A Comparative Machine Learning Study of Color Tagger Variables in VH(bb)

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Jets and their substructure from LHC data

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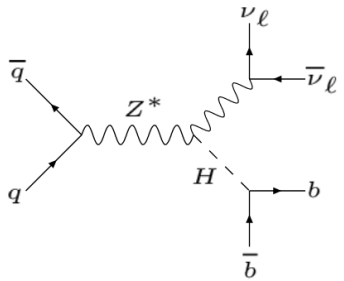
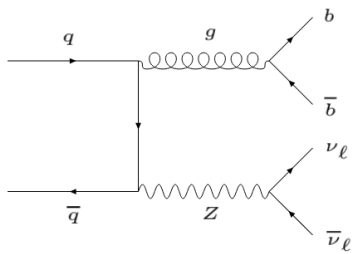
Objective

- Train machine learning algorithms to distinguish decays from color singlets vs. color octects
- Focus on two processes:
  - Signal: $pp \to ZH$, $Z \to \nu_\ell \overline{\nu}_\ell$, $H \to b\overline{b}$ (ZHbb)
  - Background: $pp \to b\overline{b}\nu_\ell \overline{\nu}_\ell$ (gbb)
- Analysis of simulated data and extraction of the **8 variables**
  - Pull vector components and pull angle $t_{\parallel a}$, $t_{\perp a}$, θ_{pa} relative to Jet J_a
  - Pull vector components and pull angle $t_{\parallel b}$, $t_{\perp b}$, θ_{pb} relative to Jet J_b
  - Color Ring (cr)
  - D_2
- Training of BDT and NNs on high-level variables

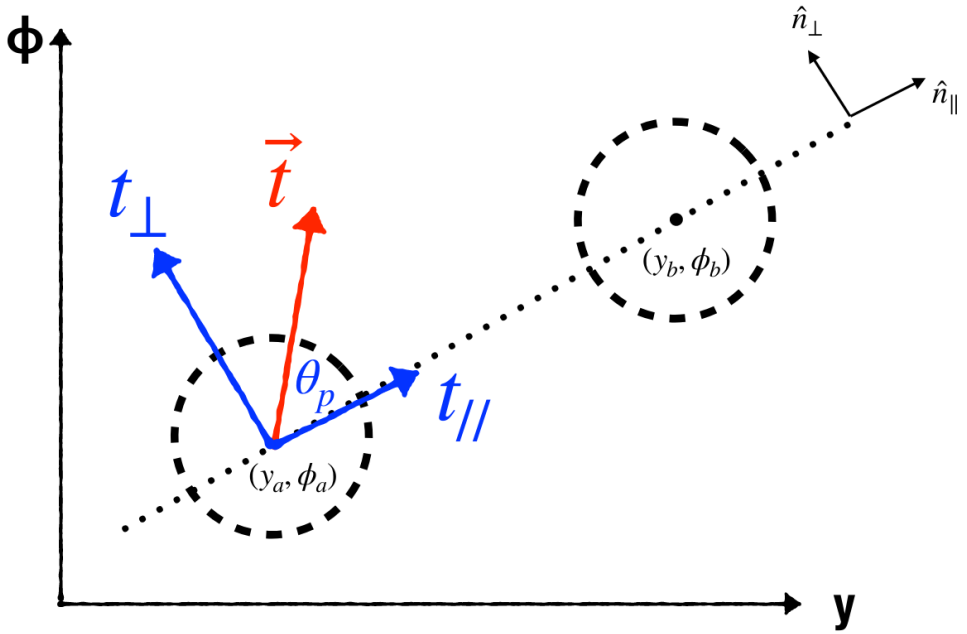


ZHbb



gbb

Jet Pull Components



Pull vector components of Jet J_a
[arXiv:1911.05090v2]

$$\vec{t} = \frac{1}{p_{t_a}} \sum_{i \in J_a} p_{t_i} |\vec{r}_i|^2 \hat{r}_i$$

$$\vec{r}_i = (y_i - y_a, \phi_i - \phi_a)$$

$$\hat{n}_\parallel = \frac{1}{\sqrt{\Delta y^2 + \Delta\phi^2}} (\Delta y, \Delta\phi)$$

$$\hat{n}_\perp = \frac{1}{\sqrt{\Delta y^2 + \Delta\phi^2}} (-\Delta\phi, \Delta y)$$

$$t_\parallel = \vec{t} \cdot \hat{n}_\parallel$$

$$t_\perp = \vec{t} \cdot \hat{n}_\perp$$

$$\theta_p = \arccos\left(\frac{t_\parallel}{|\vec{t}|}\right)$$

$t_\parallel, t_\perp$ **are IRC safe observables!**
θ_p **is Sudakov safe**

D_2

- D_2 is defined as

$$D_2^{(\beta)} = \frac{e_3^{(\beta)}}{(e_2^{(\beta)})^3}$$

- $e_n^{(\beta)}$ is the normalized n-point Energy Correlator function
- For this case,

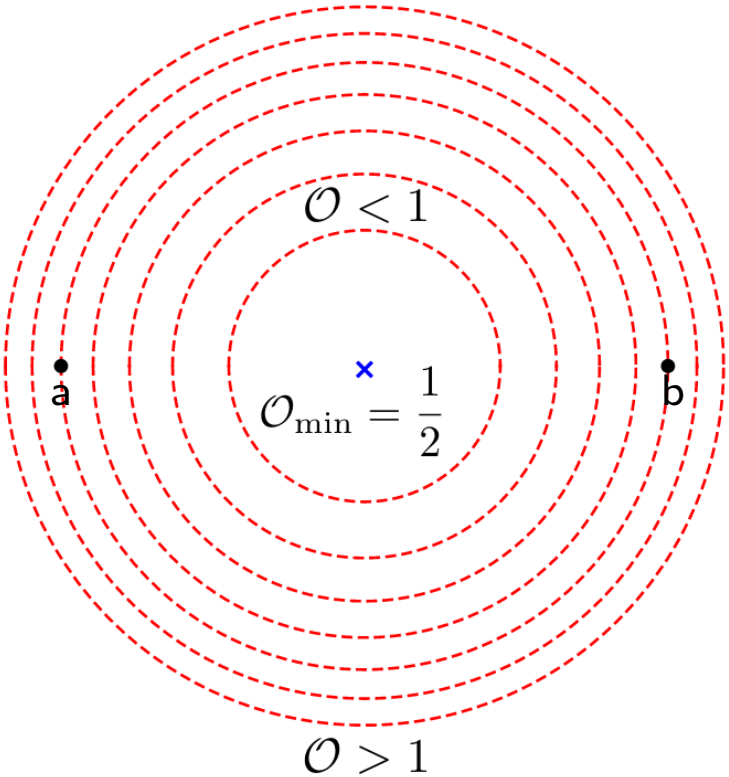
$$e_2^{(\beta)} = \frac{1}{p_{TJ}^2} \sum_{1 \leq i < j \leq n_J} p_{T_i} p_{T_j} R_{ij}^{\beta}$$

$$e_3^{(\beta)} = \frac{1}{p_{TJ}^3} \sum_{1 \leq i < j < k \leq n_J} p_{T_i} p_{T_j} p_{T_k} R_{ij}^{\beta} R_{ik}^{\beta} R_{jk}^{\beta}$$

- p_{TJ} transverse momentum of jet w.r.t. beam
- $R_{ij}^2 = (y_i - y_j)^2 + (\phi_i - \phi_j)^2$
- $\beta = 2$

[arXiv:1409.6298v1]

Color Ring



[arXiv:2006.10480v2]

$$\mathcal{O} = \frac{|\mathcal{M}_{\mathcal{B}}|^2}{|\mathcal{M}_{\mathcal{S}}|^2} \approx \frac{\theta_{ak}^2 + \theta_{bk}^2}{\theta_{ab}^2}$$

- θ_{ak} (θ_{bk}) angle between hard parton a (b) and gluon (k)
  $\Rightarrow$ Requires 3 objects!
- θ_{ab} angle between hard partons
- **IRC safe observable!**

Generation Chain

- 1 M Signal/Bkg events in MG5_aMC v2.8.3.2
- Shower in Pythia v8.235
- Run in Delphes v3.4.2 w/ modified ATLAS card
  - Extract Monte Carlo Truth
  - Extract Fast Detector Reconstruction

Truth

	Events Passed
Signal	$\sim$ 200k
Background	$\sim$ 60k

Reco

	Events Passed
Signal	$\sim$ 140k
Background	$\sim$ 60k

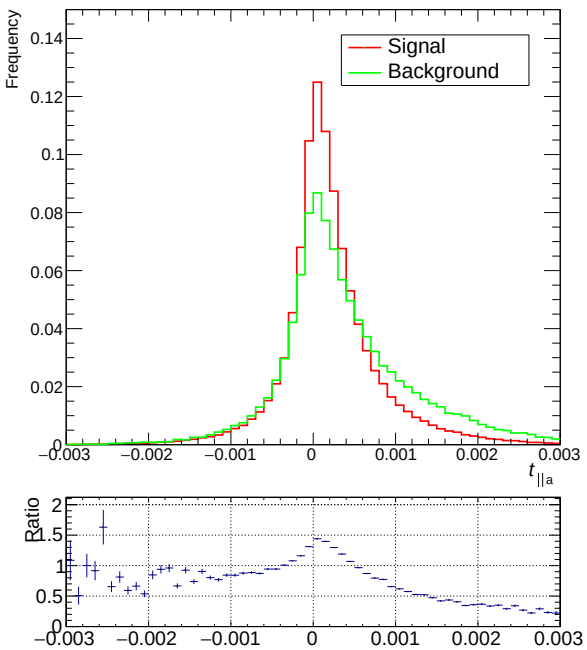
Analysis

- **Truth:** Remove ν's and cluster stable particles w/ $p_T > 0.5$ GeV into jets
- **Reco:** Cluster into jets
  - EM Calo Towers
    - $E_{min} = 0.5$ GeV
    - $S_{min} = 2.0$ (Significance)
  - Hadron Calo Towers
    - $E_{min} = 1.0$ GeV
    - $S_{min} = 2.0$ (Significance)
  - Tracks w/ $p_T > 0.5$ GeV
- Identify Large Jets and choose the hardest
  - R = 1.0
  - $p_T > 250$ GeV
  - $|y| < 1.5$
- Identify subjets
  - R = 0.2
  - $p_T > 10$ GeV
  - ΔR = 0.8 from Large Jet
- Angular b-labeling and selection of events w/ exactly 2 b-subjets
  - b-parton $p_T > 5$ GeV
  - ΔR = 0.2
  - $|\eta| < 2.5$
- Choose hardest non-b subjet for color ring
  - If not present, cr = -1

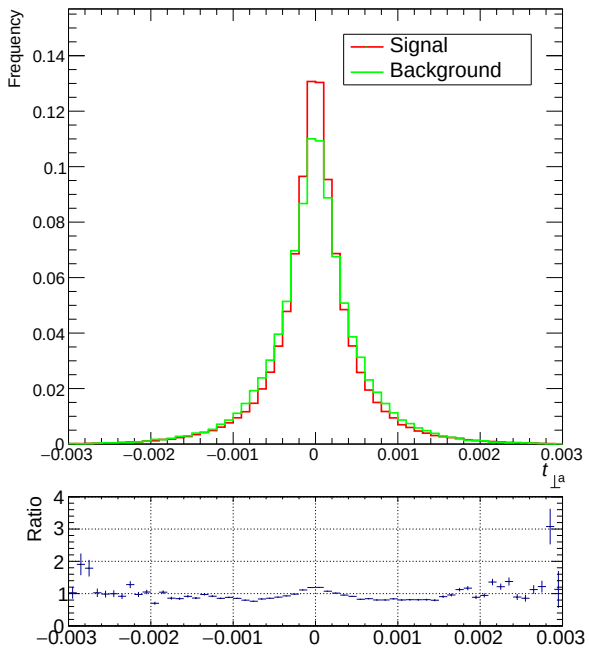
	Events Passed w/ $cr = -1$
ZHbb Truth	58%
ZHbb Reco	53%
gbb Truth	58%
gbb Reco	66%

Distributions - Signal vs. Bkg (Truth)

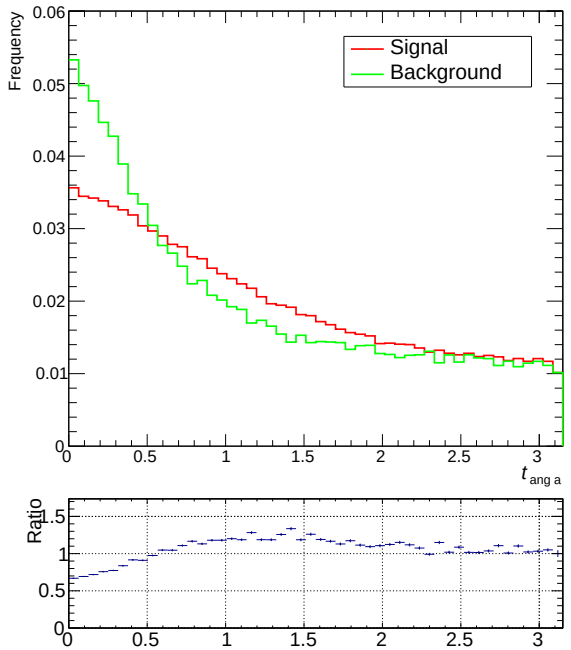
$t_{\parallel a}$



$t_{\perp a}$

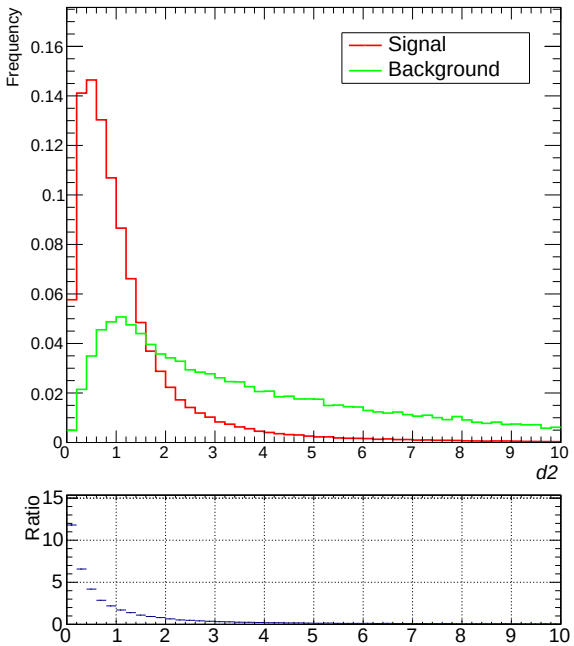


θ_{pa}

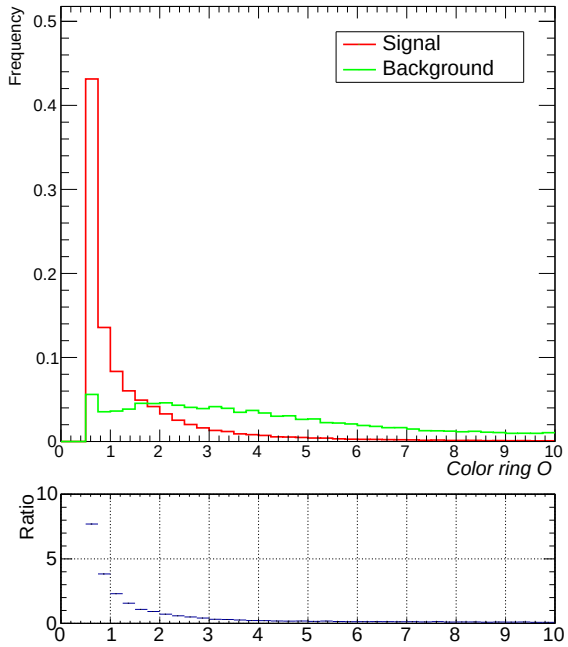


Distributions - Signal vs. Bkg (Truth)

D_2



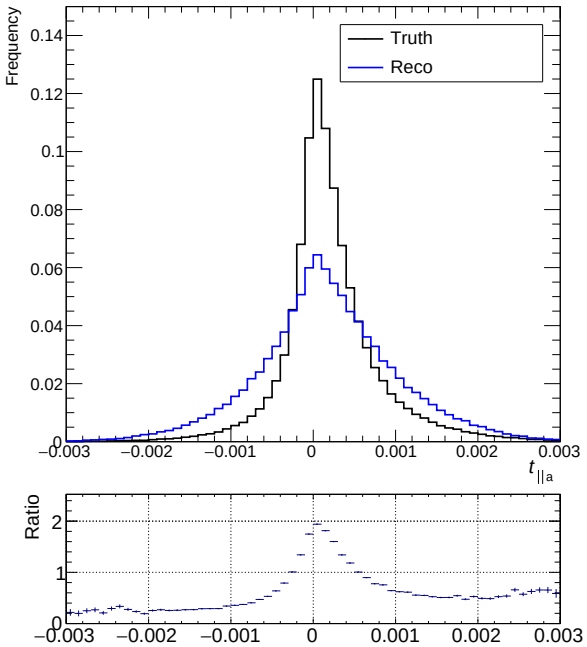
cr



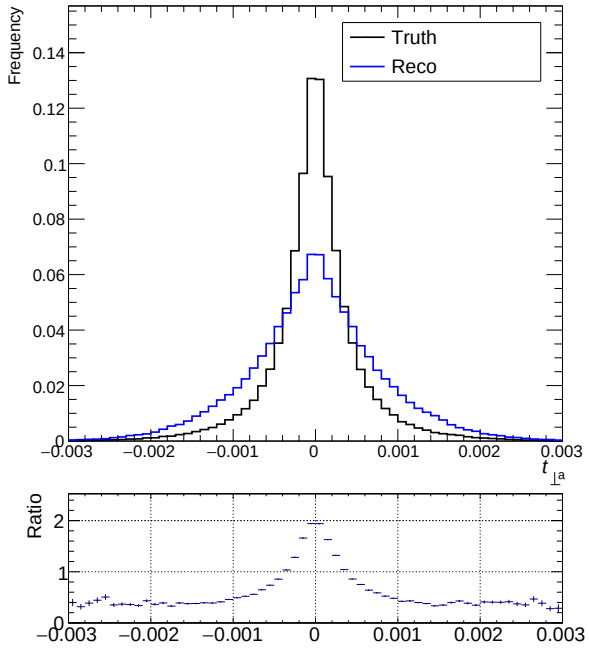
MC truth shows strong discrimination potential for the high-level variables considered

Distributions - Truth vs. Reco (ZHbb)

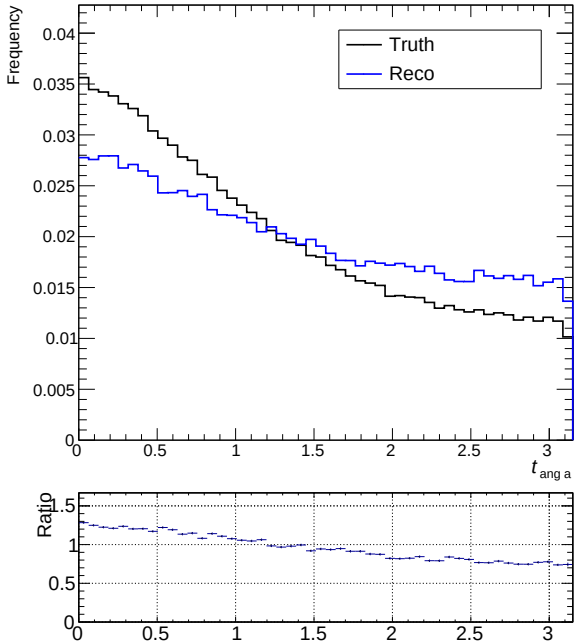
$t_{\parallel a}$



$t_{\perp a}$

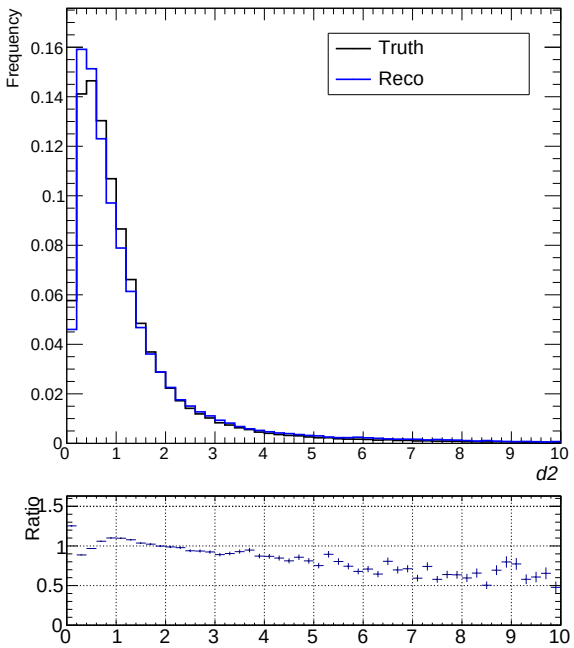


θ_{pa}

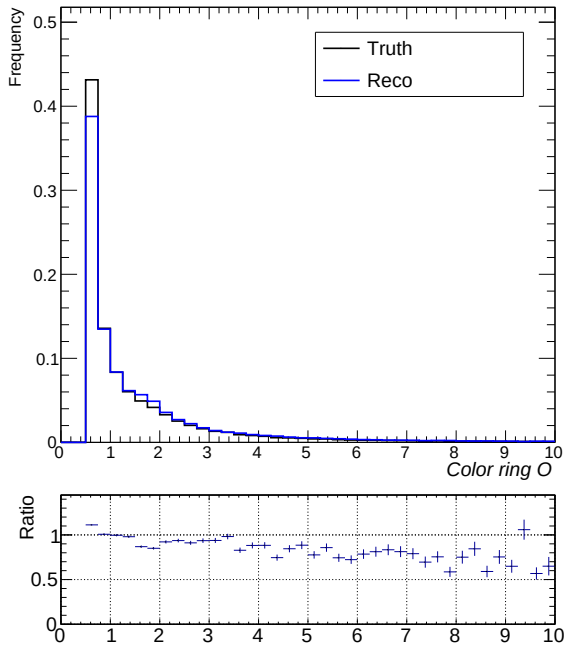


Distributions - Truth vs. Reco (ZHbb)

D_2



cr



Truth and Reco events show similar features

Machine Learning Parameters

BDT - TMVA

Parameters	Value
No. of Trees	50
Max Depth	5
MinNodeSize	2.5%
Boost Type	AdaBoost
Train/Test	60/40
No. of Cuts	80
Downsampling	No

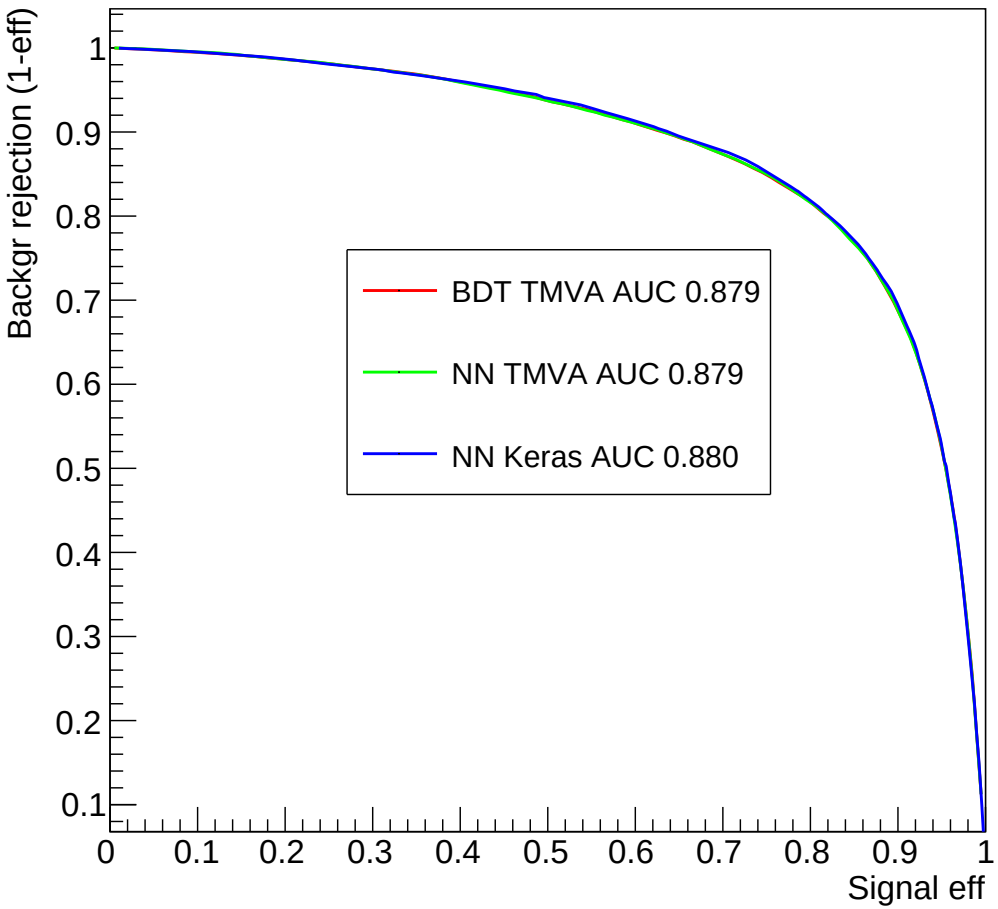
NN - TMVA

Parameters	Value
Activation	ReLU
Epochs	600
Hidden Layers	1
Neurons	9
Train/Test	60/40
Downsampling	No
Batch size	Entire Sample
Learning Rate	0.02

NN - Keras

Parameters	Value
Activation	tanh
Epochs	300
Hidden Layers	3
Neurons	9, 10, 5
Train/Test	70/30
Downsampling	Yes
Batch size	1000
Learning Rate	0.001

Results Truth

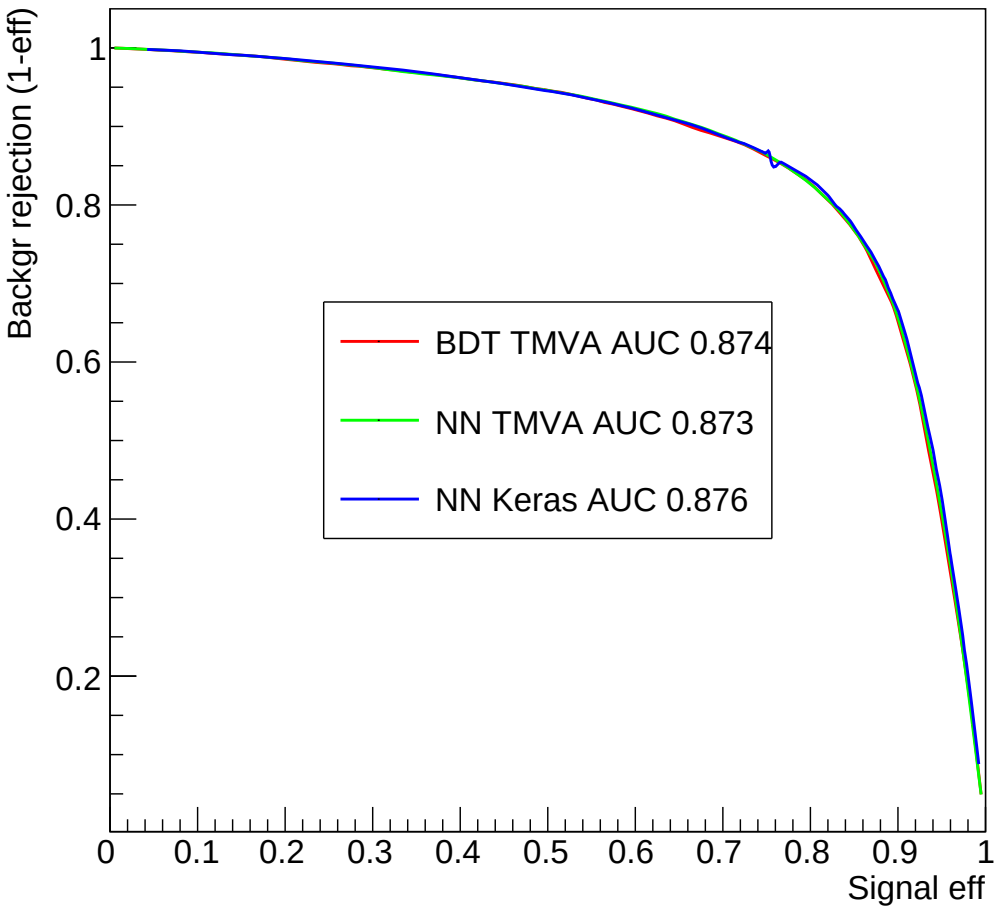


ROC curves for BDT, NN (TMVA) and NN (Keras)

Variabile Ranking - BDT

Rank	Var.	Importance
1	D_2	4.51×10^{-1}
2	cr	1.82×10^{-1}
3	$t_{\parallel a}$	6.72×10^{-2}
4	θ_{pa}	6.59×10^{-2}
5	$t_{\perp a}$	6.56×10^{-2}
6	θ_{pb}	5.90×10^{-2}
7	$t_{\parallel b}$	5.84×10^{-2}
8	$t_{\perp b}$	5.01×10^{-2}

Results Reco



ROC curves for BDT, NN (TMVA) and NN (Keras)

Variabile Ranking - BDT

Rank	Var.	Importance
1	D_2	3.29×10^{-1}
2	cr	2.29×10^{-1}
3	θ_{pb}	8.56×10^{-2}
4	$t_{\parallel b}$	8.18×10^{-2}
5	$t_{\perp b}$	7.45×10^{-2}
6	$t_{\perp a}$	6.87×10^{-2}
7	θ_{pa}	6.71×10^{-2}
8	$t_{\parallel a}$	6.38×10^{-2}

Conclusions

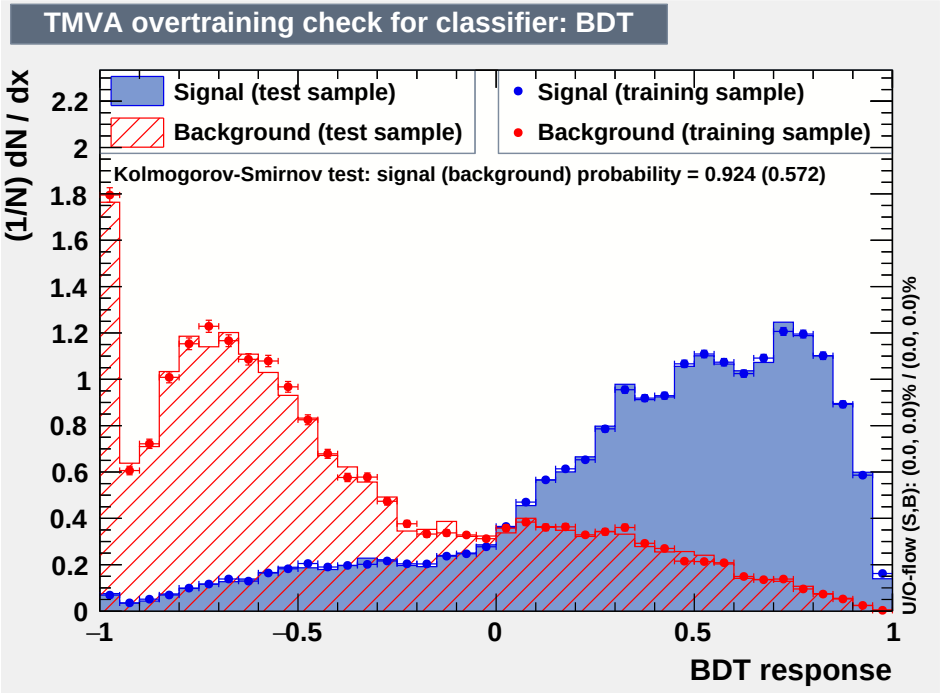
- The color-sensitive variables considered are capable of distinguishing decays from color singlets from color octects
- All ML algorithms provide excellent signal/background discirmination
- Results are comparable for Truth and Reco
- Next steps:
  - Adversarial debiasing from invariant mass dependence
  - Try using parton showers with more exact color evolution
  - Study of other possible color-sensitive variables
  - Study the interplay between these variables and others based on jet constituents (Lund-plane approach by S. Marzani and C. Kaur)

	AUC - Test Sample	
	Truth	Reco
BDT	0.879	0.874
NN - TMVA	0.879	0.873
NN - Keras	0.880	0.876

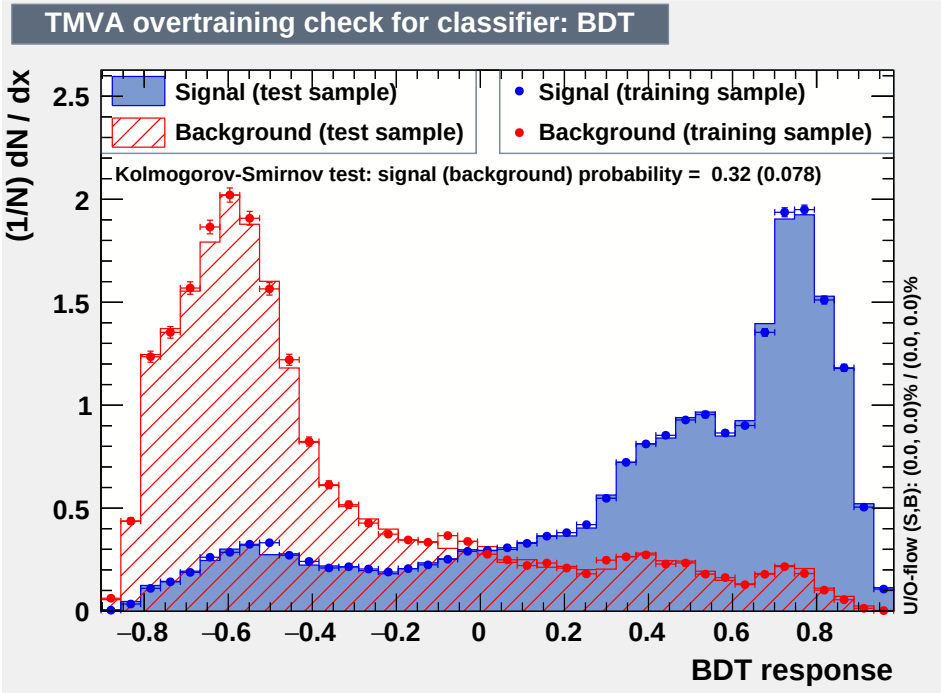
Backup

BDT - Overtraining Check

Truth

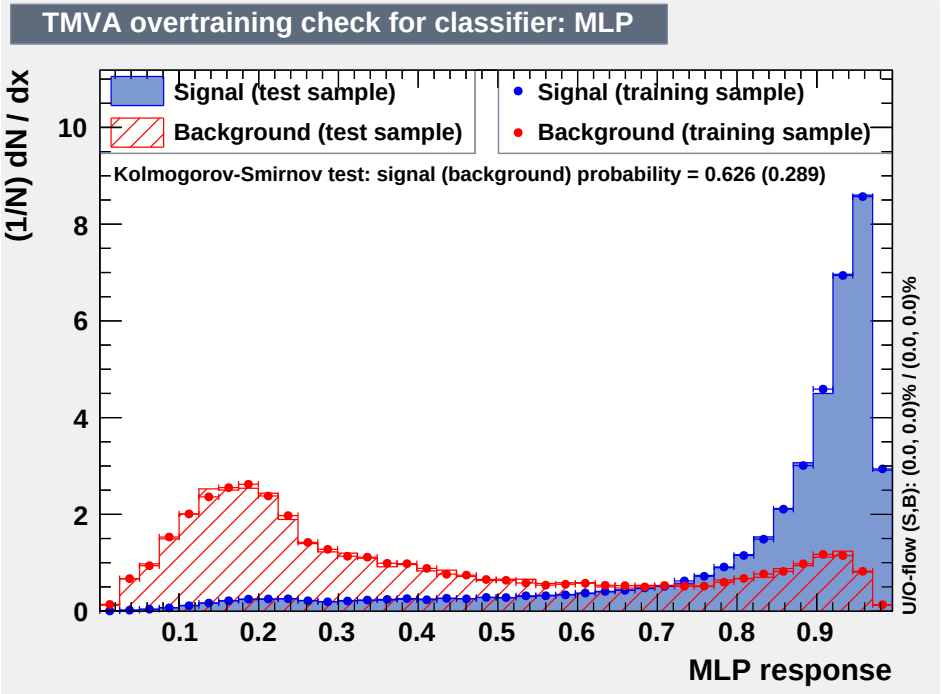


Reco

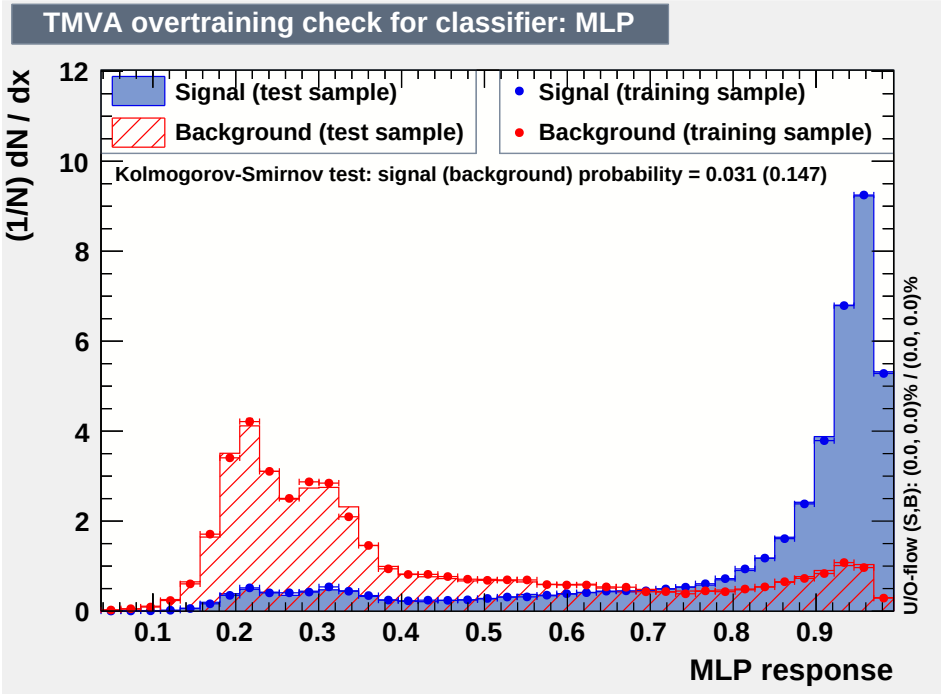


NN TMVA - Overtraining Check

Truth

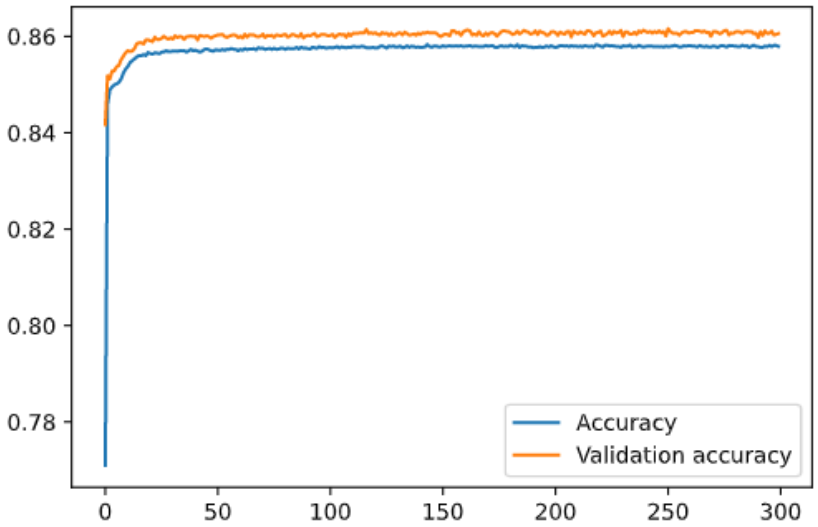


Reco

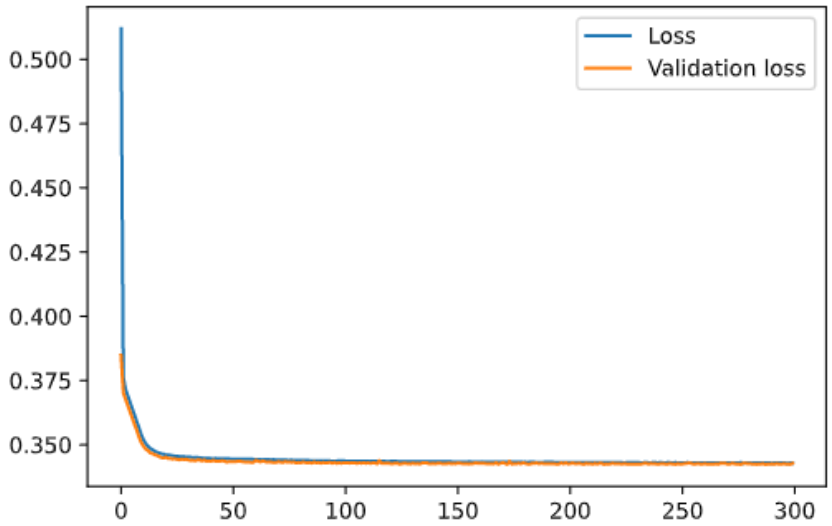


Accuracy & Loss - Keras NN (Truth)

Accuracy

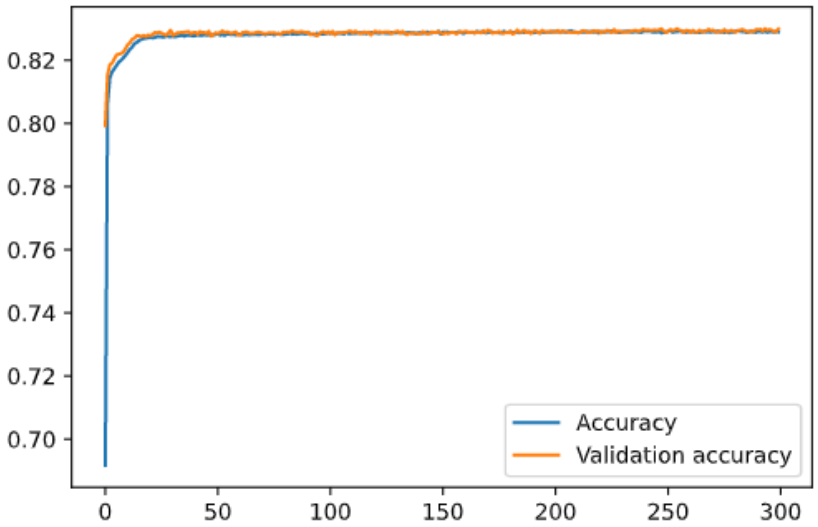


Loss

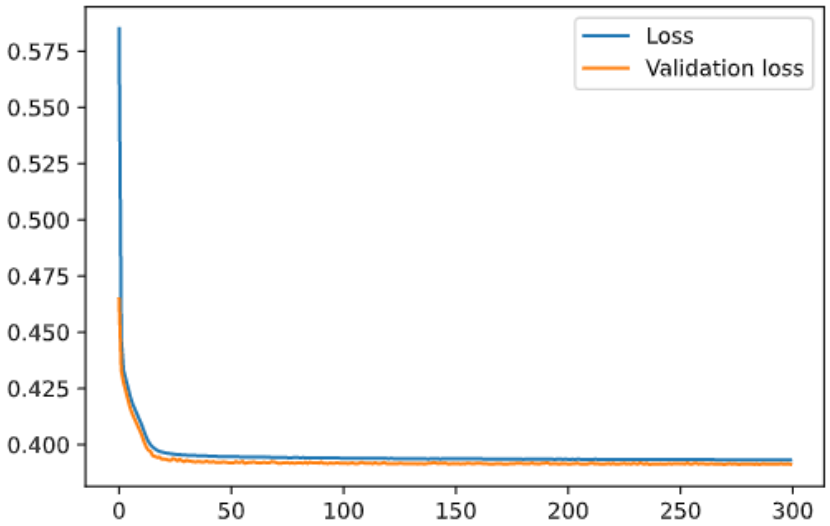


Accuracy & Loss - Keras NN (Reco)

Accuracy

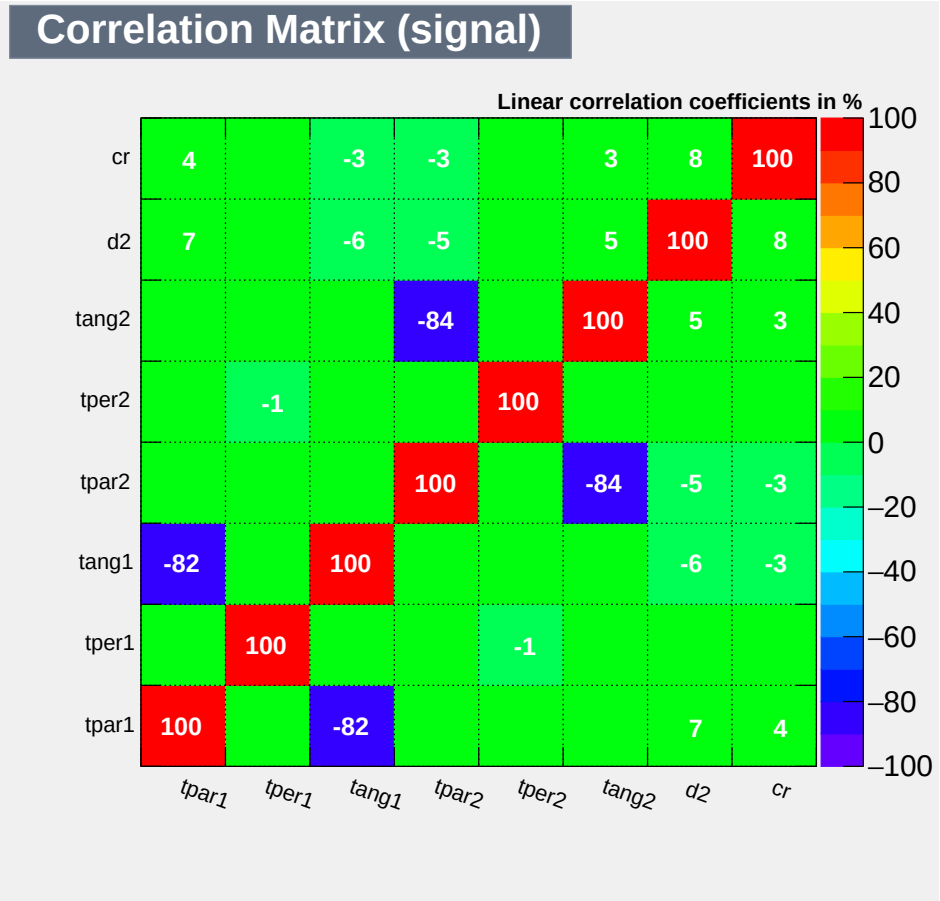


Loss

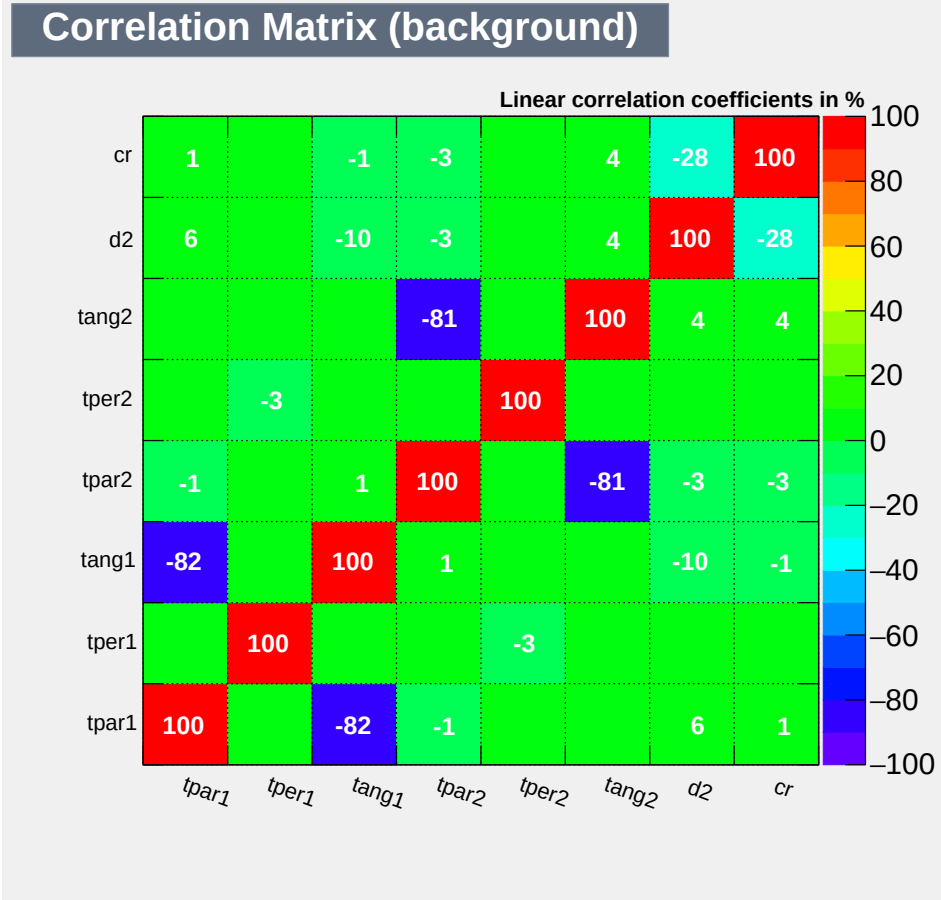


Correlation Matrix - Reco

ZHbb

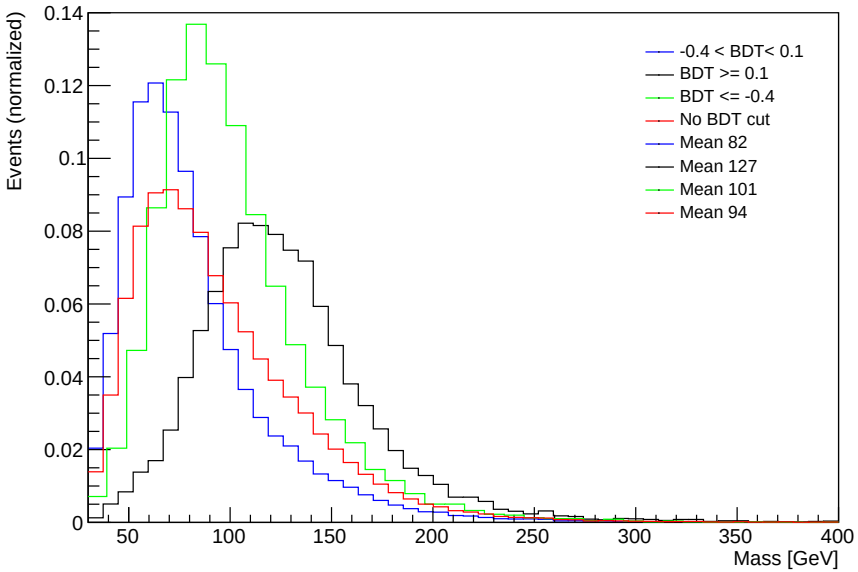


gbb

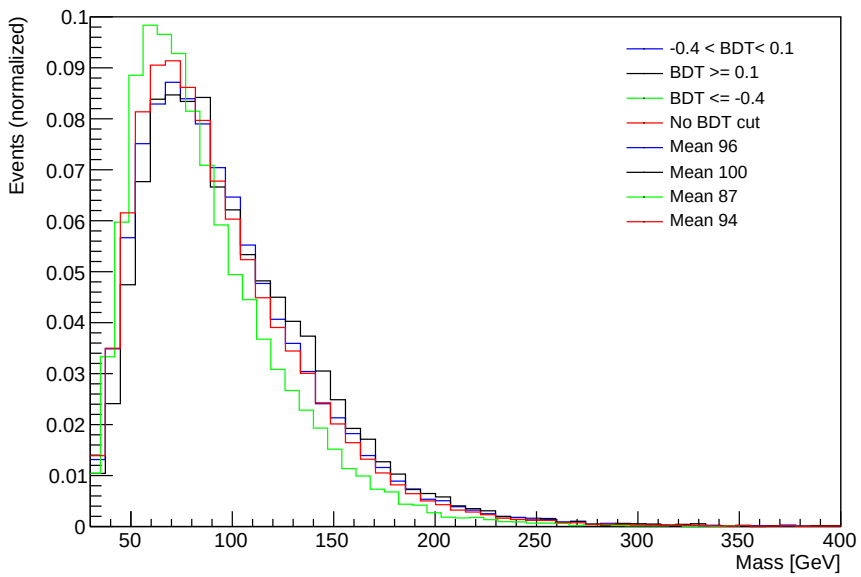


Mass Bias - Truth

All Variables



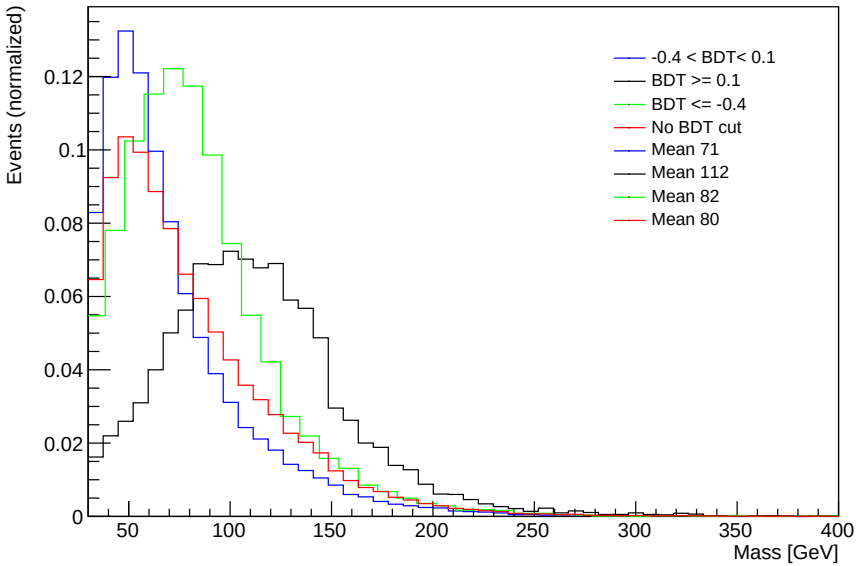
No D_2



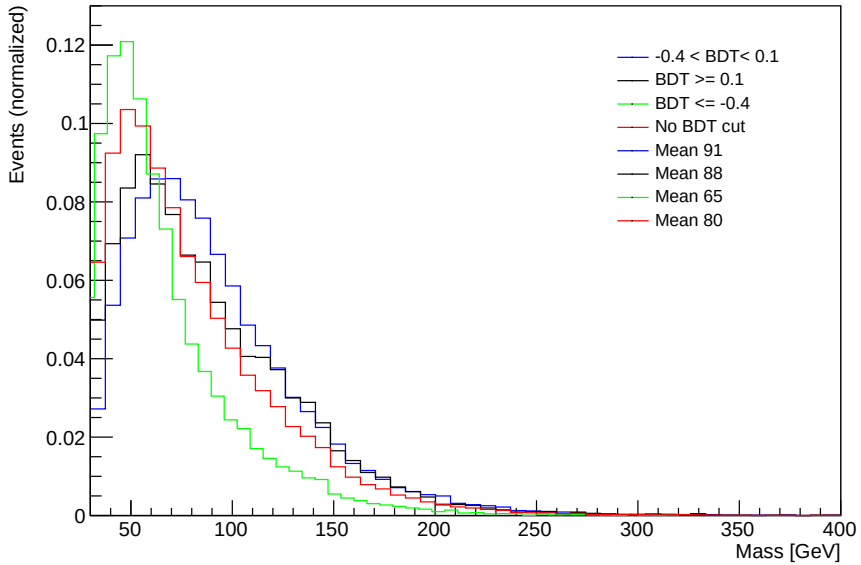
	AUC w/o D_2
BDT	0.775
NN - TMVA	0.773

Mass Bias - Reco

All Variables



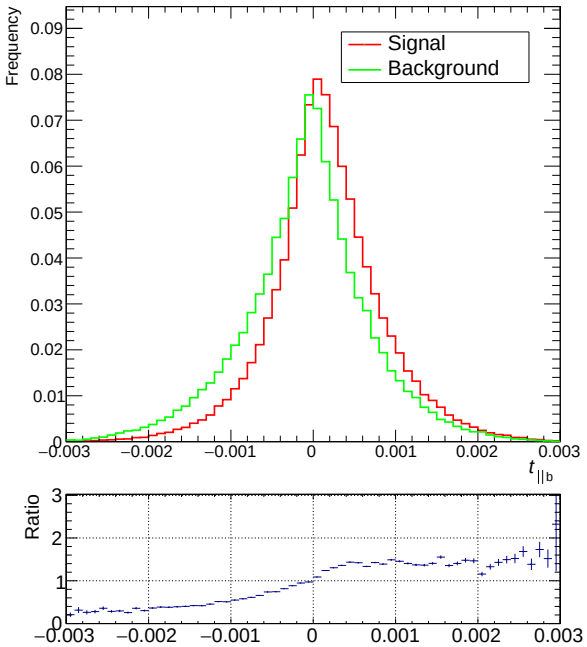
No D_2



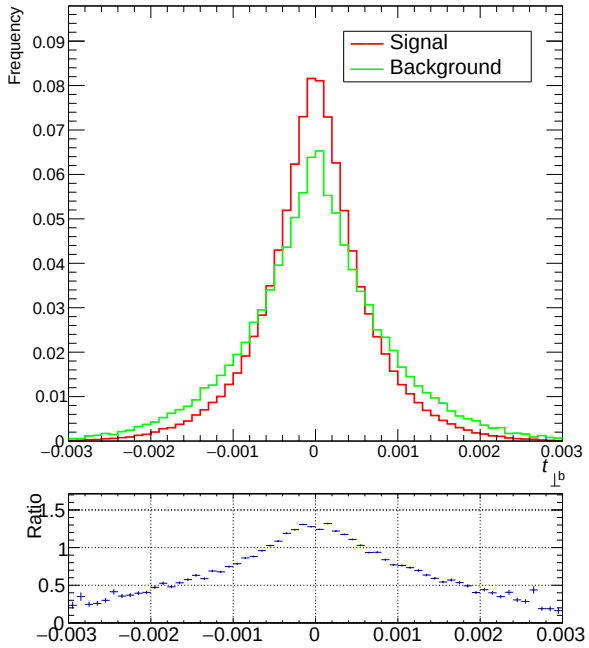
	AUC w/o D_2
BDT	0.773
NN - TMVA	0.772

Signal vs. Bkg (Truth) - Jet b Pull Variables

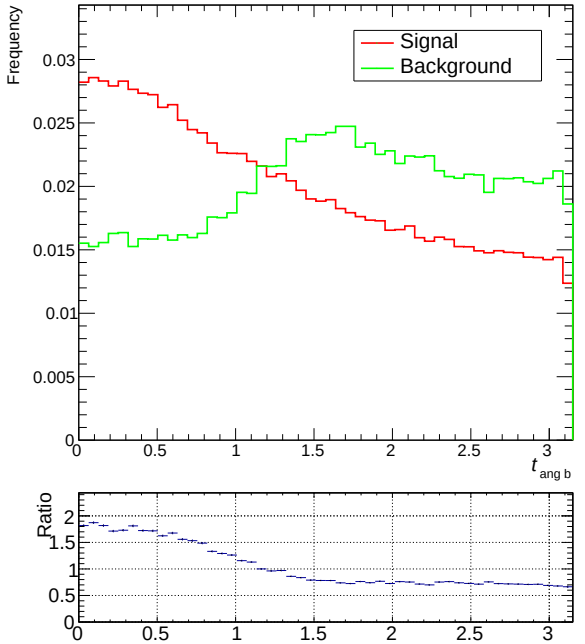
$t_{||b}$



$t_{\perp b}$

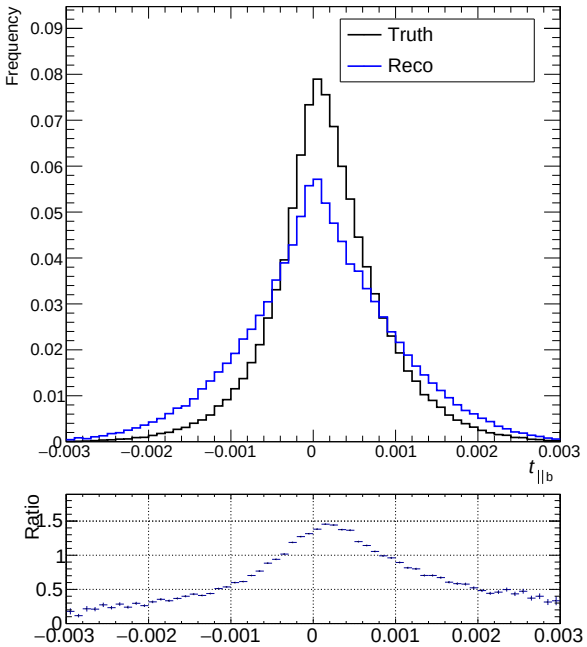


θ_{pb}

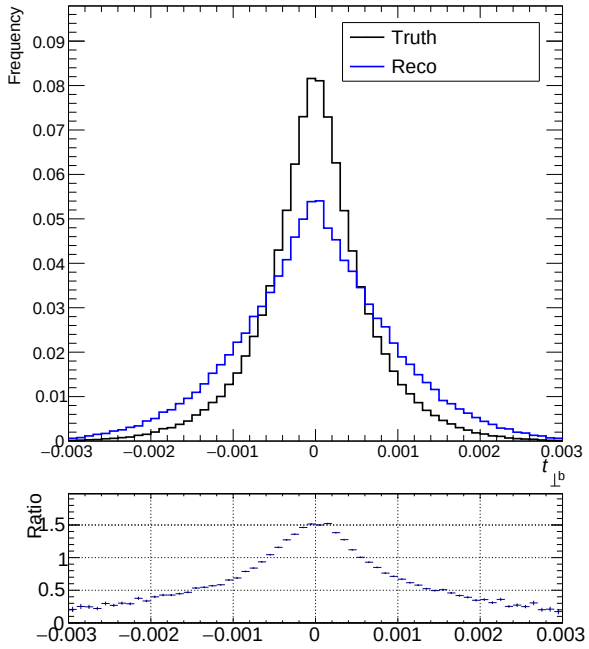


Truth vs. Reco (ZHbb) - Jet b Pull Variables

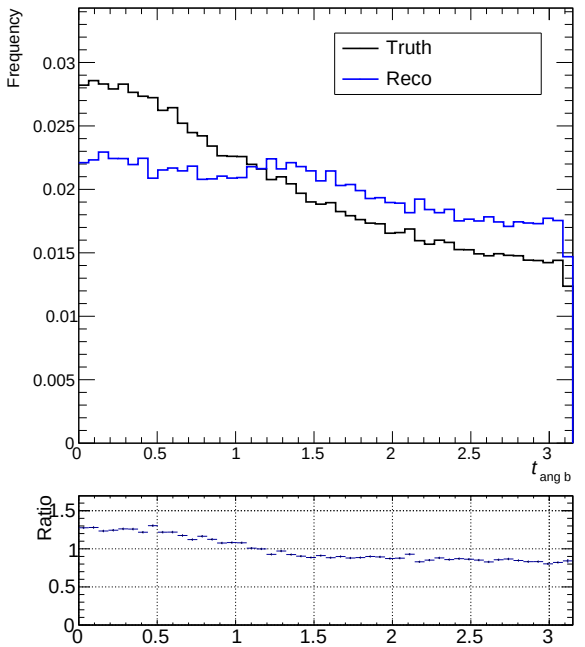
$t_{\| b}$



$t_{\perp b}$

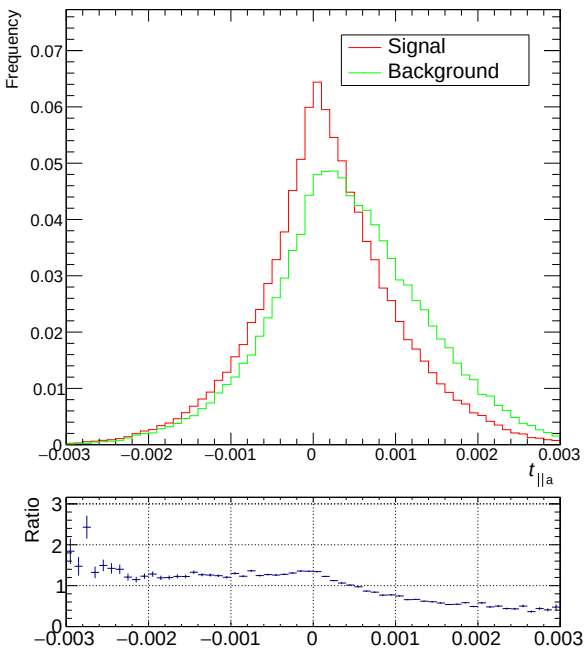


θ_{pb}

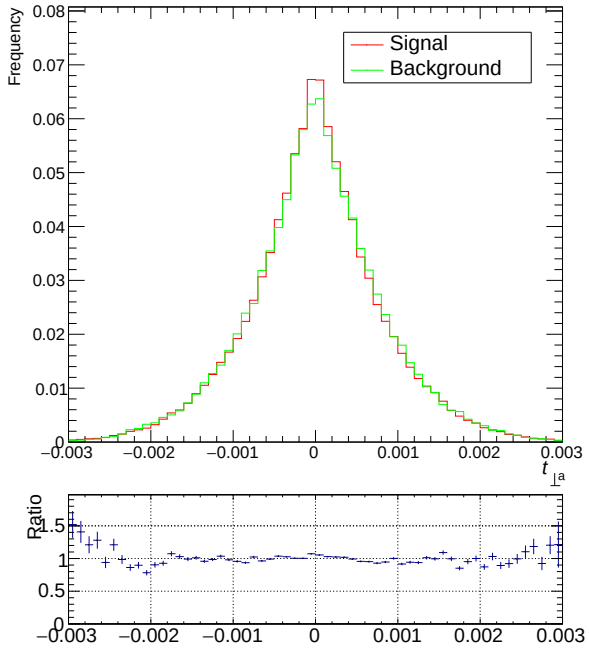


Distributions - Signal vs. Bkg (Reco)

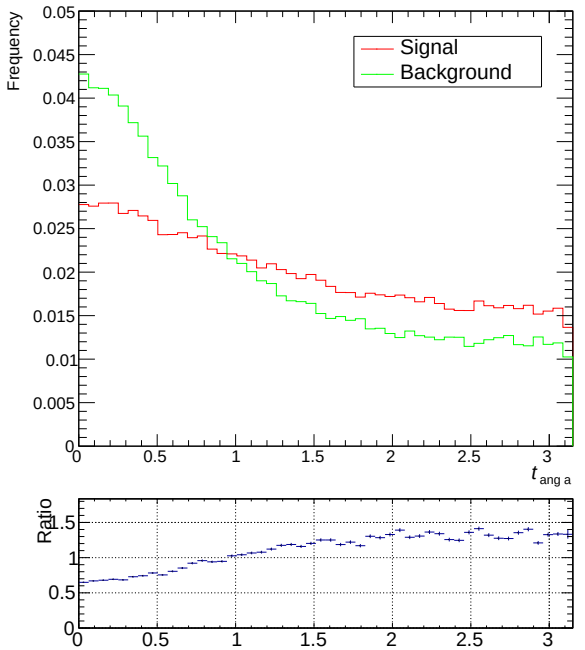
$t_{\parallel a}$



$t_{\perp a}$

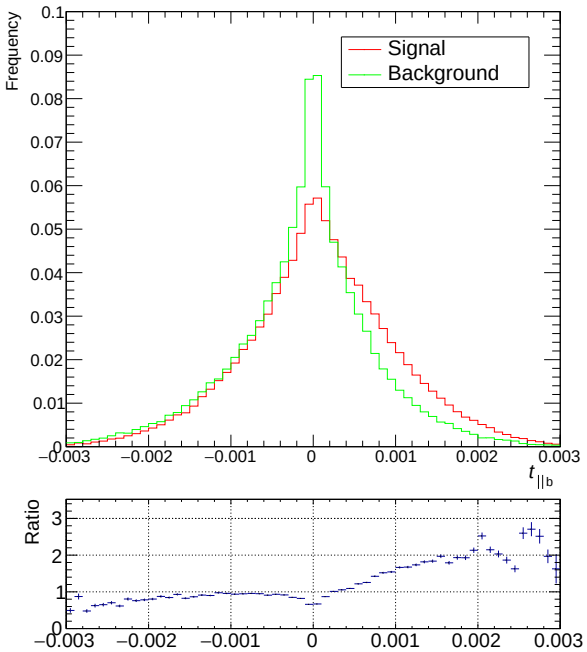


θ_{pa}

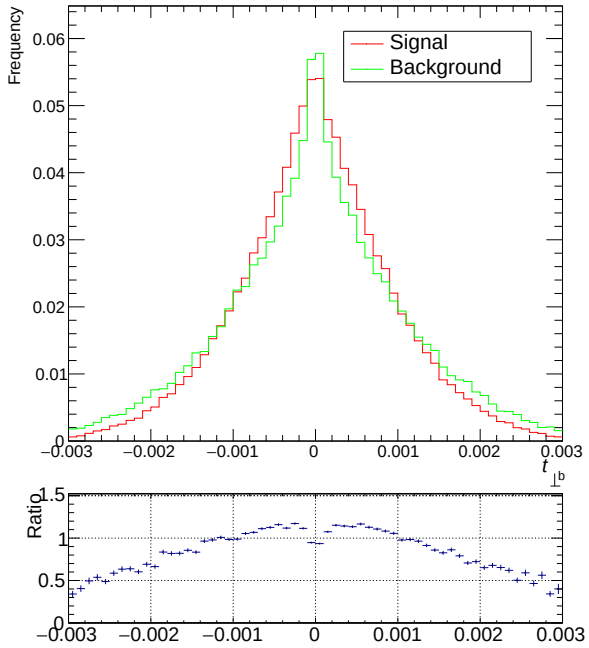


Distributions - Signal vs. Bkg (Reco)

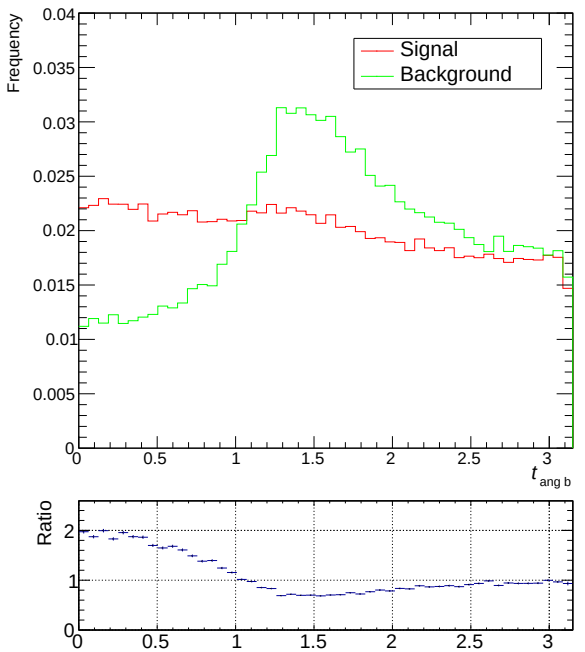
$t_{\| b}$



$t_{\perp b}$

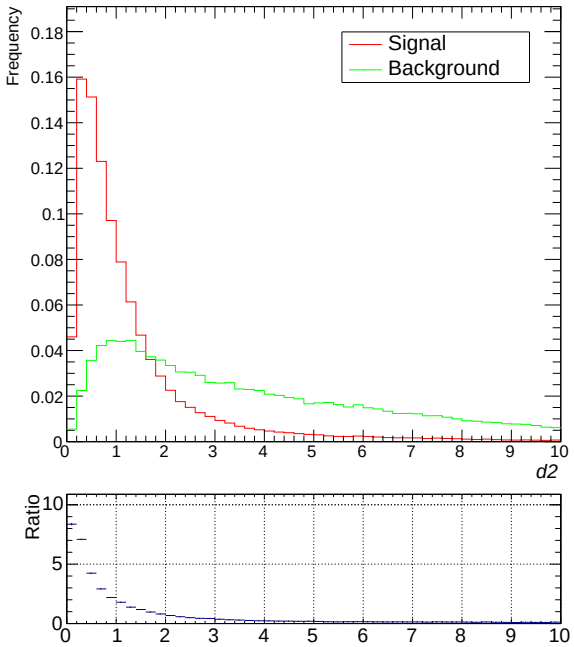


θ_{pb}



Distributions - Signal vs. Bkg (Reco)

D_2



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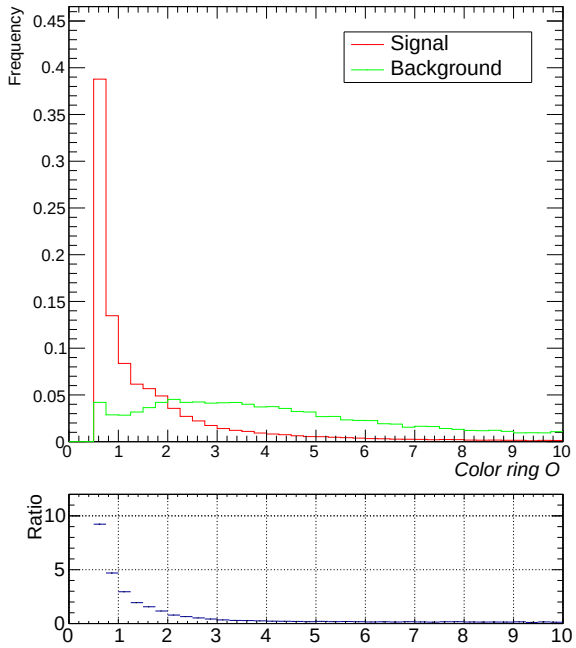
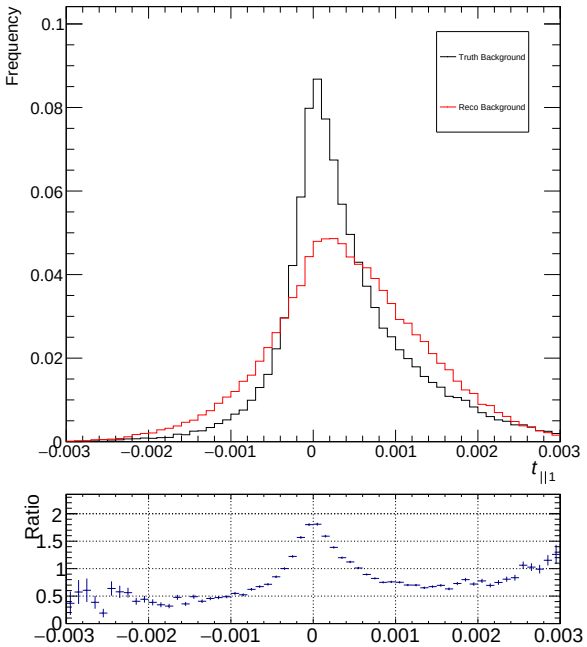
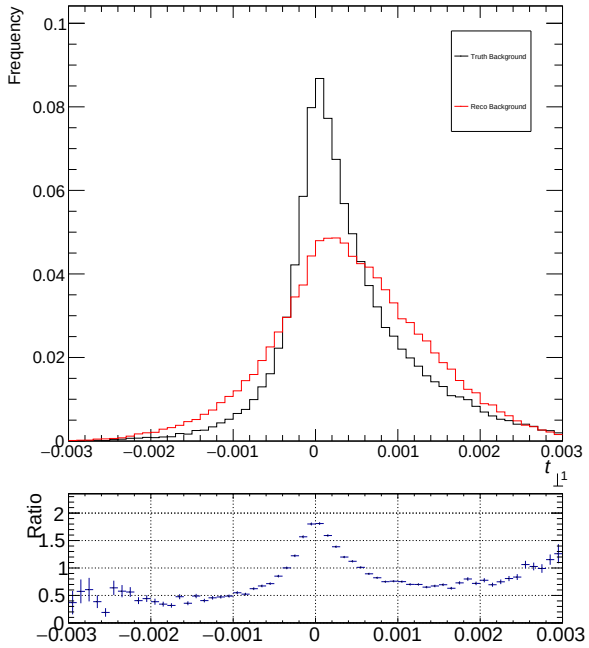


Distributions - Truth vs. Reco (gbb)

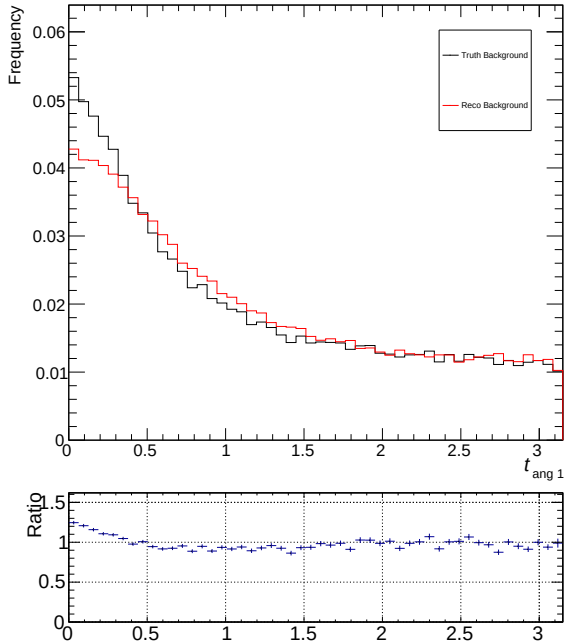
$t_{\parallel a}$



$t_{\perp a}$

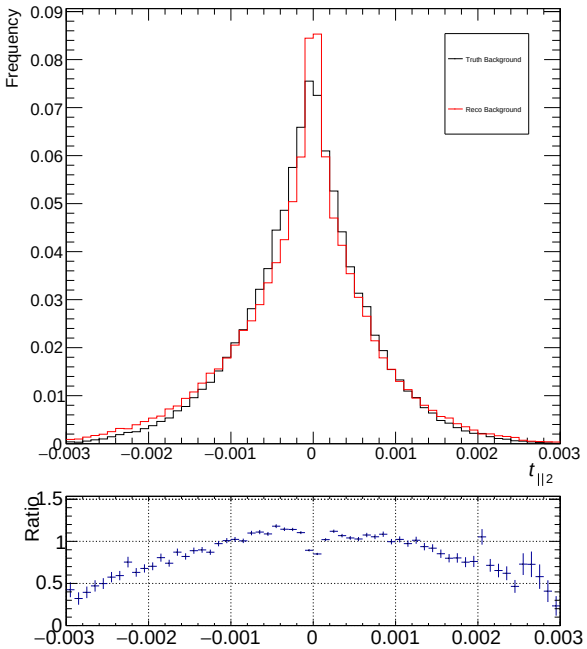


θ_{pa}

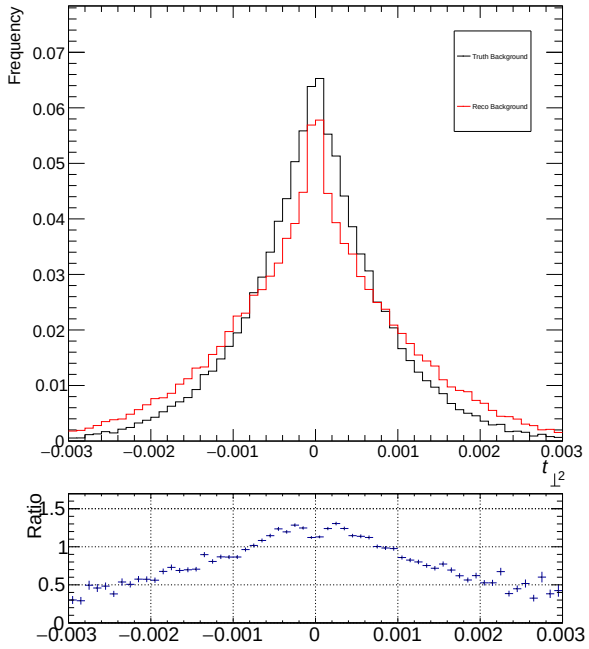


Distributions - Truth vs. Reco (gbb)

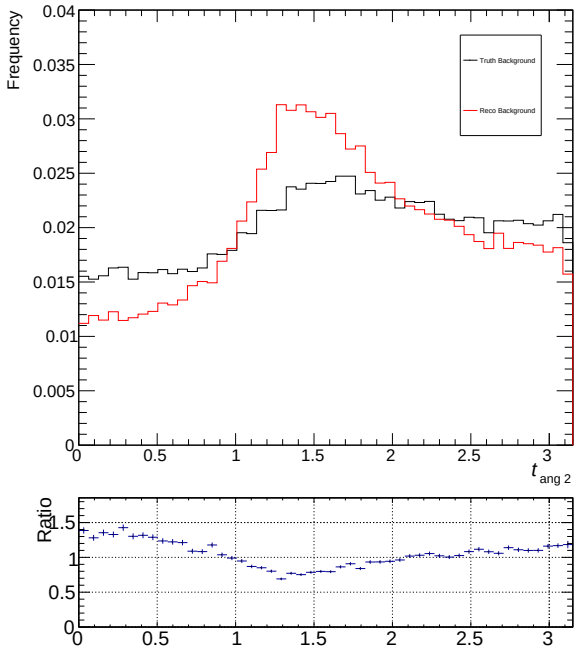
$t_{||b}$



$t_{\perp b}$

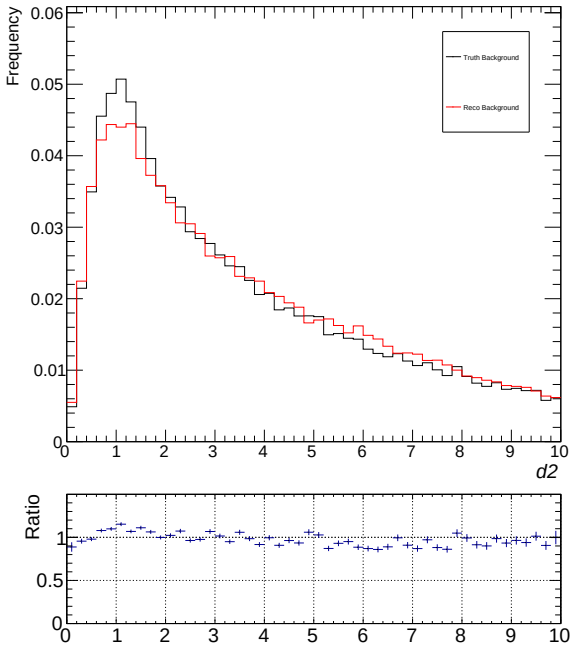


θ_{pb}



Distributions - Truth vs. Reco (gbb)

D_2



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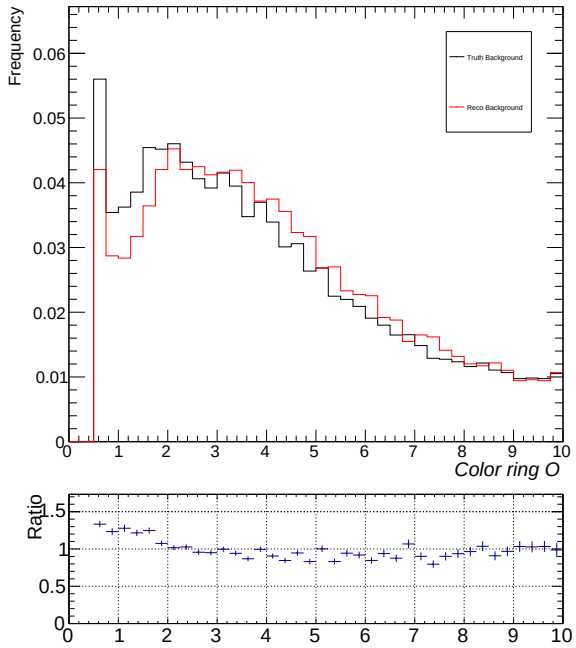
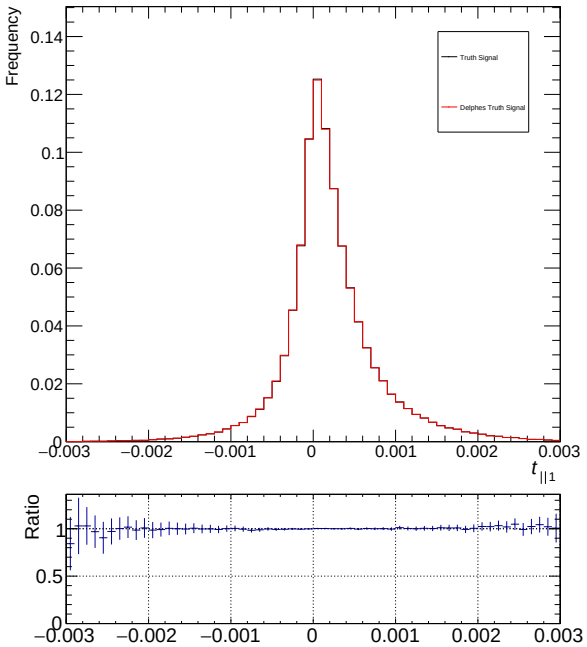
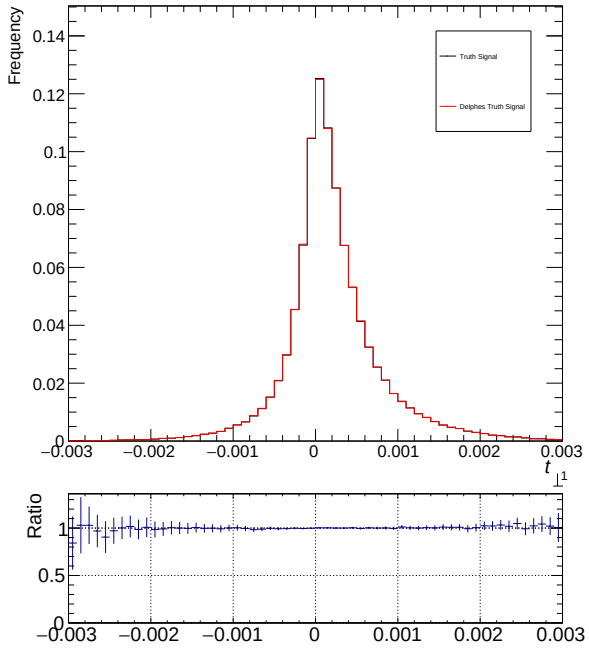


Distributions - Pythia vs. Delphes Truth (ZHbb)

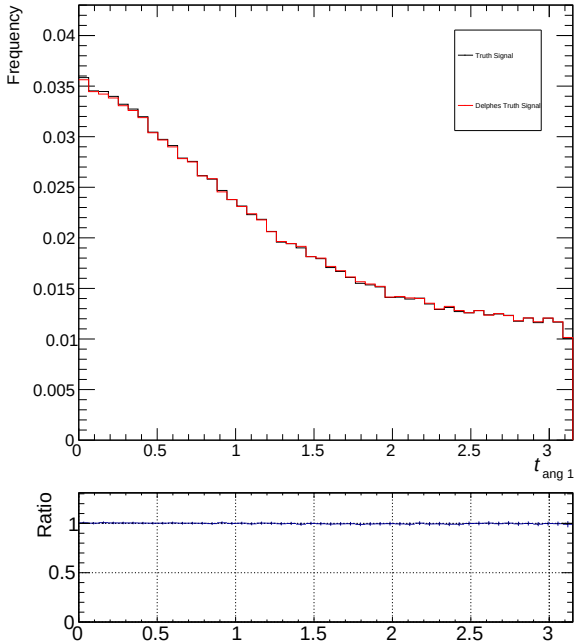
$t_{\parallel a}$



$t_{\perp a}$

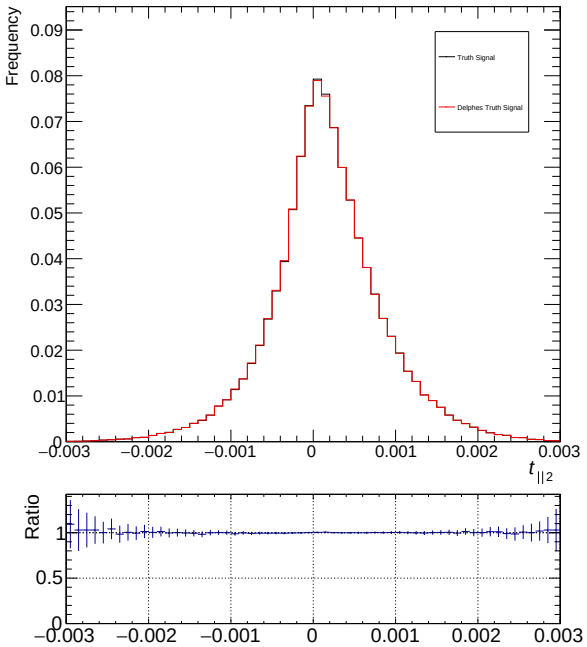


θ_{pa}

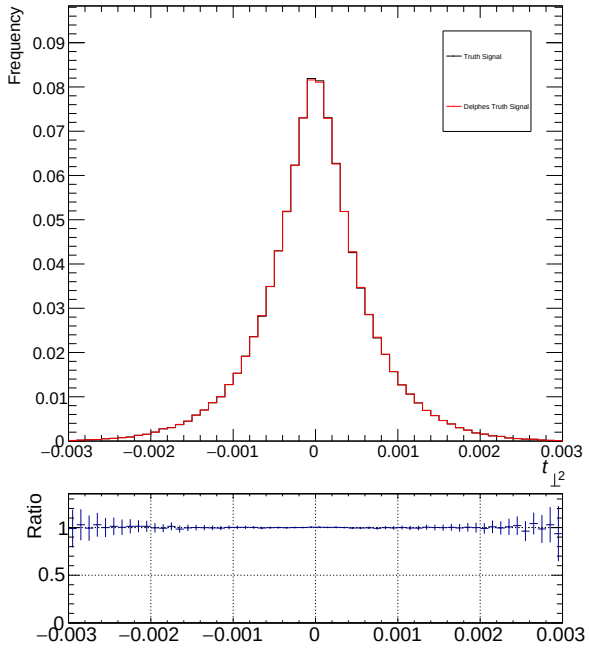


Distributions - Pythia vs. Delphes Truth (ZHbb)

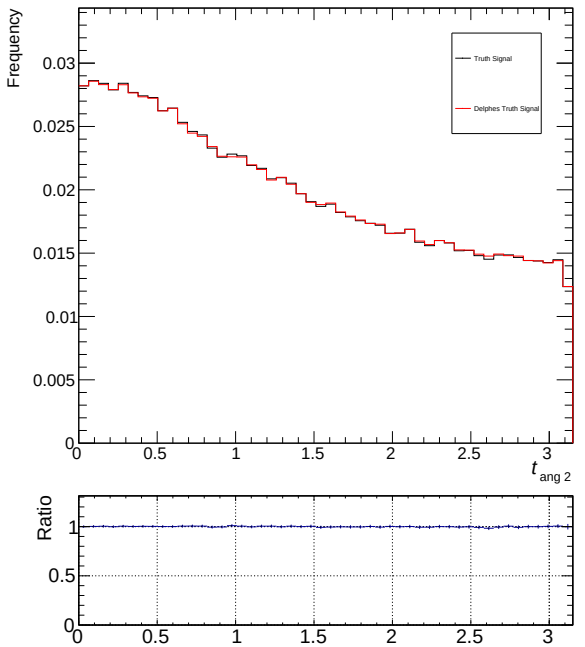
$t_{||b}$



$t_{\perp b}$

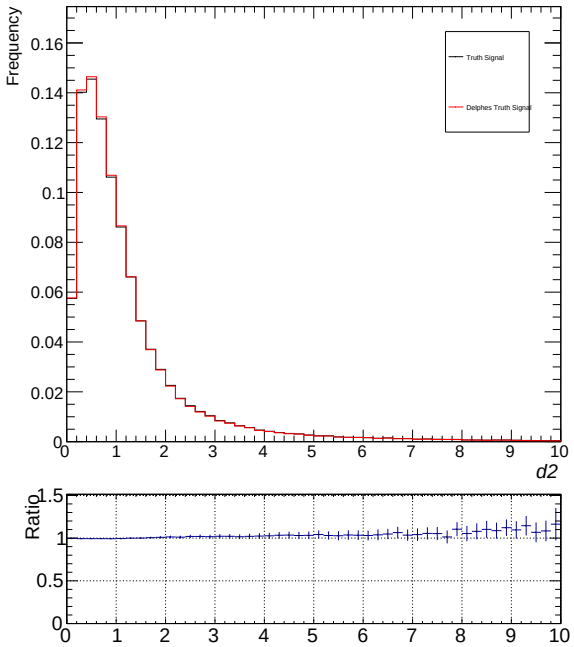


θ_{pb}



Distributions - Pythia vs. Delphes Truth (ZHbb)

D_2



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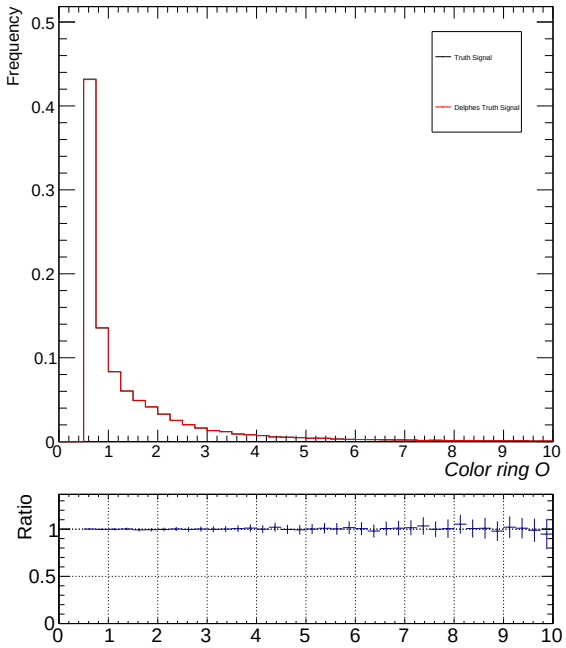
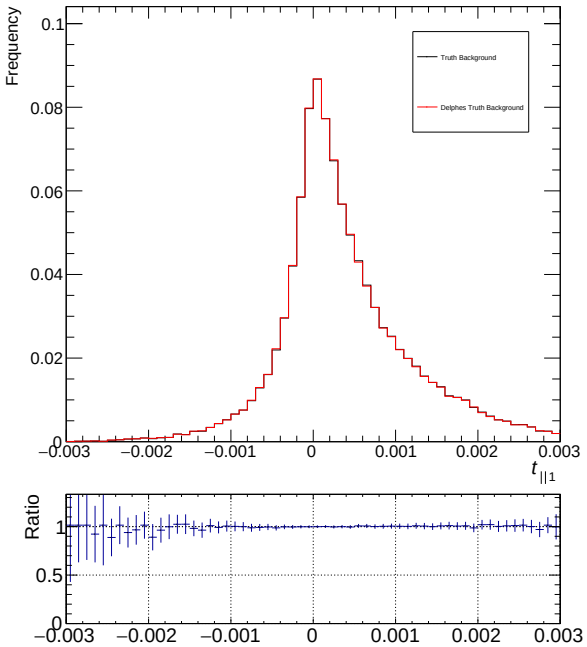
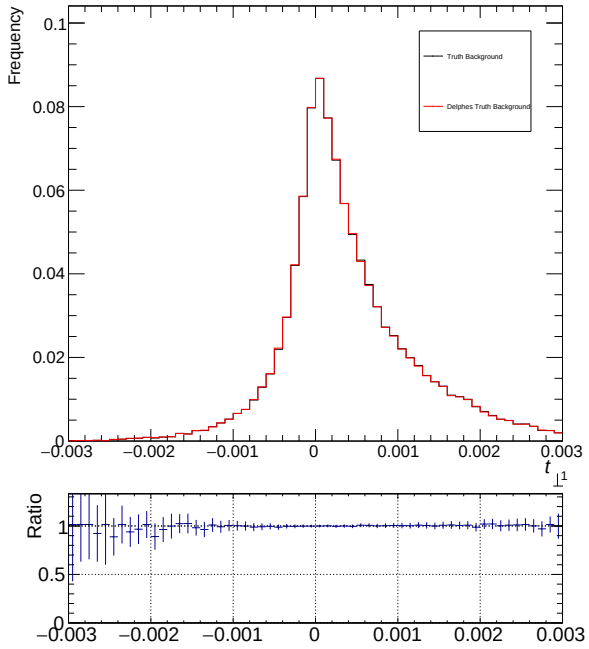


Distributions - Pythia vs. Delphes Truth (gbb)

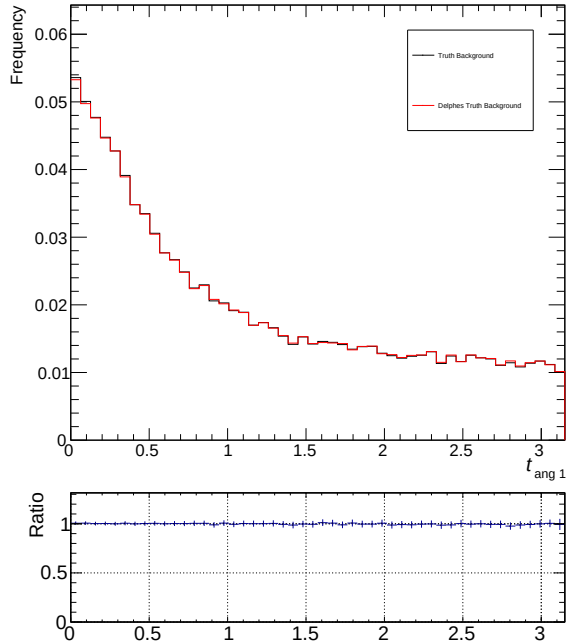
$t_{||a}$



$t_{\perp a}$

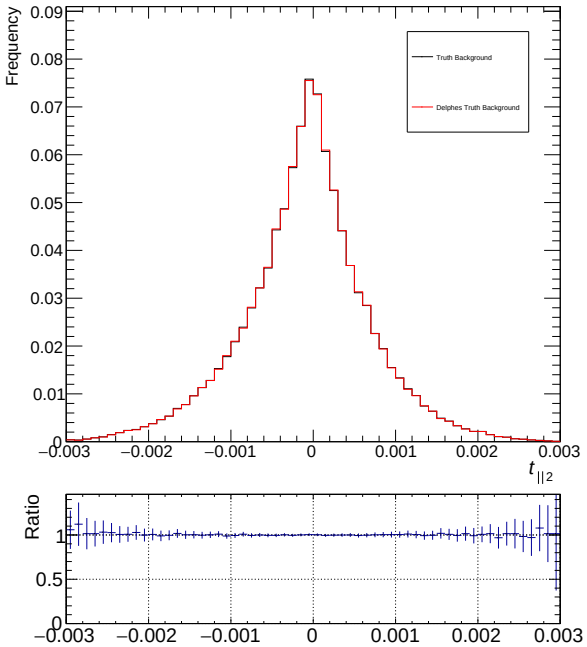


θ_{pa}

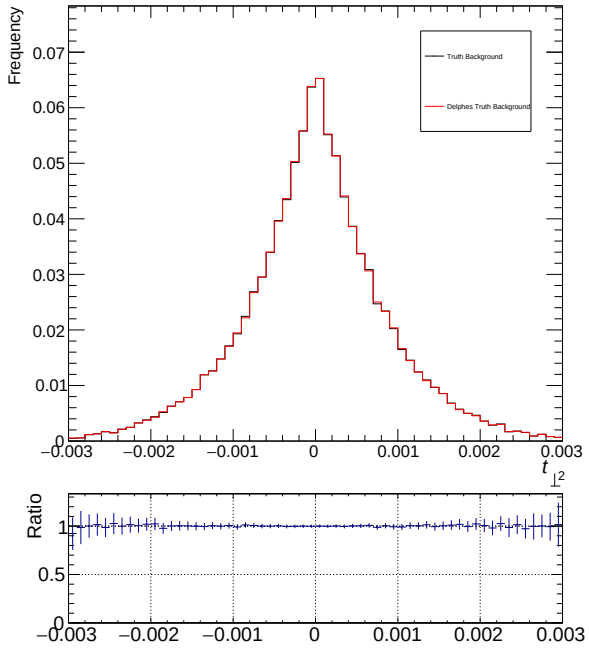


Distributions - Pythia vs. Delphes Truth (gbb)

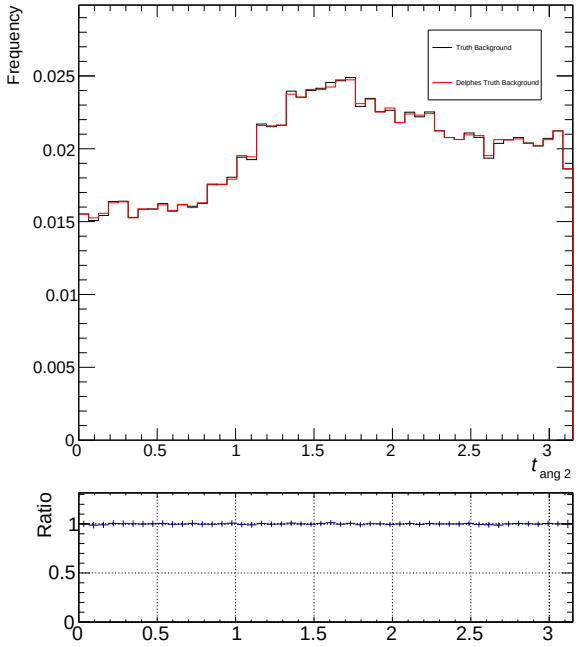
$t_{||b}$



$t_{\perp b}$

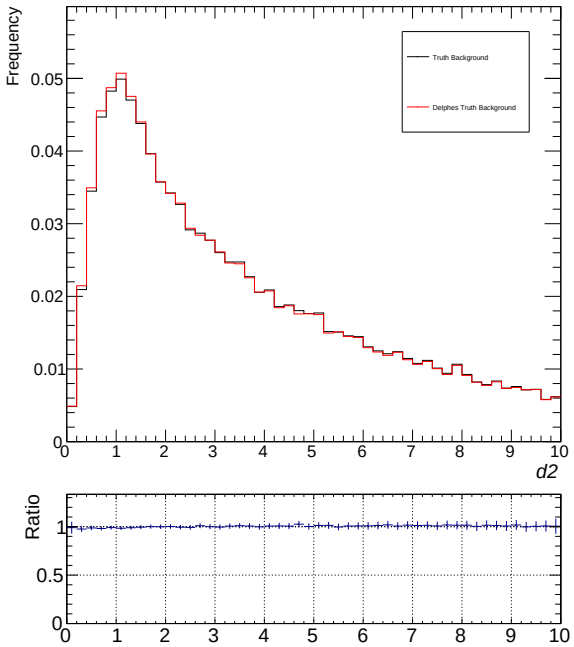


θ_{pb}



Distributions - Pythia vs. Delphes Truth (gbb)

D_2



cr