Jet Error Parametrization with Neutral Hadrons

ILD software and analysis meeting

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HELMHOLTZ
RESEARCH FOR GRAND CHALLENGES

Universität Hamburg
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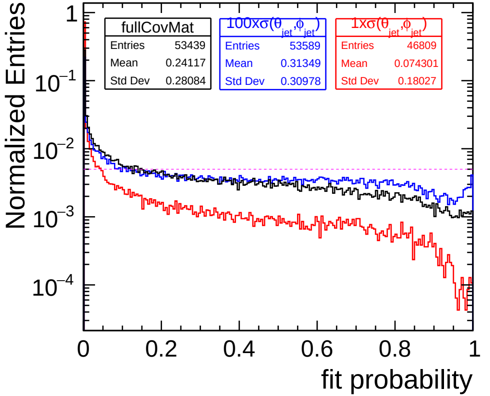
Motivation

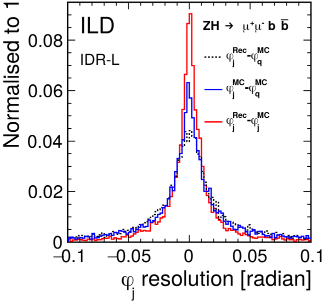
- Kinematic fit: a powerful mathematical tool to improve the measurements beyond the detector capability/resolution
  - Vary quantities within their uncertainties to satisfy the kinematic requirements
  - Provides better understanding on source of uncertainties
  - Evaluation of kinematic fit performance based on fit probability
- Last round of test samples:
  - software version: ILCSoft v02-01-02
  - $e^+e^- \to \mu\bar{\mu}H$ with $H \to b\bar{b}$ at $\sqrt{s} = 250$ GeV
- ErrorFlow: use full covariance matrix of PFOs to estimate uncertainties on jet parameters
  - Photons and Charged PFOs: simply added to the jet CovMat.
  - Neutral Hadrons: different decisive options on the pfo mass and cluster energy.

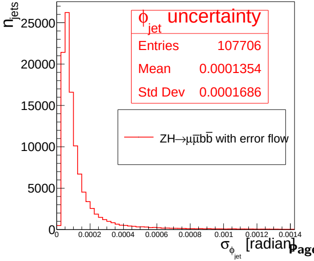
Latest updates on the jet angle uncertainties

ref.: ILD-IDR, fig. 8.15

https://agenda.linearcollider.org/event/8620







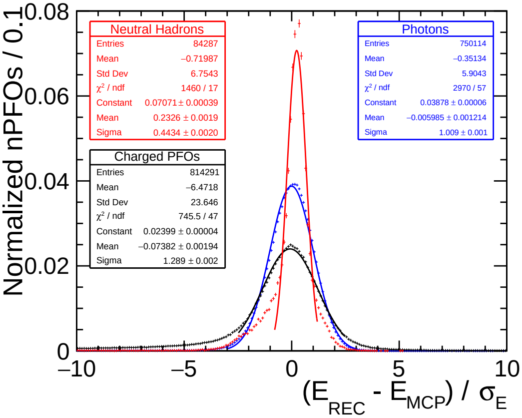
approximation: $100 \times (\sigma_{\theta_{jet}}, \sigma_{\phi_{jet}})$

Improved fit probability using full CovMat of Neutral PFOs

Uncertainty in PFO level (Energy)

Situation of error estimation in PFO level

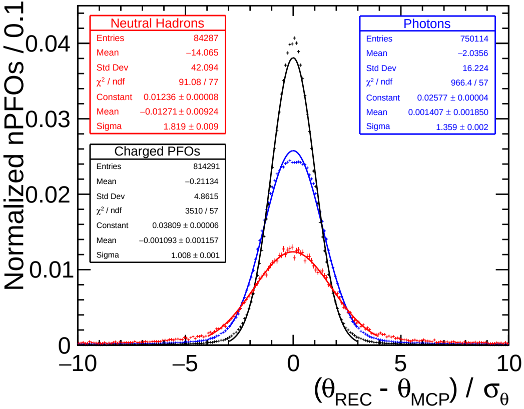
- Photons: energy error is perfectly modeled.
- Charged PFOs: possible improvement by tracks refitted with true mass hypothesis (need to be checked!).
  Charged PFOs are investigated through track parameters:
  `https://agenda.linearcollider.org/event/8341/`
- Neutral Hadrons: energy and energy error are overestimated.

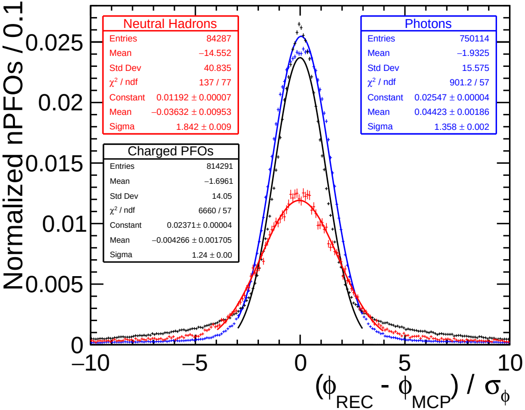


The energy error of the Neutral PFOs is directly obtained from cluster energy error. ⇒ Not easy to maneuver!

The PFOs energy error quadratically summed up ⇒ jet energy error: $\sigma^2_{E_{jet}} = \Sigma\ \sigma^2_{E_{PFO}}$

Uncertainty in PFO level (Angles)

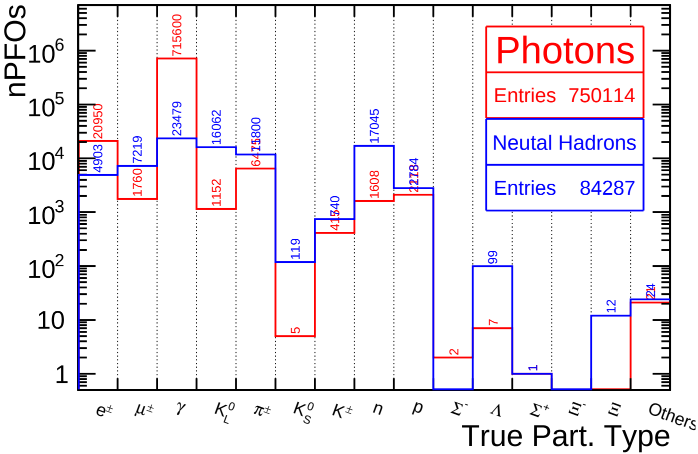




The angular uncertainties of the Neutral PFOs are obtained from cluster position error.

Underestimated σ_θ and σ_ϕ for photons (factor ∼1.3) and neutral hadrons (factor ∼1.8)

Neutral PFO identification by Pandora



Majority of identified photons are true photons.

No explicit decision for mass of identified neutral hadrons due to their multiplicity.

Pandora treatment with Neutral Hadrons

What Pandora does:

- Cluster energy is assigned to PFO(massless) energy
  $E_{PFO} = |\vec{p}_{PFO}| = E_{cluster}$
- Neutral Hadrons are identified as neutron
- neutron mass is set for PFO $\Rightarrow$ **incosistent 4-momentum!**
- CovMat of Neutral PFO is calculated (using inconsistent 4-momentum):
  CovMat$(\vec{p}, E) = J^T$ CovMat$(\vec{x}_{clu}, E_{clu})\ J$

$$J = \begin{pmatrix} \frac{\partial p_x}{\partial x_c} & \frac{\partial p_y}{\partial x_c} & \frac{\partial p_z}{\partial x_c} & \frac{\partial E}{\partial x_c} \\ \frac{\partial p_x}{\partial y_c} & \frac{\partial p_y}{\partial y_c} & \frac{\partial p_z}{\partial y_c} & \frac{\partial E}{\partial y_c} \\ \frac{\partial p_x}{\partial z_c} & \frac{\partial p_y}{\partial z_c} & \frac{\partial p_z}{\partial z_c} & \frac{\partial E}{\partial z_c} \\ \frac{\partial p_x}{\partial E_c} & \frac{\partial p_y}{\partial E_c} & \frac{\partial p_z}{\partial E_c} & \frac{\partial E}{\partial E_c} \end{pmatrix}$$

CovMat$(\vec{p}, E)$ of Neutral PFOs depend on the mass assumption.

Suggestion: Take consistent 4-momentum of massive neutral hadrons for CovMat calculations.

CovMat of Neutral PFOs

- Current CovMat calculation (MarlinReco/Analysis/AddClusterProperties)

$$E_{PFO} = |\vec{p}_{PFO}| = E_{clu} \;,\; p_x = E_{clu}\frac{x}{r} \;,\; p_y = E_{clu}\frac{y}{r} \;,\; p_z = E_{clu}\frac{z}{r}$$

- Alternative CovMat calculation (taking consistent 4-momentum of neutral hadrons)

$$E_{PFO} = \sqrt{|\vec{p}_{PFO}|^2 + m_{PFO}^2} = \sqrt{E_{clu}^2 + m_n^2}$$

$$J = \begin{pmatrix} E_{clu}\frac{r^2-x^2}{r^3} & -E_{clu}\frac{xy}{r^3} & -E_{clu}\frac{xz}{r^3} & 0 \\ -E_{clu}\frac{xy}{r^3} & E_{clu}\frac{r^2-y^2}{r^3} & -E_{clu}\frac{yz}{r^3} & 0 \\ -E_{clu}\frac{xz}{r^3} & -E_{clu}\frac{yz}{r^3} & E_{clu}\frac{r^2-z^2}{r^3} & 0 \\ \frac{x}{r} & \frac{y}{r} & \frac{z}{r} & 1 \end{pmatrix} \rightarrow J = \begin{pmatrix} E_{clu}\frac{r^2-x^2}{r^3} & -E_{clu}\frac{xy}{r^3} & -E_{clu}\frac{xz}{r^3} & 0 \\ -E_{clu}\frac{xy}{r^3} & E_{clu}\frac{r^2-y^2}{r^3} & -E_{clu}\frac{yz}{r^3} & 0 \\ -E_{clu}\frac{xz}{r^3} & -E_{clu}\frac{yz}{r^3} & E_{clu}\frac{r^2-z^2}{r^3} & 0 \\ \frac{E}{E_{clu}}.\frac{x}{r} & \frac{E}{E_{clu}}.\frac{y}{r} & \frac{E}{E_{clu}}.\frac{z}{r} & 1 \end{pmatrix}$$

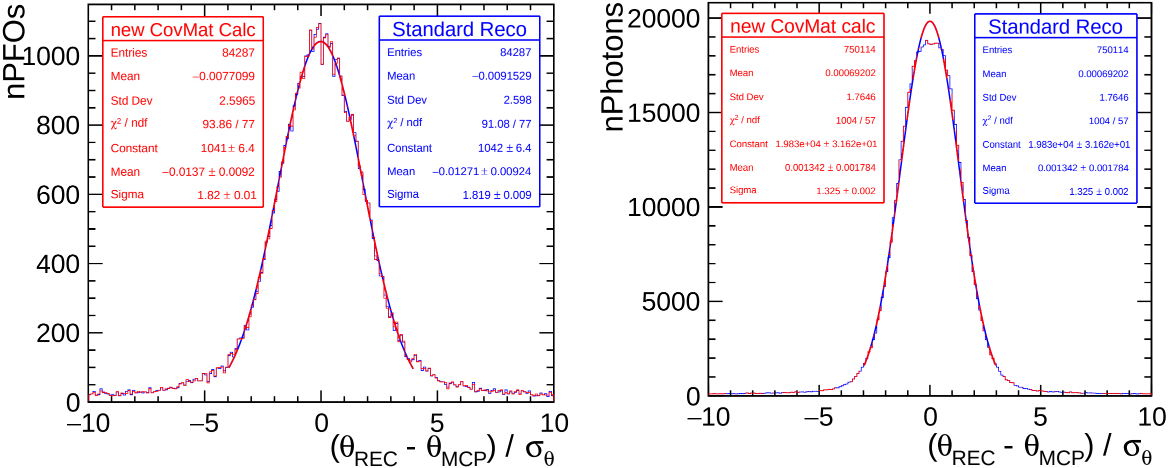
using error propagation, PFO angular uncertainties are calculated directly from cluster position error:

$$\sigma_\theta^2 = (\frac{\partial\theta}{\partial x})^2\sigma_x^2 + (\frac{\partial\theta}{\partial y})^2\sigma_y^2 + (\frac{\partial\theta}{\partial z})^2\sigma_z^2 + \frac{\partial\theta}{\partial x}\frac{\partial\theta}{\partial y}\sigma_{xy} + \frac{\partial\theta}{\partial x}\frac{\partial\theta}{\partial z}\sigma_{xz} + \frac{\partial\theta}{\partial y}\frac{\partial\theta}{\partial z}\sigma_{yz}$$

$$\sigma_\phi^2 = (\frac{\partial\phi}{\partial x})^2\sigma_x^2 + (\frac{\partial\phi}{\partial y})^2\sigma_y^2 + \frac{\partial\phi}{\partial x}\frac{\partial\phi}{\partial y}\sigma_{xy}$$

MUST: angular and energy uncertainties remain unchanged!

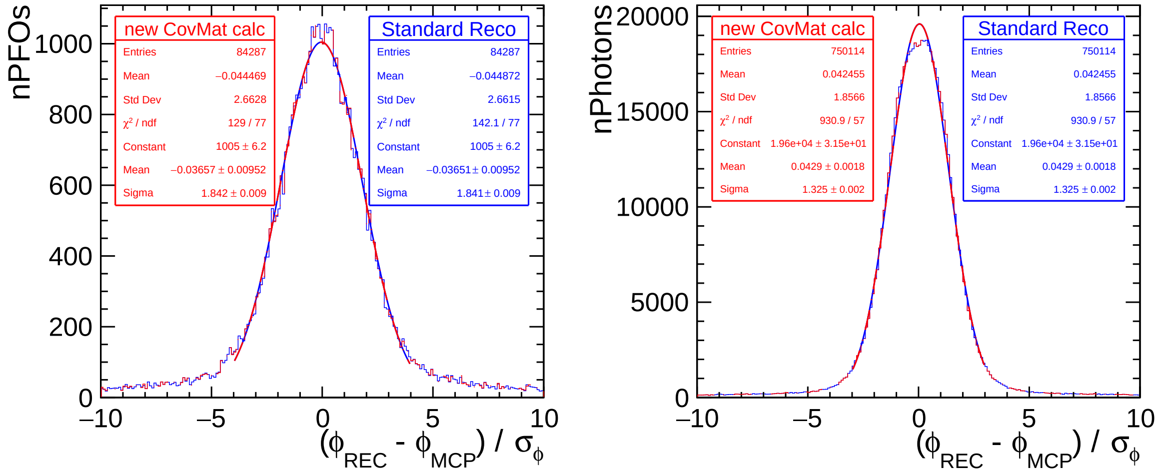
Angular Uncertaint (σ_θ) with new CovMat calc.



Same PFO normalized residual with new CovMat calculations ⇒ same σ_θ

σ_θ underestimated for neutral hadrons (by factor ∼1.8) and photons (by factor ∼1.3)

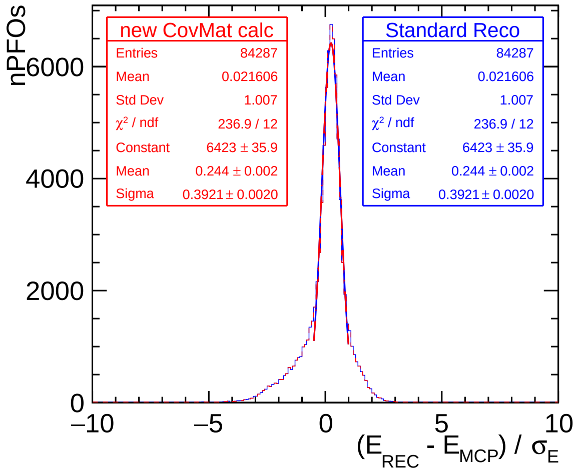
Angular Uncertainty (σ_ϕ) with new CovMat calc.

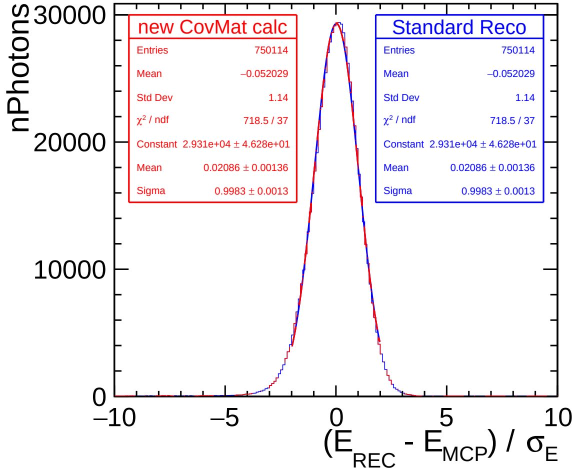


Same PFO normalized residual with new CovMat calculations $\Rightarrow$ same σ_ϕ

σ_ϕ underestimated for neutral hadrons (by factor $\sim$1.8) and photons (by factor $\sim$1.3)

Energy Uncertainty (σ_E) with new CovMat calc.





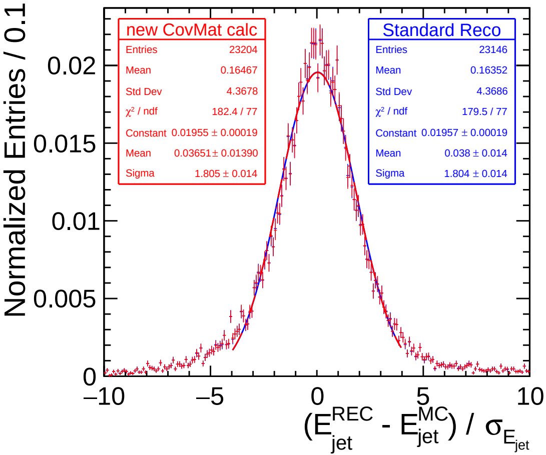
Same PFO normalized residual with new CovMat calculations $\Rightarrow$ same σ_E

Energy and σ_E overestimated for neutral hadrons (by factor $\sim$2.5). Photons: **perfect**

Uncertaities in jet-level: Energy

Jet-level truth:

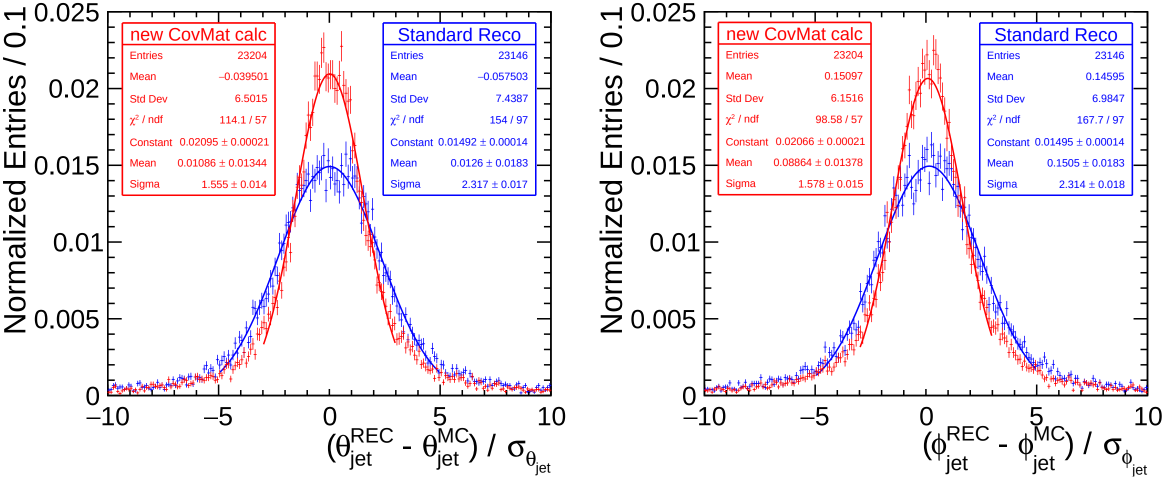
- All stable particles in MCParticleSkimmed collection (generator status = 1)
- Remove ISR photons
- Find and remove isolated muons
  look for stable $\mu/\bar{\mu}$ in daughter chain of initial muon pair
- include/exclude νs from semileptonic decay (optional)
- Run jet clustering algorithm



As expected, jet energy error is unchanged.

New calculation of CovMat has no impact on normalized jet energy residual.

Uncertaities in jet-level: θ & ϕ



By new CovMat, normalized residuals of jet angles improved by 50%!

Scaling Angular Uncertaities of Neutral PFOs (new CovMat calculations)

Scale PFO angular error by factor s = 1.8:

$$\sigma_\theta^2 = (\frac{\partial\theta}{\partial x})^2\sigma_x^2 + (\frac{\partial\theta}{\partial y})^2\sigma_y^2 + (\frac{\partial\theta}{\partial z})^2\sigma_z^2 + \frac{\partial\theta}{\partial x}\frac{\partial\theta}{\partial y}\sigma_{xy} + \frac{\partial\theta}{\partial x}\frac{\partial\theta}{\partial z}\sigma_{xz} + \frac{\partial\theta}{\partial y}\frac{\partial\theta}{\partial z}\sigma_{yz}$$

$$\sigma_\phi^2 = (\frac{\partial\phi}{\partial x})^2\sigma_x^2 + (\frac{\partial\phi}{\partial y})^2\sigma_y^2 + \frac{\partial\phi}{\partial x}\frac{\partial\phi}{\partial y}\sigma_{xy}$$

- scale $\sigma_x, \sigma_y, \sigma_z, \ldots$:

  $$\sigma(x, y.z.E) \xrightarrow{m_{PFO}} \sigma(p_x, p_y, p_z, E)$$

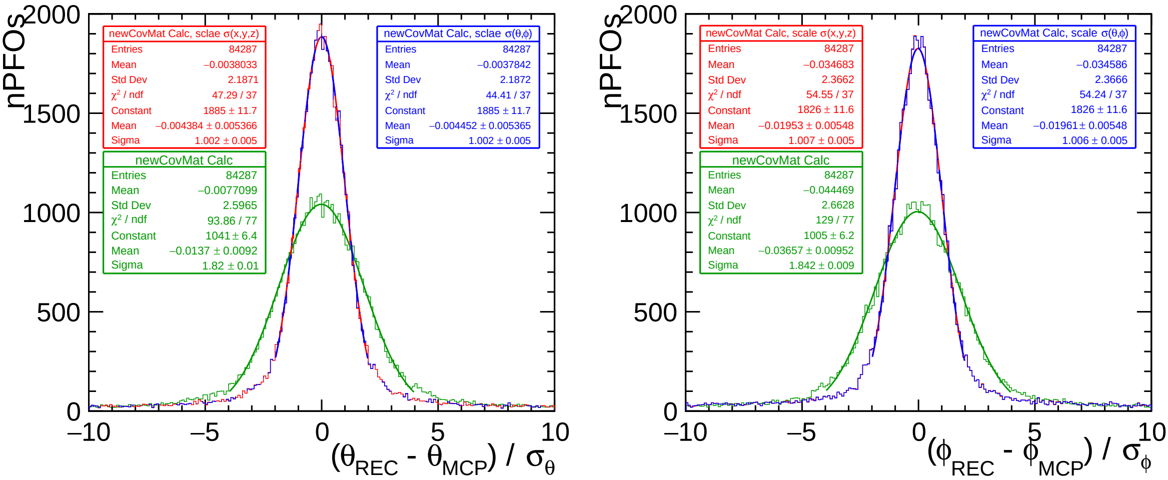
  $$\begin{pmatrix} \sigma_x^2 & \sigma_{xy} & \sigma_{xz} \\ \sigma_{xy} & \sigma_y^2 & \sigma_{yz} \\ \sigma_{xz} & \sigma_{yz} & \sigma_z^2 \end{pmatrix} \xrightarrow{Scale \oplus \sigma_E} s^2 \times \begin{pmatrix} \sigma_x^2 & \sigma_{xy} & \sigma_{xz} & 0 \\ \sigma_{xy} & \sigma_y^2 & \sigma_{yz} & 0 \\ \sigma_{xz} & \sigma_{yz} & \sigma_z^2 & 0 \\ 0 & 0 & 0 & \frac{1}{s^2} \times \sigma_E^2 \end{pmatrix} \xrightarrow{Convert} C_{(\vec{p},E)}$$

- sclae $\sigma_\theta, \sigma_\phi$:

  $$\sigma(x, y.z.E) \rightarrow \sigma(\theta, \phi, E) \xrightarrow{m_{PFO}} \sigma(p_x, p_y, p_z, E)$$

  $$\begin{pmatrix} \sigma_x^2 & \sigma_{xy} & \sigma_{xz} \\ \sigma_{xy} & \sigma_y^2 & \sigma_{yz} \\ \sigma_{xz} & \sigma_{yz} & \sigma_z^2 \end{pmatrix} \xrightarrow{Convert} \begin{pmatrix} \sigma_\theta^2 & \sigma_{\theta.\phi} \\ \sigma_{\theta.\phi} & \sigma_\phi^2 \end{pmatrix} \xrightarrow{Scale \oplus \sigma_E} s^2 \times \begin{pmatrix} \sigma_\theta^2 & \sigma_{\theta.\phi} & 0 \\ \sigma_{\phi.\theta} & \sigma_\phi^2 & 0 \\ 0 & 0 & \frac{1}{s^2} \times \sigma_E^2 \end{pmatrix} \xrightarrow{Convert} C_{(\vec{p},E)}$$

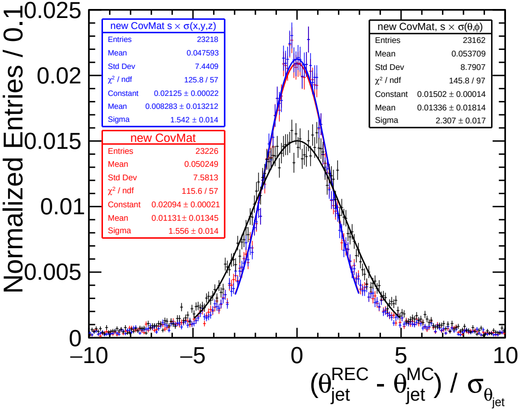
Scaling Angular Uncertaities of Neutral PFOs

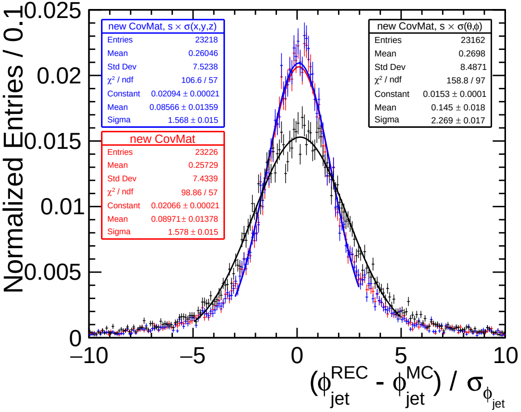


Obviously, both methods give same scaling of angular uncertanties in the PFO-level.

Improved Jet Angular Uncertaities

by scaling Neutral PFOs angular error



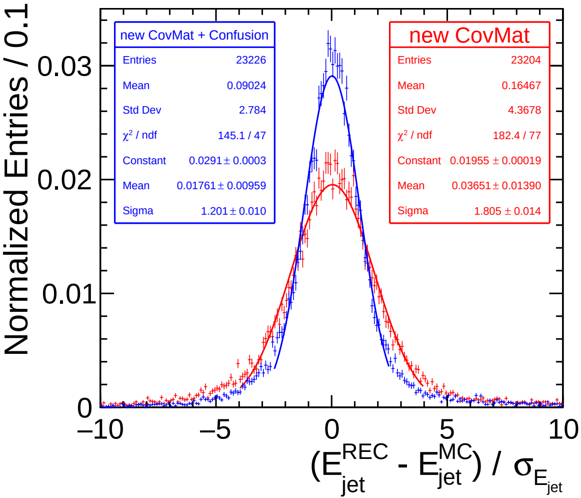


Scaling CovMat(x,y,z): no drastic impact on the jet normalized residual

Scaling CovMat(θ, ϕ) degrades normalized residual:

$$p_x = E_{clu} \sin\theta \cos\phi \Rightarrow \sigma^2_{p_x} = (\frac{\partial p_x}{\partial E_{clu}})^2 \sigma^2_{E_{clu}} + (\frac{\partial p_x}{\partial \theta})^2 \sigma^2_\theta + (\frac{\partial p_x}{\partial \phi})^2 \sigma^2_\phi + 2 \frac{\partial p_x}{\partial \theta} \frac{\partial p_x}{\partial \phi} \sigma_{\theta\phi}$$

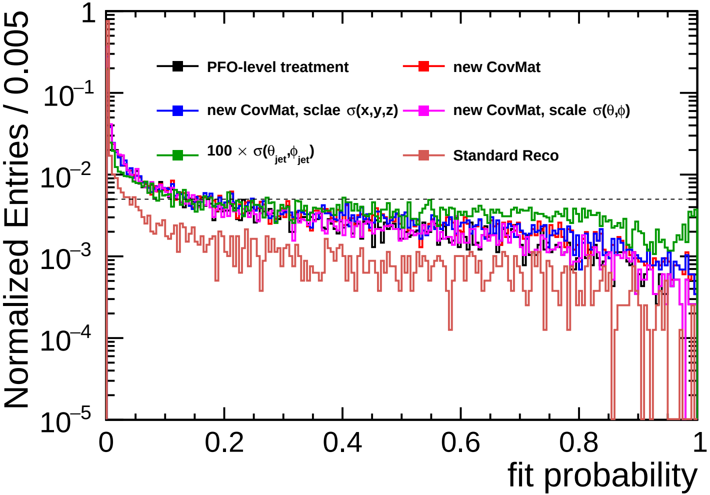
ConfusionTerm in ErrorFlow

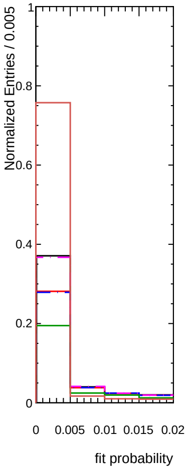


Improved normalized residual of jet energy with confusion term in ErrorFlow.

ref: **Particle flow calorimetry and the PandoraPFA algorithm, M. A. Thomson**

Angular Uncertaities in Jet-Level





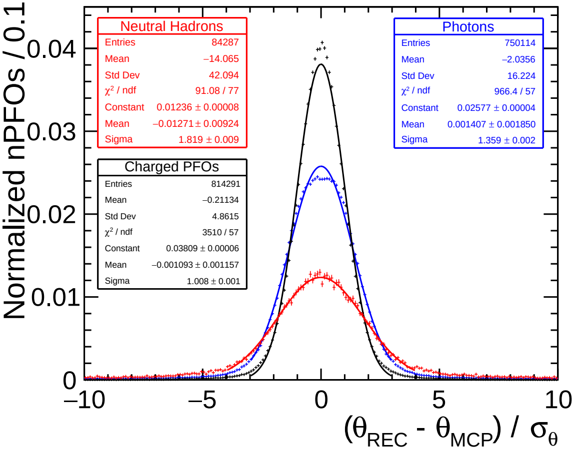
PFO-level CovMat with consistent 4-momentum of neutral hadrons improves fit probability.

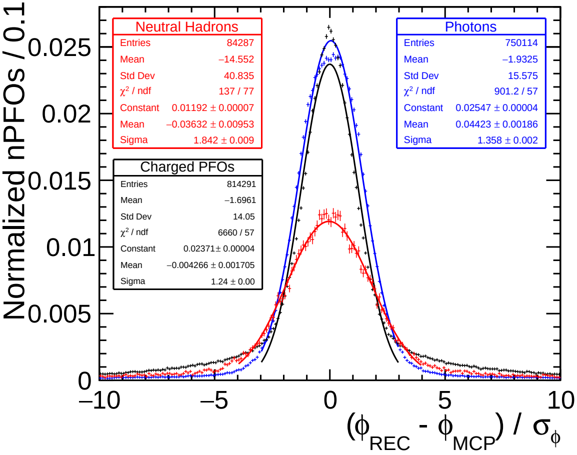
Summary

- Due to particle multiplicity, neutral hadrons are challanging to be taken massless or massive
- By assuming neutral hadrons as massive PFOs, cluster energy is assigned to momentum of PFO.
- 4-mometum of neutral hadrons is inconsistent, But CovNat is calculated using consistent 4-momentum:
- eliminate the ad-hoc scaling by 100 of the jet-level angular uncertainties by a more correct treatment of the PFO-level covariance matrices!
- Scaling (preliminary) of angular uncertainty in PFO-level, improves kinematic fit probablity $\Rightarrow$ improved fit hypothesis
- Switch to new production samples
- Further improvement on error estimation:
  - Full $(E, \vec{p})$ covariance matrix for JetFitObject (include $\sigma_{p_x E}$,$\sigma_{p_y E}$,$\sigma_{p_z E}$)
  - Estimate parton shower & hadronisation effects
  - Use proper masses, momenta and CovMatrices of PFOs from tracks refitted with correct mass hypothesis

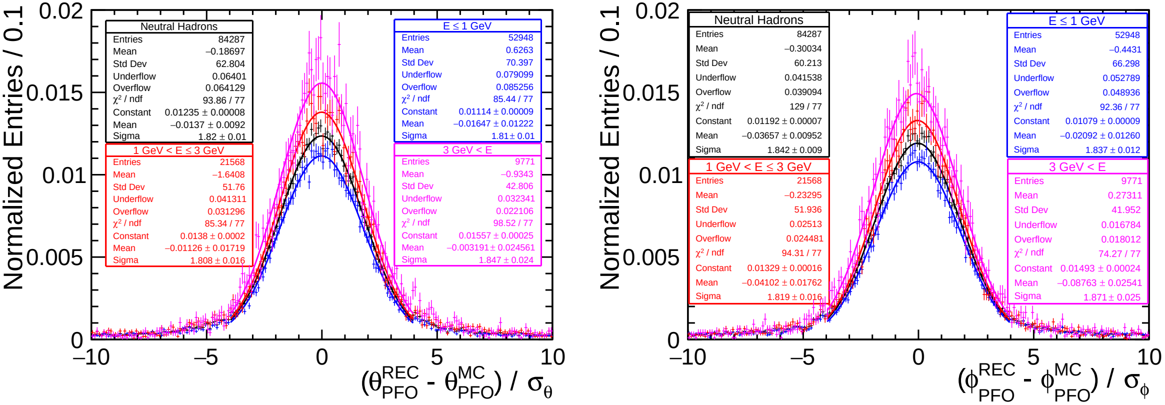
BACKUP

Angular Uncertaities of All PFOs

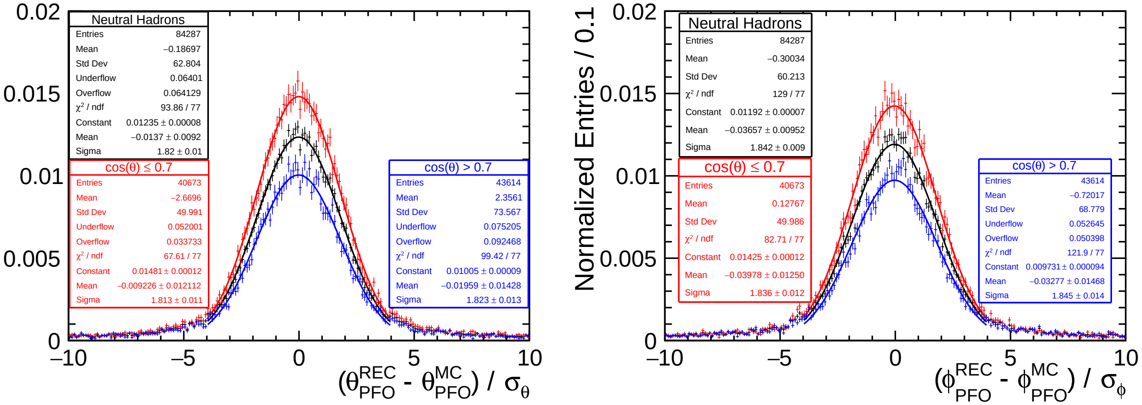




Energy dependency of normalized residuals



Energy dependency of normalized residuals



CovMat of Neutral PFOs

- Current CovMat calculation (MarlinReco/Analysis/AddClusterProperties)

$$E_{PFO} = |\vec{p}_{PFO}| = E_{clu} \ , \ p_x = E_{clu}\frac{x}{r} \ , \ p_y = E_{clu}\frac{y}{r} \ , \ p_z = E_{clu}\frac{z}{r}$$

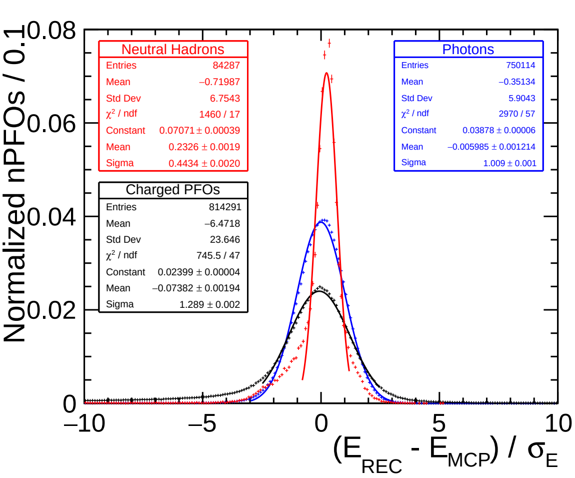
- Alternative CovMat calculation (taking consistent 4-momentum of neutral hadrons)

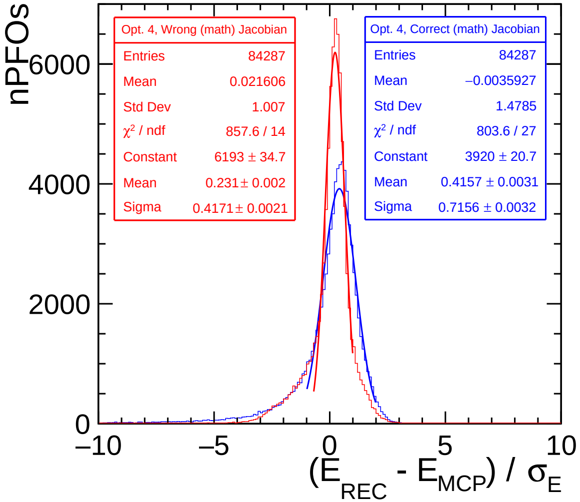
$$E_{PFO} = \sqrt{|\vec{p}_{PFO}|^2 + m_{PFO}^2} = \sqrt{E_{clu}^2 + m_n^2}$$

$$J = \begin{pmatrix} E_{clu}\frac{r^2-x^2}{r^3} & -E_{clu}\frac{xy}{r^3} & -E_{clu}\frac{xz}{r^3} & 0 \\ -E_{clu}\frac{xy}{r^3} & E_{clu}\frac{r^2-y^2}{r^3} & -E_{clu}\frac{yz}{r^3} & 0 \\ -E_{clu}\frac{xz}{r^3} & -E_{clu}\frac{yz}{r^3} & E_{clu}\frac{r^2-z^2}{r^3} & 0 \\ \frac{x}{r} & \frac{y}{r} & \frac{z}{r} & 1 \end{pmatrix} \rightarrow J = \begin{pmatrix} E_{clu}\frac{r^2-x^2}{r^3} & -E_{clu}\frac{xy}{r^3} & -E_{clu}\frac{xz}{r^3} & 0 \\ -E_{clu}\frac{xy}{r^3} & E_{clu}\frac{r^2-y^2}{r^3} & -E_{clu}\frac{yz}{r^3} & 0 \\ -E_{clu}\frac{xz}{r^3} & -E_{clu}\frac{yz}{r^3} & E_{clu}\frac{r^2-z^2}{r^3} & 0 \\ \frac{x}{r} & \frac{y}{r} & \frac{z}{r} & \frac{E_{clu}}{E} \end{pmatrix}$$

By (mathematically) correct Jacobian, the energy error doesn't remain unchanged (right-hand plot in next slide)

Energy Uncertaity of All PFOs





CovMat of Neutral PFOs

Different options for updating CovMat of neutral PFOs

- **Opt. 1** StandardReco
- **Opt. 2** Neutral PFOs are massless, $E_{cluster} = E_{kin} = |\vec{p}_{PFO}|$
- **Opt. 3** Neutral PFOs are massive, $E_{cluster} = E_{kin}(\neq |\vec{p}_{PFO}|)$, not updated 4-momentum of PFO
- **Opt. 4** Neutral PFOs are massive, $E_{cluster} = |\vec{p}_{PFO}|(\neq E_{kin})$, not updated 4-momentum of PFO
- **Opt. 5** Neutral PFOs are massive, $E_{cluster} = E_{kin}(\neq |\vec{p}_{PFO}|)$, updated 4-momentum of PFO
- **Opt. 6** Neutral PFOs are massive, $E_{cluster} = |\vec{p}_{PFO}|(\neq E_{kin})$, updated 4-momentum of PFO

momentum of PFO in options 3 and 4 (only CovMat calculation), 5 and 6:

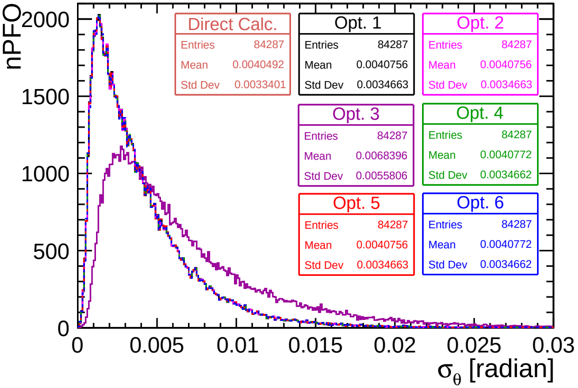
- $E_{cluster} = E_{kin}$

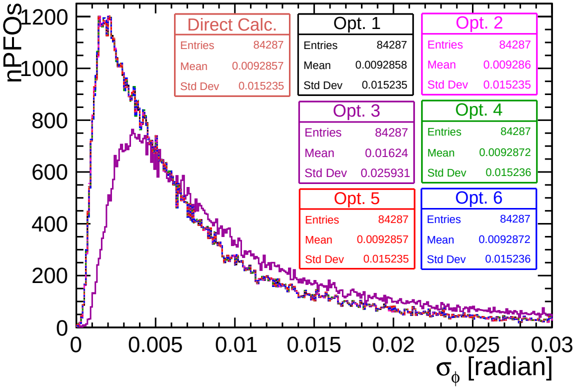
  $|\vec{p}_{PFO}| = \sqrt{E^2_{cluster} + 2m_n E_{cluster}}$, $E_{PFO} = E_{cluster} + m_n$
- $E_{cluster} = |\vec{p}_{PFO}|$

  $|\vec{p}_{PFO}| = E_{cluster}$, $E_{PFO} = \sqrt{E^2_{cluster} + m^2_n}$

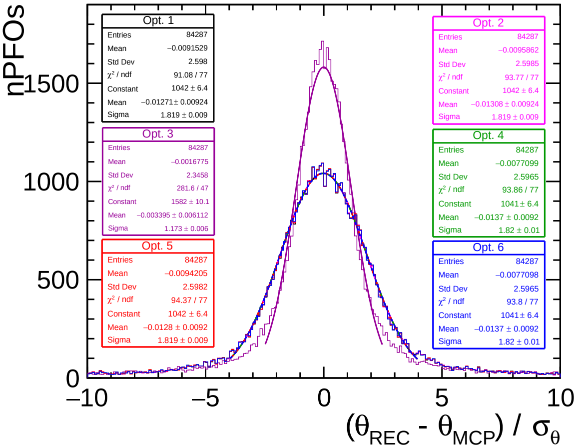
$p_x = |\vec{p}| \frac{x}{\sqrt{x^2+y^2+z^2}}$, ... , (x,y,z) from cluster position

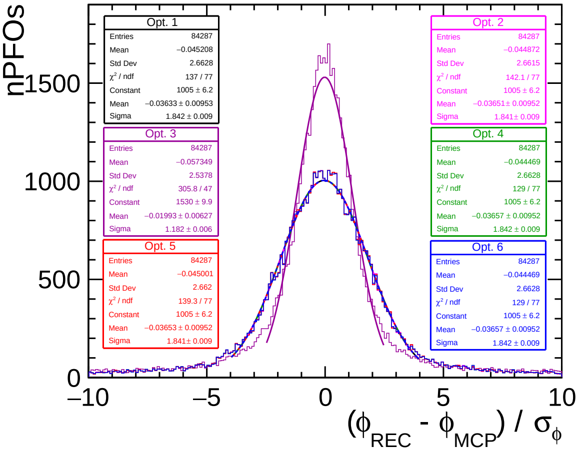
Angular Uncertaities of Neutral Hadrons





Angular Uncertainties in PFO-level





PFO angular uncertainty: obtained directly from cluster position (and errors): underestimated by factor 1.8!

σ_θ and σ_ϕ should be independent of options! ⇒ **Opt. 3** removed from list

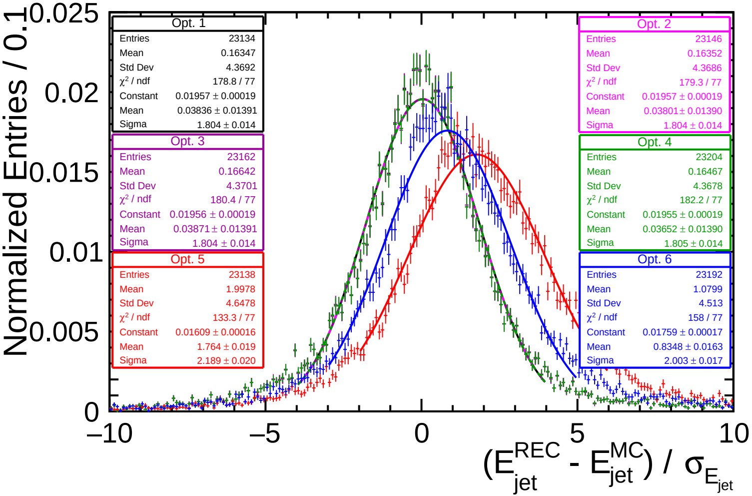
Jet Energy and Cluster Energy

- **Opt. 5** ($E_{cluster} = E_{kin}$):

$$E_{PFO} = E_{cluster} + m_{PFO}$$

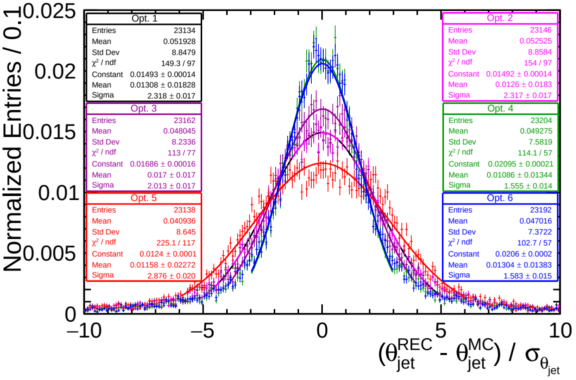
- **Opt. 6** ($E_{cluster} = |\vec{p}_{PFO}|$):

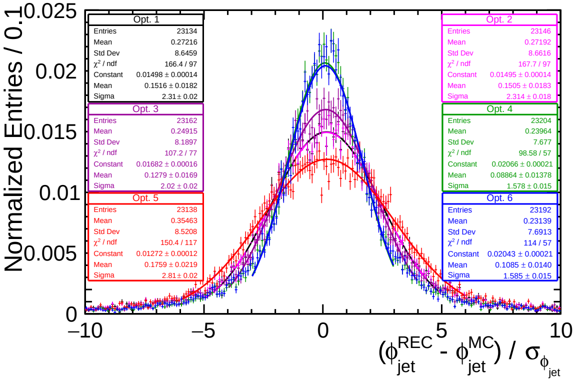
$$E_{PFO} = \sqrt{E_{cluster}^2 + m_{PFO}^2}$$



Updating 4-momentum of neutral hadrons input bias in the jet energy. ⇒ **Opt. 5** and **Opt. 6** removed from list

Angular uncertaities in jet-level

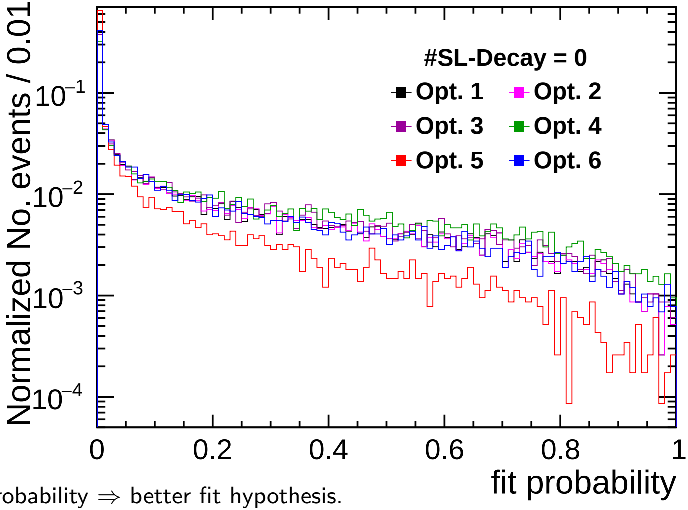




Opt. 4 gives best modeling of the neutral PFO CovMat in the jet-level.

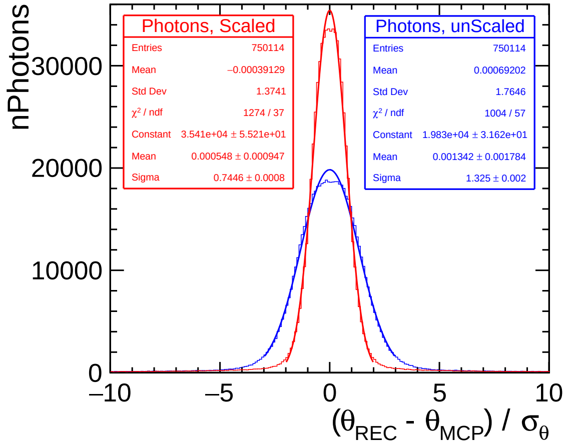
Test further improvement: scale PFO-level angular uncertainty.

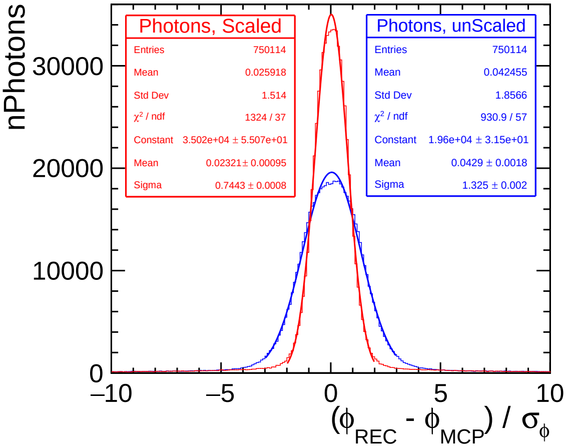
Fit Probability wrt Neutral Hadron 4-momentum



Opt. 4 gives best fit probability ⇒ better fit hypothesis.

Scaling Angular Uncertainties of Photons





Scaling degrades normalized residuals of photons

Photons need scaling factor of ∼1.3 instead of ∼1.8