Measurement of the *Moli'ere radius* from the 2014 TB data

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motivation

- A major design aim of LumiCal is it's compact structure.
- One aspect is to limit the development of the electromagnetic showers in the transverse direction.
- It allows better separation and identification of the electromagnetic elements.

Moli'ere radius definition

The transverse development of electromagnetic showers in different materials scales fairly accurately with the *Moli'ere radius* $R_{\mathcal{M}}$, given by

$$R_{\mathcal{M}} = X_0 \frac{E_s}{E_c} \tag{1}$$

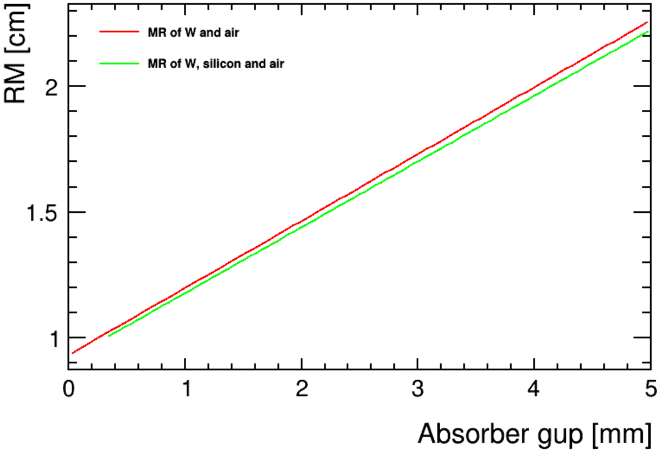
where $E_s \approx 21$ MeV, and E_c is the critical energy. In a compound the *Moli'ere radius* is given by

$$\frac{1}{R_{\mathcal{M}}} = \frac{1}{E_s} \sum \frac{w_j E_{cj}}{X_{0j}} = \sum \frac{w_j}{R_{\mathcal{M}}} \tag{2}$$

On the average,only 10% of the energy lies outside the cylinder with radius of 1 *Moli'ere radius*. The distributions are characterized by a narrow core, and broadens as the shower develops, often represented as the sum of two Gaussians.

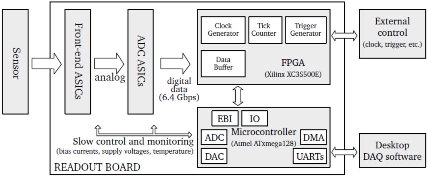
air gap

We can see the importance of the gap between absorbers in the calorimeter design on the the *Moli'ere radius* from the calculation :



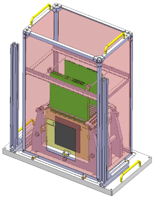
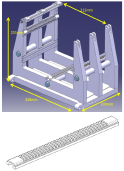
2014 TB - LumiCal basic plane

- The basic plain (layer) is a complete detector module equipped with first level DAQ.
- Its includes the complete readout chain: Si-sensor, kapton fan-out, front-end electronic and multichannel 10-bit pipeline ADC ASIC
- ASIC is controlled by FPGA based data concentrator.
- The complete module has 4 multi channels chips with 8 channels each.



TB campaign

- The performance of fully instrumented LumiCal and BeamCal detector planes was studied in previous beam test campaigns.
- A full detector prototype is needed by the end of the AIDA-2020 project.
- 3 beam tests ware done up to now, at October 2014 and in 2015, 2016.
- To allow the multiple-plane operation, a sophisticated mechanical structure was developed at CERN to meet the demanding geometrical requirements.

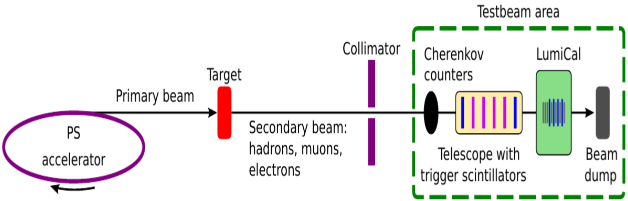
2014 TB

The first test performed in October 2014 at the T9 east area of the proton synchrotron (PS) at CERN. Test beam aims:

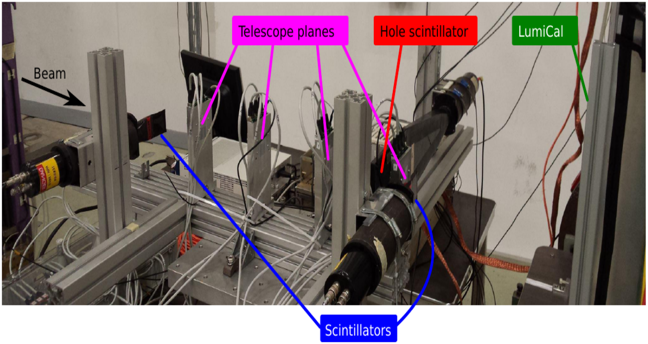
- to demonstrate for the first time that the base-design for calorimeters is reasonable and well understood.
- to test a multi-plane operation of the prototype.
- Study the development of the electromagnetic shower and compare with MC simulations.
- Try to apply a reconstruction algorithm on raw data and particle tagging (electron and hadrons).
- Attempt to measure energy resolution and the precision of the polar angle reconstruction.

2014 TB

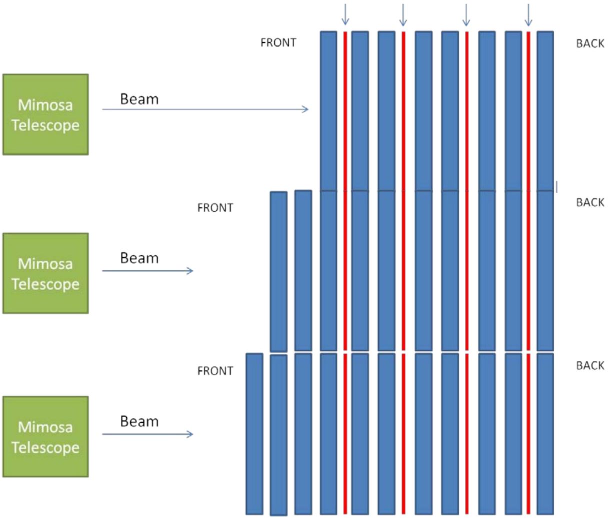
- The PS accelerator provides a primary 24 GeV/c proton beam.
- Beam for the T9 area is provided in 400 ms long spills
- The primary beam is converted using targets
- T9 provided with a $1 - 15\ GeV/c$, controlled, beam with muons, pions, hadrons and electrons.



2014 TB - setup



2014 configuration



Moli'ere radius of 2014 configuration

Summary of all the material in our setup

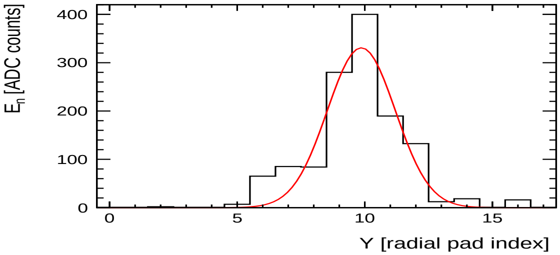
material	W	Cu	Ni	PL-95%	MGS-93%	air	Si	PCB
density	19.3	8.96	8.9	18.0*	17.8*	0.0012	2.33	1.7
$R_{\mathcal{M}}[gr/cm^2]$	18.0	14.0	13.4	17.7**	17.6**	8.8	11.5	10.3
$R_{\mathcal{M}}[cm]$	0.93	1.57	1.51	0.98	0.99	7330	4.94	6.06

Summary of calculated *Moli'ere radius*

	PL-95%	MGS-93%	air	Si	PCB	total	$R_{\mathcal{M}}[cm]$
general 93	0	0.7	0.37	0.032	0.25	1.35	1.79
general 95	0.7	0	0.37	0.032	0.25	1.35	1.78
CONF 1	1.05	1.75	1.57	0.128	1.0	5.5	1.81
CONF 2	1.75	1.75	1.77	0.128	1.0	6.4	1.71
CONF 3	2.1	1.75	1.87	0.128	1.0	6.85	1.67

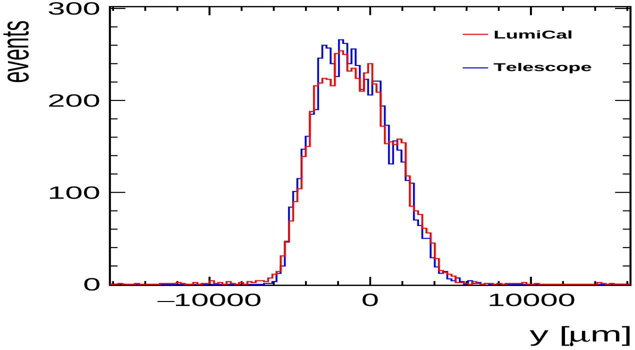
1 event

- For each event from the data or simulation, we can look on the sum of the energy deposit, along the radial direction.
- The hit position can be estimate by fitting.
- By folding all events to start in a central pad the beam profile is canceled out.
- The mean radial energy deposit distribution can be extracted from the single pad energy distribution.



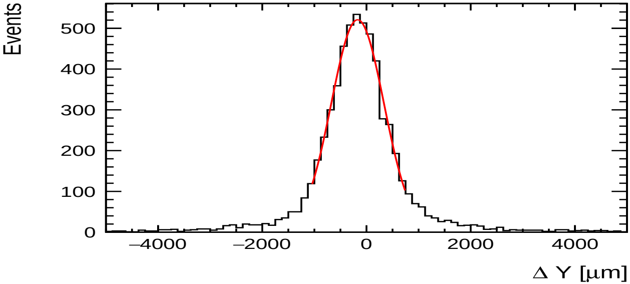
Hit position

We can compare between the LumiCal reconstructed hit position and the extrapolated hit position from the beam Telescope to the LumiCal first layer to get the beam profile.



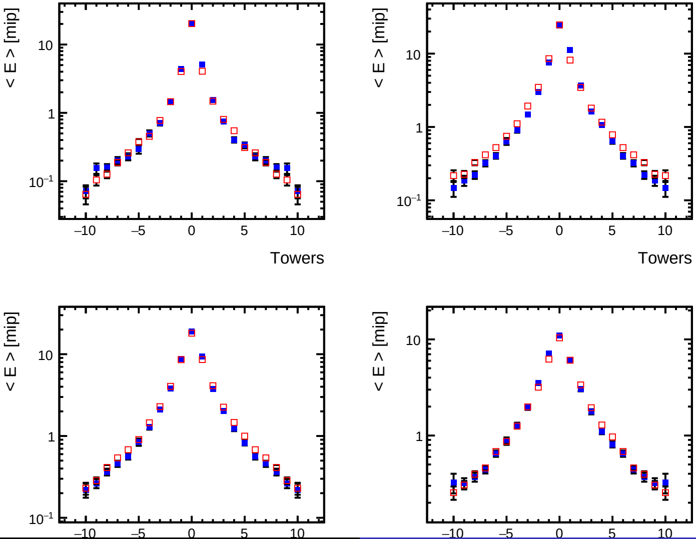
Hit position resolution

We also can get the extrapolated hit position resolution, in the order of 505 μm.



Mean radial energy per layer

The mean radial energy deposit in configuration 2:



Pad uncertainty

We define the energy in each pad as :

$$E_{pad} = C_L A_{pad} \tag{3}$$

when A_{pad} is the amplitude in ADC counts / LSB of a pad in a layer L
and the C_L is the calibration factor of this layer.
we set the uncertainty on the layer calibration to be :

$$\frac{\Delta C_L}{C_L} = 0.05 \tag{4}$$

Uncertainty for longitudinal shower

So for the longitudinal shower, we sum all pads in layer :

$$E_{layer} = \sum C_{layer} A_{pad} \tag{5}$$

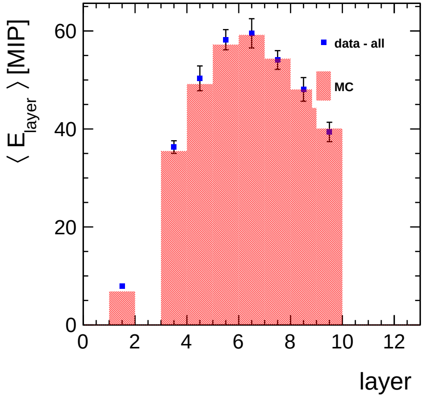
and then the uncertainty will be :

$$\Delta E_{layer} = 0.05 * \sum C_{layer} A_{pad} \tag{6}$$

except from layers 3,5,7 that was sampled in both configuration 1 and 2.

Longitudinal shower

then we can see :



Tower correlation

We try to measure the correlation between towers for the MR measurement.
we can define the correlation ρ :

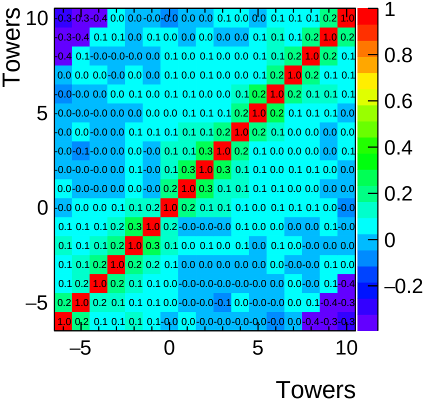
$$\rho_{i,j} = \frac{< E_i E_j > - < E_i >< E_j >}{\sigma_i \sigma_j} \quad (7)$$

where σ is :

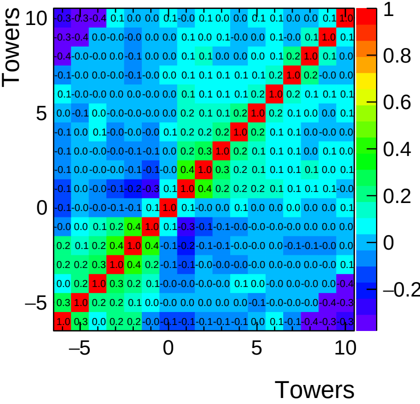
$$\sigma_i = \sqrt{< E_i E_i > - < E_i >< E_i >} \quad (8)$$

Correlation configuration 2.

MC:



Data:



Tower uncertainty

the average energy of a tower E_i is :

$$< E_i >= \frac{1}{N}\sum_{events}\sum_{Layer}\sum_{pad} C_L A_{L,i,p} = \sum_{Lyer} C_L \frac{1}{N}\sum_{events}\sum_{pad} A_{L,i,p} \tag{9}$$

if we define

$$\frac{1}{N}\sum_{events}\sum_{pad} A_{L,i,p} = D_L \tag{10}$$

then the

$$< E_i >= \sum_{Layer} C_L D_L \tag{11}$$

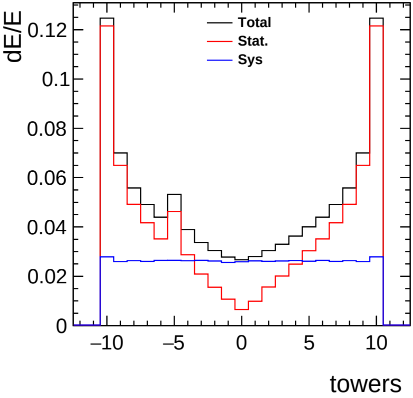
$$\Delta < E_i >= \sqrt{\sum_{L}\left((\frac{\Delta C_L}{C_L} C_L D_L)^2 + (C_L \Delta D_L)^2 \right)} \tag{12}$$

where ΔD_L is the statistical uncertainty and:

$$\frac{\Delta C_L}{C_L} = 0.05 \tag{13}$$

Tower uncertainty

then we can see :



How do we calculate?

Assuming we have an average energy density function $F_E^v(z, r, \varphi)$, We can caculate the total average energy by :

$$E_{total} = \int F_E^v(z, r, \varphi) dv = \int F_E^v(z, r, \varphi) dz d\varphi r dr \qquad (14)$$

In our case the average energy density function is assumed to have a radial symmetry. In the calculation we are using towers of pads that is equivalent to the integration along z.

$$\int F_E^v(z, r, \varphi) dz = F_E(r) \qquad (15)$$

On average, only 10% of the deposited energy lies outside an infinite long cylinder with a radius of one $R_{\mathcal{M}}$:

$$0.9 = \frac{E_{r<R_{\mathcal{M}}}}{E_{total}} = \frac{\int_0^{2\pi} r d\varphi \int_0^{R_{\mathcal{M}}} F_E(r) dr}{\int_0^{2\pi} r d\varphi \int_0^{\infty} F_E(r) dr} \qquad (16)$$

How do we calculate?

In our case LumiCal pads are long (strip like) and act like 1D integration and we do not have direct access to $F_E(r)$. Since the pads are almost straight we can define :

$$G_E(y) = \int_{X_{min}}^{X_{max}} F_E(\sqrt{x^2 + y^2})dx \tag{17}$$

the form of $G_E(y)$ is determine by integrating $F_E(\sqrt{x^2 + y^2})$ over x. So by fitting $G_E(y)$ we gain access to the parameters of $F_E(r)$.

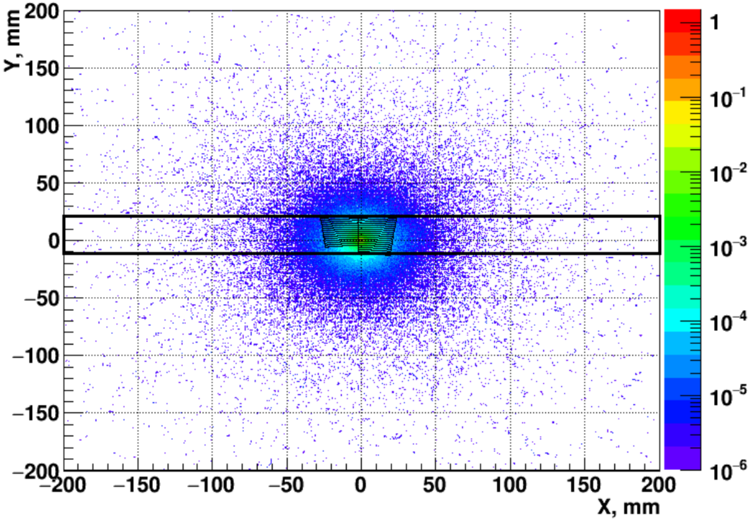
Functions

The function we used is inspired from the Grindhammer-Peters parametrisation for the tail part and a Gaussian for the core part.

$$F(r) = (A_C)e^{-(\frac{r}{R_C})^2} + (A_T)\frac{2r^\alpha R_T^2}{(r^2 + R_T^2)^2} \quad (18)$$

$$G_E(y) = \int_{X_{min}}^{X_{max}} (A_C)e^{-(\frac{\sqrt{x^2+y^2}}{R_C})^2} + (A_T)\frac{2(\sqrt{x^2+y^2})^\alpha R_T^2}{((\sqrt{x^2+y^2})^2 + R_T^2)^2} dx \quad (19)$$

Ideal simulation

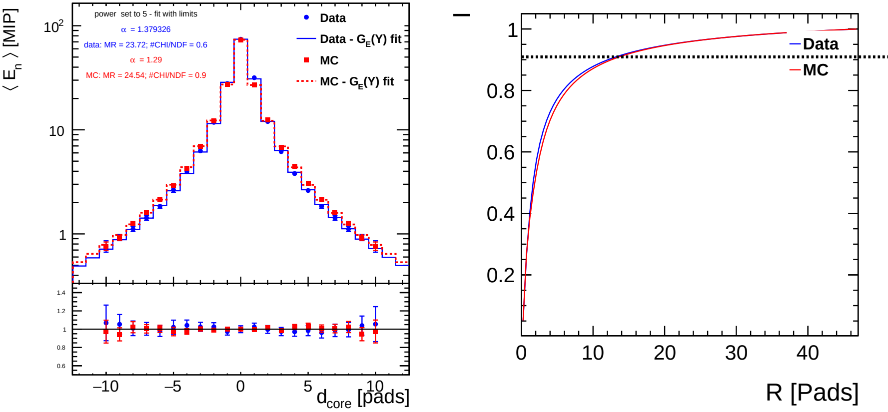


Ideal simulation

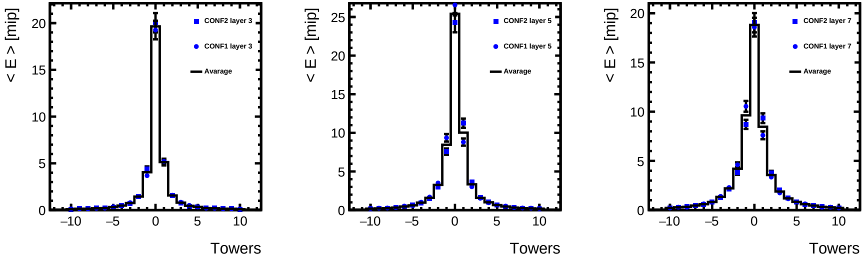
The Ideal calorimeter simulation give us :

- 99% of the energy deposited in a radius of $84 \pm 0.5\ mm$.
- inside our sensor we are measuring 90% of the total energy.
- inside our sensor we are measuring 97.8% of the energy deposited in the sensor band.
- It can by used as a sanity check to our measurement.
- Integration in the X direction is along the sensor size (2.5 cm).

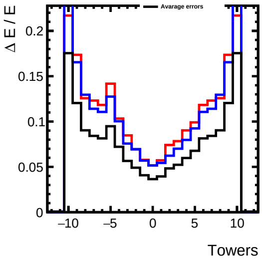
configuration 2 - results

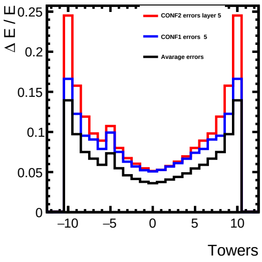


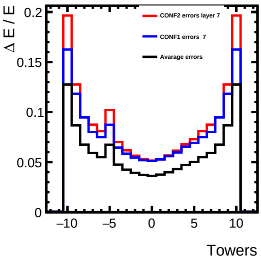
configuration 1 & and 2



configuration 1 & and 2

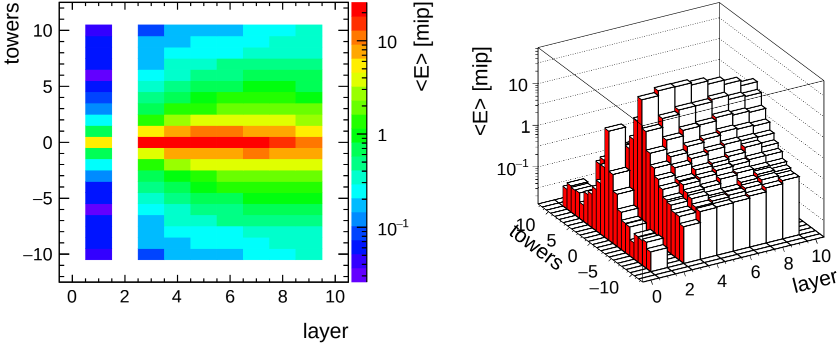






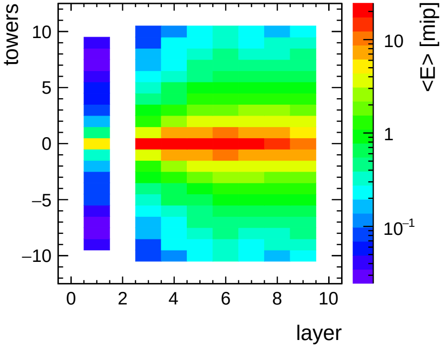
All layers- data

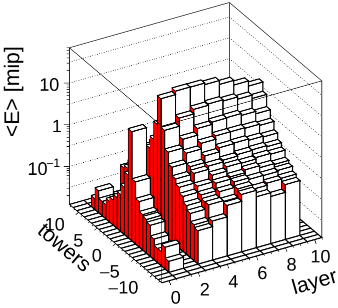
Since we have all layers we can have look on all :



All layers - MC

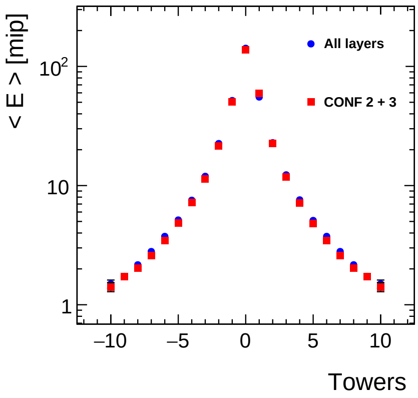
Since we have all layers we can have look on all :

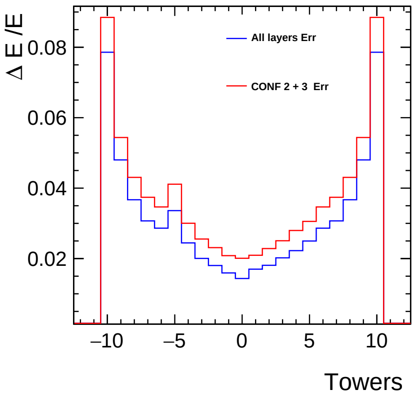




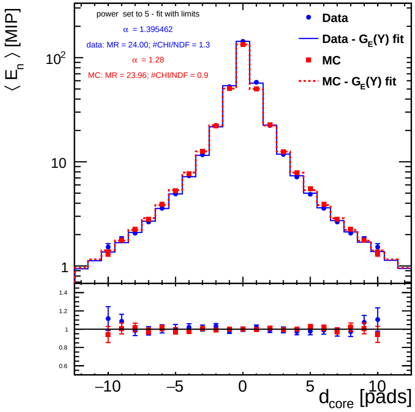
All layers together

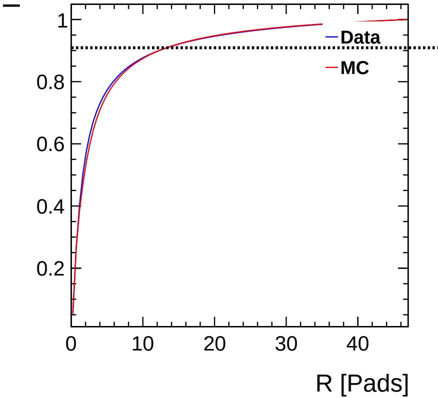
Since we have all layers we can add them together to get single profile :





All layers together- results





Summary

- We have now much better understating of the *Moli'ere radius* measurement.
- *Moli'ere radius* from the 2014 TB data is $24.00 \pm 0.65(stat.)mm$.
- The systematic uncertainty still need to be finalized.
  1. variation of fit parameters included in stat. error.
  2. sensitivity to geometry - from MC $\pm 1\%$ to be neglected.
  3. the size of sensors in x over which the integration is performed ± 0.5 *mm* .
  4. range of normalization $\pm 0.5\%$.