- **In SM:**
  **1. Pair production:** top quarks are unpolarized (vector nature of the QCD couplings).
  **2. Single top:** top quarks are left-handed ($V-A$ nature of the t−b−W coupling).

- **Any change to structure of the interaction → Change in the polarization of the produced top quark.**

- Hence, the polarization of top quarks serves as a **promising window** for exploring the existence and nature of new physics.

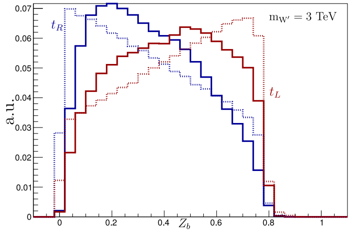
- **Measuring the polarization of boosted top quark jets in colliders is quite challenging** – several studies have already explored different kinematic variables for this purpose.

$\bar{\tilde{t}}_1 \to t\tilde{\chi}_1^0$:
$\mathcal{L} \sim \tilde{\chi}_1^0[P_L g^{\tilde{t}_{1L}} + P_R g^{\tilde{t}_{1R}}]\tilde{t}_1 t$
Higgsino like $\tilde{\chi}_1^0$: **Polarization** of t will be **opposite** to that of $\tilde{t}_1$.

---

$W' \to tb$
$\mathcal{L} \sim \bar{f}_i\gamma^\mu((1+\gamma^5)g_R + (1-\gamma^5)g_L)W'\bar{f}_j$

---




[Godbole, Guchait et al., 2019]

I will describe the use of an **image-based** convolutional neural network **(CNN)** for **detecting the polarization** of both **hadronic and leptonic** boosted top jets.

The **tagging performance** of **leptonic** (and hadronic) boosted top jets will also be shown.

**Work in progress: To be arXived soon**

## Top polarization

# Top polarization

- The **angular distribution** (in the top rest frame) of the **top decay products** is given by [Jezabek and Kuhn, 1989]:

$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta_f} = \frac{1}{2}(1 + P_0\kappa_f\cos\theta_f)$$

$$f = u, d, b, W$$

$$P_0 = \text{Polarization of the top } (-1 \leq P_0 \leq +1)$$

$$\theta_f = \text{Angle b/w fermion (or } W\text{) and top spin direction in the top rest frame}$$

$$\kappa_f = \text{Spin analyzing power } (+1, -0.3, -0.4, +0.4 \text{ for } f = d, u, b, W)$$ [Jezabek, 1984]

- **For L-handed hadronic top quarks ($P_0 = -1$)**: the $b$ and $u$ quarks are more likely to be aligned with the top spin (in the top rest frame), and hence more boosted (less separated) in the lab frame.
- **For R-handed hadronic top quarks ($P_0 = +1$)**: the $d$ quark is more likely to be aligned with the top spin (in the top rest frame), and hence more boosted in the lab frame.
- Similarly for L-handed (R-handed) **leptonic top quarks** the $b$ quark (lepton) will be harder.
- Thus the kinematics of the decay products from L and R-handed top quarks will differ – **can exploit this difference in the jet images.**

# Technical details

## Samples/processes

- $\tilde{t}\bar{\tilde{t}}$ ($\tilde{t} \to t\tilde{\chi}_1^0$, $m_{\tilde{t}} = 1$ TeV, $m_{\tilde{\chi}_1^0} = 100$ GeV)
- $W'$ ($W' \to tb$, $m_{W'} = 3$ TeV)
- $t\bar{t}$ ($\hat{p}_T^{min} = 400$ GeV)
- QCD ($\hat{p}_T^{min} = 400$ GeV)

## Simulation

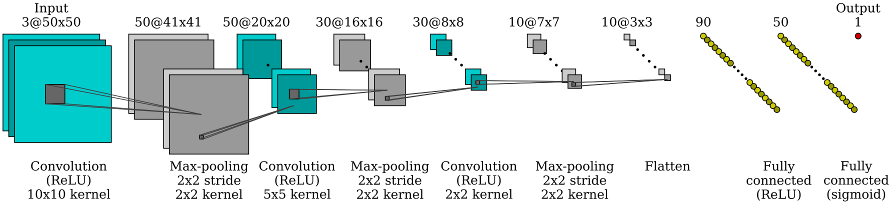
- MadGraph5 (MadSpin) → PYTHIA8 → Delphes (CMS card)

## Jet formation

- **Anti-$k_T$** jets of **radius 1.5**.
- **Soft-drop** with $z_{cut} = 0.1$ and $\beta = 0$. This choice helps to **clean the jet of both soft and soft-collinear emissions**:

$$\frac{\min(p_{T1}, p_{T2})}{p_{T1} + p_{T2}} > z_{cut} \left(\frac{\Delta R_{12}}{R}\right)^{\beta}$$

- Jet $p_T > 200$ GeV, $|\eta| < 2.4$. Jet $p_T$ and mass distributions in backup.
- **For gen-matching:**
  Hadronic top jets: $\Delta R(\text{jet}, t_{gen}^{had}) < 1$
  Leptonic top jets: $\Delta R(\text{jet}, t_{gen}^{lep\text{-}vis}) < 1$




- Based on the LeNet CNN (implemented in **Apache MXNet**).
- The **network parameters** (number of channels, kernel sizes, number of nodes, etc.) have been **slightly tweaked** in order to obtain a reasonably good compromise between performance and training time.
- The performance **improvement** offered by **GoogleNet** is quite **small** (but higher training time).
- Jet images are relatively simple and coarse (only $50 \times 50$) – **a simple network can learn most of its features.**
- **Input has three channels corresponding to the three jet components (tracks, photons, neutral hadrons).**
  This **improves** the performance for **leptonic top-tagging** and **polarization detection**.

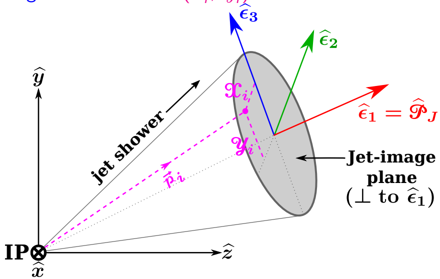
# Jet image formation (pre-processing)

## Mass rescaling and Lorentz boosting

- Follows the technique described in 1903.02032.
  1. The jet 4-mom is rescaled such its mass is $m_B$.
  2. The jet is then Lorentz boosted to a frame in which its energy is $E_B$.
- The **ratio** of these two parameters $(\gamma_B = m_B/E_B)$ **is what is of import**, and not their absolute values.
- We have chosen $\gamma_B = 2$ (**fairly optimal**).

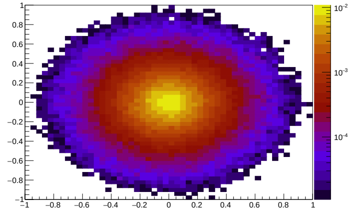
## Gram-Schmidt transformation

- **For a given jet-constituent's 4-mom** $p_i = (p_i^0, \vec{p}_i)$, its image coordinates are $(\mathcal{X}_i, \mathcal{Y}_i)$.

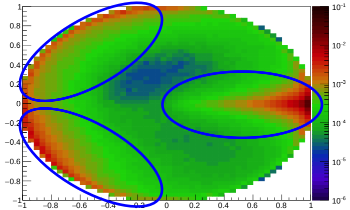



- **Image size: 50×50 pixels**
- **Color axis: Constituent energy / jet energy**

**$t^{had}$ jet image w/o pre-processing**



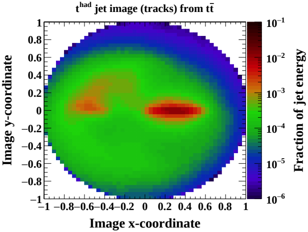

**$t^{had}$ jet image with $\gamma_B = 0$**

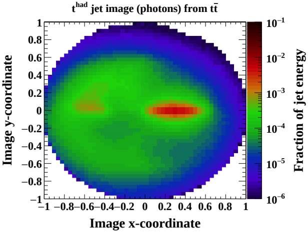


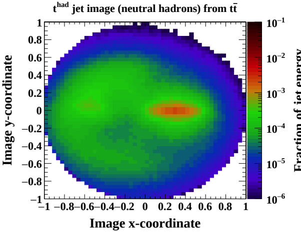
# Top tagging

# Hadronic top ($t^{had}$) vs. QCD jet images

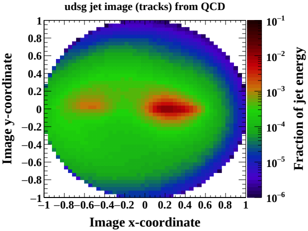
**$t^{had}$ jet images**

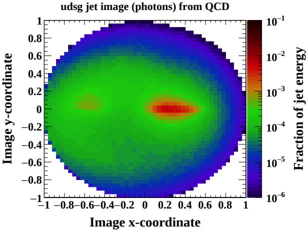


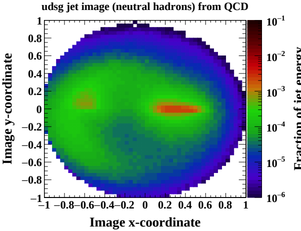



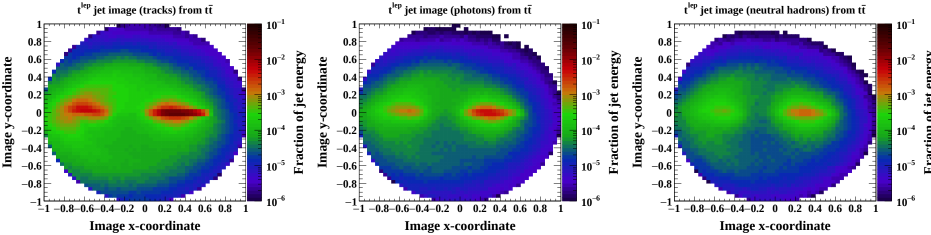

**QCD jet images**



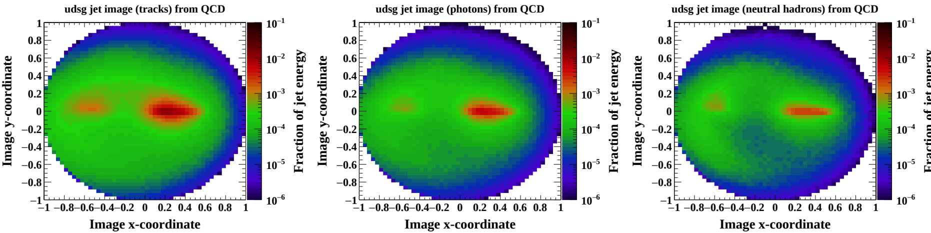



## $t^{lep}$ jet images




## QCD jet images

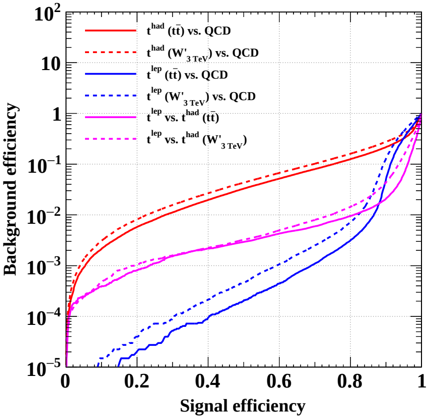


- **Trained on** $t^{had}/t^{lep}$ jets from $t\bar{t}$ **versus** udsg jets from QCD.
- Performance of the training using $t^{had}/t^{lep}$ jets from $W'_{3\,\mathrm{TeV}}$ also shown.
- **Leptonic top tagging** (using BDT: [Chatterjee, Godbole and Roy, 2020])

  **Identifying isolated leptons in highly boosted top jets** can be **challenging** in colliders.

  **Image-based leptonic top tagging is independent of lepton reconstruction and ID.**

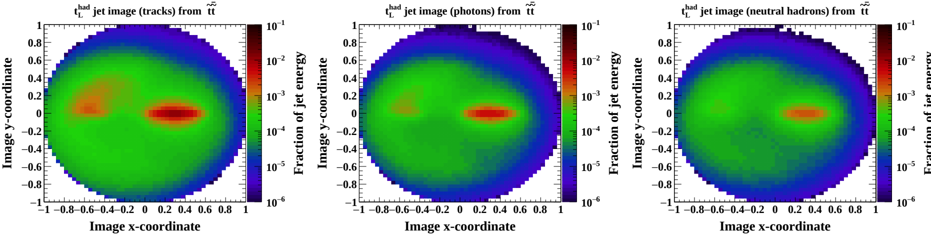
  **CNN performs well: ∼0.01−0.02% bkg. efficiency at 40% sig. efficiency.**



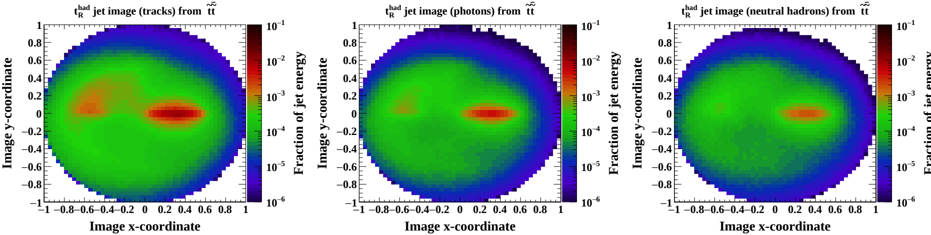
# Hadronic top polarization

# $t_L^{had}$ vs. $t_R^{had}$ jet images

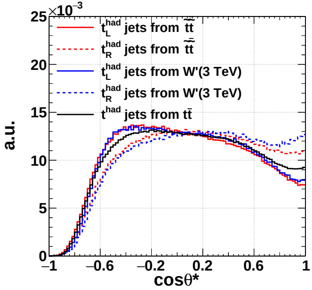
**$t_L^{had}$ jet images**

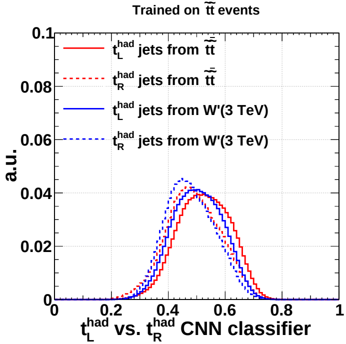


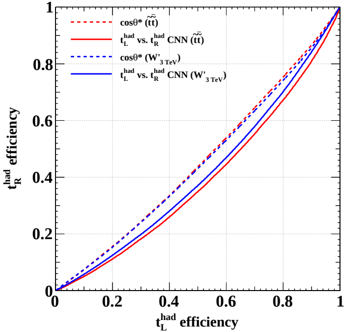

**$t_R^{had}$ jet images**



- Train on $t_L^{had}$ jets (from $\tilde{t}_L \bar{\tilde{t}}_L$) **versus** $t_R^{had}$ jets (from $\tilde{t}_R \bar{\tilde{t}}_R$).
- $\cos\theta^*$ is a **kinematic variable** that is shown to be quite sensitive to polarization [Godbole, Guchait et al., 2019].
  It's the (cosine of) **angle b/w** the top jet (in the lab frame) and the d-like subjet momenta (in the top-rest frame): $\frac{\vec{j}_t \cdot \vec{j}_d}{|\vec{j}_t||\vec{j}_d|}$
- **The CNN outperforms $\cos\theta^*$.**

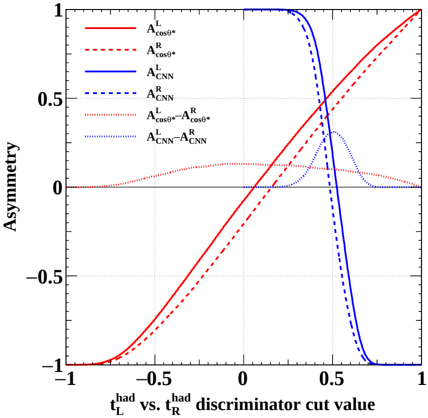


# $t_L^{had}$ vs. $t_R^{had}$ asymmetry

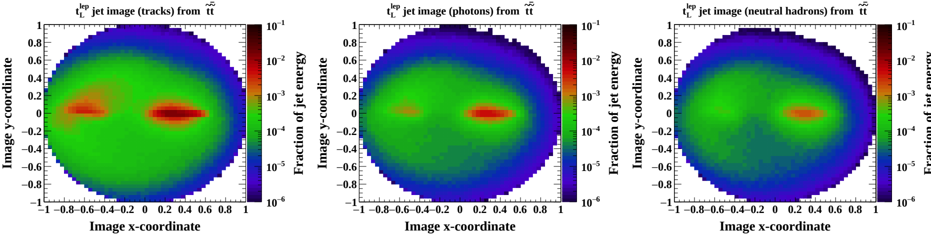
- For a given $t_L^{had}$ vs. $t_R^{had}$ discriminator ($d = \cos\theta^*$, $CNN$), **define the asymmetry** of its distribution as: $A_d^{composition} = \frac{N_{d>c} - N_{d<c}}{N_{d>c} + N_{d<c}}$
- $c$ is an arbitrary cut on the discriminator – **vary to check the optimum value.**
- **Check $A_d^{composition}$ for the two extreme compositions:** fully L-handed and fully R-handed.
- The **maximal change** b/w $A_d^L$ and $A_d^R$ is a **measure of the sensitivity** of the discriminator $d$ to the **composition** (and hence **polarization**).
- The CNN discriminator is **≈2 times more sensitive** than $\cos\theta^*$.



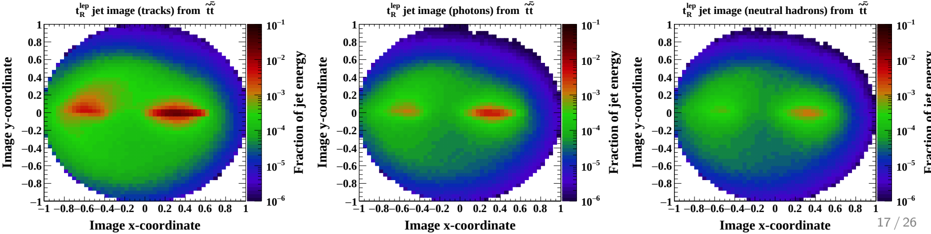
# Leptonic top polarization

- From the aforementioned formula for decay product kinematics:
  1. $t_L^{lep}$: the **b-quark** is more **boosted**.
  2. $t_R^{lep}$: the **lepton** is more **boosted**.

**$t_L^{lep}$ jet images**

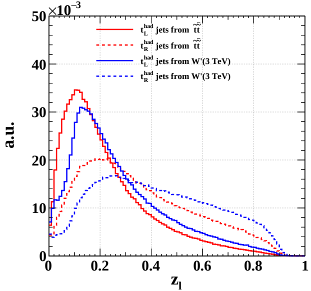


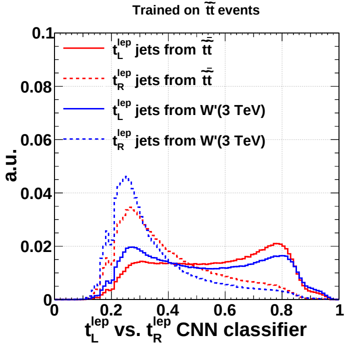

**$t_R^{lep}$ jet images**

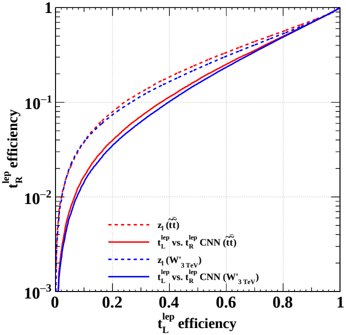


# $t_L^{lep}$ vs. $t_R^{lep}$ separation

- Train on $t_L^{lep}$ jets (from $\tilde{t}_L\bar{\tilde{t}}_L$) **versus** $t_R^{lep}$ jets (from $\tilde{t}_R\bar{\tilde{t}}_R$).
- $z_\ell$ is a **kinematic variable** that is shown to be quite sensitive to polarization [ref].
  It's the **lepton energy fraction**.
- **The CNN outperforms $z_\ell$.**
  **CNN is independent of lepton reconstruction and ID, unlike $z_\ell$.**

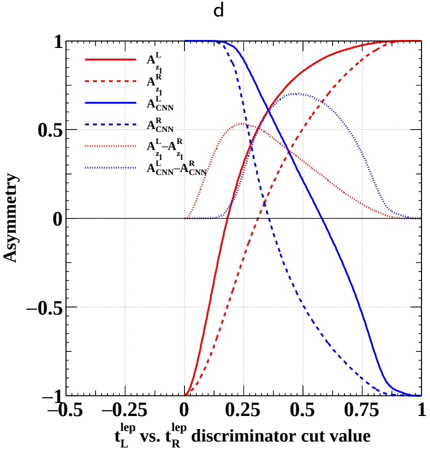


## $t_L^{lep}$ vs. $t_R^{lep}$ asymmetry

- Define asymmetry in a way similar to that mentioned earlier.
- The CNN discriminator is **≈1.3 times more sensitive** than $z_\ell$.



# Summary

# Summary

- The **polarization of top quarks** can serve as a **powerful tool in the search for new physics.**
- Have showed that leptonically decaying boosted top quarks can be well tagged by a jet-image based CNN.
- This is **free from the issues associated with reconstructing and identifying isolated leptons in a highly boosted jet.**
- The **polarization of hadronically decaying boosted top quarks** can be well identified using a CNN. It's **sensitivity to polarization is better** than the usual kinematic polarimeter variables (like $\cos\theta^*$).
- **Leptonically decaying top quarks** have a cleaner signature compared to the hadronic decay mode – can be exploited to improve sensitivities.
- The **polarization of boosted leptonic tops** have also been well identified using a CNN, whose **sensitivity to polarization is better** than the usual kinematic polarimeter variables (like $z_\ell$).

**To be arXived soon.**

**Backup**

# Soft-drop $p_T$

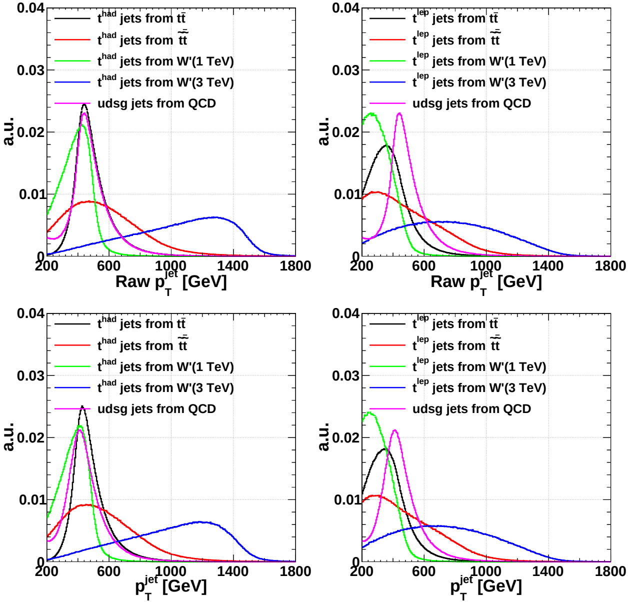



Figure: Jet $p_T$. Top: Raw. Bottom: After soft-drop.

# Soft-drop mass

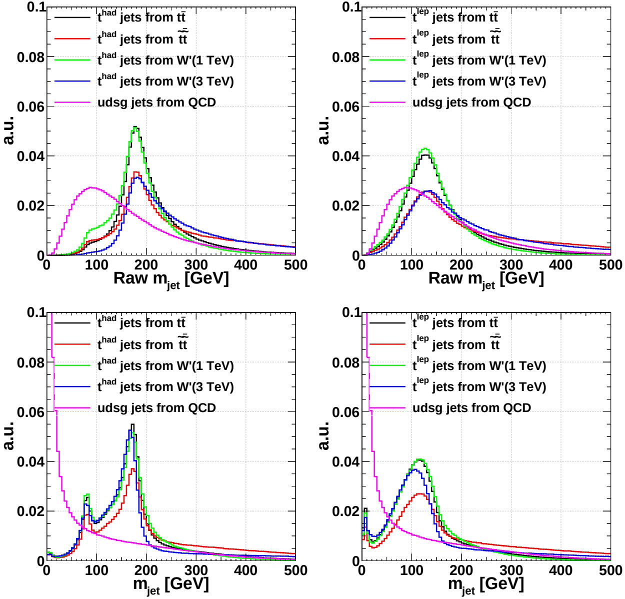
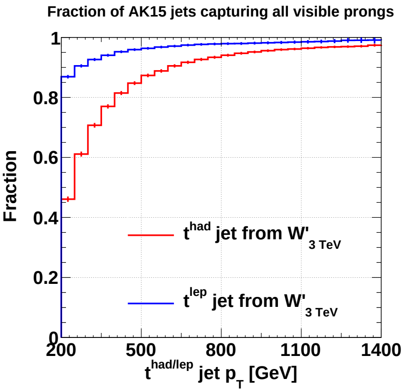
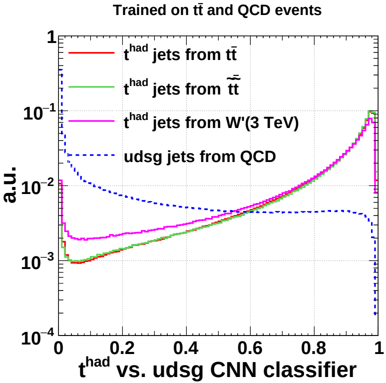
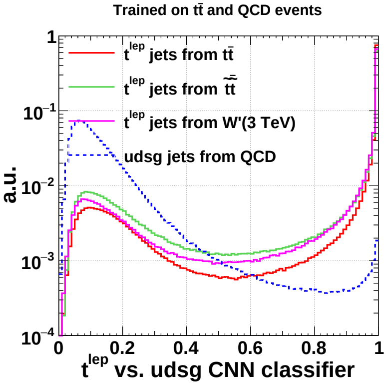



Figure: Jet mass. Top: Raw. Bottom: After soft-drop.


Fraction of AK15 jets capturing all visible prongs
Fraction
1
0.8
0.6
0.4
0.2
0
200
500
800
1100
1400
t^had/lep jet p_T [GeV]
t^had jet from W'_3 TeV
t^lep jet from W'_3 TeV


Trained on tt̄ and QCD events
1
$10^{-1}$
$10^{-2}$
$10^{-3}$
$10^{-4}$
a.u.
0
0.2
0.4
0.6
0.8
1
$t^{had}$ jets from tt̄
$t^{had}$ jets from $\tilde{t}\bar{\tilde{t}}$
$t^{had}$ jets from W'(3 TeV)
udsg jets from QCD
$t^{had}$ vs. udsg CNN classifier


Trained on tt̄ and QCD events
1
$10^{-1}$
$10^{-2}$
$10^{-3}$
$10^{-4}$
a.u.
0
0.2
0.4
0.6
0.8
1
$t^{lep}$ jets from tt̄
$t^{lep}$ jets from $\tilde{t}\bar{\tilde{t}}$
$t^{lep}$ jets from W'(3 TeV)
udsg jets from QCD
$t^{lep}$ vs. udsg CNN classifier