Jets at the LHC: from Run I to Run II and beyond
Towards an optimal use of jet substructure

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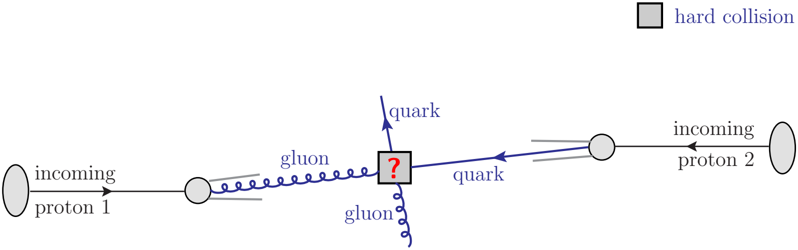
Brief plan

- Introduction: "standard" jets at the LHC
  Jets at the LHC, anti-k_t algorithm, FastJet

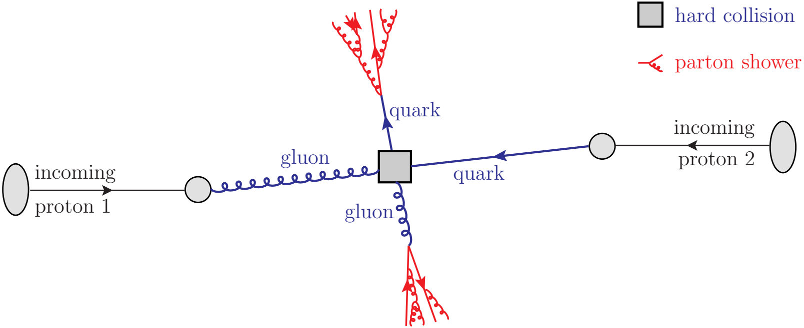
- Boosted jets and jet substructure
  - New paradigm for jets
  - several methods/tools for a few ideas
  - what can pQCD tell us?

Handle on fundamental interactions



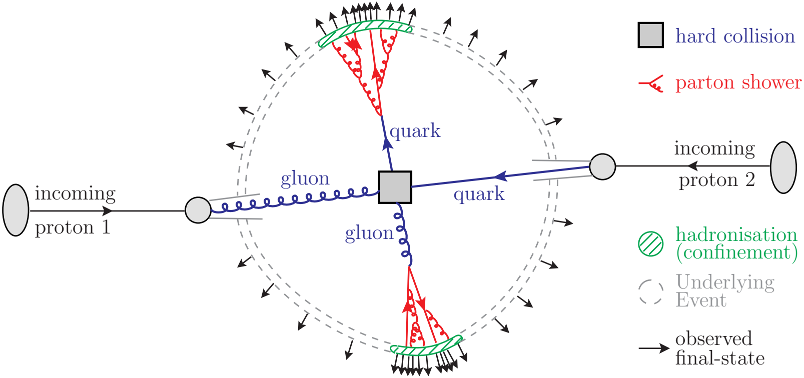
Learn about fundamental interactions by collising objects (protons) and study what comes out

Handle on fundamental interactions



- Leptons and photons are directly observed, neutrinos escape
- Quarks and gluons undergo more complex dynamics
- $H/Z/W/t$ decay in leptons/neutrinos/photons/quarks

Handle on fundamental interactions

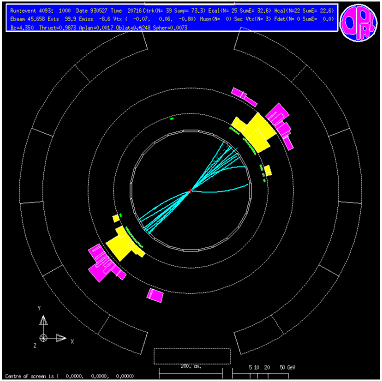


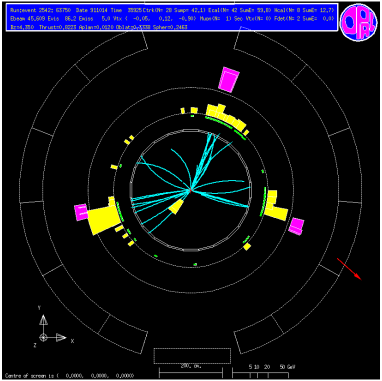
- Partially perturbative/partially non-perturbative
- collimated structures in complex final statee
- Has to be reconstructed precisely to learn abouthard interactions

Jets: basic concepts

Final-state events are pencil-like

already observed in e^+e^- collisions:





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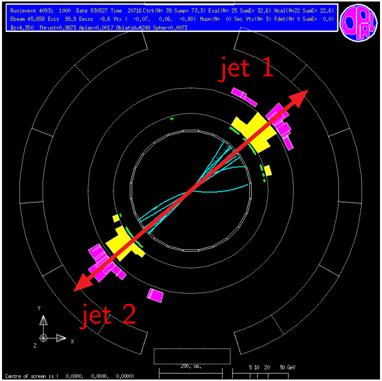

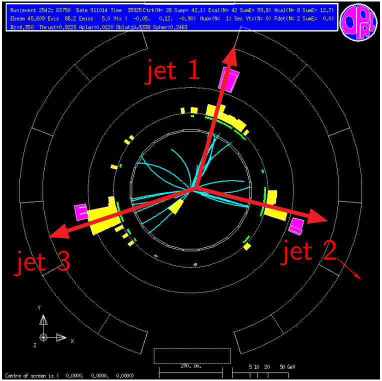

"Jets" $\equiv$ bunch of collimated particles

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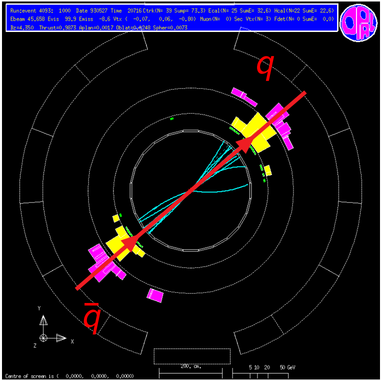

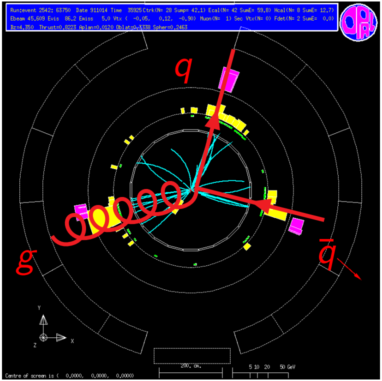

"Jets" $\equiv$ bunch of collimated particles $\cong$ hard partons

Jets and partons

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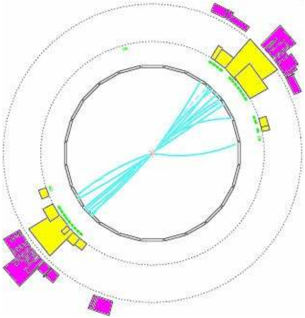
"obviously" 2 jets



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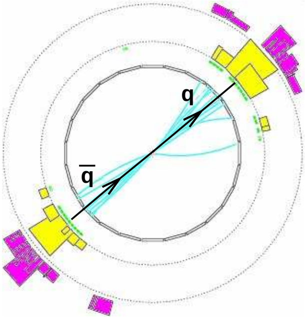

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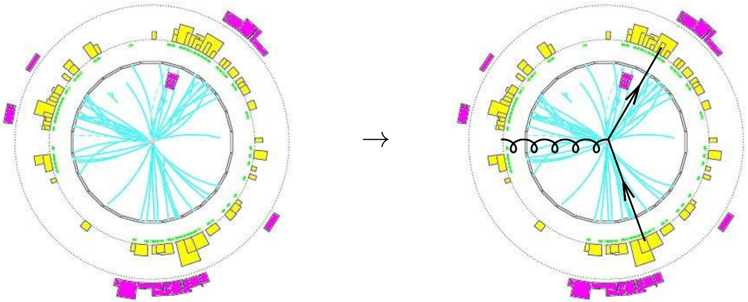
3 jets?



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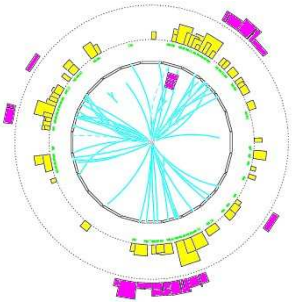
3 jets... or 4?



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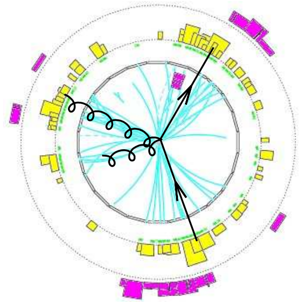

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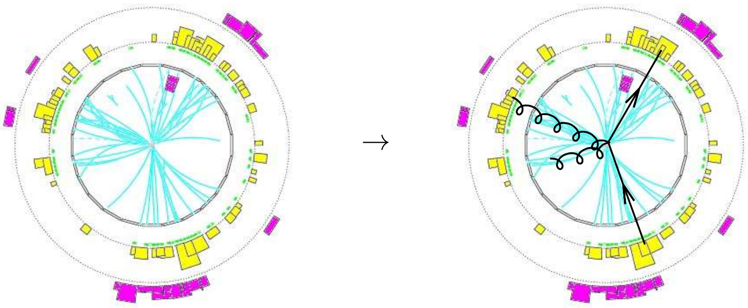
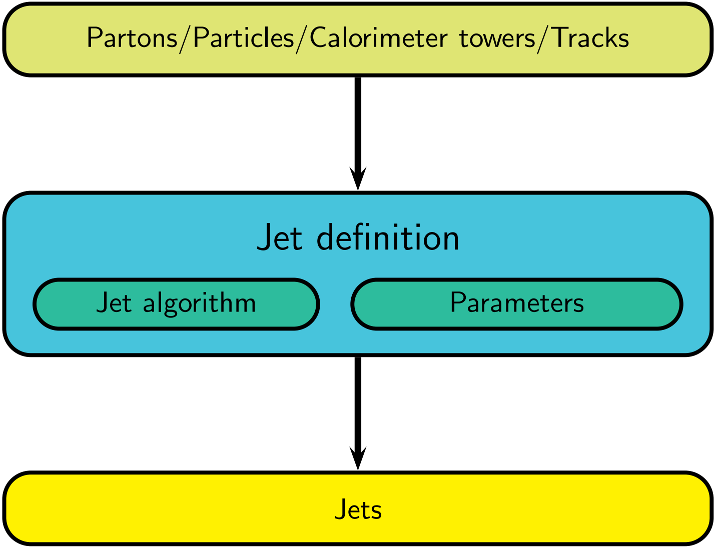


- "collinear" is arbitrary (typically needs a resolution parameter)
- "parton" concept strictly valid only at LO

Jet definition



Recombination algorithms

[M.Cacciari,G.Salam,GS,2008]

(Anti-k_t) algorithm

- From all the objects, define the distances

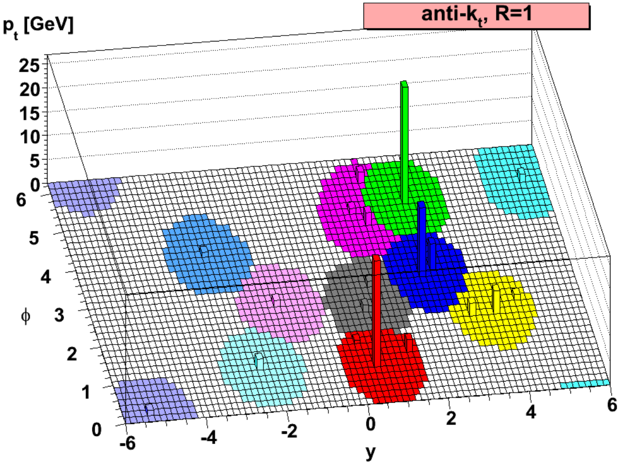
$$d_{ij} = \min(p_{t,i}^{-2}, p_{t,j}^{-2})(\Delta y_{ij}^2 + \Delta\phi_{ij}^2), \qquad d_{iB} = p_{t,i}^{-2} R^2$$

- repeatedly find the minimal distance
  if d_{ij}: recombine i and j into $k = i + j$
  if d_{iB}: call i a jet
- One parameters: R ("jet radius").

Notes

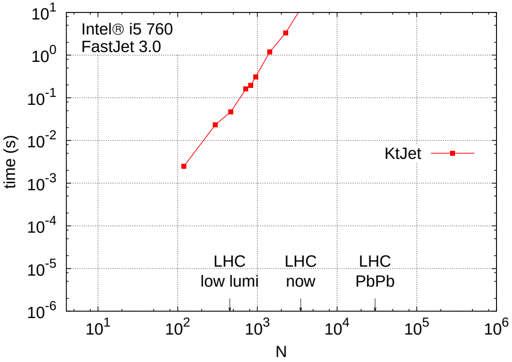
- Different R at the LHC. CMS: 0.5,0.7,0.4(soon); ATLAS: 0.4,0.6
- Several nice properties:
  - IRC-safe (i.e. can be computed theoretically in pQCD)
  - produces cone-like (circular) jets
  - fast

Main property: hard jets are circular



FastJet

[M.Cacciari, G.Salam, 2005; M.Cacciari, G.Salam, GS, 2007-2015]



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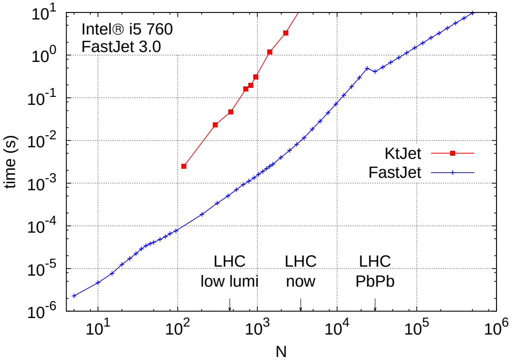

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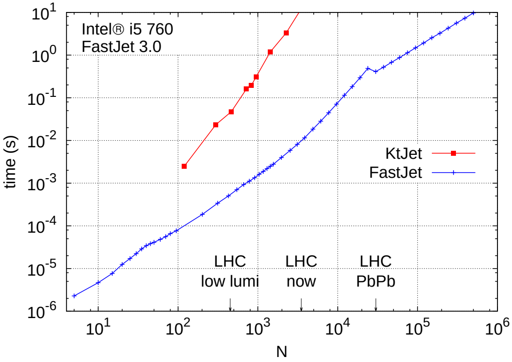

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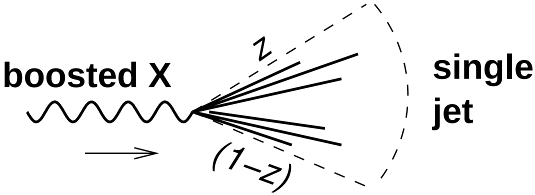
- Now: (anti-)k_t very fast: $\mathcal{O}(N^2)$ or even $\mathcal{O}(N \log(N))$
- Fastjet 3.1: typically 5-50ms for LHC (with pileup and areas)

Boosted jets

Boosted jets: main idea

Object X decaying to hadrons



$$R \gtrsim \frac{m}{p_t} \frac{1}{\sqrt{z(1-z)}}$$

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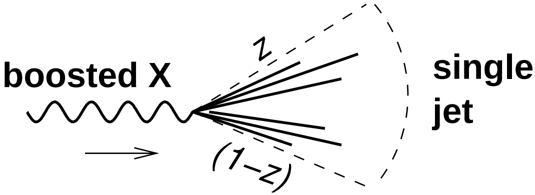


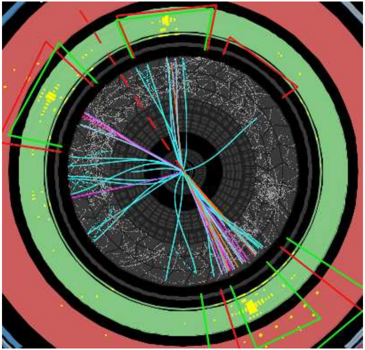
$$R \gtrsim \frac{m}{p_t} \frac{1}{\sqrt{z(1-z)}}$$

If $p_t \gg m$, reconstructed as a single jet

How to disentangle that from a QCD jet?

An illustration

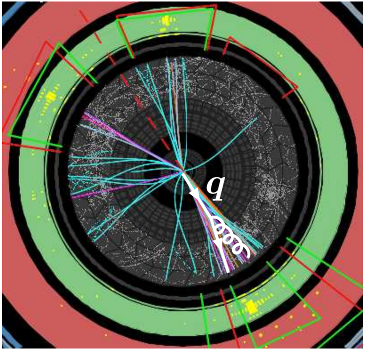
What jet do we have here?



An illustration

What jet do we have here?

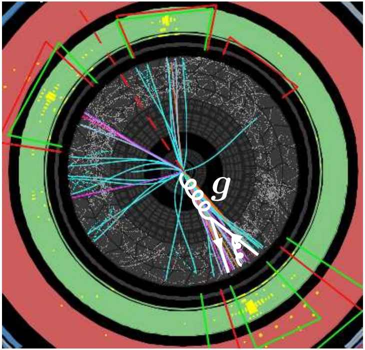
- a quark?



An illustration

What jet do we have here?

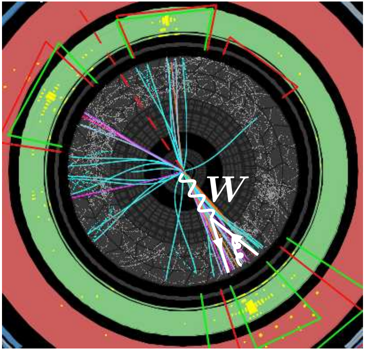
- a quark?
- a gluon?



An illustration

What jet do we have here?

- a quark?
- a gluon?
- a W/Z (or a Higgs)?



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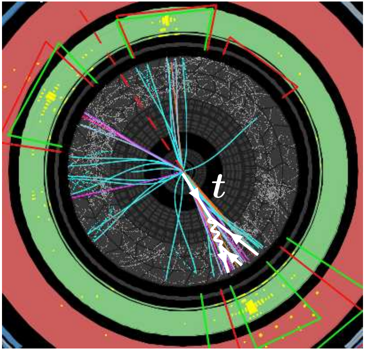

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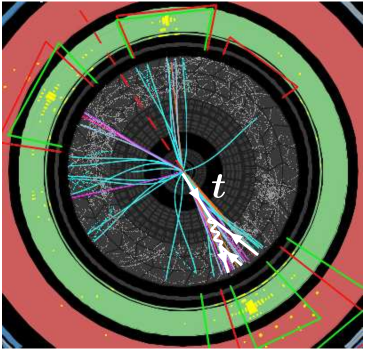

Source: ATLAS boosted top candidate

An illustration

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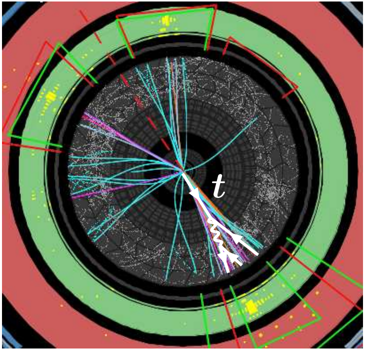

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Paradigm shift: a jet can be more than a quark or gluon

Boosted jets: applications

Many applications: (examples)

- 2-pronged decay: $W \to q\bar{q}$, $H \to b\bar{b}$
- 3-pronged decay: $t \to qqb$, $\tilde{\chi} \to qqq$
- busier combinations: $t\bar{t}H$
- new physics: *e.g.* R-parity violating $\chi \to qqq$, boosted tops in SUSY

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Increasingly important:

- Increasing LHC energy
- Increasing bounds/scales
- More-and-more discussions about yet higher-energy colliders

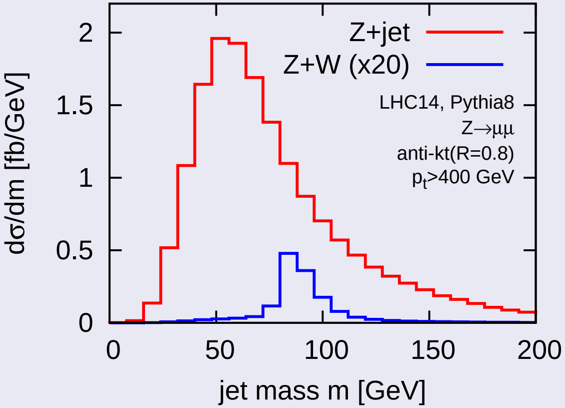
More and more boosted jets
Needs to be under control

Boosted jets

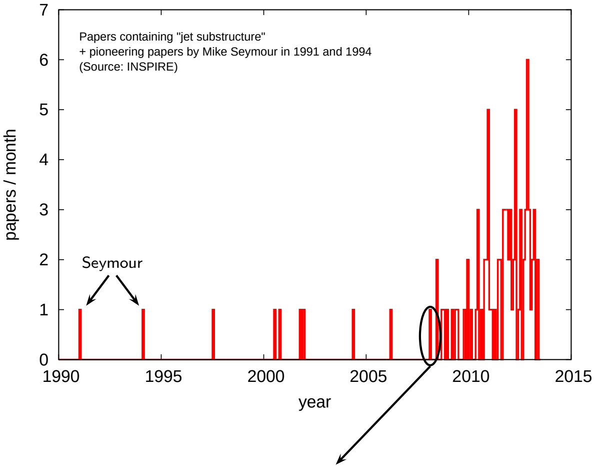
How to proceed?

Naive ideas do not work!

Looking at the jet mass is not enough



A lot of activity since 2008



Jet substructure as a new Higgs search channel at the LHC

Jon Butterworth, Adam Davison, Mathieu Rubin, Gavin Salam, 0802.2470

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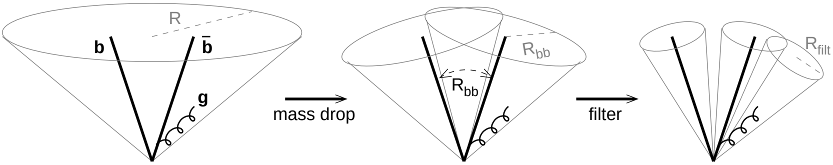

Many tools:

mass drop; filtering, trimming, pruning; soft drop, Y-splitter; N-subjettiness, planar flow, energy correlations, pull; Q-jets, ScJets; shower deconstruction; template methods; Johns Hopkins top tagger, HEPTopTagger, CASubjet tagging; ...

Implementation: Mostly in FastJet, fastjet-contrib and 3$^{\rm rd}$-party codes
See `www.fastjet.fr` and `http://fastjet.hepforge.org/contrib`

Two major ideas

Idea 1:
Find $N = 2, 3, \ldots$ hard cores

Works because different splitting

QCD jets: $P(z) \propto 1/z$

- $\Rightarrow$ dominated by soft emissions
- $\Rightarrow$ "single" hard core

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Constrain radiation patterns

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Radiation pattern is different for

- colourless $W \to q\bar{q}$
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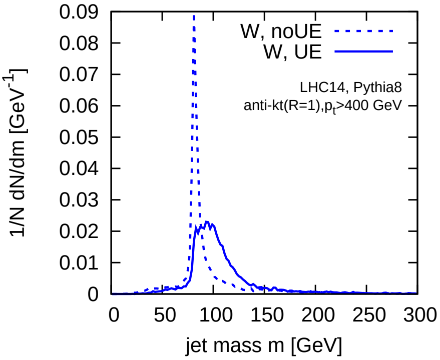
A few key approaches:

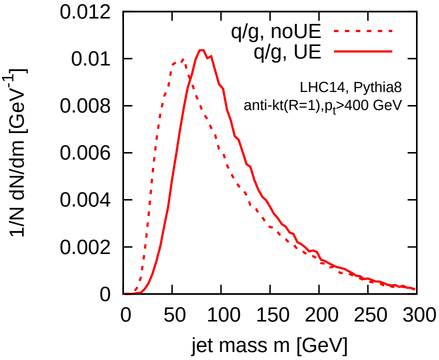
1. uncluster the jet into subjets/investigate the clustering history
2. use jet shapes (functions of jet constituents),...

Grooming

Fat Jets

One usually work with large-R jets ($R \sim 0.8 - 1.5$)
$\Rightarrow$ large sensitivity to UE (and pileup)





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"grooming" techniques reduce sensitivity to soft-and-large-angle

Example 1: Filtering/trimming

- re-cluster the jet with the k_t algorithm, $R = R_{\mathrm{sub}}$
- Filtering: keep the n_{filt} hardest subjets [J.Buterworth,A.Davison,M.Rubin,G.Salam,08]
- Trimming: keep subjets with $p_t > f_{\mathrm{trim}} p_{t,\mathrm{jet}}$ [D.Krohn,J.Thaler,L-T.Wang,10]

Methods for finding hard cores

Example 2: (modified) mass-drop tagger ((m)MDT)

- start with a jet clustered with Cambridge/Aachen
- undo the last splitting $j \to j_1 + j_2$
- if $\max(p_{t1}, p_{t2}) > z_{\rm cut} p_t$, j_1 and j_2 are the 2 hard cores
  otherwise, continue with the hardest subjet
- Original version also imposed a mass-drop: $\max(m_1, m_2) < \mu m$

[J.Buterworth,A.Davison,M.Rubin,G.Salam,08; M.Dasgupta,A.Fregoso,S.Marzani,G.Salam,13]

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SoftDrop

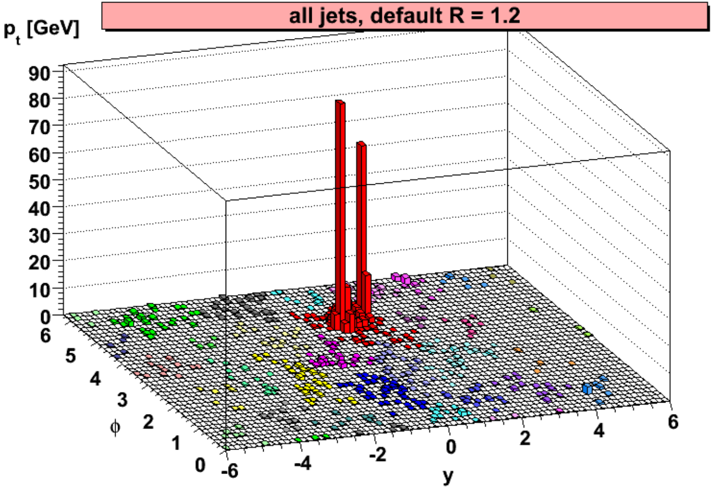
Same de-clustering procedure as the mMDT but angular-dependent cut

$$\max(p_{t1}, p_{t2}) > z_{\rm cut} p_t (\theta_{12}/R)^{\beta}$$

[A.Larkoski,S.Marzani,J.Thaler,GS,14]

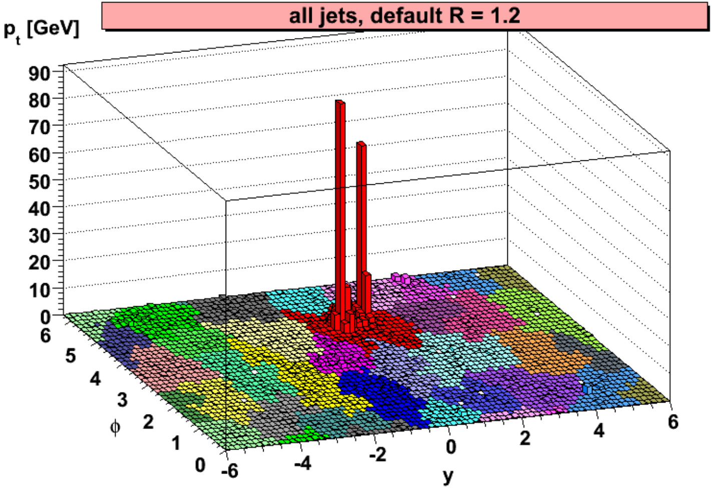
MassDrop+Filtering in action

Start with the jets in an event



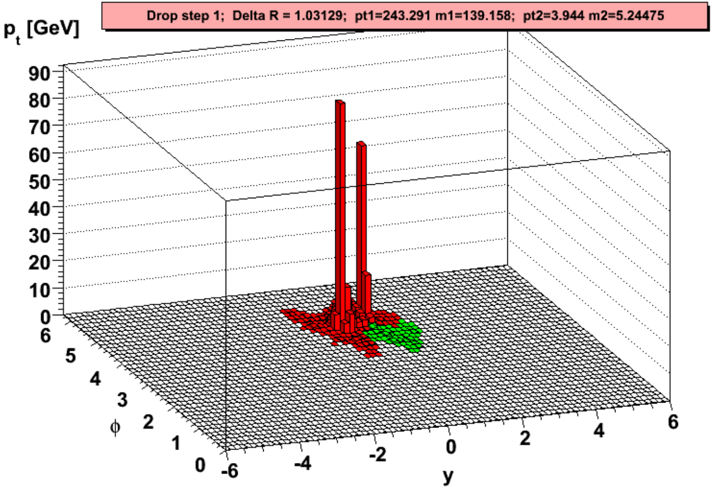
MassDrop+Filtering in action

This is what they look like with their area



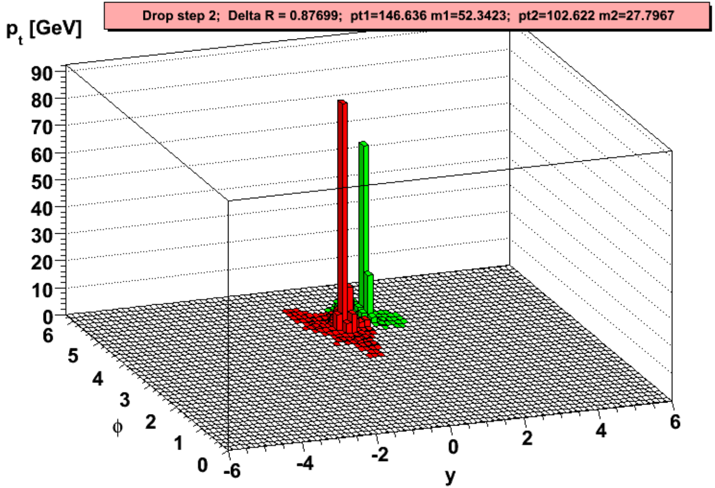
MassDrop+Filtering in action

Take the hardest, apply a step of mass-drop



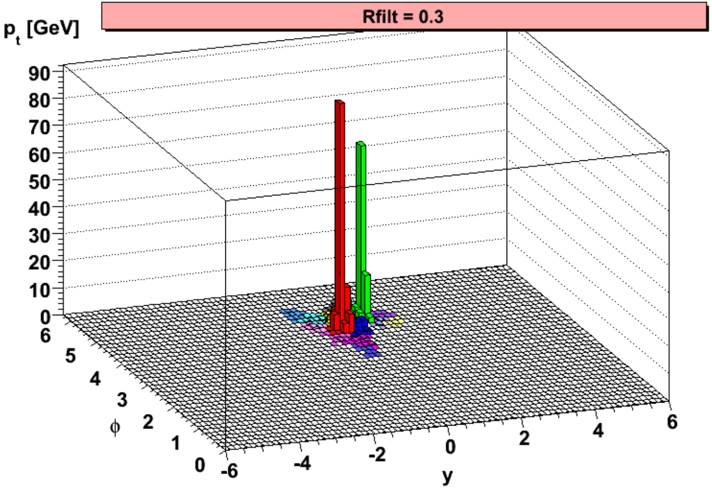
MassDrop+Filtering in action

Failed... iterate the mass drop



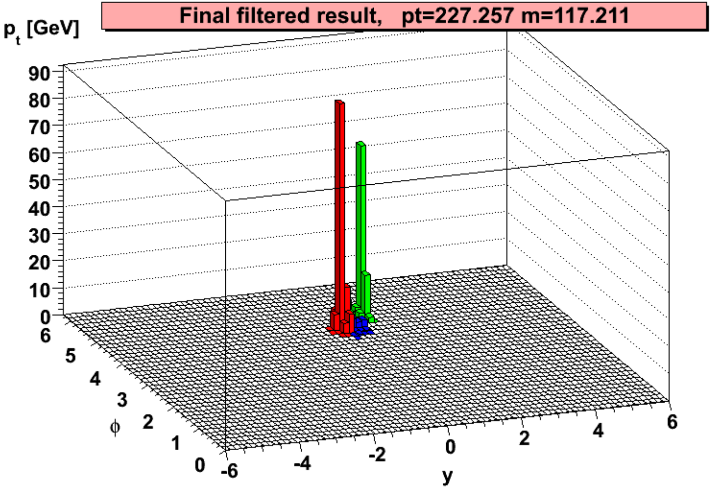
MassDrop+Filtering in action

Good... Now recluster what is left with a smaller R



MassDrop+Filtering in action

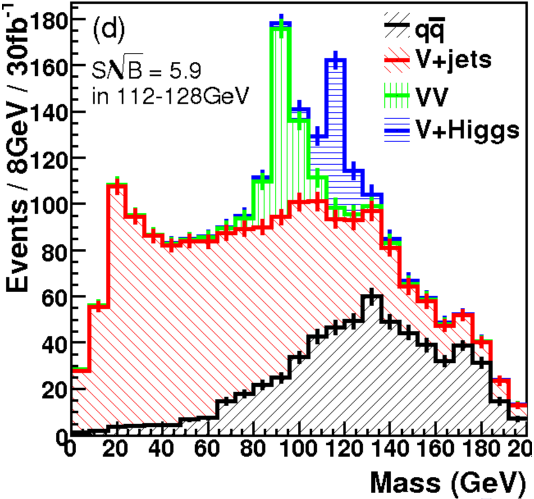
And keep only the 3 hardest



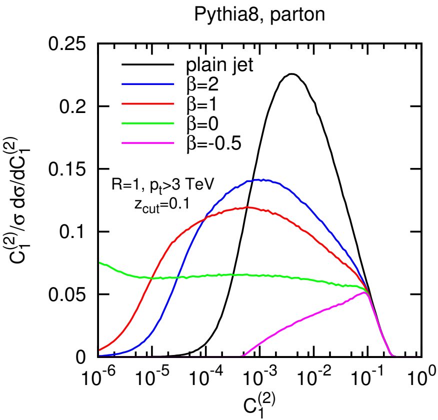
MassDrop for $H \to b\bar{b}$ searches

[J.Buterworth,A.Davison,M.Rubin,G.Salam,08]

This is the kind of Higgs reconstruction one would get



MassDrop and SoftDrop



β in SoftDrop can be seen as a control over the aggressivity

Constraining radiation

Example 3: N-subjettiness

Given N directions in a jet (axes) [$\neq$ options, e.g. k_t subjets or optimal]

$$\tau_N^{(\beta)} = \frac{1}{p_T R^\beta} \sum_{i\in\text{jet}} p_{t,i} \min(\theta^\beta_{i,a_1}, \dots, \theta^\beta_{i,a_n})$$

- Measure of the radiation from N prongs
- $\tau_{N,N-1} = \tau_N / \tau_{N-1}$ is a good variable for N-prong v. QCD

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Alternative: Energy-Correlation Functions (ECFs)

$$e_2^{(\beta)} = \frac{1}{p_t^2} \sum_{i<j} p_{t,i} p_{t,j} \theta_{ij}^\beta, \qquad e_3^{(\beta)} = \frac{1}{p_t^3} \sum_{i<j<k} p_{t,i} p_{t,j} p_{t,k} \theta_{ij}^\beta \theta_{jk}^\beta \theta_{ik}^\beta$$

In practice...

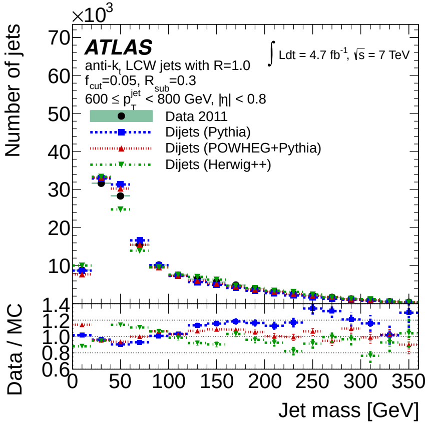
Typical workflow

Tools are

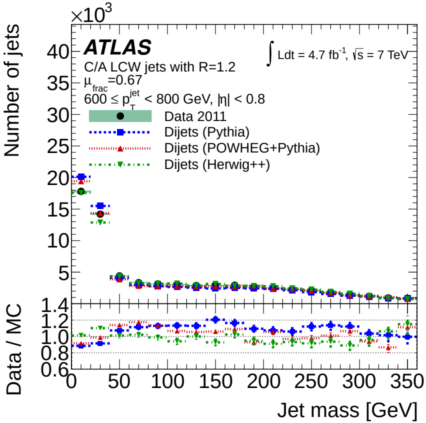
- developed/tested on Monte-Carlo simulations
- validated at the LHC (QCD backgrounds)

Example 1: Monte Carlo v. data

Trimming

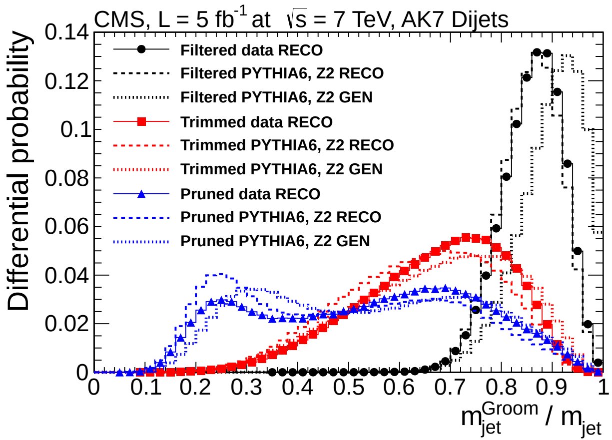


Mass-drop+filtering



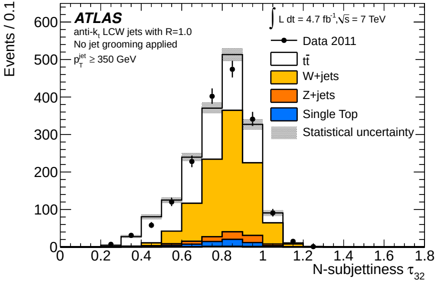
Example 1: Monte Carlo v. data

("Groomed" mass)/(plain mass)

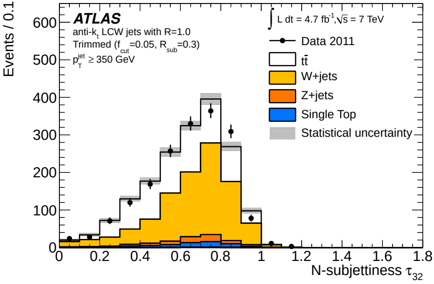


Example 1: Monte Carlo v. data

N-subjettiness τ_{32}



trimming+τ_{32}



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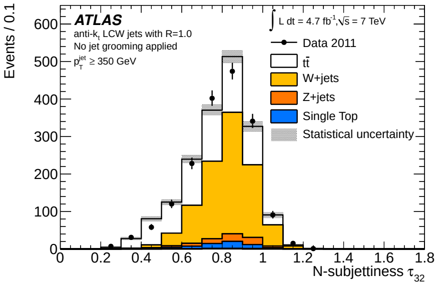

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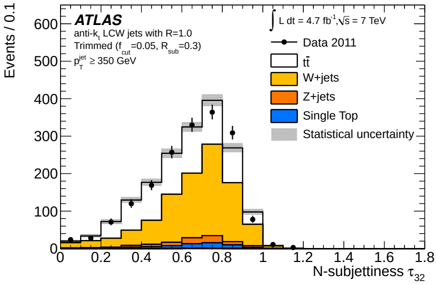


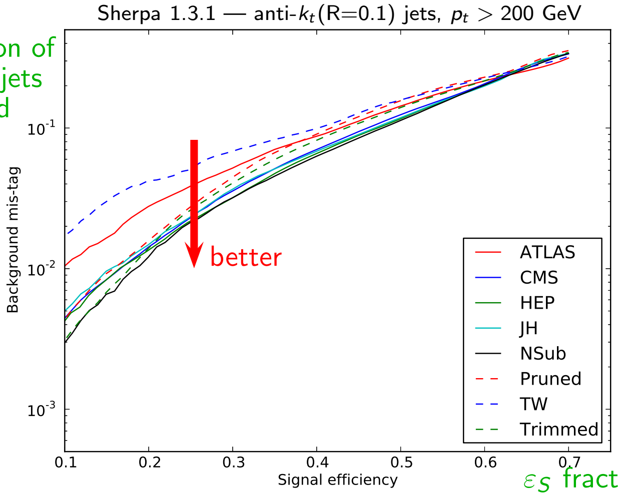
In a nutshell

- decent agreement between data and Monte-Carlo
- but some differences are observed

Example 2: top tagging MC study

[Boost 2011 proceedings]

ε_B fraction of QCD jets tagged



ε_S fraction of top jets tagged

Now,... one can get creative...

Finding N prongs works

Constraining radiation works

Now,... one can get creative...

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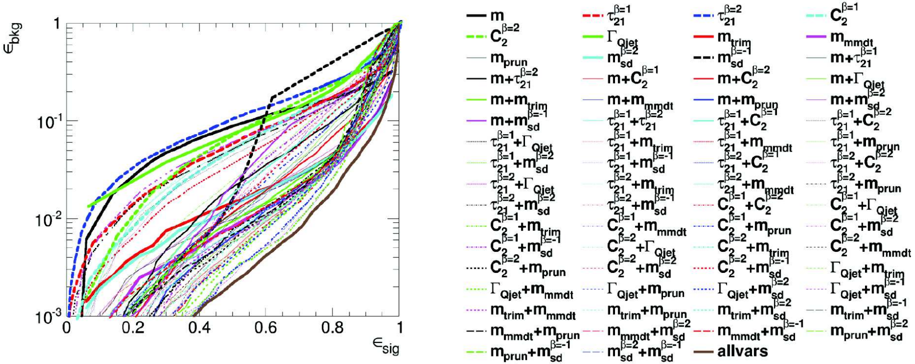
Constraining radiation works

Why not combining the two?

... or not?

[Boost 2013 WG]

W v. q jets: combination of "2-core finder" + "radiation constraint"



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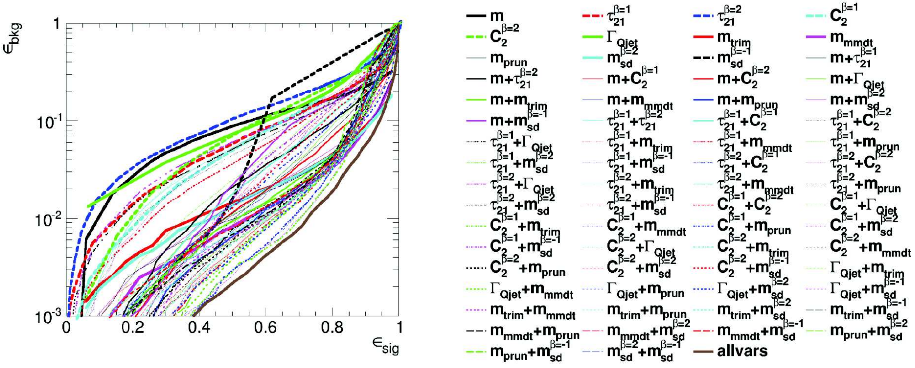

- Combination largely helps
- details not so obvious

STOP and think

can we stop blindly running Monte-Carlo and understand things better (from first-principle QCD)?

Idea

Empirical Monte-Carlo approach is limited

- Hard to extrapolate parameters
- No understanding of the details

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- Infer how to improve things further
- provide robust theory uncertainties (competition with performance?)

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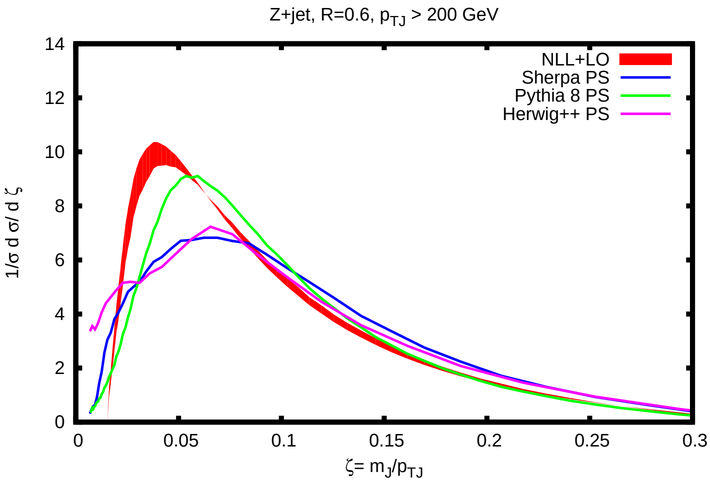
- provide robust theory uncertainties (competition with performance?)

Requires QCD techniques

- $\rho = m/(p_t R) \ll 1 \Rightarrow$ we get $\alpha_S \log^{(2)}(1/\rho)$
  $\Rightarrow$ need resummation
- matching with fixed-order for precision
- some nice QCD structures around the corner

Can reach high precision

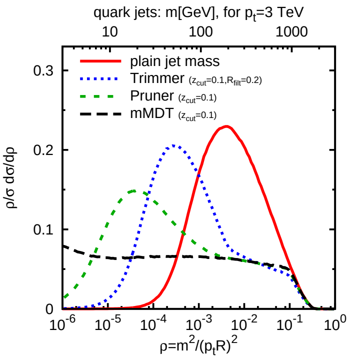


Monte-Carlo v. analytic

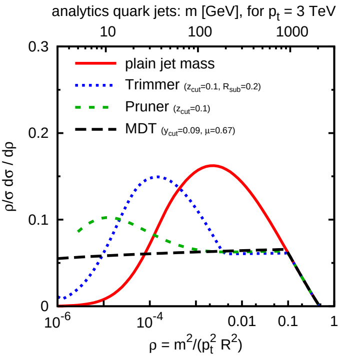
[M.Dasgupta,A.Fregoso,S.Marzani,G.Salam,13]

First analytic understanding of jet substructure:

Monte Carlo



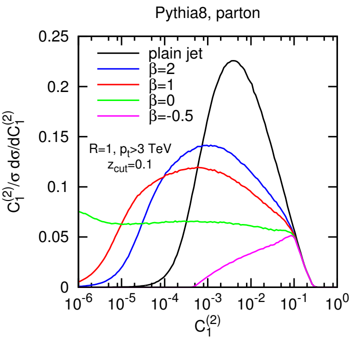
Analytics



- Similar behaviour at large mass/small boost (region tested so far)
- Significant differences at larger boost

SoftDrop

Monte Carlo



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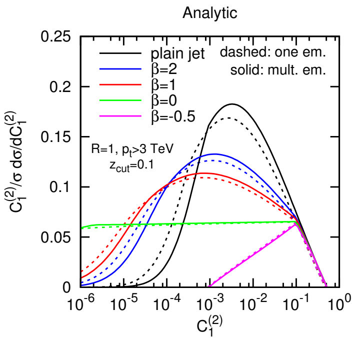

Again, analytic calculation reproduces MC features

Analytic example: mass drop

- Boosted limit: $p_t \gg m$ or $\rho = m^2/(p_t R)^2 \ll 1$

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- Plain jet mass: leading logs

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$$P(< \rho) = \exp\left[-\frac{\alpha_s C_F}{2\pi} \log^2(1/\rho)\right]$$

Various subleading ($\alpha_s \log(1/\rho)$,...) corrections:

  - Running coupling (fairly trivial/universal)
  - Hard collinear splitting (fairly trivial/universal)
  - Multiple emissions (fairly trivial/universal)
  - Soft-large-angle (not so trivial + process-dependent)
  - Non-global logs (nasty)

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$$P(<\rho) = \exp\left[-\frac{\alpha_s C_F}{2\pi}\log^2(1/\rho)\right]$$

- (modified)MassDrop has a similar but simpler structure:

$$P(<\rho) = \exp\left[-\frac{\alpha_s C_F}{\pi}\log(1/z_{\rm cut})\log(1/\rho)\right]$$

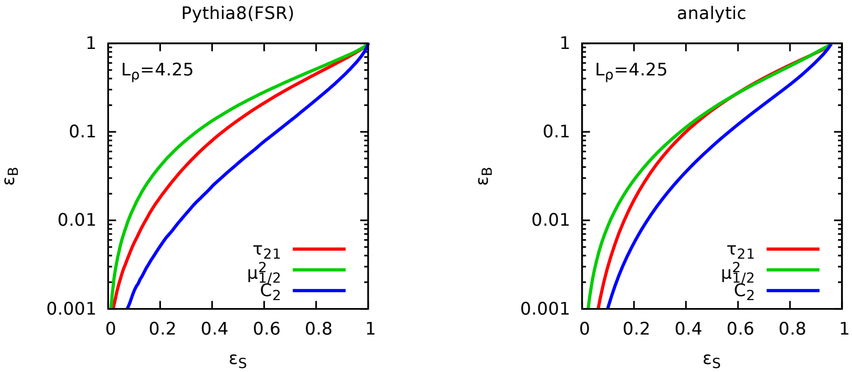
  - single log in ρ
  - no Soft-large-angle and no non-global logs (*)
  - smaller non-perturbative corrections (*)

(*) also true for Soft Drop.

Monte-Carlo v. analytic

[M.Dasgupta,L.Sarem-Schunk,GS,15]

For jet shapes ($\beta = 2$):



Monte-Carlo v. analytic

The situation/prospect today

- We start getting a basic understanding of some of the main tools
- both in terms of calculation techniques
  and in terms of physics understanding
- To come: more precise treatment
- To come: more basic tools
- To come: combination of tools
- To come: new improved tool (efficient, controlled, robust)

Summary: take-home messages

- Generic jet concepts
  - anti-k_t used almost everywhere, IRC-safe and fast
  - alternatives for specific cases
  - FastJet used as the default (fast+flexible) interface
- Boosted jets
  - More and more relevant
  - Many techniques around, validated at Run I
  - Many available in FastJet or fastjet-contrib
  - Combining tools helps
  - First-principle understanding has a large potential for more surprises

Tools: who? where?

Tool	Who[1]	Where
Mass-Drop	†Butterworth, Davison, Rubin, Salam	`fj::MassDropTagger`
	†Dasgupta, Fregoso, Marzani, Salam	`fj::contrib::ModifiedMassDropTagger`
Filtering	†Butterworth, Davison, Rubin, Salam	`fj::Filter`
Trimming	†Krohn, Thaler, Wang	`fj::Filter`
Pruning	†Ellis, Vermilion, Walsh	`fj::Pruner`
SoftDrop	†Larkoski, Marzani, Soyez, Thaler	`fj::contrib::SoftDrop`
N-subjettiness	†Thaler, Van Tilburg, Vermilion, Wilkinson	`fj::contrib::Nsubjettiness`
	†Jihun Kim	`fj::RestFrameNSubjettinessTagger`
Energy correlations	†Larkoski,Salam,Thaler	`fj::contrib::EnergyCorrelator`
Variable R	†Krohn, Thaler, Wang	`fj::contrib::VariableR`
ScJets	†Tseng, Evans	`fj::contrib::VariableR`
Johns Hopkins top tag	†Kaplan, Rehermann, Schwartz, Tweedie	`fj::JHTopTagger`
Jets without jets	†Bertolini, Chan, Thaler	`fj::contrib::...`
CASubjet tagging	†Salam	`fj::CASubJetTagger`
Y-splitter	†Butterworth, Cox, Forshaw	`fj::ClusterSequence::exclusive_subdmerge()`
Planar flow	†Almeida, Lee, Perez, Sterman, Sung, Virzi	3rd party
Pull	†Gallicchio, Schwartz	3rd party
Q-jets	†Ellis, Hornig, Krohn, Roy and Schwartz	3rd party
HEPTopTagger	†Plehn, Salam, Spannowsky, Takeuchi	3rd party
TemplateTagger	†Backovic, Juknevic, Perez	3rd party
shower deconstruction	†Soper, Spannowsky	3rd party

[1] References are incomplete

Backup slides

Example: plain-jet mass and resummation

$$\frac{1}{\sigma}\frac{d\sigma}{dm^2} = \int_0^{R^2}\frac{d\theta^2}{\theta^2}\int_0^1 dz\, P(z)\,\frac{\alpha_s}{2\pi}\delta(m^2 - z(1-z)\theta^2 p_t^2)$$

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- $(1-z)$ only need to power (of $m/(p_t R)$) corrections

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- we get a logarithmic enhancement
- Or, for the integrated distribution, using $\rho = m^2/(p_t^2 R^2)$

$$P_1(>\rho) = \int_\rho^1 dx\, \frac{1}{\sigma}\frac{d\sigma}{dx} = \alpha_s C_R \pi\, \frac{1}{2} \log^2(1/\rho)$$

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- "virtual" includes any number of the n gluons being virtual
- Leading term: **independent emissions**
- Sudakov exponentiation

Resummation in QCD

A much more general situation

For a jet shape v we will get terms enhanced by $\log^{(2)}(1/v)$ that have to be resummed at all orders

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Note: including running-coupling corrections: $P_1 = \sum_{k=1}^{n} (\alpha_s L)^k L$

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Physics idea

- Remember: (i) independent emissions, (ii) real and virtual emissions
- emissions "smaller" than v: do not contribute: real and virtual cancel
- emissions "larger" than v: real are vetoed
  $\Rightarrow$ we are left with virtuals(=-real)

Resummation in QCD

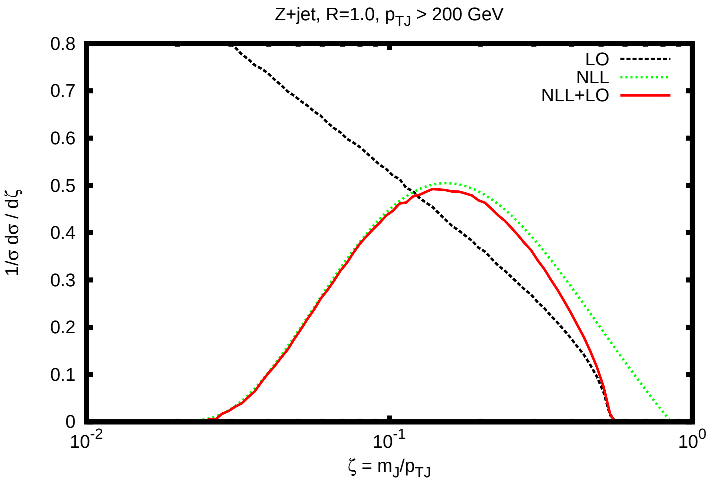
Next-to-leading log (NLL)

$$P(< v) = \exp\left[-g_1(\alpha_s L)L - g_2(\alpha_s L)\right]$$

- g_1 includes double logs (with running coupling)
- g_2 includes **single logs**
  - Finite piece in $P(z)$
  - Multiple (not independent) emissions contributing to v
  - 2-loop running coupling (+ scheme dependence)
  - Nasty non-global logs (out-of-jet emissions emitting back in)
- Can be matched to a fixed-order calculation

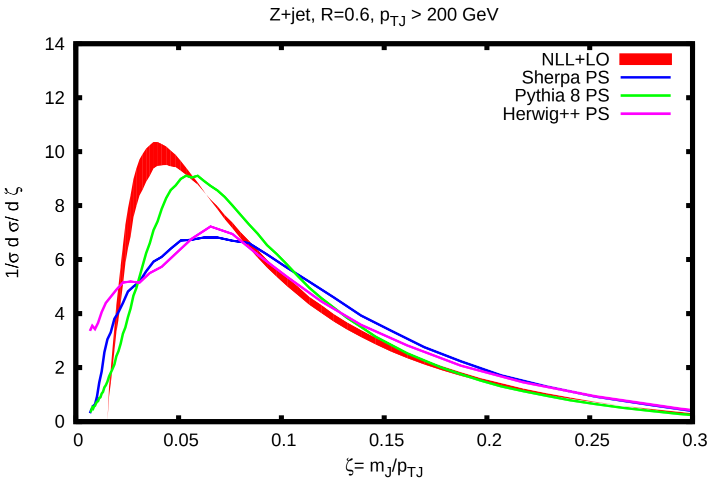
A few plots to illustrate what is going on

matching LO fixed-order with NLL resummation



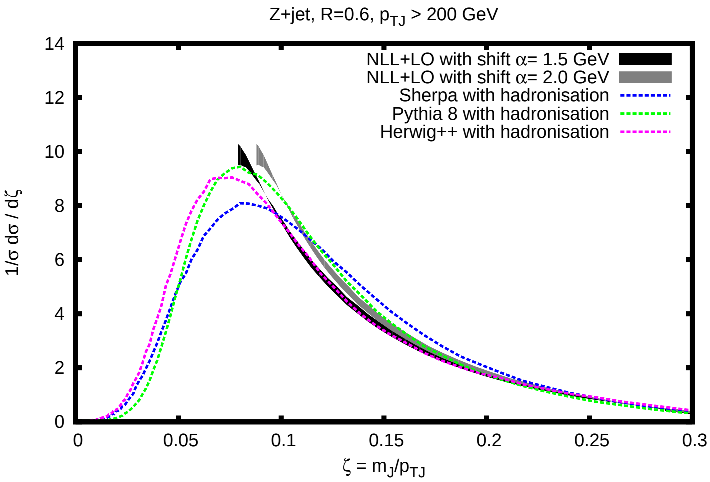
A few plots to illustrate what is going on

Comparison with parton shower



A few plots to illustrate what is going on

Including hadronisation



same approach for jet-substructure tools

Monte-Carlo v. analytic

[M.Dasgupta,A.Fregoso,S.Marzani,G.Salam,13]

First analytic understanding of jet substructure:

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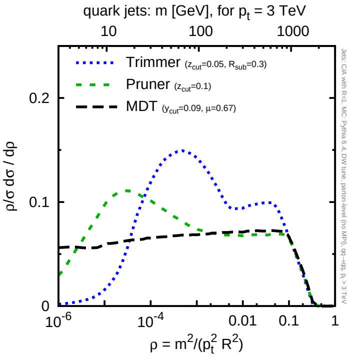
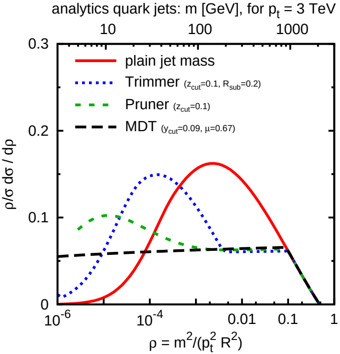


Analytics



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- Significant differences at larger boost

Analytic example: mass drop

- Boosted limit: $p_t \gg m$ or $\rho = m^2/(p_t R)^2 \ll 1$
- Emission of one gluon:

$$P_1(>\rho) = \frac{\alpha_s C_F}{\pi} \int \frac{d\theta^2}{\theta^2} dz\, P_{gq}(z) \underbrace{\Theta(z > z_{\rm cut})}_{\text{sym. cut}} \underbrace{\Theta(z(1-z)\theta^2 > \rho R^2)}_{\text{mass}}$$

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- single log in ρ!

Analytic example: extra notes

Analytic control teaches many lessons:

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- Non-perturbative corrections using similar techniques than previously

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  - Same as mass-drop for $\rho \geq f_{\rm filt}(R_{\rm filt}/R)^2$
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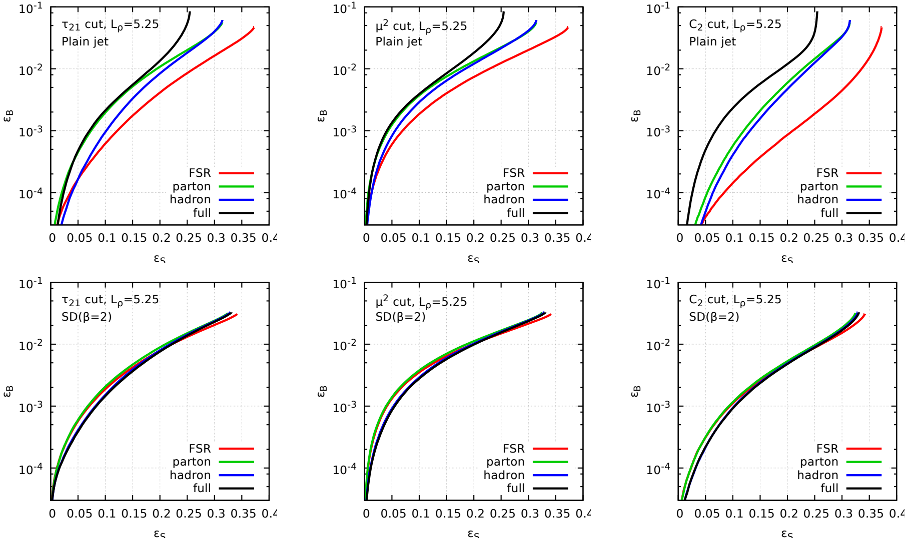
Stay tuned

First-principle understanding of jet substructure

- is still a young field but looks promising
- allows to understand what is going on
- allows control over th. uncertainties
- allows to introduce new, better, tools

NP effects and grooming for shapes



Grooming kills NP effects at a price in terms of efficiency