QCD radiation, properties and substructure of LHC jets

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Outline

- Introduction
- pQCD radiation and jet properties.
- Non-perturbative effects (without Monte Carlo)
- Optimal R and other studies
- Jet substructure
  - Boosted object searches at LHC
  - Jet masses from theory and experiment.
  - Jet grooming techniques

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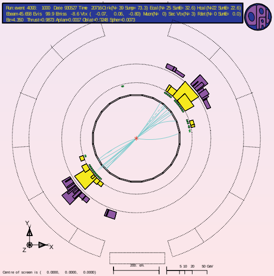
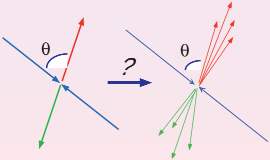
Central questions :

- Our calculations involve partons. Measurements made on hadron jets. Can we accurately connect properties of jets to those of partons?
- How well do we understand internal strutcure of QCD jets? Can we use this understanding for discoveries at the LHC?





IRC safe hadron collider jet definitions

- Cone type : SISCONE (Seedless Infrared Safe Cone)

  Salam and Soyez 2007

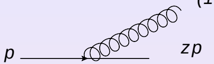
- Sequential Recombination based on a distance measure.
  1. k_t or Durham algorithm

     Catani et. al 1993, Ellis et. al 1993
  2. Cambridge-Aachen

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

Perturbative radiation and jet properties

How does jet's p_t relate back to parent parton ?



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

$$\frac{\langle \delta p_t \rangle_q}{p_t} = -0.43 \alpha_s \ln \frac{1}{R}$$

$$\frac{\langle \delta p_t \rangle_g}{p_t} = -1.02 \alpha_s \ln \frac{1}{R}$$

For $R = 0.4$ quark jet will have 5 percent less and gluon jet 11 percent less p_t than parent parton. Expect significant finite R and higher-order changes.

MD, Magnea and Salam 2008

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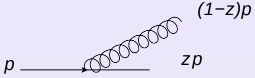

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Jet Masses

- Mean values

$$\langle M_j^2 \rangle_q \sim 0.16\, \alpha_s\, R^2 P_t^2$$

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$$\langle M_j^2 \rangle_g \sim 0.37\, \alpha_s\, R^2 P_t^2$$

SISCONE results similar with $R_{\mathrm{SISCONE}} = 0.75R$.

- Jet mass distribution Potentially significant logarithmic enhancements:

$$\frac{d\sigma}{dM^2} \sim \frac{\alpha_s}{M^2} \ln \frac{R^2 P_t^2}{M^2}.$$

Resummation? S.D. Ellis et.al 2010, Banfi, MD, Marzani, Khelifa Kerfa 2010, Dasgupta, Marzani, Spannowsky, Khelifa Kerfa (in preparation)

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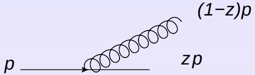
NP corrections - hadronisation



Analytical calculations of hadronisation? Use Dokshitzer Webber model: Emit a soft gluer with $k_t \sim \Lambda$.

We have

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

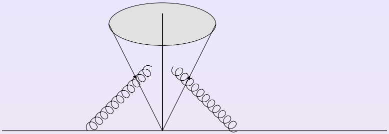
Take coupling integral from e^+e^- event shapes to get

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

For gluon jets change $C_F \to C_A$.

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

UE contribution



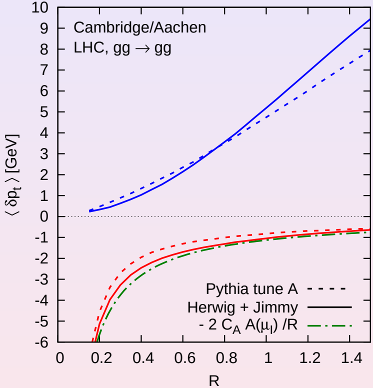
Contrast with underlying event contribution. Assume Λ_{UE} is energy per unit rapidity of soft UE particles.

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

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.

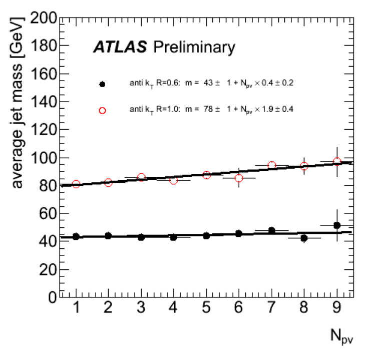
See talk by Gregory

Comparison with MC models



At LHC underlying event is a large effect.

Applications - comparison to data



Ratio of slopes $R = 4.58 \sim (1.0/0.6)^3$

The R^3 scaling is because

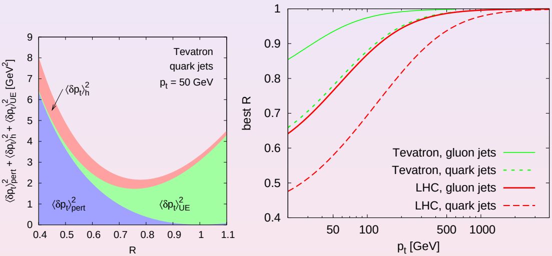
$$\delta m = \sqrt{m^2 + \delta m^2} - m \approx \frac{\delta m^2}{2m}.$$

Since δm^2 scales as R^4 and m as R ($43/78 \approx 0.55$) one gets an R^3 behaviour.

Applications-optimal R.

Knowing R dependence gives rise to concept of optimal R values. Based on minimising

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



For a more accurate treatment: Soyez 2010

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.

Jet shapes and substructure

Classic variables to test understanding/modelling of QCD radiation.
At LHC these studies acquire an important context – boosted objects such as high p_T Higgs decay to products which have narrow opening angle. Can end up in single jet.
Recall

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

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

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Example – jet masses

Invariant mass distribution is first clue to identity of jet. Significant issue arises of QCD jet backgrounds.

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

For $p_t \gg M$ this can be significant contamination even at masses of a 100 GeV. Not described well by fixed order. Need to describe jet mass well but this is a challenge for theory. Monte Carlo models readily available.

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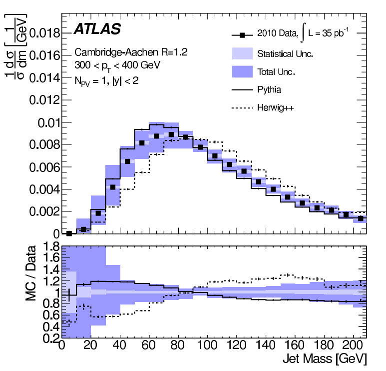
MC description of LHC jet masses



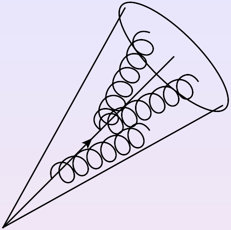
ATLAS collaboration 2012

Some points to note

- Large logs in RP_T/M_j will be significant even at electroweak scale jet masses. Resummation required.
- Some differences visible between standard MC event generators.
- Non-perturbative effects: Hadronisation for M_j^2 will go as ΛRP_t. Can easily induce $10-20$ GeV shifts in jet mass.
- UE goes as R^4. Pile-up similar but shouldnt contribute for ATLAS study.

What about analytical predictions?

Resummation for LHC jet masses



On some level a QCD jet is a QCD jet.

Jet mass distribution from e^+e^- hemisphere jets should work in some sense.

Leading (double) logs ok.

$$\alpha_s^n \ln^{2n} 1/\rho, \;\; \rho = M_j^2/P_t^2$$

Next to leading (single) logs very complex.

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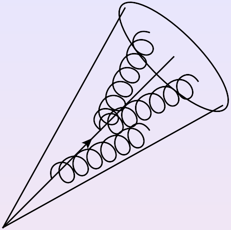

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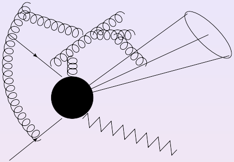
Beware of non-global logs and jet algorithms

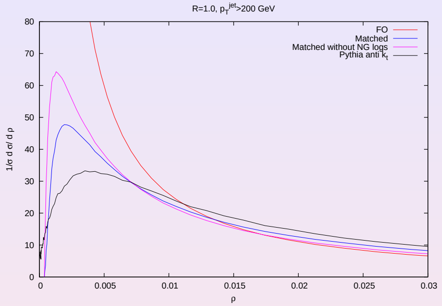


Wide-angle soft radiation is process dependent. Also very complex colour structure for non-global single logs.

Dasgupta and Salam 2001

Role of jet algorithm highly non-trivial at single-log level. Resummation possible for anti k_t algorithm in leading N_c limit.

Banfi, Dasgupta, Khelifa-Kerfa, Marzani 2010.



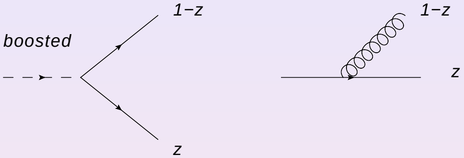
$$\rho = M_j^2/P_t^2$$

Peak is around 15 GeV.

Non-global logs play a sizable role in peak region. Easy to do the same for dijets. NLO matching in progress.

Dasgupta, Khelifa-Kerfa, Marzani, Spannowsky

An alternative approach is to reduce background and contamination by grooming jets.



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

$P(z) \propto \frac{1+z^2}{1-z}$ favours soft emission while 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

Groomed jets

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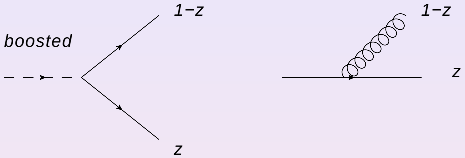

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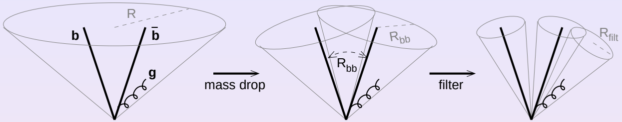
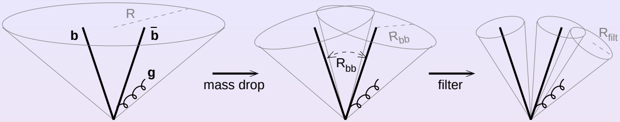


Essentially similar ideas but important differences of detail.

- mass-drop + filtering: undo jet algorithm and look for a significant mass drop of jet $M_{j1} < \mu M_j$. Also demand asymmetric splittings $1 - z > y$ where $1 - z$ can be energy fraction of softer offspring or relative k_t. Filter out UE by using smaller R at next stage.
- Pruning: In the reconstruction of a jet ignore all recombinations with angular separation $> D^2$ and energy fraction $\min\left(p_{ti}, p_{tj}\right)/p_t < z$. Cut out background and contamination in one step.

Example: Filtering and Pruning of jets



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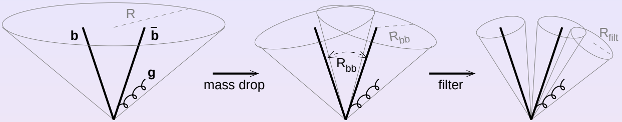

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- Mass drop (Filtering)

$$\frac{d\Sigma}{d\rho} = C_F \frac{\alpha_s(p_T)}{\pi} \frac{1}{\rho} \ln\left(\frac{1}{y} e^{-\frac{3}{4}}\right) \Theta\left(R^2 y - \rho\right)$$
$$+ C_F \frac{\alpha_s(p_T)}{\pi} \frac{1}{\rho} \ln \frac{R^2 e^{-\frac{3}{4}}}{\rho} \Theta\left(\rho - R^2 y\right) \Theta\left(R^2 - \rho\right) + \mathcal{O}(y)$$

- Pruning

$$\frac{d\Sigma}{d\rho} = C_F \frac{\alpha_s}{\pi} \left(\frac{1}{\rho} \ln \frac{D^2}{\rho} \Theta\left(zD^2 - \rho\right) + \frac{1}{\rho} \ln \frac{1}{z} \Theta\left(\rho - zD^2\right) + \frac{1}{\rho} \ln \frac{R^2}{\rho} \Theta\left(\rho - zR^2\right) \Theta\left(R^2 - \rho\right) \right).$$

Groomed masses and logarithms

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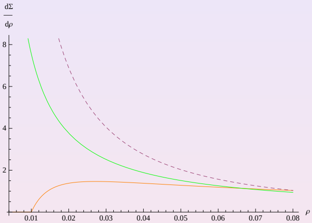
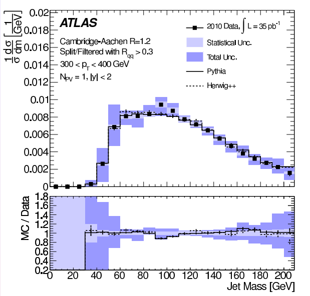
$$\left. + \frac{1}{\rho} \ln \frac{R^2}{\rho} \Theta\left(\rho - zR^2\right) \Theta\left(R^2 - \rho\right)\right).$$

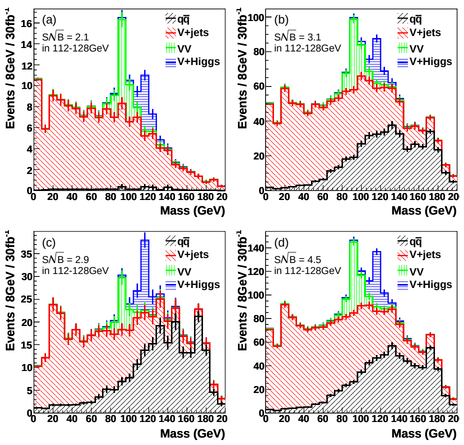
Elimination of double logarithms





Soft logs cut out. For pruning need $D^2 \sim \rho$. Single logs of a simple (pure collinear) origin remain. More convergent series so described by fixed-order?

MC models agree better here.



An unpromising channel rescued.

Butterworth, Davison, Rubin, Salam 2008

Summary

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- New ideas aimed at optimizing jet studies in the context of discoveries. Optimal R, pile up subtraction are examples.
- Substructure techniques developed at an enormous rate in context of boosted heavy particle searches.
- Fast flexible tools for jet analyses available for use (FastJet, SpartyJet)
- Substructure techniques appear experimentally viable. Some work needed on theoretical side to understand the accuracy of theory tools better.

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