Fishing for new physics decaying to boosted objects
The "why" and "how" of boosted jets

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Brief plan

- What do we mean by "boosted jets"
  Facing a change of paradigm

- Why worry about boosted jets
  No boost, no future!

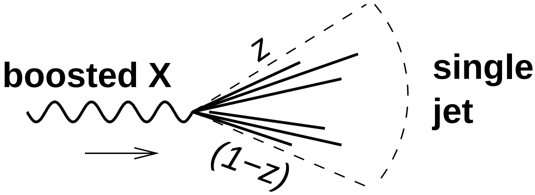
- How do we identify boosted objects
  - Run I: an army of tools
  - Run II: Towards surgical tools

What do we mean by a “boosted jet”

concept, importance, main ideas

Boosted jets

Object X decaying to hadrons



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

Boosted jets

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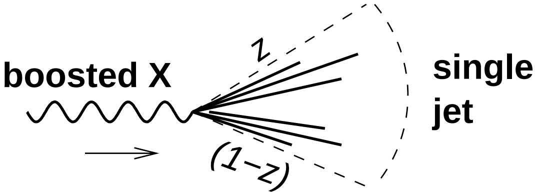


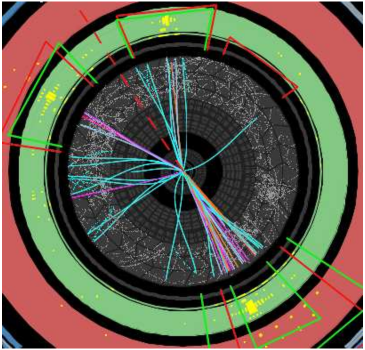
$$R \gtrsim \frac{m}{p_t} \frac{1}{\sqrt{z(1-z)}}$$

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

How to disentangle that from a QCD jet?

An illustration

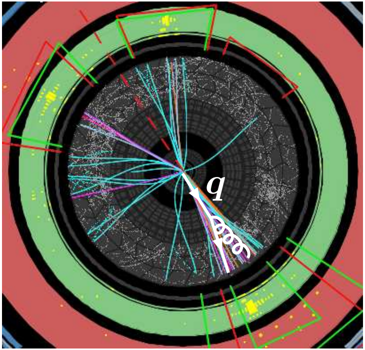
What jet do we have here?



An illustration

What jet do we have here?

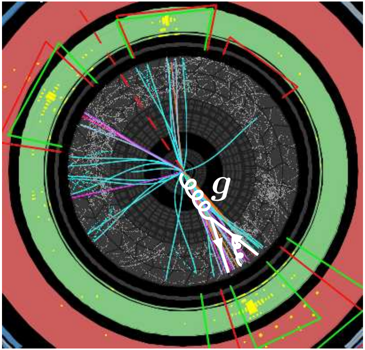
- a quark?



An illustration

What jet do we have here?

- a quark?
- a gluon?



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What jet do we have here?

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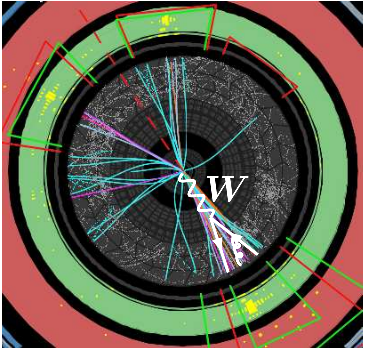
- a W/Z (or a Higgs)?



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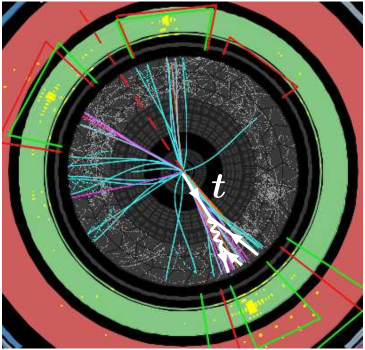

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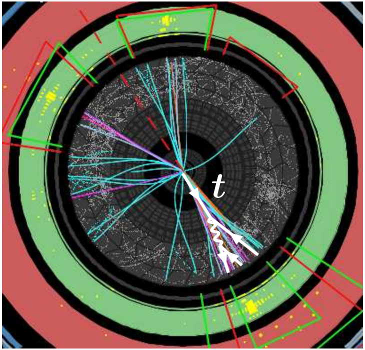

Source: ATLAS boosted top candidate

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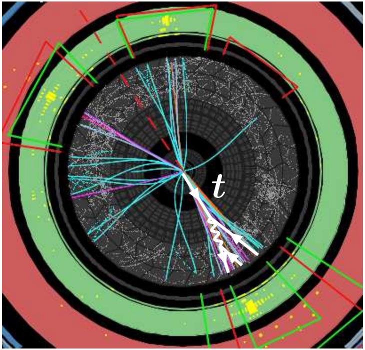

Source: ATLAS boosted top candidate

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

Why worry?

what importance, which objects?

Boosted jets

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

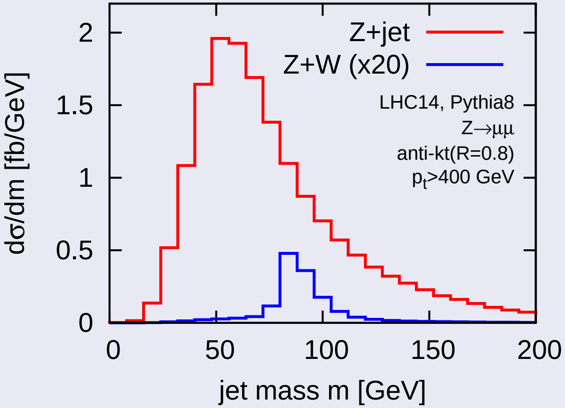
More and more boosted jets
Needs to be under control

How to proceed?

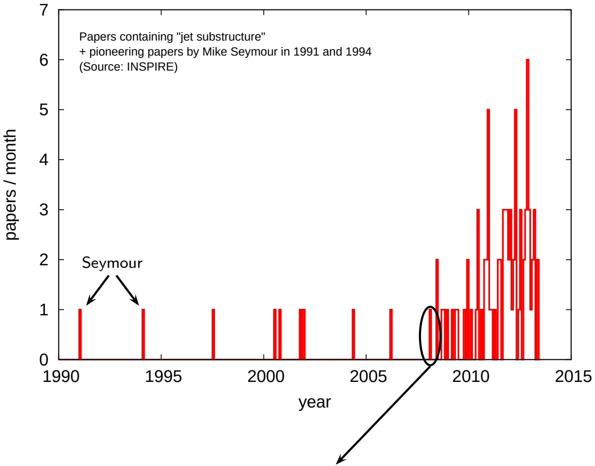
looking at jet substructure

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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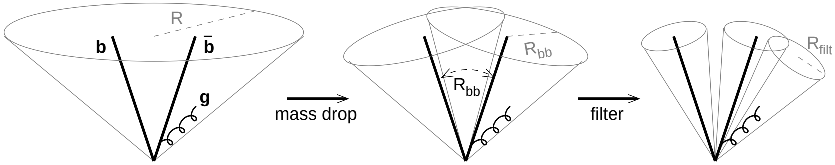

Many tools:

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 3rd-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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Idea 2: Constrain radiation patterns

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Radiation pattern is different for

- colourless $W \to q\bar{q}$
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- coloured $g \to q\bar{q}$

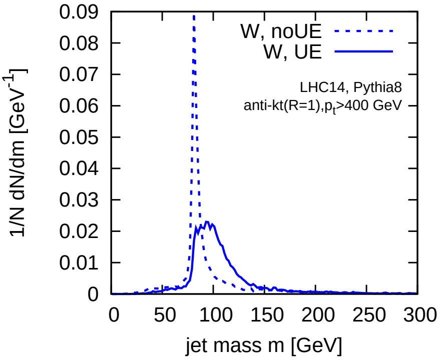
A few key approaches:

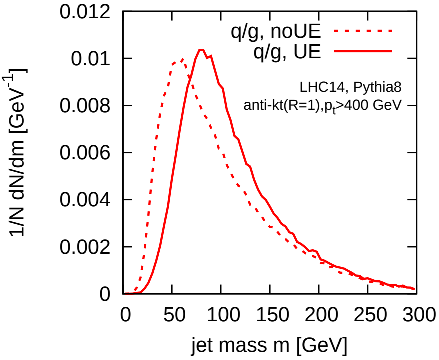
1. uncluster the jet into subjets/investigate the clustering history
2. use jet shapes (functions of jet constituents),...

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, $R = R_{\rm sub}$
- Filtering: keep the $n_{\rm filt}$ hardest subjets
  [J.Buterworth,A.Davison,M.Rubin,G.Salam,08]
- Trimming: keep subjets with $p_t > f_{\rm trim} p_{t,\rm jet}$ [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 $\max(p_{t1}, p_{t2}) > z_{\mathrm{cut}} p_t$, 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

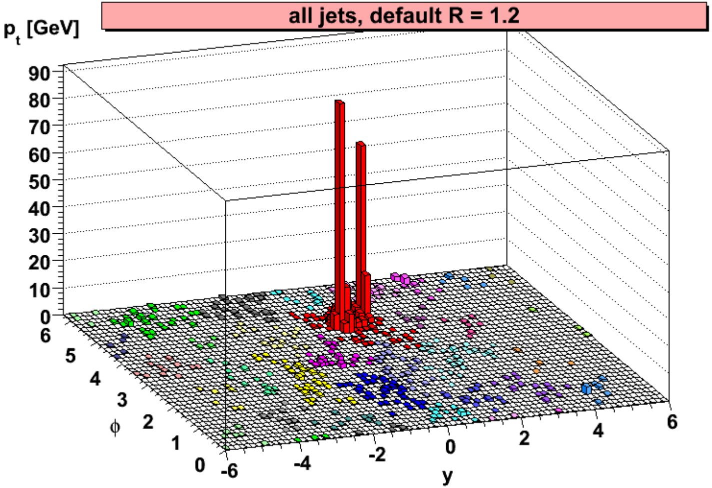
Same de-clustering procedure as the mMDT but angular-dependent cut

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

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

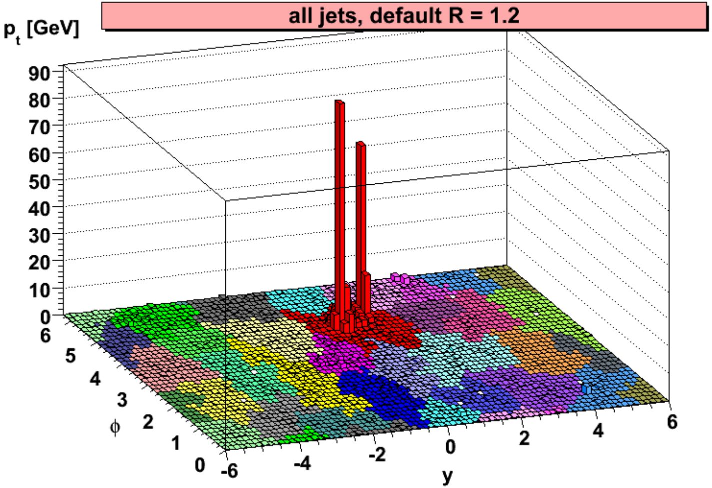
MassDrop+Filtering in action

Start with the jets in an event



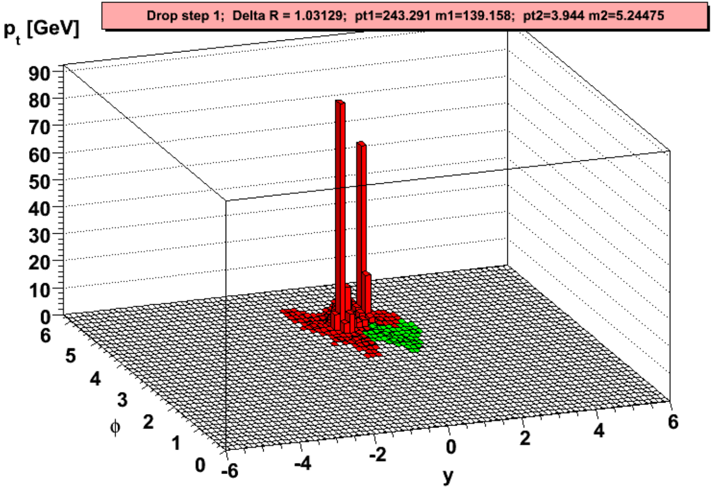
MassDrop+Filtering in action

This is what they look like with their area



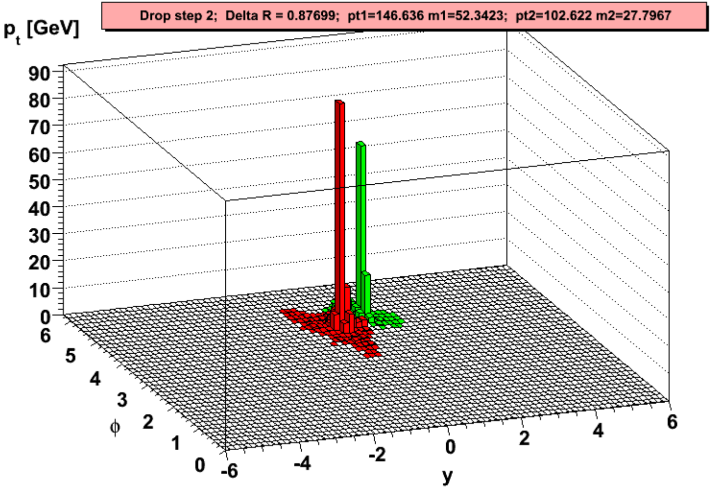
MassDrop+Filtering in action

Take the hardest, apply a step of mass-drop



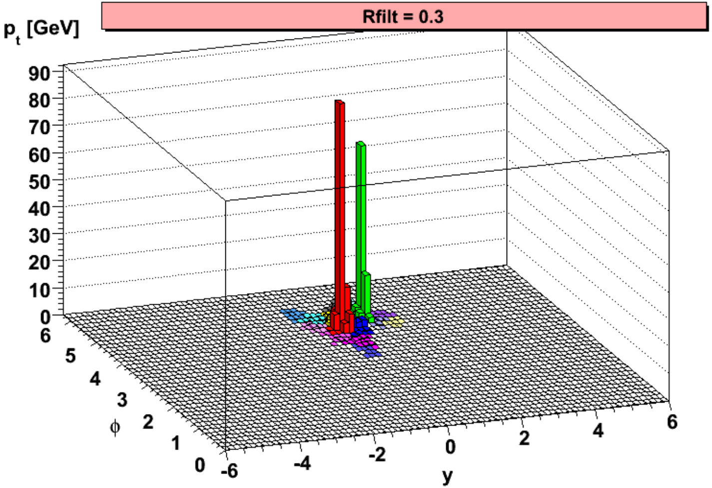
MassDrop+Filtering in action

Failed... iterate the mass drop



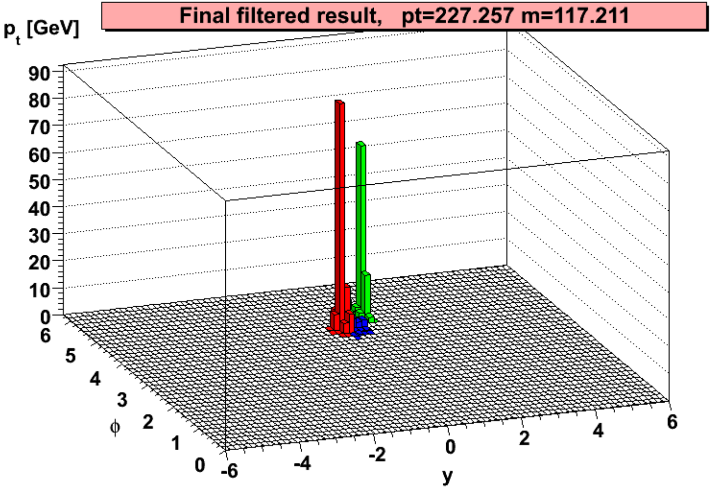
MassDrop+Filtering in action

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



MassDrop+Filtering in action

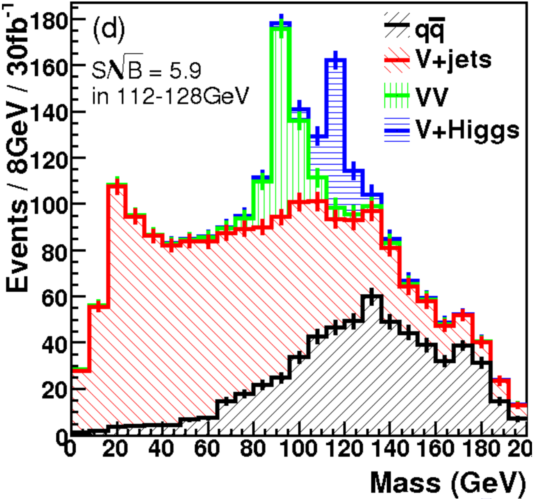
And keep only the 3 hardest



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



Constraining radiation

Example 3: N-subjettiness

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

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

- 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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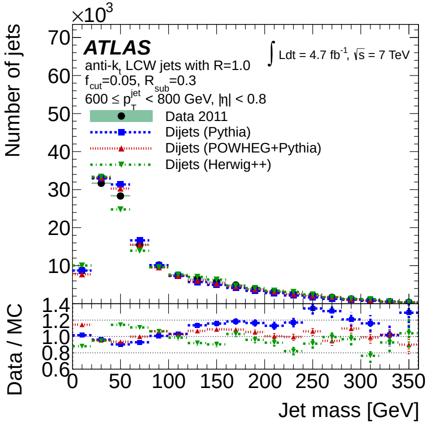
In practice

Tools are

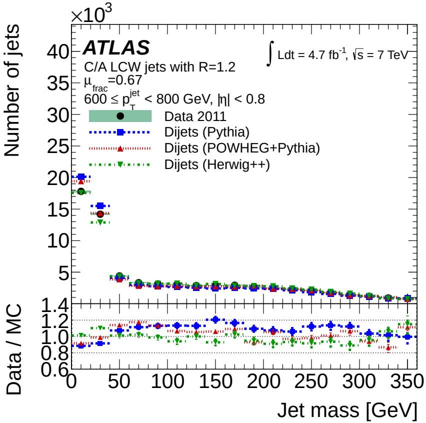
- developed/tested on Monte-Carlo simulations
- validated at the LHC (QCD backgrounds)

Example 1: Monte Carlo v. data

Trimming

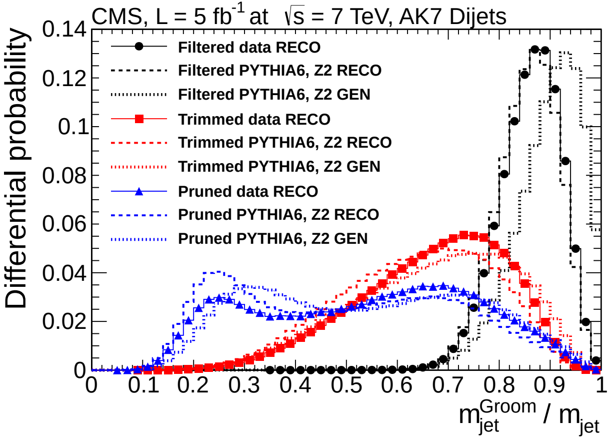


Mass-drop+filtering



Example 1: Monte Carlo v. data

("Groomed" mass)/(plain mass)



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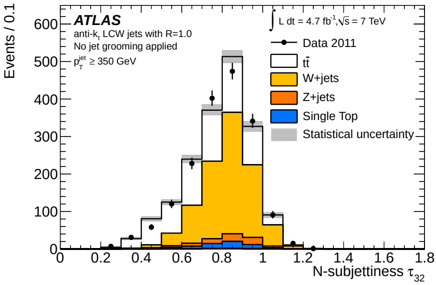
N-subjettiness τ_{32}



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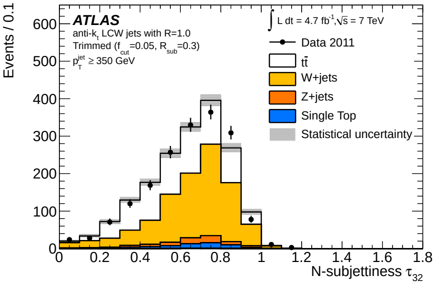

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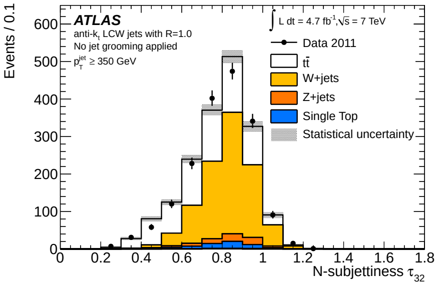

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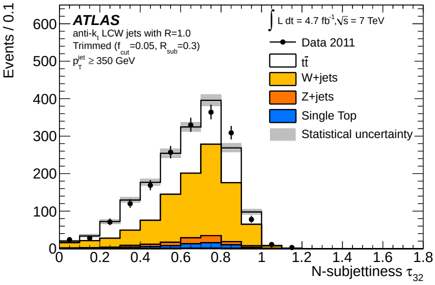


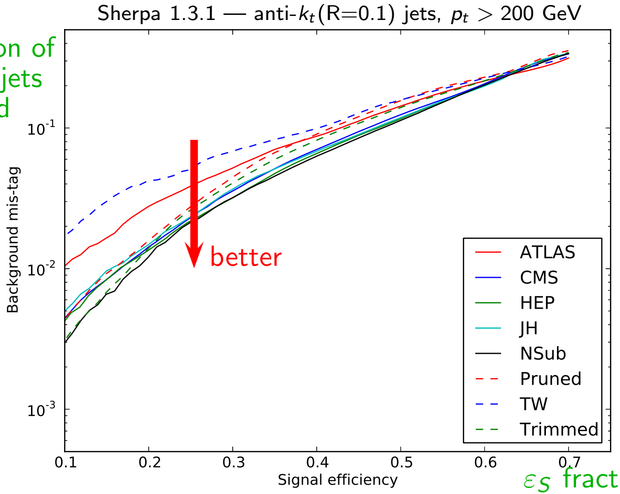
In a nutshell

- 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

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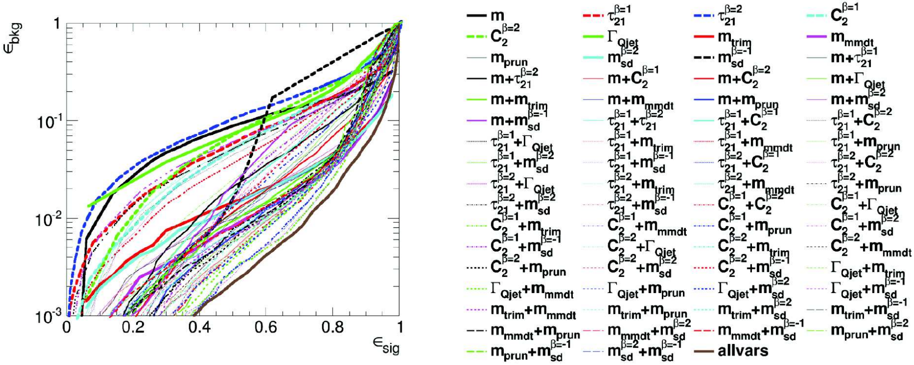
Constraining radiation works

Why not combining the two?

[Boost 2013 WG]

W v. *q* jets: combination of “2-core finder” + “radiation constraint”



... or not?

[Boost 2013 WG]

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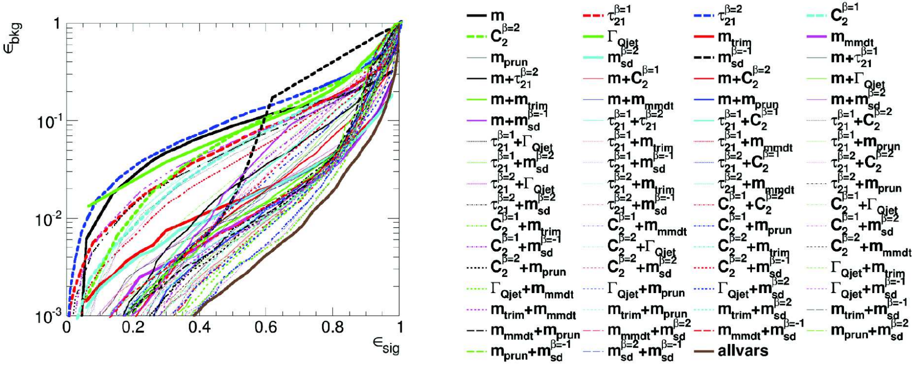

- Combination largely helps
- details not so obvious

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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- provide robust theory uncertainties (competition with performance?)

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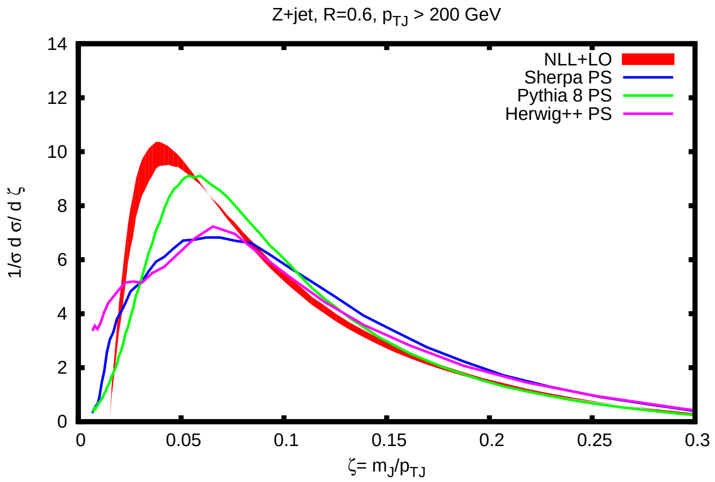
Requires QCD techniques

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

Example 1:: the jet mass

Can reach high precision

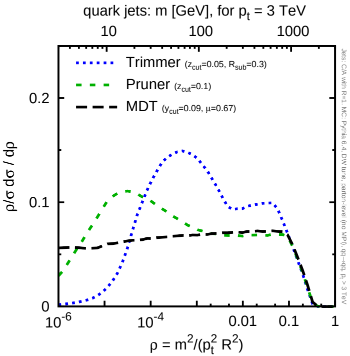


Monte-Carlo v. analytic

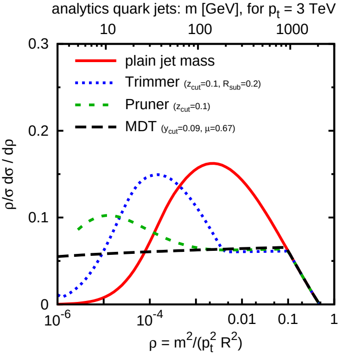
[M.Dasgupta,A.Fregoso,S.Marzani,G.Salam,13]

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

Summary: take-home messages

- Boosted jets is an emerging field
  - more and more important with higher energy/bounds/scales
  - relevant for Higgs and new physics searches
- Many tools validated at Run I
  - Many methods and tools
  - Based on a few physics ideas
  - MC/Run-I data validation
- Exciting future for Run II and beyond
  - Existing tools will be used for searches in Run II
  - 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	3$^{\rm rd}$ party
Pull	†Gallicchio, Schwartz	3$^{\rm rd}$ party
Q-jets	†Ellis, Hornig, Krohn, Roy and Schwartz	3$^{\rm rd}$ party
HEPTopTagger	†Plehn, Salam, Spannowsky, Takeuchi	3$^{\rm rd}$ party
TemplateTagger	†Backovic, Juknevic, Perez	3$^{\rm rd}$ party
shower deconstruction	†Soper, Spannowsky	3$^{\rm rd}$ party

[1] References are incomplete

Backup slides

Example: plain-jet mass and resummation

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

- We focus on small-R, $p_t R \gg m$

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- We focus on small-R, $p_t R \gg m$
- $P(z) = 2C_R/z$ up to subleading (log) corrections
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$$\approx \frac{\alpha_s C_R}{\pi}\frac{1}{m^2}\log(p_t^2 R^2/m^2)$$

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- $P(z) = 2C_R/z$ up to subleading (log) corrections
- $(1-z)$ only need to power (of $m/(p_t R)$) corrections
- we get a logarithmic enhancement

Example: plain-jet mass and resummation

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

$$\approx \int_0^{R^2}\frac{d\theta^2}{\theta^2}\int_0^1 dz\,\frac{2C_R}{z}\,\frac{\alpha_s}{2\pi}\delta(m^2 - z\theta^2 p_t^2)$$

$$\approx \frac{\alpha_s C_R}{\pi}\,\frac{1}{m^2}\log(p_t^2 R^2/m^2)$$

- We focus on small-R, $p_t R \gg m$
- $P(z) = 2C_R/z$ up to subleading (log) corrections
- $(1-z)$ only need to power (of $m/(p_t R)$) corrections
- 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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$$= \exp\left[-P_1(>\rho)\right]$$

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- Sudakov exponentiation

Resummation in QCD

A much more general situation

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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

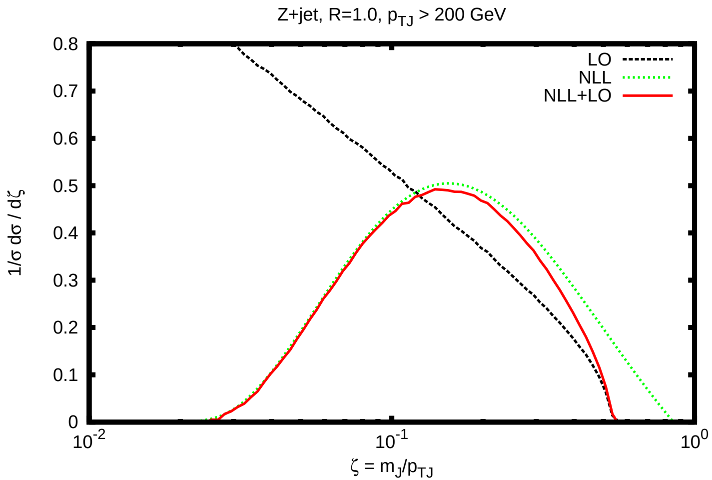
Next-to-leading log (NLL)

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

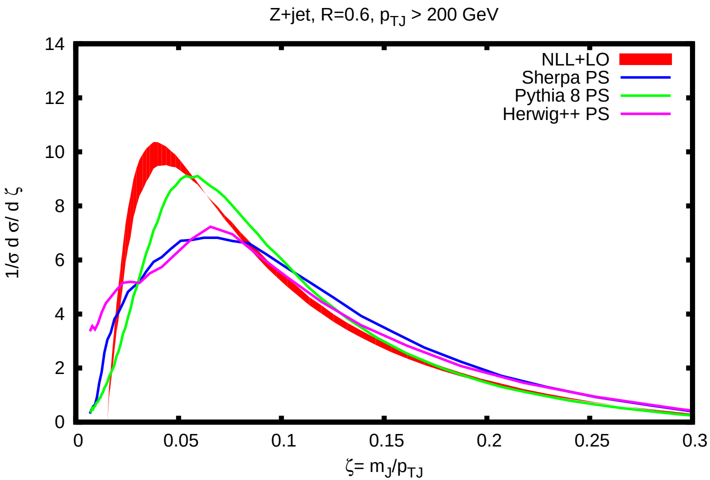
- g_1 includes double logs (with running coupling)
- g_2 includes **single logs**
  - Finite piece in $P(z)$
  - Multiple (not independent) emissions contributing to v
  - 2-loop running coupling (+ scheme dependence)
  - Nasty non-global logs (out-of-jet emissions emitting back in)
- Can be matched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

A few plots to illustrate what is going on

matching LO fixed-order with NLL resummation

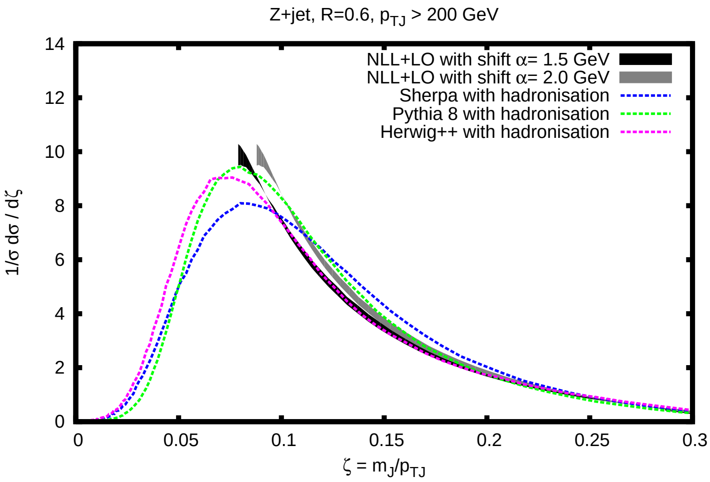


Comparison with parton shower



A few plots to illustrate what is going on

Including hadronisation

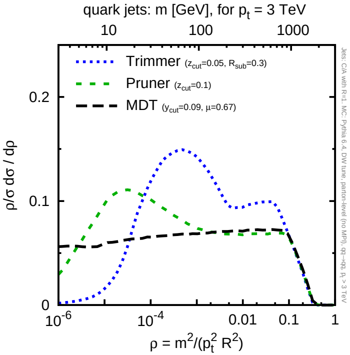


same approach for jet-substructure tools

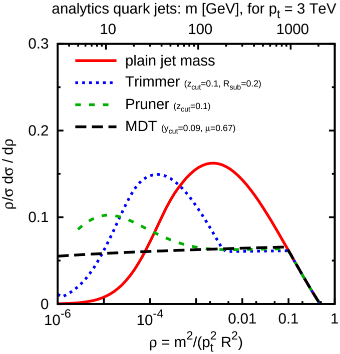
[M.Dasgupta,A.Fregoso,S.Marzani,G.Salam,13]

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

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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- Focus on logarithmically enhanced terms

$$P_1(>\rho) = \frac{\alpha_s C_F}{\pi} \left[\log(1/\rho)\log(1/z_{\rm cut}) - \frac{3}{4}\log(1/\rho) - \frac{1}{2}\log^2(1/z_{\rm cut})\right]$$

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- single log in ρ!

Analytic example: extra notes

Analytic control teaches many lessons:

- Original mass-drop tagger had an extra “mass-drop” condition:
  no contribution at this order (+work in progress)
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- Absence of problematic non-global logs
- Non-perturbative corrections using similar techniques than previously

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  - Same as mass-drop for $\rho \geq f_{\rm filt}(R_{\rm filt}/R)^2$
  - double log behaviour ($\log^2(1/\rho)$ of plain jet mass for $\rho < f_{\rm filt}(R_{\rm filt}/R)^2$

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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