Top Higgs Yukawa Coupling Analysis from

$e^+ e^- \rightarrow \bar{t}\, tH \rightarrow \bar{b}W^-\, bW^+\, \bar{b}\, b$

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Introduction

- Once Higgs is found, its coupling with fermions is interesting to study.
- $g_{ffH} = \frac{m_f}{v}, v$ is vacuum expectation value of Higgs field.
- Top is heaviest fermion, so top-Higgs Yukawa coupling is largest.
- The coupling of top to the Higgs is modified in the SUSY models
- This analysis was not done for LOI
- ILD software framework is used for this analysis

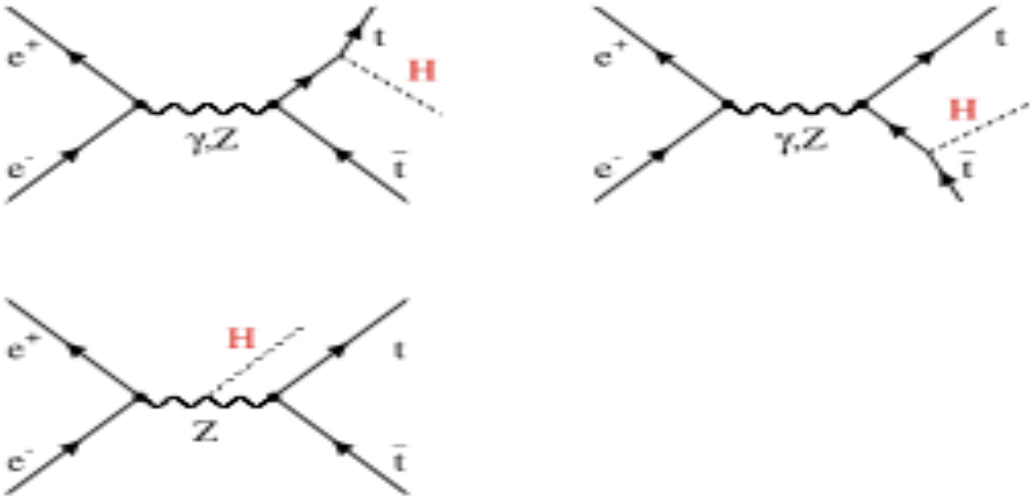


Fig. 1. Lowest order Feynman diagrams of the process $e^+e^- \to ttH$

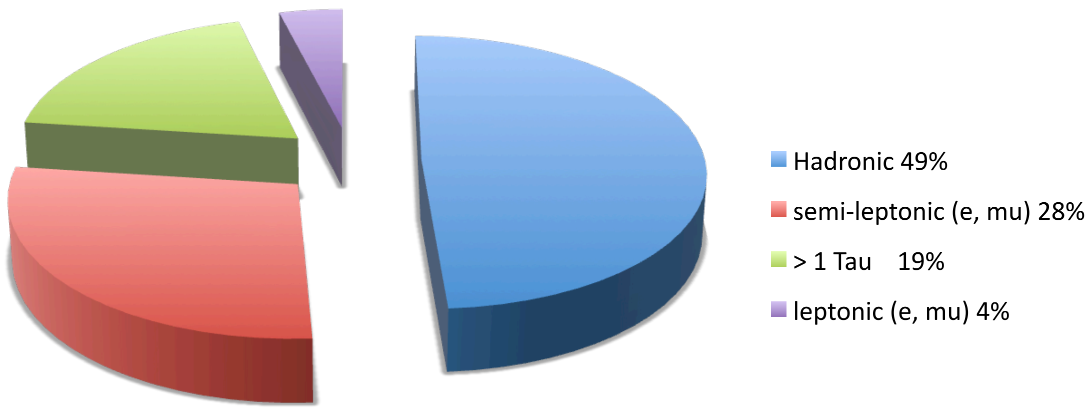
Samples

- ILD_00 centrally reconstructed sample with center of mass energy $\sqrt{s}$ = 500 GeV.
- $t\bar{t}$-Higgs events with M_h = 120 GeV/c^2, M_t = 175 GeV/c^2.
- Software version used is ILCSoft v01-06.

Process	σ (fb)	Sample	L (ab^{-1})
$e^+ e^- \rightarrow t\bar{t}H$	0.577 [arXiv:hep-ph/0604166v2]	20,000	34
$e^+ e^- \rightarrow t\bar{t}$	521	1800000	3.4
$e^+ e^- \rightarrow t\bar{t}Z$	0.58	24,000	41
$e^+ e^- \rightarrow ZZ$	577.2		
$e^+ e^- \rightarrow W^-W^+$	7890		
$e^+ e^- \rightarrow q\bar{q}$	3951.8		

Semi-Leptonic Channel

- $e^+ e^- \rightarrow \bar{t}\, tH \rightarrow \bar{b}W^- \, bW^+ \, \bar{b}\, b$
- Focus on semi-leptonic final state with one W decaying into lepton and neutrino and other W decaying into light jets
- Final state is 1 lepton, missing energy, 6 Jets with 4 b-jets
- Remove the leptons and force remaining particles into 6-jets (JetFinder Algorithm)
- High momentum Lepton and large missing momentum signature



Filtering of Semi-Leptonic Channel for Monte Carlo Sample

- Initially 20,000 MC events with full final state where Higgs and W decay into anything
- Filter events with one lepton (μ, e), and H decaying to $b\bar{b}$, 4466 events are left.

Lepton Identification

(From study of Single MC Lepton with P >15 GeV)

- Muon Identification:

  - Cut based selection is being used. Efficiency from single Muon sample is 98%.

    (1) $E_{Ecal} < 2.5$ GeV **(2) $E_{Hcal} < 15$ GeV**

    (3) $E_{Ecal} / E_{Tot} < 0.5$ **(4) $E_{tot} / p < 0.3$**

- Electron Identification:

  - Cut-based selection on single Electron sample has showed that 98.57% electron are identified by using:

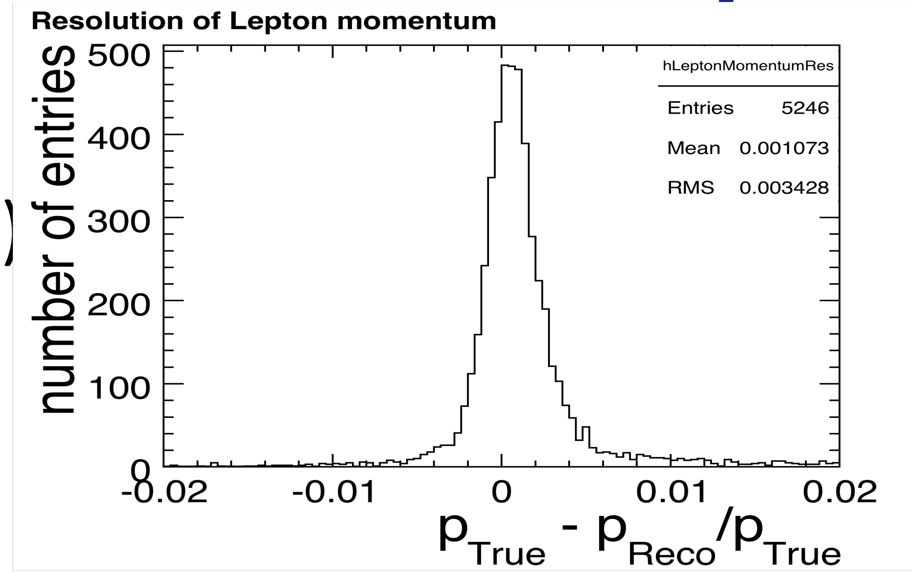
    (1) $E_{Ecal} / E_{Tot} > 0.6$

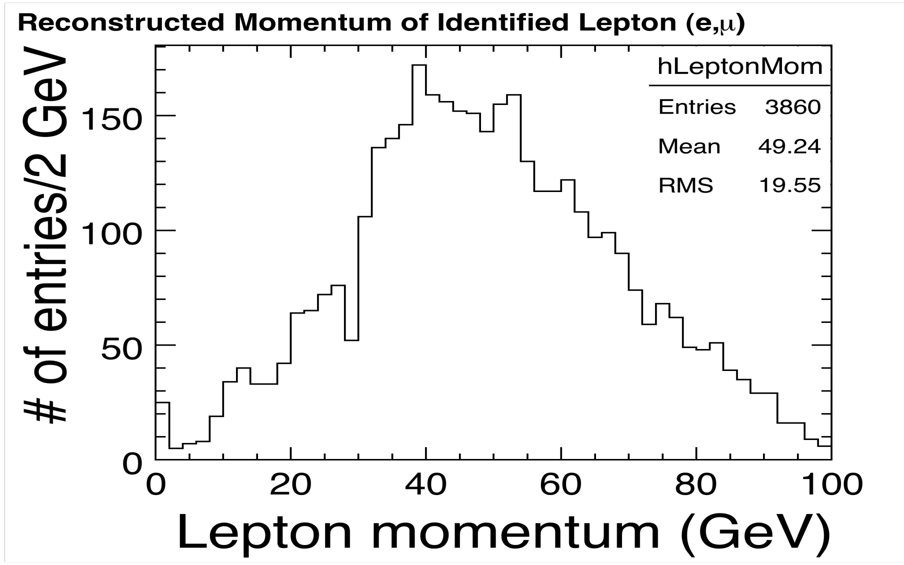
    (2) $E_{Tot} / p > 0.7$

efficiencies in %	electron cuts	muon cuts
e	98.57±0.06	~0
μ	0.03±0.01	97.5±0.05
π	3.88±0.06	0.46±0.003

$W \rightarrow \nu\ell$ (Lepton Identification)

- we identify our reconstructed leptons (e, μ) using same cut variables as for single lepton case.
- Most of the reconstructed leptons are correctly identified as leptons.
- These lepton tracks are then removed from the PandorPFOs collection.



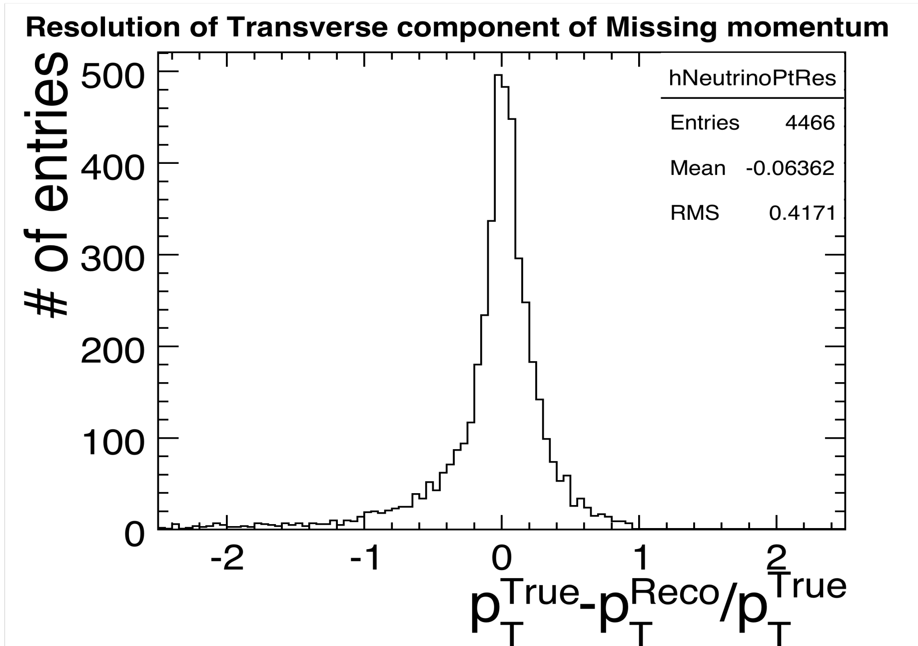


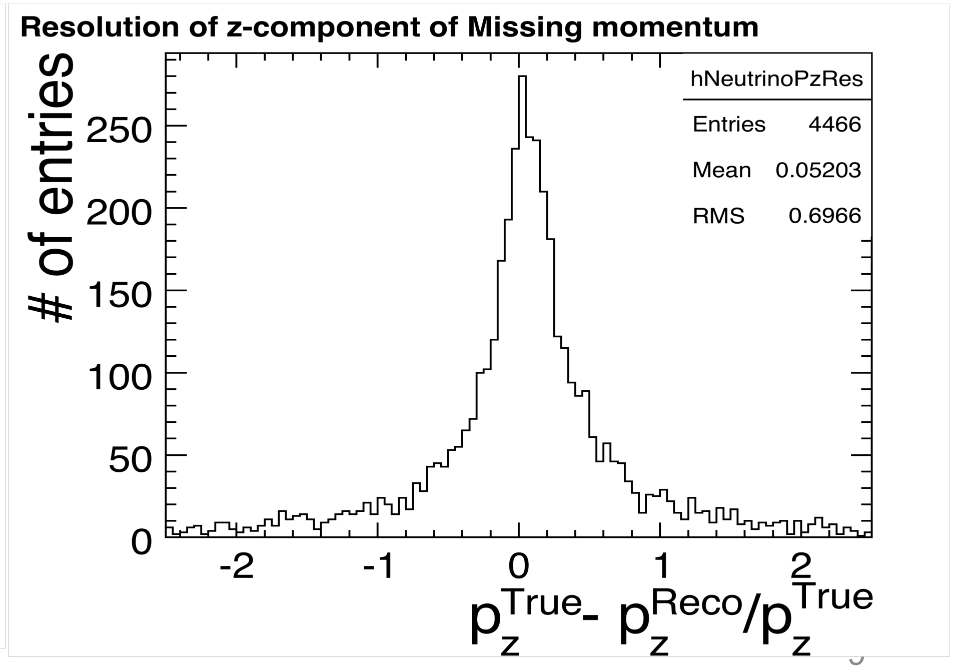
$W \to \nu\ell$ (Missing Momentum)

- Using the information for all reconstructed particles, missing momentum is reconstructed.

$$p_x^{miss} = -\Sigma_i p_{xi}, \quad p_y^{miss} = -\Sigma_i p_{yi}, \quad p_z^{miss} = -\Sigma_i p_{zi}, \qquad p_T^{miss} = \sqrt{(p_x^{miss})^2 + (p_y^{miss})^2}$$

- Z-component of missing energy isn't as accurate as x and y components
- However, z-component can be used to reconstruct Semi-leptonic W mass.

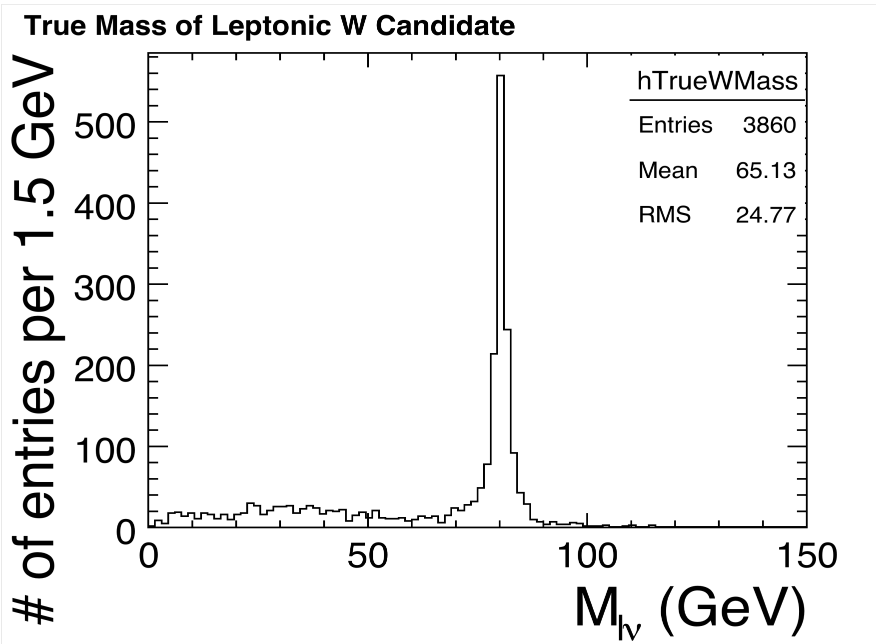


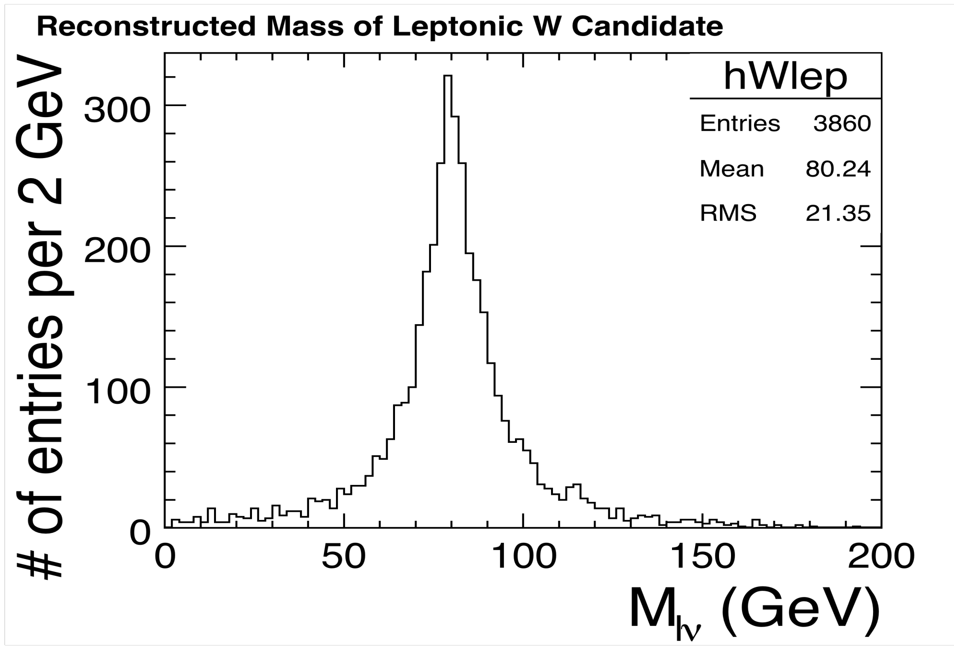


Reconstructed Mass of leptonic *W*

- To reconstruct semi-leptonic W, we select events which have lepton momentum not equal to zero and one lepton with highest momentum
- The momentum of lepton and Missing Momentum are used to reconstruct the mass of W.

$$M_W = \sqrt{(E_\nu + E_l)^2 - (p_{\nu x} + p_{lx})^2 - (p_{\nu y} + p_{ly})^2 - (p_{\nu z} + p_{lz})^2}$$



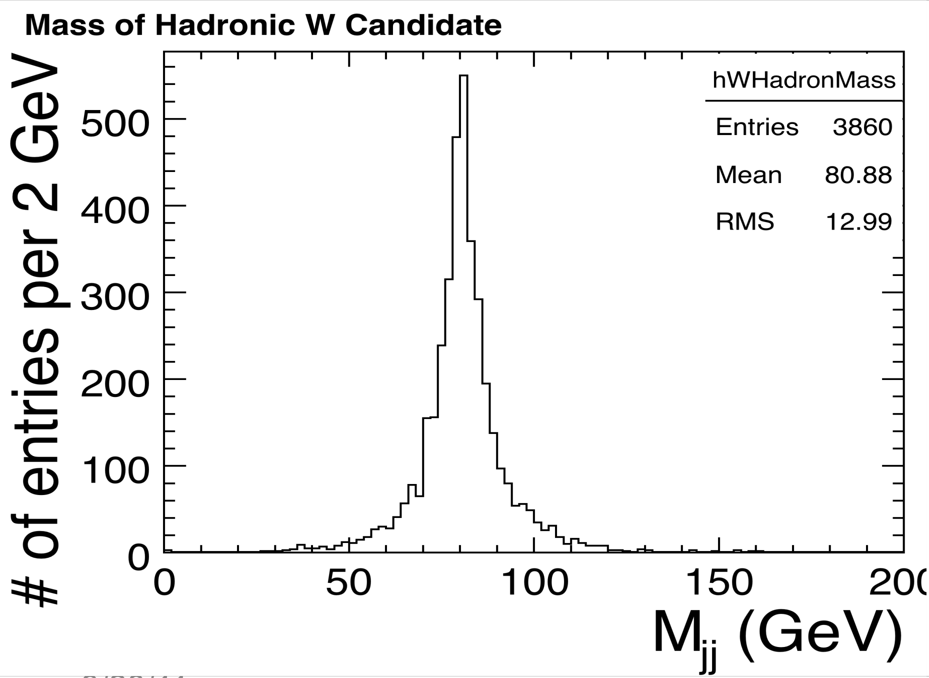


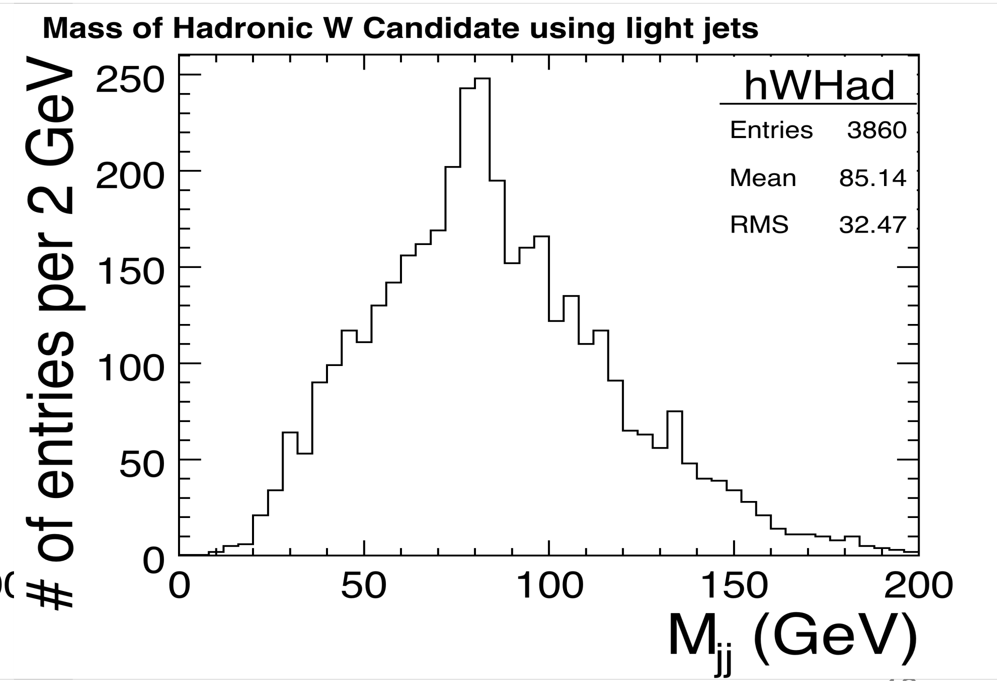
Jets reconstruction

- Identified leptons are removed from the sample
- remaining particles are forced into 6 Jets using JetFinder algorithm
- Jets pass LCFIVertex reconstruction [arXiv:0908.3019v1]
- LCFI flavour tagging is used to separate light and b-jets
- Jets are sorted in descending order of b-tag value
- top four jets with highest b-tag value are selected as b-jets
- Light jets are used to reconstruct hadronic W

Reconstructed Mass of Hadronic *W*

- Used the light jets (lowest b-tag value jets) momentum to reconstruct W mass (Right figure)
- Wrong particles are picked as light jets
- Make combinations of jets which have b-tag value less than 0.09 and pick the combination which is closest to W mass (81.4 GeV) (Left figure)





Final State Reconstruction

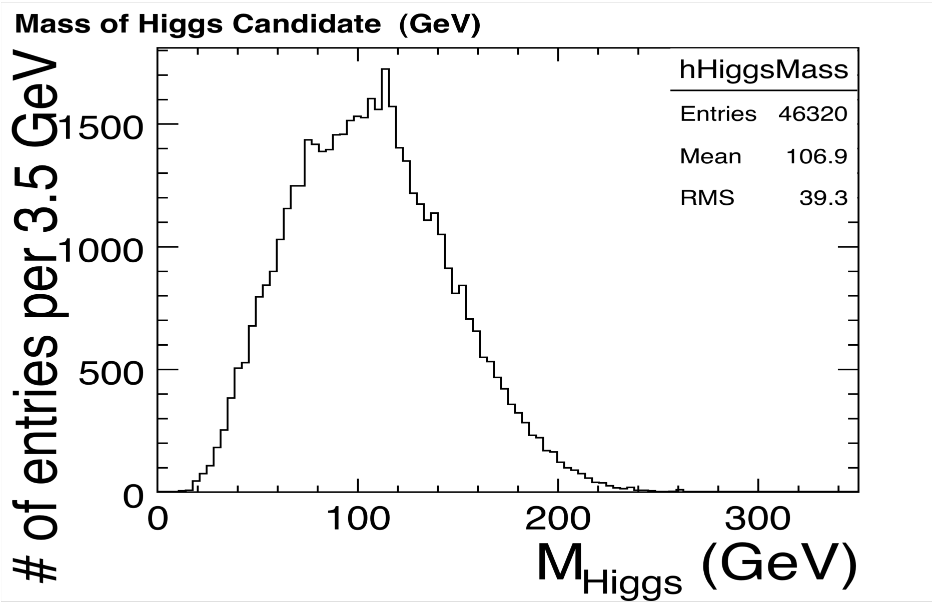
- As we have a good reconstruction of z-component of the missing momentum, it is used to reconstruct the Mass of semi-leptonic W

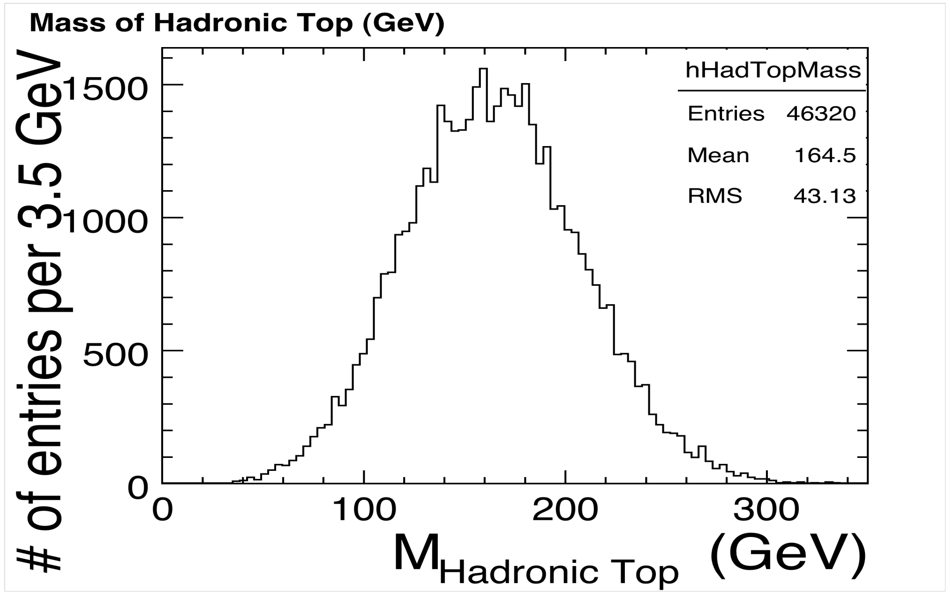
$$M_W = \sqrt{(E_\nu + E_l)^2 - (p_{\nu x} + p_{lx})^2 - (p_{\nu y} + p_{ly})^2 - (p_{\nu z} + p_{lz})^2}$$

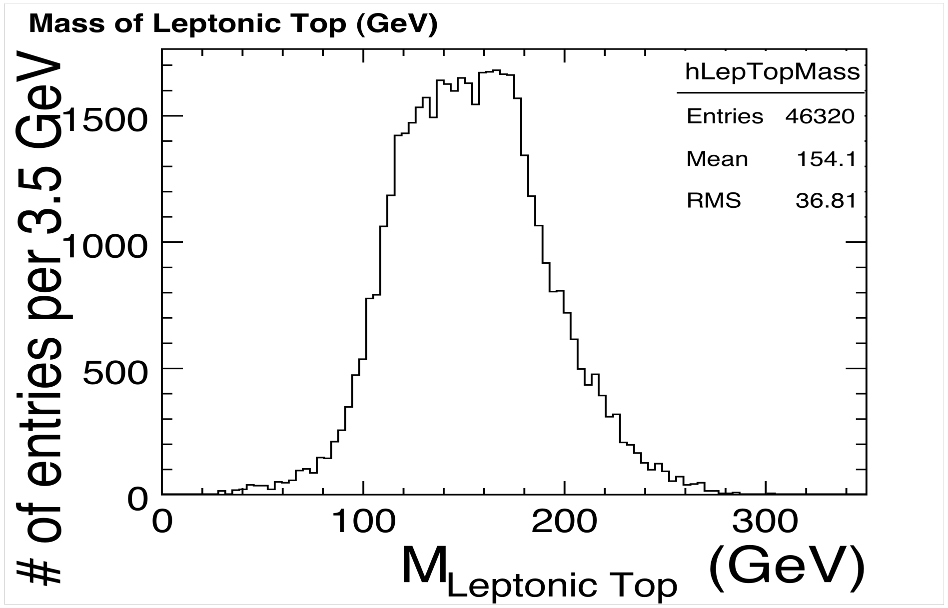
- Four b-jets are used to reconstruct two tops and Higgs particle
- To reduce combinatorial backgrounds, minimisation of χ^2 technique is used

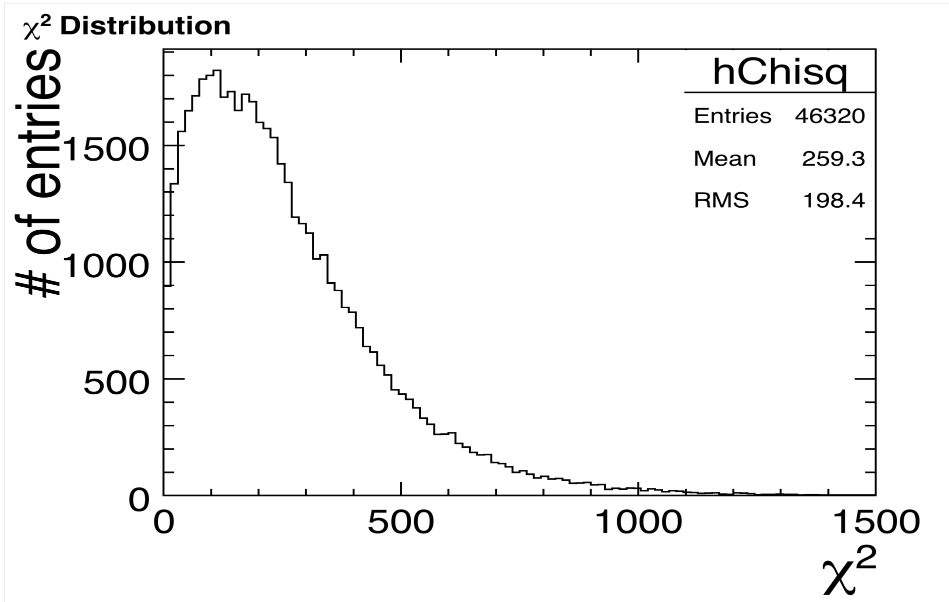
$$\chi^2 = \frac{(M_{l\nu b} - M_t)^2}{\sigma_{l\nu b}^2} + \frac{(M_{jjb} - M_t)^2}{\sigma_{jjb}^2} + \frac{(M_{bb} - M_{Higgs})^2}{\sigma_{bb}^2}$$

Reconstructed Final State



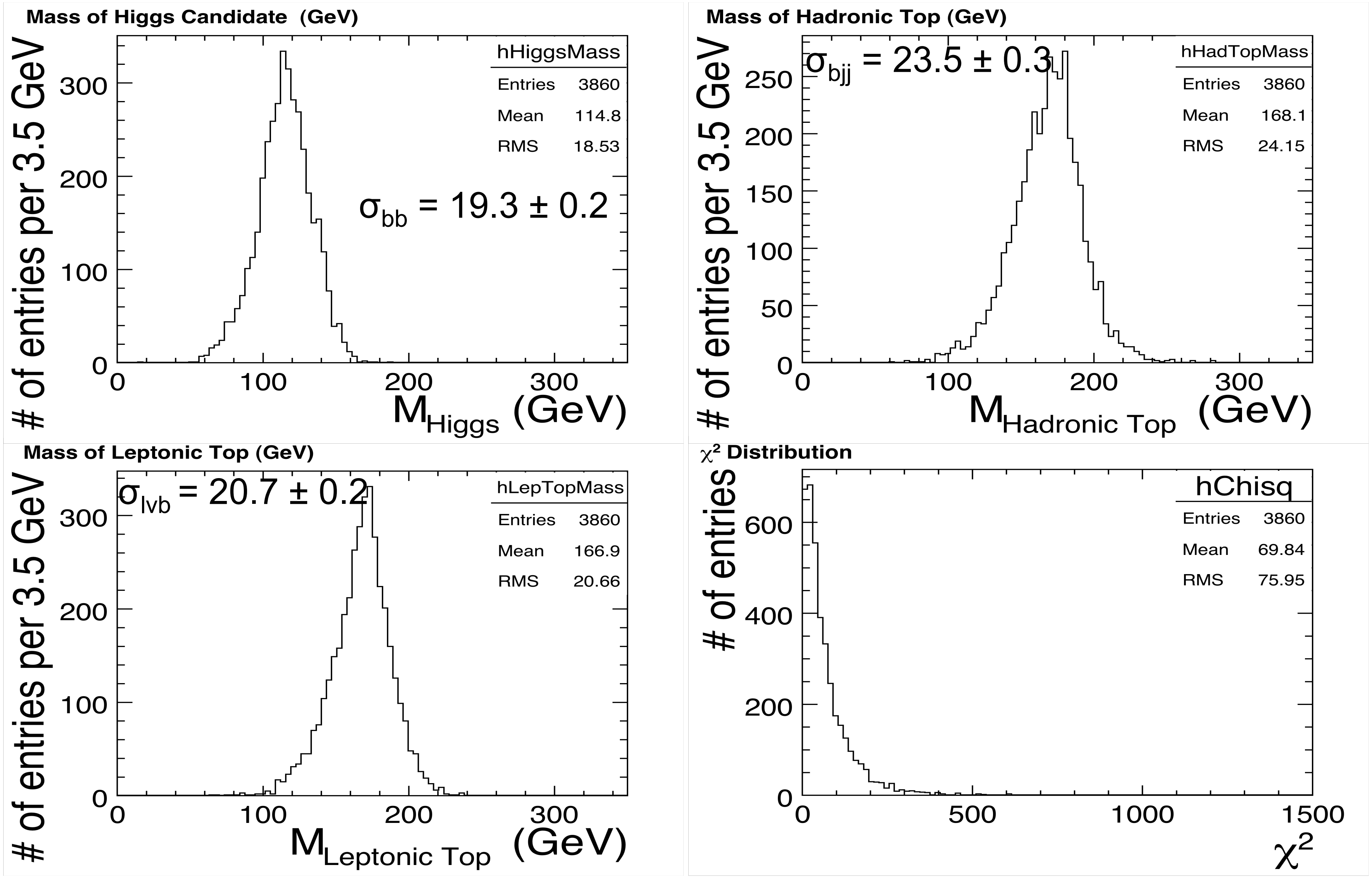




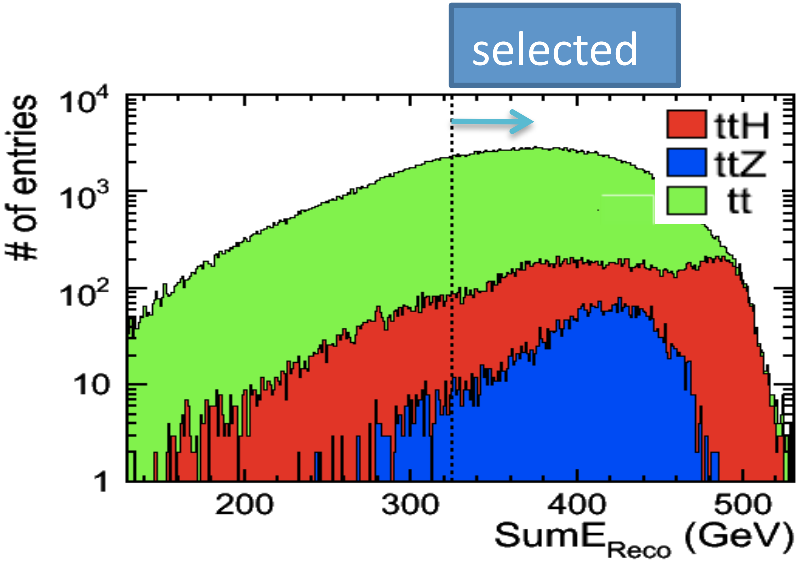


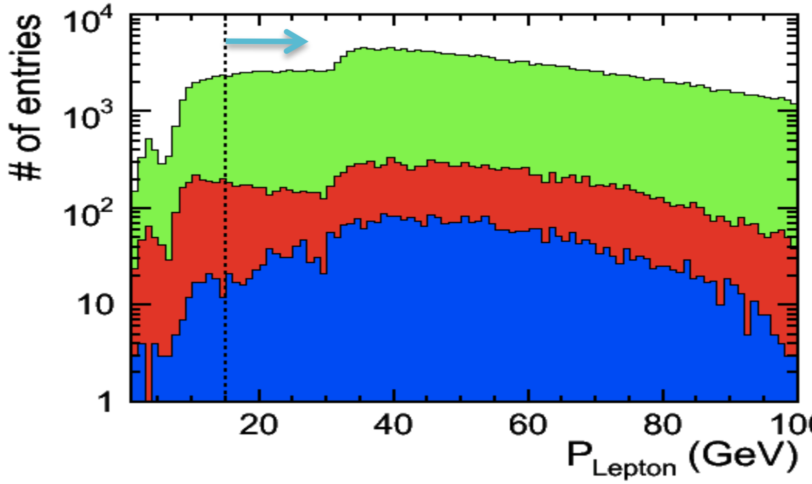
There are 12 entries for each event due to different combinations

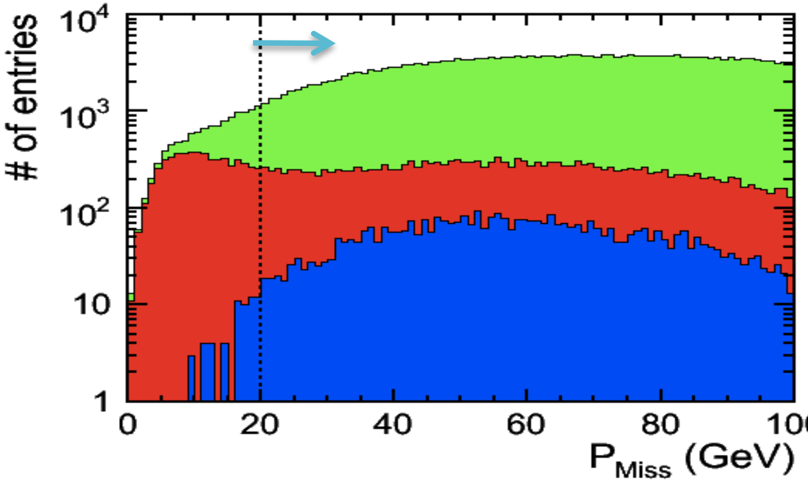
Reconstructed Final State after Minimizing χ^2

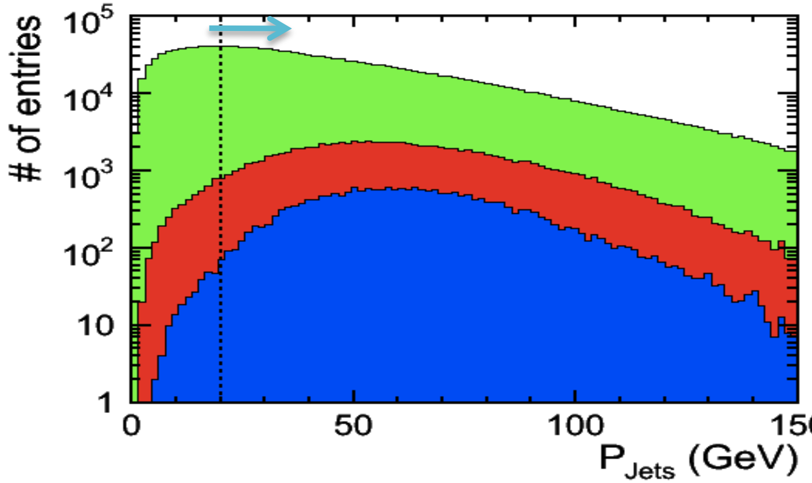


Selection variables (I)

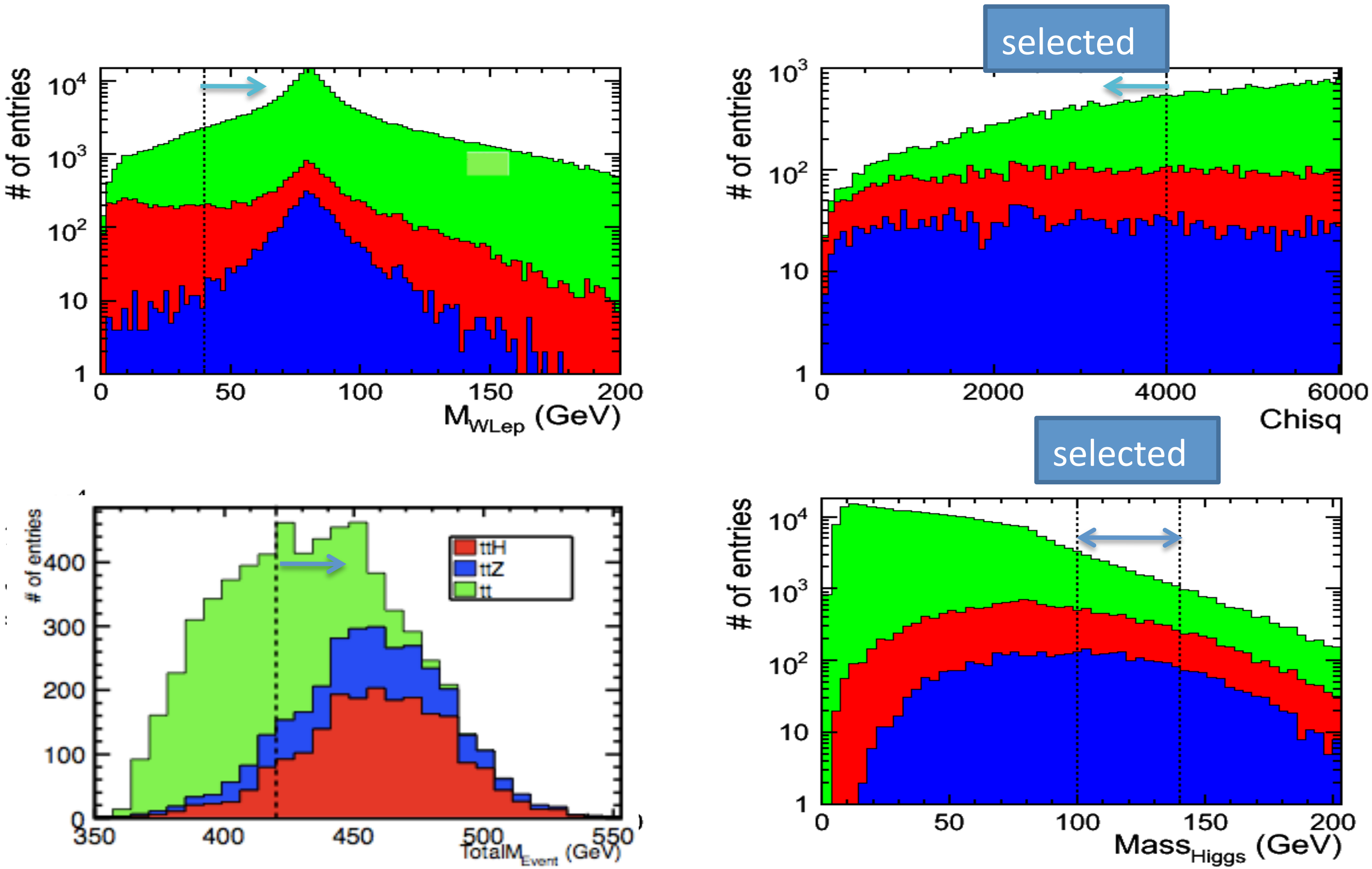






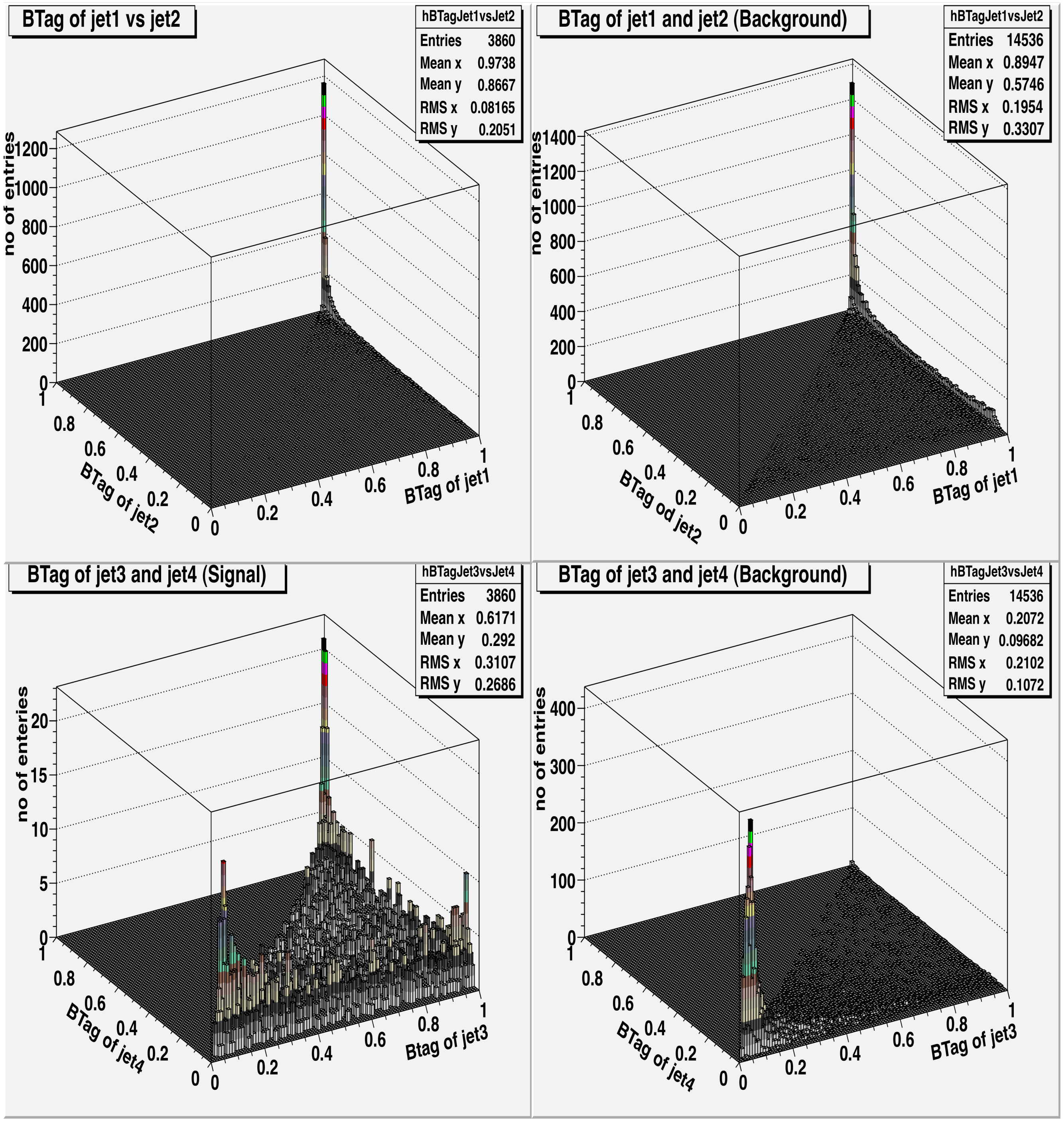


Selection variables (II)



b-tagging ttH vs ttZ

- B-tag of all 6 jets are looked at
- 4 with largest b-tag value are considered as b-jets
- Cut on b-tag values of jet3 and jet4 can reduce a significant number of background events



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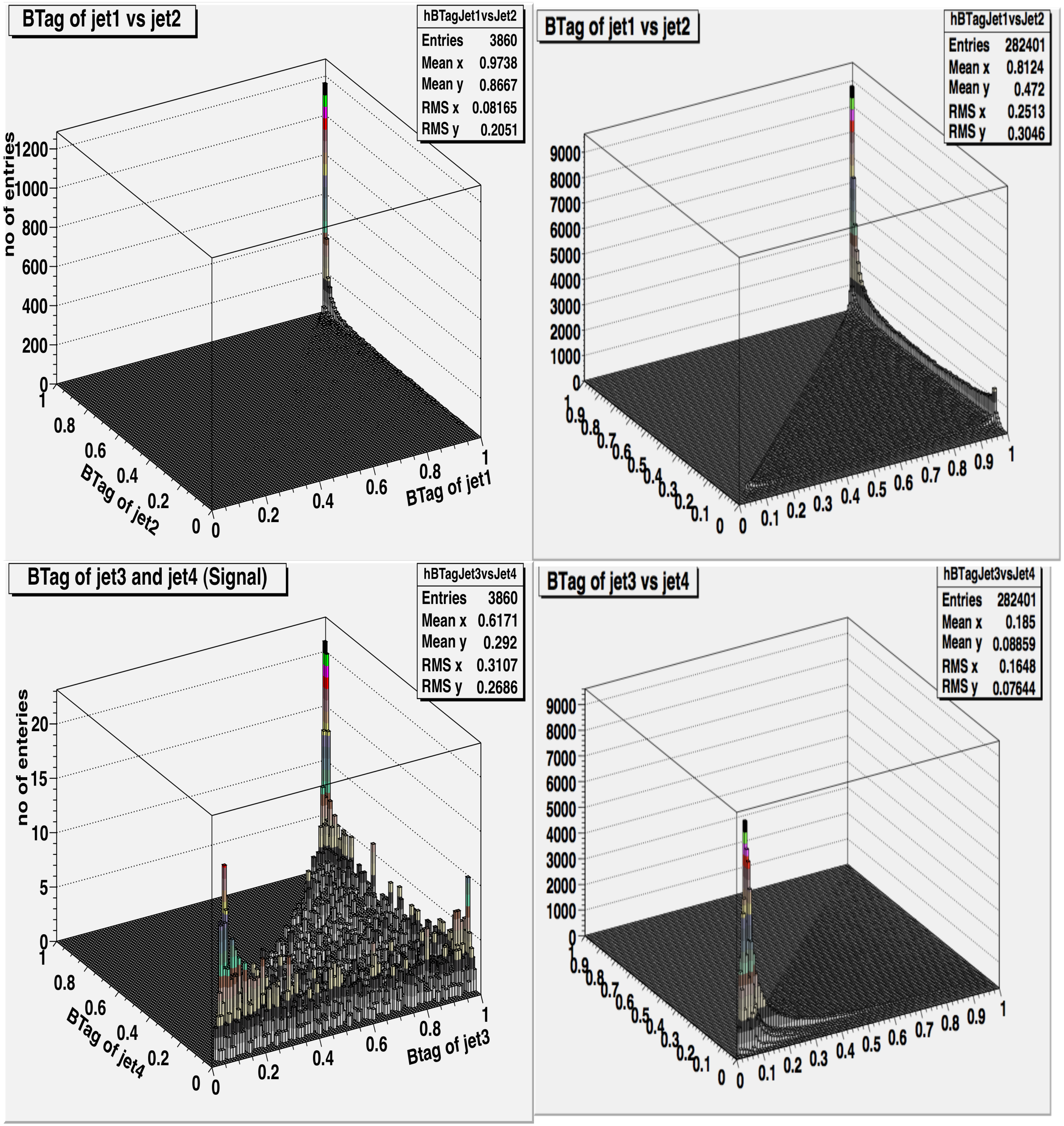


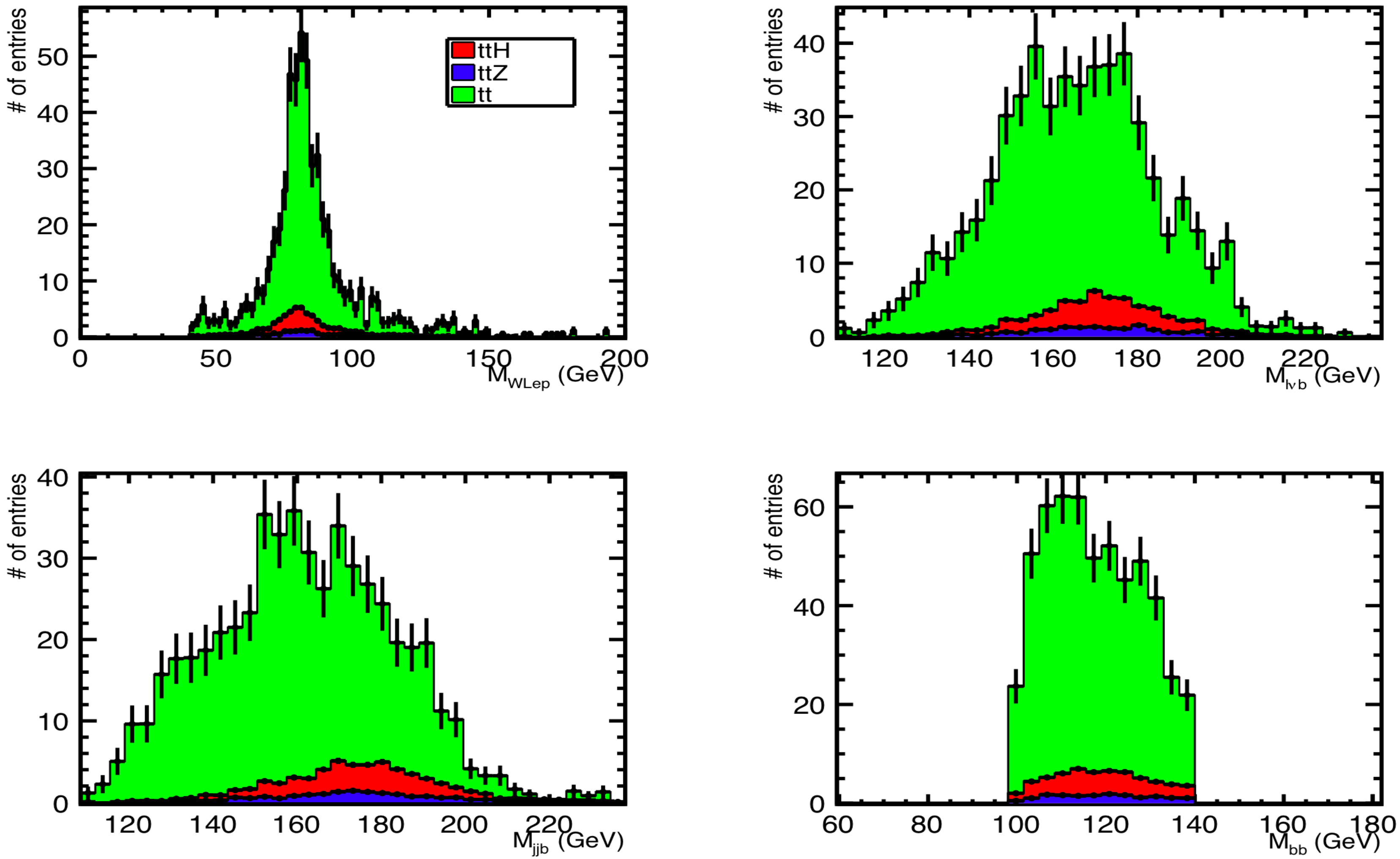
b-tag efficiency (3rd and 4th Jets)

b-tag (both jets)	No of Signal events (S)	No of bkg events (B)	S/√S+B
0	3097	7304	30.36
> 0.08	2410	2371	34.84
> 0.09	2237	1666	35.80
> 0.1	2154	1525	35.51
> 0.15	1708	771	34.30
> 0.2	1429	515	32.41
Btag (3rd jet) > 0.09 Btag (4th jets) > 0.08	2406	2282	35.14

Signal and Background separation

Cuts	$t\bar{t}H$	$t\bar{t}Z$	$t\bar{t}$
initial	20000	24000	376276
# Lep > 0	3860 ** After semi-leptonic selection	14536	282404
E_Reco > 325 GeV	3600	8021	68439
P_Lep > 15 GeV	3167	7128	55206
P_miss > 20 GeV	3119	5610	54488
P_Jet >20 GeV	2978	4837	33909
3^{rd} & 4^{th} jet b-tag > 0.09	2215	1544	11017
Chisq < 400	2161	1487	1822
M_{Lep} > 40 GeV	2135	1330	1778
$TotalM_{Event}$ > 420 GeV	1871	873	711
100 GeV < M_{bb} < 140 GeV	1513	662	464
Efficiency	7.57	2.76	0.11

Scaled Signal and Background distributions after all selection cuts



Luminosity $L = 1000\ fb^{-1}$

Measuring top-Higgs Yukawa coupling (Eur.Phys.J.C 49, 489-497(2007))

- The Yukawa coupling is scaled to the fermion mass: $g_{ffH} = \frac{m_f}{v}, v$ is the vacuum expectation value of the Higgs field = 246 GeV
- For selection efficiency of the signal (*ε*) and purity of the selected sample (*ρ*), systematic and statistical uncertainties are given by:

$$(\frac{\Delta g_{t\bar{t}H}}{g_{t\bar{t}H}})_{stat} \approx \frac{1}{S_{stat}(g^2_{t\bar{t}H})\sqrt{\epsilon^{sel}_{signal}\rho^{sel}_{sample}L}} \quad (\frac{\Delta g_{t\bar{t}H}}{g_{t\bar{t}H}})_{syst} \approx \frac{1}{S_{syst}(g^2_{t\bar{t}H})}\frac{1-\rho^{sel}_{sample}}{\rho^{sel}_{sample}}\frac{\Delta\sigma^{BG}_{eff}}{\sigma^{BG}_{eff}}$$

- Δσ/σ is the uncertainty in the residual background normalisation mainly from tt pairs. In our case it is 5%.
- The sensitivity factors $S_{stat}(g^2_{t\bar{t}H}) = \frac{1}{\sqrt{\sigma_{t\bar{t}H}}}\left|\frac{d\sigma_{t\bar{t}H}}{d(g^2_{t\bar{t}H})}\right|$ and $S_{syst}(g^2_{t\bar{t}H}) = \frac{1}{\sigma_{t\bar{t}H}}\left|\frac{d\sigma_{t\bar{t}H}}{d(g^2_{t\bar{t}H})}\right|$ express dependence of cross section on the coupling square which is inversely proportional to the square of g^2_{ttH} due to small cross section of the Higgs radiating off the Z.

Results

- Expected uncertainty on the coupling measurement. We used S_{stat} = *1.5 fb*$^{1/2}$ and S_{syst} =*1.98* with Luminosity *L = 1000 fb*$^{-1}$

Final State	ϵ_{sel} (%)	σ_{eff} (fb^{-1})
$t\bar{t}H$	7.57 ± 0.19	0.04
$t\bar{t}$	0.11 ± 0.00	0.29
$t\bar{t}Z$	2.76 ± 0.12	0.02

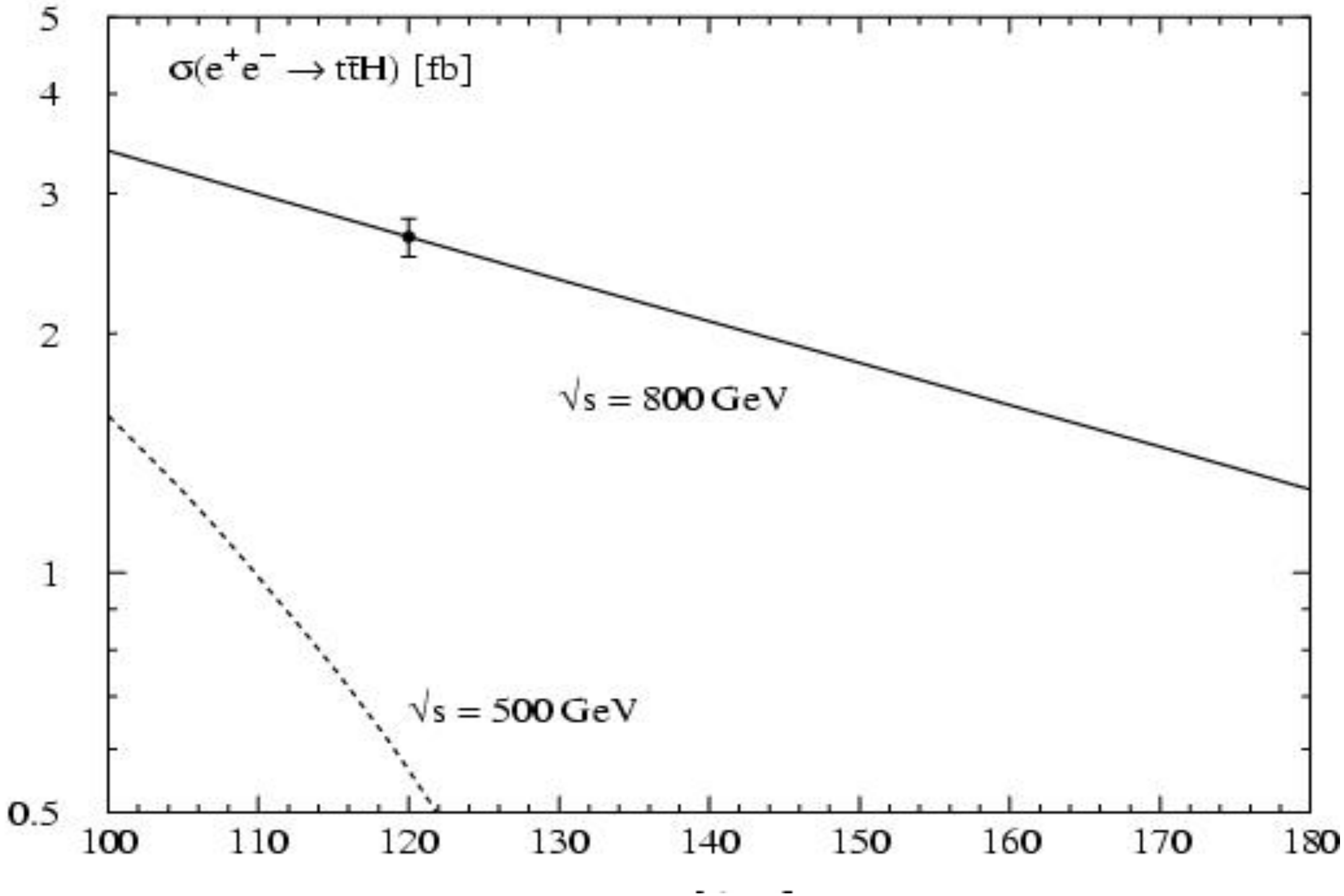
Parameter	value (%)
$\frac{\Delta\sigma_{eff}^{BG}}{\sigma_{eff}^{BG}}$	5
ϵ_{sel}	7.6 ± 0.2
ρ_{sample}^{sel}	12.5 ± 0.3
$\left(\frac{\Delta g_{t\bar{t}H}}{g_{t\bar{t}H}}\right)_{stat}$	21.6
$\left(\frac{\Delta g_{t\bar{t}H}}{g_{t\bar{t}H}}\right)_{syst}$	17.6
$\frac{\Delta g_{t\bar{t}H}}{g_{t\bar{t}H}}$	27.9

Conclusion/Discussion

- For $L = 1000\ fb^{-1}$, $\sqrt{s}$=500 GeV, the measured uncertainty in the top-Higgs-Yukawa coupling is 27.9%
- Improvements in hadronic W reconstruction, can refine the results
- Multivariate can be used to improve the background suppression
- The largest uncertainty is due to the uncertainty $\Delta\sigma/\sigma$ on the background normalisation σ_{tt}, which is taken to be 5%. Updated values of this uncertainty can change the results.
- It will be necessary to extended this study to a higher energy but b-tagging will be needed to be optimised.

Extra slides

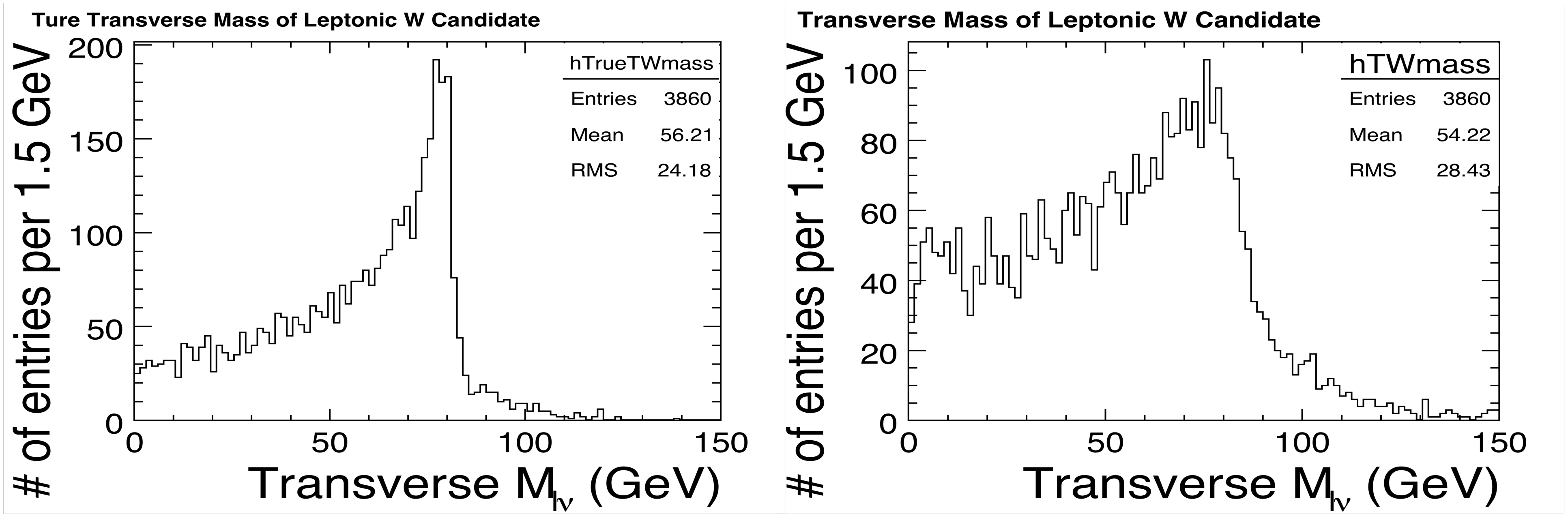
Cross section of $\bar{t}\,tH$



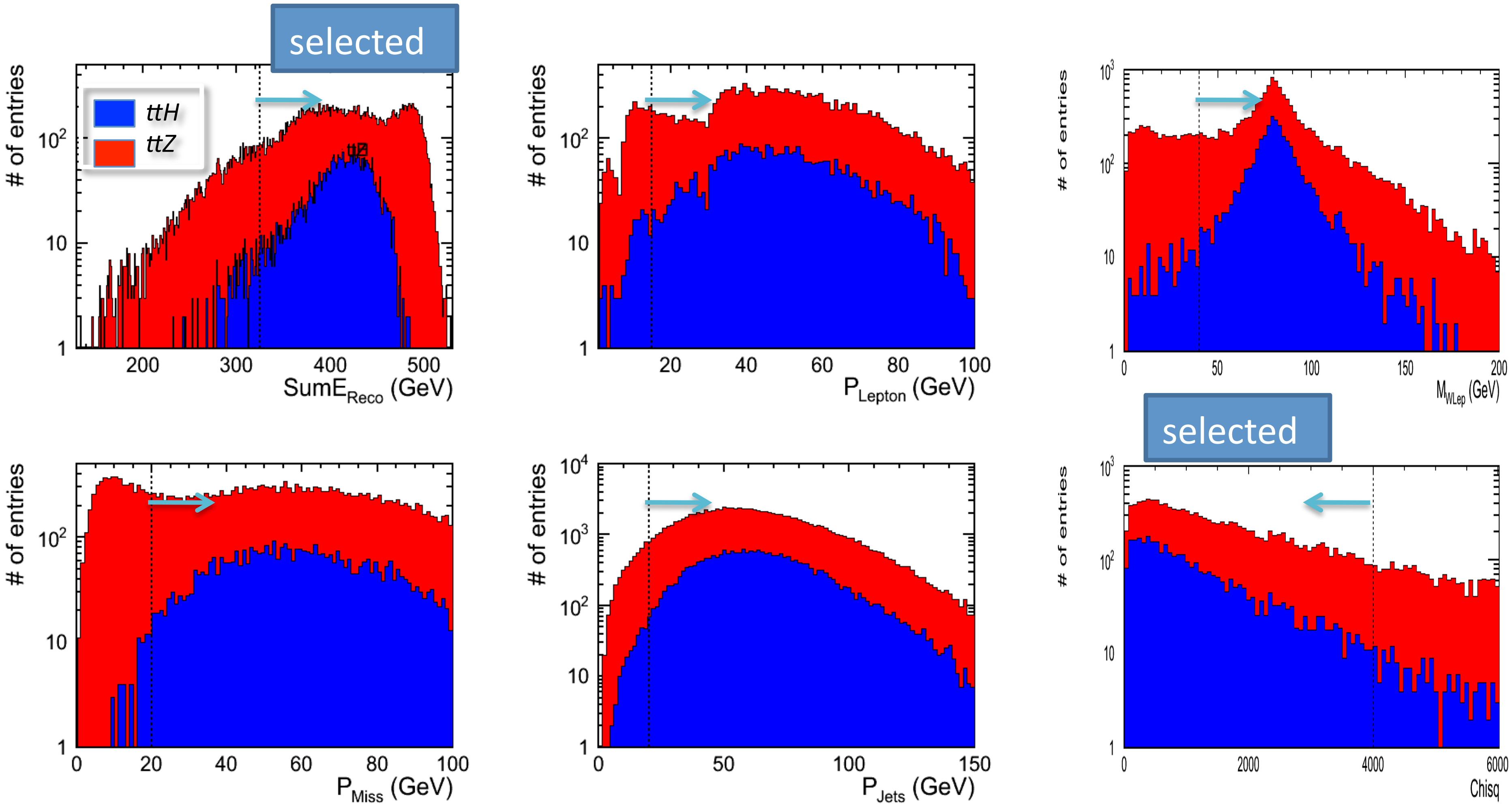
$W \rightarrow \nu\ell$ (Transverse Mass)

- It is worth trying to reconstruct the transverse mass of W.
- The transverse momentum of lepton and Missing Momentum are used to reconstruct the transverse mass of W.

$$M_{WT} = \sqrt{2p_T^l p_T^\nu (1 - cos(\phi^l - \phi^\nu))}$$

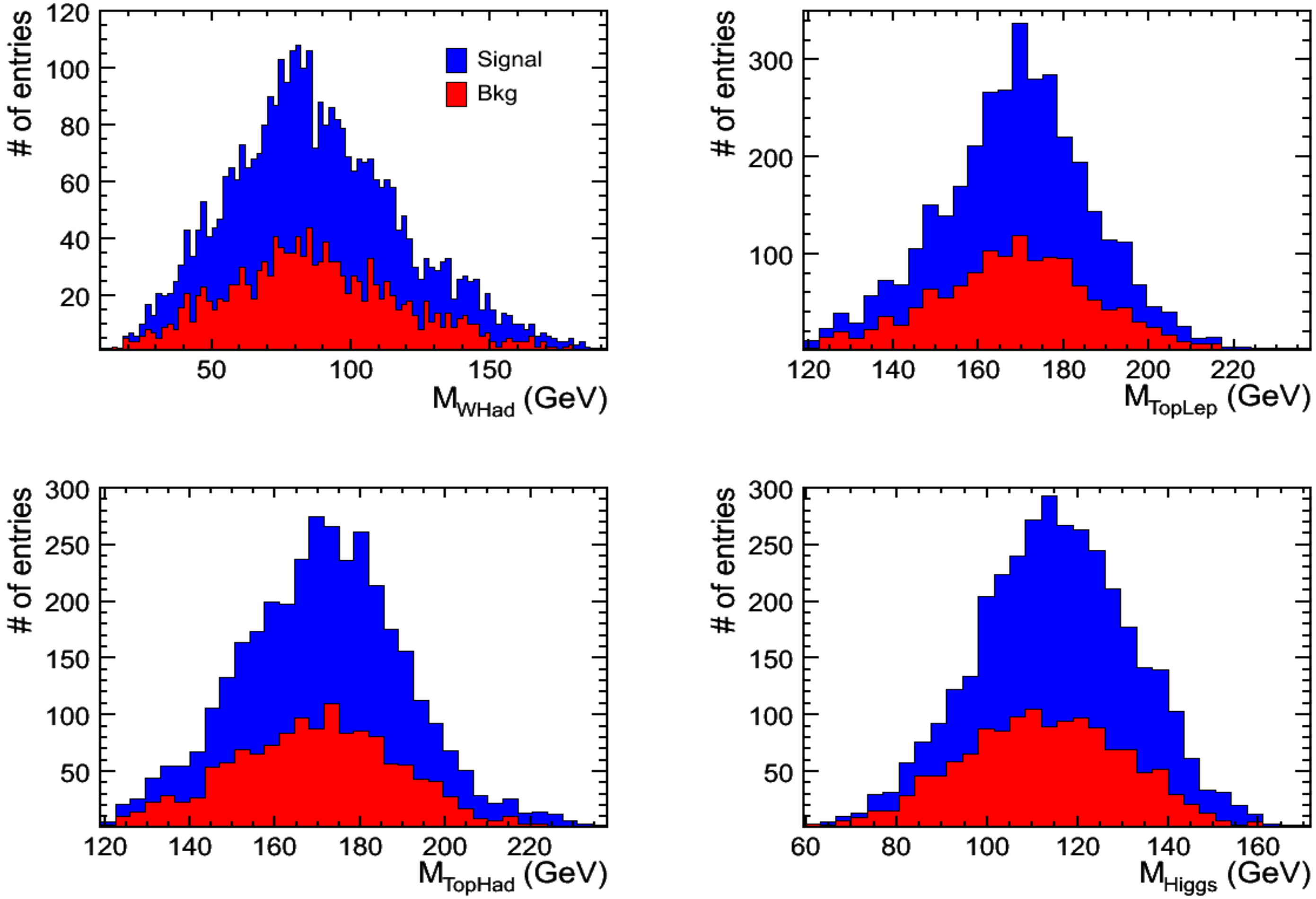


Selection variables



Signal and background are arbitrarily normalised
Cuts are selected by optimising $S/\sqrt{(S+B)}$

Signal and Background Final State after applying selection cuts



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