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The systematic errors of jet energy scale in the CMS calorimeter obtained using the γ+jet channel.

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Abstract

The systematic errors of the jet energy scale connected with the presence of the initial state radiation, deforming transverse momentum balance between the direct photon and the initial parton are considered. The possibility of the suppression of the initial state radiation and the improvement of the specified balance is investigated by imposing the restrictions on the various measured parameters of events.

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1 Introduction

The idea to use the $\gamma+$ jet channel to correct the jet energy scale is based on the high precision and linearity of the γ reconstruction in the electromagnetic calorimeter of CMS. For electrons and photons $Emeasured/Ebeam = 1$ in the wide energy range. Using the balance between the transverse energies of the initial photon and of the parton one can found the calibration coefficient which reflects the influence of underestimating energy of the charged particles because of magnetic field, e/π ratio, the cracks in the detector and other effects both of physical and detector nature. However the effect of initial and final state radiation disturb the balance and give the systematic error. Moreover, the dijets events with the energetic neutral particle or initially radiated γ are also registered by the CMS installation as γ+jet event and shift the value of the calibration coefficient.

All these problems were earlier studied with reference to the CMS in the connection with the problem of improvement of the P_T-balance of the photon and the jet [1] and with the problem of the background suppression to the "$\gamma + jet$" [2]-[4]. One of the main task appears to be the development of the rules for the events selection which allows to minimize the influence of the radiation effects and the background.

Thus it is specified necessity to impose the restriction on the following parameters of events:

- E_T^{jet2} is the transverse energy of the additional jet;
- $\Delta\phi$ is the polar angle (ϕ) between the photon ("γ") and the jet ("jet");
- $E_{T\gamma}^{isol}$ is the transverse energy allocated in the some cone around the photon;
- E_{Tjet}^{isol} is the transverse energy allocated in the some ring around the leading jet;
- E_T^{out} is the vector sum of E_T allocated in the calorimeter outside of the photon and the jet;
- E_T^{miss} is the vector sum of E_T allocated in the all calorimeter cells.

The systematic errors connected with the presence of the imbalance between the photon and the initial parton in the hard process:

$$F \equiv P_T^{\gamma} - P_T^{par}. \tag{1}$$

can be essential, and the restrictions on the parameters mentioned above can bring the additional systematic errors in the calibration.

The each of these restrictions imposing on the mentioned above parameters can increase the number of events with $P_T^{\gamma} > P_T^{par}$ or $P_T^{\gamma} < P_T^{par}$ within true γ+jet event sample.

As a result, the shift of the imbalance of the spectrum F will be observed in the selected events sample. The scale of the energy of the jet, established using such a sample will be, accordingly, shifted.

The estimation of the systematic errors obtained with the various selections are calculated at the level of particles, using fast monte-carlo and using detailed simulation of the CMS installation to separate physical and installation effects. The calculation have been performed with the program packages PYTHIA 6.156 [5], CMSJET 4.703 [6], CMSIM 121 [7] and ORCA 4.5.4 [8].

2 The description of the event sample used for the analysis ("initial sample").

The events with direct photons from the SPRING01 production (no pileup) are used [9]. Parameters of samples "1" - "4", corresponding to the different intervals on P_T^{γ}, are given in the Table 1.

Tabl.1. The description of the events samples.

Parameters	"1"	"2"	"3"	"4"
P_{Tmin}^{γ} (GeV/c)	20	40	100	200
P_{Tmax}^{γ} (GeV/c)	40	100	200	300
Numbers of events	10000	10000	10000	10000

Further these events we shall call the initial sample. Parameters for the PYTHIA generation of events are given in the Table 2.

Tabl.2. Parameters of the PYTHIA generation.

Parameters	**Values**
Processes	`ISUB=14` $(f\bar{f} \to g\gamma)$, `ISUB=29` $(fg \to f\gamma)$
$\sqrt{s}$	$14\,TeV$
Structure of multiple interactions	`MSTP(82) = 4`
$\hat{p}_\perp$ min	`CKIN(3) = 0.5` P^{γ}_{Tmin},
$\hat{p}_\perp$ max	`CKIN(4) = 2` P^{γ}_{Tmax}

The values of `CKIN` are selected so that they do not impose the essential restrictions on the P_T of parton of the hard process in the each of the P^{γ}_T intervals. It is very important for studying imbalance $P^{\gamma}_T - P^{par}_T$.

Let's note, that the initial sample which consists from separated samples, belonging to the different P^{γ}_T intervals proves usefull only to study the regression of P^{γ}_T. That is, one kind of averaging is possible only: to find the conditional mean values at fixed P^{γ}_T.

3 The analyzed errors.

On analyzing the imbalance (1) we can use one of the values:

$A)$ $\overline{P}^{par}_T(P^{\gamma}_T)$ which is the mean value of P^{par}_T at fixed P^{γ}_T,

$B)$ $\overline{P}^{\gamma}_T(P^{par}_T)$ which is the mean value of P^{γ}_T at fixed P^{par}_T.

These values can be obtained from the equations of the lines of the regression P^{par}_T depending on P^{γ}_T and P^{γ}_T depending on P^{par}_T:

$$\begin{aligned} A) \quad \overline{P}^{par}_T(P^{\gamma}_T) &= \rho(P^{\gamma}_T)P^{\gamma}_T; \qquad (2)\\ B) \quad \overline{P}^{\gamma}_T(P^{par}_T) &= \rho'(P^{par}_T)P^{par}_T. \qquad (3) \end{aligned}$$

For the initial sample we have

$$\rho'(x) \approx \rho(x) \approx 0.93 \div 0.97 \ \text{ at } \ x = 20 \div 300\,GeV/c.$$

The expressions for the average values of the balance follow (1):

$$\begin{aligned} A) \quad \overline{F}(P^{\gamma}_T) &= P^{\gamma}_T - \overline{P}^{par}_T = (1-\rho)P^{\gamma}_T \quad > 0, \qquad (4)\\ B) \quad \overline{F}(P^{par}_T) &= \overline{P}^{\gamma}_T - P^{par}_T = (\rho'-1)P^{par}_T < 0. \qquad (5) \end{aligned}$$

Thus, mean value of imbalance ($\overline{F}$) distincts from zero even before the any selections of the events. The density function of the two-dimensional distribution $f(P^{par}_T, P^{\gamma}_T)$ is shown on the Fig. 1a. Putting the cut at the fixed P^{γ}_T, we shall receive the asymmetric spectrum of P^{par}_T (Fig.1b). It has a maximum at $P^{par}_T = P^{\gamma}_T$ and mean value: $\overline{P}^{par}_T < P^{\gamma}_T$. The value ($\overline{F}$) represents the systematic error of the calibration which is not connected to the selections of events and is determined only by the coefficient of the correlation in P_T between the photon and the parton. According to the equation of the P_T-balance of the event:

$$\vec{P}^{\gamma}_T + \vec{P}^{par}_T + \vec{P}^{ISR}_T = 0, \qquad (6)$$

the value of this coefficient is determined by intensity of initial state radiation (P^{ISR}_T). Further this error we shall designate as $\overline{F}_0$.

Let's note, that the sign of the $\overline{F}_0$ depends according to (4) - (5) on the investigated regression ("A" or "B").

Imposing the restrictions on the some parameters of the events will change the initial imbalance so as. For example, restriction on $E^{isol}_{T\gamma}$ shifts the value of $\overline{F}$ to the positive area. The reason is that the vector of the $\vec{E}^{isol}_{T\gamma}$ coincides in the direction with the vector of $\vec{E}_T^{\gamma}$ and, thus, on putting the restrictions on the $E_{T\gamma}^{isol}$ the part of the events with $P_T^{\gamma} > P_T^{par}$ will be increased.

The systematic error of calibration connected with the primary selection of the events with $P_T^{\gamma} > P_T^{par}$ or $P_T^{\gamma} < P_T^{par}$, we shall designate as $\Delta\overline{F}$.

We make a little bit conditional division of the value of $\overline{F}$ into the $\overline{F}_0$ and the $\Delta\overline{F}$. The value of the $\overline{F}_0$ should characterize the component of the imbalance $\overline{F}$ dependent only on the degree of the P_T correlation between the photon and the parton, determined by the intensity of the initial state radiation in the selected events. This intensity can be expressed in the value of the RMS of the imbalance F (σ_F). As the $\overline{F}_0$ for each sample "0" received as a result of some selection, we accept values of $\overline{F}$ in sample "β" which turns out from the initial sample by trimming on P_T^{ISR} and has the same value of the RMS of the imbalance F as our sample "0":

$$\overline{F}_0(P_T^{\gamma}) = \overline{F}_{\beta}(P_T^{\gamma}) \quad \text{at } \sigma_{F,0} = \sigma_{F,\beta}. \tag{7}$$

Accordingly, the error $\Delta\overline{F}$ is defined as

$$\Delta\overline{F}(P_T^{\gamma}) = \overline{F}(P_T^{\gamma}) - \overline{F}_0(P_T^{\gamma}). \tag{8}$$

The values of the errors are calculated on studying regression on P_T^{γ}. Thus both the total error at the given regression, and its prediction for the case of the regression on the P_T^{par} is defined as

$$A) \qquad \Delta(x) = \Delta\overline{F}(x) + \overline{F}_0(x), \qquad x \equiv P_T^{\gamma}; \tag{9}$$

$$B) \qquad \Delta(x) = \Delta\overline{F}(x) - \overline{F}_0(x), \qquad x \equiv P_T^{par}. \tag{10}$$

4 The different levels of detalization of event simulation.

The reasons of the infringement of the P_T balance between the photon and the parton, arising as the result of the selection of the events, can include the both effects on the level of particles, and effects of the magnetic field, spatial and energy smearing, noise of electronics and others.

We consider the four levels of detalization:

"$PARTICLE$" – CMSJET without magnetic field, the energy and spatial smearing;

"$FIELD$" – CMSJET with magnetic field ($4T$) without the energy and spatial smearing;

"$SMEAR$" – CMSJET with magnetic field and with the energy and spatial smearing;

"$ORCA$" – CMSIM 121 $+$ ORCA 4.5.4.

As it was marked above the events with small imbalance (1) should be selected for calibration. Thus, criteria for the events choice for the calibration should include, in particular, the request to select the small values of the following quantities:

I) $\langle P_T^{ISR}\rangle$ which is the average value of P_T^{ISR};

II) σ_F which is the RMS of the imbalance $P_T^{\gamma} - P_T^{par}$;

so as the small values of systematic errors of the jet energy scale:

III) $\overline{F}_0$ which is the error determined only by the coefficient of the correlation between P_T^{γ} and P_T^{par} (see (7));

IV) $\Delta\overline{F}$ which is the error determined by the shift of the average value of the imbalance of the spectrum $P_T^{\gamma} - P_T^{par}$ due to different selections (see (8)).

The present studies are supposed to show, as far as we can supervise values of these quantities, by imposing restrictions on the various physical parameters of events measured by setup. The values of the selection cuts, naturally, are connected with the spectra of the appropriate parameters. And as these spectra in turn varies both in different intervals on P_T^{γ}, and at different levels of simulation of processes in setup ("$PARTICLE$", "$FIELD$",

"$SMEAR$" and "$ORCA$") the restrictions on the parameters appeared to be also different for the different levels of the simulation and the different values of P_T^γ. Therefore on investigating the various dependencies on the cut over the various parameters, we consider not the values of these restrictions, but the values of the efficiency of the signal suppression due to these restrictions.

Let's give more exact definitions of parameters for the selection of the events.

$\Delta\phi$ is the interval of the polar angle ϕ between vectors of E_T of the jet and the photon. The jet is gathered in calorimeters in the cone R=0.7, and the photon is gathered in 3×3 crystals in the electromagnetic calorimeter.

$E_{T\gamma}^{isol}$ is the scalar sum of the E_T of the calorimeter cells belonging to the cone $R = 0.7$, outlined around the photon, except the 7×7 crystals area in electromagnetic calorimeter, i.e. excluding area of the photon.

E_{Tjet}^{isol} is the scalar sum of E_T of the calorimeter cells belonging to the ring $0.7 < R < 1$ around the jet.

E_T^{miss} is the vector sum of transverse energy of the all calorimeter cells.

E_T^{jet2} is the maximal transverse energy of the additional jets.

E_T^{out1} is the vector sum of E_T of the calorimeter cells except the area 7×7 crystals in the electromagnetic calorimeter around the photon and the area of the radius 0.8 around the jet.

E_{Ts}^{out1} is the scalar sum of E_T of the same cells.

E_T^{out2} is the vector sum of E_T of the cells of calorimeters except those in the cone of the radius R_2=0.8 around the photon and the cone of the same size around the jet.

E_{Ts}^{out2} is the scalar sum of E_T of the same cells.

5 Results and discussion.

The dependency on the P_T^γ of the following quantities:

- $\langle P_T^{ISR}/P_T^\gamma\rangle$ which is the value of P_T^{ISR}/P_T^γ (Fig.2) averaged over all events;
- σ_f is RMS of imbalance $(P_T^\gamma - P_T^{par})/P_T^\gamma$ (Fig.3);
- $\overline{f}_0$ (Fig.4) $\Delta\overline{f}$ (Fig.5) which are the errors determined according to (7)-(8) by replacement

$$F \longrightarrow f = \frac{P_T^\gamma - P_T^{par}}{P_T^\gamma}$$

for different cuts applied to the various parameters are shown on Fig.2-5. The cuts correspond to the efficiency of the signal suppression Eff = 100 and 5 %.

The results got for "$PARTICLE$", "$FIELD$" and "$SMEAR$" levels differ unsignificantly, therefore we present only "$PARTICLE$" and "$ORCA$" levels.

The results received at the various levels of the simulation are given in Tabl.3. The values of the RMS of the imbalance f and the value of errors $\overline{f}_0$ and $\Delta\overline{f}$ are presented in here. One can see, that these values for "$PARTICLE$", "$FIELD$" and "$SMEAR$" levels of detalization practically coincide.

First of all we shall note, that according to Fig.3-4 the component of the systematic error $\overline{f}_0$ as it is supposed in section 3, appeared hardly connected with the RMS of the imbalance f. That is why we can divide the systematic error of $\overline{f}$ offered in section 3 on the independent components $\overline{f}_0$ and $\Delta\overline{f}$. $\overline{f}_0$ is determined only by the correlation coefficient of P_T of the photon and the parton, and $\Delta\overline{f}$ is determined by the shift of the imbalance $\overline{f}$ arising at some selections aside positive or negative values.

One can see from Fig.2-5 that in the case of the selections on $\Delta\phi$ at $P_T^\gamma > 40\,GeV/c$, and also in the case of the selections on $E_{T\gamma}^{isol}$, E_{Tjet}^{isol}, E_T^{jet2}, E_T^{out2}, E_{Ts}^{out1}, E_{Ts}^{out2} the results obtained with "$ORCA$" are close to the results obtained on the "$PARTICLE$" level. Thus, in these cases the effects of "$PARTICLE$" level are the basic ones.

Tabl.3. The value of imbalance (P_T^γ–P_T^{par}) with events selections using the various parameters X_0: "$PARTICLE$", "$FIELD$", "$SMEAR$" and "$ORCA$"; $40 < P_T^\gamma < 100\,GeV/c$; $Eff = 50\%$.

a) The values of σ_f in %.

X_0	*PARTICLE*	*FIELD*	*SMEAR*	*ORCA*
no cuts	21.0	21.0	21.0	21.0
$\Delta\phi$	17.2	17.2	17.2	17.7
$E_{T\gamma}^{isol}$	20.0	19.9	20.0	20.3
E_{Tjet}^{isol}	20.6	20.7	20.7	21.4
E_T^{miss}	19.9	19.7	19.3	20.1
E_T^{jet2}	13.6	13.8	14.5	15.5
E_T^{out1}	11.8	12.1	12.6	15.8
E_T^{out2}	12.3	12.7	12.8	14.8
E_{Ts}^{out1}	16.3	16.2	16.3	16.4
E_{Ts}^{out2}	16.4	16.2	16.3	16.4

b) The values of $\overline{f}_0$ in %.

X_0	*PARTICLE*	*FIELD*	*SMEAR*	*ORCA*
no cuts	5.5	5.5	5.5	5.5
$\Delta\phi$	4.5	4.6	4.5	4.6
$E_{T\gamma}^{isol}$	5.3	5.2	5.3	5.3
E_{Tjet}^{isol}	5.5	5.5	5.5	5.6
E_T^{miss}	5.2	5.2	5.1	5.2
E_T^{jet2}	3.6	3.6	3.8	4.0
E_T^{out1}	3.1	3.2	3.3	4.1
E_T^{out2}	3.2	3.3	3.4	3.9
E_{Ts}^{out1}	4.3	4.3	4.3	4.3
E_{Ts}^{out2}	4.3	4.3	4.3	4.3

c) The values of $\Delta\overline{f}$ in %.

X_0	*PARTICLE*	*FIELD*	*SMEAR*	*ORCA*
no cuts	0.0	0.0	0.0	0.0
$\Delta\phi$	-0.9	-0.9	-0.2	-0.6
$E_{T\gamma}^{isol}$	$+1.7$	$+1.8$	$+1.7$	$+1.1$
E_{Tjet}^{isol}	-4.7	-4.1	-4.5	-5.6
E_T^{miss}	$+0.6$	-0.6	0.0	-2.4
E_T^{jet2}	-0.2	-0.3	-0.2	$+0.1$
E_T^{out1}	$+0.4$	$+0.1$	$+0.6$	$+4.0$
E_T^{out2}	-1.4	-1.6	-1.6	-0.9
E_{Ts}^{out1}	$+0.7$	$+0.6$	$+0.6$	$+0.6$
E_{Ts}^{out2}	$+0.4$	$+0.4$	$+0.3$	$+0.5$

In the case of the selection on $\Delta\phi$ in the region $P_T^\gamma < 40\,GeV/c$ and for the selections on E_T^{miss} and E_T^{out1} the results for "$PARTICLE$" and "$ORCA$" levels essentially differ. Thus these variables are influenced by the detector effects.

The list of priorities of the selections established in the way that they reduce the value of the RMS of the imbalance $P_T^\gamma - P_T^{par}$ and at the same time do not disturb the mean value (according the Figs 2-5) are given in the Table 4.

As the criteria for setting the list of priorities we consider the following quantities calculated on the "$ORCA$ level (the corresponding values for "$PARTICLE$" level are given in the parenthesis) : a) Δ_{ISR} which is the difference of the values $\langle P_T^{ISR}/P_T^\gamma\rangle$ taken at $Eff = 5\%$ $Eff = 100\%$; b) $\Delta\sigma_f$ which is the difference of the values σ_f taken at the same Eff; c) the value of $\Delta\overline{f}$ at $Eff = 5\%$.

Tabl.4. The list of priorities ("PRI") of the selections on the various parameters X_0.

X_0	"Δ_{ISR}" criterion			"$\Delta\sigma_f$" criterion			"$\Delta\overline{f}$" criterion		
	PRI	Δ_{ISR} (%)		PRI	$\Delta\sigma_f$ (%)		PRI	$\Delta\overline{f}$ (%)	
$\Delta\phi$	**1**	12	(12)	**4**	5	(5)	**3**	-1.5	(-1.5)
$E_{T\gamma}^{isol}$	**6**	1	(0)	**6**	1	(1)	**5**	2.5	(2)
E_{Tjet}^{isol}	**7**	-2	(0)	**7**	-3	(-2)	**8**	-8	(-8)
E_T^{miss}	**5**	4	(2)	**5**	2	(2)	**6**	-4	(1)
E_T^{jet2}	**3**	10	(15)	**2**	8	(11)	**2**	-1	(-1)
E_T^{out1}	**4**	7	(16)	**3**	6	(12)	**7**	7	(1)
E_T^{out2}	**2**	11	(16)	**2**	8	(11)	**4**	-2	(-2.5)
E_{Ts}^{out1}	**3**	10	(12)	**1**	9	(9)	**2**	1	(1)
E_{Ts}^{out2}	**2**	11	(12)	**1**	9	(9)	**1**	0.5	(-0.5)

Except the $\Delta\phi$ selection the cuts on all other parameters give the same suppression for both the initial state radiation and the value of the RMS of the imbalance. The $\Delta\phi$ selection selection reduces P_T^{ISR} on 12%, and σ_f of all on 5% at $Eff = 5\%$.

The strongest suppression can be achieved with the cuts on E_{Ts}^{out1} and E_{Ts}^{out2}.

The isolation criteria for jet (E_{Tjet}^{isol}) is the least preferable. In particular, it results in the essential systematic error $\Delta\overline{f}$ and increases the error $\overline{f}_0$.

The error $\Delta\overline{f}$ is significant (up to 4%) also with restriction on $E_{T\gamma}^{isol}$ (Fig.5). The cuts on E_T^{miss} and E_T^{out1} this error are essential only at "$ORCA$" level (up to 6%).

The cut on E_T^{out2} also results in the error $\Delta\overline{f}$ (up to 3%). The reason is that the part of the jet might appear outside the cone and thus includes in the E_T^{out2} value. One can see from Fig.6 that the jet gives the response outside the cone $R = 0.8$. As the result the vector $\vec{E}_T^{out2}$ will be mainly directed along the jet and, thus, the cut on E_T^{out2} will result in the primary selection of the events with $P_T^{par} > P_T^{\gamma}$. The systematic error $\Delta\overline{f}$ can be reduced by the increase of the radius R_2 (see section 4). The increase of the radius R_2 from 0.8 up to 1.2 reduces the systematic error approximately in 1.5 times. At the further increase of the radius R_2 from 1.2 up to 1.5 the error $\Delta\overline{f}$ practically does not vary.

Let's note, that inspite of the large shift of the mean value of the imbalance $P_T^{\gamma} - P_T^{par}$ the position of a maximum of the $P_T^{\gamma} - P_T^{par}$ spectrum on applying the various selections is almost not shifted. For example, on applying the cuts on different parameters corresponded to $Eff = 25\%$ for the signal the shift of position of the maximum does not exceed $1\% P_T^{\gamma}$. Thus, probably, one has to use the position of the maximum of $P_T^{\gamma} - P_T^{par}$ distribution rather than mean value.

6 Conclusion.

The essential systematic errors connected with the presence of the imbalance in the $P_T^{\gamma} - P_T^{par}$ distribution can distort the jet energy scale obtained using "$\gamma + jet$" channel. The value of the systematic error depends on the restrictions which are imposed on the various parameters of events which are selected for calibration. The position of maximum of $P_T^{\gamma} - P_T^{par}$ distribution is less sensitive both to the presence of the background and to the cuts on the different parameters. Thus we propose to use the position of the maximum for the "$\gamma + jet$" calibration rather than mean value.

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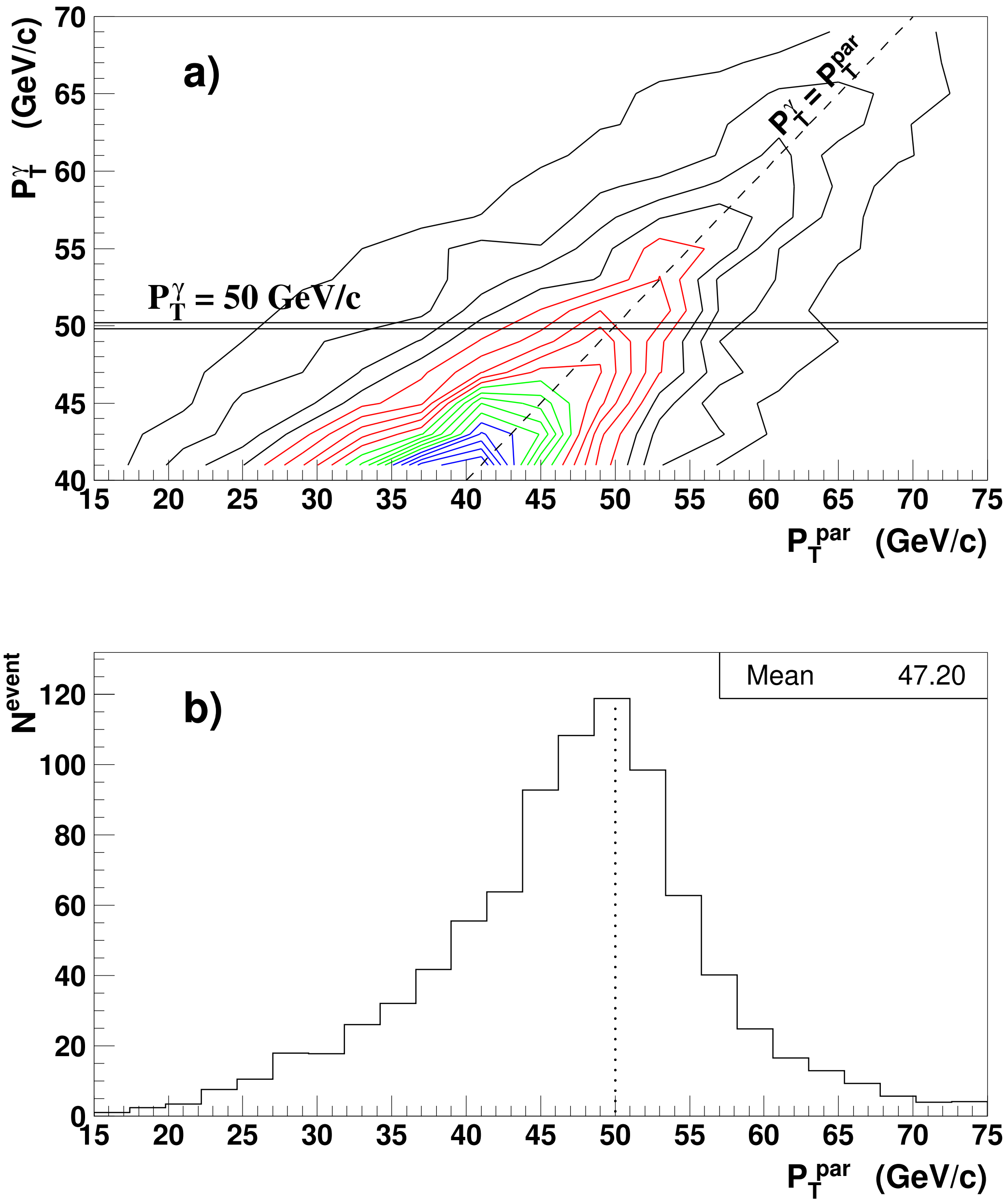

Figure 1: The density function of bidimentional distribution $f(P_T^{par}, P_T^{\gamma})$ (a) and spectrum of P_T^{par} for $P_T^{\gamma} = 50\,GeV/c$ (b) in the events with direct photons .

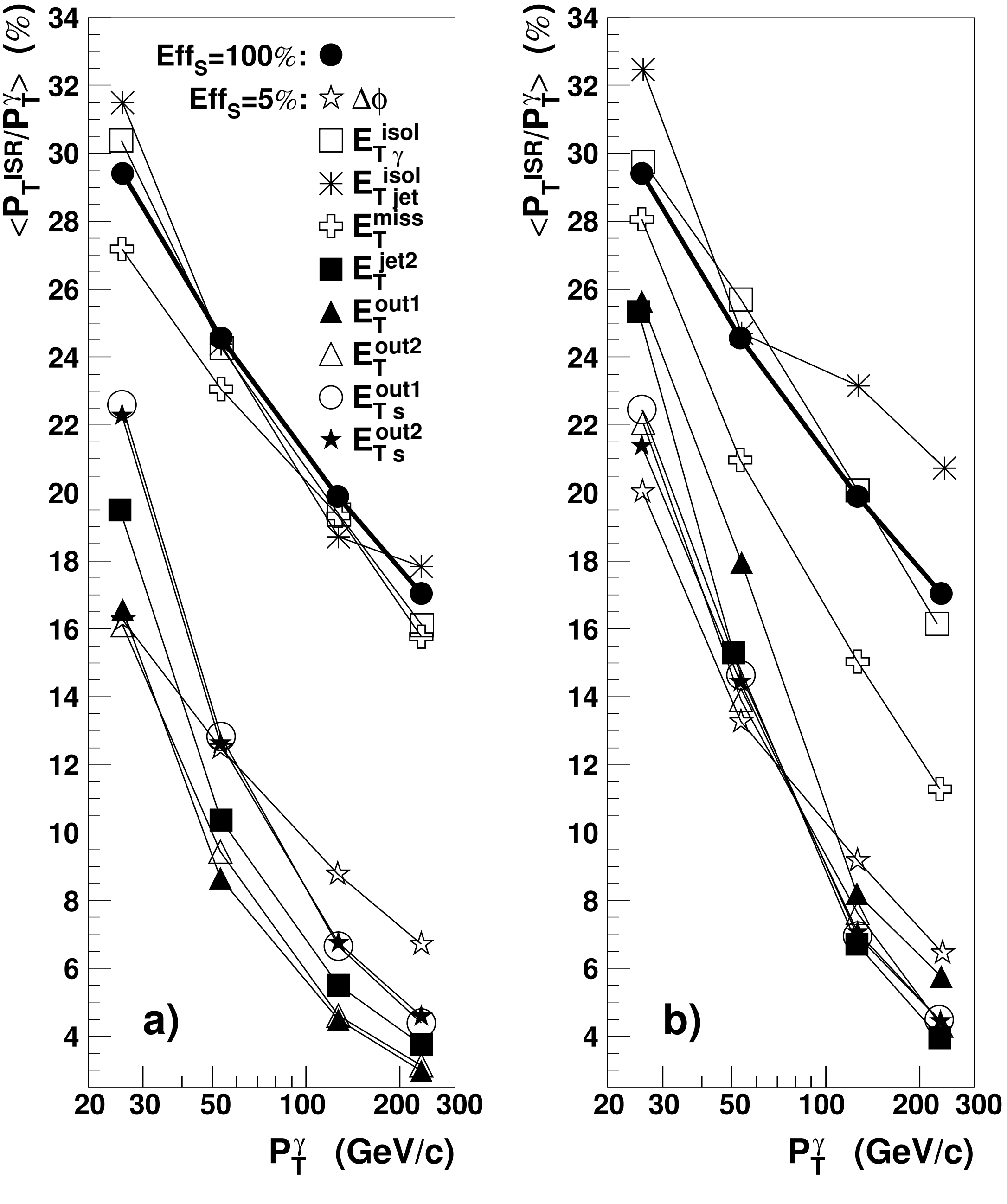

Figure 2: The mean values of the P_T of the initial state radiation for the various P_T^{γ} without selection of events (black circles) and with selections of events for signal efficiency $Eff = 5\%$ by imposing restrictions on the indicated parameters for the "$PARTICLE$" (a) and "$ORCA$" (b) levels.

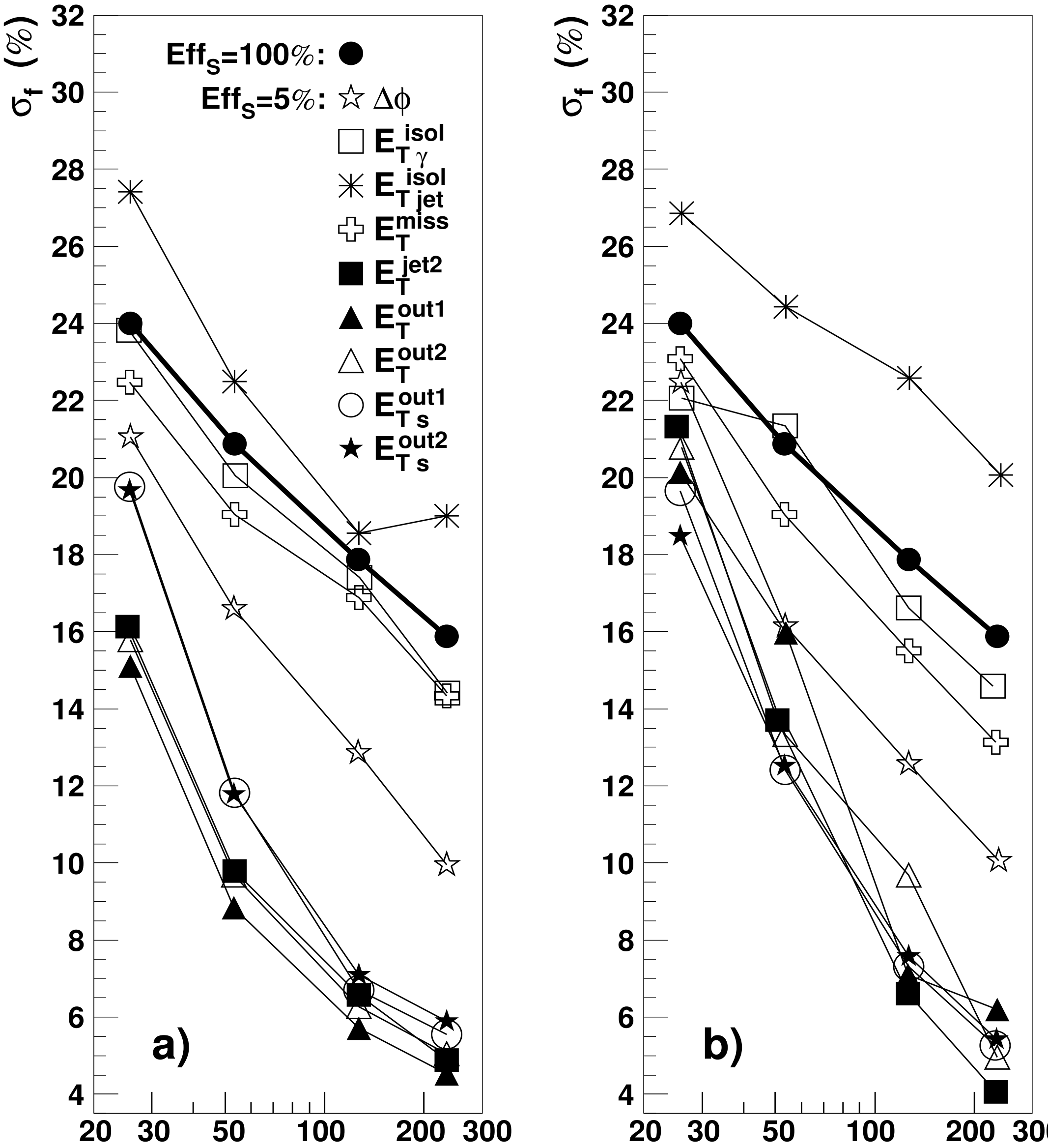

Figure 3: The mean values of the RMS of imbalance $(P_T^\gamma - P_T^{par})/P_T^\gamma$ for the various P_T^γ without selection of events (black circles) and with selections of events for signal efficiency $Eff = 5\%$ by imposing restrictions on the indicated parameters for the "$PARTICLE$" (a) and "$ORCA$" (b) levels.

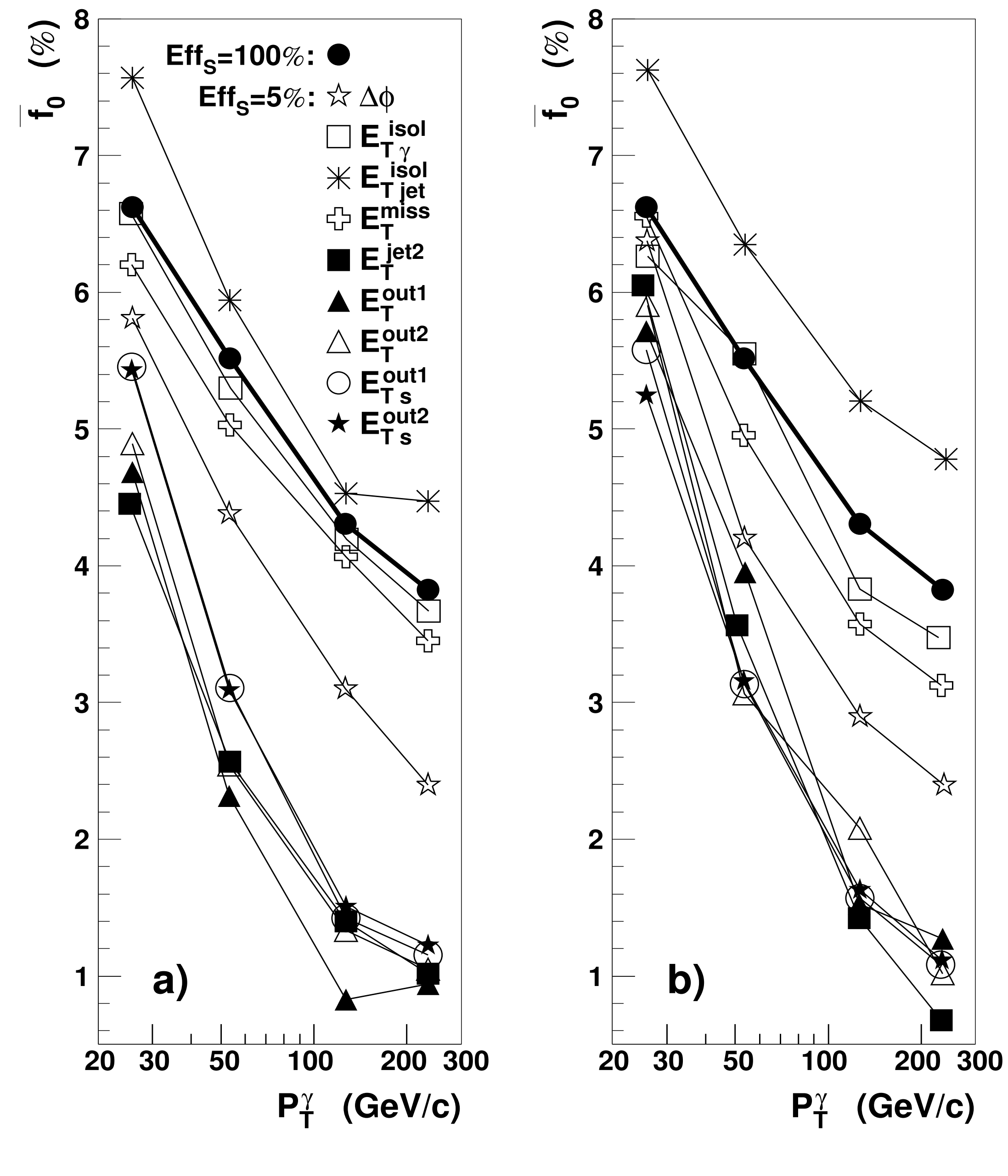

Figure 4: The values of the systematic error $\overline{f}_0$ for the various P_T^γ without selection of events (black circles) and with selections of events for signal efficiency $Eff = 5\%$ by imposing restrictions on the indicated parameters for the "$PARTICLE$" (a) and "$ORCA$" (b) levels.

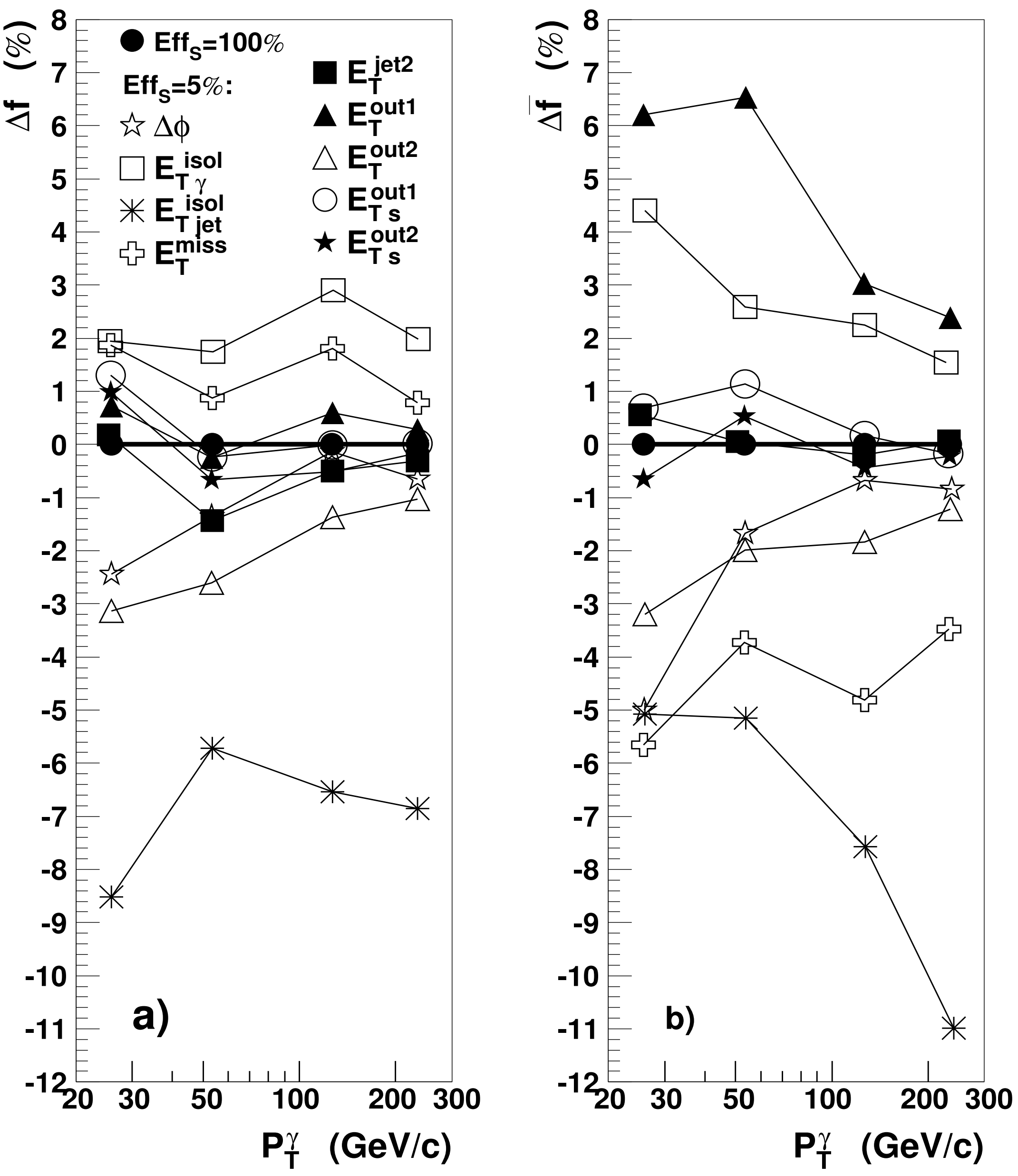

Figure 5: The values of the systematic error $\Delta\overline{f}$ for the various P_T^γ without selection of events (black circles) and with selections of events for signal efficiency $Eff = 5\%$ by imposing restrictions on the indicated parameters for the "$PARTICLE$" (a) and "$ORCA$" (b) levels.

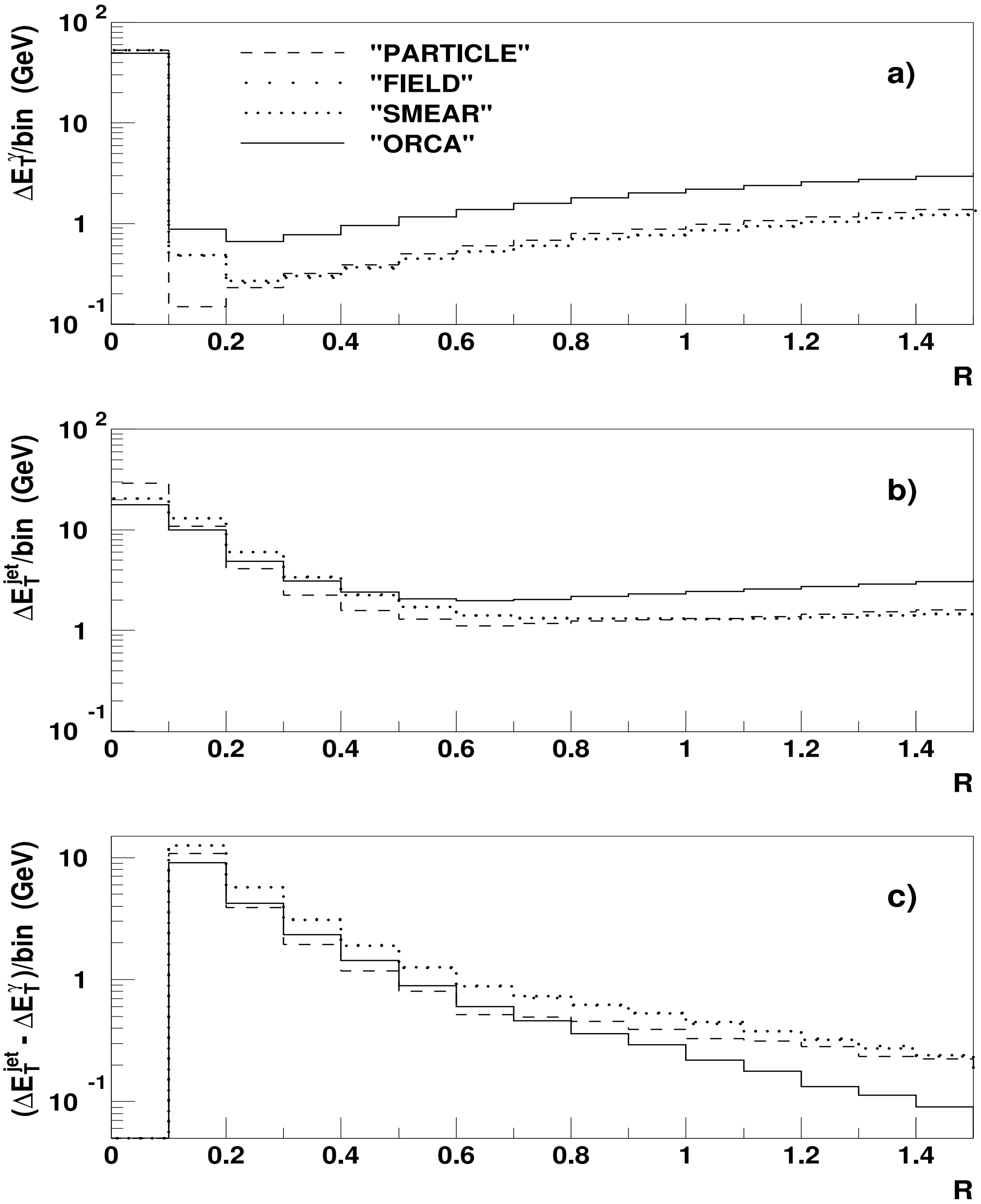

Figure 6: The average E_T in the rings in around the direct photon (a), around the jet (b) and differences of these values (c). The direct photons from the interval $40 < P_T^{\gamma} < 100\,GeV$ are used for the "$PARTICLE$", "$FIELD$", "$SMEAR$" and "$ORCA$" levels.