An Emerging Jets Analysis With Boosted Decision Trees

Jérémie LePage-Bourbonnais

Carleton University

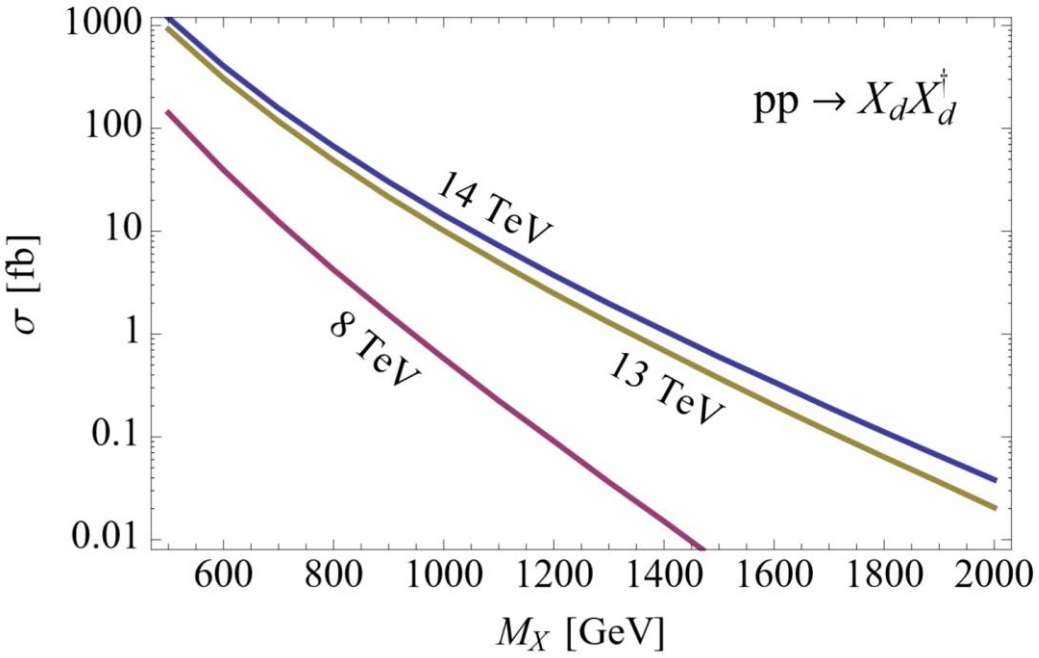
Supervisor: Kevin Graham

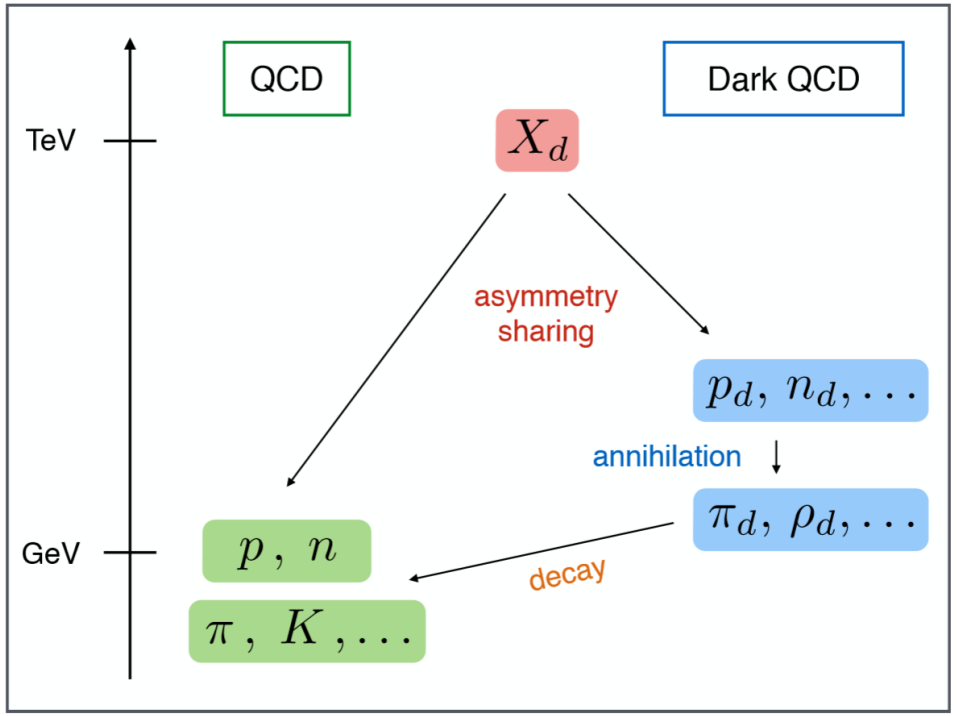
Outline

- Emerging Jet Models
- ATLAS Run 2 Analysis Summary
- Progress Towards Run 3 Analysis with BDTs

Dark QCD

Field	$SU(3) \times SU(2) \times U(1)$	$SU(3)_{\text{dark}}$	Mass	Spin
Q_d	$(1, 1, 0)$	(3)	m_d $\mathcal{O}(\text{GeV})$	Dirac Fermion
X_d	$(3, 1, \frac{1}{3})$	(3)	M_{X_d} $\mathcal{O}(\text{TeV})$	Complex Scalar
Z_d	$(1, 1, 0)$	(1)	M_{Z_d} $\mathcal{O}(\text{TeV})$	Vector Boson

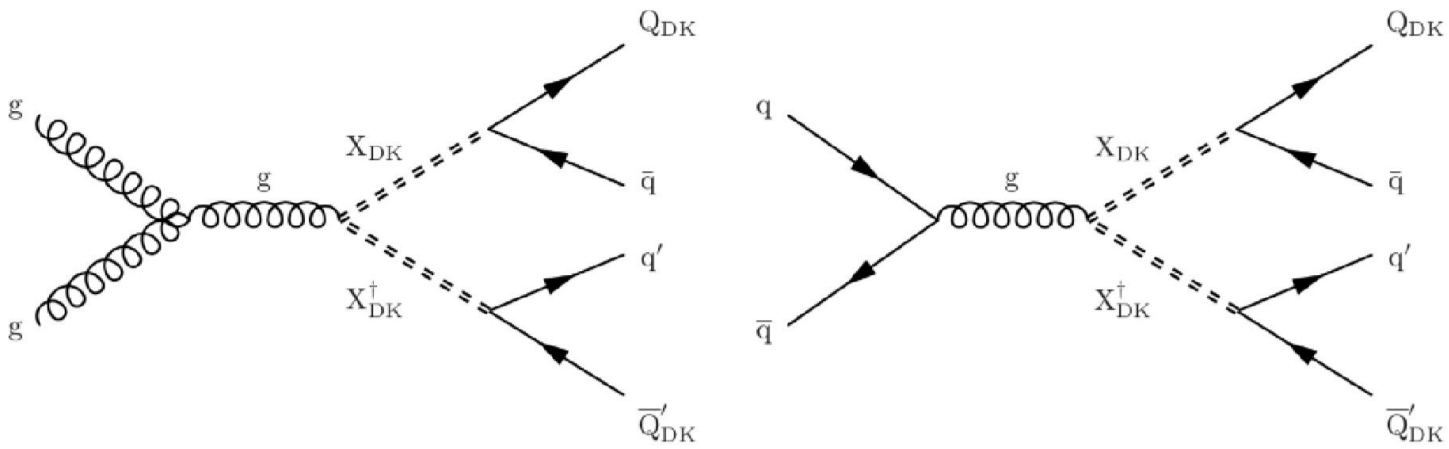




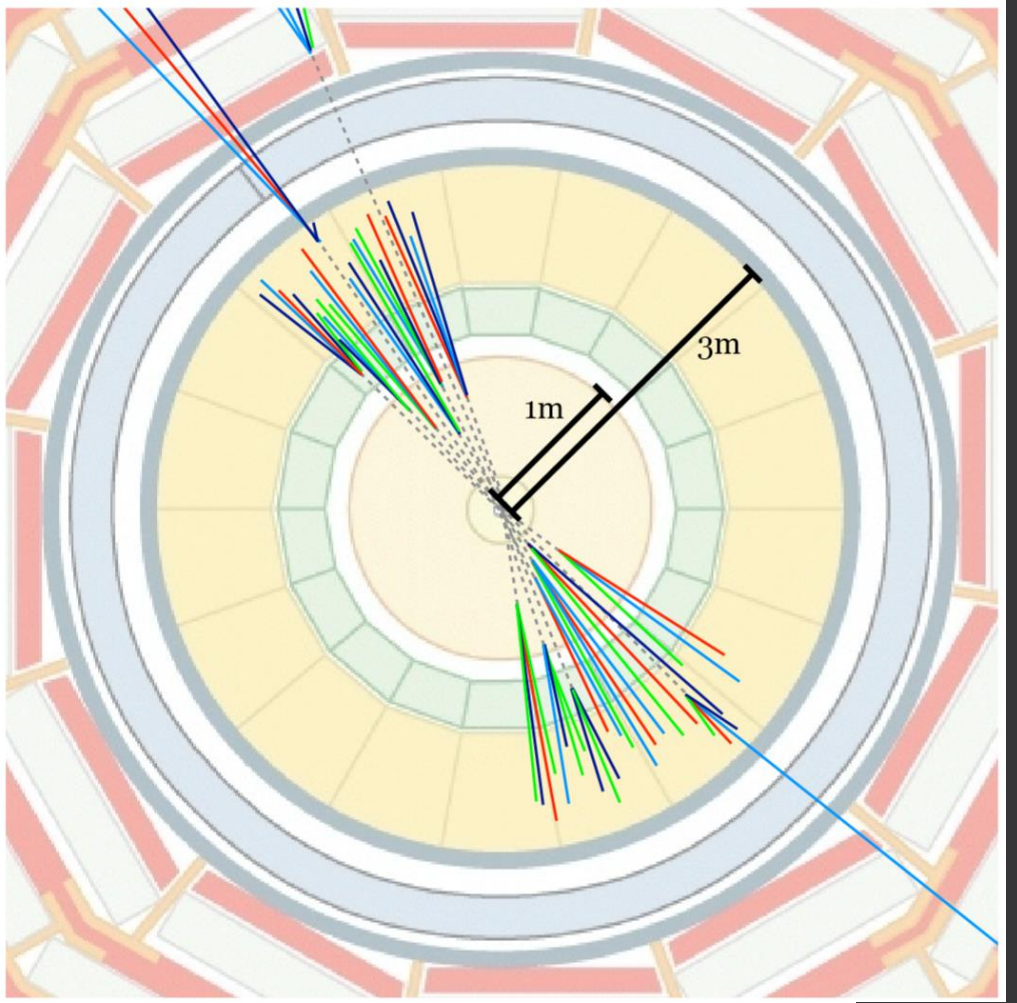
$$\mathcal{L} \supset \bar{Q}_{d_i}(\not{D} - m_{d_i})Q_{d_i} + (D_\mu X_d)(D^\mu X_d)^\dagger - M_{X_d}^2 X_d X_d^\dagger - \frac{1}{4} G_d^{\mu\nu} G_{\mu\nu,d} + \mathcal{L}_\kappa + \mathcal{L}_{\text{SM}}$$

P. Schwaller, D. Stolarski, A. Weiler - arxiv:1502.05409

Emerging Jets Models



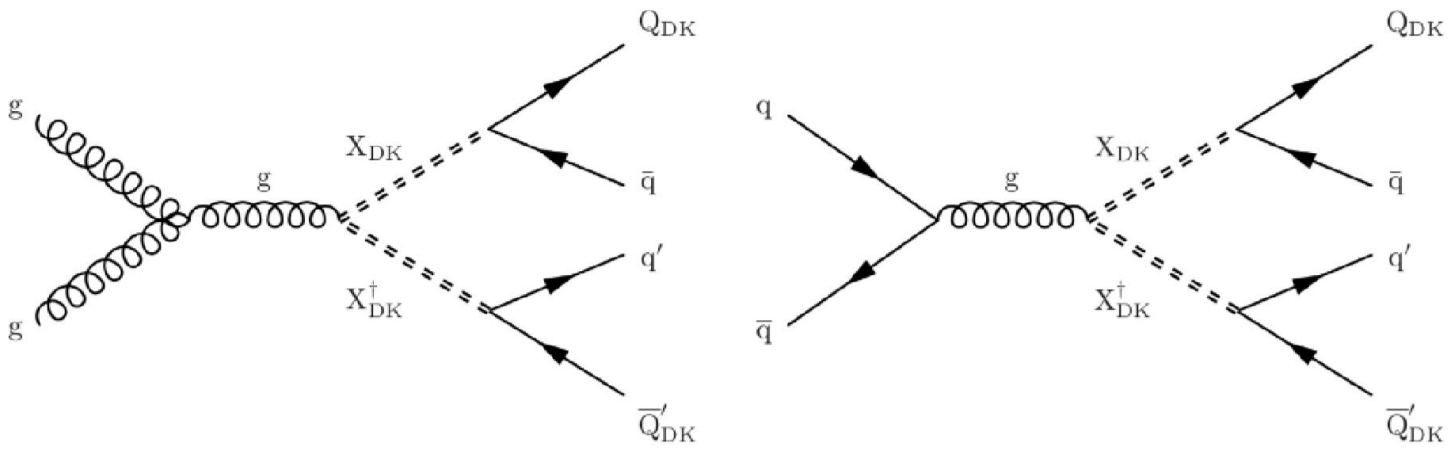
- Dark jets "emerge" as dark mesons decay to SM particles
- Look for "four jets" and many displaced vertices



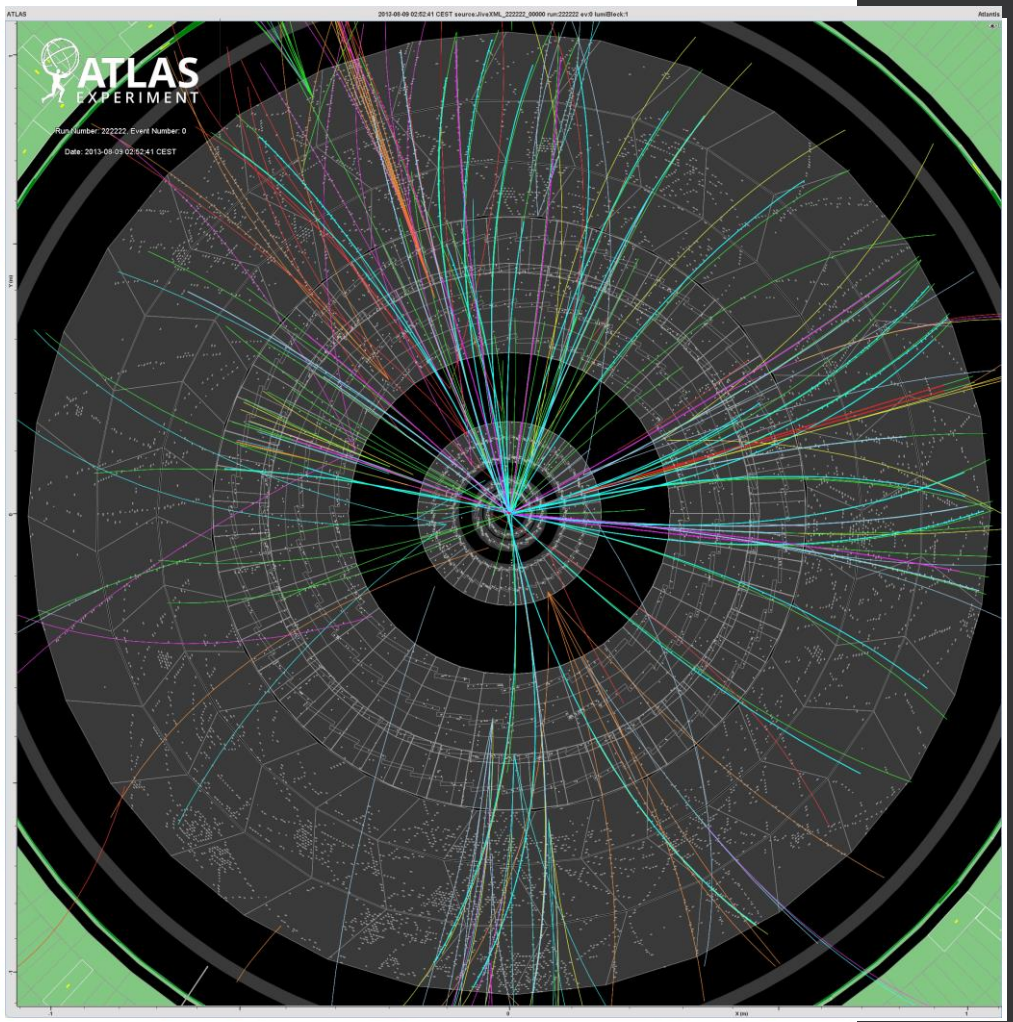
Two emerging jets shown

P. Schwaller, D. Stolarski, A. Weiler - arxiv:1502.05409

Emerging Jets Models



- Dark jets "emerge" as dark mesons decay to SM particles
- Look for "four jets" and many displaced vertices



Signal MC Event

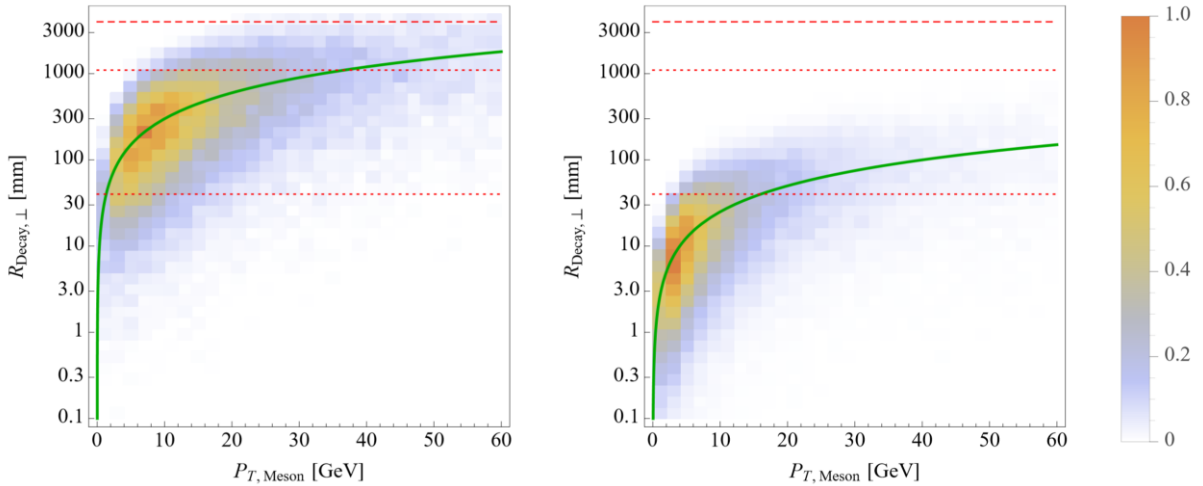
P. Schwaller, D. Stolarski, A. Weiler - arxiv:1502.05409

Simulated Signals/Backgrounds

	Model **A**	Model **B**
Λ_d	10 GeV	4 GeV
m_V	20 GeV	8 GeV
m_{π_d}	5 GeV	2 GeV
$c\tau_{\pi_d}$	150 mm	5 mm

- 90 Model points generated uses modified Pythia 8 HiddenValley modules

	Model A	Model B	Model C	Model D	Model E
Λ_d [GeV]	10	4	20	40	1.6
m_{ρ_d} [GeV]	20	8	40	80	3.2
m_{π_d} [GeV]	5	2	10	20	0.8
m_{X_d} [GeV]	1400 | 1000 | 600				
$c\tau_{\pi_d}$ [mm]	300, 150, 75, 20, 5, 2 | 300, 150, 75, 5, 2, 1 | 300, 150, 20, 2, 1, 0.5				

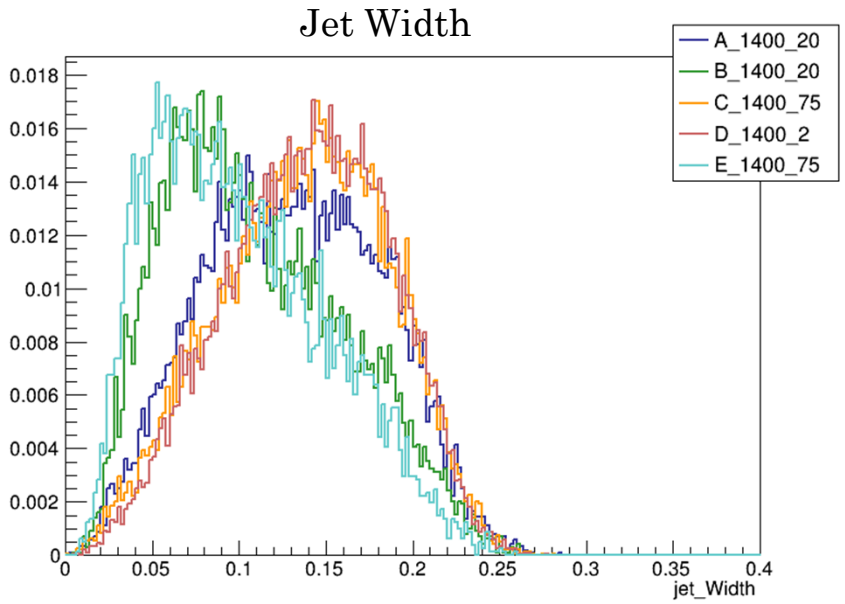


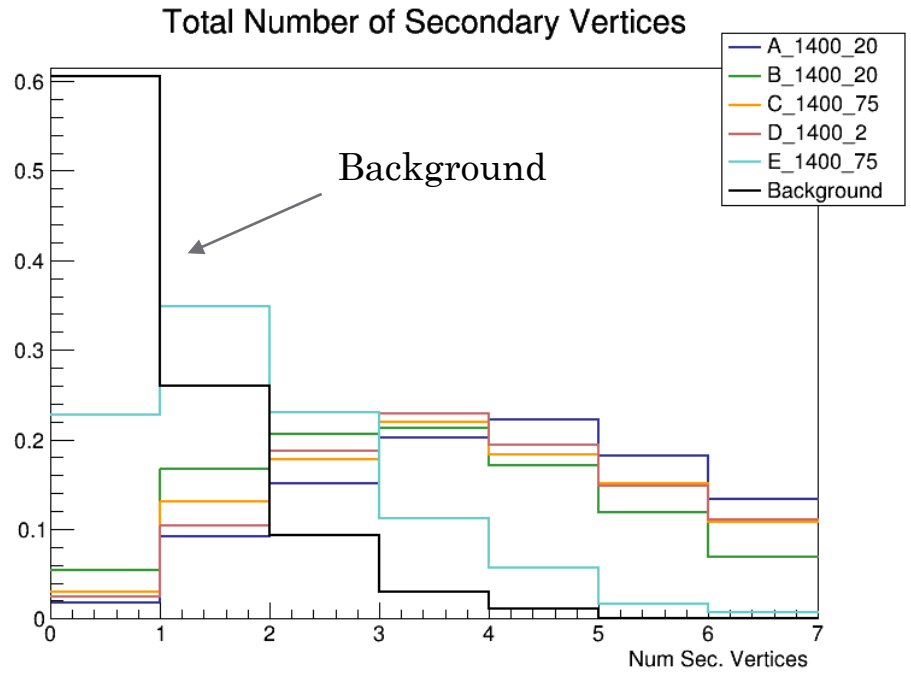
P. Schwaller, D. Stolarski, A. Weiler - arxiv:1502.05409

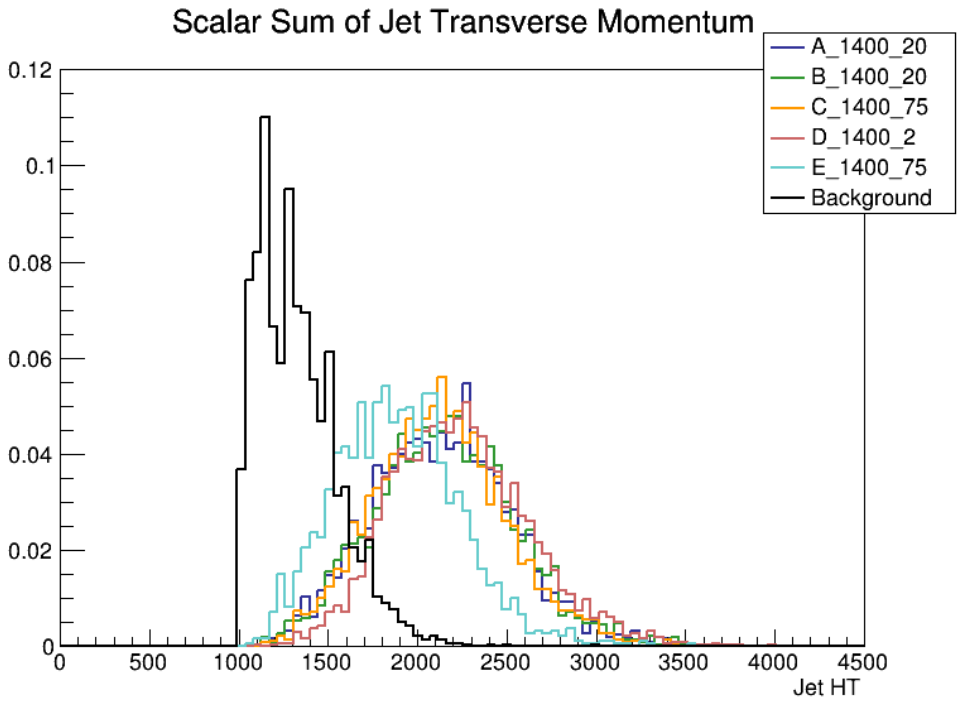
- Uses a SU(3) single flavoured Pythia model for the dark QCD sector
- Backgrounds assumed to be completely dominated by multi-jet
- Events pass through GEANT4 ATLAS detector reconstruction
- Background MC is JZ4W slice: 410 < pT < 790 GeV, other slices are currently processing

Run 2 Analysis

- Model independent approach
- Pre-Selection cuts
  - Jet multiplicity >= 4
  - 4 Leading jets each have pT >= 120 GeV
  - 4 Leading Jets each have |η| <= 2.5
  - Scalar sum of 4-Jet pT >= 1000 GeV
- ABCD implementation for data driven background estimate







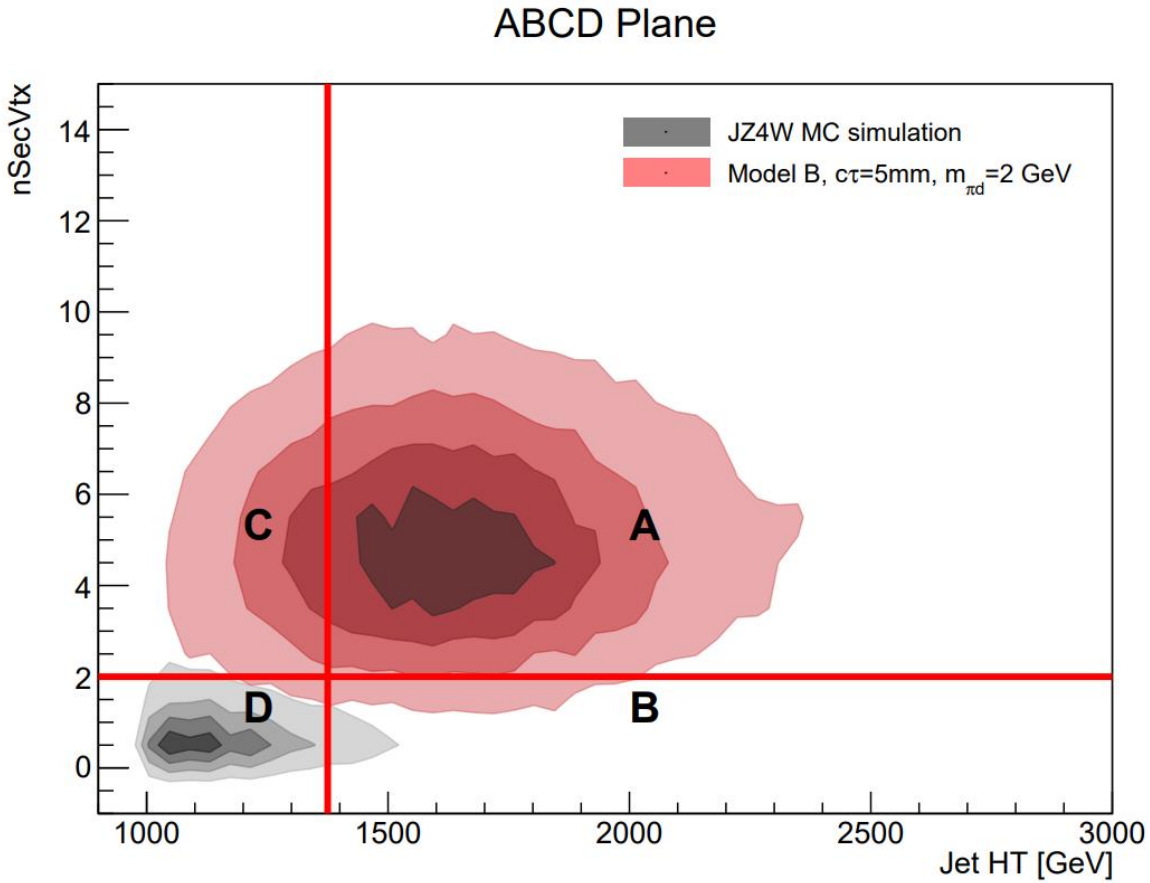
ABCD Background Estimation Method

- Data-driven background estimation method
- Cut positions may change with new MC background slices
- For un-correlated ABCD plane variables:

$$\frac{N_C^{bkg}}{N_D^{bkg}} = \frac{N_A^{bkg}}{N_B^{bkg}}$$

- Can solve for background estimate in region A

$$N_A^{bkg} = N_B^{bkg} \frac{N_C^{bkg}}{N_D^{bkg}}$$



D. Rocha / G. Gonella

BDT Motivation

- Model independent ABCD background estimation approach doesn't necessarily maximize separation between signal and background
- See what happens if machine learning approach is implemented to classify events
- Use additional weakly separating variables

Tree Training Flow

- Dark Jets are truth level jet objects composed solely of dark particles.
- Look for reconstructed jets within an angular separation of $\Delta R < 0.1$, "match" with the highest pT reconstructed jet found

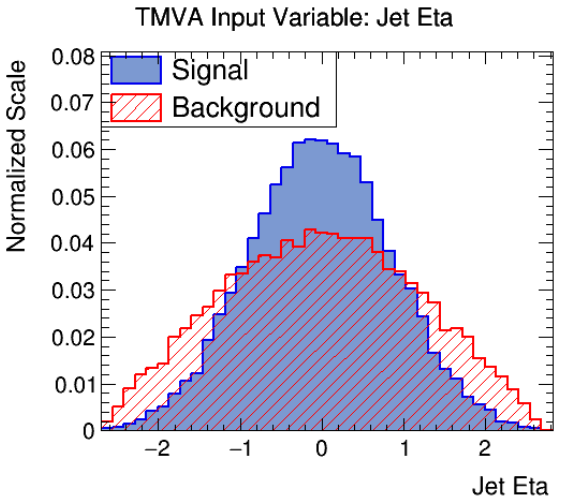
ROOT TMVA BDT Implementation – Default settings (e.g. 800 trees, max height 3)

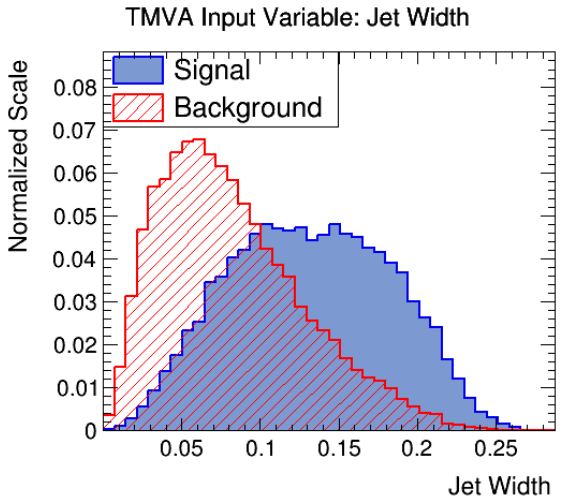
- Select Training/Testing Data
  - Apply pre-selection cuts on available data
  - Randomly select fraction of events to train on
- Train Jet Level Trees
  - Two cases:
    - Train on all **dark-matched signal jets**, all background jets
    - Train on **4 leading dark-matched signal jets**, all background jets
- Train Event Level Trees
  - Use information from jet level trees + event level variables
  - Two cases:
    - Without including HT (for ABCD comparison)
    - Including HT
- Apply to 15 signal points independently

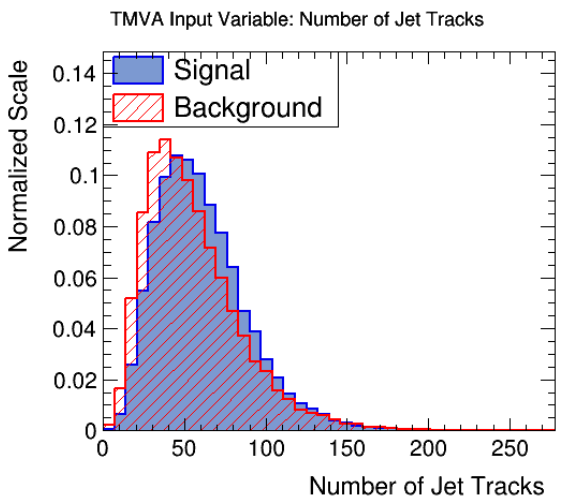
Jet-Level Input Variable Distributions

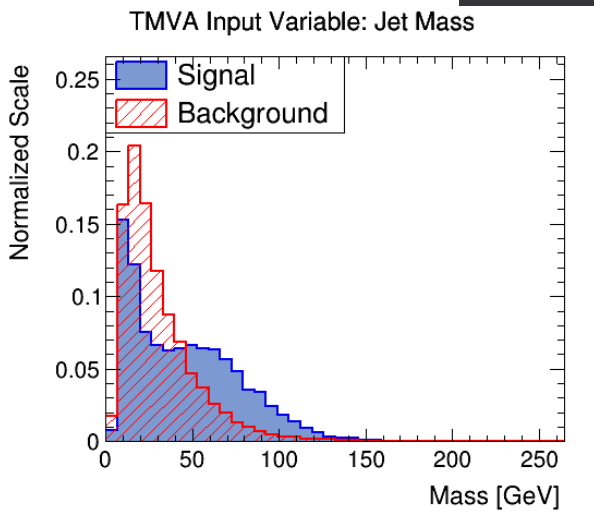
Model: A 1400 GeV 20 mm

$$\text{width} = \frac{1}{p_T^{jet}} \sum_i p_T^i \Delta R_i$$

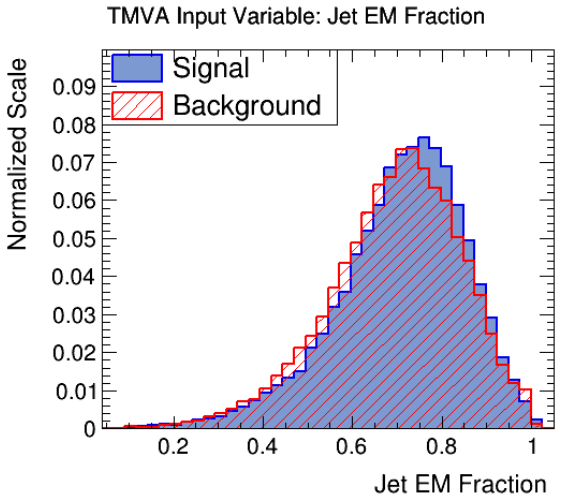


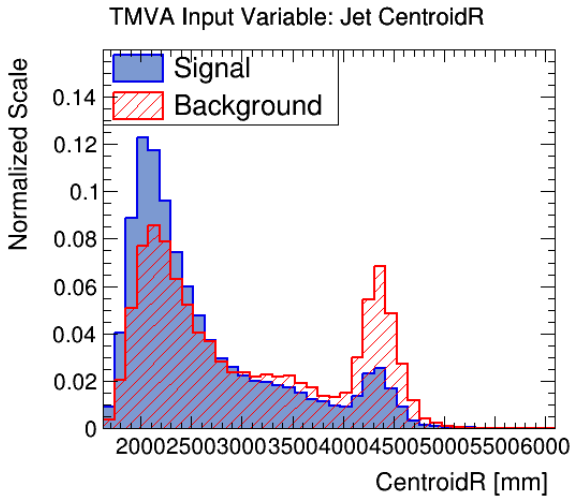


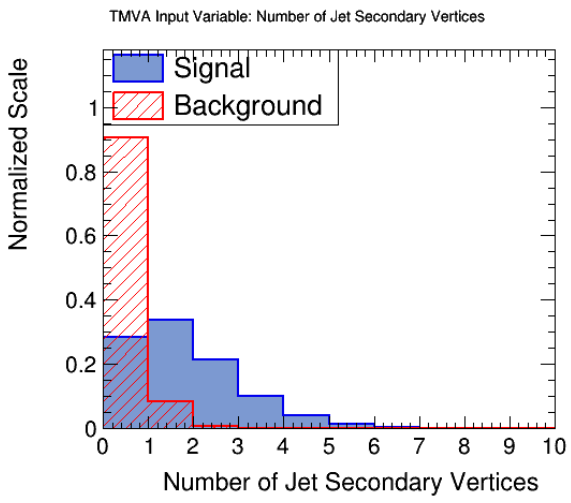




Trained on all dark jets

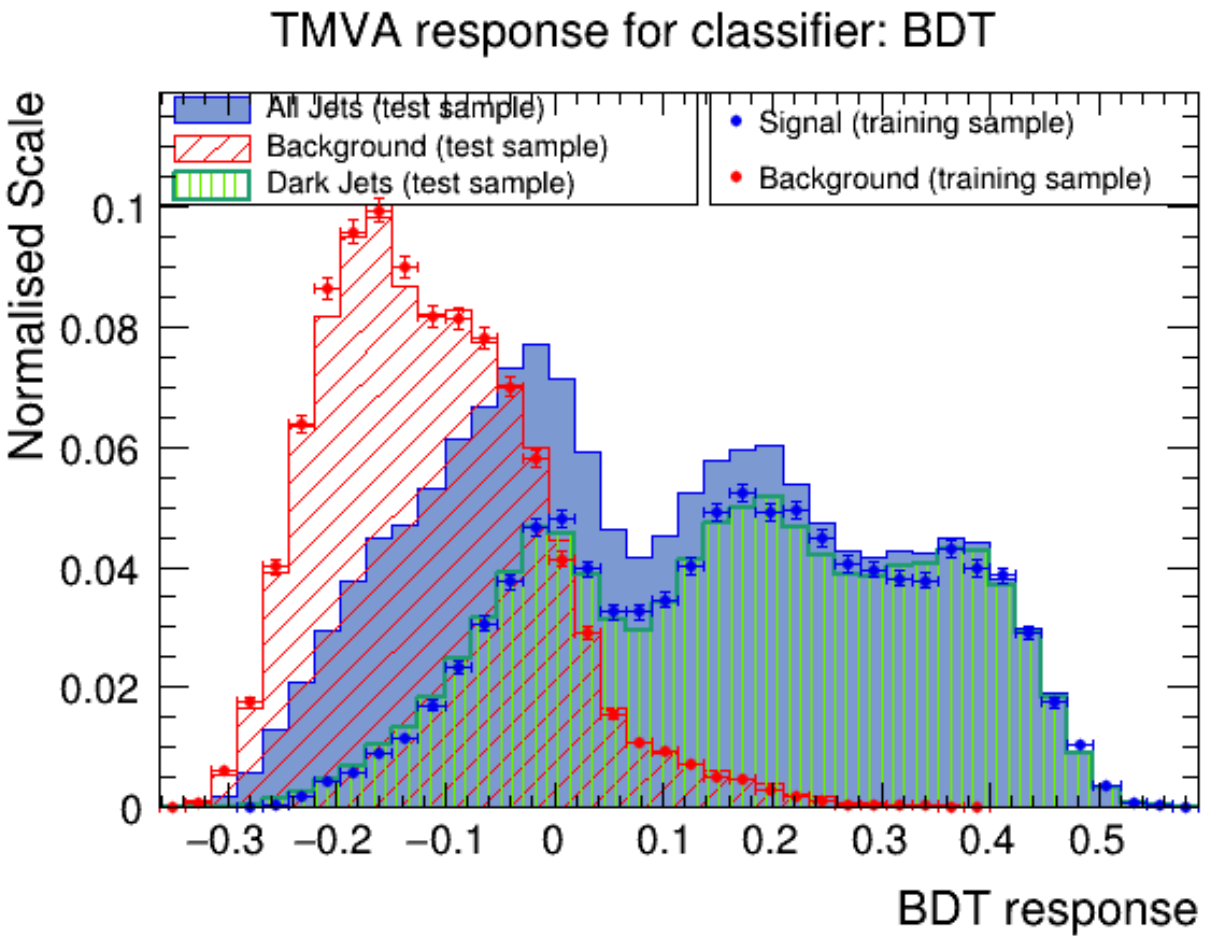




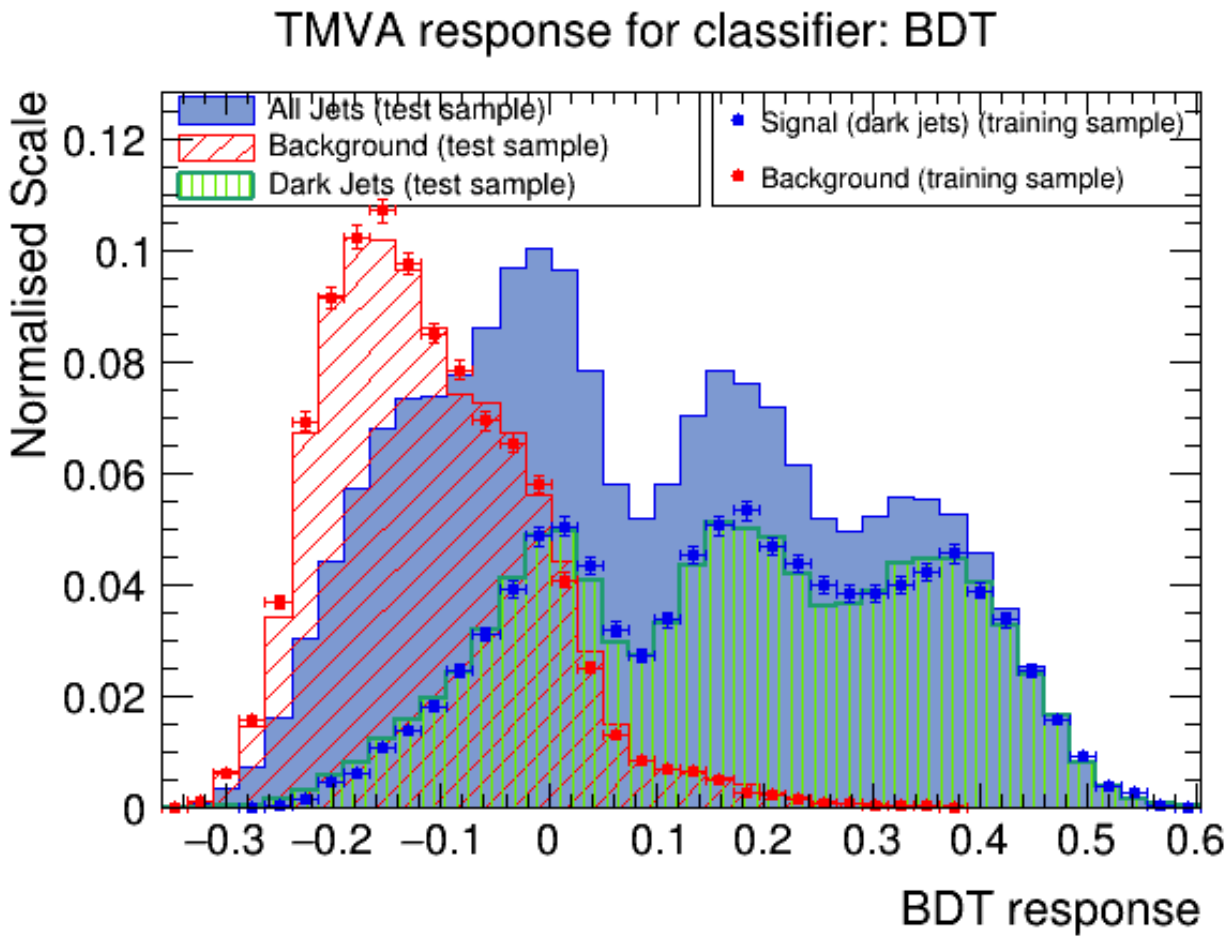


Jet Level Trees

Trained on all dark jets



Trained 4 leading dark jets

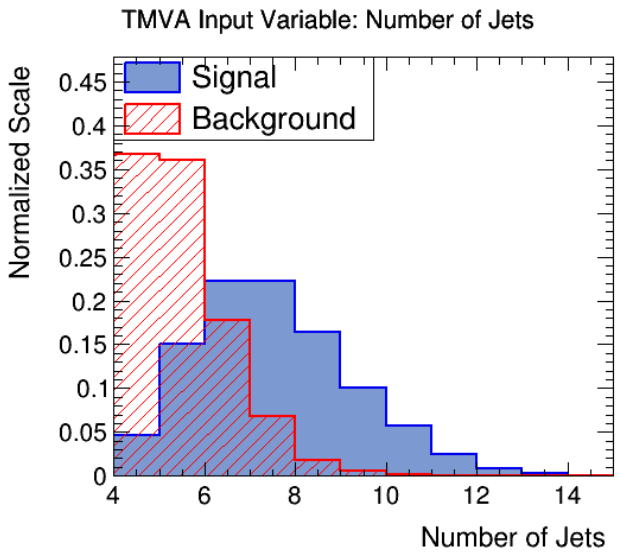


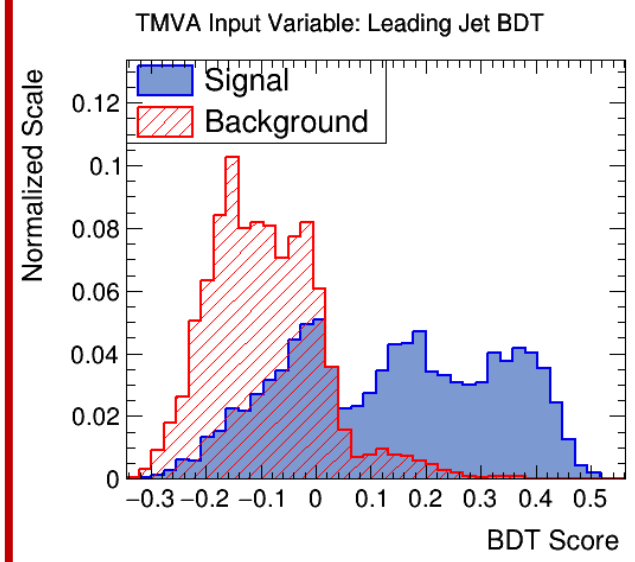
Model: A 1400 GeV 20 mm

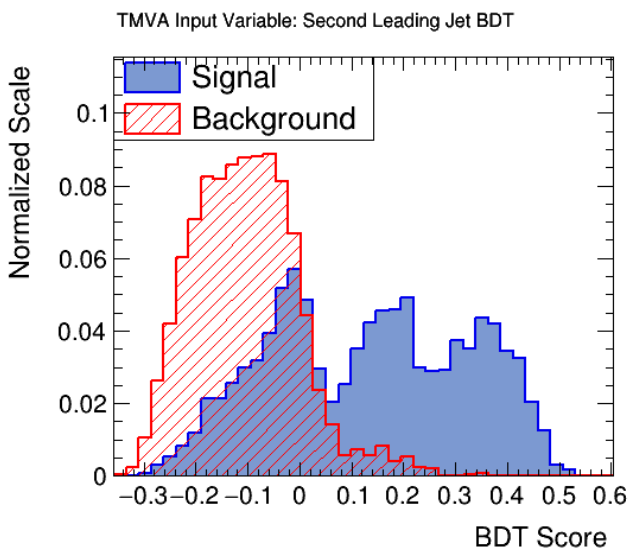
Event level BDT input variables

Output from jet-level BDT

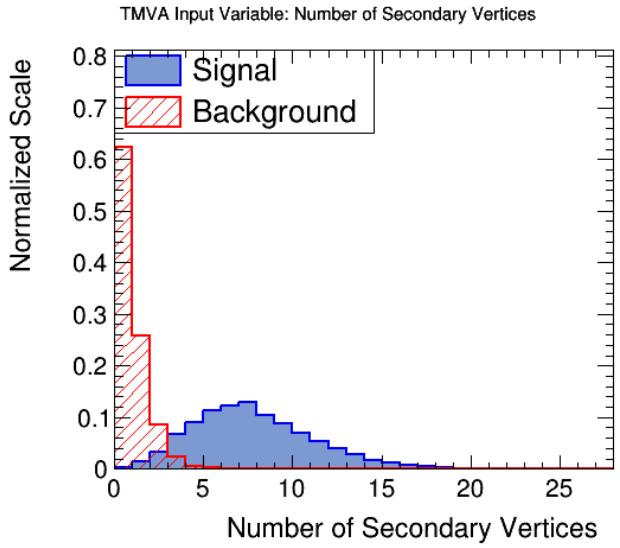
Model: A 1400 GeV 20 mm

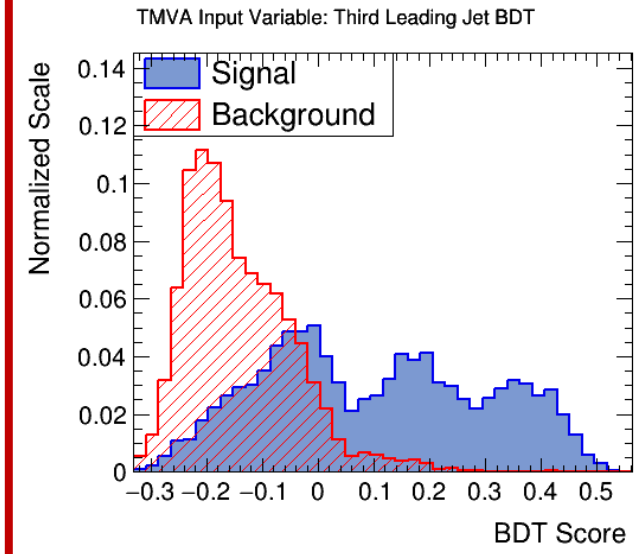


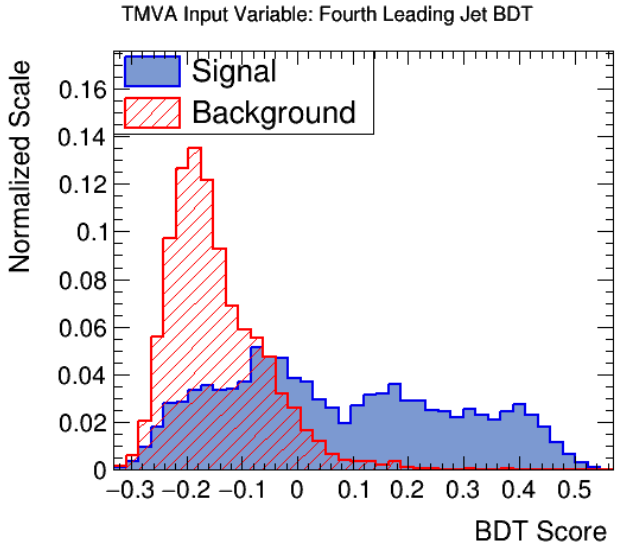




Trained on all dark jets





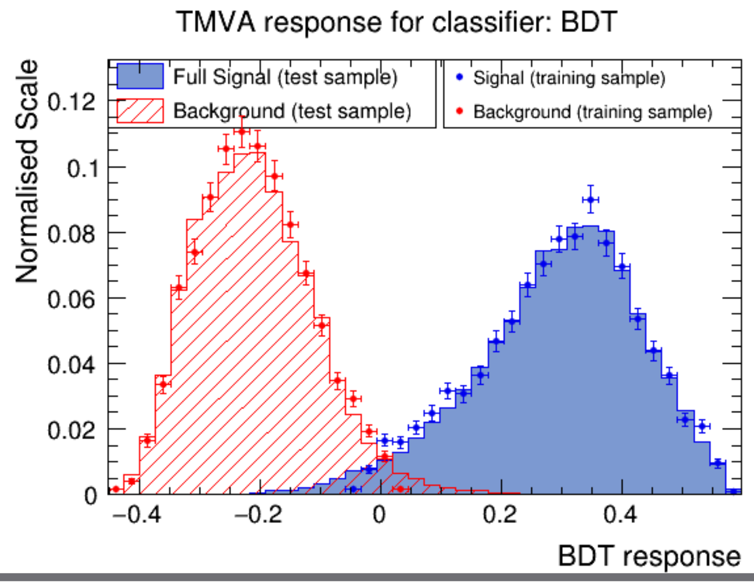


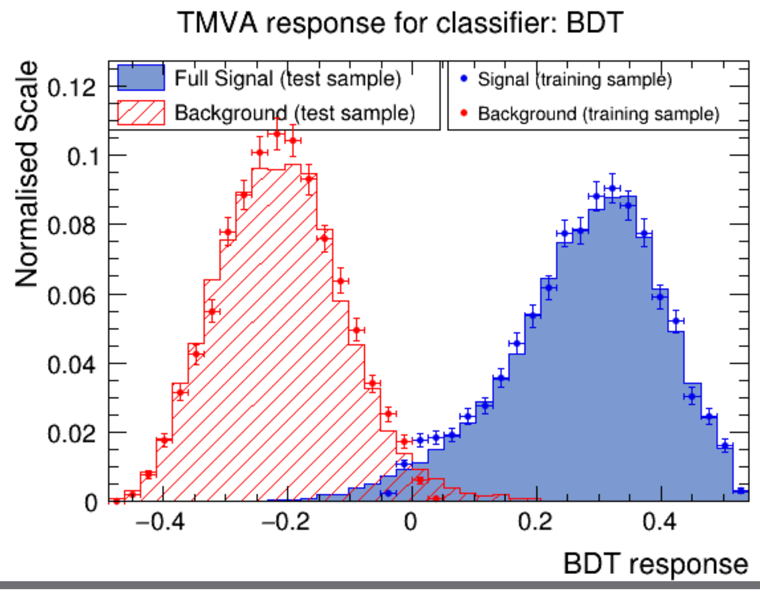
Event Level Trees

Model: A 1400 GeV 20 mm

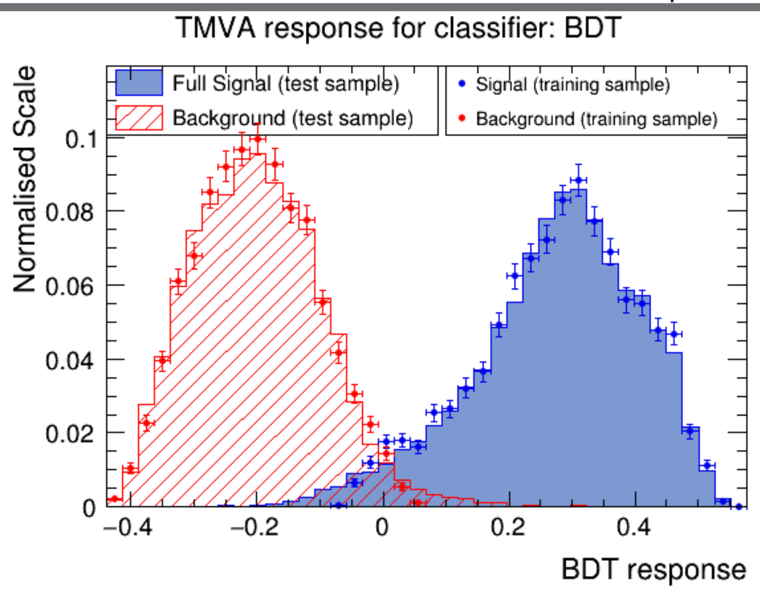
Trained on all dark jets | Trained 4 leading dark jets

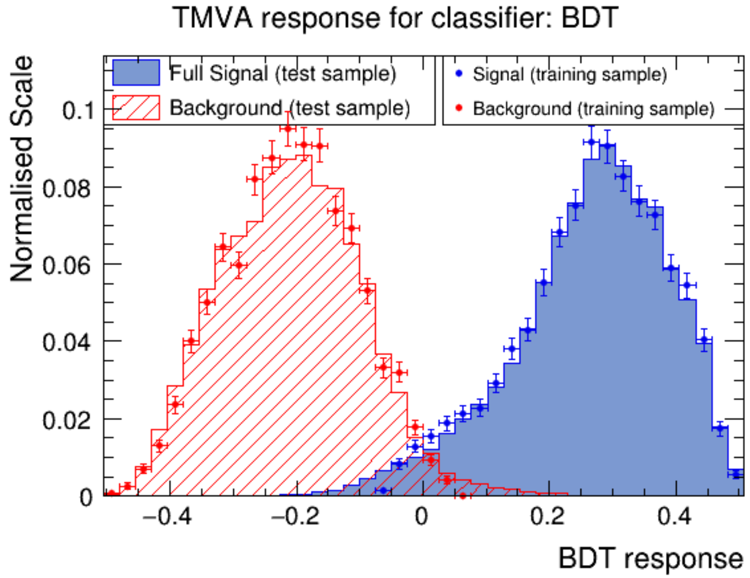
Including event HT





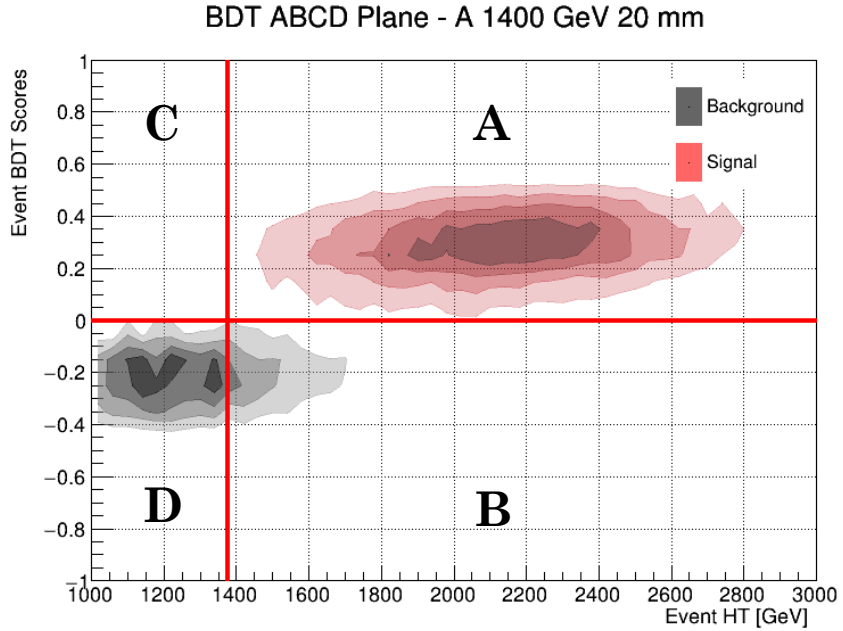
Not Including event HT

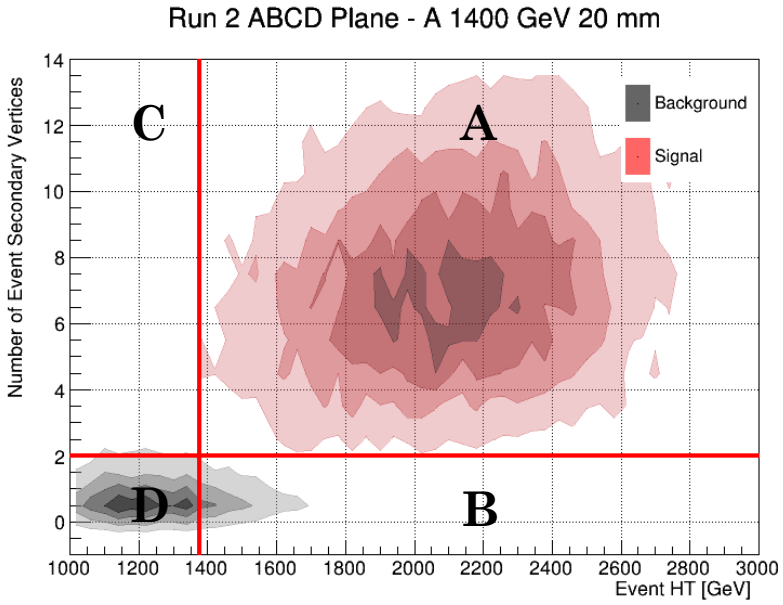


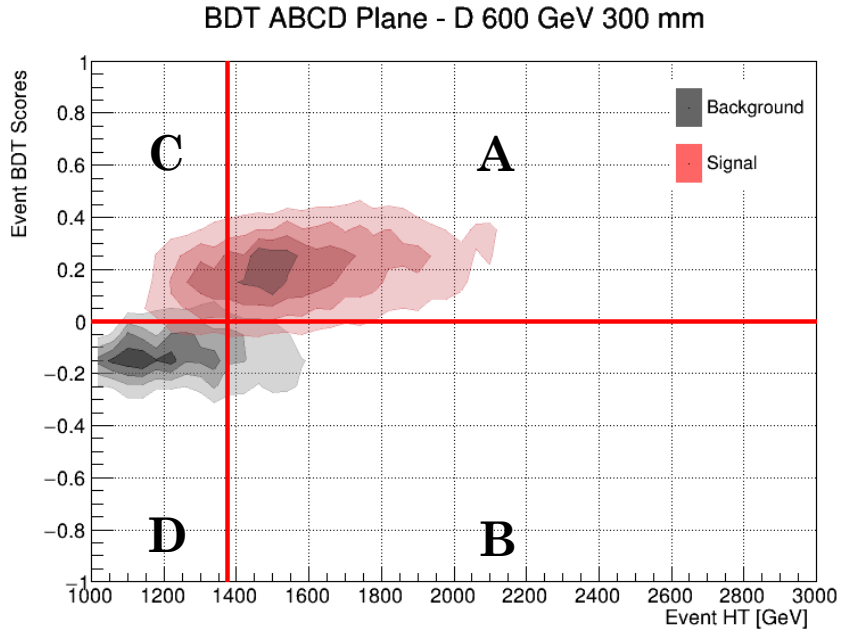


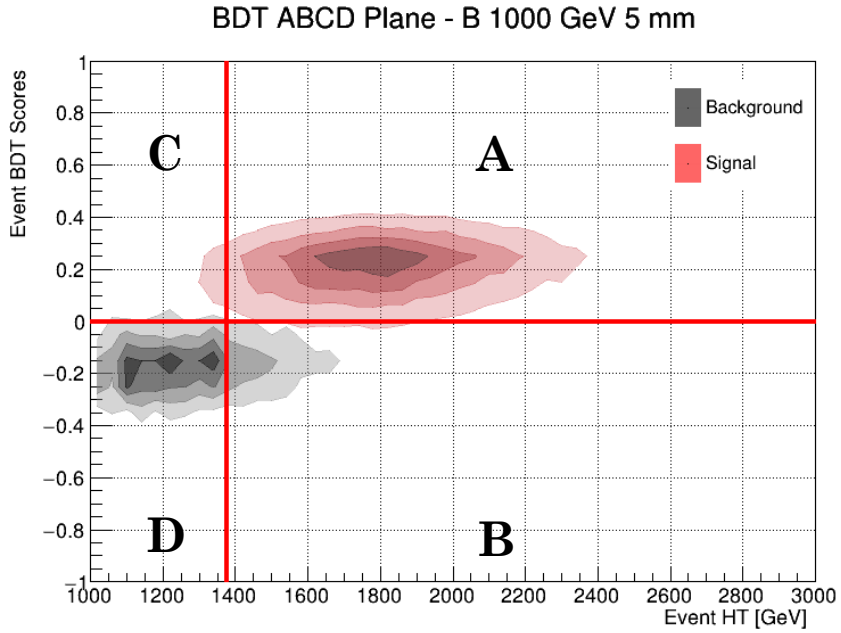
ABCD Comparisons

Trained on all dark jets









ABCD Summary Table

Trained on all dark matched jets
HT not included in training

Cuts:
HT: 1375
BDT: 0.0

Model	Signal Cross-section [fb]	Region A Signal Yield	Region A Weighted Background Yield	Signal Efficiency	Background Efficiency
A 1400 GeV 20 mm	1.1	39.2+/-0.3	6662.0+/-652.3	0.948	0.015
A 1000 GeV 150 mm	15	582.0+/-3.3	14929.1+/-1339.0	0.778	0.033
A 600 GeV 2 mm	430	4390.6+/-23.8	28838.1+/-1546.3	0.609	0.064
B 1400 GeV 20 mm	1.1	32.6+/-0.2	9864.3+/-944.9	0.932	0.022
B 1000 GeV 5 mm	15	864.3+/-4.3	13612.5+/-1315.7	0.876	0.030
B 600 GeV 300 mm	430	815.0+/-13.2	22376.4+/-1547.9	0.454	0.050
C 1400 GeV 75 mm	1.1	47.7+/-0.3	7332.5+/-908.5	0.954	0.016
C 1000 GeV 5 mm	15	796.4+/-3.3	7399.6+/-1035.0	0.896	0.016
C 600 GeV 2 mm	430	3344.2+/-27.3	18704.7+/-1417.6	0.692	0.042
D 1400 GeV 2 mm	1.1	58.6+/-0.3	6529.5+/-667.2	0.967	0.015
D 1000 GeV 1 mm	15	675.8+/-4.3	15762.7+/-1262.1	0.899	0.035
D 600 GeV 300 mm	430	1979.6+/-21.9	17023.7+/-1328.8	0.739	0.038
E 1400 GeV 75 mm	1.1	16.8+/-0.2	21367.4+/-1541.7	0.844	0.047
E 1000 GeV 150 mm	15	306.4+/-2.7	23450.8+/-1479.9	0.602	0.051
E 600 GeV 0.5 mm	430	5780.7+/-42.4	44117.9+/-2099.5	0.525	0.098

Cuts on BDT Scores

Trained on all dark matched jets
HT included in training

Cut: BDT > 0.2

Model	Cross-Section [fb]	Signal Events Above Cut	Background Events Above Cut	Signal Efficiency	Background Efficiency
A 1400 GeV 20 mm	1.1	31.8+/-0.2	629.9+/-420.8	0.770	0.001
A 1000 GeV 150 mm	15	419.5+/-2.8	343.9+/-136.2	0.560	0.001
A 600 GeV 2 mm	430	1772.7+/-15.1	659.4+/-209.3	0.246	0.001
B 1400 GeV 20 mm	1.1	23.0+/-0.2	151.5+/-58.4	0.658	0.000
B 1000 GeV 5 mm	15	507.0+/-3.3	193.3+/-71.7	0.514	0.000
B 600 GeV 300 mm	430	744.3+/-12.6	2874.2+/-1146.3	0.414	0.006
C 1400 GeV 75 mm	1.1	37.9+/-0.2	162.1+/-124.8	0.757	0.000
C 1000 GeV 5 mm	15	573.3+/-2.8	38.1+/-21.0	0.645	0.000
C 600 GeV 2 mm	430	2177.9+/-22.0	971.8+/-332.6	0.451	0.002
D 1400 GeV 2 mm	1.1	47.0+/-0.2	80.3+/-33.4	0.775	0.000
D 1000 GeV 1 mm	15	370.5+/-3.2	168.0+/-52.0	0.493	0.000
D 600 GeV 300 mm	430	1307.2+/-17.8	215.8+/-139.2	0.488	0.000
E 1400 GeV 75 mm	1.1	8.5+/-0.1	251.0+/-97.6	0.425	0.001
E 1000 GeV 150 mm	15	197.2+/-2.2	2340.4+/-781.2	0.387	0.005
E 600 GeV 0.5 mm	430	1648.5+/-22.6	4462.5+/-897.0	0.150	0.010

Conclusions

- Hidden valley models with emerging jets provide an interesting and unique signature that can be searched for at the LHC
- Run 2 model independent analysis progressing
- Progress towards a Run 3 sensitivity study started
  - Use of ML tools to optimize sensitivity looks promising
  - Could require alternate background estimate technique
  - Will necessitate careful evaluation of MC systematics
- Next Steps:
  - Evaluate additional classification variables
  - Explore alternate ML methods
  - Evaluate effects of MC systematics
  - Consider alternate background estimate strategies
- Lots of scope for expanding model space

Acknowledgements

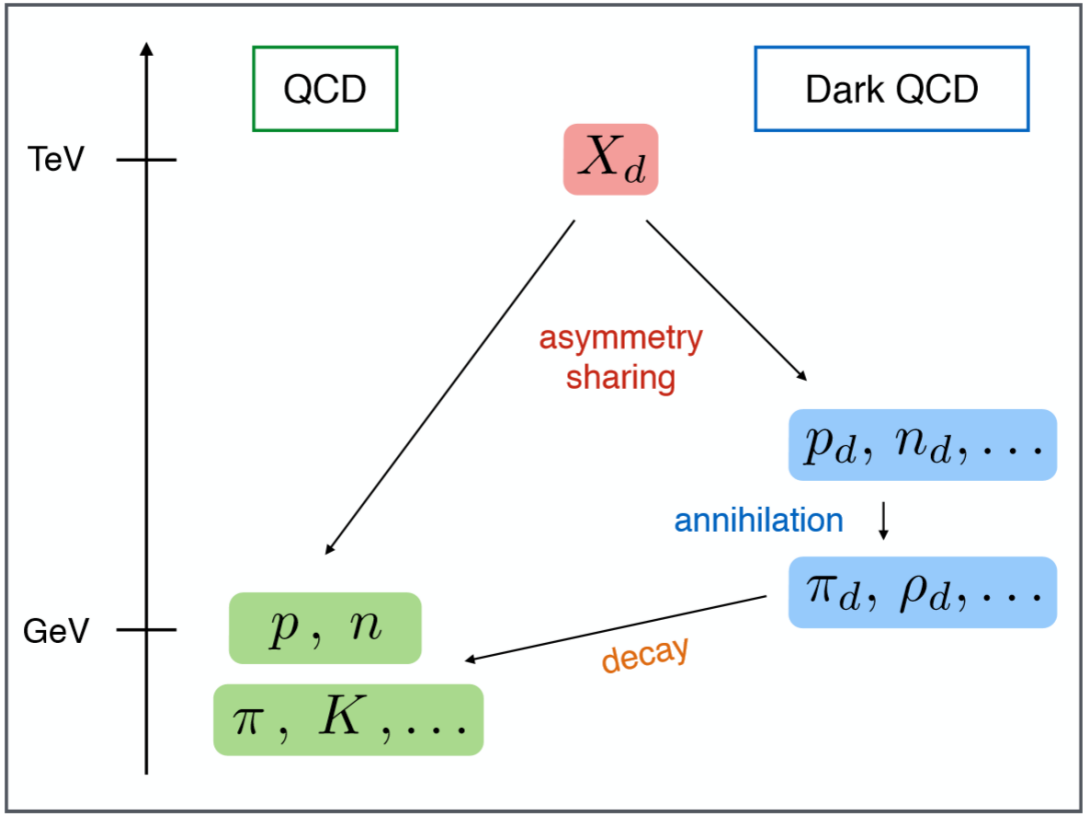
Emerging Jets Members: J. Beacham, B. Death, G. Gonella, K. Graham, A. Haas, J. Heilman, A. Kilgallon, M. Naseri, I. Ramirez-Berend, D. Rocha, D. Strom, C. Treado

Thank you to NSERC for support under USRA program

Extra Slides

Decay Structure

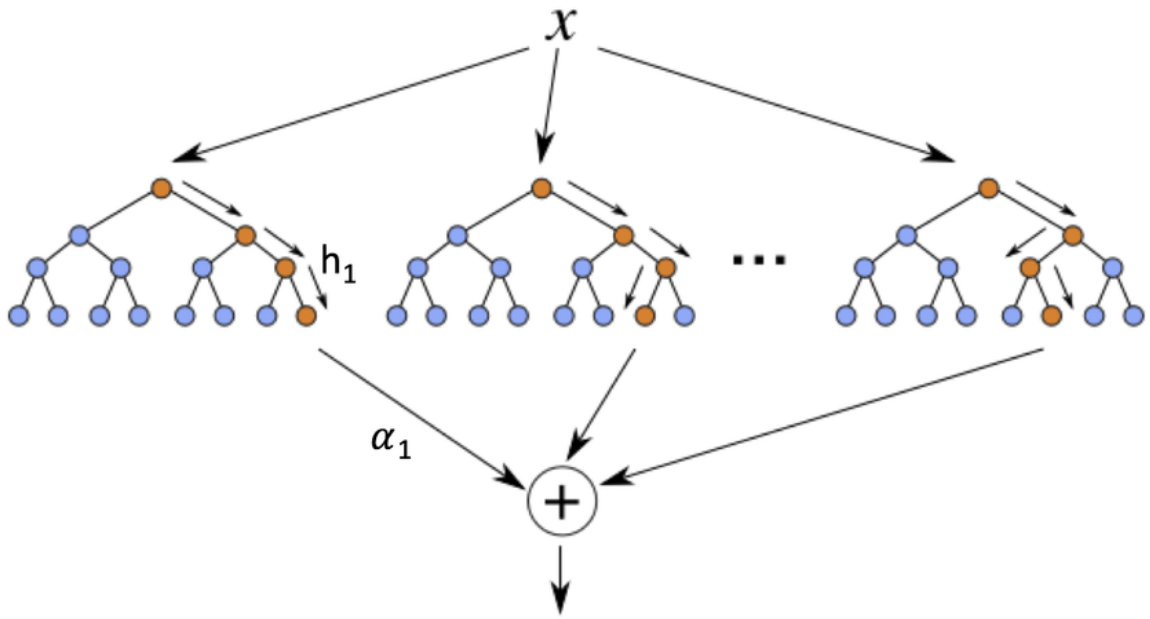
- Dark mediators decay to 2 SM down quarks and 2 dark quarks
- Dark quarks undergo QCD-like showering and hadronization
- Dark mesons decay to SM particles
- This process forms multiple displaced vertices and sub-jets



P. Schwaller, D. Stolarski, A. Weiler - arxiv:1502.05409

Boosted Decision Trees

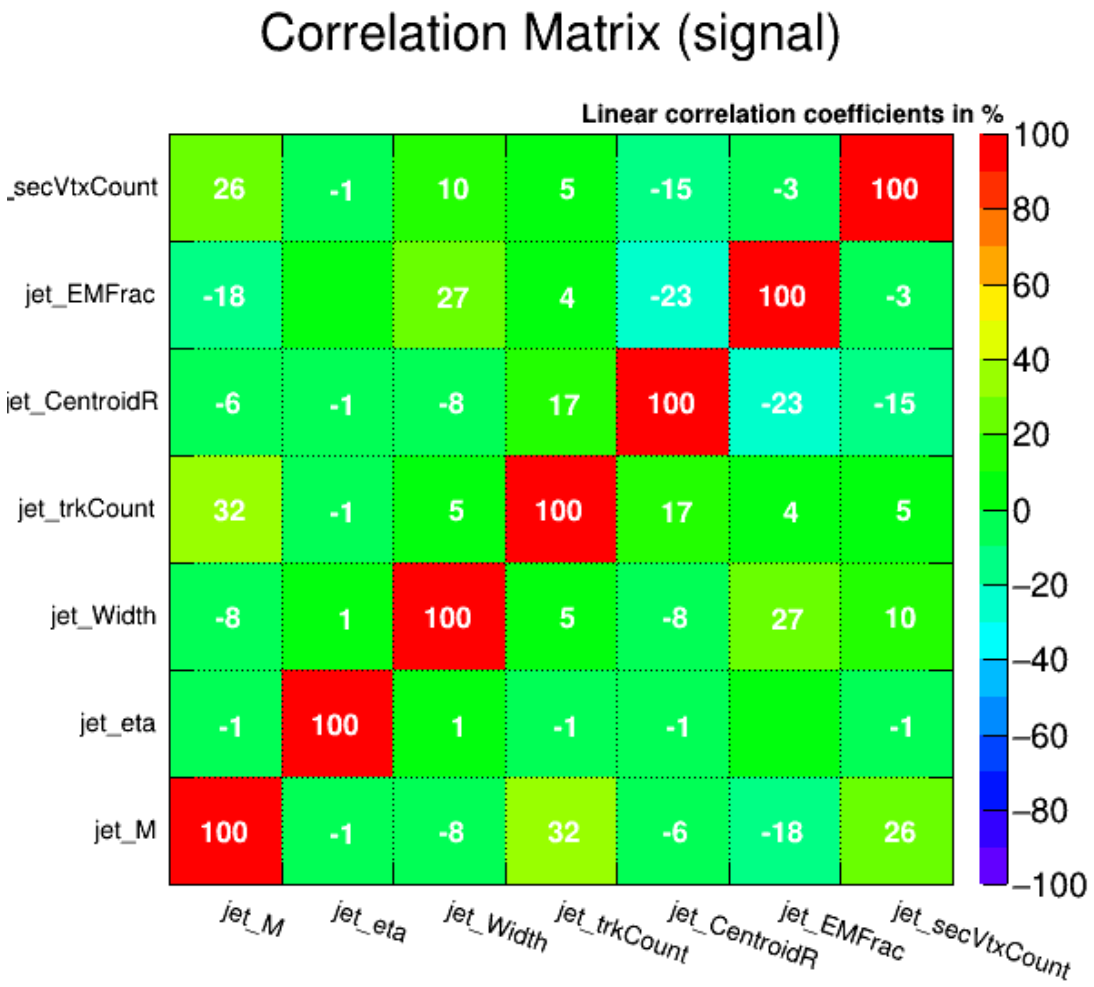
- Decision Trees – Classify events through a series of yes/no questions
- Boosting – Train many trees, ensemble scores events through weighted sum
- Default ROOT TMVA BDT settings – 800 trees, maximum height of 3

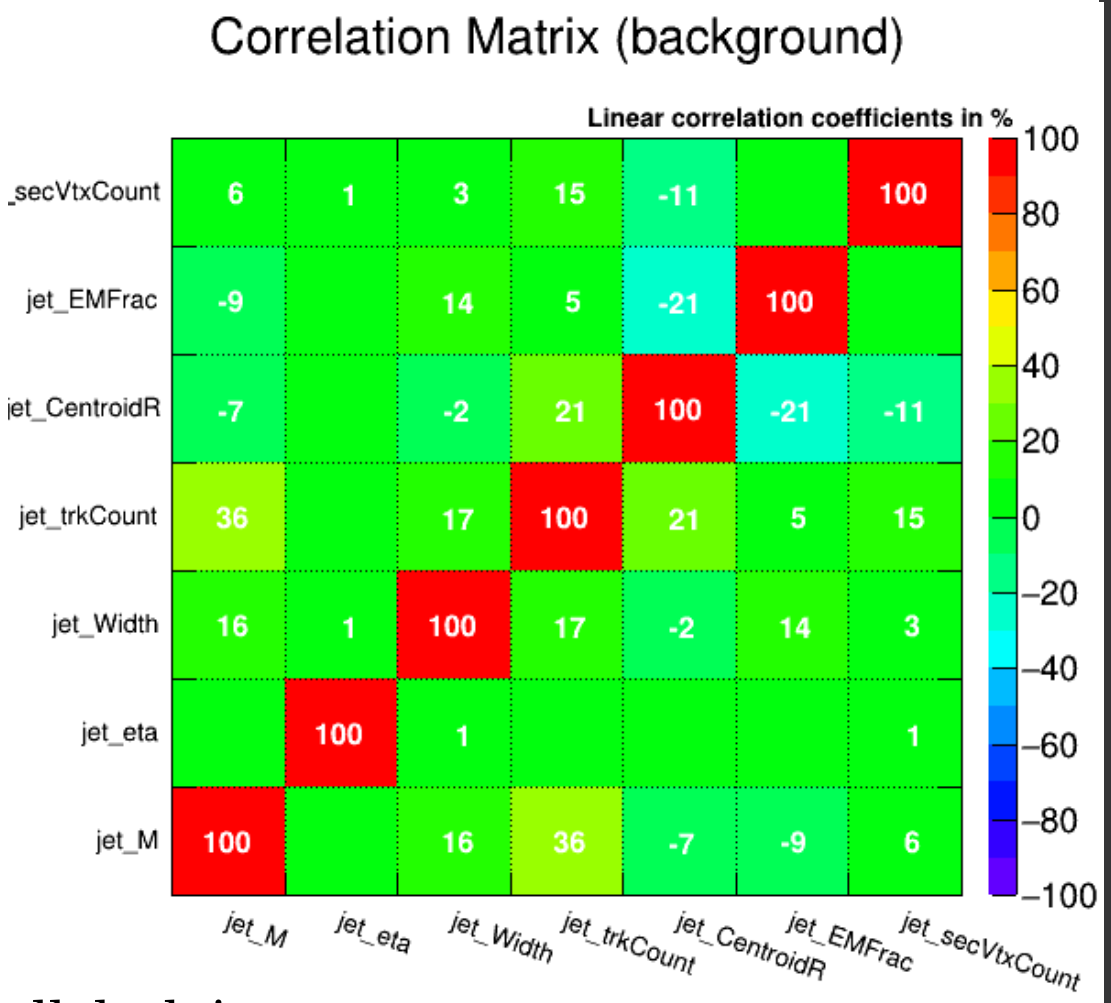


https://www.researchgate.net/figure/Schematic-diagram-of-a-boosted-ensemble-of-decision-trees_fig2_325632132

Jet-Level Input Variable Correlations

Model: A 1400 GeV 20 mm

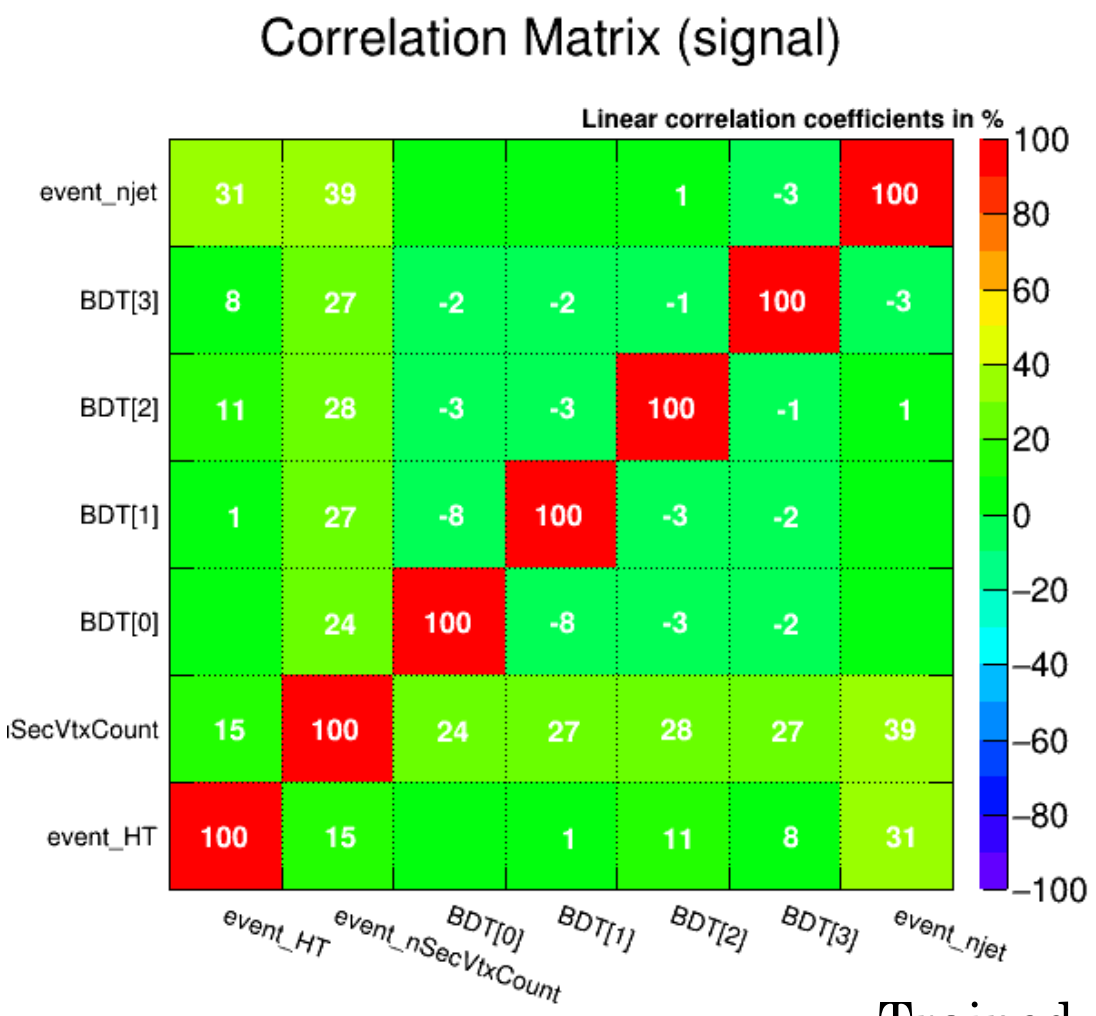


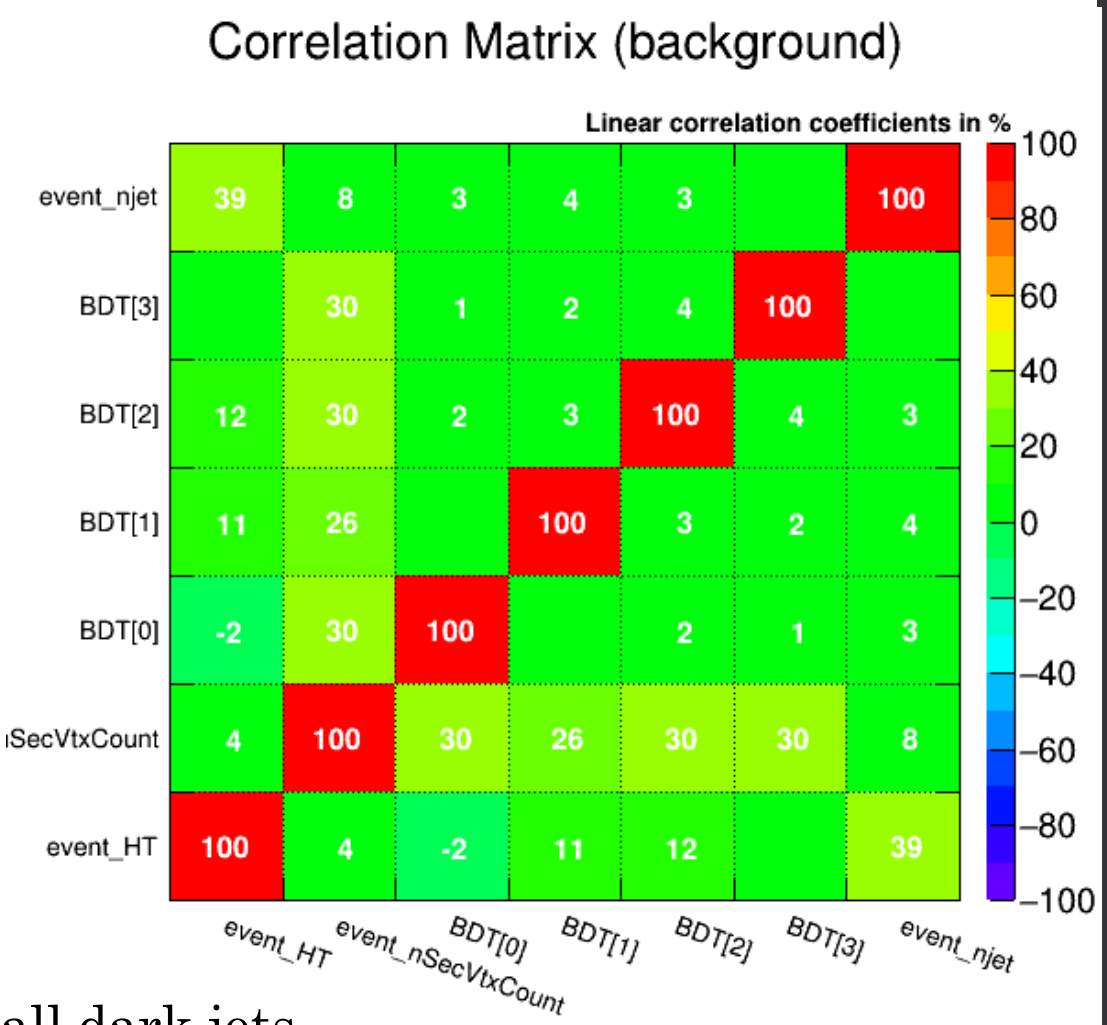


Trained on all dark jets

Event-Level Input Variable Correlations

Model: A 1400 GeV 20 mm





Trained on all dark jets

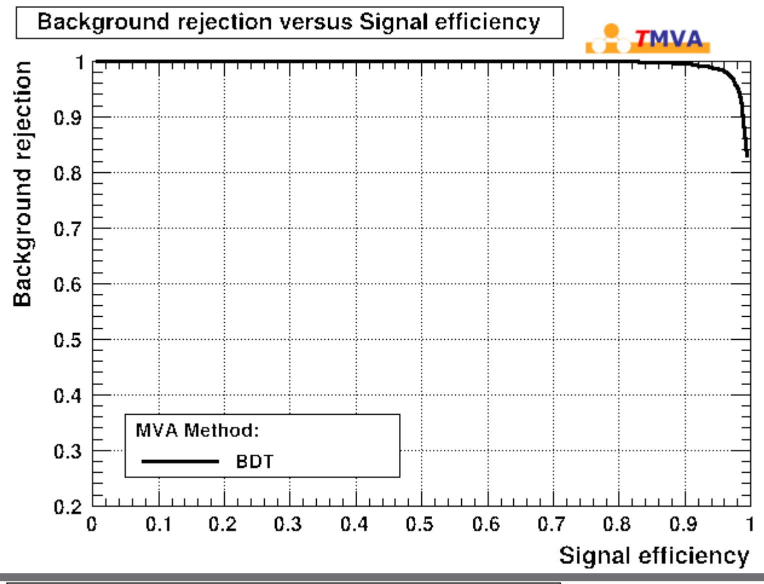
Event Level Trees ROC

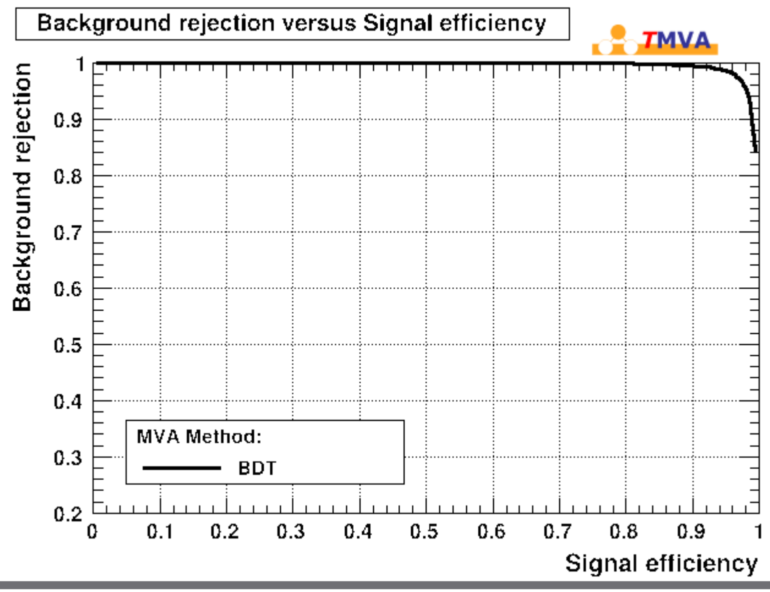
Model: A 1400 GeV 20 mm

Trained on all dark jets

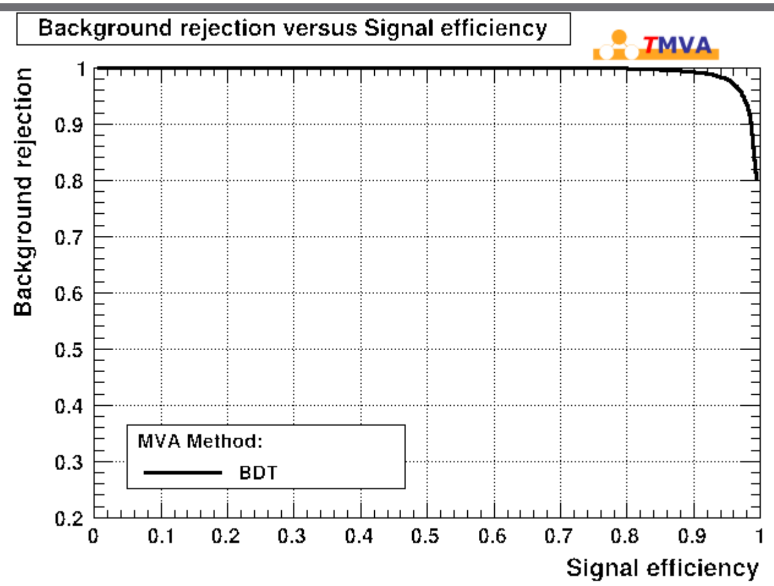
Trained 4 leading dark jets

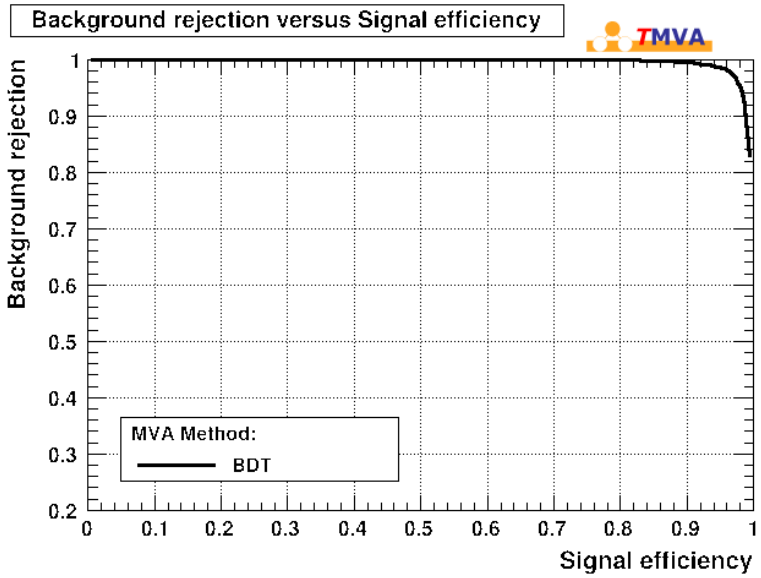
Including event HT





Not Including event HT



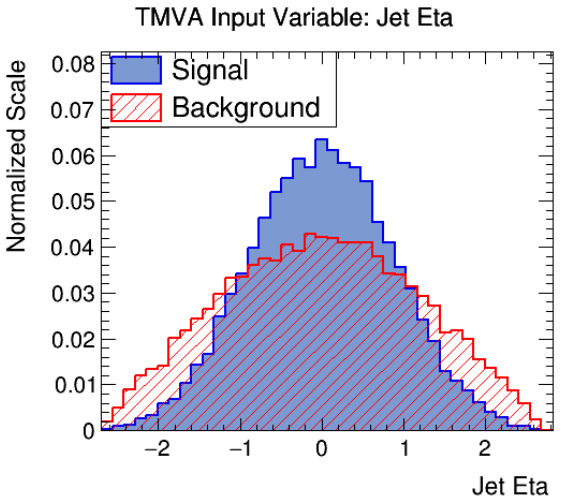


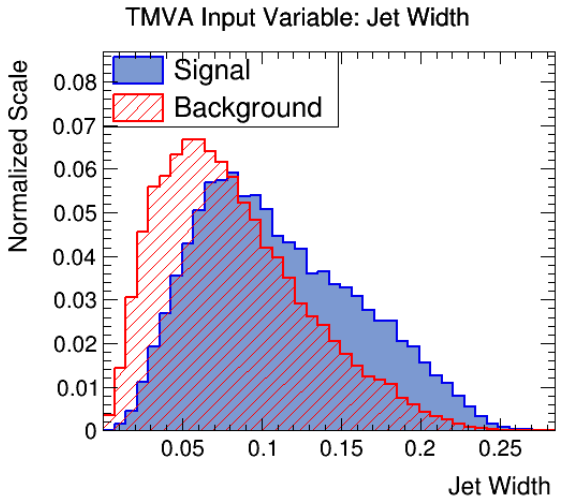
Events Unweighted

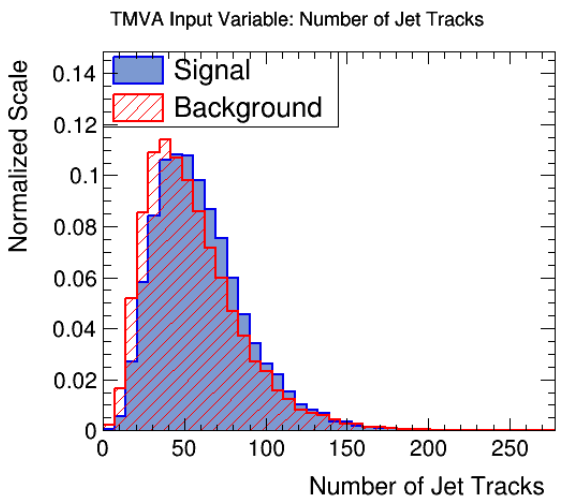
Jet-Level Input Variable Distributions

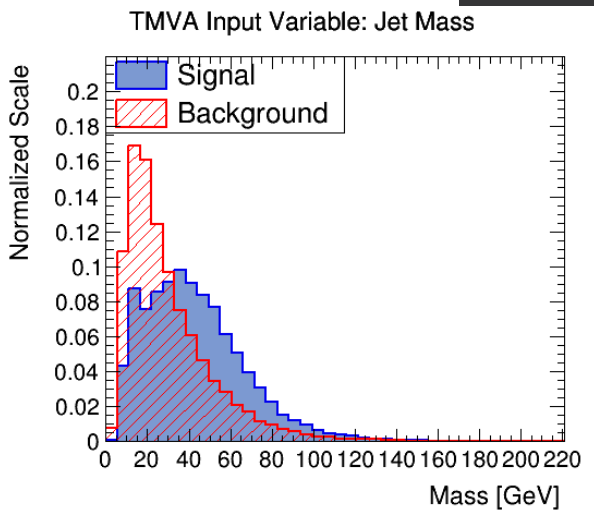
Model: B 1000 GeV 5 mm

$$\text{width} = \frac{1}{p_T^{jet}} \sum_i p_T^i \Delta R_i$$

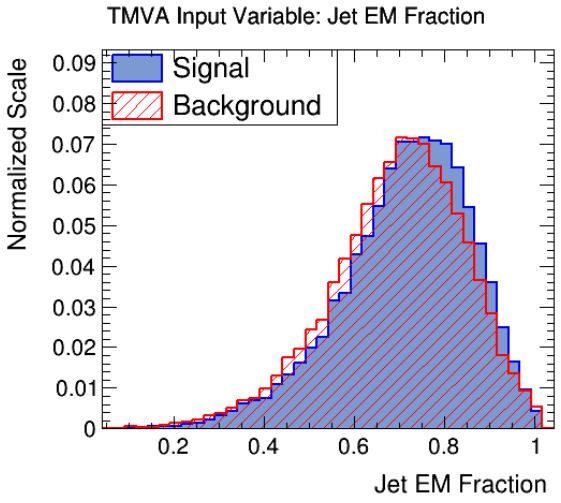


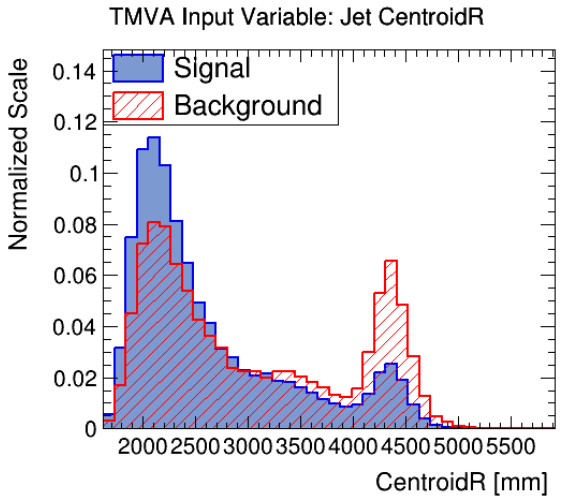


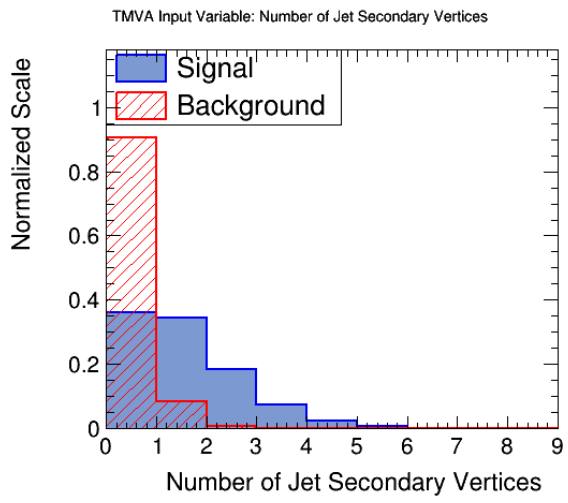




Trained on all dark jets

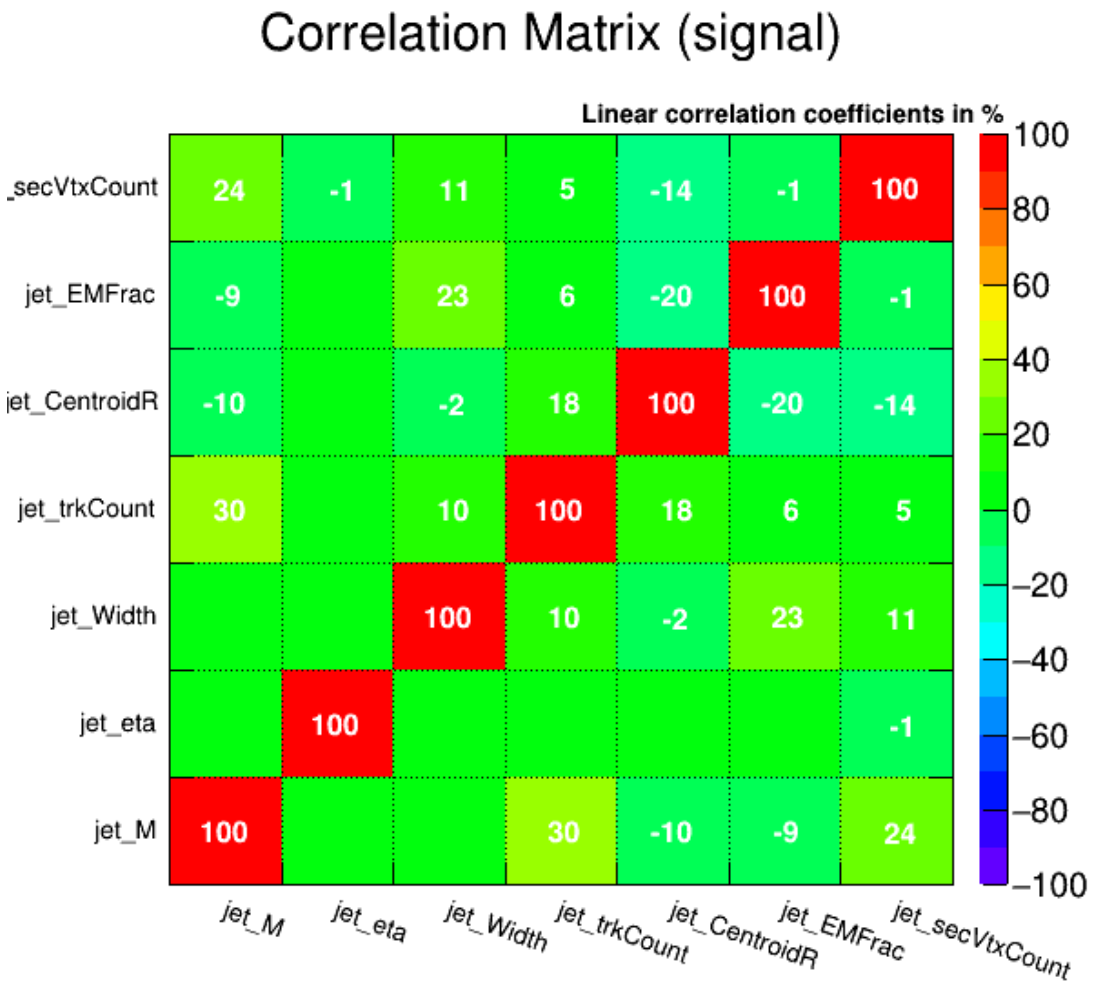


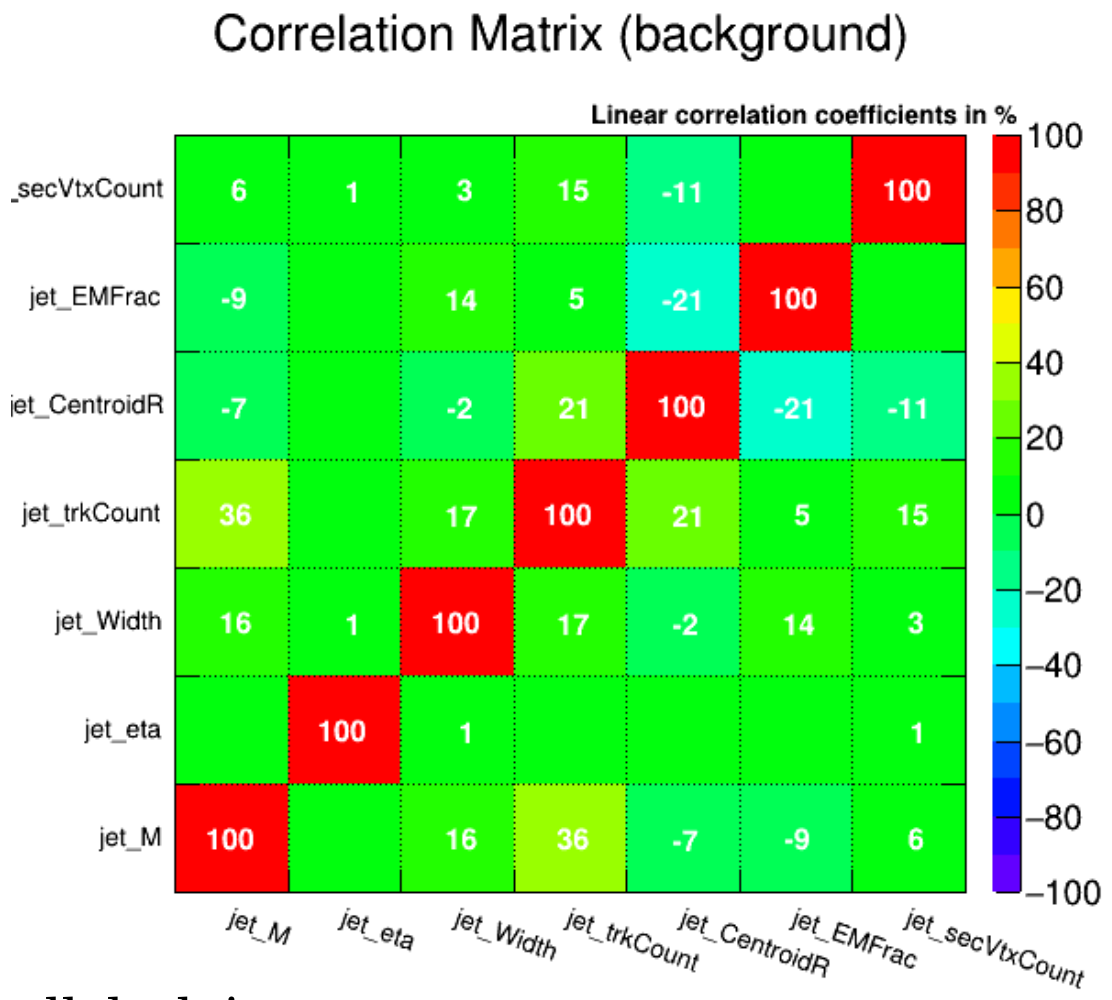




Jet-Level Input Variable Correlations

Model: B 1000 GeV 5 mm

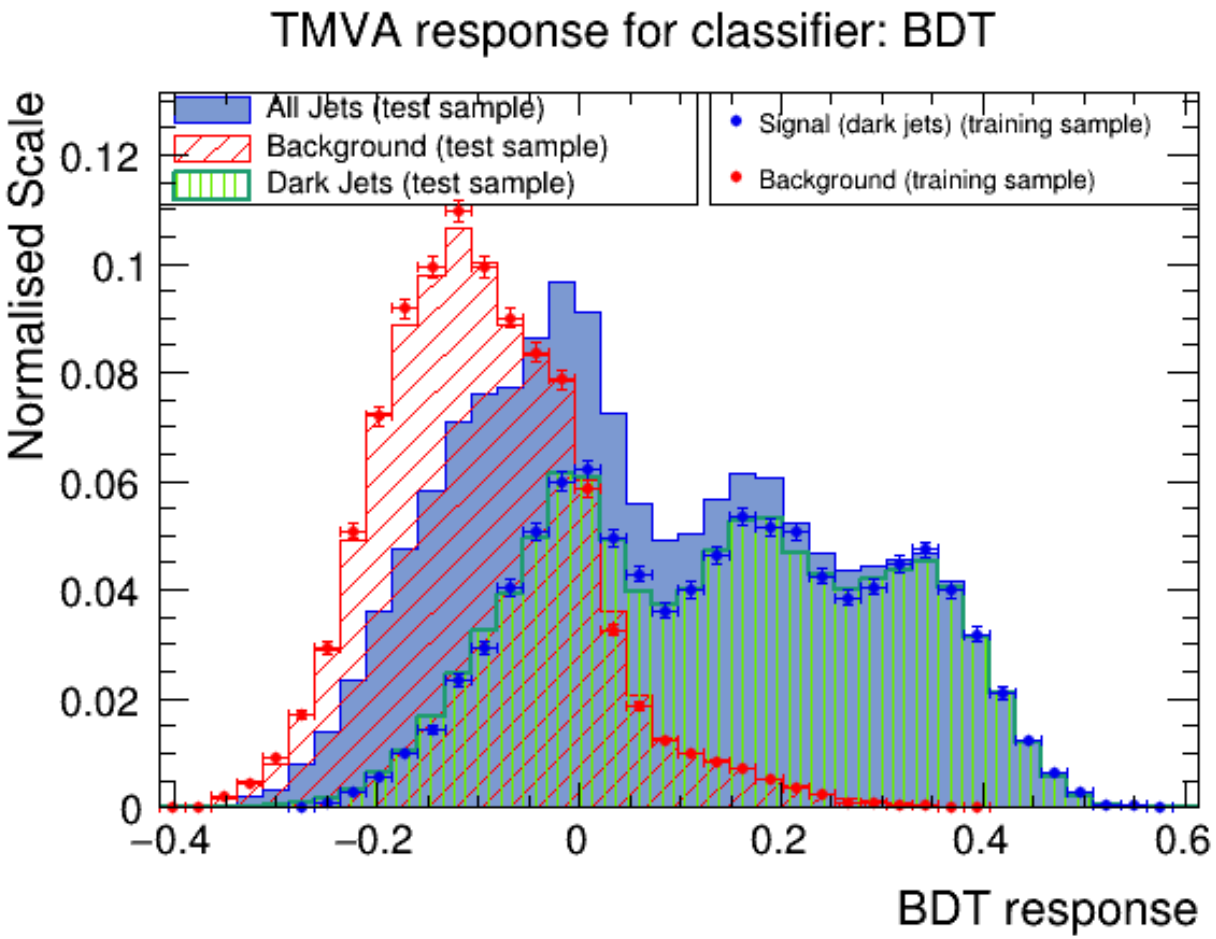




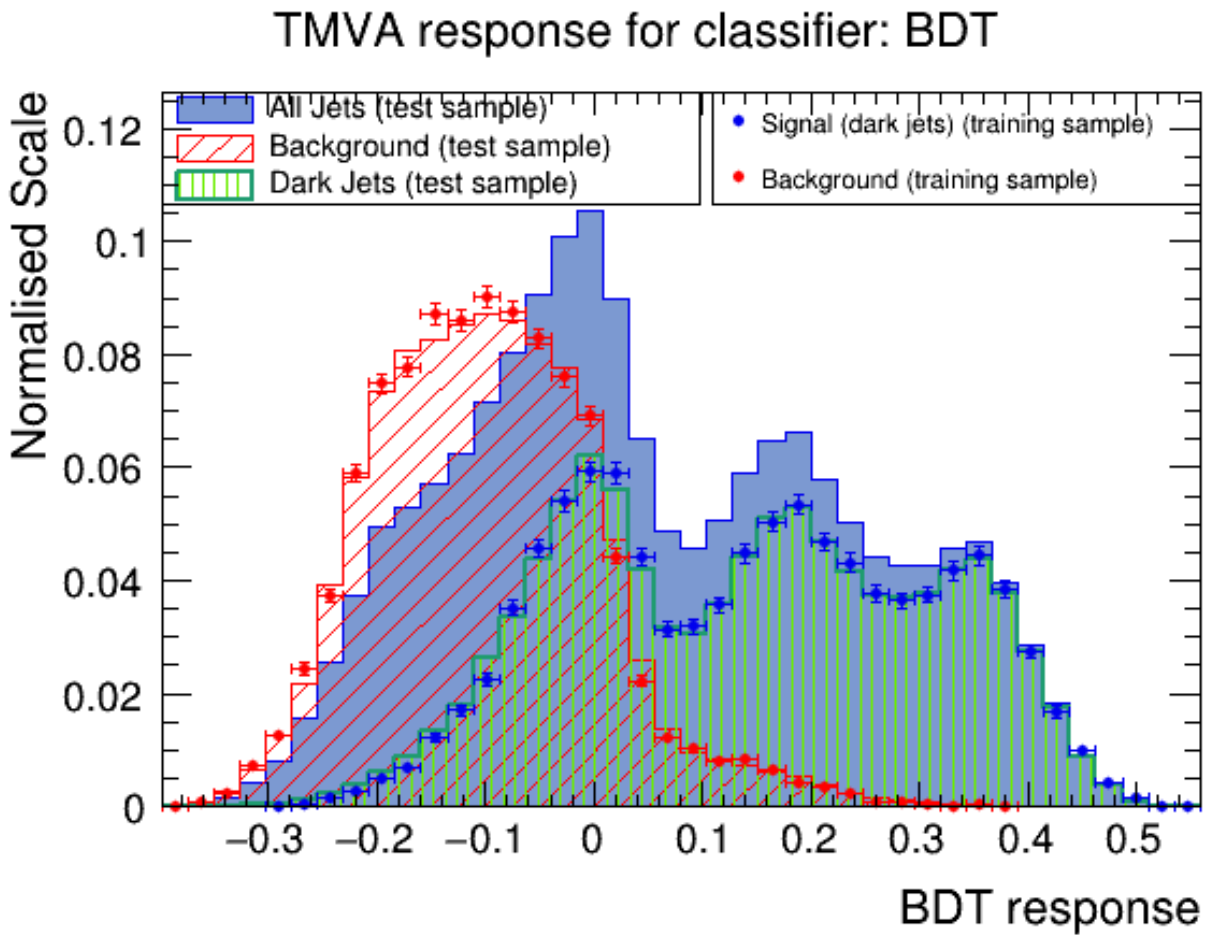
Trained on all dark jets

Jet Level Trees

Trained on all dark jets



Trained 4 leading dark jets

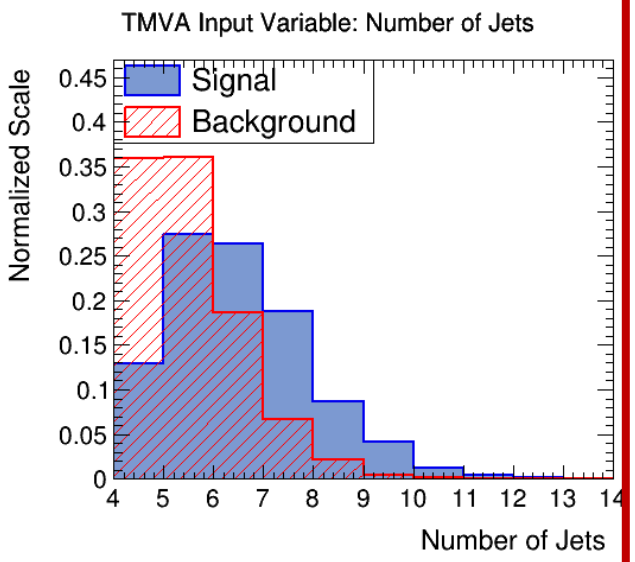


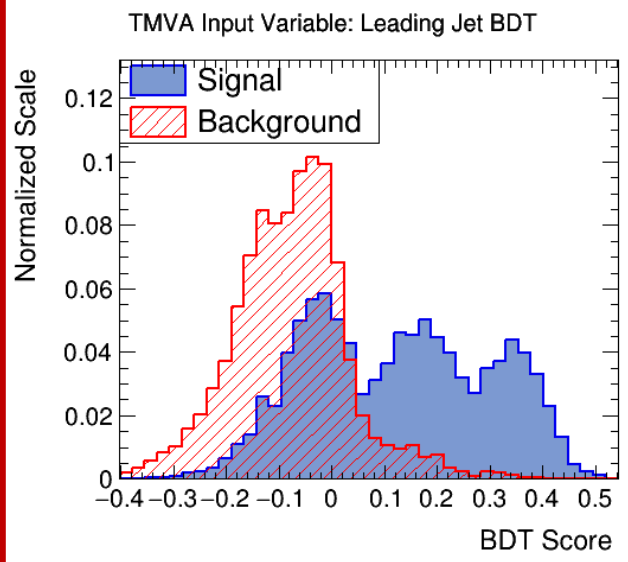
Model: B 1000 GeV 5 mm

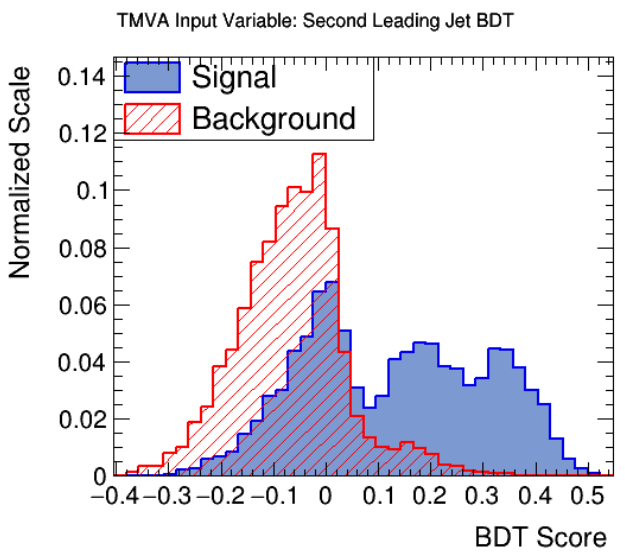
Event level BDT input variables

Output from jet-level BDT

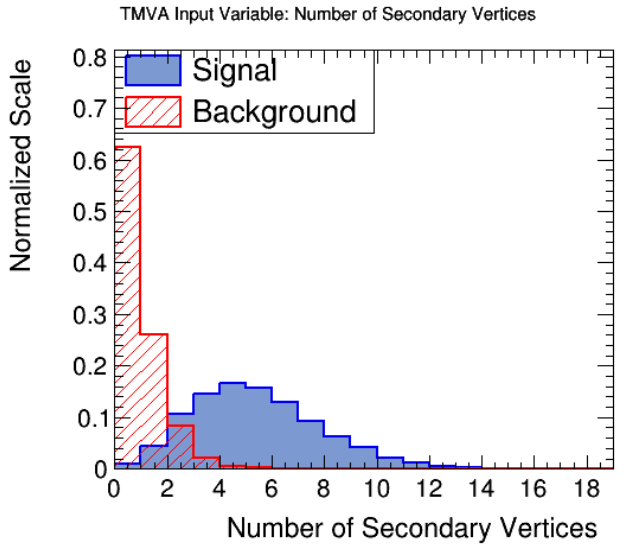
Model: B 1000 GeV 5 mm

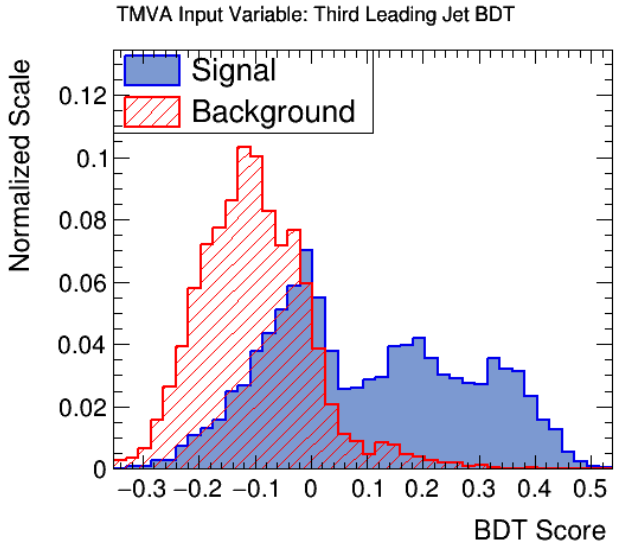


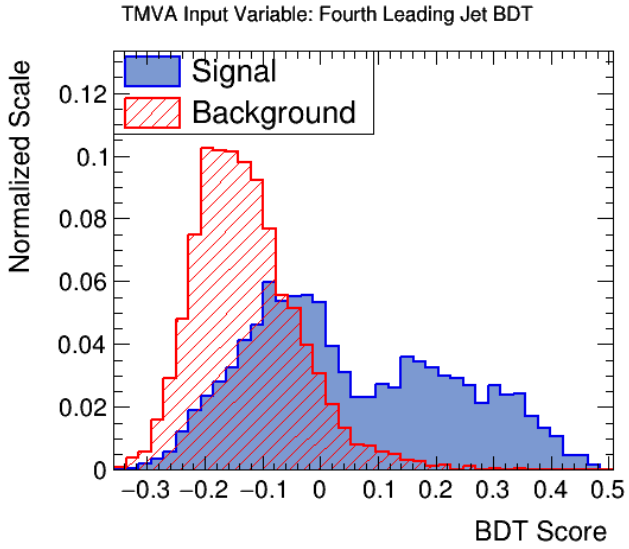




Trained on all dark jets

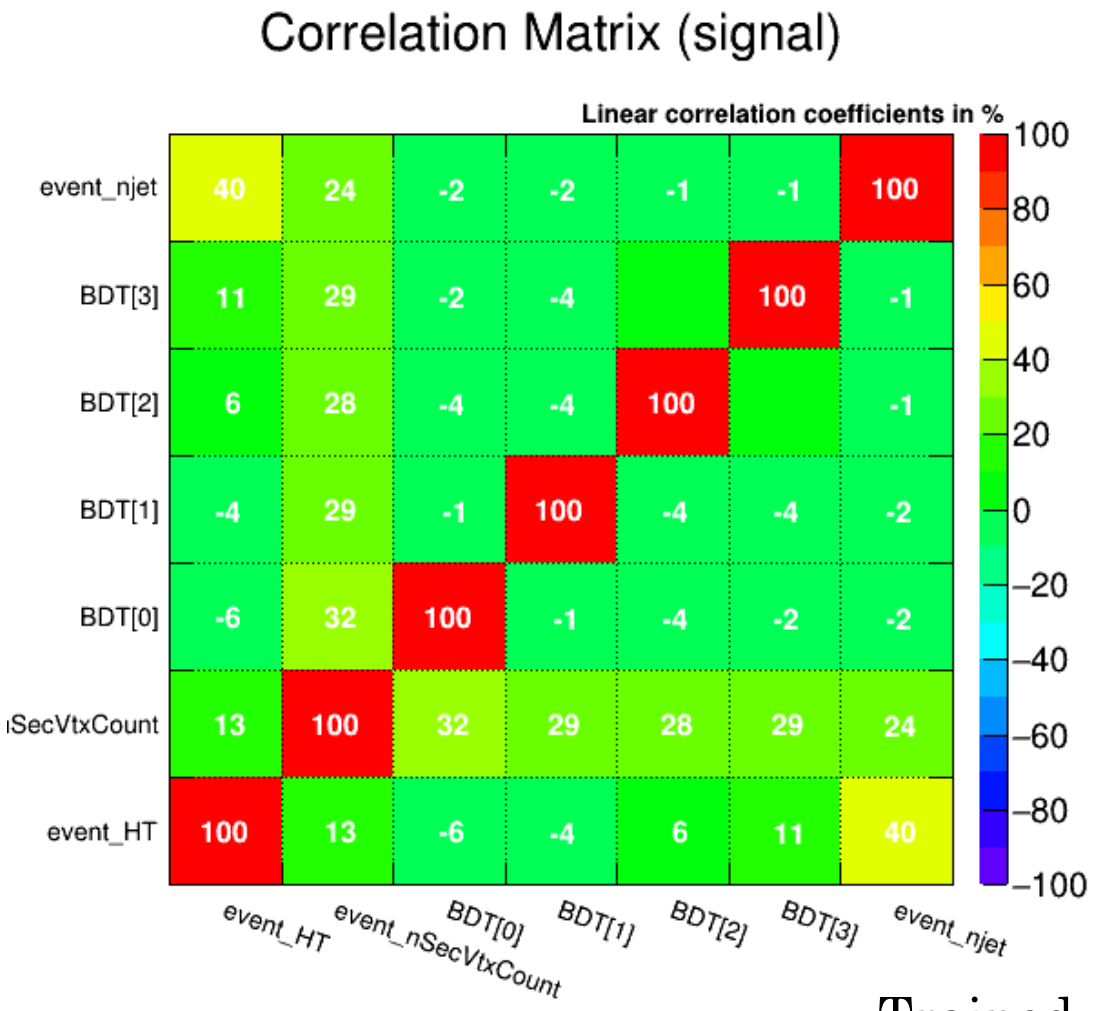


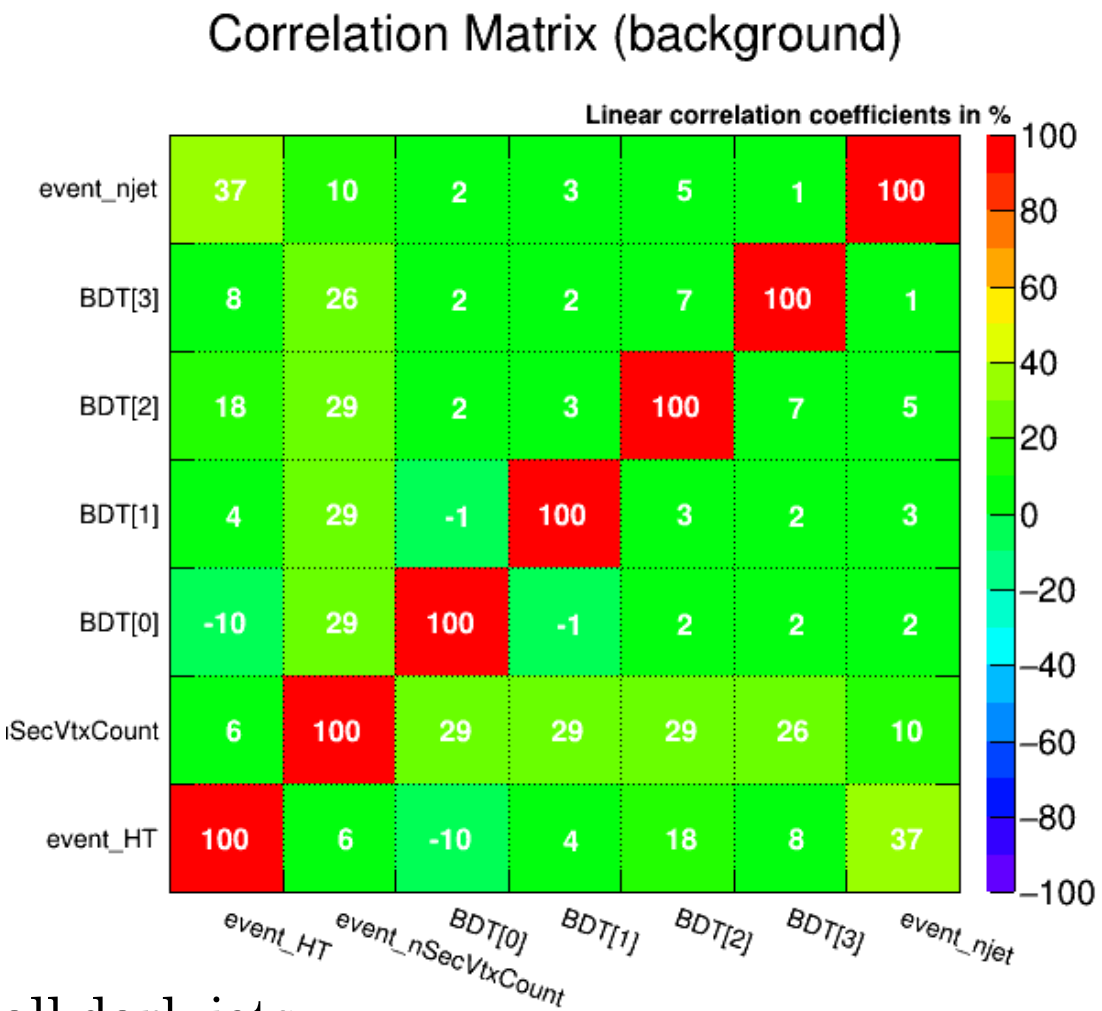




Event-Level Input Variable Correlations

Model: B 1000 GeV 5 mm





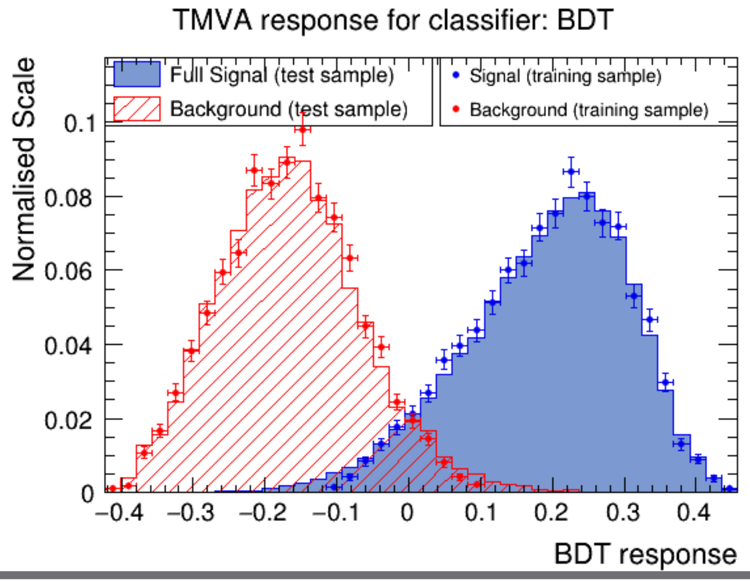
Trained on all dark jets

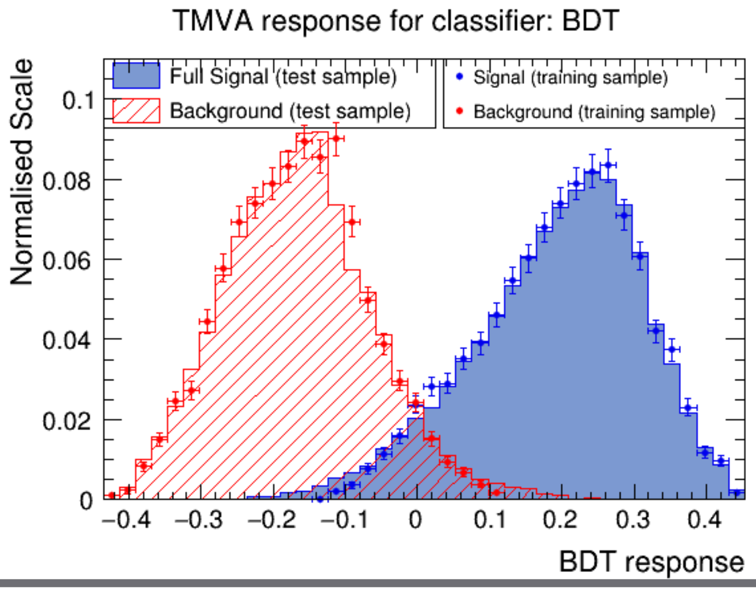
Event Level Trees

Model: B 1000 GeV 5 mm

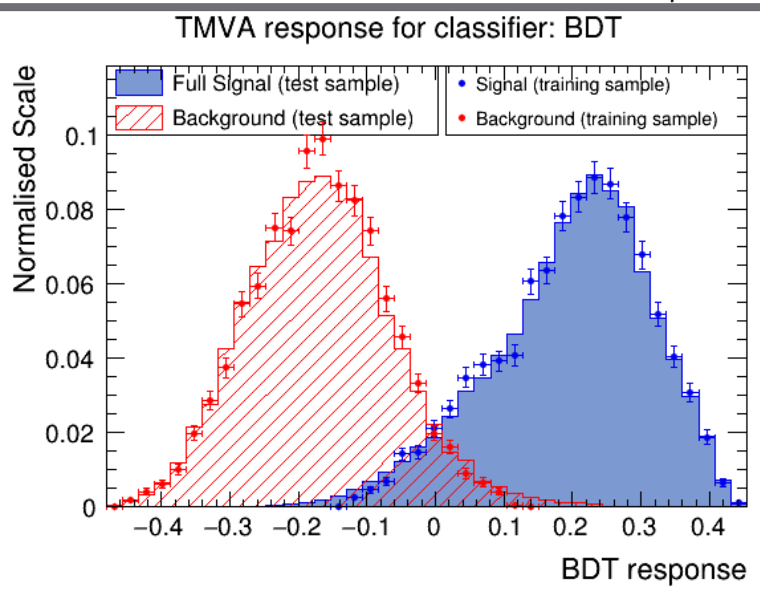
Trained on all dark jets | Trained 4 leading dark jets

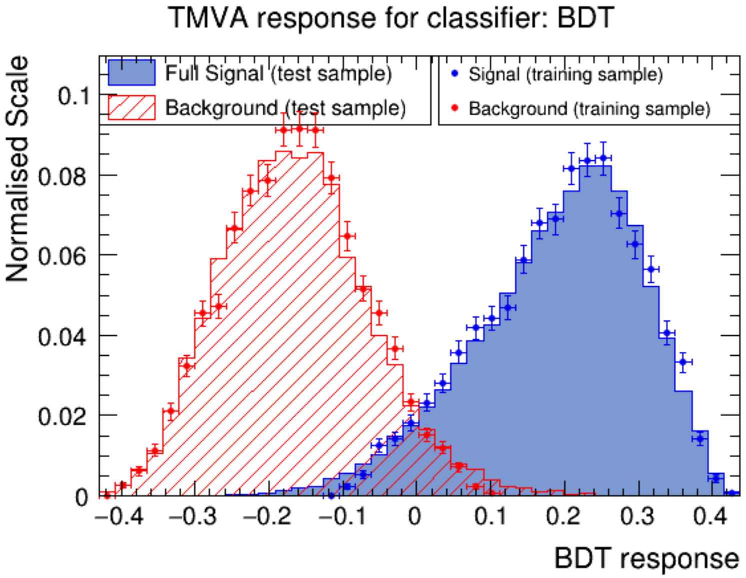
Including event HT





Not Including event HT





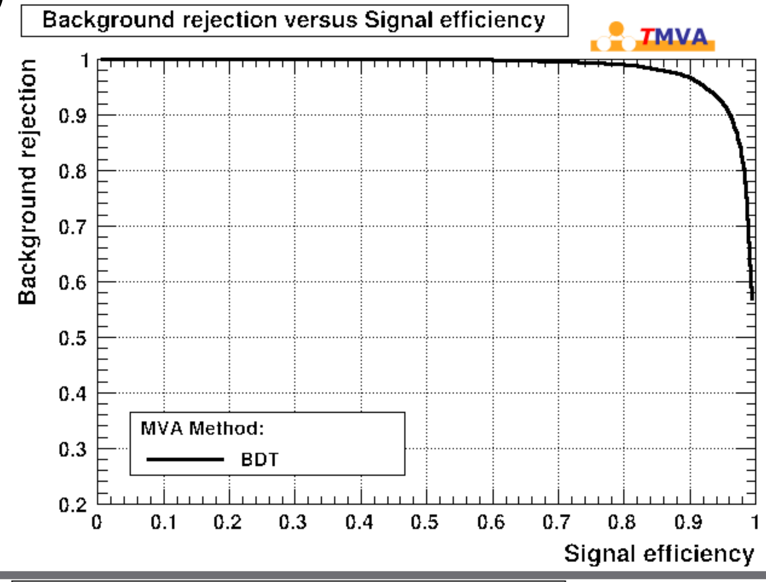
Model: B 1000 GeV 5 mm

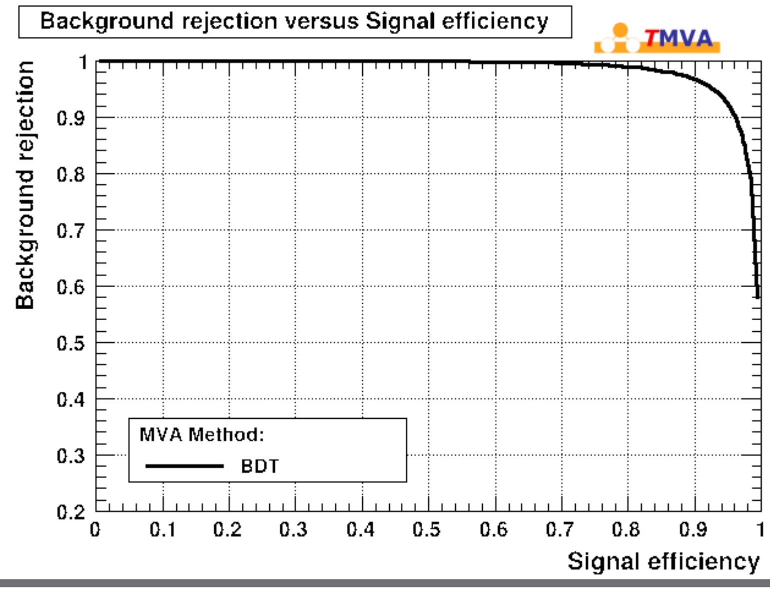
Event Level Trees ROC

Trained on all dark jets

Trained 4 leading dark jets

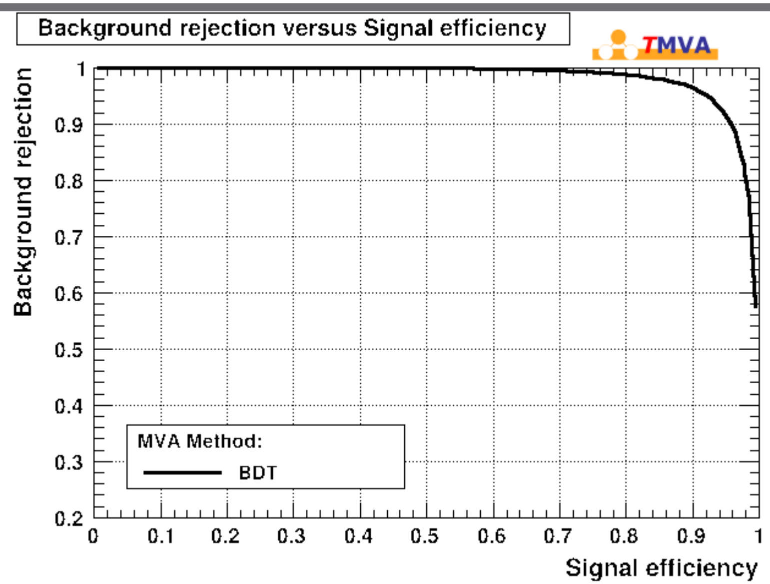
Including event HT

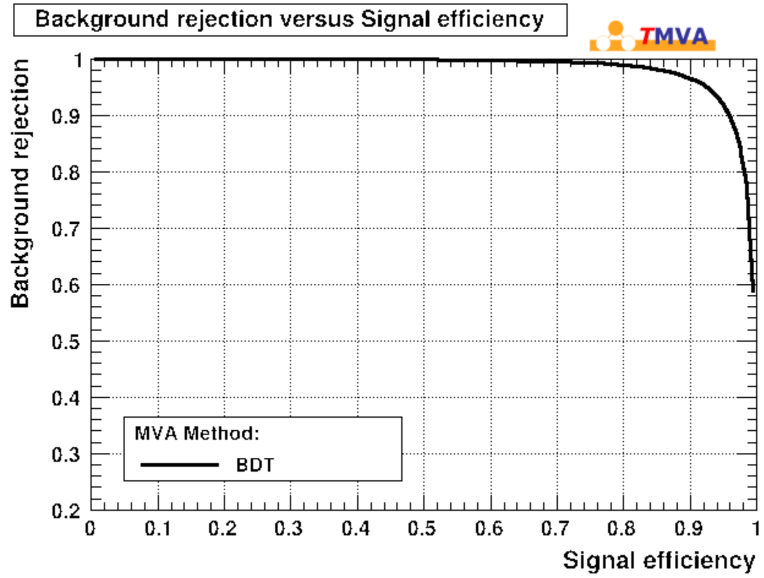




Not Including event HT

Events Unweighted

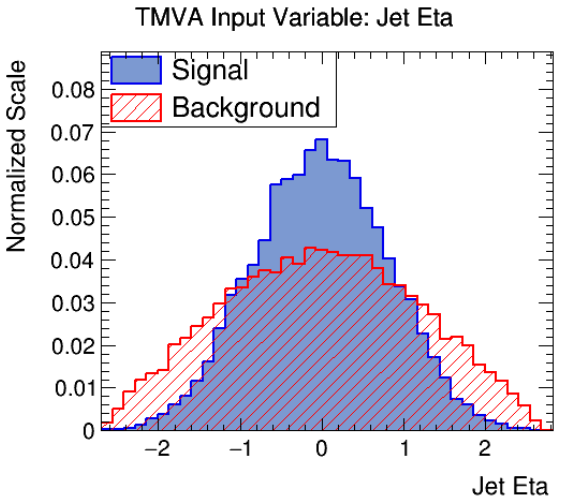


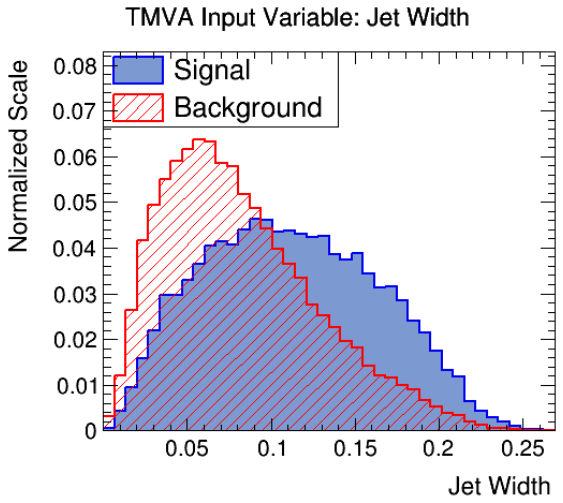


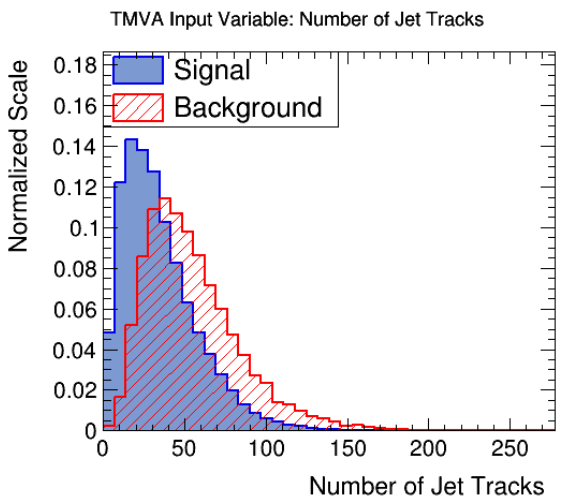
Jet-Level Input Variable Distributions

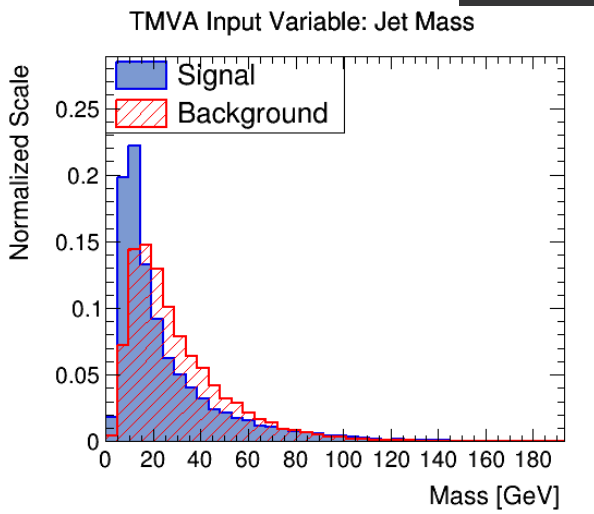
Model: D 600 GeV 300 mm

$$\text{width} = \frac{1}{p_T^{jet}} \sum_i p_T^i \Delta R_i$$

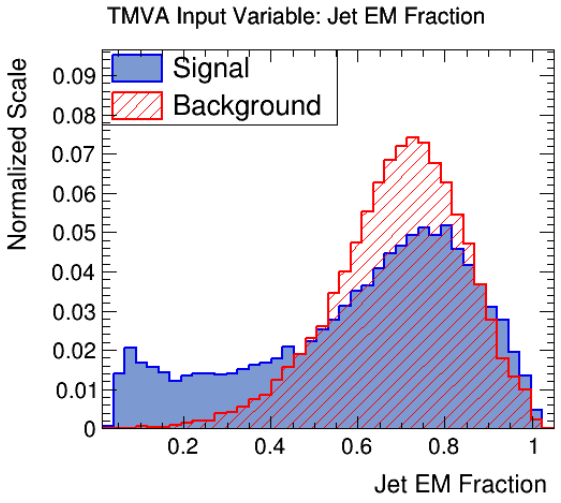


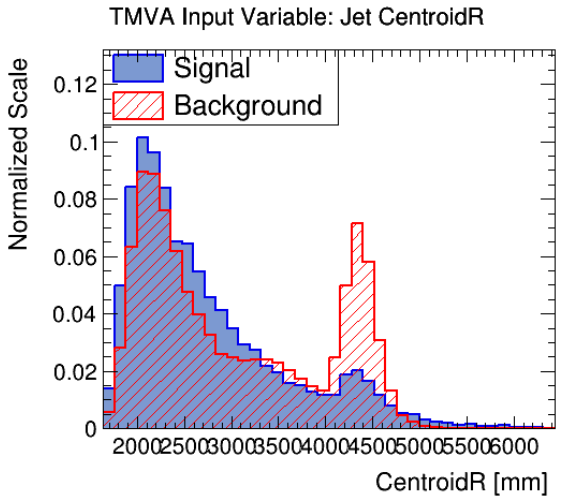


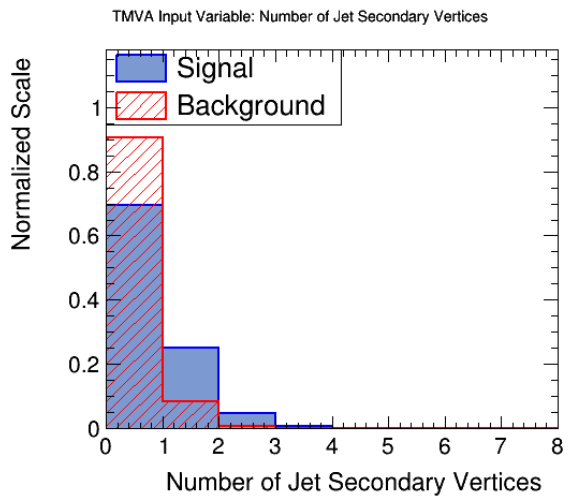




Trained on all dark jets

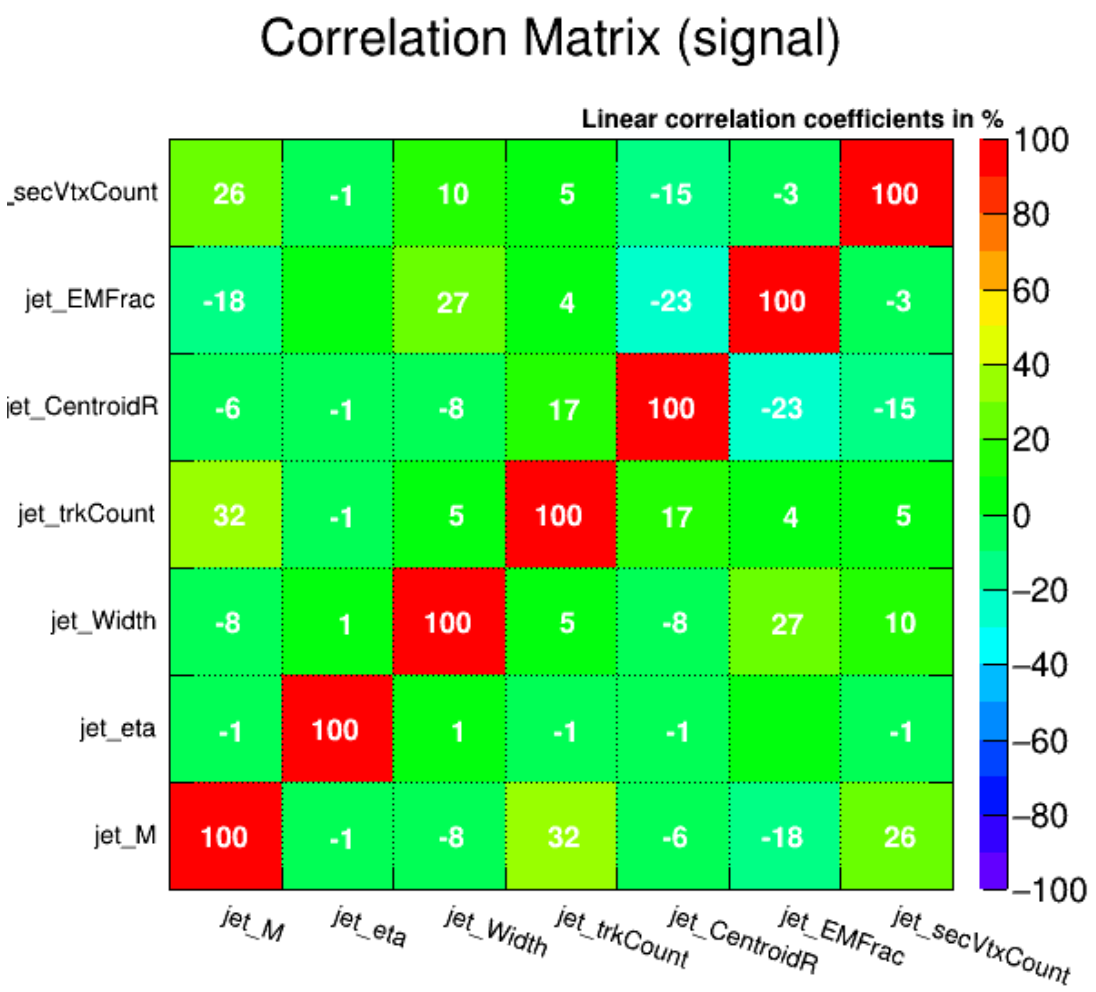


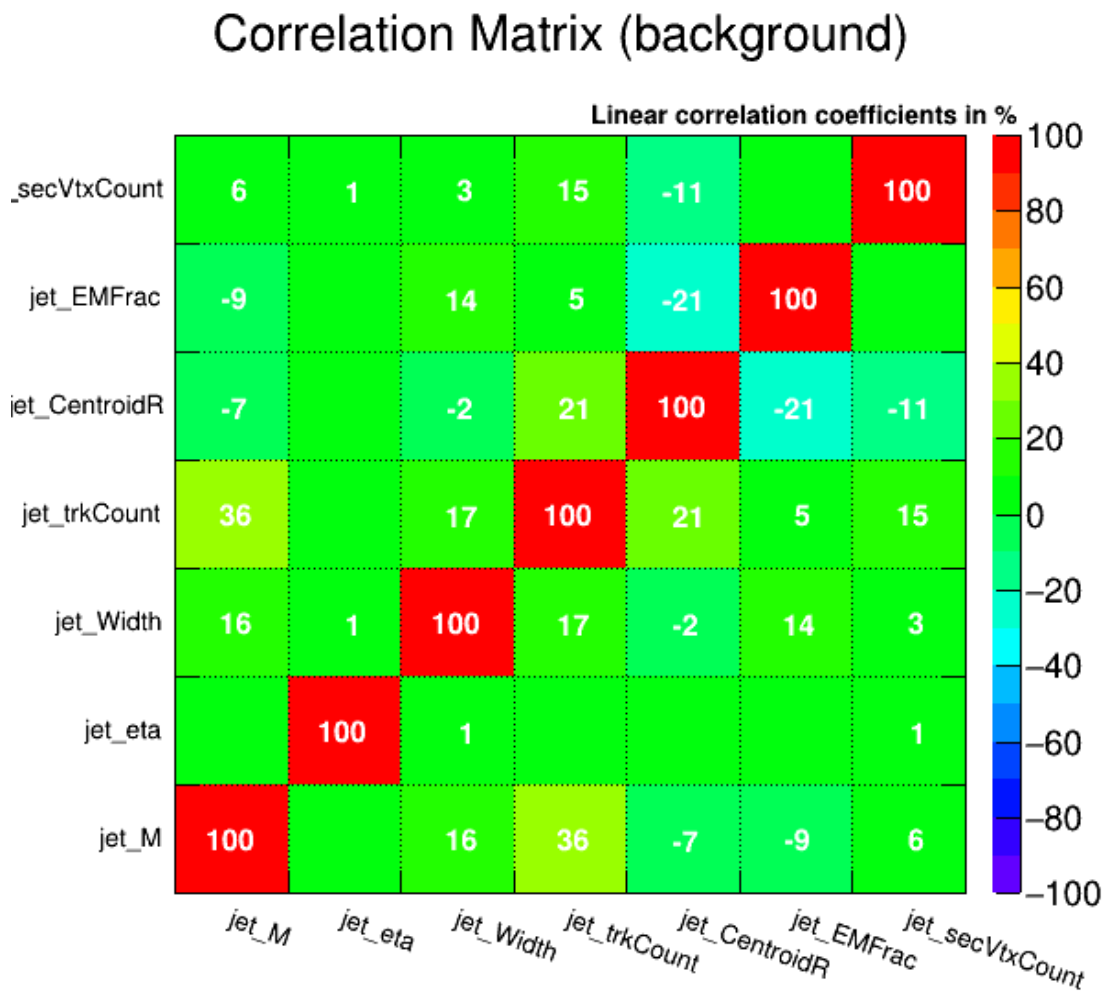




Jet-Level Input Variable Correlations

Model: D 600 GeV 300 mm

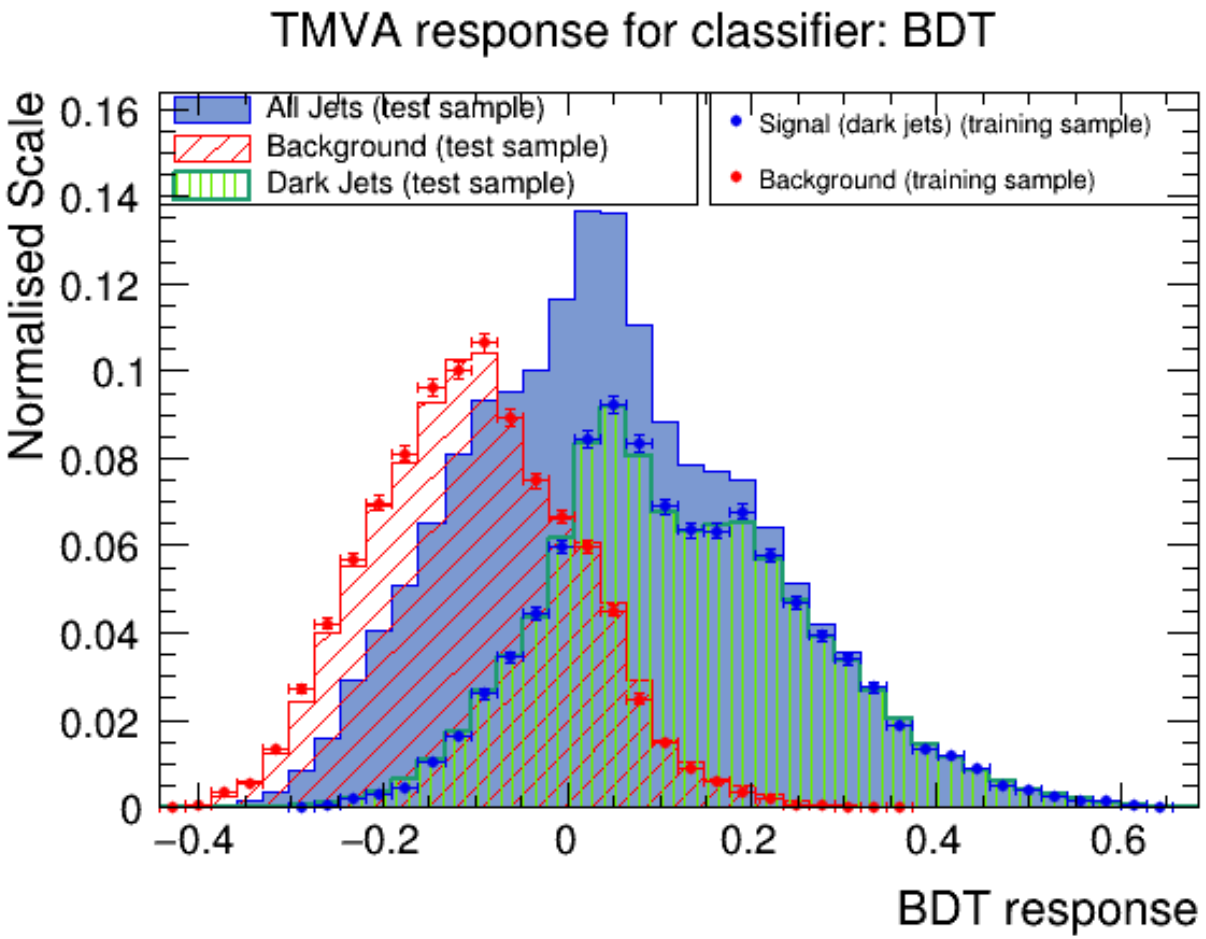




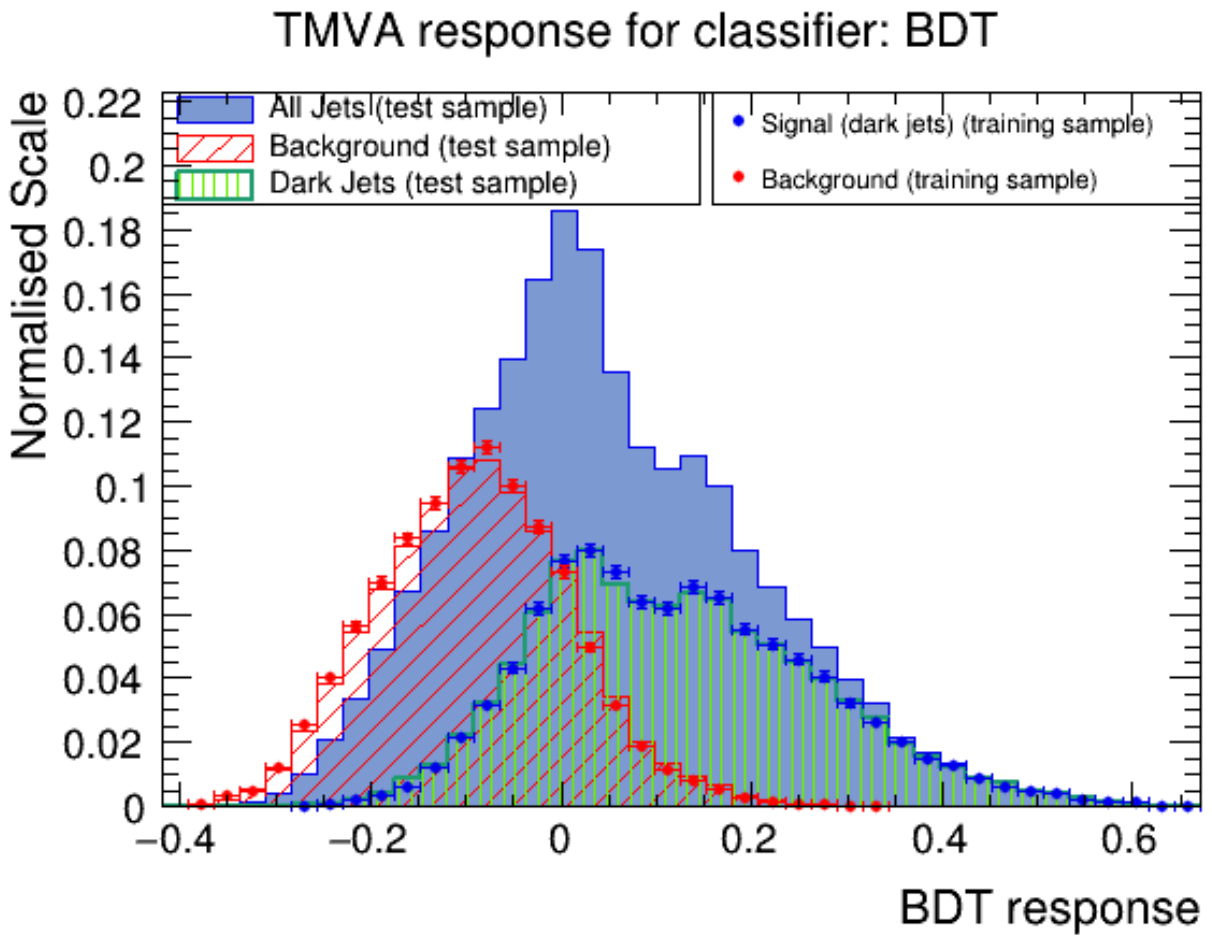
Trained on all dark jets

Jet Level Trees

Trained on all dark jets



Trained 4 leading dark jets

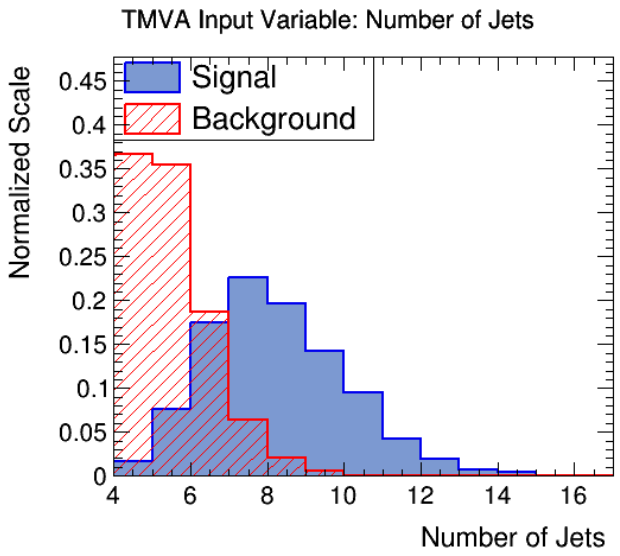


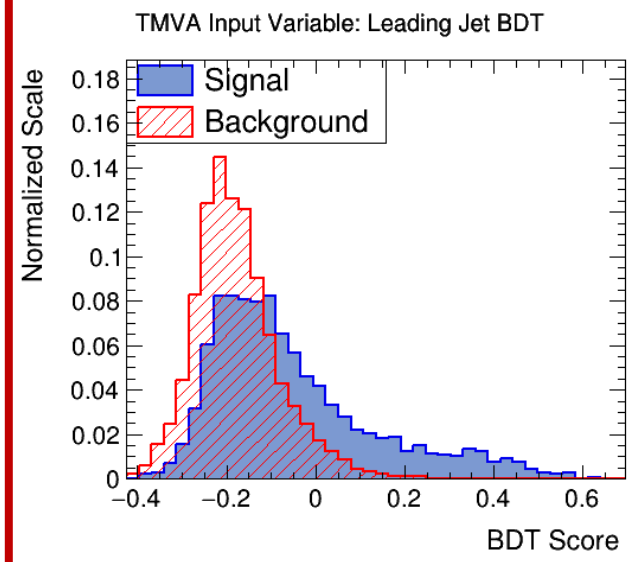
Model: D 600 GeV 300 mm

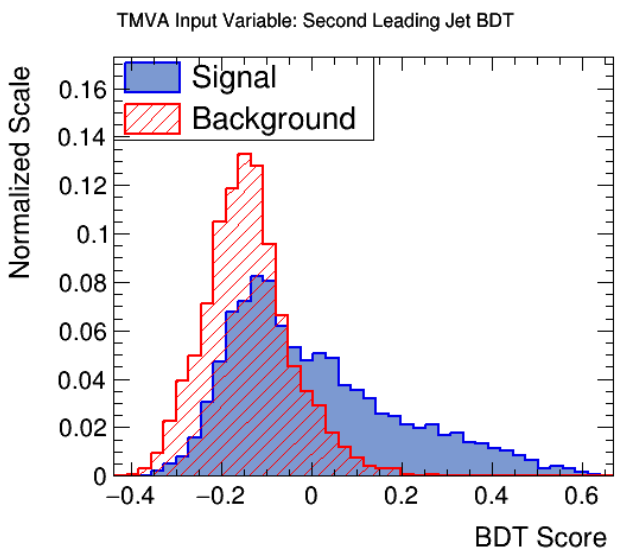
Event level BDT input variables

Output from jet-level BDT

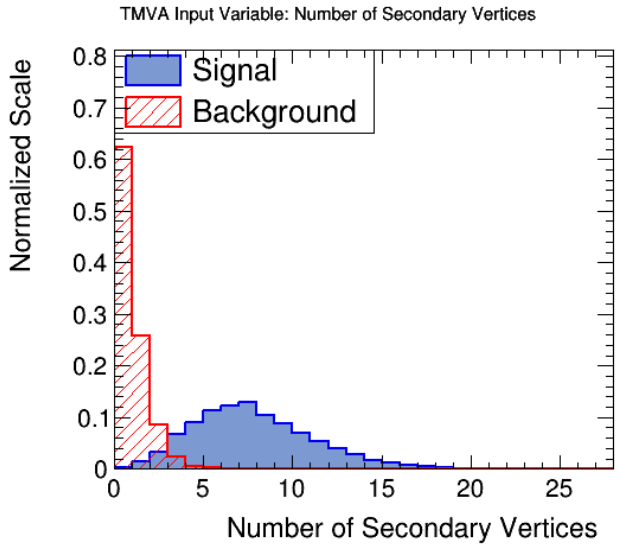
Model: D 600 GeV 300 mm

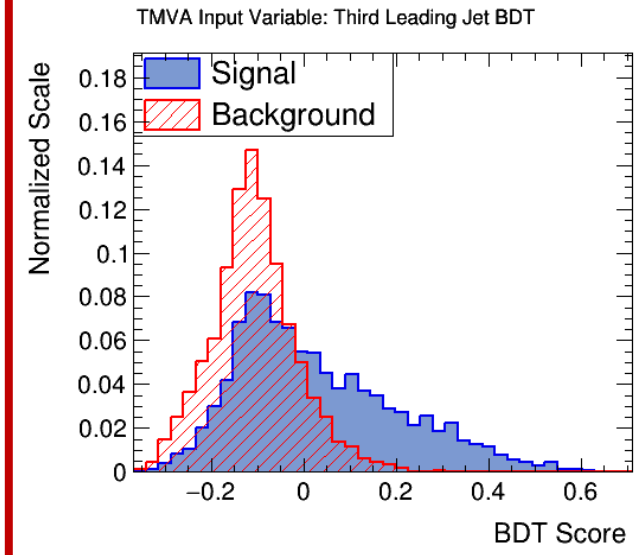


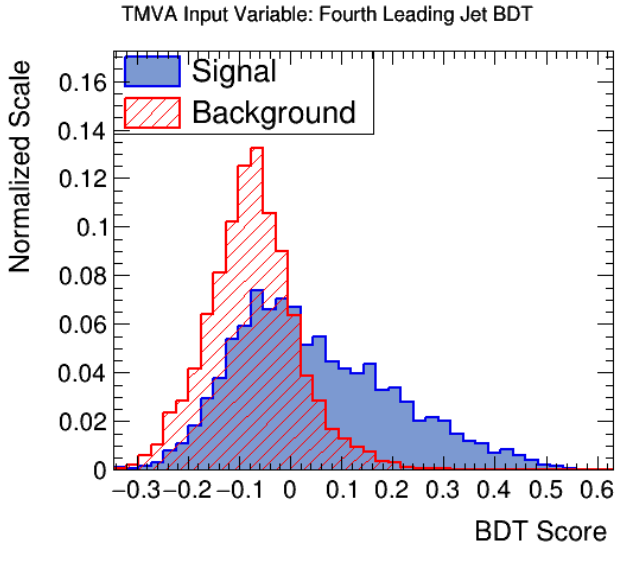




Trained on all dark jets

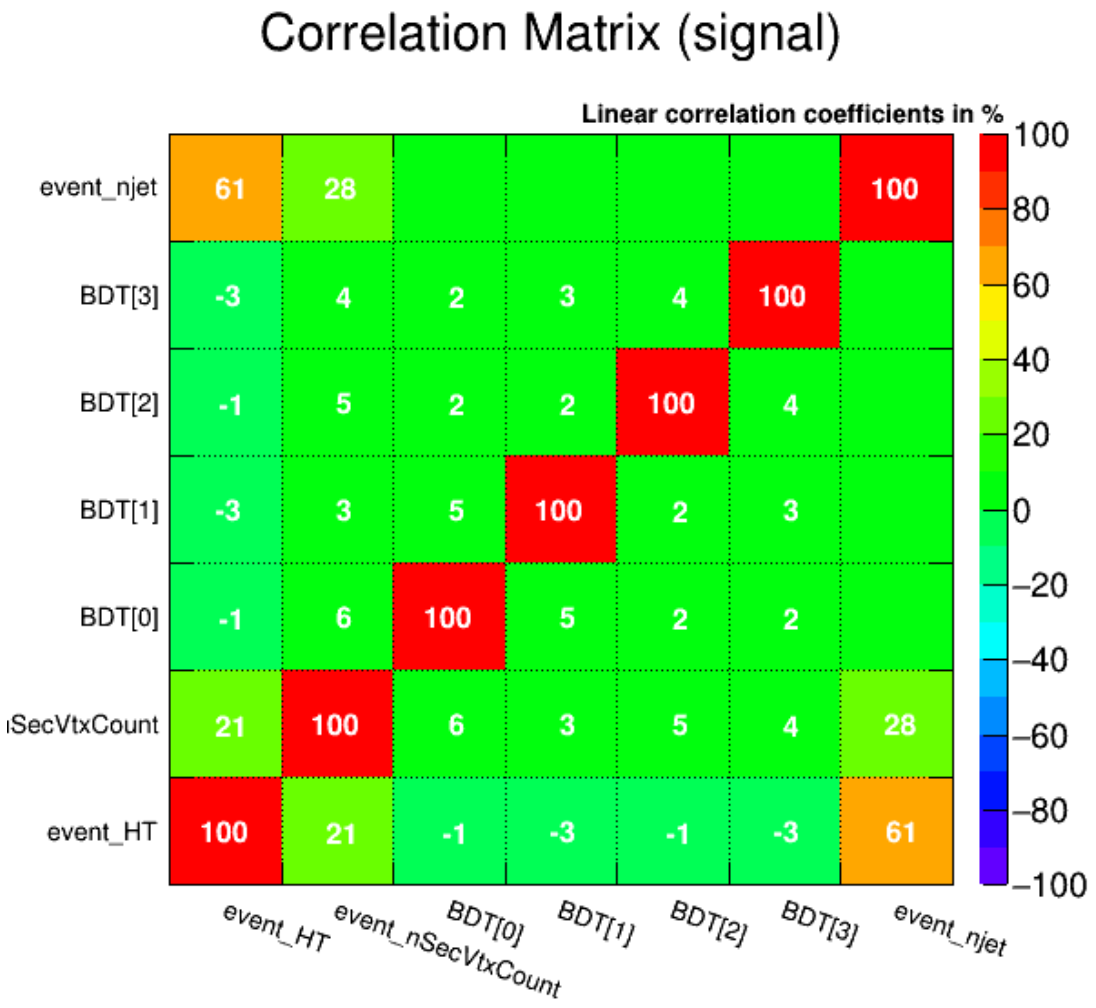


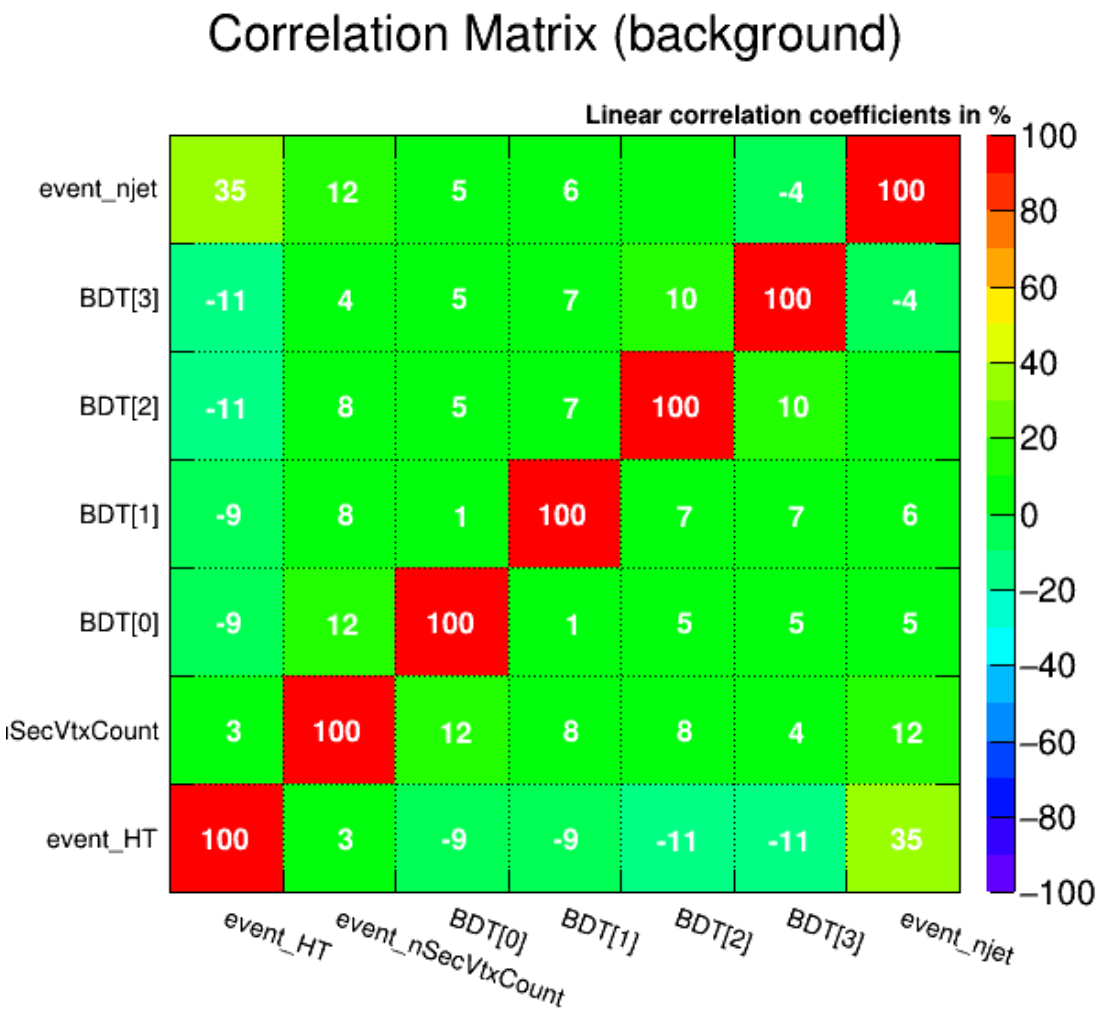




Event-Level Input Variable Correlations

Model: D 600 GeV 300 mm





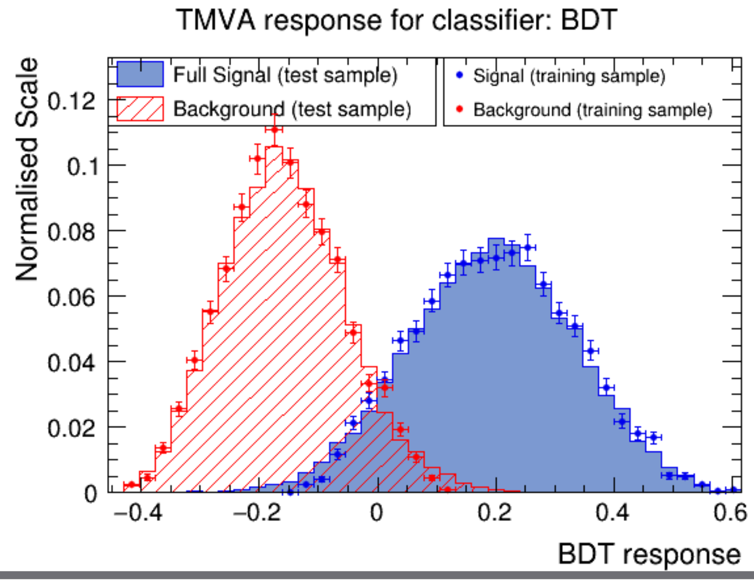
Event Level Trees

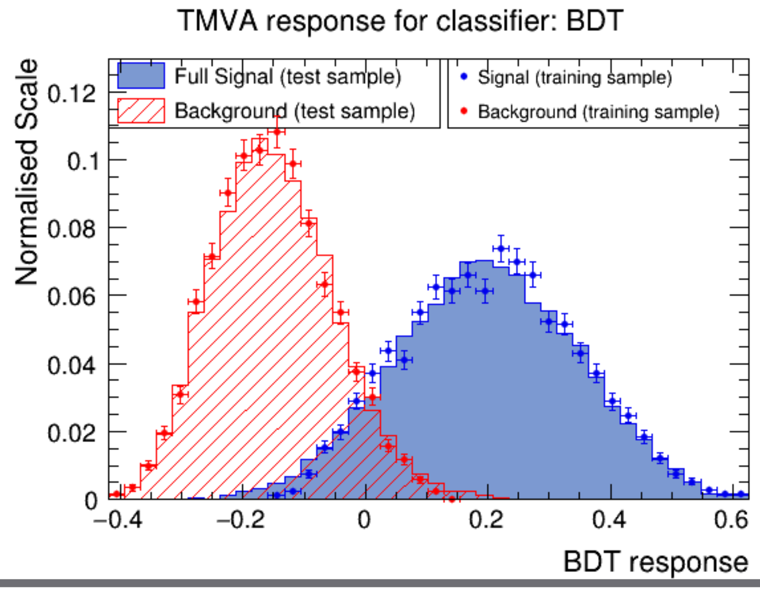
Model: D 600 GeV 300 mm

Trained on all dark jets

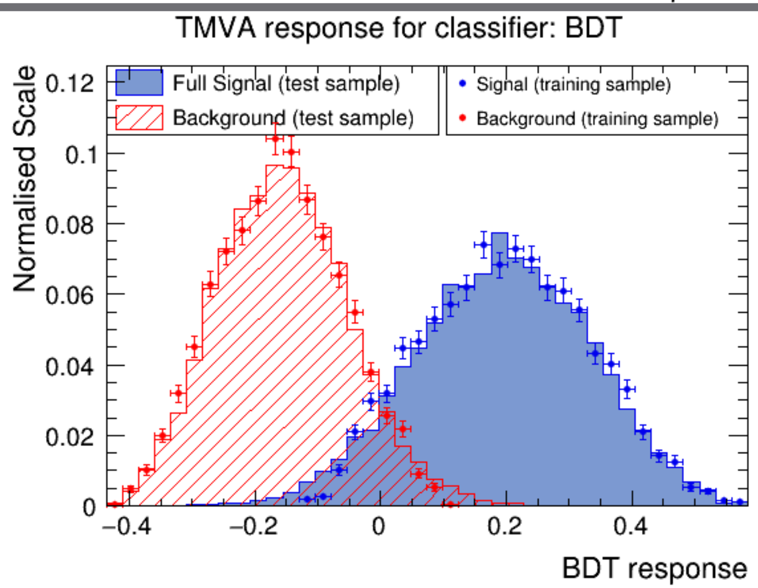
Trained 4 leading dark jets

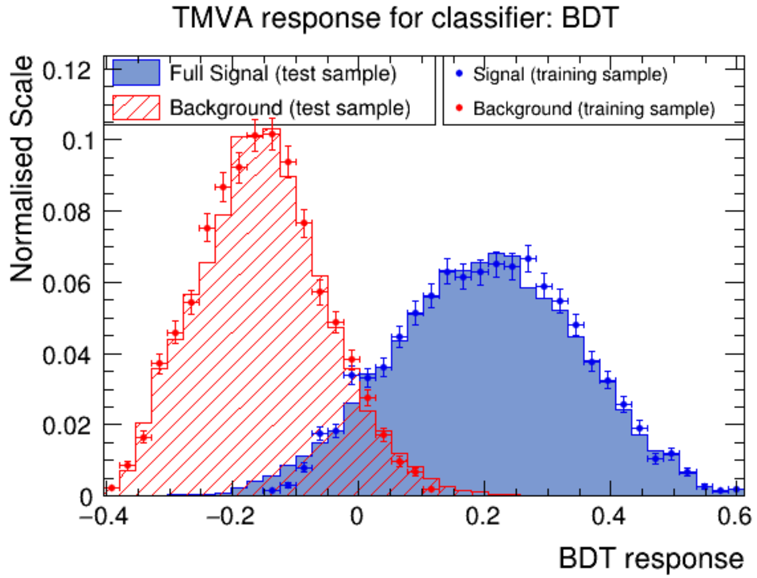
Including event HT





Not Including event HT



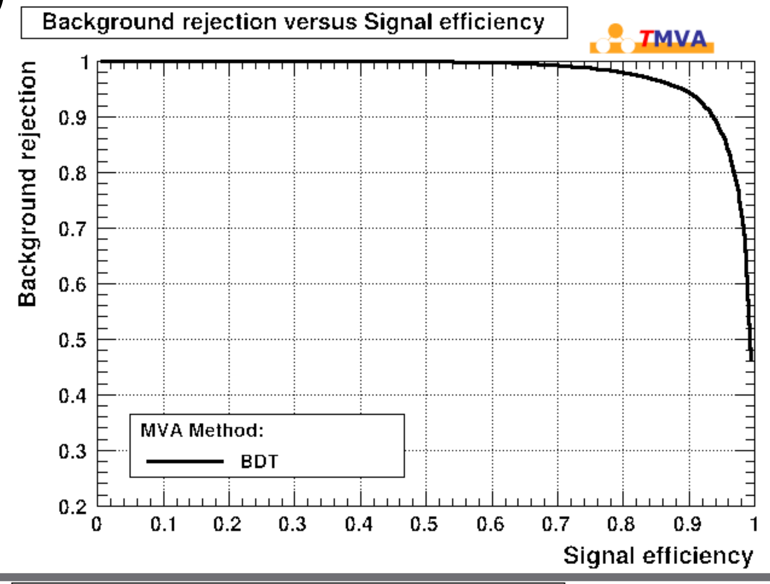


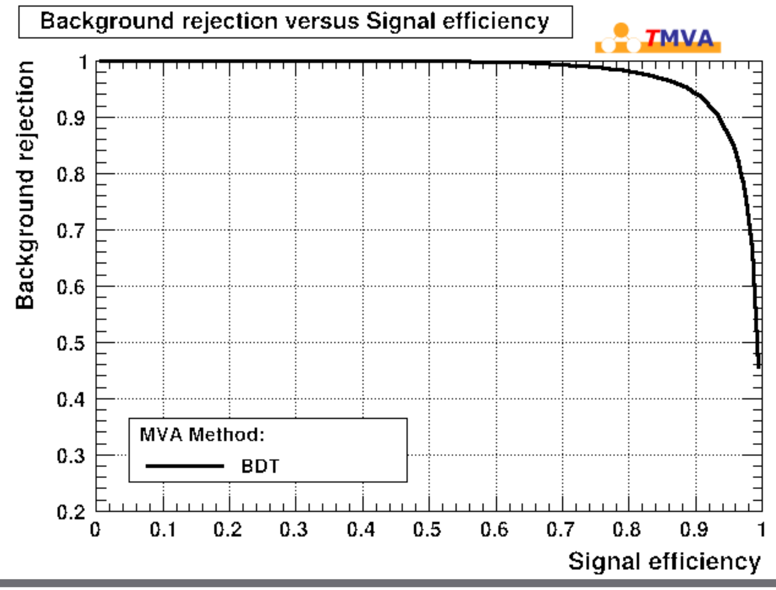
Event Level Trees ROC

Model: D 600 GeV 300 mm

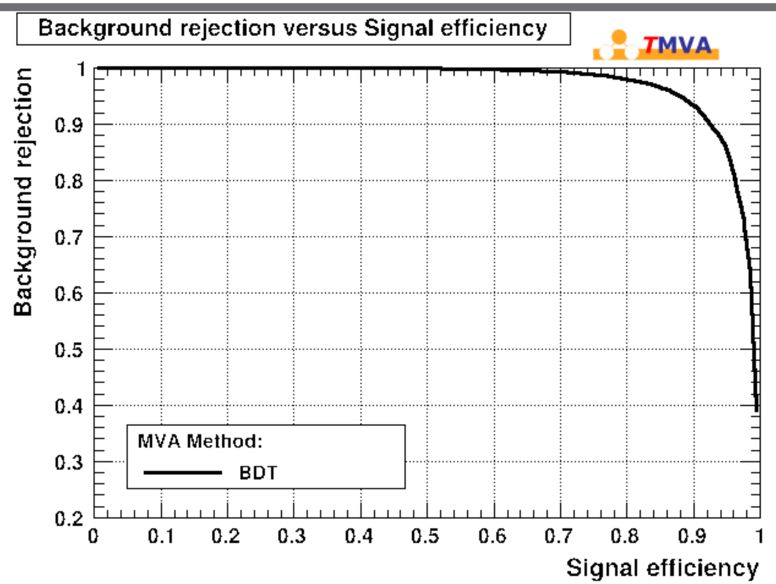
Trained on all dark jets | Trained 4 leading dark jets

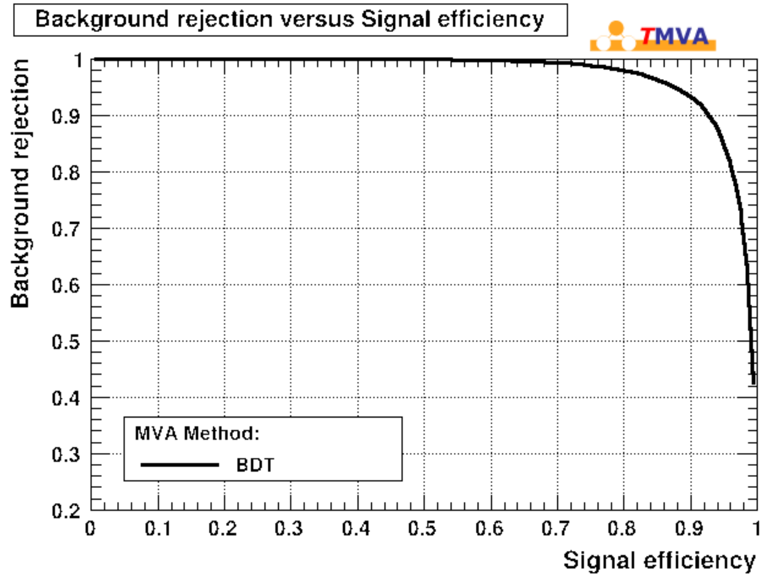
Including event HT



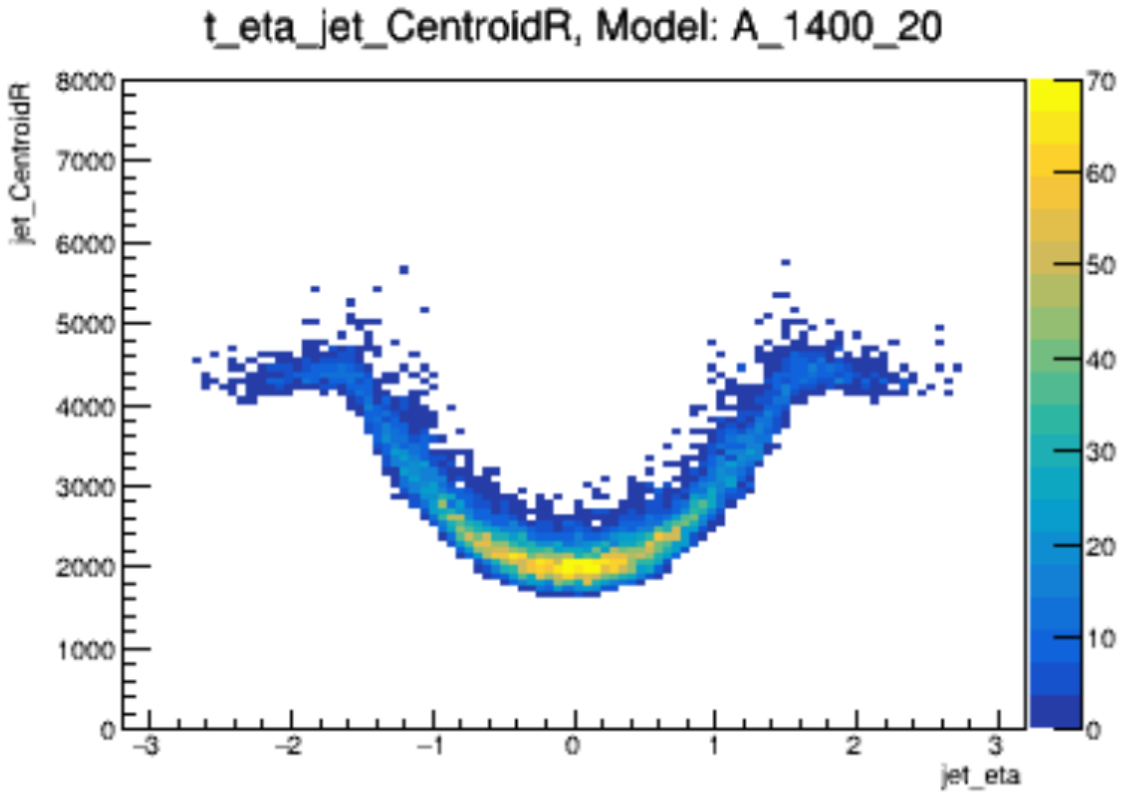


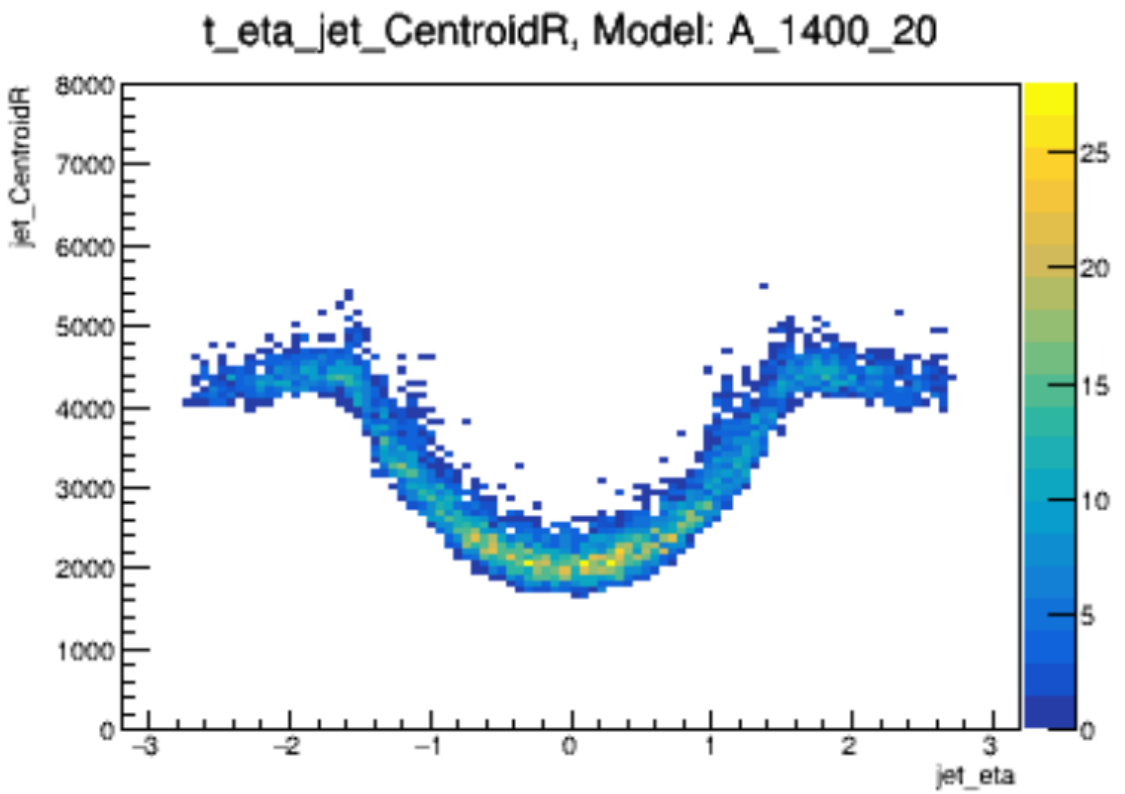
Not Including event HT





Events Unweighted


t_eta_jet_CentroidR, Model: A_1400_20
jet_CentroidR
jet_eta


t_eta_jet_CentroidR, Model: A_1400_20
jet_CentroidR
jet_eta