Theory of jets and applications to the LHC

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Outline

- Introduction and jet definitions
- Properties of jets
  - Perturbative properties
  - Non-perturbative contributions (hadronisation, UE, pile up)
- Applications – jets as tools for LHC physics.
  - Optimal R and new physics
  - Substructure and jet grooming
- Summary and outlook

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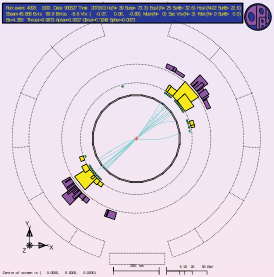
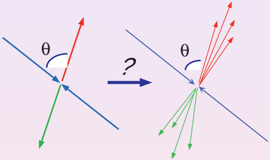
pQCD and jets

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

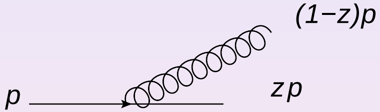




Luckily partons leave some footprints. The game of jet physics involves identifying those elusive partons.

Sterman TASI lectures

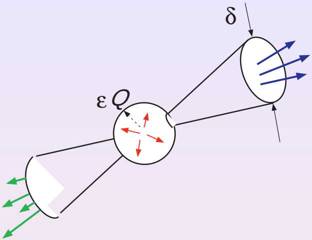
Need for jets arises from within the theory. Regulate IR divergences to make meaningful predictions in pQCD.



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

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

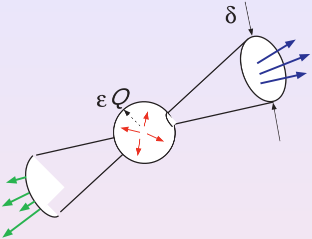
Early jet definitions



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.

Early jet definitions



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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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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.

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.

Sequential recombination algorithms

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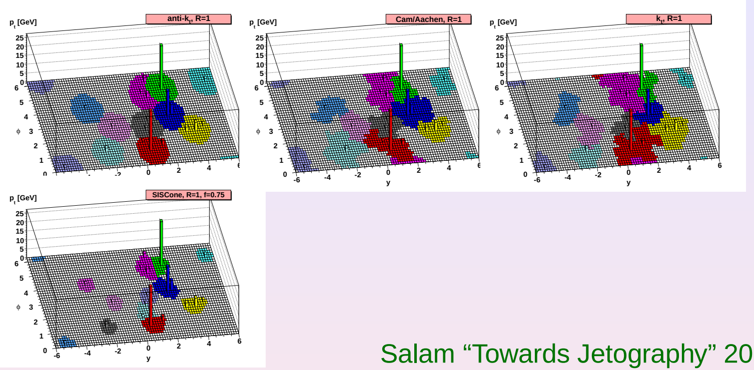
Sequential recombination algorithms

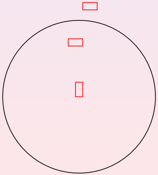
Belong to the k_t family with

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

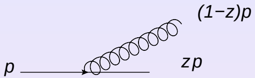
$p = 0$ is C/A algorithm while $p = -1$ is the anti-k_t algorithm. Note that C/A algorithm inverts angular ordered shower while anti-k_t not closely related to QCD dynamics.



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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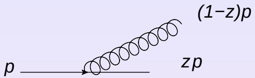

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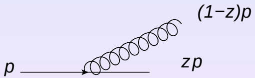

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To summarise:

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

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

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

.

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

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

- 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

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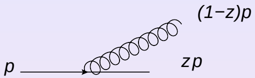


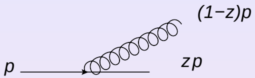
Analytical calculations of hadronisation? Use Dokshitzer Webber model:

- 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 $\theta > R$

NP corrections - hadronisation



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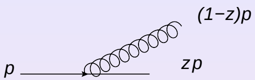

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We have

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

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

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

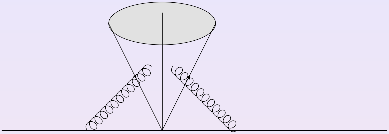
For gluon jets change $C_F \to C_A$.

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

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

MD, Magnea and Salam 2008

UE contribution

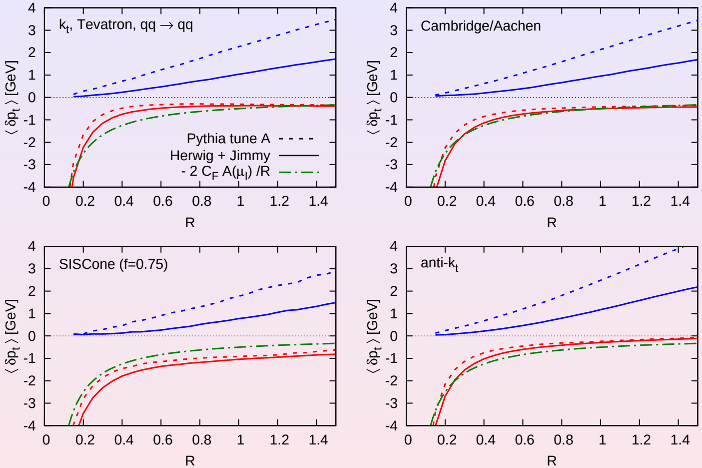


Contrast with underlying event contribution. Assume $\Lambda_{\rm UE}$ is energy per unit rapidity of soft UE particles.

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

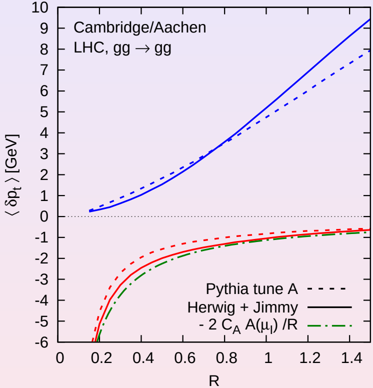
Has a regular dependence on R (comes from jet area). For jet mass UE contribution goes as R^4. Similar effects from pile-up but order of magnitude larger at the LHC.

Comparison to MC models

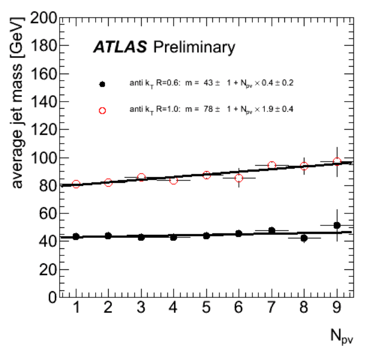


Agreement with analytical predictions. Same result for all algorithms. UE different between MC models.

Comparison with MC models



At LHC underlying event is a large effect.



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

Applications-Comparison to data

The R^3 scaling is because

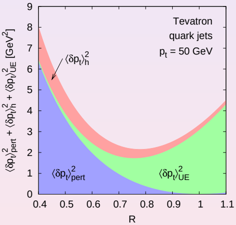
$$\delta m = \sqrt{m^2 + \delta m^2} - m \approx \frac{\delta m^2}{2m}.$$

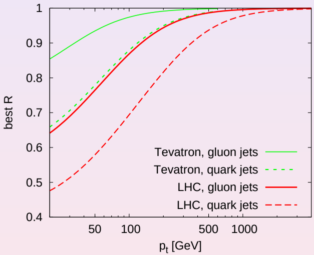
Since δm^2 scales as R^4 and m as R ($43/78 \approx 0.55$) one gets an R^3 behaviour.
Also $1/R$ hadronisation correction used to compare to inclusive jets ATLAS data. Soyez 2010

Applications-optimal R.

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

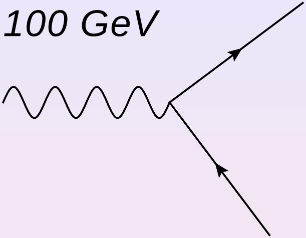
$$\langle \delta p_t^2 \rangle = \langle \delta p_t \rangle_{\rm h}^2 + \langle \delta p_t \rangle_{\rm UE}^2 + \langle \delta p_t \rangle_{\rm PT}^2$$

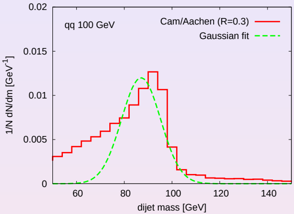




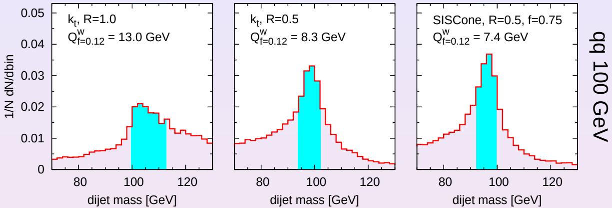
At high p_t one should use a larger R -minimises perturbative effect. Likewise for gluon jets a larger R is suggested. For LHC smaller R values than Tevatron.

Best R for peak reconstruction



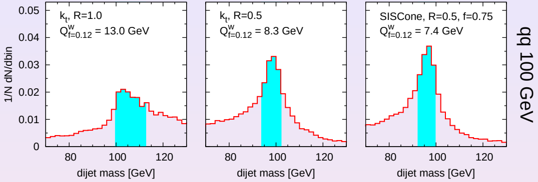


Can illustrate effect of finding best R on quality of kinematic reconstruction.
One can take a 100 GeV $q\bar{q}$ resonance to illustrate this.
Need to define a measure of the quality of reconstruction.
How to assess e.g peak width?



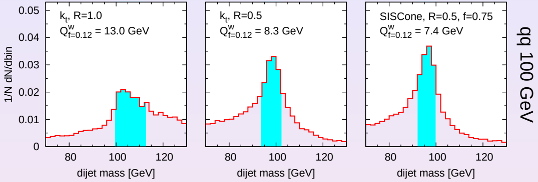
Define quality measure $Q^w_{f=z}$ as the width of the narrowest window which contains a specified fraction $f = z$ of events. Smaller Q corresponds to a better peak.

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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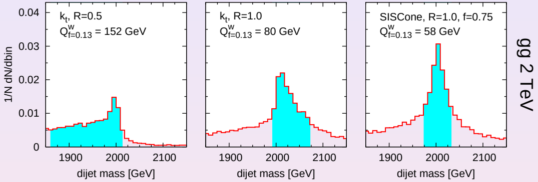
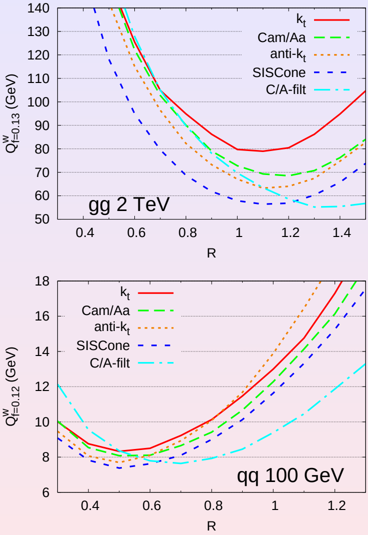
2 TeV gg resonance



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 even for optimal R.

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

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

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.

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.

Example – jet masses

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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.

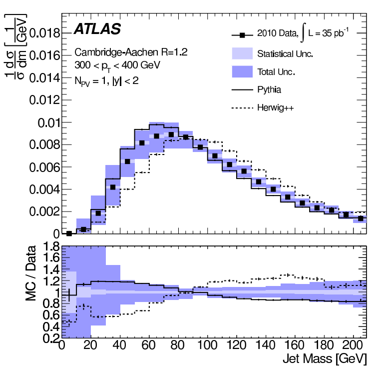
Example – jet masses

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.

MC description of LHC jet masses

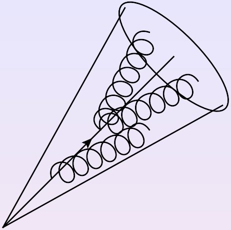


ATLAS collaboration 2012

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?



On some level a QCD jet is a QCD jet. Jet mass distribution from e^+e^- hemisphere jets should work in some sense.

Ellis, Walsh, Vermillion, Lee 2010, Perez et. al 2010, Yuan et. al 2011,2012, Stewart et. al 2011 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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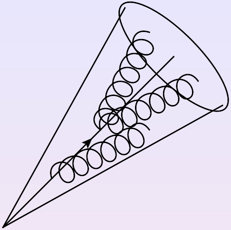

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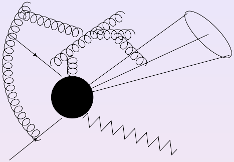
Beware of non-global logs and jet algorithms



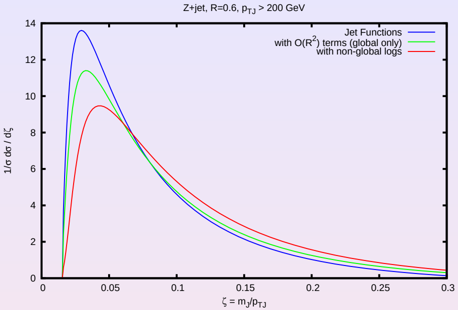
Wide-angle soft radiation (ISR) is process dependent. Also very complex colour structure for non-global single logs.

MD 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, MD, Khelifa-Kerfa, Marzani 2010.

Resummation for $Z+$ jet matched to leading order

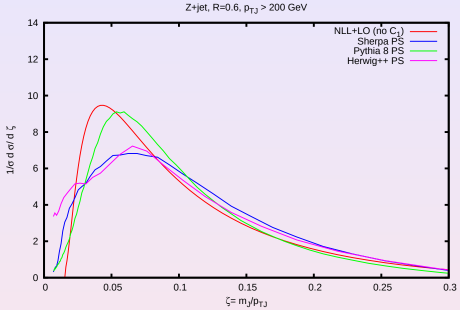


$$\zeta = M_j/P_t.$$

Peak is around 15 GeV.
ISR and non-global logs play a sizable role in peak region.
Easy to do the same for inclusive jets. NLO matching in progress.

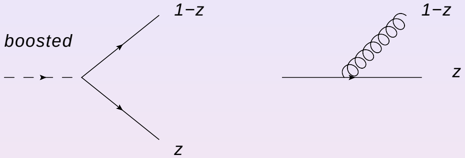
MD, Khelifa-Kerfa, Marzani, Spannowsky

Comparison to event generators



Some fairly significant differences between various showers and resummation. Imply significant theoretical uncertainty for background. Efforts on to improve resummed calculation and implement NLO matching.

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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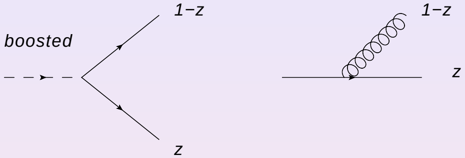

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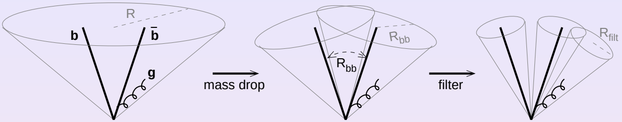
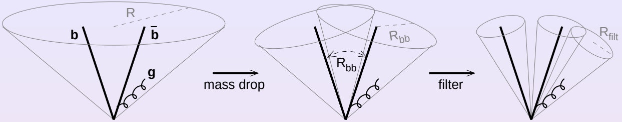
Example: Filtering and Pruning of jets



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 $1 - z$ is energy fraction of softer jet. 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.



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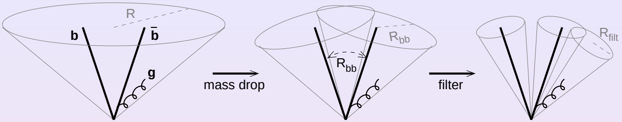

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$$\frac{d\Sigma}{d\rho} = C_F \frac{\alpha_s(p_T)}{\pi} \frac{1}{\rho} \ln\left(\frac{1}{y} e^{-\frac{3}{4}}\right) \Theta\left(R^2 y - \rho\right)$$

Only single logs –maybe use fixed-order?

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Double logs still....need to resum.

Groomed masses and logarithms

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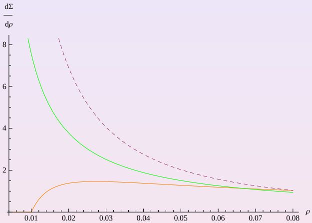
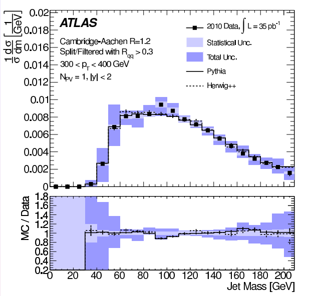
Elimination of double logarithms

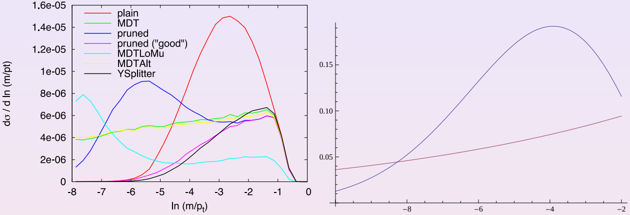




Soft logs cut out. For pruning need $D^2 \sim \rho$. Single logs of a simple (pure collinear) origin remain. More convergent series so described by fixed-order?

MC models agree better here. Better theoretical control?

All-orders behaviour analytically



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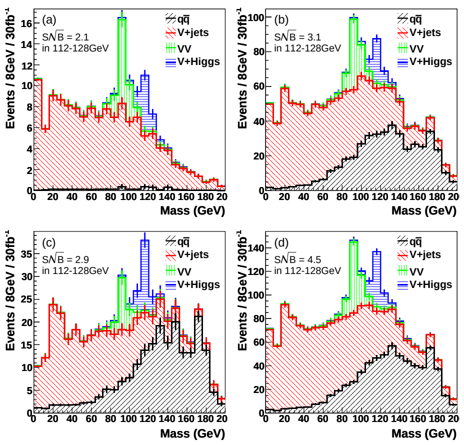
Simple exponentiation of single logarithms for mass drop.

MD, Salam, Marzani, Fregoso in progress



An unpromising channel rescued.

Butterworth, Davison, Rubin, Salam 2008

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)
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