Jet Charge and Jet Pull Performance

Boston Jet Physics Workshop

Benjamin Nachman

SLAC, Stanford University

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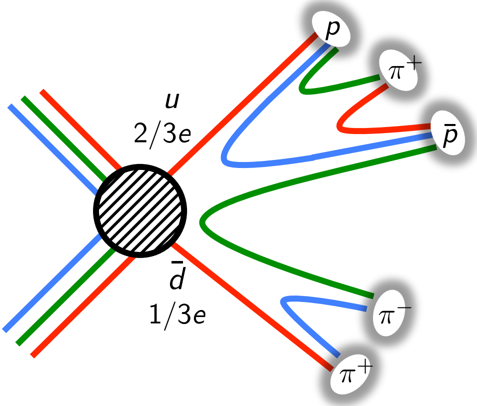
Introduction

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



However, some information is passed to the final state. Two handles on quark properties: **Jet Charge** [Part I of this talk] and **Jet Pull** [Part II].

Part I: Jet Charge

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

- Each track i in **Tr** has momentum p_T^i and charge q_i.

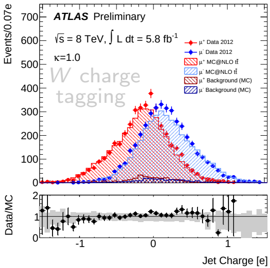
For a weighting factor $\kappa \in \mathbb{R}$, define the jet charge:

$$Q = \frac{1}{(p_{Tj})^\kappa} \sum_{i \in \mathbf{Tr}} q_i \times (p_T^i)^\kappa \qquad (1)$$

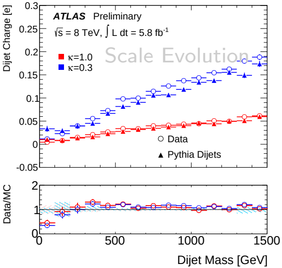
- This is not the only way charge has been defined in the past - there are variants of the denominator and the track momentum.

Jet Charge in ATLAS

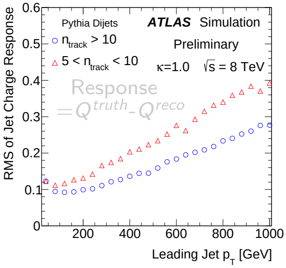
Detailed performance study on boson/quark charge tagging, detector resolution effects, and data/MC was prepared for BOOST2013: see ATLAS-CONF-2013-086. Some highlights:



W charge tagging



Scale Evolution



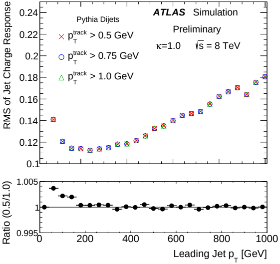
Response $= Q^{truth} - Q^{reco}$

Many more results and discussion in the conference note.

Jet Charge in ATLAS: New Developments

Three outstanding performance points to be addressed today:

Plot from BOOST CONF

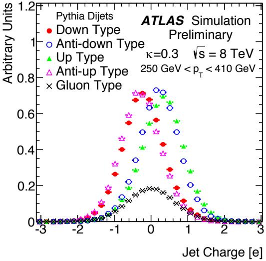


Impact of the track threshold (p_T^{track}) and the dependance on the p_T-weighting factor κ.

What is the optimal κ value?

Does this depend on p_T?

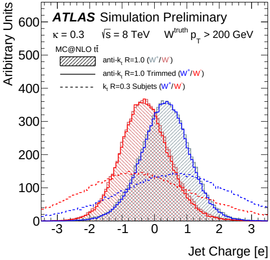
Plot from BOOST CONF



[Optimal in the sense of quark-charge tagging]

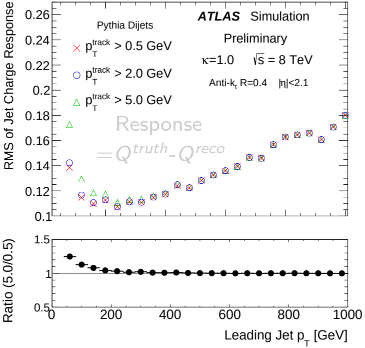
Is it still possible to do boson charge tagging at high p_T? How is jet charge impacted by boost?

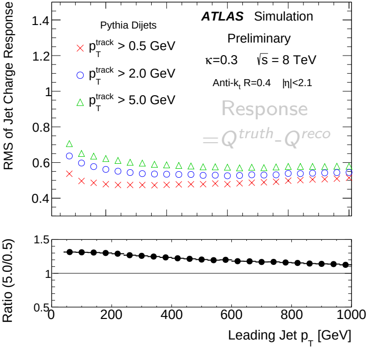
Plot from BOOST CONF



Track Thresholds

As pileup multiplicity increases, it is important to study the impact of the tracking minimum p_T threshold on our track-based variables.

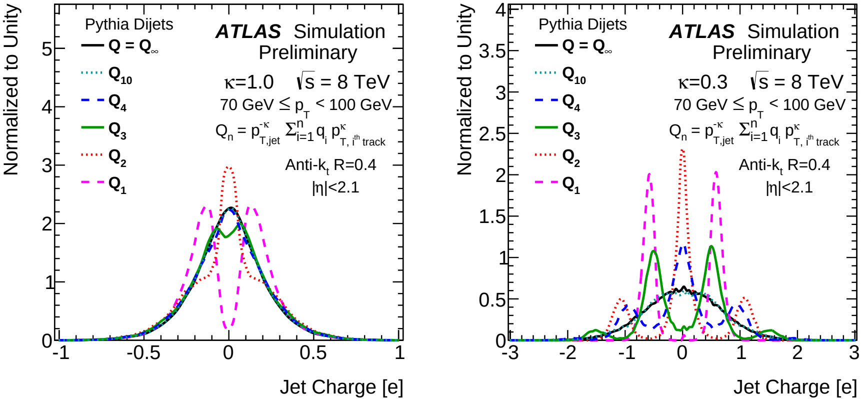




For both κ values, there is a big increase in the RMS which persists for large p_T for $\kappa = 0.3$ which gives a higher weight to lower p_T tracks.

Understanding Thresholds: Partial Charge Q_n

The partial jet charge Q_n uses only the n leading tracks.



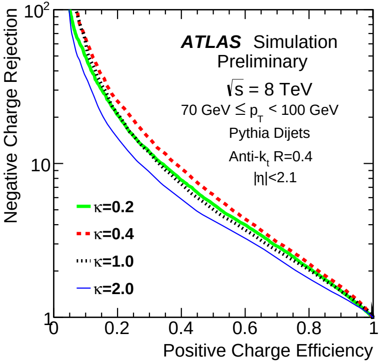
We see the convergence of jet charge with n, which allows us to understand the degradation of performance on the previous slide.

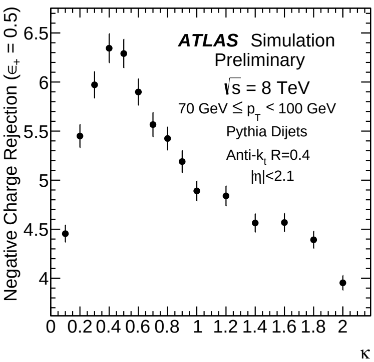
Optimal Momentum Weighting Factor

In previous studies, values of $0.3, 0.6, 1.0$ were used.

- Are these optimal?
- How does the optimal performance depend on p_T?

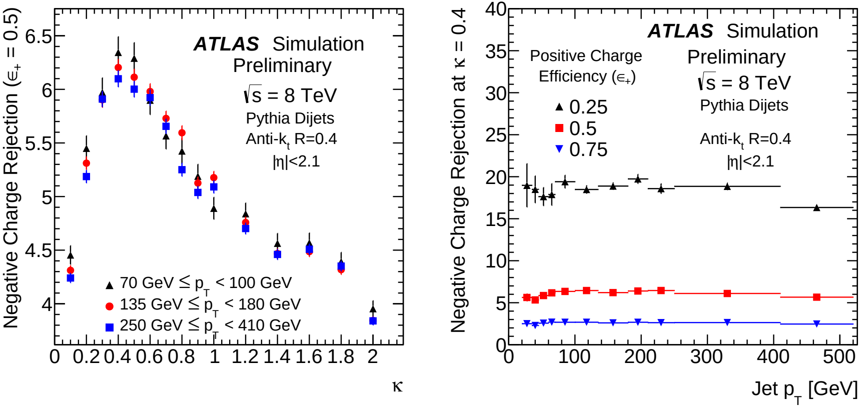
N.B. *jet flavor* is the identify of the highest energy parton in a ΔR cone.





Optimal Momentum Weighting and p_T

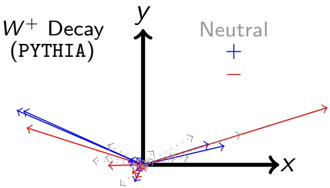
This summarizes the content of the previous slide for many p_T bins.

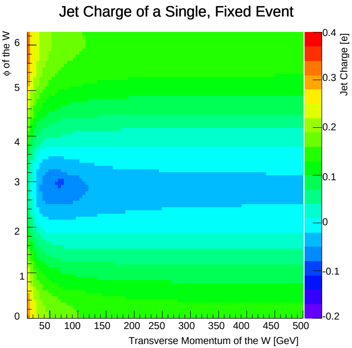


Takeaway: For a fixed positive charge efficiency, the optimal κ value (~ 0.4) and the maximum negative charge rejection vary little.

Jet Charge and Lorentz Boosts

Jet Charge is **not** Lorentz invariant.



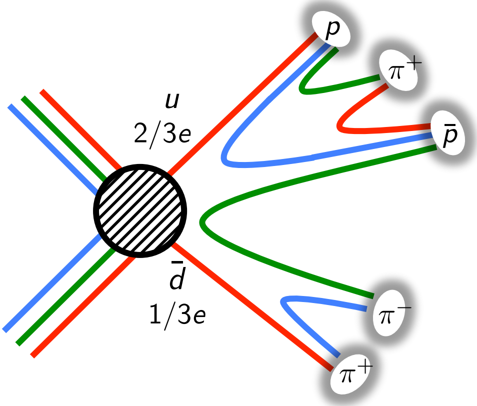


Takeaway: for a fixed event, charge can be wildly varied by picking a particular boost.

One can define a *Lorentz invariant jet charge* in one of several ways – only relevant for boson charge tagging. More details in the backup.

Reminder

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



However, some information is passed to the final state. Two handles on quark properties: **Jet Charge** [Part I of this talk] and **Jet Pull** [Part II].

Part II: Jet Pull

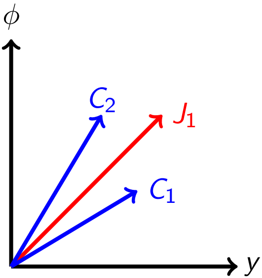
Jets: Calculate pull of J_1 with respect to J_2

Jet constituents: calorimeter clusters, (ghost associated) tracks, or stable particles (truth jets)

$\vec{r}_i = (\Delta y_i, \Delta\phi_i)$ with respect to the jet position.

Pull (Vector) $= \sum_{i \in \text{jet}} \frac{p_T^i |r_i|}{p_T^{\text{jet}}} \vec{r}_i$

Current state of the field in the backup.



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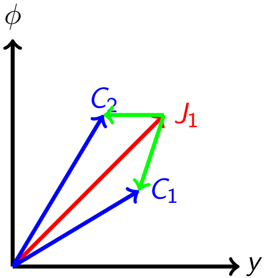

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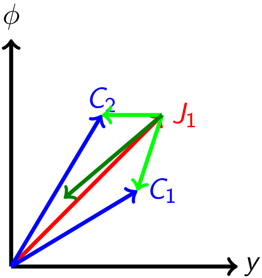

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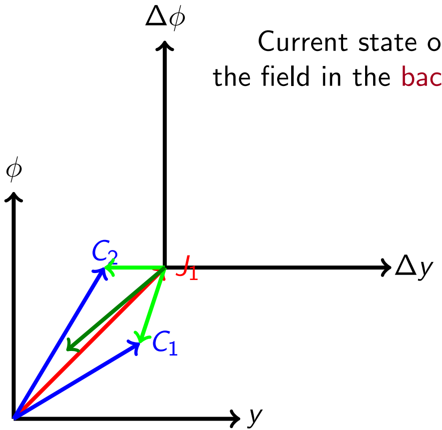

Current state of the field in the backup.

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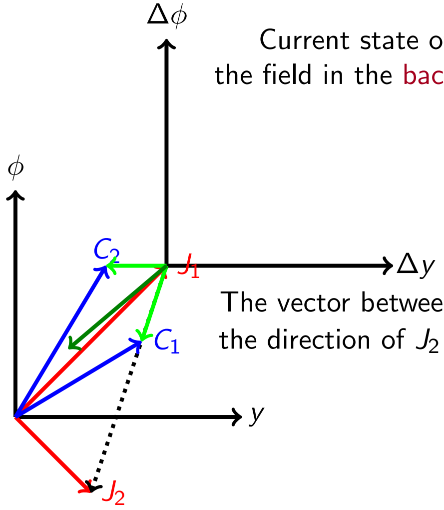

Current state of the field in the backup.

The vector between J_1 and J_2 is the direction of J_2 in $(\Delta\phi,\ \Delta y)$.

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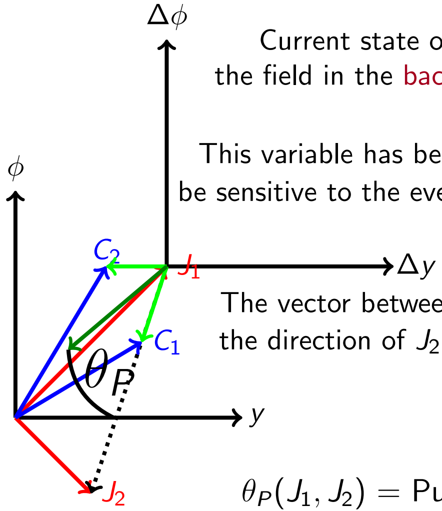


Current state of the field in the backup.

This variable has been shown to be sensitive to the event color flow.

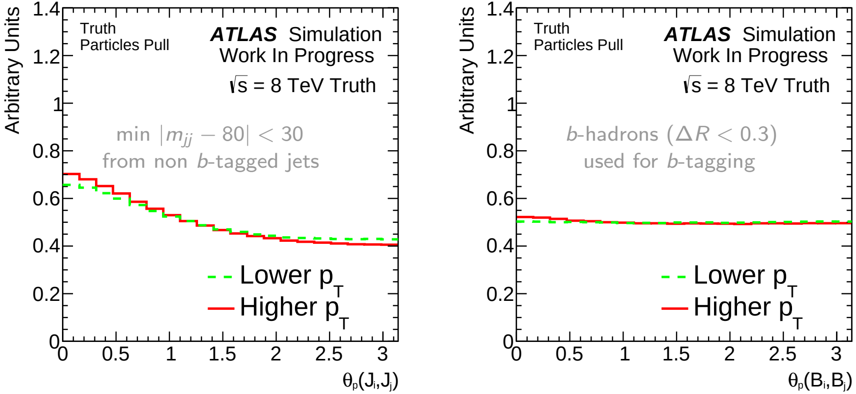
The vector between J_1 and J_2 is the direction of J_2 in $(\Delta\phi, \Delta y)$.

$\theta_P(J_1, J_2) =$ Pull Angle

Model System for Pull Performance: $t\bar{t}$

Truth pull distributions different for *b*-jets (B_i) and *W* daughter jets (J_i).

$p_T > 25$ GeV required for b and W jets; Lower p_T b (W) jet shown with a dashed line

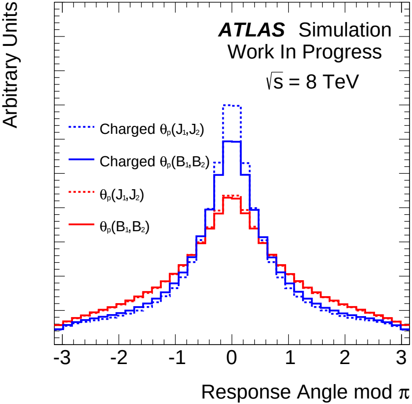


This is a performance study–these distributions provide model systems for studying **detector effects** and **jet tagging** properties.

Detector Effects: Jet Pull Response

Response = Reconstructed pull angle - Truth pull angle

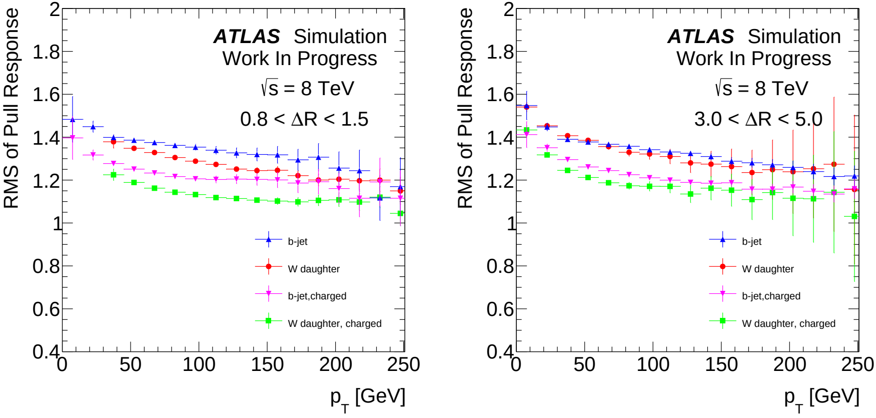
Charged pull: use tracks (charged stable particles) for reco (truth) jets



Tradeoff: More information (calo pull) versus better response (track pull).

Differential Pull Angle Response: bins of ΔR

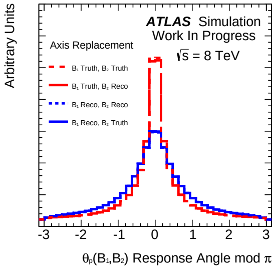
Event kinematics can impact the pull angle distributions and can also affect the response.

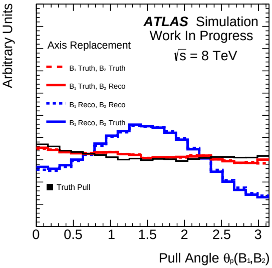


Not a strong dependence on p_T for fixed ΔR; p_T binning in the backup.

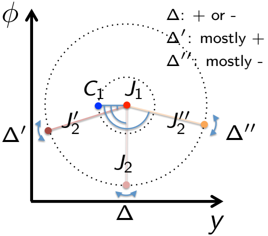
Track-based Pull Angle Response

We can systematically *remove angular resolution* by replacing tracks with corresponding truth quantities.





-Schematic-

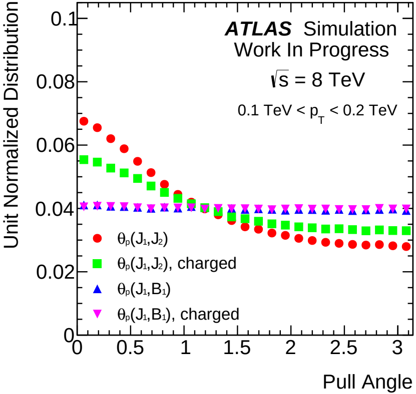


Removing the angular resolution of the constituent particles for B_1 completely restores the shape.

- Angular resolution pushes the pull toward $\pi/2$ since $0 \leq \theta_P \leq \pi$.

Jet Pull as a Jet Tagger

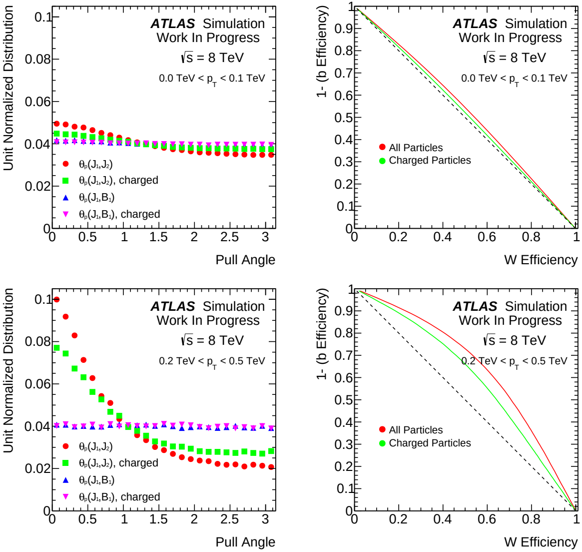
The pull distribution is different for $\theta_P(J,B)$ and $\theta_P(J,J)$ – we can use this to identify the $t\bar{t}$ topology.



Binning in ΔR or p_T, we also can explore the pull distribution with *event kinematics* effects removed.

Jet Pull-based Jet Tagger Performance

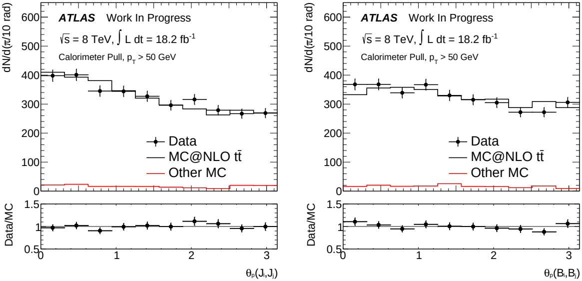
Tagging performance is strongly dependent on the dijet p_T (ΔR bins in backup).



Data/MC for Calorimeter Pull

Same selection from the Jet Charge CONF note.

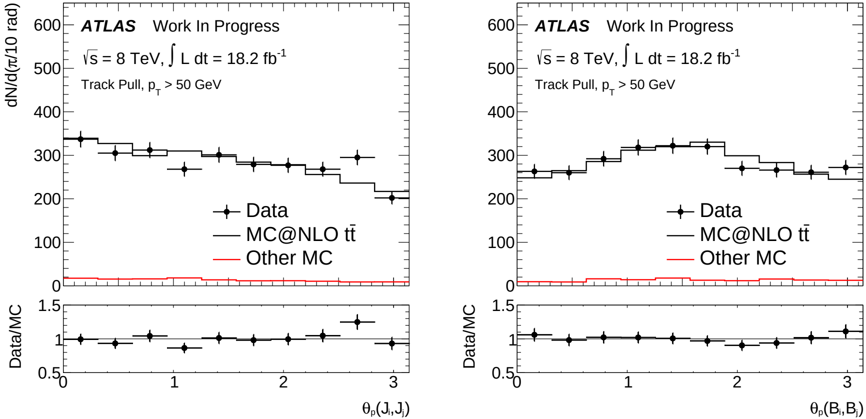
- Details of the selection are in the backup. The only modification is that $p_T > 50$ GeV for each jet.



- The MC models the data well. In particular, the general shapes are present in both distributions.

Data/MC for Track-based Pull

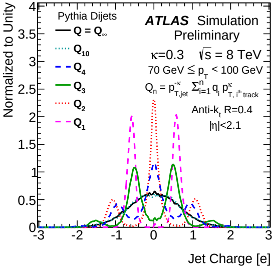
As predicted, the size of the shape for the W jets is less than for the b jets, which show a characteristic resolution peak at $\pi/2$.

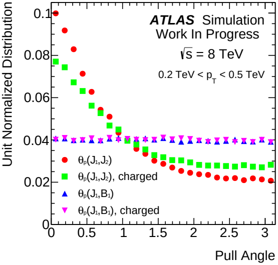


Conclusions and Outlook

Jet Pull and Jet Charge are promising tools for various applications.

- Their detector response is understood and it seems well modeled by the MC.
- Both jet pull and jet charge can be used to tag individual objects and topologies.
- Stay tuned for forthcoming documentation on both of these topics.





Backup

Backup: Table of Contents

Jet Charge

- History
- Previous uses in ATLAS
- CMS
- Background Composition
- Heavy Flavor Jet Charge
- Boosted environments
- W Boson Charge Tagging
- Quark charge tagging
- Performance

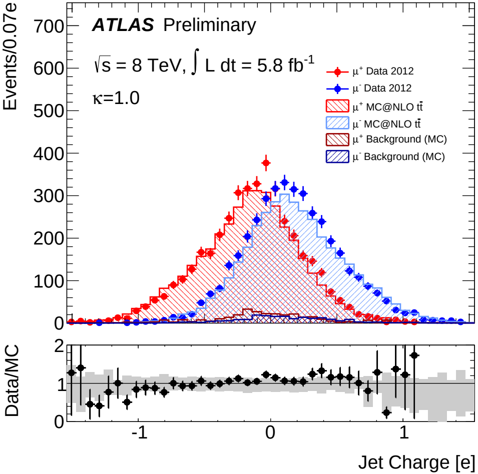
Common Content

- The ATLAS Detector
- Data and MC Samples
- Reco Event Selection

Jet Pull

- History
- Jet Pull as a jet tagger: p_T binning
- Calorimeter Pull Resolution

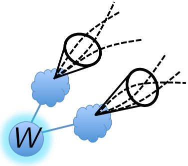
Sum of jet charges from W daughters in $t\bar{t}$ ‣ TOC



- For a $\mu^{\pm}$ event, we expect the hadronic W to be $W^{\mp}$.
- MC prediction shows that the sample is pure ($> 90\%$ $t\bar{t}$).

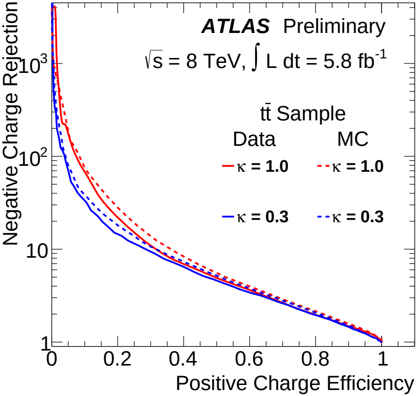
  → (MC) composition in backup
- MC agrees well with the data; normalizing by cross section.
  - Gray band includes JES, JER, tracking efficiency, and $t\bar{t}$ cross section (6%).

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

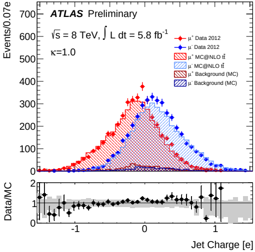


The *dijet charge* is the sum of the jet charges of the W daughter jets.

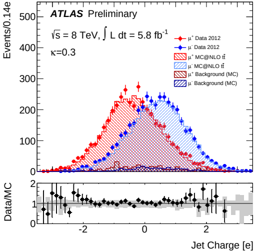
Performance of jet charge in tagging the *W* charge



From previous slide



Smaller κ

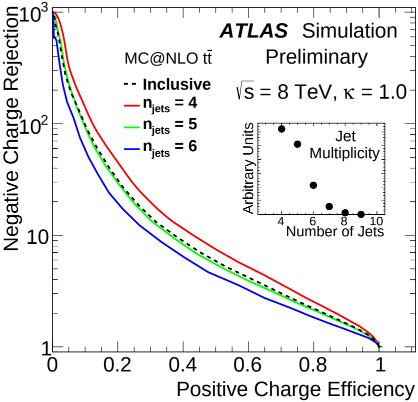


- Rejection is the inverse of efficiency.
- Discriminating power largely **independent of** κ, which is seen in both data and MC.

Combinatorics in *W* charge tagging

▸ TOC

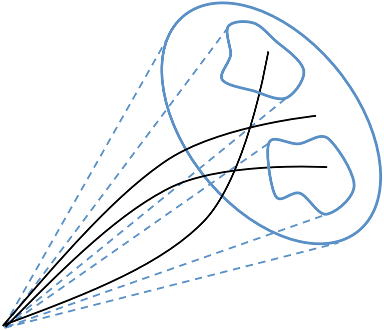
There is some degradation in performance due to combinatorics; the *W* daughters did not always come from the true *W*.



- 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.

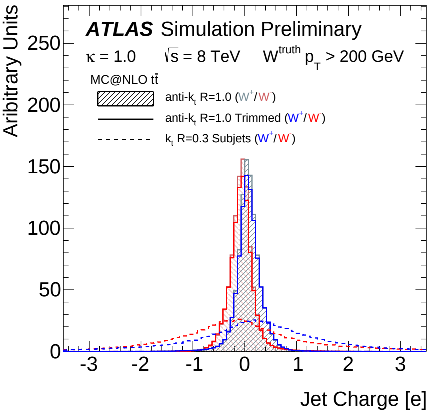
Applications of Jet Charge in $t\bar{t}$: Boosted ▸ TOC

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
  - $(\cdots)$

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



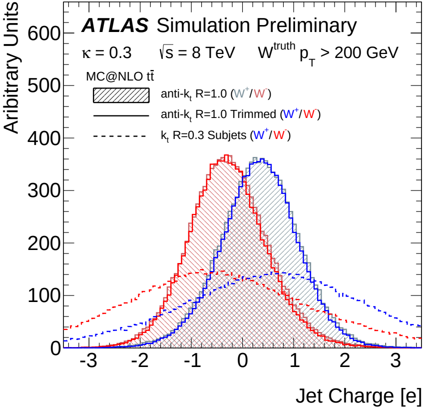
- Fat charge more peaked than for subjets, in part due to $1/p + 1/q > 1/(p+q)$

- 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

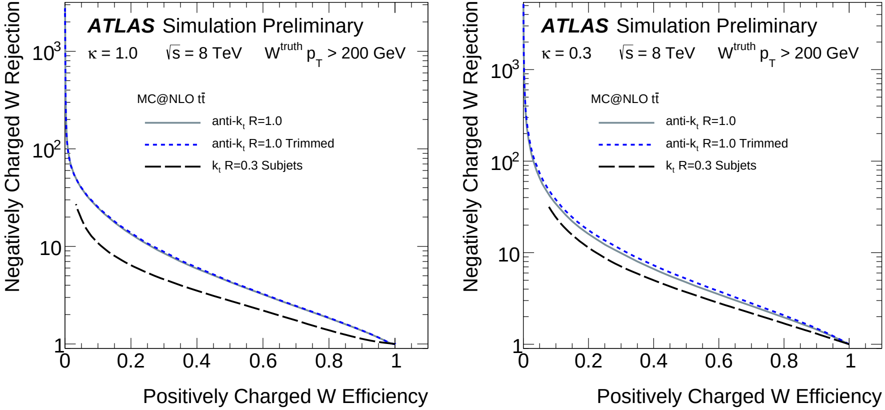
1. Ghost associate tracks to the Anti-k_t $R = 1.0$ jet
2. Trim the jet (with ghosts) using a p_T frac of 0.05 and $R = 0.4$ subjets
   - Remaining ghosts determine associated tracks
3. Use the leading subjets from (2)

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.

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

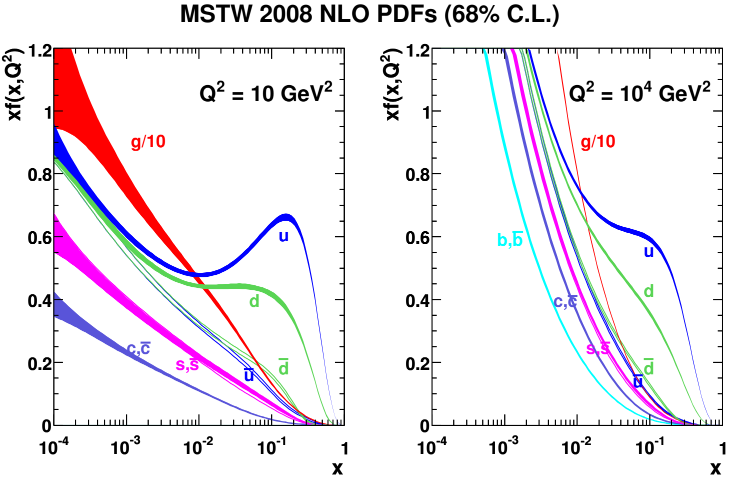


- $\kappa = 1$ [slide 15] on the left and $\kappa = 0.3$ on the right [slide 16].
- Performance in trimmed and ungroomed is the same; slightly worse for subjet dijet charge.

Jet Charge in Fully Hadronic Events

▸ TOC

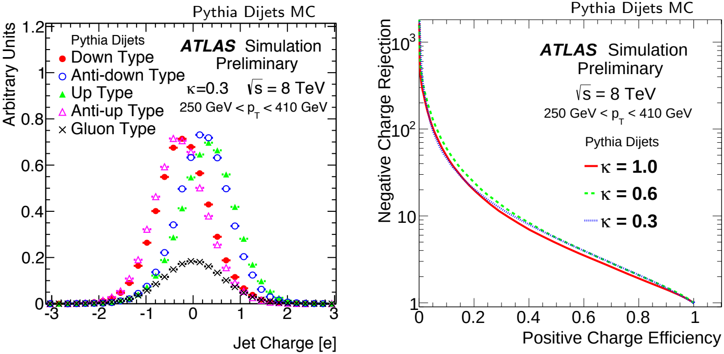
- Even when the leading order parton charge cannot be tagged with leptons, one can use jet charge to probe the charge evolution.



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

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

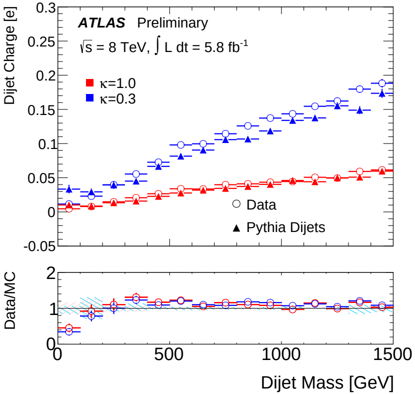
- W boson system (if hadronic).
- Matching objects to the branch (top or anti-top) of the decay.



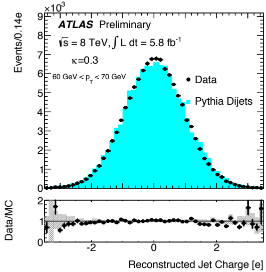
- For instance, we can use jet charge to help match b jets to the correct side of the decay (right plot shows 50% efficiency for 6 in rejection).

Jet Charge in QCD Dijets

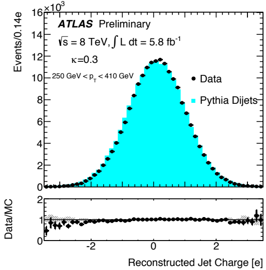
▸ TOC



Lower p_T



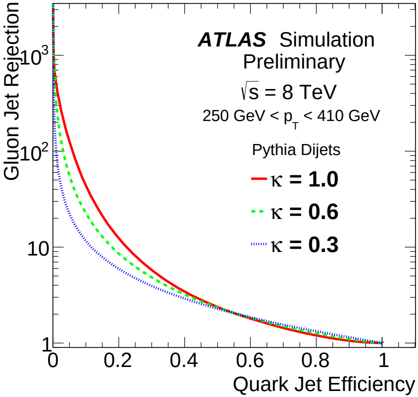
Higher p_T



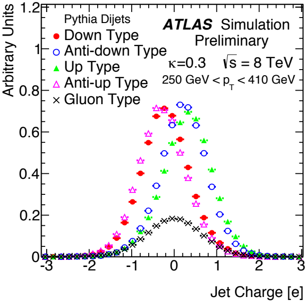
- The increase is due to the larger up valence component in the PDF.
- Theoretical calculations of the evolution of the charge with scale are now available.

Application: Jet Charge for q/g Discrimination

▸ TOC



- 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.

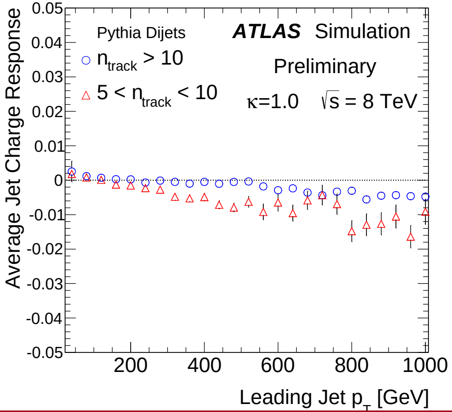


Jet Charge Performance

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

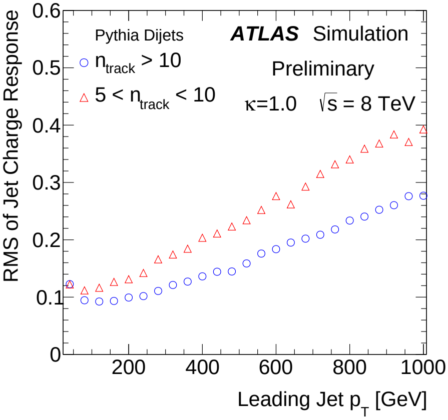
Truth jet: run the clustering algorithm with stable truth level particles.



- 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.

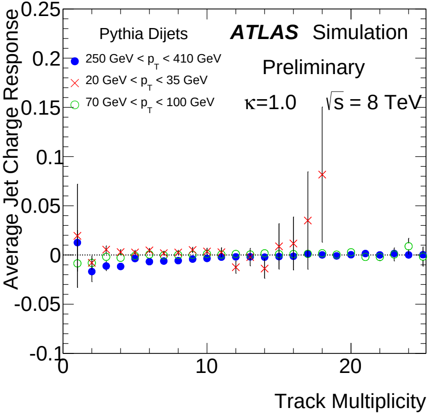
Jet Charge Response Versus Momentum

▸ TOC



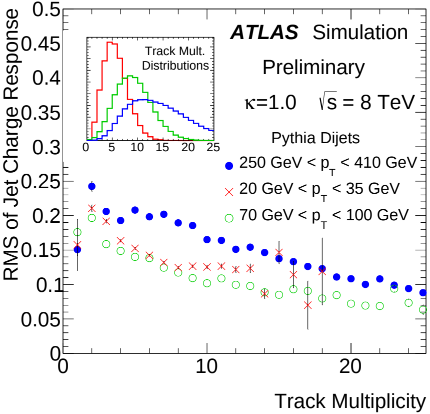
- As one expects, the RMS increases with momentum as straighter tracks lead to worse momentum resolution.
- Jets with more associated tracks have a lower response RMS due to averaging over more tracks in the defining sum for jet charge.

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).

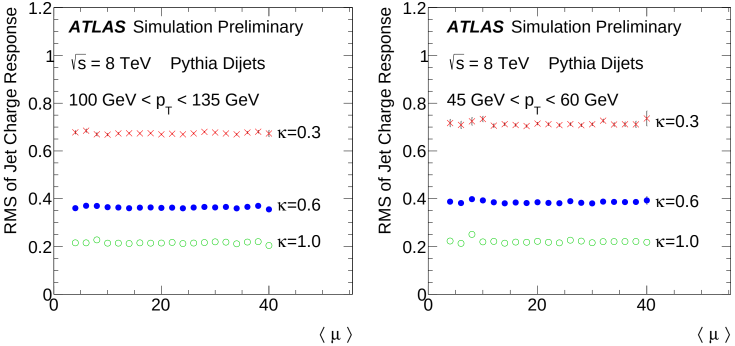
Jet Charge Response Versus Track Multiplicity II



- 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

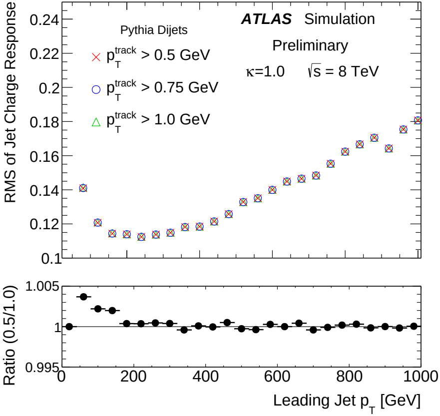
As a (mostly) track-based variable, we would expect the jet charge to be insensitive to pileup.



- 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.

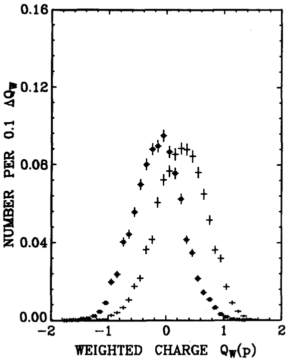
Track p_T Threshold

▸ TOC



- 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.

Brief History ▸ TOC



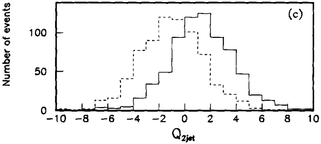


Fig. 1 The jet charge distribution for (a) B^0_d jets, (b) opposite jets and (c) the combined jet charge measure. The solid (dashed) lines are the distributions for simulated B^0_d ($\overline{B^0_d}$) events.

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).

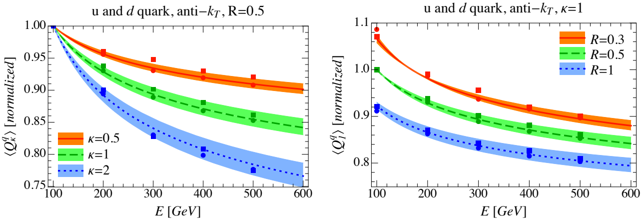
  - Used at the LHC for top quark charge.

New: Physics of Jet Charge

▸ TOC

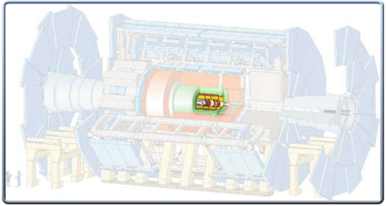
There is a a new theoretical interest in understanding jet charge as a physical phenomena - not just as a tool for other analyses.

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

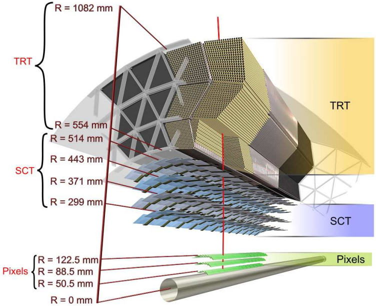


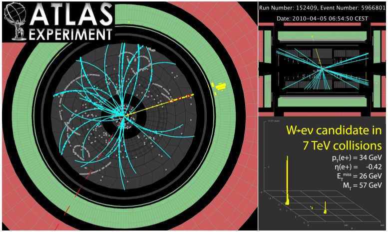
In addition, these same papers have explored a diverse set of applications of jet charge to various analyses - some of these will be presented today!

Tracks and Charge in ATLAS ▸ TOC



The inner detector inside ATLAS.





2 T longitudinal B field → bent tracks.

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

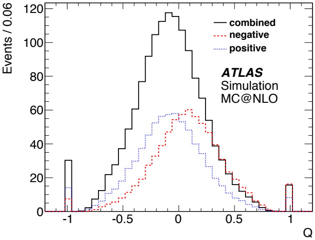
Previous Uses of Jet Charge in ATLAS

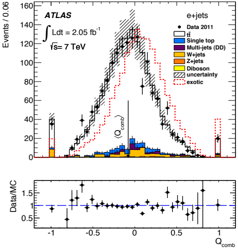
▸ TOC

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 $t\bar{t}$ ▸ TOC

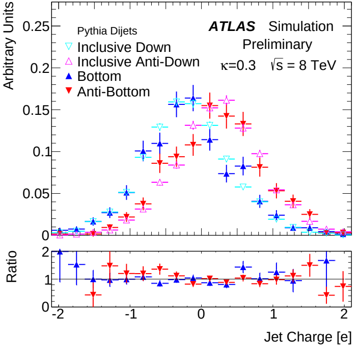
Process	N_{events} with μ^+	N_{events} with μ^-
$t\bar{t}$	3575 ± 29	3522 ± 20
Single Top	126 ± 3	97 ± 3
W+jets	170 ± 29	91 ± 15
Z+jets	23± 5	18 ± 3
Dibosons	3 ± 0.4	3 ± 0.3
Total MC	3895 ± 36	3729 ± 25
2012 Data	4095	3893

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.

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

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

Pythia Dijets MC



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.

Data and MC Samples ‣ TOC

- $W^\pm$ 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

Jet Charge in CMS PAS: JME-13-006

▸ TOC

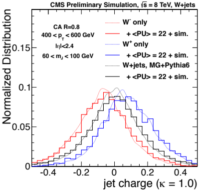


Figure 5: The jet charge distribution in simulated samples of boosted W bosons and inclusive QCD jets after a cut on the pruned jet mass. MG denotes the MADGRAPH5 generator. Thick dashed lines represent the generator predictions without pileup interactions and without CMS simulation. The histograms are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

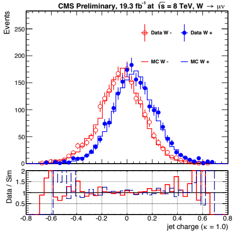
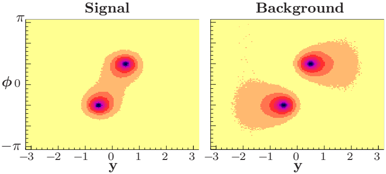


Figure 24: Jet charge distributions in the $t\bar{t}$ control sample for W^+ and W^- jets in simulation and data. Simulated distributions are a sum of all processes.

Current State of the Field ‣ TOC

The idea to measure color connections using jet substructure is not new:

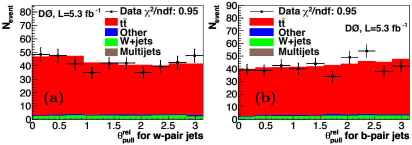
- Original Theory Paper (2010) by J. Gallicchio and M. Schwartz



$$\text{Pull (vector)} = \sum_{i \in \text{jet}} \frac{p_T^i |r_i|}{p_T^{\text{jet}}} \vec{r}_i, \qquad (3)$$

where $\vec{r}_i = (\Delta y_i, \Delta\phi_i)$ with respect to the jet position.

- Followup Pheno Paper
- D0, CMS HZ Multivariate tagger.
- D0 Color Flow Measurement
    - Very subtle (even with no pileup): W peak at 0 (in MC).
- ATLAS Performance Study
    - In preparation



Reconstructed Objects and Selections

▸ TOC

Tracks: A standard selection

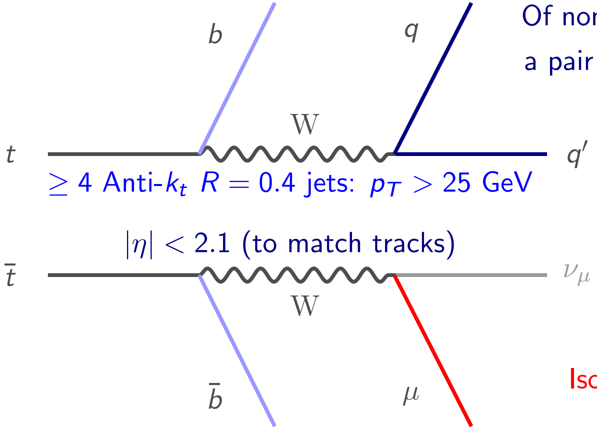
e.g. $p_T > 500$ MeV, $|d_0^{\mathrm{PV}}| \leq 2.5$ mm

Require ≥ 2 b-jets

(MV1 @ 70%)

Of non b-tagged jets, require

a pair with $|m_{jj} - m_W| < 30$



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

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

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

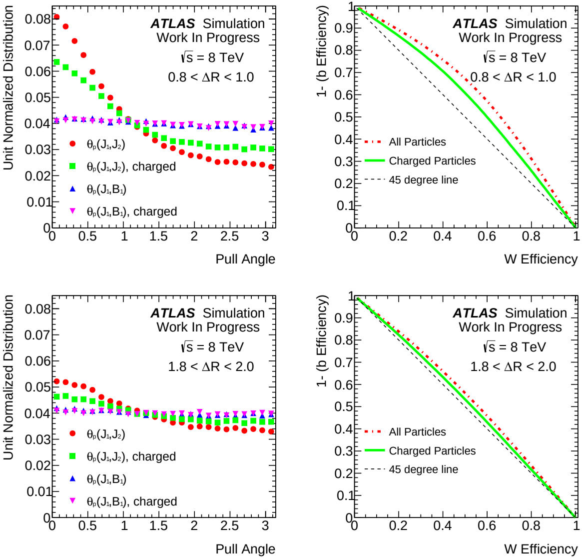
$M_T + E_T^{\mathrm{miss}} > 60$ GeV

Isolated muon trigger

(24, 36 GeV p_T)

Pull as a Tagger in bins of ΔR

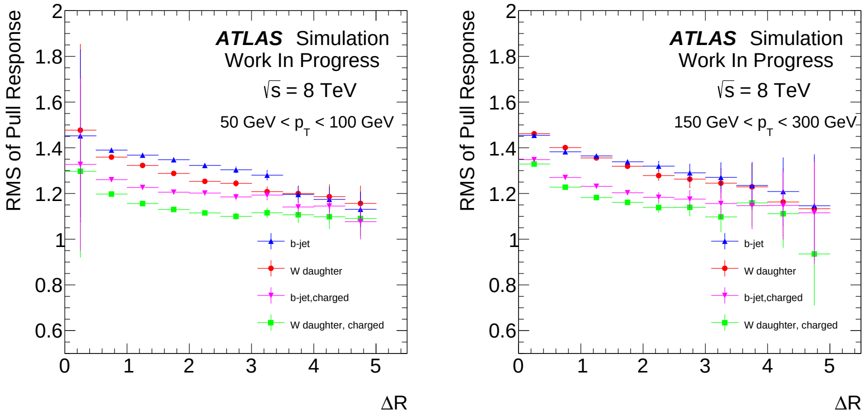
TOC



Differential Pull Angle Response: bins of p_T

▸ TOC

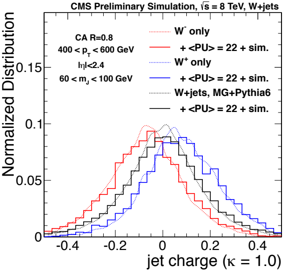
Now, fix bins of p_T and consider the pull angle response resolution as a function of ΔR:

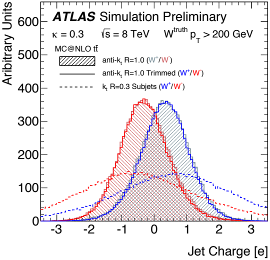


Only a slight downward slope with ΔR. Degradation for b-jets at low p_T.

Lorentz Properties of Jet Charge: Introduction ‣ TOC

Both ATLAS and CMS have investigated jet charge using large radius jets at the LHC.





As identifying the properties of boosted bosons will continue to increase in relevance and importance, we investigate some of the physical aspects of jet charge in the boosted regime.

Background ▸ TOC

For a jet J with some associated tracks T, the jet charge is most generally defined as

$$Q = \frac{1}{f(J)} \sum_{t \in T} q_t g(t), \tag{4}$$

where q_t is the charge of the track t and $f(*), g(*)$ are functions that map onto weights in $\mathbb{R}^+$.

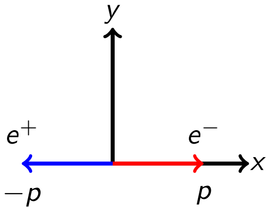
- Dedicated jet charge studies at the LHC have used $f(J) = (p_T^J)^\kappa$ and $g(t) = (p_T^t)^\kappa$
- Top quark charge studies have used $f(J) = \sum_{t \in T} (p_T^t)^\kappa$ and $g(t) = (p_T^t)^\kappa$

In both cases, Q is not Lorentz invariant. We want to understand how boosts impact the charge tagging performance of jet charge.

A Simple Example ‣ TOC

Let's focus on identifying the charge of hadronically decaying bosons, since on-shell W/Zs have a well defined rest frame.

Consider the most simple case: $Z \to e^+e^-$ and consider the electrons as the constituents of our 'Z jet':



For $f(J) = E_J^\kappa$ and $g(t) = E_t^\kappa$, in the Z rest frame ($p = m_Z/2$),

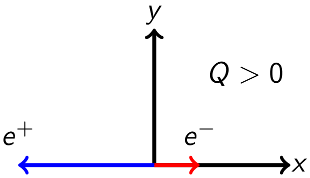
$$Q = \frac{1}{m_Z^\kappa}(p^\kappa - p^\kappa) = 0 \tag{5}$$

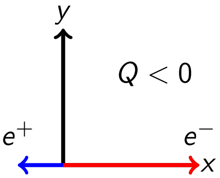
A Simple Example, continued ‣ TOC

Now, suppose that the Z has speed β along the $\pm x$ direction. Then,

$$Q = \frac{1}{(\gamma m_Z)^\kappa}\Big((\gamma p(1\pm\beta))^\kappa - (\gamma p(1\mp\beta))^\kappa\Big) \tag{6}$$

If $\kappa = 1$, then $Q = \pm\beta$. If $\kappa \ll 1$, then $Q = \pm\kappa\beta$. In either case, we can make Q *arbitrarily positive or negative* depending on the direction of the boost.





What goes wrong? ▸ TOC

More generally, Instead of 2 tracks associated to the Z/W jet, suppose now that there are n tracks. Then, we can compute

$$Q(\text{rest frame}) = \frac{1}{m_{\text{boson}}^{\kappa}} \sum_{i=1}^{n} q_i E_i^{\kappa} = \frac{1}{m_{\text{boson}}^{\kappa}} \sum_{i=1}^{n} q_i E^{\kappa} \tag{7}$$

$$= Q_{\text{boson}} \in \{0, \pm 1\} \tag{8}$$

Where we assume that all the particles causing the tracks are massless and that the energy is divided evenly amongst them, $E_i = E = m_{\text{boson}}/m$ for m the number of daughters ($n \leq m$) including $q_i = 0$ (not true in general).

What goes wrong? (continued) ‣ TOC

Now, let's perform a transverse boost in the $\hat{r}$ direction with speed β. Then,

$$Q = \frac{1}{(\gamma m_{\text{boson}})^\kappa}\sum_{i=1}^{n} q_i\gamma^\kappa(E_i - \beta\vec{P}_i\cdot\hat{r})^\kappa \tag{9}$$

When $\kappa = 1$,

$$Q = Q(\text{rest frame}) - \frac{\beta}{(m_{\text{boson}})}\sum_{i=1}^{n} q_i\vec{P}_i\cdot\hat{r} \tag{10}$$

$$= Q_{\text{boson}} - \frac{\beta}{m}\sum_{i=1}^{n} q_i\hat{P}_i\cdot\hat{r} \tag{11}$$

For a given event, the second term above will not be zero, unless all the tracks are perpendicular to the boost.

What goes wrong? (continued) ▸ TOC

For an ensemble of events, we expect the tracks to be randomly oriented and so

$$\langle Q \rangle = Q_{\text{boson}} - \beta \left\langle \frac{1}{m} \sum_{i=1}^{n} q_i \hat{P}_i \cdot \hat{r} \right\rangle \tag{12}$$

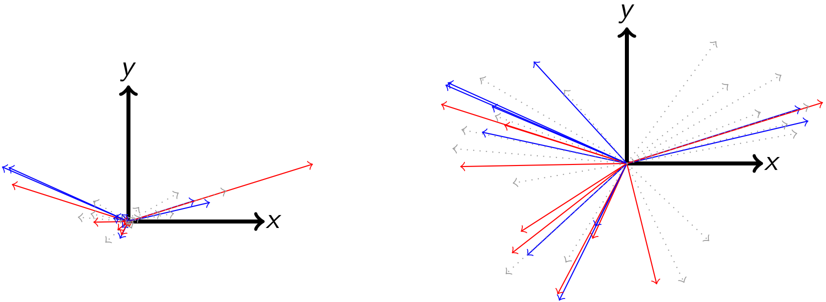
$$= Q_{\text{boson}} \tag{13}$$

However, in general the expectation of the square of the second term in (9) will not be zero. Thus, there is a boost-induced *resolution* to the jet charge that is unrelated to the detector performance. Next:

- How big is this effect?
- Can we correct for it (Lorentz invariant charge)?

A 'Real' Case Study: $W \rightarrow qq'$ ▸ TOC

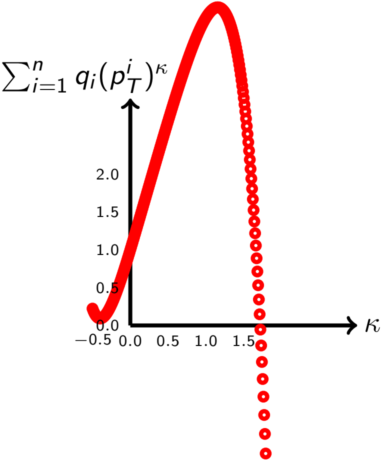
Consider the decay of a W into quarks with subsequent parton shower and hadronization. Because it is a color singlet, it is possible to uniquely associate the decay projects to the W. The event displays below visualize all the stable particles; negative hadrons, positive hadrons, and photons.



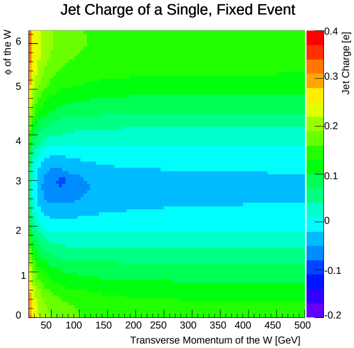
The left and right show the same event: the only difference is that the magnitudes on the right are the log of the actual magnitudes so that you can see every particle. What was the charge of the W? (A: $+1$).

Jet Charge in our Case Study ▸ TOC

- The W was generated with $\beta = 0.65$
- On the left, we can see the dependance of the jet charge numerator on κ.
  - $\kappa = 0 \implies Q = 1$
  - $\kappa \to \infty \implies Q$ dominated by leading track ($q < 0$)
- For now, we fix $\kappa = 1$ to study the boost properties

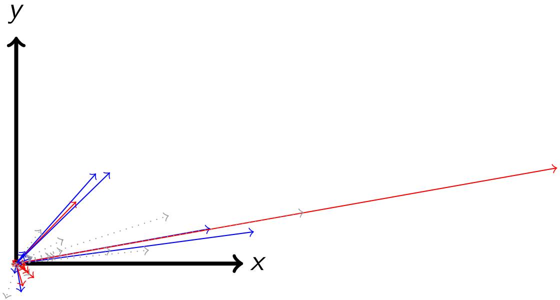


Charge as a Function of the Transverse Boost ‣ TOC



- Definition of charge from LHC performance notes - $Q \to \infty$ at $\beta = 0$.
- A boost in the transverse plane can be parameterized by the speed β [or p_T^W] and the azimuthal angle ϕ.
- Note the purple region around $\phi = \pi$ where Q is actually negative!

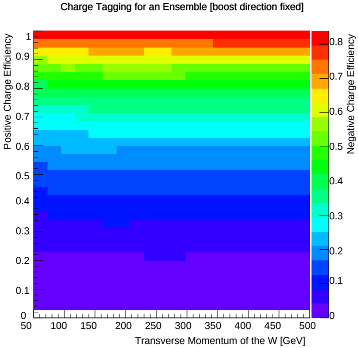
Event Display for the Boost Making $Q < 0$ ▸ TOC

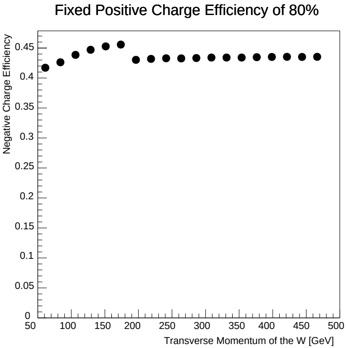


It is very clear from this figure that the large boost to the highest p_T (negatively charged) particle.

Impact on Performance ▸ TOC

Now, consider an ensemble of events. For a fixed direction, we can compute the efficiency versus rejection as a function of the boost along this direction.


Charge Tagging for an Ensemble [boost direction fixed]


Fixed Positive Charge Efficiency of 80%

There is a trend downward, indicating a decrease in performance with an increased boost. However, this is not dramatic and goes away at high p_T.

Conclusions ‣ TOC

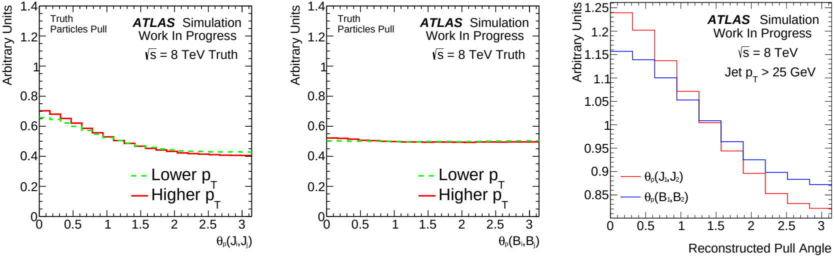
There is a physics induced resolution that worsens the performance due to the boost of the W/Z boson.

However, in terms of the impact on efficiency versus rejection, the effect is small. Nonetheless, we can *correct* for this by introducing a *boost invariant* jet charge. For example, one can use LI weights, or calculate the jet charge in the (di)jet rest frame.

For example, in boosted W charge tagging, one can i) define the jet charge in the W rest frame or ii) use weights which are Lorentz invariant. In both cases, we find that the performance is no better than the standard definition.

Calorimeter Pull Resolutions ‣ TOC

Fact: With only a truth p_T cut of 25 GeV, we see a clear difference between $\theta_P(J_1, J_2)$ and $\theta_P(B1, B_2)$ [left and middle]. However, the matched reconstructed jets do not share this difference [right].



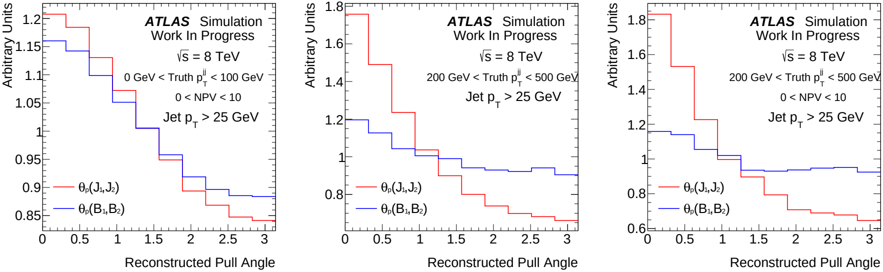
I'll show that there are two effects:

- The [truth level] strength of the W distribution increases with p_T^W.
- Resolutions are important, but come in two distinct categories.

p_T^W and Pileup

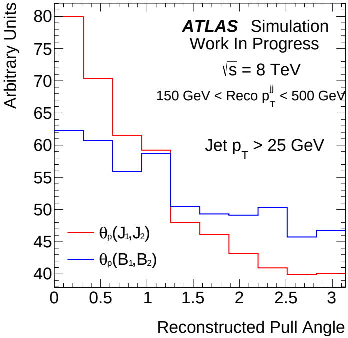
▸ TOC

- Removing pileup [left] does not improve the situation.
- Increasing the p_T^W threshold dramatically improves the difference.
- Once the p_T^W is large enough for the difference to be large, pileup is not relevant [right] (obvious).



Reconstructed Object Selection ‣ TOC

So far, plots have been based on *truth selections*. This plot was made with a reconstructed selection and will be comparable to the corresponding data plot:



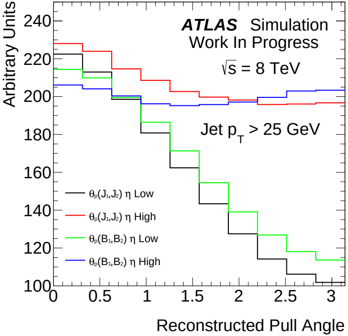
There is a tradeoff between statistics and the size of the effect.

Resolutions

So far, I've said nothing about resolutions. The best way to understand the impact of calorimeter resolutions is to divide events into two classes:

η Low $|\eta(X_1)| > |\eta(X_2)|$ where $X \in \{J, B\}$.

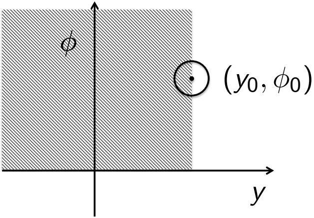
η High $|\eta(X_1)| < |\eta(X_2)|$ where $X \in \{J, B\}$.



- The next slide explains why there is a distinction. Then, I'll explain why the red and blue curves look as they do.

Why low and high η? ‣ TOC

Imagine you have a jet as shown below at the coordinates (y_0, ϕ_0). Since the distribution of jet η is **peaked at zero**, if you pick any other jet (in particular a *b*-jet or a *W* daughter jet) the most likely position of this second jet is somewhere in the hatched area.



- Angular smearing is symmetric in η and ϕ. However, if there is a contribution to the jet **not from the originating parton** i.e. from UE or pileup, then the most probable location is once again in the hatched area. If this contribution is on the outskirts of the jet, then it can increase the pull. As a result, the pull angle tends to be closer to zero. There is a peak at zero simply because of geometry; there are more angles close to zero than close to $\pm\pi$.

High η ▸ TOC

If the second (rotating) jet for pull has a larger η than the first, then the effect described on the previous slide is not relevant. Instead, you would expect mostly smearing from within the jet, which is symmetric. Such smearing leads to the U-shaped distribution. We can see this from treating a jet of a fixed p_T as a collection of massless particles which are smeared. This is the same process that leads to the peak at $\pi/2$ in track pull, but now we consider the constituents and the jet axis smearing coherently (there, only the jet axis changed).