Jets at the LHC
From Run I to Run II and beyond

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Brief plan

- Basic framework
  Jets at the LHC, anti-k_t algorithm, FastJet

- Challenge 1: pileup
  - Run I: Jet area–median pileup subtraction
  - Towards Run II: noise-reduction ans SoftKiller

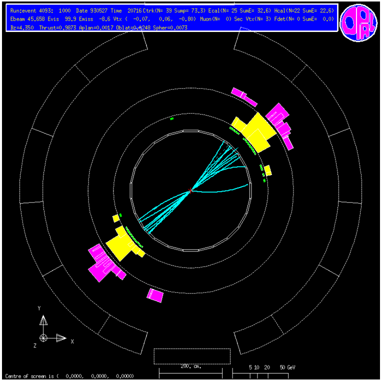
- Challenge 2: jet substructure
  - New paradigm for jets
  - boosted jet tagging

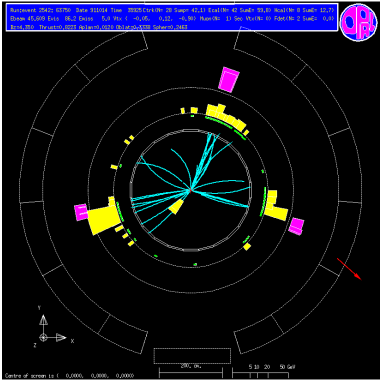
Jets: basic concepts

Jets

Final-state events are pencil-like

already observed in e^+e^- collisions:





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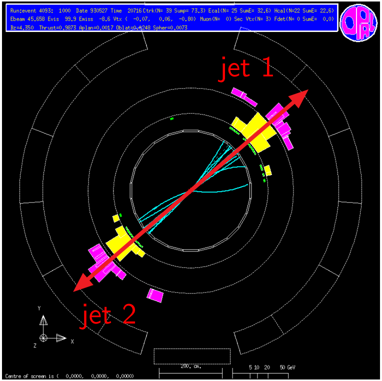

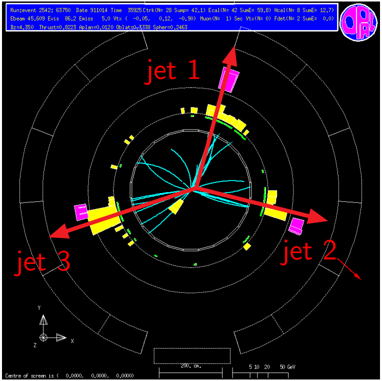

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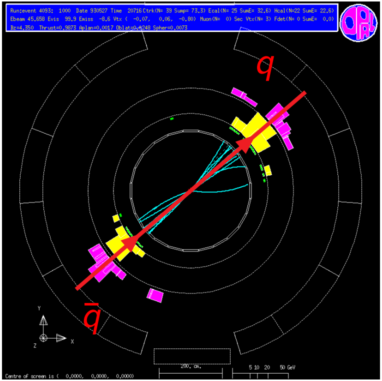

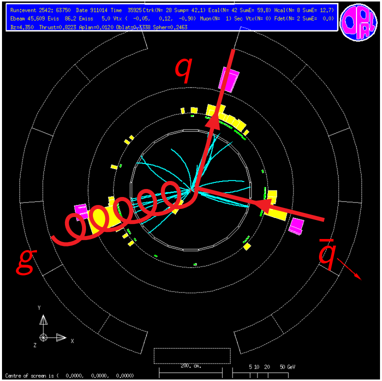

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Jets and partons

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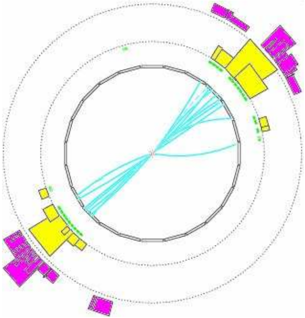
"obviously" 2 jets



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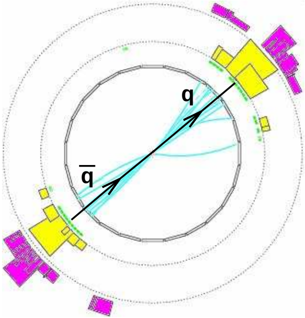

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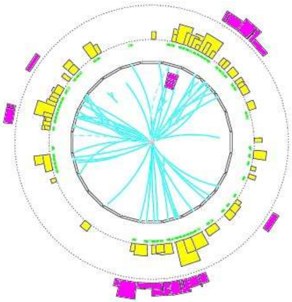
3 jets?



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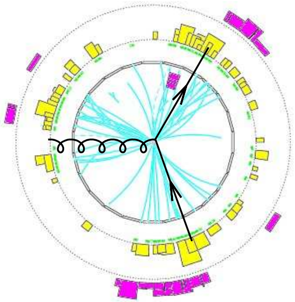

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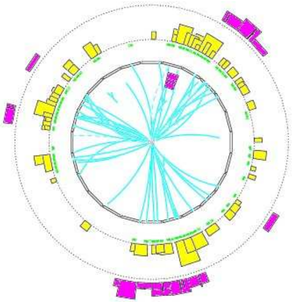

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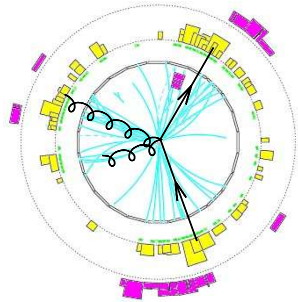

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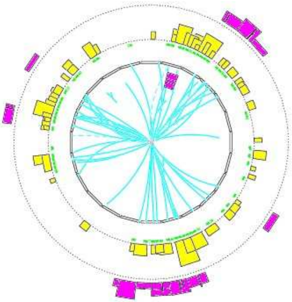

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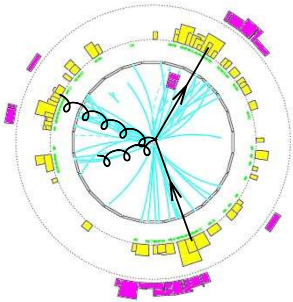
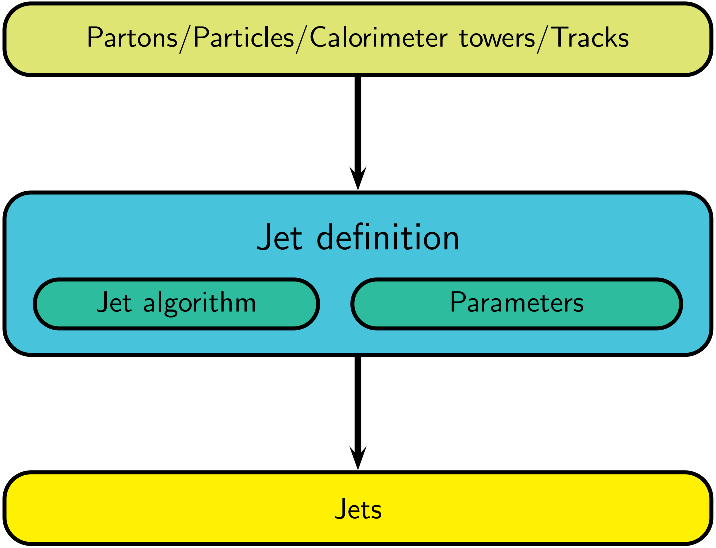


- "collinear" is arbitrary (typically needs a resolution parameter)
- "parton" concept strictly valid only at LO

Jet definition



Recombination algorithms

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

(Anti-k_t) algorithm

- From all the objects, define the distances

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

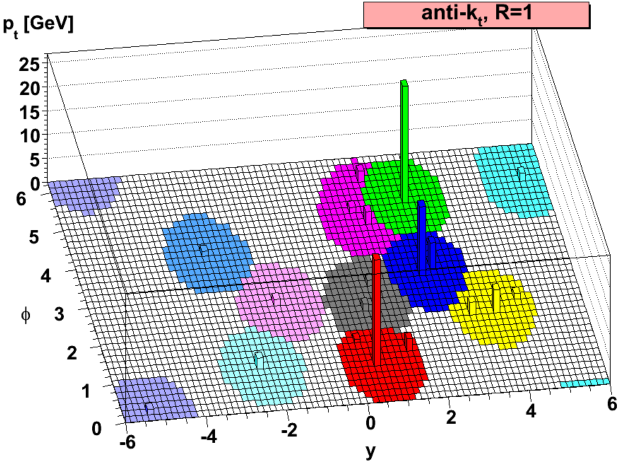
- repeatedly find the minimal distance
  if d_{ij}: recombine i and j into $k = i + j$
  if d_{iB}: call i a jet
- One parameters: R ("jet radius").

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

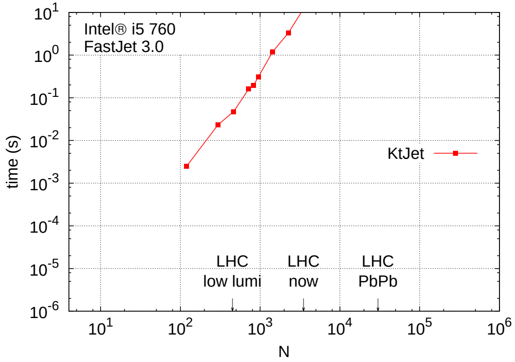
The anti-k_t jets

Main property: hard jets are circular



FastJet (1/2)

[M.Cacciari, G.Salam, 2005]



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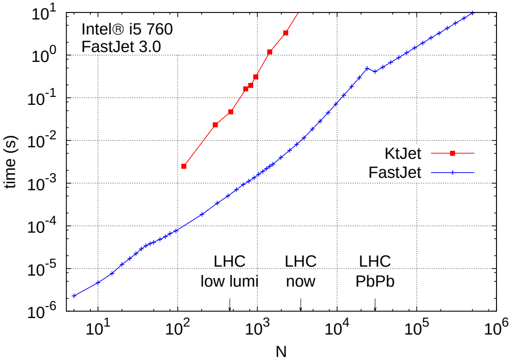

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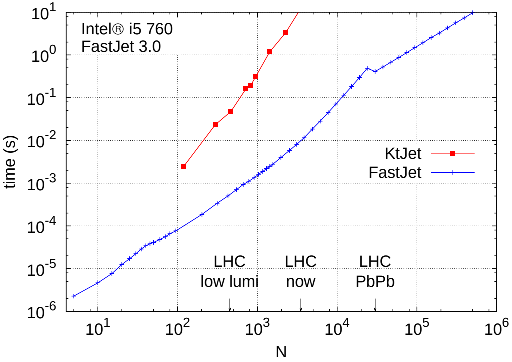

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- Fastjet 3.1: typically 5-50ms for LHC (with pileup and areas)

FastJet (2/2)

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

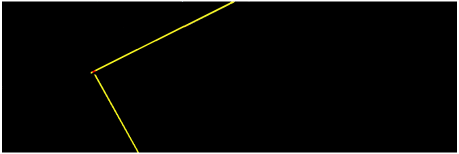
- Grown way beyond just fast recombinations:
  - plugins for used jet definitions
  - jet areas and background subtraction (see below)
  - tools for manipulating jets
  - more to come...
- FastJet 3.1.3 released in July 2015
  see `www.fastjet.fr`
- Standard interface for jet physics
  for both theorists and experimentalists

Pileup mitigation

Pileup

$Z \to \ell^+\ell^-$ candidate at ATLAS

Low luminosity
(bunch population)



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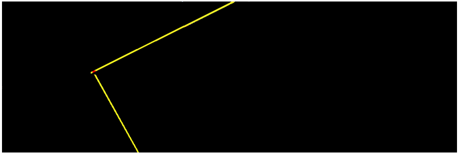

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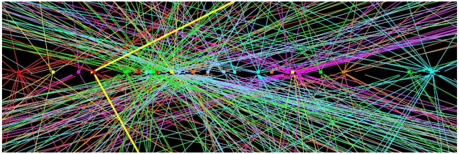


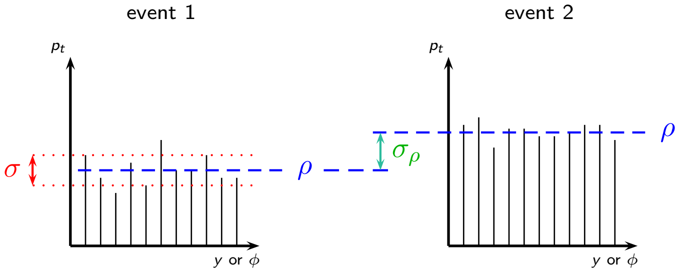
Pileup complicates things

- many (soft) *pp* interactions with the hard one (here 25)
  LHC Run I: $\sim$ 20-25, Run II: $\lesssim$ 60, upgrades: $\lesssim$ 200
- soft background in the whole detector

Basic characterisation

Pileup mostly characterised by 3 numbers $^{(*)}$:

- ρ: the average activity in an event (per unit area)
- σ: the intra-event fluctuations (per unit area)
- σ_ρ: the event-to-event fluctuations of ρ



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Jet of momentum p_t and area A:

$$\text{one event:}\;\; p_t \to p_t + \rho A \pm \sigma\sqrt{A}$$

$$\text{event average:}\;\; p_t \to p_t + \langle\rho\rangle A \pm \sigma_\rho A \pm \sigma\sqrt{A}$$

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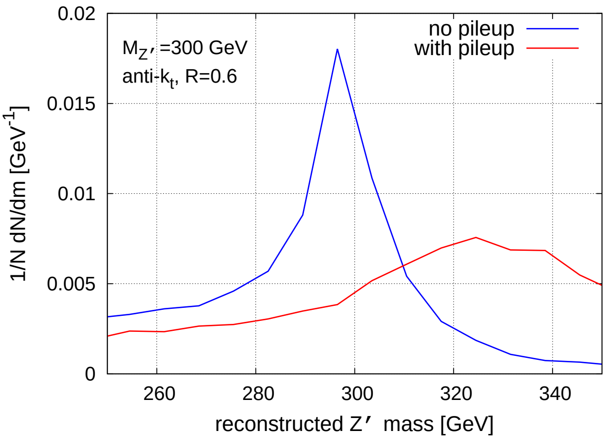
p_t shift

p_t smearing
resolution degradation

$^{(*)}$ valid also for the underlying event in heavy-ion collisions

Illustrative example



Subtraction methods (correct for the shift)

one subtracts a contribution from individual jets

subtracted	PU effects kept
constant p_t ($\langle \rho A \rangle$)	both flucts + area flucts
$\langle \rho \rangle \times A$	both flucts ($\sigma\sqrt{A}$ & $\sigma_\rho A$)
$\langle \rho \rangle_{\text{per PU vertex}} \times n_{PU} \times A$	$\sigma\sqrt{A}$ and part of $\sigma_\rho A$
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more averaged ↕ 'event-by-event'

Event-by-event determinations of the shift (are expected to) reduce the smearing effects of PU

Defining jet area

"Active" area definition:

- Add "ghosts" to the event:
  - particles with infinitesimal p_t
  - on a grid ($+$ small random fluctuations) of cell area a_0

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- Include the ghosts in the clustering
- If a jet contains N_g ghosts, its area is $N_g a_0$

Median-area-based subtraction

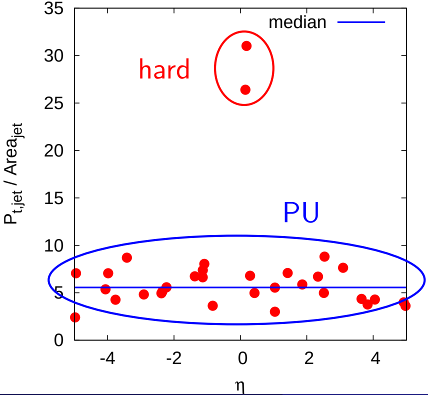
[M.Cacciari, G.P. Salam, 07; M.Cacciari, G.P. Salam, GS, 2008]

Estimation: $\rho_{\rm est} = \underset{j\in\text{patches}}{\rm median} \left\{ \frac{p_{t,j}}{A_j} \right\}$

Subtraction: $p_{t,\rm jet}^{(\rm sub)} = p_{t,\rm jet} - \rho_{\rm est} A_{\rm jet}$

per event (typically)

per jet



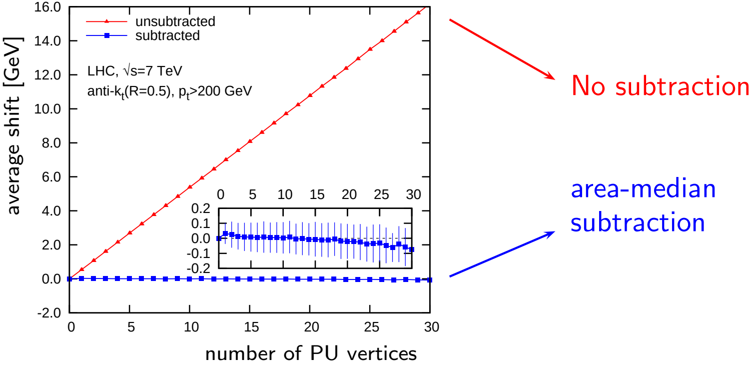
break the event in patches of similar size

e.g. cluster with k_t

or break into grid cells

Subtraction benchmarks

average p_t shift



corrected for shift

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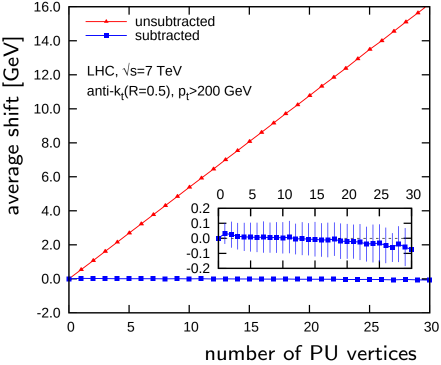
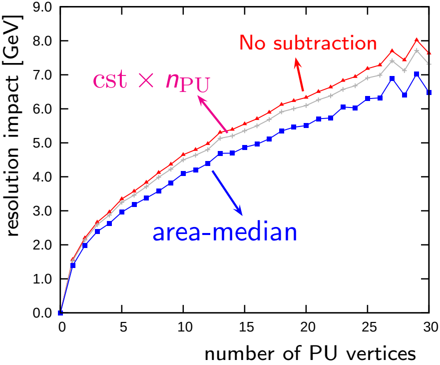


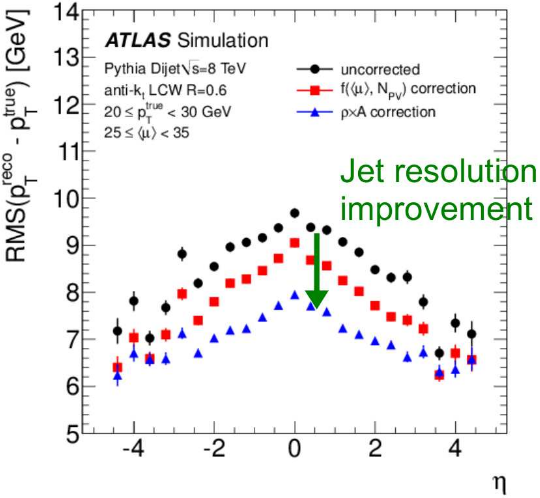
corrected for shift

impact on resolution



resolution improved

PU subtraction as seen in ATLAS



[B. Petersen, ATLAS Status report for the LHCC, 2013]

Further developments

Improvements/extensions of the basic method

- Methods to handle positional dependence of ρ
  Directly relevant for the LHC (*e.g.* rapidity dependence)
  [M.Cacciari,G.Salam,GS,2010-2011]

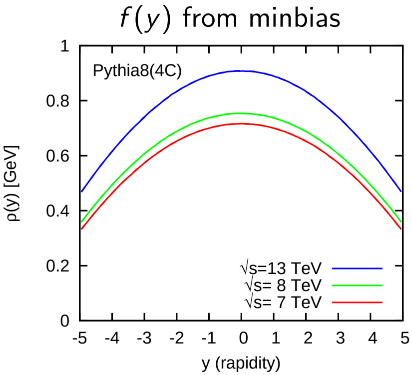
- Subtraction for jet mass and jet shapes
  Important for jet tagging ("q v. g jet", b jet, top jet, $H \to b\bar{b}$)
  [GS,G.Salam,J.Kim,S.Dutta,M.Cacciari,2013]
  [P.Berta,M.Spousta,D.Miller,R.Leitner,2014]

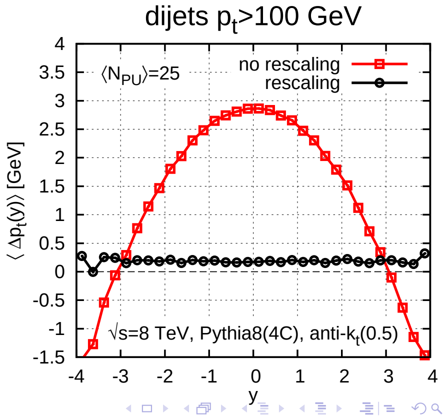
- Subtraction of fragmentation function (moments)
  Useful for quenching in *PbPb* collisions
  [M.Cacciari,P.Quiroga,G.Salam,GS,2012]

- Recommended setup: ρ estimation from a grid with cell-size=0.55 + appropriate rescaling to handle rapidity dependence

Rapidity dependence

$$\rho = \underset{j \in \text{patches}}{\text{median}} \left\{ \frac{p_{t,j}}{A_j} \right\} \quad \longrightarrow \quad \rho(y) = f(y) \underset{j \in \text{patches}}{\text{median}} \left\{ \frac{p_{t,j}}{A_j f(y_j)} \right\}$$





New techniques

Noise-reduction techniques

Overall idea

- Try to further reduce the impact on resolution $\sigma_{\Delta p_t}$
- Usually at the expense of biases on $\langle \Delta p_t \rangle$
- Requires more delicate tuning

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Several methods

- **SoftKiller**: remove low-p_t particles
  [M.Cacciari,G.Salam,GS,14]
- **PUPPI**: from CMS (charged tracks info + assignment probability)
  [D.Bertolini,P.Harris,M.Low,N.Tran,14]
- **Jet Cleansing**: charged tracks + subjets + little extra
  [D.Krohn,M.Low,M.Schwartz,L-T.Wang,13]
- **Constituent Subtractor**: ask Peter
  [P.Berta,M.Spousta,D.Miller,R.Leitner,2014]

SoftKiller

Recipe

Remove the softest particle in the event until $\rho_{\text{est}} = 0$

One parameter: a, the size of the grid used to estimate ρ

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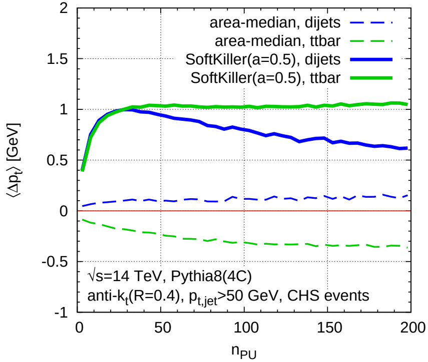

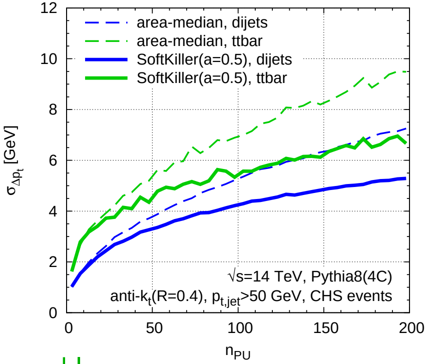

reasonable

im

bias

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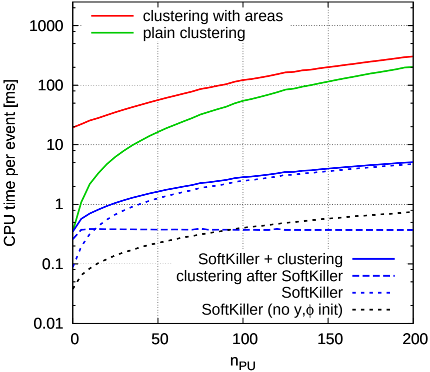


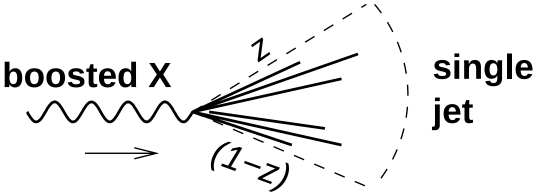
Allows very fast implementation

(see SoftKiller fastjet contrib)

Boosted jets

Boosted jets: main iea

Object X decaying to hadrons



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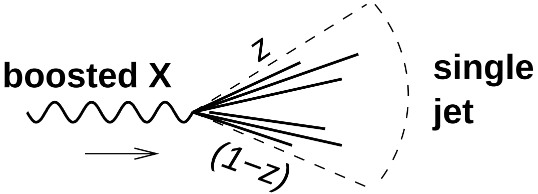

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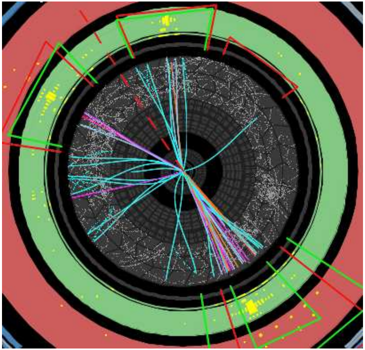
If $p_t \gg m$, reconstructed as a single jet

How to disentangle that from a QCD jet?

An illustration

What jet do we have here?



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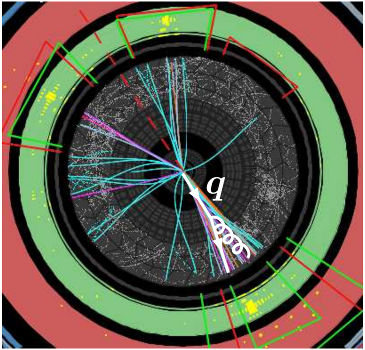
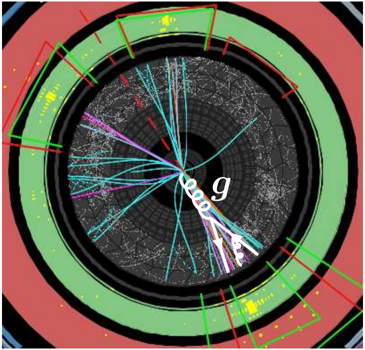


An illustration

What jet do we have here?

- a quark?
- a gluon?



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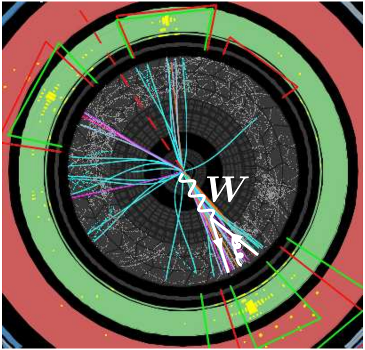

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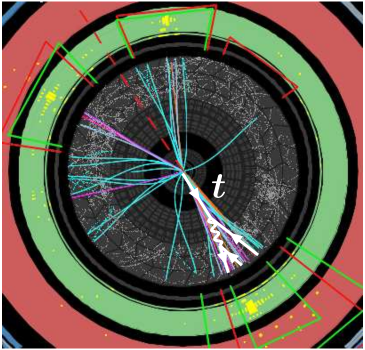

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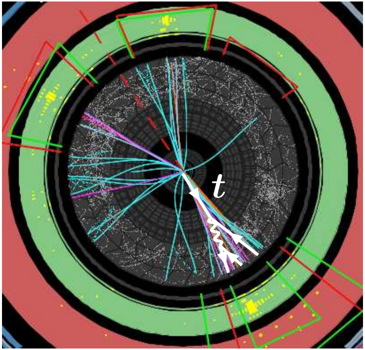

Source: ATLAS boosted top candidate

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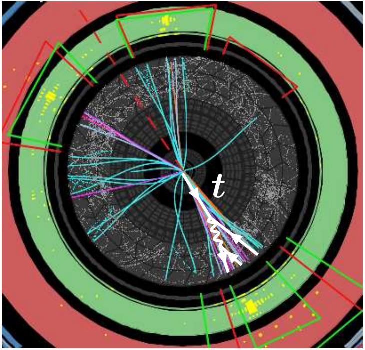

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Paradigm shift: a jet can be more than a quark or gluon

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

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

Increasingly important:

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

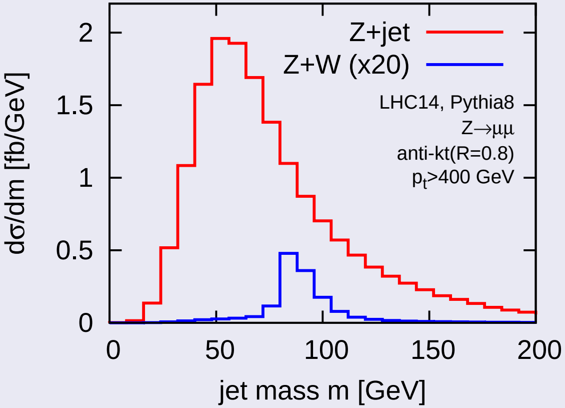
More and more boosted jets
Needs to be under control

Boosted jets

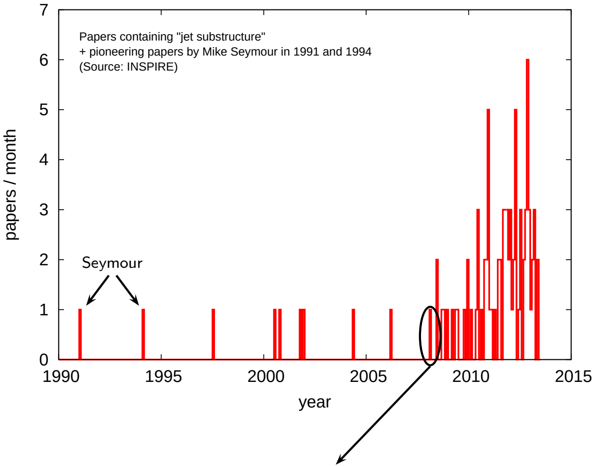
How to proceed?

Naive ideas do not work!

Looking at the jet mass is not enough



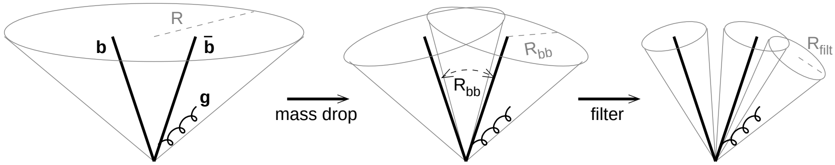
A lot of activity since 2008



Jet substructure as a new Higgs search channel at the LHC

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

A lot of activity since 2008



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$^{\text{rd}}$-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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Radiation pattern is different for

- colourless $W \to q\bar{q}$
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Radiation pattern is different for

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

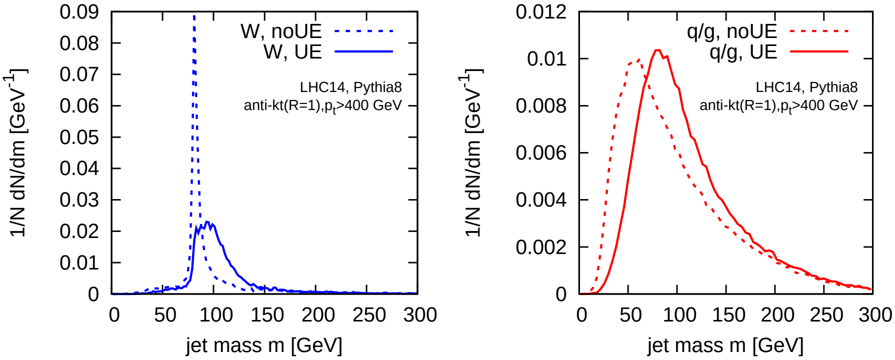
A few key approaches:

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)



Grooming

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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 $\max(p_{t1}, p_{t2}) > z_{\rm cut} p_t$, 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

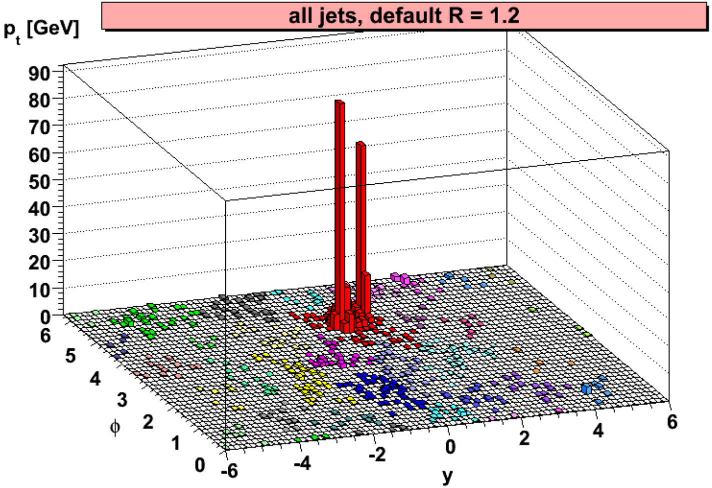
Same de-clustering procedure as the mMDT but angular-dependent cut

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

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

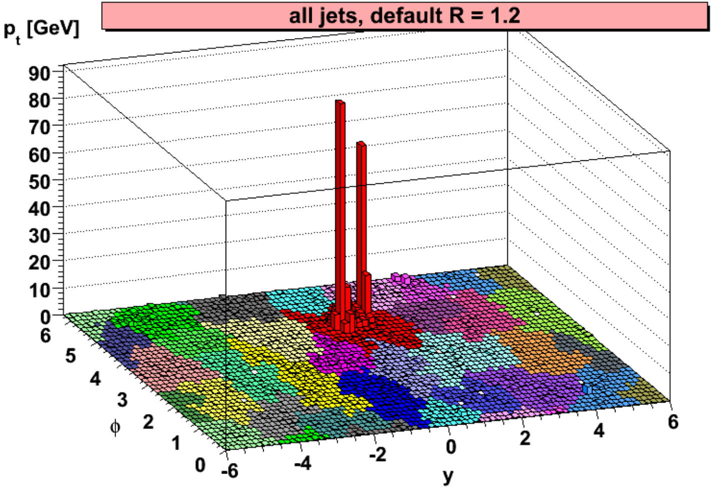
MassDrop+Filtering in action

Start with the jets in an event



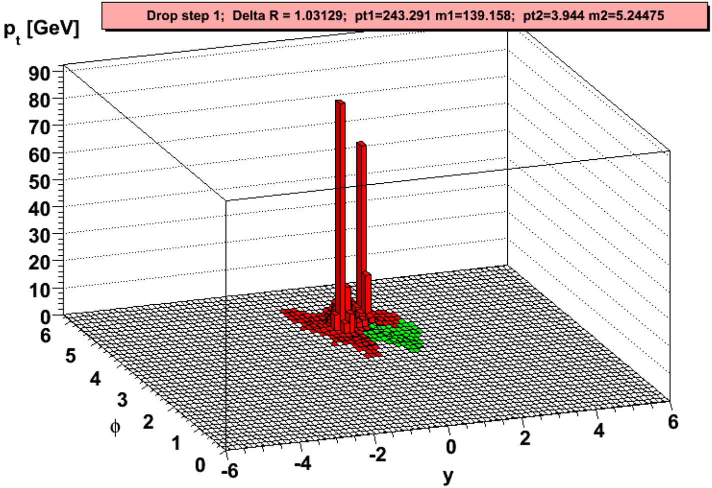
MassDrop+Filtering in action

This is what they look like with their area



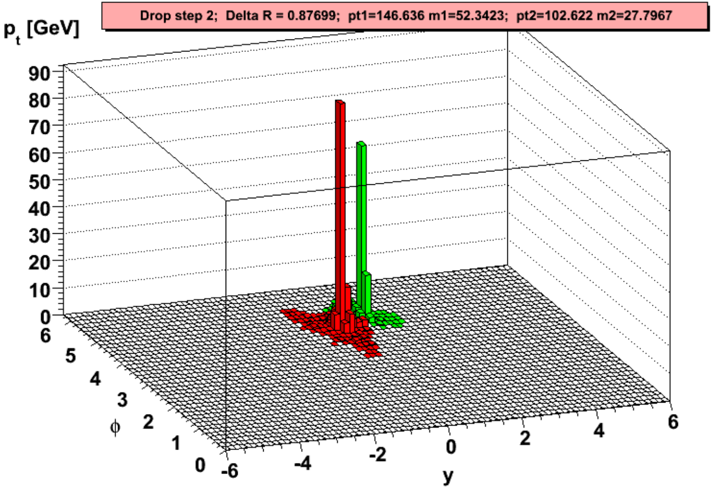
MassDrop+Filtering in action

Take the hardest, apply a step of mass-drop



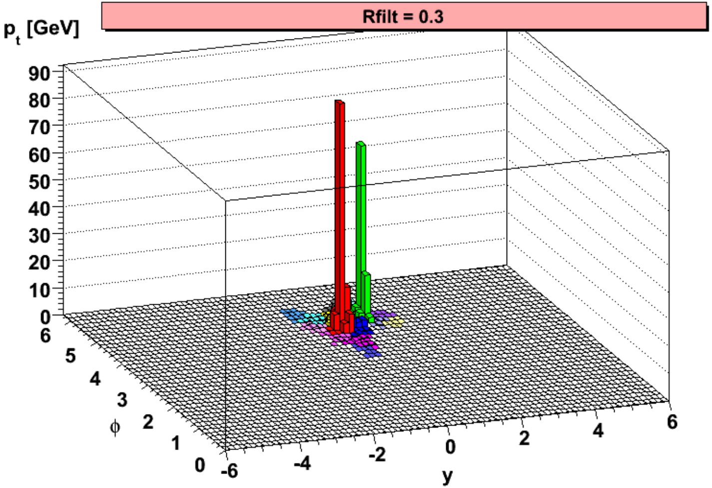
MassDrop+Filtering in action

Failed... iterate the mass drop



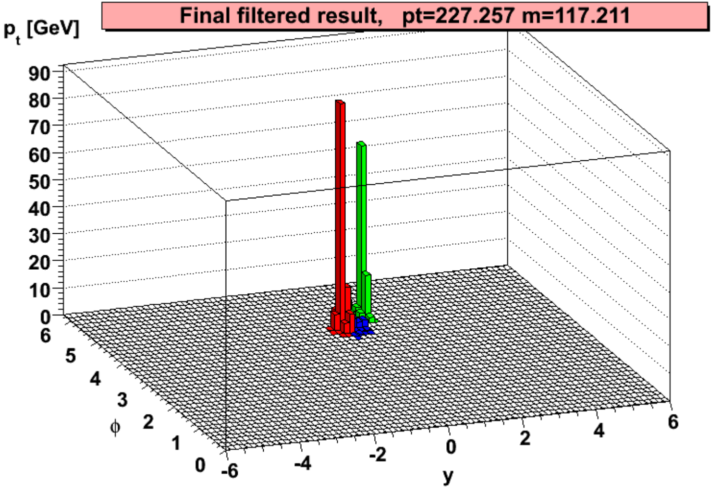
MassDrop+Filtering in action

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



MassDrop+Filtering in action

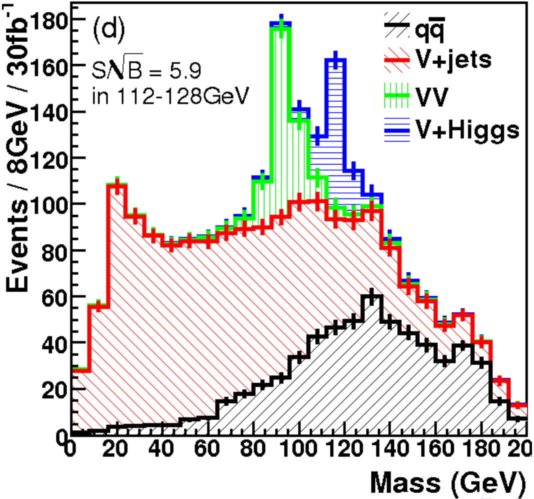
And keep only the 3 hardest



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



Constraining radiation

Example 3: N-subjettiness

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

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

- 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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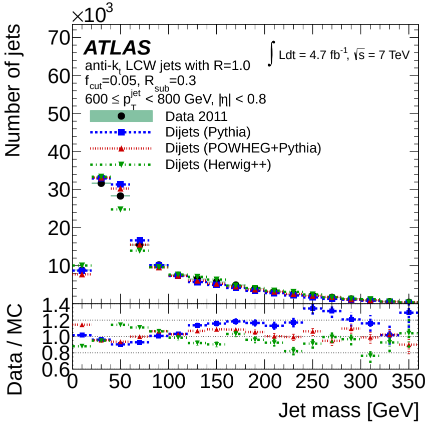
In practice

Tools are

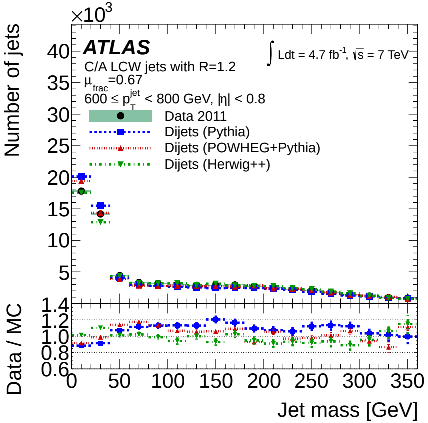
- developed/tested on Monte-Carlo simulations
- validated at the LHC (QCD backgrounds)

Example 1: Monte Carlo v. data

Trimming

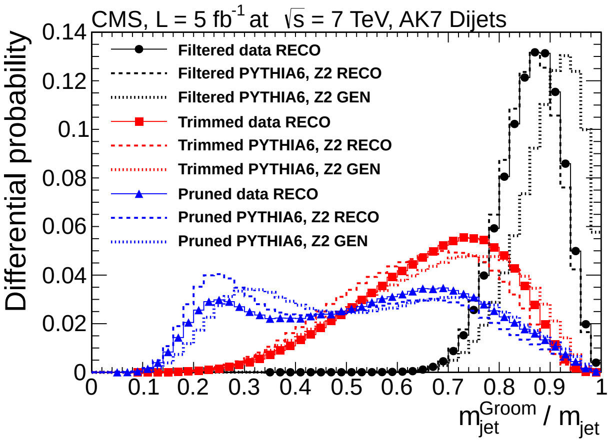


Mass-drop+filtering



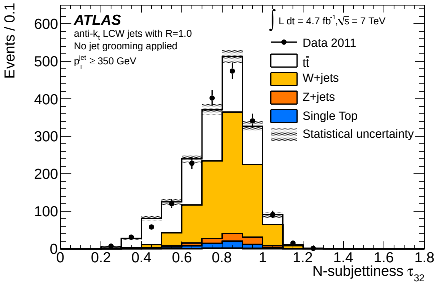
Example 1: Monte Carlo v. data

("Groomed" mass)/(plain mass)

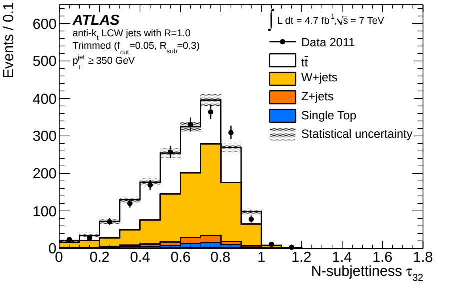


Example 1: Monte Carlo v. data

N-subjettiness τ_{32}



trimming+τ_{32}



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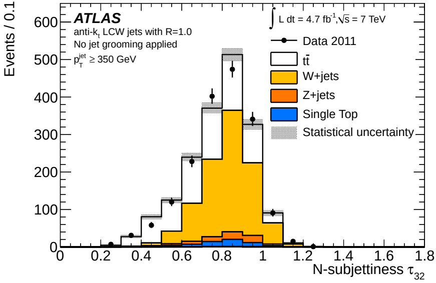

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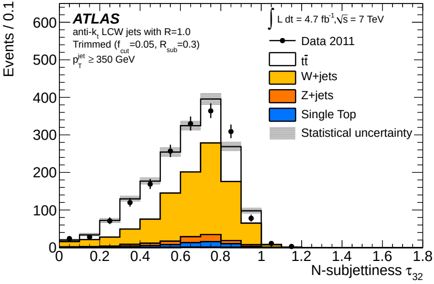


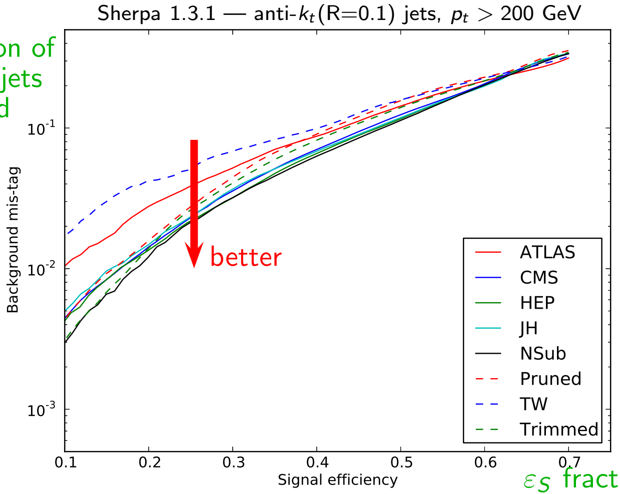
In a nutshell

- 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...

Finding N prongs works

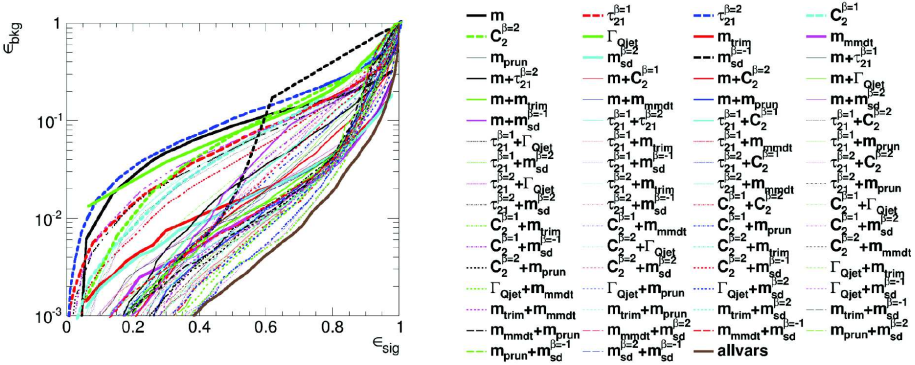
Constraining radiation works

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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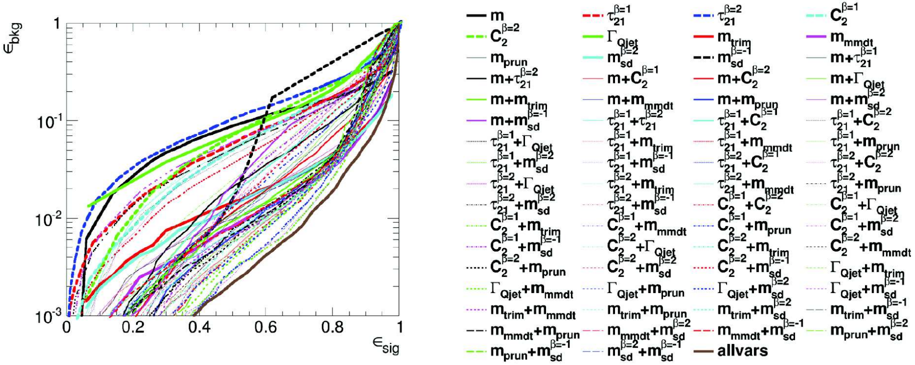

- Combination largely helps
- details not so obvious

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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Analytic/first-principle tools have a larege potential

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

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- No understanding of the details

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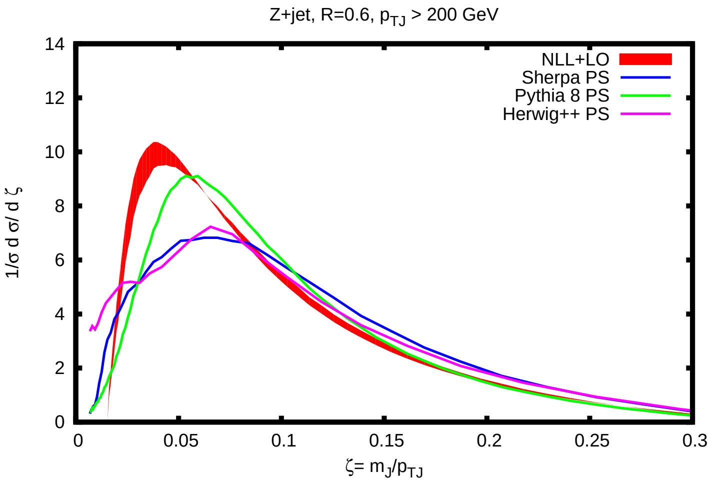
- Understand the underlying physics
- Infer how to improve things further
- provide robust theory uncertainties (competition with performance?)

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

Example 1:: the jet mass

Can reach high precision

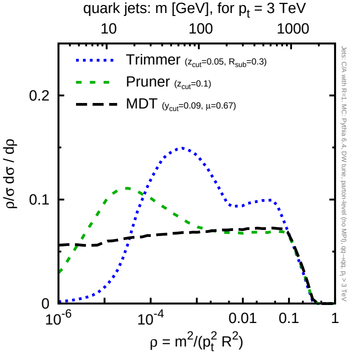


Monte-Carlo v. analytic

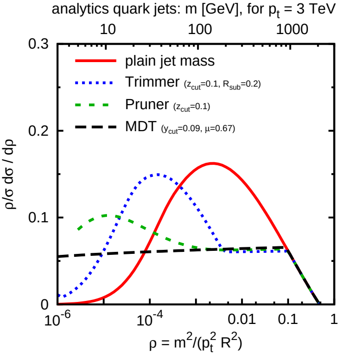
[M.Dasgupta,A.Fregoso,S.Marzani,G.Salam,13]

First analytic understanding of jet substructure:

Monte Carlo



Analytics

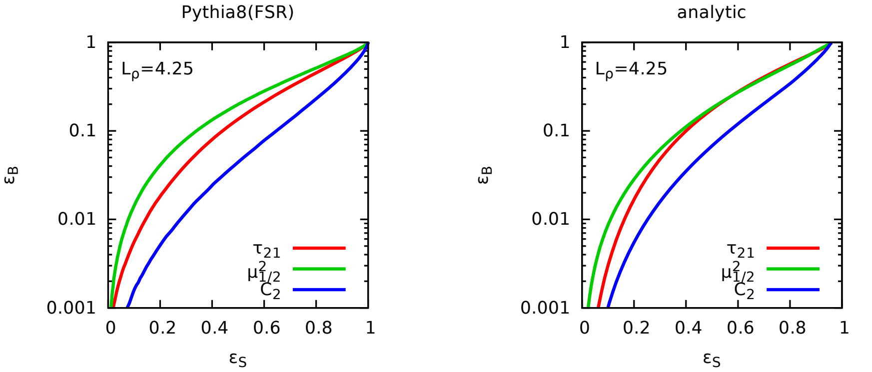


- Similar behaviour at large mass/small boost (region tested so far)
- Significant differences at larger boost

Monte-Carlo v. analytic

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

For jet shapes:



Summary: take-home messages

- Generic jet concepts
  - anti-k_t used almost everywhere, IRC-safe and fast
  - alternatives for specific cases
- Pileup mitigation
  - Area–median subtraction used in Run I: unbiased and efficient
  - Alternative methods (e.g. SoftKiller). Better resolution but need more tuning
- Boosted jets
  - More and more relevant
  - Many techniques around, validated at Run I
  - 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

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

- 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
- $(1-z)$ 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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- Leading term: **independent emissions**

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$$= \exp\left[-P_1(>\rho)\right]$$

- "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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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

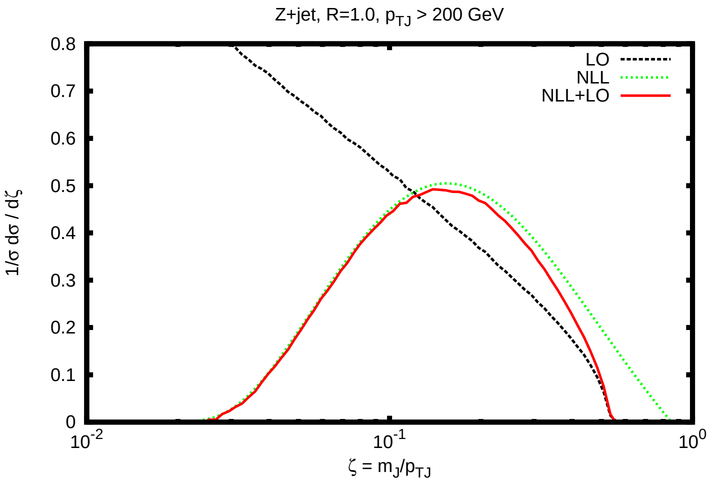
Next-to-leading log (NLL)

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

- 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

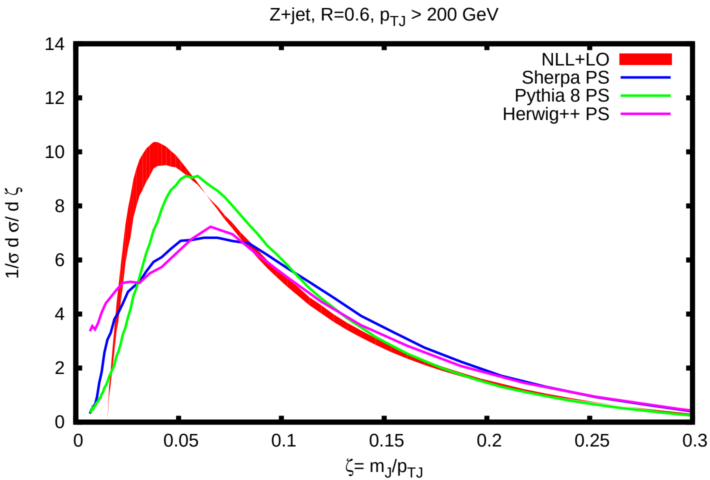
A few plots to illustrate what is going on

matching LO fixed-order with NLL resummation



A few plots to illustrate what is going on

Comparison with parton shower



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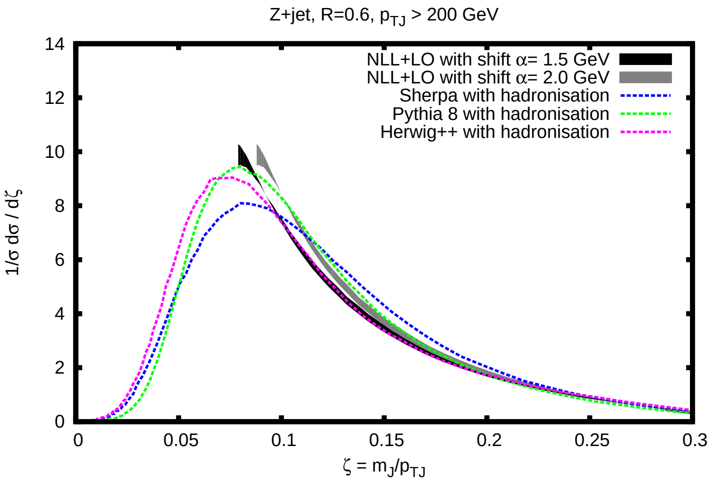
Including hadronisation



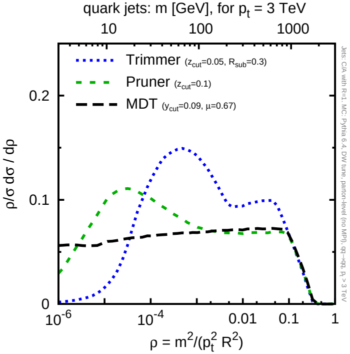
same approach for jet-substructure tools

Monte-Carlo v. analytic

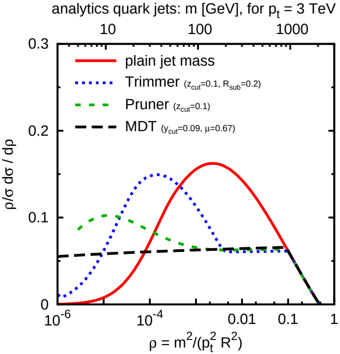
[M.Dasgupta,A.Fregoso,S.Marzani,G.Salam,13]

First analytic understanding of jet substructure:

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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- Trimming:
  - 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