Measuring $\alpha=\alpha(q^2)$ with the $\mu+e\rightarrow\mu+e$ elastic scattering

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INFN, Bologna

Mainz February 2018

Muon beam M2 at CERN

To be checked

I_{beam} ~ 10^7 muon/s, E_μ = 160 GeV

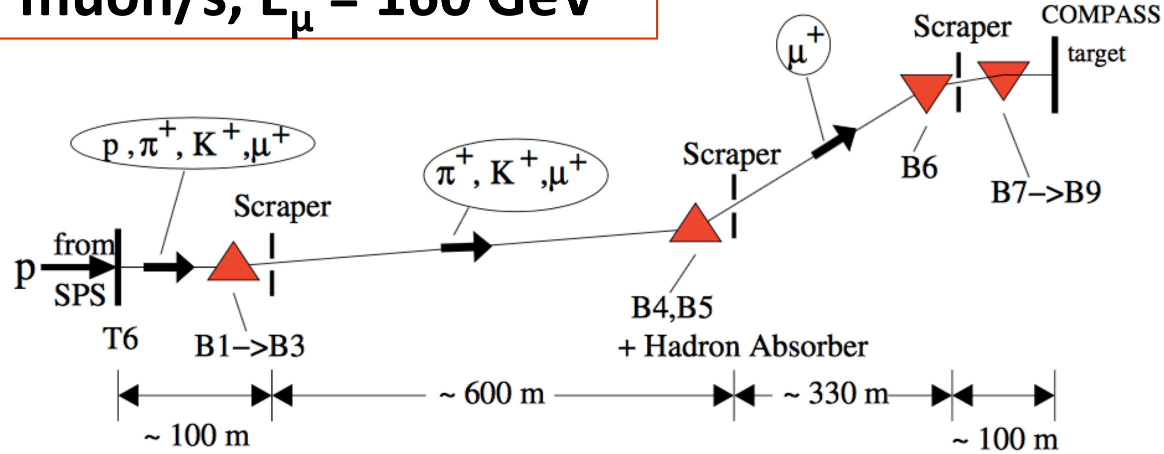


Table 3
Parameters and performance of the 160 GeV/c muon beam.

Beam parameters	**Measured**
Beam momentum $(p_\mu)/(p_\pi)$	$(160\,\mathrm{GeV}/c)/(172\,\mathrm{GeV}/c)$
Proton flux on T6 per SPS cycle	$1.2 \cdot 10^{13}$
Focussed muon flux per SPS cycle	$2 \cdot 10^{8}$
Beam polarisation	$(-80 \pm 4)\%$
Spot size at COMPASS target $(\sigma_x \times \sigma_y)$	$8 \times 8\,\mathrm{mm}^2$
Divergence at COMPASS target $(\sigma_x \times \sigma_y)$	$0.4 \times 0.8\,\mathrm{mrad}$
Muon halo within 15 cm from beam axis	16%
Halo in experiment $(3.2 \times 2.5\,\mathrm{m}^2)$ at $\lvert x,y \rvert > 15\,\mathrm{cm}$	7%

https://arxiv.org/pdf/hep-ex/0703049.pdf

Effects on the trigger strategy, event pile up

Luminosity

The instantaneous luminosity can be calculated as:

$$\mathcal{L} = I_\mu \times \rho_e \times d = I_\mu \times \frac{N_A \cdot \rho \cdot Z}{W} \times d \tag{1}$$

where I_μ is the intensity of the muon beam, ρ_e is the density of the electron scattering centers and d is the thickness of the target. ρ_e in turn can be expressed in terms of the material density ρ, the Avogadro's number N_A, the atomic number Z and the atomic weight W.

Assuming the intensity of the muon beam to be $I_\mu = 1.3 \times 10^7\ \mathrm{s}^{-1}$, the luminosity provided by Beryllium target, with $\rho_{Be} = 1.85\ \mathrm{gcm}^3$, $(Z/W)_{Be} = 0.44$, and a thickness $d = 60$ cm is:

$$\mathcal{L}_{Be} = 3.9 \times 10^{32}\ \mathrm{cm}^{-2}\mathrm{s}^{-1} = 0.39\ \mathrm{nb}^{-1}\mathrm{s}^{-1} \tag{2}$$

The required luminosity that can be collected in two years of data taking, assuming 2×10^7 s/yr is:

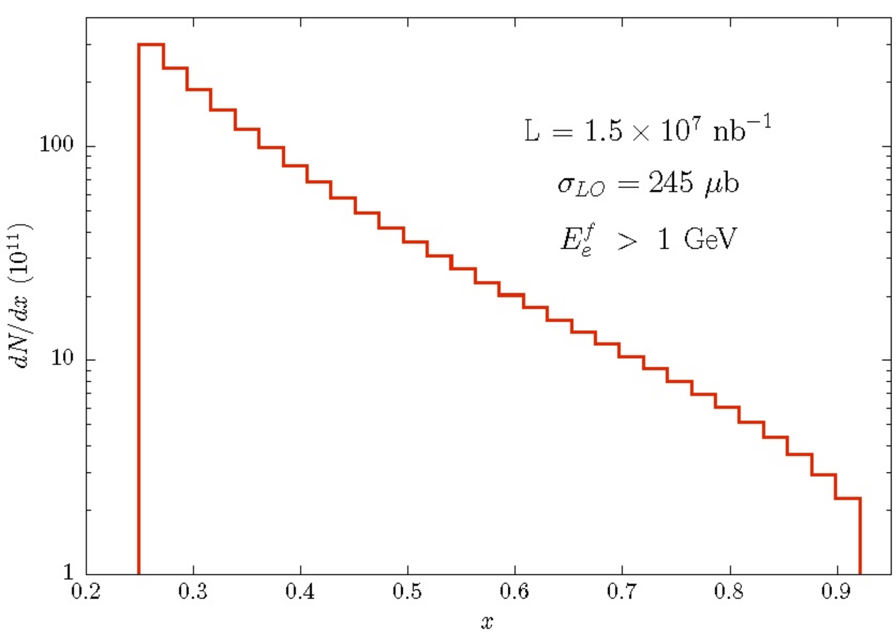
$$L_{Be} = 1.5 \times 10^7\ \mathrm{nb}^{-1} \tag{3}$$

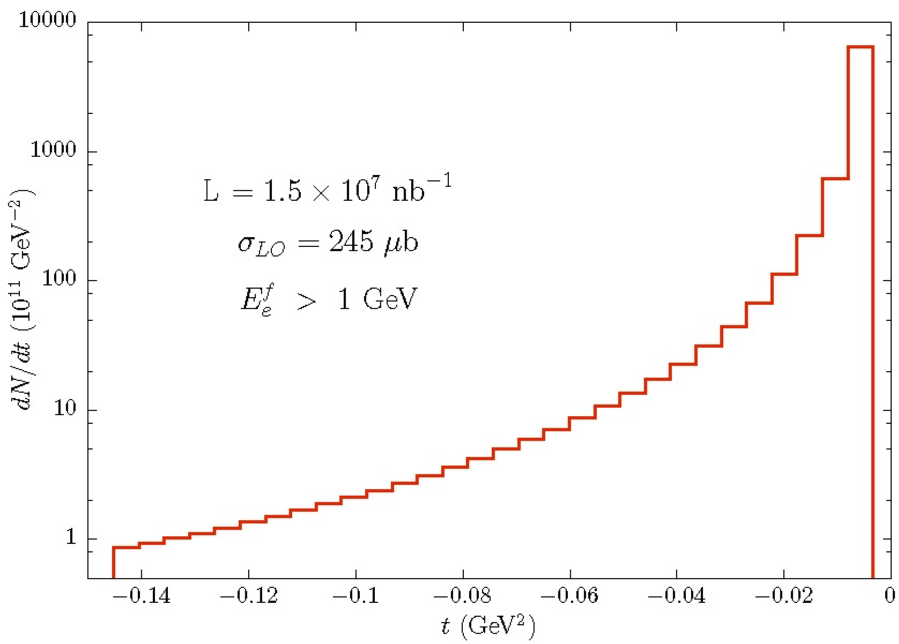
Assuming the muon electron elastic scattering cross-section, for scattered electrons of energy greater than 1 GeV is $\sigma_{\mu e} = 245\ \mu$b, then the expected event yield can be estimated to be:

$$\boxed{N = L_{Be} \times \sigma_{\mu e} \sim 4 \times 10^{12}} \tag{4}$$

Luminosity (II)

According to the LO elastic cross-section
No detection effects at this stage

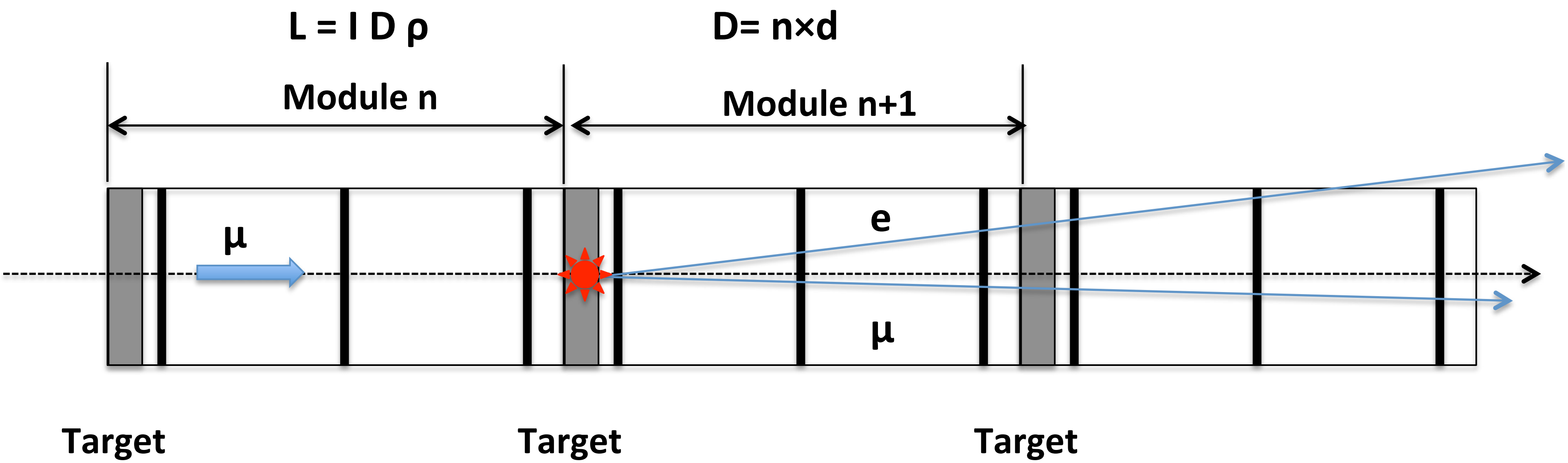




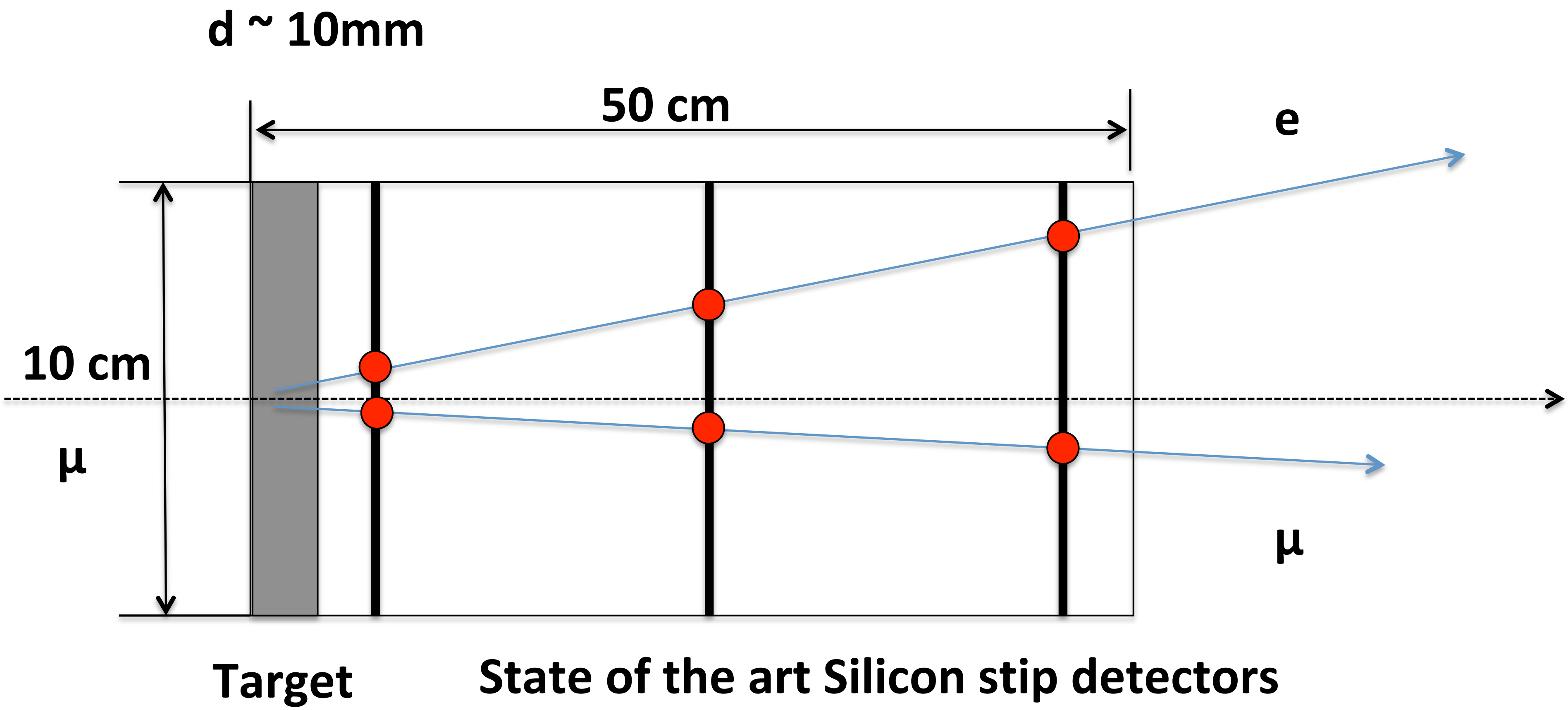
~10^{10} events in the highest energetic bins

Detection principles

- We need to use and distribute the low Z target material in thin layers. Each layer has a thickness of the order of 10 mm.
- A detection module must be transparent to non interacting muons, has to let us track muons passing through, to measure muons direction at any stage.
- A detection module, where the interaction take place, acts as a standalone, independent detector.



Measuring electron and muon angles

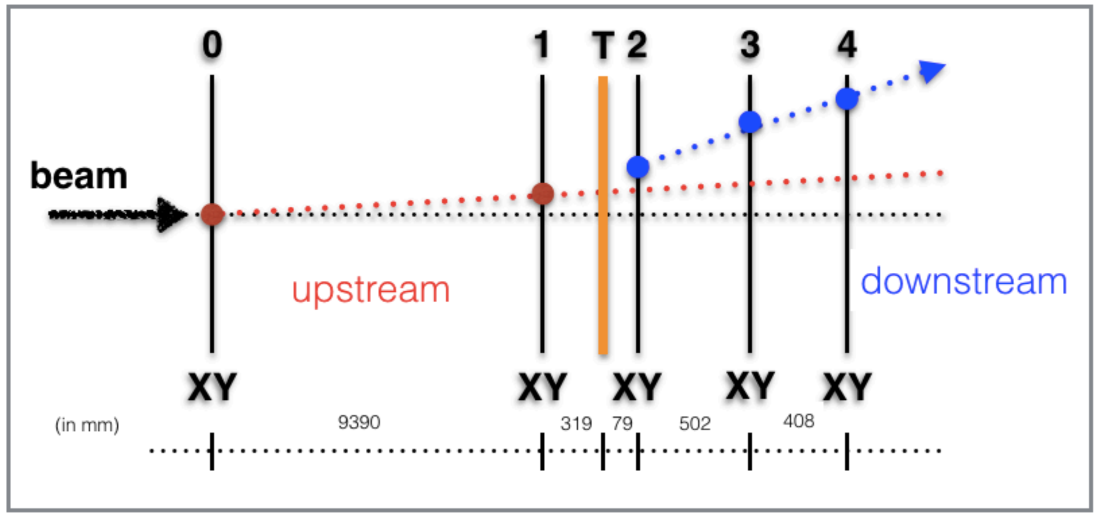


hit resolution ~10 μm Too optimistic

expected angular resolution ~ 10 μm / 0.5 m = 0.02 mrad

Detector angular resolution

	DATA with target $D\theta$ (mrad)	method resolution from DATA σ_0 (mrad)
12 GeV 8 mm (e-)	0.23924	0.13139
20 GeV 8 mm (e-)	0.14405	0.08031
20 GeV 8 mm (e+)	0.13878	0.07850 (e+)
12 GeV 20 mm (e-)	0.35377	0.13139
20 GeV 20 mm (e+)	0.20219	0.07850 (e+)



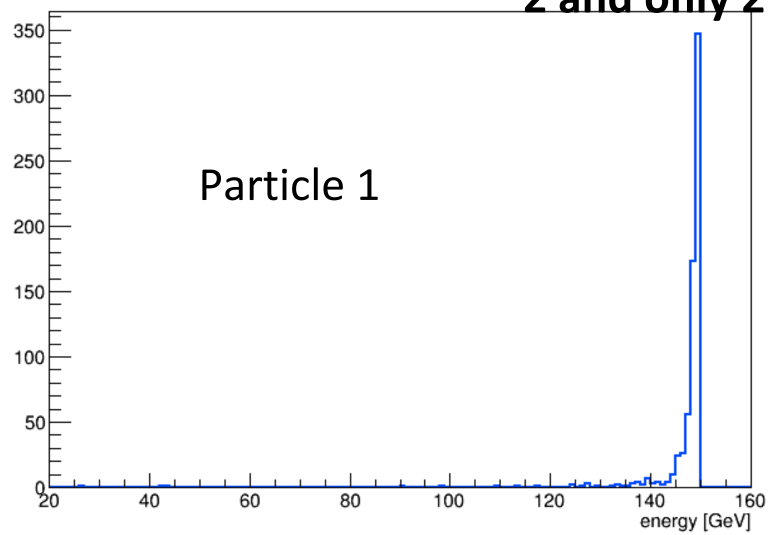
expected angular resolution ~ 0.1 mrad

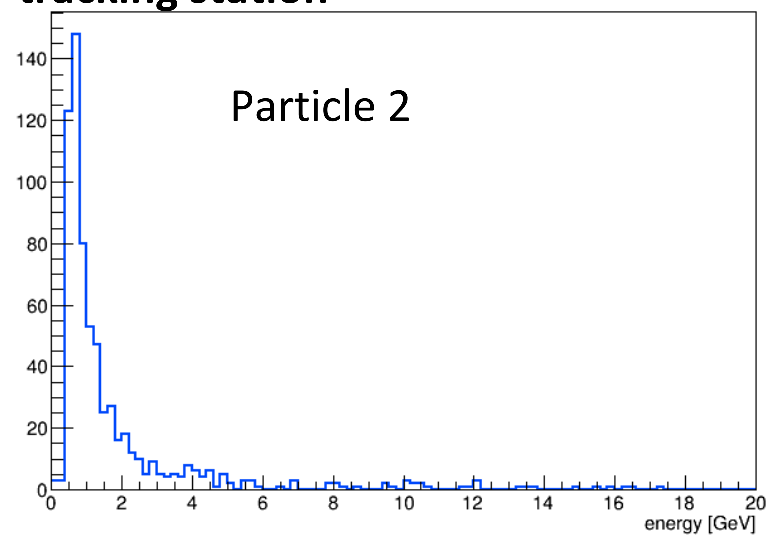
Tracking efficiency (hits detection)

- $\mathbf{m_0}$: charged particles multiplicity just outside the target
- n($\mathbf{m_0}$=2) = 864 over 1000.
- n($\mathbf{m_1}$=2 && $\mathbf{m_0}$=2) = 812: two hits at the first tracker.
- n($\mathbf{m_2}$=2 && $\mathbf{m_0}$=2 && $\mathbf{m_1}$ =2) = 740
- n($\mathbf{m_3}$=2 && $\mathbf{m_0}$=2 && $\mathbf{m_1}$ =2 && $\mathbf{m_2}$=2) = **685**
  The probability that in case of elastic collision occurs the detector records two and only two hits in each of the tracking station is ~**70%**.
- Efficiency is important of course, but **angular uniformity** is a key property we require to the tracking apparatus. Remember we plan to measure counting ratios, to get the running of : $\mathbf{N_i/N_{norm}}$

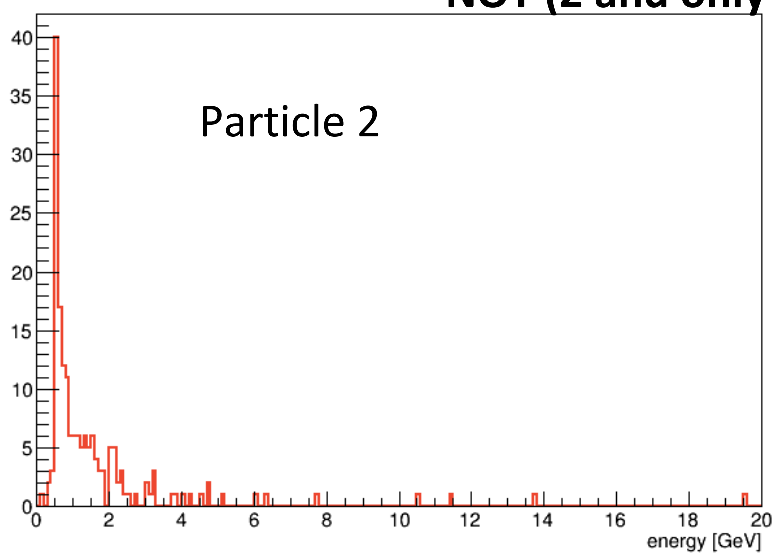
Tracking efficiency (2)

2 and only 2 hits per tracking station



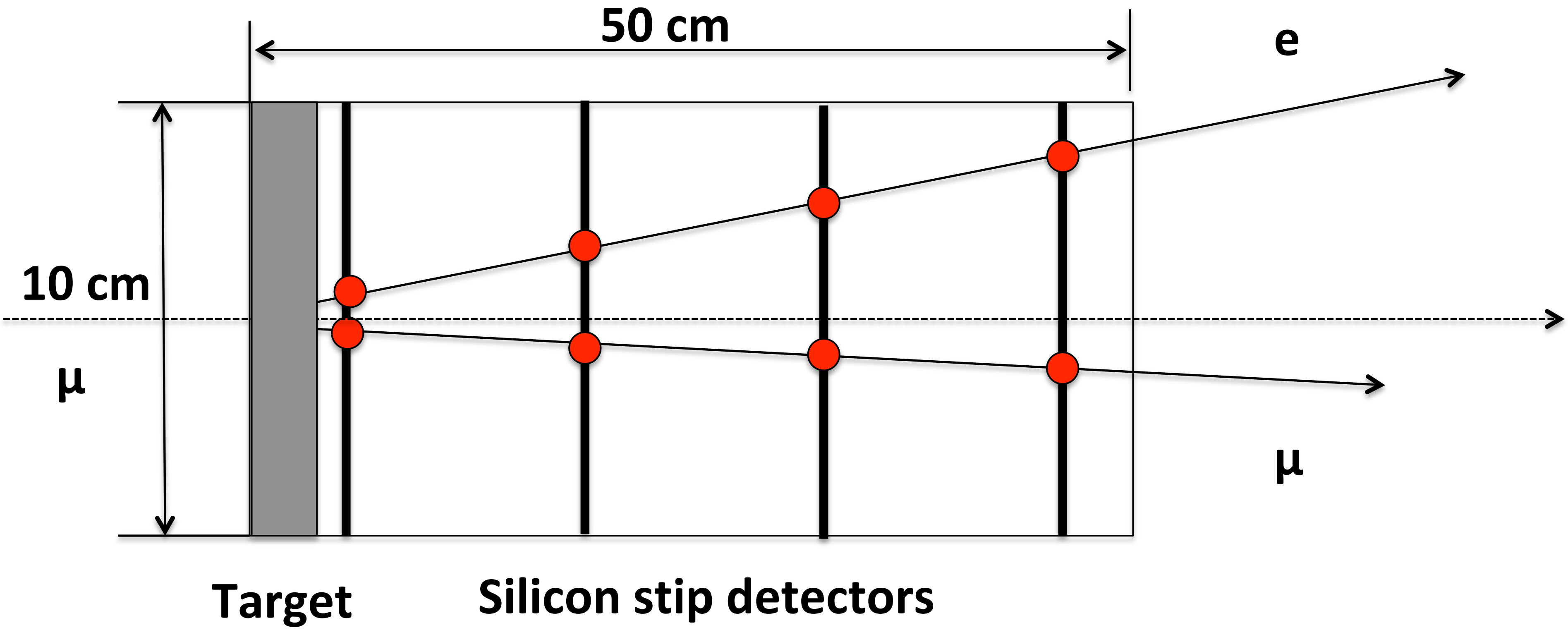


NOT (2 and only 2 hits per tracking station)



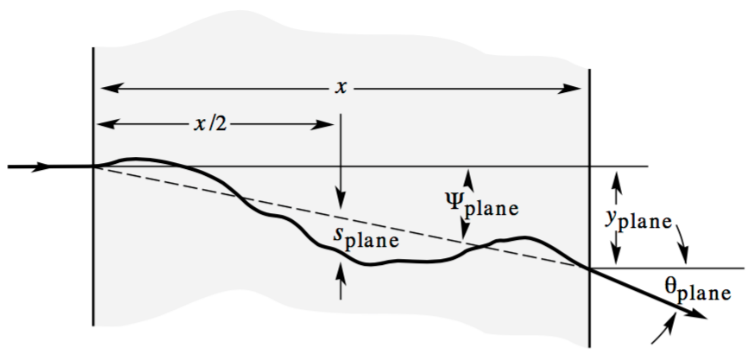
Particle 2
Energy of the particles that are not seen at all the stations

Detector variant:
4th station for efficiency,redundancy and track quality checks

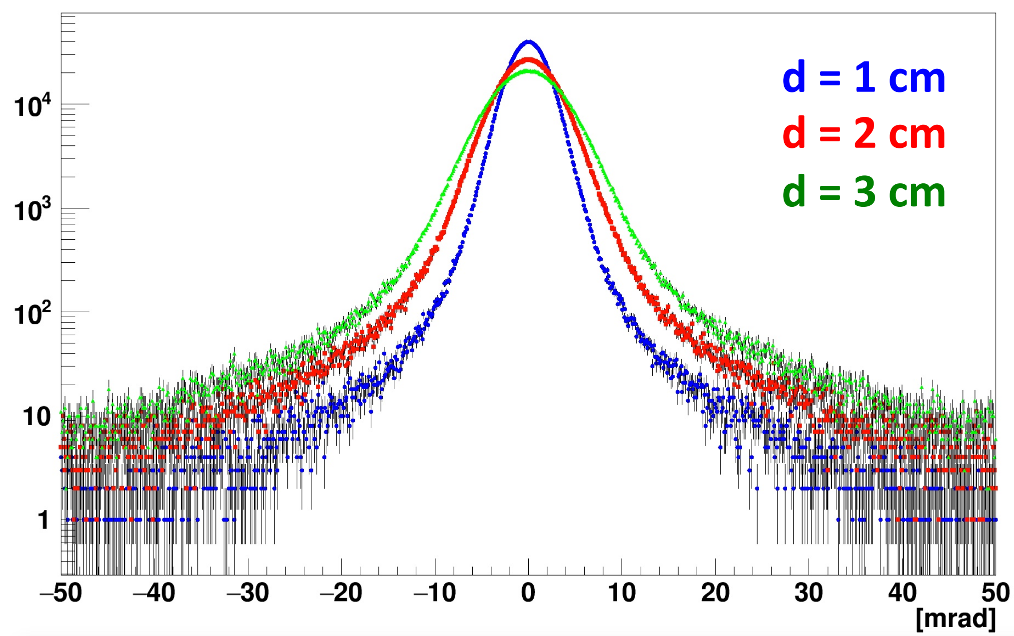


How to optimally cope with MSC?
How precisely shall we know MSC?

Effect of Multiple Scattering

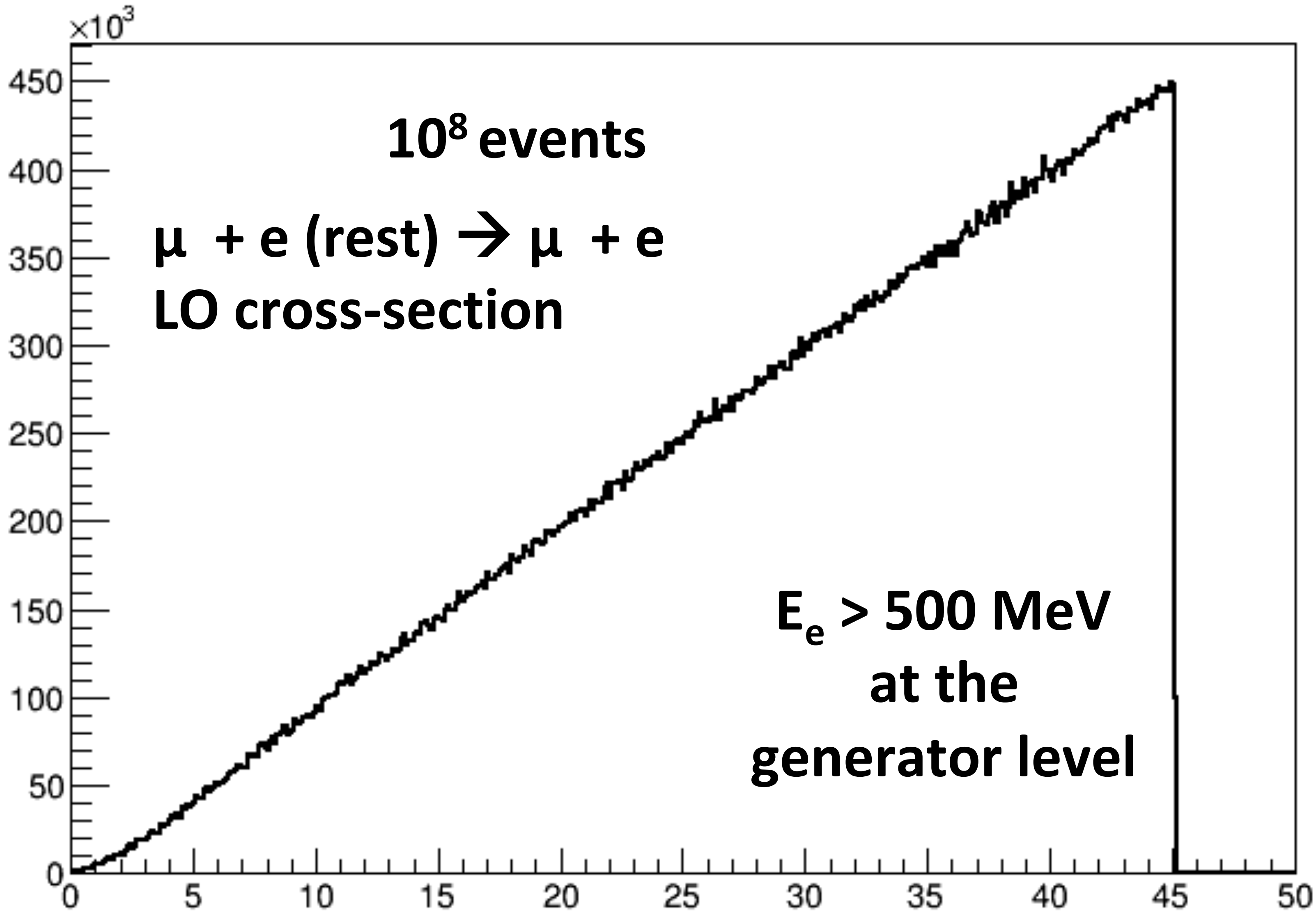


GEANT4, 1 GeV electrons, Be target



Vertices of the **μ + e → μ + e** collisions will be uniformly distributed inside the target along the direction of the beam axis.
The observable angles (electron and muon angles) depend therefore on the particles' path length inside the material and on their energies.
We need a MSC model to relate the observed angles to the scattering ones.

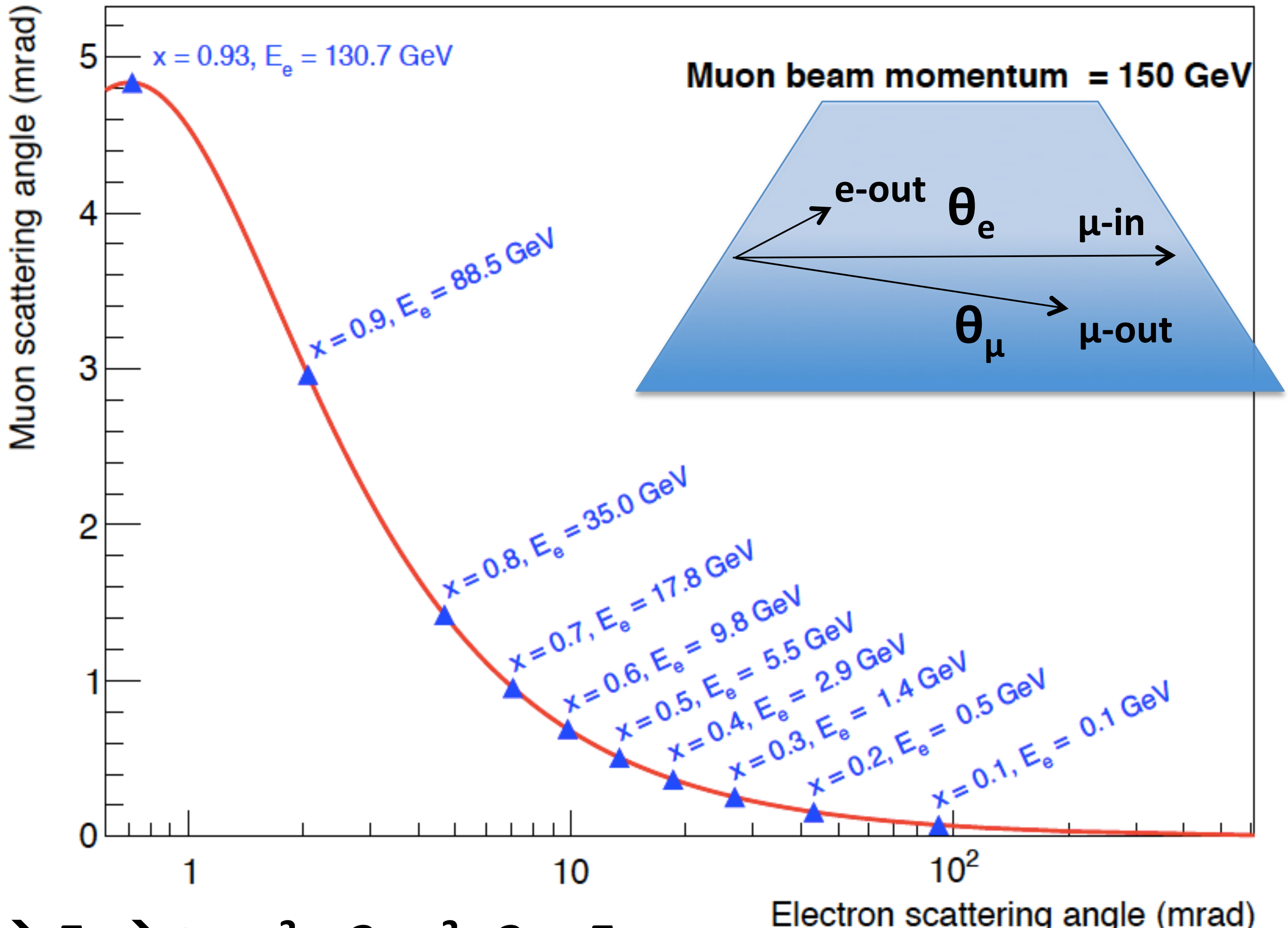
LO electrons angular distribution



electron angle (mrad)

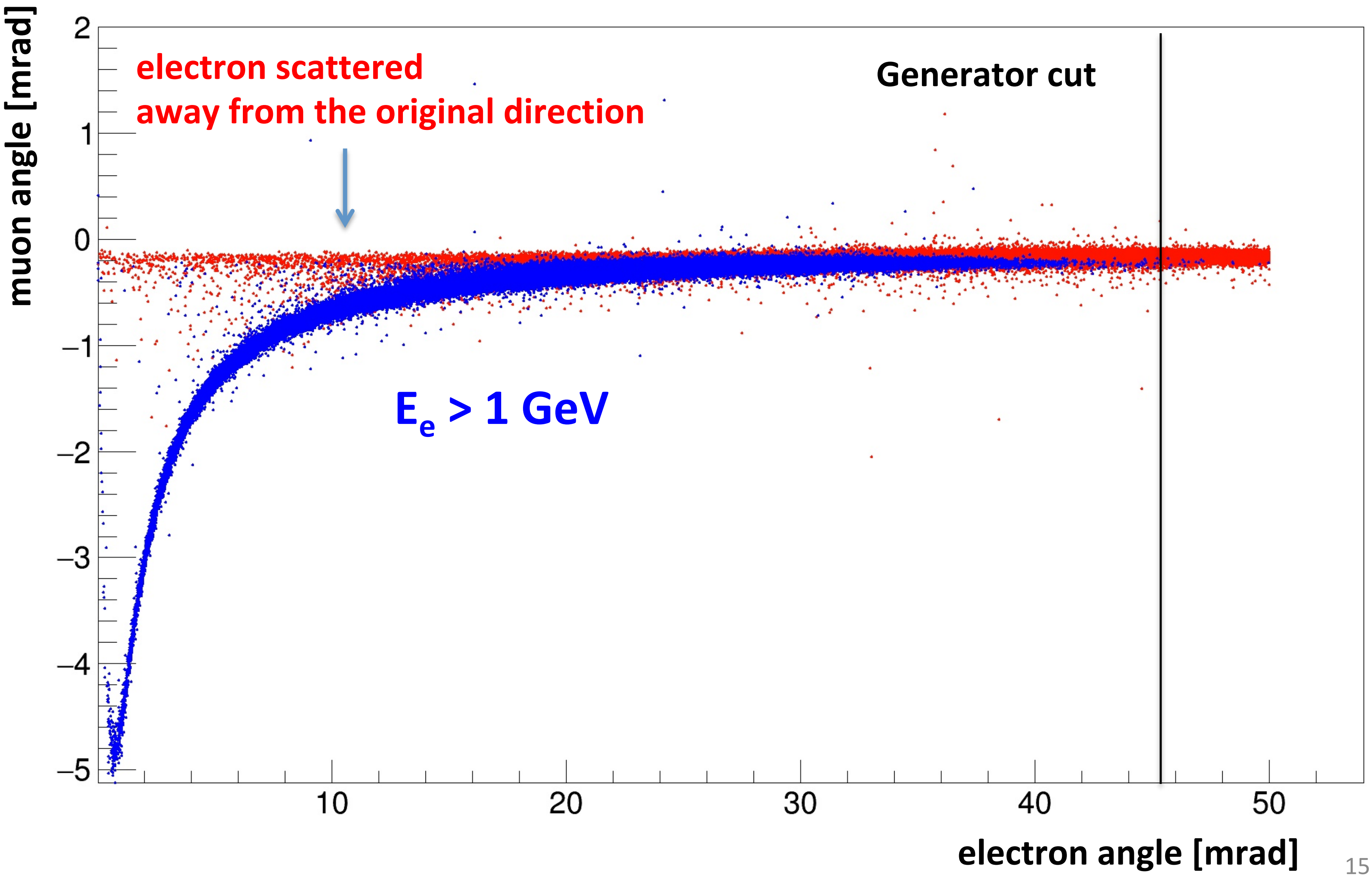
Elastic scattering in the (θ_e , θ_μ) plane

Coplanarity of the momentum vectors and angular kinematical constraint

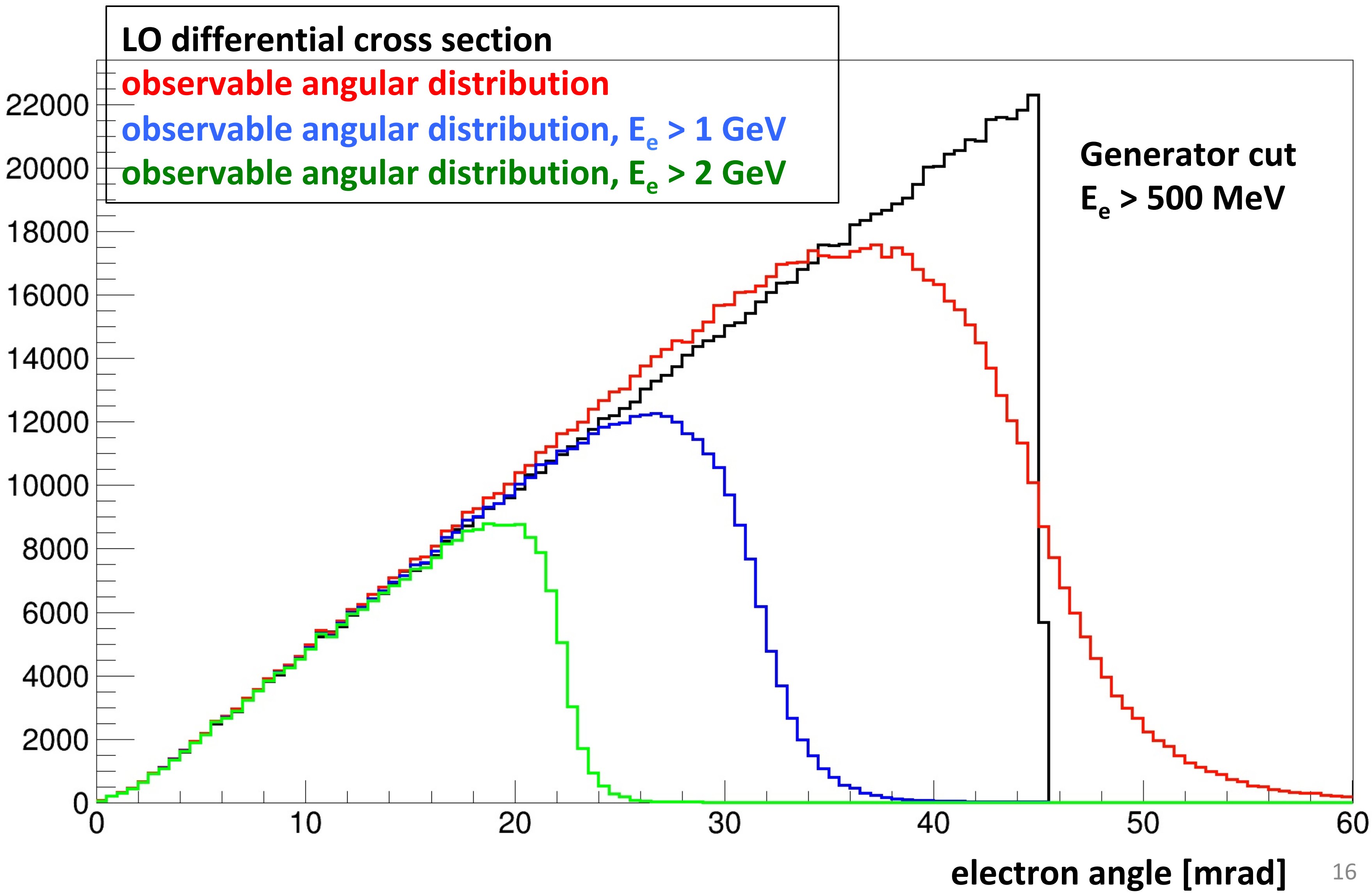


$\theta_e \rightarrow E_e \rightarrow t = q^2 = 2m_e^2 - 2m_eE_e$

Events in the (θ_e , θ_μ) plane

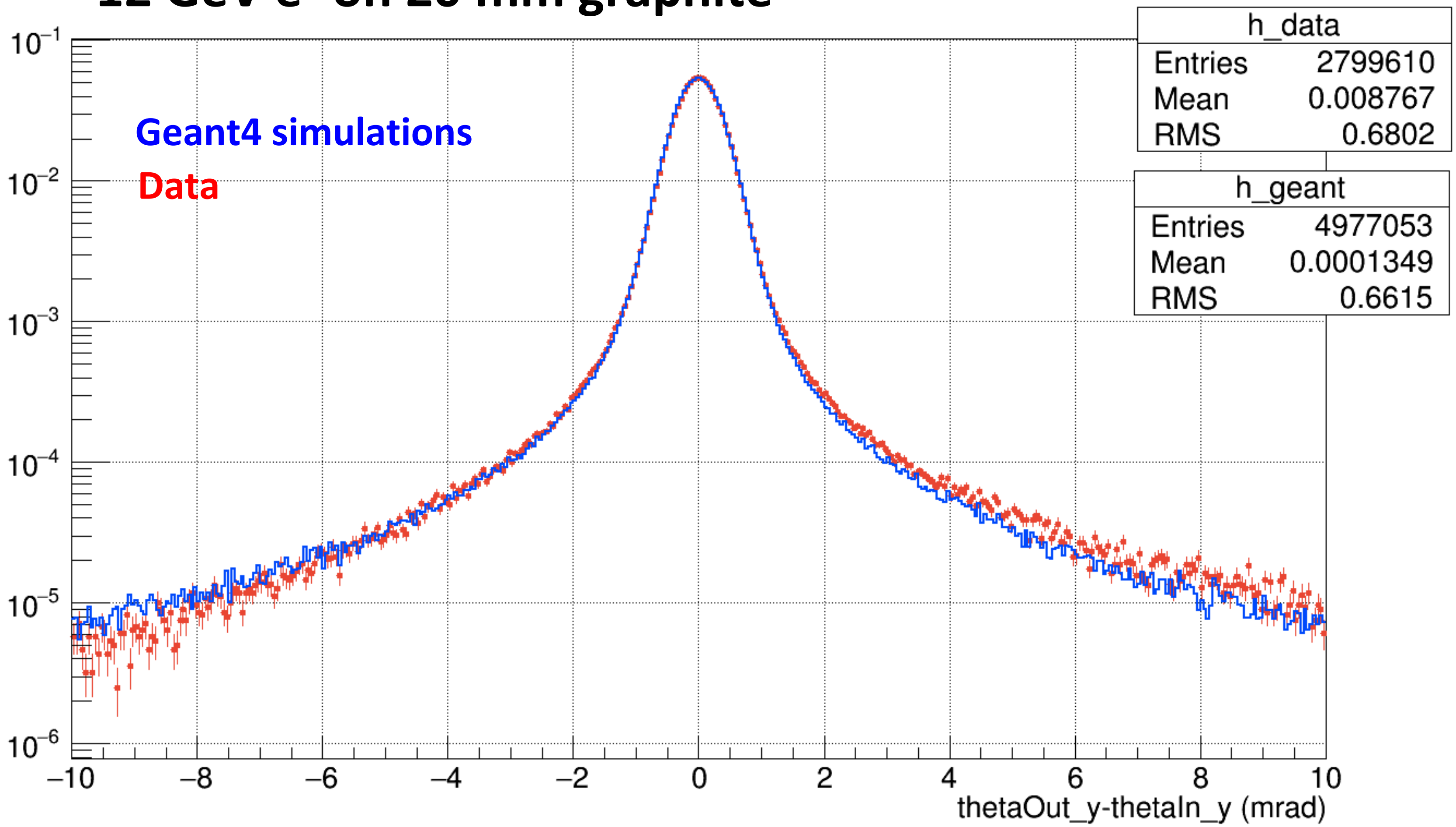


Resolution models and E_e cut



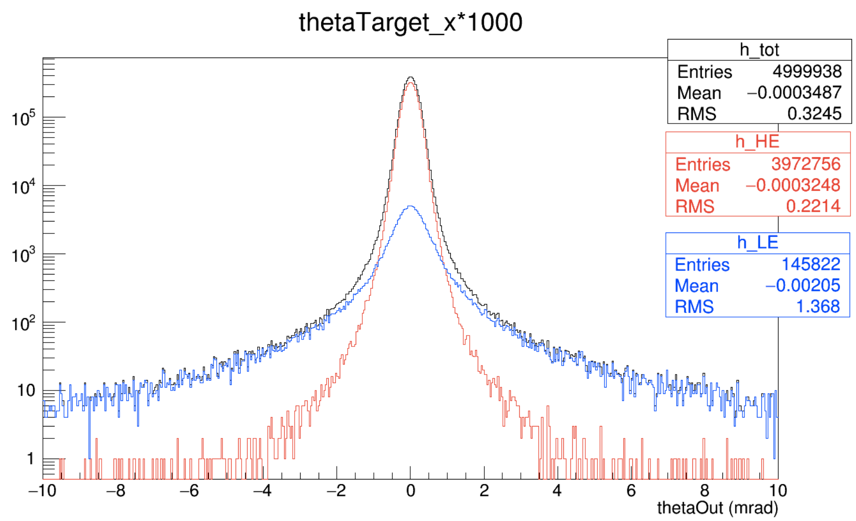
Test Beam results

12 GeV e- on 20 mm graphite

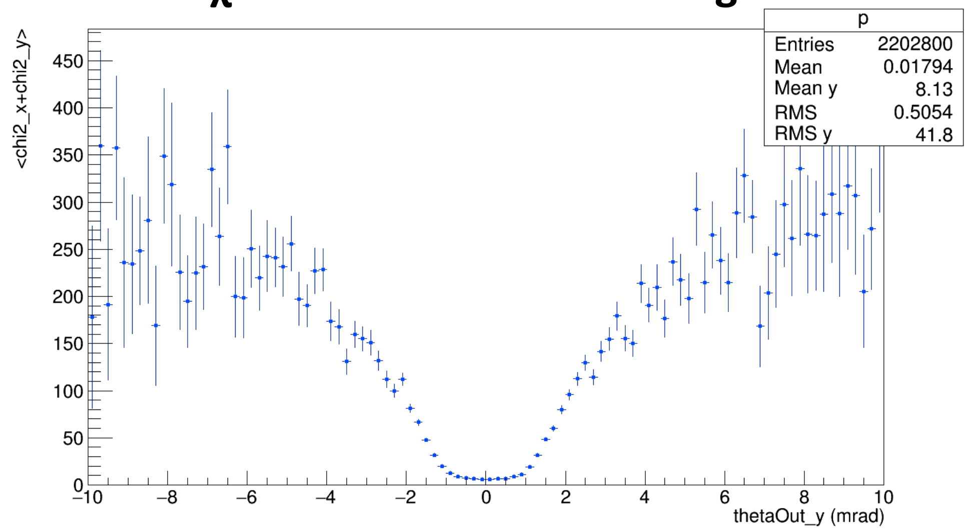


Agreement of the gaussian core of the distributions better than 1 %

Tracking low energetic electrons



χ^2 versus the diffusion angle



- Large scattering angles corresponds to low energy particles: MSC scales as 1/E.
- The χ^2 of a track can be act as an electron energy cut, to be used to get rid of events with low energy electrons Ee < 1 GeV.

Effects of the MSC

10 mm of Carbon, density 19.319 g/cm^3

Energy E = 0.1 GeV

$\sigma = 13.6/\mathbf{0.1}*\mathrm{sqrt}(0.1/19.319)*(1.+0.038*\log(0.1/19.319))$

7.82755

On the length scale of 10 cm it correspond to 80 micron.

The hit resolution of the silicon tracker is of the order of 10 micron.

Energy E = 1 GeV

$\sigma = 13.6/\mathbf{1.}*\mathrm{sqrt}(0.1/19.319)*(1.+0.038*\log(0.1/19.319))$

0.782755 mrad

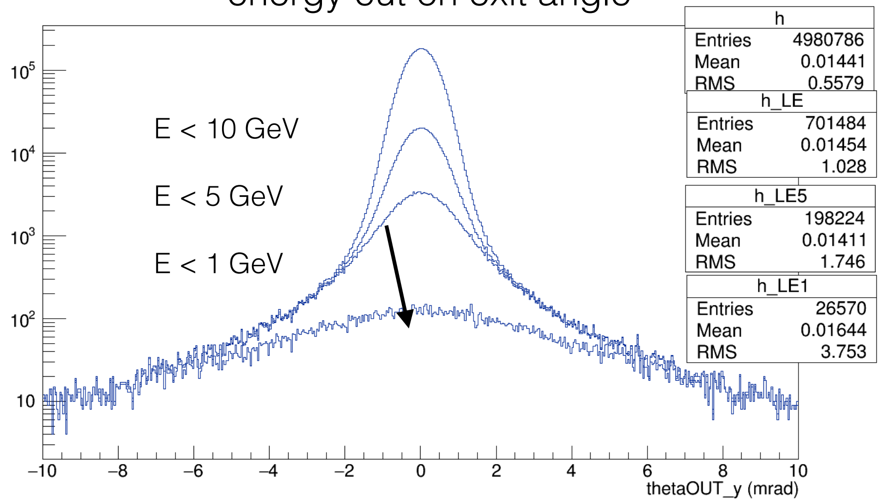
Energy E = 10 GeV

$\sigma = 13.6/\mathbf{10.}*\mathrm{sqrt}(0.1/19.319)*(1.+0.038*\log(0.1/19.319))$

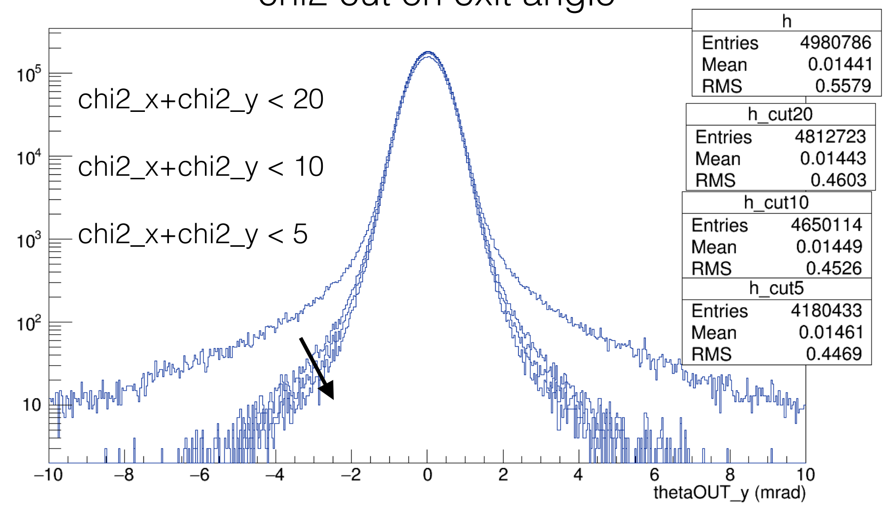
0.0782755 mrad

Effects of the MSC

energy cut on exit angle

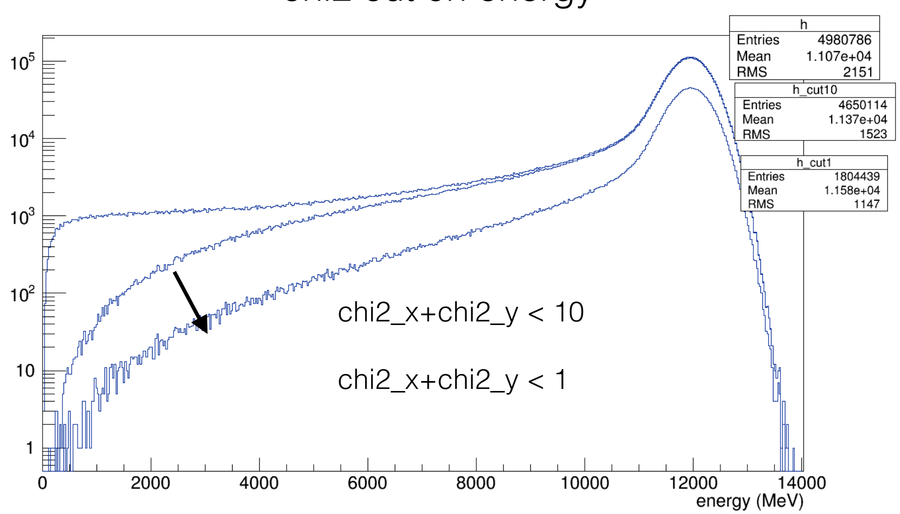


chi2 cut on exit angle

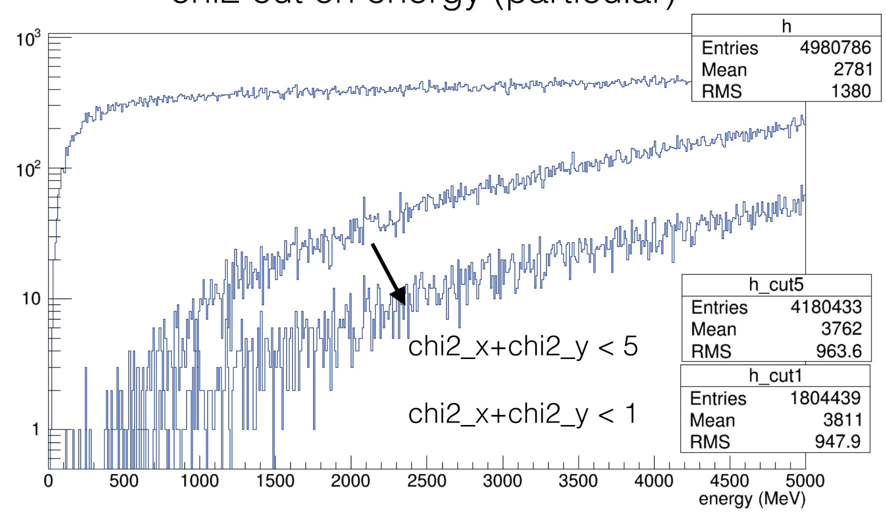


12 GeV e-, 3% uncertainty, on 8 mm C target

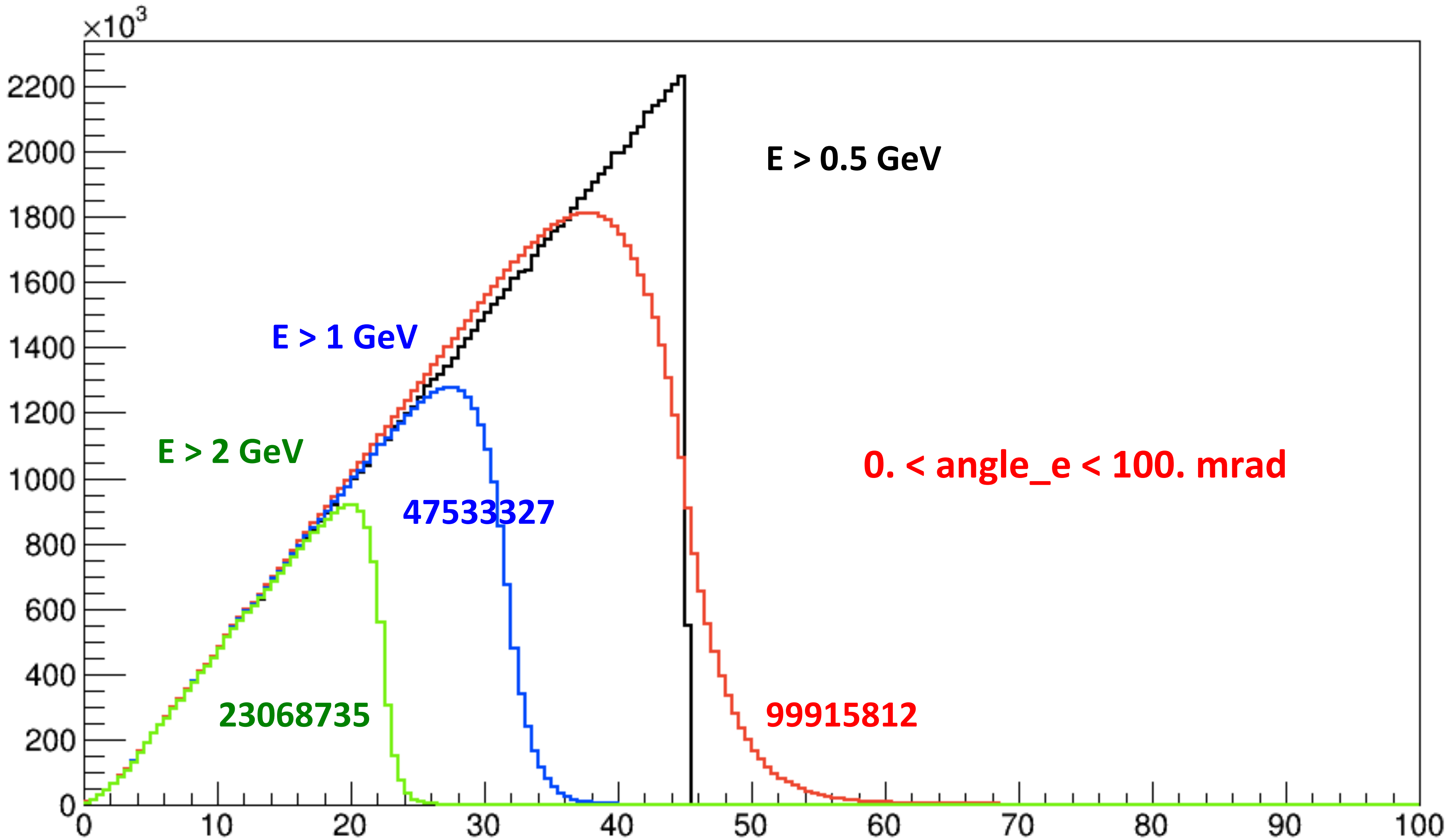
chi2 cut on energy



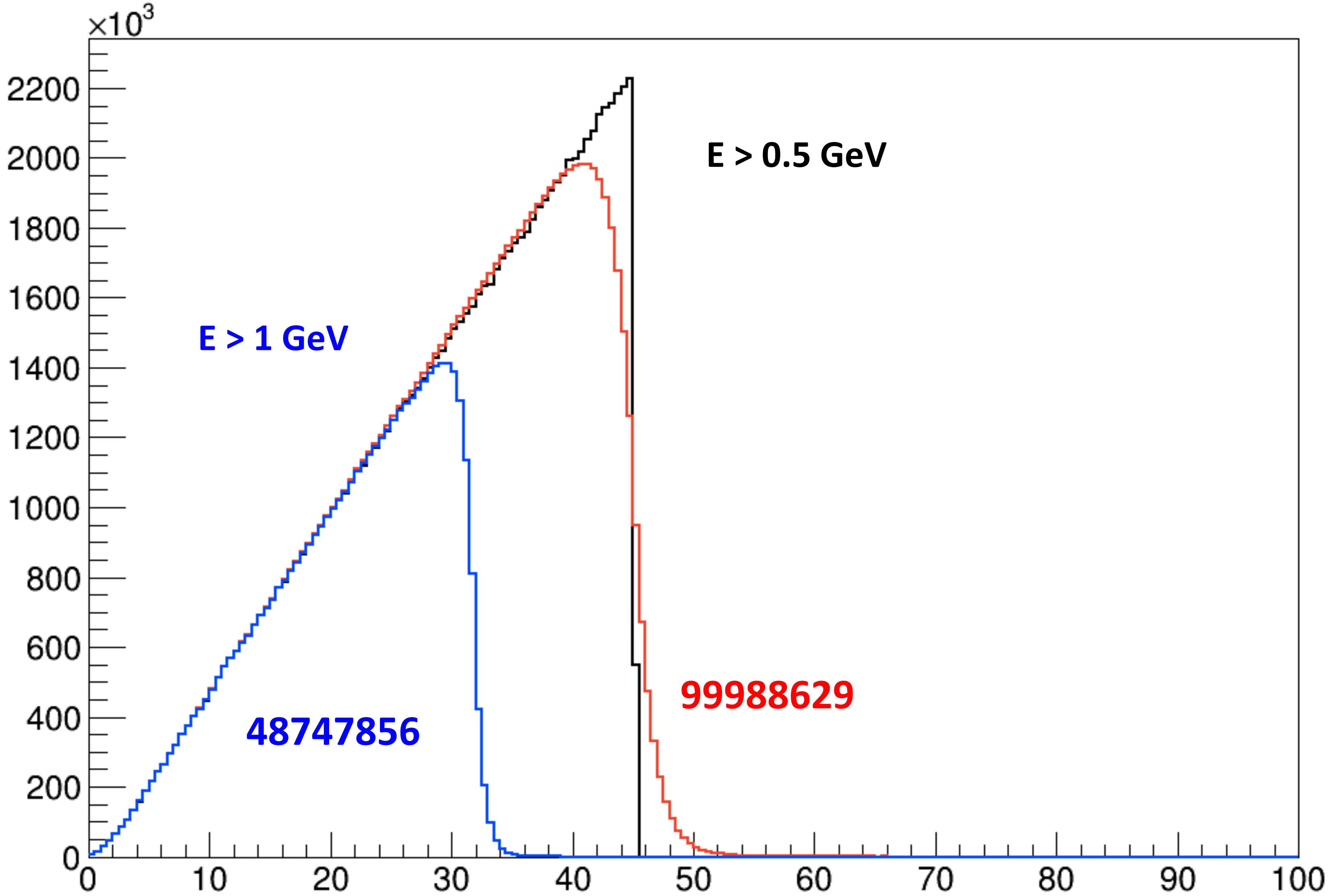
chi2 cut on energy (particular)



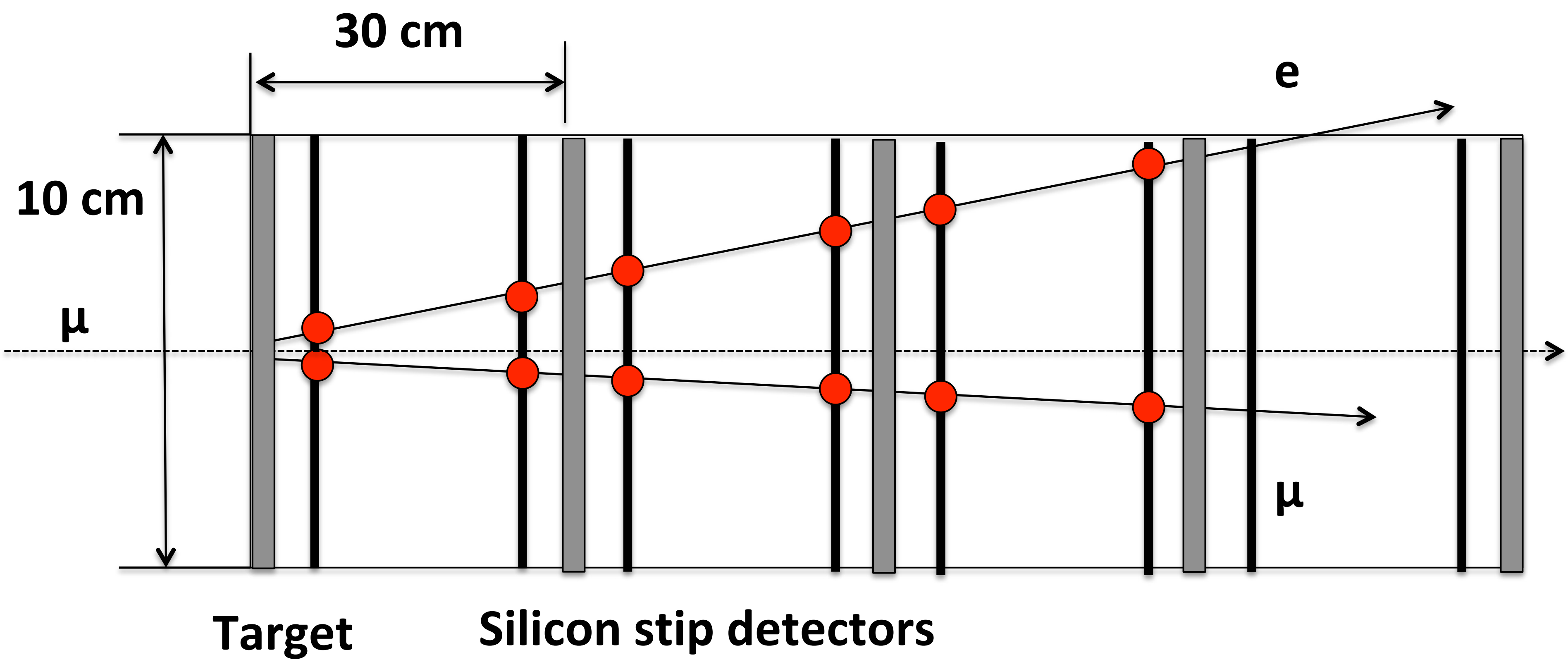
Target thickness D =20 mm



Target thickness D = 5 mm

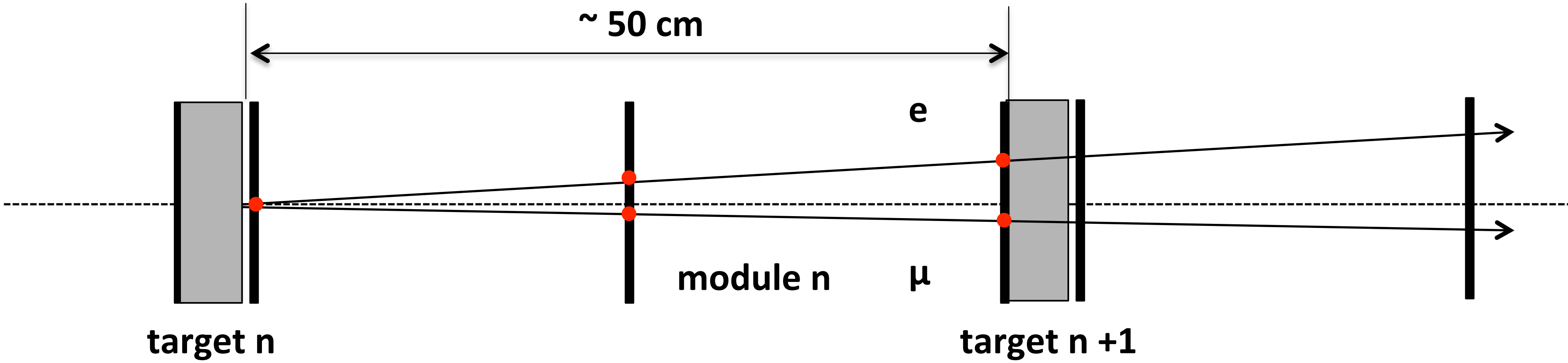


Measuring electron and muon angles

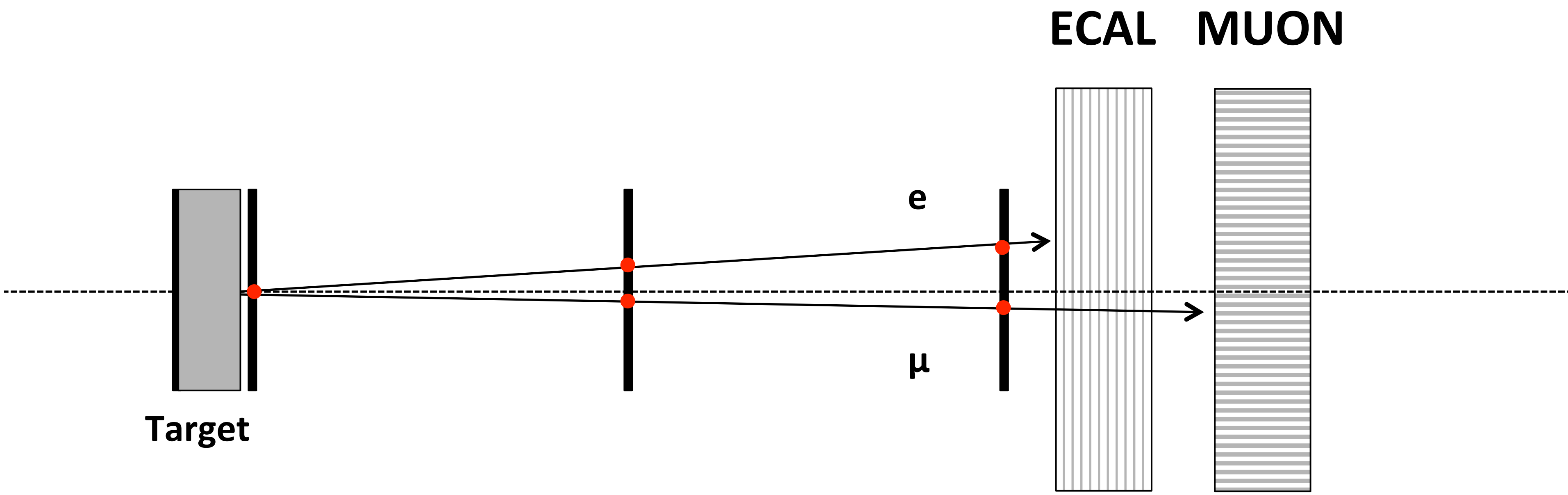


hit resolution ~10 μm

expected angular resolution ~ 10 μm / 0.5 m = 0.02 mrad

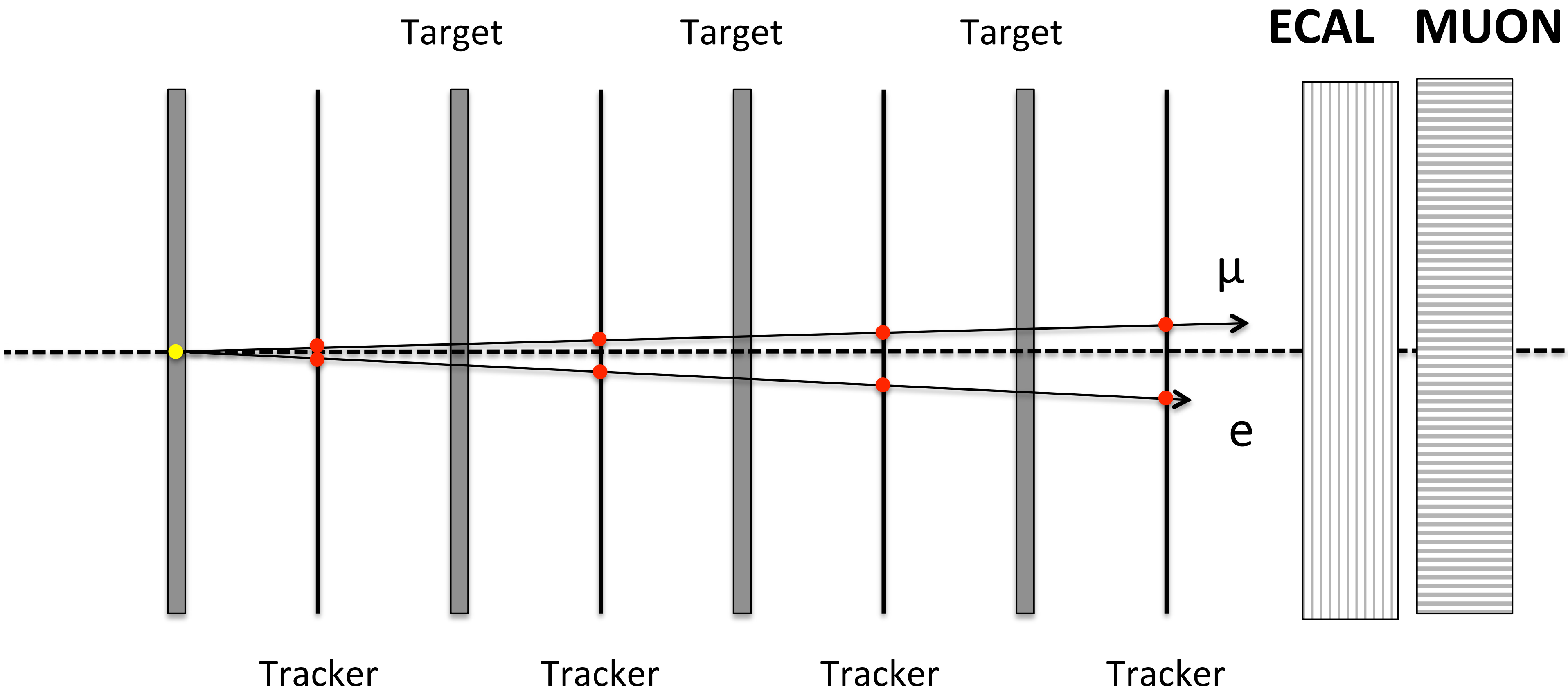


Last module of the detector



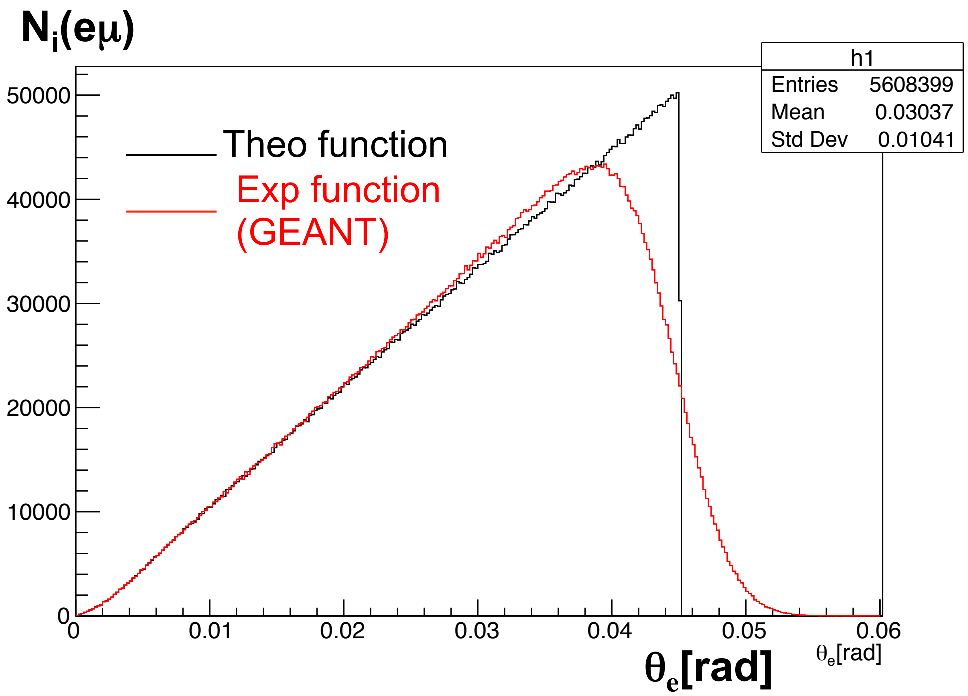
Measure both the electron angle and E_e to define the reference, calibration curve. Detailed check of GEANT

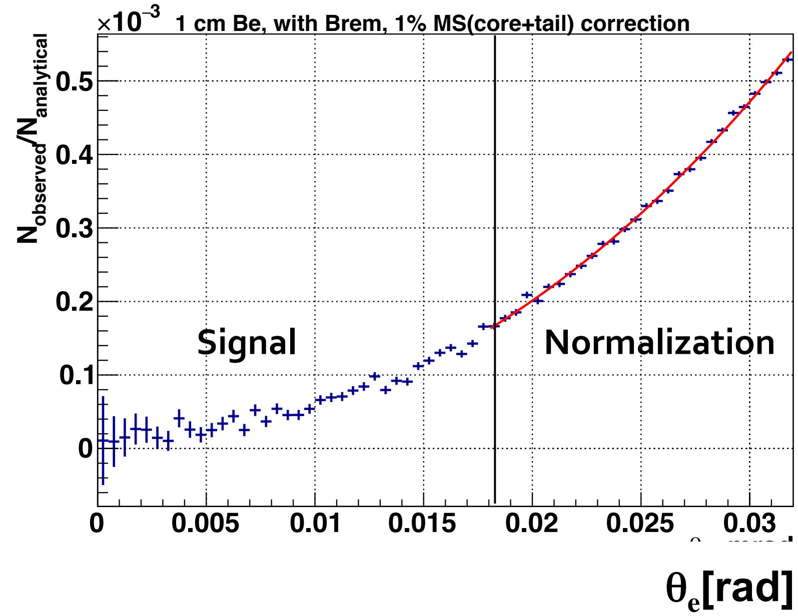
Detector layout

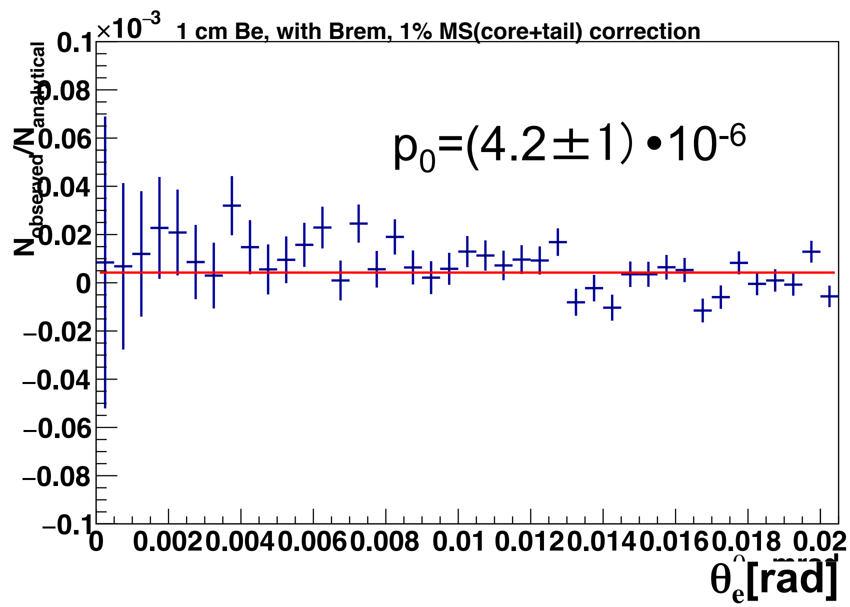


Multiple Scattering resolution:

a worst-case scenario







- The detector effects (mostly MS in the target) modify the theoretical spectrum ($N(q_e)$)
- We assume a 1% miscalibration on the GEANT model for s_{qe} MS (N_{mis})
- N_{mis} quadratically in q_e respect to NO bias (N_i)
- By correcting N_{mis}/N_i in the normalization region → residual effects $<10^{-5}$ in the signal region

Measuring the muon beam energy
The energy scale: <Eμ>

In collaboration with
F. Ignatov, G. Venanzoni

General Formalism

Observable angles

$$\theta_{e,\mu}(E_\mu, \theta^*) = \arctan \frac{p^* \sin\theta^*}{\gamma(\pm p^* \cos\theta^* + \beta E^*_{e,\mu})}$$

Center of mass

$$\gamma = \frac{E_\mu + m_e}{\sqrt{s}} = \frac{E_\mu + m_e}{\sqrt{m_\mu^2 + m_e^2 + 2\, m_e\, E_\mu}} \qquad E^*_{e,\mu} = \sqrt{p^{*\,2} + m^2_{e,\mu}} \qquad p^* = \frac{p_\mu\, m_e}{\sqrt{s}}$$

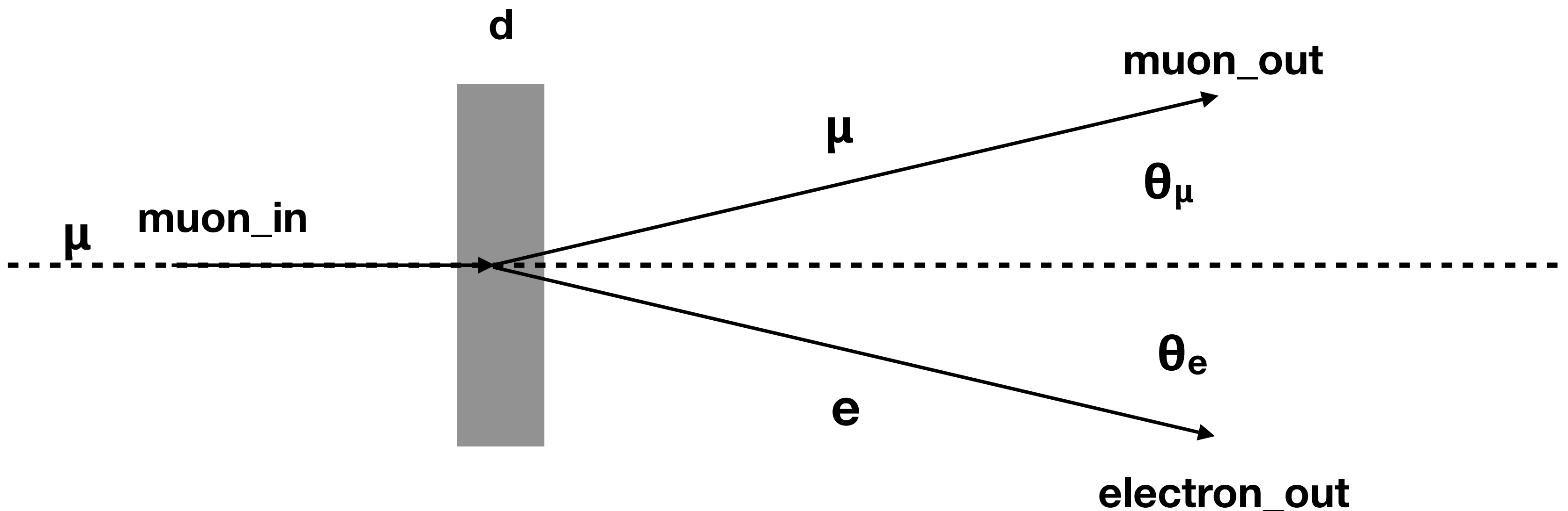
$$\chi^2 = \frac{1}{2(1-\rho^2)} \left[\frac{(\bar\theta_e - \theta_e)^2}{\sigma_e^2} + \frac{(\bar\theta_\mu - \theta_\mu)^2}{\sigma_\mu^2} - 2\rho \frac{(\bar\theta_e - \theta_e)(\bar\theta_\mu - \theta_\mu)}{\sigma_e\,\sigma_\mu} \right]$$

$$p(E_\mu | \{\bar\theta_e, \bar\theta_\mu\}_k) \sim \int d\theta^*\, e^{-\chi^2_k(E_\mu,\theta^*)} \times p_0(E_\mu)$$

$$p_0(E_\mu) = p(E_\mu | \{\bar\theta_e, \bar\theta_\mu\}_{k-1})$$

Measurement Technique

Equal angles condition $\theta_\mu = \theta_e$



You can easily check that :

E' ~ E/2 = 75 GeV

$\theta_\mu = \theta_e \sim 2.5$ mrad

Small MSC effects 0.025 mrad

X

Equal angles condition

The equal angle condition, angle_e = angle_μ, implies:

$$\boxed{E'_e = \frac{(E_\mu + m_e)^2 - m_\mu^2 + m_e^2}{2(E_\mu + m_e)}}$$

$$E'_\mu = \frac{(E_\mu + m_e)^2 + m_\mu^2 - m_e^2}{2(E_\mu + m_e)}$$

$$E'_e = m_e \frac{1 + r^2 cos^2\theta_e}{1 - r^2 cos^2\theta_e}$$

$$r^2 \equiv \frac{E_\mu^2 - m_\mu^2}{(E_\mu + m_e)^2}$$

$$\boxed{cos^2\theta_e = \frac{x-1}{x+1} \times \frac{1}{r^2}}$$

$$x \equiv \frac{(E_\mu + m_e)^2 - m_\mu^2 + m_e^2}{2m_e(E_\mu + m_e)}$$

X

Muon beam energy with 5 10^5 events

We considered a beam resolution 1%

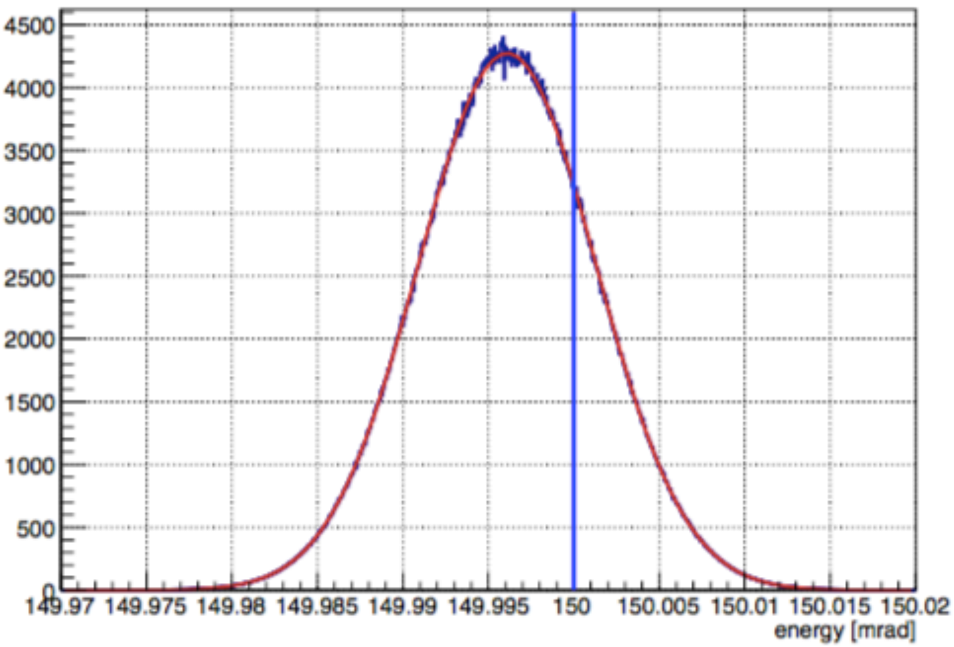


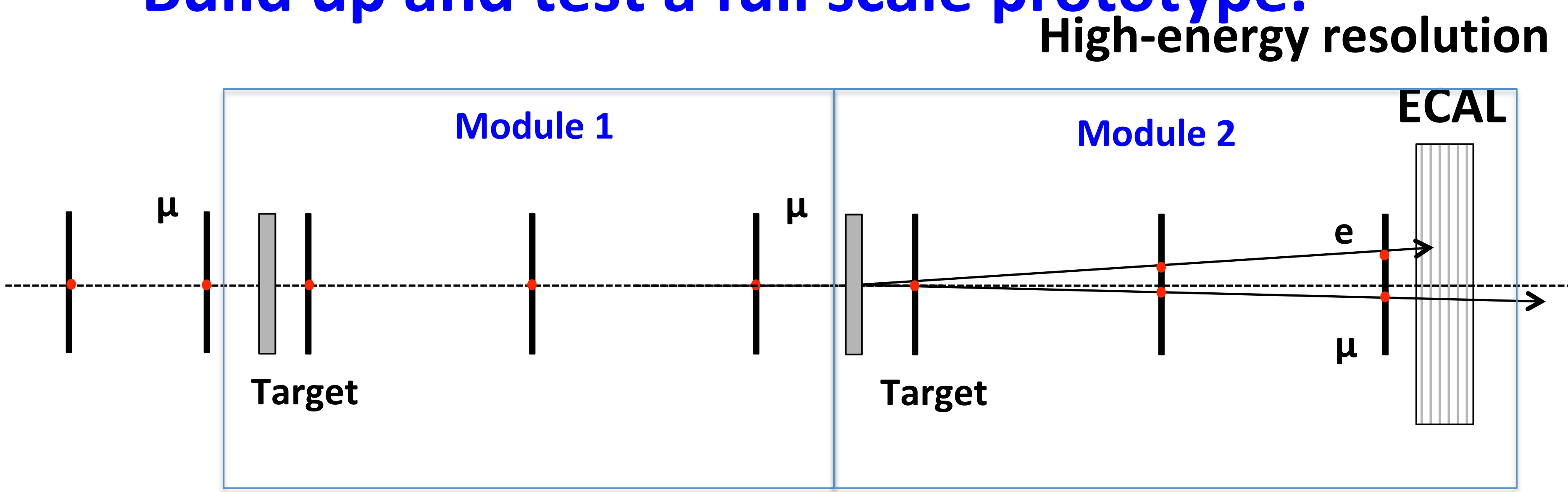
Figure 11: **Effect on the reconstructed energy of the difference between the mean value of the angular distribution and the true value of the angle for the case $E_\mu = 150$ GeV. The reconstructed energy turns out to be $E_\mu = 149.996 \pm 0.005$ GeV.**

Trigger

- Ideas in the next talk, by S. Mersi
- Triggered vs un-triggered working mode?
- Triggering on what type of a signature?
- Active scintillator targets to trigger the DAQ?

Plans for 2018

- **Build up and test a full scale prototype.**



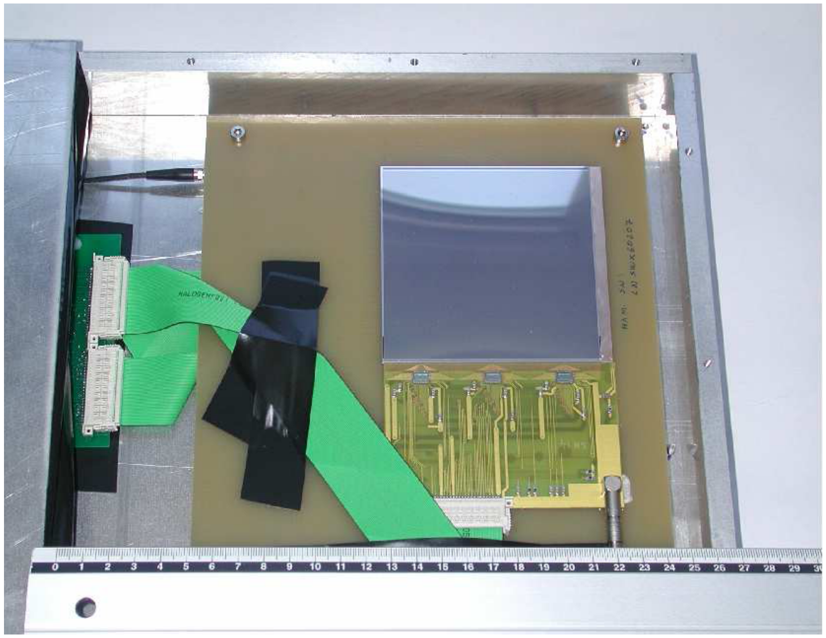
Some of the strip planes (x,y) already exist.
5 strip planes, have to be built:
10 single sided strip detectors

The silicon detectors

- Sensors developed for AGILE, being used by LEMMA

Table 1
Main features of the AGILE silicon detector

Item	Value
Dimension (cm^2)	9.5×9.5
Thickness (μm)	410
Readout strips	384
Readout pitch (μm)	242
Physical pitch (μm)	121
Bias resistor (MΩ)	40
AC coupling Al resistance (Ω/cm)	4.5
Coupling capacitance (pF)	527
Leakage current (nA/cm^2)	1.5



M. Prest et al., NIM A, 501:280–287, 2003

Daniela Lietti, PhD thesis. VISION: a Versatile and Innovative SIlicON tracking system

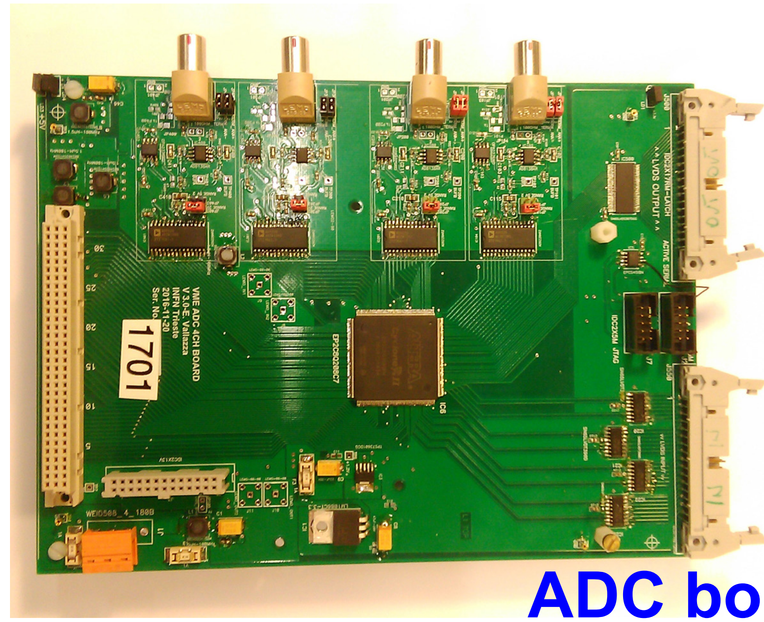
http://insulab.dfm.uninsubria.it/images/download_files/thesis_phd_lietti.pdf

Il readout

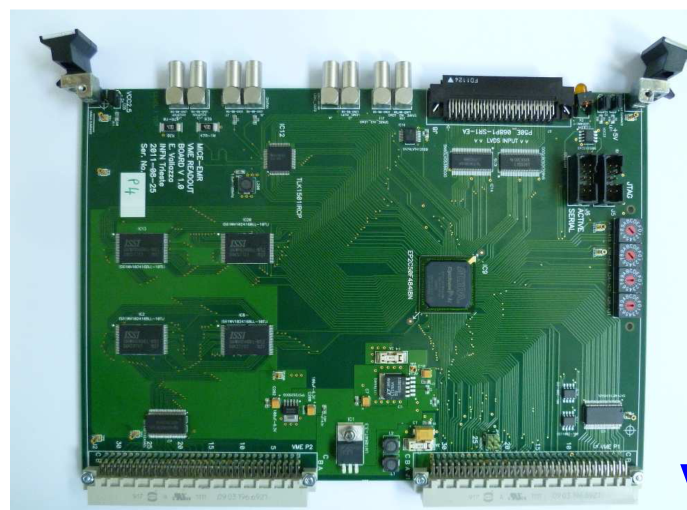
Readout electronics

- Zero suppression mode
- 1 ADC board per 4 moduli single side
- 1 VME Readout Board per leggere gli ADC e immagazzinare i dati durante la spill
- Readout speed → 6 kHz → questo numero può salire a 15 kHz se ognuno dei 3 ASIC che leggono una vista è letto in modo indipendente (e non in una daisy chain a 3 come succede adesso) → è possibile solo costruendo moduli nuovi

Abbiamo materiale per costruire ulteriori 10 viste x-y



ADC board



VRB

Remote control dei detector e della DAQ

- ✓ Sistema di slow control per i power supply (con logging delle correnti e delle temperature)
- ✓ Il sistema è implementato tramite GPIB - Ethernet
- ✓ In caso di problemi il sistema entra in shutdown automatico
- ✓ Già implementato nella prima fase dei test di UA9 nel tunnel dell'SPS

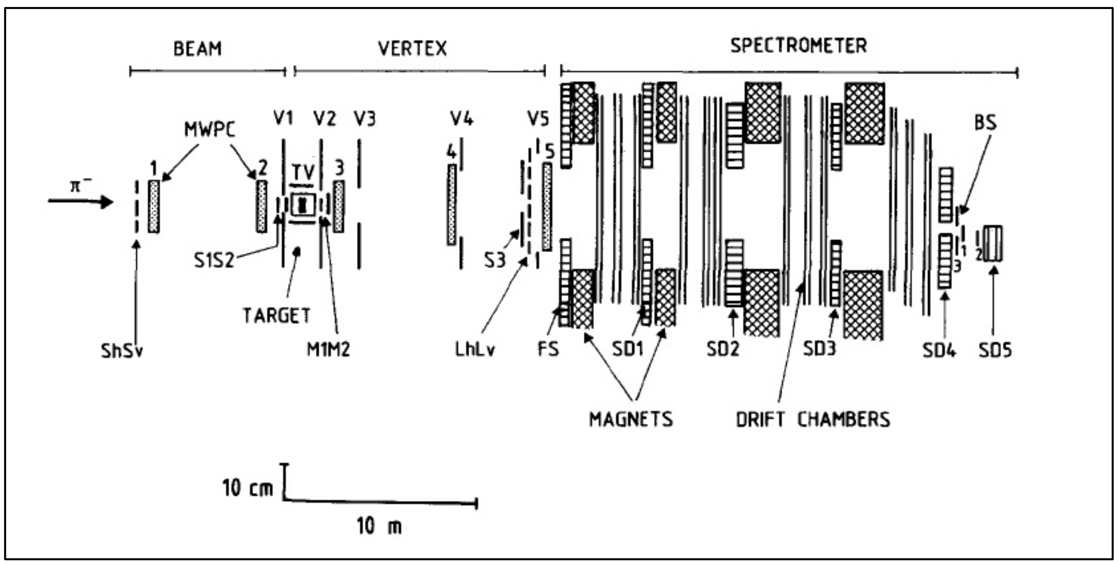
Plans

- LoI has to be ready, to be submitted to the CERN’s Physics Beyond Collider Committee, by Autumn 2018.
- By 2019 set up a Collaboration and move to a Technical Design Report with all the details to CERN’s PSSC for the experiment approval.
- Build the detector to be ready at the CERN restart

NA7 experiment

A MEASUREMENT OF THE SPACE-LIKE PION ELECTROMAGNETIC FORM FACTOR,

"The pion form factor has been measured in the space-like q^2 region 0.014 to 0.26 $(GeV/c)^2$ by **scattering 300 GeV pions from the electrons of a liquid hydrogen target**".



Target: 28 cm liquid Hydrogen
X_0 (liquid H_2) = 890.5 cm

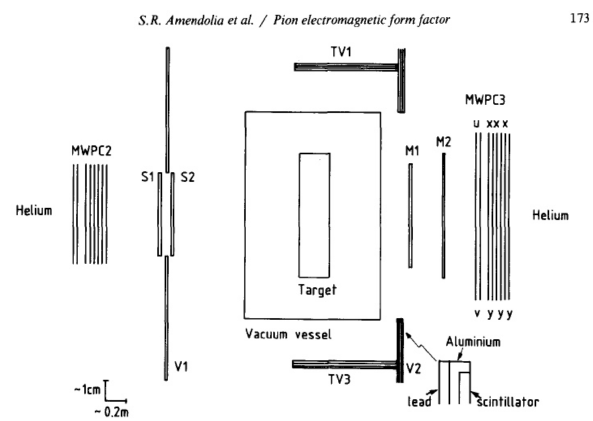


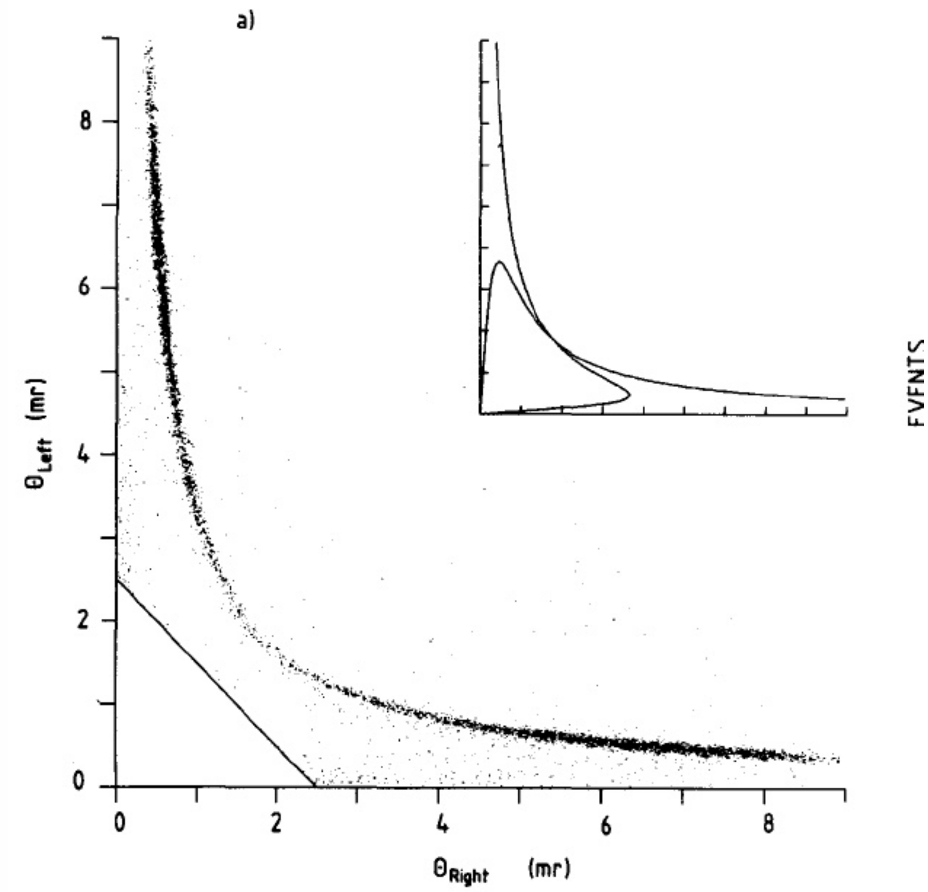
Fig. 4. Apparatus surrounding the target.

Nuclear Physics B277 (1986) 168-196

"**The q^2 variable for the final sample was determined from the angles alone**, up to the kinematic ambiguity which was resolved using the shower detectors. In this procedure the only rejection criterion involving the momenta was a cut against electrons of less than 1 GeV/c".

NA7 experiment

Elastic scattering in the (θ_R, θ_L) plane



"The scatter distribution of the measured polar angles of the right and left-going particles (θ_R, θ_L). Our estimate of q^2 was made from the point on the theoretical kinematic curve nearest to these angle coordinates".

Coplanarity

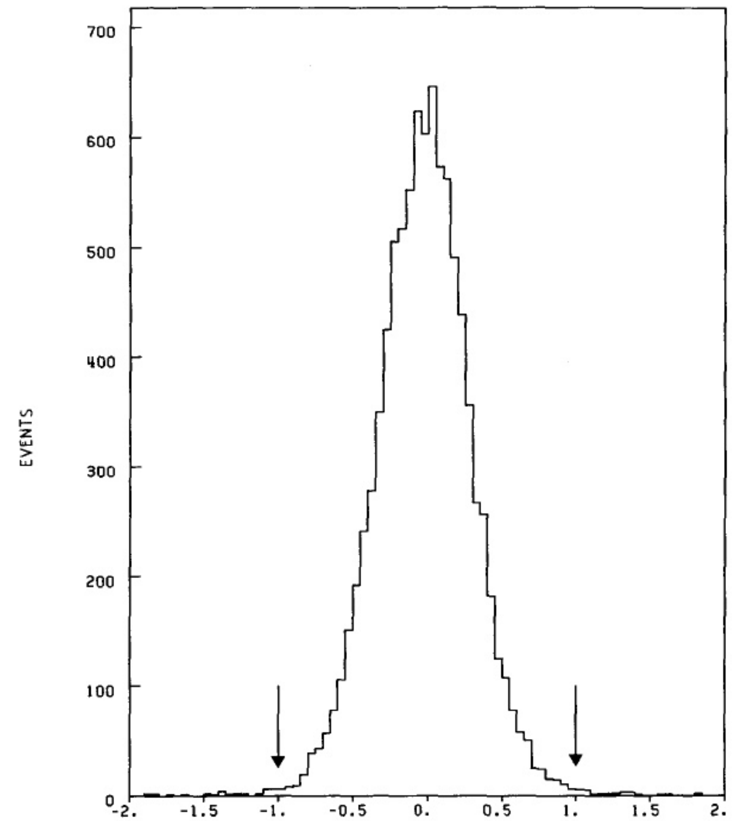


Fig. 8. The distribution of the triple scalar product of unit vectors along the incident and scattered tracks, in units of the applied cut. This varied smoothly with decreasing opening angle from 1.1×10^{-6} to 0.6×10^{-6}.

"A fraction of the hadronic background was rejected by requiring coplanarity of the incident and scattered tracks"

Detection principles (II)

PID capabilities