Defining jets at the dawn of the LHC

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Plan

- Jet algorithms and jet definitions
  - basic ideas: why jets? recombinations and cones
  - failures of the $20^{\text{th}}$-century cone algorithms
  - new algorithms without the failures

- More advanced topics: how to better use the tools we have?
  - jet areas: tool for pileup subtraction
  - new generation of algorithms
  - optimal choice (for kinematic reconstructions)
Unavoidable theory

QCD probability for gluon emission (angle $\theta$ and $\perp$-mom. $k_t$):

$$dP \propto \alpha_s \frac{d\theta}{\theta} \frac{dk_t}{k_t}$$

Two divergences:

- $\theta \approx 0$ \hspace{1cm} \text{collinear}
- $k_t \ll p_t$ \hspace{1cm} \text{soft}

Divergences cancelled by virtual corrections
Motivation: why jets

Collinear divergence $\Rightarrow$ QCD produces “jetty” showers

Example: LEP (OPAL) events

“Jets” $\equiv$ bunch of collimated particles $\approx$ hard partons
Motivation: why jets

Collinear divergence ⇒ QCD produces “jetty” showers

“Jets” ≡ bunch of collimated particles ⇐ hard partons

BUT

- a “parton” is an ambiguous concept (NLO)
- “collinear” has some arbitrariness

2 jets  3 jets  ? jets
Motivation: why jets

Collinear divergence ⇒ QCD produces “jetty” showers

“Jets” ≡ bunch of collimated particles ≈ hard partons

In practice: use of a jet definition

particles \( \{p_i\} \) \[\rightarrow\] jet definition \[\rightarrow\] jets \( \{j_k\} \)

Jet algorithm: the recipe (insufficient!)
Jet definition: algorithm + the parameters
20th century jet algorithms

Recombination:
- $k_t$ algorithm
- Cambridge/Aachen alg.

Cone:
- CDF JetClu
- CDF MidPoint
- D0 (run II) Cone
- PxCone
- ATLAS Cone
- CMS Iterative Cone
- PyCell/CellJet
- GetJet
**Recombination:**
- $k_t$ algorithm
- Cambridge/Aachen alg.

**Idea:** undo the showering

Successively
- find the closest pair of particles
- recombine them

**Distance:**

$k_t$:

$$d_{i,j} = \min(k_{t,i}^2, k_{t,j}^2)(\Delta \phi_{i,j}^2 + \Delta y_{i,j}^2)$$

Cam/Aachen:

$$d_{i,j} = \Delta \phi_{i,j}^2 + \Delta y_{i,j}^2$$

stop at a distance $R$
**20th century jet algorithms**

**Ideas:** dominant flow of energy

**Stable cone (radius \( R \):**
sum of particles in the cone points towards the cone centre

All these are iterative cones:
- start from a seed
- iterate until stable

seeds = \{particles, midpoints\}

Jet \( \equiv \) stable cone modulo overlapping

**Cone:**
- CDF JetClu
- CDF MidPoint
- D0 (run II) Cone
- PxCone
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- CMS Iterative Cone
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- GetJet
Cone with *split-merge*

Split/merge if the overlap is smaller/larger than a threshold $f$
20th century jet algorithms

Cone with **progressive removal**

Successively
- iterate from hardest particle
- call that a jet (remove particles)

**Basic property:**
- hard circular jets

**Cone:**
- CDF JetClu
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Recombination:
- $k_t$ algorithm
- Cambridge/Aachen alg.

✓ perturbative behaviour

Cone:
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✓ UE sensitivity
21st century: how does that picture change?
QCD divergences

Ingredient: QCD soft and collinear divergencies

\[ \infty \quad \infty \quad \infty \]  
(from soft gluons) cancel (inclusive x-section)
**QCD divergences**

Ingredient: QCD soft and collinear divergencies

- **LO**
- **NLO(virt)**
- **NLO(real)**

- Consider an extra (NLO) soft gluon
- Assume LO gives 2 jets \(\Rightarrow\) NLO(virt) gives 2 jets
**QCD divergences**

Ingredient: QCD soft and collinear divergencies

Consider an extra (NLO) soft gluon

Assume LO gives 2 jets  \(\Rightarrow\) NLO(virt) gives 2 jets

NLO(real) gives 2 jets  \(\Rightarrow\) \(\infty\) cancel  \(\Rightarrow\) finite jet cross-section
Ingredient: QCD soft and collinear divergencies

Consider an extra (NLO) soft gluon

Assume LO gives 2 jets $\Rightarrow$ NLO(virt) gives 2 jets

NLO(real) gives 2 jets $\Rightarrow \infty$ cancel $\Rightarrow$ finite jet cross-section

NLO(real) gives 1 jets $\Rightarrow \infty$ do not cancel $\Rightarrow$ infinite jet x-section
QCD divergences

Ingredient: QCD soft and collinear divergencies

For pQCD to make sense, the (hard) jets should not change when

- one has a soft emission \textit{i.e.} adds a very soft gluon
- one has a collinear splitting
  \textit{i.e.} replaces one parton by two at the same place ($\eta, \phi$)

[SNOWMASS Accords, Fermilab, 1990]
IR (un)safety? JetClu and Atlas Cone
Stable cones found
A soft gluon changed the number of jets

⇒ IR unsafety of JetClu and the ATLAS Cone
A soft gluon changed the number of jets

⇒ IR unsafety of JetClu and the ATLAS Cone

Fixed by MidPoint

[Blazey et al., 00]
Stable cones found
A soft gluon changed the number of jets

⇒ IR unsafety of MidPoint (1 order in $\alpha_s$ later than JetClu)
**Solution:** be sure to find **all** stable cones

**SISCones:** Seedless Infrared-Safe Cone algorithm

[http://projects.hepforge.org/siscone](http://projects.hepforge.org/siscone)

**Idea:** enumerate enclosures by enumerating pairs of particles
Collinear (un)safety? the CMS iterative cone
A colinear splitting changed the number of jets

\[ \Rightarrow \text{Collinear unsafety of the CMS iterative cone} \]
Come back to recombination-type algorithms:

\[ d_{ij} = \min(k_{t,i}^{2p}, k_{t,j}^{2p}) \left( \Delta \phi_{ij}^2 + \Delta \eta_{ij}^2 \right) \]

- \( p = 1 \): \( k_t \) algorithm
- \( p = 0 \): Aachen/Cambridge algorithm
Come back to recombination-type algorithms:

\[ d_{ij} = \min(k_{t,i}^{2p}, k_{t,j}^{2p}) (\Delta \phi_{ij}^2 + \Delta \eta_{ij}^2) \]

- \( p = 1 \): \( k_t \) algorithm
- \( p = 0 \): Aachen/Cambridge algorithm
- \( p = -1 \): anti-\( k_t \) algorithm [M.Cacciari, G.Salam, G.S., 08]

Why should that be related to the iterative cone ?!?!

- “large \( k_t \) ⇒ small distance”
  - \( i.e. \) hard partons “eat” everything up to a distance \( R \)
  - \( i.e. \) circular/regular jets, jet borders unmodified by soft radiation
- infrared and collinear safe
Recombination:
- $k_t$ algorithm
- Cambridge/Aachen alg.
- anti-$k_t$ algorithm

Cone:
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4 available safe algorithms

anti-$k_t$ adopted as default by ATLAS and CMS
Recombination:  
- $k_t$ algorithm

Cone:  
- CDF JetClu
- CDF MidPoint

#-----------------------------------------------------------
# FastJet release 2.4
# Written by M. Cacciari, G.P. Salam and G. Soyez
# http://www.fastjet.fr
#-----------------------------------------------------------

All those algorithms (and much more) implemented (efficiently) in FastJet

safe algorithms

anti-$k_t$ adopted as default by ATLAS and CMS
When does IRC safety matters?

Take *e.g.* the MidPoint cone

\[
\begin{align*}
\alpha_s^2 \times \ldots & + \alpha_s^3 \times \ldots + \alpha_s^4 \times \ldots + \alpha_s^5 \times \\
& \ldots + \ldots
\end{align*}
\]

QCD expansion (one $\alpha_s$ can be replaced by $\alpha_{\text{EW}}$)
When does IRC safety matters?

Take e.g. the MidPoint cone

\[
\begin{align*}
\alpha_s^2 \times \ldots &+ \alpha_s^3 \times \ldots + \alpha_s^4 \times \ldots + \alpha_s^5 \times \log \left( \frac{p_t}{\Lambda_{QCD}} \right) \ldots &+ \ldots
\end{align*}
\]

- QCD expansion (one \( \alpha_s \) can be replaced by \( \alpha_{EW} \))
- IRC unsafety (regulated at the hadronic scale \( \sim \Lambda_{QCD} \))
When does IRC safety matters?

Take *e.g.* the MidPoint cone

\[
\begin{align*}
\text{2 particles} & \quad \text{3 particles} & \quad \text{4 particles} & \quad \text{4 particles + 1 soft} \\
\alpha_s^2 \times \ldots & + \alpha_s^3 \times \ldots & + \alpha_s^4 \times \ldots & + \alpha_s^5 \times \log(p_t/\Lambda_{QCD}) \ldots + \ldots \\
& & & \text{cannot be trusted}
\end{align*}
\]

- **QCD expansion** (one \(\alpha_s\) can be replaced by \(\alpha_{EW}\))
- **IRC unsafety** (regulated at the hadronic scale \(\sim \Lambda_{QCD}\))
- \(\alpha_s \log(p_t/\Lambda_{QCD}) \sim 1\)
- **last meaningful order** = \(\alpha_s^3\) or \(\alpha_{EW} \alpha_s^2\)
When does IRC safety matters?

Take e.g. the MidPoint cone

\[ \alpha_s^2 \times \ldots + \alpha_s^3 \times \ldots + \alpha_s^4 \times \ldots + \alpha_s^5 \times \log \left( \frac{p_t}{\Lambda_{QCD}} \right) \ldots + \ldots \]

QCD expansion (one \( \alpha_s \) can be replaced by \( \alpha_{EW} \))

IRC unsafety (regulated at the hadronic scale \( \sim \Lambda_{QCD} \))

\( \alpha_s \log \left( \frac{p_t}{\Lambda_{QCD}} \right) \sim 1 \)

last meaningful order = \( \alpha_s^3 \) or \( \alpha_{EW} \alpha_s^2 \)

same argument for the Iterative Cone

1 order worse for JetClu or the ATLAS cone
### Physical impact

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<thead>
<tr>
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**Example: (Midpoint-SISCon)/SISCon**

- **Incl. cross-section: a few %**
- **Masses in 3-jet events: $\sim 45\%$**

**Diagram**

- **Parton-level**
- **Hadron-level (with UE)**
- **Hadron-level (no UE)**

**Legend**

- NLOJet
- $R=0.7$, $f=0.5$
- $\Delta R_{23} < 1.4$
- Mass spectrum of jet 2
- Midpoint(0) – SISCon
- SISCone

**Legend**

- Pythia 6.4
- $R=0.7$, $f=0.5$, $|y|<0.7$

**Legend**

- $p_T\ [\text{GeV}]$
- $M\ [\text{GeV}]$
- $d\sigma_{\text{midpoint}}/dp_T - 1$
- $d\sigma_{\text{SISCone}}/dp_T - 1$

**Legend**

- $\sqrt{s} = 14\ \text{TeV}$
- $p_T\ [\text{GeV}]$
- $M\ [\text{GeV}]$
- $d\sigma_{\text{midpoint}}/dp_T - 1$
- $d\sigma_{\text{SISCone}}/dp_T - 1$
## Physical impact

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Huge effort ($\sim 50 \text{ Me} \) to compute processes in pQCD

Note:  
- arXiv:0903.0814: $W + 2$ jets vs. LO QCD using CDF JetClu  
- arXiv:0903.1748: $Z + 2$ jets vs. NLO QCD using the D0runII cone  
- arXiv:0903.1801: $Z + 2$ jets vs. NLO QCD using the CMS iterative cone
We (finally) have a good set of tools

Can we do better?
A growing list

Many ideas and applications:

✓ jet areas and background subtraction  
  → UE, pileup, heavy-ion background subtraction

✓ jet substructure and filtering  
  → see below

✓ “best” jet definition  
  → kinematic dijet reconstruction

✓ boosted objects tagging  
  → $H \rightarrow b\bar{b}$, $t$, $\tilde{\chi}_0^1 \rightarrow qqq$, …

I will cover the first three (see e.g. Gavin Salam’s talk here for the 4th)
New idea #1: filtering
Filtering

cluster with Cambridge/Aachen(R)
Filtering

- cluster with Cambridge/Aachen(R)
- for each jet
Filtering

- cluster with Cambridge/Aachen(R)
- for each jet
- recluster with Cambridge/Aachen(R/2)
cluster with
Cambridge/Aachen(R)

for each jet

recluster with
Cambridge/Aachen(R/2)

keep the 2 hardest subjets
Filtering

- cluster with Cambridge/Aachen(R)
- for each jet
  - recluster with Cambridge/Aachen(R/2)
  - keep the 2 hardest subjets

**Idea:**
- ✓ keep perturb. radiation
- ✓ remove UE

- Proven useful for boosted jet $H \rightarrow b\bar{b}$ tagging

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

- Proven useful for kinematic reconstructions

  [M.Cacciari, J.Rojo, G.Salam, GS, 08]
New idea #2: jet definition optimisation
Optimisation: underlying idea

Competition between

- catching perturbative radiation

Out-of-cone radiation:

\[
\langle \delta p_t \rangle \propto - \int_R \frac{d\theta}{\theta} \sim - \log(1/R)
\]

- not catching soft background radiation (underlying event)

\[
\langle \delta p_t \rangle \sim \text{Soft contents} \propto \text{jet area} \sim R^2
\]

the coefficients depend on the algorithm
Optimisation: underlying idea

Competition between

- catching perturbative radiation
- not catching soft background radiation (underlying event)

Out-of-cone radiation:

\[
\langle \delta p_t \rangle \propto - \int_R d\theta \ \frac{d\theta}{\theta} \sim - \log(1/R)
\]

What is the optimal jet definition (algo+R!)?

\[
\langle \delta p_t \rangle \sim \text{Soft contents} \propto \text{jet area} \sim R^2
\]

the coefficients depend on the algorithm
Optimisation: dijet reconstruction

Example process to illustrate various effects:

\[ Z' \rightarrow q\bar{q} \rightarrow 2 \text{ jets} \]

- \( M_{Z'} \) can be varied (between 100 GeV and 4 TeV)
- Also valid for \( H \rightarrow gg \) to study gluon jets
- Reconstruction method:
  - get the 2 hardest jets: \( j_1 \) and \( j_2 \)
  - reconstruct the \( Z' \): \( m_{Z'} = (j_1 + j_2)^2 \)
    Look how the mass peak is reconstructed
- Also \( t\bar{t} \) with full hadronic decay for multijet tests
Measure of the jet reconstruction efficiency:

- Forget about measures related to parton-jet matching
- Forget about fits depending on the shape of the peak

⇒ maximise the signal over background ratio \( \frac{S}{\sqrt{B}} \)

a narrower peak is better.
Optimisation: quality measure (1)

Measure of the jet reconstruction efficiency:

- Forget about measures related to parton-jet matching
- Forget about fits depending on the shape of the peak

⇒ maximise the signal over background ratio ($\frac{S}{\sqrt{B}}$), a narrower peak is better.

\[ \frac{1}{N} \frac{dN}{d\text{bin}} \]

\[ \text{dijet mass [GeV]} \]

\[ \begin{array}{c}
\text{kt, } R=0.5 \\
Q_f^{w}=0.12 \\
\text{SISCone, } R=0.5, f=0.75 \\
Q_f^{w}=0.12 \\
\text{qq 100 GeV} \\
\end{array} \]

\[ R_{\text{best}} \]

\[ Q_f^{w}=0.12 \]

\[ f=0.75 \]

\[ \text{qq 100 GeV} \]
Assuming a constant background,

\[ \text{quality measure} \rightarrow \text{effective luminosity ratio} \]

\[
\rho_L(JD_2/JD_1) = \frac{\mathcal{L} \text{ needed with } JD_2}{\mathcal{L} \text{ needed with } JD_1} = \frac{Q_{f=z}^w(JD_2)}{Q_{f=z}^w(JD_1)}
\]

e.g. \( \rho_L(JD_2/JD_1) = 2 \)

\( \Leftrightarrow JD_2 \) requires 2 times the integrated luminosity of \( JD_1 \)
to achieve the same discriminative power.

Note: results cross-checked with 2 different definitions of the quality measure
Optimisation: best definition

SISCones and C/A+filt. do slightly better than $k_t$, C/A or anti-$k_t$
Optimisation: best definition

- SISCones and C/A+filt. do slightly better than $k_t$, C/A or anti-$k_t$

- $M \rightarrow R_{\text{best}} \uparrow$ (and $R_{\text{best}}(g) > R_{\text{best}}(q)$)

![Graphs showing best R vs M for different kinematic variables]
Using a single jet definition for all processes may cost a factor $\sim 2$ in time for early discoveries at the LHC.
Using a single jet definition for all processes may cost a factor $\sim 2$ in time for early discoveries at the LHC.
New idea #3: jet area and soft background subtraction
Jet areas

Area ≡ region where the jet catches soft particles

- **Recipe**: add infinitely soft particles (aka *ghosts*) and see in which jet they are clustered
- **2 methods**:
  - Passive area: add one ghost at a time and repeat many times
  - Active area: add a set of ghosts and cluster once
- **Idea**: ghost ≈ background particle
  \[ \Rightarrow \text{active area} \approx \text{uniform background} \]
  \[ \text{passive area} \approx \text{pointlike background} \]
- **Notes**:
  - passive = active for large multiplicities
  - require an IR-safe algorithm!
  - generic/universal definition (*e.g.* independent of a calorimeter)
Jet area: examples

**Example**: active area for a simple event

\[ k_t \quad \text{anti-} k_t \]

one ghost at every grid cell
**Example**: perturbative expansion of areas (at order $\alpha_s$)

$$\langle A(p_t, R) \rangle = A_0 + \frac{C_{F,A}}{b_0 \pi} \pi R^2 d \log \left( \frac{\alpha_s(Q_0)}{\alpha_s(Rp_t)} \right)$$

- area $\neq \pi R^2$, area $\neq$ const.
- coefficients computable

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<tr>
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<th>$A_0/(\pi R^2)$</th>
<th>$d$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>passive</td>
<td>active</td>
</tr>
<tr>
<td>$k_t$</td>
<td>1</td>
<td>0.81</td>
</tr>
<tr>
<td>Cam/Aachen</td>
<td>1</td>
<td>0.81</td>
</tr>
<tr>
<td>anti-$k_t$</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>SISCone</td>
<td>1</td>
<td>1/4</td>
</tr>
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$Q_0 \equiv$ IR regulator $\propto$ background density
**Pileup subtraction** *(for uniform backgrounds)*

**Basic idea:** [M.Cacciari, G.Salam, 08]

\[ p_{t,\text{subtracted}} = p_{t,\text{jet}} - \rho_{\text{pileup}} \times \text{Area}_{\text{jet}} \]

- **Jet area:** [M.Cacciari, G.Salam, G.S., 08]
  - region where the jet catches infinitely soft particles (active/passive)
  - analytic control and understanding in pQCD

- **Pileup density per unit area:** \( \rho_{\text{pileup}} \)
  - e.g. estimated from the median of \( p_{t,\text{jet}} / \text{Area}_{\text{jet}} \)
**Pileup subtraction** *(for uniform backgrounds)*

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![Diagram showing jet area and pileup density per unit area](image-url)
**Pileup subtraction** (for uniform backgrounds)

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- **Pileup density per unit area:** \( \rho_{\text{pileup}} \)
  - e.g. estimated from the median of \( p_{t,\text{jet}} / \text{Area}_{\text{jet}} \)

implemented in FastJet on an event-by-event basis
Effect on dijet reconstruction

Pileup unsubtracted

Pileup subtracted

\[ M_{J'} = 300 \text{ GeV} \]

\[ k_t (R=0.6) \]

SIS Cone (R=0.6)

no pileup

with pileup

\[
\begin{align*}
\text{width} &= 29.5 \text{ GeV} \\
\text{width} &= 21.0 \text{ GeV} \\
\text{width} &= 21.0 \text{ GeV} \\
\text{width} &= 17.7 \text{ GeV}
\end{align*}
\]

✓ position reasonable

✓ dispersion reduced (thanks to the event-by-event approach)

✓ used by STAR for the first jet analysis in heavy-ions
Example: application to HI collisions

\[ pp + \text{pileup} \] 

\[ AA \]
**Framework for study**

- **Hard event**: Pythia(v6.4) or Pythia(v6.4)+PyQuen(v1.5)
- **Background**: Hydjet(v1.5) (others under study)
- **Analysis**: FastJet(v2.4)
  - Ideally: smallest $\Delta p_t$ shift, smallest $\Delta p_t$ dispersion
- **Note**: in what follows, $R$ fixed to 0.4

![Diagram of the framework for study]

- Hard event (quenched or unquenched)
- Hard jets
- Full jets
- $\Delta p_t$ average dispersion
- Hard event + Background event
- Embed
- Cluster subtract
- Cluster subtract
Framework for study

1. Hard event (quenched or unquenched)
2. Hard jets
3. Cluster subtract

Hard jets

\[ \Delta p_t \]

- Generic trends under control
- Final numbers may change

[M.Cacciari, J.Rojo, G.Salam, GS, in prep.]

Analysis: FastJet(v2.4)

Ideally: smallest \( \Delta p_t \) shift, smallest \( \Delta p_t \) dispersion

Note: in what follows, \( R \) fixed to 0.4
Idea #1: use a local range to compute $\rho_{bkg}$

- Fluctuating background
  \[
  \rightarrow \text{determine the background density } \rho_{bkg}
  \]
  from jets in the vicinity of the jet we want to subtract

- Exclude the hardest jets from the determination of $\rho_{bkg}$
  \[
  \Rightarrow \text{reduce the bias in the computation median}
  \]
Effect of choosing a local range

- Effect $\sim 0.5$-1 GeV
- Differences between local ranges $\rightarrow$ uncertainty
- For limited acceptance, global range $\approx$ local range
- Analytic control would be nice
Results: RHIC kinematics

- average $p_t$ shift:
  anti-$k_t$ and C/A+filt. Ok
Results: RHIC kinematics

- average $p_t$ shift:
  - anti-$k_t$ and C/A+filt. Ok
- $p_t$ shift dispersion:
  - C/A+filt. better
Results: RHIC kinematics

- average $p_t$ shift:
  - anti-$k_t$ and C/A+filt. Ok
- $p_t$ shift dispersion:
  - C/A+filt. better
- watch out C/A+filt. average:
  - back-reaction compensated
Results: RHIC kinematics – quenching

Performances not much affected by quenching (need more models)

RHIC, unquenched |y|<1, R=0.4
k_t Cam/Aachen anti-k_t Cam+filt.

Donut(R,3R) range

p_t shift [GeV]

p_t,hard [GeV]

RHIC, quenched |y|<1, R=0.4
k_t Cam/Aachen anti-k_t Cam+filt.

Donut(R,3R) range

p_t shift [GeV]

p_t,hard [GeV]

RHIC, unquenched
k_t Cam/Aachen anti-k_t Cam+filt.

Donut(R,3R) range

p_t dispersion [GeV]

p_t,hard [GeV]

RHIC, quenched
k_t Cam/Aachen anti-k_t Cam+filt.

Donut(R,3R) range

p_t dispersion [GeV]

p_t,hard [GeV]
Results: LHC kinematics

- average $p_t$ shift: anti-$k_t$ and C/A+filt. Ok
Results: LHC kinematics

- average $p_t$ shift:
  - anti-$k_t$ and C/A+filt. Ok

- $p_t$ shift dispersion:
  - C/A+filt. better
  - anti-$k_t$ Ok
Large quenching effect but anti-$k_t$’s rigidity plays for it

*Results: LHC kinematics – quenching*
**Message #1:**

Use infrared-and-collinear-safe algorithms

| ATLAS Cone          | SISCones            | √ fast  
|--------------------|---------------------|---------  
| CDF/D0 MidPoint    |                     | √ safe   ।
| CMS Lt. Cone       | anti-$k_t$          | √ fast   ।
|                    |                     | √ safe   ।

Important to benefit fully from pQCD multilegs/multiloops calculations
**Message #2:**

- correct tools $\Rightarrow$ new ideas, new concepts
  $\Rightarrow$ new generation of jet definitions

- jet areas $\rightarrow$ pileup and HI background subtraction
- jet substructure improves reconstruction (Higgs, top, SUSY, ...)

**Message #3:**

- keep some flexibility in the jet definition choice

- optimisation $\rightarrow$ luminosity gains for LHC searches
- different approaches $\rightarrow$ better understanding of HI collisions
backup slides
Solution: use a seedless approach, find ALL stable cones

Naive approach: check stability of each subset of particle
The SISCone search for stable cones

- **Solution**: use a seedless approach, find **ALL** stable cones

- **Naive approach**: check stability of each subset of particle
  Complexity is $O(N2^N)$

  $\Rightarrow$ definitely unrealistic: $10^{17}$ years for $N = 100$

- **Midpoint complexity**: $O(N^3)$
The SISCone search for stable cones

Solution: use a seedless approach, find ALL stable cones

Midpoint complexity: $O(N^3)$

Idea: use geometric arguments

Each enclosure can be moved (in any dir.) until it touches a point
... then rotated until it touches a second one

$\Rightarrow$ Enumerate all pairs of particles
with 2 circle orientations and 4 possible inclusion/exclusion
$\longrightarrow$ find all enclosures
The SISCones search for stable cones

Solution: use a seedless approach, find ALL stable cones

Midpoint complexity: $O(N^3)$

Idea: use geometric arguments

⇒ Enumerate all pairs of particles
   with 2 circle orientations and 4 possible inclusion/exclusion
   → find all enclosures

Complexity: $O(N^3)$, with improvements: $O(N^2 \log(N))$

→ C++ implementation: Seedless Infrared-Safe Cone algorithm (SISCones)
G.Salam, G.S., JHEP 04 (2007) 086; http://projects.hepforge.org/siscone

NB.: also available from FastJet
   [M.Cacciari, G.Salam, G.S.]; http://www.fastjet.fr
Recombination algorithms very fast

SISCones not slower than Midpoint (even with a 1 GeV seed threshold)

[M. Cacciari, G. Salam, 06]
A technical point: Back-reaction

Additional soft background has 2 effects:

- Throw soft particles in the hard jet: dealt with by subtraction
- Modify the hard scattering (back-reaction)
  - can be pointlike or diffuse
  - gain:

```
no medium: \( p_t = p_{t1} \)
medium: \( p_t = p_{t1} + p_{t2} + p_{tm} \)
```

- loss:

```
no medium: \( p_t = p_{t1} + p_{t2} \)
medium: \( p_t = p_{t1} + p_{tm} \)
```
A technical point: Back-reaction

Additional soft background has 2 effects:

- Throw soft particles in the hard jet: dealt with by subtraction
- Modify the hard scattering (back-reaction)
  - can be pointlike or diffuse
  - tractable analytically (similar to areas)
  - $k_t \gtrsim$ Cambridge $> \text{SISCone} \gg \text{anti-}k_t$