PRELIMINARY

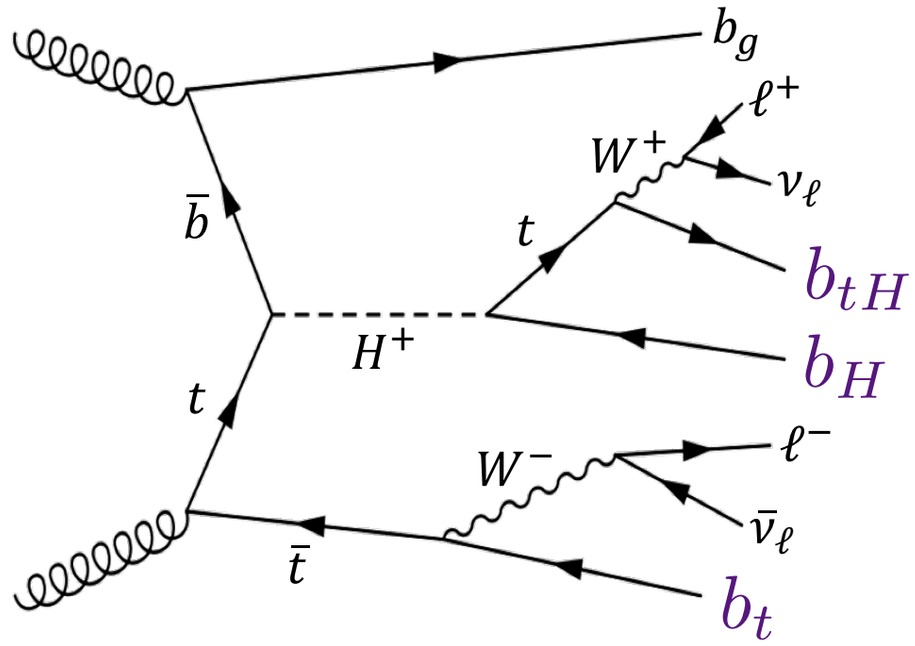
Joint APP and HEPP Annual Conference

Charged Higgs Bosons in Naturally Aligned Two Higgs Doublet Models

Emily Orgill, William Klemm, Roger Naranjo, Yvonne Peters, Apostolos Pilaftsis

Introduction

- Consider charged Higgs ($H^{\pm}$) production in association with tb and decay in dilepton channel



- Aim is to provide limits on this production and decay by using variables from reconstructing $H^{\pm}$ using boosted decision trees (BDTs) and neutrino weighting

Introduction

- Why 2HDM?
  - In supersymmetric models, one Higgs doublet cannot give mass to both charge 2/3 and -1/3 type quarks
  - Could be useful in explaining baryon asymmetry due to the flexibility of the mass spectrum and the possibility of additional sources of CP violation

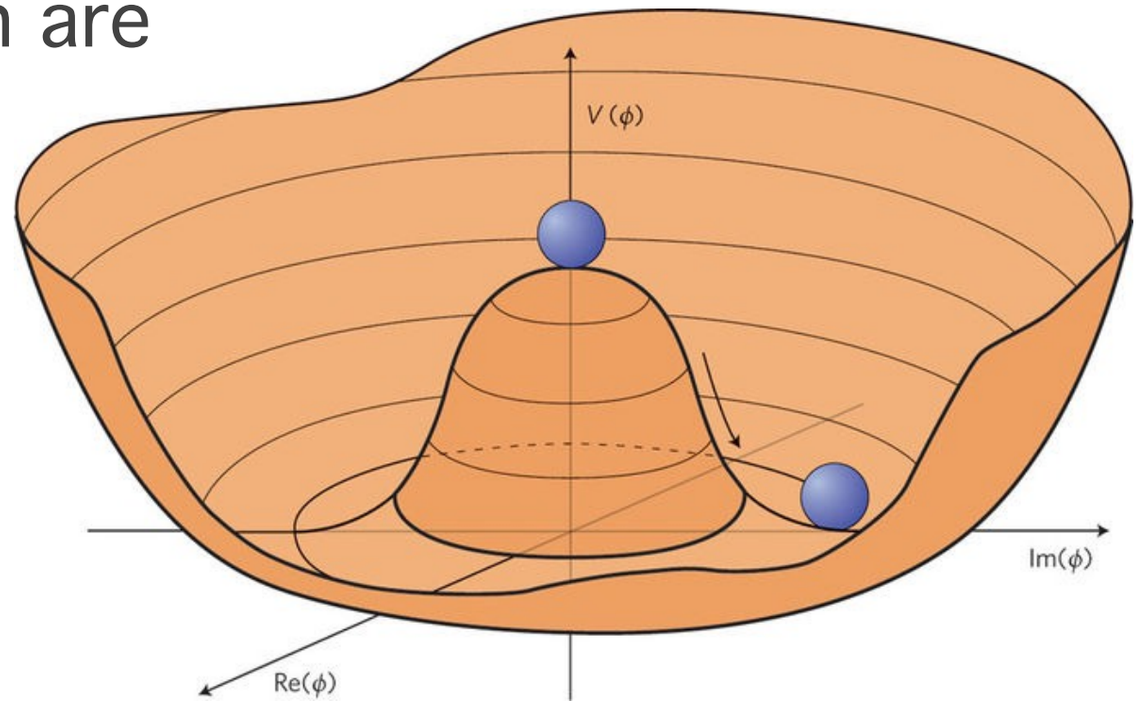
Introduction

- Extend the SM by adding a second iso-doublet that transforms under SU(2)xU(1), such that there are 8 fields
- After spontaneous symmetry breaking, there are two vacuum expectations values (vev), v_1 and v_2
- W and Z bosons 'eat' the 3 Goldstone bosons
- Leaves 5 physical scalars, which are the Higgs bosons

h	H	A	H^+	H^-

- Ratio of the vevs is an important parameter:

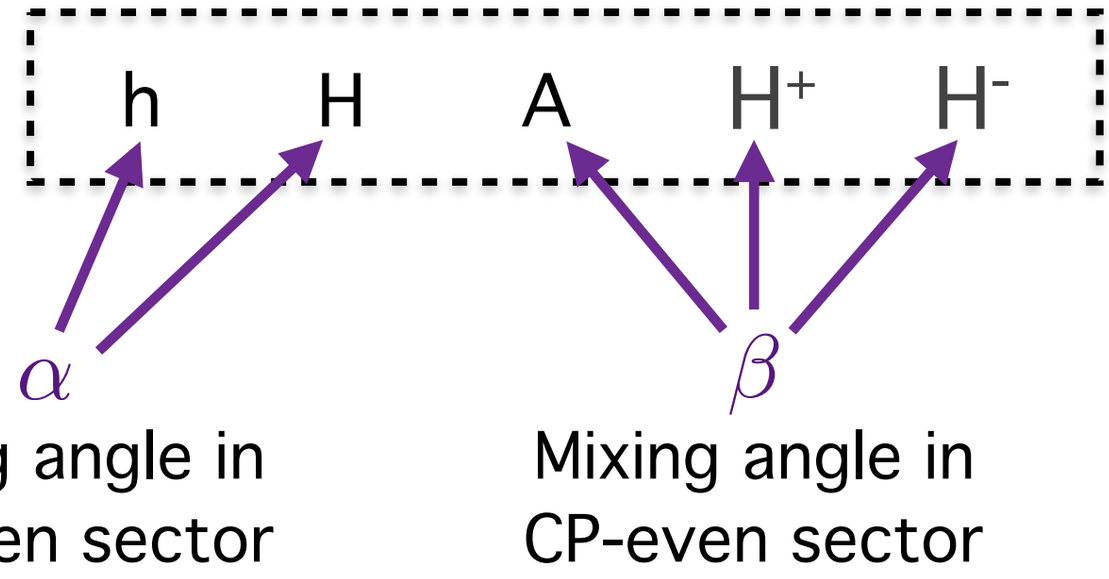
$$\tan\beta = \frac{v_1}{v_2}$$



Introduction

- Alignment limit

$$\sin(\beta - \alpha) = 1$$



Mixing angle in CP-even sector

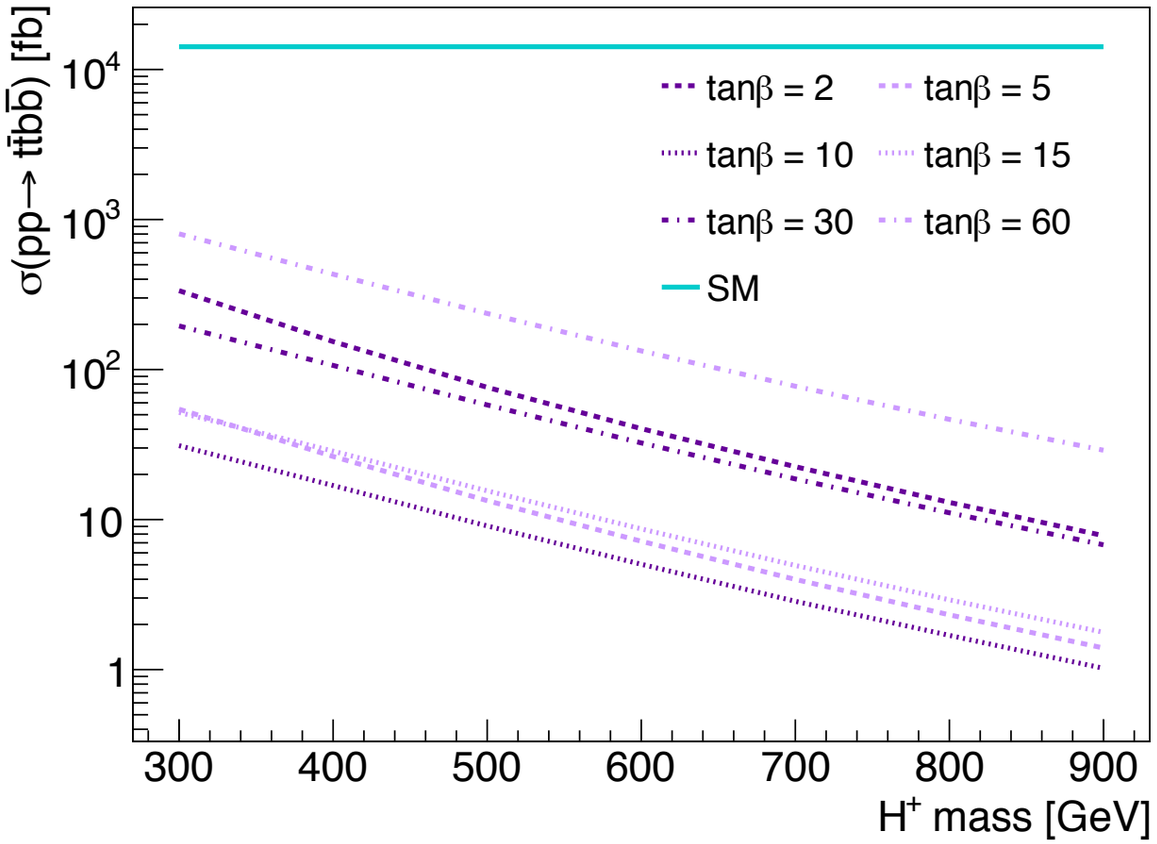
Mixing angle in CP-even sector

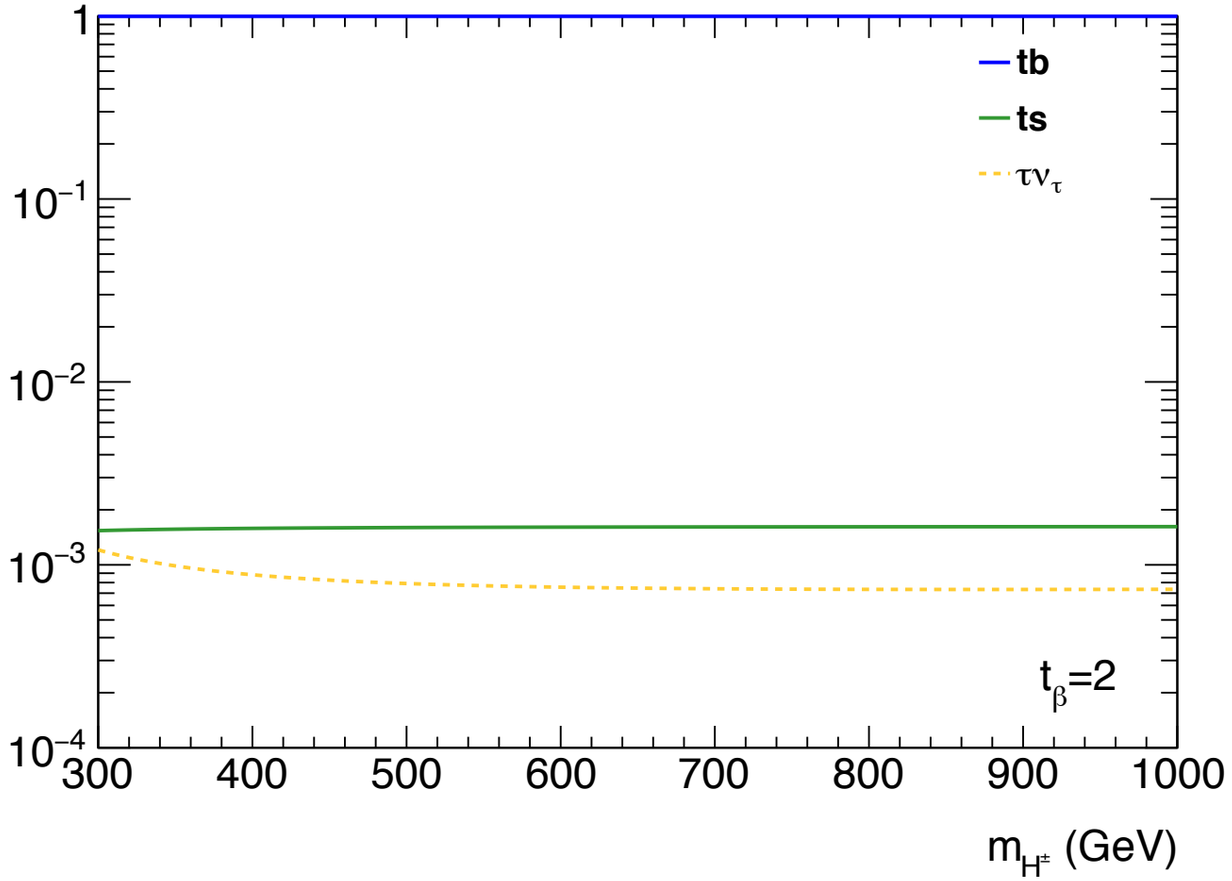
$$H_{SM} = H\cos(\beta - \alpha) + h\sin(\beta - \alpha) = h$$

- Heavy Higgs bosons are taken to be degenerate in this study.

Cross section

- $H^{\pm}$ production cross-section is much smaller than the SM
- BR($H^{\pm}\rightarrow tb$) dominates across all masses





Monte Carlo samples

- Use MadGraph, Pythia6 and Delphes software to simulate hard-scatter, showering and detector effects respectively

- Signal samples:
  - $m_{H^{\pm}}$ = {300, 400, 500, 600, 700, 800, 900} GeV
  - tanβ = {2, 5, 10, 15, 30, 60}

- Background samples:
  - $t\bar{t}b\bar{b}$
  - $t\bar{t}c\bar{c}$
  - $t\bar{t}l\bar{l}$, $(l = u, d, s)$

Analysis steps

- Apply kinematic cuts:

2 LEPTONS

$p_T > 20$ GeV
$|\eta| < 2.5$
$m_{ll} > 12$ GeV
$|m_{ll} - m_Z| > 10$ GeV
$\Delta R_{ll} > 0.4$

≥4 JETS

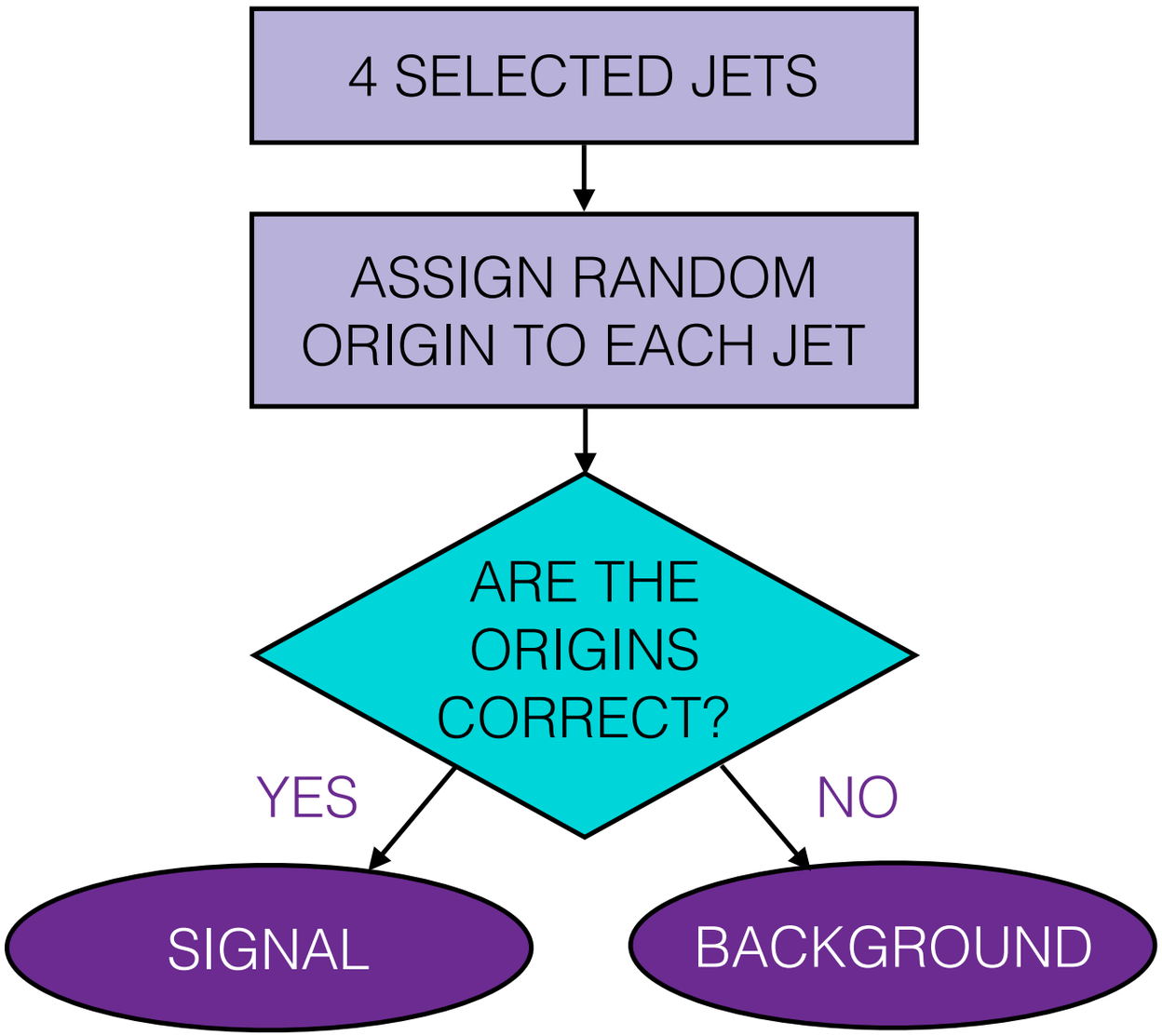
$p_T > 30$ GeV
$|\eta| < 2.4$
≥ 2 b-tagged jets

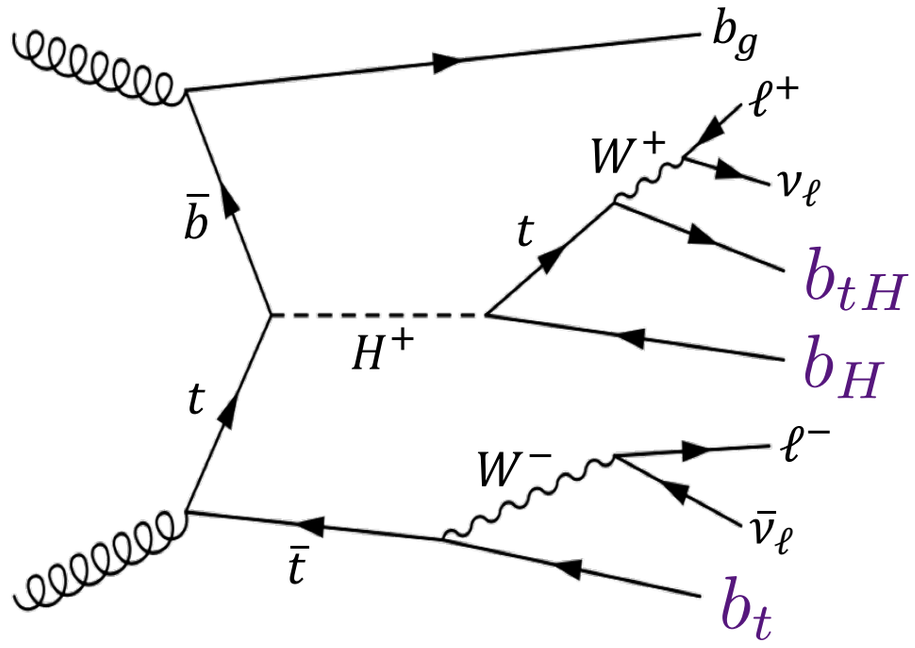
$E_T^{miss} > 40$ GeV

- Match jets to truth-level b-partons using $\Delta R < 0.4$ requirement
- Reconstruct event using:
  - Reconstruction BDT to select the correct jet permutation
  - Neutrino weighting to calculate the two neutrino 4-vectors
- Separate charged Higgs signal from background with a classification BDT and set limits on the process

Reconstruction BDT

For each event in $H^{\pm}$ sample:





VARIABLES

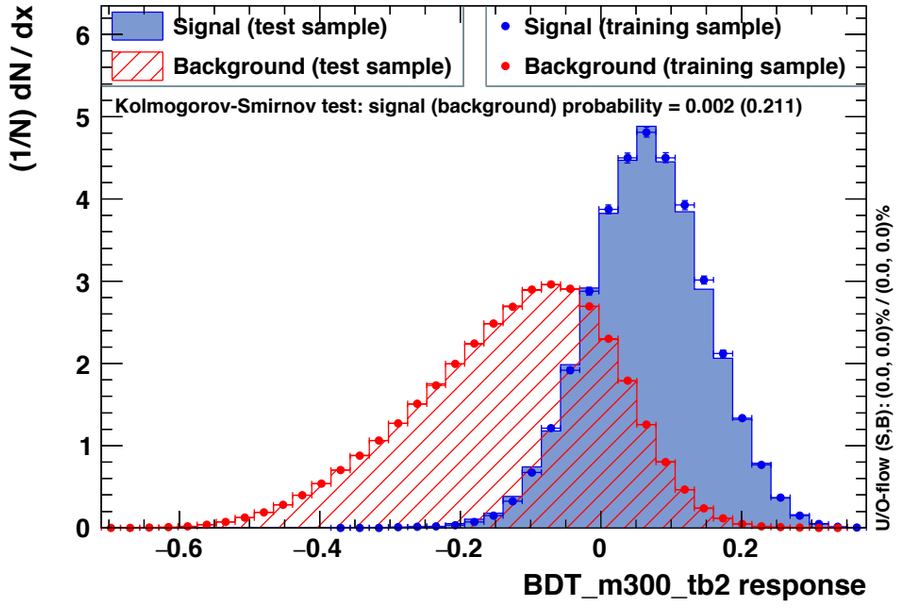
$p_T^{b_a}$	$\Delta p_T(b_a, b_c)$	$p_T^{b_a+b_c}$	$p_T^{l+b_a}$
η^{b_a}	$\Delta\eta(b_a, b_c)$	$\eta^{b_a+b_c}$	η^{l+b_a}
ϕ^{b_a}	$\Delta\phi(b_a, b_c)$	$\phi^{b_a+b_c}$	ϕ^{l+b_a}
E^{b_a}	$\Delta m(b_a, b_c)$	$E^{b_a+b_c}$	E^{l+b_a}
$m_{b_a b_c}$	$\Delta R(b_a, b_c)$		

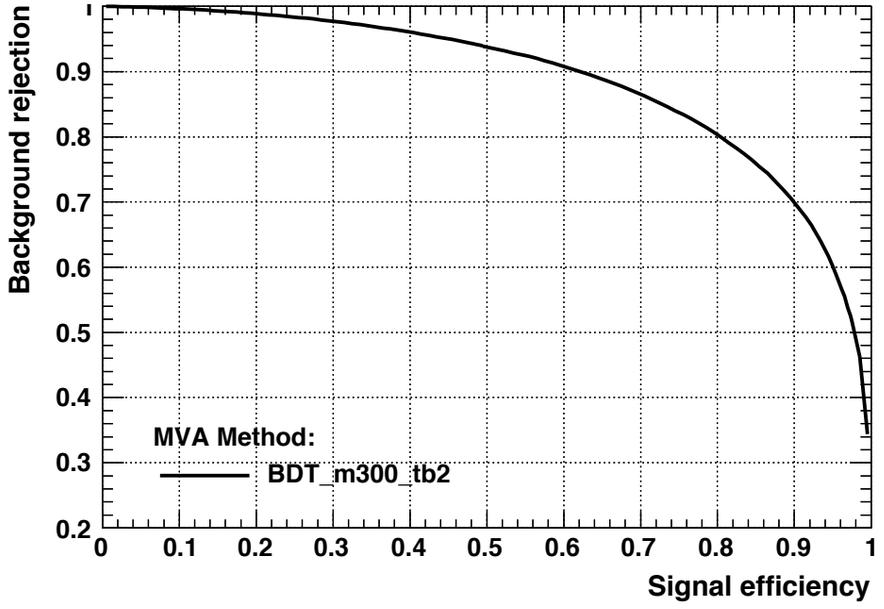
$a, c = \{tH, t, H, g\},\ a \neq c$
$l = \{e^+, e^-, \mu^+, \mu^-\}$

Reconstruction BDT

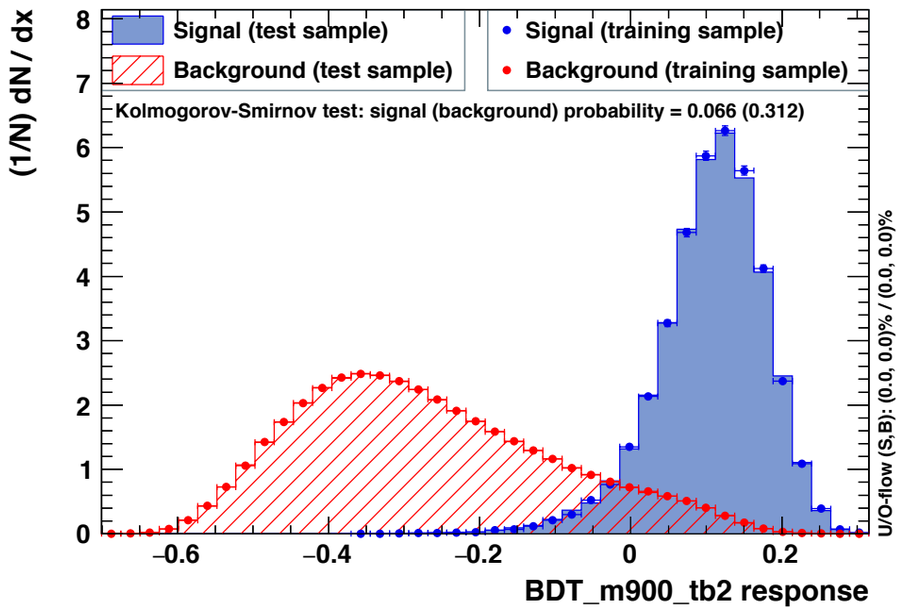
- Separation improves with increasing mass

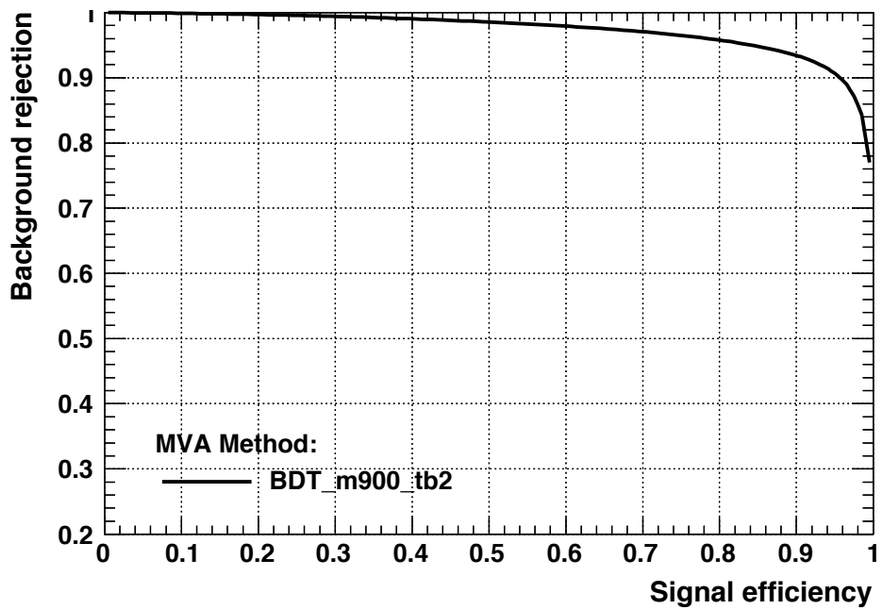
$m_{H^\pm}$ = 300 GeV
tanβ = 2





$m_{H^\pm}$ = 900 GeV
tanβ = 2



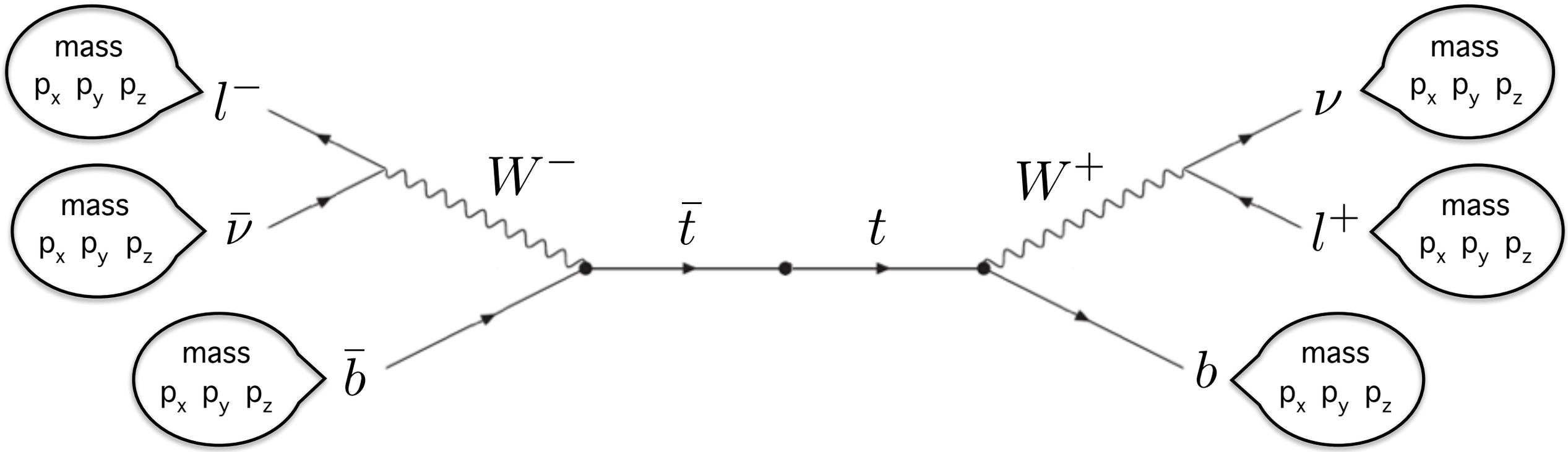


Neutrino weighting

- Neutrino weighting is a method to reconstruct the neutrino 4-vectors that has previously been used in $t\bar{t}$.
- This is the first time neutrino weighting has been used in $t\bar{t}b\bar{b}$ final state.
- How is this done?

Neutrino weighting

- How is this done? Let's look at simple $t\bar{t}$ event first.



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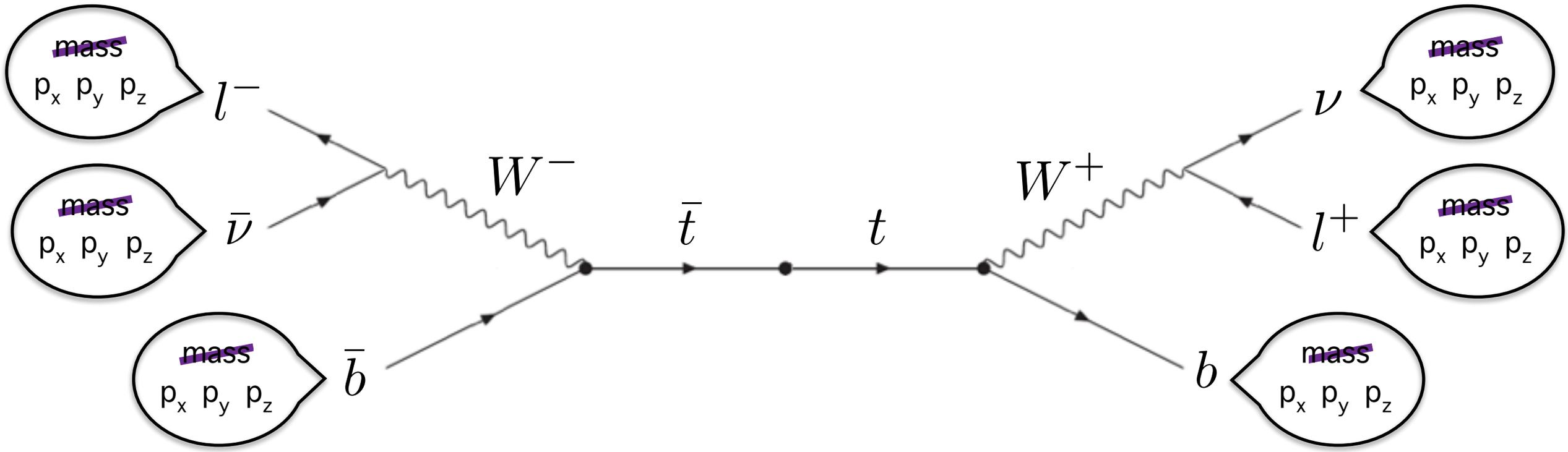

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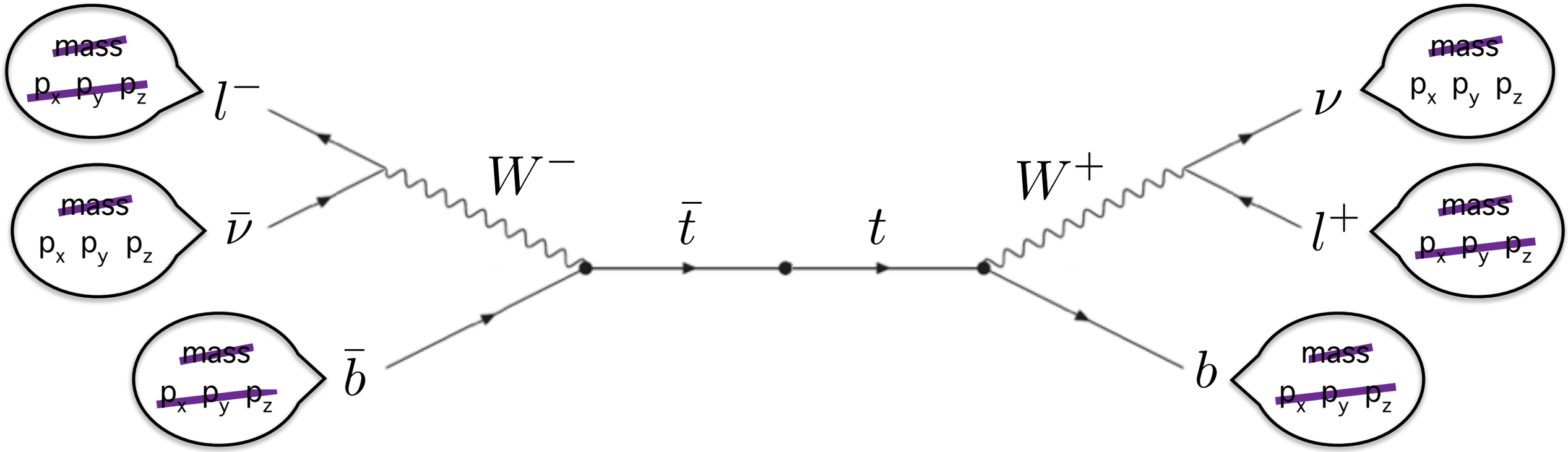

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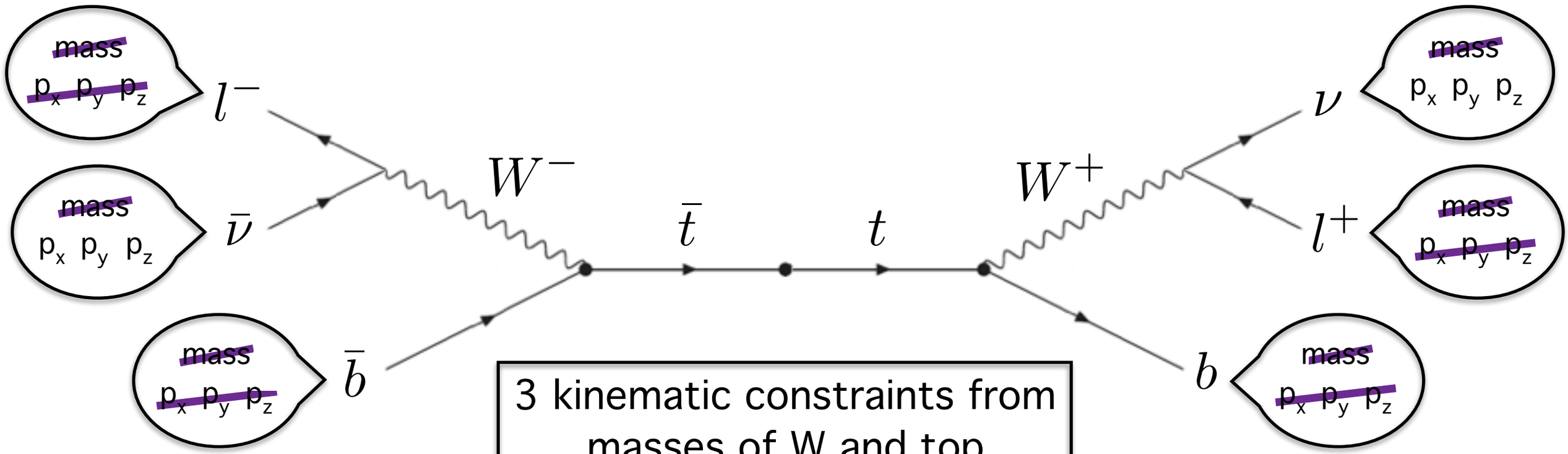


3 kinematic constraints from masses of W and top

↓

Set value for top mass

↓

Choose η for both neutrinos

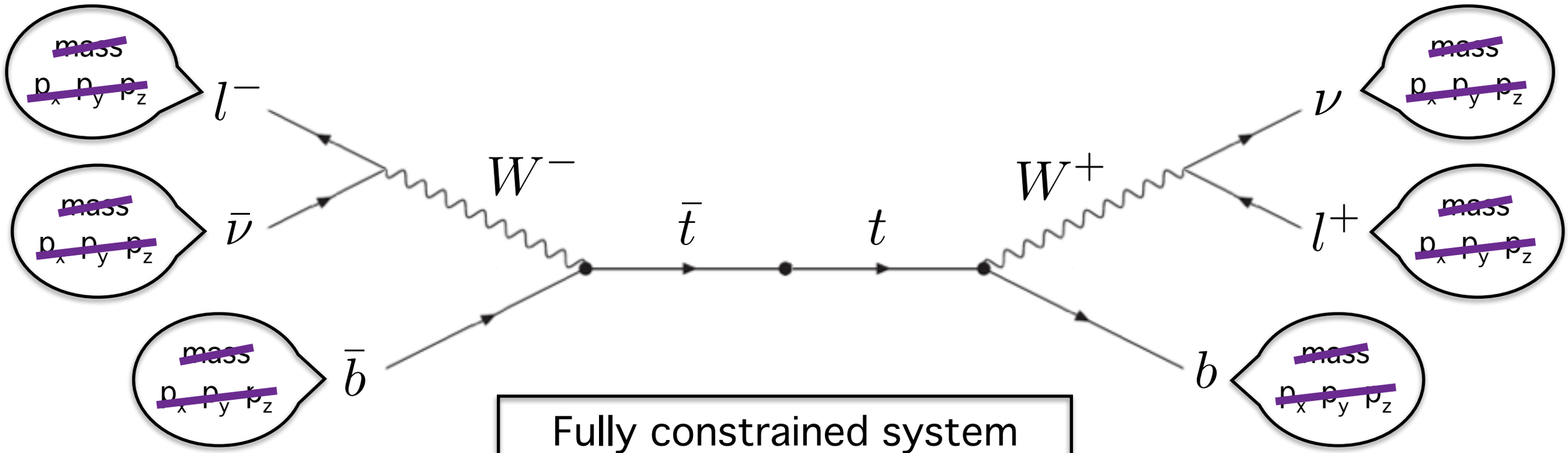
Neutrino η distribution described by Gaussian weakly dependent on top mass

↓

Fully constrained system

Neutrino weighting

- How is this done? Let's look at simple $t\bar{t}$ event first.



Fully constrained system

Smear top mass input according to width, and solve for neutrino rapidities to obtain the neutrino 4-vectors

Compare with measured E_T^{miss} and assign weight for each smear - take maximum weight as solution

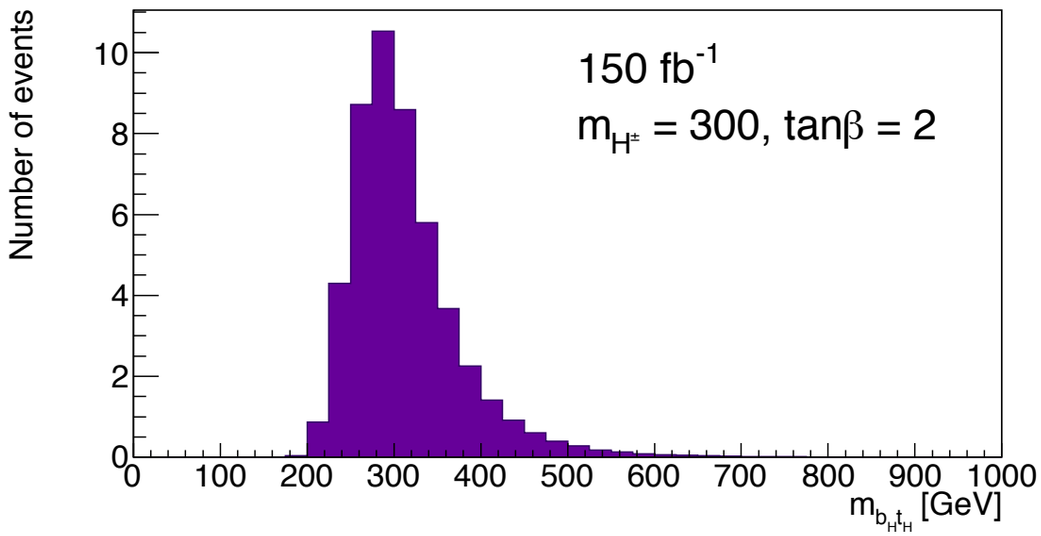
Neutrino weighting

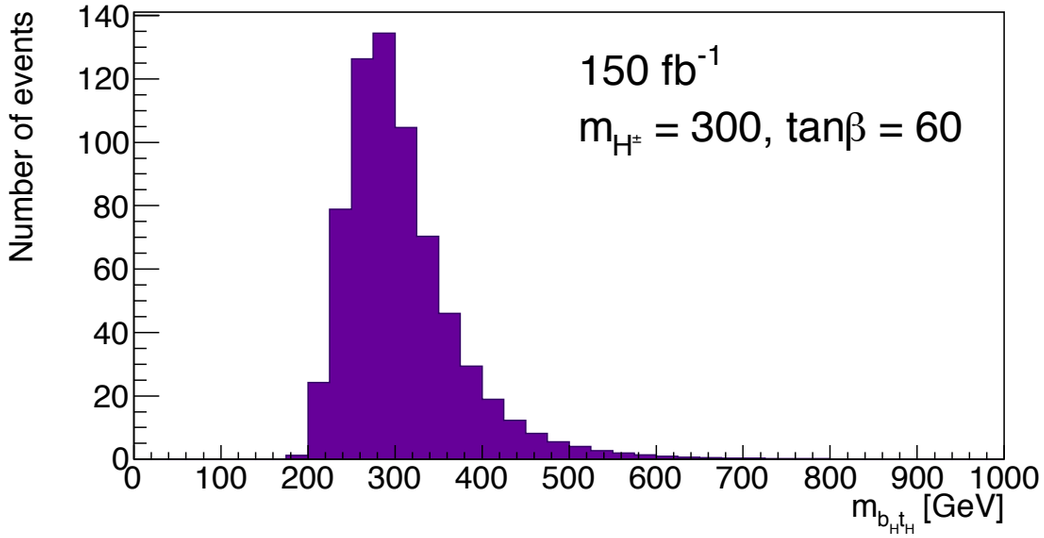
- Neutrino weighting is a method to reconstruct the neutrino 4-vectors that has previously been used in $t\bar{t}$.
- This is the first time neutrino weighting has been used in $t\bar{t}b\bar{b}$ final state.
- How is this done?

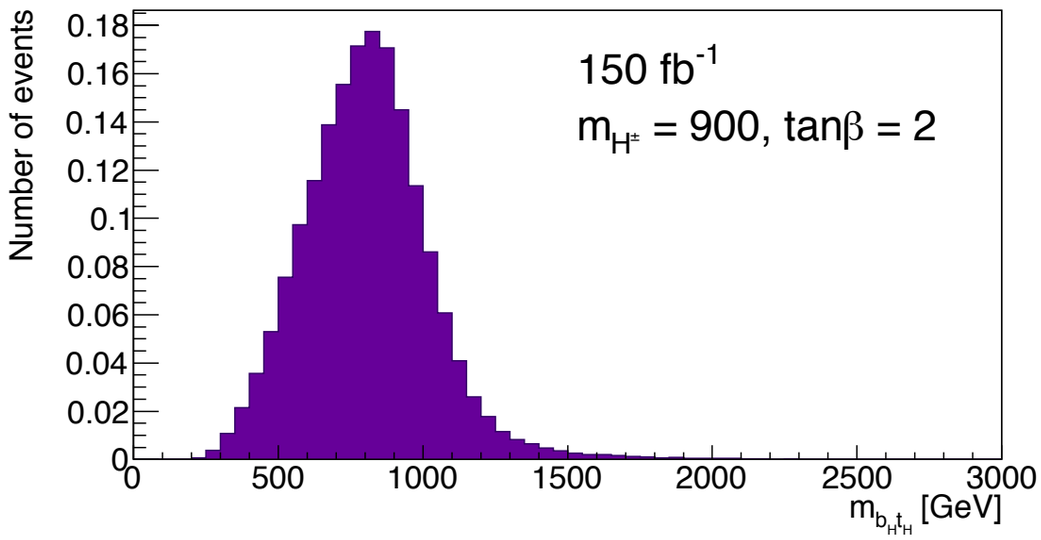
- Back to the $ttbb$ final state, as there are more jets we use the result of the reconstruction BDT
  - Know which permutation of jets gives the correct b_t, b_{tH} and b_H.
- Use b_t and b_{tH} in neutrino weighting calculation to fully reconstruct $H^{\pm}$.

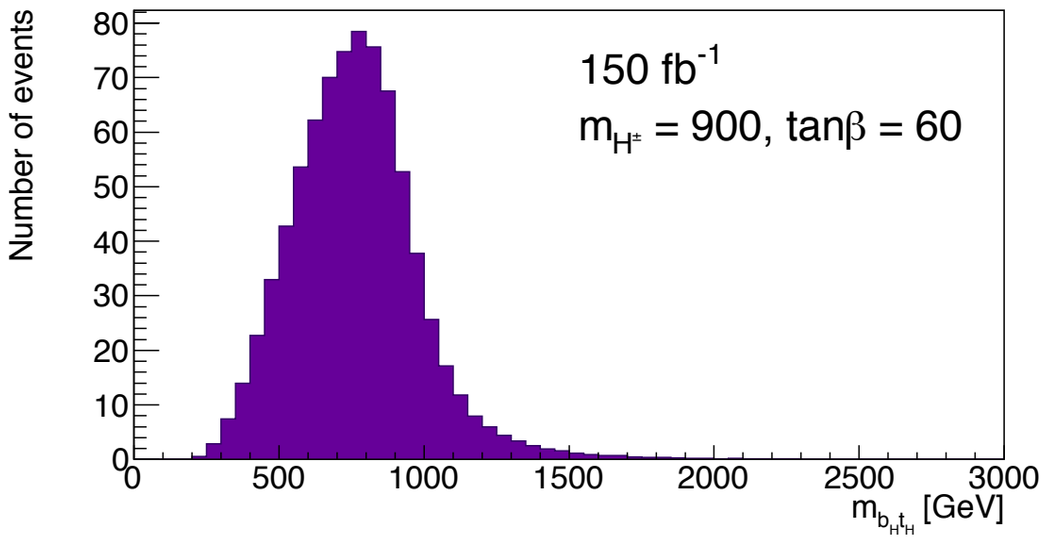
Reconstruction efficiency

$m_{H^\pm}$	300 GeV		900 GeV	
tanβ	2	60	2	60
Neutrino weighting solution	96.10%	97.37%	85.38%	89.78%
NW + (btH, bH, bt) correct	21.22%	15.94%	36.26%	37.14%









Classification BDT

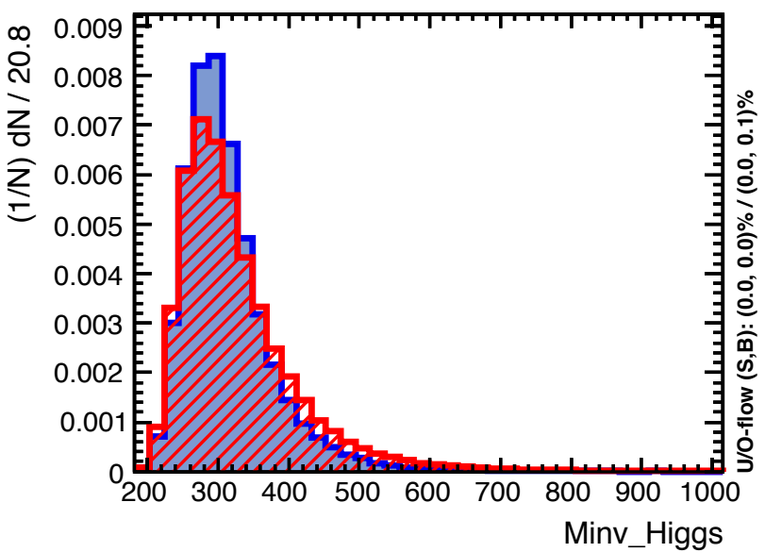
- Use a second BDT to separate signal from the $t\bar{t}+\text{jets}$ background

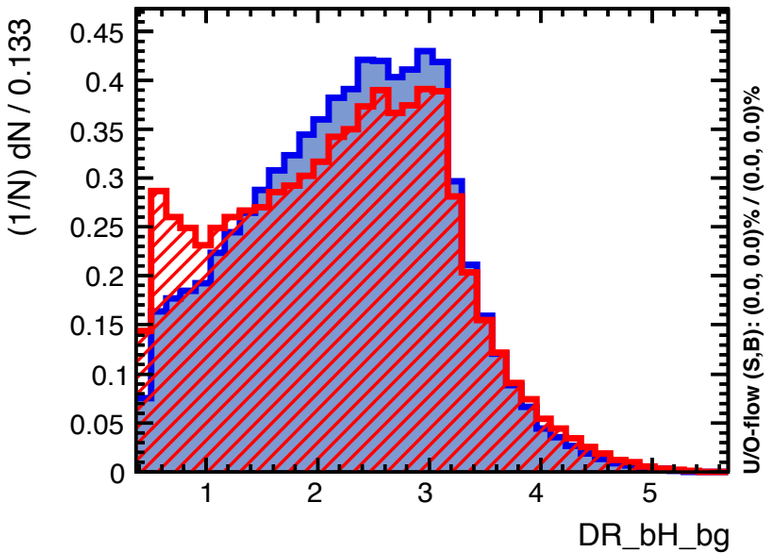
- The variables that rank highest are:

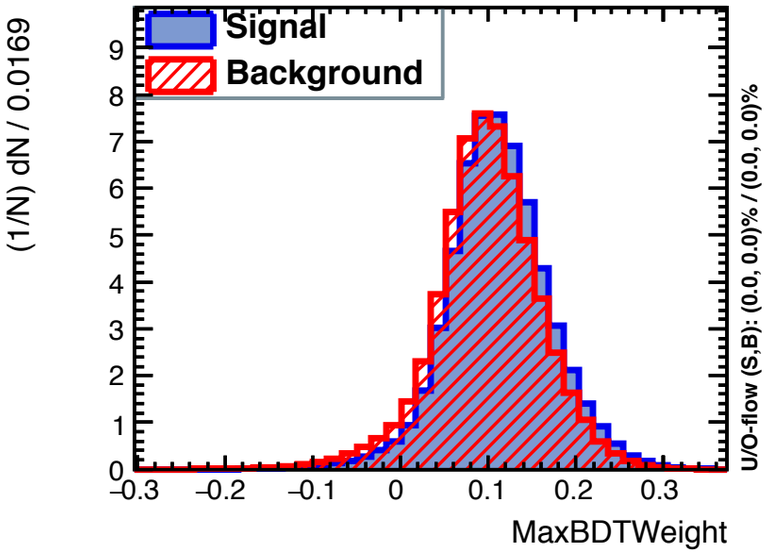
$m_{H^\pm}$ = 300 GeV, tanβ = 2

VARIABLES

$\Delta\phi(t_H, t)$	$\Delta R(b_1, t_1)$	$\max(w_{\text{recoBDT}})$
$\Delta\phi(b_a, b_c)$	$\Delta R(t_H, t)$	$m_{H=b_H t_H}$
$\Delta\phi(b_H, b_g)$	$\Delta R(b_a, b_c)$	$m_{b_i b_j}$ for i, j giving $\min(\Delta R)$
$\Delta\eta(t_H, t)$	$\Delta R(b_H, b_g)$	$\min(m_{b_i l^+})$
$\Delta\eta(b_a, b_c)$	$p_T^{b_H}$	$\min(m_{b_i l^-})$
$\Delta\eta(b_H, b_g)$	H_T	$\cos\theta_{b_H l_{tH}}$
$H_T / \sum_i^{b,l} E$	η_{b_a}	$a = \{tH, t\},\ c = \{H, g\}$







Classification BDT

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$m_{H^\pm}$ = 900 GeV, tanβ = 2

VARIABLES

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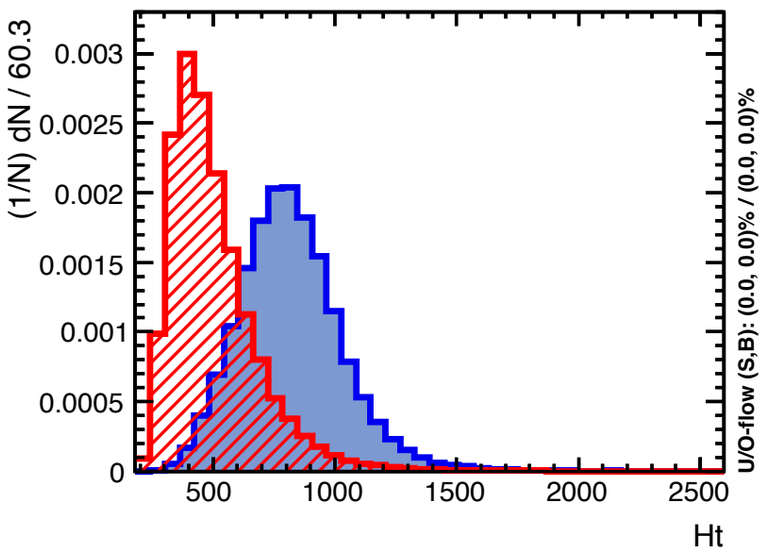
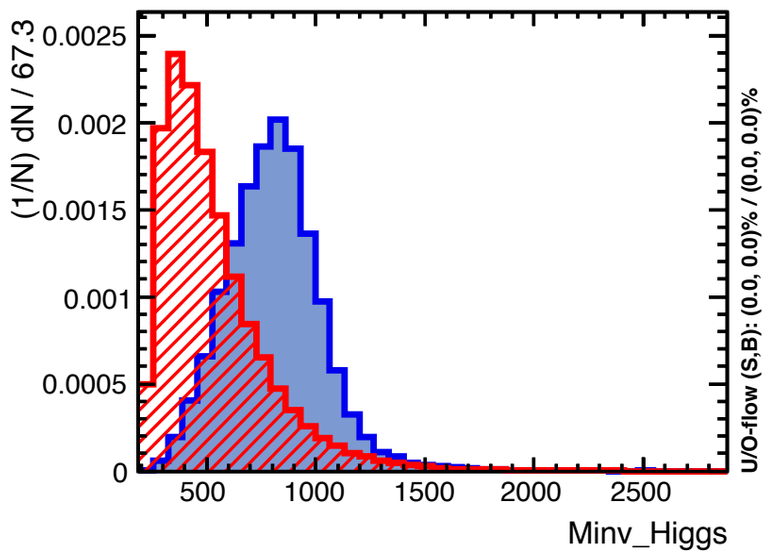
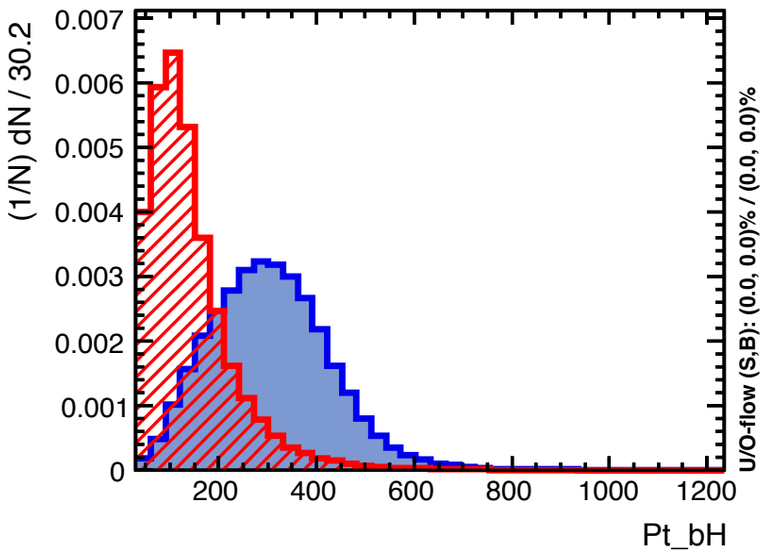




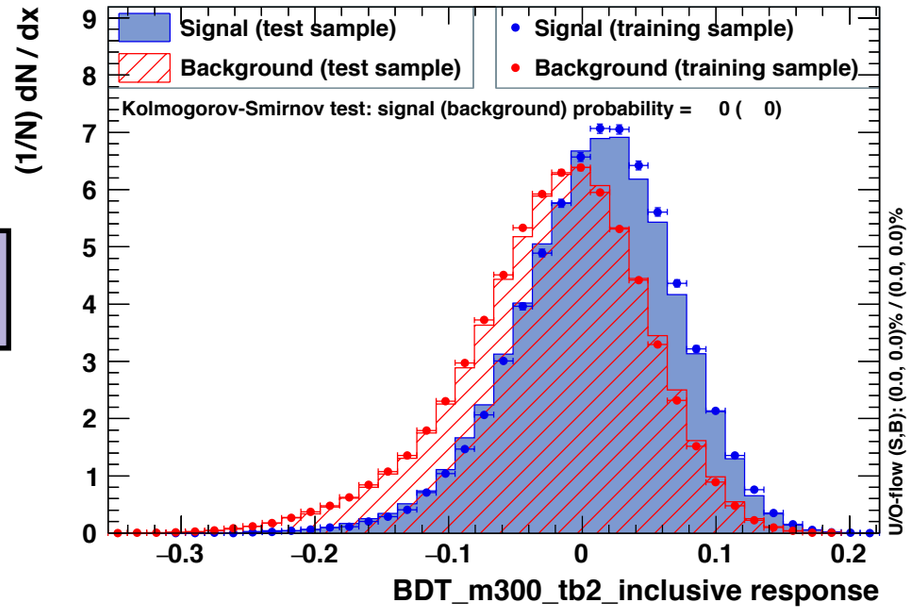


Classification BDT

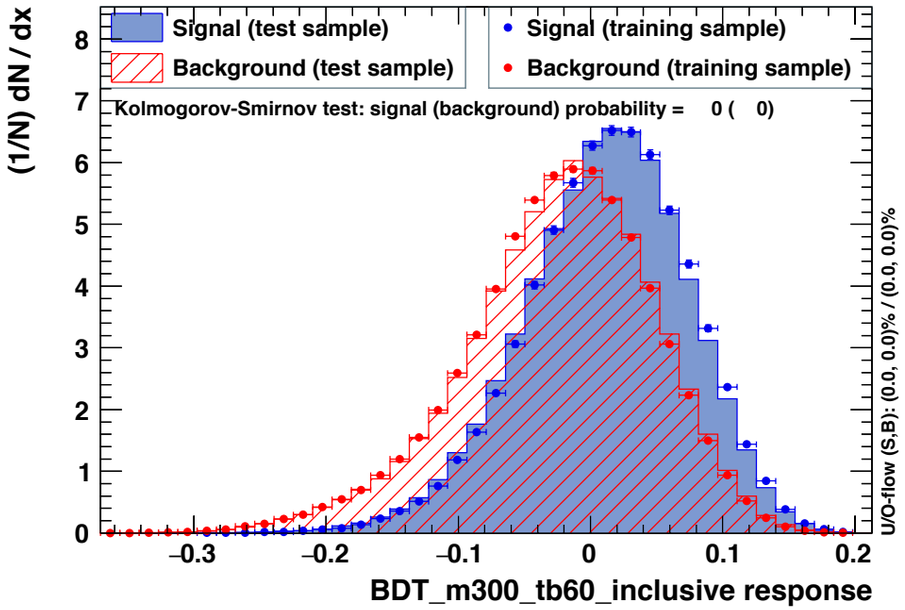
- Again, separation improves with increasing mass

$m_{H^\pm}$ = 300 GeV

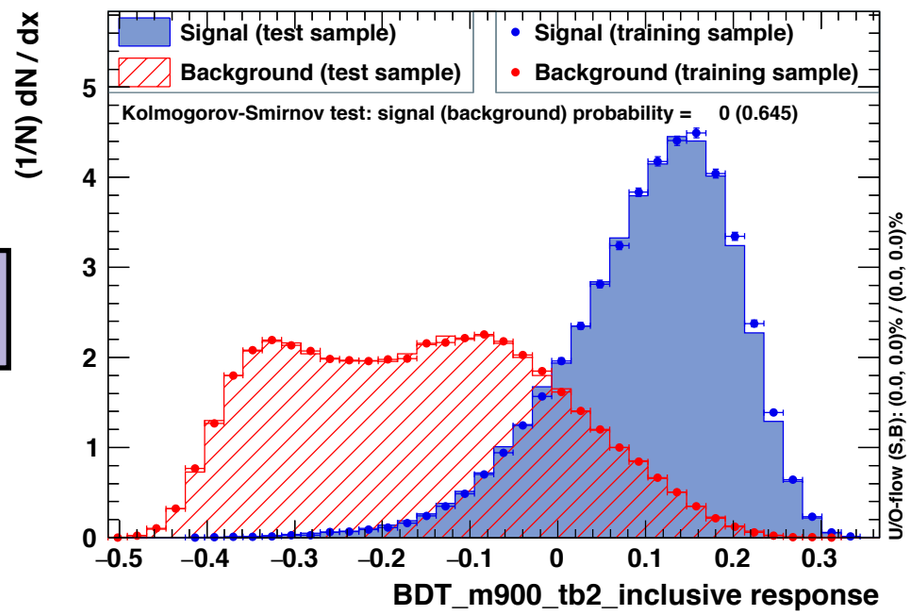
tanβ = 2

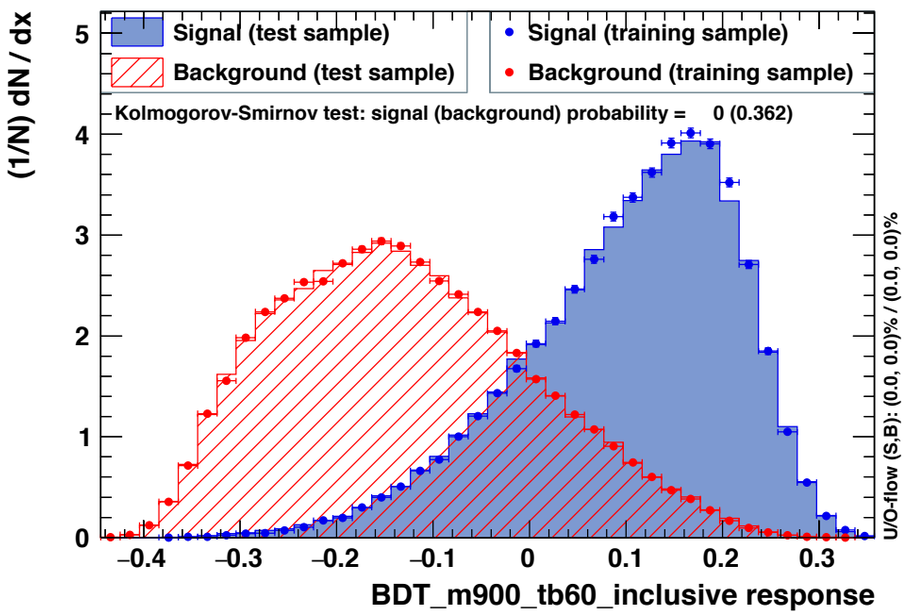


tanβ = 60



$m_{H^\pm}$ = 900 GeV



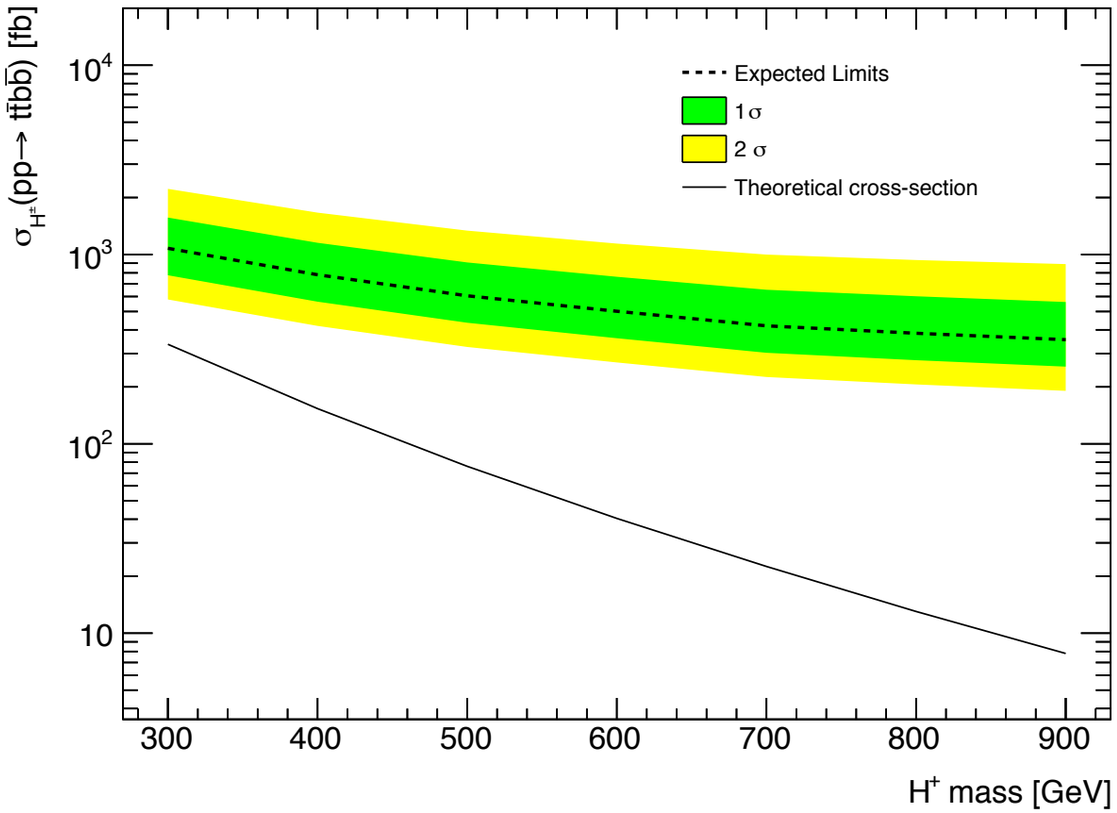


Limit-setting

VERY PRELIMINARY

- Use CLs method to place limits on signal cross-sections at a luminosity of 150 fb^{-1}

tanβ = 2



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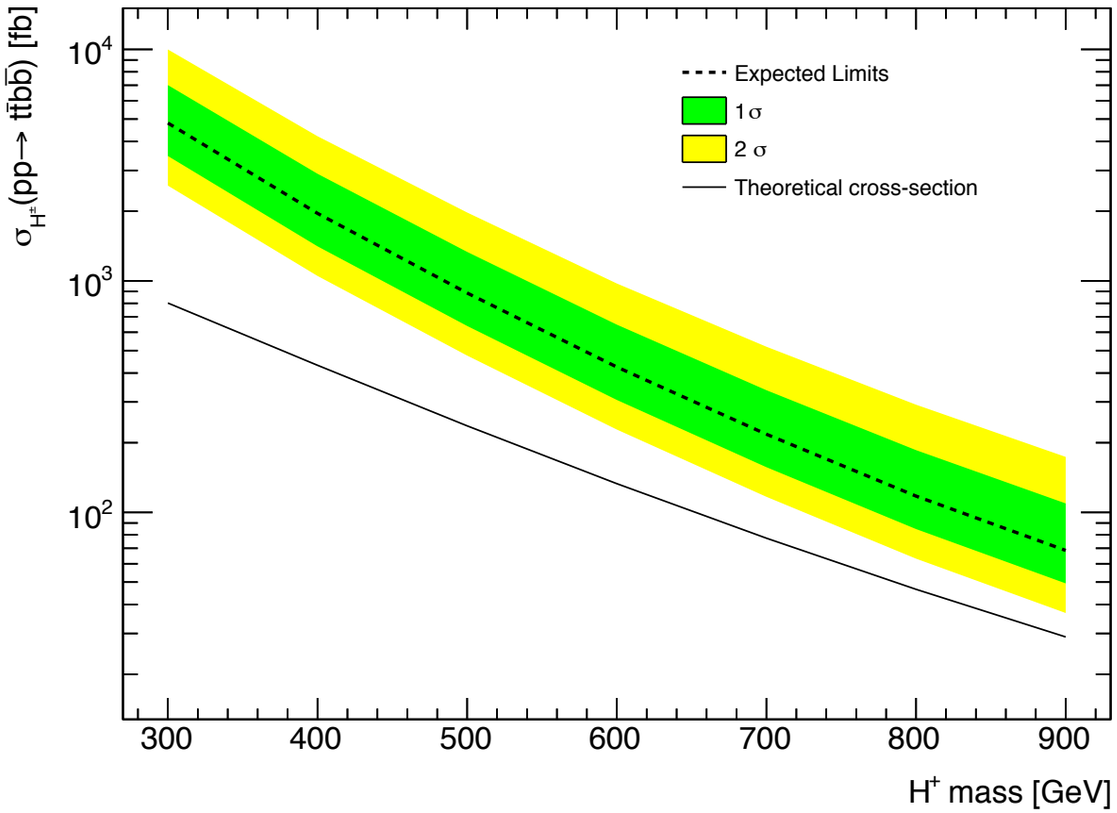


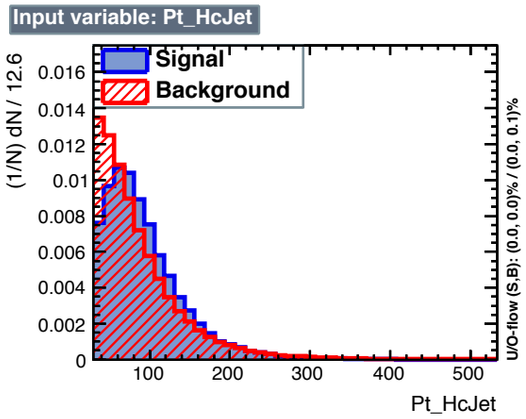
Summary

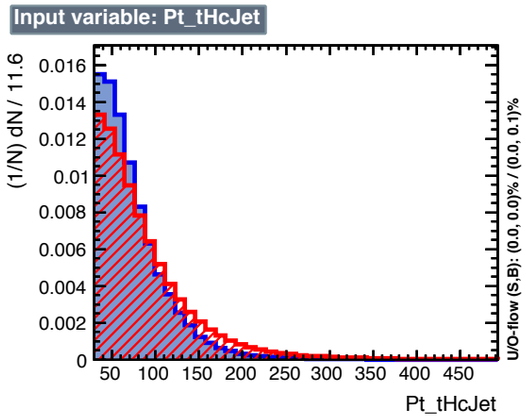
- Using MC samples, charged Higgs bosons have been successfully reconstructed using neutrino weighting and BDT methods.
- A BDT was used to separate signal from the SM background. The separation increases with increasing mass.
- Successfully reconstructed events in this channel.

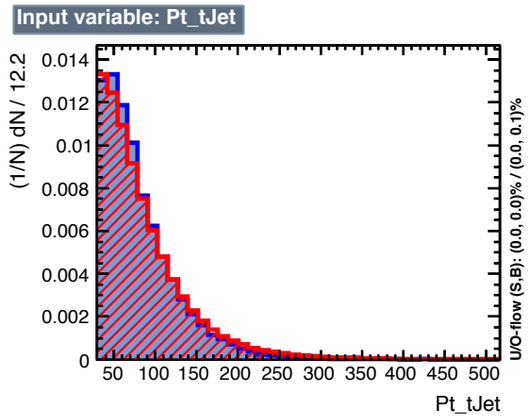
Backup

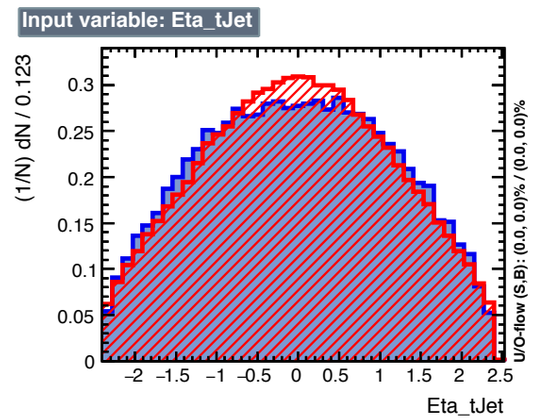
Input variables to reconstruction BDT

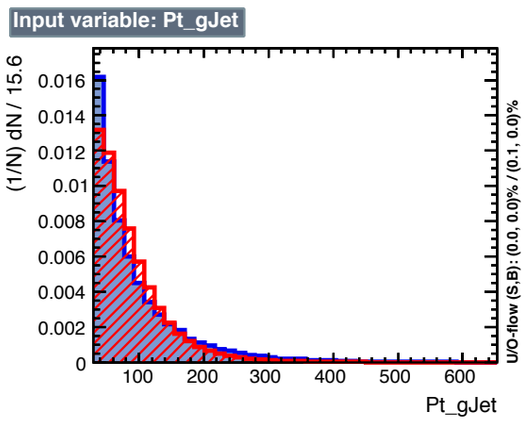
- $m_{H^{\pm}}$ = 300 GeV, tanβ = 2

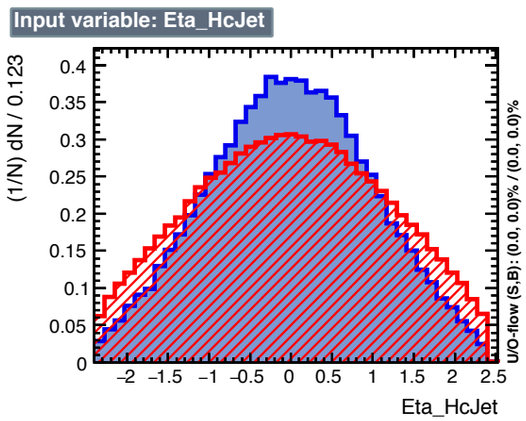


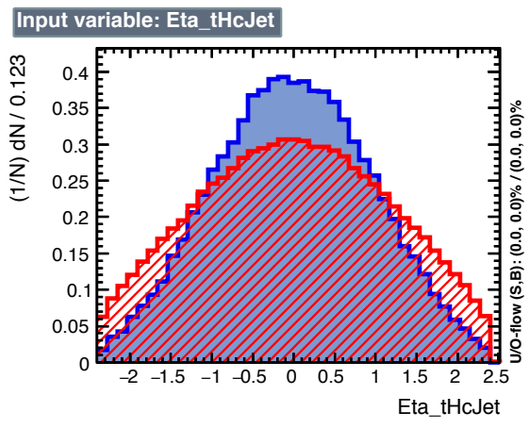


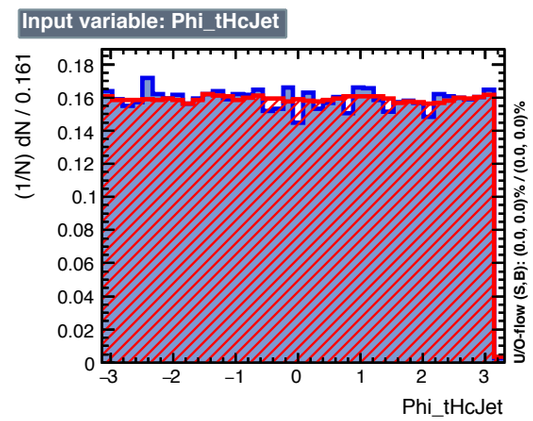


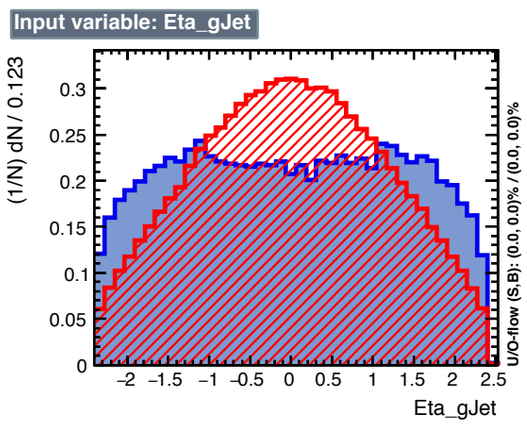


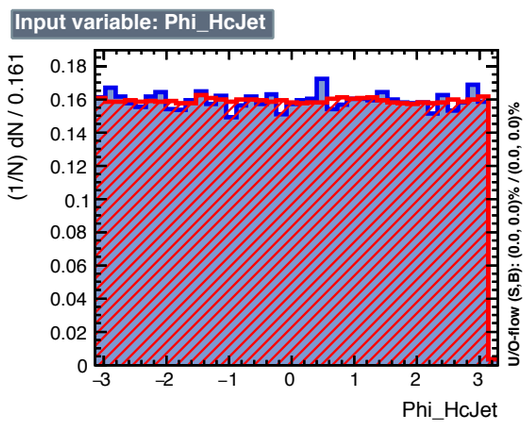


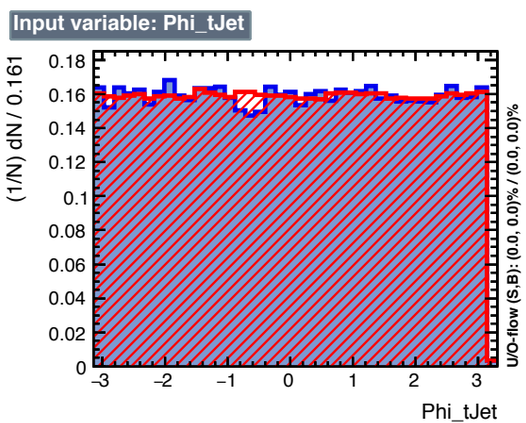


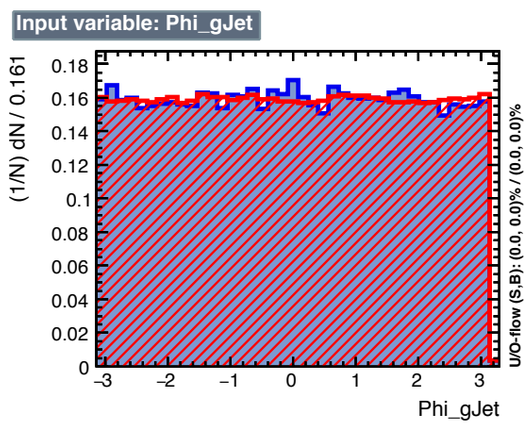






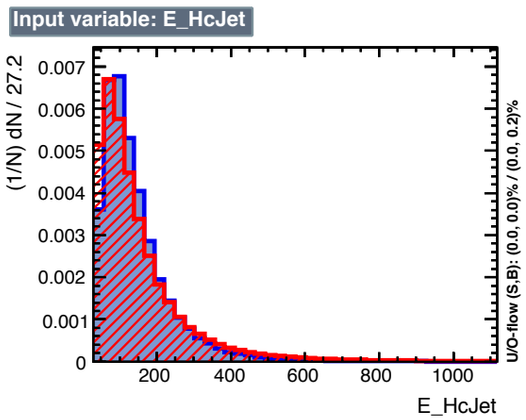


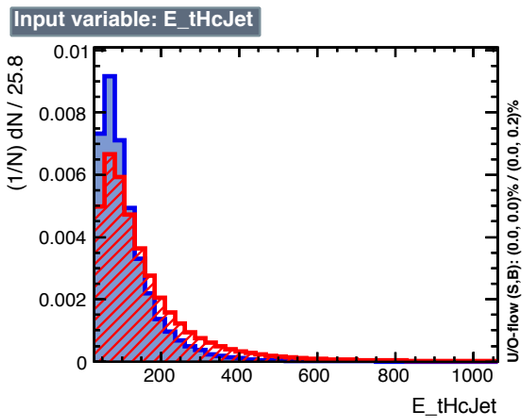


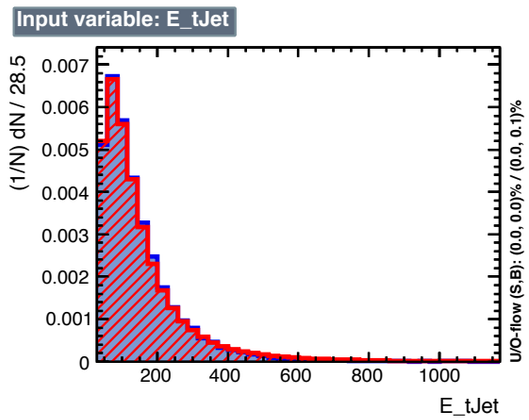


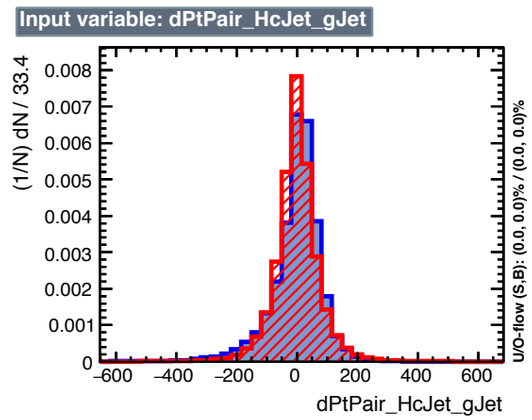
Input variables to reconstruction BDT

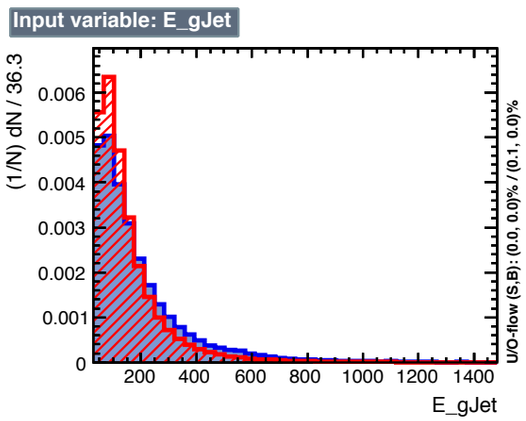
- $m_{H^{\pm}}$ = 300 GeV, tanβ = 2

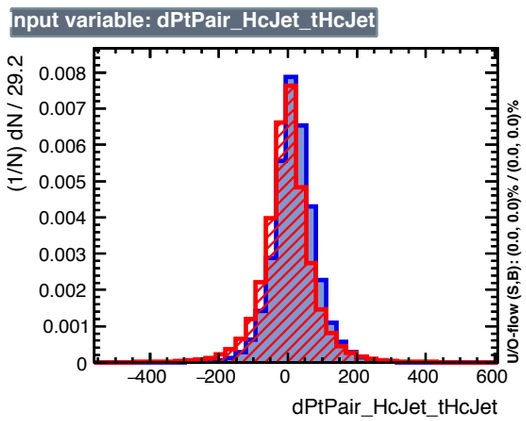


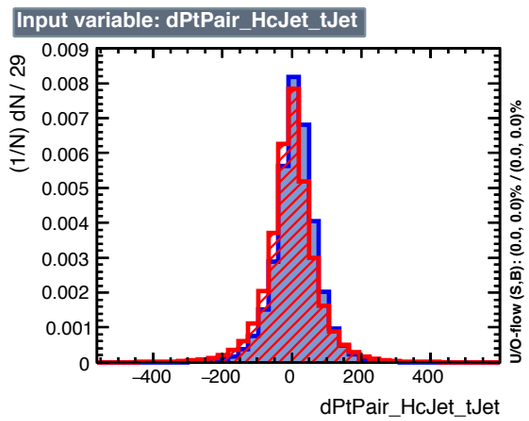


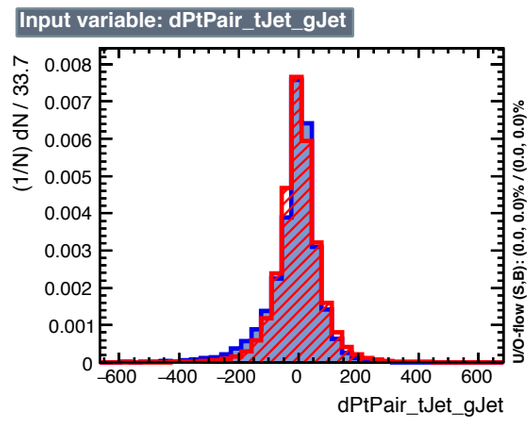


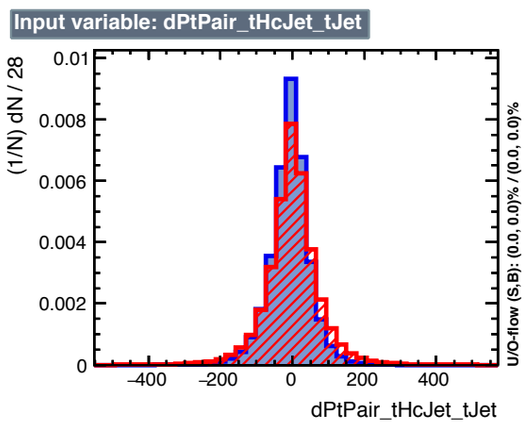


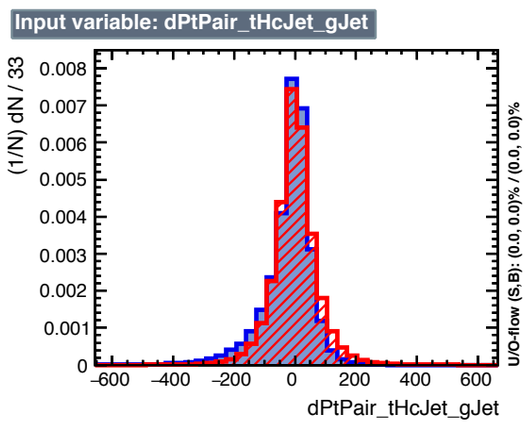


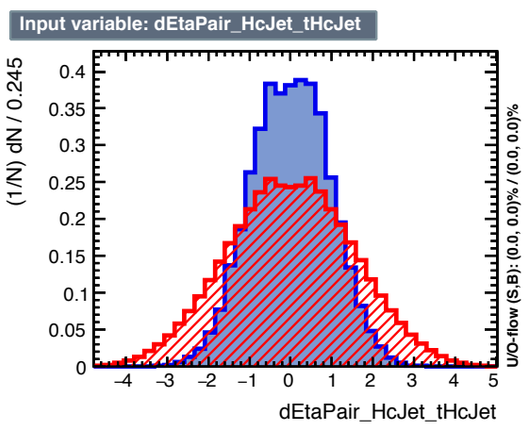


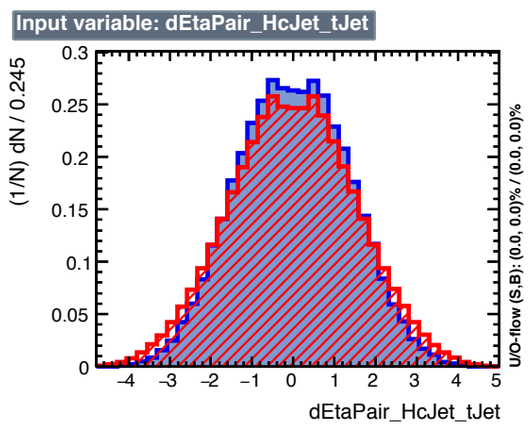






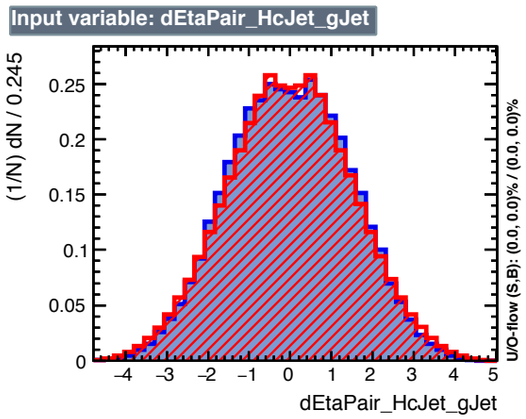


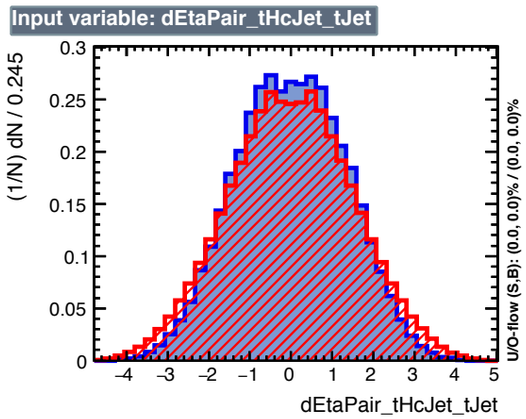


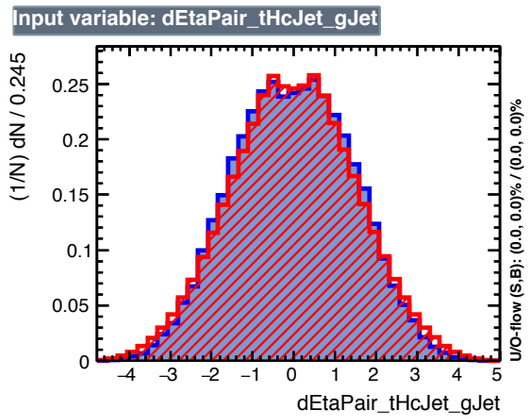


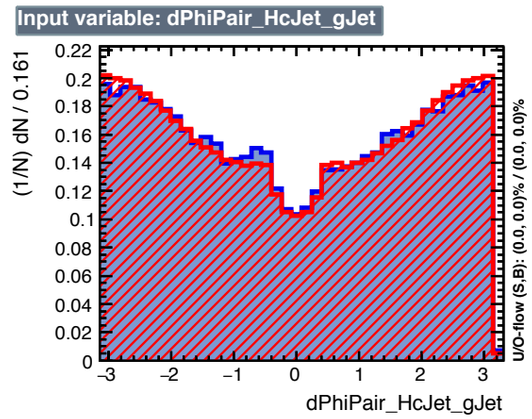
Input variables to reconstruction BDT

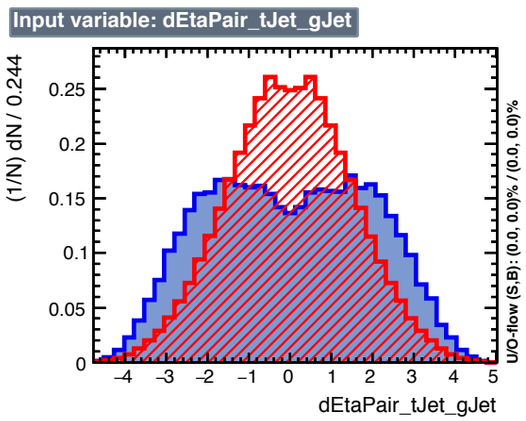
- $m_{H^{\pm}}$ = 300 GeV, tanβ = 2

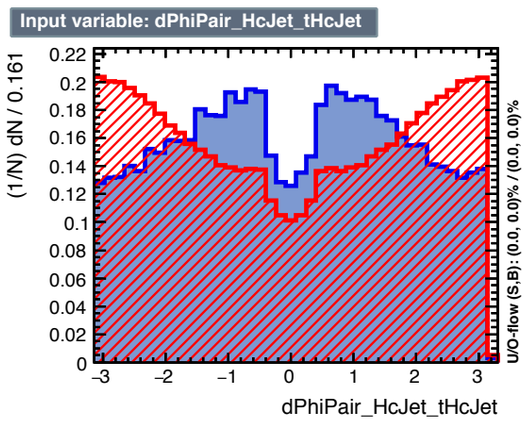


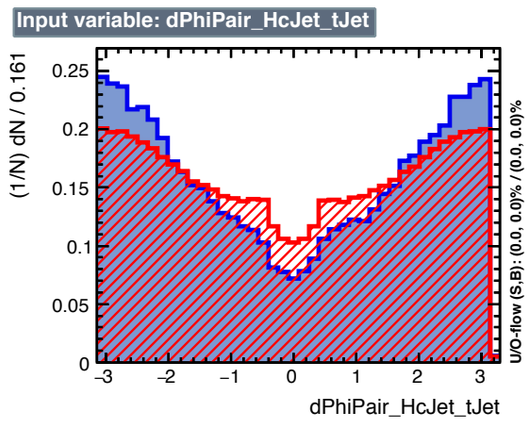


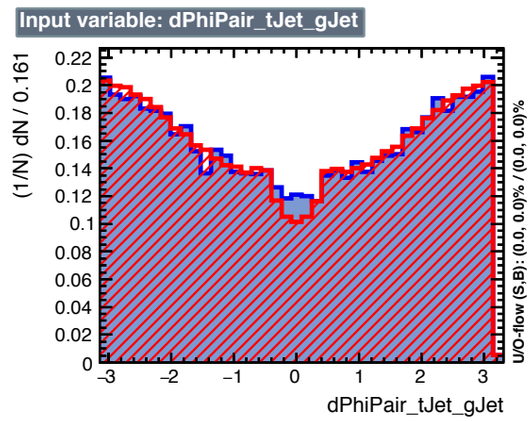


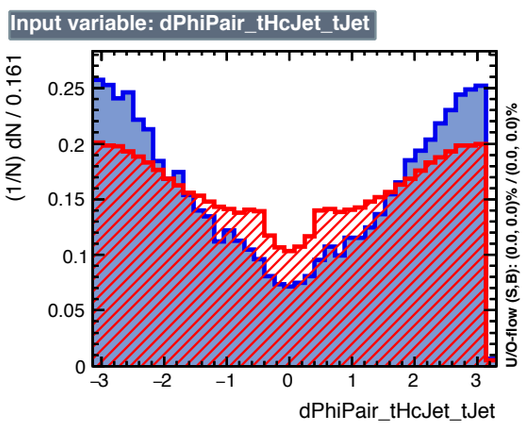


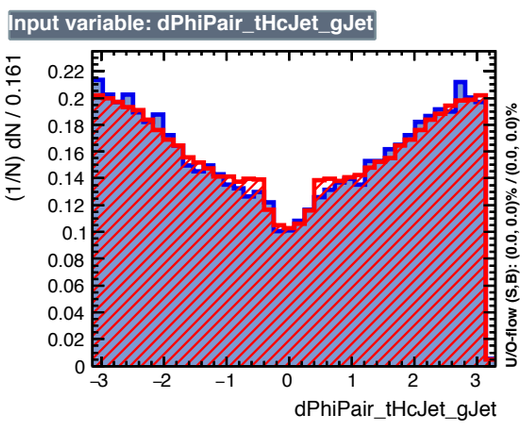


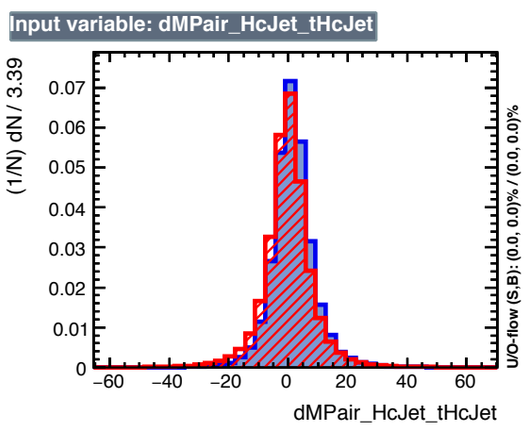


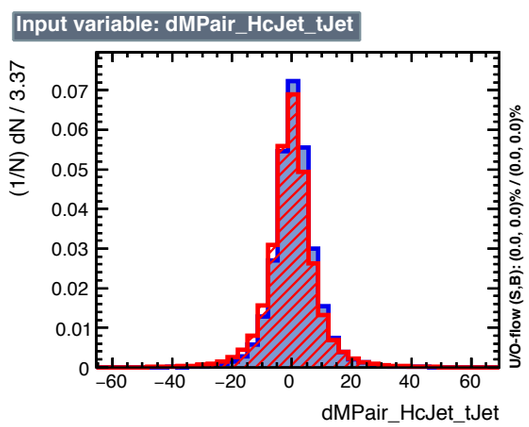






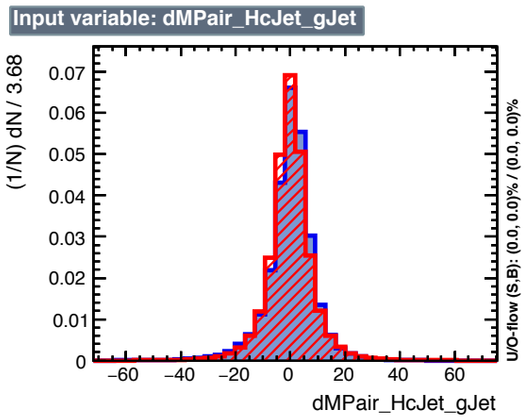


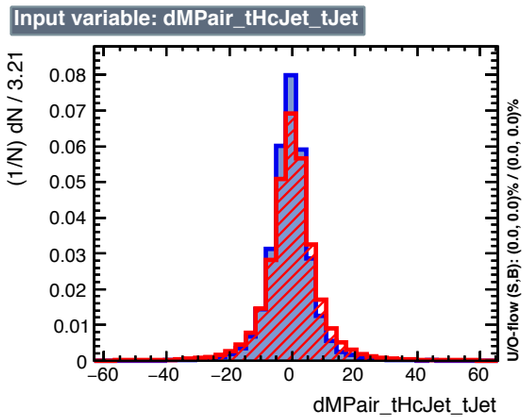


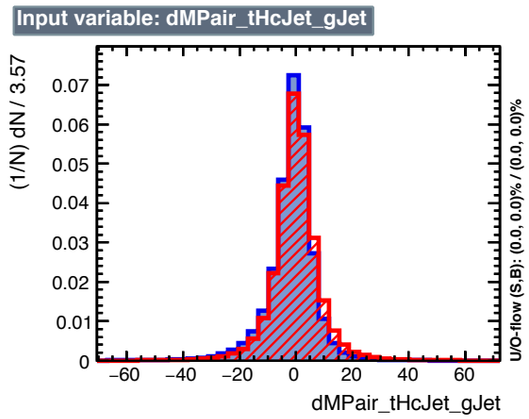


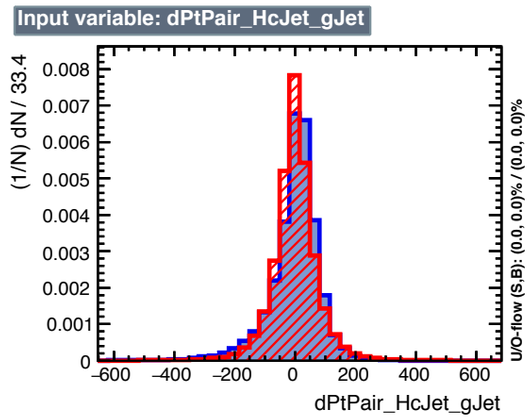
Input variables to reconstruction BDT

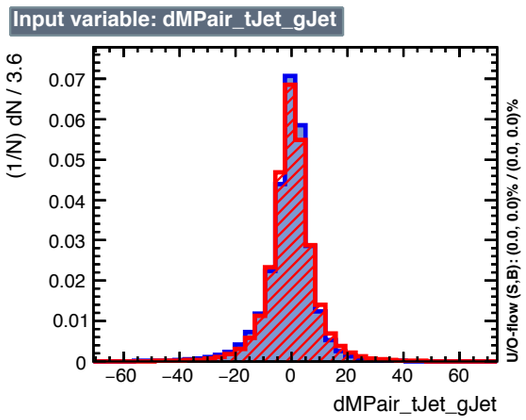
- $m_{H^{\pm}}$ = 300 GeV, tanβ = 2

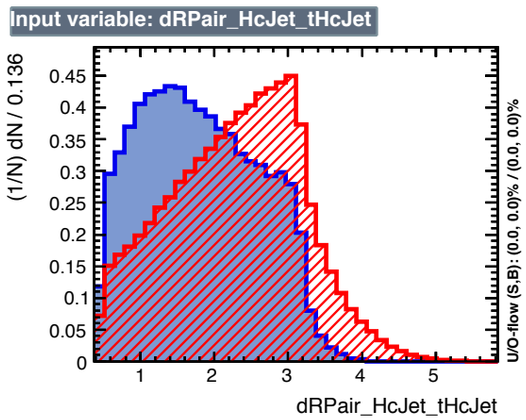


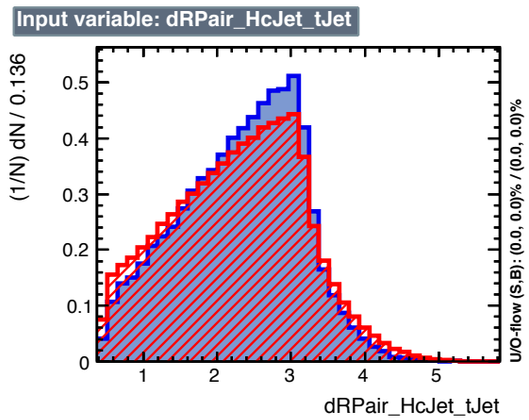


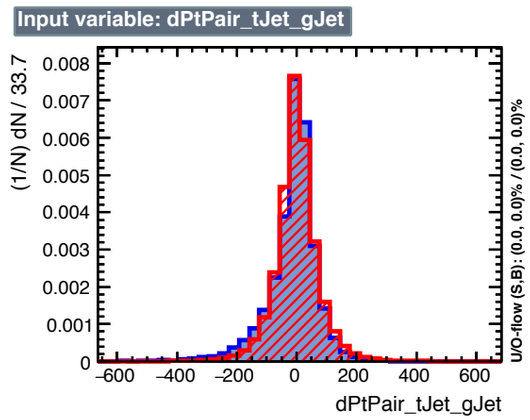


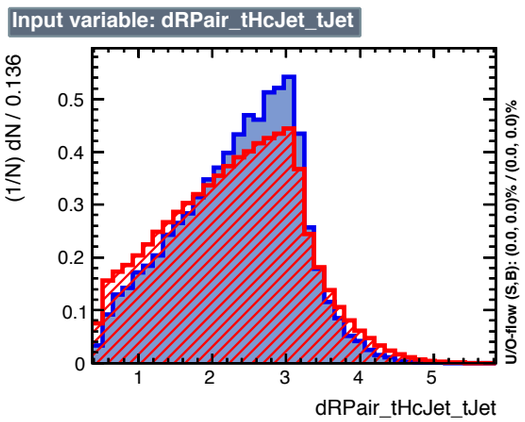


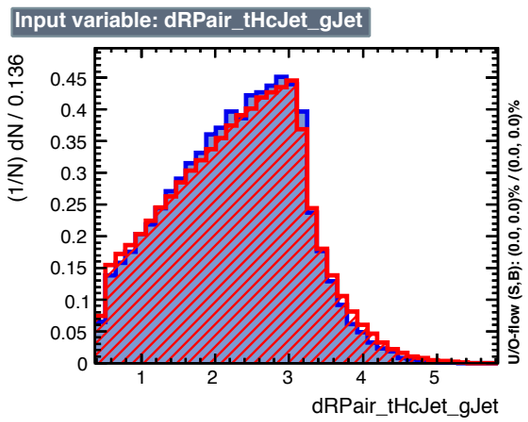


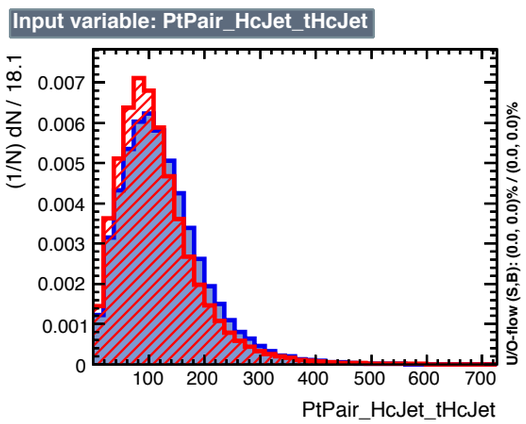


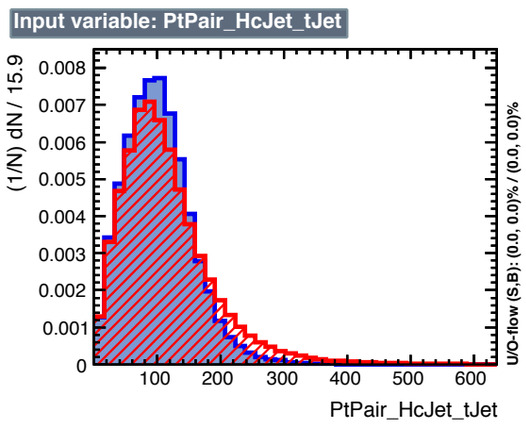






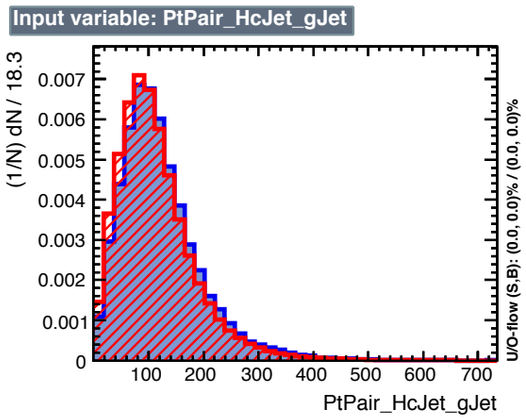


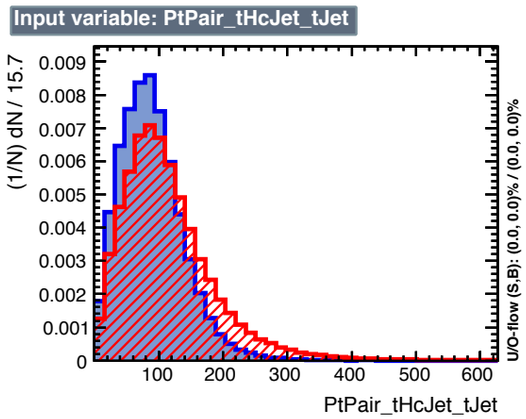


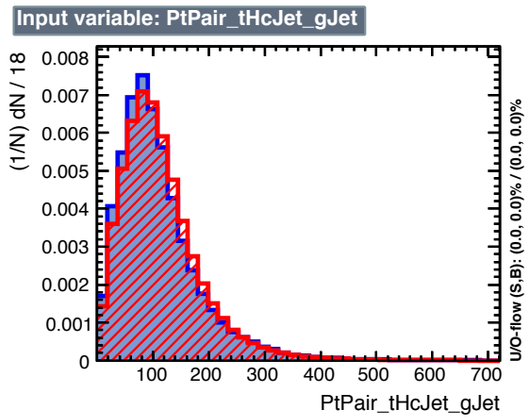


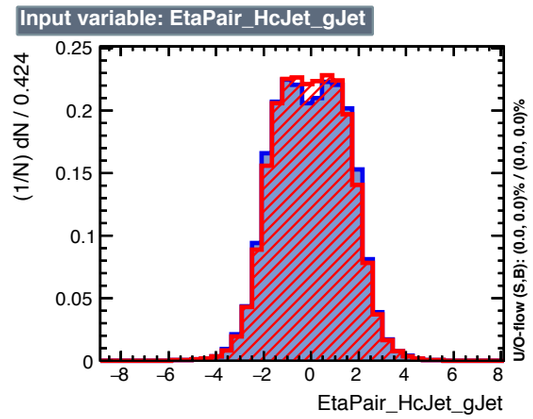
Input variables to reconstruction BDT

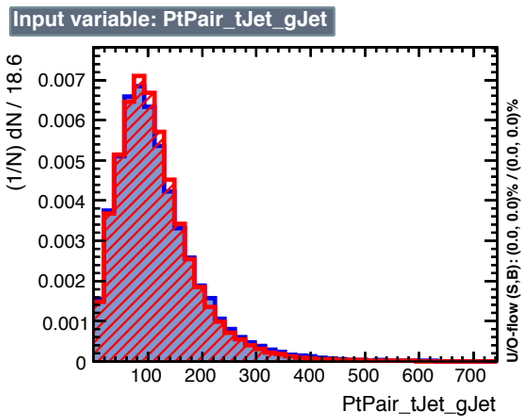
- $m_{H^{\pm}}$ = 300 GeV, tanβ = 2

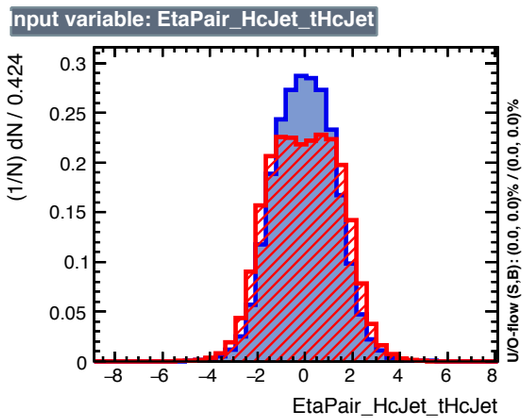


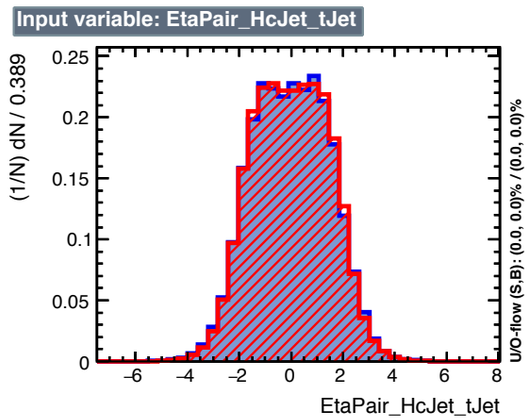


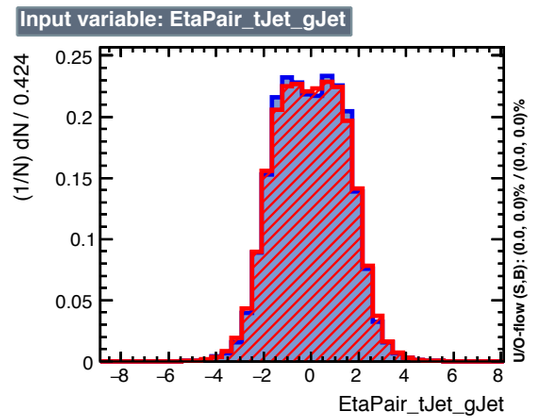


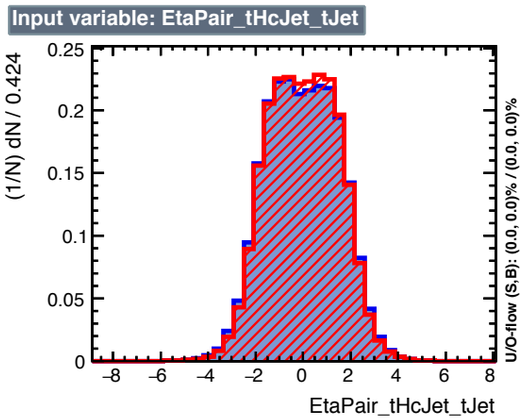


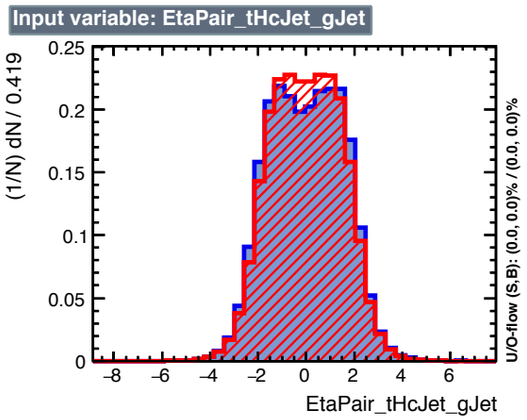


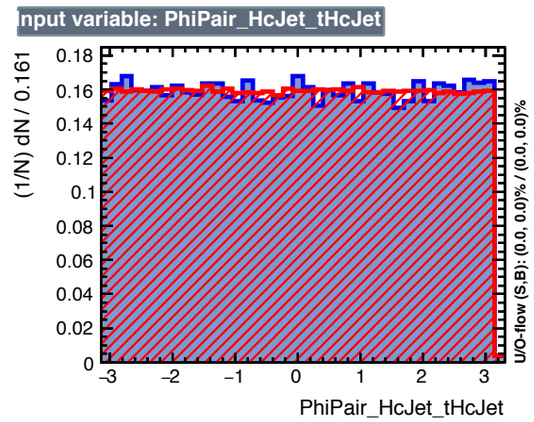


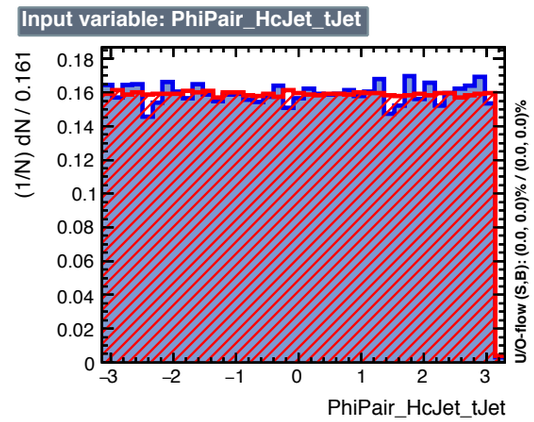






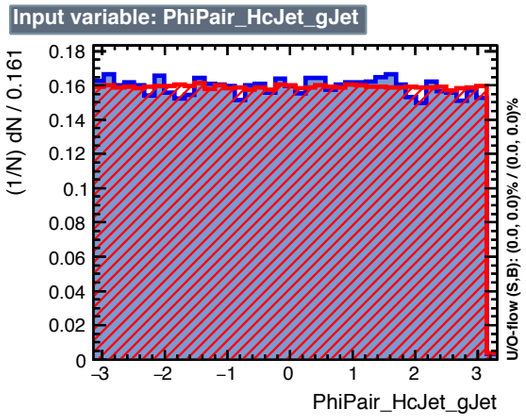


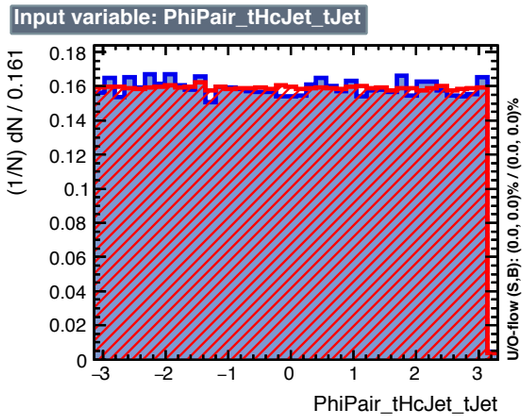


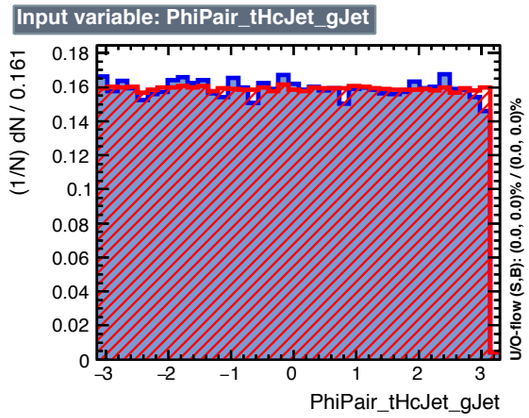


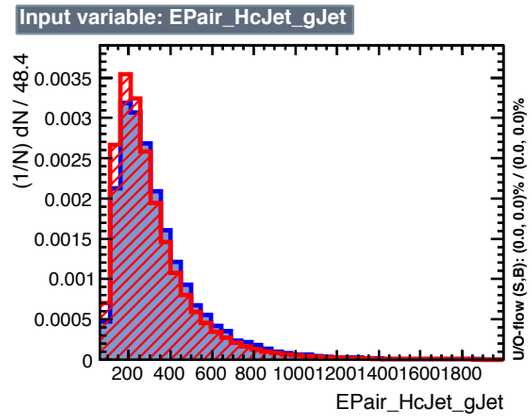
Input variables to reconstruction BDT

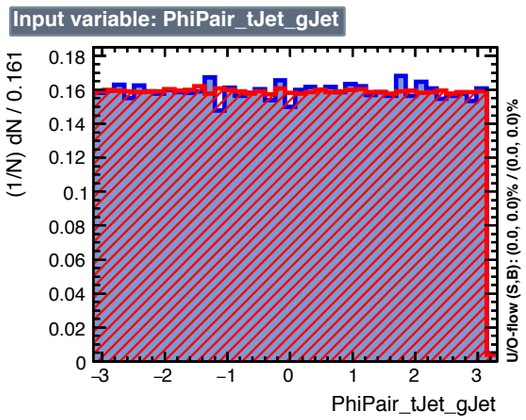
- $m_{H^{\pm}}$ = 300 GeV, tanβ = 2

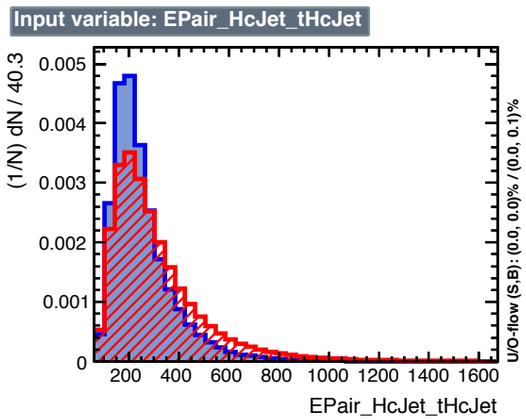


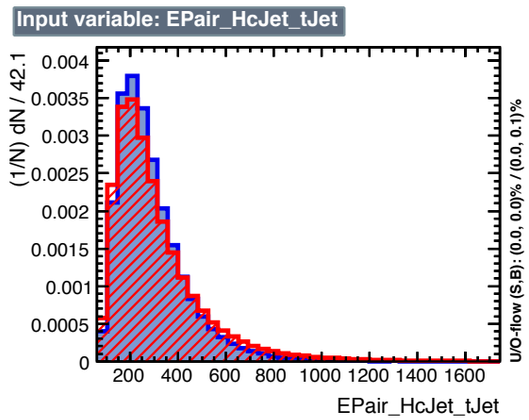


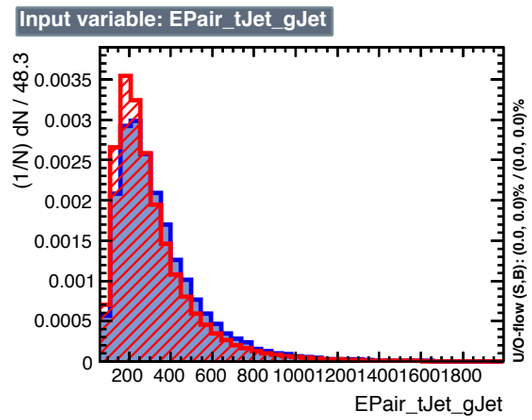


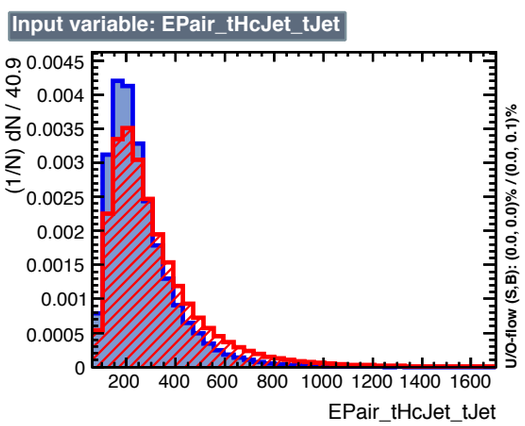


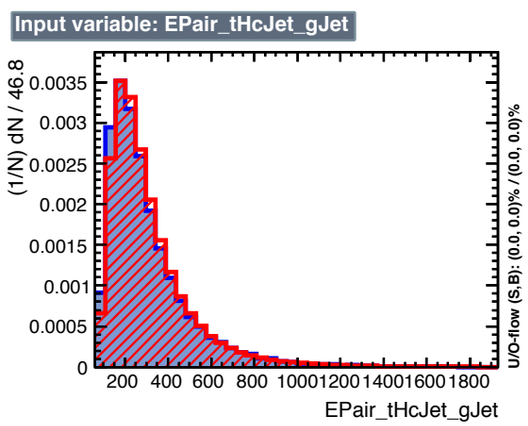


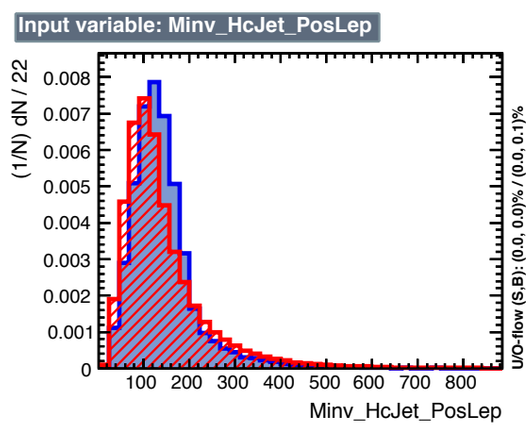


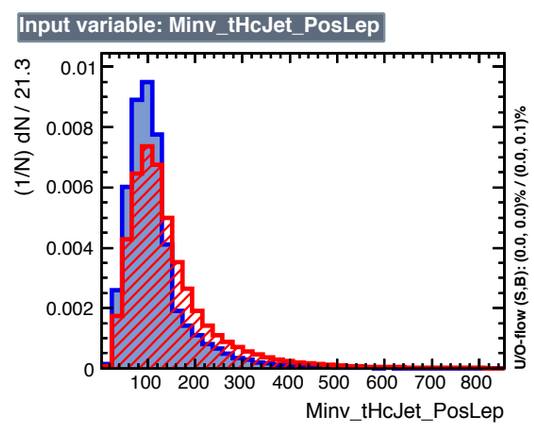






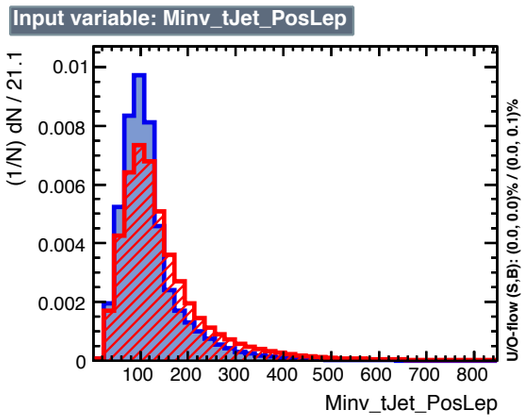


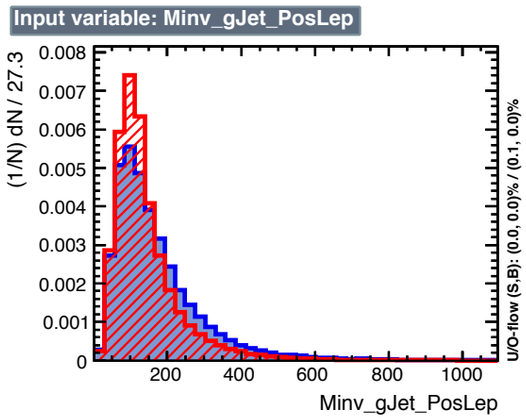


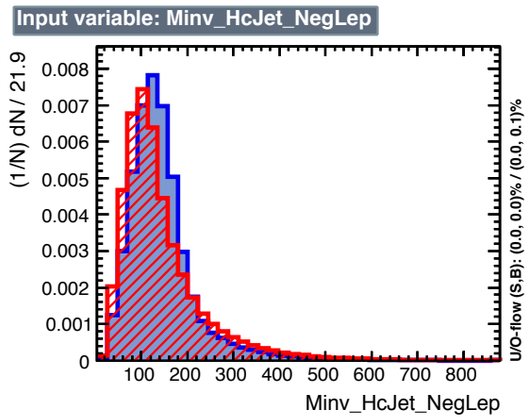


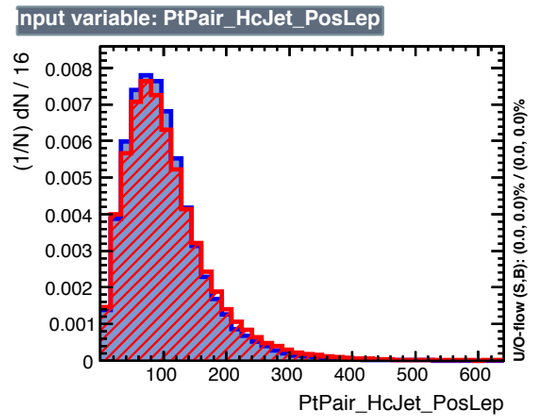
Input variables to reconstruction BDT

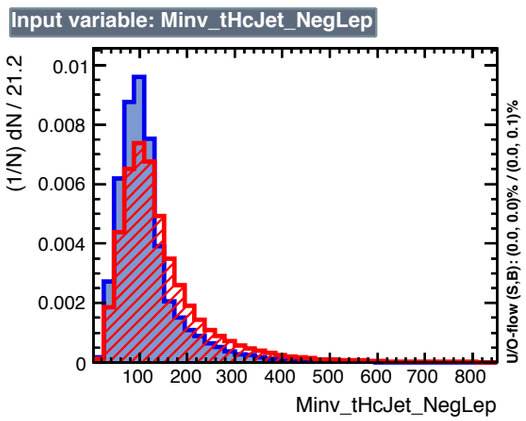
- $m_{H^{\pm}}$ = 300 GeV, tanβ = 2

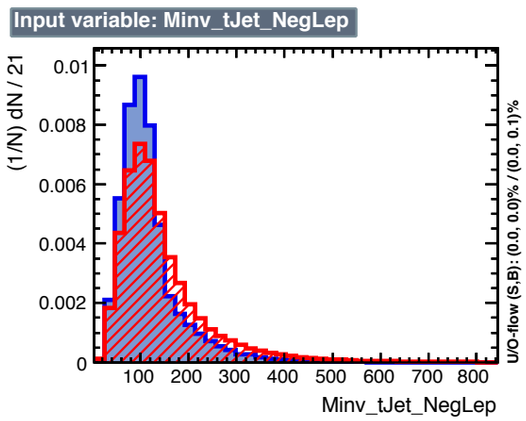


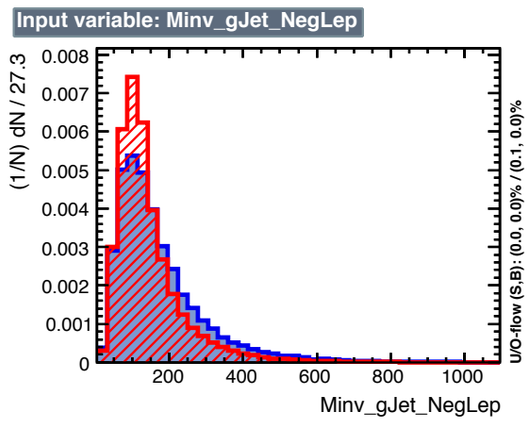


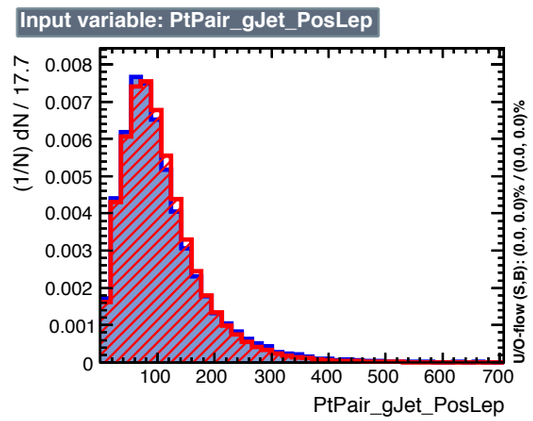


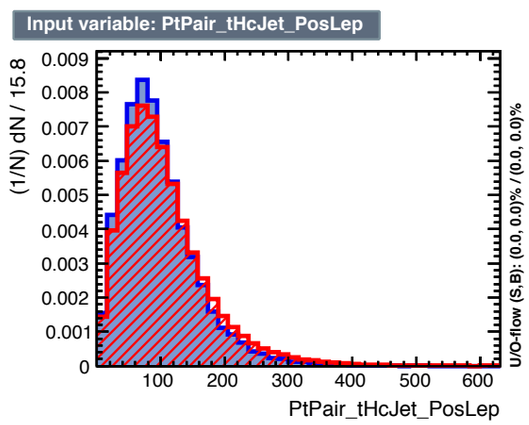


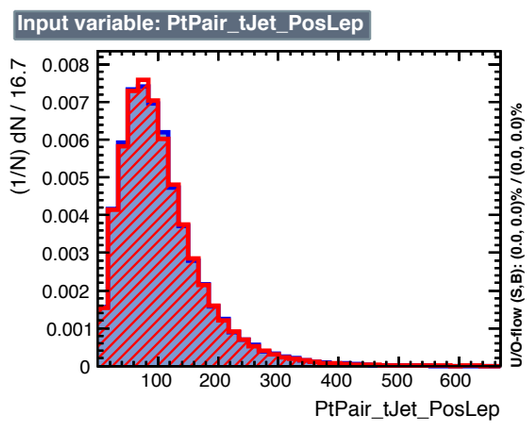


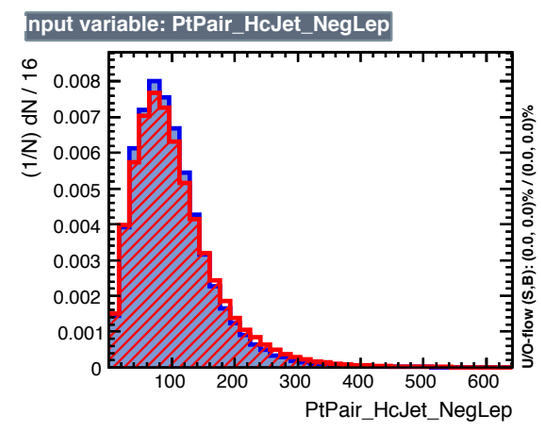


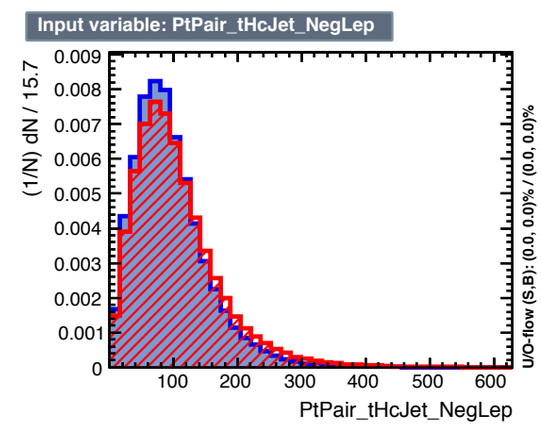






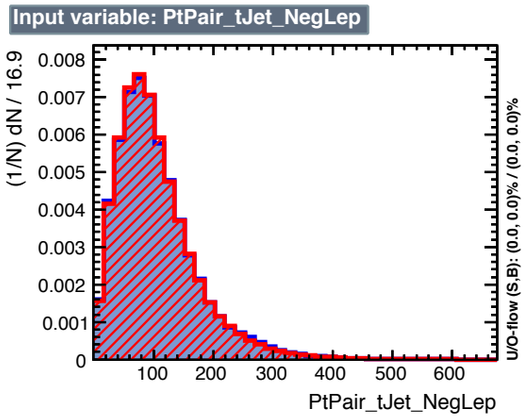


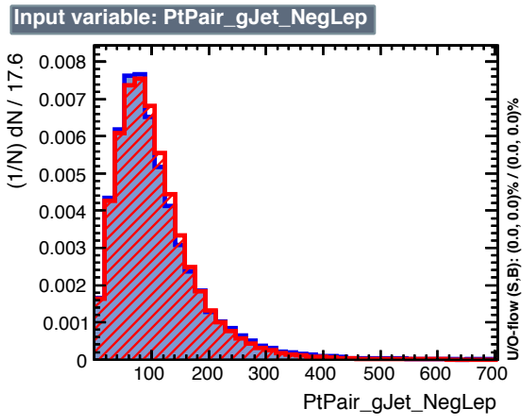


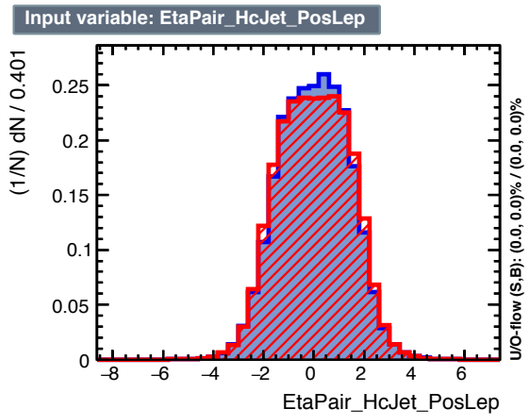


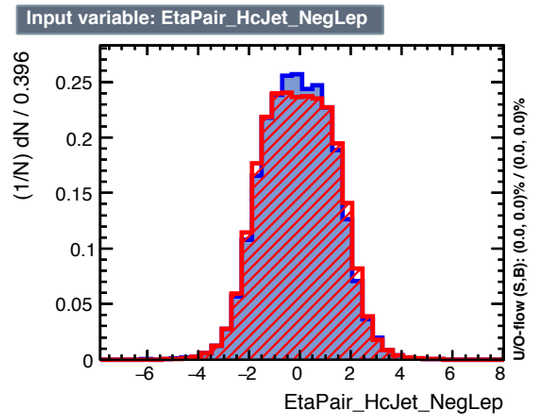
Input variables to reconstruction BDT

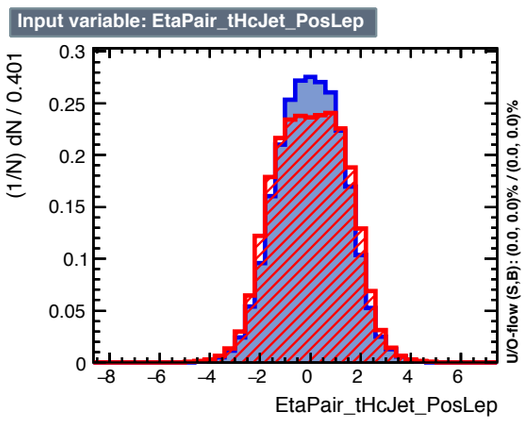
- $m_{H^{\pm}} = 300$ GeV, tanβ = 2

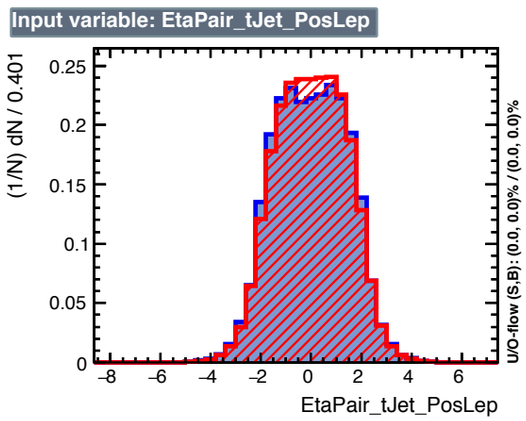


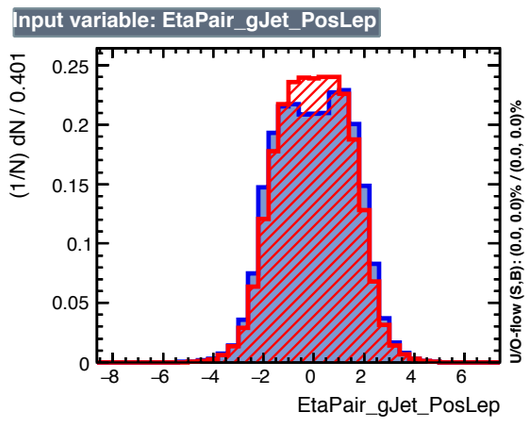


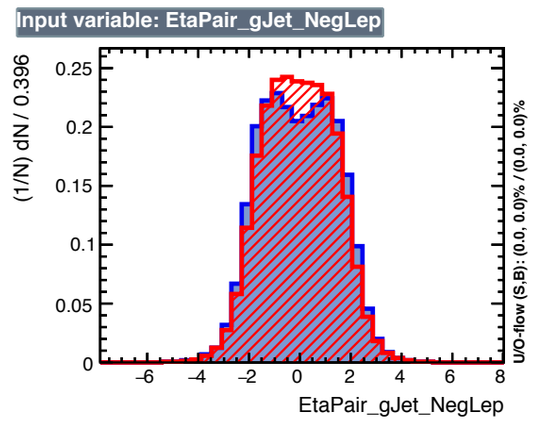


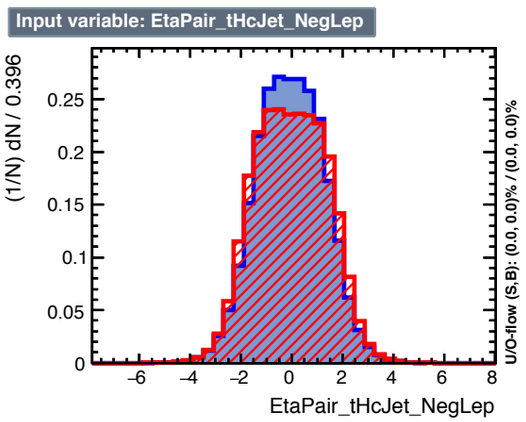


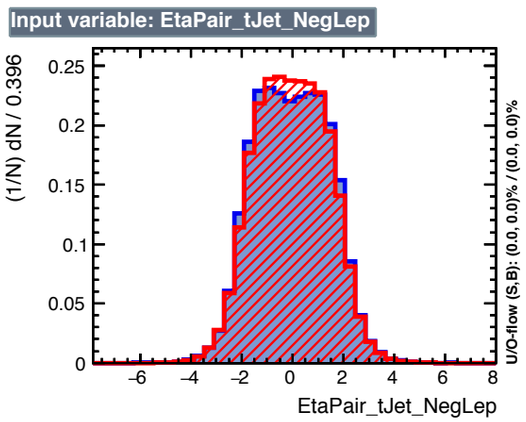


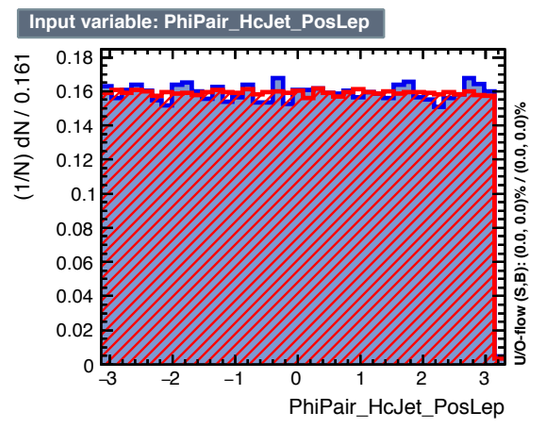


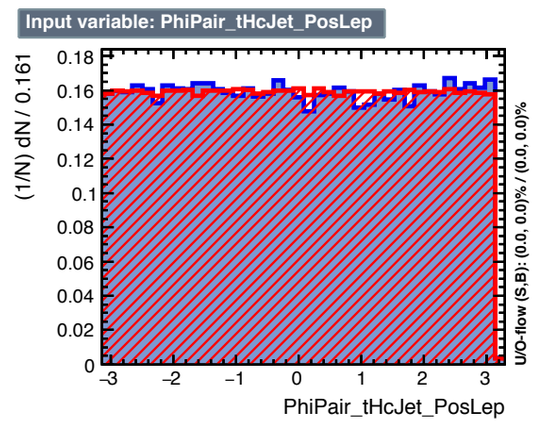






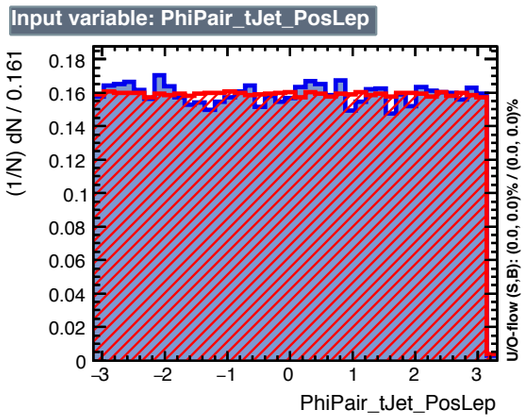


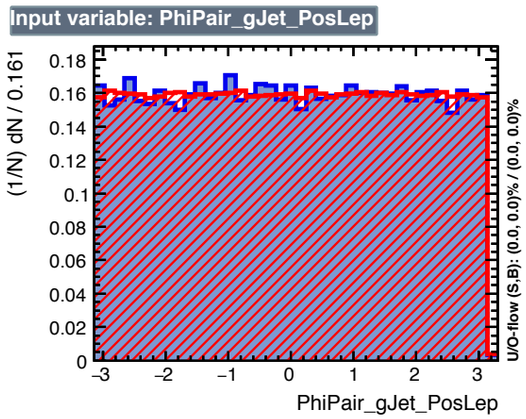


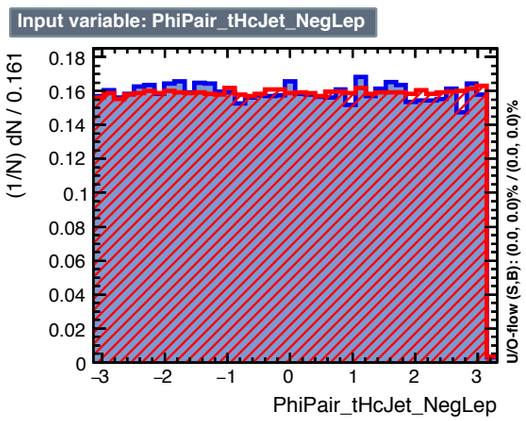


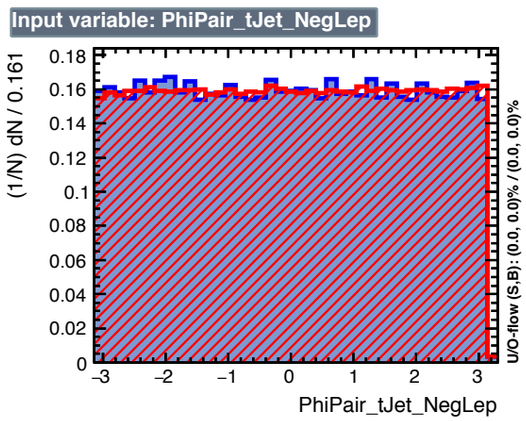
Input variables to reconstruction BDT

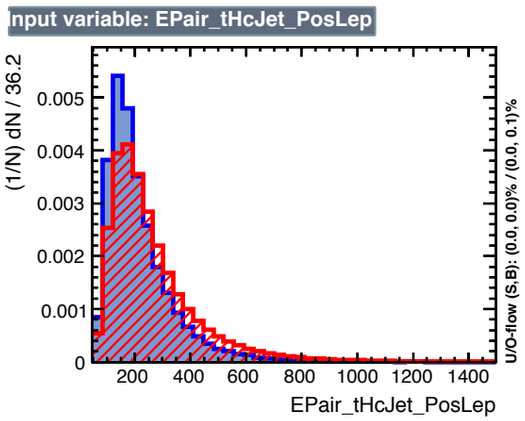
- $m_{H^{\pm}} = 300$ GeV, tanβ = 2

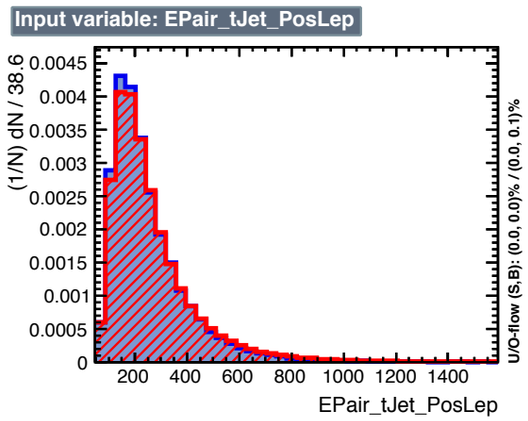


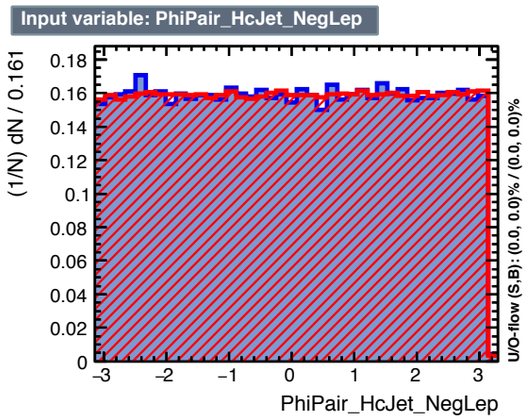


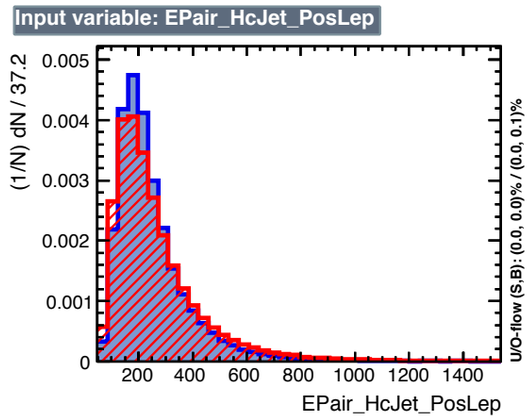


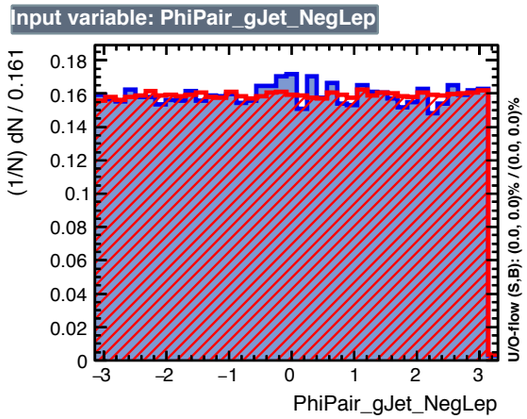


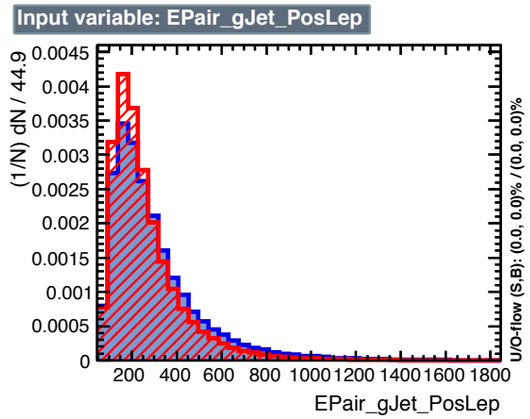


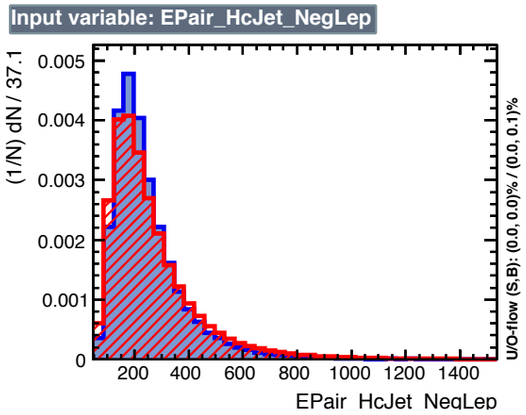


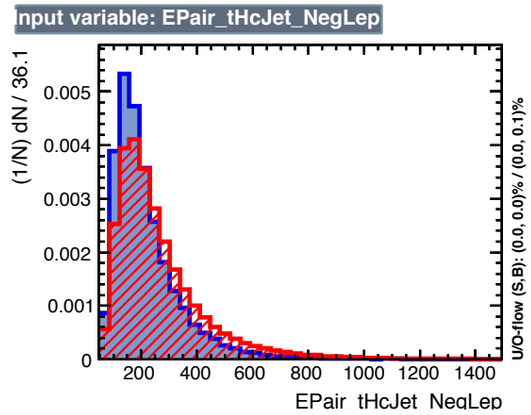


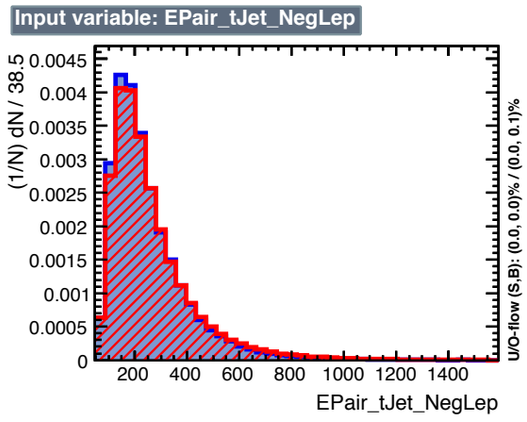


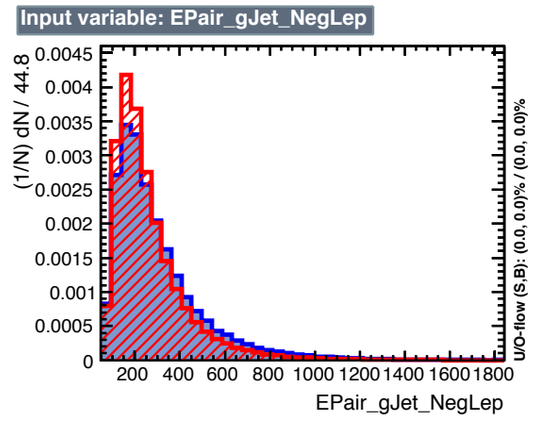






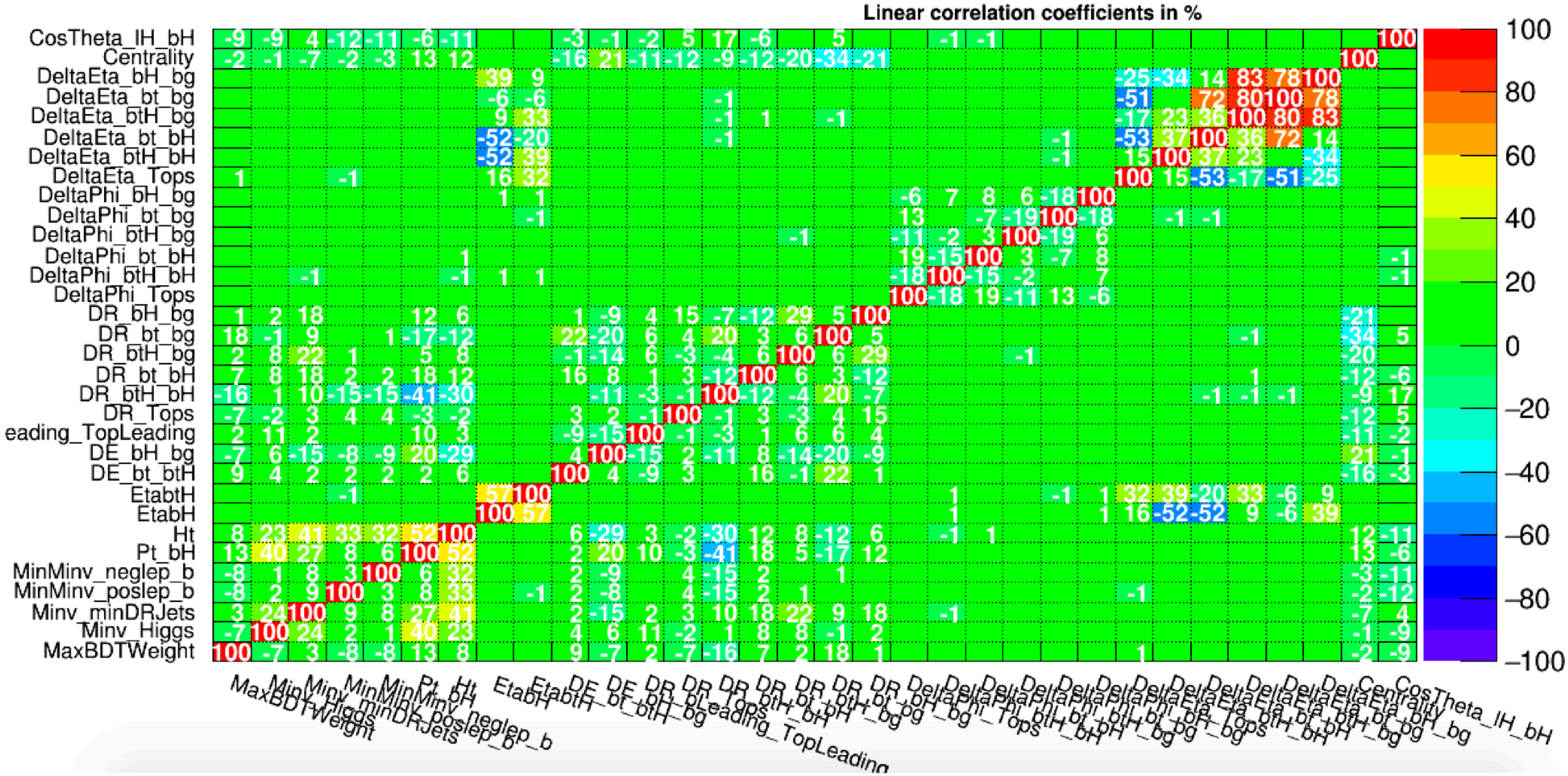






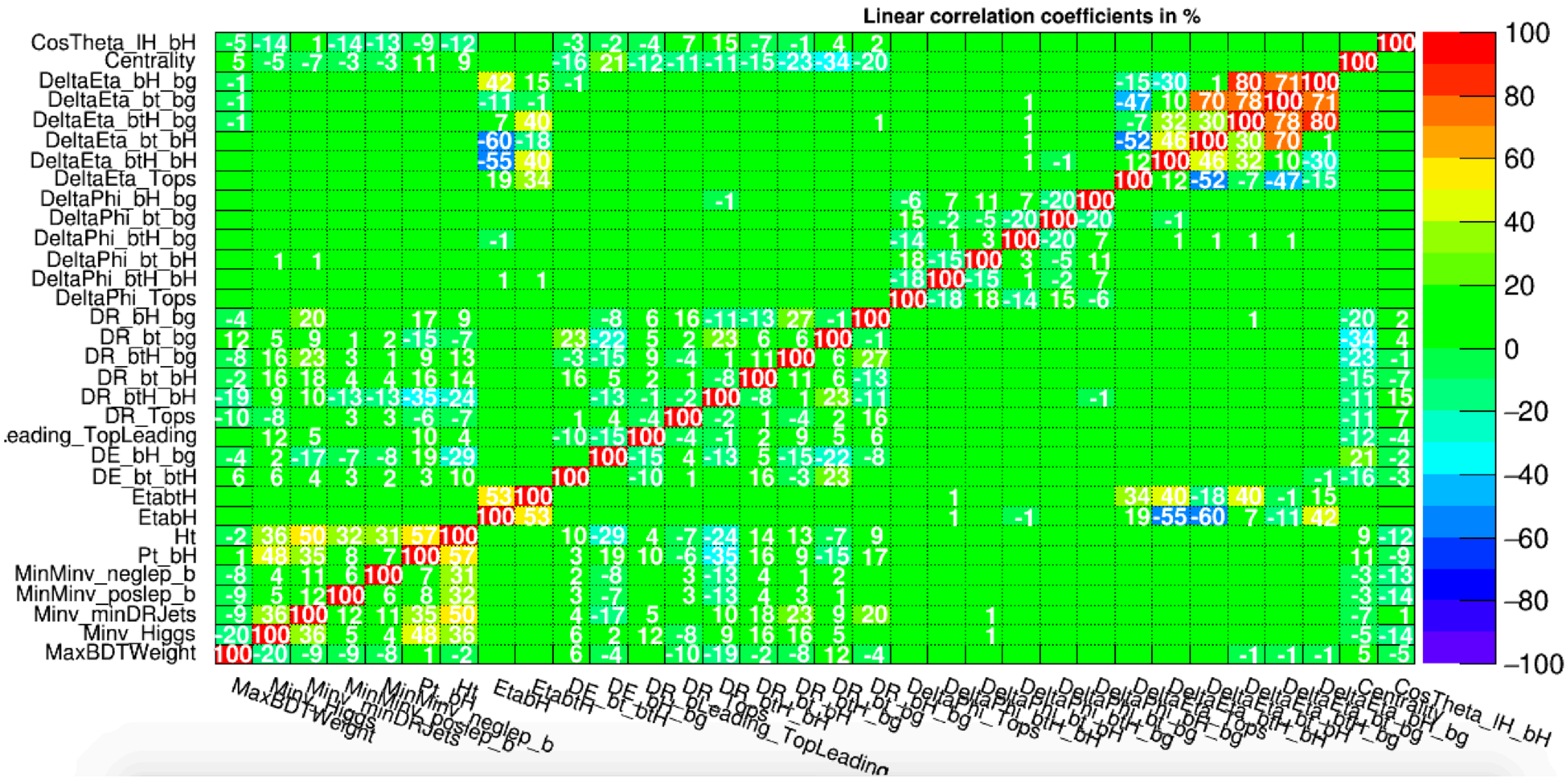
Classification BDT: Signal Correlation Matrix

- $m_{H^{\pm}}$ = 300 GeV, tanβ = 2



Classification BDT: Background Correlation Matrix

- $m_{H^{\pm}}$ = 300 GeV, tanβ = 2

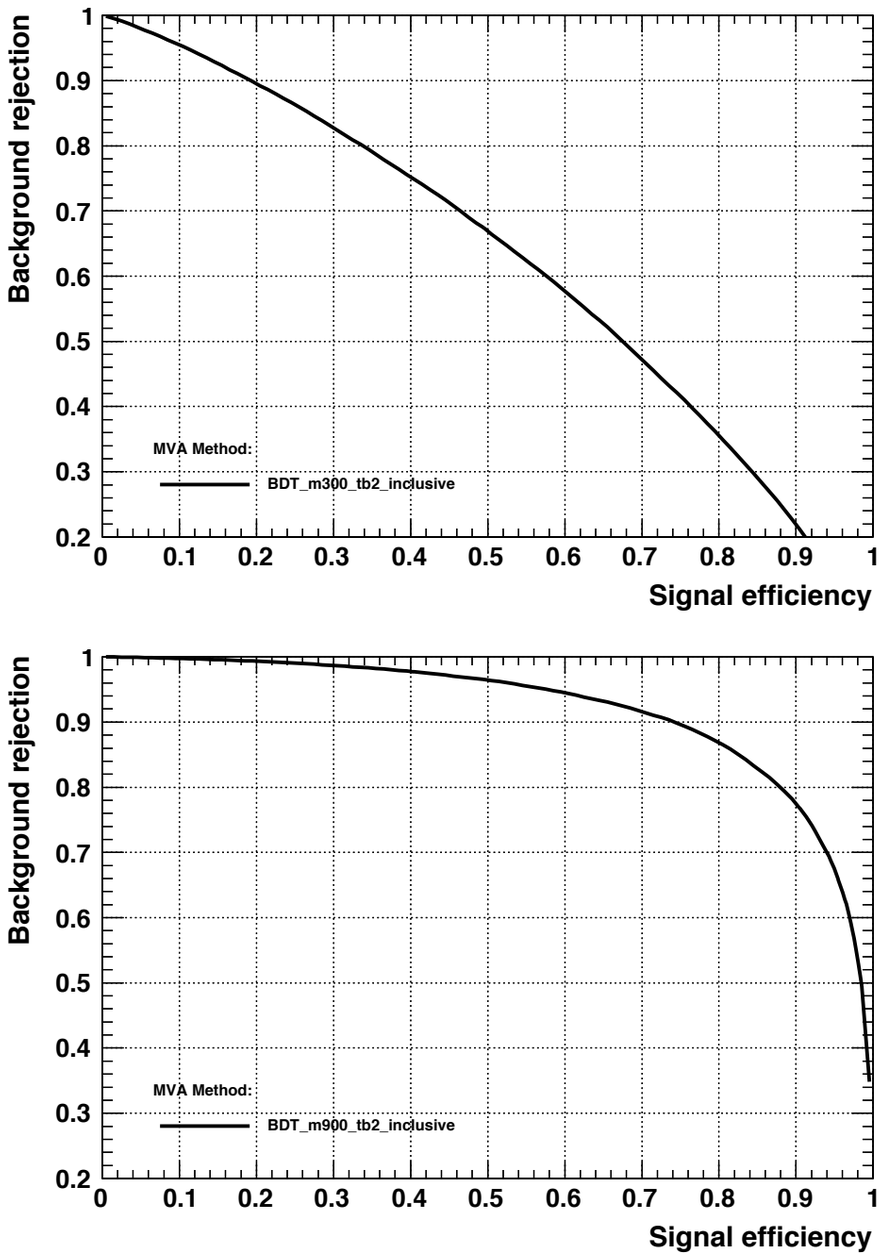


Classification BDT

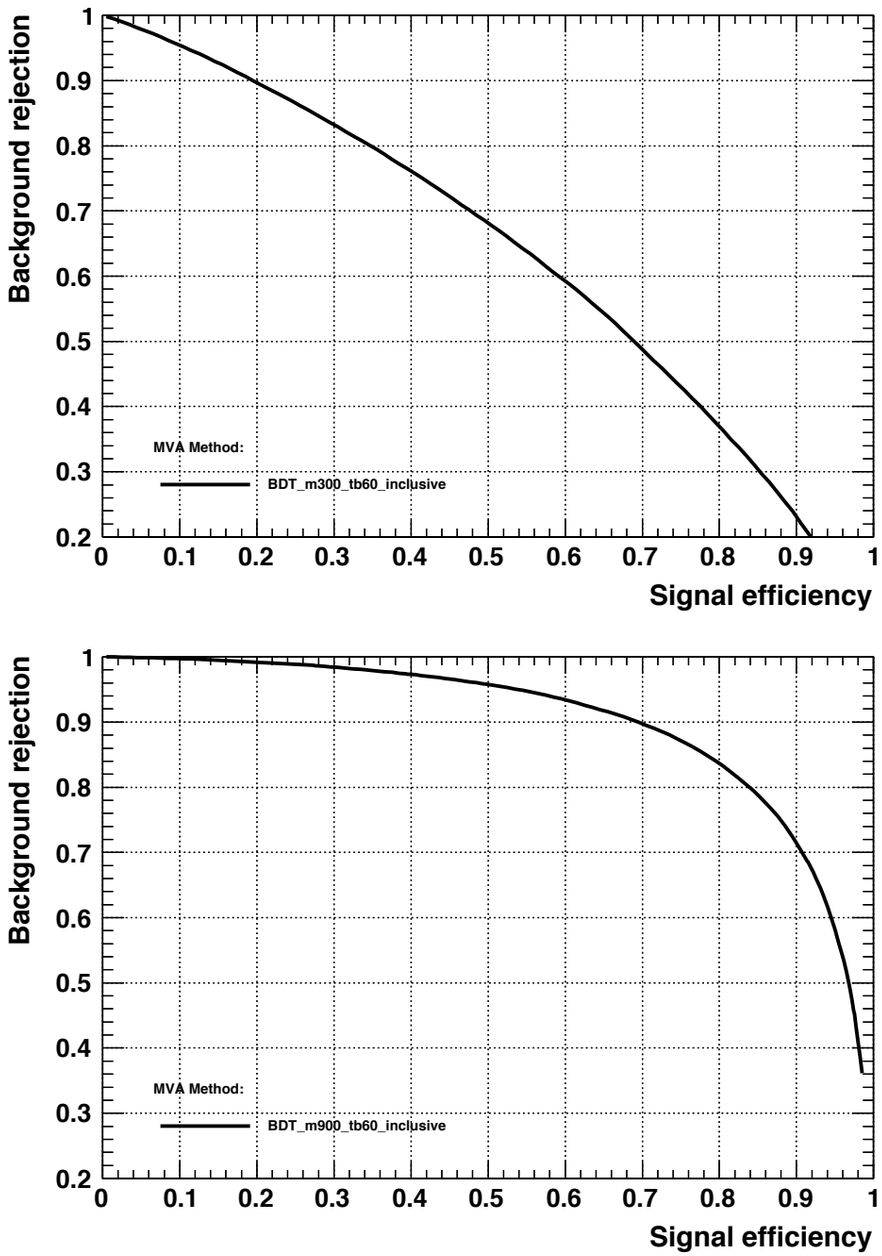
- ROC curves

$m_{H^\pm}$ = 300 GeV

tanβ = 2



tanβ = 60

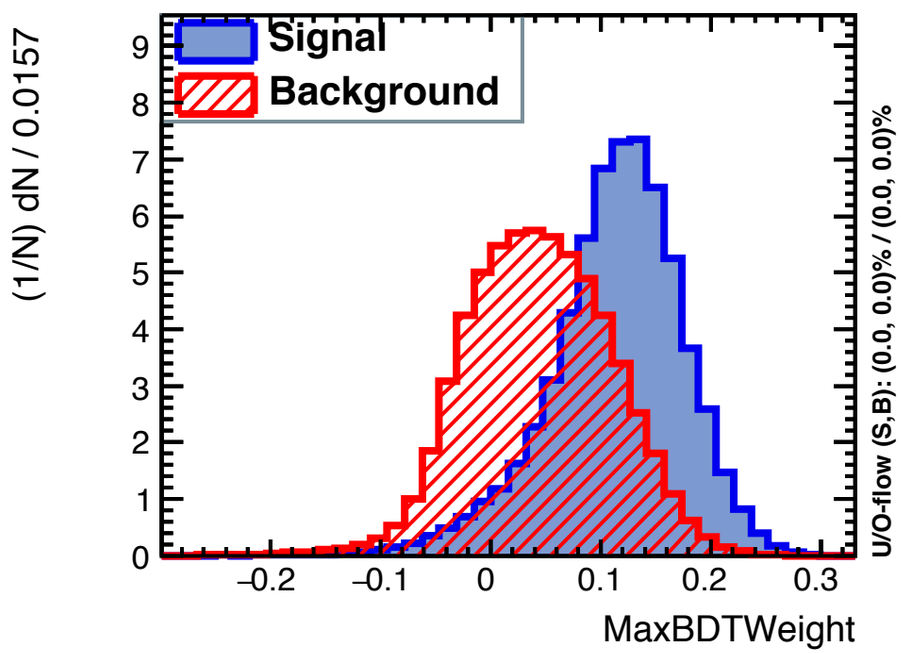


$m_{H^\pm}$ = 900 GeV

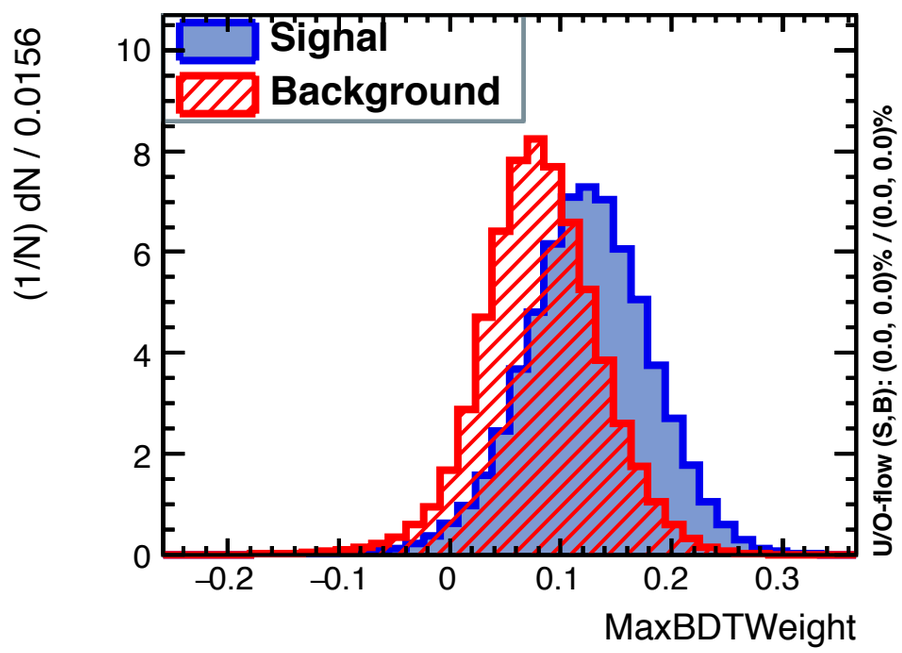
Classification BDT: Difference between tanβ at $m_{H^\pm}$ = 900 GeV

- Why is the separation different for tanβ = 2 and tanβ = 60?

tanβ = 2



tanβ = 60



- Difference seems to arise from the reconstruction BDT weight.
- Need to look further into this.