ESS Neutrino Super Beam Plus

Co-funded by the European Union

DEMOKRITOS

Low Energy Neutrino MOnitored Beam and LEnuSTORM Near Detector

LEMMOND Design
a progress report

Elizabeth Fasoula, Eirini Kasimi, George Fanourakis, Spyros Tzamarias

AUTH-DEMOKRITOS team

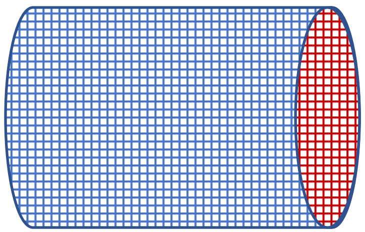
ESSnuSB+ 2nd Annual Meeting

ESS neutrino Super Beam plus

Identification of requirements for the LEMMOND

"Low Energy Neutrinos from Stored Muons and Monitored beam Detector"

- Low Energy nuStored Muons ring (LEnuSTORM)
- Low Energy Monitored Beam (LEMNB)



LEMMOND will be a cylindrical, water Cherenkov detector
- the optical elements cover the detector surface
- the detector's symmetry axis coincides with the ν-beam axis
- exploits photodector-technologies with spatial and precise (ps?) timing capabilities

This study is based on the detection of leptons produced from the ν CC Quasi elastic interactions and identifies requirements concerning:
- the size of the detector given the neutrino fluxes (and assuming a 100% efficient detector)
- the track reconstruction of the charged leptons (requirements on timing and spatial resolution)
- the particle identification of charged leptons (ν flavor)
- the momentum estimation of the charged leptons

the **final** required detector size (taking into account the neutrino fluxes and the reconstruction efficiency/resolution)
the momentum estimation of the parent neutrino (given the reconstructed lepton tracks)
the neutrino and anti-neutrino identification (Gd studies)

Determining the dimensions of the detector:

Simulated muon decays as coming from the LEnuSTORM or pion decays coming from the LEMNB are used to determine how the neutrino/antineutrino fluxes are reduced with the distance from the beam axis and estimate the number of neutrino interactions in LEMMOND. Specifically:

- the muons and the electrons from the muon (anti)neutrino and electron (anti)neutrino fluxes can be traced in the detector volume. In lack of detailed Monte Carlo interactions) the (anti)neutrino direction and energy are used to determine whether the charged lepton will be detected if an interaction took place (a threshold of ~11 MeV for electron (anti)neutrinos and ~218 MeV for muon (anti)neutrinos are used).
- for the determination of the number of events observed (assuming 100% detector efficiency) the (anti)neutrino cross sections are used as per Genie weighted by the track length of the neutrino inside the water effective volume.
- the optimal dimensions **for a given volume of the detector** are determined by changing the radius and length of the detector and computing the number of neutrino interactions. Obviously the optimal dimensions are the ones that allow for the detection of the maximum number of events.

LEnuSTORM facility: 600 MeV/c **(but also many other energies – see later)** positive muon decays (about 250,000 muons) along the 30m straight section of the racetrack have been simulated to determine the vertex and the 3-momentum parameters of each neutrino produced (muon antineutrinos and electron neutrinos). By charge conjugation the same sample has been used to simulate muon neutrino and electron antineutrino beams.

LEMNB facility: many (5.14×10^6) 1 GeV/c Monte Carlo generated positive pion decays along a 40 m long monitored decay tunnel used to determine the track parameters of each neutrino produced. By charge conjugation the same sample has been used to simulate the muon antineutrino beam.

Correlation of the ν momentum with the position entering the LEMMOND

LEnuSTORM (50m downstream)

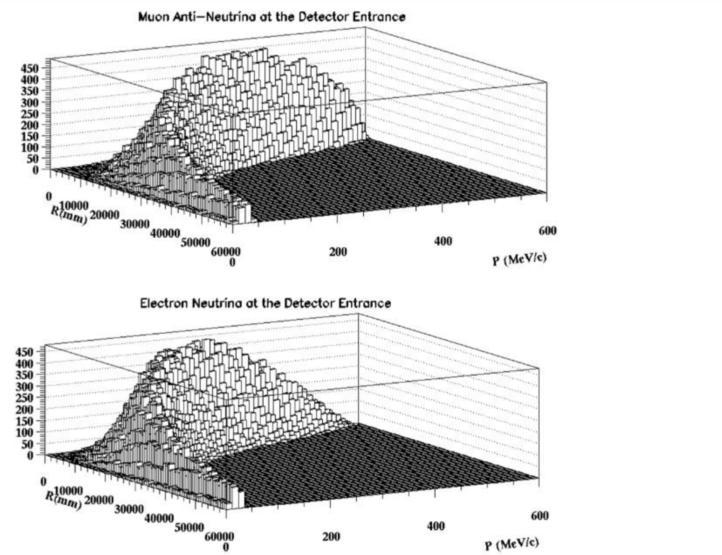


Figure A5: (a upper scatterplot) Muon antineutrino momentum vs radial position (b lower scatterplot) electron neutrino momentum vs radial position.

LEMNB

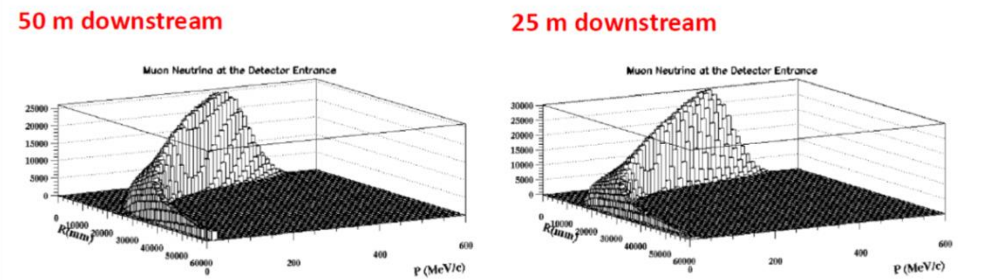


Figure B5. Radius-Momentum distribution of the neutrinos at the entrance of the detector.

LEnuSTORM
Expected number of interactions of muon and electron (anti)neutrinos in a detector volume of 100 or 200 m^3

Interactions per 10^{17} decays of 600 MeV/c μ^- in 200 m^3 volume

Muon Neutrina

Radius (m)	Length (m)	No of Events Used	No of Events Scaled	Interactions	Relative Error
1.250000	40.74366	2913.000	0.1144714E+16	4005.129	0.1852805E-01
1.500000	28.29421	4111.000	0.1615489E+16	4440.817	0.1559647E-01
1.750000	20.78759	5518.000	0.2168394E+16	4726.807	0.1346199E-01
2.000000	15.91549	7210.000	0.2833295E+16	4923.718	0.1177694E-01
2.250000	12.57521	9054.000	0.3557927E+16	5087.309	0.1050944E-01
2.500000	10.18592	11075.00	0.4352115E+16	5202.307	0.9502286E-02
2.750000	8.418113	13261.00	0.5211141E+16	5239.914	0.8683841E-02
3.000000	7.073553	15640.00	0.6146011E+16	5235.271	0.7996162E-02
3.250000	6.027170	18141.00	0.7128823E+16	5204.095	0.7424537E-02
3.500000	5.196897	20716.00	0.8140714E+16	5142.264	0.6947796E-02
3.750000	4.527074	23439.00	0.9210765E+16	5059.825	0.6531764E-02
4.000000	3.978874	26238.00	0.1031068E+17	4968.397	0.6173545E-02
4.250000	3.524539	29165.00	0.1146090E+17	4857.759	0.5855568E-02
4.500000	3.143801	32133.00	0.1262722E+17	4742.436	0.5578589E-02
4.750000	2.821584	35099.00	0.1379276E+17	4606.529	0.5337681E-02
5.000000	2.546479	38098.00	0.1497127E+17	4474.459	0.5123290E-02
5.250000	2.309732	41124.00	0.1616039E+17	4337.299	0.4931197E-02
5.500000	2.104528	44228.00	0.1738016E+17	4203.094	0.4755009E-02
5.000000	11.00000	38098.00	0.1497127E+17	17764.82	0.5123290E-02
3.385000	14.00000	19549.00	0.7682121E+16	11769.24	0.7152168E-02

corresponds to the case of a similar to the near Cherenkov detector of the ESSnuSB complex (a cylinder roughly 5 m radius and 11 m long), if it were located 50 meters downstream of the LEnuSTORM. The last line corresponds to a detector with a face of 6x6 m^2.

LEnuSTORM
Expected number of interactions of muon and electron (anti)neutrinos in a detector volume of 100 or 200 m^3

600 MeV/c μ beam

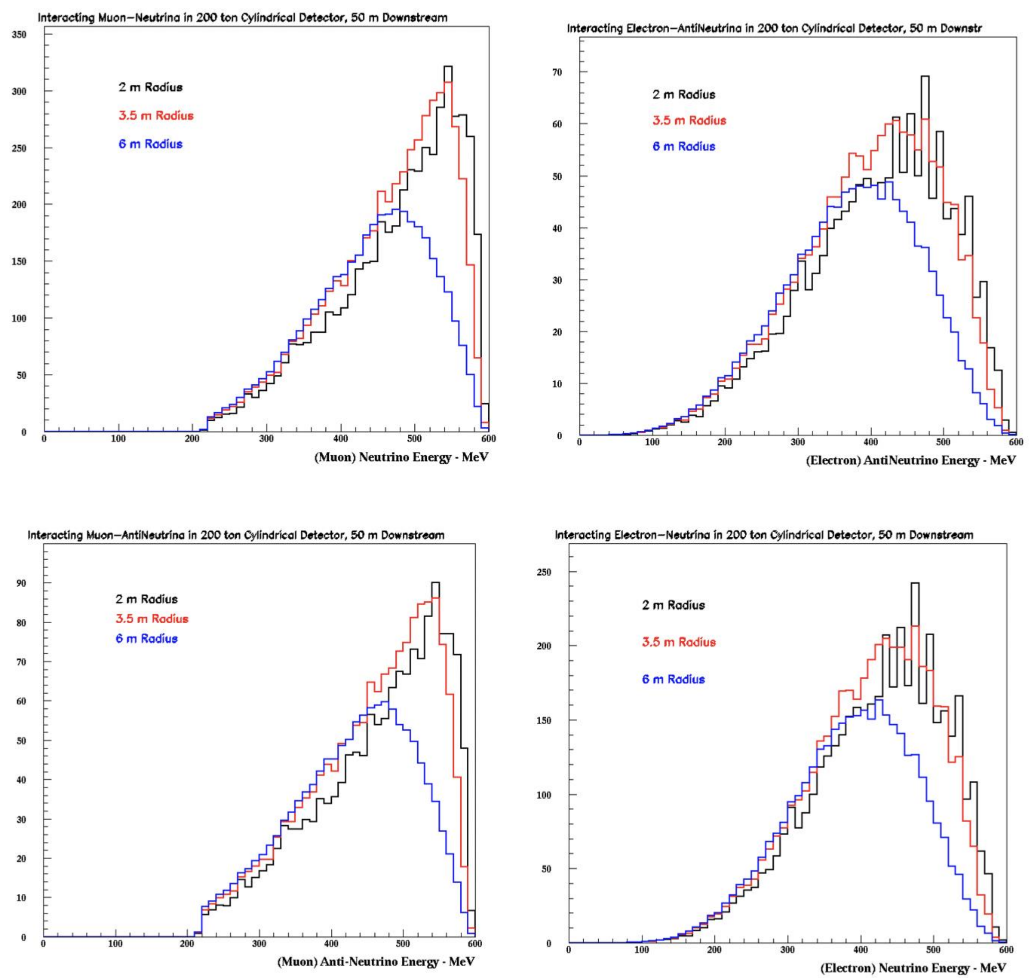


Figure A7: For a 200-ton detector at 50 m downstream: detectable muon and electron antineutrino event distribution for 2, 3.5 and 6 m radius cylindrical detectors (upper left plots) and muon antineutrino and electron neutrino distributions (lower plots)..

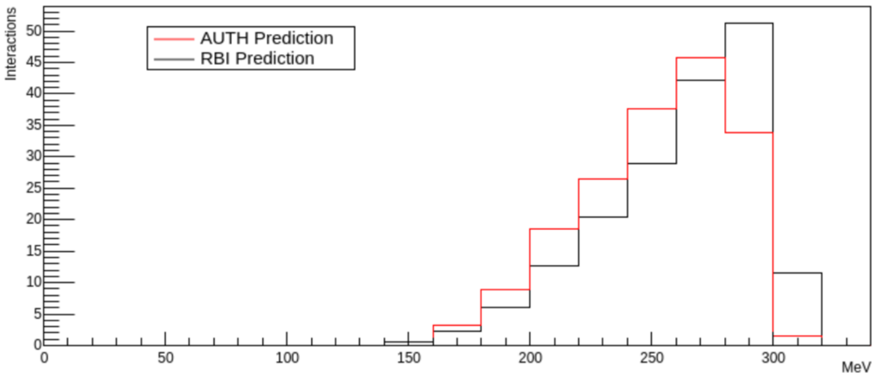


Figure 2: Energy spectrum of the detected νμ produced by 300MeV muon beam.
The red histogram corresponds to the AUTH prediction, while the black histogram corresponds to the RBI prediction normalized to the total AUTH predicted interactions.

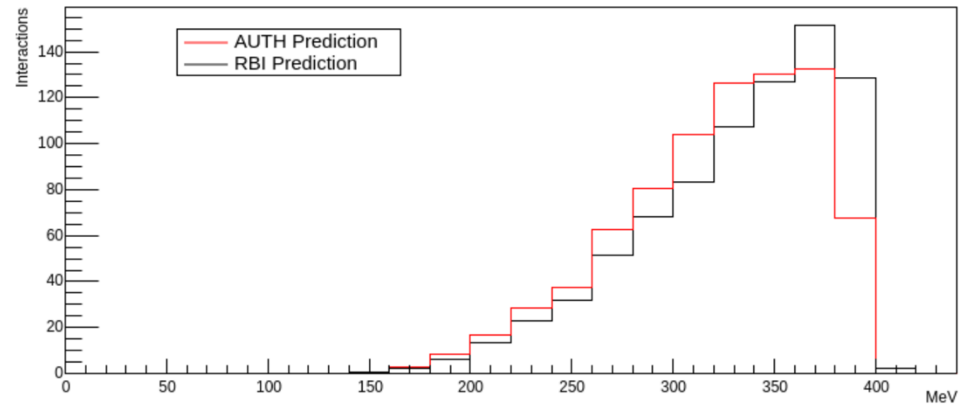


Figure 3: Energy spectrum of the detected νμ produced by 400MeV muon beam.
The red histogram corresponds to the AUTH prediction, while the black histogram corresponds to the RBI prediction normalized to the total AUTH predicted interactions.

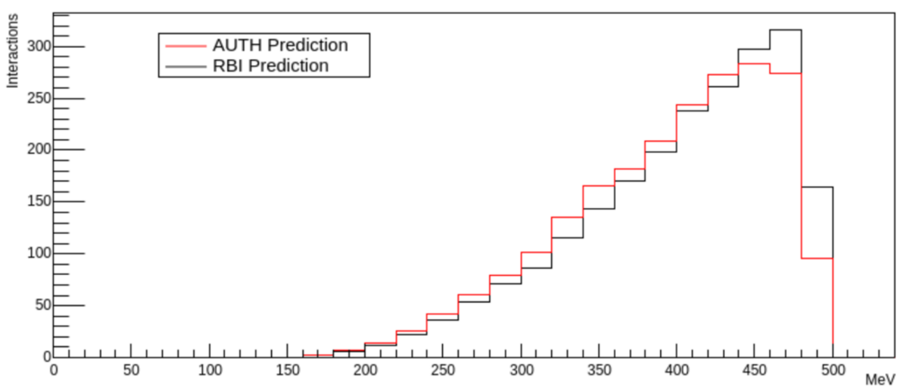


Figure 4: Energy spectrum of the detected νμ produced by 500MeV muon beam.
The red histogram corresponds to the AUTH prediction, while the black histogram corresponds to the RBI prediction normalized to the total AUTH predicted interactions.

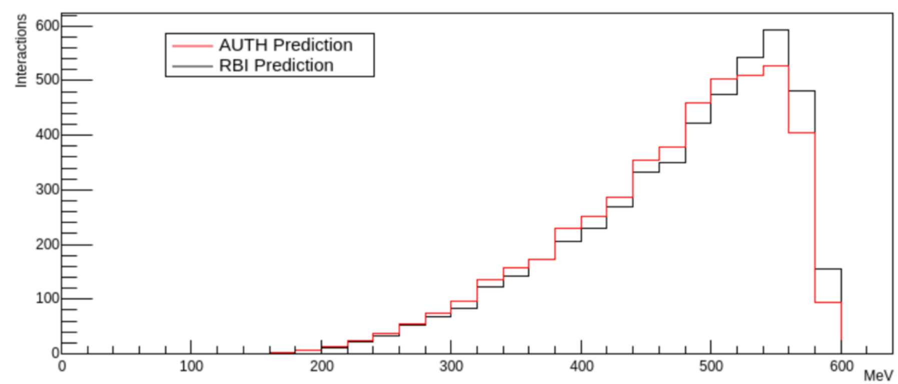


Figure 5: Energy spectrum of the detected νμ produced by 600MeV muon beam.
The red histogram corresponds to the AUTH prediction, while the black histogram corresponds to the RBI prediction normalized to the total AUTH predicted interactions.

LEnuSTORM
several μ momenta

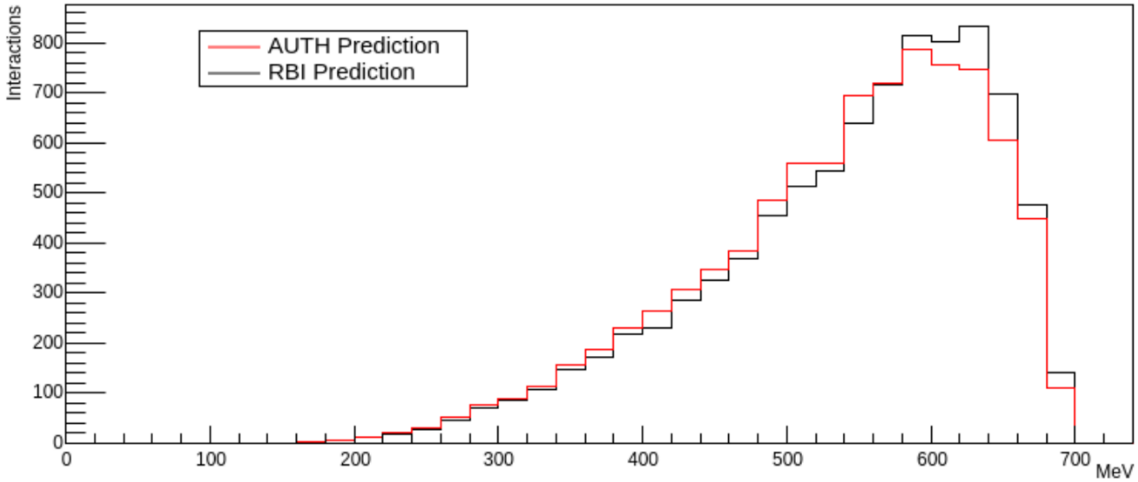


Figure 6: Energy spectrum of the detected νμ produced by 700MeV muon beam.
The red histogram corresponds to the AUTH prediction, while the black histogram corresponds to the RBI prediction normalized to the total AUTH predicted interactions.

LEnuSTORM
several μ momenta

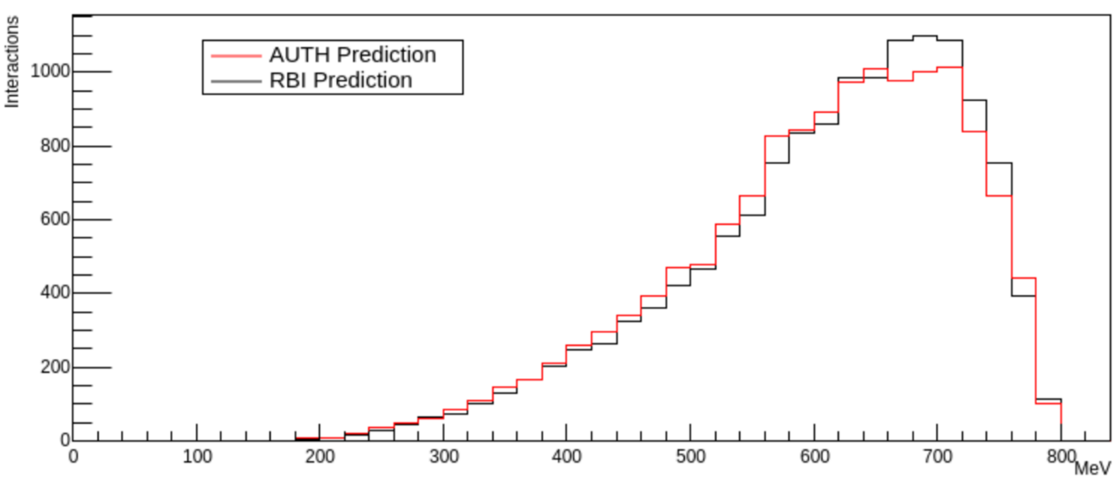


Figure 7: Energy spectrum of the detected νμ produced by 800MeV muon beam.
The red histogram corresponds to the AUTH prediction, while the black histogram corresponds to the RBI prediction normalized to the total AUTH predicted interactions.

LEnuSTORM
Expected number of interactions of muon and electron (anti)neutrinos in a detector volume 200 m^3

Interactions per 10^17 muon decays.
Cut: 160 MeV

P[MeV]	R[m]	L[m]	Muons used	No. of Events used	No. of Events Scaled	Interactions	Rel.Error
200	2.5	10.1859	76655	90	1.506E+14	8.55839	0.105409
300	2.5	10.1859	51879	409	8.8845E+14	183.077	0.0494468
400	2.5	10.1859	39319	699	1.908E+14	878.488	0.0378235
500	2.5	10.1859	31514	899	2.980E+14	2241.64	0.0333519
600	2.5	10.1859	262878	11329	4.4519E+14	4946.39	0.00939516
700	2.5	10.1859	225769	13123	5.954E+14	9011.51	0.00872938
800	2.5	10.1859	197697	14569	7.51E+14	14313.4	0.00828486

LEMNB

Expected number of interactions of muon (anti)neutrinos in a detector volume of 100 or 200 m^3 positioned at 25 or 50 m downstream of the end of the decay tunnel

50 m downstream

Interactions in 200 m^3 volume per 10^{17} decays of 1.0 GeV/c π^+

Muon Neutrina

Radius (m)	Length (m)	No of Events Used	No of Events Scaled	Interactions	Relative Error
1.250000	40.74366	84183.00	0.1440963E+16	4831.065	0.3446575E-02
1.500000	28.29421	120572.0	0.2063835E+16	5383.440	0.2879896E-02
1.750000	20.78759	162522.0	0.2781895E+16	5742.892	0.2480527E-02
2.000000	15.91549	209550.0	0.3586875E+16	5943.510	0.2184521E-02
2.250000	12.57521	261421.0	0.4474752E+16	6028.260	0.1955824E-02
2.500000	10.18592	318098.0	0.5444895E+16	6038.124	0.1773044E-02
2.750000	8.418113	379271.0	0.6491995E+16	5993.056	0.1623772E-02
3.000000	7.073553	444252.0	0.7604277E+16	5912.879	0.1500325E-02
3.250000	6.027170	513025.0	0.8781467E+16	5800.045	0.1396146E-02
3.500000	5.196897	584997.0	0.1001341E+17	5666.055	0.1307444E-02
3.750000	4.527074	658767.0	0.1127614E+17	5514.393	0.1232066E-02
4.000000	3.978874	735108.0	0.1258287E+17	5348.113	0.1166338E-02
4.250000	3.524539	812863.0	0.1391381E+17	5171.291	0.1109153E-02
4.500000	3.143801	892219.0	0.1527214E+17	4991.807	0.1058679E-02
4.750000	2.821584	972196.0	0.1664111E+17	4805.881	0.1014199E-02
5.000000	2.546479	1053171.	0.1802717E+17	4619.842	0.9744298E-03
5.250000	2.309732	1134932.	0.1942667E+17	4438.270	0.9386747E-03
5.500000	2.104528	1216800.	0.2082801E+17	4259.952	0.9065471E-03
5.750000	1.925504	1298188.	0.2222113E+17	4083.782	0.8776699E-03
6.000000	1.768388	1379820.	0.2361843E+17	3907.772	0.8513120E-03
5.000000	11.00000	1053171.	0.1802717E+17	18650.09	0.9744298E-03
3.385000	14.00000	551563.0	0.9441123E+16	13236.91	0.1346488E-02

corresponds to the case of a similar to the near Cherenkov detector of the ESSnuSB complex (a cylinder roughly 5 m radius and 11 m long), if it were located 50 meters downstream of the decay tunnel. The last line corresponds to a detector with a face of 6x6 m^2.

LEMNB
Expected number of interactions of muon (anti)neutrinos

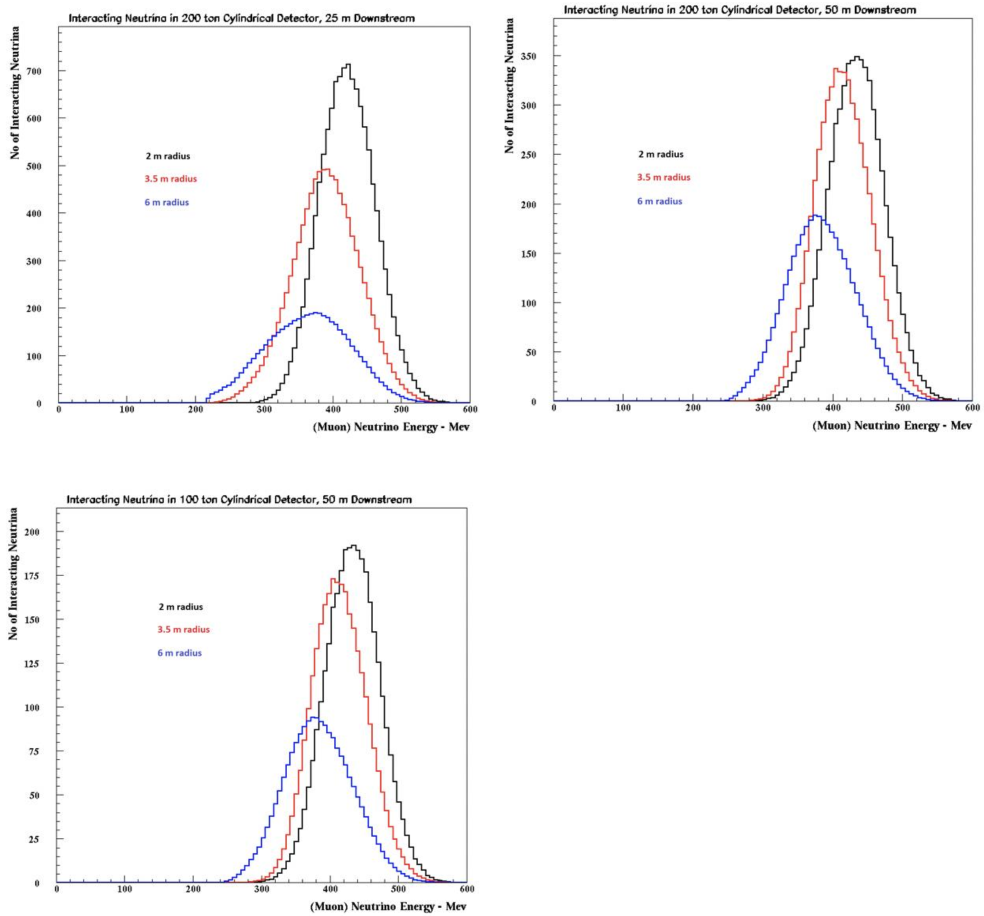
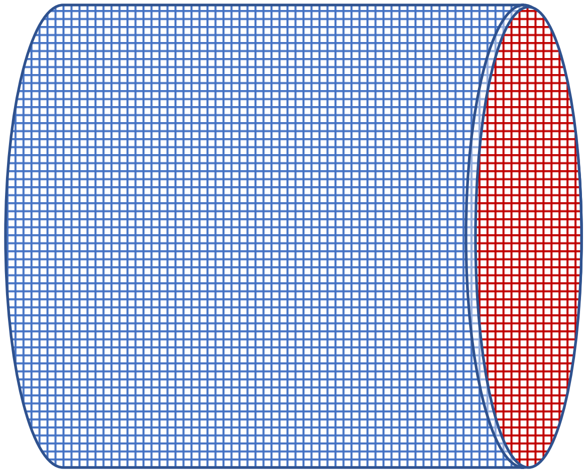


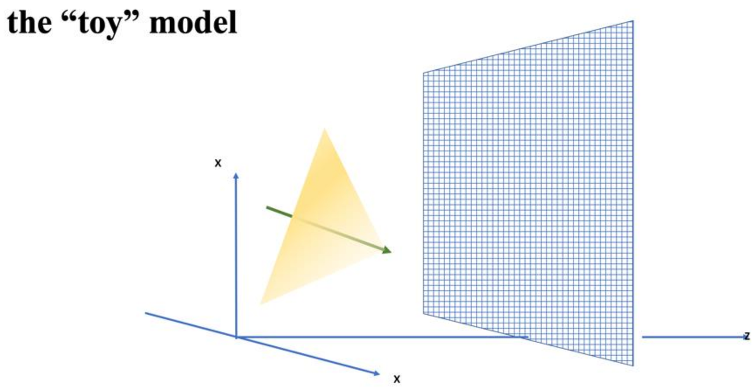
Figure B7: Detectable neutrino event distribution for 2, 3.5 and 6 m radius cylindrical detectors: a 200-ton detector at 25 m downstream (upper left plot) and at 50 m downstream (upper right) and a 100-ton detector at 50 m downstream (lower plot).

LEMMOND

ID and Track Reconstruction of Charged Leptons
A Simulation Study Report

a “toy” Detector Model

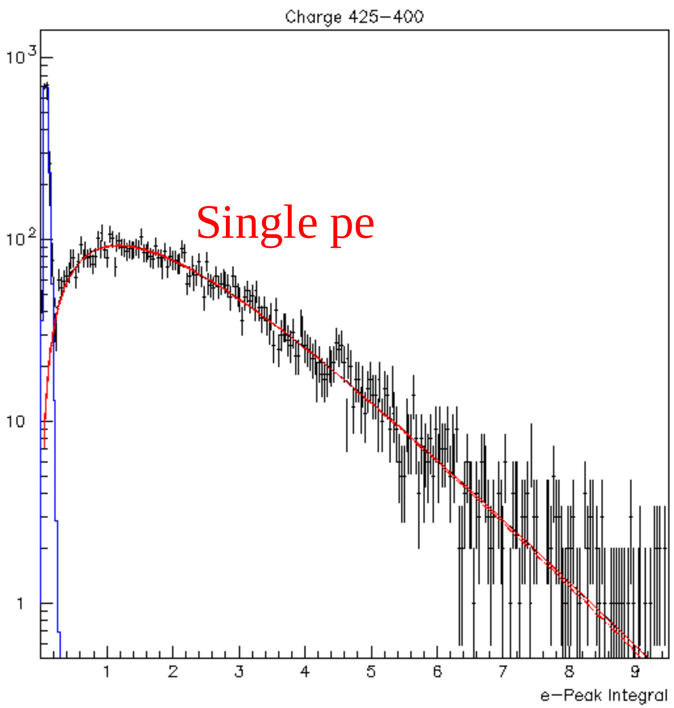




- **GEANT simulation (all scattering and absorption effects) of tracks, Cherenkov radiation, light transmission and detector response**
- **Simulate the photodetector response (but ignore ambient light in the detector, electronic noise and threshold effects)**
- **The “data” sample comprises of simulated photodetector-signals produced by Cherenkov charged lepton tracks, which have been generated with [$\theta=0^o$ or $\theta=30^o$ and $\varphi=0^o$] initial direction, wrt to the detector frame**
- **Tracks are starting ~200 cm away from the Detector**
- **The detector is a 400 x 400 cm^2 plane, comprising 6400 5x5 cm^2 active photodetector elements**

The Photodetector Response

Gaseous Photodetector Response



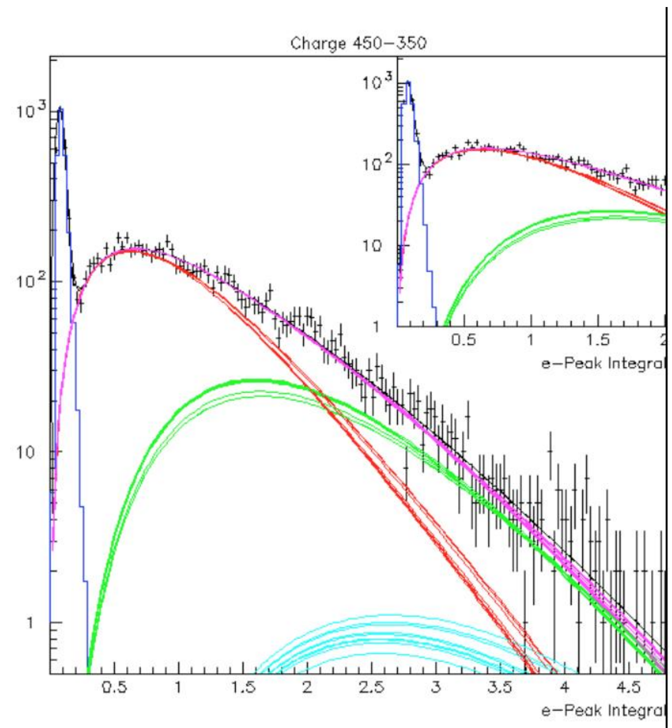
Gamma Distribution Function (Polya)

$$F\left(Q;C,\theta,\bar{Q}_e\right)=\frac{C}{Q_e}\frac{(\theta+1)^{(\theta+1)}\left(Q/\bar{Q}_e\right)^{\theta}}{\Gamma(\theta+1)}e^{-(\theta+1)Q/\bar{Q}_e}$$

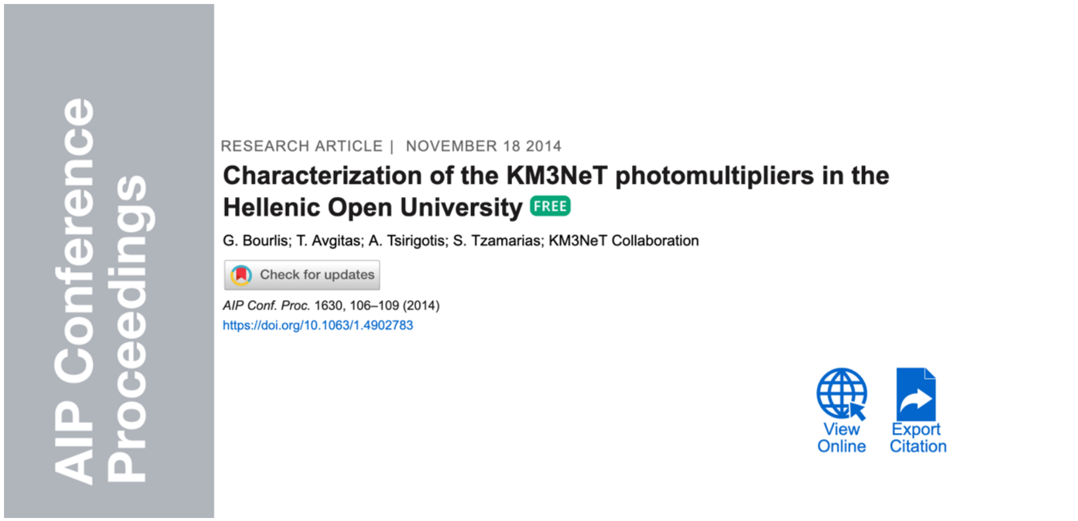
Where $\bar{Q}_e$ is the mean and θ is a parameter which (together with $\bar{Q}_e$) determines the RMS

$$G\left(Q;C_1,C_2,\cdots C_k,RMS_e,<Q_e>\right)=\sum_{N=1}^{k}\frac{C_N}{\bar{Q}_e}\frac{(\theta+1)^{N(\theta+1)}\left(Q/\bar{Q}_e\right)^{N(\theta+1)-1}}{\Gamma\left(N(\theta+1)\right)}e^{-(\theta+1)Q/\bar{Q}_e}$$

Fit the to the charge spectrum produced by several hotoelectrons



R12199-02 PMT Response


AIP Conference Proceedings

RESEARCH ARTICLE | NOVEMBER 18 2014

Characterization of the KM3NeT photomultipliers in the Hellenic Open University FREE

G. Bourlis; T. Avgitas; A. Tsirigotis; S. Tzamarias; KM3NeT Collaboration

Check for updates

AIP Conf. Proc. 1630, 106–109 (2014)

https://doi.org/10.1063/1.4902783

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The Hamamatsu 80mm diameter **R12199-02 PMTs**, proposed for KM3NeT, have been used for this work.

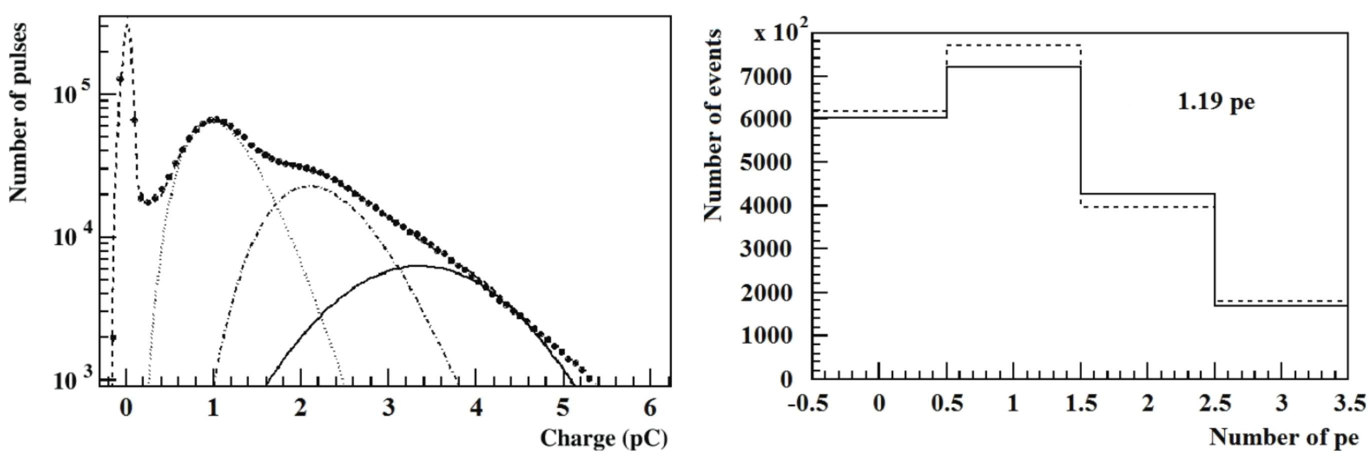
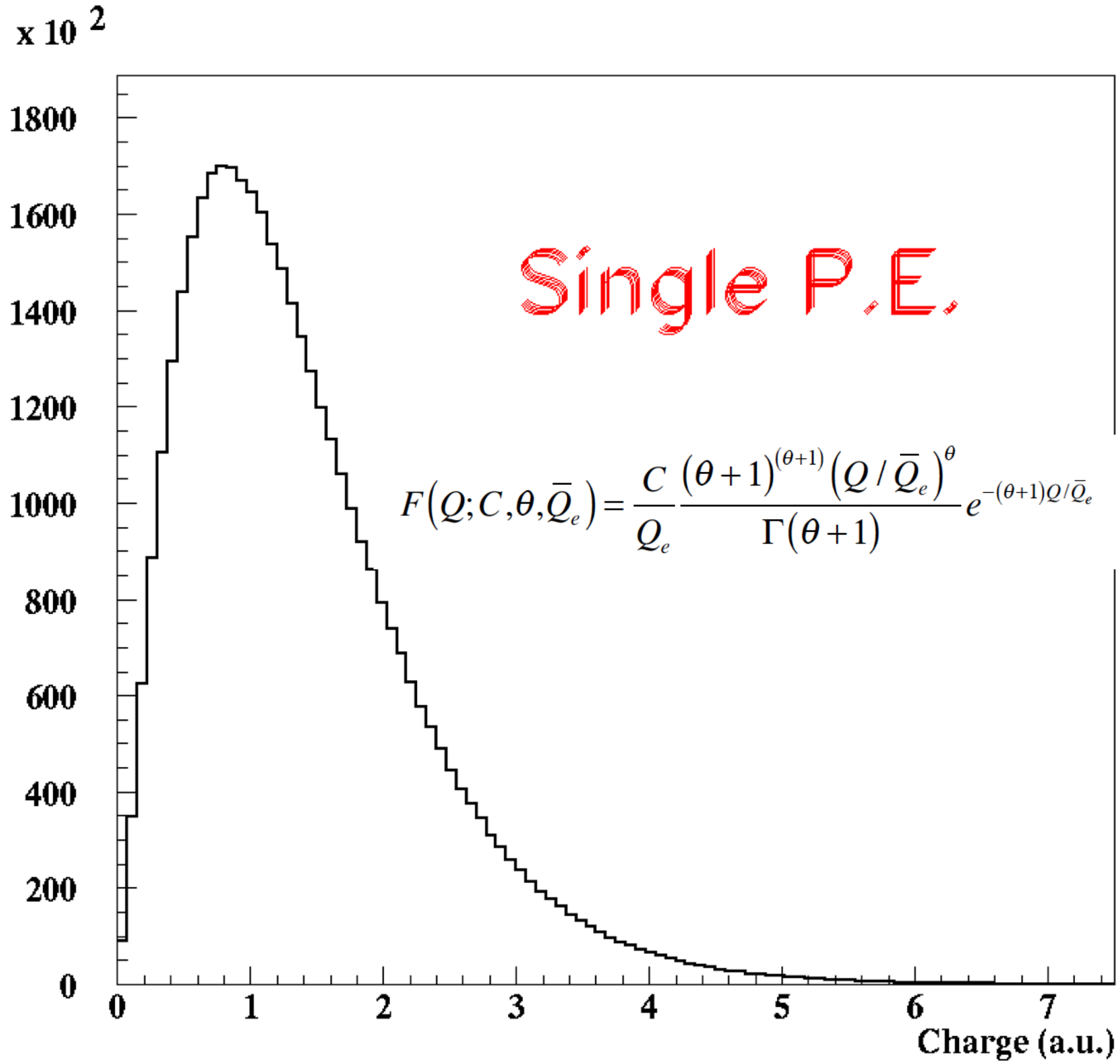


FIGURE 3. Left: Fitting the PMT charge distribution (polyas for 4 or more pe have not been used). Right: Measured (dashed line) and estimated (solid line) number of pe.



$$F\left(Q;C,\theta,\bar{Q}_e\right)=\frac{C}{Q_e}\frac{(\theta+1)^{(\theta+1)}\left(Q/\bar{Q}_e\right)^{\theta}}{\Gamma(\theta+1)}e^{-(\theta+1)Q/\bar{Q}_e}$$

$$P_{Npe}\left(Q;N,\theta,\bar{Q}_e\right)=\underbrace{P_{spe}\otimes P_{spe}\cdots\otimes P_{spe}}_{N\ times}=\frac{1}{\bar{Q}_e}\frac{(\theta+1)^{N(\theta+1)}\left(Q/\bar{Q}_e\right)^{N(\theta+1)-1}}{\Gamma\left(N(\theta+1)\right)}e^{-(\theta+1)Q/\bar{Q}_e}$$

In the case that μ, per average, pes are expected from the photocathode, then:

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

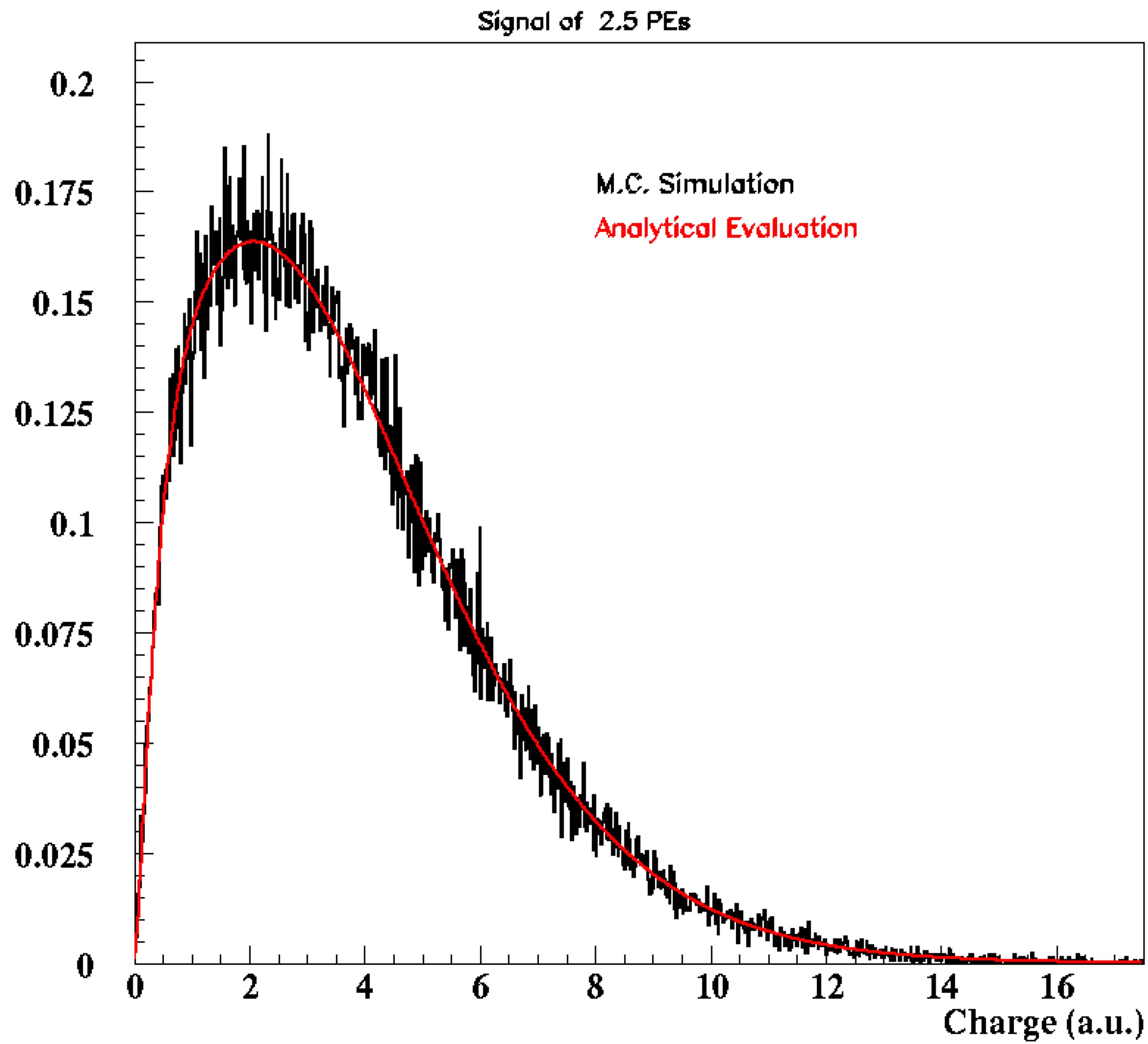
The probability that the detector responds to the N pes with a signal of charge Q is:

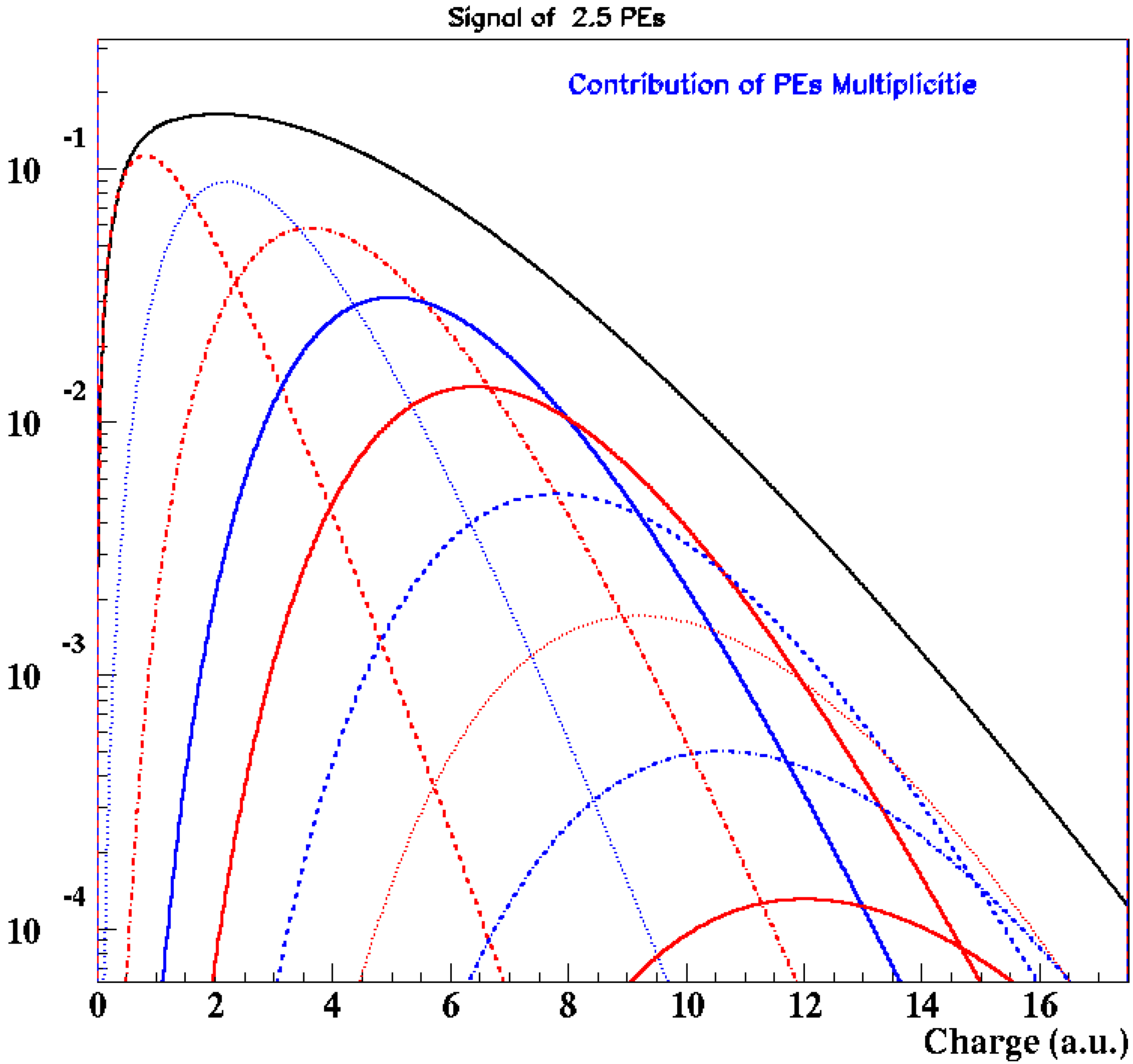
$$P_{Npe}\left(Q;N,\theta,\bar{Q}_e\right) = \underbrace{P_{spe} \otimes P_{spe} \cdots \otimes P_{spe}}_{N\ times} = \frac{1}{\bar{Q}_e} \frac{(\theta+1)^{N(\theta+1)}\left(Q/\bar{Q}_e\right)^{N(\theta+1)-1}}{\Gamma\left(N(\theta+1)\right)} e^{-(\theta+1)Q/\bar{Q}_e}$$

Then the probability of observing a detector signal with charge Q, given μ, $\bar{Q}_e$, and θ, is:

$$F(Q;\mu,\theta,\bar{Q}_e) = \sum_{N=1}^{\infty} \frac{\mu^N e^{-\mu}}{N!} P_{Npe}(Q;N,\theta,\bar{Q}_e)$$

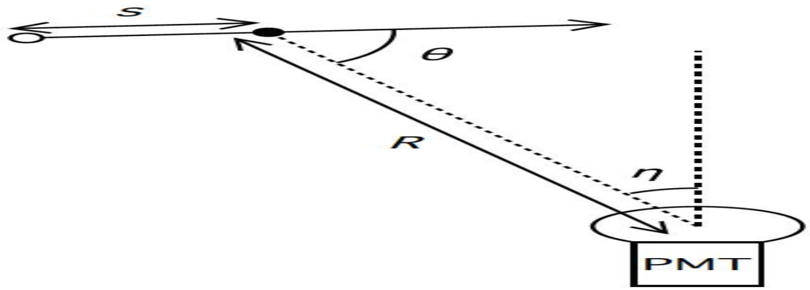
This is the pd.f. used to simulate the detector signal and it is also used in a likelihood estimation of the track parameters (i.e. the lepton track that produced the observed signals).


Signal of 2.5 PEs
M.C. Simulation
Analytical Evaluation
0
0.025
0.05
0.075
0.1
0.125
0.15
0.175
0.2
0
2
4
6
8
10
12
14
16
Charge (a.u.)



Signal of 2.5 PEs
Contribution of PEs Multiplicitie
10^{-1}
10^{-2}
10^{-3}
10^{-4}
0
2
4
6
8
10
12
14
16
Charge (a.u.)

The Reconstruction Strategy



Use maximum likelihood estimation of the track parameters using information on: charge (number of pe s) and arrival time – good results

1. **Analytical calculation of the expected No of pe's and their arrival times on each photodetector (based on pre-calculated patterns)**
2. **Use MC-Integration for calculating the expected No of pe's and the arrival time on the photodetectors (based on pre-calculated patterns)**
3. **Very precise estimation of the expected No of pe's and their arrival times on each photodetector (based on detailed information for the Ch. Emission)**

A first evaluation of reconstruction resolution

- **Study the information carried by the timing**
- **Study the momentum estimation**
- **Study the e-μ identification**

x is a vector of all the track parameters $\{t_v, x_v, y_v, z_v, P, \theta_t, \varphi_t\}$

j, i run through the detector elements (photodetectors)

q_i is the charge of the i^{th} photodetector's signal

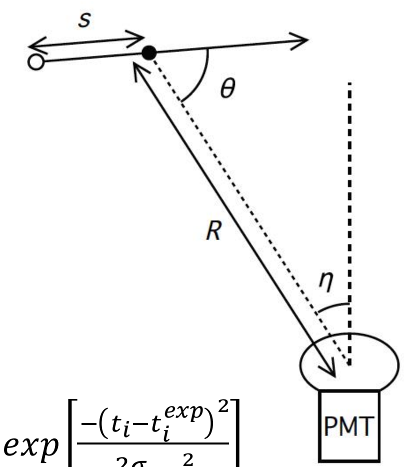
t_i is the arrival time of the i^{th} photodetector's signal

s is the length along the initial track direction

$$\mathcal{L} = \prod_j^{\text{unhit}} P_j(\text{unhit}|\mathbf{x}) \prod_i^{\text{hit}} \{1 - P_i(\text{unhit}|\mathbf{x})\} f_q(q_i|\mathbf{x}) f_t(t_i|\mathbf{x})$$

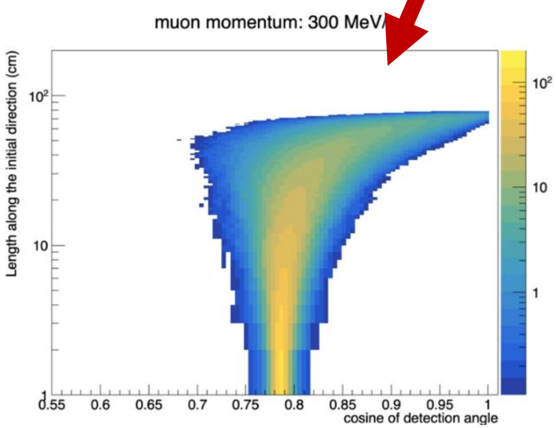
$$\mathcal{L} = \prod_j^{\text{unhit}} P_j(\text{unhit}|\mu_j) \prod_i^{\text{hit}} \{1 - P_i(\text{unhit}|\mu_i)\} f_q(q_i|\mu_i) f_t(t_i|\mathbf{x})$$

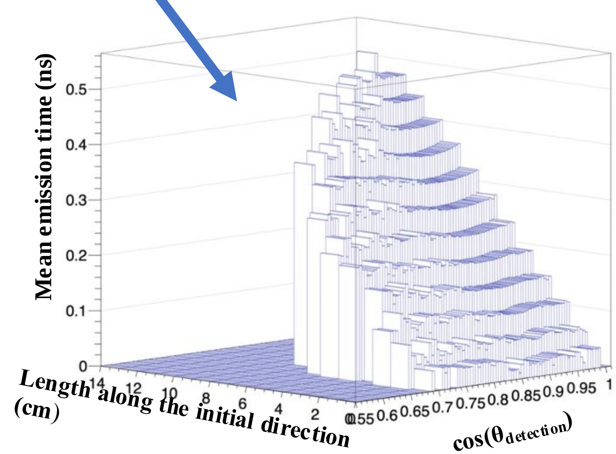
$$\mu_i^{\text{dir}} = \Phi(p) \int \text{d}s \; g(p, s, \cos\theta)\Omega(R)T(R)\underbrace{\epsilon(\eta)}_{\text{QE=cnst}}$$



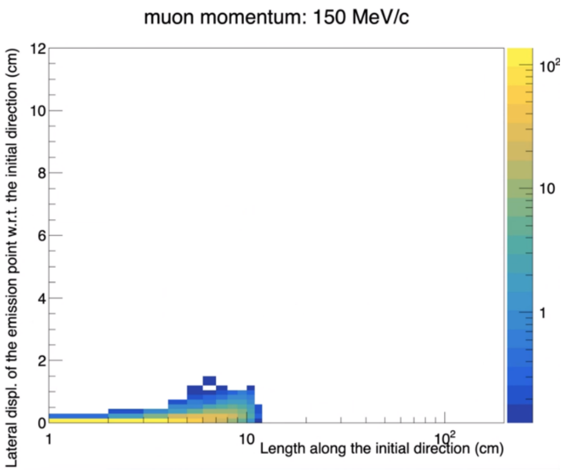
$$f_t(t_i) = \frac{1}{\sqrt{2\pi}\sigma_{res}} \, exp\left[\frac{-(t_i - t_i^{exp})^2}{2\sigma_{res}{}^2}\right]$$

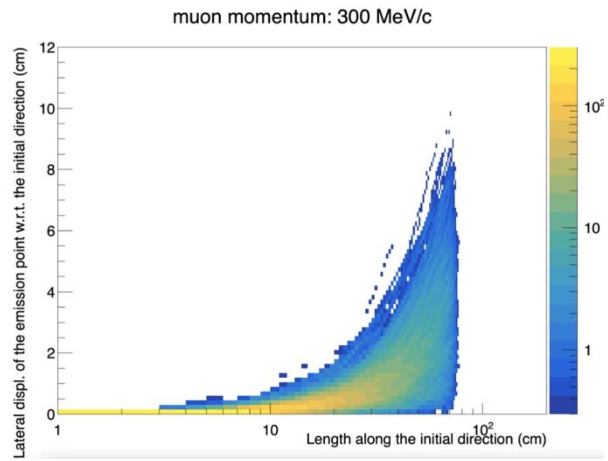
$$t_i^{exp} = \int [\tau_{em}(p, s, cos\theta) + t_{flight}(R)] g_N(p, s, cos\theta)\Omega(R)T(R)ds$$

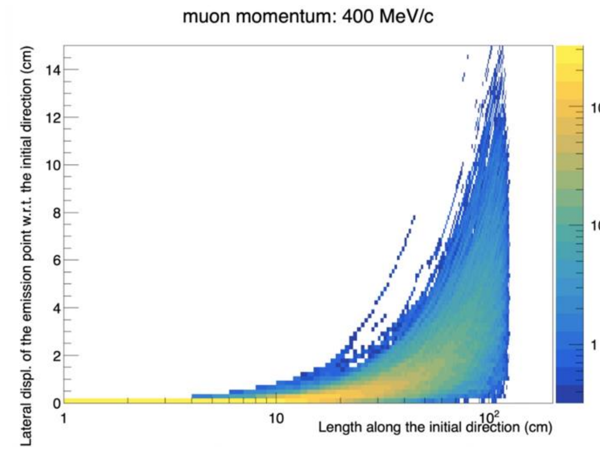


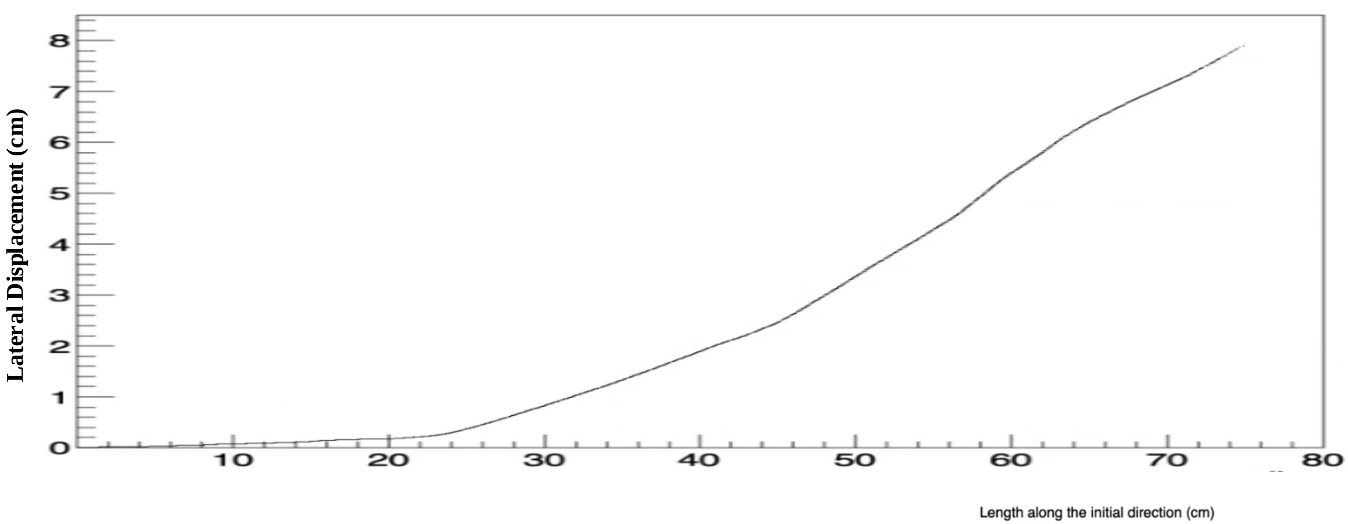


The track is assumed to be a straight line

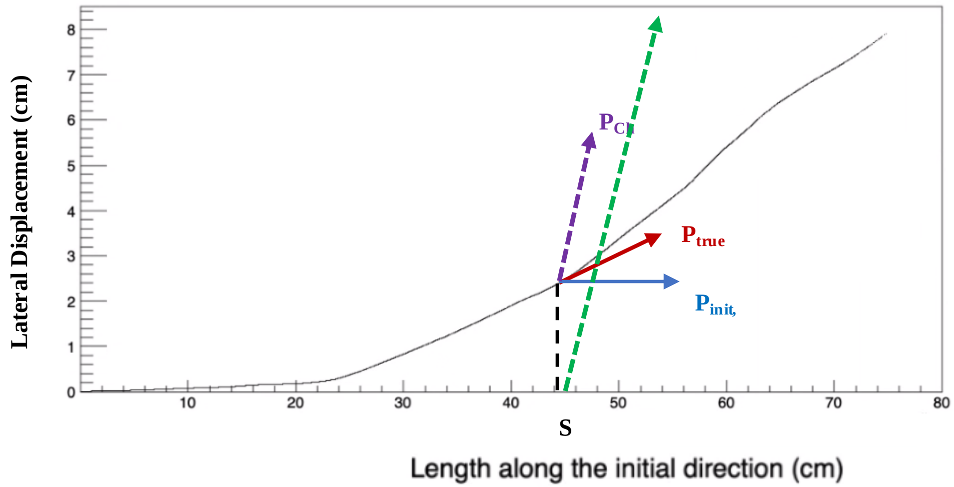

muon momentum: 150 MeV/c
Lateral displ. of the emission point w.r.t. the initial direction (cm)
Length along the initial direction (cm)

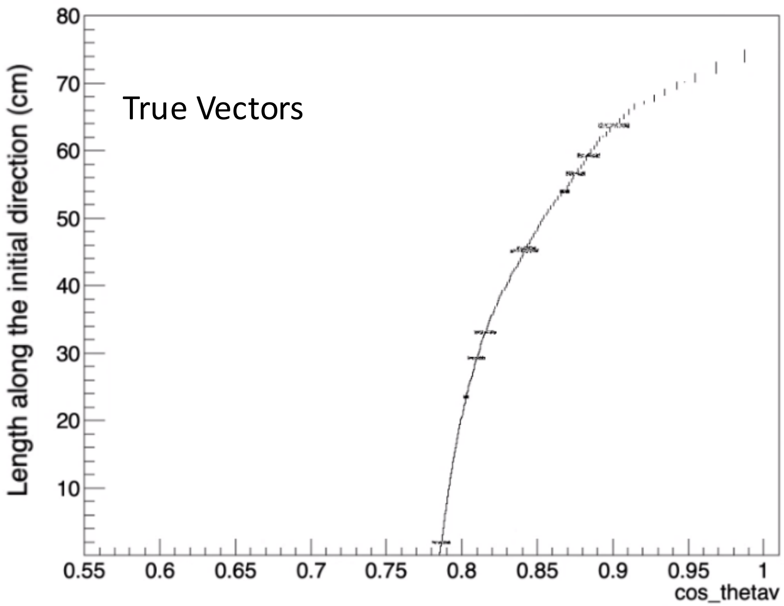

muon momentum: 300 MeV/c
Lateral displ. of the emission point w.r.t. the initial direction (cm)
Length along the initial direction (cm)

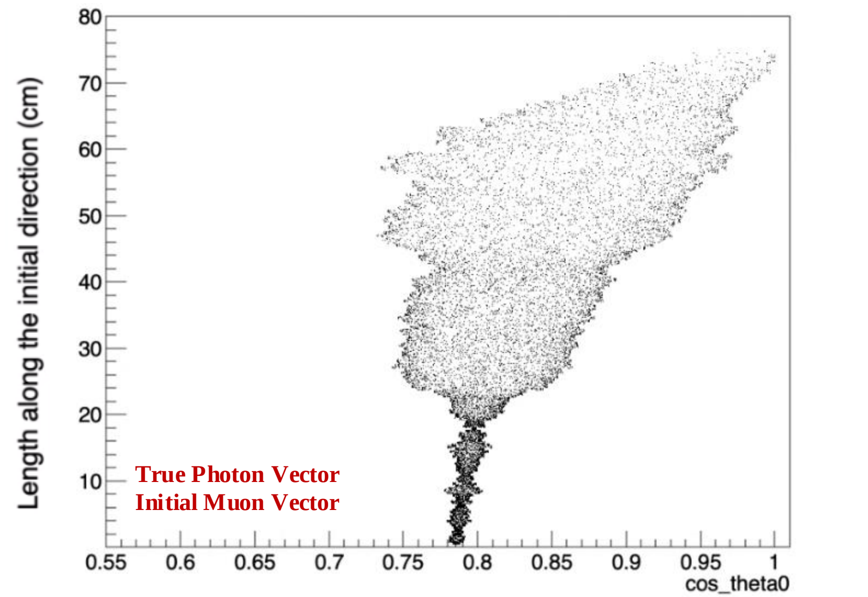

muon momentum: 400 MeV/c
Lateral displ. of the emission point w.r.t. the initial direction (cm)
Length along the initial direction (cm)


Lateral Displacement (cm)
Length along the initial direction (cm)

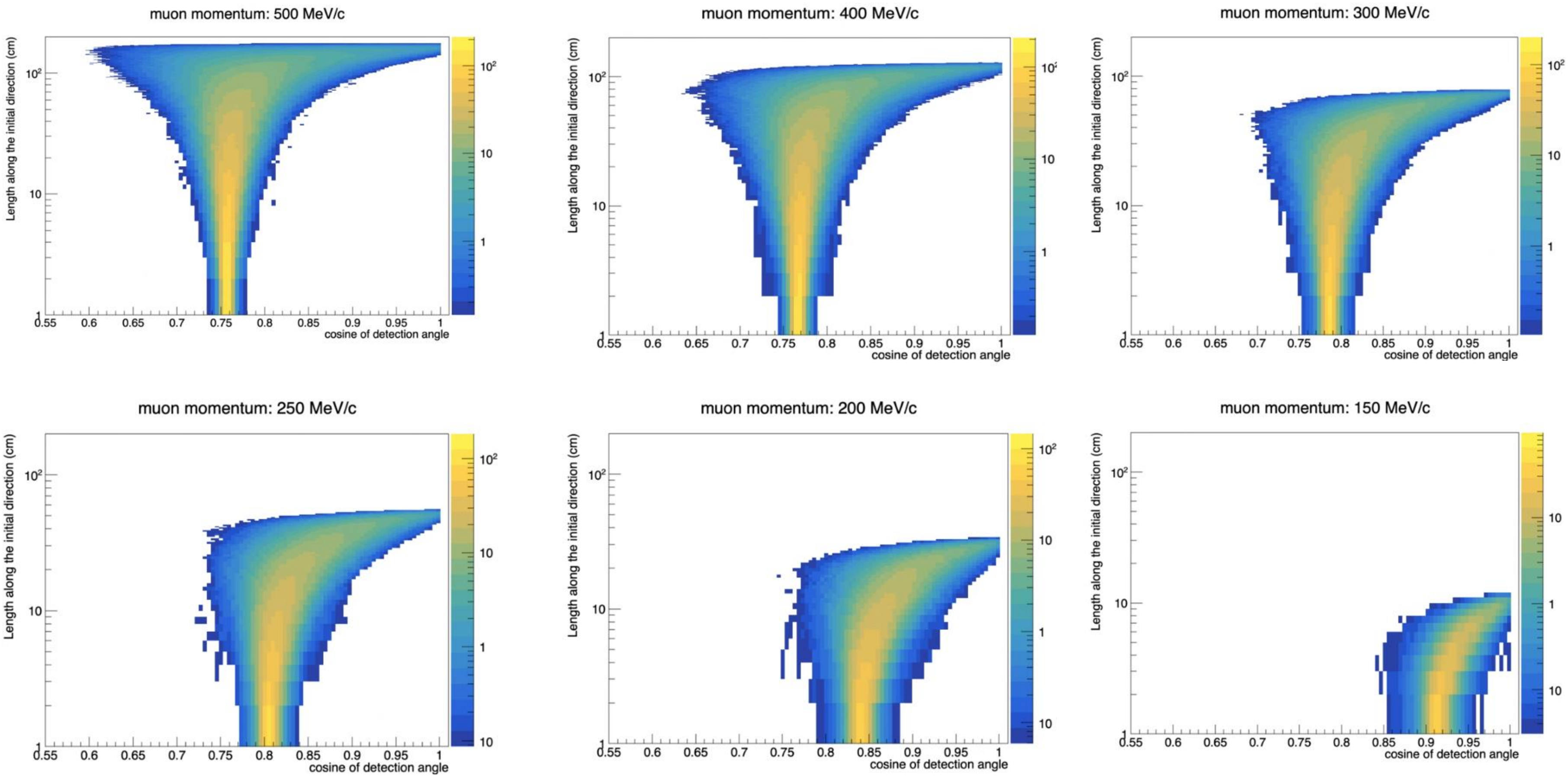
The use of the angle between the true photon vector and the initial track direction as a "Cherenkov angle" brings bias: the azimuth angle and multiple scattering are correlated



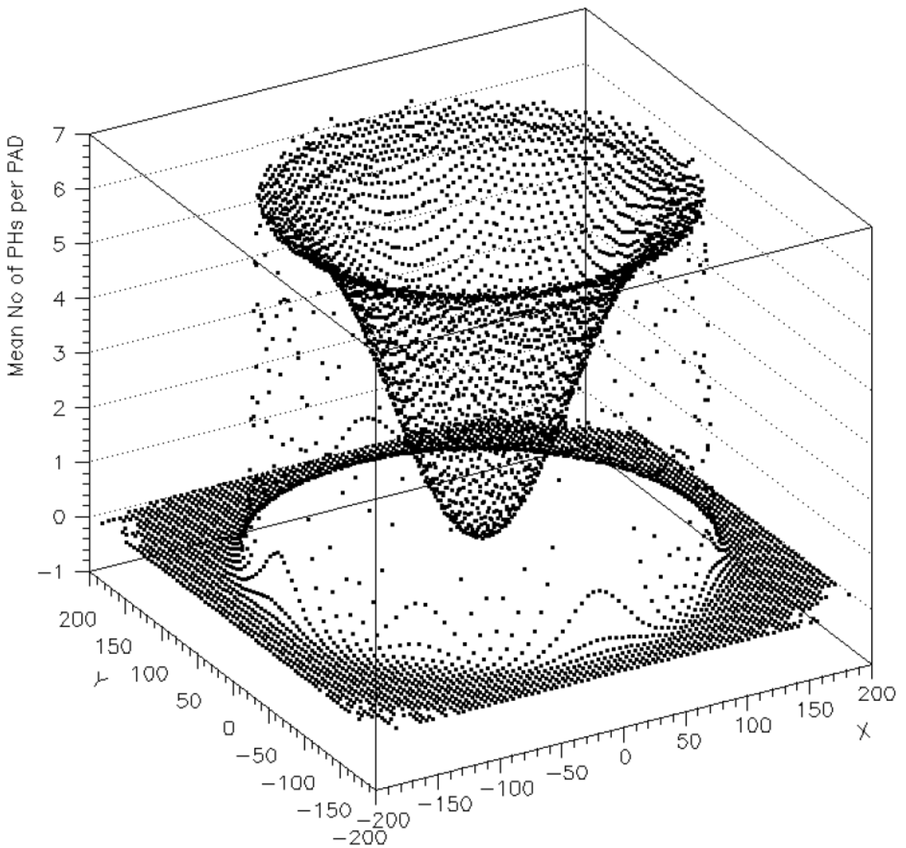


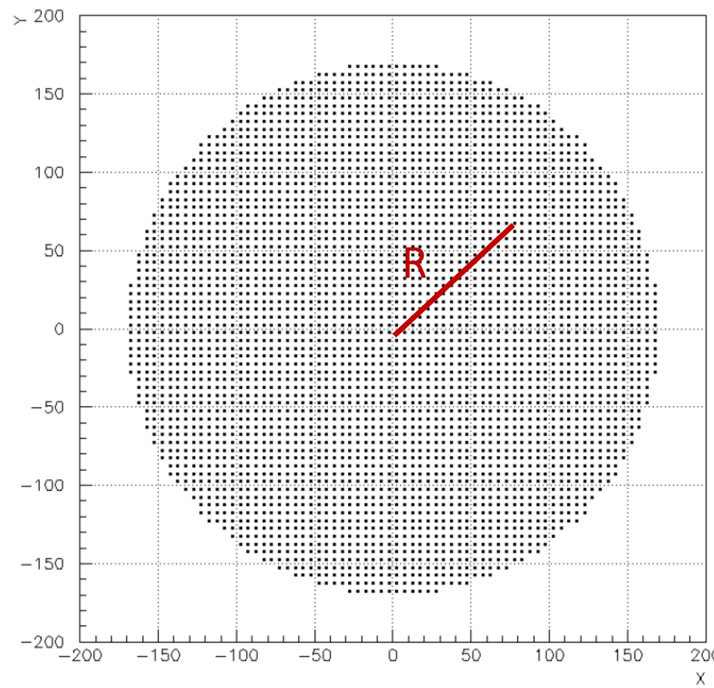


$g(p,s,\cos\theta_d)$



Consider a muon track, normal to the detector plane (xy), starting at z=-200 mm

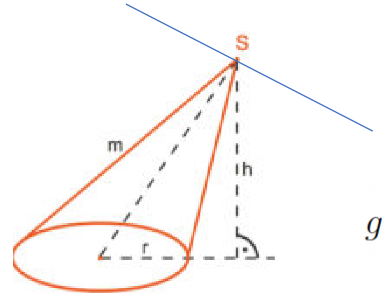




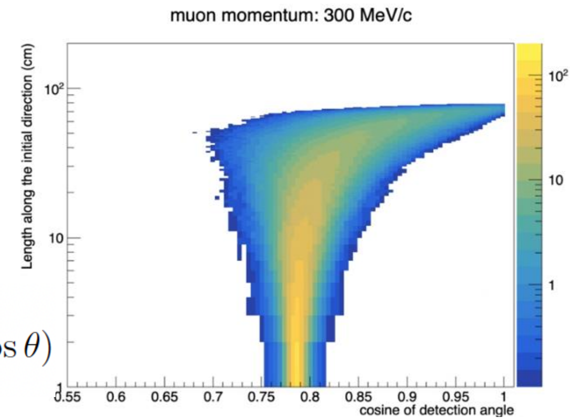
R: radial distance of a PAD w.r.t. the (initial) track impact

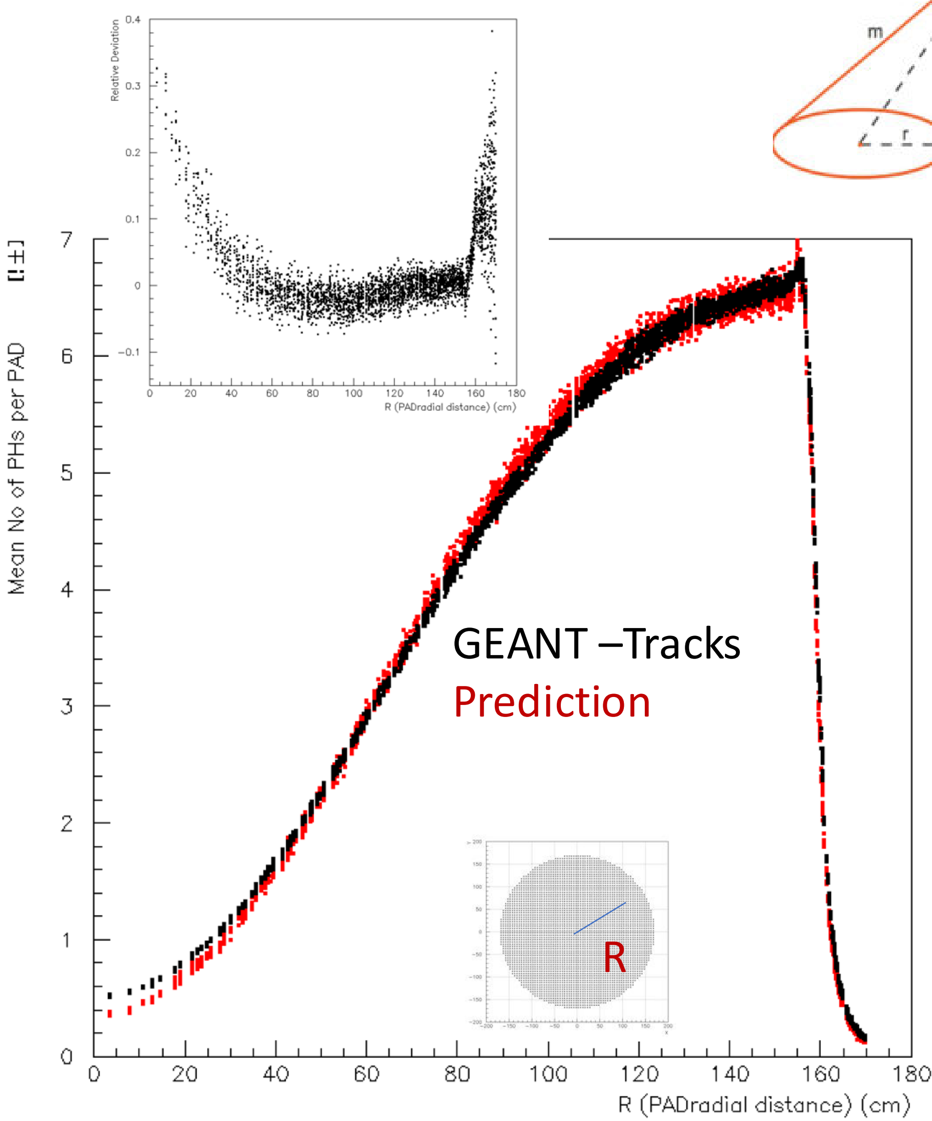
Analytical (and MC-Integration) Calculations Based on Parameterized Patterns

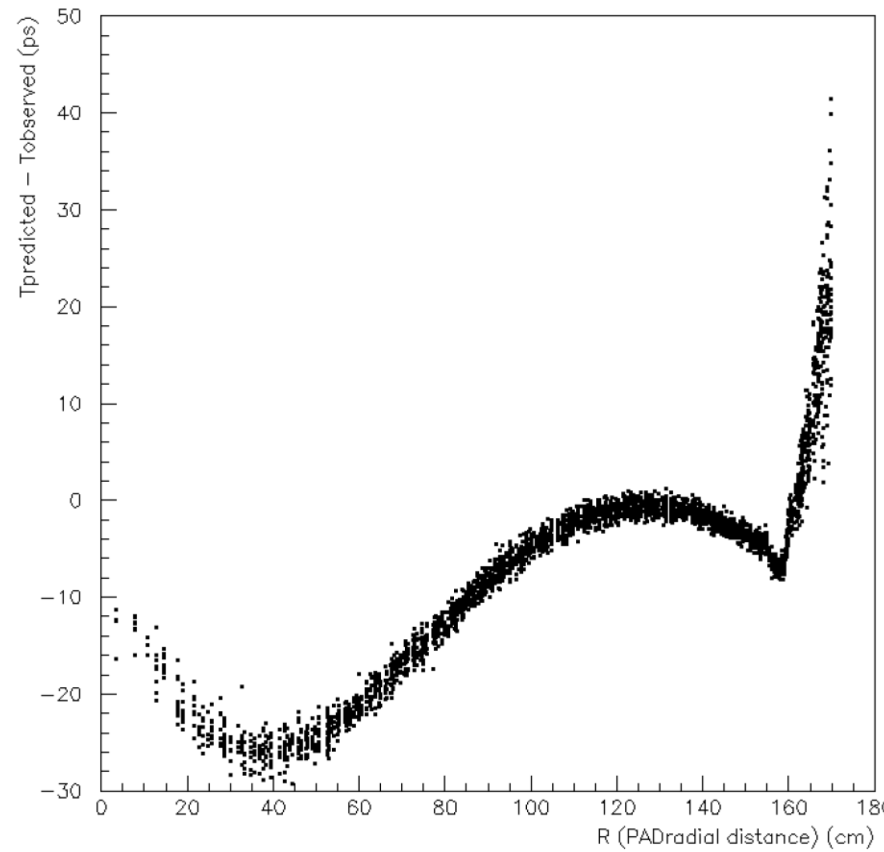
$$\mu_\iota = \int ds\; g(p, s, cos\theta)\Omega(s, \vec{r}_i)$$



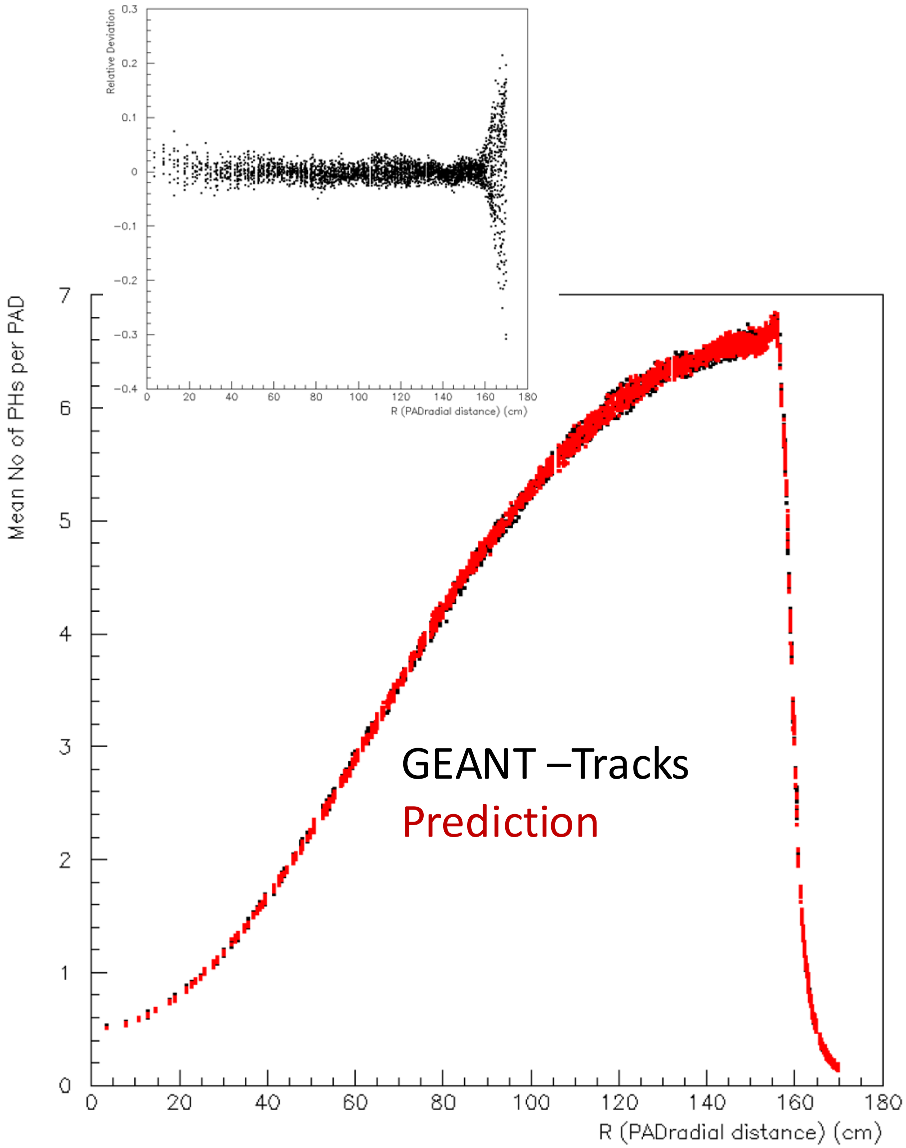
$g(p, s, \cos\theta)$

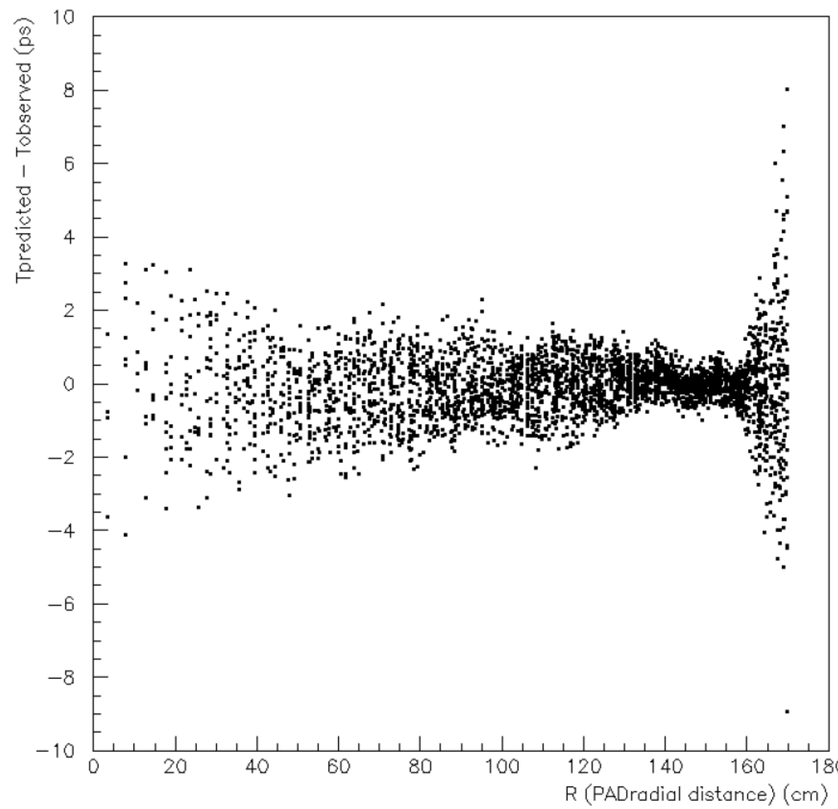






MC-Integration Calculations
Based on Detailed Ch Photon Emission Information



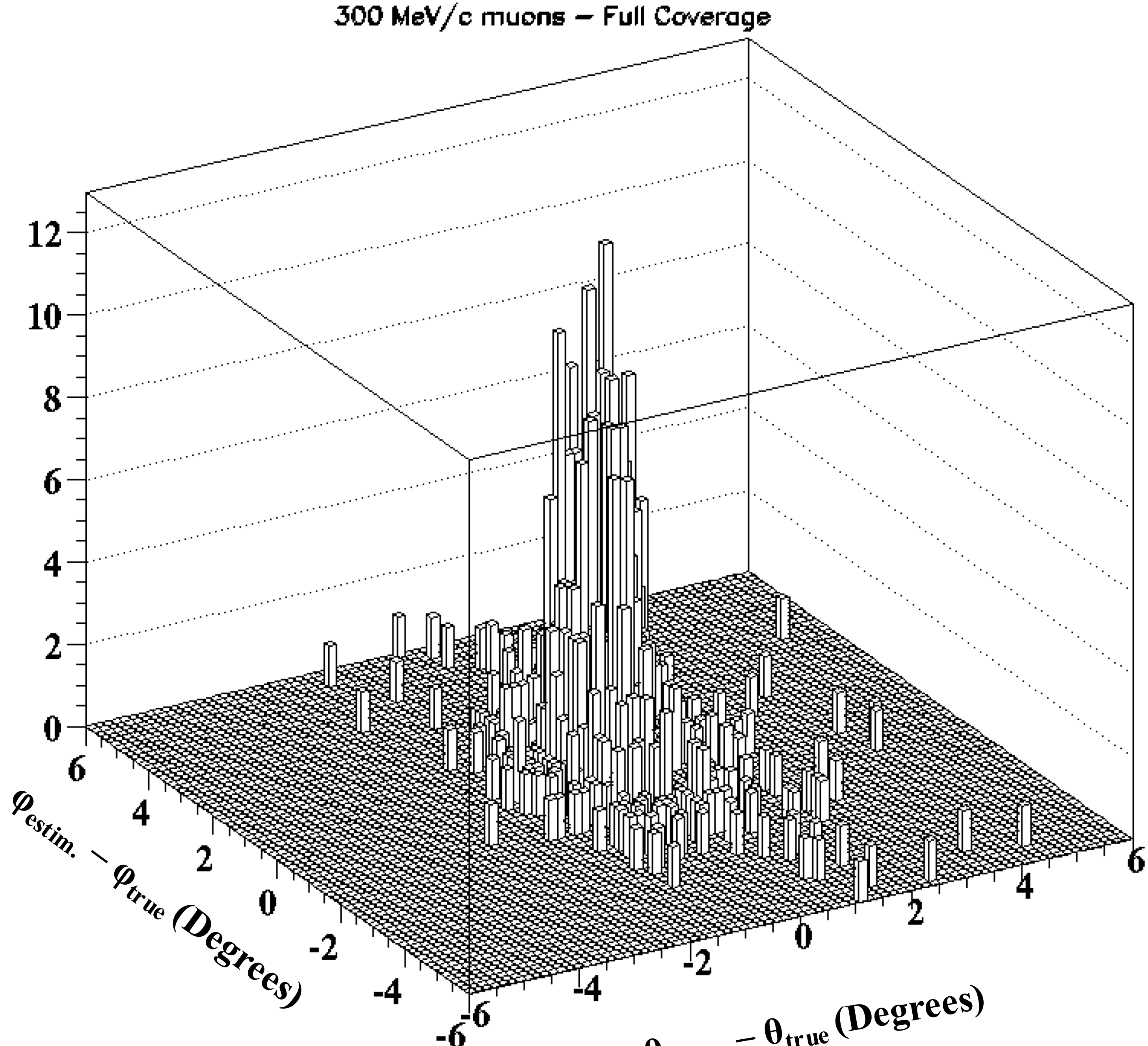


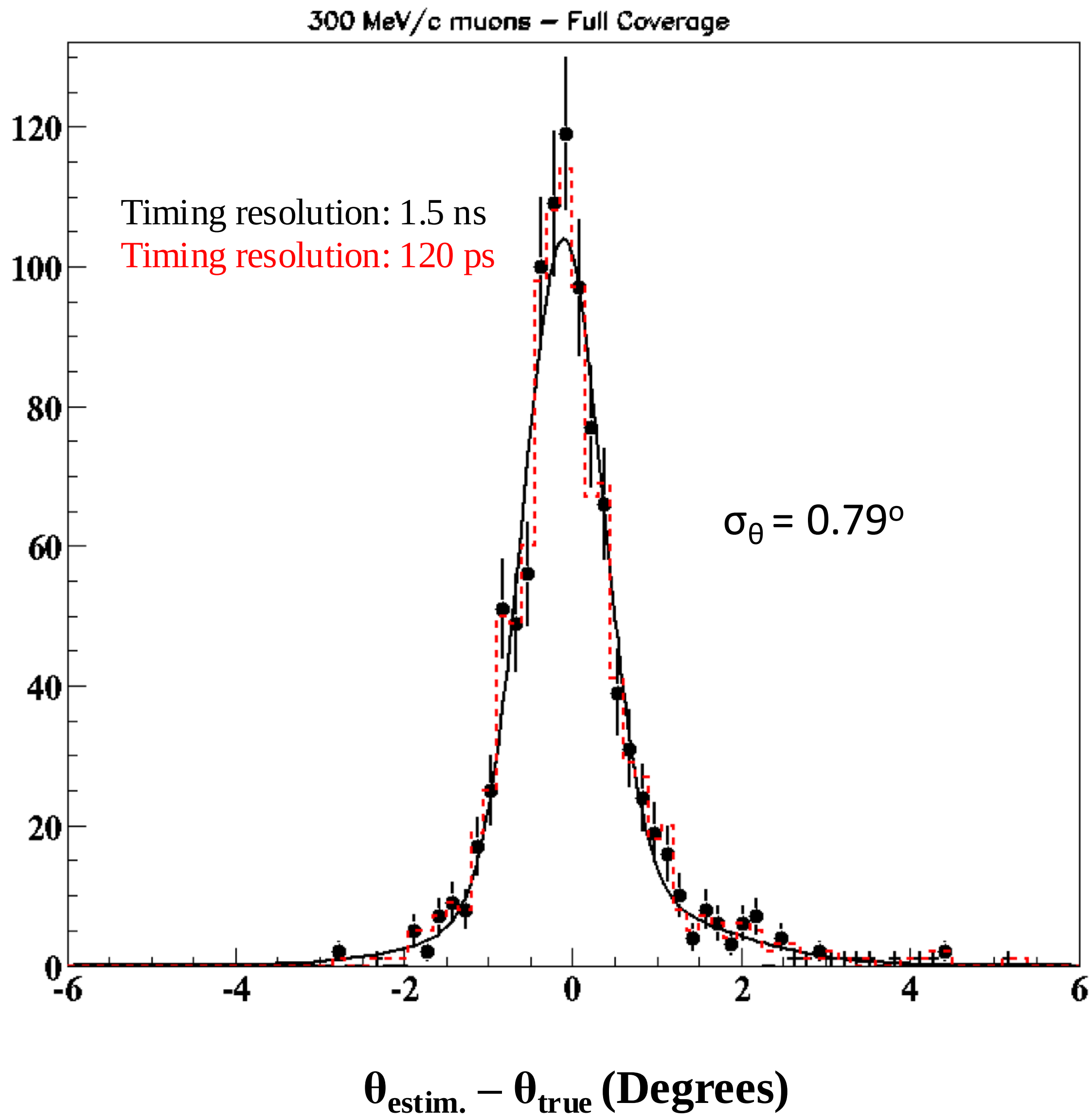
RESULTS: 300MeV/c muons

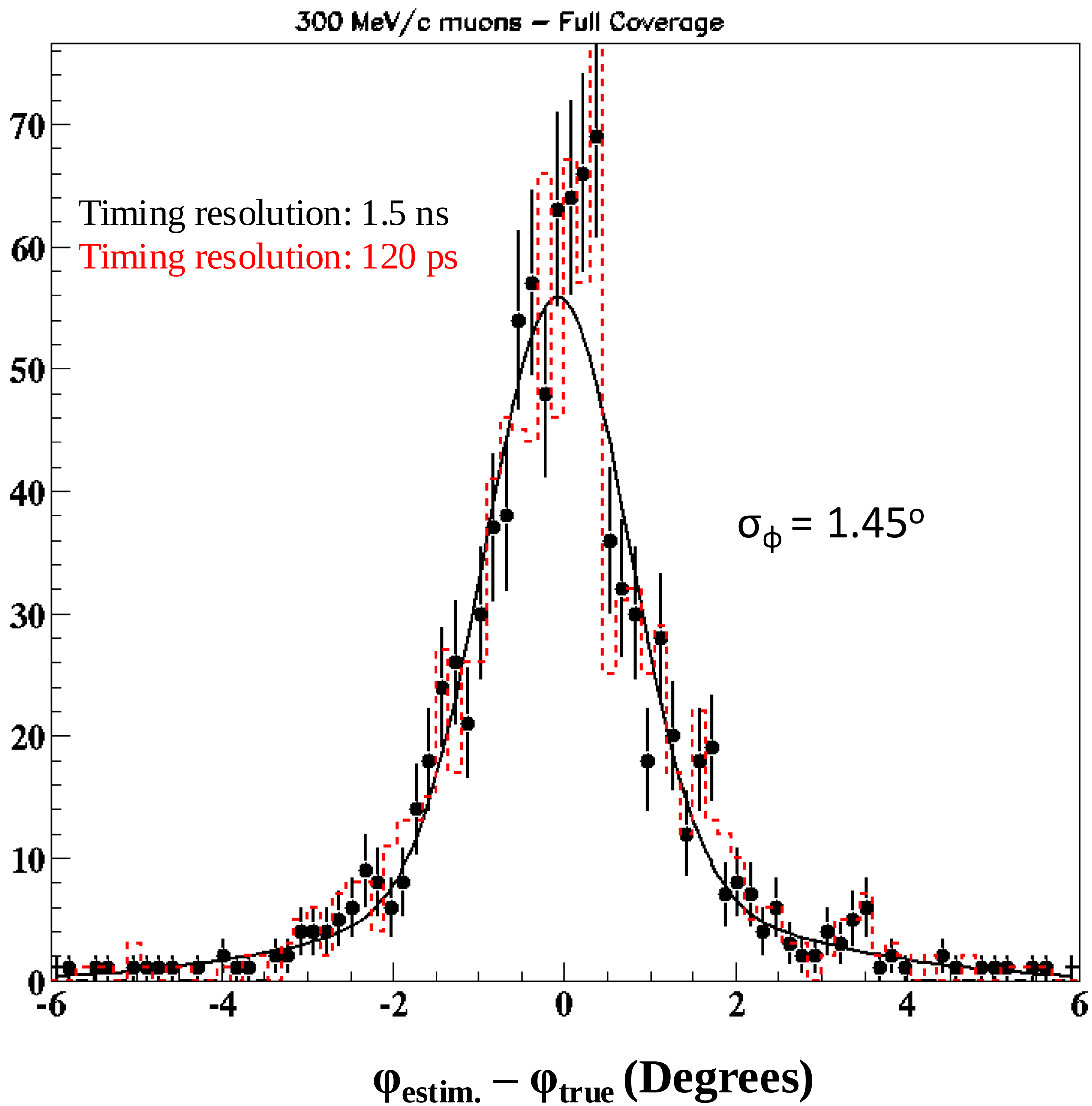
Fit for θ-ϕ

Full detector coverage

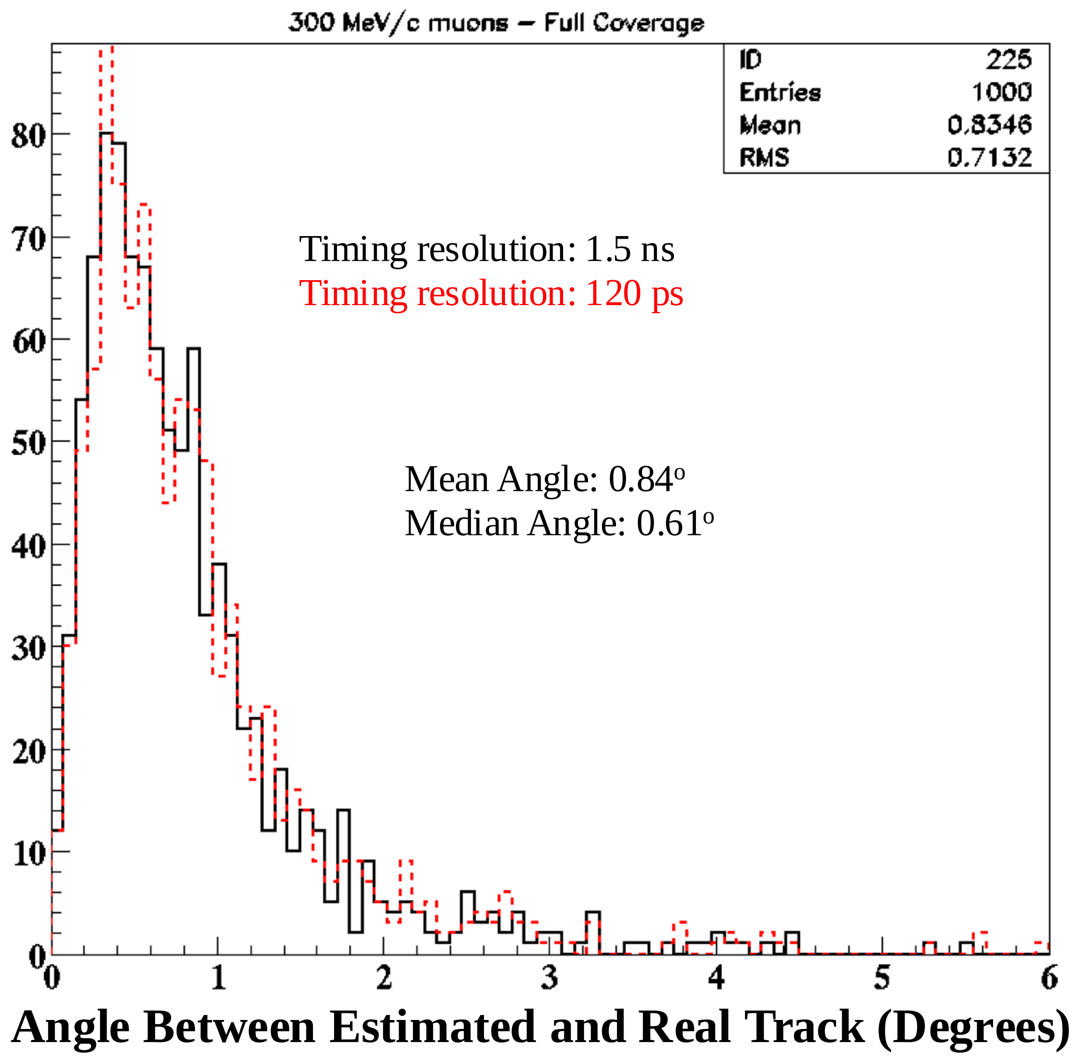
θ_{true}=30° and ϕ_{true}=0°


300 MeV/c muons – Full Coverage
12
10
8
6
4
2
0
6
4
2
0
-2
-4
-6
$\varphi_{estim.} - \varphi_{true}$ (Degrees)
-6
-4
-2
0
2
4
6
$\theta_{estim.} - \theta_{true}$ (Degrees)


300 MeV/c muons – Full Coverage
Timing resolution: 1.5 ns
Timing resolution: 120 ps
σθ = 0.79°
θestim. – θtrue (Degrees)
0
20
40
60
80
100
120
-6
-4
-2
0
2
4
6



300 MeV/c muons – Full Coverage
Timing resolution: 1.5 ns
Timing resolution: 120 ps
σ_ϕ = 1.45°
0
10
20
30
40
50
60
70
-6
-4
-2
0
2
4
6
$\varphi_{estim.} - \varphi_{true}$ (Degrees)

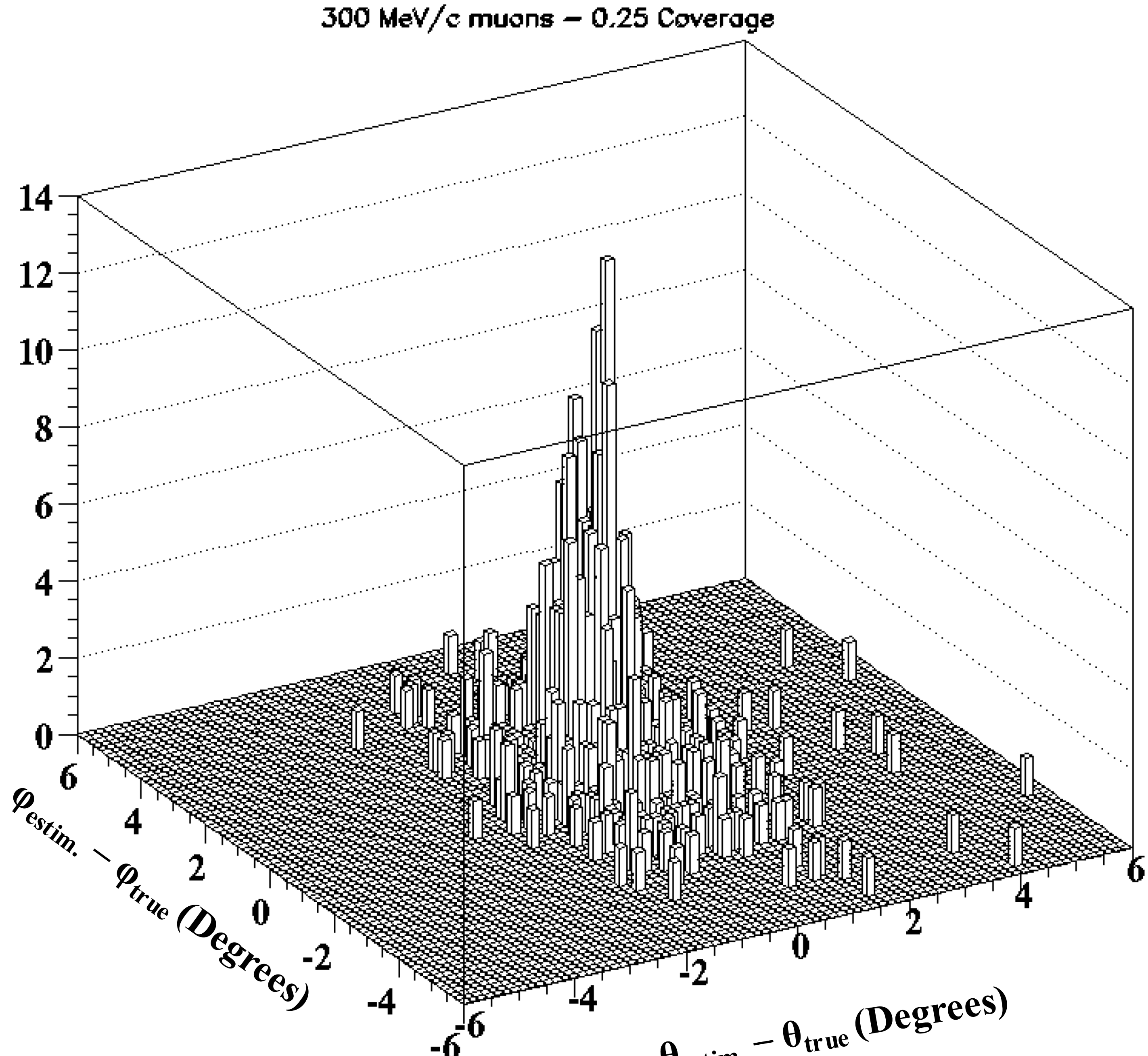

300 MeV/c muons – Full Coverage
ID 225
Entries 1000
Mean 0.8346
RMS 0.7132
Timing resolution: 1.5 ns
Timing resolution: 120 ps
Mean Angle: 0.84°
Median Angle: 0.61°
0
10
20
30
40
50
60
70
80
0
1
2
3
4
5
6
Angle Between Estimated and Real Track (Degrees)

RESULTS: 300MeV/c muons

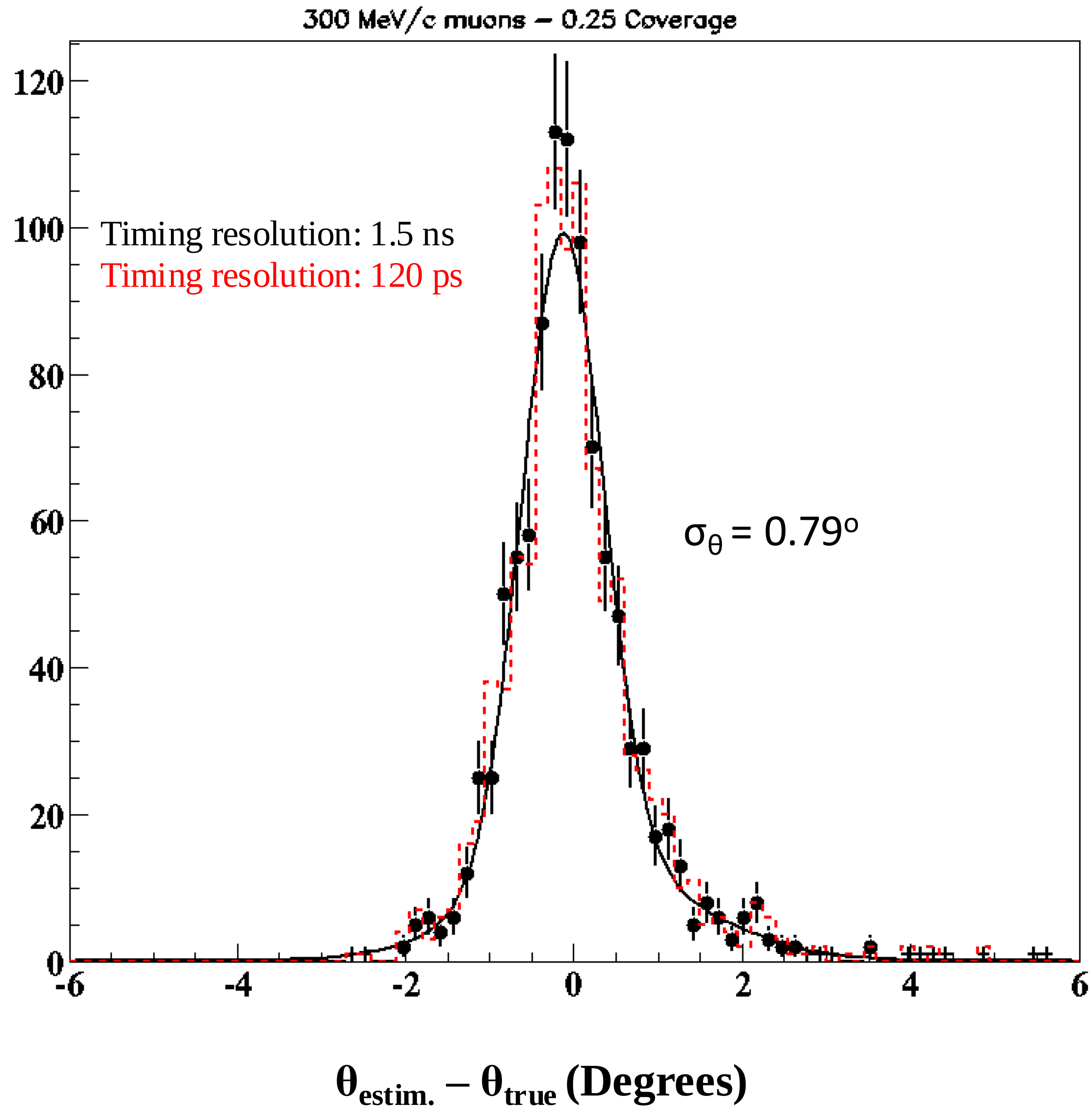
Fit for θ-φ

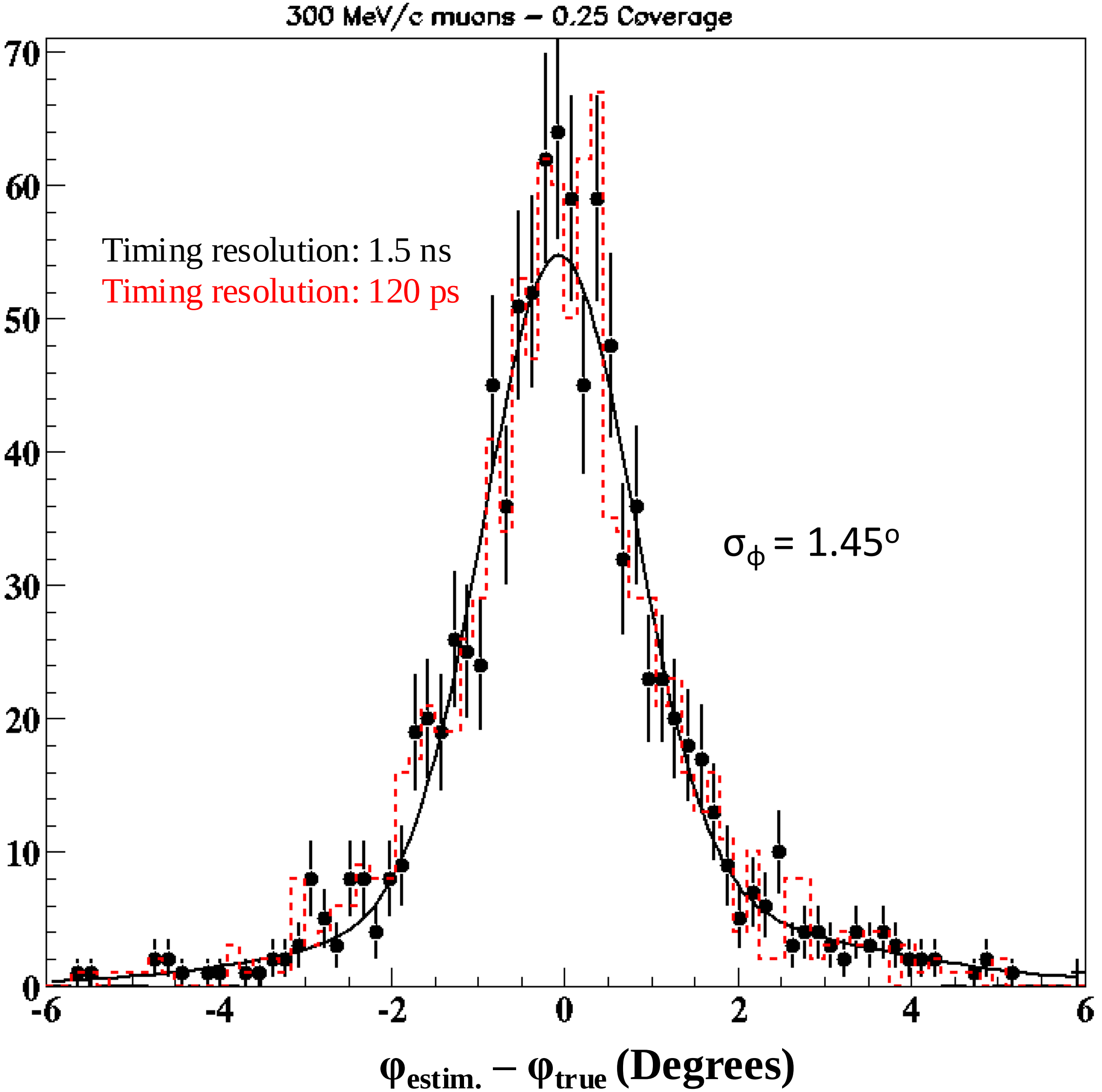
25% detector coverage

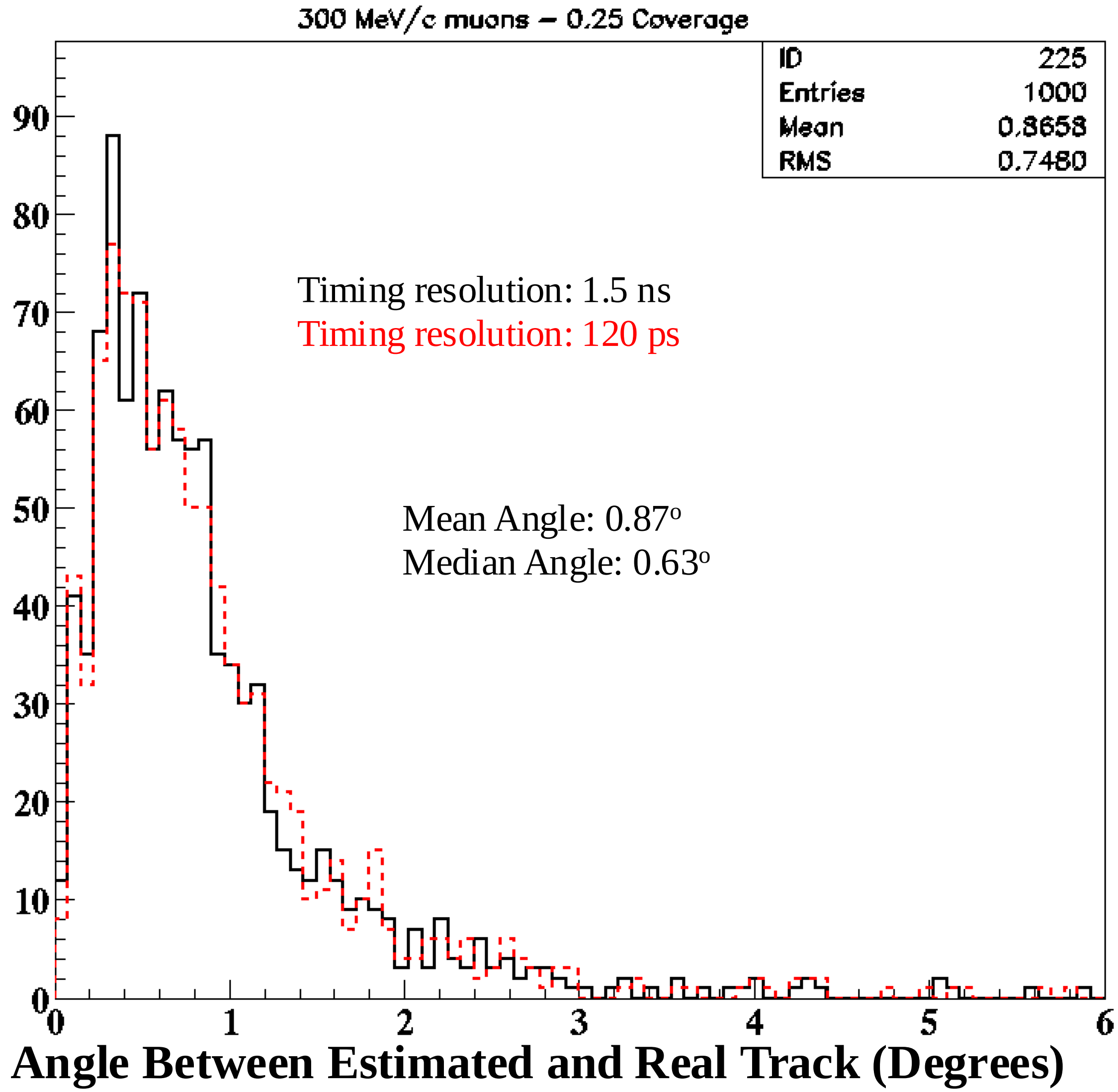
θ_{true}=30^o and ϕ_{true}=0^o



300 MeV/c muons – 0.25 Coverage
14
12
10
8
6
4
2
0
6
4
2
0
-2
-4
-6
$\varphi_{estim.} - \varphi_{true}$ (Degrees)
-6
-4
-2
0
2
4
6
$\theta_{estim.} - \theta_{true}$ (Degrees)


300 MeV/c muons – 0.25 Coverage
Timing resolution: 1.5 ns
Timing resolution: 120 ps
$\sigma_\theta = 0.79^o$
120
100
80
60
40
20
0
-6
-4
-2
0
2
4
6
$\theta_{estim.} - \theta_{true}$ (Degrees)


300 MeV/c muons – 0.25 Coverage
Timing resolution: 1.5 ns
Timing resolution: 120 ps
σ_ϕ = 1.45°
70
60
50
40
30
20
10
0
-6
-4
-2
0
2
4
6
$\varphi_{estim.} - \varphi_{true}$ (Degrees)



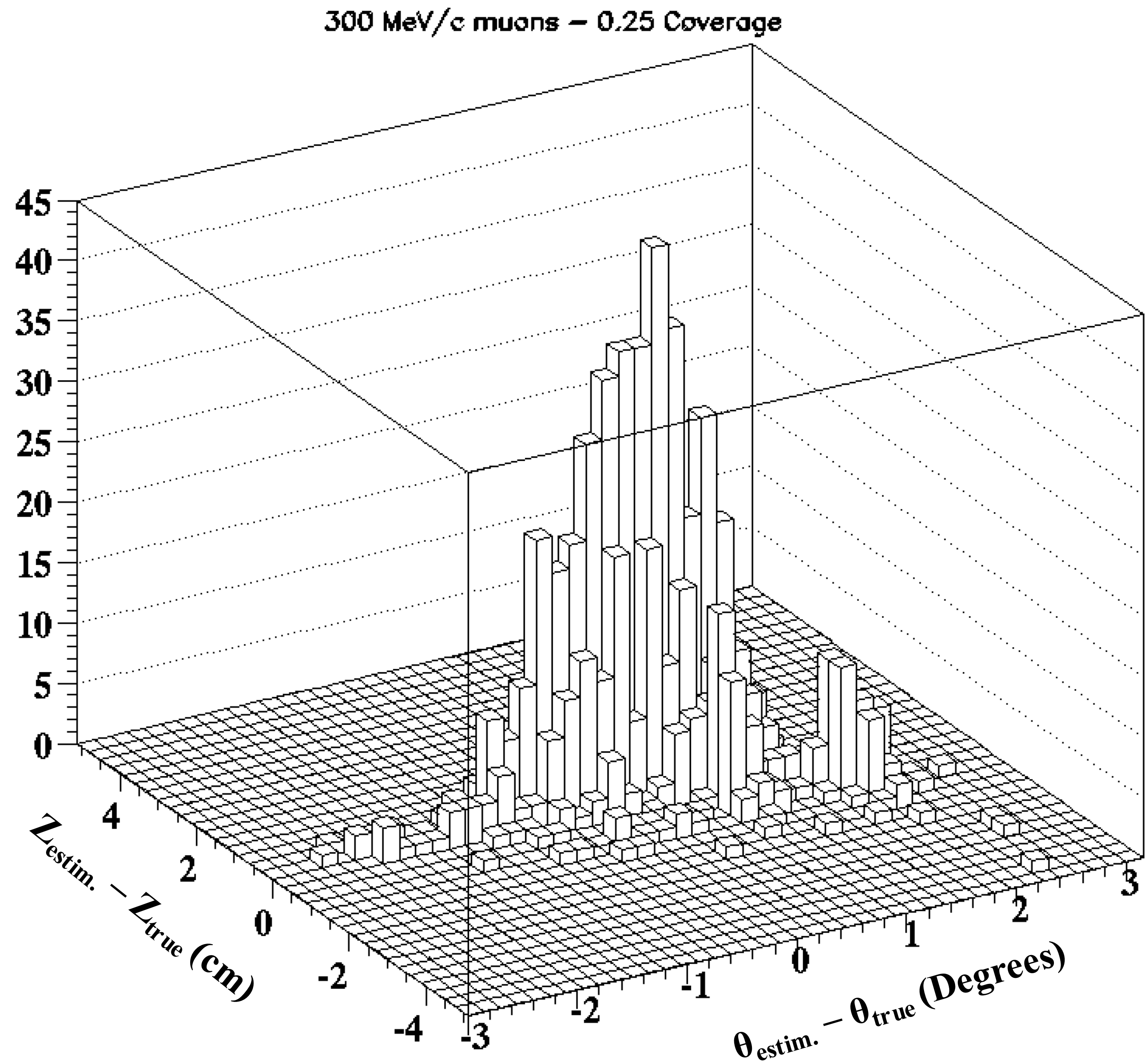
300 MeV/c muons – 0.25 Coverage
ID 225
Entries 1000
Mean 0.8658
RMS 0.7480
Timing resolution: 1.5 ns
Timing resolution: 120 ps
Mean Angle: 0.87°
Median Angle: 0.63°
0
10
20
30
40
50
60
70
80
90
0
1
2
3
4
5
6
Angle Between Estimated and Real Track (Degrees)

RESULTS: 300MeV/c muons

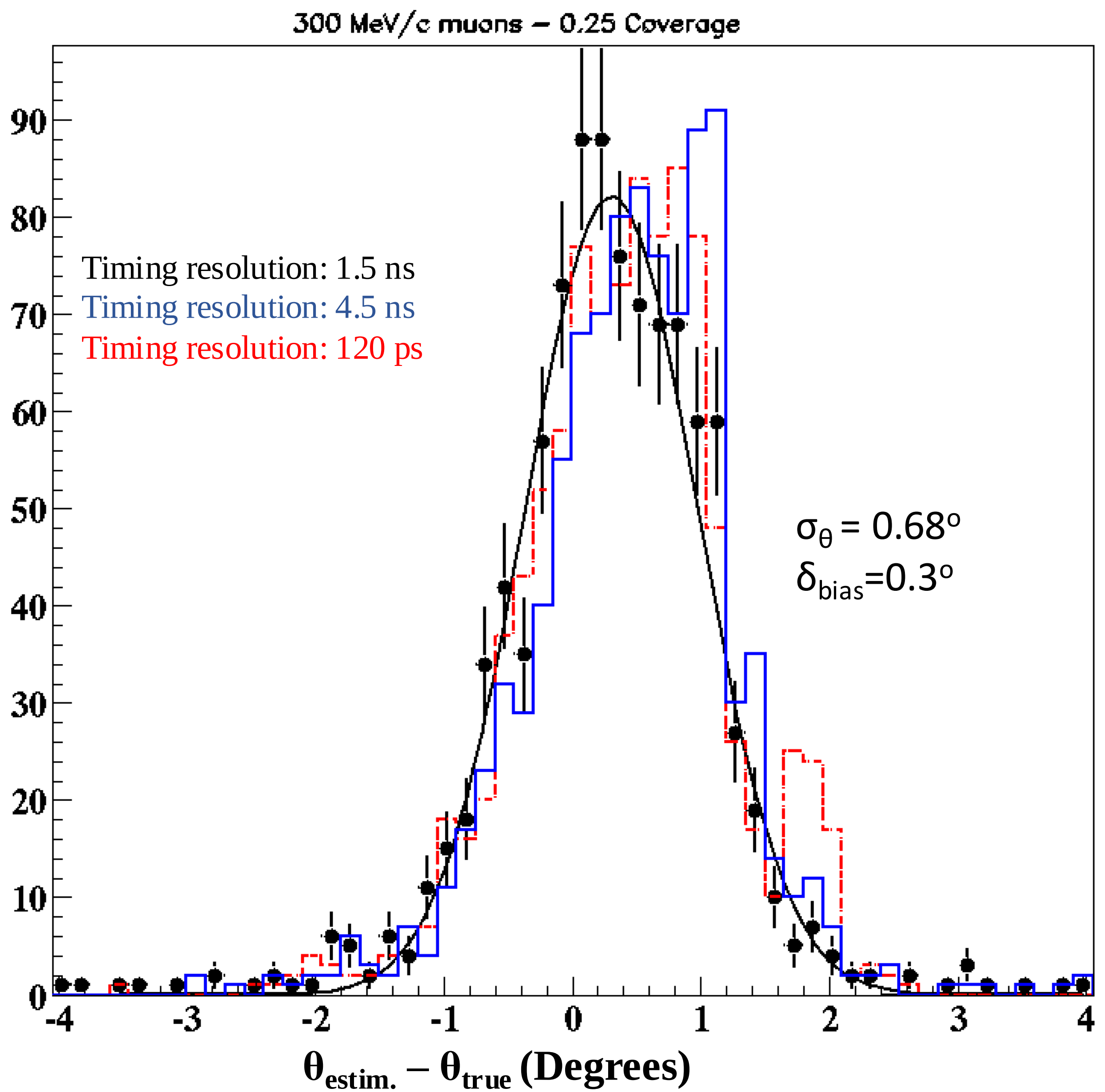
Fit for θ-Z

25% detector coverage

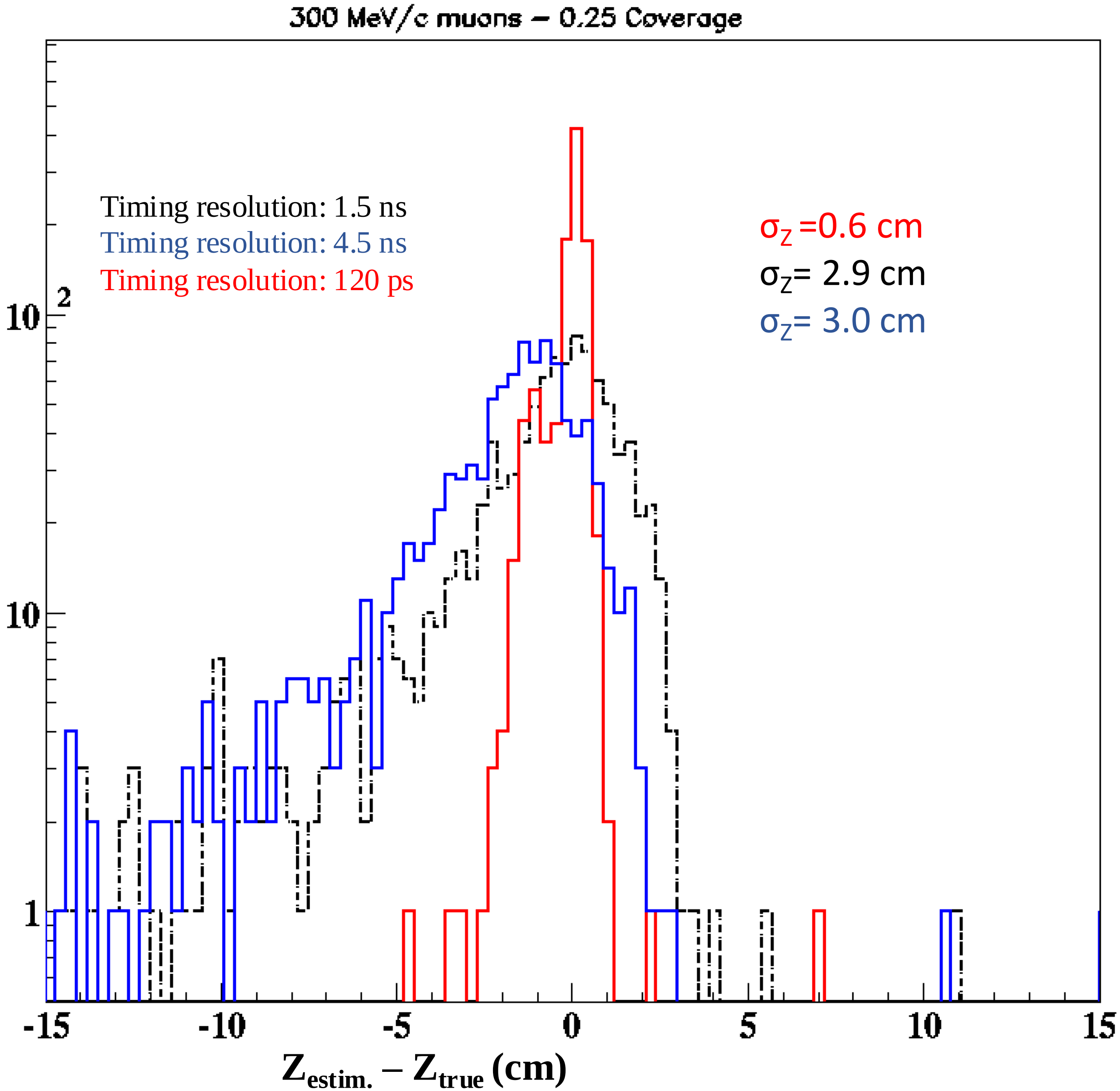
θ_{true}=30^{o} and ϕ_{true}=0^{o}



300 MeV/c muons – 0.25 Coverage
45
40
35
30
25
20
15
10
5
0
4
2
0
-2
-4
$Z_{estim.} - Z_{true}$ (cm)
-3
-2
-1
0
1
2
3
$\theta_{estim.} - \theta_{true}$ (Degrees)



300 MeV/c muons – 0.25 Coverage
Timing resolution: 1.5 ns
Timing resolution: 4.5 ns
Timing resolution: 120 ps
$\sigma_\theta = 0.68^o$
$\delta_{bias}=0.3^o$
0
10
20
30
40
50
60
70
80
90
-4
-3
-2
-1
0
1
2
3
4
$\theta_{estim.} - \theta_{true}$ (Degrees)



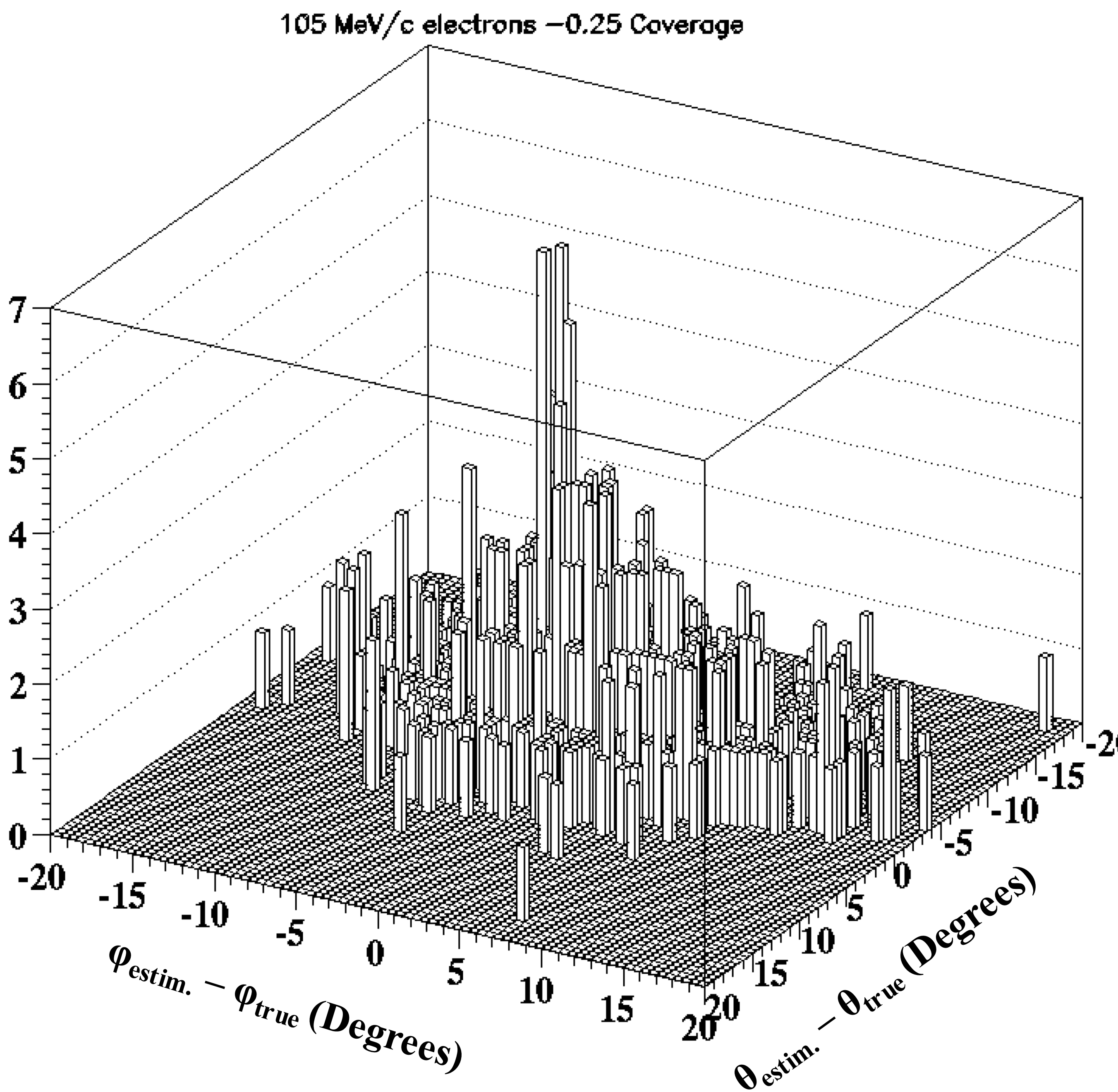
300 MeV/c muons – 0.25 Coverage
Timing resolution: 1.5 ns
Timing resolution: 4.5 ns
Timing resolution: 120 ps
σ_Z =0.6 cm
σ_Z= 2.9 cm
σ_Z= 3.0 cm
10^2
10
1
-15
-10
-5
0
5
10
15
$Z_{estim.} - Z_{true}$ (cm)

RESULTS: 105MeV/c electrons

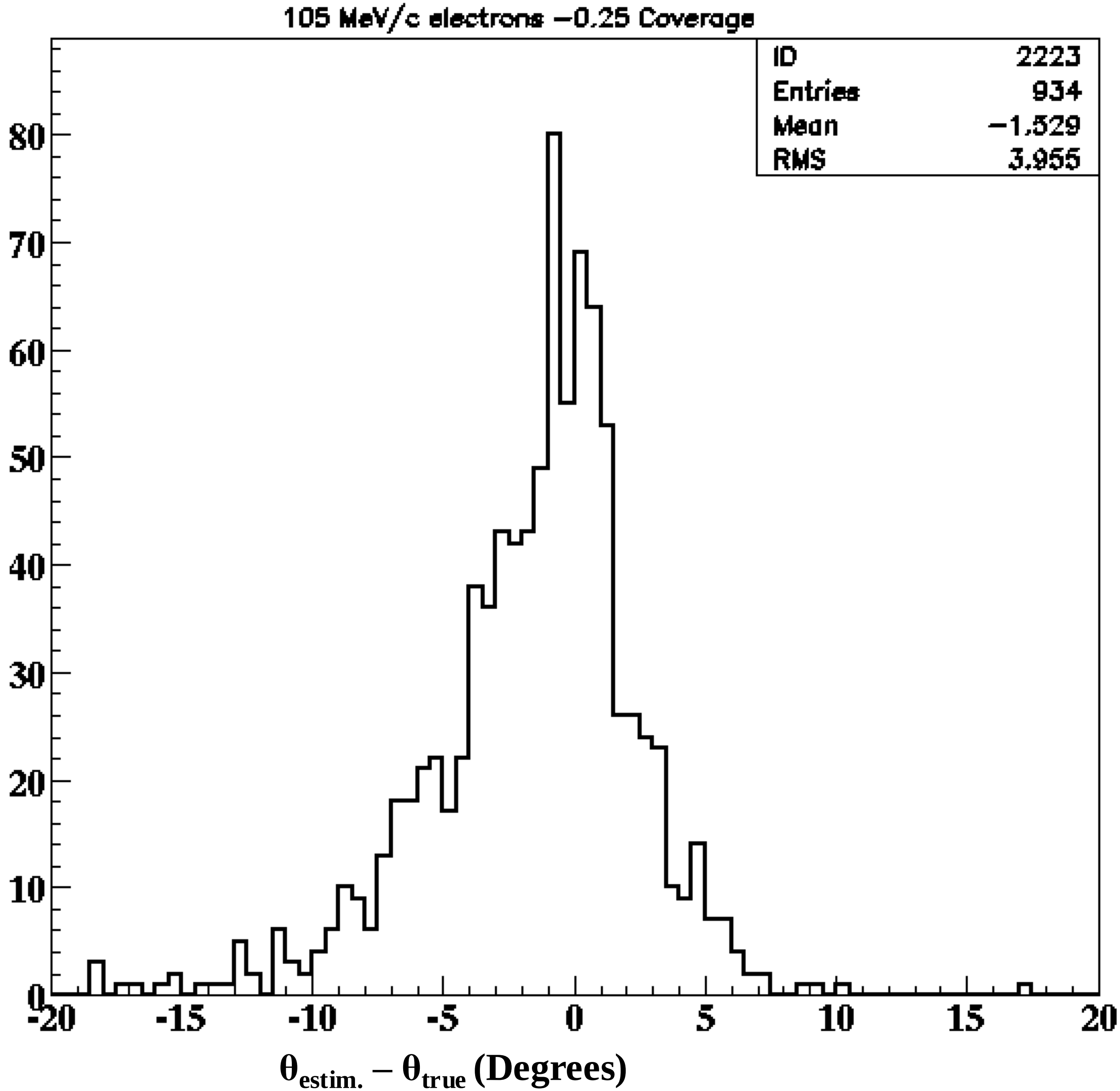
Fit for θ-φ

25% detector coverage

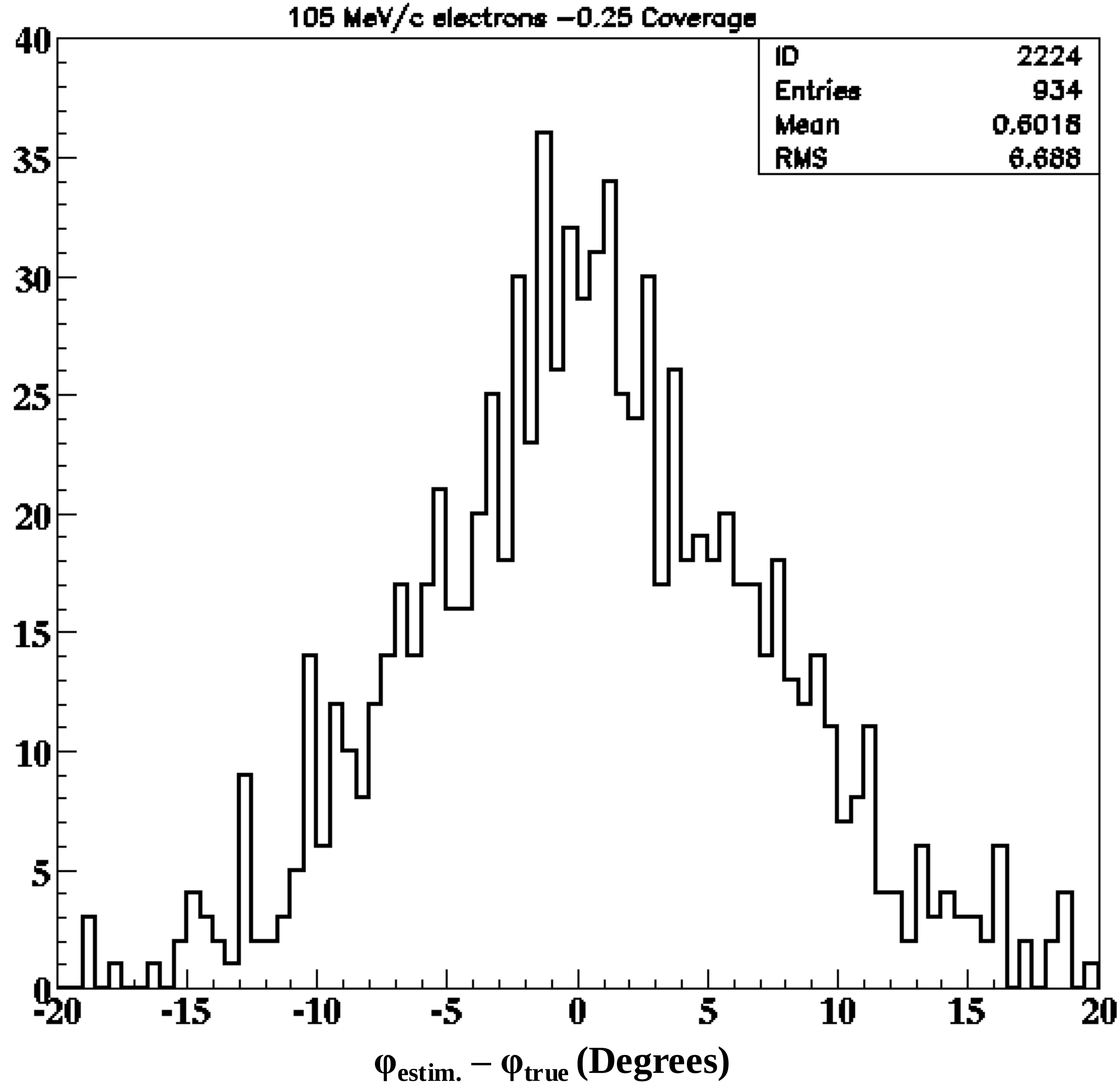
θ_{true}=30° and ϕ_{true}=0°



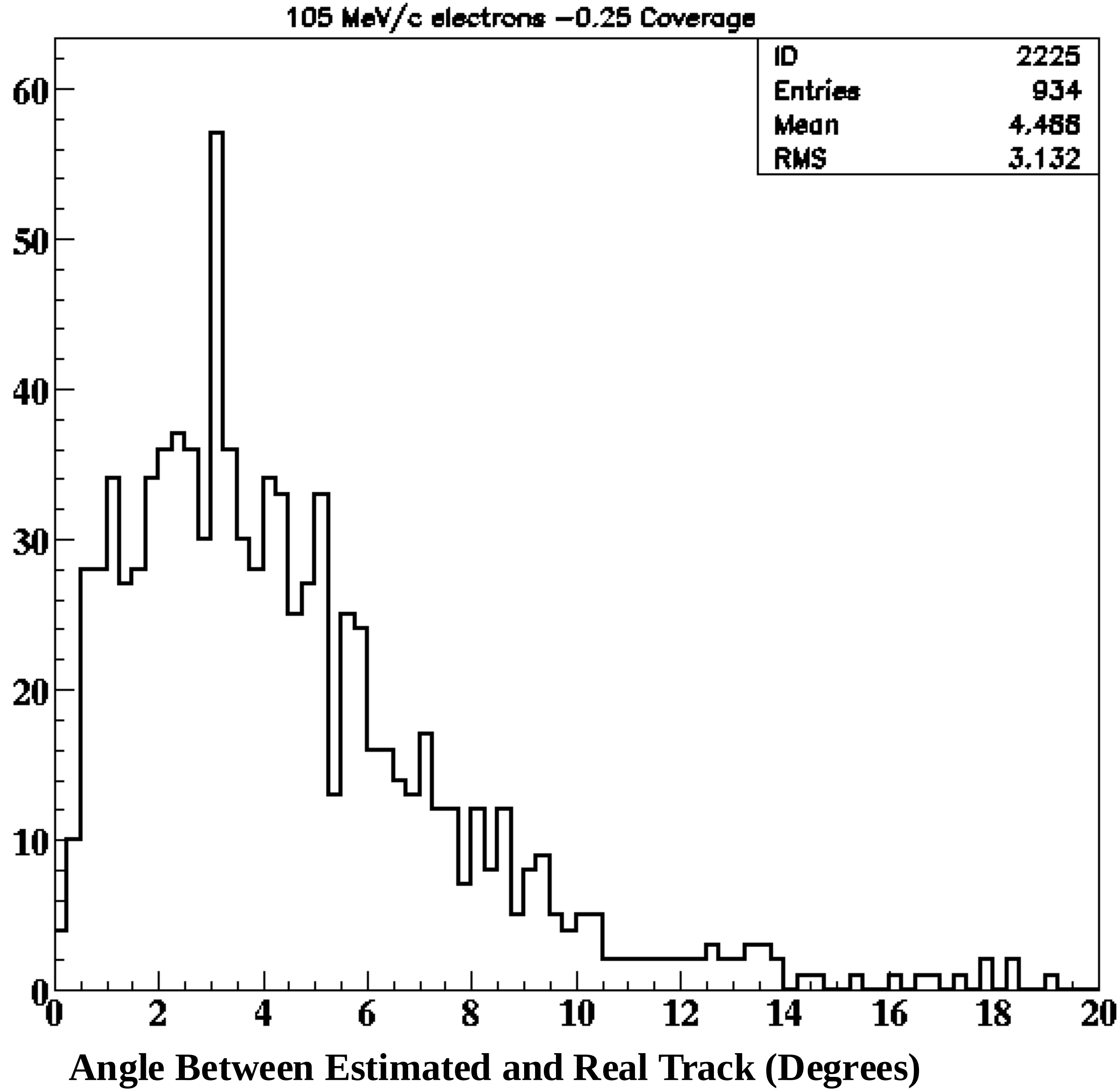
105 MeV/c electrons –0.25 Coverage
0
1
2
3
4
5
6
7
-20
-15
-10
-5
0
5
10
15
20
$\varphi_{estim.} - \varphi_{true}$ (Degrees)
$\theta_{estim.} - \theta_{true}$ (Degrees)



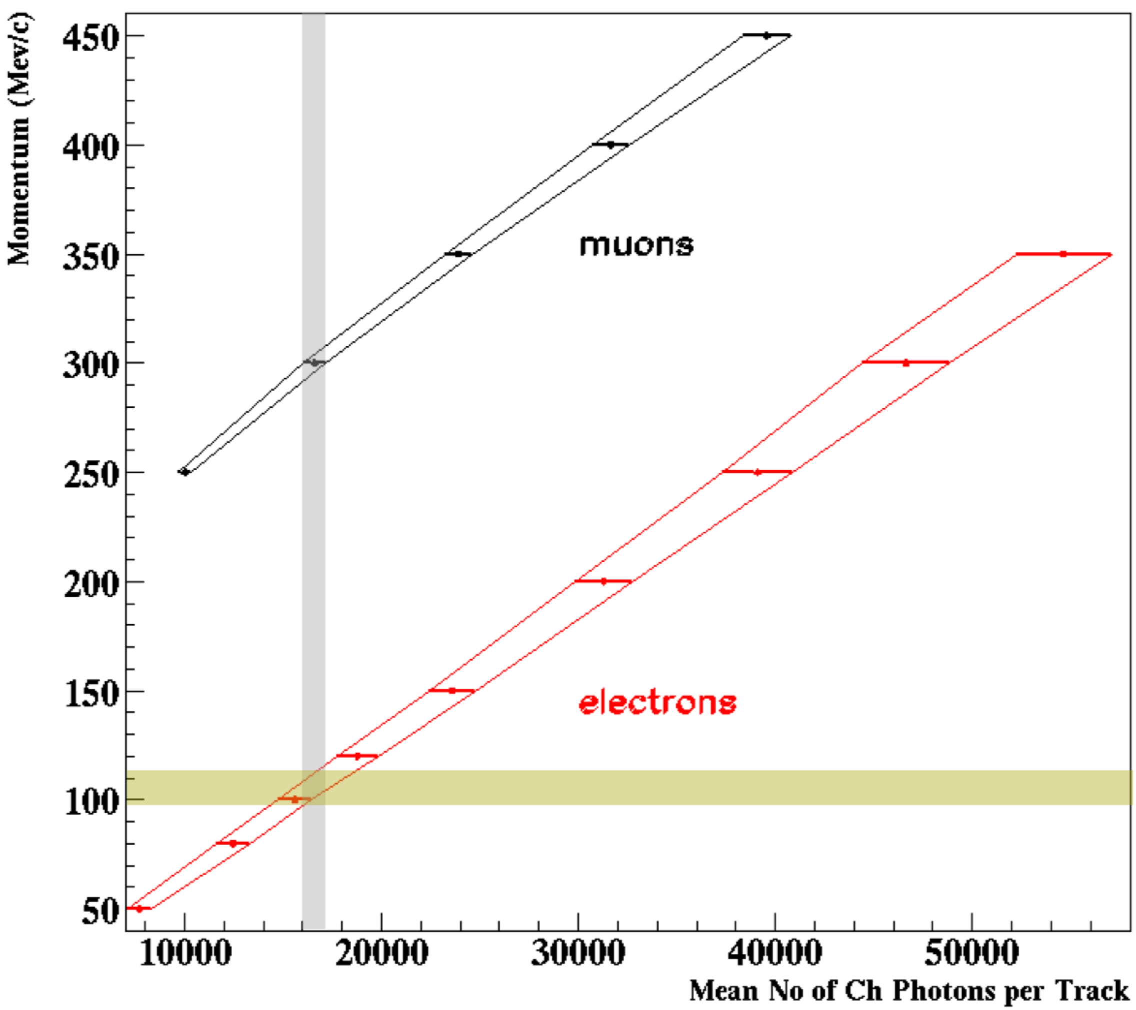
105 MeV/c electrons -0.25 Coverage
ID 2223
Entries 934
Mean -1.529
RMS 3.955
0
10
20
30
40
50
60
70
80
-20
-15
-10
-5
0
5
10
15
20
$\theta_{estim.} - \theta_{true}$ (Degrees)



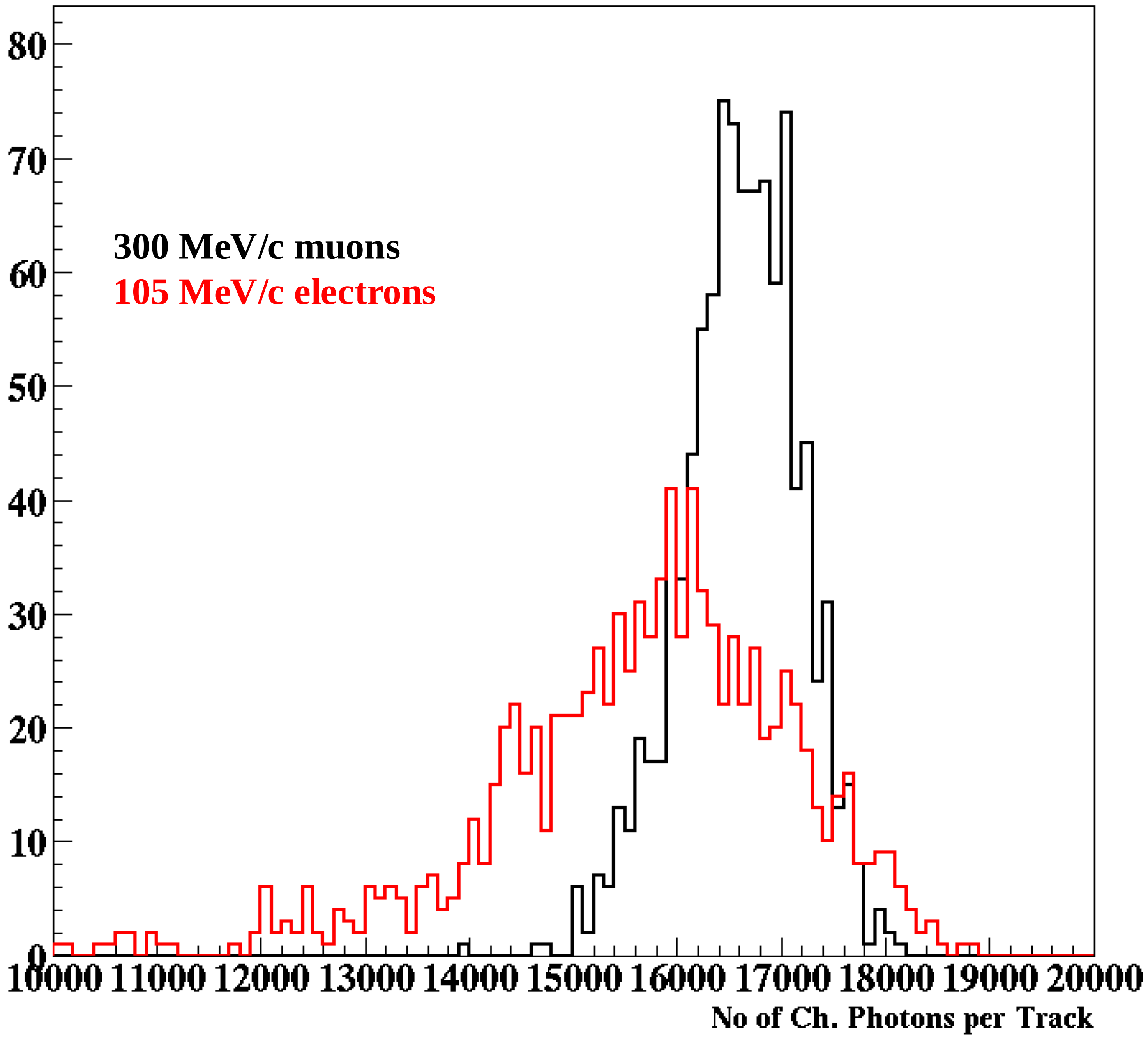
105 MeV/c electrons -0.25 Coverage
ID 2224
Entries 934
Mean 0.6018
RMS 6.688
40
35
30
25
20
15
10
5
0
-20
-15
-10
-5
0
5
10
15
20
$\varphi_{estim.} - \varphi_{true}$ (Degrees)


105 MeV/c electrons –0.25 Coverage
ID 2225
Entries 934
Mean 4.488
RMS 3.132
0
10
20
30
40
50
60
0
2
4
6
8
10
12
14
16
18
20
Angle Between Estimated and Real Track (Degrees)

Use the Cherenkov Light to Estimate the Particle's Momentum



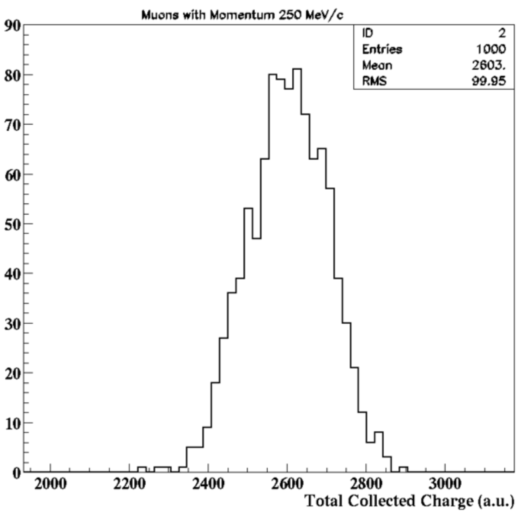
Momentum (Mev/c)
450
400
350
300
250
200
150
100
50
10000
20000
30000
40000
50000
Mean No of Ch Photons per Track
muons
electrons

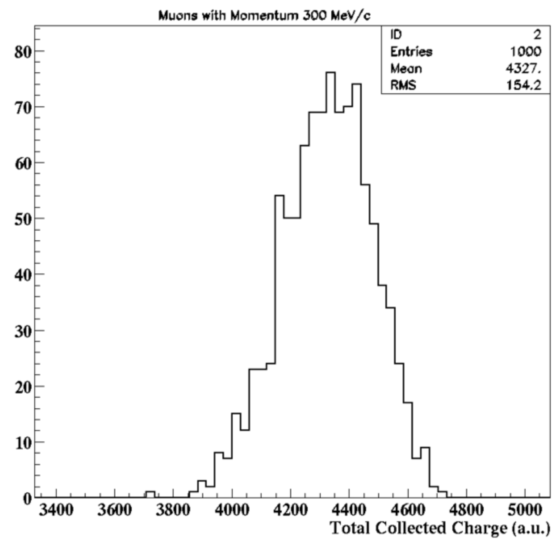


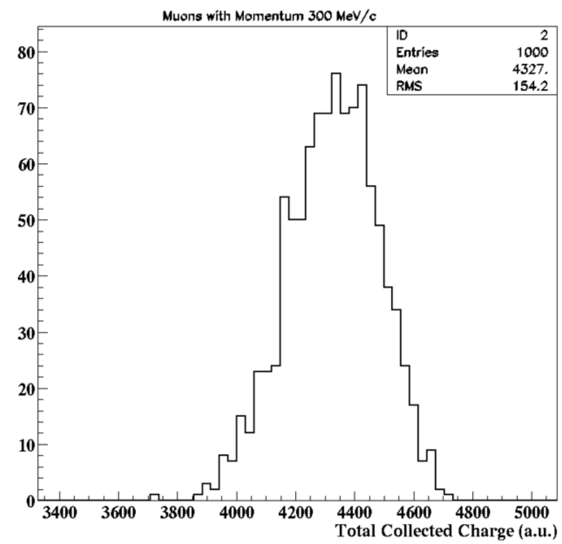
300 MeV/c muons
105 MeV/c electrons
0
10
20
30
40
50
60
70
80
10000
11000
12000
13000
14000
15000
16000
17000
18000
19000
20000
No of Ch. Photons per Track

25% Detector Coverage
0.25 Quantum Efficiency
Polya Distribution for the single-p.e. Charge

Use the total collected charge (sum of all photodetector signals) as the estimator







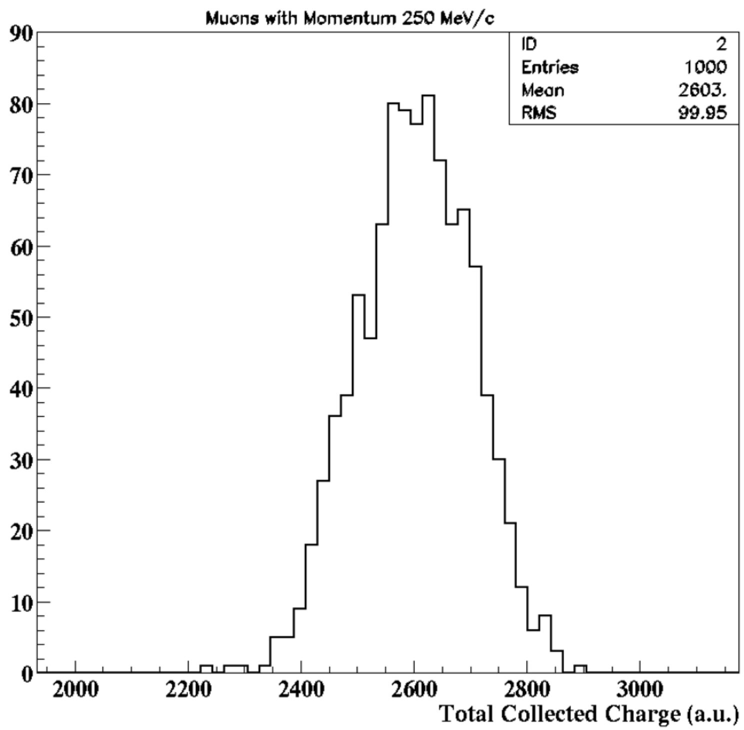
Parameterize the mean and rms of the total Cherenkov Induced Charge (Q) as a function of the particle' s momentum

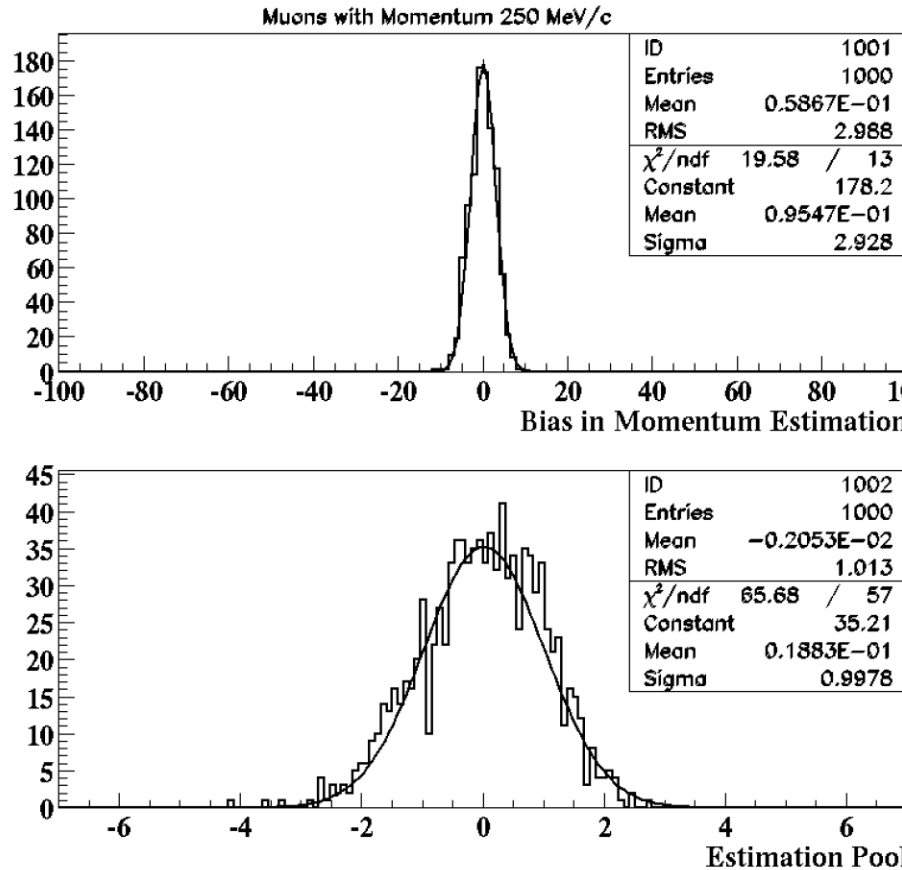
$$Q_{mean}(P) = a_1 + a_2 P + a_3 P^2$$
$$Q_{RMS}(P) = b_1 + b_2 P + b_3 P^2$$

$$\boldsymbol{\widehat{P} = \frac{a_2 + [a_2{}^2 - 4(a_1 - Q_{obs})a_3]^{\frac{1}{2}}}{2a_3}}$$

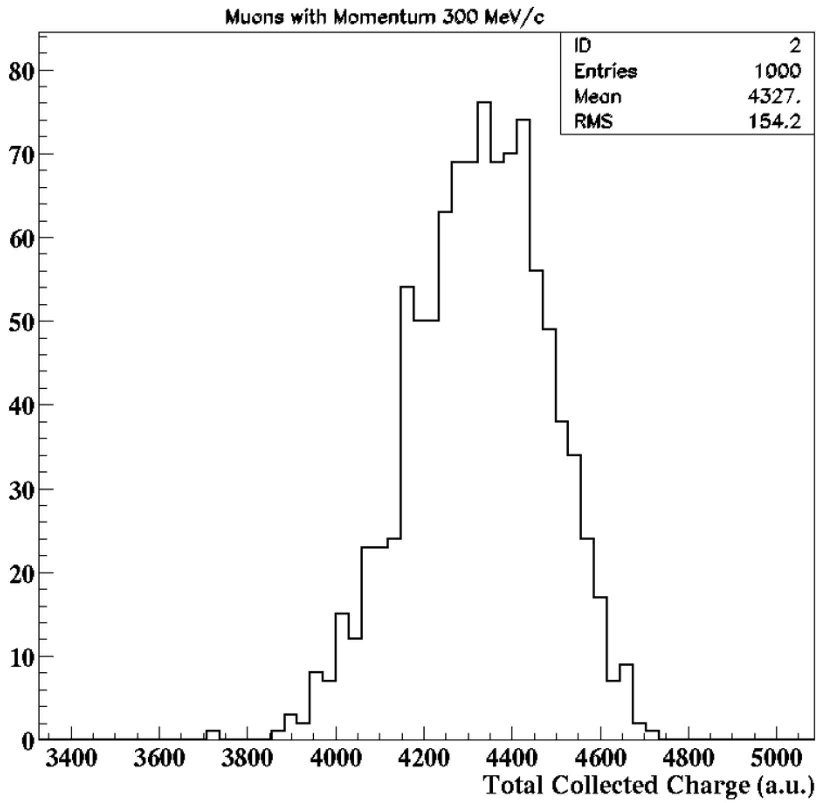
$$\boldsymbol{\delta_{\widehat{P}} = \frac{Q_{RMS}(\widehat{P})}{a_2 + [a_2{}^2 - 4(a_1 - Q_{obs})a_3]^{\frac{1}{2}}}}$$

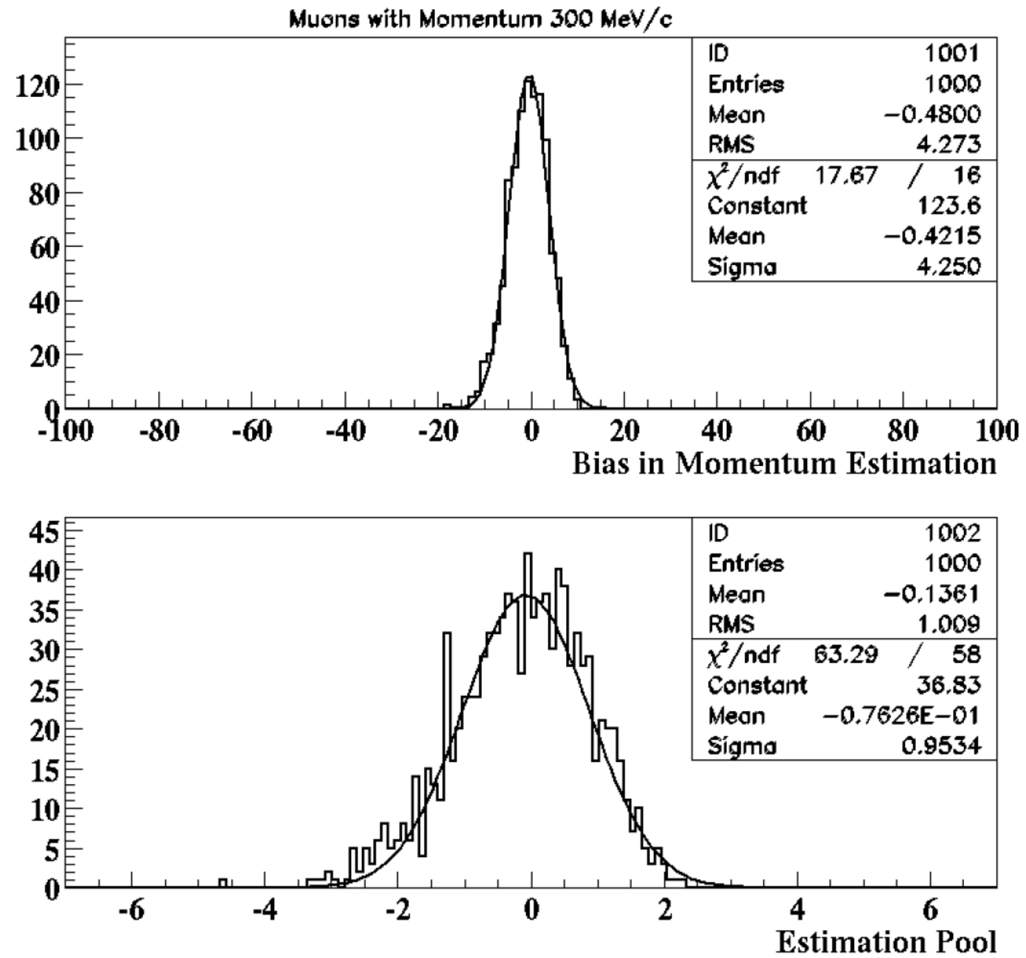
Estimating the Muon's Momentum
(muons treated as muons)



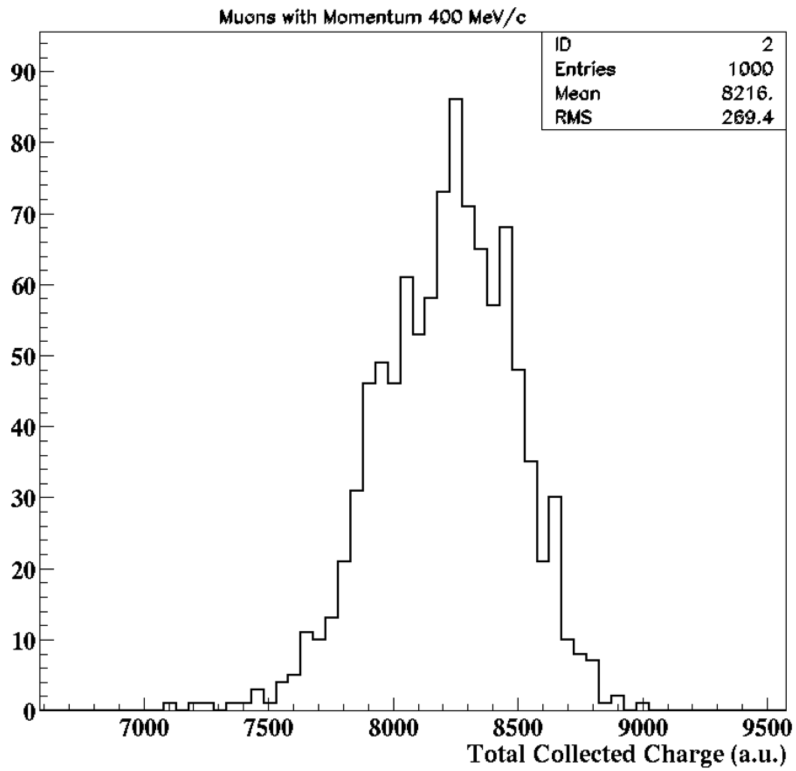


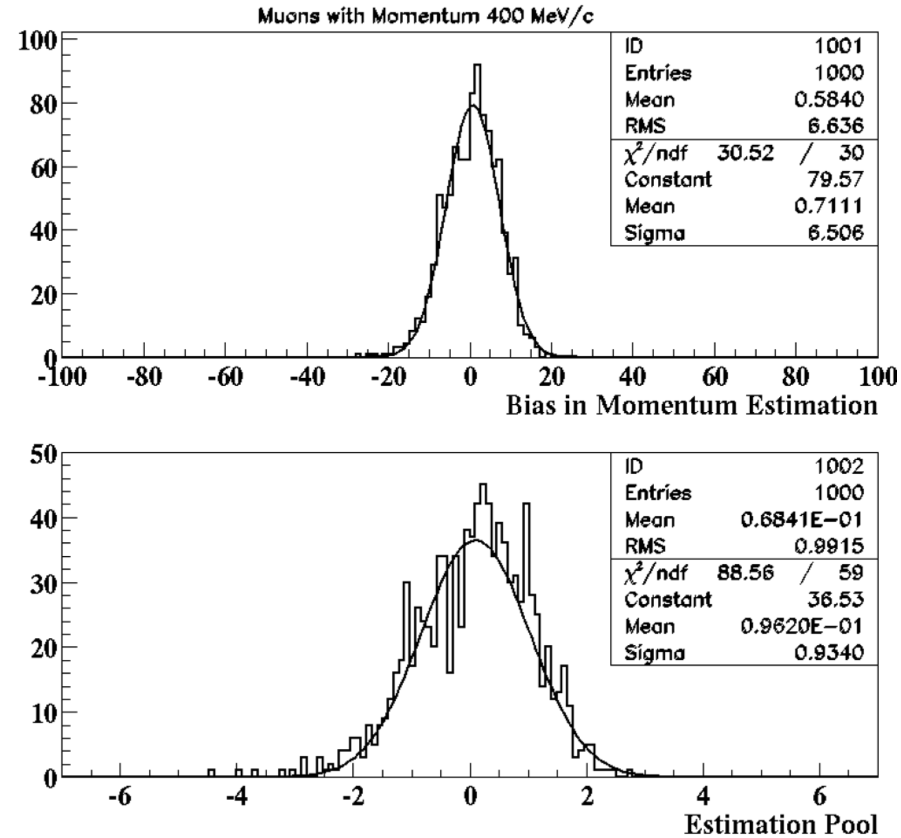
Estimating the Muon's Momentum
(muons treated as muons)



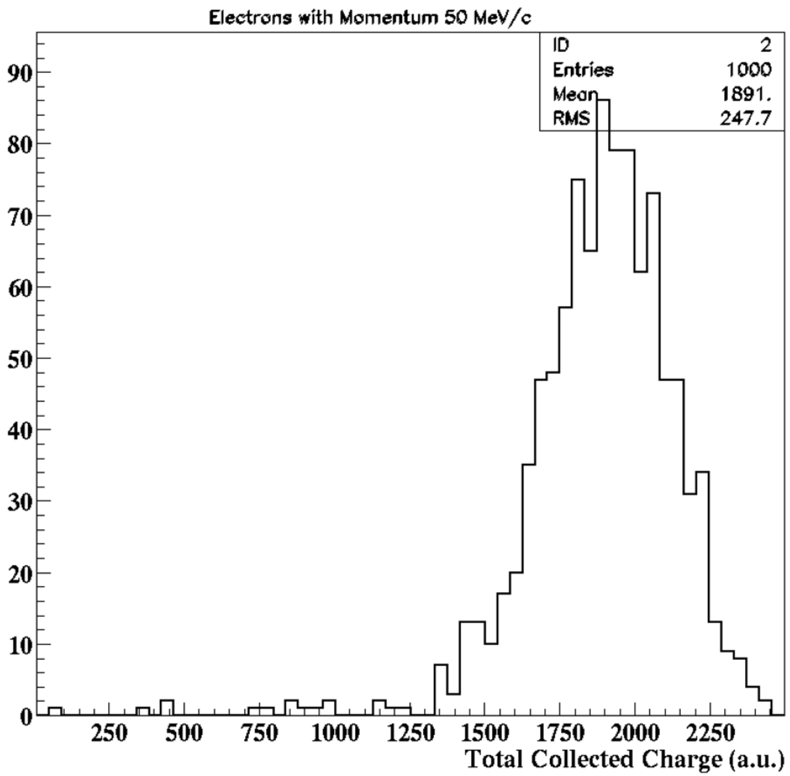


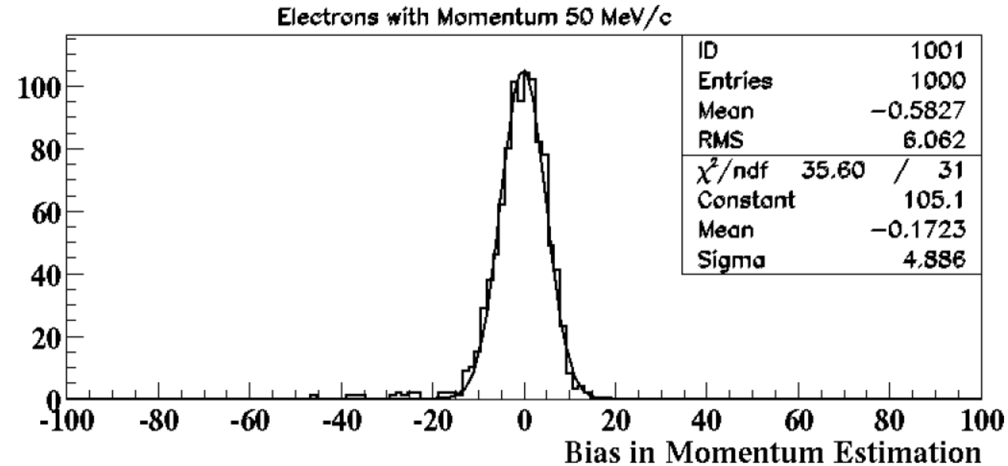
Estimating the Muon's Momentum
(muons treated as muons)

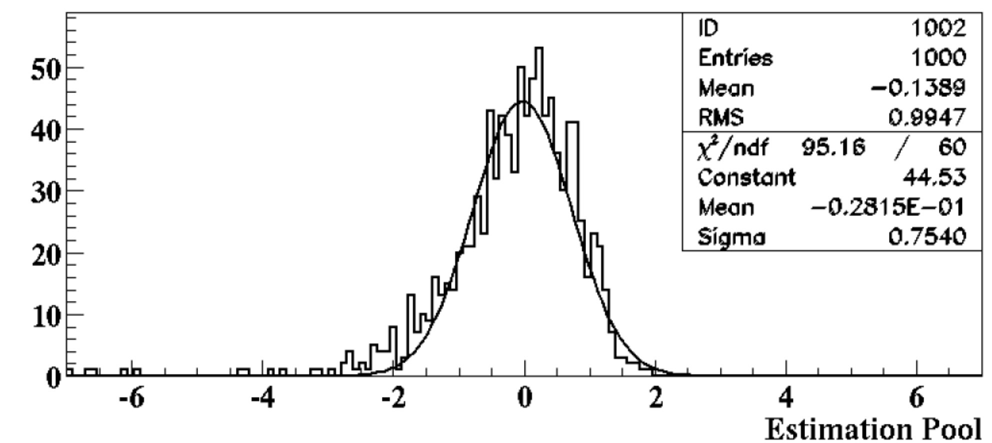




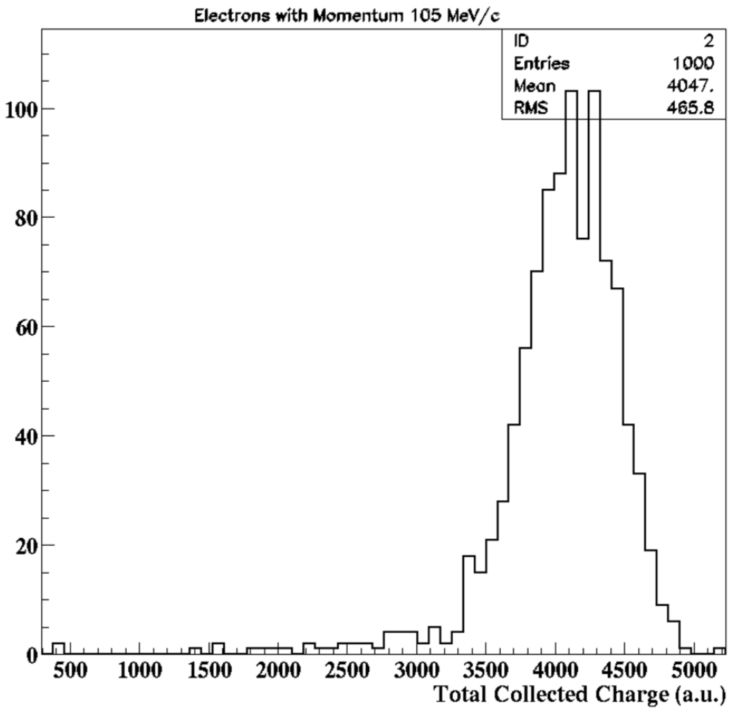
Estimating the Electron's Momentum
(electrons treated as electrons)

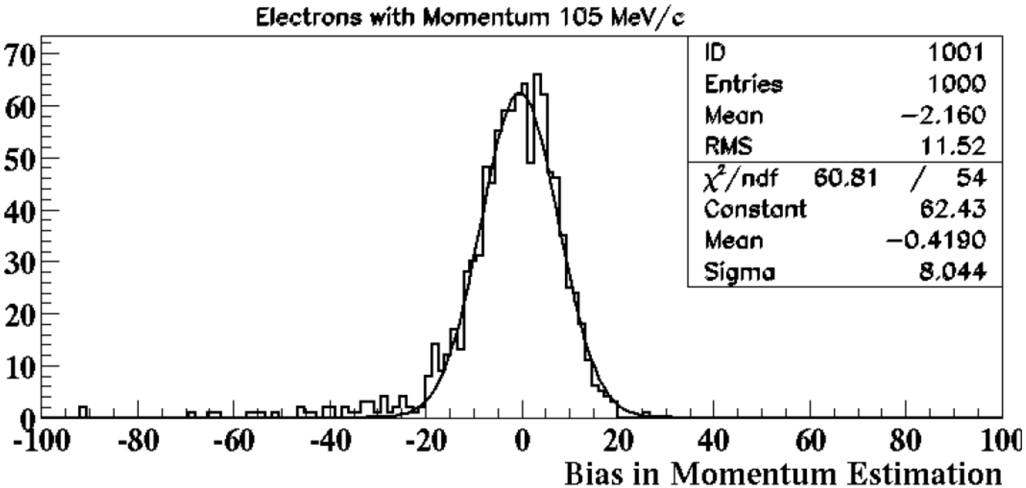


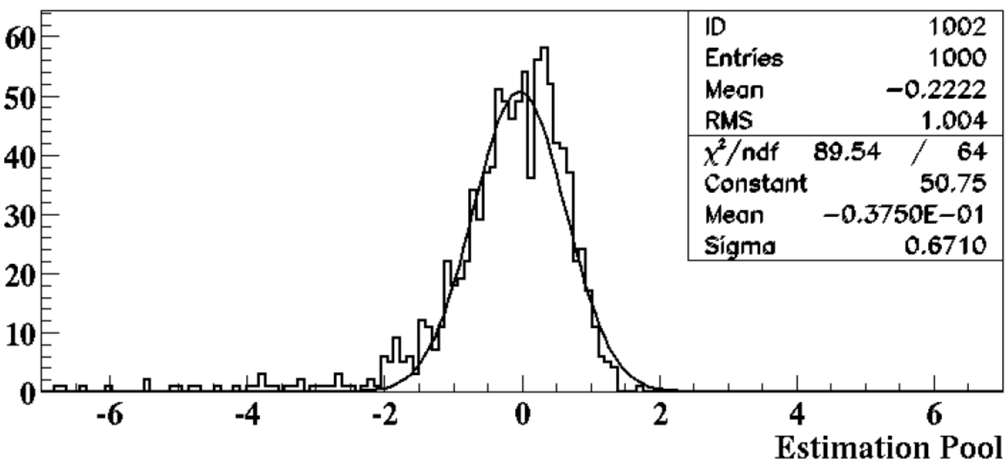




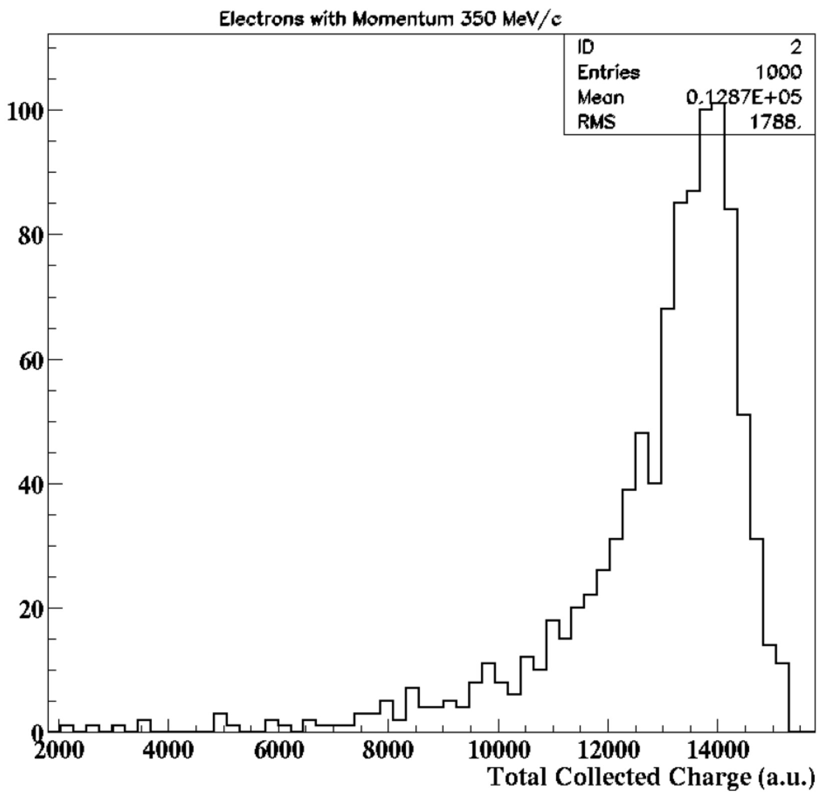
Estimating the Electron's Momentum
(electrons treated as electrons)

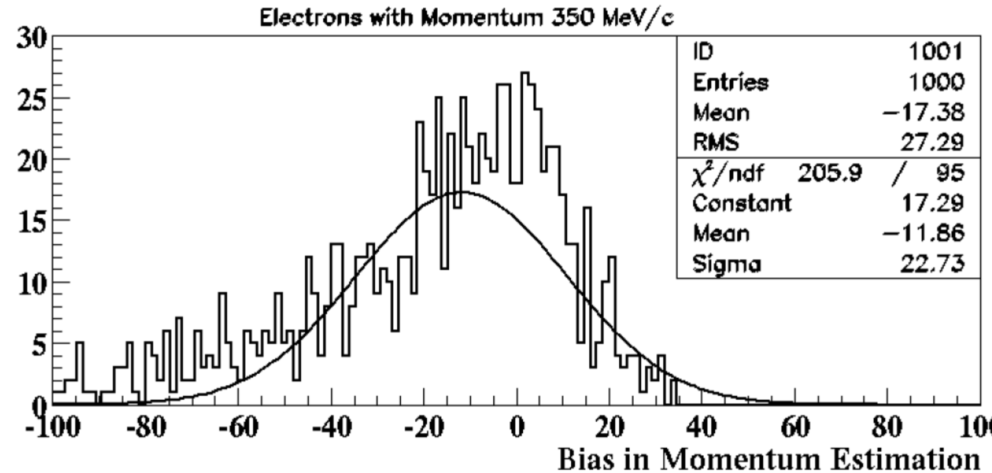


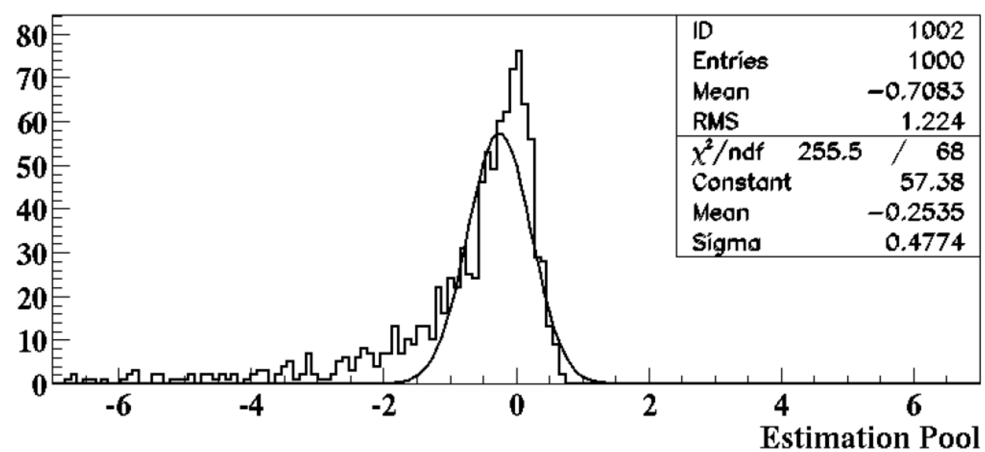




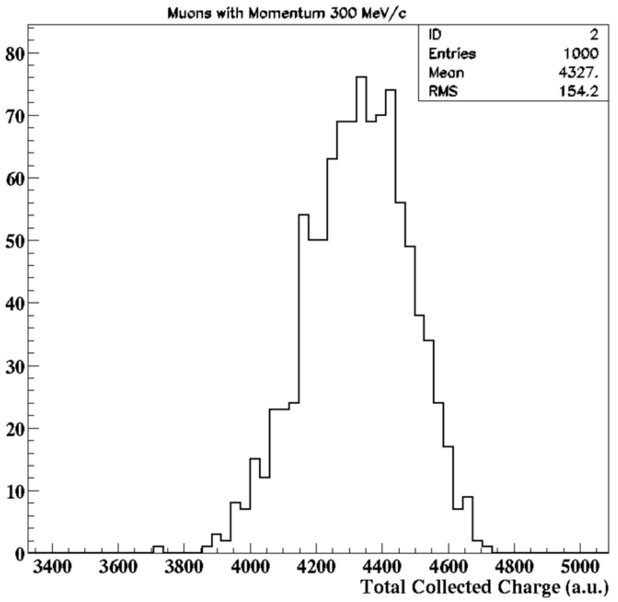
Estimating the Electron's Momentum
(electrons treated as electrons)

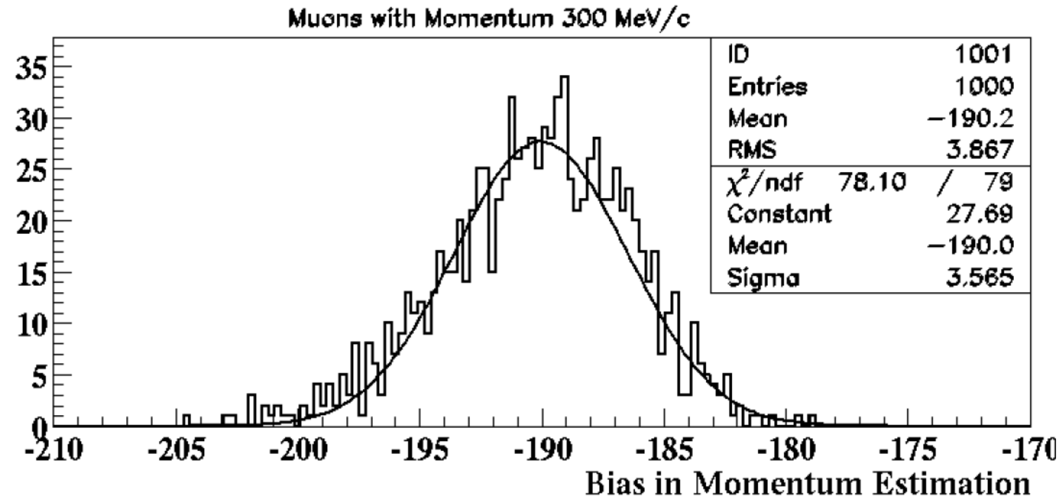


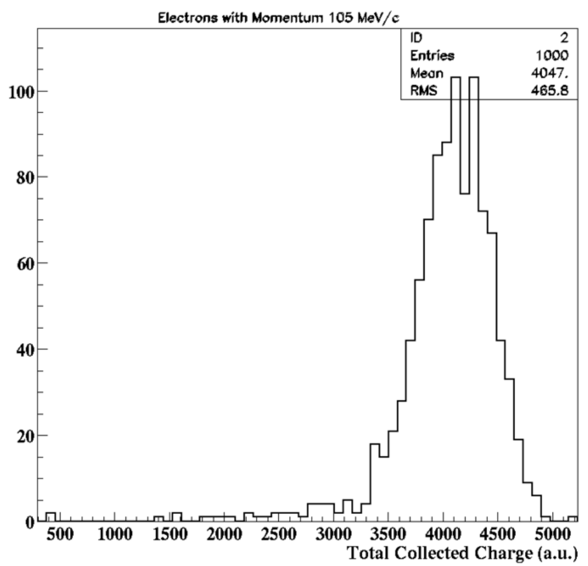


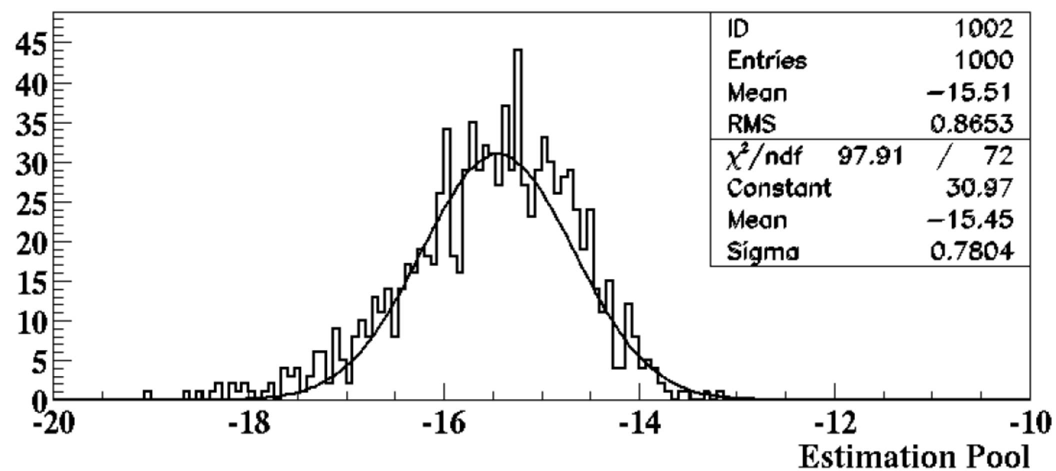


Estimating the Muon's Momentum
(muons treated as electrons)

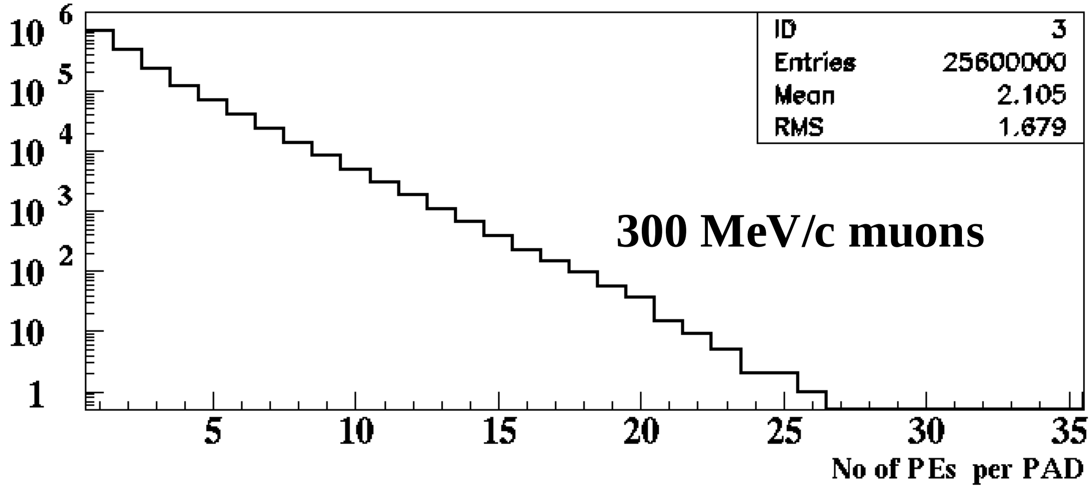


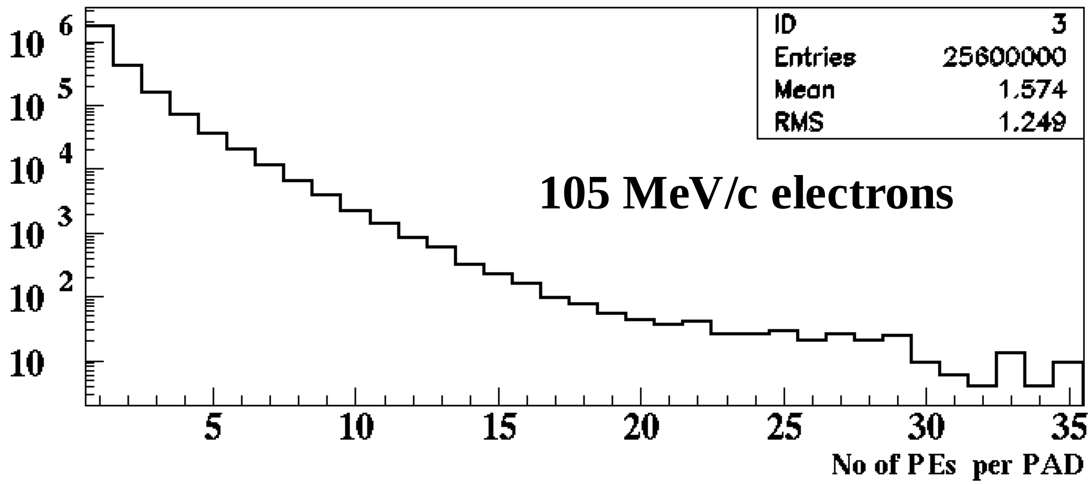






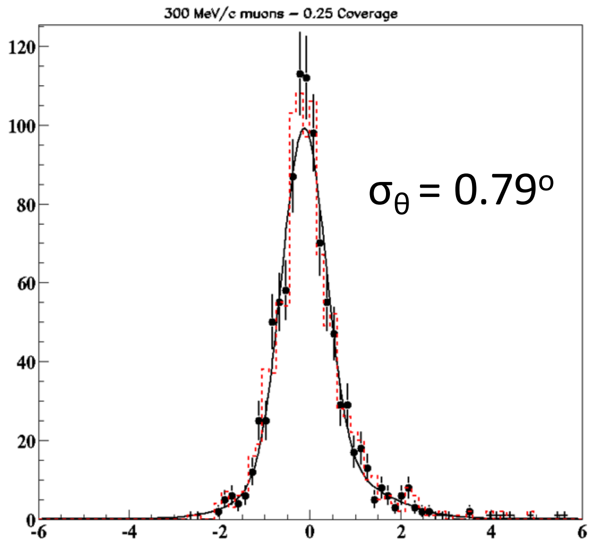
To distinguish between the electron and muon hypothesis
We should use the spatial and temporal distribution of the p.e.s in the detector



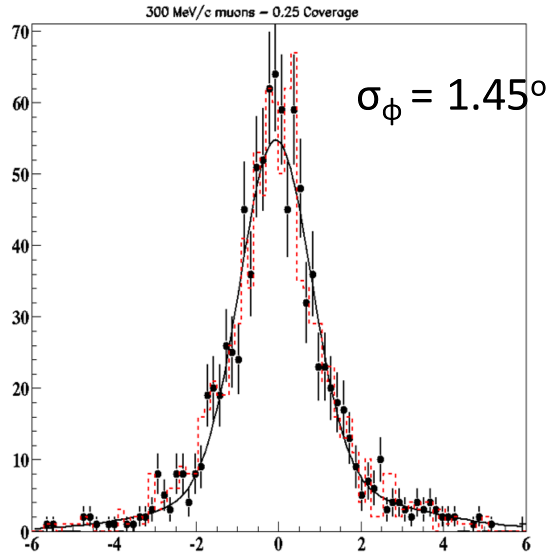


Muon vs Electron Hypothesies
300 MeV/c Muons Treated as 105 MeV/c Electrons

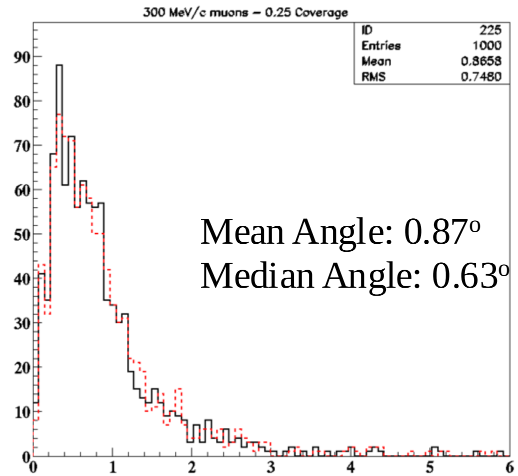
REMINDER: when 300 MeV/c muons are treated as muons (θ-ϕ fit)



$\theta_{estim.} - \theta_{true}$ **(Degrees)**

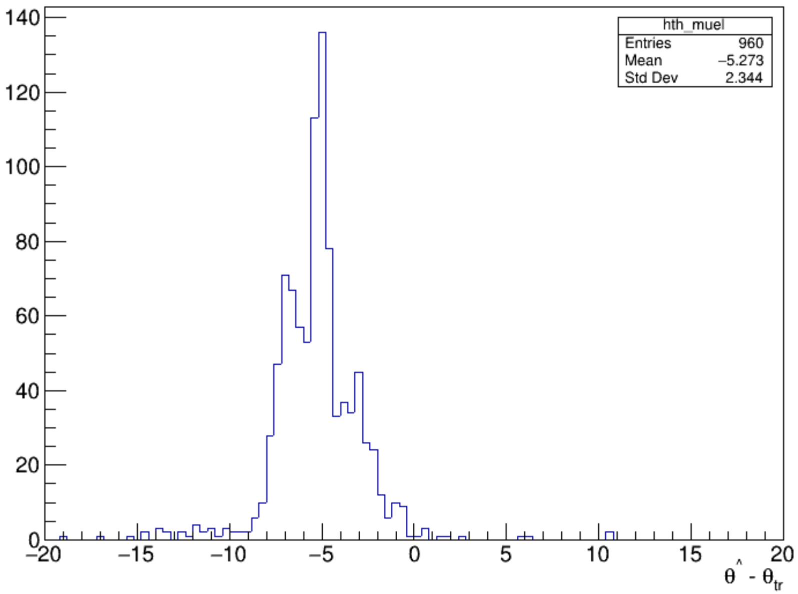


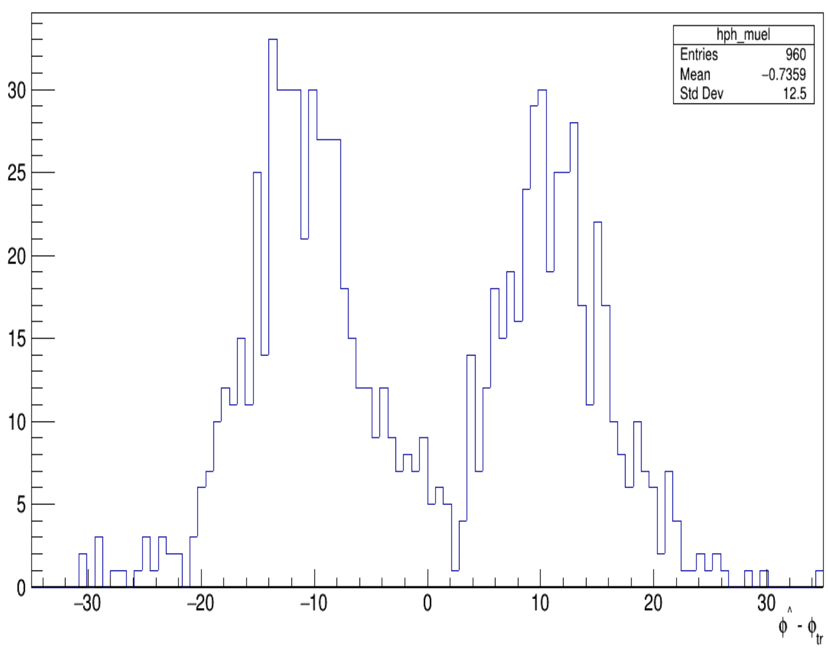
$\varphi_{estim.} - \varphi_{true}$**(Degrees)**

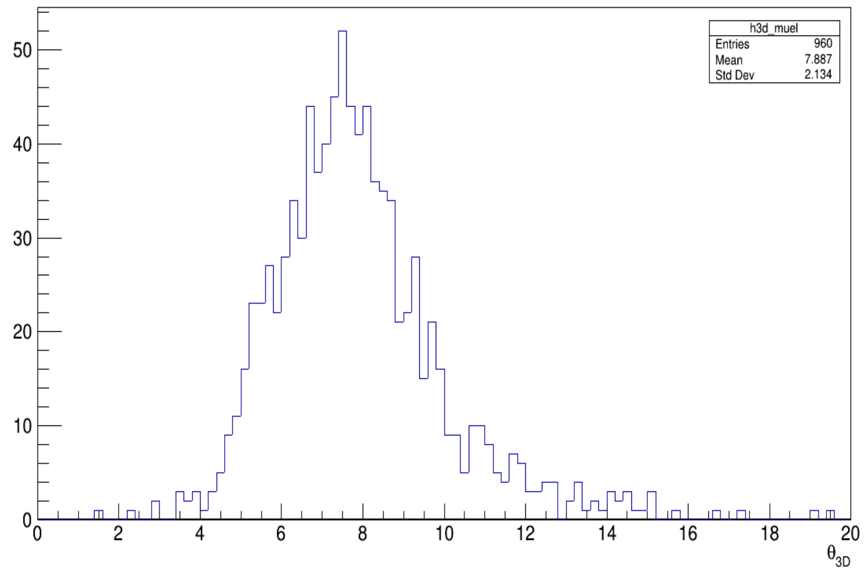


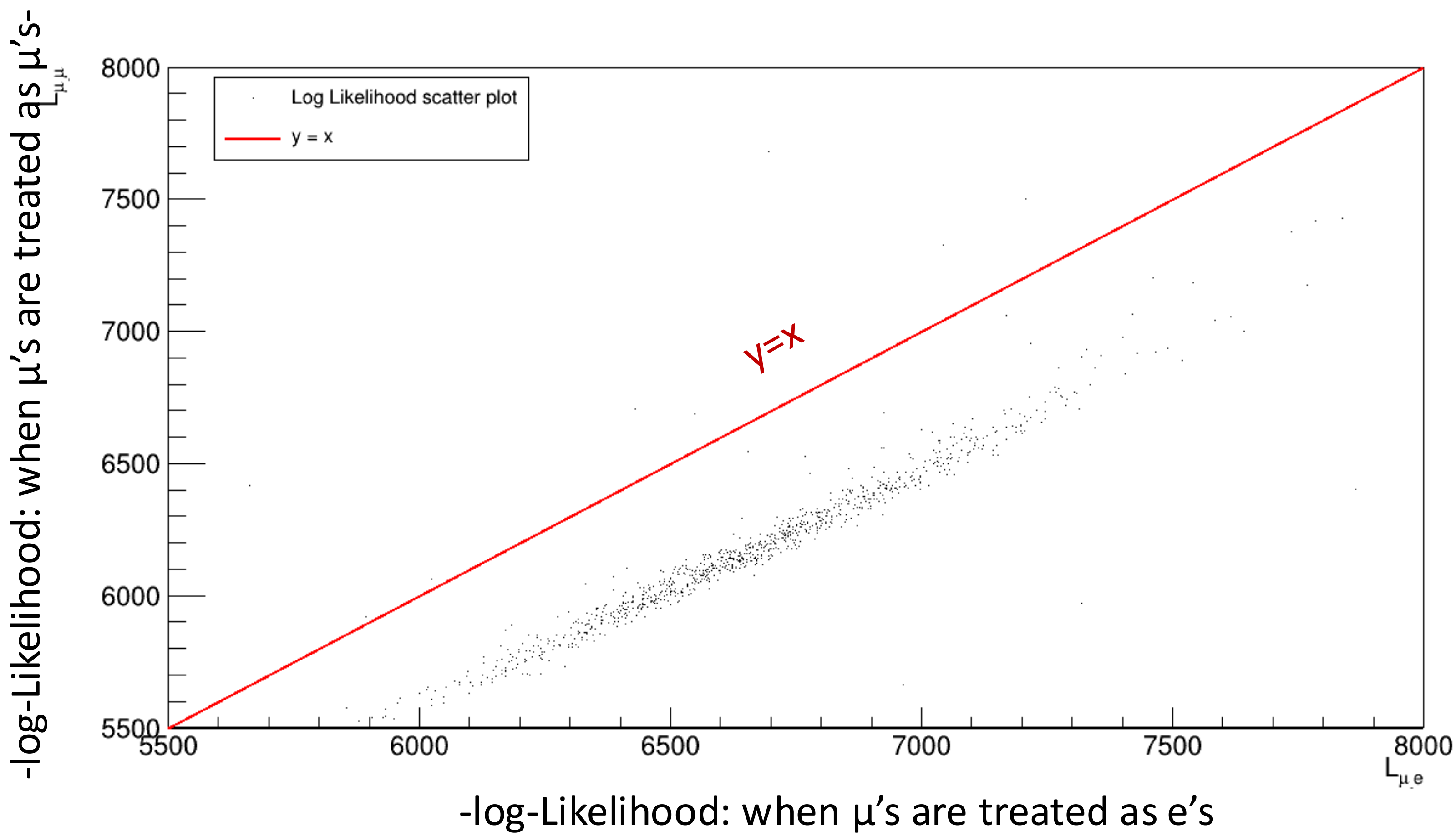
Angle Between Estimated and Real Track (Degrees)

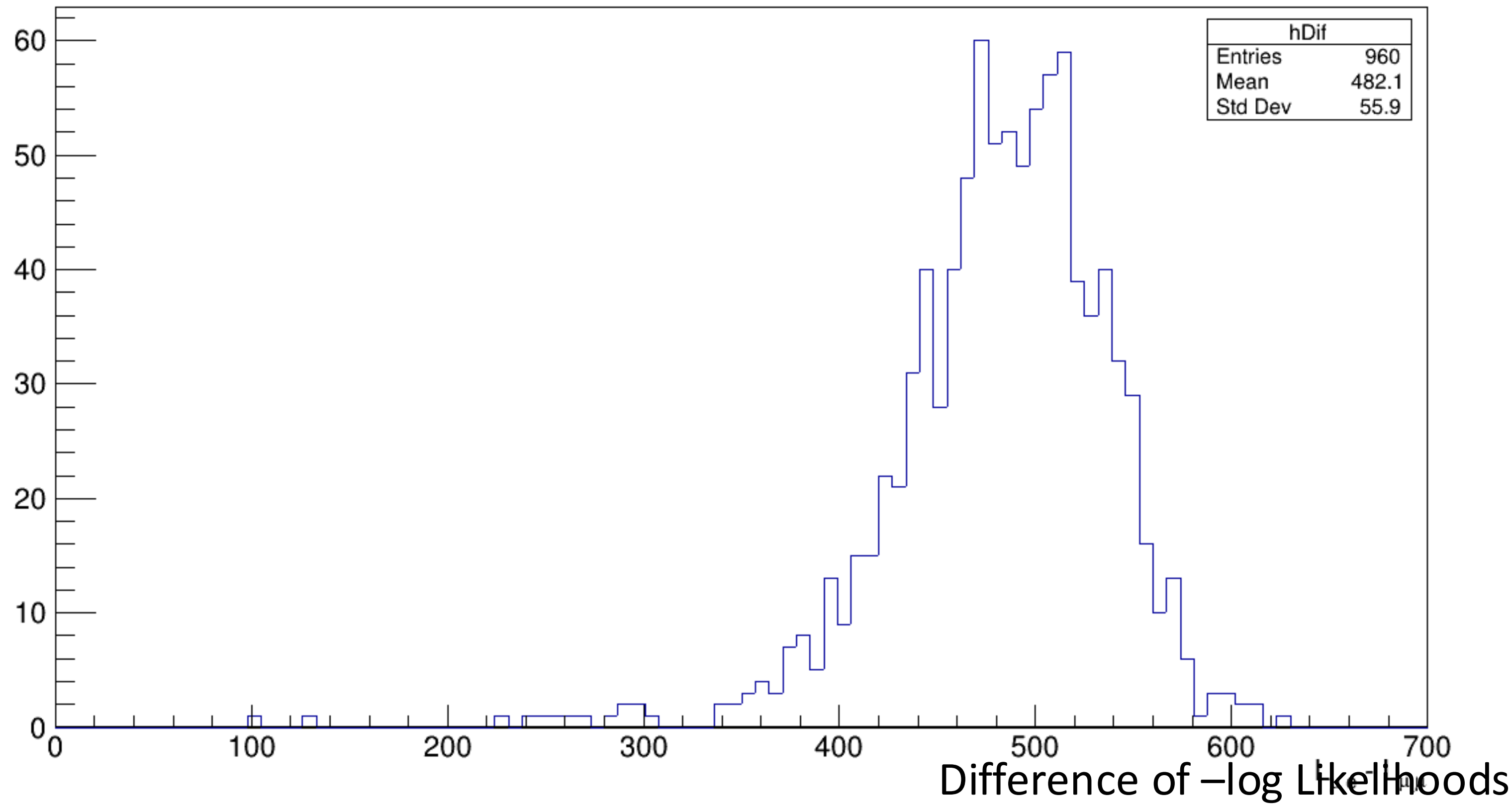
when 300 MeV/c muons are treated as (105MeV/c) electrons (θ-ϕ fit)








Log Likelihood scatter plot
y = x
y=x
8000
7500
7000
6500
6000
5500
5500
6000
6500
7000
7500
8000
$L_{\mu\mu}$
$L_{\mu e}$
-log-Likelihood: when μ's are treated as μ's-
-log-Likelihood: when μ's are treated as e's


hDif
Entries 960
Mean 482.1
Std Dev 55.9
0
10
20
30
40
50
60
0
100
200
300
400
500
600
700
Difference of –log Likelihoods

Concluding Remarks (single track reconstruction)

- It seems that we do not need very precise timing information (?)
- Strong indication for a good resolution in reconstructing direction
- Strong indication for a good vertex estimation
- Strong indication for momentum estimation
- Strong indication for e-μ identification

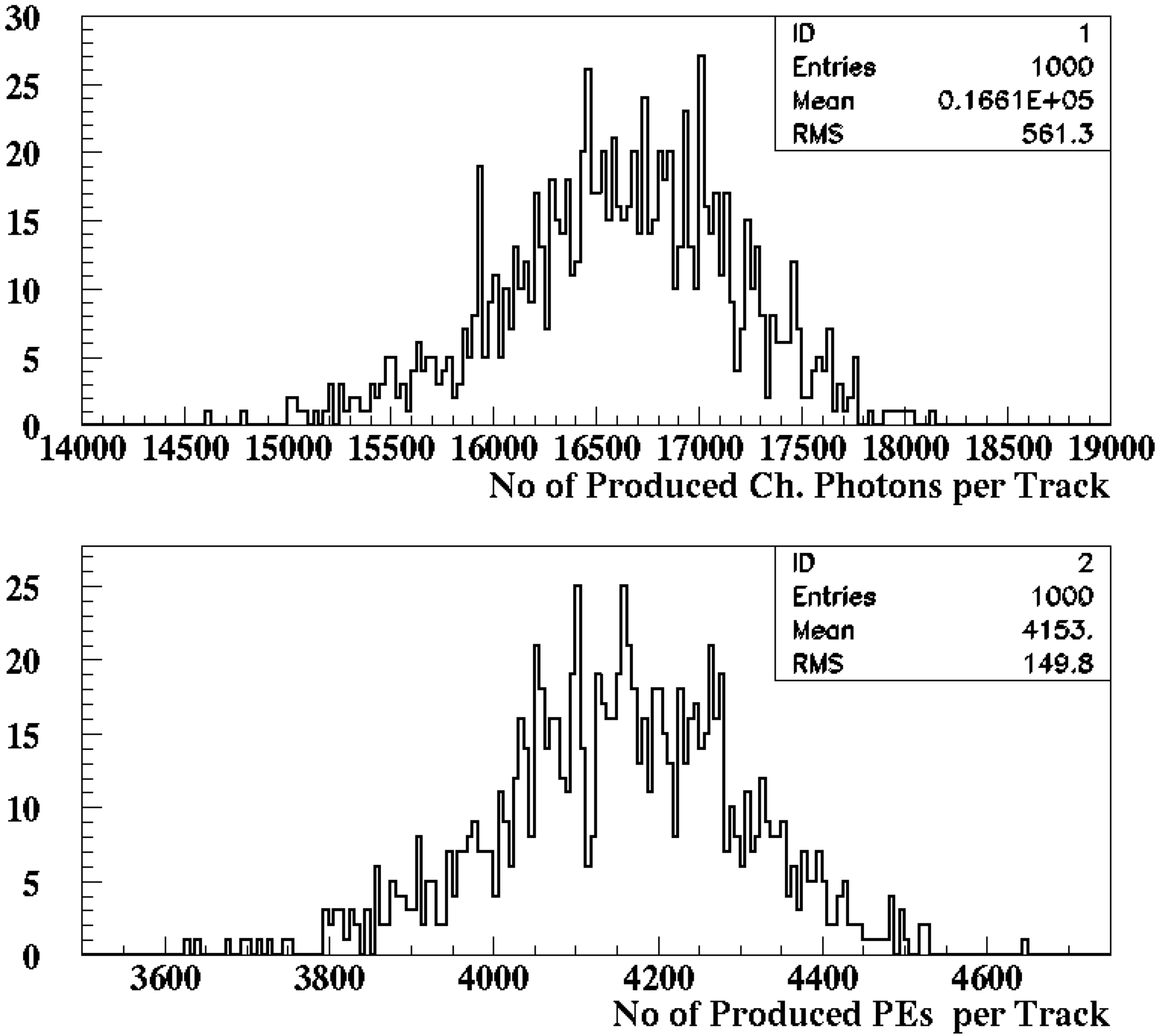
We need:

All parameters simultaneous fit in realistic conditions

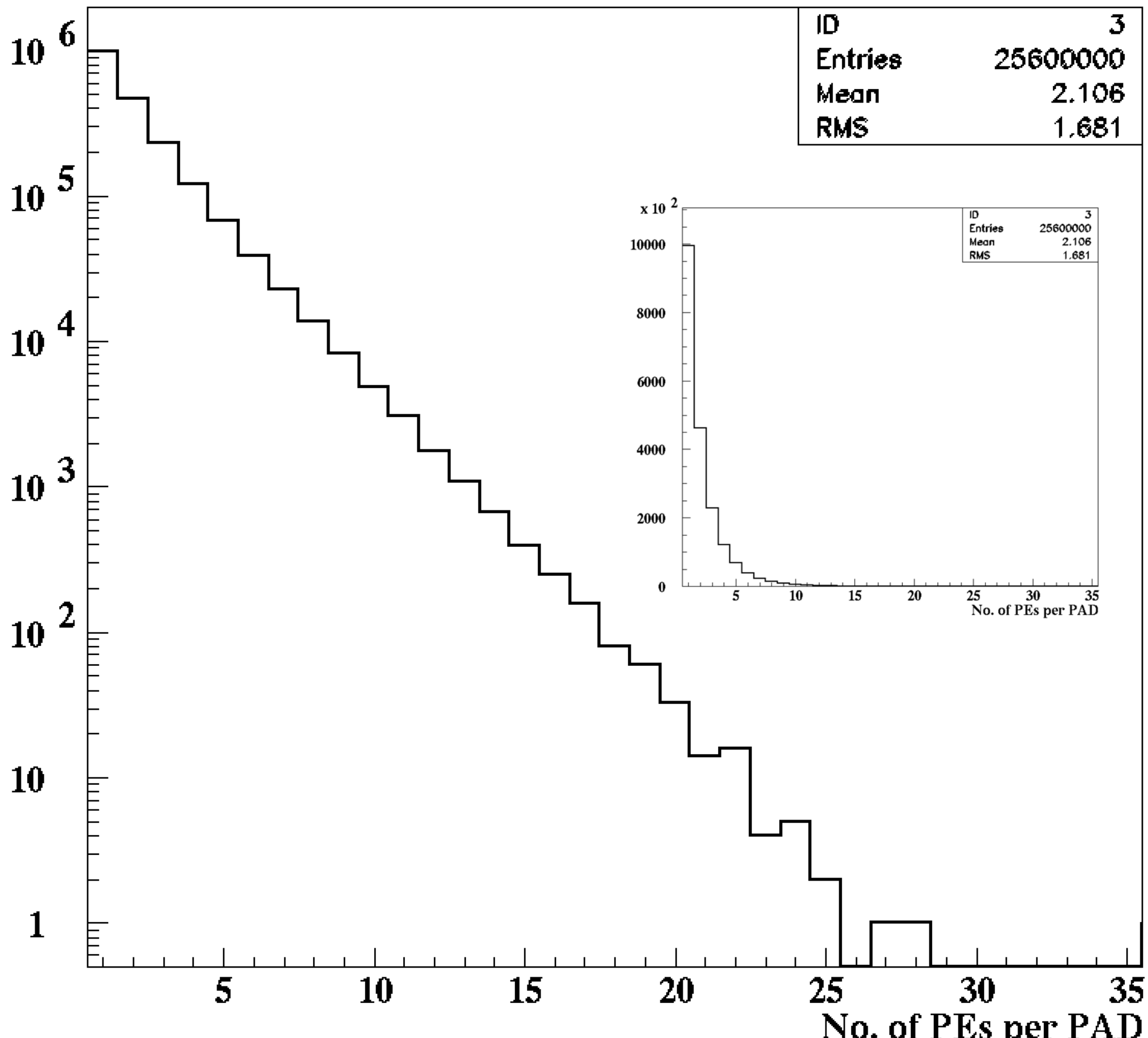
- Full detector simulation
- A practical reconstruction algorithm
    - Use a different way to tabulate the Ch. Photon emission info (ANN?)

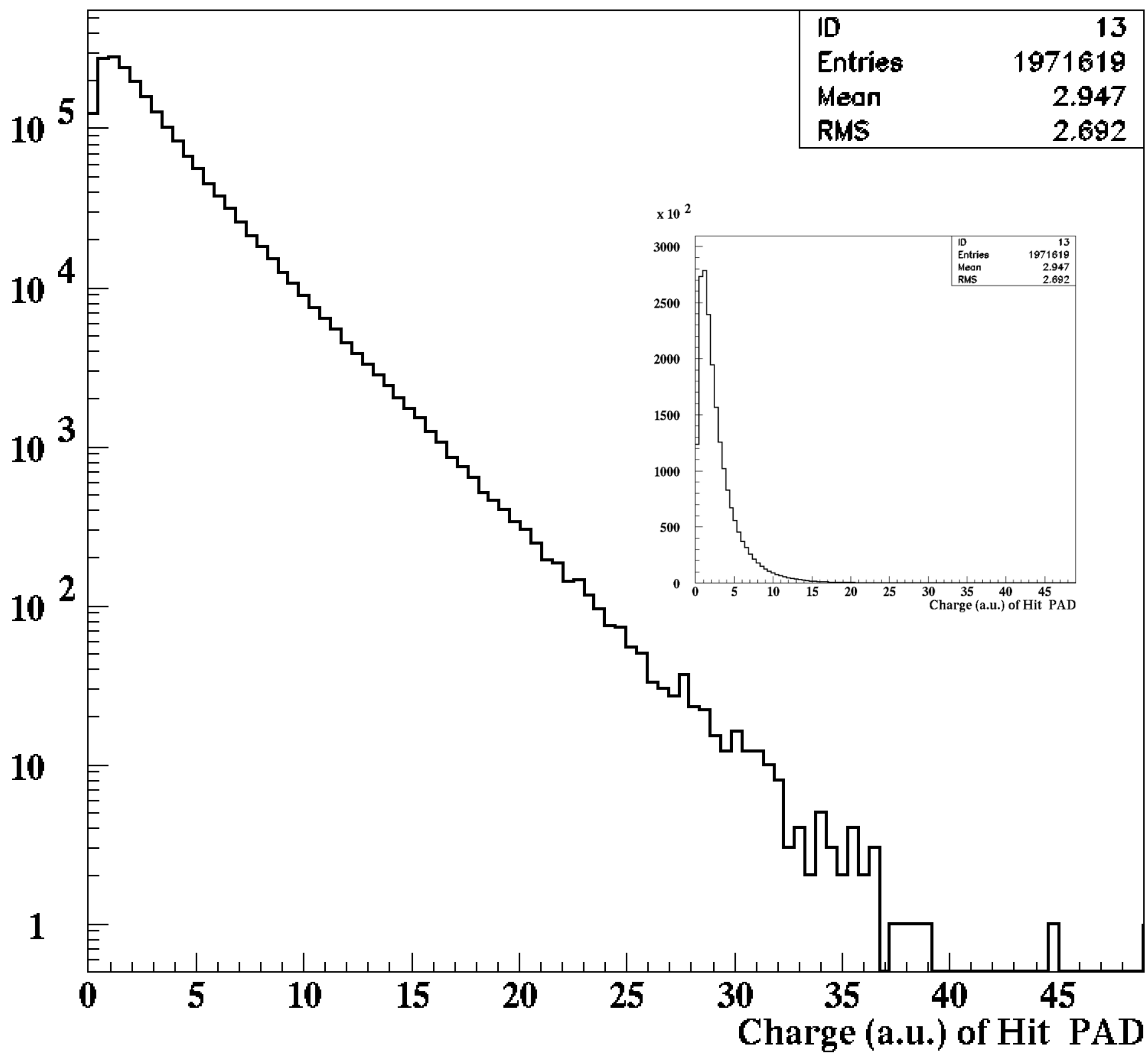
Repeat the “toy-model” and full detector studies

Backup slices

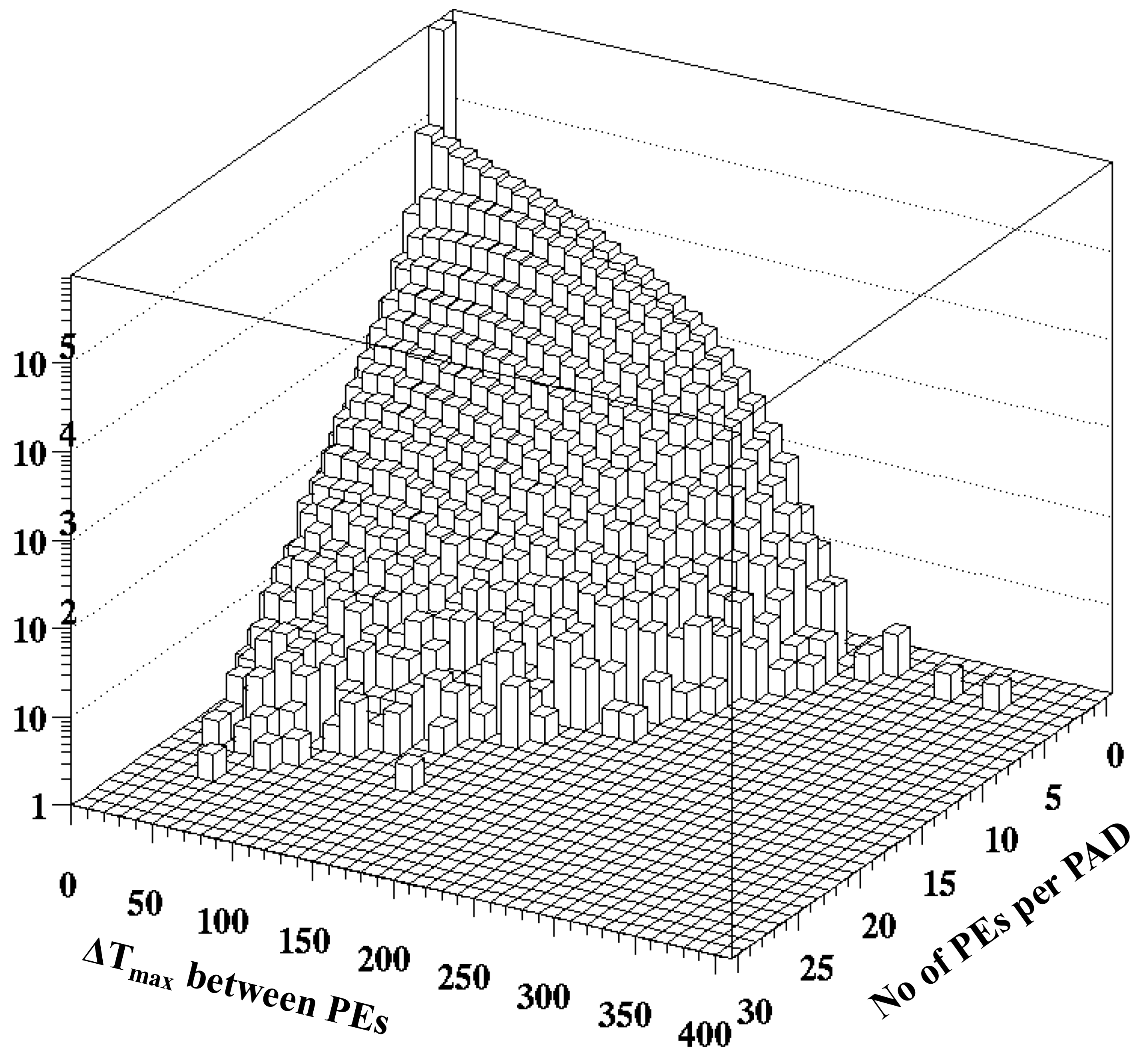


ID 1
Entries 1000
Mean 0.1661E+05
RMS 561.3
0
5
10
15
20
25
30
14000 14500 15000 15500 16000 16500 17000 17500 18000 18500 19000
No of Produced Ch. Photons per Track
ID 2
Entries 1000
Mean 4153.
RMS 149.8
0
5
10
15
20
25
3600 3800 4000 4200 4400 4600
No of Produced PEs per Track

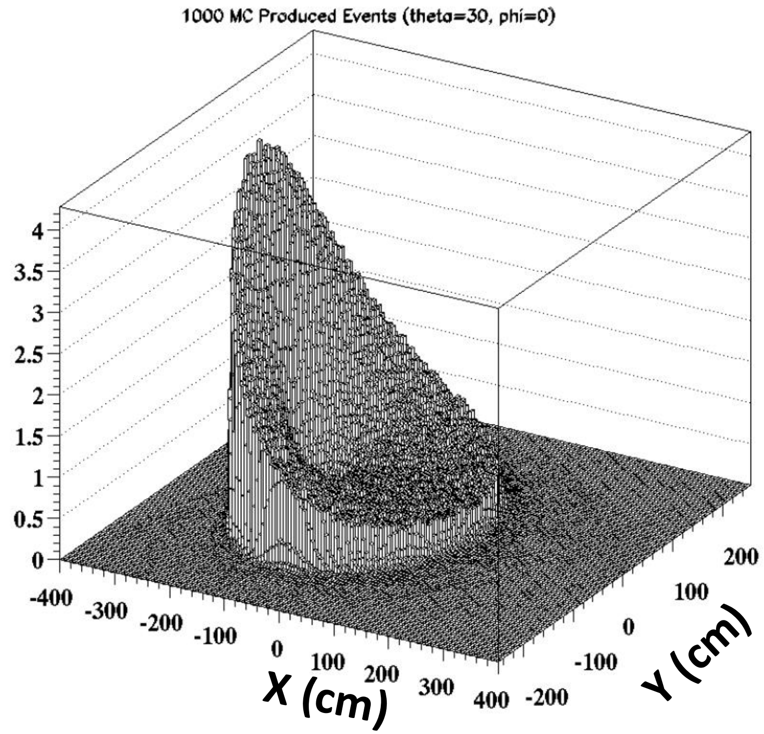

ID 3
Entries 25600000
Mean 2.106
RMS 1.681
10 6
10 5
10 4
10 3
10 2
10
1
5
10
15
20
25
30
35
No. of PEs per PAD
x 10 2
10000
8000
6000
4000
2000
0
No. of PEs per PAD



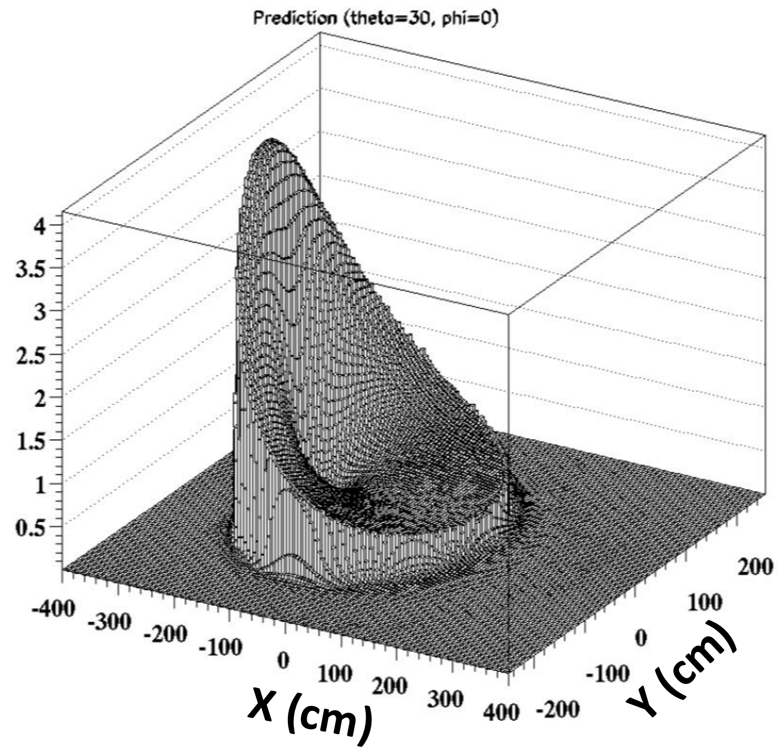
ID 13
Entries 1971619
Mean 2.947
RMS 2.692
10^5
10^4
10^3
10^2
10
1
0 5 10 15 20 25 30 35 40 45
Charge (a.u.) of Hit PAD
x 10 2
3000
2500
2000
1500
1000
500
0
Charge (a.u.) of Hit PAD



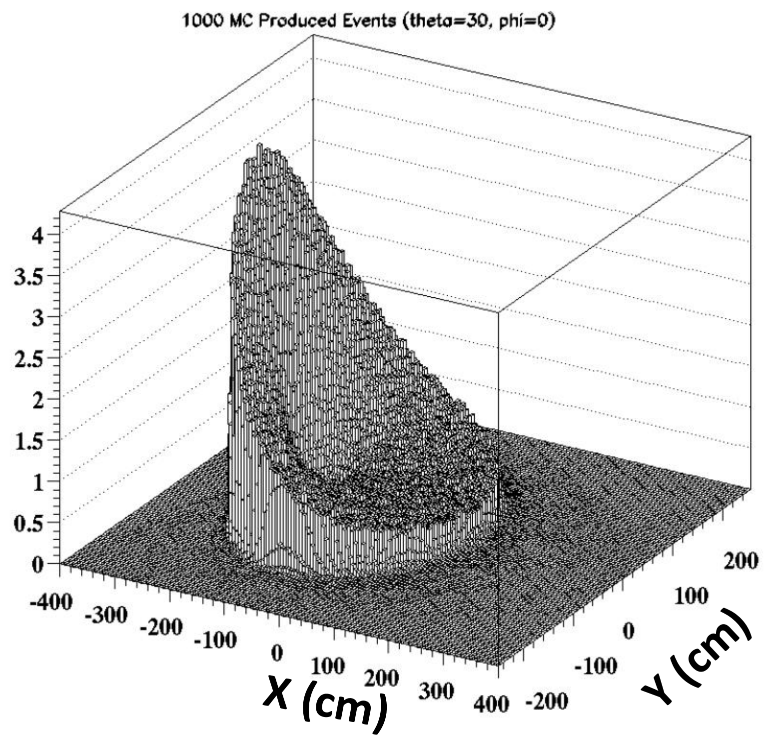
10^5
10^4
10^3
10^2
10
1
0
50
100
150
200
250
300
350
400
ΔT_{max} between PEs
0
5
10
15
20
25
30
No of PEs per PAD



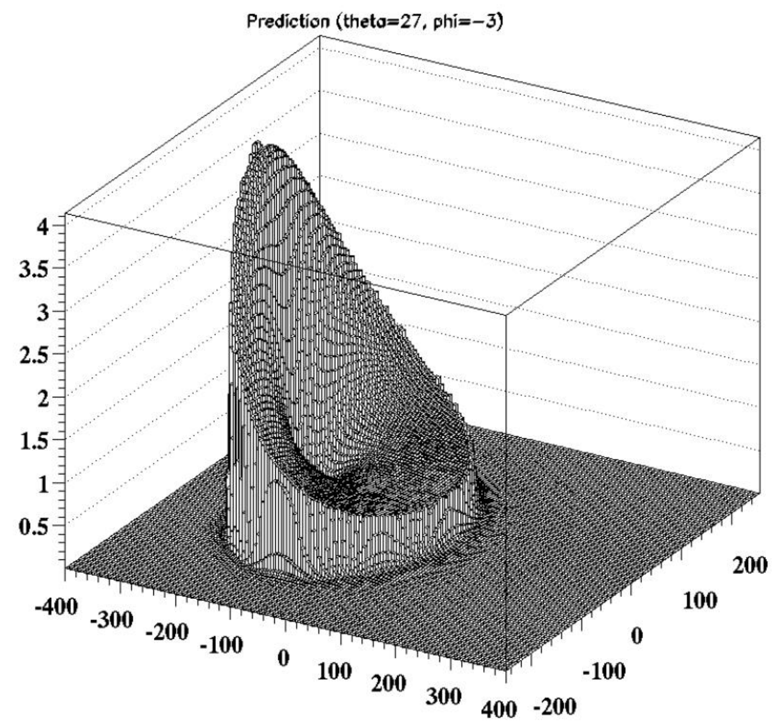
1000 MC Produced Events (theta=30, phi=0)
4
3.5
3
2.5
2
1.5
1
0.5
0
-400
-300
-200
-100
0
100
200
300
400
-200
-100
0
100
200
X (cm)
Y (cm)



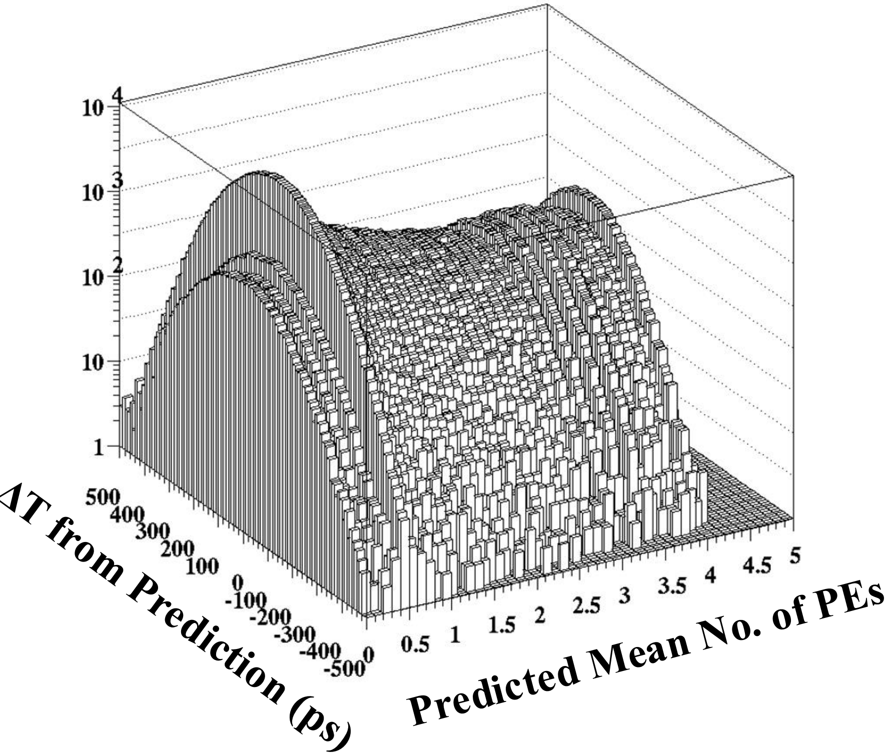
Prediction (theta=30, phi=0)
4
3.5
3
2.5
2
1.5
1
0.5
-400
-300
-200
-100
0
100
200
300
400
-200
-100
0
100
200
X (cm)
Y (cm)



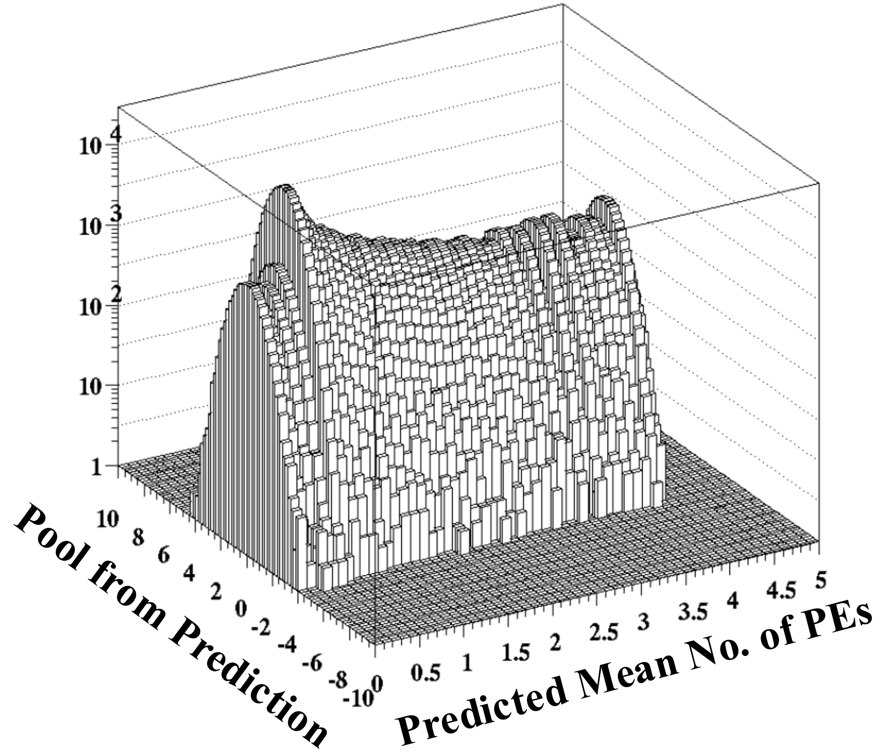
1000 MC Produced Events (theta=30, phi=0)
X (cm)
Y (cm)



Prediction (theta=27, phi=-3)

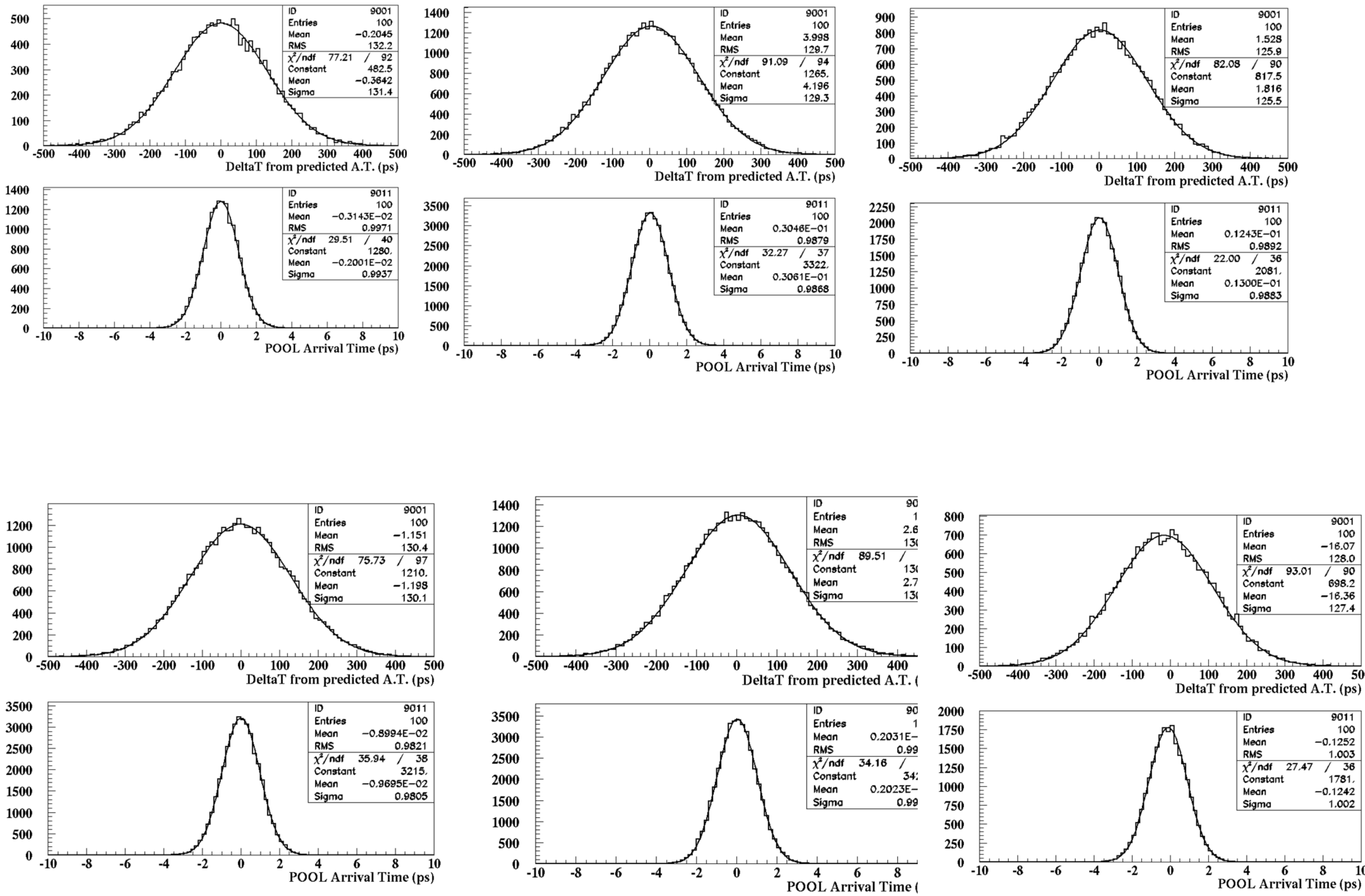


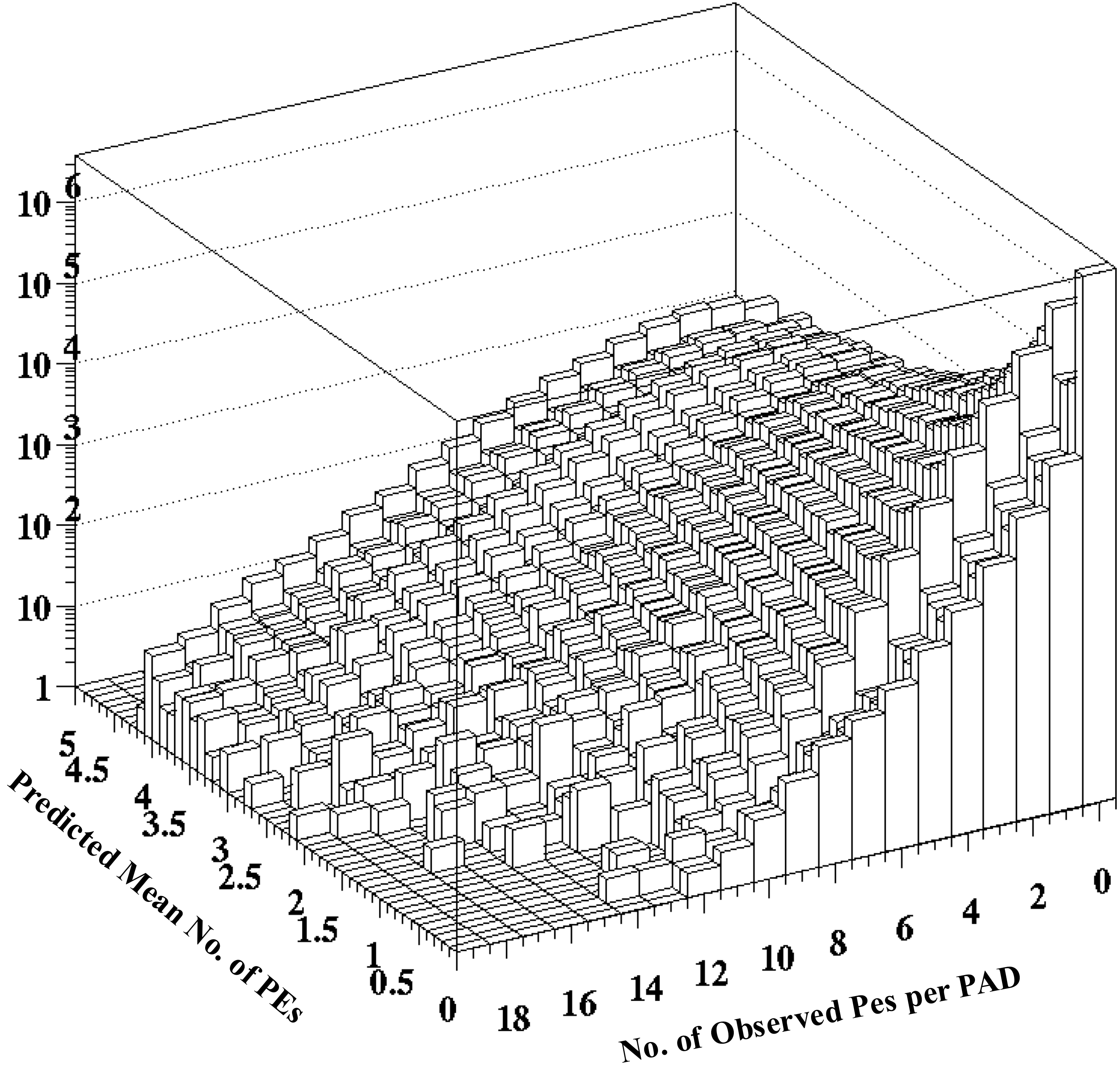
10^4
10^3
10^2
10
1
500 400 300 200 100 0 -100 -200 -300 -400 -500
ΔT from Prediction (ps)
0 0.5 1 1.5 2 2.5 3 3.5 4 4.5 5
Predicted Mean No. of PEs



10^4
10^3
10^2
10
1
10 8 6 4 2 0 -2 -4 -6 -8 -10
Pool from Prediction
0 0.5 1 1.5 2 2.5 3 3.5 4 4.5 5
Predicted Mean No. of PEs

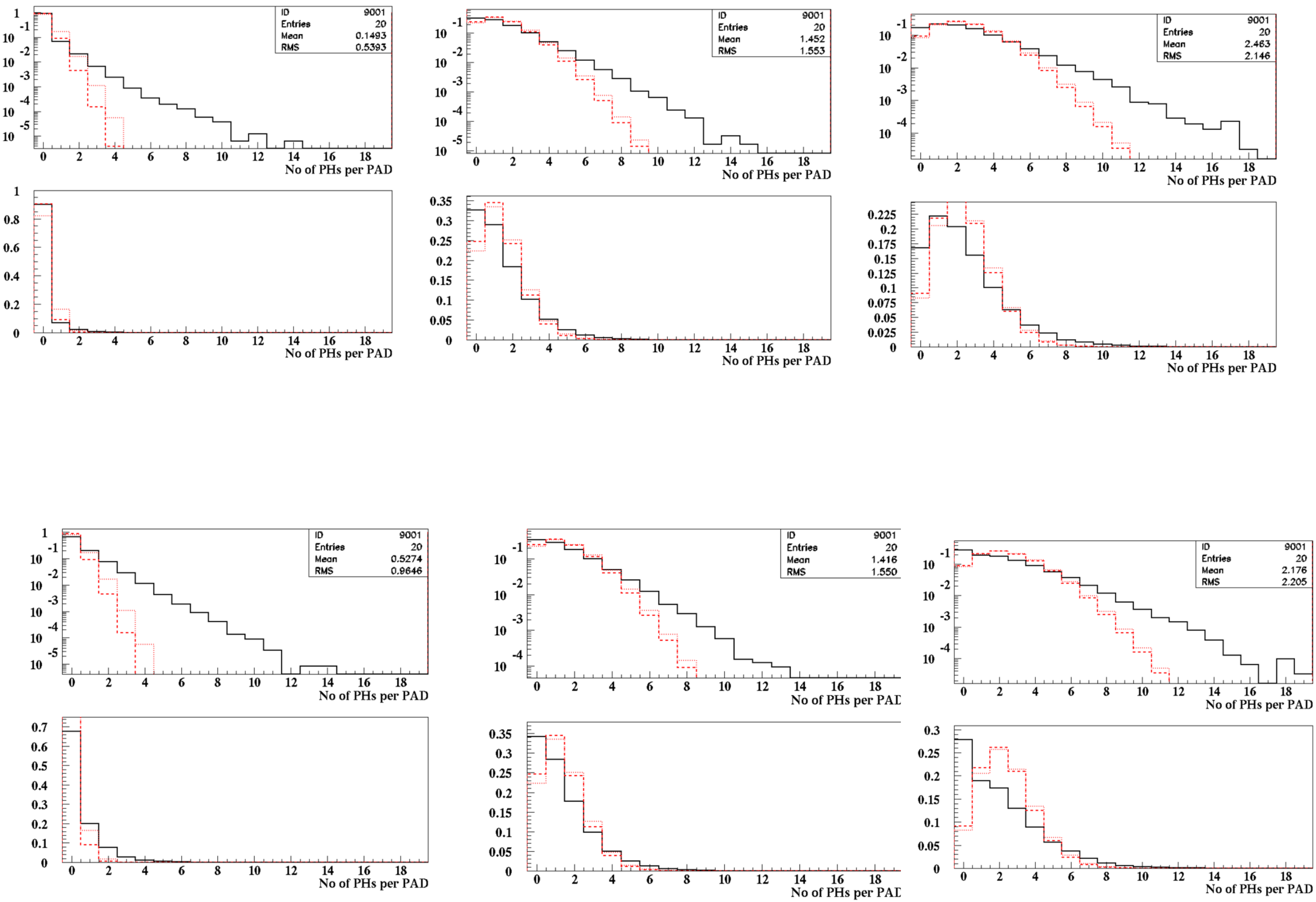
0.1-0.2 1.4-1.5 2.4-2.5

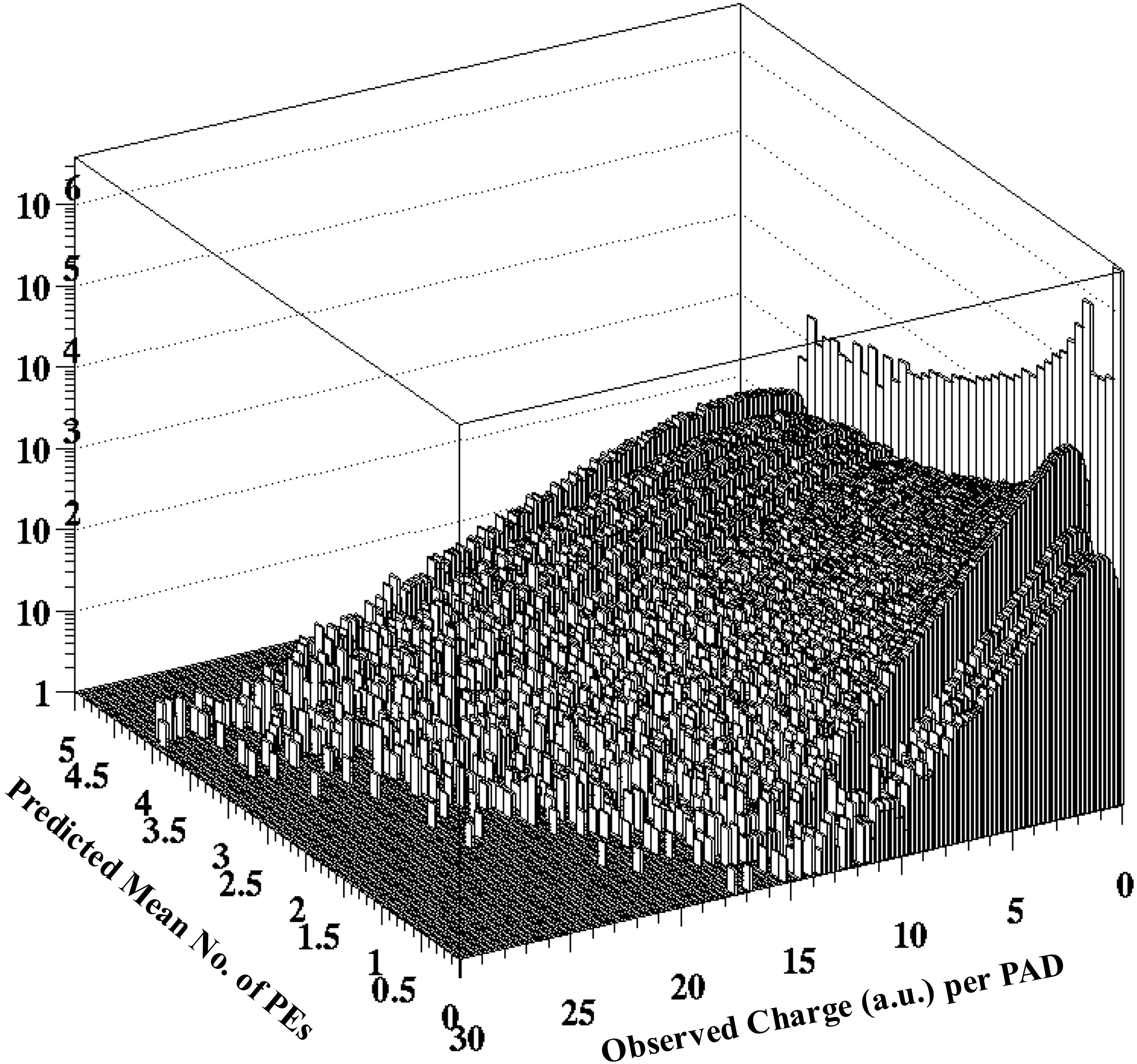




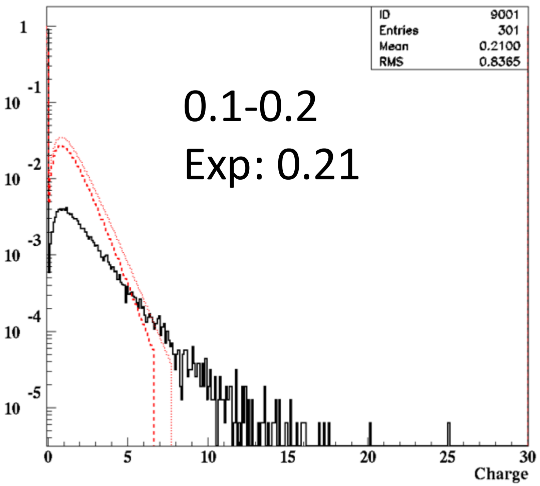
10^6
10^5
10^4
10^3
10^2
10
1
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
Predicted Mean No. of PEs
18
16
14
12
10
8
6
4
2
0
No. of Observed Pes per PAD

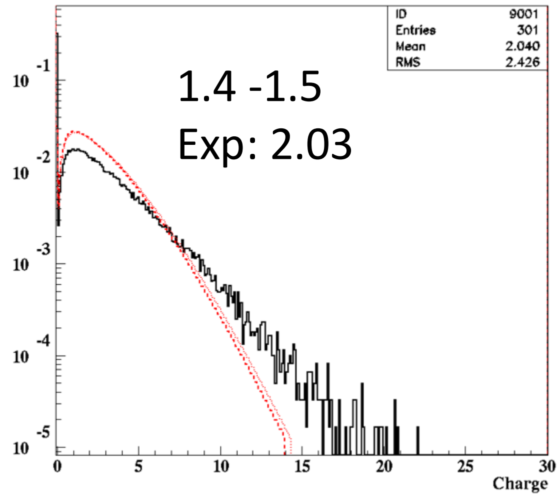
0.1-0.2 1.4-1.5 2.4-2.5

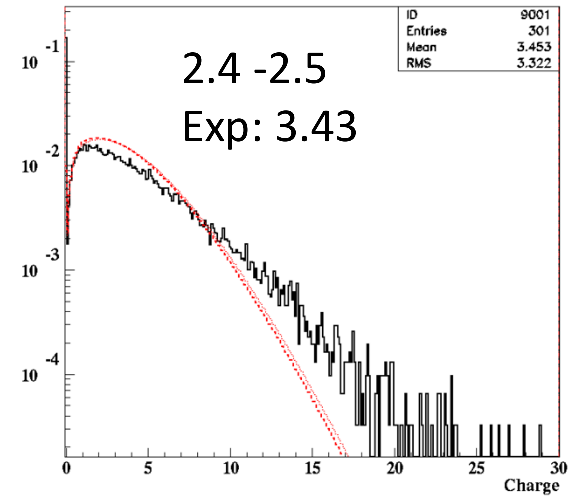


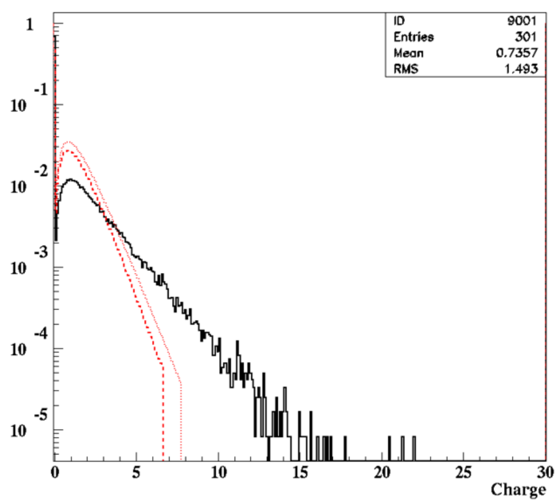


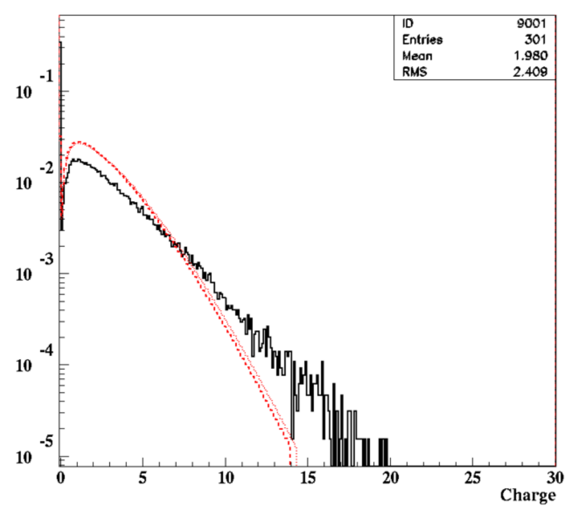
Predicted Mean No. of PEs
Observed Charge (a.u.) per PAD

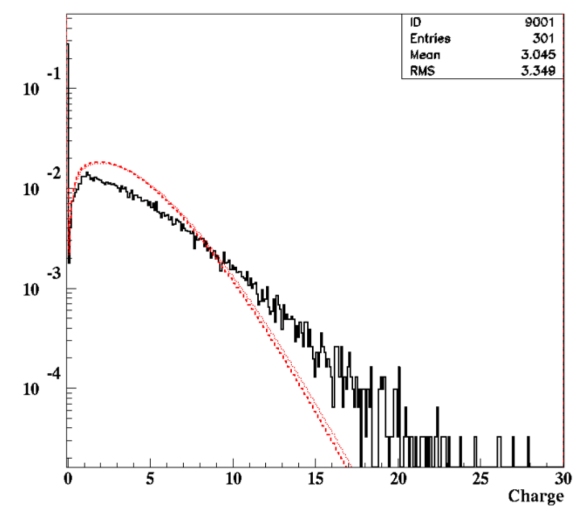

0.1-0.2
Exp: 0.21
ID 9001
Entries 301
Mean 0.2100
RMS 0.8365
Charge


1.4 -1.5
Exp: 2.03
ID 9001
Entries 301
Mean 2.040
RMS 2.426
Charge

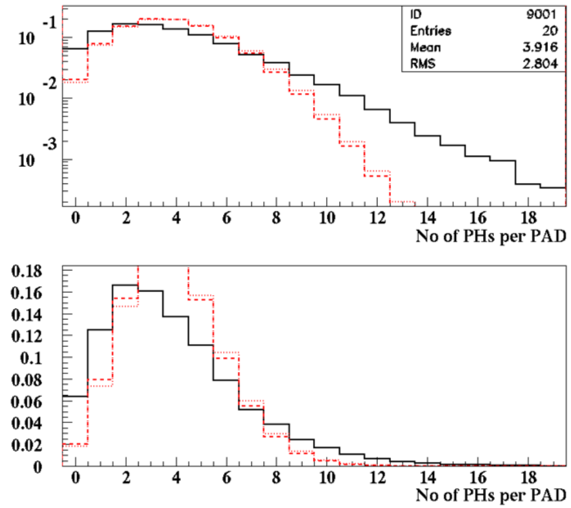

2.4 -2.5
Exp: 3.43
ID 9001
Entries 301
Mean 3.453
RMS 3.322
Charge

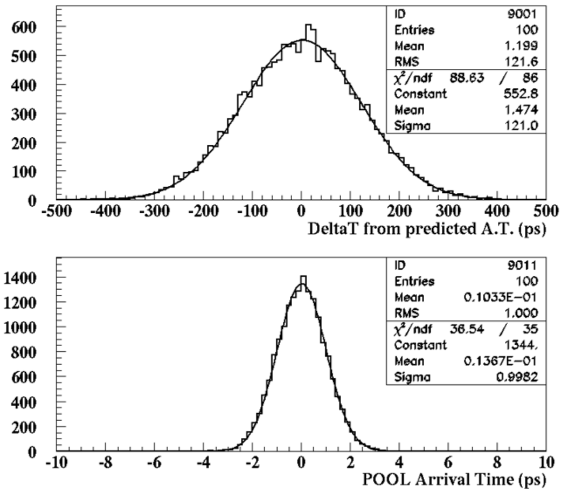

ID 9001
Entries 301
Mean 0.7357
RMS 1.493
Charge

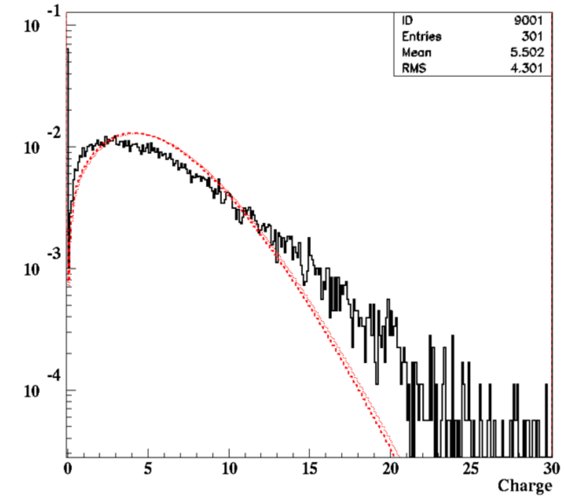

ID 9001
Entries 301
Mean 1.980
RMS 2.409
Charge

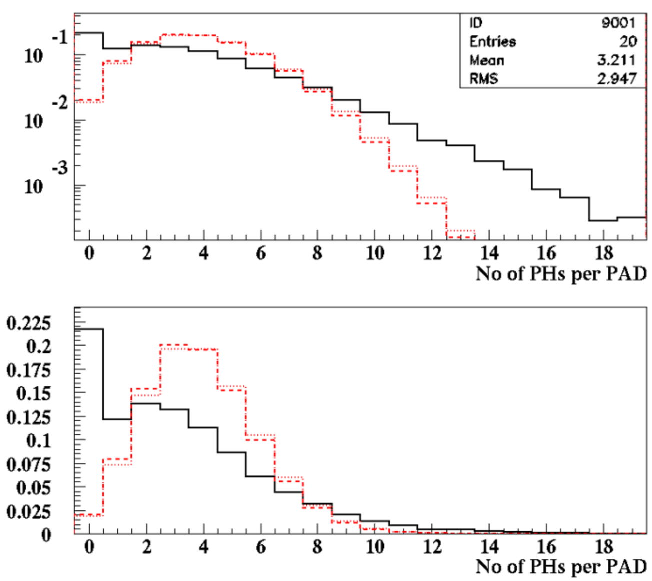

ID 9001
Entries 301
Mean 3.045
RMS 3.349
Charge

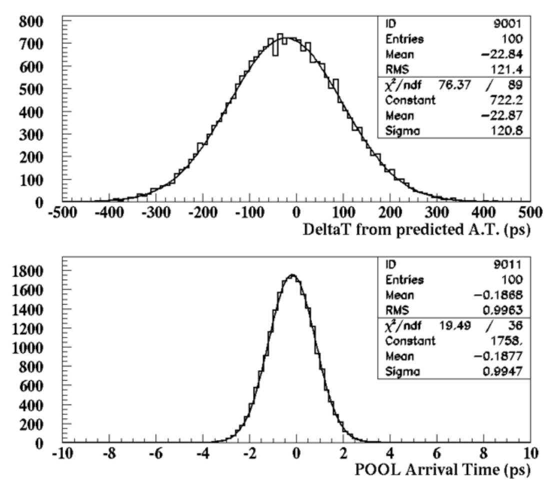
3.9-4.0 3.9-4.0 3.9-4.0

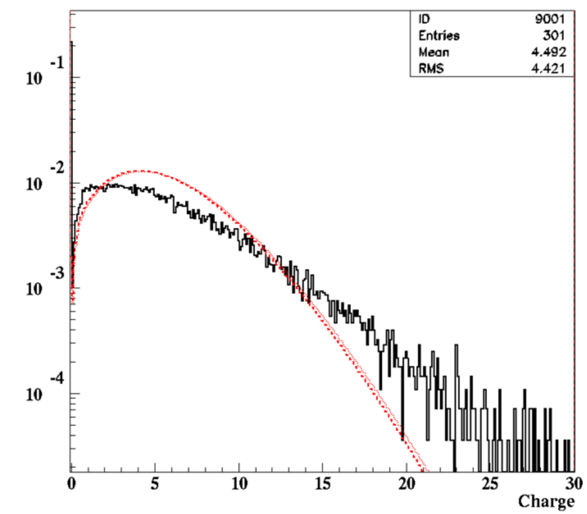












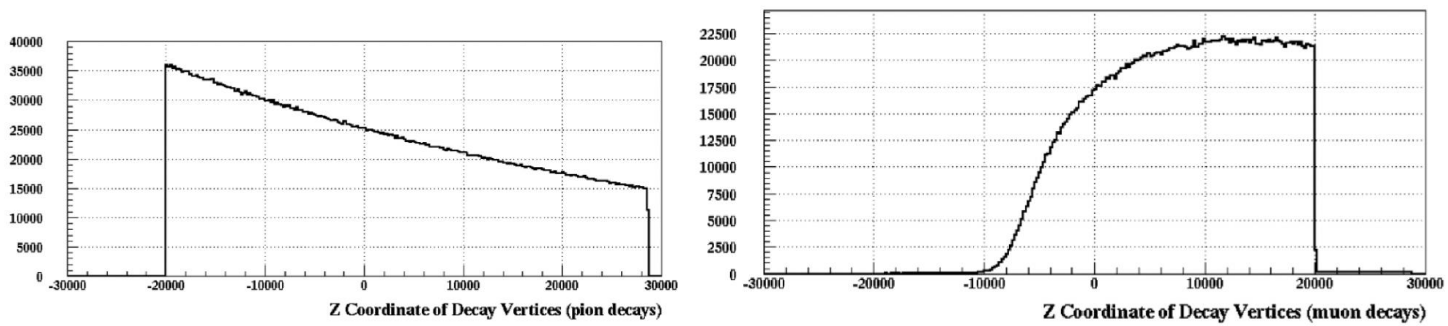


Figure B1. The Z vertex coordinate of pion and muon decays.

LENMB
μ decays

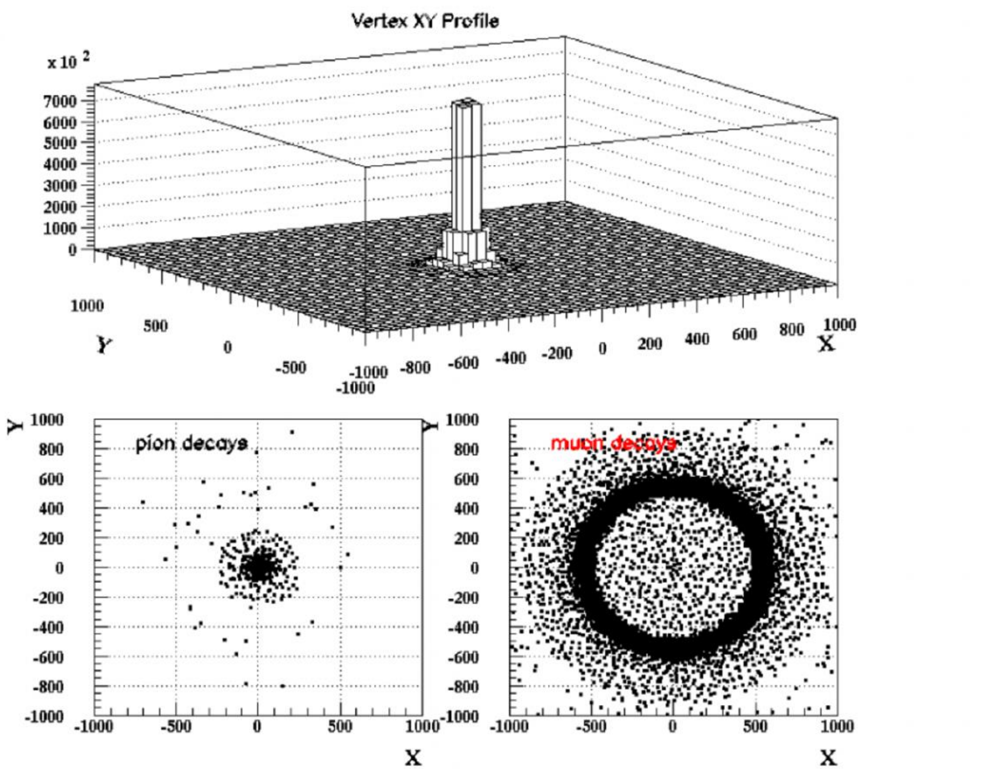


Figure B2. The X-Y vertex coordinates of pion and muon decays at the exit of LENMB tunnel.