QCD and jet physics

Lecture 2

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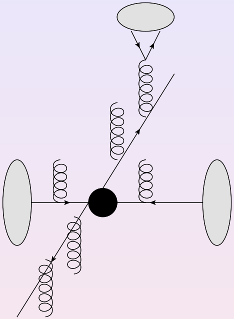
Non-perturbative effects in jets



So far dealt with PT radiation. We know that hadronisation and the UE will play an important role at the LHC. What can we learn about those? Invaluable (maybe only tools) are MC models. But....

The need for analytic input

- MC (many tunable parameters) does not reflect understanding of physics of hadronisation. Analytical models can.
- MC studies do not provide any detailed parametric understanding of NP effects. How much p_t from UE vs hadronisation? As a function of jet flavour, p_t, size?

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- Lack of parametric understanding myths e.g. the claim that cone jets suffer from hadronisation while k_t jets from the underlying event. But cant compare cone of $R = 0.4$ to k_t with $R = 1.0$.
- MC hadronisation taken from hadron parton difference and added to NLO calculations often without cross-checks.

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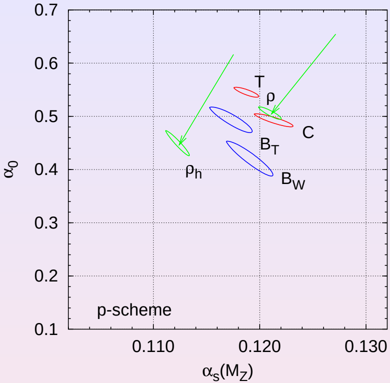
Analytical insight sorely needed!

Dokshitzer-Webber model

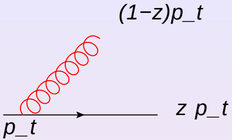


Use a univeral IR finite α_s. Extend PT calculations into IR domain and see what happens.
Define

$$\mathcal{A}(\mu_I) = \frac{1}{\pi}\int_0^{\mu_I} dk_t\, \alpha_s(k_t)$$

.
Works well at LEP and HERA !

Jet p_t or energy scale analytically



Revisit calculation for jet p_t. Hadronisation triggered by soft gluon with $k_t \sim \Lambda$.
We have $\delta p_t = zp_t - p_t = -(1-z)p_t$.
Consider same result as before in soft limit:

$$\langle p_t \rangle_q = -\frac{2C_F}{\pi} \int \alpha_s(p_t(1-z)\theta)\,(1-z)p_t \,\frac{dz}{1-z}\,\frac{d\theta}{\theta}$$

Perturbatively this does not exist. Can only do perturbative calculation above some scale μ_I.

Analytical calculation for hadronisation

Use DW prescription and proceed for the NP region.
Change variable to $k_t = p_t(1-z)\theta$

$$-\frac{2C_F}{\pi}\int_0^{\mu_I}\alpha_s(k_t)dk_t\int_R^1\frac{d\theta}{\theta^2}$$

This gives $-2C_F\frac{\mathcal{A}}{R}$. Striking singular dependence on R.
Again associated to scale of jet being RP_t.
Coefficent related to e^+e^- thrust. Prediction for quark jet $\langle\delta p_t\rangle \sim -\frac{0.5\mathrm{GeV}}{R}$. Gluon jet gives $\sim \frac{-1\mathrm{GeV}}{R}$.

MD, Magnea and Salam 2008

One can repeat the calculation for the jet mass in the same way:

$$\langle M_j^2 \rangle_q = \frac{C_F}{\pi} \int \alpha_s\left((1-z)p_t\theta\right) z(1-z)p_t^2\theta^2 \frac{dz}{1-z}\frac{d\theta^2}{\theta^2}$$

Changing variable to k_t

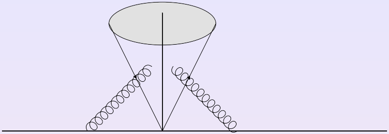
$$\langle M_j^2 \rangle_q = \frac{2C_F}{\pi} p_t \int \alpha_s(k_t) dk_t \int_0^R d\theta = 2C_F \mathcal{A} R P_t$$

$$\sim 0.5\,\mathrm{GeV} \times RP_t$$

Note that this is a small correction to yesterdays perturbative estimate $R^2 P_t^2$ as long as $RP_t \gg \Lambda$.

MD, Magnea and Salam 2008

UE contribution

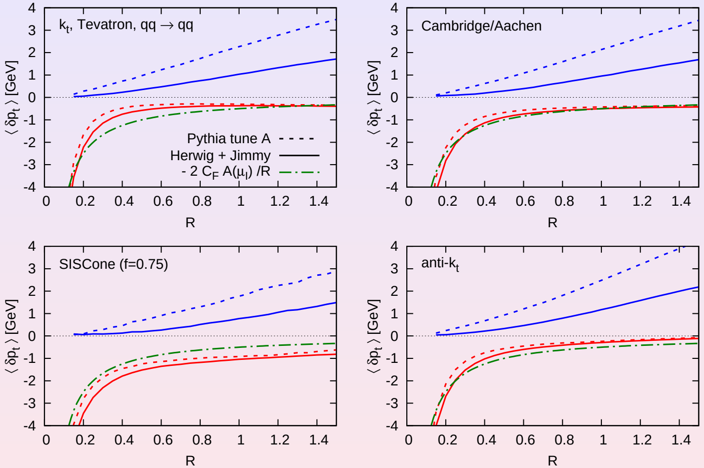


Contrast with underlying event contribution. Assume Λ_{UE} is energy per unit rapidity of soft UE particles.

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

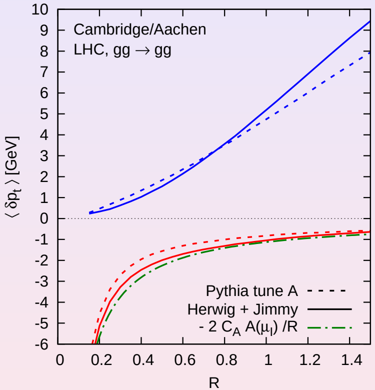
One has a regular dependence on R (comes from jet area). For jet mass UE contribution goes as R^4. Similar effects from pile-up but order of magnitude larger at the LHC.
A useful concept in assessing jets susceptability to UE and pile up is the jet area. This is only πR^2 for the anti-k_t algorithm. For more details see Cacciari, Soyez and Salam 2008

Comparison to MC models



Good 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.

Summary of findings

- Different algorithms show a similar sensitivity to NP effects. Contradicts folklore.
- UE depends on collider energy and R and also on MC model !
- Hadronisation on jet colour factor and differently on R.
- $\Lambda_{\mathrm{UE}}(1.96\mathrm{TeV}) \approx 2 - 4\mathrm{GeV}$ and $\Lambda_{\mathrm{UE}}(14\mathrm{TeV}) \approx 10\mathrm{GeV}$
- More info in variable R analytical studies than fixed R MC studies.

Using jets

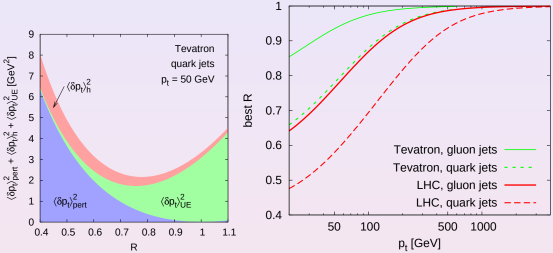
Let us study how we can put the analytics to good use. Knowing R dependence of various pieces gives rise to the question what is the optimal R for various physics studies? To minimise radiative effects and UE is desirable for reconstructing mass peaks. Take as a crude estimate

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

Find minimum as a function of R. For pQCD studies minimise just UE and hadronisation. Gives

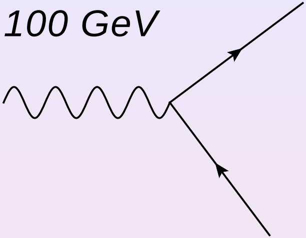
$$R = \sqrt{2} \left(\frac{C_i \mathcal{A}(\mu_I)}{\Lambda} \right)^{1/3}$$

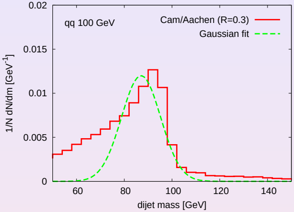
Optimal R



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.

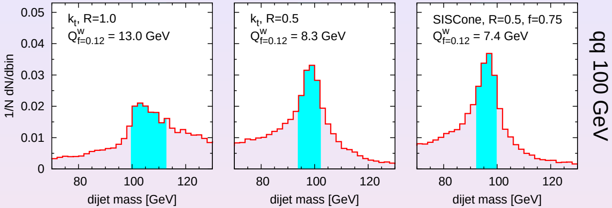
Best R for peak reconstruction





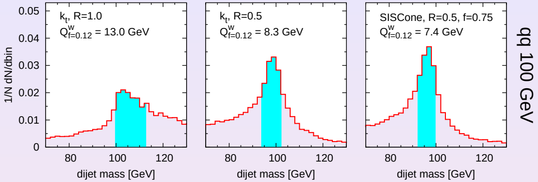
Can illustrate effect of finding best R on quality of kinematic reconstruction.
One can take a 100 GeV $q\bar{q}$ resonance to illustrate this.
Need to define a measure of the quality of reconstruction.
How to assess e.g peak width?

Salam "Towards Jetography" 2009



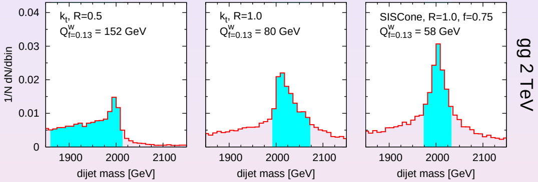
Define quality measure $Q^{w}_{f=z}$ as the width of the narrowest window which contains a specified fraction $f = z$ of events. Smaller Q corresponds to a better peak.

Cacciari, Rojo, Salam, Soyez 2008



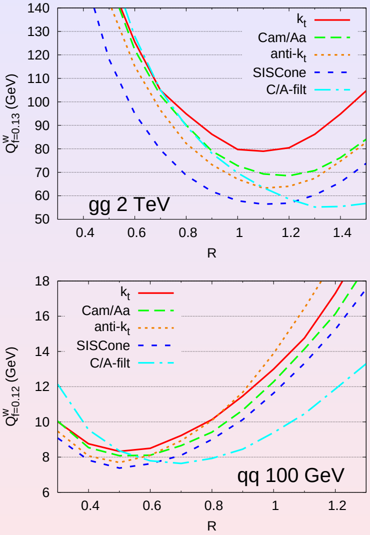
Compare different algorithms and choices of R.
For k_t algorithm a lower R value is favoured here suggesting the importance of the UE contribution.
What may we expect when we move to a 2 TeV gg resonance? We learnt that at such high p_t and for gluon jets one should favour a larger R.

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. But significant differences in Q even for optimal R. Salam 2009

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 yesterday's result

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

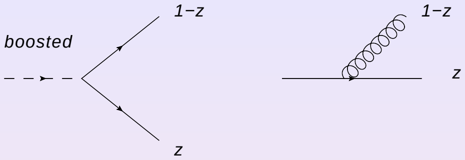
Suggests that for $R \geq \frac{M}{\sqrt{z(1-z)}p_t}$ we will get a single jet. For a p_t of 500 GeV and a mass of 100 Gev in practice taking $R \geq 0.6$ implies that 75 percent of such decays will be clustered to a jet (assuming uniform z distribution).

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 GeV.
Hence we need to know how to remove QCD background as well as how to optimise the construction of the mass.



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

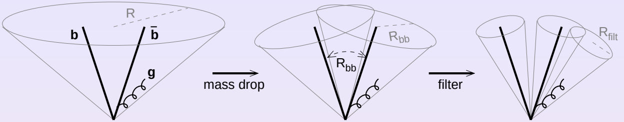
QCD splitting functions very different from those for say EW bosons like Higgs.

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

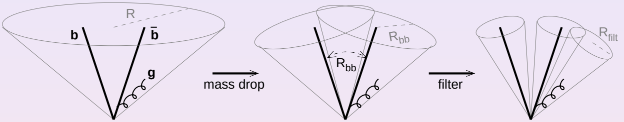


Various substructure techniques proposed e.g filtering, pruning, trimming. Essentially similar ideas but important differences of detail.

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

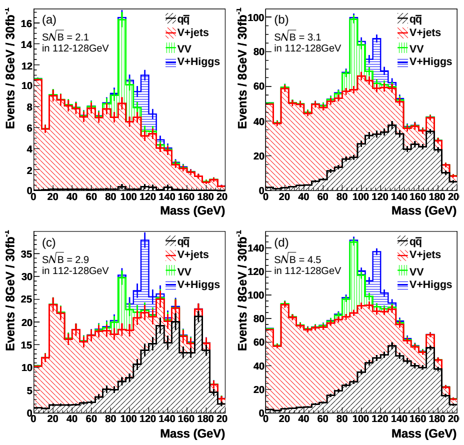
- Undo last step of algorithm so that jet j splits into $j1$ and $j2$ where $m_{j1} > m_{j2}$.
- If there was significant mass-drop $m_{j1} < \mu m_j$ and splitting is not very asymmetric $y_{ij} > y_{\rm cut}$ then j is taken to be in heavy particle neighbourhood and one exits the loop.

- 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. This keeps the LO perturbative radiation but reduces the UE contamination significantly. In practice one finds $R = \min\left(0.3, R_{b,\bar{b}}/2\right)$ is an optimum choice.



An unpromising channel rescued ! Butterworth, Davison, Rubin, Salam, 2008

In conclusion...

- We have a range of fast, flexible, jet algorithms ready in time for LHC phenomenology.
- Learning how to use jets is however still in its infancy.
- However simple ideas arising from basic QCD dynamics can give significant insight into jet properties.
- To find optimal parameters and algorithm for a given study is an important task.
- We are starting to realise the potential for jet shapes and substructure to unravel new physics signals at LHC.
- A fast moving field. Watch out for more news. LHC physics day “QCD and new physics searches” at CERN on February 4.