# Jet error parametrisations for kinematic fitting

## CLICdp WG Analysis meeting

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DER FORSCHUNG I DER LEHRE I DER BILDUNG

CLUSTER OF EXCELLENCE
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# Outline

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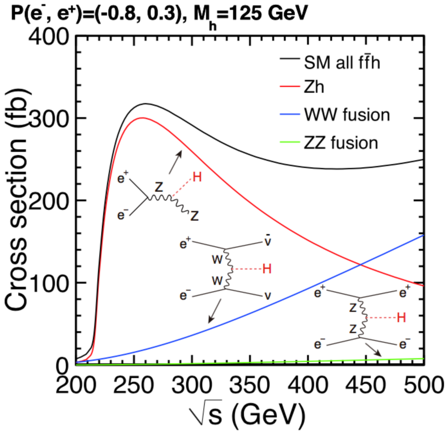
# Higgs production mechanisms at the ILC

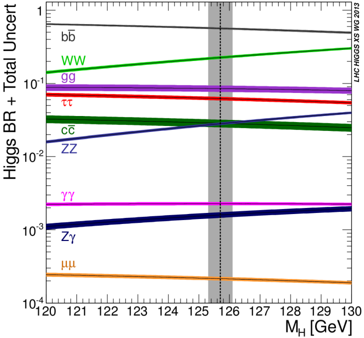



Higgs strahlung is dominant Higgs production mechanism at ILC 250 GeV

# Higgs decays into $b\bar{b}$ and $c\bar{c}$

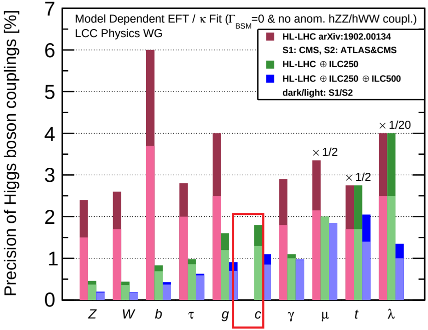
- Most frequent Higgs decay mode:

$$H \to b\bar{b}$$




- Extremly challenging in Hadron colliders:

$$H \to c\bar{c}$$



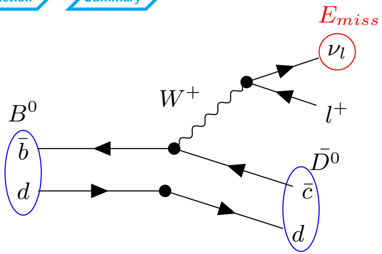

- Heavy flavour jets play key role in Higgs physics.

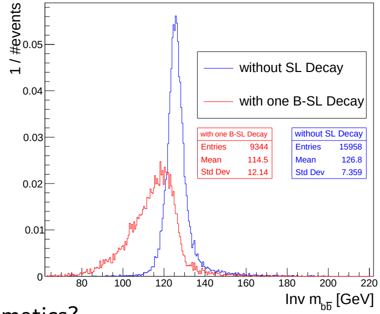
# Semi-leptonic $b$ / $c$ decays

- Semi-leptonic decay (SLD) rate in $e^+e^- \to b\bar{b}$ samples

| | | nBSLD | | |
|---|---|---|---|---|
| | | 0 | 1 | 2 |
| nCSLD | 0 | 34% | 24% | 4% |
| | 1 | 18% | 12% | 2% |
| | 2 | 3% | 2% | 0% |

  - nBSLD: number of B-hadron semi-leptonic decays
  - nCSLD: number of C-hadron semi-leptonic decays
- Mis-reconstruction of $b\bar{b}$ invariant mass due to missing neutrino energy from semi-leptonic decays

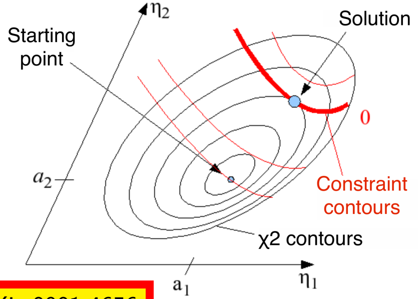



- Can the missing momentum be retrieved from event and decay kinematics?

# Kinematic fit

- Kinematic fit: adjustment of measured quantities under certain kinematic constraints:
  - Energy and momentum conservation
  - Invariant masses of particles




arXiv:0901.4656

Exploit well-known initial state in $e^+e^-$ colliders

- Minimize $\chi^2$:

$$\chi^2(\boldsymbol{a}, \boldsymbol{\xi}, \boldsymbol{f}) = (\boldsymbol{\eta} - \boldsymbol{a})^T \boldsymbol{V}^{-1} (\boldsymbol{\eta} - \boldsymbol{a}) - 2\boldsymbol{\lambda}^T \boldsymbol{f}(\boldsymbol{a}, \boldsymbol{\xi})$$

  $\boldsymbol{\eta}$: vector of measured kinematic variables ($x$)
  $\boldsymbol{a}$: vector of fitted quantities
  $\boldsymbol{\xi}$: vector of unmeasured kinematic variables
  $\boldsymbol{V}$: covariance matrix
  $\boldsymbol{\lambda}$: Lagrange multipliers
  $\boldsymbol{f}(\boldsymbol{a}, \boldsymbol{\xi})$: vector of constraints

- Measures of performance:
  $F(\chi^2;\text{ndf})$: cumulative $\chi^2$ distribution for a certain ndf
  $P(\chi^2)$: fit probability

$$pull(x) = \frac{x_{fitted} - x_{measured}}{\sqrt{\sigma^2_{fitted} - \sigma^2_{measured}}}$$

$$P(\chi^2) = 1 - F(\chi^2;\text{ndf})$$

# Outline

# Simple neutrino correction for Higgs mass reconstruction

- Neutrino energy correction:

  Estimating neutrino energy as a fraction of corresponding lepton energy:

$$E_{jet}^{corr} = E_{jet} + E_{\nu} = E_{jet} + (\frac{1}{x} - 1)E_{lep}$$

- Uncertainty on jet energy parametrised as:

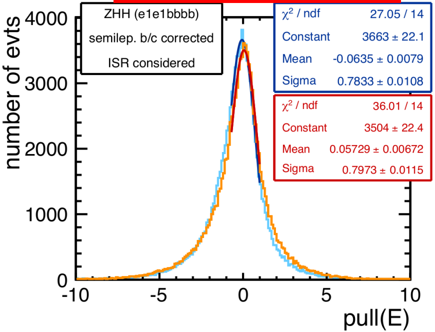
$$\sigma_{E_{jet}}^{corr} = \frac{100\%}{\sqrt{E_{jet}}} \oplus \sigma_{\nu}$$

$$\sigma_{\nu}^2 = (\frac{\sigma_{\langle x \rangle}}{\langle x \rangle^2})^2 E_{lep}^2 + (\frac{1}{x} - 1)\Delta E_{lep}^2$$

- Fixed uncertainties on angles:

$$\Delta\theta_{jet} = \Delta\phi_{jet} = 100\,\text{mrad}$$

DESY-THESIS-2016-027




Blue: before neutrino energy correction

Orange: After neutrino energy correction

Simple correction to jet energy improves jet energy pull distribution as a measure of fit performance.

# Jet specific energy resolution

Parametrize sources of uncertainties (assumed uncorrelated) in jet energy measurements `(ErrorFlow)`:

$$\sigma_{E_{jet}} = \sigma_{Had} \oplus \sigma_{Det} \oplus \sigma_{Conf} \oplus \sigma_{\nu} \oplus \sigma_{Clus}$$

DESY-THESIS-2017-045

- QCD effects in parton shower and hadronization, $\sigma_{Had}$
- Detector resolution using track and cluster parameters, $\sigma_{Det}$
  MarlinReco: `AddClusterProperties` and `FourMomentumCovMat`
- Particle confusion in PFA, $\sigma_{Conf}$
  Estimated based on jet energy and neutral hadron / photon energy fractions, based on arXiv:0907.3577
- Semi-leptonic decays: now treated in analysis level, $\nu$-correction
  in previous: $\sigma_{\nu}^2 = (\frac{\sigma_{\langle x \rangle}}{\langle x \rangle^2})^2 E_{lep}^2 + (\frac{1}{x} - 1)\Delta E_{lep}^2$
- Misassignment of particles in the jet clustering, $\sigma_{Clus}$

# Error flow and application in kinematic fit

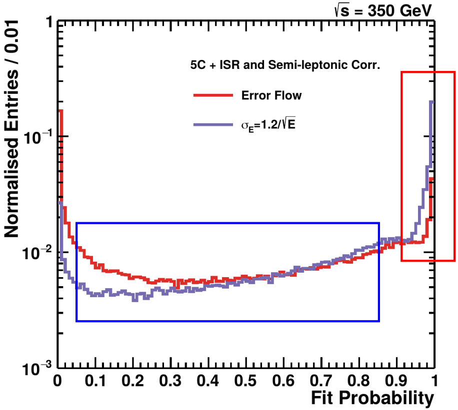
DESY-THESIS-2017-045

Jet specific energy resolution for $e^+e^- \to ZH \to q\bar{q}b\bar{b}$ process at $\sqrt{s} = 350$ GeV

- Full $4 \times 4$ CovMatrix on 4-momentum of jets $\sigma(\vec{p}, E)$:
  - $\sigma_{Det}$: computed using subdetector momentum/energy resolution
  - $\sigma_{Conf}$: computed using jet energy and particle content (charged, neutral and photon)
  - $\sigma_{\nu} = 0.73.E_l$
  - $\sigma_{Had}$, $\sigma_{Clus}$ are not accounted for error flow procedure yet.
- Fixed (and wide) angular resolution: $\sigma_\theta = \sigma_\phi = 100$ mrad

Kinematic fit: vary jet quantities ($E$,$\theta$,$\phi$) within uncertainties ($\sigma_E$,$\sigma_\theta$,$\sigma_\phi$)

Improved fit probability by applying Error Flow on jet energy



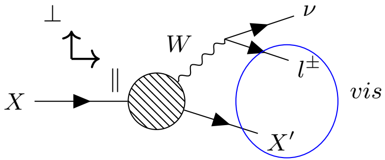

⇒ Further improvements by error parametrization and handling sl-decays

# Outline

# Concept of correction in a semi-leptonic decay

- Find heavy-quark jets: Identify $b$ or $c$ jet $\to$ flavour tag
- Find semi-leptonic decay(s): Identify lepton in jet if present $\to$ possible using detector's high granularity
- Estimate neutrino energy from decay kinematics:
  - Assign $B^0$ or $D^0$ meson mass to mother hadron.
  - Reconstruct flight direction of mother hadron from position of primary and secondary vertex.
  - Calculate neutrino momentum: up to 3-fold ambiguity.
- As proof-of-principle: CHEAT from MC truth

- Lepton ID
- Flavour tag
- Mother hadron mass
- **Associate of reconstructed particles to secondary vertex**
- Momenta of visible decay products

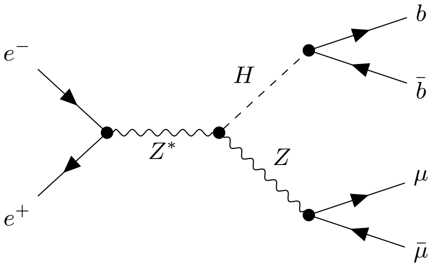



The neutrino momentum can be determined up to a two-fold ambiguity
Can we use overall event kinematics to decide between solutions? $\Rightarrow$ kinematic fit!

# $ZH \to \mu\bar{\mu}b\bar{b}$ event preparation

## Overview

- Test sample for upcoming 250 GeV MC production: $e^+e^- \to ZH$ samples with $Z \to \mu\bar{\mu}$ and $H \to b\bar{b}$ (57016 events, no $\gamma\gamma \to hadrons$ overlay):
  - Event generator: WHIZARD-2
  - Software version: iLCSoft v02-01
  - Detector model: ILD_l5_v02
- Event selection:
  - $Z \to \mu\bar{\mu}$: `IsolatedLeptonTagging`
  - $H \to b\bar{b}$: `FastJetProcessor`: Durham jet clustering
- CovMatrix of jets: `ErrorFlow`
- Neutrino correction from semi-leptonic decays (($E, \vec{p}$)-based approach, 3-fold ambiguity: $E_\nu^+$, $E_\nu^-$, 0)
- Kinematic fit (2-jets + 2-leptons)
  - Add constraints to fit
  - Choose best $\nu$-correction (highest fit probability)



# Error parametrisations for jets and leptons

**ZHllqq5CFit**

- Jets parametrized by $(E_{jet}, \theta_{jet}, \phi_{jet}, \sigma_{E_{jet}}, \sigma_{\theta_{jet}}, \sigma_{\phi_{jet}}, m_{jet})$:

$( p_x , p_y , p_z , E$ , CovMat( $\vec{p} , E$ ) ) $\rightarrow ( E , \theta , \phi , \sigma_E , \sigma_\theta , \sigma_\phi , m )$

$\tan\theta = \frac{\sqrt{p_x^2+p_y^2}}{p_z}$ , $\tan\phi = \frac{p_y}{p_x}$ , $m = \sqrt{E^2 - (p_x^2 + p_y^2 + p_z^2)}$

$\sigma_\theta^2$: Error propagation of $(\sigma_{p_x}^2, \sigma_{p_z}^2, \sigma_{p_z}^2, ...)$ , $\sigma_\phi^2$: Error propagation of $(\sigma_{p_x}^2, \sigma_{p_z}^2, ...)$

$\sigma_\theta$ and $\sigma_\phi$ are not fixed $\Rightarrow$ Angular resolutions are calculated for each individual jet
Planned TO DO: input full CovMatrix to fit objects

- Leptons are parametrized by $(\frac{1}{p_T}, \theta_{lep}, \phi_{lep}, \sigma_{\frac{1}{p_T}}, \sigma_{\theta_{lep}}, \sigma_{\phi_{lep}}, m_{lep})$:

$( \Omega , \tan\lambda , \phi$ , CovMatrix(track) , $m ) \rightarrow ( \frac{1}{p_T} , \theta , \phi , \sigma_{\frac{1}{p_T}}, \sigma_\theta, \sigma_\phi, m )$

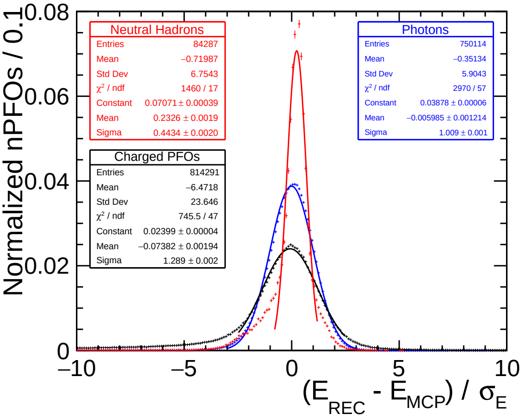
$\frac{1}{p_T} = \frac{\Omega}{eB}$ , $\theta = \frac{\pi}{2} - \lambda \Rightarrow \sigma_{\frac{1}{p_T}} = \frac{1}{eB}\sigma_\Omega$ , $\sigma_\theta = \frac{\sigma_{\tan\lambda}}{1+\tan^2\lambda}$

Parameters are obtained from tracks $\Rightarrow$ precisely measured parameters

# 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 agenda.linearcollider.org/event/8341
- Neutral Hadrons: energy and energy error are overestimated.



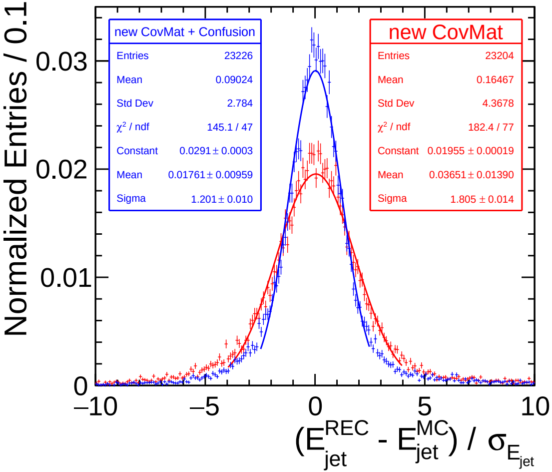

The energy error of the neutral PFOs is directly obtained from cluster energy error. ⇒ Not easy to maneuver!

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

# Uncertaities in jet-level: Energy

Jet-level truth:

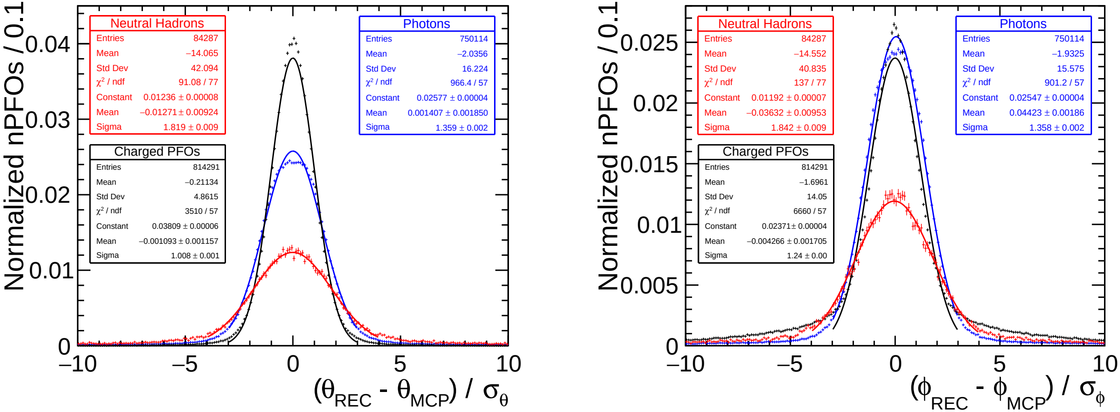
- All stable particles in MCParticleSkimmed collection (generator status = 1)
- Remove ISR photons
- Find and remove isolated muons
  look for stable $\mu/\bar{\mu}$ in daughter chain of initial muon pair
- include/exclude $\nu$s from semileptonic decay (optional)
- Run jet clustering algorithm




Confusion term improves estimating uncertainty on the jet energy

# Uncertainty in PFO level (Angles)

Obtained directly from track parameters / cluster position errors




The angular uncertainties of the neutral PFOs are obtained from cluster position error.
Underestimated $\sigma_\theta$ and $\sigma_\phi$ for photons (factor ∼1.3) and neutral hadrons (factor ∼1.8)

# CovMat of Jets

- `AddClusterProperties/FourMomentumCovMat`: CovMat(cluster/track) $\to$ CovMat($\vec{p}, E$)
  - Current CovMat calculation (inconsistent 4-momentum of neutral hadrons):

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

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

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

$$J_{(wrong)} \to J_{(right)}$$

$$\begin{pmatrix} E_{clu}\frac{r^2-x^2}{r^3} & -E_{clu}\frac{xy}{r^3} & -E_{clu}\frac{xz}{r^3} & 0 \\ -E_{clu}\frac{xy}{r^3} & E_{clu}\frac{r^2-y^2}{r^3} & -E_{clu}\frac{yz}{r^3} & 0 \\ -E_{clu}\frac{xz}{r^3} & -E_{clu}\frac{yz}{r^3} & E_{clu}\frac{r^2-z^2}{r^3} & 0 \\ \frac{x}{r} & \frac{y}{r} & \frac{z}{r} & 1 \end{pmatrix}_{wrong} \to \begin{pmatrix} E_{clu}\frac{r^2-x^2}{r^3} & -E_{clu}\frac{xy}{r^3} & -E_{clu}\frac{xz}{r^3} & 0 \\ -E_{clu}\frac{xy}{r^3} & E_{clu}\frac{r^2-y^2}{r^3} & -E_{clu}\frac{yz}{r^3} & 0 \\ -E_{clu}\frac{xz}{r^3} & -E_{clu}\frac{yz}{r^3} & E_{clu}\frac{r^2-z^2}{r^3} & 0 \\ \frac{E}{E_{clu}}.\frac{x}{r} & \frac{E}{E_{clu}}.\frac{y}{r} & \frac{E}{E_{clu}}.\frac{z}{r} & 1 \end{pmatrix}_{right}$$

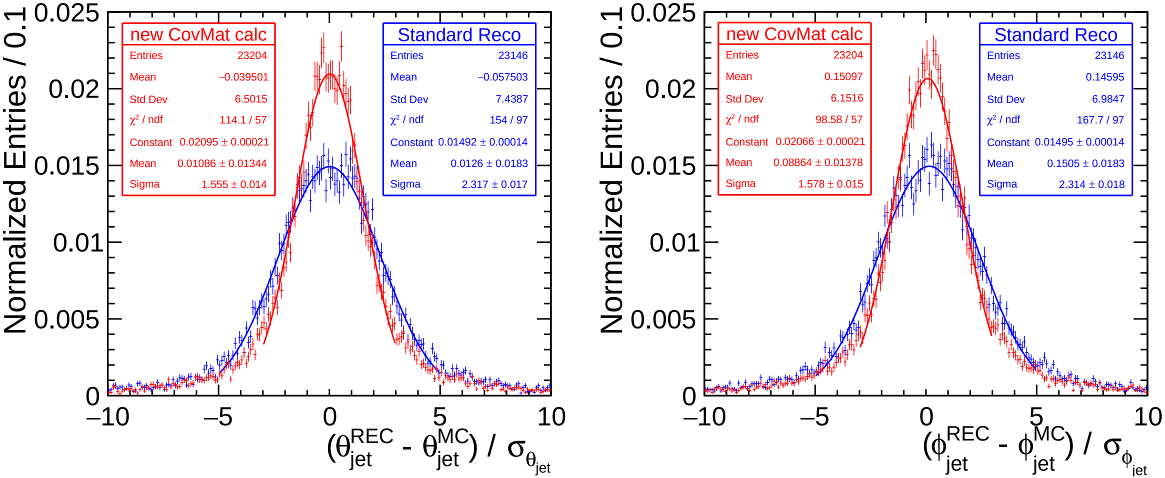
- `ErrorFlow`:

$$\text{CovMat}(\vec{p}_{jet}, E_{jet}) = \sum_{PFO} \text{CovMat}(\vec{p}, E) \quad : \quad \sigma_{E_{jet}}^2 = \sigma_{conf}^2 + \sum_{PFO} \sigma_{E_{PFO}}^2$$

- `MarlinKinfitProcessors`:

$$\text{CovMat}(\vec{p}_{jet}, E_{jet}) \to (\sigma_{\theta_{jet}} \ , \ \sigma_{\phi_{jet}} \ , \ \sigma_{E_{jet}})$$

# Uncertaities in jet-level: $\theta$ & $\phi$




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

# 5C Kinematic fit

## in 2-leptons + 2-jets events

Parameters of jets and leptons are variated within their uncertainties to satisfy 5 constraints:
Conservation of momentum (hard constraints):

- $p_x$: $e^+e^-$ crossing angle: 14 mrad
  $\Sigma p_x = \sqrt{s} \times \sin 0.007 \approx 1.75$ GeV
- $p_y$: $\Sigma p_y = 0$
- $p_z$: $\Sigma p_z = 0$

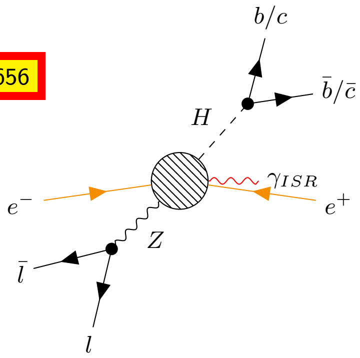
Conservation of total energy (hard constraint):

- $E_{lab} = 2\sqrt{(\frac{\sqrt{s}}{2})^2 + (\Sigma p_x)^2}$

Constrain di-muon mass to agree with $m_Z$ within its natural width (soft constraint):

- $m_Z = 91.2$ GeV , $\sigma_{m_Z} = \frac{2.4952}{2}$

arXiv:0901.4656

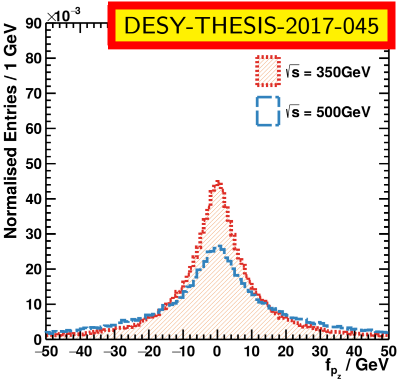


# Fit constraints

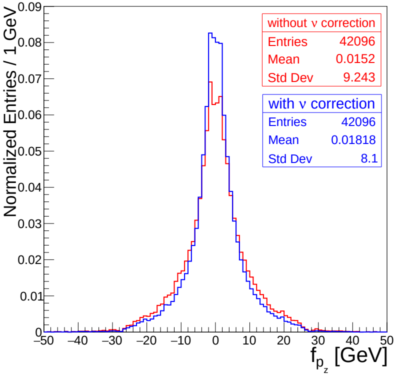
## Momentum conservation: $p_z$

Adding 4-momentum of neutrino improves jet fit object initialization

- DBD 350/500 GeV samples




- MC-2020 250 GeV prod. samples



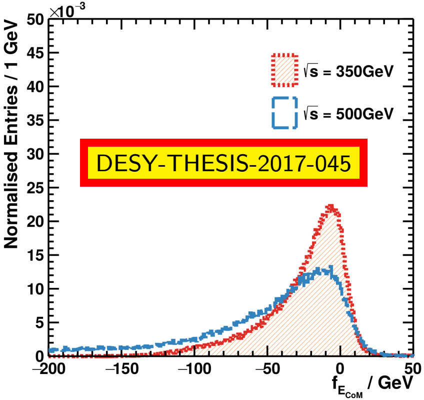

Proper neutrino correction for jets: improved constraint on momentum

# fit constraints

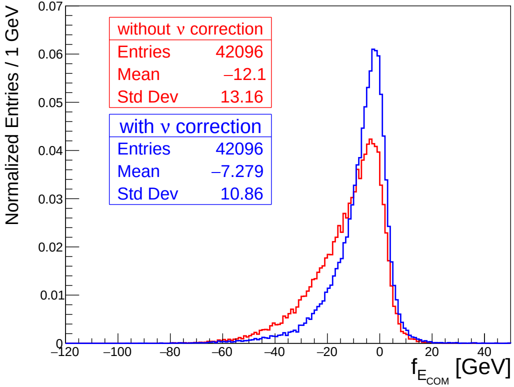
**energy conservation: $E$**

Neutrino correction (best pre-fit $\vec{p}_\nu$ for succesful fits) improves start values ⇒ better fit object initialization

- DBD 350/500 GeV samples




- MC-2020 250 GeV prod. samples



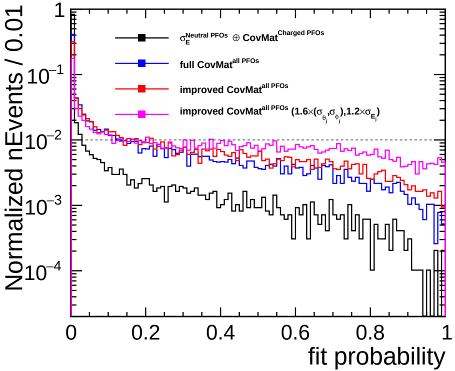

By neutrino correction, inital value of constraint function closer to target ⇒ fit should work better!

# Kinematic fit performance

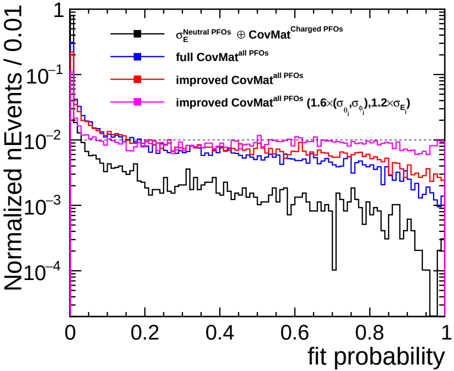
## fit probability

$e^+e^- \to ZH \to \mu\bar{\mu}b\bar{b}$ at $\sqrt{s} = 250$ GeV (without semi-leptonic decays)

- without confusion term in `ErrorFlow`




- with confusion term in `ErrorFlow`




Improved fit probability with: right Jacobian (improved CovMat of Neutral PFOs) + including confusion term
flat fit probability with scaling jet uncertainties ⇒ further improvement with tracks refitted with true mass!

# Higgs mass with $\nu$-correction

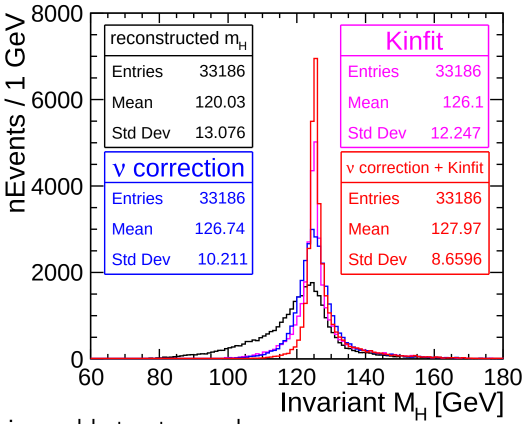
**Reconstructed $m_H$:**
Higgs mass by standard reconstruction: $m_H =$ Inv. $M_{b\bar{b}}$

$\nu$ correction:
Higgs mass by standard reconstruction with
$\vec{p}_{jet}^{\,corr} = \vec{p}_{jet} + \vec{p}_{\nu}$
Run fit for all $\vec{p}_{\nu}$ solutions and use best pre-fit $\vec{p}_{\nu}$

Kinfit (with improved CovMat + confusion):
Kinematic fit without $\nu$ correction

$\nu$ correction + Kinfit:
Kinematic fit with corrected jet momenta
$\vec{p}_{jet}^{\,corr} = \vec{p}_{jet} + \vec{p}_{\nu}$

all $H \to b\bar{b}$ 's




- Improvement by individual $\nu$-correction or kinematic fit is good but not enough
- Applying kinematic fit and $\nu$-correction gives huge improvement on Higgs mass reconstruction
- $\nu$ correction still partially cheated

# Outline

# Outlook

open issues:

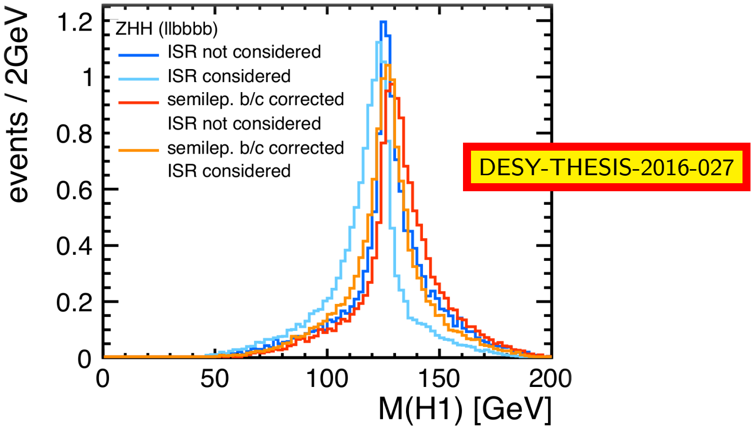
- Further improve error estimation:
  - Full $(E, \vec{p})$ covariance matrix for JetFitObject (include $\sigma_{p_x E}$,$\sigma_{p_y E}$,$\sigma_{p_z E}$)
  - Estimate parton shower & hadronisation effects
  - Use proper masses, momenta and CovMatrices of PFOs from tracks refitted with correct mass hypothesis
  - Move neutrino correction from cheated to fully-reconstructed

# Conclusions

- Heavy flavour jets are essential for Higgs physics
- Correction of semi-leptonic decays of heavy flavour jets is important for Higgs mass reconstruction
- Kinematic fit provides a useful framework for:
  - Improving Higgs mass reconstruction / resolution
  - Better understanding on source of uncertainties / errors
- New in MarlinKinFit: uncertainties on jet angles are parametrized for individual jets
- Cheated $\nu$ correction shows very interesting potential $\Rightarrow$ try on reco level!

# BACKUP

# Simple neutrino correction for Higgs mass reconstruction (Cntd.)

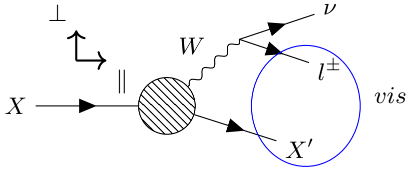



- Bias and assymetry in $m_H$ is removed by correcting jet energy and adding ISR

# correcting neutrino energy

## 4-vector based approach

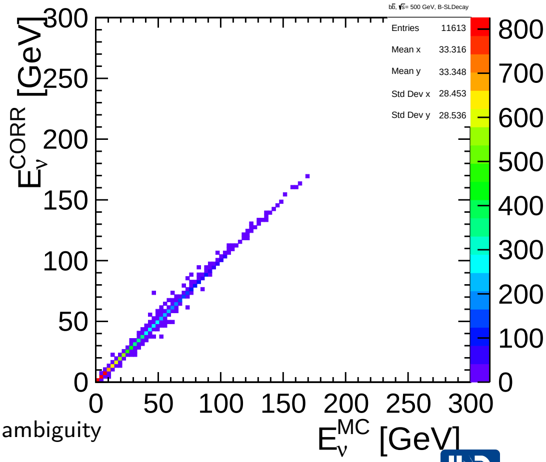
- $(E, \vec{p})$-based approach




$$\vec{p}_{\nu,\perp} = -\vec{p}_{vis,\perp}$$
$$\vec{p}\nu, \| = \frac{1}{2D}(-A \pm \sqrt{A^2 - BD})\hat{n}$$
$$A = p_{vis,\|}(2p^2_{vis,\perp} + m^2_{vis} - m^2_X)$$
$$B = 4p^2_{vis,\perp}E^2_{vis} - (2p^2_{vis',\perp} + m^2_{vis} - m^2_X)^2$$
$$D = E^2_{vis} - p^2_{vis,\|}$$
$$\hat{n} = \frac{p_{v\vec{i}s,\|}}{|p_{v\vec{i}s,\|}|}$$

The neutrino momentum can be determined up to a two-fold ambiguity

- closure test: apply correction with fully cheated information and compare with true neutrino energy

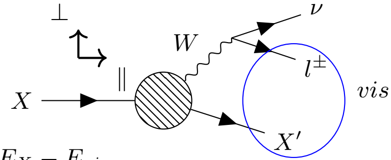


# Correcting neutrino energy

## Rapidity based approach

Rapidity under Lorents-transformations $\sim$ velocity under Galileo-transformations: $\omega = \omega_X + \omega'$ ; $\omega = \frac{1}{2} ln \frac{E+p'_{\parallel}}{E-p'_{\parallel}}$

$\omega$: rapdity in lab frame , $\omega'$: rapdity in rest frame of $X$ , $\omega_X$: rapdity of $X$ in lab frame



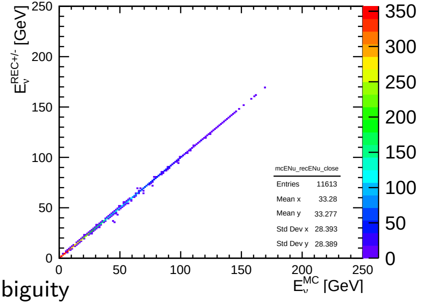

$$E_\nu = E_X - E_{vis}$$

$$E_X = \frac{E_{vis} E'_{vis} - p_{vis_{\parallel}} p'_{vis_{\parallel}}}{m^2_{vis} + p^2_{vis_{\perp}}} m_X$$

$$E'_{vis} = \frac{m^2_X + m^2_{vis}}{2m_X}$$

$$p'_{vis_{\parallel}} = \pm \sqrt{(\frac{m^2_X - m^2_{vis}}{2m_X})^2 - p^2_{vis_{\perp}}}$$

- Closure test: fully cheated information ($e^+e^- \rightarrow b\bar{b}$ at $\sqrt{s} = 500$ GeV)



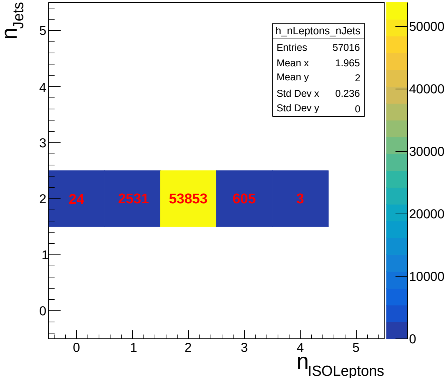

The neutrino momentum can be determined up to a two-fold ambiguity

Can we use overall event kinematics to decide between solutions? $\Rightarrow$ kinematic fit!

# Event selection

Select $e^+e^- \to ZH \to \mu\bar{\mu}b\bar{b}$ events at $\sqrt{s} = 250$ GeV with (exactly) 2-leptons + 2-jets final state:

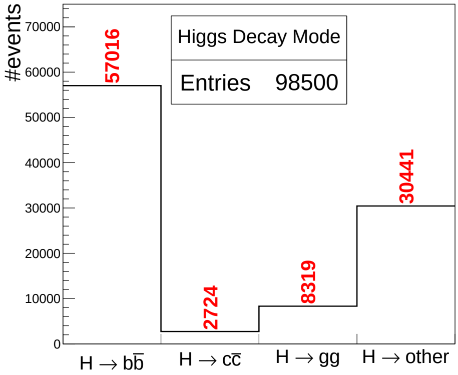
- IsolatedLeptonTagging
  Training for the IDR 500 GeV samples is used,
  1. Lepton ID: $\mu^{\pm}$
     Deposited energy in subdetectors
  2. Vertex: primary or secondary
     Significance of impact parameters ($d_0$ , $z_0$)
  3. Isolated: not belong to jets
- FastJetProcessor
  - Exclusive $k_t$ (Durham) algorithm (no overlay)
  - Find smallest of ($d_{ij}$,$d_{iB}$)
    $d_{ij} = 2\min(E_i^2, E_j^2)(1 - \cos\theta_{ij})$
    $i$,$j$: particles, $B$: Beam
  - $d_{ij} < d_{iB}$: combine $i$&$j$ as pseudojet($p$): $p_i + p_j$
  - $d_{iB} < d_{ij}$: remove particle $i$ from list
  - Repeat iteration until $d_{ij}$ or $d_{iB} > d_{cut}$(threshold)




IsolatedLeptonTagging has not been trained for new software at 250 GeV yet!

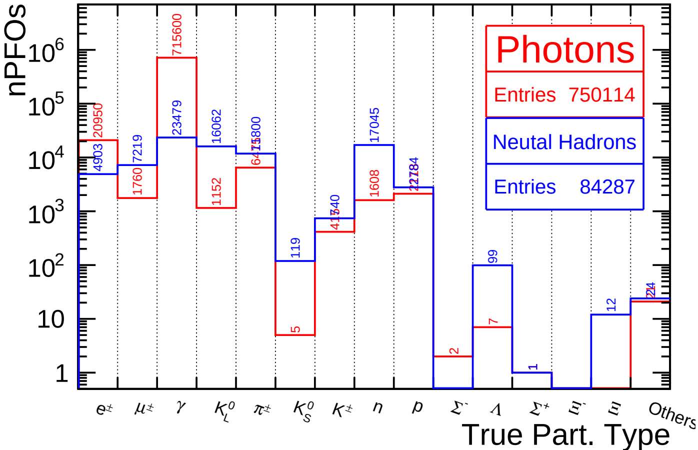
# event selection

separate Higgs decay modes: $H \to b\bar{b}$ , cheat from MCTruth




$\frac{2}{3}$ of $b\bar{b}$ jets contain at-least one semi-leptonic decay $\Rightarrow$ Frequent $H \to b\bar{b}$ needs neutrino correction.

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

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

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!

# Neutrino correction hypothesis

- Assign semi-leptonic decays to jets
- Add neutrino momentum to 4-momentum of assigned jet:
  Test three hypothesis for neutrino energy in each semi-leptonic decay: $E_{\nu}^{+}$ , $E_{\nu}^{-}$ , $0$
  $3^{nSLD}$ combination of $E_{\nu}$'s for adding to jet 4-momentum:
  Number of semileptonic decays in a jet: nSLD = nSLDB + nSLDC
  Example:
  If an event contains two jets: jet-1 contains 2 semi-leptonic decays and jet-2 contains 1 semi-leptonic decay, **27**($=3^2 \times 3^1$) combinations of $E_{\nu}$'s are available for neutrino correction in the event:

- jet-1:

| comb. | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|---|---|---|---|---|---|---|---|---|---|
| $\vec{p}_{\nu,1}$ | - | + | 0 | - | + | 0 | - | + | 0 |
| $\vec{p}_{\nu,2}$ | - | - | - | + | + | + | 0 | 0 | 0 |

- jet-2:

| comb. | 1 | 2 | 3 |
|---|---|---|---|
| $\vec{p}_{\nu,3}$ | - | + | 0 |

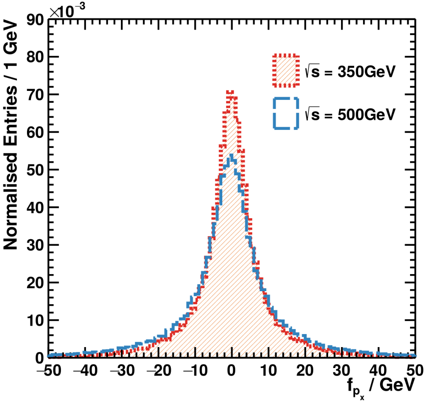
$\vec{p}_{\nu,1} + \vec{p}_{\nu,2}$ is added to 4-momentum of jet-1 and $\vec{p}_{\nu,3}$ is added to 4-momentum of jet-2.
$\vec{p}_{\nu,1} + \vec{p}_{\nu,2} + \vec{p}_{\nu,3} = 0$ allows fitter to neglect neutrino correction
Combination with highest fit probability is chosen as best neutrino correction.

# fit constraints

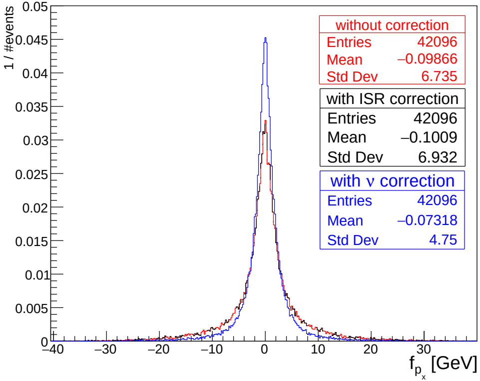
## momentum conservation: $p_x$

ISR is initialized to satisfy momentum conservation on $x$ direction

- by error flow on jet energy (Ali)




- by error flow on CovMatrix (new)



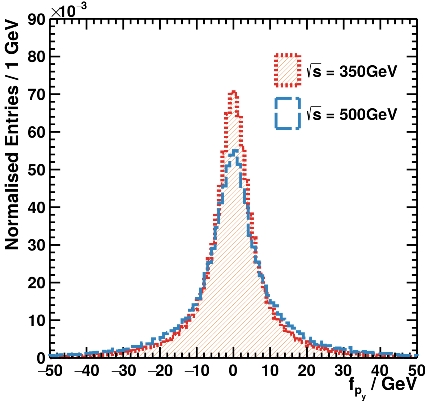

angular resolution for individual jets: improved constraint on momentum conservation

# fit constraints

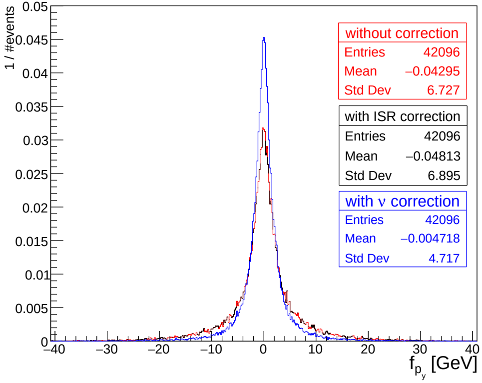
## momentum conservation: $p_y$

ISR is initialized to satisfy momentum conservation on $z$ direction

- by error flow on jet energy (Ali)




- by error flow on CovMatrix (new)




angular resolution for individual jets: improved constraint on momentum conservation

# fit probability