# Jet properties from ATLAS data A M Cooper-Sarkar Low-x, 2016

Measurement of transverse energy-energy correlations in mutijet events from 7TeV data and determination of  $\alpha_{s}(M_{z})$ arXiv: 1508.01579, Phys.Lett.B750(2015)427

Measurement of 4-jet differential cross sections in 8 TeV data arXiv:1509.07335, JHEP12(2015)105

Measurement of charged multiplicity inside jets from 8TeV data arXiv:1602.00988

Measurement of jet charge in dijets events from 8TeV data arXiv:1509.05190, Phys.Rev.D93(2016)052003 Measurement of transverse energy-energy correlations in multijet events from 7TeV data and determination of  $\alpha_{s}(M_{z})$ arXiv: 1508.01579, Phys.Lett.B750(2015)427

Energy-energy correlations were proposed in e+ e- collisions as an alternative event shape variable not affected by soft divergences

Transverse energy-energy correlations were proposed as the analogous variables at hadron colliders. They have been calculated to NLO in QCD using NLOjet++

The TEEC is defined a normalised angular distribution weighted by transverse energy fractions

$$\frac{1}{\sigma}\frac{\mathrm{d}\Sigma}{\mathrm{d}(\cos\phi)} = \frac{1}{\sigma}\sum_{ij}\int\frac{\mathrm{d}\sigma}{\mathrm{d}x_{\mathrm{T}i}\mathrm{d}x_{\mathrm{T}j}\mathrm{d}(\cos\phi)}x_{\mathrm{T}i}x_{\mathrm{T}j}\mathrm{d}x_{\mathrm{T}i}\mathrm{d}x_{\mathrm{T}j},\tag{1}$$

where the sum runs over all pairs of jets in the final state with azimuthal<sup>1</sup> angular difference  $\phi = \Delta \varphi_{ij}$ and  $x_{Ti} = E_{Ti}/E_T$  is the transverse energy carried by jet *i* in units of the sum of jet transverse energies  $E_T = \sum_i E_{Ti}$ . In order to cancel uncertainties that are constant over  $\cos \phi \in [-1, 1]$ , it is useful to define the azimuthal asymmetry of the TEEC (ATEEC) as

$$\frac{1}{\sigma} \frac{d\Sigma^{asym}}{d(\cos\phi)} \equiv \left. \frac{1}{\sigma} \frac{d\Sigma}{d(\cos\phi)} \right|_{\phi} - \left. \frac{1}{\sigma} \frac{d\Sigma}{d(\cos\phi)} \right|_{\pi-\phi}.$$
 (2)

The point of a measurement of TEECs is that the shapes depends on the value of  $a_s(M_z)$  and are not very sensitive to the choice of PDF



## Data Selection / Correction

Jet algorithm anti-kt, R=0.4 applied to topological clusters in the calorimeter  $E_T$ >135GeV, effective luminosity of 158pb-1 Require one event vertex,with at least 5 tracks with pt>400MeV At least two jets  $p_T$ >50GeV,  $|\eta| < 2.5$  and  $p_{T1}+p_{T2} > 500GeV$ TEEC distribution is obtained by calculating the cosines of the angles in the transverse plane between all possible pairs of jets weighted by  $w_{ij} = x_{Ti} x_{Tj} = E_{Ti} E_{Tj} / (\sum_k E_{tk})^2$ 

# MC simulations are used to unfold from detector level to particle level

Pythia 6.423 LO 2 $\rightarrow$ 2 Matrix elements with PDF MRST2007\*LO and UE tune AUET2B (pt ordered parton showers PS, Lund string hadronisation) Herwig++2.5.1 LO 2 $\rightarrow$ 2 Matrix elements with PDF CTEQ6.6 and UE tune UE7 (angular ordered PS, cluster hadronisation, UE uses Jimmy) AND for comparison to the data ALPGEN LO 2 $\rightarrow$  n matrix elements interfaced to HERWIG+JIMMY for PS, hadronisation and UE

The detector level spectra are corrected to particle level by a bin by bin correction using the Pythia AUET2B simulated detector and particle level spectra. This is checked by Iterative Bayesian unfolding using RooUNFOLD.



The sources of experimental uncertainty come from Jet Energy Scale Jet Energy Resolution Pile-up Parton shower modelling Unfolding procedure



The particle level distributions are compared with Pythia, Herwig and Alpgen here. The Herwig description is poor

# In order to use these data to make a measurement of $a_s(M_z)$ , we need fixed order predictions. We use NLOJet++ interfaced with various PDFs MSTW2008, CT10, NNPDF2.3 and HERAPDF1.5

This involves calculations of  $2\rightarrow 3$  subprocesses to NLO and  $2\rightarrow 4$  processes at tree level. Angular range is restricted to  $|\cos \phi| < 0.92$  to avoid collinear singularities

The renormalisation and factorisation scales are taken to be  $\mu_R = \mu_F = (p_{T1} + p_{T2})/2$ Hadronisation and UE corrections are applied using Pythia and AUET2B

Uncertainties on the theoretical predictions are:

- Scale uncertainties, estimated by varying up and down by a factor of two
- PDF uncertainties, estimated using the PDF eigenvectors of CT10 and by using different PDFs
- Hadronisation and UE corrections, checked by using HERWIG and other UE tunes

Determination of  $a_{S}(M_{Z})$ 

To determine  $a_S(M_Z)$  we use an analytic expression  $\psi(a_S)$  to parameterise the dependence of the predictions for each bin of the TEEC or ATEEC. Then a  $\chi^2$  fit is made to the data accounting for correlated systematic uncertainties using nuisance parameters

$$\chi^2(\alpha_{\rm s},\vec{\lambda}) = \sum_i \frac{(x_i - F_i(\alpha_{\rm s},\vec{\lambda}))^2}{\Delta x_i^2 + \Delta \tau_i^2} + \sum_k \lambda_k^2,\tag{6}$$

where the NLOJET++ predictions are varied according to

$$F_i(\alpha_{\rm s},\vec{\lambda}) = \psi_i(\alpha_{\rm s}) \left( 1 + \sum_k \lambda_k \sigma_k^{(i)} \right). \tag{7}$$

In these expressions,  $x_i$  corresponds to the data points in each distribution (TEEC or ATEEC), and  $\Delta x_i$  are their statistical uncertainties.  $\Delta \tau_i$  are the statistical errors on the NLOJET++ predictions, while  $\sigma_k^{(i)}$  correspond to the k-th source of experimental uncertainty in the bin *i*.

Theoretical uncertainties are dealt with by varying the prediction to account for the source of uncertainty and repeating the fit –offset method



The unfolded distributions compared to the theoretical predictions from CT10 for the best fit values of  $a_S(M_Z)$ 

PDF	$\alpha_{\rm s}(m_Z)$ value	$\chi^2/N_{\rm dof}$
MSTW 2008	$0.1175 \pm 0.0010$ (exp.) $^{+0.0059}_{-0.0019}$ (scale) $\pm 0.0006$ (PDF) $\pm 0.0002$ (NPC)	29.0/21
CT10	$0.1173 \pm 0.0010$ (exp.) $^{+0.0063}_{-0.0020}$ (scale) $\pm 0.0017$ (PDF) $\pm 0.0002$ (NPC)	28.4/21
NNPDF 2.3	$0.1183 \pm 0.0010$ (exp.) $^{+0.0059}_{-0.0013}$ (scale) $\pm 0.0009$ (PDF) $\pm 0.0002$ (NPC)	29.3 / 21
HERAPDF 1.5	$0.1167 \pm 0.0007 \text{ (exp.)} ^{+0.0040}_{-0.0008} \text{ (scale)} ^{+0.0007}_{-0.0024} \text{ (PDF)} \pm 0.0001 \text{ (NPC)}$	28.7 / 21

The fitted values with uncertainties for different PDFs for the TEEC

PDF	$\alpha_{\rm s}(m_Z)$ value	$\chi^2/N_{ m dof}$
MSTW 2008	$0.1195 \pm 0.0017 \text{ (exp.)} ^{+0.0055}_{-0.0015} \text{ (scale)} \pm 0.0006 \text{ (PDF)}$	12.7 / 10
CT10	$0.1195 \pm 0.0018$ (exp.) $^{+0.0060}_{-0.0015}$ (scale) $\pm 0.0016$ (PDF)	12.6 / 10
NNPDF 2.3	$0.1206 \pm 0.0018$ (exp.) $^{+0.0057}_{-0.0013}$ (scale) $\pm 0.0009$ (PDF)	12.2 / 10
HERAPDF 1.5	$0.1182 \pm 0.0013$ (exp.) $^{+0.0041}_{-0.0008}$ (scale) $^{+0.0007}_{-0.0025}$ (PDF)	12.1 / 10

The fitted values with uncertainties for different PDFs for the ATEEC

The CT10 value from TEEC is chosen as the most experimentally accurate with PDF uncertainties which cover the PDF variations



# Measurement of 4-jet differential cross sections in 8 TeV data arXiv:1509.07335, JHEP12(2015)105

The current state of the art for predictions of 4-jet production is  $2 \rightarrow 4$  NLO fixed order calculations e.g Blackhat/Sherpa or Njet/Sherpa but these have no parton showers PS or hadronisation

Results can also be compared to HEJ which approximates the hard scatter to all orders - this would be exact for large separation in rapidity between partons

Generators such as Pythia and Herwig which use  $2\rightarrow 2$  LO Matrix elements and parton showers (PS) with resummation of leading logs are still remarkably successful in some kinematic regions

Multi-leg  $2 \rightarrow n$  LO calculations such as Madgraph are also successful if matched to PS using MLM matching

Name	Hard scattering	LO/NLO	PDF	PS/UE	Tune	Factor
Pythia	Рутнія 8	LO $(2 \rightarrow 2)$	CT10	Рутнія 8	AU2-CT10	0.6
Herwig++	Herwig++	LO $(2 \rightarrow 2)$	CTEQ6L1	Herwig++	UE-EE-3-CTEQ6L1	1.4
MadGraph+Pythia	MadGraph	LO $(2 \rightarrow 4)$	CTEQ6L1	Рутніл б	AUET2B-CTEQ6L1	1.1
HEJ	HEJ	All <sup>†</sup>	CT10	_	_	0.9
BlackHat/Sherpa	BLACKHAT/SHERPA	NLO $(2 \rightarrow 4)$	CT10	—	—	_
NJet/Sherpa	NJET/SHERPA	NLO $(2 \rightarrow 4)$	CT10	—	—	—

Theoretical uncertainties are computed for HEJ and the NLO predictions

- Factorisation and renormalisation scales are varied by factors of 2 around the central value  $H_{T}/2$ 12
- PDF uncertainties use the eigenvector variations and variation of  $\alpha_{s}$  (M<sub>z</sub>).

# Data Selection / Correction

At least four jets anti-kt algorithm, R=0.4 The four with the largest place within |y| < 2.8 well s

The four with the largest  $p_T$  are within |y| < 2.8, well separated,  $\Delta R > 0.65$ ,

all  $p_T > 64$  GeV and at least one  $p_T > 100$  GeV Distributions are unfolded from detector to particle-jet level by Iterative Bayesian unfolding using RooUnfold using Pythia as the prior.

Biases from the prior are investigated by reweighting the simulated detector level spectrum to be more like the data

# Experimental

uncertainties come from:

- Jet Energy Scale
- Jet Energy Resolution
- Pile-up
- Jet Angular resolution
- Unfolding procedure
- Efficiency of selection at detector and particle level



(a)  $H_{\rm T}$ 

(b)  $\Delta \phi_{2j}^{\min}$ 

# A variety of kinematic variables are explored to test the validity of the theoretical descriptions

Name	Definition	Comment	
$p_{\mathrm{T}}^{(i)}$	Transverse momentum of the ith jet	Sorted descending in $p_{\rm T}$	
$H_{\mathrm{T}}$	$\sum_{i=1}^{4} p_{\mathrm{T}}^{(i)}$	Scalar sum of the $p_{\rm T}$ of the four jets	
m <sub>4j</sub>	$\left(\left(\sum_{i=1}^{4} E_i\right)^2 - \left(\sum_{i=1}^{4} \mathbf{p}_i\right)^2\right)^{1/2}$	Invariant mass of the four jets	
$m_{2j}^{\min}/m_{4j}$	$\min_{\substack{i,j \in [1,4]\\ i \neq j}} \left( \left( E_i + E_j \right)^2 - \left( \mathbf{p}_i + \mathbf{p}_j \right)^2 \right)^{1/2} / m_{4j}$	Minimum invariant mass of two jets re- lative to invariant mass of four jets	
$\Delta \phi_{2j}^{\min}$	$\min_{\substack{i,j \in [1,4]\\i \neq j}} \left(  \phi_i - \phi_j  \right)$	Minimum azimuthal separation of two jets	
$\Delta y_{2j}^{\min}$	$\min_{\substack{i,j\in[1,4]\\i\neq j}} \left(  y_i - y_j  \right)$	Minimum rapidity separation of two jets	
$\Delta \phi_{3j}^{\min}$	$\min_{\substack{i,j,k\in[1,4]\\i\neq j\neq k}}\left( \phi_i-\phi_j + \phi_j-\phi_k \right)$	Minimum azimuthal separation between any three jets	
$\Delta y_{3j}^{\min}$	$\min_{\substack{i,j,k \in [1,4]\\ i \neq j \neq k}} \left(  y_i - y_j  +  y_j - y_k  \right)$	Minimum rapidity separation between any three jets	
$\Delta y_{2j}^{\max}$	$\Delta y_{ij}^{\max} = \max_{i,j \in [1,4]} \left(  y_i - y_j  \right)$	Maximum rapidity difference between two jets	
$\Sigma p_{\mathrm{T}}^{\mathrm{central}}$	$ p_{\rm T}^c  +  p_{\rm T}^d $	If $\Delta y_{2j}^{\text{max}}$ is defined by jets <i>a</i> and <i>b</i> , this is the scalar sum of the $p_{\text{T}}$ of the other two jets, <i>c</i> and <i>d</i> ('central' jets)	

In general the NLO 2 $\rightarrow$ 4 generators give an excellent description Madgraph which is LO but 2  $\rightarrow$ n is also not bad --apart from  $p_T^{-1}$  and  $p_T^{-2}$ HEJ is good apart from  $\Delta y_{2j}^{min}$  and  $\Delta y_{2j}^{max}$  when  $p_T^{-1}$  is small. However when  $p_T^{-1}$ is large it gives the best description of  $\Delta y_{2j}^{max}$ Herwig and Pythia do not fare very well- apart from  $H_T$ 

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#### dσ / d(m<sub>4j</sub>) [fb/GeV] 10<sup>5</sup> ATLAS Data Vs=8 TeV, 95 pb<sup>-1</sup> - 20.3 fb 10 Pythia 8 ( $\times$ 0.6) Herwig++ $(\times 1.4)$ MadGraph+Pythia ( $\times$ 1.1) ← p\_(1)>100 GeV 10 10<sup>-2</sup> Total experimental Theory/Data systematic uncertainty 0.5 2000 4000 6000 m<sub>4i</sub> [GeV] dσ / d(m<sub>4j</sub>) [fb/GeV] 10<sup>5</sup> ATLAS Data Is=8 TeV, 95 pb<sup>-1</sup> - 20.3 fb 10 HEJ (× 0.9) BlackHat/Sherpa ( $\times$ 1.0) 10 NJet/Sherpa (× 1.0) ← p\_T^(1)>100 GeV 10 $10^{-2}$ Total experimental Theory/Data systematic uncertainty NLO (scale PDF) 0.5 0 uncertainty 6000 4000 2000 m<sub>4i</sub> [GeV]

# Momentum variables

PYTHIA gives an amazingly good description of  $p_T^4$ Could HEJ and Njet benefit from matching the calculations to PS?

# Mass variables

MadGraph+Pythia does very well HEJ and Njet have a bump structure around 1-2TeV 15



Angular variables- high  $p_{\rm T}$  large angle radiation should be well described by HEJ and Madgraph

HEJ is good for  $p_T^1$ >400 GeV,

Madgraph is good apart from the tail of  $\Delta y_{2j}^{min}$  and extreme values of  $\Delta y_{2j}^{max}$  <sup>16</sup> Njet/Sherpa is good except for an upward trend in  $\Delta y_{2j}^{max}$ 



 $\Sigma p_T^{central}$  variables – the scalar sum of the  $p_T$  of the two central jets for a minimum rapidity spacing of the other two jets.

Pythia/Herwig have difficulties so only the others are shown here. In general the description worsens with increasing  $\Delta y$  and  $p_T^1$ 

HEJ and Njet/Sherpa are good --this could be improved after interfacing to a PS 17 generator.

Measurement of charged multiplicity inside jets from 8TeV data arXiv:1602.00988

The number of charged particles within a jet can serve to discriminate gluon initiated jets from quark initiated jets.

Gluon initiated jets produce more charge particles due to their larger colour charge.

Furthermore the average multiplicity within a jet increases with jet-energy for all types of jets, but it should increase faster for gluon initiated jets



Jets are selected with the anti-kt algorithm R=0.4 Two jets with  $p_T > 50$ GeV,within  $|\eta| < 2.1$ To make the jets balance in  $p_T$  their  $p_T$  values are required to be within 1.5 of each other. This enriches a sample of well separated jets. Thus quarks and gluons from the hard scatter can be cleanly matched in the simulations A forward jet is somewhat more likely to be uquark initiated and a central jet is somewhat more likely to be gluon initiated

### Data Selection / Correction

# There also need to be requirements on the charged tracks $p_T > 500 \text{ MeV}, |\eta| < 2.$ Good $\chi 2$ for track fit. Originating from the vtx. Sufficient numbers of track hits Matching to the calorimeter based jets

The reconstructed charged particle multiplicity spectrum is unfolded to particle level to remove distortions from detector effects using Iterative Bayesian RooUnfold with PYTHIA 8.175, CT10 PDFs and AU2 tune for the underlying event as the prior.

Biases from the prior are investigated by reweighting the simulated detector level spectrum to be more like the data



Corrections for events which pass either detector level or particle level fiducial selection but not both are estimated by comparing Pythia and Herwig

Uncertainties in the charge particle  $p_T$  spectra and jet  $p_T$  spectra affect the response matrix in unfolding. Those deriving from the track reconstruction matter more than the jet energy scale or resolution. The dominant uncertainty is the loss of charged particles' tracks in the jet core due to track merging which can be estimated using data/MC differences in the ratio of the track-based jet  $p_T$  to the calorimeter based jet pt. More charged energy is lost in data than in MC.





The charged particle multiplicity in a jet vs Jet  $P_T$ , combining central and forward jets, for various cuts on  $p_T^{track}$  for the charge tracks.

The data are compared to simulations using Pythia and Herwig and various PDFs and various UE tunes' In general tunes developed for Run-2 do better. It is also noticeable that the value of  $\alpha_s$  governing final state radiation affects the predictions. The value is ~10% lower for A14 than Monash tunes



#### Number of charged particles per gluon and quark jet

We can measure the number of charged tracks in central and forward jets separately. The figure shows the difference in these quantities. A forward jet is somewhat more likely to be u quark initiated and a central jet is somewhat more likely to be gluon initiated, so we expect a positive difference



$$\begin{split} \langle n_{\text{charged}}^{f} \rangle &= f_{q}^{f} \langle n_{\text{charged}}^{q} \rangle + f_{g}^{f} \langle n_{\text{charged}}^{g} \rangle \\ \langle n_{\text{charged}}^{c} \rangle &= f_{q}^{c} \langle n_{\text{charged}}^{q} \rangle + f_{g}^{c} \langle n_{\text{charged}}^{g} \rangle \\ \\ \text{Where } f_{q}^{f} + f_{g}^{f} = 1, \, f_{q}^{c} + f_{g}^{c} = 1 \end{split}$$

In fact since we can measure  $n_{charged}^{f}$  and  $n_{charged}^{c}$  we can extract  $n_{charged}^{q}$  and  $n_{charged}^{g}$  if we know the fractions, which we get from simulation

We use CT10 and Pythia8 and assess PDF uncertainties from CT10 eigenvectors and by comparison with NNPDF. Non-perturbative uncertainties are assessed from comparison of Pythia and Herwig (for the same PDFs)



The result of the number of charged particles per gluon and quark jet as a function of jet  $p_T$  are compared to the simulation and to an N<sup>3</sup>LO calculation.

We see that the multiplicity is higher in gluon jets and rises more steeply with Jet  $p_T$  for gluon jets.

# Measurement of jet charge in dijets events from 8TeV data arXiv:1509.05190, Phys.Rev.D93(2016)052003

The momentum weighted sum of the charges of tracks associated to a jet is sensitive to the charge of the initial quark or gluon

Dijet events are best because one can have cleanly separated jets

The probability for positively charged quarks to be produced is of course higher than for negatively and it increases with the parton centre of mass energy. Thus the average jet charge should also increase.

Such a measurement is clearly related to the initial PDFs, but further non-perturbative input such as the modelling of fragmentation is also important. Thus these data are a useful check on such models.

#### **Data Selection**

Anti-kt algorithm R=0.4, two jets pT > 50 GeV Ratio of Pt values < 1.5 to select clean dijet topologies. One more central one more forward. Jets within  $|\eta| < 2.1$ , charged tracks within  $|\eta| < 2.5$ Also there are requirements on the tracks as for the multiplicity study



## Simulation

Pythia 8.175, CT10 and AU2 (pt ordering, string fragmentation) HERWIG ++2.63 with CTEQ6L and EE3 (angular ordering, cluster fragmentation) These are used for unfolding from detector to particle level.

But other simulations with different PDFs are also used for comparison.

Each one has a dedicated UE (AU2) with its own PDF



Here we see the simulated flavour fractions for the more forward and more central jets

How to define jet charge? Using the tracks assigned to a jet construct

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

Where  $\kappa$  regularises the sensitivity of the jet charge to soft radiation. The higher the value of  $\kappa$  the more that high-p<sub>T</sub> tracks contribute. The value  $\kappa = 0.5$  is most sensitive to the charge of the initiating parton

In simulation there is a clear relation between jet charge and initiating parton charge But the jet charge distribution is already broad at particle level and the resolution from particle level to detector level smears this further. So particular attention must be paid to unfolding.

# **Data Correction**



The difference between particle level and detector level grows with jet pt due to track-merging. Iterative Bayesian unfolding is used via RooUnfold. Pythia was used as prior.

Similar systematics apply as for the case of multiplicity:

Correction factors are needed for events which pass either particle level or detector level fiducial selection but not both. Pythia and Herwig are compared to estimate this.

Uncertainties on the response matrix from calorimeter jet PT (JES, JER) measurement and track reconstruction and resolution

Unfolding procedure bias from the prior- reweight the simulated detector level spectrum to be more like the data and use the corresponding particle spectrum to be the prior

The unfolded mean jet charge and its standard deviation are shown here as a function of jet pt for the forward jet and central jet, for three values of  $\kappa = 0.3, 0.5, 0.7$ 



The jet charge for the forward jet is greater than that of the central jet due to the larger fraction of upflavour jets

The mean charge increases with  $p_T$  for both, because the fraction of up-flavour jets also increases with  $p_T$ 

#### Unfolded mean jet charge





The relative flavour fractions do differ with the specific PDF chosen for modelling. CTEQ6L1 at LO seems in better agreement than CT10 NLO Comparisons are shown here using PYTHIA 8.175 and A2 tune



However differences in PDFs are not the whole story, there are differences in the MC simulations:

- Pythia and Herwig
- Different tunes for the underlying event
- The value of  $\alpha_s$  also affects the amount of final state radiation (radLo,radHi)

# Average charges of up- and down-type quark jets

The average jet charges of the forward and central jets can be written in terms of the average charges of up- and down-type quark initiated jets

$$Q_{J}^{\text{forward}} \rangle_{i} = \left( f_{\text{up},i}^{\text{forward}} - f_{\text{anti-up},i}^{\text{forward}} \right) Q_{i}^{\text{up}} + \left( f_{\text{down},i}^{\text{forward}} - f_{\text{anti-down},i}^{\text{forward}} \right) Q_{i}^{\text{down}}$$
$$\langle Q_{J}^{\text{central}} \rangle_{i} = \left( f_{\text{up},i}^{\text{central}} - f_{\text{anti-up},i}^{\text{central}} \right) Q_{i}^{\text{up}} + \left( f_{\text{down},i}^{\text{central}} - f_{\text{anti-down},i}^{\text{central}} \right) Q_{i}^{\text{down}},$$

in each bin of jet  $p_T$ 

Such that the charges of these up- and down-type jets can be extracted if the flavour fractions are known.





These fractions are taken from simulation

#### Scaling of mean jet charge

We can now examine the  $p_T$  dependence of a fixed jet flavour which is calculable perturbatively as a function of the regularisation parameter  $\kappa$ 

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$$\frac{p_{\rm T}}{\langle Q_{\kappa} \rangle} \frac{d}{dp_{\rm T}} \langle Q_{\kappa} \rangle = \frac{\alpha_{\rm s}}{\pi} \widetilde{P}_{qq}(\kappa) \equiv c_{\kappa} \approx \begin{cases} -0.024 \pm 0.004 & \kappa = 0.3 \\ -0.038 \pm 0.006 & \kappa = 0.5 \\ -0.049 \pm 0.008 & \kappa = 0.7 \end{cases}$$



The data support the prediction that  $c_{\kappa}$  and  $\partial c_{\kappa}/\partial \kappa$  are both < 0

# Summary

Jet properties like the average jet multiplicity and average jet charge can be related to the flavour of the initiating parton and give information on the modelling of nonperturbative effects, both of the PDFs used and the hadronisation and underlying event models

There is now a large sample of 4-jet events which can be confronted with exact fixed order calculations and MC simulations

Event shape variables such as transverse-energy-energy correlations can be used for a measurement of  $\alpha_{S}(M_{Z})$