Theory of jets

Mrinal Dasgupta

University of Manchester

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Outline

- Introduction and jet definitions
  - QCD perturbation theory and jets.
  - IRC safety and jet algorithms
  - IRC safe jet definitions for hadron colliders.
- Properties of jets
  - Perturbative properties
  - Non-perturbative contributions (hadronisation, UE, pile up)
- Using jets at hadron colliders
  - Optimal R and new physics
  - Substructure and jet grooming
- Summary and outlook

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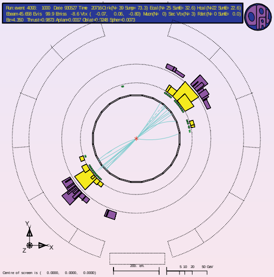
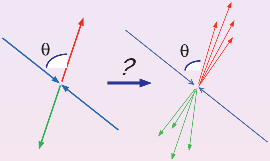
pQCD and jets

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

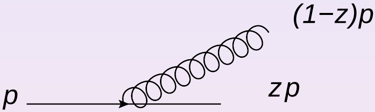




Luckily partons leave some footprints. The game of jet physics involves identifying those elusive partons.

Sterman TASI lectures

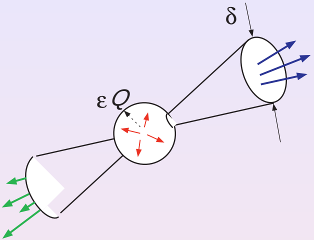
Need for jets arises from within the theory. Regulate IR divergences to make meaningful predictions in pQCD.



$$P = C_i \int \frac{\alpha_s((1-z)\theta)}{\pi} \frac{dz}{1-z} \frac{d\theta^2}{\theta^2}$$

Probability for extra particle production diverges in PT. For calcs. need to introduce energy and angular resolution.

Early jet definitions



Define a dijet event by including anything below energy ϵ or within angle δ in dijet. Sterman and Weinberg 1978

Probability of particle production can be $\mathcal{O}(1)$. Probability of producing extra jet costs us α_s. Jet cross-sections computable in pQCD. But we need IRC safe jet definition at all orders.

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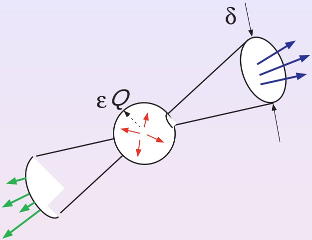

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Jet definitions

SW algorithm too basic. Where to place cones? What to do with overlapping cones? How to generalise to hadron collisions? More sophisticated cones were devised.

Snowmass accord 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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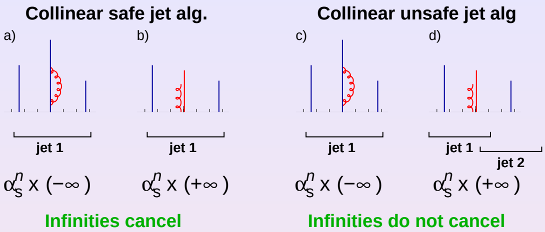
Long history of problems



Seeded cone - emission of a collinear parton changes the jet structure and leads to a divergence.

- Cone algorithms have been problematic including all the cones used at the Tevatron to date.
- There are also algorithms based on sequential recombination. These are IRC safe but have in the past not been commonly used at hadron colliders.
- Finally we have a set of algorithms of various kinds all of which satisfy Snowmass.

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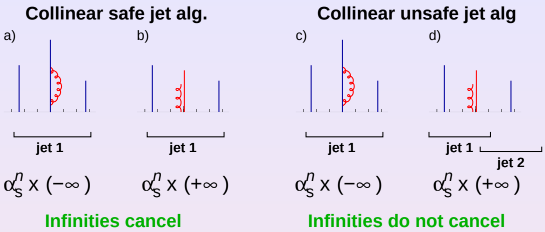

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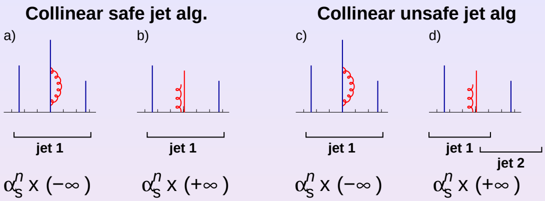

Infinities cancel

Infinities do not cancel

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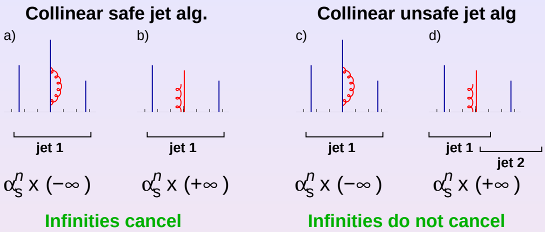

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IRC safe hadron collider jet definitions

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, Ellis et. al 1993
   - Cambridge-Aachen

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

Sequential recombination algorithms

Most common is inclusive k_t algorithm with distance measures

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

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

Ellis and Soper 1993

All quantites defined wrt beam. 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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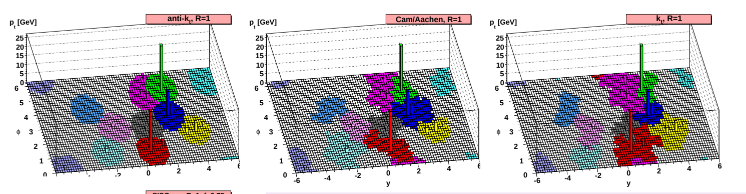
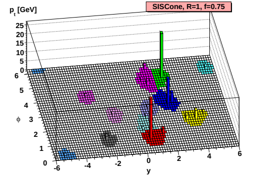
Belong to the k_t family with

$$d_{ij} = \min(p_{t,i}^{2p}, p_{t,j}^{2p})\frac{\Delta_{ij}}{R^2}$$

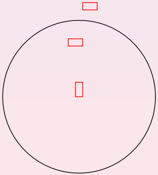
$p = 0$ is C/A algorithm while $p = -1$ is the anti-k_t algorithm. Note that C/A algorithm inverts angular ordered shower while anti-k_t not closely related to QCD dynamics.

Appearance of hadron collider jets

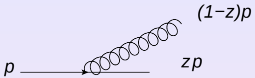




Salam “Towards Jetography” 2009



Properties of jets at hadron colliders

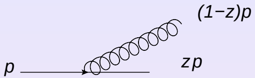


$$\langle \delta p_t \rangle_q = -\frac{C_F \alpha_s}{2\pi} p_t \int_{R^2}^{1} \frac{d\theta^2}{\theta^2} \frac{1+z^2}{1-z} \min\left[(1-z), z\right]$$

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

$$\langle \delta p_t \rangle_g = -\frac{\alpha_s}{\pi} p_t \ln \frac{1}{R} \left[C_A \left(2\ln 2 - \frac{43}{96} \right) + T_R n_f \frac{7}{48} \right]$$

MD, Magnea and Salam 2008



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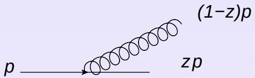

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To summarise:

$$\frac{\langle \delta p_t \rangle_q}{p_t} = -0.43\alpha_s \ln\frac{1}{R}$$
$$\frac{\langle \delta p_t \rangle_g}{p_t} = -1.02\alpha_s \ln\frac{1}{R}$$

For $R = 0.4$ quark jet will have 5 percent less and gluon jet 11 percent less p_t than parent parton.

- Above results are subject to significant finite R and higher order changes.
- SISCONE has different recombination. Draw cone centred on $p_1 + p_2$ and require one parton to fall outside it. Similar result with $R_{kt} \sim 1.3 R_{\mathrm{SIS}}$

MD, Magnea and Salam 2008

- 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 $R_{\mathrm{SISCONE}} = 0.75 R$.

- 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

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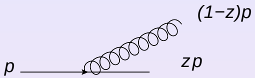
NP corrections - hadronisation



Analytical calculations of hadronisation? Use Dokshitzer Webber 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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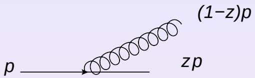

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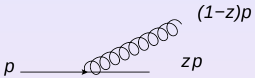

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We have

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

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

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

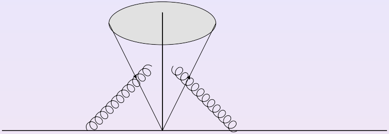
For gluon jets change $C_F \to C_A$.

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

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

MD, Magnea and Salam 2008

UE contribution

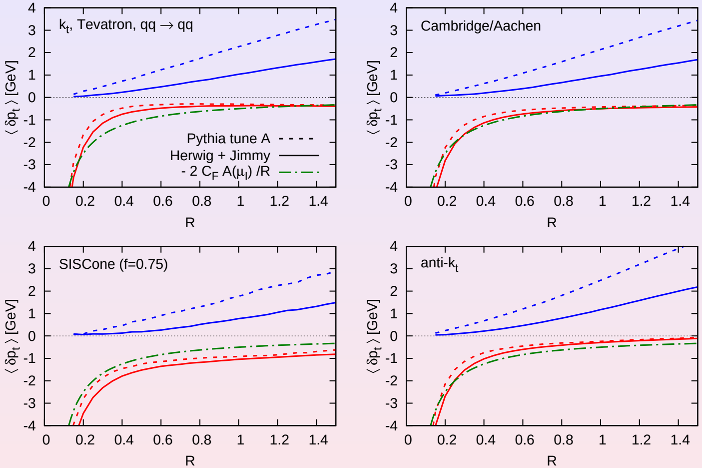


Contrast with underlying event contribution. Assume Λ_{UE} is energy per unit rapidity of soft UE particles.

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

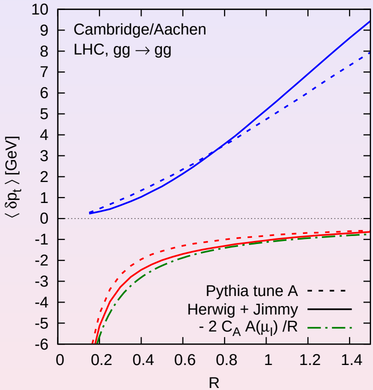
Has a regular dependence on R (comes from jet area). For jet mass UE contribution goes as R^4. Similar effects from pile-up but order of magnitude larger at the LHC.

Comparison to MC models

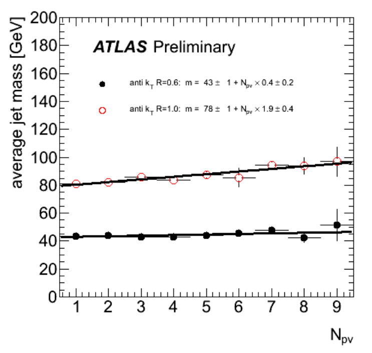


Agreement with analytical predictions. Same result for all algorithms. UE different between MC models.

Comparison with MC models



At LHC underlying event is a large effect.



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-Comparison to data

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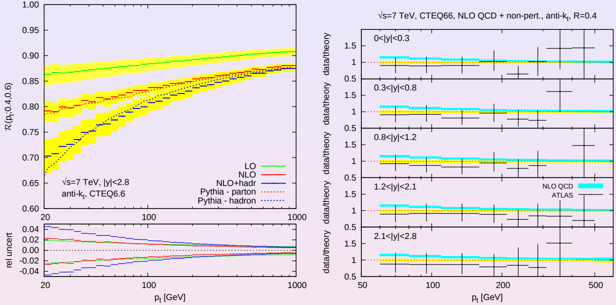
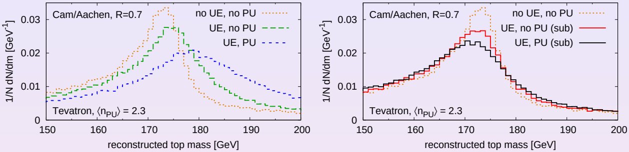


$$R = \frac{\frac{d\sigma}{dp_t}(R_1)}{\frac{d\sigma}{dp_t}(R_2)}$$

Soyez 2010

Applications - pile up subtraction



Removal of pile-up crucial to quality of kinematic reconstructions.

$$p_{t,j} \longrightarrow p_{t,j} - \rho A_j$$

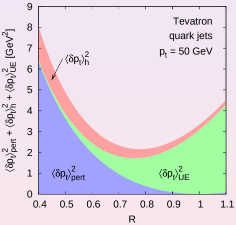
Area dependence of UE and pile-up behind FASTJET subtraction of UE and pile up. Event by event determination of pile-up with jet-by–jet subtraction based on area.

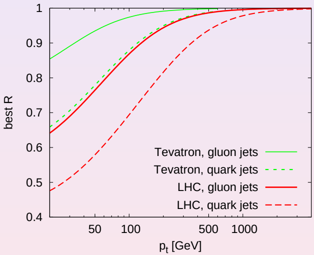
Cacciari and Salam 2007

Applications-optimal R.

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

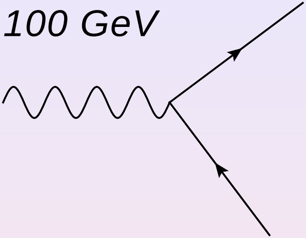
$$\langle \delta p_t^2 \rangle = \langle \delta p_t \rangle_{\rm h}^2 + \langle \delta p_t \rangle_{\rm UE}^2 + \langle \delta p_t \rangle_{\rm PT}^2$$

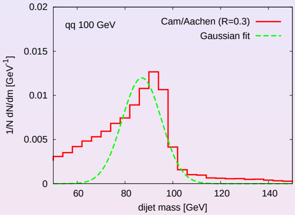




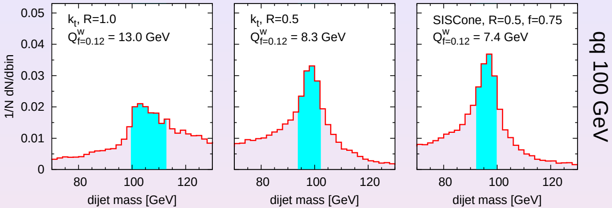
At high p_t one should use a larger R -minimises perturbative effect. Likewise for gluon jets a larger R is suggested. For LHC smaller R values than Tevatron.

Best R for peak reconstruction



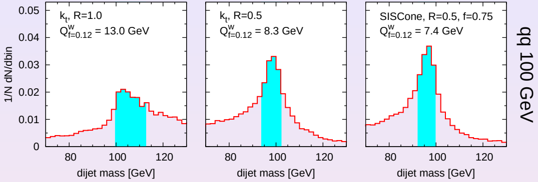


Can illustrate effect of finding best R on quality of kinematic reconstruction.
One can take a 100 GeV $q\bar{q}$ resonance to illustrate this.
Need to define a measure of the quality of reconstruction.
How to assess e.g peak width?



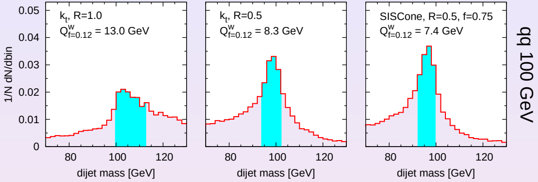
Define quality measure $Q^w_{f=z}$ as the width of the narrowest window which contains a specified fraction $f = z$ of events. Smaller Q corresponds to a better peak.

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.



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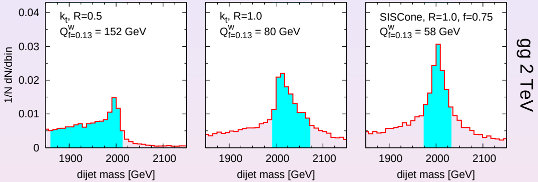
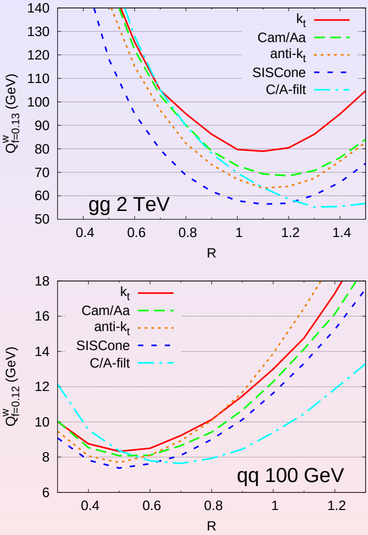


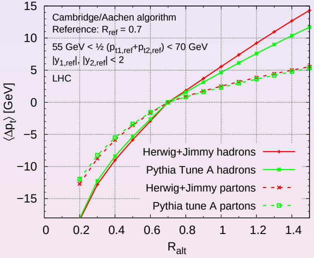
Here $R = 0.5$ would be a bad choice. Larger R is favoured as expected. SISCONE seems to perform markedly better than k_t in this case.

Comparing algorithms



Optimal R doesnt vary too much across algorithms. Q does even for optimal R.

Already seen some applications to data. One further idea could be to directly extract the scale of UE from data. Study e.g δp_t by using a reference and alternative jet



$$\langle \delta p_t \rangle = \langle \delta p_t \rangle_{\mathrm{NLO}} - 2\langle C_i \rangle \left(\frac{1}{R_{\mathrm{alt}}} - \frac{1}{R_{\mathrm{ref}}} \right) \mathcal{A}(\mu_I) + \left(R_{\mathrm{alt}} J_1(R_{\mathrm{alt}}) - R_{\mathrm{ref}} J_1\left(R_{\mathrm{ref}}\right)\right) \Lambda_{\mathrm{UE}}$$

Highly boosted objects such as high p_T Higgs decay to products which have narrow opening angle. Can end up in single jet.
Recall

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

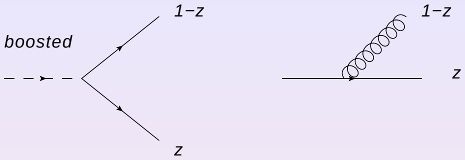
For $R \geq \frac{M}{\sqrt{z(1-z)}p_t}$ we will get a single jet. For $p_t \sim 500$ GeV , $M \sim 100$ Gev $R \geq 0.6$ implies that 75 percent of such decays will be clustered to a jet.

Jet substructure

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.
Remove QCD background and 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 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

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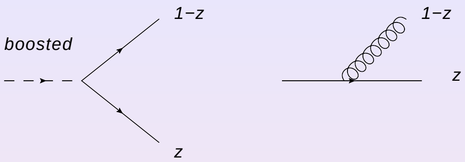

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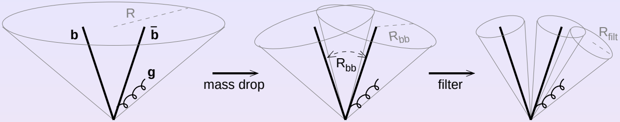
Filtering



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

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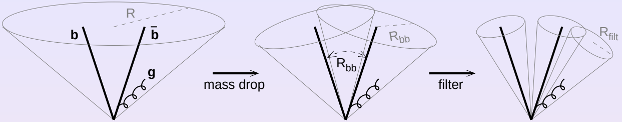

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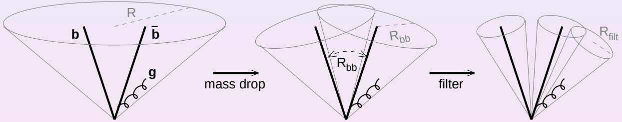
- Otherwise one redefines j to be j_1 and reverts to step 1. Final jet j considered as Higgs candidate if both j_1 and j_2 have b tags.



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

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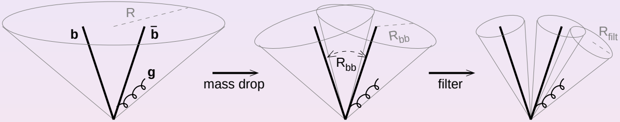

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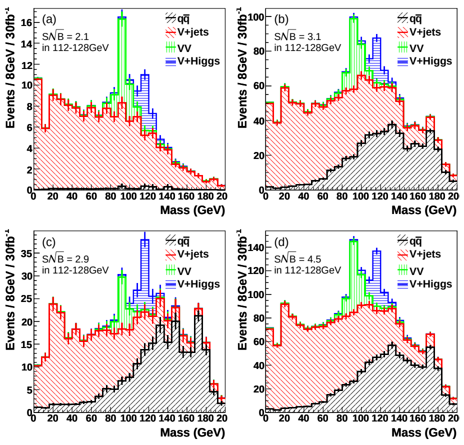

An unpromising channel rescued.

Other techniques aimed at reducing contamination and eliminating background:

- Pruning — Ellis, Vermillion, Walsh 2009
- Trimming — Krohn, Thaler, Wang 2009

Common issues: Introduce extra parameters in jet finding which need to be tuned

For more details and recent developments see: http://boost2011.org

Summary

- Significant progress in defining, speeding up and understanding jets.
- 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)

Need for continued dialogue between theory and experiment to ensure utilisation of these ideas.

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