Jet Charge Determination at the LHC

On behalf of the ATLAS and CMS collaborations

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Topics in This Talk

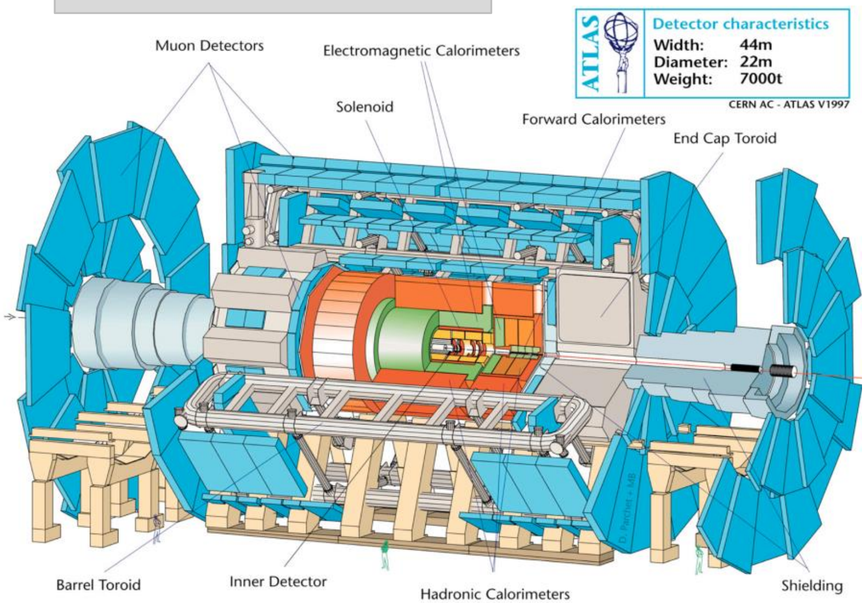
- About the ATLAS and CMS experiments
- A bit of jet charge history
- On theoretical approach
- Jet charge used for determination of the top quark charge
- Jet charge in boosted *W* boson studies
- Studies of charge of jets initiated by quarks and gluons
- Conclusion

ATLAS and CMS detectors

- collisions: p→ ← p, $\sqrt{s}$ = 7, 8 and 13 TeV
- Peak luminosities: 3 - 4×10^{32}cm^{-2}s^{-1} .
- ATLAS and CMS detectors are multipurpose detectors aiming mainly on deep inelastic ***pp*** collisions

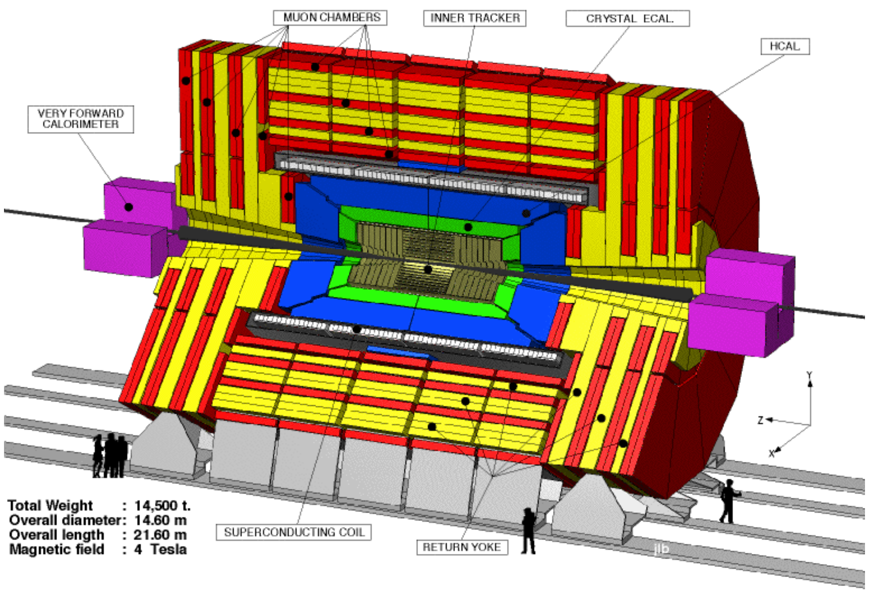
ATLAS detector

JINST 3, S08003 (2008)



CMS detector

2008 JINST 3 S08004



A bit of jet charge history

Jet charge: Field and Feynman, Nucl. Phys. B136, 1 (1978) $\rightarrow$ an observable sensitive to the electric charge of quarks as the momentum weighted charge sum constructed from charged-particle tracks in a jet.

Experimental use of jet charge:

First in deep inelastic scattering studies ($\nu p, \bar{\nu} p$ ...) (Nucl. Phys. B184, 13 (1981), Phys. Lett. 144B, 302 (1984).) – evidence of quarks in nucleons.

- Tagging the charge of b-quark jets
  - ✓ Asymmetry of b-production (Z. Phys. C 48, 433 (1990), Phys. Lett. B 259, 377 (1991)...)
  - ✓ Neutral B-meson oscillation (Phys. Lett. B 327, 411 (1994), Phys. Rev. D 60, 072003(1999)...)
  - ✓ Determination of top quark charge (PRL 98,41801 (2007), PRD 88,032003 (2013), JHEP 11 (2013) 031)
- Hadronically decaying W bosons - to distinguish them from QCD jets (PLB 422,369 (1998), PLB 502, 9 (2001),...., JHEP 12 (2014) 017.)
- To distinguish jets from quarks and gluons (NP B276, 253 (1986), PLB 302, 523 (1993), EPJC 74, 3023 (2014))

The role of the jet charge

Calculation of jet charge (Q_J):

$$Q_{\mathrm{J}} = \frac{1}{\left(p_{\mathrm{T,J}}\right)^{\kappa}} \sum_{h\in\mathrm{Jet}} q_h \times \left(p_{\mathrm{T},h}\right)^{\kappa}, \quad Q_{\mathrm{J}} = \frac{\sum_{h\in\mathrm{Jet}}^{N} q_h \left|\vec{j}\cdot\vec{p}_h\right|^{\kappa}}{\sum_{h\in\mathrm{Jet}}^{N} \left|\vec{j}\cdot\vec{p}_h\right|^{\kappa}}, \quad Q_{\mathrm{J}} = \sum_{h\in\mathrm{Jet}} z_h^{\kappa} q_h\,, \; z_h = \frac{E_h}{E_{\mathrm{J}}}$$

q_h, $p_{\mathrm{T},h}$, $\vec{p}_h$ ≡ the h^{th} track charge, transverse momentum, momentum

κ ≡ an exponent (free parameter), $\vec{j}$ ≡ jet direction unit vector

ATLAS and CMS: big potential to go beyond treating jets simply as 4-momenta to treating them as objects with substructure and quantum numbers.

Theory:

- calculation of jet charge is challenging as it is not an infrared-safe quantity $\rightarrow$ sensitivity to hadronization $\rightarrow$ knowledge of fragmentation functions.
- Soft collinear effective theory (SCET) is used - factorization of hard and soft contribution.

Phys. Rev. D 86,094030 (2013)

Theoretical approach – mean jet charge

Calculation of jet charge is challenging: it is not an infrared-safe quantity.

- Jet charge is sensitive to hadronization
- knowledge of the fragmentation functions is needed.

PRL 110, 212001 (2013)

The average jet charge:

coefficients depending on jet definition and flavor ***i*** init. the jet

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

NLO

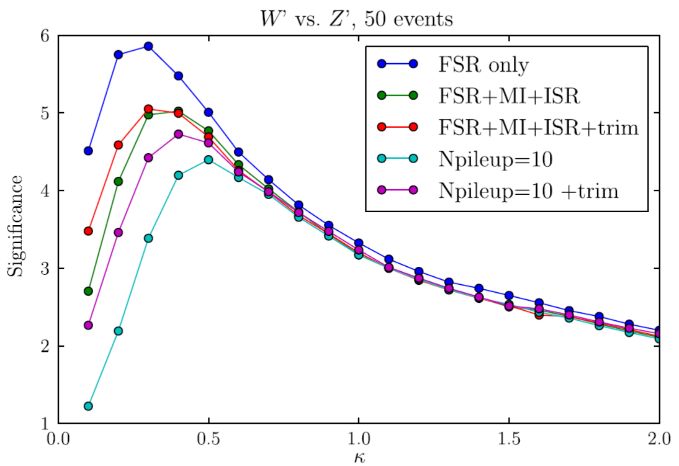
$$z = E_h / E_{\text{jet}} \approx p_{\text{T}}^h / p_{\text{T}}^{\text{jet}}$$

Jet function vs jet energy E and size R (collinear radiation in jet)

$$\tilde{D}_i^h(\nu,\mu) = \int_0^1 dx\, x^\nu D_i^h(x,\mu)$$ ≡ Mellin moment of the fragmentation function $D^h{}_i$.

For $\kappa > 0$ the charge – dominated by collinear and not soft radiation.

The effects of pileup and contamination on jet charge: significance of W' vs Z' (***m***=1TeV, 50 events) separation vs exponent **κ**.



Theoretical approach - jet charge width

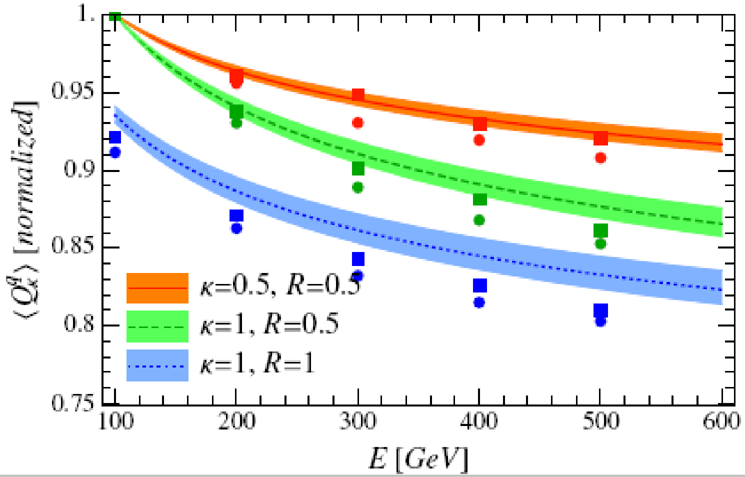
Width of the jet charge: correlations among hadrons are required!

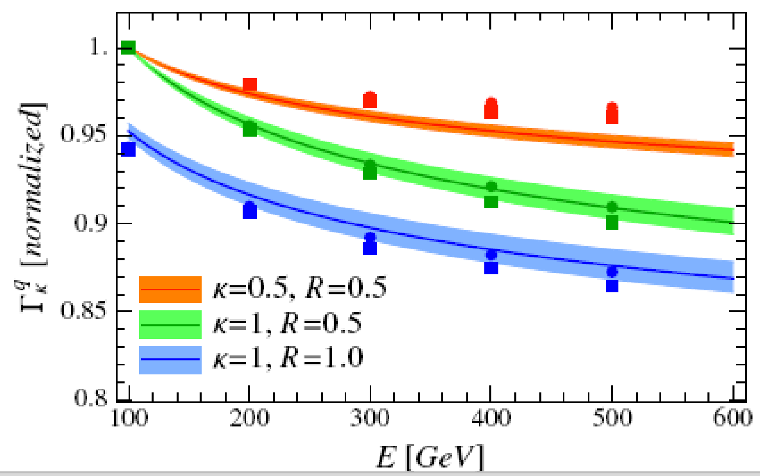
$$\left(\Gamma_\kappa^i\right)^2 = \left\langle \left(Q_\kappa^i\right)^2 \right\rangle - \left\langle Q_\kappa^i \right\rangle^2 \qquad \Rightarrow \text{the moment} \left\langle \left(Q_\kappa^i\right)^2 \right\rangle:$$

$$\left\langle \left(Q_\kappa^i\right)^2 \right\rangle = \int dz\, z^{2\kappa} \sum_h Q_h^2 \frac{1}{\sigma_{\text{jet}}} \frac{d\sigma_{h\in\text{jet}}}{dz} + \int dz_1 dz_2\, z_1^\kappa z_2^\kappa \sum_{h_1, h_2} Q_{h_1} Q_{h_2} \frac{1}{\sigma_{\text{jet}}} \frac{d\sigma_{h_1 h_2 \in \text{jet}}}{dz_1 dz_2} = \cdots$$

1st term can be expressed: in terms of products of fragmentation and jet functions
2nd term: via dihadron fragmenting jet functions

Comparison of theory prediction (bands) for the average (left) and width (right) of the jet charge distribution to PYTHIA (□ and □ for ***d*** and ***u*** quarks) for e^+e^- collisions).





Normalizing to 1 at E = 100 GeV and R = 0.5 removes dependence on nonpert. input and quark flavor

Top quark charge: via decay products' charges

ATLAS experiment at √s = 7 TeV, data of 2.1 fb^{-1}

Phys. Rev.D 88, 032003 (2013)

SM (Q_{top} = 2/3): $t^{2/3} \to b^{-1/3} + W^{+1}$ vs exotics (Q_X = -4/3): $t_X^{-4/3} \to b^{-1/3} + W^{-1}$

for top quark determination

- ✓ Charge of W via its lept-decay
- ✓ Determination of b-quark charge
- ✓ Correct lepton – b-jet pairing

$$Q_{b-jet} = \frac{\sum_i^N q_i \left|\vec{j}\cdot\vec{p}_i\right|^\kappa}{\sum_i^N \left|\vec{j}\cdot\vec{p}_i\right|^\kappa}$$

$q_i \equiv$ ith particle charge
$\vec{p}_i \equiv$ ith particle momentum
$\vec{j} \equiv$ b-jet direction
$\kappa \equiv$ an exponent (=0.5)

Soft lepton decay of ***b*** quark, $b \to l^- \nu_l X$,
Sign(Q_b) = sign(Q_l)

lepton+jets case (1 high-p_T lepton)

$$m(l, b_{jet}^{(1,2)}) < m_{cr} \;\;\&\;\; m(l, b_{jet}^{(2,1)}) > m_{cr}$$

optimization: m_{cr} = 155 GeV

alternative: Kinematic fitter (KLFitter)

Combined charge: $\langle Q_l \times Q_{bjet} \rangle$ <0: SM; >0: XM

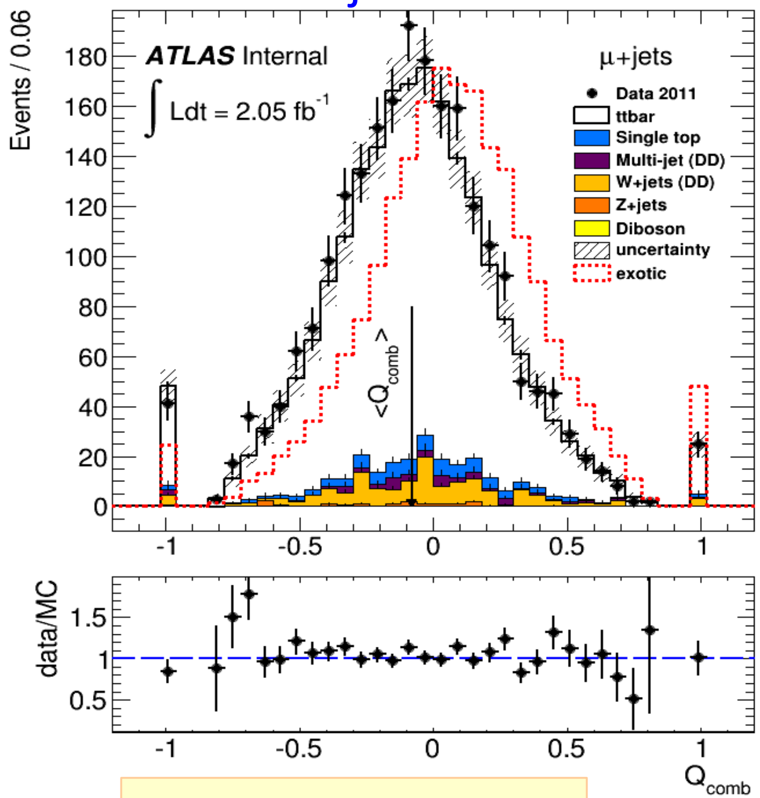
Purity o *b* quark determination: 61%

Combined b-jet charge: Data vs MC

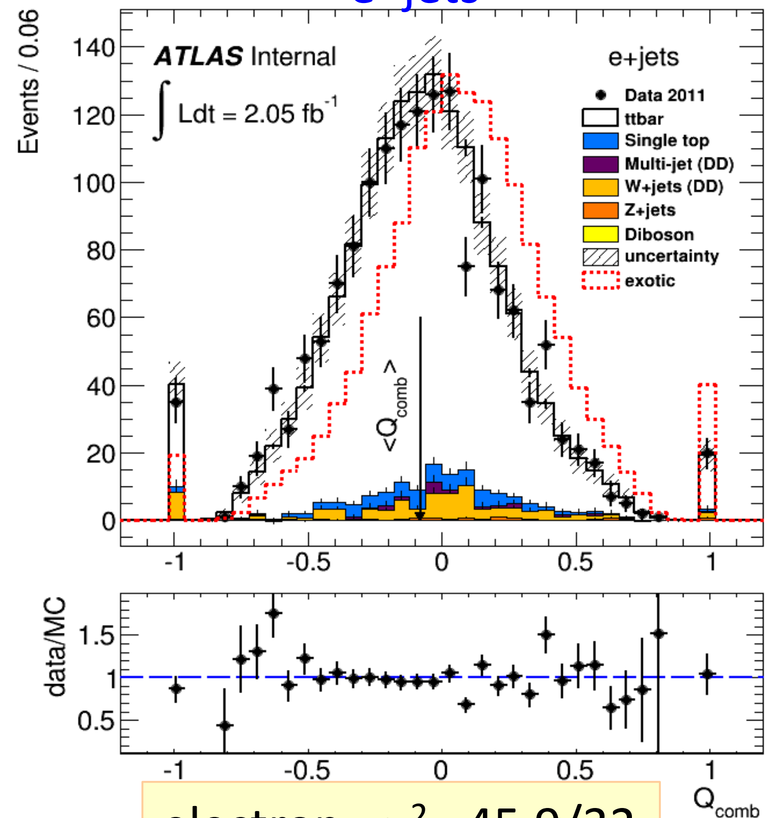
ATLAS

Data of $\int Ldt = 2.05\ fb^{-1}$ are compared with MC signal expectations.

mu+jets



e+jets



Muon: χ^2 =31.6/32

electron: χ^2 =45.9/32

Data vs MC: compatibility with SM within statistical errors!

XM exclusion: >8σ

CMS: boosted W boson and jet charge

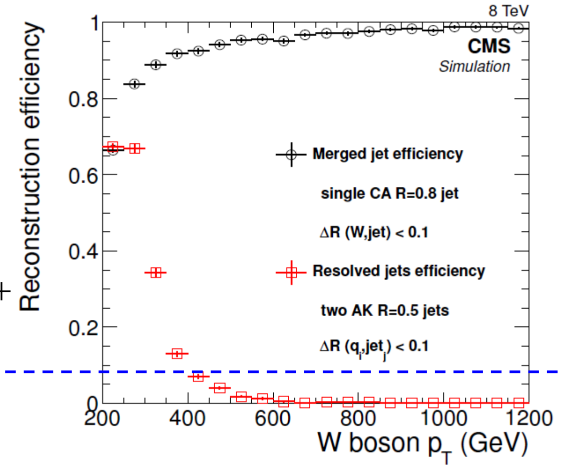
$\sqrt{s} = 8$ TeV , $\int L dt = 19.7$ fb^{-1}

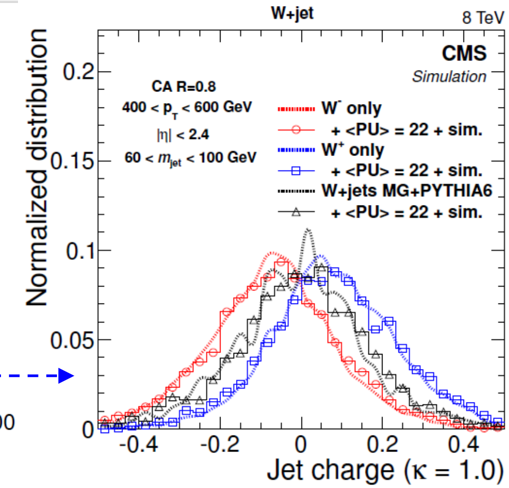
JHEP12(2014)017

Topologies studied:

$t\bar{t}$ ℓ+jets, W+jets, dijets events

Jet charge used with 5 other variables for W boson ID in boosted regime





CMS simulation with pileup for W^-, W^+ and W+jets vs generator MG+Pythia

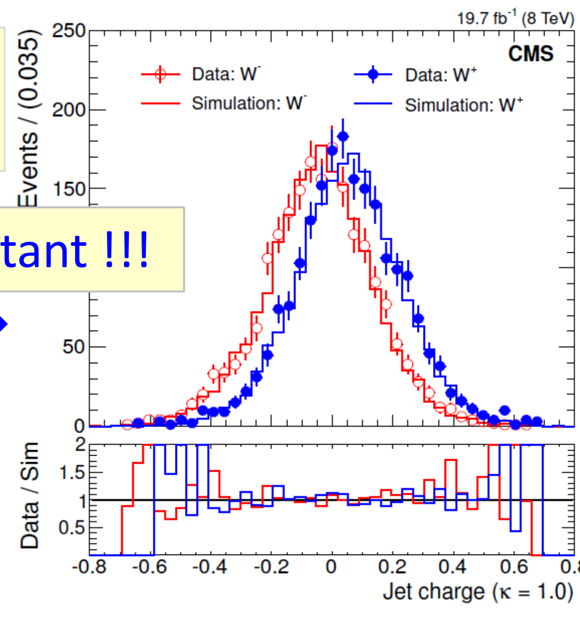
- jet mass: $60 < m_{\text{jet}} < 100$ GeV
- W jet p_T: $400 < p_T < 600$ GeV
- Jet charge *via* track p_T weighting

$$Q^\kappa = \frac{1}{(p_T)^\kappa} \sum_i Q_i \times (p_{T,i})^\kappa$$

Jet charge distributions in $t\bar{t}$ sample: simulation and data for W^+ and W^- jets from $t\bar{t}$

- Lepton charge determines W sign.
- W^+ and W^- jets contributions to the $t\bar{t}$ data can be separated with ≥ 5 SD.
- Jet charge: data vs MC → good agreement.

Important !!!



ATLAS: jet charge in dijet events

Measurement of jet charge in dijet events, *pp* collisions at √s=8 TeV, 20.3 fb^{-1}.

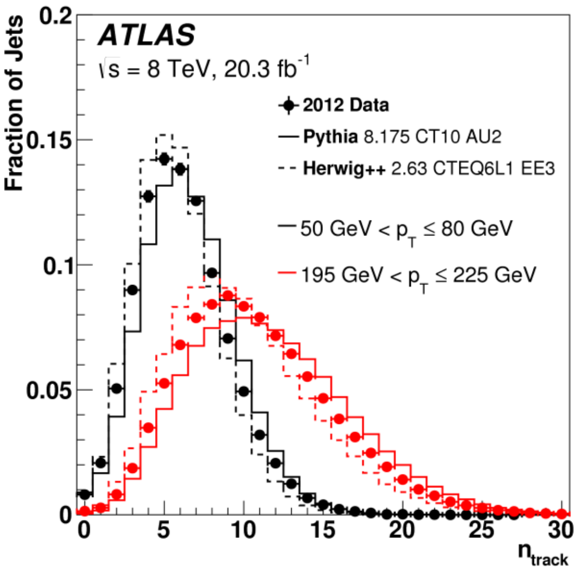
- ✓ Single-jet trigger with jet p_T threshold from 25 to 360 GeV.

PRD 93, 052003 (2016)

- ✓ Jet charge ≡ momentum-weighted sum of the charges of tracks associated to a jet

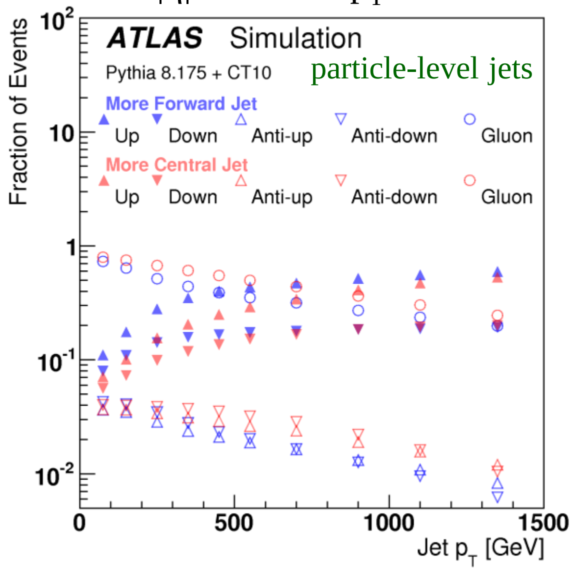
$$Q_J = \frac{1}{(p_{TJ})^\kappa} \sum_{i \in \mathrm{Tracks}} q_i \times (p_{T,i})^\kappa$$

q_i $(p_{T,i}) \equiv i^{th}$ track charge (p_T)
$p_{TJ} \equiv$ jet p_T, $\kappa \equiv$ regularization parameter

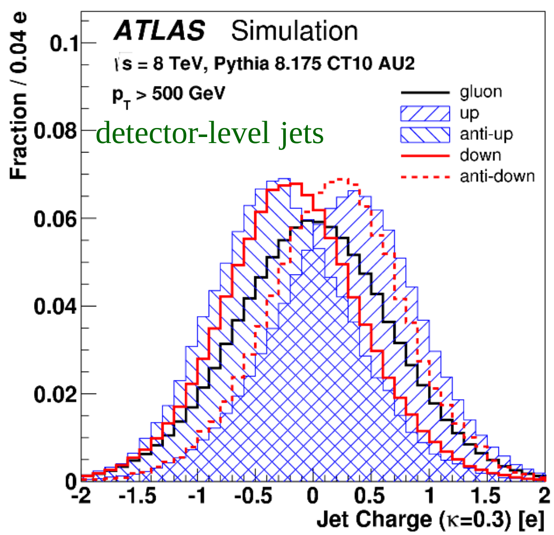


Data vs MC: # tracks in two jet p_T ranges

|η| < 2.1 and p_T > 50 GeV



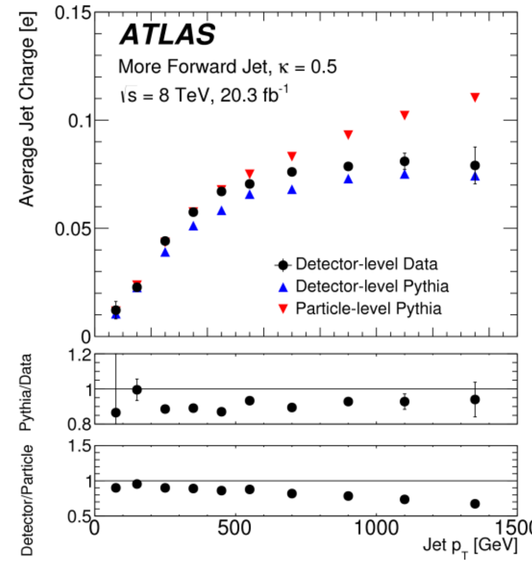
Fraction of dijet events with different jet flavor

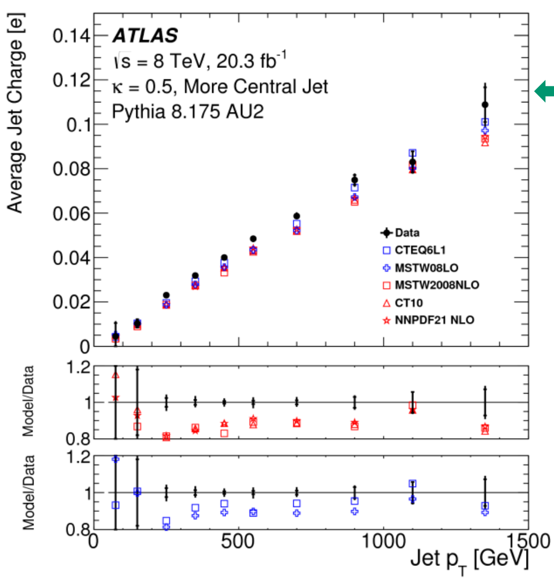


Jet charge distribution for various jet flavors

ATLAS: jet charge unfolding, systematics, PDFs

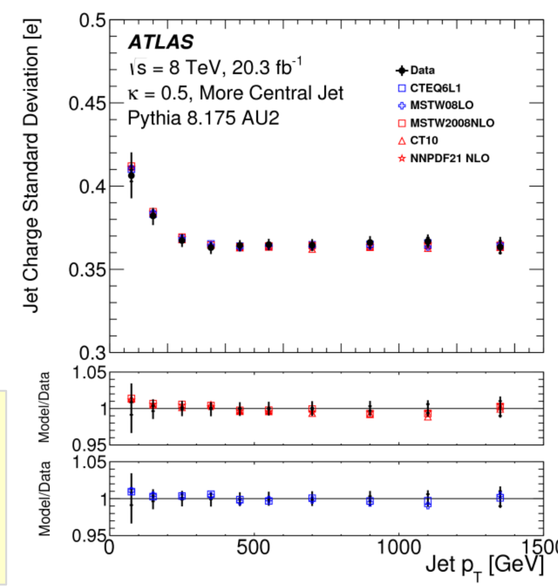
- Unfolding of jet charge (15 bins) distribution vs jet p_T (10 bins) to particle level: iterative Bayesian technique (RooUnfoldframework)
- Systematic uncertainties: a few percent
  - ✓ **Correction factors** (fake, inefficiency factors) from MC
  - ✓ **Response matrix**: experimental uncertainties on jet p_T and charge (track reconstruction)
  - ✓ **Unfolding procedure**: data-driven technique used to estimate bias from prior and number of iteration





The average jet charge vs jet p_T, more central jets, data vs theory (diff. PDFs) ⇒ increase due to ***u*** quark jets

The standard deviation of jet charge vs jet p_T

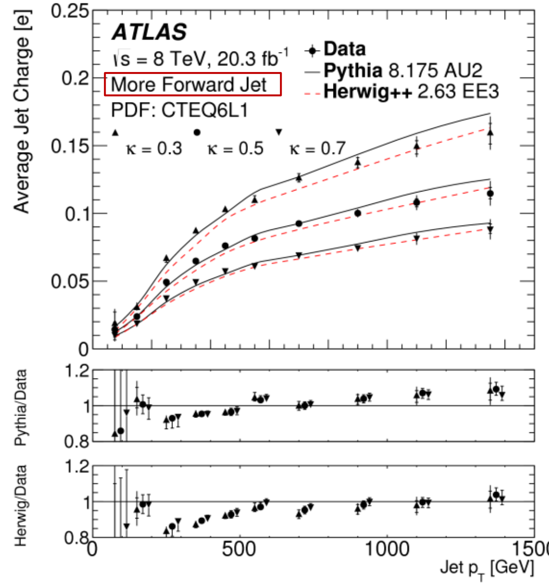


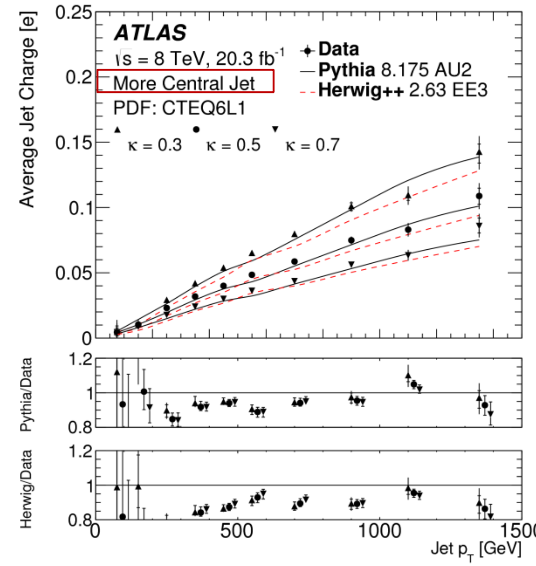
The best: CTEQ6L1 ⇒ difference in MC/data up to 10% (15%) for forward (central) jets

ATLAS: jet charge data vs theory

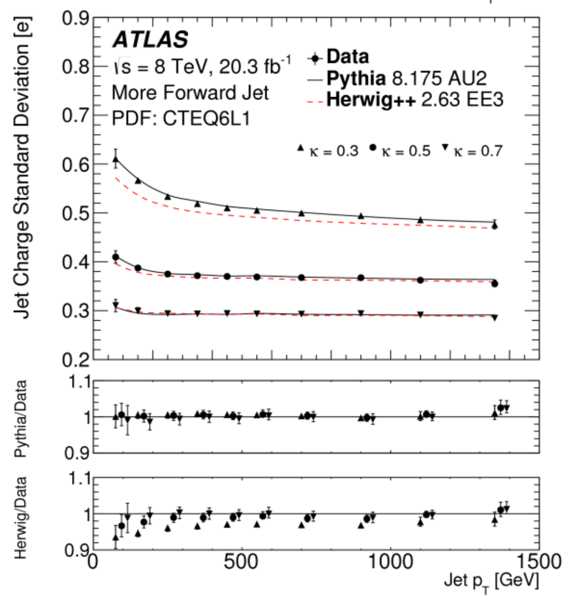
Data vs theory ⇒ Pythia / Herwig models using CTEQ6L1 PDFs
- 3 values of κ: 0.3, 0.5, 0.7

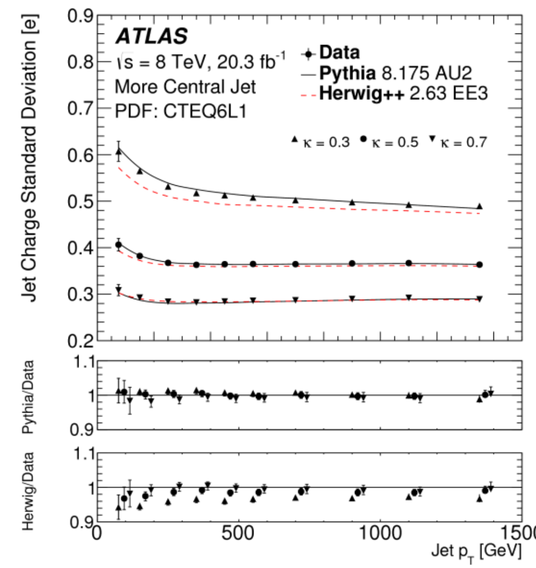
The average jet charge vs jet p_T, more central jets, data vs theory (diff. PDFs) →





The standard deviation of jet charge vs jet p_T , Data vs Pythia/Herwig →





Using CTEQ6L1 ⇒
at low p_T MC below data ≤ 5%
For CT10 NLO PDF: ≤ 10%

ATLAS: up- and down-quark jet charge

Flavor-fractions from PDFs + matrix element calculations used to extract the average ***u***- and ***d***-quark jet charge in each p_T bin.

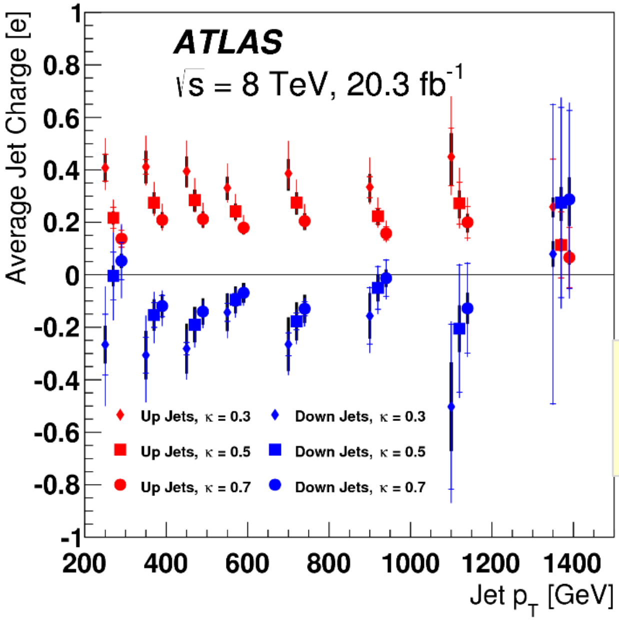
PRD 86, 094030 (2012)
PRL110, 212001 (2013)

Theory gives for average jet charge:

$$\langle Q_J \rangle = \bar{Q}\left(1 + c_\kappa \ln\left(p_T / \bar{p}_T\right)\right) + O\left(c_\kappa^2\right) \quad c_\kappa \approx \begin{cases} -0.024 \pm 0.004 & \kappa = 0.3 \\ -0.038 \pm 0.006 & \kappa = 0.5 \\ -0.049 \pm 0.008 & \kappa = 0.7 \end{cases}$$

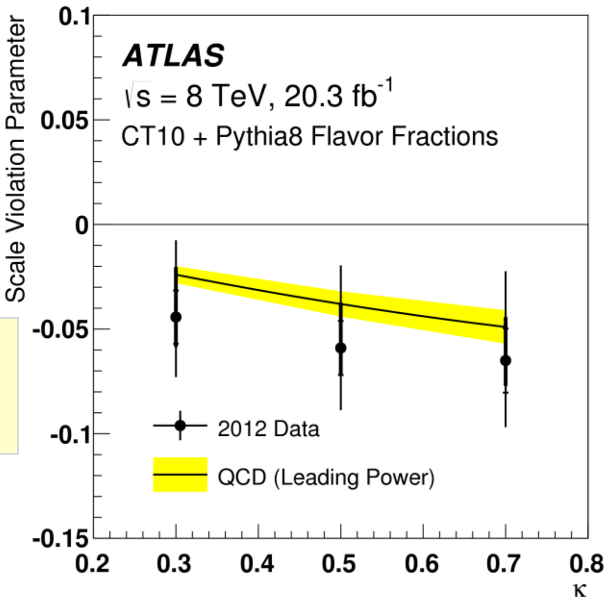
$\bar{Q} = \langle Q_J \rangle (\bar{p}_T)$ for some fixed $\bar{p}_T$

scaling violation parameter



Average jet charge vs jet p_T for up jet and down jet and κ=0.3, 0.5, 0.7

Measured values of c_κ thick error bar – PDF uncertainties



CMS: jet charge in dijet events

Jet charge for a quark, antiquark or gluon initiating a jet.

$\sqrt{s} = 8\,\mathrm{TeV},\ \int L dt = 19.7\,\mathrm{fb}^{-1}$

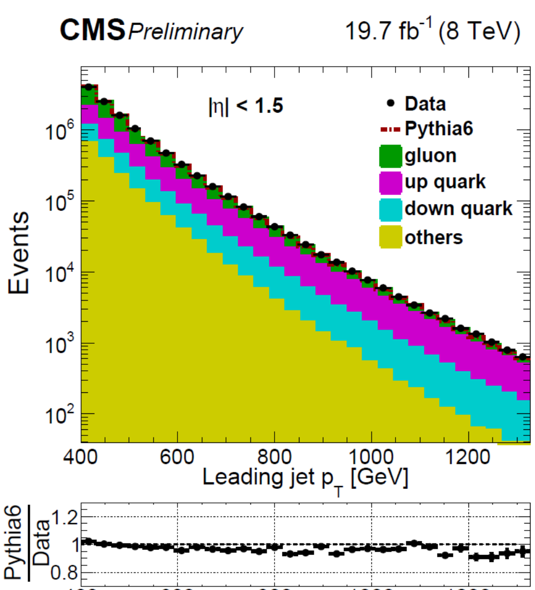
PAS SMP-15-003

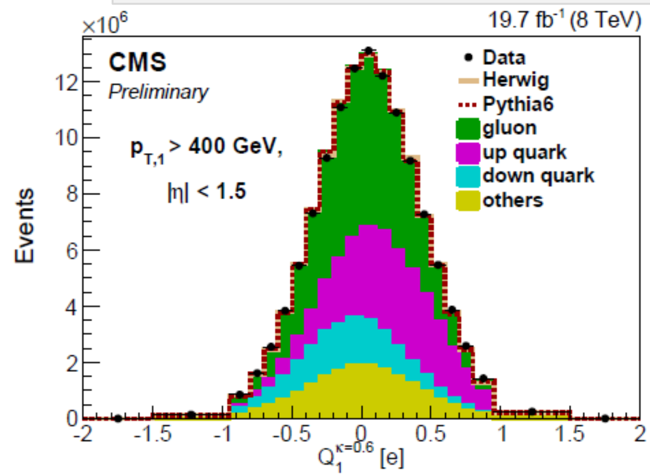
- ✓ Dijet events selected for the analysis
- ✓ 3 jet charge variables considered:

$$Q^{\kappa} = \frac{1}{(p_{\mathrm{T}})^{\kappa}} \sum_i Q_i \times (p_{\mathrm{T},i})^{\kappa}$$

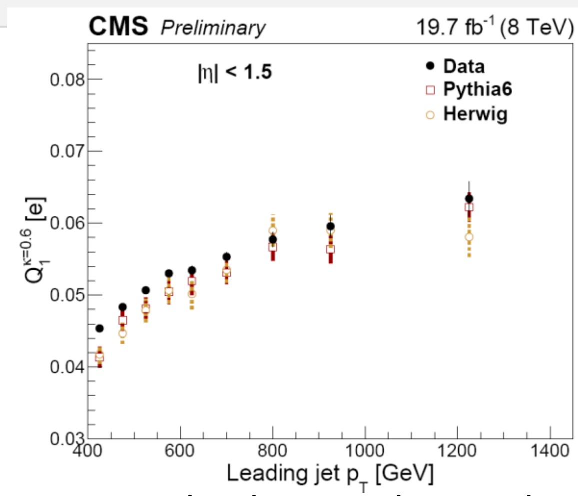
$$Q_L^{\kappa} = \sum_i Q_i \times \frac{(p_{\parallel,i})^{\kappa}}{\sum_j (p_{\parallel,j})^{\kappa}} \qquad Q_{\mathrm{T}}^{\kappa} = \sum_i Q_i \times \frac{(p_{\perp,i})^{\kappa}}{\sum_j (p_{\perp,j})^{\kappa}}$$

$p_{\parallel,i}\ (p_{\perp,i}) \equiv$ the momentum component of the constituent ***i*** parallel (transverse) to the jet axis.





Reconstructed jet charge distribution data vs MC (u-, d-, g- ...and others jets) for jet charge Q^{κ}



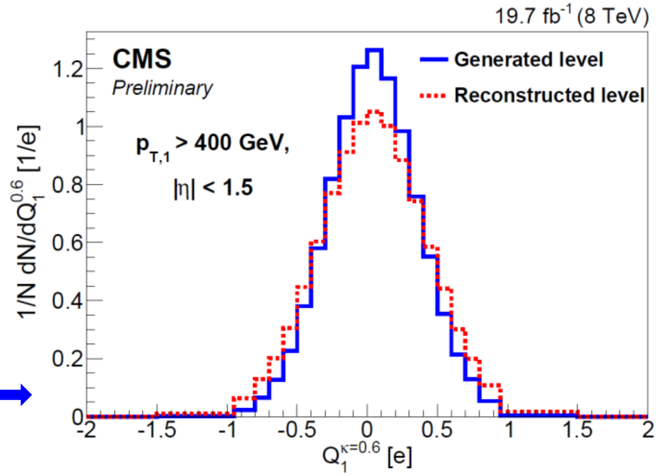
Average leading jet charge data vs PYTHIA6 and HERWIG++ as a function of leading jet p_{T}.

CMS: jet charge unfolding and systematics

The measured jet charge distribution is unfolded from **detector level** to **particle level** (iterative Bayesian meth.)

- Response matrix from Pythia 6 simulation
- SVD approach also used
- Bayesian and SVD approaches: agreement within 1%

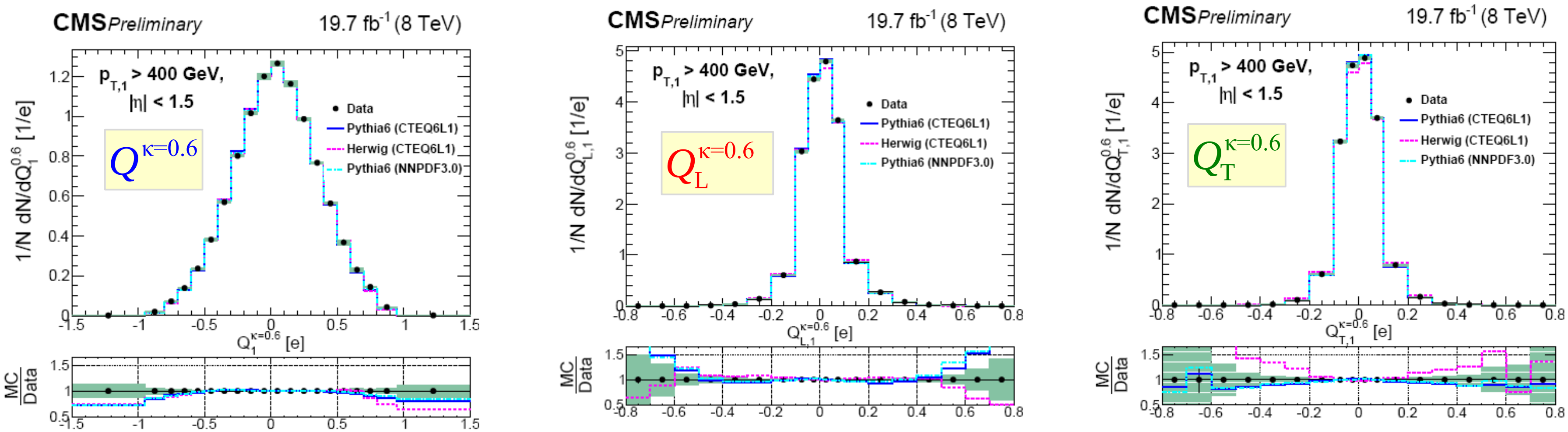
Average leading jet charge: Difference between detector and particle level vs leading jet p_T (Pythia 6).



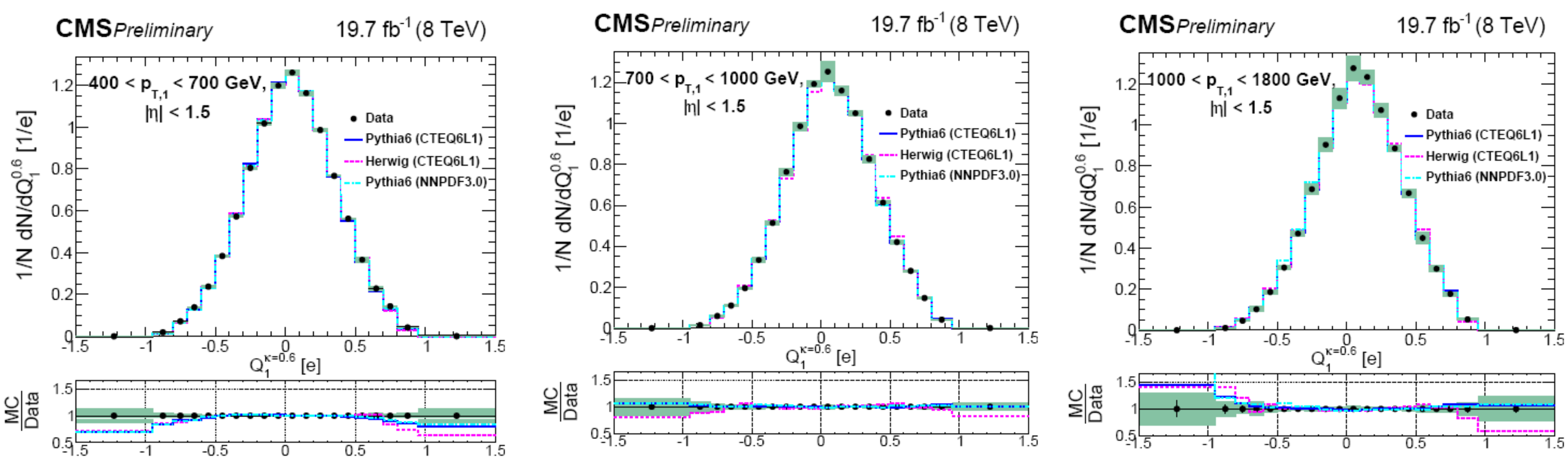
Syst. effect in percent (%)	$\kappa = 1.0$			$\kappa = 0.6$			$\kappa = 0.3$		
	Q^κ	Q_L^κ	Q_T^κ	Q^κ	Q_L^κ	Q_T^κ	Q^κ	Q_L^κ	Q_T^κ
Jet energy scale	0.7	<0.1	<0.1	0.4	<0.1	<0.1	0.3	<0.1	<0.1
Jet energy resolution	0.1	<0.1	<0.1	0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Track reconstruction	0.4	0.4	0.5	0.5	0.4	0.5	0.5	0.4	0.4
Track p_T resolution	1.4	1.0	0.8	1.0	0.6	0.7	1.5	0.4	0.4
Response matrix modeling	1.6	1.6	1.8	1.0	0.8	1.3	1.5	1.3	1.3
Response matrix statistics	0.9	0.9	0.6	0.6	0.6	0.5	0.6	0.5	0.4

CMS: jet charge results after unfolding

Leading jet charge distributions for charges Q^{κ}, Q_{L}^{κ} and Q_{T}^{κ}, $\kappa = 0.6$; data vs MC/PDFs



Leading jet charge distributions of Q^{κ} for different jet p_T intervals; data vs MC/PDFs



Summary

- LHC experiments, ATLAS and CMS have shown that the variable jet charge can be effectively used to distinguish jets initiated by partons of different electric charges in pp collisions.

- Jet charge, especially using it with other variables (like jet invariant mass, etc.) within multivariate techniques, can be used in:
  - ✓ Study of asymmetries in $q\bar{q}$ production – to distinguish q from $\bar{q}$
  - ✓ Studies with W bosons decaying hadronically
  - ✓ 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

Thank you!