Jet Energy Scale Calibration using $e^+e^- \rightarrow \gamma Z$ process at the ILC

Takahiro Mizuno
SOKENDAI

Introduction

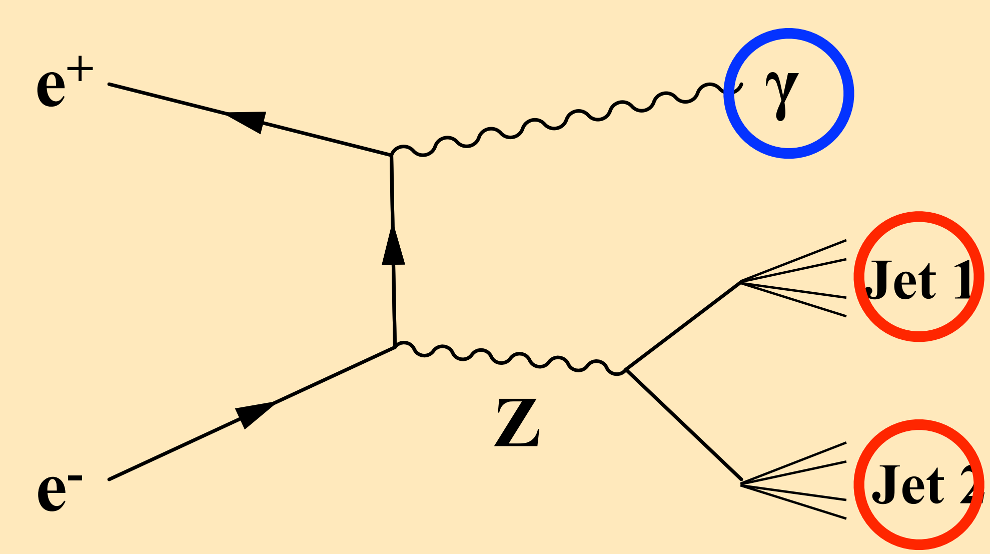
Detector Benchmark Motivation

- Primary Target of ILC 250: to precisely measure *the coupling constants between Higgs boson and various other particles*
-> **For this, we need to precisely calibrate energy scales for various particles.**

- Jet energies can be reconstructed using measured direction of 2 jets and γ and mass of 2 jets in the $e^+e^- \to \gamma Z$, $Z \to 2$ Jets process. Taking advantage of its large cross sections, ~80 million events are expected @ ILC250.

- In this talk, I will show how useful the $e^+e^- \to \gamma Z$ process is for the jet energy calibration **by full simulation.**

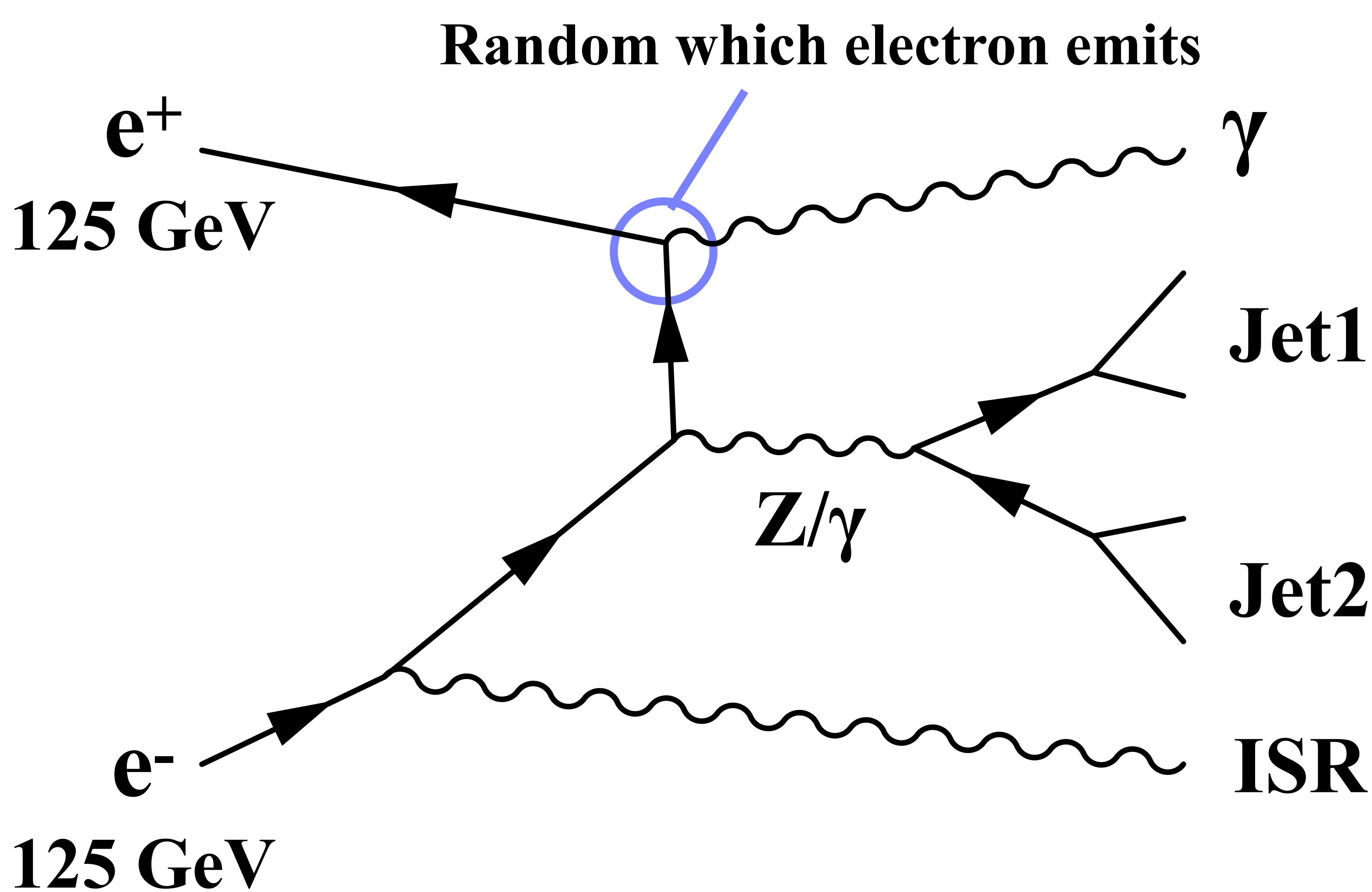
Jet Energy Scale Calibration



Full simulation

(ILCSOFT version v01-16-02)

- **Geant4-based full detector simulation** is performed for the $e^+e^- \rightarrow \gamma Z$, $Z \rightarrow$ 2 Jets process using a **realistic ILD detector model**, at **E_{CM}= 250 GeV** with $\int Ldt$=900fb^{-1} each for 2 beam polarizations: (P_{e^-}, P_{e^+}) = (-0.8, +0.3) and (+0.8, -0.3).



Event selection

Signal Photon Selection

Events signature = **1 isolated energetic photon + 2 jets**

Signal photon is selected as follows:

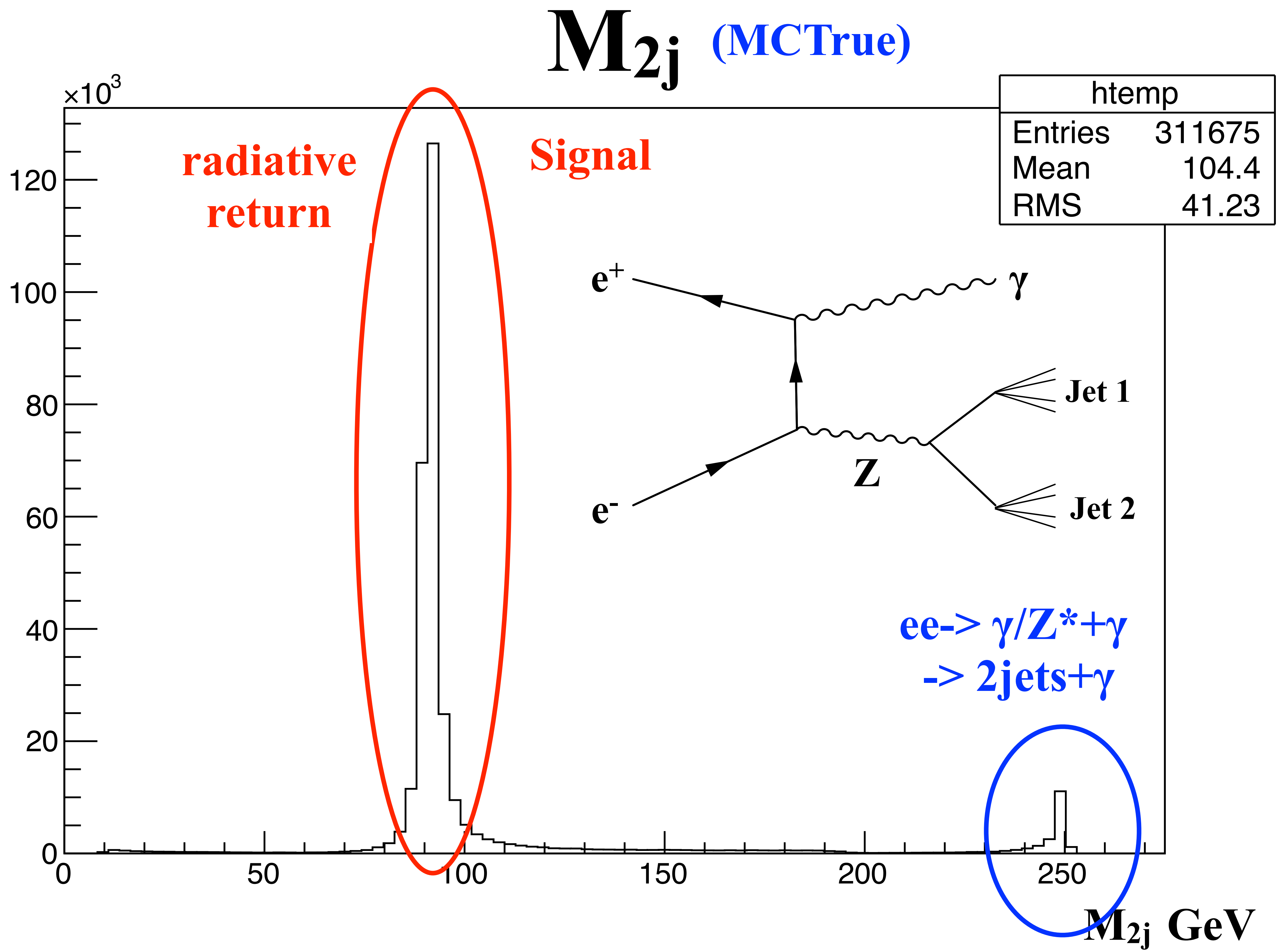
1. choose neutral particles with particle ID = 22 (Pandora PFA ID)
2. require energy > 50 GeV
3. choose the photon candidate with energy closest to 108.4 GeV

Other photons inside the cone (with the angle $\cos\theta > 0.998$ from the signal photon) are merged with the signal photon.

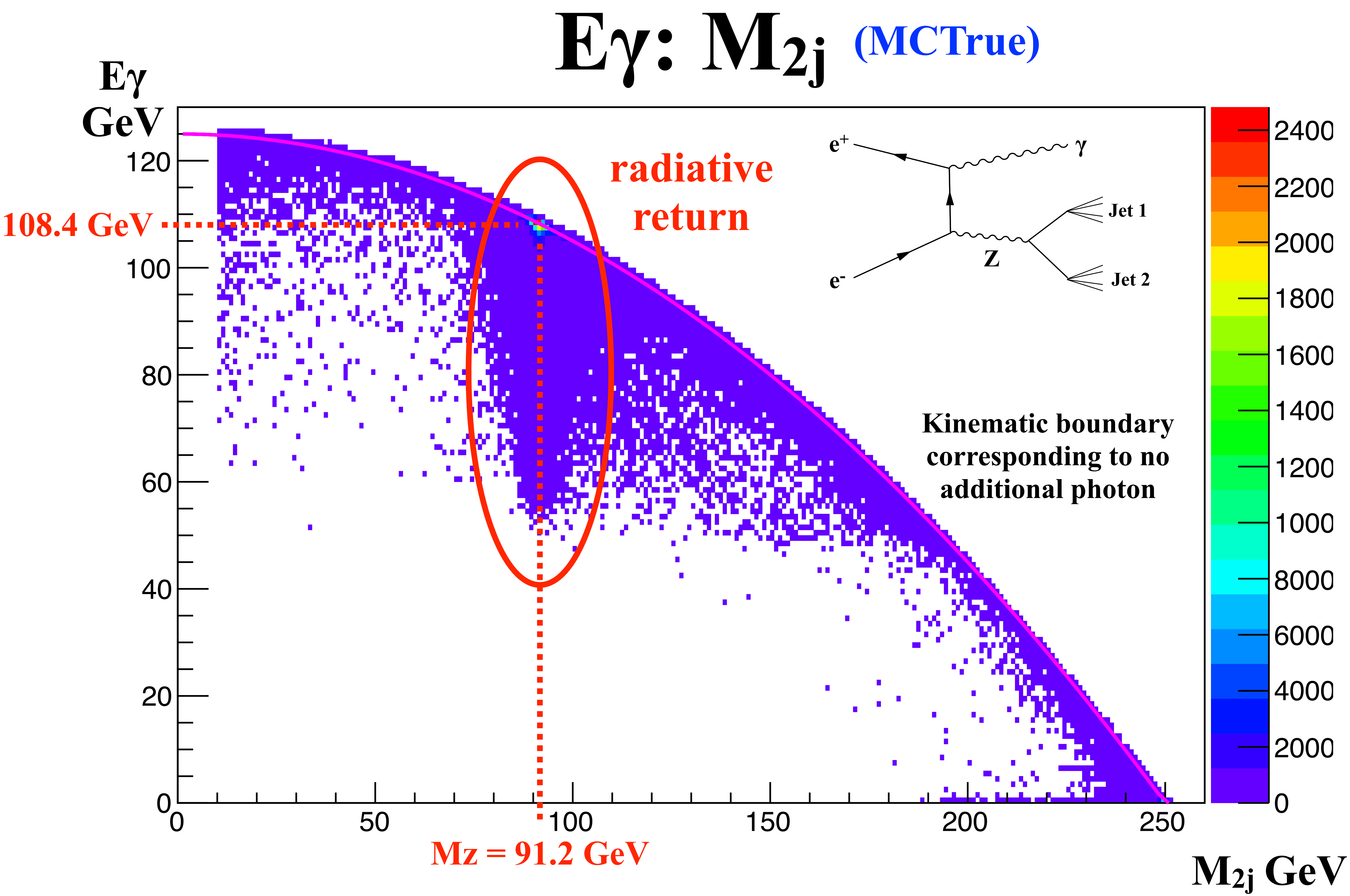
Jet Clustering

- All Particle Flow Objects (PFOs) other than the selected photon are clustered into 2 jets with Durham algorithm (done by LCFIPlus)
- The jet with higher reconstructed energy is defined as “jet 1” and the other as “jet 2”

M_{2j} distribution



Photon energy & M_{2j} distribution

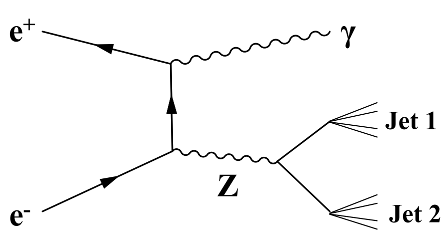


Correct photon selection

E_{vis} (=$E_{j1}+E_{j2}+E_\gamma$) vs. $\Delta\theta_\gamma = \theta_\gamma(\text{meas})-\theta_\gamma(\text{MC})$

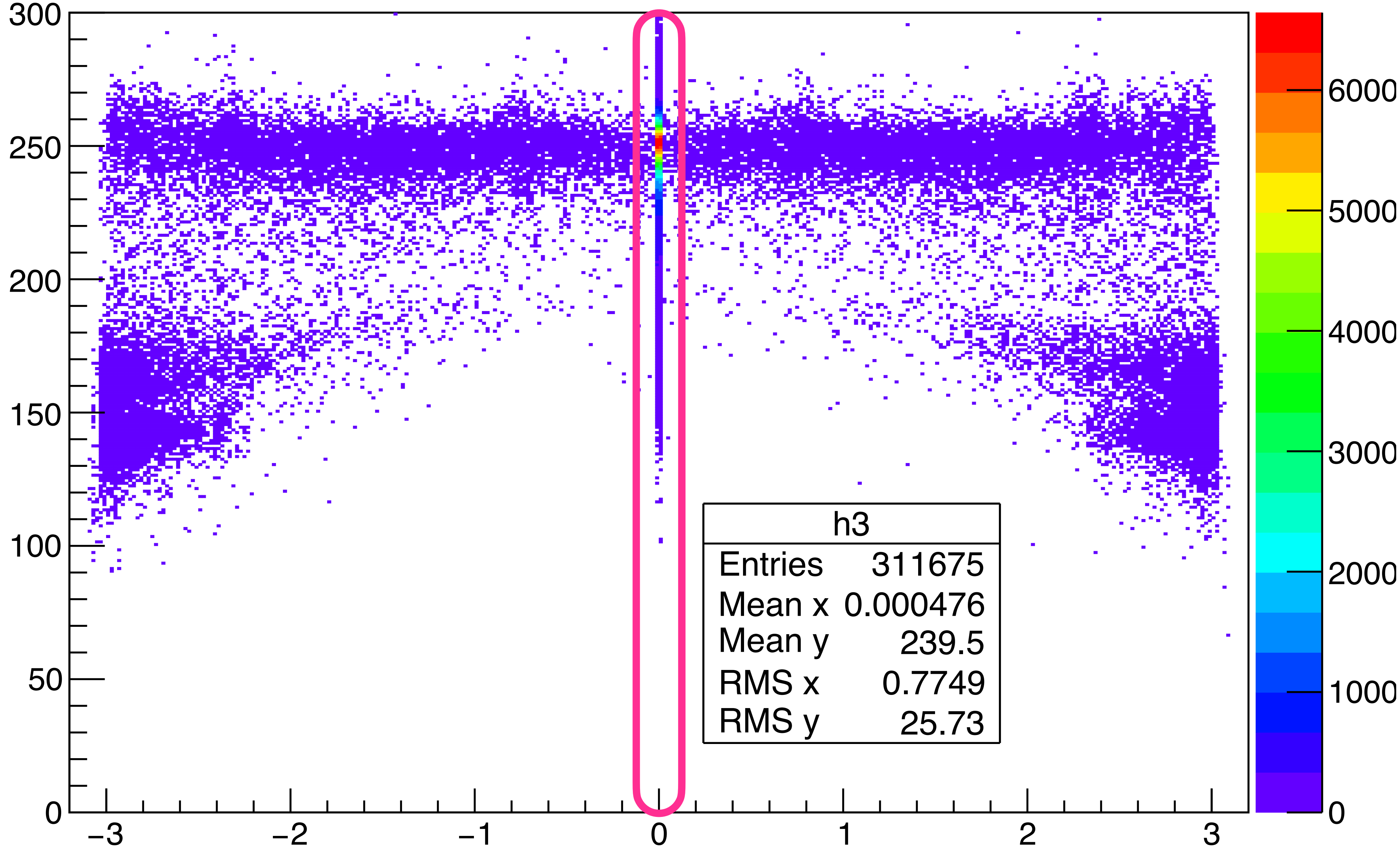
E_{vis} (GeV)

True signal photon: feeble and missing



True signal photon: energetic but missing

Selected photon: from jets



$|\Delta\theta_\gamma| < 0.01$ events: 87.8%

$|\Delta\theta_\gamma| > 0.01$ events: 12.2%

Correct Photon

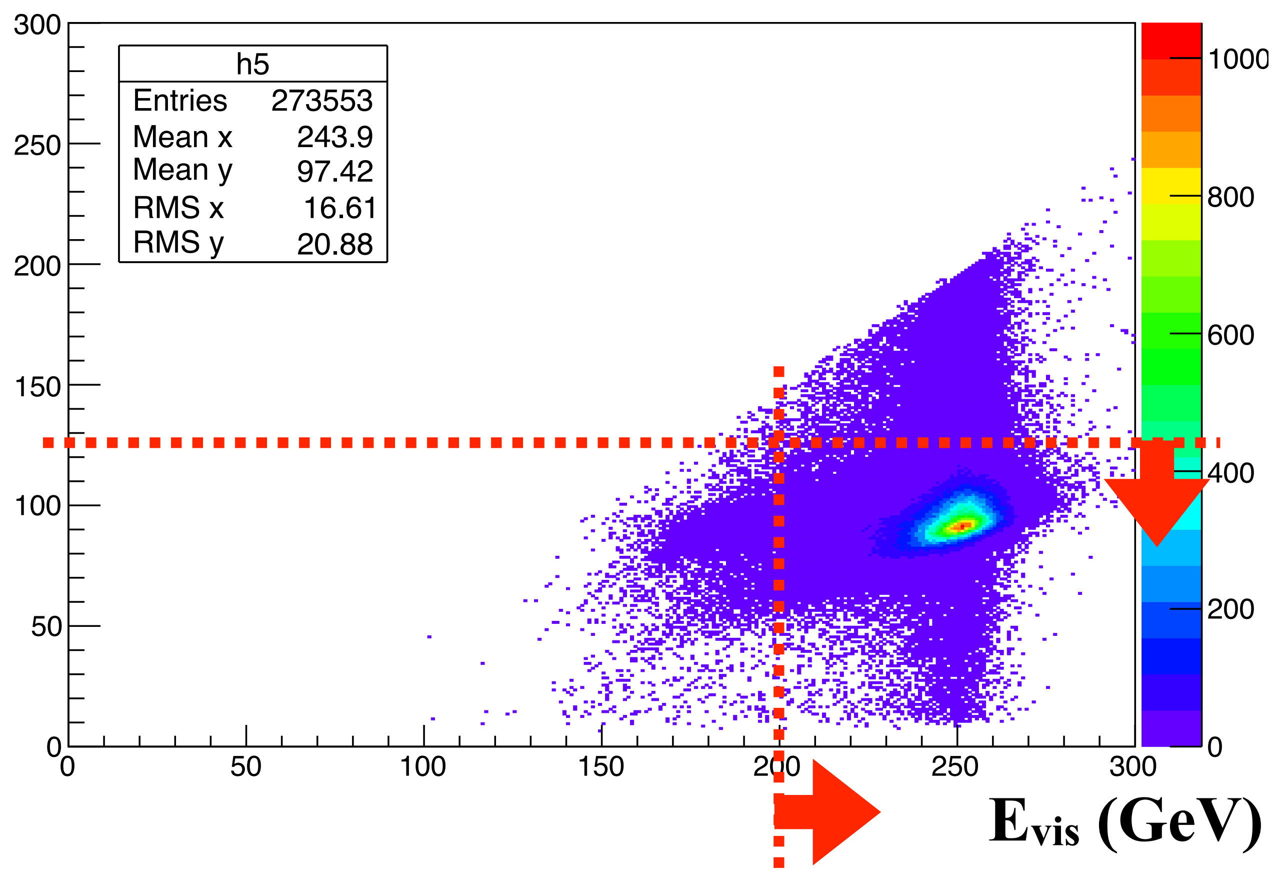
$\Delta\theta_\gamma$ (rad)

Correct photon selection cut 1

M_{2j} vs. E_{vis} (=Ej1+Ej2+Eγ)

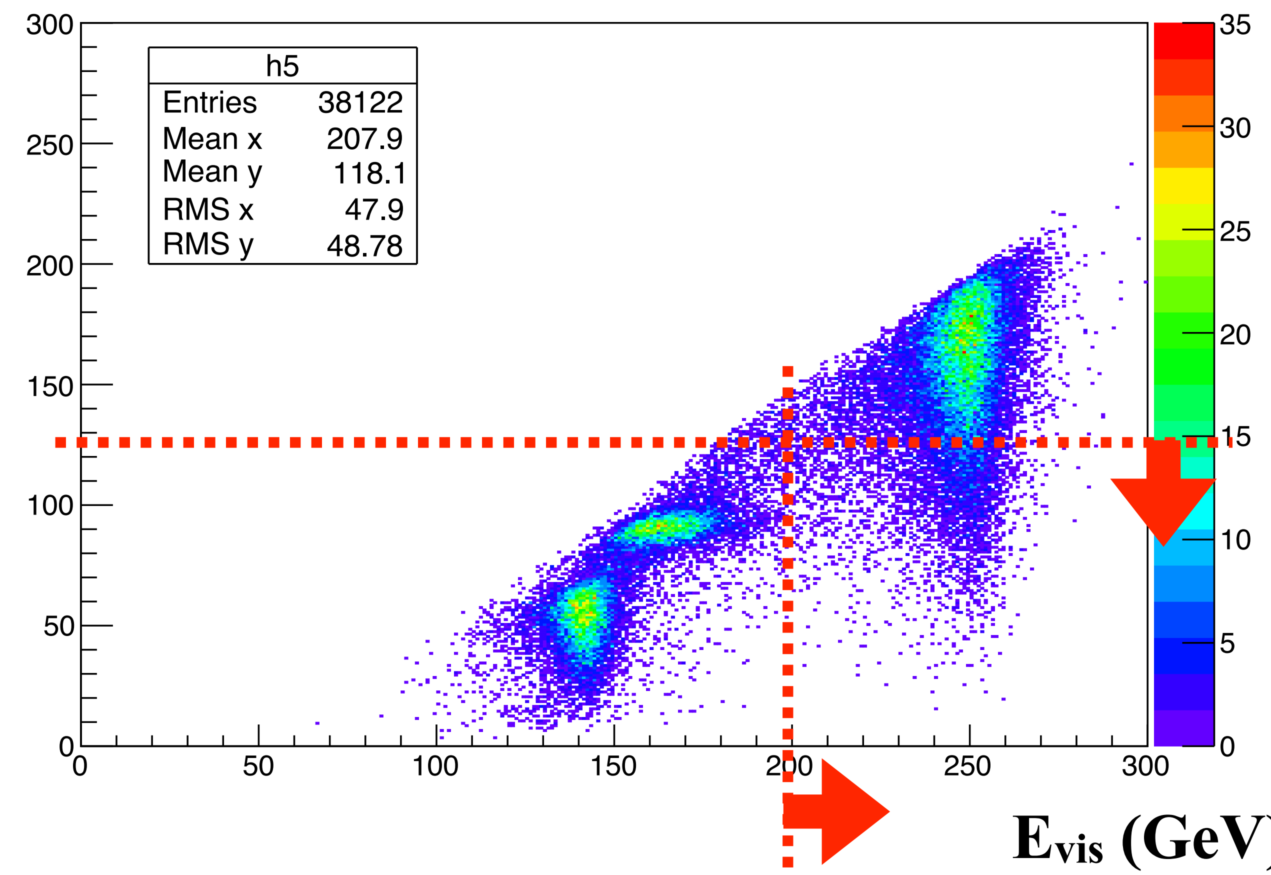
correct photon case
$|\Delta\theta_\gamma| < 0.01$

M_{2j} (GeV)



wrong photon case
$|\Delta\theta_\gamma| > 0.01$

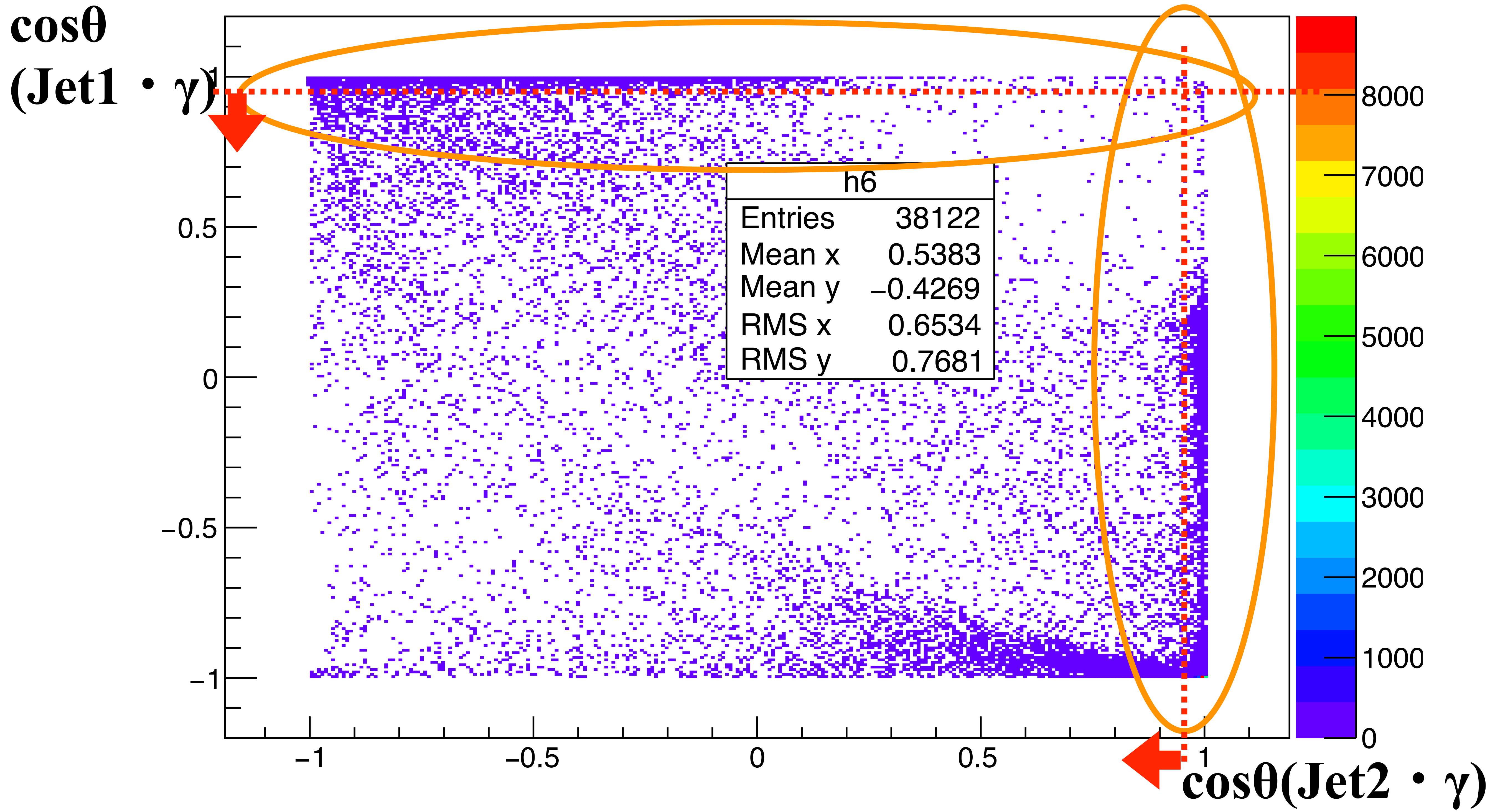
M_{2j} (GeV)



Cut1: M_{2j} <125 GeV && E_{vis} >200 GeV

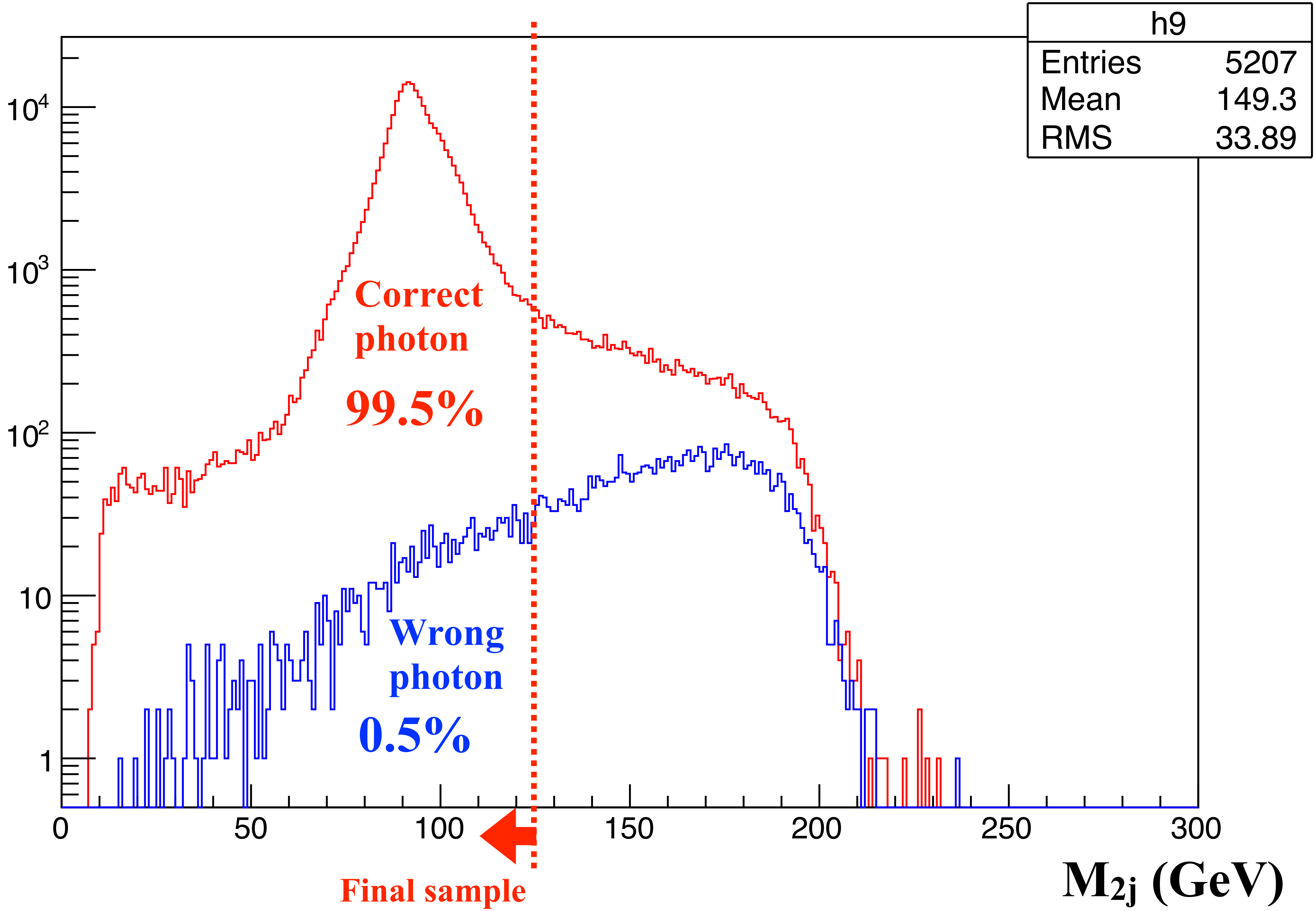
Correct photon selection cut 2

Wrong photons are near jet axes



Cut2: cosθ(Jet1・γ)<0.95 && cosθ(Jet2・γ)<0.95

M_{2j} distribution after all but M_{2j} cut

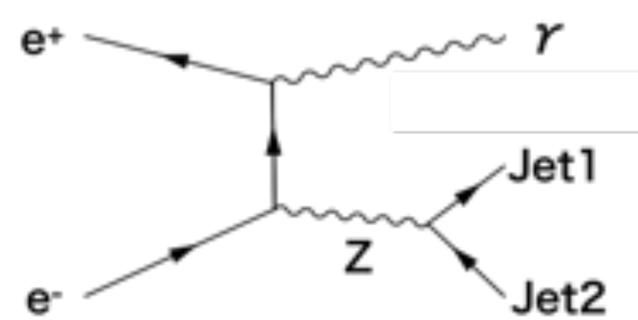


Reconstruction Method

Main idea: it is possible to reconstruct jet energies based on jet angles and masses using 4-momentum conservation

Inputs and outputs

Using ($\theta_{J1}, \theta_{J2}, \theta_{\gamma}, \varphi_{J1}, \varphi_{J2}, \varphi_{\gamma}, m_{J1}, m_{J2}$)
-> Determine ($P_{J1}, P_{J2}, P_{\gamma}, P_{ISR}$)



Direction Angle
θ: polar angle
ϕ: azimuthal angle

$$\begin{cases} \sqrt{P_{J1}^2 + m_{J1}^2} + \sqrt{P_{J2}^2 + m_{J2}^2} + |P_\gamma| + |P_{ISR}| = E_{CM} \quad ① \\ \begin{pmatrix} sin\theta_{J1}cos\phi_{J1} & sin\theta_{J2}cos\phi_{J2} & sin\theta_\gamma cos\phi_\gamma \\ sin\theta_{J1}sin\phi_{J1} & sin\theta_{J2}sin\phi_{J2} & sin\theta_\gamma sin\phi_\gamma \\ cos\theta_{J1} & cos\theta_{J2} & cos\theta_\gamma \end{pmatrix} \begin{pmatrix} P_{J1} \\ P_{J2} \\ P_\gamma \end{pmatrix} = \begin{pmatrix} (E_{CM} - |P_{ISR}|)sin\alpha \\ 0 \\ \pm|P_{ISR}|cos\alpha \end{pmatrix} \end{cases}$$

Matrix A — Inverse

Beam Crossing Angle ≡2α = 14.0 mrad
ISR photon = additional unseen photon

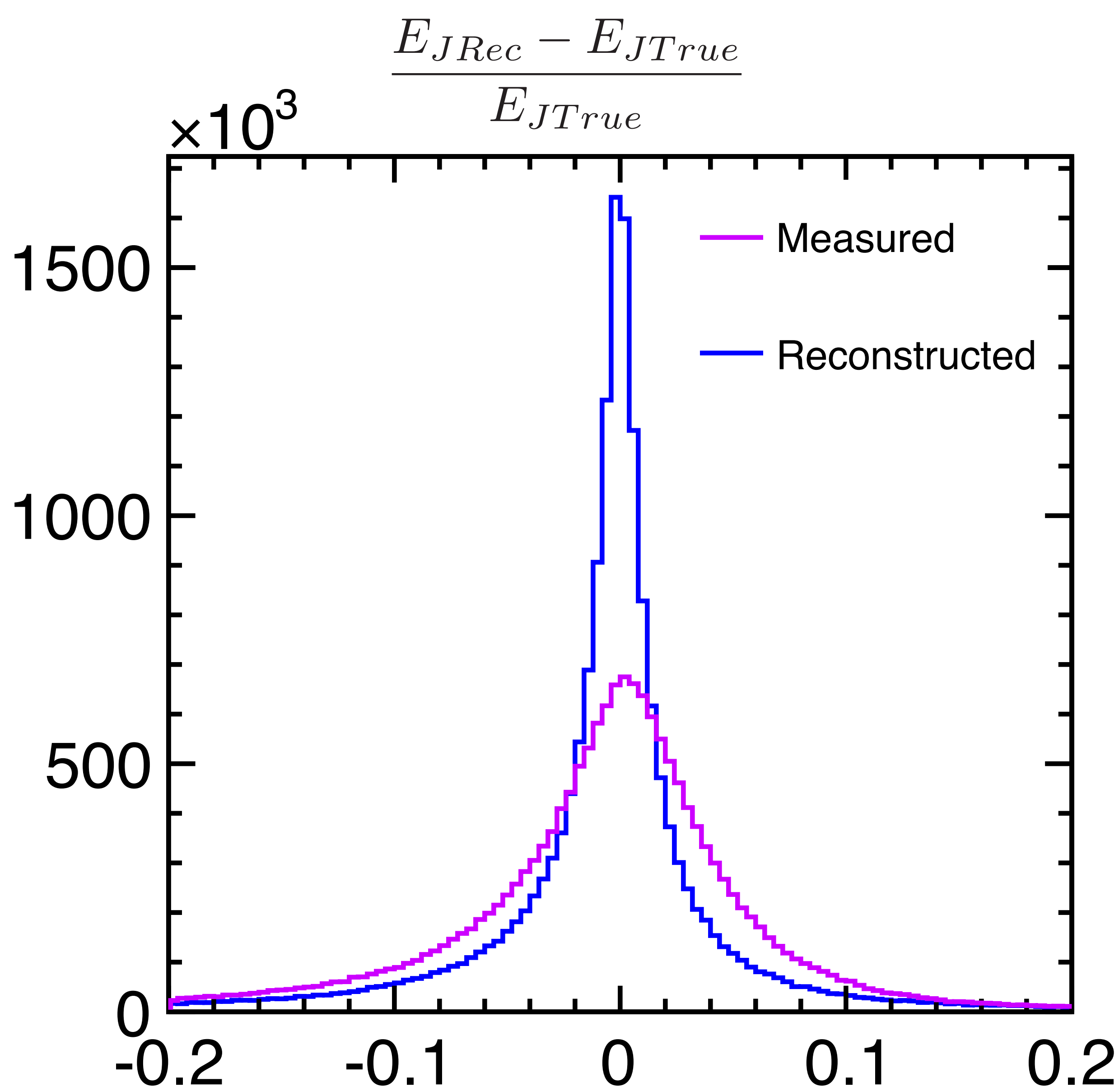
Irrational equation for each sign of the ISR -> 8 possible solutions

Choose the solution with

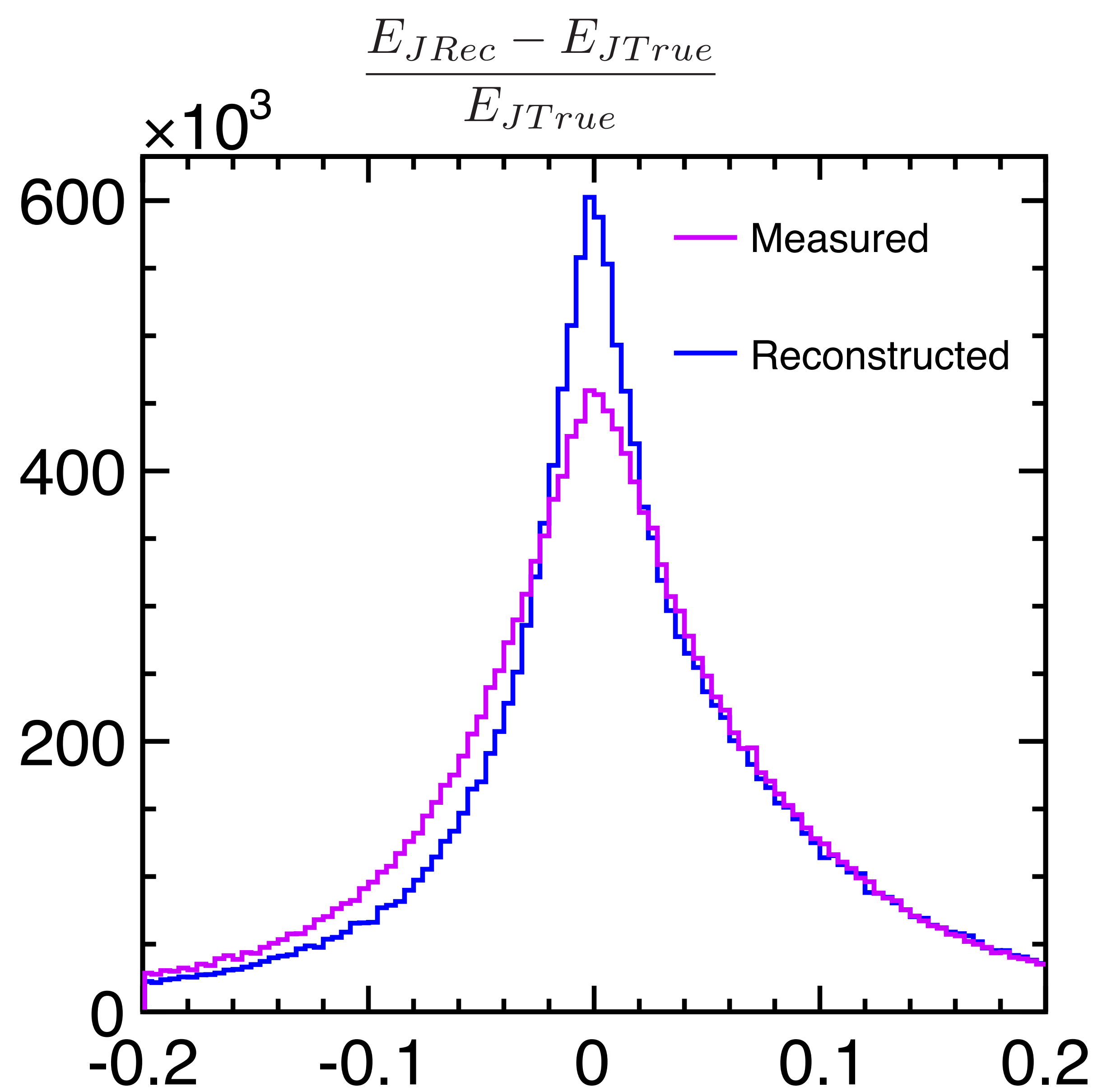
- **(i) Real and positive value with <$E_{CM}/2$**
- **(ii) $\sqrt{P_{J1}^2 + m_{J1}^2}$ >0 and $\sqrt{P_{J2}^2 + m_{J2}^2}$ >0**
- **(iii) P_{J1}, P_{J2}, P_γ >0**
- **(iv) solved P_γ closest to the measured P_γ**

Jet Energy Reconstruction Result

Jet 1



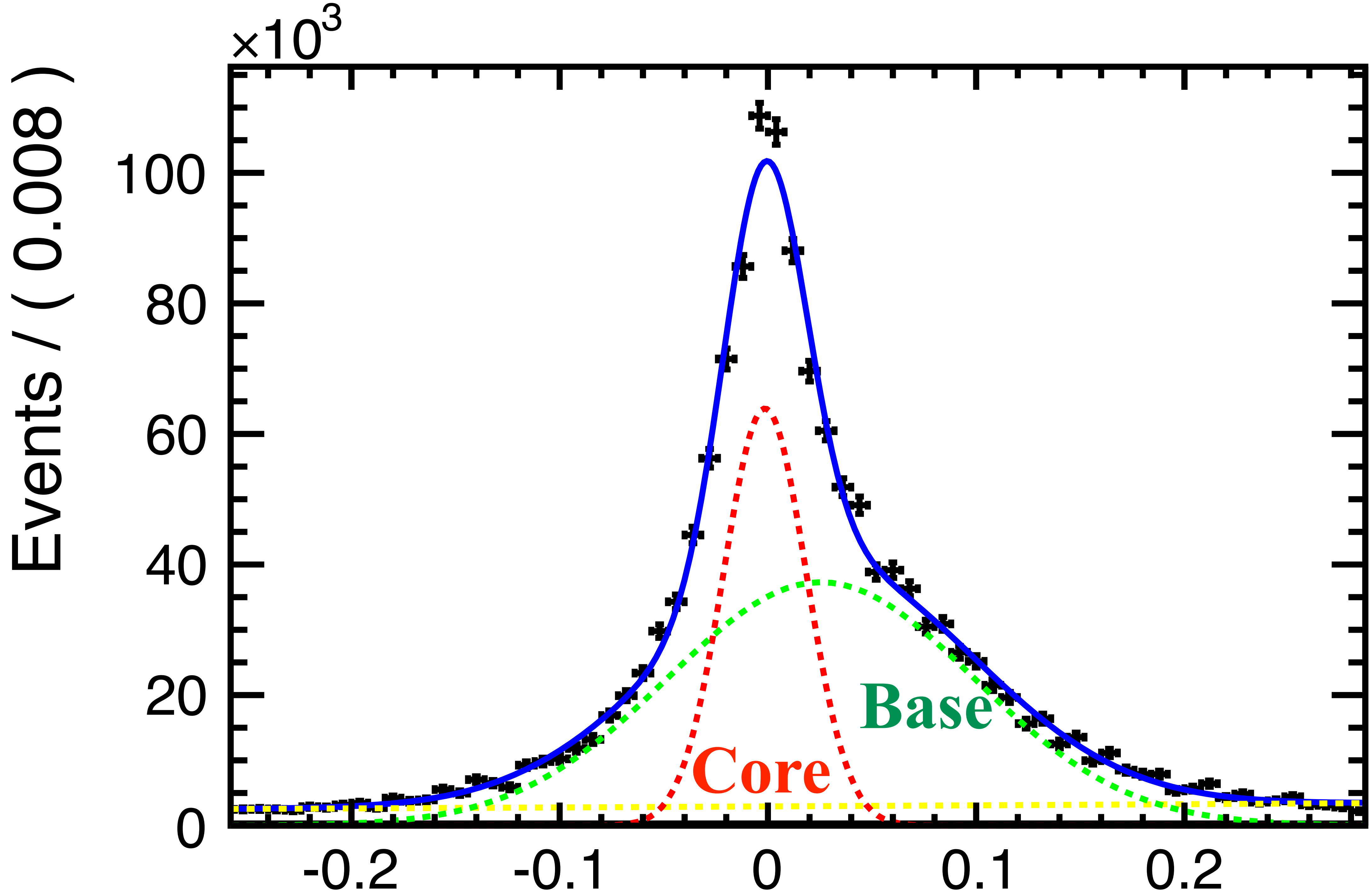
Jet 2



Reconstructed energy not only can calibrate the measured energy, but also has better resolution.

Fit the relative difference of reconstructed jet energy with Gaus (Core)+Gaus (Base)+exponential

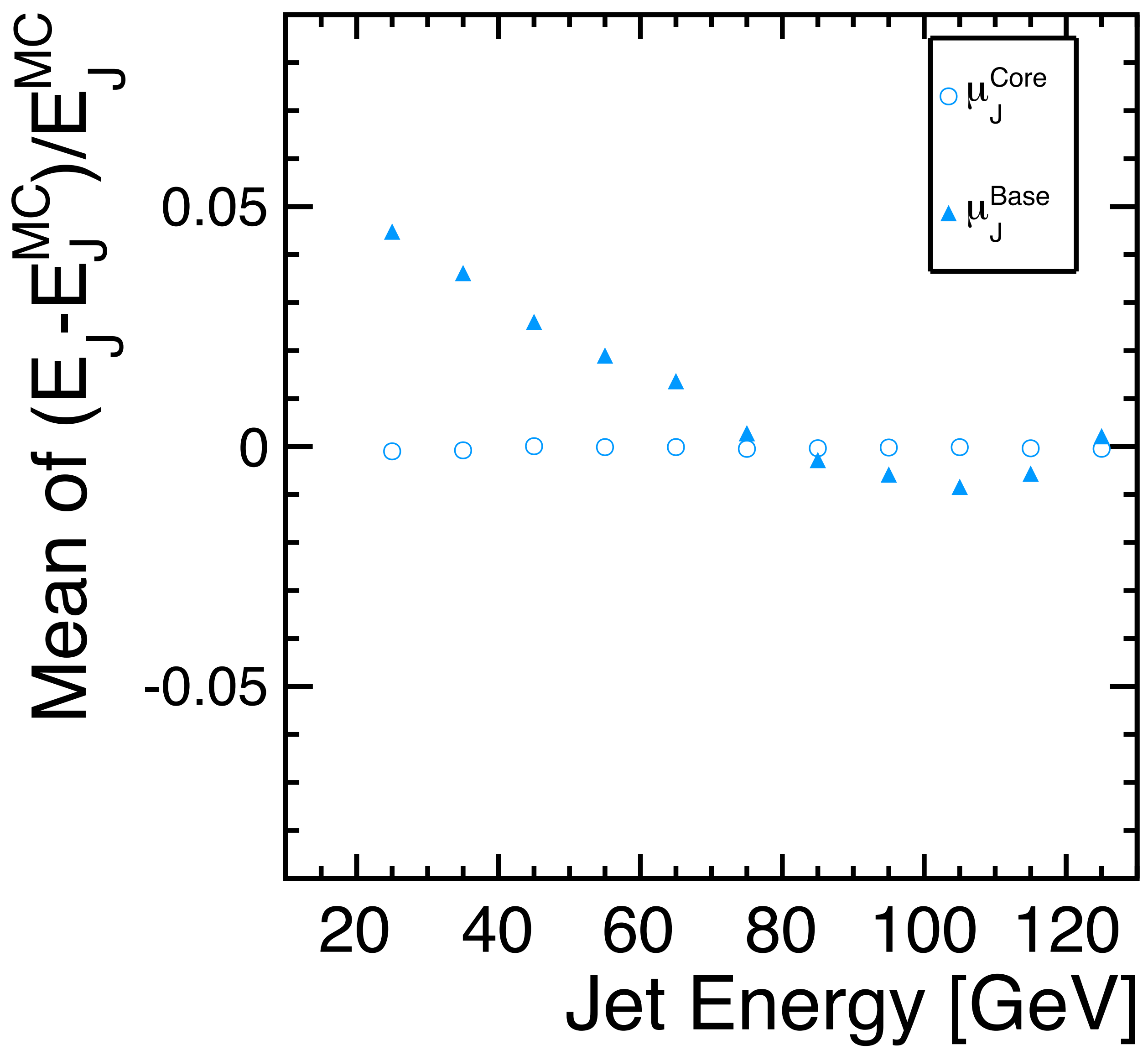
Calibration is based on the mean value of the Gaus (Core).



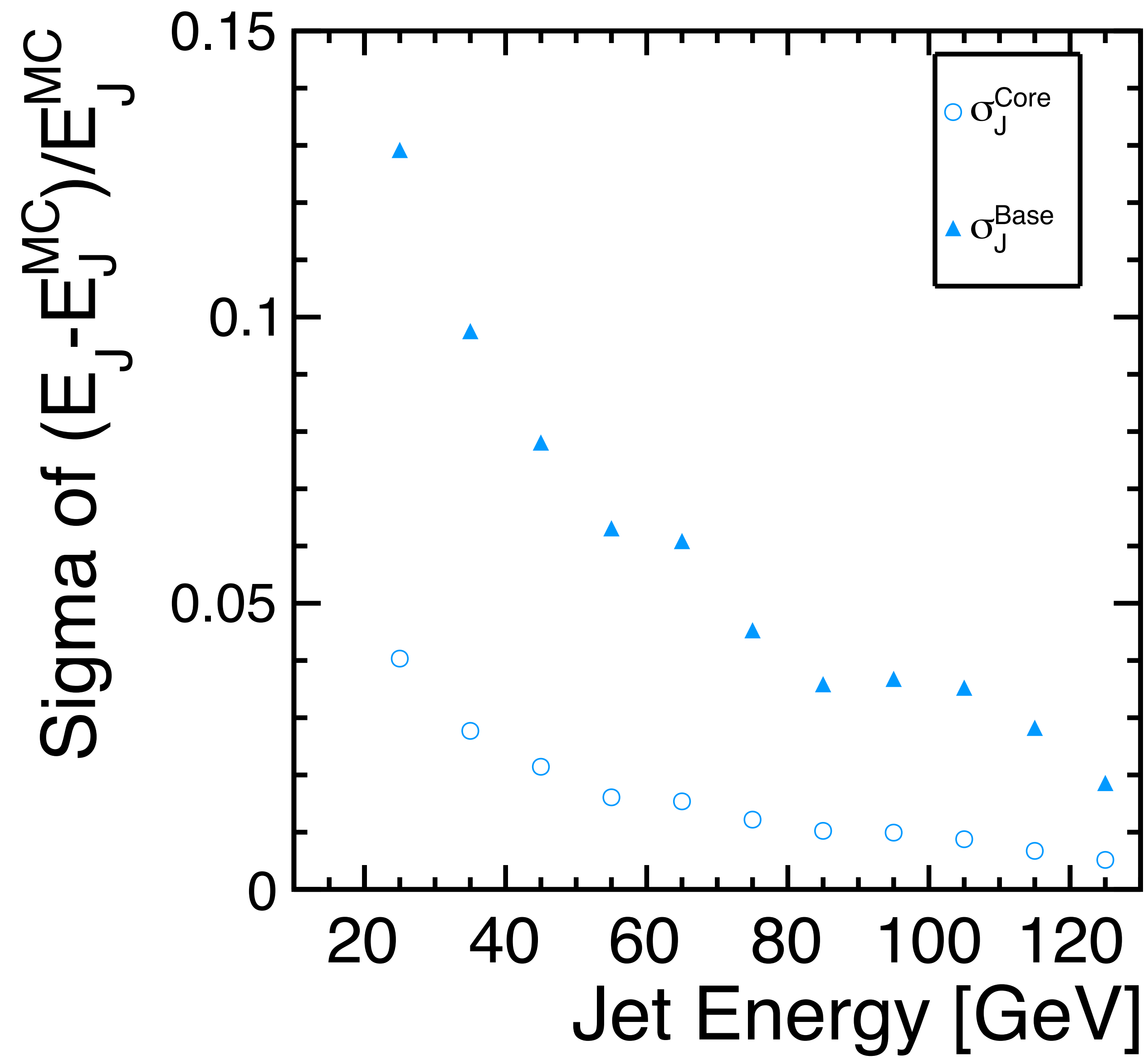
-> Check the theta and energy dependence.

Mean and Sigma Energy Dependence

Mean of the Fitting Gaussian



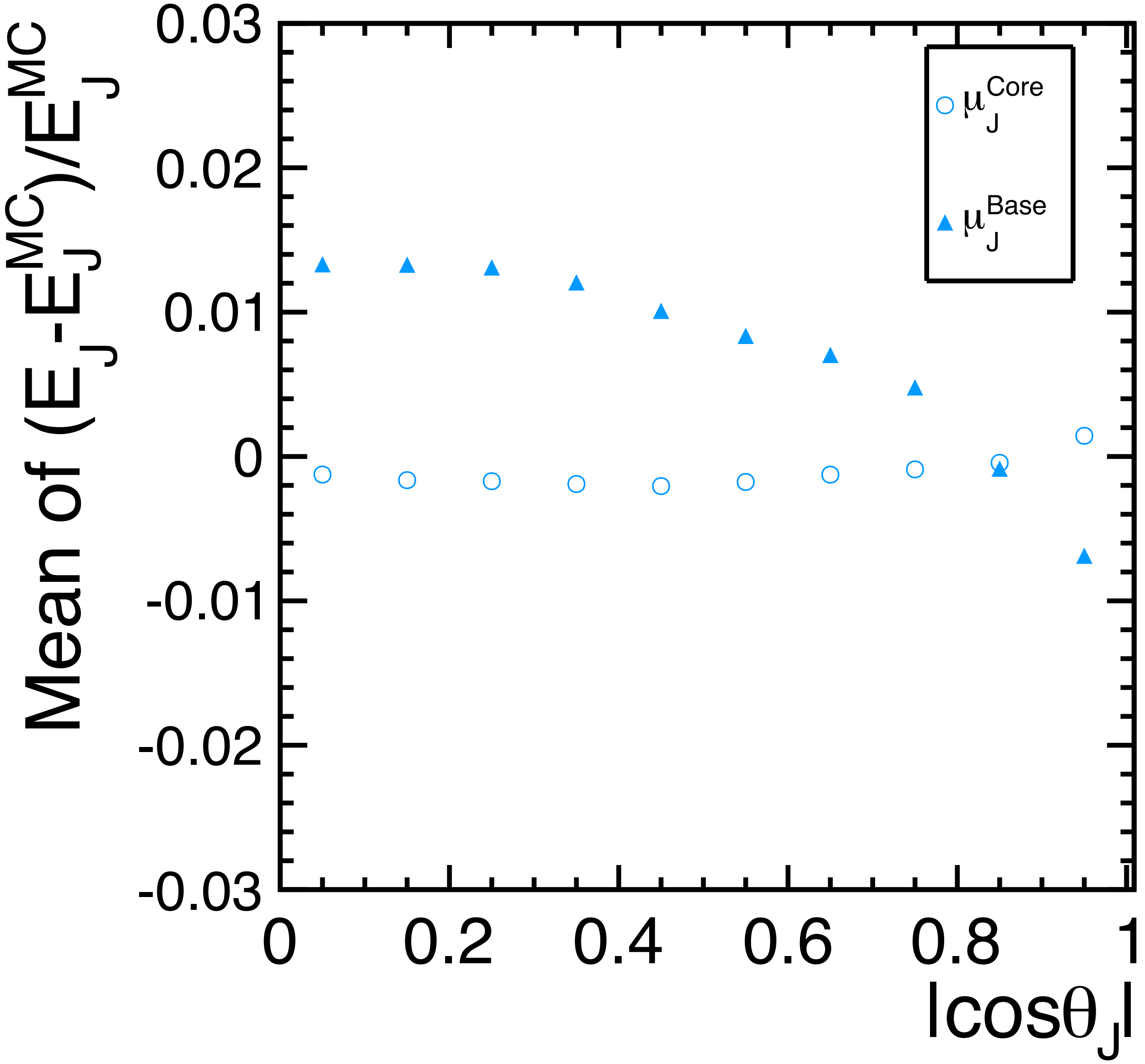
Sigma of the Fitting Gaussian



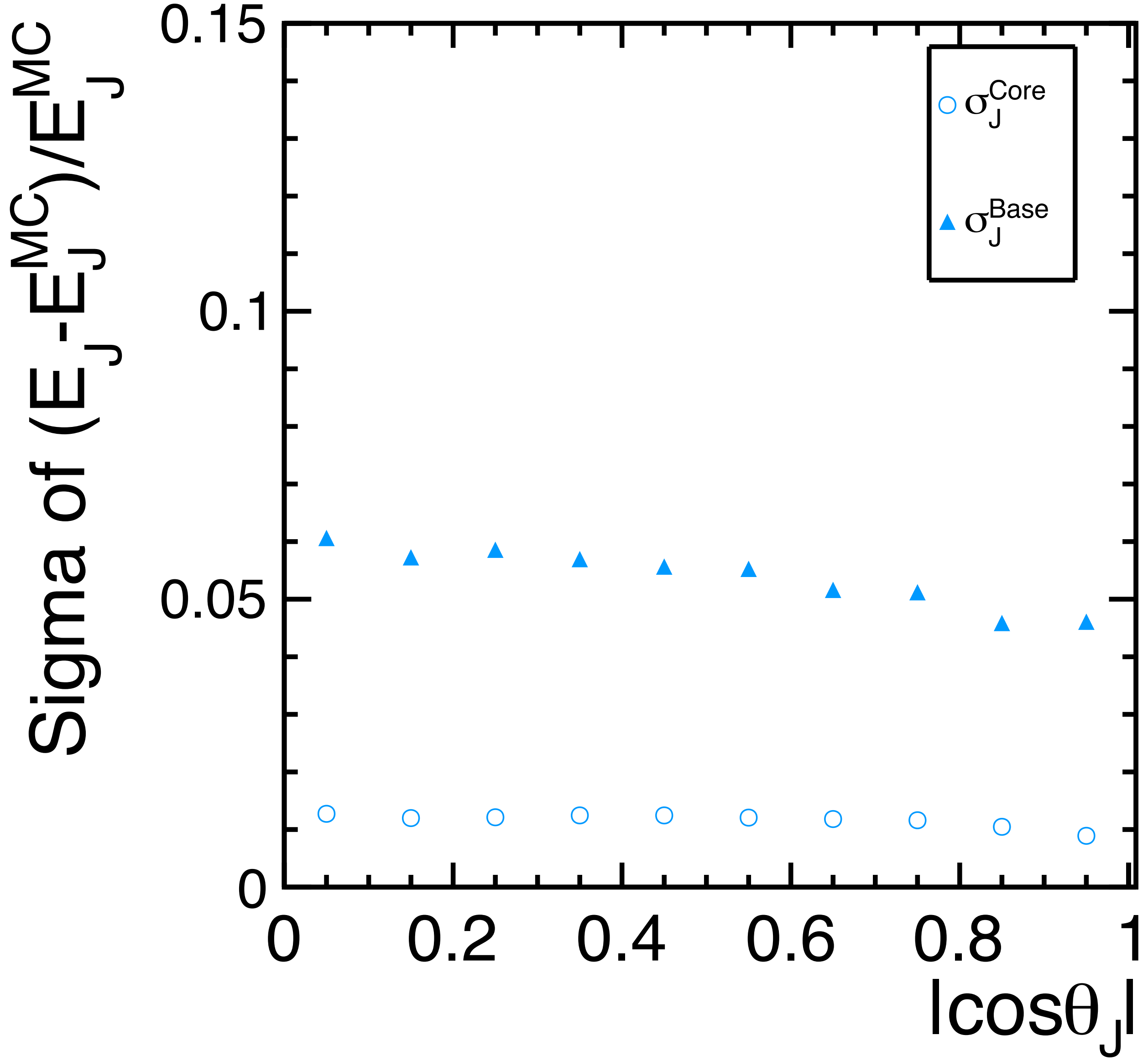
Mean value of the core gaussian is order of 10^{-4} independent on the jet energy.
Sigma value is smaller in the higher energy.

Mean and Sigma Polar Angle Dependence

Mean of the Fitting Gaussian



Sigma of the Fitting Gaussian



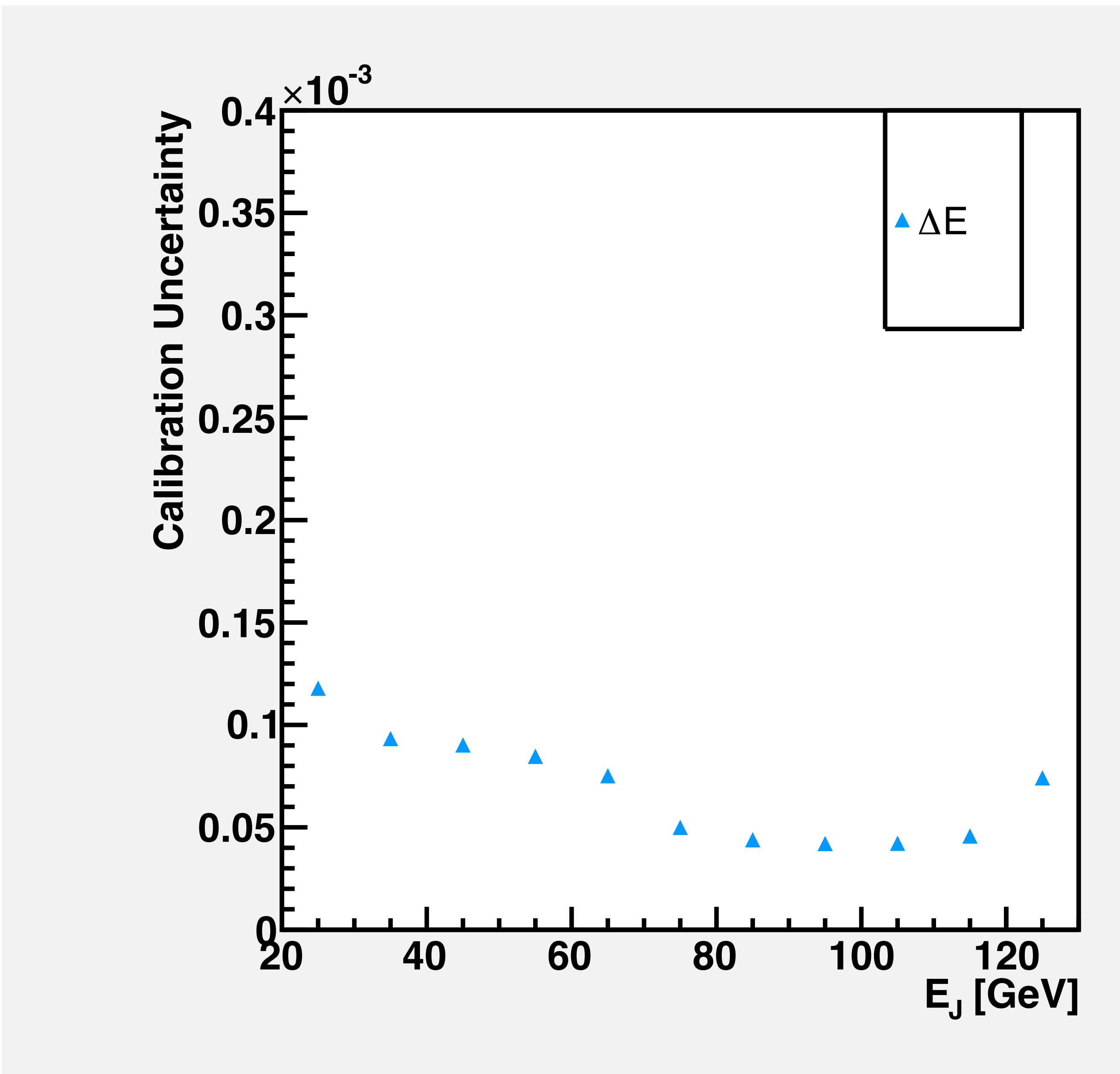
Forward jet makes slight positive bias on the core gaussian and barrel region jet makes slight negative bias on the core gaussian.

Calibration Uncertainty

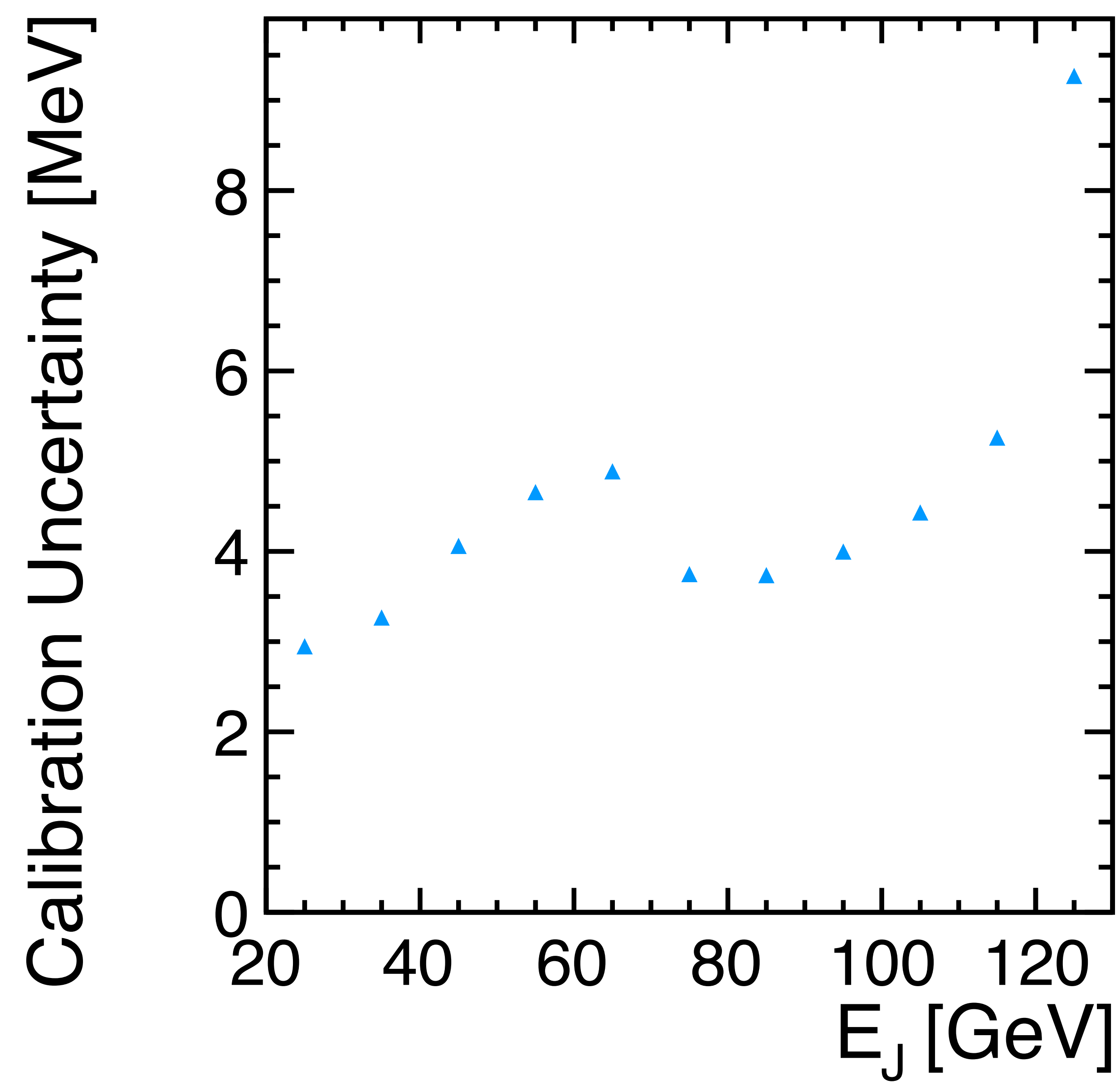
Calibration uncertainty := $\sqrt{(\Delta\mu_{Detector})^2 + (\Delta\mu_{Reconstructed})^2}$

Square root of the squared sum of the error of the mean

Relative uncertainty



Absolute uncertainty



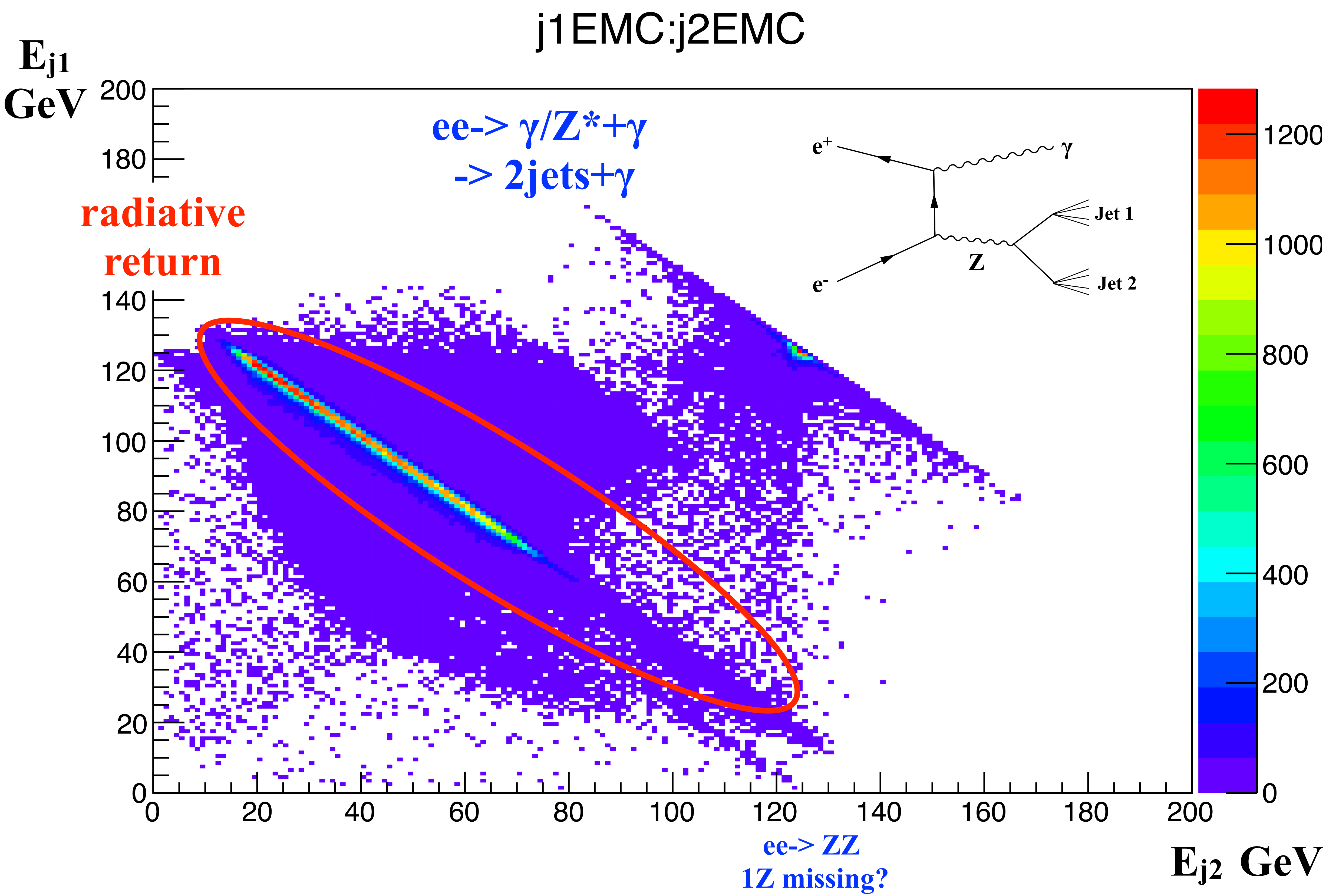
We can calibrate the jet energy scale with about 10^{-4} accuracy, which corresponds to several MeV.

Conclusion

- Full simulation is performed in order to reconstruct the jet energy using the $e^+e^- \to \gamma Z$, $Z \to 2$ Jets process.
- Jet energy can be reconstructed using the $e^+e^- \to \gamma Z$, $Z \to 2$ Jets process. Reconstructed jet energy resolution is better than the measured one.
- Calibration uncertainty is calculated as a function of energy. It is $<10^{-4}$ accuracy which corresponds to several MeV.

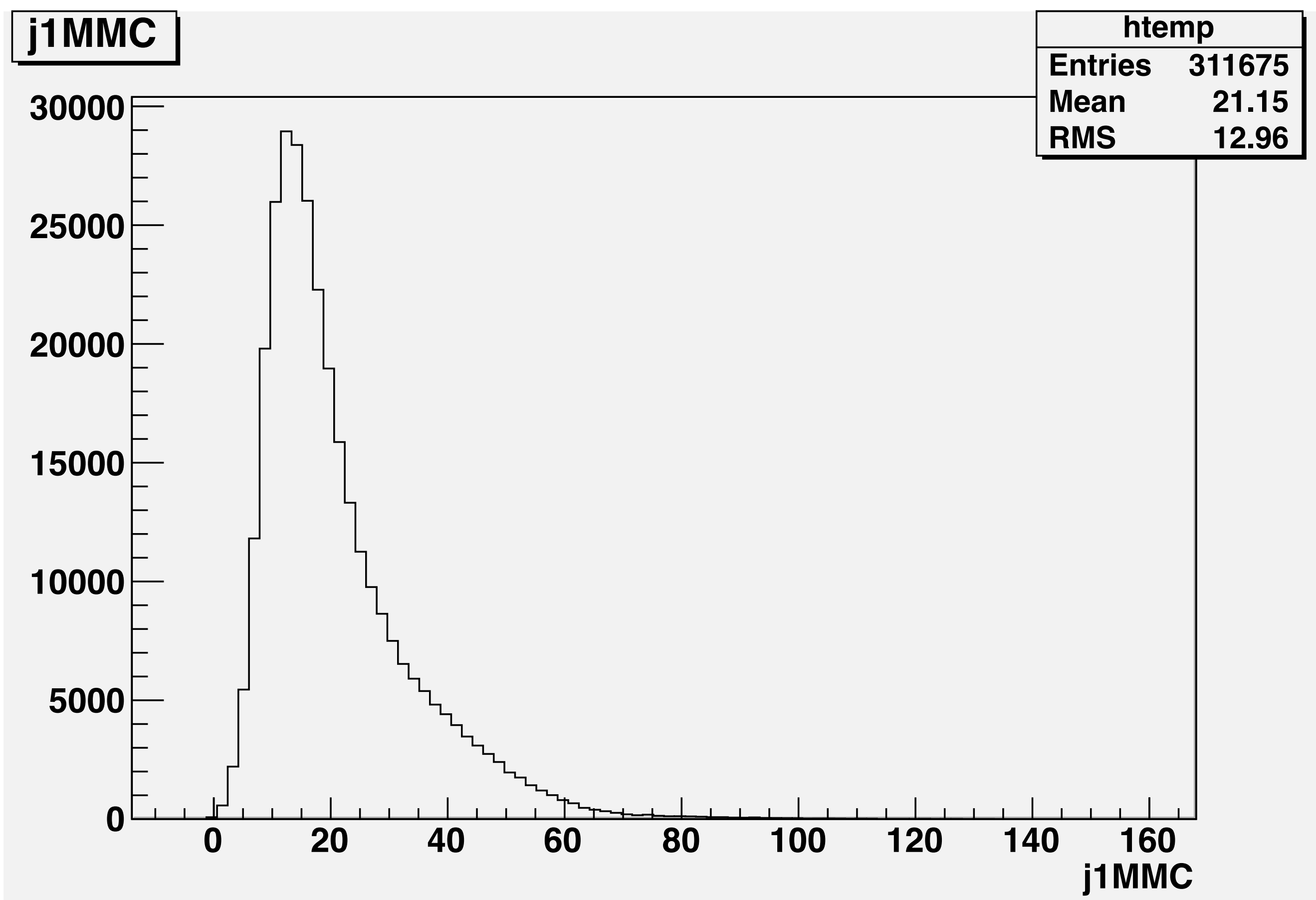
Backup

Jet energy distribution



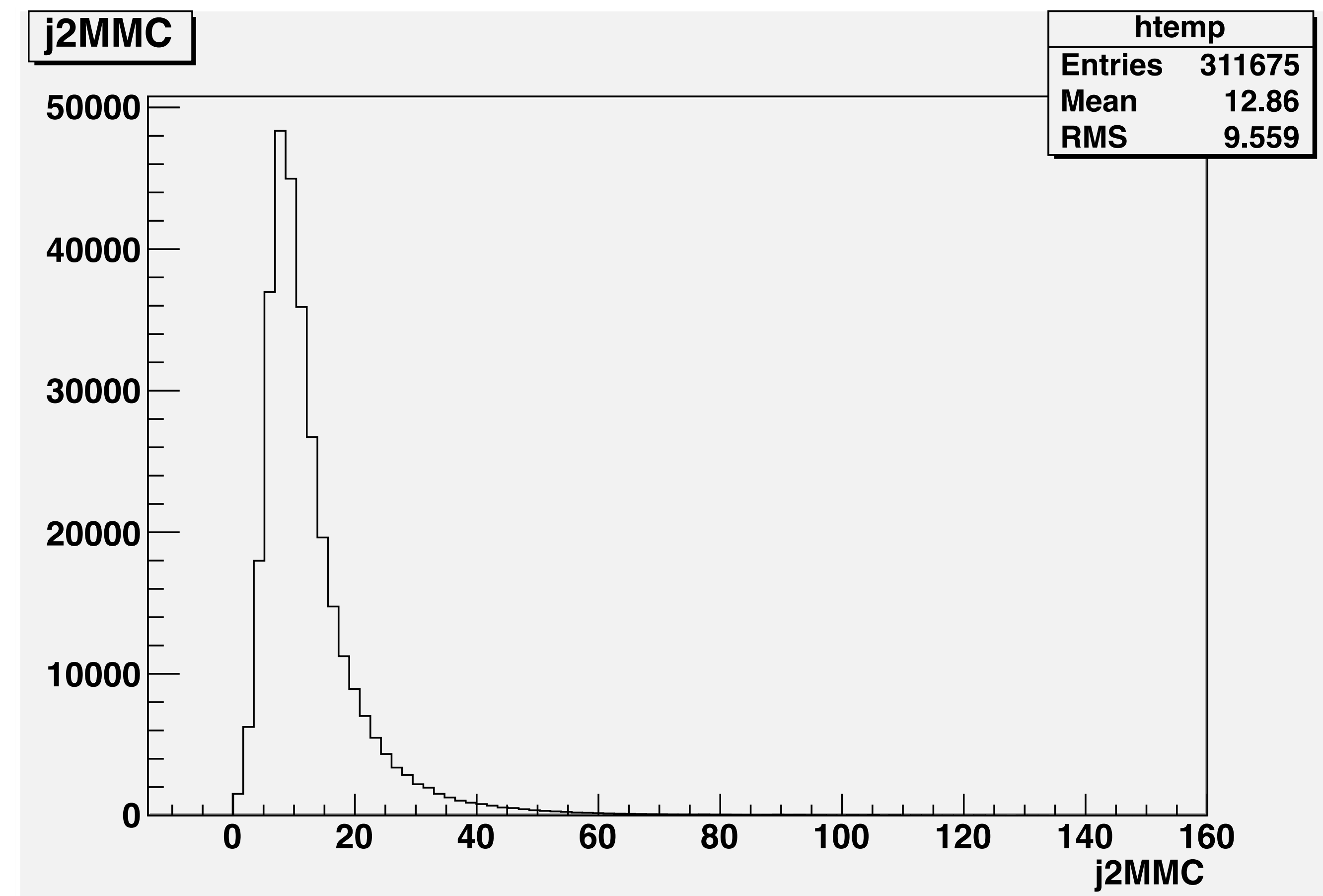
Jet mass distribution

Jet1



M_{Jet1} GeV

Jet2



M_{Jet2} GeV

Source of the bias

Source of the bias is investigated.
-> 2 major source are found.

Inputs and outputs
Using (θ_{J1},θ_{J2},θ_γ,φ_{J1},φ_{J2},φ_γ,m_{J1},m_{J2}) -> Determine (P_{J1},P_{J2},P_γ,P_{ISR})

$$\begin{cases} \sqrt{P_{J1}^2 + m_{J1}^2} + \sqrt{P_{J2}^2 + m_{J2}^2} + |P_\gamma| + |P_{ISR}| = E_{CM} \quad ① \\ \begin{pmatrix} sin\theta_{J1}cos\phi_{J1} & sin\theta_{J2}cos\phi_{J2} & sin\theta_\gamma cos\phi_\gamma \\ sin\theta_{J1}sin\phi_{J1} & sin\theta_{J2}sin\phi_{J2} & sin\theta_\gamma sin\phi_\gamma \\ cos\theta_{J1} & cos\theta_{J2} & cos\theta_\gamma \end{pmatrix} \begin{pmatrix} P_{J1} \\ P_{J2} \\ P_\gamma \end{pmatrix} = \begin{pmatrix} (E_{CM} - |P_{ISR}|)sin\alpha \\ 0 \\ \pm|P_{ISR}|cos\alpha \end{pmatrix} \end{cases}$$

Matrix A

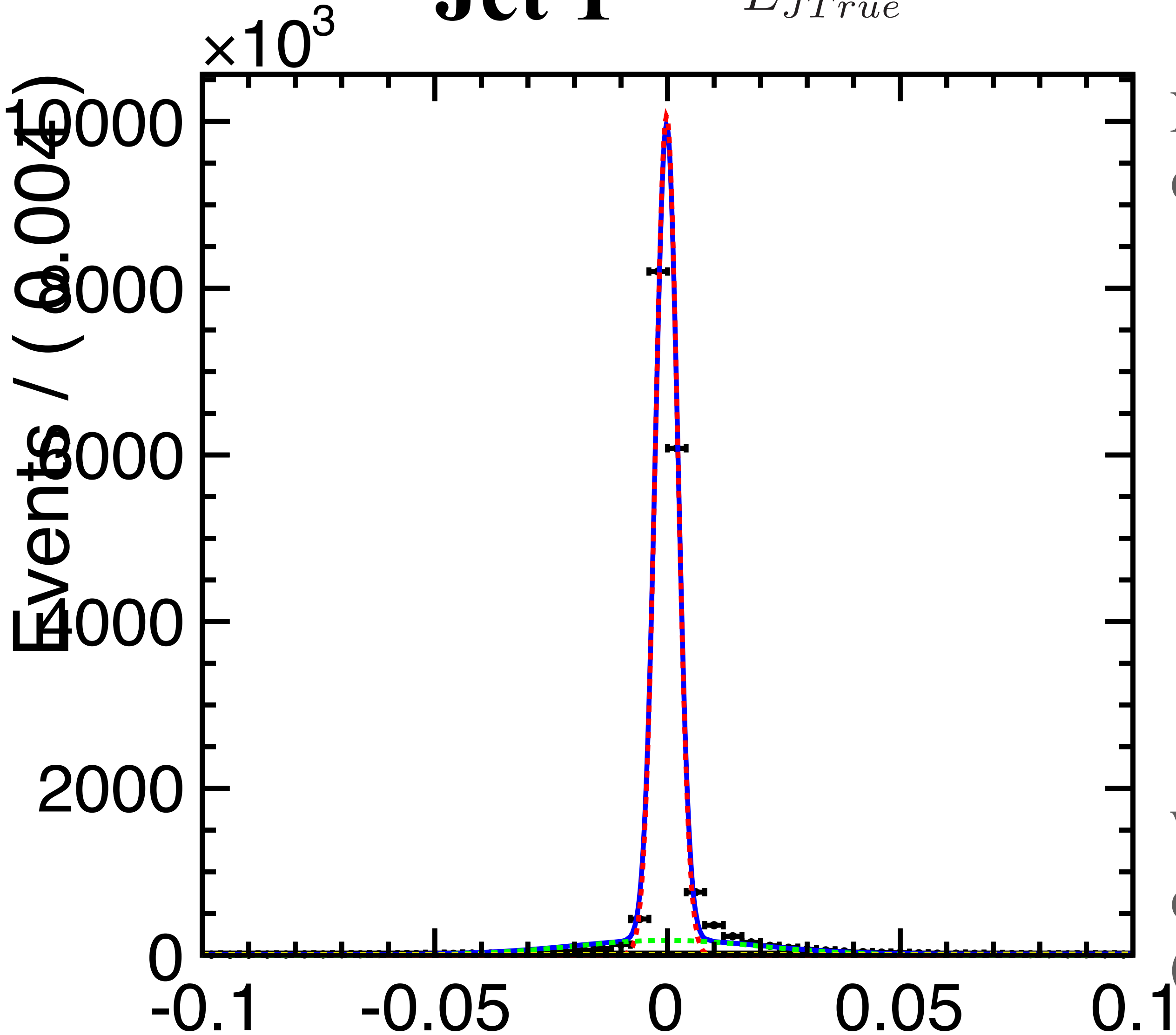
Inverse

(A) Beam energy spread
(B) Error of the jet mass inputs

Source (A): Beam energy spread

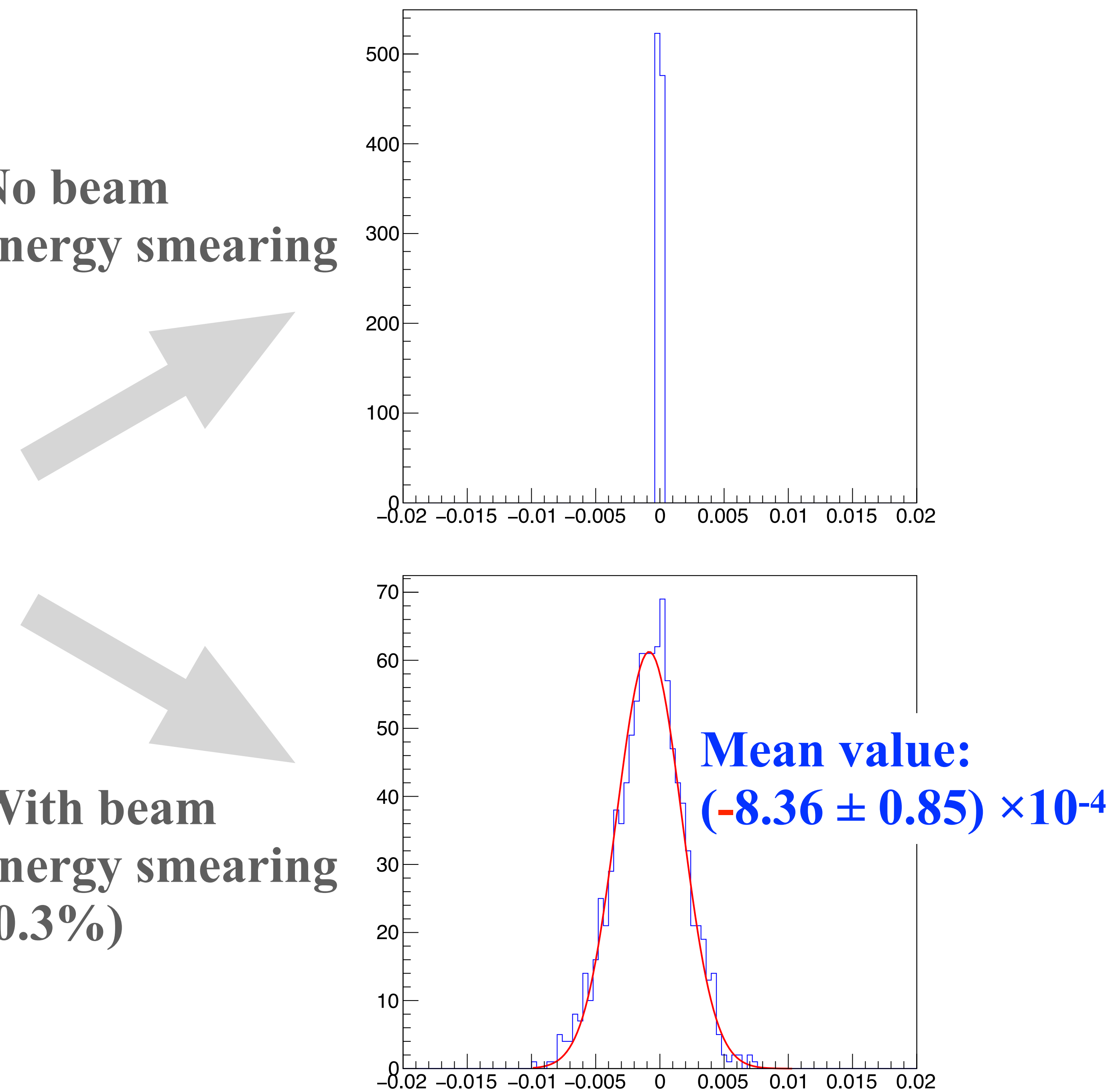
When all inputs are all MCtruth,

Jet 1 $\frac{E_{JRec} - E_{JTrue}}{E_{JTrue}}$



Mean value: (-1.97 ± 0.01) ×10⁻⁴

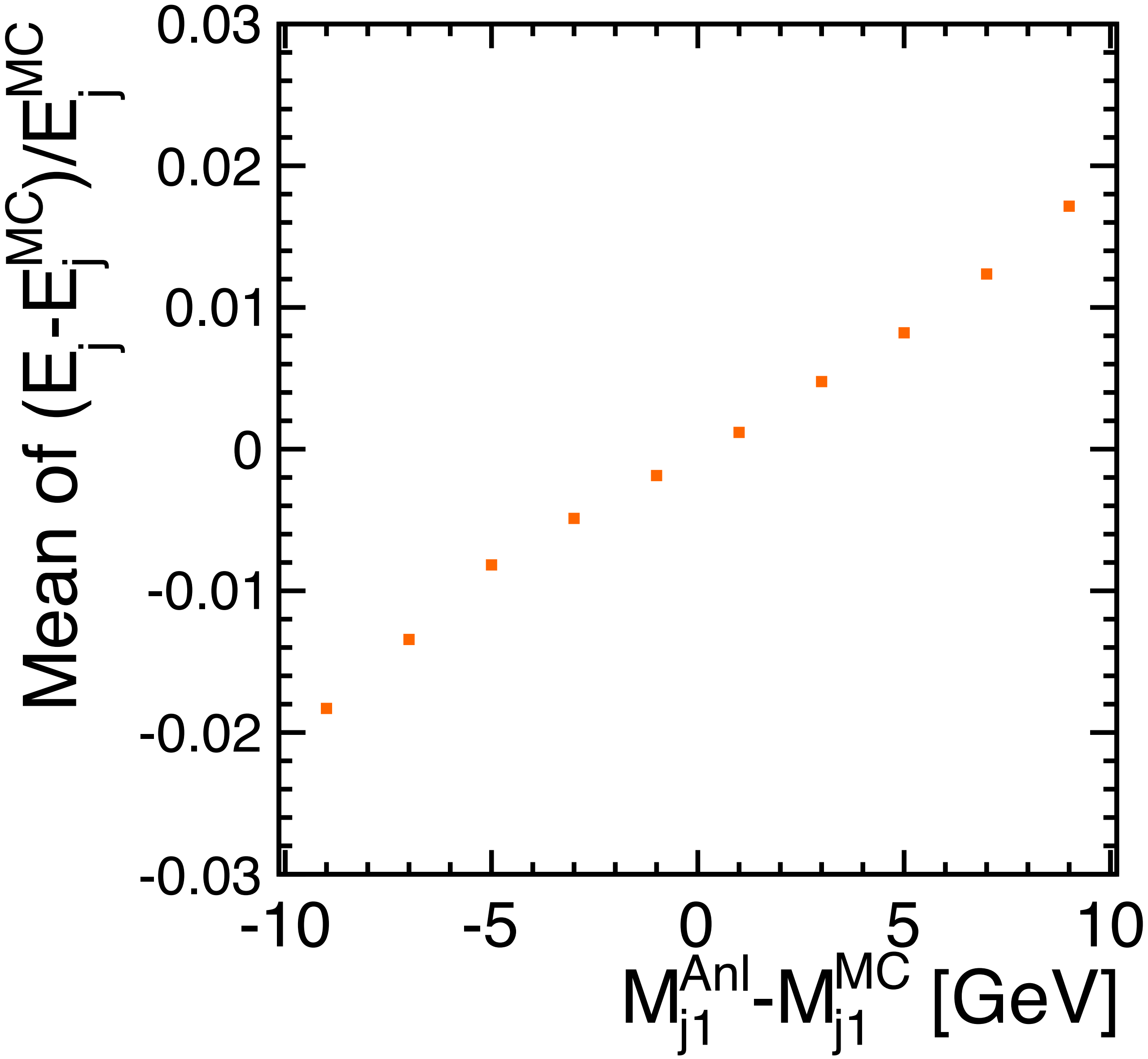
Toy MC Simulation

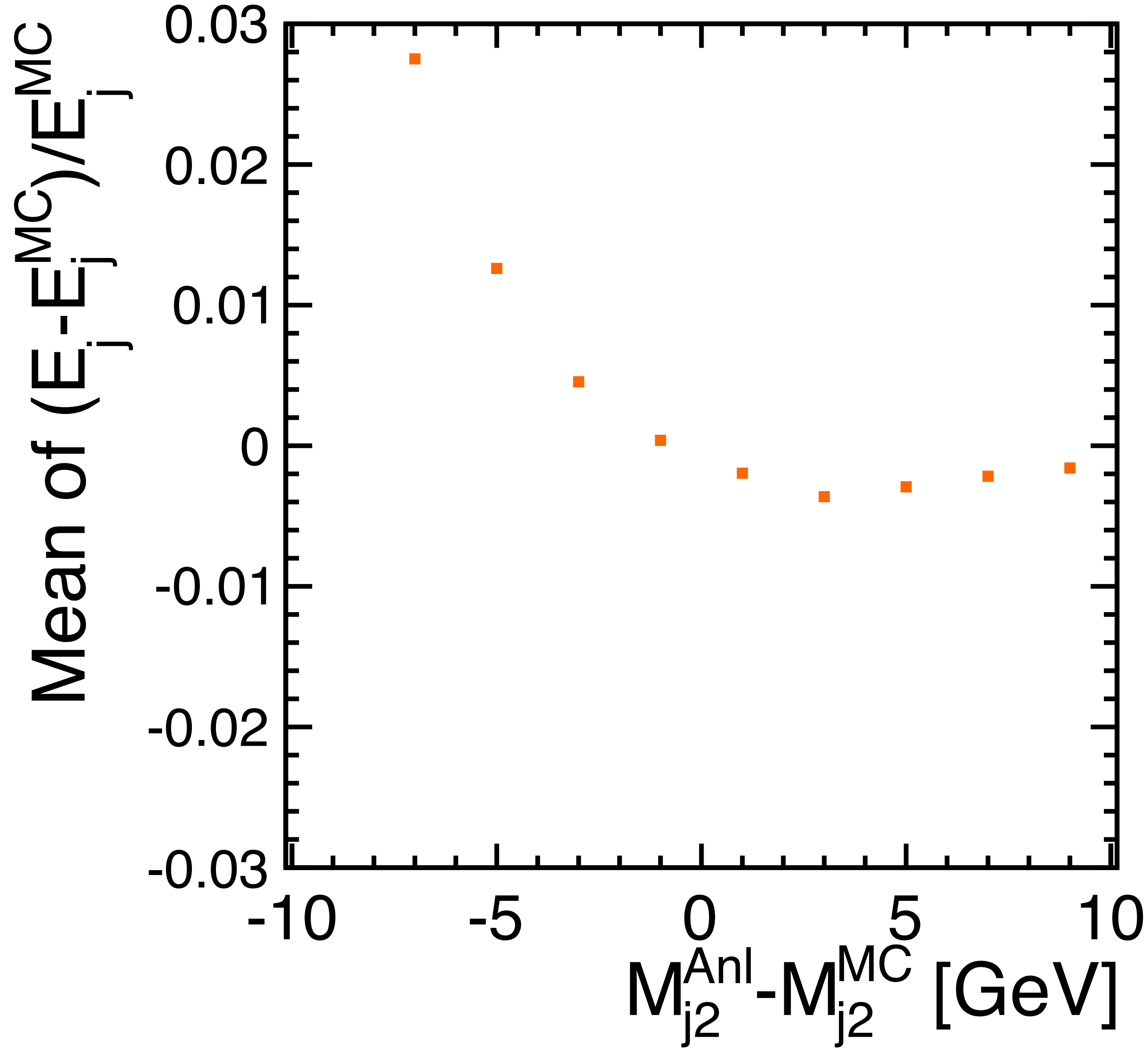


Beam energy spread causes negative bias in jet 1 reconstructed energy.
Positive bias in Jet 2 is also confirmed as well.

Source (B): Error of the jet mass inputs

Mean value of the fitting function for the Jet 1 $\frac{E_{JRec} - E_{JTrue}}{E_{JTrue}}$
as a function of the input jet mass deviation





Large dependence on both jet 1 mass and jet 2 mass input deviations. If $<8 \times 10^{-4}$ accuracy is necessary, compensation to the reconstructed jet energy should be introduced.