Calibration of the ATLAS hadronic barrel calorimeter TileCal using 2008, 2009 and 2010 cosmic rays data

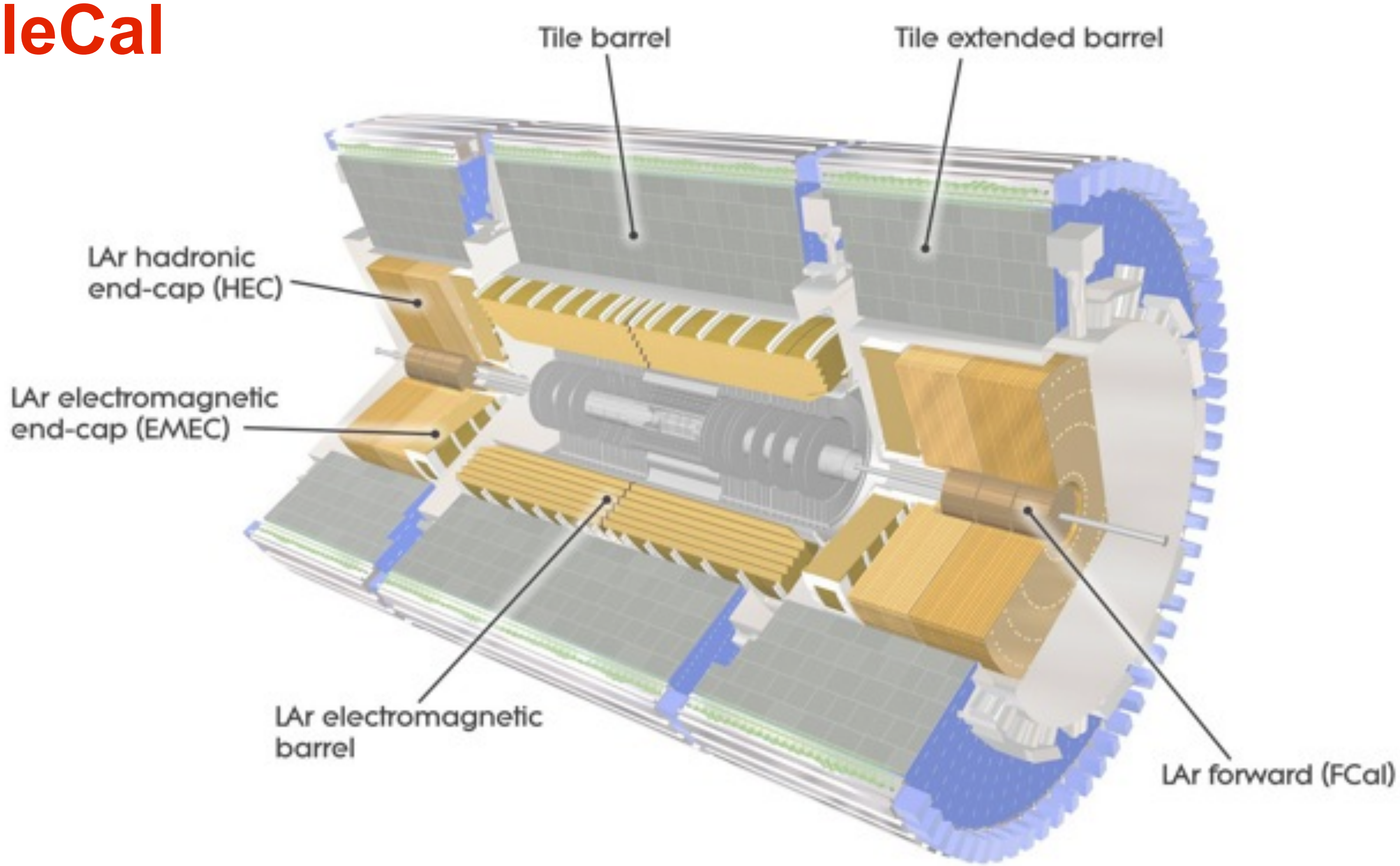
Zhili.Weng (zweng@cern.ch)
Institute of Physics, Academia Sinica, Taiwan

on behalf of the ATLAS Tile Calorimeter Group

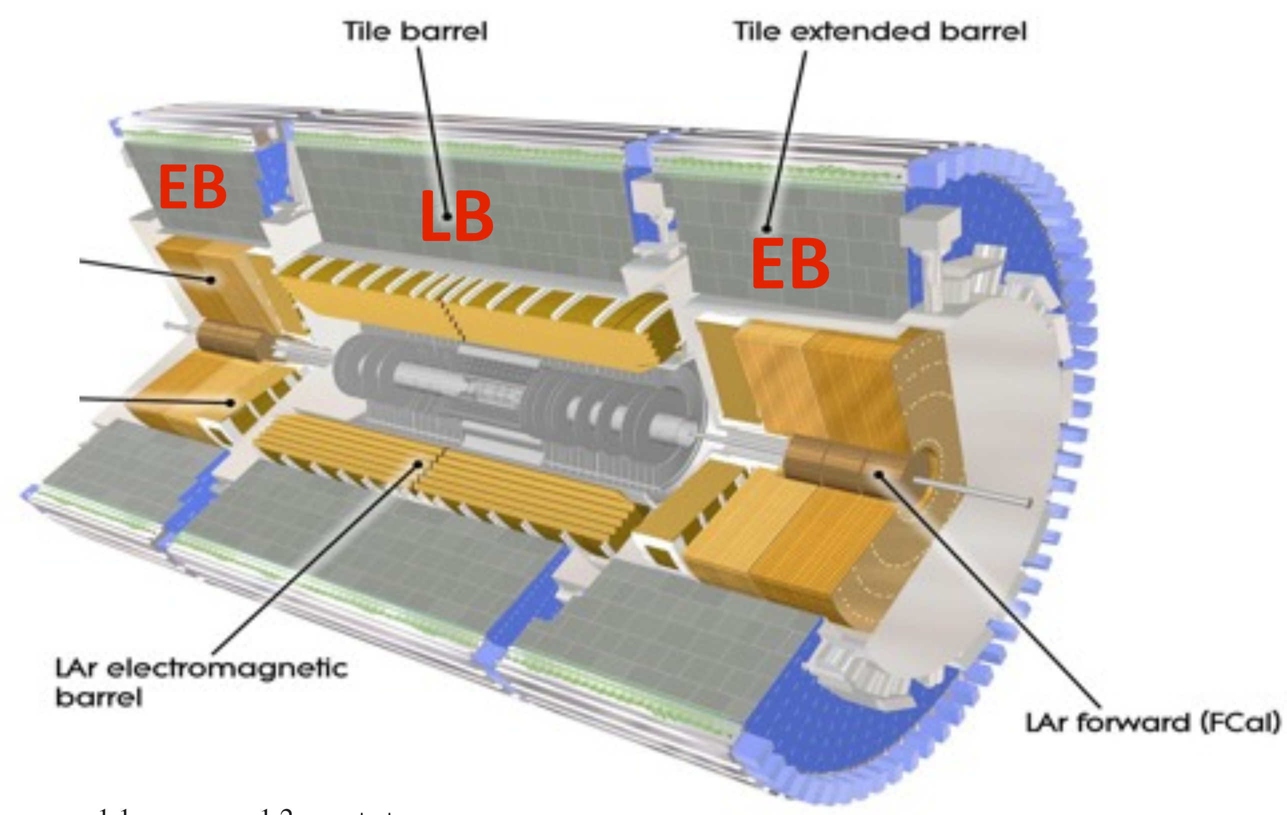
For TIPP 2011, 9-14 June 2011, Chicago

Outline

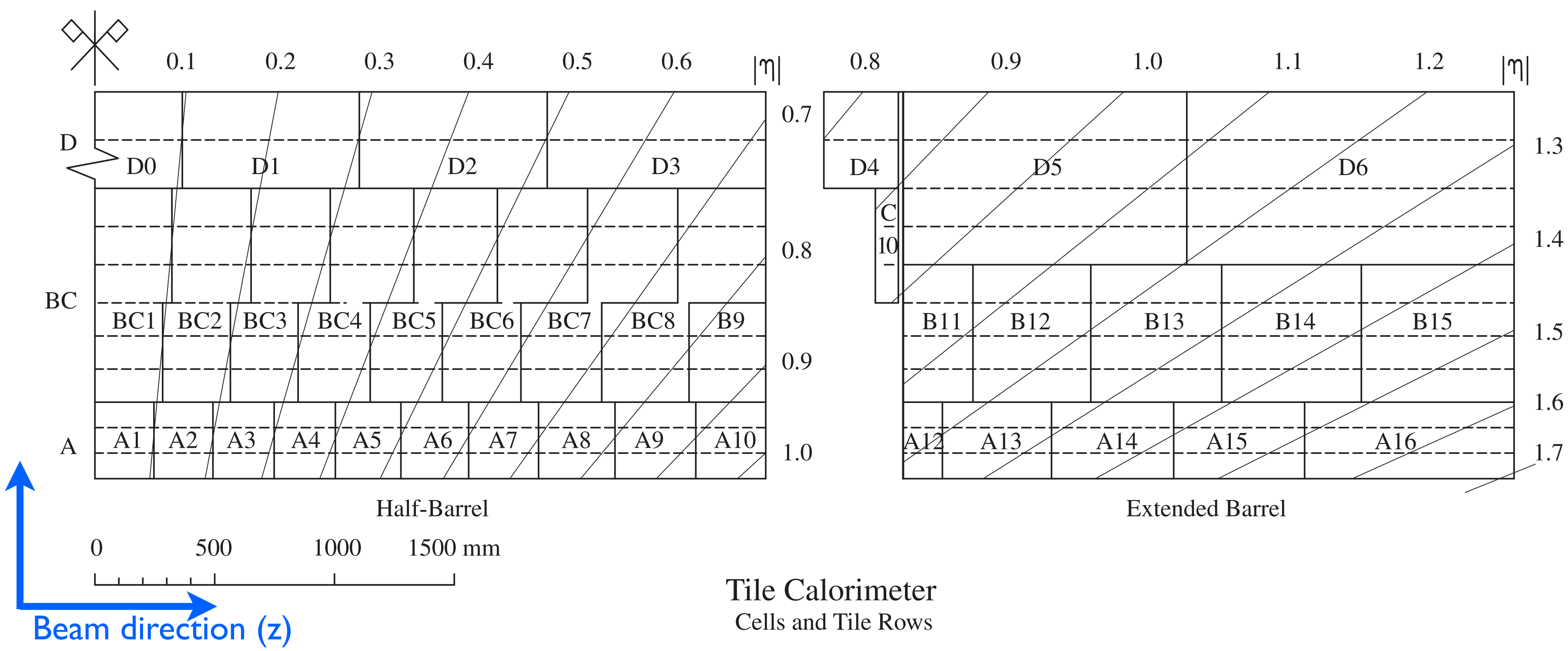
- Tile Calorimeter in ATLAS
- Cosmic event in ATLAS
- Check for energy response uniformity
- Check for Inter-Calibration status
- Check for response stability
- Absolute EM scale in TileCal

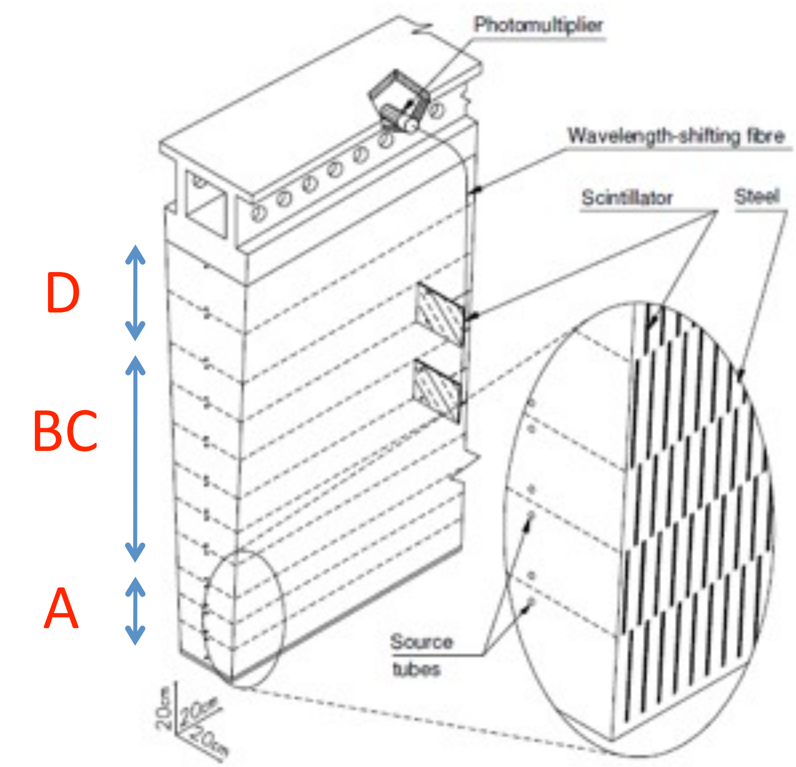


Tile Calorimeter in ATLAS



- Sampling Calorimeter composed of steel and scintillating tiles
- Divided into three cylinders one Barrel (LB) and two Extended Barrels (EB)





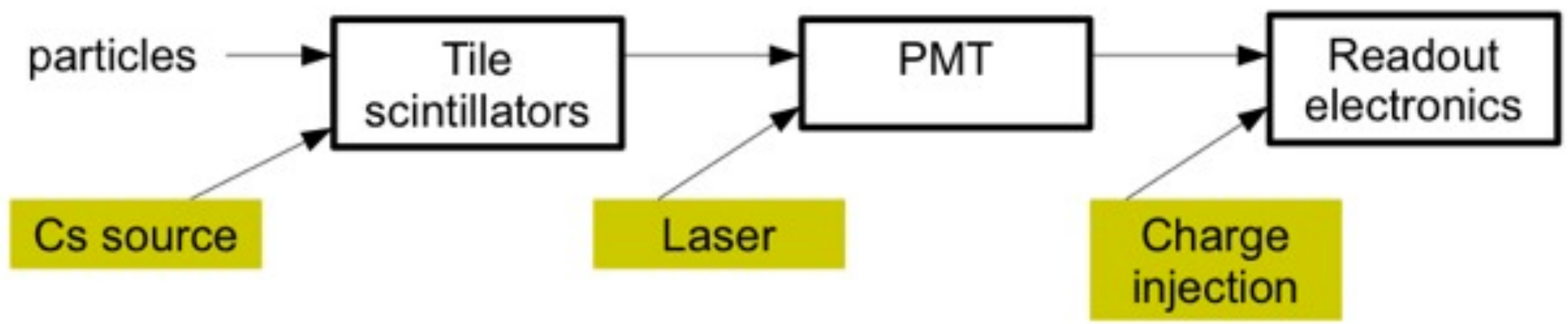
- Each cylinder is composed of 64 azimuthal **modules**
- Each module is segmented in radial depth **(three layers)** and in z **(cells)**
- For each cell, scintillating tiles are read out by two separate PMT's.

Tile Calorimeter in ATLAS: Energy scale Calibration

$$E_{PMT} = A \times C_{ADC\to pC} \times \overbrace{\boxed{C_{pC\to GeV}}}^{\text{EM scale}} \times C_{Cs}$$

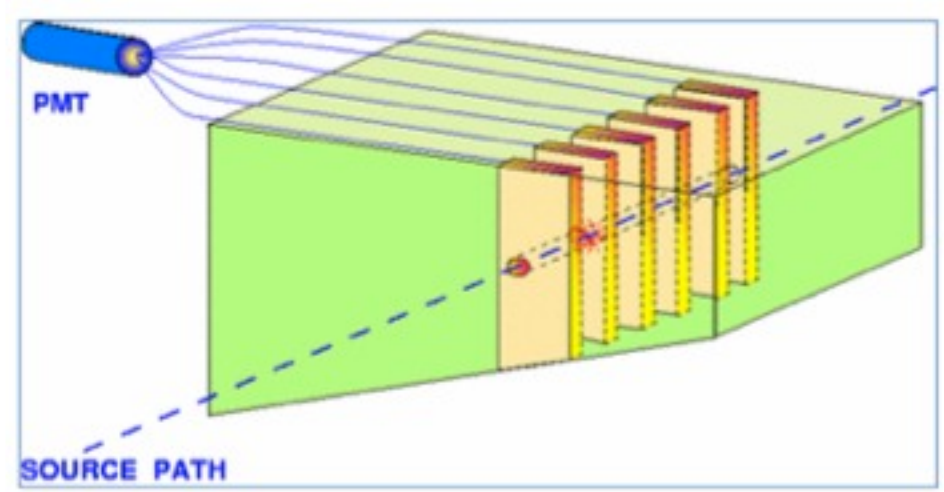
ElectroMagnetic(EM) scale determination:

- Channels equalized in pC level.
- Set with a beam of electrons on 11% of the modules and propagated to all the others with the calibration systems.
- **First step toward Jet energy**



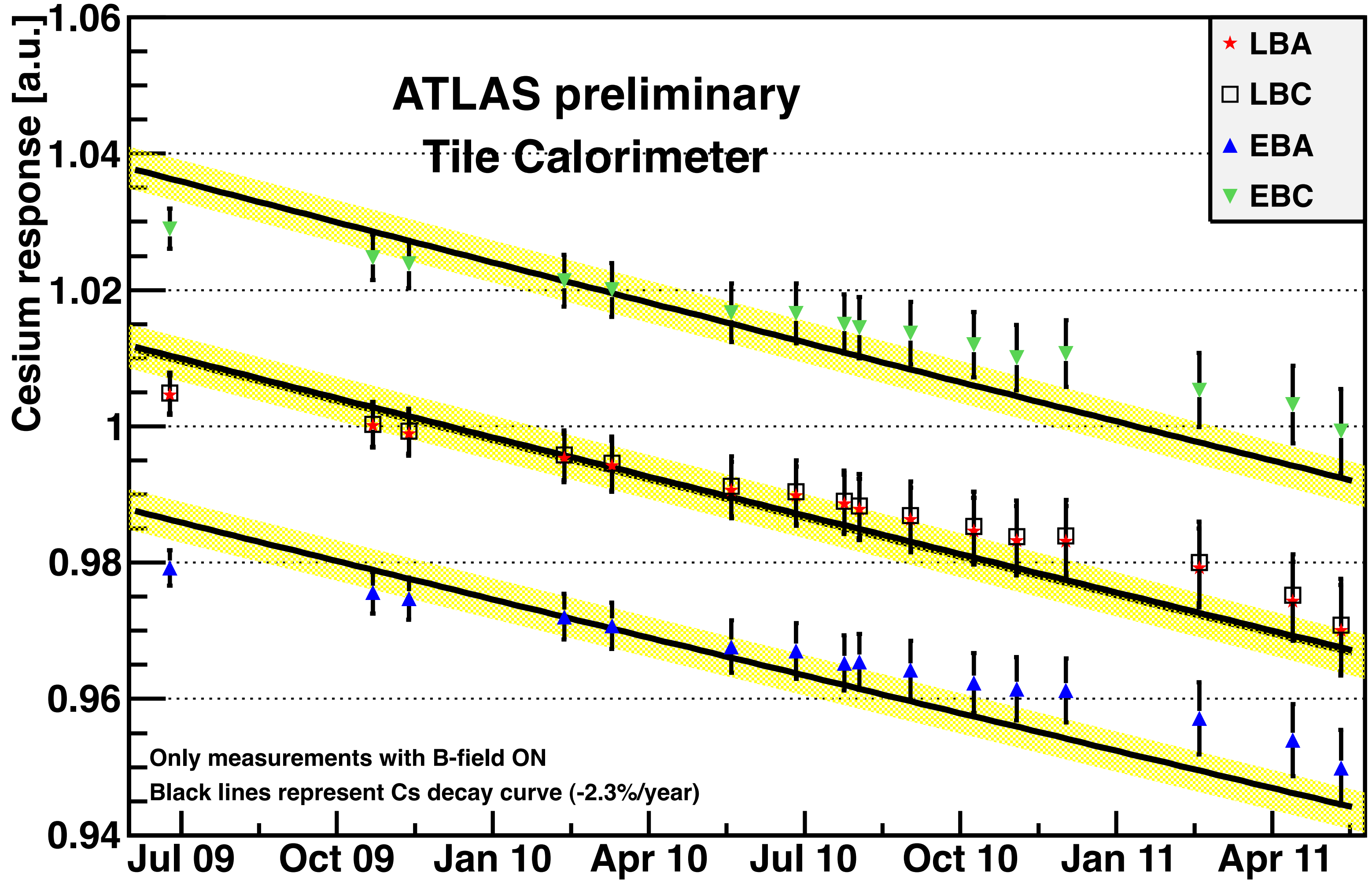
Calibration systems:

- **Charge injection**: Calibration and monitoring ADC counts to pC
- **Laser**: Calibration and monitoring the PMT gain, and the timing of the channels
- ^{137}**Cesium:** Allow to equalize cell response (precision 0.3%)



Tile Calorimeter in ATLAS: Stability over time

- Over several years, ^{137}**Cesium** constantly monitoring the PMT response, up-drift effect observed.

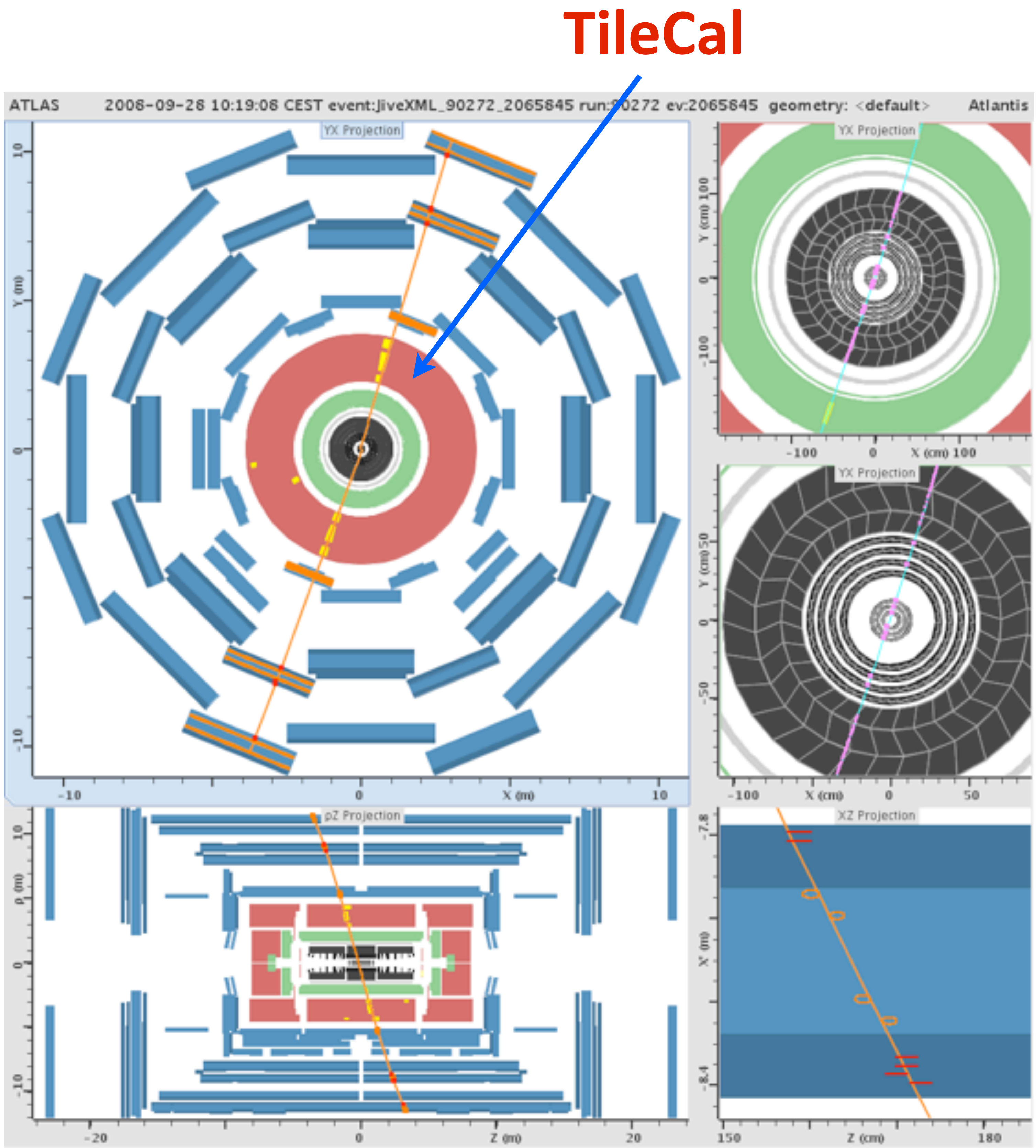


- Correction is applied to make the response equal to the one when the EM scale was measured.

Tile Calorimeter in ATLAS

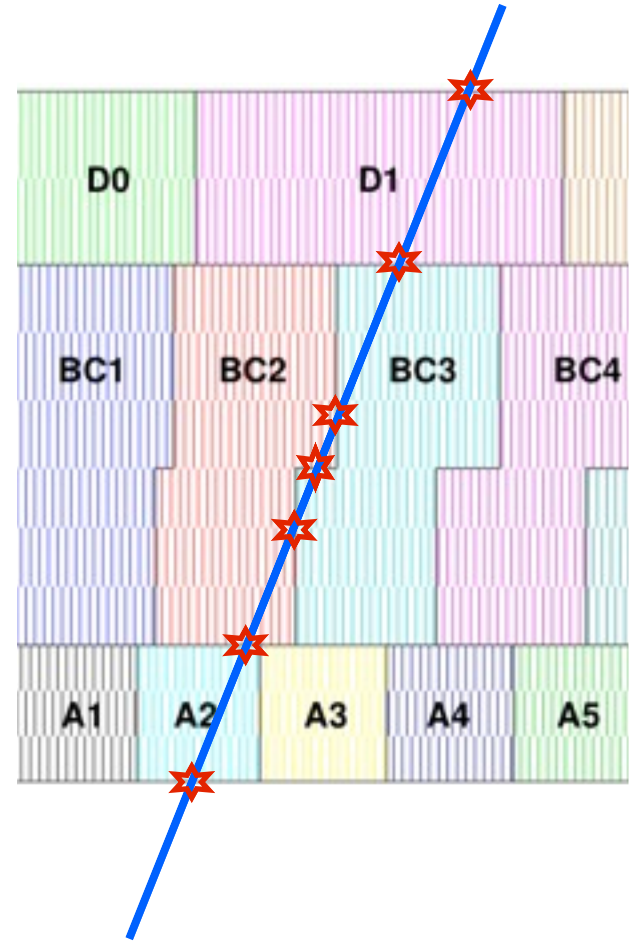
Cosmic event in ATLAS

- Cosmic data are taken in three period: 2008,2009,2010
- Magnetic Field(Solenoid and Toroid) ON, allowing precise measurement for Muon Momentum
- Geant4 Full simulation with expected spectrum, Good agreement Data/MC (~2%)
- Tracks crossing TileCal are used to study **energy response and stability.**



Cosmic event in ATLAS : Analysis procedure

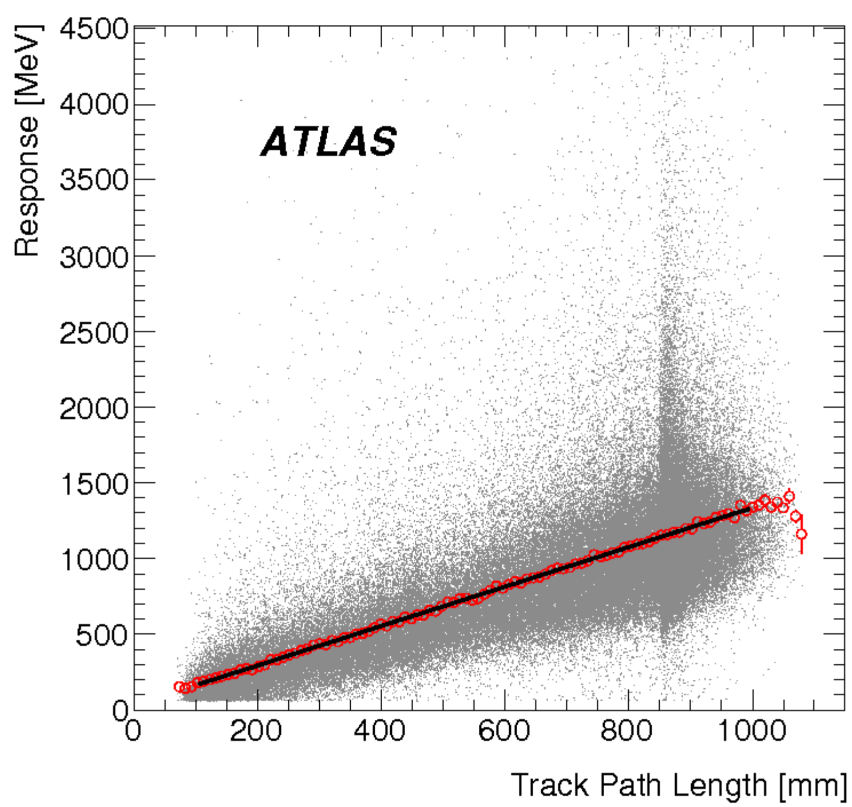
- Track reconstructed in Inner Detectors
- Muon momentum: 10~30 GeV/c
- Projective Muon, contained within one module
- Track extrapolated to Tile Cells
- Path length in each Cell calculated using a precise geometry description

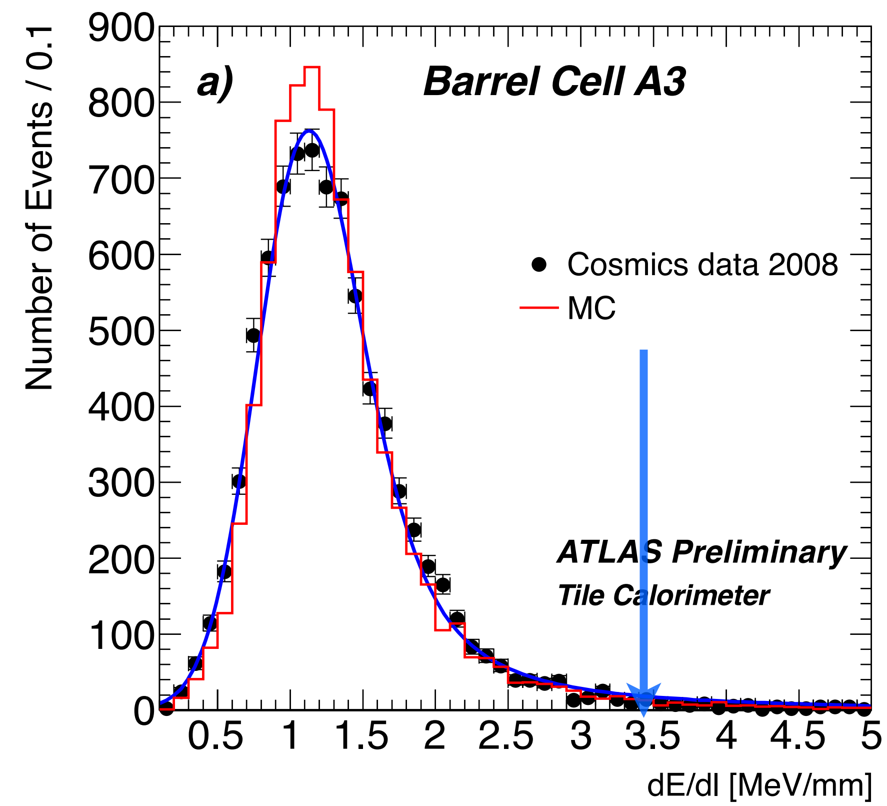


Cosmic event in ATLAS : TileCal Cell Response

- Good linearity for Cell response vs. Path length

- **Estimator of the response:** The mean value of the dE/*dl* distribution, computed using 99% events in the lower region.

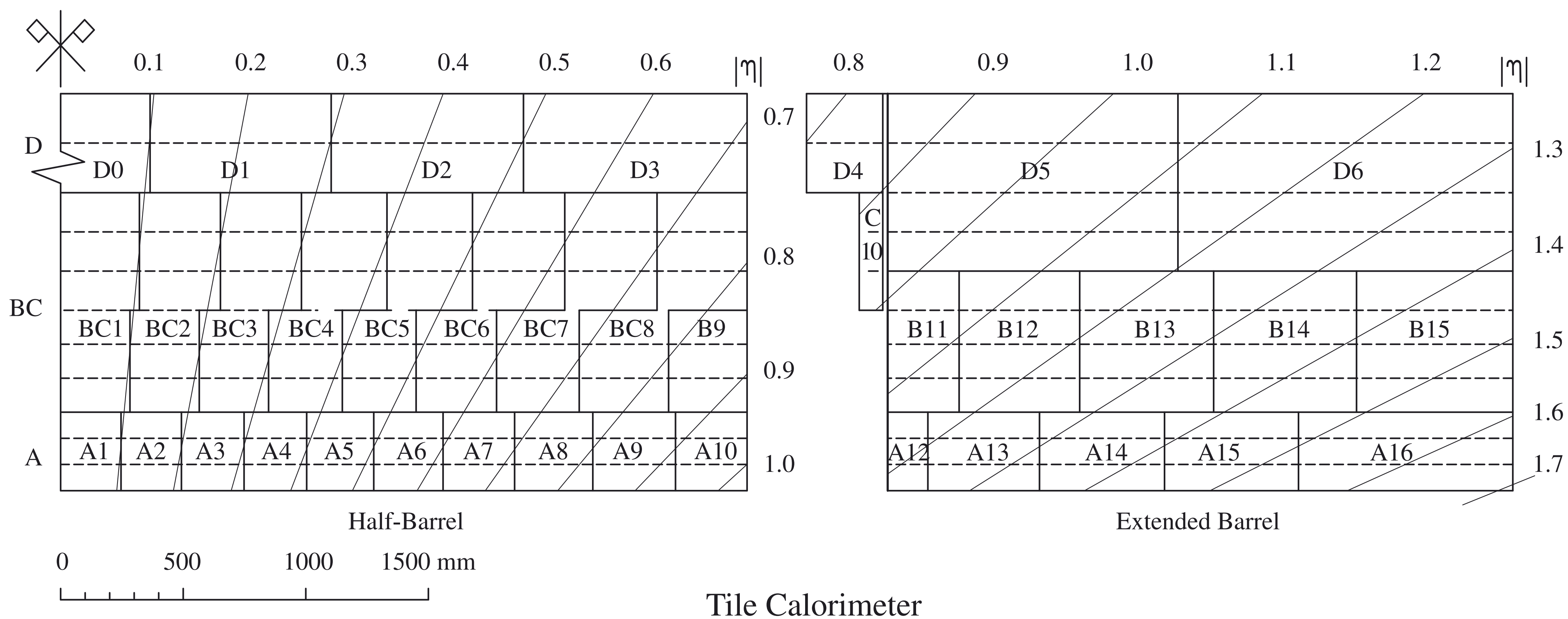




Tile Calorimeter in ATLAS

Cosmic event in ATLAS

Check for Cell Energy response uniformity



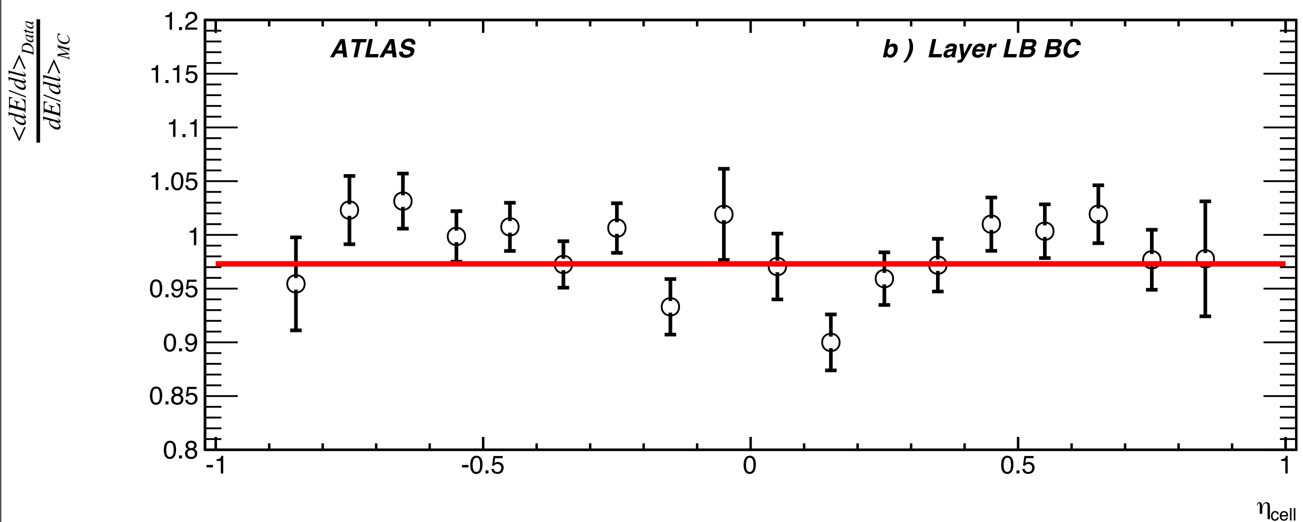
Tile Calorimeter

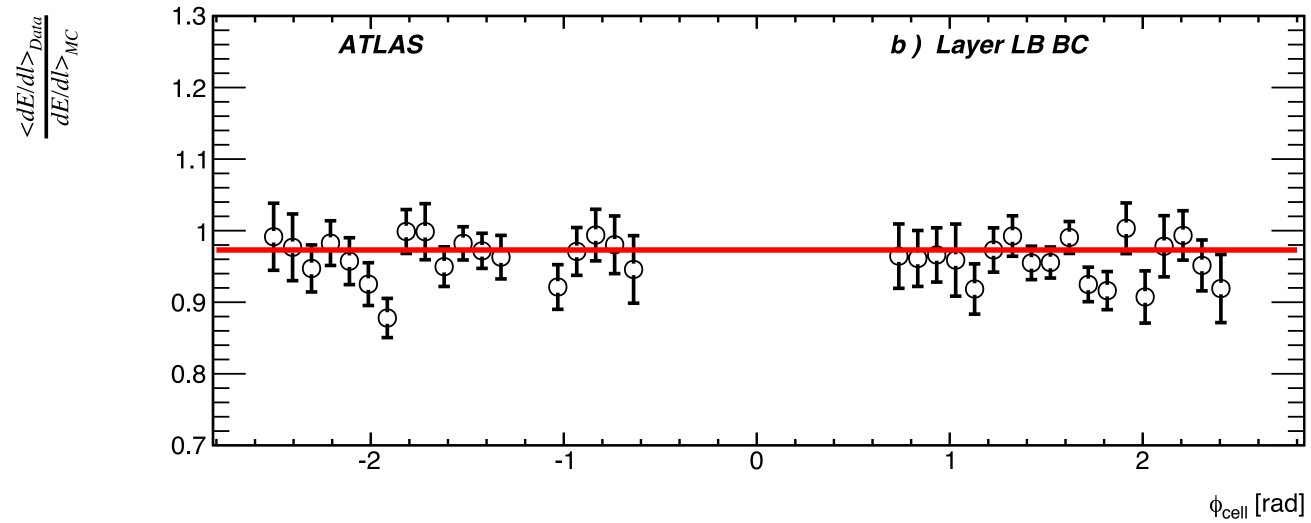
Cells and Tile Rows

Check for Cell Energy response uniformity

- To minimize potential systematic bias, we use the **data/mc ratio of the mean dE/dl**, to check the equalization of the cell response:

$$\frac{\langle dE/dl \rangle_r}{\langle dE/dl \rangle_r^{MC}}$$





Ideal Case
(Uniform detector):

$$\frac{1}{\sigma_s\sqrt{2\pi}}e^{-\frac{1}{2}\left(\frac{R_c^j-\mu}{\sigma_s}\right)^2}$$

- Expect the same value(with gaussian fluctuation) within each layer
- **Rejected by Hypothesis test:** fluctuation is larger than statistic error

Check for Cell Energy response uniformity

Non-Uniform detector
(or non perfect measurement):

$$\frac{1}{\sqrt{\sigma_s^2+\sigma_{non}^2}\sqrt{2\pi}}\, e^{-\frac{1}{2}\left(\frac{R_c^j-\mu}{\sqrt{\sigma_s^2+\sigma_{non}^2}}\right)^2}$$

- For a non-uniform detector, we assume cell response follows a gaussian distribution with additional "spread" : σ_{non} .
- Estimate the parameter of the bordered gaussian by maximum likelihood approach.

Conclusion on Cell Uniformity :

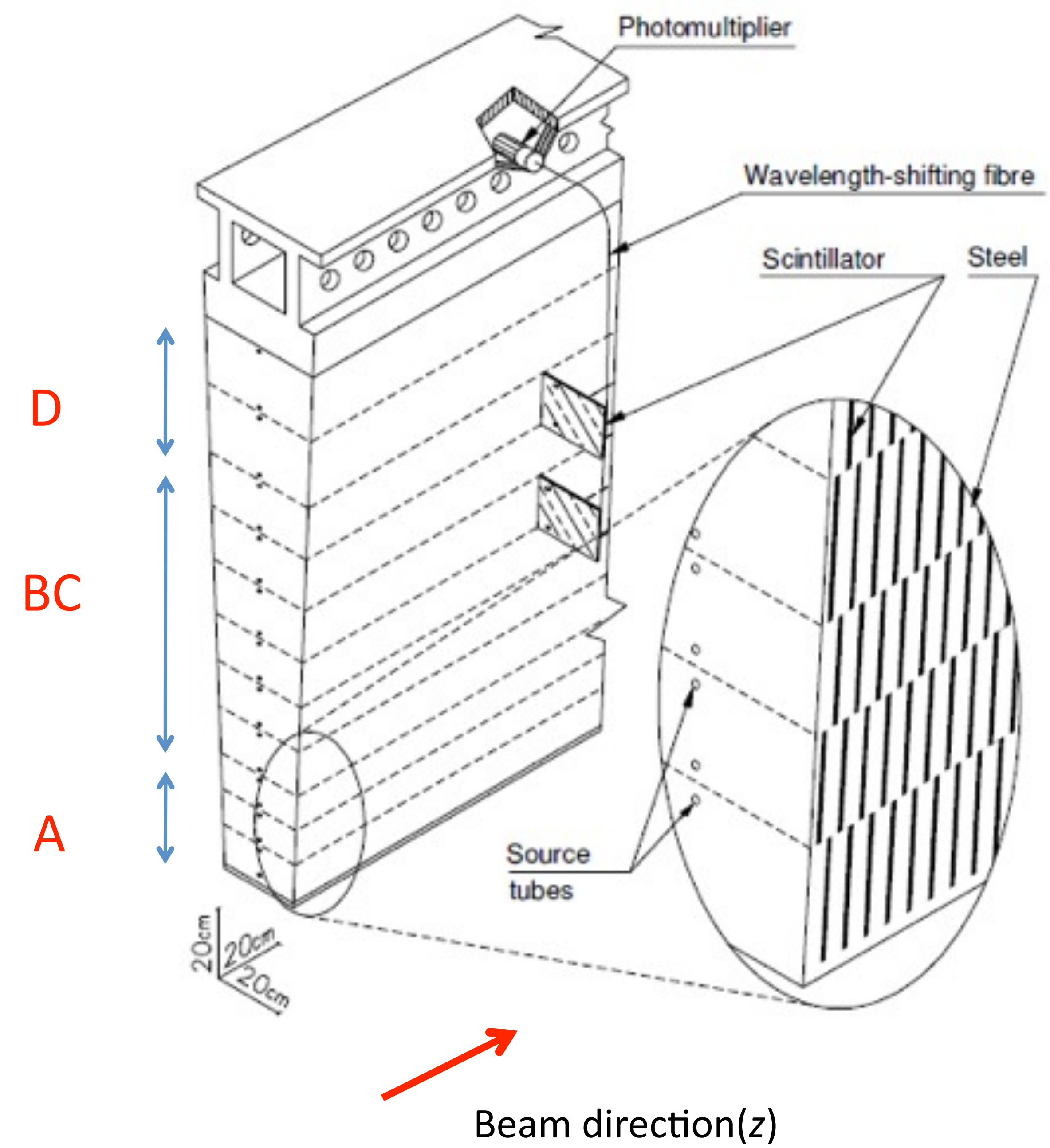
- Good cell uniformity within layers: Non-uniformity effect for each layer is **~2% .**
- Stable result obtained in three periods.

Origin of σ_{non} :

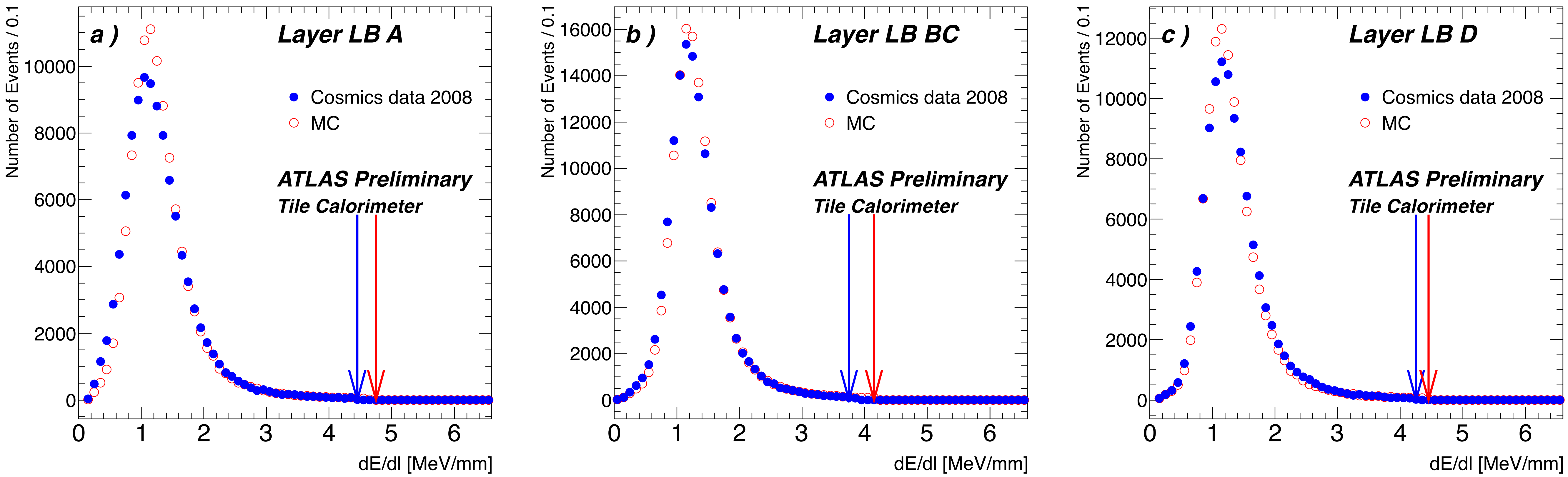
- Systematic effect in the measurement for different cells.
- Known non uniformity in the light collection observed using electrons.
- Unknown cell non-uniformity effect.

	2008 Data	
Layer	$\hat{R}_c^l$	$\hat{s}^l$
LB-A	0.964 ± 0.003	0.023 ± 0.004
LB-BC	0.971 ± 0.002	0.020 ± 0.003
LB-D	1.005 ± 0.003	0.017 ± 0.003
EB-A	-	-
EB-B	0.974 ± 0.020	0.014 ± 0.043
EB-D	0.979 ± 0.008	0.027 ± 0.010

- [x] Tile Calorimeter in ATLAS
- [x] Cosmic event in ATLAS
- [x] Check for Energy response uniformity
- [ ] **Check for Layer Inter-Calibration status**



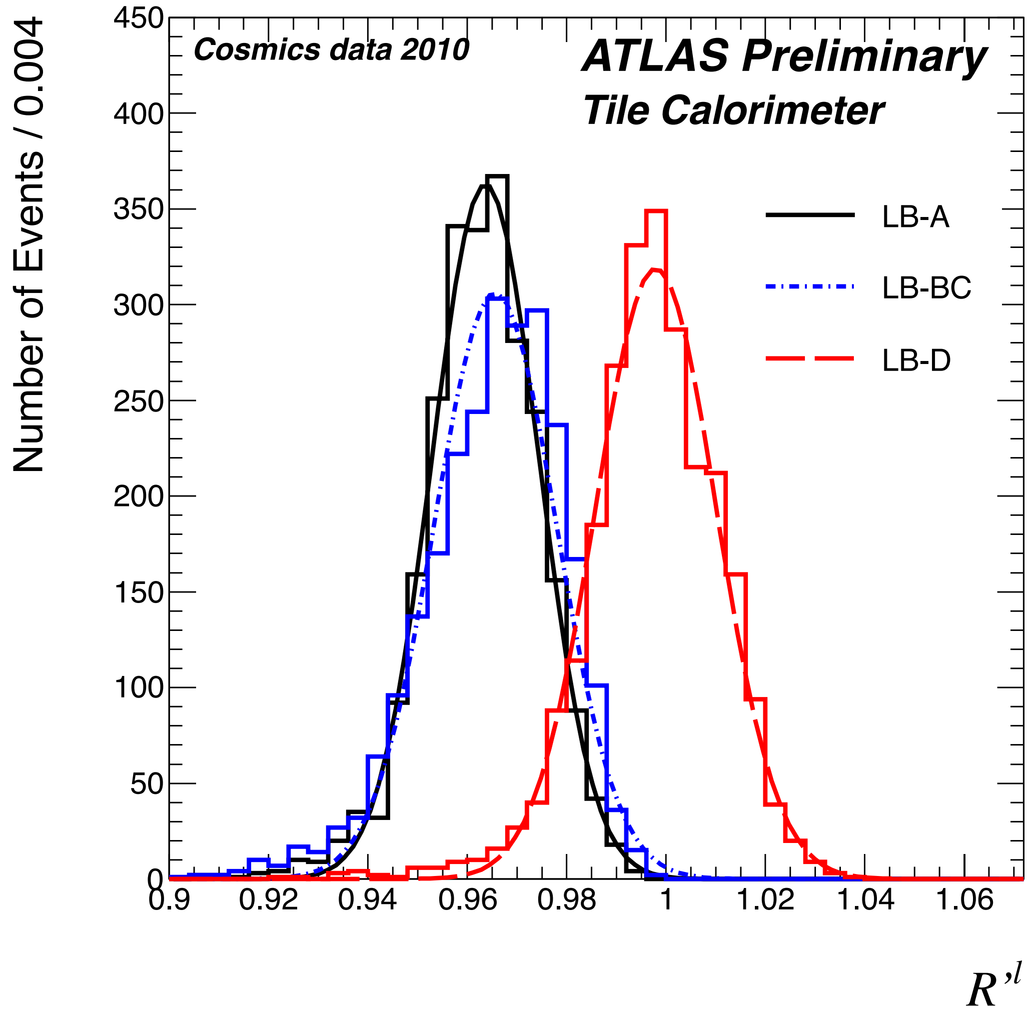
Check for Inter-Calibration status



Layer	$\langle\langle dE/dl\rangle_r^{MC}\rangle^l$ [MeV/mm]	$\langle\langle dE/dl\rangle_r\rangle^l$ [MeV/mm] 2008 data	$\langle\langle dE/dl\rangle_r\rangle^l$ [MeV/mm] 2009 data	$\langle\langle dE/dl\rangle_r\rangle^l$ [MeV/mm] 2010 data
LB-A	1.322±0.001	1.277±0.002	1.285±0.002	1.284±0.002
LB-BC	1.360±0.001	1.328±0.001	1.334±0.002	1.334±0.001
LB-D	1.347±0.001	1.354±0.002	1.364±0.002	1.360±0.002
EB-A	1.316±0.005	1.269±0.008	1.270±0.008	1.311±0.009
EB-B	1.325±0.003	1.294±0.005	1.288±0.005	1.309±0.005
EB-D	1.349±0.003	1.330±0.004	1.315±0.004	1.325±0.004

- We loot at the **data/mc ratio of the mean dE/dl**, for every layer: $\dfrac{\langle dE/dl\rangle_r}{\langle dE/dl\rangle_r^{MC}}$
- Expect to see the same value for 6 layers
- Remaining systematic errors (Muon momentum, path length, selection cuts, calibration constants...) need to be studied.
- To compare between layers, the correlation of systematic error between layers must be taken into account.

Check for Inter-Calibration status



Estimating systematic error:

- Potential sys. error from analysis: define certain ranges where the selection cuts can change coherently between layers, between Data/MC .
- Uncorrelated errors: Gaussian smearing.
- Produce 2000 "pseudo measurements" using different selection criteria with smearing.
- **dE/dl measurement have RMS ~2%, LB-D layer deviate from the others by 4%**
- Need to determine wether this deviation is statistically significant

- To take into account the correlation of systematic error: for every pair of layer, calculate covariance σ_{xy} ,

$$V^{l,l'} = \frac{\sum_{i=1}^{N}(R'^{l} - \hat{R'^{l}})(R'^{l'} - \hat{R'^{l'}})}{N}$$

i, j	1	2	3	4	5	6
1	0.00013	0.00011	0.00010	0.00005	0.00010	0.00006
2	0.00011	0.00020	0.00015	0.00002	0.00014	0.00005
3	0.00010	0.00015	0.00018	0.00010	0.00012	0.00005
4	0.00005	0.00002	0.00010	0.00291	0.00015	-0.00015
5	0.00010	0.00014	0.00012	0.00015	0.00031	0.00007
6	0.00006	0.00005	0.00005	-0.00015	0.00007	0.00022

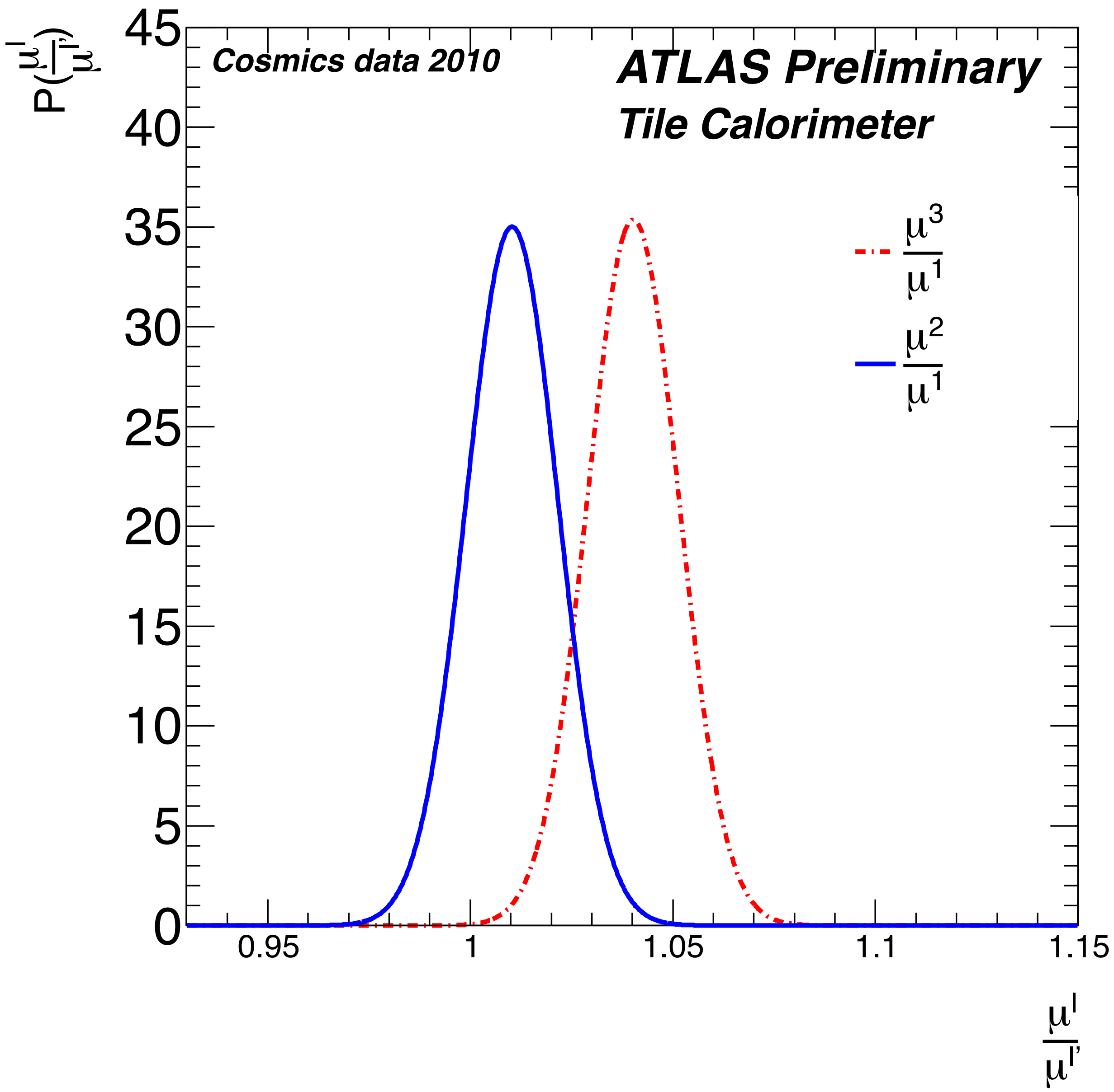
- Correlation as high as ~100%: strong correlation between layers.

Check for Inter-Calibration status

- We introduce Bayesian inference to get the Posterior Distribution Function(PDF) of the “true” response of each layer.
- Consider the energy response of 6 layers come from a **multivariate Gaussian**, with a covariance matrix *V* discussed in previous slide:

$$f(\mu^1,...,\mu^6 \mid R^1,...,R^6) = K\mathcal{L}(\mu^1,...,\mu^6;R^1,...,R^6) = K'exp[-\frac{1}{2}(\vec{R}-\vec{F})^T V^{-1}(\vec{R}-\vec{F})]$$

- Get the PDF for ratio between every other two layers.
- For pair LB-D/LB-A, LB-D/LB-BC, the probability for the ratio being 1 is very small:**The response of LB-D layer is likely deviated from the others.**
- **All the other 5 layers are well equalized.**
- Our result suggests that there are systematic effects / deviations needed to be understood.



Check for Response Stability

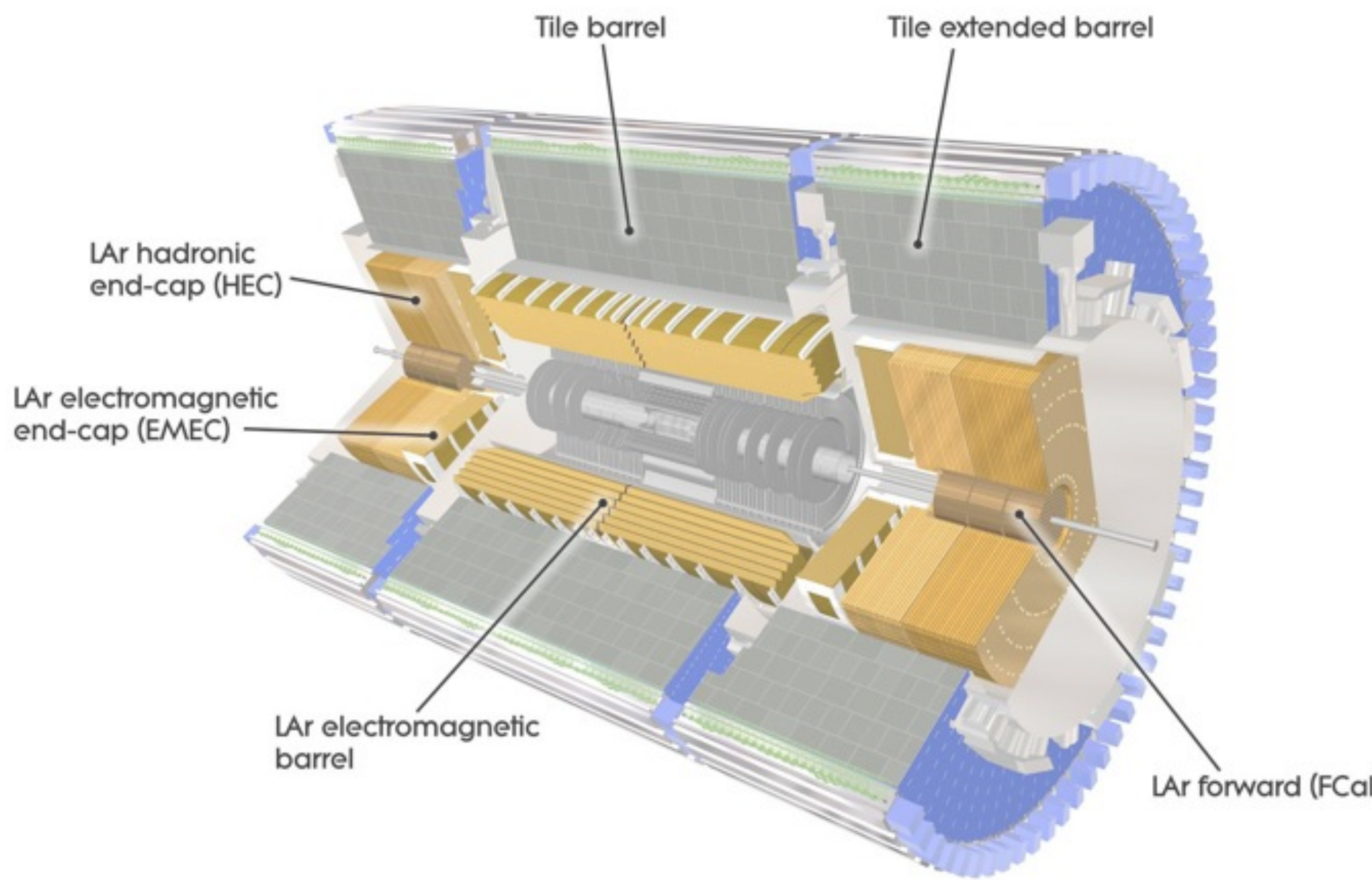
Layer	2008	2009	2010
LB-A	0.966 ± 0.012	0.972 ± 0.015	0.971 ± 0.011
LB-BC	0.976 ± 0.015	0.981 ± 0.019	0.981 ± 0.015
LB-D	1.005 ± 0.014	1.013 ± 0.014	1.010 ± 0.013
EB-A	0.964 ± 0.042	0.965 ± 0.032	0.996 ± 0.037
EB-B	0.977 ± 0.018	0.966 ± 0.016	0.988 ± 0.014
EB-D	0.986 ± 0.012	0.975 ± 0.012	0.982 ± 0.014

- Similar analysis can estimate the stability of the response for every layer over the three years of cosmic data taking: $f(\mu_1^l, \mu_2^l, \mu_3^l \mid R_1^l, R_2^l, R_3^l) = K exp[-\frac{1}{2}(\vec{P} - \vec{G})^T W^{-1} (\vec{P} - \vec{G})]$

- We get the ratio between two period for every layer
- **For All 6 layers, response stable over three period**
- Result proves that the Cs corrections applied during this 3-years period are validated

	μ_2^l/μ_1^l	μ_3^l/μ_1^l	μ_3^l/μ_2^l
$l = 1$ (LB-A)	1.006 ± 0.009	1.005 ± 0.008	0.999 ± 0.008
$l = 2$ (LB-BC)	1.005 ± 0.007	1.005 ± 0.005	1.000 ± 0.006
$l = 3$ (LB-D)	0.998 ± 0.007	1.005 ± 0.006	1.007 ± 0.006
$l = 4$ (EB-A)	0.998 ± 0.028	1.030 ± 0.033	1.032 ± 0.025
$l = 5$ (EB-B)	0.989 ± 0.016	1.011 ± 0.013	1.023 ± 0.013
$l = 6$ (EB-D)	0.989 ± 0.011	0.996 ± 0.017	1.007 ± 0.016

- [x] Tile Calorimeter in ATLAS
- [x] Cosmic event in ATLAS
- [x] Check for Energy response uniformity
- [x] Check for Inter-Calibration status
- [x] Check for Response Stability
- [ ] **Absolute EM scale in TileCal**



Absolute EM scale in TileCal

- EM scale set by electron, for Data and MC.

EM scale

$$E_{rec}^{\mu data} = E_{pC}^{\mu data} \times \left(\boxed{\frac{E_{beam}^{eTB}}{E_{pC}^{eTB}}}\right)$$

$$E_{rec}^{\mu MC} = E_{vis}^{\mu MC} \times \left(\frac{E^{e}}{E_{vis}^{eMC}}\right) \times R_{instr}$$

- Assuming valid simulation for EM process:
  Expected muon response(MIP signal) ratio Data/MC to be 1.00.

- **Deviation from 1.00 implies possible changes of the "True" EM scale in ATLAS from the EM scale set at Test Beam**

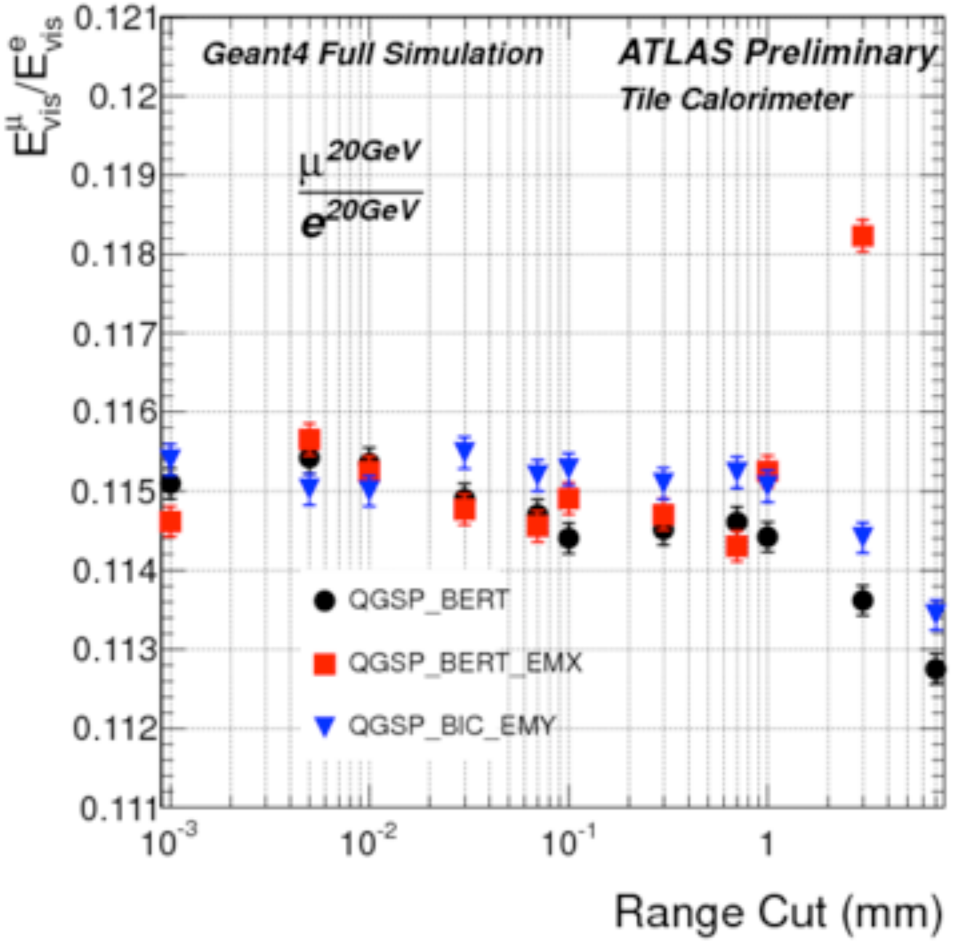
EM scale

$$R = \frac{E_{rec}^{\mu data}}{E_{rec}^{\mu MC}} = \frac{E_{pC}^{\mu data}}{E_{vis}^{\mu MC}} \times E_{vis}^{eMC} \times \boxed{\frac{E_{beam}^{eTB}}{E_{pC}^{eTB}}} \times \frac{f_{instr}^{\mu}}{f_{instr}^{e}} \times \frac{1}{E_{beam}^{eMC}}$$

$$\sigma_R = \sigma\left(\frac{E_{pC}^{\mu data}}{E_{vis}^{\mu MC}}\right) \oplus \sigma\left(\frac{E_{vis}^{eMC}}{E_{vis}^{\mu MC}}\right) \oplus \sigma\left(\frac{f_{instr}^{\mu}}{f_{instr}^{e}}\right) \oplus \sigma(EM)$$

Absolute EM scale in TileCal

- Uncertainty on E_{pC}/E_{vis} Ratio from analysis: **~1.5%**
- Uncertainty from Geant4 simulation: **~1%**
  (Multiple scattering model, Range cut, ...)
- Uncertainty from instrumental effect: **~0.6%.**
  (Implementation of Birk's law, light attenuation)
- Error on Uncertainty from EM scale setting: **~0.5%**



$$\sigma_R = \sigma\left(\frac{E^{\mu data}_{pC}}{E^{\mu MC}_{vis}}\right) \oplus \sigma\left(\frac{E^{eMC}_{vis}}{E^{\mu MC}_{vis}}\right) \oplus \sigma\left(\frac{f^{\mu}_{instr}}{f^{e}_{instr}}\right) \oplus \sigma(EM)$$

- The total error of each layer determinations is **~2%.**
- The ratio between the actual value of the EM energy scale in ATLAS and the value set at test beams was determined to be around **0.97(LBA)** to **1.01 (LBD)** with **±2%** error respectively

Layer	$R^l = EM_{ATLAS}/EM$	Δ_{cosm}	Δ_{cal}	Δ_{MC}	Δ_{Tot}
2010 data					
LB-A	0.971	± 0.011	±0.005	±0.013	±0.018
LB-BC	0.981	± 0.015	±0.005	±0.013	±0.020
LB-D	1.010	± 0.013	±0.005	±0.013	±0.019
EB-A	0.996	± 0.037	±0.005	±0.013	±0.040
EB-B	0.988	± 0.014	±0.005	±0.013	±0.020
EB-D	0.982	± 0.014	±0.005	±0.013	±0.020

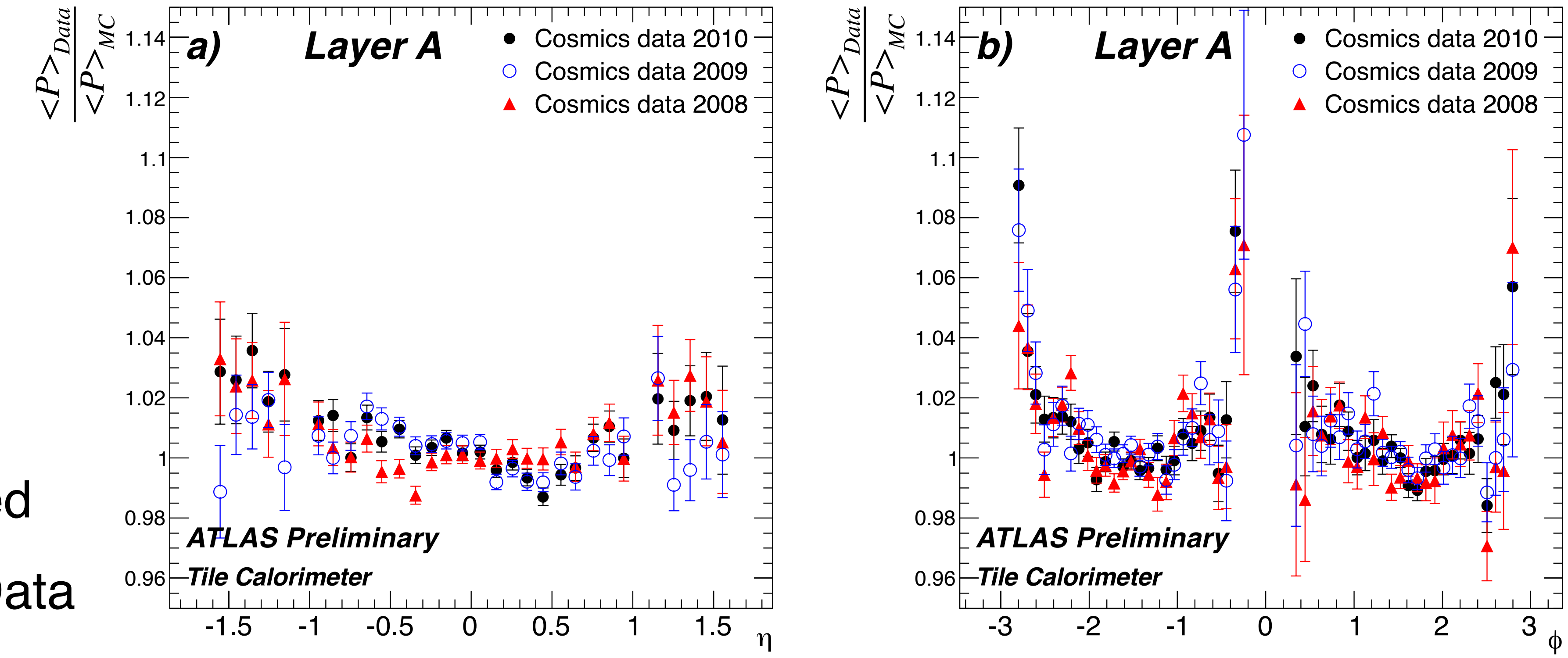
Conclusion

- The calibration of the hadronic barrel calorimeter has been tested using 2008,2009,2010 cosmic data.
- The non uniformity of the cell energy response in each layer is **~ 2%.**
- The maximum difference in energy response between different layers is **~4% ;**
- All the layers seem to be well equalized except for the last layer in Long Barrel partition (LB-D).
- The response for every layer is stable over the three analyzed periods.
- The EM scale for each layer agrees with the value set at test beams using electrons.

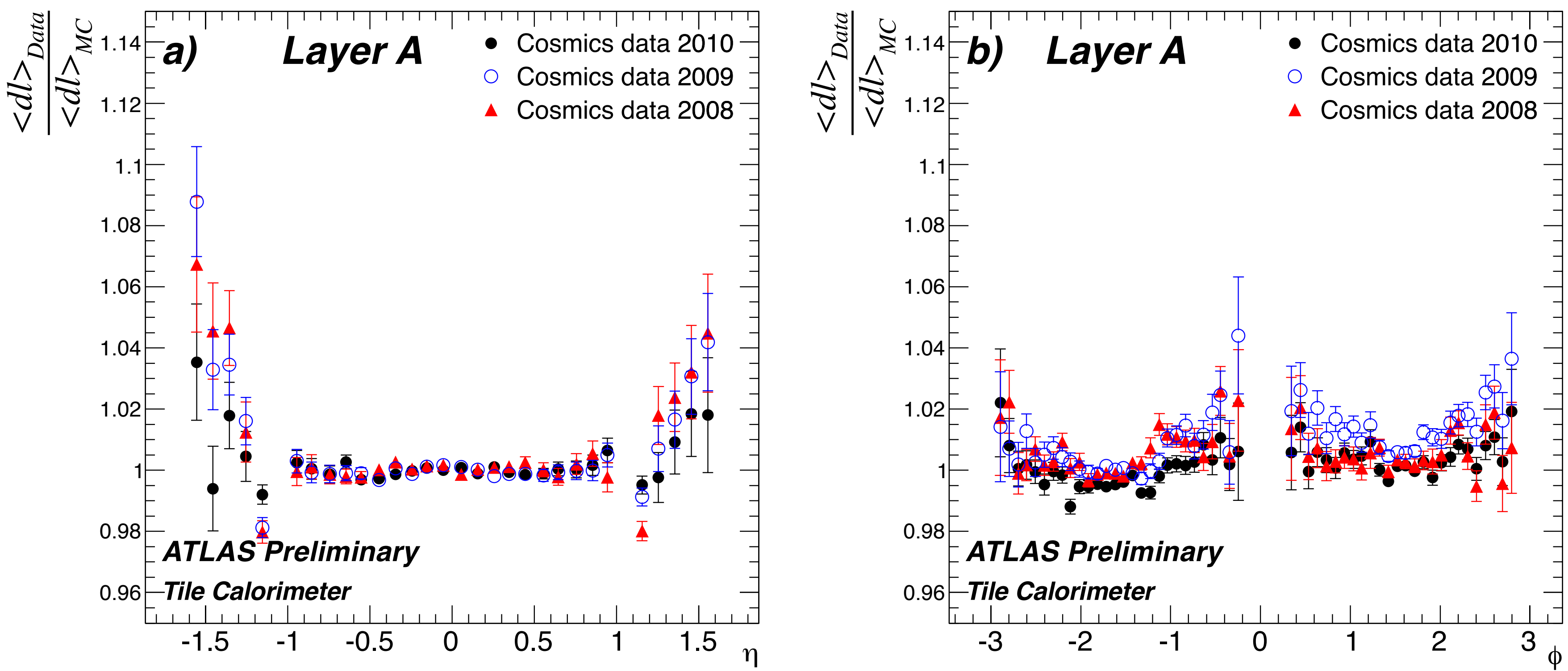
Backup Slides

Cosmic event in ATLAS : MC Simulation

- Geant4 Full simulation
- Cosmic spectrum well simulated
- Agreement between MC and Data within 2%



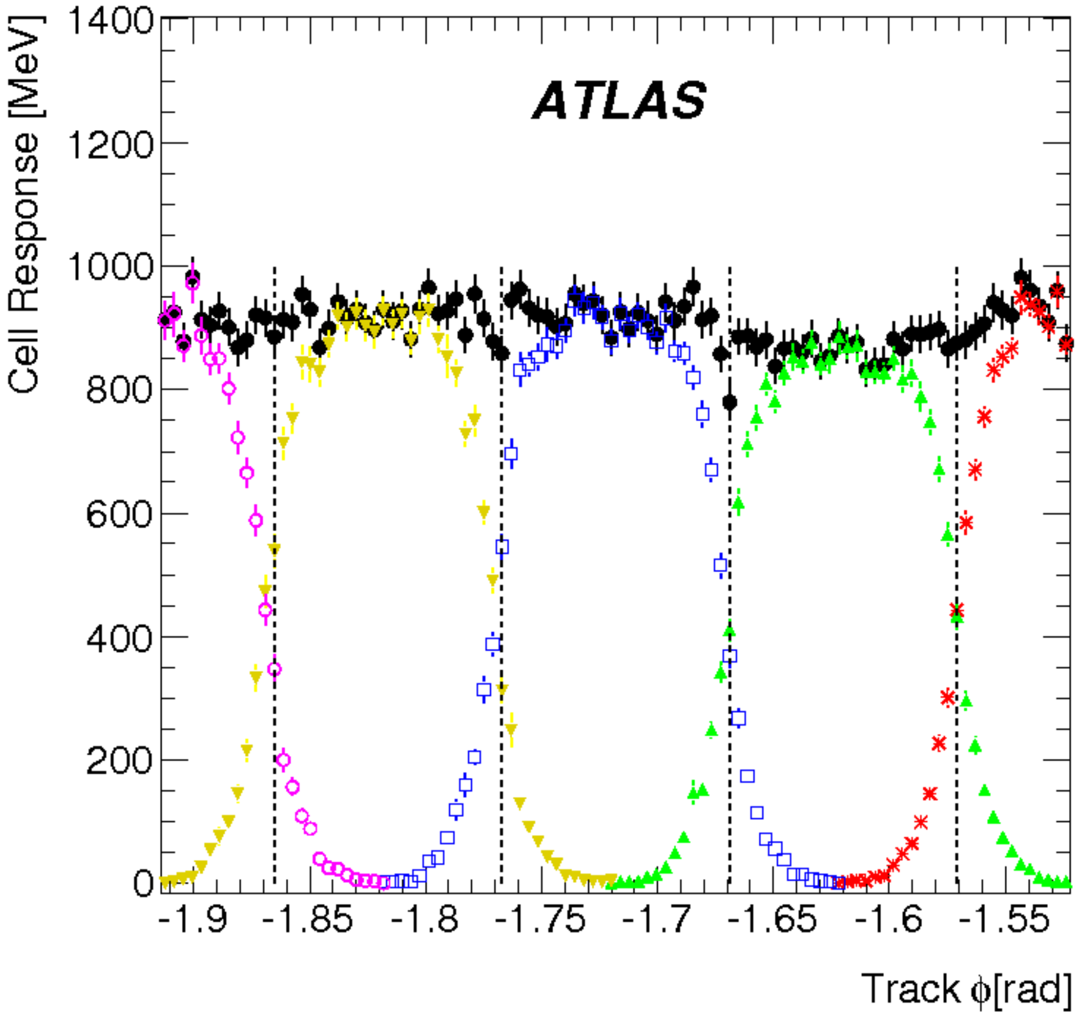
Ratio of <P> Data/MC vs. eta, phi



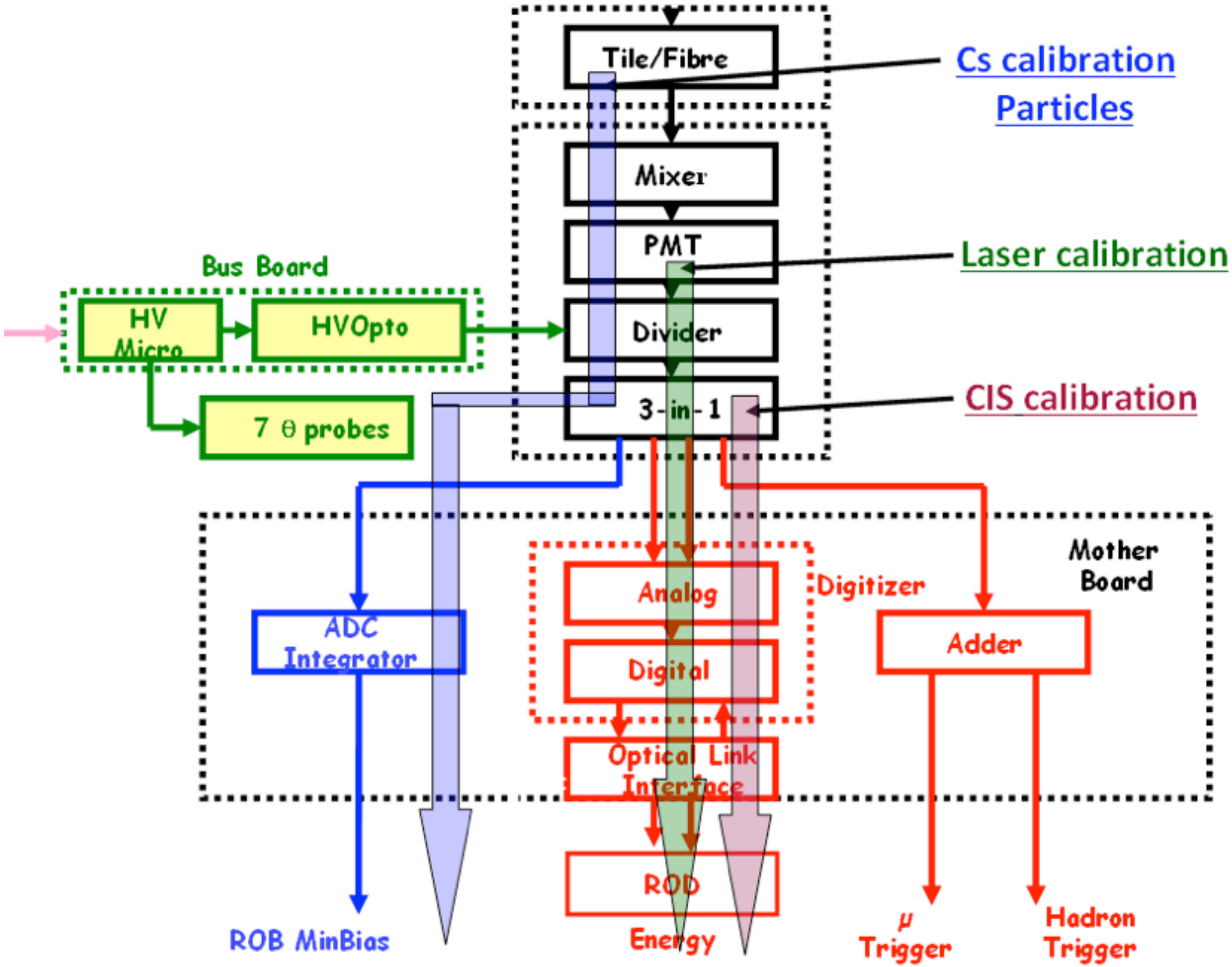
Ratio of <dl> Data/MC vs. eta, phi

Cosmic event in ATLAS : TileCal Cell Response

- Precise measurement:
  Geometry effect at cell level
  clearly seen

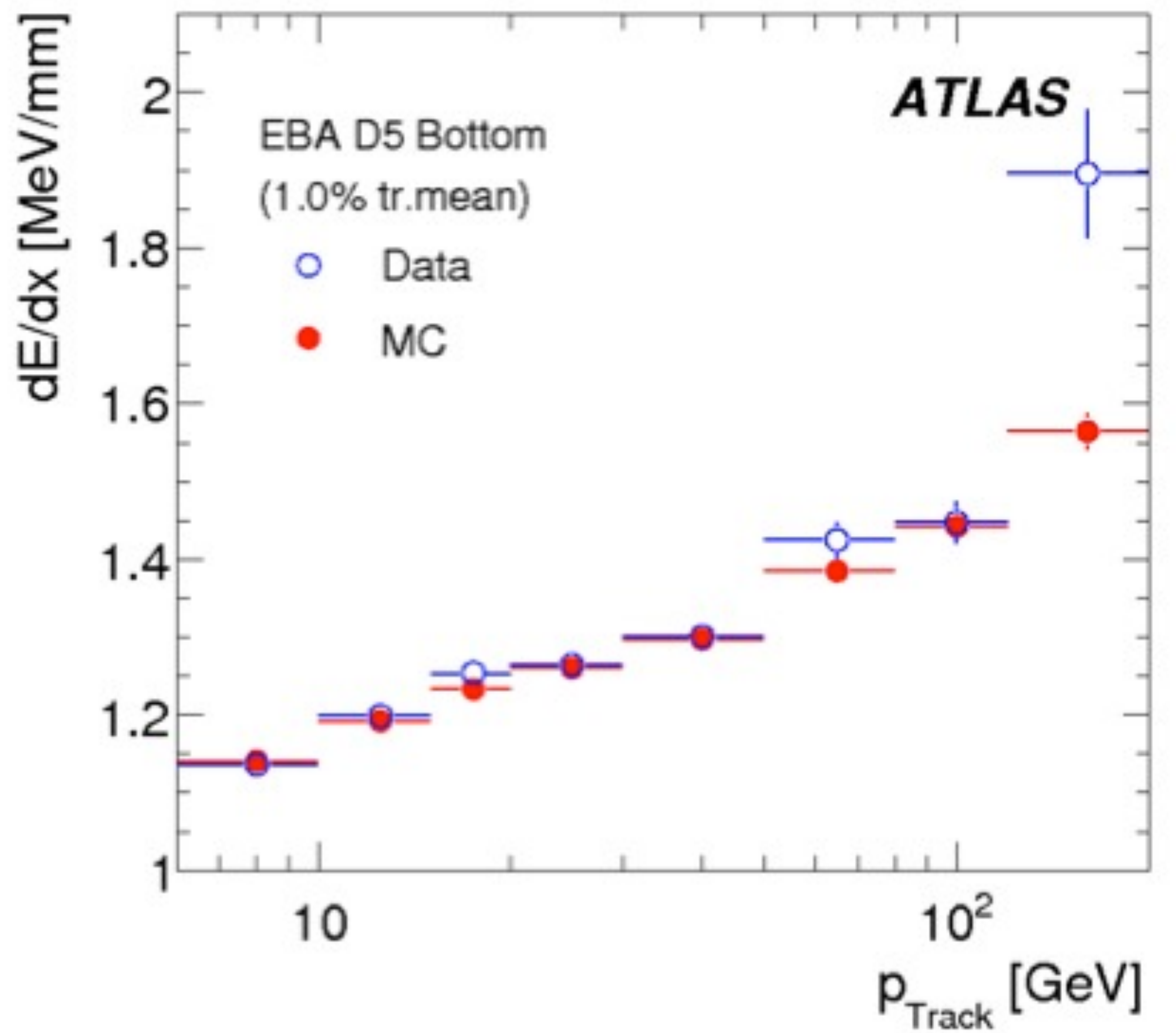


Calibration schema in Tile Calorimeter



TileCal response to Muon vs. Muon Momentum

- dE/dl changes w.r.t. Muon momentum
- Good agreement between Data and MC.



Selection Cut for Cosmic Events and possible systematic effect

- Only One track reconstructed in inner detector
- At least eight hits in the silicon detectors
- Track momentum: 10~30 GeV/c
- Tracks are well within a module (Projective requirement)
- Track entering in certain angle (Track crossing multiple scintilator)
- Track extrapolated to Tile Cells, path length in cell *dl* > 20 cm
- Remove residual noise contribution : dE > 60MeV
- Use Bottom part of the detector for inter-Calibration and EM scale study.

Systemati errors sources	Distributions of the parameters S_m
1. S_1: the $\lvert\Delta\phi_{inner}\rvert$, $\lvert\Delta\phi_{outer}\rvert$ cut (f)	Flat: $0.03 \leq S_1 \leq 0.05$
2. S_2: the $\lvert\theta\rvert$ cut (h)	Flat: $0.10 \leq S_2 \leq 0.15$
3. S_3: the range $[dl_{min}, dl_{max}]$ (e)	dl_{min} flat in the range $(MaxPath)/2$-100 [mm] $dl_{max} = dl_{min}+(MaxPath)/2$ [mm]
4. S_4: The dE_{cut} cut (g)	Flat: $30MeV \leq S_4 \leq 90MeV$
5. S_5: the p range (d):	Flat: S_5 : $5 < p < 10$ GeV, $10 < p < 30$ GeV and $30 < p < 50$ GeV
6. S_6: the ϕ_c range:	Flat: S_6 : $< 0, > 0$
7. S_7: the dE/dl truncation cut F (Section 3.3)	Flat: S_7 : 0%, 1%, 2%
8. S_8: smearing of the simulated dE/dl distribution (Section 4.2)	Gauss (μ, S_8): $\mu = 0, S_8 = 0.3\%$
9. S_9: uncertainty on the radial calibration correction (Section 3.3)	Gauss (μ, S_9): $\mu = 0, S_9 = 0.3\%$
10. S_{10}: uncertainty on the up-drift and magnetic field effect	Gauss (μ, S_{10}): $\mu = 0, S_{10} = 1\%$ for the LB and $S_{10} = 0.6\%$ for the EB cells

Assuming that the measured cell response follow a Gaussian distribution

The non uniformity s^l is obtained maximizing the likelihood function:

$$L = \prod_{c=1}^{N^l} \frac{1}{\sqrt{(\sigma_c^{l2} + s^{l2})2\pi}} e^{-\frac{1}{2}\left(\frac{R_c^l - \mu^l}{\sqrt{\sigma_c^{l2} + s^{l2}}}\right)^2}$$

Where N^l is the number of cells in the layer l , by maximizing the likelihood function for every layer within one period:

	2008 Data		2009 Data		2010 Data	
Layer	$\hat{R}_c^l$	$\hat{s}^l$	$\hat{R}_c^l$	$\hat{s}^l$	$\hat{R}_c^l$	$\hat{s}^l$
LB-A	0.964 ± 0.003	0.023 ± 0.004	0.968 ± 0.003	0.026 ± 0.003	0.968 ± 0.003	0.028 ± 0.003
LB-BC	0.971 ± 0.002	0.020 ± 0.003	0.976 ± 0.002	0.021 ± 0.003	0.974 ± 0.002	0.020 ± 0.002
LB-D	1.005 ± 0.003	0.017 ± 0.003	1.011 ± 0.003	0.019 ± 0.003	1.005 ± 0.003	0.024 ± 0.003
EB-A	-	-	-	-	-	-
EB-B	0.974 ± 0.020	0.014 ± 0.043	0.971 ± 0.012	0.014 ± 0.033	0.995 ± 0.017	-
EB-D	0.979 ± 0.008	0.027 ± 0.010	0.975 ± 0.007	0.026 ± 0.007	0.986 ± 0.010	0.053 ± 0.009

Bayesian inference for Layer inter-calibration

We introduce Bayesian theorem to estimate the posterior PDF of muon response for 6 layers, **given the measurement we obtained (Data):**

$$f(\mu^1, ..., \mu^6 \mid R^1, ..., R^6) = \frac{f(R^1, ..., R^6 \mid \mu^1, ..., \mu^6) f_0(\mu^1, ..., \mu^6)}{\int f(R^1, ..., R^6 \mid \mu^1, ..., \mu^6) f_0(\mu^1, ..., \mu^6) d\mu^1 .... d\mu^6}$$

We consider our knowledge of the six true value “vague” and hence introduce a flat "Pior" for the probability for the six parameters, and we have

$$f(\mu^1, ..., \mu^6 \mid R^1, ..., R^6) \propto f(R^1, ..., R^6 \mid \mu^1, ..., \mu^6) \propto \mathcal{L}(\mu^1, ..., \mu^6; R^1, ..., R^6).$$

Where the likelihood L(μ1...μ6) is a function w.r.t. parameters μ1... μ6
We consider our measurement for 6 layers comes from a **multivariate Gaussian**, with a covariance matrix V obtained previously:

$$f(\mu^1, ..., \mu^6 \mid R^1, ..., R^6) = K\mathcal{L}(\mu^1, ..., \mu^6; R^1, ..., R^6) = K' exp[-\frac{1}{2}(\vec{R} - \vec{F})^T V^{-1} (\vec{R} - \vec{F})]$$

where K and K' are normalization constants, $\vec{R} = (R^1, ..., R^6)$ and $\vec{F} = (\mu^1, ..., \mu^6)$.

PDF of ratio between layers

Full table concerning the inter-calibration check between every two layers, showing the mean value of the the ratio between two layers, together with the RMS

	$l = 1$	$l = 2$	$l = 3$	$l = 4$	$l = 5$	$l = 6$
$l' = 1$	-	1.010 ± 0.011	1.040 ± 0.011	1.027 ± 0.048	1.018 ± 0.016	1.011 ± 0.016
$l' = 2$	1.010 ± 0.011	-	1.030 ± 0.010	1.017 ± 0.048	1.007 ± 0.016	1.001 ± 0.018
$l' = 3$	0.961 ± 0.010	0.971 ± 0.009	-	0.989 ± 0.044	0.978 ± 0.016	0.972 ± 0.017
$l' = 4$	0.979 ± 0.043	0.988 ± 0.045	1.015 ± 0.047	-	0.994 ± 0.045	0.990 ± 0.047
$l' = 5$	0.983 ± 0.016	0.993 ± 0.016	1.022 ± 0.017	1.010 ± 0.047	-	0.994 ± 0.020
$l' = 6$	0.989 ± 0.016	0.999 ± 0.018	1.029 ± 0.018	1.016 ± 0.051	1.006 ± 0.020	-

Table 6: Mean values of the distributions of the ratios $\mu^l/\mu^{l'}$ obtained using 2010 data. The errors correspond to the RMS of the distributions.