Jet Charge Studies with ATLAS

Cornell LEPP Journal Club

Benjamin Nachman

SLAC, Stanford University

November 1, 2013

Outline

- Introduction, History, and the ATLAS Detector
- Jet Charge Physics in Several Final States
- A New Jet Moment: Charge Performance
- Outlook and Conclusion

ATLAS NOTE

ATLAS-CONF-2013-086

August 10, 2013

Jet Charge Studies with the ATLAS Detector Using $\sqrt{s} = 8$ TeV Proton-Proton Collision Data

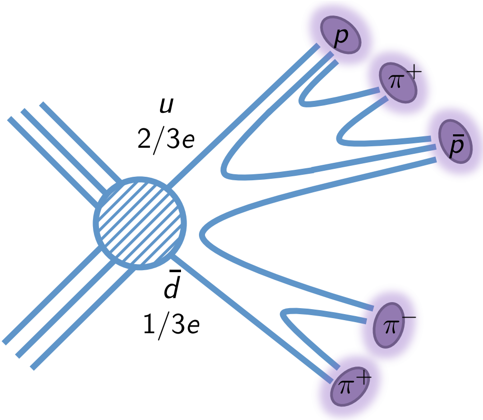
The ATLAS Collaboration

Abstract

The momentum-weighted sum of the charges of tracks associated to a jet provides an experimental handle on the electric charge of fundamental strongly-interacting particles. Presented here is a study of this *jet charge* observable for jets produced in dijet, W+jets, and semileptonic $t\bar{t}$ events using 5.8-15.2 fb^{-1} of data with the ATLAS detector at $\sqrt{s} = 8$ TeV. In addition to providing a constraint on hadronization models, jet charge has many possible applications in measurements and searches. This note documents the study of the modelling of jet charge and its performance as a charge-tagger, in order to establish this observable as a tool for future physics analyses.

Introduction

Of the all the Standard Model particles, quarks carry the most (non-trivial) quantum numbers; none of these properties are directly observable.

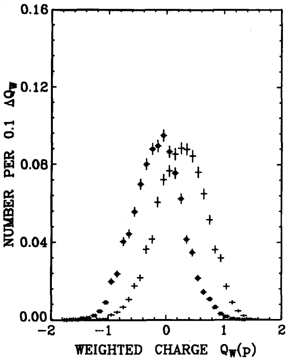


- However, some info is passed to the final state.
  - $\rightarrow$ Familiar example: jet p_T.
- The quark charge is another example.
  - We can only measure $q \in \mathbb{Z}$ so some information is lost.

$\rightarrow$ Weighted sum over track/particle charges is a proxy to the quark charge known as

Jet Charge

SLAC



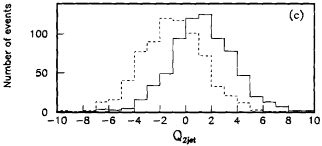


Fig. 1 The jet charge distribution for (a) B_d^0 jets, (b) opposite jets and (c) the combined jet charge measure. The solid (dashed) lines are the distributions for simulated $B_d^0(\overline{B_d^0})$ events.

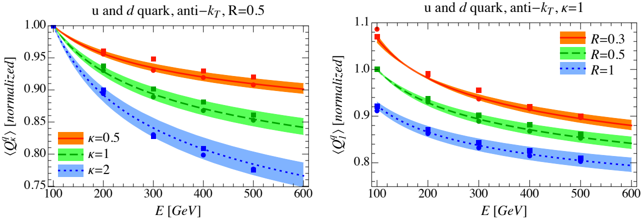
Jet Charge has a long history.

- Feynman and Field ('78) first studied different schemes for quark charge proxies.
  - ← Top plot on the left from their paper
- First used in DIS to establish a relationship between the quark model and hadrons.
- Since that time, jet charge has been used to measure many SM parameters at LEP, SLD, Tevatron, and the LHC.
  - ← e.g. Opal measurement ('94) of time dependance in $\overline{B_0^d} \leftrightarrow B_0^d$ (charged used to tag b flavor).
  - Used at the LHC for top quark charge.

New: Physics of Jet Charge

There is a a new theoretical interest in understanding jet charge as a physical phenomena - not just as a tool for other analyses.

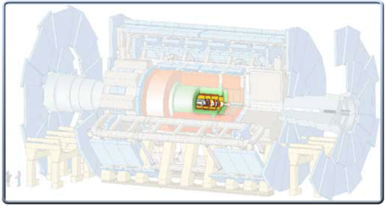
- Jet Charge at the LHC [D. Krohn, M. Schwartz, T. Lin, W. Waalewijn]
  $\rightarrow$ Phys. Rev. Lett. 110, 212001 (2013)
- Calculating the Charge of a Jet [W. Waalewijn]
  $\rightarrow$ Phys.Rev. D86 (2012) 094030



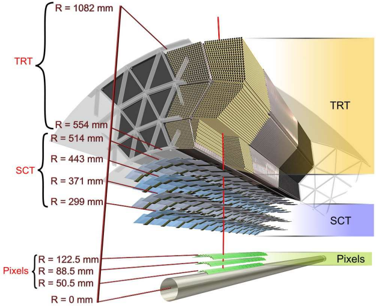
In addition, these same papers have explored a diverse set of applications of jet charge to various analyses - some of these will be presented today!

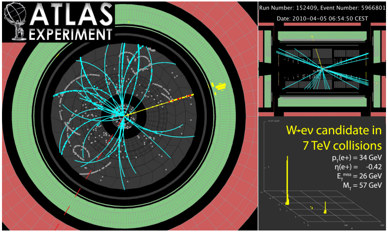
Tracks and Charge in ATLAS

SLAC



The inner detector inside ATLAS.





2 T longitudinal B field → bent tracks.

- Tracks are reconstructed from the *inner detector* ($|\eta| < 2.5$).
- Charge ($\mathrm{sign}(q)/p$) is a parameter in fitting hits to tracks.
- Consider $p_T > 500$ MeV.

Definition of Jet Charge

- For a jet j with transverse momentum $(p_T)_j$, let Tr be the set of *ghost associated* tracks.

  Ghost association: Add to the set of topological calorimeter clusters tracks with the momentum rescaled to ~ 0. Rerun the clustering and then associate a track to a jet j if the *ghosted* track is in the jet.
- Each track in Tr has momentum p_T^i and charge (determined from the curvature) q_i.

For a weighting factor $\kappa \in \mathbb{R}$, define the jet charge of j:

$$Q_j = \frac{1}{(p_{T\,j})^\kappa} \sum_{i \in \mathrm{Tr}} q_i \times (p_T^i)^\kappa, \quad (1)$$

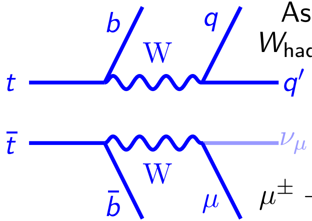
- This is not the only way charge has been defined in the past - there are variants of the denominator & the track momentum.

Analysis Overview

We have studied jet charge in three scenarios:

- $W^{\pm}$ discrimination in $t\bar{t}$

In semileptonic $t\bar{t}$, observe the charge of the μ & measure the charge from the hadronic W.



Add jet charges As proxy for W_{hadronic} charge

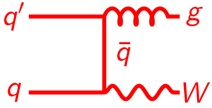
$\mu^{\pm} \rightarrow W^{\mp}_{\text{hadronic}}$

- Single jet charge in W+jets

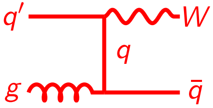
Measure the charge of the μ, which is anti-correlated to the leading jet charge.

- Jet charge in QCD dijets

Comparing to (recent) theoretical calculations will constrain MC models.



In pp, this is PDF suppressed



q & q' differ in charge by ± 1

For more details, see ATLAS-CONF-2013-086

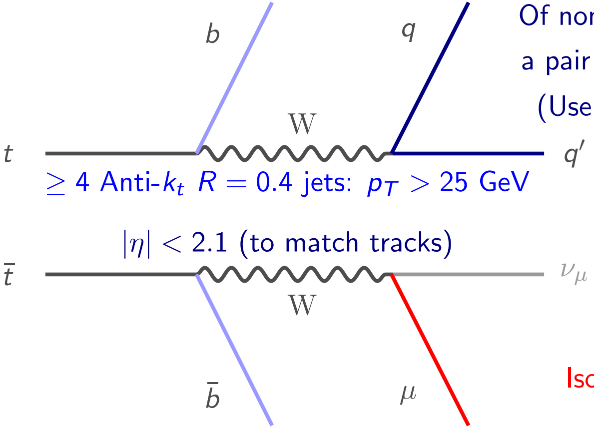
Objects and Selections in $t\bar{t}$

Tracks: A standard selection

e.g. $p_T > 500$ MeV, $|d_0^{\mathrm{PV}}| \leq 2.5$ mm

Require ≥ 2 b-jets

(MV1 @ 70%)



Of non b-tagged jets, require a pair with $|m_{jj} - m_W| < 30$

(Use these for the charge)

≥ 4 Anti-k_t $R = 0.4$ jets: $p_T > 25$ GeV

$|\eta| < 2.1$ (to match tracks)

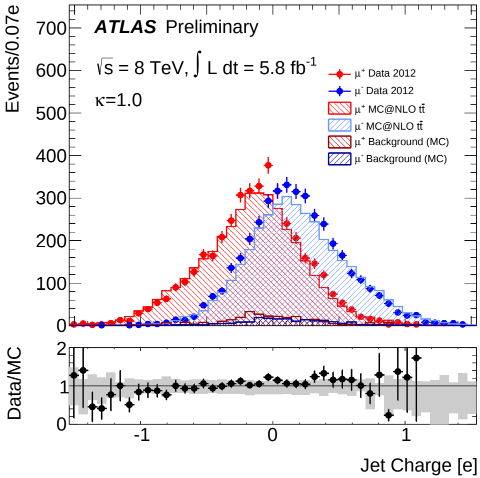
$E_T^{\text{miss}} > 20$ GeV

$M_T + E_T^{\text{miss}} > 60$ GeV

Isolated muon trigger

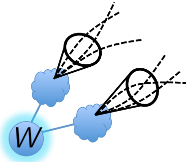
(24, 36 GeV p_T)

Sum of jet charges from W daughters in $t\bar{t}$



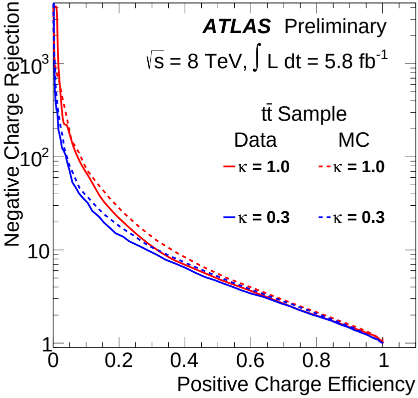
N.B: Jet charge is measured in units [e] of the (anti)electron charge.

- For a $\mu^{\pm}$ event, we expect the hadronic W to be $W^{\mp}$.
- MC prediction shows that the sample is pure ($> 90\%$ $t\bar{t}$).
  - → (MC) composition in backup
- MC agrees well with the data; normalizing by cross section.
  - Gray band includes JES, JER, tracking efficiency, and $t\bar{t}$ cross section (6%).

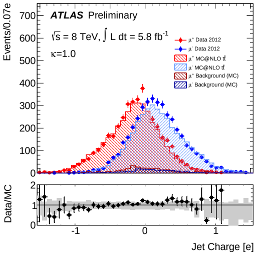


The *dijet charge* is the sum of the jet charges of the W daughter jets.

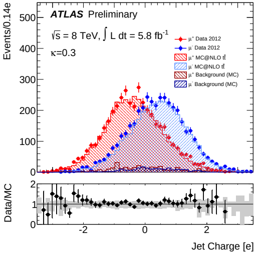
Performance of jet charge in tagging the W charge



From previous slide



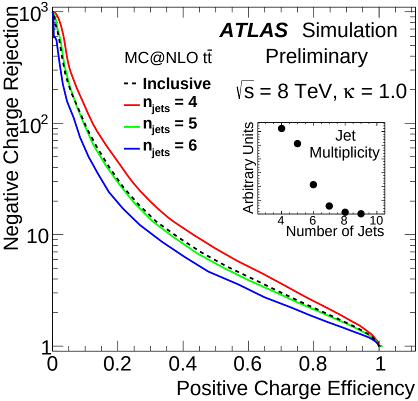
Smaller κ



- Rejection is the inverse of efficiency.
- Discriminating power largely **independent of** κ, which is seen in both data and MC.

Combinatorics in W charge tagging

There is some degradation in performance due to combinatorics; the W daughters did not always come from the true W.

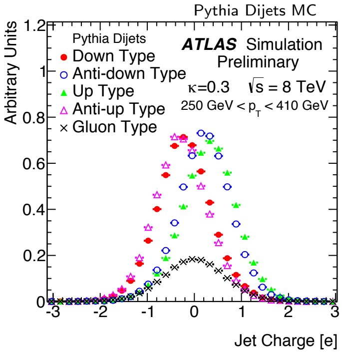


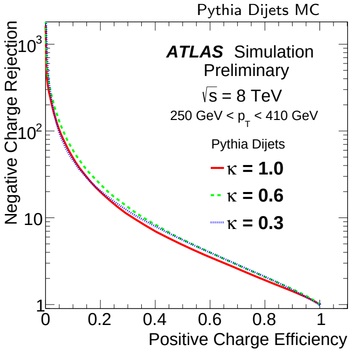
- This effect will be present in both data and MC.
- However, we can estimate how we might perform given a more pure selection.
    - Compute the ROC curve for various jet multiplicities. For exactly four jets (2 b-tagged) the sample purity is higher.
    - For example, at 50% efficiency, this could be a 20% effect on the rejection.

Applications of Jet Charge in $t\bar{t}$: Topology

In many analyses, one needs to reconstruct the entire $t\bar{t}$ event topology.

- W boson system (if hadronic).
- Matching objects to the branch (top or anti-top) of the decay.

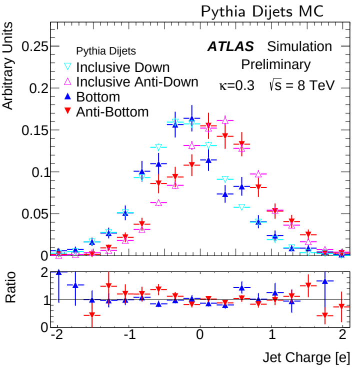




- For instance, we can use jet charge to help match b jets to the correct side of the decay (right plot shows 50% efficiency for 6 in rejection).

Applications of Jet Charge in $t\bar{t}$: Topology II

In addition to (or instead of) kinematic fitting or ΔR matching, one could tag the charge in order to do the matching.



We can compute the prob. that the $\bar{b}$ jet has $Q_{\bar{b}} > 0$ & the b jet has $Q_b < 0$: $\sim 25\%$.

However, we can do better - suppose we know two jets that come from a b and a $\bar{b}$. One can use the difference in charges:

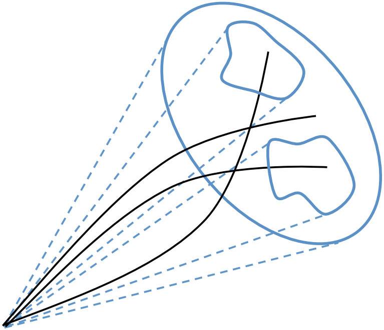
$$\Pr(Q_{\bar{b}} > Q_b) = \sum_Q \Pr(Q_{\bar{b}} = Q) \Pr(Q > Q_b)$$

This probability is about 70%

- In combination with other variables, purity can be improved.

Applications of Jet Charge in $t\bar{t}$: Boosted

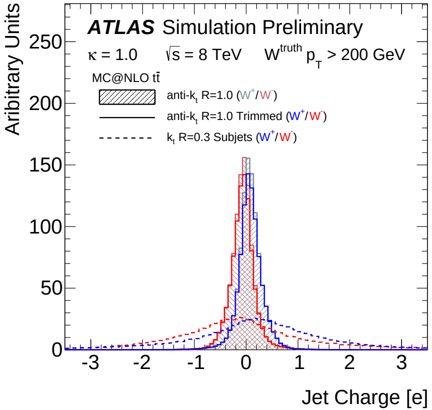
When $p_T^{W_{\text{hadronic}}} \sim 2m_W$ its daughters can merge, obscuring the resolved $R = 0.4$ jets.



- There are many ways to define jet charge in such a topology
  - Continue using the $R = 0.4$ jets
  - Ghost associate to large $R(\sim 1)$ jets
  - Utilize jet grooming to remove pileup
  - Compute charge using subjets
  - For the weight, use the fat jet p_T
  - $(\cdots)$

None of these techniques have ever been before BOOST2013! See next slides for the first plots of jet charge in *boosted environments*.

Applications of Jet Charge in $t\bar{t}$: Boosted $\kappa = 1.0$



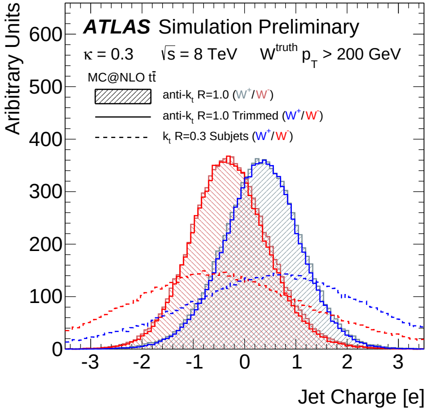
- Fat charge more peaked than for subjets, in part due to $1/p + 1/q > 1/(p+q)$

- Require the true W^{hadronic} $p_T > 200$ GeV for boosted topology
- With this p_T, expect $R = 1.0$ to capture W decay

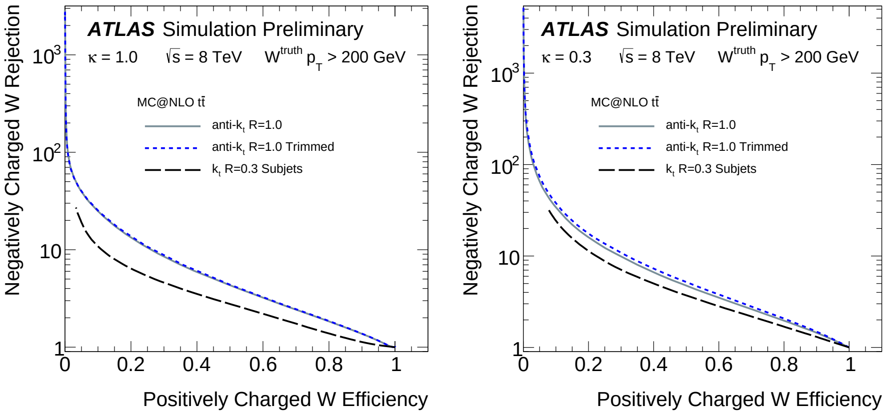
Three Charge Definitions

1. Ghost associate tracks to the Anti-k_t $R = 1.0$ jet
2. Trim the jet (with ghosts) using a p_T frac of 0.05 and $R = 0.4$ subjets
   - Remaining ghosts determine associated tracks
3. Use the leading subjets from (2)

Applications of Jet Charge in $t\bar{t}$: Boosted $\kappa = 0.3$



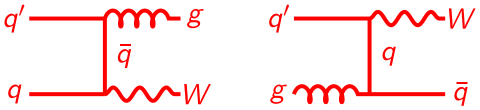
- The distributions look similar (but stretched horizontally) for a smaller κ.
- Note that there is essentially no difference between trimmed and ungrommed charge:
  - The tracks removed in trimming carry a small momentum fraction of the jet, so charge is not affected.



- $\kappa = 1$ [slide 15] on the left and $\kappa = 0.3$ on the right [slide 16].
- Performance in trimmed and ungroomed is the same; slightly worse for subjet dijet charge.

Extension of Charge Tagging

- In $t\bar{t}$, the muon charge is always opposite the hadronic W charge.
- Furthermore, since the W is a color singlet, the hadronic W charge does not change with energy.

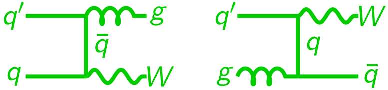


In pp, this is PDF suppressed

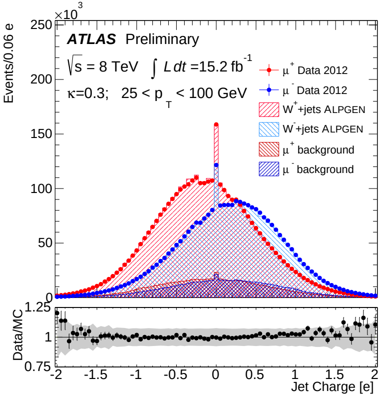
q & q' differ in charge by ± 1

- In leptonic W+jets, the charge of the lepton is *anti-correlated* ($R < 1$) with the leading-order parton charge.
  - Define jet flavor with the highest energy parton within a $R = 0.4$ cone.
- The leading jet is color connected with the initial state; the charge evolves with the energy scale.

Single jet charge in W+jets



For a $\mu^{\pm}$ event, we expect that on average, the leading jet charge is $\mp$.



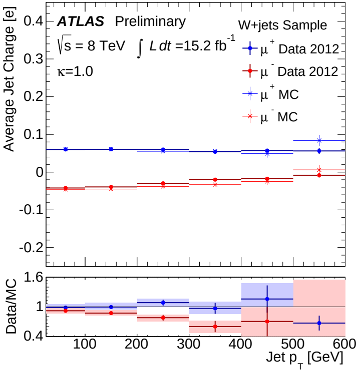
N.B. Spike at zero from jets with no tracks.

The background is larger than in $t\bar{t}$.

→ Composition in backup

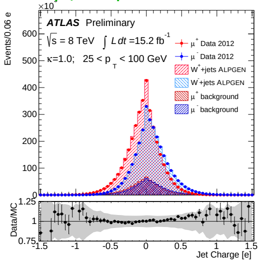
- A matrix method is used to estimate the multijet contribution and then a fit is performed in $\Delta\phi = \phi_{\text{jet}} - \phi_{\mu}$ to fix the W+jets and multijet normalizations.
- Gray band includes JES, JER, tracking efficiency and the difference in the normalizations from fitting $\Delta\phi$ and fitting m_T.

Charge evolution in W+jets

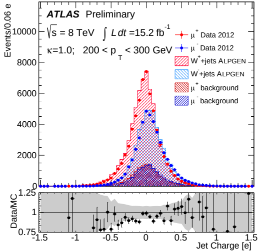


- At pp, more W^+ than W^-.
- Unlike in $t\bar{t}$, leading order partons are color connected to initial state; discrimination decreases with p_T.

Same p_T as previous slide; larger κ

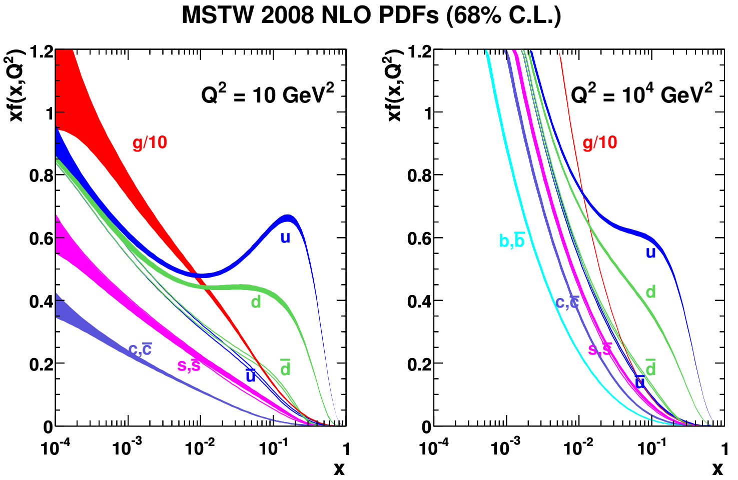


Higher p_T

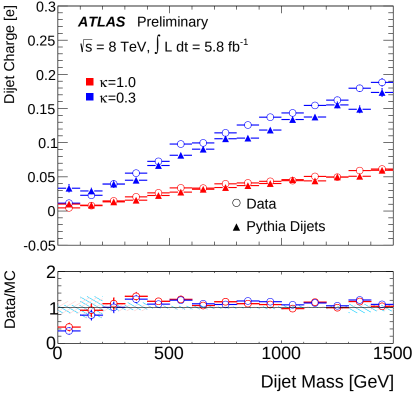


Jet Charge in Fully Hadronic Events

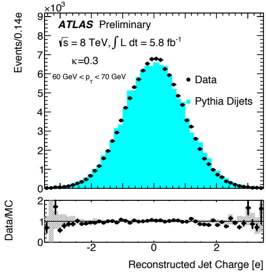
- Even when the leading order parton charge cannot be tagged with leptons, one can use jet charge to probe the charge evolution.



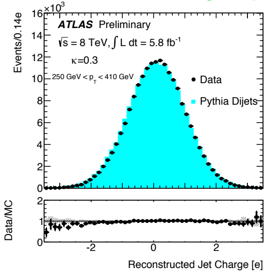
Jet Charge in QCD Dijets



Lower p_T

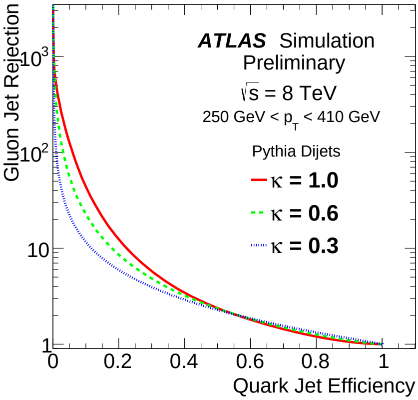


Higher p_T

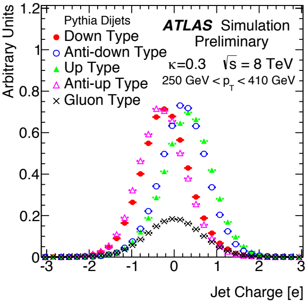


- The increase is due to the larger up valence component in the PDF.
- Theoretical calculations of the evolution of the charge with scale are now available.

Application: Jet Charge for q/g Discrimination



- It is possible to use jet charge for q/g and double *b* taggers.
- On its own, charge is not competitive, but may be useful as an additional input to a multivariable discriminate.

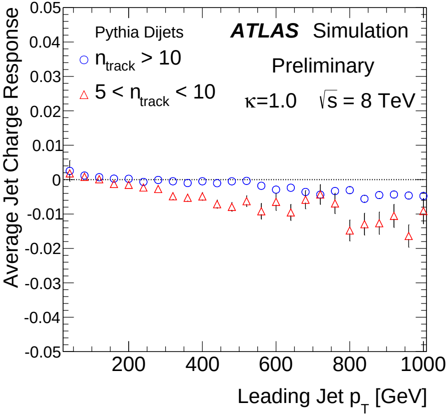


Jet Charge Performance

Taking a step back from physics applications of jet charge, we have studied the jet charge detector response.

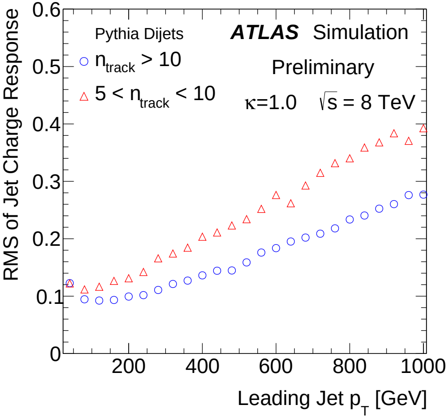
Response = Reconstructed jet charge - Truth jet charge

Truth jet: run the clustering algorithm with stable truth level particles.



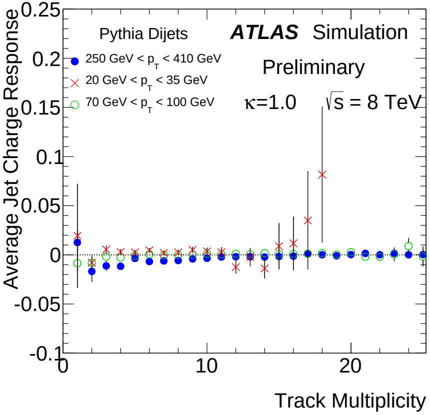
- As desired, the response is rather flat with the momentum.
- There is some residual slope from merged and missing tracks that lead to a jet charge with lower magnitude. Since the charge also increases with energy, this leads to a decrease in the average response.

Jet Charge Response Versus Momentum



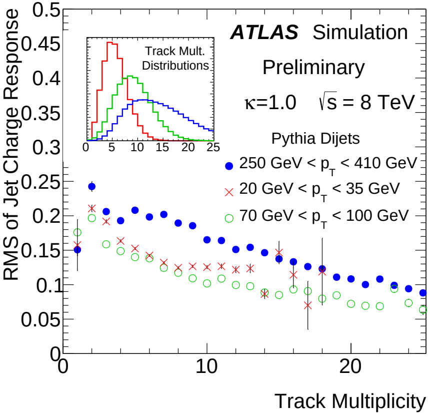
- As one expects, the RMS increases with momentum as straighter tracks lead to worse momentum resolution.
- Jets with more associated tracks have a lower response RMS due to averaging over more tracks in the defining sum for jet charge.

Jet Charge Response Versus Track Multiplicity



- No noticeable trend in the average response with track multiplicity.
- The average gives a sense of the bias, but the RMS gives a sense of the resolution (next slide).

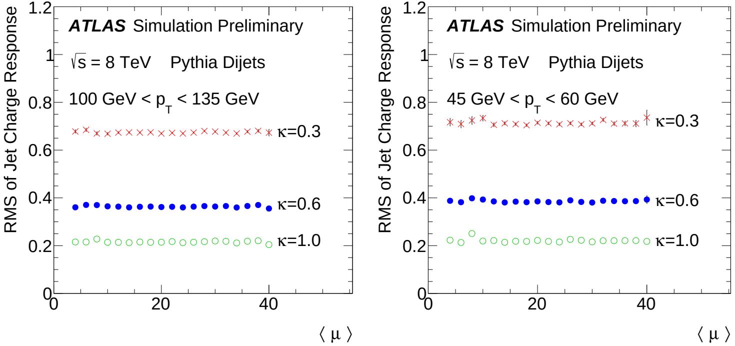
Jet Charge Response Versus Track Multiplicity II



- As observed earlier, the response RMS decreases with the number of associated tracks.
- With straighter tracks at high momentum, the resolution degrades from green to blue.
- The inset also shows that there is a strong correlation between the momentum and the track multiplicity.

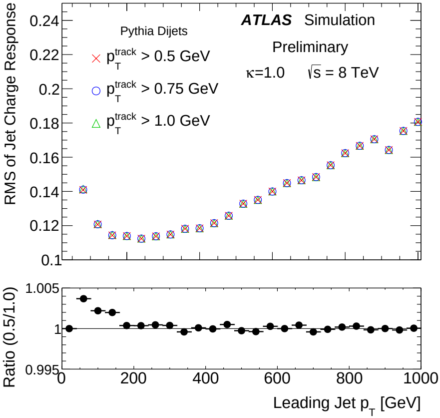
Pileup

As a (mostly) track-based variable, we would expect the jet charge to be insensitive to pileup.



- Our expectation is mostly true. At low p_T, there is some dependance, which we understand due to the calorimeter based p_T in the definition of the jet charge.

Track p_T Threshold

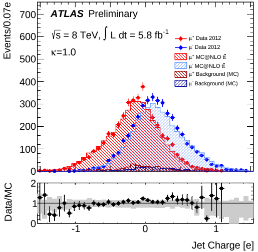


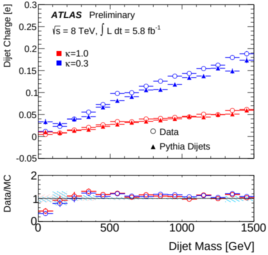
- Of all the track requirements, the only one we may expect to have an appreciable affect on the jet charge is the p_T threshold (500 MeV).
- However, there seems to be no effect for small changes in the threshold.
  - The tracks removed by the threshold carry a small momentum fraction of the jet, so charge is not affected.

Conclusions and Outlook

Jet Charge is a promising tool for various applications.

- Using theoretical calculations, it can be used to constrain modeling in MC simulations (unfolded charge measurements).
- We plan to further develop jet charge to be a standard jet moment in ATLAS by further studying its properties in general (boosted) scenarios and considering applications to particular analyses.





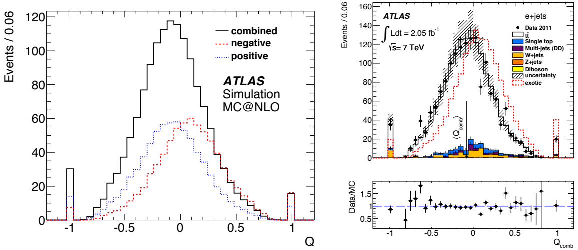
Backup

Previous Uses of Jet Charge in ATLAS

Measurement of the top quark charge (arXiv:1307.4568).

$$Q_j = \frac{\sum_{i\in \mathrm{Tr}} q_i \times |j \cdot p_T^i|^\kappa}{\sum_{i\in \mathrm{Tr}} |j \cdot p_T^i|^\kappa}, \tag{2}$$

where Tr is the list of tracks above 1 GeV within a ΔR cone of 0.25 of the jet and j is the (calorimeter) jet axis. Q_{comb} is the product of this charge and the lepton charge.



Background composition in $t\bar{t}$

Process	N_{events} with μ^+	N_{events} with μ^-
$t\bar{t}$	3575 ± 29	3522 ± 20
Single Top	126 ± 3	97 ± 3
W+jets	170 ± 29	91 ± 15
Z+jets	23 ± 5	18 ± 3
Dibosons	3 ± 0.4	3 ± 0.3
Total MC	3895 ± 36	3729 ± 25
2012 Data	4095	3893

Table : The data and MC signal and background yields after all selections for the 5.8 fb^{-1} sample, shown separately for μ^+ and μ^- final states. The MC uncertainties are purely statistical and included solely for the purposes of illustrating the sample composition.

Background composition in W+jets

Process	$N_{events}(15.2\text{fb}^{-1})$	f_{quark}	$f_{correct}$
$W \to \mu\nu$+jets	5852000 ± 8500	0.7365 ± 0.0009	0.960 ± 0.003
$t\bar{t}$	306000 ± 570	0.9154 ± 0.0003	0.622 ± 0.001
$Z \to \ell\ell$+jets	407000 ± 1100	0.663 ± 0.002	0.494 ± 0.004
$W \to \tau\nu$+jets	177000 ± 1300	0.705 ± 0.004	0.97 ± 0.02
Multi-jets	607000 ± 470		

Table : Estimated dominant contributions to the selected W+jets sample. The f_{quark} column gives the fraction of events in which the leading jet is expected to be a quark jet and the $f_{correct}$ column shows the fraction of such events in which the parton charge is opposite the μ charge. Statistical errors are shown on the predicted number of events.

Data and MC Samples

- $W^{\pm}$ discrimination in $t\bar{t}$
- Single jet charge in W+jets
- Jet charge in QCD dijets

Violet in the right column indicates an overlap between red and blue.

- Isolated Muon Trigger
- Single jet triggers (periods A & B, 2012)
- Single jet triggers (periods A & B, 2012)
- MC@NLO for $t\bar{t}$
- PowHeg for $t\bar{t}$
- ALPGEN for V + jets
- MC@NLO for s- & Wt-channel single top
- AcerMC for t-channel single top
- HERWIG for dibosons
- Data-driven for Multijet
- Pythia8 for QCD

Background Fit in W+jets

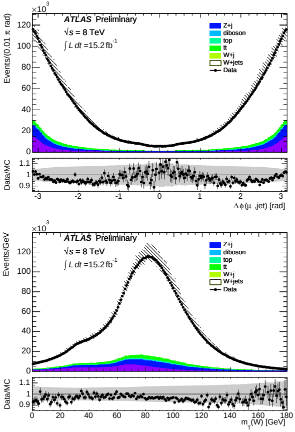


Figure : The $\Delta\phi(\mu, \text{jet})$ and W transverse mass distributions before (left) and after (right) the fit used to determine the W/Z+jets and QCD background normalisations. The data is superimposed on the total prediction in each plot. The uncertainty band in the lower plot of each figure is symmetrized and includes jet energy scale and resolution effects and cross section uncertainties on the fixed background components.

Jet Charge in CMS JME-13-006

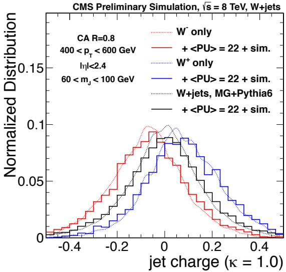


Figure 5: The jet charge distribution in simulated samples of boosted W bosons and inclusive QCD jets after a cut on the pruned jet mass. MG denotes the MADGRAPH5 generator. Thick dashed lines represent the generator predictions without pileup interactions and without CMS simulation. The histograms are the distributions after CMS simulation with two different pileup scenarios corresponding to an average number of interactions of 12 and 22.

Jet Charge in CMS JME-13-006 II

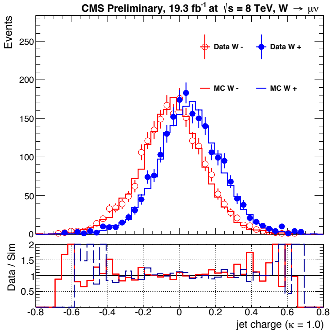


Figure 24: Jet charge distributions in the $t\bar{t}$ control sample for W^+ and W^- jets in simulation and data. Simulated distributions are a sum of all processes.