

Boosted top quark tagging and polarization using jet images

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- 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** \rightarrow **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.

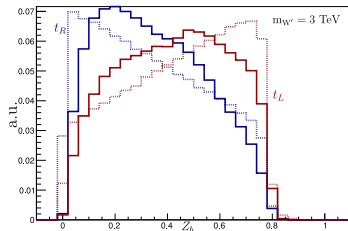
$$\tilde{t}_1 \rightarrow t\tilde{\chi}_1^0$$

$$\mathcal{L} \sim \tilde{\chi}_1^0 [P_L g^{\tilde{t}_1 L} + P_R g^{\tilde{t}_1 R}] \tilde{t}_1 t$$

Higgsino like $\tilde{\chi}_1^0$: Polarization of t will be **opposite** to that of \tilde{t}_1 .

$$W' \rightarrow tb$$

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



[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

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

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

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

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

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

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

- 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.

Samples/processes

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

Simulation

- MADGRAPH5 (MadSpin) \rightarrow PYTHIA8 \rightarrow Delphes (CMS card)

Jet formation

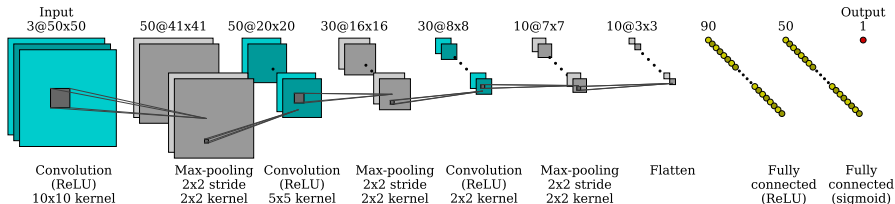
- Anti- k_T jets of radius 1.5.
- Soft-drop with $z_{\text{cut}} = 0.1$ and $\beta = 0$. This choice helps to clean the jet of both soft and soft-collinear emissions:

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

- Jet $p_T > 200 \text{ GeV}$, $|\eta| < 2.4$. Jet p_T and mass distributions in backup.
- For gen-matching:

Hadronic top jets: $\Delta R(\text{jet}, t_{\text{gen}}^{\text{had}}) < 1$

Leptonic top jets: $\Delta R(\text{jet}, t_{\text{gen}}^{\text{lep-vis}}) < 1$



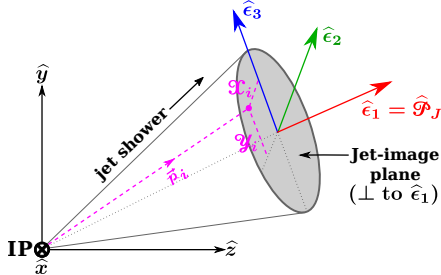
- Based on the **LeNet CNN** (implemented in **Apache MXNet**).
- The **network parameters** (number of channels, kernel sizes, number of nodes, etc.) have been **slightly tweaked** in order to obtain a **reasonably good compromise between performance and training time**.
- The **performance improvement** offered by **GoogLeNet** is quite **small** (but higher training time).
- Jet images are **relatively simple and coarse** (only 50×50) – 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**.

Mass rescaling and Lorentz boosting

- Follows the technique described in [1903.02032](#).
 - The jet 4-mom is rescaled such its mass is m_B .
 - 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).

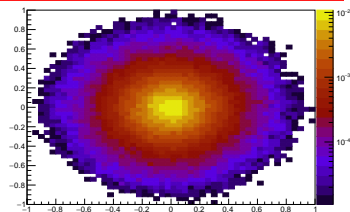
Gram-Schmidt transformation

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

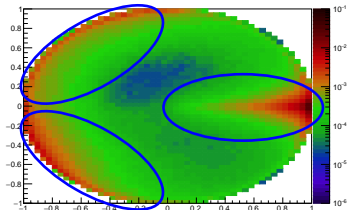


- Image size: **50 × 50 pixels**
- Color axis: **Constituent energy / jet energy**

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

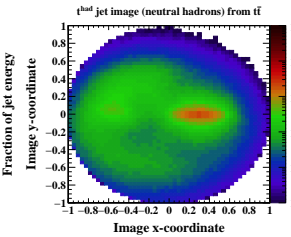
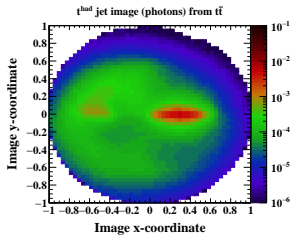
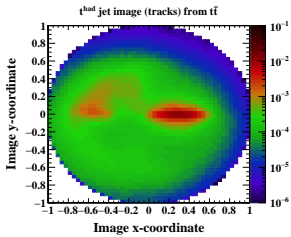


t^{had} jet image with $\gamma_B = 0$

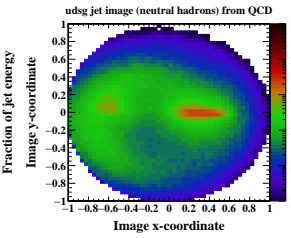
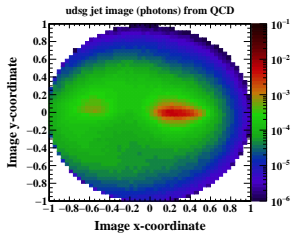
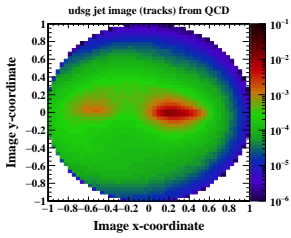


Top tagging

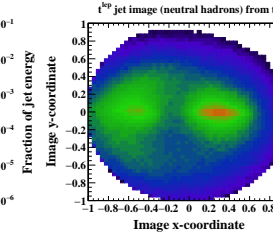
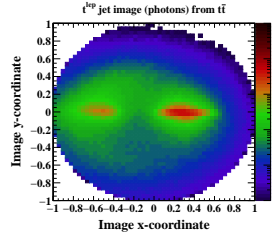
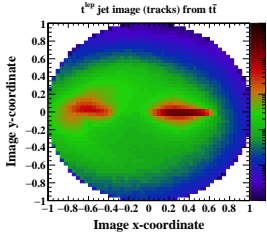
t^{had} jet images



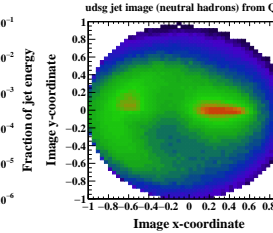
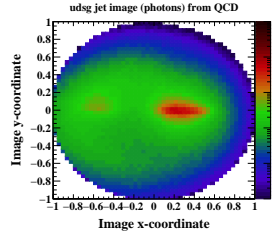
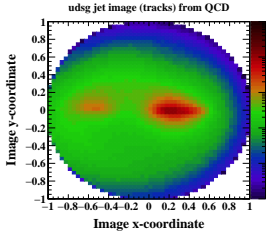
QCD jet images



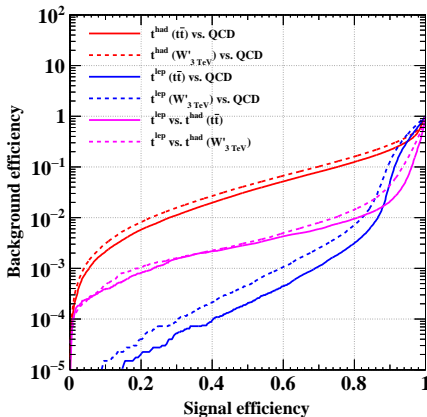
t^{lep} jet images



QCD jet images

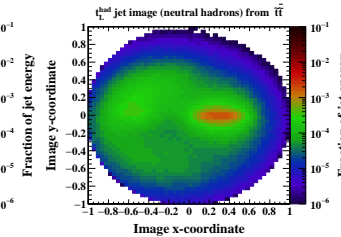
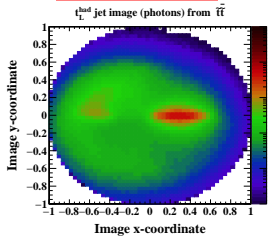
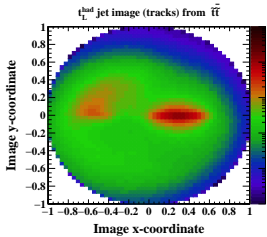


- Trained on $t^{\text{had}}/t^{\text{lep}}$ jets from $t\bar{t}$ versus $udsg$ jets from QCD.
- Performance of the training using $t^{\text{had}}/t^{\text{lep}}$ jets from $W'_{3\text{TeV}}$ also shown.
- **Leptonic top tagging** (using BDT: [Chatterjee, Godbole and Roy, 2020])
Identifying isolated 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: $\sim 0.01\text{--}0.02\%$ bkg. efficiency at 40% sig. efficiency.

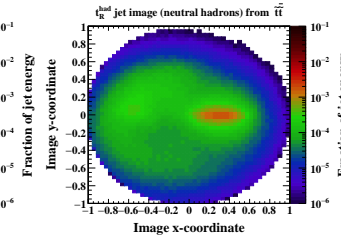
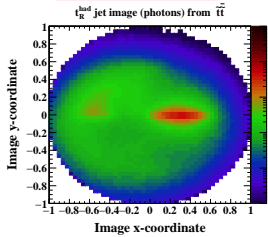
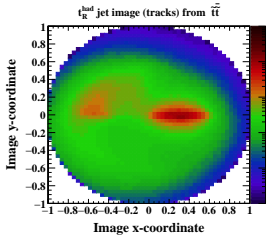


Hadronic top polarization

t_L^{had} jet images



t_R^{had} jet images



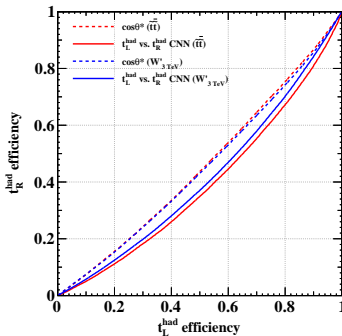
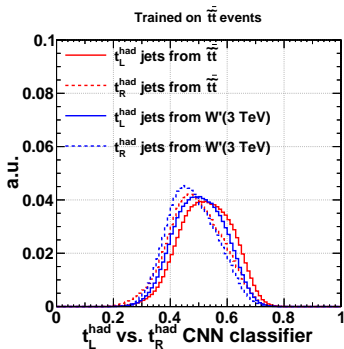
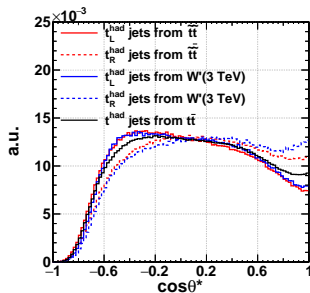
- Train on t_L^{had} jets (from $\tilde{t}_L \tilde{t}_L$) versus t_R^{had} jets (from $\tilde{t}_R \tilde{t}_R$).

- $\cos \theta^*$ is a kinematic variable that is shown to be quite sensitive to polarization [Godbole, Guchait et al., 2019].

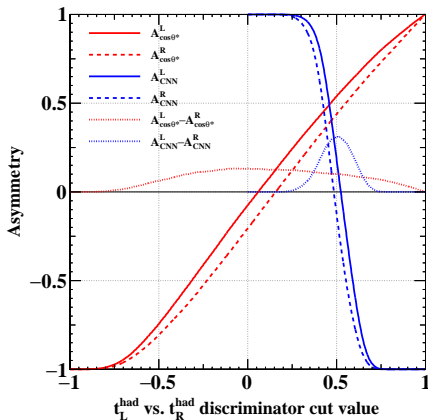
It's the (cosine of) angle **b/w** the top jet (in the lab frame) and the d-like subjet momenta (in the

top-rest frame): $\frac{\vec{J}_t \cdot \vec{J}_d}{|\vec{J}_t| |\vec{J}_d|}$

- The CNN outperforms $\cos \theta^*$.



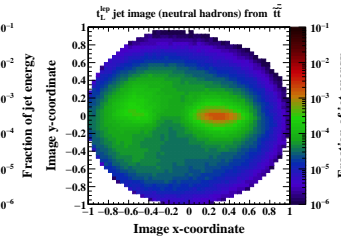
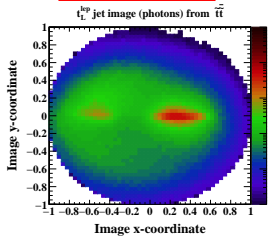
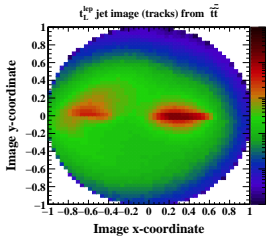
- For a given t_L^{had} vs. t_R^{had} discriminator ($d = \cos \theta^*$, CNN), define the asymmetry of its distribution as: $A_d^{\text{composition}} = \frac{N_{d>c} - N_{d<c}}{N_{d>c} + N_{d<c}}$
- c is an arbitrary cut on the discriminator – vary to check the optimum value.
- Check $A_d^{\text{composition}}$ 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 $\cos \theta^*$.



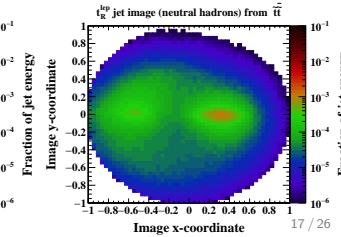
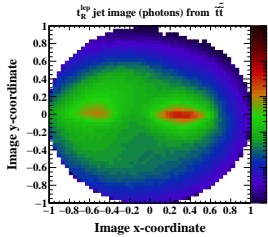
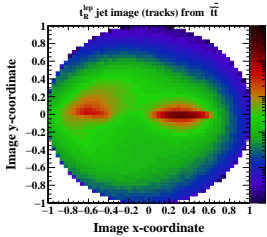
Leptonic top polarization

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

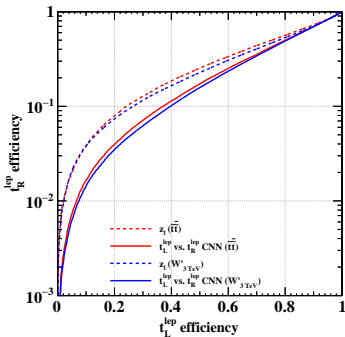
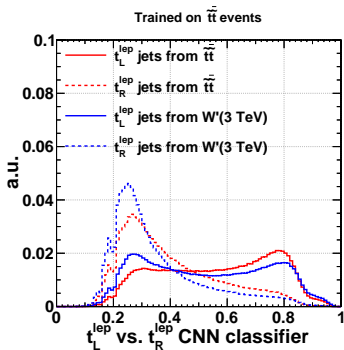
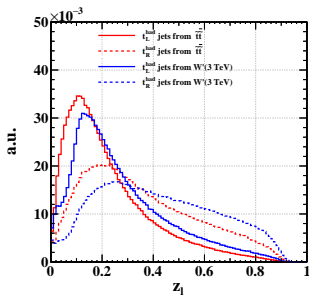
t_L^{lep} jet images



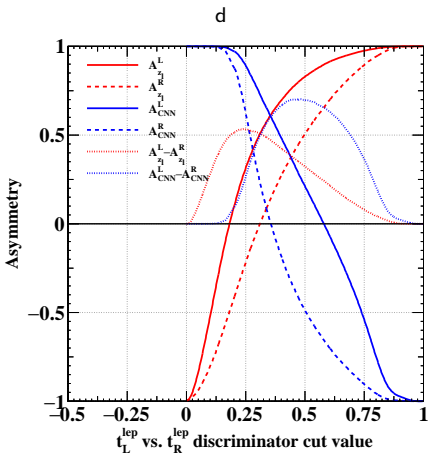
t_R^{lep} jet images



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



- Define asymmetry in a way similar to that mentioned earlier.
- The CNN discriminator is ≈ 1.3 times more sensitive than z_ℓ .



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_ℓ).

To be arXived soon.

Backup

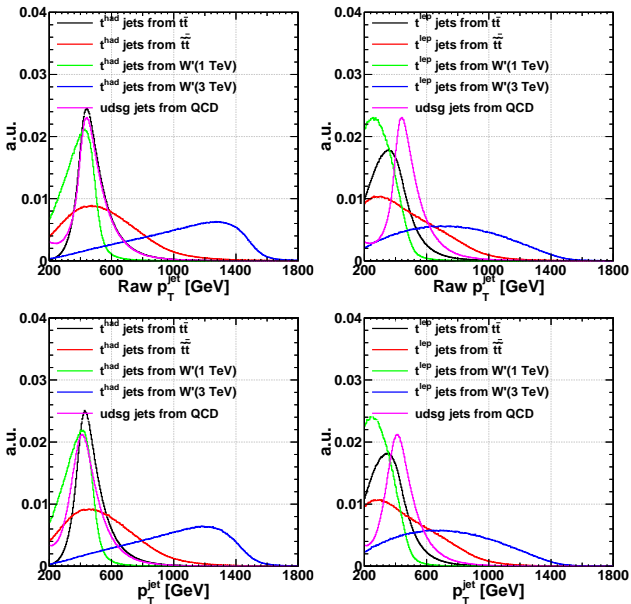


Figure: Jet p_T . Top: Raw. Bottom: After soft-drop.

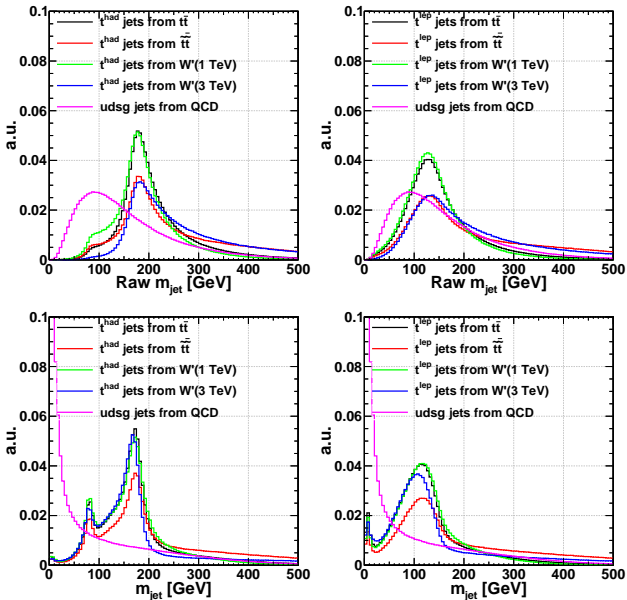


Figure: Jet mass. Top: Raw. Bottom: After soft-drop.

Fraction of AK15 jets capturing all visible prongs

