Photon reconstruction and performance in ATLAS and CMS

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Introduction

♦ Photon performance of utmost importance for:
  - $H \rightarrow \gamma\gamma$
  - SM prompt photon
  - SUSY
  - exotics

♦ Higgs-oriented talk

♦ Di-photon invariant mass:

$$m_{\gamma\gamma}^2 = 2E_1E_2(1-\cos\Delta\alpha(\gamma_1;\gamma_2))$$
**Electromagnetic calorimeters**

**CMS:**
- Homogeneous PbWO$_4$ crystal calorimeter
  - $\Delta \eta \times \Delta \phi = 0.0174 \times 0.0174$

**ATLAS:**
- Lead-LAr sampling calorimeter
  - accordion geometry
  - $\Delta \eta \times \Delta \phi = 0.025 \times 0.025$

$$\frac{\sigma_E}{E} = 2.8\% \oplus \frac{12\%}{\sqrt{E}} \oplus 0.3\%$$

$$\frac{\sigma_E}{E} = 10\% \frac{1}{\sqrt{E}} \oplus 0.7\%$$
Photon reconstruction, CMS

♦ in 5x5 crystal clusters and 50 GeV photons:
  - ~97% of **unconverted** photon energy

♦ >50% probability to convert into $e^+e^-$ pair
  ⇒ spreads in $\phi$ due to B-field
  ⇒ super-clusters (SC)

♦ Barrel:
  - narrow in $\eta$: 5 crystals
  - long in $\phi$: ±10-15 crystals

♦ Endcap:
  - from 5x5 crystal around most energetic + pre-shower

♦ Conversion: use of $R_9$ variable ($E_{3x3}/E_{SC}$)
  - unconverted: $E_{5x5}$ energy
  - converted: $E_{SC}$ energy
Photon energy: $E_\gamma \propto F(\eta) \sum c_i \cdot L_i \cdot E_i$

corrections (losses, containment)
intercalibration ($\phi$ symmetry, $\pi\nu$, $E/p$, ...)
laser response correction

Corrections with MC or BDT
- pile-up independent

Even-by-event estimate of energy uncertainty

Absolute energy scale: $Z \rightarrow ee$

Energy resolution: $Z \rightarrow ee$ line-shape
- in $\eta$, $R_9$, run period bins

Energy scale stable at per mill level

CMS-DP-2013-007
Cluster reconstruction
- $\Delta\eta \Delta \phi = 0.075 \times 0.175 = 3 \times 5 / 3 \times 7$ cells, in barrel
- $\Delta\eta \Delta \phi = 0.125 \times 0.125 = 5 \times 5$ cells, in end-caps

Conversion: matched track from vertex in inner detector
- stable with pile-up

Photon energy: $E_\gamma = E_{\text{front}} + E_{\text{calo}} + E_{\text{back}}$
- loss before calo: $\propto E_{PS}$
- loss after calo: $\propto E_1 + E_2 + E_3$

Corrections from MC

Absolute energy scale: corrected from $Z \rightarrow ee$ events

Energy resolution: $Z \rightarrow ee$ line-shape
High photon efficiency vs high jet rejection

- hadronic leakage
- main background: $\pi^0 \rightarrow \gamma\gamma$
  $\Rightarrow$ shower topology
- photon isolation
  (cluster + track)

Electron veto
- no hits in inner layers
Identification, CMS (1)

♦ Preselection
- electron veto
- hadronic leakage \( \left( \frac{E_{\text{had}}}{E_{\gamma}} \right) \)
- isolation (PF) + shape
- efficiency: 92-99%
- good data-MC agreement: 1.0-2.6% uncertainty

♦ Cut-based identification
- separated for barrel/endcap and converted/unconverted
- lateral shower shape
- isolation (3 variables)
- uncertainty:
  - 1% (barrel)
  - 1.6% (end-cap)

♦ MVA identification
- shower topology (7 variables)
- isolation (3 variables)
- energy density per unit area (pile-up)
- checked with \( Z \to e e \) and \( Z \to \mu \mu \gamma \)
good data-MC agreement
- a few % uncertainty

CMS-PAS-HIG-13-001
♦ Cut-based:
  - slight dependence on pile-up
  - good agreement data-MC

♦ MVA:
  - pile-up independent

CMS-PAS-HIG-13-001
Identification, ATLAS (1)

- Use of fine segmentation of calo
  - 8 shower shape variables
  - 2 hadronic leakage variables
  - in $\eta$ bins

- Optimised to be $\sim$pile-up independent

CERN-OPEN-2008-020

ATLAS-CONF-2012-123
Efficiency measured with 3 data-driven measurements

- $Z$ radiative decay
  (see talk by C. Rangel)
- Extrapolation from $Z \rightarrow ee$
- Matrix method isolation-identification

Efficiency $> 85\%$ for $E_T > 40$ GeV

Uncertainty: 2.5-1.5%
♦ Computed from topological clusters in calorimeter with $\Delta R < 0.4$

♦ Corrected for pileup and underlying event by subtracting ambient energy density event-by-event

$E_T^{iso}$ independent from $E_T$, pile-up, Underlying Event

Uncertainty on data/MC comparison ($Z \rightarrow ee$): 1%
Correlations between di-photon system and recoiling tracks
- unconverted photons

Conversion vertex
- converted photons

Information in BDT

Efficiency of finding vertex 10 mm from true one: > 80%

Slight dependence on pile-up
Di-photon vertex, ATLAS

♦ Use of longitudinal segmentation of calo
  - unconverted photons
  - "calo pointing"

♦ Conversion vertex
  - converted photons

♦ NN algorithm
  - calo pointing
  - $\Sigma p_T$ and $\Sigma p_T^2$ of tracks
  - conversion info
  - $\Delta \phi$ (all tracks, di-photon)

♦ Efficiency of finding vertex 10 mm from true one: $\sim 100$

♦ Slight dependence on pile-up

ATLAS-CONF-2011-161
ATLAS-CONF-2013-012
Conclusions

♦ Photon energy reconstruction, identification, pointing essential for $H \rightarrow \gamma\gamma$ reconstruction

♦ Different strategies for ATLAS-CMS for different calorimeters and tracking
  - but overall similar performance!

♦ $m_{\gamma\gamma}$ resolution < 1.8 GeV

♦ Pile-up robust reconstruction

♦ Now more information on $H \rightarrow \gamma\gamma$ physics in O.Davignon and F.Couderc talks
Back-up slides
Relative response to laser light measured by the ECAL laser monitoring system, averaged over all crystals in bins of $\eta$

Response change in ECAL channels: a few % in barrel, up to 25% in most forward endcap regions used for electron and photon reconstruction. Response change observed in ECAL channels: up to 6% in barrel, up to 30% at $\eta \approx 2.5$ (limit of tracker acceptance). Response change up to 70% in region closest to beam pipe. Measurements are used to correct physics data.
♦ Reconstruction with latest calibration and alignment conditions (Winter2013 reconstruction);

♦ $W \rightarrow ev$ decays

♦ Before (red points) and after (green points) corrections to ECAL crystal response variations due to transparency loss

♦ ECAL Barrel: average signal loss $\sim 5\%$, RMS stability after corrections 0.09%

♦ ECAL Endcap: average signal loss $\sim 18\%$, RMS stability after corrections 0.28%
2012 inter-calibration

φ-symmetry, π⁰ → γγ and η → γγ decays, W and Z decay electrons

Precision of the phi-symmetry and photon calibrations at the level of the systematic errors. Precision of the electron calibration is still dominated by the statistical errors for η > 1.

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CMS-DP-2013-007
Impact on the $Z \rightarrow ee$ energy scale and resolution obtained from applying energy scale corrections to account for the intrinsic spread in crystal and photo-detector response, and time-dependent corrections to compensate for channel response loss.
Impact on the $Z \rightarrow e^+e^-$ energy scale and resolution from the incorporation of more sophisticated clustering and cluster correction algorithms.
Mass resolution of the Z peak, reconstructed from ee decay mode

Width of the Z peak is fitted with a convolution of a Crystal Ball with a Breit-Wigner line shape. The Gaussian width parameter of the Crystal Ball function is taken as a measure of the mass resolution.
Relative electron (ECAL) energy resolution unfolded in bins of $\eta$ (electrons from $Z \rightarrow ee$)

Resolution extracted from an unbinned likelihood fit to $Z \rightarrow ee$ events, using a Voigtian (Landau convoluted with Gaussian) as the signal model.

Resolution affected by the amount of material in front of the ECAL and is degraded in the vicinity of the eta cracks between ECAL modules.

Resolution, especially in the endcaps, improves significantly after a dedicated calibration using the full 2012 CMS dataset (blue points) with respect to the prompt calibration from early 2012 CMS data (gray points).
 Dependence of the reconstructed energy on the number of reconstructed vertices in the event.

The default reconstruction of the data (open red circles) and MC (filled red circles) is compared to MC-driven corrections to the energy based on a multivariate analysis (MVA) of the energy response which includes pileup sensitive global event variables, for the data (open green circles) and MC (filled green circles).
Photon energy reconstruction, ATLAS

- $E_\gamma = E_{\text{front}} + E_{\text{calo}} + E_{\text{back}}$

- $E_{\text{calo}} = C_{\text{cal}}(X, \eta)(1 + f_{\text{out}}(X, \eta)) \sum_{i=1}^{3} E_i$
  - $X$: longitudinal barycentre
  - $\eta$: cluster barycenter
  - $f_{\text{out}}$: fraction of energy deposited outside cluster (<7%)
  - $C_{\text{cal}}$: calibration factor (0.98-1)

- $E_{\text{front}} = a(E_{\text{cal}}, \eta) + b(E_{\text{cal}}, \eta)E_{\text{PS}} + c(E_{\text{cal}}, \eta)E_{\text{PS}}^2$

- $f_{\text{leak}} = \frac{E_{\text{back}}}{E_{\text{cal}}} = f_{\text{leak}}^0(\eta)X + f_{\text{leak}}^1(\eta)e^X$
  - < 3%

$X = \frac{\sum_{i=1}^{3} E_i X_i + E_{\text{PS}} X_{\text{PS}}}{\sum_{i=1}^{3} E_i + E_{\text{PS}}}$
Radiative Z decay
- signal extraction with signal+background template:
  96-98% purity

ATLAS-CONF-2012-123
EgammaPublicPlots
Extrapolation from $Z \rightarrow ee$ tag-and-probe

- transformation to match electron to photon shower-shapes

Matrix method

- $N_{\text{pass}} = \varepsilon_S \cdot N^S_{\text{pass}} + \varepsilon_B \cdot N^B_{\text{pass}}$

- isolation efficiencies estimated from data
Efficiency measurements comparison:

**unconverted**

- ATLAS Preliminary
- $\sqrt{s} = 7$ TeV
- $\int L \, dt = 4.9$ fb$^{-1}$
- Unconverted $\gamma$

**converted**

- ATLAS Preliminary
- $\sqrt{s} = 7$ TeV
- $\int L \, dt = 4.9$ fb$^{-1}$
- Converted $\gamma$

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ATLAS-CONF-2012-123
data-MC comparison:

unconverted

converted

ATLAS-CONF-2012-123
♦ Pile-up dependence:

ATLAS identification (5)

ATLAS-CONF-2012-123