Performence of CMS ECAL with first LHC data

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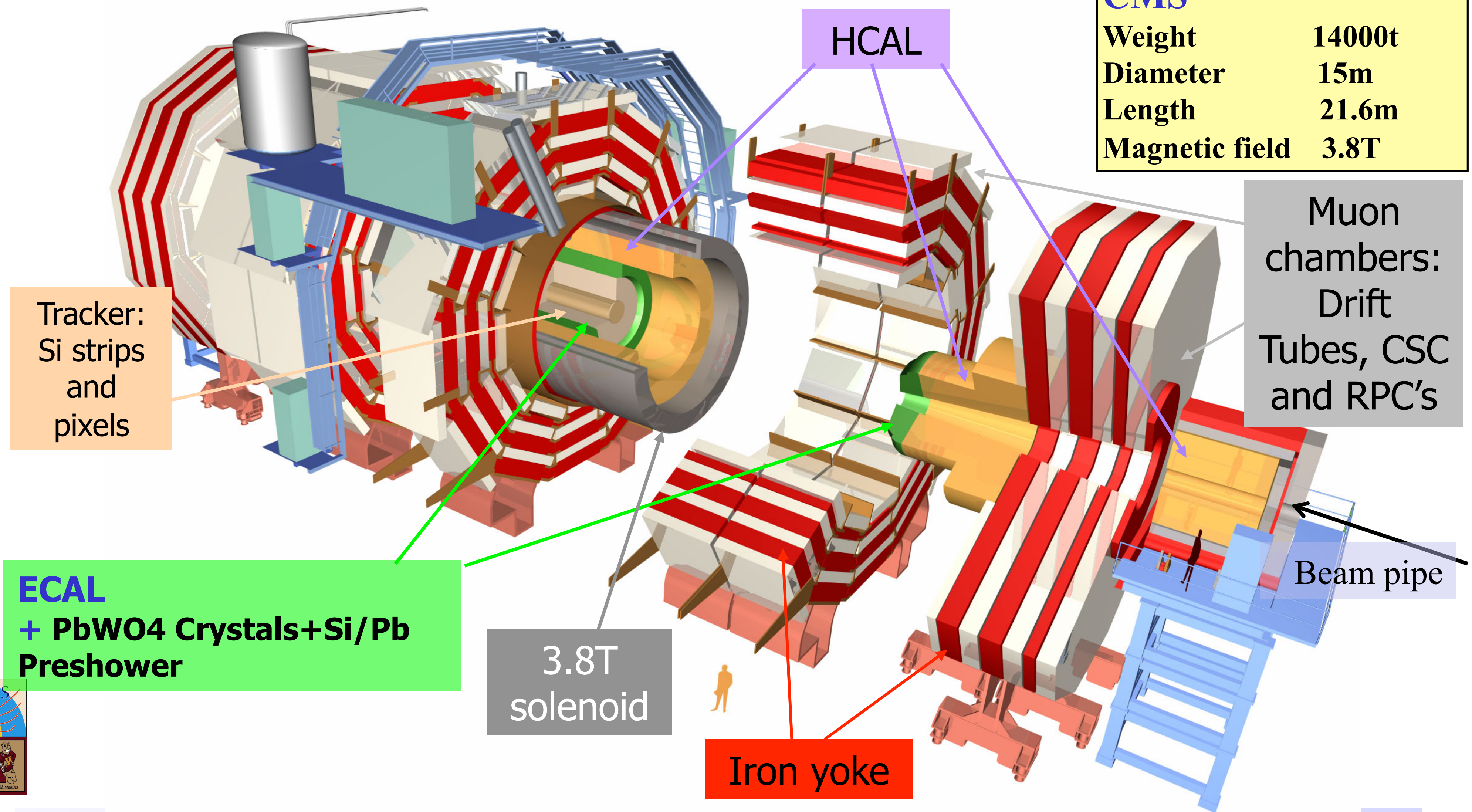
Outline

- Electromagnetic calorimeter at CMS
  - System description
  - Current status
- Results from cosmic rays
  - Muon stopping power in $PbWO_4$
  - Verification of global and regional energy scale
- Results from beam splash
  - Time measurement performances
- First collisions
  - π^0 observation for in-situ calibration

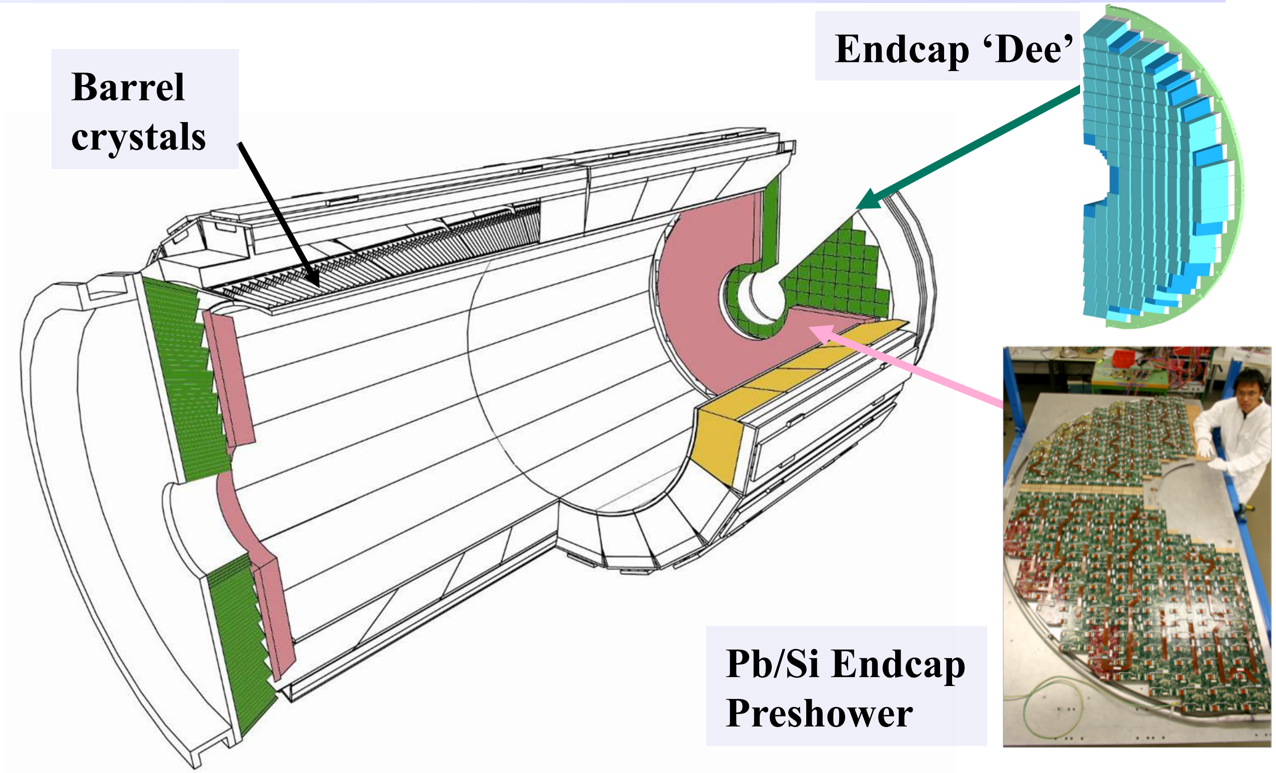
Electromagnetic calorimeter in CMS

CMS	
Weight	14000t
Diameter	15m
Length	21.6m
Magnetic field	3.8T



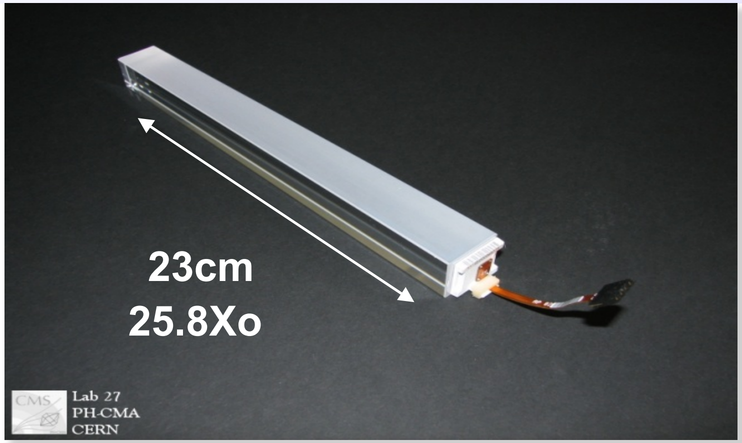
ECAL layout

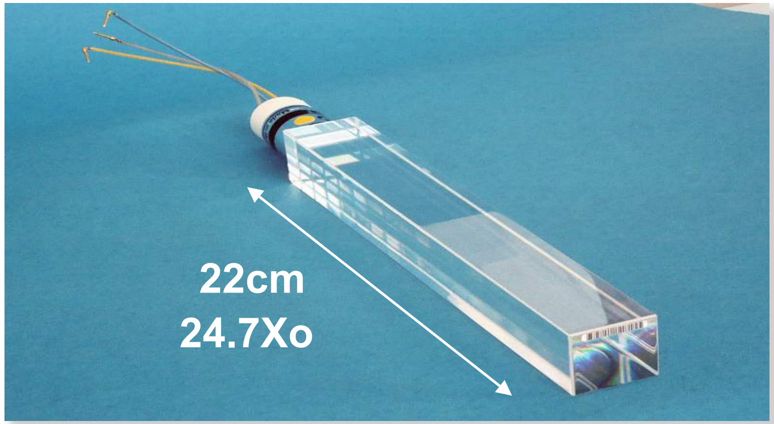
- Physics target:
  - Excellent resolution for di-photon systems; benchmark: $H \rightarrow \gamma\gamma$
  - Target resolution for unconverted γ at high energy: 0.5%
- Challenges:
  - Fast response
  - Tolerant to harsh LHC radiation environment



Barrel (EB)	Endcaps (EE)	Endcap Preshower (ES)
36 Supermodules (18 per half barrel)	4 Dees (2 per endcap)	Pb $(2X_0, 1X_0)$ / Si
61200 crystals	14648 crystals	2 planes per endcap
Total crystal mass 67.4t	Total crystal mass 22.9t	137216 Si strips, each 1.8x61mm2
$\vert\eta\vert < 1.48$	$1.48 < \vert\eta\vert < 3$	$1.65 < \vert\eta\vert < 2.6$
$\Delta\eta \times \Delta\varphi = 0.0175 \times 0.0175$	$\Delta\eta \times \Delta\varphi = 0.0175^2 \leftrightarrow 0.05^2$	

PbWO4 crystals and photodetectors





+ EB crystal, tapered
34 types, ~2.6x2.5 cm^2 at rear

+ Two avalanche photodiodes (APD), 5x5 mm2 each, QE ~75%, Temperature coeff.: -2.4%/°C

+ EE crystal, tapered 1 type, 3x3 cm^2 at rear
+ Vacuum phototriodes (VPT), more rad hard than silicon diodes; gain 8 -10 (B=3.8T), Q.E. ~20% at 420nm

Reasons for choice:

Homogeneous medium	
Fast light emission	~80% in 25 ns
Short radiation length	$X_0 = 0.89$ cm
Small Molière radius	$R_M = 2.10$ cm
Emission peak	425nm
Reasonable radiation resistance to very high doses	

Challenges:

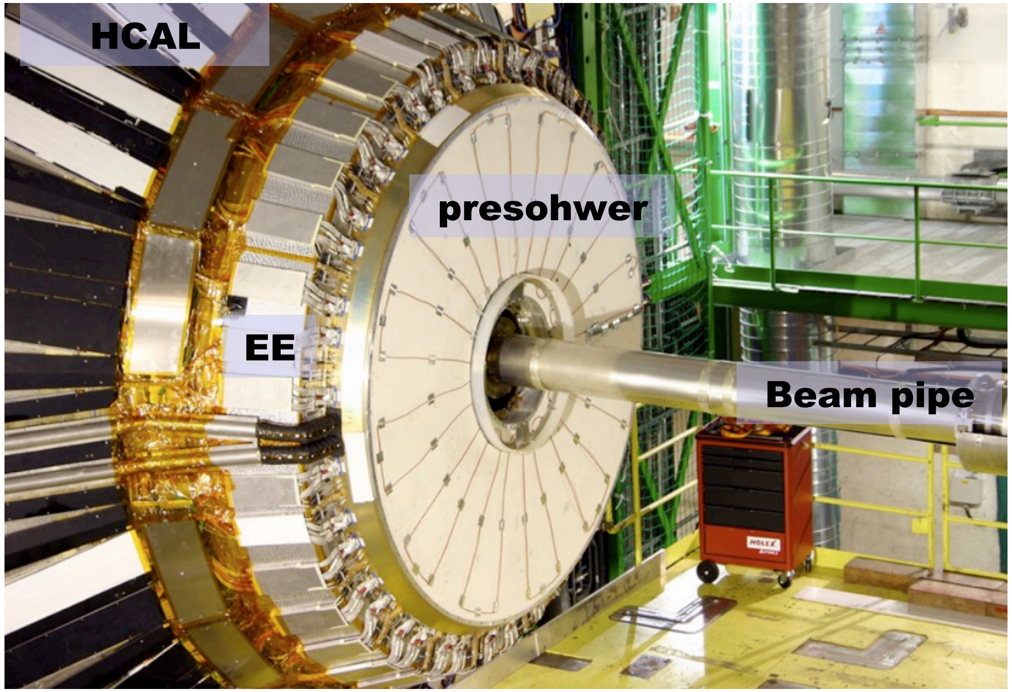
Crystal LY temperature dependence -2.2%/^{O}C
Need excellent thermal stability

Formation/decay of colour centres
Need precise light monitoring system

Low light yield (1.3% NaI)
Need photodetectors with gain in magnetic field

Status of the calorimeter

- **Preshower**:
  - Installed in Spring 2009
  - Fully active throughout 2009 and LHC operations
  - Excellent health and operational efficiency
  - 99.7% of 137k channels perfectly functional for physics



- **Crystal calorimeter:**
  - EB and EE fully active throughout 2009 and LHC operations
  - More than 99.2% of the 76k channels are in good health for physics
    - Of the remaining, 0.45% can be recovered using trigger data
  - Triggers relying on ECAL cornerstones of CMS level-1 trigger:
    - Barrel: commissioned since 2008
    - Endcap: deployed and successfully commissioned in 2009

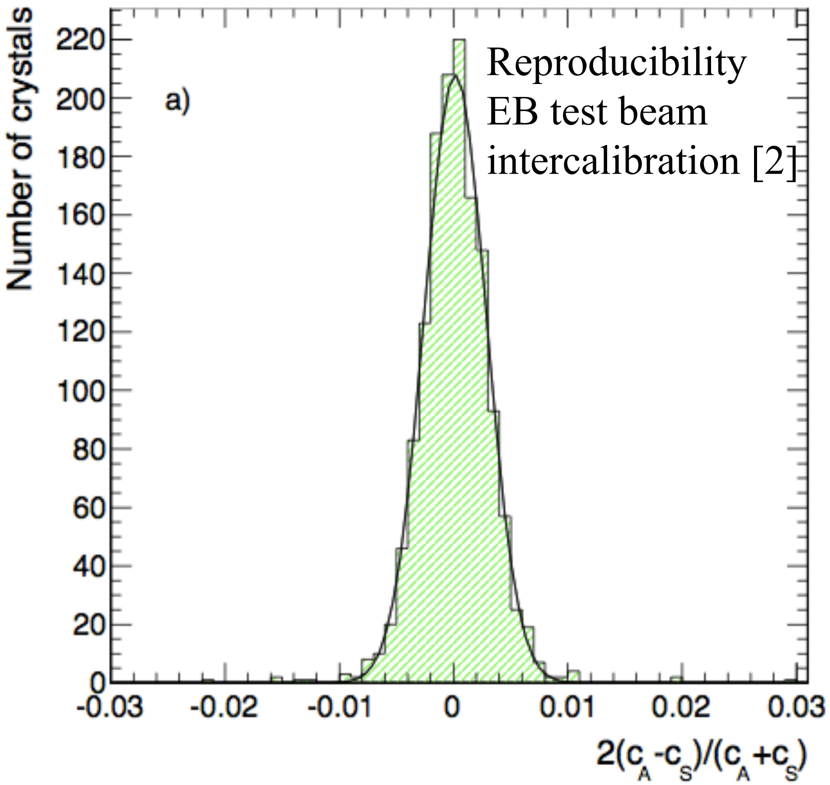
Pre-calibration

- **Inter-calibration** precision determines resolution at high energies
- Prior to installation @CMS, extensive campaigns of laboratory and test beams measurements to provide precalibrations:
  - **Barrel**:
    - 0.3% on 9 SM (electron beams)
    - 1.5-2.5% on 27 SM (cosmic rays)
  - **Endcaps**:
    - 7.4% (crystal LY ⊕ VPT gain)
    - 0.3% on 460 channels (electron test beam)
  - **Preshower**
    - 2% (cosmic rays)
- **Global energy scale**: tied to test beam for **EB**, **EE**, **ES**

$$\sigma(E) = \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c$$

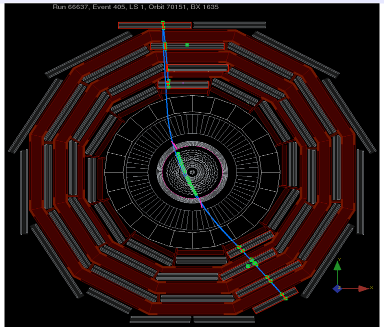
[1] EB study with 20-250 GeV beam electrons, 3x3 matrix:

a=2.8% **b**=127 MeV **c**=0.3%



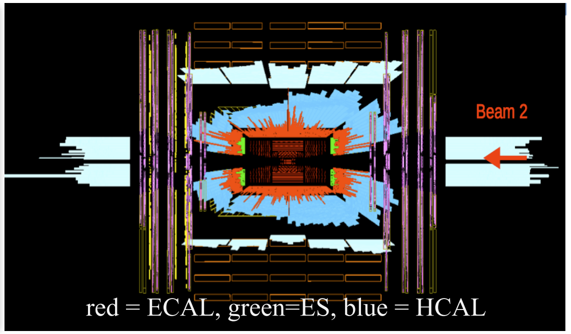
Overview of results I'll show

Extended cosmic rays data taking: with and without solenoidal magnetic field 3.8 T



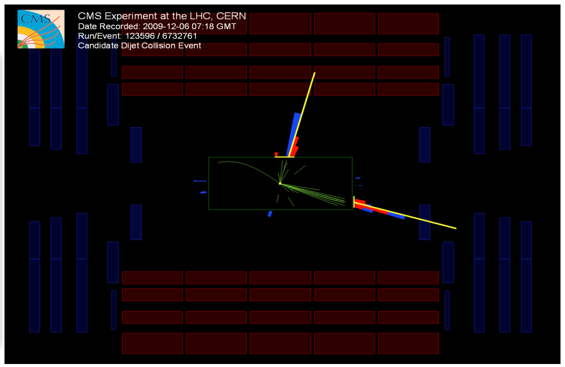
- Measurement of **stopping power** for muons
- Validation of local **energy scale for EB**

Beam splashes 2008&09: LHC 450 GeV beam dumped on collimators 150m from CMS



- Validation and improvement of **intercalibration for EE**
- Detector synchronization and **time measurement** performances

LHC collisions first collisions in 2009. $\sqrt{s}$ =0.9 TeV and 2.36 TeV



- Recorded collisions, verified synchronization
- Observation of π^0 and preparation for in-situ calibration

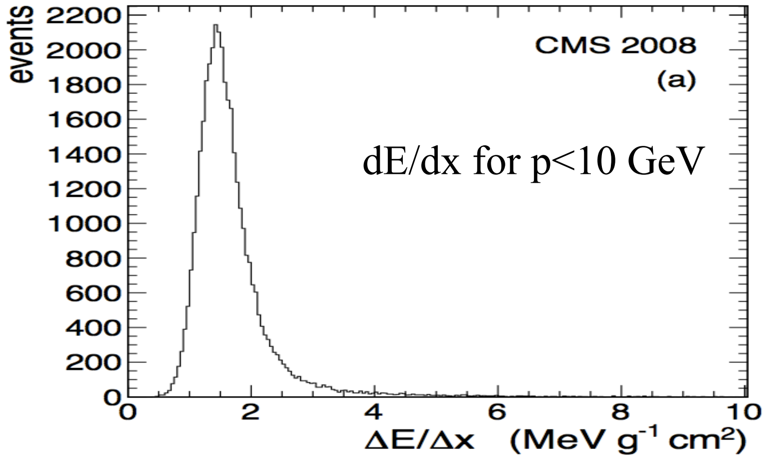
Cosmics rays

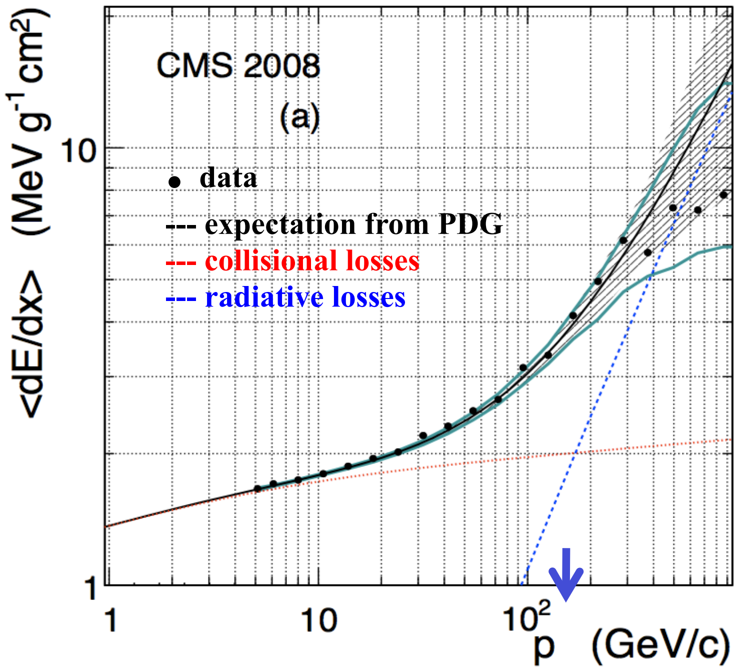
Muon stopping power in $PbWO_4$ [3]

- dE/ ρ dx as a function of muon momentum
- 88M cosmic muons 5GeV < p < 1 TeV
  - dE: ECAL clusters (typical E: 300 MeV)
  - momentum measured by CMS silicon tracker
  - dx is length traversed in ECAL crystals
- **Energy scale set at test beam validated in situ** in EB with an overall uncertainty <2%:
  - Statistical accuracy: 0.3%
  - Systematic uncertainty: 1.6%
    - 1.2% online thresholds of online data reduction and clustering
    - 1.0% uncertainty on containment corrections
- Muon critical energy for $PbWO_4$:

$$160^{+5}_{-6}\,(\text{stat.}) \pm 8\,(\text{syst.})\ \text{GeV}$$

(PDG calculated: 169.5 GeV)



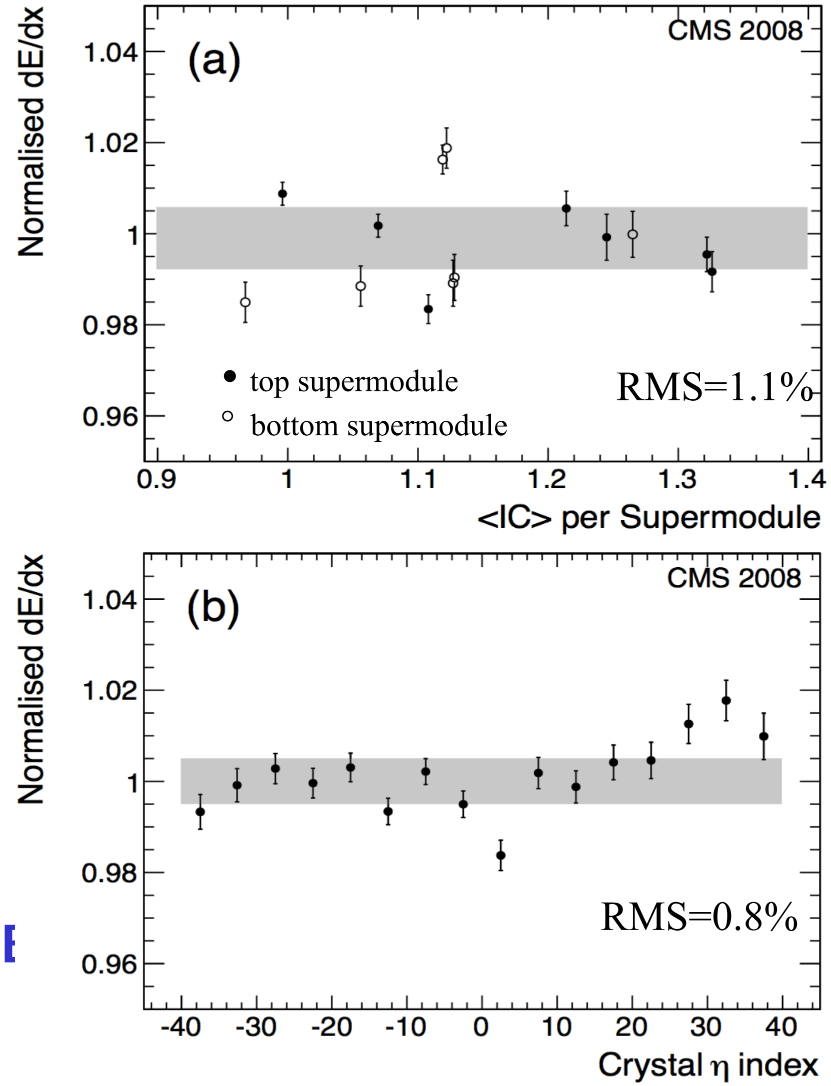


Validation of EB local energy scale [4]

- dE/dx across supermodules (SM: 1.7k Xtal) compared to average intercalibration (different light yield)

- Selections:
  - Restrict to top-bottom SM
  - Collisional losses only: 5GeV<p<10 GeV
  - Angle muon-crystal <30˚
- Statistical uncertainty: 0.4%
- Systematic uncertainty (grey band)
  - Scale dependence on muon-crystal angle (0.5%)
  - Variation of average muon momentum across SM's (<0.5%)

- Same cross check for group of 5 const-η rings (1.8k Xtal), vs η
- **Response uniformity verified across EB regions at 1% level**

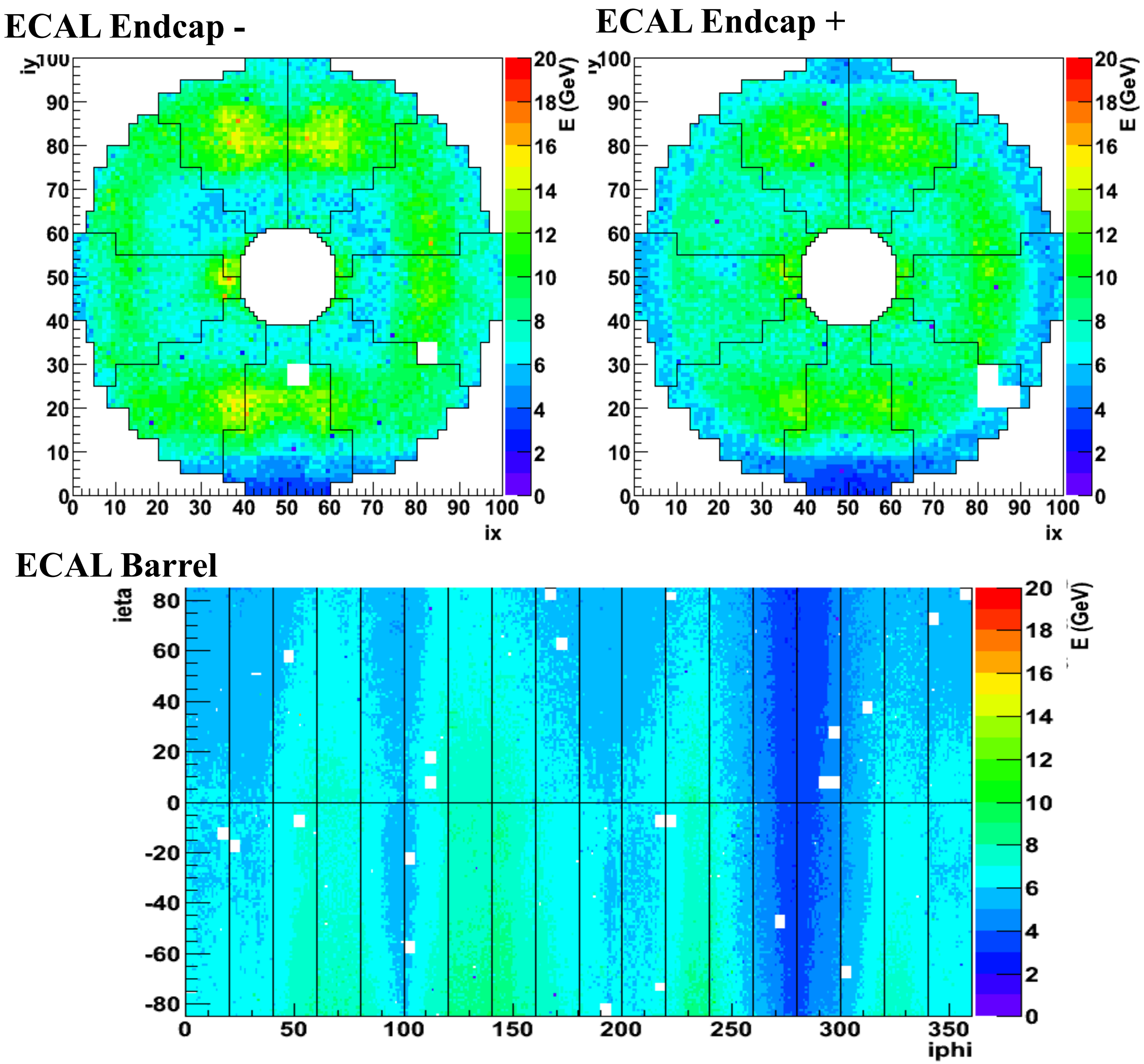


Beam splashes

Crystal ECAL: response to beam splashes 2009

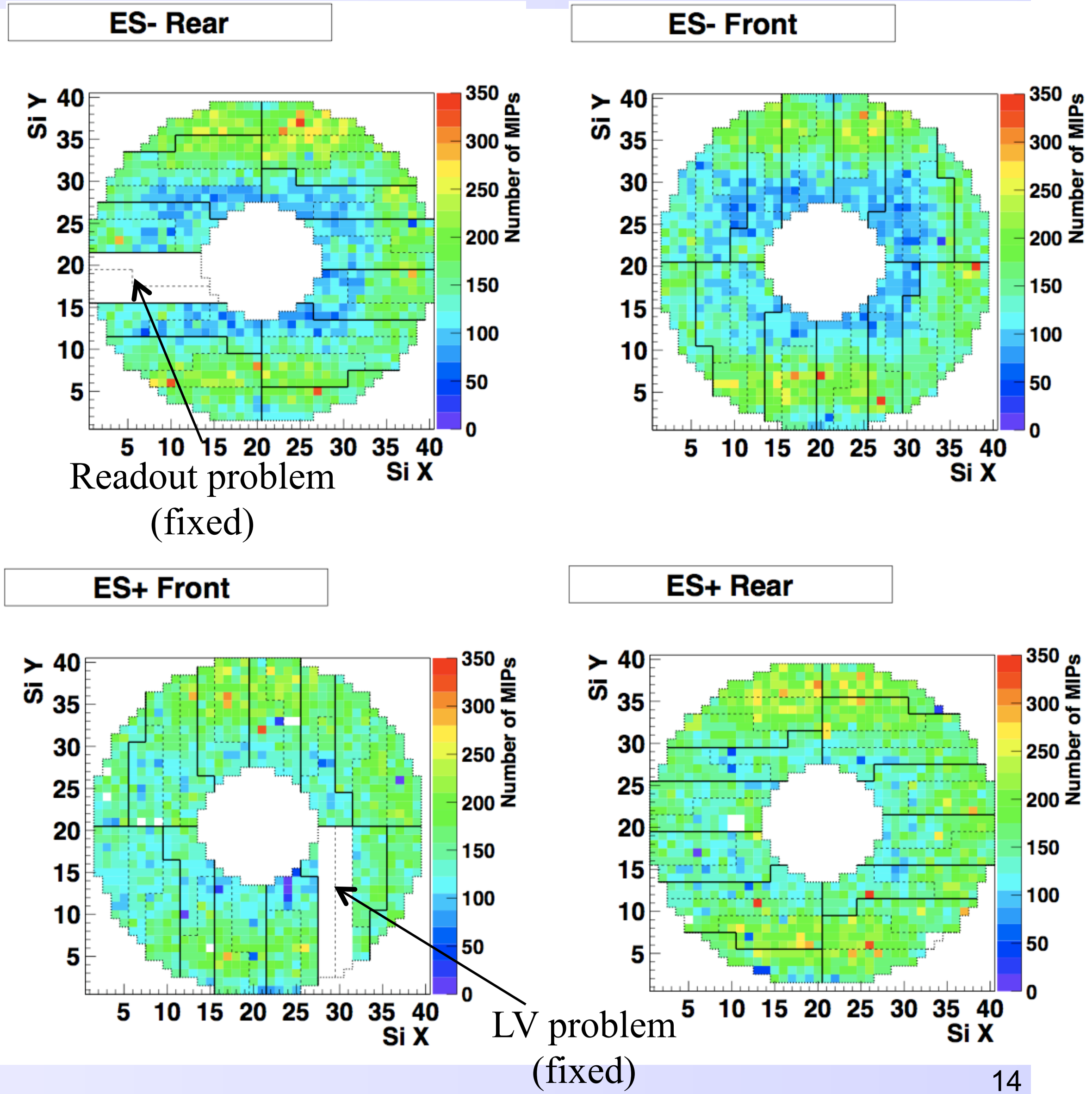
- Average energy per crystal over ~800 splashes: 6-12 GeV
- White regions excluded from readout
- ECAL barrel was the trigger source for CMS for the splashes

- Modulation in plots results from combination of energy flow and CMS geometry effects:
  - shielding structures (square) and floor of the LHC tunnel (bottom)
  - Lower energy at large radius of downstream EE, due to shielding effect of barrel; indicates reduction of muon flux of 25%
  - The average muon fluence is about 5 muons cm^{-2}



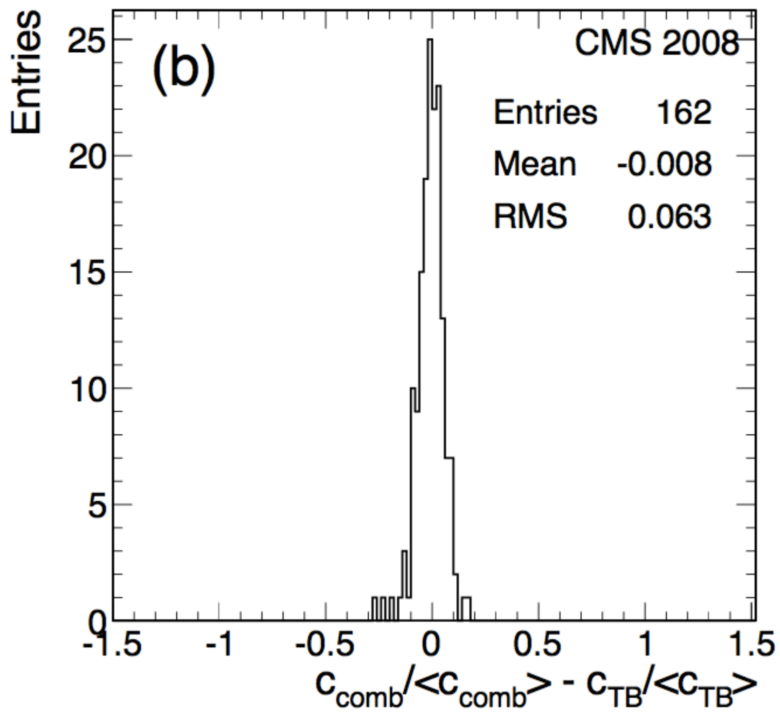
Preshower: response to beam splashes 2009

- Preshower was installed (Spring) & commissioned in 2009. It successfully operated during all beam splash events.
- White regions were excluded from readout: both fixed
- Number of muons per sensor crossing the ECAL preshower in a single beam splash:
  - Flux modulations consistent with the energy maps seen in the ECAL Endcaps
  - Isolated hot spots attributed to muon bremsstrahlung
  - Sensors cover 37.1 cm^2, thus the average muon fluence is about 5 muons cm^{-2}.



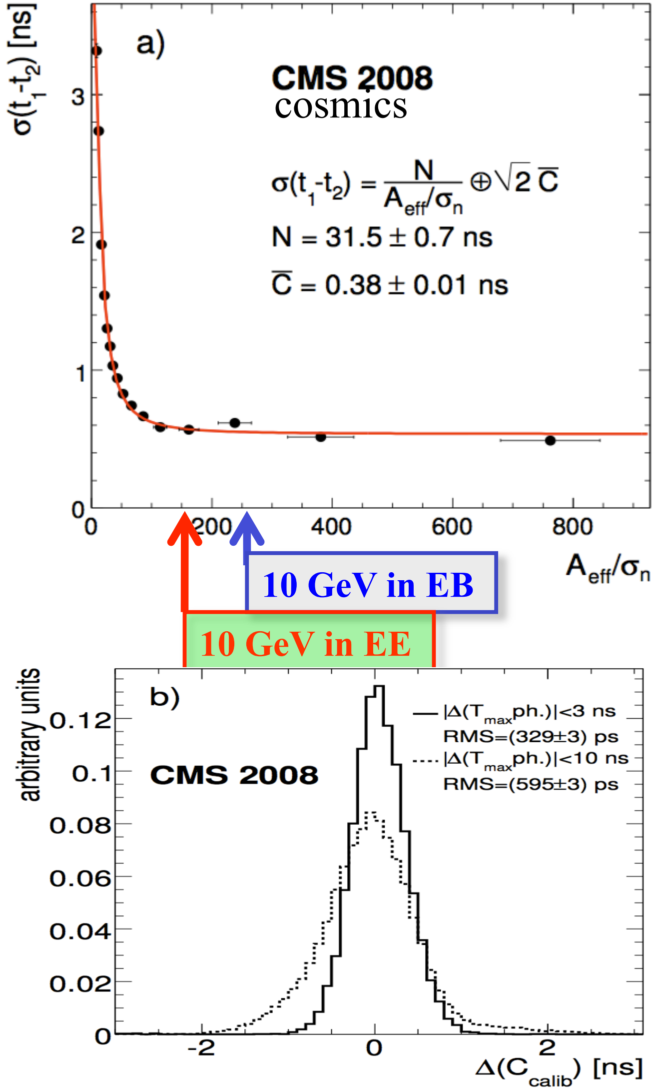
Improvement of EE inter-calibrations [4]

- Assume local uniformity of splash energy deposits:
  - Equalize response within 5x5 matrix
  - Inter-calibrate 5x5 matrices using laboratory pre-calibrations
- Combine splash-derived intercalibrations (10.4%) with laboratory pre-calibrations (7.4%)
- Validate the combination against EE region which was inter-calibrated at test-beam
- **Pre-calibration of EE improved to 6.3%**



Time measurement and ECAL synchronization [5]

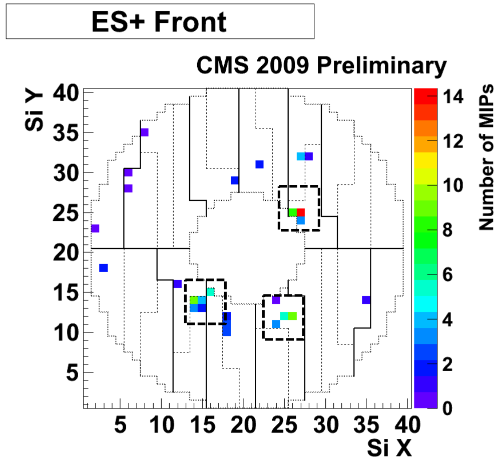
- Physics case: delayed particles (HSCP, GMSB γ)
- Time resolution: $$\sigma(t) = \frac{N}{A/\sigma_N} \oplus C$$
  - **A**: amplitude in ADC
  - σ_N: single sample noise (EB: 1.06, EE: 2.06)
  - **N**: noise term
  - **C**: constant term
- Resolution comparing 2 Xtal within the same cluster
- E>10 GeV performance determined by single channel **time calibration** (**C**) to account for:
  - Hardware time misalignment: O(1ns)
  - Non-universality of ECAL signal shapes
- Time pre-calibration set against μ TOF in splash events:
  - Statistical: <100 ps
  - Systematic: dependence on absolute value of μ TOF (<600ps)
- **ECAL synchronized with splashes for sub-ns time precision at high energy**

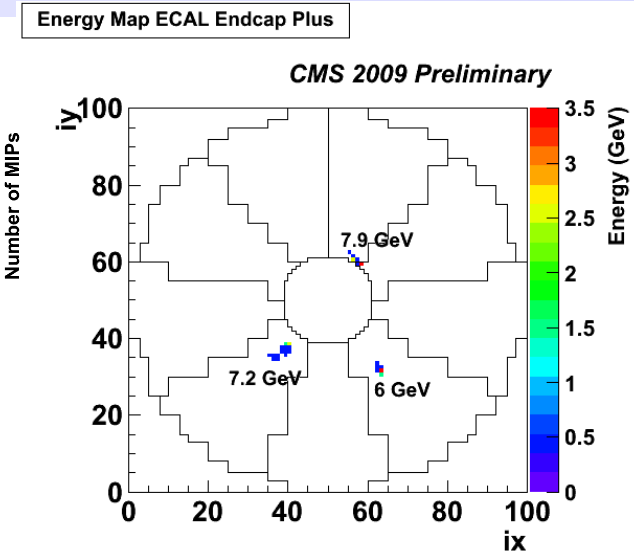


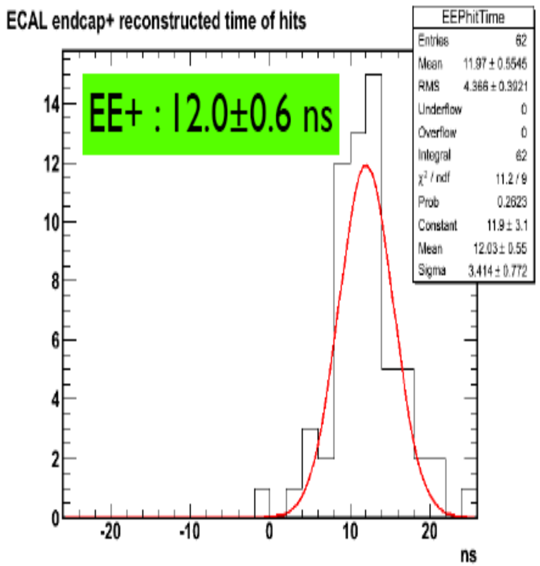
LHC collisions

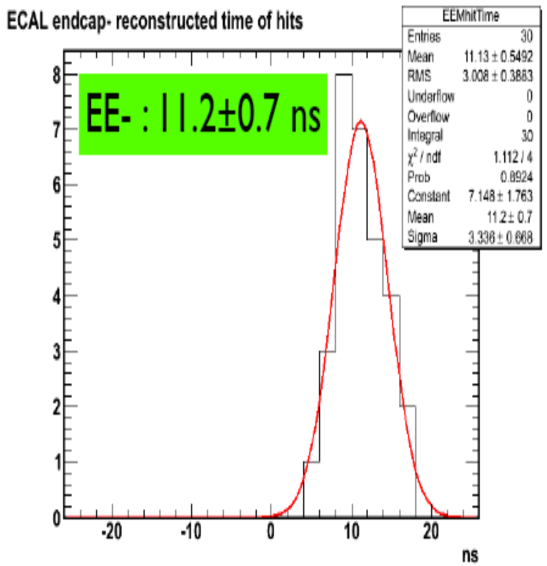
November 23rd: first 900 GeV collisions

- First collisions immediately visible in the endcap
- clusters matching between two preshower planes and ECAL crystals



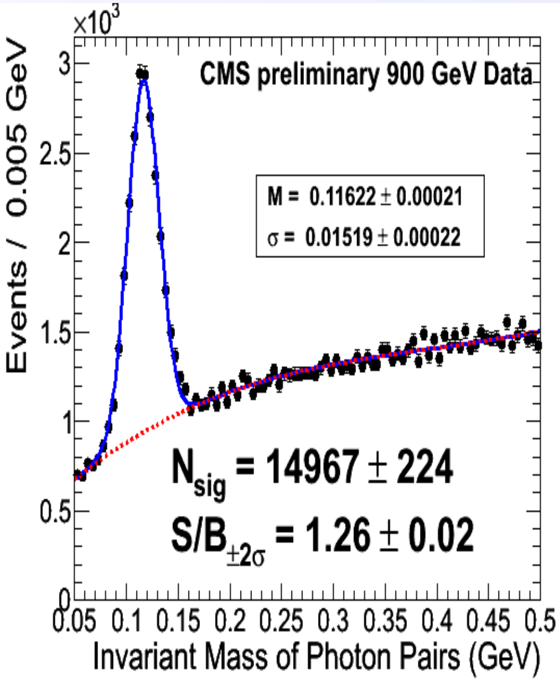


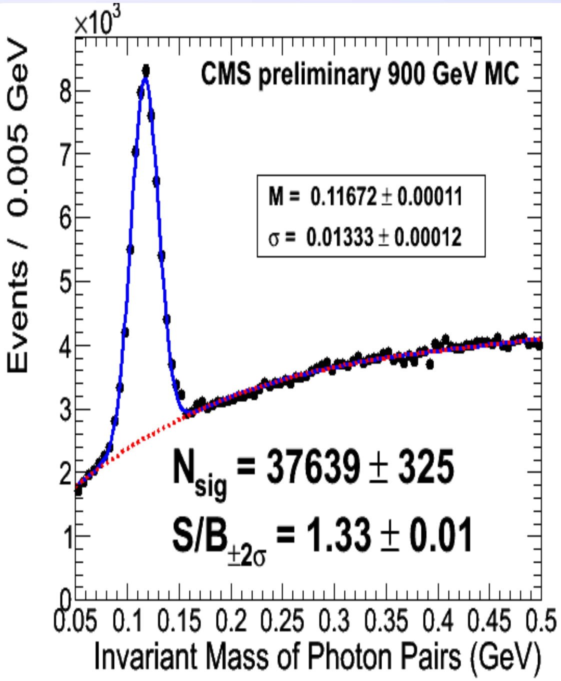




- First events validate relative synchronization EE+/EE- and indicate collisions cantered in CMS:
  - Time averages compatible (value determined by LHC-CMS clock phase)
  - 3.4 ns width compatible with O(1GeV) deposits

Observation of $\pi^0 \rightarrow \gamma\gamma$ and ECAL calibration





- Uncorrected MC and data distributions:
  - Compatible S/B, average and width
- π^0 mass low due to readout threshold (100 MeV) and 3x3 matrix energy containment.

- π^0 mass constraint inter-calibration
  - Dedicated filter in high level trigger: up to 1 kHz π^0
  - Precision 0.5% with 2000 π^0/Xtal (EB)➔ (~10pb^{-1})
- Prospects:
  - Commissioning of HLT selections for high rate π^0 stream
  - Measuring from data corrections D(η,φ)
  - Deploy in-situ inter-calibration

CMS ECAL: conclusions

- Crystal part and preshower of CMS Electromagnetic calorimeter are fully operational at the CERN LHC

- Cosmic ray data:
  - Measure muon stopping power and critical energy in $PbWO_4$
  - Validate global energy scale (2%) and regional uniformity (1%)

- Beam splash events allow to validate and improve:
  - Endcap startup calibrations (6.3%)
  - Internal synchronization (<600ps) and time measurement performances

- ECAL successfully recorded collision events at LHC
  - Neutral pion observed
  - Commissioning of in-situ calibration

References

- [1] P. Adzic et. al. *"Energy resolution of the barrel of the CMS Electromagnetic Calorimeter"*, JINST 2 P0400 (2007)
- [2] The CMS Electromagnetic Calorimeter Group "*Intercalibration of the Barrel Electromagnetic Calorimeter of the CMS Experiment at start-up*". JINST 3 P10007 (2008).
- [3] CMS collaboration "*Measurement of the Muon Stopping Power in Lead Tungstate*". arXiv:0911.5397
- [4] CMS collaboration "*Performance and Operation of the CMS Electromagnetic Calorimeter*" arXiv:0910.3423 accepted by JINST.
- [5] CMS collaboration "*Time Reconstruction and Performance of the CMS Electromagnetic Calorimeter*" arXiv:0911.4044 accepted by JINST.

dE/ ρ dx in $PbWO_4$ [3]: errors discussion

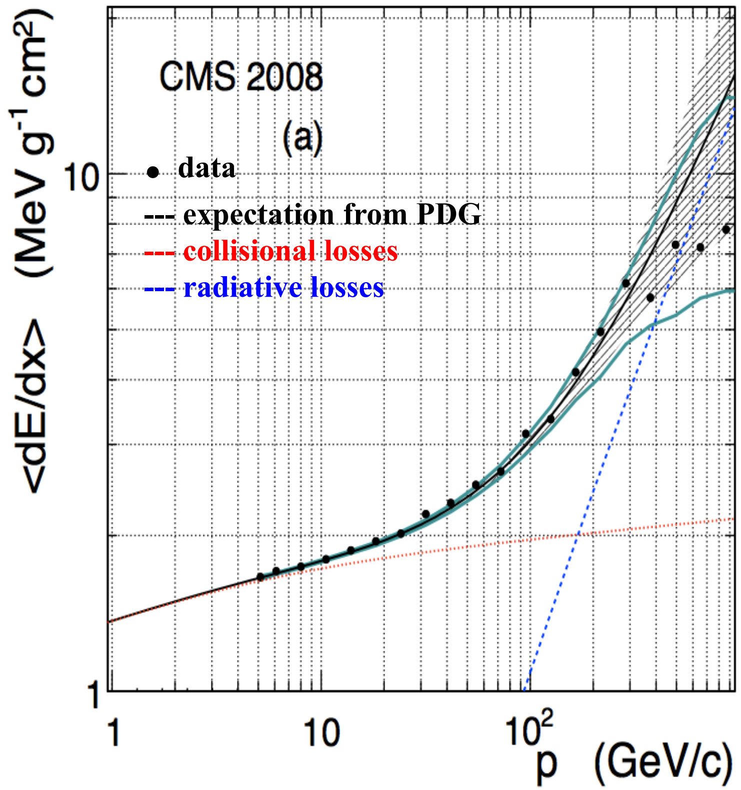
- dE/ ρ dx fitted with:

$$(dE/dx)_{meas} = \alpha \left[\left(\frac{dE}{dx}\right)_{coll} + \beta \times \left(\frac{dE}{dx}\right)_{rad} \right]$$

$$\alpha = 1.004^{+0.002}_{-0.003}\,(\text{stat.}) \pm 0.016\,(\text{syst.})$$
$$\beta = 1.07^{+0.05}_{-0.04}\,(\text{stat.}) \pm 0.6\,(\text{syst.}).$$

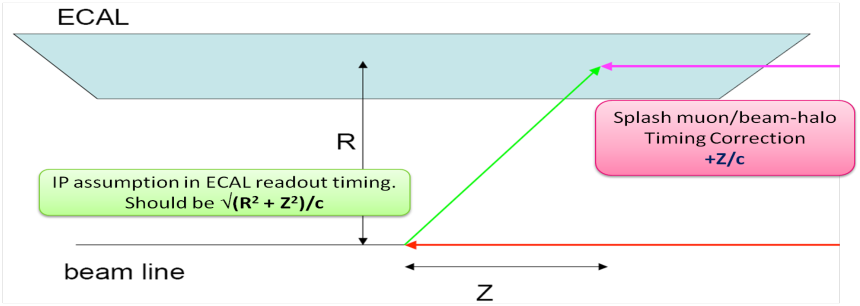
- β controls critical energy
- α controls energy scale; syst. uncertainty: 1.6%
  - 1.2% online thresholds of online data reduction and clustering
  - 1.0% uncertainty on containment corrections

- dE/ ρ dx p>50 GeV: skewed distributions w/ decreasing stat. ➔ mean converging slowly
- Uncertainties used in the fit take this into account
- P.D.F. for <dE/ρdx> from 10k Geant4 pseudo-experiments using the same statistics as the measurement. Define:
  - Central 68% interval: shaded region
  - Minimum width 68% interval (containing the most probable value): green limits
- Most probable <dE/ρdx> lower than expectation value



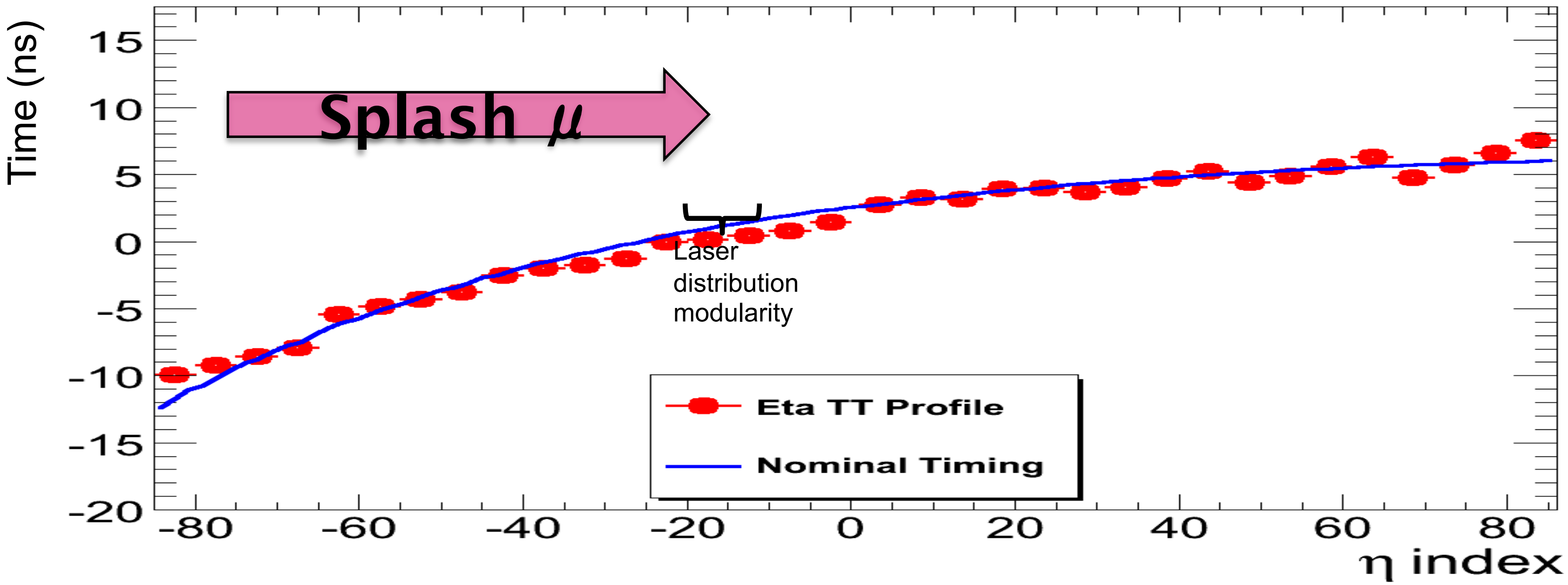
Beam splashes and synchronization

ECAL synchronization schema for collisions:



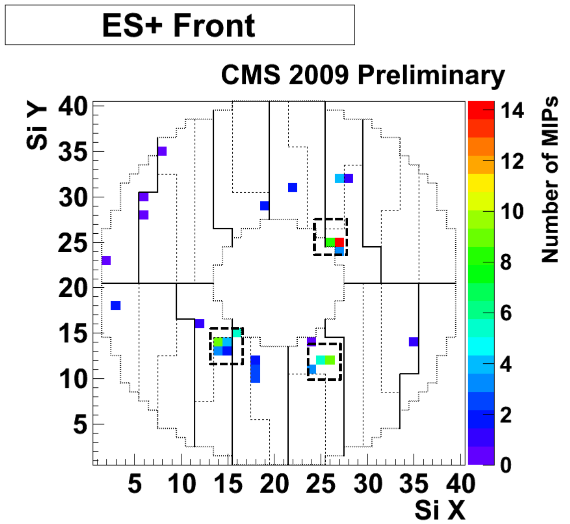
Measuring time inter-calibration with splash events:

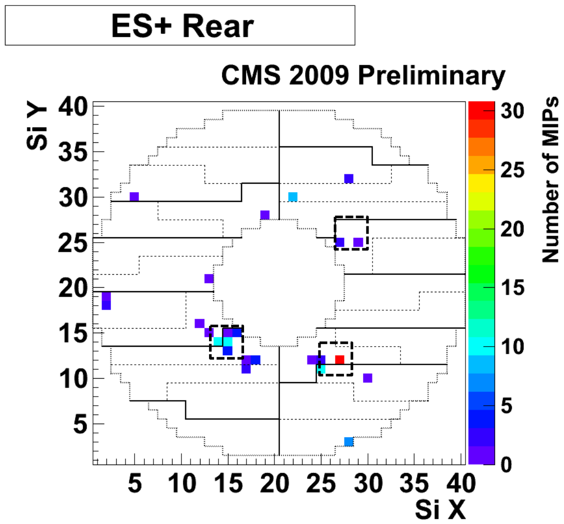
$$\Delta t = \Delta t_{Readout} + \Delta t_{PlaneWave} = (\sqrt{x^2 + y^2 + z^2} - R \pm z)/c$$

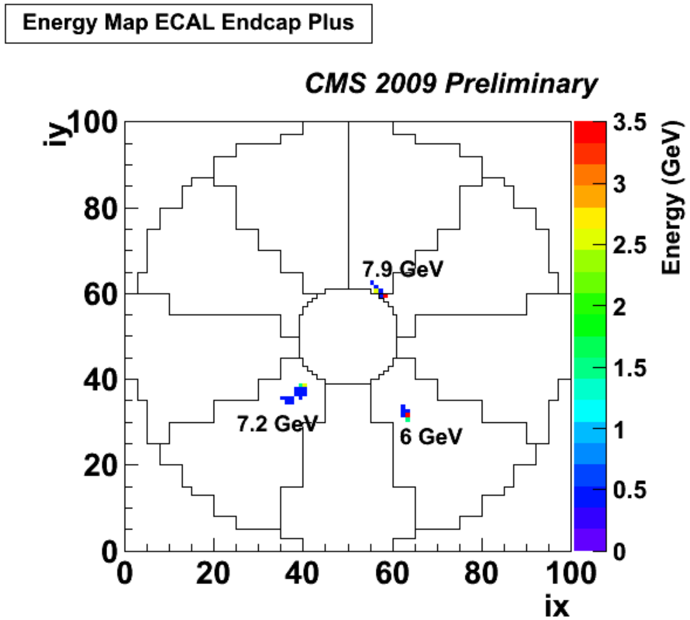


Cluster matching

- First collisions immediately visible in the endcap
- clusters matching between two preshower planes and ECAL crystals
- Showing here both preshower planes

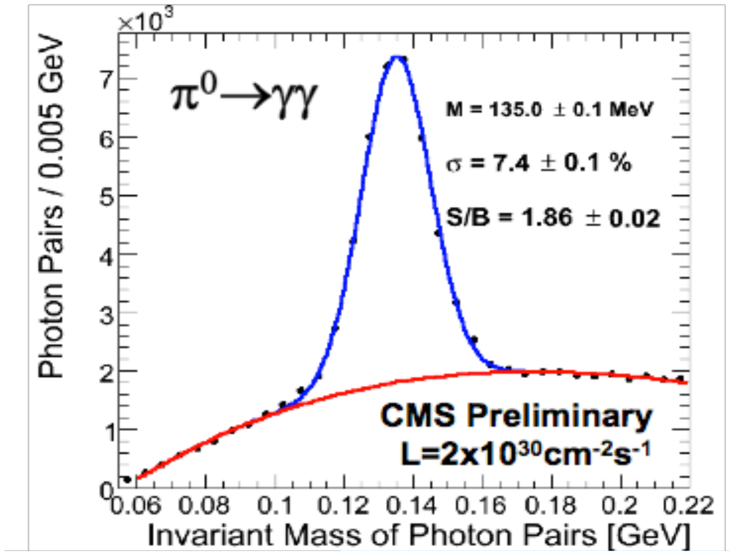


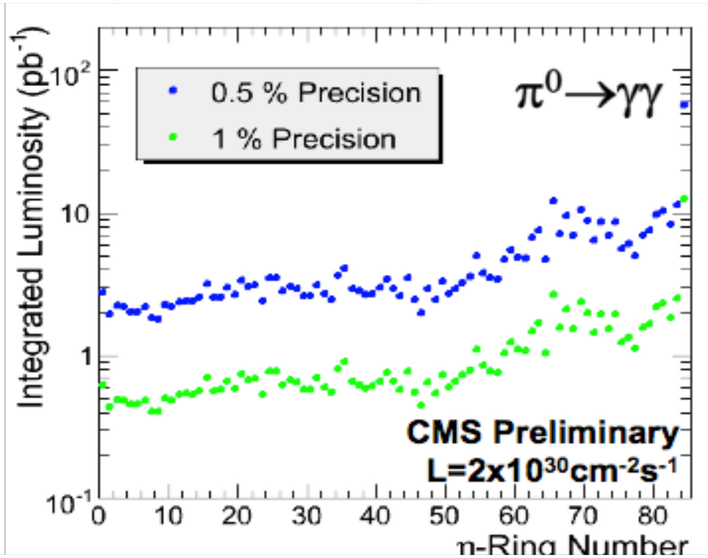




In-situ calibration strategy

Strategy	Time	Precision
ϕ symmetry: use invariance of mean energy deposited by jets at fixed η	Few hours	~2-3%
$\pi^0 \to \gamma\gamma$: mass peak at low L	Few days	≤1%
$Z \to ee$: energy scale calibration	100 pb^{-1}	<1%
$W \to e\nu$: E/p measurement	5-10 fb^{-1}	0.5%





Observation of $\pi^0 \rightarrow \gamma\gamma$ and ECAL calibration

- Raw π^0 mass low due to readout threshold (100 MeV) and 3x3 matrix energy containment

- Applying corrections measured from MC: