Energy scale calibration of the CMS Hadron Calorimeter with isolated charged hadrons: status and plans

Marina Chadeeva (for the Isotrack calibration group)

1. CMS HCAL calibration workflow
2. Calibration technique with isolated charged hadrons
3. Results of hadron energy scale calibration in 2016
4. Preliminary calibration results for 2018 data

CMS HCAL calibration workflow

Radiation damage monitoring

HB: monitoring with laser; HE and HF: relative corrections from laser and collision data

In situ calibration with collision data

HB	HE	HF	HO
Intercalibration with ϕ-symmetry	Intercalibration with ϕ-symmetry	Intercalibration with ϕ-symmetry	Intercalibration with muons
	Since 2018: interdepth calibration with muons		
Energy scale calibration with isolated charged hadrons	**Energy scale calibration with isolated charged hadrons**	Energy scale calibration with $Z \to ee$	*Energy scale calibration under development (dijets, MET)*

In this talk: focus on calibration with isolated charged hadrons

Calibration with isolated charged hadrons

Goal

Equalisation of response in $i\eta$ rings to establish absolute energy scale in HB and HE

Technique

- Inherited from L3 experiment
- Momentum of the isolated hadron, p_{track}, is measured in the tracker.
  - high track reconstruction quality
  - momentum range $40 < p_{\mathrm{track}} < 60$ GeV
- Energy in the HCAL, E_{hcal}, is measured from all cells within a cone of 35 cm around the track impact point at the HCAL front face.
- Response is defined as $E_{\mathrm{hcal}}/(p_{\mathrm{track}} - E_{\mathrm{ecal}})$
  E_{ecal} is energy in a cone of radius 14 cm around the track impact point in the ECAL.
- Selection conditions:
  - MIP in ECAL: $E_{\mathrm{ecal}} < 1$ GeV;
  - no MIP in HCAL: $E_{\mathrm{hcal}} > 10$ GeV;
  - max momentum of neighbour track within a cone of radius 64 cm does not exceed
    2 GeV (tight charge isolation)
    10 GeV (loose charge isolation) *!! requires correction for pileup !!*
- Response is equalised in iterations (details in DN-2016/029 and backup slides).
- MPV and width of response are obtained from two-step Gaussian fit.

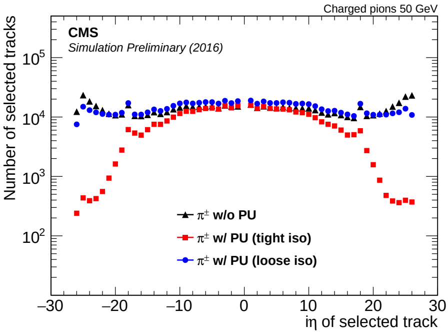
Result

One response correction factor per each $i\eta$ ring and (optionally) per depth segment

Motivation for loose isolation in isotrack calibration

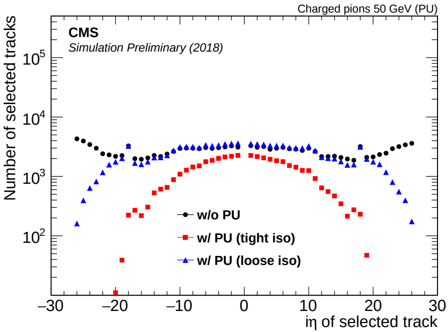
- Statistical uncertainty of response corrections is expected to be ∼1–2%.
- Selection efficiency in HE decreases with increasing pileup ⇒ loose isolation is needed.
- Loose isolation requires correction for pileup on an event-by-event basis.

MC 2016: $\langle N_{vtx} \rangle \sim 20$



No significant difference between loose and tight charge isolation in HB. The efficiency for loose isolation is similar to that w/o pileup.

MC 2018: $\langle N_{vtx} \rangle \sim 40$



Number of tracks with tight isolation drops dramatically already in HB. For loose isolation, the sharp decrease starts from $|i\eta| = 20$.

N.B.: Initial number of events in two MC samples is different by factor of 5.

Correction for pileup for isotrack calibration

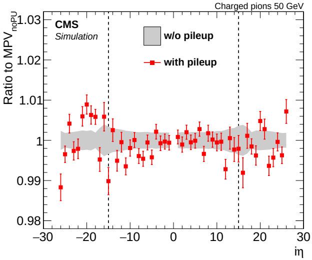
Technique of correction for pileup based on the local energy deposition

- Standard selection conditions are applied.
- Uncorrected energy, E, is the sum of hits in the basic cone of $R_{\rm cone} = 35$ cm; p is the track momentum measured in tracker.
- Excess energy, Δ, is the energy in the "extra" cone between $R_{\rm cone}+$ 10 cm and $R_{\rm cone}+$ 30 cm (see details of Δ behaviour on backup slides).
- Corrected energy is calculated on the event-by-event basis:

$$E_{\rm cor} = \begin{cases} E, & \text{if } \frac{\Delta}{p} < d_{\rm thr} \\ E \cdot (1 + a_1 \cdot \frac{E}{p} \cdot \frac{\Delta}{p}(1 + a_2 \cdot \frac{\Delta}{p})), & \text{if } \frac{\Delta}{p} \geq d_{\rm thr} \end{cases}$$

Tuning of pileup correction coefficients a_1 and a_2

- MC 50 GeV pion samples with and w/o pileup;
- fit to reference MC sample w/o pileup, $d_{\rm thr}$ – threshold for correction (see backup for details);
- in 2016–2017, tuned with MC 2016 ($\langle N_{vtx}\rangle \sim 20$); Ratio: corrected MPV with pileup / MPV w/o pileup ⇒
- in 2018, retuned with MC 2018 ($\langle N_{vtx}\rangle \sim 40$).

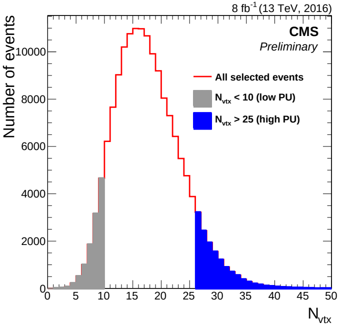


Impact of pileup on response to hadrons from collision data

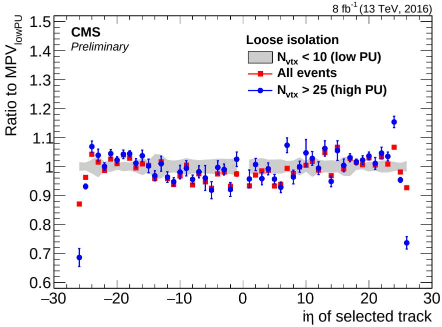
Crosscheck of correction for pileup with collision data

- correction for pileup is tuned on MC 2016 pion samples;
- data sample was split based on the number of reconstructed vertices, $N_{\rm vtx}$, into low-pileup ($N_{\rm vtx} < 10$) and high-pileup ($N_{\rm vtx} > 25$) subsamples.

Mean number of reconstructed vertices



Ratio to response of low-pileup subsample



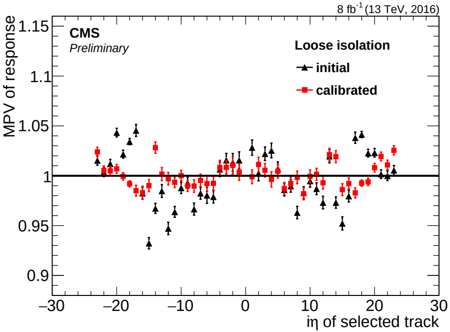
Large discrepancy is observed between low- and high-pileup response at $|i\eta| > 23$.
Decision: apply isotrack calibration at $|i\eta| \leq 23$ and extrapolate correction factors to $|i\eta| > 23$.
Residual uncertainty of MPV is ∼3% in HB ($|\eta| \leq 1.2$) and ∼2% in HE ($1.2 < |\eta| \leq 2.0$).

HCAL response in 2016 collision data

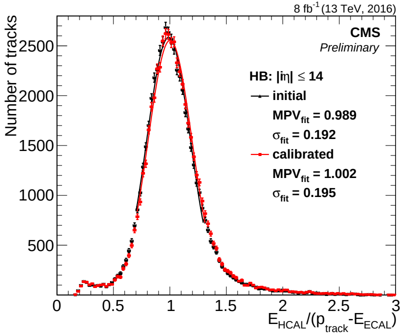
Conditions

Loose isolation, event-by-event correction for pileup, one correction factor per $i\eta$ ring

Response before and after calibration



HB: $|\eta| \leq 1.2$



Uncertainty of the energy scale from 8 fb^{-1} is 3.4% in HB ($|\eta| \leq 1.2$) and 2.6% in HE ($1.2 < |\eta| \leq 2.0$) for loose isolation (incl. statistical uncertainty of 0.5%).

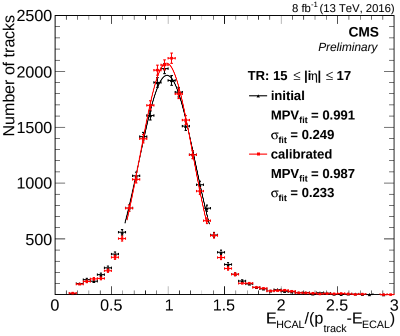
Systematic uncertainties dominate, see backup for details on contributions.

Response distribution in HE for 2016 collision data

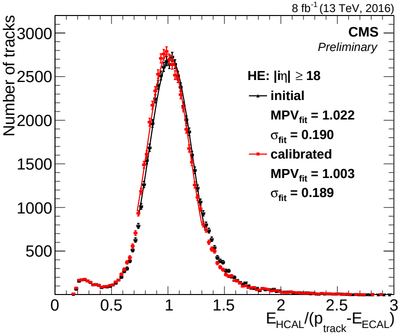
Conditions

Loose isolation, event-by-event correction for pileup, one correction factor per $i\eta$ ring

Transition region: $1.2 < |\eta| < 1.5$



Endcap: $1.5 \leq |\eta| \leq 2.0$



Energy resolution in transition region is improved by 6%.

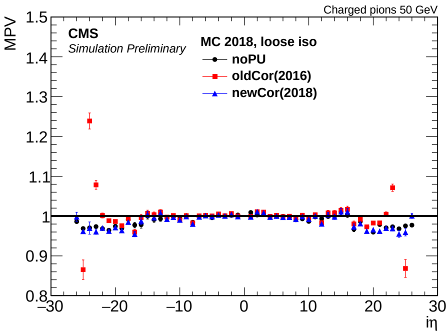
Energy scale in HE for $\eta < 2$ is improved by 2%.

The same correction for pileup and calibration range are used for 2017 data.

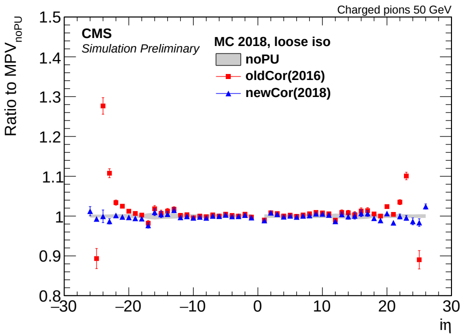
MC: correction for pileup for isotrack calibration in 2018

- correction for pileup retuned using MC 2018 pion samples with $\langle N_{vtx} \rangle \sim 40$;
  N.B.: MC samples before energy scale calibration are used.
- **MC2016-based correction** and **MC2018-based correction** are applied to the same 2018 MC pion samples. The sample w/o pileup is used as a reference.

MPV of response vs. $i\eta$



Ratio to $\mathrm{MPV}_{\mathrm{noPU}}$



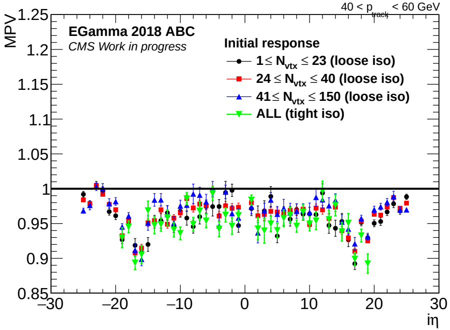
Much better agreement for **MC2018-based correction at $|i\eta| > 23$**.
Residual uncertainty w.r.t. response w/o pileup is $\sim$0.8% up to $|i\eta| = 26$.

Crosscheck of pileup corrections on 2018 data !! Work in progress !!

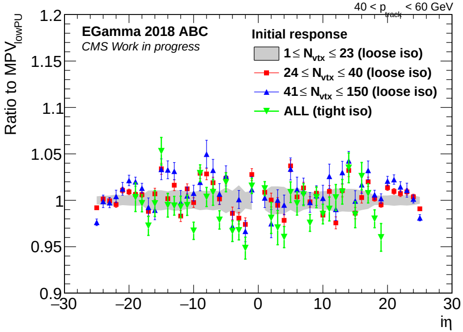
Response before calibration: EGamma dataset (eras A, B and C)

- more than 300000 selected tracks in HB+HE for loose isolation (from ∼30/fb);
- correction for pileup from MC2018 pion samples;
- **tight charge isolation is shown for comparison (up to $|i\eta| = 19$ for the available statistics)**

MPV of response



Ratio to $\mathrm{MPV}_{\mathrm{lowPU}}$



Agreement between **low** and **high** pileup within uncertainties except for $|i\eta| = 25$ and $\langle N_{vtx} \rangle > 40$

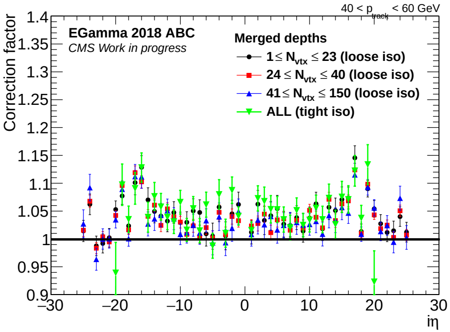
Good agreement in the all range for $\langle N_{vtx} \rangle < 40$ with residual uncertainty of ∼1.5%

Crosscheck of correction factors for 2018 data !! Work in progress !!

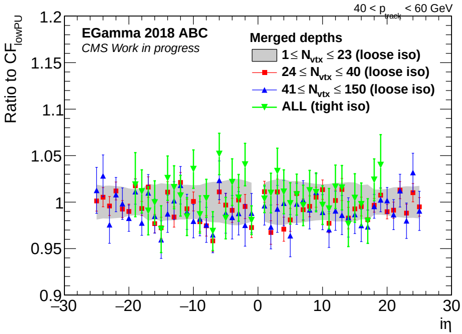
Correction factors (CF) from EGamma AlcaReco dataset (eras A, B and C)

obtained in the range $-25 \leq i\eta \leq 25$ for merged depths

Correction factors after 30 iterations



Ratio to CF_{lowPU}



Good agreement within uncertainties ($\sim$2%) up to $|i\eta| = 25$

Additional constraint $\langle N_{vtx} \rangle < 40$ can be used to reliably extract CFs up to $|i\eta| = 25$

CFs extracted from 2018AB datasets implemented in the reconstruction since 2018D

Summary

HCAL energy scale calibration with isolated charged hadrons

- Isotrack technique allows HCAL energy scale calibration within tracker coverage.
- Selection efficiency drops dramatically in HE with increasing pileup.
- Loose isolation constraint is used with event-by-event correction for pileup.
- Correction for pileup is tuned using MC pion samples and is pileup dependent.

Results of HCAL energy scale calibration

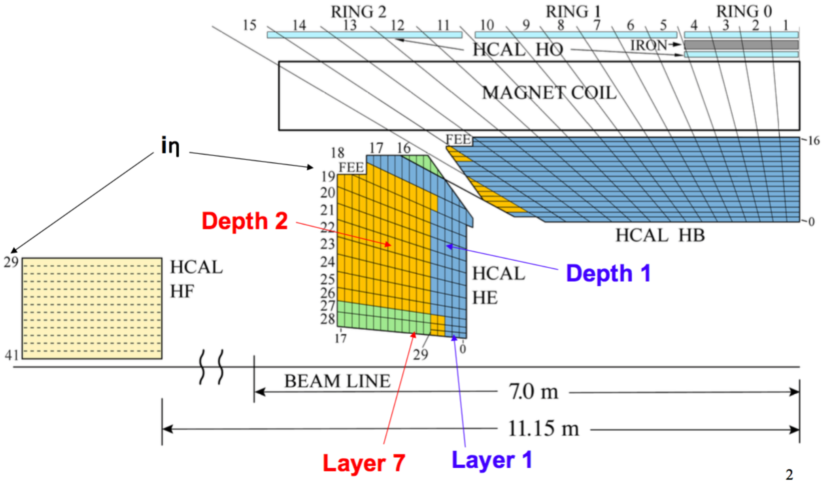
- In 2016 and 2017, the HCAL energy scale was calibrated and equalised using isotrack technique with an accuracy of $\sim$3.5% in HB and $\sim$2.5% in HE at $|i\eta| \leq 23$.
- In 2018, isotrack calibration is extended up to $|i\eta| = 25$ with the same level of precision.

Plans:

- improvement of pileup correction for ultralegacy rereco of 2016 and 2017 data;
- studies of isotrack calibration using lower energy range (e.g. 25–35 GeV);
- monitoring of relative response of phi-segments in HE;
- development of MVA-based pileup correction techniques for isotrack.

Backup slides

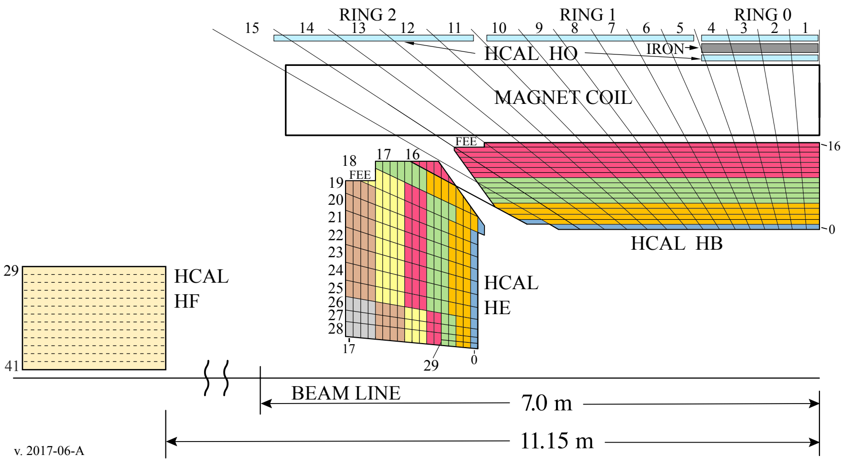
Subdetectors: barrel (HB), endcap (HE), outer (HO) and forward (HF) hadron calorimeters



Layer 1 and Layer 7 are instrumented with the laser system.
$i\eta$ is a number of η ring

CMS Hadron Calorimeter layout since 2018

Subdetectors: barrel (HB), endcap (HE), outer (HO) and forward (HF) hadron calorimeters



$i\eta$ is a number of η ring

Calibration with isolated hadrons: iterative L3 method

Calculation of correction factor $C_i^{(m+1)}$ at $(m+1)$ iteration

$$C_i^{(m+1)} = C_i^{(m)} \left(1 - \frac{\sum_j w_{ij}^{(m)} \cdot (E_j^{(m)}/p_j - RR)}{\sum_j w_{ij}^{(m)}} \right), \quad w_{ij}^{(m)} = \frac{e_{ij}^{(m)}}{E_j^{(m)}}, \quad E_j^{(m)} = \sum_i e_{ij}^{(m)}$$

p_j - track momentum in j-th event, $e_{ij}^{(m)}$ - energy in i-th subdetector, $e_{ij}^{(m)} = e_{ij}^{(0)} C_i^{(m)}$, $C_i^{(0)} = 1$
$1 \leq i \leq M$ (M_j - number of subdetectors in cluster), $1 \leq j \leq N_i$ (N_i - number of events),
RR - is the target reference response, $RR = 1$ by default.

Uncertainty of correction factors

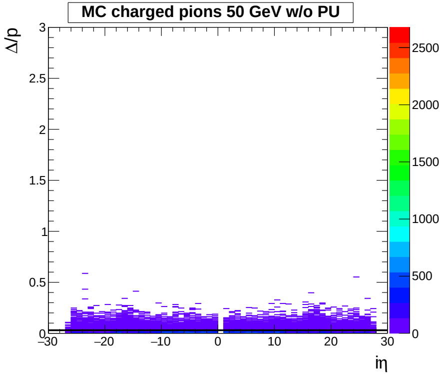
- Statistical uncertainty: $\Delta C_i = \Delta R_i \frac{\sqrt{\sum_j (w_{ij})^2}}{\sum_j w_{ij}}$, where ΔR_i is the r.m.s. of response of the subsample used for the i-th subdetector (r.m.s.$\sim$0.3 for the whole sample)
- Systematic uncertainty: difference between iterations

Target reference response for asymmetric distributions

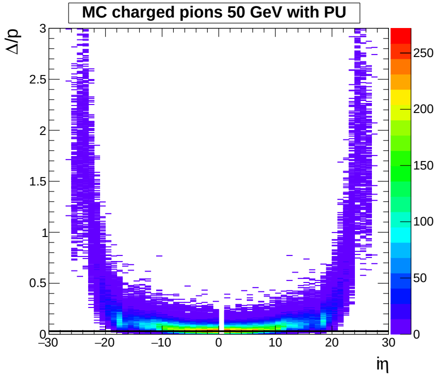
The iterative procedure shifts the **mean** of the distribution to the target value $\boldsymbol{RR}$.
Applying $RR = 1$ when mean $\neq$ mpv will result in mpv $\neq 1$ after iterations.
To get mpv $= 1$ one should use $RR =$ mean/mpv of the initial sample.

MC 2018: Relative energy deposition in the "extra" cone vs. $i\eta$

$\frac{\Delta}{p}$ is the fraction of deposited energy in the region surrounding the main cluster.



Fluctuations in pion-induced showers can give $\frac{\Delta}{p}$ up to 0.3, but for the overwhelming majority, $\frac{\Delta}{p}$ is below few percent.

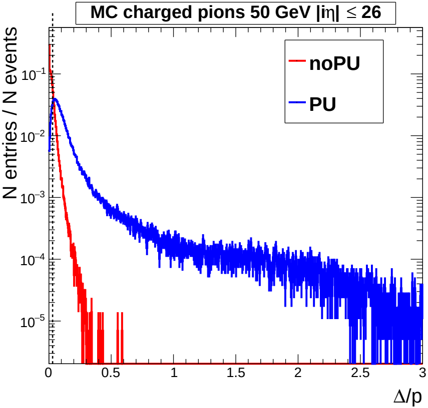


Due to pileup contribution, deposition in the "extra" cone at $|i\eta| > 20$ is always higher than for the pure pions without pileup.

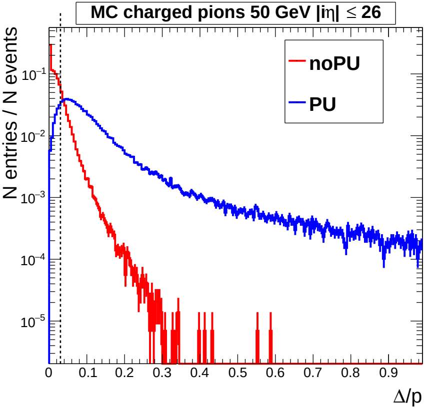
MC 2018: distribution of $\frac{\Delta}{p}$

Distributions are η-dependent, plot shows merged distributions for all $|i\eta| \leq 26$.

All range



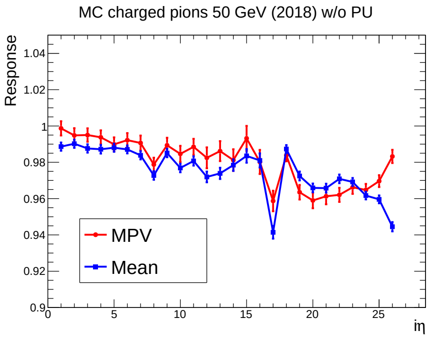
Zoomed

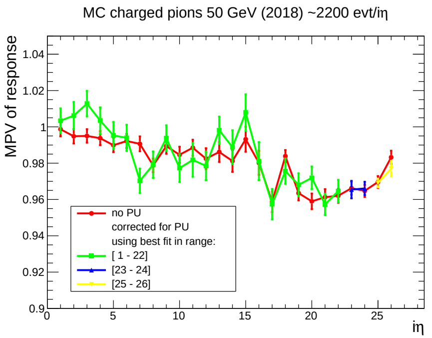


About 75% of events w/o pileup in HB have $\frac{\Delta}{p} < 0.03$.
Threshold $d_{\rm thr}$ to apply correction for pileup must help to balance between shower fluctuations and pileup contribution. **The threshold is set near intersection: $d_{\rm thr} = 0.03$.**

MC 2018: extraction of a_1 and a_2 from fit

- $i\eta+$ and $i\eta-$ are merged in training samples;
- training subsamples with equal number of events per $i\eta$ ($\sim$2200) were used;
- functor calculates the mean of corrected energy distribution at each $|i\eta|$.





For the sample w/o pileup, mean and MPV are consistent up to $|i\eta| < 25$. Left tail on distributions appears at $|i\eta| = 26$.

Fit was performed separately in 3 $|i\eta|$ ranges: [1,22]; [23,24]; [25,26]. For the last range, target mean was biased by 1.05.

Uncertainties of MPV from isotrack calibration in 2016

Standard isotrack selections, loose isolation and event-by-event correction for pileup

Uncertainties of MPV

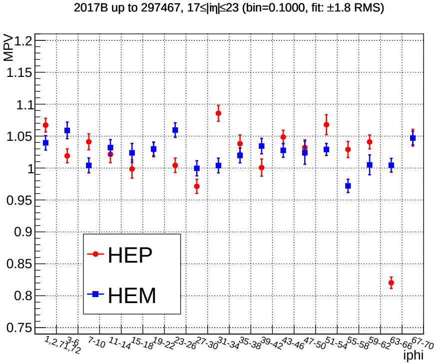
	Data (8/fb) 13 TeV for $\|i\eta\| \leq 23$		MC double π (5 mln) for $\|i\eta\| \leq 26$	
	HB	**HE**	**HB**	**HE**
Statistical uncertainties	0.5%	0.5%	0.2%	0.2%
Systematic uncertainties, including:	3.3%	2.5%	0.4%	1.2%
residuals after iterations	1.0%	1.3%	0.3%	1%
trigger bias	~1%	~1%	-	-
pileup contribution	3.0%	1.9%	0.3%	0.6%
Total	**3.4%**	**2.6%**	**0.5%**	**1.2%**

Crosscheck of ϕ-symmetry with isotrack: HEP17 tests

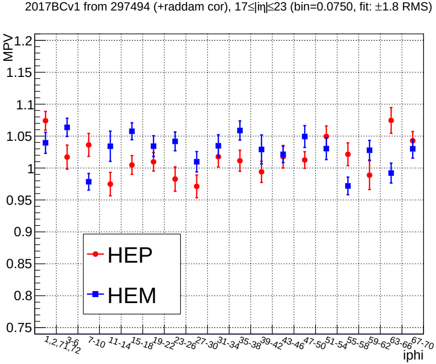
2017 data: response in HE before calibration

- merged $i\eta$ rings ($17 \leq i\eta \leq 23$);
- merged 4 neighbour $i\phi$ sectors (18 sectors in HE), so that 63-66 are together;
- standard isotrack selections applied (loose charge isolation + correction for pileup).

Before *in situ* calibration



With raddam corrections and HEP17 scaling



Changes of response at $i\phi$=63-66 after corrections $\sim$30%