Jet charge determination at the LHC

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Abstract: Knowing the charge of the parton initiating a jet could be very useful both for testing different aspects of the Standard model and for searching signals of a beyond-the-standard-model physics. A weighted sum of the charges of jet constituents can be used at the LHC experiments to distinguish among jets from partons with different charges. A few applications of the jet charge variable are presented here. The jet charge was used to distinguish jets initiated by b quarks from those initiated by $\bar{b}$ quarks, for distinguishing between boosted hadronically decaying W^+ and W^-, and for distinguishing jets initiated by quarks from those initiated by gluons.

Introduction

The LHC experiments, ATLAS [1] and CMS [2], are aimed at precision measurements on deep inelastic scattering processes. To test different aspects of the strong interaction requires to reconstruct identity of the produced final state partons. In the case of quarks and gluons their identity is diluted by hadronization. Using jet charge as an observable sensitive to the electric charge of quarks defined as the momentum weighted charge sum constructed from charged-particle tracks in a jet, was suggested in Ref. [3]. Since then the jet charge was investigated from the theoretical as well as from the experimental point of view. For the theoretical studies see Ref. [4] and references inside. The first experimental use of jet charge was in deep inelastic scattering studies (neutrino-proton scattering) [6], [7] providing evidence of quarks in nucleons. In the LEP era, the jet charge variable was employed for tagging the charge of b-quark jets which was used for determination of asymmetry in the production of b quark pairs ([8], [9]) and for neutral B meson oscillation studies, see Refs. [10] and [11]. Later the jet charge technique was applied for tagging of b-quark-jet type within determination of top-quark charge ([12], [13], [14]), for boosted W decaying hadronically – to distinguish them from quark and gluon jets ([15], [16], [17]) as well as for distinguishing jets from quarks and gluons ([18], [19], [20]).

There are a few approaches used for calculation of jet charge:

$$Q_{\mathrm{J}}^{(1)} = \frac{1}{p_{\mathrm{T,J}}^{\kappa}} \sum_{h\in\mathrm{Jet}} q_h \times (p_{\mathrm{T},h})^{\kappa}\,,\ Q_{\mathrm{J}}^{(2)} = \frac{\sum_{h\in\mathrm{Jet}} q_h |\vec{j}\cdot\vec{p_h}|^{\kappa}}{\sum_{h\in\mathrm{Jet}} |\vec{j}\cdot\vec{p_h}|^{\kappa}},\ Q_{\mathrm{J}}^{(3)} = \sum_{h\in\mathrm{Jet}} z_h^{\kappa} q_h,\ z_h = \frac{E_h}{E_{\mathrm{J}}} \quad (1)$$

where q_h, $p_{\mathrm{T},h}$, E_h and $\vec{p}_h$ are the hadron (h) track charge, transverse momentum, energy and momentum, respectively, κ is an exponent (a free parameter), E_{J} is the jet energy, and $\vec{j}$ is the jet direction unit vector.

Theoretical approach

Calculation of jet charge is challenging as it is not an infrared-safe quantity [4]. Difficulties arise due to fact that the jet charge is sensitive to hadronization and also knowledge of the fragmentation functions is needed. In theoretical framework the jet charge is calculated within a soft-collinear effective theory (SCET) – see Ref. [21]. Using the SCET approach the average jet charge is

$$\left\langle Q_\kappa^i \right\rangle = \int dz z^\kappa \sum_h Q_h \frac{1}{\sigma_{\text{jet}}} \frac{d\sigma_{h\in\text{jet}}}{dz} = \frac{1}{16\pi^3} \frac{\tilde{J}_{ii}\left(E,R,\kappa,\mu\right)}{J_i\left(E,R,\mu\right)} \sum_h Q_h \tilde{D}_i^h\left(\kappa,\mu\right) \tag{2}$$

where $z = E_h/E_{\text{jet}} \approx p_{\text{T}}^h/p_{\text{t}}^{\text{jet}}$, $\tilde{J}_{ii}$ are coefficients depending on jet definition and flavor i, J_i is the jet function depending on jet energy (E), and jet cone (R), $\tilde{D}_i^h\left(\kappa,\mu\right) = \int_0^1 dx x^\nu D_i^h\left(x,\mu\right)$ is the Mellin moment of the fragmentation function D_i^h, and μ is the factorization scale.

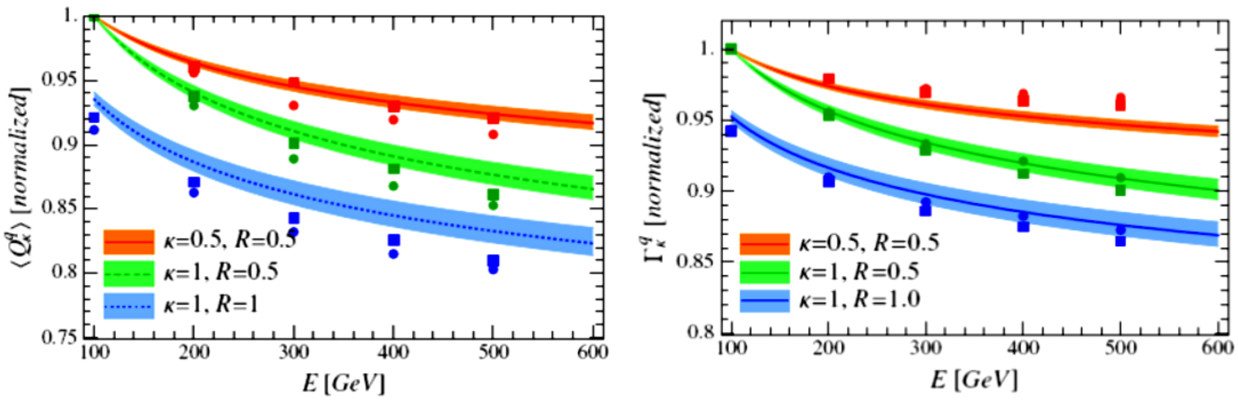

Figure 1: Comparison of theory prediction (bands) for the average (left) and width (right) of the jet charge distribution to Pythia 8 (squares and circles for d and u quarks) for e^+e^- collisions – see text.

Within the SCEP approach, also the jet charge width $\left(\Gamma_\kappa^i\right)^2 = \left\langle \left(Q_\kappa^i\right)^2 \right\rangle - \left\langle Q_\kappa^i \right\rangle^2$ can be calculated. The calculation is similar to that of the average jet charge but is a bit more complicated as the correlation between hadrons should be taken into account [4]. The theoretical prediction for the average and width of the jet charge is shown in Fig. 1 as a function of jet energy (E) for the exponent $\kappa = 0.5$ and 1 and the shower size parameter: R= 0.5 and 1.0. The theoretical uncertainty is found from varying the factorization scale by a factor of 2. The distribution are normalized to 1 at $E = 100$ GeV and $R = 0.5$ and compared to Pythia 8 [22] predictions – square and circles represent d and u quarks, respectively.

Determination of top-quark charge

The jet-charge technique was used by the ATLAS experiment for determination of the top-quark charge [14], where it was used to distinguish between two hypotheses: the SM hypothesis, which assumes the top quark with the electric charge 2/3 and the decay $t \to W^+b$, and the exotic hypothesis based on an exotic quark with the charge -4/3 which assumes the decay $t_{\text{X}} \to W^-b$. Solution of the problem requires to distinguish between b jets from b quark and $\bar{b}$ quark. ATLAS used a data sample of 2.05 fb^{-1} collected in proton-proton (pp) collisions at a center-of-mass energy $\sqrt{s} = 7$ TeV. For the analysis, the $t\bar{t}$ events of the lepton+jets channel, $t\bar{t} \to WWb\bar{b} \to (\ell\nu_\ell)(j_1 j_2)\bar{b}$ with two b tags, were used. To determine the top-quark charge one needs to know the charges of the top quark decay products, W boson and b quark, and also a correct W–b-jet pairing is needed to provide they come from the same decaying object. The charge of W can be found through its leptonic decay, $W^\pm \to \ell^\pm\nu_\ell(\bar{\nu}_\ell)$

– sign of lepton , ℓ, is the same as that of W. As to the b-quark charge, a correlation between b-jet charge, calculated using the second term in Eq. 1, and the charge of the initiating quark, was used. Within the SM a correct pairing requires ℓ^+ to be associated with b quark ($Q_b = -1/3$), if they come from the same top quark, while in the exotic case the pairing of ℓ^- with b should occur. For the lepton–b-jet pairing the following condition based on invariant mass of lepton and b-jet, $m(\ell, b)$, was used: $m(\ell, b^{(1)}_{\rm jet}) < m_{\rm cr}$ and $m(\ell, b^{(2)}_{\rm jet}) > m_{\rm cr}$. The threshold $m_{\rm cr} = 155$ GeV was found by optimization. As a sensitive variable, to decide between these two hypotheses, a combined charge $Q_{\rm comb} = Q_\ell \times Q_{\rm bjet}$ was employed. If the average $Q_{\rm comb}$ is less than zero, then the SM hypothesis is valid and if it is bigger than zero, the exotic hypothesis occurs. Distribution of $Q_{\rm comb}$ reconstructed from the data and compared to MC expectations for the SM and exotic hypotheses is shown in Fig. 2 for the muon+jets channel. A similar distribution also for electron+jets channel is shown in Ref. [14]. As is seen from this figure, the data are in excellent agreement with the SM expectation. Statistical treatment based on pseudoexperiments and taking into account all uncertainties (theoretical and experimental) revealed that the exotic hypothesis was excluded at a confidence level better than 8σ [14].

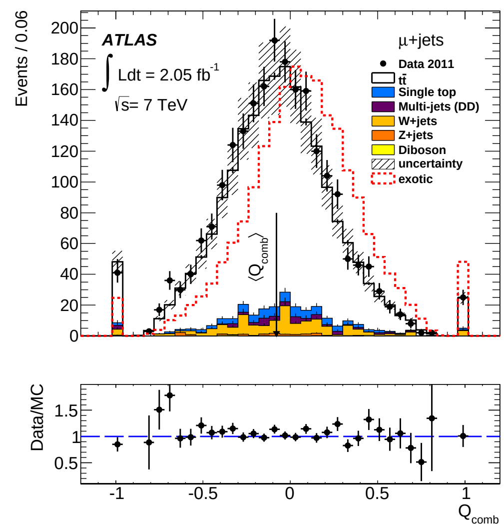

Figure 2: Distribution of $Q_{\rm comb}$ reconstructed from data is compared to MC expectations for the SM and exotic hypotheses.

Boosted W boson and jet charge

The CMS collaboration employed the jet charge along with five other variables for the W boson identification in the boosted regime [23]. The analysis was carried out at $\sqrt{s} = 8$ TeV using data sample of 19.7 fb^{-1}. The boosted W boson was studied in topologies of $t\bar{t}$ (ℓ+jets), W+jets and dijet events. In the ℓ+jets $t\bar{t}$ topology events contain in final state two b quarks and two W bosons, one of which decays leptonically and the other one hadronically. The W boosted topology was selected requiring the W jet mass, $m_{\rm jet}$, and its $p_{\rm T}$ to fulfill: 60 GeV $< m_{\rm jet} <$ 100 GeV and 400 GeV $< p_{\rm T} <$ 600 GeV. The jet charge was calculated using the first term of Eq. 1. The same criteria were applied for boosted jets also in other topologies. Fig. 3 (left) shows the expected jet charge distributions of boosted W^+ and W^- bosons with pileup and detector simulation (histograms), and without pileup and detector simulation (dashed thick lines). The color lines correspond to the boosted W bosons from $t\bar{t}$ events while the black lines represent W+jets events. Fig. 3 (right) compares the $t\bar{t}$ boosted W^+ and W^- jet charge distributions reconstructed from data with the simulated ones (Powheg [24] with Pythia 6) representing a sum of signal and background. Good agreement between the data and simulated jet charge distributions can be stated. In addition, the W^+ and W^- jets distributions for the $t\bar{t}$ data can be separated with $\geq 5\sigma$ [23].

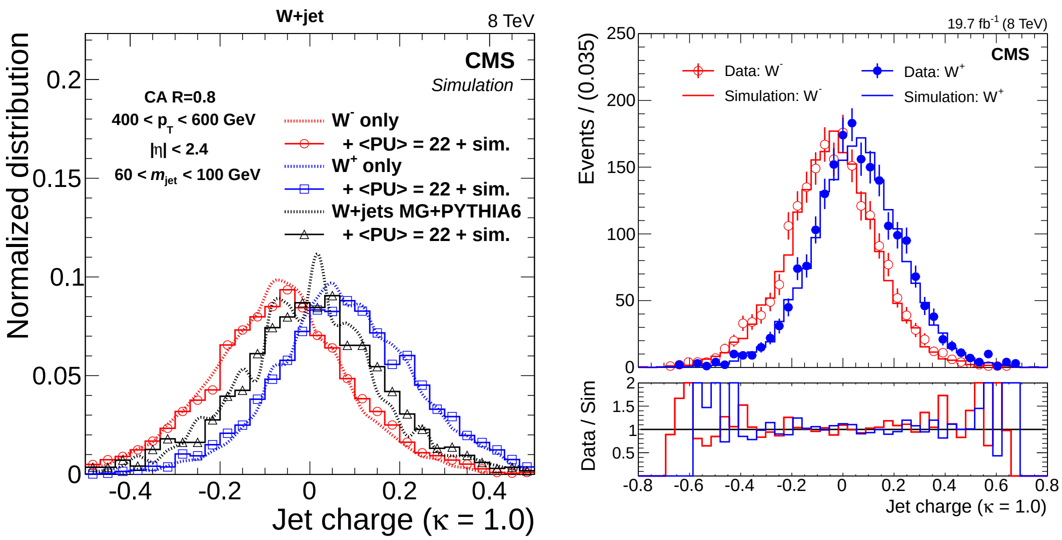

Figure 3: Jet charge boosted W^+ and W^- with and without pileup compared with MADGRAPH/PYTHIA W+jets (left) and the jet charge for W^+ and W^- reconstructed from data and compared with MC (right).

Jet charge in dijet events

A measurement of jet charge in dijet events was carried out by ATLAS in pp collisions at $\sqrt{s} = 8$ TeV using a sample of 20.3 fb^{-1} [25]. Events were selected by a single jet trigger with jet p_T threshold from 25 to 360 GeV. The jet charge was calculated using the first term of Eq. 1. Within the analysis an unfolding of jet charge distribution to particle level as a function of jet p_T was performed. The systematic uncertainty was estimated to be a few percents.

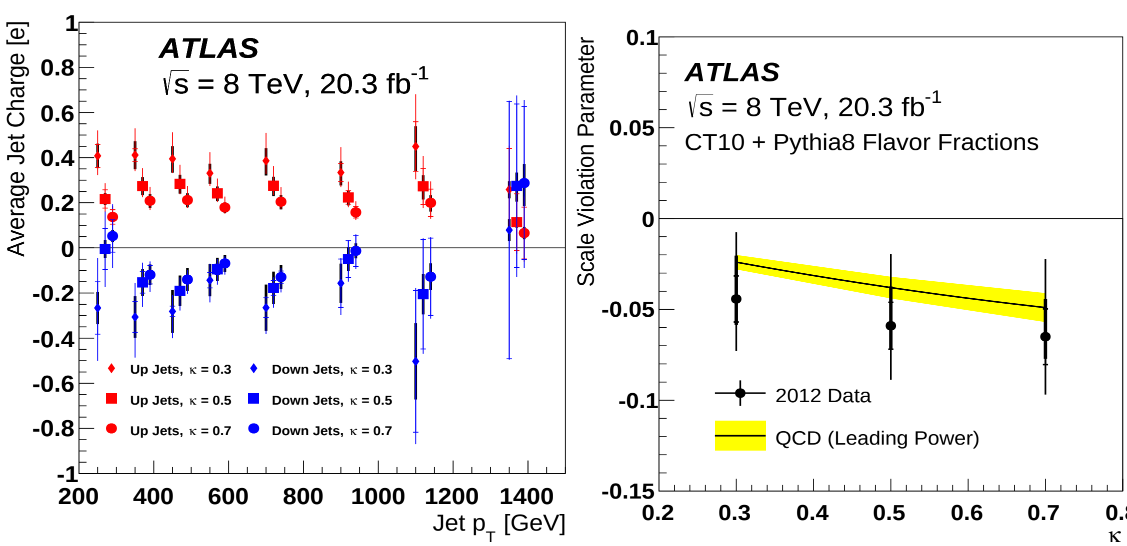

Figure 4: The extracted average u and d quark jet charges in bins of jet p_T for κ=0.3, 0.5, and 0.7 (left) and the extracted scale violation parameter c_κ from the data compared to theoretical calculations [5]. The error bars include statistical, experimental systematic, and PDF uncertainties added in quadrature (right).

Fig. 4 (left) shows the extracted average u- and d-quark-jet charges as a function of jet p_{T} for κ=0.3, 0.5, and 0.7. Theory predicts that the energy dependence of jet charge moments is calculable perturbatively – see e.g. Refs. [4] and [5]. At the leading power of α_{S}, the p_{T} dependence of the average jet charge reads

$$\langle Q_{\mathrm{J}} \rangle = \bar{Q}\left(1 + c_{\kappa} \ln\left(p_{\mathrm{T}}/\bar{p}_{\mathrm{T}}\right)\right) + O\left(c_{\kappa}^{2}\right), \;\; c_{\kappa} \approx -0.38 \pm 0.006 \;\kappa = 0.5 \tag{3}$$

where $\bar{Q} = \langle Q_{\mathrm{J}} \rangle (\bar{p}_{\mathrm{T}})$ for some fixed $\bar{p}_{\mathrm{T}}$, c_{κ} is the scaling violation parameter [25]. The measured values of c_{κ} are, within uncertainties, in agreement with the theoretical prediction, as can be seen from Fig. 4 (right).

Jet charge in dijet events was also investigated by CMS. The analysis was carried out with a data sample of 19.7 fb^{-1} collected in pp collisions at $\sqrt{s}$ = 8 TeV [26]. A measurement of three different charge observables of the dijet leading jet was performed. The first two observables Q and Q_{L} are identical with the first two terms of Eq. 1, while the third observable, Q_{T}, is similar to Q_{L} but track perpendicular momentum to the jet axis is taken instead of the parallel momentum component. The measured jet charge distribution is unfolded from detector to particle level. Fig. 5

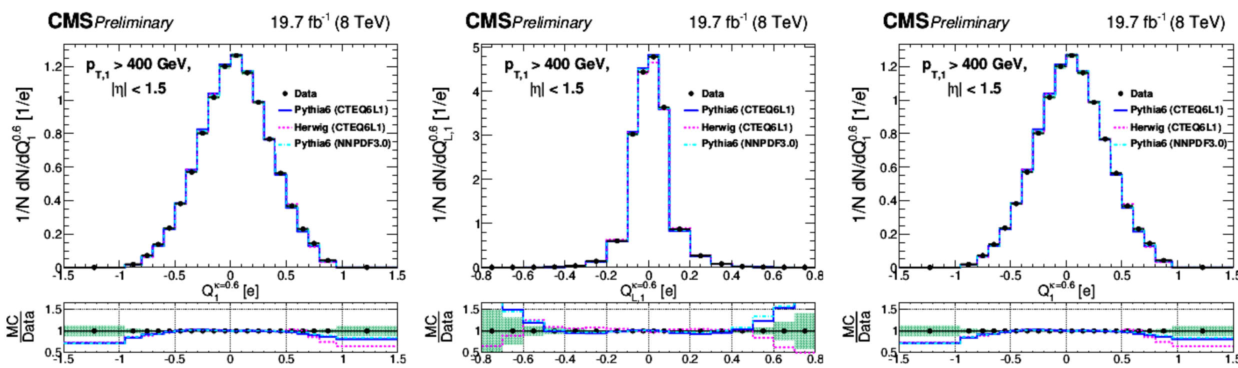

Figure 5: Comparison of unfolded leading jet charge distributions for the charges Q (left), Q_{L} (middle) and Q_{T} (right) with Pythia 6, Herwig++ [27] generators, the used κ = 0.6.

shows a comparison of unfolded leading jet charge distributions for the charges Q, Q_{L} and Q_{T} with Pythia 6, Herwig++ generators. From the comparison it follows that the measured jet charge distributions are in good agreement with expectations.

Conclusion

The ATLAS and CMS experiments have shown that in pp collisions the jet charge variable can be effectively used to distinguish jets initiated by partons of different electric charges. The jet charge, especially when combined with other variables within multivariate techniques, can be used in: studies of asymmetries in $q\bar{q}$ production - to distinguish quarks from antiquarks, studies with W bosons decaying hadronically and many other studies where flavour of jets should be determined. A good perspective of using jet charge is in boosted approaches, especially at 13 – 14 TeV collisions, to distinguish heavy charged and neutral vector bosons.

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