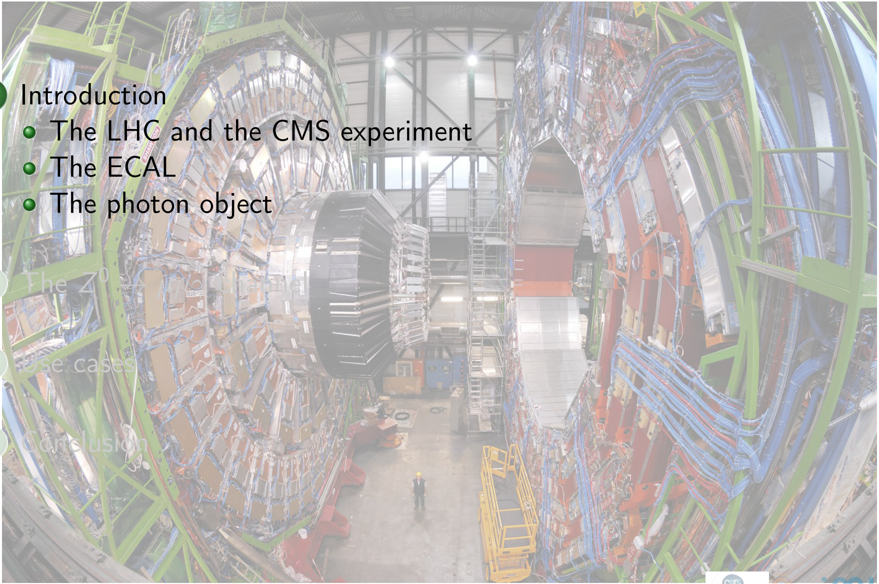
Photon energy scale

Study of radiative Z^0 decays in the CMS experiment

C. Bâty, O. Bondu, H. Brun, G. Chen, S. Gascon-Shotkin, M. Lethuillier, L. Sgandurra, J. Tao, H. Xiao, Z. Zhang

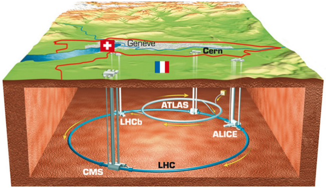
IPN Lyon, IHEP Beijing (in collaboration with CMS Caltech group)

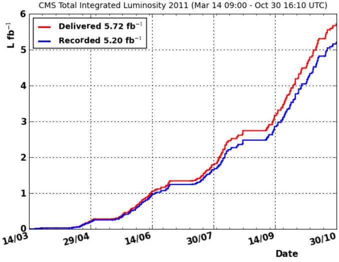
12.03.22 - 5th France China Particle Physics Laboratory Workshop



1. Introduction
   - The LHC and the CMS experiment
   - The ECAL
   - The photon object
2. The $Z^0 \to \mu\mu\gamma$ channel
3. Use cases
4. Conclusion

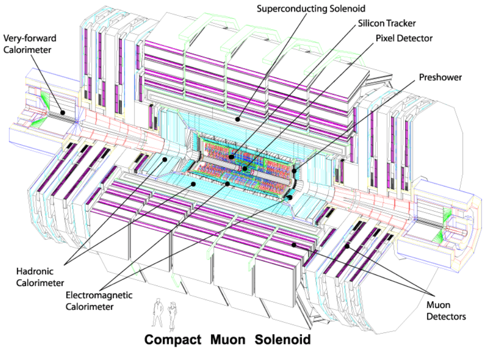
The Large Hadron Collider (LHC)

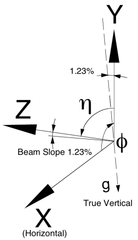




- Proton-proton collider
- Built at CERN, at the France-Switzerland border
- Energy reaching 3.5 TeV per beam, 4 TeV since last week, 2 squeezed beams currently circulating!
- 27 km in circumference : 1232 superconducting magnets (1.9 K, up to 8.3 T)
- Bunch crossing every 50 ns
- 10^{14} protons per beam
- Instantaneous luminosity about 4×10^{33} cm^{-2}s^{-1}
- Four collision points: CMS is at one of them
- More than 5 fb^{-1} of integrated luminosity recorded by CMS

The Compact Muon Solenoid (CMS)



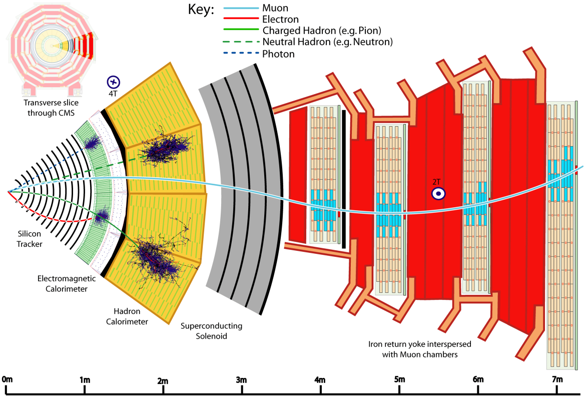


Coordinates

- $\eta = -\ln\left[\tan\left(\frac{\theta}{2}\right)\right]$
- $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$

- One of the two multi-purposes apparati at the LHC
- 21.6 m in length, 7.5 m in radius, weighting 12 500 t
- Superconducting solenoid (3.8 T)
- Compactness : tracker, electromagnetic and hadronic calorimeters within the solenoid
- Several types of muon chambers interleaved with the return yoke

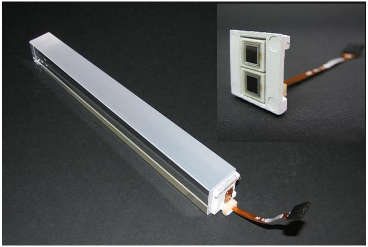
Subdetectors

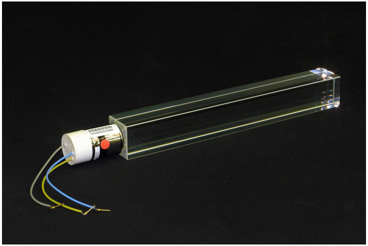


- Pixel detector: determination of the primary vertex of the event
- Silicon tracker: measure transverse momentum of charged particles
- Electromagnetic calorimeter (ECAL): energy of photons and electrons
- Brass hadronic calorimeter: (HCAL): energy of hadrons and jets
- Muon chambers: RPC, DT, CSC: muon momentum

Design: scintillating crystals

Barrel ↓

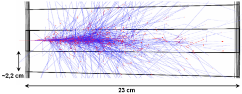




Endcaps ↑

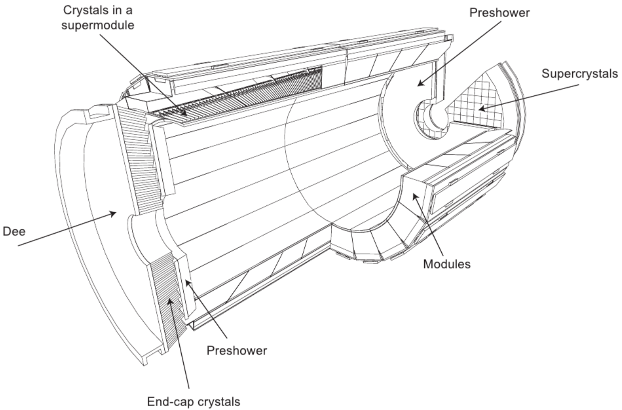
- Scintillating lead tungstate ($PbWO_4$) crystals: very dense material, radiation length 0.89 cm, Molière radius 2.2 cm
- Collection of scintillation light:
  - Avalanche Photo-Diodes in barrel
  - Vacuum Photo-Triodes in endcaps

- Good resolution (homogeneous crystal)
- 80 % of scintillation light emitted in 25 ns
- Radiation hard



ECAL designed to be fast, compact, radiation-hard with fine granularity and excellent energy resolution

Geometry layout



- Central part (EB: ECAL Barrel) composed of 61 200 crystals
- Each endcaps (EE : ECAL Endcap) composed of 7 324 crystals
- Crystals pointing to the interaction point
- Silicon sampling preshower detector (ES : ECAL preShower) for γ / π^0 discrimination

Energy resolution & laser monitoring

- ECAL energy resolution parametrized in electron test-beams:

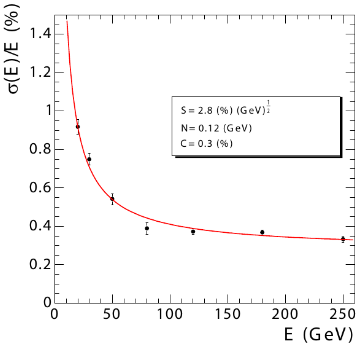
$$\frac{\sigma(E)}{E} = \frac{2.8\,\%}{\sqrt{E(\mathrm{GeV})}} \oplus \frac{0.12\,\%}{E(\mathrm{GeV})} \oplus 0.3\,\%$$

stochastic $\oplus$ noise $\oplus$ constant

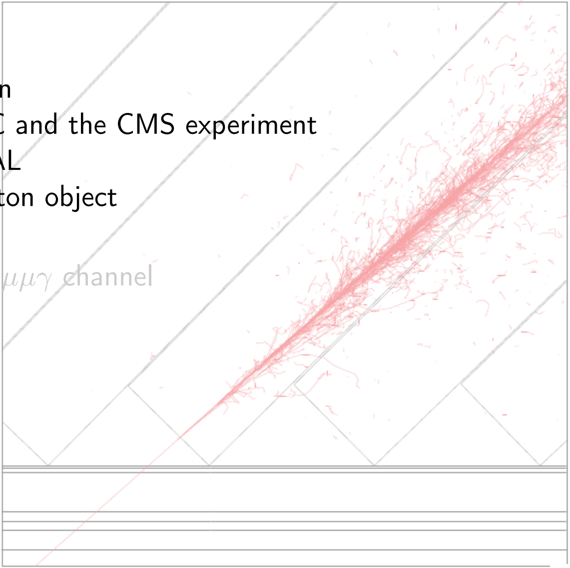
- For photons of $E \approx 100$ GeV, energy resolution is dominated by the constant term

Goal: constant term $< .5\,\%$ during data taking: importance of quality of calibration and monitoring

CMS Collaboration, J. Instrum. 2, (2008), S08004



- Transparency loss due to ionisation provoked by radiations $\rightarrow$ dedicated laser system
- High-voltage and temperature monitoring
- Intercalibration



1. Introduction
   - The LHC and the CMS experiment
   - The ECAL
   - The photon object
2. The $Z^0 \to \mu\mu\gamma$ channel
3. Use cases
4. Conclusion

From rechits towards particle energy

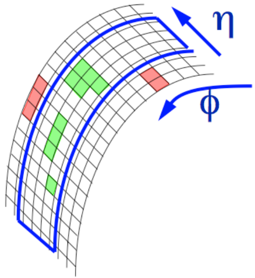
$$E_{e,\gamma} = F_{e,\gamma}(\eta) \cdot \sum_{\text{cluster crystals}} G(\text{GeV}/ADC) \cdot S_i(T,t) \cdot c_i \cdot A_i$$

- A_i 'rechit'
- c_i intercalibration constant
- S_i correction for crystal transparency loss T as a function of time t
- G global energy scale
- F energy correction: depends on the particle type, energy, pseudo-rapidity, contains the cluster energy corrections

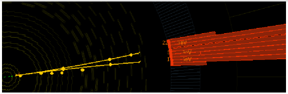
↓ Energy ↓

- Different physics channels for calibration:
  - ϕ-symmetry of minimum bias events
  - $\pi^0 \to \gamma\gamma$, $\eta \to \gamma\gamma$ decays
  - $J/\Psi \to e^+e^-$ decays
  - E/p ratio of electrons from $W^\pm \to e^\pm\nu$ decays
  - $Z^0 \to e^+e^-$ decays
  - $Z^0 \to \mu\mu\gamma$ decays
- Laser monitoring for crystal transparency loss

Clustering algorithms



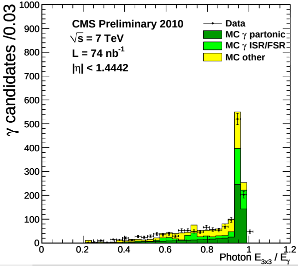
- A particle deposits its energy in several crystals: optimize clustering to give the best energy resolution
  - L'algorithme "hybrid" dans le tonneau
  - L'algorithme "multi-5x5" dans les bouchons
- About 50 % of photons convert in electron-positron pairs, due to material budget
- $R_9 = \frac{E_{3\times3}}{E_{SC}}$ to identify conversions at the cluster level

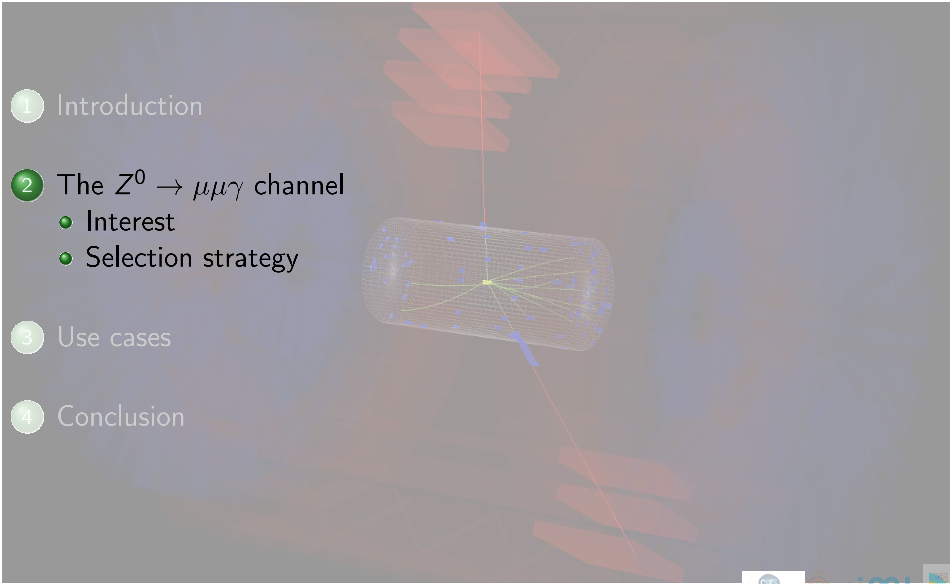


Photon reconstruction and identification at sqrt(s) = 7 TeV (CMS-PAS-EGM-10-005)

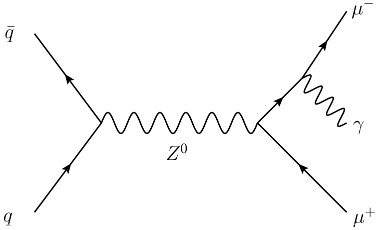
Four categories of assignment of the photon energy:

- photon in EB and $R_9 > 0.94$: $E^\gamma = E_{5\times5}$
- photon in EB and $R_9 < 0.94$: $E^\gamma = E_{hybrid}$
- photon in EE and $R_9 > 0.95$: $E^\gamma = E_{5\times5}$
- photon in EE and $R_9 < 0.95$: $E^\gamma = E_{multi5\times5}$





The $Z \to \mu\mu\gamma$ channel



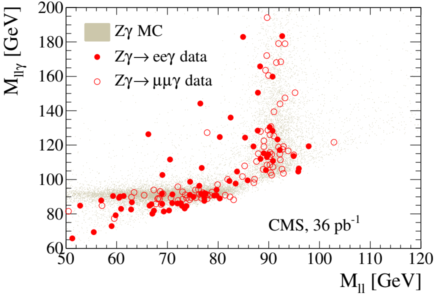
- Final State Radiation event
- Precise measurement on Z^0 boson mass and width from LEP
- Precision on muon momentum scale in CMS: 0.05 %
- Three-body decay: photon kinematics fully determined by the rest of the event
- Purely EWK process: clear signal in hadronic collisions
- Z^0 decays to muons: photon sole object in the ECAL
- 5 GeV $\lesssim E_\gamma \lesssim$ 100 GeV

Channel source of "certified" unbiased photons
with very high purity and relatively high p_T

Selection of $Z^0 \to \mu\mu\gamma$ events

Current selection based on work of
Junquan Tao (IHEP, thesis defense 2008), Zhen Zhang (IHEP, thesis defense 2009),
Clément Bâty (IPNL, thesis defense 2009)

CMS Collaboration, Phys. Lett. B701, (2011) 535-555, CMS-EWK-10-008

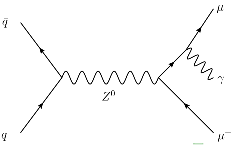


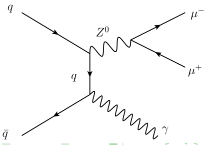
Selection

- Muon selection: standard CMS muon ID criteria, tracker muon isolation only
- Photon selection: fiducial cuts only (no ID applied, to keep it unbiased for later)

Main background: Initial State Radiation events

- Dimuon invariant mass: rejection of non-radiative Z^0 events
- Maximum angular separation between photon and closest muon
- Three-body invariant mass required to be around the Z^0 mass peak





1 Introduction

2 The $Z \to \mu\mu\gamma$ channel

3 Use cases

- Photon energy scale: the V + gamma analysis
  - CMS ECAL 2010 performance results, (CMS-DP-2011-008)
  - Phys. Lett. B701, (2011) 535-555, CMS-EWK-10-008
- Photon identification: the $H \to \gamma\gamma$ analysis
  - Search for a Higgs boson decaying into two photons in the CMS detector, (CMS-PAS-HIG-11-010 & CMS-PAS-HIG-11-021)

4 Conclusion

Photon energy scale: definition

Definition

We call photon energy scale the quantity:

$$s = \frac{E^{\gamma}_{measured}}{E^{\gamma}_{expected}} - 1$$

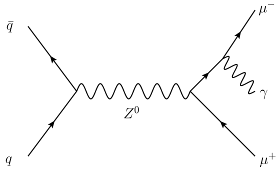
(offset with respect to expected scale)

The $Z^0 \to \mu\mu\gamma$ case

From the FSR kinematics:

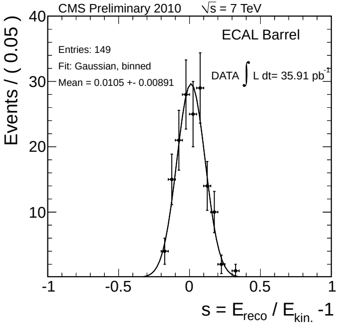
$$s_{RECO} = \frac{m^2_{\mu\mu\gamma} - m^2_{\mu\mu}}{m^2_{Z^0} - m^2_{\mu\mu}} - 1 = \frac{E^{\gamma}_{reco}}{E^{\gamma}_{kinematics}} - 1$$

(assuming uncertainty in muon momentum small compared to photon energy uncertainty)



- Photon absolute energy scale can be measured separately in data and simulation

Photon energy scale in data



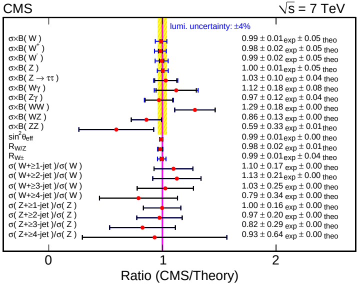
CMS Collaboration, ***CMS ECAL 2010 performance results***, **(CMS-DP-2011-008)**

Results on 2010 data ($36\ pb^{-1}$)

Simulation predicts 216 ± 3 events, where 196 events are observed in data

	Barrel		Endcaps
Data	0.011 ± 0.009	Data	-0.041 ± 0.021
MC	0.000 ± 0.001	MC	-0.003 ± 0.003
Data - MC	0.011 ± 0.009	Data - MC	-0.037 ± 0.021

Impact in the V + gamma analysis



Source	$W\gamma \to e\nu\gamma$	$W\gamma \to \mu\nu\gamma$	$Z\gamma \to ee\gamma$	$Z\gamma \to \mu\mu\gamma$
	Effect on $A \cdot \epsilon_{MC}$			
Lepton energy scale	2.3%	1.0%	2.8%	1.5%
Lepton energy resolution	0.3%	0.2%	0.5%	0.4%
Photon energy scale	4.5%	4.2 %	3.7%	3.0%
Photon energy resolution	0.4%	0.7%	1.7%	1.4%
Pile-up	2.7%	2.3%	2.3%	1.8%
PDFs	2.0%	2.0%	2.0%	2.0%
Total uncertainty on $A \cdot \epsilon_{MC}$	6.1%	5.2%	5.8%	4.3%
	Effect on $\epsilon_{data}/\epsilon_{MC}$			
Trigger	0.1%	0.5%	$< 0.1\%$	$< 0.1\%$
Lepton identification and isolation	0.8%	0.3%	1.1%	1.0%
E_T^{miss} selection	0.7%	1.0%	N/A	N/A
Photon identification and isolation	1.2%	1.5%	1.0%	1.0%
Total uncertainty on $\epsilon_{data}/\epsilon_{MC}$	1.6%	1.9%	1.6%	1.5%
Background	6.3%	6.4%	9.3%	11.4%
Luminosity	4%			

CMS Collaboration, Phys. Lett. B701, **(2011) 535-555, CMS-EWK-10-008**

Work in progress

- Dominating uncertainty on acceptance
- Currently refining measurment in 2011 data: differential scale as a function of p_T^γ
- Work with Louis Sgandurra (IPNL - visit to IHEP (end of 2012) - FCPPL 2012 proposal - thesis defense 2014)

Use in the $H \to \gamma\gamma$ analysis

Use of tag-and-probe techniques to measure photon identification efficiencies in data

R_9 categorization

- photon categorisation is related to resolution: uncertainty in class assignment (migration) is a source of systematic error for $H \to \gamma\gamma$ analysis

$R_9 > .94$ efficiency uncertainty	
barrel	4 %
endcaps	6.5 %

CMS Collaboration, *Search for a Higgs boson decaying into two photons in the CMS detector*, (CMS-PAS-HIG-11-010 & CMS-PAS-HIG-11-021)

Lepton veto efficiency

- Lepton veto can't be studied with $Z^0 \to e^+e^-$ decays
- Need of $Z^0 \to \mu\mu\gamma$ events

Category	$\epsilon_{data}(\%)$	$\epsilon_{MC}(\%)$	$\epsilon_{data}/\epsilon_{MC}$
EB, $R_9 > .94$	$99.78^{+0.13}_{-0.16}$	$99.59^{+0.13}_{-0.17}$	$1.002^{+0.002}_{-0.002}$
EB, $R_9 < .94$	$98.77^{+0.59}_{-0.73}$	$97.70^{+0.32}_{-0.37}$	$1.011^{+0.007}_{-0.008}$
EE, $R_9 > .94$	$99.32^{+0.51}_{-1.02}$	$99.29^{+0.30}_{-0.42}$	$1.000^{+0.006}_{-0.011}$
EE, $R_9 < .94$	$93.0^{+2.1}_{-2.3}$	$93.34^{+0.79}_{-0.86}$	$0.996^{+0.024}_{-0.027}$

CMS Collaboration, *Search for a Higgs boson decaying into two photons in the CMS detector*, (CMS-PAS-HIG-11-010 & CMS-PAS-HIG-11-021)

Photon ID efficiency

- Work on 2011 data: started during Hong Xiao (IHEP, thesis defense 2012) visit to IPNL last summer
- π^0/γ Neural Network discriminator developped by IHEP-IPNL (see Junquan Tao's presentation): use of $Z^0 \to \mu\mu\gamma$ events to validate training

Conclusion

Current and possible uses for radiative Z^0 decays:

- Photon-related trigger paths efficiency
- Photon energy scale
- Validation of photon cluster shape variables
- Efficiency of photon identification criteria,
- Validation on photon energy corrections
- Complementary calibration channel

Future:

- Growing interest as the statistics grows
- Looking forward to continue IHEP-IPNL collaboration on the topic!

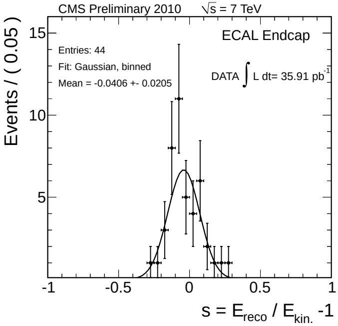
Thank you for your attention

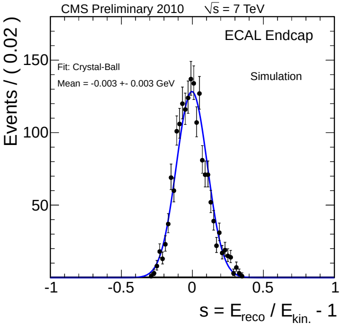
Thank you for your attention

Thanks to the FCPPL!

BACKUP

Photon energy scale in data: CMS-DP-2011-008





Barrel	
Data	0.011 ± 0.009
MC	0.000 ± 0.001
Data - MC	0.011 ± 0.009

Endcaps	
Data	-0.041 ± 0.021
MC	-0.003 ± 0.003
Data - MC	-0.037 ± 0.021

No crystal transparency loss is applied in the endcaps. Photon scale agrees with expectation at the 1 % level in EB and 4 % level in EE. These numbers are within the estimated accuracy of the method, and are found to be consistent between three different methods. Work in progress for 2011 data : differential + categories