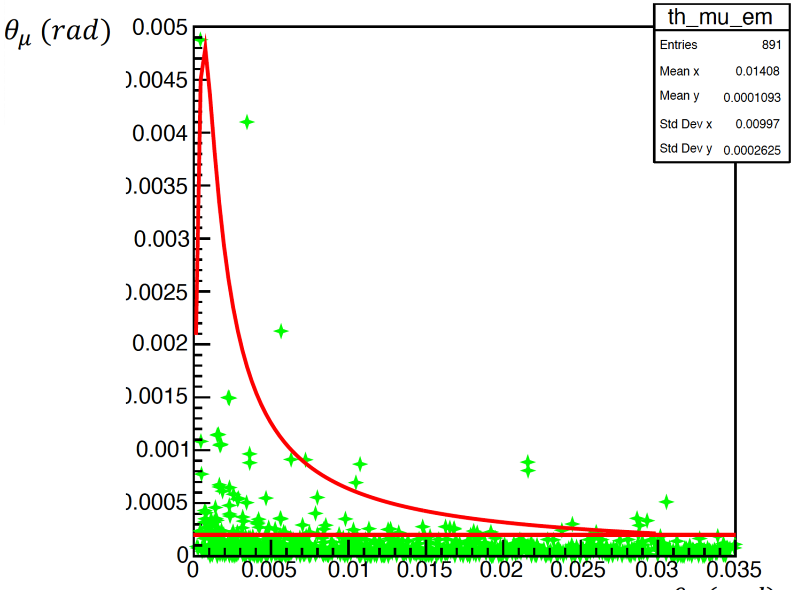


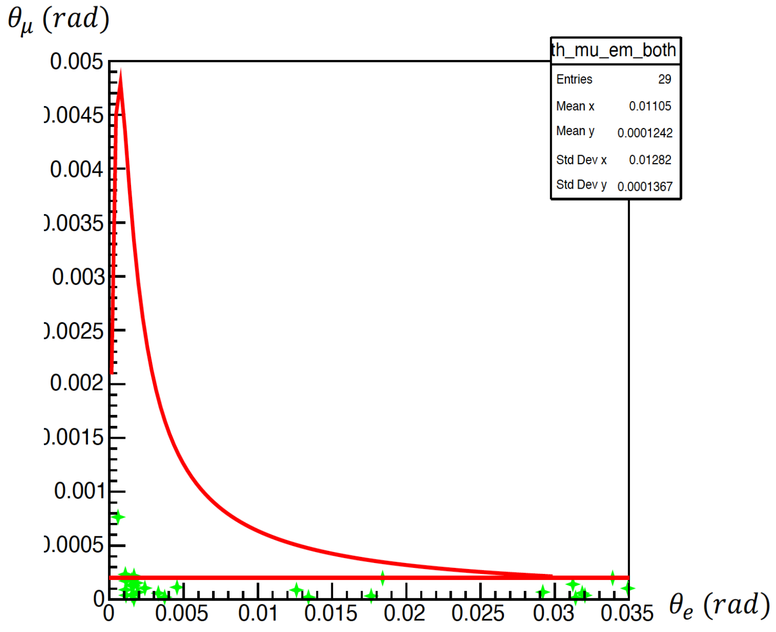
SIGNAL

Cuts on:

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

BACKGROUND

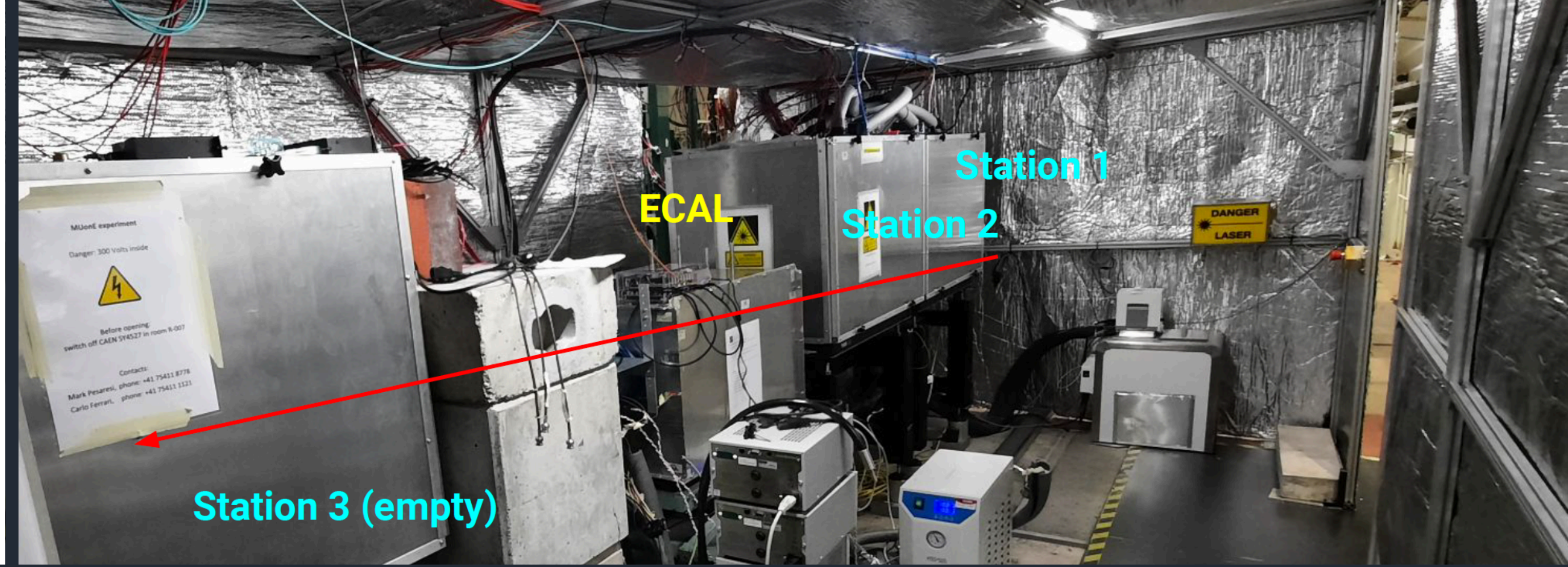


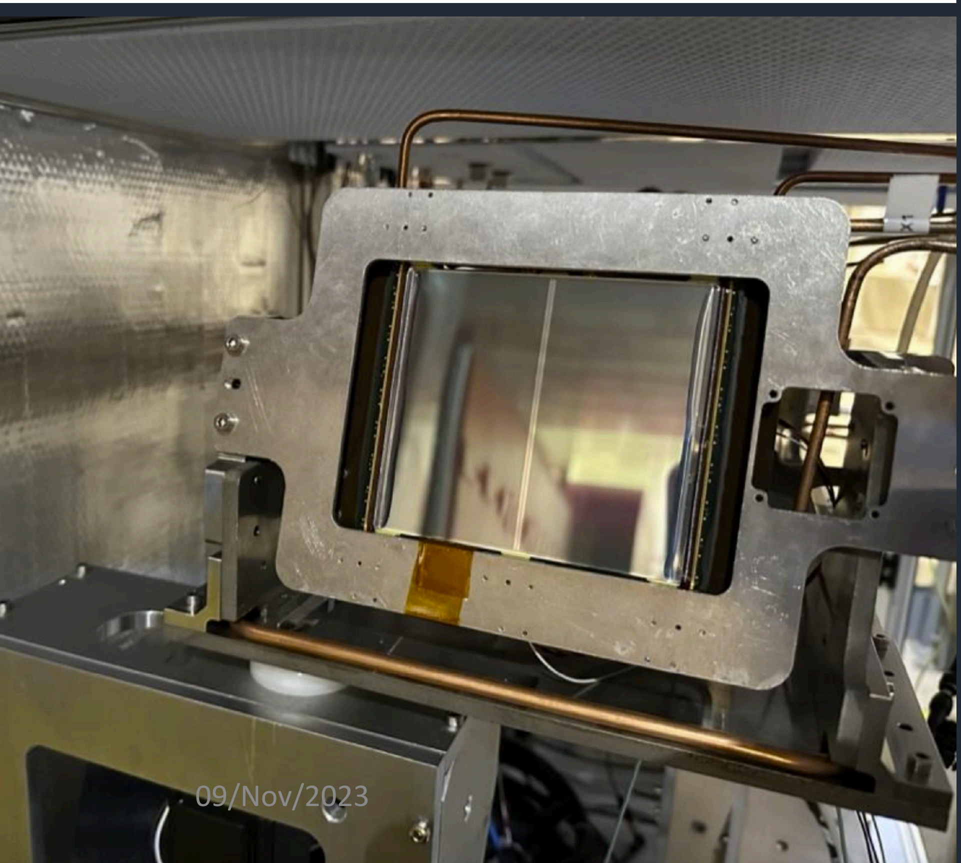


BACKGROUND

TEST RUN PRELIMINARY ANALYSIS

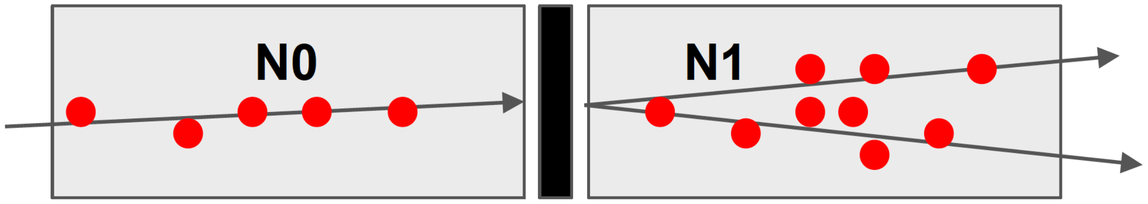
MUonE Test Run





- MUonE Test Run at CERN North Area (M2 beam) (Aug/Sep)
- 160 GeV muons, max asynchronous rate of 50 MHz ($2x10^8$ muons per spill)
  - stubs recorded to disk for every single ‘BX’ (40 MHz)
  - Low intensity runs for commissioning
- 2/3cm graphite target between stations
  - also runs without target (for alignment purpose)
- Continuous readout of the two stations at 40 MHz for long runs
- 300 TB raw stub data recorded to disk → ~5 trillion stubs
- See more in David’s talk

Trigger concept



Interesting events can be efficiently selected by just looking at the number of stubs recorded in two consecutive stations

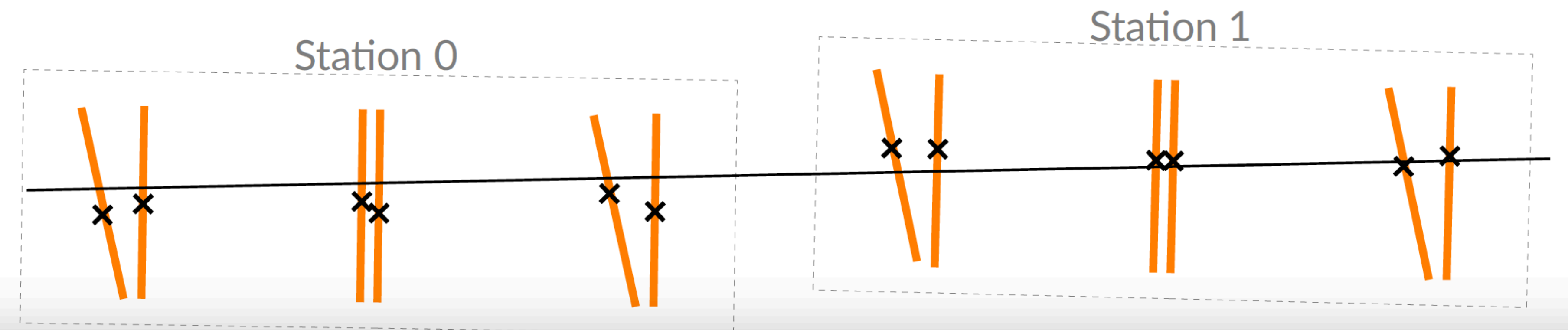
N0: number of stubs recorded in station 0, upstream of a given target
N1: number of stubs recorded in station 1, downstream

D = N1 – N0

A selection like N0 >= 5, N1 >=5, D>=S with S=3÷5 reduces the event yield to **1-2%**

This can be easily implemented in FPGA

Alignment



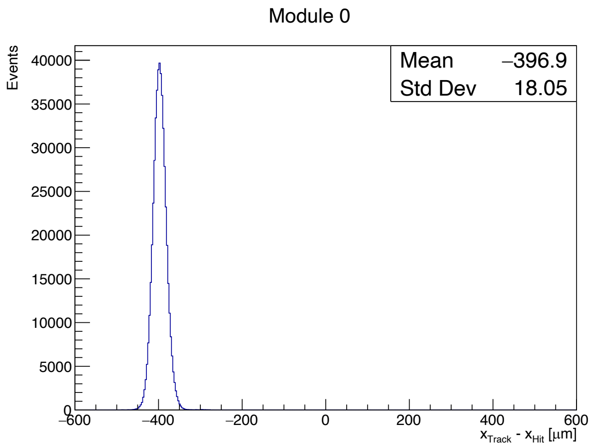
Test Run setup: 2 complete stations. Station: 6 modules (X, Y, U, V, X, Y)

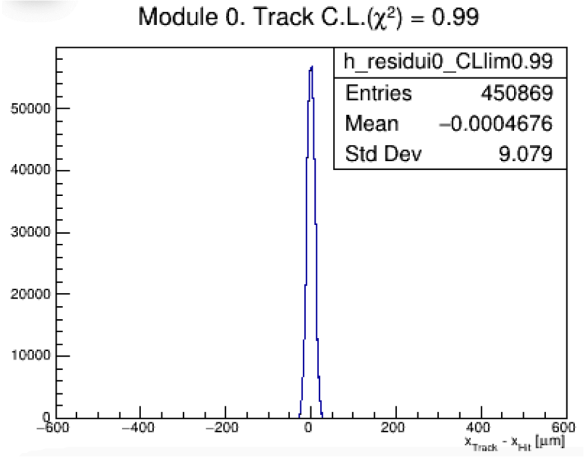
Currently

- simple iterative alignment of two parameters per module from the distributions of residuals
  - transverse offset in the measured coordinate
  - rotation angle around the Z axis
- orthogonal coordinate (along the strips) can be aligned from measured image of the sensor's middle line
- Z and transverse tilt angles measured in HW (on-site laser survey and precision metrology in laboratory)

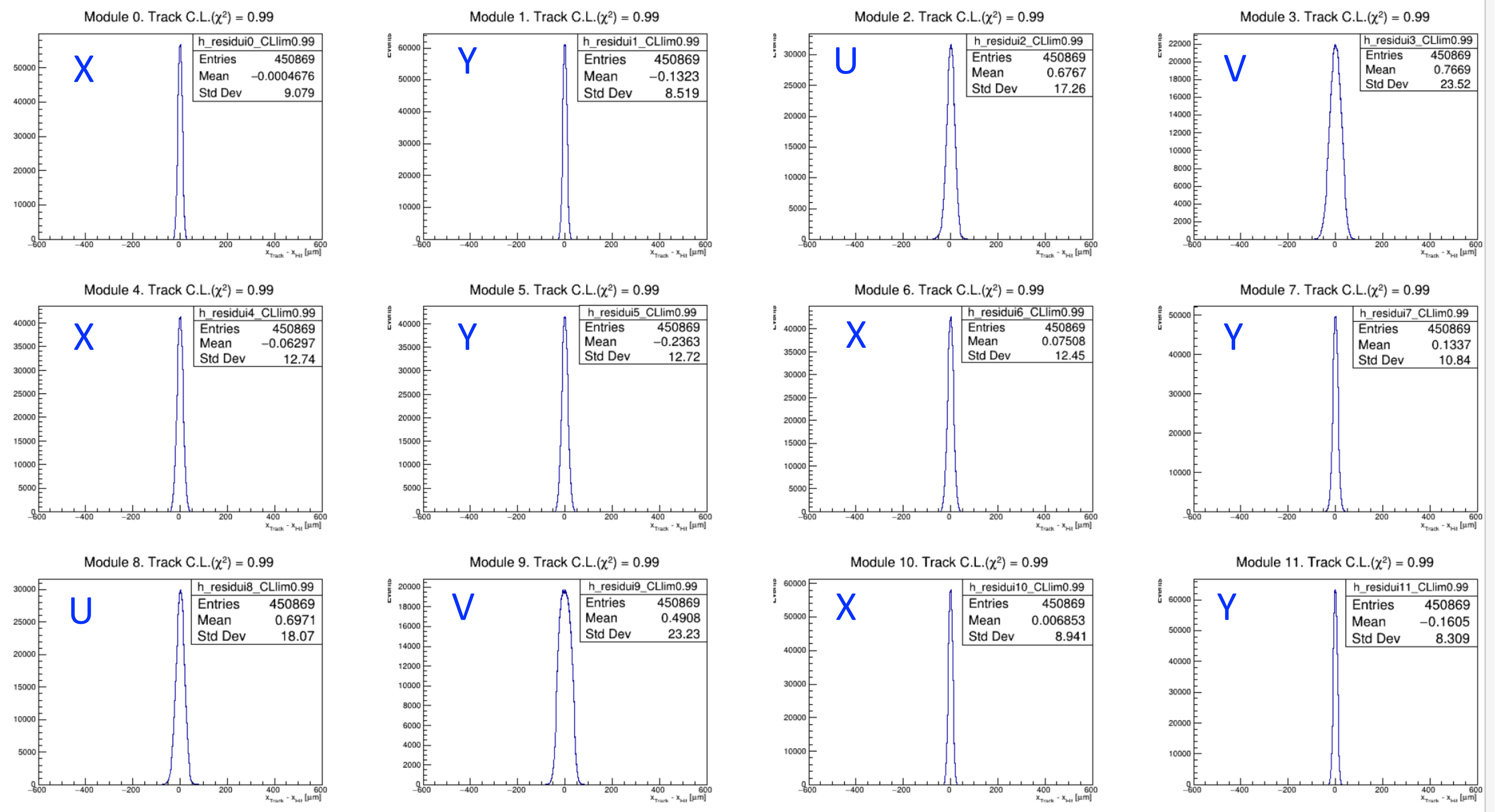
Ongoing work

- Use the HW measurements as starting point for the track-based alignment
- Global alignment





Preliminary Alignment of Test Run data



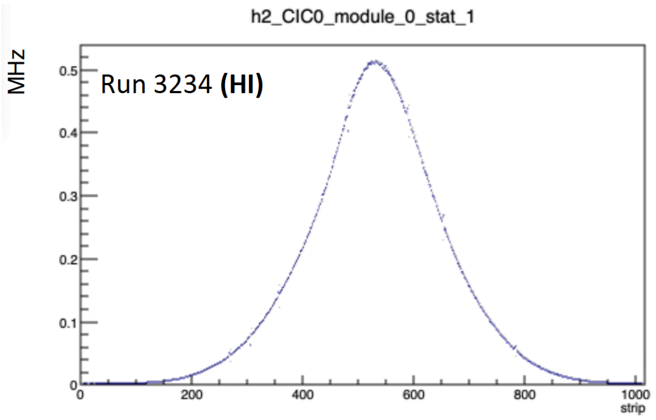
Widths of the Residual distributions after alignment agree with expectations: X,Y modules have better resolution (tilted modules) than U,V modules (orthogonal to the beam direction)

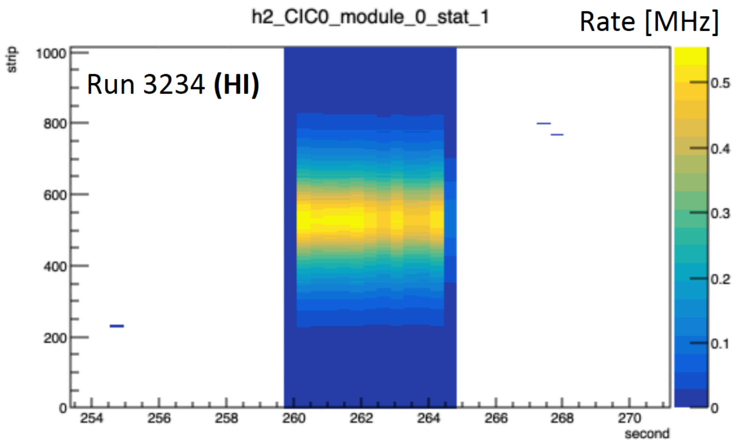
Muon beam profile and intensity

M2 muon beam: spills of ~5 s every ~20 s

Beam size fully contained in our detector for the high intensity

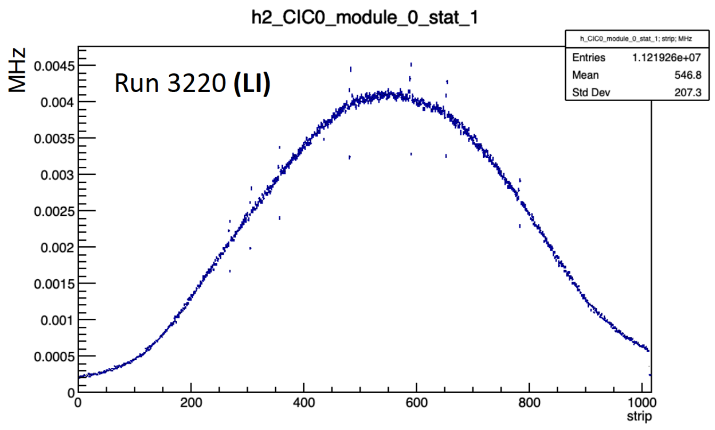
Broader size for low intensity, still almost fully contained

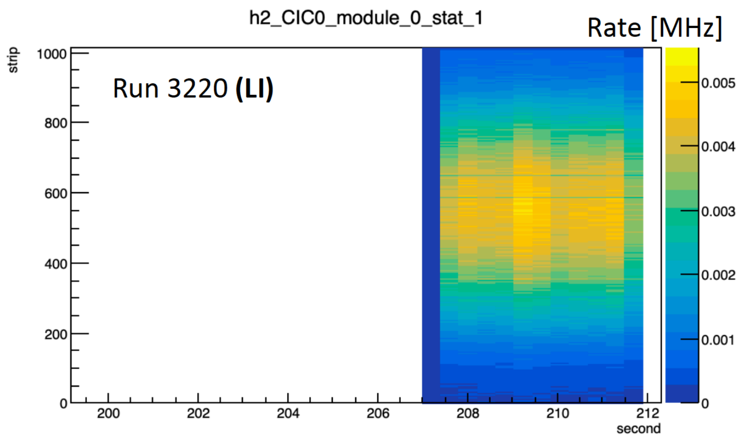




High Intensity runs:

1-2 x 10^8 μ/spill

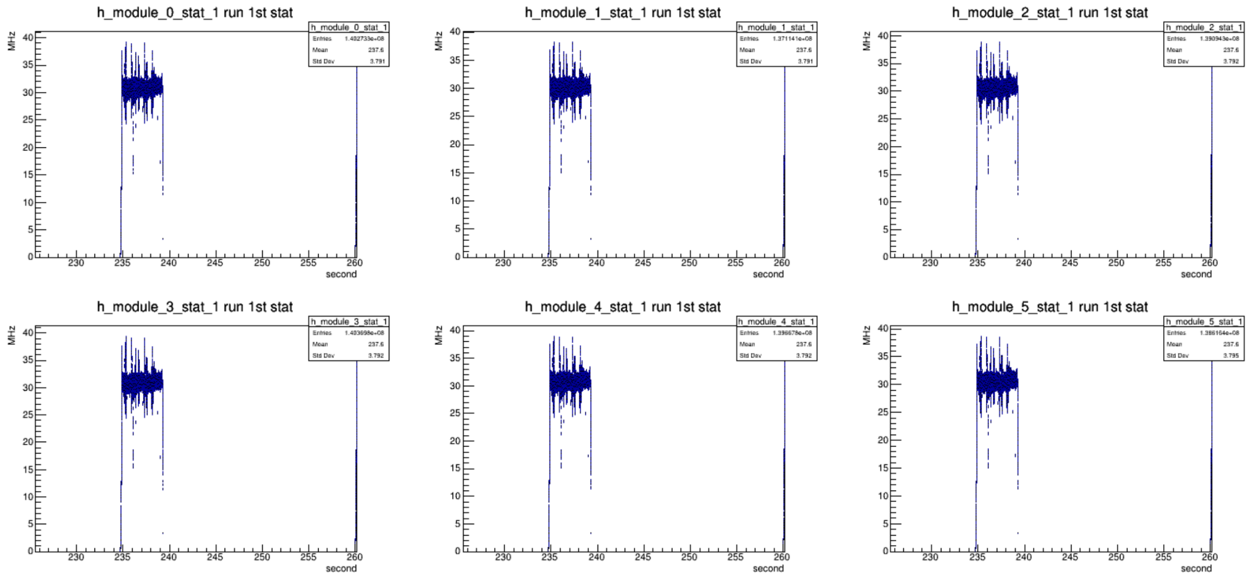




Low Intensity runs:

~1 x 10^7 μ/spill

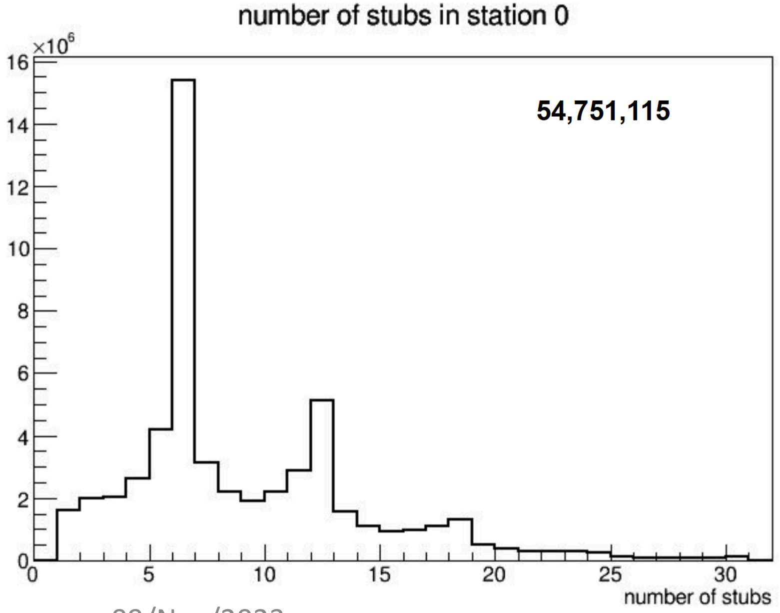
Muon stub rates

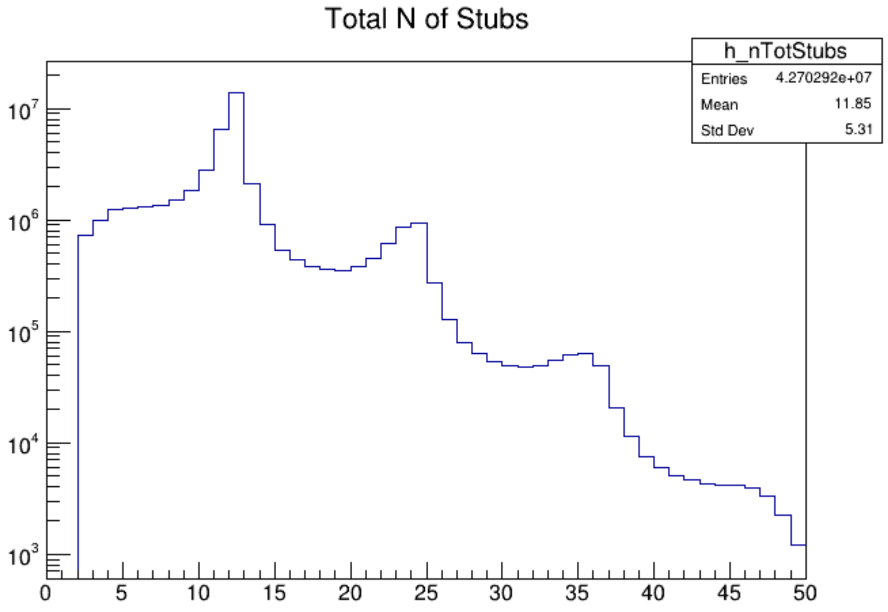


High Intensity run:
stub rate per module ~30 MHz

Clear peaks in stub multiplicity in first station at 6, 12, 18 corresponding to 1, 2, 3 pileup muons

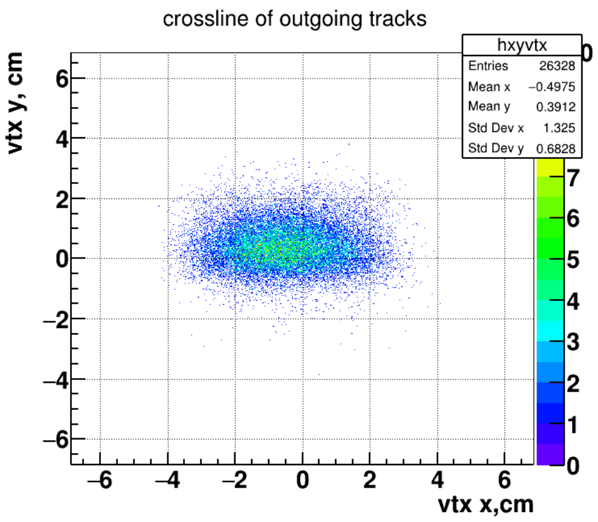
Corresponding peaks at 12, 24, 36 for the total stub multiplicity in the two stations



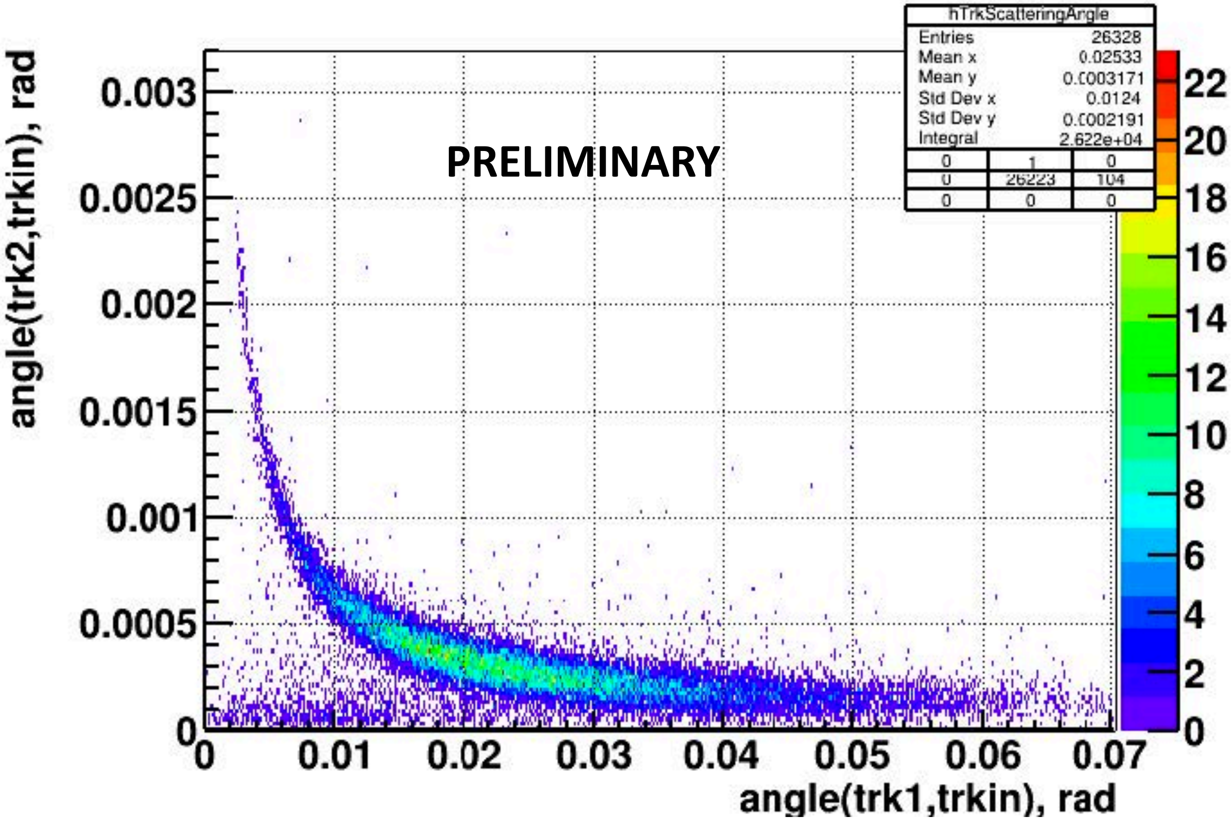


Observed number of muons per spill in agreement with estimate by SPS managers (~1.4-1.6 x 10^8 muons/spill)

Prompt offline analysis



First preliminary data analysis of a high-intensity run with 3cm target



Golden selection of events:

- One stub per module in the first station
- Two stubs per module in the second station
- All three reconstructed tracks with good normalised χ^2
- Loose vertex cut on the longitudinal crossing point of the outgoing tracks around the target position

Conclusions / todos

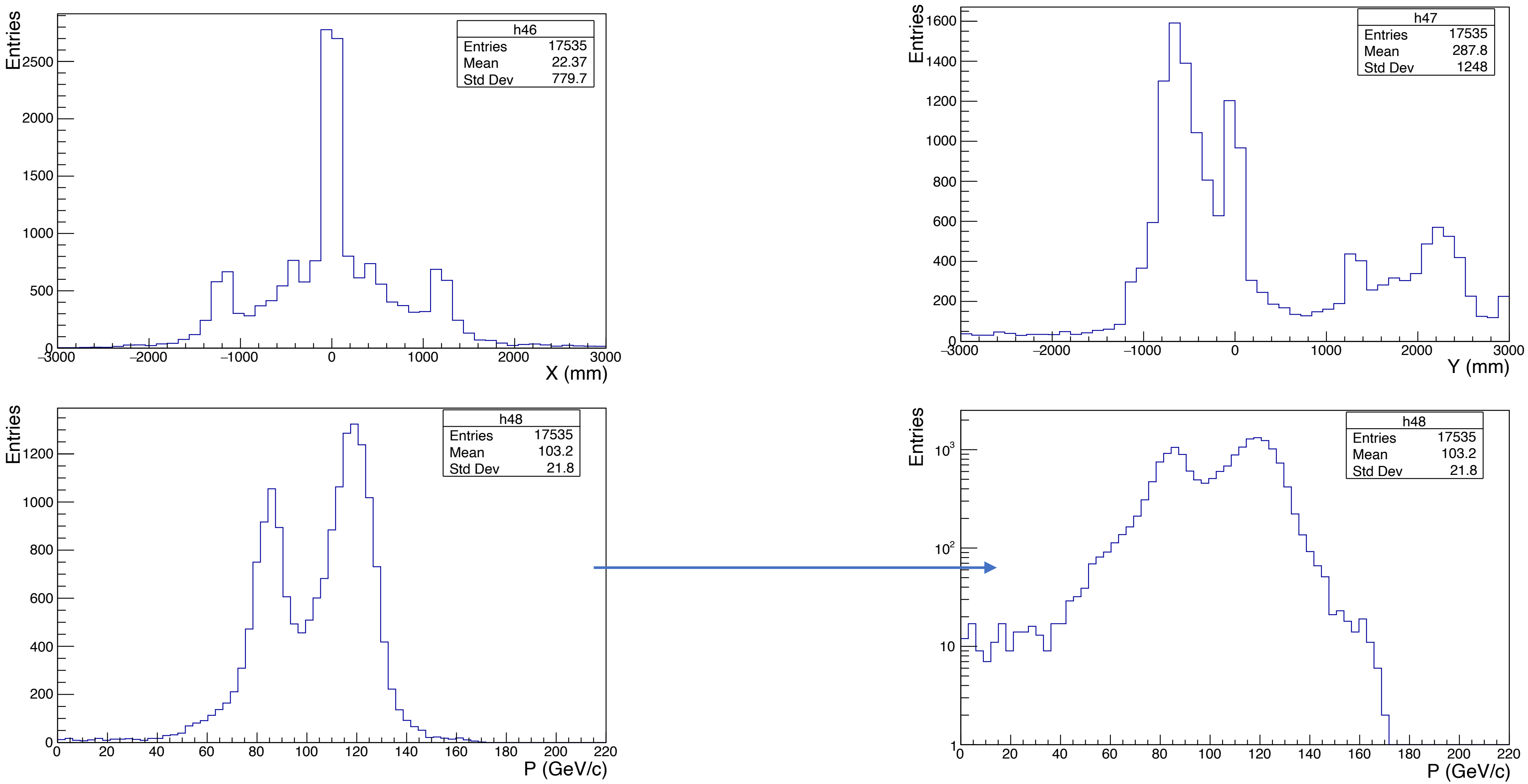
- FairMUonE: convenient environment for MUonE software (integrating MC generation, detector simulation, reconstruction, analysis). Expected / possible improvements:
  - MESMER generator (μe at NNLO), soon provided with pair production in μN
  - Geant4-based simulation rather stable
    - biasing of rare background processes could be finalised
    - additional geometries for Muon detector and detailed mechanical structure of stations
  - Digitisation: timing effects in the tracker, detailed ECAL digitisation
  - Reconstruction: improved treatment of multiple scattering, and better vertexing algorithm
- Tracker 2S modules were designed for CMS @LHC, the 2S concept is not ideal for MUonE: bend info not always beneficial in reconstruction (see more on Kirika's talk)
- Particle ID needs to be developed using the ECAL and Muon detectors in association with the tracker. Reconstruction has to provide alternative paths to correctly interpret the events
- Event selection to be systematically studied to provide as flat as possible efficiency
- Data-driven background studies necessary, using as a proxy events with 3 outgoing tracks (from e+e- pair production) and large statistics MC simulations to estimate the residual background in the 2-track event selection
- Alignment workflow has to include the HW metrology as first step for the track-based algorithm. Global alignment necessary for maximum accuracy.
- The first preliminary results from the Test Run are encouraging, although much is on-going and much more has still to be done
  - We have collected a huge dataset that needs to be fully exploited
- Complete analysis of the Test Run dataset: target is the measurement of the leptonic contribution to the running α, with a precision of ~5%
  - Extraction of the $\Delta\alpha$ has to be carried out on real data and fully reconstructed MC events

BACKUP

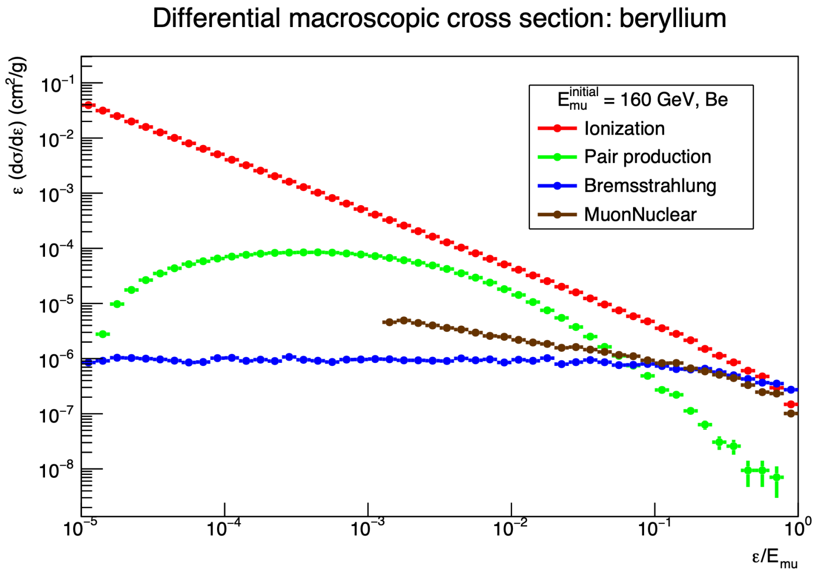
Halo Muons

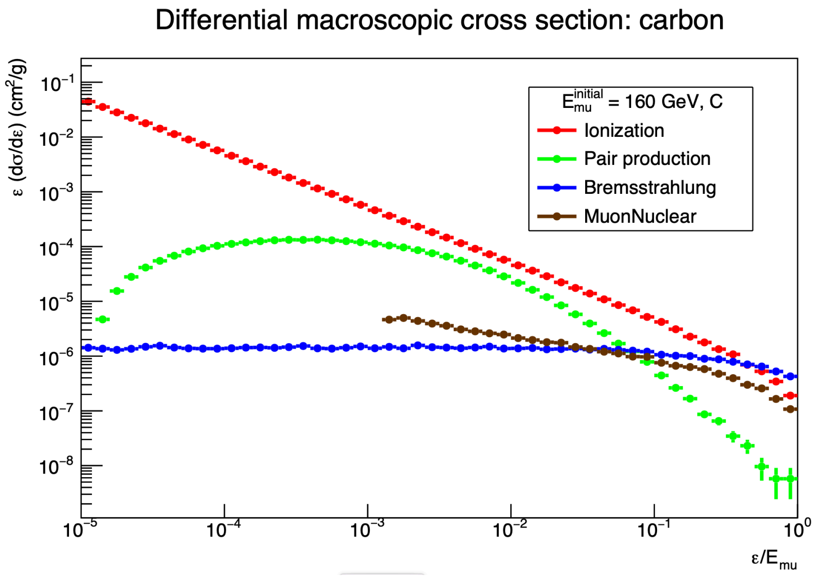
- Halo muons span to almost 3m x 3m transversely and has a rate of about 10 – 13 % of the core of the beam.

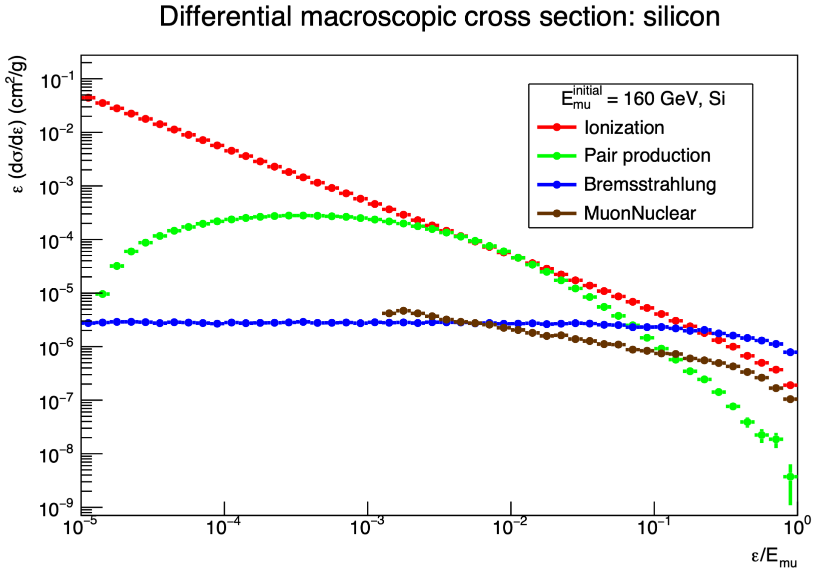
Plots show beam outside of a 300 mm radius circle and within 3 m x 3 m rectangle.



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

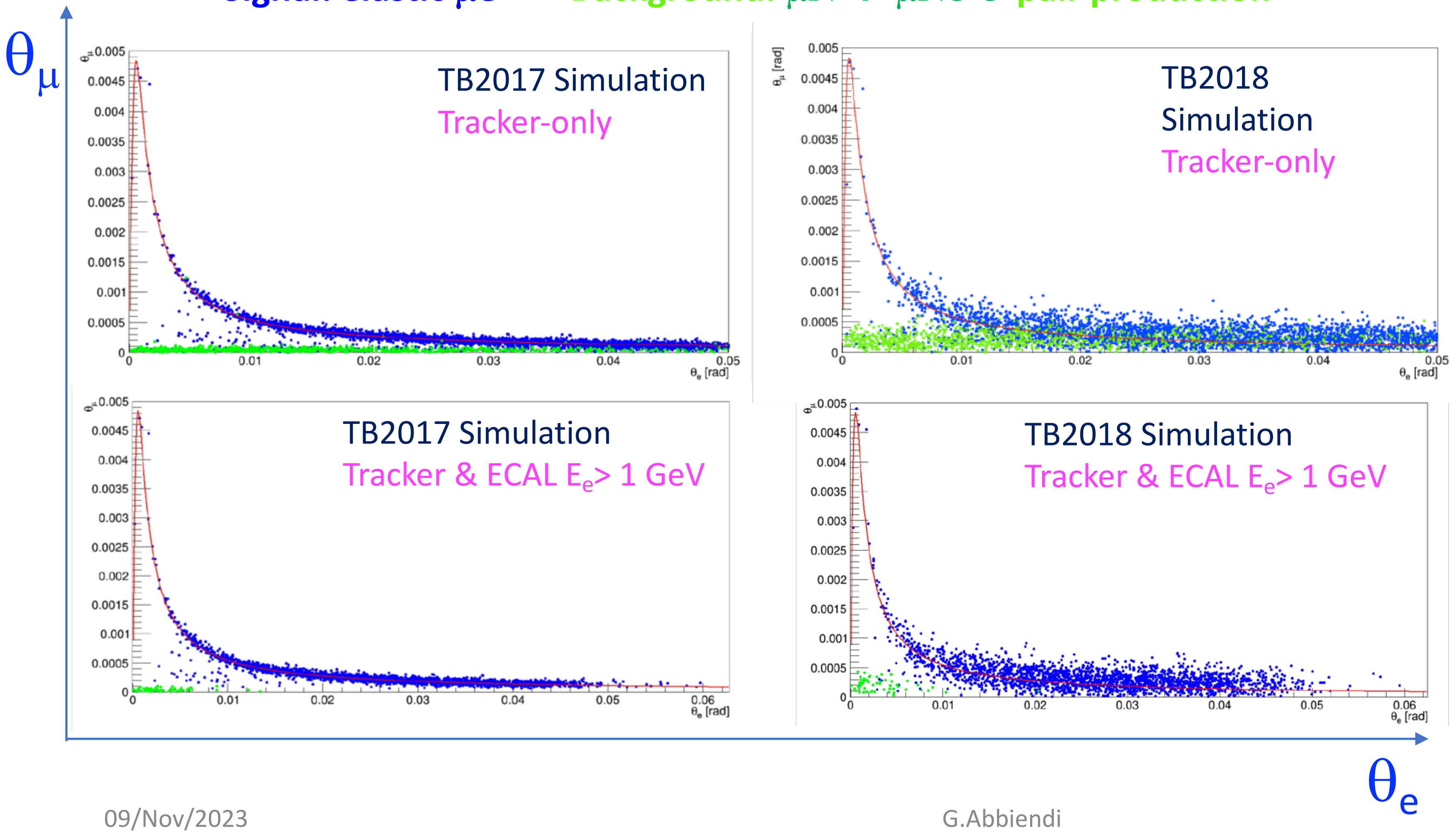
n_A density of atoms per unit volume

ρ_A material density in g/cm^3

Background and Detector Resolution

Effect of the position resolution on θ_μ vs θ_e distribution:
(Left) TB2017: UA9 resolution 7μm ; (Right) TB2018: resolution ~35-40μm

Signal: elastic μe **Background: $\mu N \rightarrow \mu N e^+ e^-$ pair production**



Pair production in μN interactions is the dominant background

NEW Geant4 version with improved description of pair production being used.

NEW MC generator for pair production in nuclear interactions under development by Pavia's group

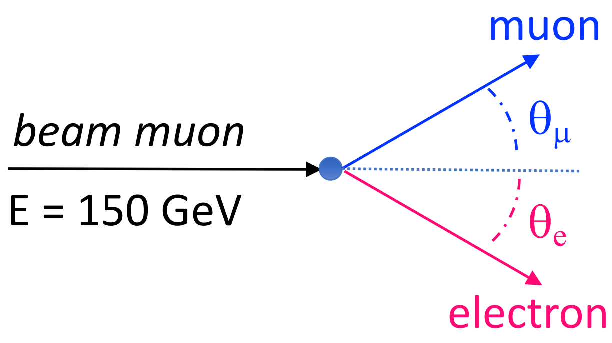
Beam Energy scale

Time dependency of the beam energy profile has to be continuously monitored during the run:

- SPS monitor
- COMPASS BMS

} needed external infos

However, the absolute beam energy scale has to be calibrated by a physics process:
kinematical method on elastic μe events

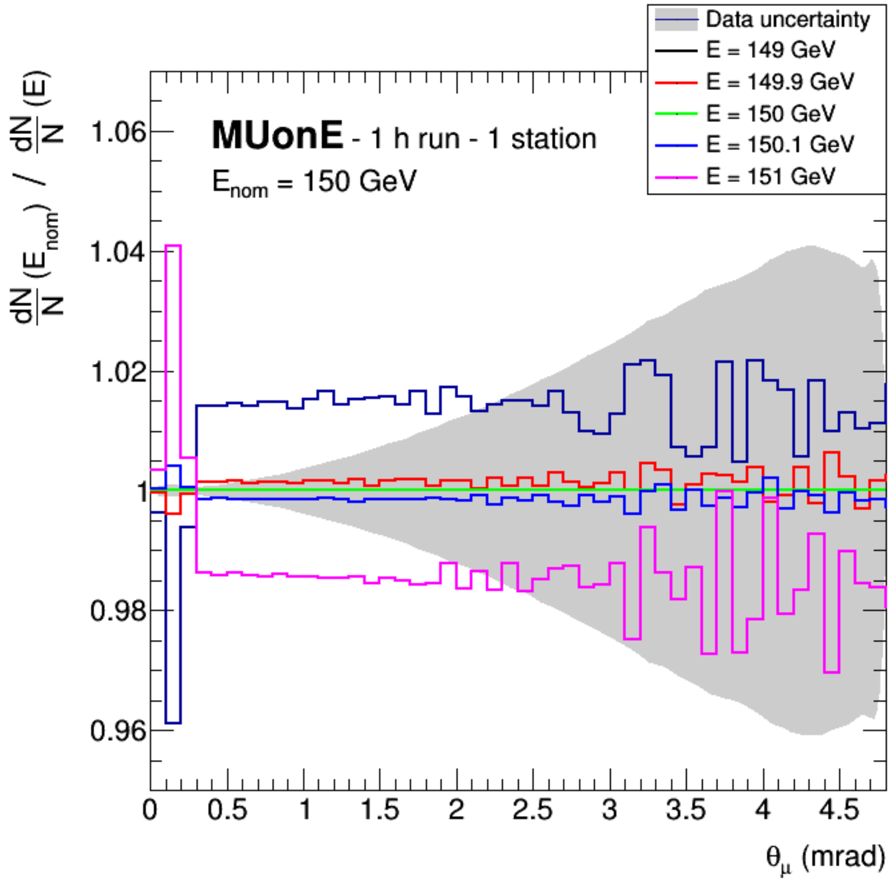


For equal angles:
$\theta_\mu = \theta_e \equiv \theta$

$$\theta \simeq \sqrt{\frac{2m_e}{E}}$$

Can reach <3 MeV uncertainty in a single station in less than one week
From SPS E scale ~1% : 1.5 GeV

Effect of a syst shift of the average beam energy on the θ_μ distribution: 1h run / 1 station

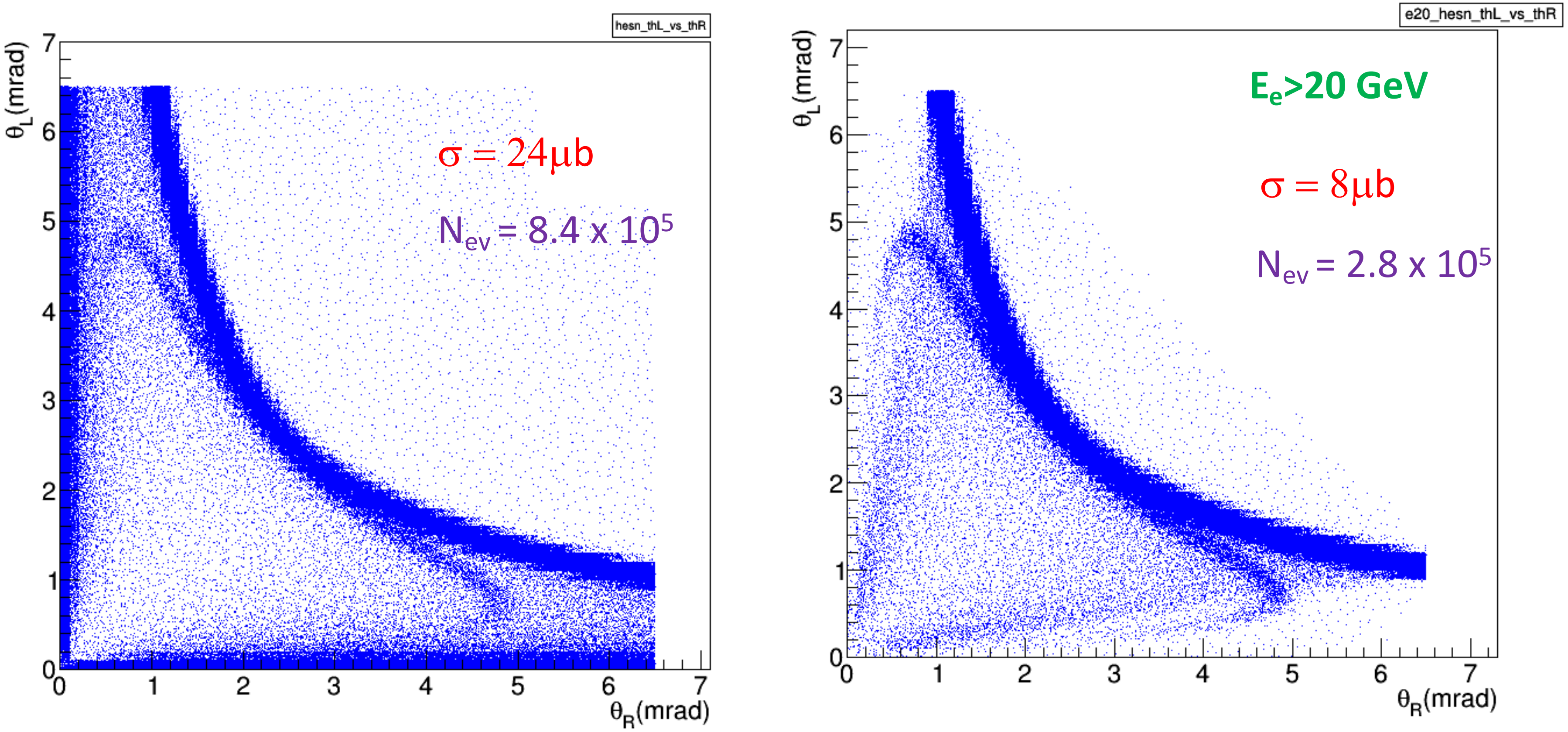


Beam Energy scale: 2D angular selection

θ_L, θ_R < 6.5 mrad (no ID necessary)

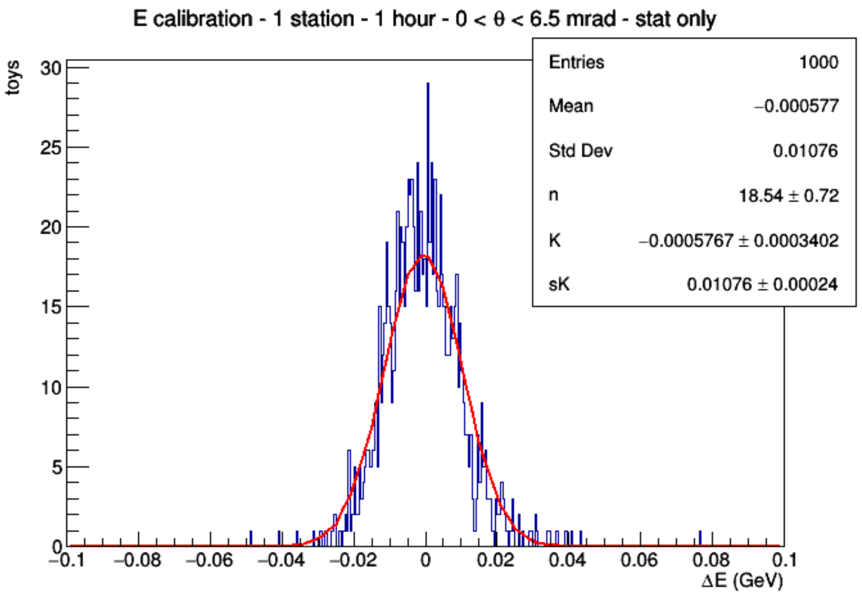
- Additionally a possible calorimeter cut E_e>20 GeV

1h run – 1 station – 1.5 cm Be target – duty cycle (0.25) included

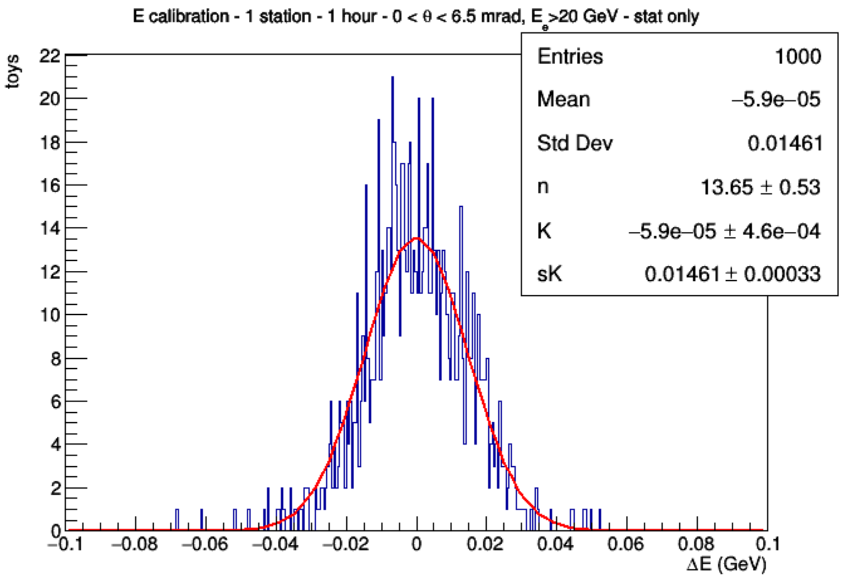


Beam Energy scale: statistical accuracy

- Template fit of (θ_L, θ_R) with Beam energy as fit parameter in the range 150 GeV ±100 MeV.
- Considering 1 hour run time in one station (1.5cm Be) → ~35nb^{-1}
- Angular selection: 0<(θ_L, θ_R)<6.5mrad → 24μb
  - With additional CALO E_e>20 GeV → 8μb
- 1000 toys (each one with 8.4x10^5 / 2.8x10^5 events)



With additional CALO E_e>20 GeV



$\sigma \simeq$ 10.8 MeV   Bias ~ 0 $\sigma \simeq$ 14.6 MeV

Beam Energy Scale

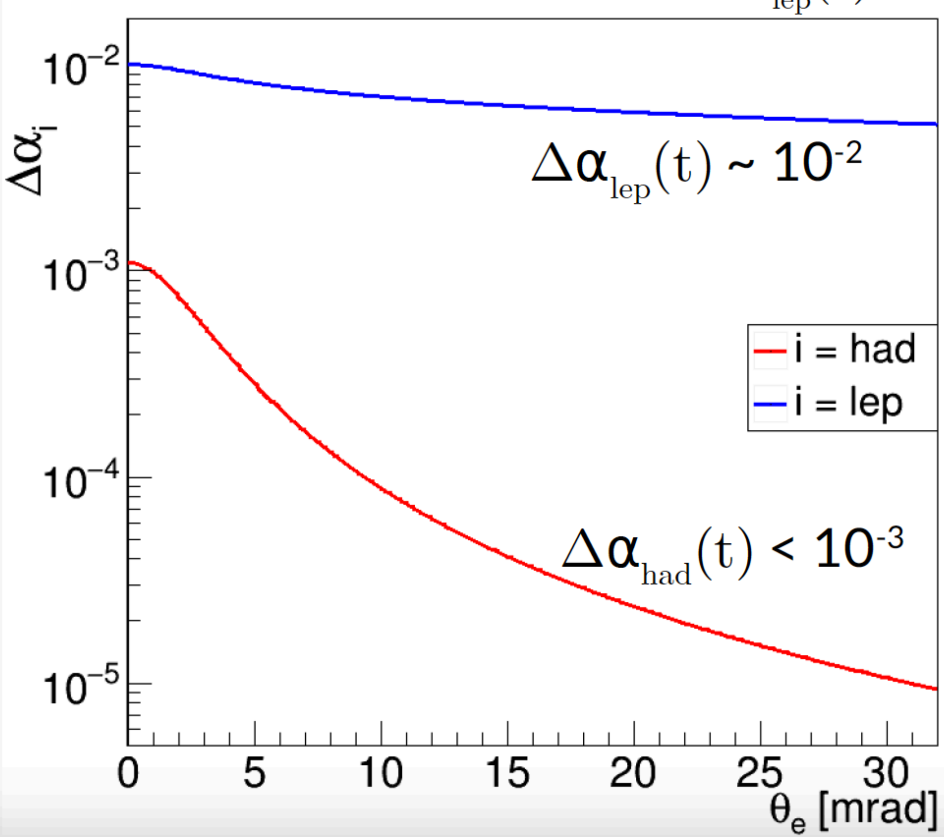
- We could test the method with one-few runs of ~1h time
- The fitted average beam energy could be compared with the one from the SPS monitors
- If Compass-AMBER could provide a beam profile referring to the same run period we could compare with it too

- If everything goes as predicted we should have our measurement of average beam energy with good statistical precision (<100 MeV)
  - Systematics could be dominating, especially related to the real energy profile of the beam (non-Gaussian tails, low-energy peaks…) but having a reasonable model for the beam profile they could be reduced

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

Expected ~10^{12} μ on target, ~2.5×10^{8} elastic events E_e > 1 GeV
(Expected luminosity: ~ $1 pb^{-1}$)

Not enough for $\Delta\alpha_{had}(t)$,
but we can measure $\Delta\alpha_{lep}(t)$



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

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

Expected precision: ~5%