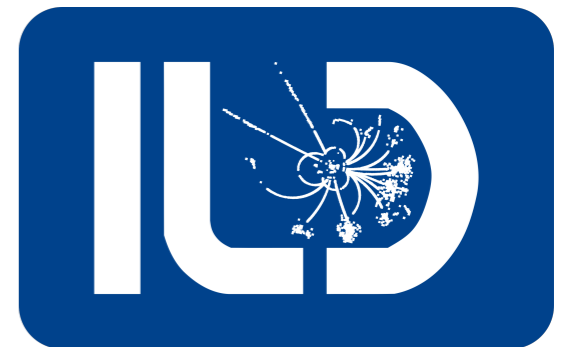


# Jet Energy Calibration using $e^+e^- \rightarrow \gamma Z$ process at the ILC

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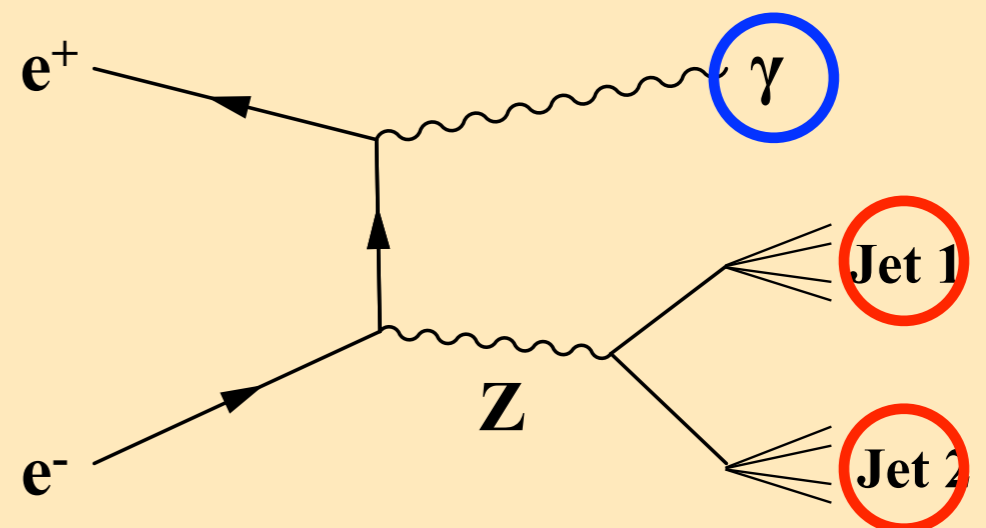


# Introduction

## Detector Benchmark Motivation

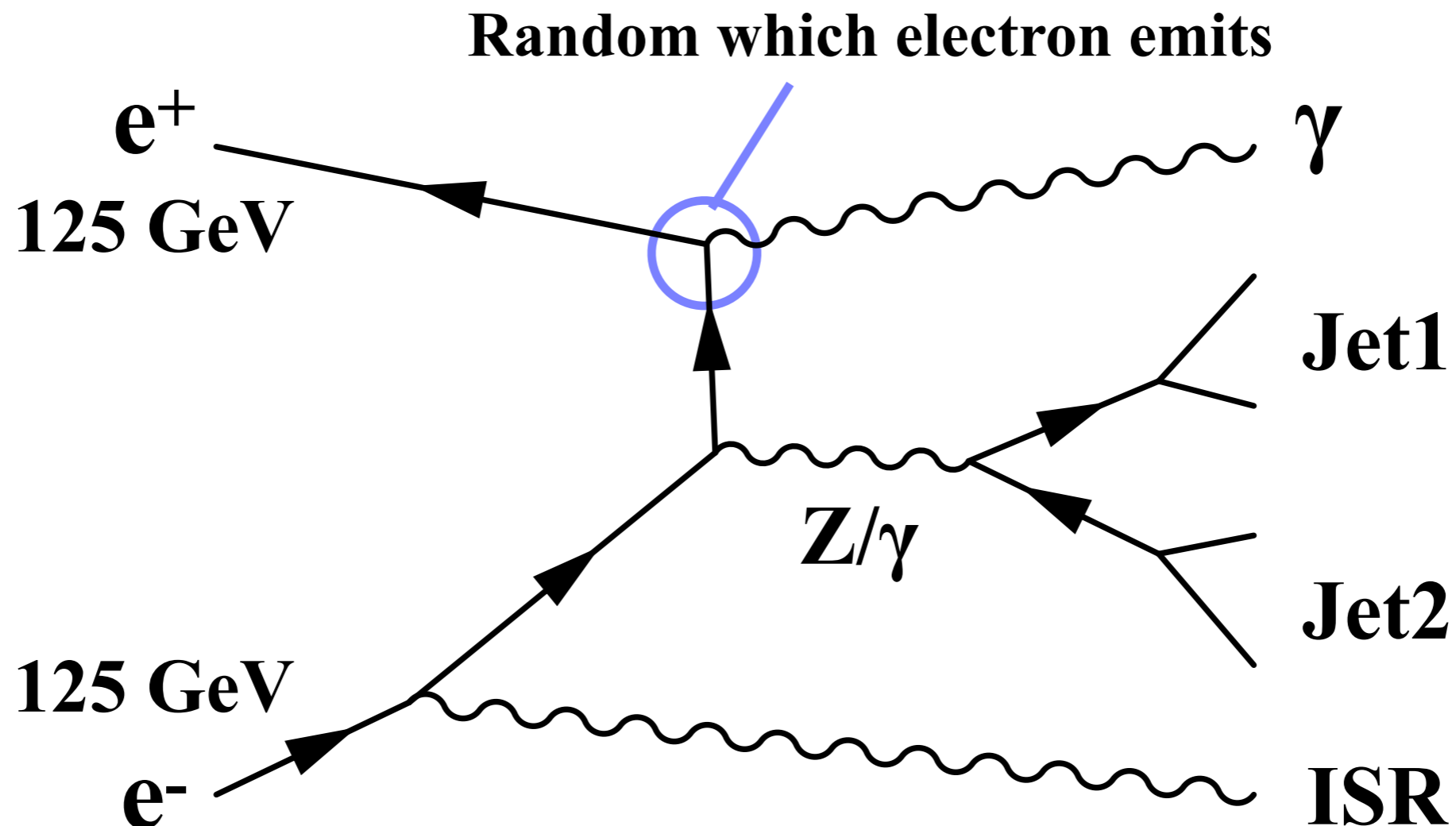
- Primary Target of ILC 250: to precisely measure the coupling constants between Higgs boson and various other particles  
 -> **For this, we need to precisely calibrate energy scales for various particles.**
- Jet energies can be reconstructed using measured direction of 2 jets and  $\gamma$  and mass of 2 jets in the  $e^+e^- \rightarrow \gamma Z, Z \rightarrow 2 \text{ Jets}$  process. Taking advantage of its large cross sections,  $\sim 80$  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



# Full simulation

- Event generation by Whizard 1.95 with beamstrahlung and additional ISR photon effects
- **Geant4-based full detector simulation** is performed using a **realistic ILD detector model**
- $e^+e^- \rightarrow \gamma Z, Z \rightarrow 2 \text{ Jets}$  process at  $E_{\text{CM}}=250 \text{ GeV}$  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:

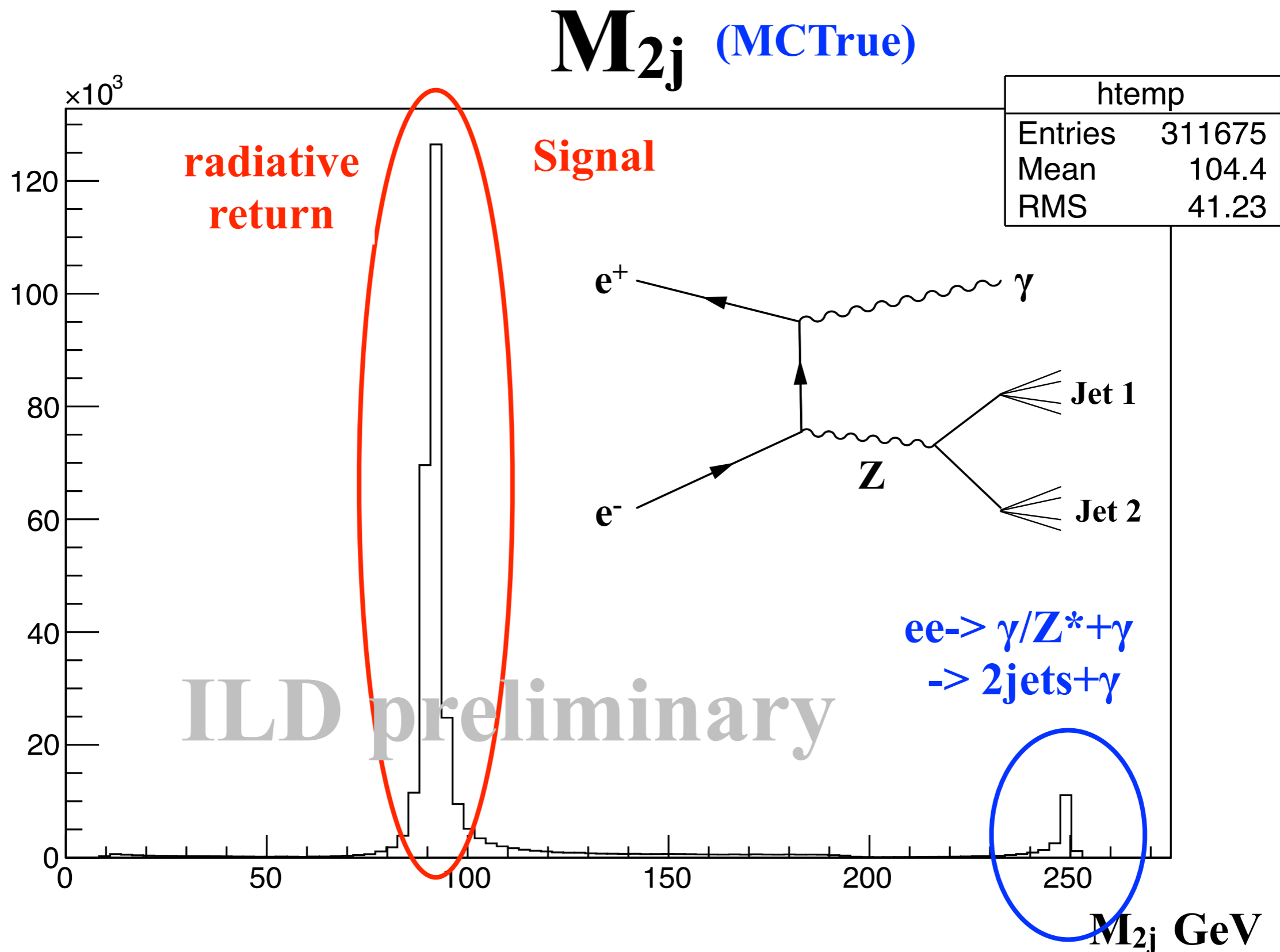
1. choose neutral particles with particle ID = 22 (Pandora PFA ID)
2. require energy  $> 50$  GeV
3. choose the photon candidate with energy closest to 108.4 GeV

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

## Jet Clustering

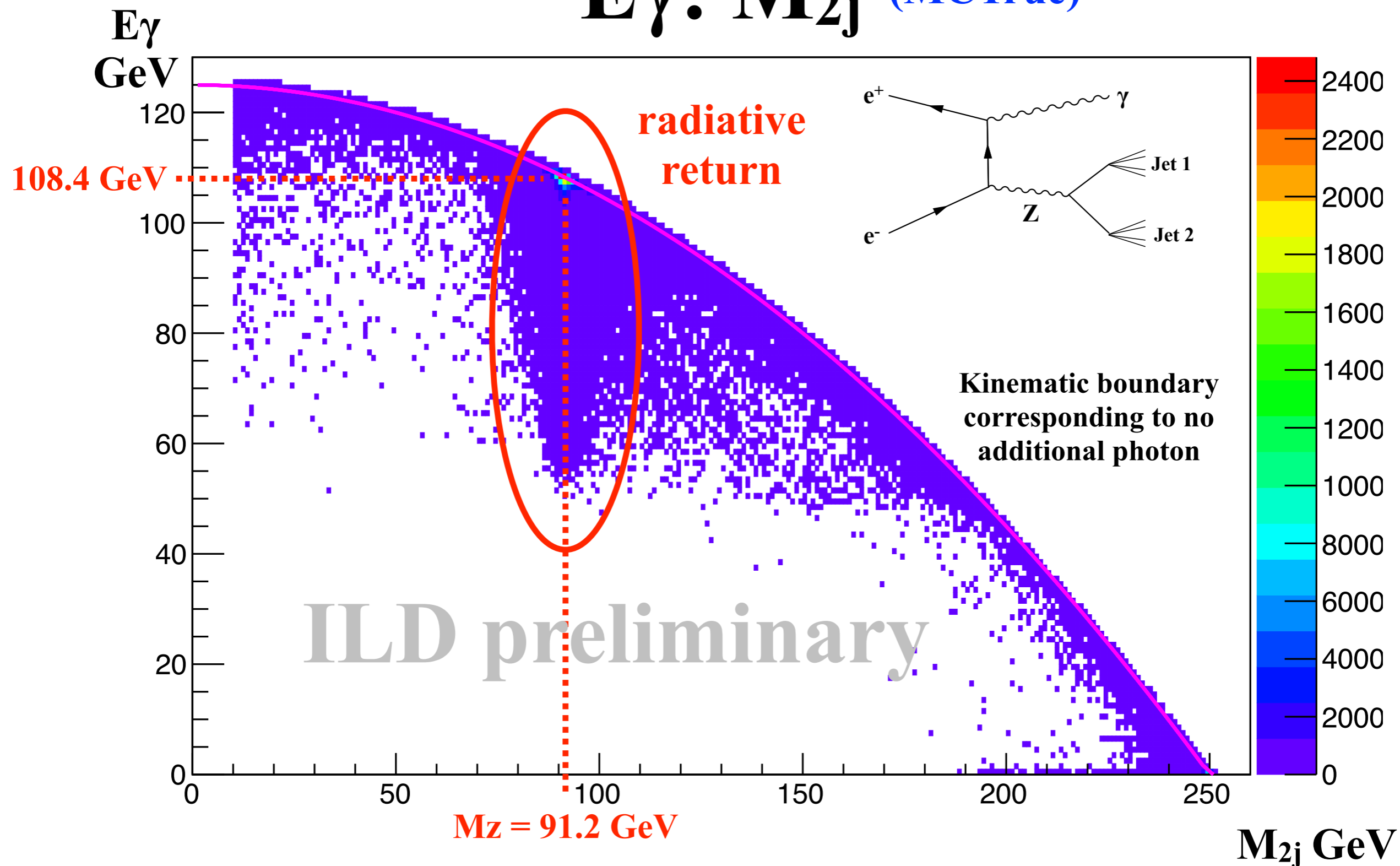
- All Particle Flow Objects (PFOs) other than the selected photon are clustered into 2 jets with Durham algorithm (done by LCFIPlus)
- The jet with higher reconstructed energy is defined as “jet 1” and the other as “jet 2”

# $M_{2j}$ distribution



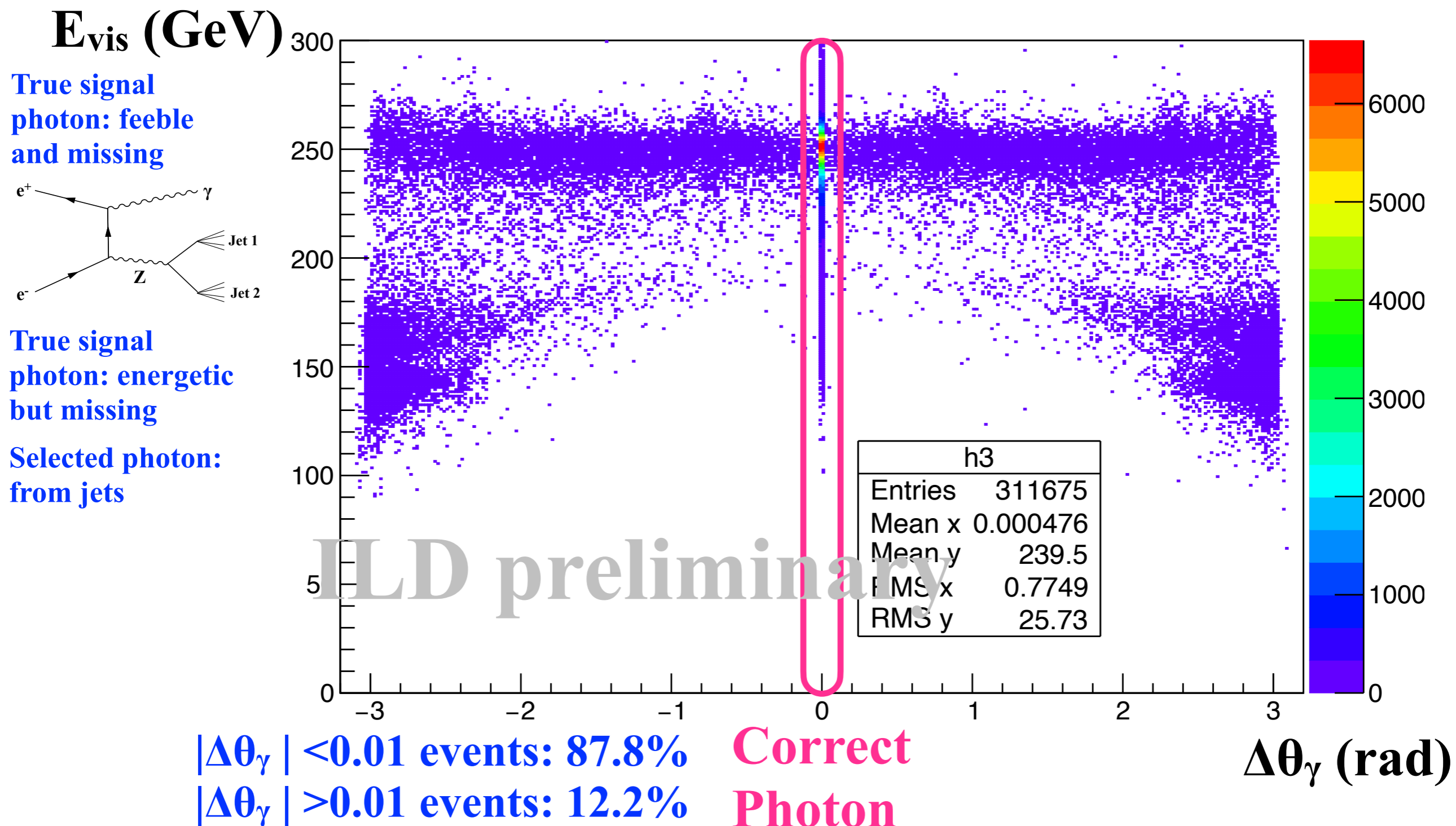
# Photon energy & $M_{2j}$ distribution

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



# Correct photon selection

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



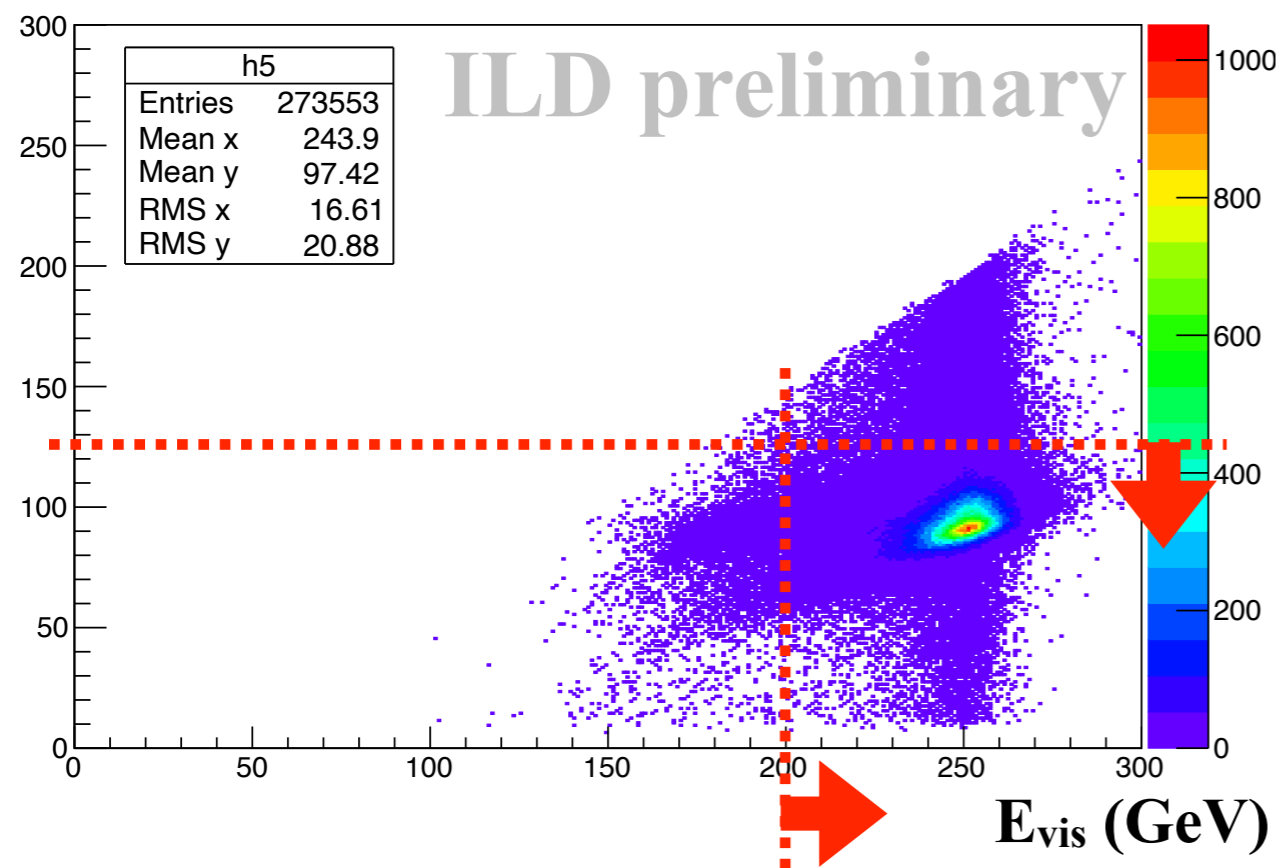
# Correct photon selection cut 1

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

correct photon case

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

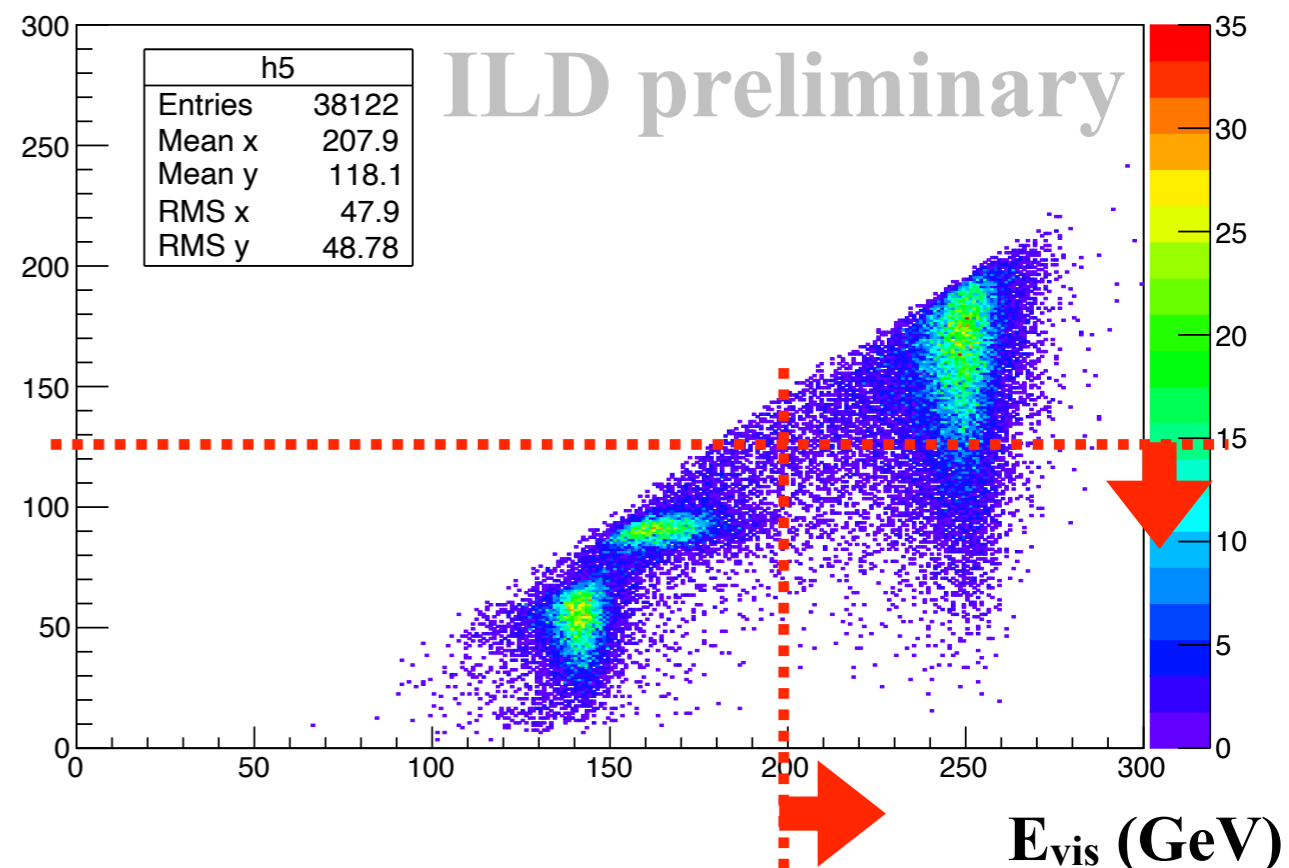
$M_{2j}$   
(GeV)



wrong photon case

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

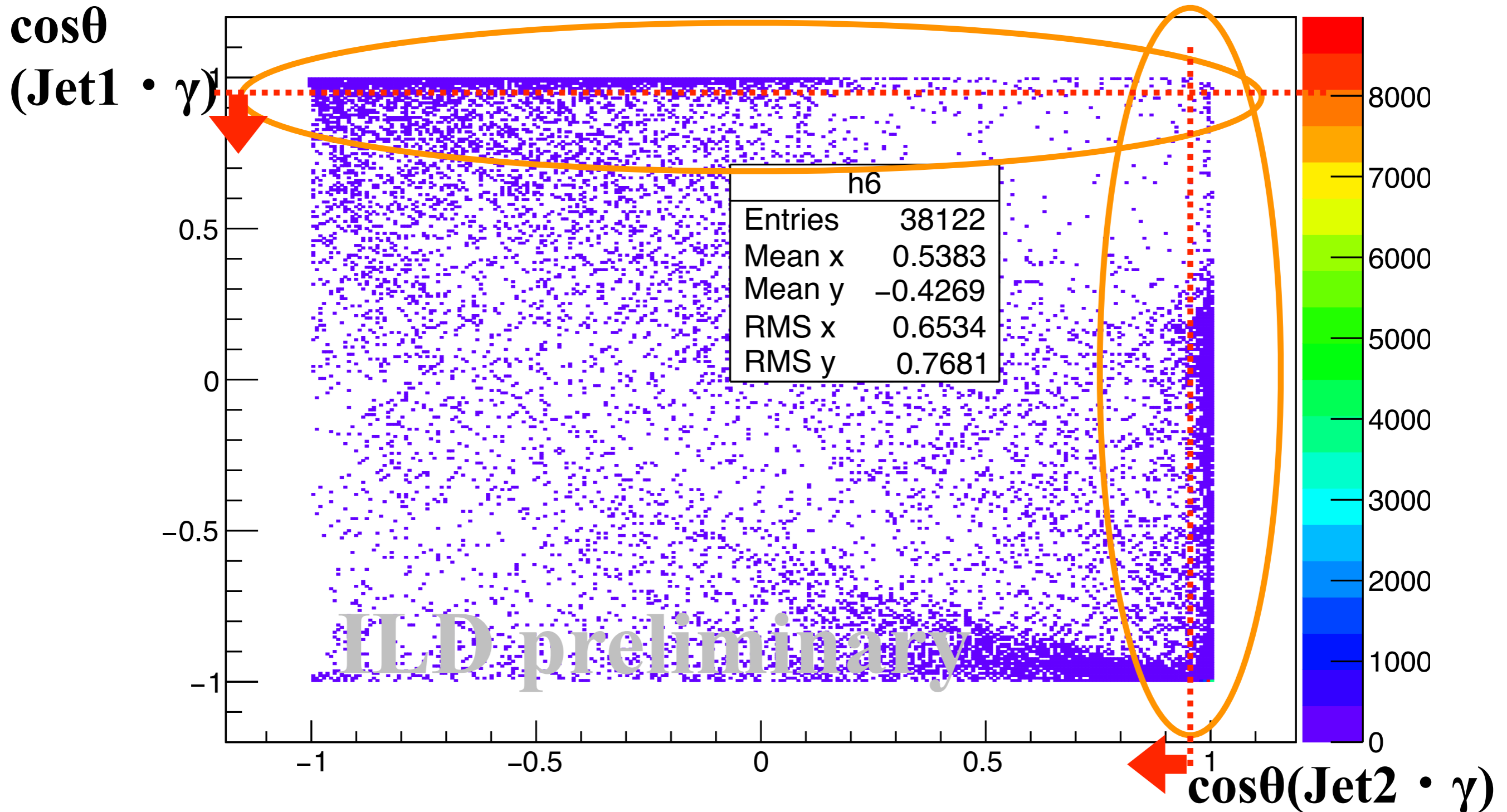
$M_{2j}$   
(GeV)



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

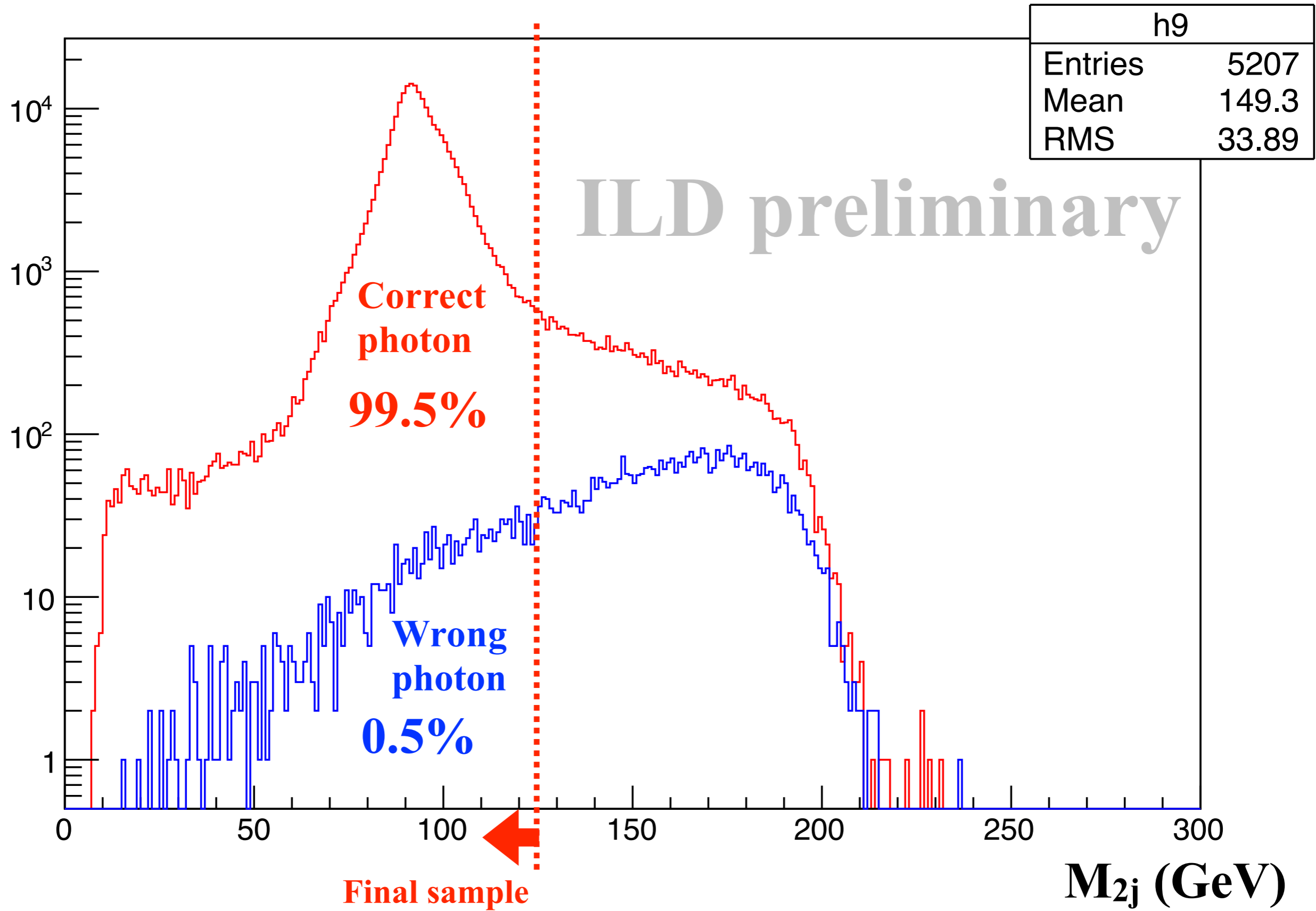
# Correct photon selection cut 2

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



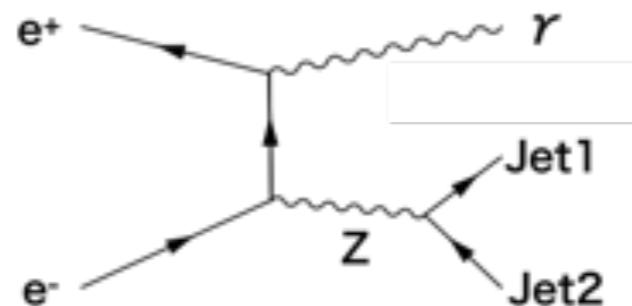
# Reconstruction Method

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

## Inputs and outputs

Using  $(\theta_{J1}, \theta_{J2}, \theta_{\gamma}, \phi_{J1}, \phi_{J2}, \phi_{\gamma}, m_{J1}, m_{J2})$

-> Determine  $(P_{J1}, P_{J2}, P_{\gamma}, P_{ISR})$



Direction Angle  
 $\theta$ : polar angle  
 $\phi$ : 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

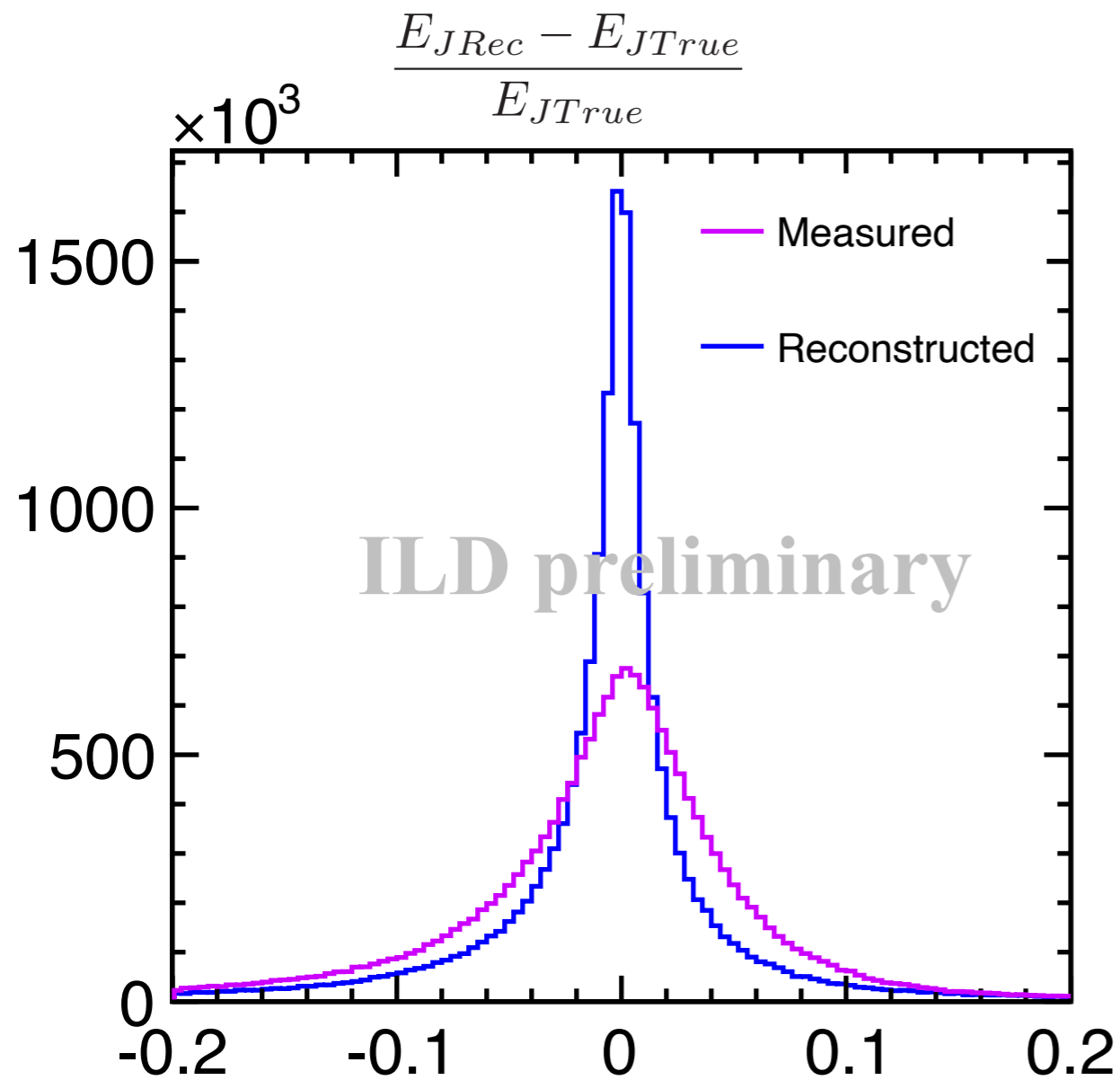
**Irrational equation for each sign of the ISR -> 8 possible solutions**

Choose the solution with

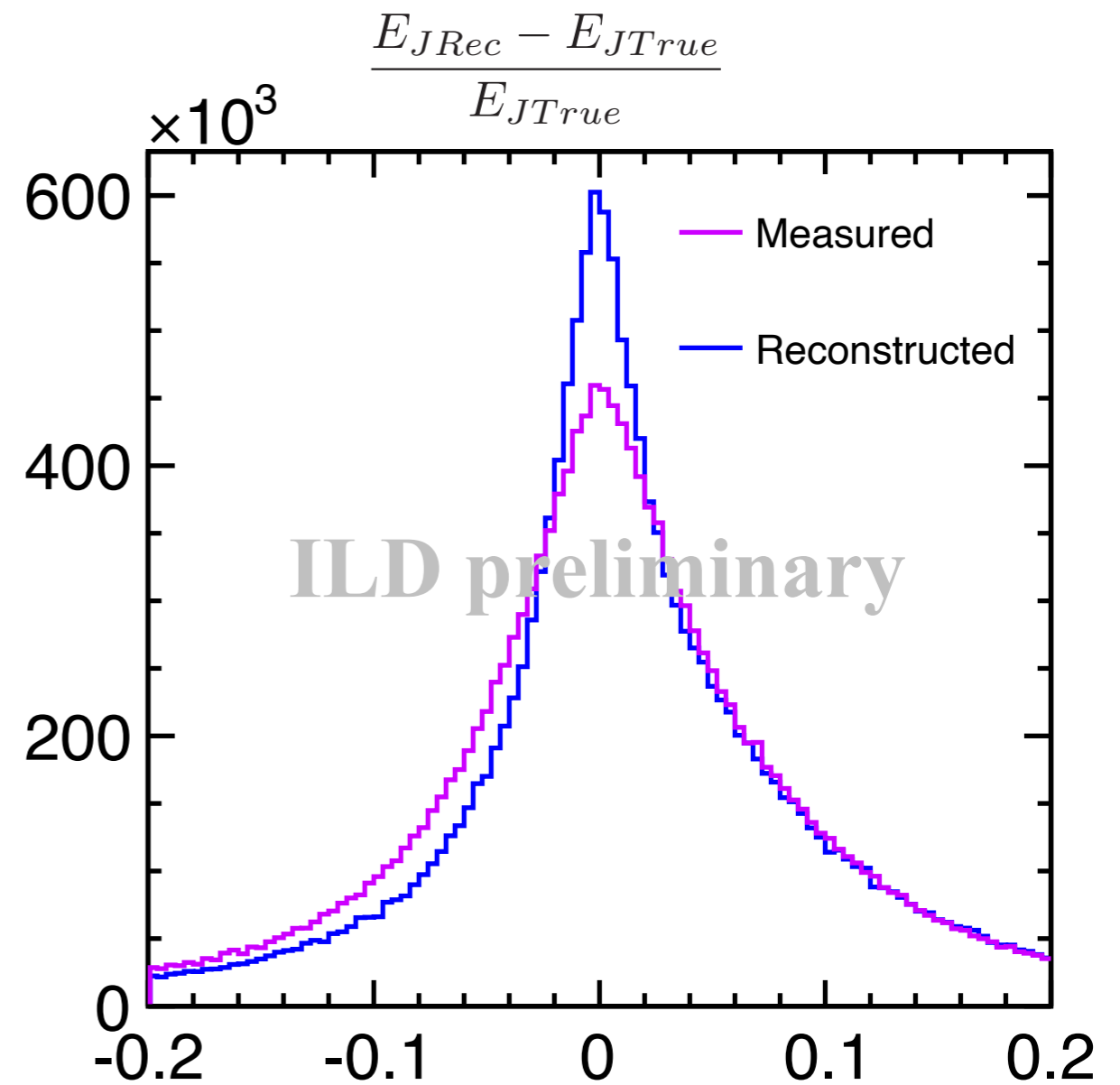
- (i) Real and positive value with  $< E_{CM}/2$
- (ii)  $\sqrt{P_{J1}^2 + m_{J1}^2} > 0$  and  $\sqrt{P_{J2}^2 + m_{J2}^2} > 0$
- (iii)  $P_{J1}, P_{J2}, P_{\gamma} > 0$
- (iv) solved  $P_{\gamma}$  closest to the measured  $P_{\gamma}$

# Jet Energy Reconstruction Result

## Jet 1



## Jet 2

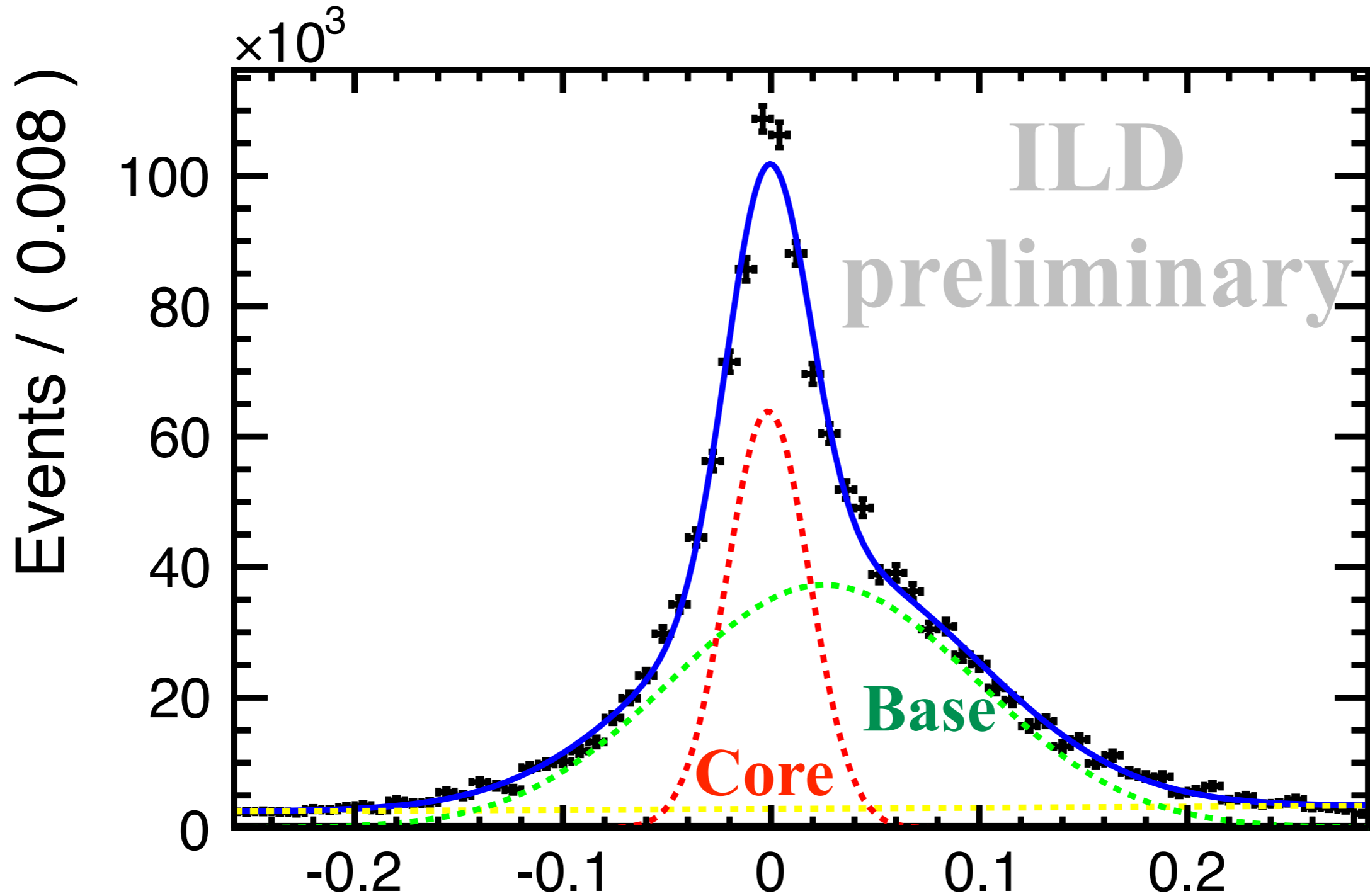


**Reconstructed energy not only can calibrate the measured energy, but also has better resolution.**

Fit the relative difference of reconstructed jet energy with

**Gaus (Core)+Gaus (Base)+exponential**

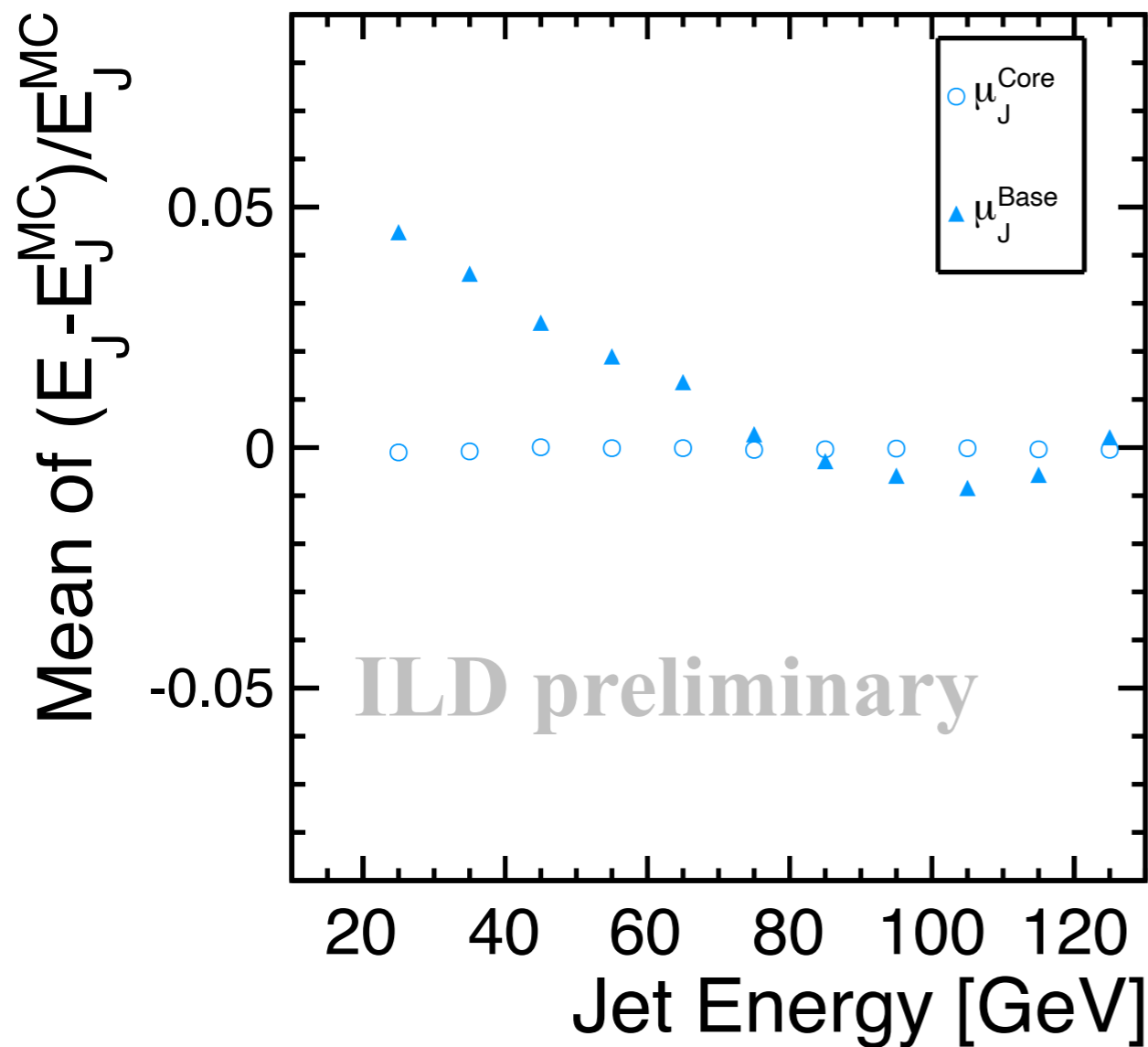
Calibration is based on **the mean value of the Gaus (Core)**.



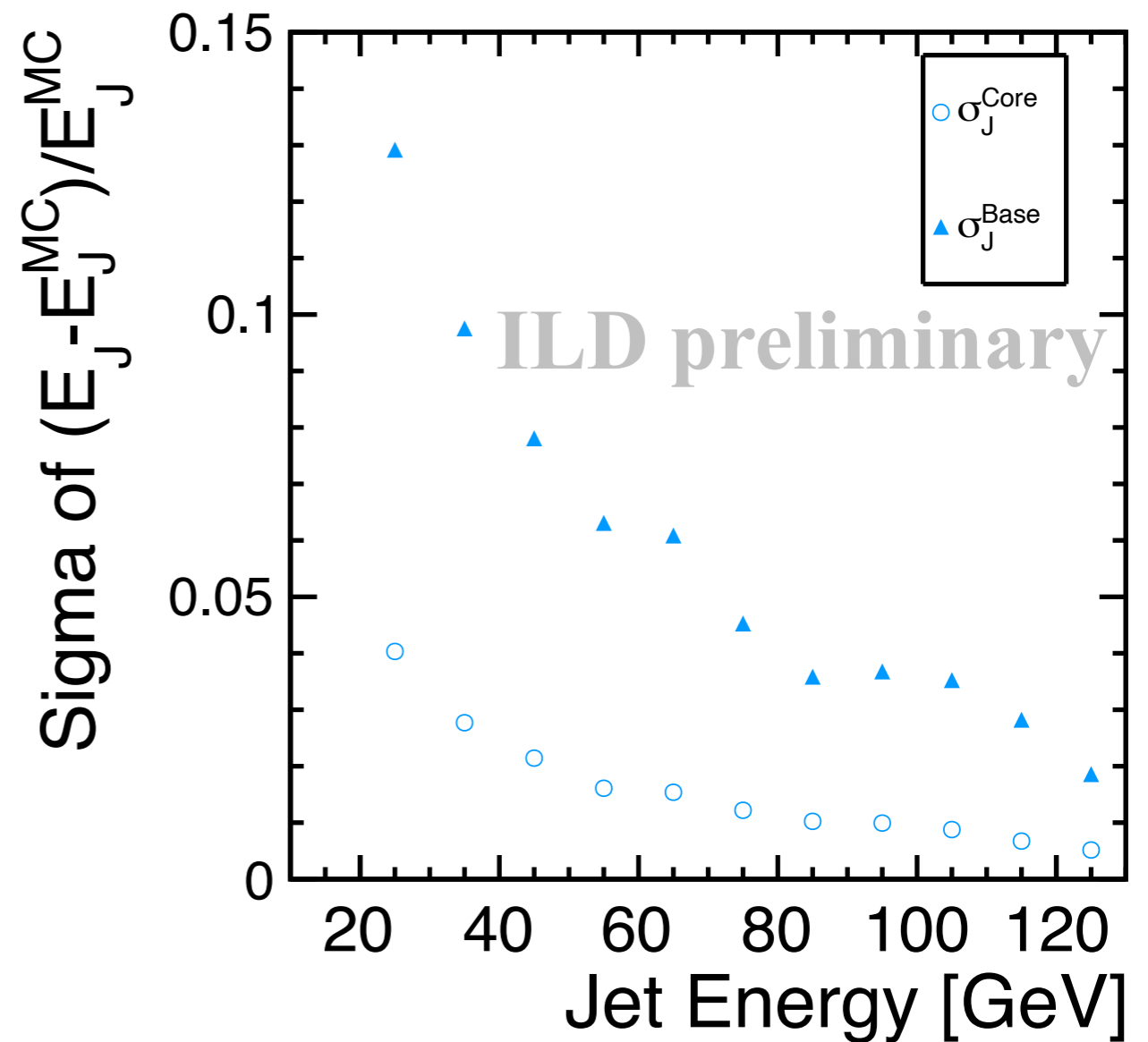
-> Check the **theta and energy** dependence.

# Mean and Sigma Energy Dependence <sup>14</sup>

## Mean of the Fitting Gaussian



## Sigma of the Fitting Gaussian

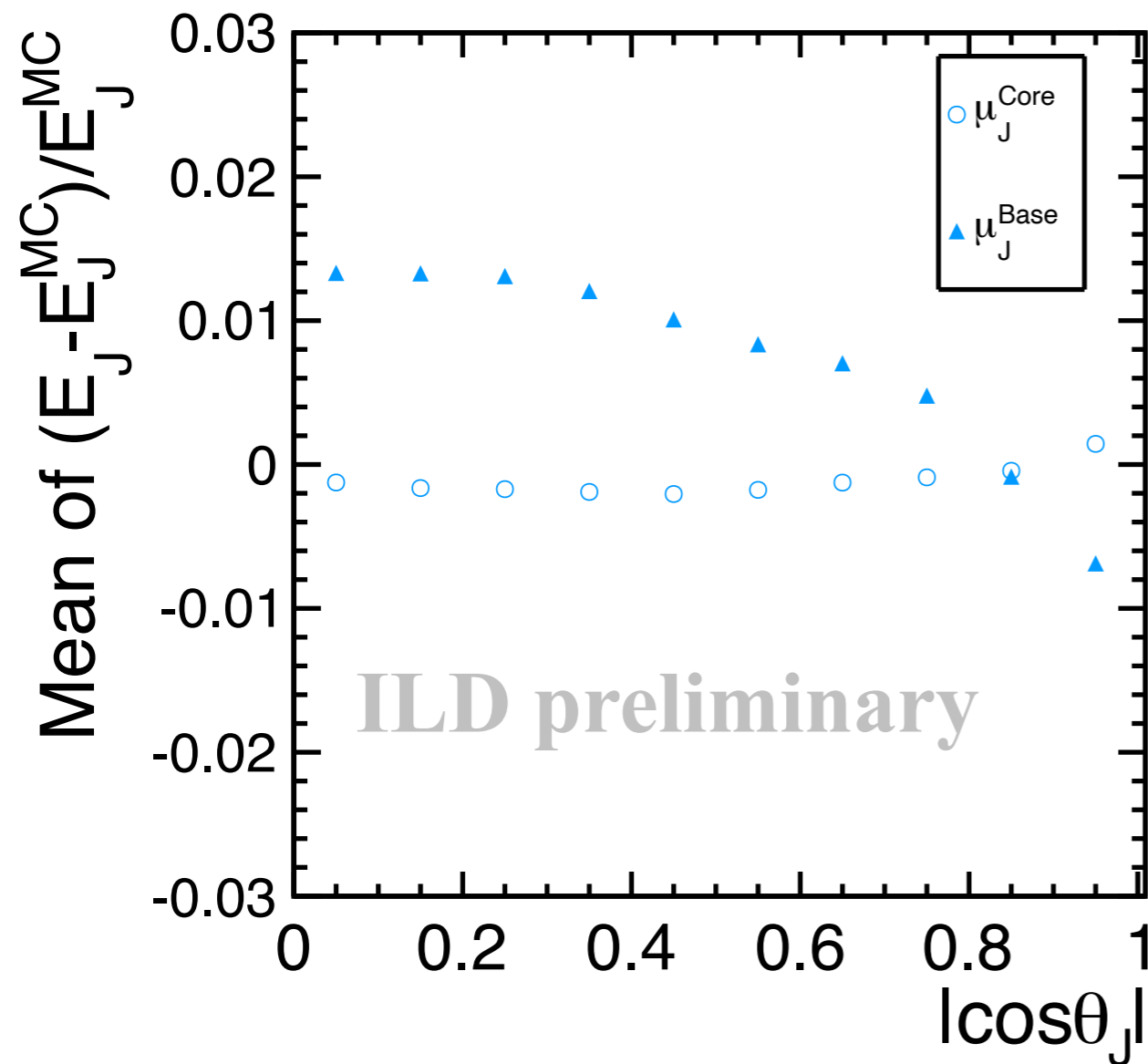


Mean value of **the core gaussian** is order of  $10^{-4}$  independent on the jet energy.

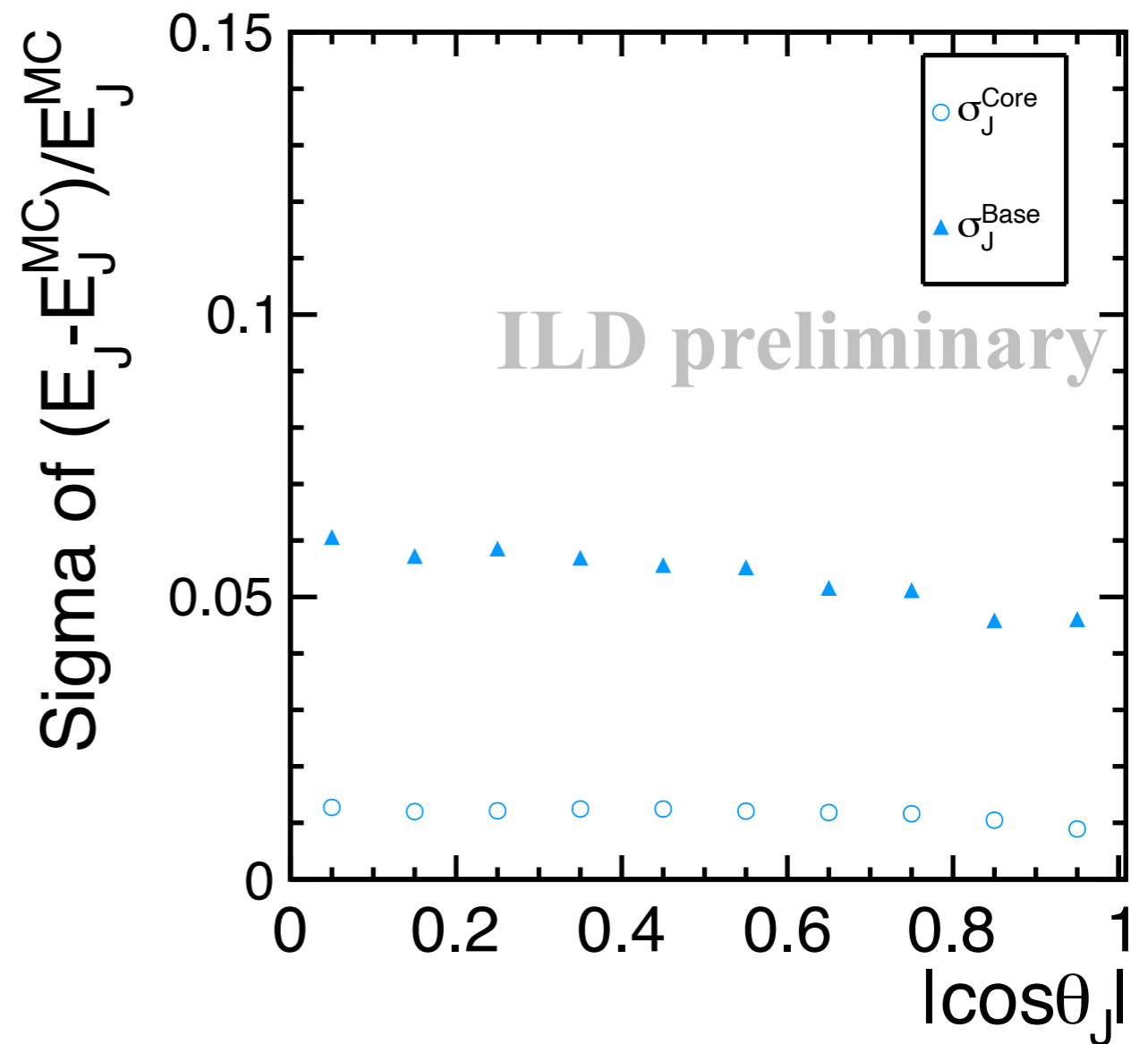
Sigma value is smaller in the higher energy.

# Mean and Sigma Polar Angle Dependence<sup>15</sup>

## Mean of the Fitting Gaussian



## Sigma of the Fitting Gaussian



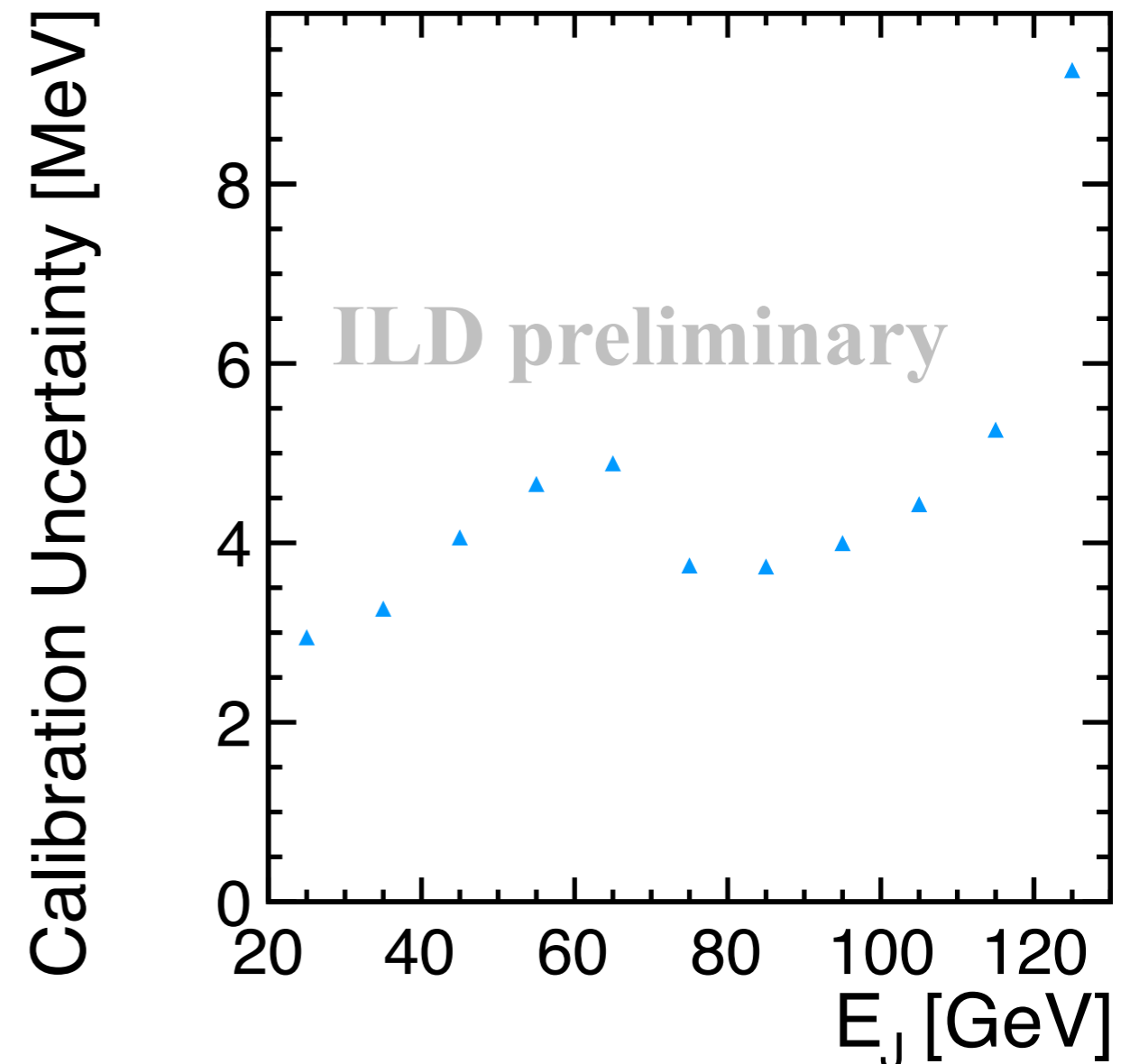
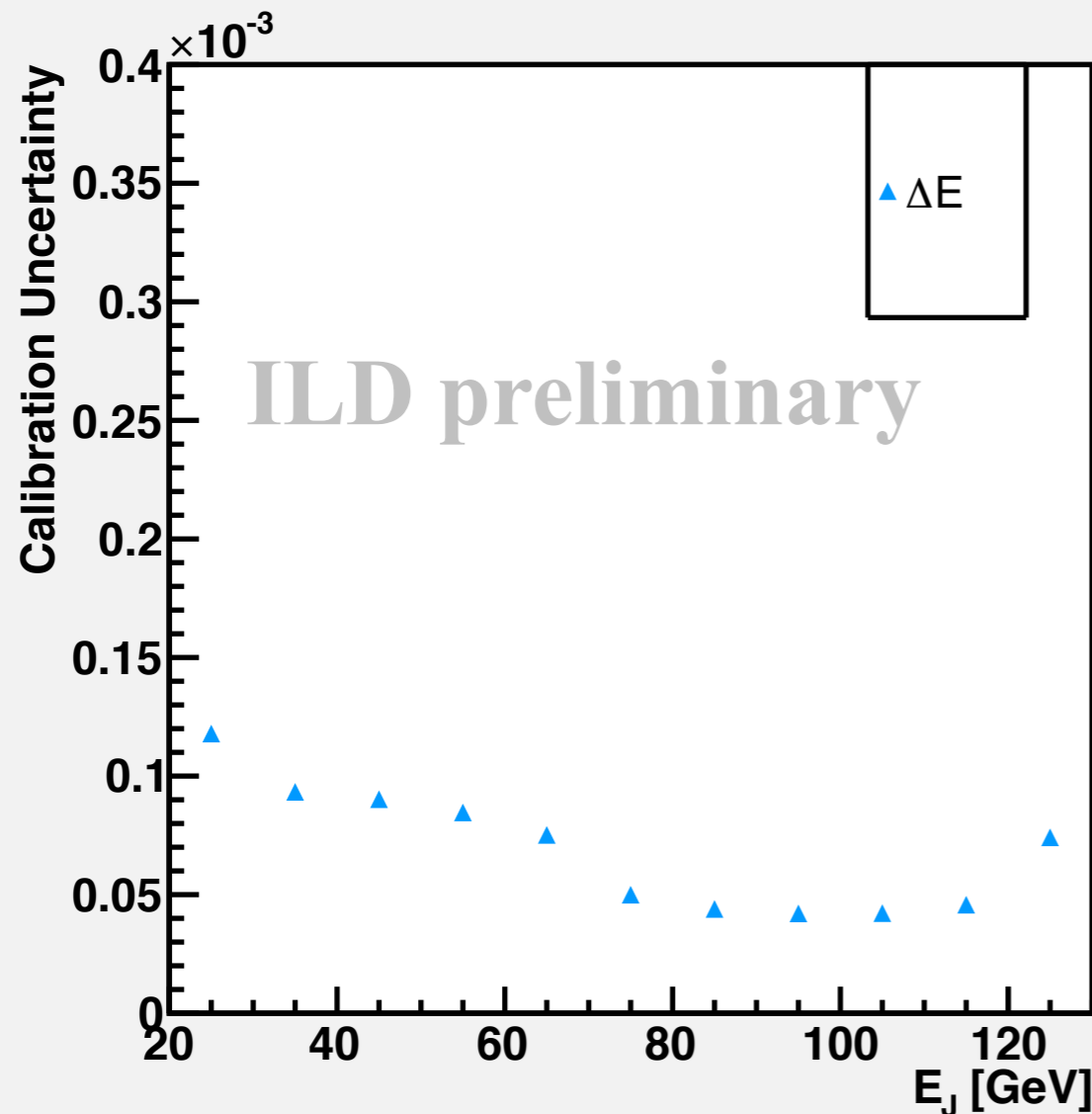
Forward jet makes slight positive bias on the core gaussian and barrel region jet makes slight negative bias on **the core gaussian**.

# 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.**

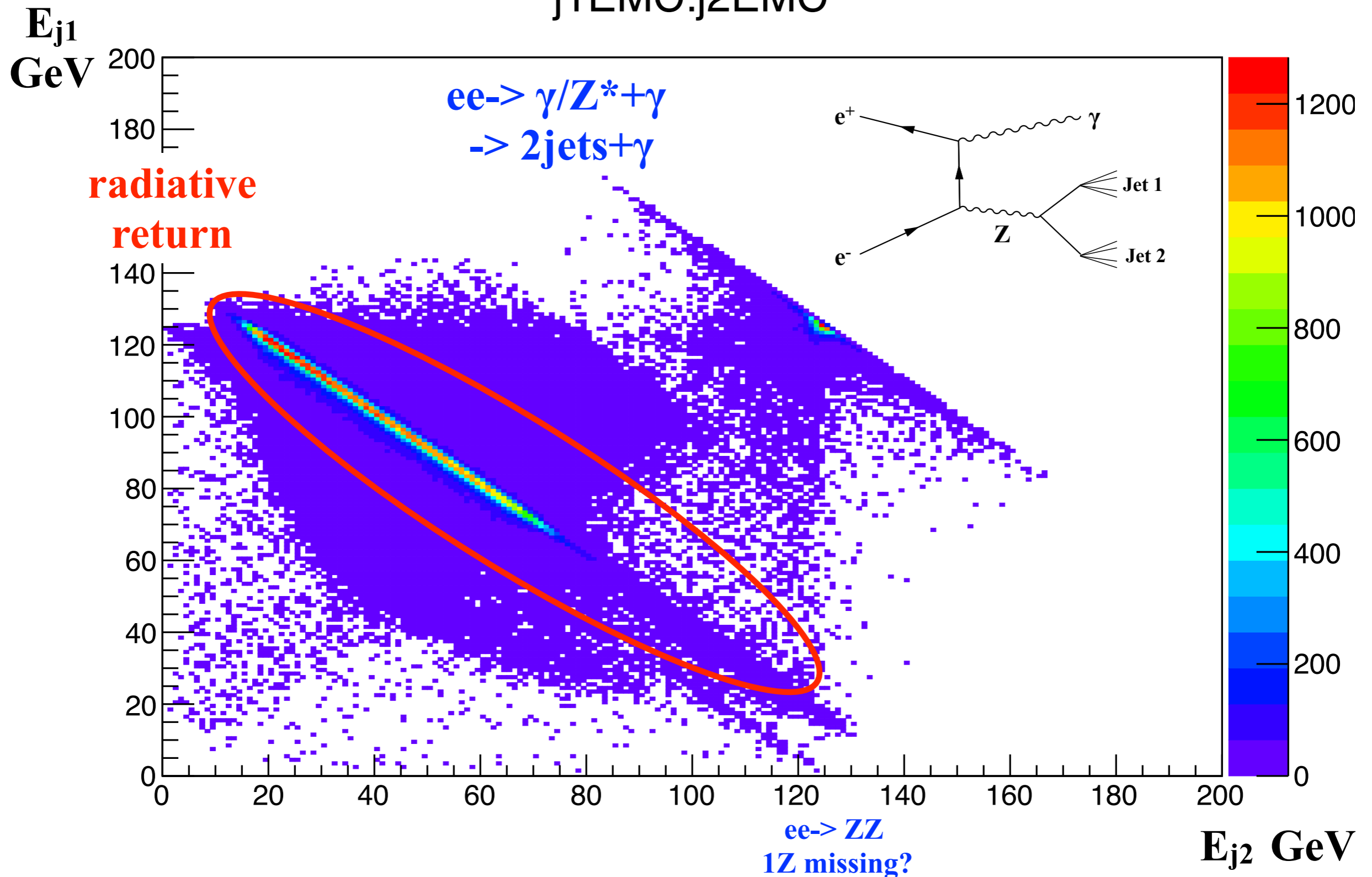
# Conclusion

- Full simulation is performed in order to reconstruct the jet energy using the  $e^+e^- \rightarrow \gamma Z, Z \rightarrow 2 \text{ Jets}$  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. It is  $<10^{-4}$  accuracy which corresponds to several MeV.

# Backup

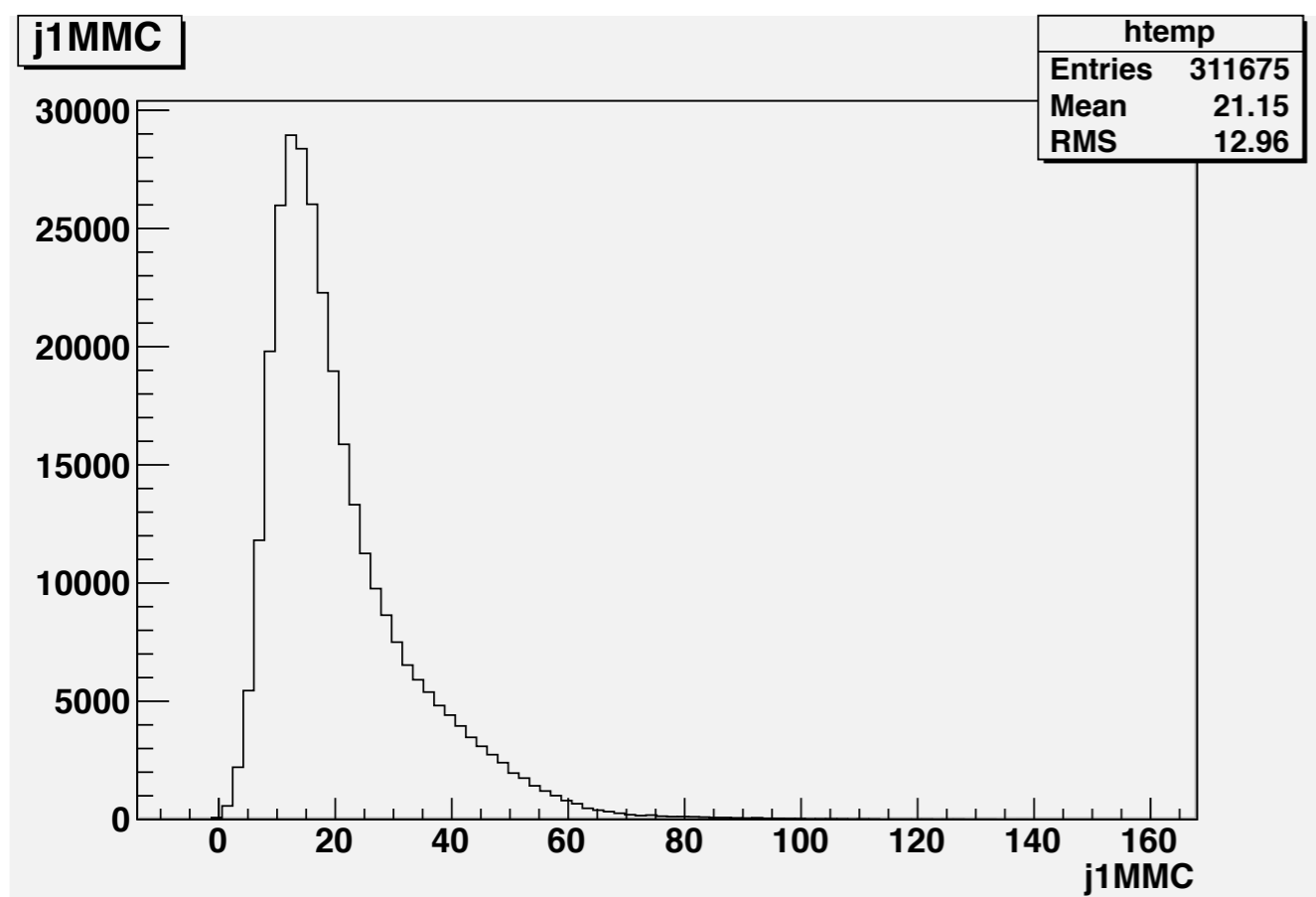
# Jet energy distribution

j1EMC:j2EMC



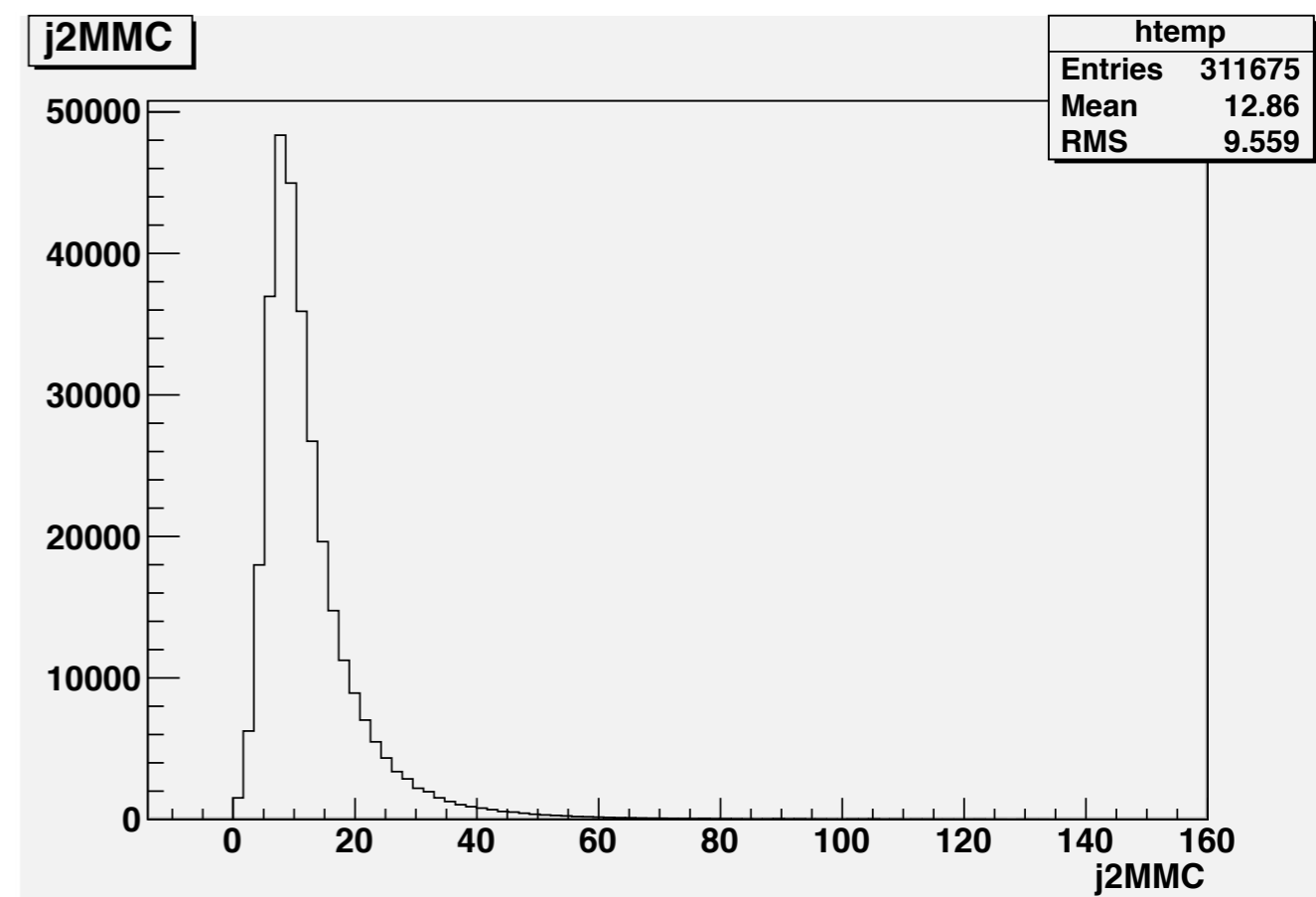
# Jet mass distribution

## Jet1



**$M_{\text{Jet1}}$  GeV**

## Jet2



**$M_{\text{Jet2}}$  GeV**

# 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

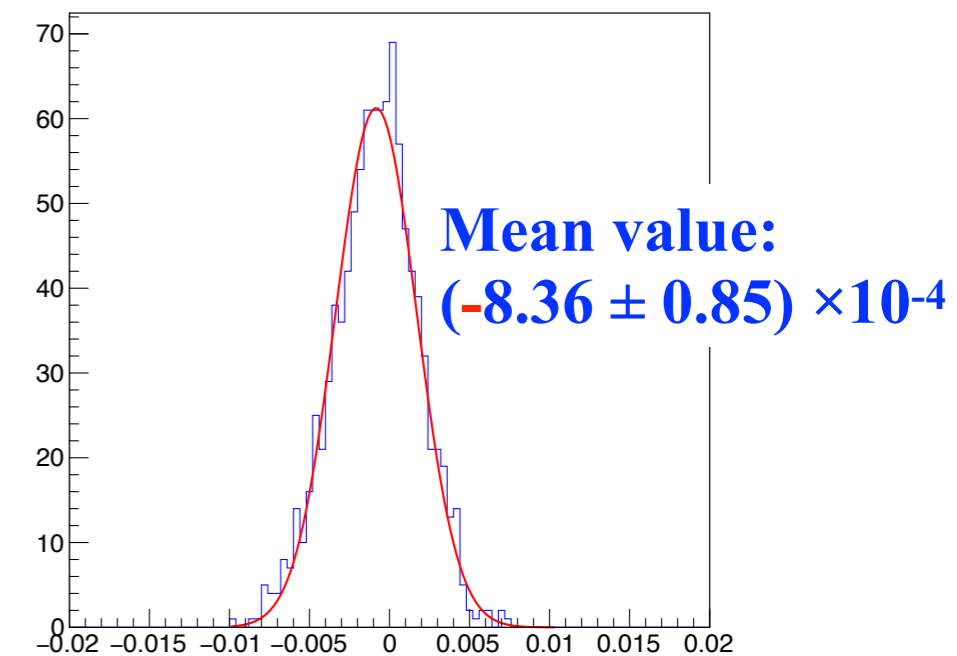
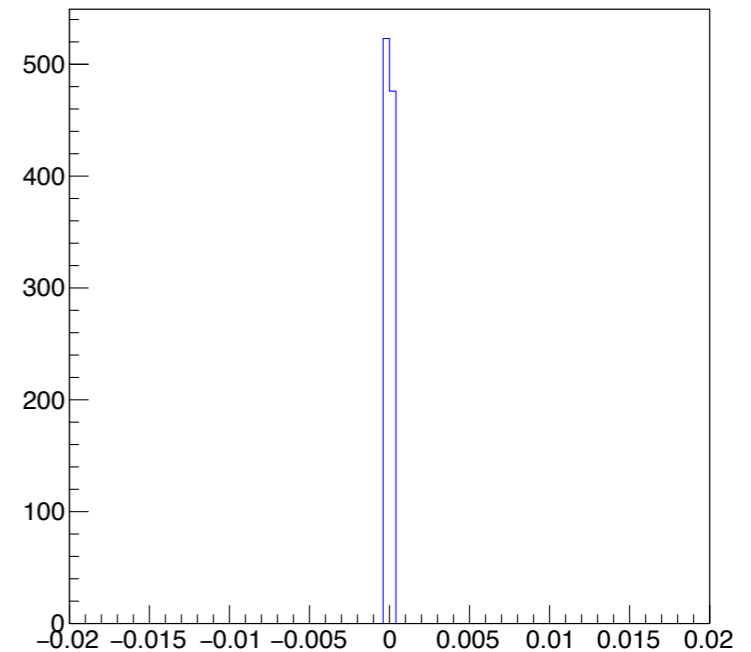
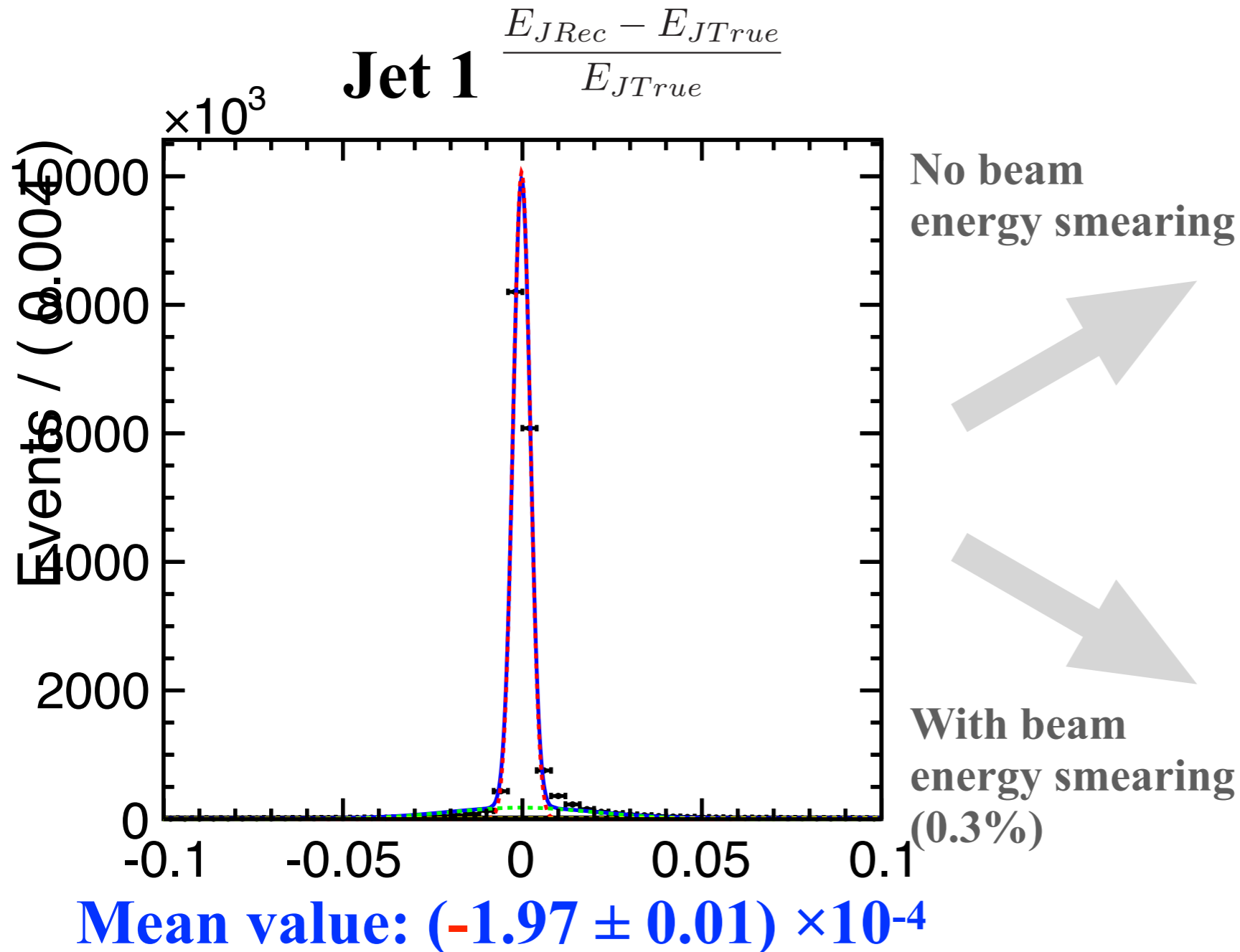
**(A)** Beam energy spread

**(B)** Error of the jet mass inputs

# Source (A): Beam energy spread

When all inputs are all MCtruth,

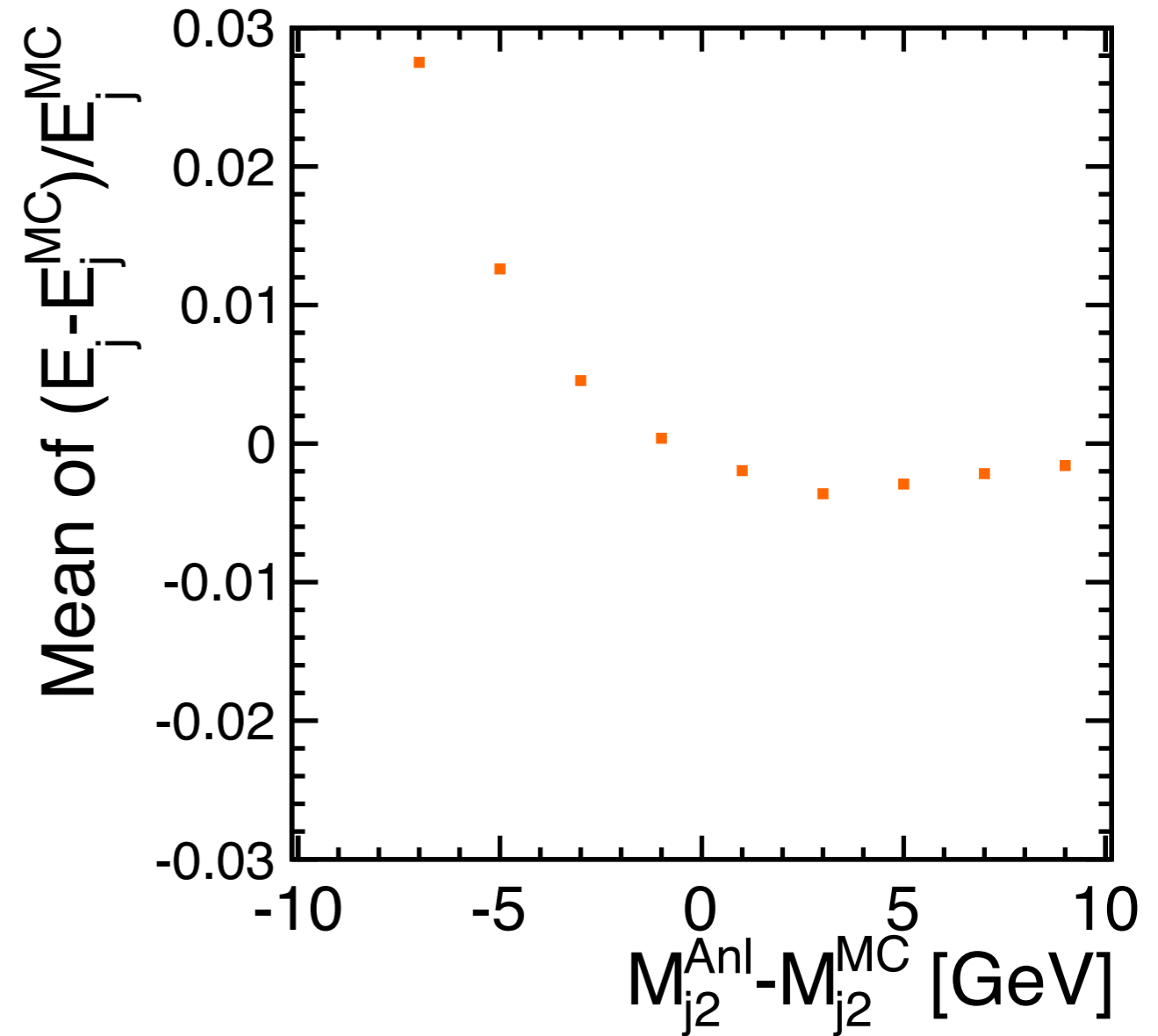
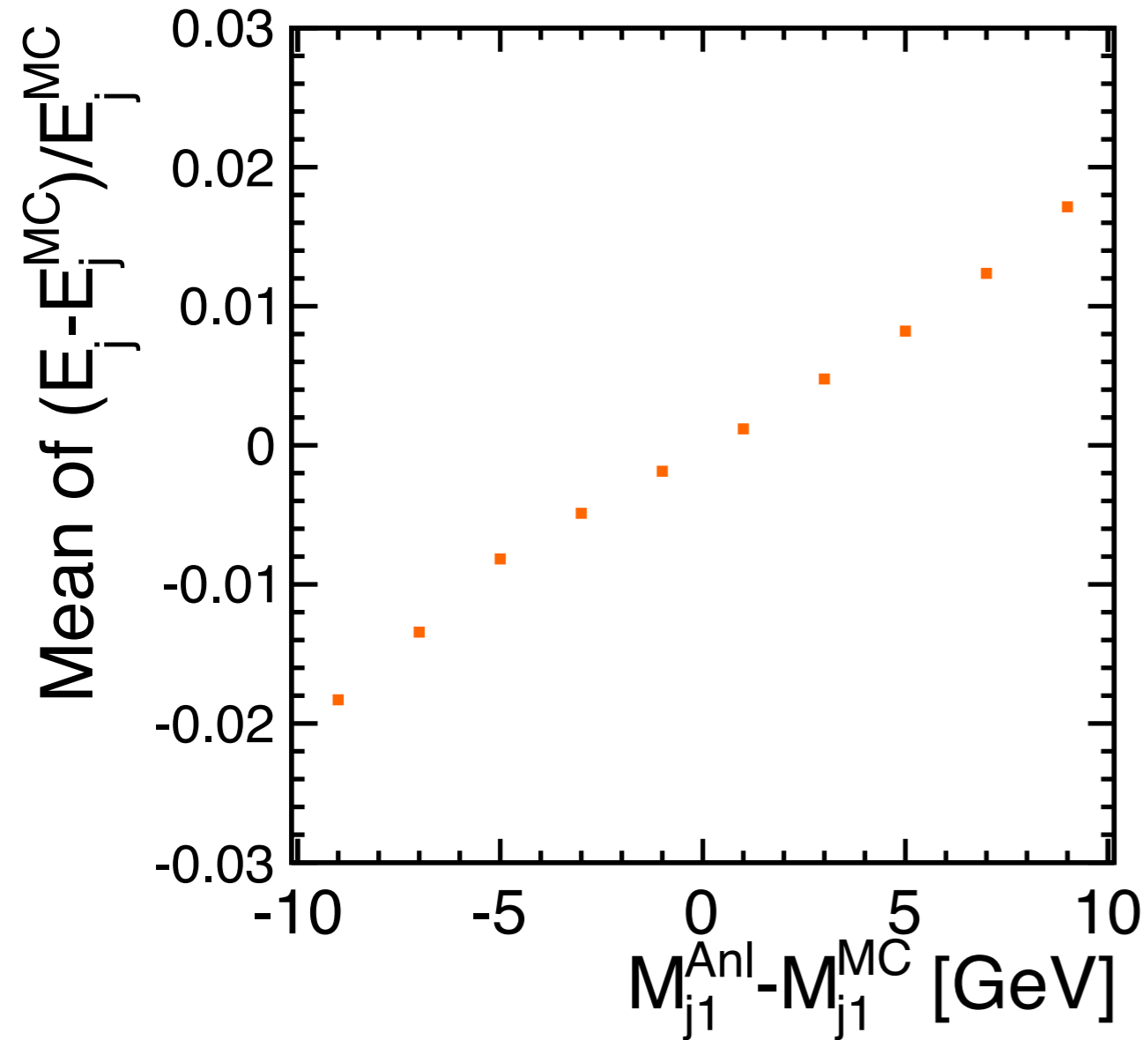
Toy MC Simulation



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 inputs<sup>23</sup>

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.**