Jets, Boosted jets, FastJet

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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

<table>
<thead>
<tr>
<th>Th/Pheno</th>
<th>Exp</th>
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<tbody>
<tr>
<td>$\ell(e, \mu)$</td>
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<tr>
<td>$q, g$</td>
<td>???</td>
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| $W/Z/H/top/\tau/BSM/...$ | decay in the above |

- Quarks and gluons (i.e. partons) branch predominantly at small angles

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

\[
\rightarrow \text{(mostly) collimated parton shower}
\]

- One does not observe partons but hadrons ($\pi, K, ...$)

\[
\rightarrow \text{collimated bunch of hadrons called “jets”}
\]
Basic phenomenologist dictionary/view

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at least within the context of this talk
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not trivial at all... but not covered here
complex collimated structures
decay in the above
In the most simple terms:

\[ \text{jet} \equiv \text{bunch of collimated particles} \approx (\text{hard/high-energy}) \text{ quark or gluon} \]
Measure jets $\rightarrow$ access $q/g$ $\rightarrow$ learn about fundamental collision
Measure jets $\rightarrow$ access $q/g$ $\rightarrow$ learn about fundamental collision

- 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 ($H \rightarrow 2\mu 2e$ & 4 jets)]

- **Rapidity $y$**: longitudinal component (along the beam axis)
- **Azimuthal angle $\phi$**: 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?
“Jets” ≡ bunch of collimated particles ≈ hard partons

obviously 2 jets
“Jets” ≡ bunch of collimated particles ≈ hard partons

How many jets
“Jets” ≡ bunch of collimated particles ≈ hard partons

3 jets
Jets and partons

“Jets” ≡ bunch of collimated particles ≅ hard partons

3 jets... or 4?
Jets and partons

“Jets” ≡ bunch of collimated particles ≈ hard partons

3 jets... or 4?

- “collinear” is arbitrary
- “parton” concept strictly valid only at LO
Jet definition

Partons/Particles/Calorimeter towers/Tracks

Jet definition

Jet algorithm
Parameters

Jets
(Anti-\(k_t\)) algorithm

- From all the objects, define the distances
  \[ d_{ij} = \min(p_{t,i}^{-2}, p_{t,j}^{-2})(\Delta y_{ij}^2 + \Delta \phi_{ij}^2), \quad d_{iB} = p_{t,i}^{-2}R^2 \]

- 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
Recombination algorithms

(Anti-\(k_t\)) algorithm

- From all the objects, define the distances
  \[ d_{ij} = \min(p_{t,i}^{-2}, p_{t,j}^{-2})(\Delta y_{ij}^2 + \Delta \phi_{ij}^2), \quad d_{iB} = p_{t,i}^{-2}R^2 \]
- repeatedly find the minimal distance
  if \(d_{ij}\): recombine \(i\) and \(j\) into \(k = i + j\)
  if \(d_{iB}\): call \(i\) a jet
- One parameter: \(R\) ("jet radius").

Other algorithms

- "generalised-\(k_t\)"
  \[ d_{ij} = \min(p_{t,i}^{2p}, p_{t,j}^{2p})(\Delta y_{ij}^2 + \Delta \phi_{ij}^2), \quad d_{iB} = p_{t,i}^{2p}R^2 \]
- \(p = 1\): \(k_t\) algorithm (oldest in the family)
- \(p = 0\): Cambridge/Aachen algorithm ("just" angular ordering)
The anti-$k_t$ jets

Main property of anti-$k_t$: hard jets are circular
FastJet

http://fastjet.fr
Software for jet clustering

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

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- Now: (anti-)$k_t$ very fast: $\mathcal{O}(N^2)$ or even $\mathcal{O}(N \log(N))$
Software for jet clustering

- 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: $O(N^3)$

- works for all algs
- prohibitively slow
Observations:

- No need to keep track of all the distances:
  \[ \min_{i,j}\{d_{ij}\} = \min_i\{d_{i,\text{NN}(i)}\} \]
  with \( \text{NN}(i) = \min_j\{d_{ij}\} \)
  only keep track of the nearest neighbour (NN) of each particle

- Do not recalculate all NNs at each step; if \( i + j \rightarrow k \), we need \( \text{NN}(k) \) and \( \text{NN}(\ell) \) when \( \text{NN}(\ell) = i \) or \( j \)
Geometrical (Camb./Aachen) case: Nearest neighbours

Observations:
- No need to keep track of all the distances:
  \[ \min_{i,j}\{d_{ij}\} = \min_i\{d_{i,NN(i)}\} \quad \text{with} \quad NN(i) = \min_j\{d_{ij}\} \]
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- Do not recalculate all NNs at each step; if \( i + j \rightarrow k \), we need \( NN(k) \) and \( NN(\ell) \) when \( NN(\ell) = i \) or \( j \)

New implementation:

<table>
<thead>
<tr>
<th>Operation</th>
<th>Complexity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Init: compute all ( NN(i) )</td>
<td>( N^2 )</td>
</tr>
<tr>
<td>find smallest ( d_{i,NN(i)} )</td>
<td>( N )</td>
</tr>
<tr>
<td>recombine ( i + j )</td>
<td>1</td>
</tr>
<tr>
<td>compute ( NN(k) ) and ( NN(\ell) )'s</td>
<td>( N )</td>
</tr>
<tr>
<td>iterate</td>
<td>( \times N )</td>
</tr>
<tr>
<td>total</td>
<td>( \mathcal{O}(N^2) )</td>
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</tbody>
</table>

- works for all algs
- efficient for \( N \) not too large
Geometrical (Camb./Aachen) case: Tiling

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

**total** \( \mathcal{O}(Nn) \)

- \( NN \) only in current or neighbouring tile
- \( \Rightarrow NN \) search is \( \mathcal{O}(n = N/N_{\text{tiles}}) \)
Geometrical (Camb./Aachen) case: Tiling

Init: create tiling

Init: compute all $NN(i)$

Init: sort the $d_{i,NN(i)}$

Find smallest $d_{i,NN(i)}$

Recombine $i + j$

Compute $NN(k)$ and $NN(\ell)$'s

Iterate

Total

$N$

$Nn$

$N \log(N)$

$1$

$1$

$n$

$\times N$

$\mathcal{O}(Nn)$

- $NN$ only in current or neighbouring tile
- $\Rightarrow$ $NN$ search is $\mathcal{O}(n = N/N_{\text{tiles}})$
- Valid for Cambr./Aachen ($d_{ij} = \Delta R_{ij}^2$)
- Variants for finding $\min\{d_{i,NN(i)}\}$
- Tricks to avoid neighbour tiles when possible
Geometrical (Camb./Aachen) case: Tiling

- **Init: create tiling**
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- **find smallest** $d_{i,NN(i)}$
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- **iterate**

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- $NN$ only in current or neighbouring tile
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- Valid for Cambr./Aachen ($d_{ij} = \Delta R_{ij}^2$)
- Variants for finding $\min\{d_{i,NN(i)}\}$.
- Tricks to avoid neighbour tiles when possible

- **Optimal for** $30 \lesssim N \lesssim 5 \times 10^5$
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

\[
d_{ik} = \min(p_{ti}^{2p}, p_{tk}^{2p}) \Delta R_{ik}^2 < p_{ti}^{2p} \Delta R_{ij}^2 = d_{ij},
\]

a contradiction.
Other algorithms

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

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\]

a contradiction.

⇒ 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
Main FastJet classes

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

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

```cpp
#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

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

- The jets know about their clustering structure

```cpp
// 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
Massive object $X$ decaying to hadrons

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

boosted $X$  \hspace{1cm} single jet

\hspace{1cm} (1-z)
**Boosted jets: main idea**

Massive object $X$ decaying to hadrons

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

How to disentangle that from a QCD jet?

$$\theta \sim \frac{m_X}{p_t} \frac{1}{\sqrt{z(1-z)}}$$
An illustration

What jet do we have here?
What jet do we have here?

- a quark?
What jet do we have here?

- a quark?
- a gluon?
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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Source: ATLAS boosted top candidate
An illustration

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- a gluon?
- a $W/Z$ (or a Higgs)?
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Source: ATLAS boosted top candidate

Paradigm shift: a jet can be more than a quark or gluon
Many applications: (examples)

- 2-pronged decay: \( W/Z \rightarrow q\bar{q}, H \rightarrow b\bar{b} \)
- 3-pronged decay: \( t \rightarrow qqb, \tilde{\chi} \rightarrow qqq \)
Boosted jets: why is this interesting?

Many applications: (examples)

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

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
Looking at the jet mass is not enough

**Graph:**
- **Z+jet**
- **Z+W** (x20)

- **LHC14, Pythia8**
- **Z→μμ**
- **anti-kt(R=0.8)**
- **p_t>400 GeV**
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
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Works because different splitting
QCD jets: $P(z) \propto 1/z$
⇒ dominated by soft emissions
⇒ “single” hard core

Idea 2:
Constrain radiation patterns

Works because different colours
Radiation pattern is different for
- colourless $W \rightarrow q\bar{q}$
- coloured $g \rightarrow q\bar{q}$
Two-prong finder: MassDrop ($z_{\text{cut}} = 0.1$) + filtering

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

Grégory Soyez (IPhT, CEA Saclay)
Two-prong finder: MassDrop \( (z_{\text{cut}} = 0.1) \) + filtering

[J. Butterworth, A. Davison, M. Rubin, G. Salam, 08]
Two-prong finder: MassDrop ($z_{\text{cut}} = 0.1$) + filtering

MassDrop

- undo the last clustering step until $z > z_{\text{cut}}$
- $z = 0.016 < 0.1$ carry on
Two-prong finder: MassDrop \((z_{\text{cut}} = 0.1) + \text{filtering}\)

\[z > z_{\text{cut}}\]

\[z = 0.41 > 0.1\]

stop

MassDrop

undo the last clustering step until

\[z > z_{\text{cut}}\]

\[z = 0.41 > 0.1\]

stop

Drop step 2; Delta R = 0.87699; \(p_{t1}=146.636\); \(m_{1}=52.3423\); \(p_{t2}=102.622\); \(m_{2}=27.7967\)
Two-prong finder: MassDrop ($z_{\text{cut}} = 0.1$) + filtering

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

Filter
- recluster
Two-prong finder: MassDrop \((z_{\text{cut}} = 0.1)\) + filtering

---

MassDrop

- undo the last clustering step until \(z > z_{\text{cut}}\)
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Filter

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- keep 3 hardest

---

[J.Butterworth, A.Davison, M.Rubin, G.Salam, 08]
Two-prong finder: \textbf{MassDrop} \((z_{\text{cut}} = 0.1) +\) filtering

\begin{itemize}
  \item MassDrop
    \begin{itemize}
    \item undo the last clustering step until \(z > z_{\text{cut}}\)
    \item \(z = 0.41 > 0.1\) stop
    \end{itemize}
  \item Filter
    \begin{itemize}
    \item recluster
    \item keep 3 hardest
    \end{itemize}
\end{itemize}

\textbf{Variant}: \textbf{SoftDrop}: impose \(z > z_{\text{cut}} \theta^\beta\)

\cite{10.1007/JHEP01(2012)115,10.1140/epjc/s10052-017-4822-9}
MassDrop for $H \rightarrow b\bar{b}$ searches

This is the kind of Higgs reconstruction one would get

(d)

SN/$\sqrt{B} = 5.9$
in 112-128GeV
Boosted jets

What do we do with all these methods?
excess observed for a dijet invariant mass around 2 TeV in the $WW$ channel ($X \rightarrow WW \rightarrow$ 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

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

- Look for substructure (and double $b$-tag) in high-$p_T$ jets
- $5.1\sigma$ evidence for $Z \rightarrow b\bar{b}$
- $1.5\sigma$ evidence for $H \rightarrow b\bar{b}$
Recent theory progress

Understanding of substructure from QCD first-principles

First analytic understanding of jet substructure:

Monte Carlo

Jet mass: $m$ [GeV], for $p_t = 3$ TeV

- Trimmer ($z_{cut}=0.05, R_{sub}=0.3$)
- Pruner ($z_{cut}=0.1$)
- MDT ($y_{cut}=0.09, \mu=0.67$)

Analytics

Jet mass: $m$ [GeV], for $p_t = 3$ TeV

- Plain jet mass
- Trimmer ($z_{cut}=0.1, R_{sub}=0.2$)
- Pruner ($z_{cut}=0.1$)
- MDT ($y_{cut}=0.09, \mu=0.67$)

- Similar behaviour at large mass/small boost
- Significant differences at larger boost
- Improved methods: mMDT and $Y$-pruning
### Tools: who? where?

<table>
<thead>
<tr>
<th>Tool</th>
<th>Who</th>
<th>Where</th>
</tr>
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<tbody>
<tr>
<td>hline Mass-Drop</td>
<td>†Butterworth, Davison, Rubin, Salam</td>
<td>fj::MassDropTagger</td>
</tr>
<tr>
<td></td>
<td>†Dasgupta, Fregoso, Marzani, Salam</td>
<td>fj::contrib::ModifiedMassDropTagger</td>
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<td></td>
<td>†Butterworth, Davison, Rubin, Salam</td>
<td>fj::Filter</td>
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<tr>
<td>Filtering</td>
<td>†Krohn, Thaler, Wang</td>
<td>fj::Filter</td>
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<td>N-subjettiness</td>
<td>†Jihun Kim</td>
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<td>Energy correlations</td>
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<td>fj::contrib::EnergyCorrelator</td>
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<td>Variable $R$</td>
<td>†Krohn, Thaler, Wang</td>
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<td>†Bertolini, Chan, Thaler</td>
<td>fj::contrib:::...</td>
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<td>CASubjet tagging</td>
<td>†Salam</td>
<td>fj::CASubJetTagger</td>
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<td>Y-splitter</td>
<td>†Butterworth, Cox, Forshaw</td>
<td>fj::ClusterSequence::exclusive_submerge()</td>
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<tr>
<td>Y-splitter+grooming</td>
<td>†Dasgupta, Schunk, Soyez</td>
<td>combination of others</td>
</tr>
<tr>
<td>Planar flow</td>
<td>†Almeida, Lee, Perez, Sterman, Sung, Virzi</td>
<td>3rd party</td>
</tr>
<tr>
<td>Pull</td>
<td>†Gallicchio, Schwartz</td>
<td>3rd party</td>
</tr>
<tr>
<td>Q-jets</td>
<td>†Ellis, Hornig, Krohn, Roy and Schwartz</td>
<td>3rd party</td>
</tr>
<tr>
<td>HEPTopTagger</td>
<td>†Plehn, Salam, Spannowsky, Takeuchi</td>
<td>3rd party</td>
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<tr>
<td>TemplateTagger</td>
<td>†Backovic, Juknevic, Perez</td>
<td>3rd party</td>
</tr>
<tr>
<td>Shower deconstruction</td>
<td>†Soper, Spannowsky</td>
<td>3rd party</td>
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1 References are incomplete