

# **Detection Technique (Geant4 v10.3 Studies)**

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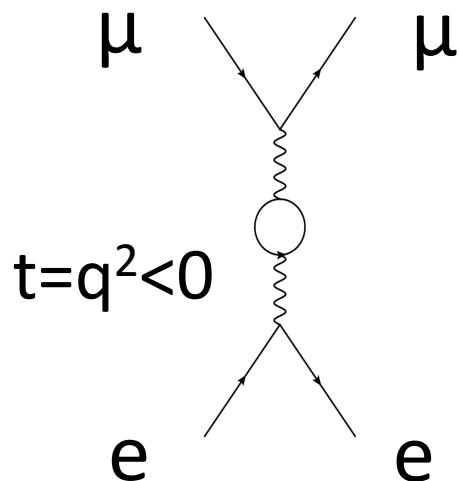
Padova, 04/09/2017

# The elastic scattering

$\mu + e(\text{rest}) \rightarrow \mu + e$

$\alpha(t)$  through:

$$\frac{d\sigma}{dt} = \frac{d\sigma_0}{dt} \left| \frac{\alpha(t)}{\alpha(0)} \right|^2$$

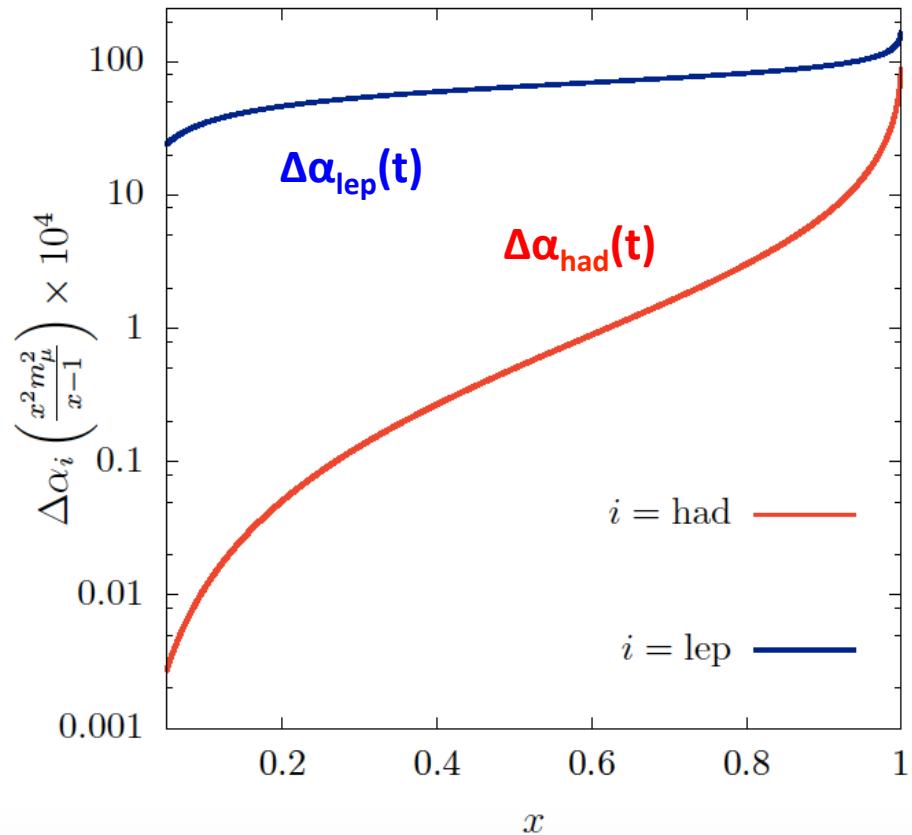


$$\alpha(t) = \frac{\alpha(0)}{1 - \Delta\alpha(t)}$$

$$\Delta\alpha(t) = \Delta\alpha_{\text{lep}}(t) + \Delta\alpha_{\text{had}}(t)$$

$$t = -m_\mu^2 \frac{x^2}{1-x} (10^{-3} \text{GeV}^2)$$

0.55      2.98      10.5      35.7       $\infty$



# $a_\mu^{HLO}$ space-like approach

- It requires just the single process  
 $\mu + e \rightarrow \mu + e$  elastic

High intensity CERN muon beam of  
 $E_\mu \sim 150$  GeV colliding on atomic  
electrons at rest.

- Highly boosted final state:**

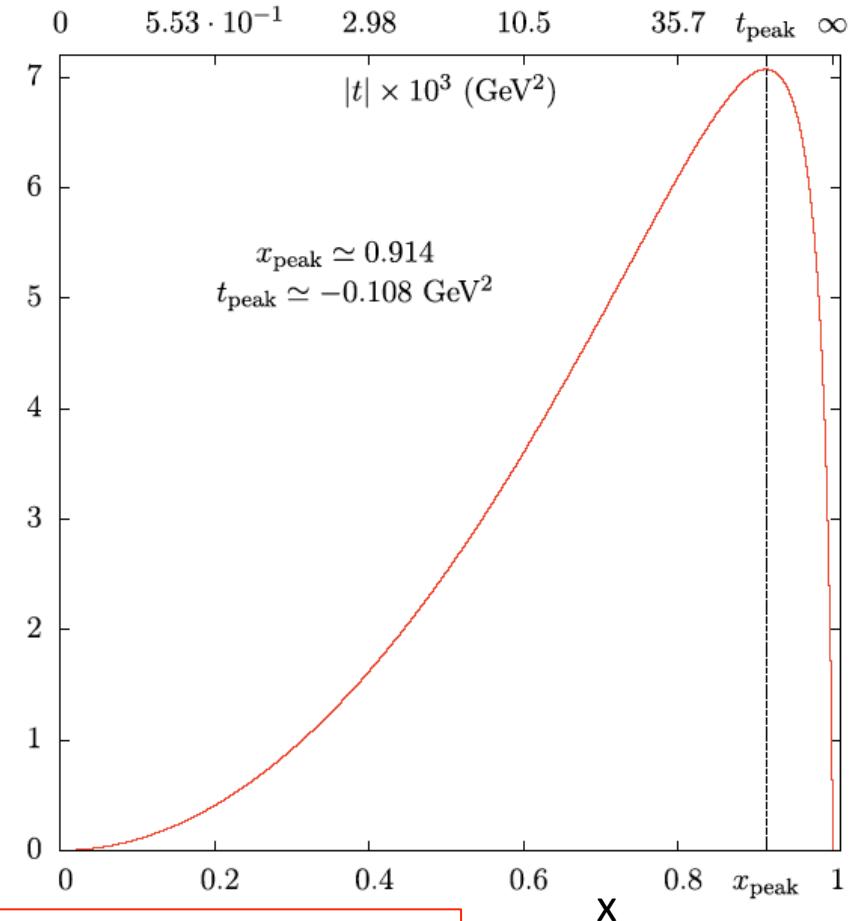
$$0 < -t < 0.161 \text{ GeV}^2$$

$$0 < x < 0.93 \text{ (peak is at } x = 0.914)$$

The range covers **87%** of the integral.

- Beyond the kinematics limit the  
integral (13%) can be determined using  
pQCD & time-like data, and/or lattice  
QCD results.

The expected shape of integral function



$$a_\mu^{HLO} = \frac{\alpha}{\pi} \int_0^1 dx (1-x) \cdot \Delta\alpha_{had} \left( -\frac{x^2 m_\mu^2}{1-x} \right)$$

# Muon beam M2 at CERN

“Forty years ago, on 7 May 1977, CERN inaugurated the world’s largest accelerator at the time – the Super Proton Synchrotron”.

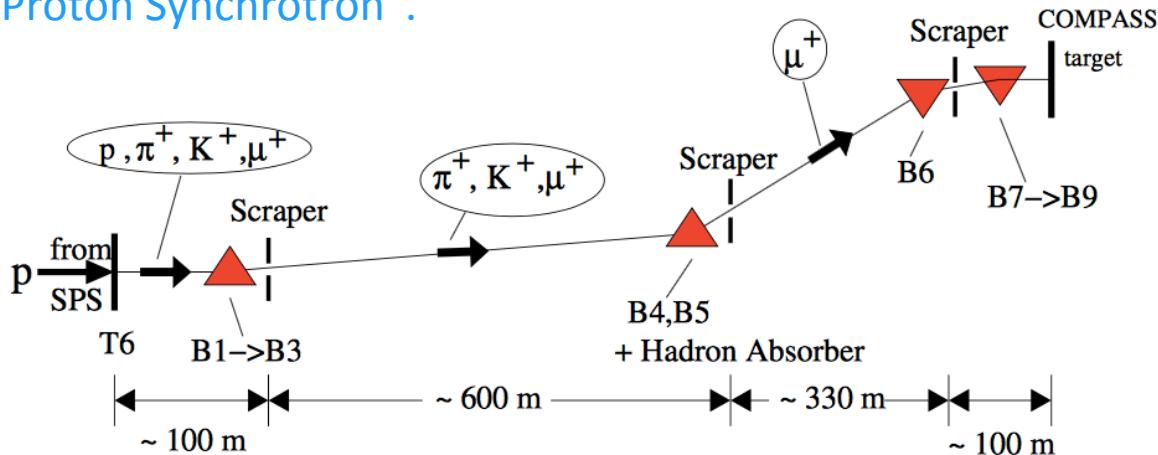


Table 3  
Parameters and performance of the 160 GeV/c muon beam.

Beam parameters	Measured
Beam momentum ( $p_\mu)/(p_\pi)$	(160 GeV/c)/(172 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 ( $\sigma_x \times \sigma_y$ )	$8 \times 8 \text{ mm}^2$
Divergence at COMPASS target ( $\sigma_x \times \sigma_y$ )	$0.4 \times 0.8 \text{ mrad}$
Muon halo within 15 cm from beam axis	16%
Halo in experiment ( $3.2 \times 2.5 \text{ m}^2$ ) at $ x, y  > 15 \text{ cm}$	7%

$I_{\text{beam}} > 10^7 \text{ muon/s}, E_\mu = 160 \text{ GeV}$

# Luminosity

The instantaneous luminosity can be calculated as:

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

where  $I_\mu$  is the intensity of the muon beam,  $\rho_e$  is the density of the electron scattering centers and  $d$  is the thickness of the target.  $\rho_e$  in turn can be expressed in terms of the material density  $\rho$ , the Avogadro's number  $N_A$ , the atomic number  $Z$  and the atomic weight  $W$ .

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

$$\mathcal{L}_{Be} = 3.9 \times 10^{32} \text{ cm}^{-2}\text{s}^{-1} = 0.39 \text{ nb}^{-1}\text{s}^{-1} \quad (2)$$

The required luminosity that can be collected in two years of data taking, assuming  $2 \times 10^7 \text{ s/yr}$  is:

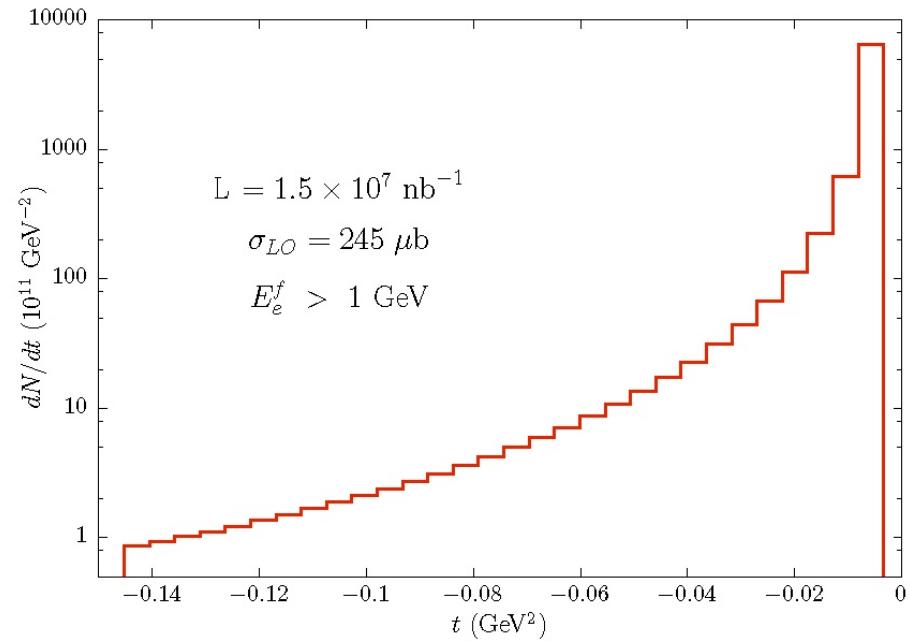
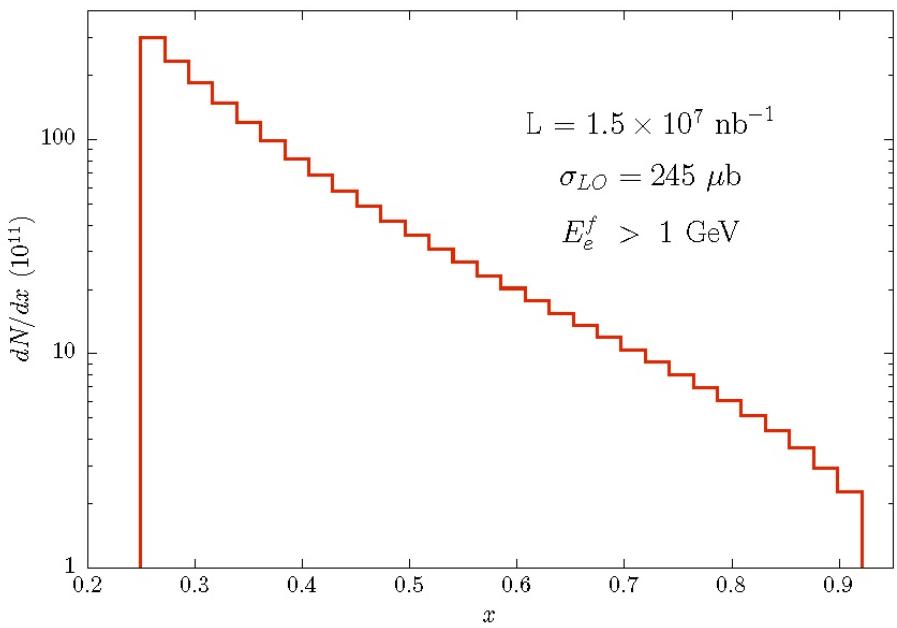
$$L_{Be} = 1.5 \times 10^7 \text{ nb}^{-1} \quad (3)$$

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

$$N = L_{Be} \times \sigma_{\mu e} \sim 4 \times 10^{12} \quad (4)$$

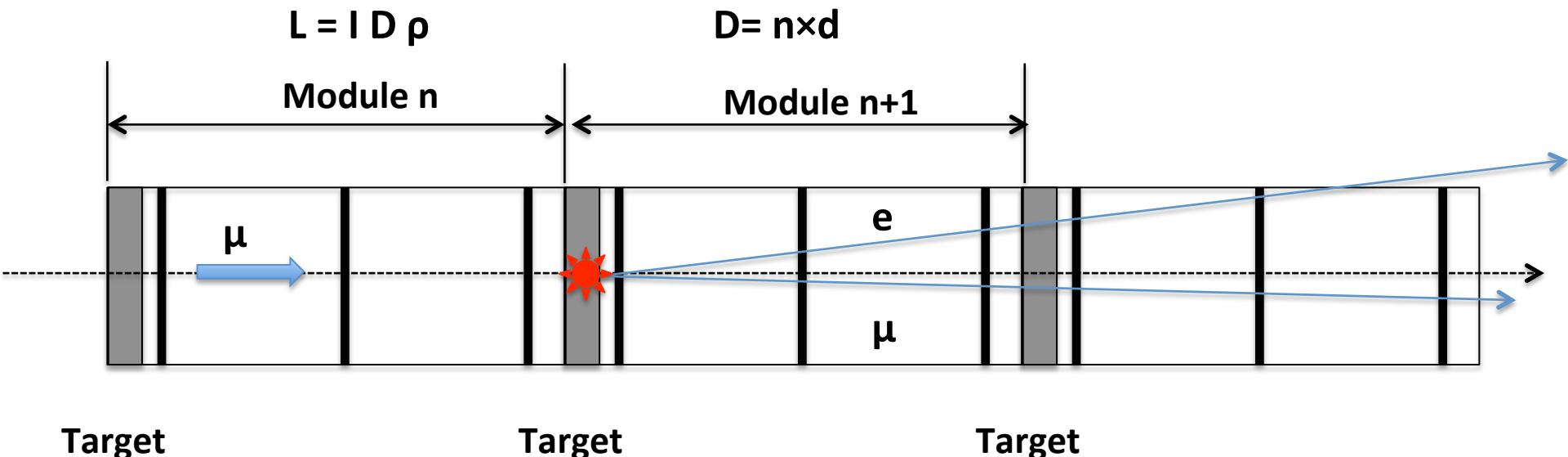
# Luminosity (II)

Monte Carlo Generated events



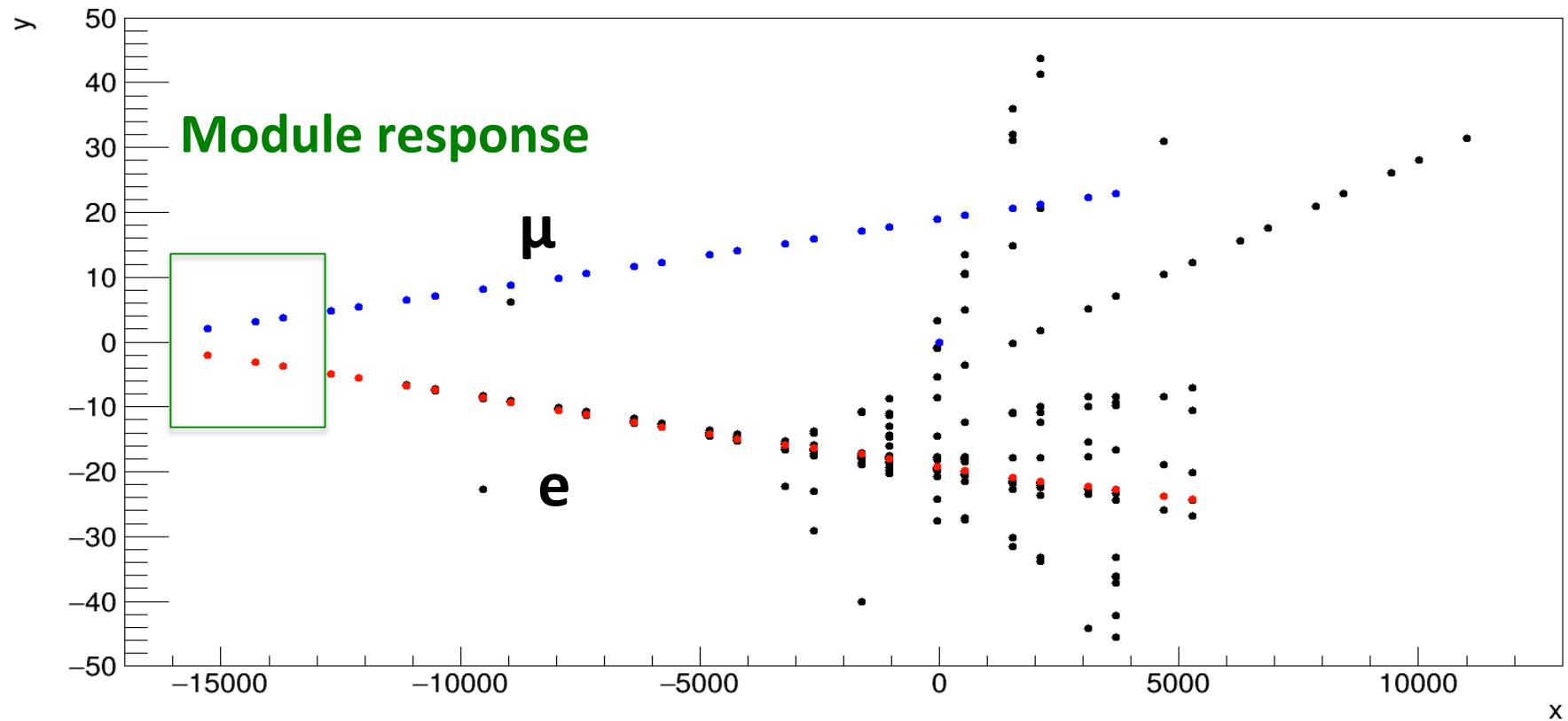
# Detection principles

- We need to 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, but has to let us track muons while passing through, in order to measure the muon direction at any stage.
- The detection module where the interaction would take place must act as a standalone, independent detector.

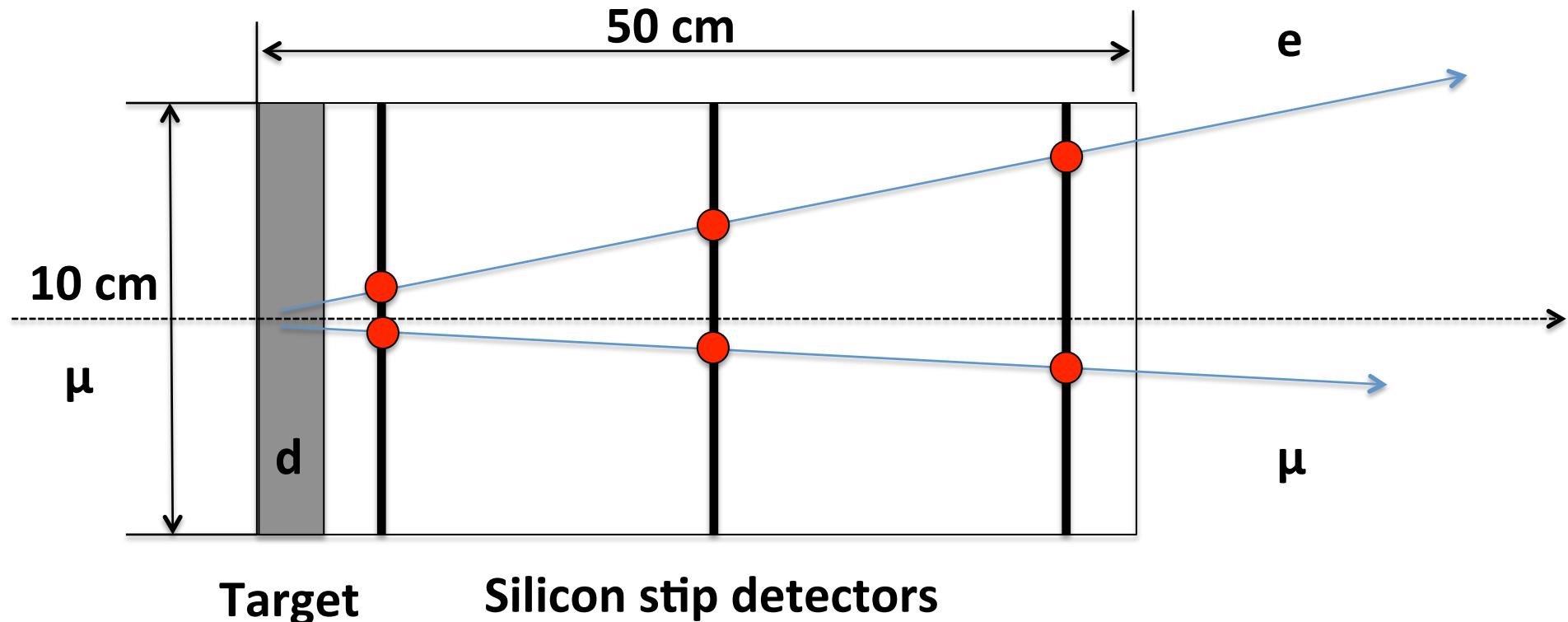


# Detection principle (II)

PID capabilities



# Measuring electron and muon angles

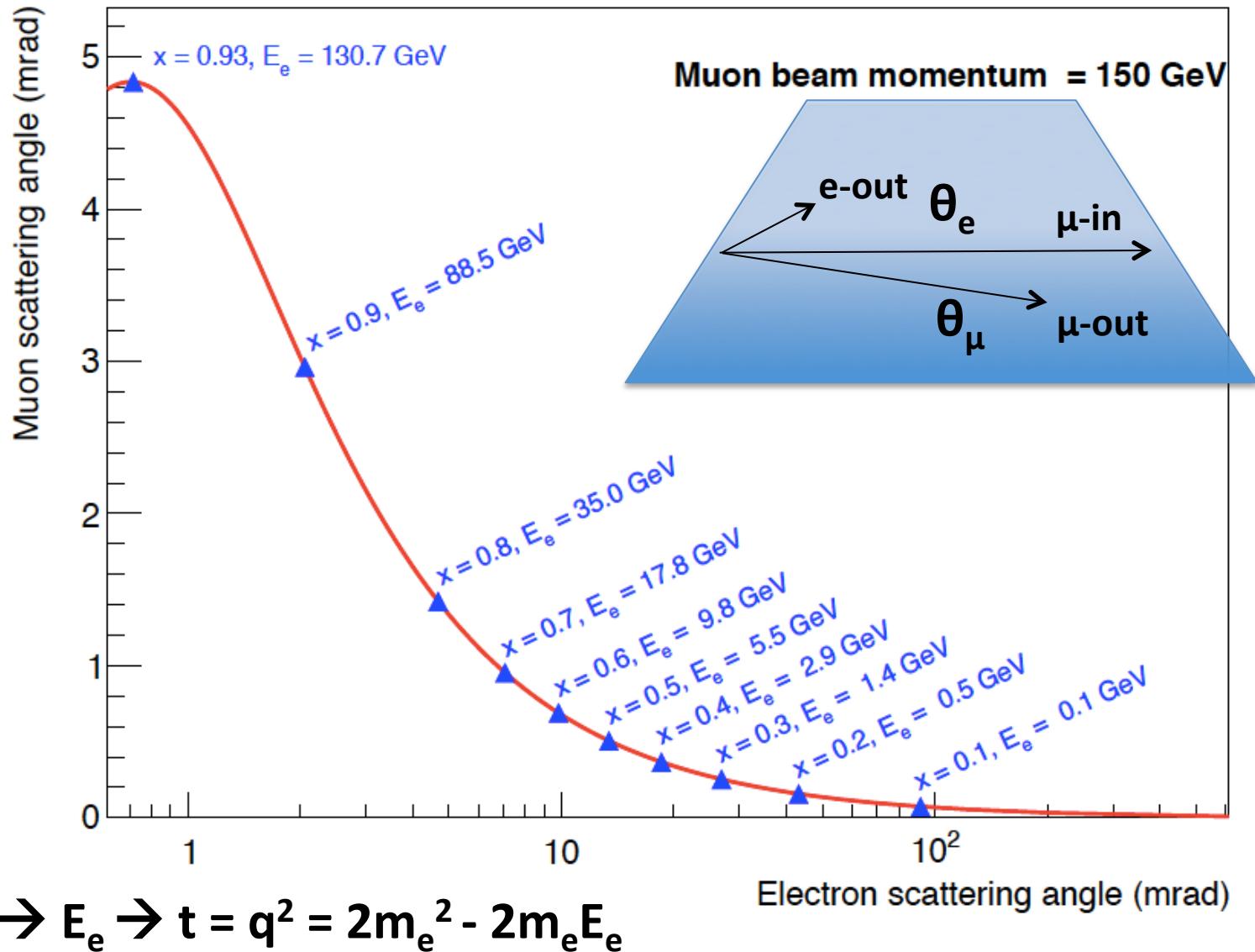


hit resolution  $\sim 10 \mu\text{m}$

expected angular resolution  $\sim 10 \mu\text{m} / 0.5 \text{ m} = 0.02 \text{ mrad}$

# Elastic scattering in the $(\theta_e, \theta_\mu)$ plane

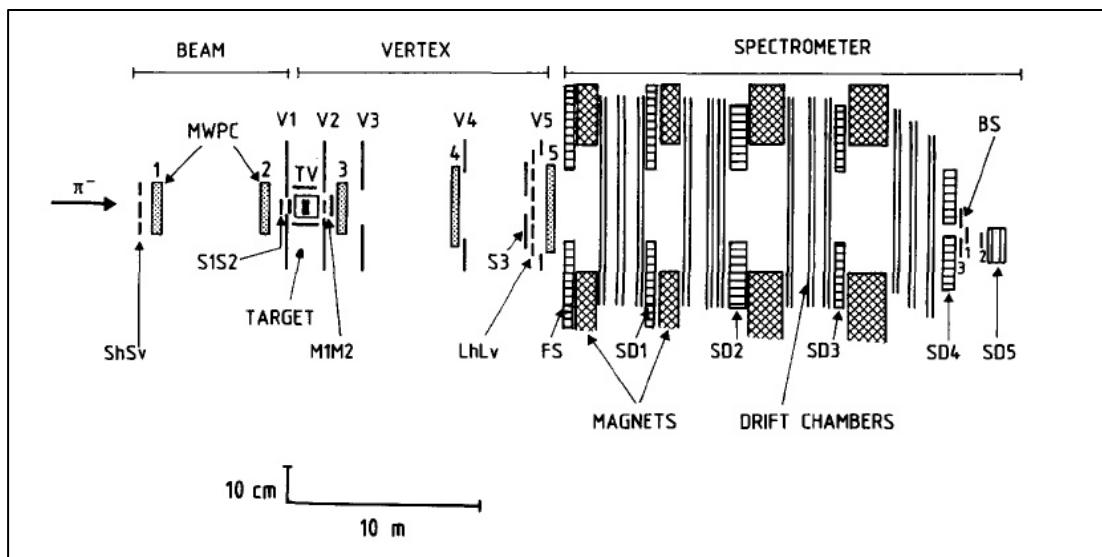
Coplanarity of the momentum vectors and angular kinematical constraint



# 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  $(\text{GeV}/c)^2$  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

S.R. Amendolia et al. / Pion electromagnetic form factor

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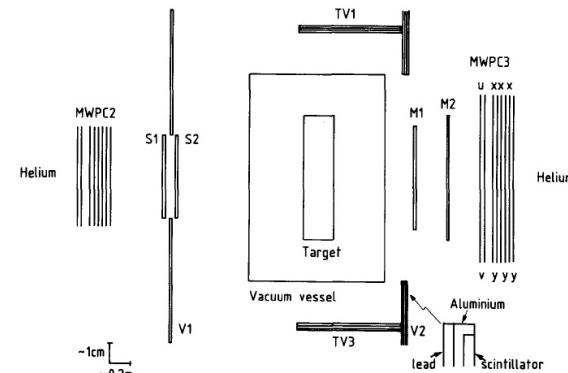
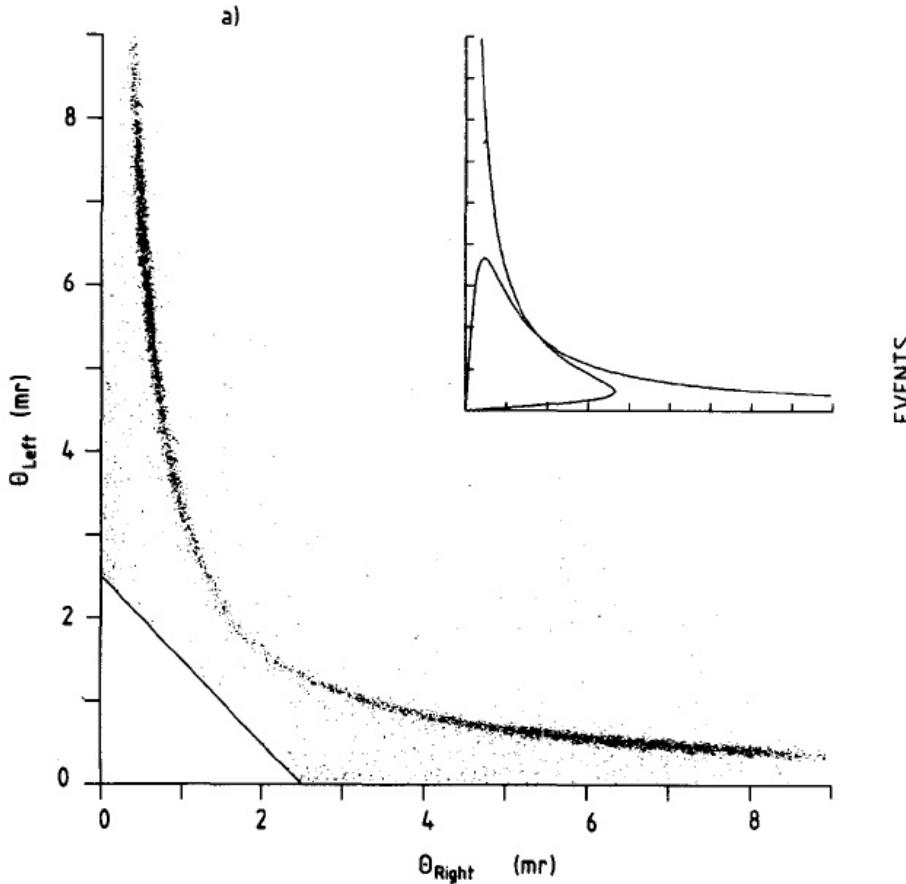


Fig. 4. Apparatus surrounding the target.

“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  $\text{GeV}/c$ ”.

# NA7 experiment

## Elastic scattering in the $(\theta_R, \theta_L)$ plane



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FVFNNTS

## Coplanarity

S.R. Amendolia et al. / Pion electromagnetic form factor

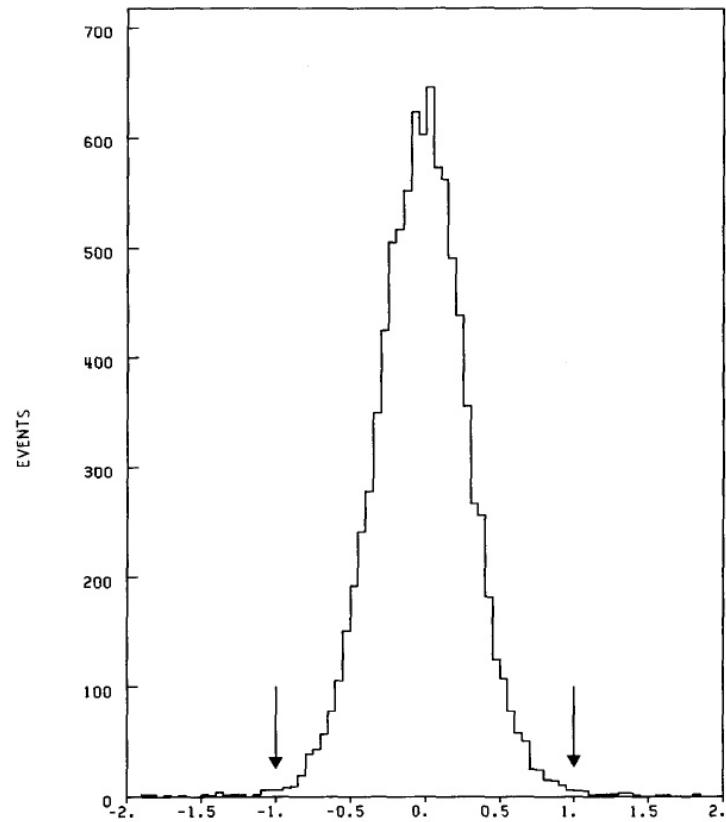


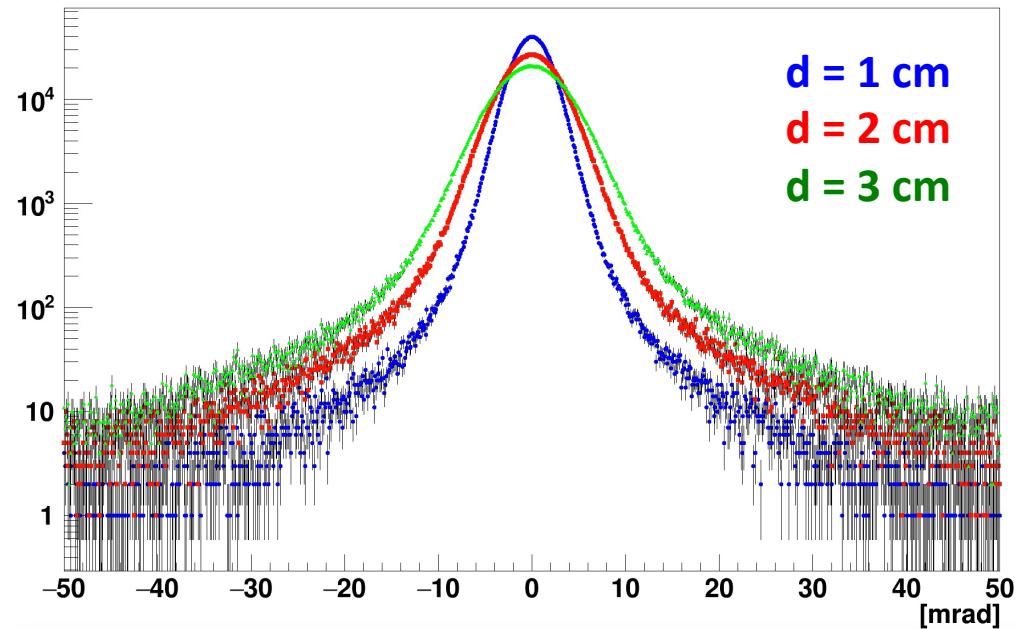
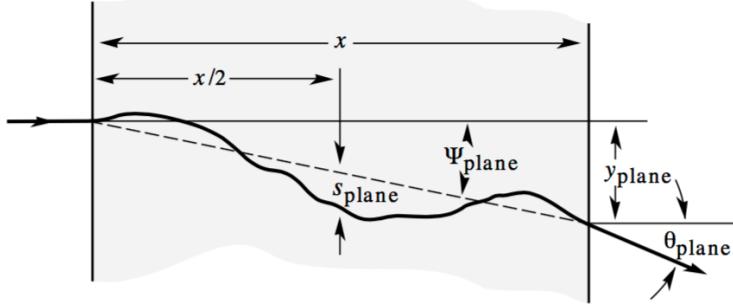
Fig. 8. The distribution of the triple scalar product of unit vectors along the incident and scattered tracks, in units of the applied cut. This varied smoothly with decreasing opening angle from  $1.1 \times 10^{-6}$  to  $0.6 \times 10^{-6}$ .

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

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

# Effect of Multiple Scattering (MSC)

GEANT4, 1 GeV electrons, Be target

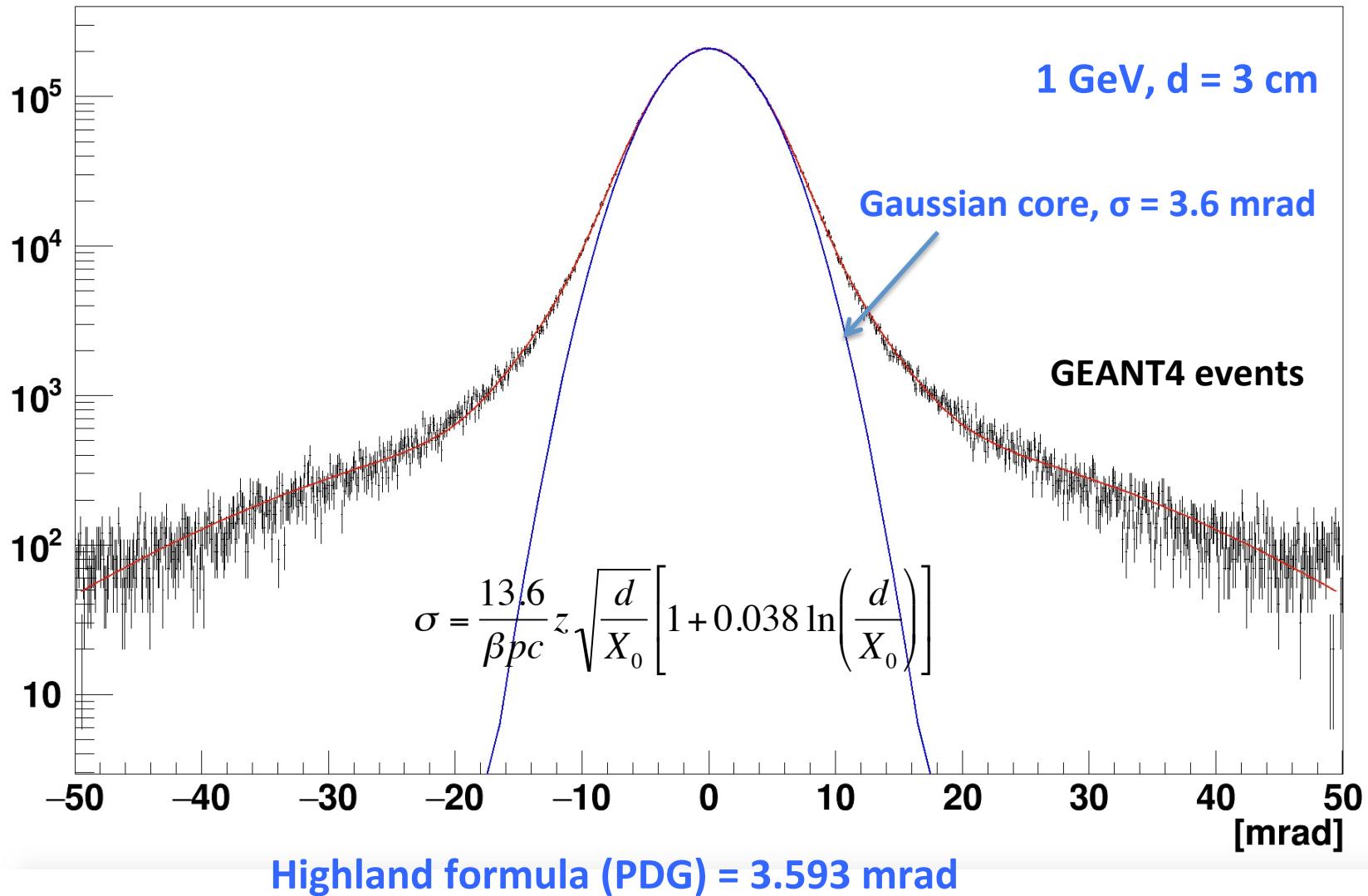


Vertices of the  $\mu + e \rightarrow \mu + e$  collisions will be uniformly distributed inside the target along the direction of the beam axis.

The observable angles (electron and muon angles) depend therefore on the particles' path length inside the material and on their energies.

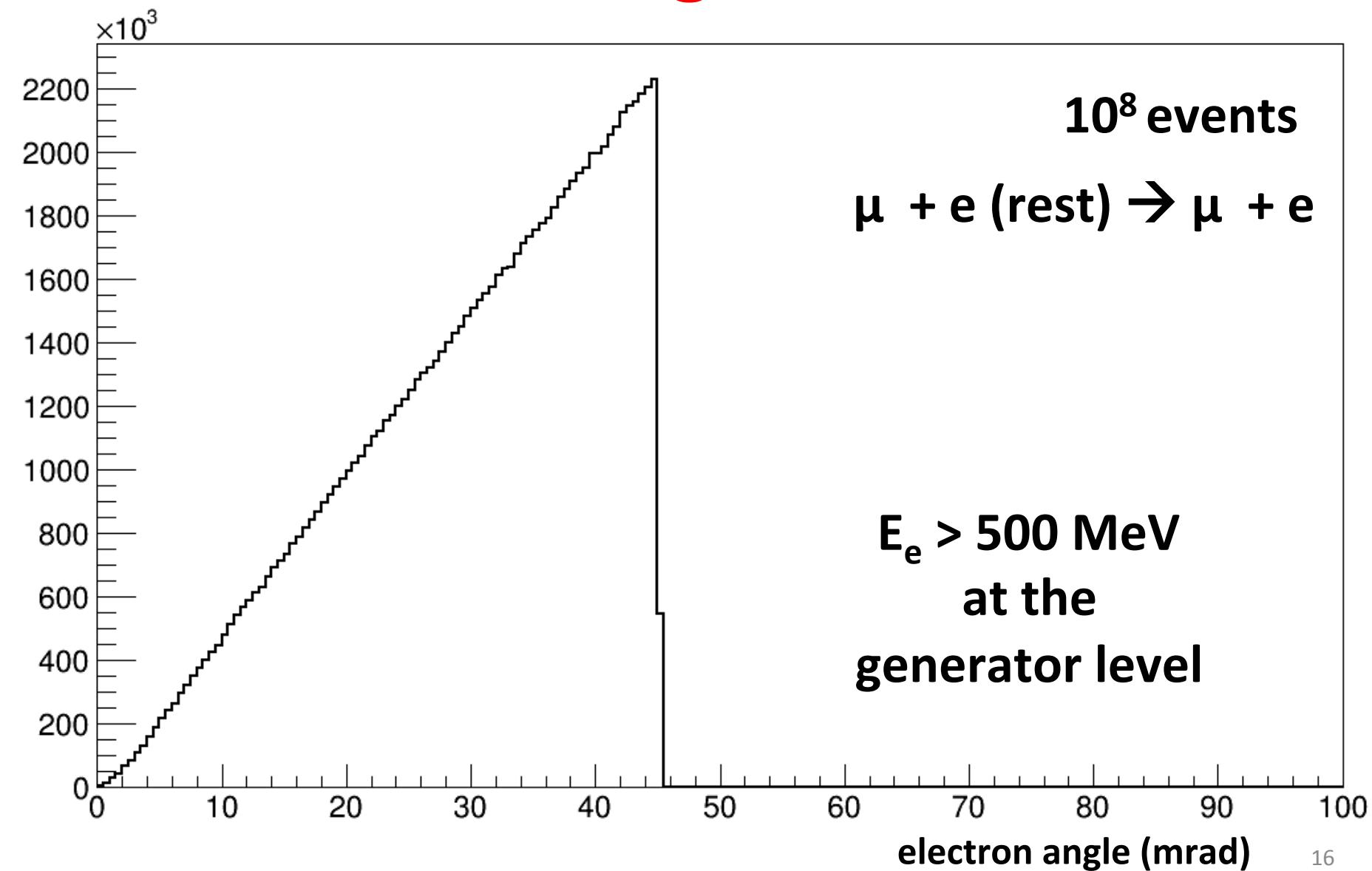
We need a **MSC model** to relate the observed angles to the scattering ones.

# Modeling the MSC

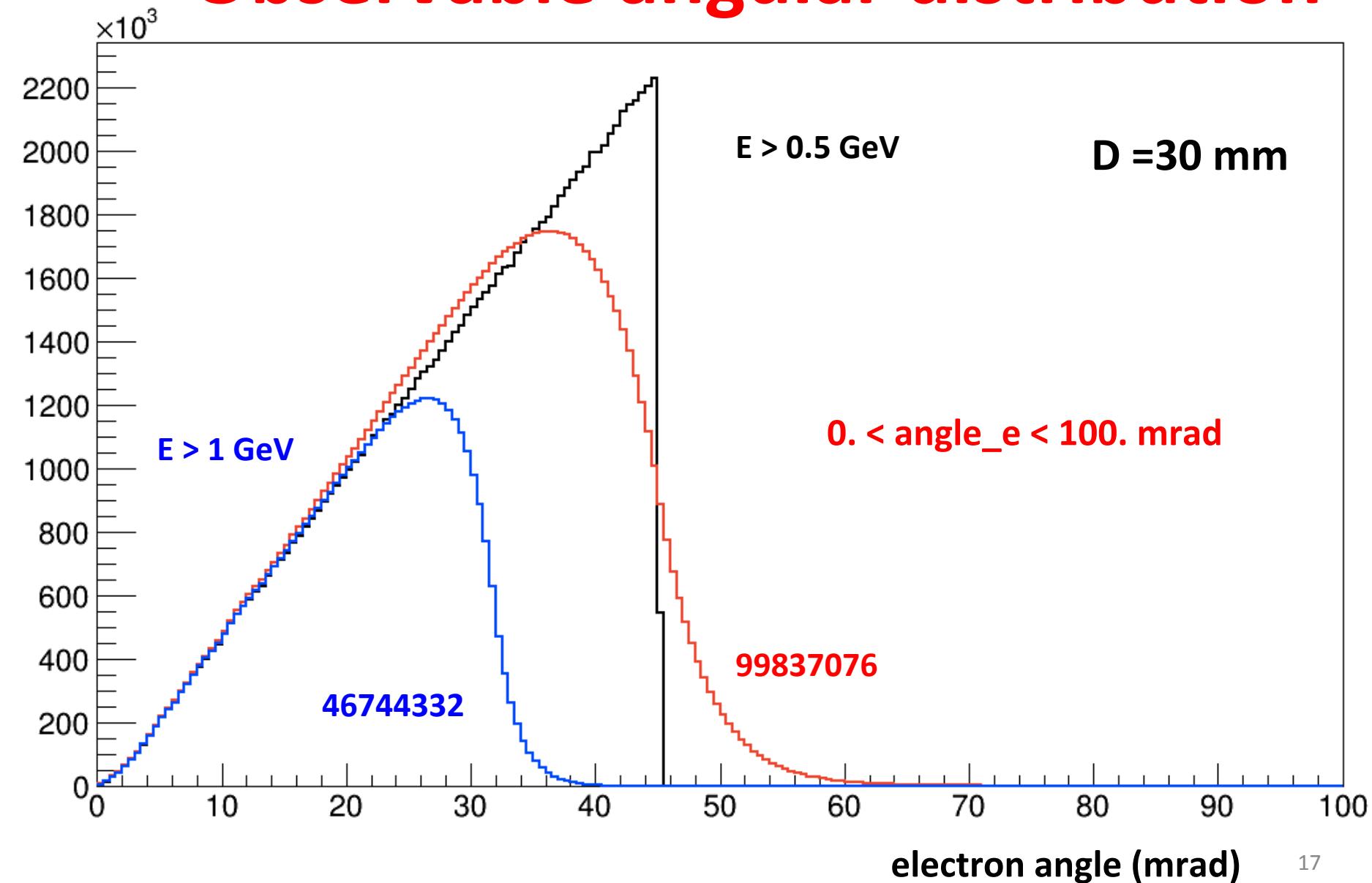


**20 detection modules**  
**Beryllium target of  $d = 30$  mm**

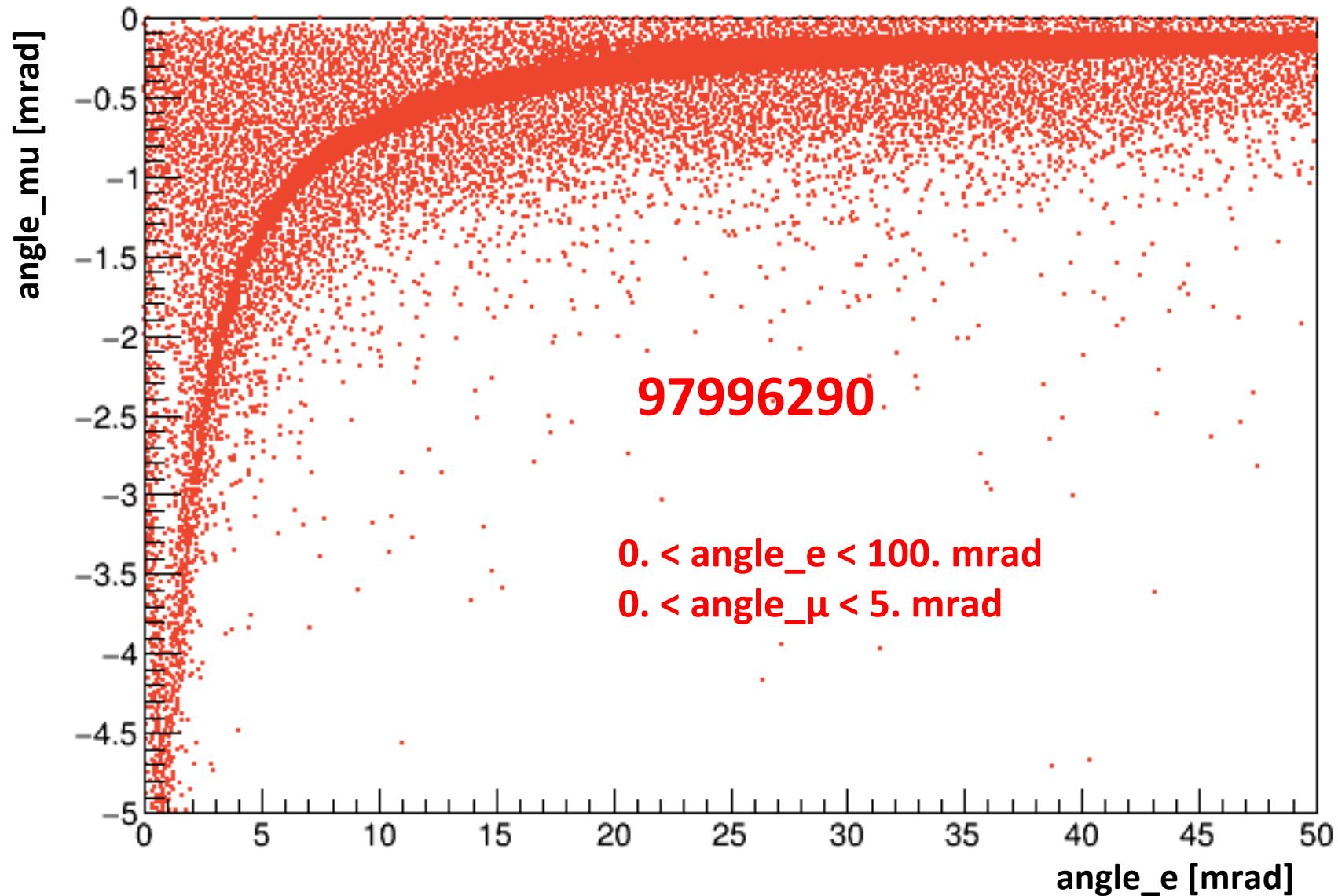
# electrons angular distribution



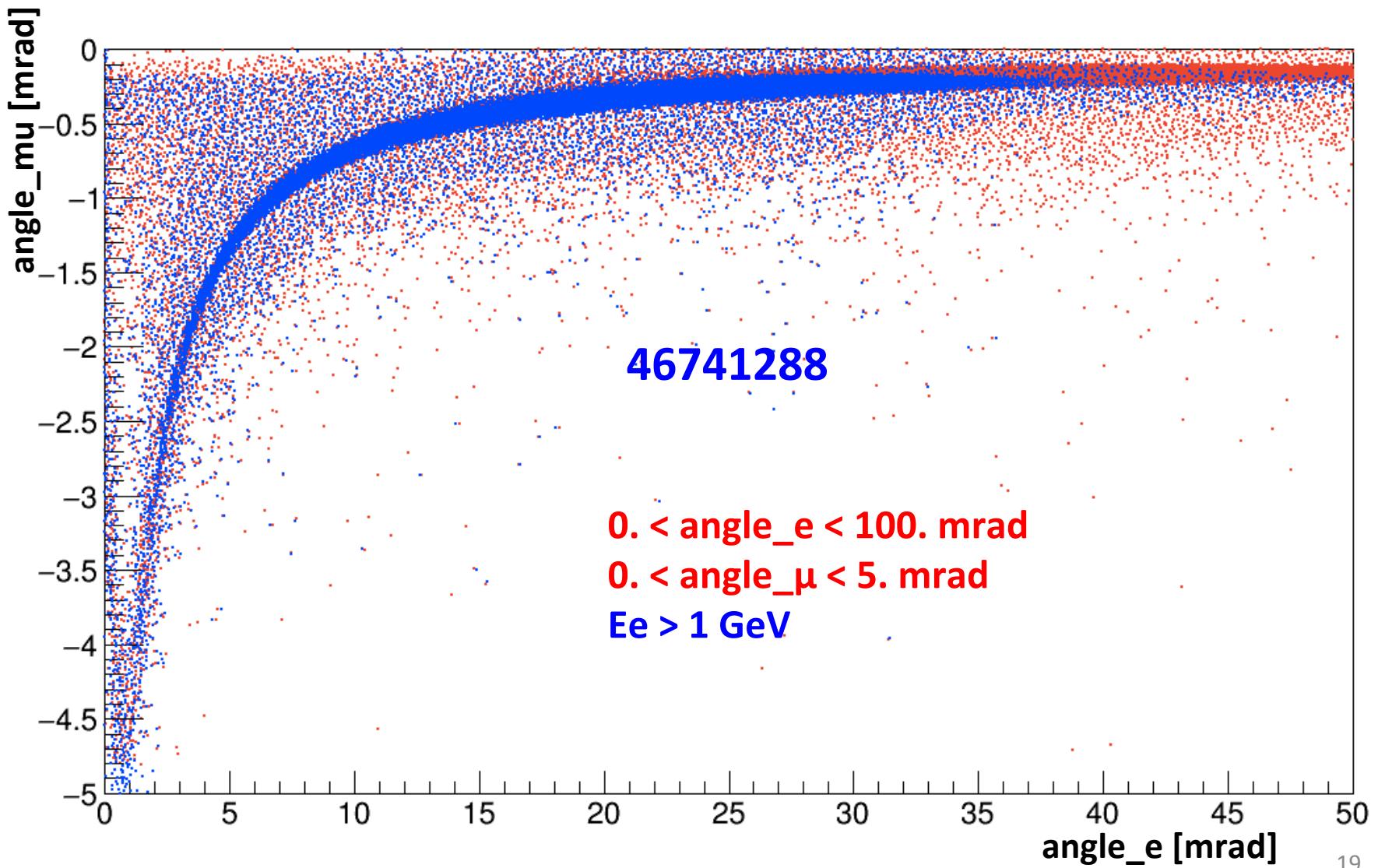
# Observable angular distribution



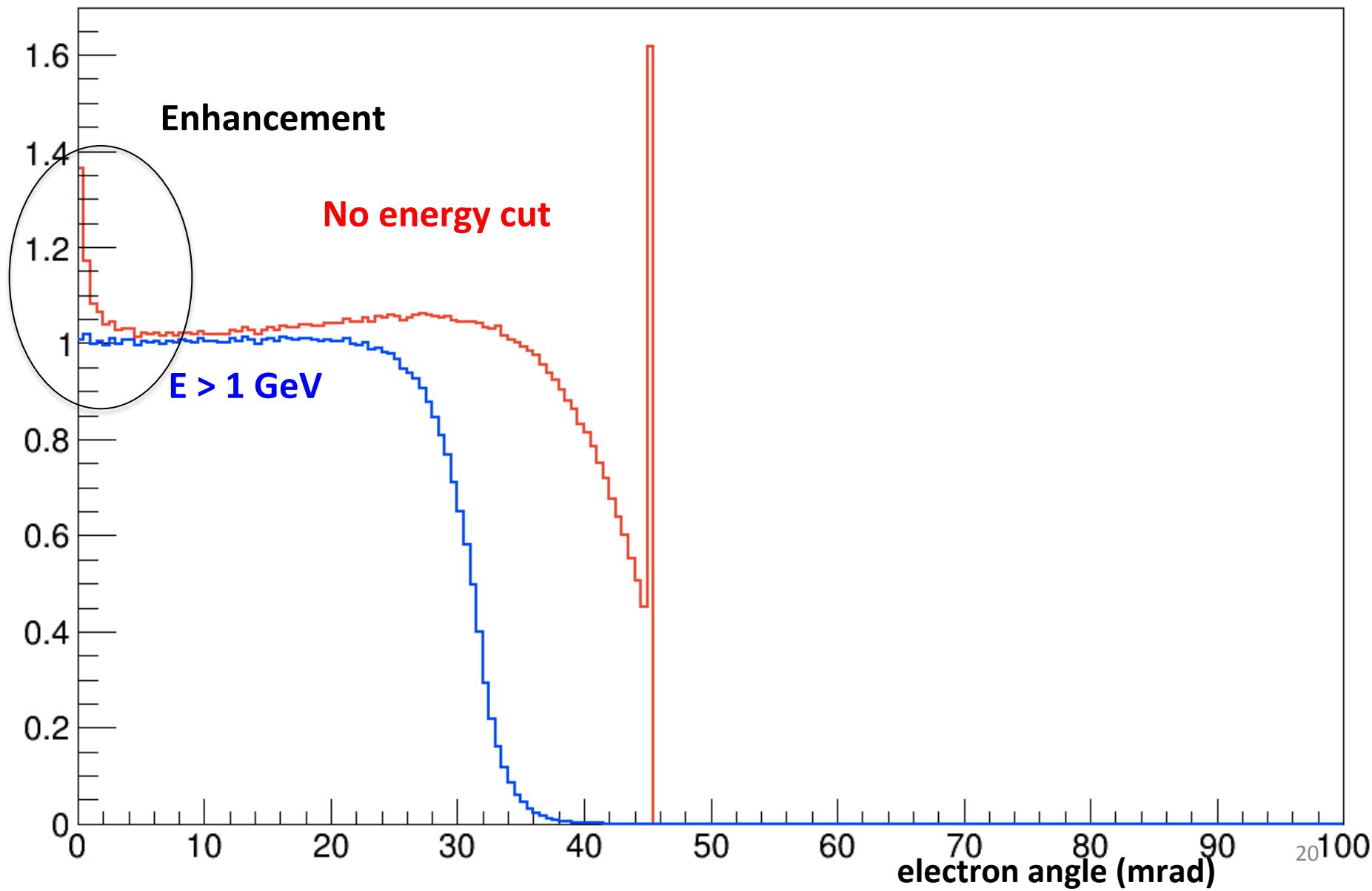
# Observable 2D distribution



# Observable 2D distribution



# Ratios Beryllium d= 30mm



## No energy cut

## Ratios

## E > 1 GeV

1 1.36456	21 1.01907	1 1.00759	21 1.00321
2 1.17188	22 1.02001	2 1.01764	22 1.00402
3 1.08106	23 1.01851	3 0.999437	23 1.00218
4 1.06502	24 1.01821	4 1.00531	24 1.00136
5 1.03915	25 1.0275	5 0.996328	25 1.00983
6 1.04478	26 1.02305	6 1.01035	26 1.00531
7 1.02638	27 1.0327	7 0.998516	27 1.01385
8 1.03087	28 1.02592	8 1.00633	28 1.00673
9 1.02947	29 1.01759	9 1.00795	29 0.997822
10 1.0136	30 1.02757	10 0.994549	30 1.00677
11 1.02227	31 1.03269	11 1.00478	31 1.01088
12 1.01763	32 1.0279	12 1.00082	32 1.00544
13 1.02187	33 1.0367	13 1.0053	33 1.01321
14 1.01443	34 1.03324	14 0.998777	34 1.00858
15 1.02077	35 1.03377	15 1.00503	35 1.0079
16 1.01715	36 1.03778	16 1.00232	36 1.0104
17 1.02284	37 1.03779	17 1.00762	37 1.0089
18 1.02102	38 1.0362	18 1.00529	38 1.00614
19 1.018	39 1.0372	19 1.00248	39 1.00501
20 1.02547	40 1.04158	20 1.00979	40 1.00742

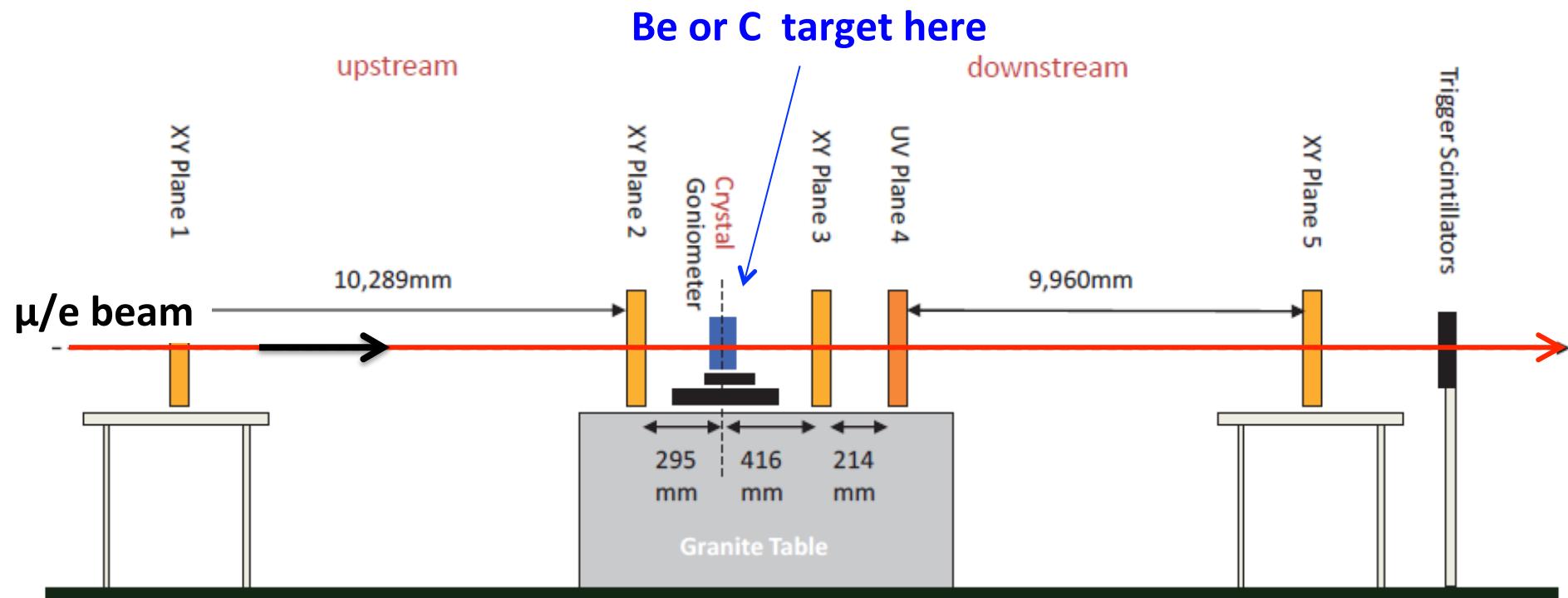
# Remarks

- With the condition  $E_e > 1\text{GeV}$  the ratio:  
 $r = \text{obs\_angle}_e / \text{true\_angle}_e$   
turns out to be 1. within 1%.
- We aim to  $r = 1.001$ : 1. within 0.1%.
- Decrease the targets thickness.
- The ratio could be evaluated bin per bin by means of GEANT, provided that GEANT is precise enough: 1% would be fine.
- How to measure the electron energy, in order to assess whether the required condition  
 $E_e > 1\text{ GeV}$  holds?

# Test Beam

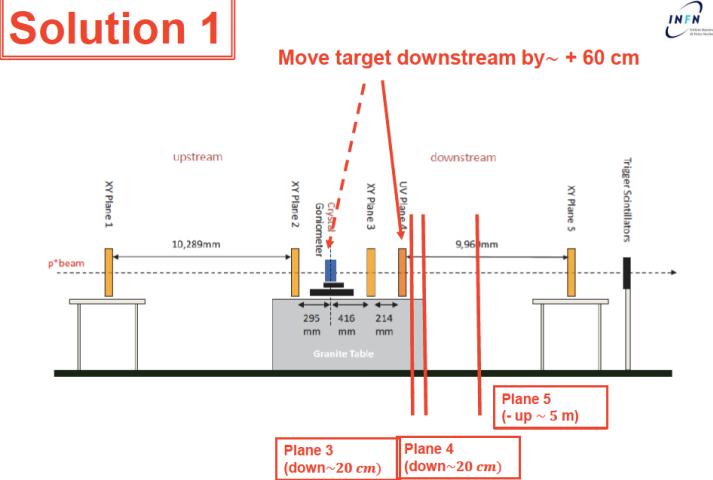
Check Geant4 MSC prediction and populate the 2D ( $\theta_e$ ,  $\theta_\mu$ ) scattering plane

- 27 Sep-3 October 2017 allocated at CERN in "H8 Beam Line"
- 5 Si strips planes: 2 before (upstream) and 3 after the target
- Max rate 10 kHz
- Beam energy in the range 90 - 190 GeV

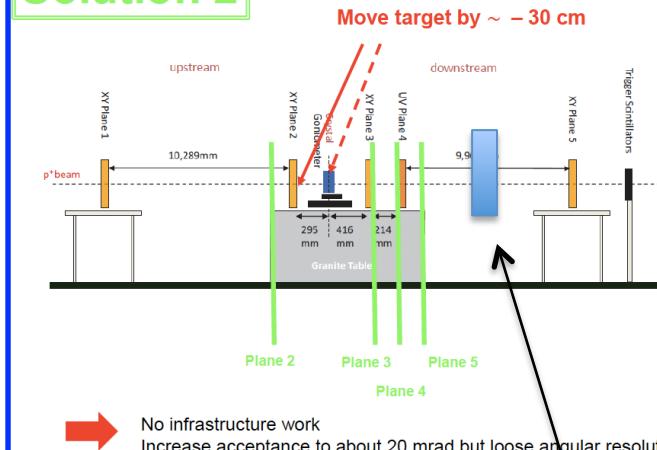


# Test Beam (II)

## Solution 1



## Solution 2



### ★ Solution 1

move upstream plane #5 (by  $\sim 5$  m ) and move downstream the target (by  $\sim 50$  cm )  
acceptance  $\sim 4.0$  mrad

need infrastructure work  
need recabling plane #5  
(same comment for large angle electrons as solution 0)

### Calorimeter

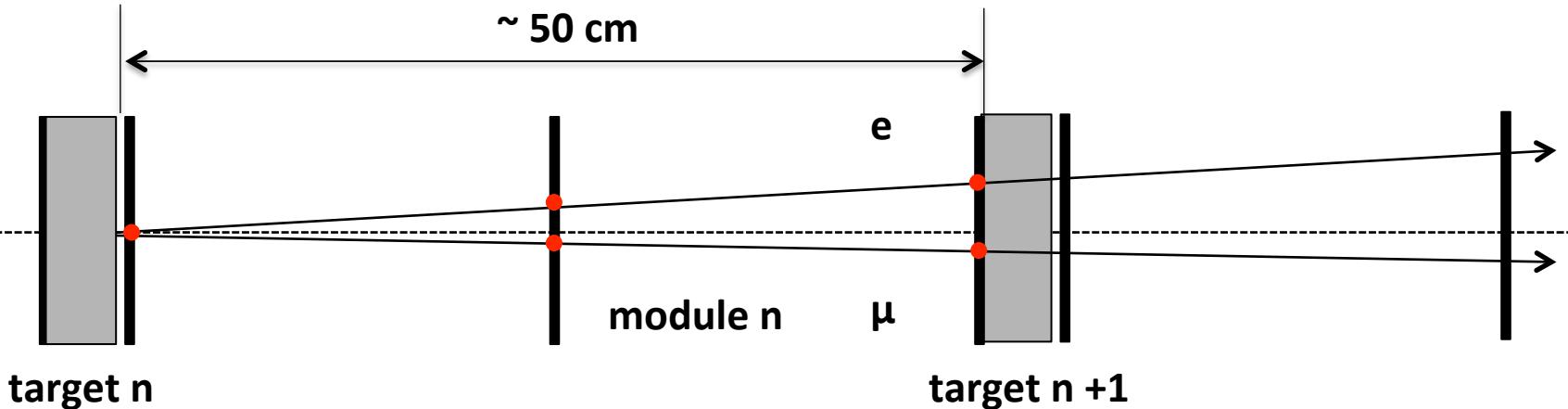
### ★ Solution 2

change position of 4 planes (# 2,3,4,5)  
housing all of them on the existing table.  
acceptance  $\sim 20$  mrad

need recabling the optical fibers of pl 5  
no need of infrastructure work  
loose angular precision

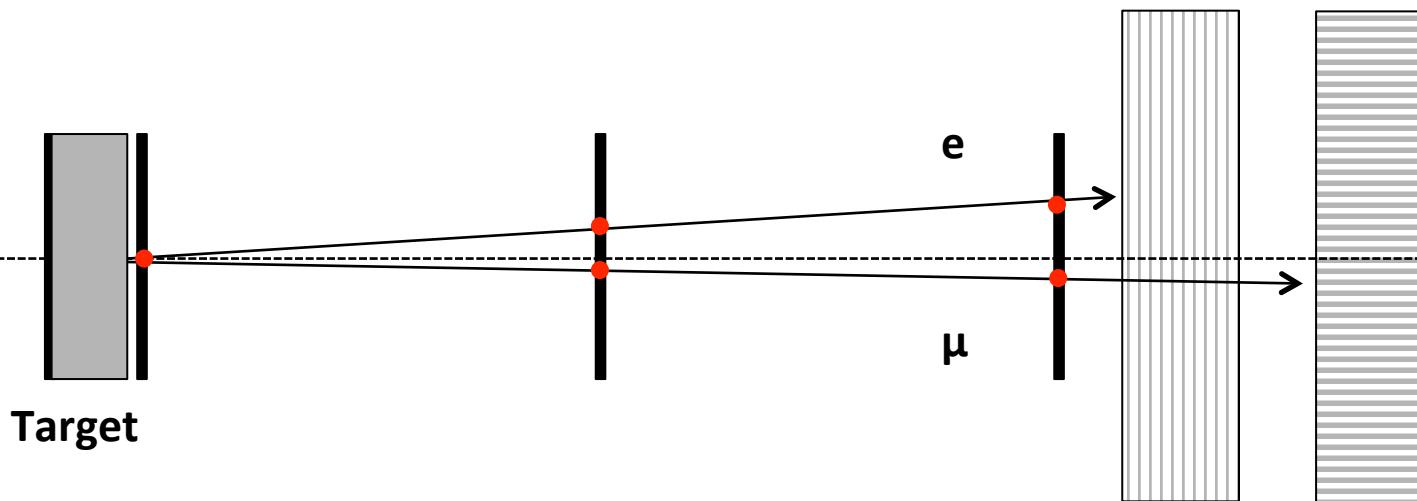
(\*) acceptance defined at the last plane

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## Last module of the detector

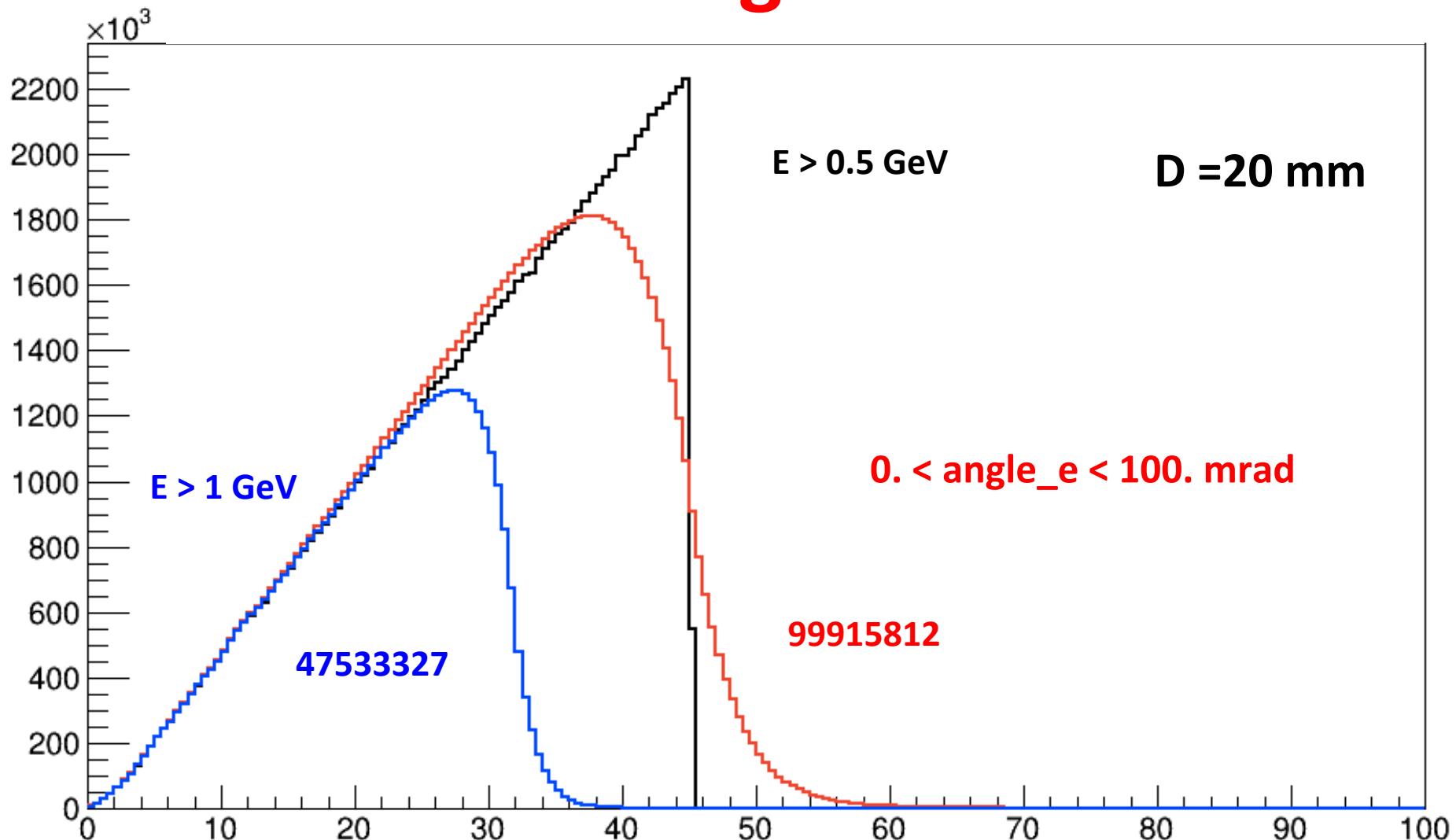
ECAL MUON



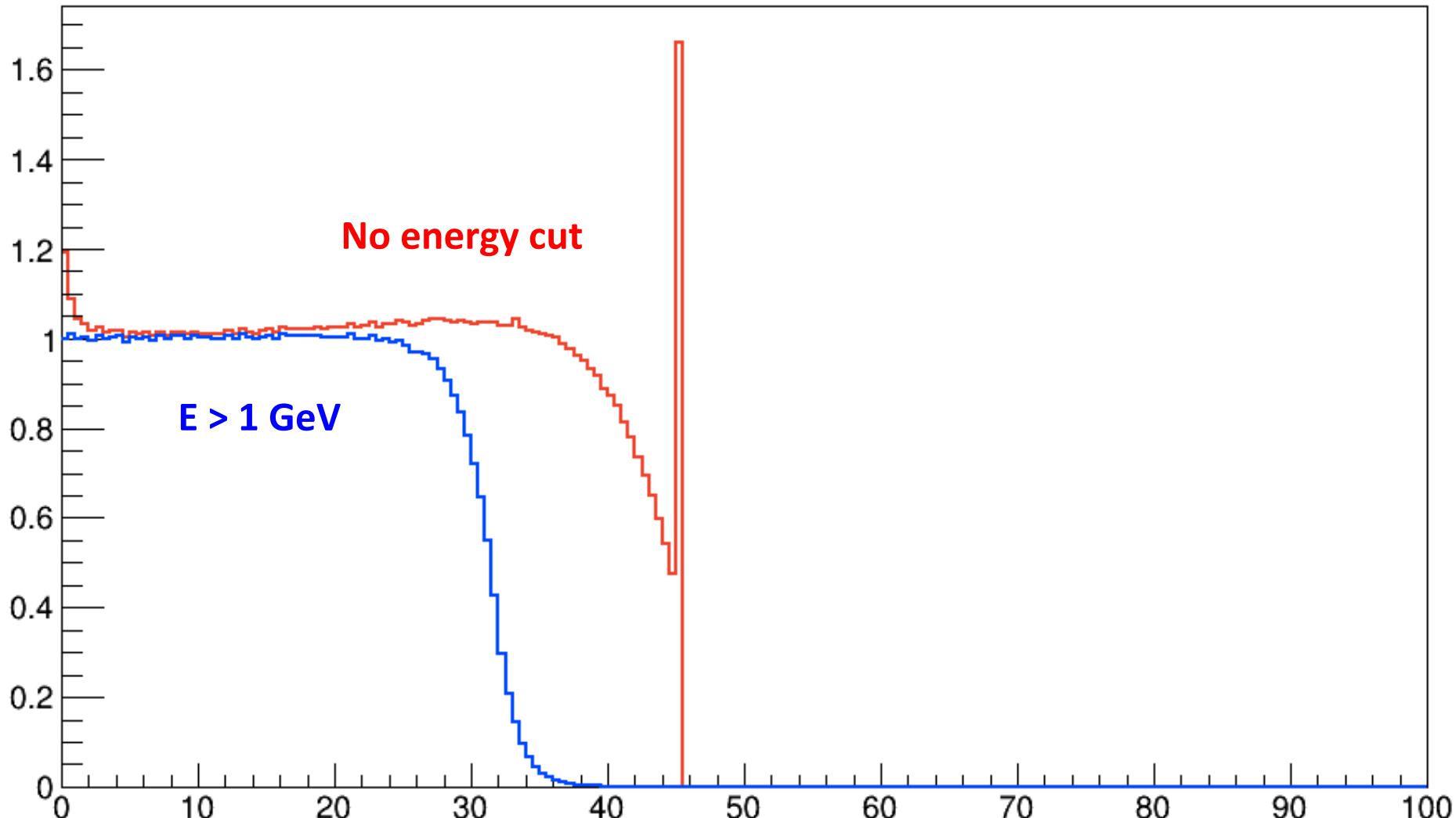
**Measure both  $\text{angle}_e$  and  $E_e$  to define the reference, calibration curve. Detailed check of GEANT predictions.**

**D = 20 mm**

# Observable angular distribution

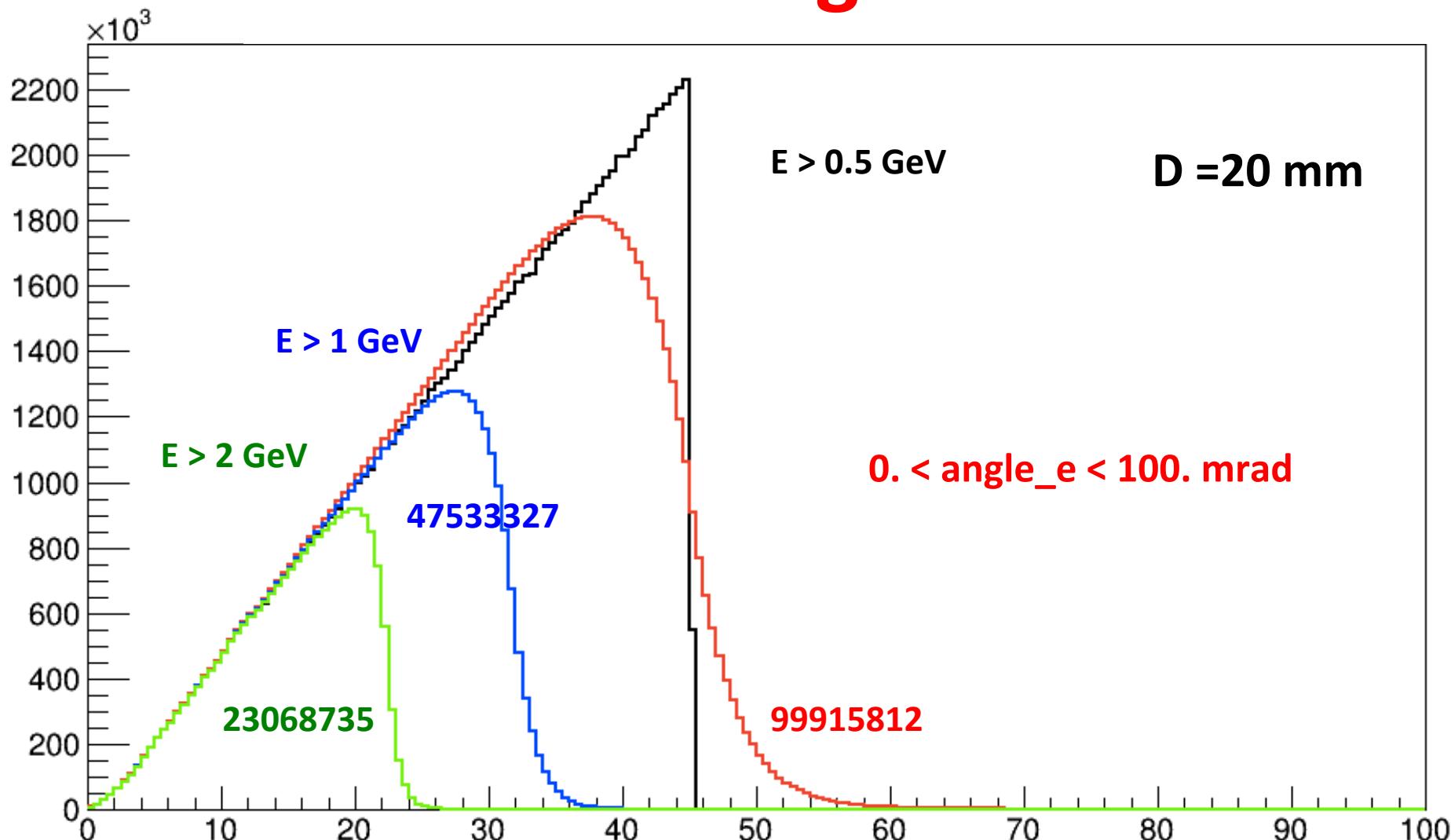


# Ratios Beryllium d= 20mm



1	1.19309	1	1.00096	21	1.01225	21	1.00323	41	1.02574	41	1.00432
2	1.08886	2	1.00889	22	1.01173	22	1.00275	42	1.02706	42	1.00434
3	1.04524	3	1.0004	23	1.01013	23	1.0007	43	1.03396	43	1.00975
4	1.03398	4	1.00391	24	1.01071	24	1.0011	44	1.02646	44	1.00033
5	1.0173	5	0.996003	25	1.01855	25	1.00853	45	1.02733	45	0.999697
6	1.02618	6	1.00775	26	1.01135	26	1.00082	46	1.03529	46	1.00499
7	1.01393	7	0.998485	27	1.0224	27	1.01157	47	1.0271	47	0.994047
8	1.01658	8	1.00318	28	1.01534	28	1.00421	48	1.03381	48	0.997874
9	1.0194	9	1.00748	29	1.00949	29	0.997773	49	1.03274	49	0.993085
10	1.0044	10	0.993426	30	1.01689	30	1.00478	50	1.03892	50	0.994343
11	1.01432	11	1.00464	31	1.02039	31	1.00734	51	1.03623	51	0.986071
12	1.00881	12	0.999535	32	1.01412	32	1.00071	52	1.02796	52	0.971313
13	1.01282	13	1.00403	33	1.02374	33	1.00968	53	1.03448	53	0.96847
14	1.00564	14	0.99684	34	1.02165	34	1.00692	54	1.04138	54	0.964214
15	1.01356	15	1.00504	35	1.02047	35	1.00514	55	1.04564	55	0.952927
16	1.00786	16	0.999135	36	1.02246	36	1.00601	56	1.04313	56	0.932623
17	1.01358	17	1.00529	37	1.02272	37	1.00579	57	1.03974	57	0.905642
18	1.01372	18	1.00502	38	1.02401	38	1.0061	58	1.03706	58	0.8722
19	1.00975	19	1.00065	39	1.02129	39	1.00228	59	1.04133	59	0.837489
20	1.01411	20	1.00508	40	1.02346	40	1.00347	60	1.03571	60	0.783976

# Observable angular distribution



**0 GeV**

bin 1 ratio 1.19309  
bin 2 ratio 1.08886  
bin 3 ratio 1.04524  
bin 4 ratio 1.03398  
bin 5 ratio 1.0173  
bin 6 ratio 1.02618  
bin 7 ratio 1.01393  
bin 8 ratio 1.01658  
bin 9 ratio 1.0194  
bin 10 ratio 1.0044  
bin 11 ratio 1.01432  
bin 12 ratio 1.00881  
bin 13 ratio 1.01282  
bin 14 ratio 1.00564  
bin 15 ratio 1.01356  
bin 16 ratio 1.00786  
bin 17 ratio 1.01358  
bin 18 ratio 1.01372  
bin 19 ratio 1.00975  
bin 20 ratio 1.01411  
bin 21 ratio 1.01225  
bin 22 ratio 1.01173  
bin 23 ratio 1.01013  
bin 24 ratio 1.01071  
bin 25 ratio 1.01855  
bin 26 ratio 1.01135  
bin 27 ratio 1.0224  
bin 28 ratio 1.01534  
bin 29 ratio 1.00949  
bin 30 ratio 1.01689

**1 GeV**

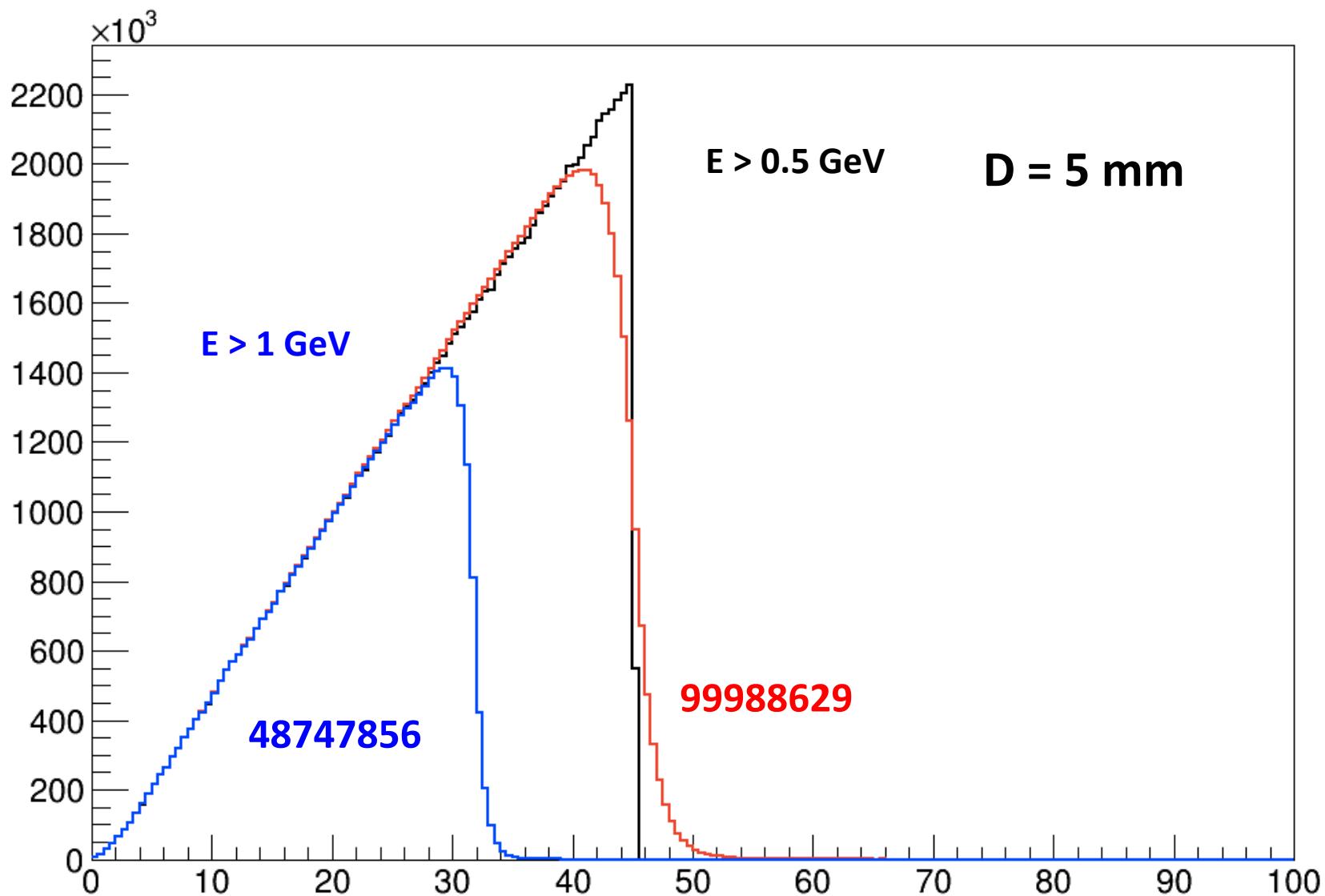
bin 1 ratio 1.00096  
bin 2 ratio 1.00889  
bin 3 ratio 1.0004  
bin 4 ratio 1.00391  
bin 5 ratio 0.996003  
bin 6 ratio 1.00775  
bin 7 ratio 0.998485  
bin 8 ratio 1.00318  
bin 9 ratio 1.00748  
bin 10 ratio 0.993426  
bin 11 ratio 1.00464  
bin 12 ratio 0.999535  
bin 13 ratio 1.00403  
bin 14 ratio 0.99684  
bin 15 ratio 1.00504  
bin 16 ratio 0.999135  
bin 17 ratio 1.00529  
bin 18 ratio 1.00502  
bin 19 ratio 1.00065  
bin 20 ratio 1.00508  
bin 21 ratio 1.00323  
bin 22 ratio 1.00275  
bin 23 ratio 1.0007  
bin 24 ratio 1.0011  
bin 25 ratio 1.00853  
bin 26 ratio 1.00082  
bin 27 ratio 1.01157  
bin 28 ratio 1.00421  
bin 29 ratio 0.997773  
bin 30 ratio 1.00478

**2 GeV**

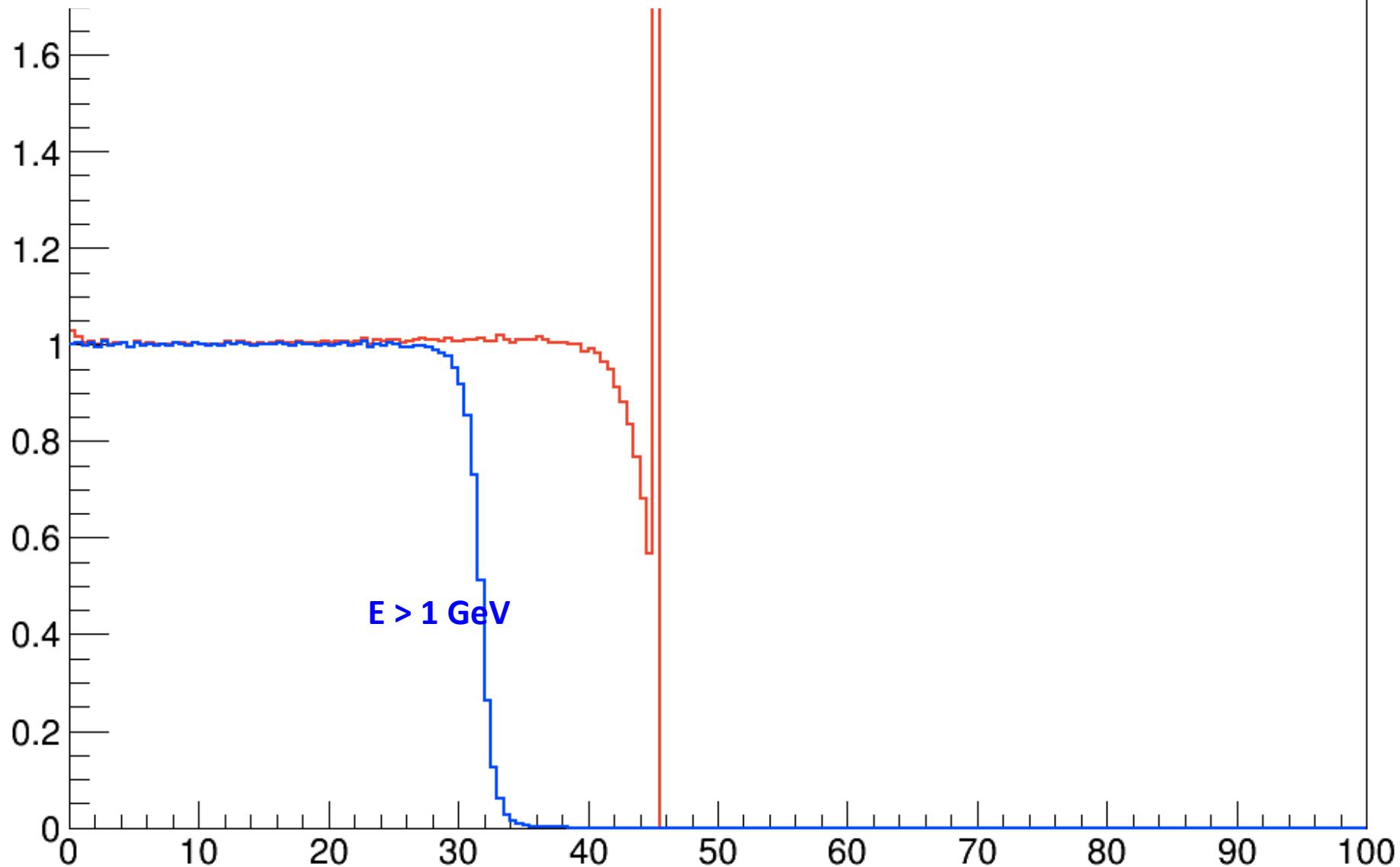
bin 1 ratio 0.996624  
bin 2 ratio 1.0054  
bin 3 ratio 0.998382  
bin 4 ratio 1.00245  
bin 5 ratio 0.994901  
bin 6 ratio 1.00657  
bin 7 ratio 0.997231  
bin 8 ratio 1.00177  
bin 9 ratio 1.00598  
bin 10 ratio 0.99185  
bin 11 ratio 1.00301  
bin 12 ratio 0.997863  
bin 13 ratio 1.00205  
bin 14 ratio 0.994623  
bin 15 ratio 1.00263  
bin 16 ratio 0.996467  
bin 17 ratio 1.00242  
bin 18 ratio 1.00182  
bin 19 ratio 0.997101  
bin 20 ratio 1.00116  
bin 21 ratio 0.998962  
bin 22 ratio 0.997866  
bin 23 ratio 0.995547  
bin 24 ratio 0.995385  
bin 25 ratio 1.00223  
bin 26 ratio 0.993994  
bin 27 ratio 1.00383  
bin 28 ratio 0.995649  
bin 29 ratio 0.988656  
bin 30 ratio 0.994456

**D = 5 mm**

# Observable angular distribution

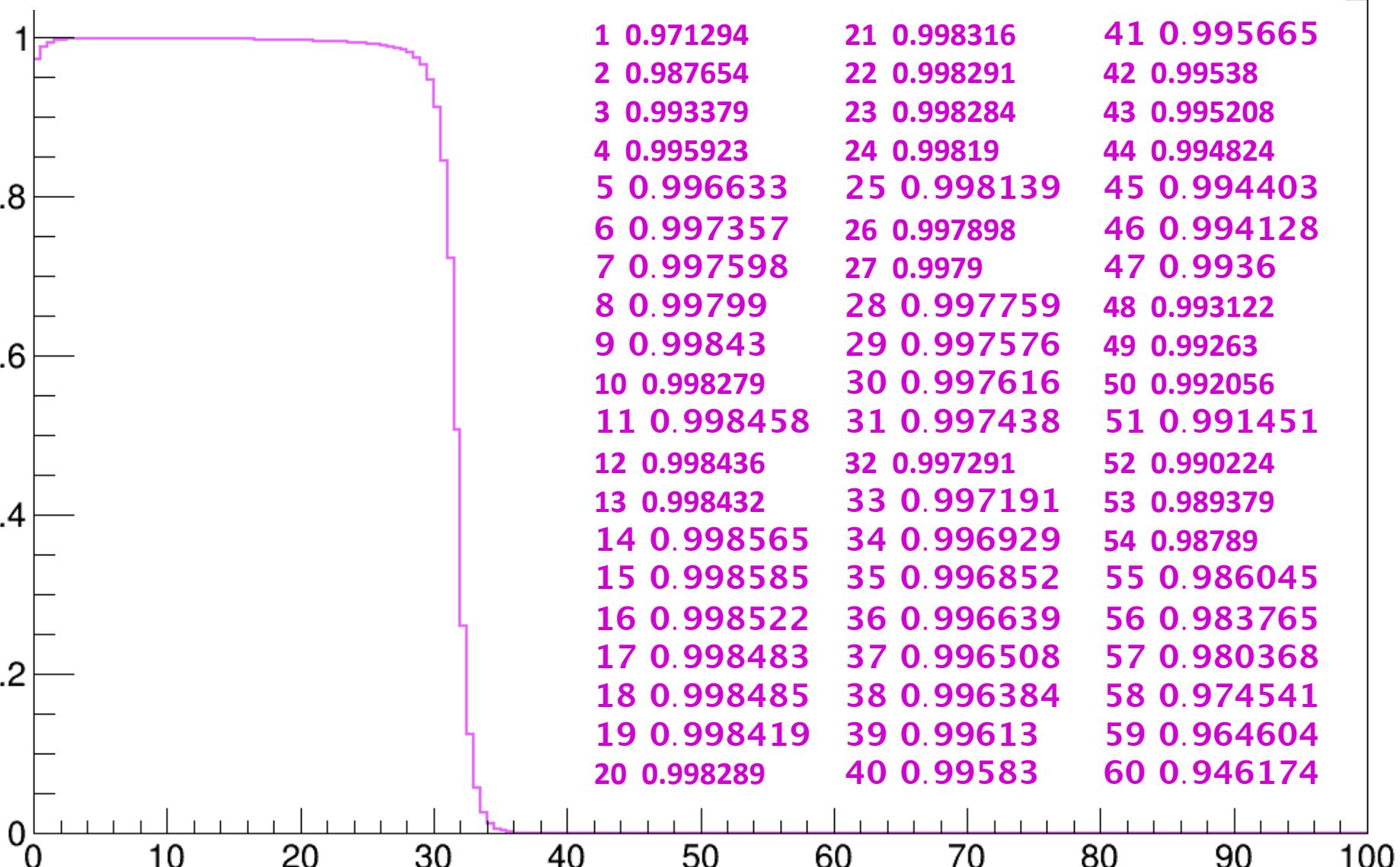


# Ratios Beryllium d= 5 mm



1	1.02939	1	0.999839	21	1.00122	21	0.999531
2	1.01557	2	1.00304	22	1.00116	22	0.999446
3	1.0049	3	0.998245	23	1.00245	23	1.00073
4	1.00692	4	1.00281	24	1.00037	24	0.998558
5	0.999663	5	0.996298	25	1.00581	25	1.00394
6	1.00873	6	1.00606	26	1.00176	26	0.999656
7	0.99971	7	0.997309	27	1.0065	27	1.00438
8	1.00279	8	1.00078	28	1.00257	28	1.00033
9	1.0046	9	1.00302	29	0.999569	29	0.997146
10	0.995461	10	0.993748	30	1.00268	30	1.00029
11	1.00569	11	1.00414	31	1.00245	31	0.999884
12	1.00027	12	0.998707	32	1.0034	32	1.00068
13	1.0039	13	1.00233	33	1.00835	33	1.00552
14	1.00045	14	0.999013	34	1.00553	34	1.00244
15	1.00223	15	1.00081	35	1.00261	35	0.99945
16	0.999789	16	0.998311	36	1.00658	36	1.0032
17	1.00436	17	1.00284	37	1.00409	37	1.00058
18	1.00325	18	1.00173	38	1.00431	38	1.00068
19	1.0007	19	0.999116	39	1.0028	39	0.998918
20	1.00538	20	1.00366	40	1.00606	40	1.00186

# Ratios ratio Beryllium d= 5 mm



# Conclusions

- Corrections to the observed electrons' angular distributions of the 0.1% level seems to be achievable by using thin ~10mm low Z targets.
- GEANT 4 predictions can be compared to the calibration module (CM: the last module) response. The CM will provide both the electron angle and energy measurements.
- We are working to build the calibration module to be tested next year.
- Test of MSC description in Geant4 coming soon.