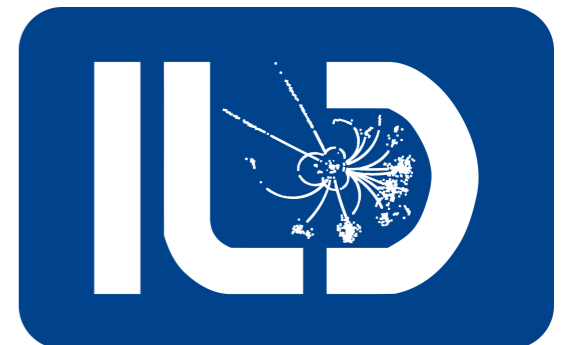


Jet Energy Scale Calibration

using $e^+e^- \rightarrow qq\gamma$

Takahiro Mizuno
SOKENDAI



Contents

1. Introduction

2. Full simulation / Event selection

3. E_{jet} reconstruction

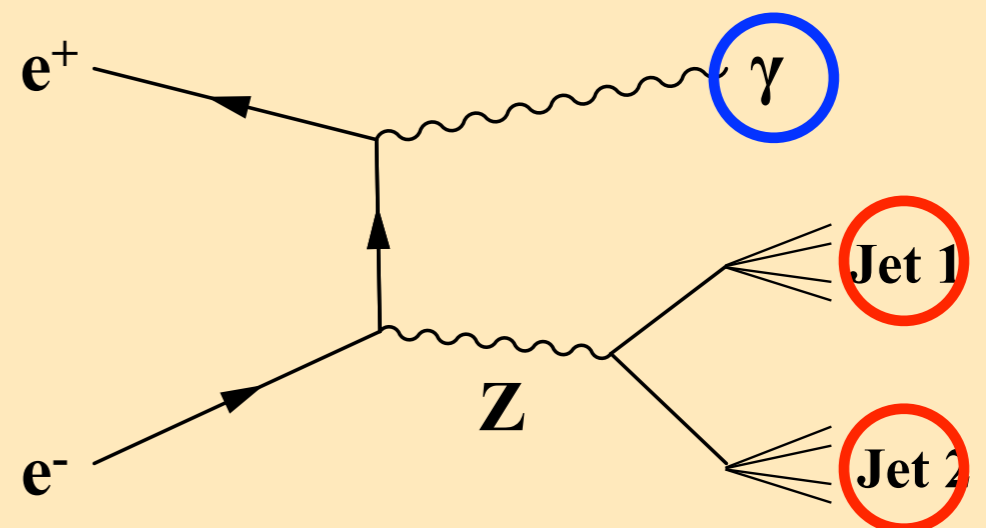
4. Conclusion

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 $e^+e^- \rightarrow \gamma Z, Z \rightarrow 2 \text{ Jets}$ process. Taking advantage of its large cross sections, ~ 80 million events are expected @ ILC250.
- In this talk, I will show how useful the $e^+e^- \rightarrow \gamma Z$ process is for the jet energy calibration **by full simulation.**

Jet Energy Scale Calibration



Contents

1. Introduction

2. Full simulation / Event selection

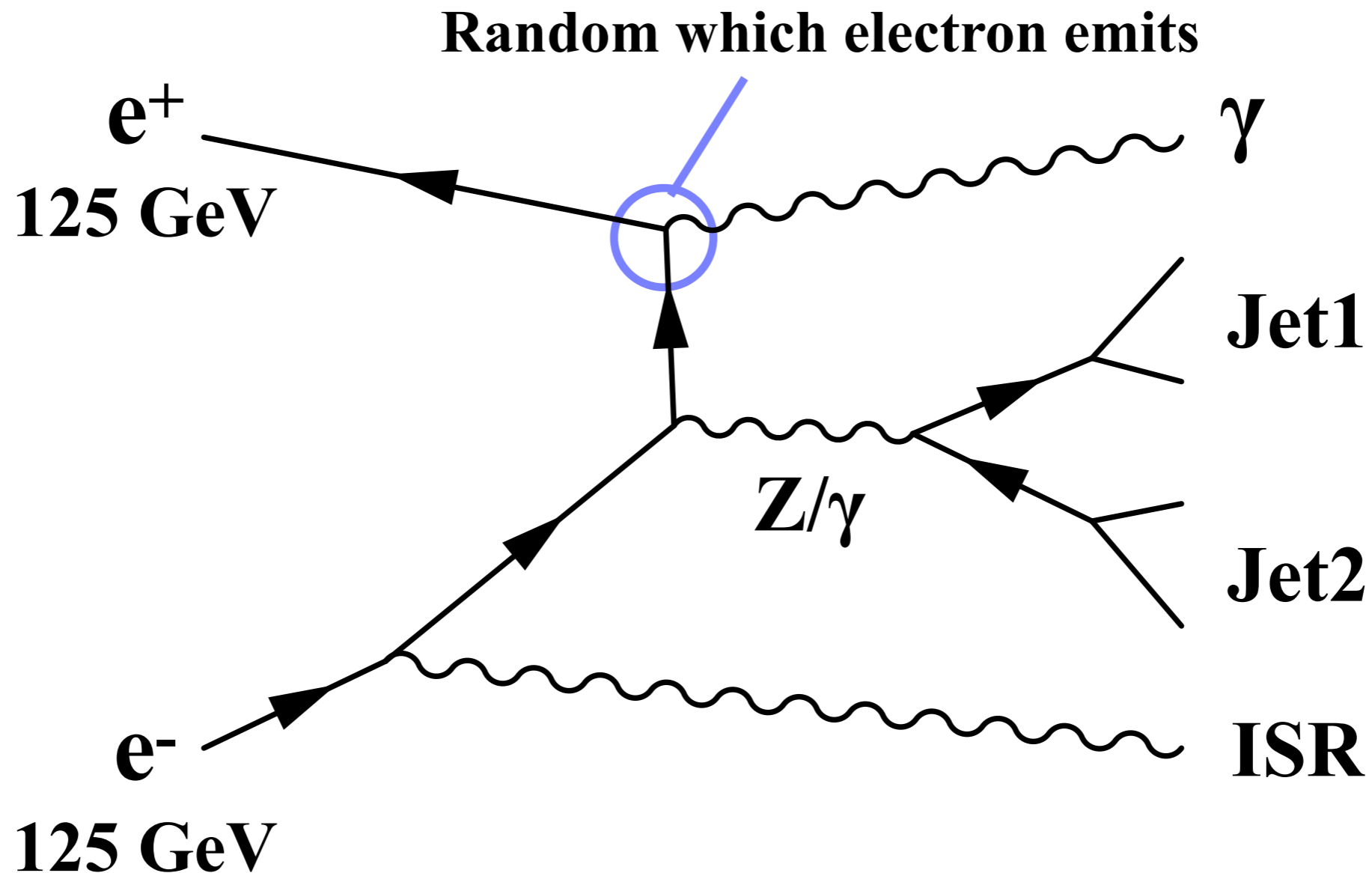
3. E_{jet} reconstruction

4. Conclusion

Full simulation

(ILCSOFT version v01-16-02)

- **Geant4-based full detector simulation** is performed for the $e^+e^- \rightarrow \gamma Z, Z \rightarrow 2 \text{ Jets}$ process using a **realistic ILD detector model**, at **$E_{CM}=250 \text{ GeV}$** with $\int L dt = 900 \text{ fb}^{-1}$ 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:

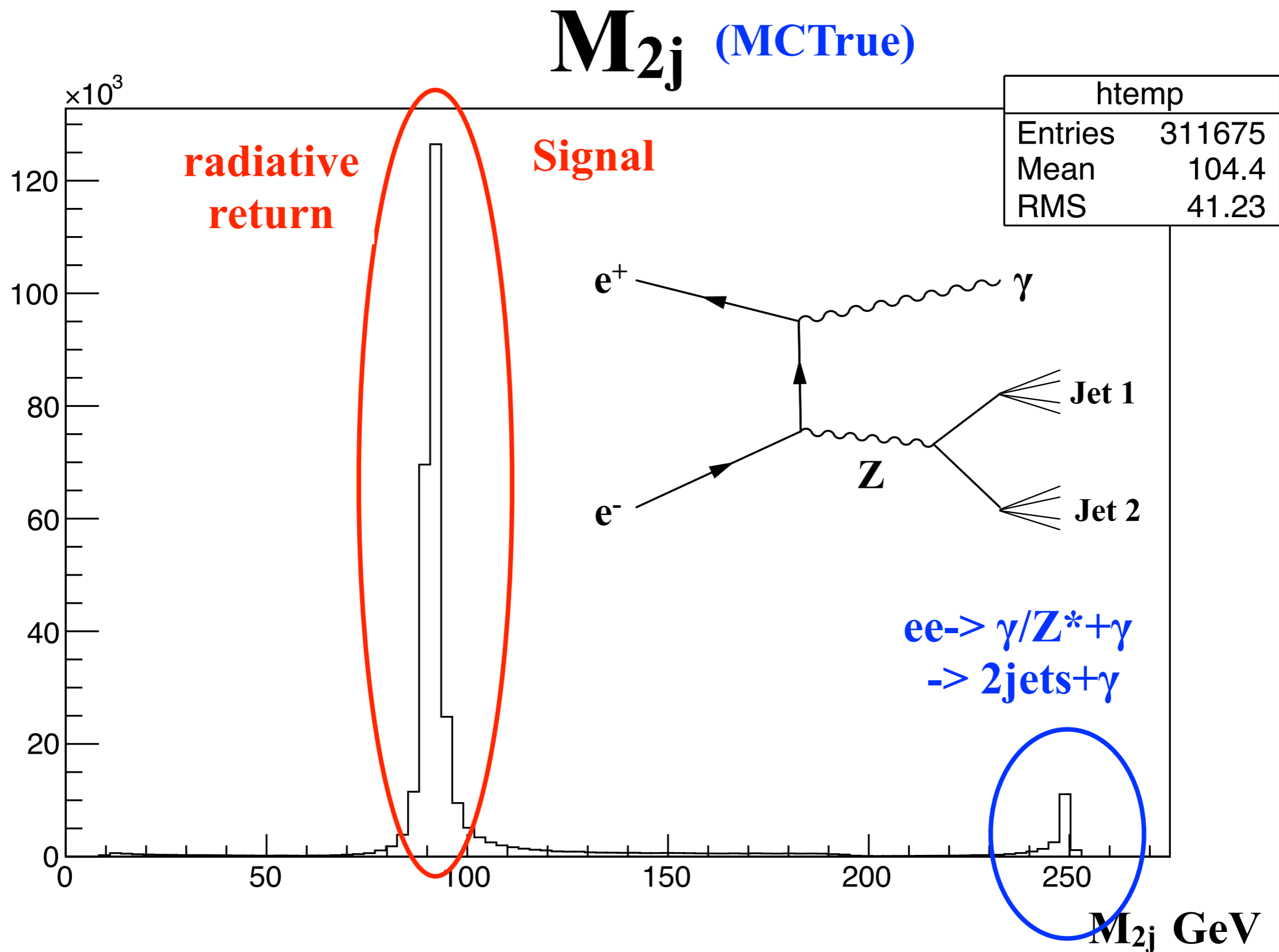
1. choose neutral particles with particle ID = 22 (Pandora PFA ID)
2. require energy > 50 GeV
3. choose the photon candidate with energy closest to 108.4 GeV

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

Jet Clustering

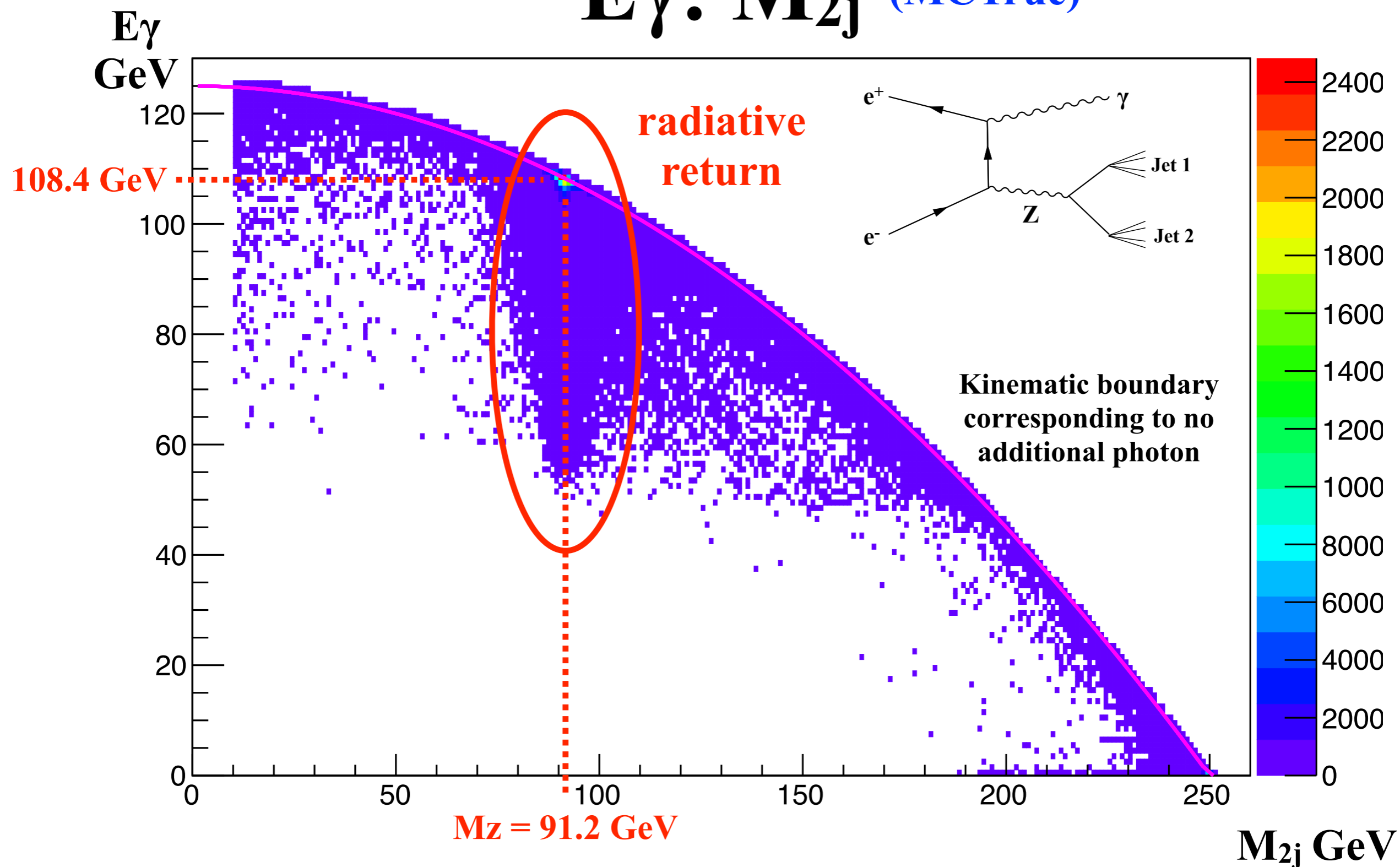
- All Particle Flow Objects (PFOs) other than the selected photon are clustered into 2 jets with Durham algorithm (done by LCFIPlus)
- The jet with higher reconstructed energy is defined as “jet 1” and the other as “jet 2”

M_{2j} distribution



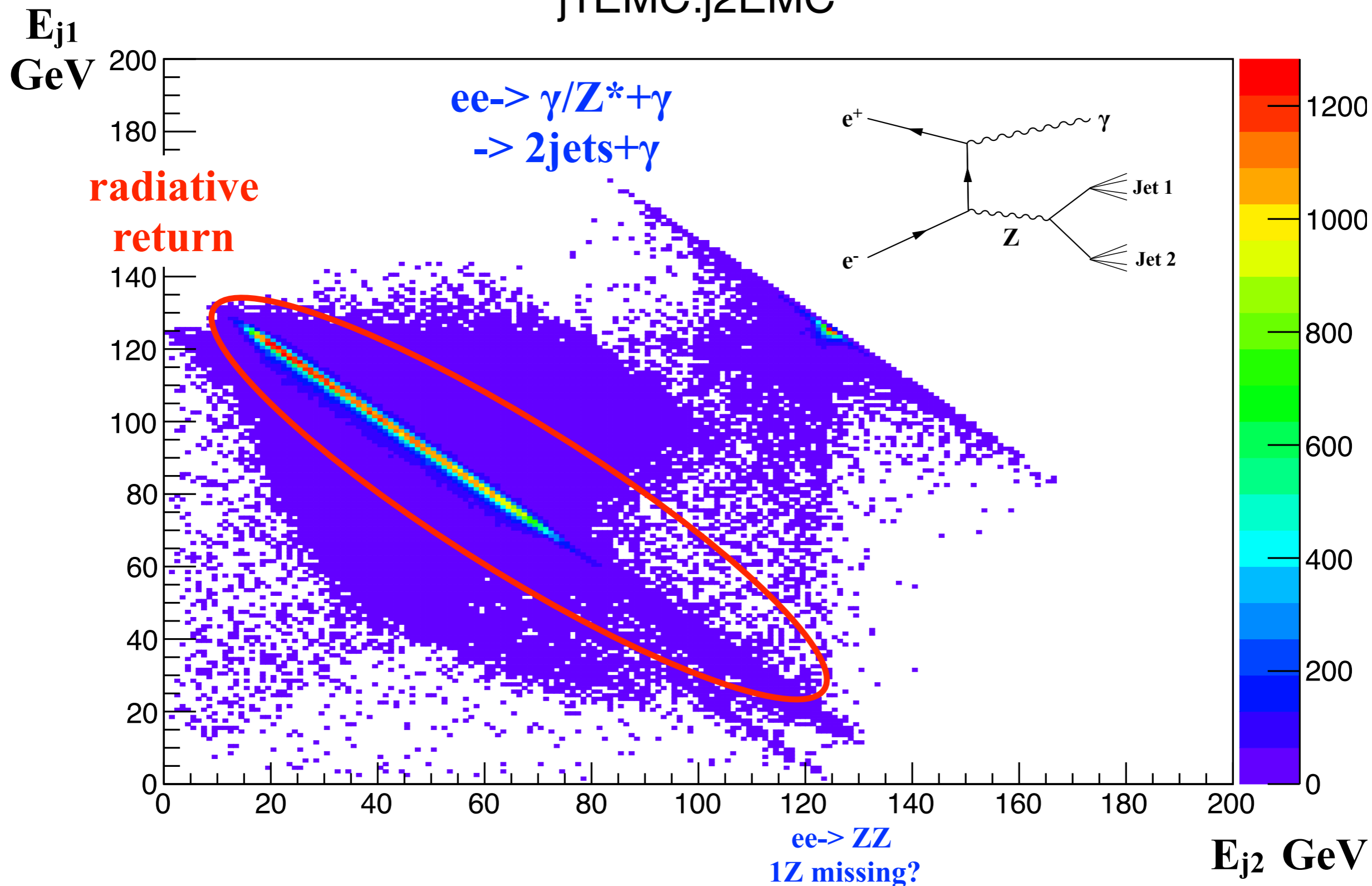
Photon energy & M_{2j} distribution

$E_\gamma: M_{2j}$ (MCTrue)



Jet energy distribution

j1EMC:j2EMC



Contents

1. Introduction

2. Full simulation / Event selection

3. E_{jet} reconstruction

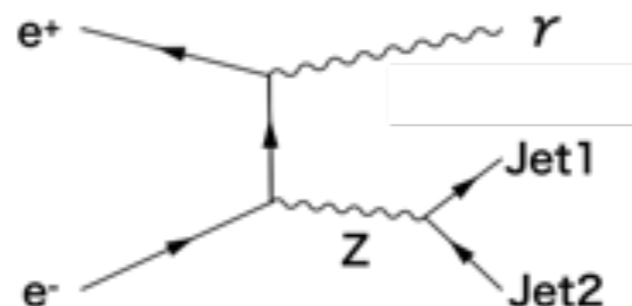
4. Conclusion

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 $(\theta_{J1}, \theta_{J2}, \theta_{\gamma}, \phi_{J1}, \phi_{J2}, \phi_{\gamma}, m_{J1}, m_{J2})$
 \rightarrow Determine $(P_{J1}, P_{J2}, P_{\gamma}, P_{ISR})$



Direction Angle
 θ : polar angle
 ϕ : azimuthal angle

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

Matrix A **Inverse**

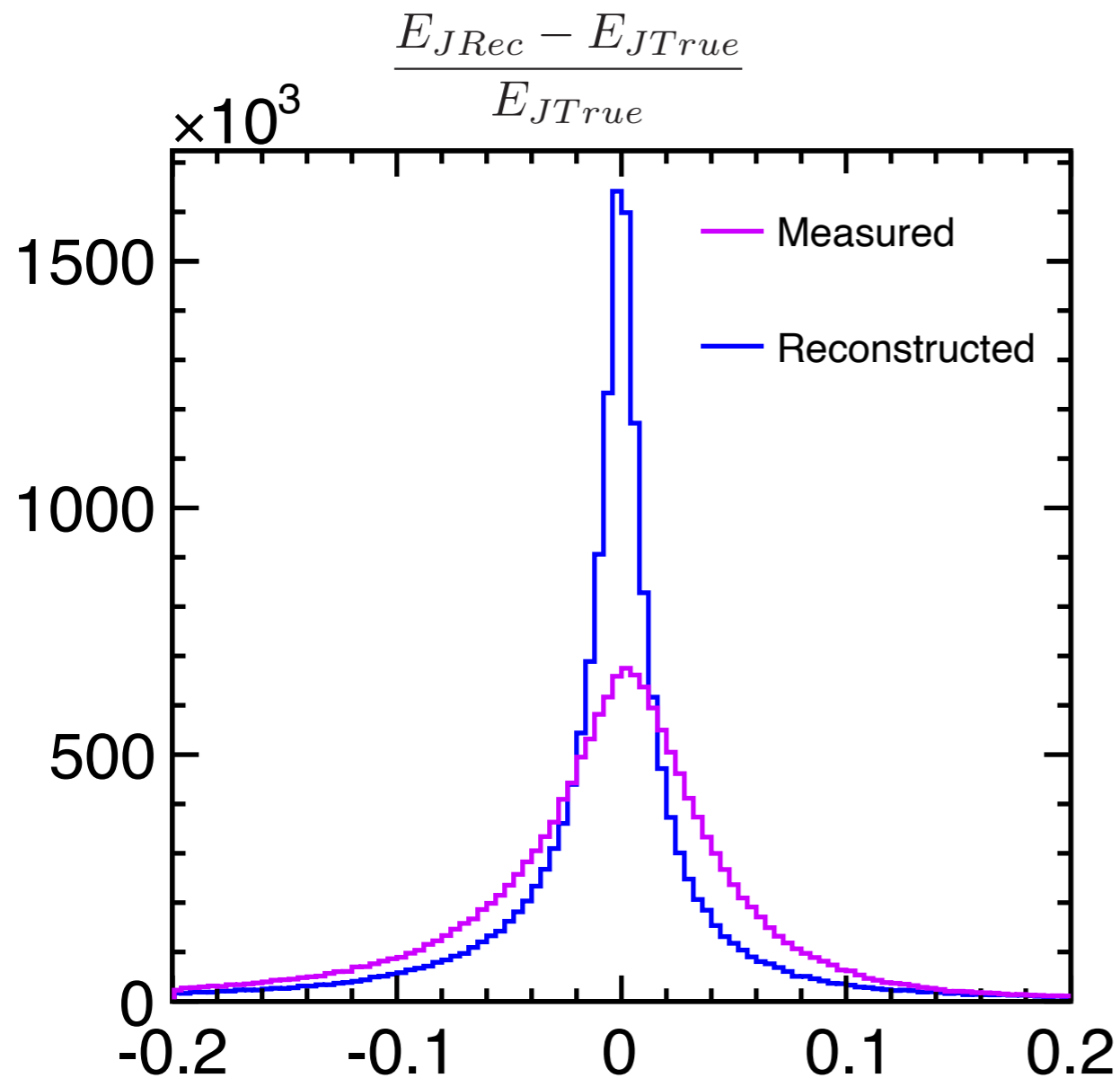
Beam Crossing Angle $\equiv 2\alpha = 14.0$ mrad
 ISR photon = additional unseen photon

Irrational equation for each sign of the ISR \rightarrow 8 possible solutions

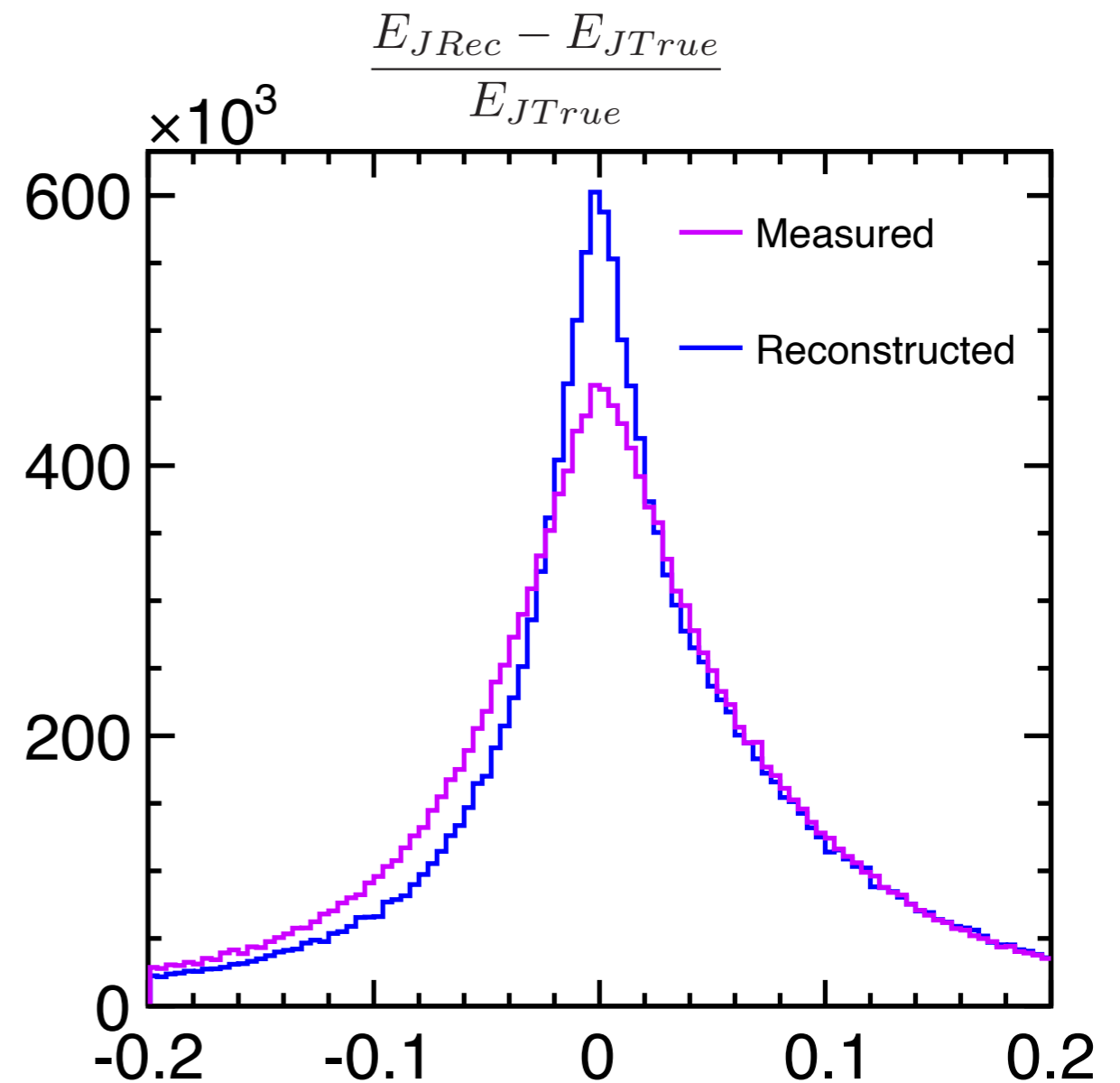
- Choose the solution with**
- (i) Real and positive value with $< E_{CM}/2$
 - (ii) $\sqrt{P_{J1}^2 + m_{J1}^2} > 0$ and $\sqrt{P_{J2}^2 + m_{J2}^2} > 0$
 - (iii) $P_{J1}, P_{J2}, P_{\gamma} > 0$
 - (iv) solved P_{γ} closest to the measured P_{γ}

Jet Energy Reconstruction Result

Jet 1



Jet 2

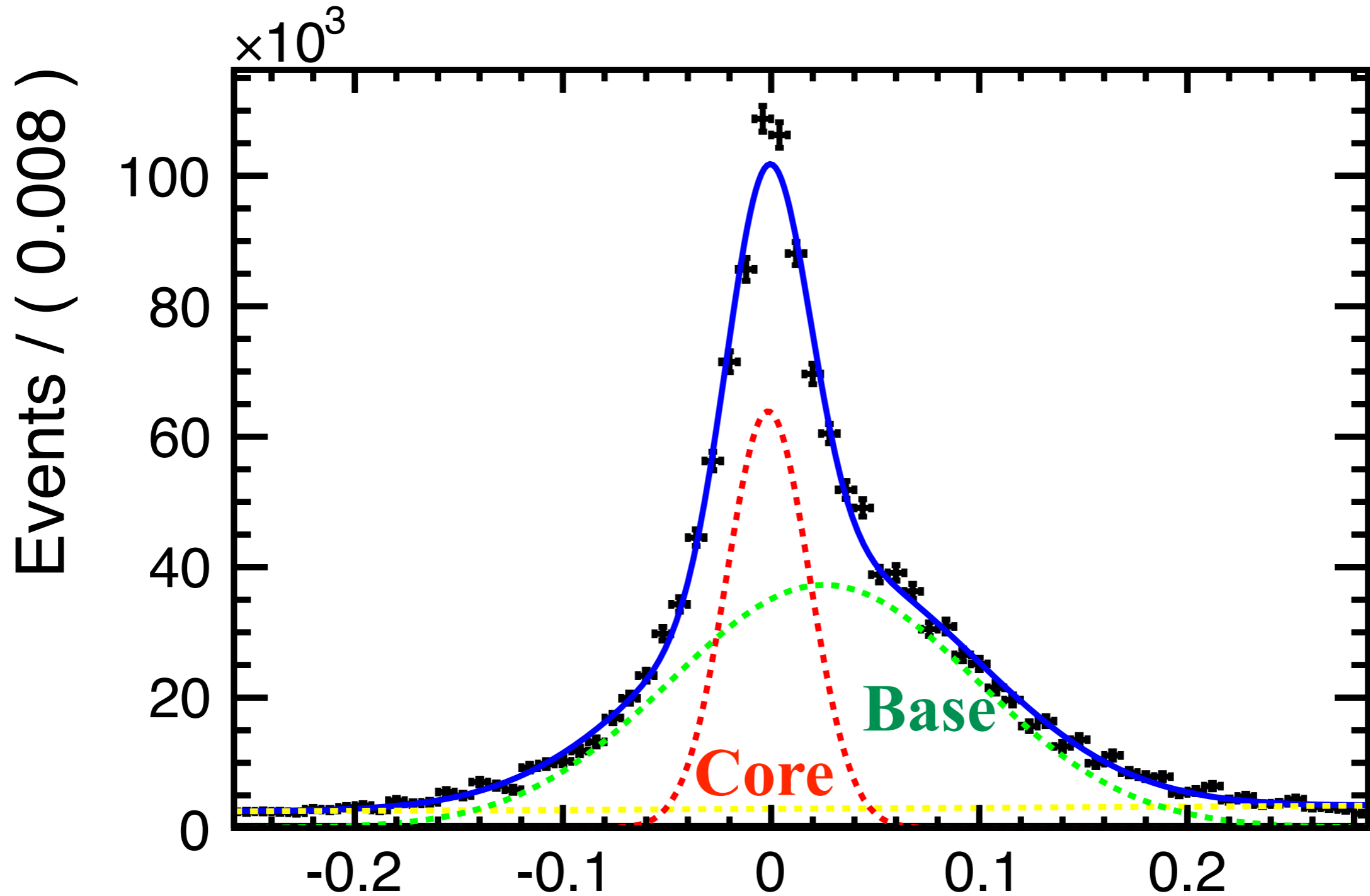


Reconstructed energy not only can calibrate the measured energy, but also has better resolution.

Fit the relative difference of reconstructed jet energy with

Gaus (Core)+Gaus (Base)+exponential

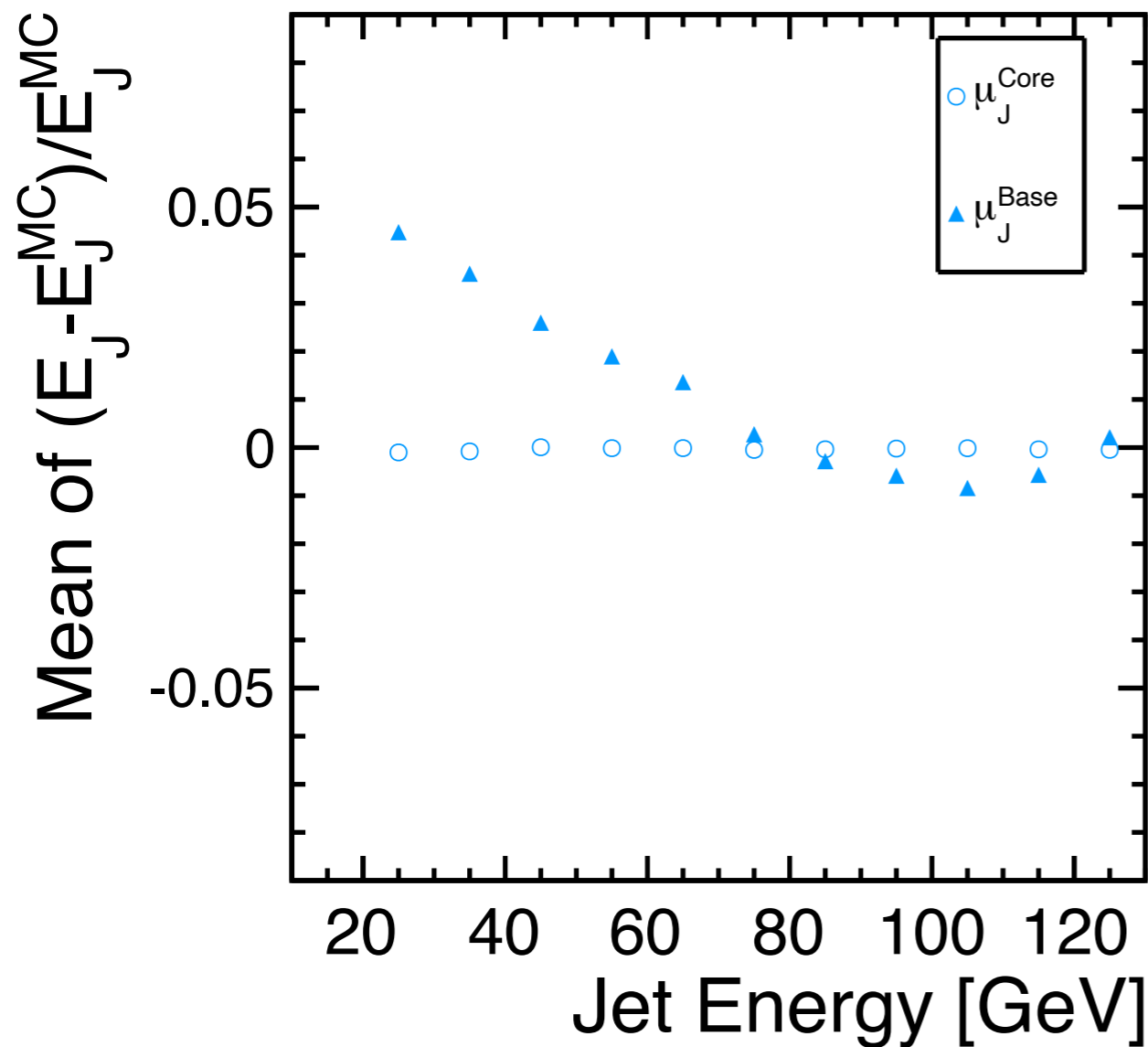
Calibration is based on **the mean value of the Gaus (Core).**



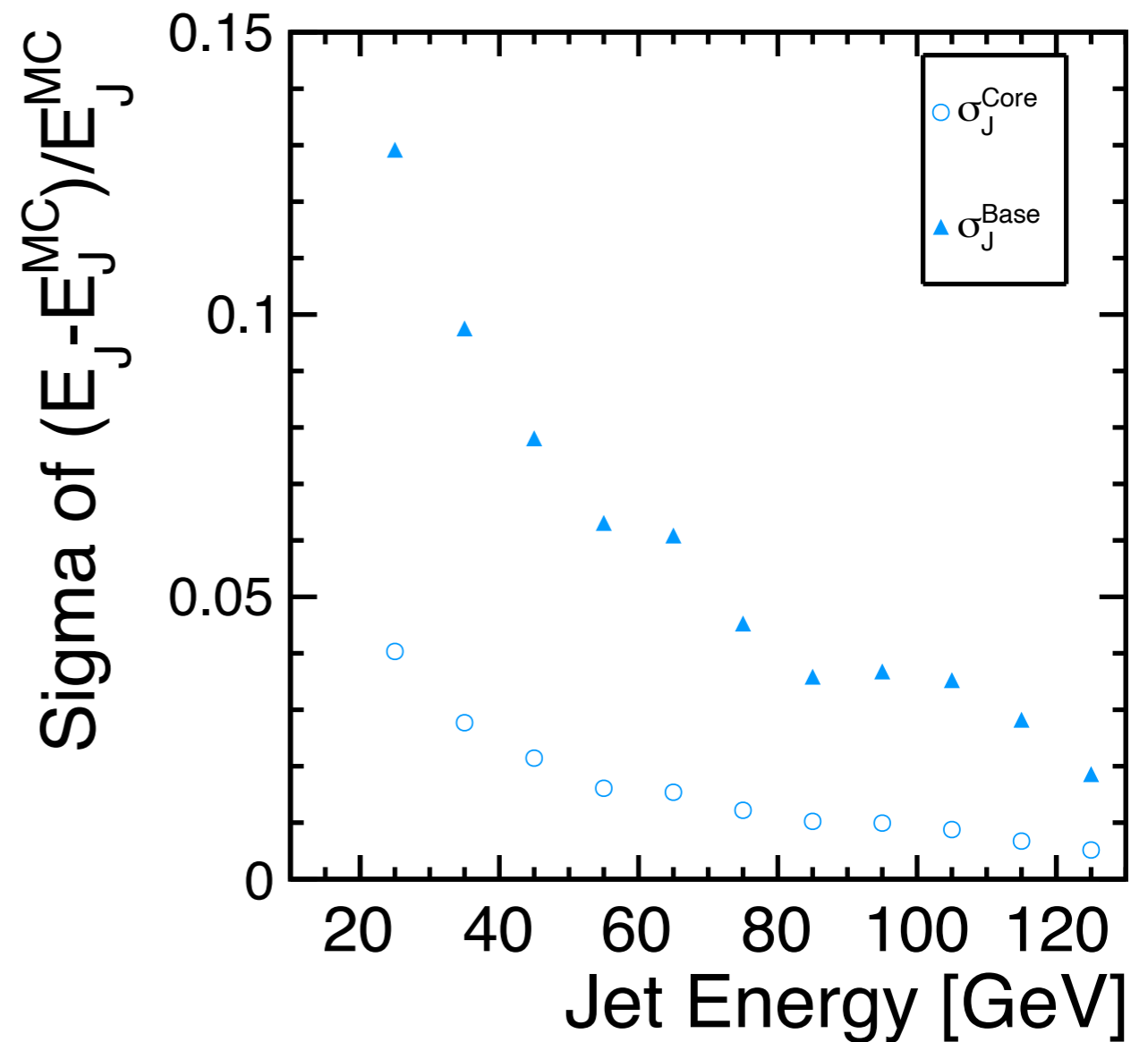
-> Check the **theta and energy** dependence.

M3 Energy dependence

Mean of the Fitting Gaussian



Sigma of the Fitting Gaussian

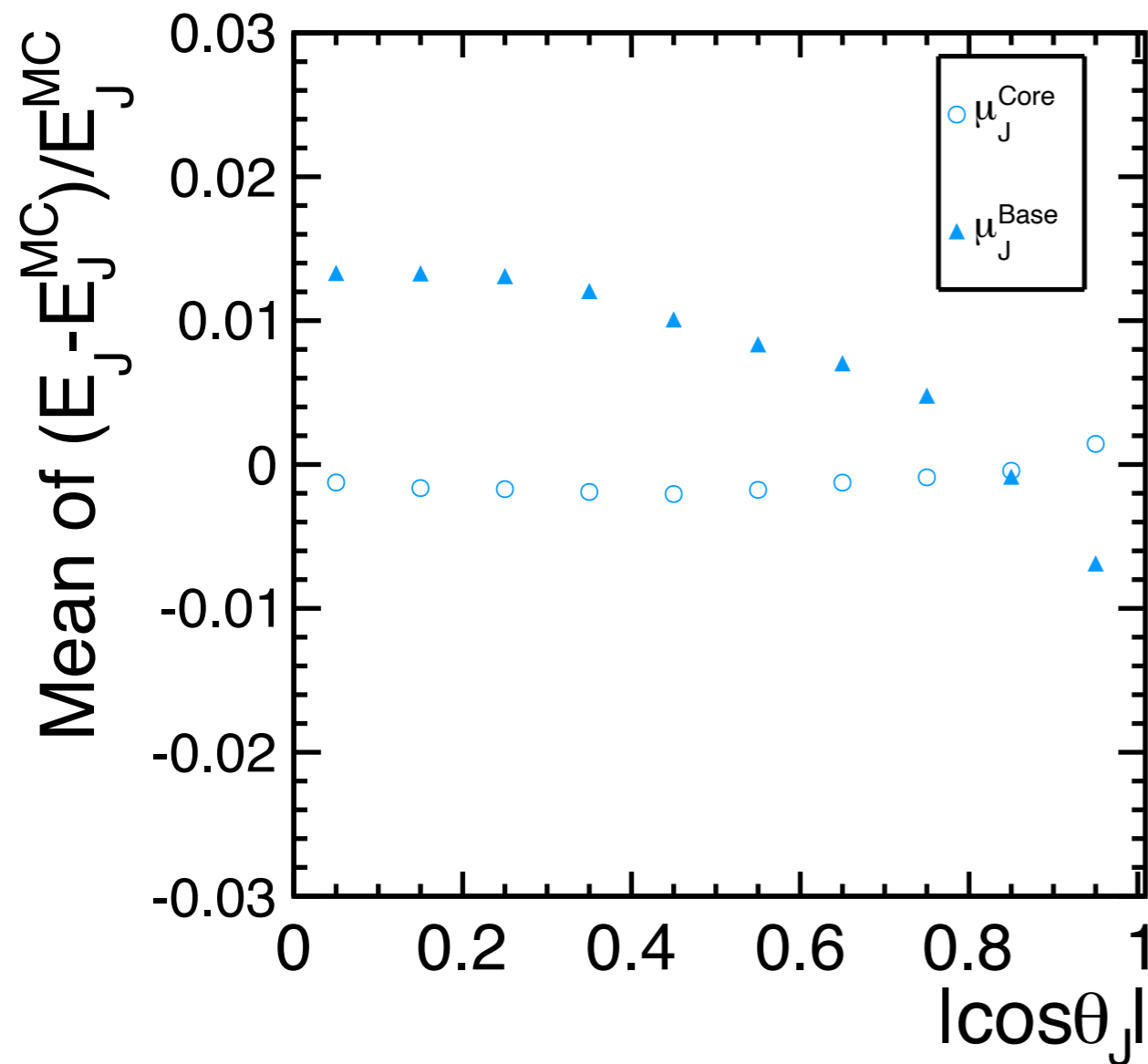


Mean value of **the core gaussian** is order of 10^{-4} independent on the jet energy.

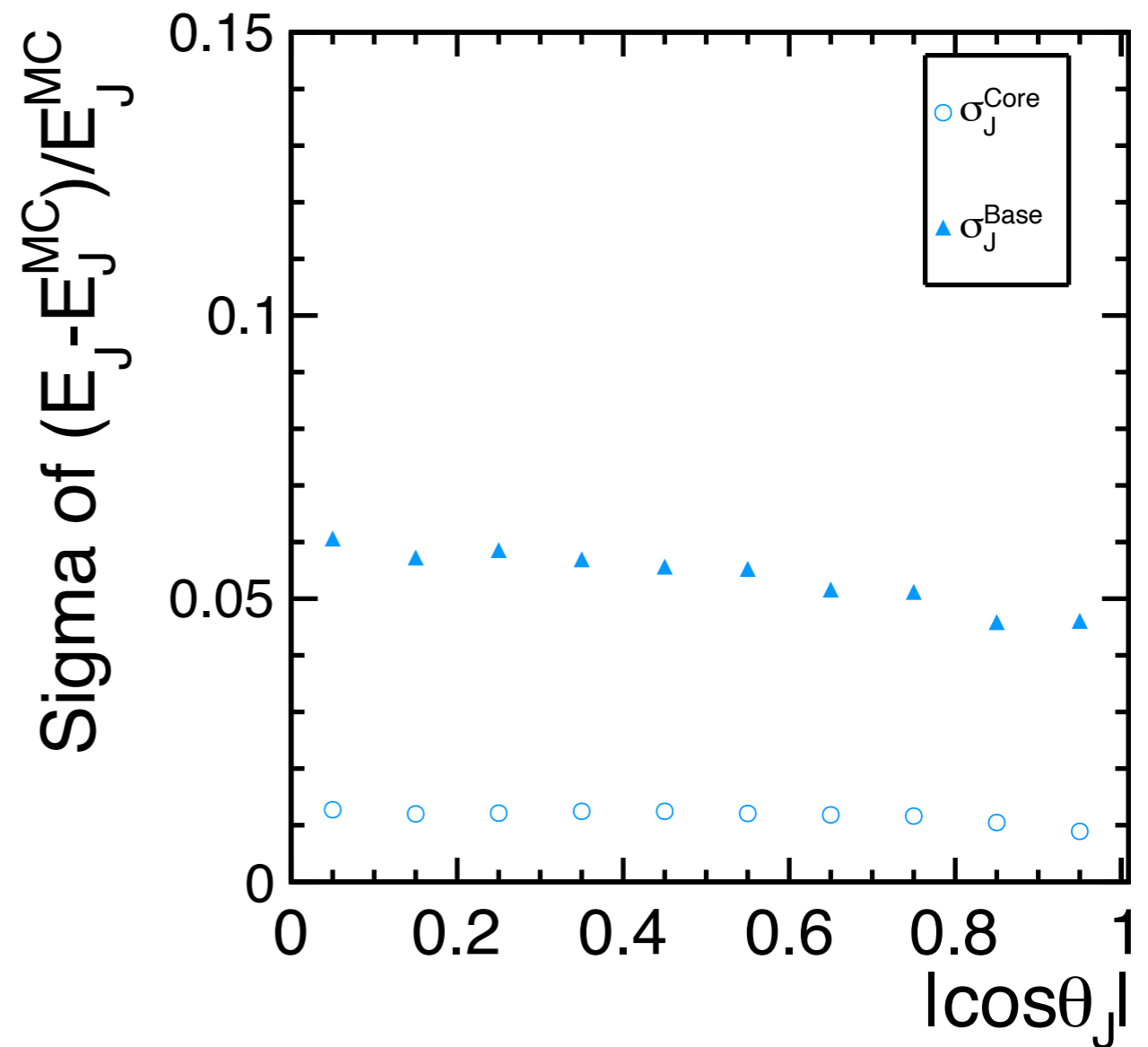
Sigma value is smaller in the higher energy.

M3 Polar angle dependence

Mean of the Fitting Gaussian



Sigma of the Fitting Gaussian



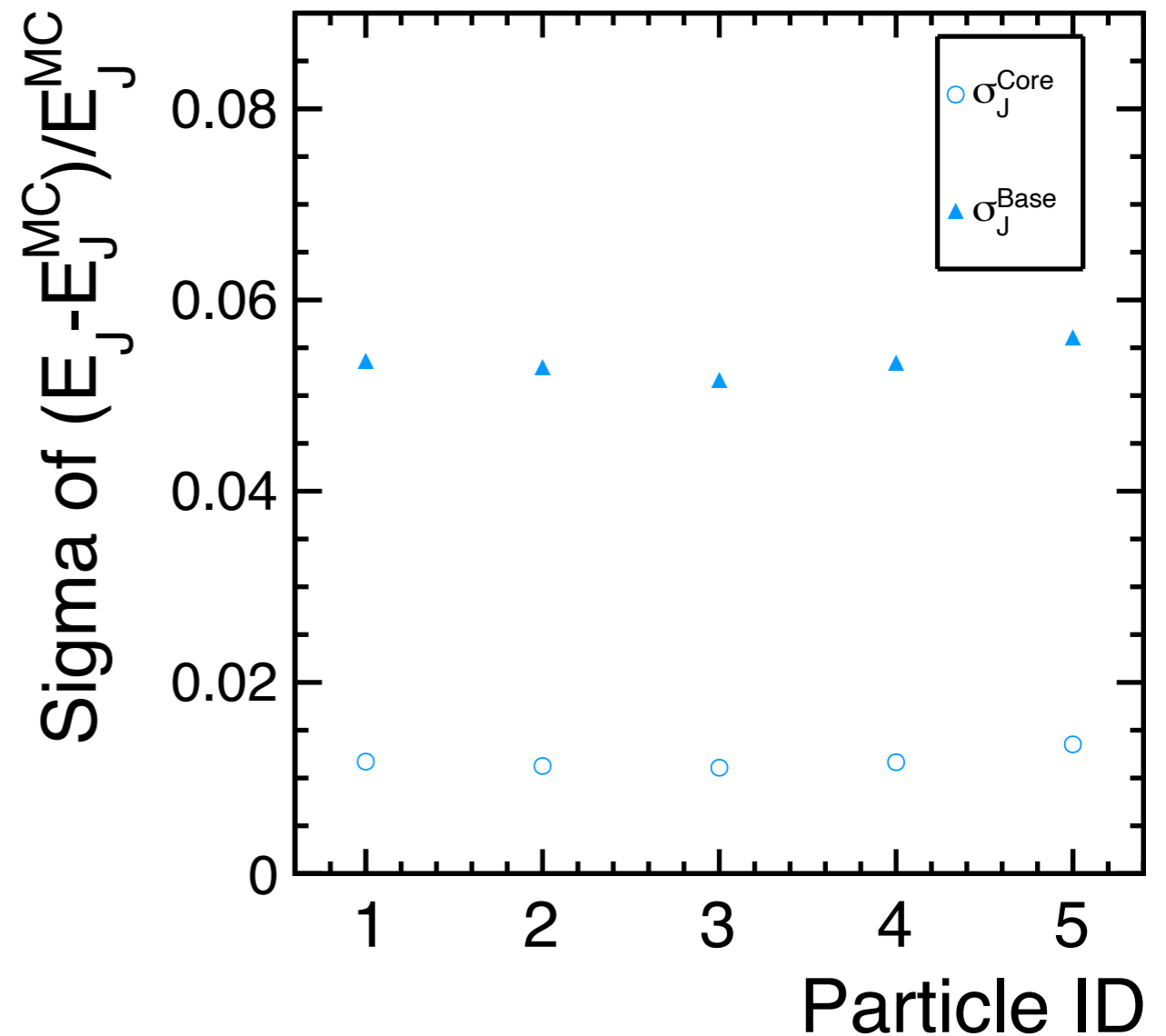
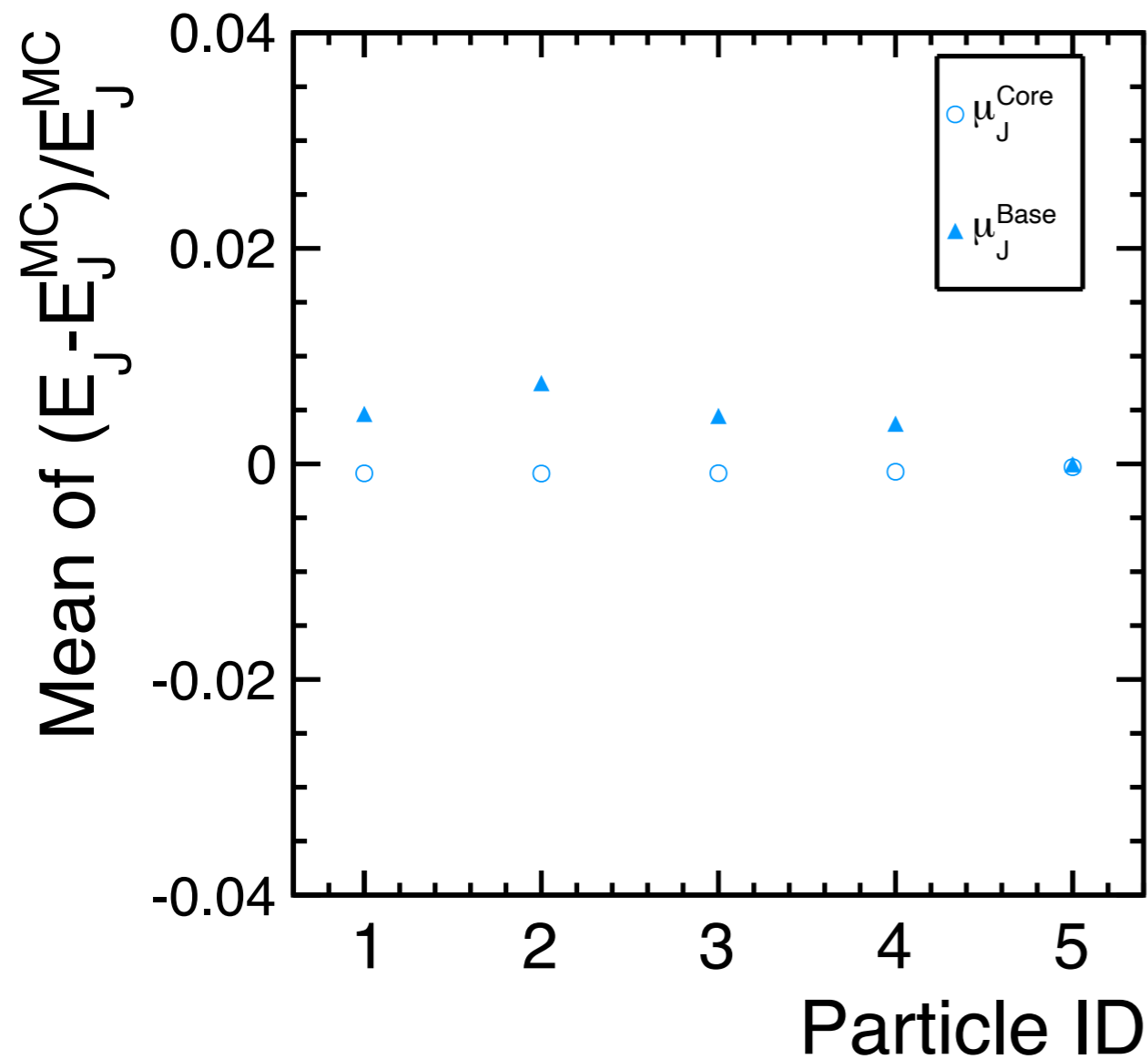
Forward jet makes slight positive bias on the core gaussian and barrel region jet makes slight negative bias on **the core gaussian**.

M3 Flavor dependence

Showing dependence on flavor of the seed of the jet

Mean of the Fitting Gaussian

Sigma of the Fitting Gaussian

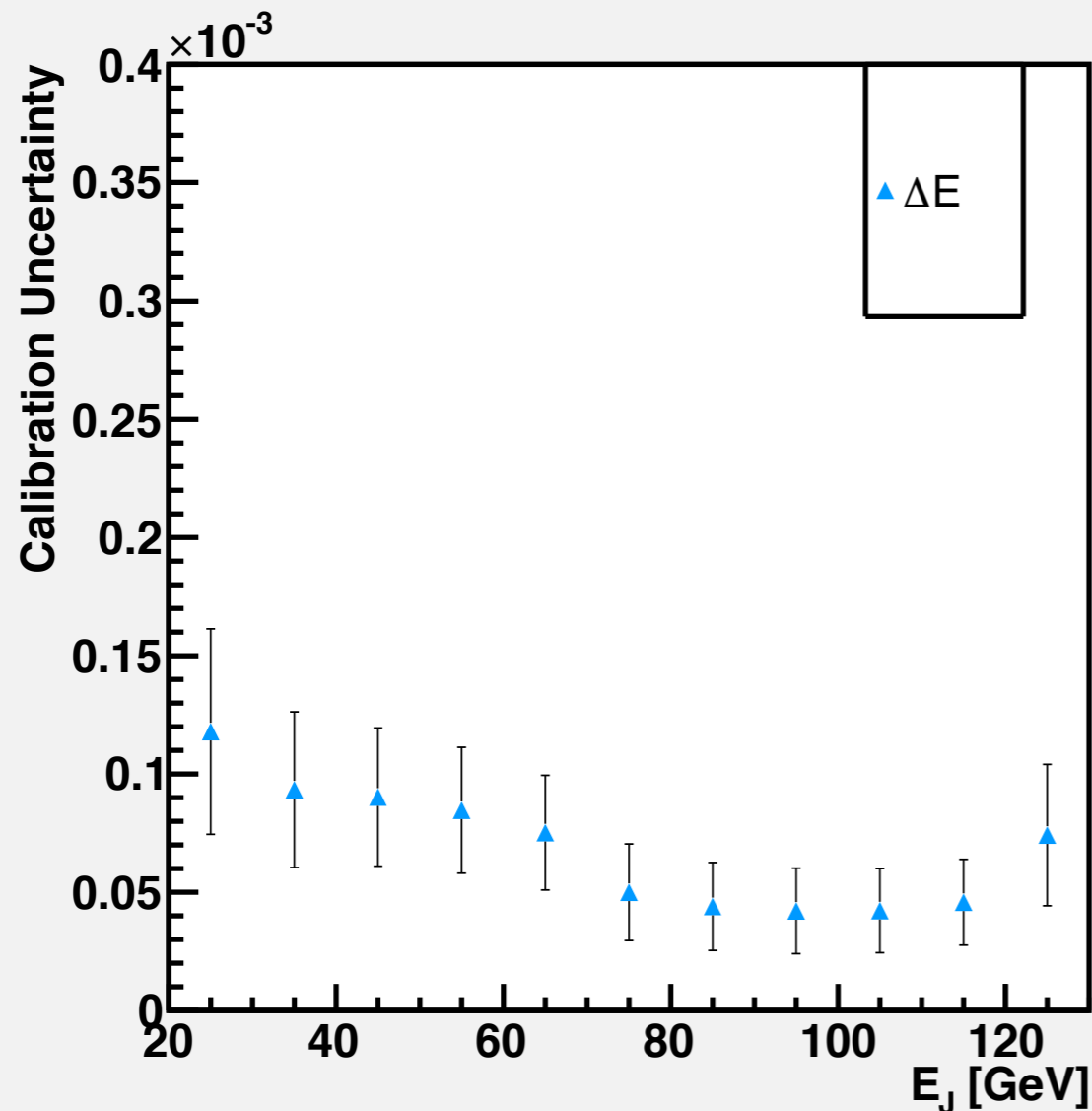


Mean value of **the core gaussian** is order of 10^{-4} . Negative bias of the core gaussian is smaller in the b-jets.

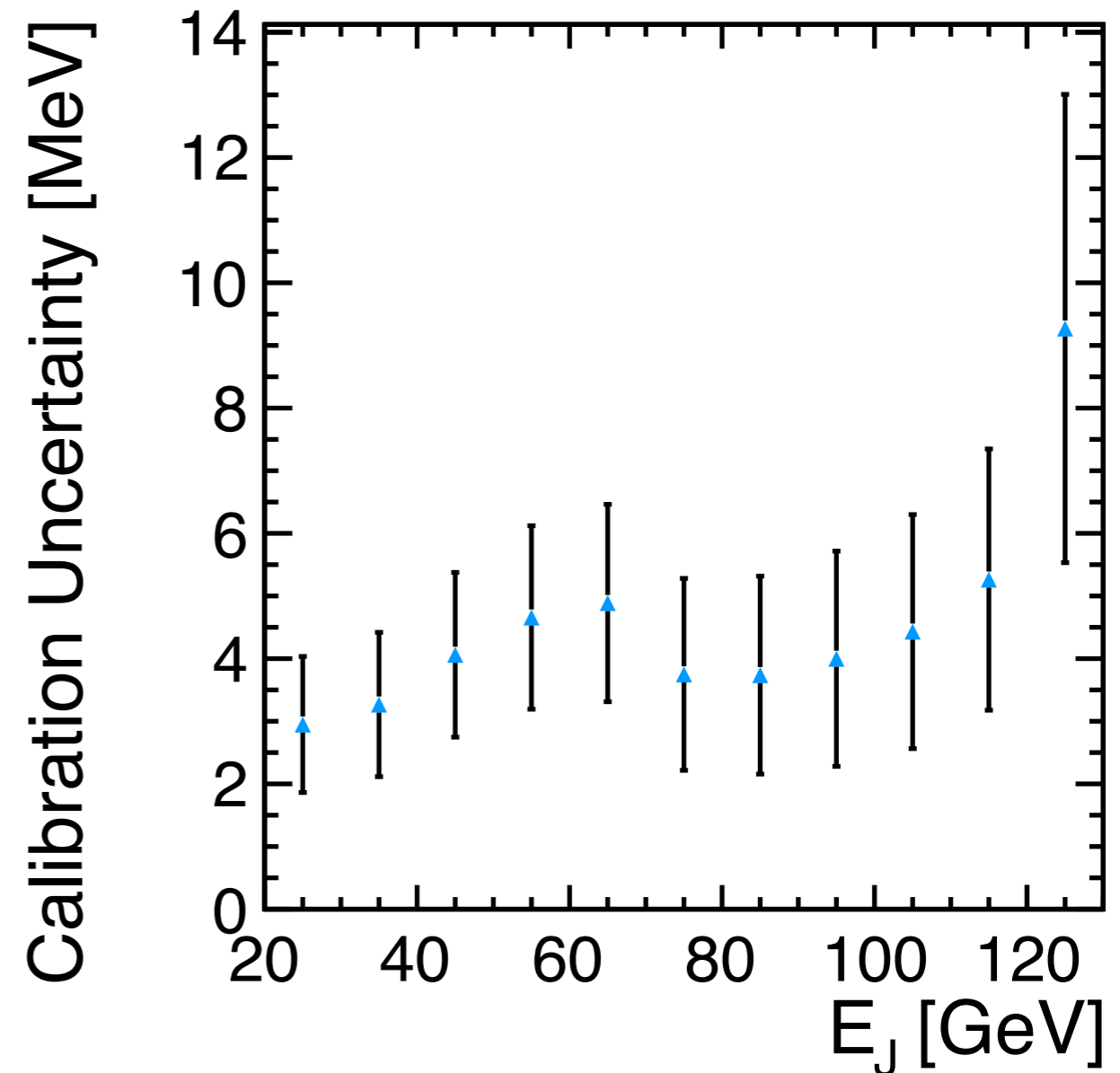
Calibration Uncertainty

Calibration uncertainty := $\sqrt{(\Delta\mu_{Detector})^2 + (\Delta\mu_{Reconstructed})^2}$
Error of the uncertainty := $\frac{\sqrt{(\Delta\mu_{Detector})^2 + (\Delta\mu_{Reconstructed})^2}}{\sqrt{2 \times \#events(CoreGaussian)}}$

Relative uncertainty



Absolute uncertainty



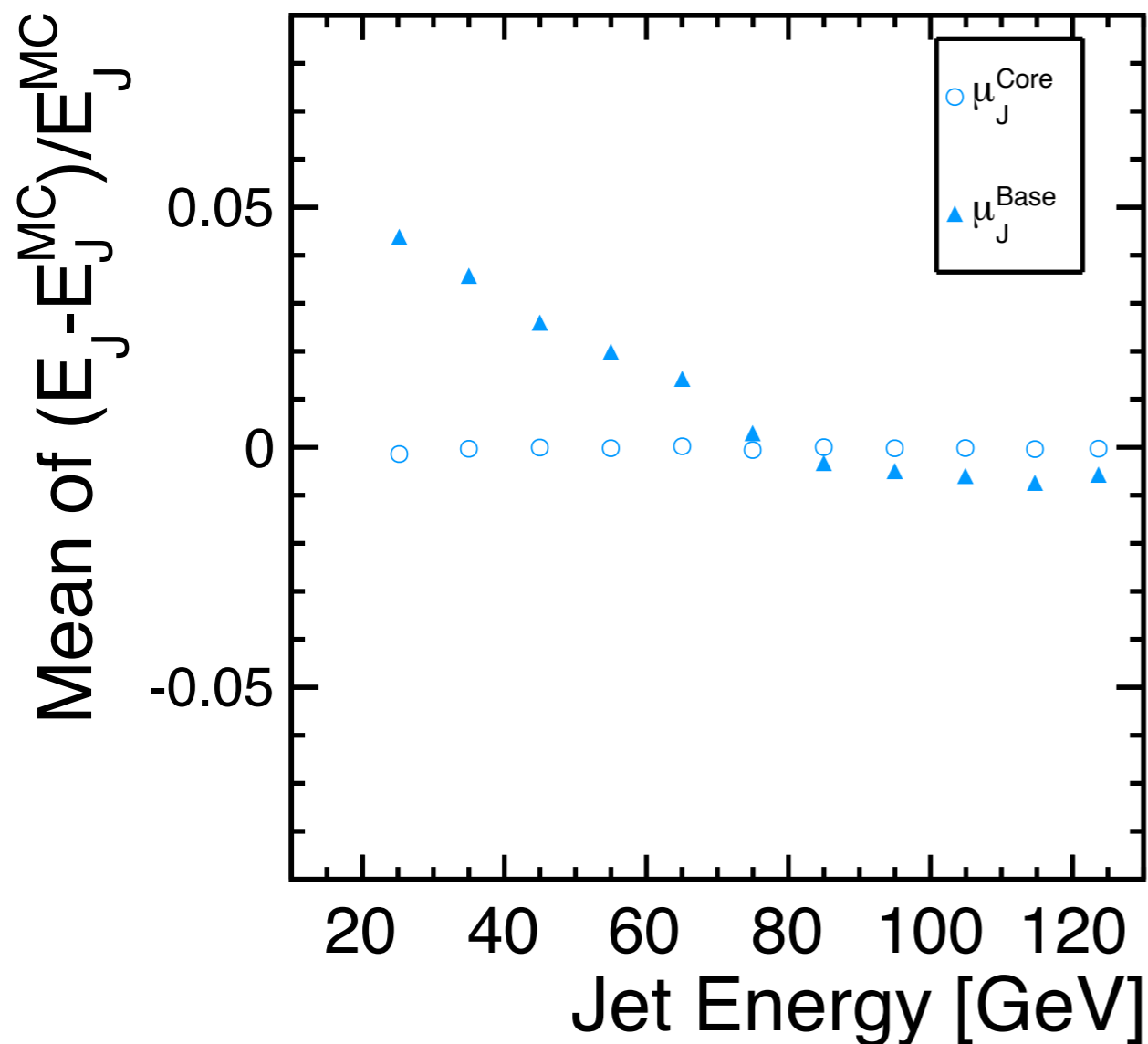
We can calibrate the jet energy scale with about 10^{-4} accuracy, which corresponds to several MeV.

Energy dependence (M3 reconstruction)¹⁸

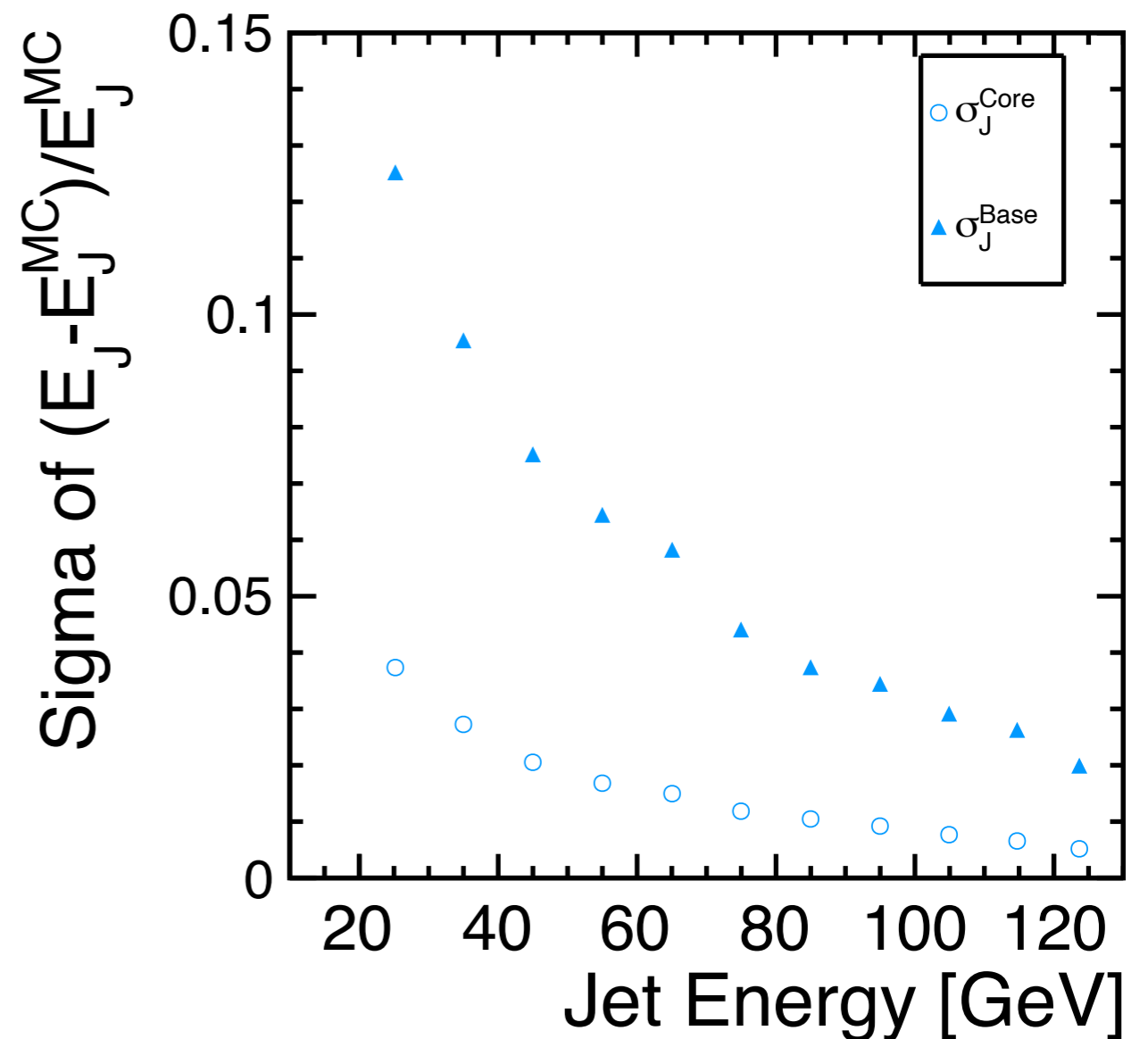
We perform the calibration based on PFO energy.

Now horizontal axis is PFO and the plotting point is on the mean value of each bin.

Mean of the Fitting Gaussian



Sigma of the Fitting Gaussian

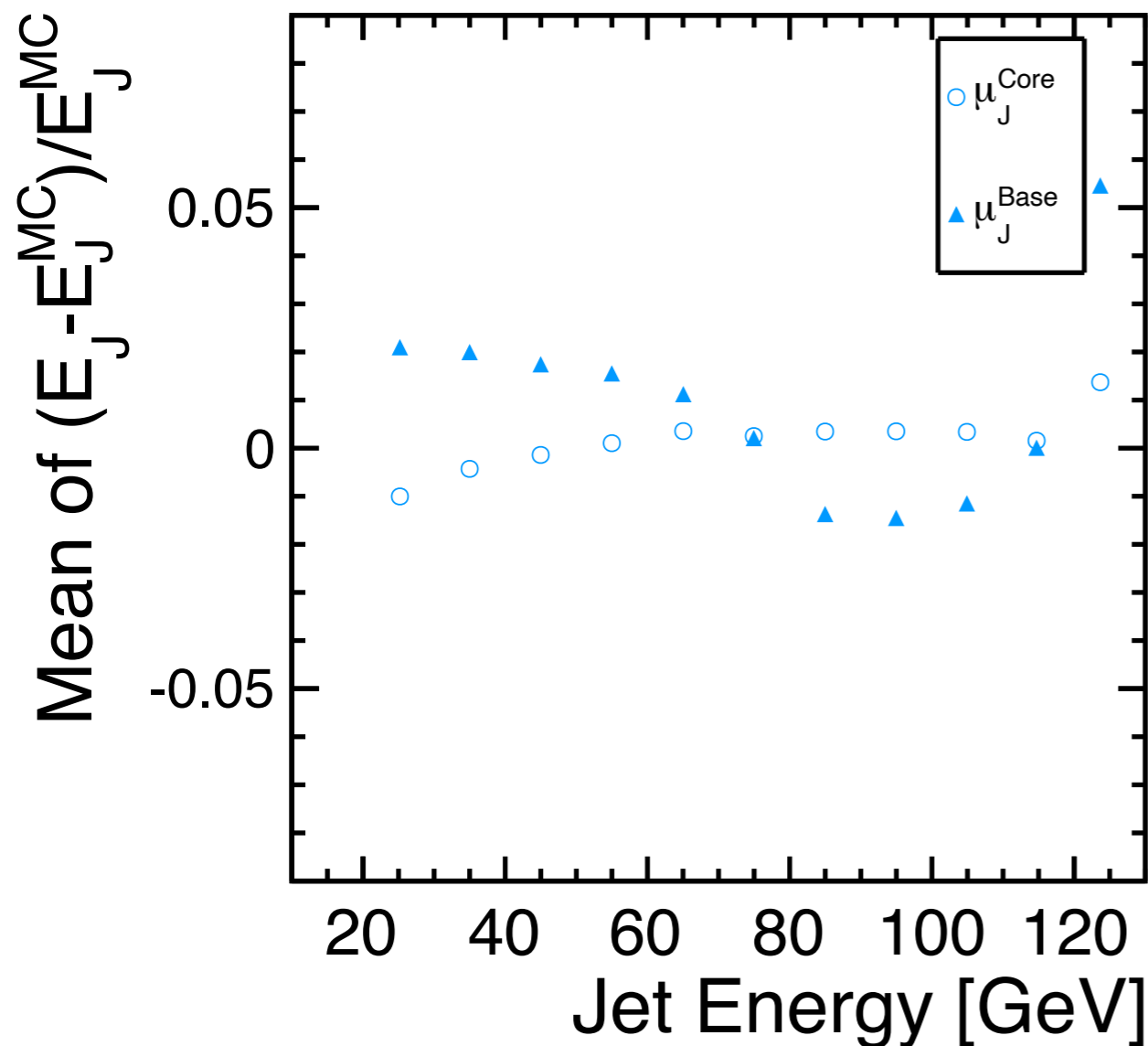


Energy dependence (PFO reconstruction)¹⁹

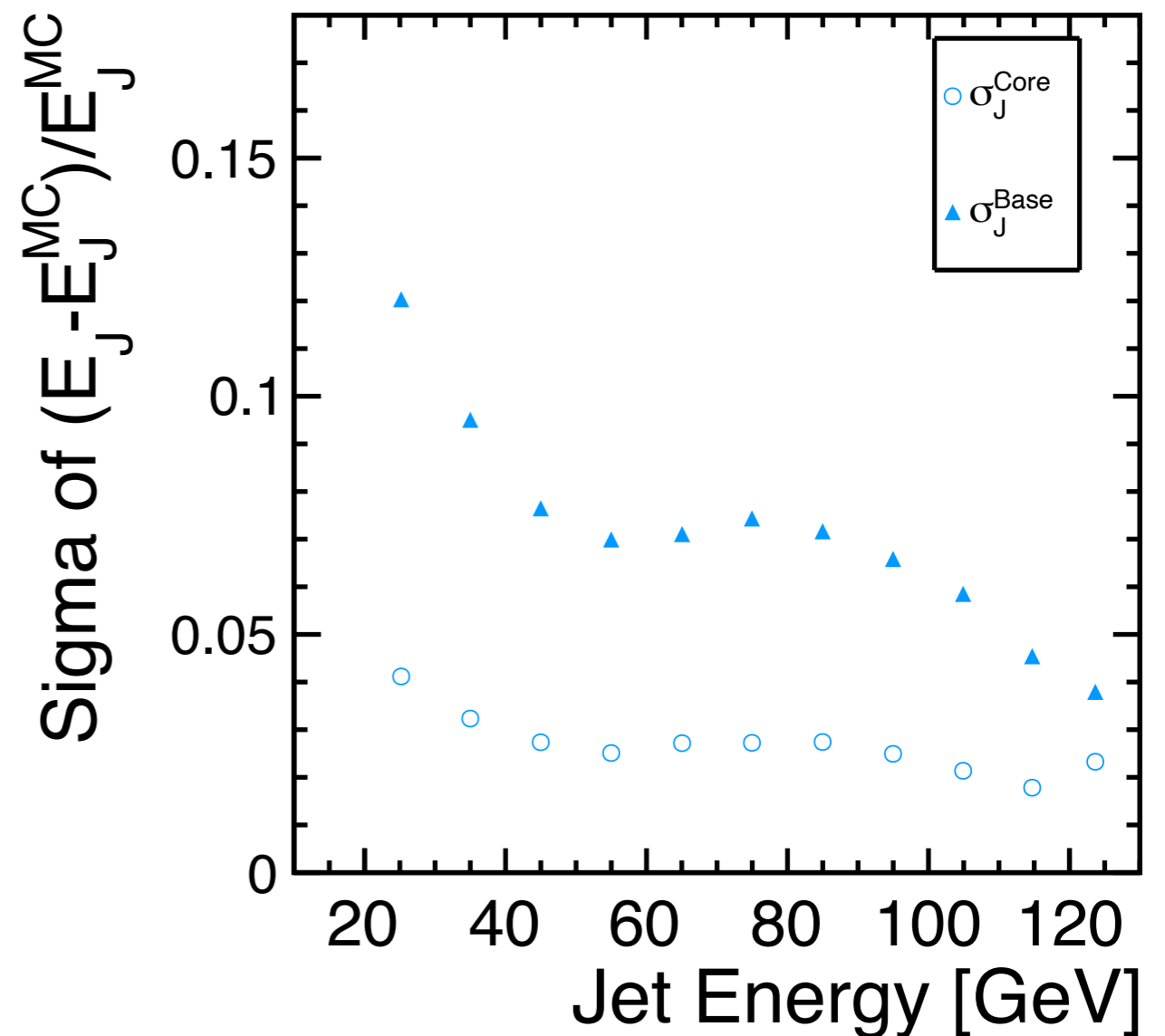
We perform the calibration based on PFO energy.

Now horizontal axis is PFO and the plotting point is on the mean value of each bin.

Mean of the Fitting Gaussian



Sigma of the Fitting Gaussian



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1. Introduction

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3. E_{jet} reconstruction

4. Conclusion

Conclusion & Future Work

- Full simulation is performed in order to reconstruct the jet energy using the $e^+e^- \rightarrow \gamma Z, Z \rightarrow 2 \text{ Jets}$ process.
- Jet energy can be reconstructed using the $e^+e^- \rightarrow \gamma Z, Z \rightarrow 2 \text{ Jets}$ 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 several MeV.
- Try to show the 2D (energy and sigma) dependence
- Determine the calibration constant

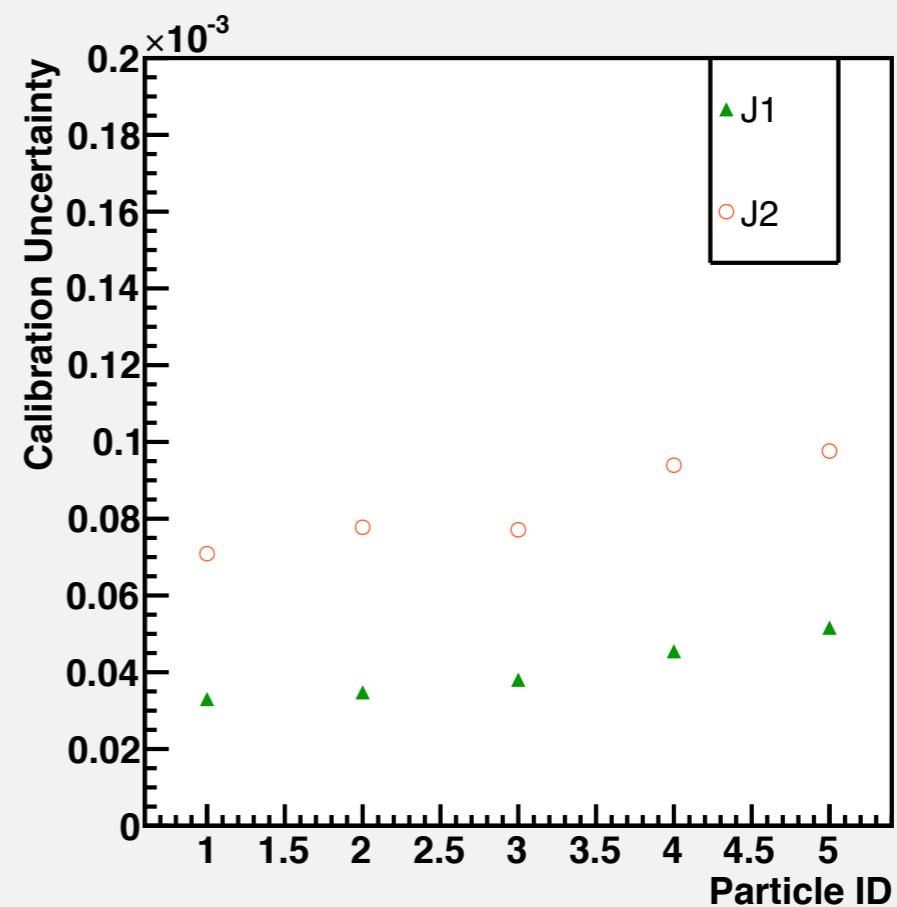
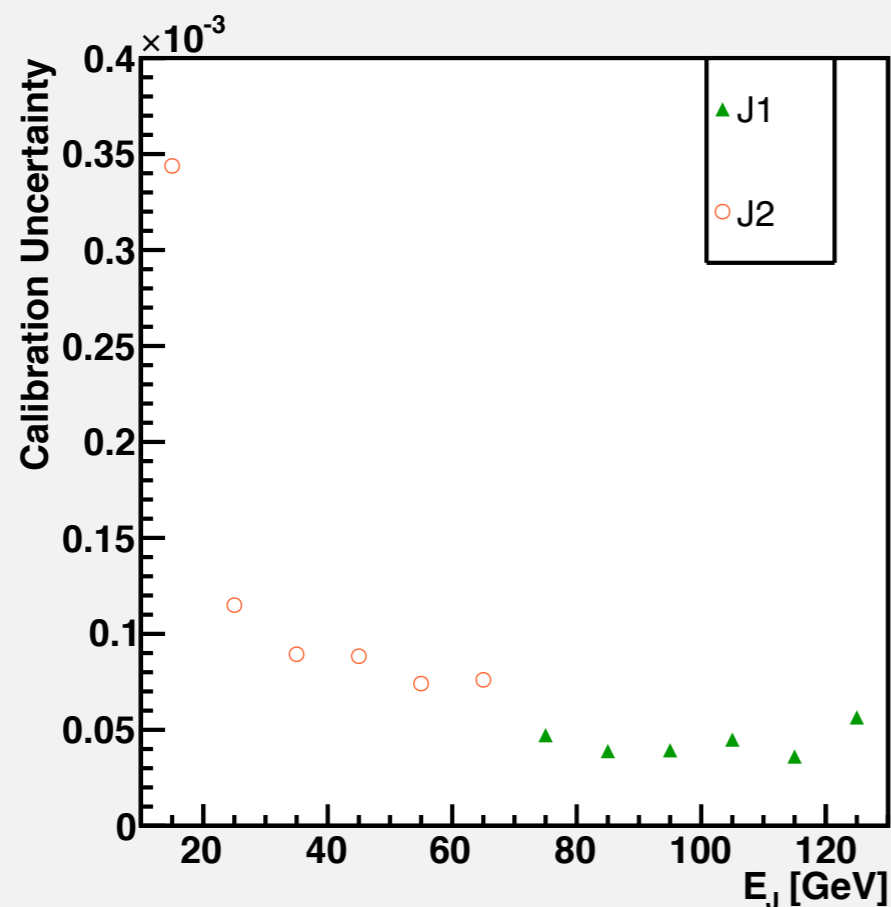
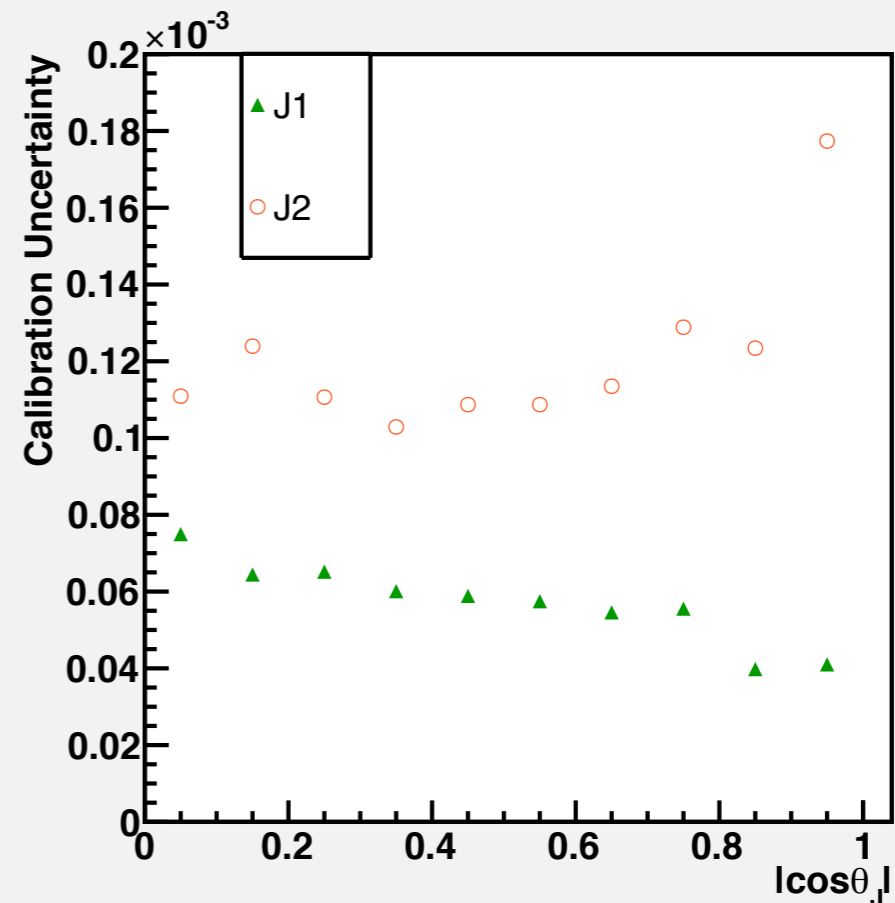
Backup

Calib. Uncertainty

Calibration uncertainty :=

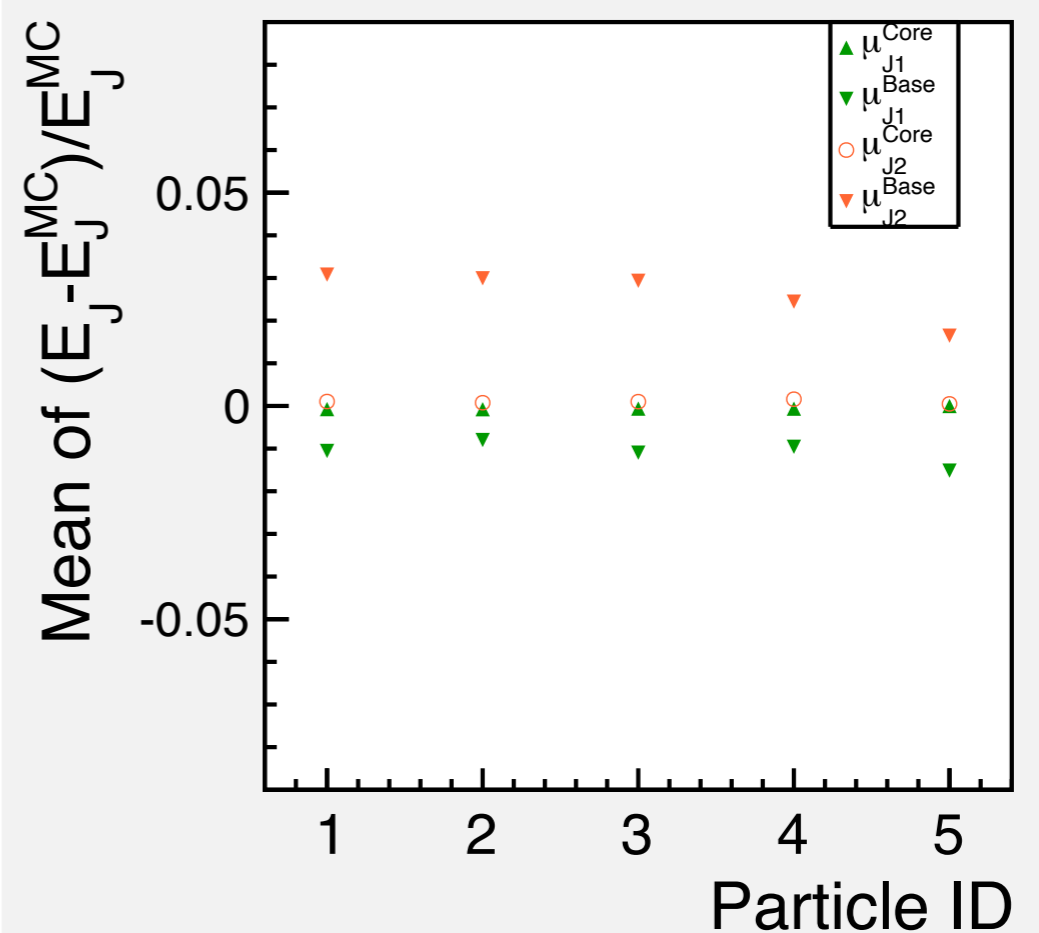
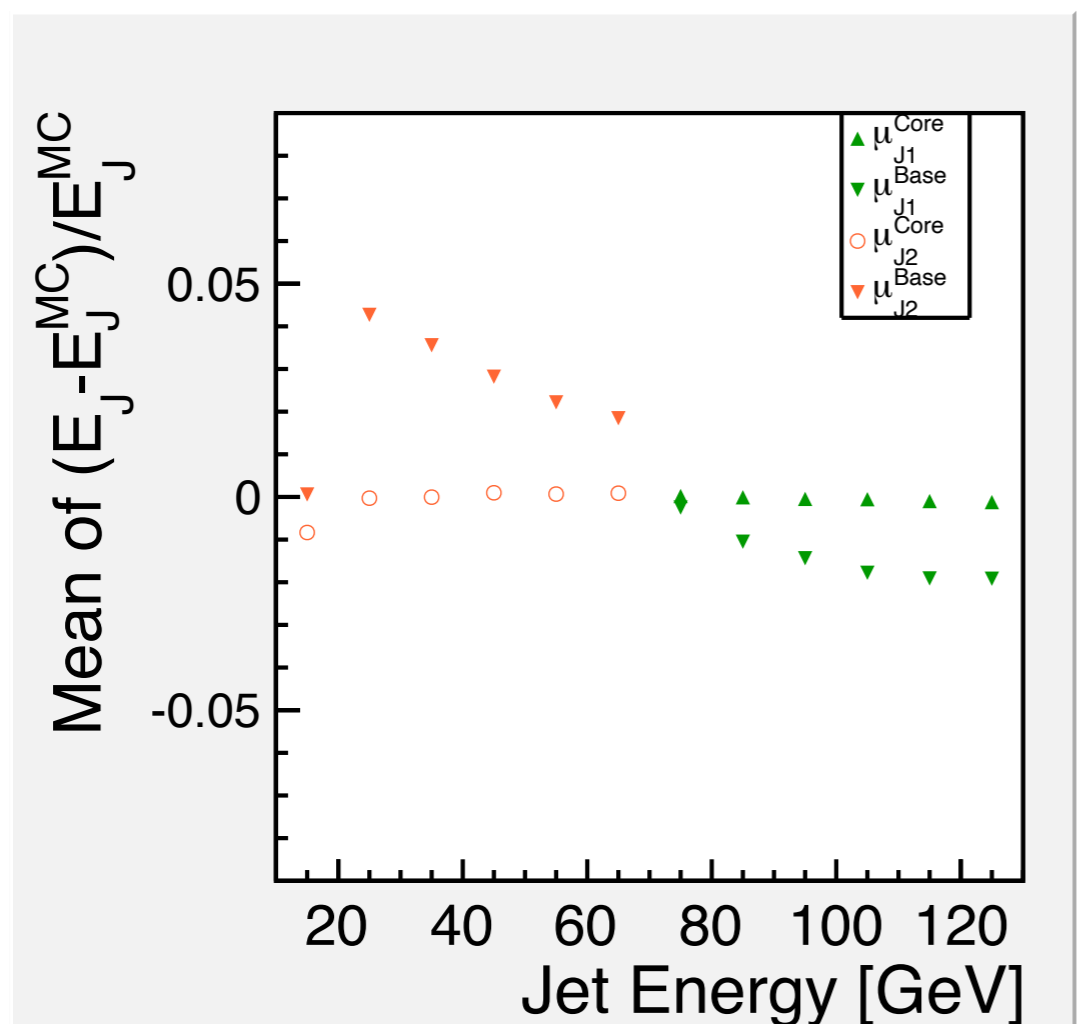
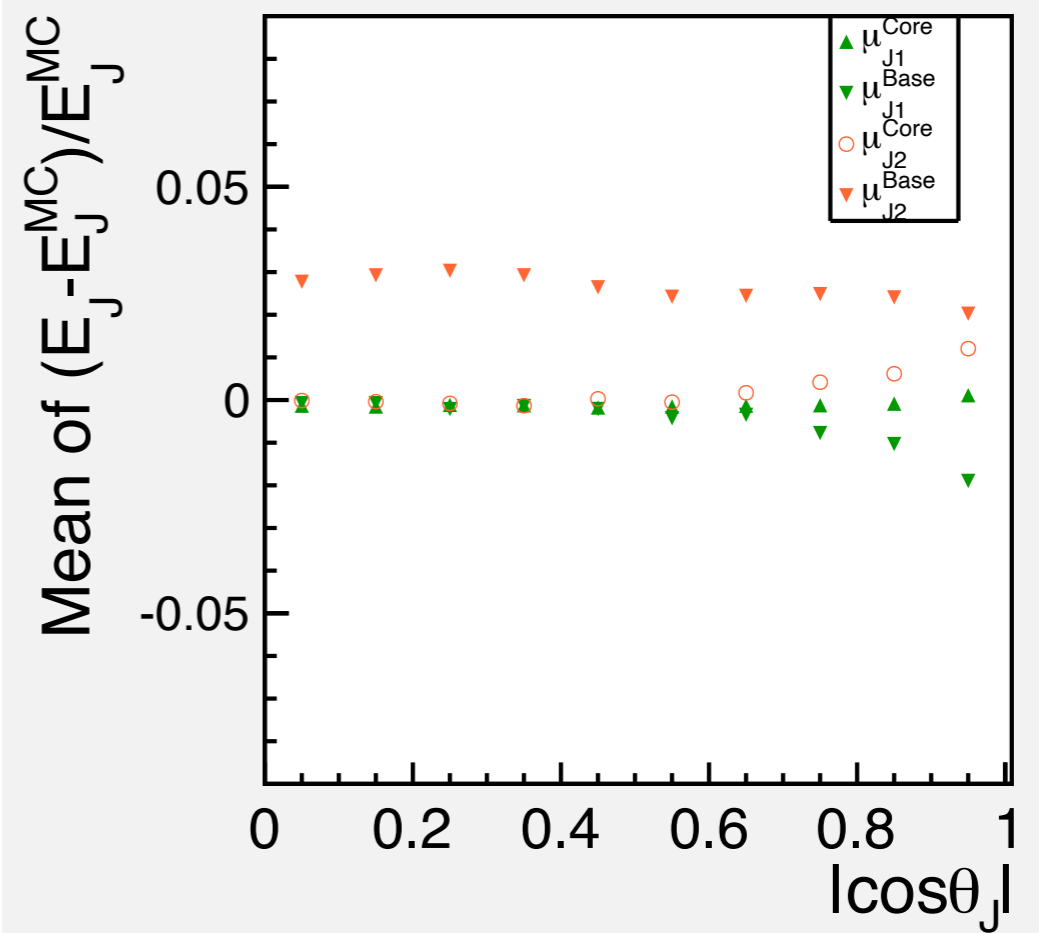
$$\sqrt{(\Delta\mu_{PFO})^2 + (\Delta\mu_{M3})^2}$$

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

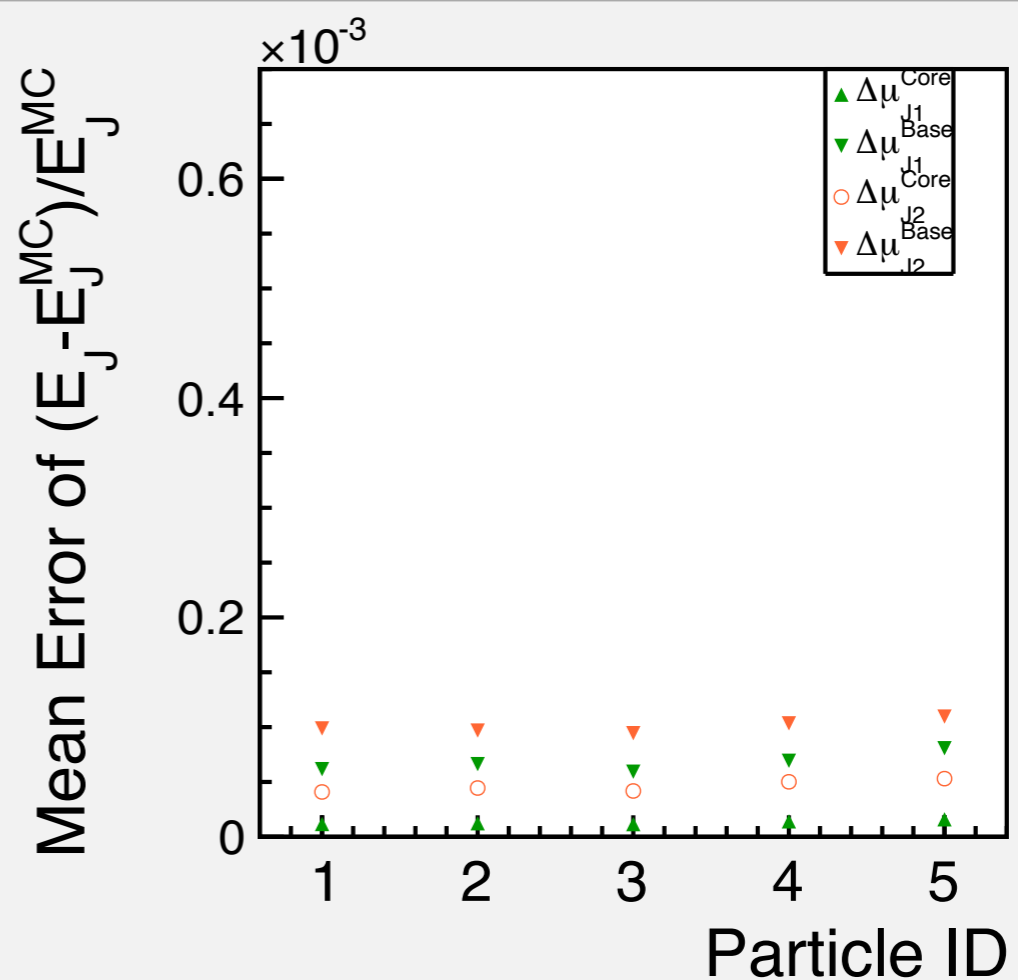
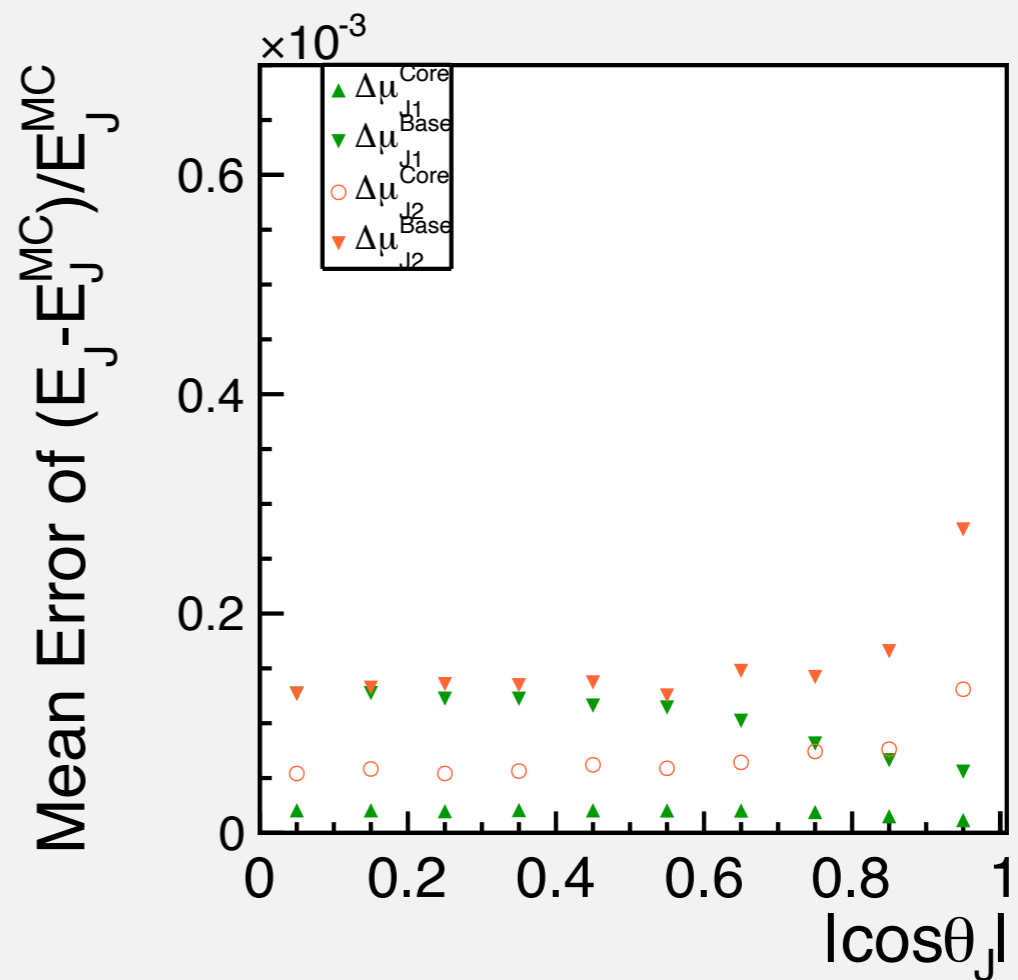
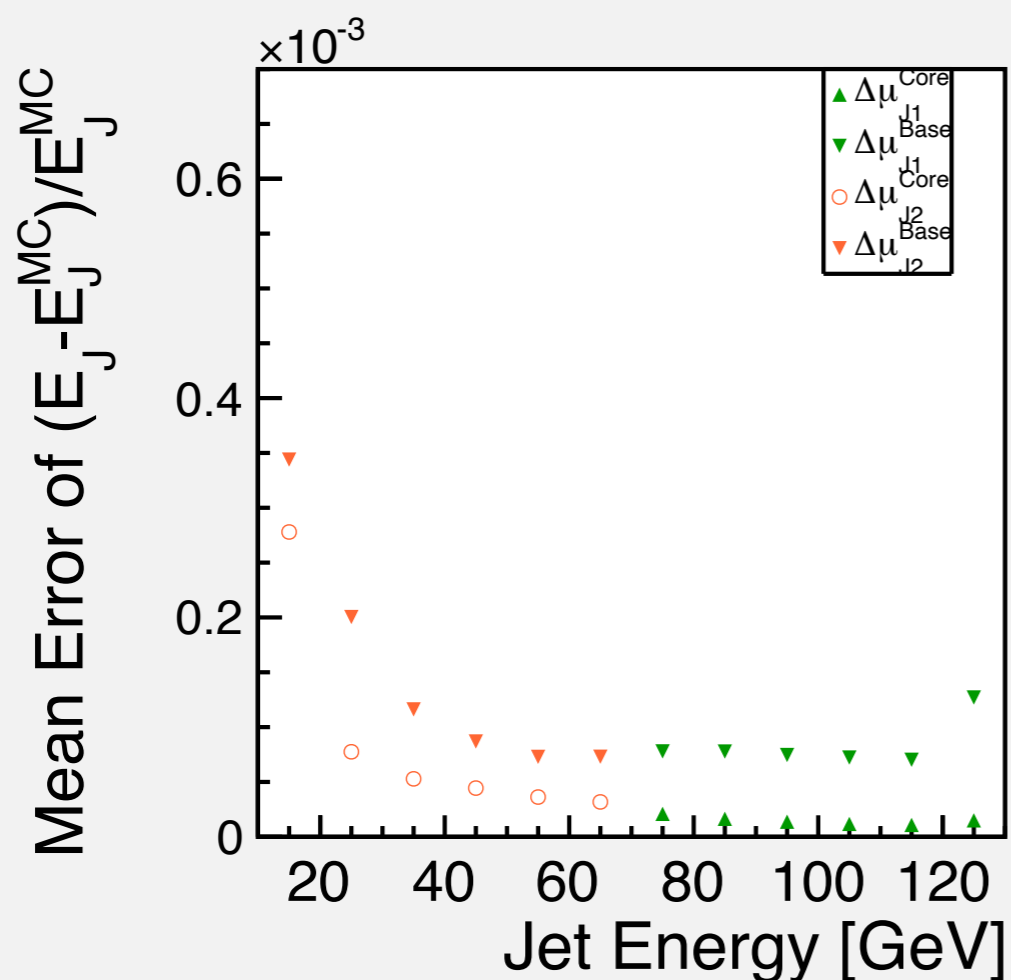


Mean Value

Particle ID := flavor of the seed of the jet

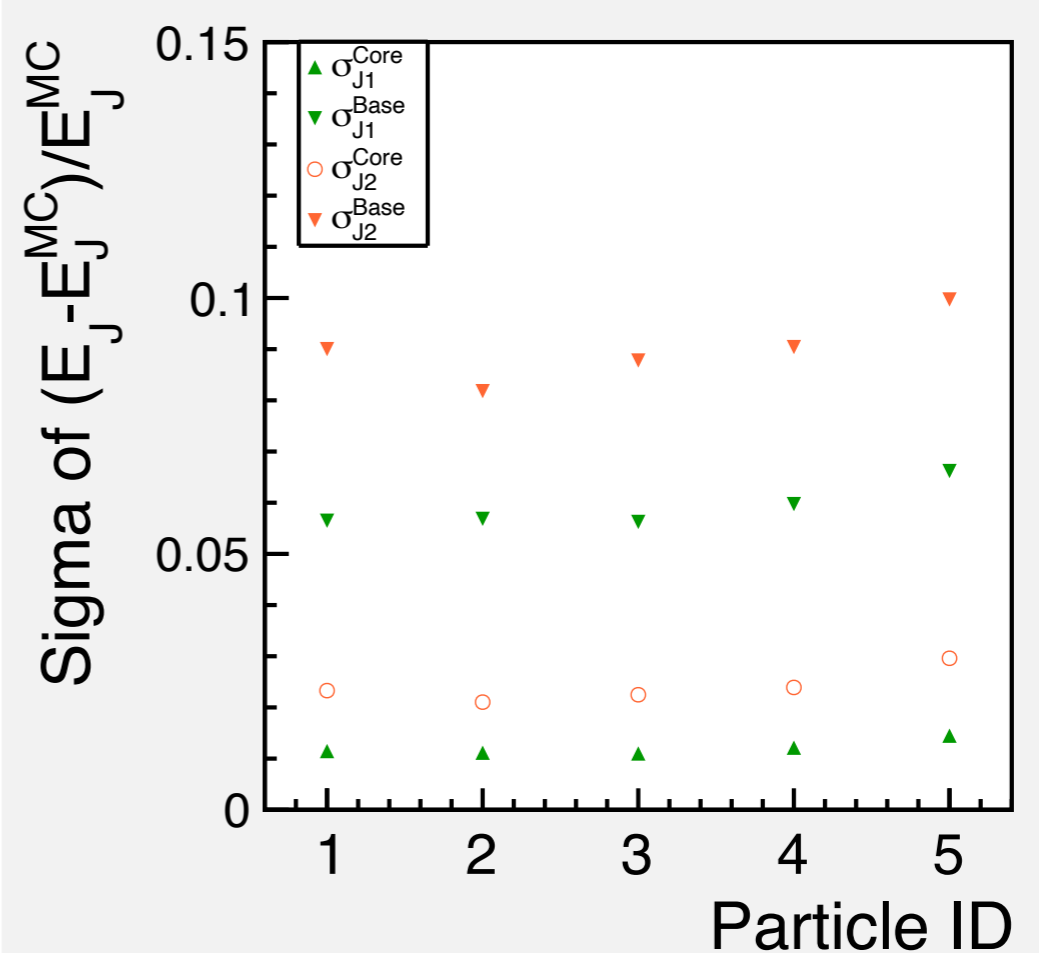
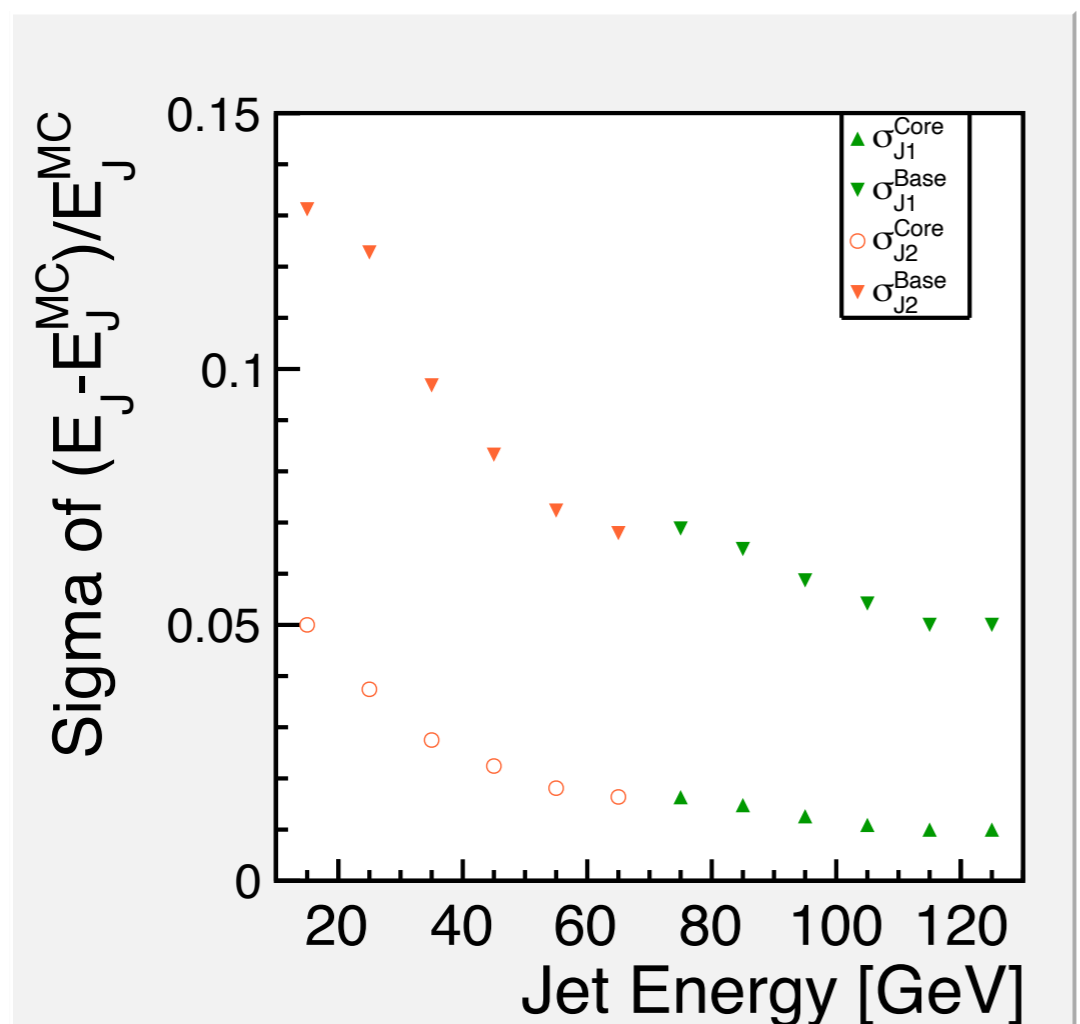
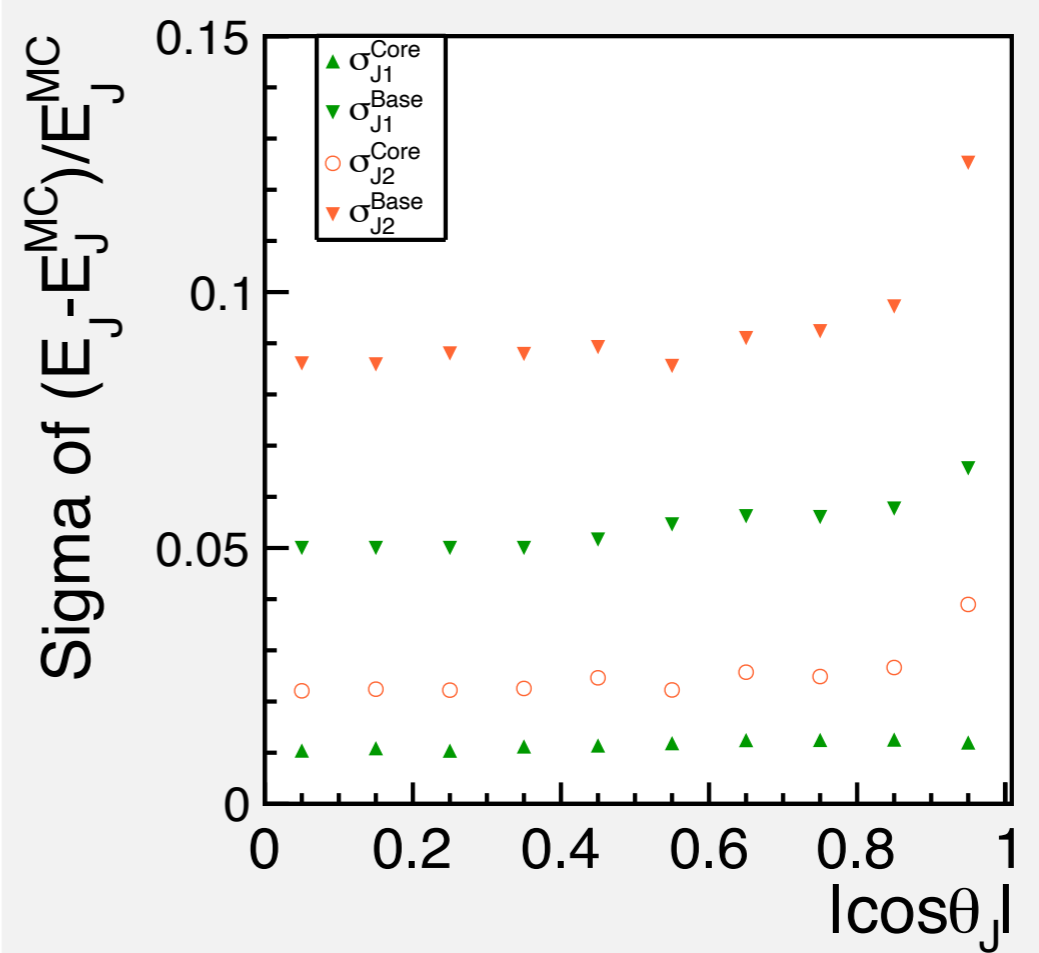


Mean Error



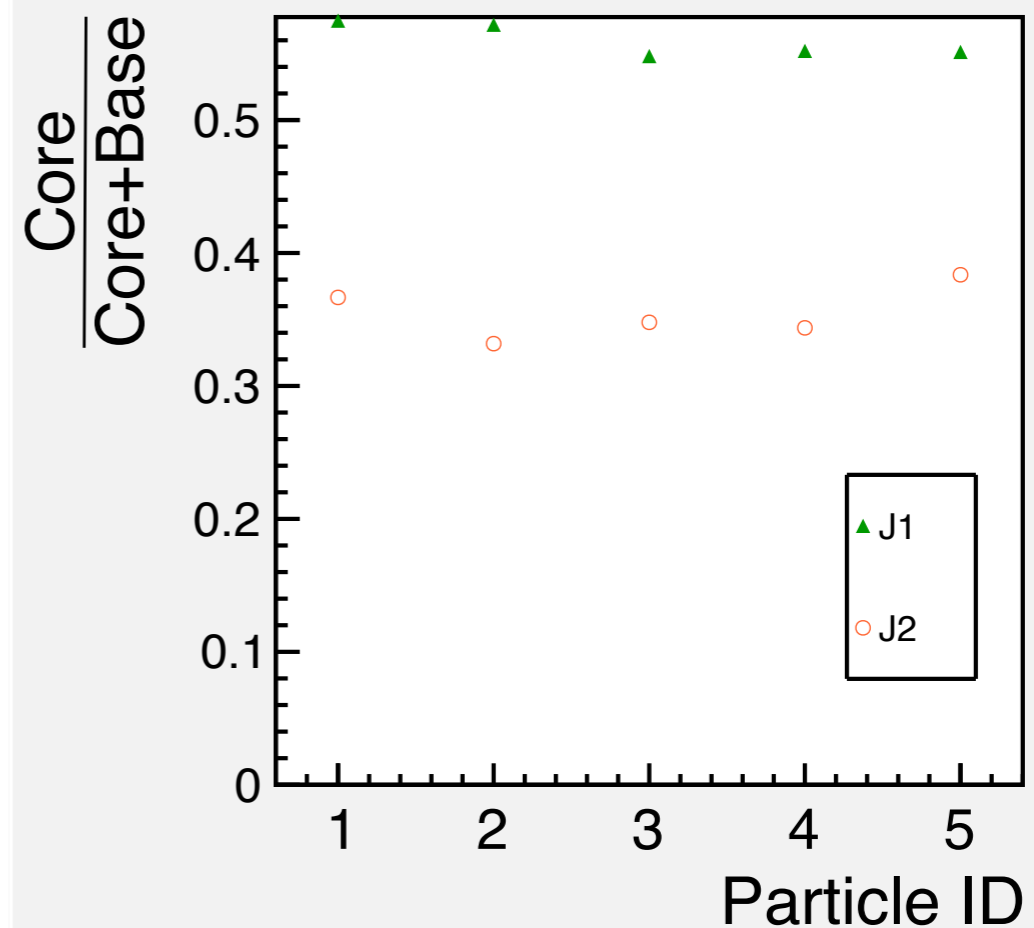
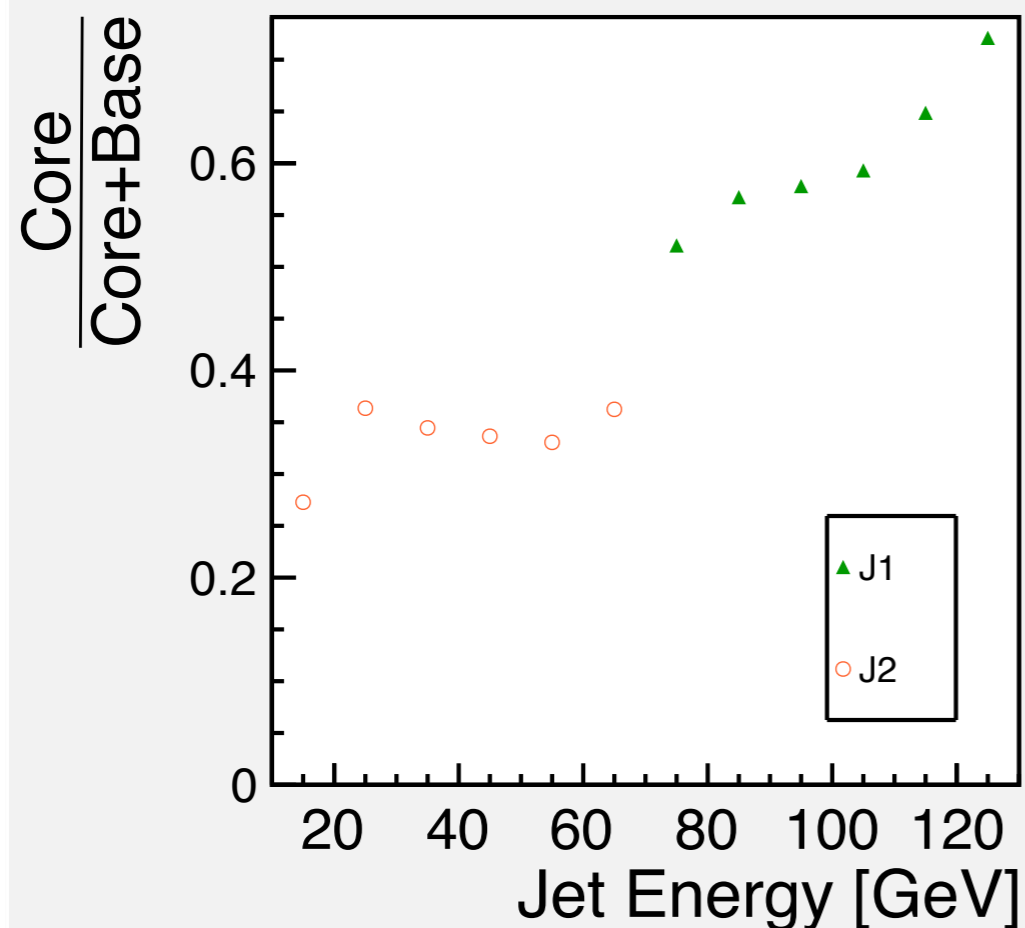
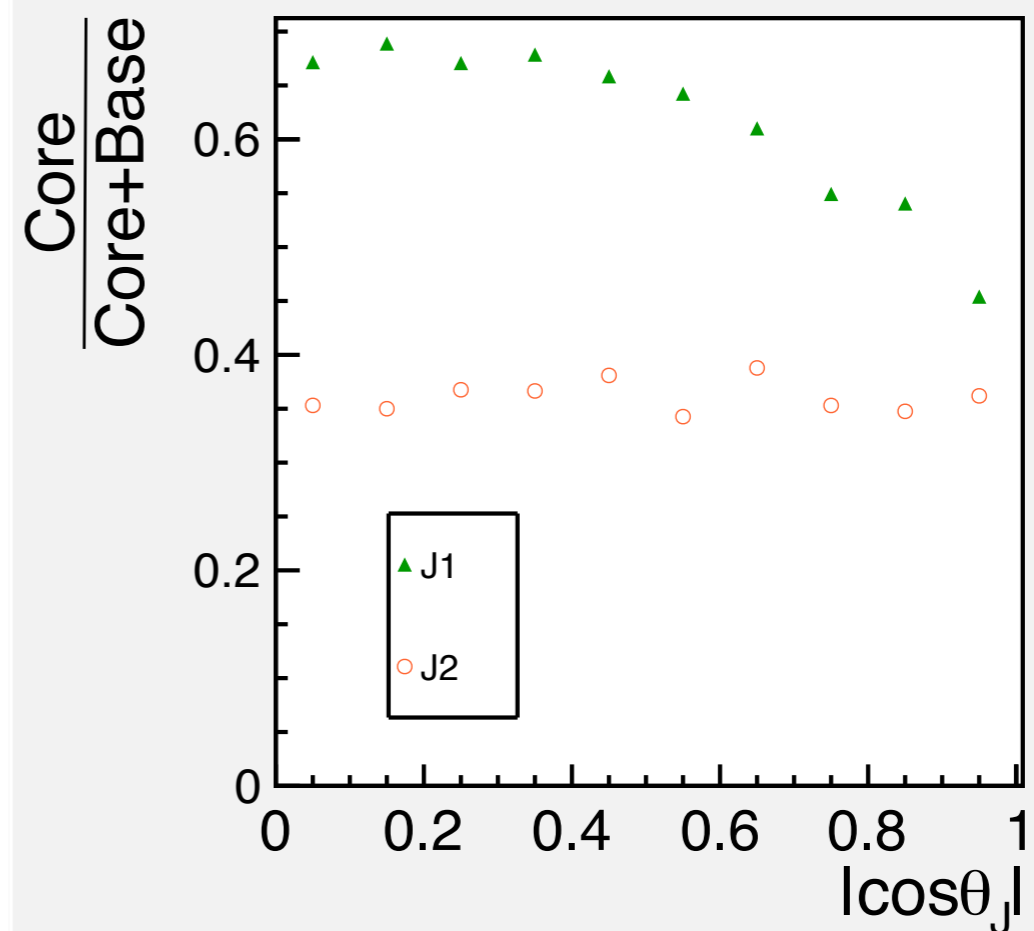
Sigma Value

Particle ID := flavor of the seed of the jet



Fraction

**Fraction := Size of the fitting
Gaussian
Core/(Core+Base)**

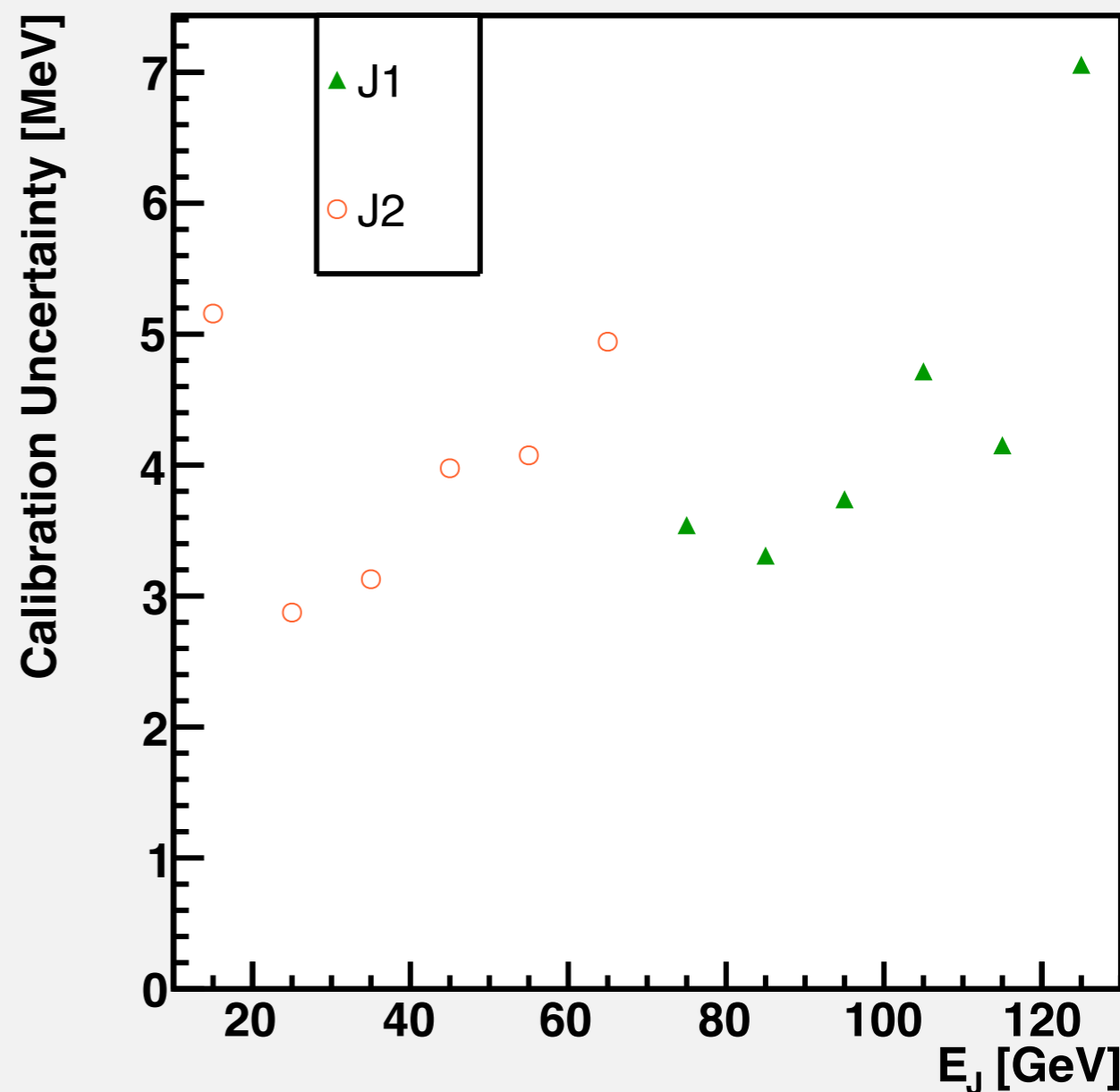


Calib. Uncertainty

Calibration uncertainty :=

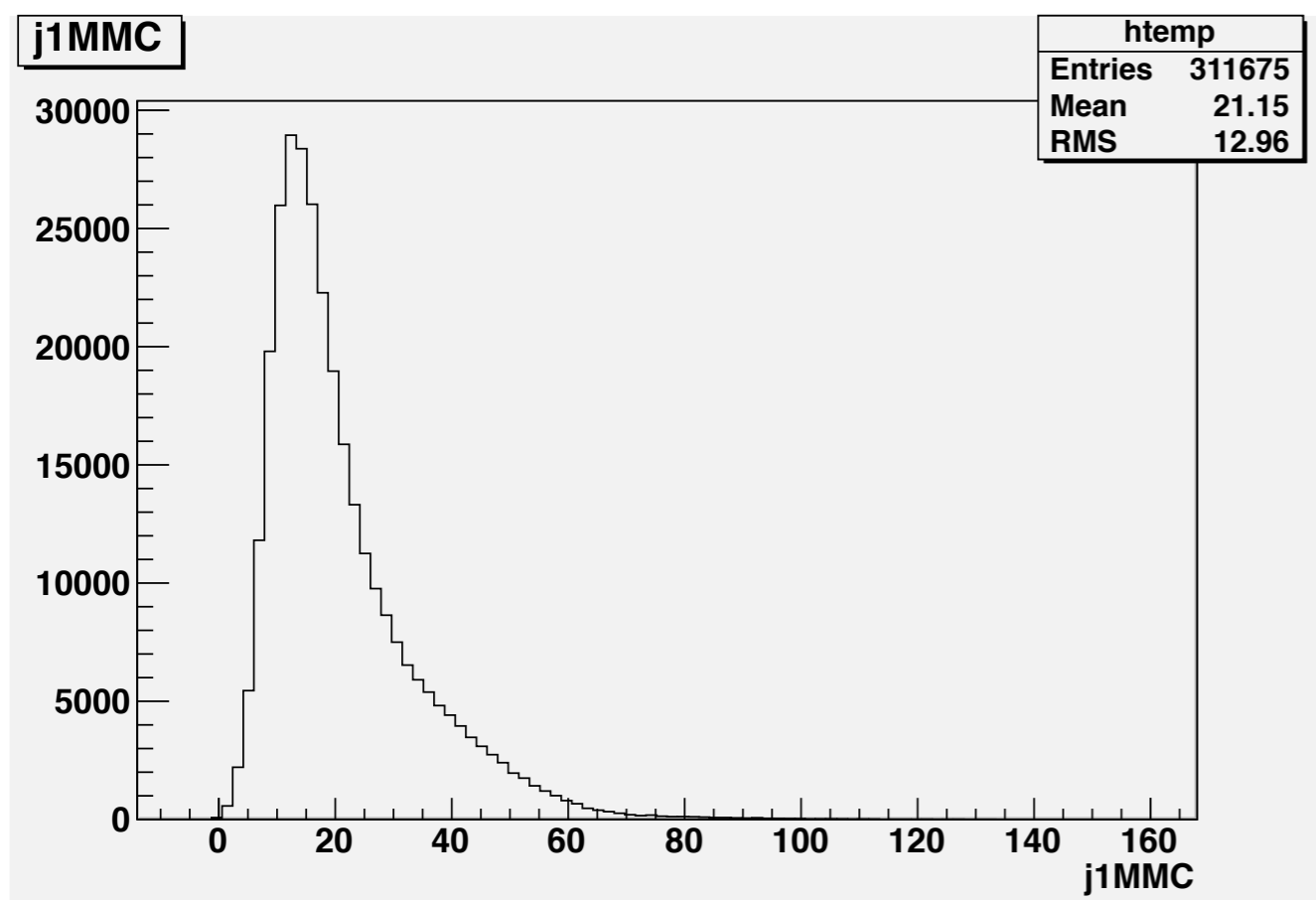
$$\sqrt{(\Delta\mu_{PFO})^2 + (\Delta\mu_{M3})^2}$$

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



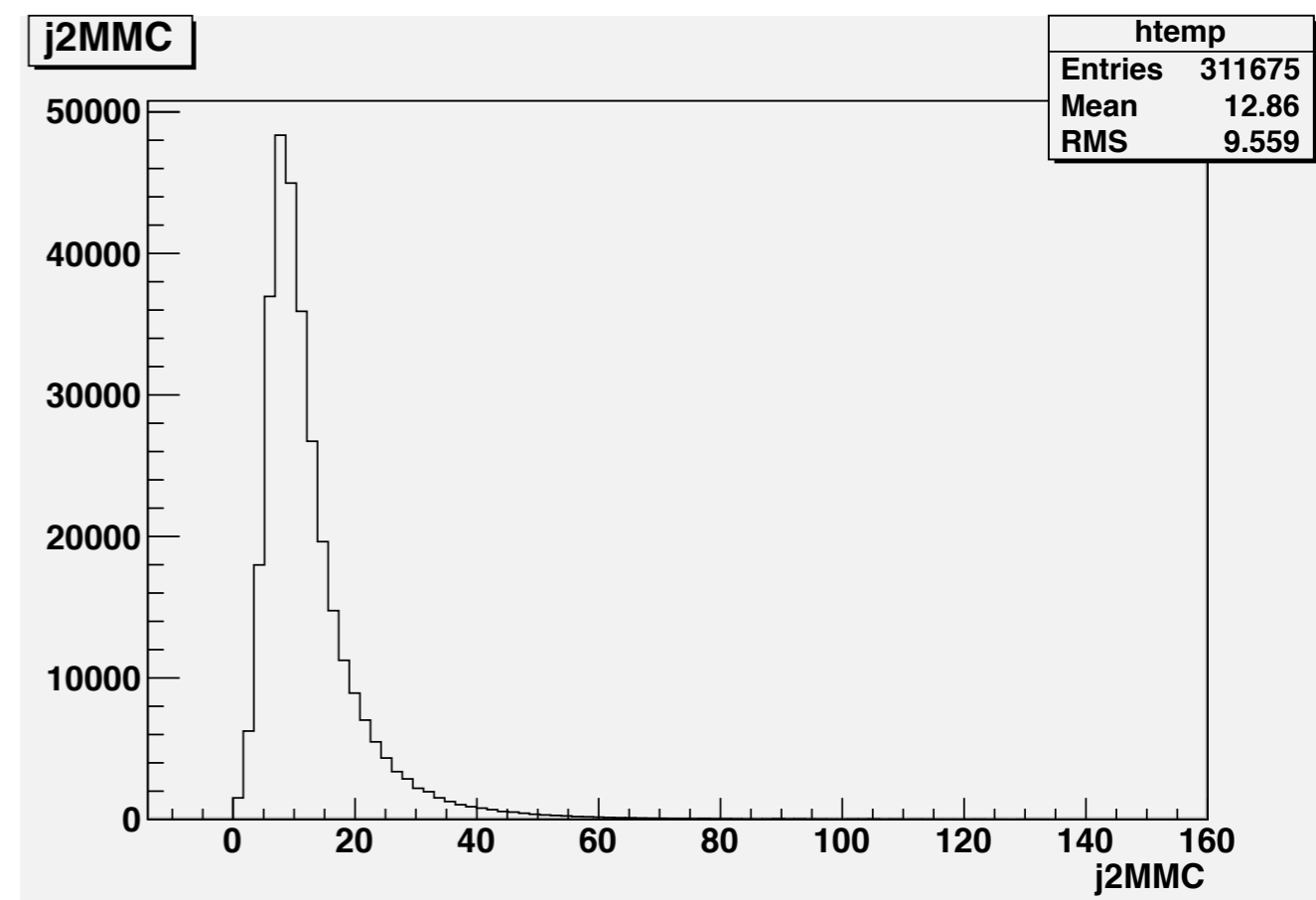
Jet mass distribution

Jet1



M_{Jet1} GeV

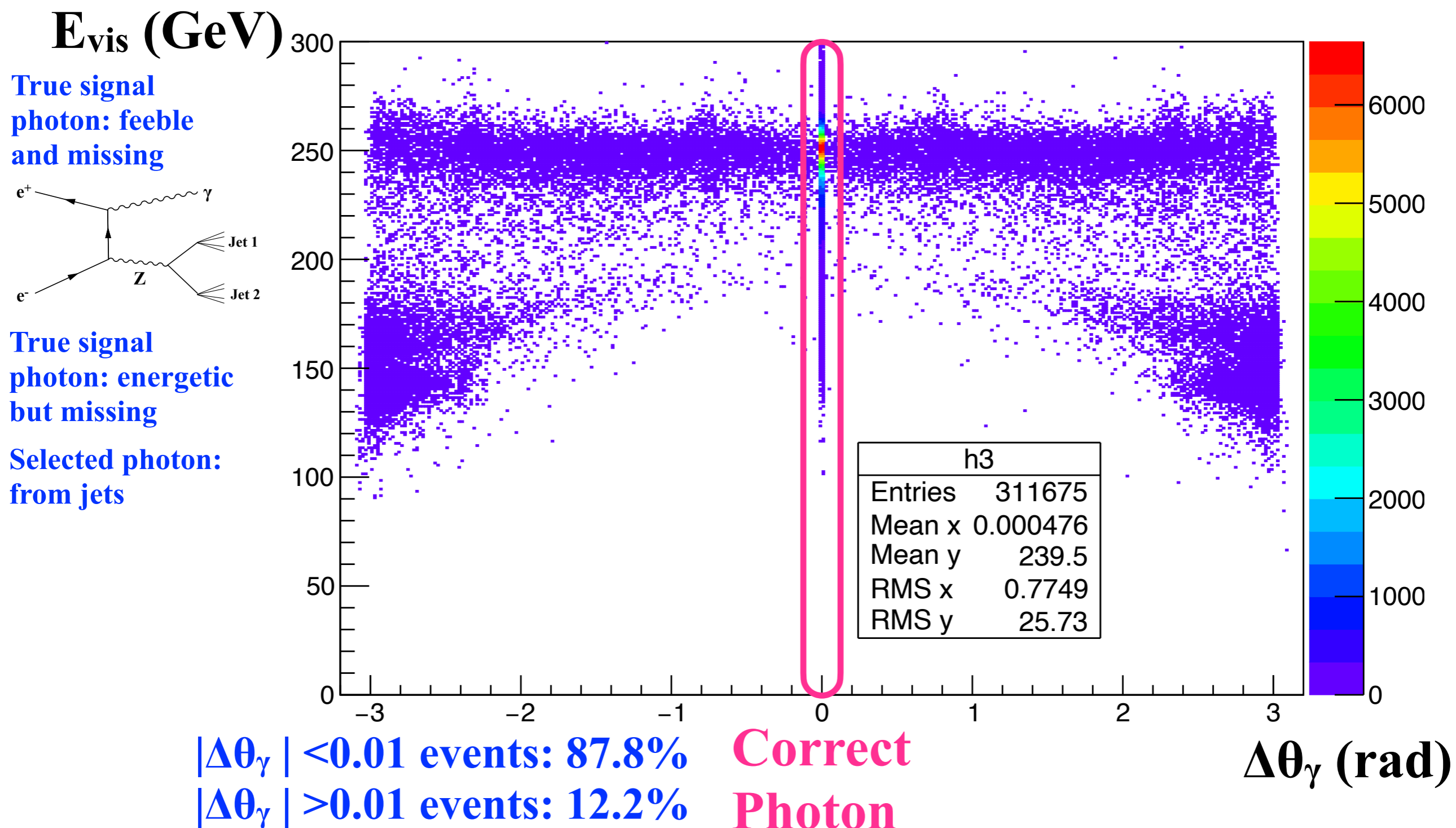
Jet2



M_{Jet2} GeV

Correct photon selection

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



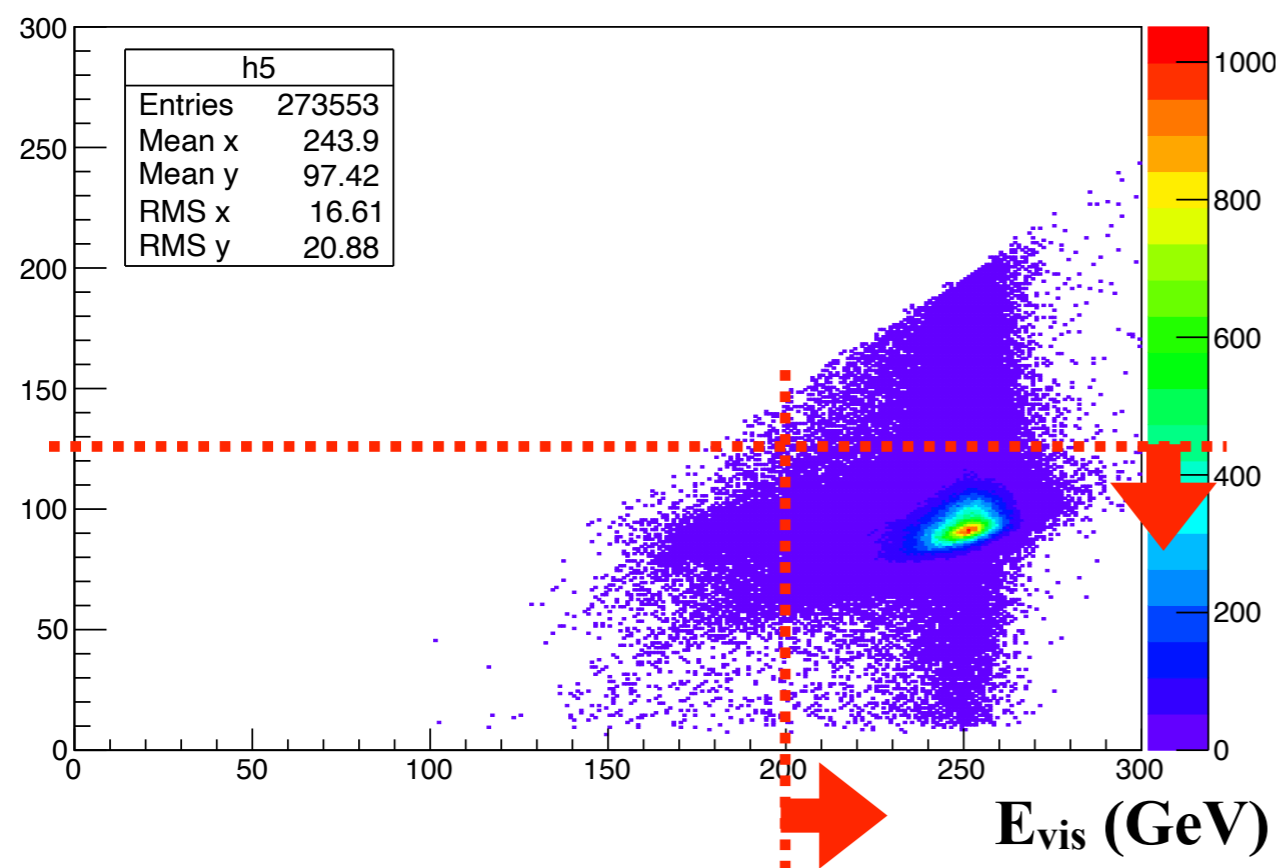
Correct photon selection cut 1

M_{2j} vs. E_{vis} ($=E_{j1}+E_{j2}+E_{\gamma}$)

correct photon case

$$|\Delta\theta_{\gamma}| < 0.01$$

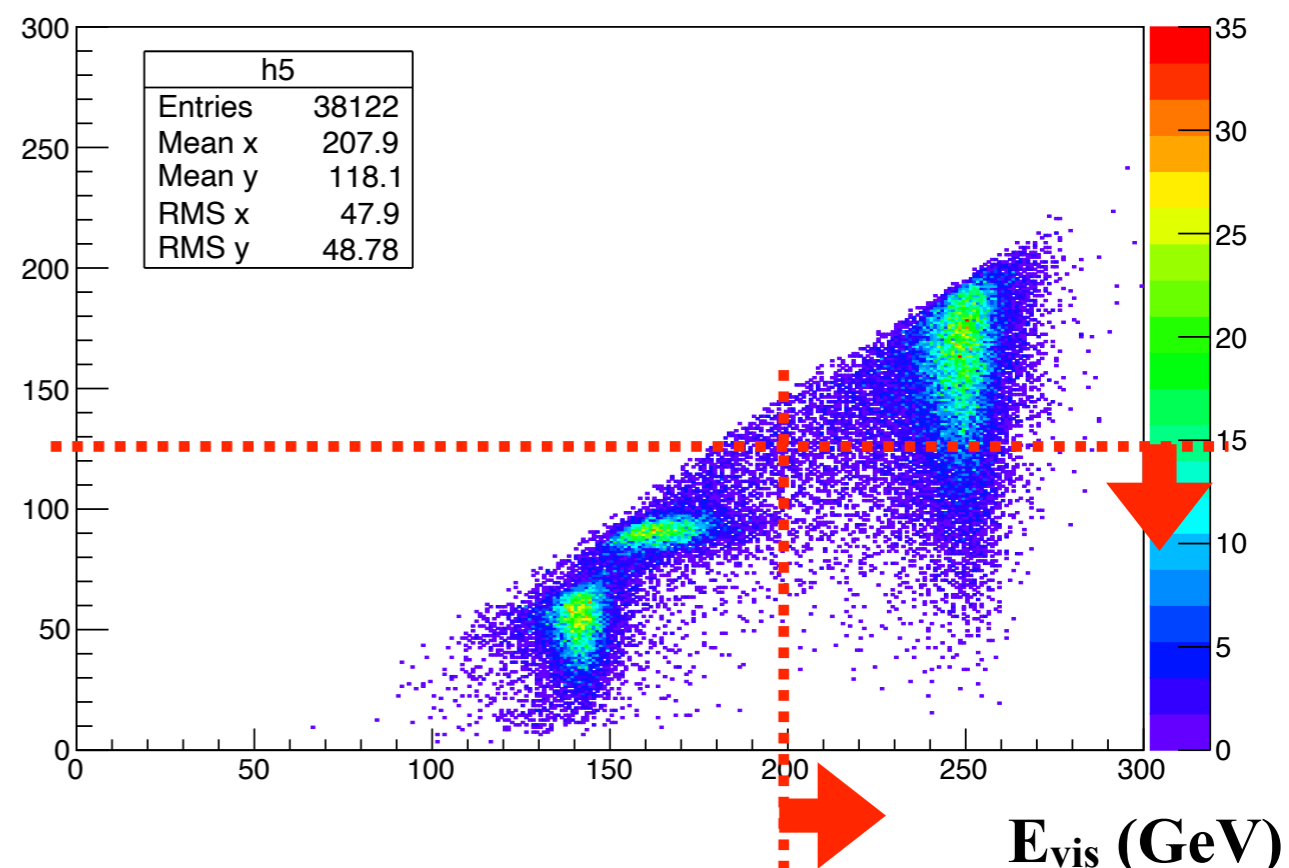
M_{2j}
(GeV)



wrong photon case

$$|\Delta\theta_{\gamma}| > 0.01$$

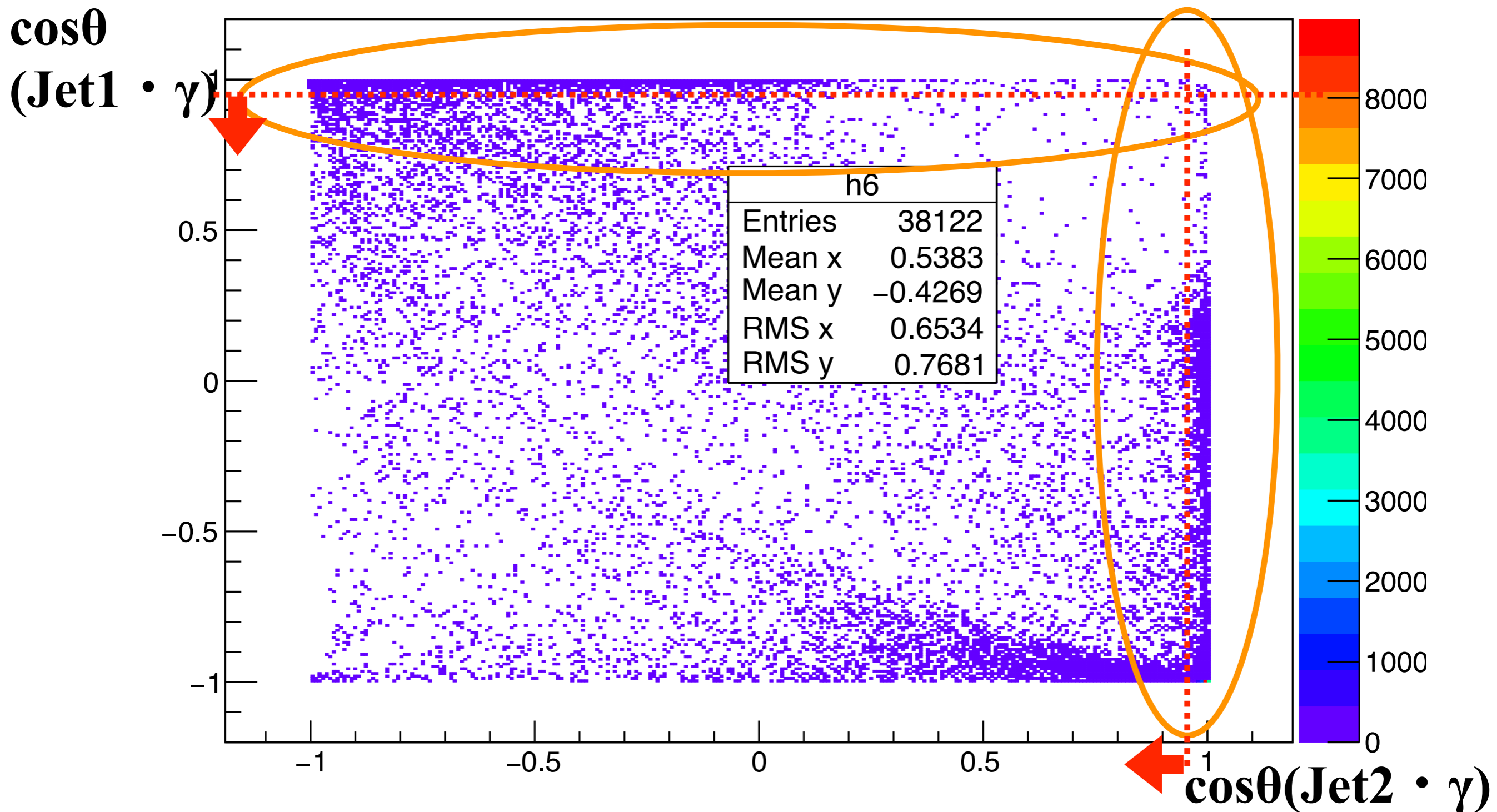
M_{2j}
(GeV)



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

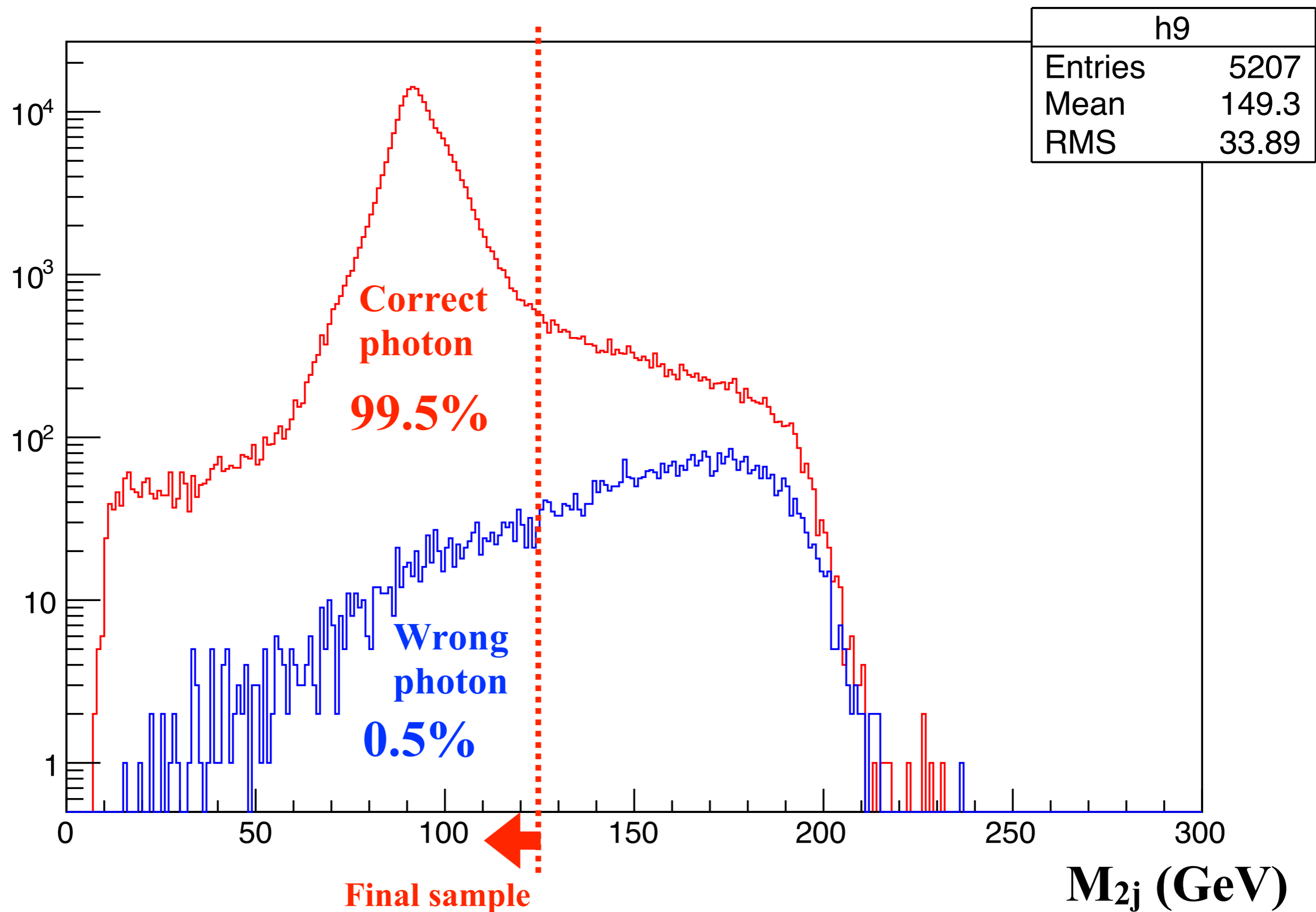
Correct photon selection cut 2

Wrong photons are near jet axes



Cut2: $\cos\theta(\text{Jet1} \cdot \gamma) < 0.95$ && $\cos\theta(\text{Jet2} \cdot \gamma) < 0.95$

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



Source of the bias

Source of the bias is investigated.

-> 2 major source are found.

Inputs and outputs

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

$$\left\{ \begin{array}{l} \sqrt{P_{J1}^2 + m_{J1}^2} + \sqrt{P_{J2}^2 + m_{J2}^2} + |P_\gamma| + |P_{ISR}| = \text{ECM} \text{ (1)} \\ \begin{pmatrix} \sin\theta_{J1}\cos\phi_{J1} & \sin\theta_{J2}\cos\phi_{J2} & \sin\theta_\gamma\cos\phi_\gamma \\ \sin\theta_{J1}\sin\phi_{J1} & \sin\theta_{J2}\sin\phi_{J2} & \sin\theta_\gamma\sin\phi_\gamma \\ \cos\theta_{J1} & \cos\theta_{J2} & \cos\theta_\gamma \end{pmatrix} \begin{pmatrix} P_{J1} \\ P_{J2} \\ P_\gamma \end{pmatrix} = \begin{pmatrix} (\text{ECM} - |P_{ISR}|)\sin\alpha \\ 0 \\ \pm|P_{ISR}|\cos\alpha \end{pmatrix} \end{array} \right.$$

Matrix A Inverse

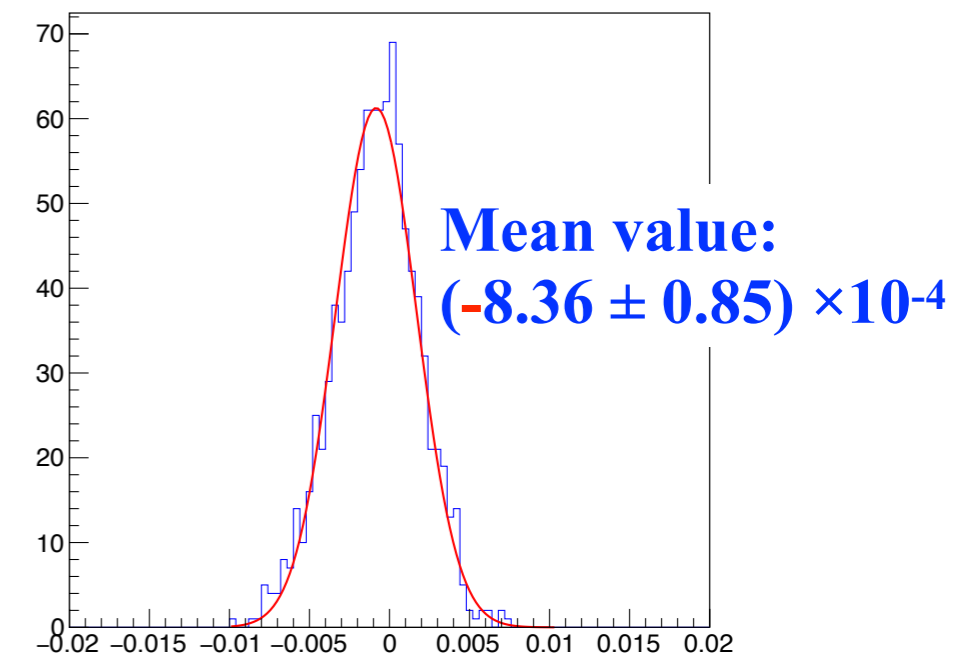
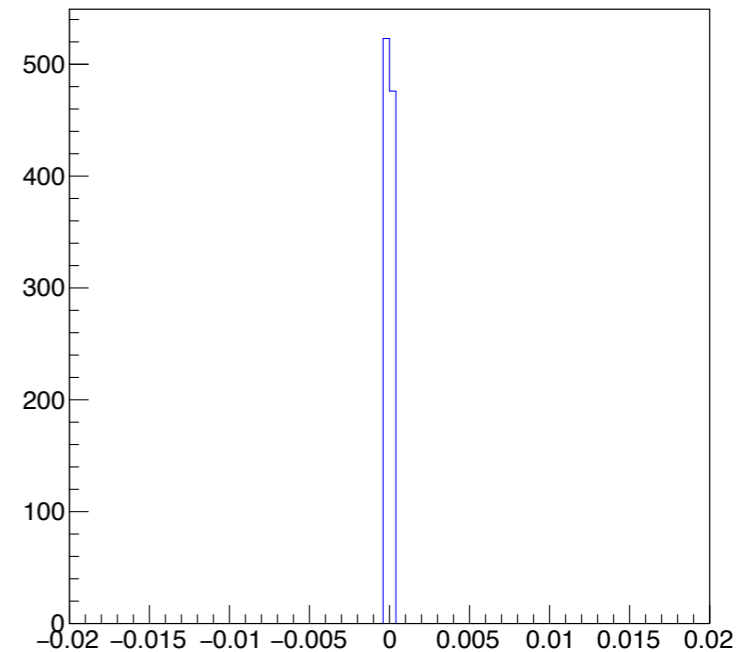
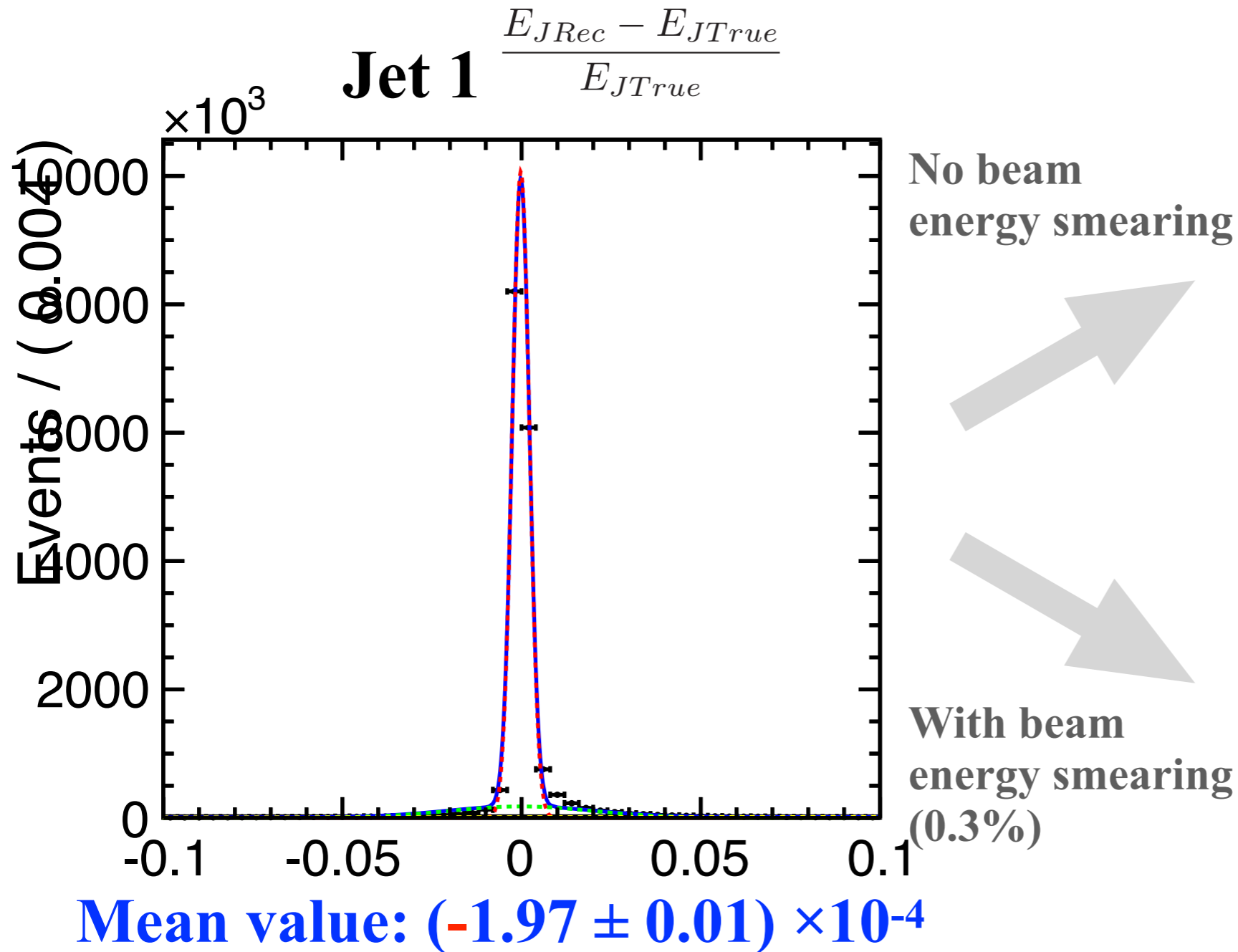
(A) Beam energy spread

(B) Error of the jet mass inputs

Source (A): Beam energy spread

When all inputs are all MCtruth,

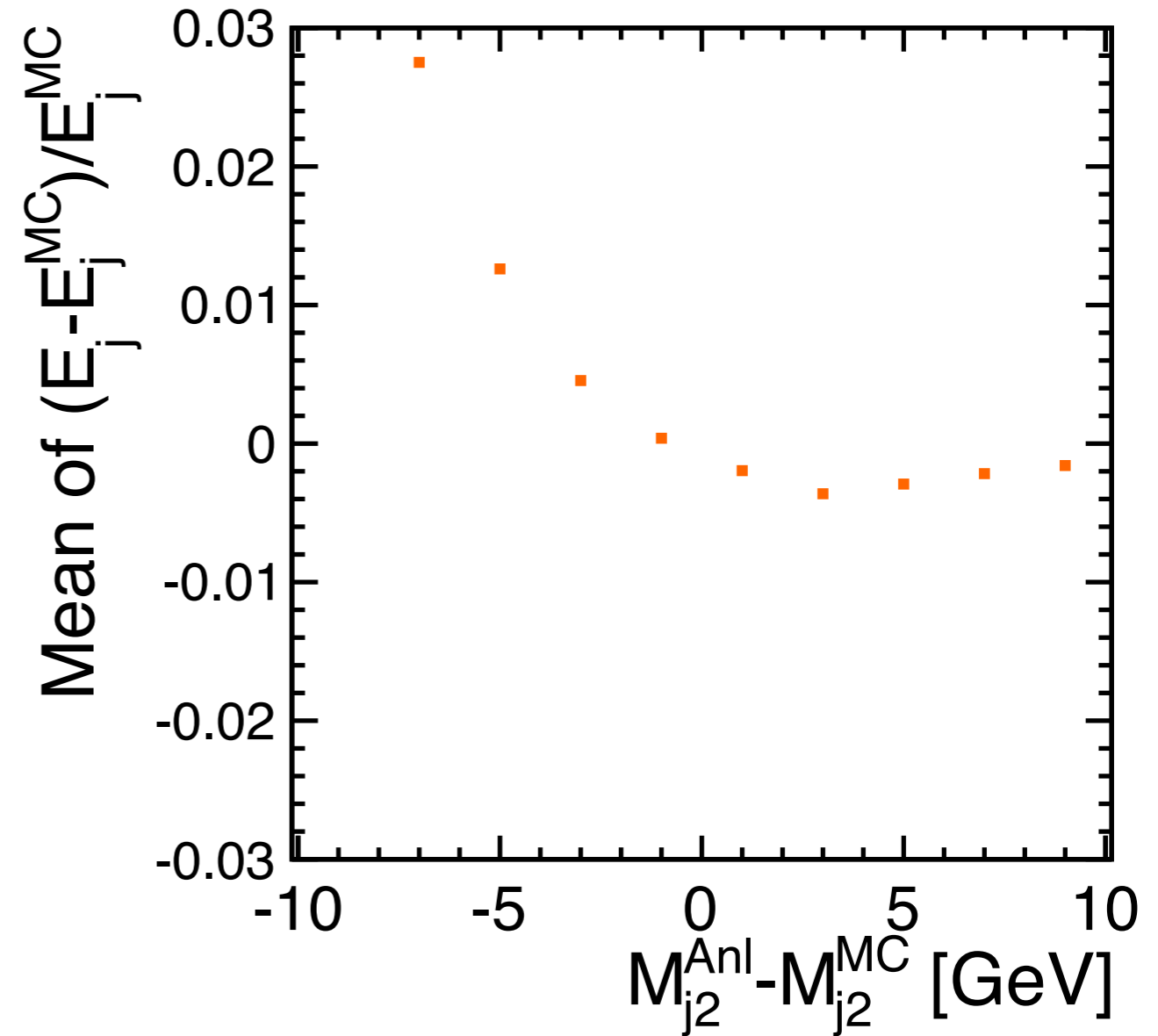
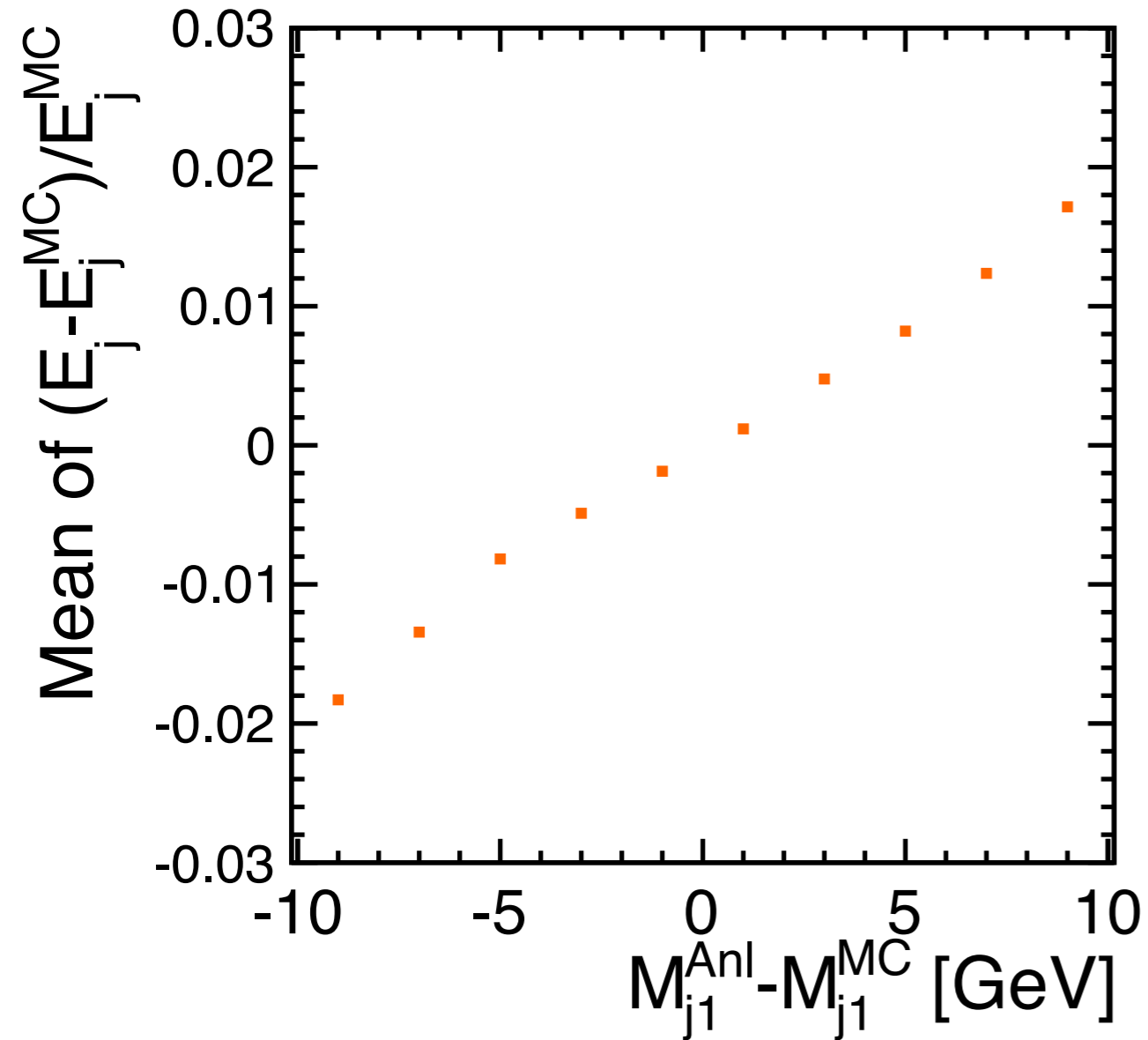
Toy MC Simulation



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 inputs³⁶

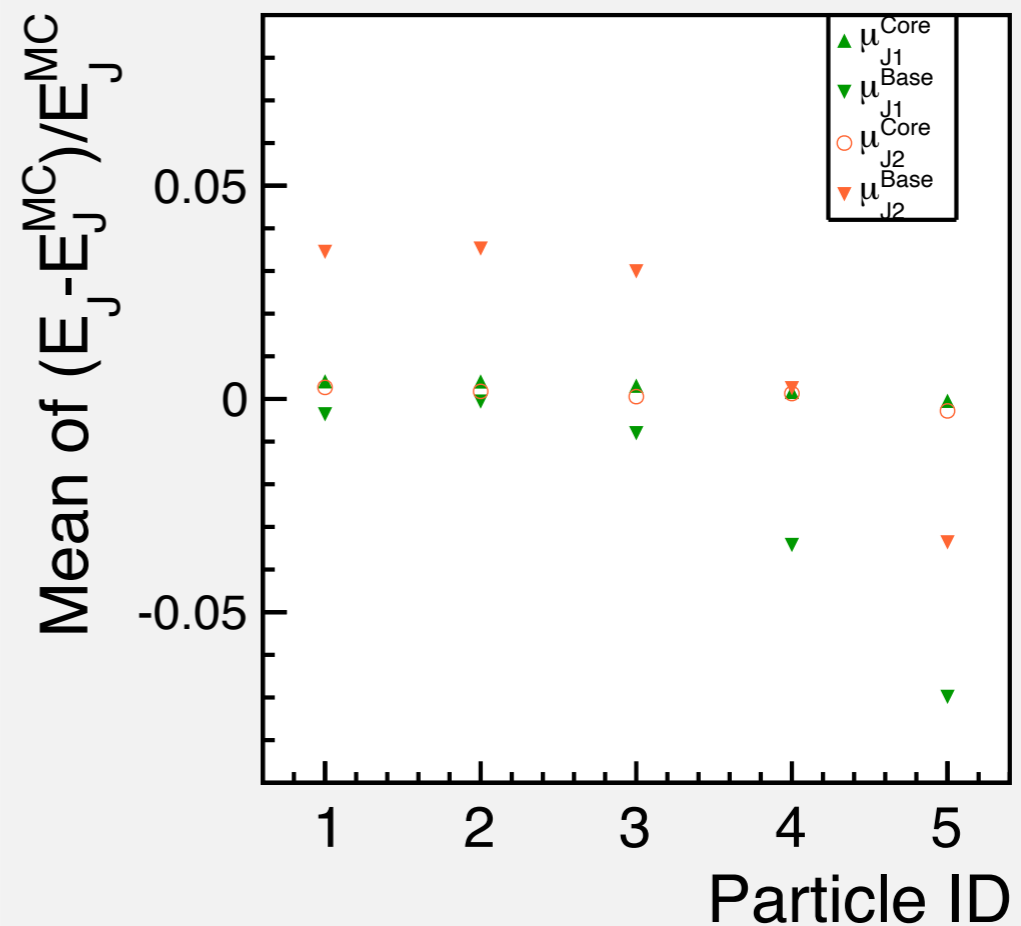
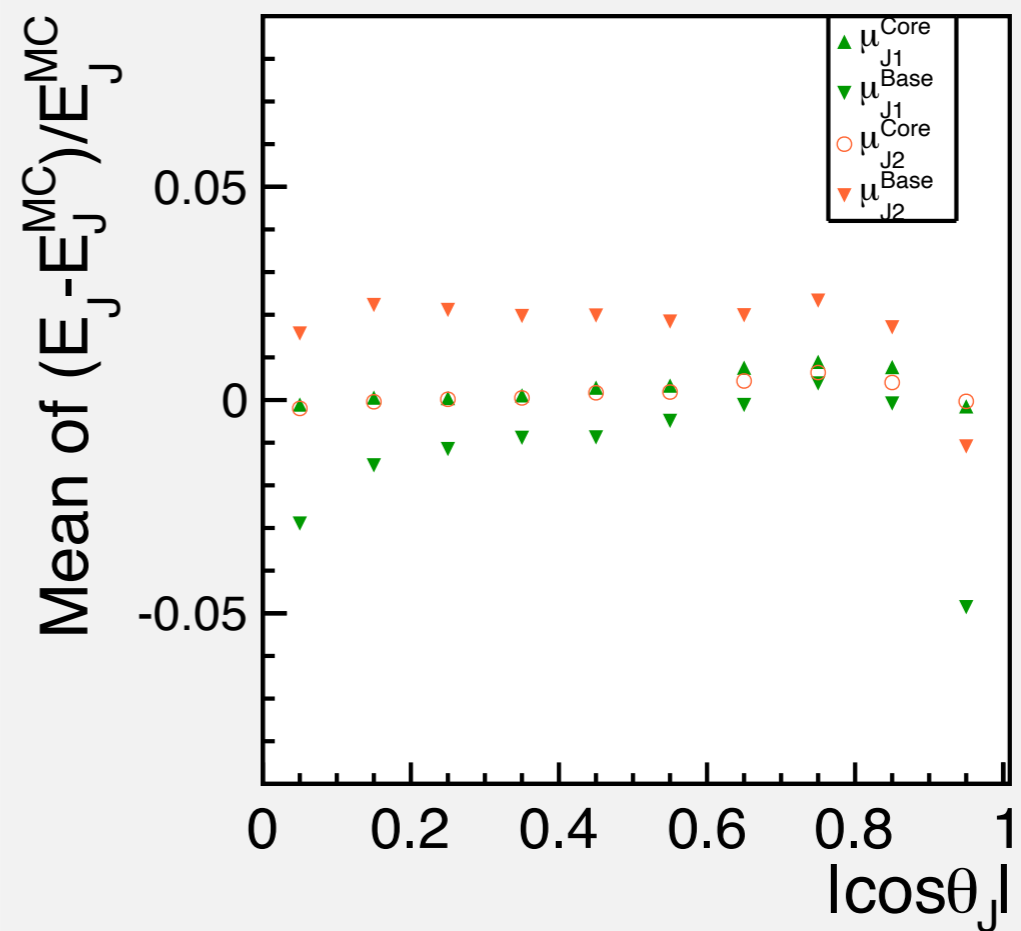
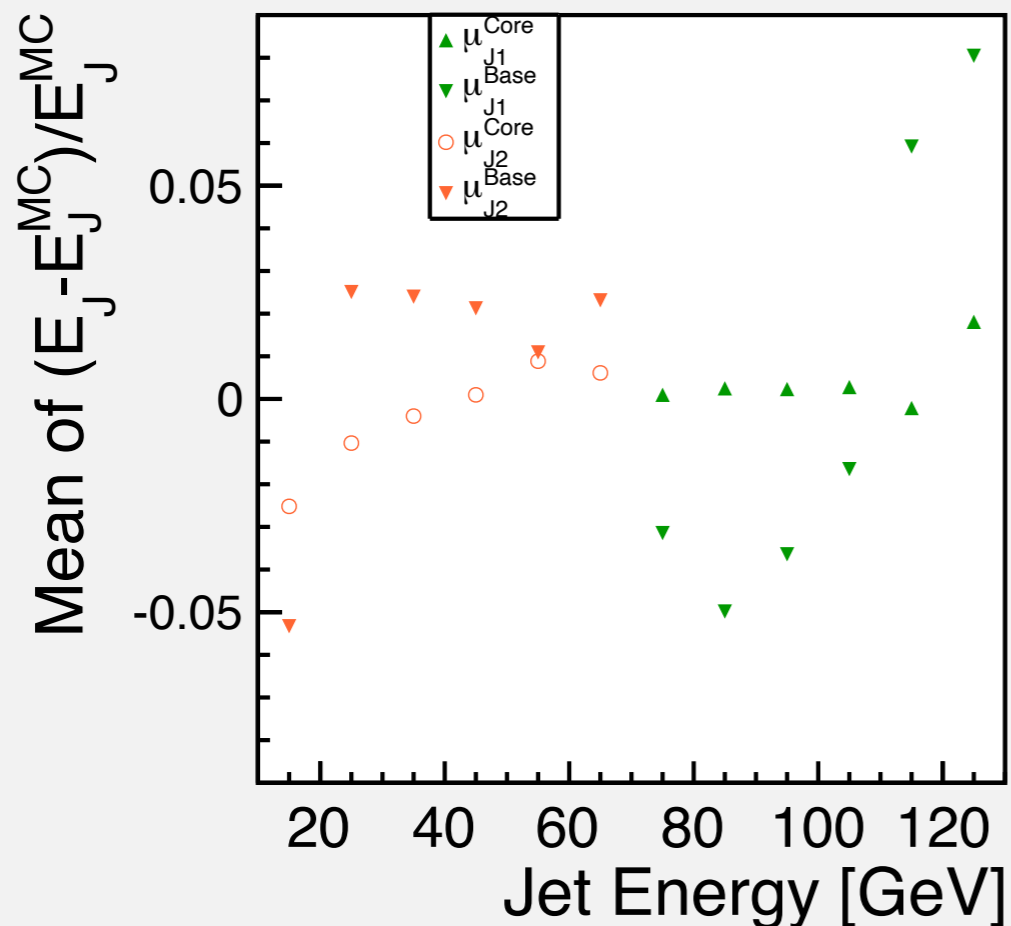
Mean value of the fitting function for the Jet 1 $\frac{E_{JRec} - E_{JTrue}}{E_{JTrue}}$
as a function of the input jet mass deviation



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.

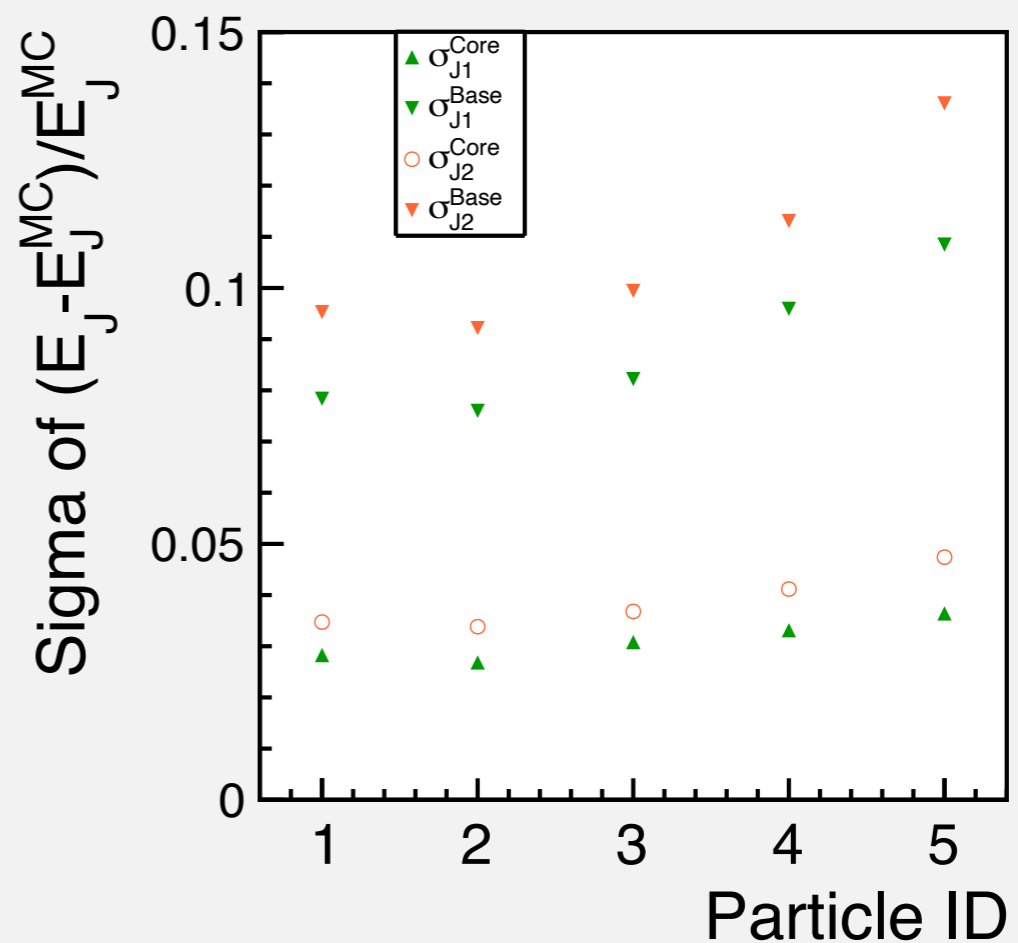
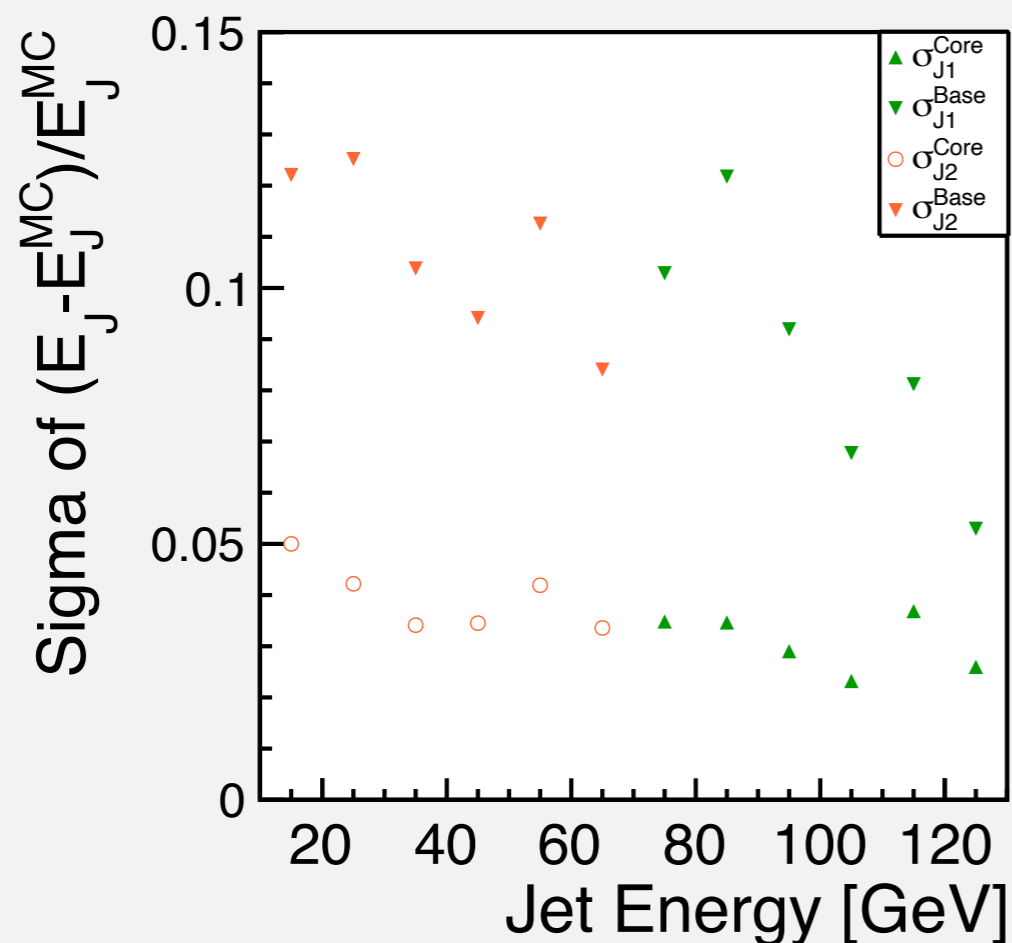
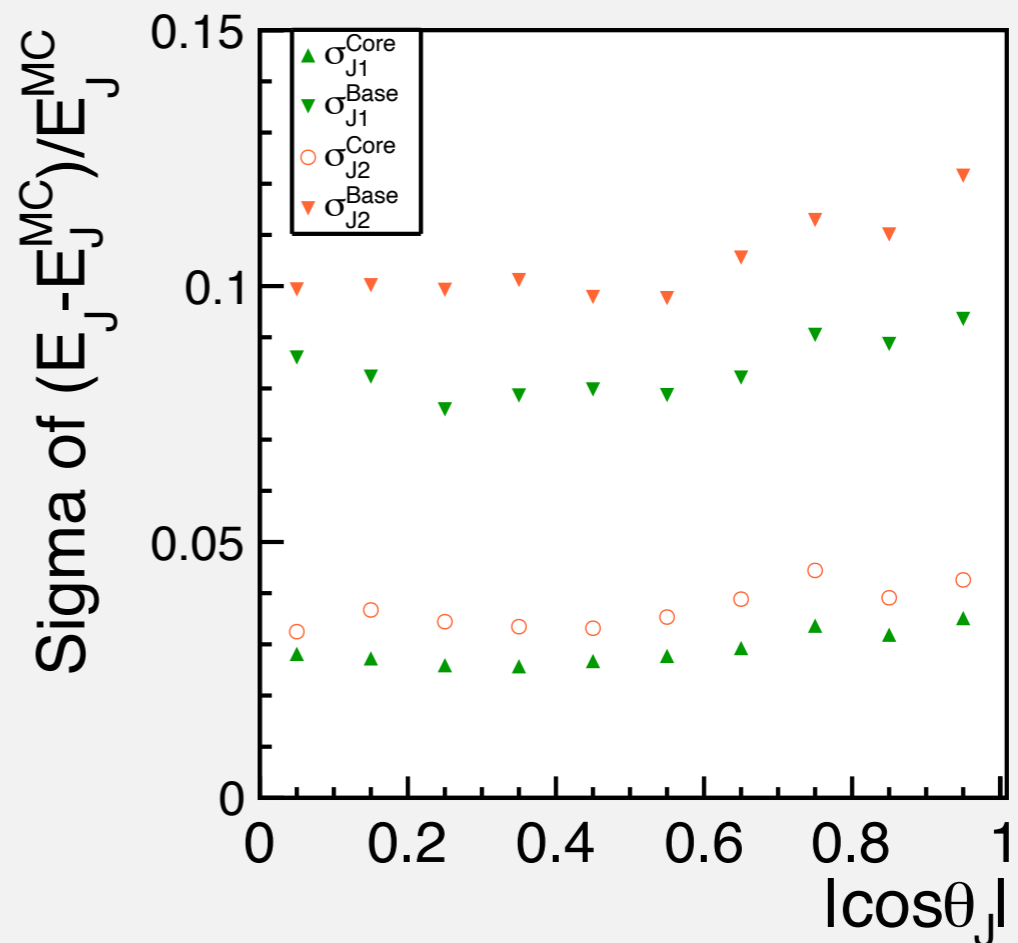
PFO Mean Value

Particle ID := flavor of the seed of the jet

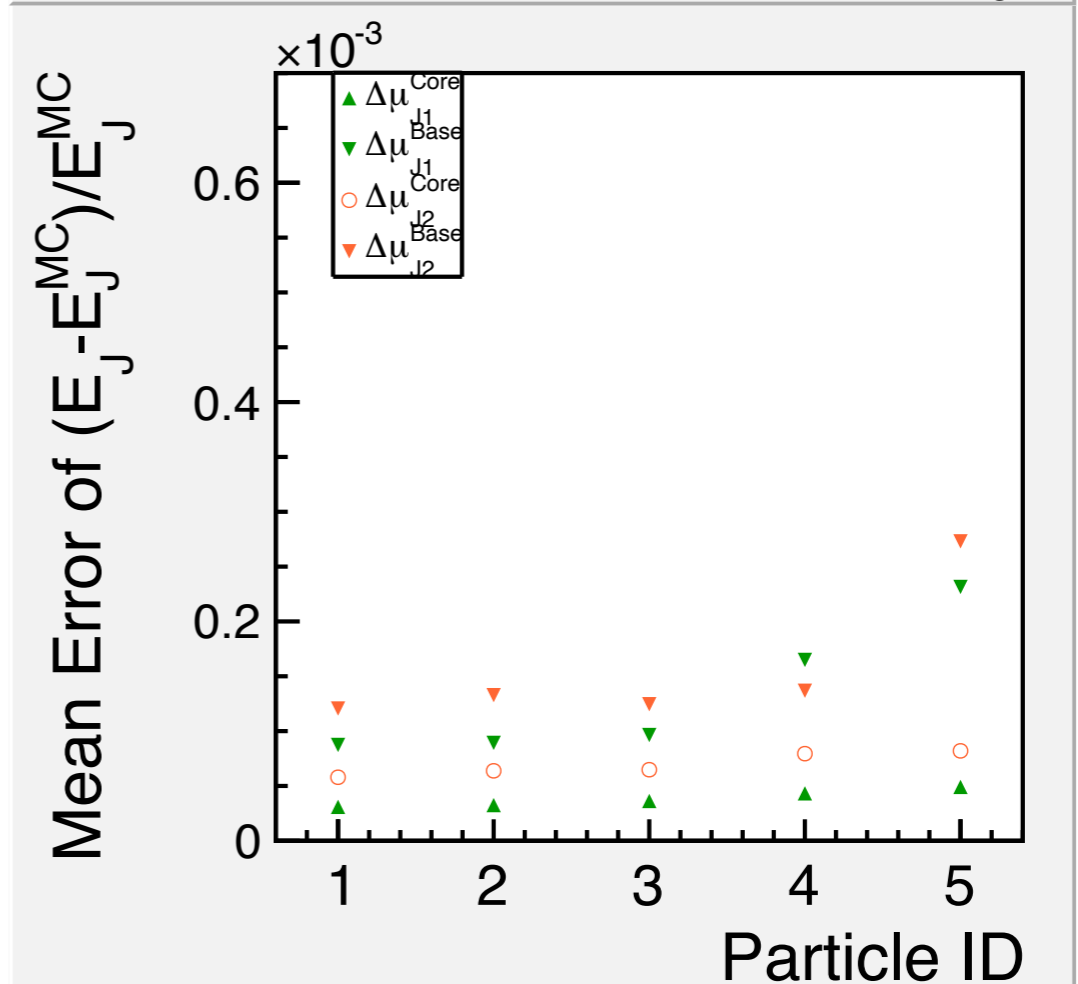
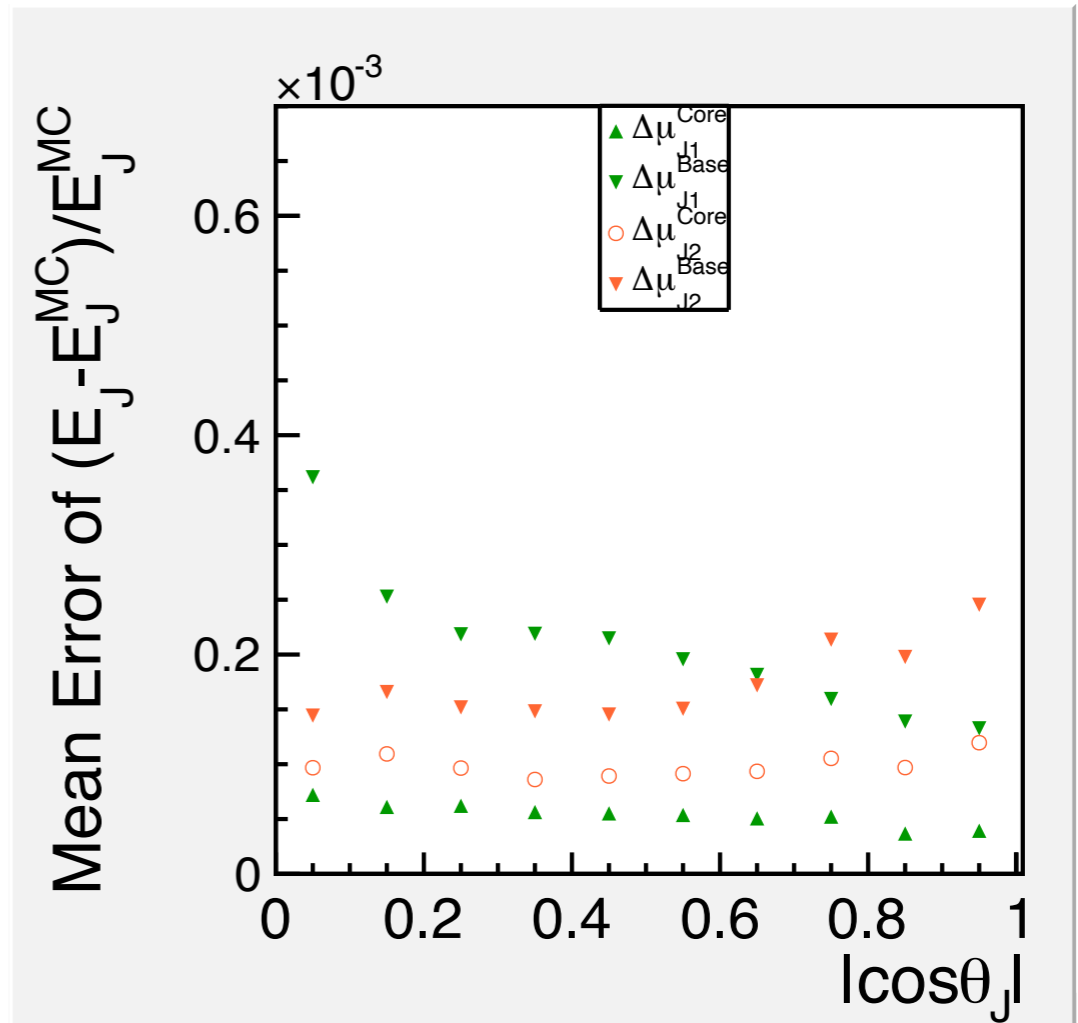
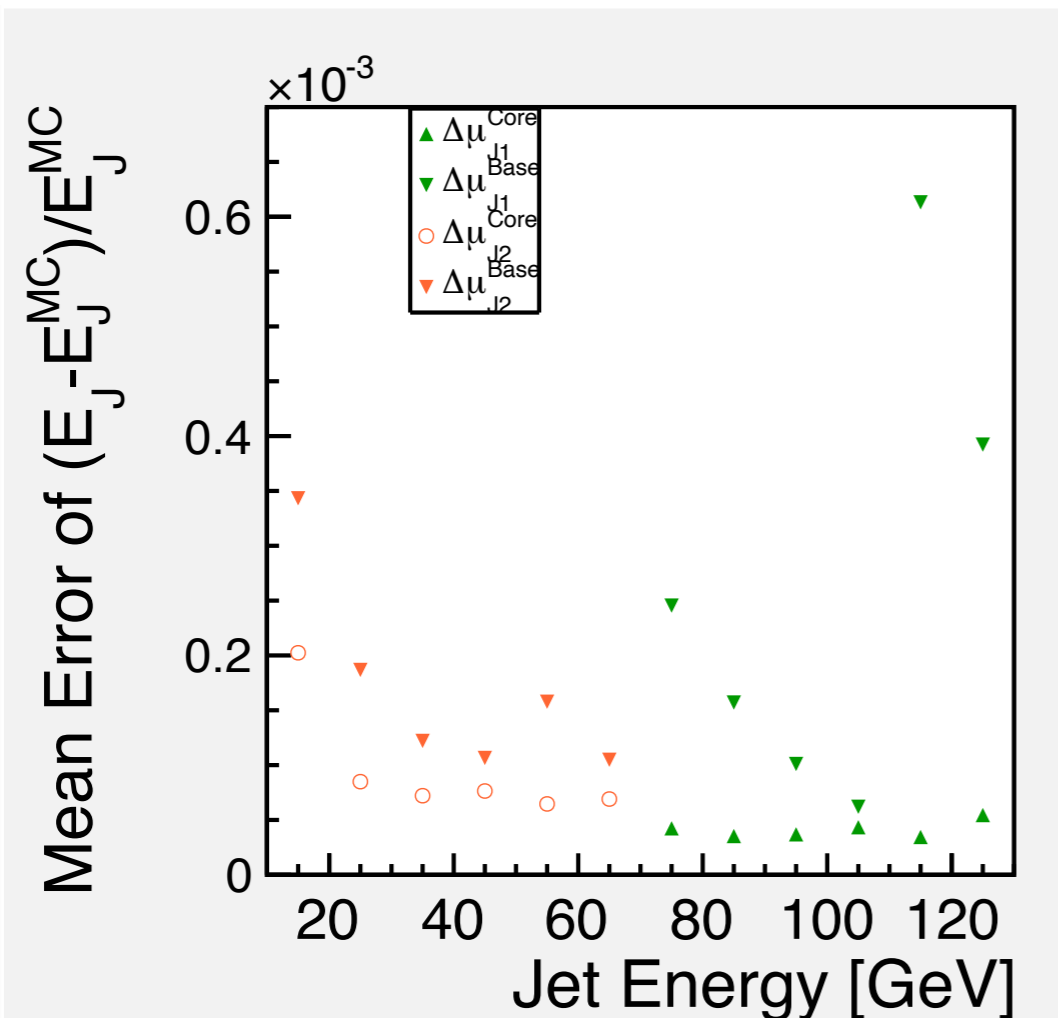


PFO Sigma Value

Particle ID := flavor of the seed of the jet



PFO Mean Error



PFO Fraction

Fraction := Size of the fitting
Gaussian
 $\text{Core}/(\text{Core}+\text{Base})$

