Beyond Kinematics for Optimal Hadronic Top Quark Polarimetry I

Based on arXiv:2405.XXXXX with Z. Dong, D. Gonçalves, K. Kong and A. Larkoski

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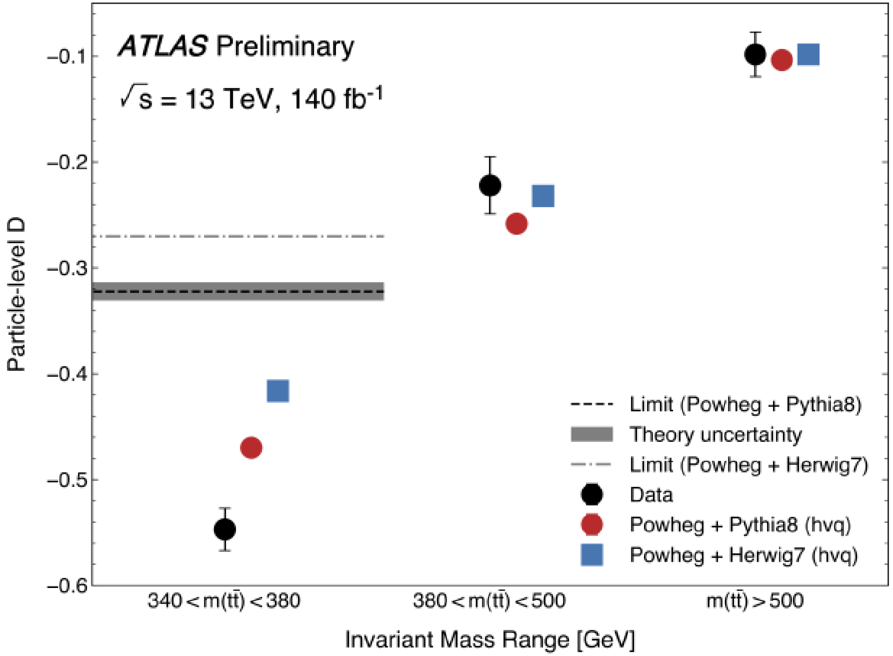
Motivation

- Top quark polarization allows us to measure spin correlations in top-pair production.
- Spin correlations in top-pair production have been known for a long time.
- Recently, spin correlations in top-pair production have been recently used to measure entanglement at high energies.



ATLAS (2023)
See also talk by Andreas Jung on May 16

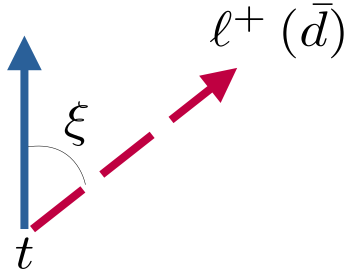
Top polarization

Top quarks decay before hadronization and spin decorrelation effects take place.

This implies that the top decay products correlate with its polarization axis as

$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\xi_k} = \frac{1}{2}\left(1 + \beta_k p \cos\xi_k\right) \qquad \beta_k = \begin{cases} +1, & \text{for } l^+ \text{ or } \bar{d}\text{-quark.} \\ -0.31, & \text{for } \bar{\nu} \text{ or } u\text{-quark.} \\ -0.41, & \text{for } b\text{-quark.} \end{cases}$$

The charged lepton and down-type quark have the highest spin analyzing power.



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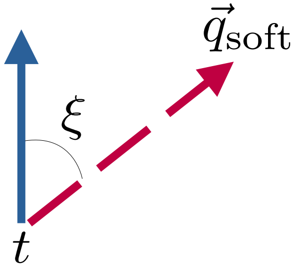

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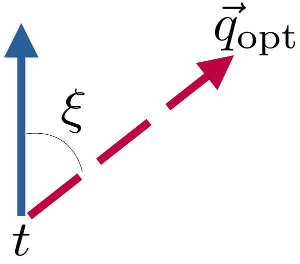

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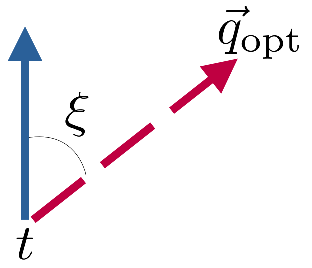

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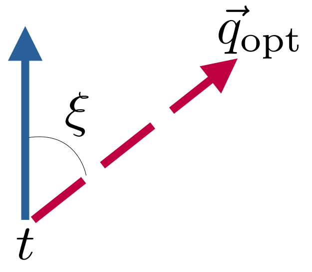


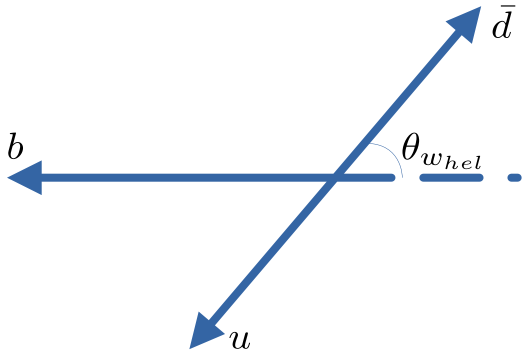
Tweedie (2014)

Optimal hadronic direction

The soft and hard-quark each have a probability of being the d-quark equal to

$$\text{prob}(d \to q_{\text{hard}}) = \frac{\rho(|c_{w_{\text{hel}}}|)}{\rho(|c_{w_{\text{hel}}}|)+\rho(-|c_{w_{\text{hel}}}|)}$$

$$\text{prob}(d \to q_{\text{soft}}) = \frac{\rho(-|c_{w_{\text{hel}}}|)}{\rho(|c_{w_{\text{hel}}}|)+\rho(-|c_{w_{\text{hel}}}|)}$$



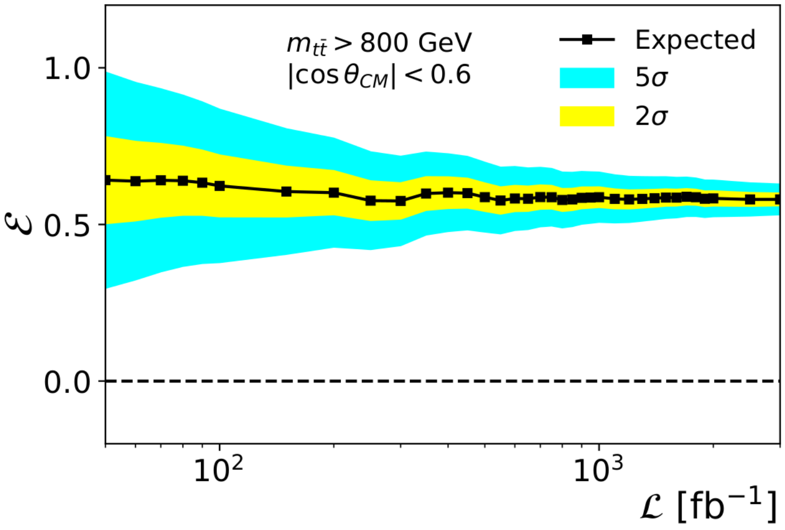
The optimal hadronic direction is defined as the weighted sum of the soft and hard-quark directions

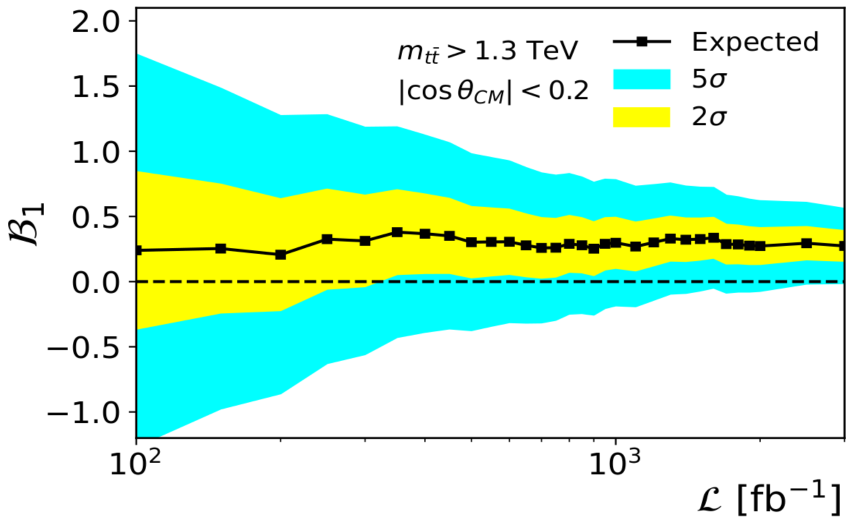
$$\vec{q}_{\text{opt}} = \text{prob}(d \to q_{\text{hard}})\hat{q}_{\text{hard}} + \text{prob}(d \to q_{\text{soft}})\hat{q}_{\text{soft}}$$

Tweedie (2014)

Applications in recent problems

The optimal direction can be used to addressed the measurement of entanglement and violation of Bell's inequality with semileptonic tops

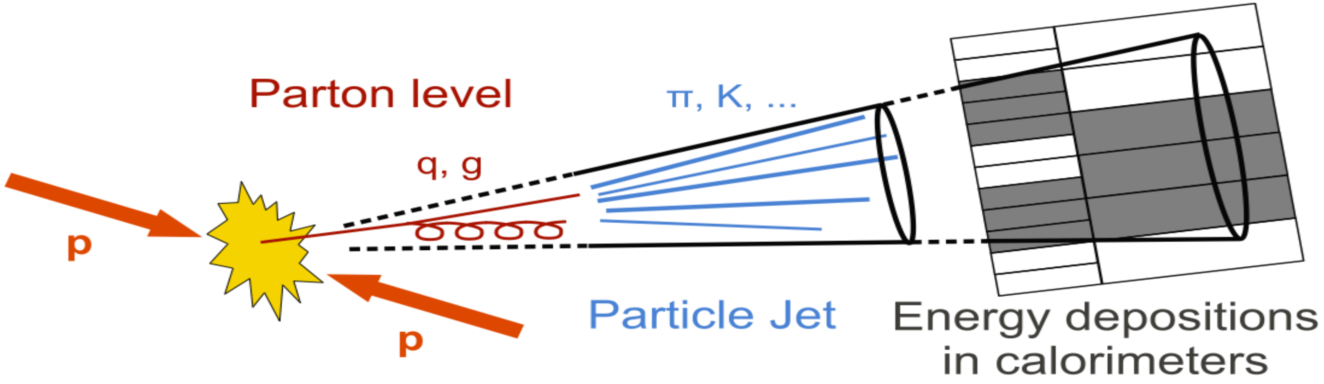




Dong, Gonçalves, Kong, **AN** (2023)
See also Han, Low and Wu (2023)

Beyond kinematic information

The optimal hadronic direction uses all the kinematic information (momentum) of the top decay products. At particle-level, jets contain more information than just momentum.

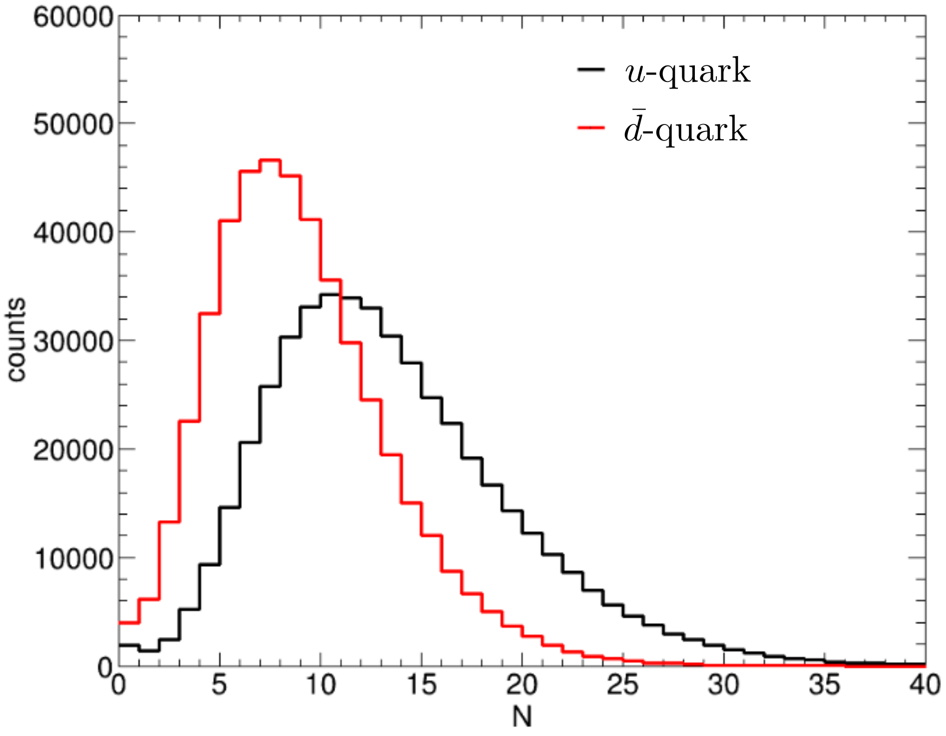


Other observables such as jet charge and particle multiplicity can be measured.

Particle multiplicity

Particle multiplicity can also give information about the up and down quark jets.

Down-quark jet multiplicity distribution peaks at lower multiplicity than up jet.



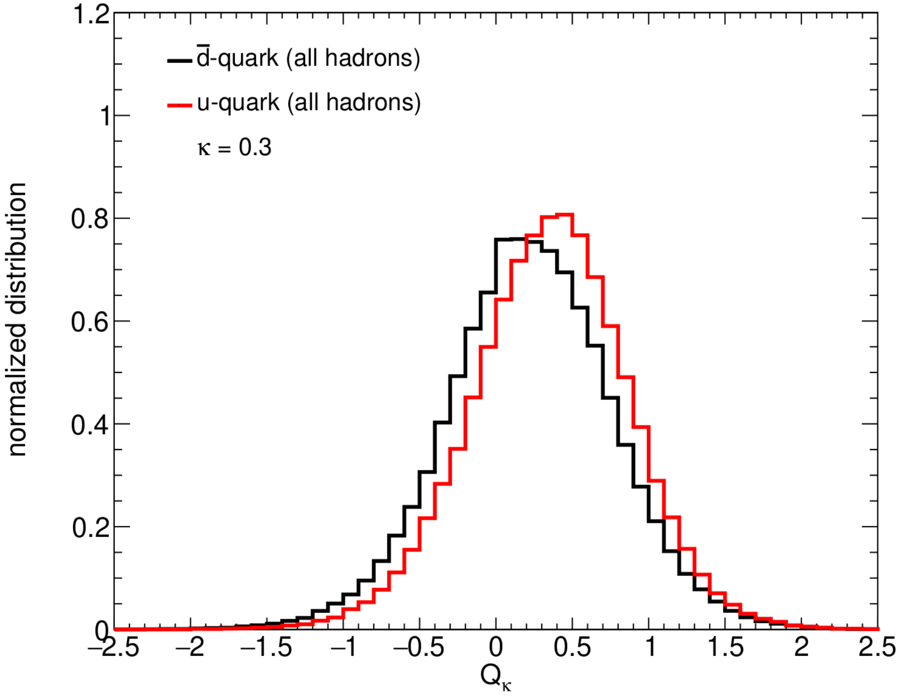
Jet charge

A definition of jet charge is

$$Q_\kappa = \sum_i Q_i \, z_i^\kappa = \sum_i Q_i \left(\frac{E_i}{E}\right)^\kappa$$

Field and Feynman (1978)

The jet charge distributions for up and down-type quarks are approximately Gaussian with means centered around the quark charges.



Jet charge

Under a few assumptions, the the probability distribution of the jet charge conditioned on the multiplicity may be approximated as Gaussian with mean and variance

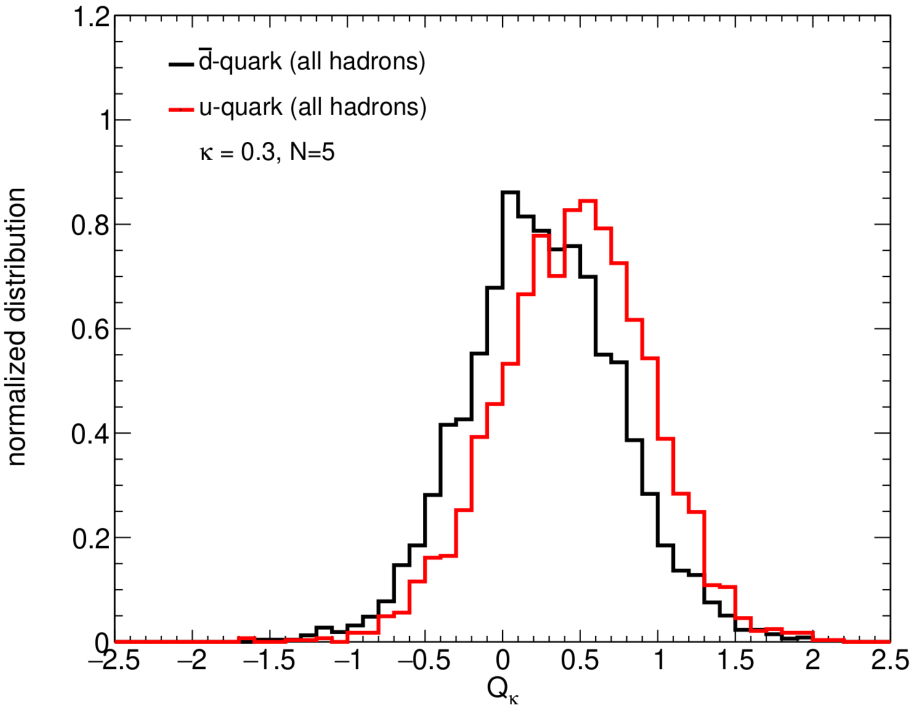
$$\langle Q_\kappa \rangle_u = \tfrac{2}{3}\langle z^\kappa \rangle \,,\ \langle Q_\kappa \rangle_{\bar{d}} = \tfrac{1}{3}\langle z^\kappa \rangle \,,\ \sigma_\kappa^2 = \tfrac{2}{3} N \langle z^{2\kappa} \rangle$$

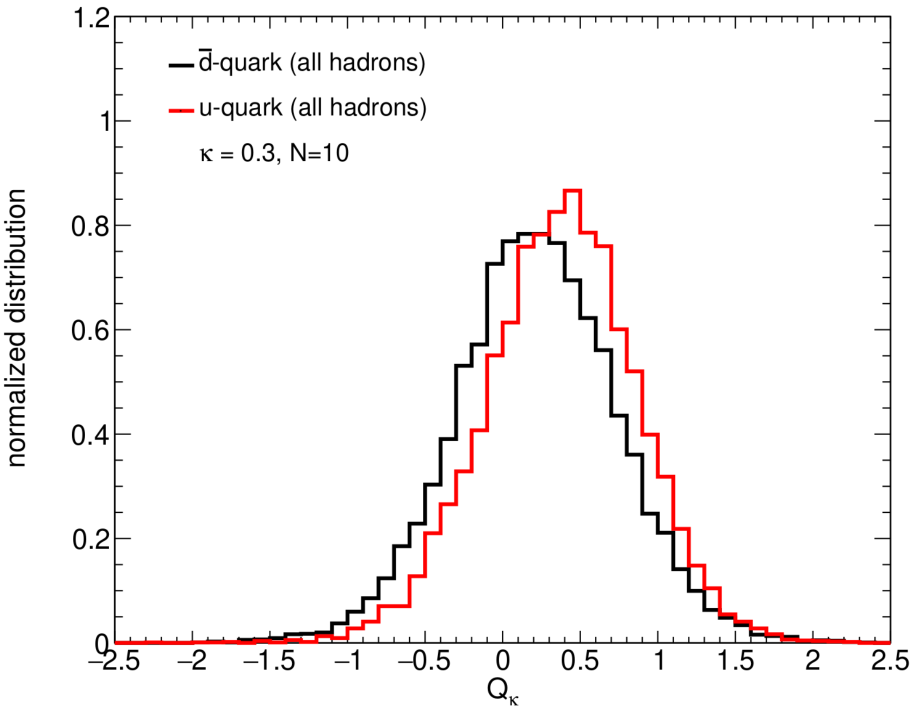
Kang, Larkoski and Yang (2023)

One can define the discrimination power

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

Jet charge and multiplicity





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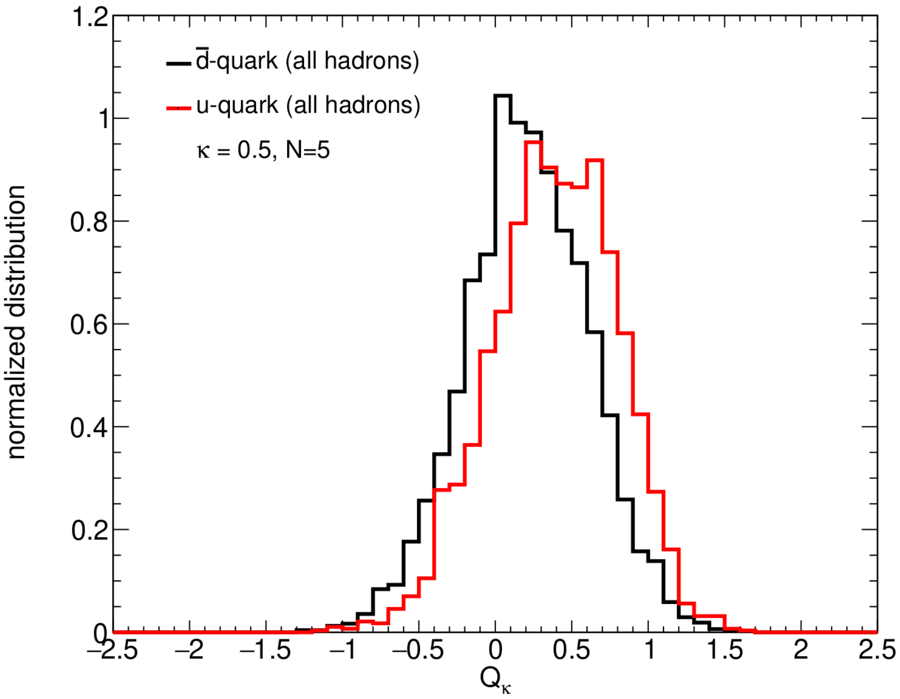
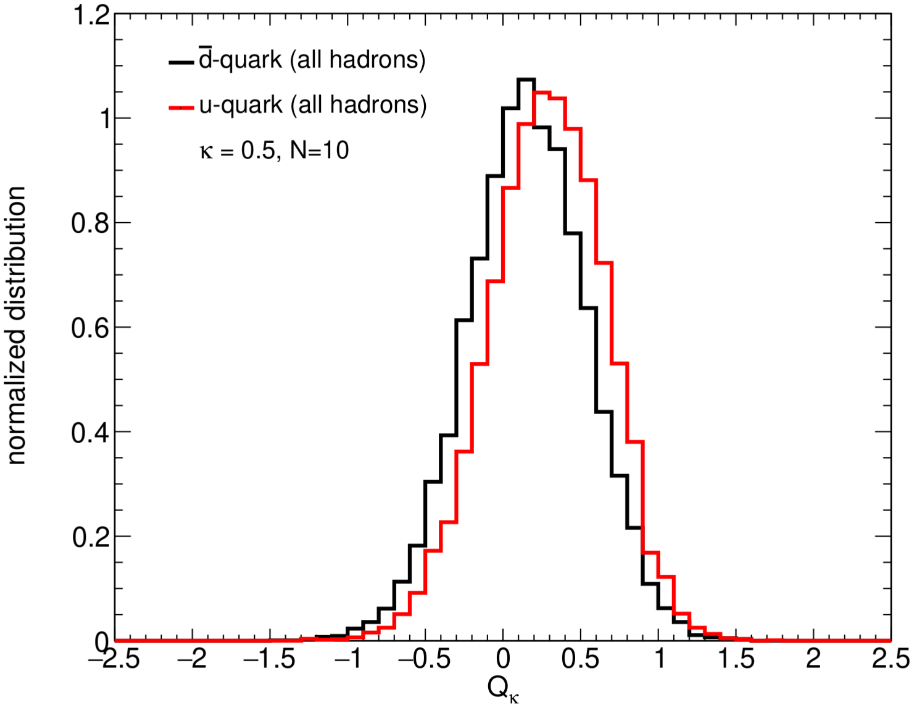
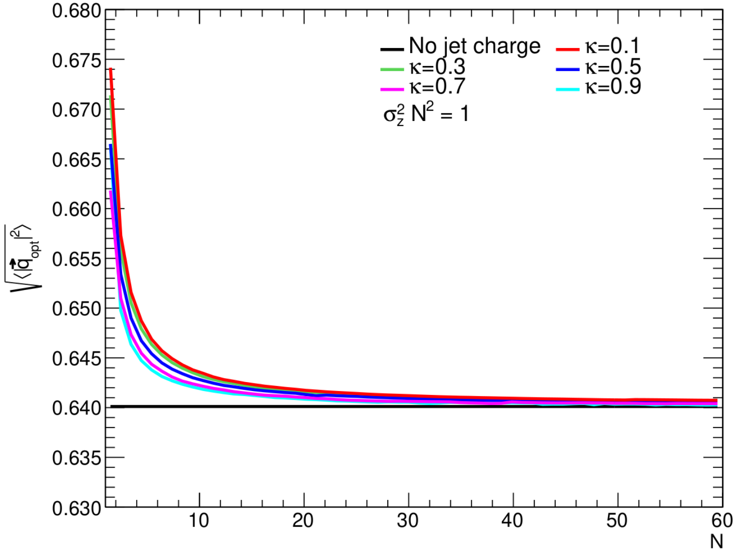
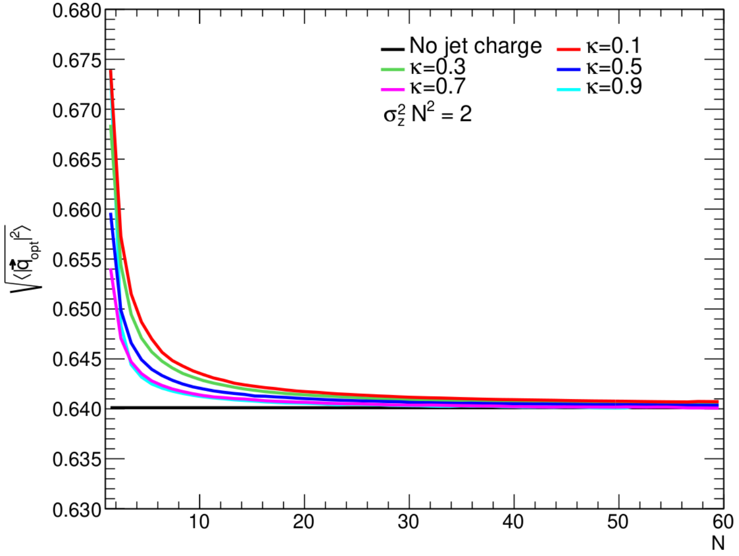




Jet charge and spin analyzing power

$$p(d \to q_{\text{hard}}|c_W, Q_{\kappa,h}, N_h, Q_{\kappa,s}, N_s) = \frac{p(Q_{\kappa,h}|d \to q_{\text{hard}}, N_h)}{p(Q_{\kappa,h}|d \to q_{\text{hard}}, N_h)p(d \to q_{\text{hard}}|c_W) + p(Q_{\kappa,h}|\bar{u} \to q_{\text{hard}}, N_h)p(\bar{u} \to q_{\text{hard}}|c_W)}$$
$$\times \frac{p(Q_{\kappa,s}|\bar{u} \to q_{\text{soft}}, N_s)}{p(Q_{\kappa,s}|d \to q_{\text{soft}}, N_s)p(d \to q_{\text{soft}}|c_W) + p(Q_{\kappa,s}|\bar{u} \to q_{\text{soft}}, N_s)p(\bar{u} \to q_{\text{soft}}|c_W)}$$
$$\times p(d \to q_{\text{hard}}|c_W)\,.$$





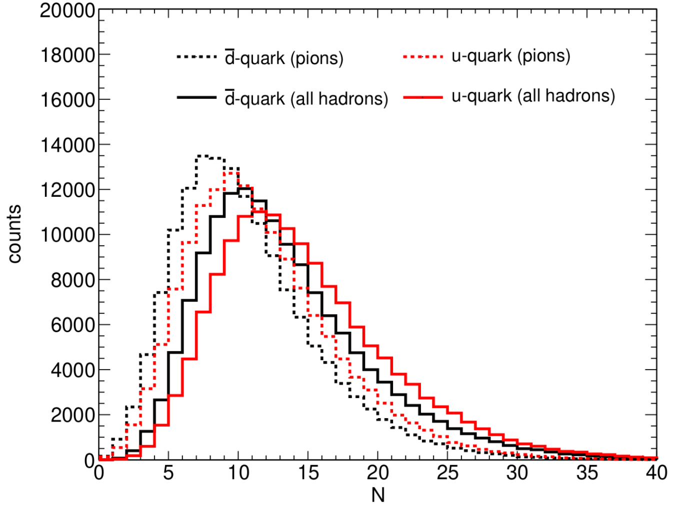
Summary

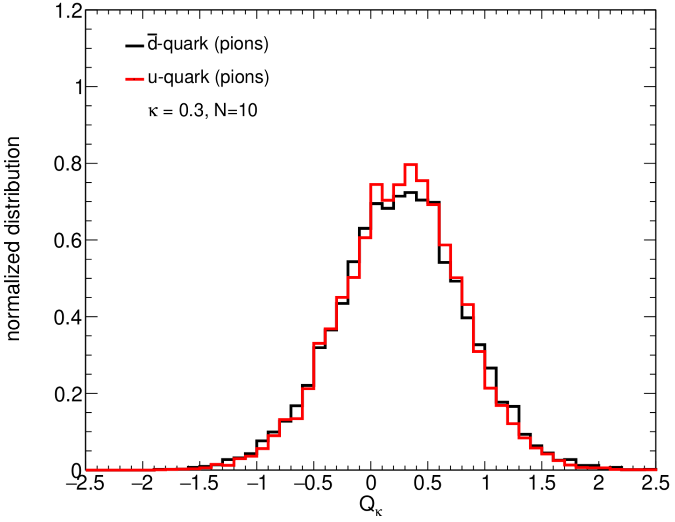
- Hadronic top quark polarimetry can be crucial to boost spin correlation measurements due to its higher event rate.
- Including global features of the subjets, such as jet charge and multiplicity, improves the spin analyzing power. Though the improvement is relatively small.
- A possible way to further improve this result is to include more information of the jet constituents. Similar to what ParticleNet does for quark vs gluon tagging. For more details, see the next talk by Z. Dong.

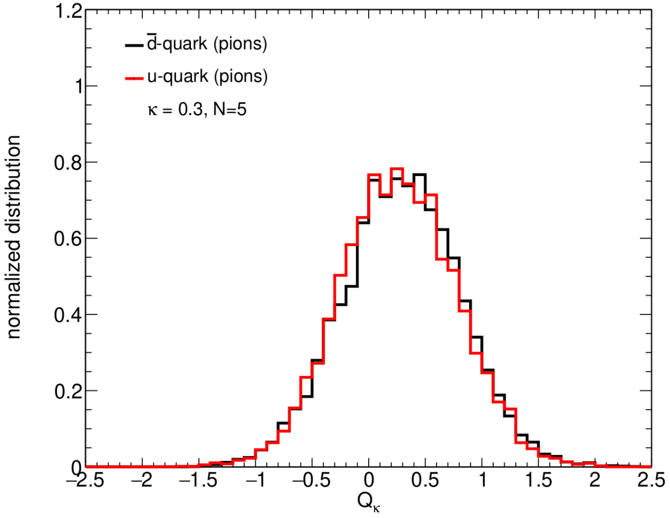
Backup

Separating multiplicities

Considering pions only for the jet charge leaves to no discrimination between up and down jets.







Separating multiplicities

We can look at the jet charge distributions for different type of particle, e.g., kaons and kaons + baryons