Jets, Boosted jets, FastJet

Grégory Soyez

IPhT, CEA Saclay

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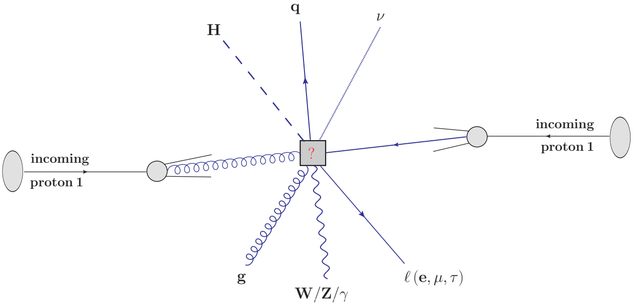
Anatomy of collider physics

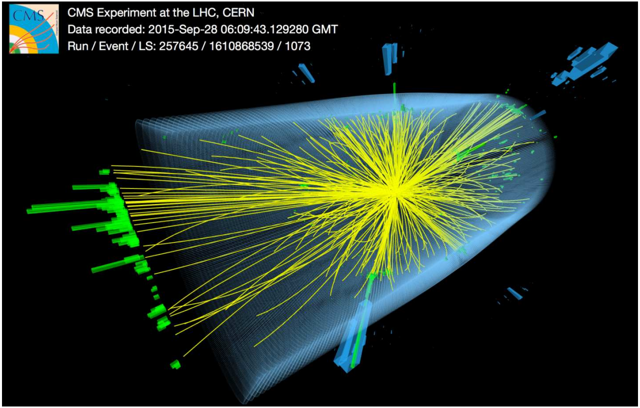
A Theorist's view:



- Learn about fundamental interactions
- Produce standard model particles

Anatomy of collider physics

Experimental realm:



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

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

- quarks ang gluon (i.e. partons) branch predominantly at small angles

$$d\text{Prob}_{\text{branching}} \propto \alpha_s \frac{d\theta}{\theta}$$

$\longrightarrow$ (mostly) collimated parton shower

- one does not observe partons but hadrons (π, K, ...)
  $\longrightarrow$ collimated bunch of hadrons called "jets"

Basic phenomenologist dictionary/view

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q, g	jets	complex collimated structures
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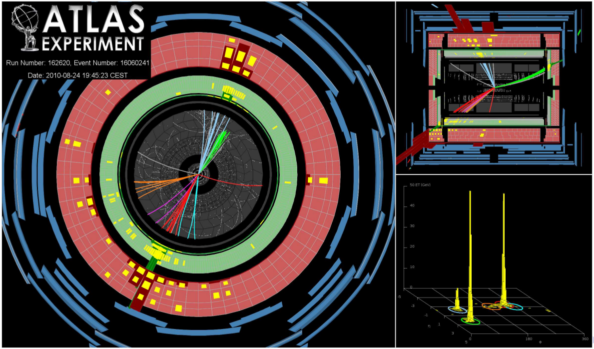

In the most simple terms:

jet $\equiv$ bunch of collimated particles

$\simeq$ (hard/high-energy) quark or gluon

Jetography

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

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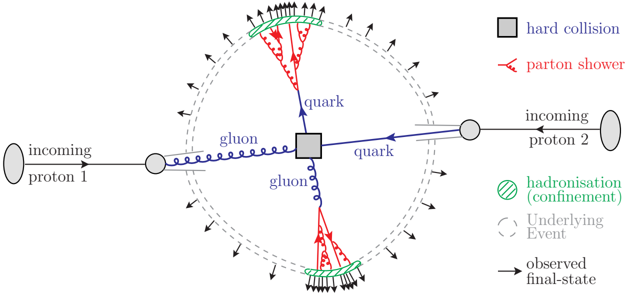
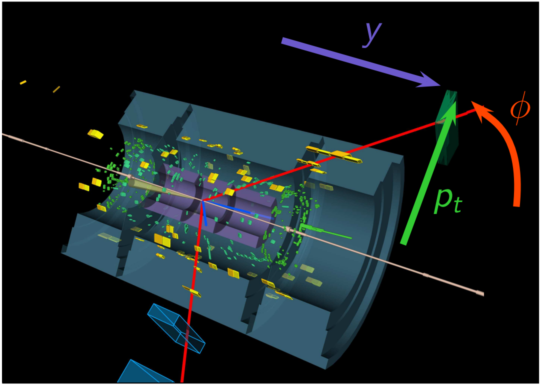
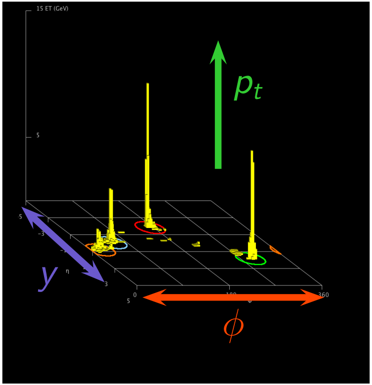


- Parton showers: require state-of-the-art (all-orders) perturbative QCD
- Hadronisation/UE: Non-pertur. effects: limit sensitivity to that

A bit of useful kinematics

[Both: ATLAS public events ($H \to 2\mu 2e$ & 4 jets)]



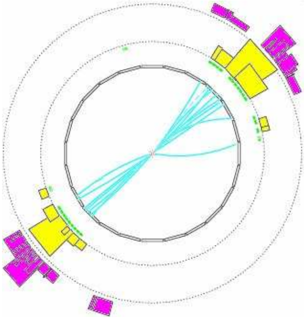


- Rapidity y: longitudinal component (along the beam axis)
- Azimuthal angle ϕ: around the beam axis
- Transverse momentum p_t: "energy" transverse to the beam

Jets 101

"Jets" ≡ bunch of collimated particles ≅ hard partons

How many jets?



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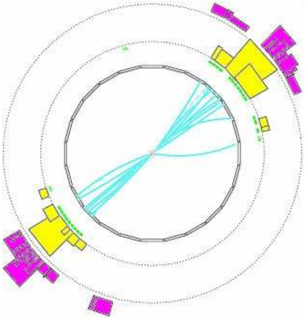
obviously 2 jets



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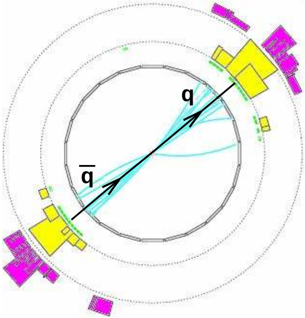

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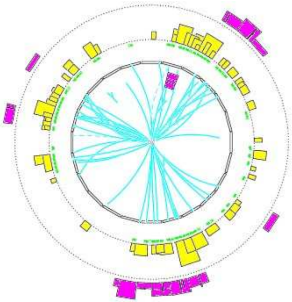
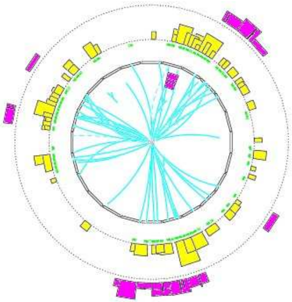


Jets and partons

“Jets” $\equiv$ bunch of collimated particles $\cong$ hard partons

3 jets



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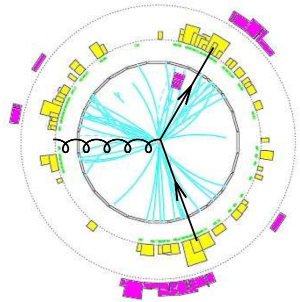

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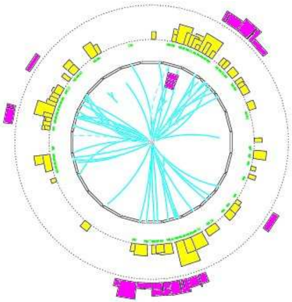

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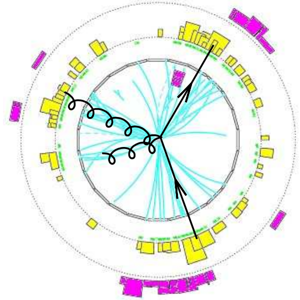

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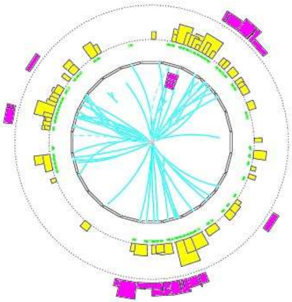

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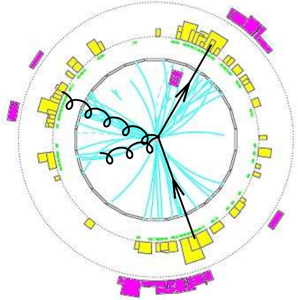
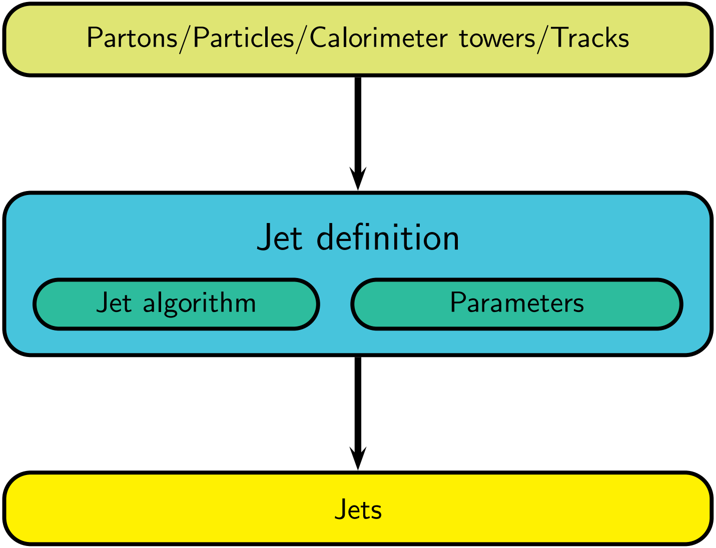


- "collinear" is arbitrary
- "parton" concept strictly valid only at LO

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

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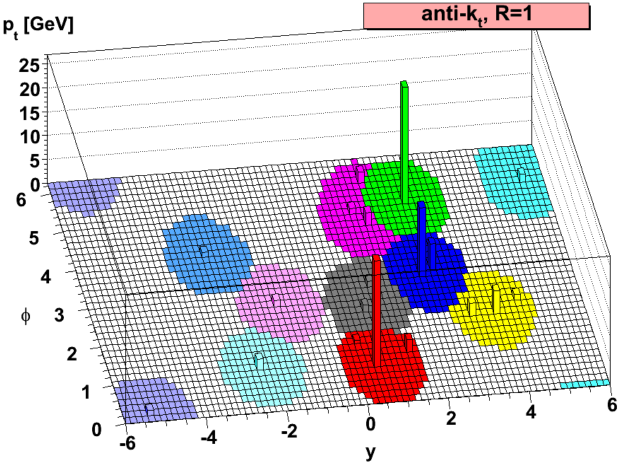
Other algoritms

- "generalised-k_t":

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

- $p = 1$: k_t algorithm (oldest in the family)
- $p = 0$: Cambridge/Aachen algorithm ("just" angular ordering)

Main property of anti-k_t: hard jets are circular



FastJet

`http://fastjet.fr`

FastJet

Software for jet clustering

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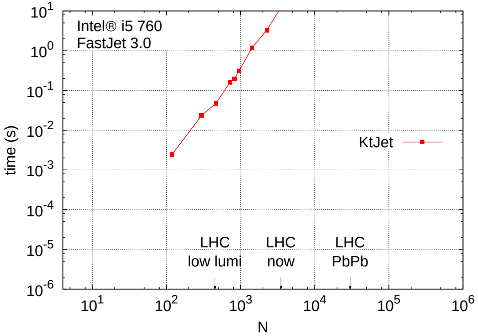

- Tevatron era: k_t too slow: $\mathcal{O}(N^3)$ for N particles

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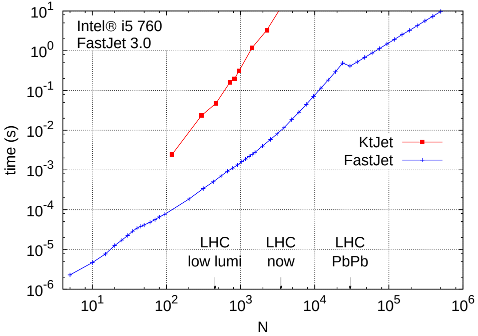

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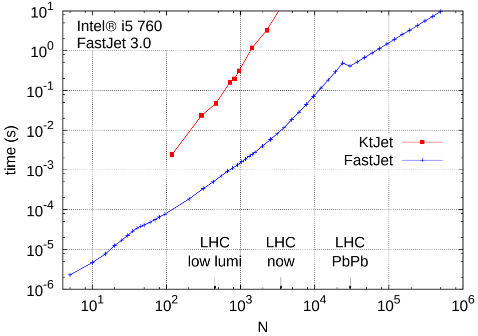

- Tevatron era: k_t too slow: $\mathcal{O}(N^3)$ for N particles
- Now: (anti-)k_t very fast: $\mathcal{O}(N^2)$ or even $\mathcal{O}(N \log(N))$
- Fastjet 3.1: typically 5-50ms at the LHC

Geometrical (Camb./Aachen) case: Naive approach

compute all d_{ij}	N^2
find minimum	N^2
recombine $i+j$	1
iterate	$\times N$
total	$\mathcal{O}(N^3)$

- works for all algs
- prohibitively slow

Geometrical (Camb./Aachen) case: Nearest neighbours

Observations:

- No need to keep track of all the distances:

  $$\min_{i,j}\{d_{ij}\} = \min_i\{d_{i,NN(i)}\} \qquad \text{with} \quad NN(i) = \min_j\{d_{ij}\}$$

  only keep track of the nearest neighbour (NN) of each particle
- Do not recalculate all NNs at each step; if $i + j \to k$, we need $NN(k)$ and $NN(\ell)$ when $NN(\ell) = i$ or j

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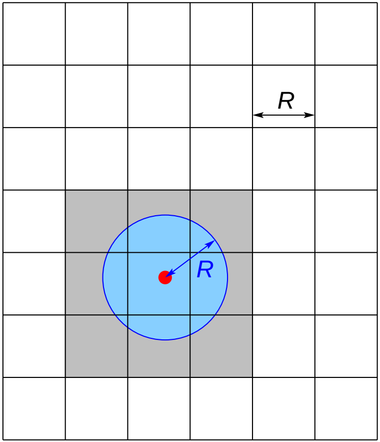
New implementation:

Init: compute all $NN(i)$	N^2
find smallest $d_{i,NN(i)}$	N
recombine $i+j$	1
compute $NN(k)$ and $NN(\ell)$'s	N
iterate	$\times N$
total	$\mathcal{O}(N^2)$

- works for all algs
- efficient for N not too large

Geometrical (Camb./Aachen) case: Tiling



- *NN* only in current or neighbouring tile
- $\Rightarrow$ *NN* search is $\mathcal{O}\left(n = N/N_{\text{tiles}}\right)$

Geometrical (Camb./Aachen) case: Tiling

Init: create tiling	N
Init: compute all $NN(i)$	Nn
Init: sort the $d_{i,NN(i)}$	$N\log(N)$
find smallest $d_{i,NN(i)}$	1
recombine $i+j$	1
compute $NN(k)$ and $NN(\ell)$'s	n
iterate	$\times N$
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- Variants for finding $\min\{d_{i,NN(i)}\}$.
- Tricks to avoid neighbour tiles when possible

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- Tricks to avoid neighbour tiles when possible
- **Optimal for** $30 \lesssim N \lesssim 5\,10^5$

Other algorithms

What about $d_{ij} = \min(p_{ti}^{2p}, p_{tj}^{2p})\,\Delta R_{ij}^2$?

Other algorithms

What about $d_{ij} = \min(p_{ti}^{2p}, p_{tj}^{2p})\,\Delta R_{ij}^2$?

FastJet lemma

If the pair (i,j) minimises d_{ij} and $p_{ti}^{2p} < p_{tj}^{2p}$,
then j is the geometrical NN of i.

Proof: Assume there is k s.t. $\Delta R_{ik} < \Delta R_{ij}$. We would have

$$\begin{aligned} d_{ik} &= \min(p_{ti}^{2p}, p_{tk}^{2p})\,\Delta R_{ik}^2 \\ &< p_{ti}^{2p}\,\Delta R_{ij}^2 = d_{ij}, \end{aligned}$$

a contradiction.

Other algorithms

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a contradiction.

$\Rightarrow$ all the above strategy (working with geometrical NN) work

Main FastJet classes

Basic classes:

- `PseudoJet`: particle/4-vector
- `JetDefinition`: jet definition for the clustering (alg+params)
- `ClusterSequence`: the jet clustering itself

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More advanced classes:

- `Selector`: various cuts, e.g. `SelectorPtMin(100)`
- `Transformer`: base class for manipulating jets, e.g. `MassDropTagger`, `Subtractor`,...
- `AreaDefinition` and `ClusterSequenceArea`: includes jet area calculation in the clustering

consult the FastJet **examples, manual, FAQ and doxygen documentation for help**

Basic FastJet example

```
#include <iostream>
#include "fastjet/ClusterSequence.hh"
using namespace fastjet;
using namespace std;

int main() {
  vector<PseudoJet> particles; //    px     py   pz      E
  particles.push_back( PseudoJet(   99.0,  0.1,  0, 100.0) );
  particles.push_back( PseudoJet(    4.0, -0.1,  0,   5.0) );
  particles.push_back( PseudoJet(  -99.0,    0,  0,  99.0) );

  // choose a jet definition                   R
  JetDefinition jet_def(antikt_algorithm, 0.7);

  // run the clustering, extract the jets
  ClusterSequence cs(particles, jet_def);
  vector<PseudoJet> jets = sorted_by_pt(cs.inclusive_jets());
  cout << "hardest jet: pt=" << jets[0].pt() << endl;
  return 0;
}
```

Additional tricks

- The ClusterSequence can often be kept hidden

```
vector<PseudoJet> jets = jet_def(particles); // pt-sorted
```

- The jets know about their clustering structure

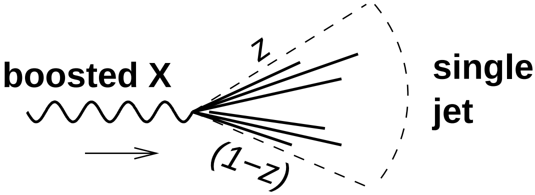
```
// the jet constituents
vector<PseudoJet> constituents = jet.constituents();

// clustering information
PseudoJet j1, j2;
if (jet.has_parents(j1, j2))
  cout << "Jet obtained by recombining ..." << endl;

// access to the underlying ClusterSequence (if still on scope)
ClusterSequence *cs = jet.associated_cluster_sequence();
```

- A PseudoJet has a user_index and can be associated a UserInfo

Boosted jets

Boosted jets: main idea

Massive object X decaying to hadrons



$$\theta \simeq \frac{m_X}{p_t} \frac{1}{\sqrt{z(1-z)}}$$

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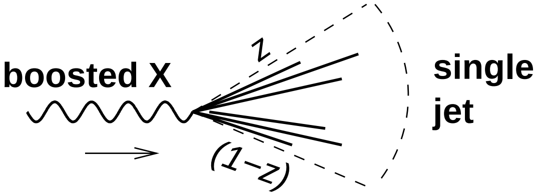


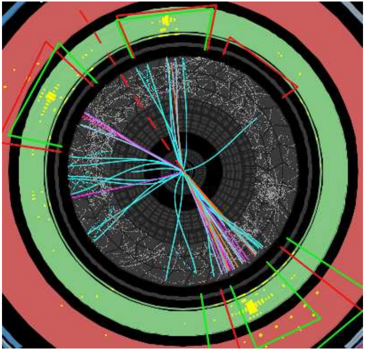
$$\theta \simeq \frac{m_X}{p_t}\frac{1}{\sqrt{z(1-z)}}$$

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

How to disentangle that from a QCD jet?

An illustration

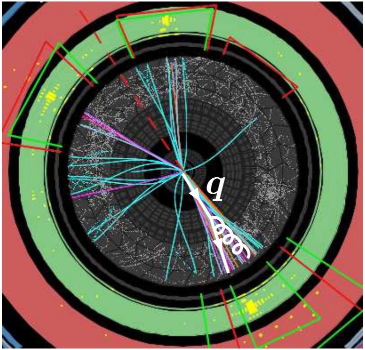
What jet do we have here?



An illustration

What jet do we have here?

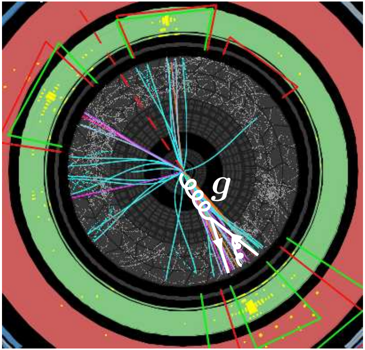
- a quark?



An illustration

What jet do we have here?

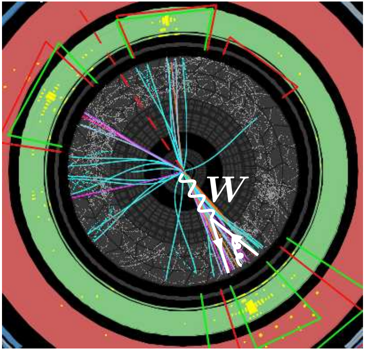
- a quark?
- a gluon?



An illustration

What jet do we have here?

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



An illustration

What jet do we have here?

- a quark?
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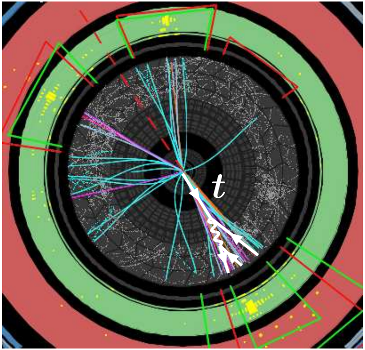
- a top quark?



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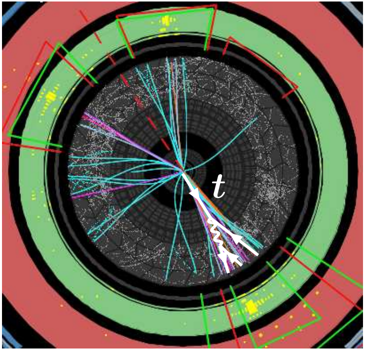

Source: ATLAS boosted top candidate

An illustration

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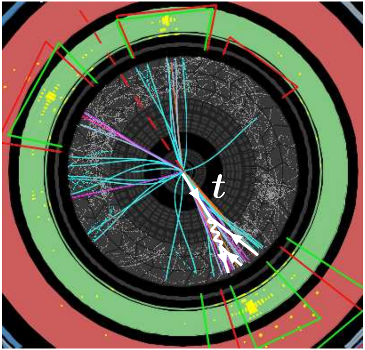

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Paradigm shift: a jet can be more than a quark or gluon

Boosted jets: why is this interesting?

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: why is this interesting?

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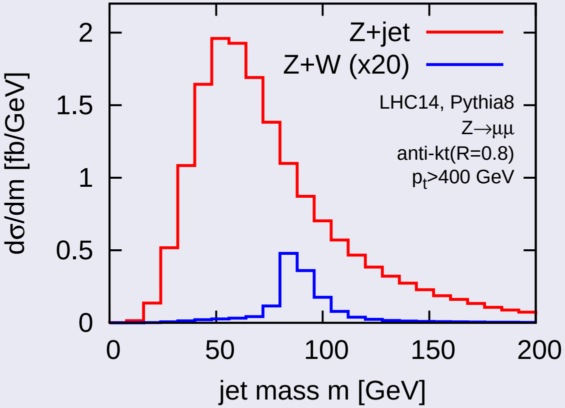
Increasingly important:

- 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

Naive ideas do not work!

Looking at the jet mass is not enough



A lot of activity since 2008

Many tools introduced since 2008:

(modified) mass drop; filtering, trimming, pruning; (recursive/iterated) soft drop, $Y_{(m)}$-splitter; N-subjettiness, planar flow, energy correlations, pull, dichroic ratios; 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

A lot of activity since 2008

Many tools introduced since 2008:

(modified) mass drop; filtering, trimming, pruning; (recursive/iterated) soft drop, $Y_{(m)}$-splitter; N-subjettiness, planar flow, energy correlations, pull, dichroic ratios; Q-jets, ScJets; shower deconstruction; template methods; Johns Hopkins top tagger, HEPTopTagger, CASubjet tagging; ...

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

Idea 2:
Constrain radiation patterns

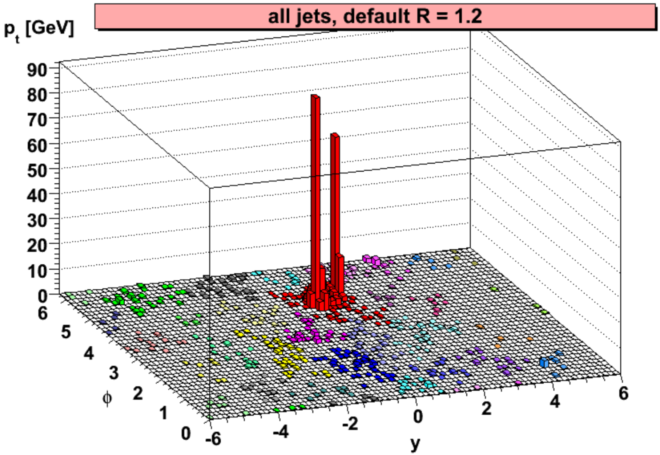
Works because different colours

Radiation pattern is different for

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

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

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



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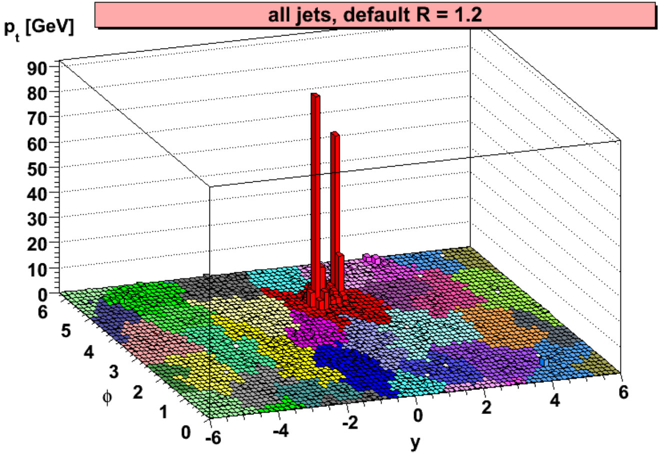

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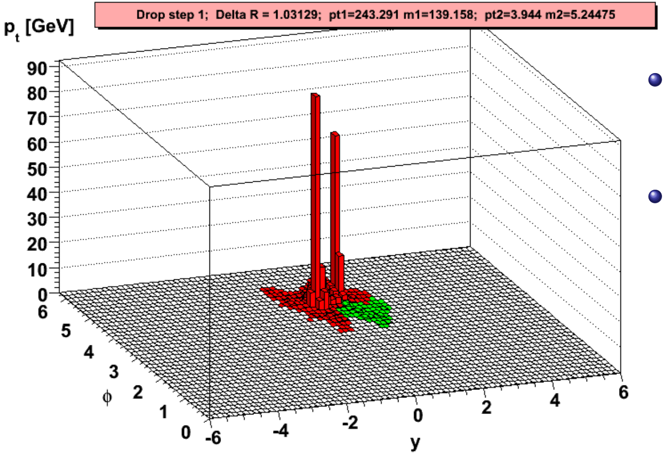
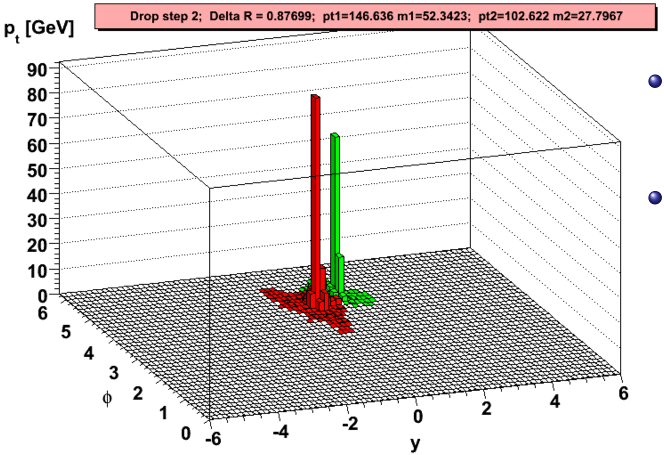


MassDrop

- undo the last clustering step until $z > z_{cut}$
- $z = 0.016 < 0.1$ carry on

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

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

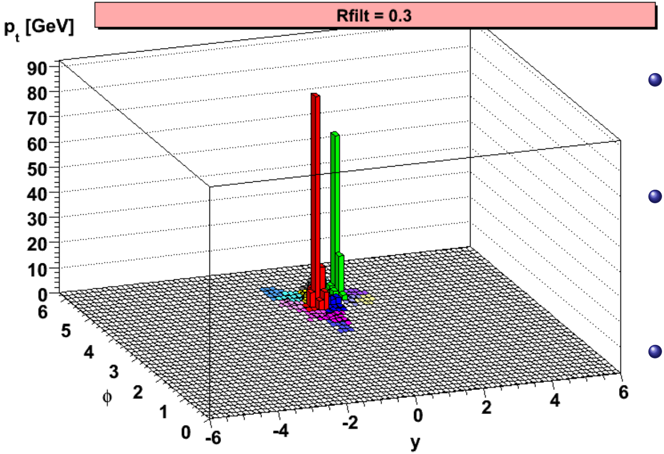


MassDrop

- undo the last clustering step until $z > z_{cut}$
- $z = 0.41 > 0.1$ stop

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

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



MassDrop

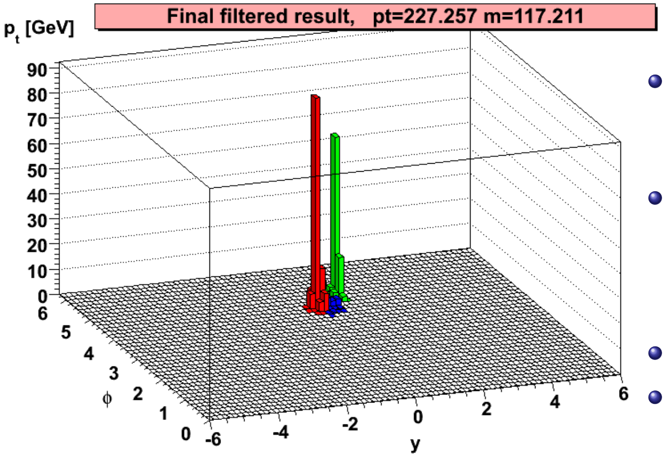
- undo the last clustering step until $z > z_{cut}$
- $z = 0.41 > 0.1$ stop

Filter

- recluster

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

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



MassDrop

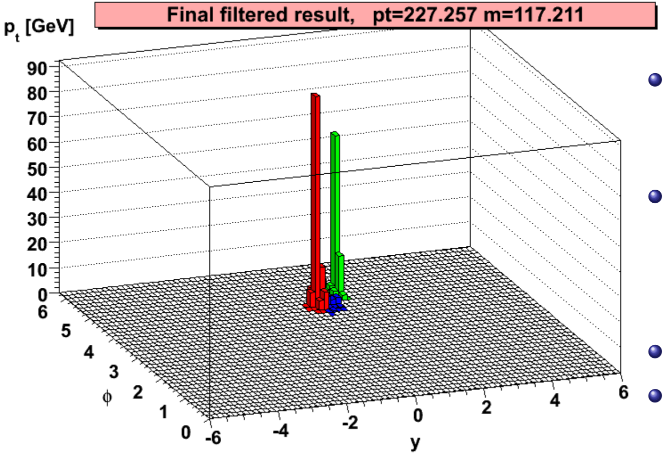
- undo the last clustering step until $z > z_{cut}$
- $z = 0.41 > 0.1$ stop

Filter

- recluster
- keep 3 hardest

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

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



MassDrop

- undo the last clustering step until $z > z_{cut}$
- $z = 0.41 > 0.1$ stop

Filter

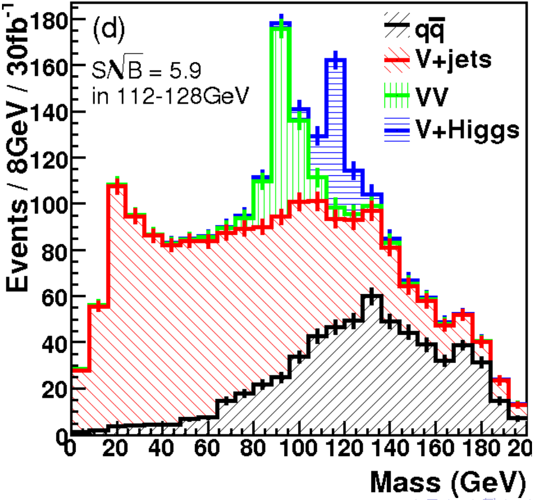
- recluster
- keep 3 hardest

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]

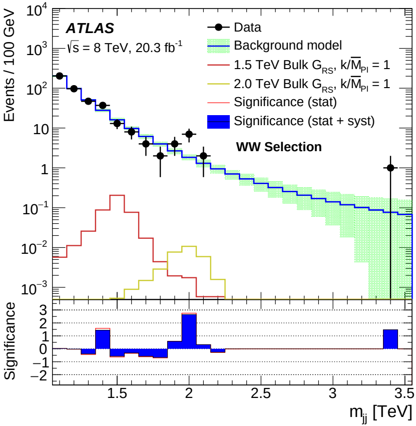
This is the kind of Higgs reconstruction one would get



Boosted jets

What do we do with all these methods?

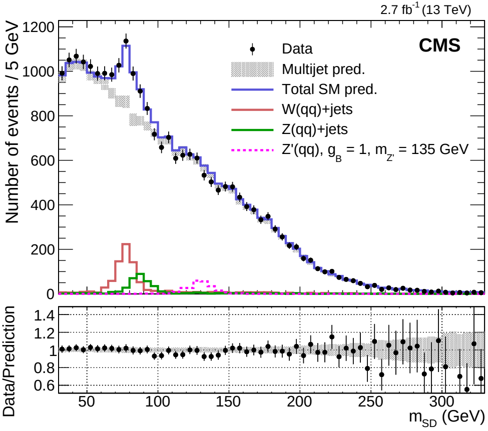
Diboson excess



[arXiv:1506.00962 (ATLAS)]

- excess observed for a dijet invariant mass around 2 TeV in the *WW* channel ($X \to WW \to$ jets)
- $m_X \approx 2\,TeV \Rightarrow$ boosted W jets
- This was with 8 TeV data (20 fb^{-1}). Gone with more stat in 13 TeV data

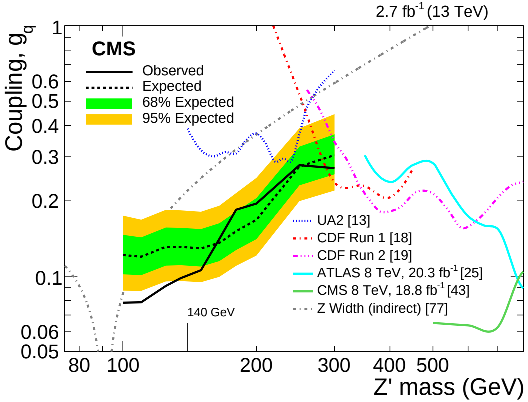
Low-mass resonance search



[arXiv:1705.10532 (CMS)]

- Search for $X \to q\bar{q}$
- Use high-p_t jets
- Look for substructure

Low-mass resonance search

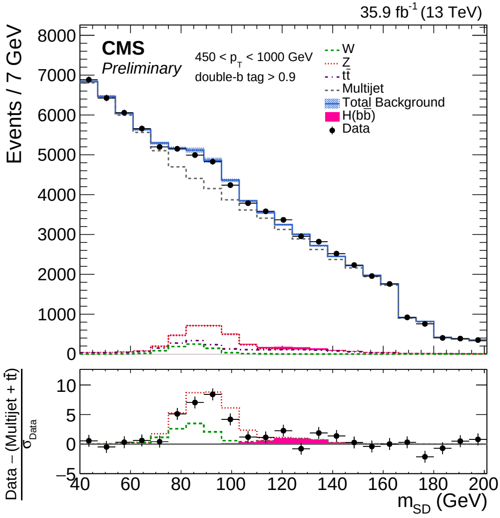


[arXiv:1705.10532 (CMS)]

- Search for $X \to q\bar{q}$
- Use high-p_t jets
- Look for substructure
- first direct exclusion for $100 < m < 140$ GeV

$H \to b\bar{b}$ measurement

[CMS-PAS-HIG-17-010]



- Look for substructure (and double b-tag) in high-p_t jets
- 5.1σ evidence for $Z \to b\bar{b}$
- 1.5σ evidence for $H \to b\bar{b}$

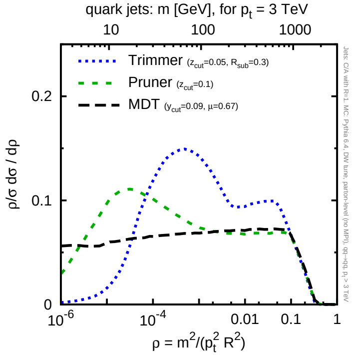
Recent theory progress

Understanding of substructure from QCD first-principles

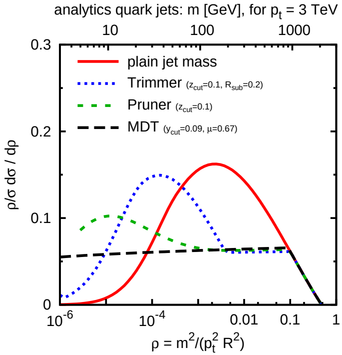
[M.Dasgupta,A.Fregoso,S.Marzani,G.Salam,13]

First analytic understanding of jet substructure:

Monte Carlo



Analytics



- Similar behaviour at large mass/small boost
- Significant differences at larger boost
- Improved methods: mMDT and Y-pruning

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()`
Y-splitter+grooming	†Dasgupta, Schunk, Soyez	combination of others
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