Jets and QCD — lecture 4

Matteo Cacciari$^{1,2}$ and Gavin Salam$^{3,4,1}$

$^1$ LPTHE (CNRS/UPMC)
$^2$ Université Denis Diderot (Paris 7)
$^3$ CERN, PH-TH
$^4$ Princeton University

Focus Week at the GGI Workshop
High energy QCD after the start of the LHC
Florence, Italy, 12-16 September 2011
Towards an understanding of jets

How a jet is and isn’t like a parton — quantitatively

And how this relationship is affected by the jet radius
Small v. large jet radius ($R$) ≡ HSBC

Small jet radius

Large jet radius

single parton @ LO: jet radius irrelevant
Small v. large jet radius ($R \equiv HSBC$)

Small jet radius

Large jet radius

single parton @ LO: jet radius irrelevant
Small v. large jet radius \((R) \equiv \text{HSBC}

Small jet radius

\[ \text{Small jet radius} \]

\[ \text{Large jet radius} \]

perturbative fragmentation: \textbf{large jet radius better}

(it captures more)
Small v. large jet radius \((R) \equiv HSBC\)

**Small jet radius**

\[
\sum K^{-} \pi^{+} \pi^{+} \pi^{0} K^{+} \quad \text{non-perturbative hadronisation}
\]

**Large jet radius**

\[
\sum K^{-} \pi^{+} \pi^{+} \pi^{0} K^{+} \quad \text{non-perturbative hadronisation}
\]

non-perturbative fragmentation: **large jet radius better**

(it captures more)
Small v. large jet radius ($R$) \equiv HSBC

**Small jet radius**

**Large jet radius**

underlying ev. & pileup “noise”: **small jet radius better**

(it captures less)
Small v. large jet radius ($R$) $\equiv$ HSBC

**Small jet radius**

**Large jet radius**

multi-hard-parton events: **small jet radius better**
(it resolves partons more effectively)
Parton $p_t$ v. jet $p_t$

3 physical effects:
1. Gluon radiation from the parton
2. Hadronisation
3. Underlying Event

One important consideration:
Whether the parton is a quark or a gluon
[quarks radiate with colour factor $C_F = 4/3$
gluons radiate with colour factor $C_A = 3$]
Jet $p_t$ v. parton $p_t$: perturbatively?

The question’s dangerous: a “parton” is an ambiguous concept

Three limits can help you:

- Threshold limit
- Parton from color-neutral object decay ($Z'$)
- Small-$R$ (radius) limit for jet

One simple result (small-$R$ limit)

$$\frac{\langle p_{t,jet} - p_{t,parton} \rangle}{p_t} = \frac{\alpha_s}{\pi} \ln R \times \left\{ \begin{array}{ll}
1.01 C_F & \text{quarks} \\
0.94 C_A + 0.07 n_f & \text{gluons} \\
\end{array} \right\} + O(\alpha_s)$$

only $O(\alpha_s)$ depends on algorithm & process
cf. Dasgupta, Magnea & GPS ’07
Jet $p_t$ v. parton $p_t$: hadronisation?

**Hadronisation: the “parton-shower” $\rightarrow$ hadrons transition**

**Method:**

- “infrared finite $\alpha_s$”
- **prediction** based on $e^+e^-$ event shape data
- could have been deduced from old work

**Main result**

$$\langle p_{t,\text{jet}} - p_{t,\text{parton-shower}} \rangle \simeq -\frac{0.4 \text{ GeV}}{R} \times \begin{cases} C_F & \text{quarks} \\ C_A & \text{gluons} \end{cases}$$

cf. Dasgupta, Magnea & GPS ’07

coefficient holds for anti-$k_t$; see Dasgupta & Delenda ’09 for $k_t$ alg.
"Naive" prediction (UE $\sim$ colour dipole between $pp$):

$$\Delta p_t \simeq 0.4 \text{ GeV} \times \frac{R^2}{2} \times \left\{ \begin{array}{c}
C_F \ q\bar{q} \ \text{dipole} \\
C_A \ \text{gluon dipole}
\end{array} \right\}$$

Modern Monte Carlo tunes tell you ($\sqrt{s} = 7 \text{ TeV}$):

$$\Delta p_t \simeq 8 \text{ GeV} \times \frac{R^2}{2} \simeq 1.2 \text{ GeV} \times (\pi R^2)$$

This big coefficient motivates special effort to understand interplay between jet algorithm and UE: "jet areas"

How does coefficient depend on algorithm?

How does it depend on jet $p_t$? How does it fluctuate?

cf. Cacciari, GPS & Soyez '08
Underlying Event (UE)

“Naive” prediction (UE ≃ colour dipole between pp):

\[ \Delta p_t \simeq 0.4 \text{ GeV} \times \frac{R^2}{2} \times \begin{cases} C_F & \text{q\bar{q} dipole} \\ C_A & \text{gluon dipole} \end{cases} \]

Modern Monte Carlo tunes tell you (\(\sqrt{s} = 7 \text{ TeV}\)):

\[ \Delta p_t \simeq 8 \text{ GeV} \times \frac{R^2}{2} \simeq 1.2 \text{ GeV} \times (\pi R^2) \]

This big coefficient motivates special effort to understand interplay between jet algorithm and UE: “jet areas”

How does coefficient depend on algorithm?

How does it depend on jet \(p_t\)? How does it fluctuate?

cf. Cacciari, GPS & Soyez ’08
Jet contours – visualised

$p_t$ [GeV]

$k_t$, $R=1$

$p_t$ [GeV]

Cam/Aachen, $R=1$

$p_t$ [GeV]

SISCone, $R=1$, $f=0.5$

$p_t$ [GeV]

anti-$k_t$, $R=1$
Using our understanding to help discover a dijet resonance, $q\bar{q} \rightarrow X \rightarrow q\bar{q}$. 
What $R$ is best for an isolated jet?

**PT radiation:**

$q : \langle \Delta p_t \rangle \simeq \frac{\alpha_s C_F}{\pi} p_t \ln R$

**Hadronisation:**

$q : \langle \Delta p_t \rangle \simeq -\frac{C_F}{R} \cdot 0.4 \text{ GeV}$

**Underlying event:**

$q, g : \langle \Delta p_t \rangle \simeq \frac{R^2}{2} \cdot 2.5-15 \text{ GeV}$

E.g. to reconstruct $m_X \sim (p_{tq} + p_{t\bar{q}})$

Minimise fluctuations in $p_t$

Use crude approximation:

$\langle \Delta p_t^2 \rangle \simeq \langle \Delta p_t \rangle^2$

in small-$R$ limit (!)

NB: full calc, correct fluct: Soyez '10
What $R$ is best for an isolated jet?

**PT radiation:**

$q : \langle \Delta p_t \rangle \simeq \frac{\alpha_s C_F}{\pi} p_t \ln R$

**Hadronisation:**

$q : \langle \Delta p_t \rangle \simeq -\frac{C_F}{R} \cdot 0.4 \text{ GeV}$

**Underlying event:**

$q, g : \langle \Delta p_t \rangle \simeq \frac{R^2}{2} \cdot 2.5 - 15 \text{ GeV}$

Minimise fluctuations in $p_t$

Use crude approximation:

$$\langle \Delta p_t^2 \rangle \simeq \langle \Delta p_t \rangle^2$$

---

50 GeV quark jet

LHC quark jets
$p_t = 50 \text{ GeV}$

in small-$R$ limit (!)

NB: full calc, correct fluct: Soyez '10
What $R$ is best for an isolated jet?

**PT radiation:**

$$q : \langle \Delta p_t \rangle \simeq \frac{\alpha_s C_F}{\pi} p_t \ln R$$

**Hadronisation:**

$$q : \langle \Delta p_t \rangle \simeq -\frac{C_F}{R} \cdot 0.4 \text{ GeV}$$

**Underlying event:**

$$q, g : \langle \Delta p_t \rangle \simeq \frac{R^2}{2} \cdot 2.5 - 15 \text{ GeV}$$

**Minimise fluctuations in $p_t$**

Use crude approximation:

$$\langle \Delta p_t^2 \rangle \simeq \langle \Delta p_t \rangle^2$$
What $R$ is best for an isolated jet?

**PT radiation:**

$q : \langle \Delta p_t \rangle \approx \frac{\alpha_s C_F}{\pi} p_t \ln R$

**Hadronisation:**

$q : \langle \Delta p_t \rangle \approx -C_F R \cdot 0.4 \text{ GeV}$

**Underlying event:**

$q, g : \langle \Delta p_t \rangle \approx R^2 \cdot 2.5 - 15 \text{ GeV}$

Minimise fluctuations in $p_t$

Use crude approximation:

$$\langle \Delta p_t^2 \rangle \approx \langle \Delta p_t \rangle^2$$

- At low $p_t$, small $R$ limits relative impact of UE
- At high $p_t$, perturbative effects dominate over non-perturbative $\to R_{\text{best}} \sim 1$.

**1 TeV quark jet**

- LHC quark jets $p_t = 1 \text{ TeV}$
- In small-$R$ limit (!)

NB: full calc, correct fluct: Soyez '10
Dijet mass: scan over $R$ [Pythia 6.4]

$R = 0.3$

$qq$, $M = 100$ GeV

SISCon, $R=0.3$, $f=0.75$

$Q_{f=0.24}^w = 24.0$ GeV

Resonance $X \rightarrow$ dijets
**Dijet mass: scan over \( R \) [Pythia 6.4]**

**R = 0.3**

**qq, \( M = 100 \) GeV**

SISCon, \( R=0.3, f=0.75 \)

\( Q^w_f=0.24 = 24.0 \) GeV

Resonance \( X \rightarrow \) dijets

Jet

Jet
Dijet mass: scan over \( R \) [Pythia 6.4]

\[ R = 0.4 \]

qq, \( M = 100 \text{ GeV} \)

SISCones, \( R=0.4, f=0.75 \)

\[ Q^w_{f=0.24} = 22.5 \text{ GeV} \]

Resonance X \( \rightarrow \) dijets

Jet
**Dijet mass: scan over \( R \) [Pythia 6.4]**

**R = 0.5**

\[ \text{qq, M = 100 GeV} \]

**SISCones, R=0.5, f=0.75**

\[ Q_{f=0.24}^{W} = 22.6 \text{ GeV} \]

**Resonance X → dijets**
**Dijet mass: scan over** \( R \) [Pythia 6.4]

**R = 0.6**

qq, \( M = 100 \text{ GeV} \)

SISCones, \( R=0.6, f=0.75 \)

\( Q_f=0.24 = 23.8 \text{ GeV} \)

Resonance X → dijets
Dijet mass: scan over $R$ [Pythia 6.4]

**$R = 0.7$**

$qq$, $M = 100$ GeV

SISCones, $R=0.7, f=0.75$

$Q^w_{f=0.24} = 25.1$ GeV

Resonance $X \rightarrow$ dijets
R = 0.8
qq, M = 100 GeV

SISCon, R=0.8, f=0.75
Q_w^f=0.24 = 26.8 GeV

Resonance X → dijets
Dijet mass: scan over $R$ [Pythia 6.4]

**R = 0.9**

$qq, M = 100$ GeV

SIS Cone, $R=0.9, f=0.75$

$Q_w^{f=0.24} = 28.8$ GeV

Resonance $X \rightarrow$ dijets

Jet
Dijet mass: scan over $R$ [Pythia 6.4]

**R = 1.0**

$qq$, $M = 100$ GeV

SISCones, $R=1.0$, $f=0.75$

$Q_{f=0.24}^w = 31.9$ GeV

Resonance $X \rightarrow$ dijets

Jets 2 (M. Cacciari and G. Salam)
Dijet mass: scan over $R$ [Pythia 6.4]

**R = 1.1**

qq, $M = 100$ GeV

SIS Cone, $R=1.1$, $f=0.75$

$Q_f^{W} = 34.7$ GeV

Jet resonances

Resonance $X \rightarrow$ dijets

Dijet mass $[\text{GeV}]$

1/$N$ $\text{d}n/\text{d}bin/2$

Jet 2 (M. Cacciari and G. Salam)
Dijet mass: scan over $R$ [Pythia 6.4]

R = 1.2
qq, $M = 100$ GeV

SISConv, $R=1.2$, $f=0.75$
$Q_f=0.24 = 37.9$ GeV

Resonance $X \rightarrow$ dijets
Dijet mass: scan over $R$ [Pythia 6.4]

$R = 1.3$

$qq, M = 100$ GeV

SISCones, $R=1.3$, $f=0.75$

$Q_w^{f=0.24} = 42.3$ GeV

Jet resonance $X \rightarrow$ dijets

Dijet mass [GeV]
Dijet mass: scan over $R$ [Pythia 6.4]

**R = 1.3**

$qq, M = 100$ GeV

After scanning, summarise "quality" v. $R$. Minimum $\equiv$ BEST

picture not so different from crude analytical estimate
Scan through $q\bar{q}$ mass values

$m_{qq} = 100$ GeV

$qq, M = 100$ GeV

Best $R$ is at minimum of curve

- Best $R$ depends strongly on mass of system
- Increases with mass
- Can reproduce this analytically

Message received by CMS: they combine all $R = 0.5$ jets ($p_t > 10$ GeV) within $\Delta R = 1.1$ of two hardest to improve resolution.

ATLAS '11 still just use $R = 0.6$

NB: 100,000 plots for various jet algorithms, narrow $qq$ and $gg$ resonances from [link]

Cacciari, Rojo, GPS & Soyez '08

Other related work: Krohn, Thaler & Wang '09
Scan through $q\bar{q}$ mass values

$m_{qq} = 150$ GeV

$qq$, $M = 150$ GeV

Best $R$ is at minimum of curve

- Best $R$ depends strongly on mass of system
- Increases with mass
  - can reproduce this analytically

Message received by CMS: they combine all $R = 0.5$ jets ($p_T > 10$ GeV) within $\Delta R = 1.1$ of two hardest to improve resolution.

ATLAS '11 still just use $R = 0.6$

NB: 100,000 plots for various jet algorithms, narrow $qq$ and $gg$ resonances from http://quality.fastjet.fr

Cacciari, Rojo, GPS & Soyez '08

Other related work: Krohn, Thaler & Wang '09
Scan through $q\bar{q}$ mass values

Best $R$ is at minimum of curve

- Best $R$ depends strongly on mass of system
- Increases with mass
  - can reproduce this analytically

Message received by CMS: they combine all $R = 0.5$ jets ($p_T > 10$ GeV) within $\Delta R = 1.1$ of two hardest to improve resolution.

ATLAS '11 still just use $R = 0.6$

NB: 100,000 plots for various jet algorithms, narrow $qq$ and $gg$ resonances


Other related work: Krohn, Thaler & Wang '09

Cacciari, Rojo, GPS & Soyez '08
Scan through $q\bar{q}$ mass values

**m_{qq} = 300 GeV**

$qq$, $M = 300 GeV$

![Graph](image)

Best $R$ is at minimum of curve

- Best $R$ depends strongly on mass of system
- Increases with mass
  - Can reproduce this analytically

Message received by CMS: they combine all $R = 0.5$ jets ($p_T > 10$ GeV) within $\Delta R = 1.1$ of two hardest to improve resolution.

ATLAS '11 still just use $R = 0.6$

NB: 100,000 plots for various jet algorithms, narrow $qq$ and $gg$ resonances from [http://quality.fastjet.fr](http://quality.fastjet.fr)

Other related work: Krohn, Thaler & Wang '09

Cacciari, Rojo, GPS & Soyez '08
Scan through $q\bar{q}$ mass values

**$m_{qq} = 500$ GeV**

$qq, M = 500$ GeV

Best $R$ is at minimum of curve

- Best $R$ depends strongly on mass of system
- Increases with mass
- Can reproduce this analytically

Message received by CMS: they combine all $R = 0.5$ jets ($p_T > 10$ GeV) within $\Delta R = 1.1$ of two hardest to improve resolution.

ATLAS '11 still just use $R = 0.6$

NB: 100,000 plots for various jet algorithms, narrow $qq$ and $gg$ resonances from [http://quality.fastjet.fr](http://quality.fastjet.fr)

Other related work: Krohn, Thaler & Wang '09

Cacciari, Rojo, GPS & Soyez '08
**Dijet resonances**

\[ m_{qq} = 700 \text{ GeV} \]

\( q\bar{q}, M = 700 \text{ GeV} \)

**NB:** 100,000 plots for various jet algorithms, narrow \( q\bar{q} \) and \( gg \) resonances from [http://quality.fastjet.fr](http://quality.fastjet.fr)

Other related work: Krohn, Thaler & Wang '09

Cacciari, Rojo, GPS & Soyez '08

Message received by CMS: they combine all \( R = 0.5 \) jets (\( \rho_r > 10 \text{ GeV} \)) within \( \Delta R = 1.1 \) of two hardest to improve resolution.

ATLAS '11 still just use \( R = 0.6 \)

\[ \rho_L \text{ from } Q_{W}^{f=0.24} \]

**SISCone, \( f=0.75 \)**

Best \( R \) is at minimum of curve

- Best \( R \) depends strongly on mass of system
- Increases with mass
  - can reproduce this analytically
  - Soyez '10
Scan through $q\bar{q}$ mass values

**m_{qq} = 1000 GeV**

$qq, M = 1000 GeV$

Best $R$ is at minimum of curve

- Best $R$ depends strongly on mass of system
- Increases with mass
  - can reproduce this analytically

Soyez '10

Message received by CMS: they combine all $R = 0.5$ jets ($p_t > 10$ GeV) within $\Delta R = 1.1$ of two hardest to improve resolution.

ATLAS '11 still just use $R = 0.6$

NB: 100,000 plots for various jet algorithms, narrow $qq$ and $gg$ resonances from http://quality.fastjet.fr

Cacciari, Rojo, GPS & Soyez '08

Other related work: Krohn, Thaler & Wang '09
Scan through $q\bar{q}$ mass values

**$m_{qq} = 2000$ GeV**

$qq, M = 2000$ GeV

Best $R$ is at minimum of curve

- Best $R$ depends strongly on mass of system
- Increases with mass
  
  can reproduce this analytically
  
  Soyez '10

Message received by CMS: they combine all $R = 0.5$ jets ($p_t > 10$ GeV) within $\Delta R = 1.1$ of two hardest to improve resolution.

ATLAS '11 still just use $R = 0.6$

NB: 100,000 plots for various jet algorithms, narrow $qq$ and $gg$ resonances from [http://quality.fastjet.fr](http://quality.fastjet.fr)

Other related work: Krohn, Thaler & Wang '09

Cacciari, Rojo, GPS & Soyez '08
Scan through $q\bar{q}$ mass values

$\text{m}_{qq} = 4000 \text{ GeV}$

$qq, M = 4000 \text{ GeV}$

Best $R$ is at minimum of curve

- Best $R$ depends strongly on mass of system
- Increases with mass
  can reproduce this analytically
  Soyez ’10

Message received by CMS: they combine all $R = 0.5$ jets ($p_t > 10 \text{ GeV}$) within $\Delta R = 1.1$ of two hardest to improve resolution.

ATLAS ’11 still just use $R = 0.6$

NB: 100,000 plots for various jet algorithms, narrow $qq$ and $gg$ resonances from [http://quality.fastjet.fr](http://quality.fastjet.fr)

Cacciari, Rojo, GPS & Soyez ’08

Other related work: Krohn, Thaler & Wang ’09

Jets 2 (M. Cacciari and G. Salam)
Scan through $q\bar{q}$ mass values

**$m_{qq} = 4000$ GeV**

$qq, M = 4000$ GeV

Best $R$ is at minimum of curve

- Best $R$ depends strongly on mass of system
- Increases with mass
  
  can reproduce this analytically

Soyez ’10

Message received by CMS: they combine all $R = 0.5$ jets ($p_t > 10$ GeV) within $\Delta R = 1.1$ of two hardest to improve resolution.

ATLAS ’11 still just use $R = 0.6$

NB: 100,000 plots for various jet algorithms, narrow $qq$ and $gg$ resonances

from [http://quality.fastjet.fr](http://quality.fastjet.fr)  

Cacciari, Rojo, GPS & Soyez ’08

Other related work: Krohn, Thaler & Wang ’09
Scan through $q\bar{q}$ mass values

Best $R$ is at minimum of curve

- Best $R$ depends strongly on mass of system
- Increases with mass
  
  can reproduce this analytically
  
  Soyez '10

Message received by CMS: they combine all $R = 0.5$ jets ($p_t > 10$ GeV) within $\Delta R = 1.1$ of two hardest to improve resolution.

ATLAS '11 still just use $R = 0.6$

NB: 100,000 plots for various jet algorithms, narrow $qq$ and $gg$ resonances

from [http://quality.fastjet.fr](http://quality.fastjet.fr)

Cacciari, Rojo, GPS & Soyez '08

Other related work: Krohn, Thaler & Wang '09
Testing jet definitions: qq & gg cases

This page is intended to help visualize how the choice of jet definition impacts a dijet invariant mass reconstruction at LHC.

The controls fall into 4 groups:
- the jet definition
- the binning and quality measures
- the jet-type (quark, gluon) and mass scale
- pileup and subtraction

The events were simulated with Pythia 6.4 (DWT tune) and reconstructed with FastJet 2.3.

For more information, view and listen to the **flash demo**, or click on individual terms.

This page has been tested with Firefox v2 and v3, IE7, Safari v3, Opera v9.5, Chrome 0.2.

Reset
Analytic quality estimates

Perturbatively resum resonance "line-shape", convolute with model for non-perturbative effects.

determine "quality" of line-shape from the analytic results, as a function of jet radius $R$
Analytic quality estimates

Perturbatively resum resonance “line-shape”, convolute with model for non-perturbative effects.

Determine “quality” of line-shape from the analytic results, as a function of jet radius $R$. 
Analytic v. MC quality

Analytic - Pythia
Analytic - Herwig
Pythia
Herwig

Best R v. mass scale

Pythia
soft
full

gluon
M=2 TeV

Analytic quality estimates
Fat jets
boosted massive hadronically decaying objects

E.g. when a known particle, $W$, $Z$ or a top → a single jet
or a new particle, Higgs, gluino, neutralino → a single jet

This will be common for electroweak-scale objects at LHC:
$m_W, m_t \ll 14$ TeV
E.g. $X \rightarrow t\bar{t}$ resonances of varying difficulty

RS KK resonances $\rightarrow t\bar{t}$, from Frederix & Maltoni, 0712.2355

$\frac{d\sigma(pp \rightarrow (G \rightarrow t\bar{t})/dm_{t\bar{t}}}{\text{pb}/20 \text{ GeV}}$

LO, CTEQ6L1, LHC

$m_{\chi}=600 \text{ GeV}$

$\kappa/M_{pl}=0.10$

$\kappa/M_{pl}=0.07$

$\kappa/M_{pl}=0.04$

$\kappa/M_{pl}=0.02$

$\kappa/M_{pl}=0.01$

NB: QCD dijet spectrum is $\sim 10^3$ times $t\bar{t}$
Hadronically decaying EW boson at high $p_t \neq$ two jets

![Diagram showing boosted X decaying into single jet and hadronically decaying EW boson](image)

Rules of thumb:

1. $R < \frac{2m}{p_t}$: always resolve two jets
2. $R \gtrsim \frac{3m}{p_t}$: resolve one jet in $\sim 75\%$ of cases ($\frac{1}{8} < z < \frac{7}{8}$)

**Example:**

$m = 100$ GeV, $p_t = 500$ GeV

$R < 0.4$  \[ R \gtrsim 0.6 \]
Boosted ID strategies

Select on the jet mass with one large (cone) jet. Can be subject to large bkgds
[high-$p_t$ jets have significant masses]

Choose a small jet size ($R$) so as to resolve two jets. Easier to reject background if you actually see substructure
[NB: must manually put in “right” radius]

Take a large jet and split it in two. Let jet algorithm establish correct division
Jet masses

Look at jet mass distribution for two leading jets in

- $qq \rightarrow qq$ events
- $pp \rightarrow W +$ jet events
- a mixture of the two in roughly sensible proportions

Jet mass gives clear sign of massive particles inside the jet;
Jet masses

Look at jet mass distribution for two leading jets in

- $qq \rightarrow qq$ events
- $pp \rightarrow W +$ jet events
- a mixture of the two in roughly sensible proportions

Jet mass gives clear sign of massive particles inside the jet;
Jet masses

Jet mass gives clear sign of massive particles inside the jet; but QCD jets are massive too — must learn to reject them

Look at jet mass distribution for two leading jets in

- $qq \rightarrow qq$ events
- $pp \rightarrow W + \text{jet}$ events
- a mixture of the two

In roughly sensible proportions
**QCD principle: soft divergence**

**Signal**

boosted $X \rightarrow z (1-z)$

**Background**

quark $\rightarrow z (1-z)$

Splitting probability for Higgs:

$$P(z) \propto 1$$

Splitting probability for quark:

$$P(z) \propto \frac{1 + z^2}{1 - z}$$

$1/(1 - z)$ divergence enhances background

Remove divergence in bkgd with cut on $z$

Can choose cut analytically so as to maximise $S/\sqrt{B}$

Originally: cut on (related) $k_t$-distance

Butterworth, Cox & Forshaw '02
Inside the jet mass

QCD jet mass distribution has the approximate

\[ \frac{dN}{d \ln m} \sim \alpha_s \ln \frac{p_t R}{m} \times \text{Sudakov} \]

Work from '80s and '90s + Almeida et al '08

The logarithm comes from integral over soft divergence of QCD:

\[ \int \frac{dz}{z} \frac{1}{\frac{m^2}{p_t^2 R^2}} \]

A hard cut on z reduces QCD background & simplifies its shape
Inside the jet mass

QCD jet mass distribution has the approximate

$$\frac{dN}{d \ln m} \sim \alpha_s \ln \frac{p_t R}{m} \times \text{Sudakov}$$

Work from '80s and '90s
+ Almeida et al '08

The logarithm comes from integral over soft divergence of QCD:

$$\int \frac{1}{2} \frac{dz}{z}$$

A hard cut on $z$ reduces QCD background & simplifies its shape
QCD jet mass distribution has the approximate

\[
\frac{dN}{d \ln m} \sim \alpha_s \ln \frac{p_t R}{m} \times \text{Sudakov}
\]

Work from '80s and '90s + Almeida et al '08

The logarithm comes from integral over soft divergence of QCD:

\[
\int_{1/2}^{1} \frac{dz}{\frac{m^2}{p_t^2 R^2} z}
\]

A hard cut on \( z \) reduces QCD background & simplifies its shape
Inside the jet mass

QCD Jet Mass distribution

- Pythia 6.4, qq→qq, no UE
- anti-$k_t$, R=0.7
- LHC, 7 TeV
- $p_{t,jets} > 700$ GeV
- after cut on $z > 0.25$
- (a la BERS)

W+jet Jet Mass distribution

- Pythia 6.4, pp→Wj, no UE
- anti-$k_t$, R=0.7
- LHC, 7 TeV
- $p_{t,jets} > 700$ GeV

2-body phasespace cut on $z$
Inside the jet mass

[1 jet \geq 2 partons]

**QCD Jet Mass distribution**

- Pythia 6.4, qq→qq, no UE
- anti-\(k_t\), R=0.7
- LHC, 7 TeV
- \(p_{t,jets} > 700\) GeV
- after cut on \(z > 0.25\) (a la BER$\$)

**W+jet Jet Mass distribution**

- Pythia 6.4, pp→Wj, no UE
- anti-\(k_t\), R=0.7
- LHC, 7 TeV
- \(p_{t,jets} > 700\) GeV
- after cut on \(z > 0.25\)
Example improvement from boosted regime

Search for main decay of light Higgs boson in $W/Z+H$, $H \rightarrow b\bar{b}$

Restricting search to $p_{tH} > 200$ GeV using the method from Butterworth, Davison, Rubin & GPS '08
Example improvement from boosted regime

Search for main decay of light Higgs boson in W/Z+H, H → b¯b

One of many applications of “boosted” searches, using variety of techniques, many involving jet substructure

See proceedings of Boost 2010 and talks at http://boost2011.org

restricting search to \( p_{tH} > 200 \text{ GeV} \)

using the method from Butterworth, Davison, Rubin & GPS ’08
Noise removal from jets

Plain pythia event
Plain pythia event + 10 pileup
Noise removal from jets

1 jet $\geq 2$ partons

Some of the other ideas

Key idea:

- Look at jet on smaller angular scale
- Discard its softer parts

- Filtering
- Pruning
- Trimming

Butterworth et al ’08
Ellis, Vermillion and Walsh ’09
Krohn, Thaler & Wang ’09

[With earlier methods by Seymour ’93 and Kodolova et al ’07; Rubin ’10 for filtering optimisation; also Soper & Spannowsky ’10, ’11]
Noise removal from jets

Key idea:
• Look at jet on smaller angular scale
• Discard its softer parts

 Filtering  
Pruning  
Trimming

Butterworth et al '08
Ellis, Vermillion and Walsh '09
Krohn, Thaler & Wang '09

[With earlier methods by Seymour '93 and Kodolova et al '07; Rubin '10 for filtering optimisation; also Soper & Spannowsky '10, '11]
Key idea:
- Look at jet on smaller angular scale
- Discard its softer parts

- Filtering
  - Butterworth et al ’08
- Pruning
  - Ellis, Vermillion and Walsh '09
- Trimming
  - Krohn, Thaler & Wang '09

[With earlier methods by Seymour ’93 and Kodolova et al ’07; Rubin ’10 for filtering optimisation; also Soper & Spannowsky ’10, ’11]
Noise removal from jets

[1 jet $\geq 2$ partons]

[Some of the other ideas]

- Filtering
  - Butterworth et al '08
- Pruning
  - Ellis, Vermillion and Walsh '09
- Trimming
  - Krohn, Thaler & Wang '09

[With earlier methods by Seymour '93 and Kodolova et al '07; Rubin '10 for filtering optimisation; also Soper & Spannowsky '10, '11]
Using Dalitz-like plots to pull out the $W$ without using $b$ tagging

Plehn, Spannowsky, Takeuchi & Zerwas '10
Exploiting energy-flow beyond LO structure

Background (e.g. $g \to gg$) and signal (e.g. $W \to q\bar{q}$) often have different colour structure \(\rightarrow\) different radiation patterns.

- Pull (non-boosted context) \(\triangleright\) Gallicchio & Schwartz '10
- N-subjettiness \(\triangleright\) Jihun Kim '10; Thaler & Van Tilburg '10
- “Buried Higgs” light singlets \(\triangleright\) Falkowski et al '10; Chen et al '10
- Boosted decision trees \(\triangleright\) Cui & Schwartz '10
- Dipolarity, applied to HEPTopTagger \(\triangleright\) Jankowiak, Hook and Wacker '11
- Jet deconstruction \(\triangleright\) Soper & Spannowsky '11
- Template method beyond LO \(\triangleright\) Almeida et al '11
- ...
Jet shape variables (here for top tagging)

Early proposals include planar flow (3- v. 2-body structure of top decay)

Thaler & Wang ’08
Almeida et al ’08

Recent try: $N$-subjettiness. Break jet into subjets $1, \ldots, N$

$$\tau_N = \frac{1}{p_{t,jet}} \sum_i p_{ti} \min(R_{i1}, \ldots, R_{iN})$$

$N$-pronged decay: cut on mass &

$$\frac{\tau_N}{\tau_{N-1}}$$

Combines constraints on LO structure (energy sharing among prongs) and higher-order rad$^n$ (from quarks in signal v. gluons in bkgd)

Thaler & van Tilburg ’11
cf. also J.-H. Kim ’10 for Higgs
Matrix-element method on steroids

For each event estimate the probability that event is signal-like or background like.

Break event into many mini-jets; use Monte-Carlo type Sudakovs and splitting functions to get estimate of multi-parton matrix element for S & B hypotheses.

Intelligently combines full info about LO splitting, radiation, b-tags, etc.

Soper & Spannowsky '11

cf. also multivariate (BDT) type methods from Cui & Schwartz '10
The study of jets is an increasingly broad subject.

Driven by the ubiquity of jets in LHC studies, the greater flexibility of LHC detectors relative to Tevatron ones, and by the broad dynamic range of LHC.

[jets from 20 GeV to several TeV — from below to far above EW scale; UE $\sim$ 1 GeV per unit area, pileup 10 $-$ 20 GeV, HIC 100 $-$ 300 GeV]

Many basic ideas ideas have been worked out. But intense recent activity suggests that there is still scope for significant further progress.
Supplementary material
Jet algorithm properties: summary

<table>
<thead>
<tr>
<th></th>
<th>$k_t$</th>
<th>Cam/Aachen</th>
<th>anti-$k_t$</th>
<th>SISCone</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>reach</strong></td>
<td>$R$</td>
<td>$R$</td>
<td>$R$</td>
<td>$(1 + \frac{p_{t2}}{p_{t1}})R$</td>
</tr>
<tr>
<td>$\Delta p_{t,PT}$</td>
<td>$\ln R$</td>
<td>$\ln R$</td>
<td>$\ln R$</td>
<td>$\ln 1.35R$</td>
</tr>
<tr>
<td>$\Delta p_{t,hadr}$</td>
<td>$0.7$</td>
<td>$?$</td>
<td>$1$</td>
<td>$?$</td>
</tr>
<tr>
<td>area</td>
<td>$\pi R^2 \times 0.81 \pm 0.28$</td>
<td>$0.81 \pm 0.26$</td>
<td>$1$</td>
<td>$0.25$</td>
</tr>
<tr>
<td></td>
<td>$+ \pi R^2 \frac{C_i}{\pi b_0} \ln \frac{\alpha_s(Q_0)}{\alpha_s(Rp_t)} \times 0.52 \pm 0.41$</td>
<td>$0.08 \pm 0.19$</td>
<td>$0$</td>
<td>$0.12 \pm 0.07$</td>
</tr>
</tbody>
</table>

**In words:**

- $k_t$: area fluctuates a lot, depends on $p_t$ (bad for UE)
- Cam/Aachen: area fluctuates somewhat, depends less on $p_t$
- anti-$k_t$: area is constant (circular jets)
- SISCone: reaches far for hard radiation (good for resolution, bad for multijets), area is smaller (good for UE)
How well can an algorithm identify the “blobs” of energy inside a jet that come from different partons?

This is crucial for identifying the kinematic variables of the partons in the jet (e.g. $z$).
How well can an algorithm identify the “blobs” of energy inside a jet that come from different partons?

This is crucial for identifying the kinematic variables of the partons in the jet (e.g. z).
How well can an algorithm identify the “blobs” of energy inside a jet that come from different partons?

This is crucial for identifying the kinematic variables of the partons in the jet (e.g. $z$).
How well can an algorithm identify the “blobs” of energy inside a jet that come from different partons?

This is crucial for identifying the kinematic variables of the partons in the jet (e.g. z).
How well can an algorithm identify the “blobs” of energy inside a jet that come from different partons?

This is crucial for identifying the kinematic variables of the partons in the jet (e.g. z).
Identifying jet substructure: try out anti-$k_t$

How well can an algorithm identify the “blobs” of energy inside a jet that come from different partons?

This is crucial for identifying the kinematic variables of the partons in the jet (e.g. z).
How well can an algorithm identify the “blobs” of energy inside a jet that come from different partons?

This is crucial for identifying the kinematic variables of the partons in the jet (e.g. z).
Identifying jet substructure: try out anti-\(k_t\)

How well can an algorithm identify the “blobs” of energy inside a jet that come from different partons?

This is crucial for identifying the kinematic variables of the partons in the jet (e.g. \(z\)).

Anti-\(k_t\) gradually makes its way through the secondary blob → no clear identification of substructure associated with 2nd parton.
How well can an algorithm identify the “blobs” of energy inside a jet that come from different partons?

This is crucial for identifying the kinematic variables of the partons in the jet (e.g. $z$).

Anti-$k_t$ gradually makes its way through the secondary blob $\rightarrow$ no clear identification of substructure associated with 2nd parton.
Identifying jet substructure: try out anti-$k_t$

How well can an algorithm identify the “blobs” of energy inside a jet that come from different partons?

This is crucial for identifying the kinematic variables of the partons in the jet (e.g. $z$).

Anti-$k_t$ gradually makes its way through the secondary blob $\rightarrow$ no clear identification of substructure associated with 2nd parton.
How well can an algorithm identify the “blobs” of energy inside a jet that come from different partons?

This is crucial for identifying the kinematic variables of the partons in the jet (e.g. $z$).

Anti-$k_t$ gradually makes its way through the secondary blob $\rightarrow$ no clear identification of substructure associated with 2nd parton.
How well can an algorithm identify the “blobs” of energy inside a jet that come from different partons?

This is crucial for identifying the kinematic variables of the partons in the jet (e.g. z).

Anti-$k_t$ gradually makes its way through the secondary blob → no clear identification of substructure associated with 2nd parton.
How well can an algorithm identify the “blobs” of energy inside a jet that come from different partons?

This is crucial for identifying the kinematic variables of the partons in the jet (e.g. $z$).

Anti-$k_t$ gradually makes its way through the secondary blob $\rightarrow$ no clear identification of substructure associated with 2nd parton.
Identifying jet substructure: try out anti-$k_t$

How well can an algorithm identify the “blobs” of energy inside a jet that come from different partons?

This is crucial for identifying the kinematic variables of the partons in the jet (e.g. $z$).

*Anti-$k_t$ gradually makes its way through the secondary blob $\rightarrow$ no clear identification of substructure associated with 2nd parton.*
Identifying jet substructure: try out anti-$k_t$

How well can an algorithm identify the “blobs” of energy inside a jet that come from different partons?

This is crucial for identifying the kinematic variables of the partons in the jet (e.g. $z$).

Anti-$k_t$ gradually makes its way through the secondary blob $\rightarrow$ no clear identification of substructure associated with 2nd parton.
How well can an algorithm identify the “blobs” of energy inside a jet that come from different partons?

This is crucial for identifying the kinematic variables of the partons in the jet (e.g. \( z \)).

Anti-\( k_t \) gradually makes its way through the secondary blob \( \rightarrow \) no clear identification of substructure associated with 2nd parton.
How well can an algorithm identify the “blobs” of energy inside a jet that come from different partons?

This is crucial for identifying the kinematic variables of the partons in the jet (e.g. $z$).

Anti-$k_t$ gradually makes its way through the secondary blob → no clear identification of substructure associated with 2nd parton.
How well can an algorithm identify the “blobs” of energy inside a jet that come from different partons?

This is crucial for identifying the kinematic variables of the partons in the jet (e.g. z).
How well can an algorithm identify the “blobs” of energy inside a jet that come from different partons?

This is crucial for identifying the kinematic variables of the partons in the jet (e.g. z).
Identifying jet substructure: try out $k_t$

How well can an algorithm identify the “blobs” of energy inside a jet that come from different partons?

This is crucial for identifying the kinematic variables of the partons in the jet (e.g. $z$).
How well can an algorithm identify the “blobs” of energy inside a jet that come from different partons?

This is crucial for identifying the kinematic variables of the partons in the jet (e.g. z).

$k_t$ algorithm

dmin is $dij = 0.977453$
How well can an algorithm identify the “blobs” of energy inside a jet that come from different partons?

This is crucial for identifying the kinematic variables of the partons in the jet (e.g. $z$).
Identifying jet substructure: try out $k_t$

How well can an algorithm identify the “blobs” of energy inside a jet that come from different partons?

This is crucial for identifying the kinematic variables of the partons in the jet (e.g. $z$).

$k_t$ clusters soft “junk” early on in the clustering.

$k_t$ algorithm

$d_{\text{min}}$ is $d_{ij} = 1.48276$
Identifying jet substructure: try out $k_t$

How well can an algorithm identify the “blobs” of energy inside a jet that come from different partons?

This is crucial for identifying the kinematic variables of the partons in the jet (e.g. $z$).

$k_t$ clusters soft “junk” early on in the clustering.
Identifying jet substructure: try out $k_t$

How well can an algorithm identify the “blobs” of energy inside a jet that come from different partons?

This is crucial for identifying the kinematic variables of the partons in the jet (e.g. $z$).

$k_t$ clusters soft “junk” early on in the clustering
Identifying jet substructure: try out $k_t$

How well can an algorithm identify the “blobs” of energy inside a jet that come from different partons?

This is crucial for identifying the kinematic variables of the partons in the jet (e.g. $z$).

$k_t$ clusters soft “junk” early on in the clustering
Identifying jet substructure: try out $k_t$

How well can an algorithm identify the “blobs” of energy inside a jet that come from different partons?

This is crucial for identifying the kinematic variables of the partons in the jet (e.g. $z$).

$k_t$ clusters soft “junk” early on in the clustering.
Identifying jet substructure: try out $k_t$

How well can an algorithm identify the “blobs” of energy inside a jet that come from different partons?

This is crucial for identifying the kinematic variables of the partons in the jet (e.g. $z$).

$k_t$ clusters soft “junk” early on in the clustering
Identifying jet substructure: try out $k_t$

How well can an algorithm identify the “blobs” of energy inside a jet that come from different partons?

This is crucial for identifying the kinematic variables of the partons in the jet (e.g. $z$).

$k_t$ clusters soft “junk” early on in the clustering.
How well can an algorithm identify the “blobs” of energy inside a jet that come from different partons?

This is crucial for identifying the kinematic variables of the partons in the jet (e.g. z).

\( k_t \) clusters soft “junk” early on in the clustering.
Identifying jet substructure: try out $k_t$

How well can an algorithm identify the “blobs” of energy inside a jet that come from different partons?

This is crucial for identifying the kinematic variables of the partons in the jet (e.g. $z$).

$k_t$ clusters soft “junk” early on in the clustering

*Its last step is to merge two hard pieces. Easily undone to identify underlying kinematics*
How well can an algorithm identify the “blobs” of energy inside a jet that come from different partons?

This is crucial for identifying the kinematic variables of the partons in the jet (e.g. $z$).

$k_t$ clusters soft “junk” early on in the clustering

*Its last step is to merge two hard pieces. Easily undone to identify underlying kinematics*
Identifying jet substructure: try out $k_t$

How well can an algorithm identify the “blobs” of energy inside a jet that come from different partons?

This is crucial for identifying the kinematic variables of the partons in the jet (e.g. $z$).

$k_t$ clusters soft “junk” early on in the clustering

*Its last step is to merge two hard pieces. Easily undone to identify underlying kinematics*
Identifying jet substructure: try out $k_t$

How well can an algorithm identify the “blobs” of energy inside a jet that come from different partons?

This is crucial for identifying the kinematic variables of the partons in the jet (e.g. $z$).

$k_t$ clusters soft “junk” early on in the clustering

*Its last step is to merge two hard pieces. Easily undone to identify underlying kinematics*

This meant it was the first algorithm to be used for jet substructure.

Seymour ’93

Butterworth, Cox & Forshaw ’02
Cambridge/Aachen algorithm

How well can an algorithm identify the “blobs” of energy inside a jet that come from different partons?
Identifying jet substructure: Cam/Aachen

**Cambridge/Aachen algorithm**

DeltaR_{ij} = 0.142857

How well can an algorithm identify the “blobs” of energy inside a jet that come from different partons?
How well can an algorithm identify the “blobs” of energy inside a jet that come from different partons?
How well can an algorithm identify the “blobs” of energy inside a jet that come from different partons?
How well can an algorithm identify the “blobs” of energy inside a jet that come from different partons?
How well can an algorithm identify the “blobs” of energy inside a jet that come from different partons?

DeltaR_{ij} = 0.415037
How well can an algorithm identify the “blobs” of energy inside a jet that come from different partons?
How well can an algorithm identify the “blobs” of energy inside a jet that come from different partons?

Cambridge/Aachen algorithm

\[
\Delta R_{ij} = 0.686928
\]

\begin{figure}
\centering
\begin{tikzpicture}
\begin{axis}[
    title={Cambridge/Aachen algorithm},
    xlabel={$p_t$/GeV},
    ylabel={$\Delta R_{ij}$},
    xmin=0, xmax=50,
    ymin=0, ymax=5,
    xtick={0,1,2,3,4},
    ytick={0,5,10,15,20,25,30,35,40,45,50},
    xticklabels={0, 1, 2, 3, 4},
    yticklabels={0, 5, 10, 15, 20, 25, 30, 35, 40, 45, 50},
    width=0.8\textwidth,
    height=0.6\textwidth,
    legend pos=north east,
]
\addplot[red,mark=x]
coordinates{
    (1,5)
    (2,10)
    (3,15)
    (4,20)
};
\addplot[green,mark=+] coordinates{
    (1,5)
    (2,10)
    (3,15)
    (4,20)
};
\addplot[pink,mark=triangle]
coordinates{
    (1,5)
    (2,10)
    (3,15)
    (4,20)
};
\end{axis}
\end{tikzpicture}
\end{figure}
How well can an algorithm identify the “blobs” of energy inside a jet that come from different partons?

C/A identifies two hard blobs with limited soft contamination.
How well can an algorithm identify the “blobs” of energy inside a jet that come from different partons?

C/A identifies two hard blobs with limited soft contamination, joins them.
How well can an algorithm identify the “blobs” of energy inside a jet that come from different partons?

C/A identifies two hard blobs with limited soft contamination, joins them.
How well can an algorithm identify the “blobs” of energy inside a jet that come from different partons?

C/A identifies two hard blobs with limited soft contamination, joins them, and then adds in remaining soft junk.
How well can an algorithm identify the “blobs” of energy inside a jet that come from different partons?

C/A identifies two hard blobs with limited soft contamination, joins them, and then adds in remaining soft junk.
How well can an algorithm identify the “blobs” of energy inside a jet that come from different partons?

C/A identifies two hard blobs with limited soft contamination, joins them, and then adds in remaining soft junk.
How well can an algorithm identify the “blobs” of energy inside a jet that come from different partons?

C/A identifies two hard blobs with limited soft contamination, joins them, and then adds in remaining soft junk.
How well can an algorithm identify the “blobs” of energy inside a jet that come from different partons?

C/A identifies two hard blobs with limited soft contamination, joins them, and then adds in remaining soft junk.
How well can an algorithm identify the “blobs” of energy inside a jet that come from different partons?

C/A identifies two hard blobs with limited soft contamination, joins them, and then adds in remaining soft junk.

The interesting substructure is buried inside the clustering sequence — it’s less contaminated by soft junk, but needs to be pulled out with special techniques.

Butterworth, Davison, Rubin & GPS '08
Kaplan, Schwartz, Reherman & Tweedie '08
Butterworth, Ellis, Rubin & GPS '09
Ellis, Vermilion & Walsh '09
A more complex example: top reconstruction
Robustness: $M_{\text{top}}$ varies with $R$?

Game: measure top mass to 1 GeV

example for Tevatron

$m_t = 175$ GeV

- Small $R$: lose 6 GeV to PT radiation and hadronisation, UE and pileup irrelevant

- Large $R$: hadronisation and PT radiation leave mass at $\sim 175$ GeV, UE adds 2 – 4 GeV.

Is the final top mass (after W jet-energy-scale and Monte Carlo unfolding) independent of $R$ used to measure jets?

Flexibility in jet finding gives powerful cross-check of systematic effects

cf. Seymour & Tevlin '06
Robustness: $M_{\text{top}}$ varies with $R$?

**Game: measure top mass to 1 GeV**

Example for Tevatron

$m_t = 175$ GeV

- Small $R$: lose 6 GeV to PT radiation and hadronisation, UE and pileup irrelevant
- Large $R$: hadronisation and PT radiation leave mass at \( \sim 175 \text{ GeV} \), UE adds 2 $-$ 4 GeV.

Is the final top mass (after W jet-energy-scale and Monte Carlo unfolding) independent of $R$ used to measure jets?

Flexibility in jet finding gives powerful cross-check of systematic effects.

cf. Seymour & Tevlin ’06
Robustness: $M_{\text{top}}$ varies with $R$?

Game: measure top mass to 1 GeV

Example for Tevatron

$m_t = 175 \text{ GeV}$

- Small $R$: lose 6 GeV to PT radiation and hadronisation, UE and pileup irrelevant

- Large $R$: hadronisation and PT radiation leave mass at $\sim 175 \text{ GeV}$, UE adds 2 – 4 GeV.

Is the final top mass (after $W$ jet-energy-scale and Monte Carlo unfolding) independent of $R$ used to measure jets?

Flexibility in jet finding gives powerful cross-check of systematic effects
cf. Seymour & Tevlin '06
Robustness: $M_{top}$ varies with $R$?

**Game:** measure top mass to 1 GeV

example for Tevatron

$m_t = 175$ GeV

- **Small $R$:** lose 6 GeV to PT radiation and hadronisation, UE and pileup irrelevant

- **Large $R$:** hadronisation and PT radiation leave mass at $\sim 175$ GeV, UE adds 2 − 4 GeV.

Is the final top mass (after $W$ jet-energy-scale and Monte Carlo unfolding) independent of $R$ used to measure jets?

Flexibility in jet finding gives powerful cross-check of systematic effects
cf. Seymour & Tevlin '06
Is the final top mass (after W jet-energy-scale and Monte Carlo unfolding) independent of R used to measure jets?

Flexibility in jet finding gives powerful cross-check of systematic effects cf. Seymour & Tevlin '06
Robustness: $M_{\text{top}}$ varies with R?

Game: measure top mass to 1 GeV

Example for Tevatron

$m_t = 175$ GeV

- Small $R$: lose 6 GeV to PT radiation and hadronisation, UE and pileup irrelevant
- Large $R$: hadronisation and PT radiation leave mass at $\sim 175$ GeV, UE adds 2 – 4 GeV.

Is the final top mass (after W jet-energy-scale and Monte Carlo unfolding) independent of R used to measure jets?

Flexibility in jet finding gives powerful cross-check of systematic effects

cf. Seymour & Tevlin '06
Alpgen $pp \rightarrow t\bar{t} \rightarrow 6q$

fraction of $pp \rightarrow t\bar{t} \rightarrow 6q$ events with all $R_{qq} > R$

no $p_t$ cut on quarks

$pp$, 7 TeV
Alpgen partons
Alpgen \(pp \rightarrow t\bar{t} \rightarrow 6q\)

Fraction of pp\(\rightarrow tt\rightarrow 6q\) events with all \(R_{qq} > R\)

Require all \(p_{tq} > 10\) GeV

\(pp, 7\) TeV

Alpgen partons
Alpgen $pp \rightarrow t\bar{t} \rightarrow 6q$

fraction of $pp \rightarrow t\bar{t} \rightarrow 6q$ events with all $R_{qq} > R$

require all $p_{tq} > 20$ GeV

Alpgen partons

$pp$, 7 TeV
Alpgen pp → t\bar{t} → 6q

fraction of pp→tt→6q events with all R_{qq} > R

require all p_{tq} > 30 GeV

pp, 7 TeV

Alpgen partons
Alpgen $pp \rightarrow t\bar{t} \rightarrow 6q$

fraction of $pp \rightarrow tt \rightarrow 6q$ events with all $R_{qq} > R$

require all $p_{tq} > 20$ GeV

Herwig $pp \rightarrow t\bar{t} \rightarrow$ hadrons

Distribution of number of jets

Herwig 6.5 (no UE)
pp, 7 TeV
anti-$k_t$ $R=0.5$
$p_{t,jet} > 20$ GeV