Jet Energy Scale Calibration using $e^+e^- \to q\bar{q}\gamma$

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Contents

Introduction

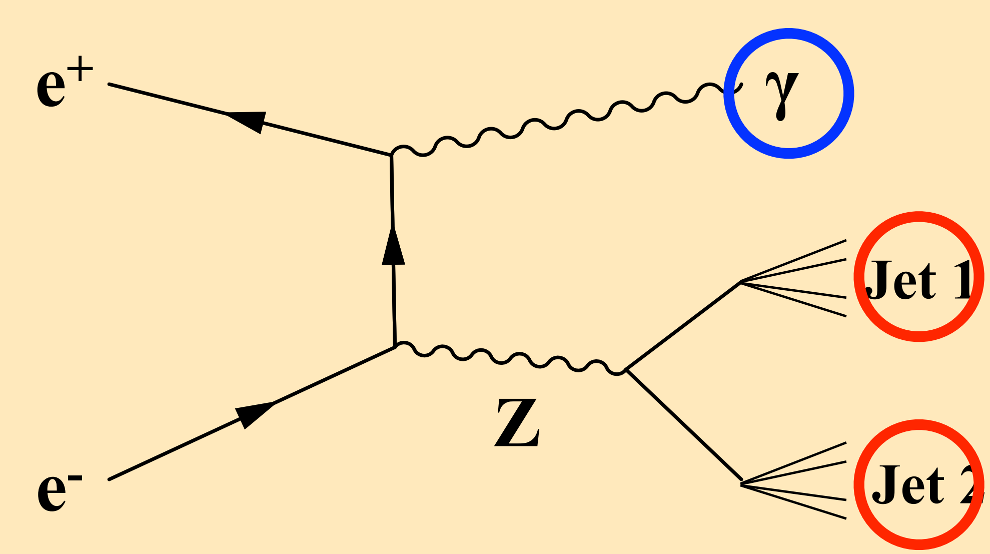
Detector Benchmark Motivation

- 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



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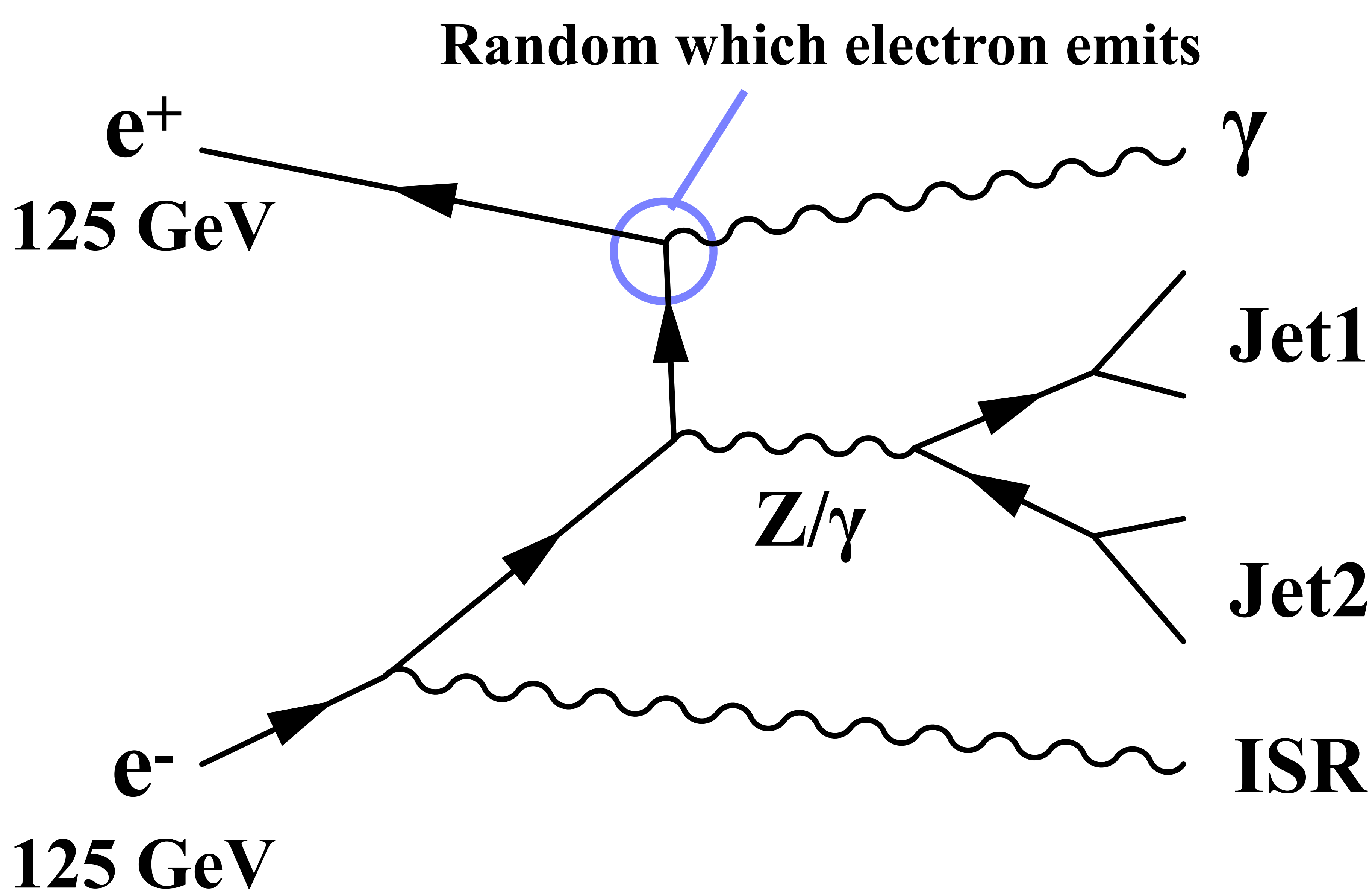
Full simulation

(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 $\int L dt$=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.

#Signal Photon

- nPhoton=0: 82.2% of the generated eLpR samples
- nPhoton=1: 17.8% of the generated eLpR samples

Event selection

Jet Clustering

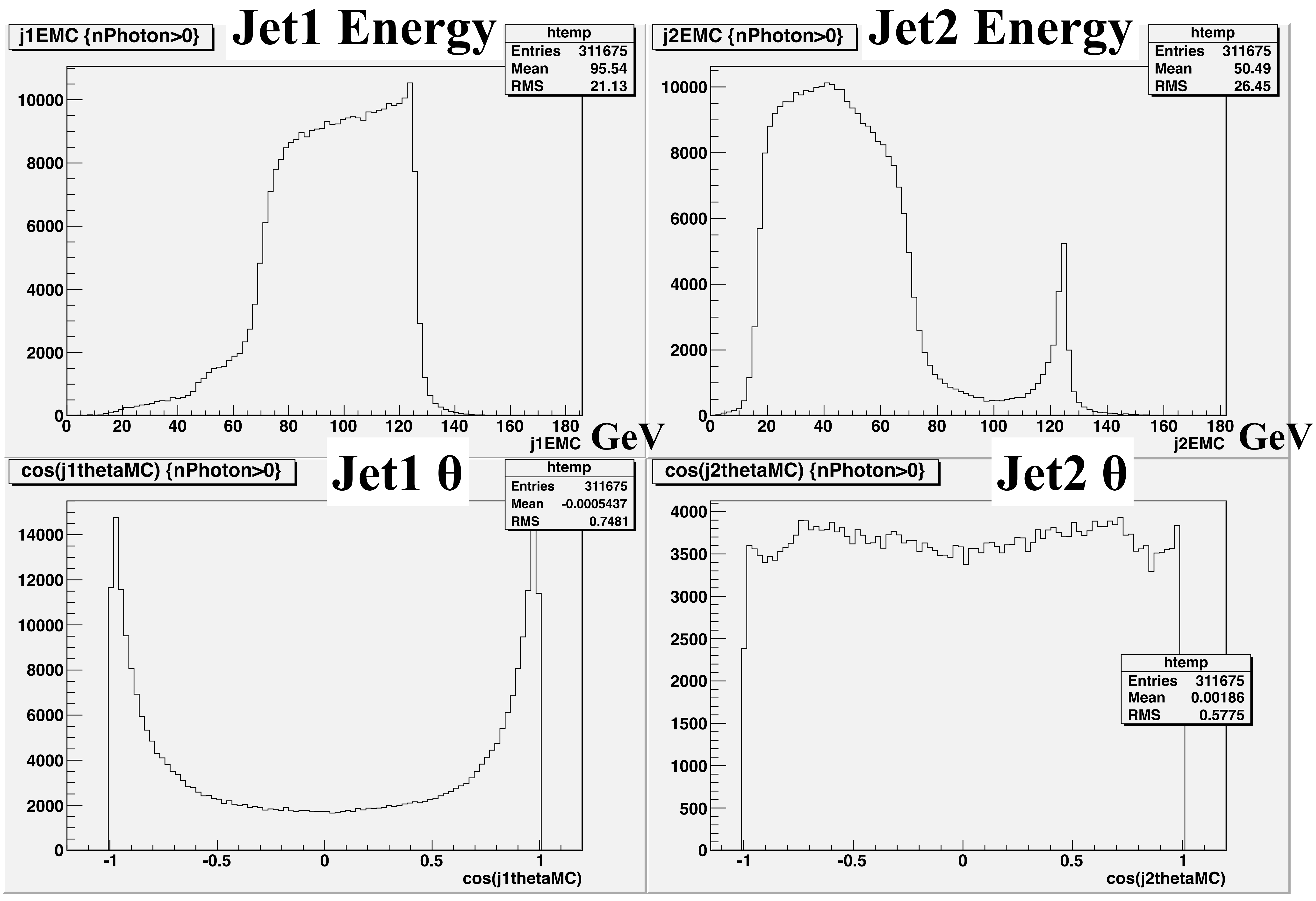
- All Particle Flow Objects (PFOs) other than the selected photon are clustered into 2 jets with Durham algorithm (done by LCFIPlus)
- The jet with higher reconstructed energy is defined as “jet 1” and the other as “jet 2”

2 Definitions for MCTruth

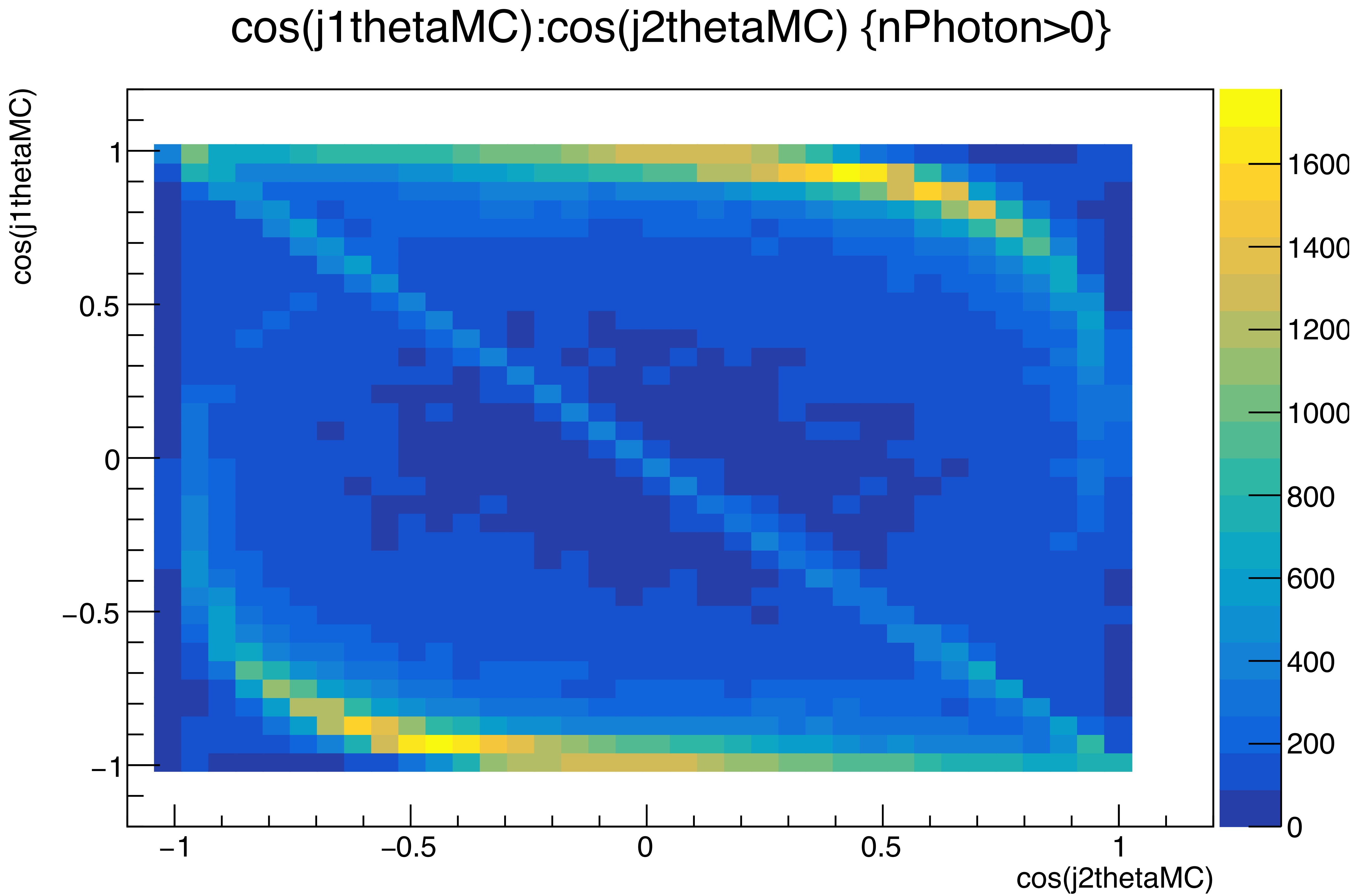
- All-MC
- Detected-MC : contains only particles linked to the detected PFOs

  Both are used in order to evaluate reconstructed jet energy difference

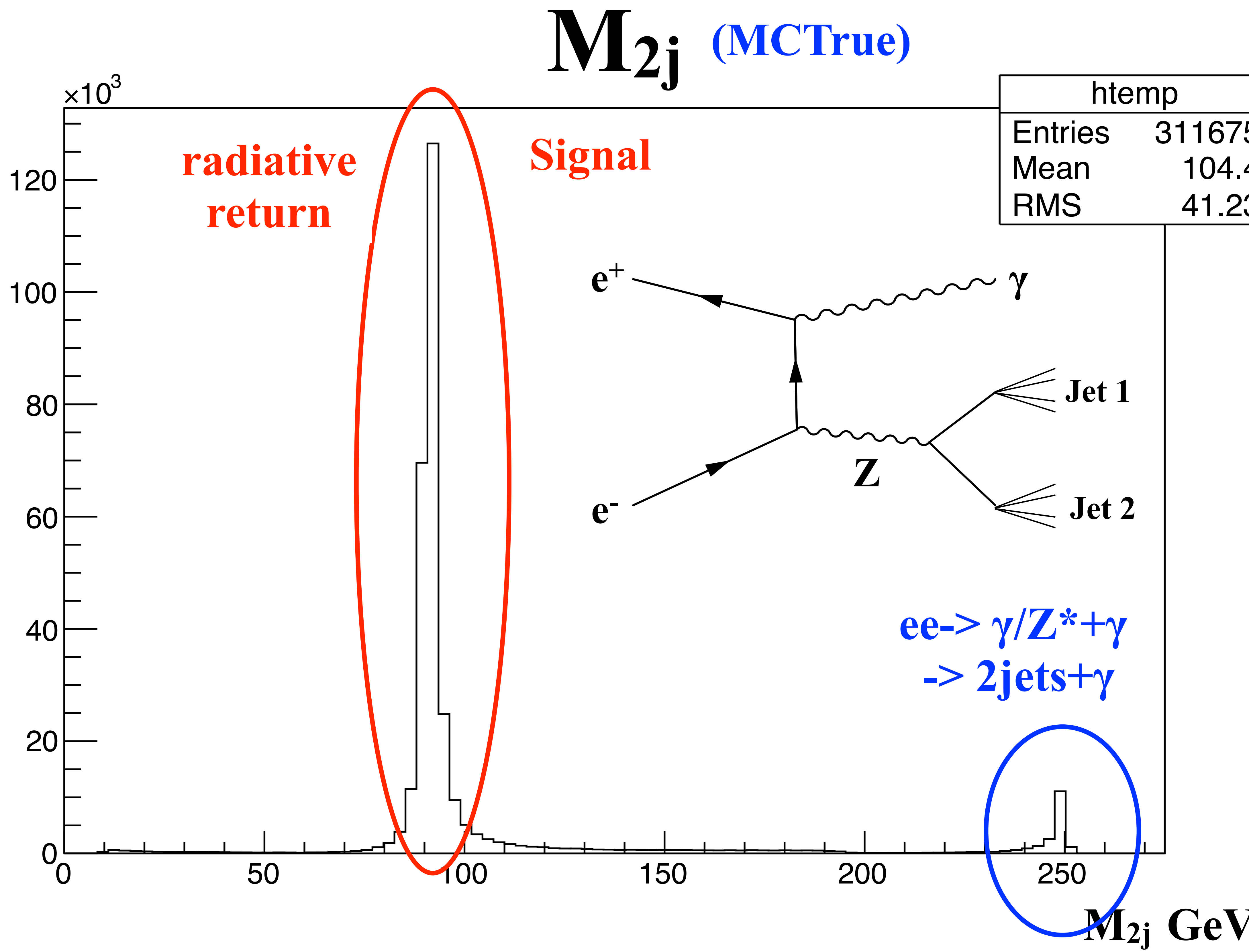
Energy and theta of jets (#photon>0)



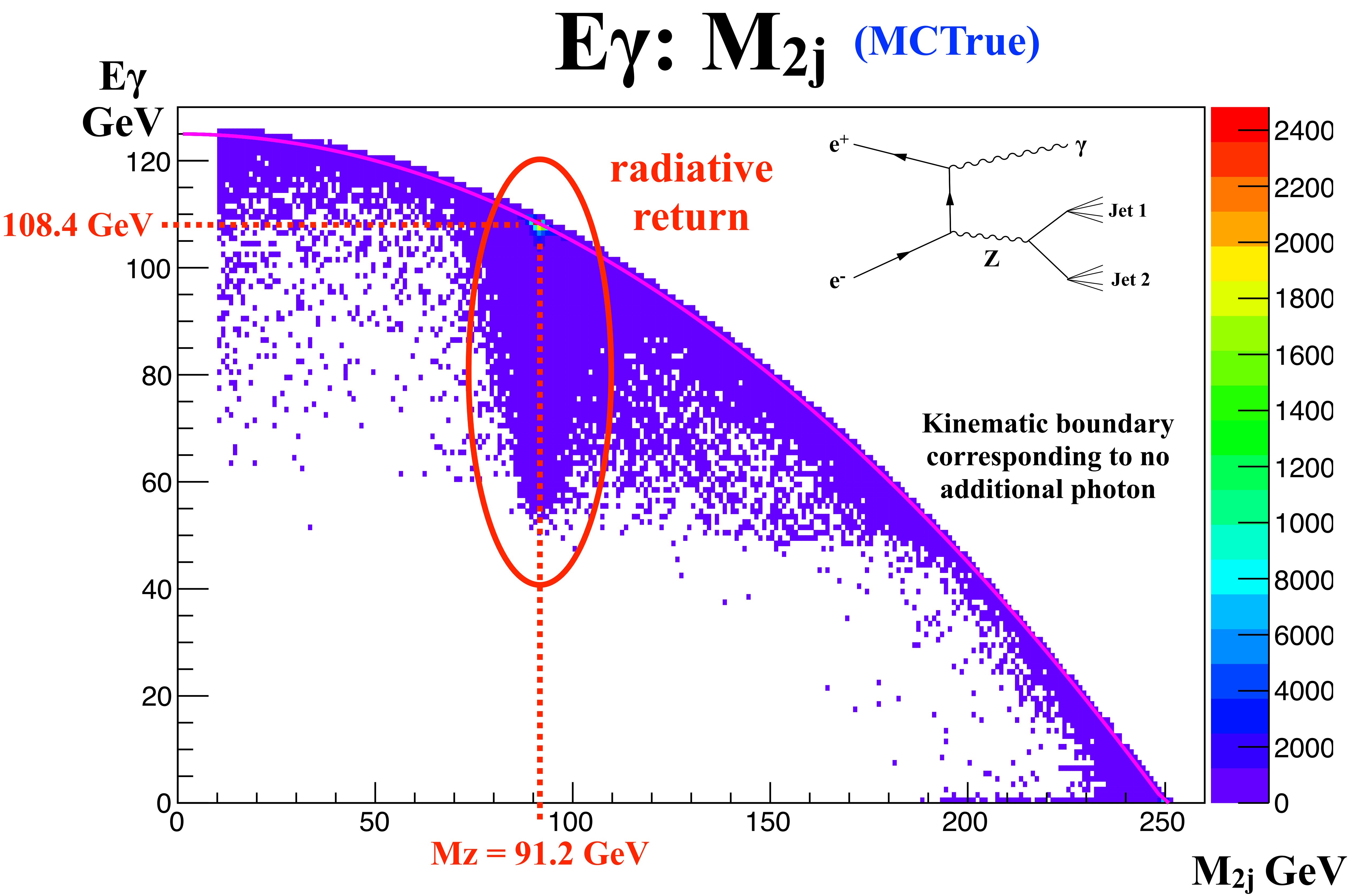
Energy and theta of jets (#photon>0)



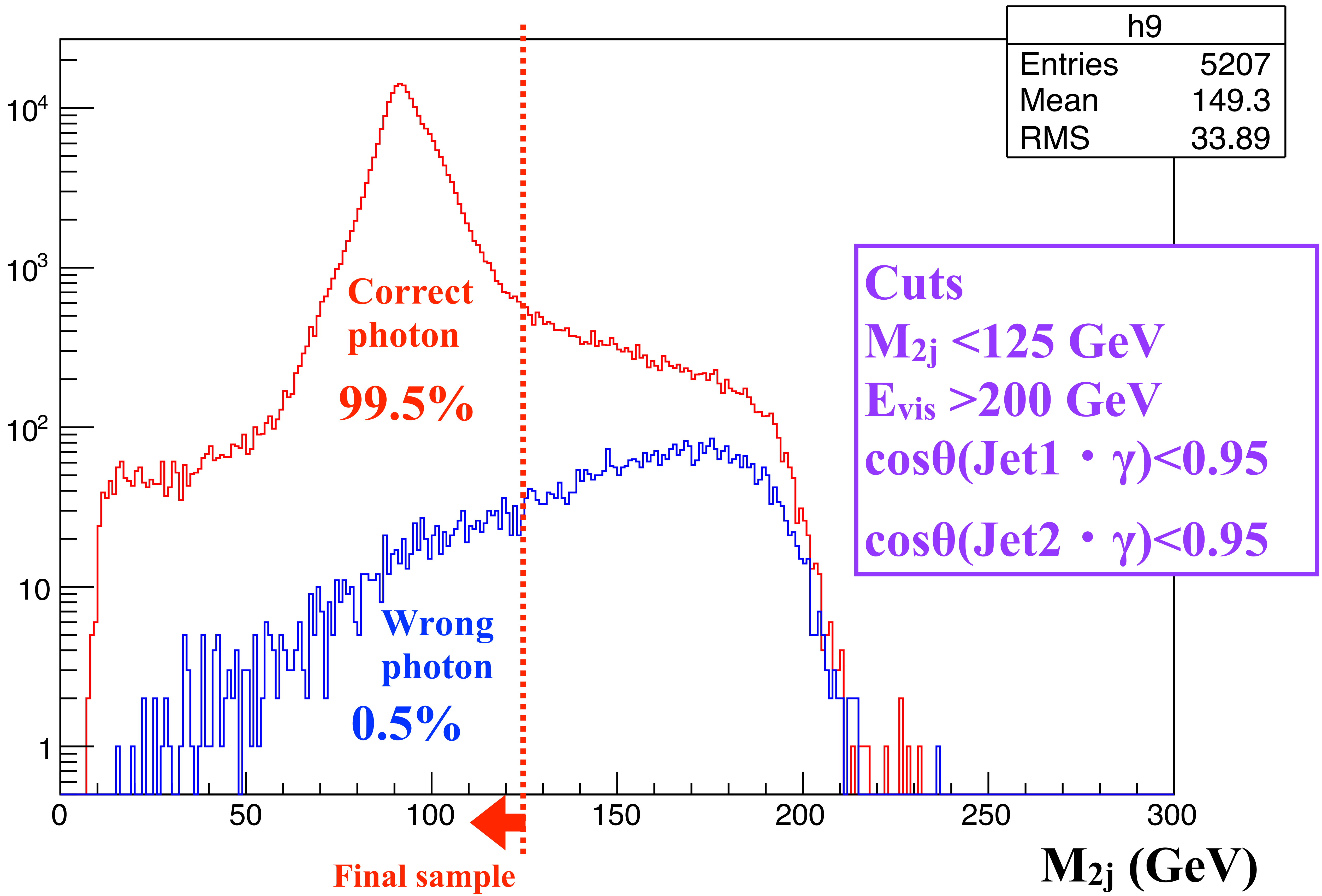
M_{2j} distribution



Photon energy & M_{2j} distribution



Correct photon selection cuts



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1. Introduction

2. Full simulation / Event selection

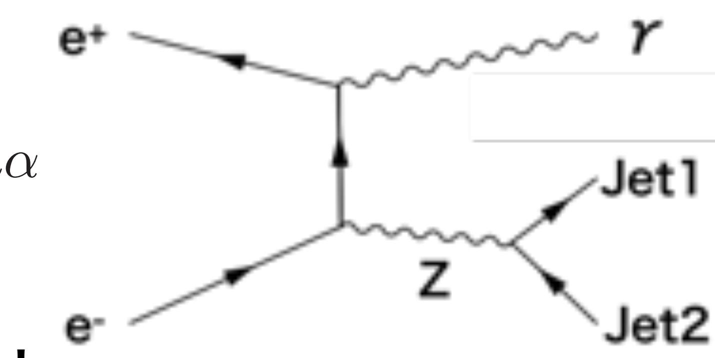
3. E_{jet} reconstruction

4. Conclusion

Reconstruction Method

Based on 4-momentum conservation

$$\begin{cases} \sqrt{P_{J1}^2+m_{J1}^2}+\sqrt{P_{J2}^2+m_{J2}^2}+|P_\gamma|+|P_{ISR}|=500 \\ P_{J1}sin\theta_{J1}cos\phi_{J1}+P_{J2}sin\theta_{J2}cos\phi_{J2}+P_\gamma sin\theta_\gamma cos\phi_\gamma+|P_{ISR}|sin\alpha=500sin\alpha \\ P_{J1}sin\theta_{J1}sin\phi_{J1}+P_{J2}sin\theta_{J2}sin\phi_{J2}+P_\gamma sin\theta_\gamma sin\phi_\gamma=0 \\ P_{J1}cos\theta_{J1}+P_{J2}cos\theta_{J2}+P_\gamma cos\theta_\gamma \pm |P_{ISR}|cos\alpha=0 \end{cases}$$



Beam Crossing Angle ≡2α : α = 7.0 mrad

Direction Angle
θ: polar angle
ϕ: azimuthal angle

- ISR photon = **additional** unseen photon
- Several reconstruction methods (Method 1, 2', 2, 3, **and** 4) are considered.

Method 1: Ignore ISR

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

$$\begin{cases} \sqrt{P_{J1}^2+m_{J1}^2}+\sqrt{P_{J2}^2+m_{J2}^2}+|P_\gamma|=500 \\ \begin{pmatrix} sin\theta_{J1}cos\phi_{J1} & sin\theta_{J2}cos\phi_{J2} & sin\theta_\gamma cos\phi_\gamma \\ sin\theta_{J1}sin\phi_{J1} & sin\theta_{J2}sin\phi_{J2} & sin\theta_\gamma sin\phi_\gamma \\ cos\theta_{J1} & cos\theta_{J2} & cos\theta_\gamma \end{pmatrix} \begin{pmatrix} P_{J1} \\ P_{J2} \\ P_\gamma \end{pmatrix} = \begin{pmatrix} 500sin\alpha \\ 0 \\ 0 \end{pmatrix} \end{cases}$$

Matrix A —— Inverse

Reconstruction Method

Method 2: Use measured P_γ as input and Consider ISR
Using $(\theta_{J1},\theta_{J2},\theta_\gamma,\varphi_{J1},\varphi_{J2},\varphi_\gamma,m_{J1},m_{J2},P_\gamma)$ -> Determine (P_{J1},P_{J2},P_{ISR})

$$\begin{cases} \sqrt{P_{J1}^2+m_{J1}^2}+\sqrt{P_{J2}^2+m_{J2}^2}+|P_\gamma|+|P_{ISR}|=500 \quad ① \\ \begin{pmatrix} sin\theta_{J1}cos\phi_{J1} & sin\theta_{J2}cos\phi_{J2} & sin\alpha \\ sin\theta_{J1}sin\phi_{J1} & sin\theta_{J2}sin\phi_{J2} & 0 \\ cos\theta_{J1} & cos\theta_{J2} & \pm cos\alpha \end{pmatrix}\begin{pmatrix} P_{J1} \\ P_{J2} \\ |P_{ISR}| \end{pmatrix}=\begin{pmatrix} 500sin\alpha - sin\theta_\gamma cos\phi_\gamma P_\gamma \\ -sin\theta_\gamma sin\phi_\gamma P_\gamma \\ -cos\theta_\gamma P_\gamma \end{pmatrix} \end{cases}$$

Matrix A

Inverse

2 solutions for each sign of P_{ISR}
-> choose the best answer which satisfies ① better

Method 2': Use measured P_γ as input and Ignore ISR
Using $(\theta_{J1},\theta_{J2},\theta_\gamma,\varphi_{J1},\varphi_{J2},\varphi_\gamma,m_{J1},m_{J2},P_\gamma)$ -> Determine (P_{J1},P_{J2})

$$\left\{ \begin{pmatrix} sin\theta_{J1}cos\phi_{J1} & sin\theta_{J2}cos\phi_{J2} \\ sin\theta_{J1}sin\phi_{J1} & sin\theta_{J2}sin\phi_{J2} \end{pmatrix}\begin{pmatrix} P_{J1} \\ P_{J2} \end{pmatrix}=\begin{pmatrix} 500sin\alpha - sin\theta_\gamma cos\phi_\gamma P_\gamma \\ -sin\theta_\gamma sin\phi_\gamma P_\gamma \end{pmatrix} \right.$$

Reconstruction Method

Method 3: Consider ISR and solve the full equation
Using ($\theta_{J1},\theta_{J2},\theta_\gamma,\varphi_{J1},\varphi_{J2},\varphi_\gamma,m_{J1},m_{J2}$) -> Determine ($P_{J1},P_{J2},P_\gamma,P_{ISR}$)

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

Matrix A → Inverse

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**

Reconstruction Method

Jet mass "m" can be expressed as "P/γβ" (P: momentum of the jet)
-> Irrational equation ① is reduced to be a linear equation!

Method 4: Represent the equation with P_{ISR}
Using ($\theta_{J1}, \theta_{J2}, \theta_\gamma, \varphi_{J1}, \varphi_{J2}, \varphi_\gamma$, **$\gamma\beta_{J1}, \gamma\beta_{J2}$**) -> Determine ($P_{J1}, P_{J2}, P_\gamma, P_{ISR}$)

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

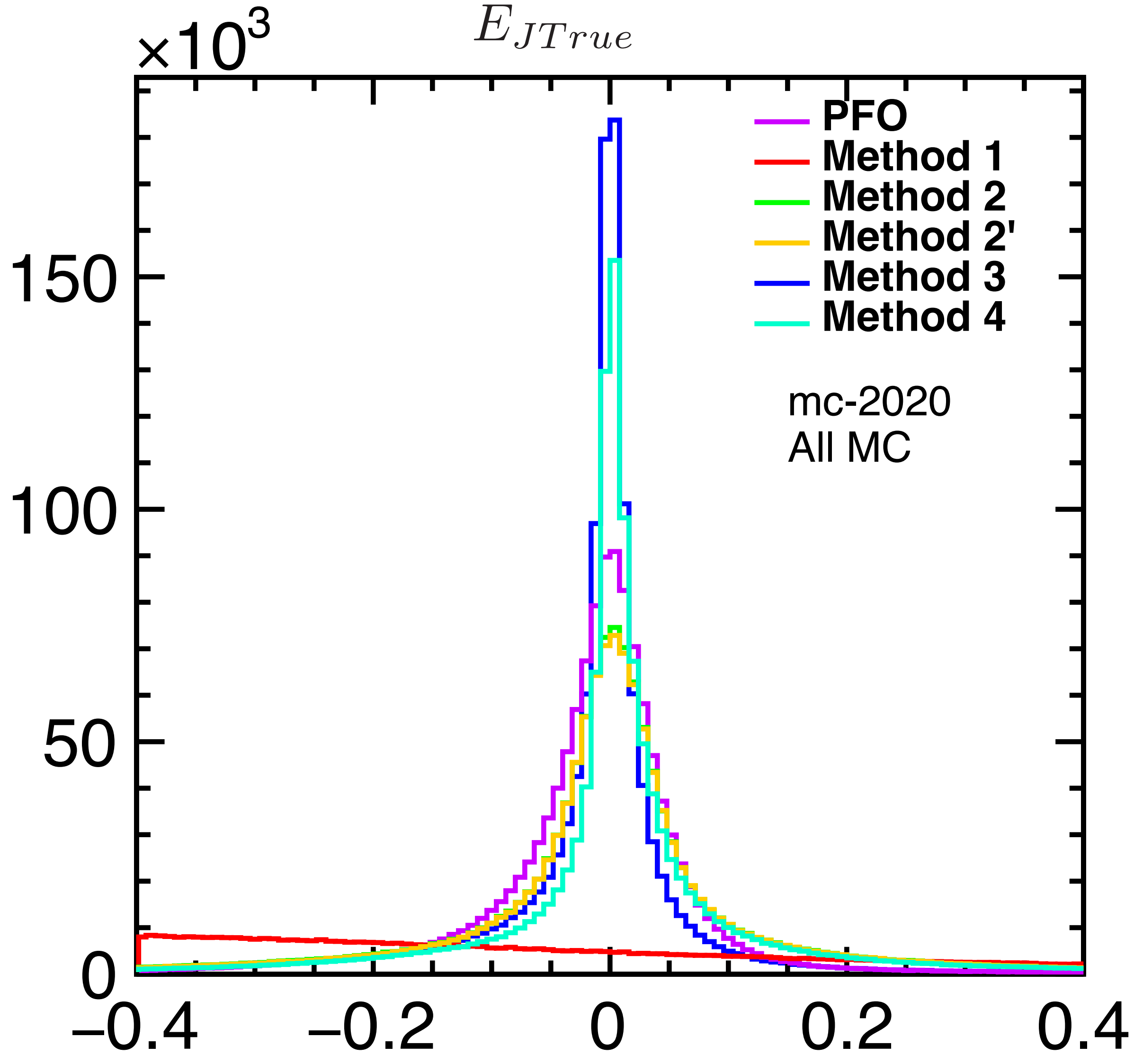
Choose the solution with solved P_γ closest to the measured P_γ

Jet Energy Reconstruction Result (All-MC)

eLpR Samples
MC Cut:
Correct photon selection
Method 3 has answer

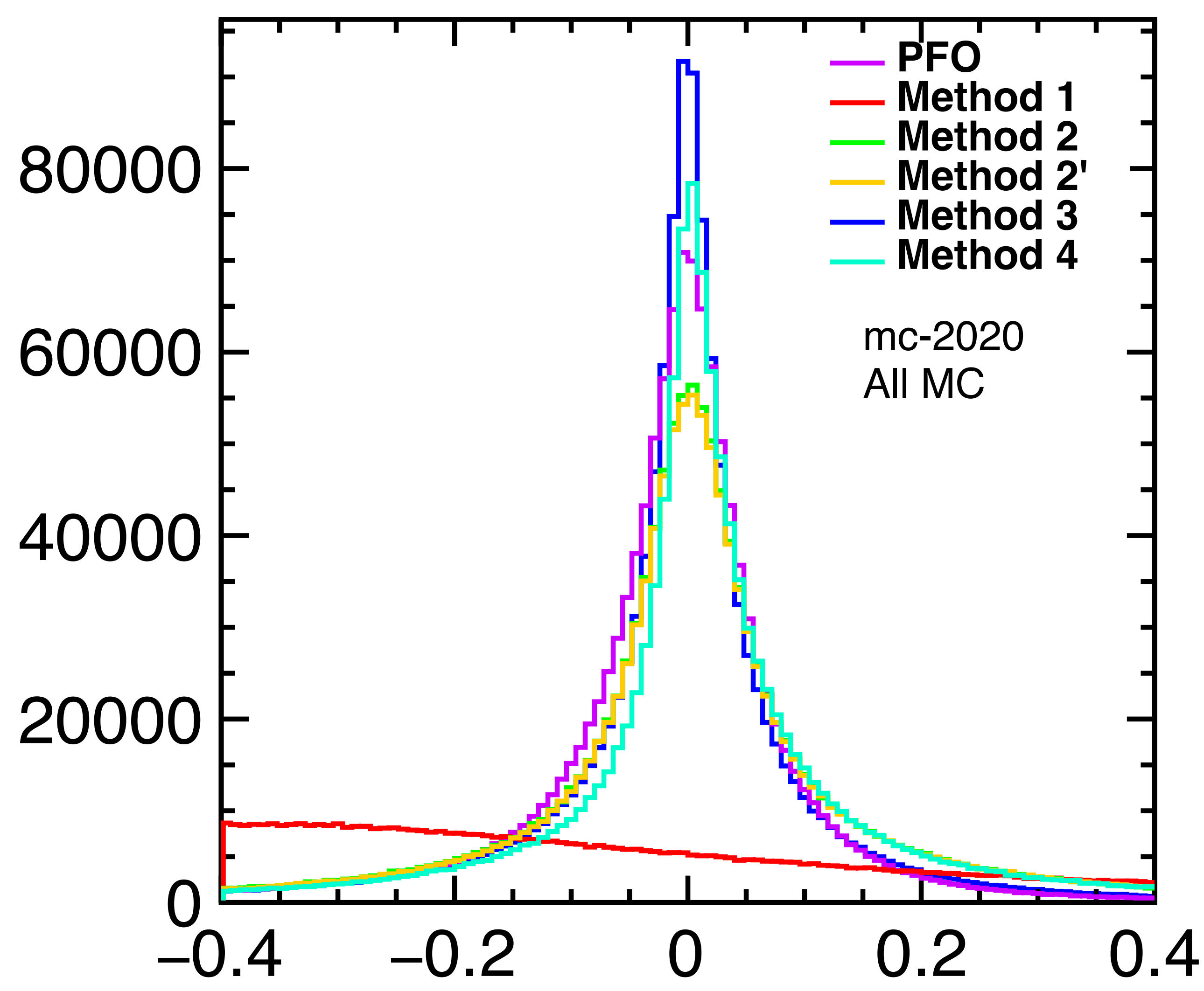
Jet 1

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



Jet 2

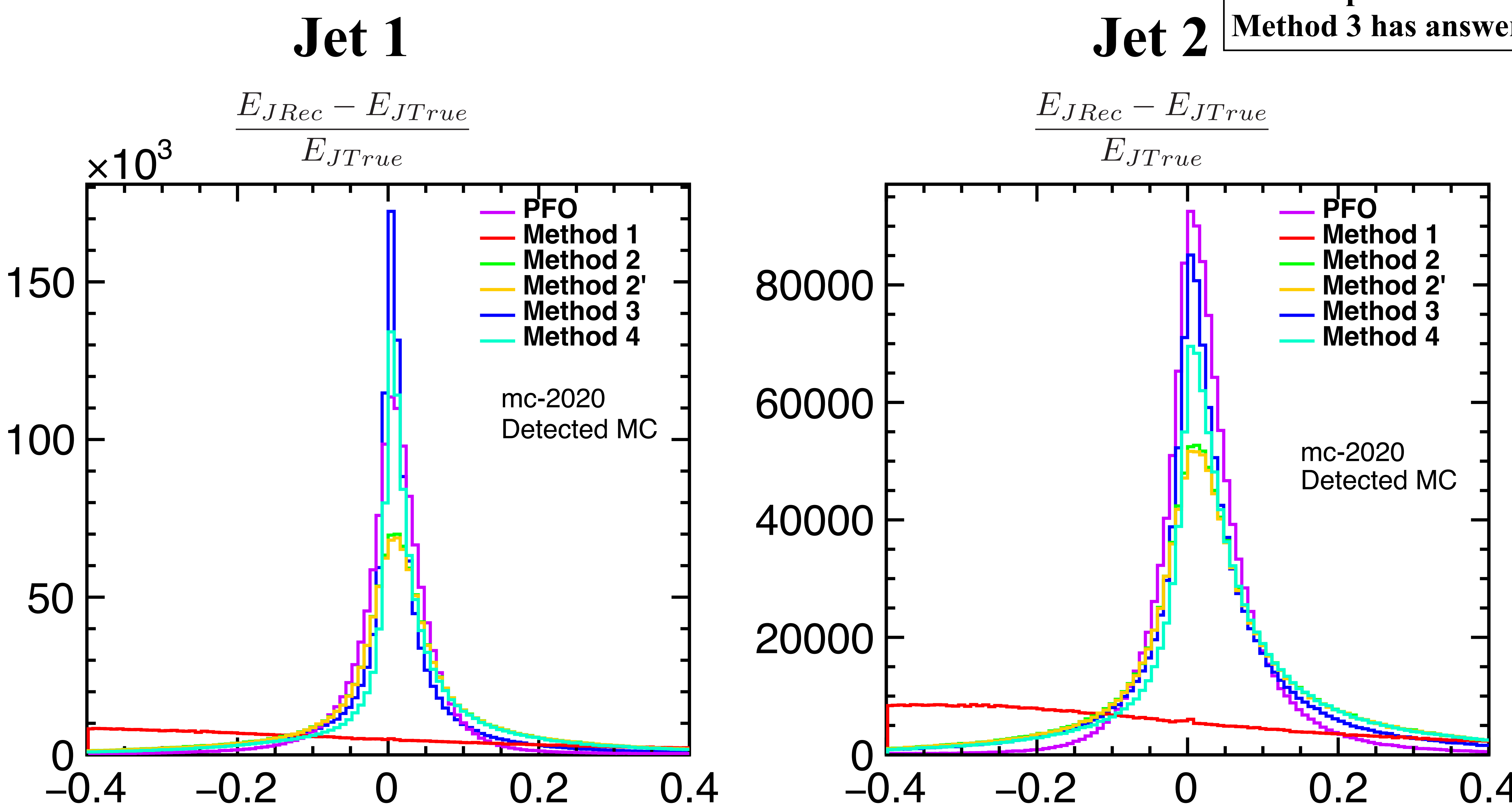
$$\frac{E_{JRec} - E_{JTrue}}{E_{JTrue}}$$



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

Jet Energy Reconstruction Result (Detected-MC)

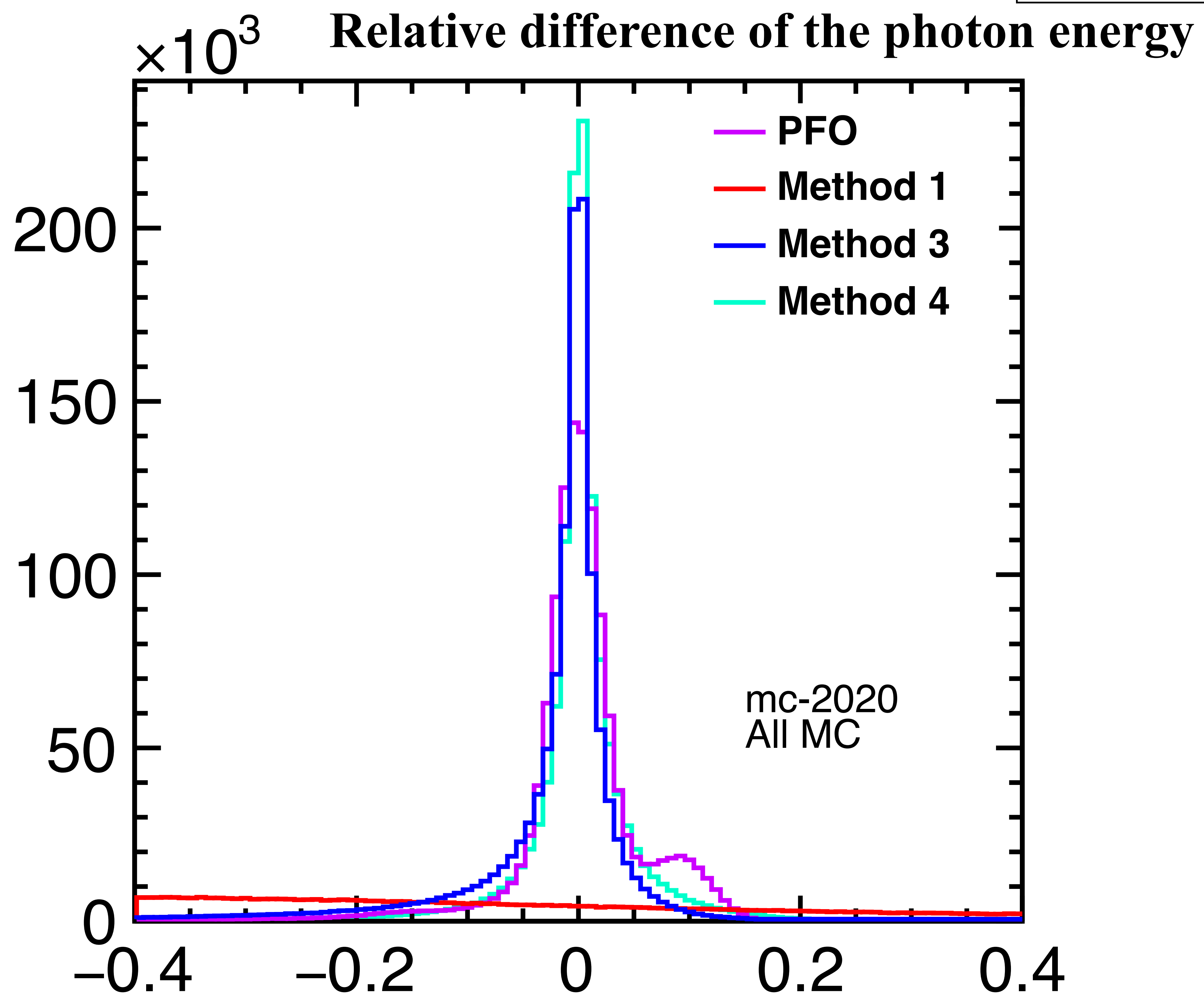
eLpR Samples
MC Cut:
Correct photon selection
Method 3 has answer



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

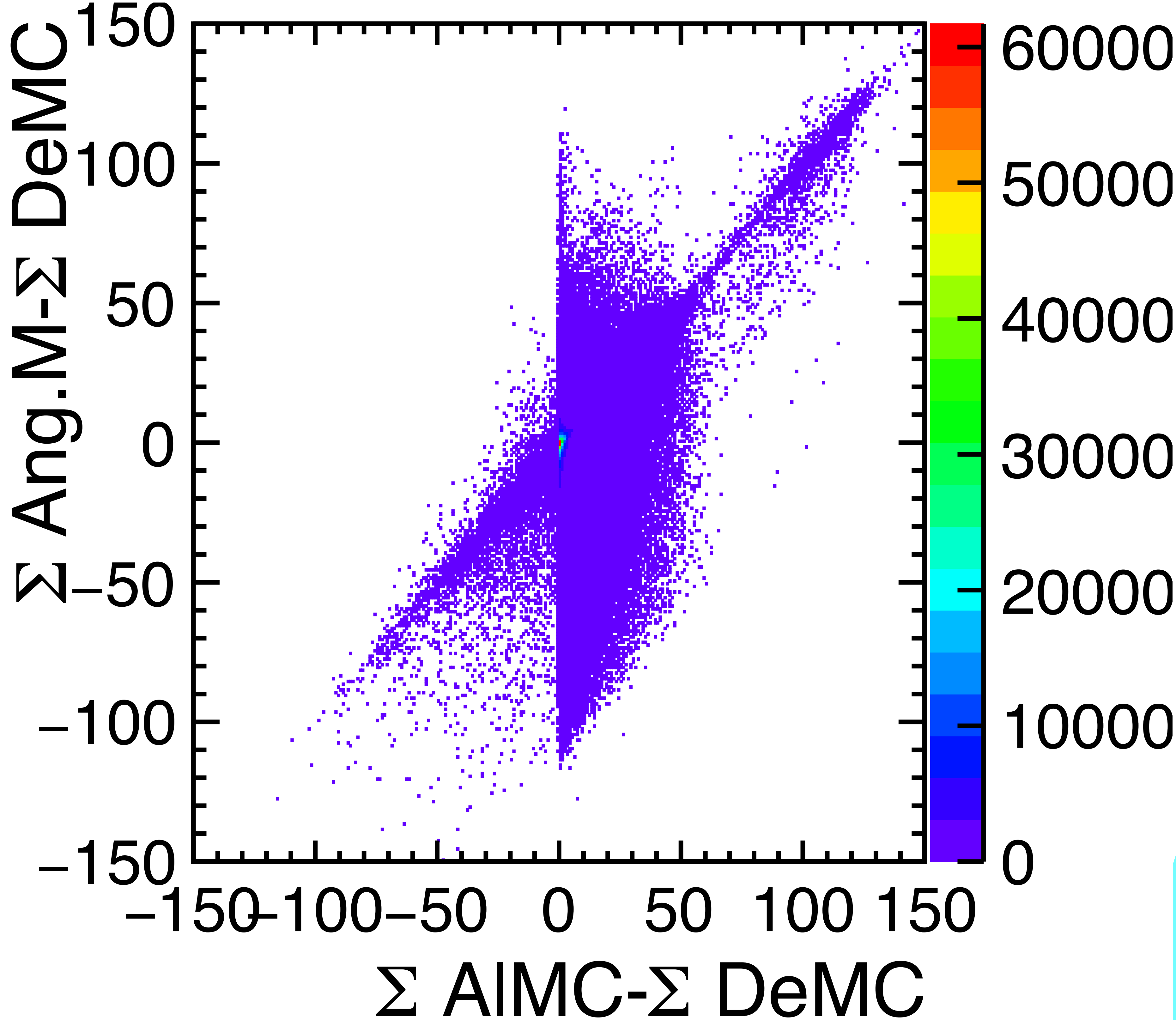
Photon Energy Reconstruction Result (All-MC)

eLpR Samples
MC Cut:
Correct photon selection
Method 3 has answer



Missing particles recovery in Method 3

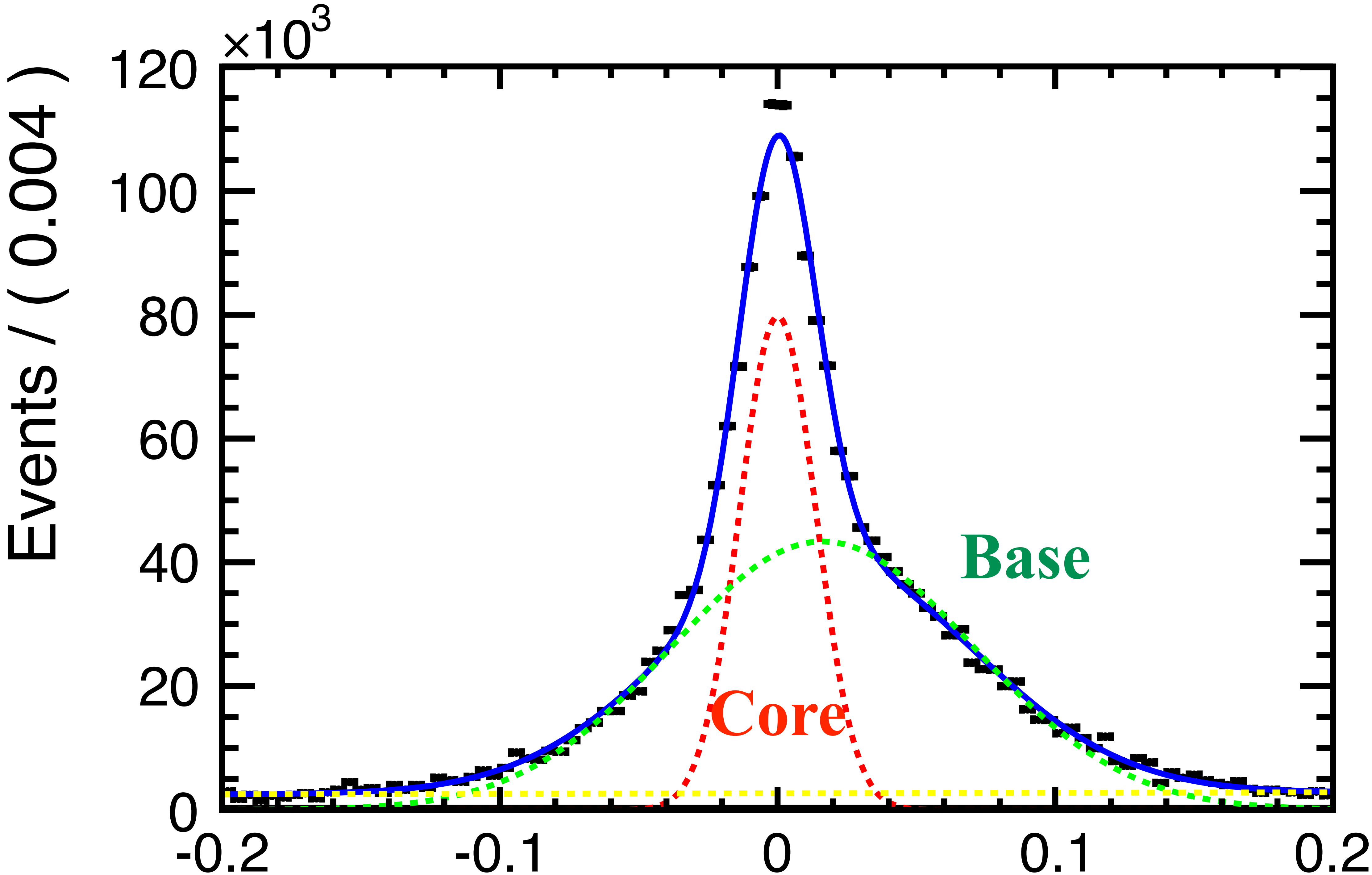
eLpR Samples
MC Cut:
Correct photon selection
Method 3 has answer



This will be more clear in the flavor dependence plot

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

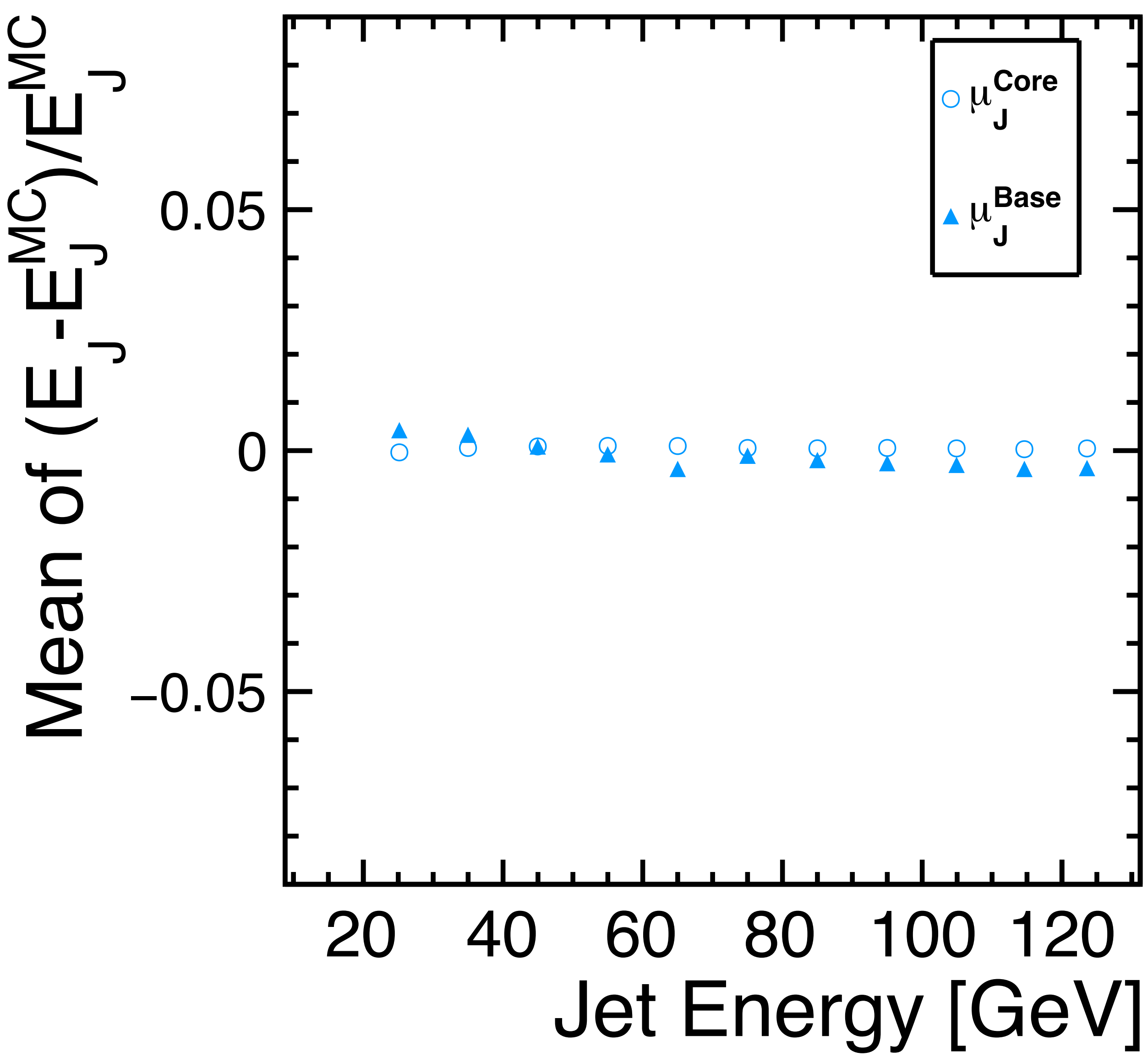
Calibration is based on the mean value of the Gaus (Core).



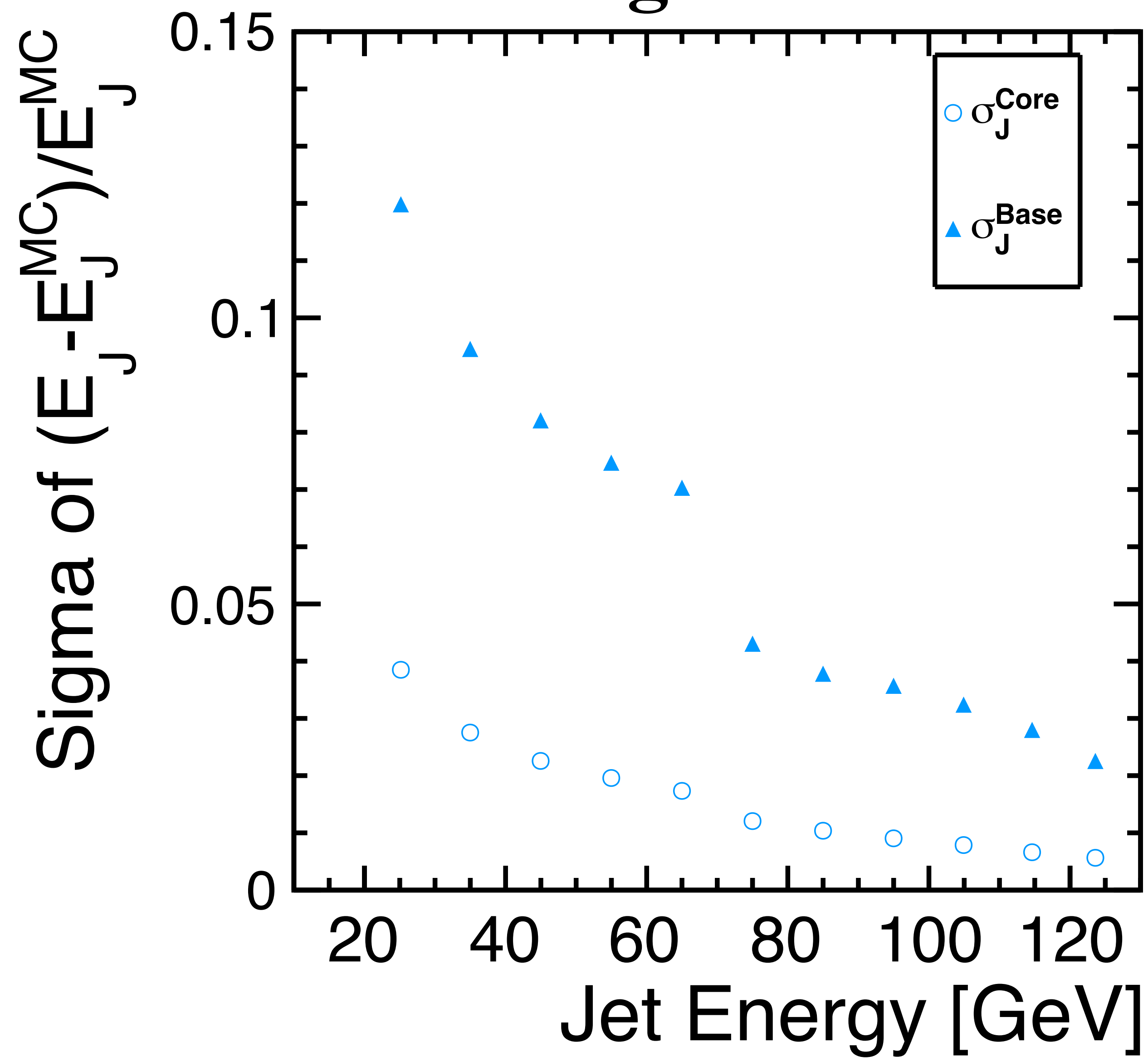
-> Check the theta, energy, and flavor dependence.

Ang. Method E-Dep (Al-MC)

Mean

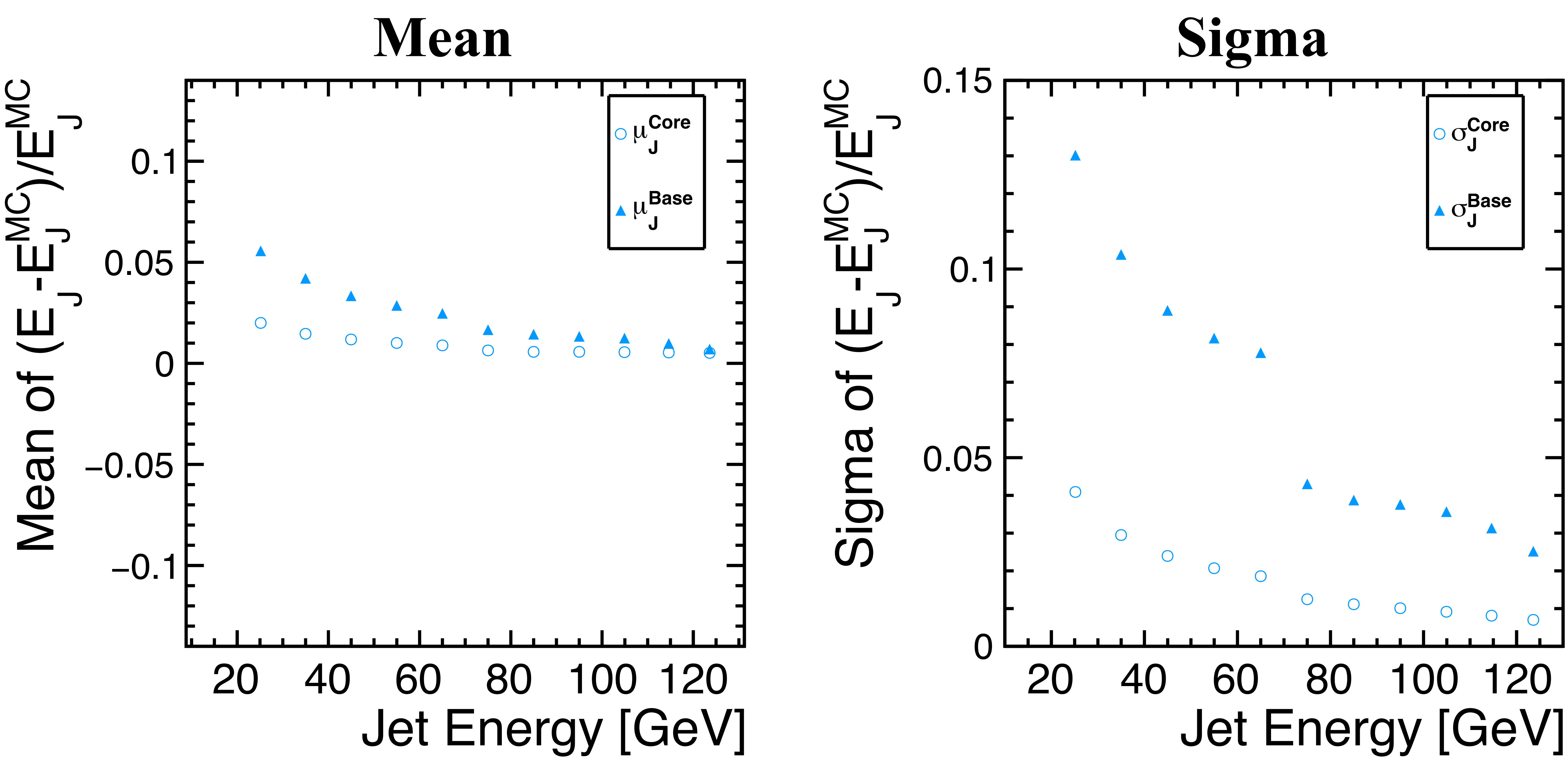


Sigma



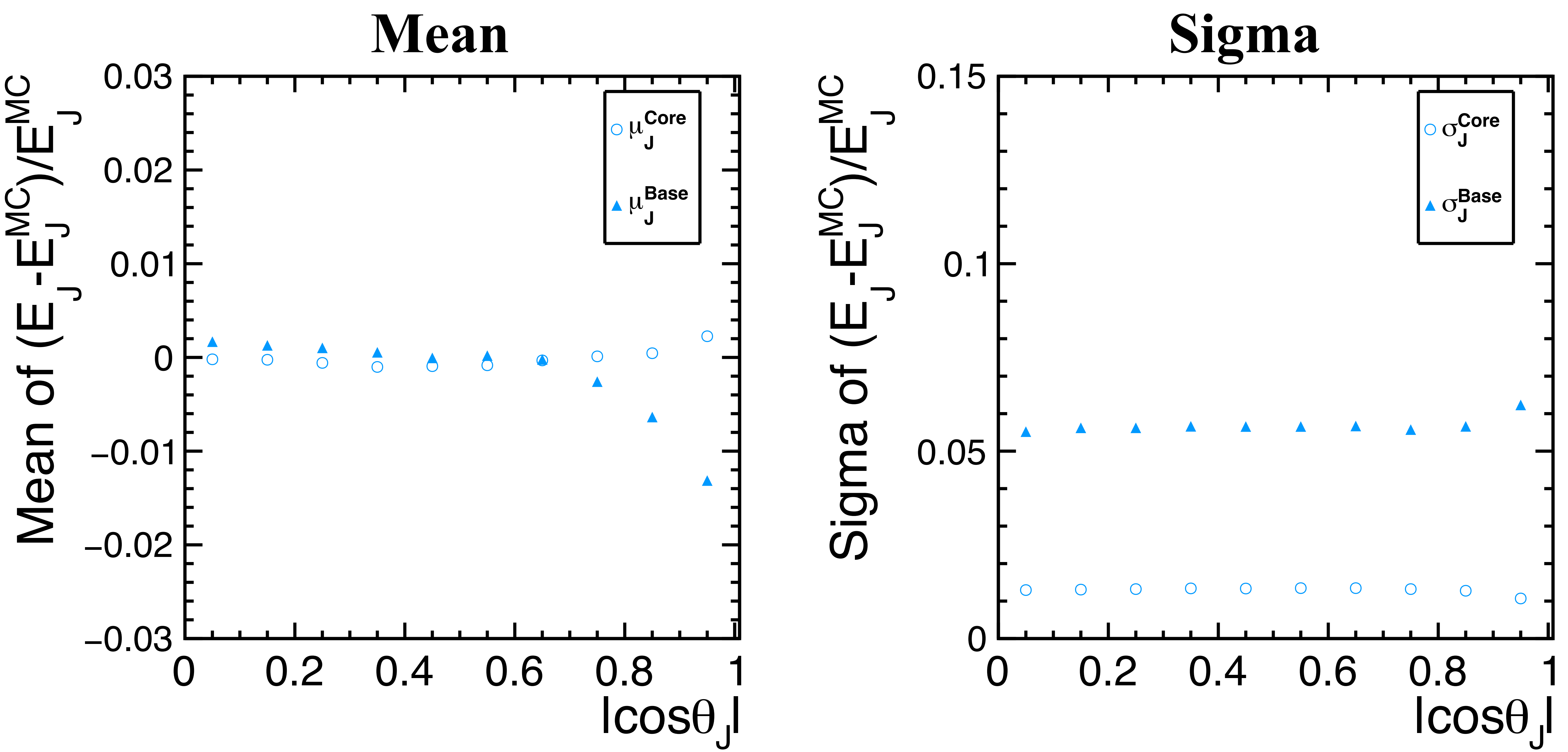
Mean value of the core gaussian is order of 10^{-4} independent on the jet energy.
Higher energy jet has negative bias and lower one has positive bias.

Ang. Method E-Dep (De-MC)



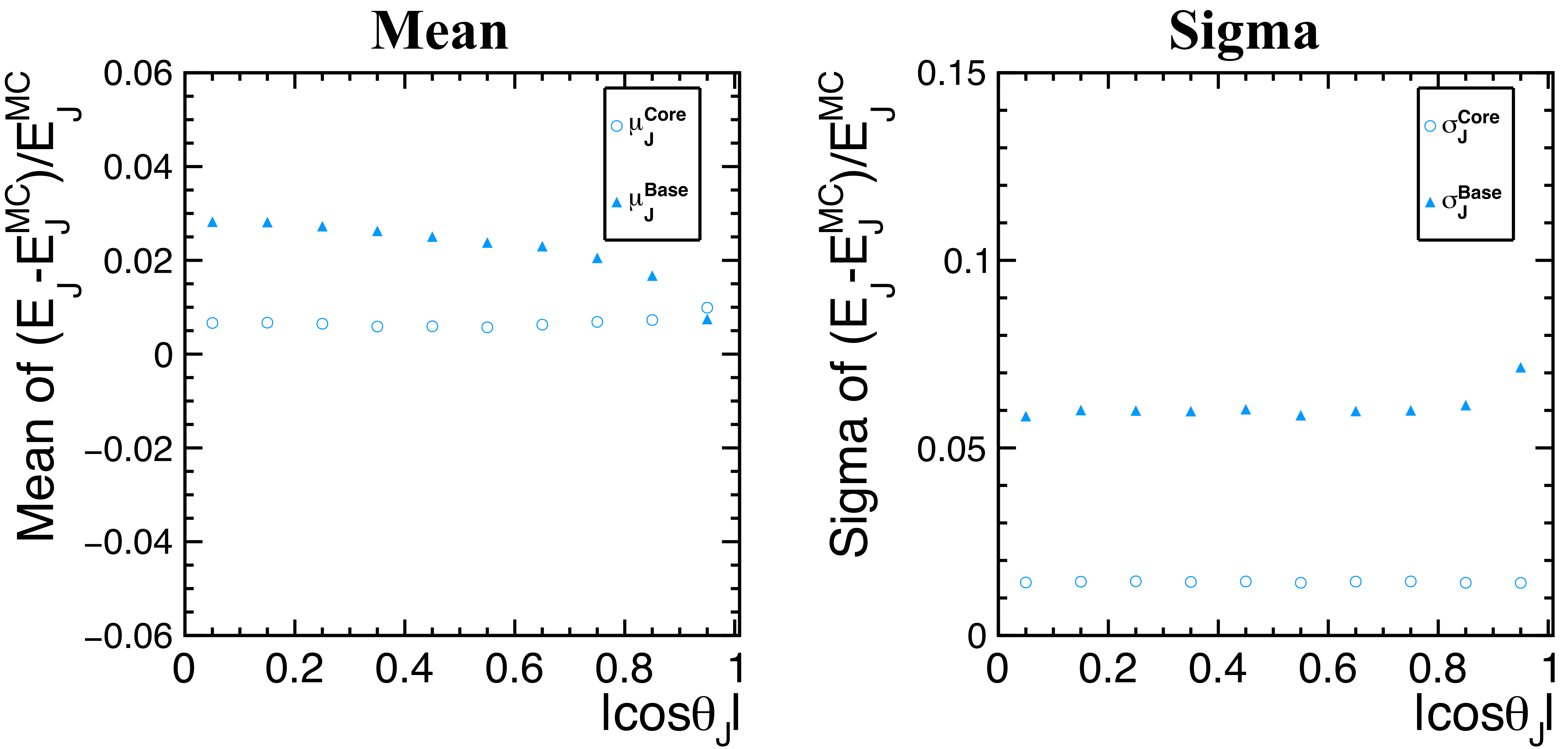
Values are positive as Ang. Method recovers missing particles.

Ang. Method T-Dep (Al-MC)

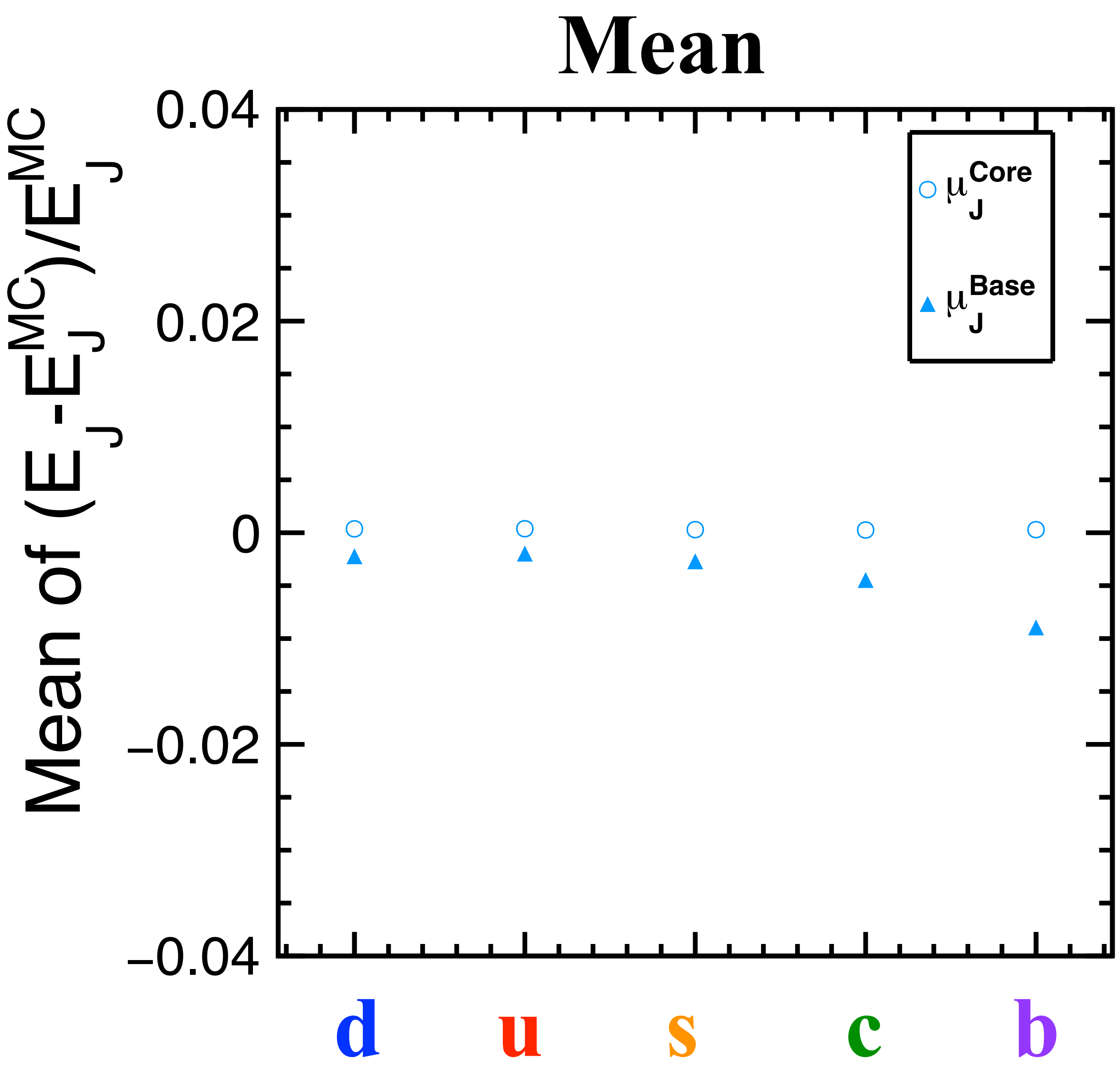


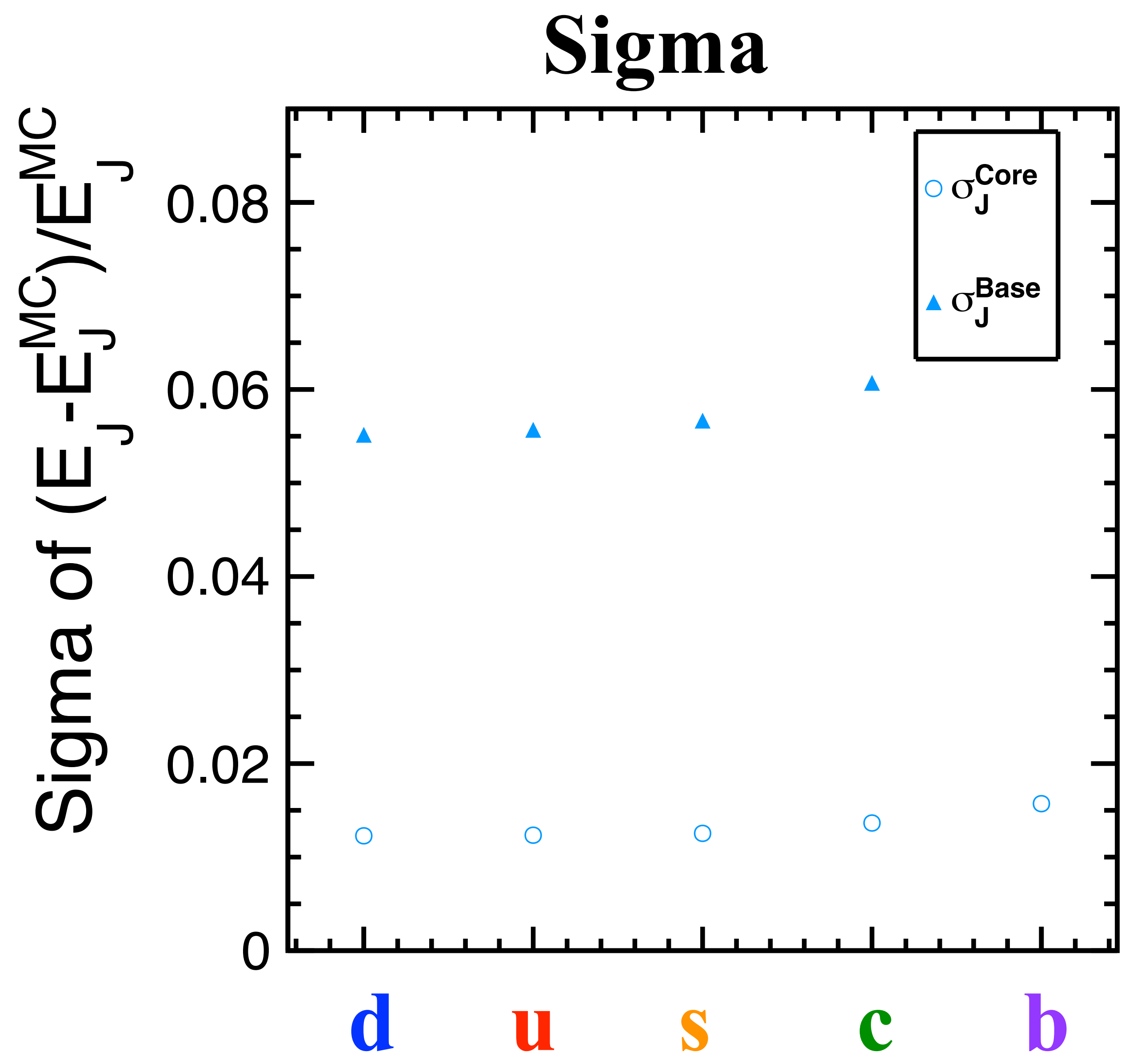
Forward jet makes slight positive bias on the core gaussian and barrel region jet makes slight negative bias on the core gaussian.

Ang. Method T-Dep (De-MC)



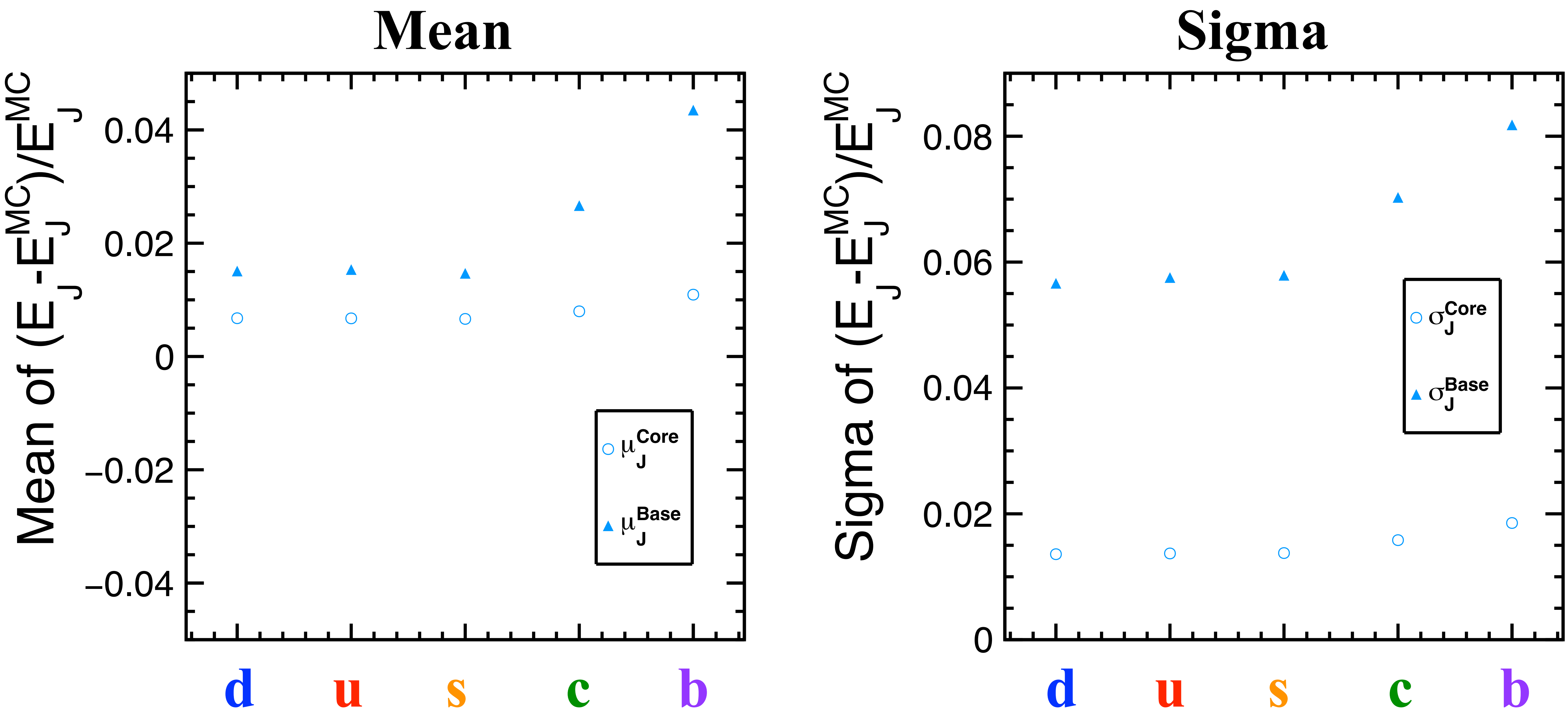
Ang. Method F-Dep (Al-MC)





Mean value of the core gaussian is order of 10^{-4} independent on the flavor.

Ang. Method F-Dep (De-MC)



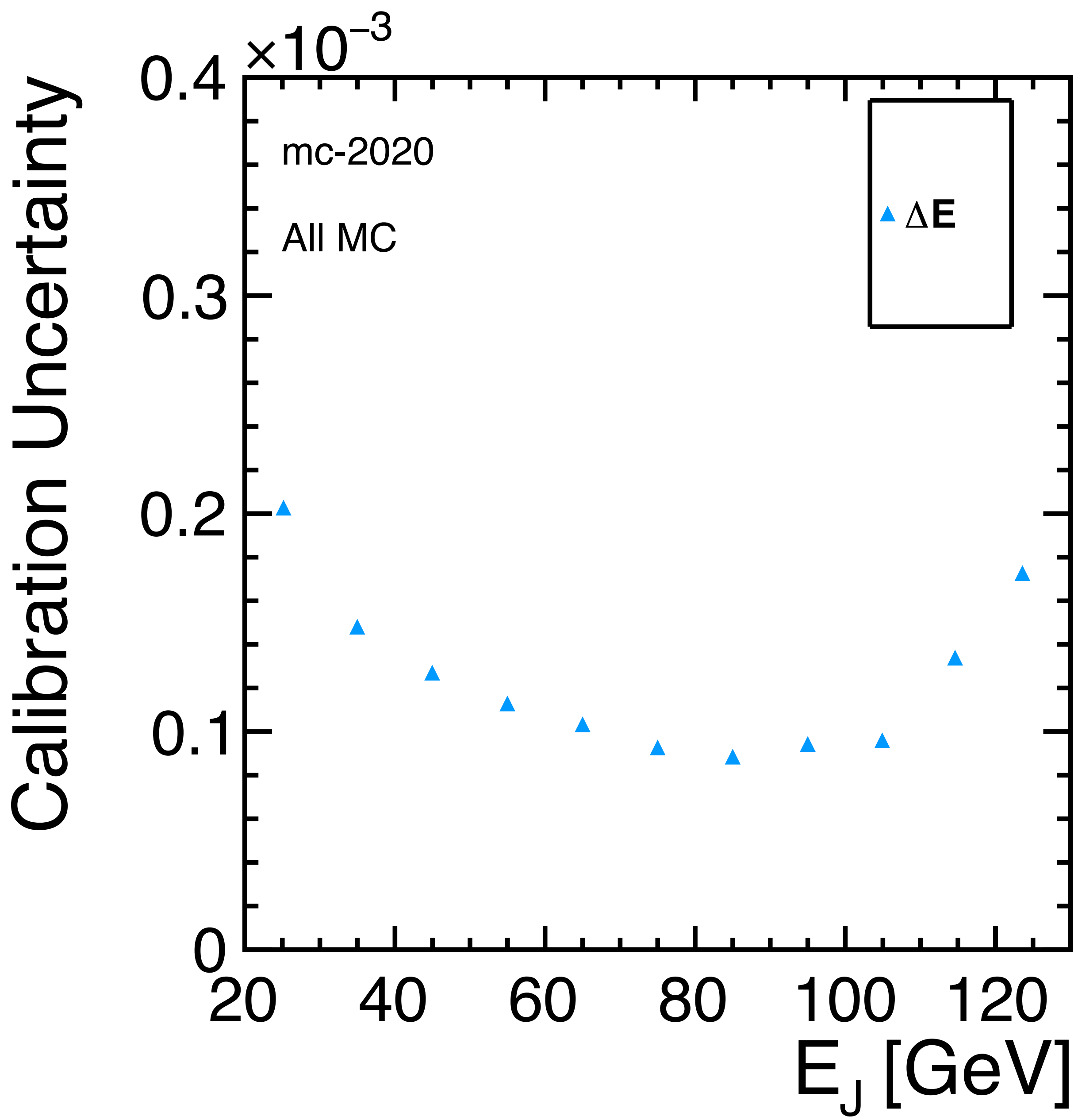
Mean value of the core gaussian is larger in the heavy flavor. This is because heavy flavor jet emits more neutrinos and Ang. Method recovers the missing energy.

Calibration Uncertainty (Al-MC)

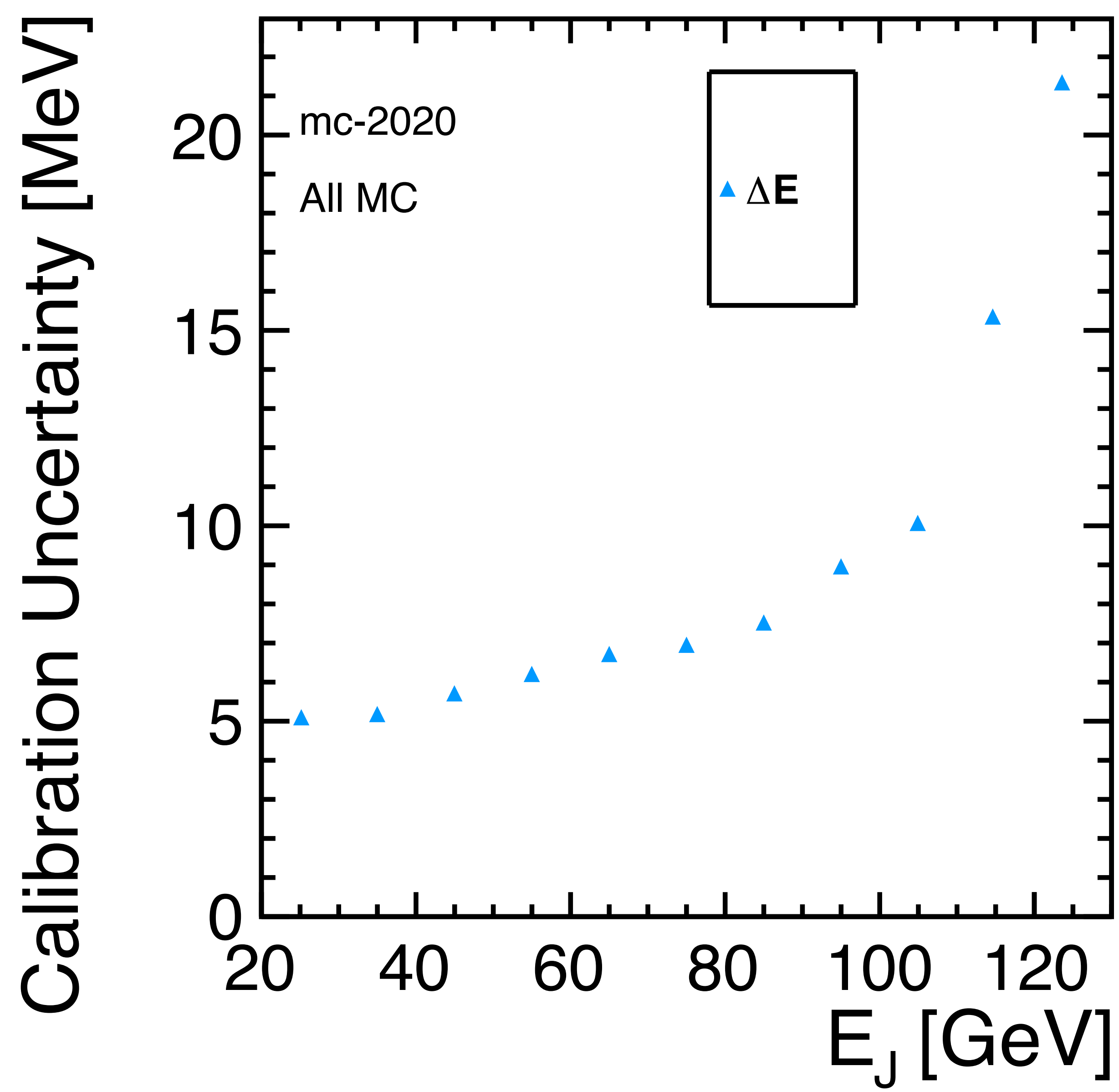
Calibration uncertainty := $\sqrt{(\Delta\mu_{Detector})^2 + (\Delta\mu_{Reconstructed})^2}$

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

Relative uncertainty



Absolute uncertainty



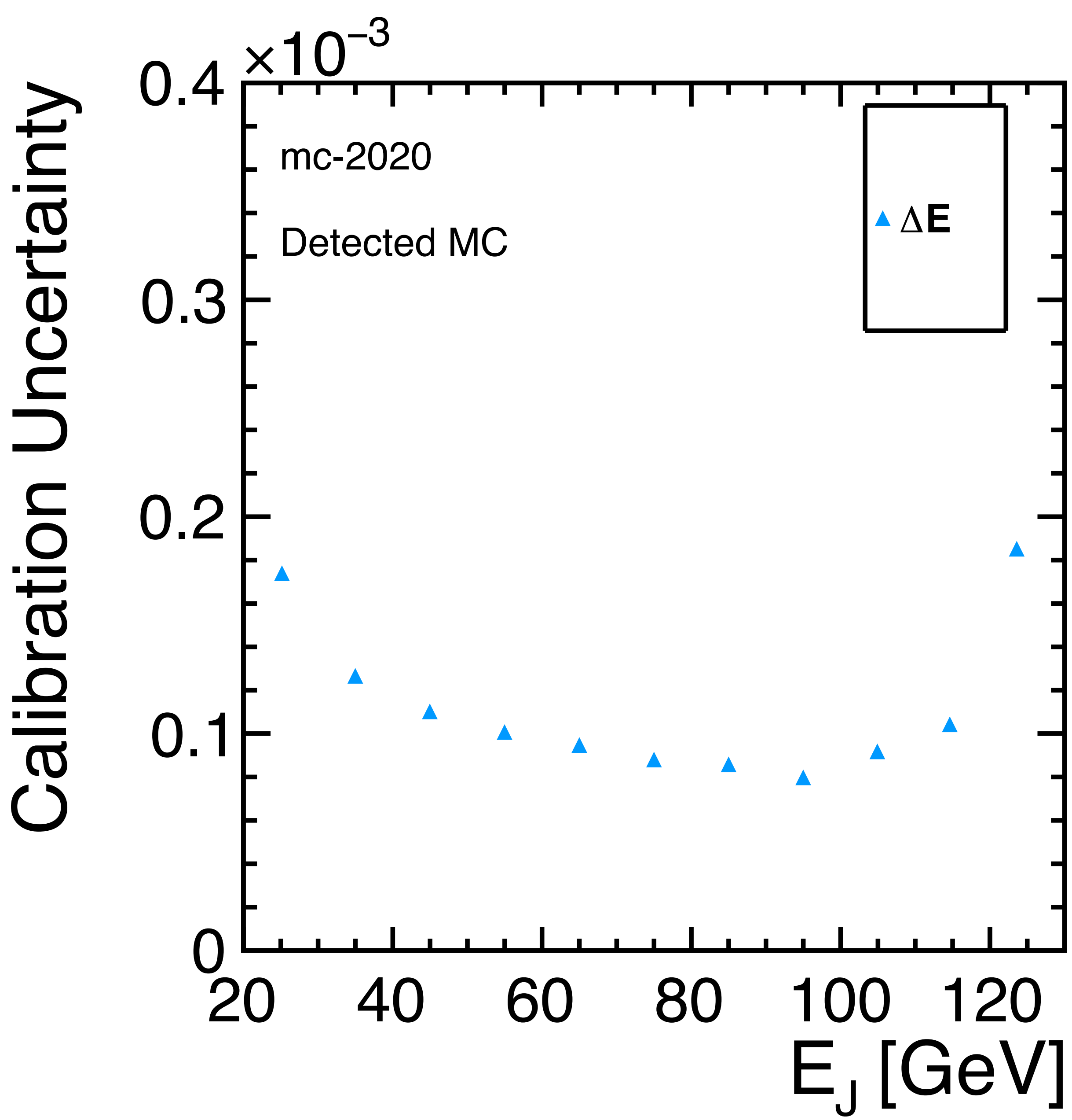
We can calibrate the jet energy scale with about 10^{-4} accuracy, which corresponds to ~10 MeV.

Calibration Uncertainty (De-MC)

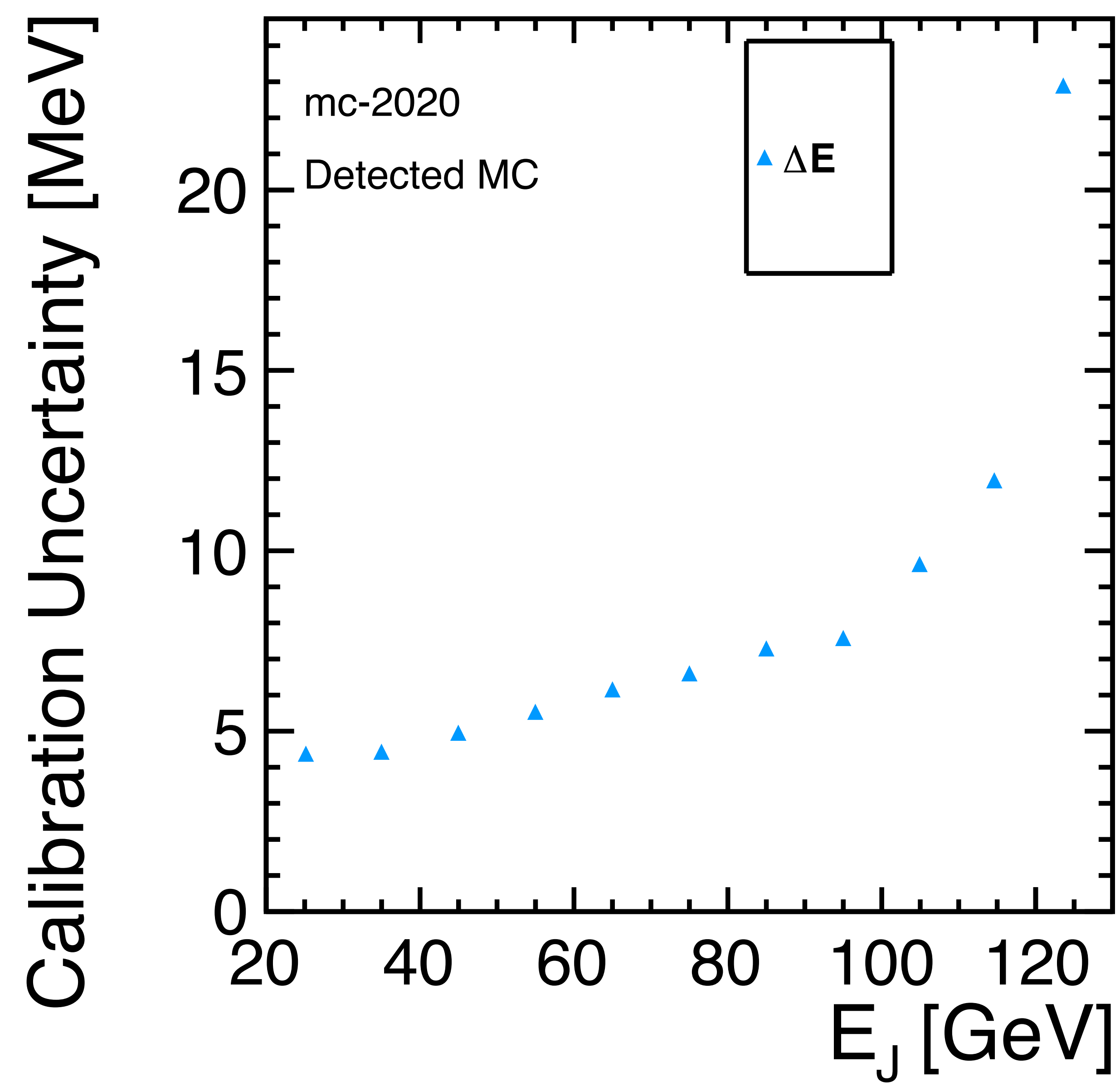
Calibration uncertainty := $\sqrt{(\Delta\mu_{Detector})^2 + (\Delta\mu_{Reconstructed})^2}$

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 ~10 MeV.

Contents

Conclusion

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