Towards a standardised approach to jet reconstruction

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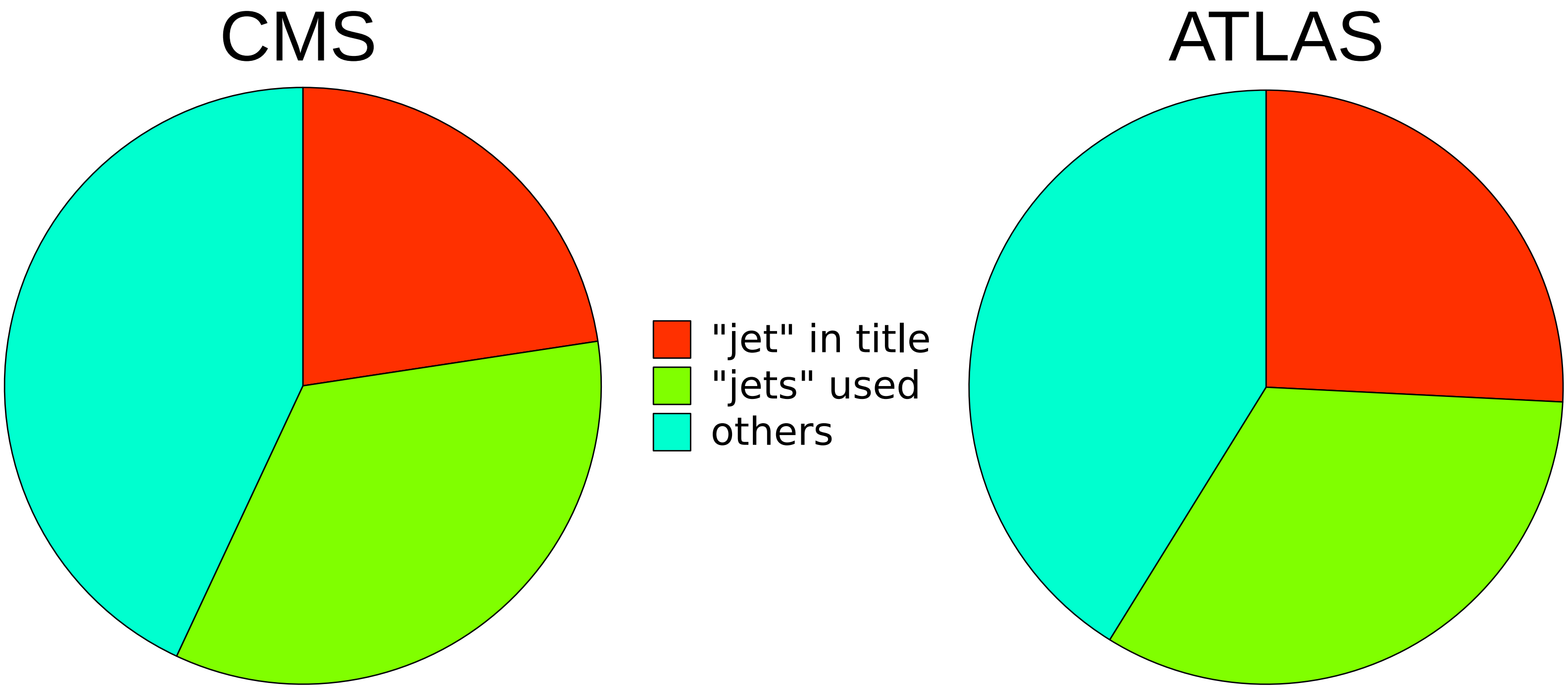
MIT — May 20th 2013

Jets are widely used objects at the LHC

$\sim$ 60% of the LHC paper use jets!



Brief plan

- Jets (pre-LHC history)
  Concept and importance, *jet definitions*, illustrations
- Goal #1: robust/standard jet definitions
  anti-k_t algorithm
- Goal #2: public and standard interface
  FastJet and its contrib
- Goal #3: jets at high luminosity *i.e.* handling pileup
  context, area-median pileup subtraction
- Goal #4: Jet substructure
  tagging boosted objects

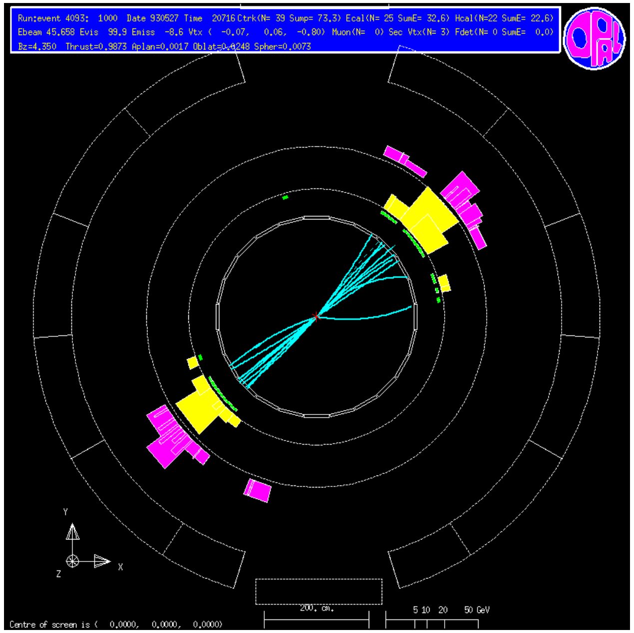
What is a “jet”?

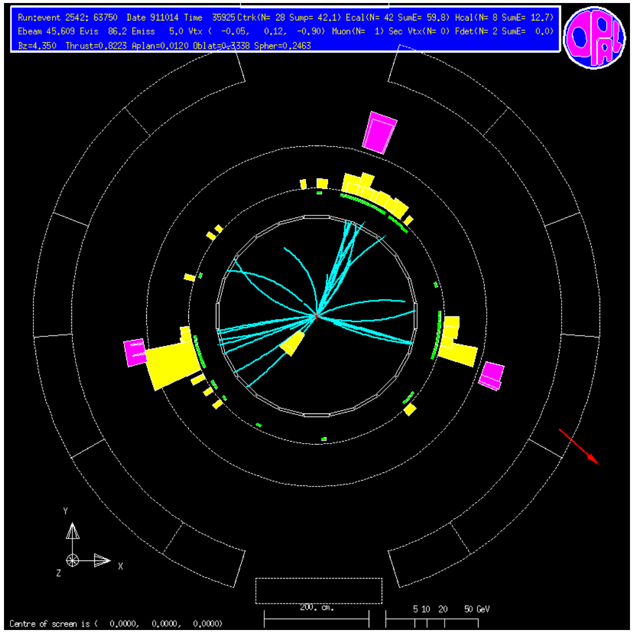
concept/idea

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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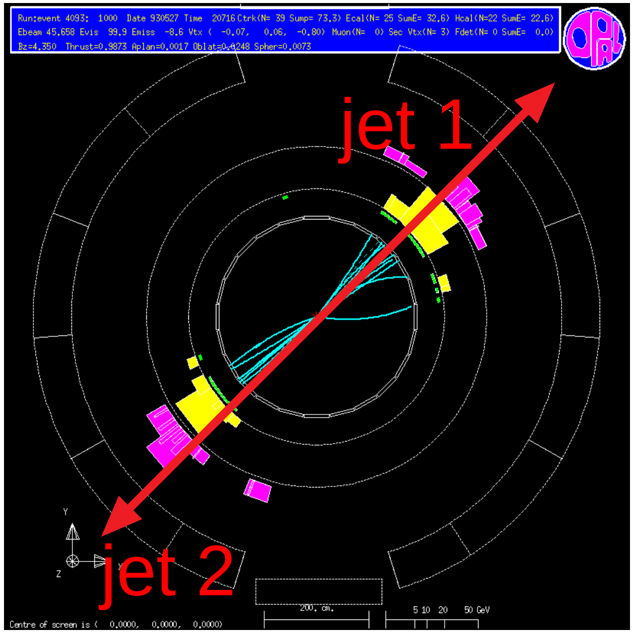

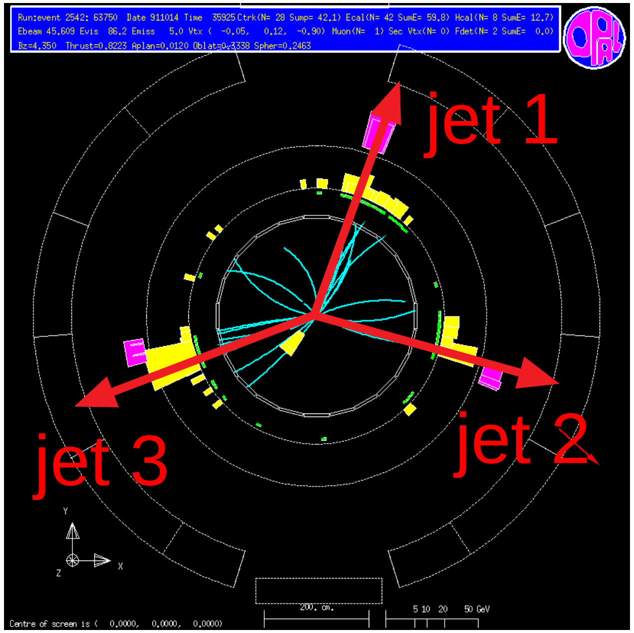

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Jets

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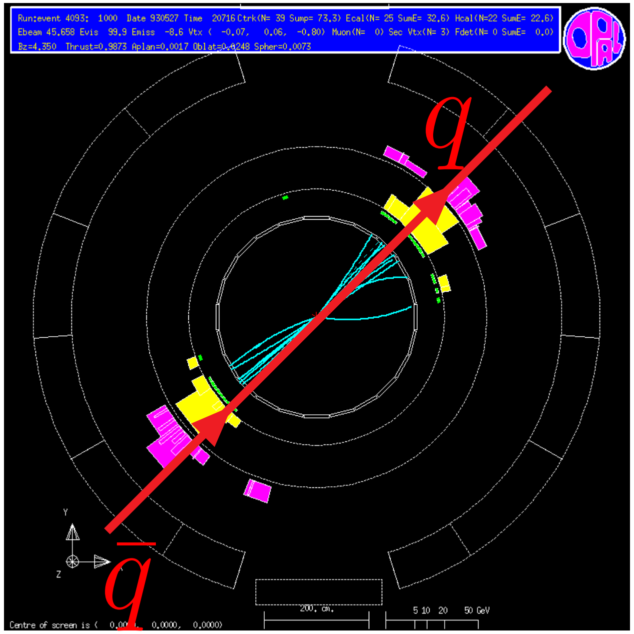

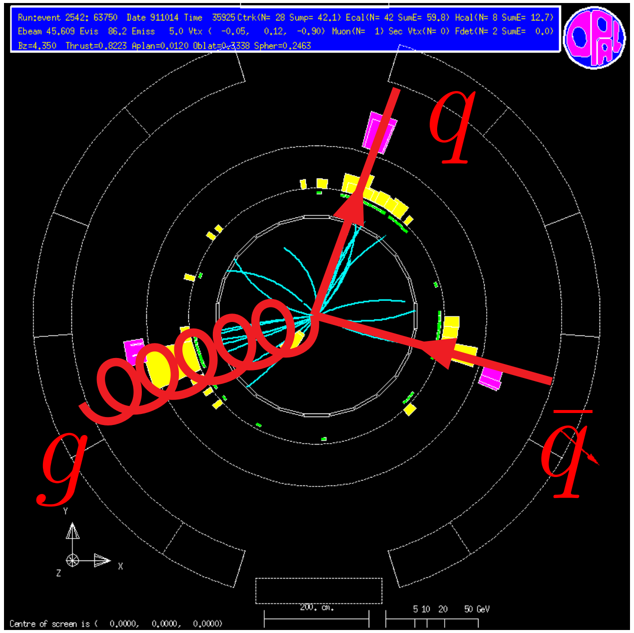

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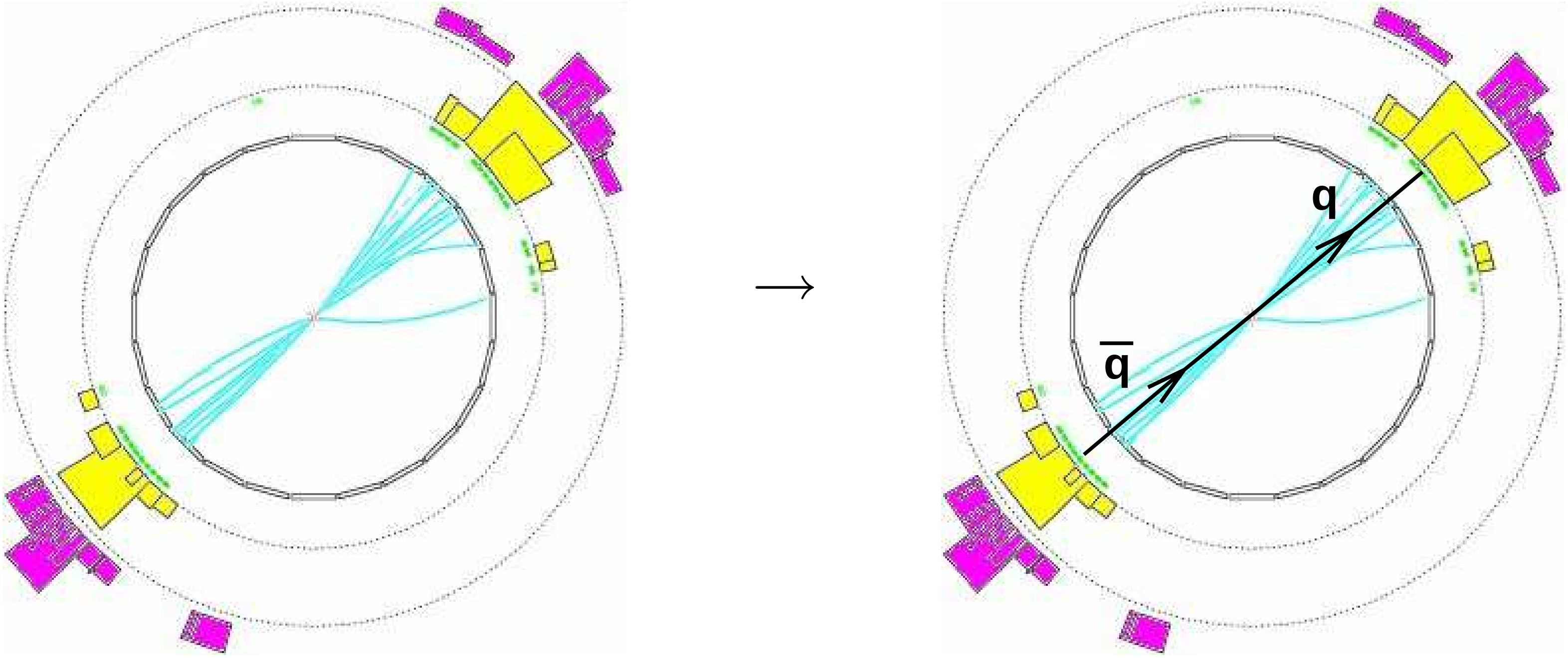
“Jets” $\equiv$ bunch of collimated particles $\cong$ hard partons

Jets and partons

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

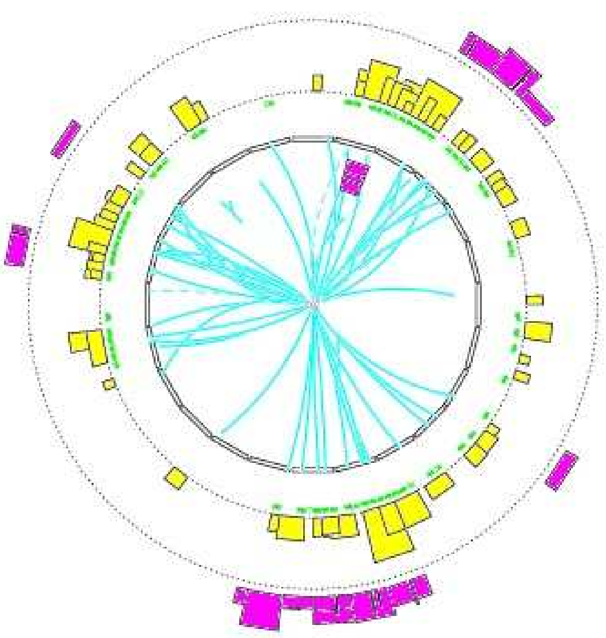
obviously 2 jets



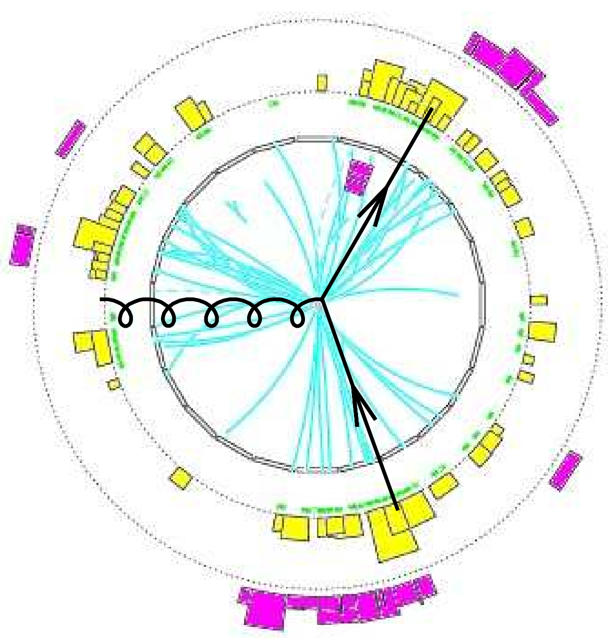
Jets and partons

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

3 jets



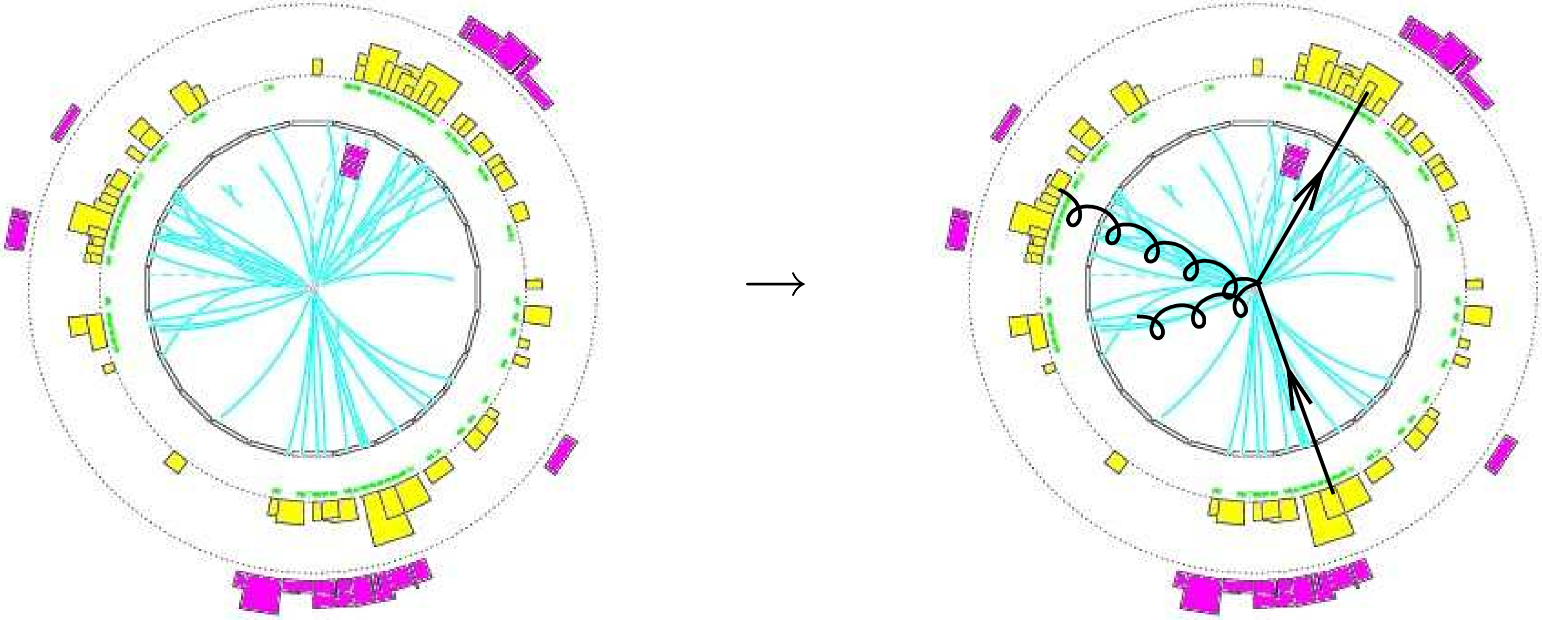
$\longrightarrow$



Jets and partons

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

3 jets... or 4?

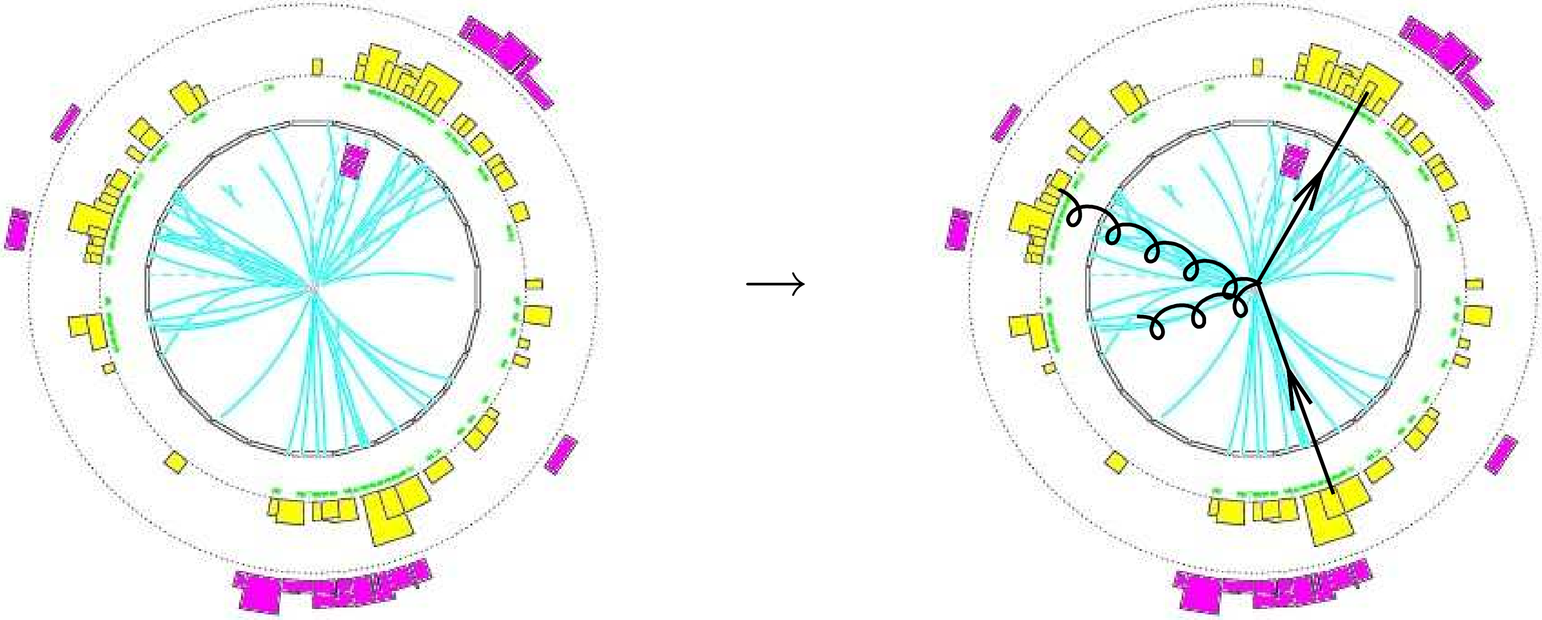


- “collinear” is arbitrary

Jets and partons

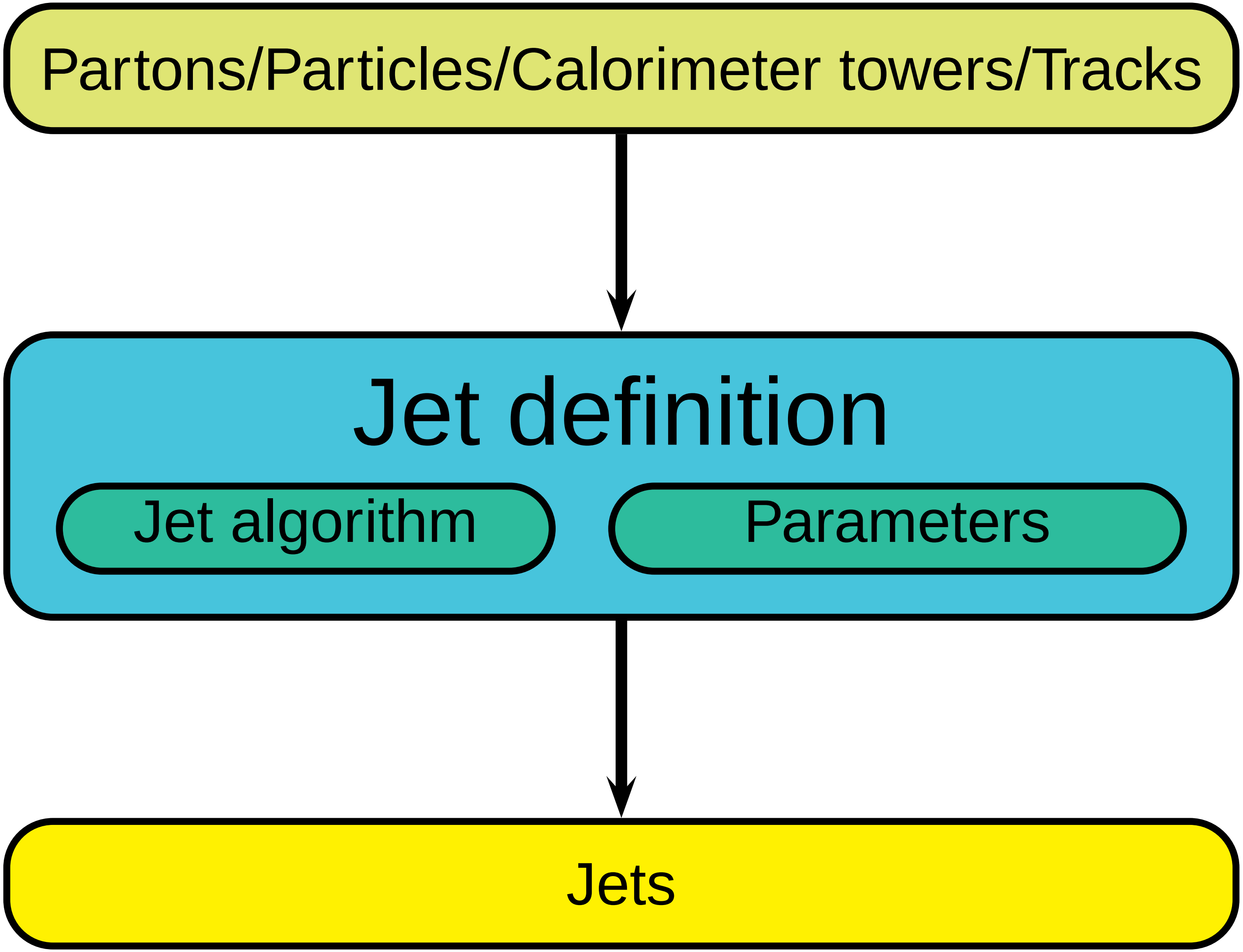
“Jets” $\equiv$ bunch of collimated particles $\cong$ hard partons

3 jets... or 4?



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

Jet definition



Partons/Particles/Calorimeter towers/Tracks

Jet definition

Jet algorithm

Parameters

Jets

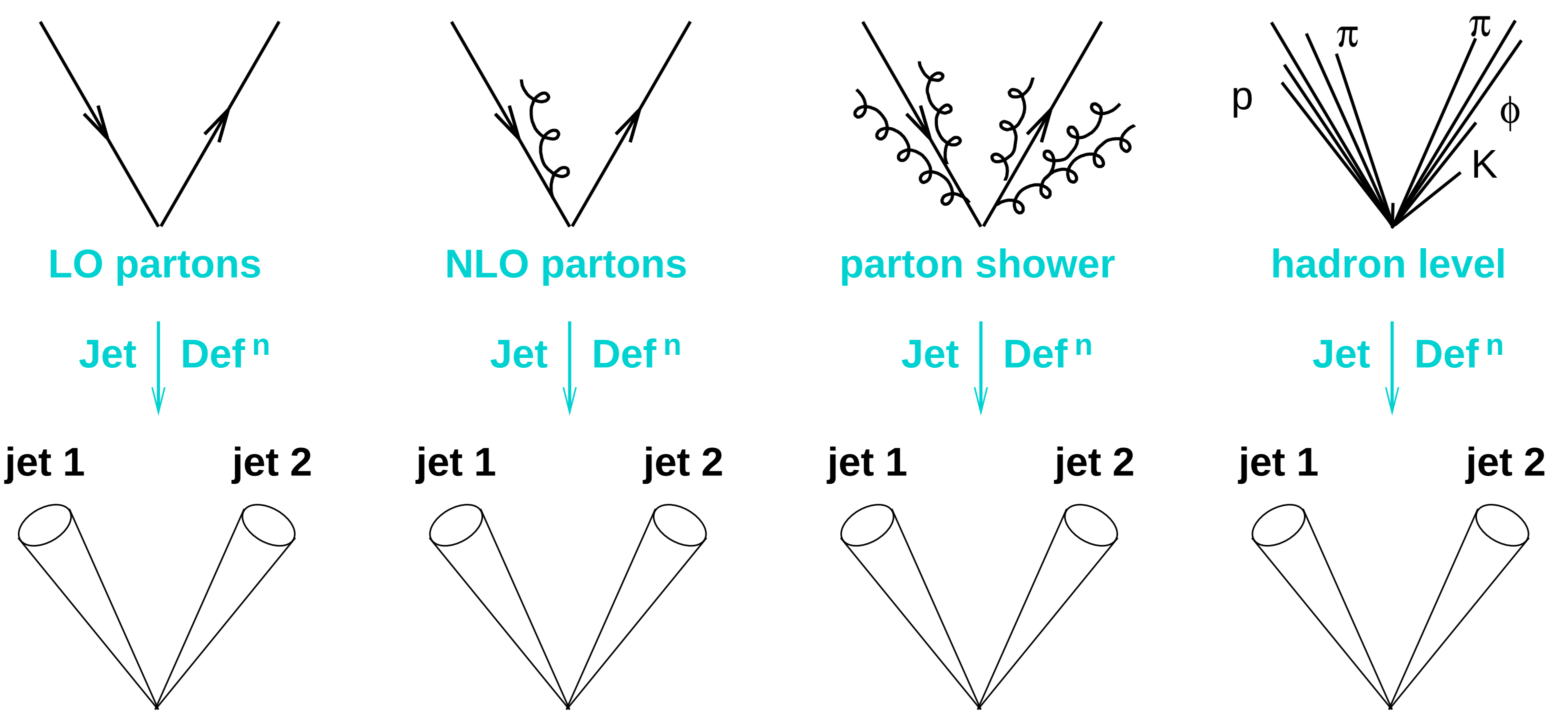
What is a “jet”?

jet definition(s)

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)



LO partons — **Jet ↓ Def^n** — **jet 1**, **jet 2**

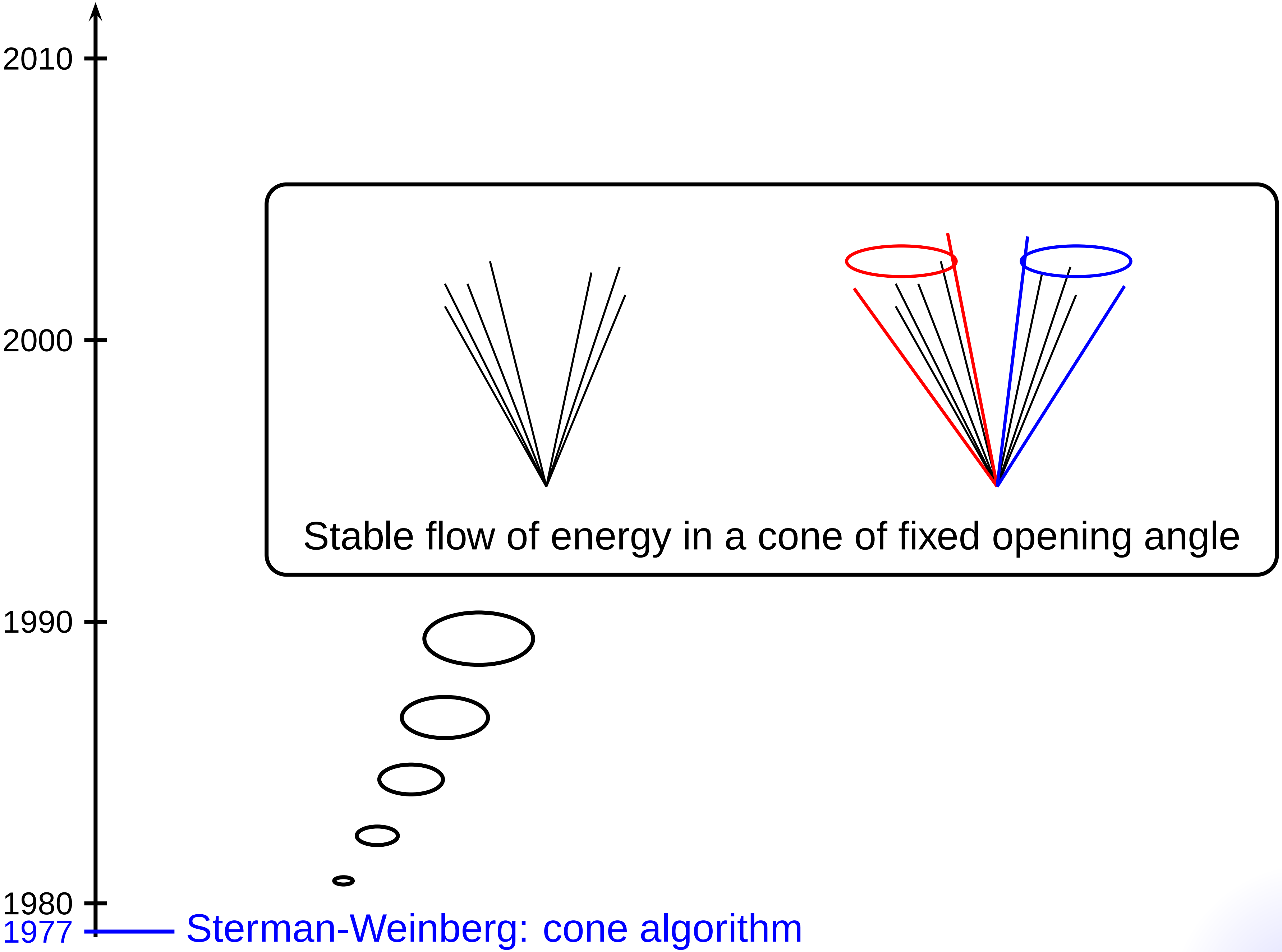
NLO partons — **Jet ↓ Def^n** — **jet 1**, **jet 2**

parton shower — **Jet ↓ Def^n** — **jet 1**, **jet 2**

hadron level — **Jet ↓ Def^n** — **jet 1**, **jet 2**

A brief/rough flight over the history of jets

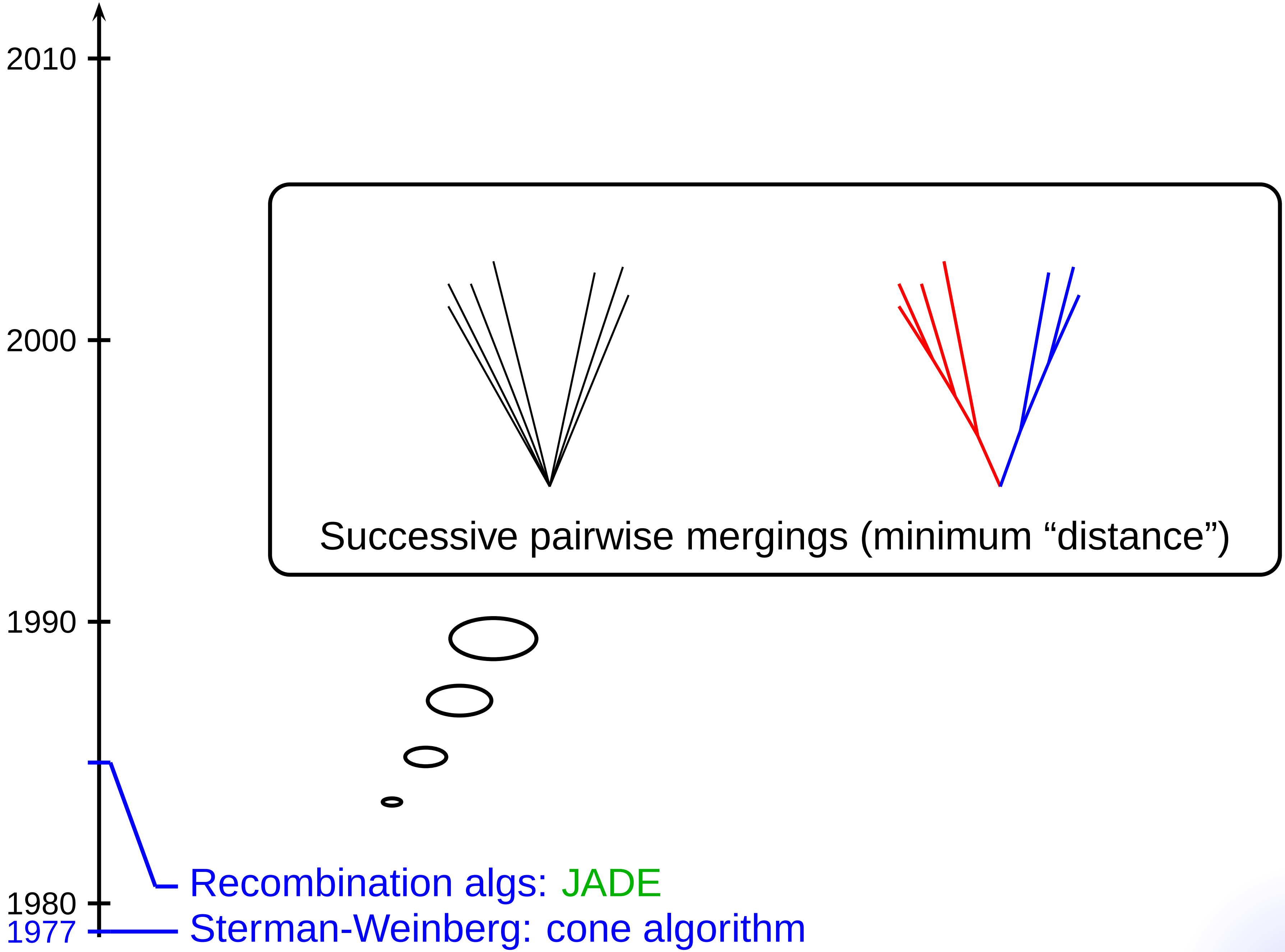
A brief/rough flight over the history of jets



Stable flow of energy in a cone of fixed opening angle

Sterman-Weinberg: cone algorithm

A brief/rough flight over the history of jets



Successive pairwise mergings (minimum “distance”)

Recombination algs: JADE

Sterman-Weinberg: cone algorithm

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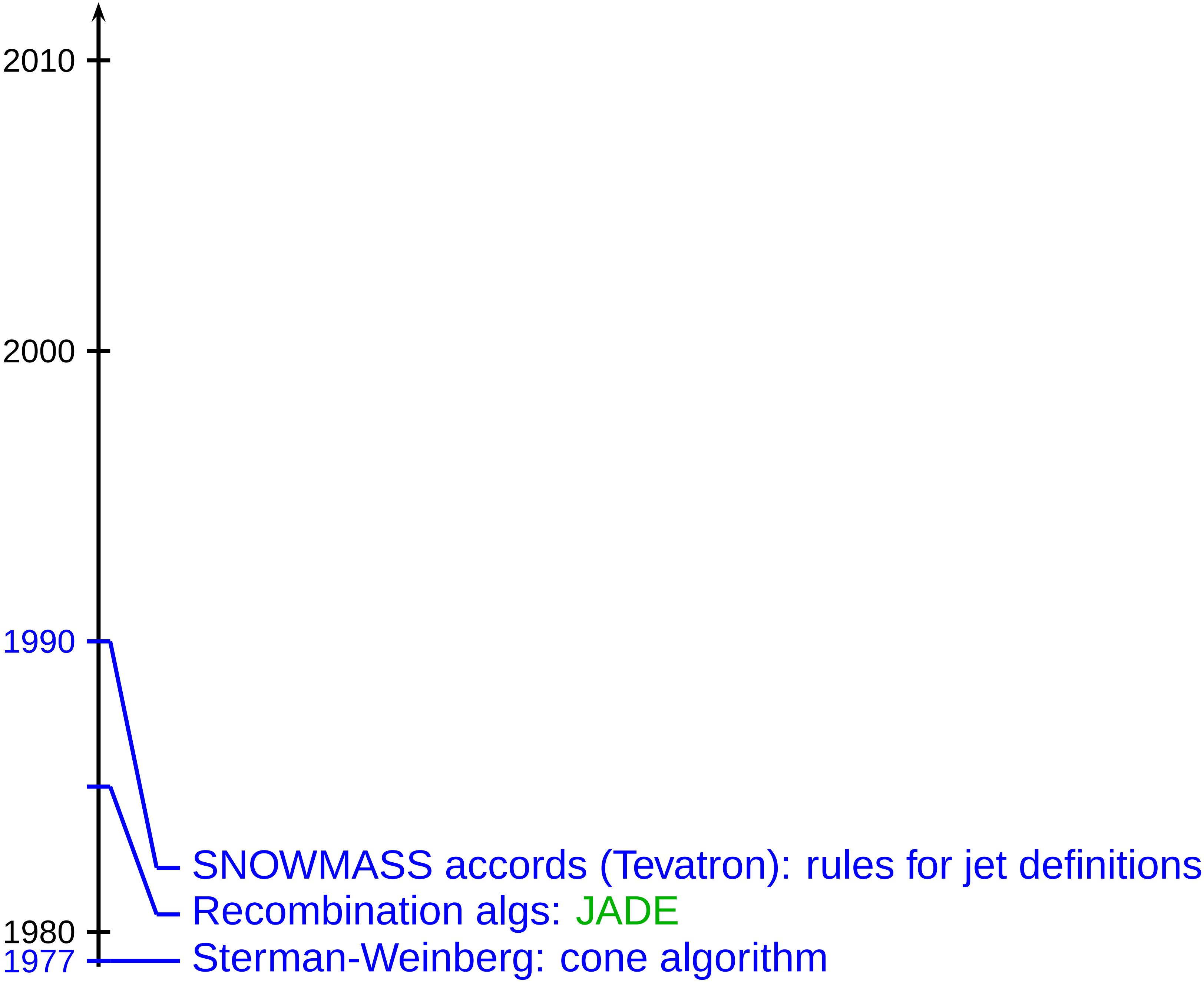
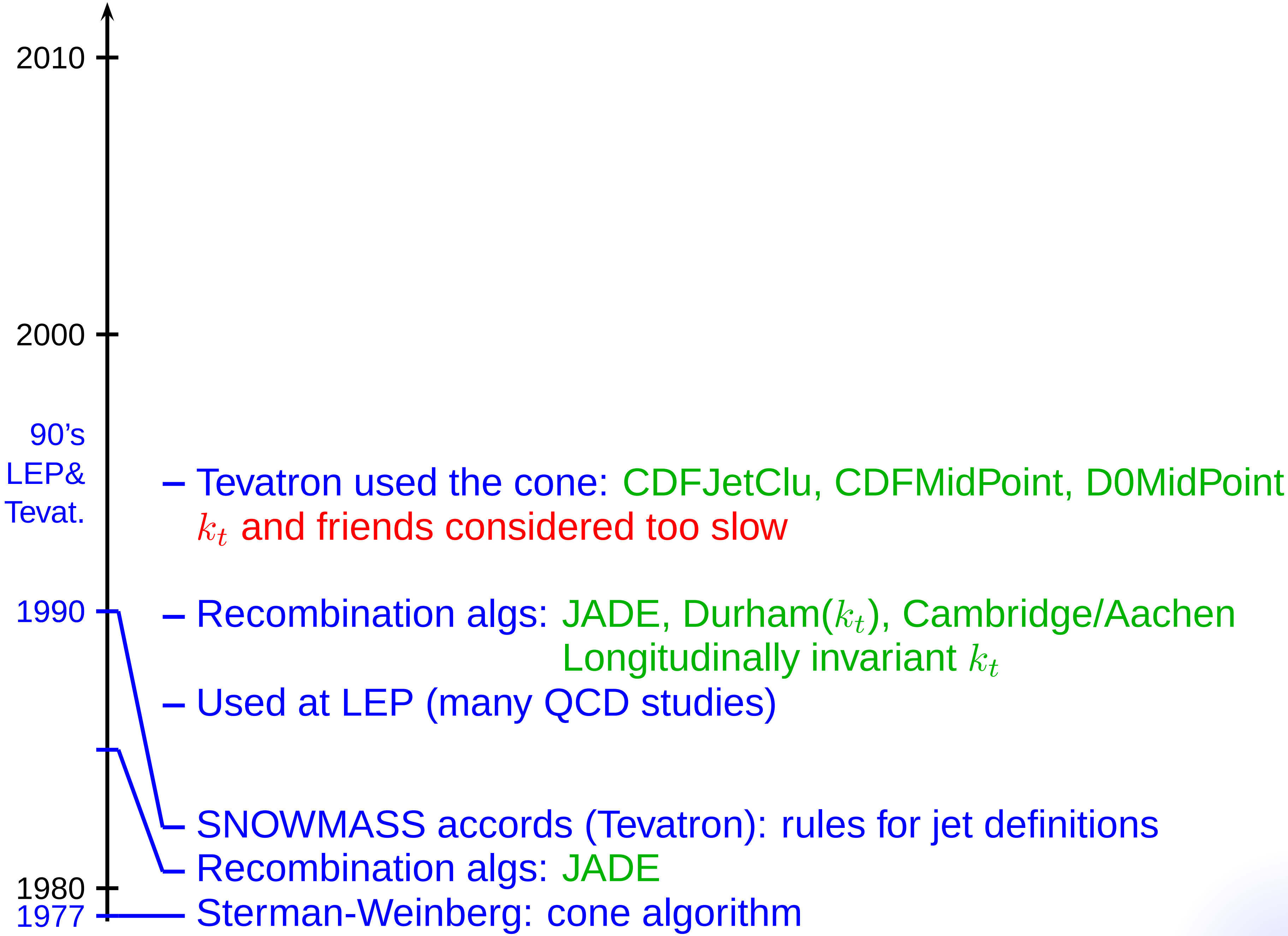


SNOWMASS accords (Tevatron): rules for jet definitions

Recombination algs: JADE

Sterman-Weinberg: cone algorithm

A brief/rough flight over the history of jets



- Tevatron used the cone: CDFJetClu, CDFMidPoint, D0MidPoint
  k_t and friends considered too slow

- Recombination algs: JADE, Durham(k_t), Cambridge/Aachen
  Longitudinally invariant k_t
- Used at LEP (many QCD studies)

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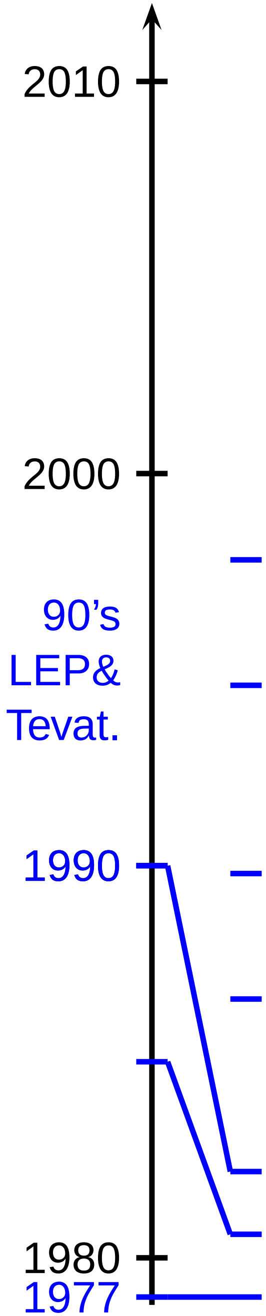

- Getting ready for the LHC: ATLASCone, CMSIterativeCone

- Tevatron used the cone: CDFJetClu, CDFMidPoint, D0MidPoint
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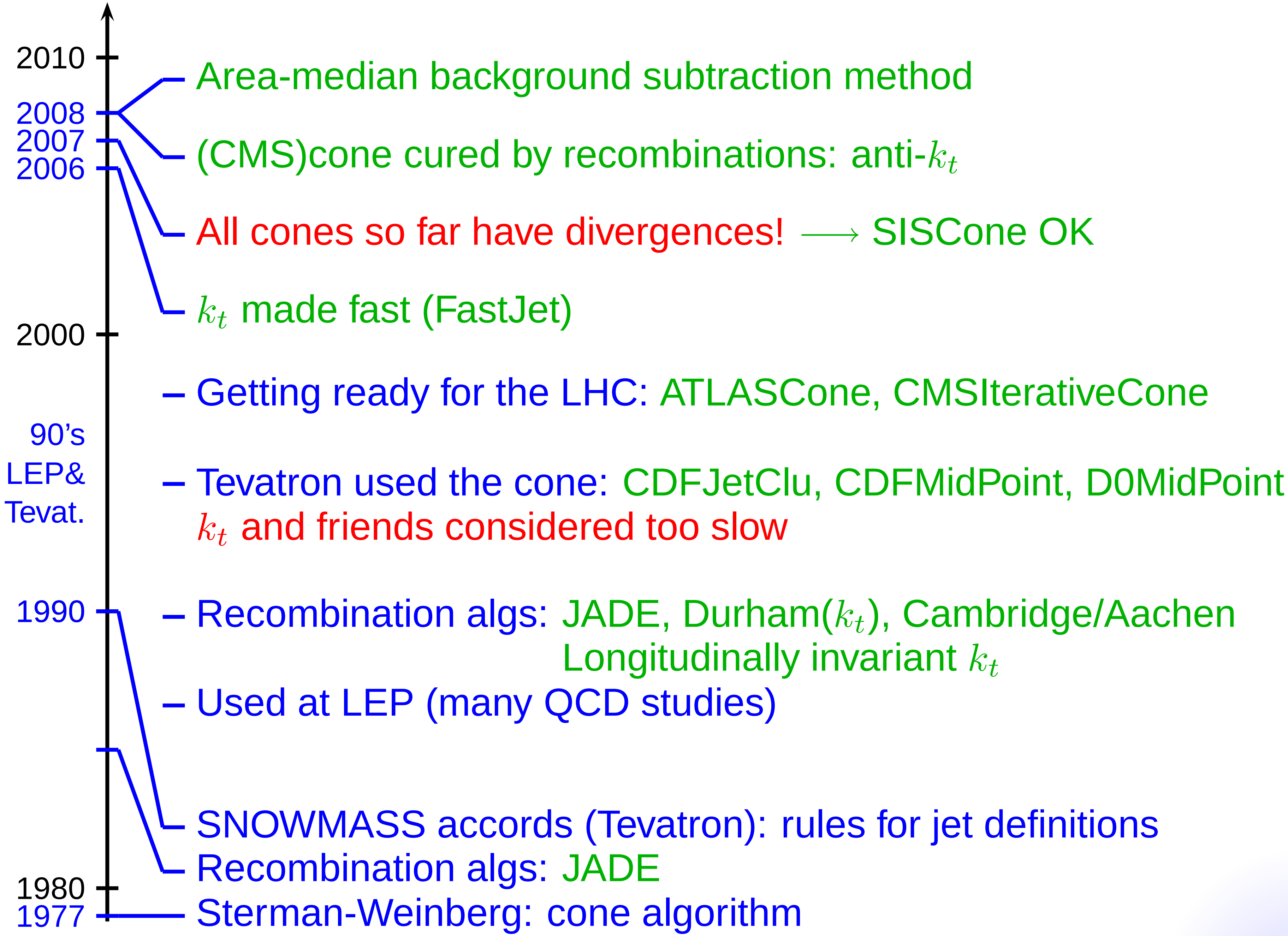

2010

2008 – Area-median background subtraction method

– (CMS)cone cured by recombinations: anti-k_t

2007 – All cones so far have divergences! $\longrightarrow$ SISCone OK

2006 – k_t made fast (FastJet)

2000

– Getting ready for the LHC: ATLASCone, CMSIterativeCone

90's
LEP&
Tevat.

– Tevatron used the cone: CDFJetClu, CDFMidPoint, D0MidPoint
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1990

– Recombination algs: JADE, Durham(k_t), Cambridge/Aachen
Longitudinally invariant k_t

– Used at LEP (many QCD studies)

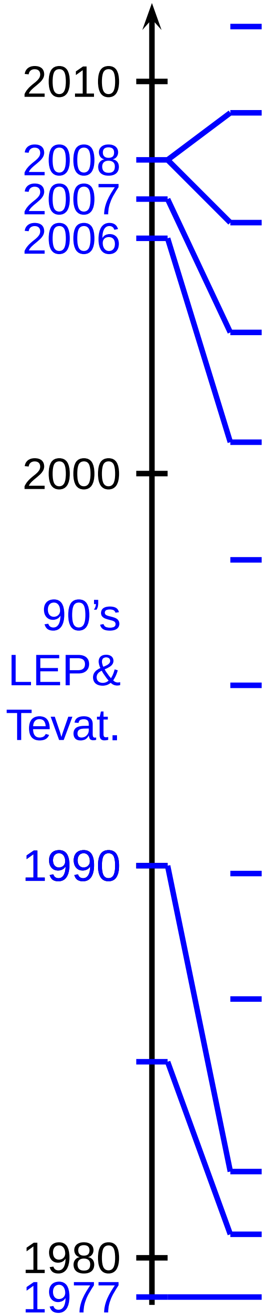
– SNOWMASS accords (Tevatron): rules for jet definitions

– Recombination algs: JADE

1980

1977 – Sterman-Weinberg: cone algorithm

A brief/rough flight over the history of jets



- The LHC uses anti-k_t, FastJet and area-median subtraction
- Area-median background subtraction method
  [M.Cacciari,G.Salam, 0707.1378; M.Cacciari,G.Salam,GS, 0802.1188]
- (CMS)cone cured by recombinations: anti-k_t
  [M.Cacciari,G.Salam,GS, 0802.1189]
- All cones so far have divergences! $\longrightarrow$ SISCone OK
  [G.Salam,GS, 0704.0292]
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  [M.Cacciari,G.Salam, 0512210; M.Cacciari,G.Salam,GS,1111.6097]
- Getting ready for the LHC: ATLASCone, CMSIterativeCone
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- Sterman-Weinberg: cone algorithm

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

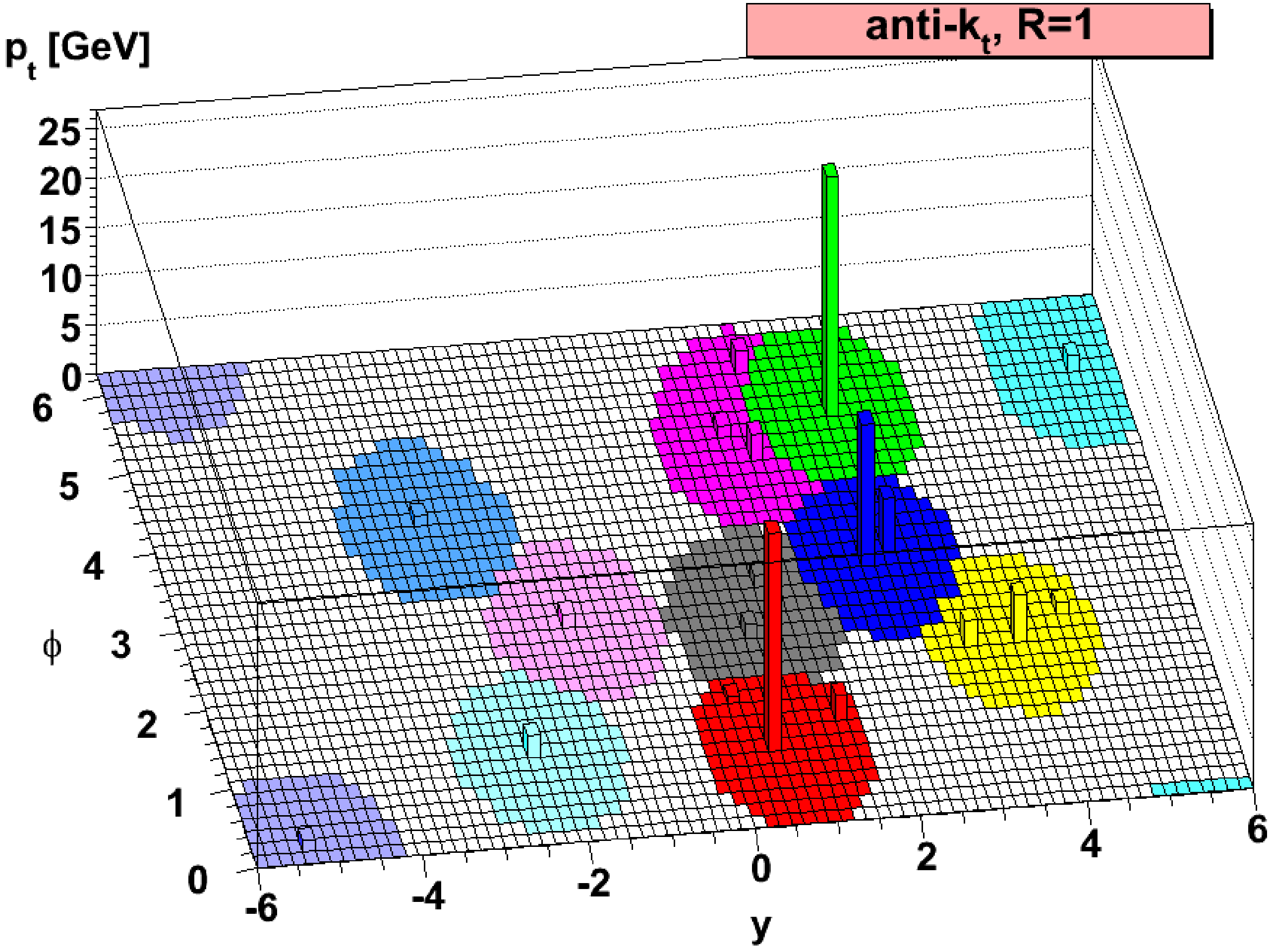
$$d_{ij} = \min(k_{t,i}^{-2}, k_{t,j}^{-2})(\Delta y_{ij}^2 + \Delta\phi_{ij}^2), \qquad d_{iB} = k_{t,i}^{-2} R^2$$

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

- R is a size parameter (*e.g.* CMS: 0.5,0.7, ATLAS: 0.4,0.6)

The anti-k_t jets

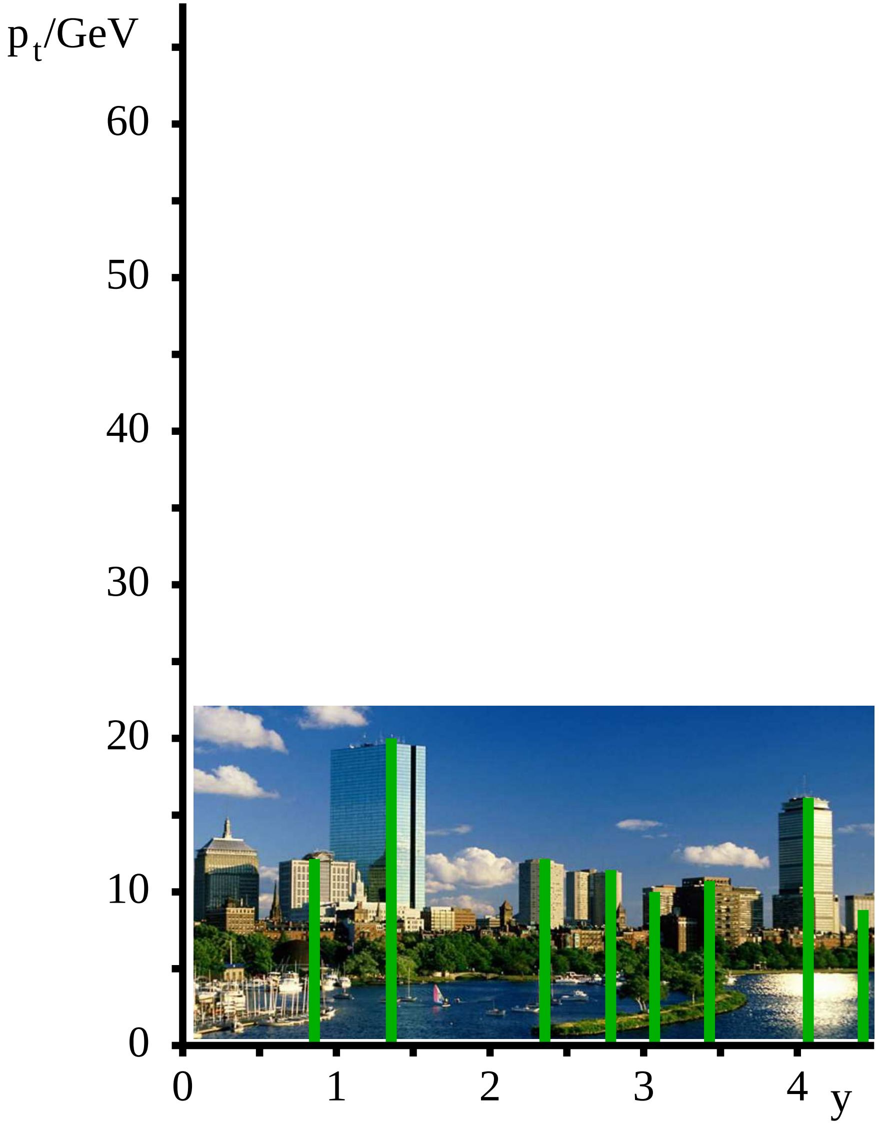
Main property: hard jets are circular



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

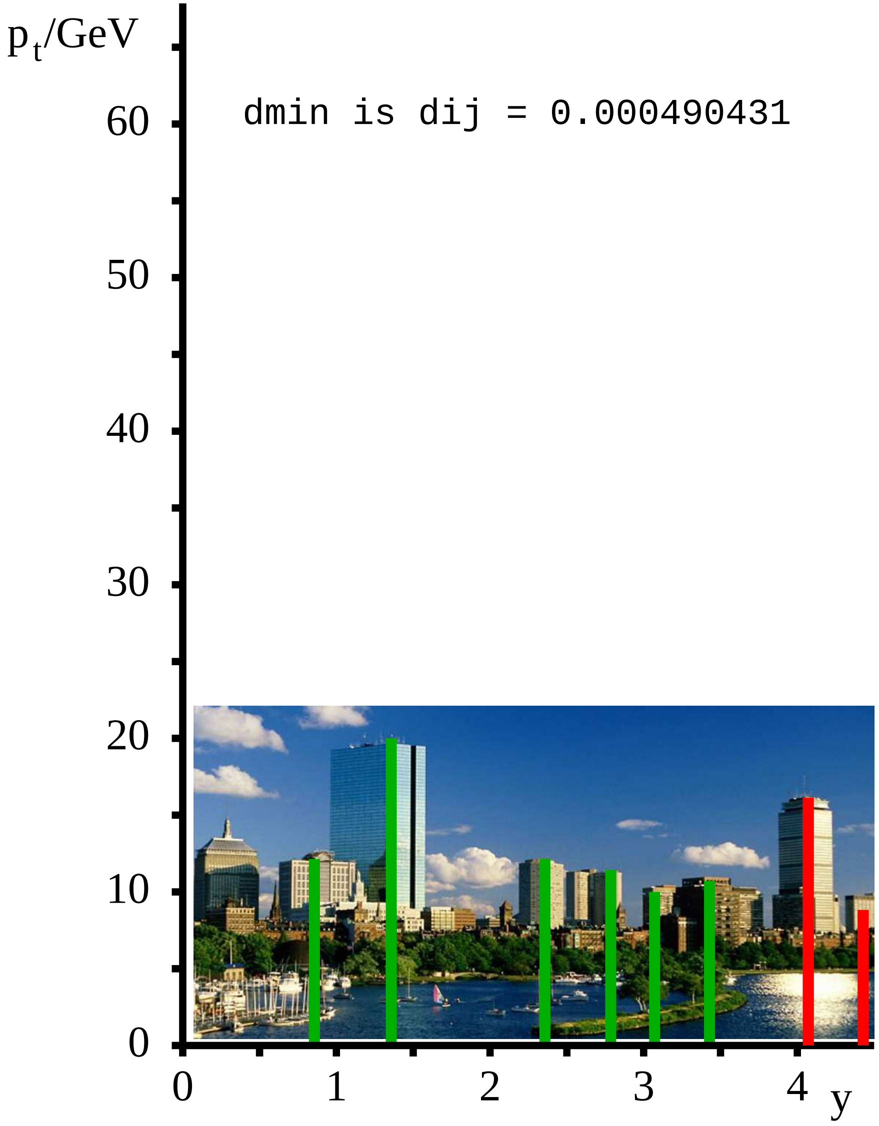
Start with your favourite picture

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



Start with your favourite ~~picture~~ event

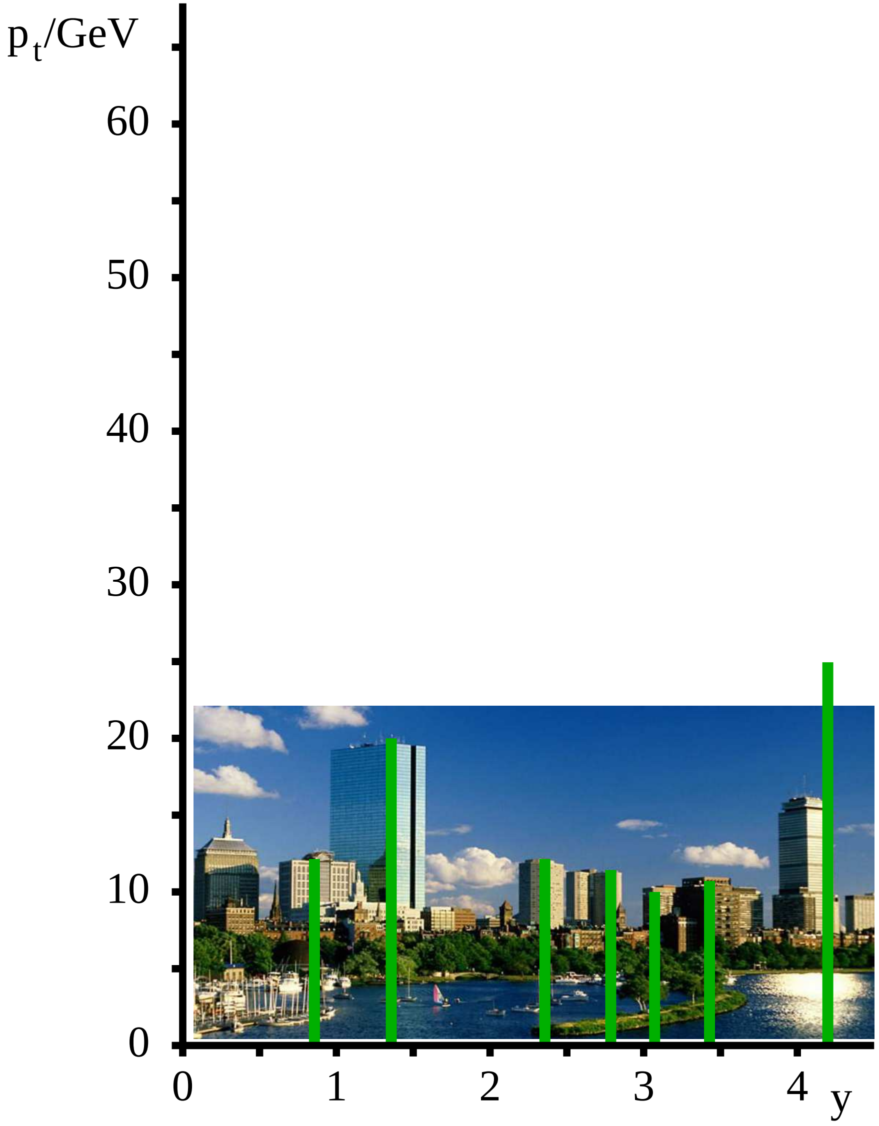
Clustering in action: anti-k_t ($R = 0.7$)



```
dmin is dij = 0.000490431
```

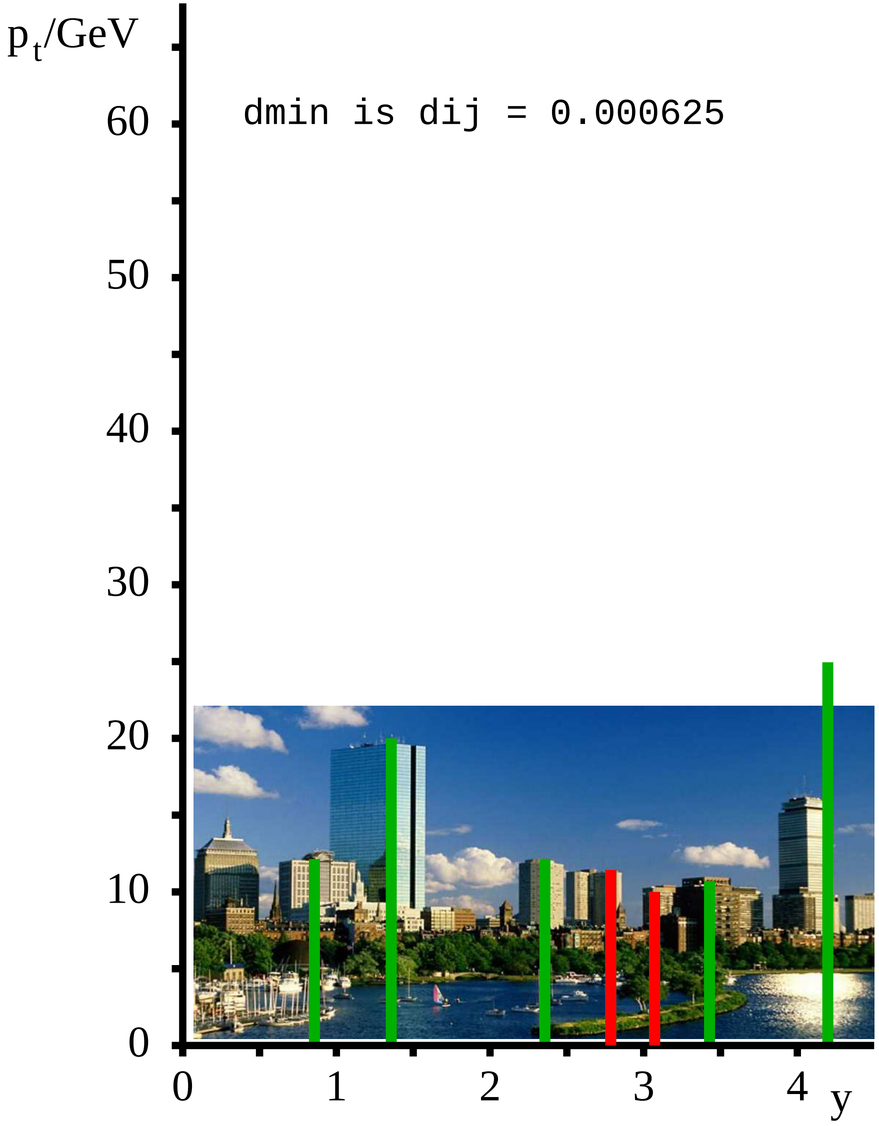
min is $d_{ij} = 4.9\,10^{-4}$

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



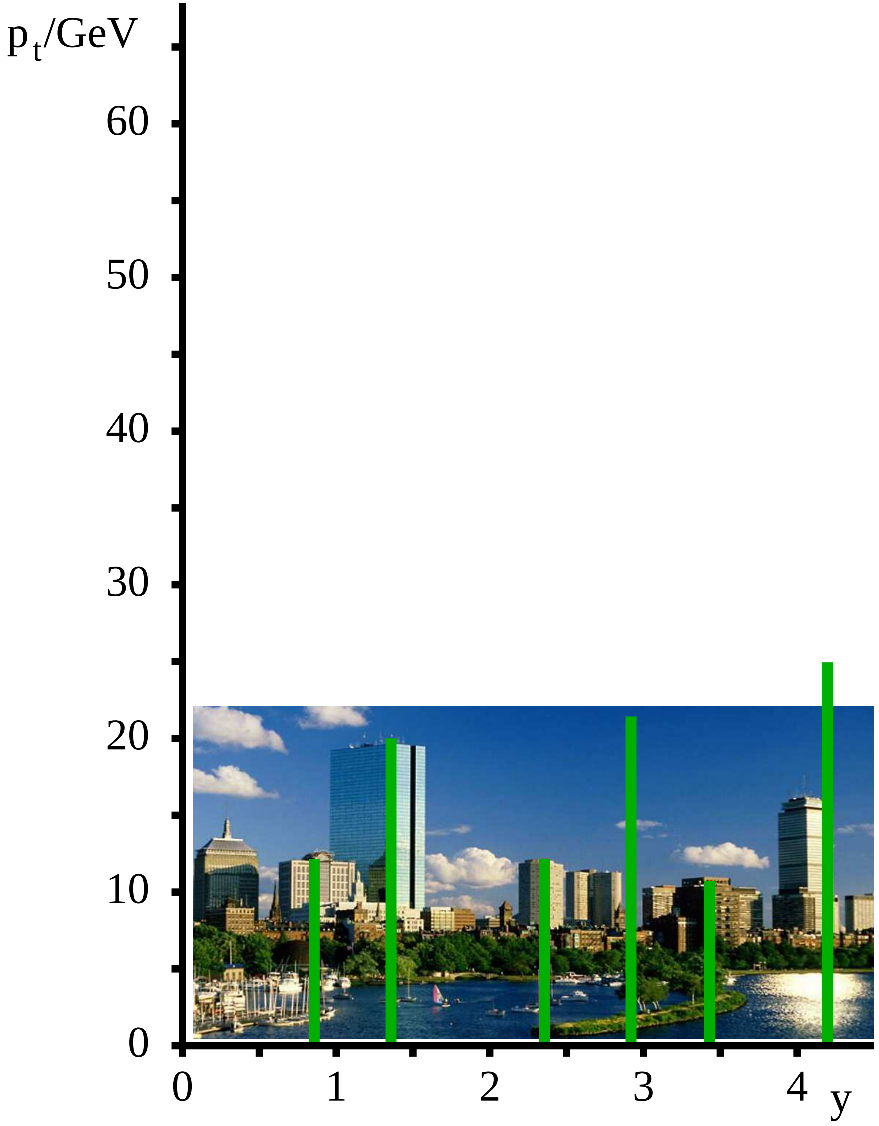
recombine them

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



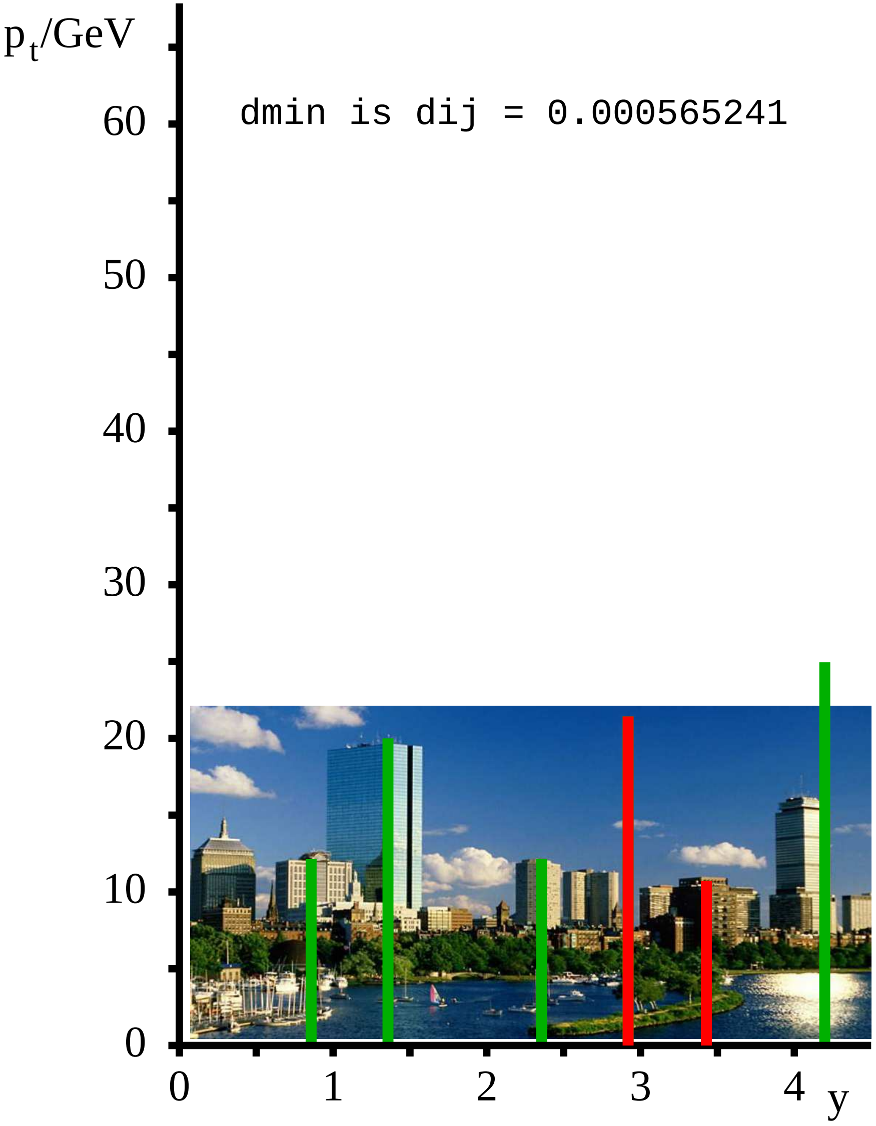
min is $d_{ij} = 6.3\,10^{-4}$

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



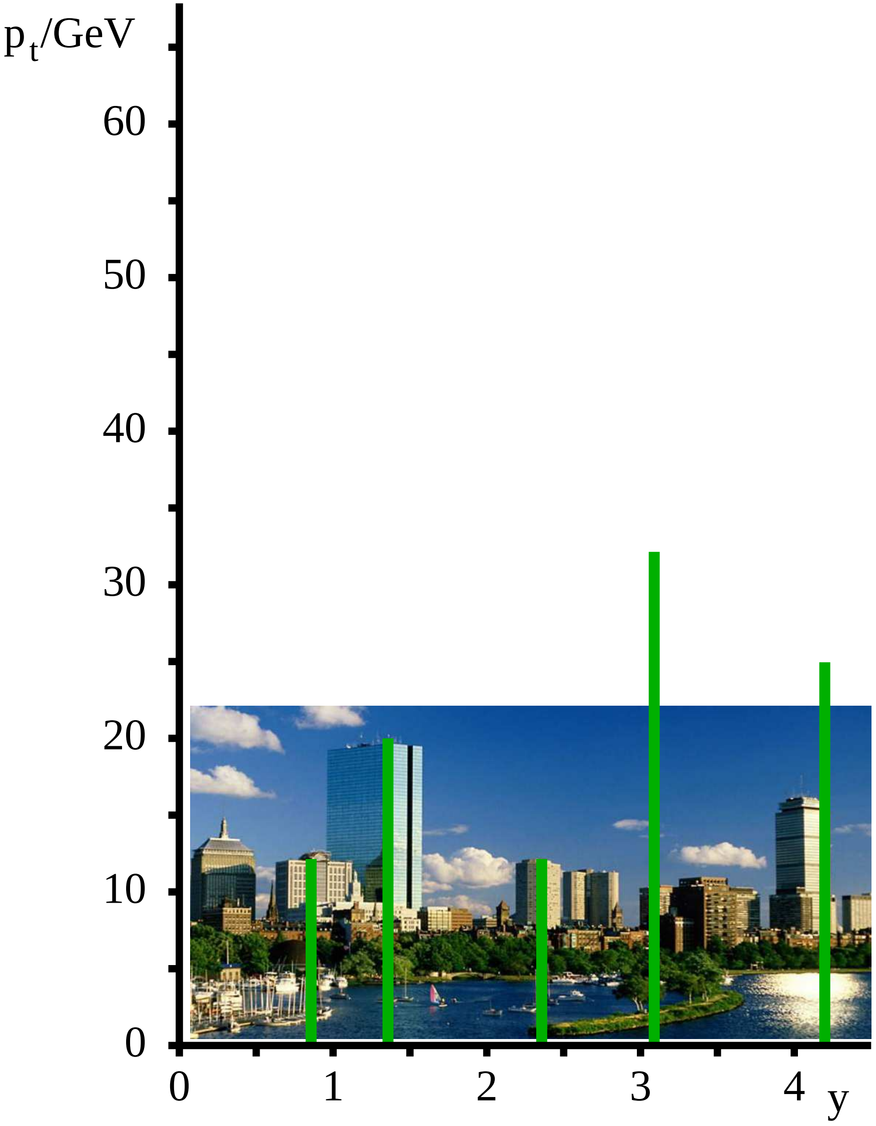
recombine them

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



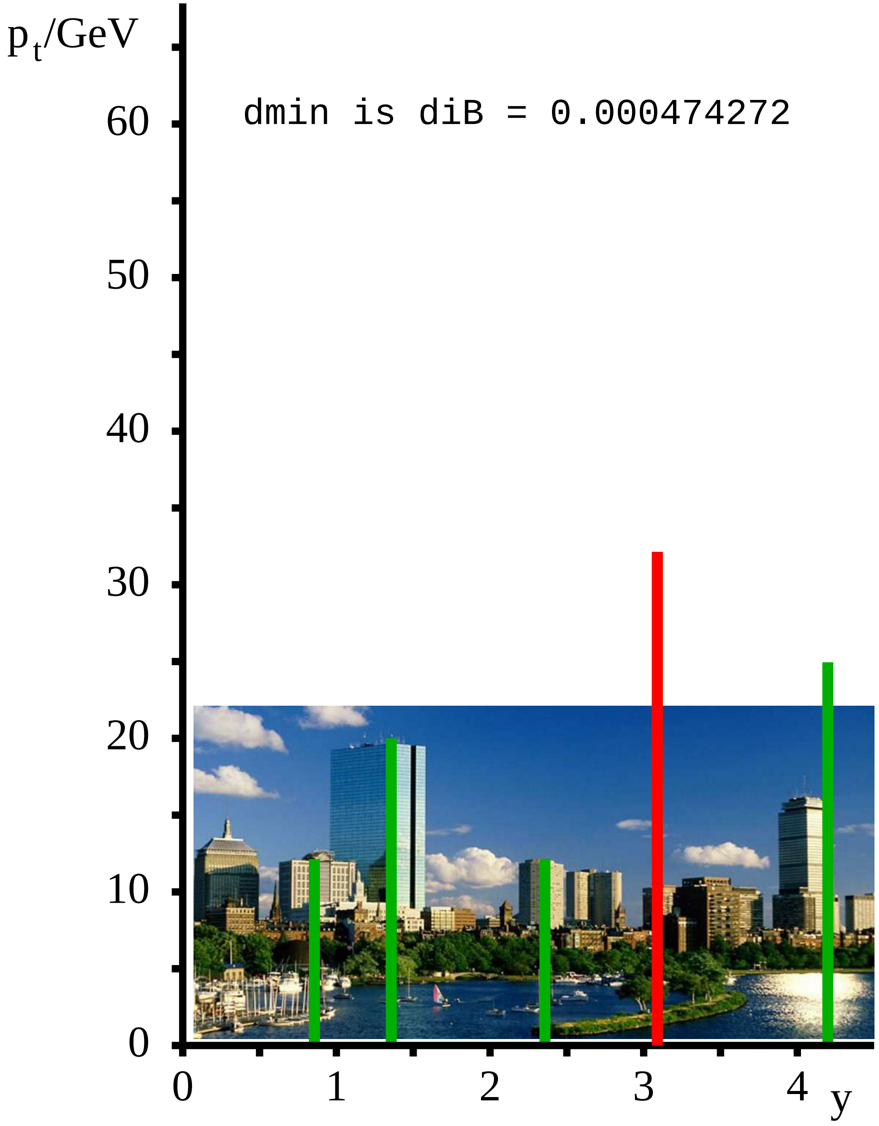
min is $d_{ij} = 5.7\,10^{-4}$

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



recombine them

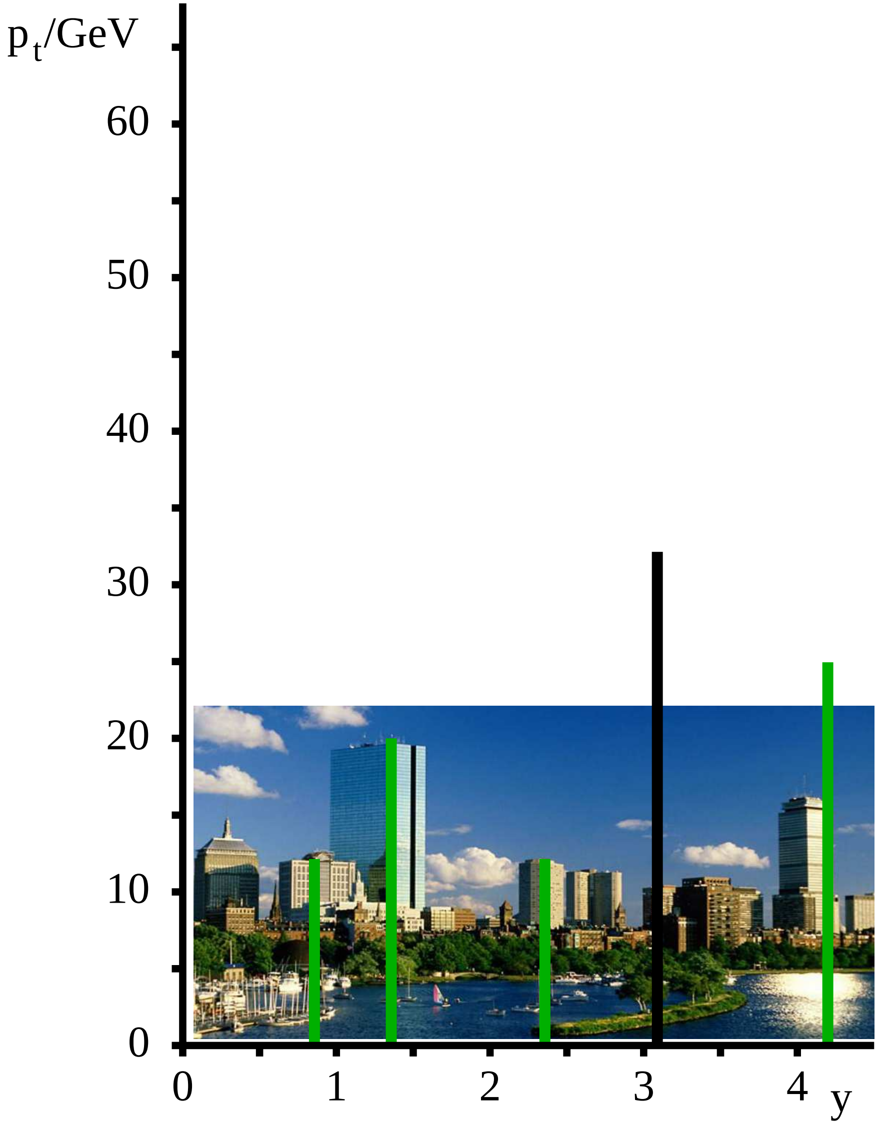
Clustering in action: anti-k_t ($R = 0.7$)



```
dmin is diB = 0.000474272
```

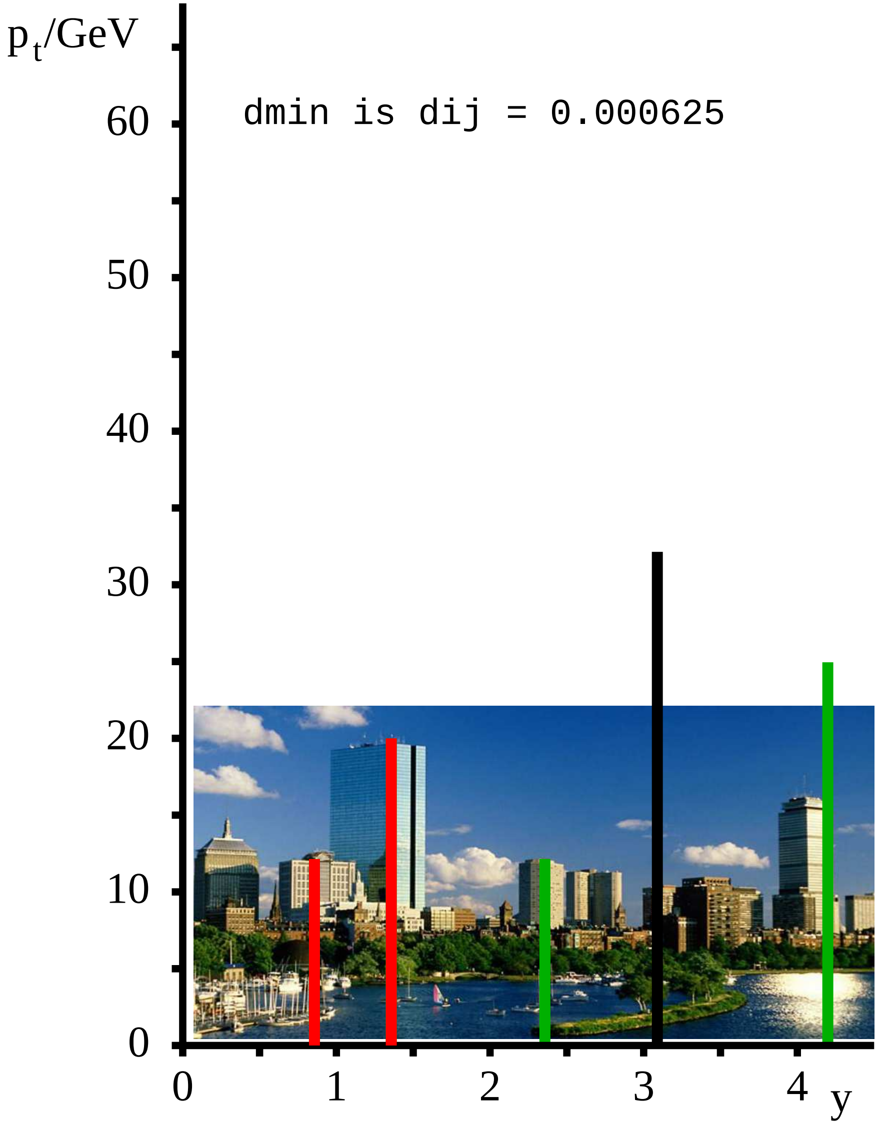
min is $d_{iB} = 4.7\,10^{-4}$

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



declare as a jet

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



min is $d_{ij} = 6.3\,10^{-4}$

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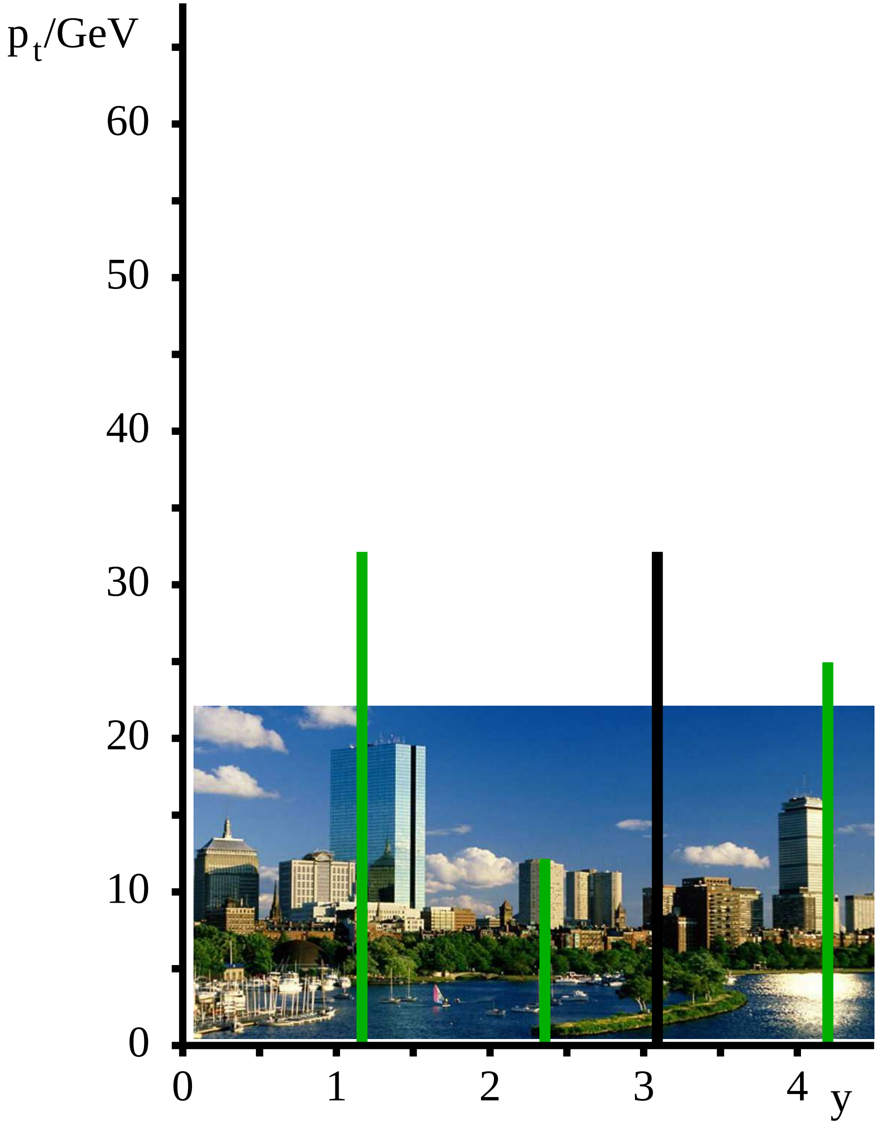

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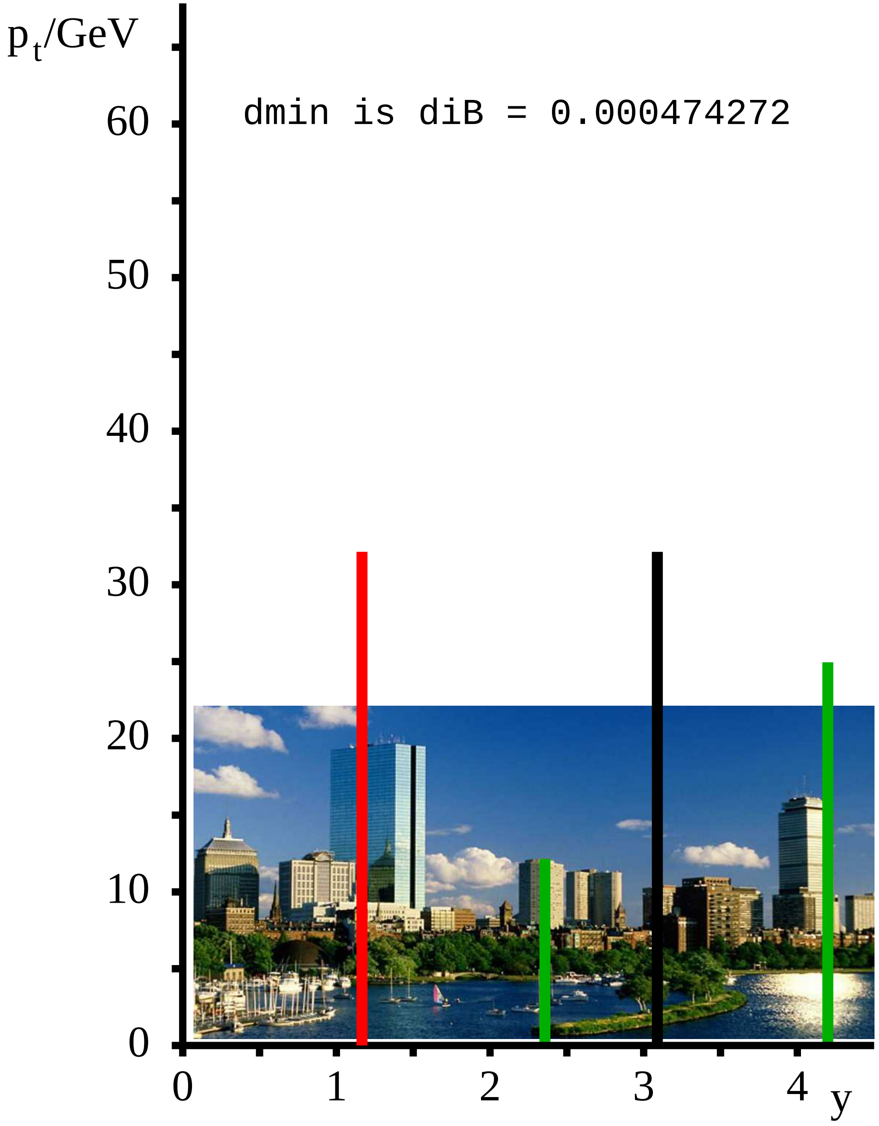

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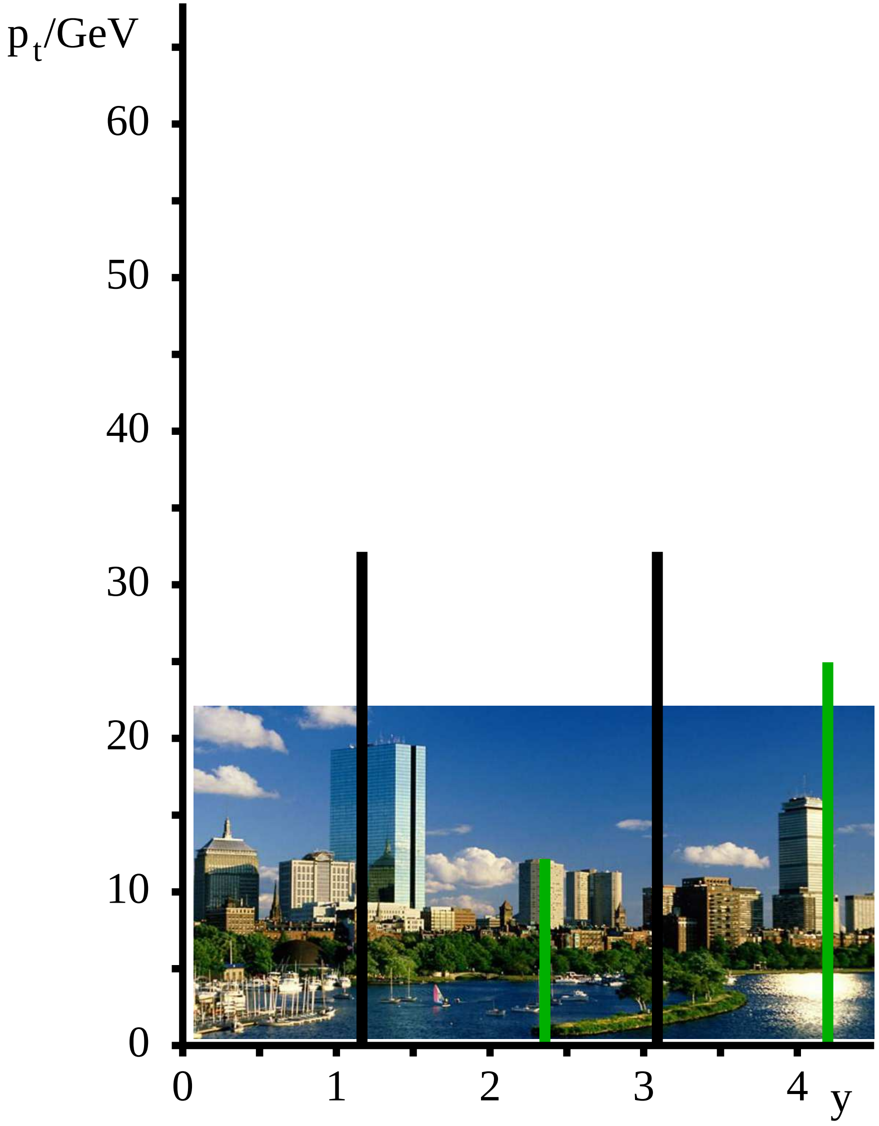
Clustering in action: anti-k_t ($R = 0.7$)



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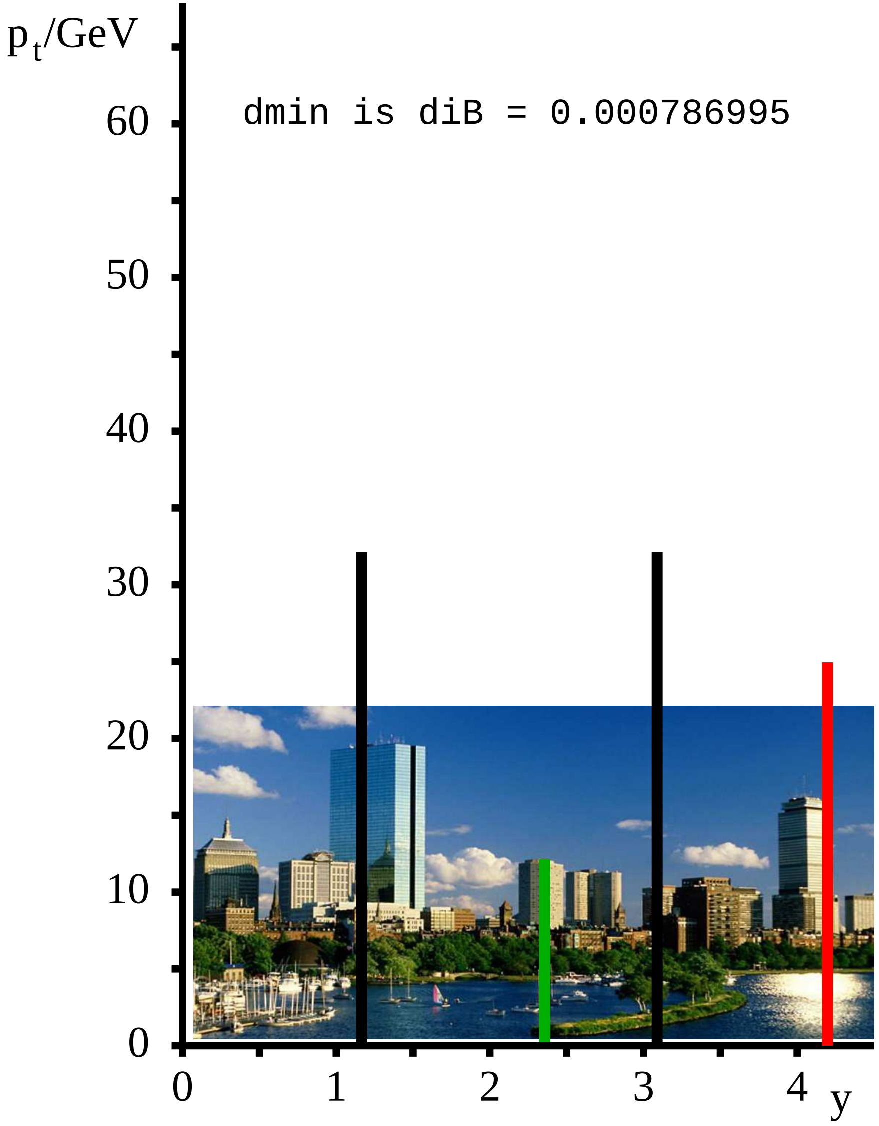
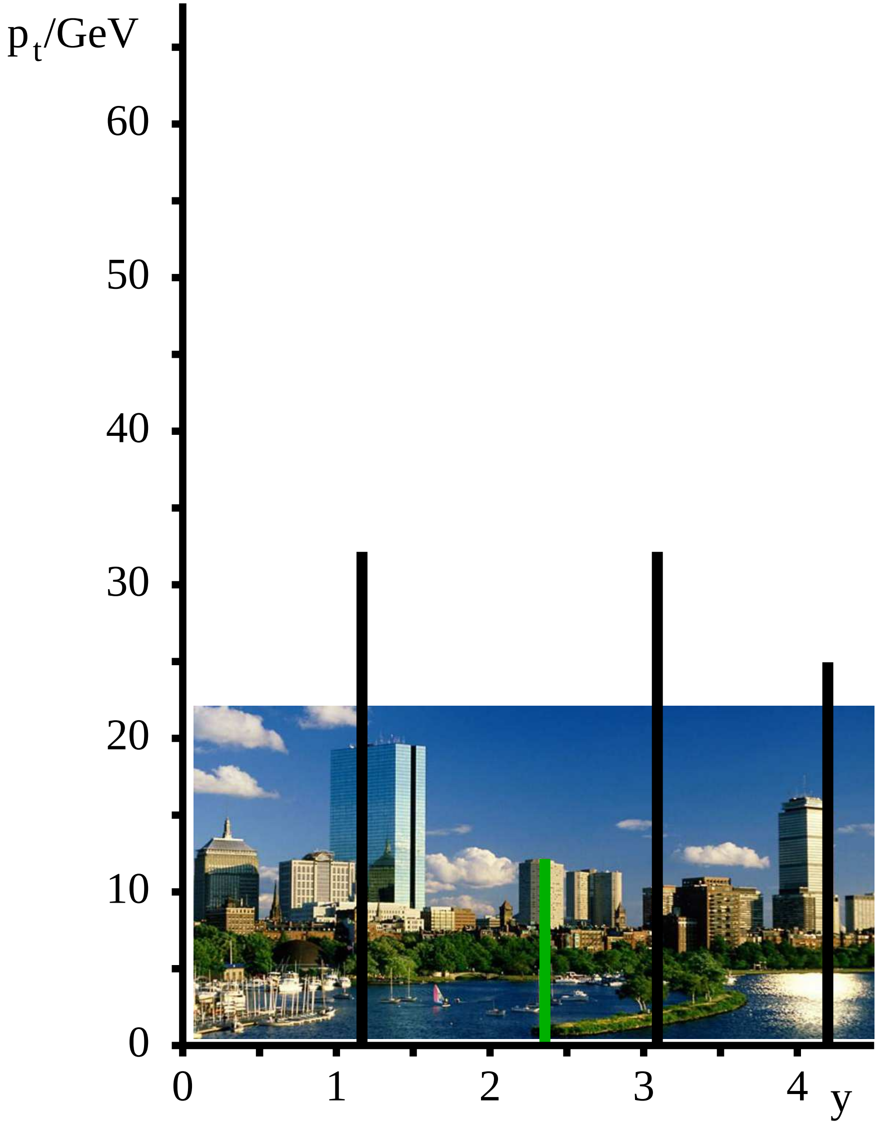


min is $d_{iB} = 7.9\,10^{-4}$

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



declare as a jet

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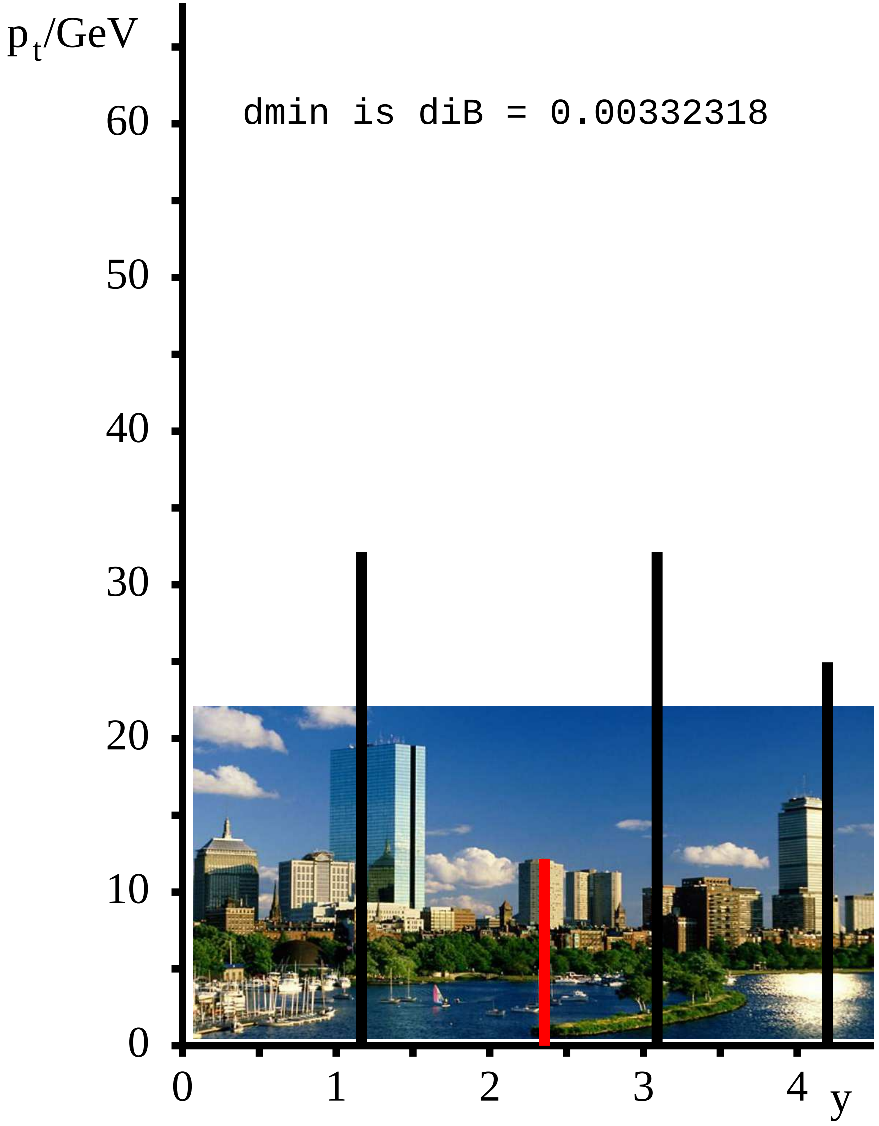
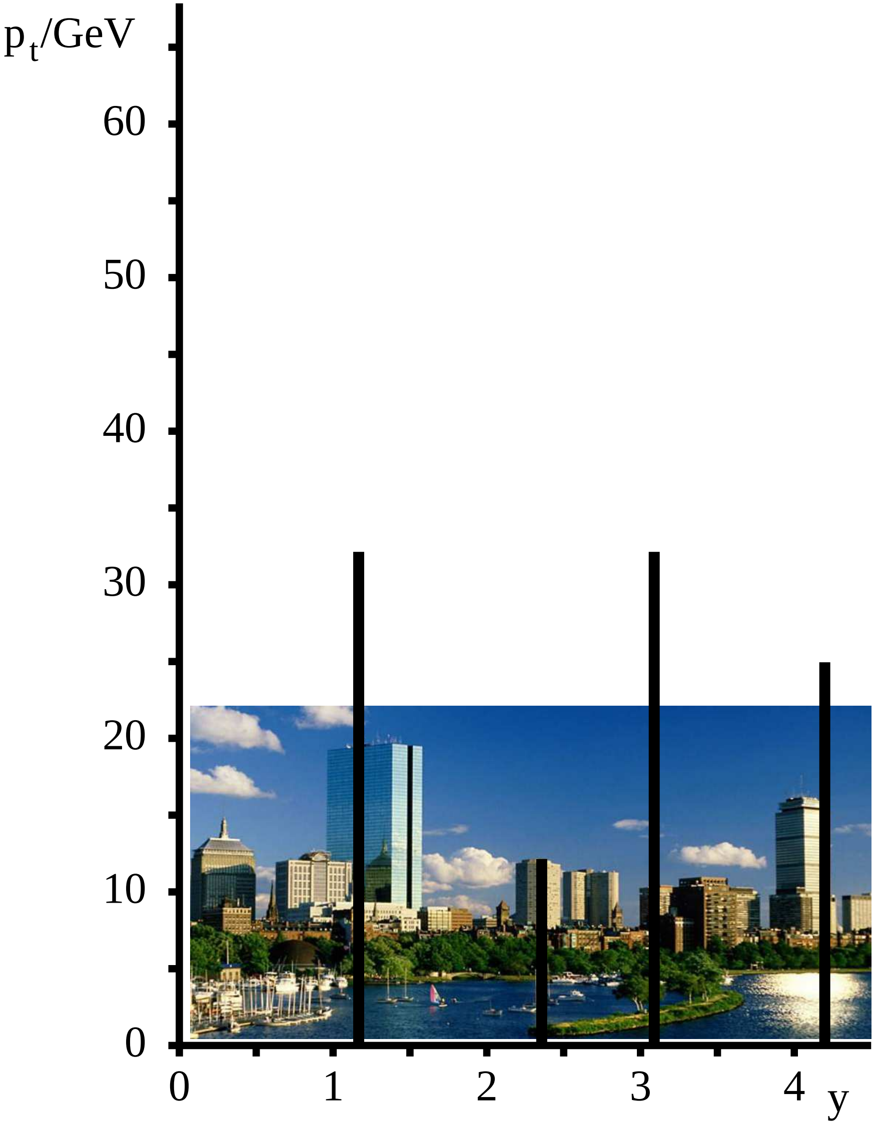


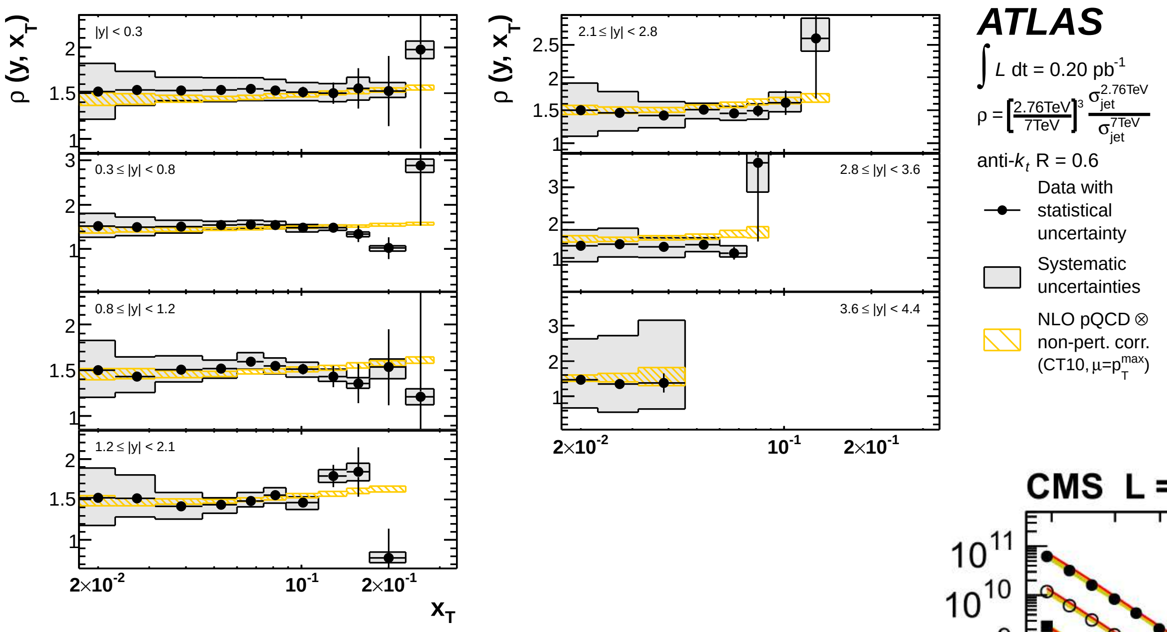
min is $d_{iB} = 3.3\,10^{-3}$

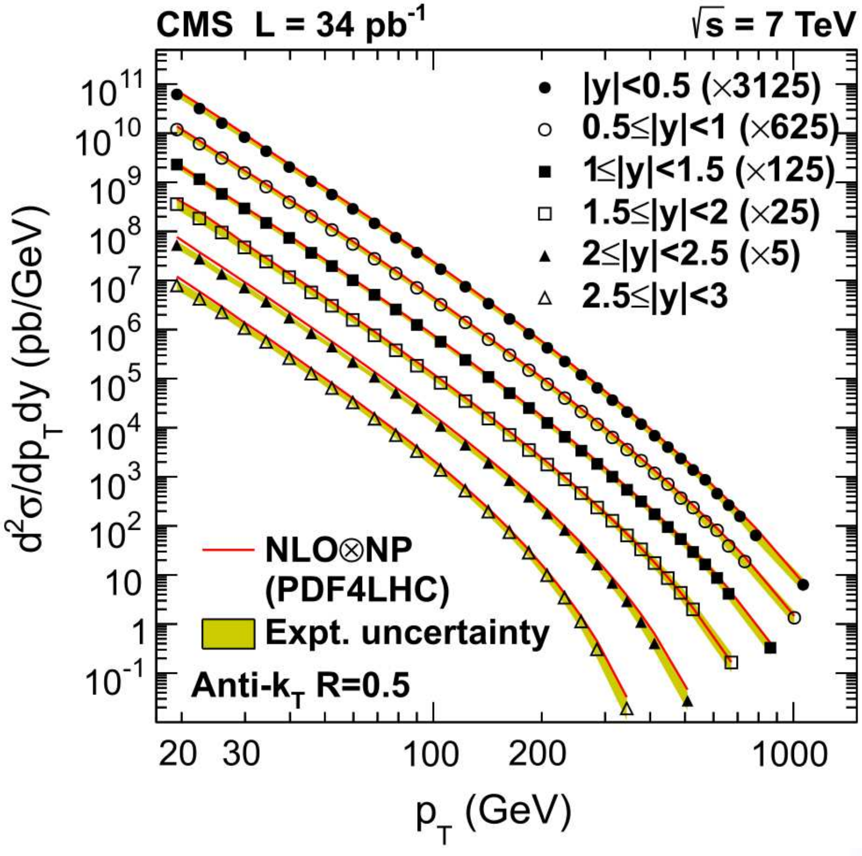
Clustering in action: anti-k_t ($R = 0.7$)



declare as a jet

Examples


ATLAS
$\int L\,dt = 0.20\ \mathrm{pb}^{-1}$
$\rho = \left[\frac{2.76\mathrm{TeV}}{7\mathrm{TeV}}\right]^3 \frac{\sigma_{\mathrm{jet}}^{2.76\mathrm{TeV}}}{\sigma_{\mathrm{jet}}^{7\mathrm{TeV}}}$
anti-k_t R = 0.6
Data with statistical uncertainty
Systematic uncertainties
NLO pQCD ⊗ non-pert. corr. (CT10, $\mu = p_T^{\max}$)
|y| < 0.3
0.3 ≤ |y| < 0.8
0.8 ≤ |y| < 1.2
1.2 ≤ |y| < 2.1
2.1 ≤ |y| < 2.8
2.8 ≤ |y| < 3.6
3.6 ≤ |y| < 4.4
$\rho\ (y, x_T)$
x_T
2×10^{-2}
10^{-1}
2×10^{-1}
1
1.5
2
2.5
3

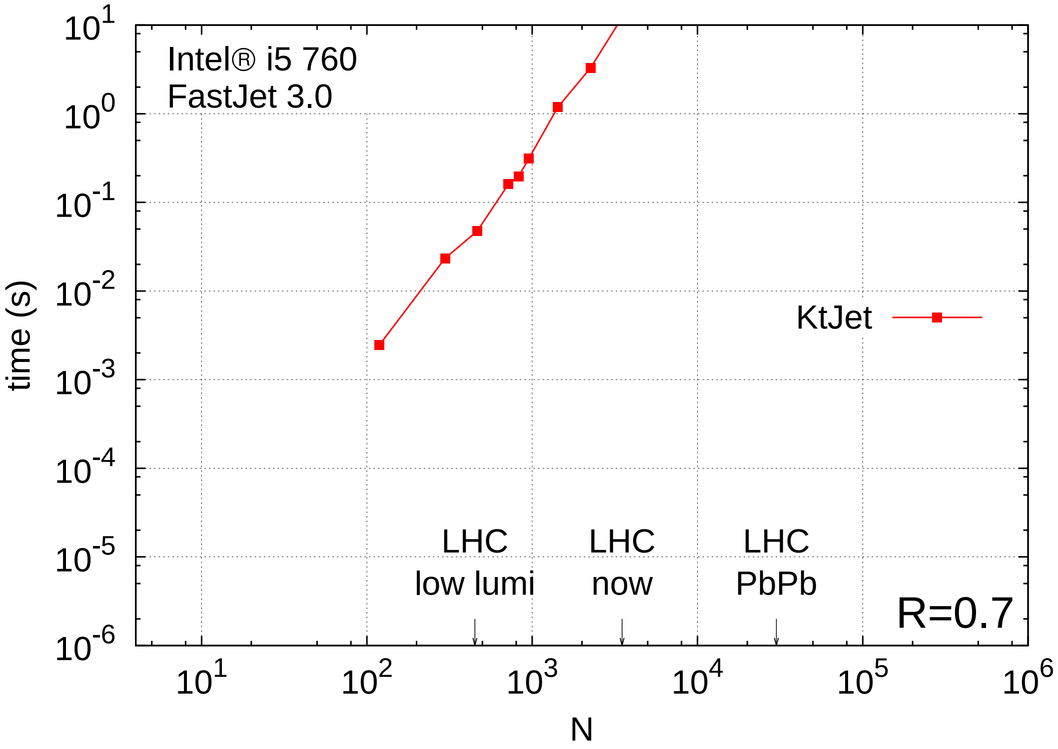

CMS L = 34 pb^{-1}
$\sqrt{s}$ = 7 TeV
● |y|<0.5 (×3125)
○ 0.5≤|y|<1 (×625)
■ 1≤|y|<1.5 (×125)
□ 1.5≤|y|<2 (×25)
▲ 2≤|y|<2.5 (×5)
△ 2.5≤|y|<3
NLO⊗NP (PDF4LHC)
Expt. uncertainty
Anti-k$_T$ R=0.5
$d^2\sigma/dp_T dy$ (pb/GeV)
p_T (GeV)
20
30
100
200
1000
10^{-1}
1
10
10^{2}
10^{3}
10^{4}
10^{5}
10^{6}
10^{7}
10^{8}
10^{9}
10^{10}
10^{11}

Implementation

FastJet (1/2)

[M.Cacciari, G.Salam, 2005]

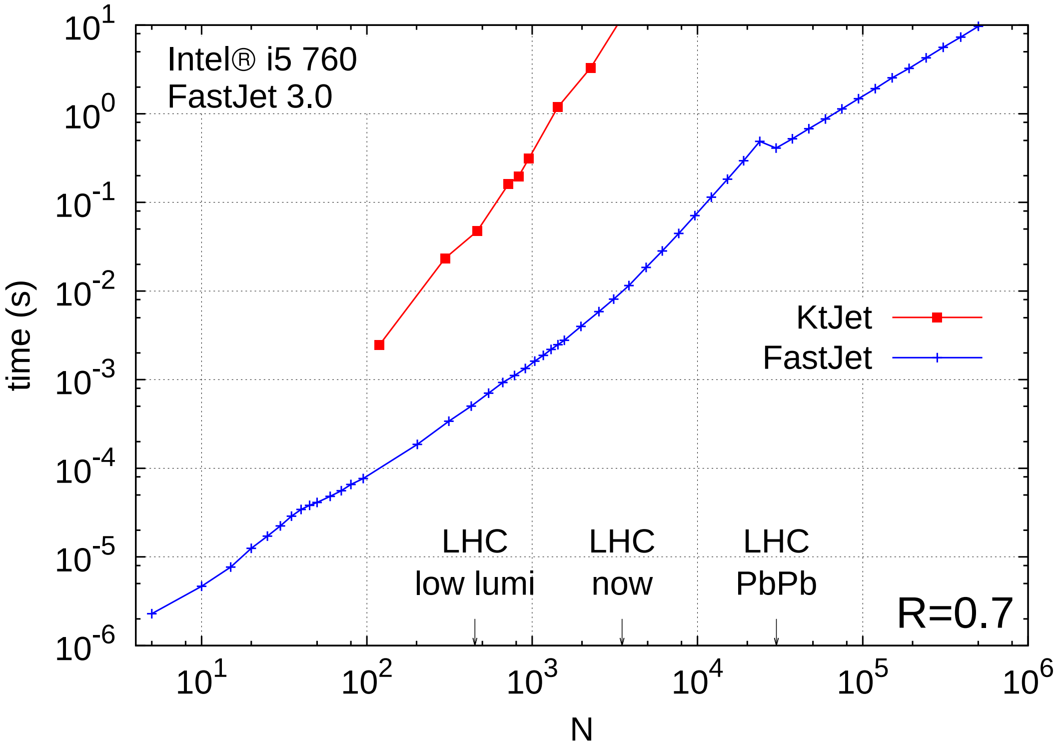
- Tevatron era: k_t too slow: $\mathcal{O}(N^3)$ for N particles



FastJet (1/2)

[M.Cacciari, G.Salam, 2005]

- 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



FastJet (2/2)

[M.Cacciari, G.Salam, GS, 2007-2013]

- 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`

- Standard interface for jet physics
  for both theorists and experimentalists

FastJet contrib (New: Feb 2013)

- fastjet.fr
- fastjet-contrib
- contrib svn

FastJet Contrib

The fastjet-contrib space is intended to provide a common location for access to 3rd party extensions of FastJet.

Download the current version: fjcontrib-1.003 (released 1 May 2013), which contains these contributions. Changes relative to earlier versions are briefly described in the NEWS file.

Package	Version	Information
GenericSubtractor	1.1.0	README NEWS
JetFFMoments	1.0.0	README NEWS
VariableR	1.0.1	README NEWS
Nsubjettiness	1.0.2	README NEWS
EnergyCorrelator	1.0.1	README NEWS

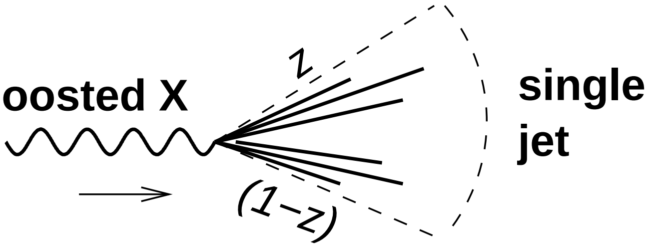
- a quick and uniform access to 3rd-party code
- contributors are welcome (please contact us)

Jet substructure
Boosted object taggers

Fat jets

Problem:

boosted heavy object ⇒ decays in a single jet



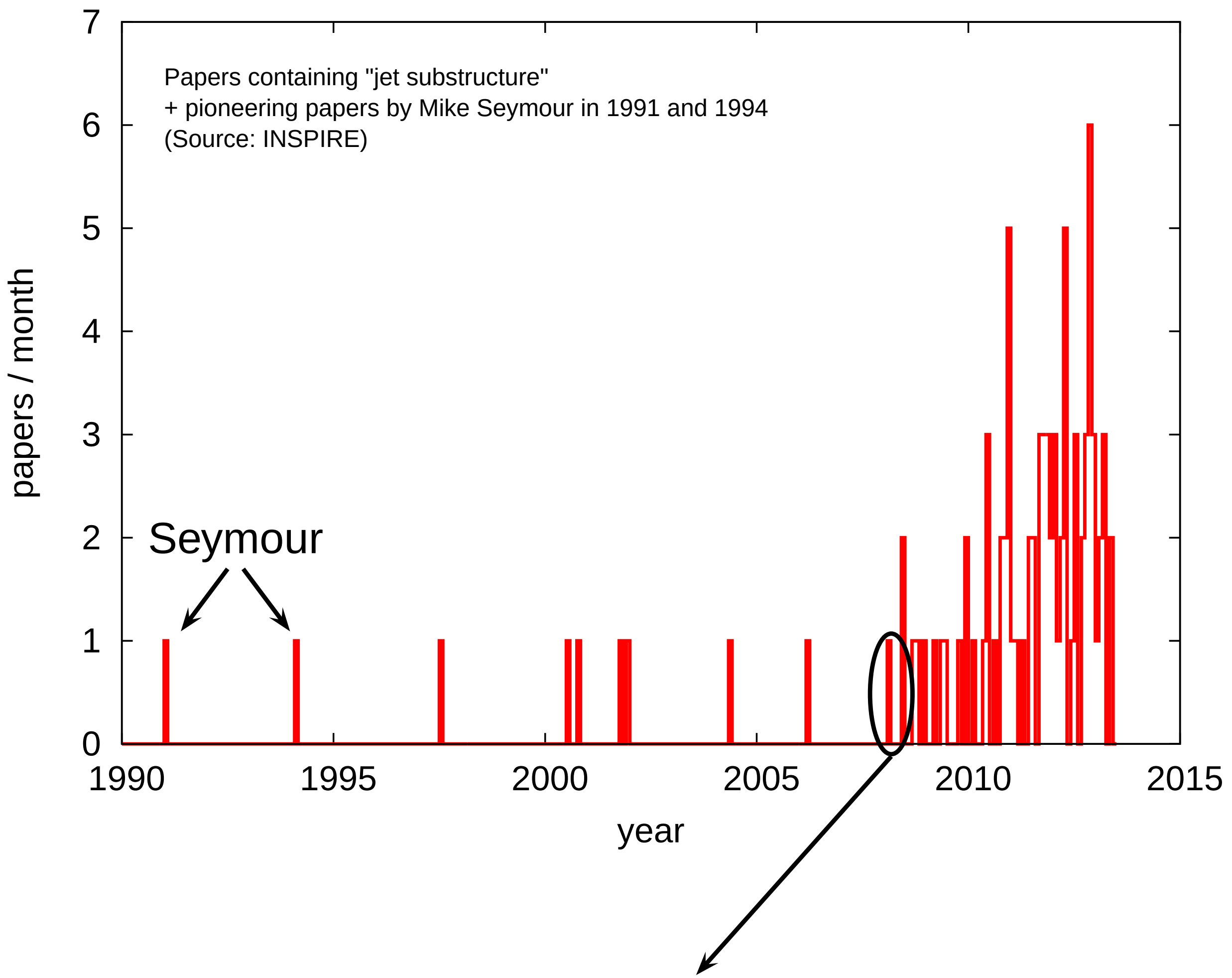
$$R \gtrsim \frac{m}{p_t} \frac{1}{\sqrt{z(1-z)}}$$

How to disentangle that from a QCD jet?

Many applications: (examples)

- 2-pronged decay: $W \to q\bar{q}$, $H \to b\bar{b}$
- 3-pronged decay: $t \to qqb$, $\tilde{\chi} \to qqq$
- busier combinations: $t\bar{t}H$
- new physics: *e.g.* heavy SUSY → boosted top

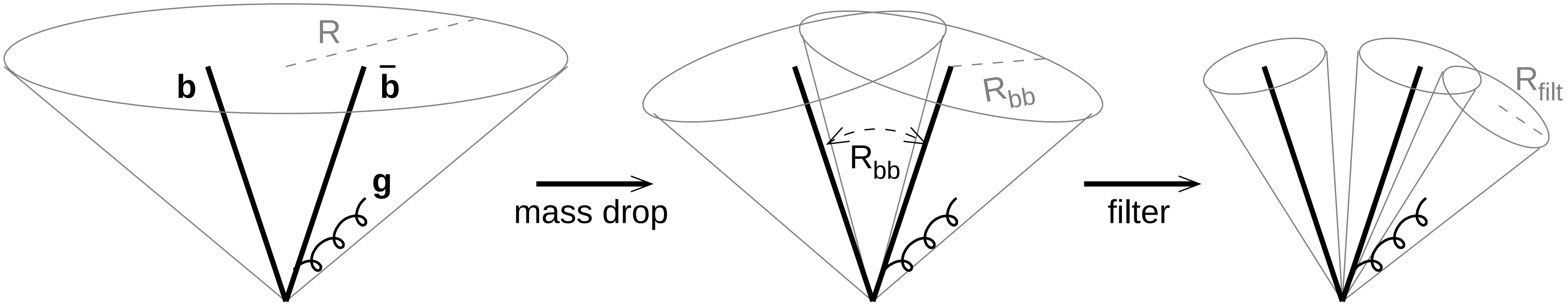
A lot of activity since 2008



Jet substructure as a new Higgs search channel at the LHC

Jon Butterworth, Adam Davison, Mathieu Rubin, Gavin Salam, 0802.2470

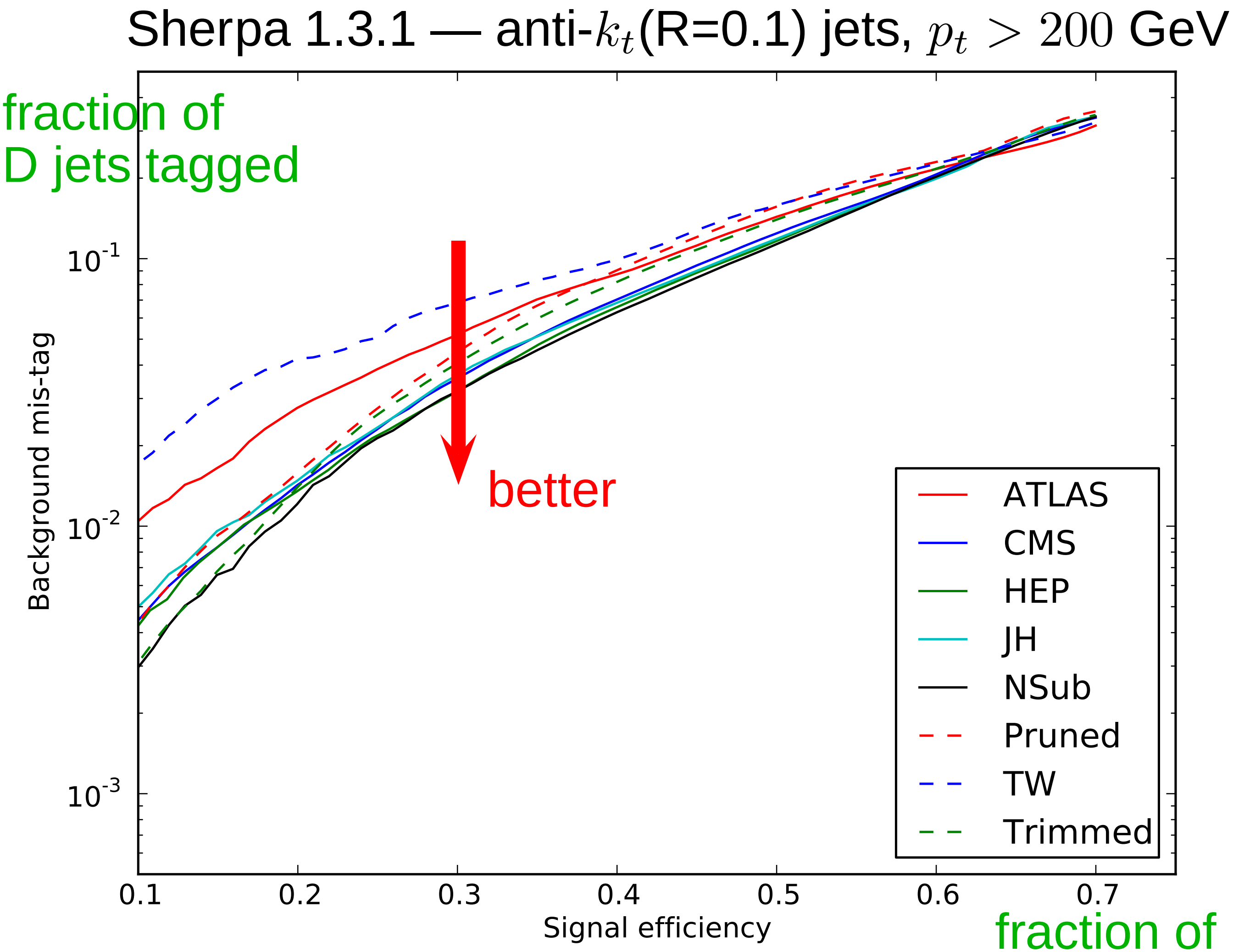
Many tools



- Main idea: get rid of soft/collinear branchings (typical of QCD)
- Many approaches:
  - uncluster the jet into subjets/investigate the clustering history
  - constrain radiation pattern imposing kinematic cuts...
  - ... or using jet shapes (functions of jet constituents)
- Many tools: mass drop; filtering, trimming, pruning; N-subjettiness, planar flow, energy correlations, pull; template methods; Johns Hopkins top tagger, HEPTopTagger; ...

Example: top tagging

[Boost 2011 proceedings]



fraction of
QCD jets tagged

better

fraction of
t-jets tagged

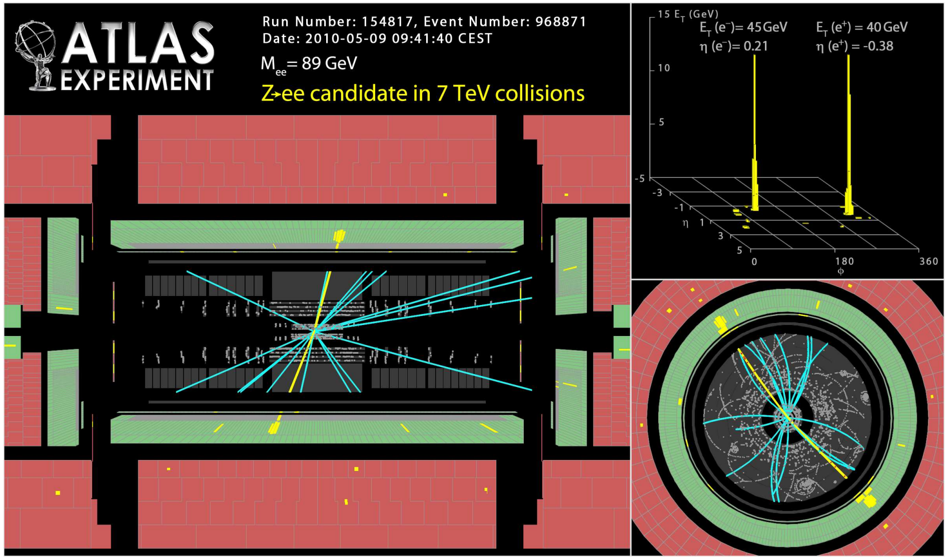
Jets in soft background

Pileup

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

Low luminosity

(bunch population)



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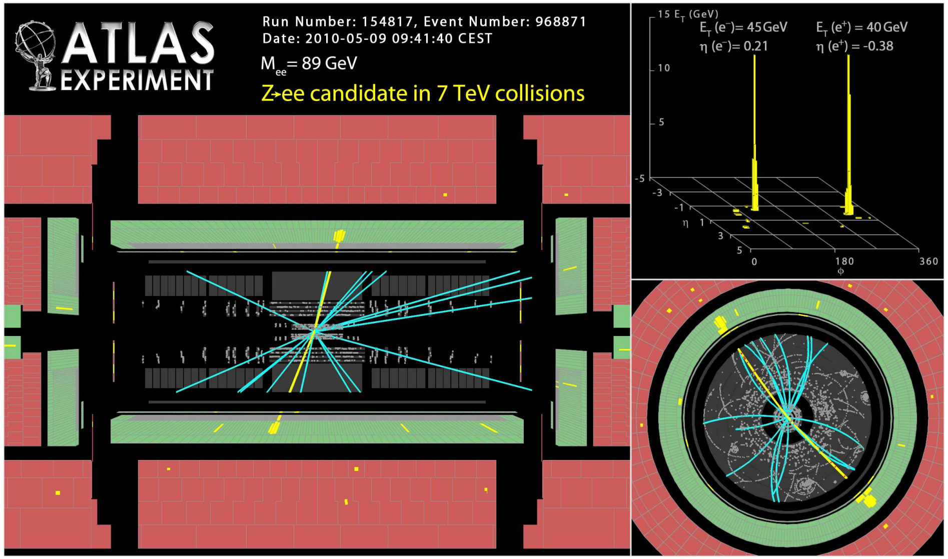

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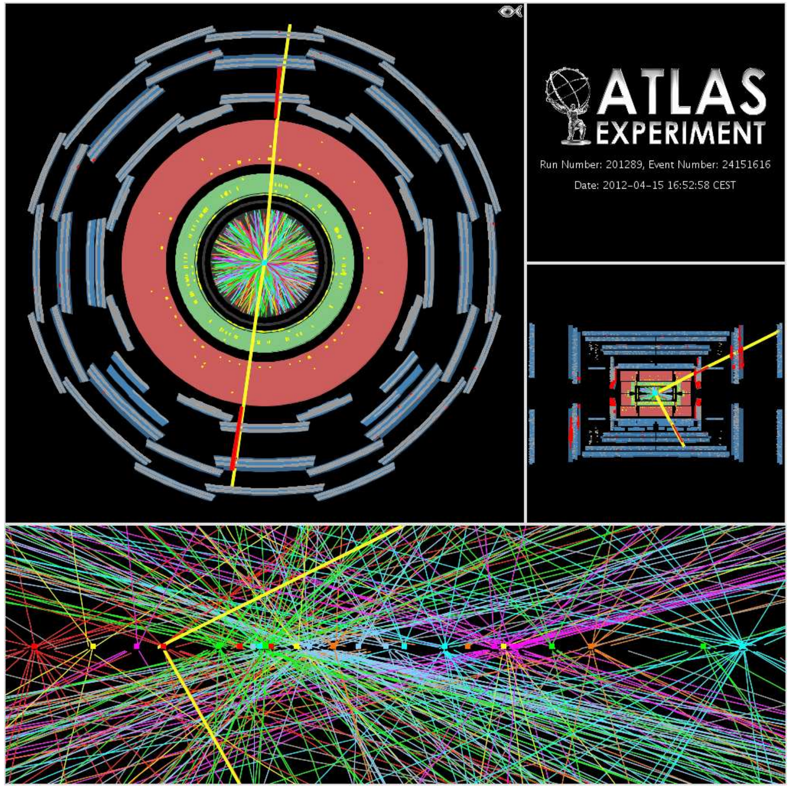
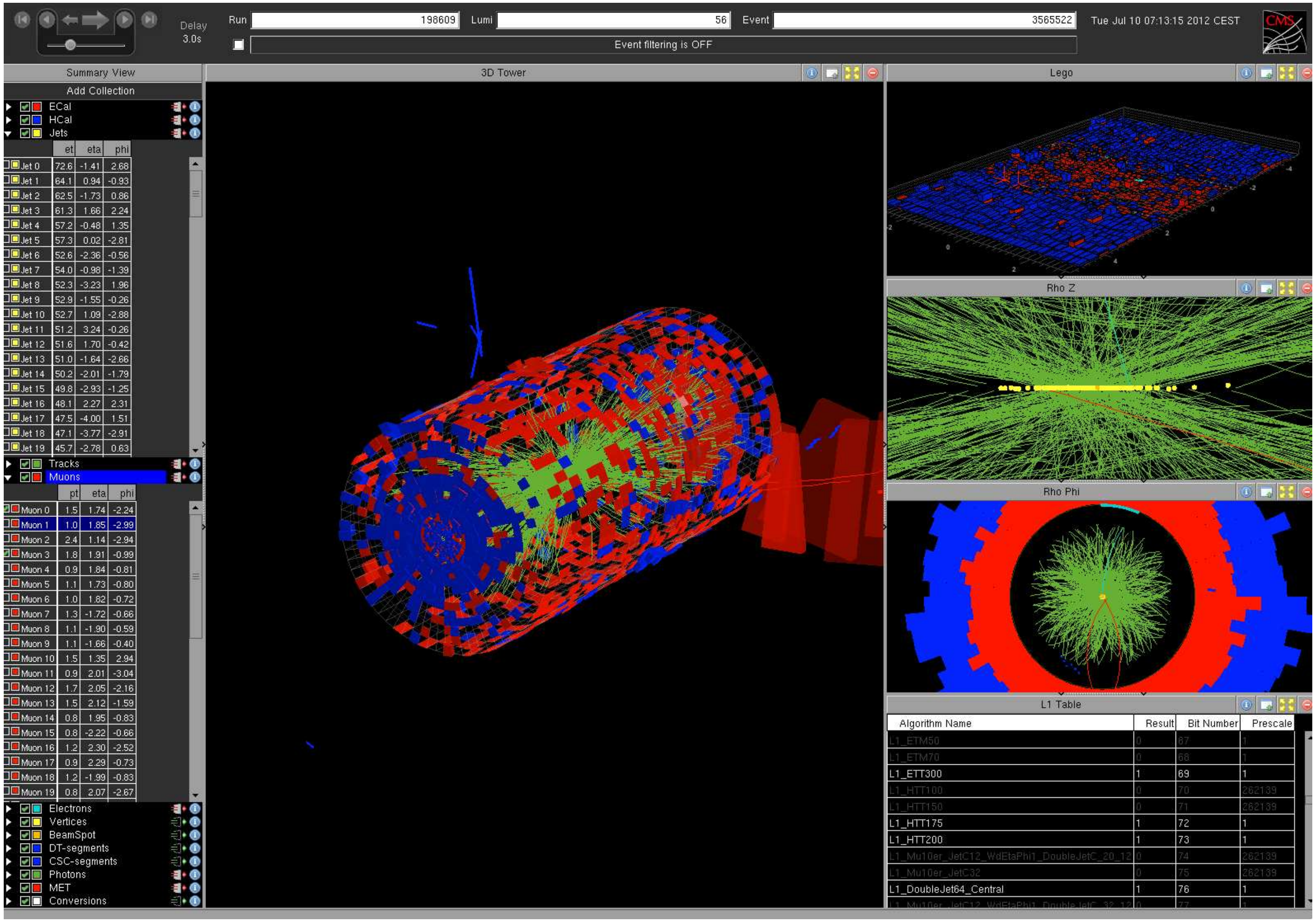


- many (soft) pp interactions with the hard one (here 25)
- soft background in the whole detector

Pileup

A CMS event with 78 pile-up vertices!



Delay 3.0s

Run 198609

Lumi 56

Event 3565522

Tue Jul 10 07:13:15 2012 CEST

Event filtering is OFF

- ☑ ECal
- ☑ HCal
- ☑ Jets

	et	eta	phi
☐ Jet 0	72.6	-1.41	2.68
☐ Jet 1	64.1	0.94	-0.93
☐ Jet 2	62.5	-1.73	0.86
☐ Jet 3	61.3	1.66	2.24
☐ Jet 4	57.2	-0.48	1.35
☐ Jet 5	57.3	0.02	-2.81
☐ Jet 6	52.6	-2.36	-0.56
☐ Jet 7	54.0	-0.98	-1.39
☐ Jet 8	52.3	-3.23	1.96
☐ Jet 9	52.9	-1.55	-0.26
☐ Jet 10	52.7	1.09	-2.88
☐ Jet 11	51.2	3.24	-0.26
☐ Jet 12	51.6	1.70	-0.42
☐ Jet 13	51.0	-1.64	-2.66
☐ Jet 14	50.2	-2.01	-1.79
☐ Jet 15	49.8	-2.93	-1.25
☐ Jet 16	48.1	2.27	2.31
☐ Jet 17	47.5	-4.00	1.51
☐ Jet 18	47.1	-3.77	-2.91
☐ Jet 19	45.7	-2.78	0.63

- ☑ Tracks
- ☑ Muons

	pt	eta	phi
☑ Muon 0	1.5	1.74	-2.24
☐ Muon 1	1.0	1.85	-2.99
☐ Muon 2	2.4	1.14	-2.94
☑ Muon 3	1.8	1.91	-0.99
☐ Muon 4	0.9	1.84	-0.81
☐ Muon 5	1.1	1.73	-0.80
☐ Muon 6	1.0	1.82	-0.72
☐ Muon 7	1.3	-1.72	-0.66
☐ Muon 8	1.1	-1.90	-0.59
☐ Muon 9	1.1	-1.66	-0.40
☐ Muon 10	1.5	1.35	2.94
☐ Muon 11	0.9	2.01	-3.04
☐ Muon 12	1.7	2.05	-2.16
☐ Muon 13	1.5	2.12	-1.59
☐ Muon 14	0.8	1.95	-0.83
☐ Muon 15	0.8	-2.22	-0.66
☐ Muon 16	1.2	2.30	-2.52
☐ Muon 17	0.9	2.29	-0.73
☐ Muon 18	1.2	-1.99	-0.83
☐ Muon 19	0.8	2.07	-2.67

- ☑ Electrons
- ☑ Vertices
- ☑ BeamSpot
- ☑ DT-segments
- ☑ CSC-segments
- ☑ Photons
- ☑ MET
- ☑ Conversions

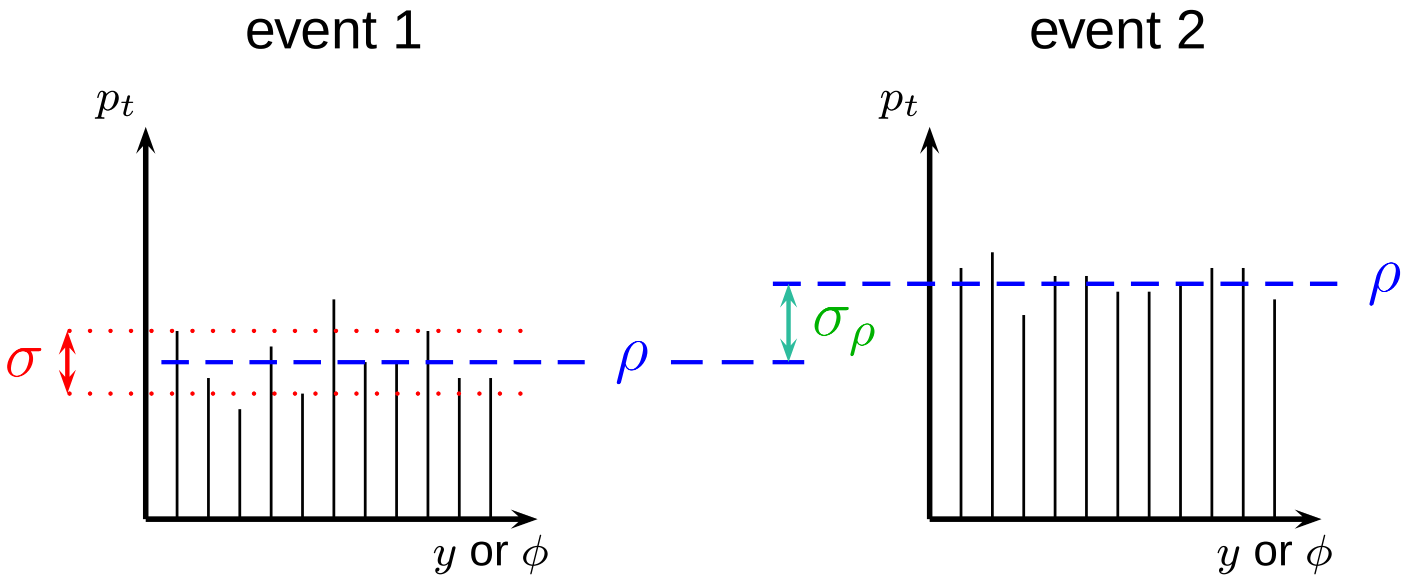
Algorithm Name	Result	Bit Number	Prescale
L1_ETM50	0	67	1
L1_ETM70	0	68	1
L1_ETT300	1	69	1
L1_HTT100	0	70	262139
L1_HTT150	0	71	262139
L1_HTT175	1	72	1
L1_HTT200	1	73	1
L1_Mu10er_JetC12_WdEtaPhi1_DoubleJetC_20_12	0	74	262139
L1_Mu10er_JetC32	0	75	262139
L1_DoubleJet64_Central	1	76	1
L1_Mu10er_JetC12_WdEtaPhi1_DoubleJetC_32_12	0	77	1

End of Run I: 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



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Jet of momentum p_t and area A:

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

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

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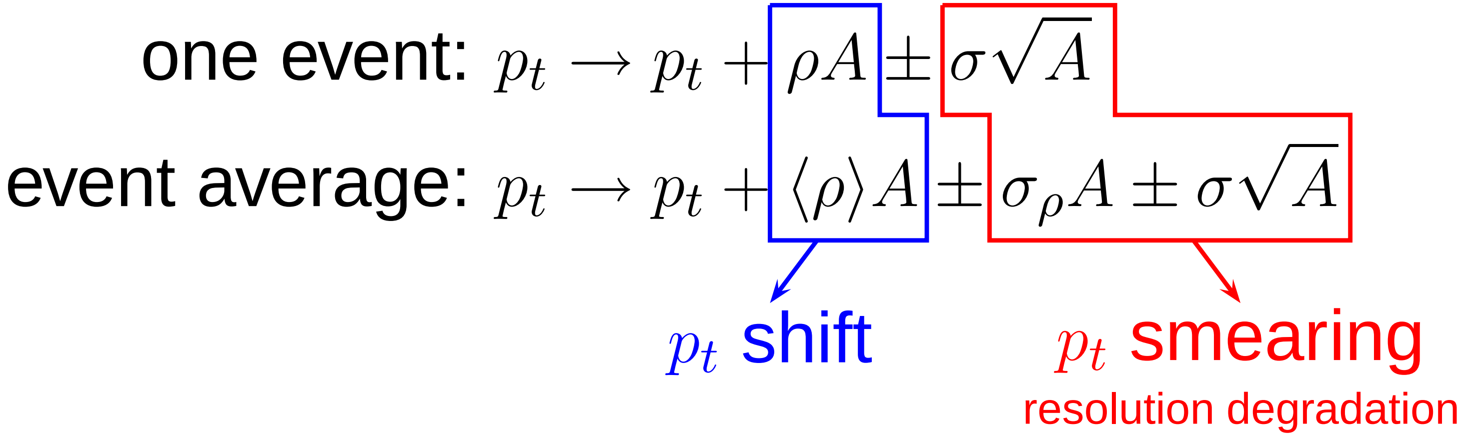
Jet of momentum p_t and area A:



one event: $p_t \to p_t + \boxed{\rho A} \pm \boxed{\sigma \sqrt{A}}$

event average: $p_t \to p_t + \boxed{\langle \rho \rangle A} \pm \boxed{\sigma_\rho A \pm \sigma \sqrt{A}}$

p_t shift

p_t smearing

resolution degradation

$^{(*)}$ valid also for the underlying event in heavy-ion collisions

Median-area-based subtraction

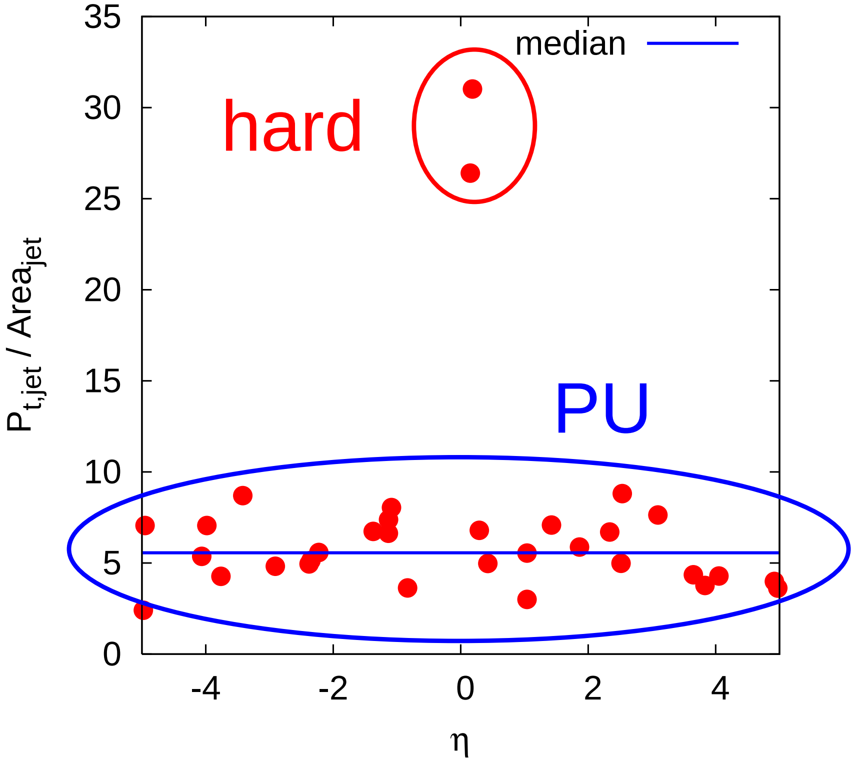
[M.Cacciari, G.P. Salam, 07; M.Cacciari, G.P. Salam, GS, 2008]

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

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

per jet

per event (typically)



break the event in patches of similar size

e.g. cluster with k_t

Subtraction methods (correct for the shift)

one subtracts a contribution from individual jets

subtracted	PU kept
constant p_t ($\langle \rho A \rangle$)	both flucts + area flucts
$\langle \rho \rangle \times A$	both flucts ($\sigma\sqrt{A}$ & $\sigma_\rho A$)
$\langle \rho \rangle_{\text{per PU vertex}} \times n_{PU} \times A$	$\sigma\sqrt{A}$ and part of $\sigma_\rho A$
$\rho_{\text{event}} \times A$	only $\sigma\sqrt{A}$

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$\rho_{\text{event}} \times A$	only $\sigma\sqrt{A}$

more averaged

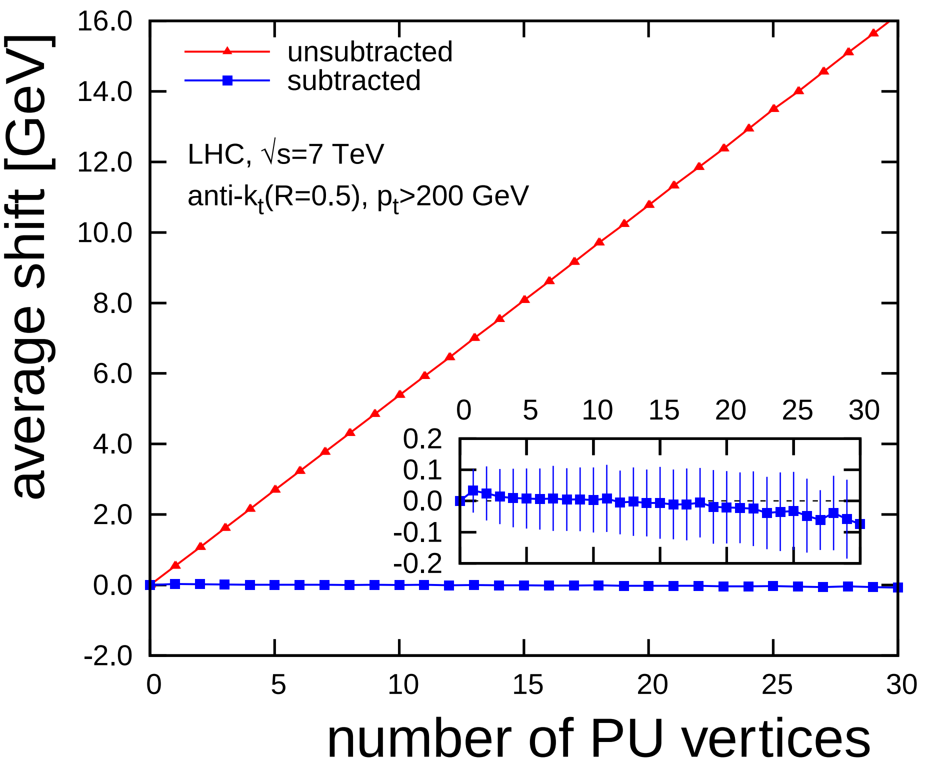
↕

’event-by-event’

Event-by-event determinations of the shift (are expected to) reduce the smearing effects of PU

Subtraction benchmarks

average p_t shift

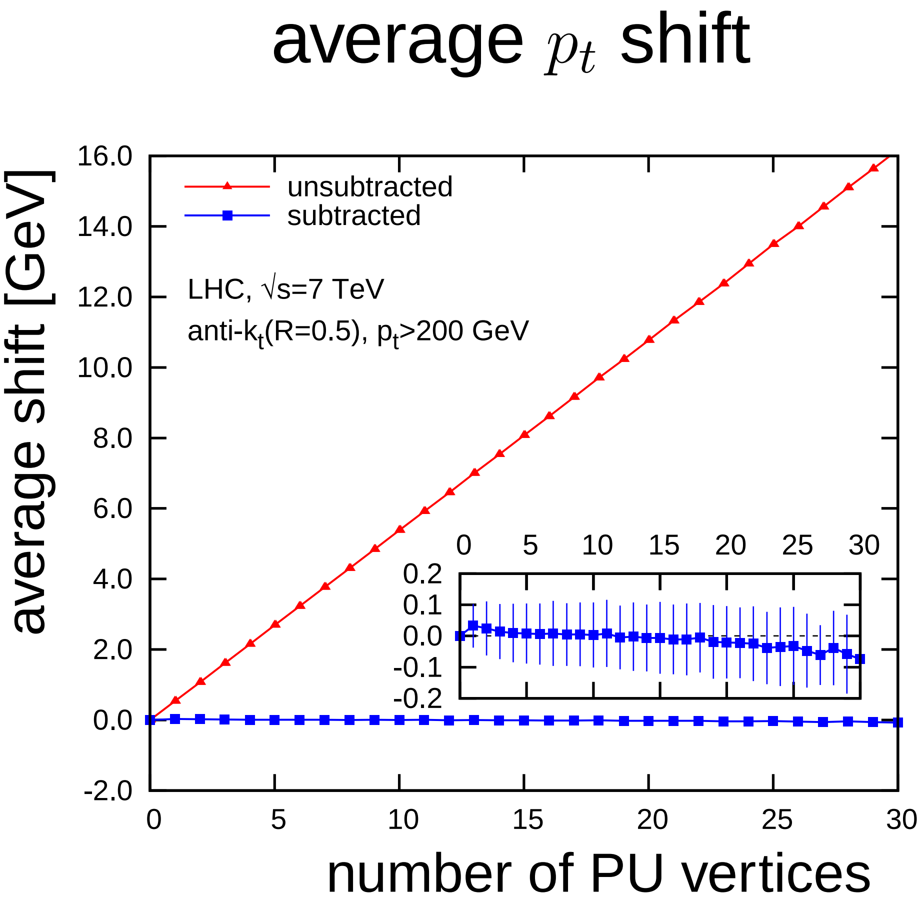


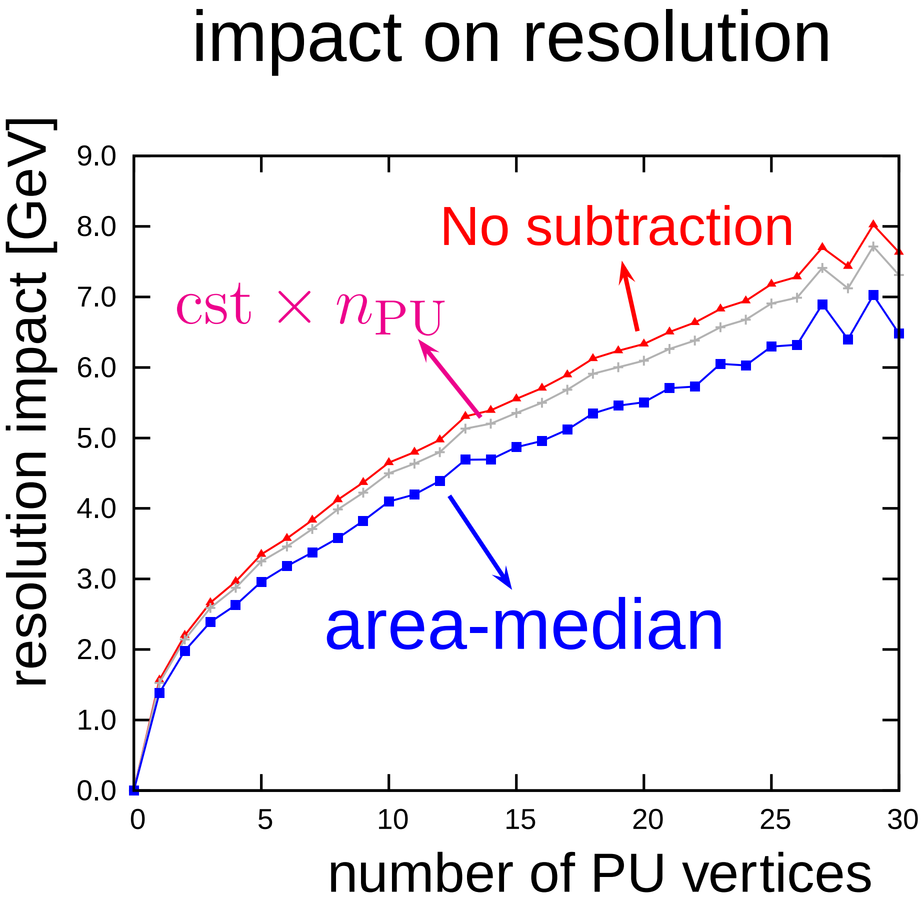
No subtraction

area-median subtraction

corrected for shift

Subtraction benchmarks

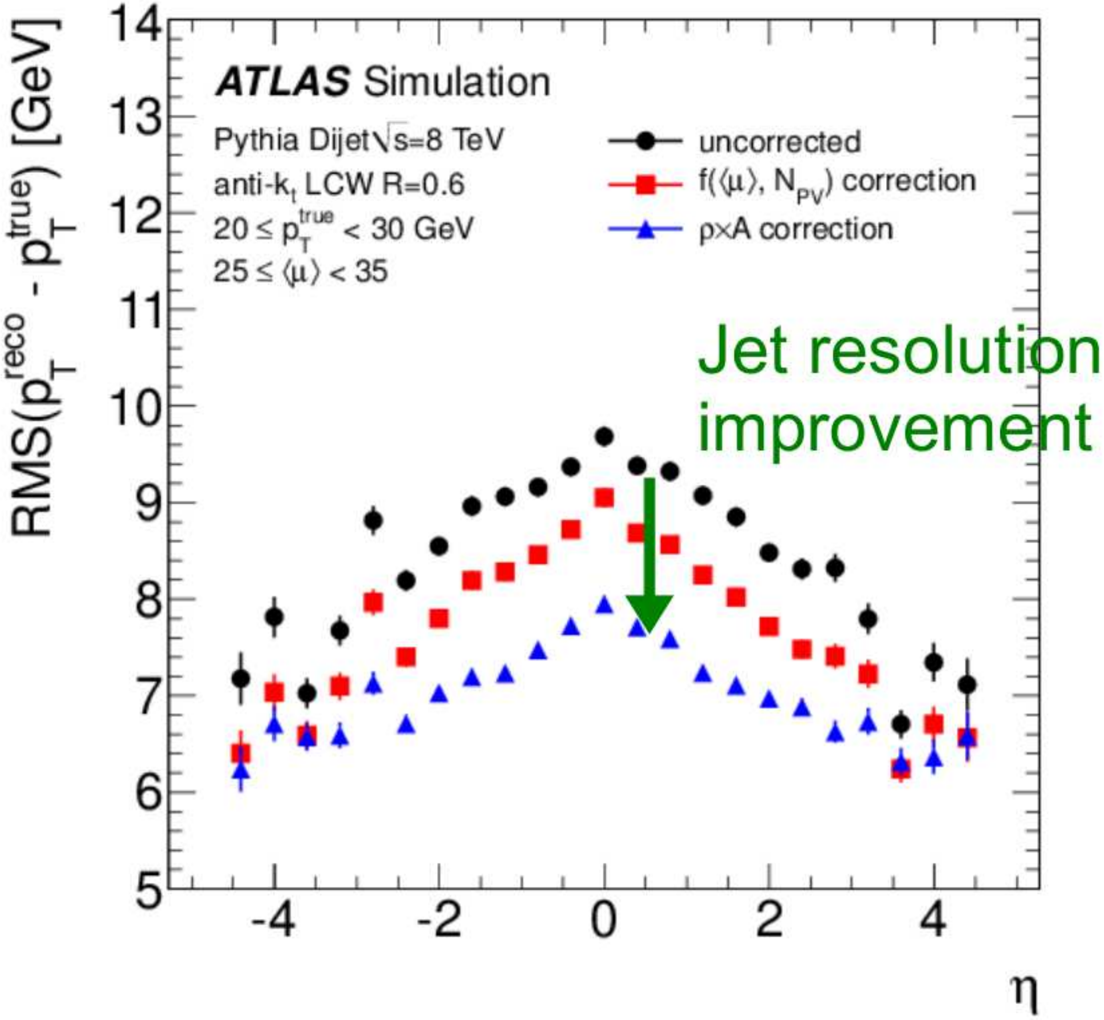




corrected for shift

resolution improved

PU subtraction as seen in ATLAS



Jet resolution improvement

[B. Petersen, ATLAS Status report for the LHCC, 2013]

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 for jet mass and jet shapes

  Important for jet tagging ("q v. g jet", b jet, top jet, $H \to b\bar{b}$)

  [GS,G.Salam,J.Kim,S.Dutta,M.Cacciari,2013]

- Subtraction of fragmentation function (moments)

  Useful for quenching in $PbPb$ collisions

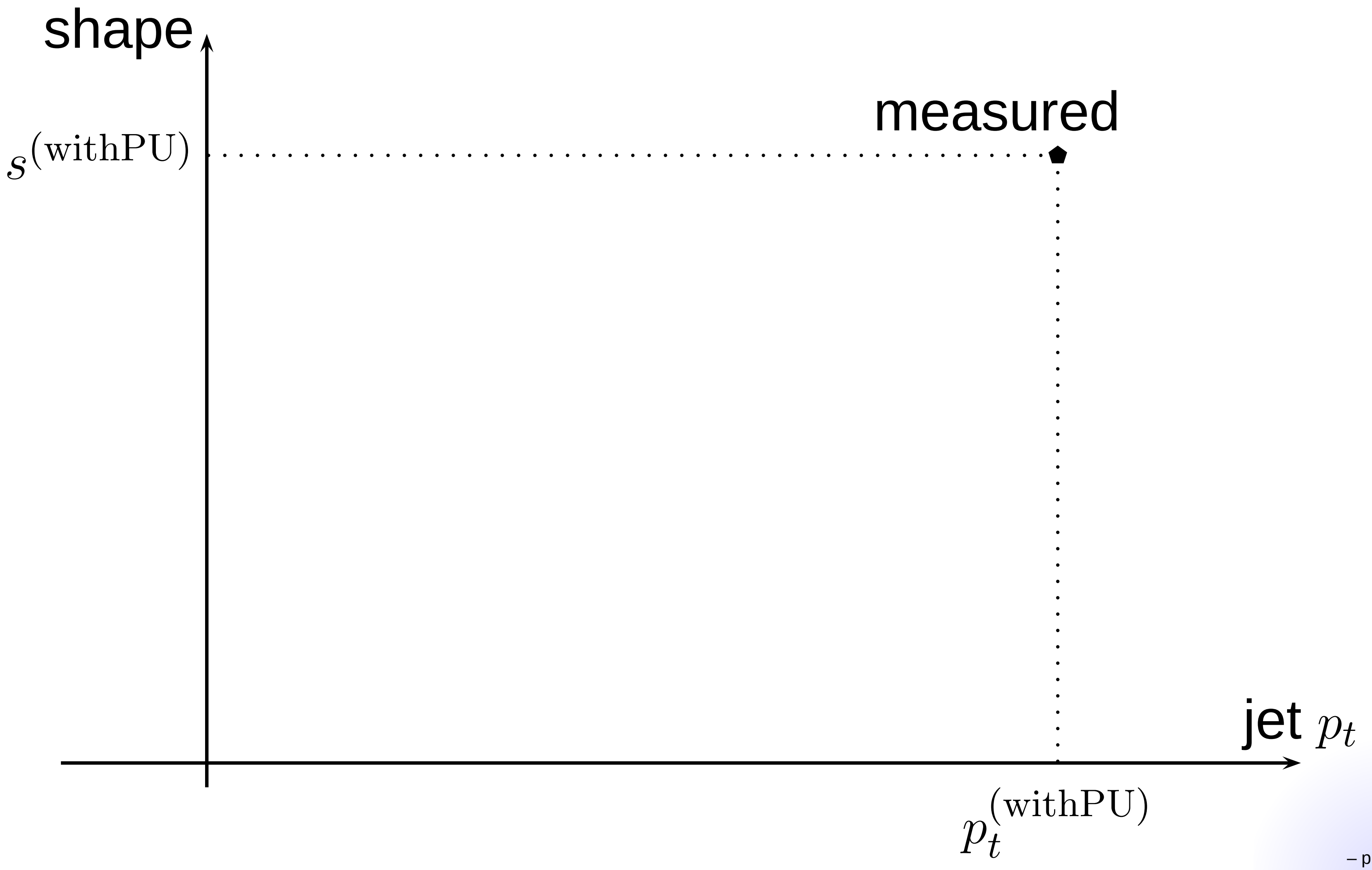
  [M.Cacciari,P.Quiroga,G.Salam,GS,2012]

Example: jet shapes

(function of the jet constituents –** e.g.* ***the jet mass)

Idea: area-median + extrapolation to 0 PU

[M.Cacciari, S.Dutta, J.Kim, G.Salam, GS, 2013]



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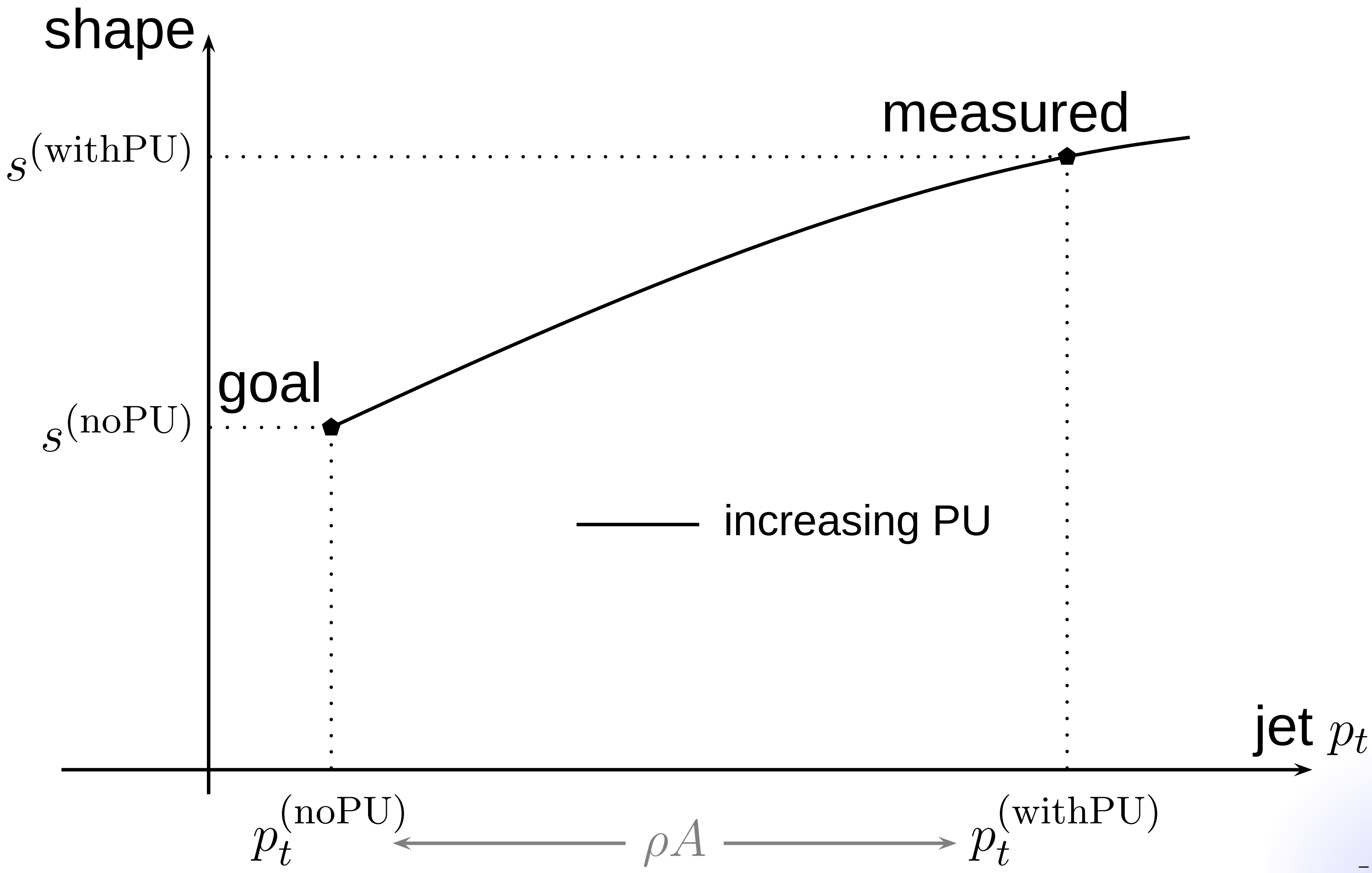

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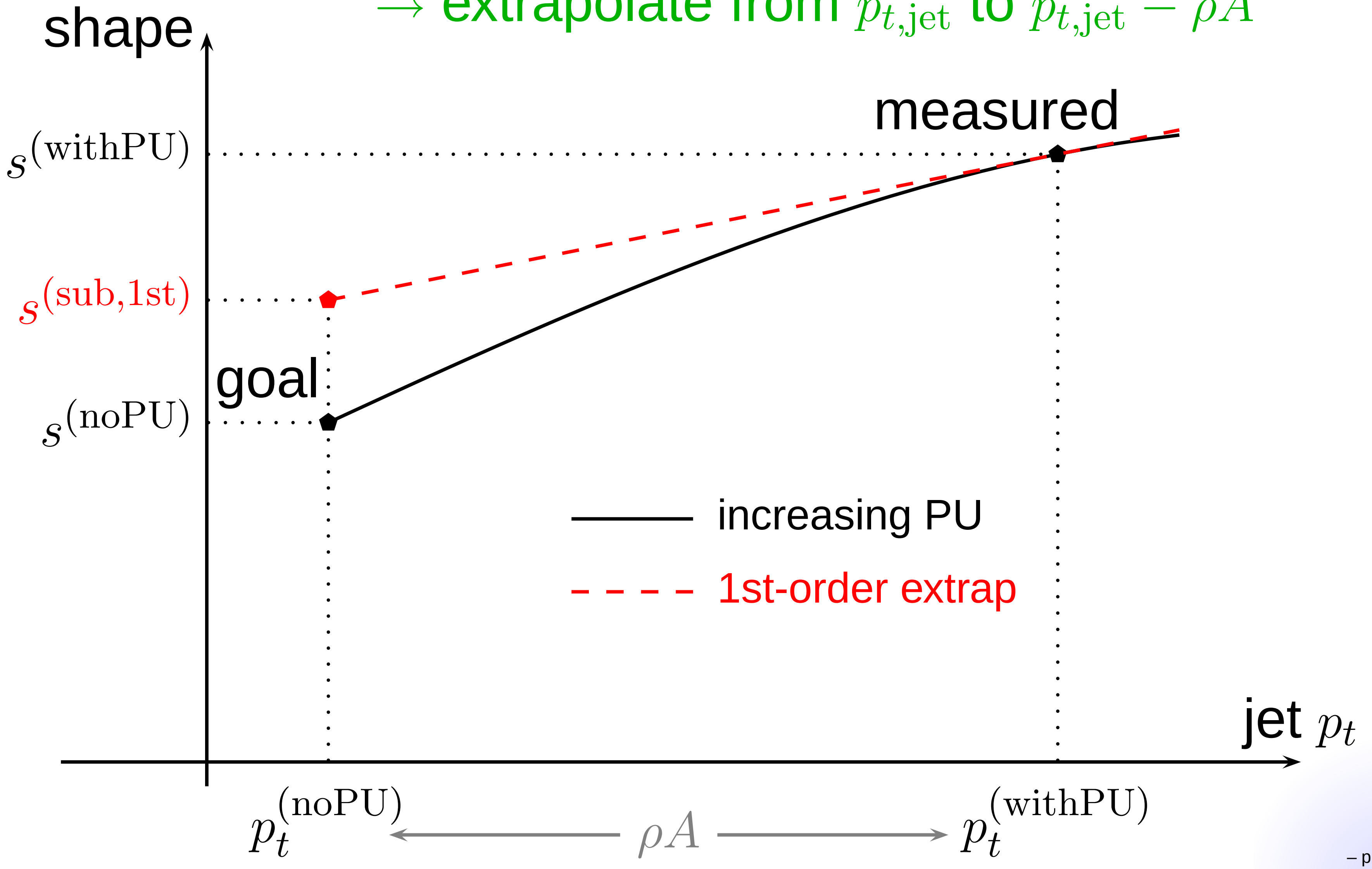
[M.Cacciari, S.Dutta, J.Kim, G.Salam, GS, 2013]

knowledge of the derivarives wrt uniform shift of PU

→ extrapolate from $p_{t,\mathrm{jet}}$ to $p_{t,\mathrm{jet}} - \rho A$



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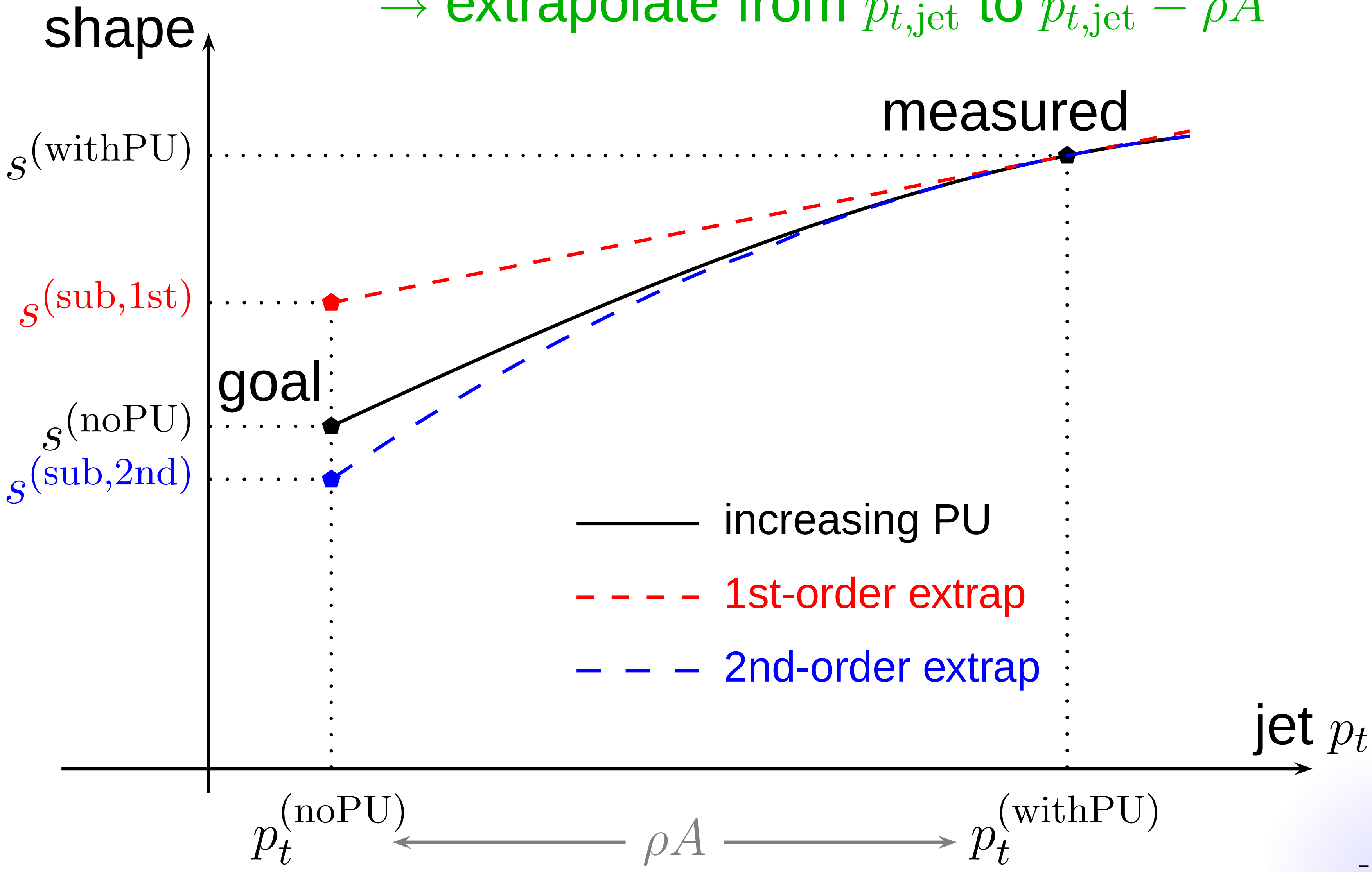
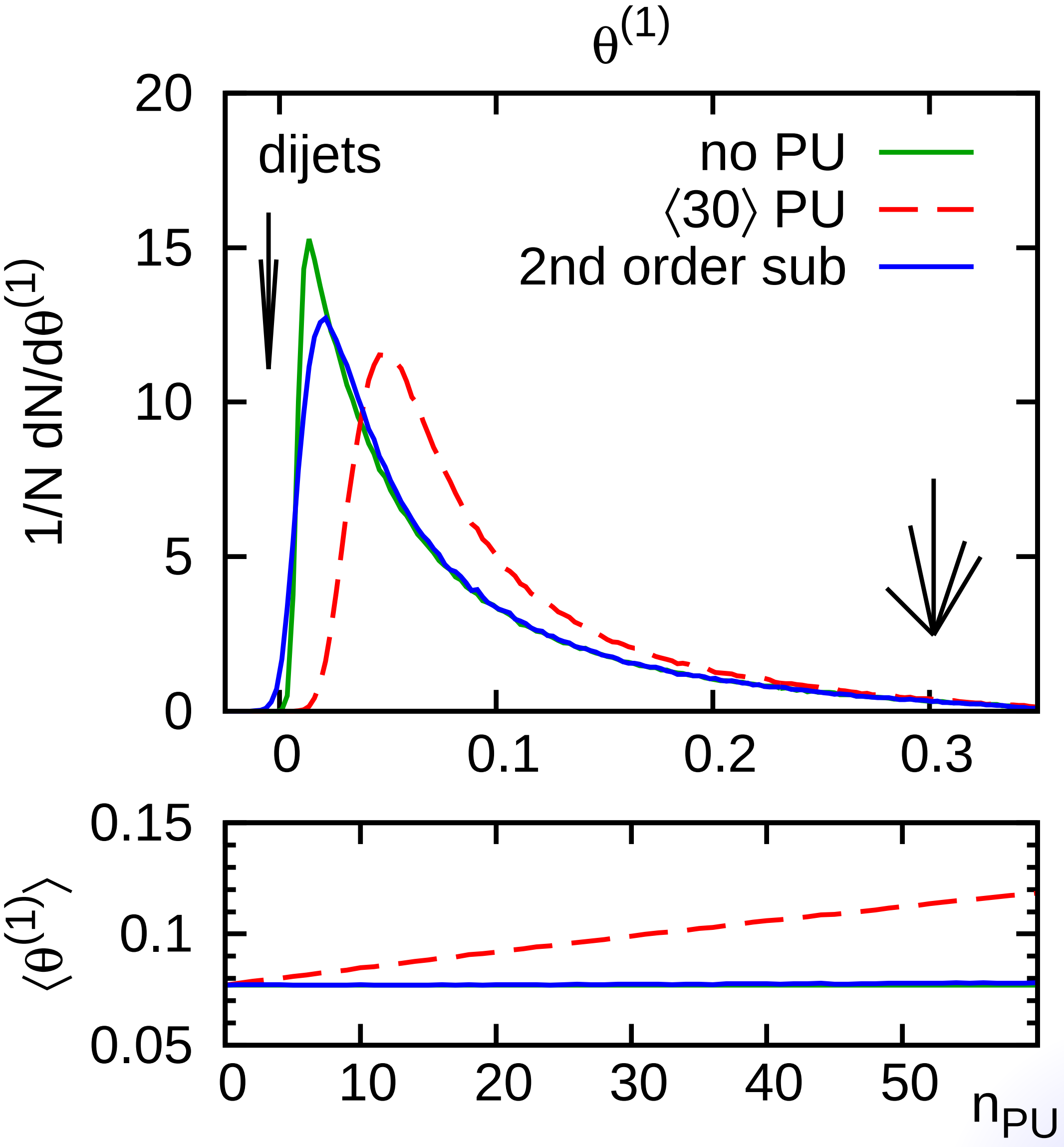


Application 1: quark/gluon discrimination

Use a cut on girth/broadening/width $\theta^{(1)} < 0.05$

$$\theta^{(1)}(\text{jet}) = \frac{1}{\tilde{p}_t} \sum_{i \in \text{jet}} p_{t,i} \Delta R_{i,\text{jet}}$$



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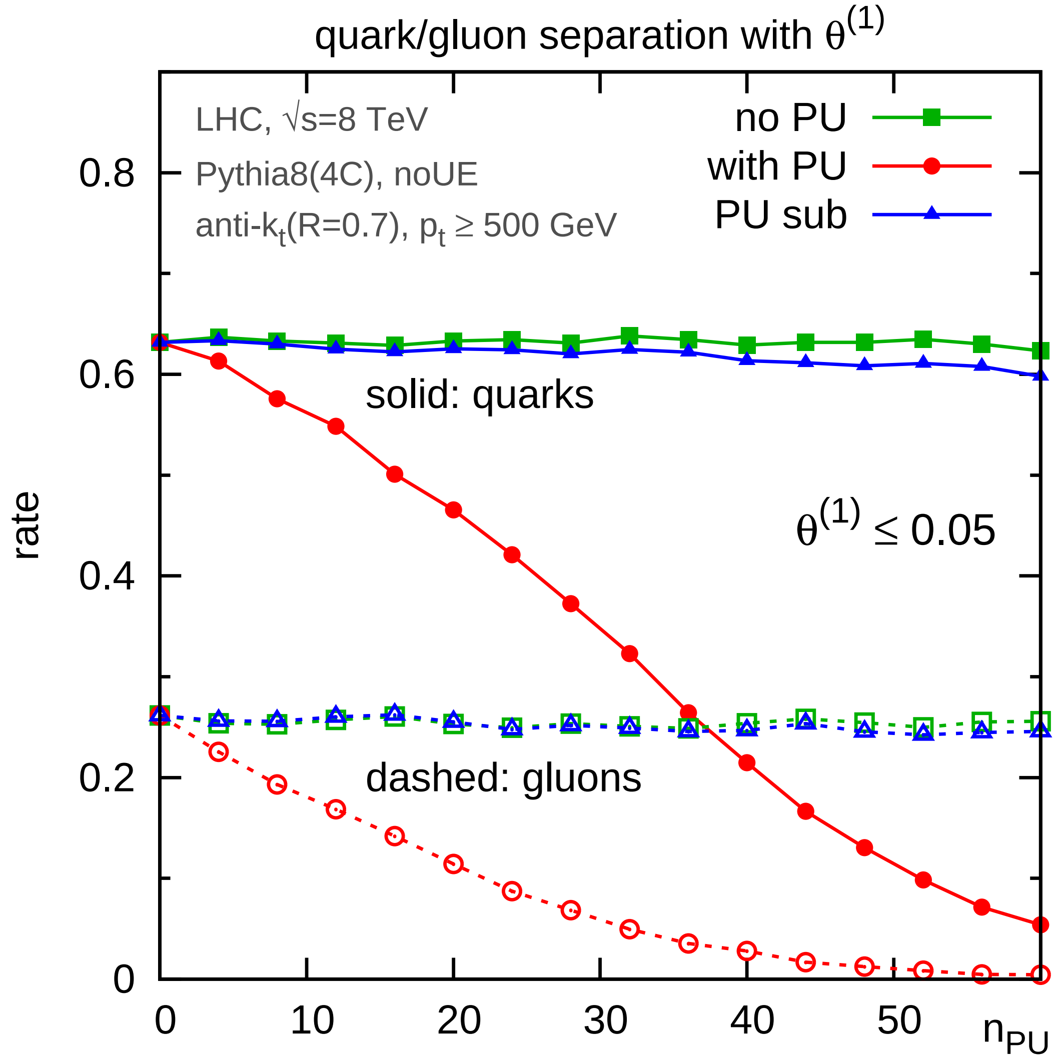
efficiencies very well recovered

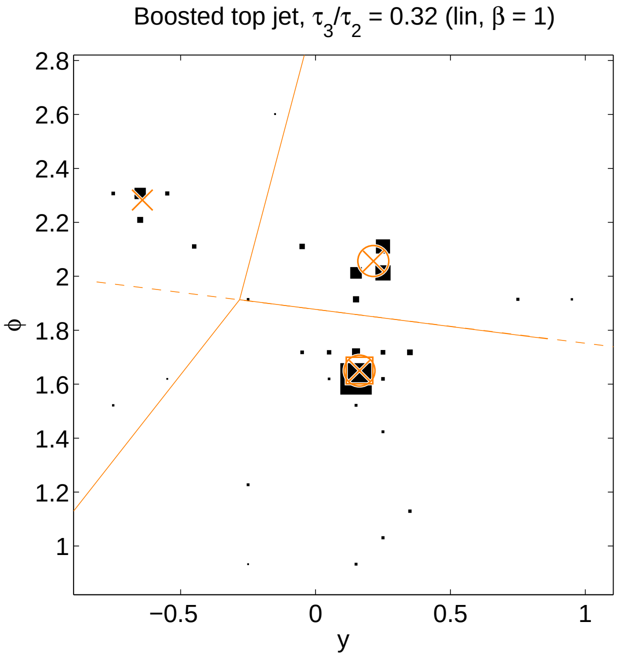


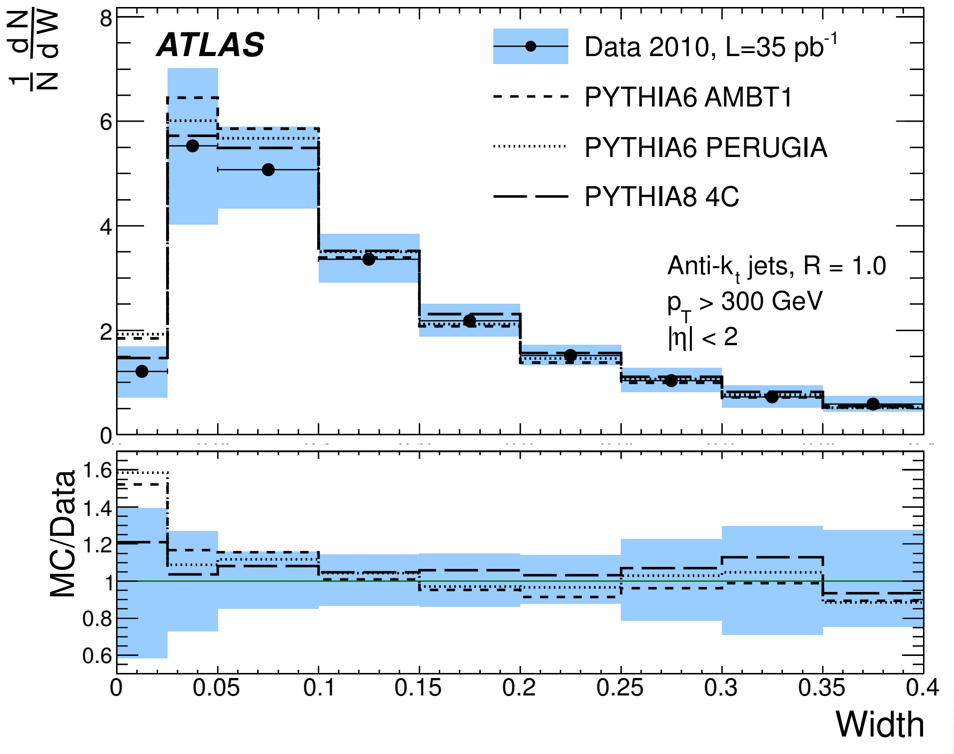
Application 2: N-subjettiness top tagging

Top tagging: cut on τ_3/τ_2 and on the filtered mass

N axes (*e.g.* excl. k_t subjets)

$$\tau_N^{(\text{axes},\beta)}(\text{jet}) = \frac{1}{\tilde{p}_t} \sum_{i\in\text{jet}} p_{t,i} \min_{a\in\text{axes}} (\Delta R_{i,a})^\beta$$





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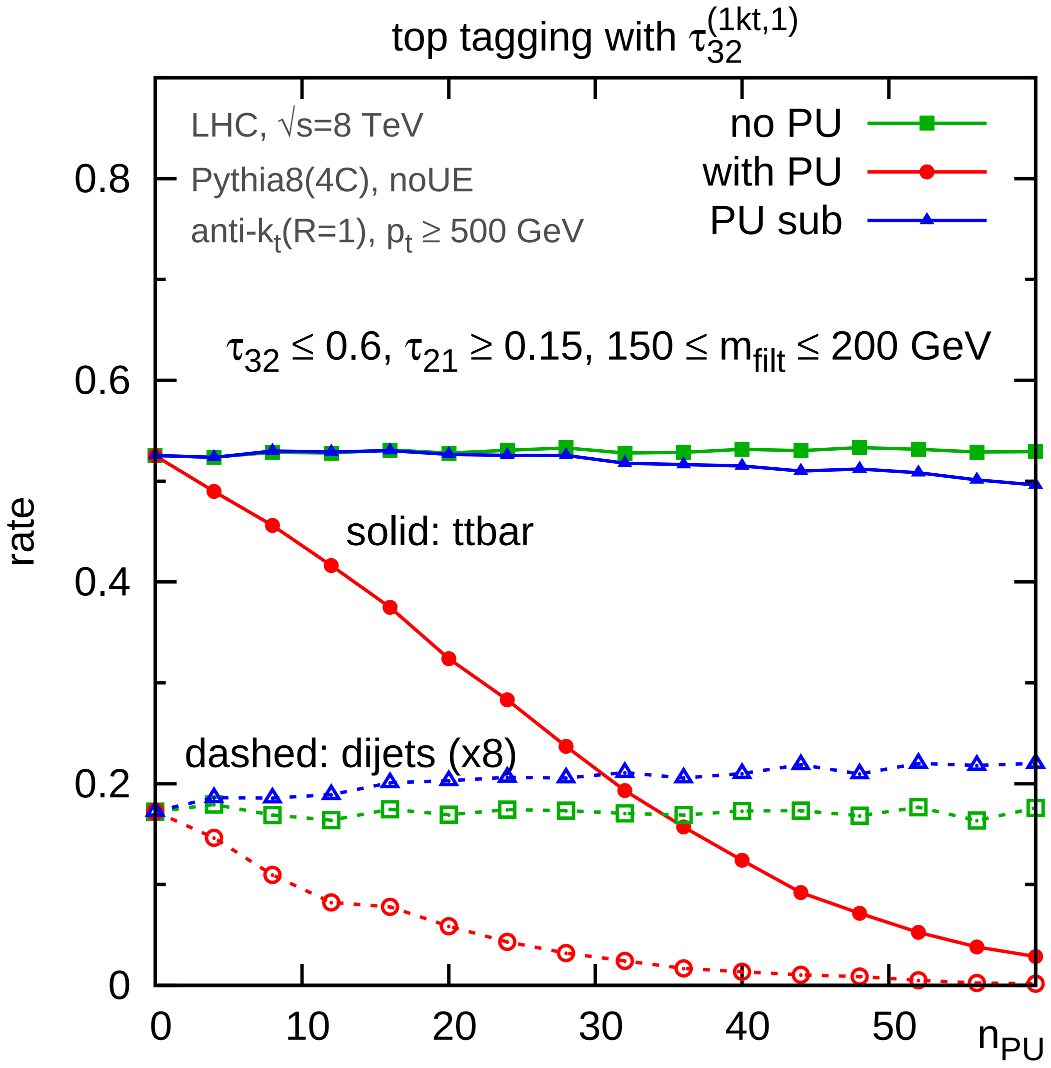


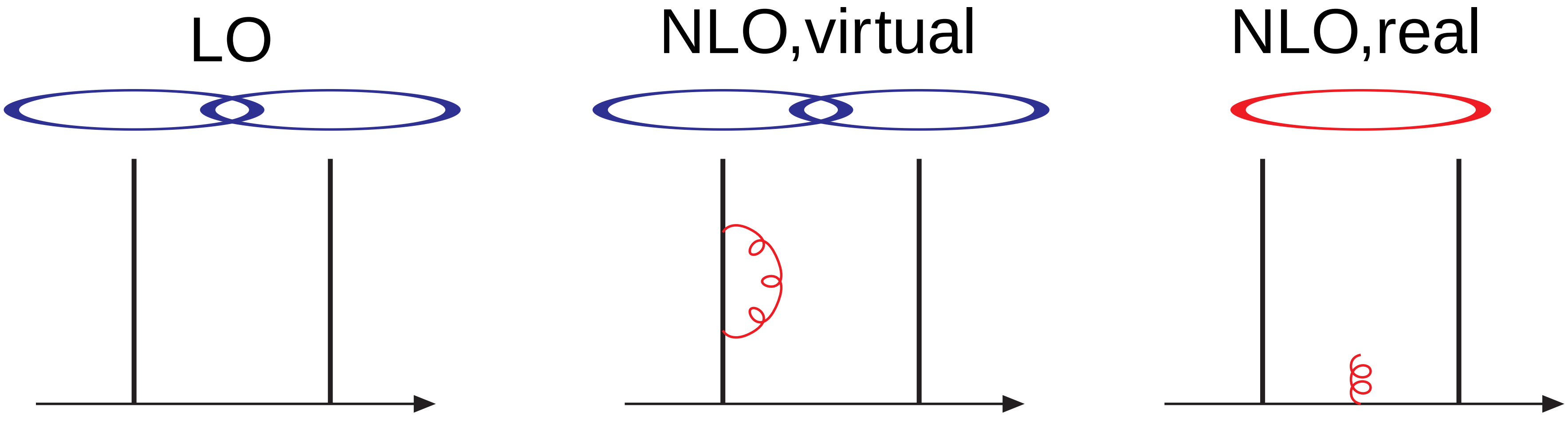
Conclusion and perspectives

- Many recent developments in use at the LHC:
  - robust and finite jet algs. In particular: anti-k_t
  - FastJet: fast and standard interface for jets
  - efficient and generic PU subtraction method

- Future
  - FastJet keeps improving (3.1 to be released)
  - PU: reduce noise sensitivity (*e.g.* dynamic filter)
  - Boosted tags: analytic understanding needed
    $\rightarrow$ design better taggers

IR safety

Example: JetClu



cancellation between real and virtual spoiled

JetClu, ATLASCone:	IR unsafety with 2+1 particles	(NLO for inclusive jet x-sect)
CDF/D0MidPoint:	IR unsafety with 2+1 particles	(NNLO for inclusive jet x-sect)
CMSIterativeCone:	collinear unsafety with 2+1 particles	(NNLO for inclusive jet x-sect)

Origin: incomplete determination of the stable (*i.e.* self-consistent) cones

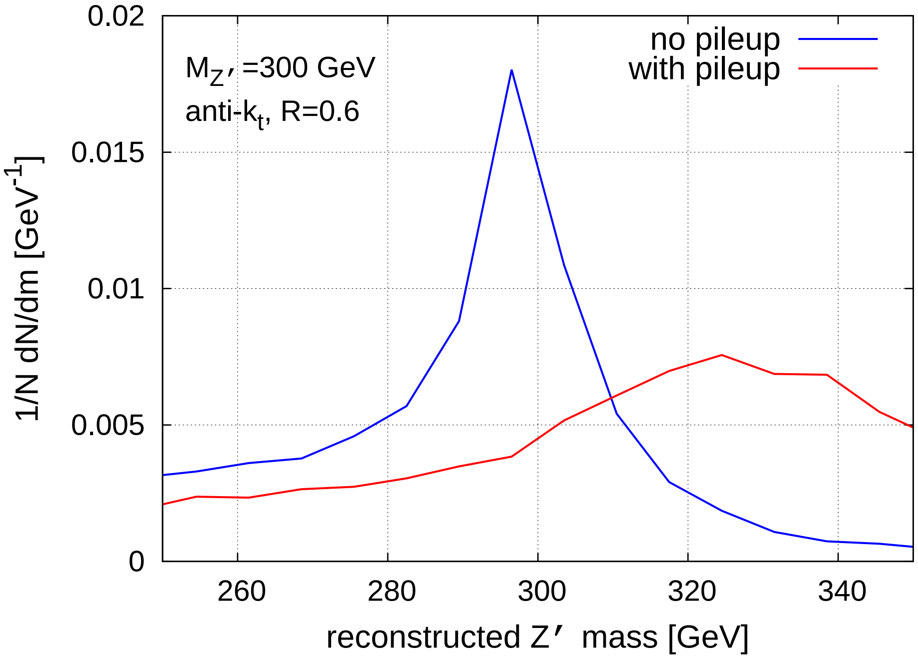
The FastJet lemma

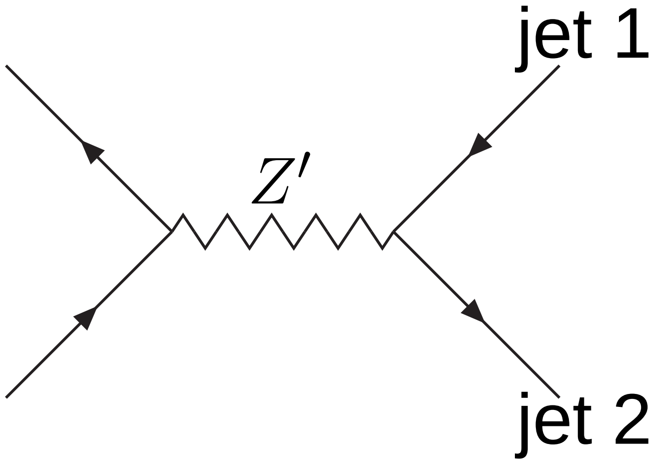
It (i,j) is the pair that minimize the k_t distance and $k_{t,i} < k_{y,j}$, then j is i's nearest neighbour

Proof: assume it is not, then $\exists k$ s.t. $\Delta R_{ik} < \Delta R_{ij}$ and

$$\begin{aligned}\min(k_{t,i}^2, k_{t,l}^2)\Delta R_{il}^2 &\leq k_{t,i}^2 \Delta R_{il}^2 \\ &\leq \min(k_{t,i}^2, k_{t,j}^2)\Delta R_{il}^2 \\ &< \min(k_{t,i}^2, k_{t,j}^2)\Delta R_{ij}^2\end{aligned}$$

Illustration of PU effects





- Shift due to the "ρA" term
- Smearing due to the "$\sigma_\rho A$" and "$\sigma\sqrt{A}$" terms

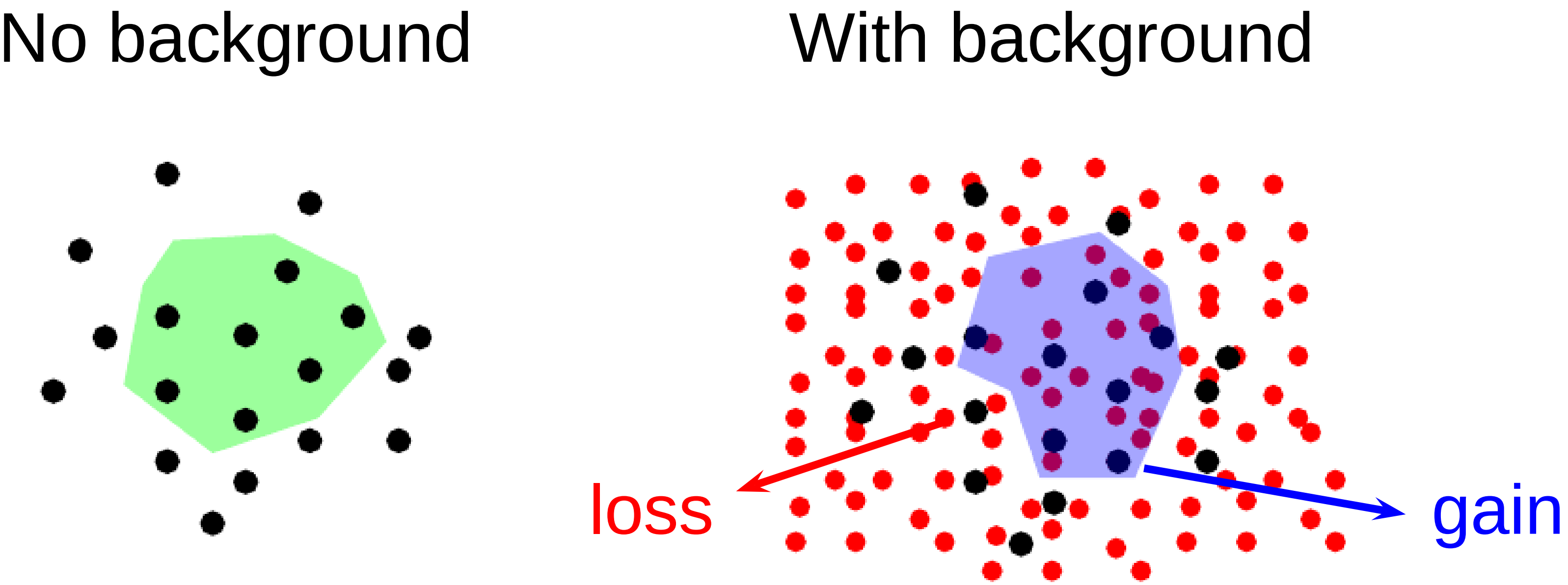
Heavy ions

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
$\delta p_{t,\mathrm{jet}}$	7.5 GeV	100 GeV
σ_{jet}	3.5 GeV	16 GeV

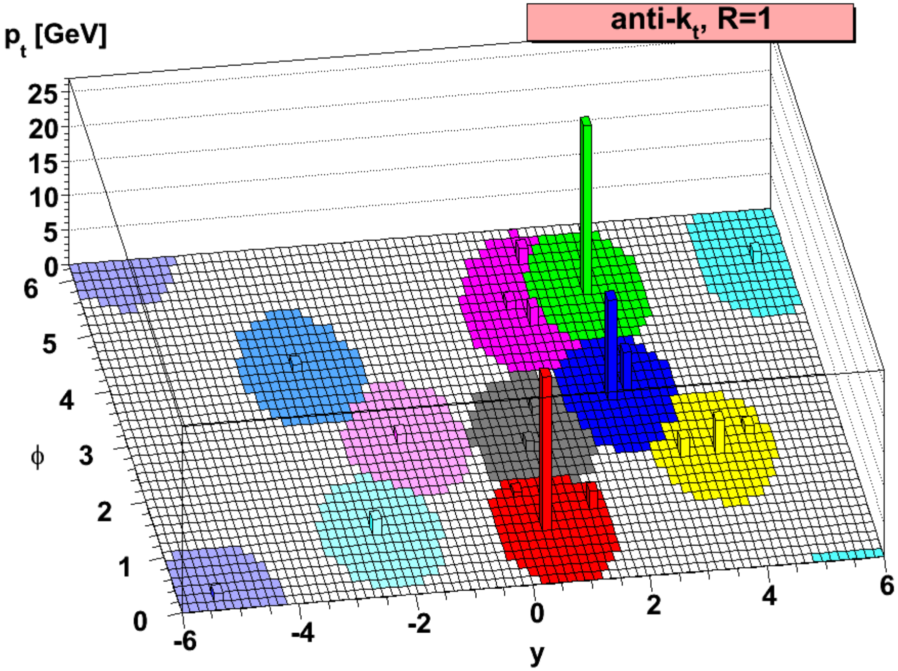
Back reaction



Negligible for anti-k_t
(a nice consequence of its soft resilience)

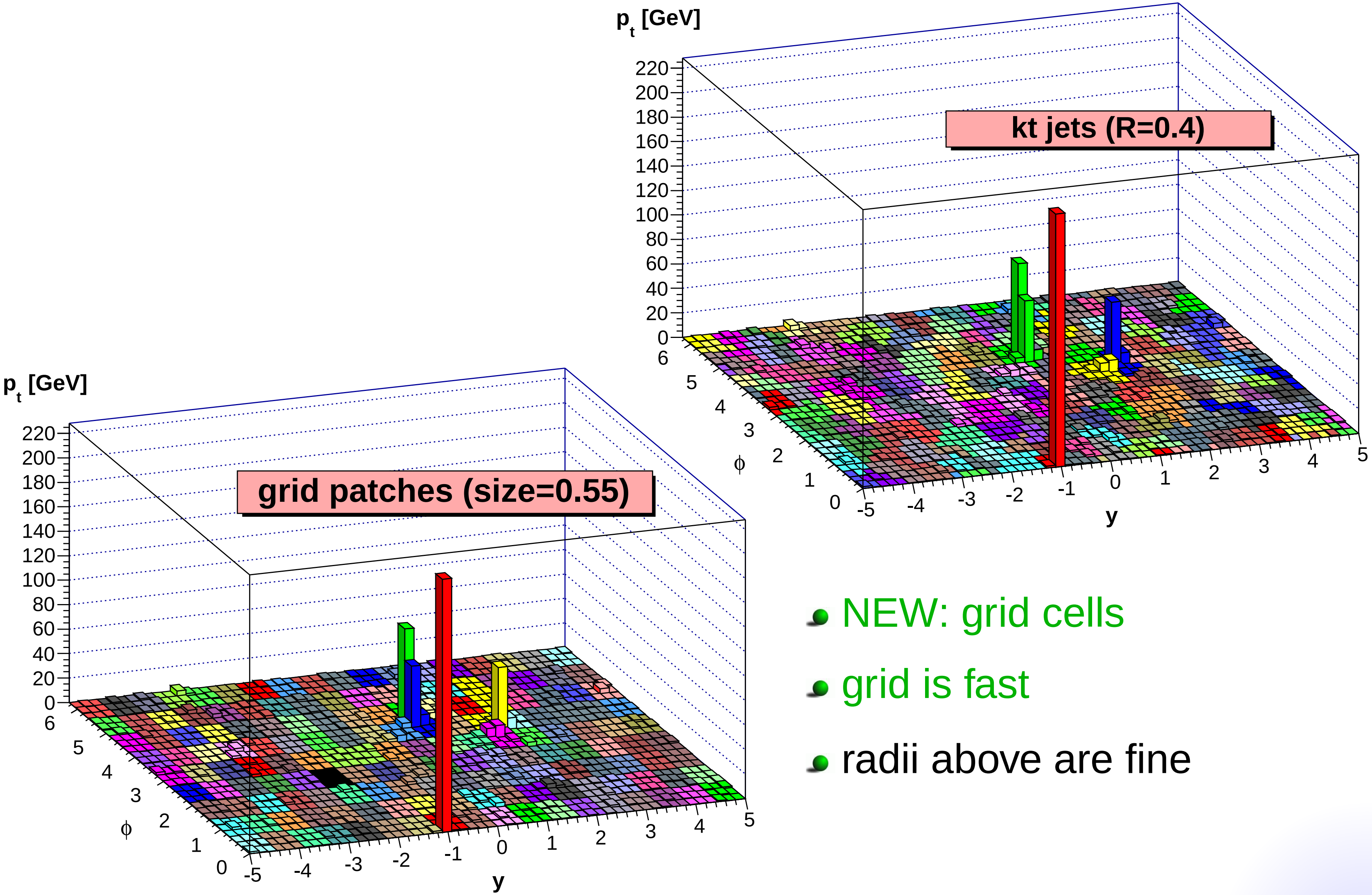
Determining jet area

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



Patches of similar size

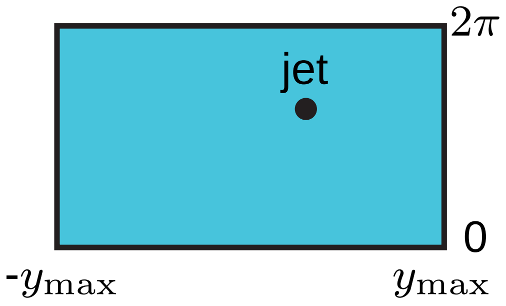
Patched are typically one of the 2 following types



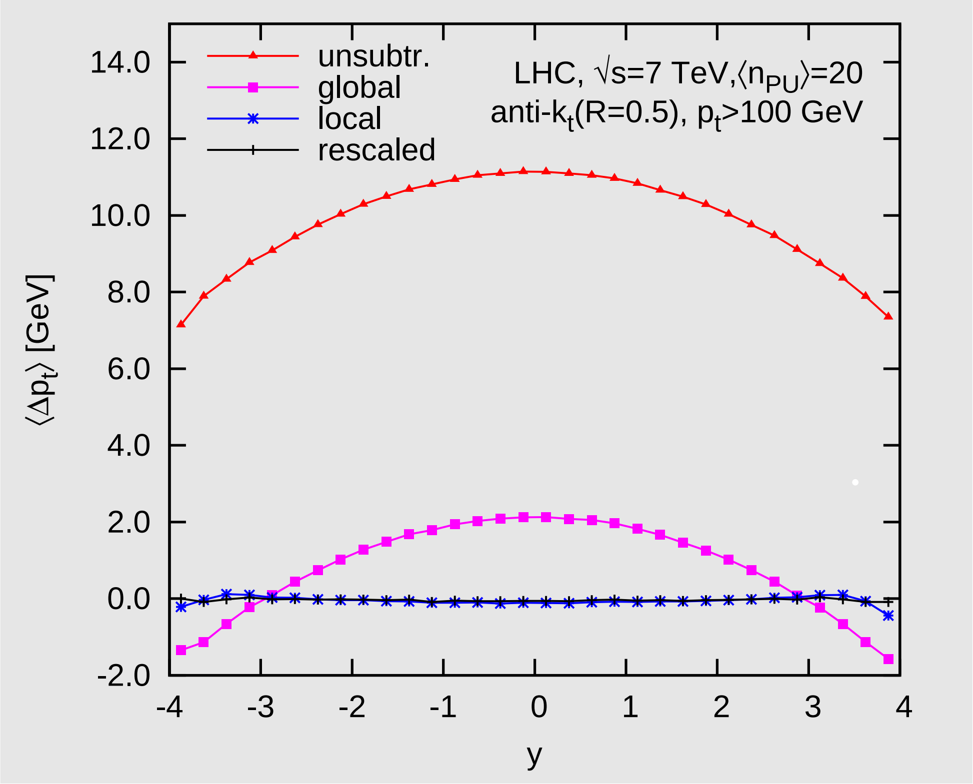
- NEW: grid cells
- grid is fast
- radii above are fine

Rapidity/positional dependence

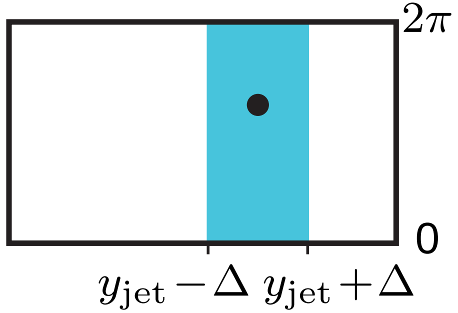
Global



$$\rho_{\rm est} = \underset{\text{all patches}}{\text{median}} \left\{ \frac{p_{t,j}}{A_j} \right\}$$

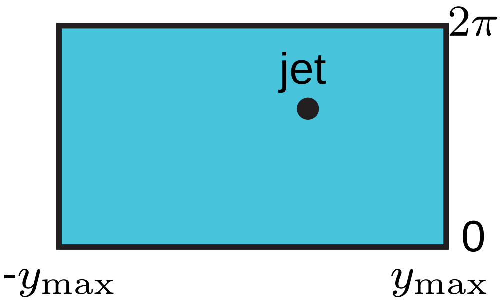


Local (strip)



$$\rho_{\rm est}(y) = \underset{\text{local patches}}{\text{median}} \left\{ \frac{p_{t,j}}{A_j} \right\}$$

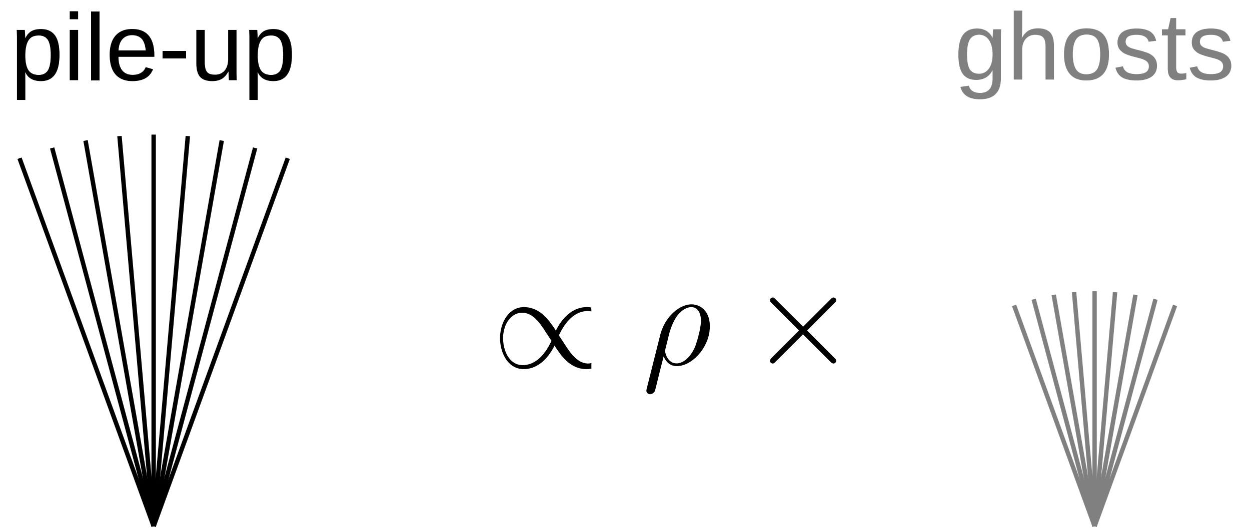
Rescaled



$$\rho_{\rm est}(y) = f(y)\, \underset{\text{all patches}}{\text{median}} \left\{ \frac{p_{t,j}}{f(y_j)\,A_j} \right\}$$

Computing derivatives: back to the concepts

Idea of area-median subtraction:



pile-up $\propto \rho \times$ ghosts

Computing derivatives: back to the concepts

Idea of area-median subtraction:

pile-up ghosts

$$\{p_i^\mu\} \propto \rho \times \{g_i^\mu\}$$

Computing derivatives: back to the concepts

Idea of area-median subtraction:

pile-up ghosts

$$\{p_i^\mu\} \sim \rho \times \{g_i^\mu\}\,\frac{a_{\mathrm{ghost}}}{\bar{g}_t}$$

The set of ghosts mimics the uniform background

$\longrightarrow$ use that to compute the derivatives numerically

$\bar{g}_t =$ ghost $p_t =$ ghostscale

Jet shape subtraction

No pileup: $s_{\rm noPU}(\text{jet}) = s(\{p_{t,i}\}_{\rm hard})$

With pileup: $s_{\rm wPU}(\text{jet}) = s(\{p_{t,i}\}_{\rm hard}, \{p_{t,i}\}_{\rm PU})$

- Assume $\rho \ll p_t$ and expand in series of ρ
- PU $\propto$ ghosts $\Rightarrow \partial_\rho \propto \partial_{\rm ghostscale}$
- numerically: vary the ghost scale to compute the derivatives

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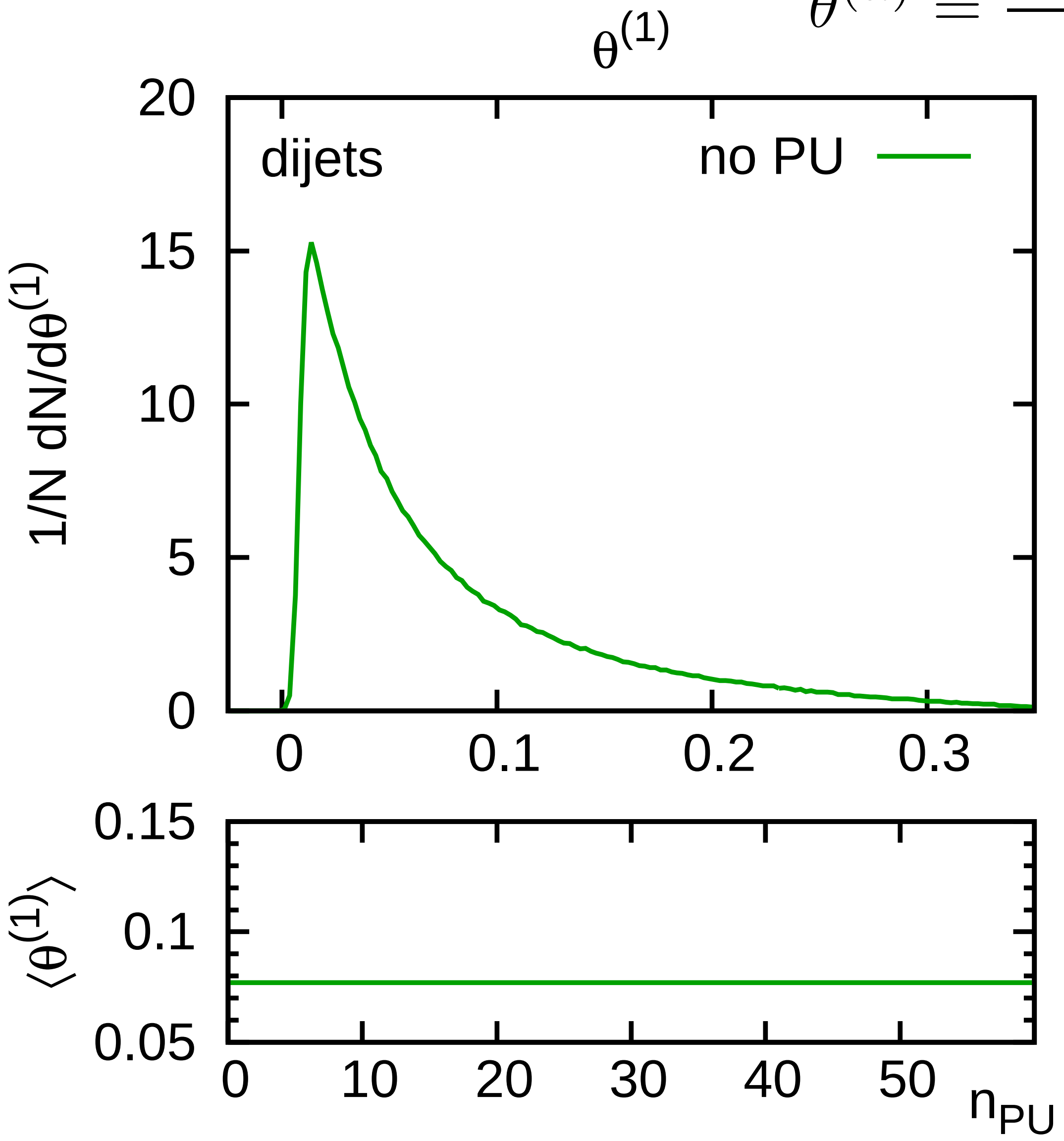
Subtraction:

$$\begin{aligned} s_{\rm sub}(\text{jet}) &= s_{\rm wPU}(\text{jet}) - \rho\, a_{\rm ghost}\, \partial_{\rm ghostscale} s_{\rm wPU}(\text{jet}) \\ &+ \frac{1}{2}(\rho\, a_{\rm ghost})^2\, \partial^2_{\rm ghostscale} s_{\rm wPU}(\text{jet}) + \dots \end{aligned}$$

detailed example: angularities

$$\theta^{(\alpha)} = \frac{\sum_{i\in\text{constits}} p_{t,i} \Delta R_{i,\text{jet}}^{\alpha}}{\sum_{i\in\text{constits}} p_{t,i}}$$



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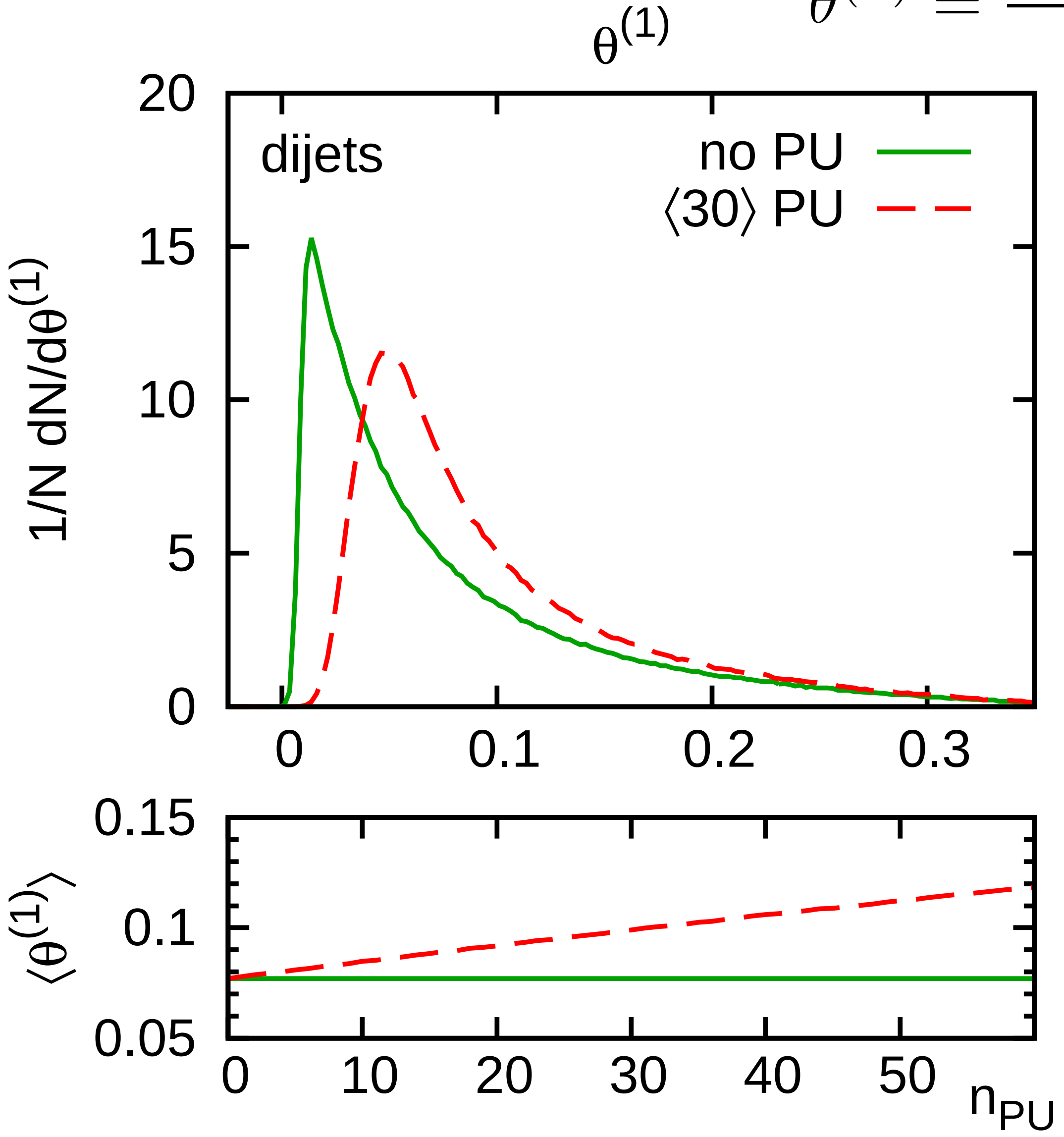

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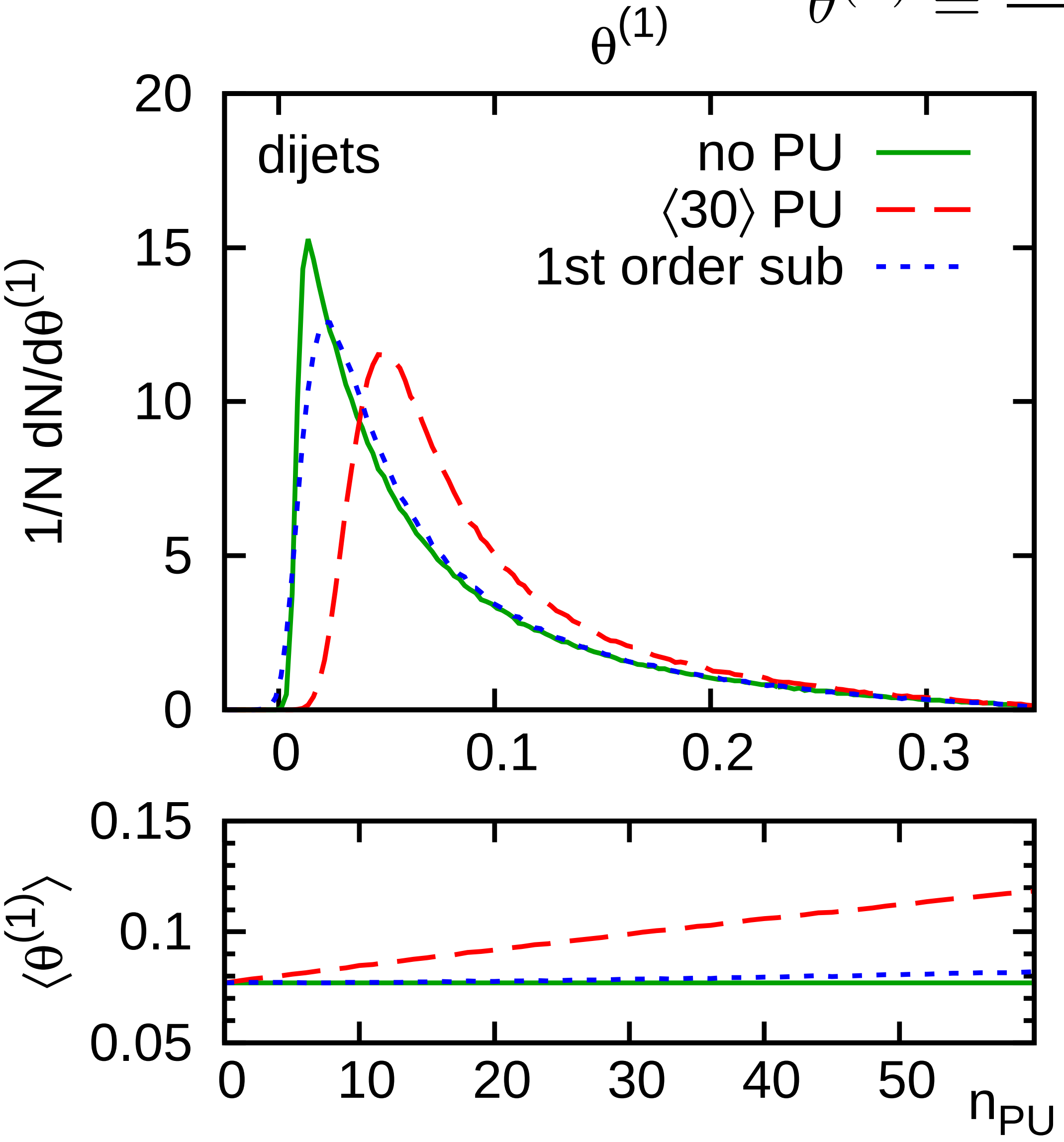

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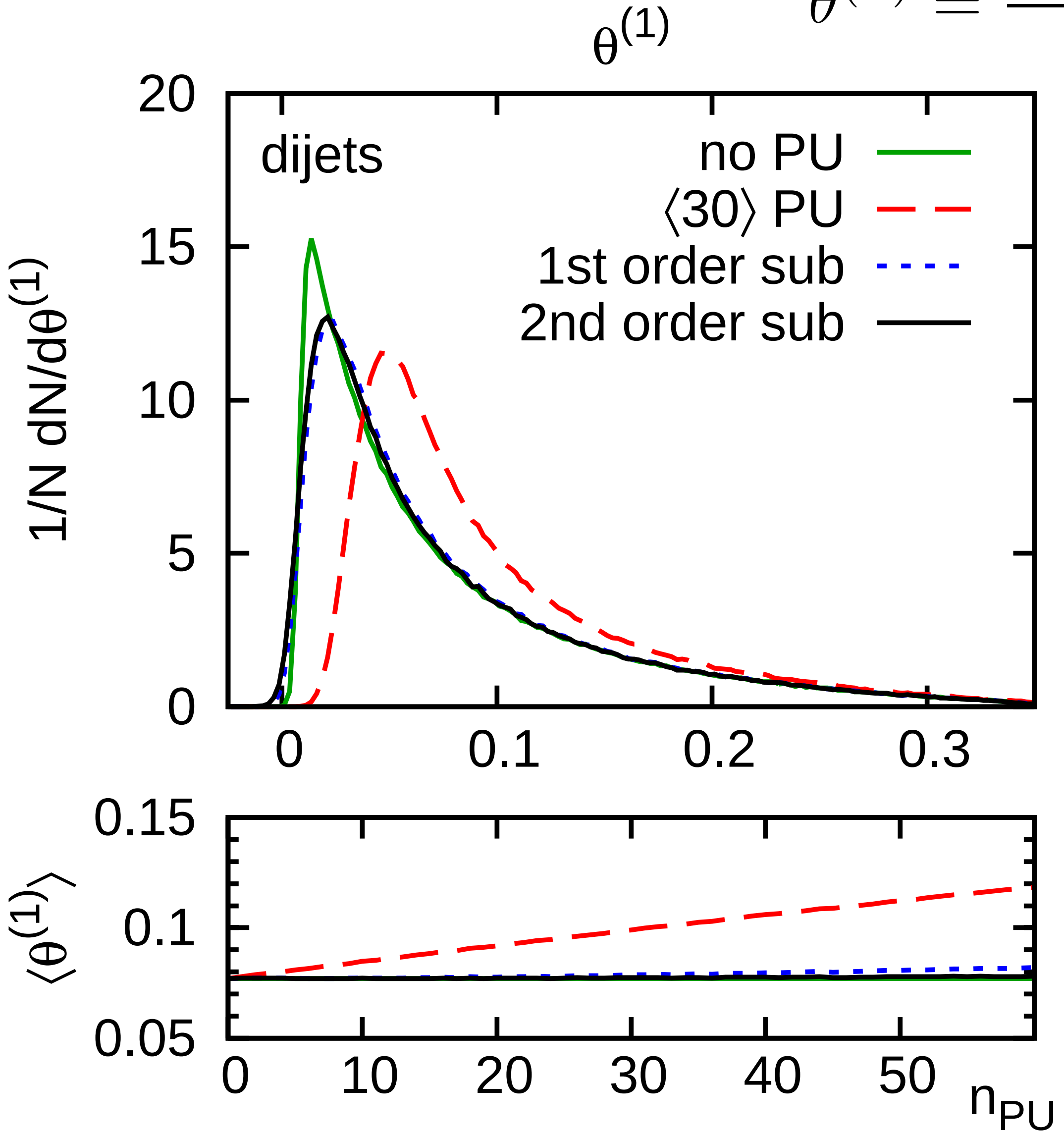
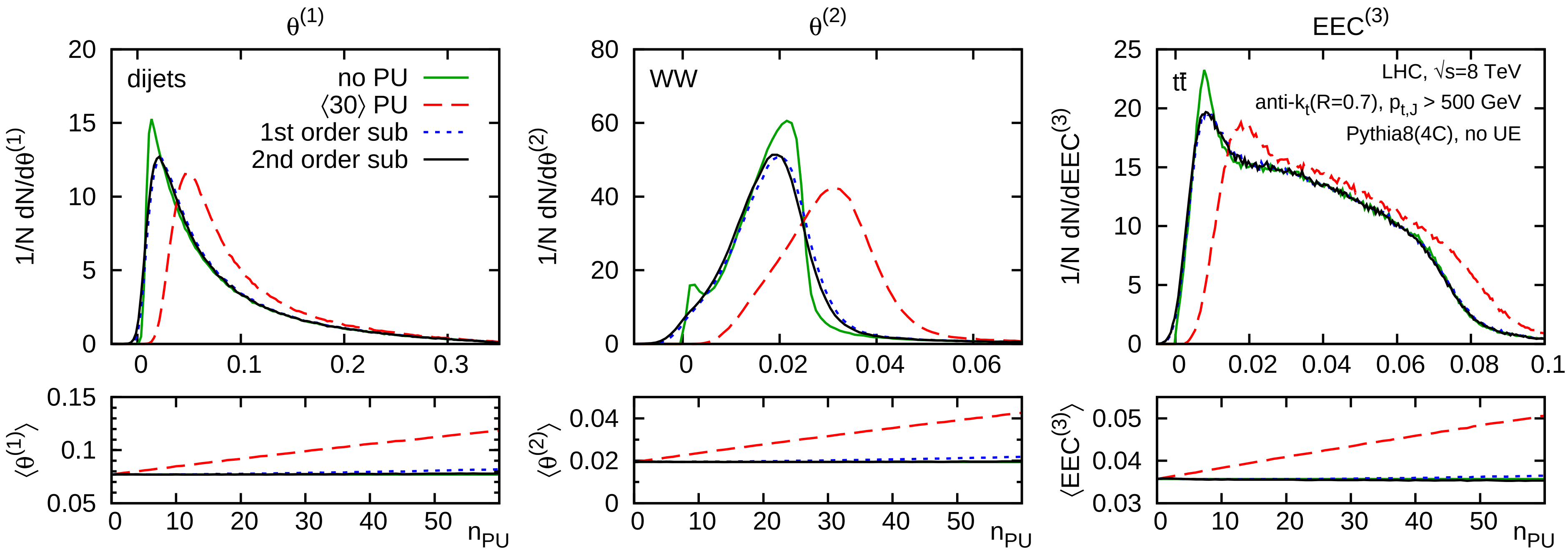
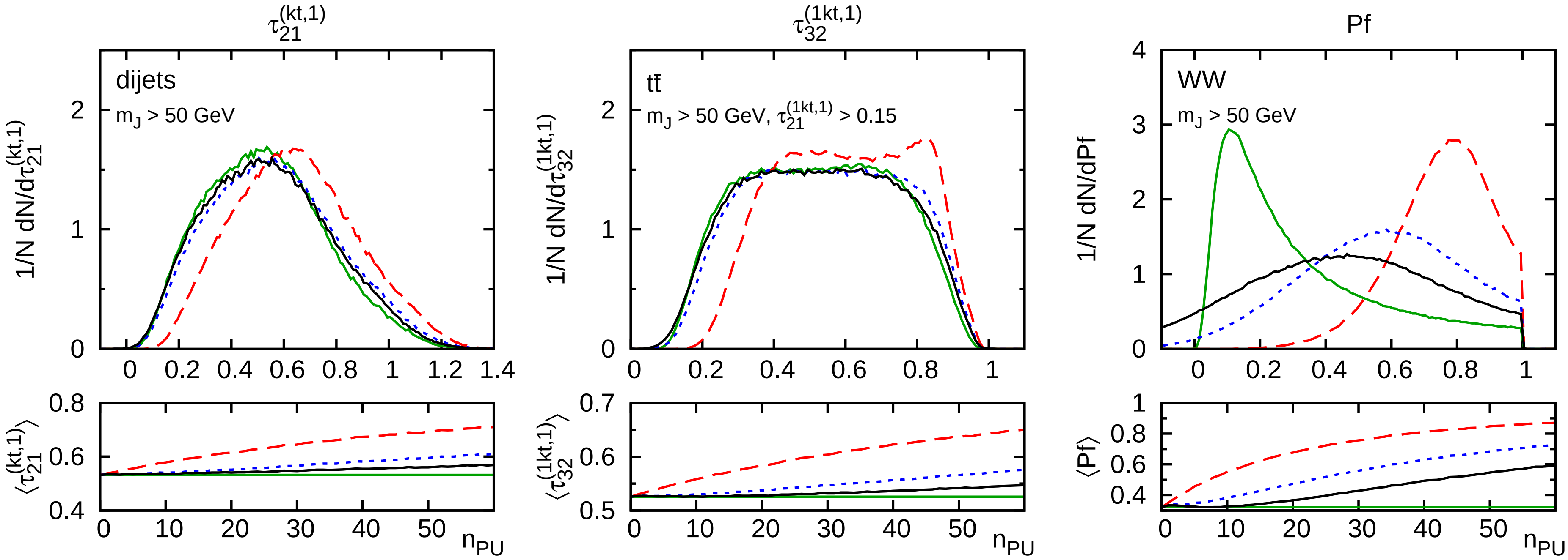


Shape subtraction examples (1/2)



- PU has a 50-100% effect (5-10% for p_t)
- Subtraction works (very) well generically
- Broadening of sharp peaks (PU fluctuations!)

Shape subtraction examples (2/2)



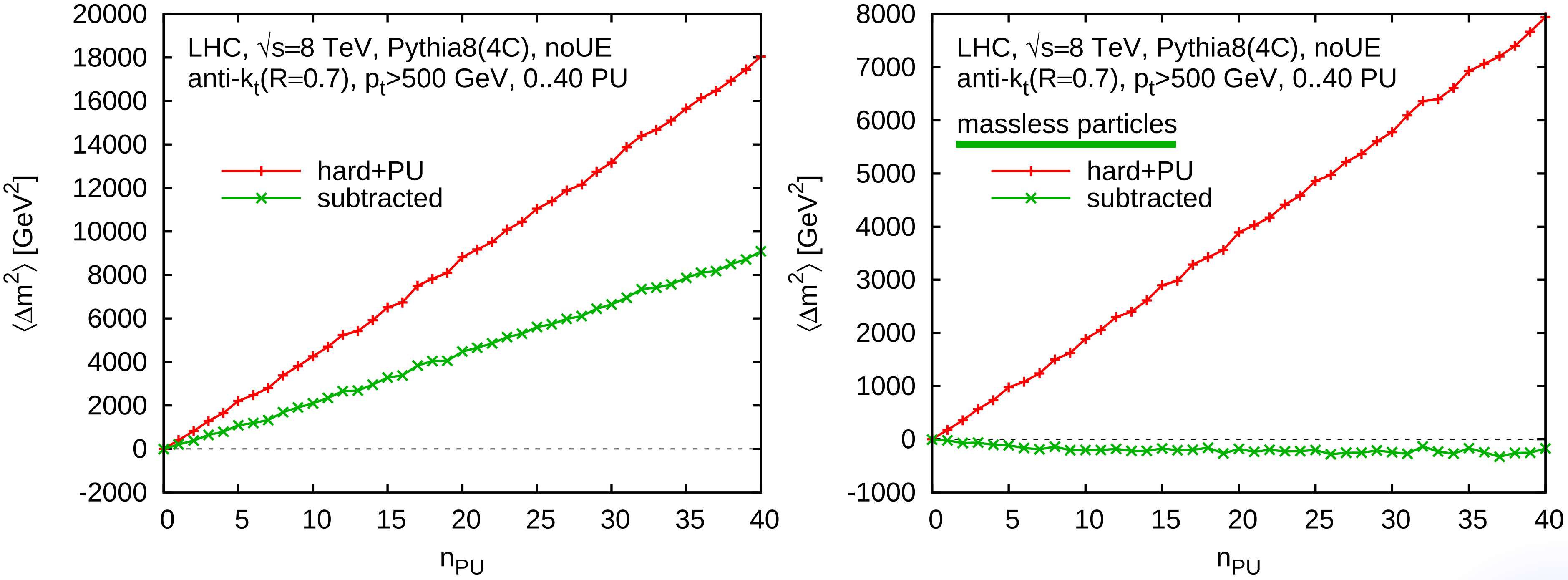
- 2nd derivative sometimes helpful
- Planar flow very poor
  - very PU-sensitive! (from $Pf = 0$ to $Pf = 1$)
  - series expansion breaks for $n_{\rm PU} \gtrsim 15$

Jet mass: the problem

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

applies to the jet 4-momentum

How do we do for the jet mass?



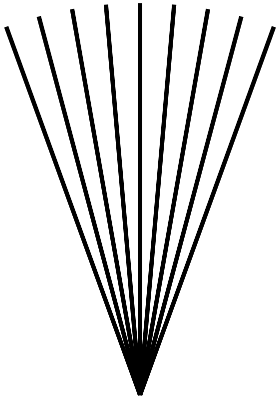
OK for massless particles... but if one want massive ones...

Back to the concepts in pictures

area-median subtraction:

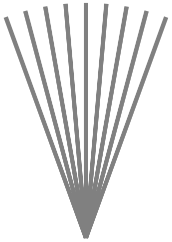
$$m_t = \sqrt{p_t^2 + m^2}$$

pile-up



$$\propto \rho \times$$

ghosts



$$\sum_i p_i^\mu$$

$$(p_t \cos(\phi_i), p_t \sin(\phi_i),$$
$$m_t \sinh(y_i), m_t \cosh(y_i))$$

$$\sum_i g_i^\mu$$

$$g_t(\cos(\phi_i), \sin(\phi_i),$$
$$\sinh(y_i), \cosh(y_i))$$

Need an extra term to account for $m_t \neq p_t$

Back to the concepts: subtraction

New 4-vector subtraction formula:

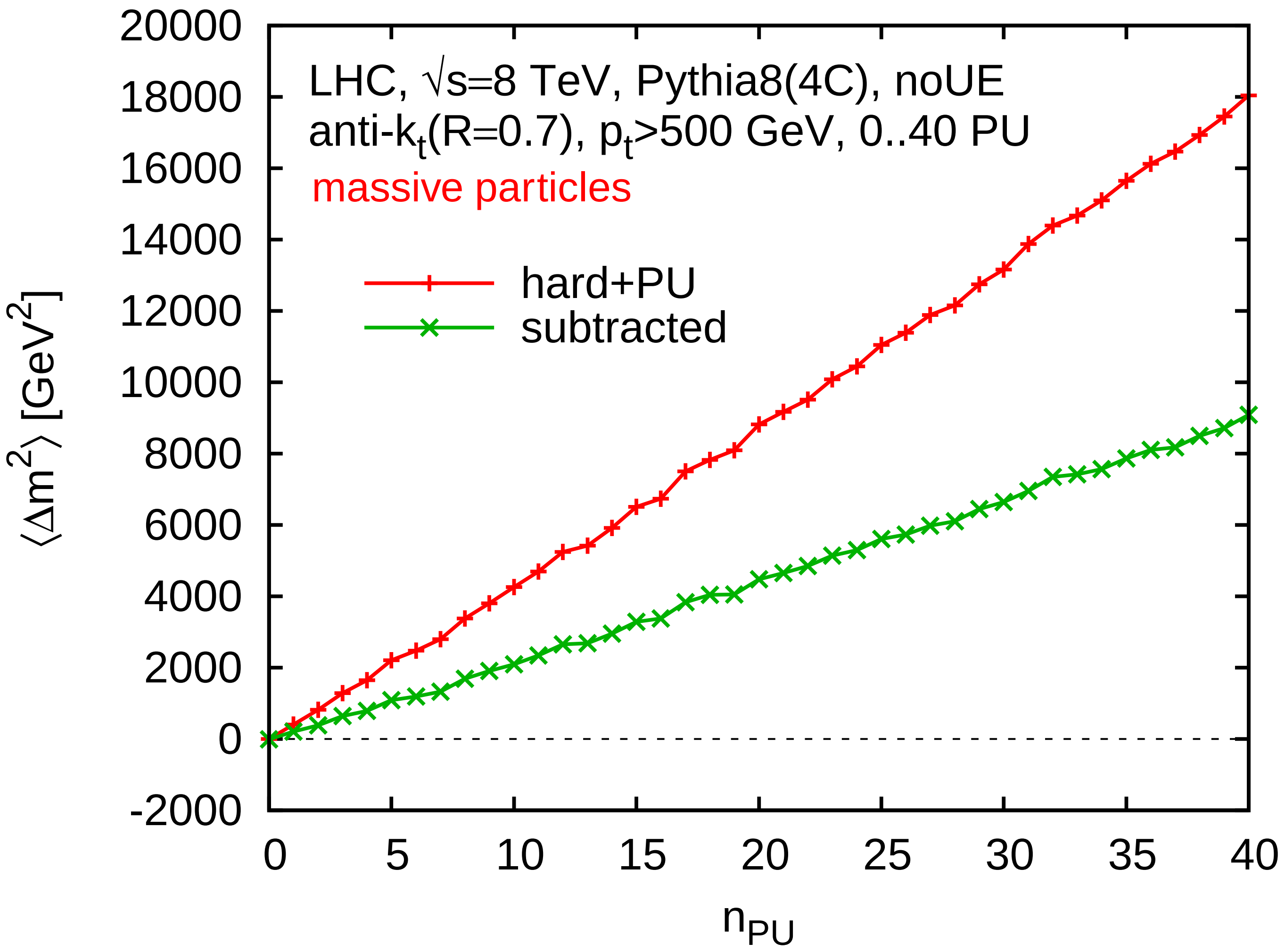
$$p^{\mu}_{\text{sub}} = p^{\mu} - \rho A^{\mu} - \rho_m A^{\mu}_m$$

with

$$\begin{aligned}
\rho &= \operatorname*{median}_{j\in\text{patches}} \left\{ \frac{p_{t,j}}{A_t} \right\} \\
\rho_m &= \operatorname*{median}_{j\in\text{patches}} \left\{ \frac{\sum_{i\in j} m_{t,i} - p_{t,i}}{A} \right\} \\
A^{\mu}_m &\equiv (0, 0, A_z, A_E)
\end{aligned}$$

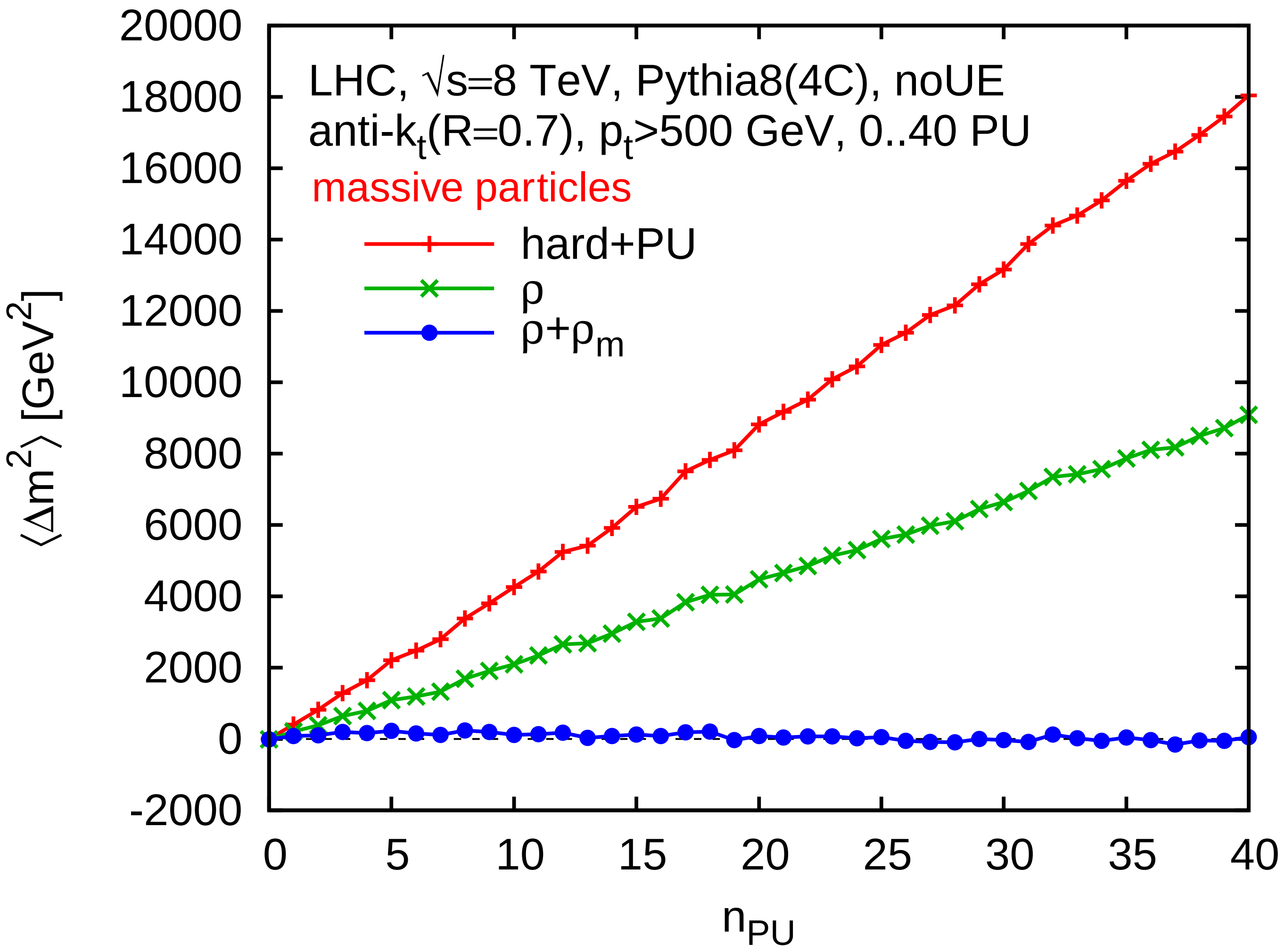
Jet mass subtraction revisited

$$p^{\mu}_{\rm sub} = p^{\mu} - \rho A^{\mu}$$



Jet mass subtraction revisited

$$p^\mu_{\rm sub} = p^\mu - \rho A^\mu - \rho_m A^\mu_m$$



Usage in tools

Subtraction can be used internally in tools

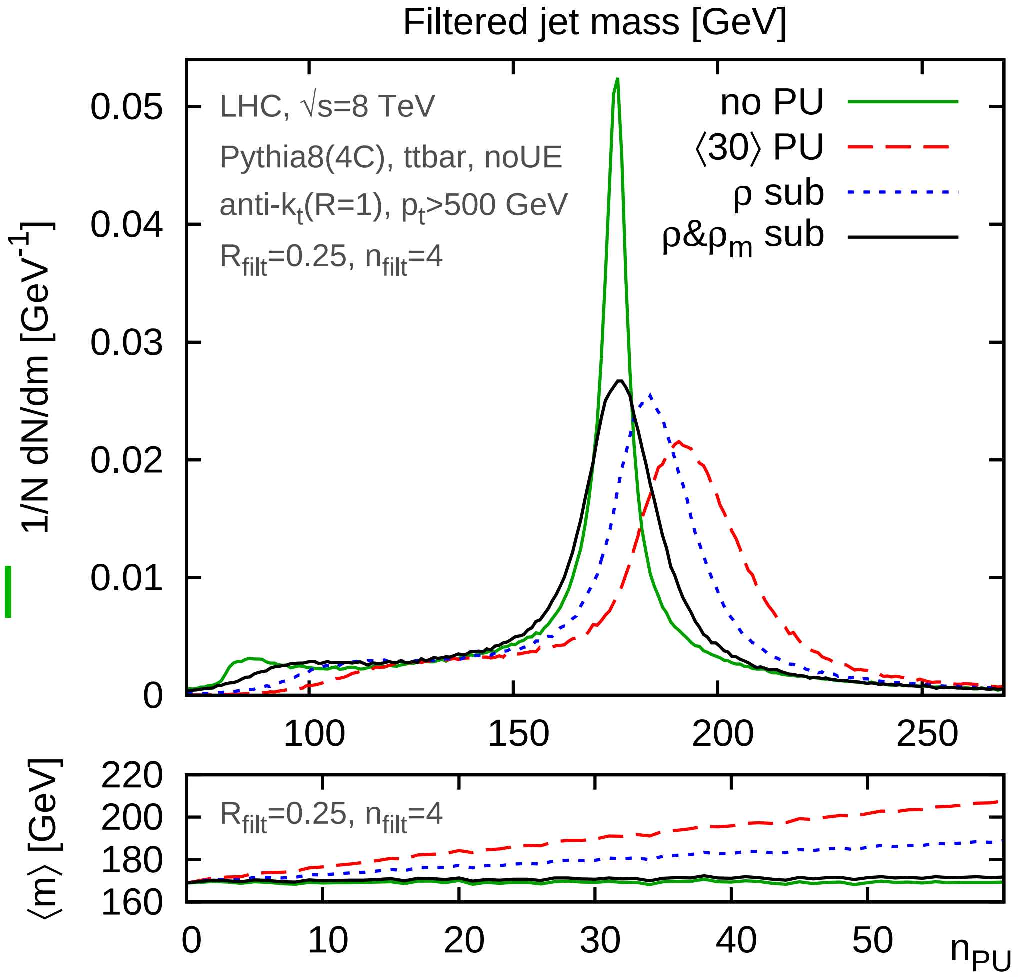
Examples:

- subtract each subjet before selecting the n hardest in filtering
- subtract each subjet before applying the p_t cut in trimming
- subtract at each unclustering step in pruning

Usage in tools

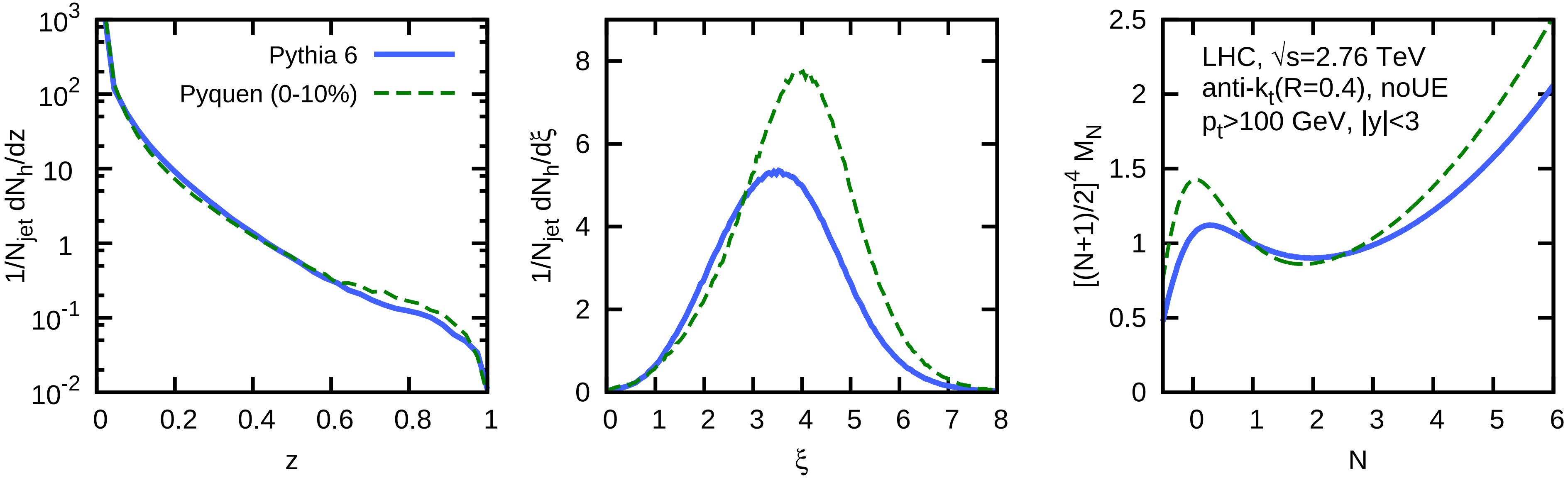
Subtraction can be used internally in tools

grooming+subtraction
can prove very powerful



Fragmentation function in HI

Example ($\xi = \log(1/z)$):



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

“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

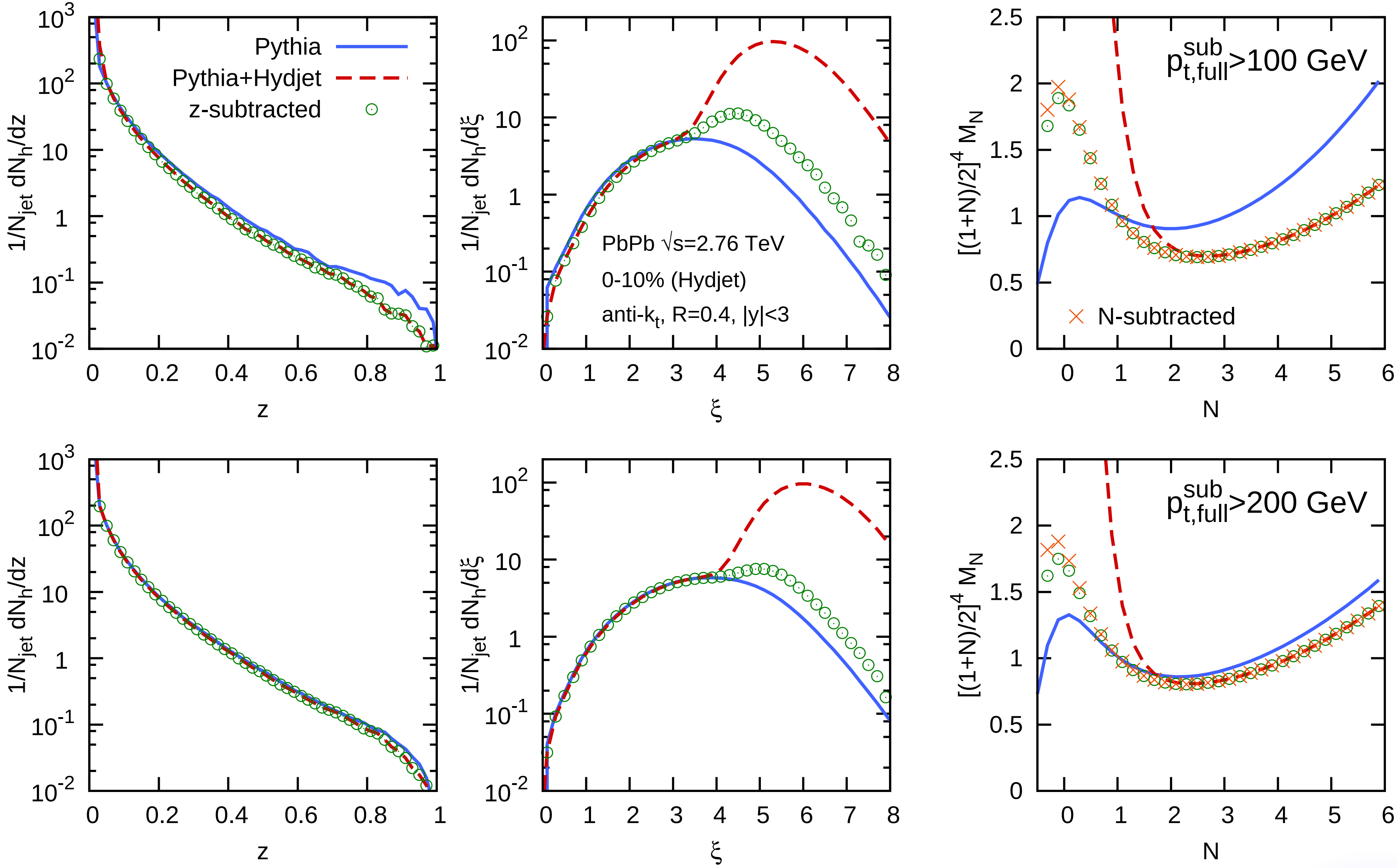
Introduce a new background property ρ_N

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

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



similar improvement for both methods 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:

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

Improved subtraction

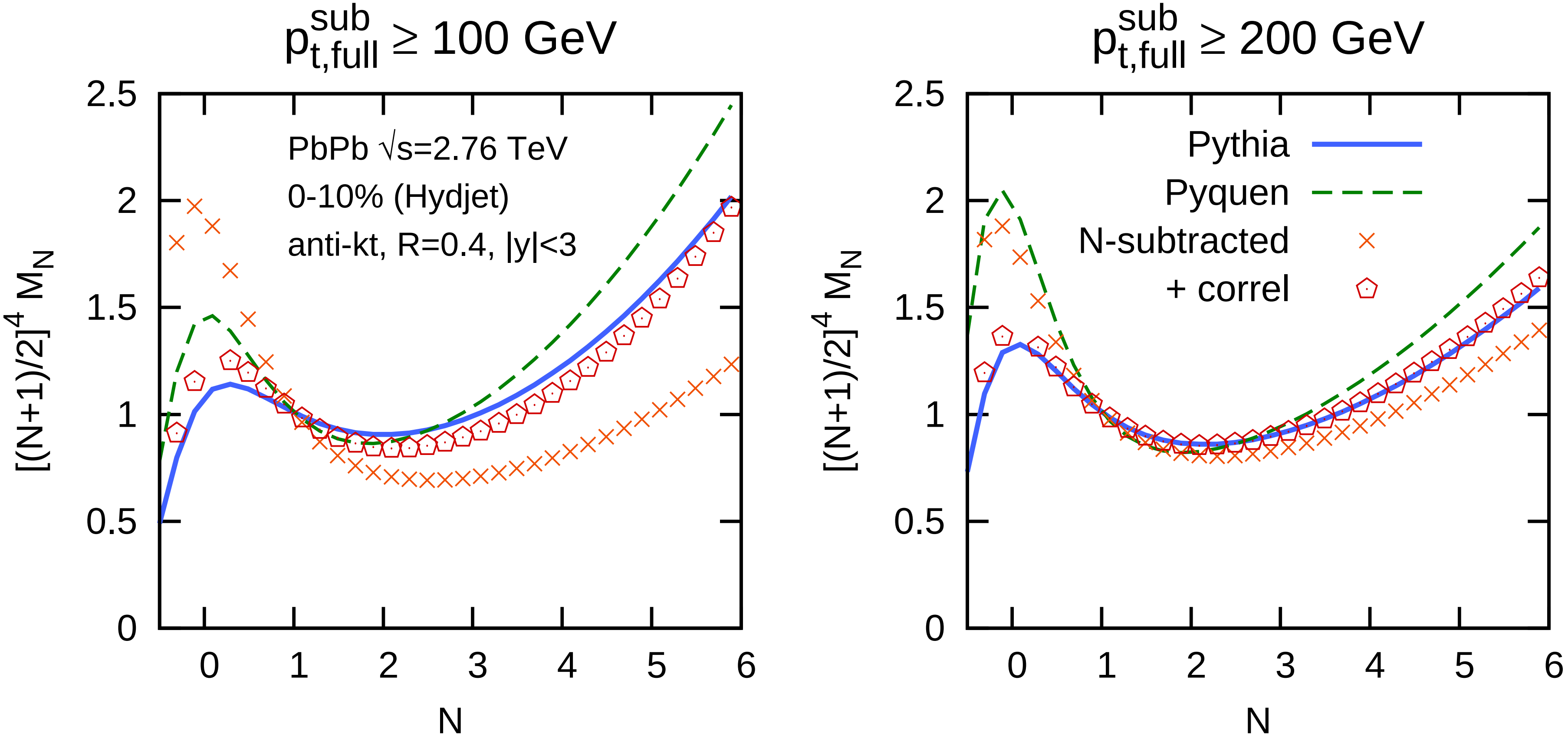
A simple unfolding can be analytically computed in moment space

- assuming fluctuations (σ) are small
- the (unfolded) inclusive jet spectrum locally: $dN/dp_t \propto \exp(-p_t/\mu)$
- statistical info (event-by-event) on fluctuations σ in p_t and σ_N in $\sum p_t^N$ (obtained like ρ and ρ_N)
- info on how fluctuations on $\sum p_t^N$ are correlated to fluctuations in p_t: r_N (from patches in the event)

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

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!