Aspects of jets at the LHC

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IOP, half day meeting, Liverpool 12th January 2011

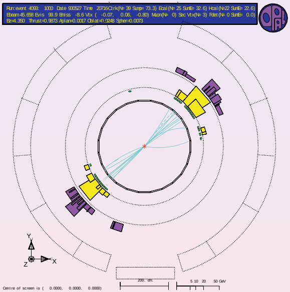
Outline

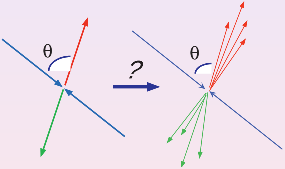
The modern theory of jets is concerned with the following main aspects:

- Defining jets
- Calculating properties of jets
- Understanding jets
- Optimally using jets at the LHC.

Why jets?

QCD is a weird theory ! Lagrangian involves partons which never make it to detectors.
Measured final state involves collimated sprays of energetic particles or jets!





Luckily partons leave some footprints. The game of jet physics involves identifying those elusive partons.

Sterman TASI lectures

Jet definitions

Snowmass accord (1990) developed laying out properties of an acceptable algorithm:

- Simple to implement in experimental analyses as well as theory calculations.
- Defined at any order in pQCD and yields finite results for rates at any order.
- Yields a cross-section relatively insensitive to hadronisation

ESW "More honoured in the breach than the observance!"

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Jet algorithms circa 2010

We shall only discuss IRC safe ones! Two main categories

1. Cone type : SISCONE (Seedless Infrared Safe Cone)

   Salam and Soyez 2007
2. Sequential Recombination based on a distance measure.
   - k_t or Durham algorithm

     Catani et. al 1993
   - Cambridge-Aachen

     Dokshitzer et. al 1997, Wobisch and Wengler 1998
   - Anti-k_t Cacciari, Salam, Soyez 2008.

Hadron collider SR jet definitions

Distance measures

Definition

$$d_{ij} = \min(p_{t,i}^{2p}, p_{t,j}^{2p})\frac{\Delta_{ij}}{R^2}, \ \Delta_{ij} = (y_i - y_j)^2 + (\phi_i - \phi_j)^2$$

$$d_{iB} = p_{t,i}^{2p}$$

1. $p = 1$,k_t algorithm.
2. $p = 0$, C-A algorithm.
3. $p = -1$ Anti-k_t algorithm
   Note the introduction of a radius like parameter R.

- Find the smallest among d_{ij} and d_{iB}. If it is a d_{iB} call the object a jet and remove from list. If d_{ij} then merge i and j.
- Repeat until all particles are removed.

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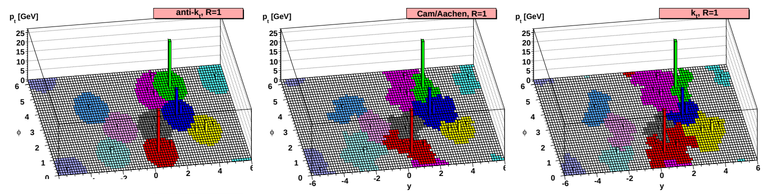
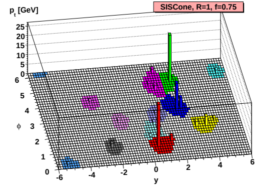
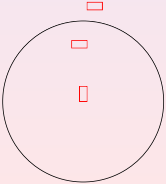
Appearance of hadron collider jets

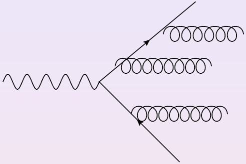




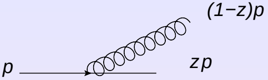
Salam “Towards Jetography” 2009



Computing jet properties at hadron colliders



Consider jet energy or p_t used in kinematic reconstruction. Need to know how this relates to hard scale such as mass of heavy decaying particle or original parton.Study impact of PT radiation, ISR, UE and hadronisation.



$$\delta p_t = (1-z)p_t - p_t = -zp_t, \; 1-z > z$$
$$\delta p_t = zp_t - p_t = -(1-z)p_t, \; z > 1-z$$

Note $\theta^2 > R^2$.

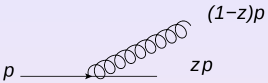
$$\langle \delta p_t \rangle_q = -\frac{C_F \alpha_s}{2\pi} p_t \int_{R^2}^{1} \frac{d\theta^2}{\theta^2} \frac{1+z^2}{1-z} \min\left[(1-z), z\right]$$

This gives

$$\langle \delta p_t \rangle_q = -C_F \frac{\alpha_s}{\pi} p_t \ln \frac{1}{R} \left(2 \ln 2 - \frac{3}{8} \right)$$

Perturbative loss goes as $\ln R$ in any algorithm.

Non-perturbative effects



Analytical calculations of hadronisation? Use DW model:

- Emit a soft gluer (a gluon that actually glues!) with $k_t \sim \Lambda$.
- Consider the change in jet energy $-(1-z)p_t = -\frac{k_t}{\theta}$.
- Apply the emission probability to compute the average

$$\langle \delta p_t \rangle_q = -C_F \int \frac{\alpha_s(k_t)}{\pi} \frac{dk_t}{k_t} \frac{d\theta^2}{\theta^2} \frac{k_t}{\theta}$$

for $\theta > R$

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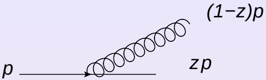

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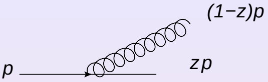

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for $\theta > R$

We have

$$\langle \delta p_t \rangle_q = -\frac{2C_F}{\pi} \int_0^{\mu_I} \alpha_s(k_t) dk_t \times \frac{1}{R}$$

Take couping integral (assumed to exist !) from e^+e^- event shapes to get

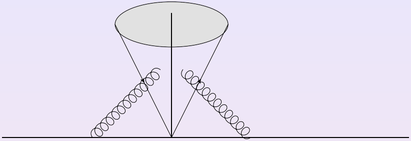
$$\langle \delta p_t \rangle = \frac{-0.5\mathrm{GeV}}{R}$$

For gluon jets change $C_F \to C_A$.

$$\langle \delta p_t \rangle = -\frac{1\mathrm{GeV}}{R}$$

Striking singular dependence of hadronisation on R. Same for all algorithms!

UE contribution

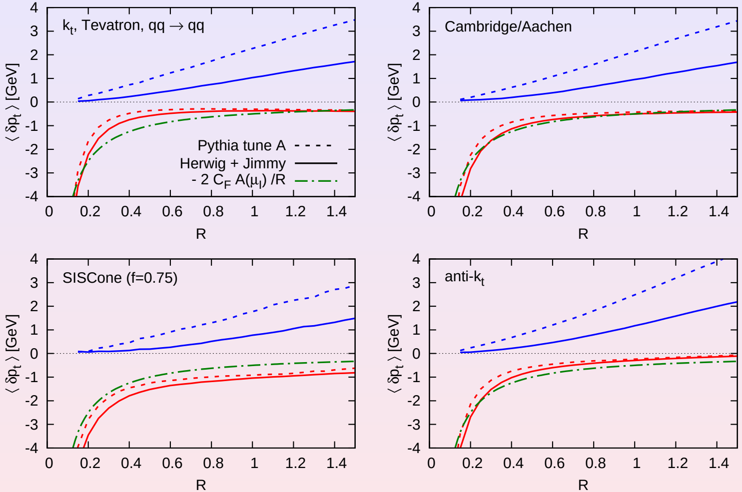


Contrast with underlying event contribution. Assume Λ_{UE} is energy per unit rapidity of soft UE particles.

$$\langle \delta p_t \rangle_{\mathrm{UE}} = \Lambda_{\mathrm{UE}} \int_{\eta^2+\phi^2<R^2} d\eta \frac{d\phi}{2\pi} = \Lambda_{\mathrm{UE}} \frac{R^2}{2}$$

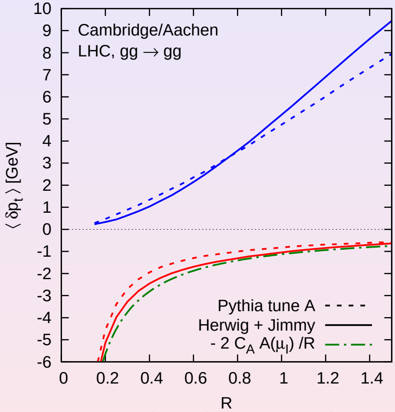
Has a regular dependence on R (comes from jet area). For jet mass UE contribution goes as R^4. Similar effects from pile-up but order of magnitude larger at the LHC.

Comparison to MC models



Agreement with analytical predictions. Same result for all algorithms. UE different between MC models.

Comparison with MC models

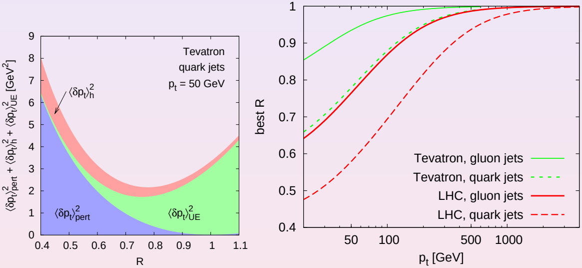


At LHC underlying event is an enormous effect.

Optimal *R*

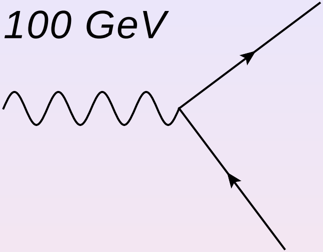
Based on minimising

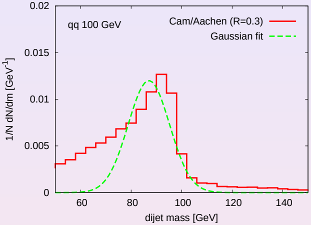
$$\langle \delta p_t^2 \rangle = \langle \delta p_t \rangle_{\mathrm{h}}^2 + \langle \delta p_t \rangle_{\mathrm{UE}}^2 + \langle \delta p_t \rangle_{\mathrm{PT}}^2$$



At high p_t one should use a larger *R* -minimises perturbative effect. Likewise for gluon jets a larger *R* is suggested. For LHC smaller *R* values than Tevatron.

Best *R* for peak reconstruction

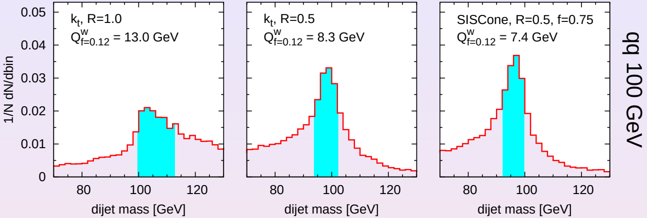




Can illustrate effect of finding best *R* on quality of kinematic reconstruction.

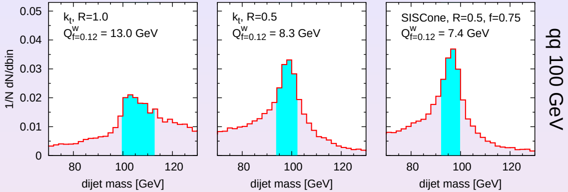
One can take a 100 GeV $q\bar{q}$ resonance to illustrate this.

Need to define a measure of the quality of reconstruction. How to assess e.g peak width?



Define quality measure $Q^{w}_{f=z}$ as the width of the narrowest window which contains a specified fraction $f = z$ of events. Smaller Q corresponds to a better peak.

Salam, 2009



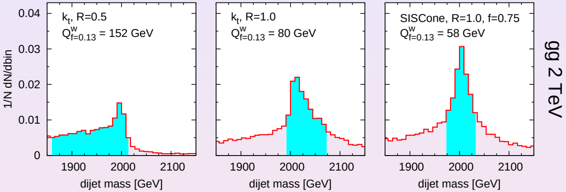
Compare different algorithms and choices of R.

For k_t algorithm a lower R value is favoured here suggesting the importance of the UE contribution.

What may we expect when we move to a 2 TeV gg resonance?

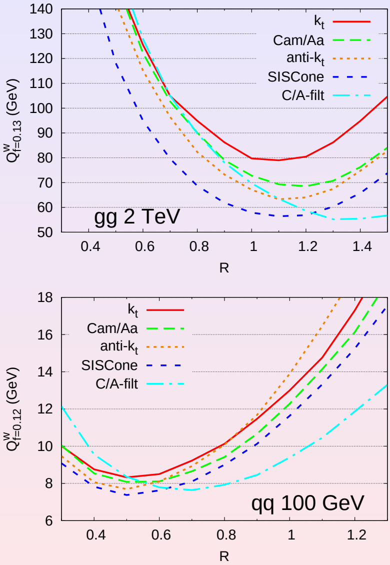
We learnt that at such high p_t and for gluon jets one should favour a larger R.

2 TeV gg resonance



Here $R = 0.5$ would be a bad choice ! Larger R is favoured as expected. SISCONE seems to perform markedly better than k_t in this case.

Comparing algorithms



Optimal *R* doesnt vary too much across algorithms. *Q* does

Substructure techniques for highly boosted objects

At LHC one can expect

- Decay of heavy particles (e.g Z') to lighter ones that appear highly boosted
- One can exploit the large phase space to look for highly boosted light particles e.g Higgs. There will be a reduction in the production cross-section but the benefits can outweigh this.

Boosted objects

The key point is that highly boosted objects such as Higgs or other EW bosons decay to products which have narrow opening angle. Can end up in a single jet !
Recall

$$\boxed{M^2 = z(1-z)p_t^2\theta_{12}^2}$$

Suggests that for $R \geq \frac{M}{\sqrt{z(1-z)}p_t}$ we will get a single jet. For a p_t of 500 GeV and a mass of 100 Gev in practice taking $R \geq 0.6$ implies that 75 percent of such decays will be clustered to a jet.

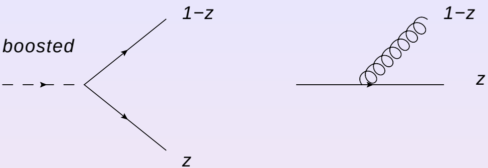
Jet substructure

One can then look at the invariant mass distribution of the jet as a clue to its identity i.e to tag the jet.
Significant issue arises however of QCD jet backgrounds.
Again recall yesterdays result for jet mass distribution

$$\frac{1}{\sigma}\frac{d\sigma}{dM^2} \sim \frac{1}{M^2}\alpha_s \ln \frac{R^2 p_t^2}{M^2}$$

For $p_t \gg M$ this can be significant contamination even at masses of a $100\,\mathrm{GeV}$.
Hence we need to know how to remove QCD background as well as how to optimise the construction of the mass.

Substructure techniques



To distinguish jets from QCD from those from heavy particle decays it pays to look at jet substructure.

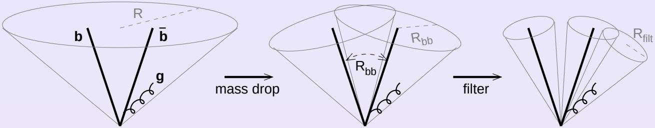
QCD splitting functions very different from those for say EW bosons like Higgs.

$P(z) \propto \frac{1+z^2}{1-z}$ heavily favours soft emission while say for Higgs there is a uniform distribution $\phi(z) \propto 1$.

looking at energy sharing within the jet gives a clue to its origin. Since QCD jets dramatically favour large z cutting on z will reduce background.

Seymour 1993, Butterworth et.al 1994, Butterworth et. al 2008, Ellis et.al 2009

Filtering

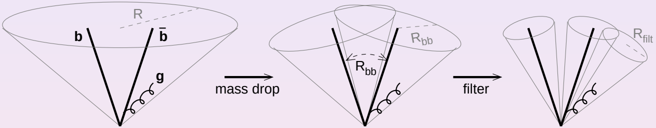


Various substructure techniques proposed e.g filtering, pruning, trimming. Essentially similar ideas but important differences of detail.

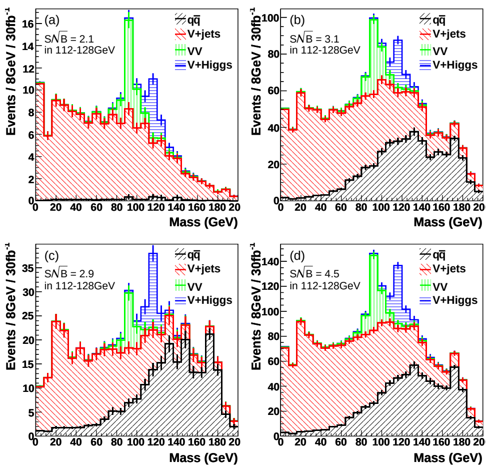
Let's take example of filtering with Cambridge-Aachen algorithm for Higgs production in association with a vector boson. One goes through the following steps

- Undo last step of algorithm so that jet j splits into $j1$ and $j2$ where $m_{j1} > m_{j2}$.
- If there was significant mass-drop $m_{j1} < \mu m_j$ and splitting is not very asymmetric $y_{ij} > y_{\text{cut}}$ then j is taken to be in heavy particle neighbourhood and one exits the loop.

- Otherwise one redefines j to be j_1 and reverts to step 1. Final jet j considered as Higgs candidate if both j_1 and j_2 have b tags.



Due to angular ordering jet j will contain nearly all radiation from $b\bar{b}$.
But note that UE contributon $\propto R^4$.
We can rerun algorithm on a smaller scale to keep only 3 hardest subjets. Reduce UE but keep dominant PT radiation.



An unpromising channel rescued !