

*Nature and Nature's laws
lay hid in night. God said,
'Let Newton be!' and all
was light.*

Alexander Pope

W boson mass in $W \rightarrow e\nu$

Wajid Ali Khan¹

¹Ph.D Student
National Centre for Physics
Islamabad

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Outline

- 1 Introduction
 - Theoretical Background
 - Transverse Mass of W boson
 - Plots of Different Quantities
 - Reconstructed W boson
 - Summary

Transverse Energy and Momentum Definitions

- Transverse Momentum: momentum perpendicular to beam direction: $p_T^2 = p_x^2 + p_y^2$
- Transverse Energy defined as the energy if p_z is identically 0:
- $E_T \equiv E(p_z = 0)$ or $E_T^2 = p_x^2 + p_y^2 + m^2 = p_T^2 + m^2 = E^2 - p_z^2$
- Using $\frac{p_z}{E} = \tanh y$
 - $\Rightarrow E_T^2 = E^2 - p_z^2$
 - $\Rightarrow E_T^2 = E^2 - E^2 \tanh^2 y = E^2(1 - \tanh^2 y) = E^2 \operatorname{sech}^2 y$
 - $\Rightarrow E_T = E \operatorname{sech} y$
- How does E and p_z change with the boost along beam direction?
 - Using $\tanh y = \frac{v}{c} = \frac{mvc}{mc^2} = \frac{p_z c}{E} = \frac{p_z}{E}$
 - Also $p_z = p \cos \theta \Rightarrow \frac{p \cos \theta}{E} = \tanh y$
 - $\beta \cos \theta = \tanh y$

Transverse Mass of W boson Cont'd.

- Invariant mass is defined as:

$$M_{1,2}^2 = (P_1 + P_2)^2 = P_1^2 + P_2^2 + 2(E_1 E_2 - \vec{p}_1 \cdot \vec{p}_2)$$

- Now we switch form $(p_x, p_y, p_z, E) \rightarrow (p_T, y, m, \phi)$

- Now $\vec{p}_1 \cdot \vec{p}_2 = p_{x1} p_{x1} + p_{y1} p_{y1} + p_{z1} p_{z1}$

- Using $p_z = E_T \sinh y$

$$\Rightarrow p_{z1} = E_{T1} \sinh y_1$$

$$\Rightarrow p_{z2} = E_{T2} \sinh y_2$$

$$\Rightarrow p_{z1} p_{z1} = E_{T1} E_{T2} \sinh y_1 \sinh y_2$$

- Azimuthal angle is given by $\tan \phi = \frac{p_y}{p_x}$, $\sin \phi = \frac{p_y}{p_z} \Rightarrow \frac{p_y}{\sqrt{p_x^2 + p_y^2}} = \frac{p_y}{p_T}$

$$\Rightarrow p_y = p_T \sin \phi$$

$$\Rightarrow p_{y1} = p_{T1} \sin \phi_1$$

$$\Rightarrow p_{y2} = p_{T2} \sin \phi_2$$

$$\Rightarrow p_{y1} p_{y2} = p_{T1} p_{T2} \sin \phi_1 \sin \phi_2$$

Transverse Mass of W boson Cont'd

- Also $\cos \phi = \frac{p_x}{p_z} \Rightarrow \frac{p_x}{\sqrt{p_x^2 + p_y^2}} = \frac{p_x}{p_T}$

$$\Rightarrow p_x = p_T \cos \phi$$

$$\Rightarrow p_{x_1} = p_{T_1} \cos \phi_1$$

$$\Rightarrow p_{x_2} = p_{T_2} \cos \phi_2$$

- Since $E_1 = E_{T_1} \sinh y_1$ & $E_2 = E_{T_2} \sinh y_2$

- Using all these values in

$$M_{1,2}^2 = (P_1 + P_2)^2 = P_1^2 + P_2^2 + 2(E_1 E_2 - \vec{p}_1 \cdot \vec{p}_2)$$

- We have the following:

$$M_{1,2}^2 = 2(E_{T_1} E_{T_2} y_2 \cosh y_1 \cosh y_2 - p_{T_1} p_{T_2} \cos \phi_1 \cos \phi_2 - p_{T_1} p_{T_2} \sin \phi_1 \sin \phi_2 - E_{T_1} E_{T_2} \sinh y_1 \sinh y_2)$$

Transverse Mass of W boson Cont'd ...

- Using $\beta \equiv \frac{p}{E} \Rightarrow \beta_T E_T = p_T$ in above we have

$$M_{1,2}^2 \cong 2(E_{T_1} E_{T_2} \cosh \Delta y - E_{T_1} E_{T_2} \beta_{T_1} \beta_{T_2} \cos \Delta \phi)$$

$$M_{1,2}^2 \cong 2(E_{T_1} E_{T_2} \cosh \Delta y - E_{T_1} E_{T_2} \beta_{T_1} \beta_{T_2} \cos \Delta \phi)$$

$$\text{With } \beta_{T_1} = \beta_{T_2} \cong 1$$

- We have the following result:

$$M_{1,2}^2 = 2E_{T_1} E_{T_2} (\cosh \Delta y - \cos \Delta \phi)$$

- We note that $\Delta y \rightarrow 0$ & $\Delta \phi \rightarrow 0$ the mass of the particle "M" $\rightarrow 0$
- Hence we can say that "angles" generate Mass.

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Transverse Mass...

- Since we don't measure the p_z of neutrino, we cannot construct invariant mass of W boson.
- What measurements or constraints we have
 - Electron's Four Vector.
 - Neutrino 2-D momentum (p_T) and $m=0$.
- We construct "Transverse Mass M_T " by
 1. Form "transverse" 4-momentum by ignoring p_z (or set $p_z = 0$)

$$p_T \equiv (E_T, \vec{p}_T, 0)$$
 2. Form "transverse mass" from these 4-vectors;

$$M_{T_{1,2}}^2 = (P_{T_1} + P_{T_2})^\mu (P_{T_1} + P_{T_2})_\mu$$

Transverse Mass Cont'd...

- $M_{T_{1,2}}^2 = P^\mu P_\mu = (E_T^\nu + E_T^e)^2 - (\mathbf{p}_T^\nu + \mathbf{p}_T^e)^2$
- $M_{T_{1,2}}^2 = (E_T^e)^2 + (E_T^\nu)^2 + 2E_T^e E_T^\nu - (\mathbf{p}_T^e)^2 - (\mathbf{p}_T^\nu)^2 - 2\mathbf{p}_T^e \cdot \mathbf{p}_T^\nu$
- Since $E_T^\nu = p_T^\nu$ & $(E_T^e)^2 - (\mathbf{p}_T^e)^2 = m_e^2 \rightarrow 0$
- we have $M_{T_{1,2}}^2 = 2E_T^e E_T^\nu - 2p_T^e p_T^\nu \cos \Delta\phi$
- Since $m_e^2 \rightarrow 0$ we have $M_{T_{1,2}}^2 = 2E_T^e E_T^\nu (1 - \cos \Delta\phi)$

Transverse Mass Cont'd...

- $M_W^2 = M_{e,\nu}^2 = 2E_{T1}E_{T2}(\cosh \Delta y - \cos \Delta \phi)$
- Constrain $M_W = 80 \text{ GeV}$ and $P_T(W) = 0$
 - $\cos \Delta \phi = -1$
 - $E_T^e = E_T^\nu$
 - From this we have $E_T^e E_T^\nu$ VS $\Delta \eta$
 - $E_T^e E_T^\nu = \frac{80}{2(\cosh \Delta \eta + 1)}$
- The transverse mass is given by $M_{T_{e,\nu}}^2 = 2E_T^e E_T^\nu (1 - \cos \Delta \phi)$
- Using $\cos \Delta \phi = -1$ and $E_T^e E_T^\nu = \frac{80}{2(\cosh \Delta \eta + 1)}$
- We have the "Transverse Mass" $M_{T_{e,\nu}}^2 = 2 \frac{80^2}{(\cosh \Delta \eta + 1)}$
- Clearly $M_T = M_W$ when $\eta_e = \eta_\nu = 0$

Transverse Mass Cont'd...

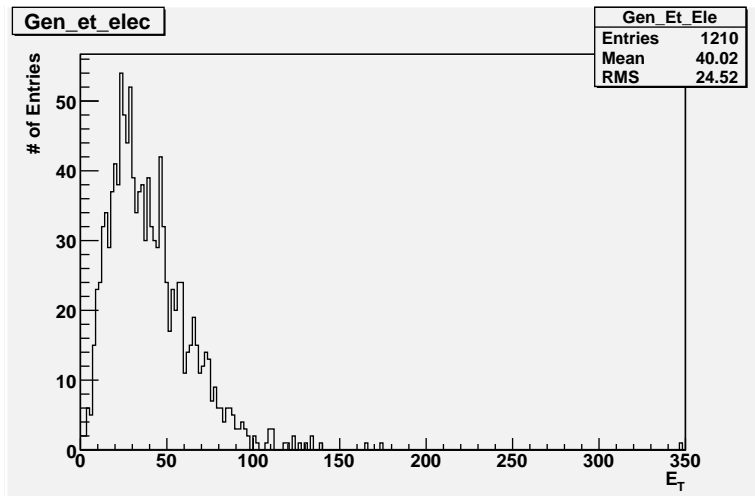
- If we know η_e we can find η_ν Since $\Delta\eta = \eta_e - \eta_\nu$
- Also if $\Delta\phi = 0 \Rightarrow M_T \rightarrow 0$
- If $\Delta\phi = \pi$ then $M_T^2 = 2.2E_T^e E_T^\nu$
 - If $E_T^e \equiv E_T^\nu$ then $M_T^2 = 4E_T^e$
 - From this we have $E_T^e \simeq \frac{M_T}{2}$
 - Similarly we have $E_T^\nu \simeq \frac{M_T}{2}$

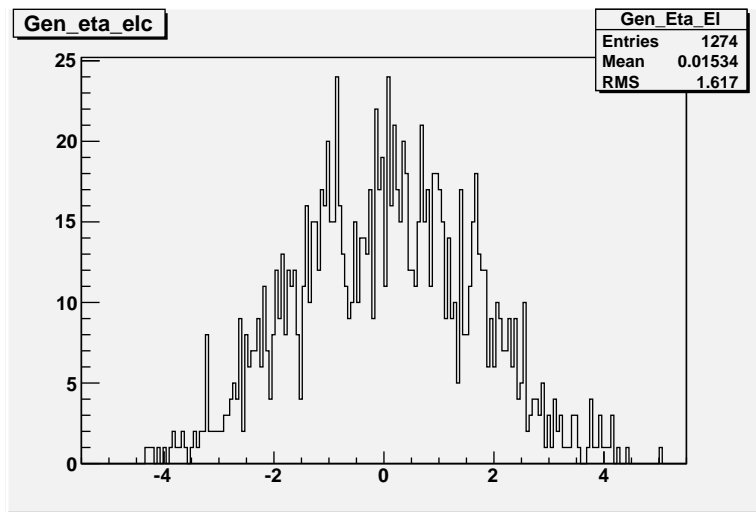
Outline

1 Introduction

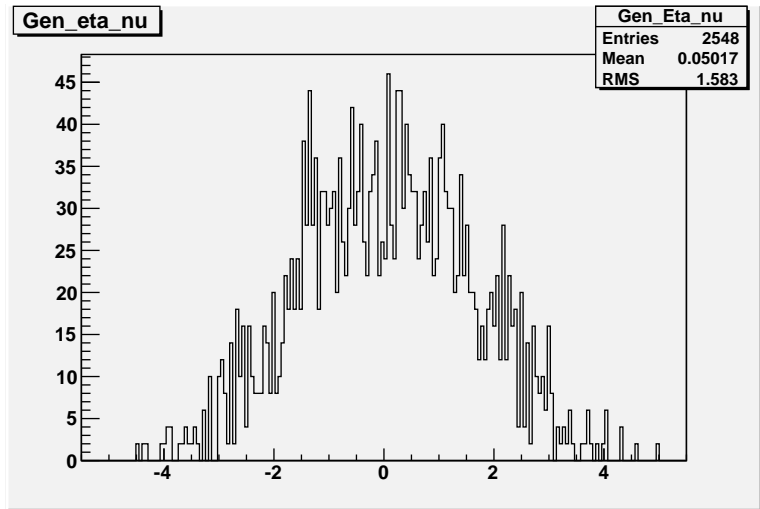
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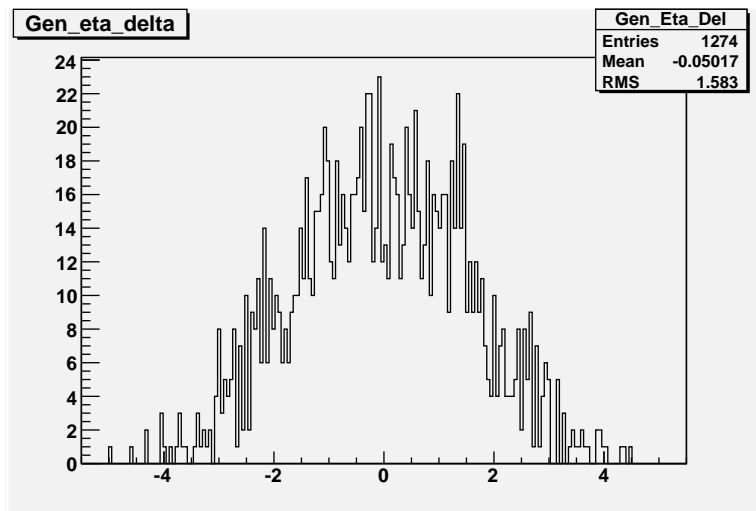
Transverse Energy of Electron...



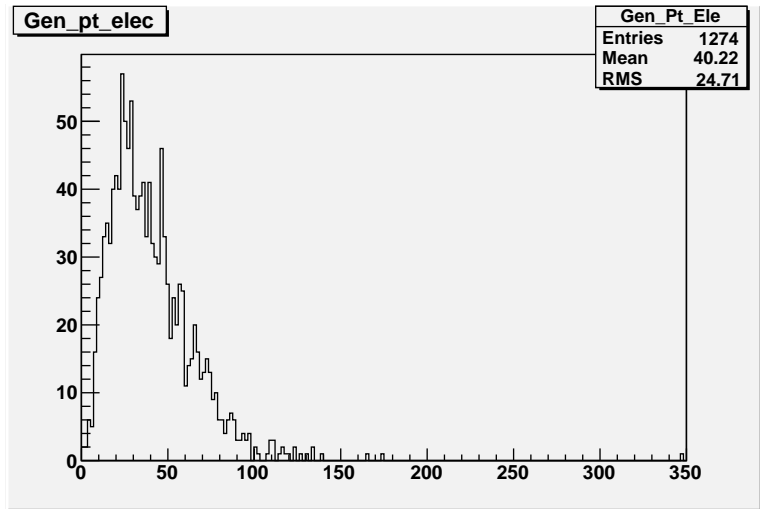
η Electron ...

η Neutrino ...

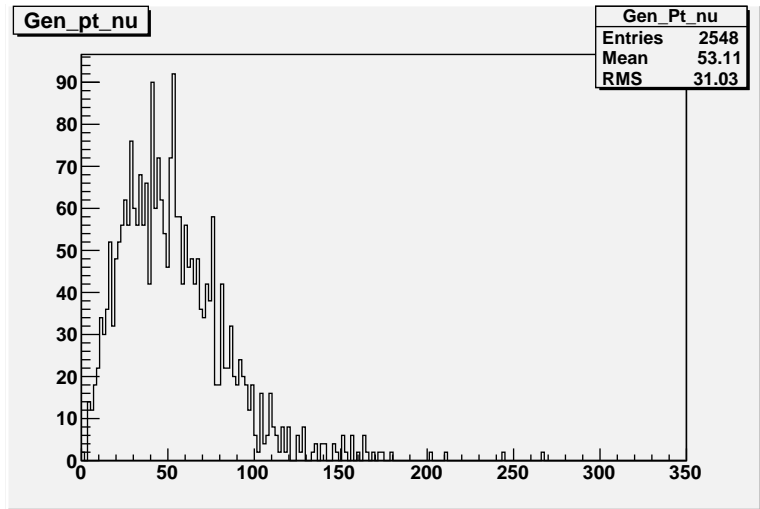


Delta η ...

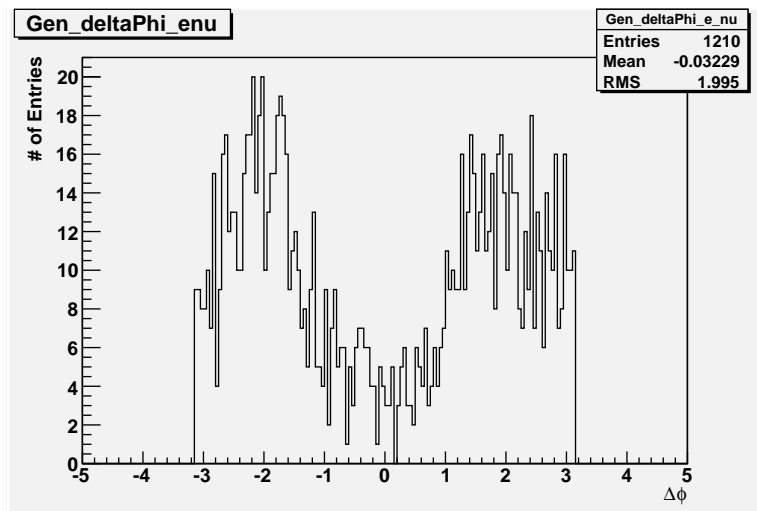
Transverse Momentum of Electron...



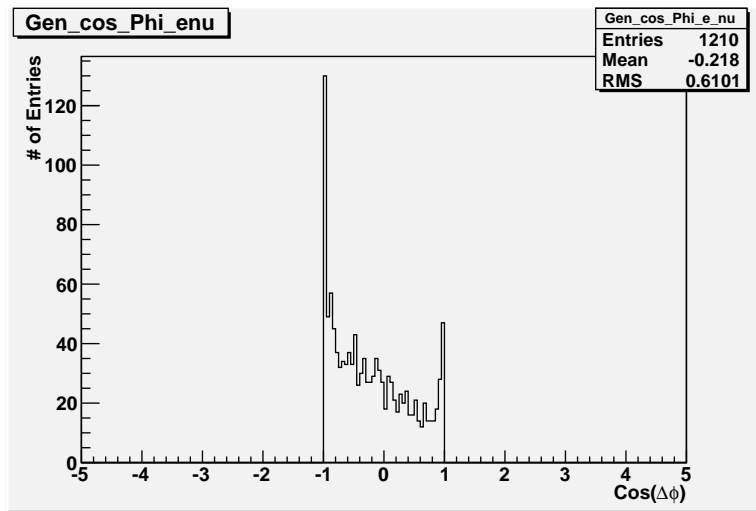
Transverse Momentum of Neutrino...



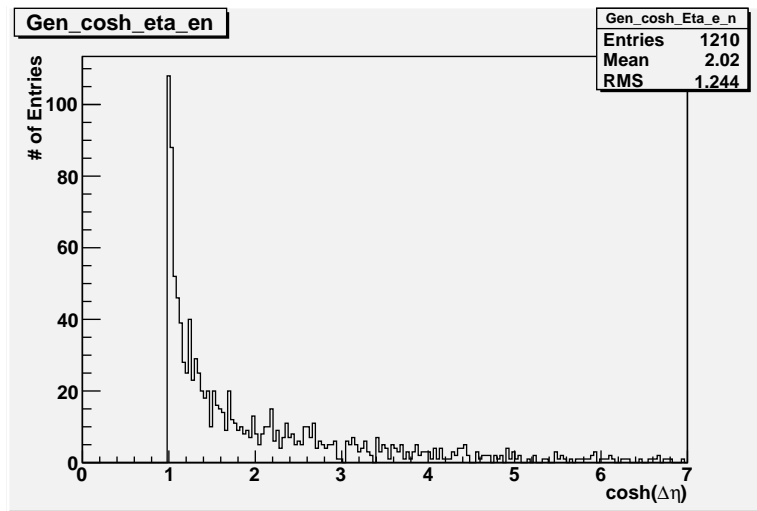
Generator level delta phi elec & ν ...



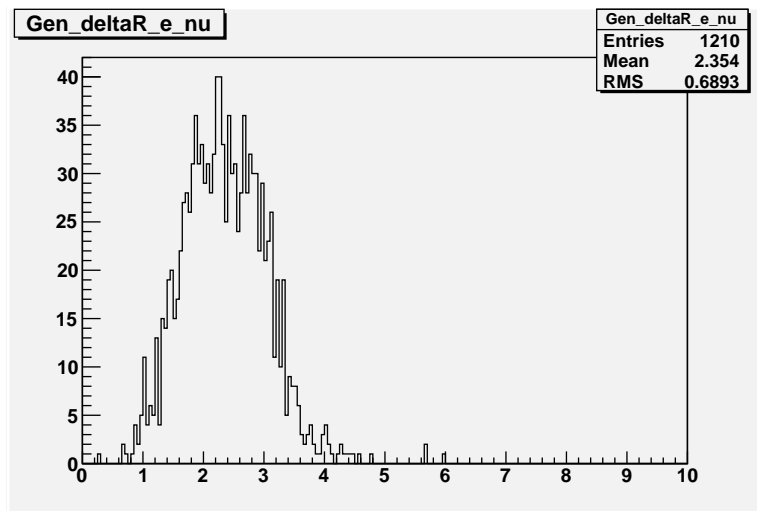
Gen cos phi elec and nu. . .



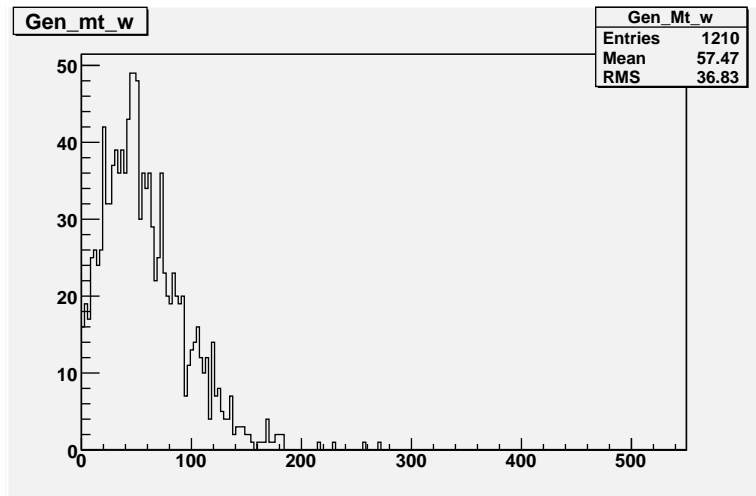
Gen cosh eta elec and nu. . .



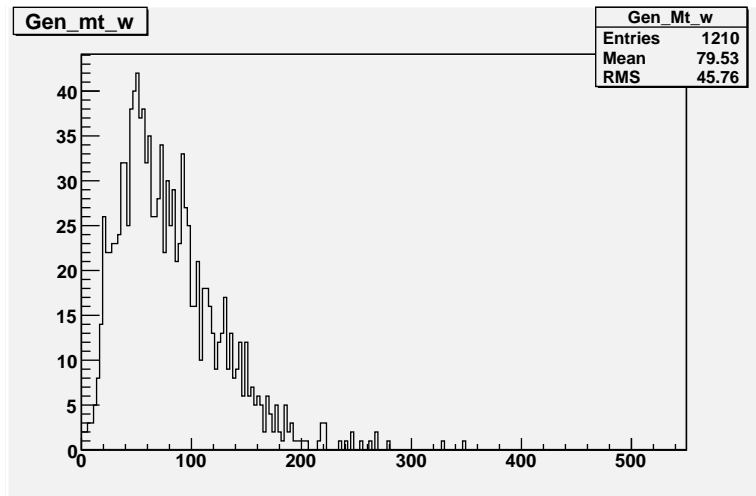
Gen deltaR Electron and Nuetrino...



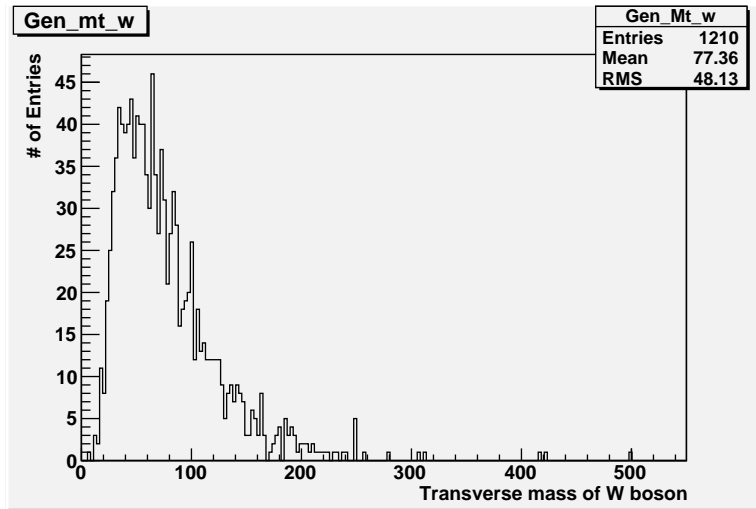
Transver Mass of W boson with $(1 - \cos \Delta\phi)$...



Transver Mass of W boson with ($\cos \Delta\phi = -1$)...



Transver Mass of W boson. . .

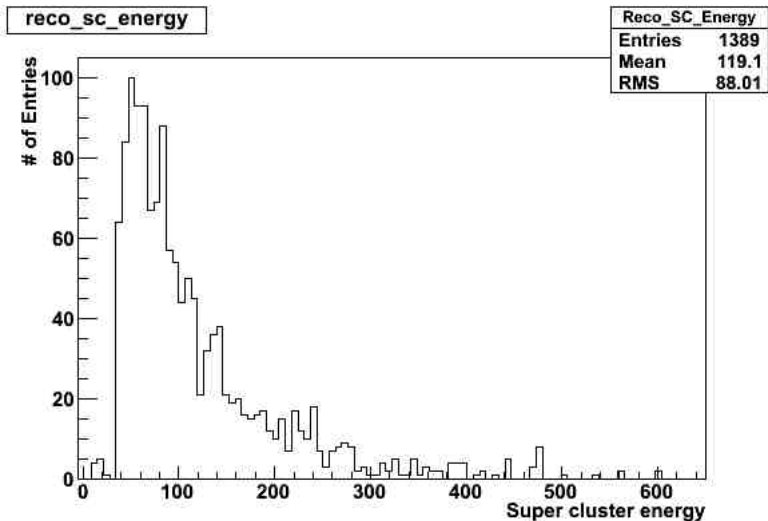


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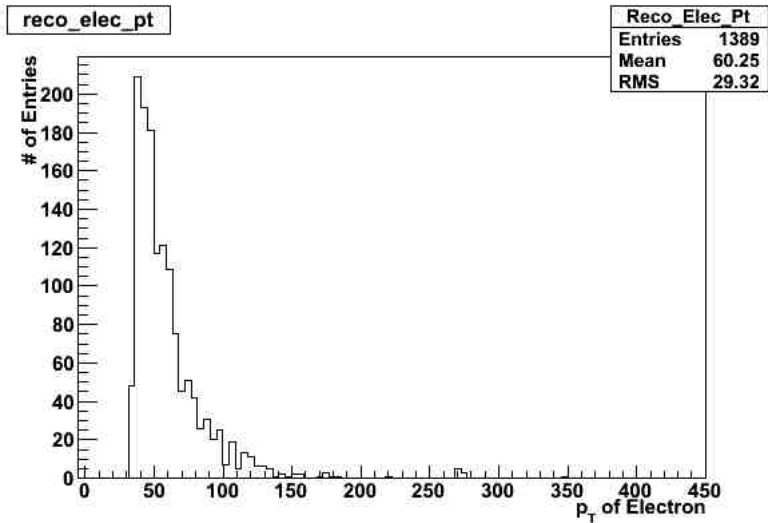
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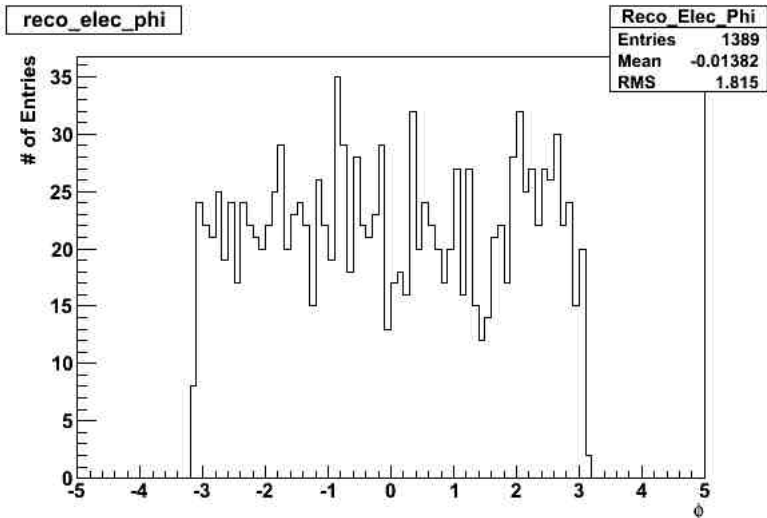
Total energy in ECAL by Electron...



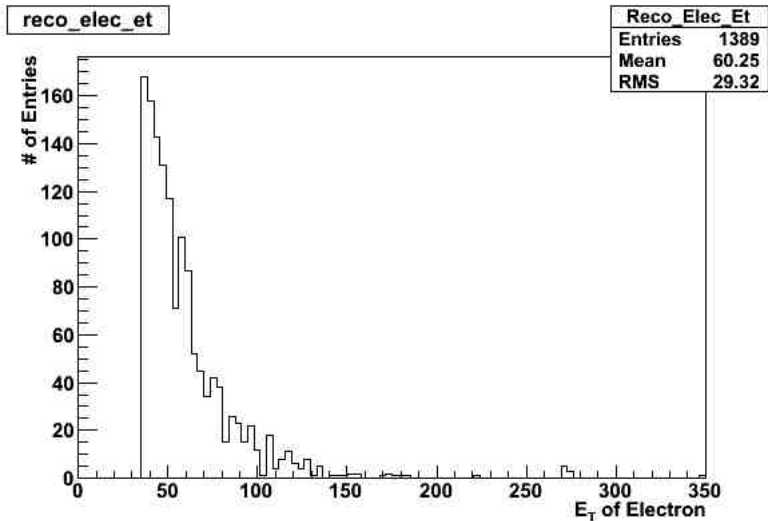
Reconstructed Electron's Transverse Momentum...



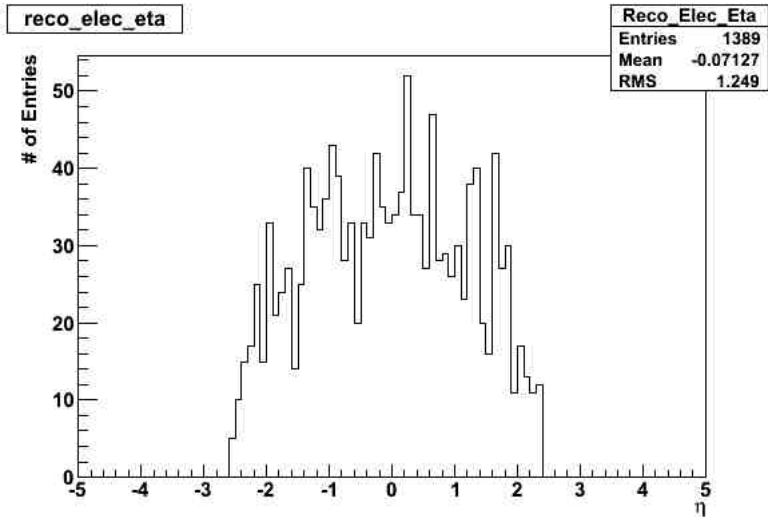
Reconstructed Electron's ϕ ...



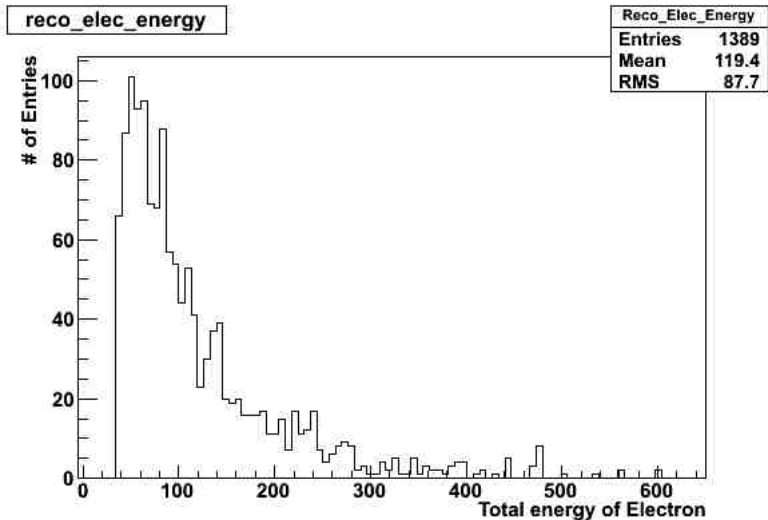
Reconstructed Electron's E_T ...



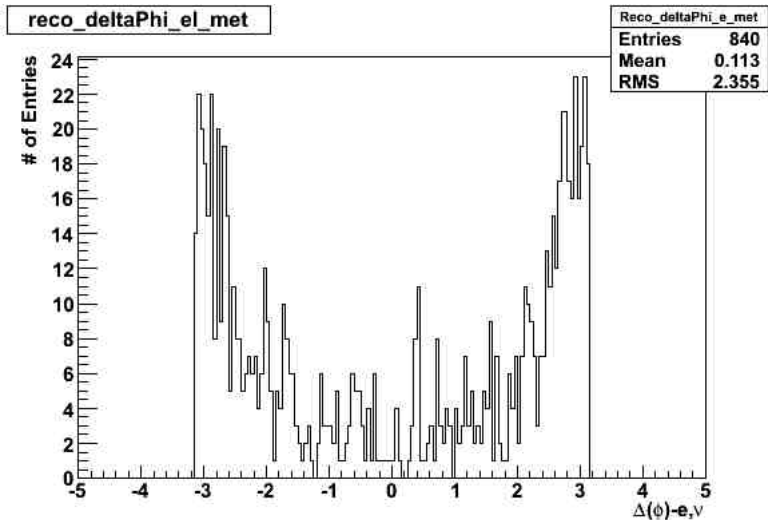
Reconstructed Electron's η ...



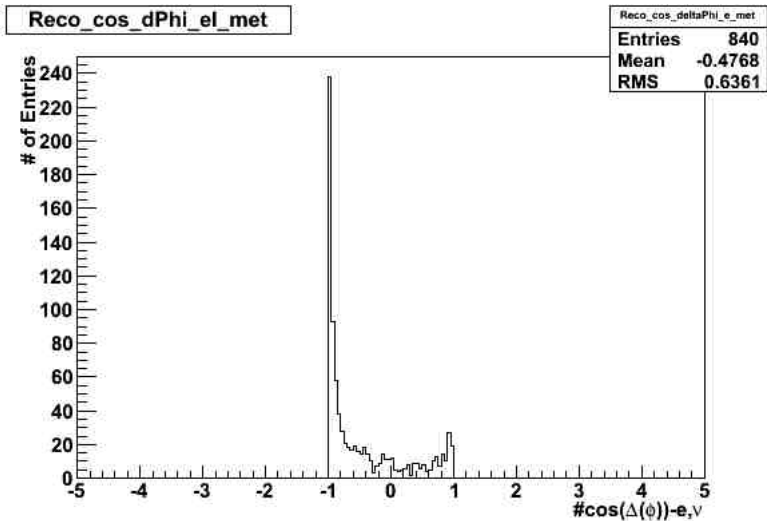
Reconstructed Electron's Energy...



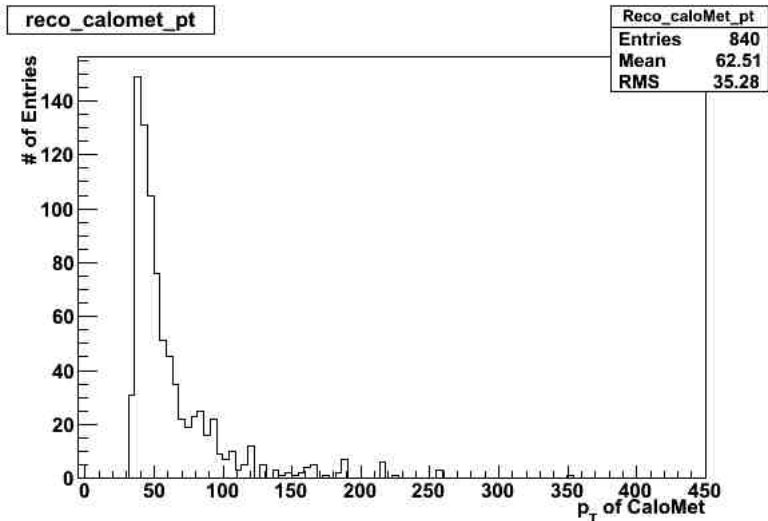
Reconstructed $\Delta\phi$ of electron & ν ...

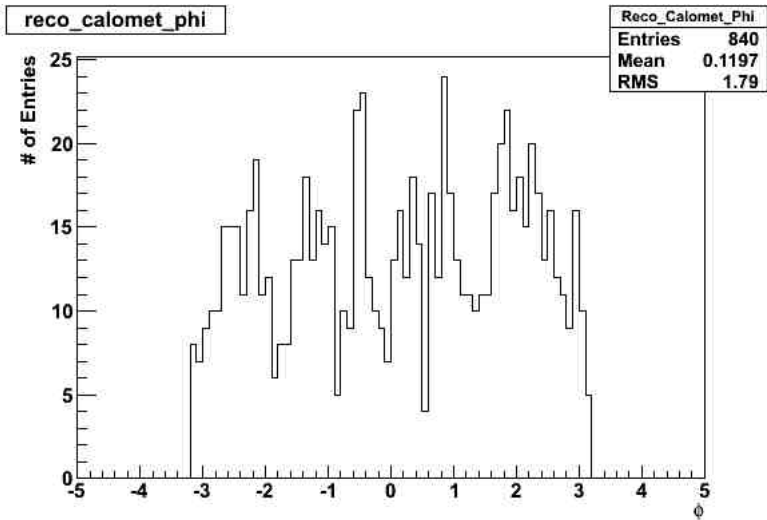


Reconstructed $\cos \Delta\phi$ of elect & ν ...

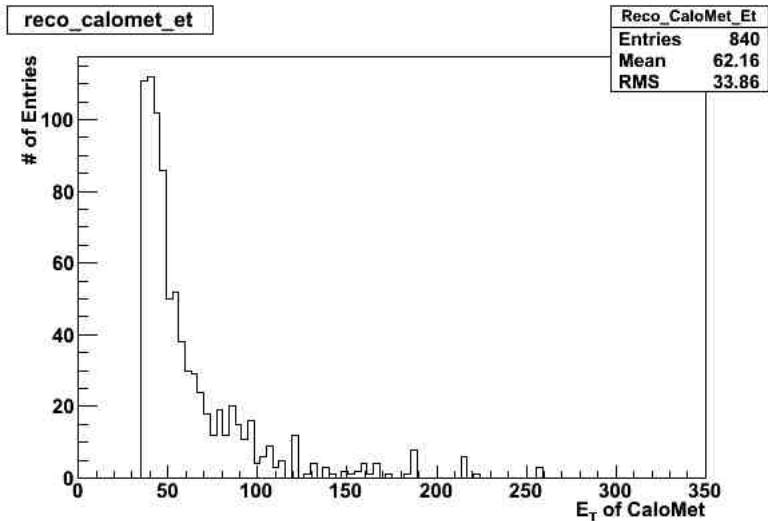


Reconstructed CaloMet p_T ...

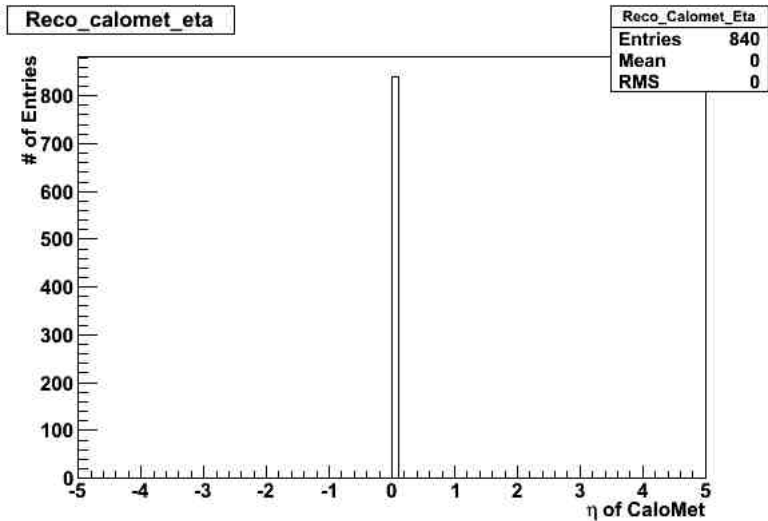


Reconstructed CaloMet ϕ ...

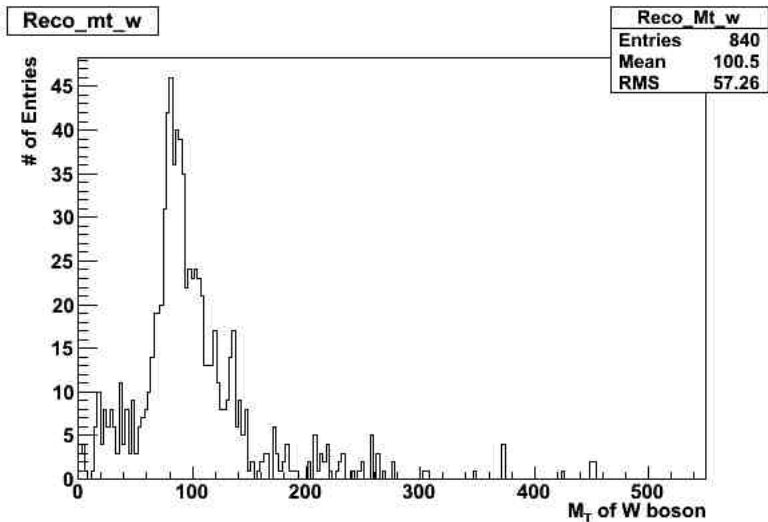
Reconstructed CaloMet E_T ...



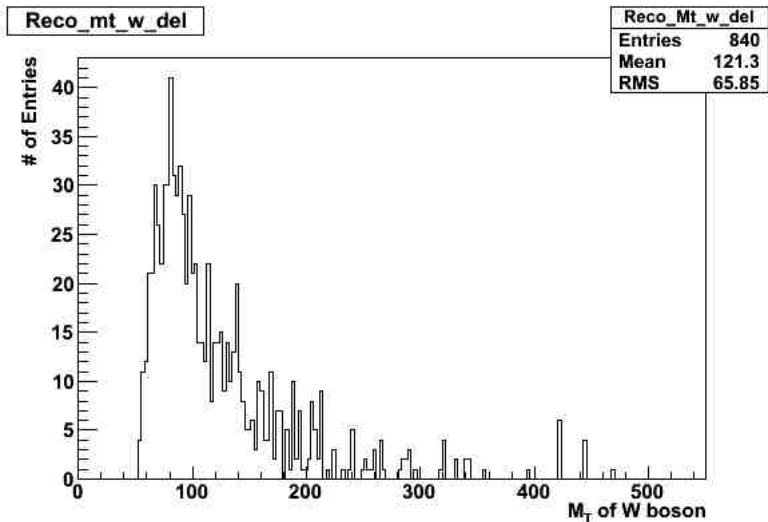
Reconstructed CaloMet η ...



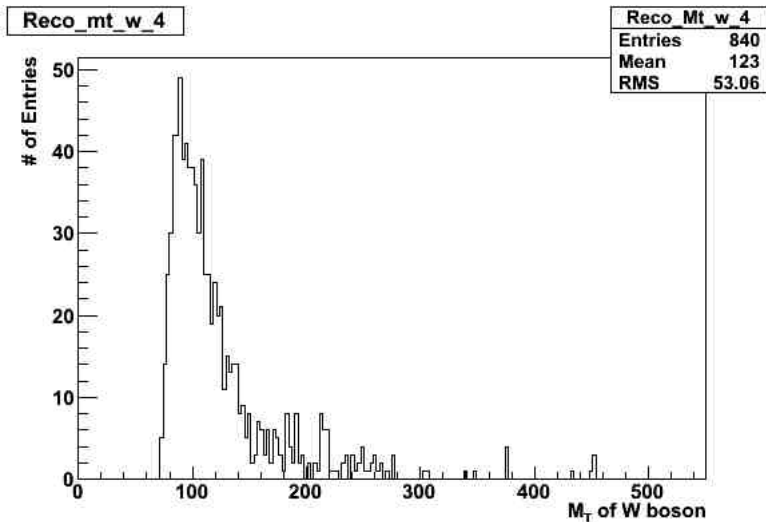
Reconstructed M_T^W with $(1 - \cos \Delta\phi)$...



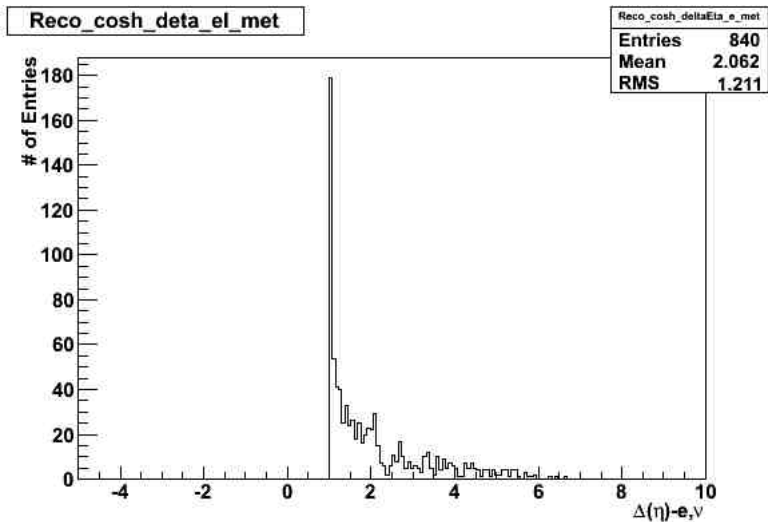
Reconstructed M_T^W with $(\cosh \Delta\eta - \cos \Delta\phi) \dots$



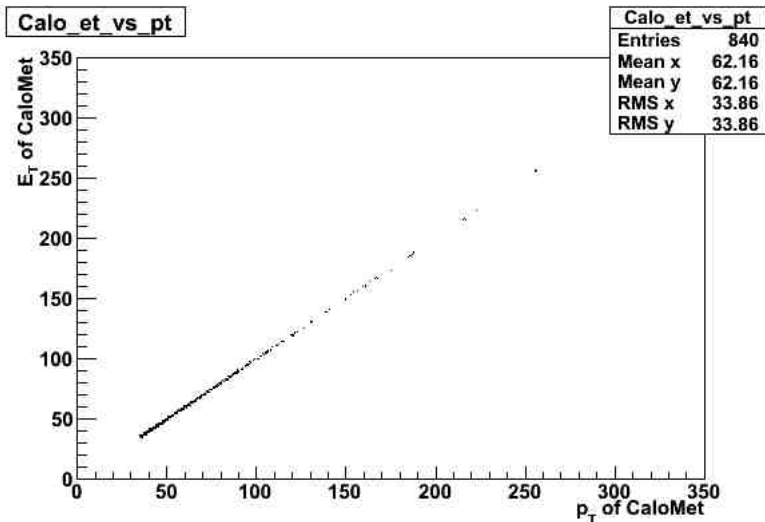
Reconstructed M_T^W with $(\cosh \Delta\eta = \cos \Delta\phi = 1)$...



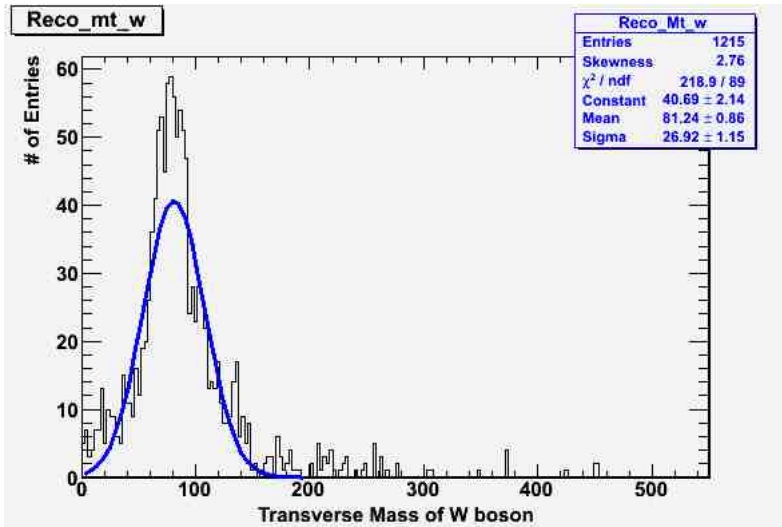
Reconstructed cosh $\Delta\eta$ between electron & ν ...



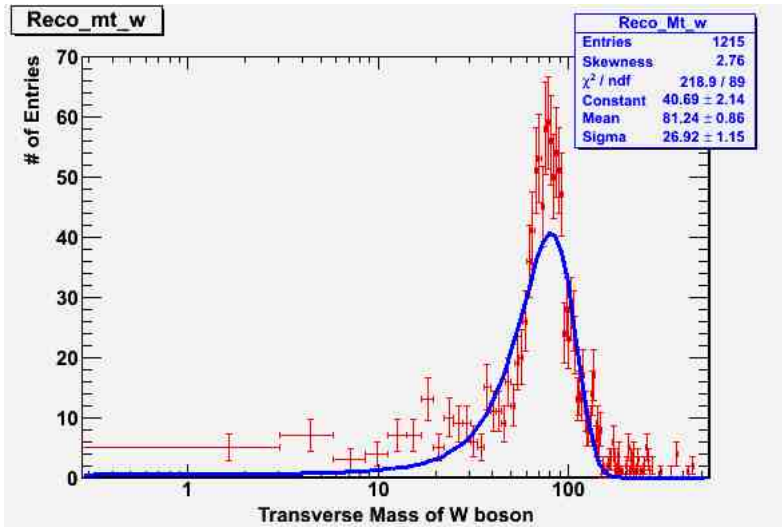
Just to verify that E_T^ν & p_T^ν have same value...



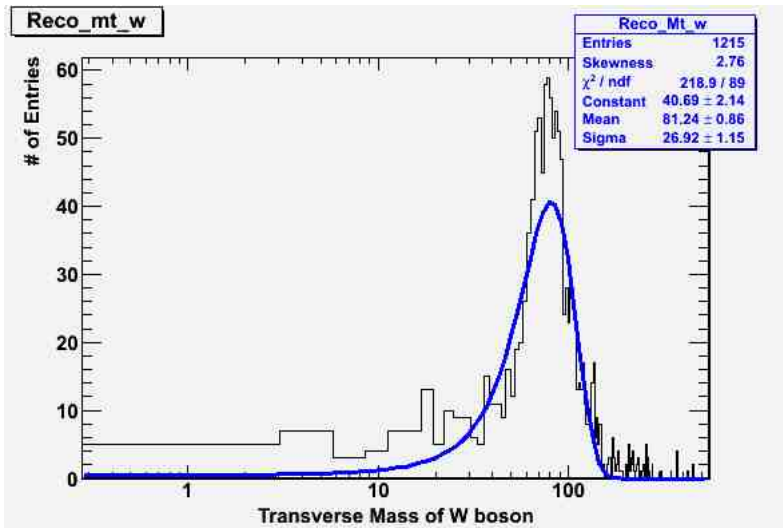
Mass of W after Gaussian Fit...



Mass of W after Gaussian Fit, Log scale ...



Mass of W after Gaussian Fit, Log scale ...



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Summary

- It is seen that E_T cut on both E_T & E_T^ν lower than 30 GeV (28,26,24,22,20) mass peak shifts towards the lower values.
- Also if E_T cut on both E_T & E_T^ν above that 30 GeV (32,34,36,38,40,42) mass peak shifts towards the higher values.
- Reason is that in both the cases we pick the wrong combinations of Electrons and Neutrinos.
- Using

$$M_{1,2}^2 = 2E_{T_1}E_{T_2}(\cosh \Delta y - \cos \Delta \phi)$$

We can veto the Pseudo Rapidity of neutrino by constraining the $M_W = 80\text{GeV}$.

- Reference "Transverse Mass and Width of the W boson" by J.smith, W.L.neervan, J.A.M. Vermaseren at Institute of Theoretical Studies, State University of New York.



LHC.....Way to the future....

Thanks.....