Fun with Jets
From Run I to Run II and beyond

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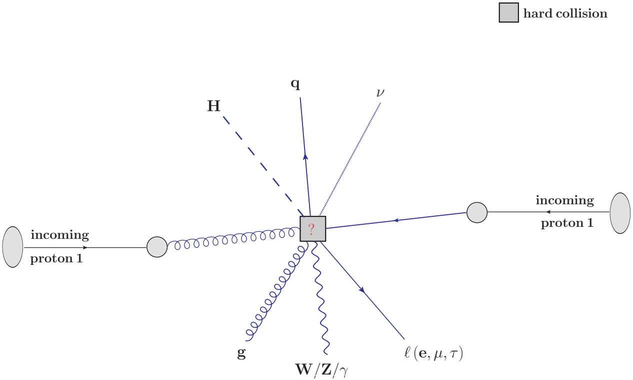
Anatomy of collider physics

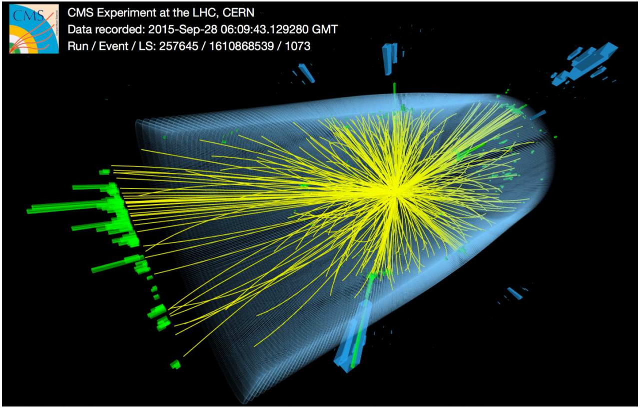
A Theorist's view:



- Learn about fundamental interactions
- Produce standard model particles

Anatomy of collider physics

Experimental realm:

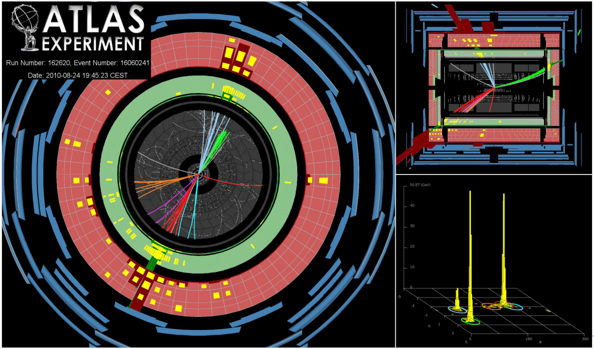


- Learn about fundamental interactions
- Observe energy deposits and charged tracks

Elementary phenomenologist dictionary/view

Th/Pheno	Exp	
$\ell(e,\mu)$	$\ell(e,\mu)$	at least within the contect of this talk
γ	γ	at least within the contect of this talk
ν	missing E_T	not trivial at all... but not covered here
q, g	jets	complex collimated structures

$W/Z/H/\text{top}/\tau/\text{BSM}/\ldots$ decay in the above



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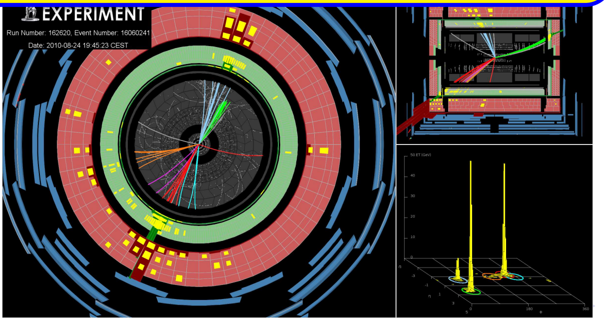
		structures
$W/Z/H$		

jet $\equiv$ bunch of collimated particles

$\equiv$ (hard) quark or gluon



Jetography

Measure jets $\longrightarrow$ access q/g $\longrightarrow$ learn about fundamental collision

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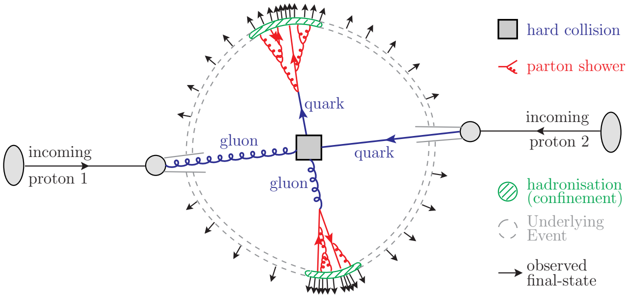
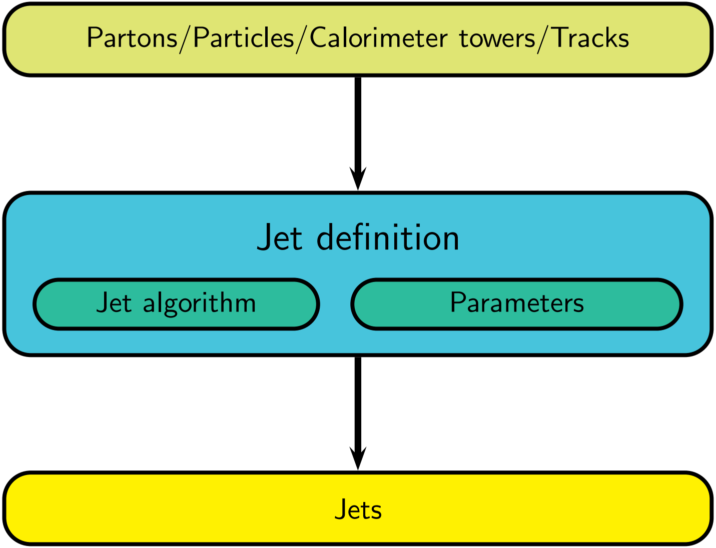


- Jets come from collinear branchings in pQCD
- Parton showers: require state-of-the-art (all-orders) perturbative QCD
- Hadronisation/UE: Non-pertur. effects: limit sensitivity to that

Jet definition



Recombination algorithms

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

(Anti-k_t) algorithm

- From all the objects, define the distances

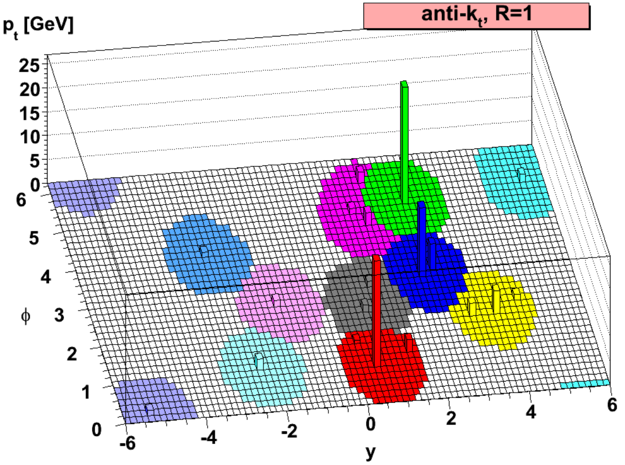
$$d_{ij} = \min(p_{t,i}^{-2}, p_{t,j}^{-2})(\Delta y_{ij}^2 + \Delta\phi_{ij}^2), \qquad d_{iB} = p_{t,i}^{-2} R^2$$

- 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

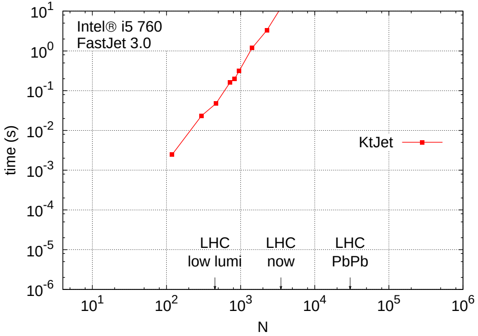
Main property: hard jets are circular



FastJet

[M.Cacciari, G.Salam, 2005]

[M.Cacciari, G.Salam, GS, 2011]



- Tevatron era: k_t too slow: $\mathcal{O}(N^3)$ for N particles

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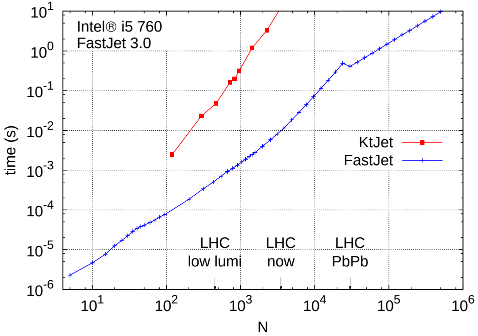

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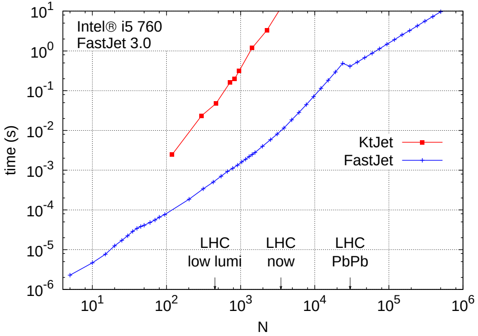

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- Fastjet 3.1: typically 5-50ms for LHC (with pileup and areas)

2 challenges

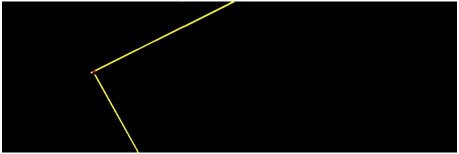
- Challenge 1: pileup
  - Run I: Jet area–median pileup subtraction
  - Towards Run II: noise-reduction and SoftKiller
- Challenge 2: jet substructure
  - New paradigm for jets
  - boosted jet tagging

Pileup mitigation

Pileup

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

Low luminosity
(bunch population)



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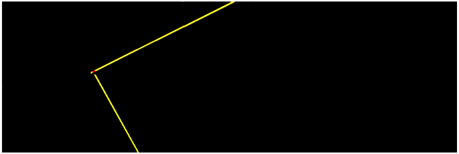

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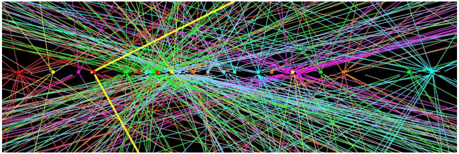
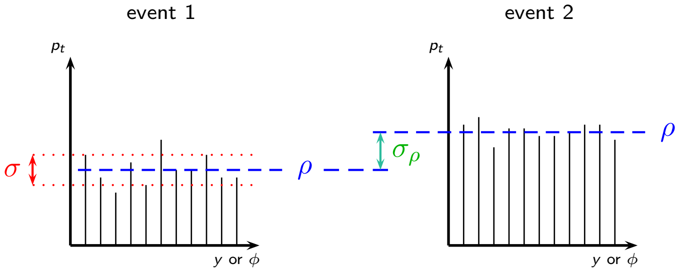


Pileup complicates things

- 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

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



Basic characterisation

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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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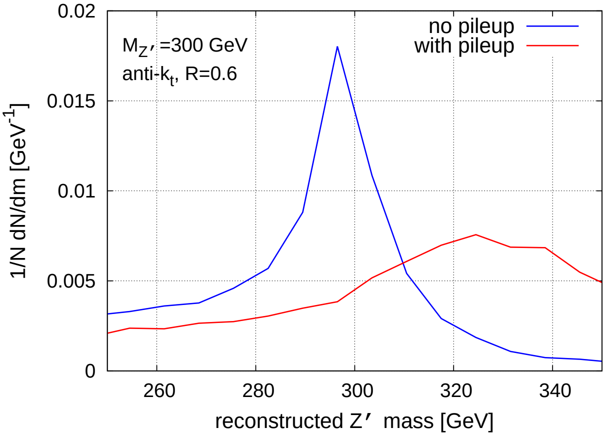
p_t shift

p_t smearing
resolution degradation

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

Illustrative example



Area–median ingredient 1: jet area

Proper definition of the ("Active") area of a jet:

- 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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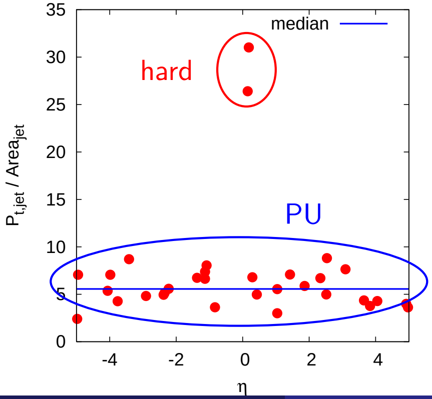
  - on a grid (+ small random fluctuations) of cell area a_0
- Include the ghosts in the clustering
- If a jet contains N_g ghosts, its area is $N_g a_0$

Area–median ingredient 2: estimate ρ

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

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

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



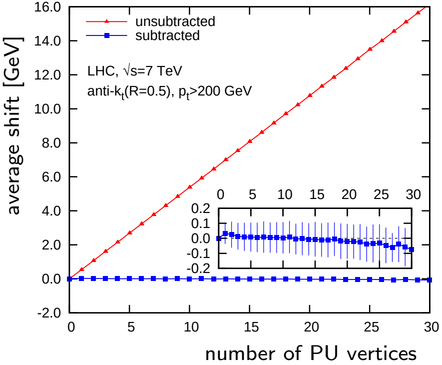
per jet

per event
(typically)

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



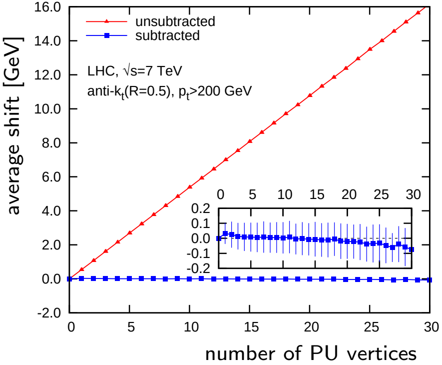
No subtraction

area-median subtraction

corrected for shift

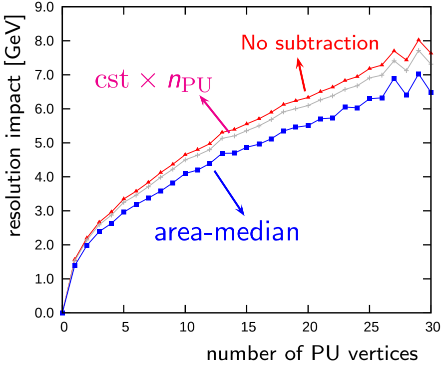
Subtraction benchmarks

average p_t shift



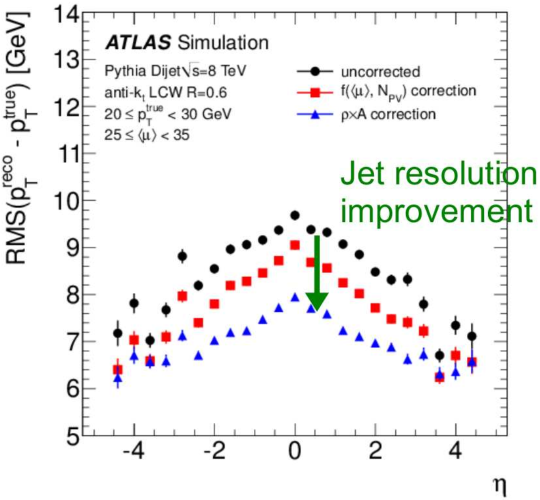
corrected for shift

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]

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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- Requires more delicate tuning

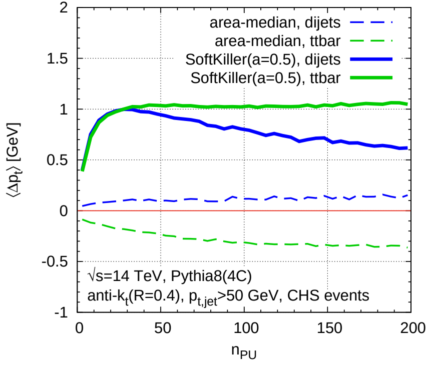
Several methods

- **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: improvement for mass and shapes
  [P.Berta,M.Spousta,D.Miller,R.Leitner,2014]

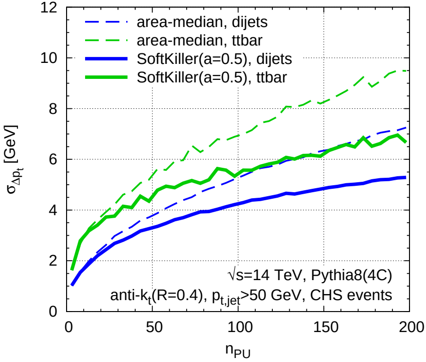
Recipe

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

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



reasonable bias



improved resolution

SoftKiller

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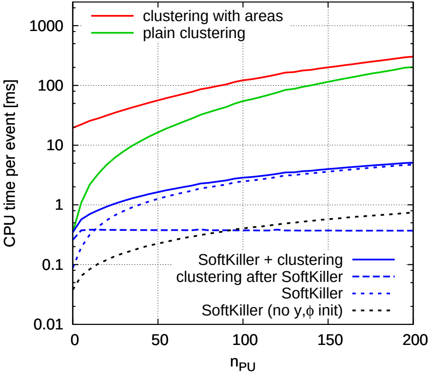
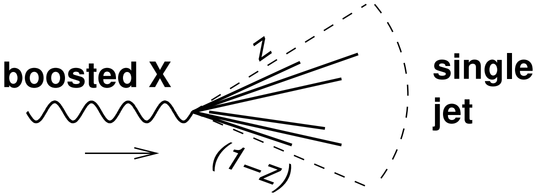


Allows very fast implementation

(see SoftKiller fastjet contrib)

Boosted jets

Object X decaying to hadrons



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

Boosted jets: main iea

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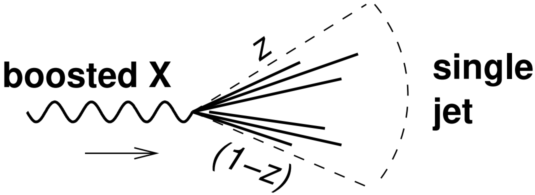


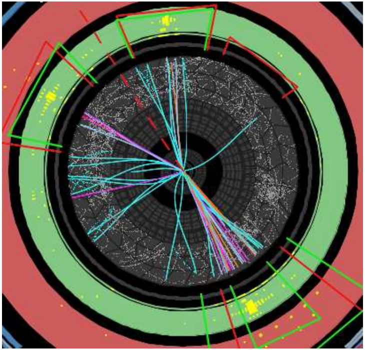
$$R \gtrsim \frac{m}{p_t} \frac{1}{\sqrt{z(1-z)}}$$

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

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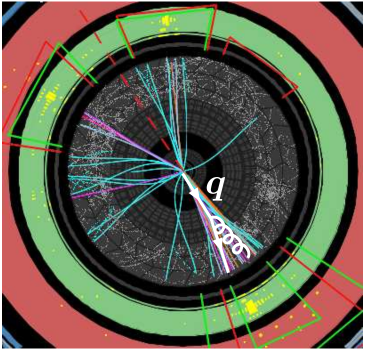
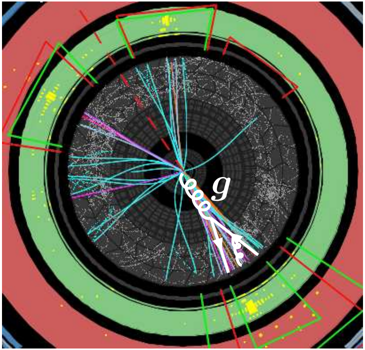


An illustration

What jet do we have here?

- a quark?
- a gluon?



An illustration

What jet do we have here?

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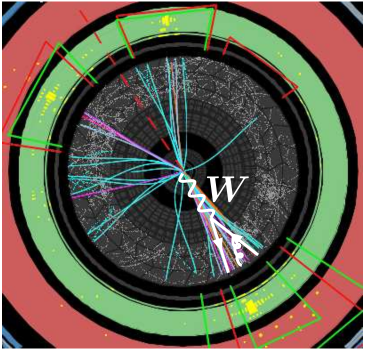
- a gluon?
- a W/Z (or a Higgs)?



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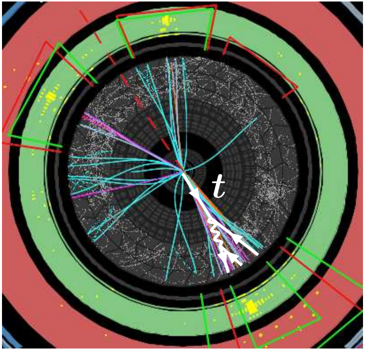

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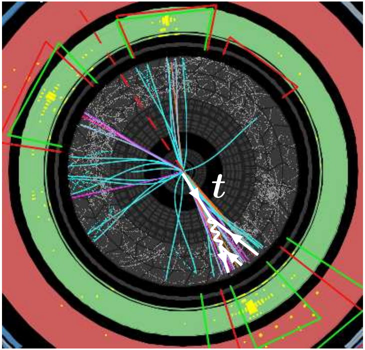

Source: ATLAS boosted top candidate

An illustration

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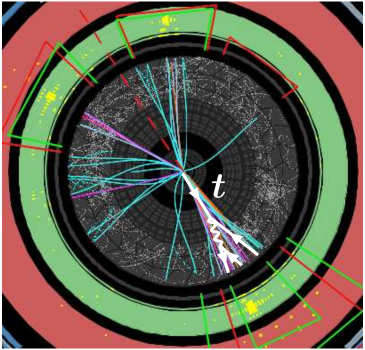

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Paradigm shift: a jet can be more than a quark or gluon

Boosted jets: applications

Many applications: (examples)

- 2-pronged decay: $W/Z \to q\bar{q}$, $H \to b\bar{b}$
- 3-pronged decay: $t \to qqb$, $\tilde{\chi} \to qqq$

Boosted jets: applications

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Increasingly important:

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

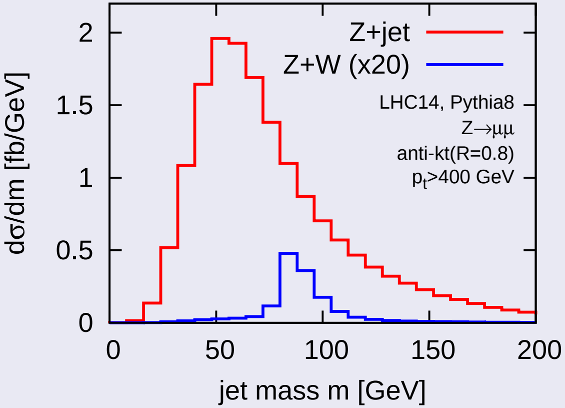
More and more boosted jets
Needs to be under control

Boosted jets

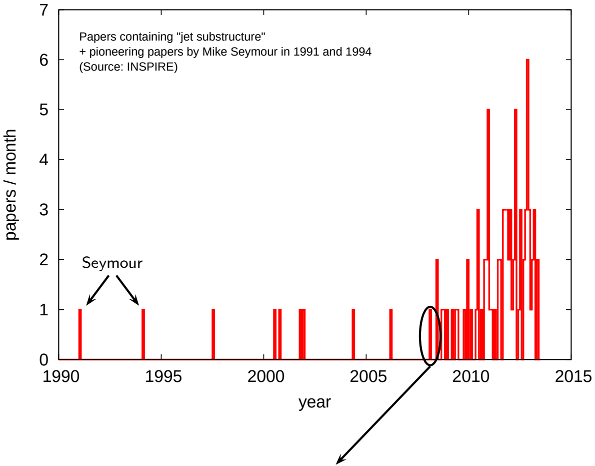
How to proceed?

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

Many tools, two major ideas

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; ...

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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

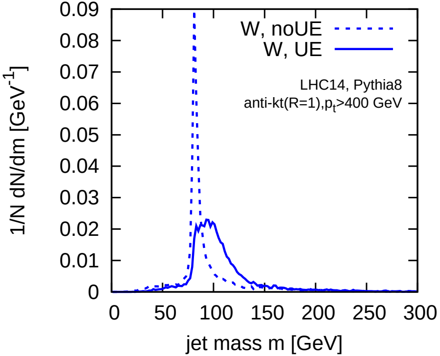
Works because different colours

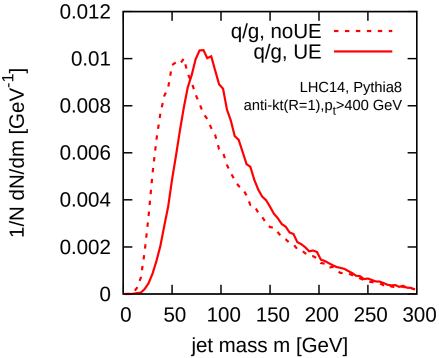
Radiation pattern is different for

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

Fat Jets

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





3rd idea: Grooming

Fat Jets

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

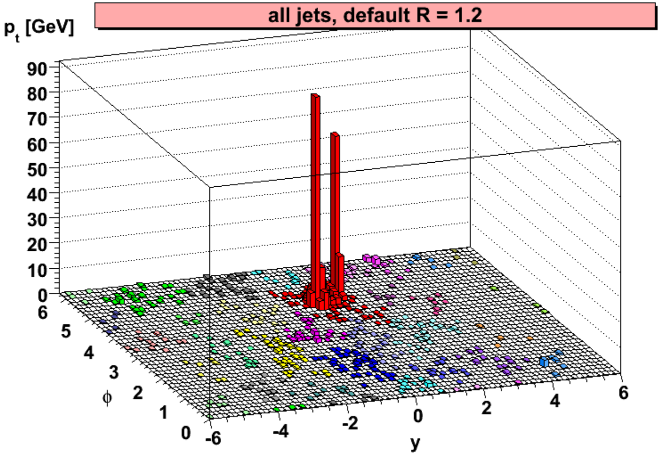
"grooming" techniques reduce sensitivity to soft-and-large-angle

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]

Two-prong finder: MassDrop ($z_{cut} = 0.1$)+filtering

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



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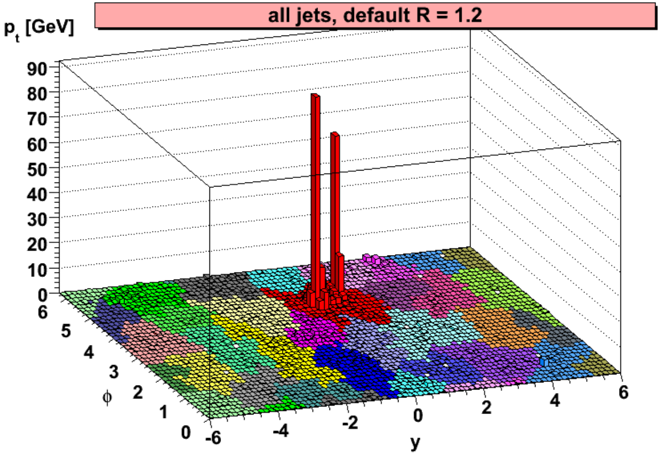

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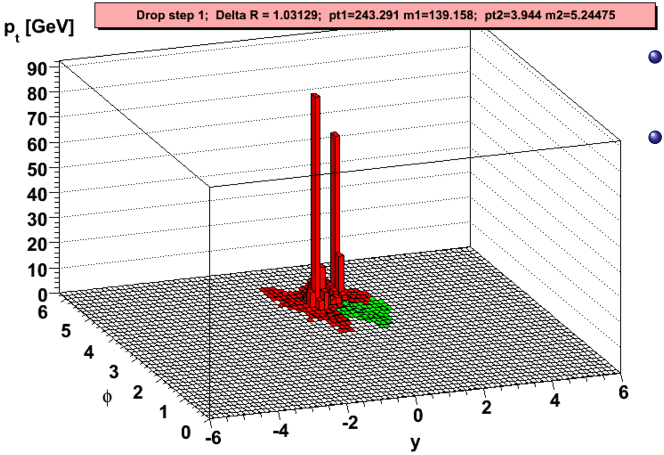

MassDrop

- undo the last clustering step
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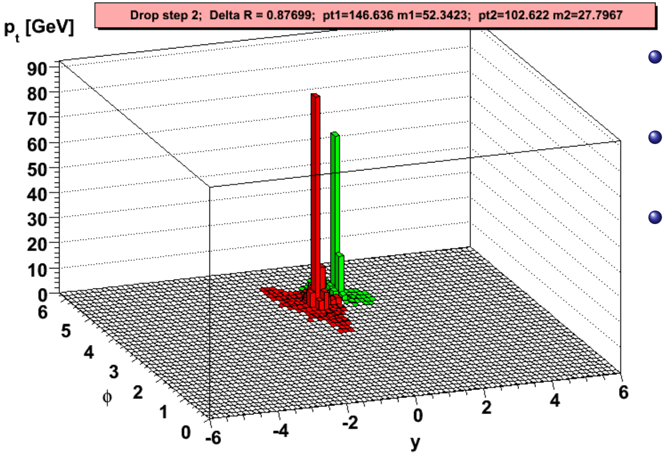

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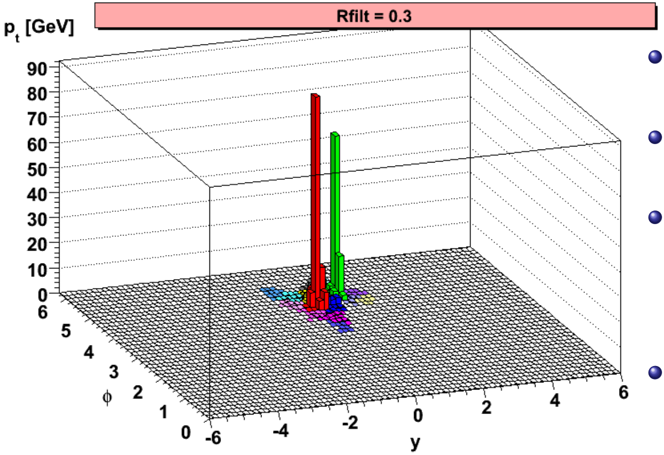

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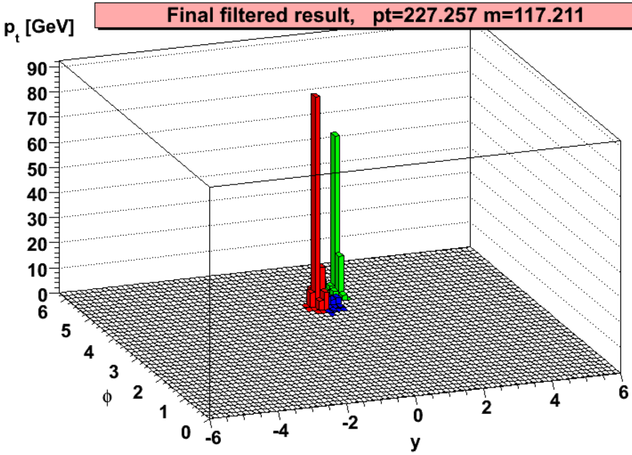

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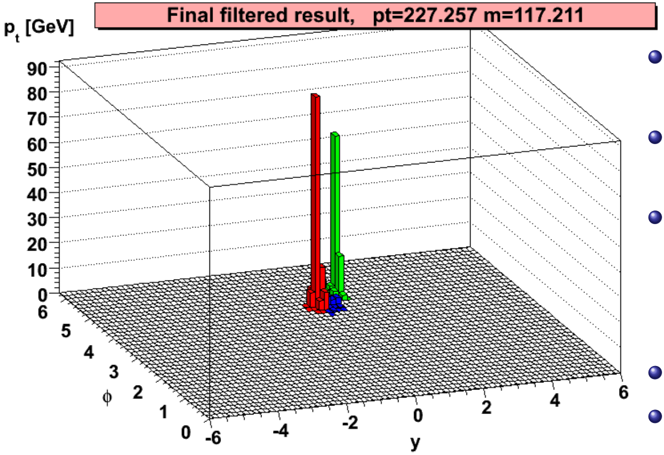

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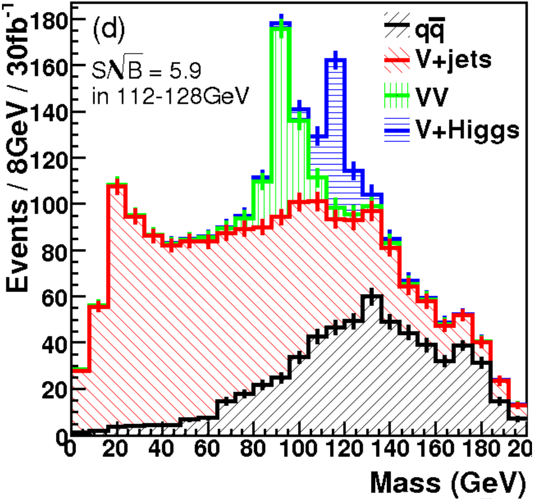
Variant: **SoftDrop**: impose $z > z_{cut}\theta^{\beta}$ [A.Larkoski,S.Marzani,GS,J.Thaler,14]

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: N-subjettiness

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

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

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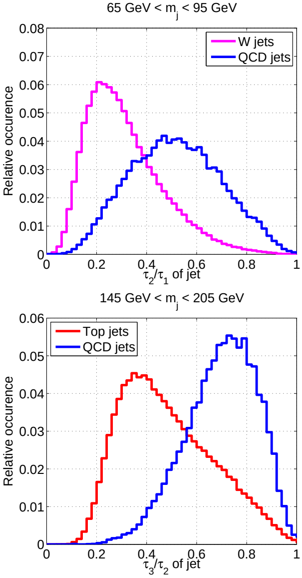
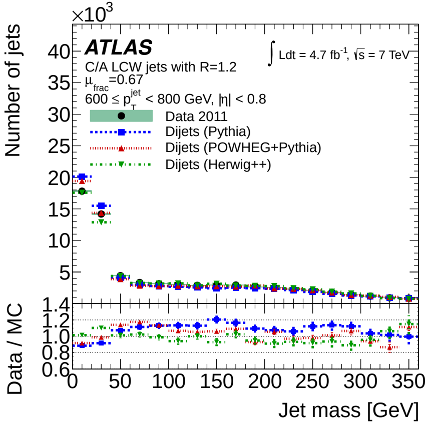
- Measures the radiation from N prongs
- $\tau_{N,N-1} = \tau_N / \tau_{N-1}$ discriminates N-prong v. QCD
- τ_{21} smaller for W than for QCD
- τ_{32} smaller for top than for QCD



Monte Carlo v. data

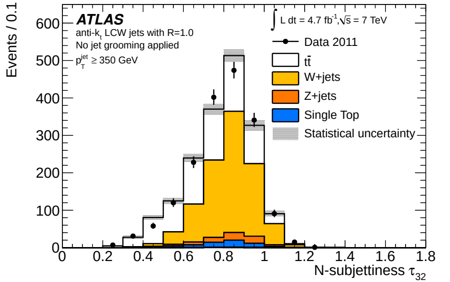
Mass-drop+filtering



In practice

- developed/tested on Monte-Carlo simulations
- validated at the LHC

N-subjettiness τ_{32}



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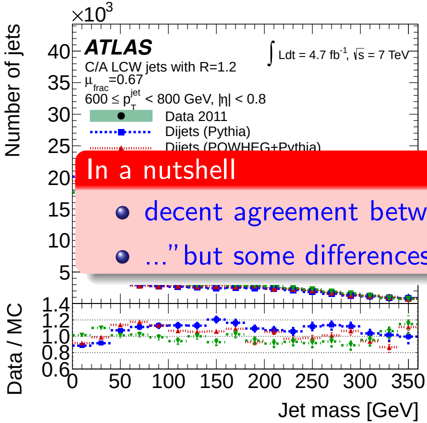

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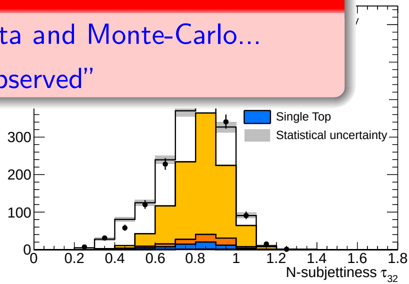
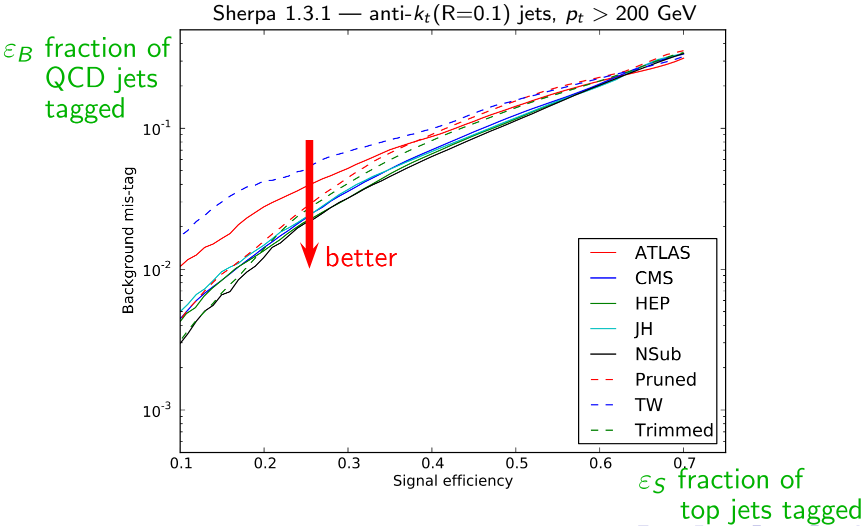


In a nutshell

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

Example 2: top tagging MC study

[Boost 2011 proceedings]



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

Finding N prongs works

Constraining radiation works

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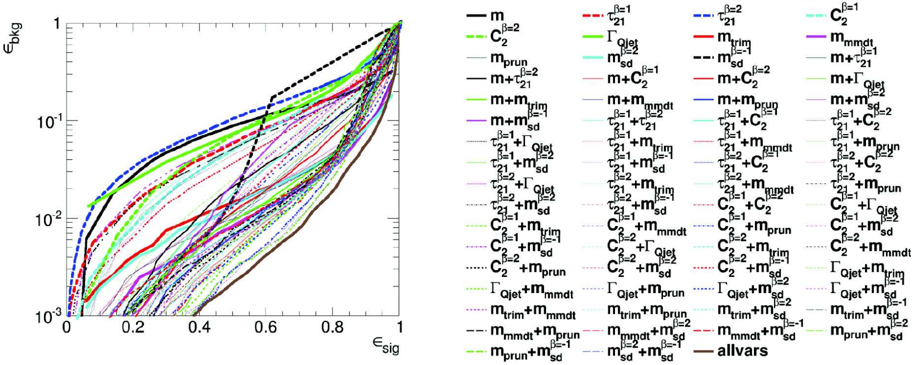
Finding N prongs works

Constraining radiation works

Why not combining the two?

[Boost 2013 WG]

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



[Boost 2013 WG]

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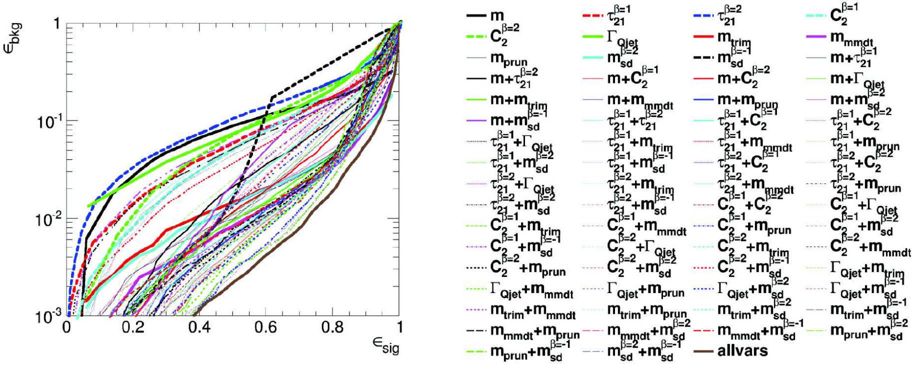

- Combination largely helps
- details not so obvious

STOP and think

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

Motivation and idea

Empirical Monte-Carlo approach is limited

- Hard to extrapolate parameters
- No understanding of the details

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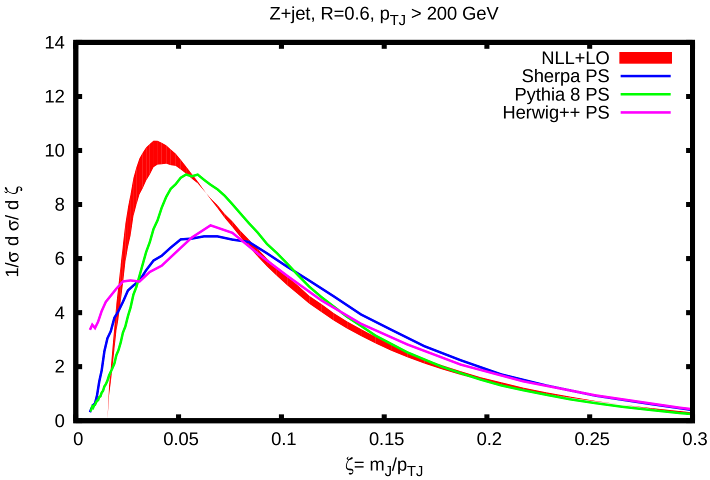
Requires QCD techniques

- $\rho = m/(p_t R) \ll 1 \Rightarrow$ 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

[M.Dasgupta, K.Khelifa-Kerfa, S.Marzani, M.Spannowsky, 2012]

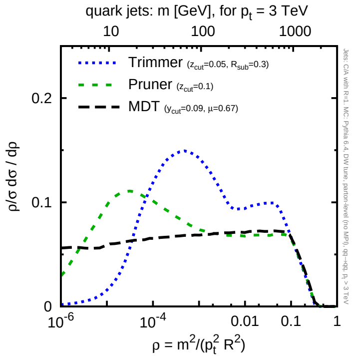
"Plain" Jet mass



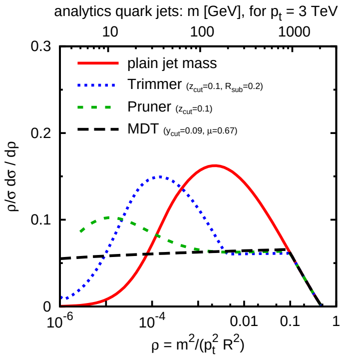
[M.Dasgupta,A.Fregoso,S.Marzani,G.Salam,13]

First analytic understanding of jet substructure:

Monte Carlo



Analytics

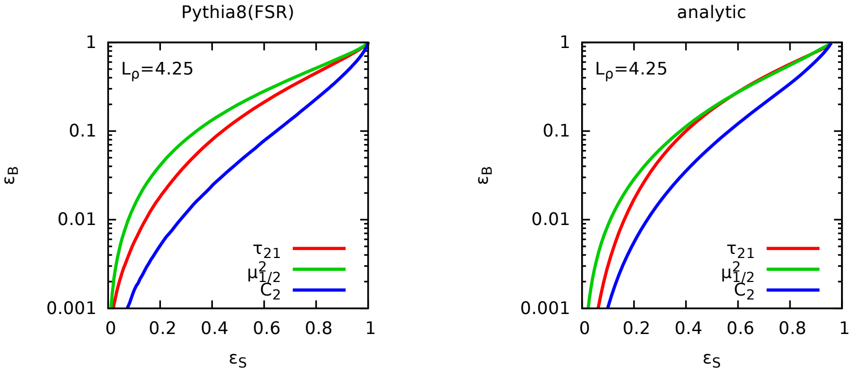


- Similar behaviour at large mass/small boost (region tested so far)
- Significant differences at larger boost

Monte-Carlo v. analytic

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

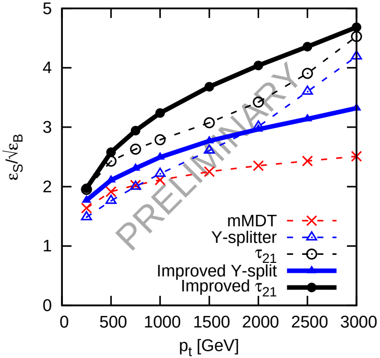
First understanding for jet shapes:



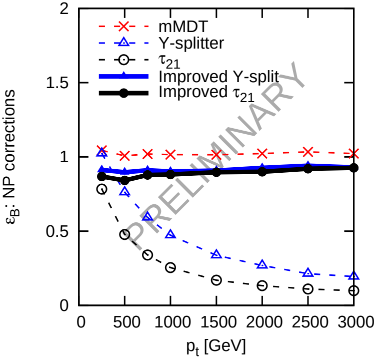
[M.Dasgupta,A.Powling,L.Schunk,GS,in prep]

Transition towards using that info to build better tools [G.Salam,GS,in prep]

Significance



NP correction factor



- Improvement in discriminative power
- and/or reduced sensitivity to NP effects

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
  - New methods (e.g. SoftKiller). Better resolution but more tuning
  - Can one get hints from (first-principle) substructure?
- 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
hline 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^{rd} party
Pull	†Gallicchio, Schwartz	3^{rd} party
Q-jets	†Ellis, Hornig, Krohn, Roy and Schwartz	3^{rd} party
HEPTopTagger	†Plehn, Salam, Spannowsky, Takeuchi	3^{rd} party
TemplateTagger	†Backovic, Juknevic, Perez	3^{rd} party
Shower deconstruction	†Soper, Spannowsky	3^{rd} party

[1] References are incomplete