Pile-up subtraction for jets at the LHC

Grégory Soyez
IPhT, CEA Saclay

with Matteo Cacciari, Gavin Salam and Jihun Kim
Brief plan

- Jets
  - Concept and importance
  - Milestones
  - Jet definition
  - A few examples

- Jets and soft backgrounds
  - an unprecedented challenge at the LHC
  - area-based background subtraction
What is a “jet”? concept/idea
Final-state events are pencil-like already observed in $e^+e^-$ collisions:

Consequence of the collinear divergence
QCD (quark & gluon) branching proba: $\frac{dP}{d\theta} \propto \frac{\alpha_s}{\theta}$
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“Jets” $\equiv$ bunch of collimated particles $\simeq$ hard partons
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“Jets” $\equiv$ bunch of collimated particles $\cong$ hard partons
Jets and partons

“Jets” ≡ bunch of collimated particles ≈ hard partons

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

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

3 jets... or 4?

“collinear” is arbitrary
“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
What is a “jet”?

jet definition(s)
Naive approach

Have students/postdocs look at the events

The LHC records $\sim 500$ events/second
Looking at one event takes, say, 5 seconds

$\Rightarrow$ hire 2500 students/postdocs
cost $\sim 20$M euros/year.

Impractical!

Use computer code
Jet definition

A jet definition is supposed to
- give finite jet cross sections (th)
- be fast enough (exp)
- be (as) consistent (as possible) across different view of an event (th&exp)

LO partons

NLO partons

parton shower

hadron level
A brief/rough flight over the history of jets
A brief/rough flight over the history of jets

Sterman-Weinberg: cone algorithm

Stable flow of energy in a cone of fixed opening angle
A brief/rough flight over the history of jets

1979
Sterman-Weinberg: cone algorithm

1980
SNOWMASS accords (Tevatron): rules for jet definitions
A brief/rough flight over the history of jets

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- **80’s**
  - Recombination algs: JADE, Durham($k_t$), Cambridge/Aachen
  - Used at LEP (many QCD studies)

- **1990**

- **2000**

- **2010**

Successive pairwise mergings (minimum “distance”)

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- **2008**
  - Jet-area-based background subtraction methods

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Jet-area-based background subtraction methods

[M.Cacciari,G.Salam, 0707.1378; M.Cacciari,G.Salam,GS, 0802.1188]

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- The LHC uses anti-$k_t$, FastJet and Jet-area-based subtraction

Jet-area-based background subtraction methods
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SNOWMASS accords (Tevatron): rules for jet definitions
What is a “jet”?  

jets at the LHC
The anti-$k_t$ jets

- All experiments use the anti-$k_t$ algorithm:
  - [M. Cacciari, G. Salam, GS, 2008]
  - From all the objects, define the distances
    \[
    d_{ij} = \min(k_{ti}^{-2}, k_{tj}^{-2})(\Delta y_{ij}^2 + \Delta \phi^2), \quad d_{iB} = k_{ti}^{-2}R^2
    \]
  - repeatedly find the minimal distance
    if $d_{ij}$: recombine $i$ and $j$ into $k = i + j$
    if $d_{iB}$: call $i$ a jet

- $R$ is a size parameter (eg CMS: 0.5, 0.7, ATLAS: 0.4, 0.6)
- Main property: hard jets are circular
Clustering in action: anti-$k_t$ ($R = 0.6$)

Start with your favourite picture
Clustering in action: anti-$k_t$ ($R = 0.6$)

Start with your favourite picture event
Clustering in action: anti-$k_t$ ($R = 0.6$)

$p_t$/GeV

dmin is $d_{ij} = 3.90625 \times 10^{-5}$

min is $d_{ij} = 3.9 \times 10^{-5}$
Clustering in action: anti-$k_t$ ($R = 0.6$)

recombine them
Clustering in action: anti-$k_t$ ($R = 0.6$)

$d_{\text{min}}$ is $d_{ij} = 8.91301 \times 10^{-5}$

$\min$ is $d_{ij} = 8.9 \times 10^{-5}$
Clustering in action: anti-$k_t$ ($R = 0.6$)

recombine them
Clustering in action: anti-$k_t$ ($R = 0.6$)

\[ \text{min is } d_{ij} = 7.6 \times 10^{-5} \]

\[ \text{dmin is } d_{ij} = 7.59102 \times 10^{-5} \]
Clustering in action: anti-\(\kappa_t\) \((R = 0.6)\)

recombine them
Clustering in action: anti-$k_t$ ($R = 0.6$)

\[ d_{\text{min}} \text{ is } d_{iB} = 7.3 \times 10^{-5} \]
Clustering in action: anti-$k_t$ ($R = 0.6$)

$p_t/\text{GeV}$

declare as a jet
Clustering in action: anti-$k_t$ ($R = 0.6$)

$p_t/\text{GeV}$

$d_{\text{min}}$ is $d_{ij} = 0.000277778$

$\text{min is } d_{ij} = 2.8 \times 10^{-4}$
Clustering in action: anti-$k_t$ ($R = 0.6$)

recombine them
Clustering in action: anti-$k_t$ ($R = 0.6$)

dmin is $d_{ij} = 0.00018523$

min is $d_{ij} = 1.9 \times 10^{-4}$
Clustering in action: anti-$k_t$ ($R = 0.6$)

recombine them
Clustering in action: anti-$k_t$ ($R = 0.6$)

$p_t/\text{GeV}$

$d_{\min} \text{ is } d_{i\text{B}} = 0.00020975$

$\min \text{ is } d_{i\text{B}} = 2.1 \times 10^{-4}$
Clustering in action: anti-$k_t$ ($R = 0.6$)

declare as a jet
Clustering in action: anti-$k_t$ ($R = 0.6$)

\[
\begin{align*}
\text{dmin is } d_{iB} &= 0.00145785 \\
\text{min is } d_{iB} &= 1.5 \times 10^{-3}
\end{align*}
\]
Clustering in action: anti-$k_t$ ($R = 0.6$)

DECLARE AS A JET
Tevatron era: $k_t$ too slow: $O(N^3)$ for $N$ particles
FastJet (1/2)

- 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 $\mathcal{O}(N \log(N))$

- the “FastJet lemma”: min distance is a Nearest Neighbour
- use of computational geometry e.g. Voronoi diagram
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 3.0.3 released in June 2012
see [www.fastjet.fr](http://www.fastjet.fr)

Standard interface for jet clustering
for both theorists and experimentalists
Jets in a soft background
$Z \rightarrow \ell^+ \ell^-$ candidate at ATLAS

Low luminosity
(bunch population)
$Z \rightarrow \ell^+ \ell^-$ candidate at ATLAS

Low luminosity (bunch population)

High luminosity (bunch population)

- many (soft) $pp$ interactions with the hard one (here 25)
- soft background in all the detector
A CMS event with 78 pile-up vertices!

Today (2012 run), 30 PU vertices on average
Basic characterisation

Pileup mostly characterised by 3 numbers:

- $\rho$: the average activity in an event (per unit area)
- $\sigma$: the intra-event fluctuations (per unit area)
- $\sigma_\rho$: the event-to-event fluctuations of $\rho$
Basic characterisation

Pileup mostly characterised by 3 numbers:

- $\rho$: the average activity in an event (per unit area)
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For a jet (of area $A$) in a given event that means:

$$p_t \rightarrow p_t + \rho A \pm \sigma \sqrt{A}$$

When averaging over many events

$$p_t \rightarrow p_t + \langle \rho \rangle A \pm \sigma_\rho A \pm \sigma \sqrt{A}$$
Illustration of the consequences

- Shift due to the “$\rho A$” term
- Smearing due to the “$\sigma A$” and “$\sigma \sqrt{A}$” terms
Heavy ions

Note: same considerations for “spectator $p$ and $n$” in heavy ion collisions

Typical case: anti-$k_t$ $R = 0.4$, 20 PU or $0-10\%$ centrality

<table>
<thead>
<tr>
<th>Estimates</th>
<th>LHC, $pp$</th>
<th>LHC, $PbPb$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\rho$</td>
<td>15 GeV</td>
<td>200 GeV</td>
</tr>
<tr>
<td>$\sigma_\rho$</td>
<td>4 GeV</td>
<td>40 GeV</td>
</tr>
<tr>
<td>$\sigma$</td>
<td>5 GeV</td>
<td>20 GeV</td>
</tr>
<tr>
<td>$A_{\text{jet}}$</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>$\delta p_{t,\text{jet}}$</td>
<td>7.5 GeV</td>
<td>100 GeV</td>
</tr>
<tr>
<td>$\sigma_{\text{jet}}$</td>
<td>3.5 GeV</td>
<td>16 GeV</td>
</tr>
</tbody>
</table>
Naive subtraction methods

Shift: one subtracts a contribution from the jet
Examples:

• subtract a constant number from each jet
  Keep both PU fluctuations + area fluctuations

• subtract a constant density from each jet
  Keep both PU fluctuations \((\sigma \sqrt{A} & \sigma_\rho A)\)

• subtract a constant density for each PU vertex from each jet
  Keeps \(\sigma \sqrt{A}\) and part of \(\sigma_\rho A\)
Jet-area-based subtraction

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

\[ p_{t,\text{jet}}^{(\text{sub})} = p_{t,\text{jet}} - \rho_{\text{est}} A_{\text{jet}} \]

- jet area: available with jet clustering
  - add a dense coverage of particles with tiny $p_t$ (≡ area quanta)
  - jet area $\propto$ number of these “ghosts” in the jet
Jet-area-based subtraction

\[ p^{(\text{sub})}_{t,\text{jet}} = p_{t,\text{jet}} - \rho_{\text{est}} A_{\text{jet}} \]

- jet area: available with jet clustering
- \( \rho_{\text{bkg}} \), the background \( p_t \) density per unit area
  - break the event in patches of similar size
    - e.g. cluster with \( k_t \)
  - Estimate \( \rho_{\text{bkg}} \) using
    \[
    \rho_{\text{bkg}} = \text{median} \left\{ \frac{p_{t,j}}{A_j} \right\}
    \]
Jet-area-based subtraction

Jet area $A_{\text{jet}}$: per jet
Bkg density $\rho$: (typically) per event

Consequences:
- corrects for the $\rho A$ shift
- gets rid of the $\sigma_{\rho A}$ smearing (across events)
- left with the fluctuations $\sigma \sqrt{A}$ (in-event)
Subtraction efficiency study:

Generate a hard event → hard jets
Add PU events → full jets
Apply subtraction → subtracted jets
Subtraction benchmarks

Subtraction efficiency study:

Generate a hard event $\rightarrow$ hard jets
Add PU events $\rightarrow$ full jets
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$\Delta p_t^{unsub}$
$\Delta p_t^{sub}$
Subtraction benchmarks

Subtraction efficiency study:

- Generate a hard event → hard jets
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\[ \Delta p_t^{\text{unsub}} \]
\[ \Delta p_t^{\text{sub}} \]

\( n_{\text{PU}} \quad \langle \Delta p_t \rangle \quad \text{[GeV]} \)

\( \langle \Delta p_t^{\text{sub}} \rangle \quad \text{OK} \)

LHC, \( \sqrt{s} = 7 \) TeV
anti-\( k_t \)(R=0.5), \( p_t > 200 \) GeV
Subtraction benchmarks

Subtraction efficiency study:

- Generate a hard event → hard jets
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\[ \Delta p_t^{\text{unsub}} \]
\[ \Delta p_t^{\text{sub}} \]

\( \langle \Delta p_t \rangle \) [GeV]

\( \sigma_{\Delta p_t} \) [GeV]

\( n_{\text{PU}} \)

LHC, \( \sqrt{s}=7 \text{ TeV} \)
anti-\( k_t(R=0.5) \), \( p_t>200 \text{ GeV} \)

- shift \( \langle \Delta p_t^{\text{sub}} \rangle \) OK
- resol \( \sigma_{\Delta p_t^{\text{sub}}} \) better

- p. 24
Recent developments

Improvements/extensions of the method

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

- **Subtraction of fragmentation function (moments)**
  - Useful for quenching in $PbPb$ collisions

  [M.Cacciari, P.Quiroga, G.Salam, GS, 2012]

- **Subtraction for jet mass and jet shapes**
  - Important for jet tagging ("$q$ v. $g$ jet", $b$ jet, top jet, $H \rightarrow b\bar{b}$)

  [M.Cacciari, J.Kim, G.Salam, GS, soon]
Many recent developments in use at the LHC:

- jet algorithms with finite cross-sect. at all orders
- in particular the anti-$k_t$ algorithm
- FastJet: fast implementations and jet package
- efficient PU subtraction method
- constant interaction with the experiments

Future

- Release FastJet 3.1
- Study filtering/noise-reduction techniques for reduction of the $\sigma\sqrt{A}$ term