ILCにおける$e^+e^- \to \gamma Z$反応を用いた測定器較正シミュレーション

総合研究大学院大学 高エネルギー加速器科学研究科

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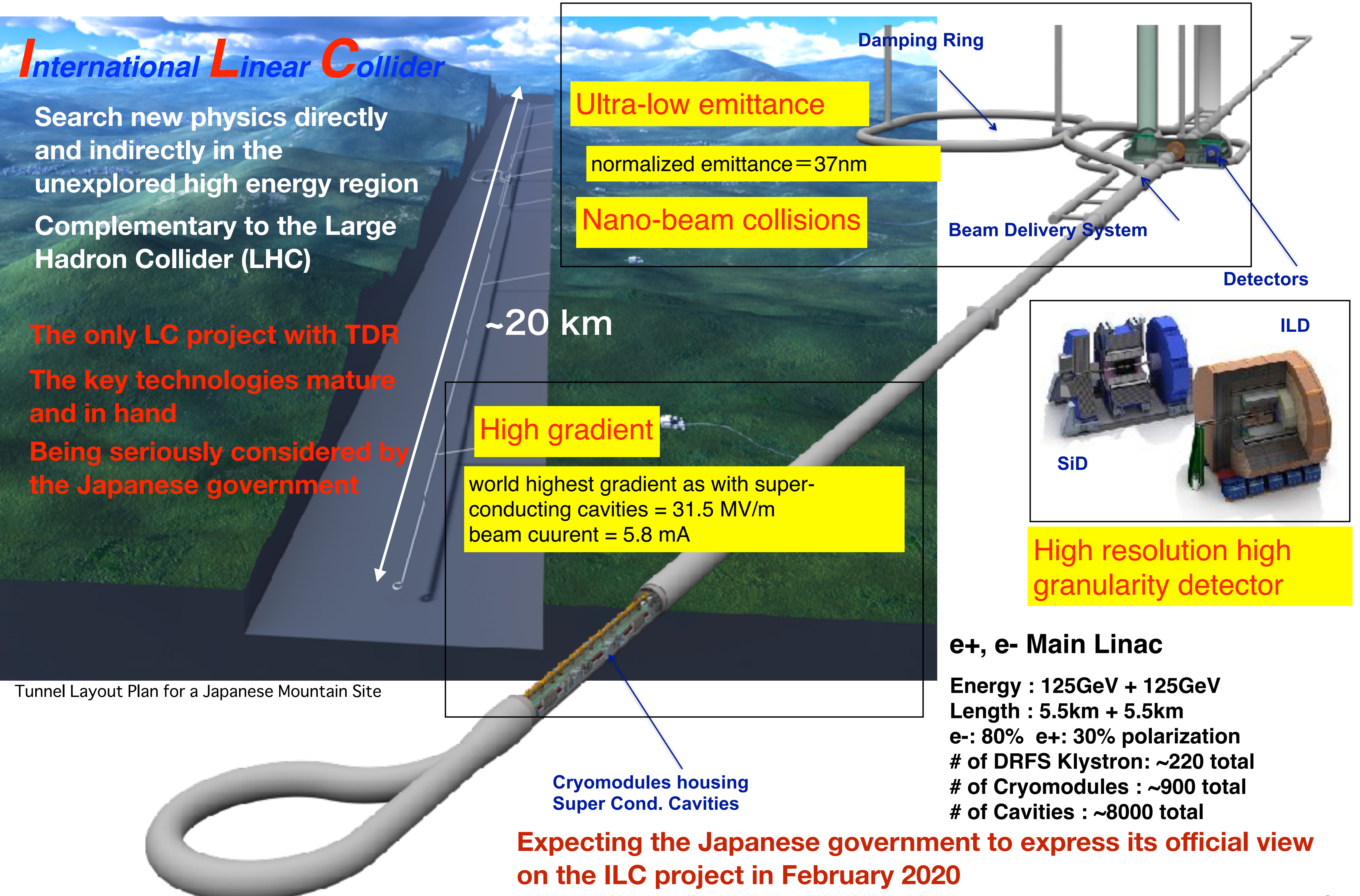
Bird’s Eye View of the ILC Accelerator



Tunnel Layout Plan for a Japanese Mountain Site

International Linear Collider

Search new physics directly and indirectly in the unexplored high energy region

Complementary to the Large Hadron Collider (LHC)

The only LC project with TDR

The key technologies mature and in hand

Being seriously considered by the Japanese government

Ultra-low emittance

normalized emittance＝37nm

Nano-beam collisions

High gradient

world highest gradient as with super-conducting cavities = 31.5 MV/m
beam cuurent = 5.8 mA

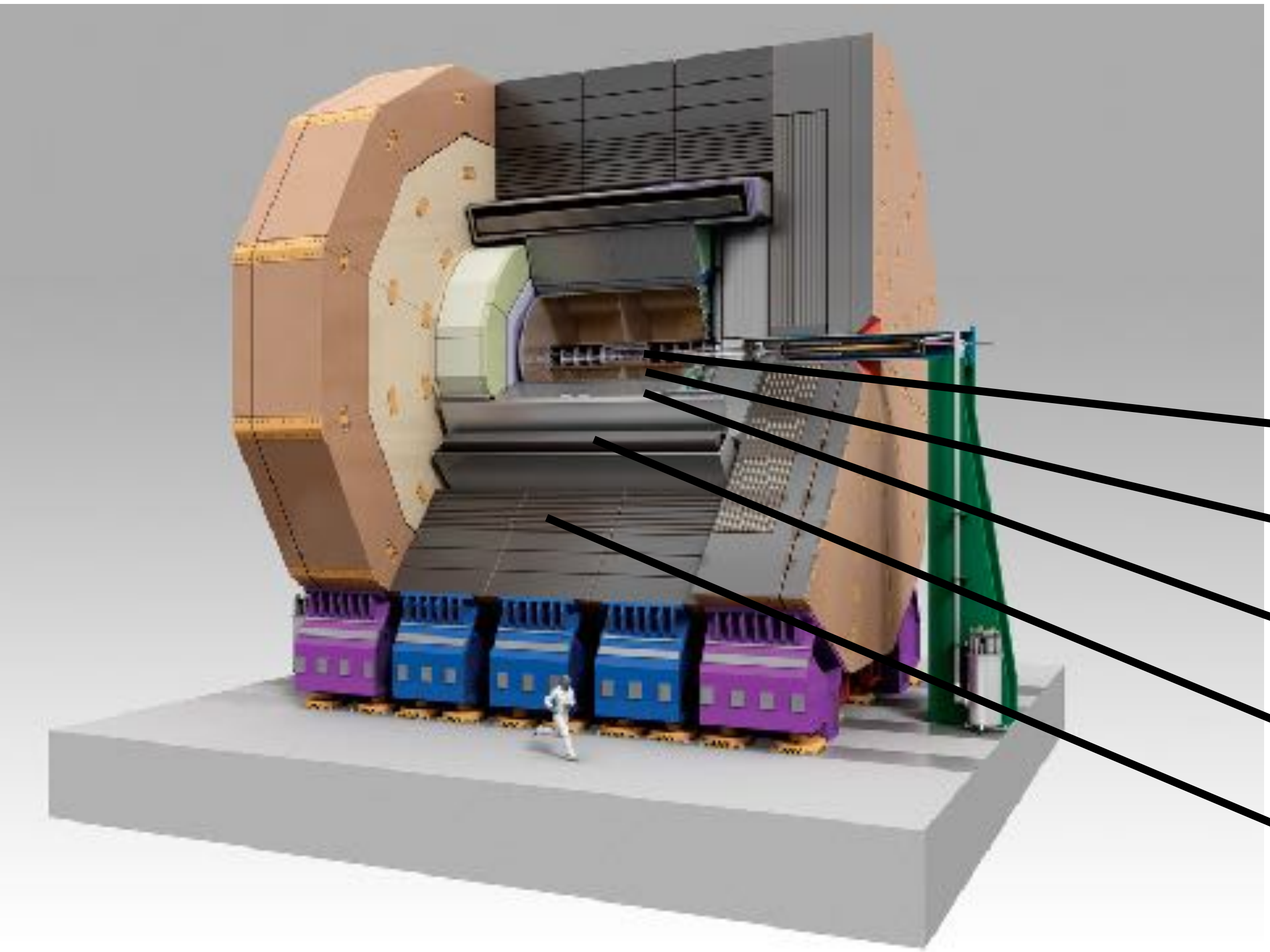
High resolution high granularity detector

e+, e- Main Linac

Energy : 125GeV + 125GeV
Length : 5.5km + 5.5km
e-: 80% e+: 30% polarization
# of DRFS Klystron: ~220 total
# of Cryomodules : ~900 total
# of Cavities : ~8000 total

Expecting the Japanese government to express its official view on the ILC project in February 2020

International Large Detector (ILD)



A detector concept for the ILC designed for Particle Flow Analysis (PFA)

- Vertex Detector (VTX) -> Heavy Flavor ID
- Time Projection Chamber (TPC) -> Charged Particles
- Electromagnetic Calorimeter (ECAL) -> Photons
- Hadron Calorimeter (HCAL) -> Neutral Hadrons
- Muon Detector -> Muons

Reconstruct final states in terms of fundamental particles

Large ILD model (IDR-L)
TPC outer radius: 180 cm
B Field ~3.5 T

Small ILD model (IDR-S)
TPC outer radius: 146 cm
B Field ~4 T

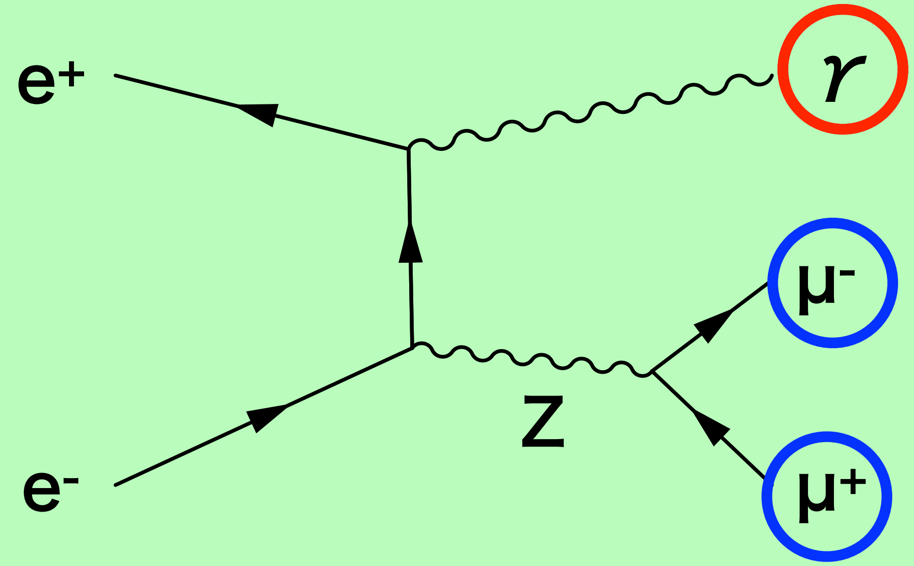
Introduction

Detector Benchmark Motivation

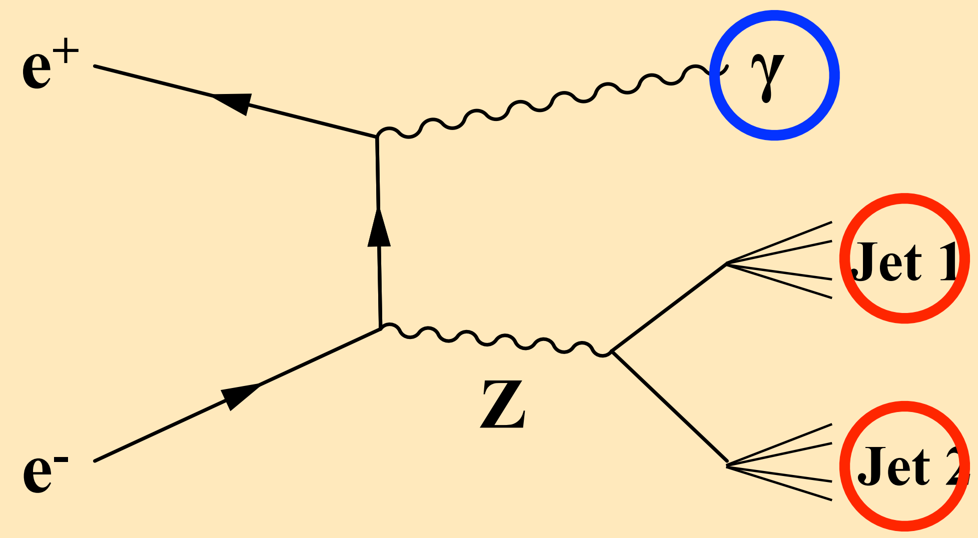
Primary Target of ILC 250: to precisely measure *the coupling constants between Higgs boson and various other particles*
-> For this, we need to precisely calibrate energy scales for various particles.

- In this talk, we focus on photon energy calibration and jet energy calibration (additionally), using the $e^+e^- \rightarrow \gamma Z$ process.

Photon Energy Scale Calibration



Jet Energy Scale Calibration



Introduction

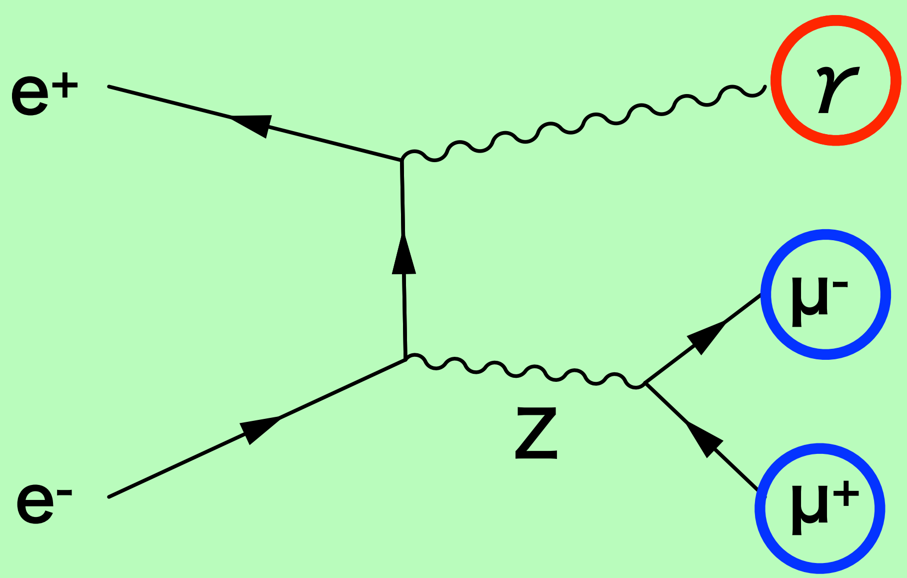
Detector Benchmark Motivation

Primary T... *onstants*
between H...
-> For this ... ious
particles.

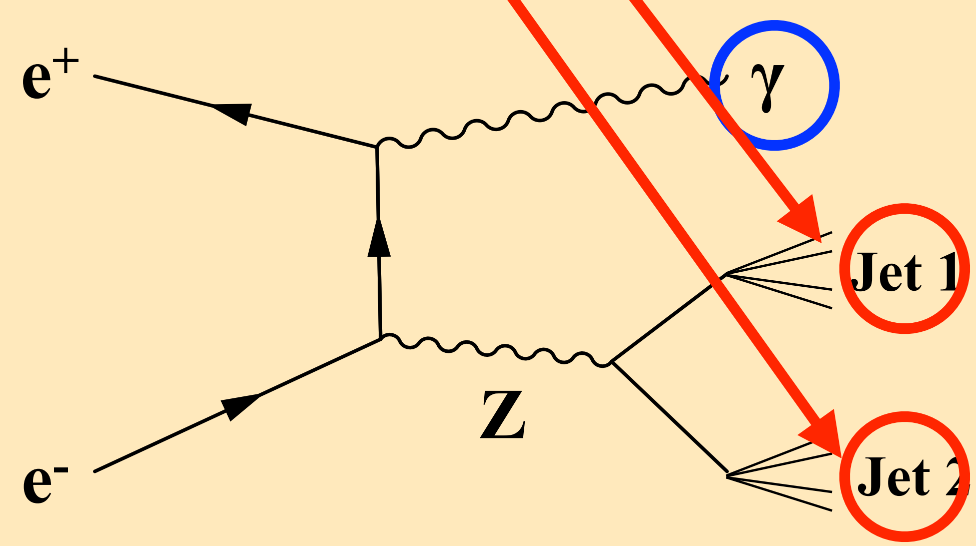
Energy can be reconstructed
using measured direction of γ and μ^- , μ^+
or (γ and 2 jets) information.

- In this talk, we focus on photon energy calibration and jet energy calibration (additionally), using the $e^+e^- \to \gamma Z$ process.

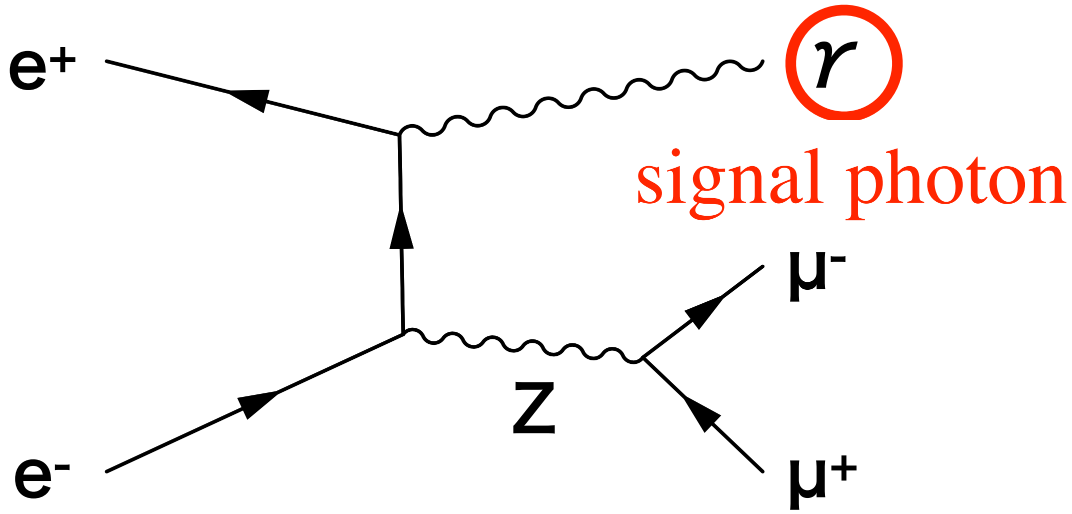
Photon Energy Scale Calibration



Jet Energy Scale Calibration



Photon Energy Reconstruction Method



- 4-momentum conservation is considered.
- The mass of muon is neglected.
- Several reconstruction methods (Method A, B, C) are considered.
- Consider Beamstrahlung and Crossing Angle

Direction Angle
θ: polar angle
ϕ: azimuthal angle

Method A: Using Only Angles
Using (θ_{μ^-}, θ_{μ^+}, θ_γ, φ_{μ^-}, φ_{μ^+}, φ_γ) -> Determine (E_{μ^-}, E_{μ^+}, E_γ, E_{ISR})

$$\begin{cases} E_\mu + E_{\mu^+} + E_\gamma + |P_{ISR}| = 500 \\ E_\mu sin\theta_\mu cos\phi_\mu + E_{\mu^+} sin\theta_{\mu^+} cos\phi_{\mu^+} + E_\gamma sin\theta_\gamma cos\phi_\gamma + |P_{ISR}| sin\alpha = 500 sin\alpha \\ E_\mu sin\theta_\mu sin\phi_\mu + E_{\mu^+} sin\theta_{\mu^+} sin\phi_{\mu^+} + E_\gamma sin\theta_\gamma sin\phi_\gamma = 0 \\ E_\mu cos\theta_\mu + E_{\mu^+} cos\theta_{\mu^+} + E_\gamma cos\theta_\gamma \pm |P_{ISR}| cos\alpha = 0 \end{cases}$$

ISR photon = **additional** unseen photon

Beam Crossing Angle (≡2α)
α = 7.0 mrad

Reconstruction Method

Method B, C: Also using Muons' Energies
Using ($\theta_{\mu-}, \theta_{\mu+}, \theta_\gamma, \varphi_{\mu-}, \varphi_{\mu+}, \varphi_\gamma, E_{\mu-}, E_{\mu+}$) -> Determine ($E_\gamma, E_{ISR}$)

- **Method B: Energy and Pz Conservation**

$$\begin{cases} E_\mu + E_{\mu^+} + E_\gamma + |P_{ISR}| = 500 \\ E_\mu sin\theta_\mu cos\phi_\mu + E_{\mu^+} sin\theta_{\mu^+} cos\phi_{\mu^+} + E_\gamma sin\theta_\gamma cos\phi_\gamma + |P_{ISR}| sin\alpha = 500 sin\alpha \\ E_\mu sin\theta_\mu sin\phi_\mu + E_{\mu^+} sin\theta_{\mu^+} sin\phi_{\mu^+} + E_\gamma sin\theta_\gamma sin\phi_\gamma = 0 \\ E_\mu cos\theta_\mu + E_{\mu^+} cos\theta_{\mu^+} + E_\gamma cos\theta_\gamma \pm |P_{ISR}| cos\alpha = 0 \end{cases}$$

Need to decide P_{ISR}.

- **Method C: Energy and Py Conservation**

$$\begin{cases} E_\mu + E_{\mu^+} + E_\gamma + |P_{ISR}| = 500 \\ E_\mu sin\theta_\mu cos\phi_\mu + E_{\mu^+} sin\theta_{\mu^+} cos\phi_{\mu^+} + E_\gamma sin\theta_\gamma cos\phi_\gamma + |P_{ISR}| sin\alpha = 500 sin\alpha \\ E_\mu sin\theta_\mu sin\phi_\mu + E_{\mu^+} sin\theta_{\mu^+} sin\phi_{\mu^+} + E_\gamma sin\theta_\gamma sin\phi_\gamma = 0 \\ E_\mu cos\theta_\mu + E_{\mu^+} cos\theta_{\mu^+} + E_\gamma cos\theta_\gamma \pm |P_{ISR}| cos\alpha = 0 \end{cases}$$

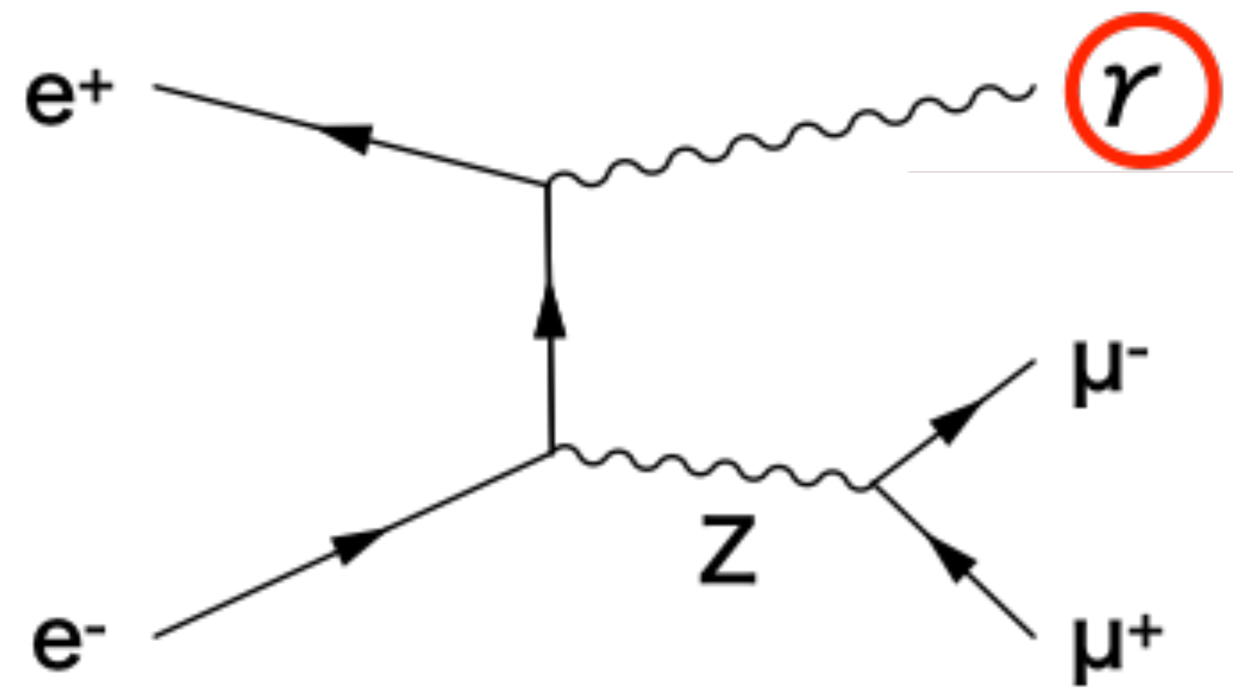
This is of no use when $sin\theta_\gamma$ or $sin\varphi_\gamma = 0$??

However, photon energy can be determined without calculating P_{ISR}.

Simulation Setup

Full simulation (ILCSOFT version v02-00-02)

- Event generation by Whizard 1.95 with beamstrahlung and additional ISR photon effects
- Geant4 based full simulation of 2 realistic detector models IDR-L and IDR-S
- realistic event reconstruction from detector signals



Signal sample: $e^+e^- \rightarrow \gamma Z, Z \rightarrow l^+l^-$

E_{CM} of e^+e^- is 500 GeV.

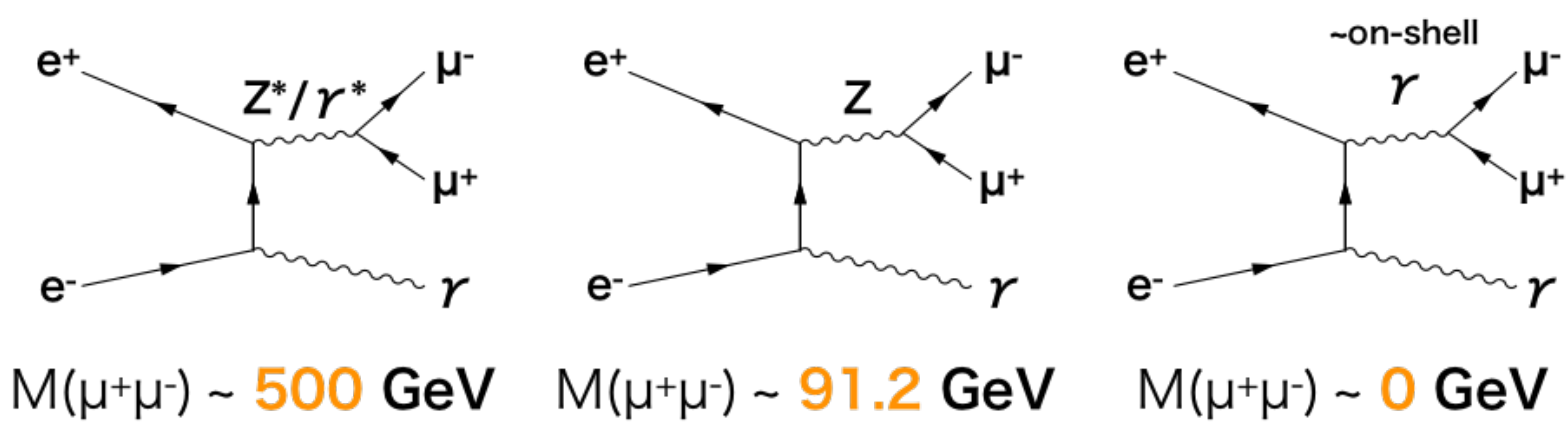
Two detector models IDR-L and IDR-S are compared.

Event Selection

Signatures of the signal events:
$\mu^+\mu^-$ pair (inv. mass ~Z boson) + one energetic isolated photon

In order to pick up our required process, following cuts are applied.

Step1: Select events with two isolated muons.
-> 3 types of events remain:



Event Selection

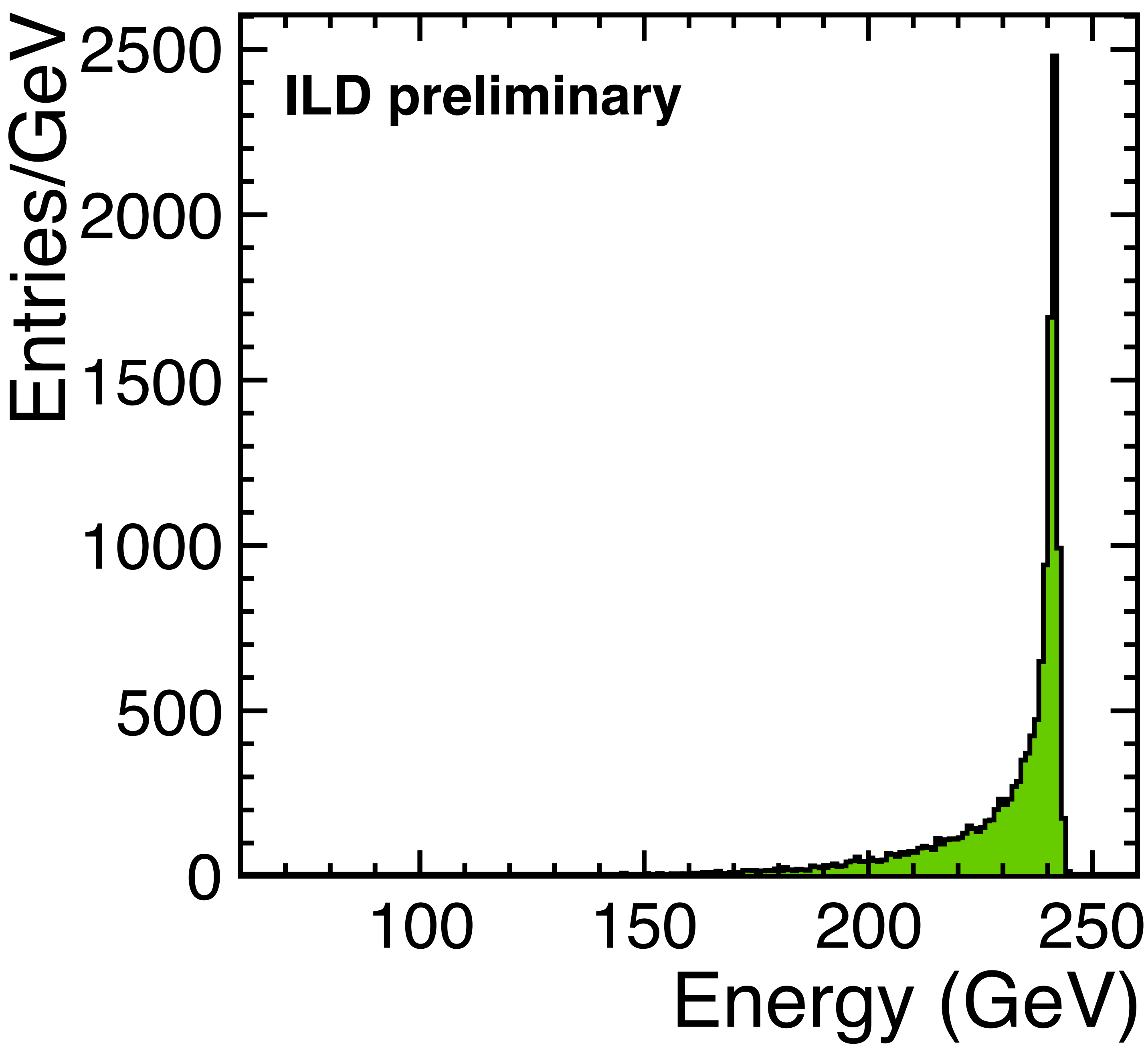
Step2:

- Require invariant mass of two muons $M(\mu^{+}\mu^{-})$ to satisfy $|M(\mu^{+}\mu^{-}) - 91.2| < 10$ GeV

Step3:

- Demand events to have one isolated photon with more than 50 GeV

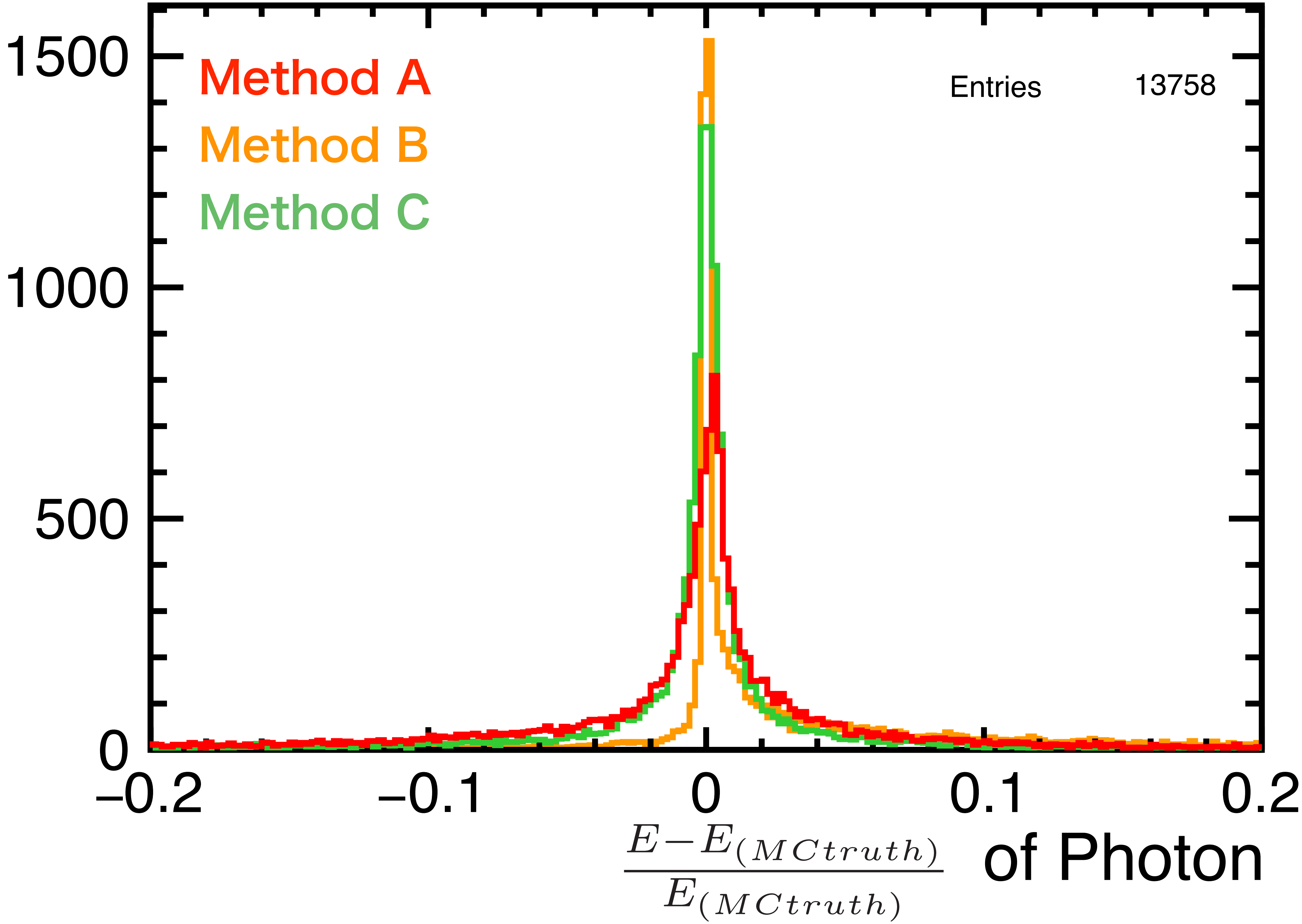
MCTruth Energy of Photon



Method Comparison

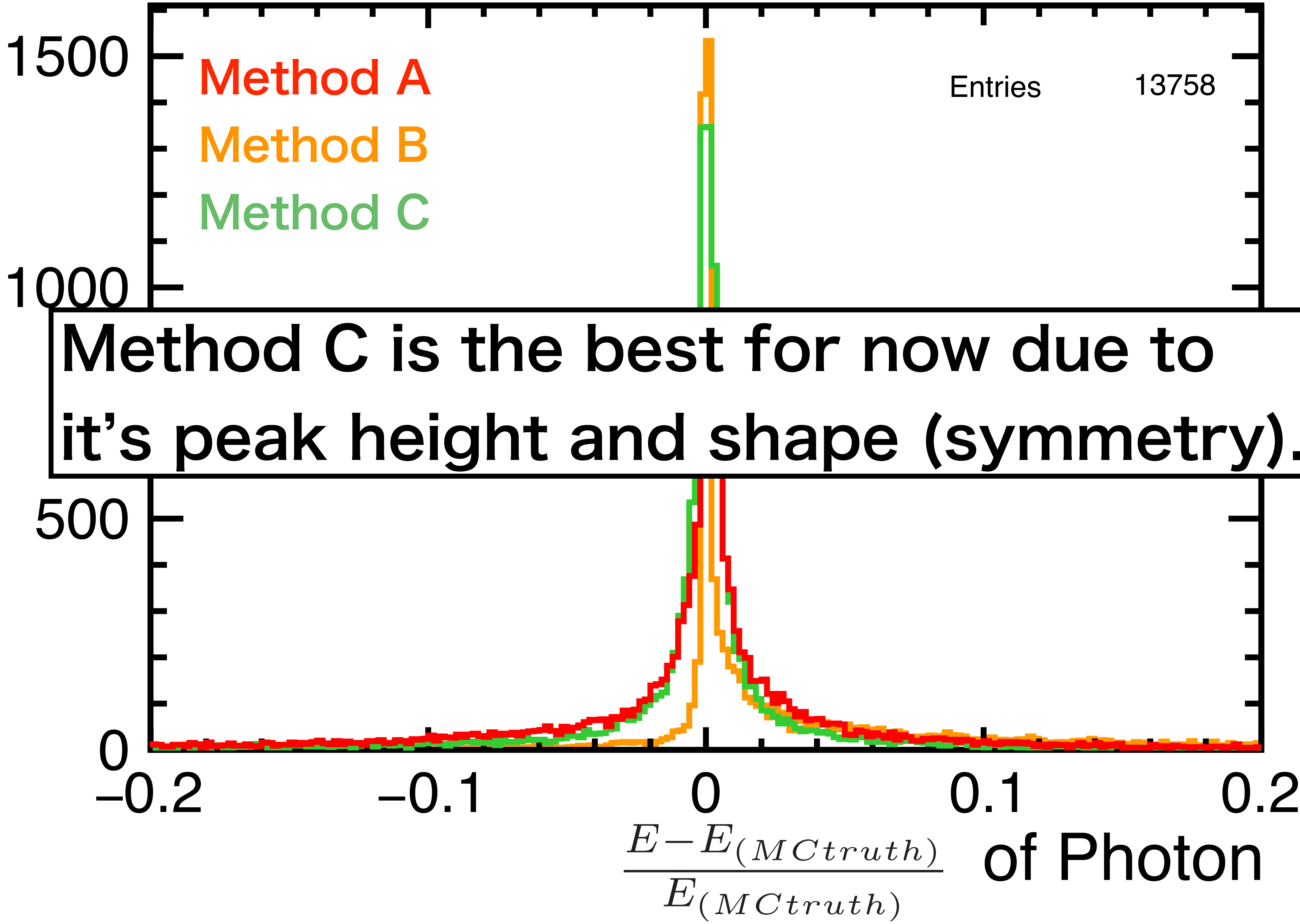
$\frac{E - E_{(MCtruth)}}{E_{(MCtruth)}}$ of Photon

Samples:
|M(μ+μ-)-91.2| < 10 GeV
Large ILD model



Method Comparison $\frac{E - E_{(MCtruth)}}{E_{(MCtruth)}}$ of Photon

Samples:
$|M(\mu^+\mu^-) - 91.2| < 10$ GeV
Large ILD model

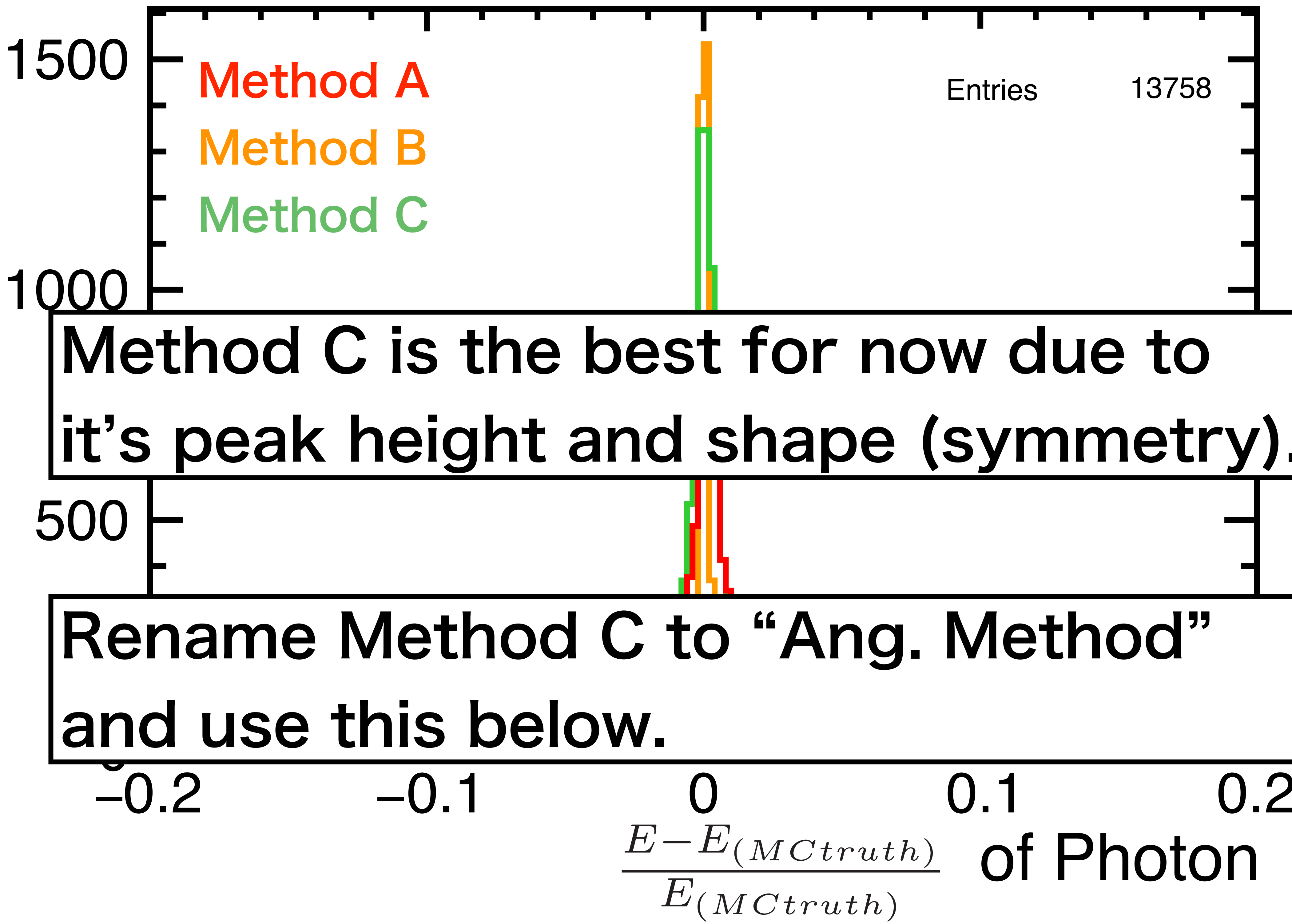


Method C is the best for now due to it's peak height and shape (symmetry).

Method Comparison

$\frac{E-E_{(MCtruth)}}{E_{(MCtruth)}}$ of Photon

Samples:
$|M(\mu^+\mu^-)-91.2| < 10$ GeV
Large ILD model



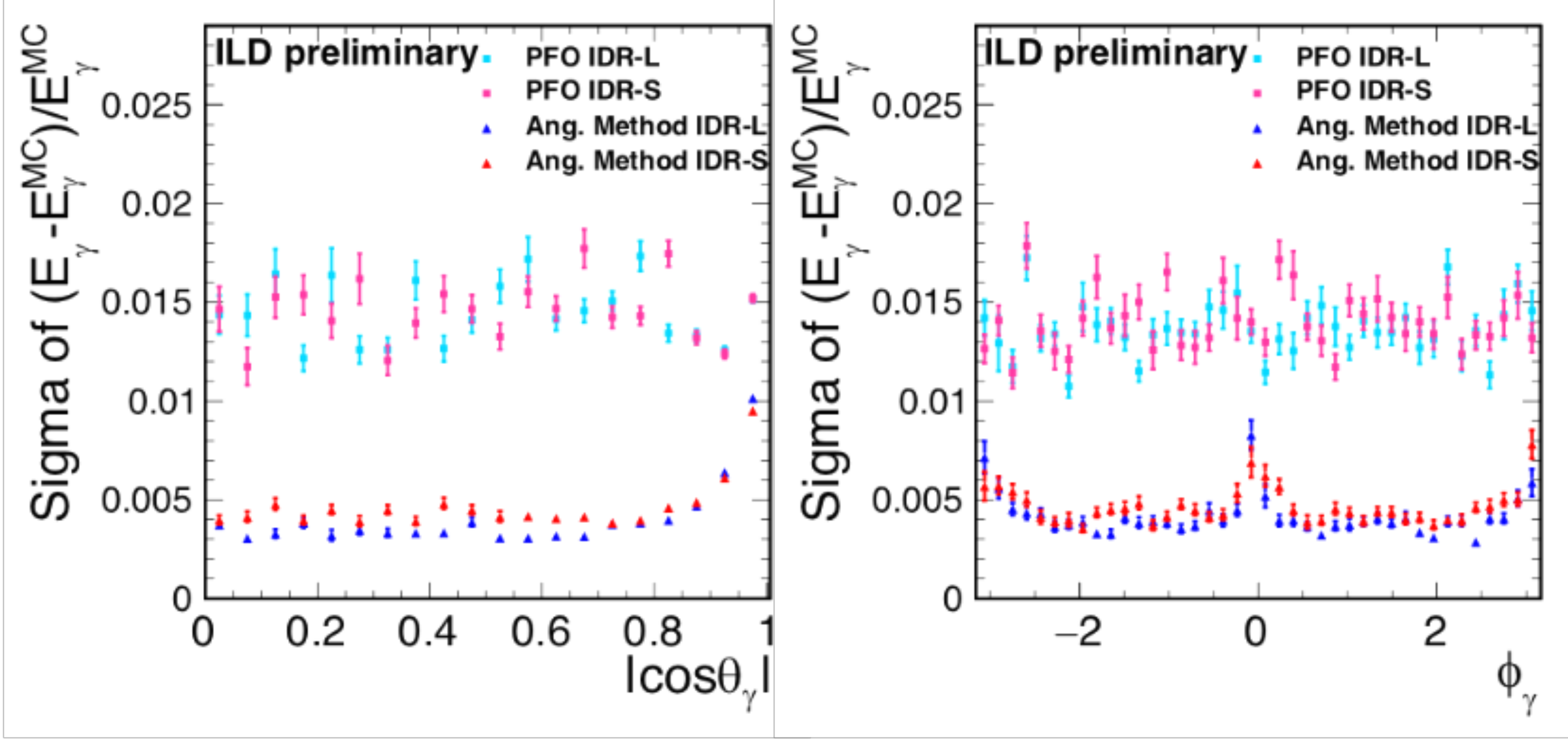
Method C is the best for now due to it’s peak height and shape (symmetry).

Rename Method C to “Ang. Method” and use this below.

Demonstration of the Validity of Ang. Method

Sigma of $(E-E_{MC})/E_{MC}$
dependence on $|\cos\theta_\gamma|$

dependence on φ_γ

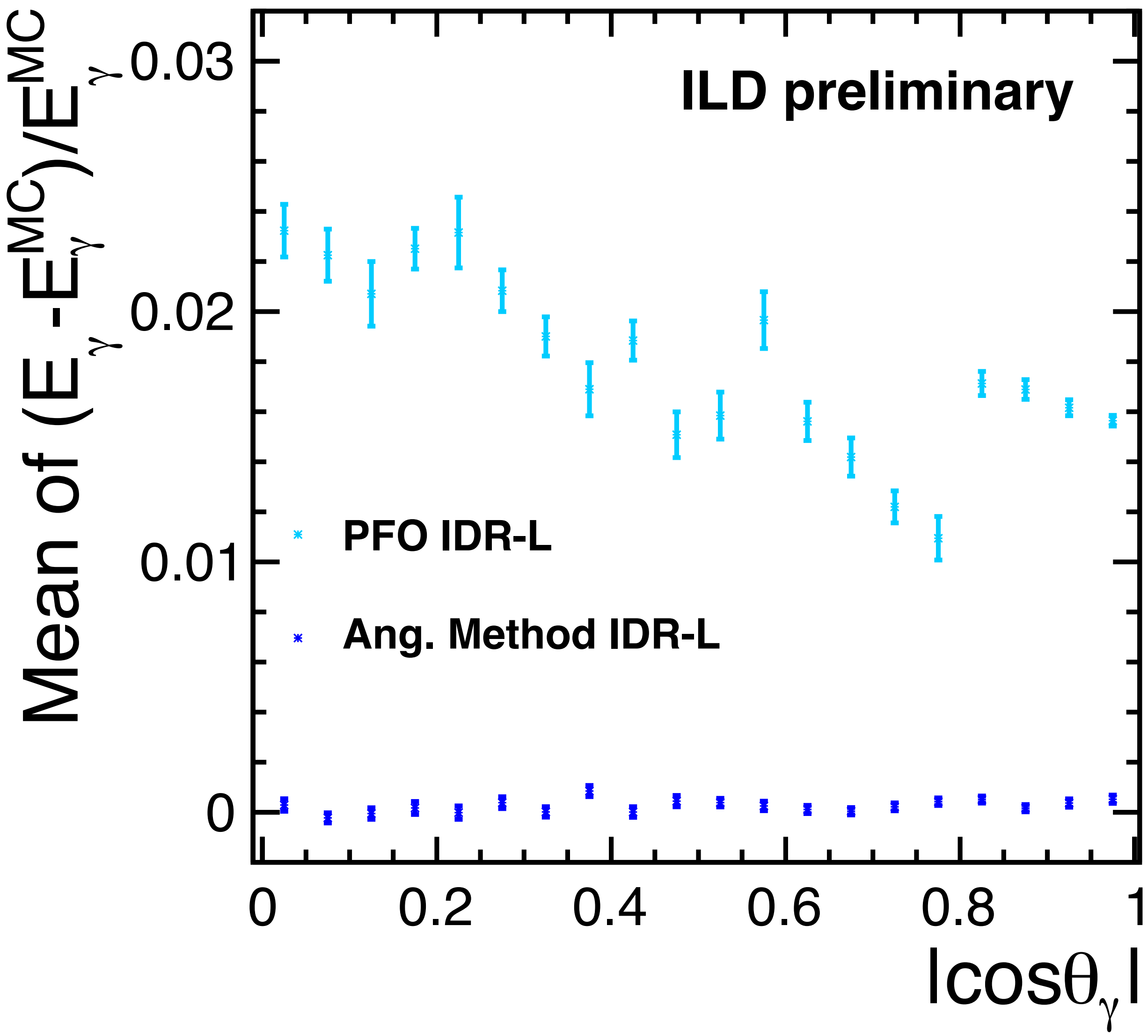


$|\cos\theta\gamma| < 0.95$

$\pi/40 < |\phi\gamma| < 39\pi/40$

Calibration of the Measured Energy

- It is shown that the PFO has large dependence on $|\cos\theta_\gamma|$.



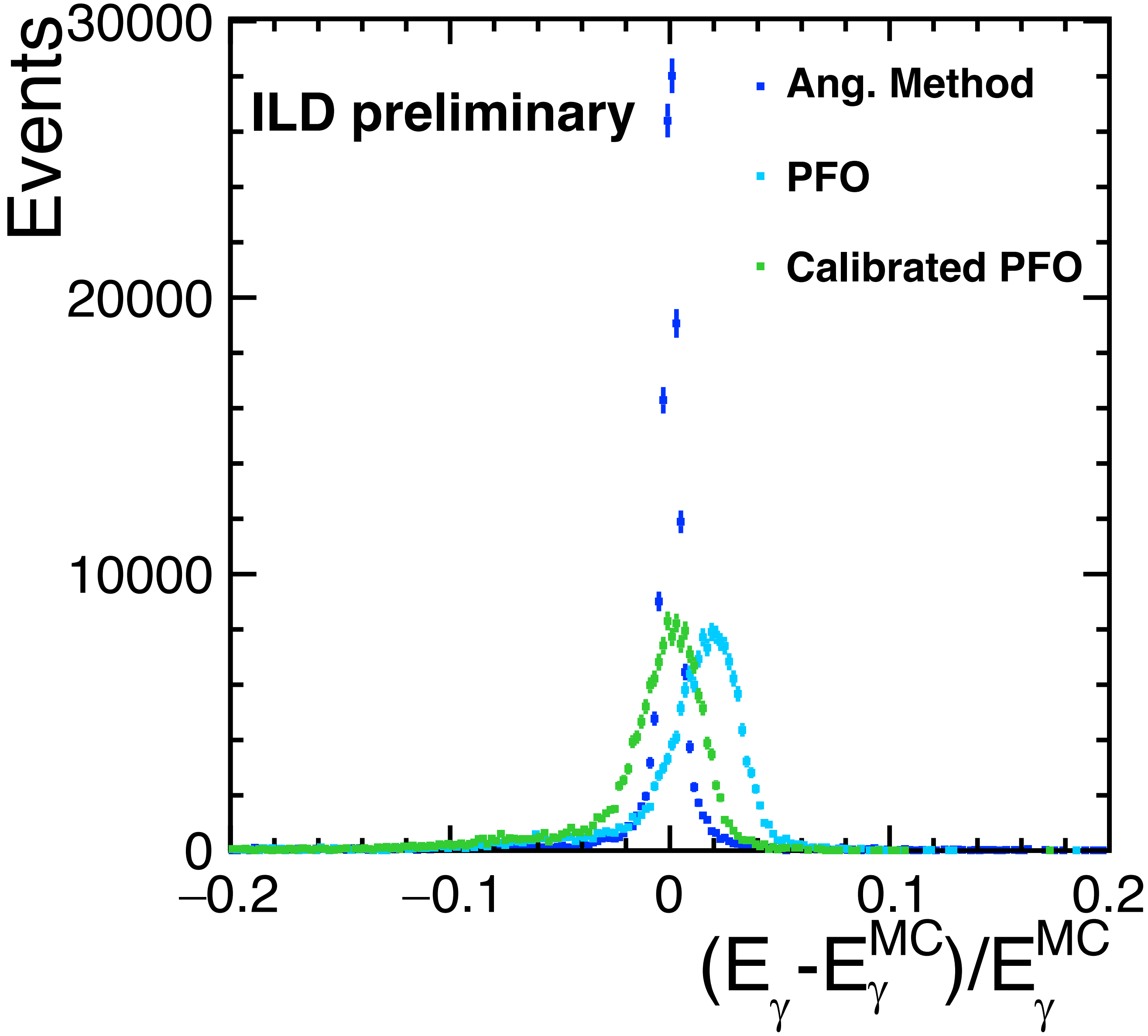
-> PFO energy data is divided into 20 groups by the value of $|\cos\theta_\gamma|$.
Calibration is performed by each value range of $|\cos\theta_\gamma|$.

$$Calibration\ Factor\ (\theta_\gamma) = Mean\ E_{Ang.Method}(\theta_\gamma) / Mean\ E_{PFO}(\theta_\gamma)$$

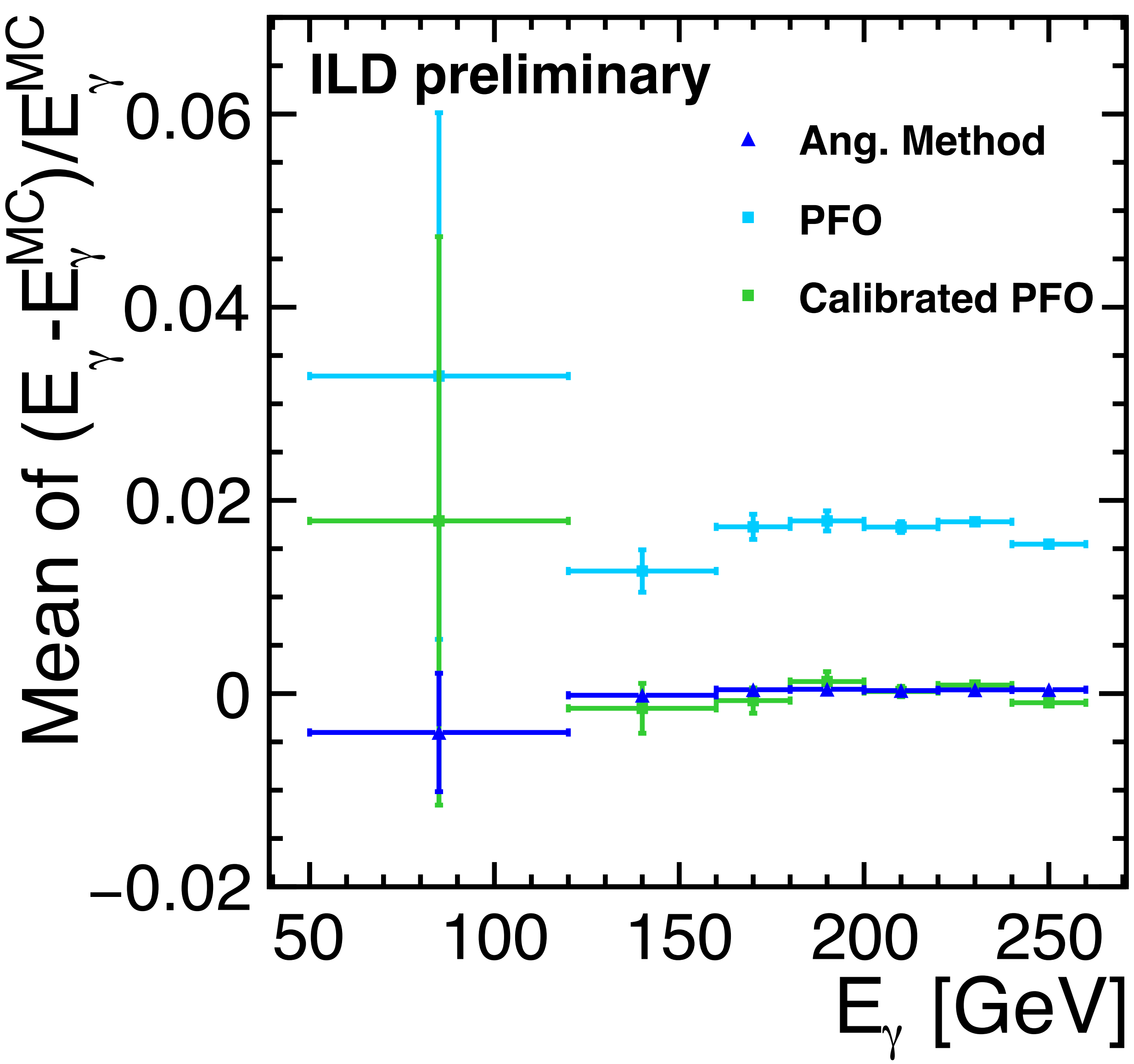
$$Calibrated\ PFO\ Energy = PFO\ Energy \times Calibration\ Factor\ (\theta_\gamma)$$

Calibration Result

Comparison of $(E-E_{MC})/E_{MC}$ among PFO, calibrated PFO, and Ang. Method



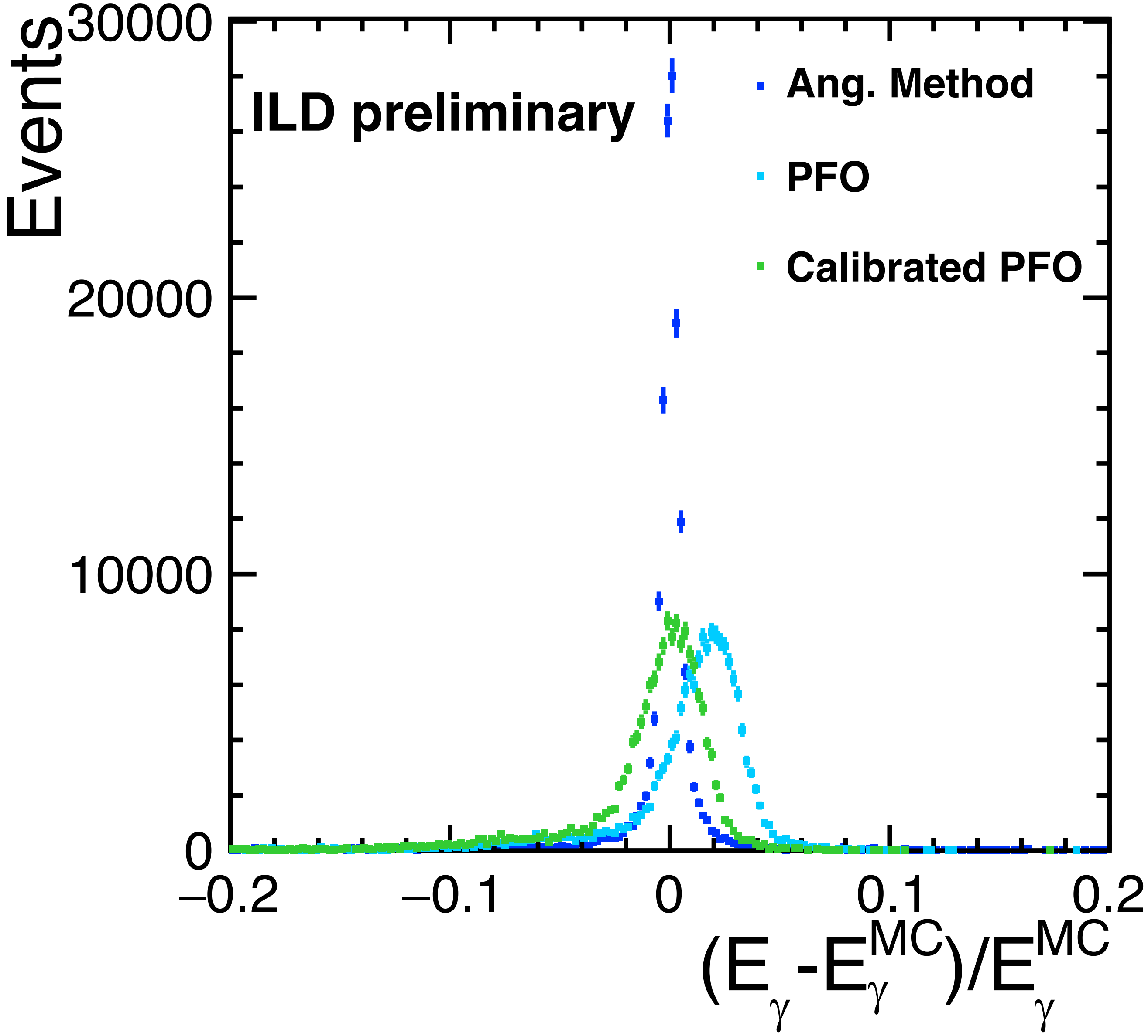
Mean of $(E-E_{MC})/E_{MC}$ dependence on E_γ

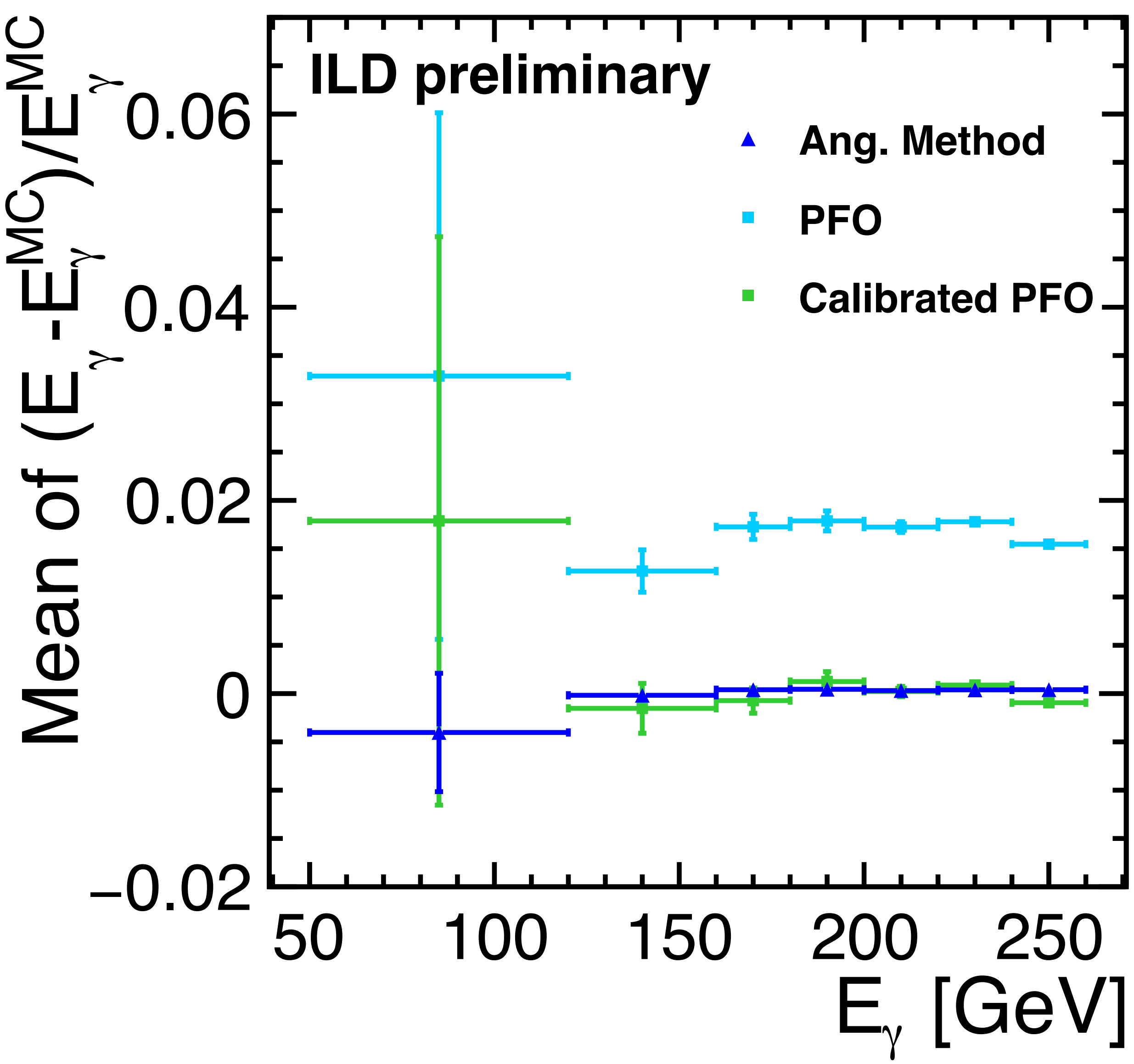


Calibration Result

- The calibration procedure removes the overall bias in the raw PFO photon energy.

Co … e on E_γ
PF…

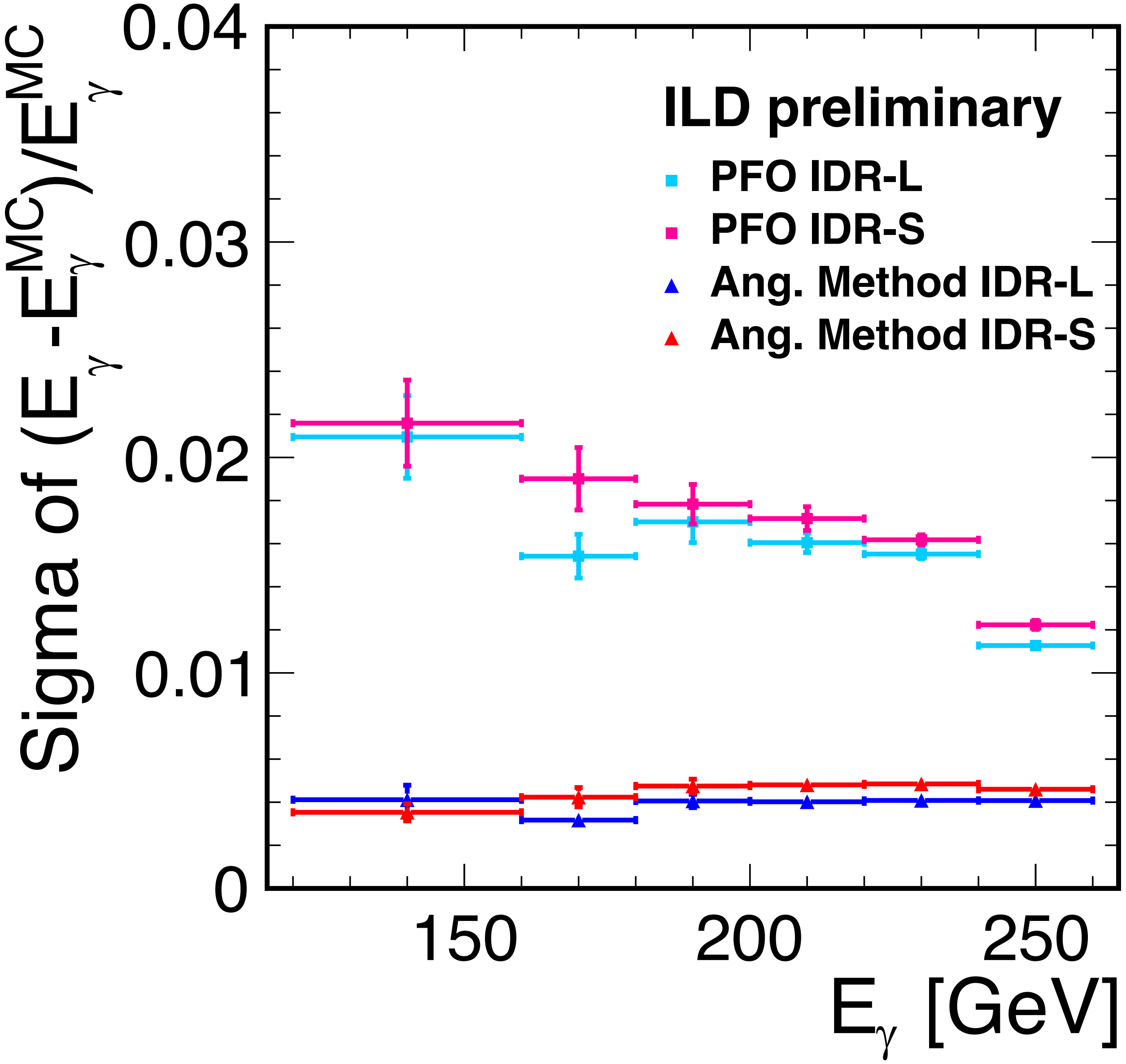




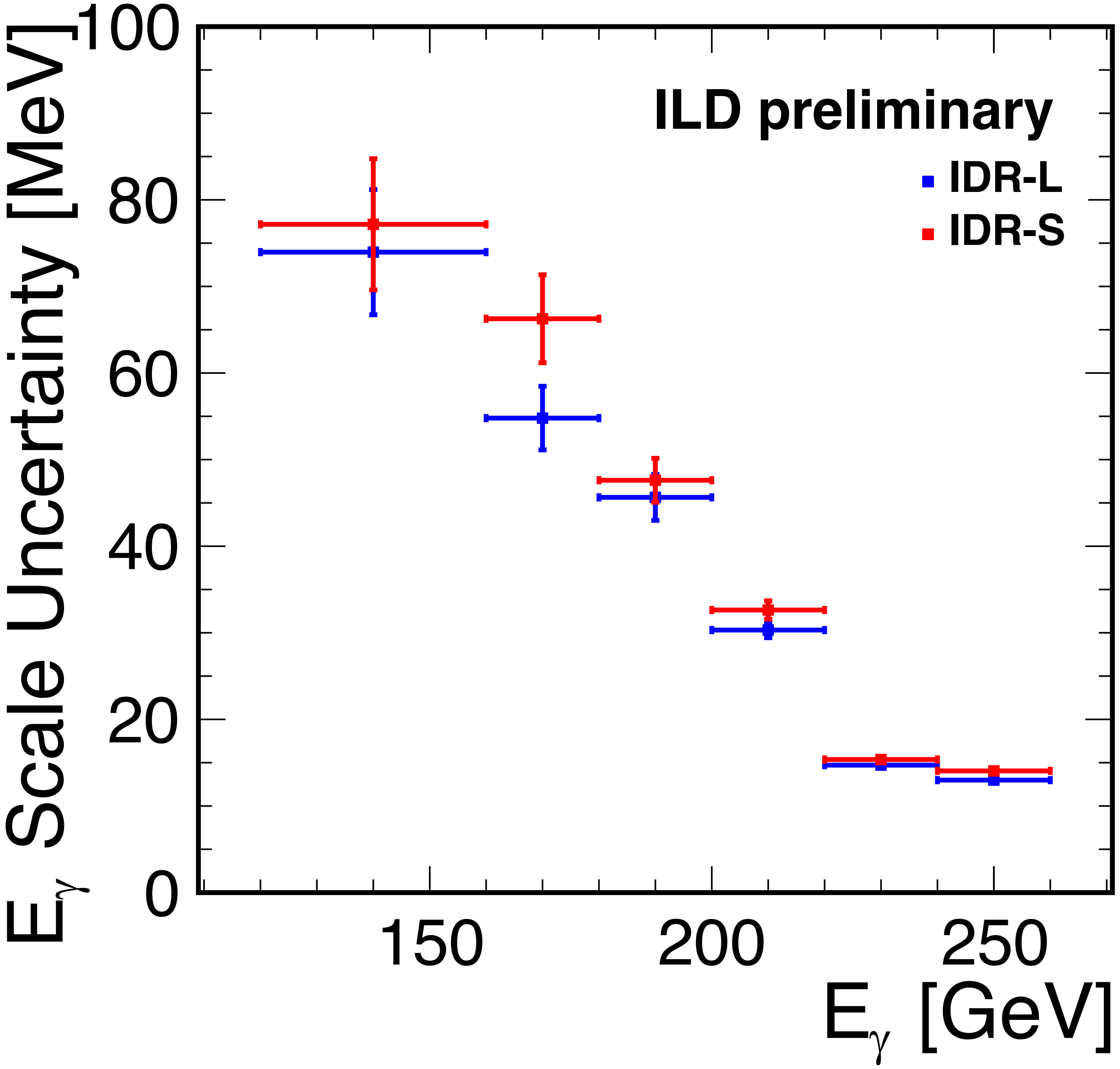
E_γ Scale Uncertainty

- $E_\gamma\ Scale\ Uncertainty = \sqrt{(PFO\ Uncertainty)^2 + (Ang.Method\ Uncertainty)^2}$

Sigma of $(E-E_{MC})/E_{MC}$ dependence on E_γ

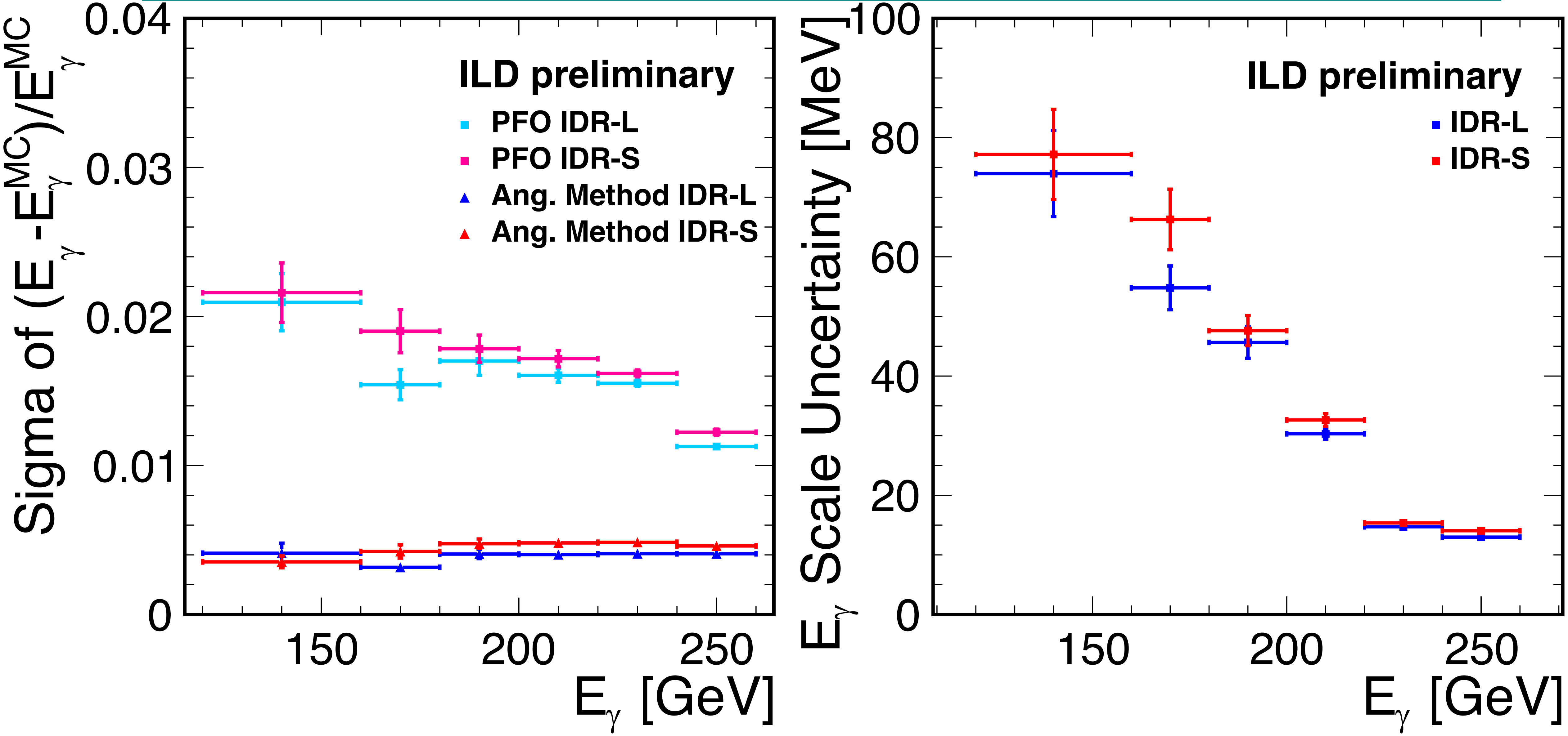


E_γ Scale Uncertainty



E_γ Scale Uncertainty

- It is concluded that the photon energy scale uncertainty is less than 100 MeV when the energy of photon is > 120 GeV.



Jet Energy Reconstruction

Based on 4-momentum conservation

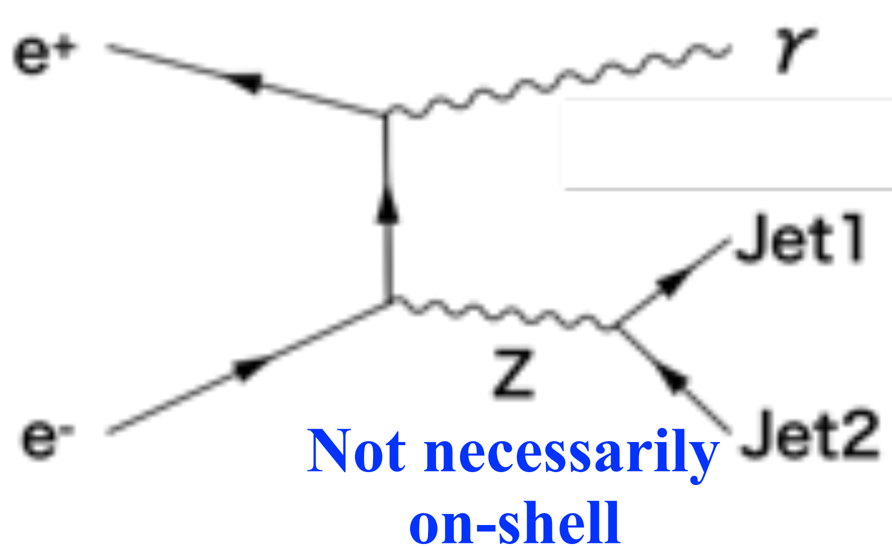
$$\begin{cases} \sqrt{P_{J1}^2 + m_{J1}^2} + \sqrt{P_{J2}^2 + m_{J2}^2} + |P_\gamma| + |P_{ISR}| = 500 \\ P_{J1} sin\theta_{J1} cos\phi_{J1} + P_{J2} sin\theta_{J2} cos\phi_{J2} + P_\gamma sin\theta_\gamma cos\phi_\gamma + |P_{ISR}| sin\alpha = 500 sin\alpha \\ P_{J1} sin\theta_{J1} sin\phi_{J1} + P_{J2}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

Beam Crossing Angle ≡ 2α : α = 7.0 mrad

ISR photon = additional unseen photon

Signal sample: $e^+e^- \to \gamma + 2$Jets

On-shell Z is not required.

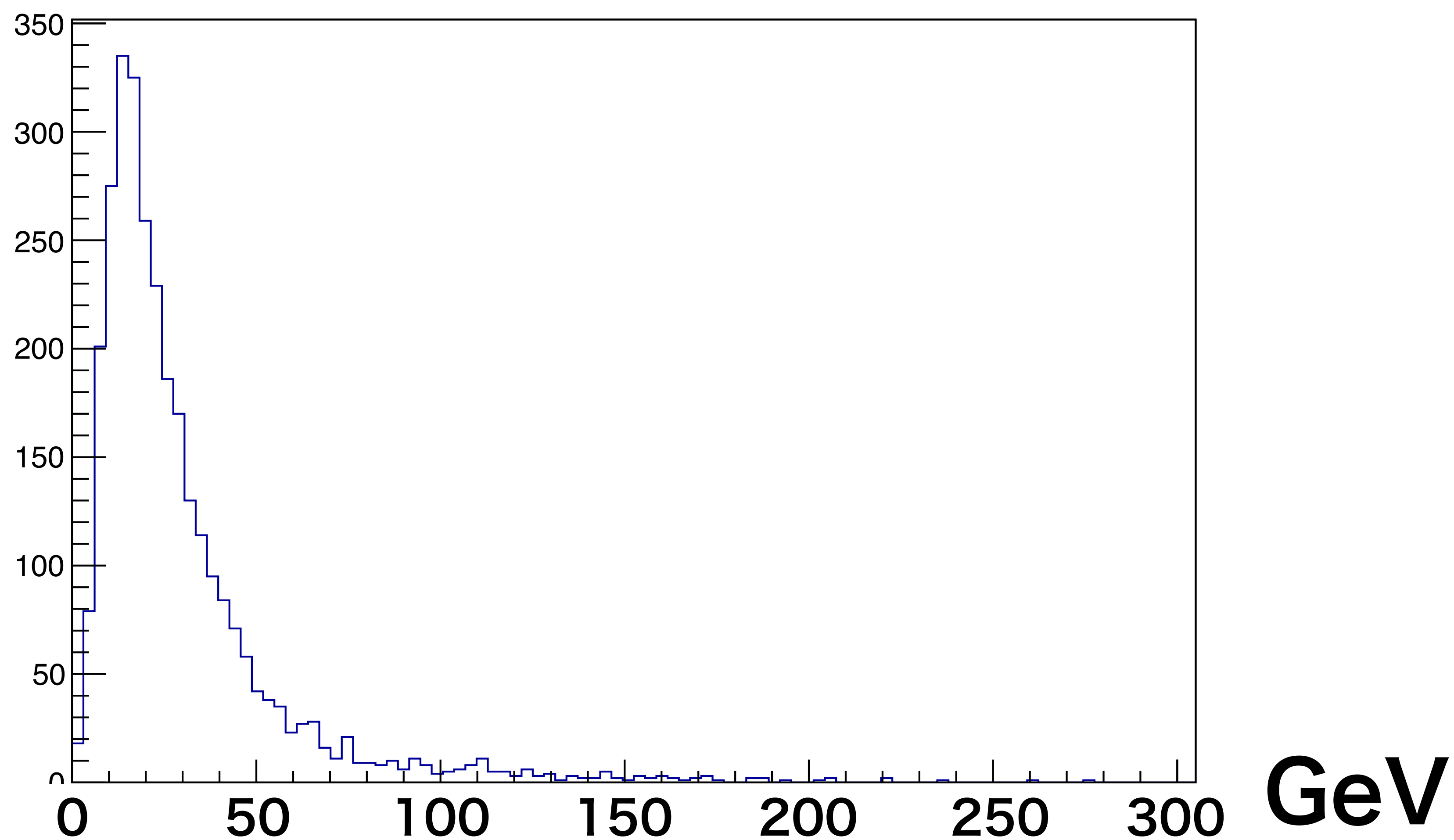


Direction Angle

θ : polar angle

ϕ : azimuthal angle

Jet Mass Distribution



Reconstruction Method

Method : 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 ($P_{J1},P_{J2},P_\gamma,P_{ISR}$)

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

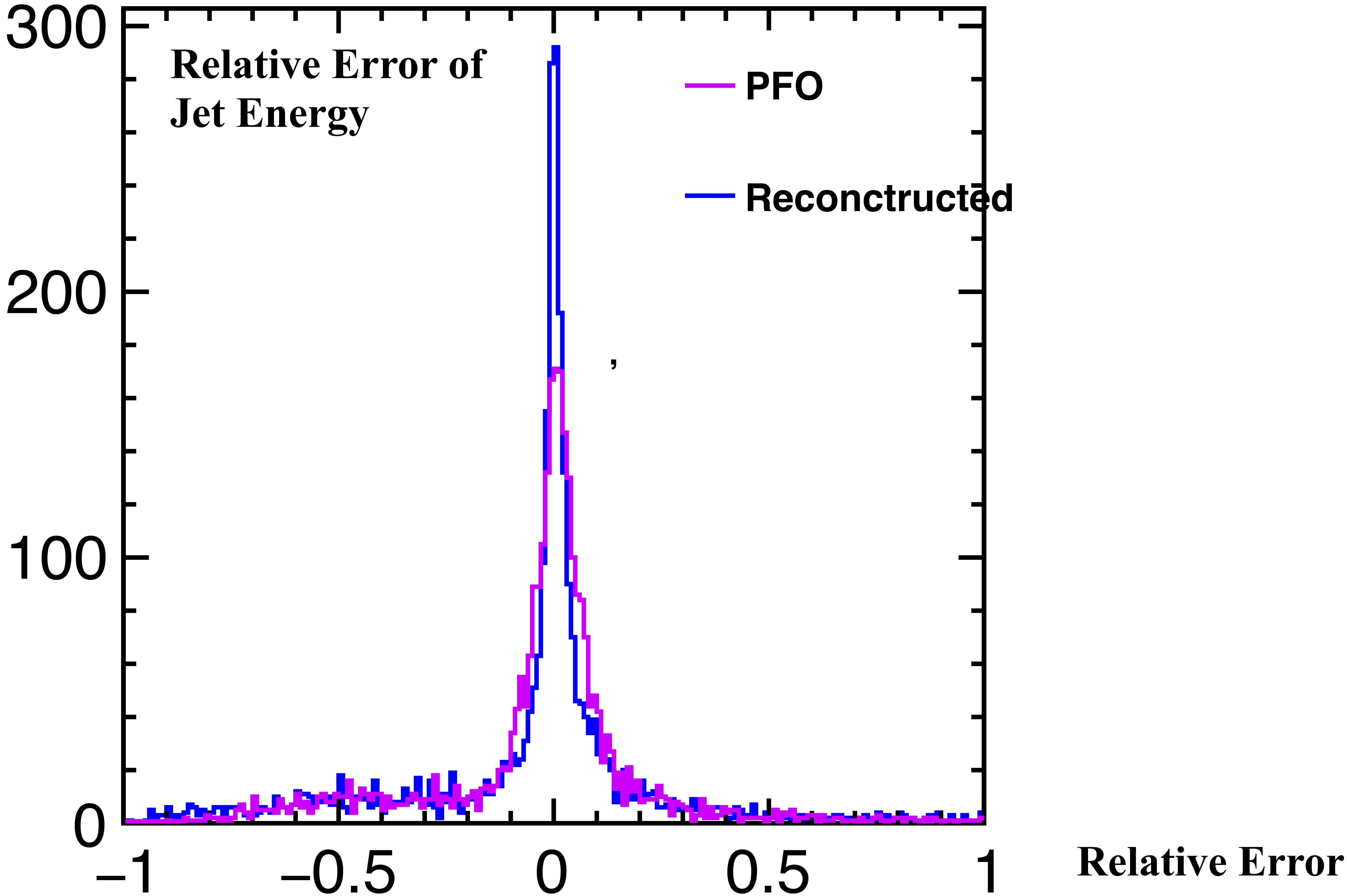
Matrix A

Inverse

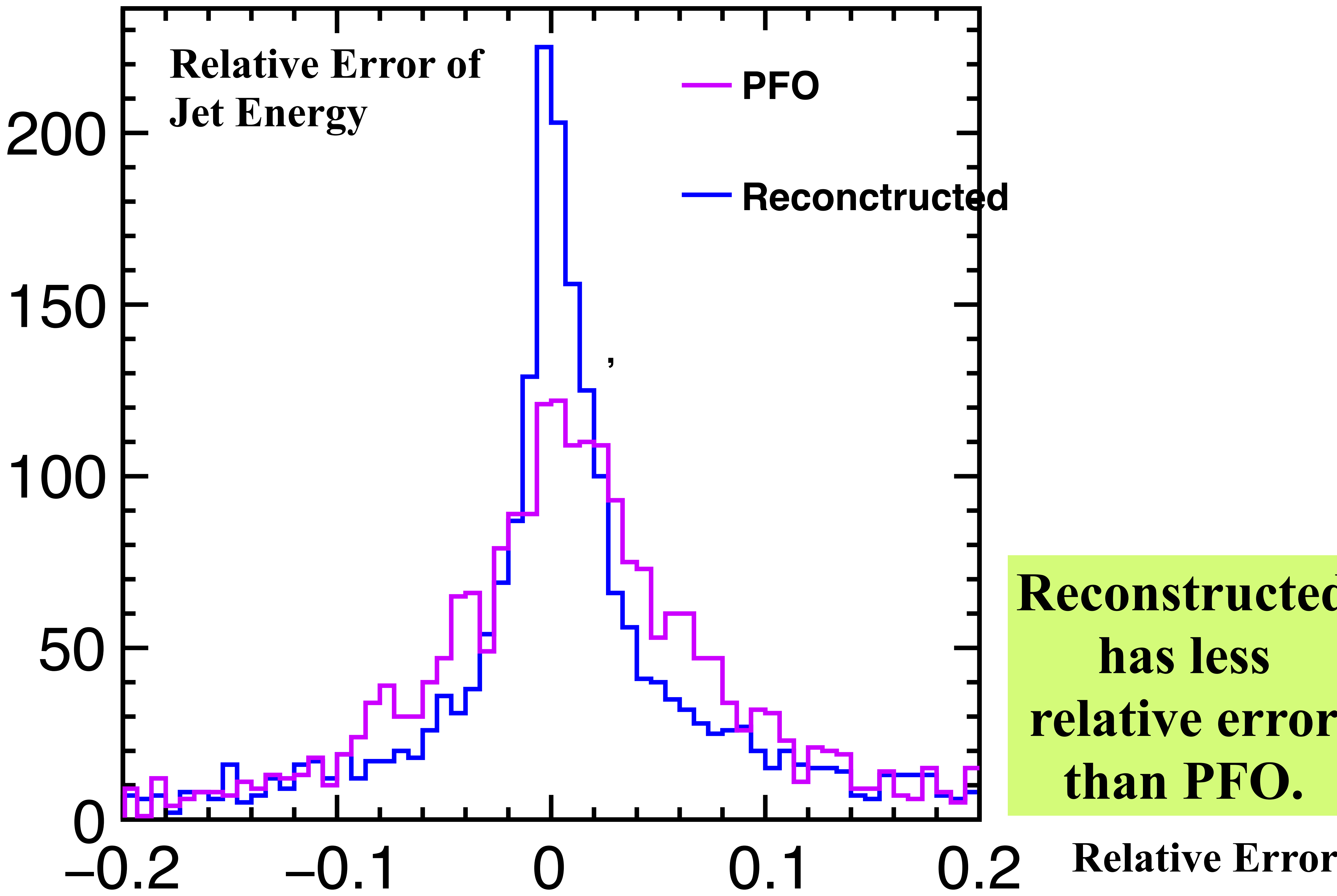
Inserting P_{J1},P_{J2},P_γ into the first equation
-> 8 Possible Solutions!
4: Quartic Equation of $|P_{ISR}|$ X 2: sign of ISR

- **Choose real and positive solutions**
- **Solved P_γ close to the measured P_γ**

Result


Relative Error of
Jet Energy
PFO
Reconctructed
300
200
100
0
–1
–0.5
0
0.5
1
Relative Error

Result



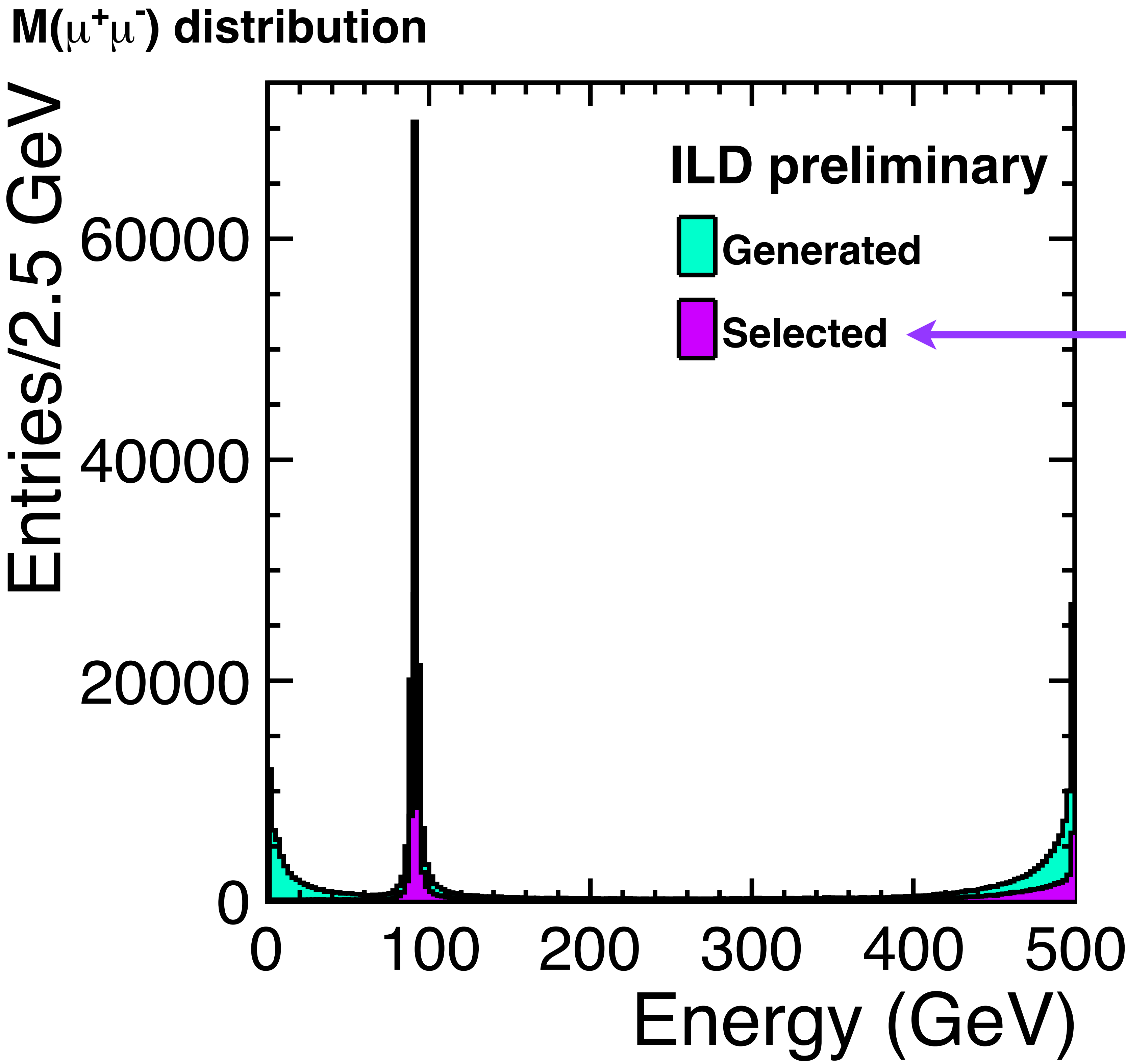
Reconstructed has less relative error than PFO.

Conclusion

- The methods to calibrate photon energy using e^+e^- -> γZ process are studied.
- Among the kinematical reconstruction methods studied, the Ang. Method is found to be the best due to its good resolution and its symmetric response.
- The resolution of the photon energy kinematically reconstructed by the Ang. Method is better than that of the PFO photon energy for $|\cos\theta\gamma| < 0.95$ and $\pi/40 < |\varphi\gamma| < 39\pi/40$. We have hence shown that in this region, PFO photon energy can be calibrated using Ang. Method.
- It is concluded that the photon energy scale uncertainty is less than 100 MeV for photon energy > 120 GeV.
- The methods to calibrate jet energy using e^+e^- -> γZ process are being studied.
  Kinematical reconstruction methods studied has better resolution than the measured.

Backup

Invariant mass distribution of the $\mu^-\mu^+$ of Large ILD model samples ($e^-_L e^+_R$ polarization)

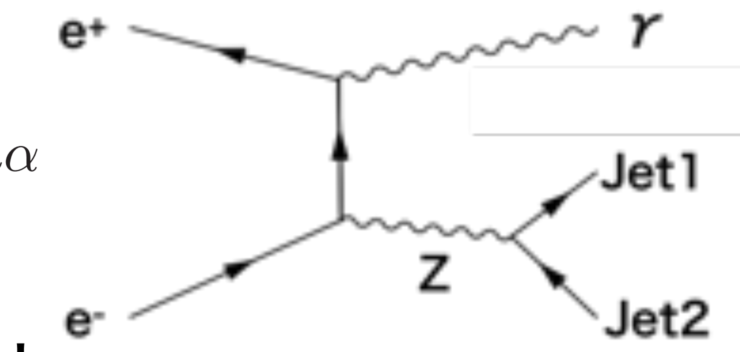


After the Step1 Event Selection

Jet Energy Reconstruction

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,and 3) 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

Jet Energy Reconstruction

Method 2': Ignore ISR and use smeared P_γ

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

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

Method 2: Consider ISR and use smeared P_γ

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})

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

Matrix A

Inverse

2 solutions for each sign of P_{ISR}

-> choose the best answer which satisfies ① better

Jet Energy Reconstruction

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

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

Matrix A

Inverse

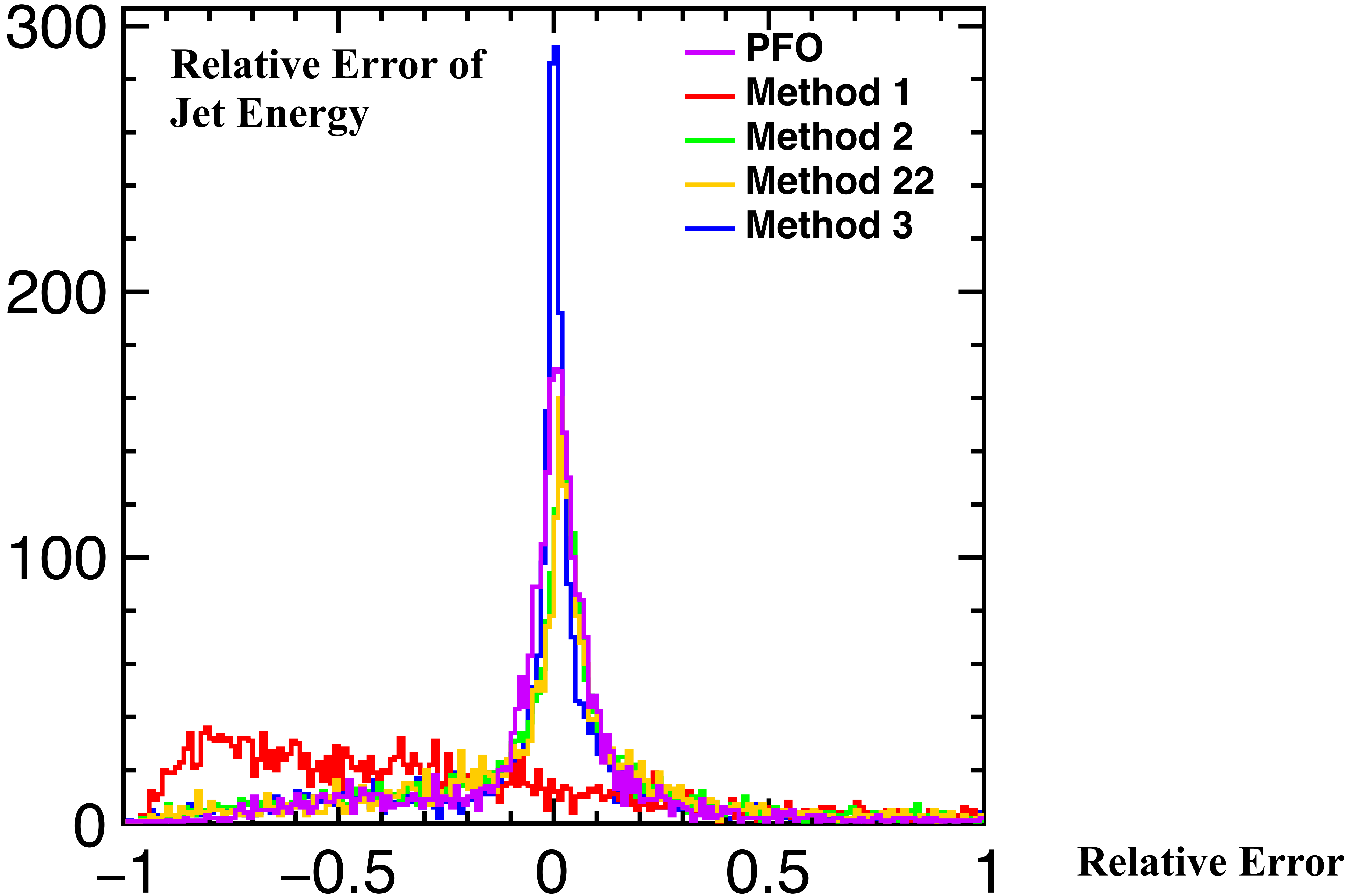
Inserting P_{J1},P_{J2},P_γ into the first equation

-> 8 Possible Solutions!

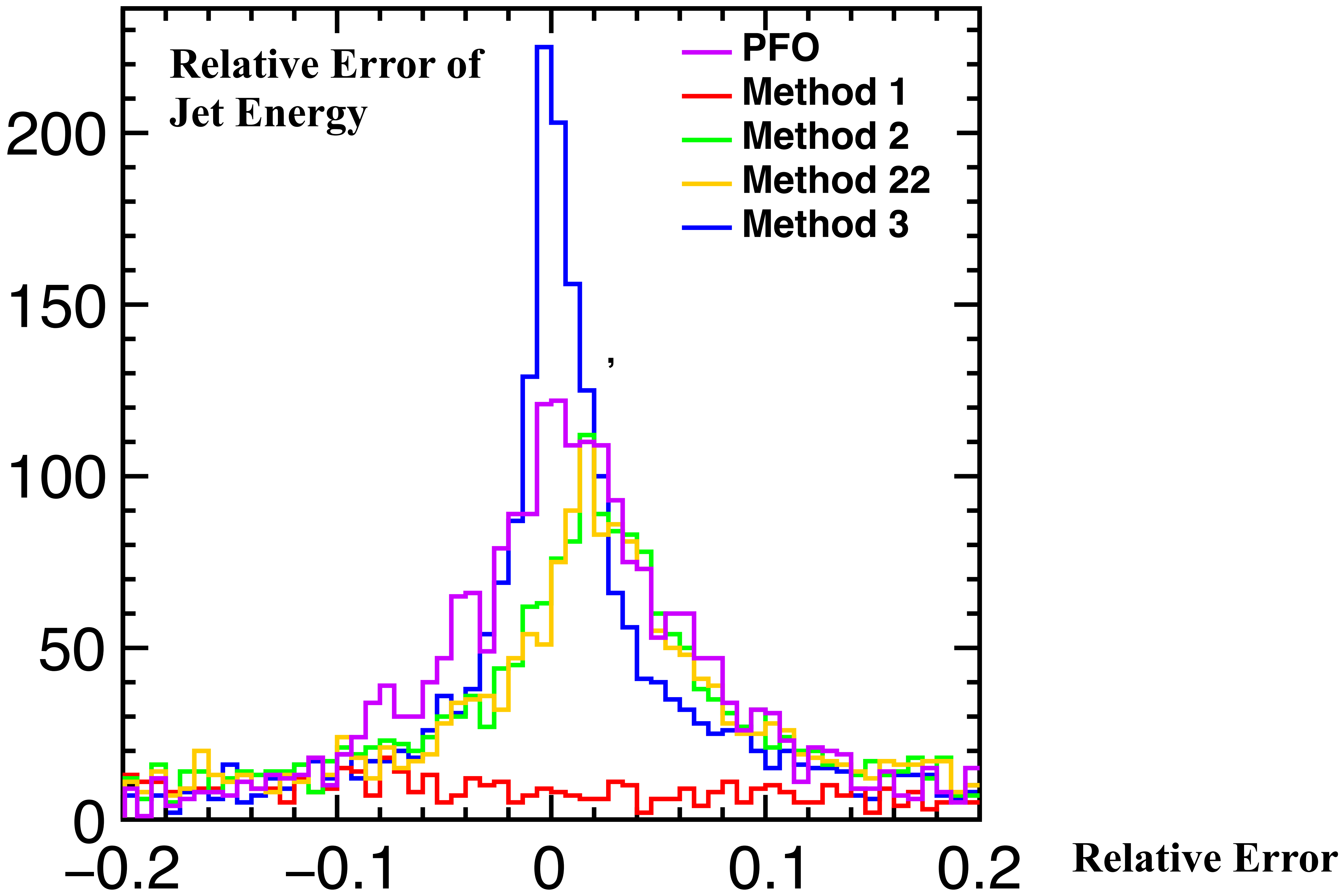
4: Quartic Equation of $|P_{ISR}|$ X 2: sign of ISR

- **Choose real and positive solutions**
- **Solved P_γ close to the measured (smeared) P_γ**

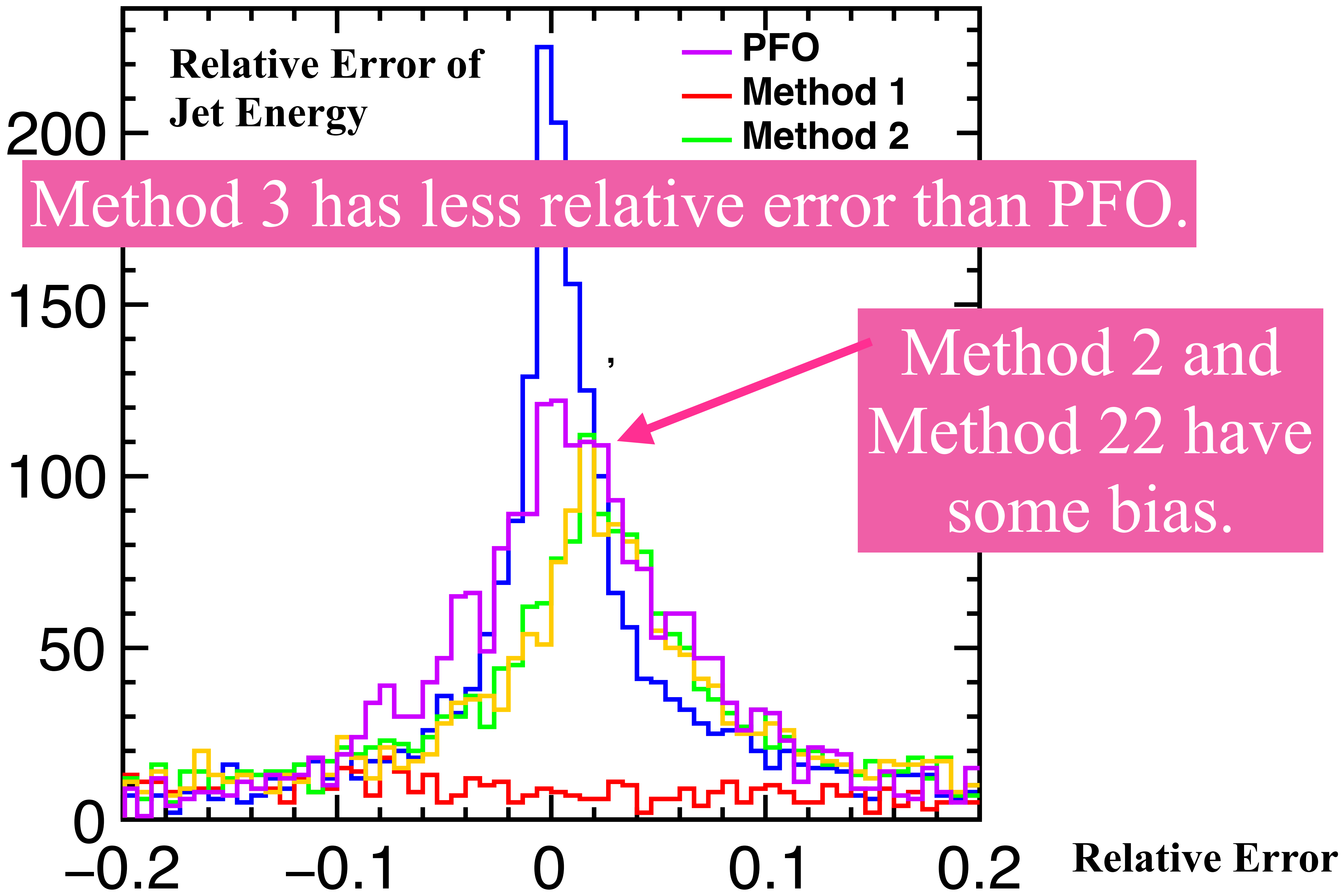
Method Comparison Result



Method Comparison Result



Method Comparison Result[2]



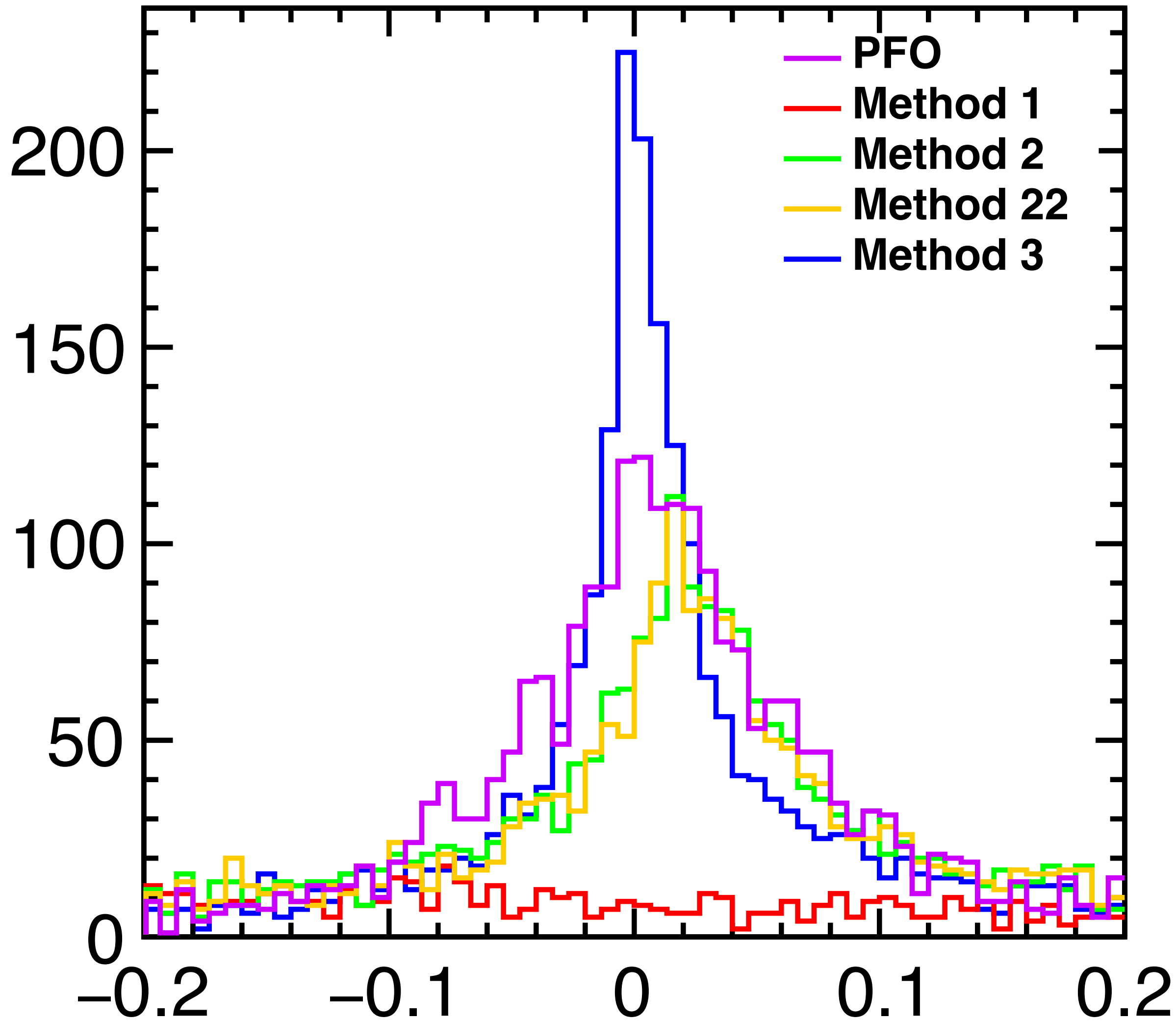
Method 3 has less relative error than PFO.

Method 2 and Method 22 have some bias.

Method Comparison Result

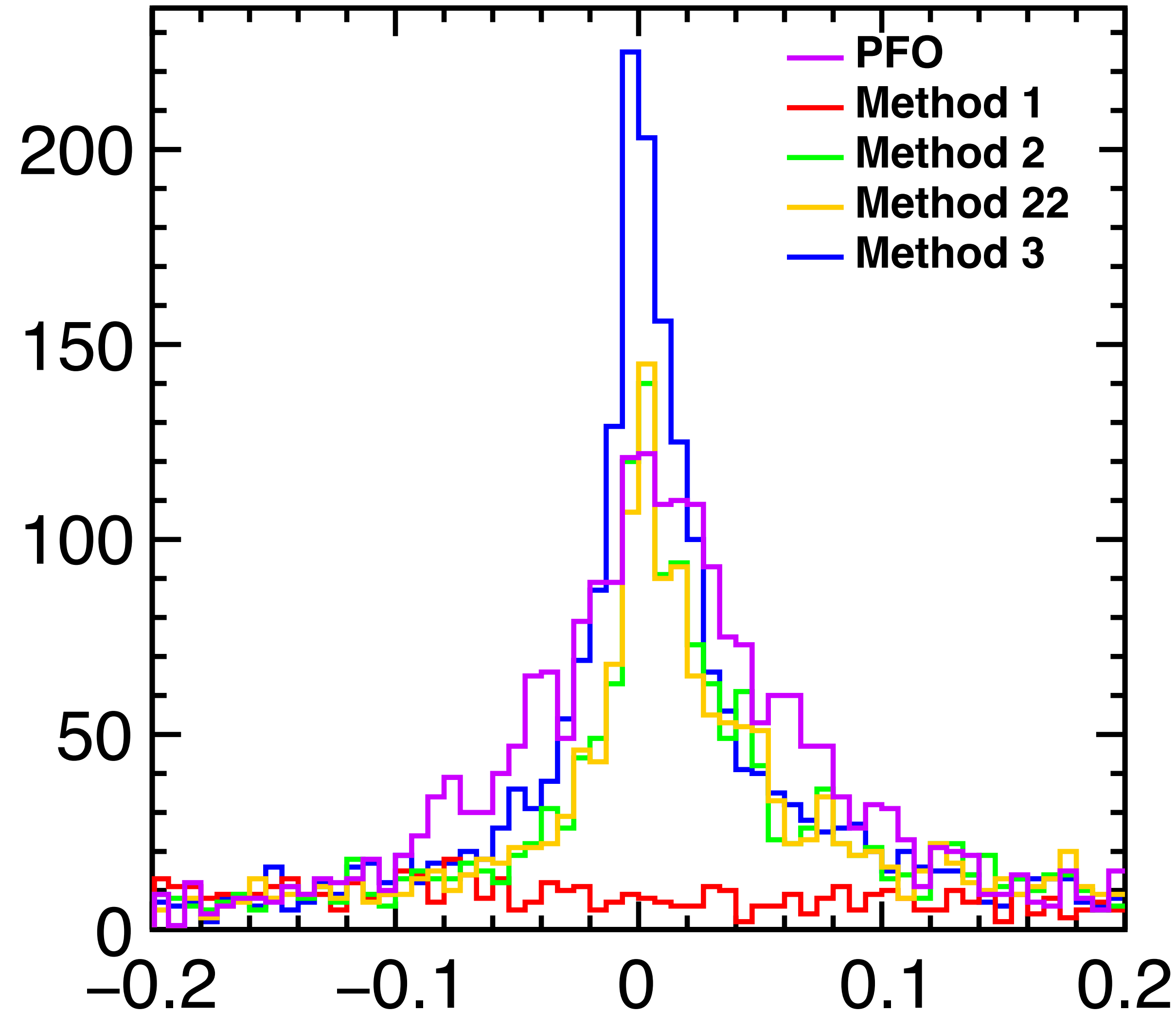
If using MCtrue photon energy as input,

PFO photon E as input



,

MC photon E as input

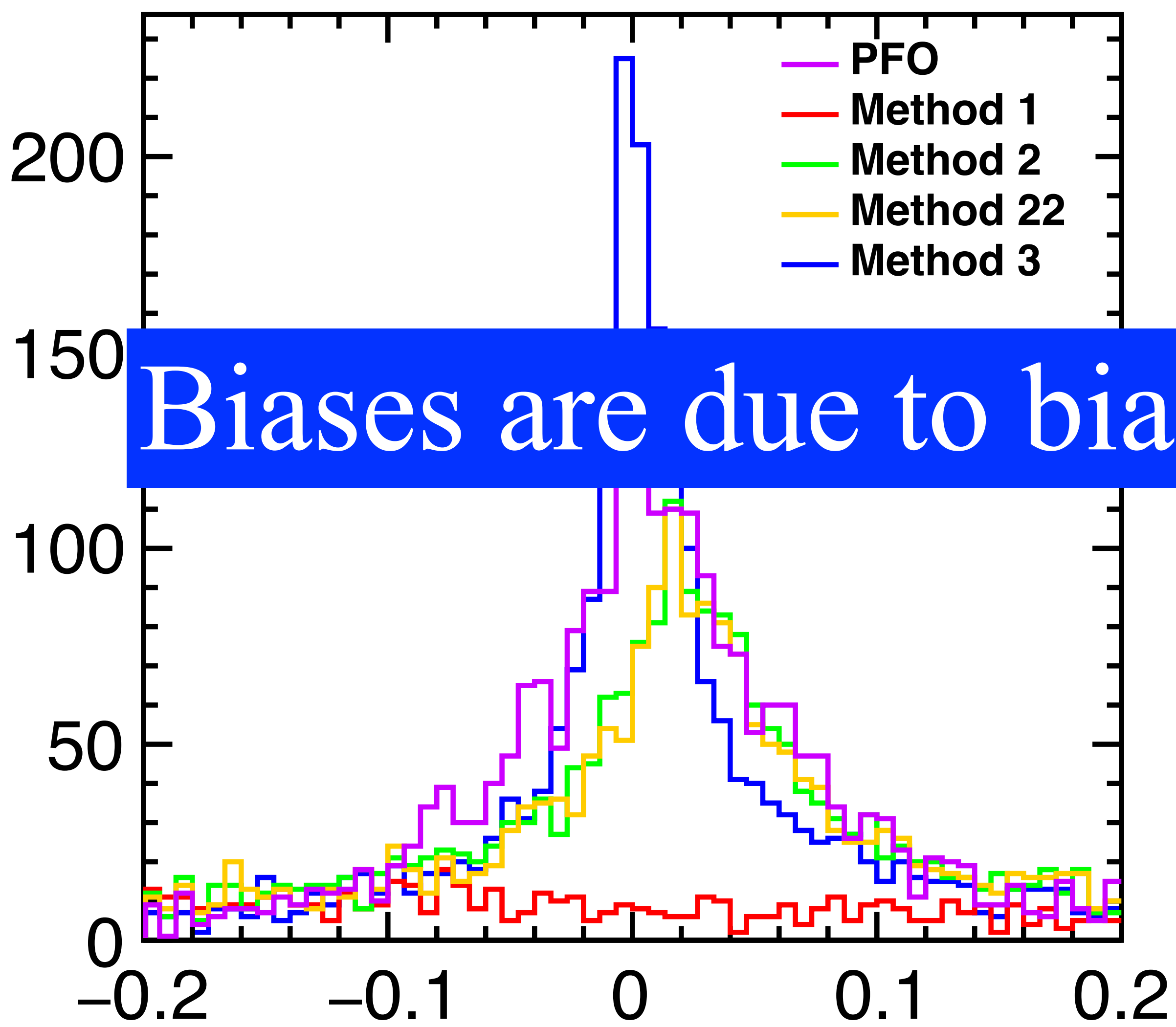


Biases in Method 2 and 22 disappeared.

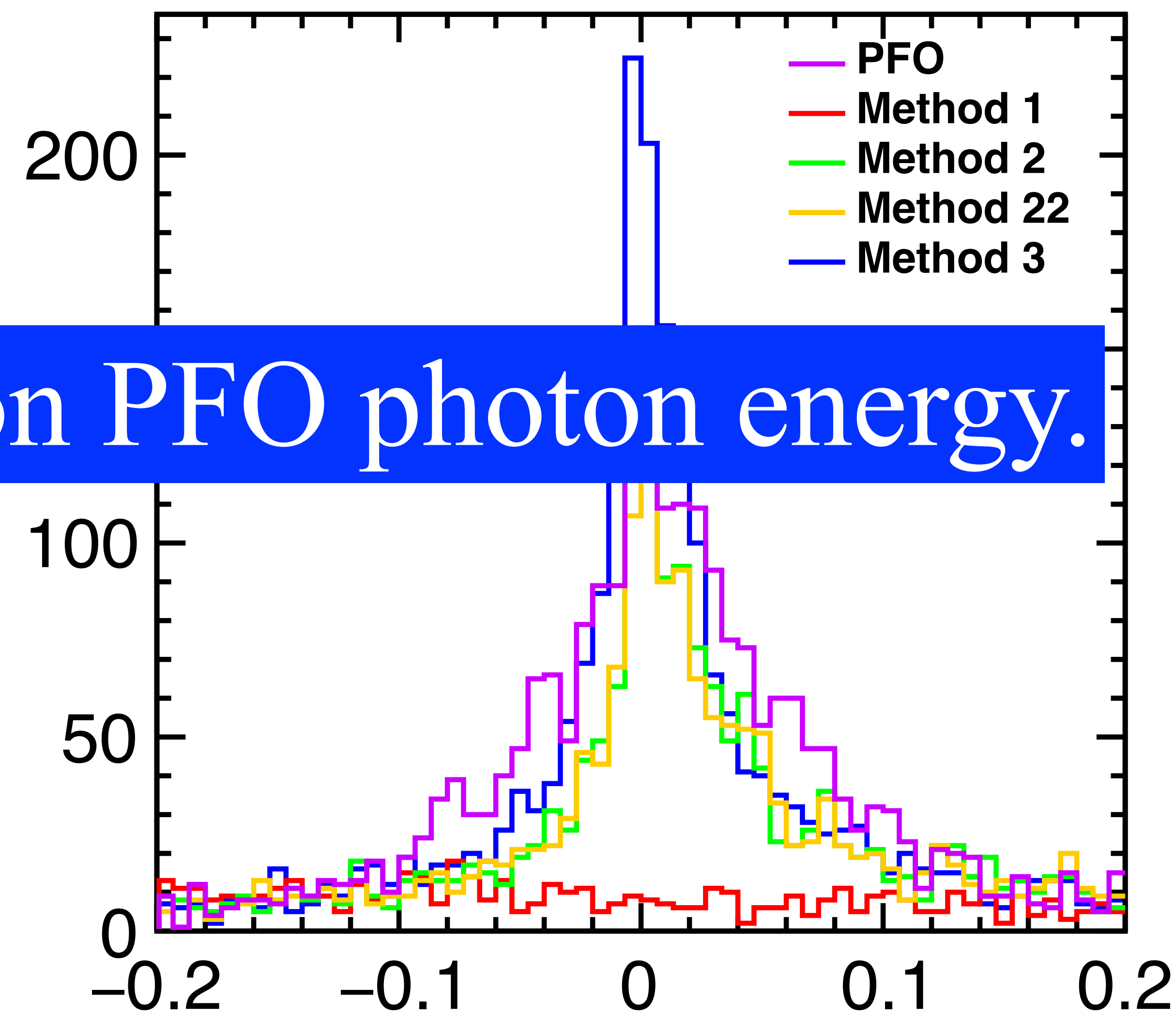
Method Comparison Result

If using MCtrue photon energy as input,

PFO photon E as input



MC photon E as input



Biases are due to bias on PFO photon energy.

Biases in Method 2 and 22 disappeared.