Jets in LHC soft backgrounds
Jet fragmentation function moments

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HI meeting — Novembre 2012

Brief plan

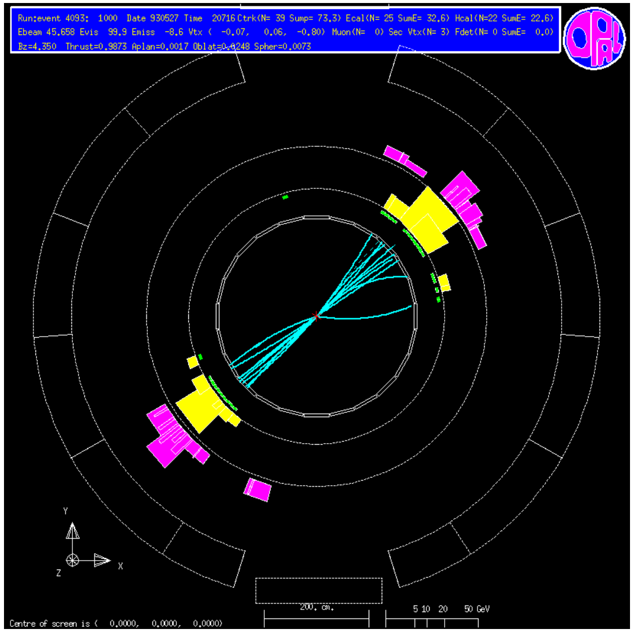
- Introduction
  - Concept of a jet
  - jets at the LHC
- Jets and soft backgrounds
  - effect on jets
  - area-median background subtraction
- Jet fragmentation function
  - moments of the fragmentation function
  - extending the area-median subtraction

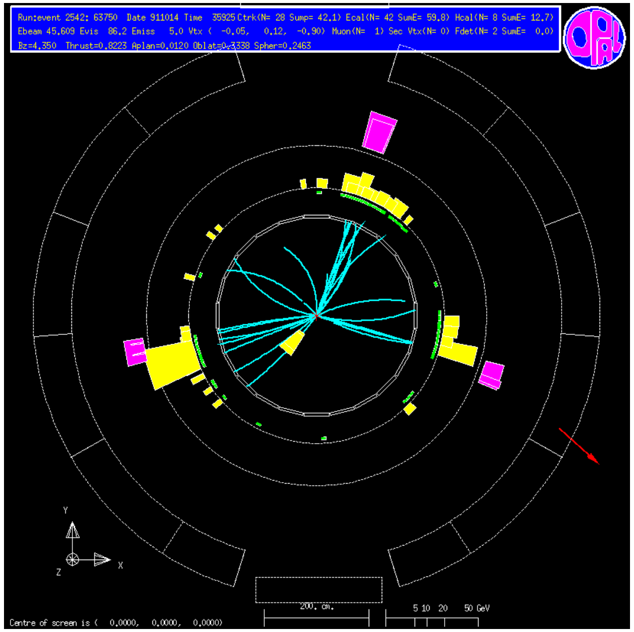
What is a “jet”?

concept/idea

Jets

- Final-state events are pencil-like
  already observed in e^+e^- collisions:





- Consequence of the collinear divergence
  QCD (quark & gluon) branching proba: $\frac{dP}{d\theta} \propto \frac{\alpha_s}{\theta}$

Jets

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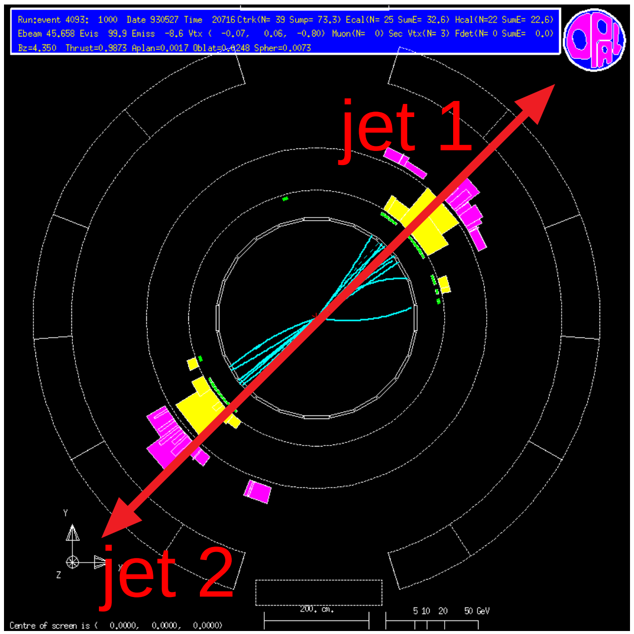

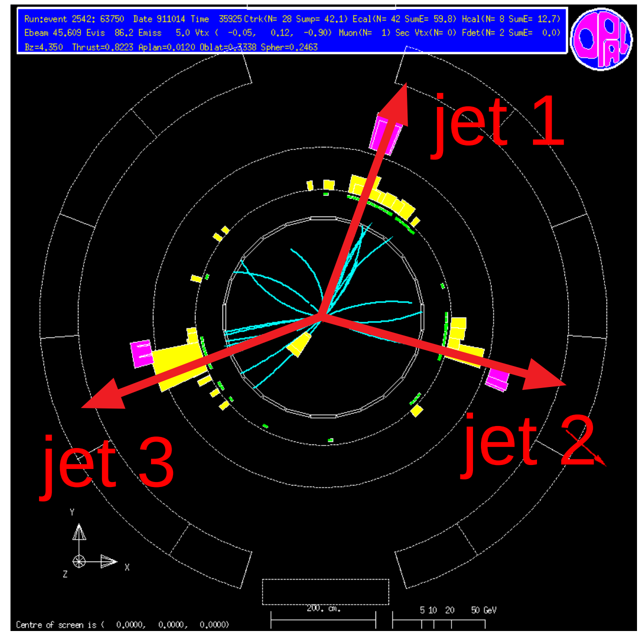

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"Jets" $\equiv$ bunch of collimated particles $\cong$ hard partons

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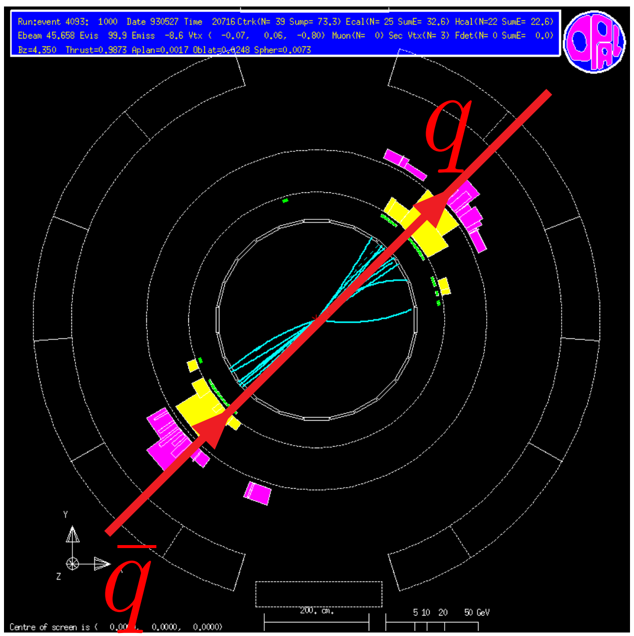

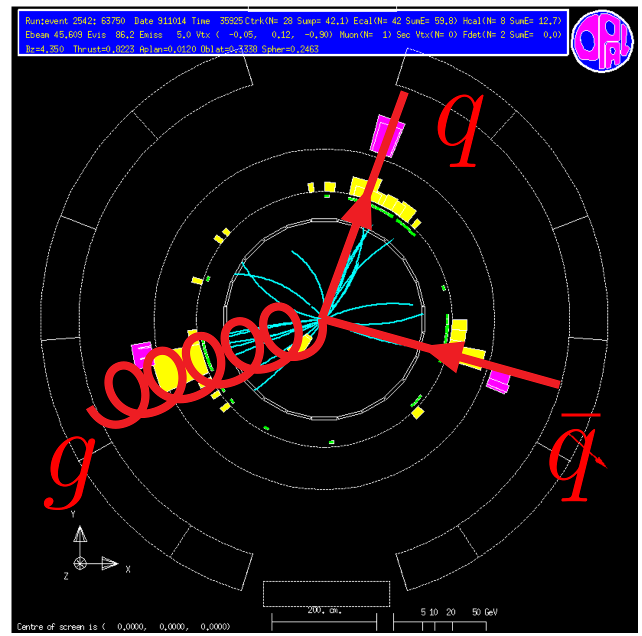

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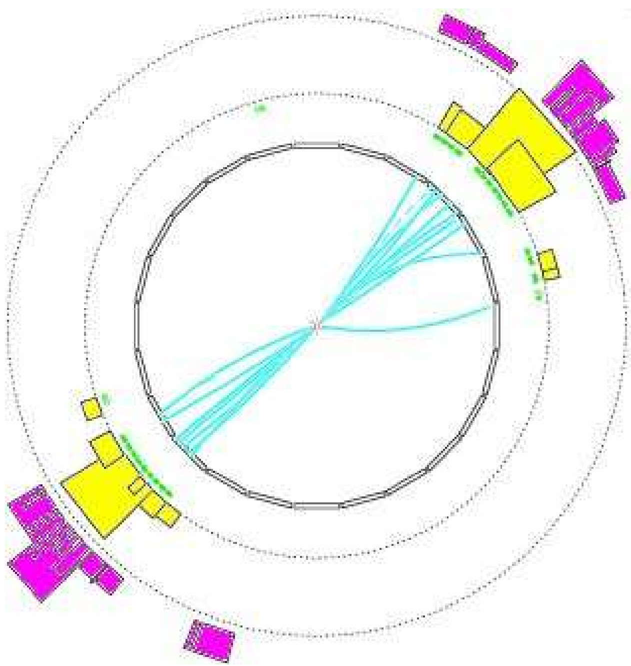
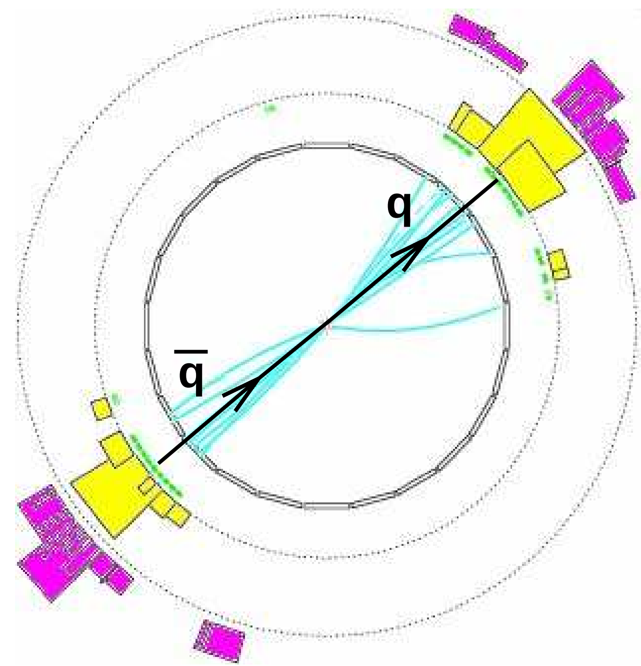
Jets and partons

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

obviously 2 jets



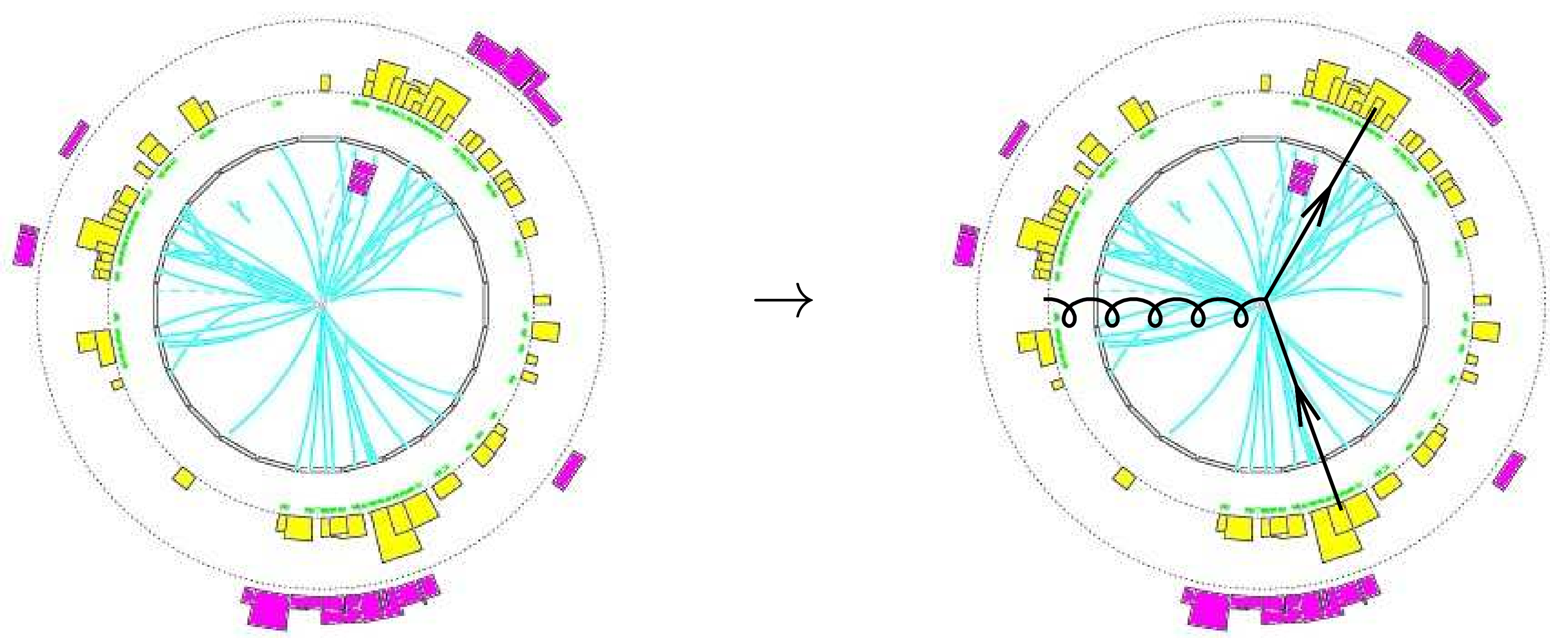
$\rightarrow$



Jets and partons

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

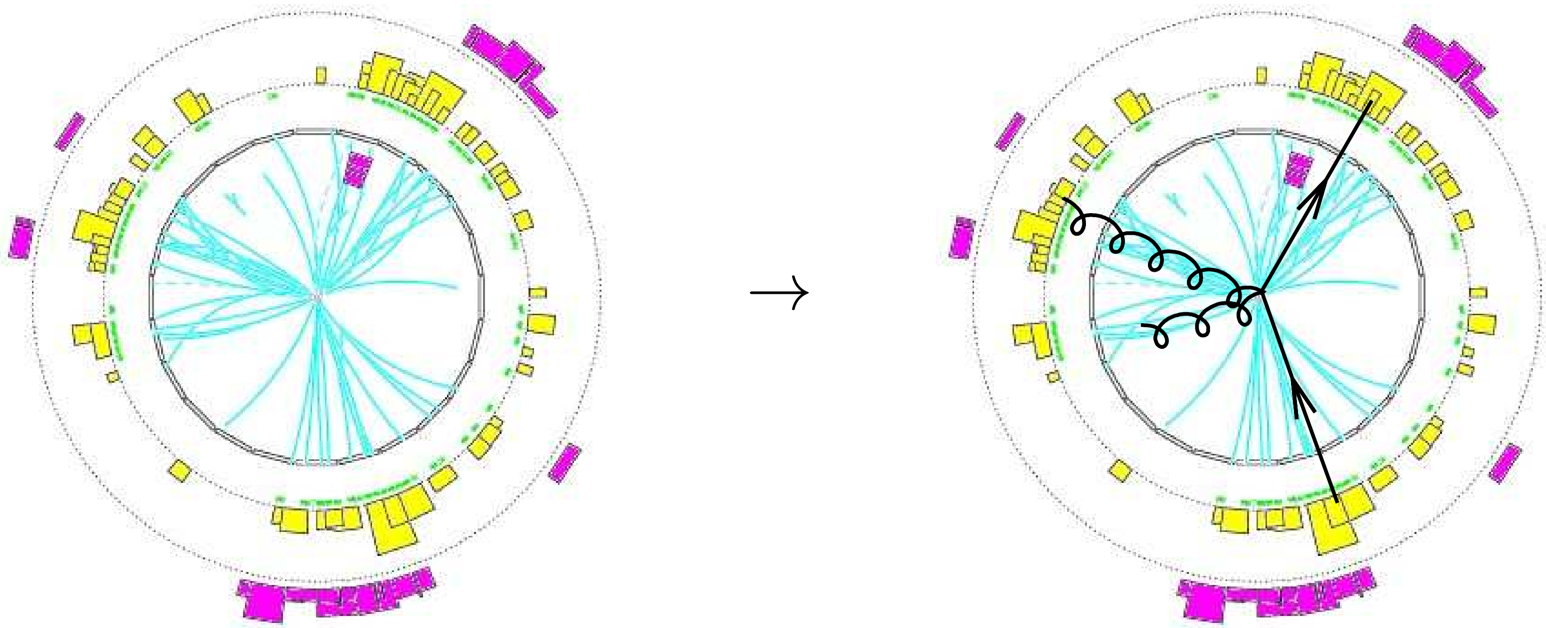
3 jets



Jets and partons

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

3 jets... or 4?

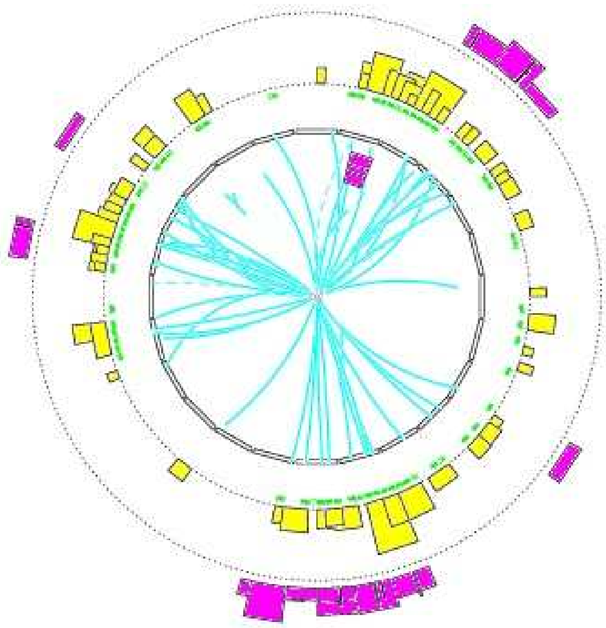


- “collinear” is arbitrary

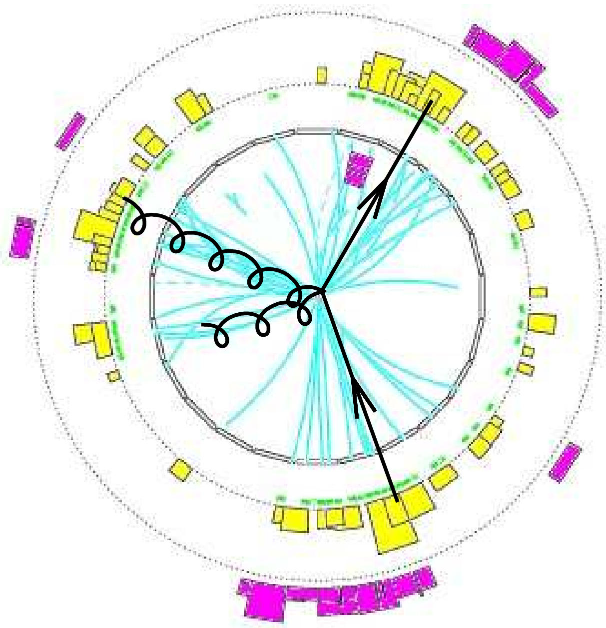
Jets and partons

"Jets" $\equiv$ bunch of collimated particles $\cong$ hard partons

3 jets... or 4?

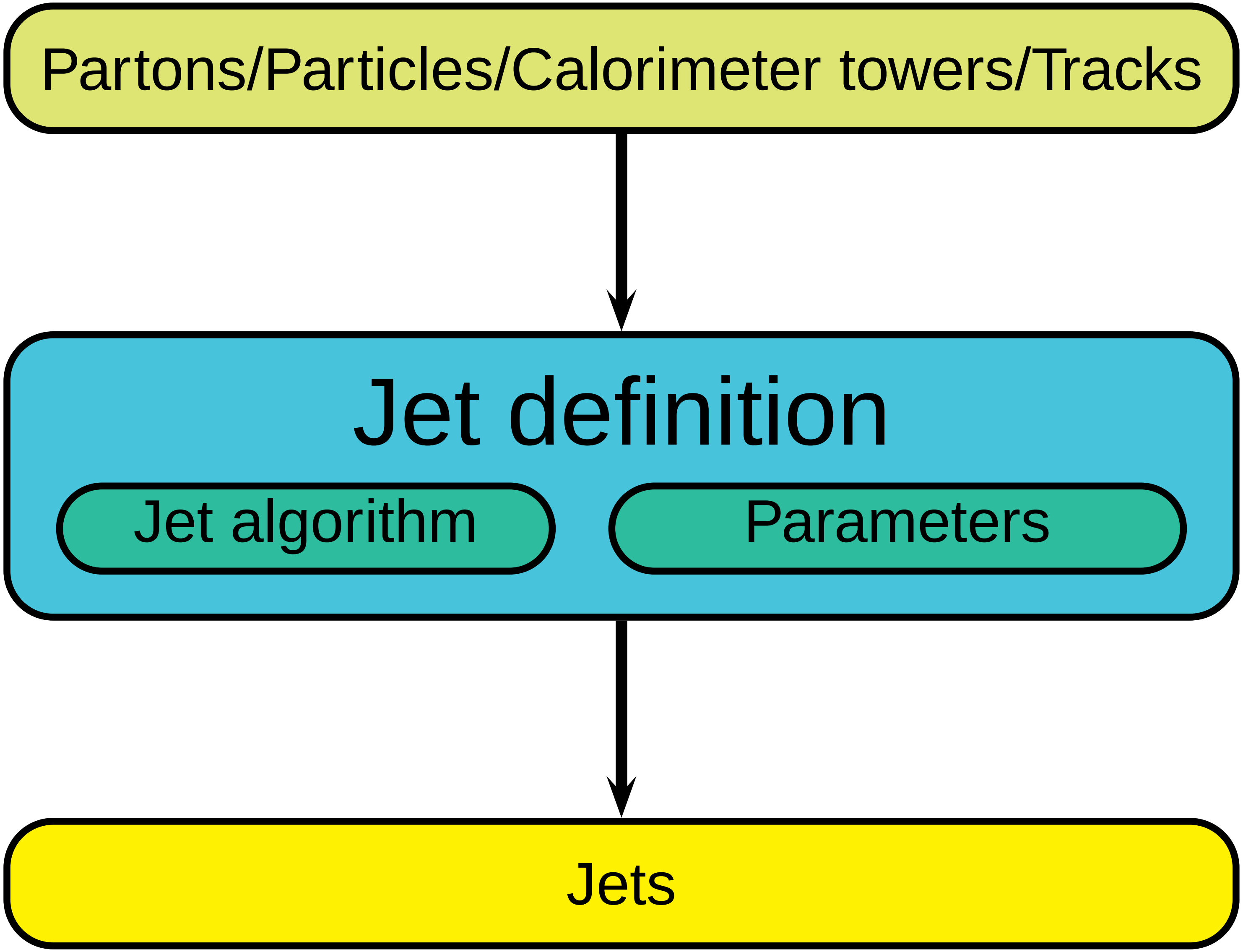


$\longrightarrow$



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

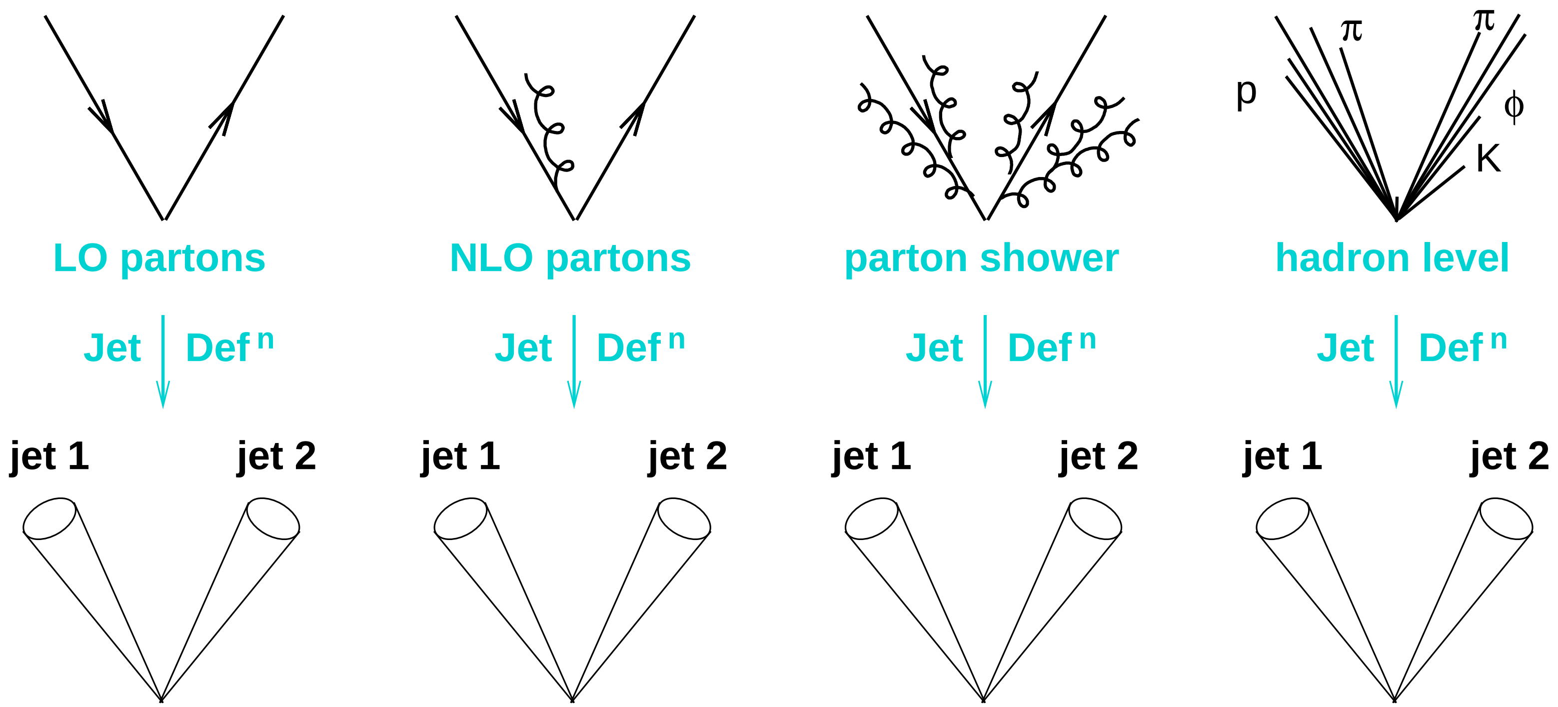
Jet definition



Jet definition

A jet definiton 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)



Note

This talk IS

how to reconstruct the jets and their properties from the final-state particles

This talk IS NOT

about theoretical descriptions of Heavy-ion data

What is a “jet”?

jets at the LHC

2 major achievements

- perturbative finiteness

  Tevatron & LHC initial plans: cone algorithm

  - CDFJetClu, CDFMidPoint, D0MidPoint, ATLASCone: IR-unsafe
  - CMSIterativeCone: collinear-unsafe

2 major achievements

- perturbative finiteness

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  - CMSIterativeCone: collinear-unsafe

  Recently cured

  - IR-safe cone: SISCone

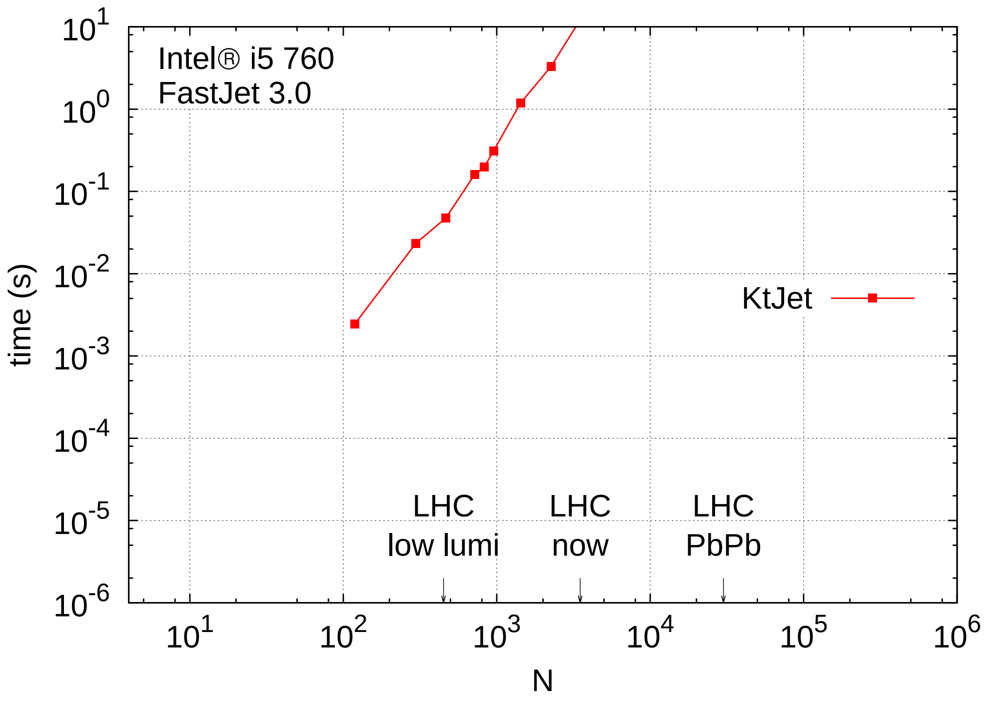
    [G.Salam,GS, 0704.0292]

  - Collinear-safe cone-like: anti-k_t

    [M.Cacciari,G.Salam,GS, 0802.1189]

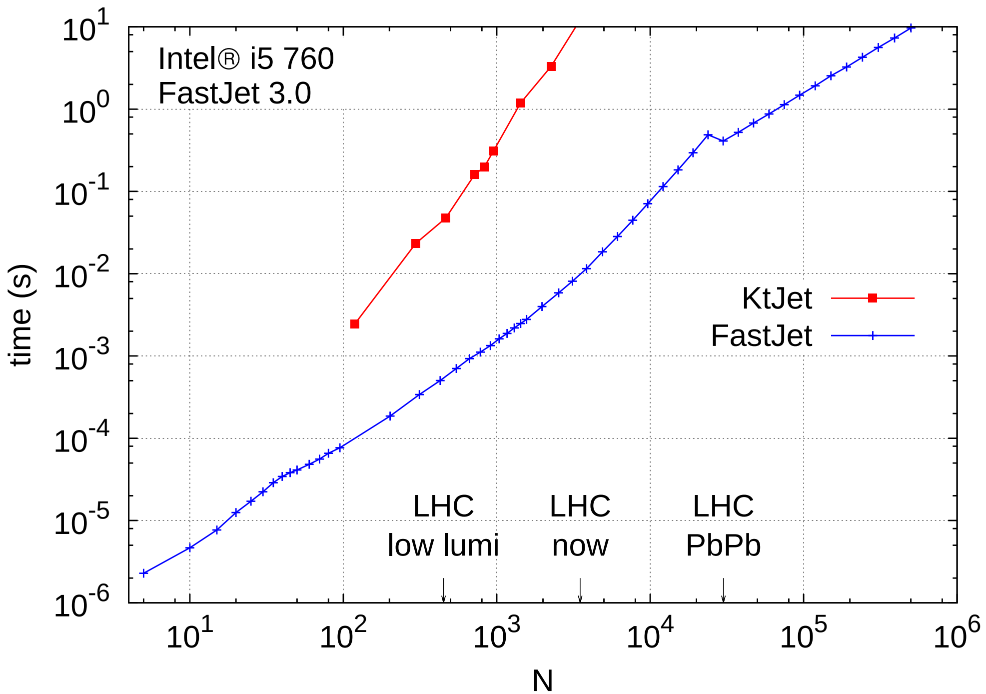
2 major achievements

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



2 major achievements

- perturbative finiteness
- fast recombination algorithms
  - Tevatron era: k_t too slow: $\mathcal{O}(N^3)$ for N particles
  - Now: (anti-)k_t very fast: $\mathcal{O}(N^2)$ or $\mathcal{O}(N \log(N))$



FastJet

[M.Cacciari, G.Salam, 2005]

2 major achievements

- perturbative finiteness
- fast recombination algorithms

[M.Cacciari, G.Salam, GS, `www.fastjet.fr`]

- Grown way beyond just fast recombinations:
  - plugins for used jet definitions
  - jet areas, background subtraction (see below)
  - tools for manipulating jets
  - more to come...
- FastJet 3.0.3 in June 2012
- Standard interface for jet clustering
  for both theorists and experimentalists

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

$$d_{ij} = \min(k_{ti}^{-2}, k_{tj}^{-2})(\Delta y_{ij}^2 + \Delta\phi^2), \qquad d_{iB} = k_{ti}^{-2} R^2$$

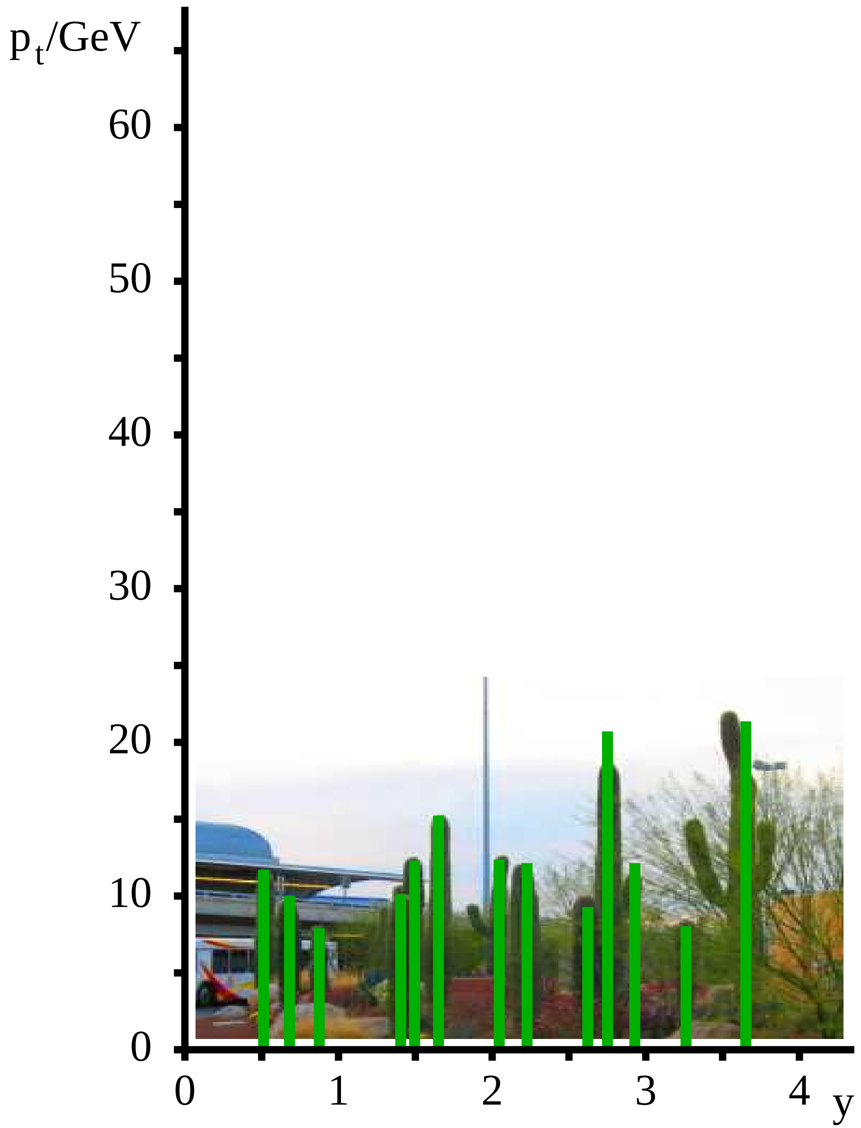
  - repeatedly find the minimal distance
    if d_{ij}: recombine i and j into $k = i + j$
    if d_{iB}: call i a jet

- 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 ($R = 0.7$)

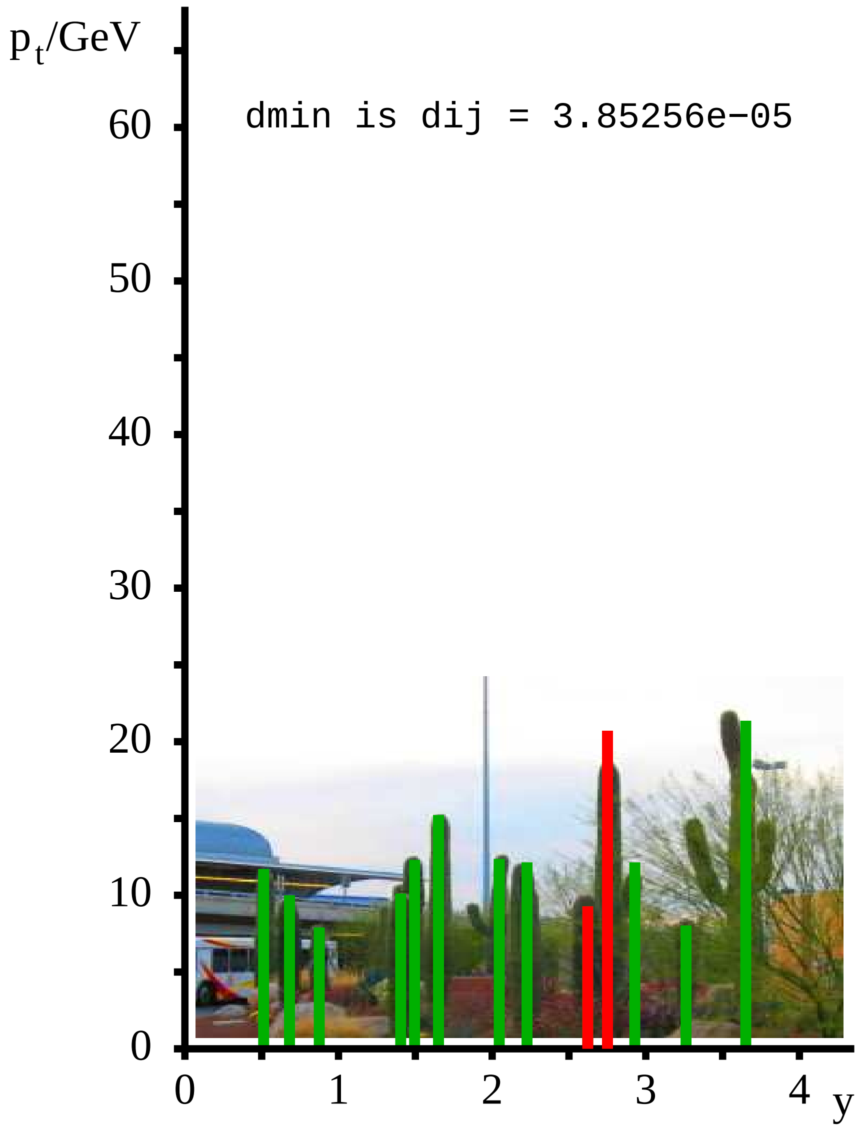
Start with your favourite picture

Clustering in action: anti-k_t ($R = 0.7$)



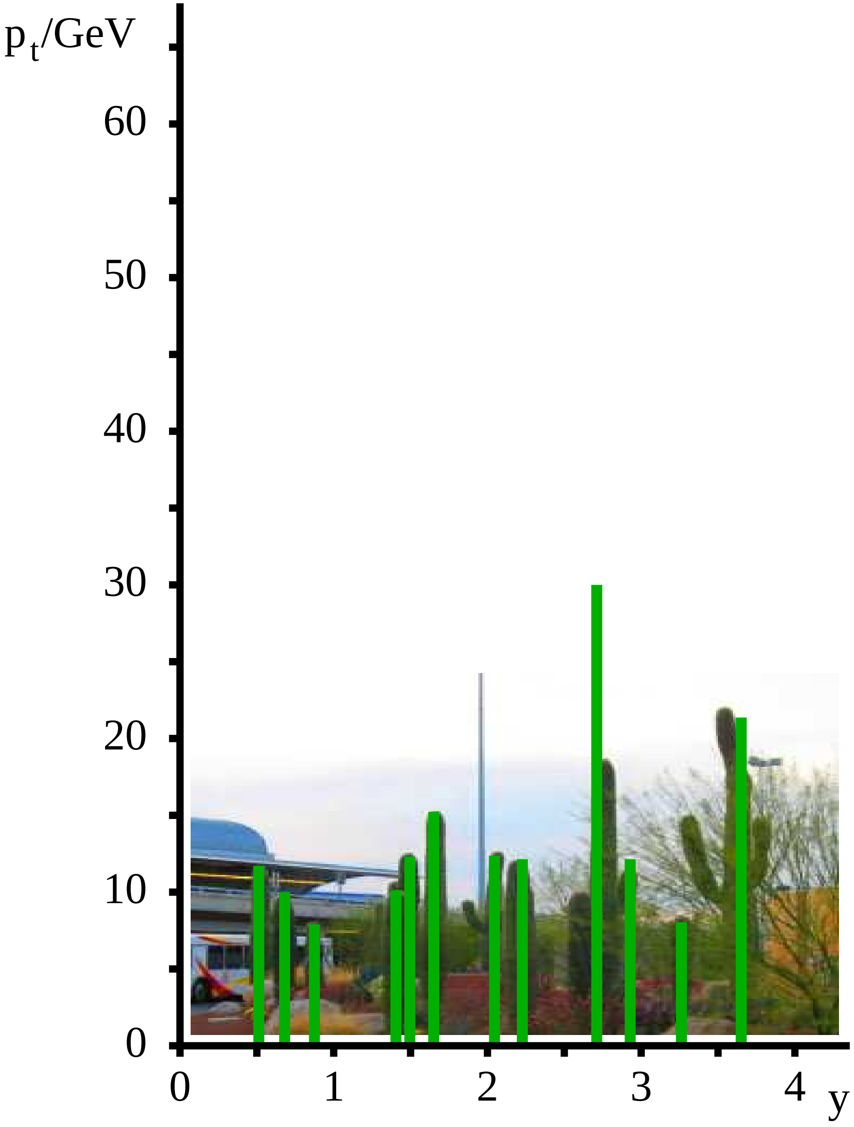
Start with your favourite ~~picture~~ event

Clustering in action: anti-k_t ($R = 0.7$)



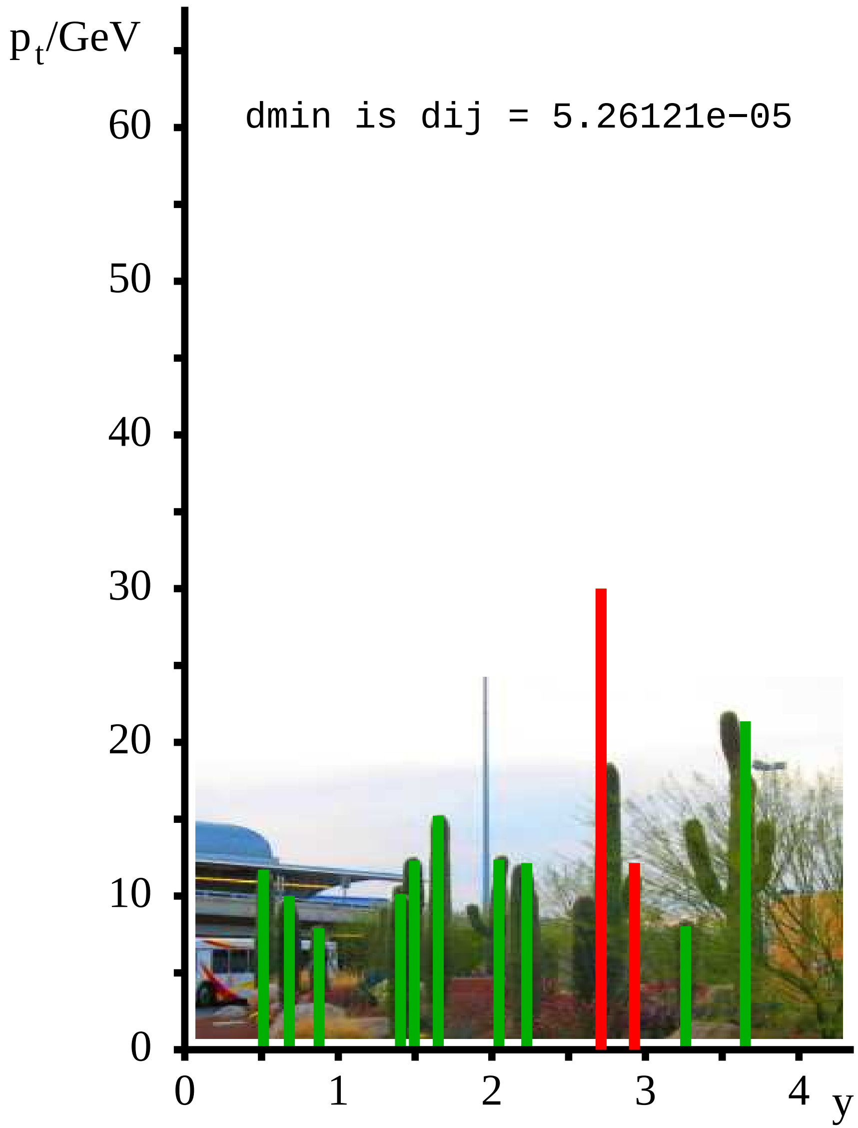
min is $d_{ij} = 3.9\,10^{-5}$

Clustering in action: anti-k_t $(R = 0.7)$



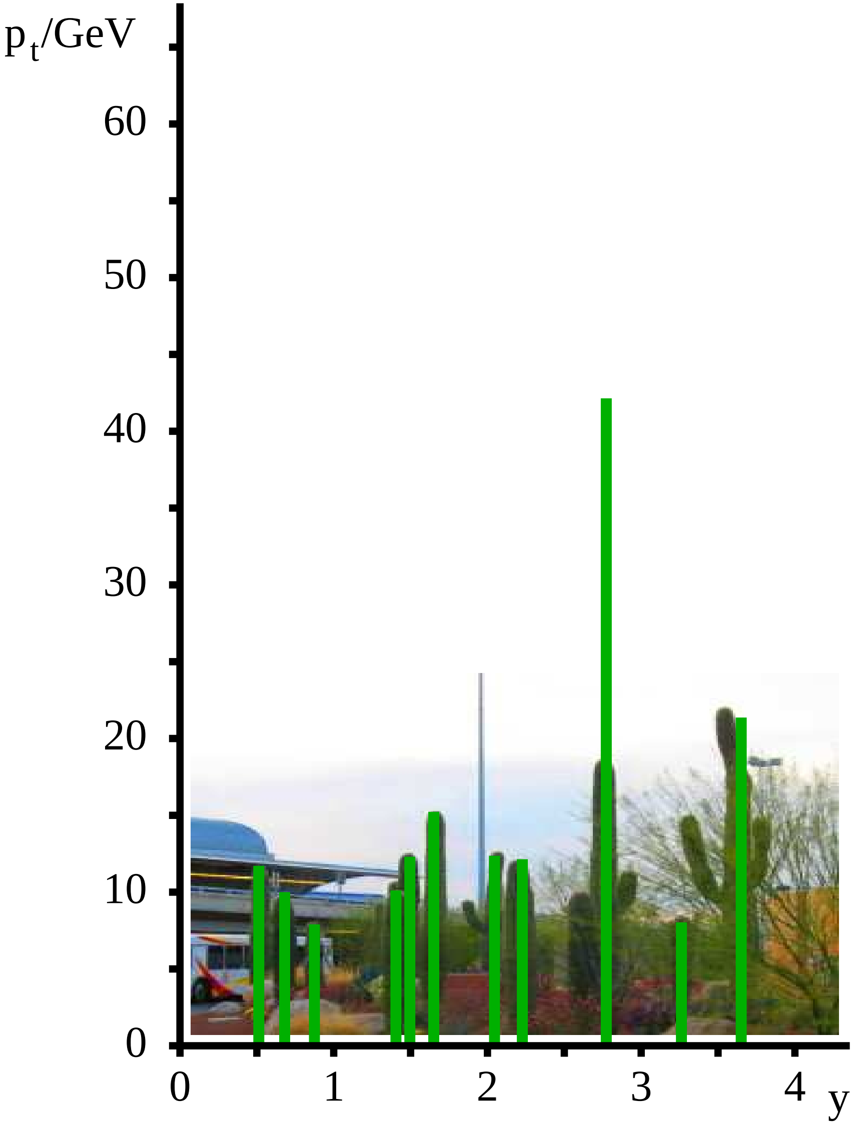
recombine them

Clustering in action: anti-k_t ($R = 0.7$)



min is $d_{ij} = 5.3\,10^{-5}$

Clustering in action: anti-k_t ($R = 0.7$)



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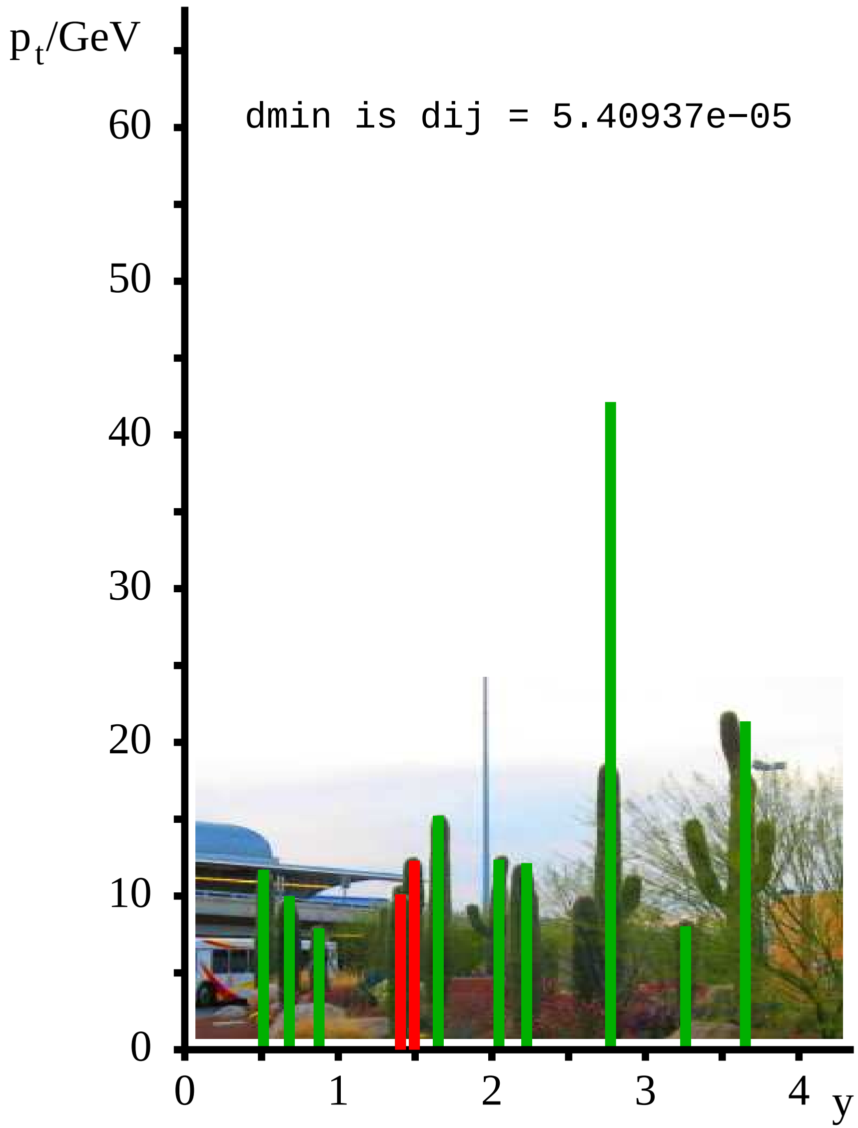
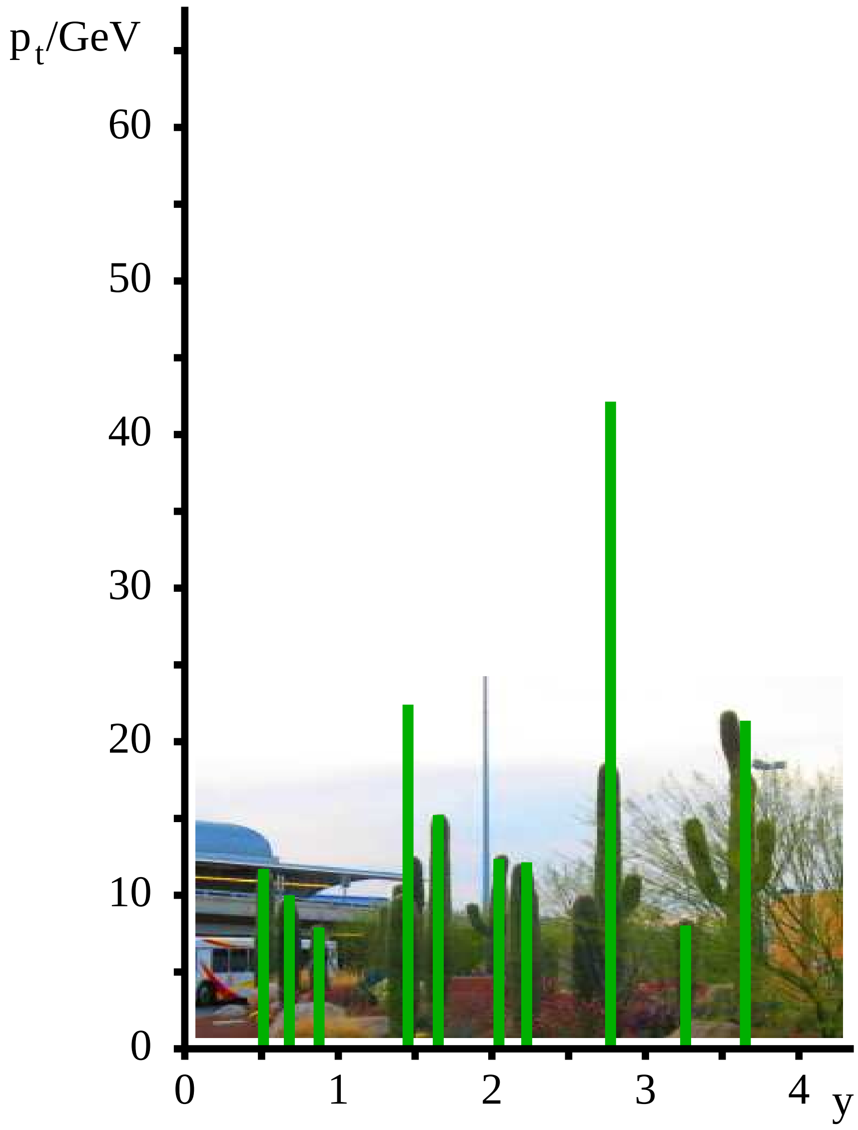


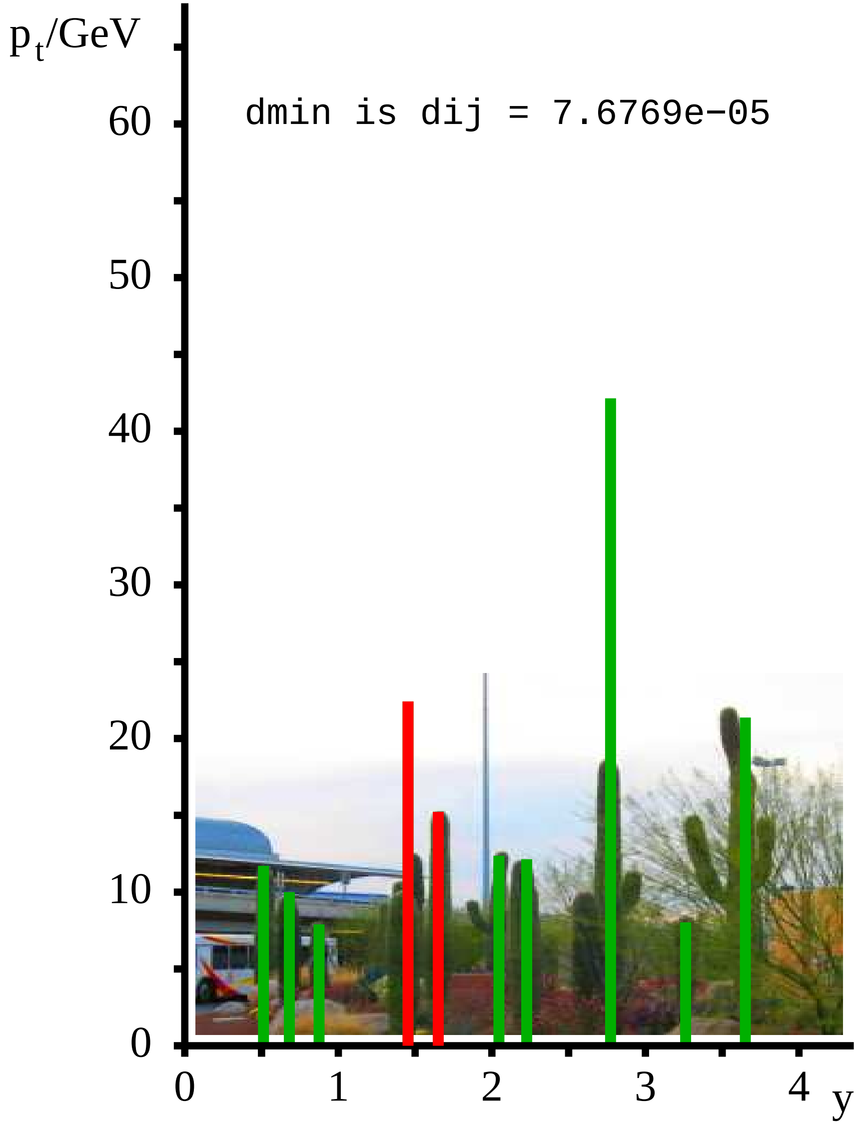
min is $d_{ij} = 5.4\,10^{-5}$

Clustering in action: anti-k_t ($R = 0.7$)



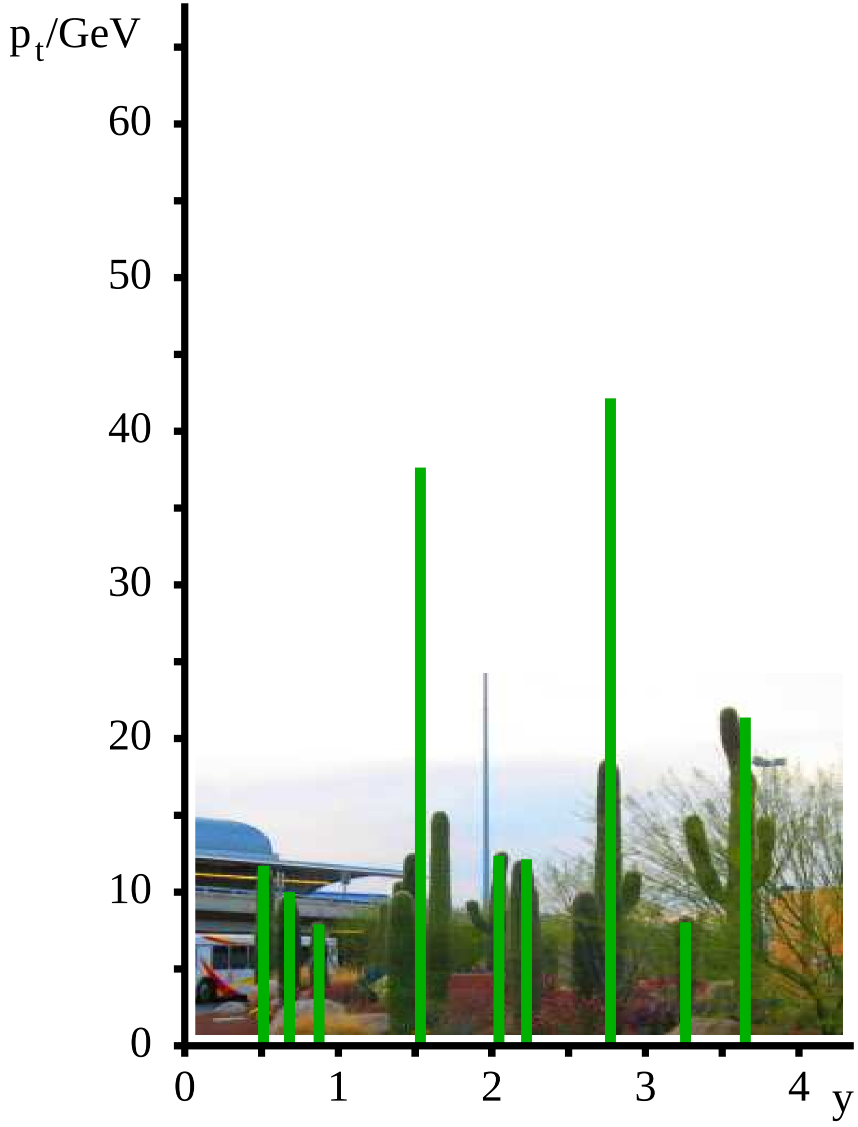
recombine them

Clustering in action: anti-k_t ($R = 0.7$)



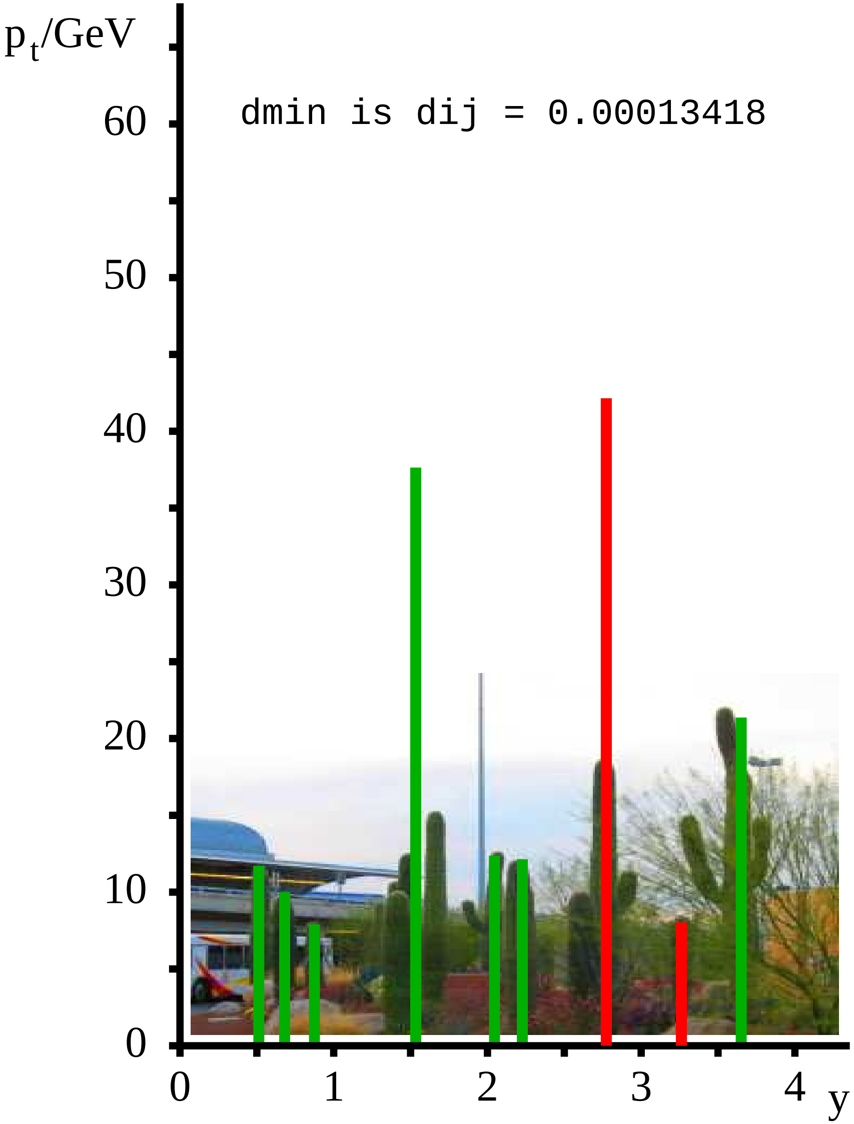
min is $d_{ij} = 7.7\,10^{-5}$

Clustering in action: anti-k_t ($R = 0.7$)



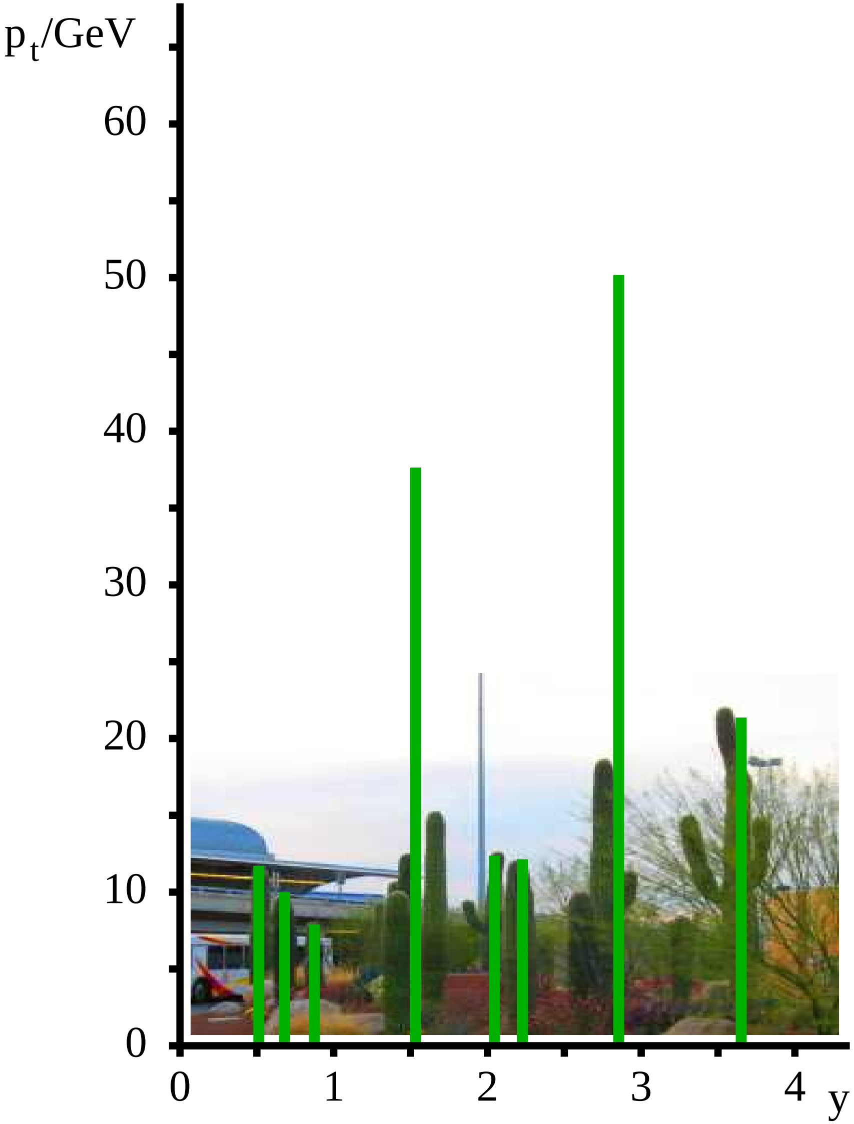
recombine them

Clustering in action: anti-k_t ($R = 0.7$)



min is $d_{ij} = 1.3\,10^{-4}$

Clustering in action: anti-k_t ($R = 0.7$)



recombine them

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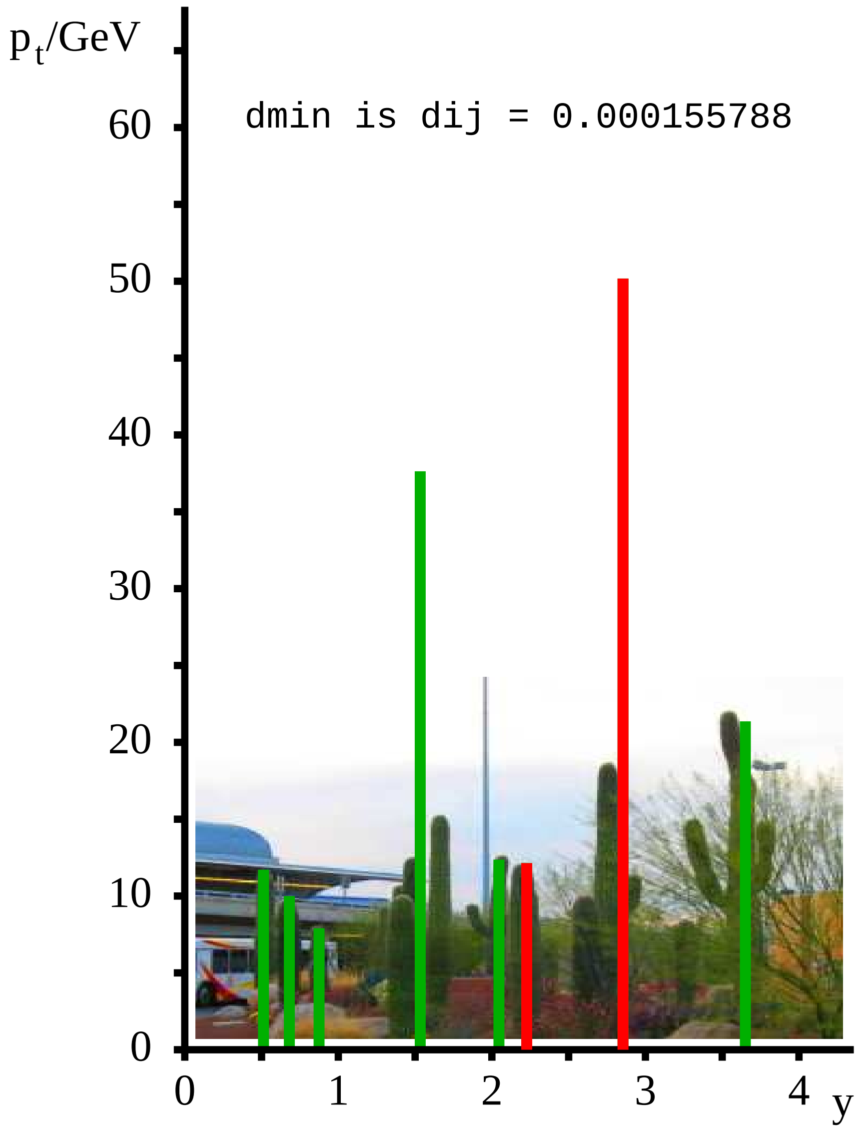
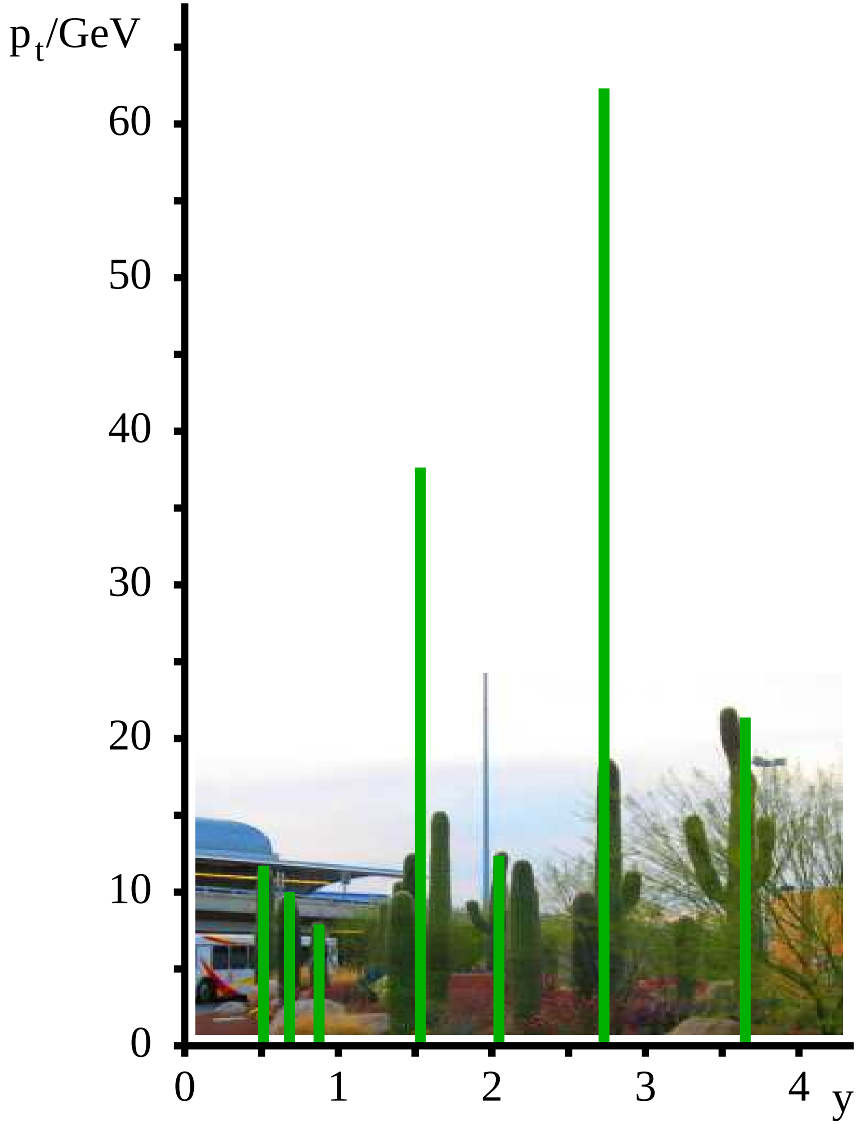


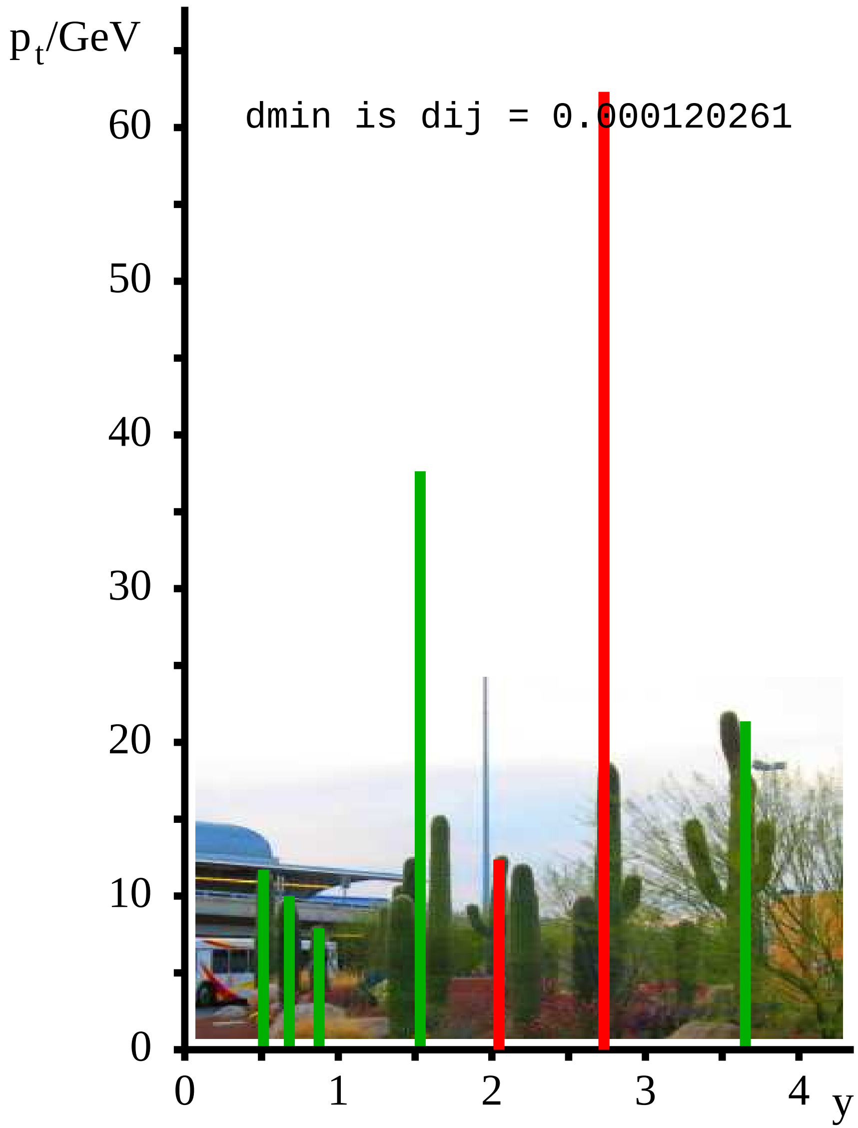
min is $d_{ij} = 1.6\,10^{-4}$

Clustering in action: anti-k_t ($R = 0.7$)



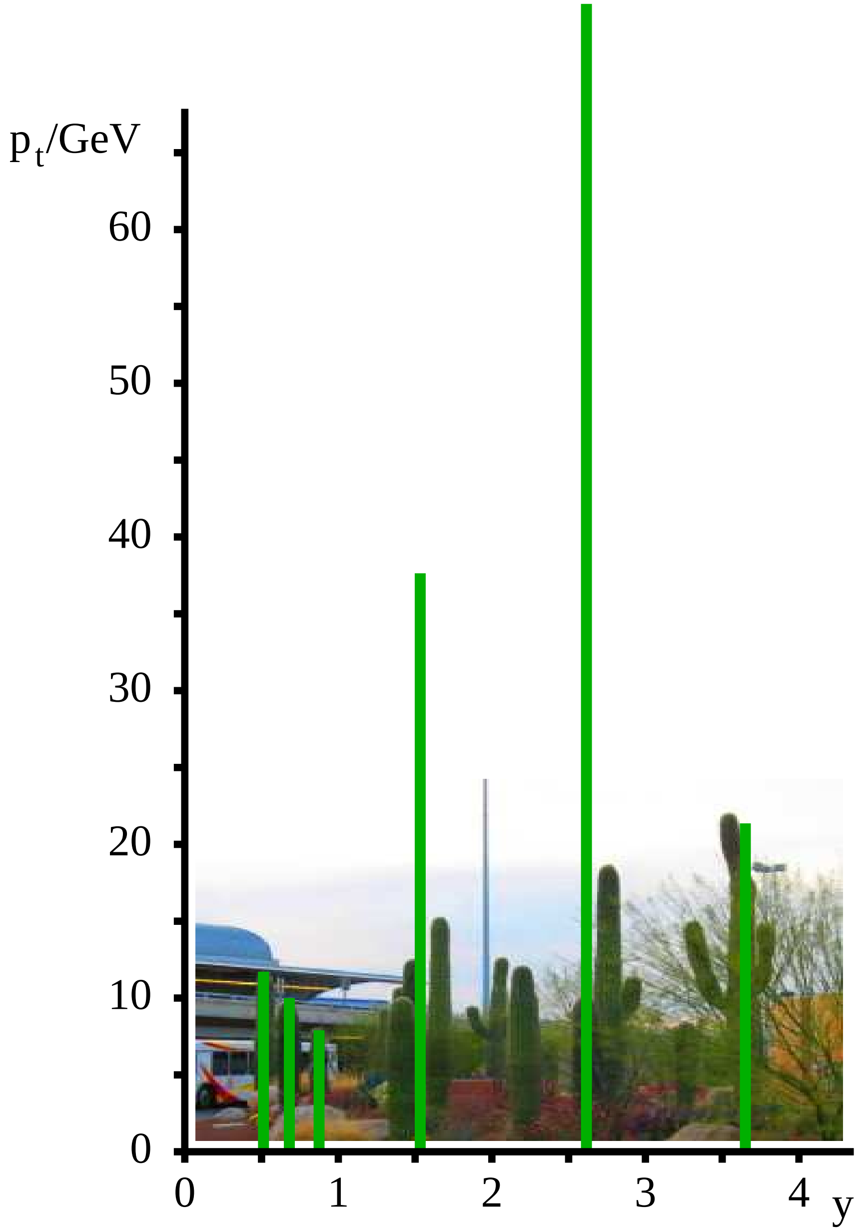
recombine them

Clustering in action: anti-k_t ($R = 0.7$)



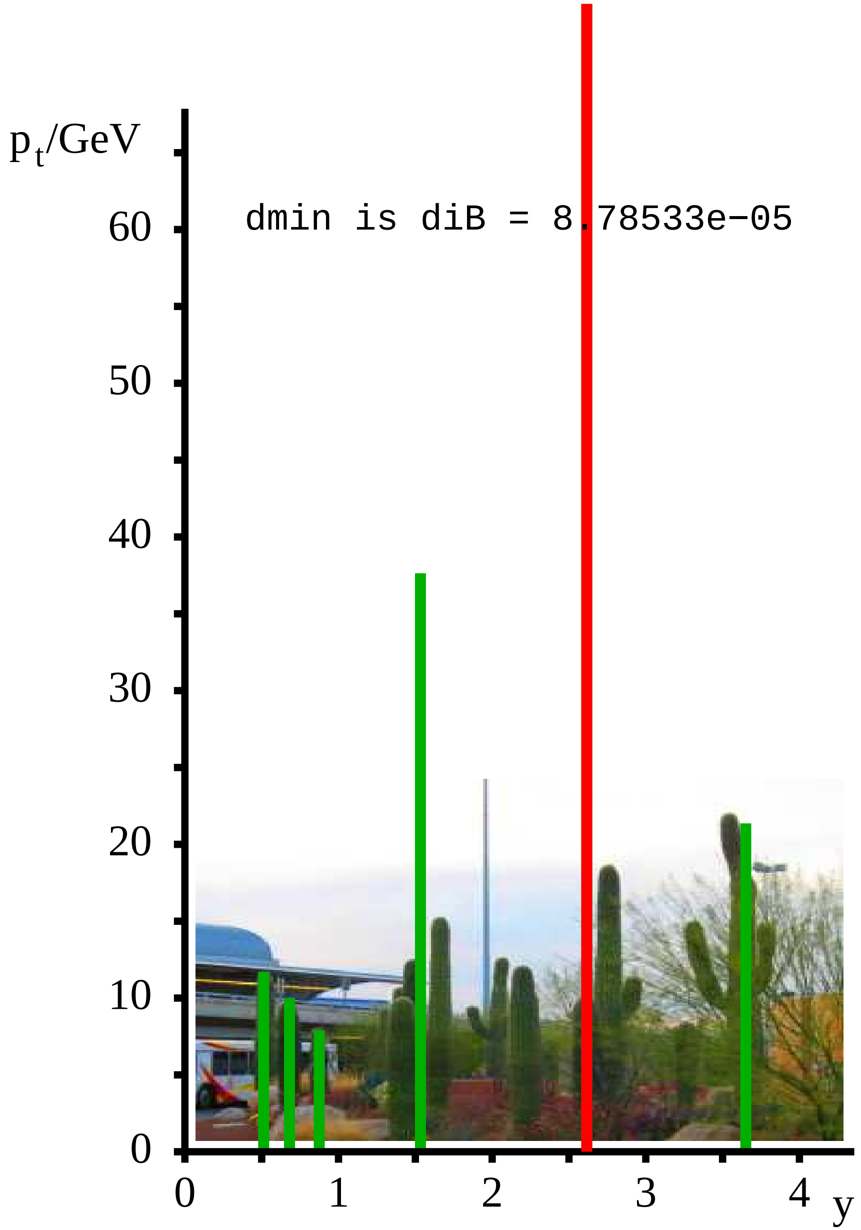
min is $d_{ij} = 1.2\,10^{-4}$

Clustering in action: anti-k_t ($R = 0.7$)



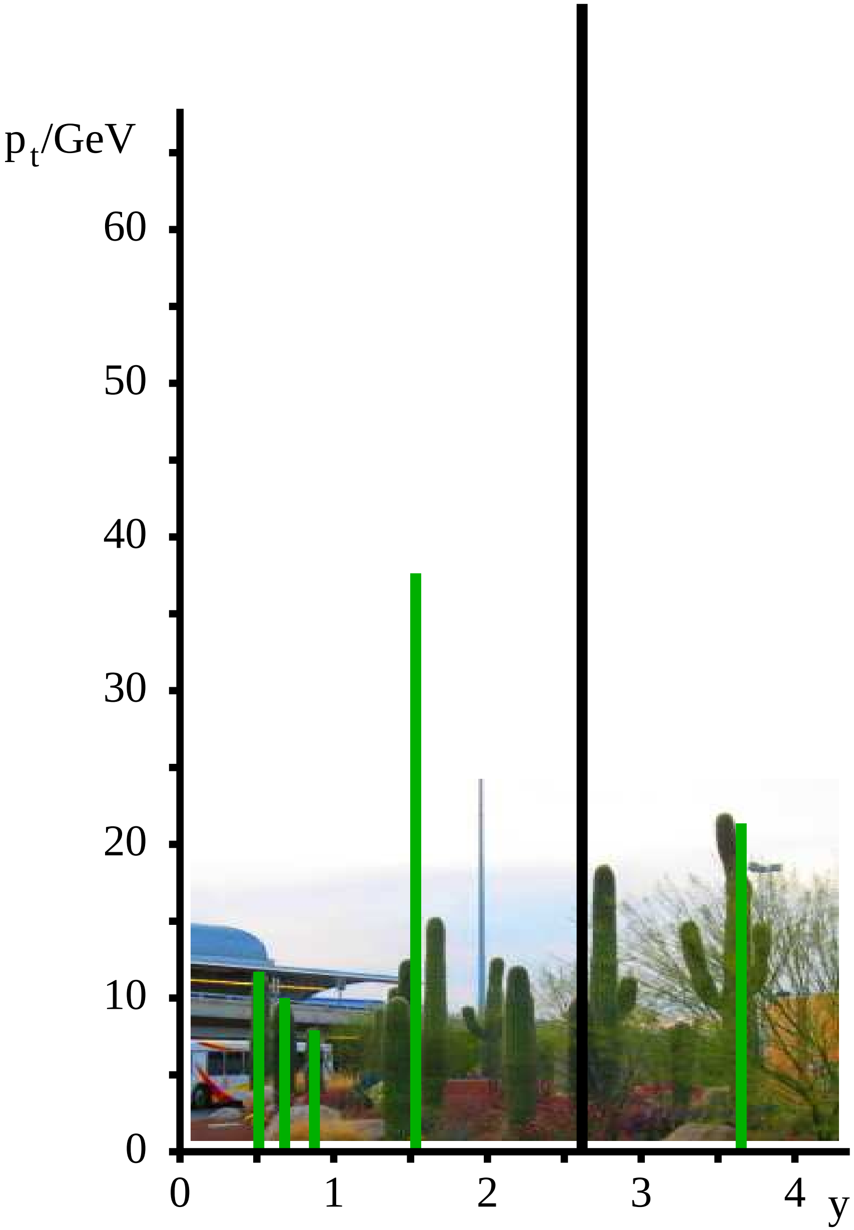
recombine them

Clustering in action: anti-k_t ($R = 0.7$)



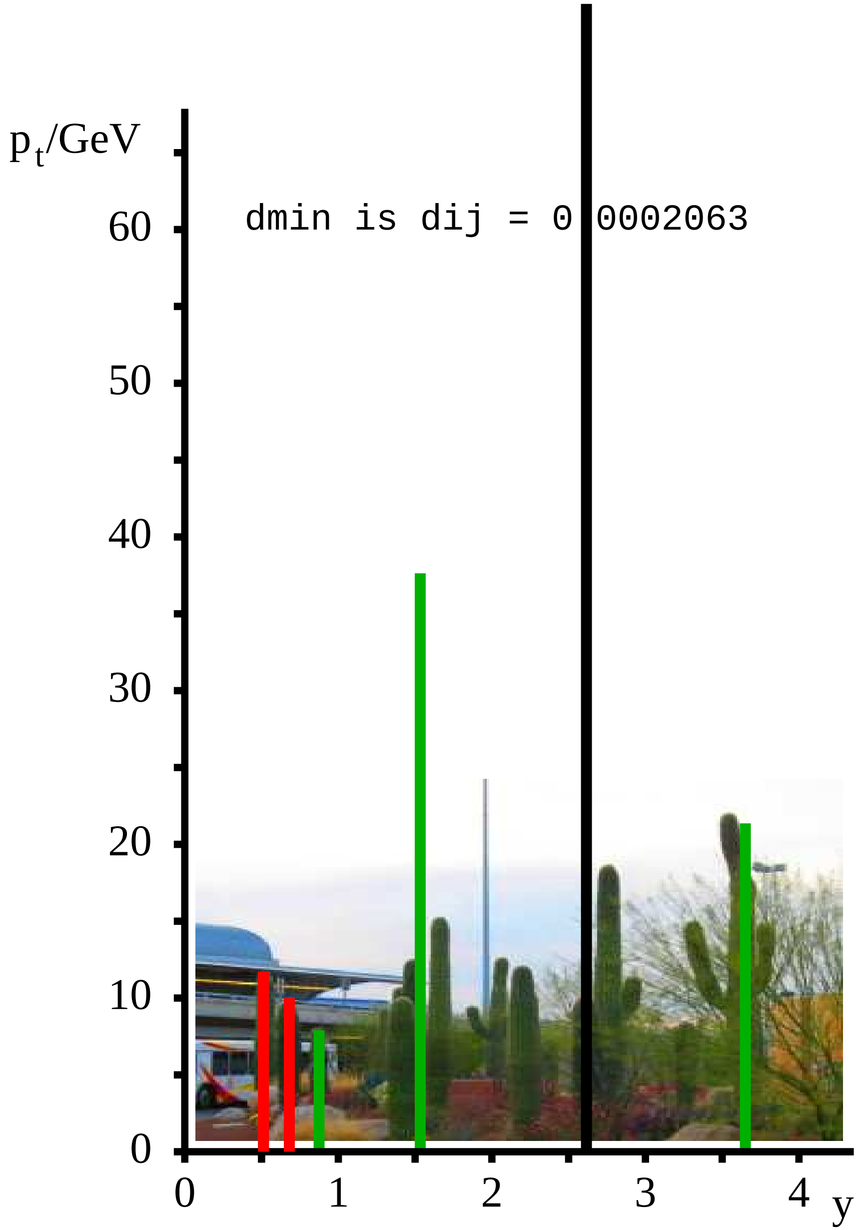
min is $d_{iB} = 8.8\,10^{-5}$

Clustering in action: anti-k_t ($R = 0.7$)



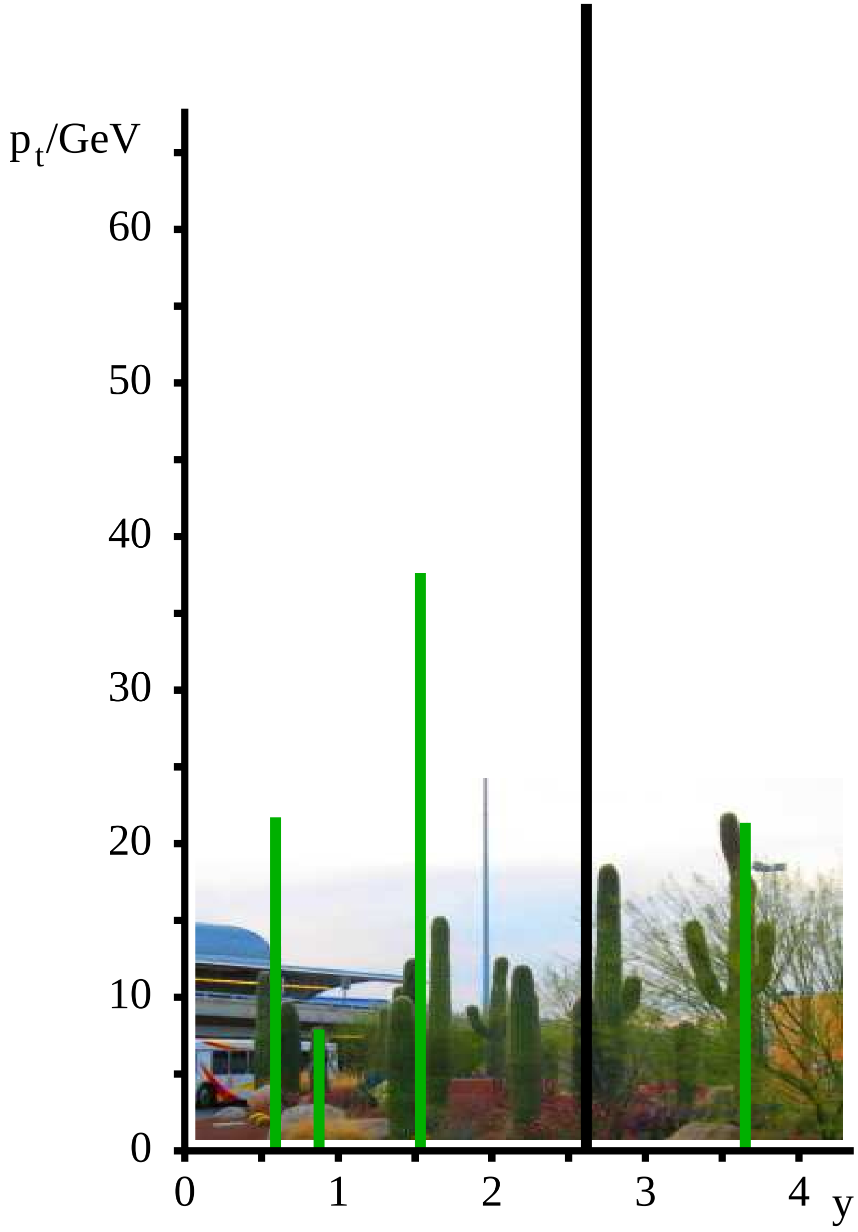
declare as a jet

Clustering in action: anti-k_t ($R = 0.7$)



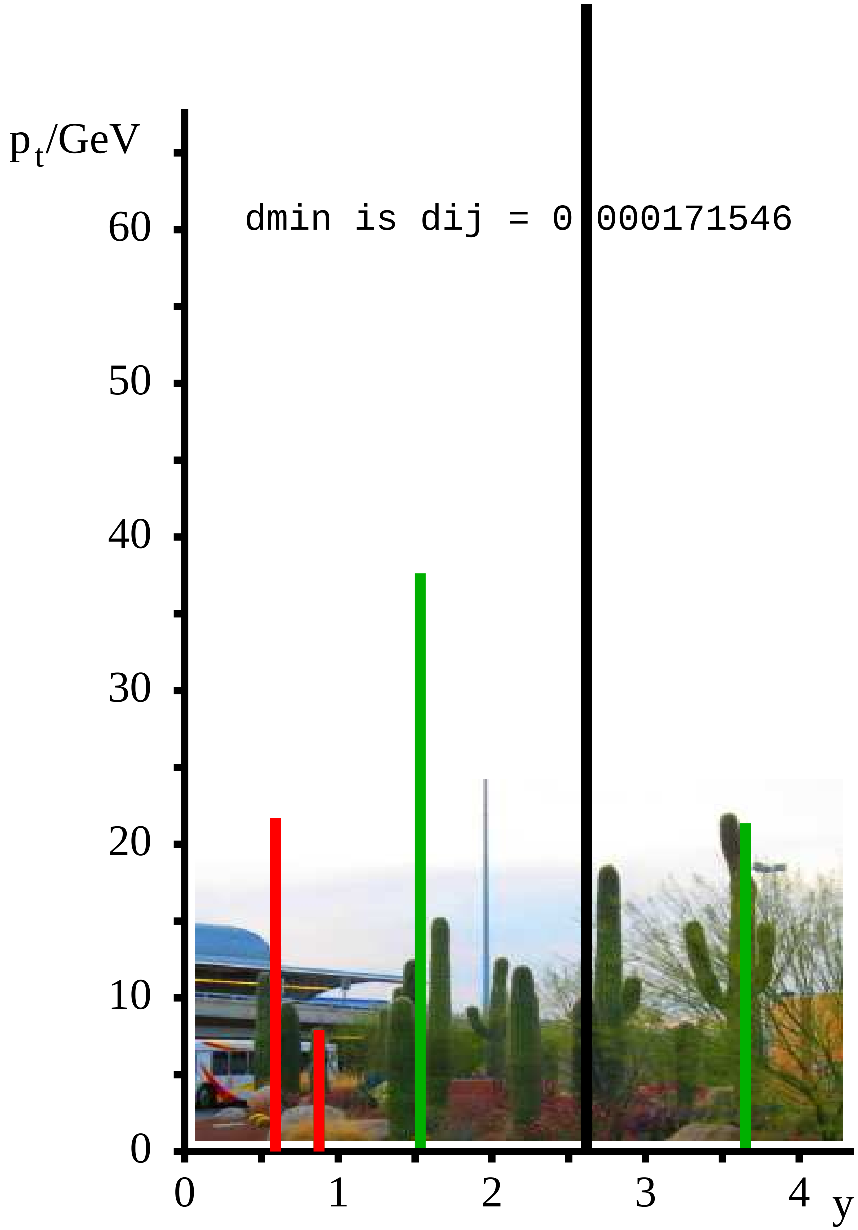
min is $d_{ij} = 2.1\,10^{-4}$

Clustering in action: anti-k_t ($R = 0.7$)



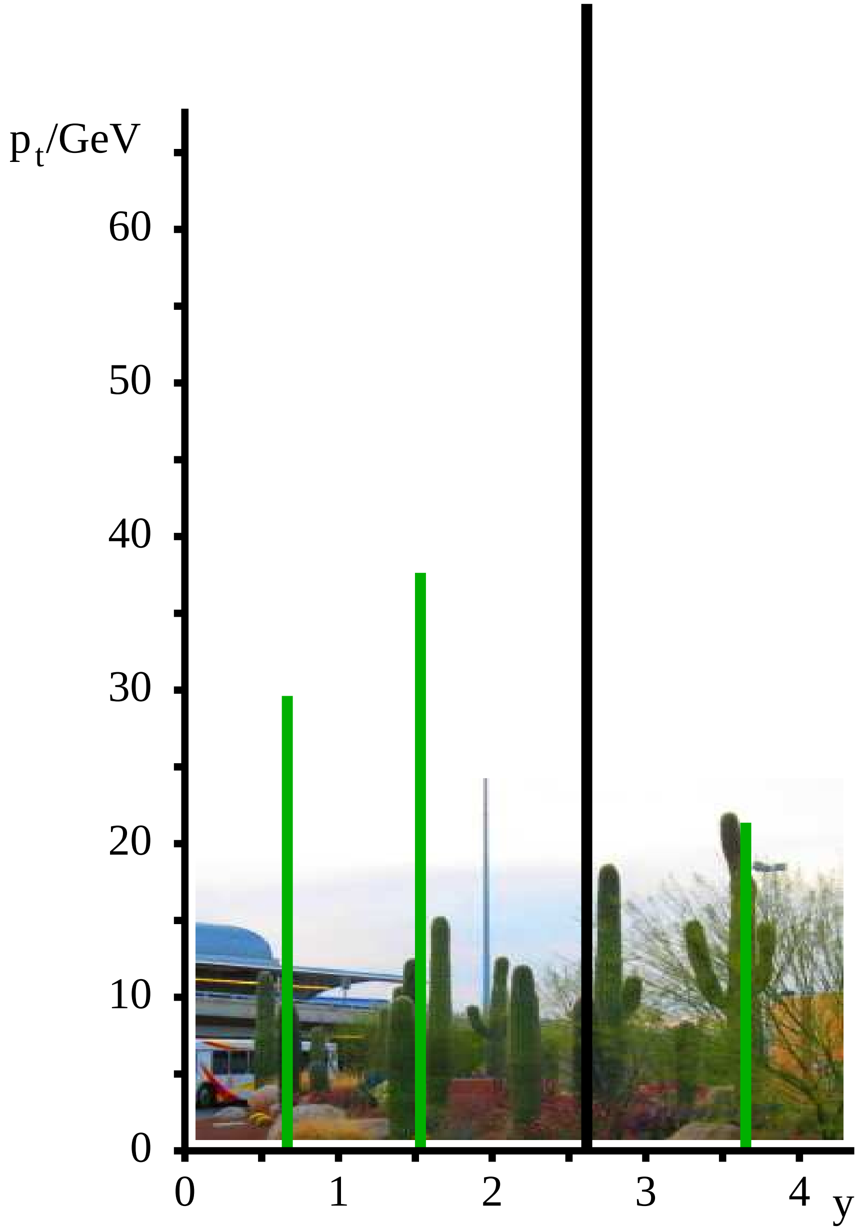
recombine them

Clustering in action: anti-k_t ($R = 0.7$)



min is $d_{ij} = 1.7\,10^{-4}$

Clustering in action: anti-k_t ($R = 0.7$)



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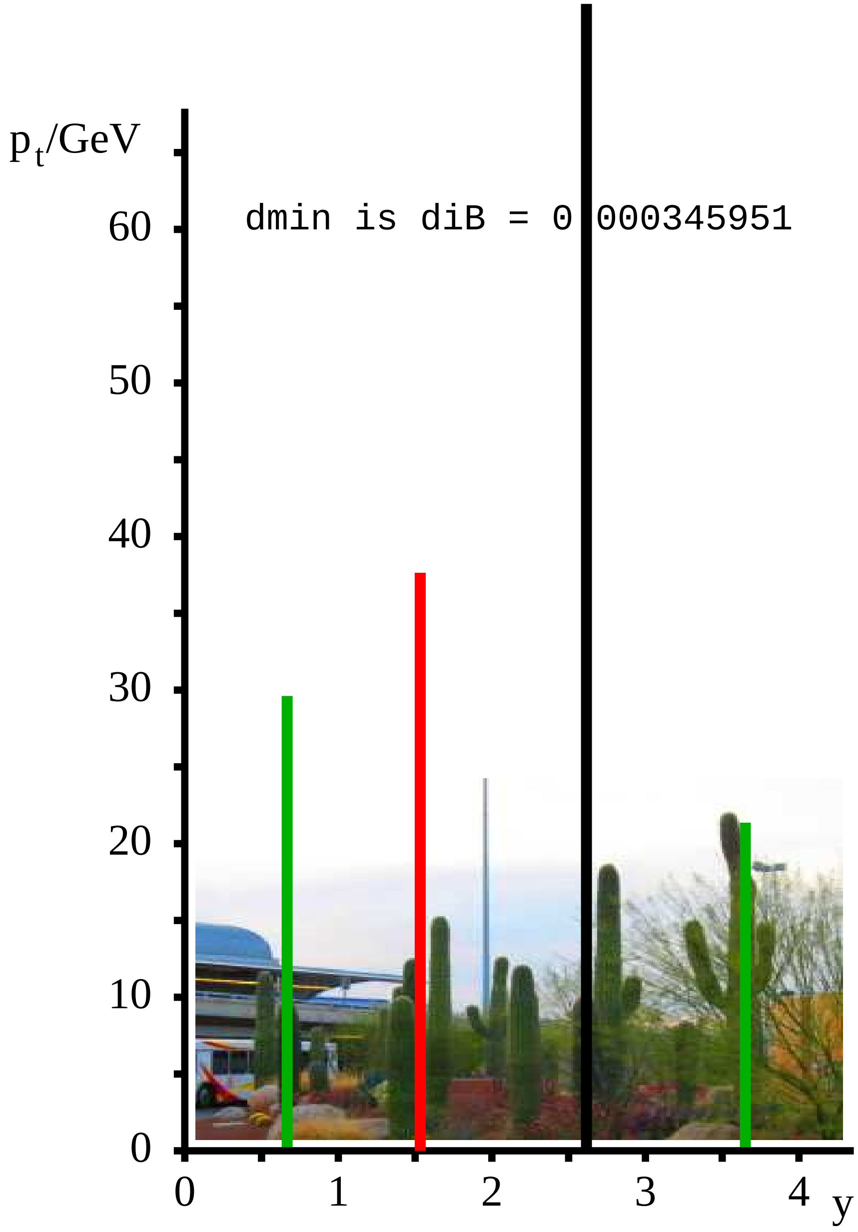
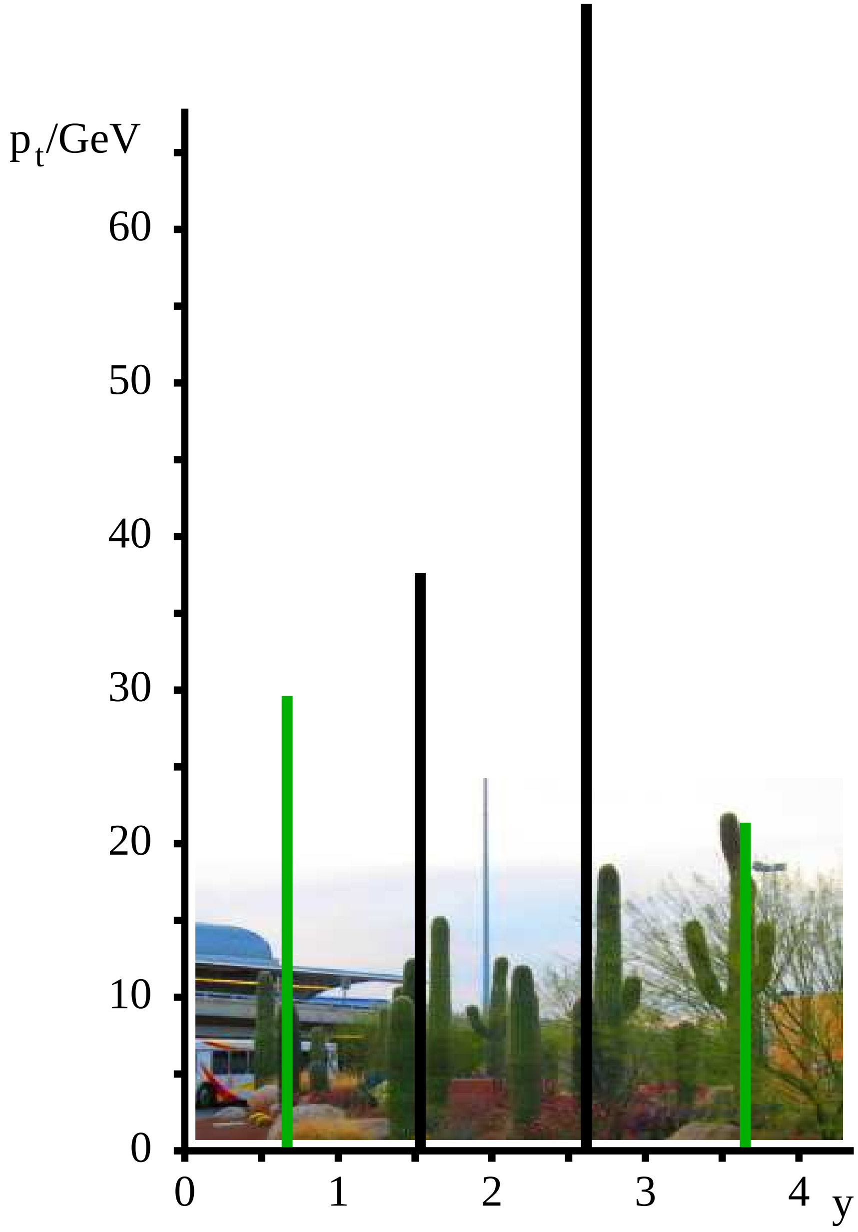


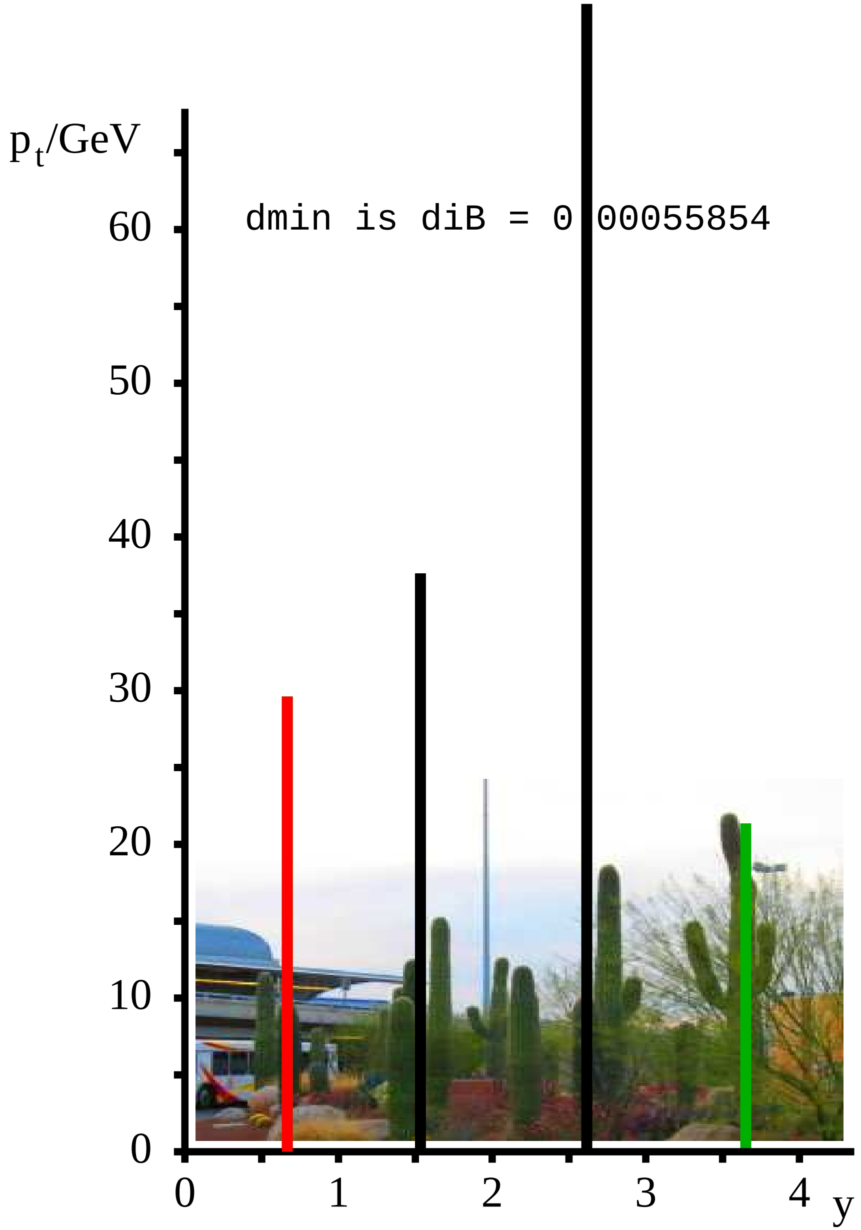
min is $d_{iB} = 3.5\,10^{-4}$

Clustering in action: anti-k_t ($R = 0.7$)



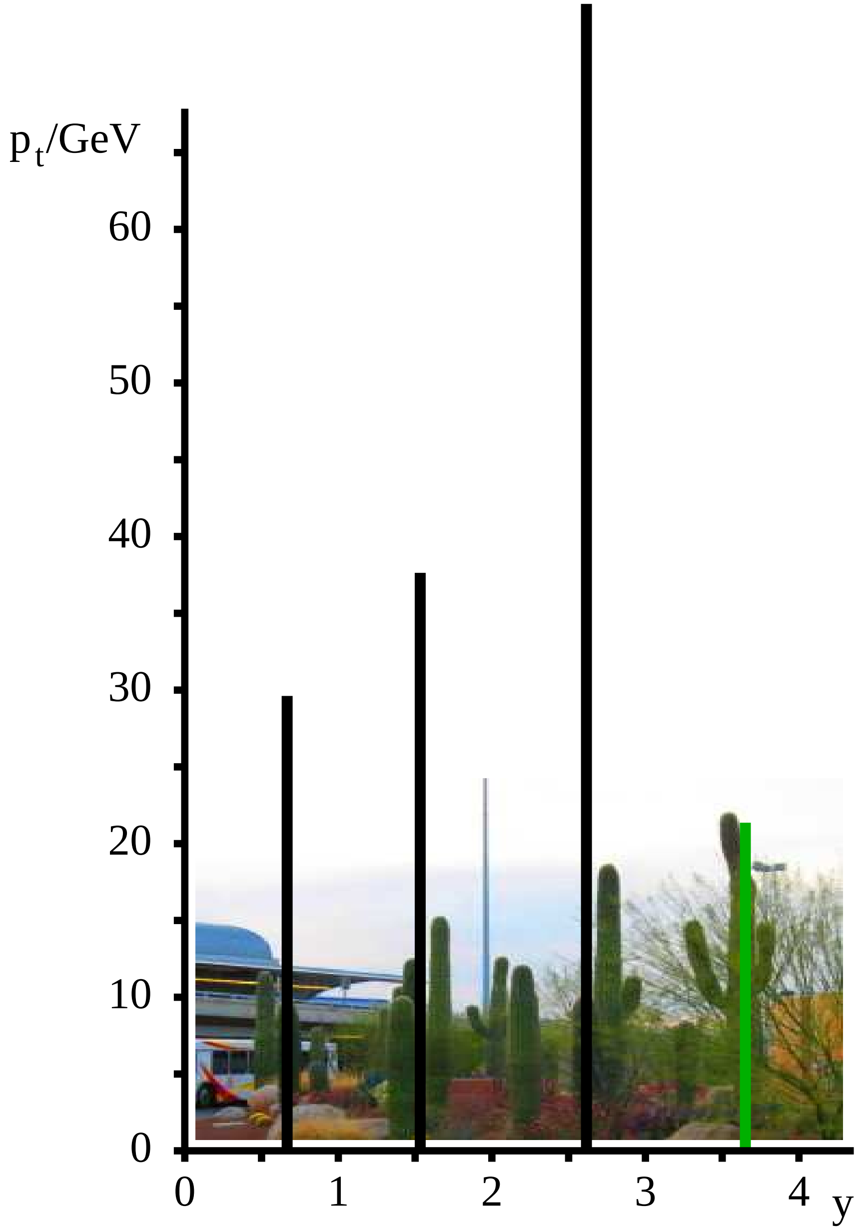
declare as a jet

Clustering in action: anti-k_t ($R = 0.7$)



min is $d_{iB} = 5.6\,10^{-4}$

Clustering in action: anti-k_t ($R = 0.7$)



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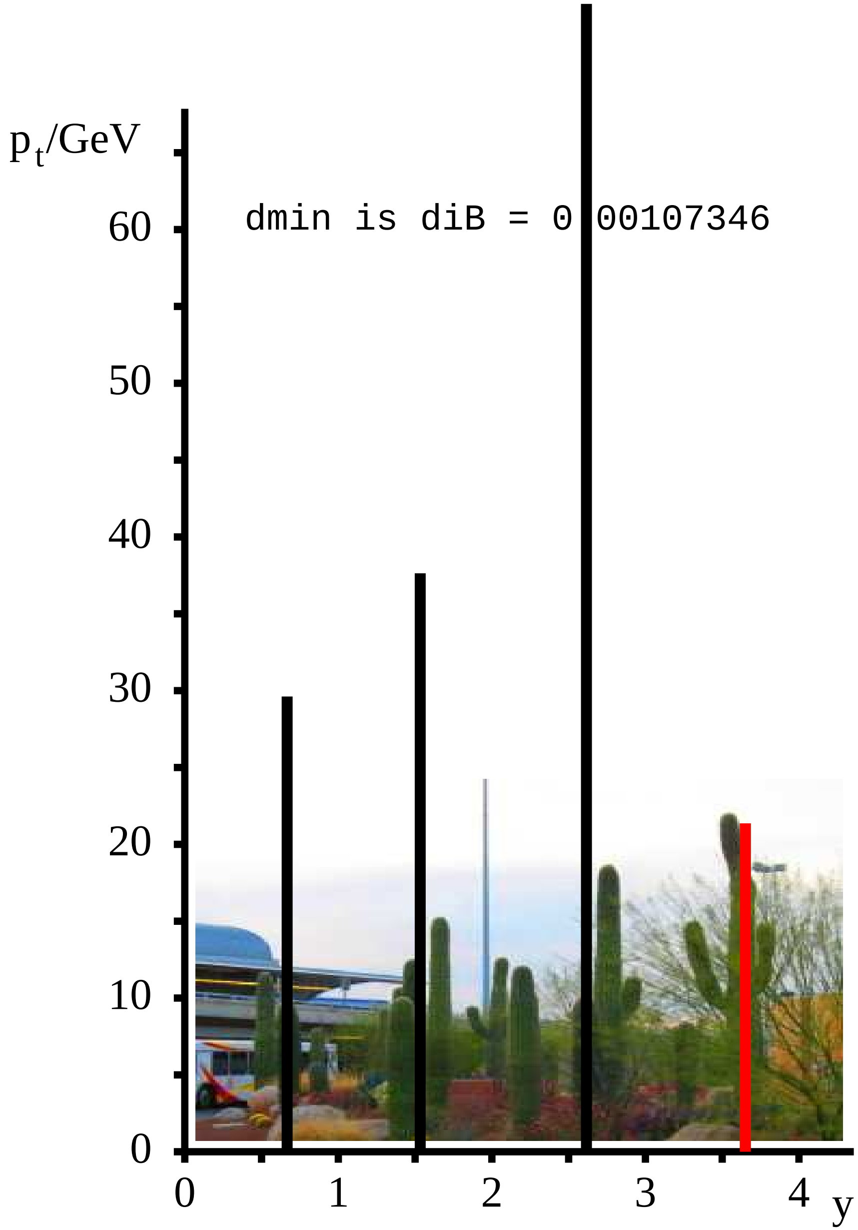
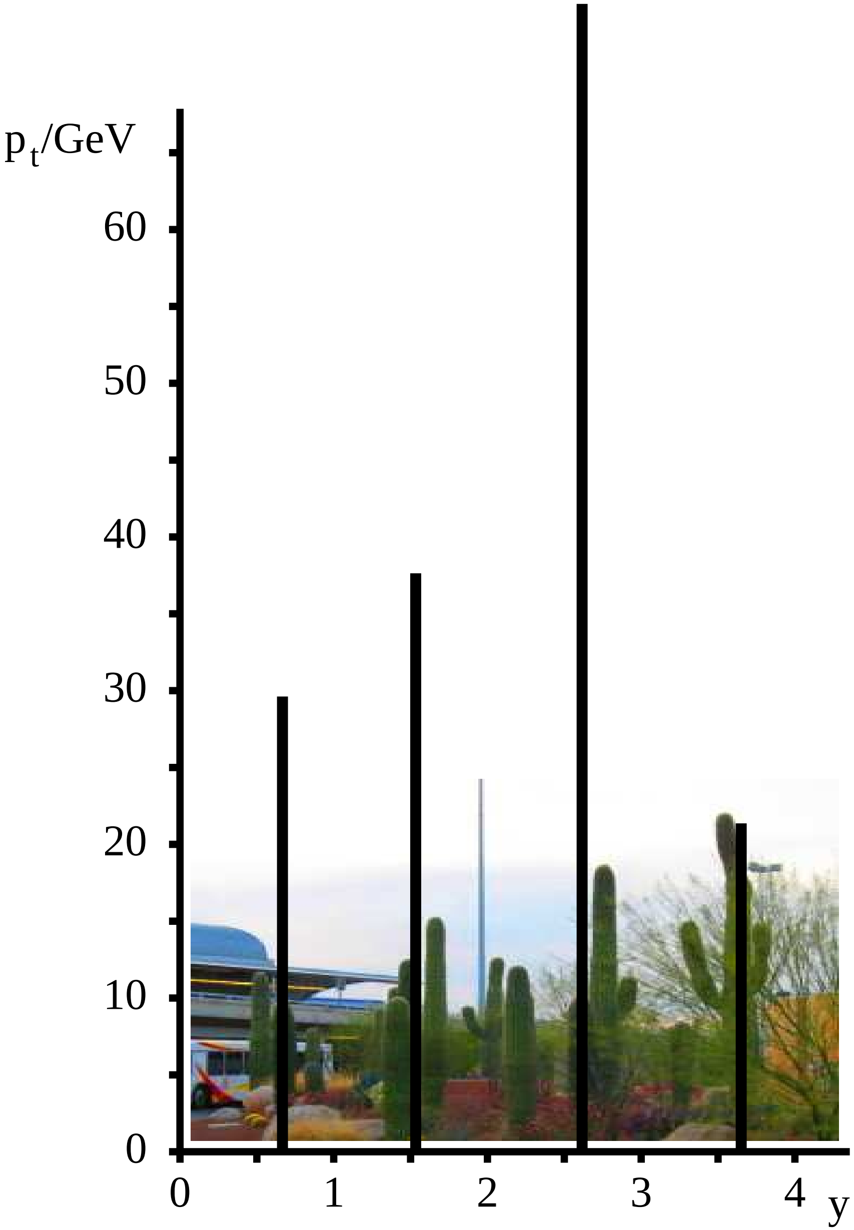
Clustering in action: anti-k_t ($R = 0.7$)



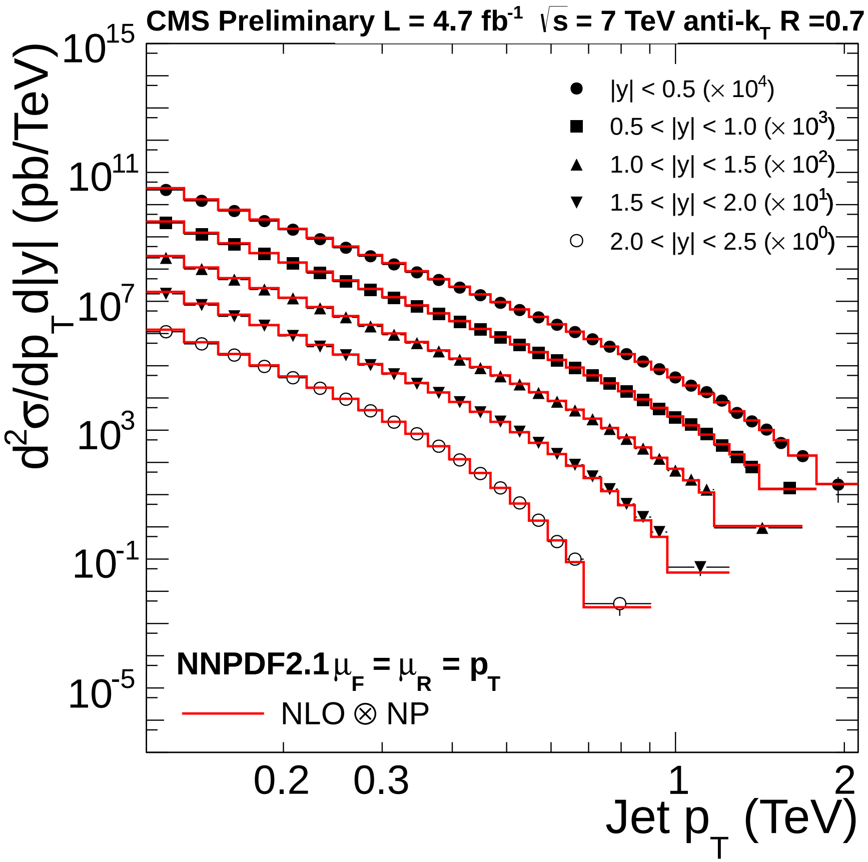
min is $d_{iB} = 1.1\,10^{-3}$

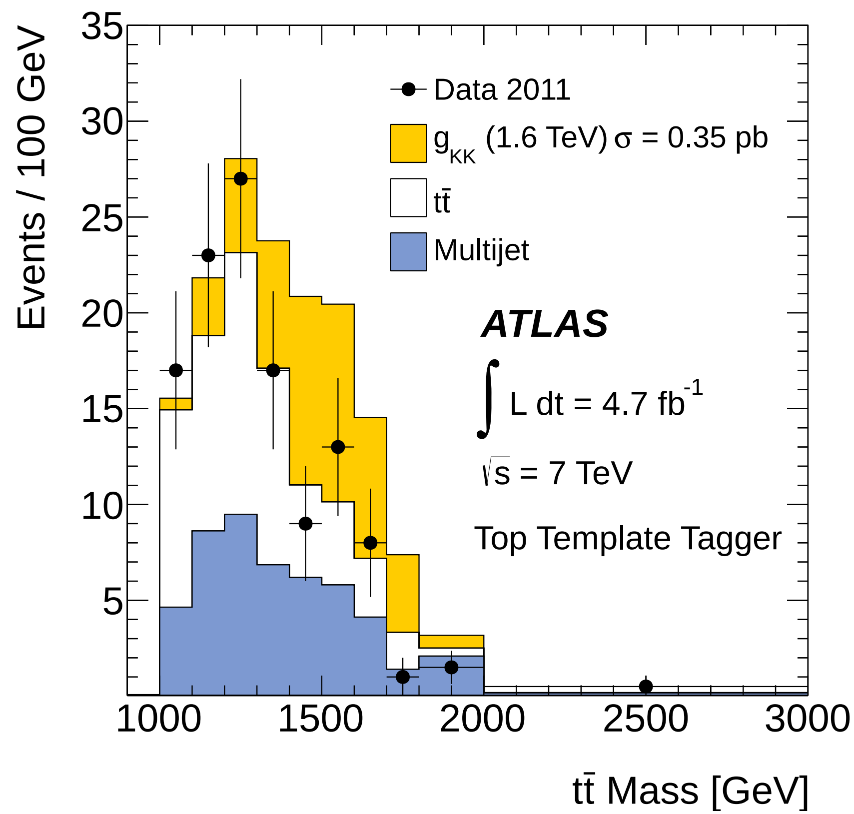
Clustering in action: anti-k_t ($R = 0.7$)



declare as a jet

LHC examples





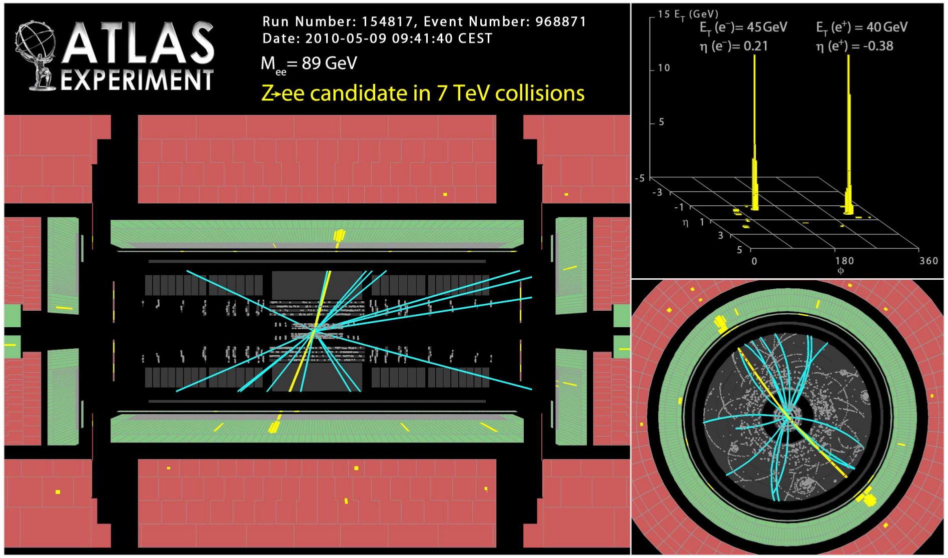
Jets in a soft background

Pileup

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

Low luminosity

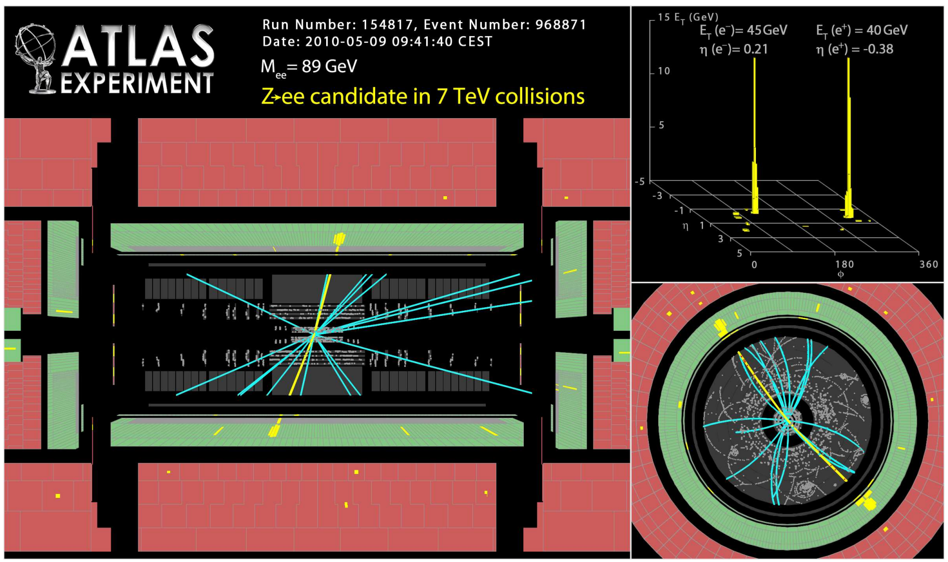
(bunch population)

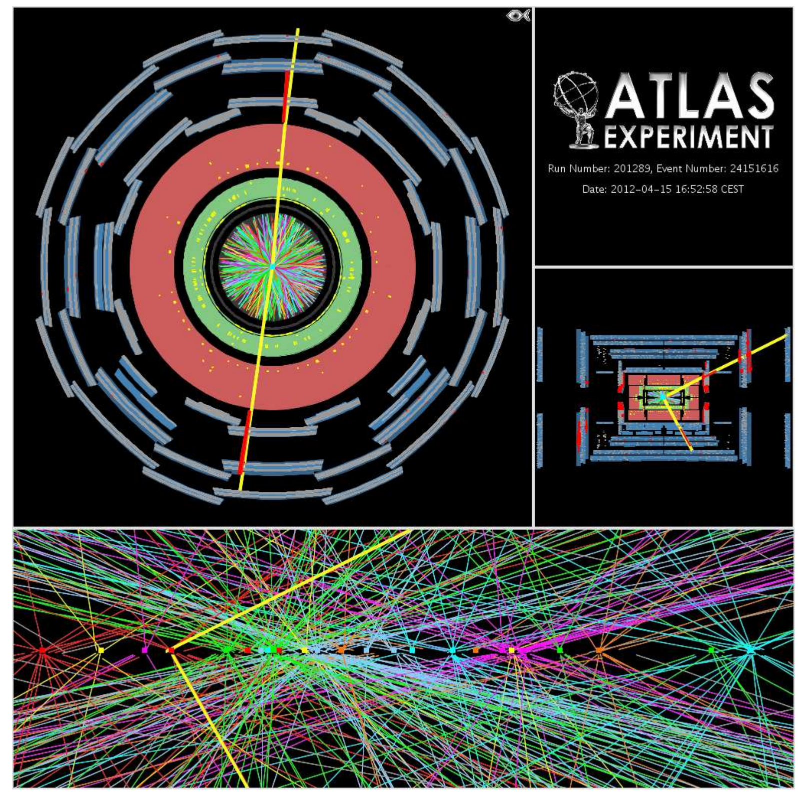


Pileup

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

Low luminosity (bunch population)	High luminosity (bunch population)

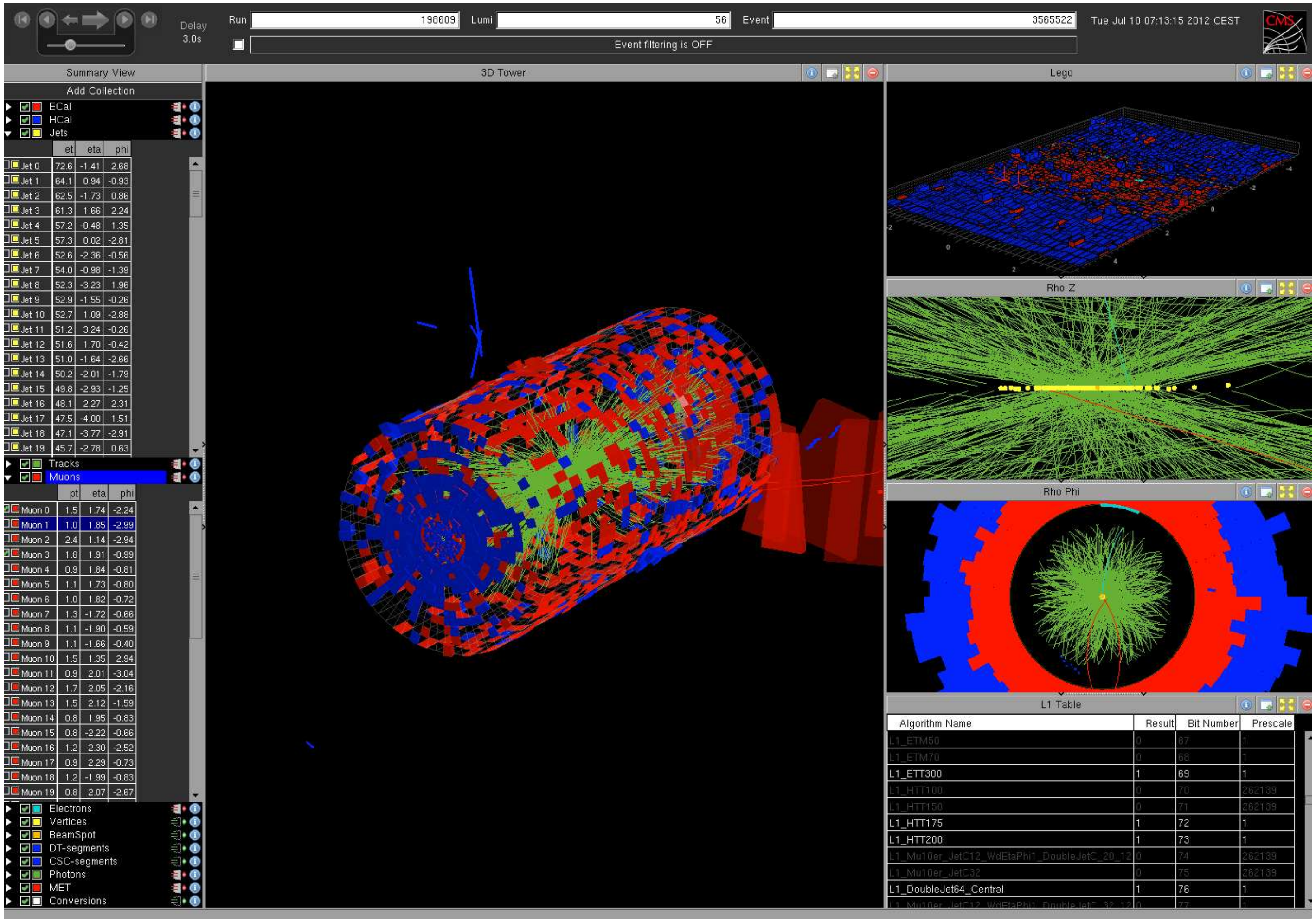




- many (soft) pp interactions with the hard one (here 25)
- soft background in all the detector

Pileup

A CMS event with 78 pile-up vertices!

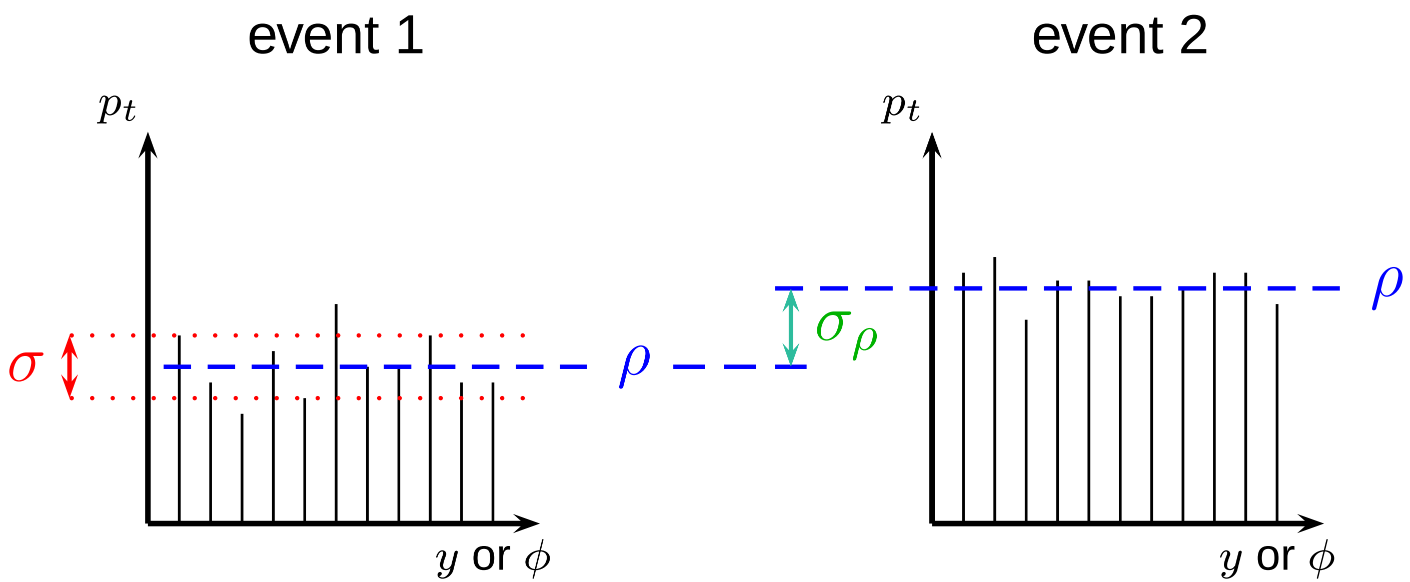


Today (2012 run), 30 PU vertices on average

Basic characterisation

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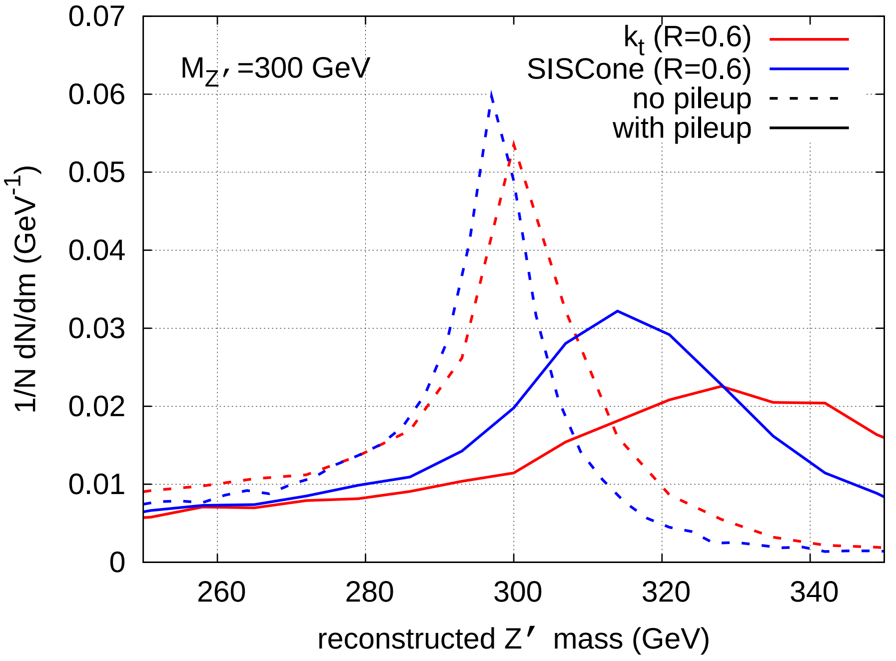
For a jet (of area A) in a given event that means:

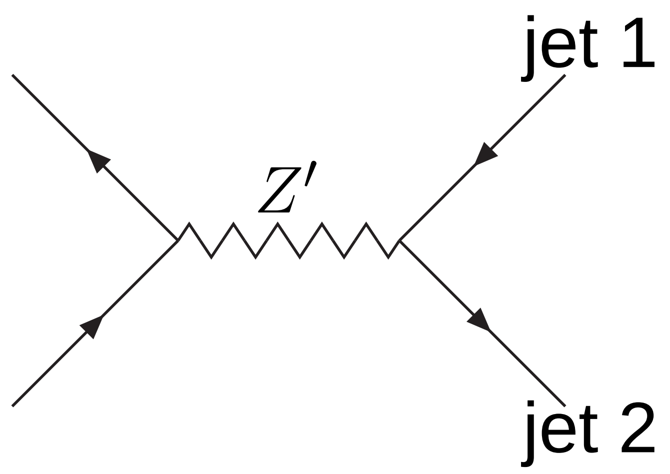
$$p_t \to p_t + \rho A \pm \sigma\sqrt{A}$$

When averaging over many events

$$p_t \to p_t + \langle\rho\rangle A \pm \sigma_\rho A \pm \sigma\sqrt{A}$$

Illustration of the consequences





- Shift due to the "ρA" term
- Smearing due to the "$\sigma_\rho A$" 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

Estimates	LHC, pp	LHC, $PbPb$
ρ	15 GeV	200 GeV
σ_ρ	4 GeV	40 GeV
σ	5 GeV	20 GeV
A_{jet}	0.5	0.5
$\delta p_{t,\text{jet}}$	7.5 GeV	100 GeV
σ_{jet}	3.5 GeV	16 GeV

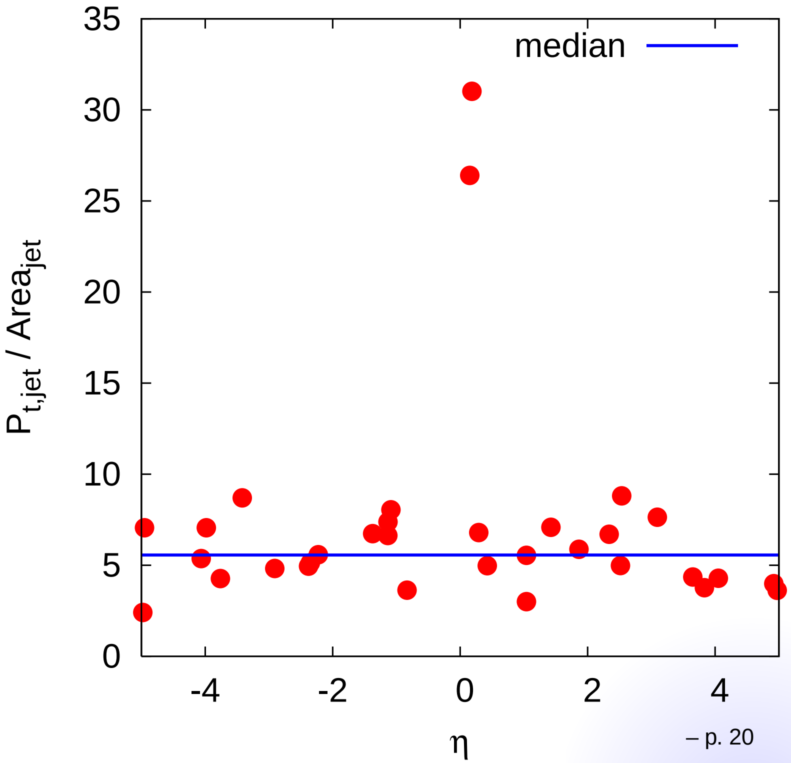
Jet-area-based subtraction

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

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

- jet area: see e.g. M.Cacciari,G.P.Salam,GS,arXiv:0802.1188
- ρ_{bkg}, the background p_t density per unit area
  - break the event in patches of similar size
    e.g. cluster with k_t
  - Estimate ρ_{bkg} using

$$\rho_{\mathrm{bkg}} = \operatorname*{median}_{j \in \mathrm{patches}} \left\{ \frac{p_{t,j}}{A_j} \right\}$$



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

- Jet area A_{jet}: per jet
- Bkg density ρ: (typically) per event

Consequences:

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

Subtraction benchmarks

Subtraction efficiency study:

Generate a hard event $\longrightarrow$ hard jets
Add PU events $\longrightarrow$ full jets
Apply subtraction $\longrightarrow$ subtracted jets

Subtraction benchmarks

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Generate a hard event $\longrightarrow$ hard jets

Add PU events $\longrightarrow$ full jets — $\Delta p_t^{\mathrm{unsub}}$

Apply subtraction $\longrightarrow$ subtracted jets — $\Delta p_t^{\mathrm{sub}}$

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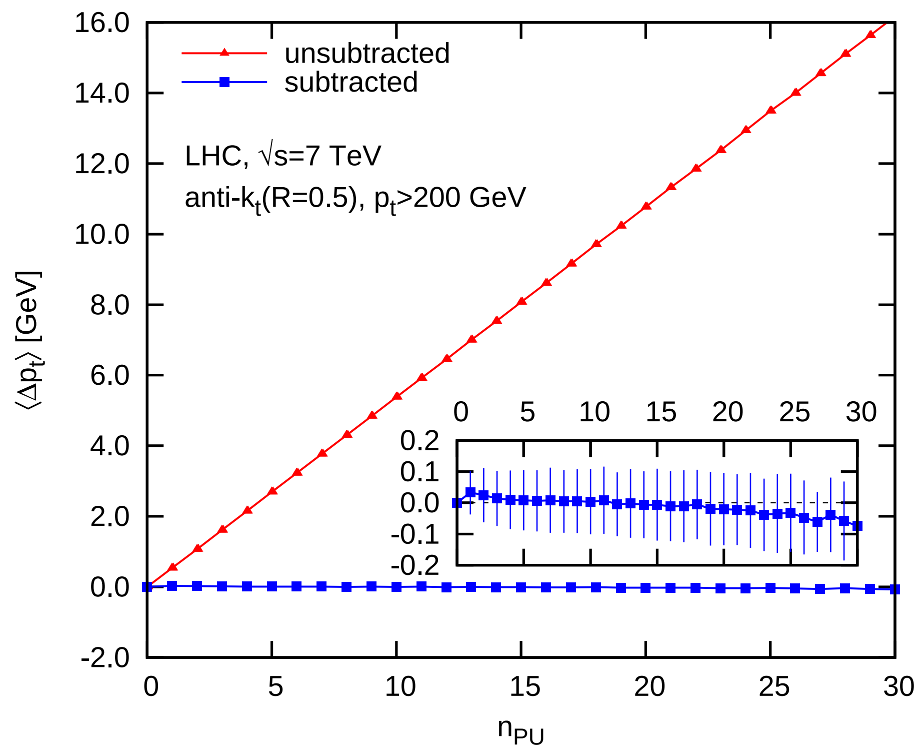
$\Delta p_t^{\mathrm{unsub}}$

$\Delta p_t^{\mathrm{sub}}$



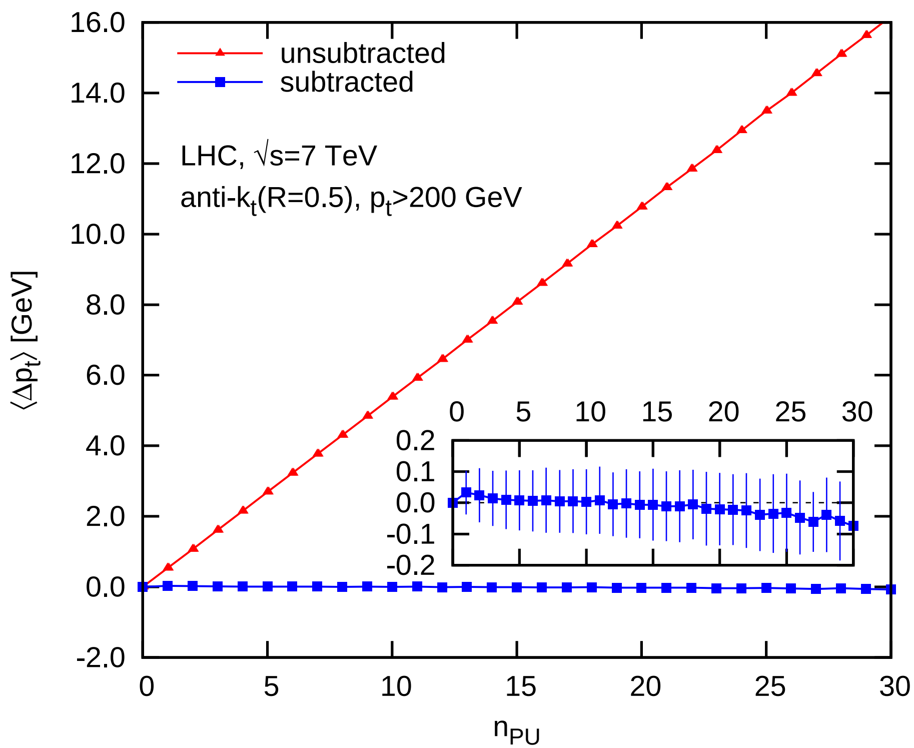
shift $\langle \Delta p_t^{\mathrm{sub}} \rangle$ OK

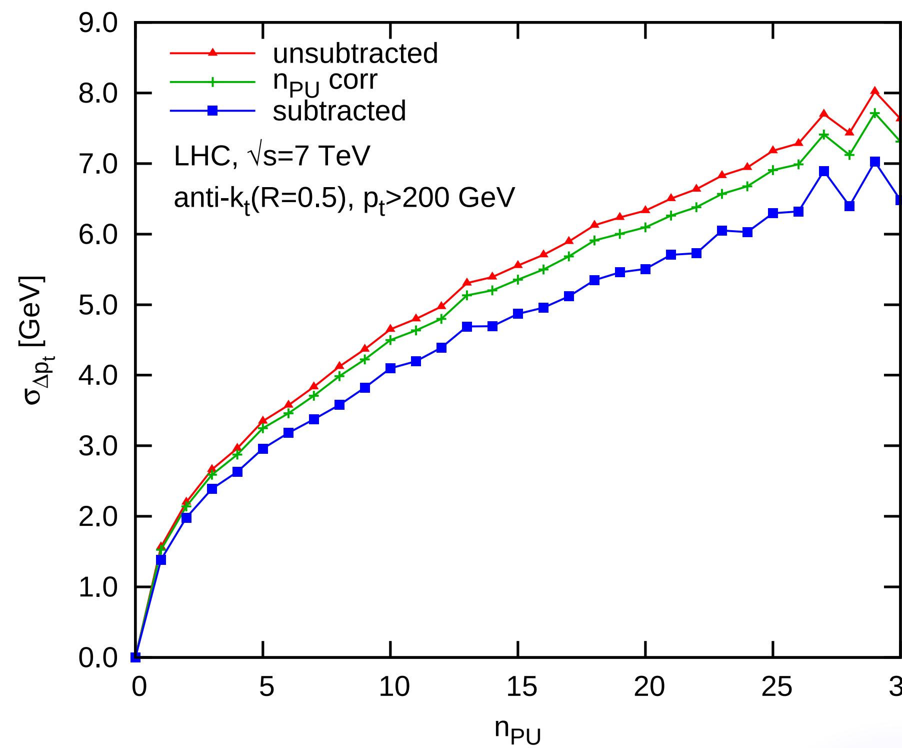
Subtraction benchmarks

Subtraction efficiency study:

Generate a hard event ⟶ hard jets
Add PU events ⟶ full jets
Apply subtraction ⟶ subtracted jets

$\Delta p_t^{\mathrm{unsub}}$
$\Delta p_t^{\mathrm{sub}}$





shift $\langle \Delta p_t^{\mathrm{sub}} \rangle$ OK

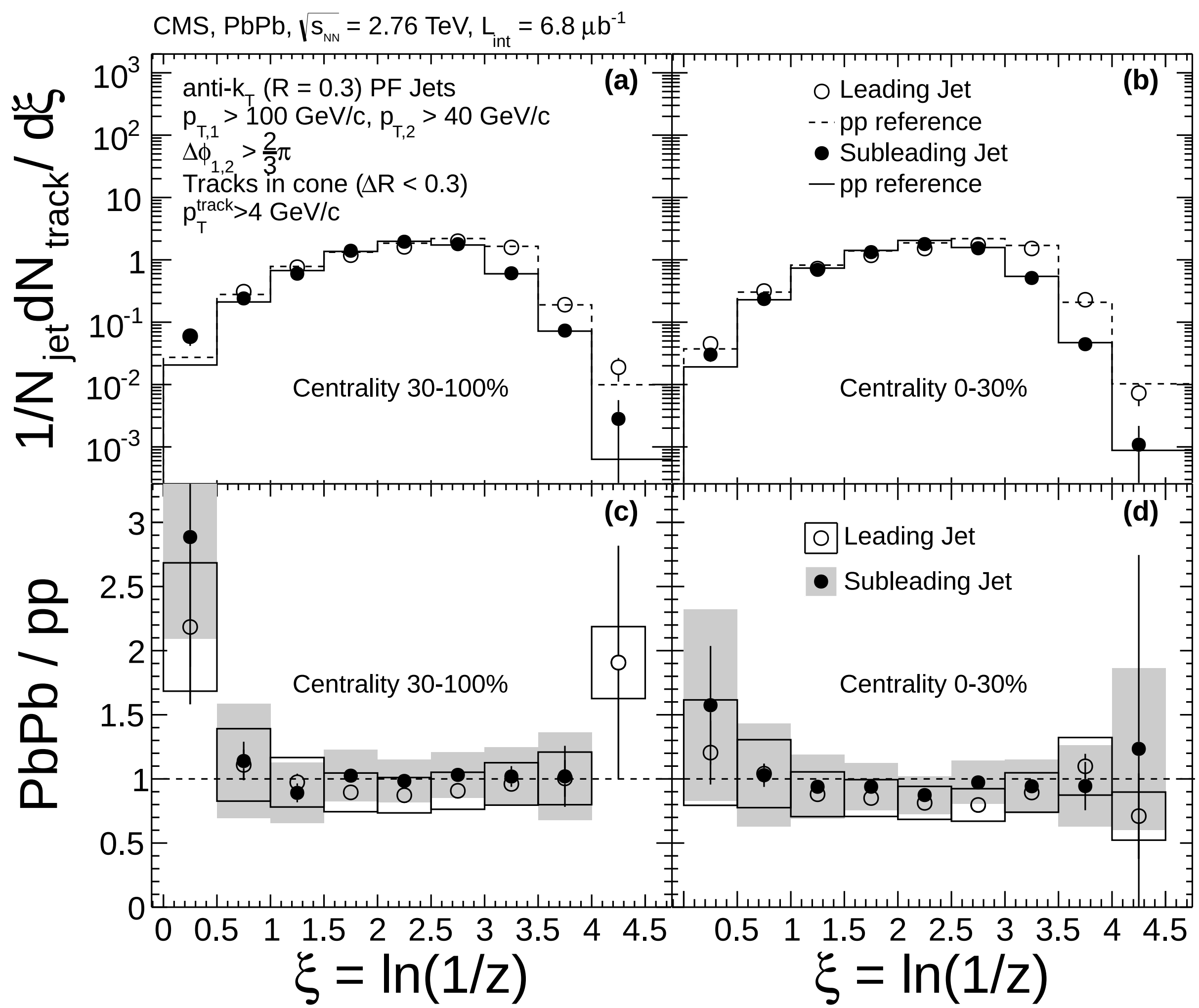
resol $\sigma_{\Delta p_t^{\mathrm{sub}}}$ better

Recent developments

Improvements/extensions of the 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 of fragmentation function (moments)
  Useful for quenching in $PbPb$ collisions
  [M.Cacciari,P.Quiroga,G.Salam,GS,arXiv:1209.6086]
- Subtraction for jet mass and jet shapes
  Important for jet tagging ("q v. g jet", b jet, top jet, $H \to b\bar{b}$)
  [M.Cacciari,J.Kim.G.Salam,GS,arXiv:1211.2811]

Fragmentation function in HI collisions



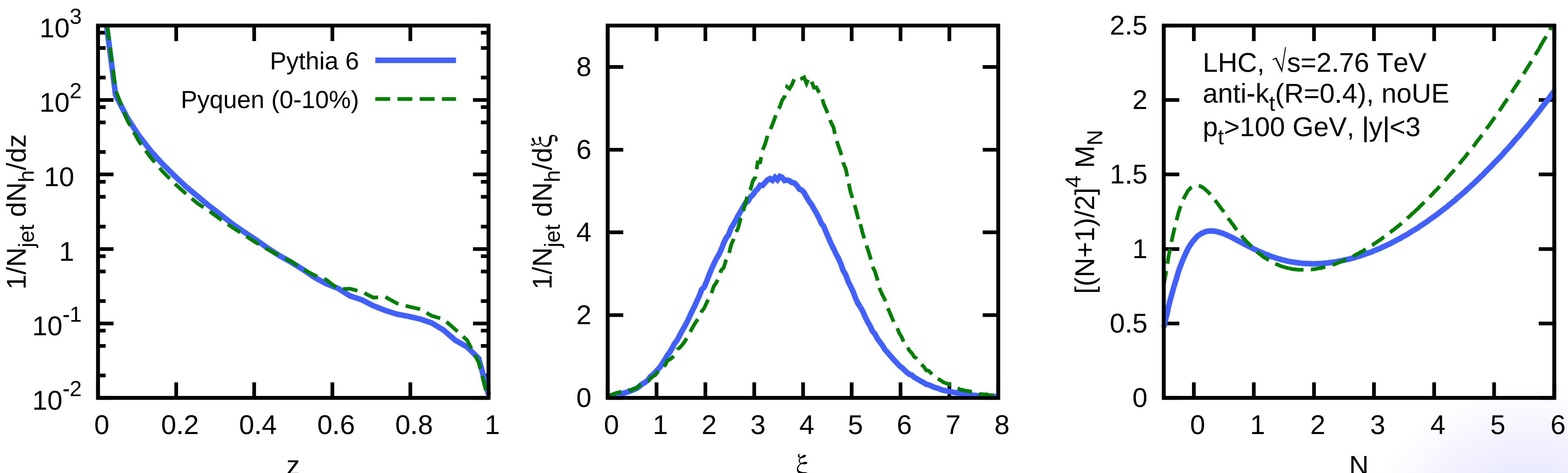
Fragmentation function in HI

Fragmentation function: momenta of the constituents

$$\frac{dN_\mathrm{h}}{dz} \quad \text{with} \quad z = \frac{p_{t,\mathrm{h}}}{p_{t,\mathrm{jet}}}, \xi = \log(1/z)$$

Idea: consider moments of the fragmentation function

$$M_N = \int_0^1 dz\, z^N \frac{dN_\mathrm{h}}{dz} \quad \text{or} \quad M_N^{\mathrm{jet}} = \frac{\sum_{\mathrm{h}\in\mathrm{jet}} p_{t,\mathrm{h}}^N}{p_{t,\mathrm{jet}}^N}$$



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affected by the large $PbPb$ Underlying event

- reconstructed jet p_t: see before
- additional soft particles: apply e.g. a p_t cut

“Standard” background subtraction

Underlying idea:

- measure the medium where it is not affected by the hard jets
- subtracts that from the fragmentation function

Simple test:

region transverse to the dijet event with the same area

Subtraction in moment space

Alternative approach:
use jet-area-based techniques in moment space

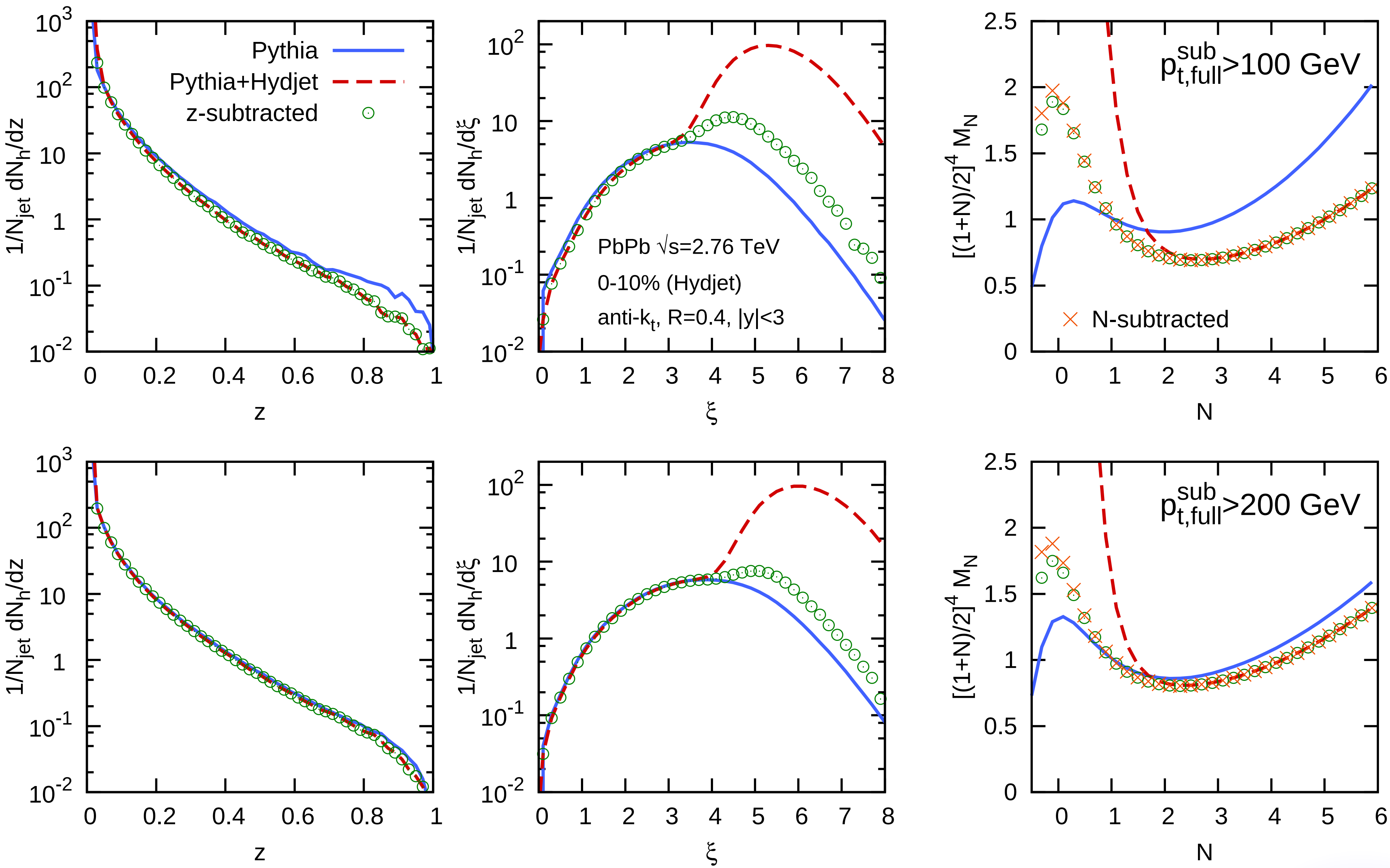
Introduce a new background property ρ_N

$$\rho = \underset{\text{patches}}{\text{median}} \left\{ \frac{p_{t,\text{patch}}}{A_{\text{patch}}} \right\} \qquad \rho_N = \underset{\text{patches}}{\text{median}} \left\{ \frac{\sum_{i \in \text{patch}} p_{t,i}^N}{A_{\text{patch}}} \right\}$$

and subtract using

$$M_N^{\text{sub}} = \frac{\sum_{i \in \text{jet}} p_{t,i}^N - \rho_N A}{(p_t - \rho A)^N}$$

Fragmentation function subtraction

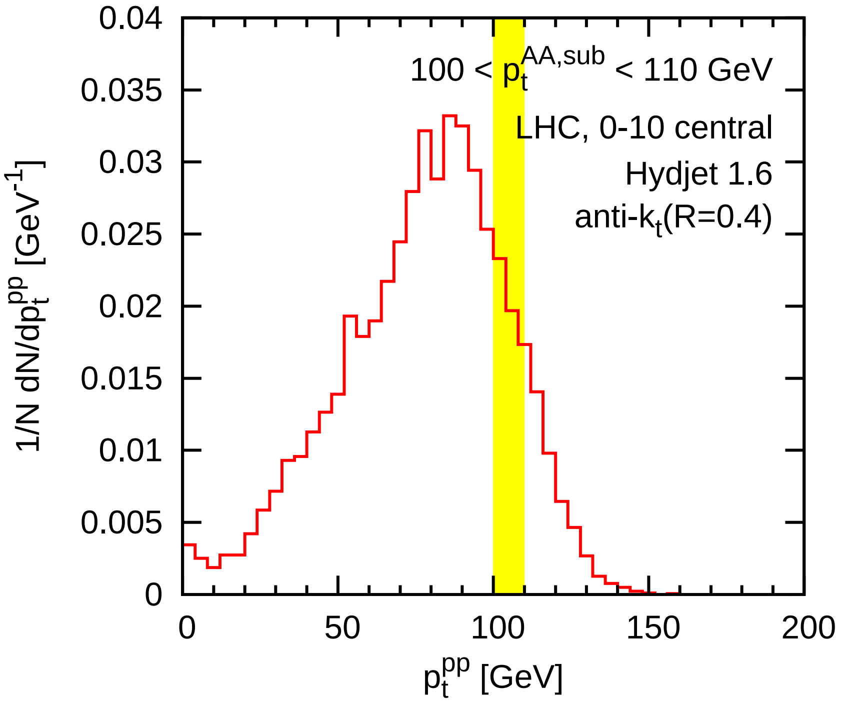


improvement but not better than a p_t cut

Improved subtraction

Problem:

- steeply falling jet spectrum
- cut on $p_{t,\mathrm{full}}^{\mathrm{sub}}$ tends to pick smaller $p_{t,\mathrm{hard}}$
  with upwards fluctuations



Consequences:

- $p_{t,\mathrm{jet}}$ overestimated i.e. z underestimated: underestimation at large N
- extraneous soft particles in the medium: overestimation at small N

Improved subtraction

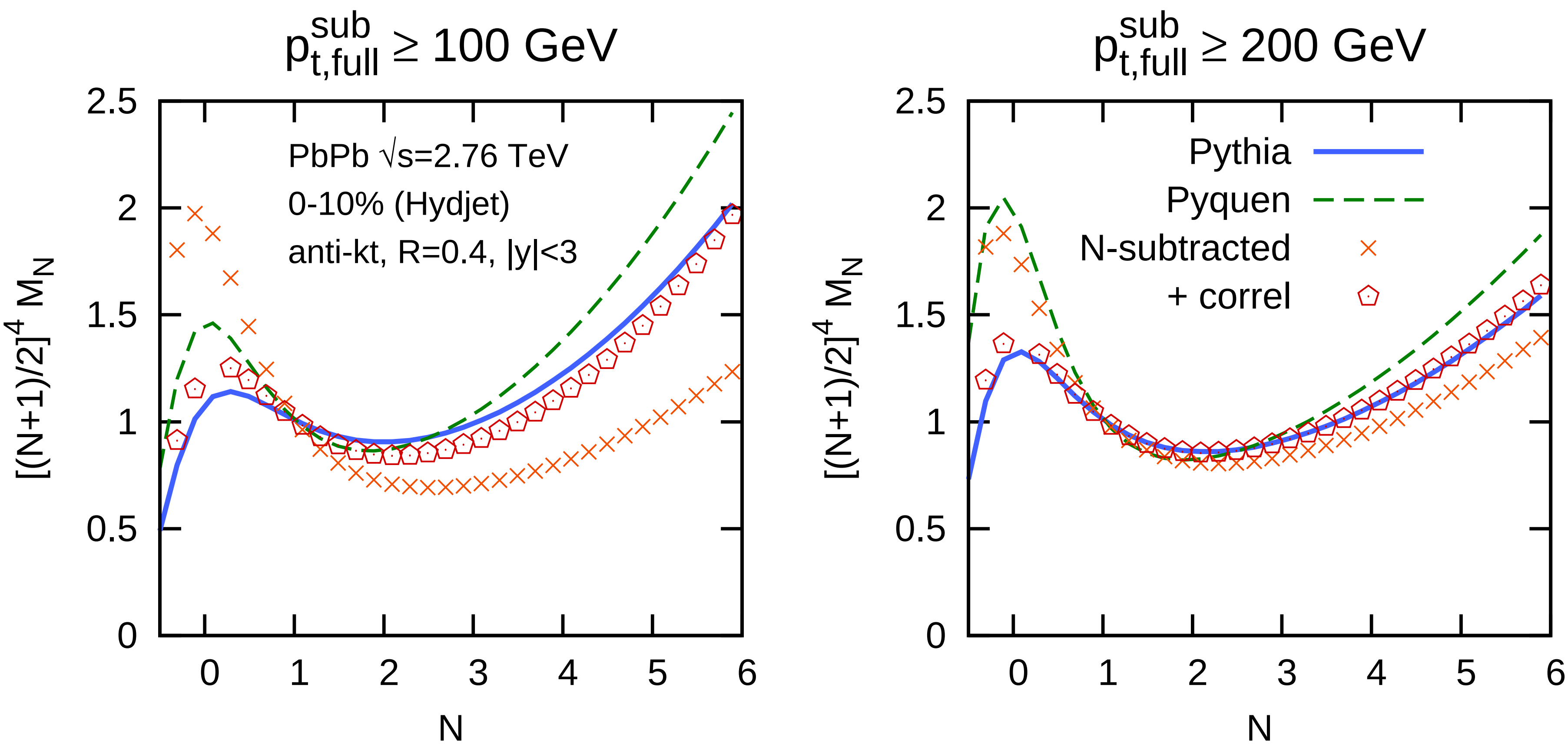
Simple unfolding computed analytically in moment space

- assuming small fluctuations (σ)
- (unfolded) inclusive jet spectrum
  $dN/dp_t \propto \exp(-p_t/\mu)$ (locally)
- compute event-by-event:
  - fluctuations σ in p_t
  - fluctuations σ_N in $\sum p_t^N$
  - correlations r_N between $\sum p_t^N$ and p_t

$$M_N^{\text{sub,imp}} = M_N^{\text{sub}} \times \left(1 + N \frac{\sigma^2 A}{\mu p_{t,\text{jet}}}\right) - r_N \frac{\sigma \sigma_N A}{\mu p_{t,\text{jet}}^N}$$

Improved subtraction

$$M_N^{\text{sub,imp}} = M_N^{\text{sub}} \times \left(1 + N\frac{\sigma^2 A}{\mu p_{t,\text{jet}}}\right) - r_N \frac{\sigma \sigma_N A}{\mu p_{t,\text{jet}}^N}$$



Much nicer and only easily done in moments!

Conclusion and perspectives

- 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
- Pile-up and HI background subtraction:
  - 2 key ingredients: jet area & median ρ
  - Now many applications
    - jet p_t and 4-momentum
    - fragmentation function
    - jet shapes

Backup slides

FF moments: interesting N

Some interesting values of N:

- $N = 0$ is the particle multiplicity
- with only charged tracks $N = 1$ is the charged fraction of momentum
- Hadron spectrum $\propto p_t^{-n}$
  $\Rightarrow M_{n-1}$ is the ratio of the hadron and jet spectra