DHCAL Results from Fermilab Test Beam

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Calibration/Performance Parameters

Efficiency (ε) and pad multiplicity (μ)

Track Fits:

- specifically for muon calibration runs
- Identify a muon track that traverse the stack with no identified interaction
- Measure all layers

Track Segment Fits:

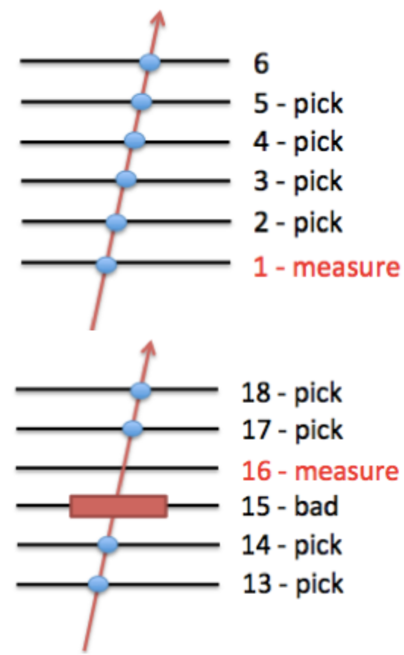
- for online calibration
- Identify a track segment of four layers with aligned clusters within 3 cm
- Measure only one layer (if possible)

- Fit to the parametric line: $x=x_0+a_x t$; $y=y_0+a_y t$; $z=t$

A cluster is found in the measurement layer within 2 cm of the fit point?

Yes → $\varepsilon=1$
μ=size of the found cluster

No → $\varepsilon=0$
No μ measurement



Average efficiency to detect MIP: $\varepsilon_0 \sim 96\%$
Average pad multiplicity: $\mu_0 \sim 1.6$

Calibration Procedures

1. Full Calibration: $$H_{calibrated} = \sum_{i=RPC_0}^{RPC_n} \frac{\varepsilon_0 \mu_0}{\varepsilon_i \mu_i} H_i$$ H_i: Number of hits in layer i

2. Density-weighted Calibration: Developed due to the fact that a pad will fire if it gets contribution from multiple traversing particles regardless of the efficiency of this RPC. Hence, the full calibration will overcorrect. Classifies hits in density bins (number of neighbors in a 3 x 3 array).

3. Hybrid Calibration: Density bins 0 and 1 receive full calibration.

Density-weighted Calibration Overview

Warning: This is rather COMPLICATED

Derived entirely based on Monte Carlo

Assumes correlation between

Density of hits ↔ Number of particles contributing to signal of a pad

Mimics different operating conditions with

Different thresholds

Utilizes the fact that hits generated with the

Same GEANT4 file, but different operating conditions can be correlated

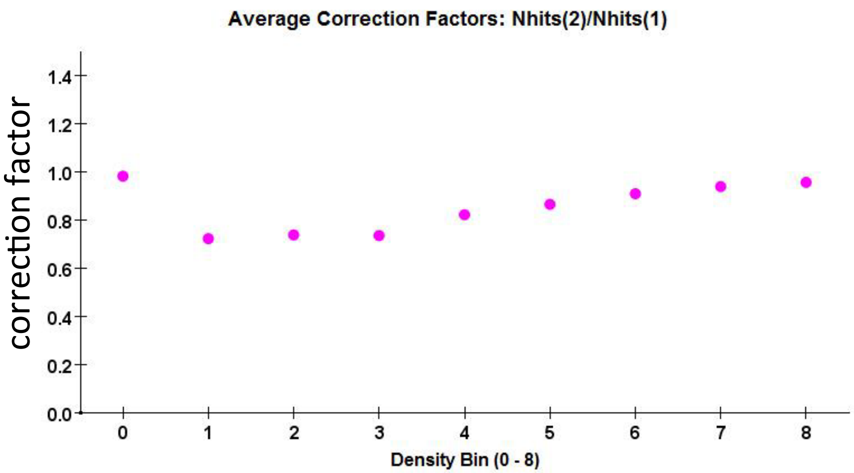
Defines density bin for each hit in a 3 x 3 array

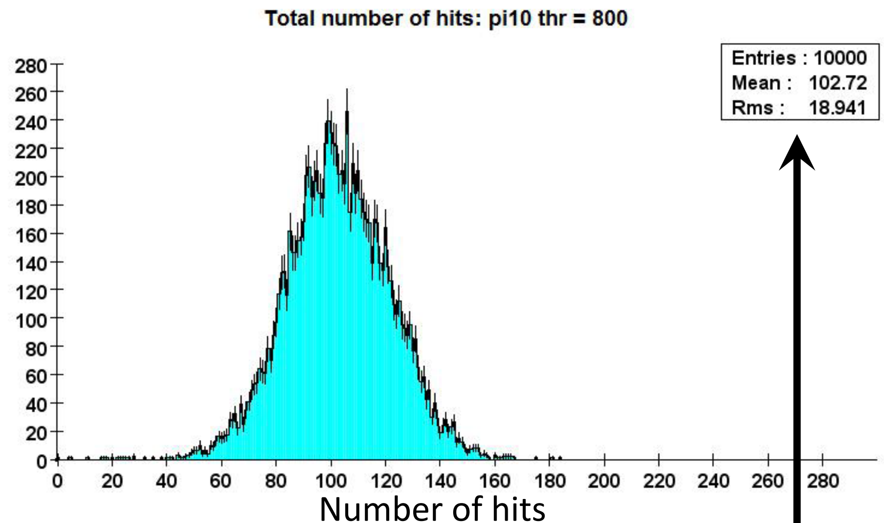
Bin 0 – 0 neighbors, bin 1 – 1 neighbor …. Bin 8 – 8 neighbors

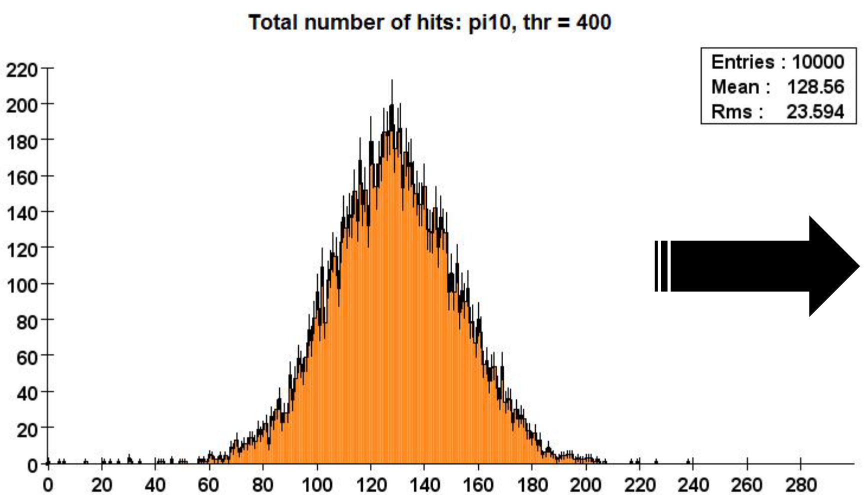
Weighs each hit

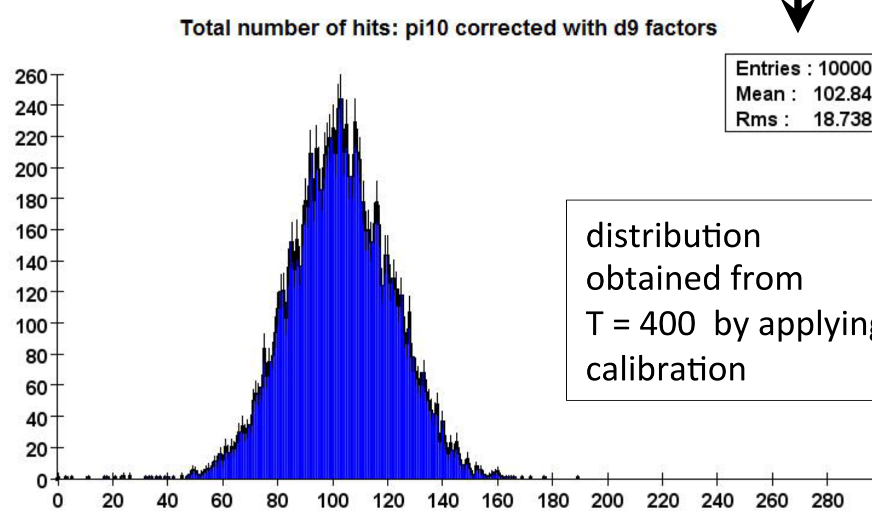
To restore desired density distribution of hits

Density-weighted Calibration Example: 10 GeV pions: Correction from T=400→ T=800









distribution obtained from T = 400 by applying calibration

Mean response and the resolution reproduced.
Similar results for all energies.

T: threshold, a.u.

Density-weighted Calibration: Expanding technique to large range of performance parameters

GEANT4 files

Positrons: 2, 4, 10, 16, 20, 25, 40, 80 GeV
Pions: 2, 4, 8, 10, 10, 25, 40, 80 GeV

Digitization with RPC_sim

Thresholds of 200, 400, 600, 800, 1000 (~ x 1fC)

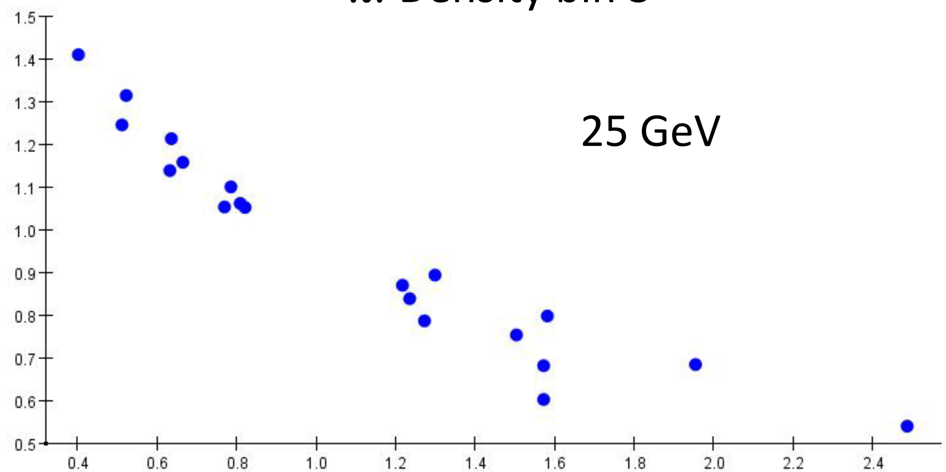
Calculate correction factors (C)

- for each density bin separately
- as a function of ε_i, μ_i, ε_0 and μ_0 (i : RPC index)

Plot C as a function of $R = (\varepsilon_i \mu_i)/(\varepsilon_0 \mu_0)$

→ Some scattering of the points, need a more sophisticated description of dependence of calibration factor on detector performance parameters

π: Density bin 3



$R = (\varepsilon_i \mu_i)/(\varepsilon_0 \mu_0)$

Only very weak dependence on energy:
Common calibration factor for all energies!

Density-weighted Calibration: Empirical Function of ε_i, μ_i, ε_0, μ_0

Positrons

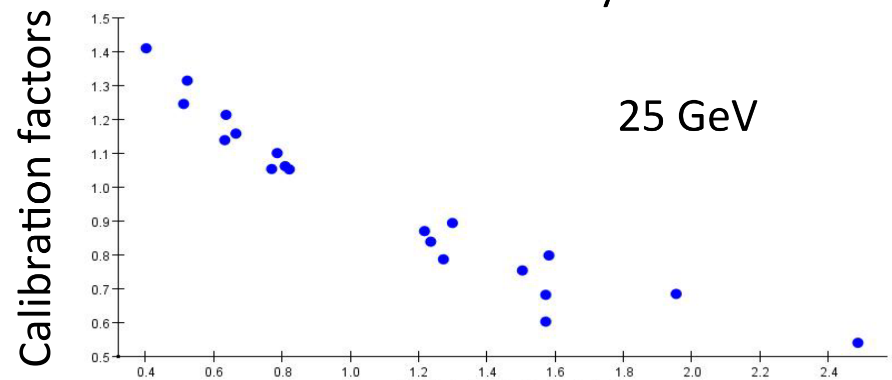
$$R_e = \frac{\varepsilon_i^{0.3}\mu_i^{2.0}}{\varepsilon_0^{0.3}\mu_0^{2.0}}$$

Pions

$$R_\pi = \frac{\varepsilon_i^{0.3}\mu_i^{1.5}}{\varepsilon_0^{0.3}\mu_0^{1.5}}$$

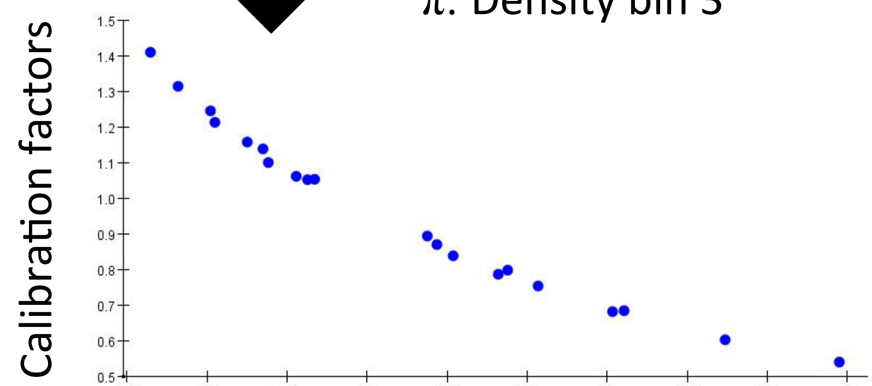
Functional dependence of calibration factors depends on particle type!
(Due to different shower topologies: Different density distribution leads to different impact of performance)

π: Density bin 3



$R = (\varepsilon_i\mu_i)/(\varepsilon_0\mu_0)$

π: Density bin 3

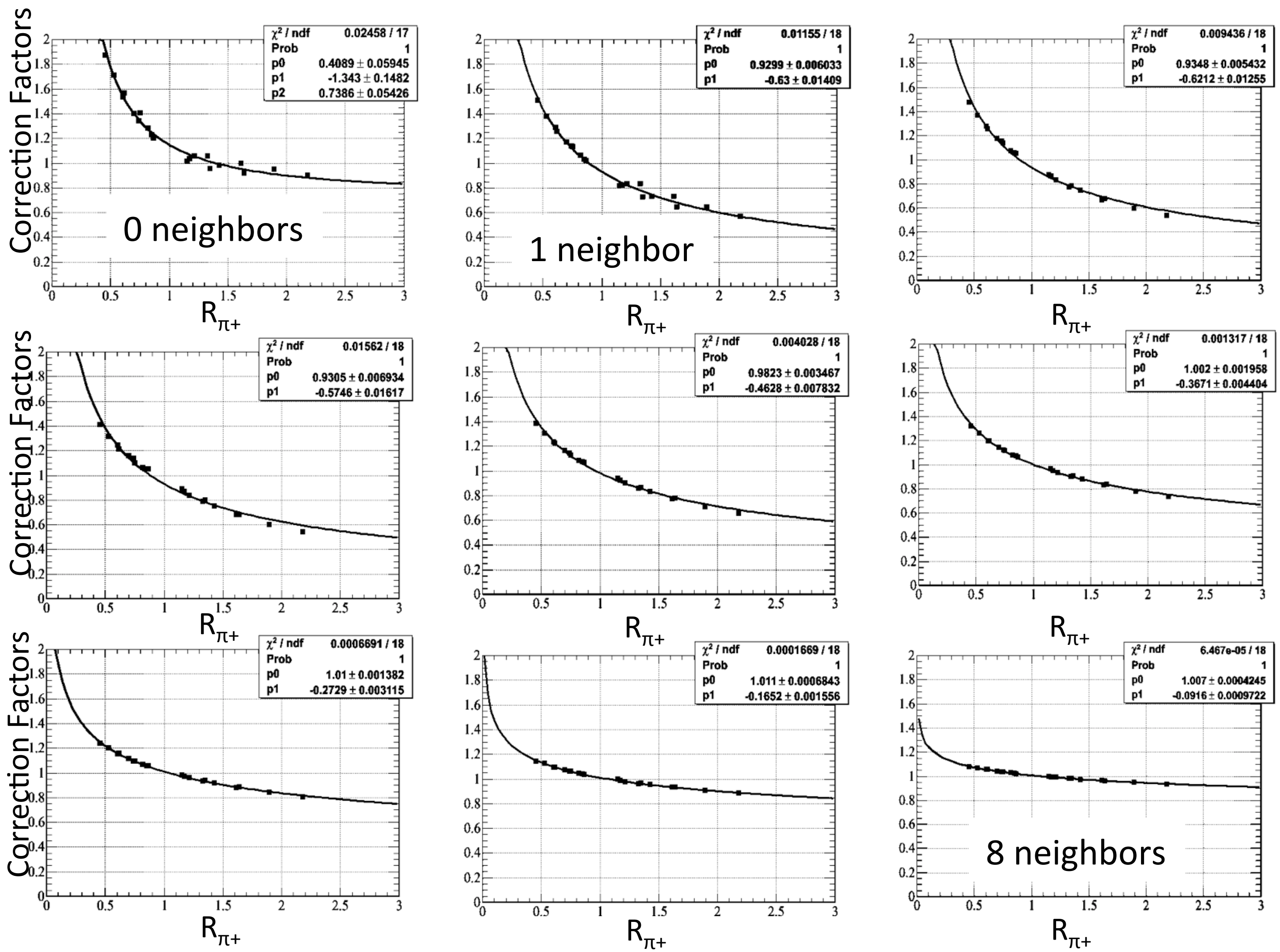


$R = (\varepsilon_i^{0.3}\mu_i^{1.5}) / (\varepsilon_0^{0.3}\mu_0^{1.5})$

Density-weighted Calibration: Fits of Correction Factors as a Function of R

Power law $C = \alpha R_p^{\beta}$

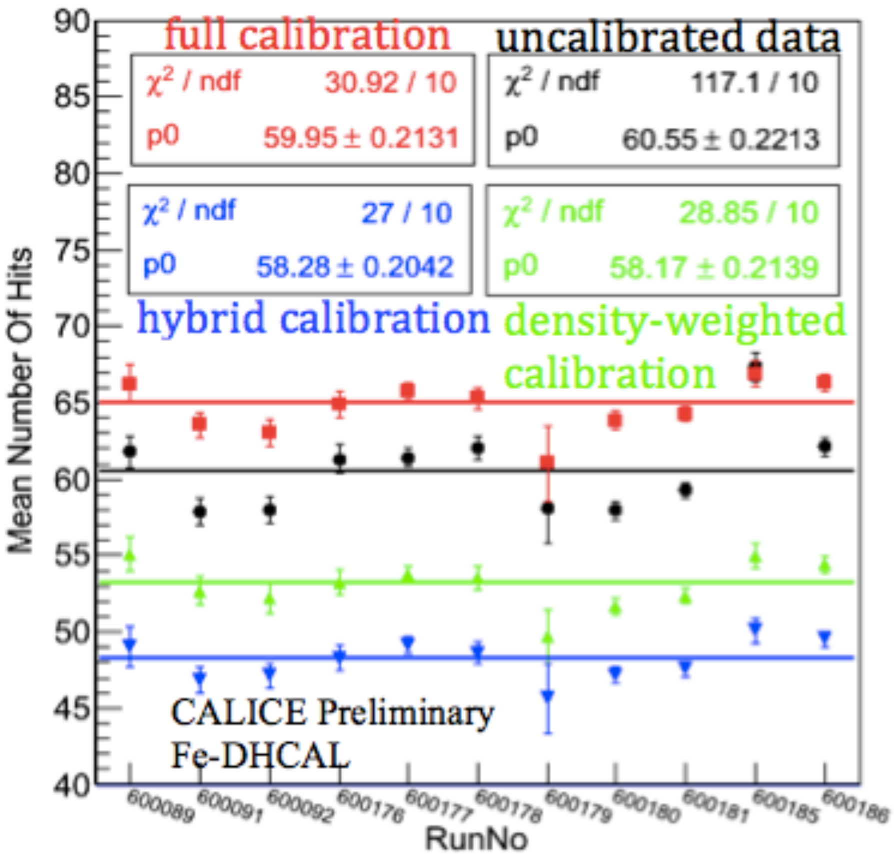
Fit results for p=pion, similar results for p=positron



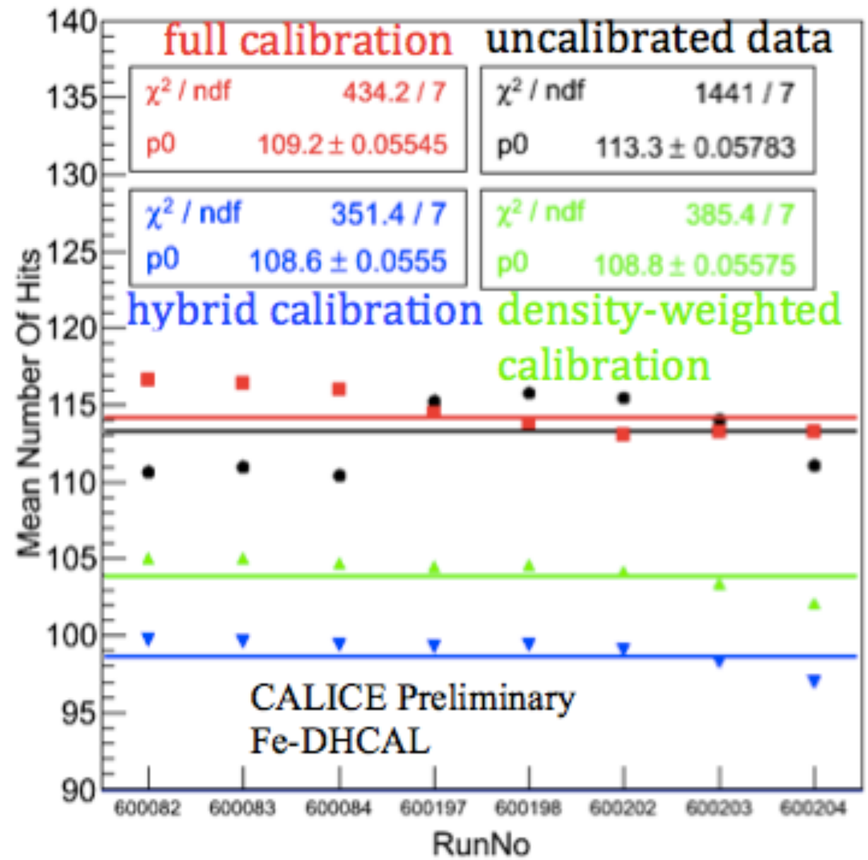
All 9 density bins

Calibrating Different Runs at Same Energy

4 GeV π^+



8 GeV e^+

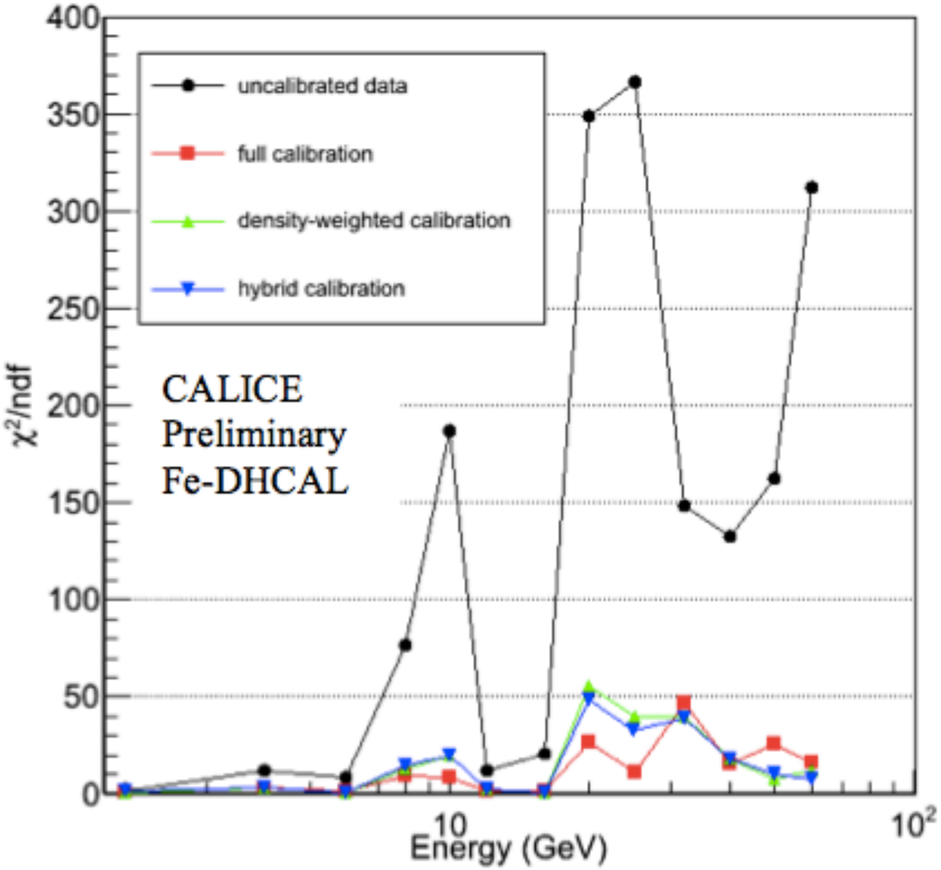


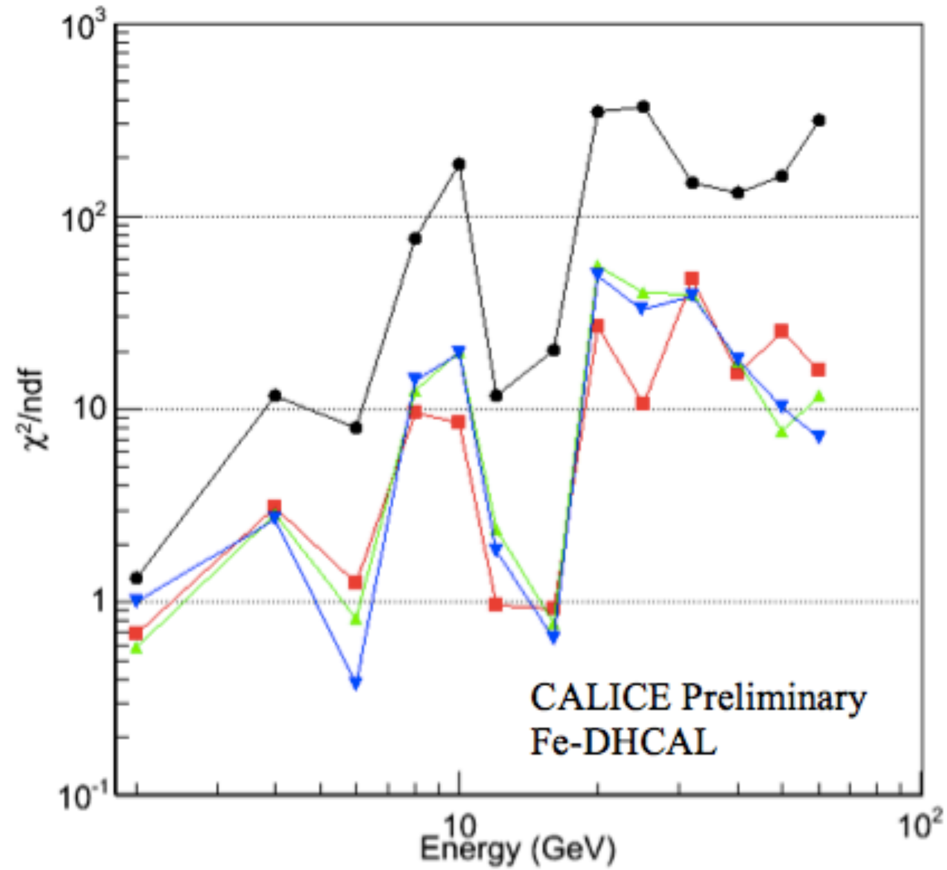
Uncalibrated response (0)
Full calibration (5)
Density – weighted calibration (-5)
Hybrid calibration (-10)

(Offsets applied to the values for better visibility)

Comparison of Different Calibration Schemes

χ^2/ndf of constant fits to the means for different runs at same energy





→ **All three schemes reduce the spread of data points: Benefits of calibration!**

No obvious "winner": Similar performance of different techniques

DHCAL Simulation Strategy

GEANT4 → points in the gas gap with energy loss

RPC_sim → generates and distributes the charge over pads
applies a threshold to determine pad hits

Simulated data → pad hits

RPC_sim tuning

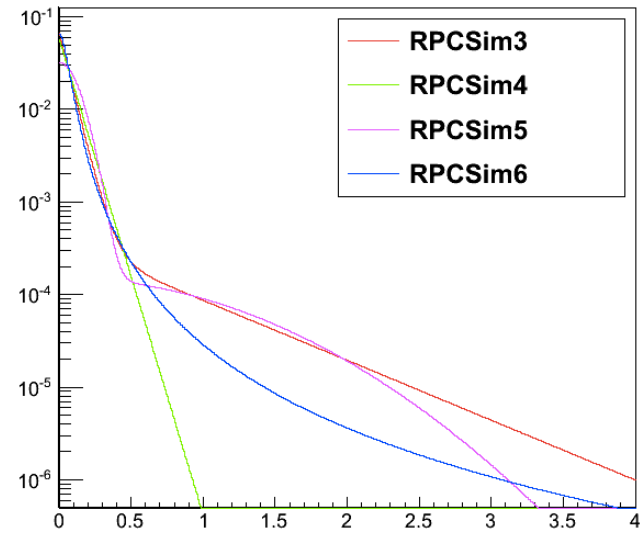
Tune major parameters to reproduce the muon response (José)
- Match number of hits per layer in the clean regions
- Tune charge at edges of chambers to reproduce tapering off of efficiency

Tune the remaining parameters to reproduce the **positron** response (Kurt → Burak)
- Match mean and sigma of Nhits distributions, longitudinal profiles, density plots

No tuning based on pion response

The 4 RPC_sim Versions

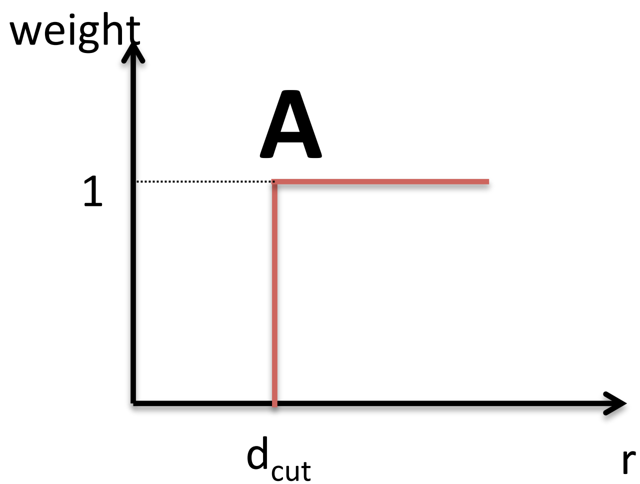
RPC_sim_	Spread functions	Comments
3	$R\, e^{-ar} + (1-R)\, e^{-br}$	To help the tail
4	e^{-ar}	Measurement from STAR
5	$R\, e^{-(r/\sigma 1)^{\wedge}2} + (1-R)\, e^{-(r/\sigma 2)^{\wedge}2}$	Commonly used
6	$1/(a + r^2)^{3/2}$	Recently came across

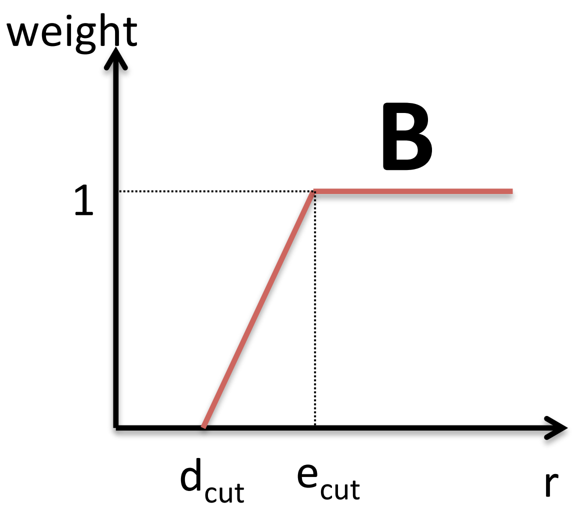


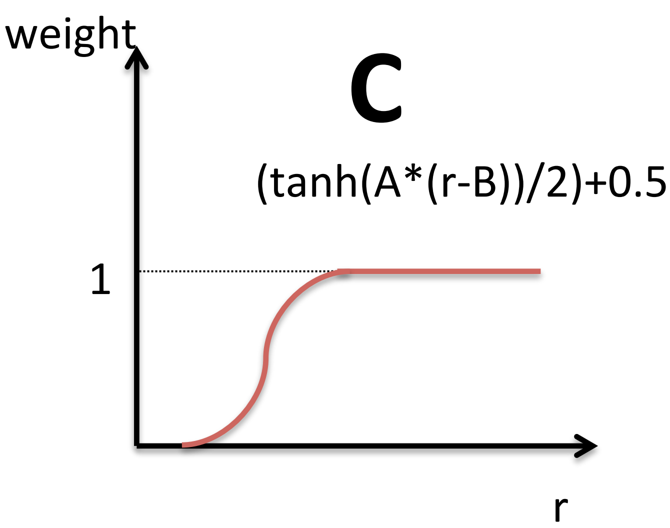
RPC_sim_	Slope a	Slope b	$Sigma_1$	$Sigma_2$	R	Q_0	d_{cut}	T
3	0.0678	0.671			0.345	0.201	0.262	0.3645
4	0.0843					0.199	0.092	0.286
5			0.120	0.983	0.241	0.114	0.092	0.250
6	0.0761					0.384	0.092	0.3405

3 Versions of the d_{cut}

d_{cut} suppresses avalanches close to others
Can not be tuned with μ's







Tuning of d_{cut} Values

Use Positron distributions at 8 GeV

Mean of hit distribution
Sigma of hit distribution
Density distribution (0÷8)
Longitudinal profile

Measure difference to measured distributions

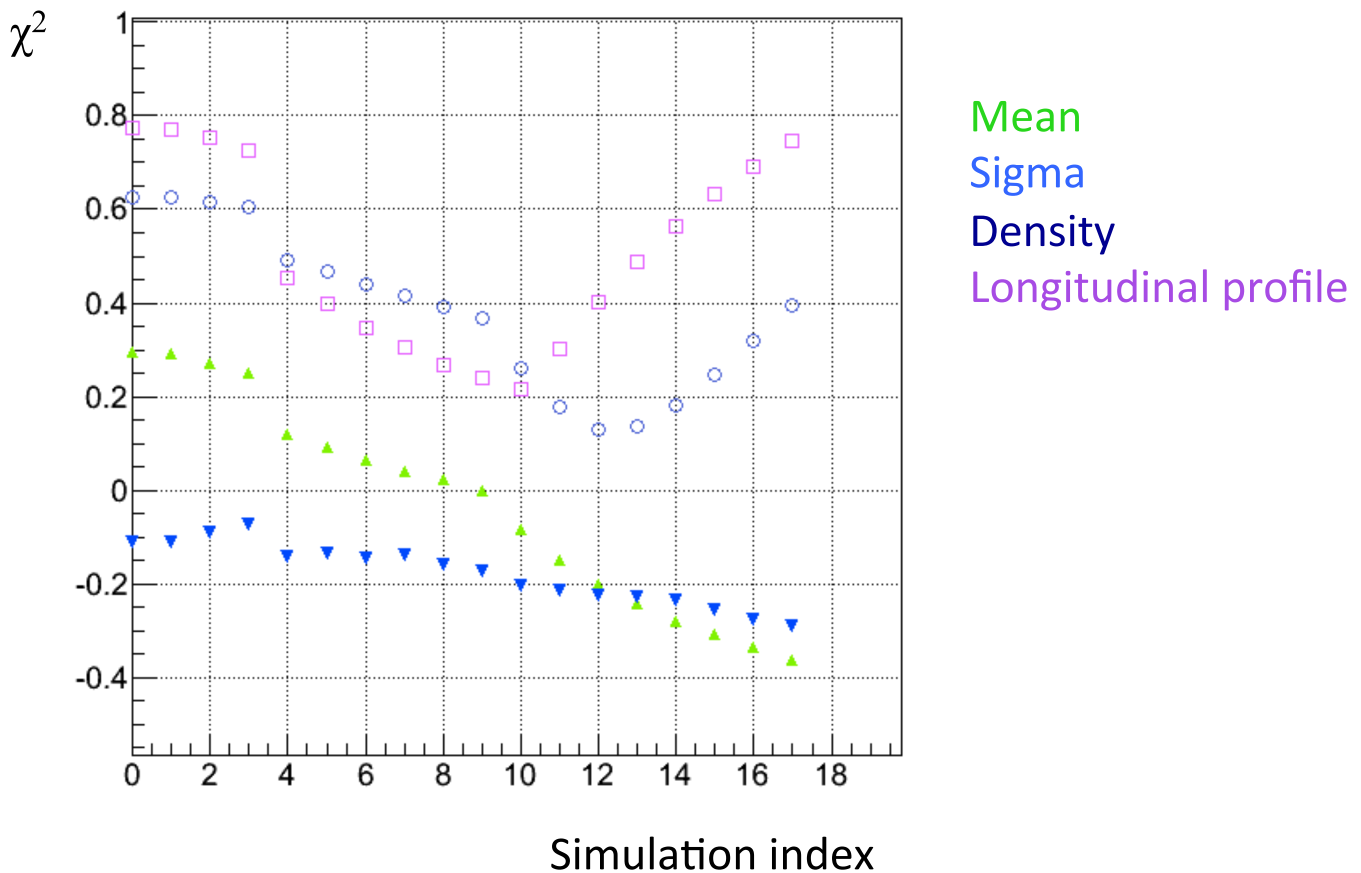
Define a χ^2

Tuning

Identify smallest χ^2

RPC_sim_3_A

2 exponential lateral charge distribution
1 d_{cut} parameter

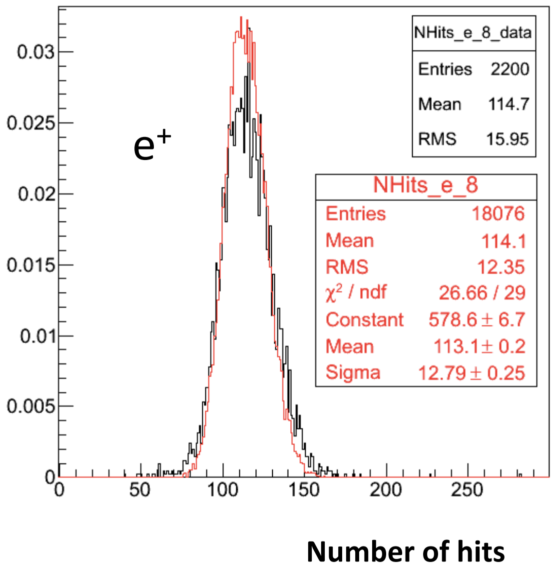


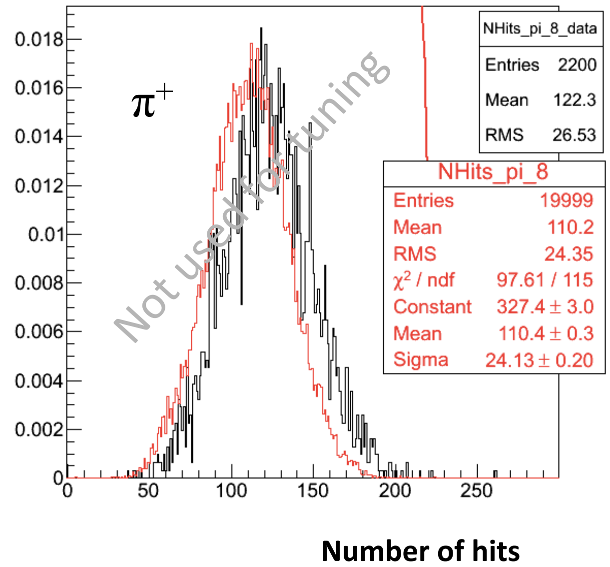
Simulation index	d_{cut}
0	0
1	0.001
2	0.005
3	0.01
4	0.05
5	0.06
6	0.07
7	0.08
8	0.09
9	0.1
10	0.15
11	0.2
12	0.25
13	0.3
14	0.35
15	0.4
16	0.45
17	0.5

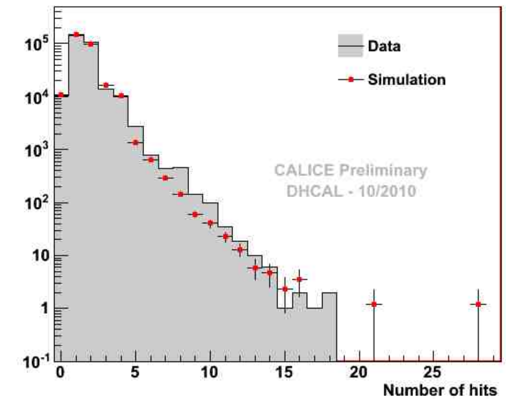
Best result for d_{cut} = 0.1

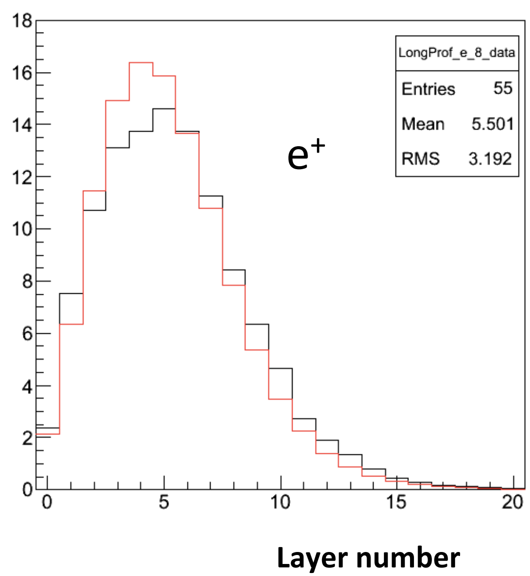
RPC_sim_3_A with d_{cut} = 0.1

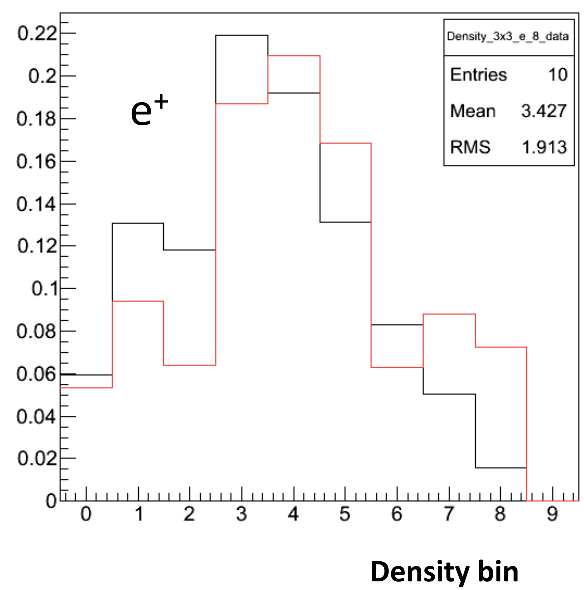
Data
RPC_sim

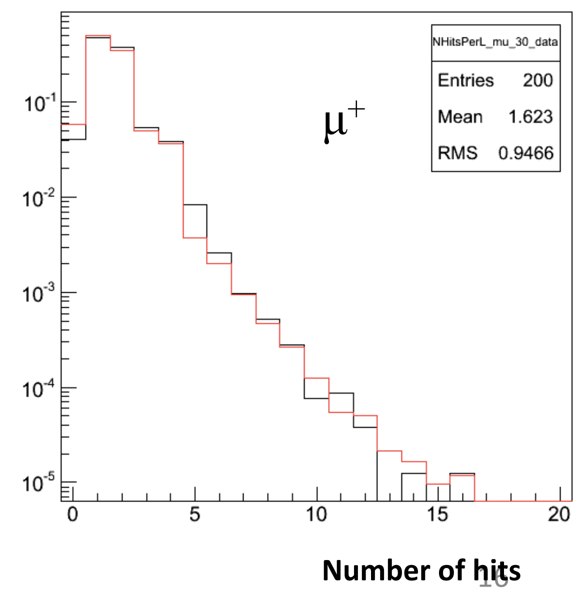






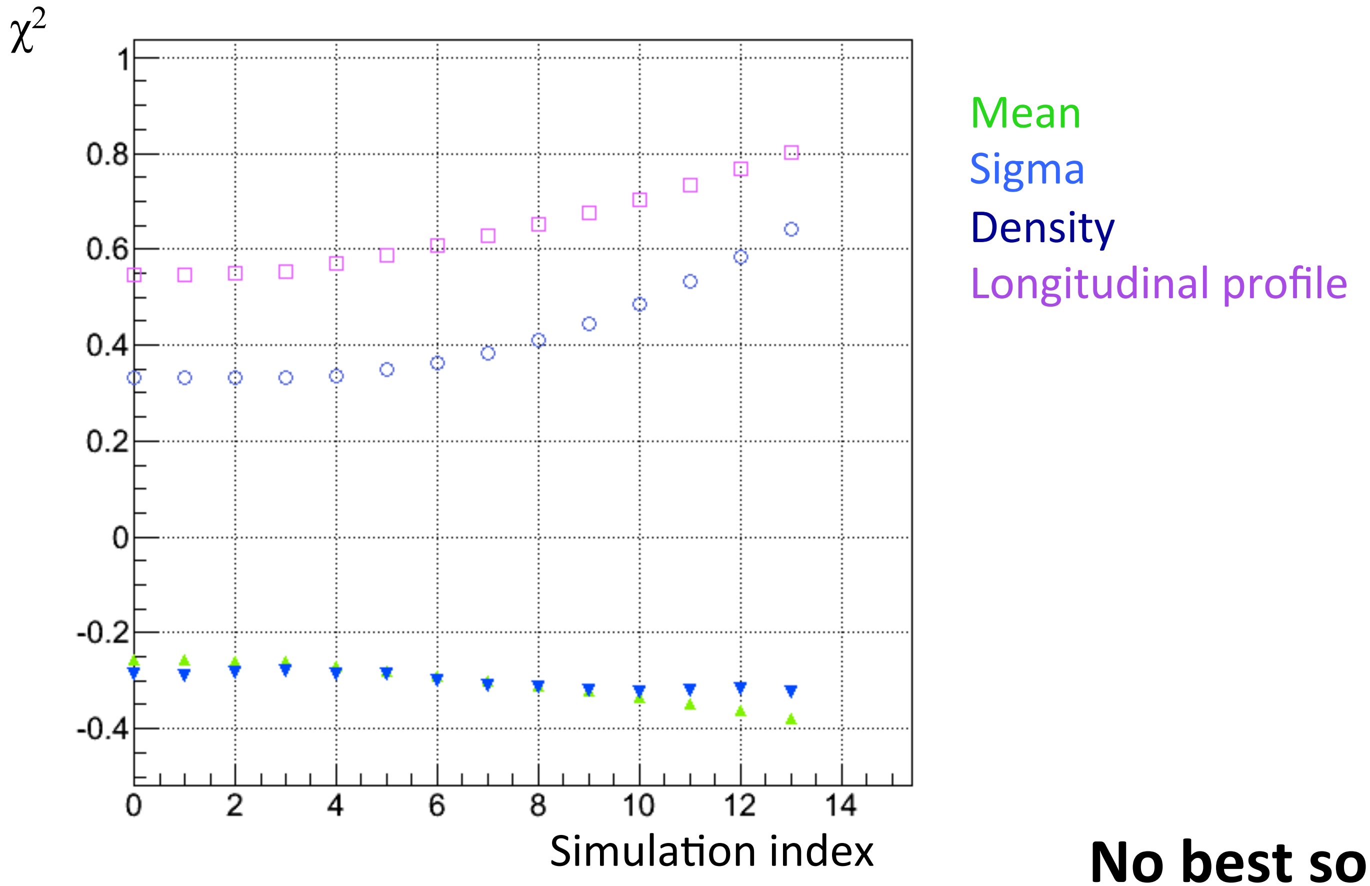






RPC_sim_4_A

1 exponential lateral charge distribution
1 d_{cut} parameter

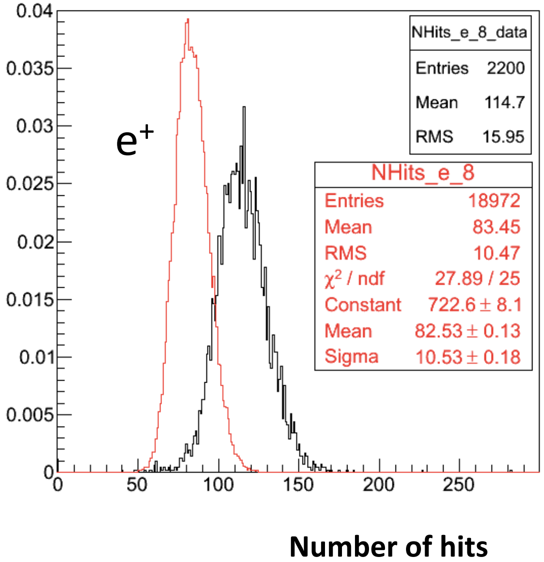


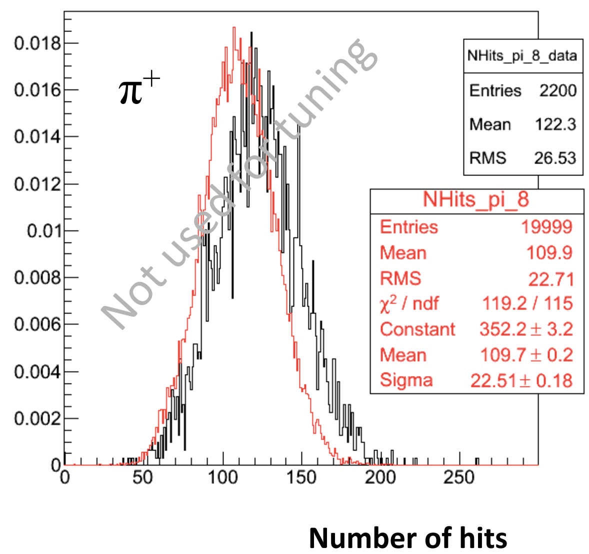
Simulation index	d_{cut}
0	0
1	0.001
2	0.005
3	0.01
4	0.05
5	0.1
6	0.15
7	0.2
8	0.25
9	0.3
10	0.35
11	0.4
12	0.45
13	0.5

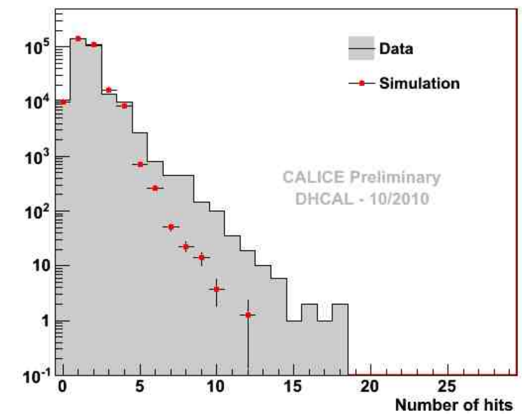
No best solution

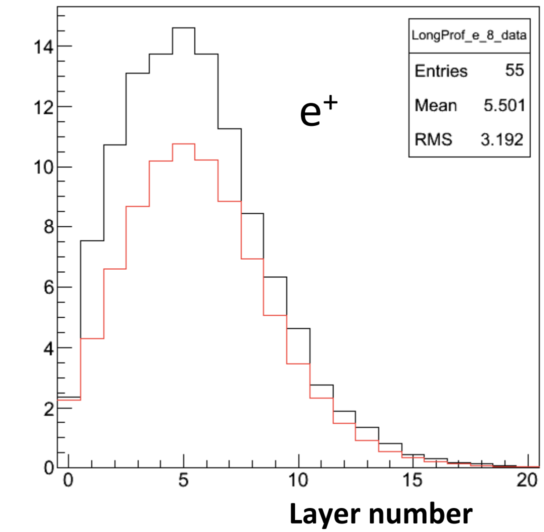
RPC_sim_4_A with d_{cut} = 0.05

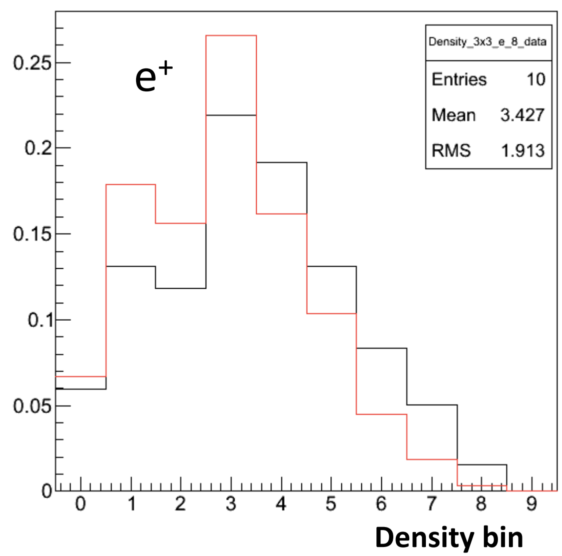
Data
RPC_sim

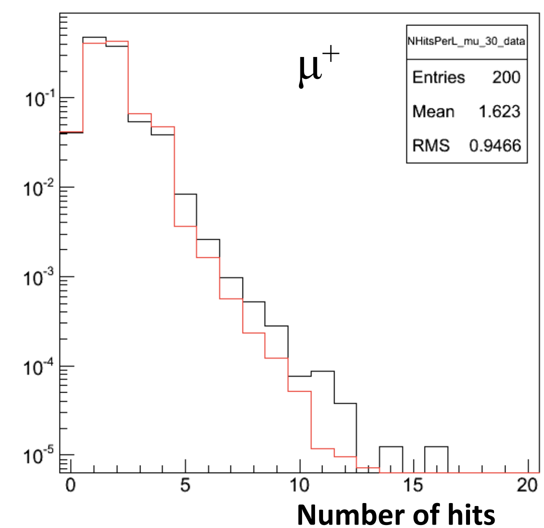








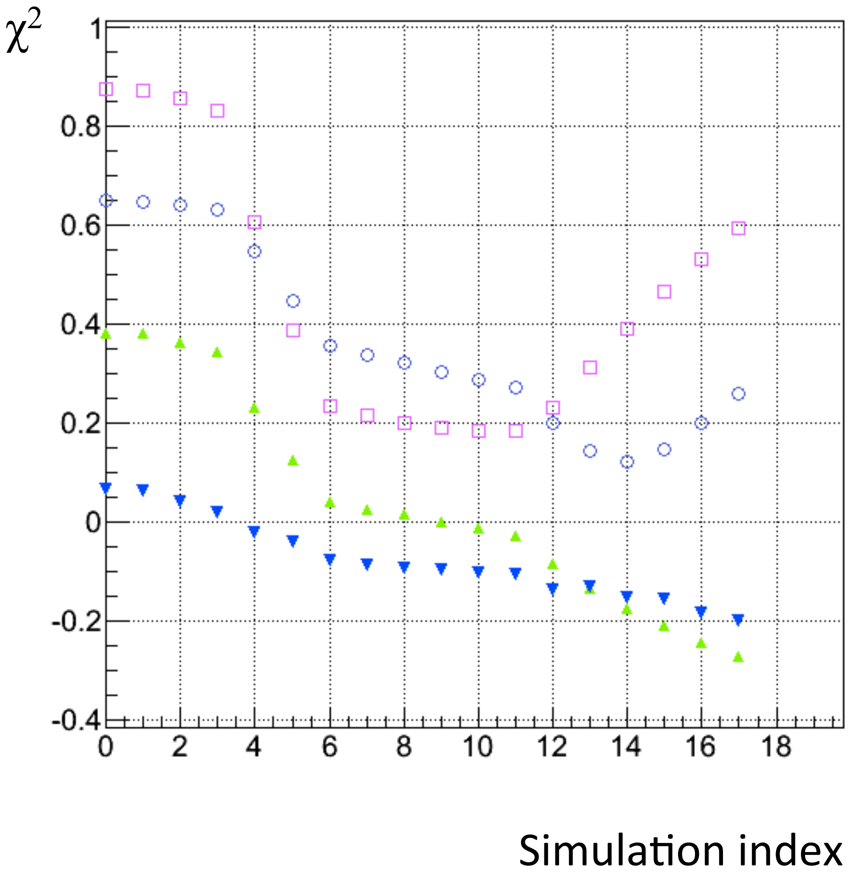




RPC_sim_5_A

2 Gaussian lateral charge distribution

1 d_{cut} parameter



Mean

Sigma

Density

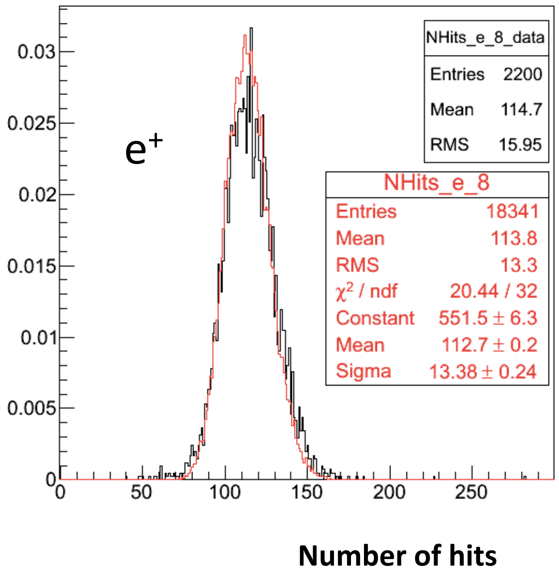
Longitudinal profile

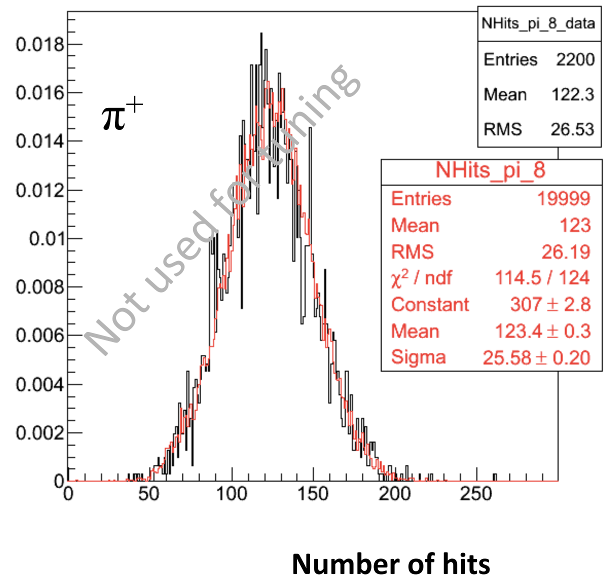
Simulation index	d_{cut}
0	0
1	0.001
2	0.005
3	0.01
4	0.05
5	0.1
6	0.15
7	0.16
8	0.17
9	0.18
10	0.19
11	0.2
12	0.25
13	0.3
14	0.35
15	0.4
16	0.45
17	0.5

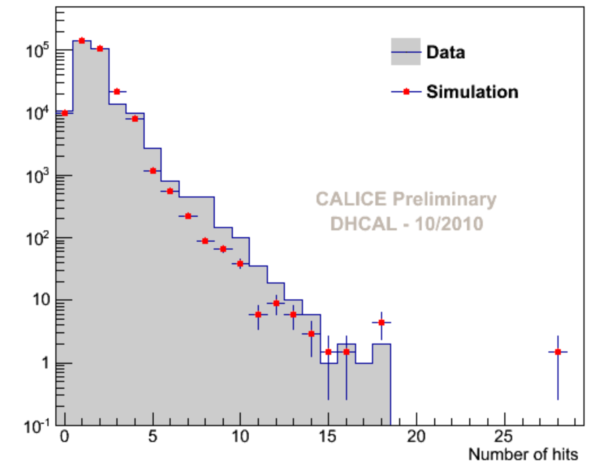
Best result for d_{cut} = 0.18

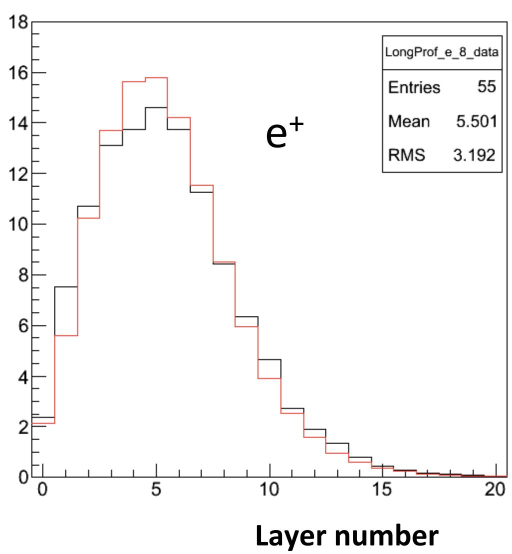
RPC_sim_5_A with d_{cut} = 0.18

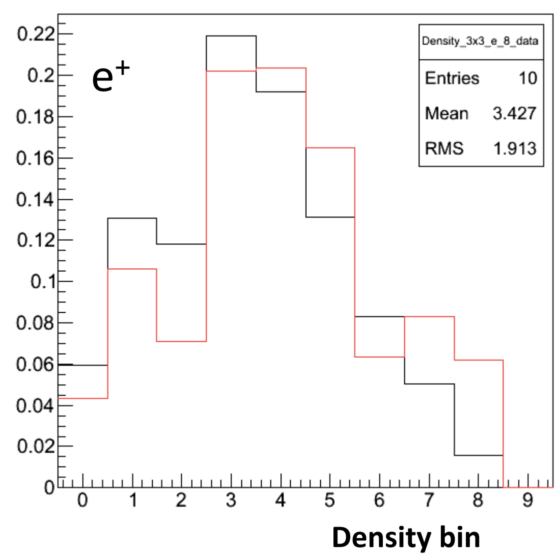
Data
RPC_sim

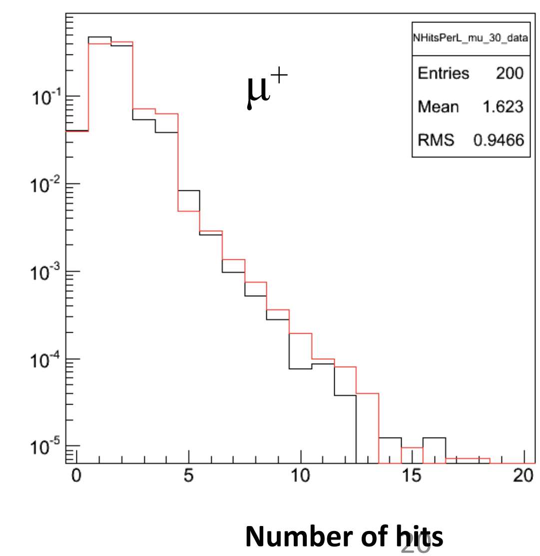






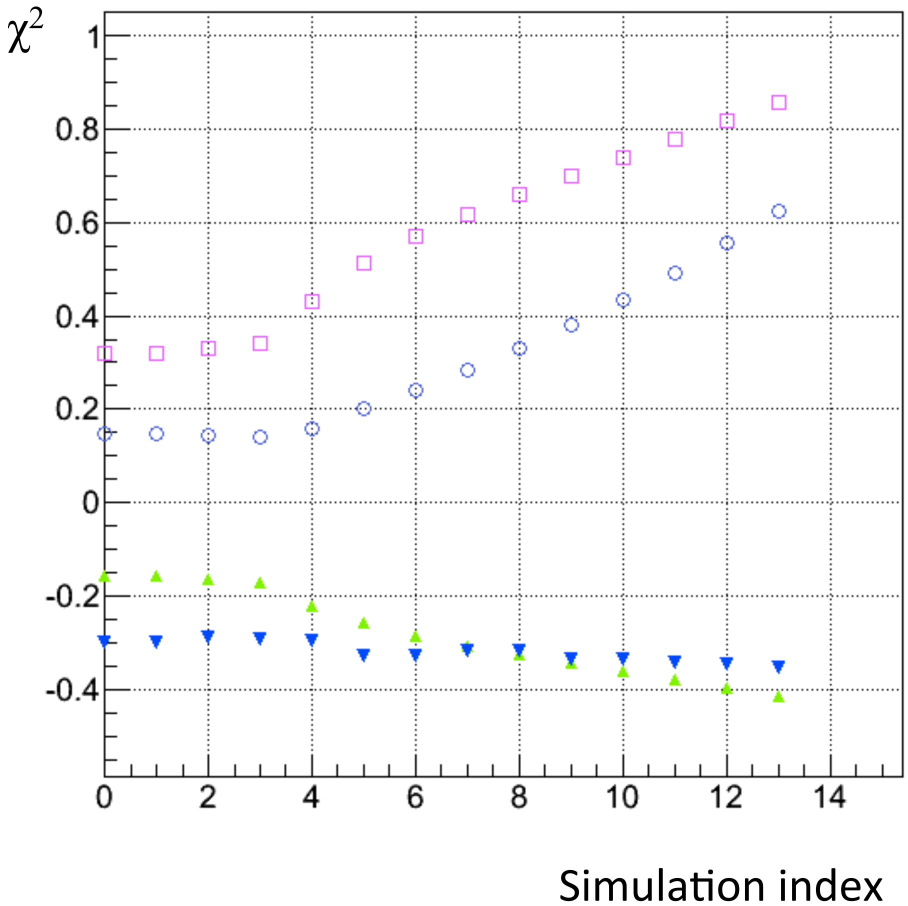






RPC_sim_6_A

Lateral charge distribution with $1/(a+r^2)^{3/2}$
1 d_{cut} parameter



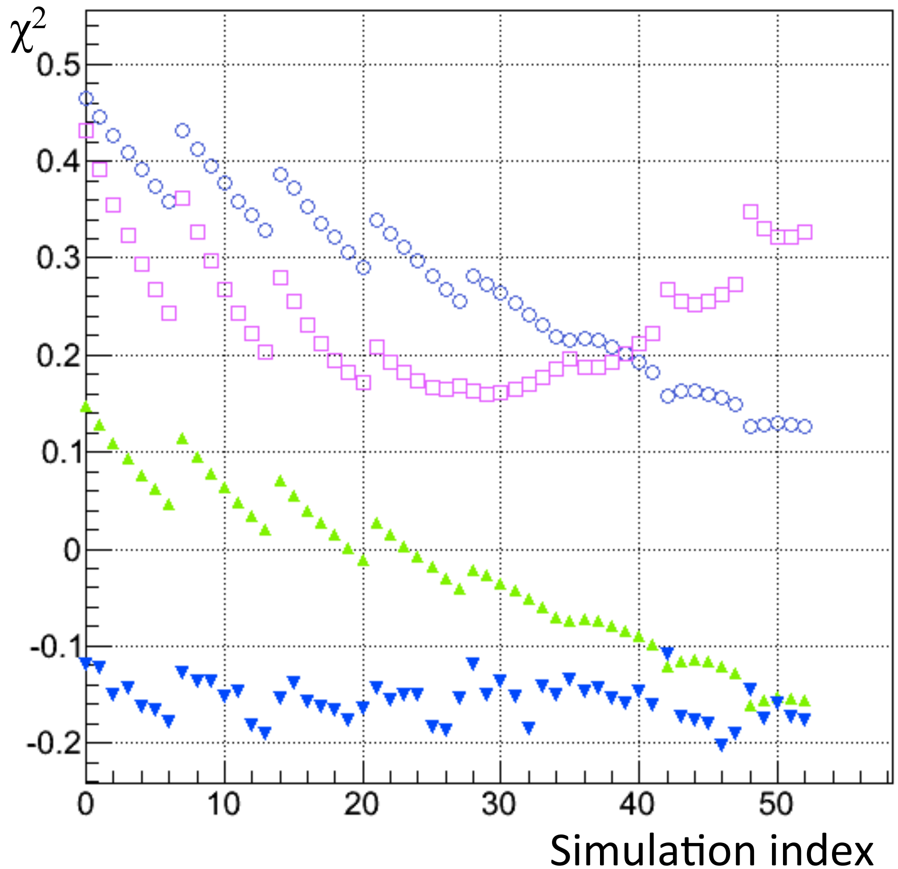
Mean
Sigma
Density
Longitudinal profile

Simulation index	d_{cut}
0	0
1	0.001
2	0.005
3	0.01
4	0.05
5	0.1
6	0.15
7	0.2
8	0.25
9	0.3
10	0.35
11	0.4
12	0.45
13	0.5

No best solution

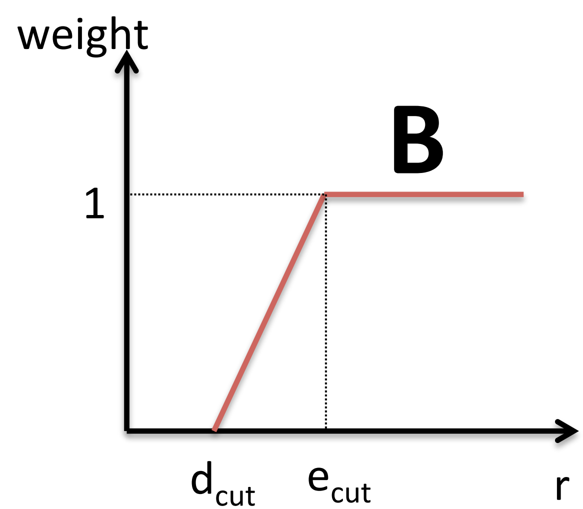
RPC_sim_5_B

2 Gaussian lateral charge distribution
2 d_{cut} parameters



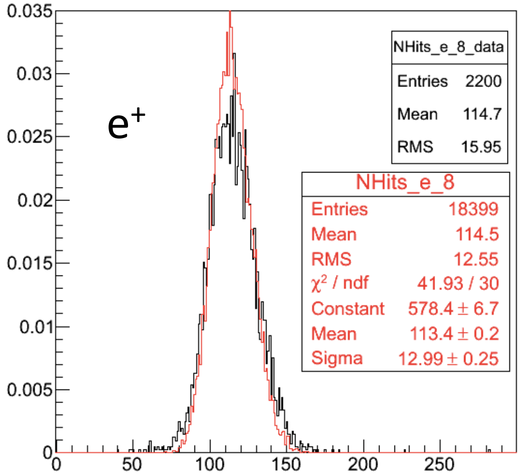
Mean
Sigma
Density
Longitudinal profile

Best result with 0.15/0.40

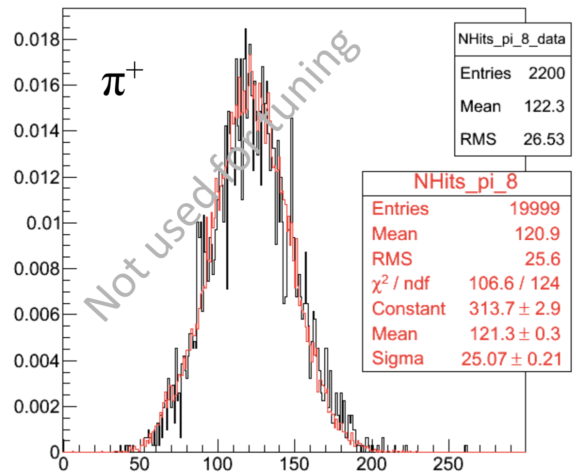


RPC_sim_5_B with d_{cut} / e_{cut} = 0.15/0.40

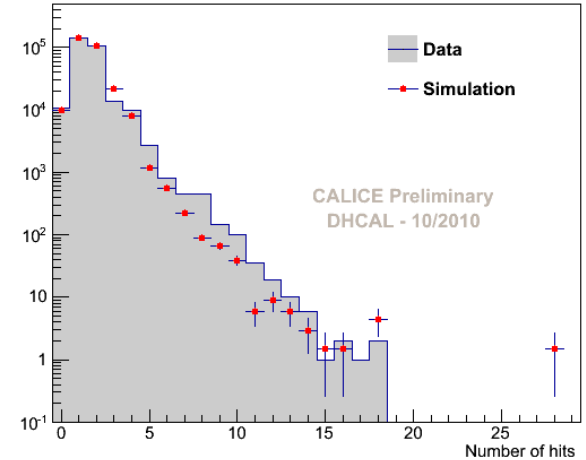
Data
RPC_sim

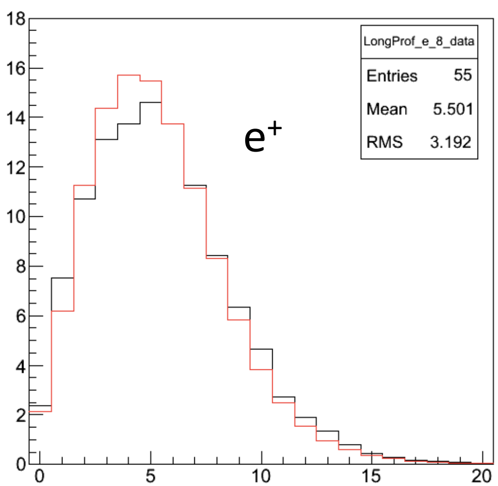


Number of hits

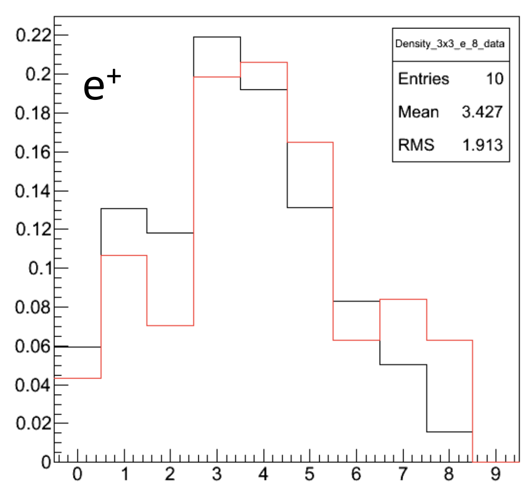


Number of hits

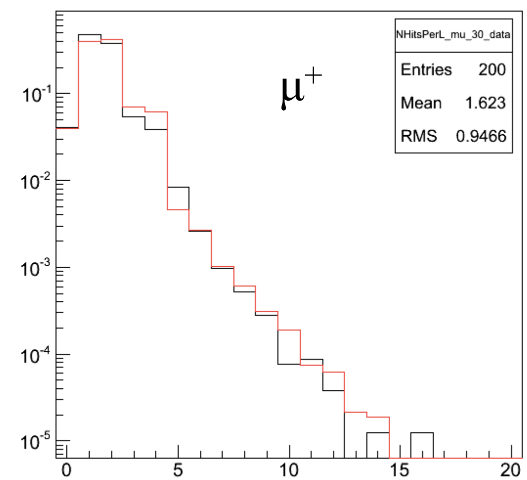




Layer number



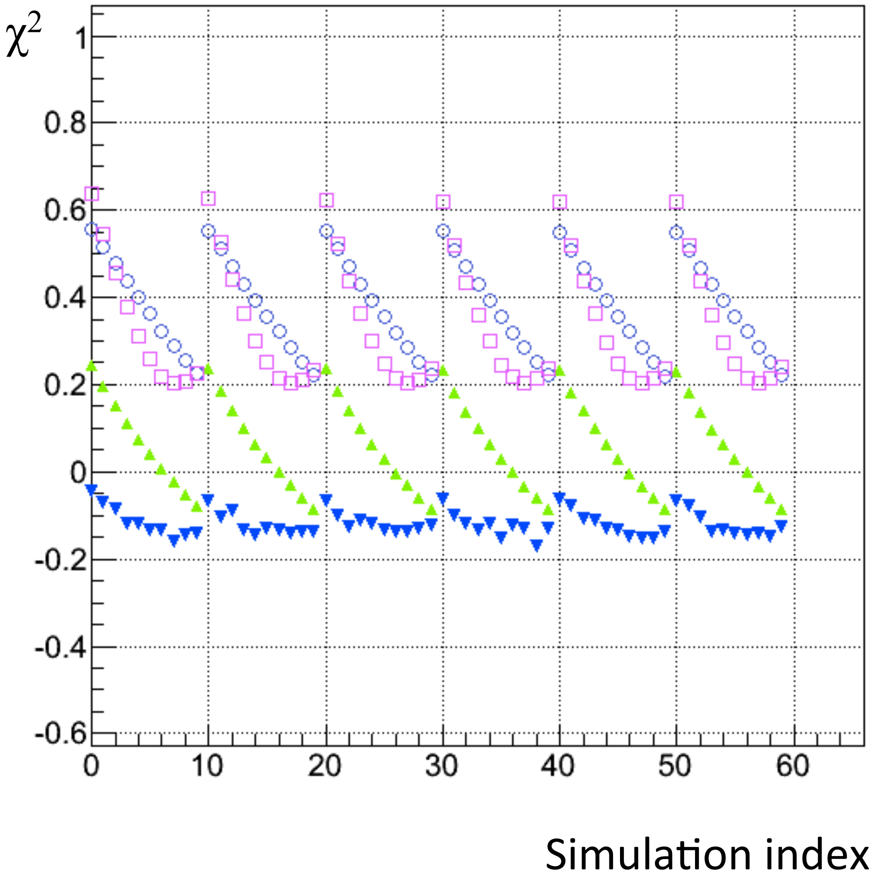
Density bin



Number of hits

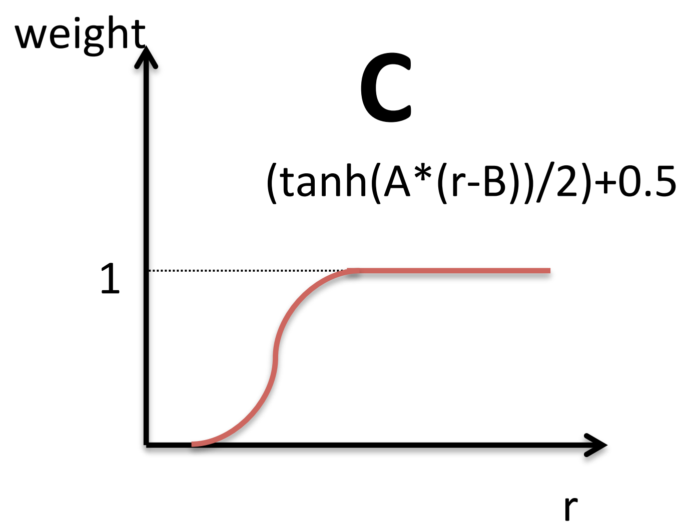
RPC_sim_5_C

2 Gaussian lateral charge distribution
Smooth transition with 2 parameters



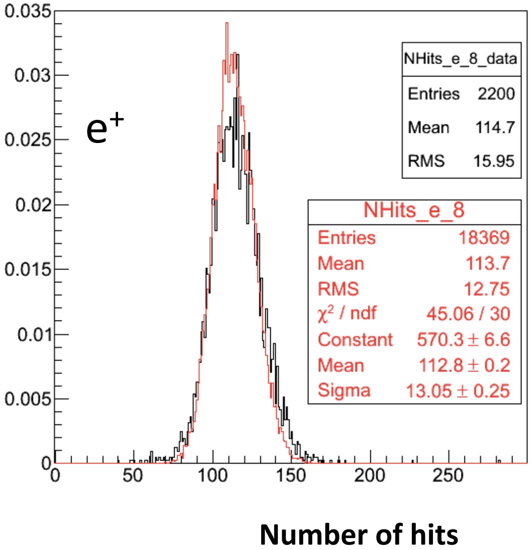
Mean
Sigma
Density
Longitudinal profile

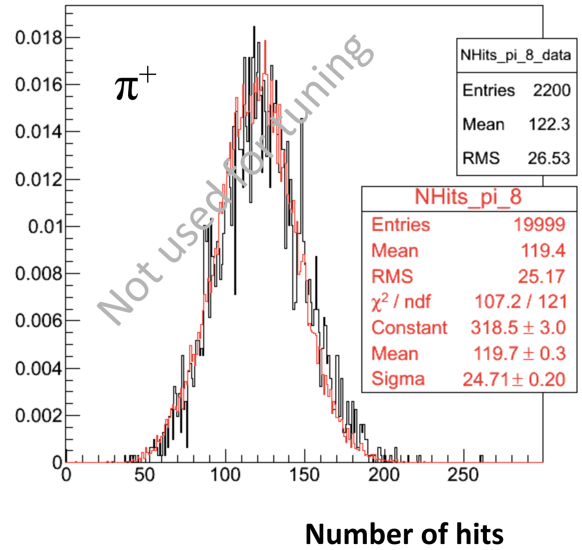
Best result with 40.0/0.40

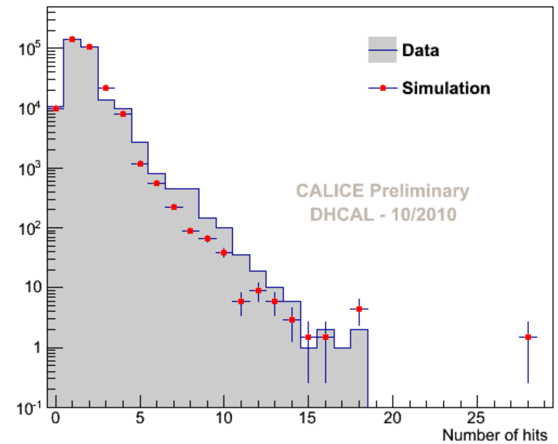


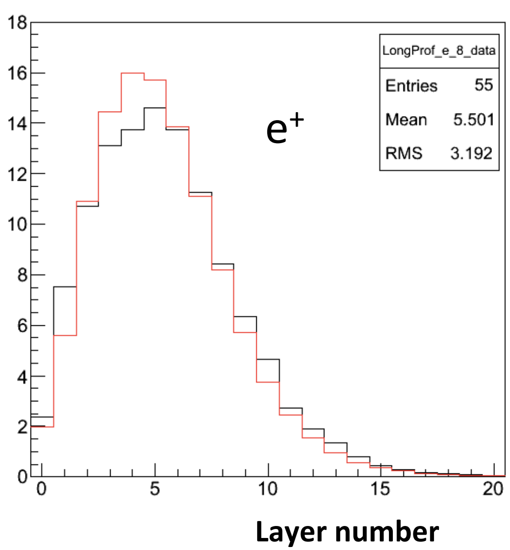
RPC_sim_5_C with A/B = 40.0/0.40

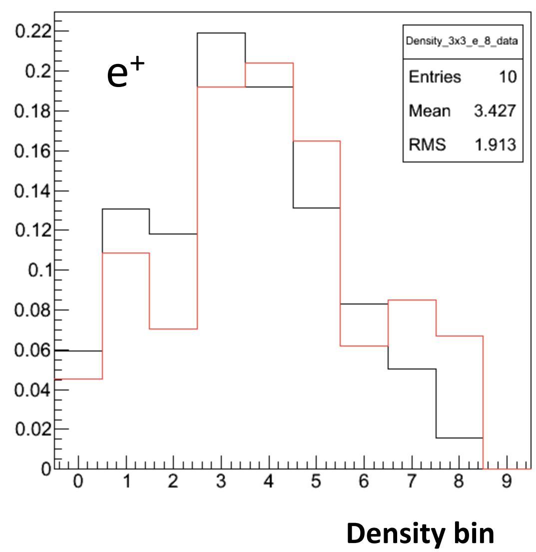
Data
RPC_sim

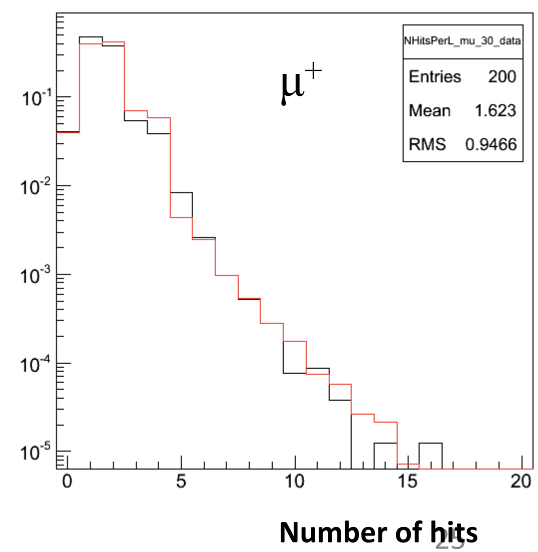












SUB-CONCLUSIONS

Major ingredients missing in MC → recently attributed to the poor simulation of the photon response in the gas

- Change the lower range cut limit from 990 eV to 10 eV → better photoionization simulation

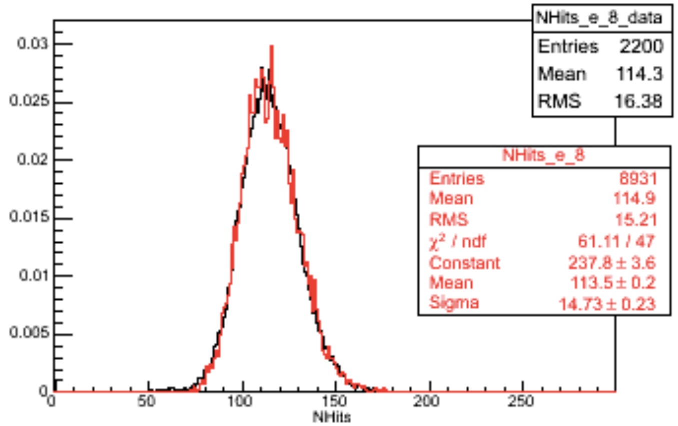
→ Re-optimize MC with all parameters floating (In progress)

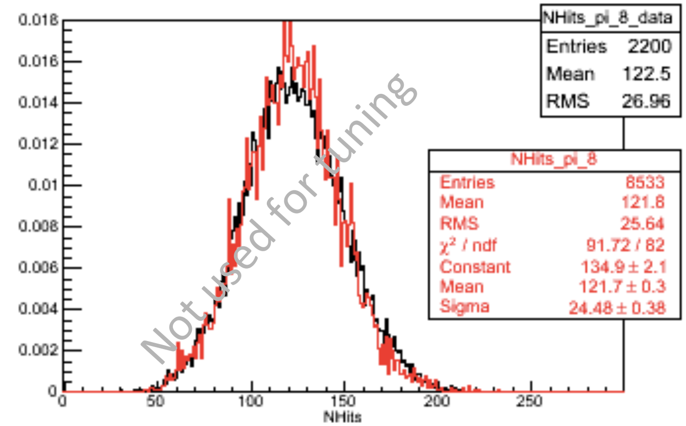
Fit range is modified (effects linearity and resolution plots) (Final)

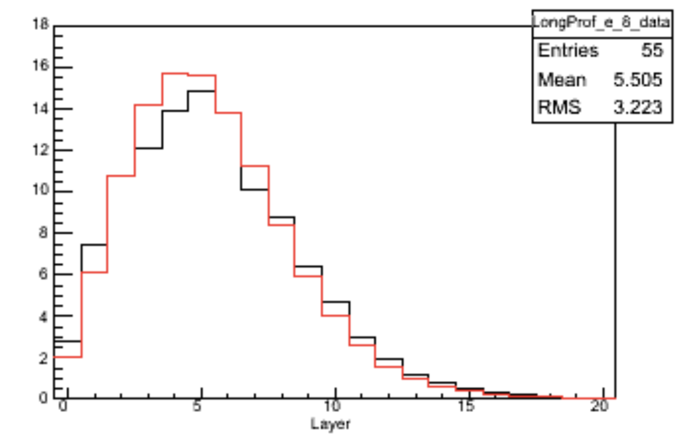
- Change the Gaussian fit limits to rms90 from later 90% of the statistics

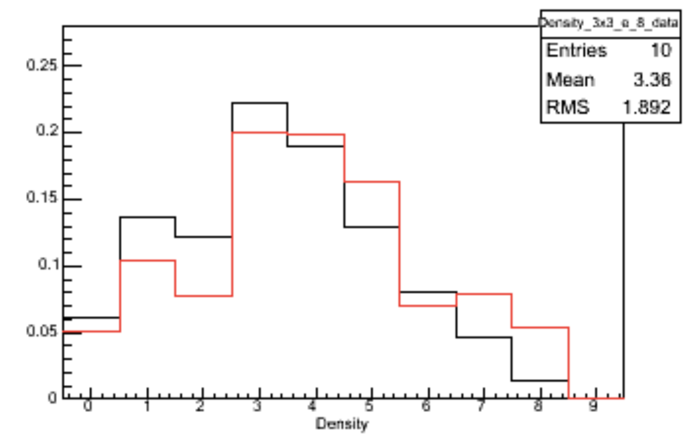
Non-linearity correction is implemented for the resolution plots (Final)

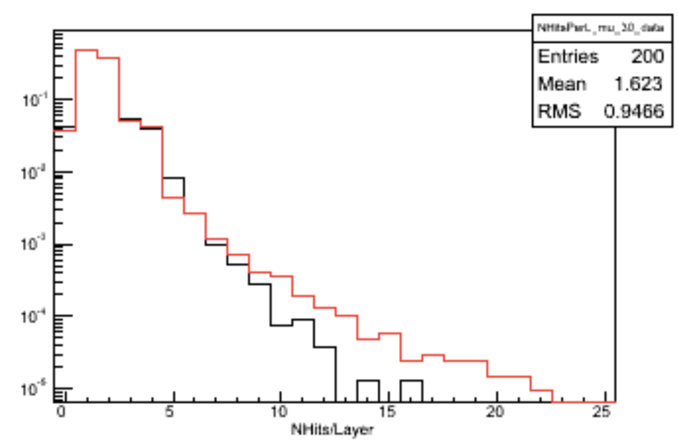
Calibration is performed far away from inefficiencies (RPC boundaries – 6 cm, dead cells – 1 cm, fishing lines – 1 cm) (Almost final)











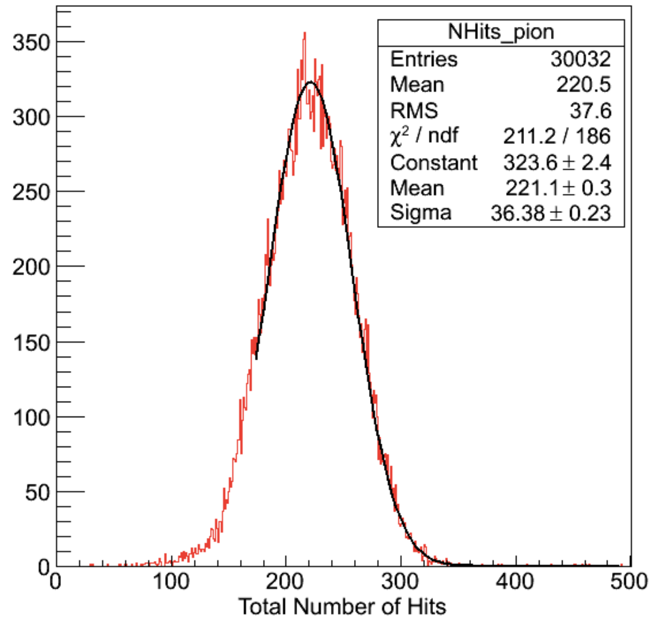
Current best optimization after MC changes

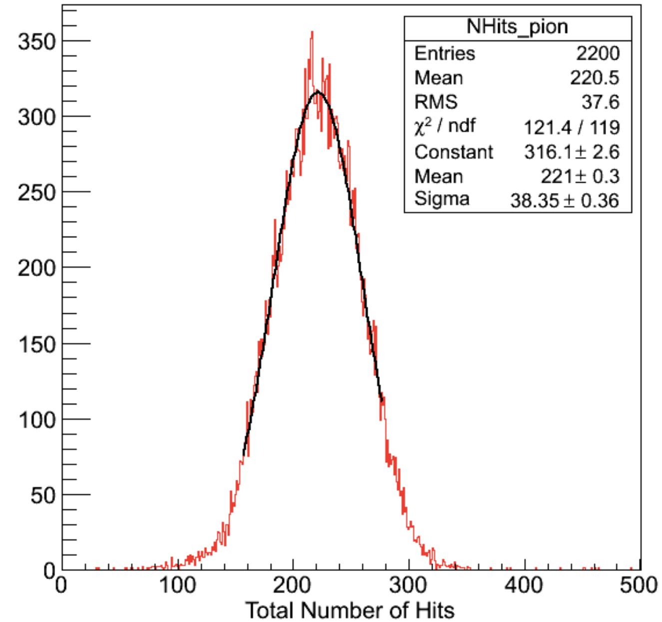
RPC_sim_5A

Still evolving…

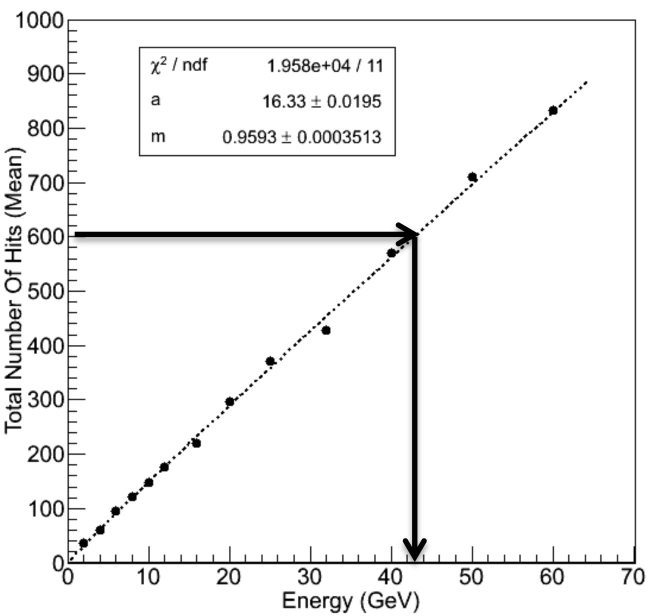
Changes to the fits + non-linearity correction

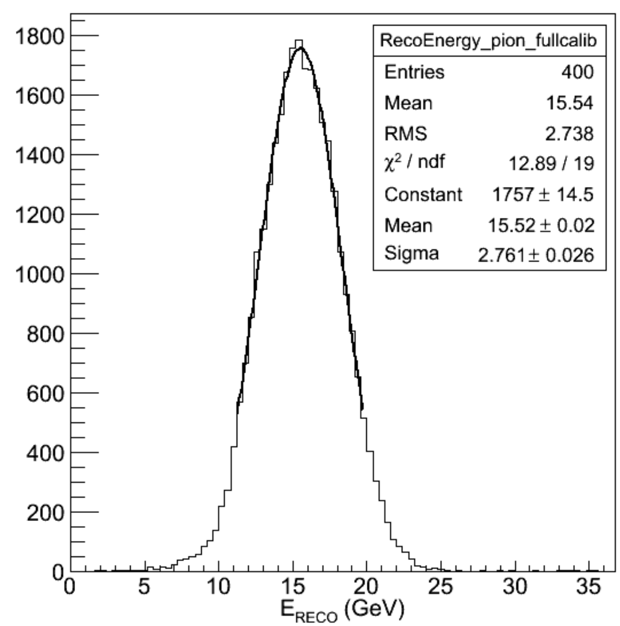
16 GeV pions



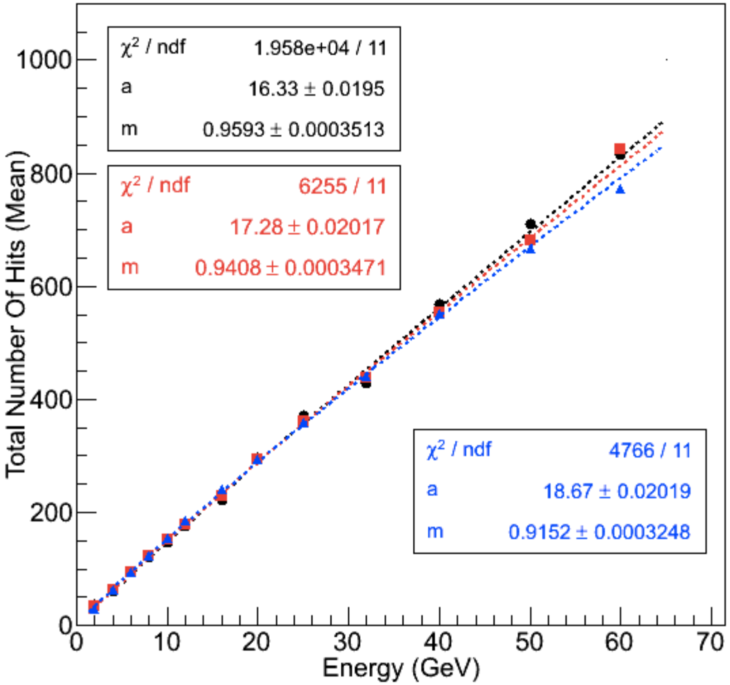


linearity





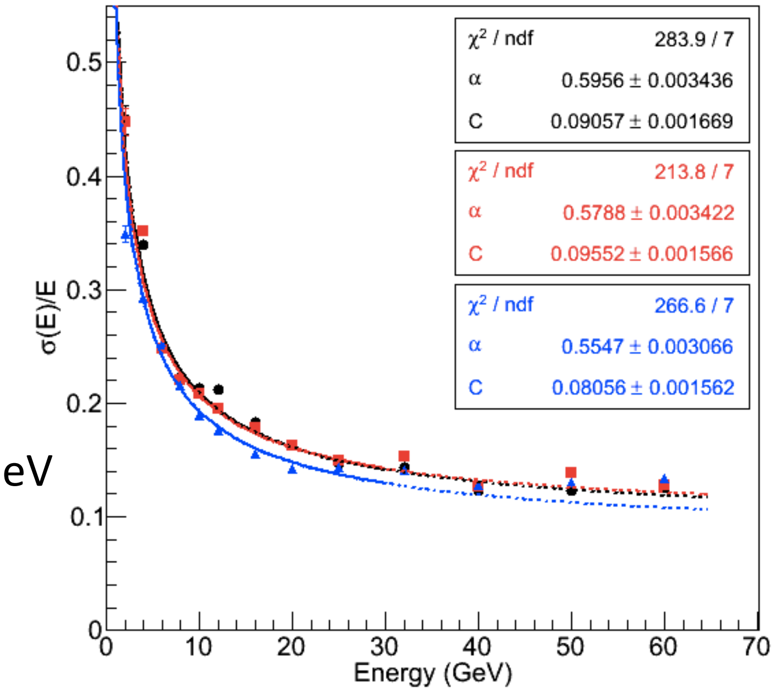
resolution

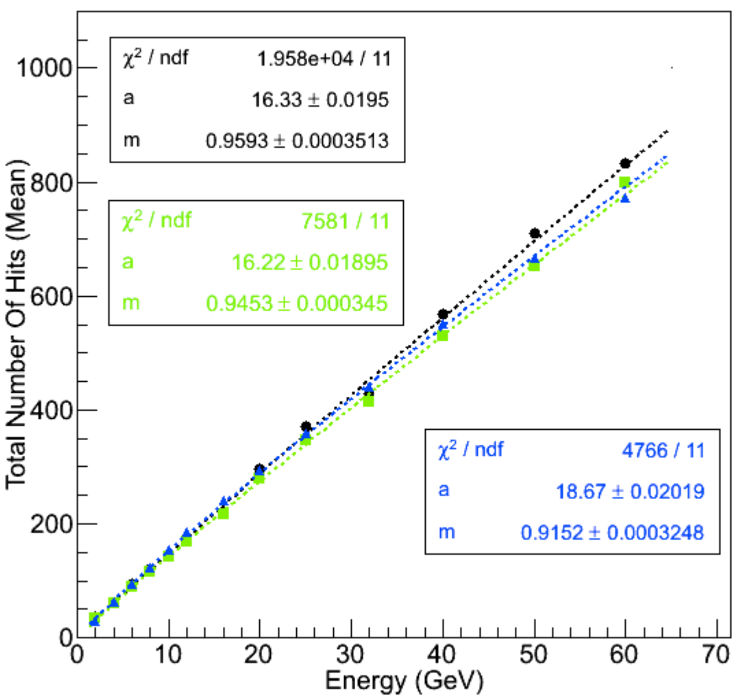


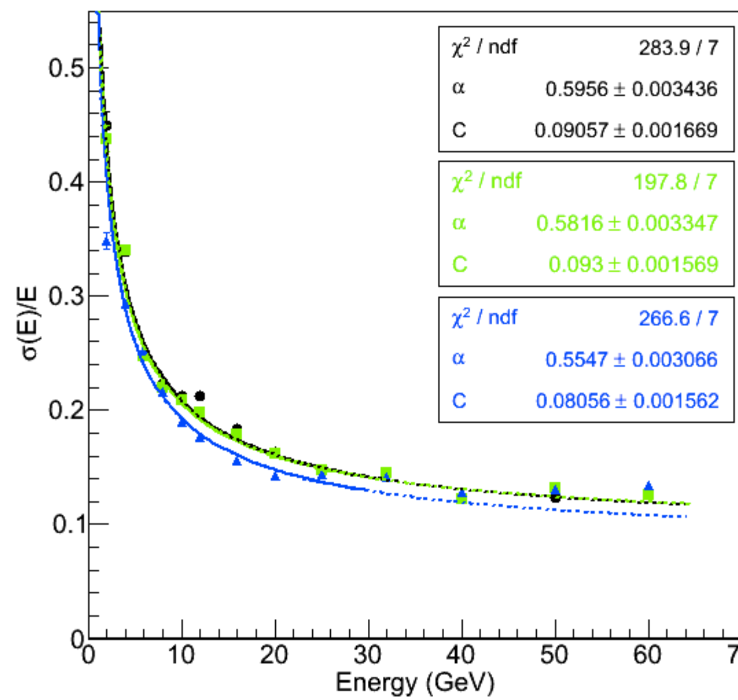
Uncalibrated
Full calibration
Density Weighted calibration
MC

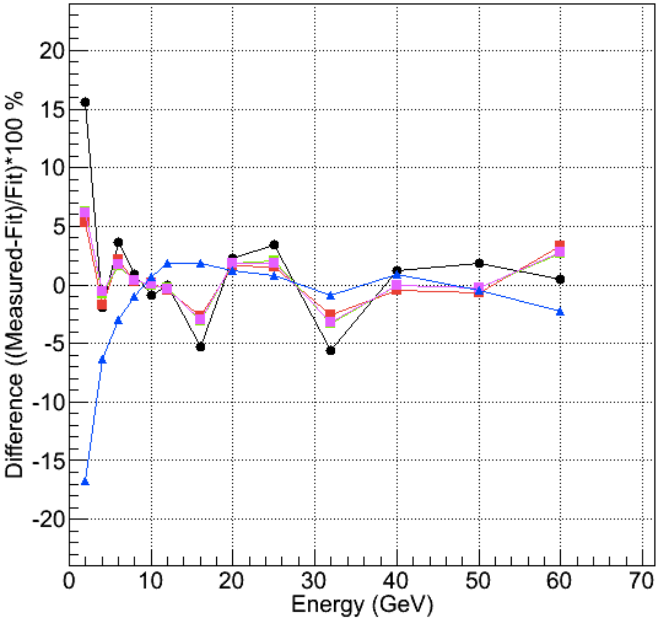
Pions

Res. Fit up to 25 GeV

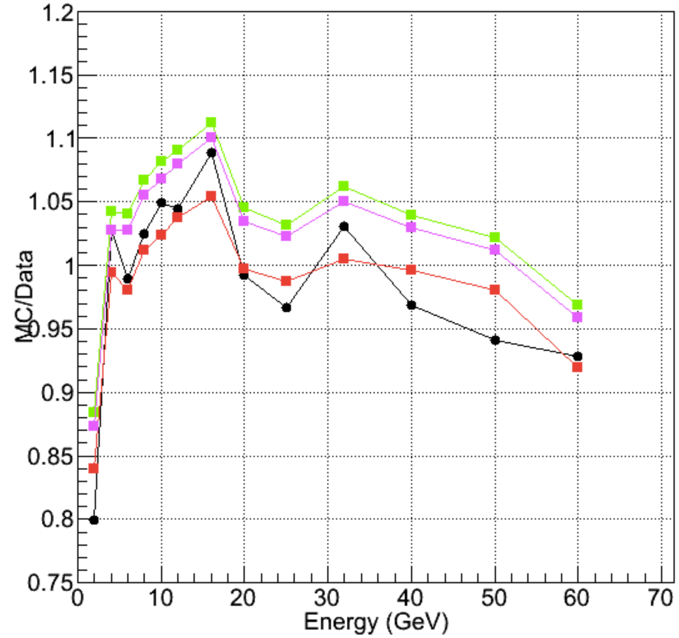


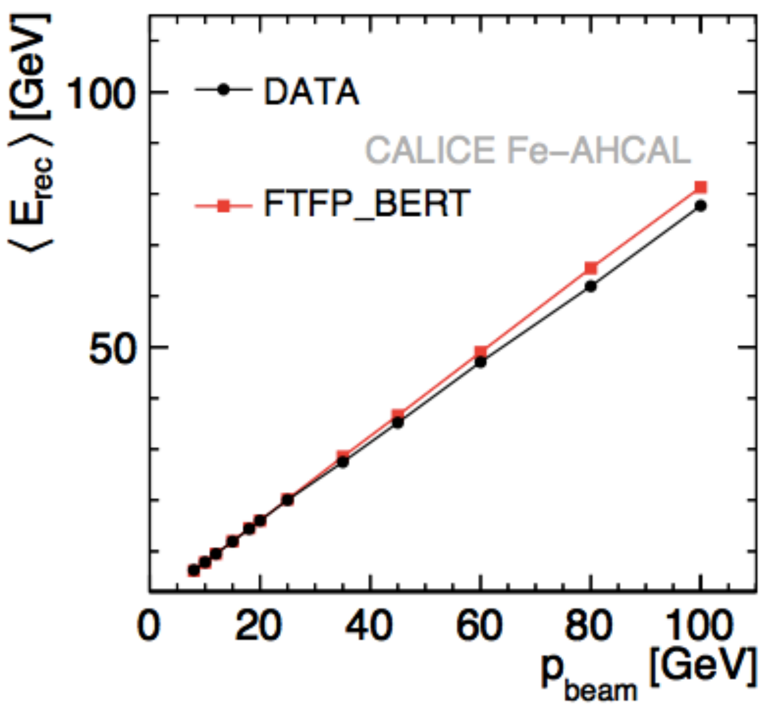


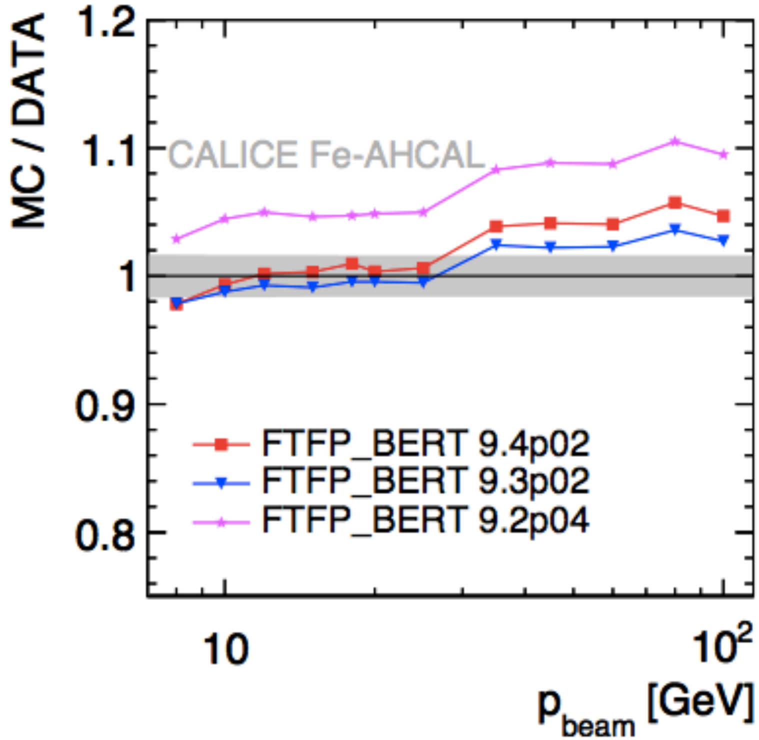




Uncalib
Full
Density
Hybrid
MC







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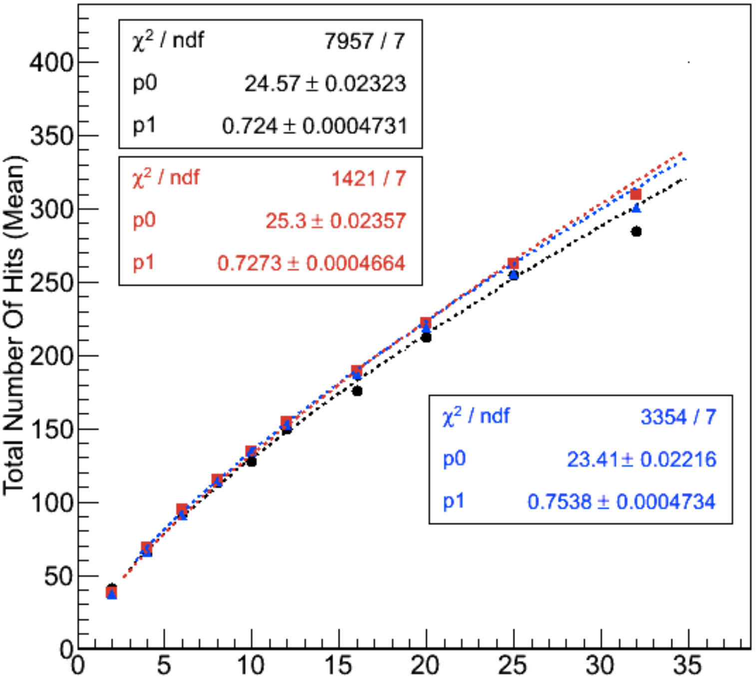


Uncalibrated

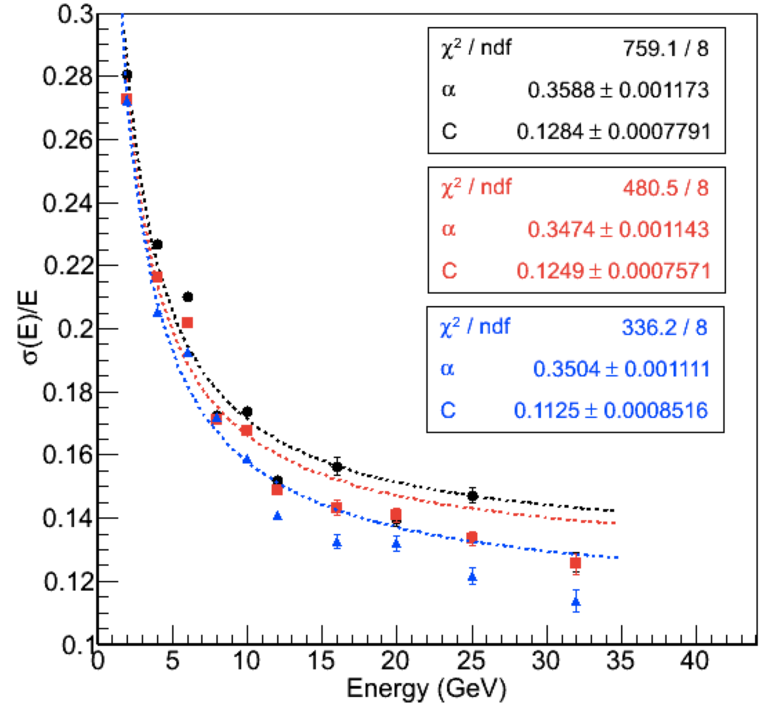
Full calibration

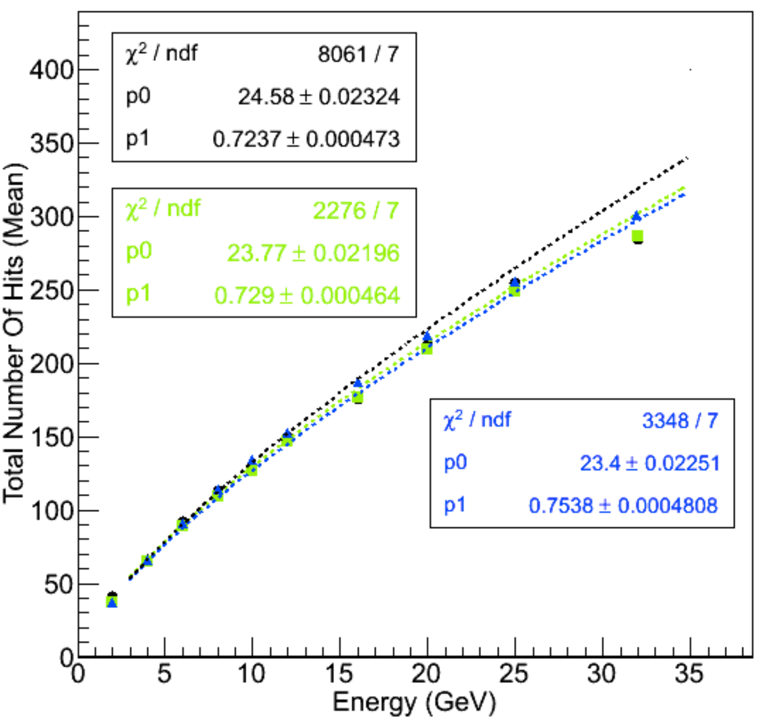
Density Weighted calibration

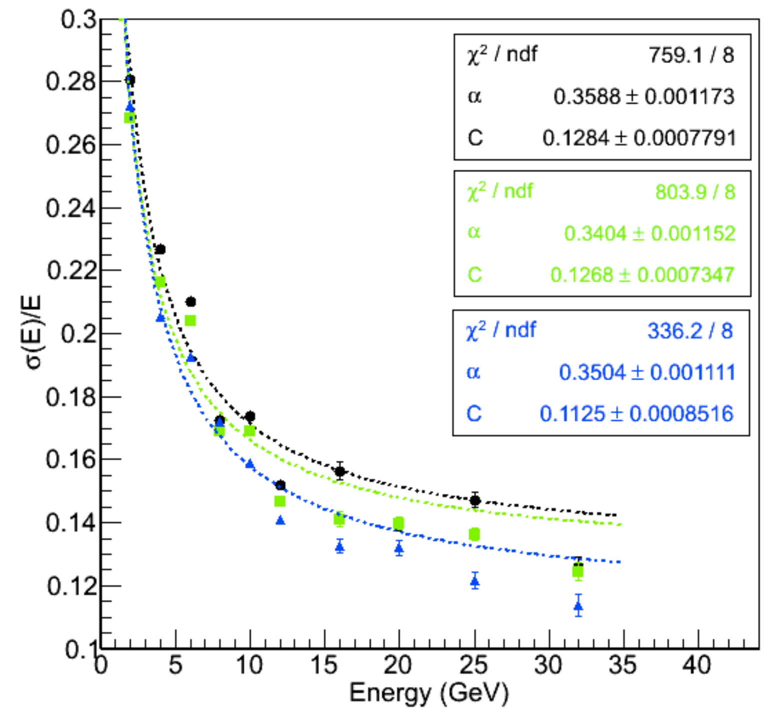
MC

Positrons

Lin. Fits: 4-32 GeV







Conclusions

The muon response is simulated successfully with all RPC_sim versions

The simulation of positrons:

- depends strongly on the RPC_sim version,
- depends strongly on the d_{cut} parameter/implementation,
- is not trivial.

None of the digitizers satisfactory yet

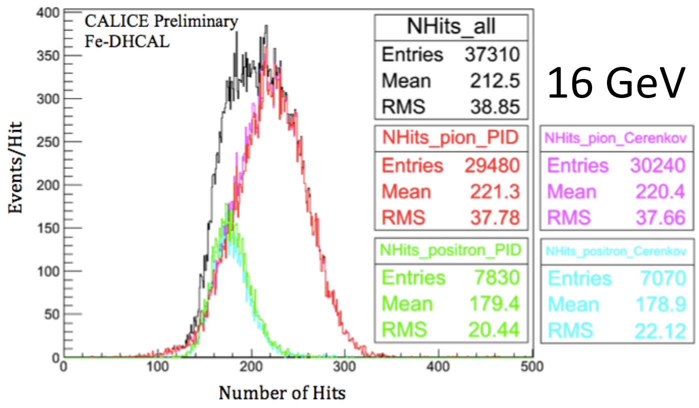
RPC_sim_5 with 2 Gaussians performs best

Backup

Particle Identification (PID)

0. Čerenkov counter based PID (good for 6, 8, 10, 12, 16, and 20 GeV)

1. Topological PID: Starts with the trajectory fit (used for 2, 4, 25 and 32 GeV)



Visually inspect the positron events in the ~10% excess in the topological PID

→ They are positrons

→ 10 % compatible with the inefficiency of the Čerenkov counter, which was ≥ 90% for most energies

→ Topological PID works nicely!

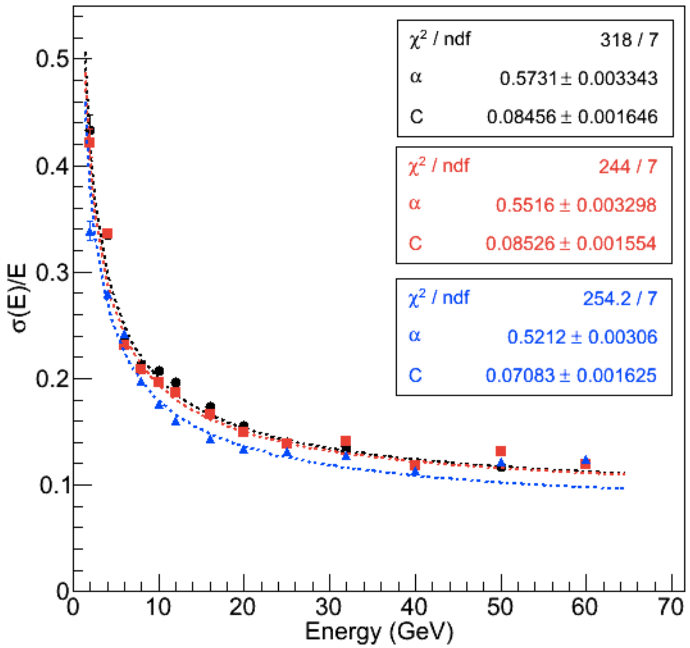
Topological Variables

- Interaction Layer *IL*: If there are hits with a *ΔR* between 1.5 and 20 cm with respect to the trajectory point in two consecutive layers *i* and *i*+1, the interaction layer is identified as *i*-1.
- Longitudinal Barycenter: Average z-position of the event: $LB = \frac{\sum N_i z_i}{\sum N_i}$ (sum is over all layers).
- Average cluster size: $AC = \frac{N_{Hits}}{N_{Clusters}}$
- Last layer with at least one hit: *LL*
- Lateral shower shape: $R_{rms} = \sqrt{\frac{\sum r_i^2}{N}}$ where r_i is the distance from the trajectory line and N is the total number of hits in the entire stack.
- R_{90}: 90% confinement radius measured with respect to the trajectory (i.e. 90% of the hits in the event are contained in a cylinder of radius R_{90} where the cylinder axis is coincident with the particle trajectory).
- Compactness Index: $\frac{\sqrt{\sum |\vec{r}_i - \vec{r}_{BC}|^2}}{N}$ where $\vec{r}_i$ is the position vector of the hit and $\vec{r}_{BC}$ is the position vector on the trajectory at the longitudinal barycenter. The sum is over all hits.
- $\frac{N_{10}}{N_{20}}$: (Number of hits within 10 cm) / (Number of hits within 20 cm) of the particle trajectory.

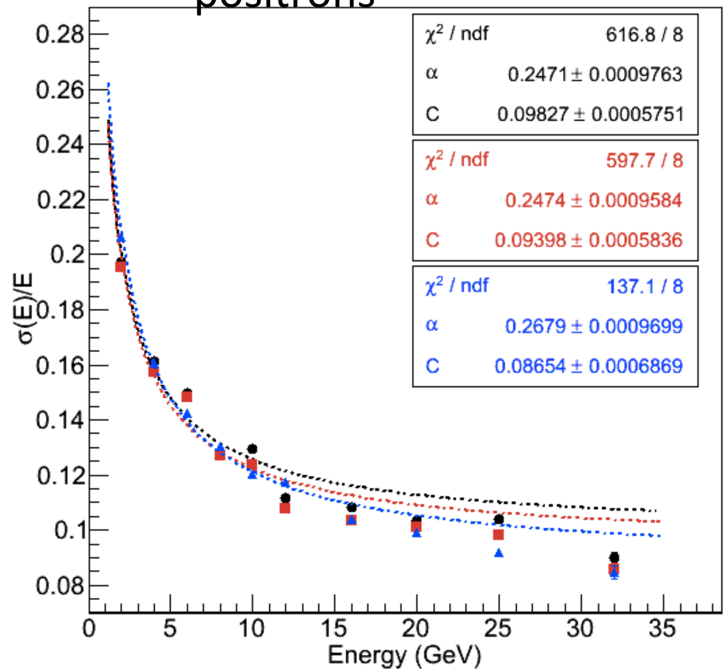
The effect of non-linearity correction

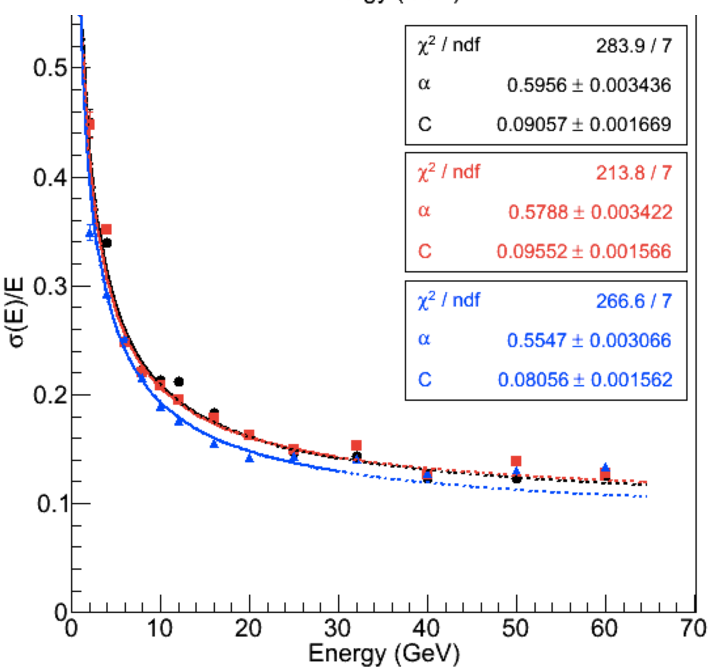
pions

positrons



Not corrected





Corrected