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Studies of Electron and Photon Energy Scales

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Abstract

This is a supporting documentation of CDF 9590, "Measurement of the inclusive and isolated prompt photon cross section at CDF". The energy scale, in our context, is the ratio of the reconstructed energy in the electromagnetic calorimeter to the true energy. Shift in the energy may change the shape of differential cross section of photons and the energy scale is one major source of systematic uncertainty in the cross-section measurement. In this documentation, we present our studies on the energy scales of electrons and photons, using $Z^0 \rightarrow e^+e^-$ MC and data, single electron and photon MC, and inclusive photon MC samples. Through various comparisons, we find a $\pm 1.5\%$ difference between data and MC and use this uncertainty on the energy scale to study the uncertainty on the photon cross section.

1 Introduction

The energy scale is defined as the ratio of the reconstructed energy in the electromagnetic calorimeter to the true energy[1]. Throughout this documentation, we use the term E_{scale} to denote the energy scale:

$$E_{\text{scale}} = \frac{E_{\text{rec}}}{E_{\text{true}}}. \tag{1}$$

Section 2 describes the samples and selections for this study. Section 3 briefly shows how we extract E_{scale}. In Section 4, we first compare the overall, average electron E_{scale} in $Z^0 \rightarrow e^+e^-$ data and MC. Then, we use single particle MC and inclusive photon MC samples to cover a wide range of energy and study the dependence of E_{scale} on the reconstructed energy. Section 5 presents the conclusion.

[1] Note it is energy, not E_T.

Table 1: Production and Stntuple sample IDs.

Category	Production ID	Stntuple ID
$Z^0 \to e^+e^-$ data	`bhel0d`	`bhelbd`
	`bhel0h`	`bhelbh`
	`bhel0i`	`bhelbi`
	`bhel0j`	`bhelbj`
	`bhel0k`	`bhelbk`
$Z^0 \to e^+e^-$ MC	`zewkad`	`ze1sad`
Inclusive γ MC	`gqcdqd`	`gq0sqd`
	`gqcd07`	`gq0s07`
	`gqcd15`	`gq0s15`

2 Data and MC samples and electron/photon identifications

Table 1 lists the dataset IDs of $Z^0 \to e^+e^-$ data and MC, and inclusive photon MC samples. The $Z^0 \to e^+e^-$ data cover periods 0 through 17 (runs 138425-261005). The single electron and photon MC samples were generated by the authors, using `FakeEv` module and Gen 6 and Gen 7 tar balls provided by the MC production group [1]. Only one electron or photon is generated for each event, with an E_T in the range of 10–600 GeV, and η in the range of -1.5 to 1.5. There are no underlying events or multiple interactions in the single particle MC.

Table 2 lists the central photon and photon-like electron identification requirements for this energy scale study; they are almost identical to those in Ref. [2], except the Z_{CES} cuts[2].

3 How to extract E_{scale} in each sample

$Z^0 \to e^+e^-$ decays

We first apply the following selections:

- ELECTRON_CENTRAL_18 trigger bit is set (only for data).

[2]Ref. [2] requires $9 < |Z_{\text{CES}}| < 200$ cm.

Table 2: Central tight photon and photon-like electron identifications for the energy scale study. These are almost identical to those in Ref. [2] except the requirement on Z_{CES}.

Variable	Photon ID	Photon-like electron ID
Central	Yes	Yes
Had/Em	$\leq 0.055 + 0.00045 \cdot E$	$\leq 0.055 + 0.00045 \cdot E$
Average Scaled CES χ^2	≤ 20	≤ 20
for $E_T < 90$ GeV		
$\lvert X_{\mathrm{CES}} \rvert$	≤ 21 cm	≤ 21 cm
$\lvert Z_{\mathrm{CES}} \rvert$	9 – 230 cm	9 – 230 cm
Calor. isolation (GeV)	< 2.0	< 2.0
$\mathrm{N_{trk}}$	≤ 1	≤ 2
	or $= 0$ if p_T^{1sttrk}	or $= 1$ if p_T^{2ndtrk}
	$> 1 + 0.005 \cdot E_T$	$> 1 + 0.005 \cdot E_T$
Track isolation	no cut	no cut
2^{nd} E_{CES} for $E_T < 18$ GeV	$< 0.14 \cdot E_T$	$< 0.14 \cdot E_T$
2^{nd} E_{CES} for $E_T \geq 18$ GeV	$< 2.4 + 0.01 \cdot E_T$	$< 2.4 + 0.01 \cdot E_T$
E/p for $p_T < 50$ GeV/c	–	0.8 — 1.2

- ≥ 1 class 12 vertex, the z position of the vertex with the highest sum p_T of tracks must be within ± 60 cm
- A pair of oppositely-charged central photon-like electrons which satisfy the requirements in Table 2
- z_0 difference < 5 cm

For each pair of electrons, their invariant mass, M_{ee}, is calculated. We fit the M_{ee} distribution to a sum of double Gaussian (signal) and a second-order polynomial (background). The means and widths of the two Gaussians are not fixed. We take the mean of the narrower Gaussian as the reconstructed Z^0 boson mass. The ratio of reconstructed Z^0 boson mass to that in the PDG, 91.1876 GeV/c^2, is the E_{scale}. We have also simply fit the region near the Z^0 peak to a single Gaussian and obtained results which in general differ by 0.1 GeV/c^2 and at most 0.4 GeV/c^2. Figures 1–2 show the examples of mass fits for each bin of the sum of reconstructed electron energies, $E(e_1) + E(e_2)$, from data and MC, respectively.

Single electron and photon MC, inclusive photon MC

For each generator-level electron/photon which has the highest E_T and status = 1 (stable particle), we look for a reconstructed electron/photon within a cone of $\Delta R = 0.2$. The ratio of reconstructed energy to the generator-level energy is E_{scale}. When making profile plots, we take the average of electrons/photons whose E_{scale} are within the range of 0.9 to 1.1.

4 Results

Data and MC comparison from $Z^0 \to e^+e^-$ decays

We compare electron energy scales in data and MC, particularly for the energy region 30–50 GeV, using $Z^0 \to e^+e^-$ decays. Figure 3 shows the E_{scale} for each run period in data and MC. Figure 4 shows the E_{scale} in data after applying corrections to the energy of each electron for each run period, according to the values in Figure 3. Figure 4 serves as a sanity check: after corrections, the E_{scale} is flat and consistent with 1.000.

Figure 5 shows the E_{scale} vs. the detector η of each electron, respectively. The major differences between data and MC are in the large η region, where the Gen 6 MC is known for its underestimate of energy response in towers 8 and 9. In the inclusive photon cross-section measurement [2], we made a requirement, $|Z_{\text{CES}}| < 200.0$ cm, to reduce to the discrepancy between data and MC. Figure 6 shows the E_{scale} vs. the detector η of one electron leg when restricting the η range of the other electron leg. The dependence of E_{scale} on the detector η requires additional checks when applying this overall energy scale from Z sample to a sample with different η distributions.

Figure 7 shows the E_{scale} vs. the sum of reconstructed electron energies, $E(e_1) + E(e_2)$, with and without the requirement, $|Z_{\mathrm{CES}}| < 200.0$ cm. The data/MC ratio has a slope for $E(e_1) + E(e_2) = 90 \sim 150$ GeV. However, we do not have enough data for $E(e_1) + E(e_2)$ above 170 GeV to see if this trend will continue or become flat.

Note that the E_{scale} in Figures 5–7 do not have the run-dependent correction from Figure 3, yet. Therefore, the average of data/MC ratio is about 0.99.

The largest difference between the energy scale from each $E(e_1)+E(e_2)$ bin and the average is 0.019 for comparison without Z_{CES} requirement, and 0.015 for comparison with Z_{CES} requirement (see Figure 8, correction from Figure 3 is applied).

Electron and photon E_{scale} from single particle MC

Although we do not have enough $Z^0 \rightarrow e^+e^-$ decays to cover a wide range of energies, we may try to understand the dependence of E_{scale} on the energy from MC. Figure 9 shows the electron and photon E_{scale} from the single particle MC, as a function of reconstructed energy and detector η.

The decrease of E_{scale} vs. reconstructed energy for energy above 100 GeV, may be explained by the increase of leakage into the hadron calorimeter. Photons are expected to have a larger effect than electrons since they shower later in the calorimeter. The increase of E_{scale} at lower energy may be due to two reasons [3]. The reconstructed energy may be lost due to lateral shower and the fractional loss is larger at lower energy. In addition, electrons may lose energy via bremsstrahlung and photons may lose energy via first conversion and then bremsstrahlung. There is a momentum cutoff of ≈ 500 MeV for the photons from bremsstrahlung to miss the cluster, so the fractional loss is larger at lower energy as well.

Nevertheless, we expect the E_{scale} to be less than unity due to the loss of reconstructed energy as discussed above, while we have seen E_{scale} larger than unity for all energies of photons and most of the energy region of electrons. The well-known overestimate of average E_{scale} in the Gen 6 MC, 0.4–0.5%, is not enough to explain this. We further check Gen 7 single particle MC, where we expect to have a more realistic tunning of MC, and the E_{scale} shows the same behavior. See Appendix A for the E_{scale} comparison in Gen 6 and Gen 7 single particle MC.

The E_{scale} from the inclusive photon MC

Figure 10 shows the E_{scale} vs. reconstructed energy for the three inclusive photon MC samples (with various $\hat{p_T}$). Except the turn-on region[3], the dependence is somewhat flatter compared to that in the single particle MC and the absolute value of E_{scale} is even higher. However, the environment of single particle MC is much simpler and cleaner, the presence of underlying events and multiple interactions in the inclusive photon MC

[3]We plot E_{scale} vs. reconstructed energy, and there are minimum requirements on the E_T of generator-level photons for each MC sample.

samples might have complicated the dependence of E_{scale} on the reconstructed energy[4].

5 Conclusion

Using $Z^0 \to e^+e^-$ decays, we find the average difference of data and MC E_{scale} to be $\approx 1\%$, with an uncertainty of 1.5% in general. The energy dependence of E_{scale} has been studied using single particle MC and inclusive photon MC samples: the trend of energy dependence is inconclusive, and the absolute value of E_{scale} in MC is larger than expected. However, both effects are covered by the 1.5% uncertainty. We use this uncertainty to study the systematic shift in the inclusive photon cross section in Ref. [2].

A Comparison of Gen 6 and Gen 7 single particle MC

Figures 11 and 12 show the E_{scale} from the single electron and photon MC samples, as a function of reconstructed energy, CEM tower, detector η, X_{CES}, and Z_{CES}, respectively.

B How do we relate the Z^0 mass shift to E_{scale}?

The shift in the mass of Z^0 boson, can be expressed as:

$$\frac{dM}{M} = 0.5\sqrt{\left(\frac{dE_1}{E_1}\right)^2 + \left(\frac{dE_2}{E_2}\right)^2}. \tag{2}$$

If dE_1/E_1 and dE_2/E_2 are small, and the energy shift is a first-order polynomial function of energy, i.e. $dE/E = aE + b$, dM/M may be approximated by:

$$\begin{aligned} \frac{dM}{M} &\approx 0.5\sqrt{\left(\frac{dE_1}{E_1} + \frac{dE_2}{E_2}\right)^2}, \\ &= 0.5\left(\frac{dE_1}{E_1} + \frac{dE_2}{E_2}\right) \\ &= 0.5a\left(E_1 + E_2\right) + b \end{aligned} \tag{3}$$

[4]The difference in the absolute value of E_{scale} between Figure 9 and Figure 10 is $\approx 0.005 - 0.015$. But each extra interaction only adds ≈ 0.06 GeV to the photon energy, which is much smaller in terms of fractional increase.

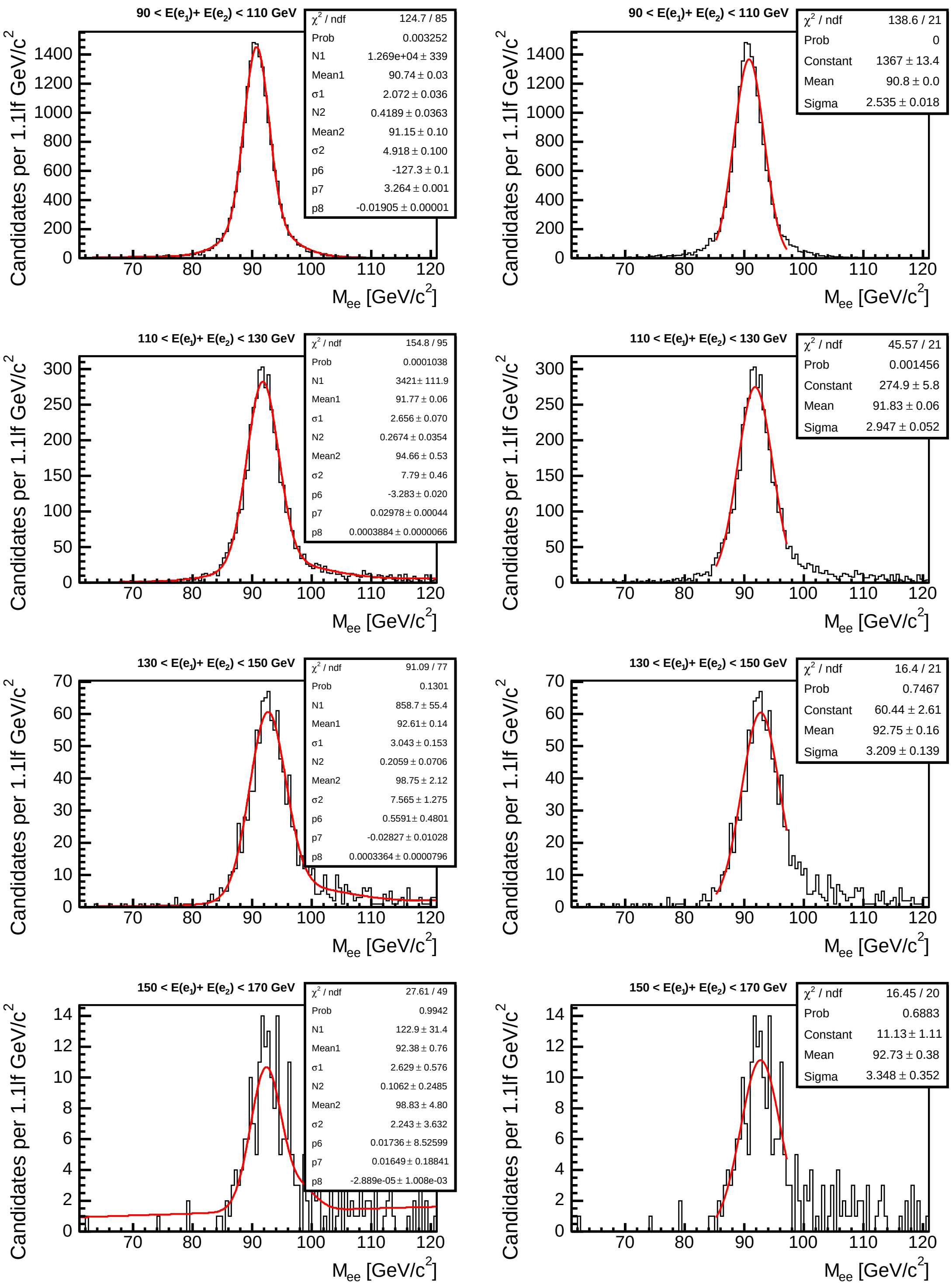

Figure 1: The M_{ee} distributions from $Z^0 \rightarrow e^+e^-$ data in each bin of $E(e_1) + E(e_2)$. The curves indicate results of the fits to double Gaussian and a second-order polynomial background (left), and single Gaussian near the peak (right). The means of the narrower Gaussians on the left differ from the means of the single Gaussians on the right by at most 0.4 GeV$/c^2$.

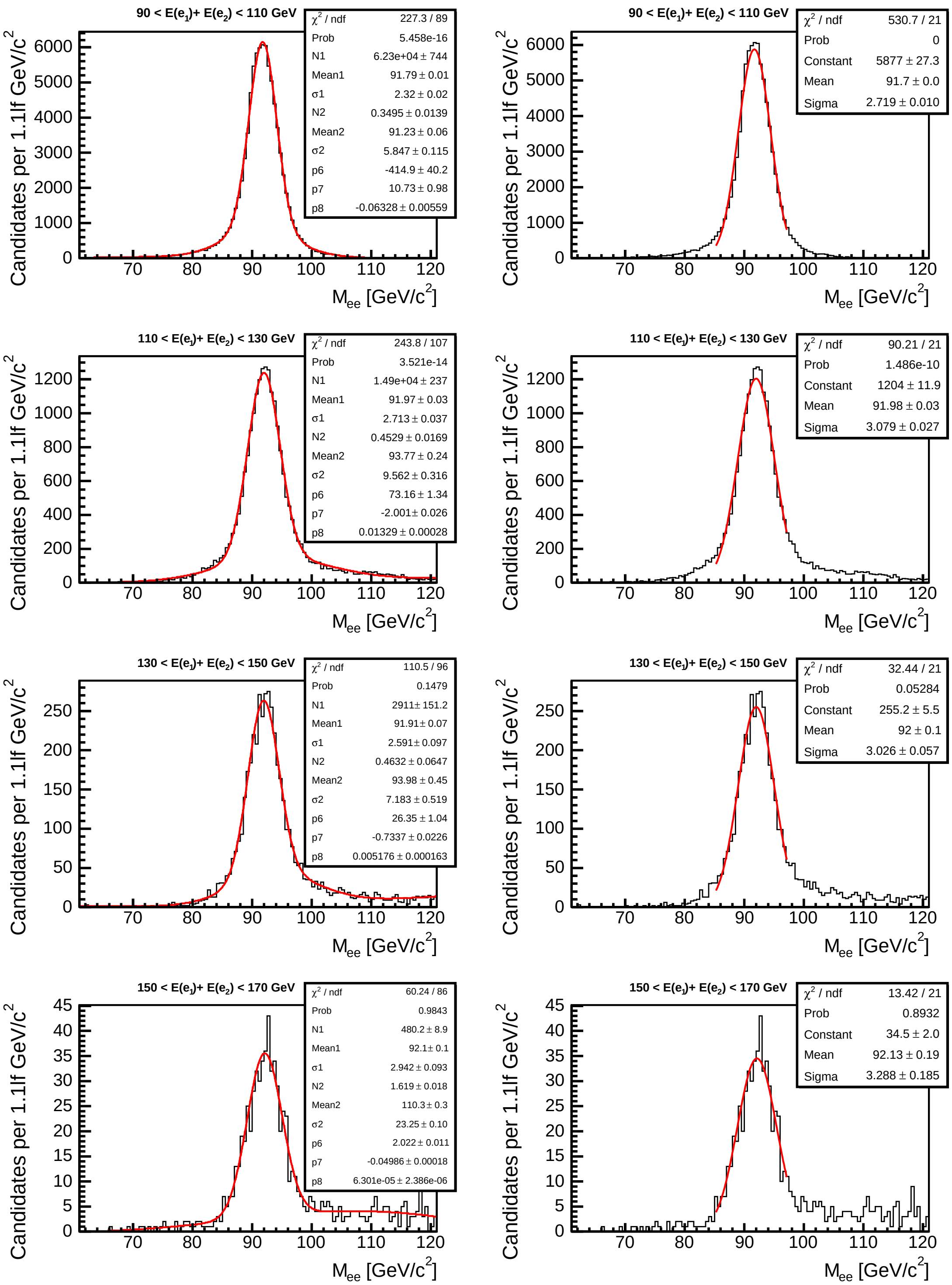

Figure 2: The M_{ee} distributions from $Z^0 \to e^+e^-$ MC (`ze1sad`) in each bin of $E(e_1) + E(e_2)$. The curves indicate results of the fits to double Gaussian and a second-order polynomial background (left), and single Gaussian near the peak (right). The means of the narrower Gaussians on the left differ from the means of the single Gaussians on the right by at most 0.1 GeV/c^2.

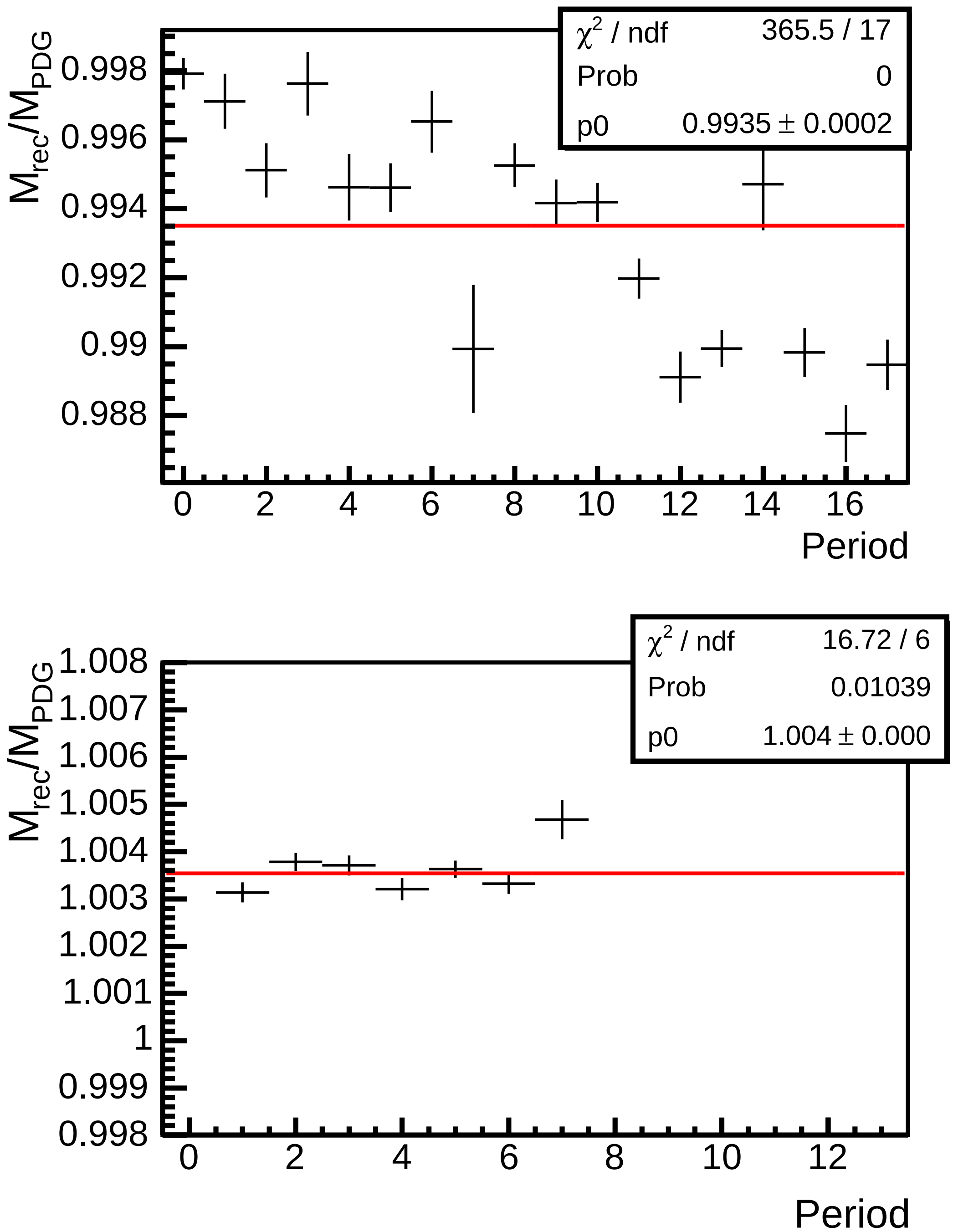

Figure 3: The $E_{\rm scale}$ in each run period from $Z^0 \to e^+e^-$ data (top) and MC (bottom).

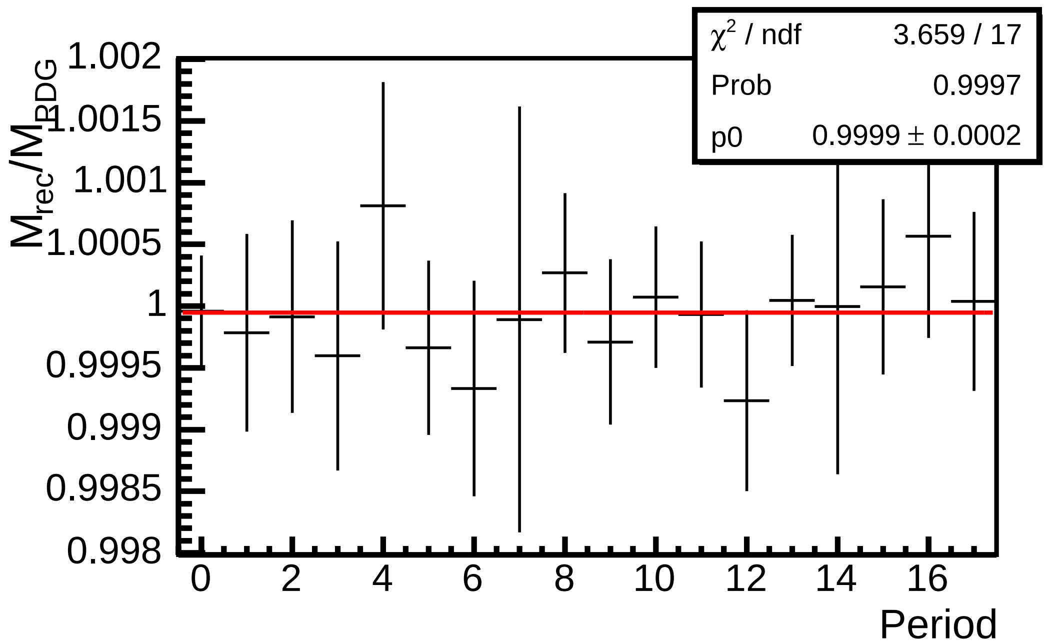

Figure 4: The E_{scale} in each run period from $Z^0 \rightarrow e^+e^-$ data, after applying corrections to the energy of each electron, according to the numbers in Figure 3.

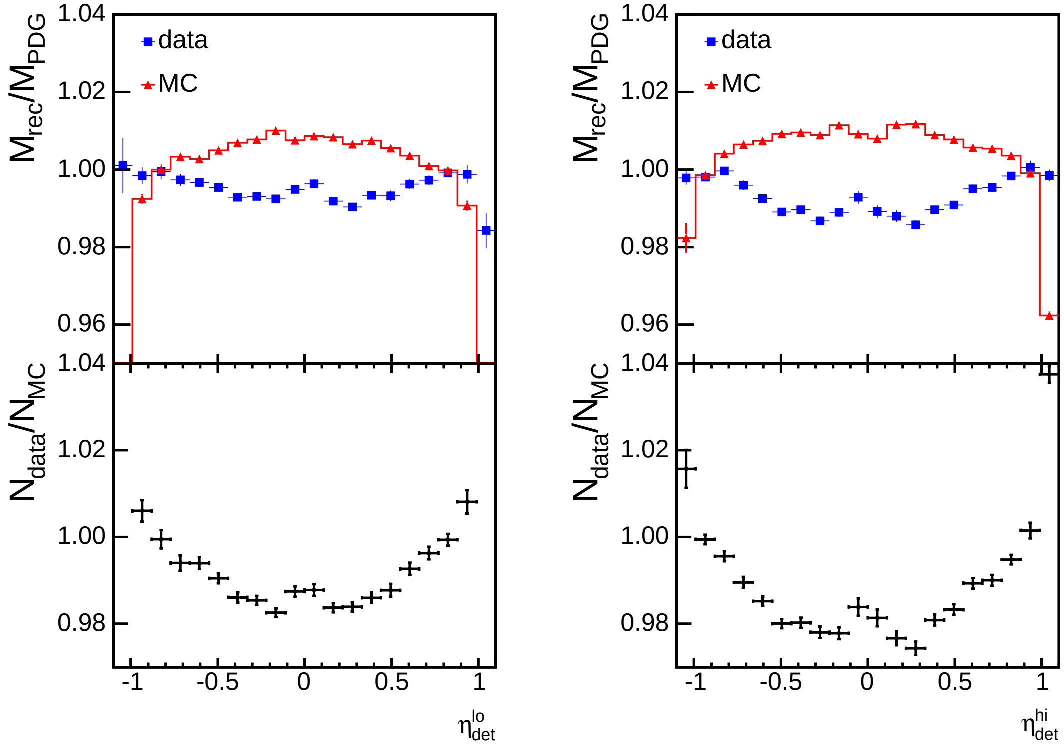

Figure 5: The E_{scale} vs. detector η of electrons from Z^0 decays with lower (left) and higher (right) energy.

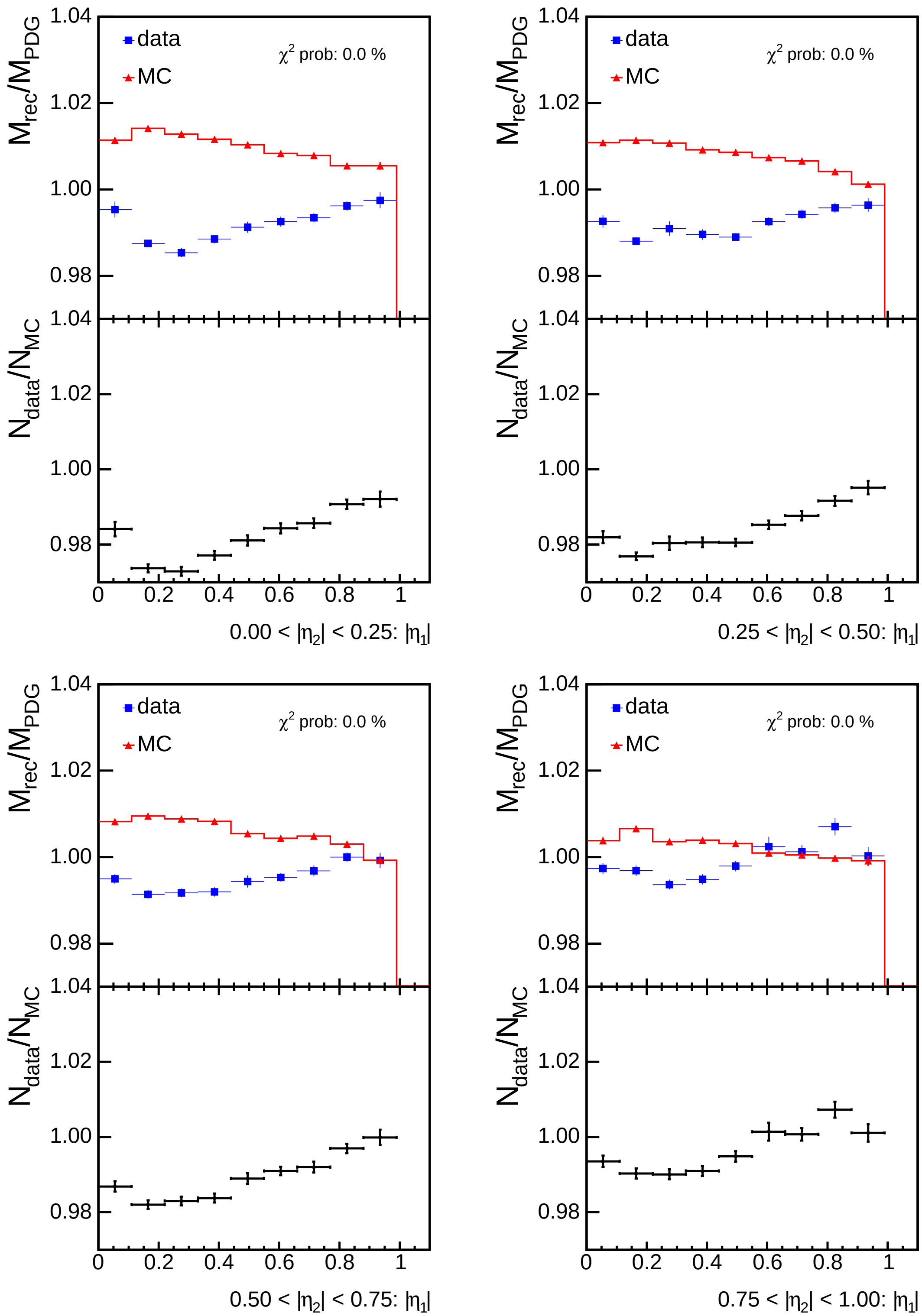

Figure 6: The E_{scale} vs. detector η of one electron leg in Z^0 decays when the other electron leg is restricted to the η range of 0.00–0.25, 0.25–0.50, 0.50–0.75, and 0.75–1.00. Here, the requirement $|Z_{\mathrm{CES}}| < 200.0$ cm is applied to both electrons.

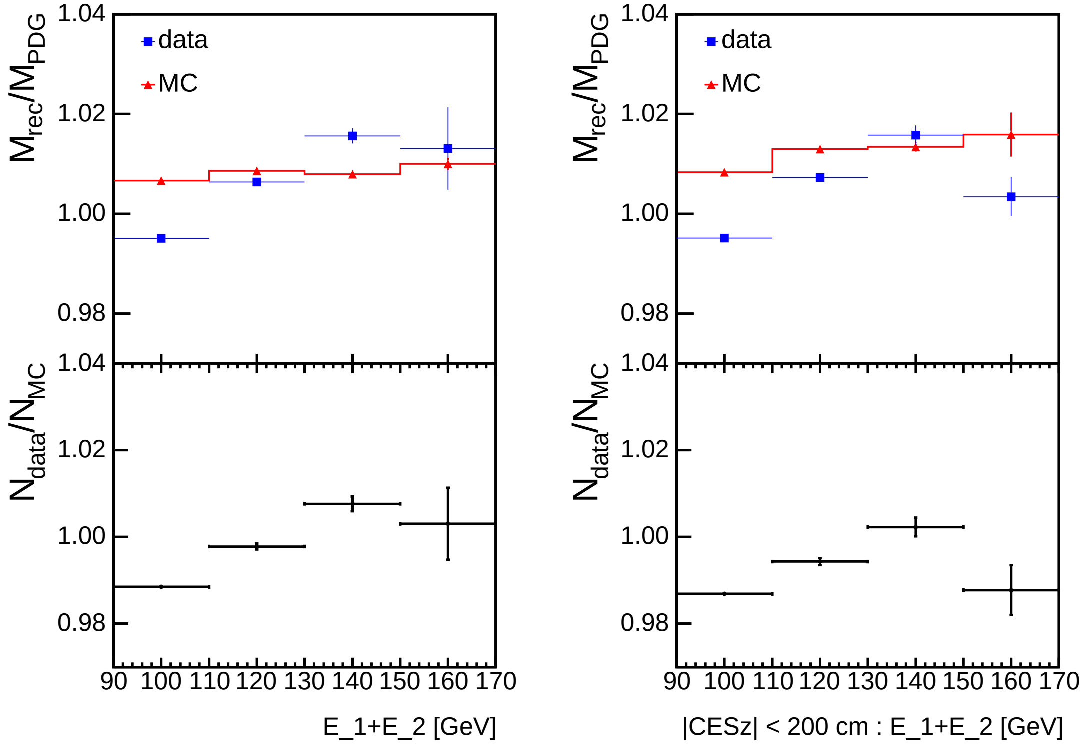

Figure 7: Comparison of the E_{scale} in $Z^0 \to e^+e^-$ data and MC, vs. the sum of the reconstructed energy of two electrons, $E(e_1) + E(e_2)$, without (left) and with (right) the requirement, $|Z_{\text{CES}}| < 200.0$ cm.

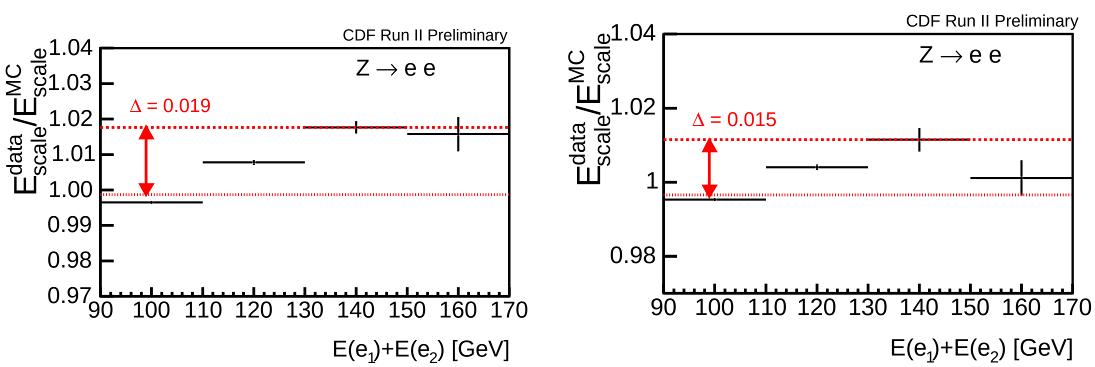

Figure 8: The ratio of energy scale in $Z^0 \to e^+e^-$ data to that in $Z^0 \to e^+e^-$ MC, vs. the sum of the reconstructed energy of two electrons, $E(e_1) + E(e_2)$, without (left) and with (right) the requirement, $|Z_{\text{CES}}| < 200.0$ cm. Corrections from Figure 3 are applied here. The largest difference between the energy scale from each bin (dashed line) and the average (dotted line) is 0.019 and 0.015, respectively.

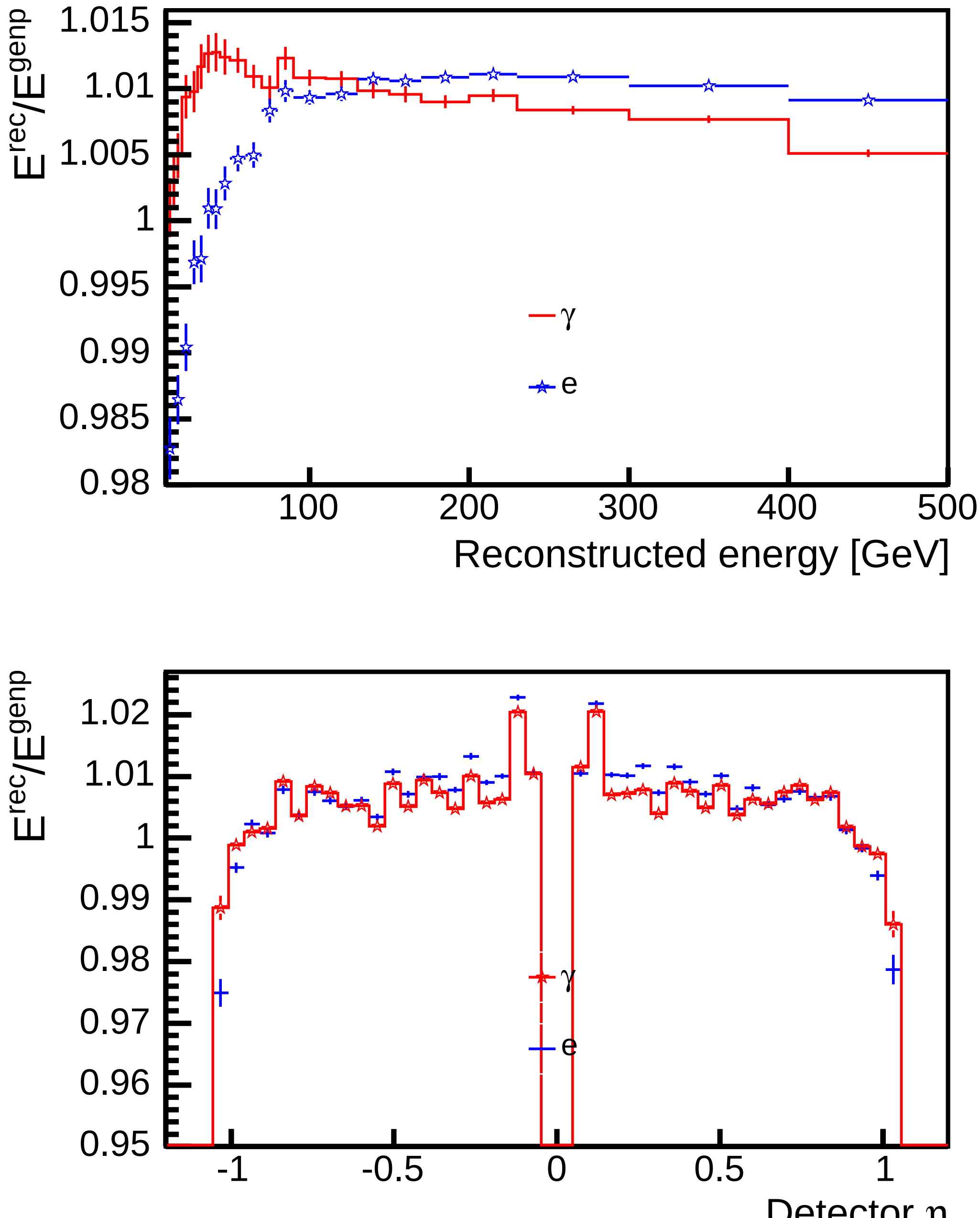

Figure 9: The electron and photon E_{scale} vs. reconstructed energy (top) and detector η (bottom), from the single particle MC.

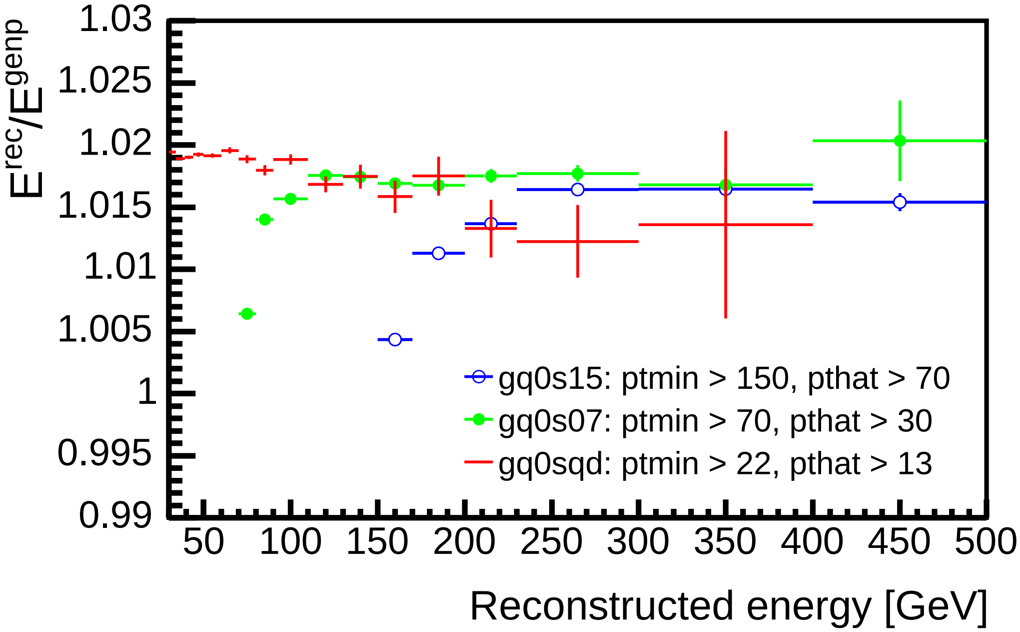

Figure 10: The E_{scale} from the three inclusive photon MC samples, as a function of reconstructed energy.

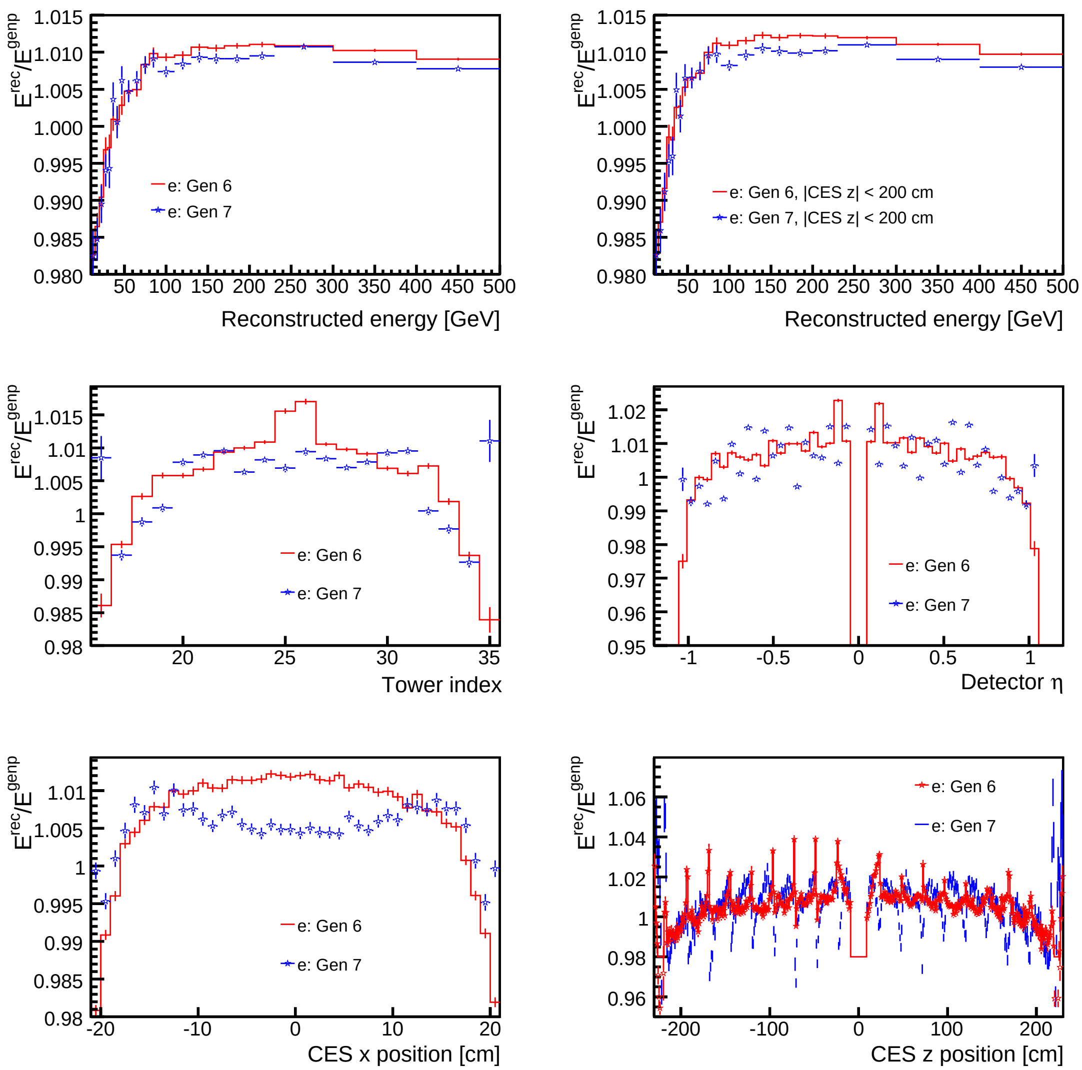

Figure 11: Comparison of the electron E_{scale} from the Gen 6 and Gen 7 single particle MC, as a function of reconstructed energy, CEM tower, detector η, CES x and z positions.

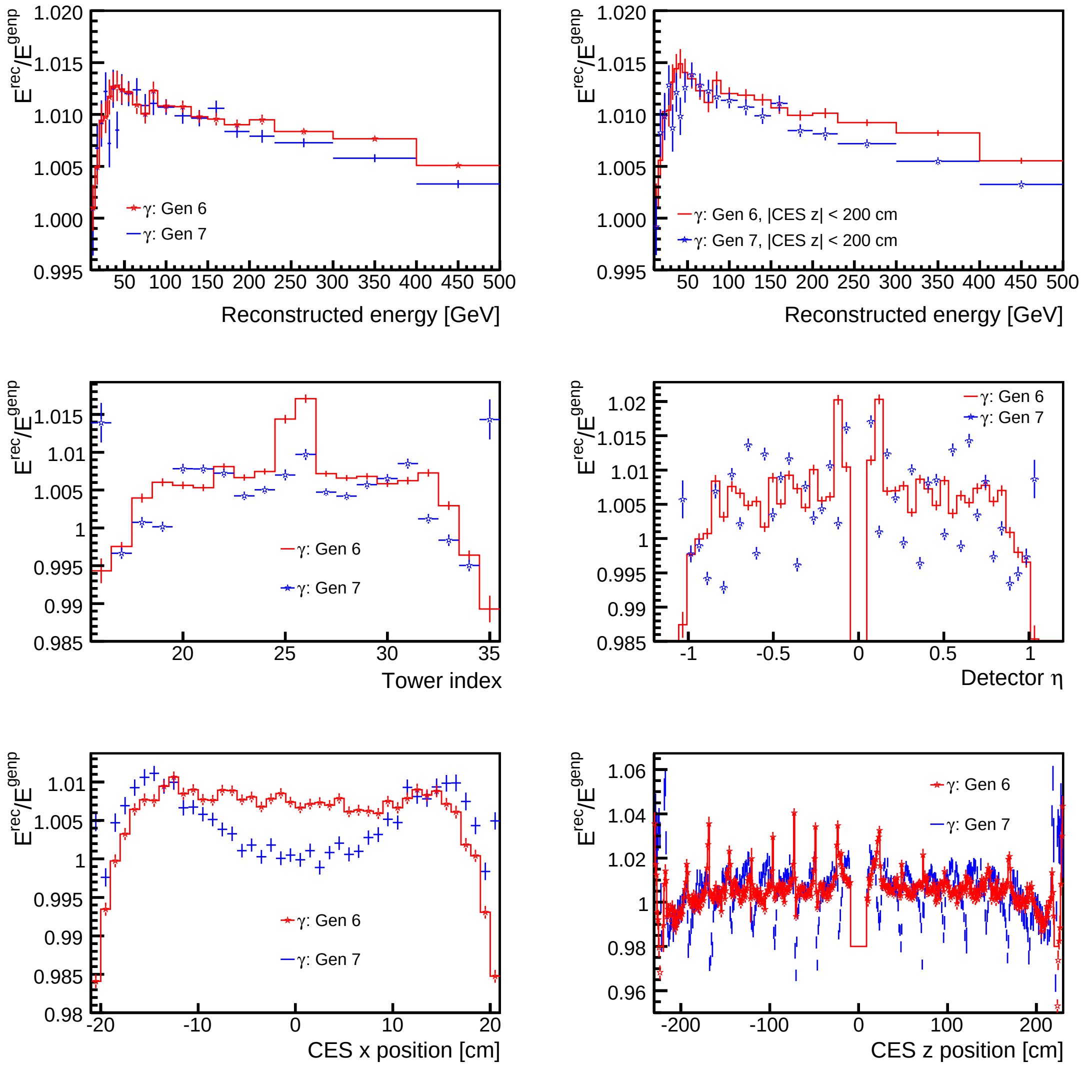

Figure 12: Comparison of the photon E_{scale} from the Gen 6 and Gen 7 single particle MC, as a function of reconstructed energy, CEM tower, detector η, CES x and z positions.

References

[1] *http://www-cdf.fnal.gov/tiki/tiki-index.php?page=McProduction*; *http://www-cdf.fnal.gov/internal/mcProduction/Build_gen7tarball.html*.

[2] R. Culberston, C. Deluca, S. Grinstein, M. Martinez, S.-S. Yu, CDF note **9590** (2008).

[3] C. Hays and L. Nodulman, private communication.