Hadronic Top-quark Polarimetry with ParticleNet

LHCTopWG meeting, Nov 12, 2024

Alberto Navarro

Based on arXiv:2407.01663 and arXiv:2407.07147

with Z. Dong, D. Gonçalves, K. Kong, and A. J. Larkoski

Motivation

- Spin correlation studies in top quark physics plays an important role in new physics searches (e.g., resonant or non-resonant searches), observation of entanglement, etc.
- Polarization is a valuable tool when studying top-quark physics.

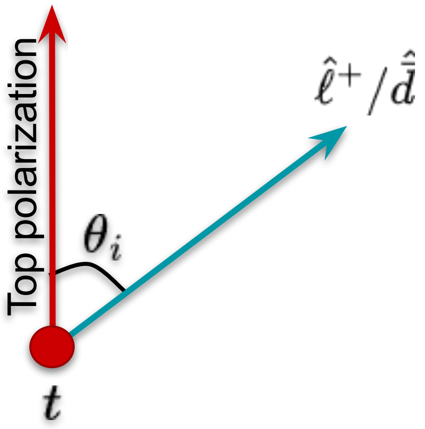
$$\left\{ \begin{array}{l} \tau_{\rm top} \approx 5 \times 10^{-25}\ {\rm s} \\ \tau_{\rm had} \approx 2 \times 10^{-24}\ {\rm s} \\ \tau_{\rm flip} \approx 10^{-24}\ {\rm s} \end{array} \right.$$

- The top polarization can be probed from the kinematics of its decay products.

Top polarization

- The direction of the top decay products correlates with the top polarization axis

$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta_i} = \frac{1}{2}(1 + p\beta_i \cos\theta_i)$$



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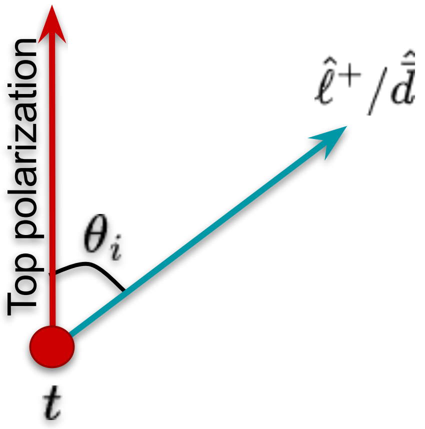
Spin analyzing power

$\ell^+/\bar{d}$	ν/u	b
1	-0.32	-0.41



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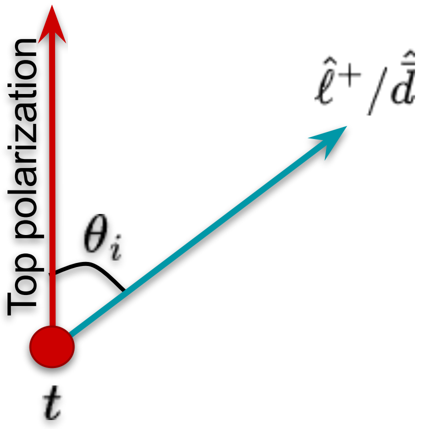

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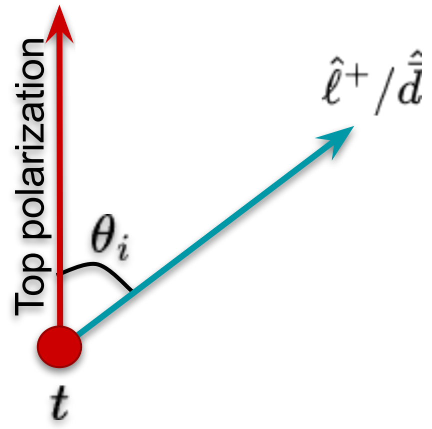
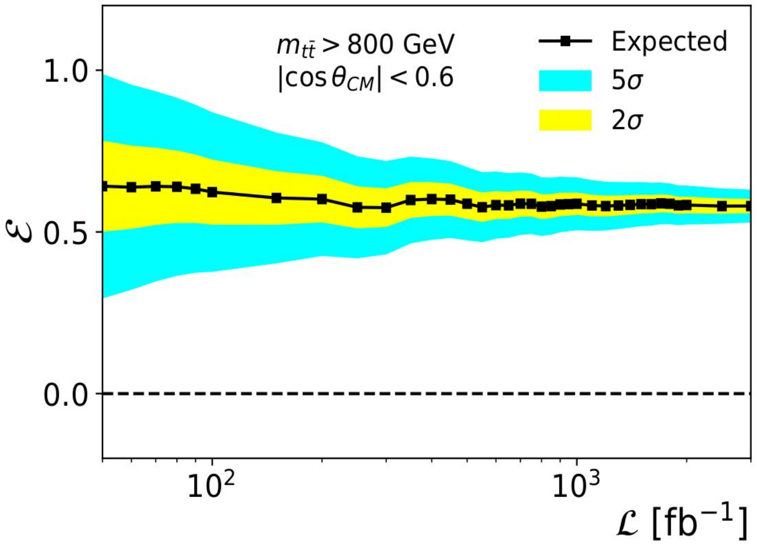


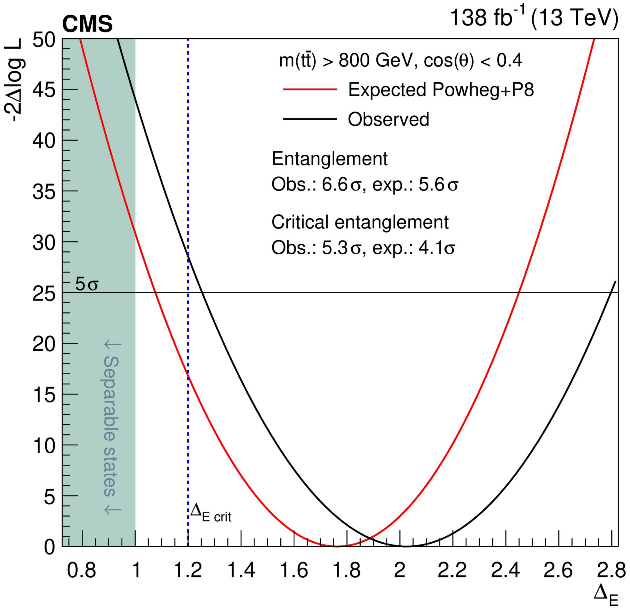
- The charged lepton and down quark have the largest spin analyzing power.
- Hadronic decaying top offers higher statistics so fully recovering its polarization is crucial.

Entanglement with semileptonic tops

➢ very recent application of hadronic top polarization in measuring entanglement with semileptonic top quarks



Dong, Gonçalves, Kong and AN (2023)
See also Han, Low, Wu (2023)



CMS (2024)

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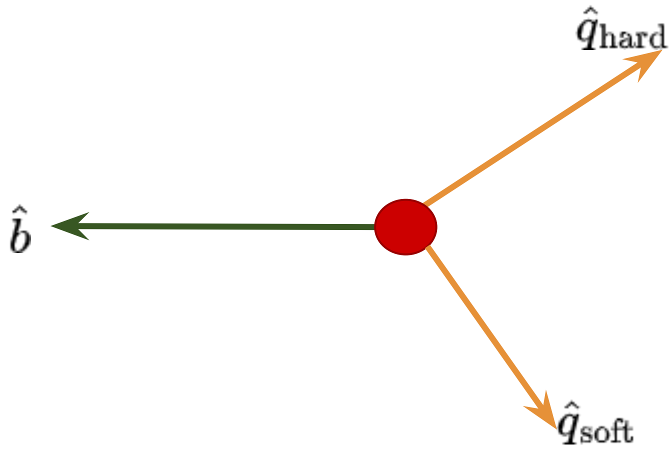
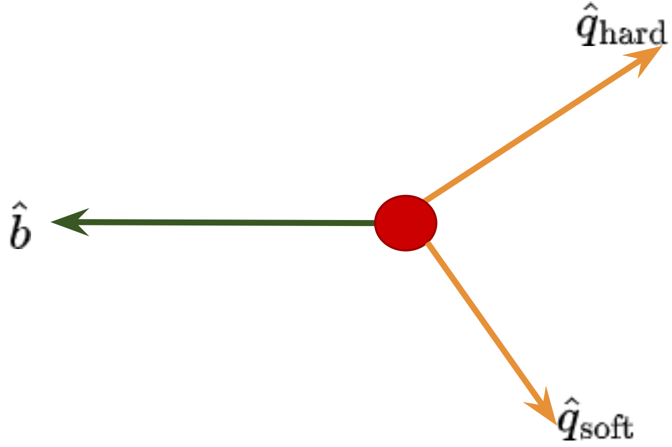
Hadronic top polarimetry

- Identifying a down-quark in a collider environment is challenging.



Hadronic top polarimetry

- Identifying a down-quark in a collider environment is challenging.
- An alternative approach is to use the light jet that is softest in the top rest frame.
- This choice gives a spin analyzing power equals to 0.5 Ježabek (1994)



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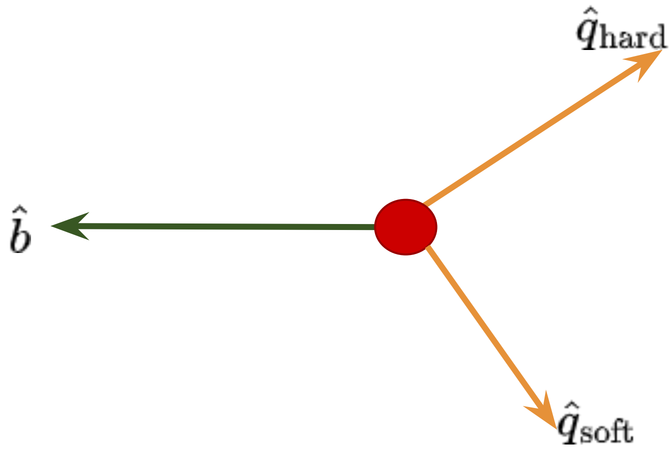
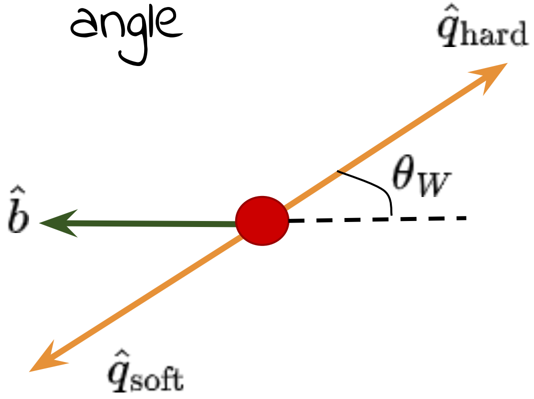


- A better polarimeter can be constructed using the kinematic information of the top decay.

Spin analyzing power through kinematics

➢ Look at the top decay from the W-rest frame and define the helicity angle



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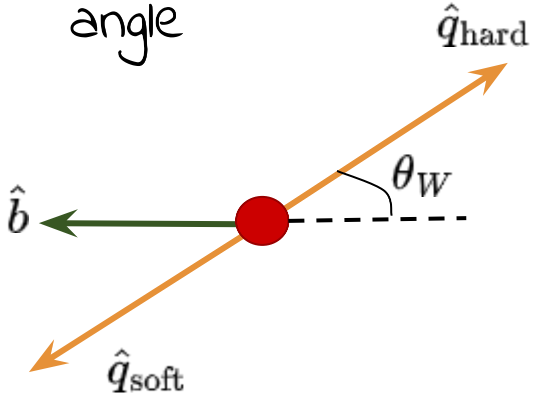

$$p(d \to q_{\rm hard}|c_W) = \frac{p(|c_W|)}{p(|c_W|) + p(-|c_W|)}$$

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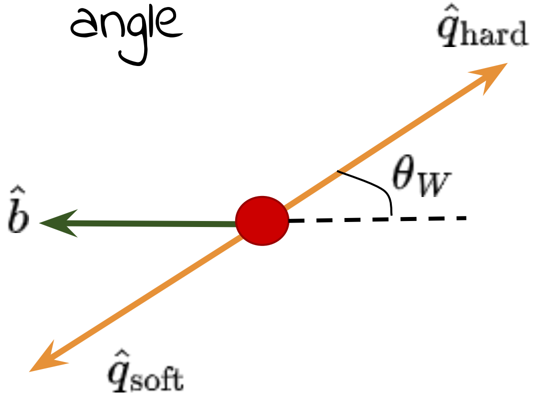

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} down-quark emitted in forward hemisphere

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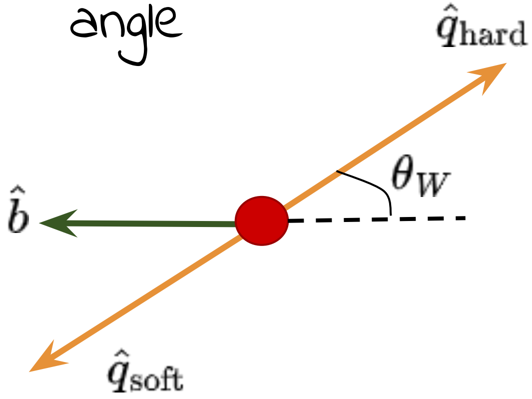

$$p(d \to q_{\text{hard}}|c_W) = \frac{p(|c_W|)}{p(|c_W|) + p(-|c_W|)}$$ } down-quark emitted in forward hemisphere

$$p(d \to q_{\text{soft}}|c_W) = \frac{p(-|c_W|)}{p(|c_W|) + p(-|c_W|)}$$ } down-quark emitted in backward hemisphere

➢ Define the optimal hadronic direction through kinematics as

$$\vec{q}^{\,\text{kin}}_{\text{opt}} = p(d \to q_{\text{hard}}|c_W)\hat{q}_{\text{hard}} + p(d \to q_{\text{soft}}|c_W)\hat{q}_{\text{soft}}$$

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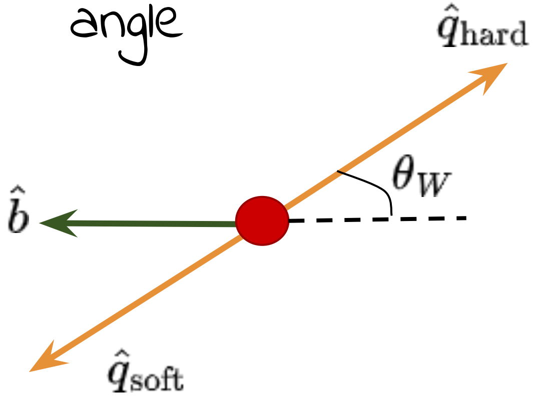

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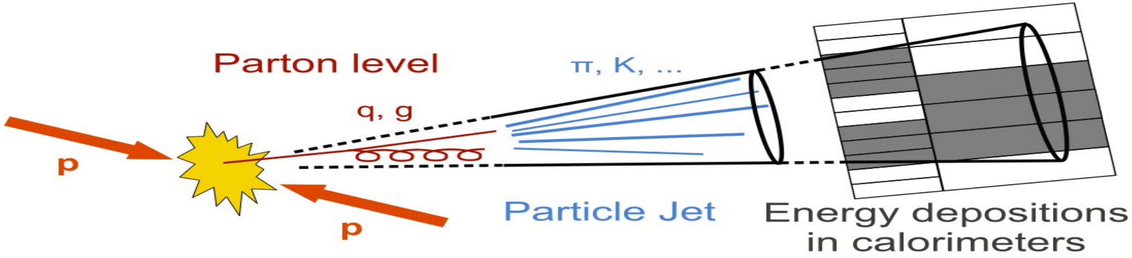
➢ The length of this vector is the spin analyzing power and equals 0.64.

Tweedie (2014)

Going beyond kinematics

➢ At particle level, there's more information available from the jets.



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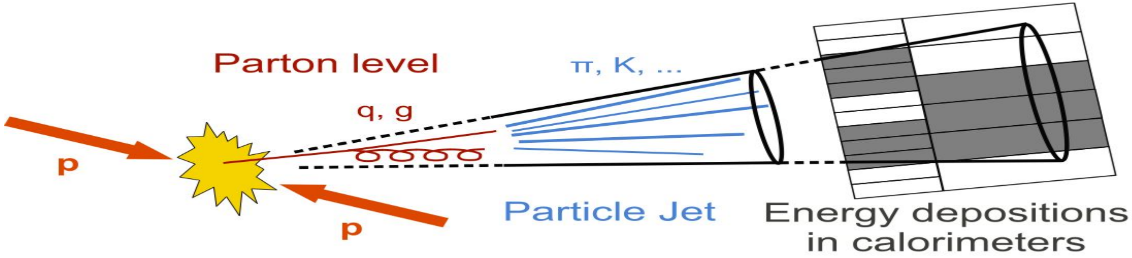

➢ Assume some set of observables $\{\mathcal{O}\}$ is measured and generalized the optimal hadronic direction to

$$\vec{q}_{\rm opt} = p(d \to q_{\rm hard}|\{\mathcal{O}\})\hat{q}_{\rm hard} + p(d \to q_{\rm soft}|\{\mathcal{O}\})\hat{q}_{\rm soft}$$

Dong, Gonçalves, Kong, Larkoski and AN (2024)
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The analytical approach

➢ Start by considering "global jet observables" such as kinematics, jet charge and particle multiplicity.

$$p(\bar{d} \to q_{\text{hard}} | c_W, \mathcal{Q}_{\kappa,h}, N_h, \mathcal{Q}_{\kappa,s}, N_s) = \frac{1}{p(\bar{d} \to q_{\text{hard}} | c_W) + \frac{p(\mathcal{Q}_{\kappa,h} | u \to q_{\text{hard}}, N_h)}{p(\mathcal{Q}_{\kappa,h} | \bar{d} \to q_{\text{hard}}, N_h)} p(u \to q_{\text{hard}} | c_W)}$$
$$\times \frac{1}{\frac{p(\mathcal{Q}_{\kappa,s} | \bar{d} \to q_{\text{soft}}, N_s)}{p(\mathcal{Q}_{\kappa,s} | u \to q_{\text{soft}}, N_s)} p(\bar{d} \to q_{\text{soft}} | c_W) + p(u \to q_{\text{soft}} | c_W)}$$
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Dong, Gonçalves, Kong, Larkoski and **AN** (2024)

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$$\times p(\bar{d} \to q_{\text{hard}}|c_W)\,.$$

Likelihood ratio of the up and down being the hard jet

Likelihood ratio of the down and up being the soft jet

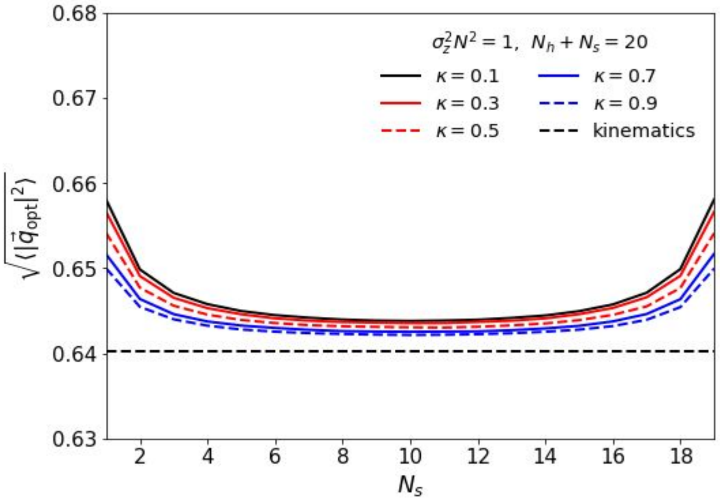
Dong, Gonçalves, Kong, Larkoski and AN (2024)

Improvements with analytical approach

- Jet charge distributions conditioned on multiplicity are Gaussians.

  Kang, Larkoski and Yang (2023)
- Compute the spin analyzing power as the square root of the mean squared-vector length

$$\langle|\vec{q}_{\rm opt}|^2\rangle = \int dc_W\, p(c_W) \int dQ_{\kappa,h}\, dQ_{\kappa,s}\, p(Q_{\kappa,h}, Q_{\kappa,s}|c_W, N_h, N_s)\, |\vec{q}_{\rm opt}|^2$$



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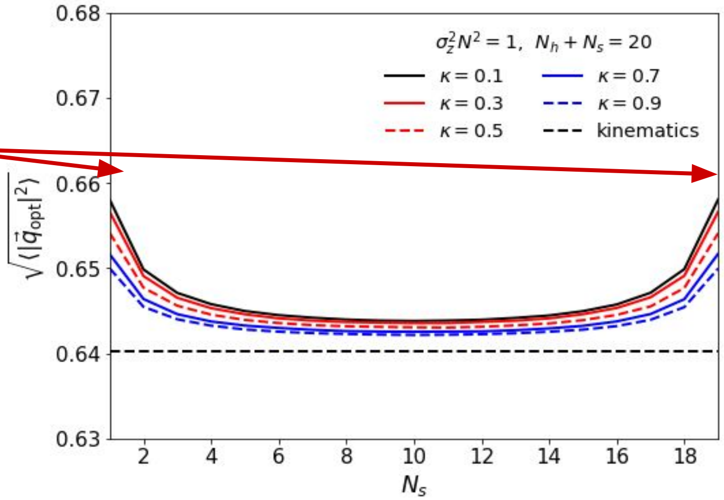
Better discrimination for low N_s and N_h



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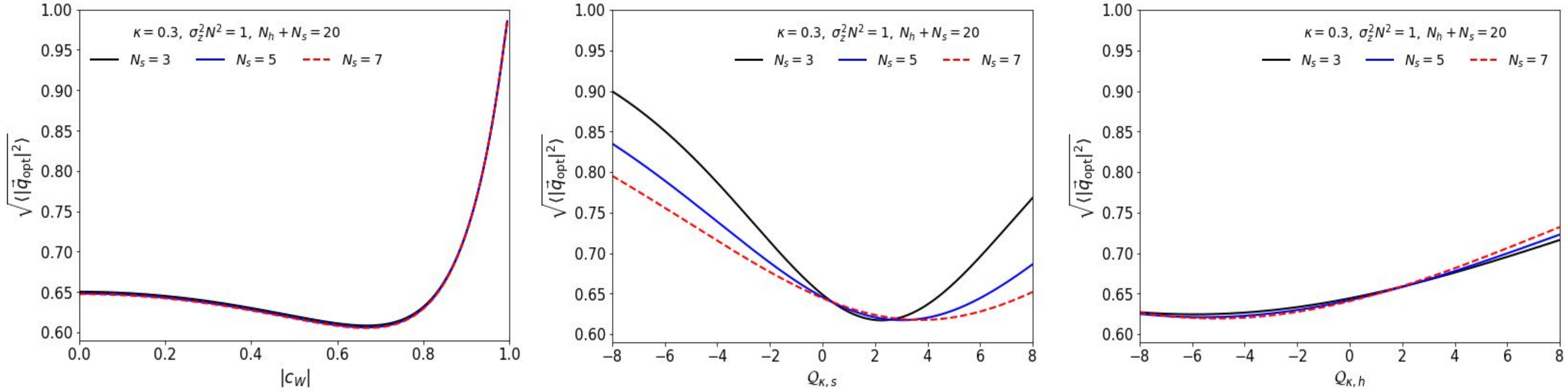

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Improvements with analytical approach

$$\frac{p(\mathcal{Q}_{\kappa,s}|\bar{d}\to q_{\rm soft},N_s)}{p(\mathcal{Q}_{\kappa,s}|u\to q_{\rm soft},N_s)} \to \infty$$

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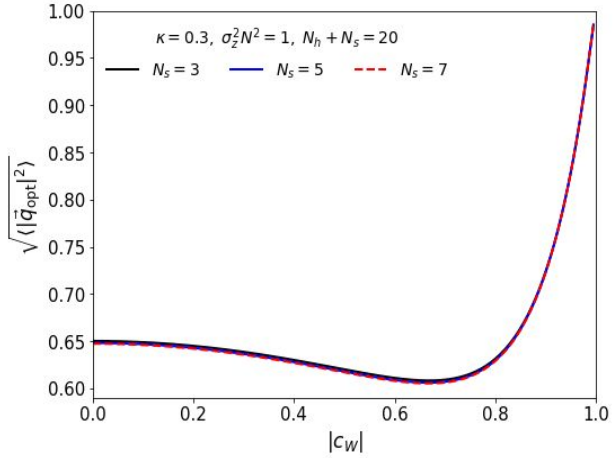

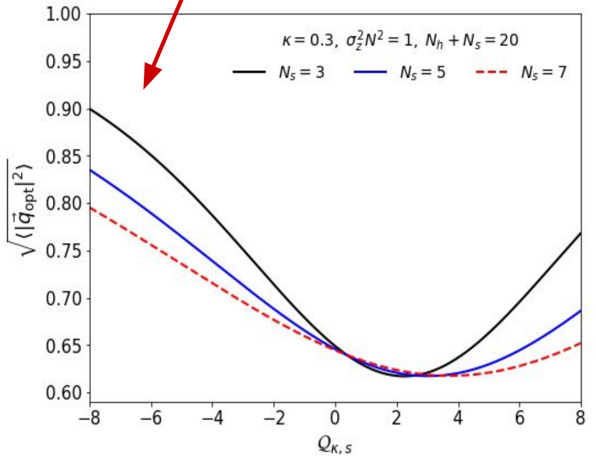

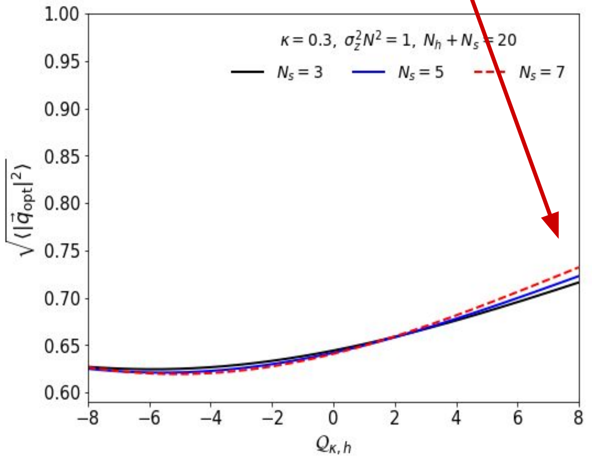

Improvements with analytical approach

$$p(\bar{d} \to q_{\text{hard}} | c_W, \mathcal{Q}_{\kappa,h}, N_h, \mathcal{Q}_{\kappa,s}, N_s) \to 0$$

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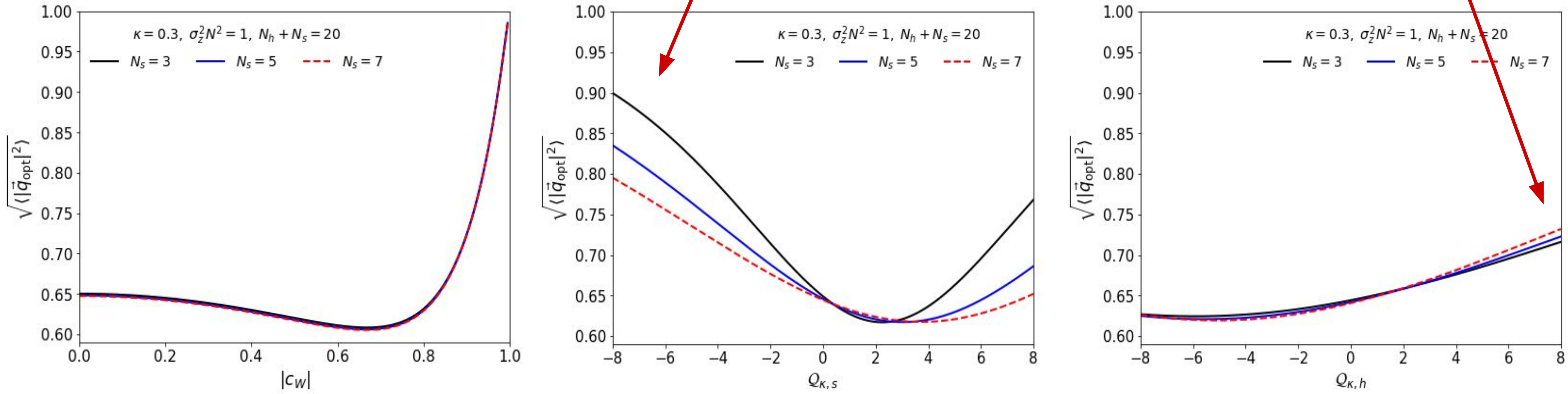

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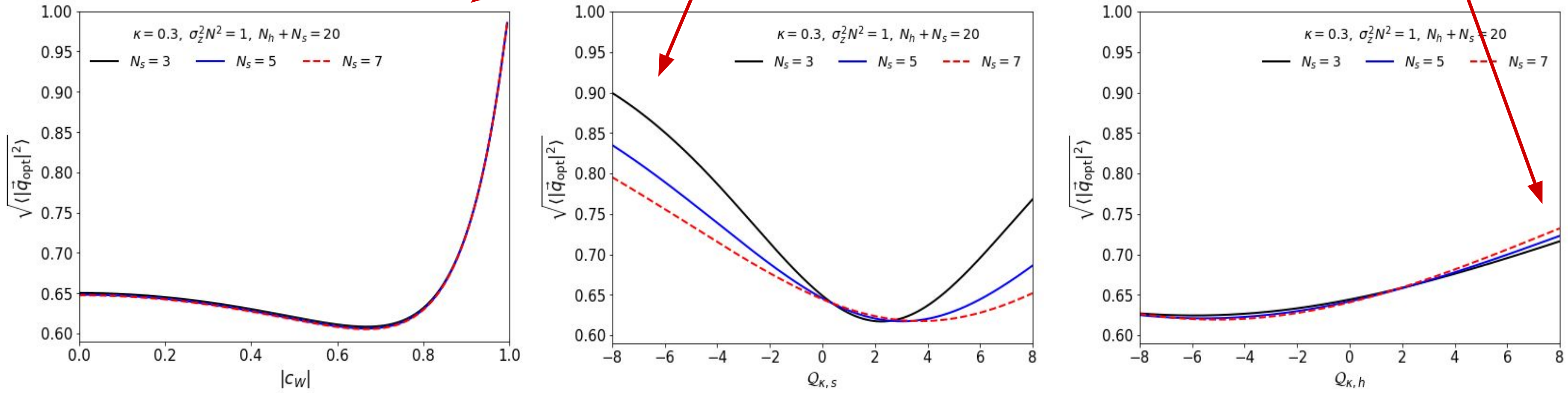

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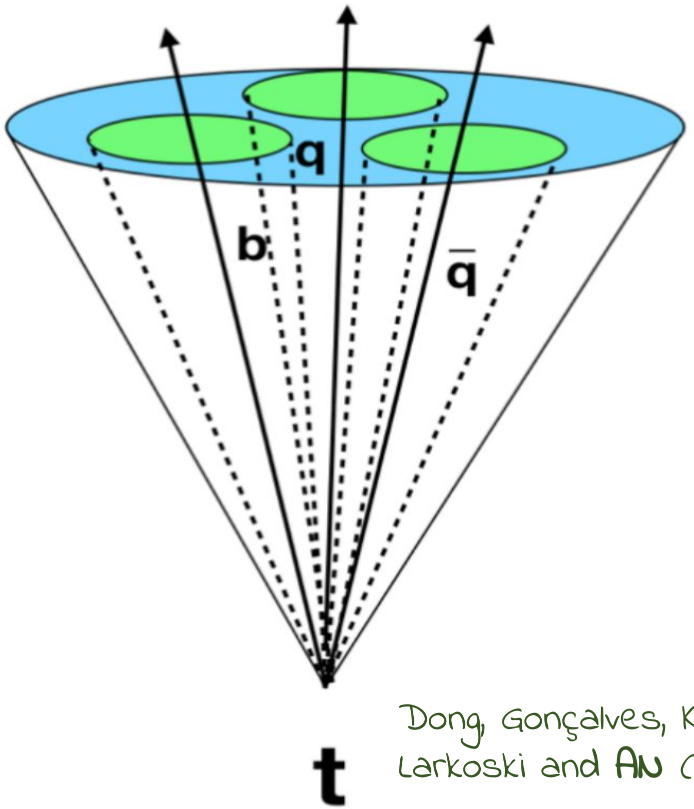
The ML approach

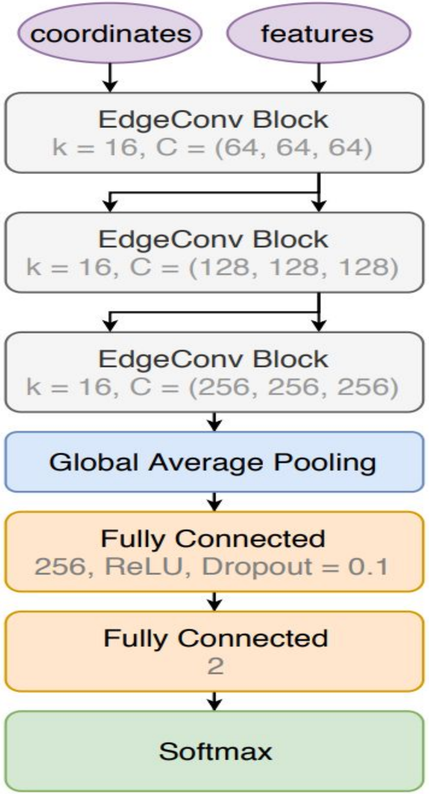
- Could improve result further by incorporating information of jet constituents such as charge, momenta and ID.
- Train network to identify the down jet within the top jet.
- Using a simple DNN may not be ideal due to complexity of data and number of features.



Dong, Gonçalves, Kong, Larkoski and AN (2024)

ParticleNet

- Idea is to represent a jet as an unordered, permutation invariant set of particles (a particle cloud).
- Analogous to the point cloud representation of 3D shapes used in computer vision.
- Has been successfully used for top and quark-gluon tagging.
- Need to modify for our purpose.

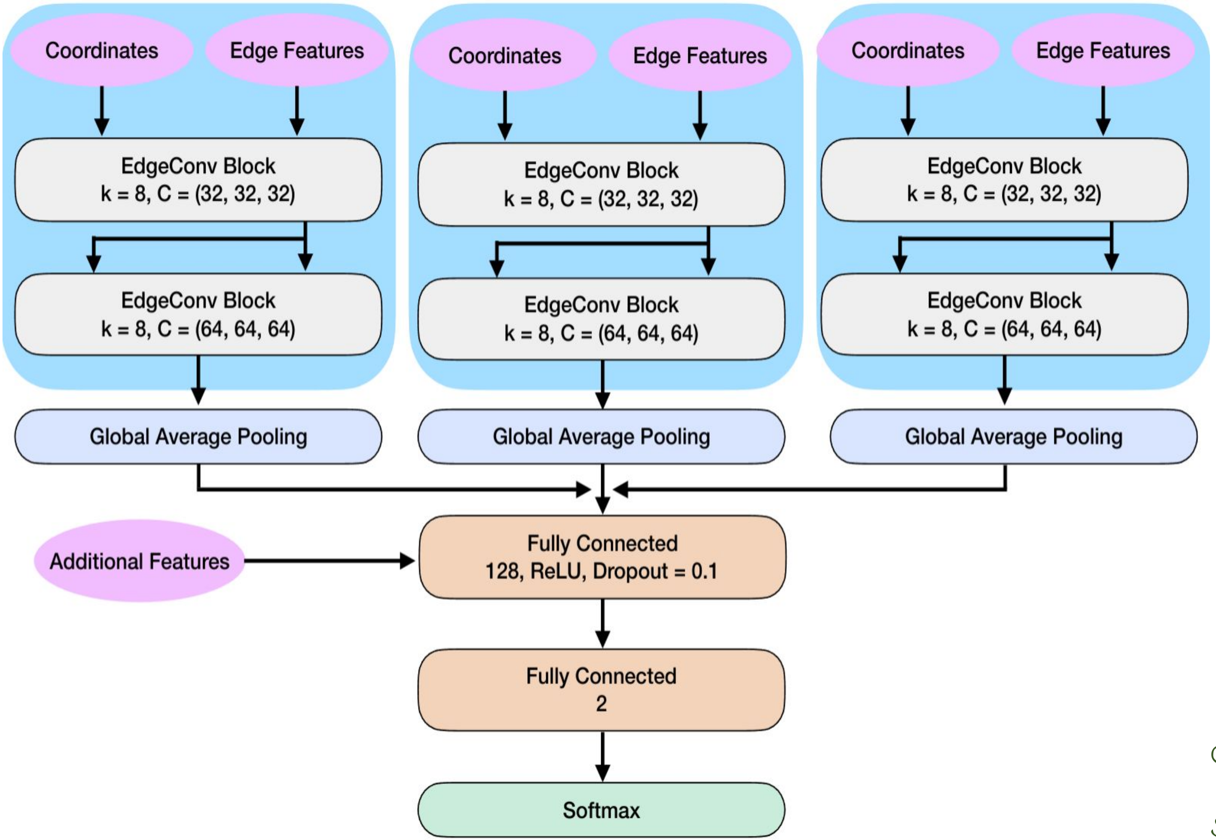


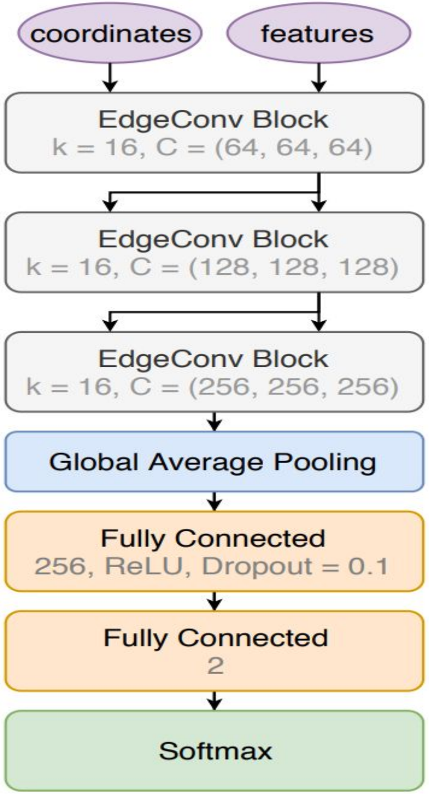
Qu, Gouskos (2019)

See also Gong et al. (2022)

Bogatskiy, Hoffman, Miller, Offermann (2022)

ParticleNet





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GNN performance

Variable	Definition
$\Delta\eta_t$	difference in pseudorapidity between the particle and the top jet axis
$\Delta\phi_t$	difference in azimuthal angle between the particle and the top jet axis
$\Delta\eta_j$	difference in pseudorapidity between the particle and the subjet axis
$\Delta\phi_j$	difference in azimuthal angle between the particle and the subjet axis
$\log p_T$	logarithm of the particle's p_T
$\log E$	logarithm of the particle's Energy
q	electric charge of the particle
isElectron	if the particle is an electron
isMuon	if the particle is a muon
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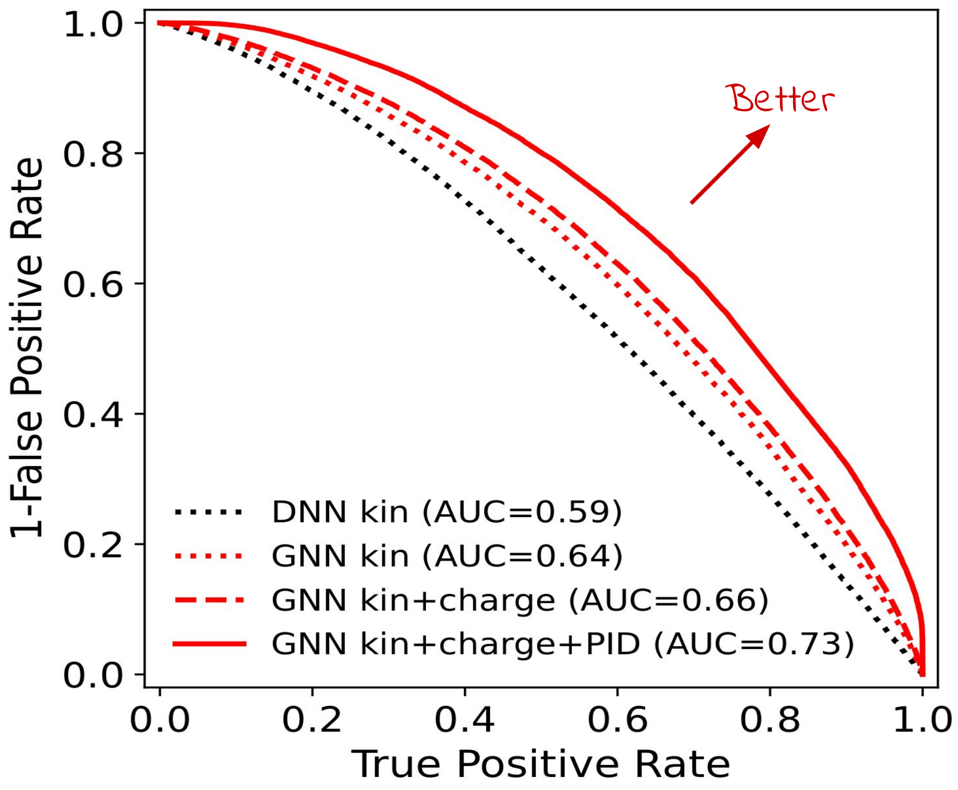

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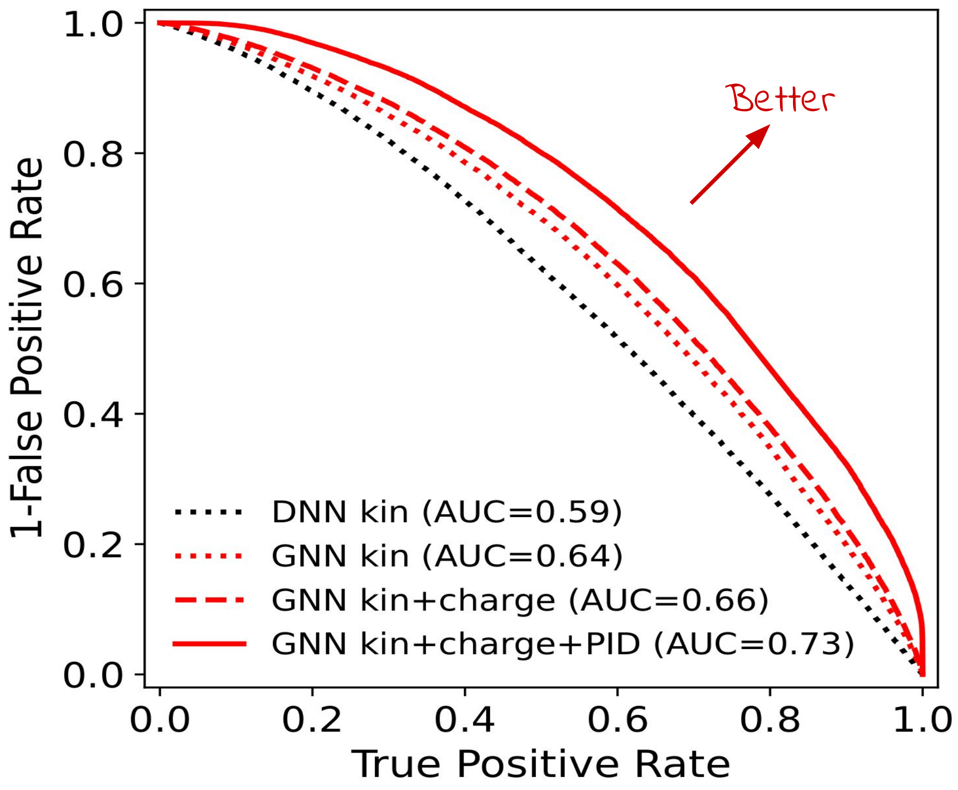

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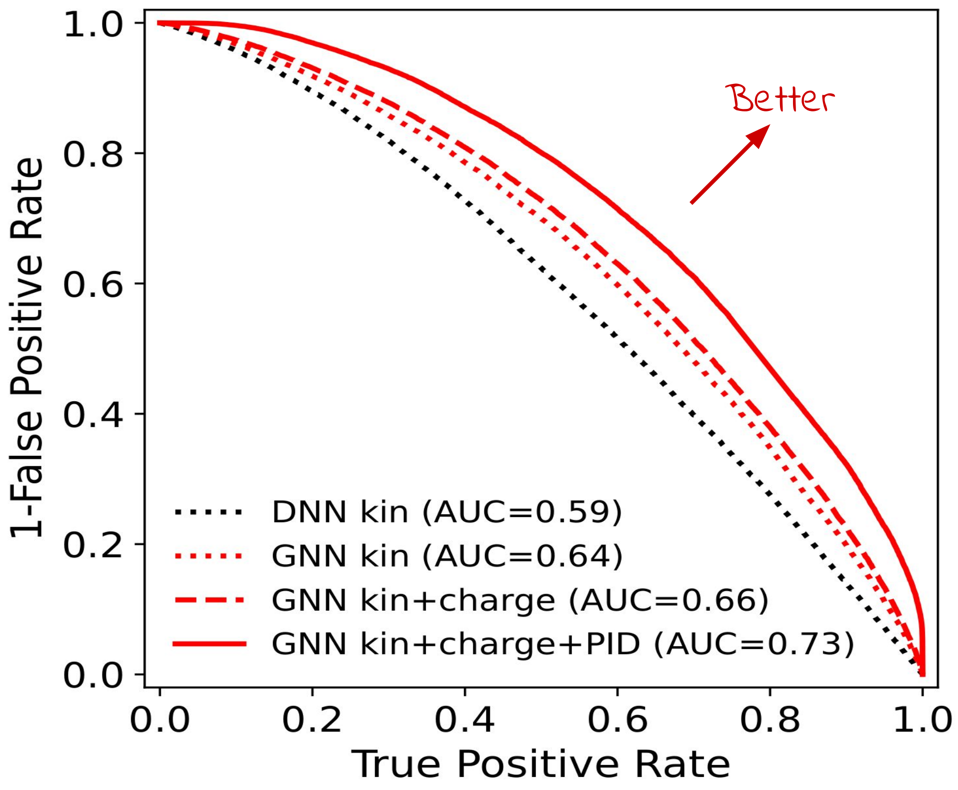

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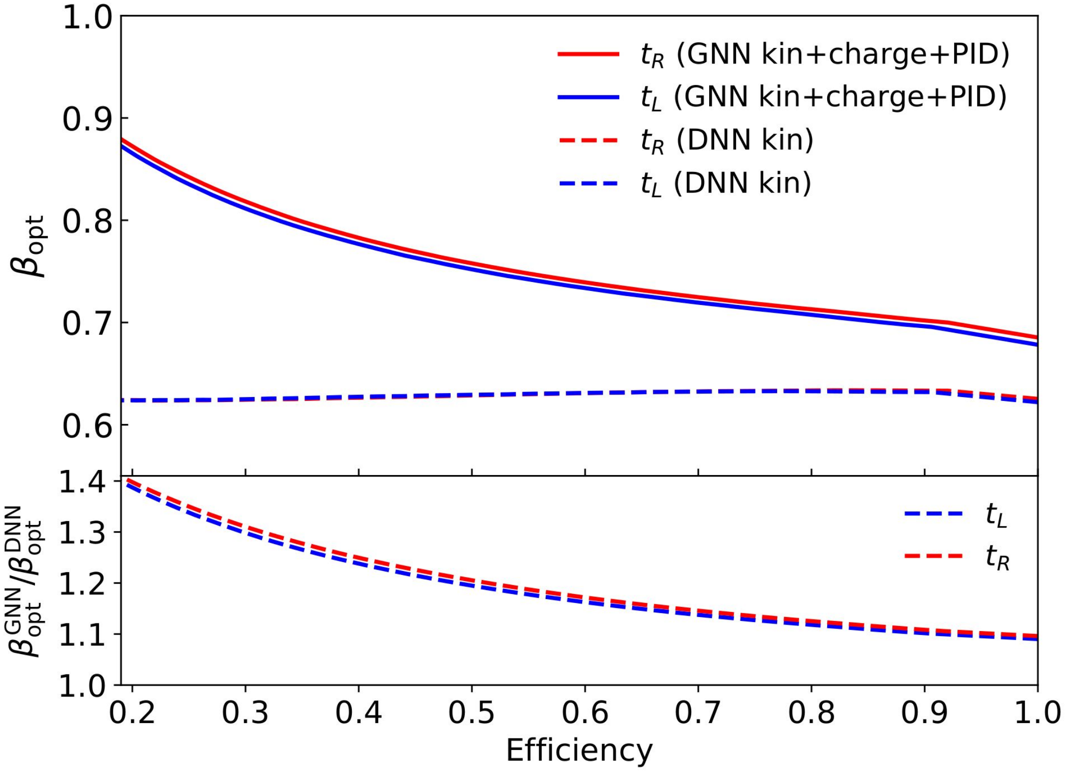
Improvements with ML approach

- Use network score as the probability of the down-type jet being the soft jet.
- Apply cuts on the network score to enhanced the results as long as total rate is still larger than in di-leptonic case.



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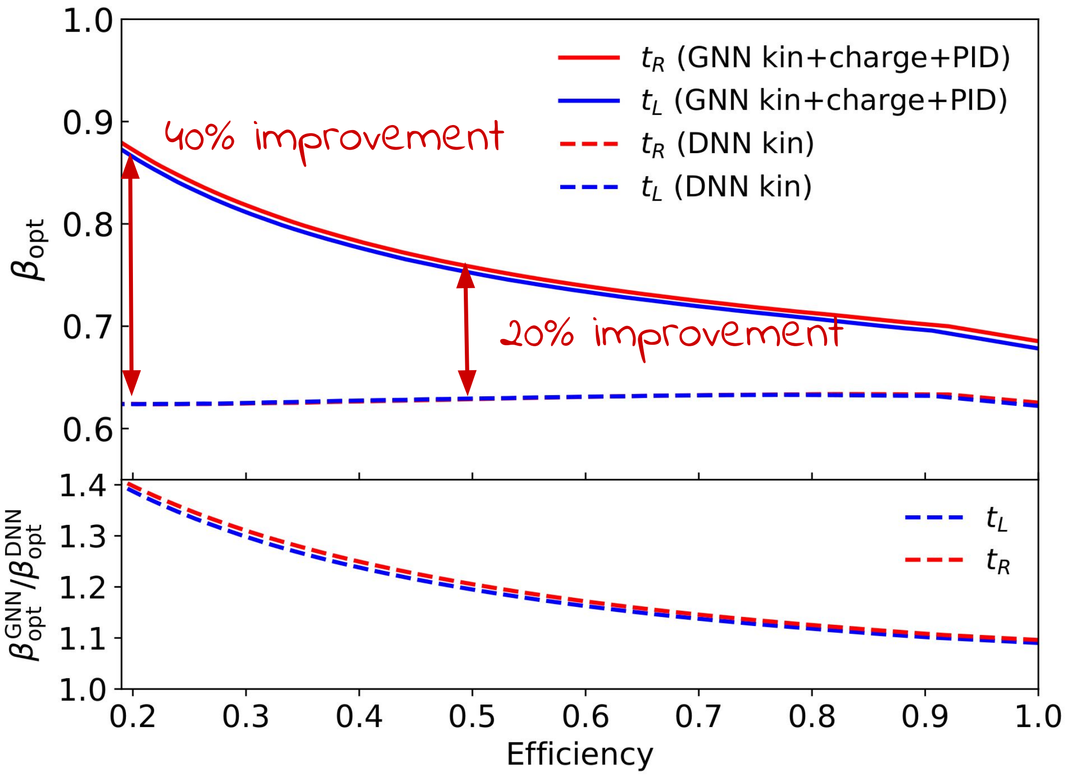


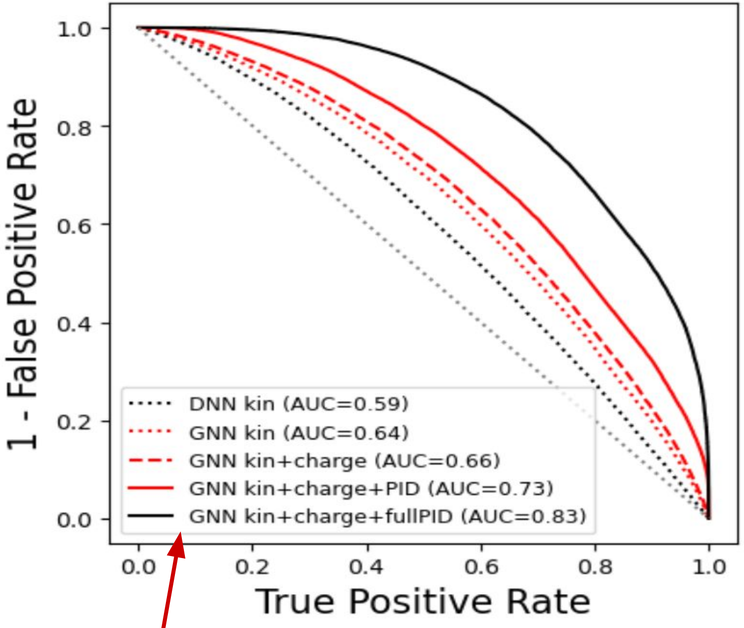
Summary

- Hadronic top-quark polarization can be improved by incorporating information of global jet dynamics and constituents.
- Owing to the larger rate (factor of for semileptonic w.r.t dileptonic case), the spin analyzing power in hadronic decays can improve by approximately 20% (40%) compared to the kinematic approach, assuming an efficiency of 0.5 (0.2) for the GNN.
- This results could be used to further improve studies were the top polarization is relevant such as new physics searches, spin correlations, etc.

Backup

Path for further improvements

- Performance can be improved with pion/kaon discrimination.
- They are not well distinguished at the LHC. This may change with future detectors, though.
- Charm tagging can also be incorporated.



with Kaon/pion ID.

- Any extra information should further improve our current results.

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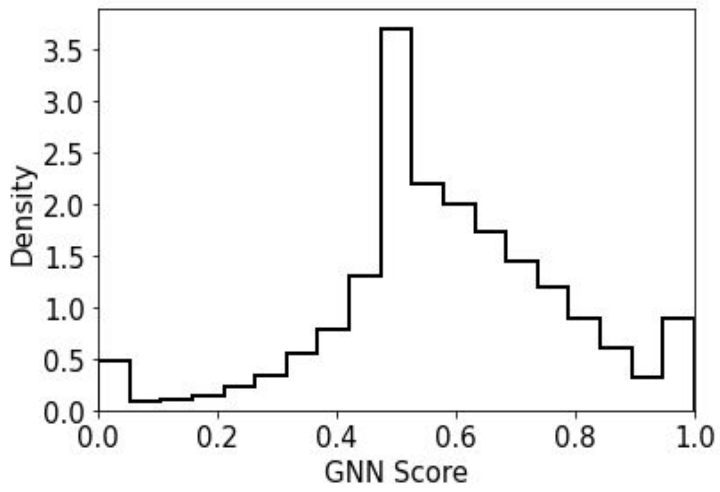
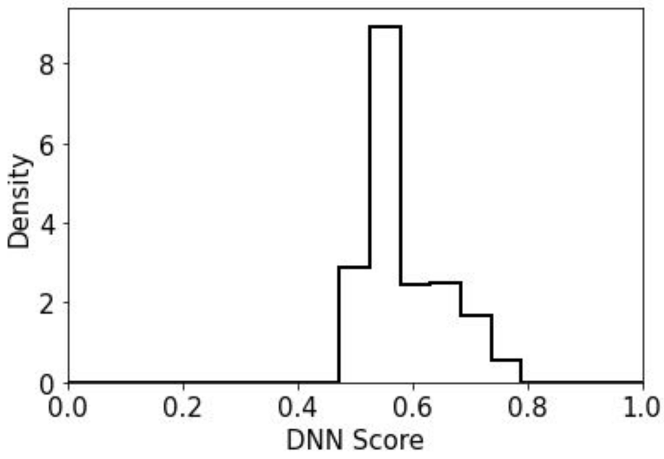
GNN score

- Total of 77k trainable parameters.
- Trained on 200k unpolarized sample.
- Tested on 50k right-hand and left-hand polarized samples.



DNN score

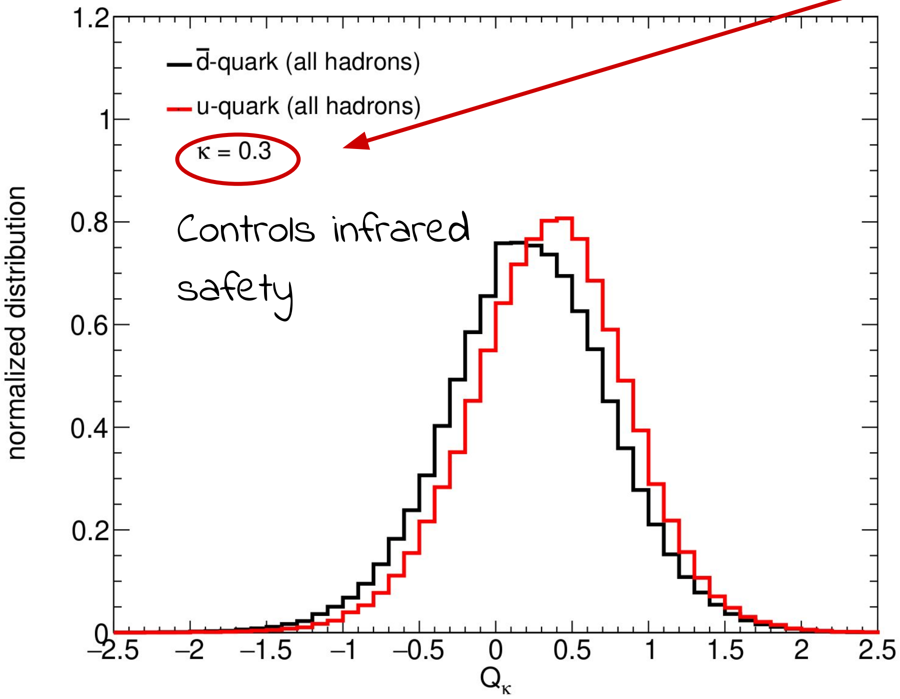
- Using jets momenta as input.
- Total of 20k trainable parameters.
- Trained on 200k unpolarized sample.
- Tested on 50k right-hand and left-hand polarized samples.



Jet charge

➢ A definition of jet charge is given by $\mathcal{Q}_\kappa \equiv \sum_{i \in J} z_i^\kappa Q_i$

Field and Feynman (1978)
Kang, Larkoski and Yang (2023)



Controls infrared safety

$$z^\kappa = \left(\frac{E_i}{E_J}\right)^\kappa$$

Energy fraction of jet constituent

Charge of jet constituent

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Parametric form of jet charge distributions

Kang, Larkoski and Yang (2023)

- Assume hadrons in the jet are produced through identical independent processes and the multiplicity is large

$$p(\mathcal{Q}_\kappa|u,N)=\frac{1}{\sqrt{2\pi\sigma^2}}e^{-\frac{(\mathcal{Q}_\kappa-\mu_u)^2}{2\sigma^2}} \qquad p(\mathcal{Q}_\kappa|\bar{d},N)=\frac{1}{\sqrt{2\pi\sigma^2}}e^{-\frac{(\mathcal{Q}_\kappa-\mu_{\bar{d}})^2}{2\sigma^2}}$$

- Assume particles in the jets are pions and the SU(2) isospin of the pions is exact

$$\mu_u=\frac{2}{3}N^{-\kappa}\left(1+\frac{\kappa}{2}(\kappa-1)\sigma_z^2N^2+\cdots\right) \quad \mu_{\bar{d}}=\frac{1}{3}N^{-\kappa}\left(1+\frac{\kappa}{2}(\kappa-1)\sigma_z^2N^2+\cdots\right) \quad \sigma^2=\frac{2}{3}N^{1-2\kappa}\left(1+\kappa(2\kappa-1)\sigma_z^2N^2+\cdots\right)$$

- The discrimination power

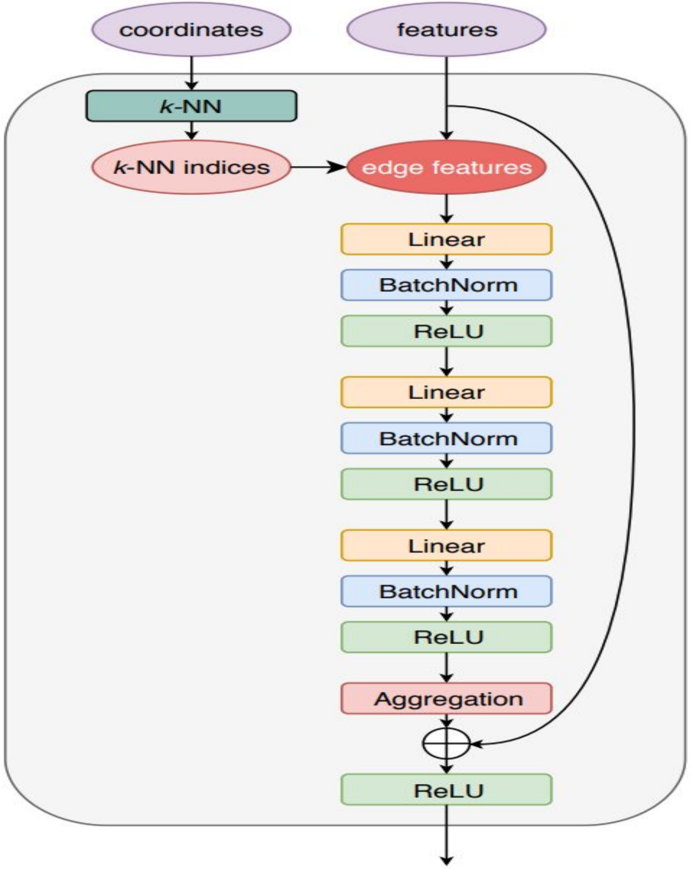
$$\eta=\frac{(\langle Q_\kappa\rangle_u-\langle Q_\kappa\rangle_{\bar{d}})^2}{\sigma^2}\sim\frac{1}{N}\left(1-\kappa^2\sigma_z^2N^2+\dots\right)$$

Data preparation

- we generate 14 TeV $pp \to t\bar{t} \to \ell^{\pm}\nu 2b2j$ events using MG5, with no cuts except for $pT(t) > 200$ GeV.
- Three sets of samples where the top quark is unpolarized, left hand polarized and right hand polarized in the $t\bar{t}$ rest frame.
- Parton shower and hadronization are done with PYTHIA8 without MPI.
- Identify the top jet using CA algorithm with $R = 1.5$, and $pT > 250$ GeV. And decluster to find the subjets with m < 30 GeV.
- Keep the three subjets that satisfy 165 GeV < m(top) < 195 GeV.
- Match the hadron level jets with true parton level momenta, by using the smallest ΔR between the two.

EdgeConv block

- Represents a point cloud as a graph, whose vertices are the points themselves, and the edges are constructed as connections between each point to its k nearest neighboring points
- A local patch needed for convolution is defined for each point as the k nearest neighboring points connected to it.
- Can be viewed as a mapping from a point cloud to another point cloud with the same number of points.



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