Jets playing hide and seek

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Plan

- e^+e^- collisions:

  the most simple case

- pp collisions:

  jets in hadronic environments

  $\longrightarrow$ 20 years of jet definitions

- pileup:

  jets in the background

  $\longrightarrow$ jet areas, background subtraction

- AA:

  more background!

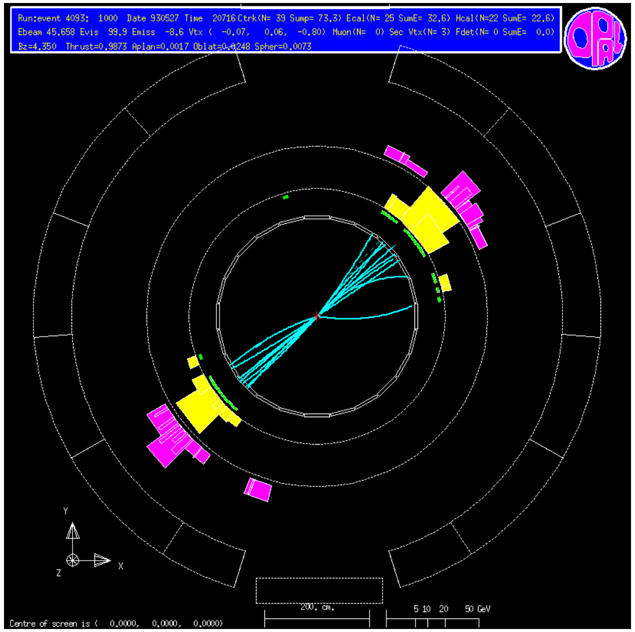
  $\longrightarrow$ improved techniques

Foreword: what are jets?

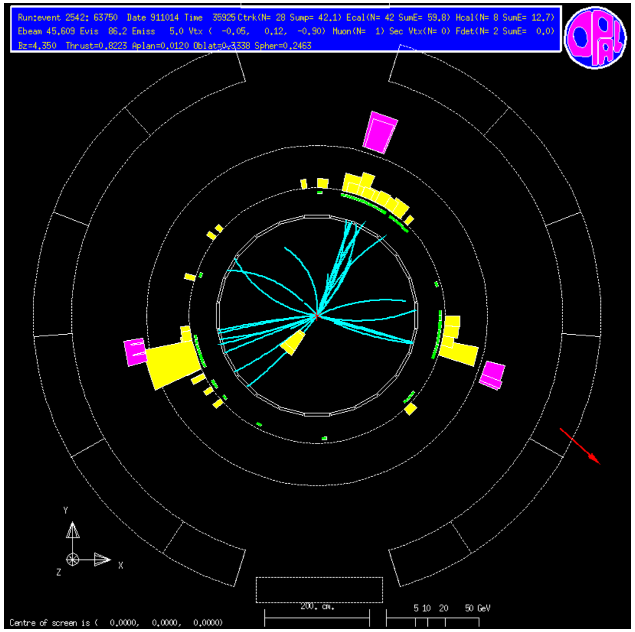
QCD collinear divergence ⟶ collimated showers

$$\mathrm{d}P \propto \alpha_s \frac{\mathrm{d}\theta}{\theta}$$

Example: LEP (OPAL) events



2 jets



3 jets

Idea: jet $\equiv$ collimated shower $\simeq$ initial hard partons

Foreword: what are jets?

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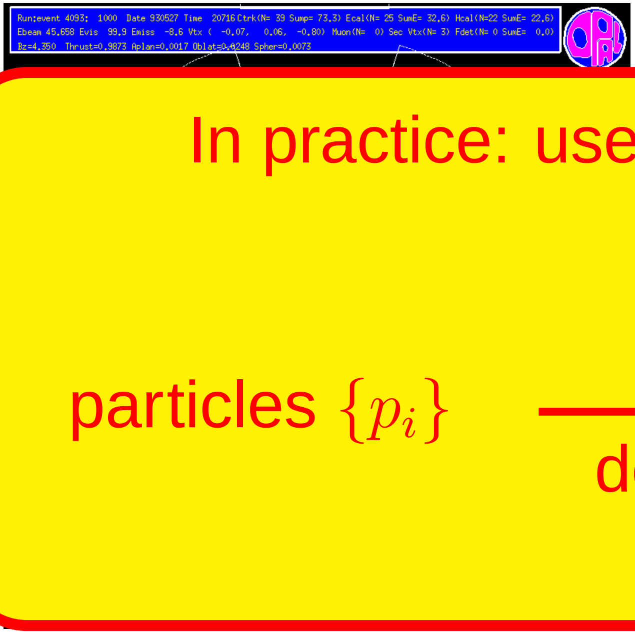
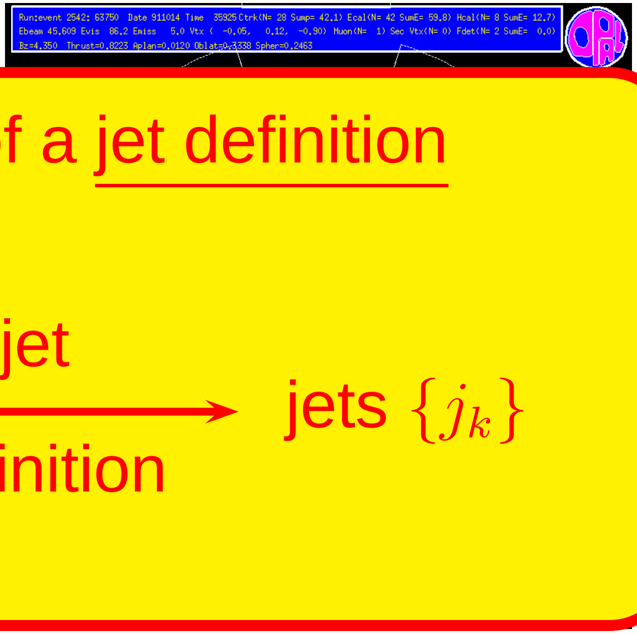
Example: LEP (OPAL) events



2 jets



3 jets

In practice: use of a jet definition

$$\text{particles } \{p_i\} \xrightarrow[\text{definition}]{\text{jet}} \text{jets } \{j_k\}$$

Idea: jet $\equiv$ collimated shower $\simeq$ initial hard partons

Foreword: an illustrative example

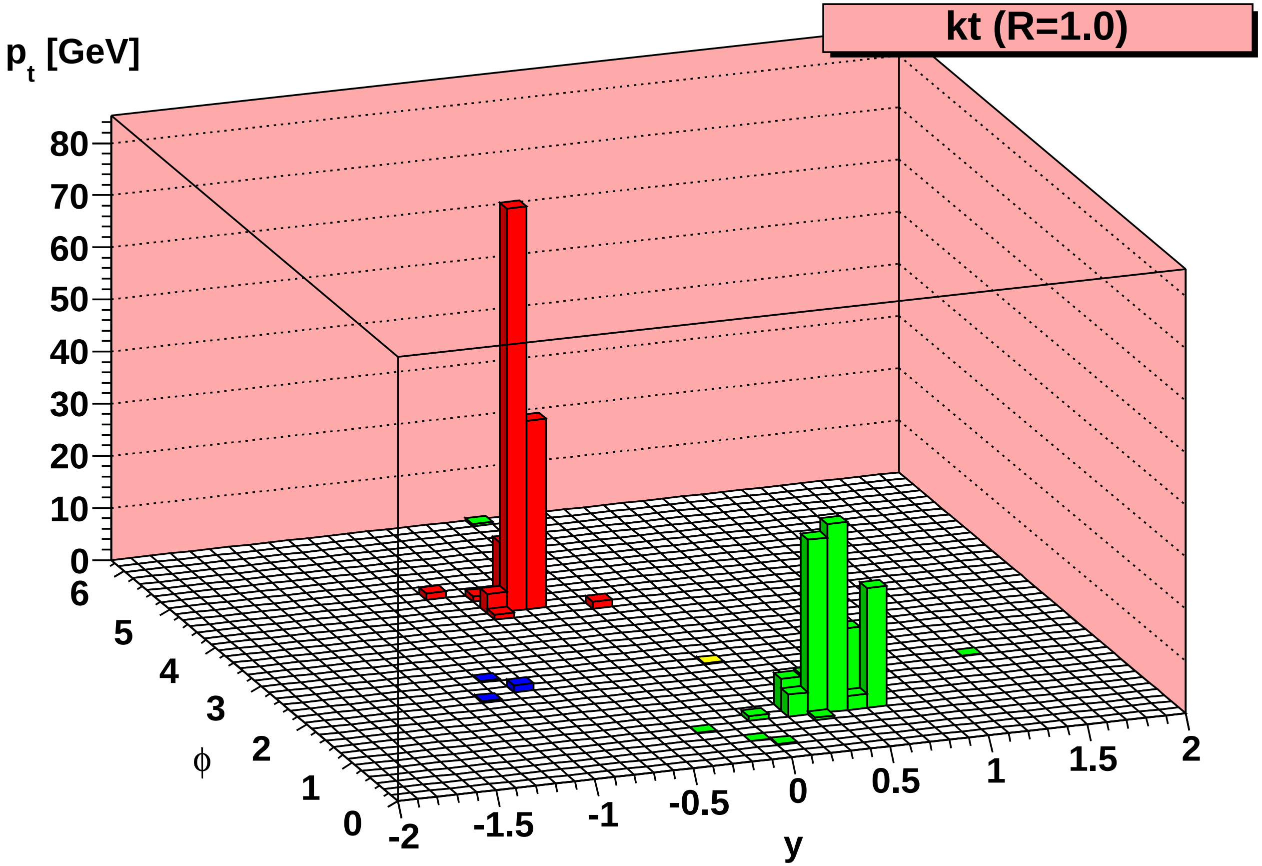
Example process to illustrate various effects:

$$Z' \to q\bar{q} \to 2 \text{ jets}$$

- $M_{Z'} = 300$ GeV (width < 1 GeV)
- 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

Part 1

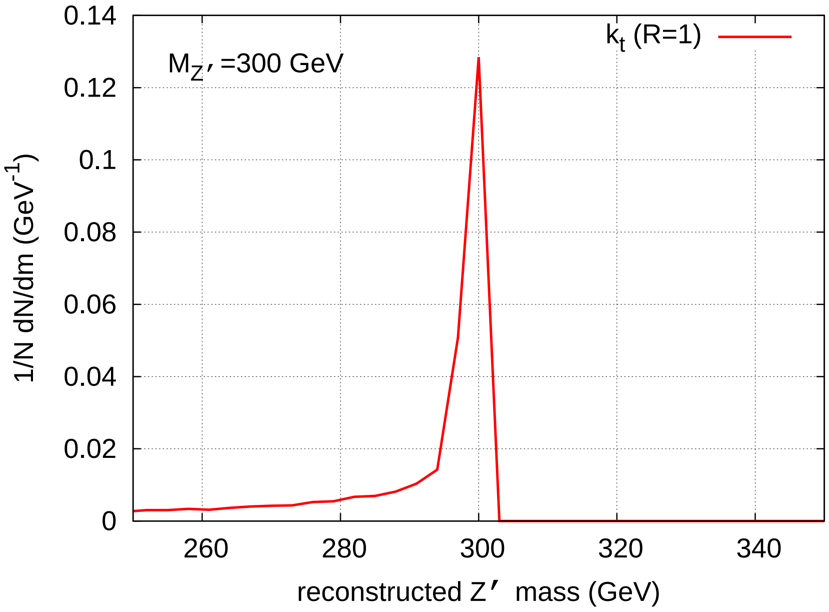
e^+e^- collisions: the most simple case



Recombination algorithms

Recipe:

- find the pair (i,j) with the smallest d_{ij} distance
- recombine i and j
- repeat (until objects more than R apart)



Distance: k_t algorithm

$$d_{ij} = \min(E_i^2, E_j^2)[1 - \cos(\theta_{ij})]$$

- $d_{ij} \rightarrow 0$ for soft and collinear splittings

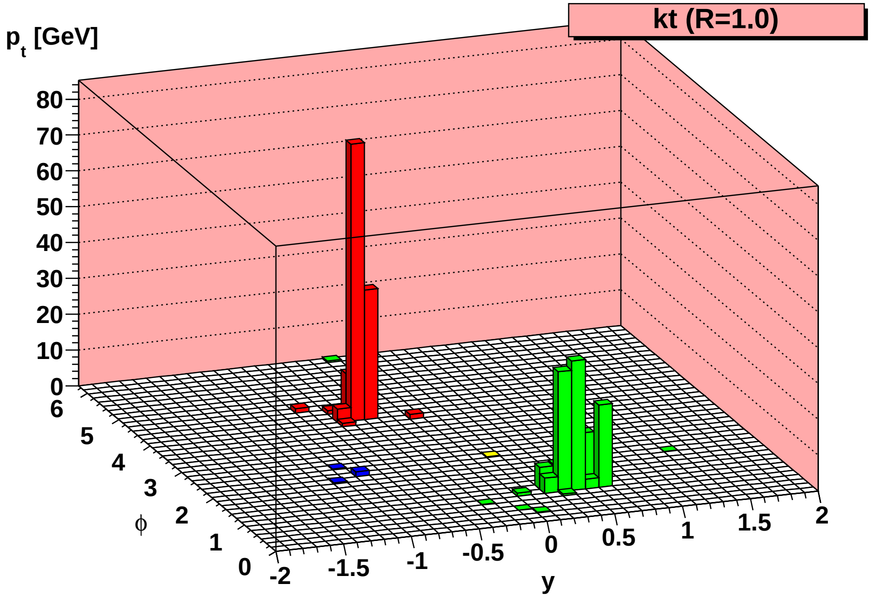
$$\mathrm{d}P = \alpha_s \frac{\mathrm{d}\theta}{\theta} \frac{\mathrm{d}p_t}{p_t}$$

- without the prefactor: Cambridge/Aachen or Durham algorithm

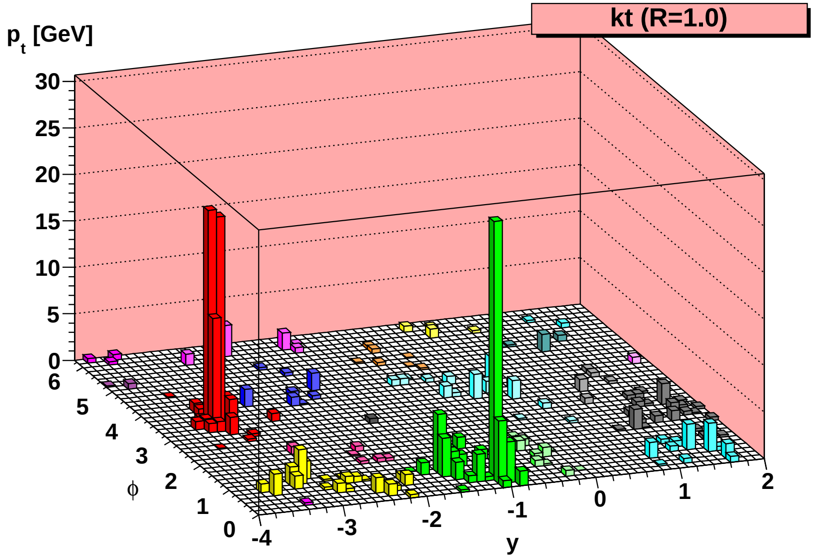
Part 2

pp collisions: jets in hadronic environments

e^+e^-



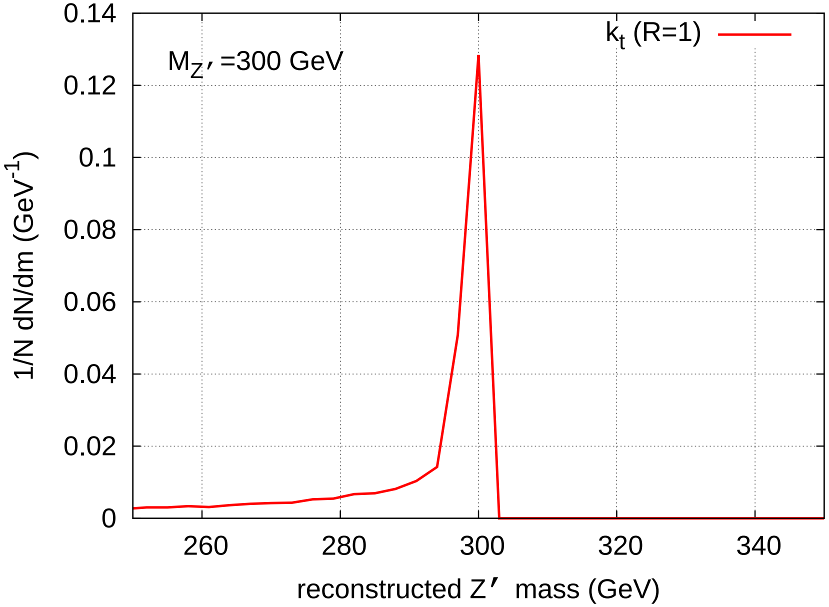
pp



$$d_{ij} = \min(E_i^2, E_j^2)[1 - \cos(\theta_{ij})] \qquad d_{ij} = \min(k_{t,i}^2, k_{t,j}^2)(\Delta y_{ij}^2 + \Delta\phi_{ij}^2)$$

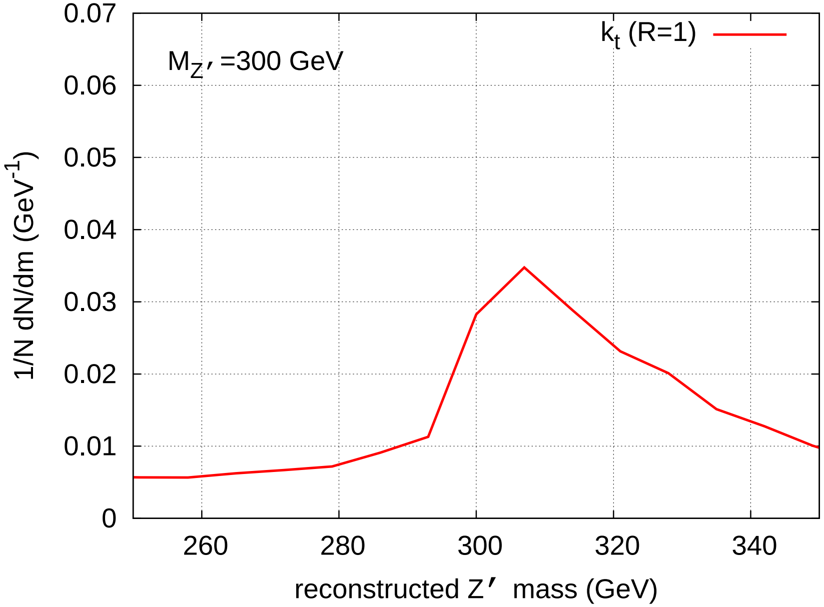
Our example: moving to jets in pp

e^+e^-



width = 0.9 GeV

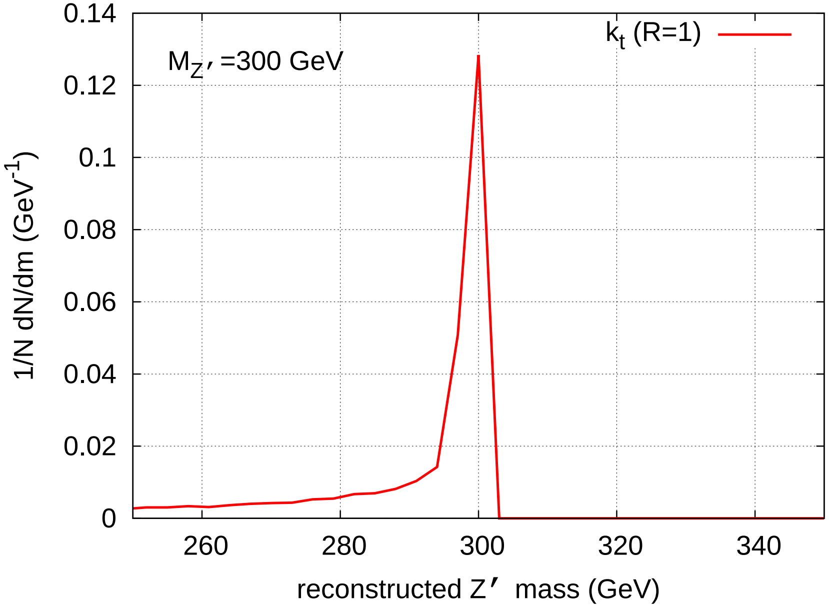
pp



width = 19.7 GeV

Our example: moving to jets in pp

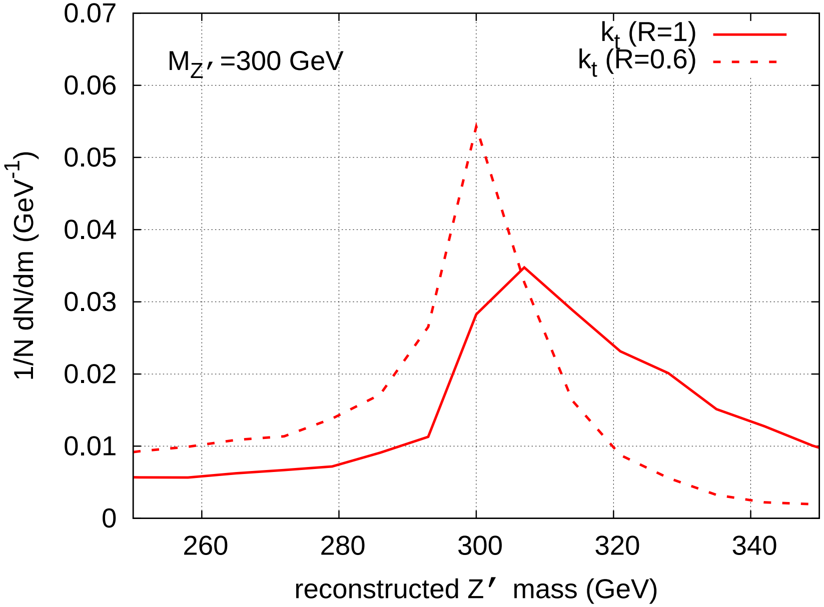
e^+e^-



width = 0.9 GeV

- Reduce R

pp

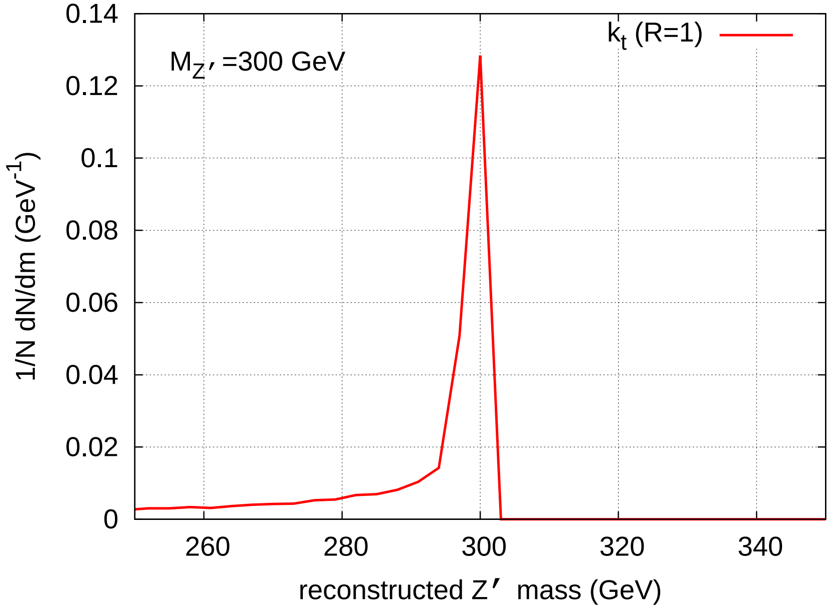


width = 19.7 GeV

width = 14.2 GeV

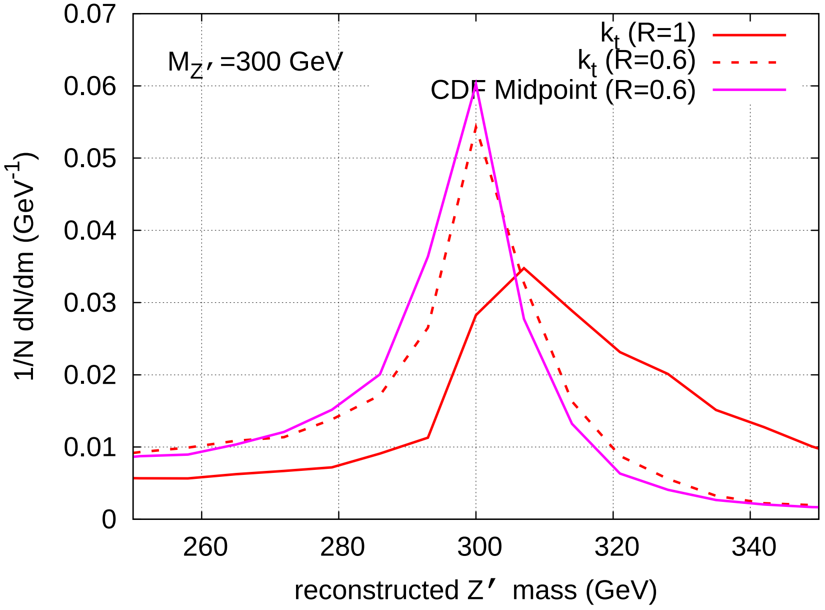
Our example: moving to jets in pp

e^+e^-



width = 0.9 GeV

pp



width = 19.7 GeV

width = 14.2 GeV

width = 11.8 GeV

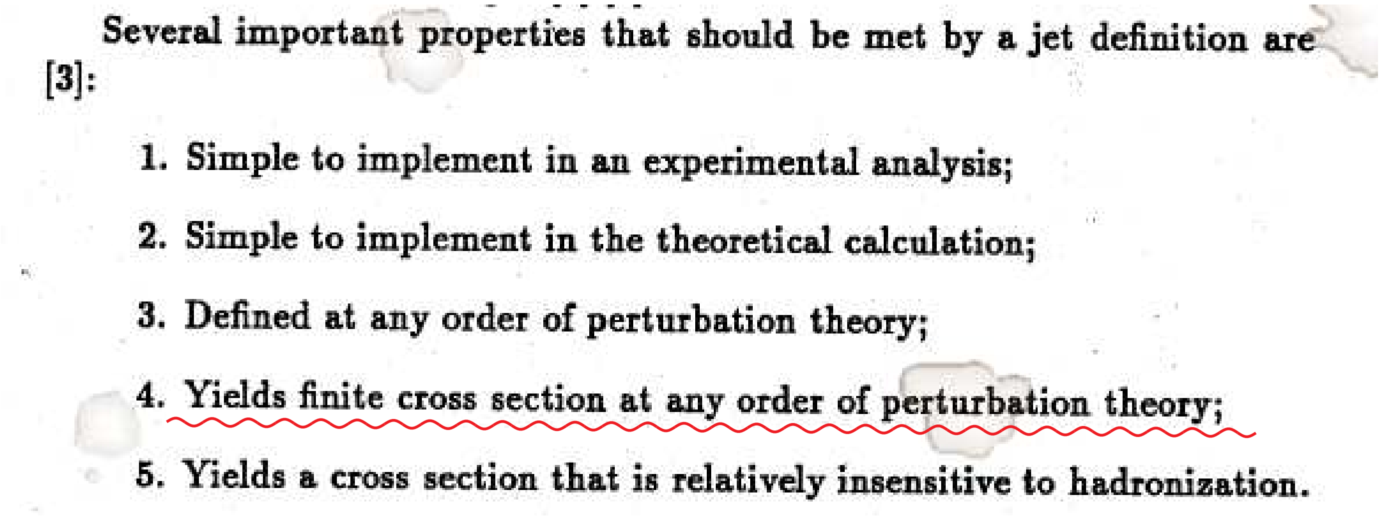
- Reduce R
- Use the cone algorithm

The cone algorithm

- Idea: find directions of energy flow
- Stable cone (fixed radius R):
  sum of all constituents points in the direction of the centre
- Search: iterate from initial directions (seeds)
- Stable cones $\rightarrow$ jets: deal with overlaps
  - Solution 1: split/merge depending on the amount of overlap
    Examples: CDF JetClu, CDF MidPoint, D0 runII, ATLAS Cone
  - Solution 2: progressive removal starting from the hardest seed
    Examples: CMS Iterative Cone
    Benchmark: circular/rigid jets

Constraints

1990: SNOWMASS accords – constraints to fulfil



Several important properties that should be met by a jet definition are [3]:

1. Simple to implement in an experimental analysis;
2. Simple to implement in the theoretical calculation;
3. Defined at any order of perturbation theory;
4. Yields finite cross section at any order of perturbation theory;
5. Yields a cross section that is relatively insensitive to hadronization.

Infrared and collinear (IRC) safety:

- ✓ recombination algorithms: Ok
- ✗ Cone: problem inherent to the “seeded” search of stable cones

New algorithms

- Cone with split–merge
  - Idea: Find an efficient seedless implementation that provably identifies all stable cones
  - Solution: SISCone: Seedless Infrared-Safe Cone

[G.Salam, GS, 07]

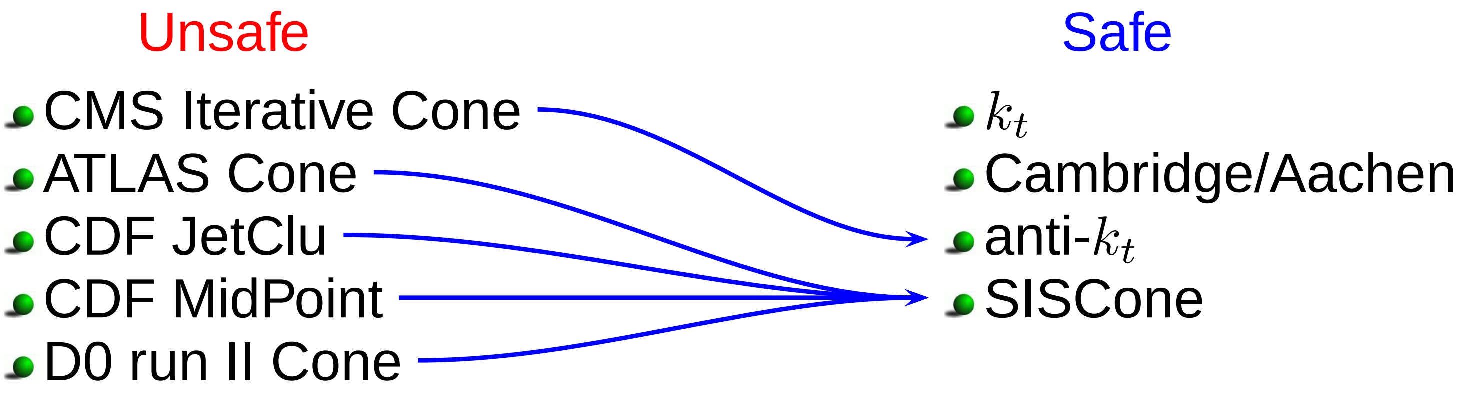
- Cone with progressive removal
  - Idea: keep the rigidity of the jets + restore IRC-safety
  - Solution: anti-k_t:

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

[M.Cacciari, G.Salam, GS, 08]

Impact of these new algorithms

Summary



Unsafe

- CMS Iterative Cone
- ATLAS Cone
- CDF JetClu
- CDF MidPoint
- D0 run II Cone

Safe

- k_t
- Cambridge/Aachen
- anti-k_t
- SISCone

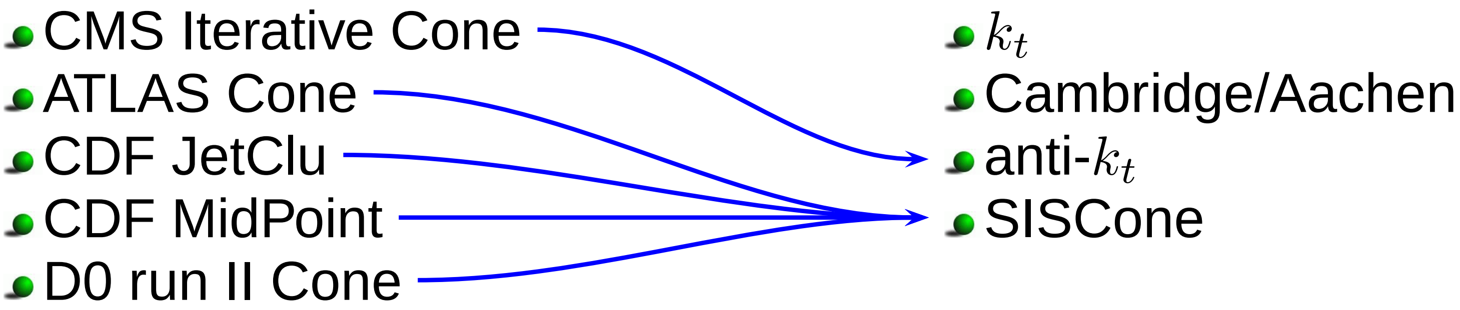
Impact

Observable	Last meaningful order
Inclusive jet cross section	NLO
3 jet cross section	LO (NLO in NLOJet)
$W/Z/H$ + 2 jet cross sect.	LO (NLO in MCFM)
jet masses in 3 jets	none (LO in NLOJet)

! Huge effort (~ 100 M$) to compute processes in pQCD

Impact of these new algorithms

Summary



Unsafe

- CMS Iterative Cone
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- CDF JetClu
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Safe

- k_t
- Cambridge/Aachen
- anti-k_t
- SISCone

Impac

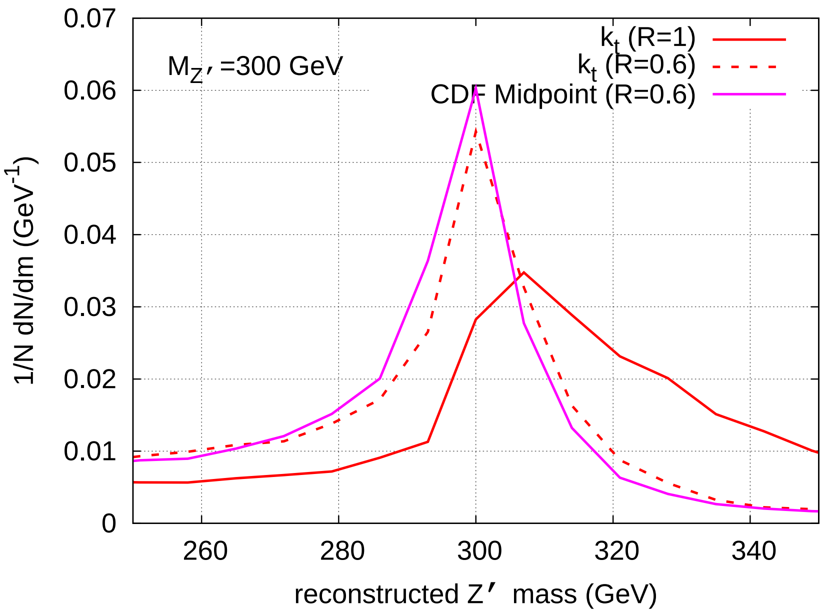
```
#--------------------------------------------------------------------------
#                        FastJet release 2.4
#        Written by M. Cacciari, G.P. Salam and G. Soyez
#                       http://www.fastjet.fr
#--------------------------------------------------------------------------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

All those algorithms (and much more) implemented in FastJet

processes in pQCD

Our example: safe jet definitions

1990

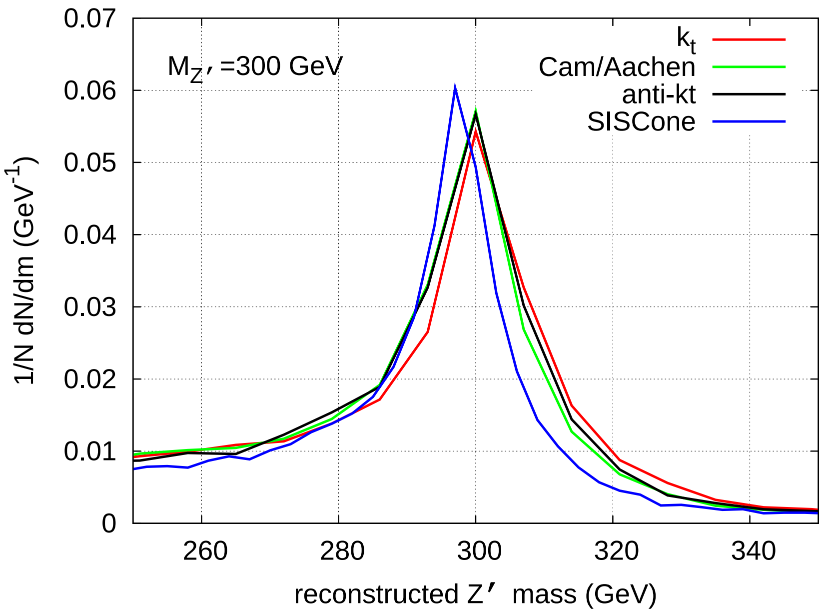


width = 19.7/14.2 GeV

width = 11.8 GeV

For the width
SISCone slightly preferred

2009



width = 14.2 GeV

width = 12.2 GeV

width = 13.1 GeV

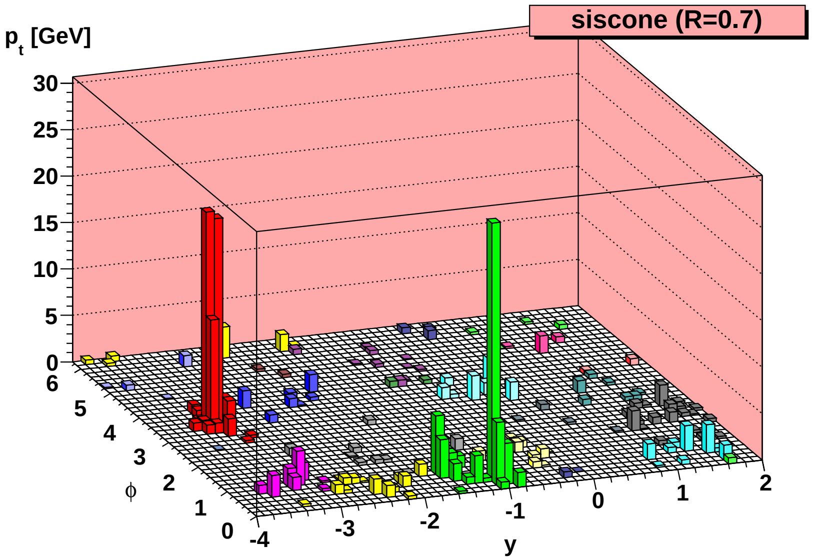
width = 11.6 GeV

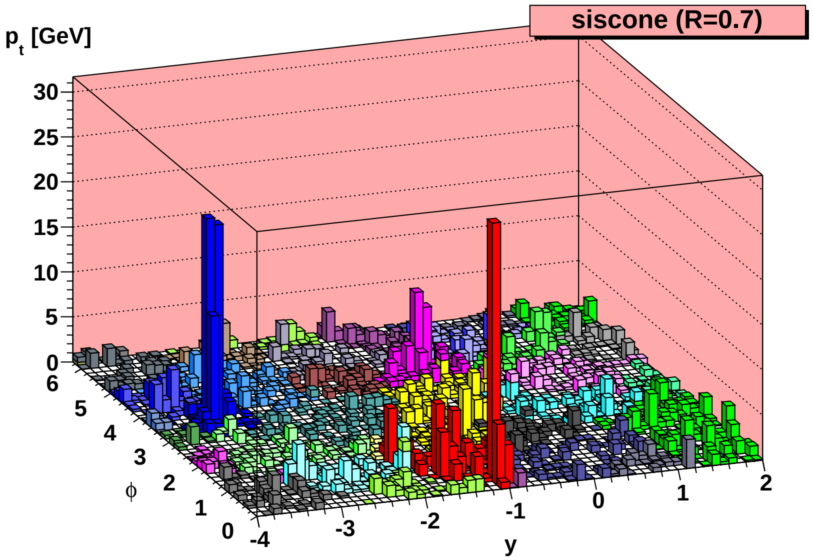
Part 3

pileup: jets in the background

No pileup

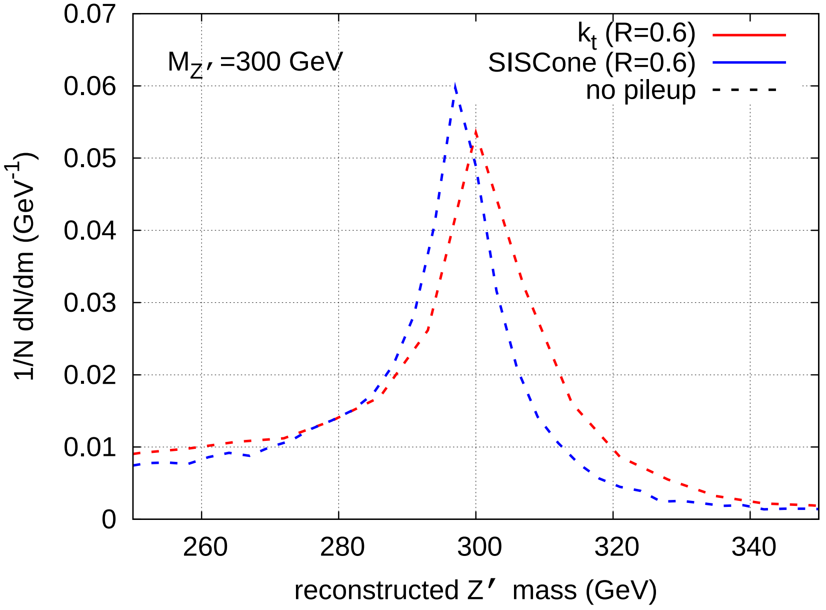
With pileup





Our example: the effect of pileup

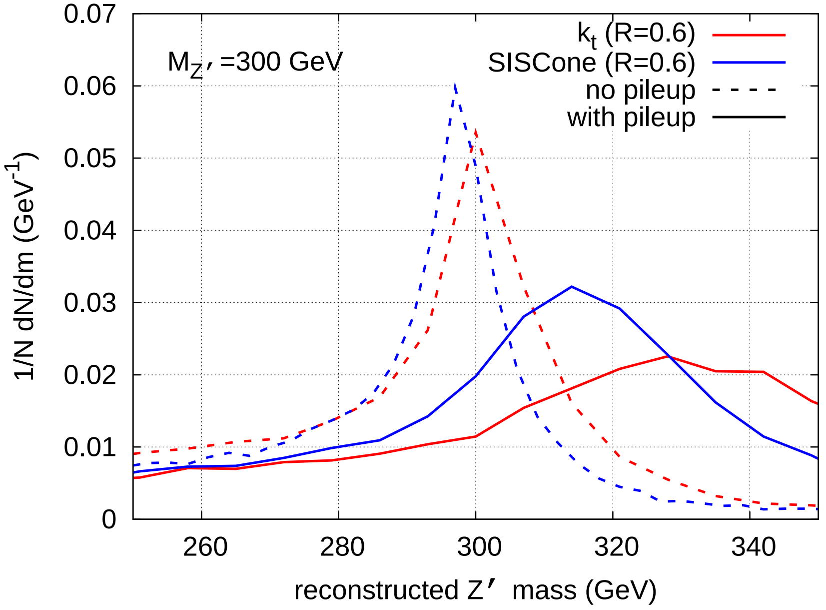
No pileup



width = 14.2 GeV

width = 11.6 GeV

With pileup



width = 29.5 GeV

width = 21.0 GeV

- ✗ shifted towards larger masses
- ✗ width increased

Jet areas

[M.Cacciari, G.Salam, GS, 08]

Area $\equiv$ 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 $\approx$ background particle

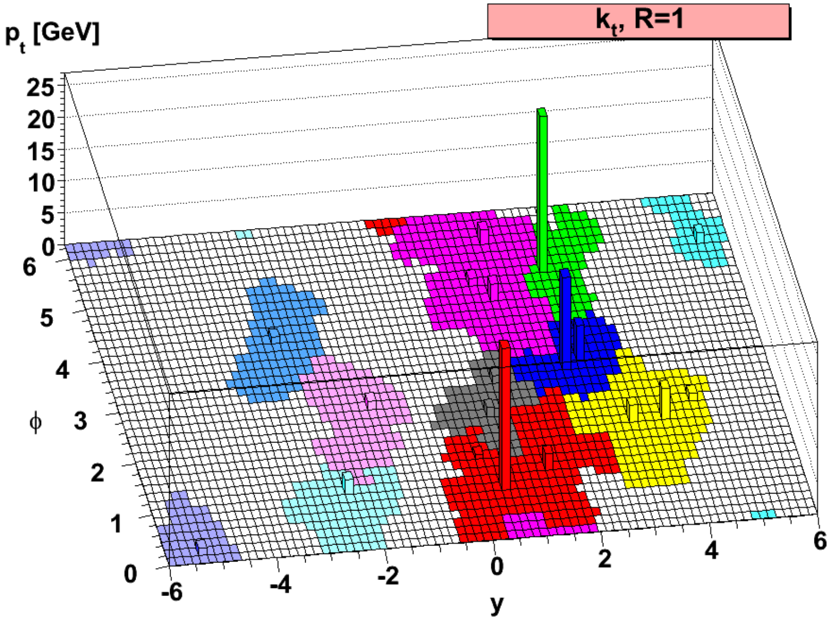
  $\Rightarrow$ active area $\approx$ uniform background

  passive area $\approx$ pointlike background
- Notes:
  - passive = active for large multiplicities
  - require an IR-safe algorithm!

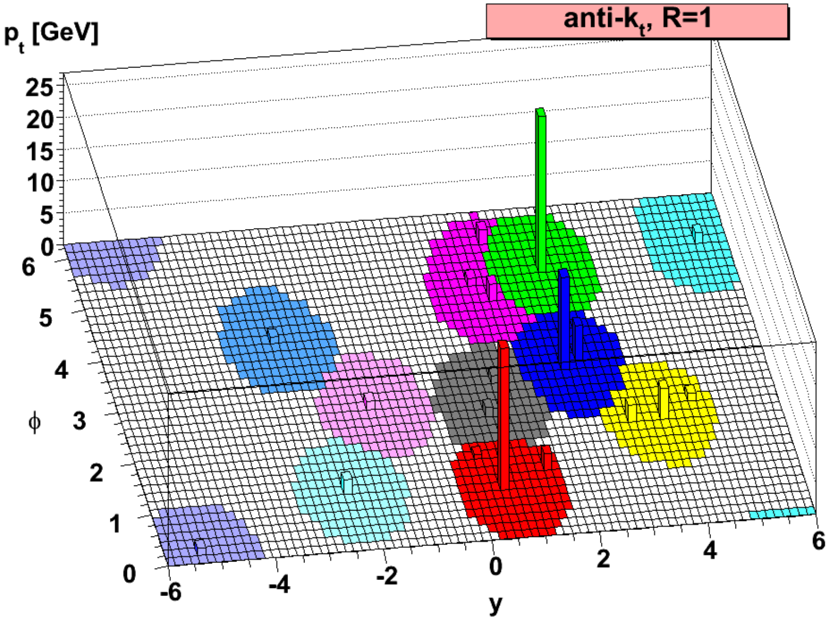
Jet area: examples

Example: active area for a simple event

k_t



anti-k_t



one ghost at every grid cell

Note: analytic control

Example: perturbative expansion of areas (at order α_s)

$$\langle \mathcal{A}(p_t, R)\rangle = \mathcal{A}_0 + \frac{C_{F,A}}{b_0 \pi} \pi R^2 \, d \, \log\left(\frac{\alpha_s(Q_0)}{\alpha_s(Rp_t)}\right)$$

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

	$\mathcal{A}_0/(\pi R^2)$		d	
	passive	active	passive	active
k_t	1	0.81	0.56	0.52
Cam/Aachen	1	0.81	0.08	0.08
anti-k_t	1	1	0	0
SISCone	1	1/4	-0.06	0.12

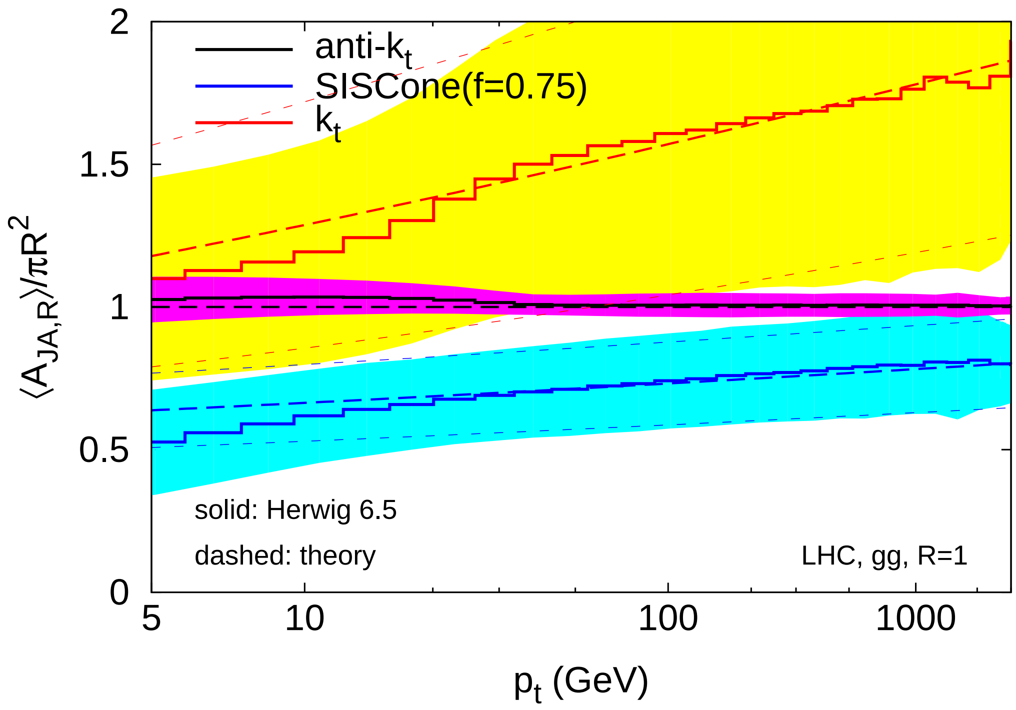
- $Q_0 \equiv$ IR regulator $\propto$ background density

Note: analytic control

Example: perturbative expansion of areas (at order α_s)

$$\langle \mathcal{A}(p_t, R)\rangle = \mathcal{A}_0 + \frac{C_{F,A}}{b_0\pi}\pi R^2\, d \log\left(\frac{\alpha_s(Q_0)}{\alpha_s(Rp_t)}\right)$$

- area $\neq \pi R^2$, area $\neq$ const.
- in agreement with Monte-Carlo simulations



Pileup subtraction

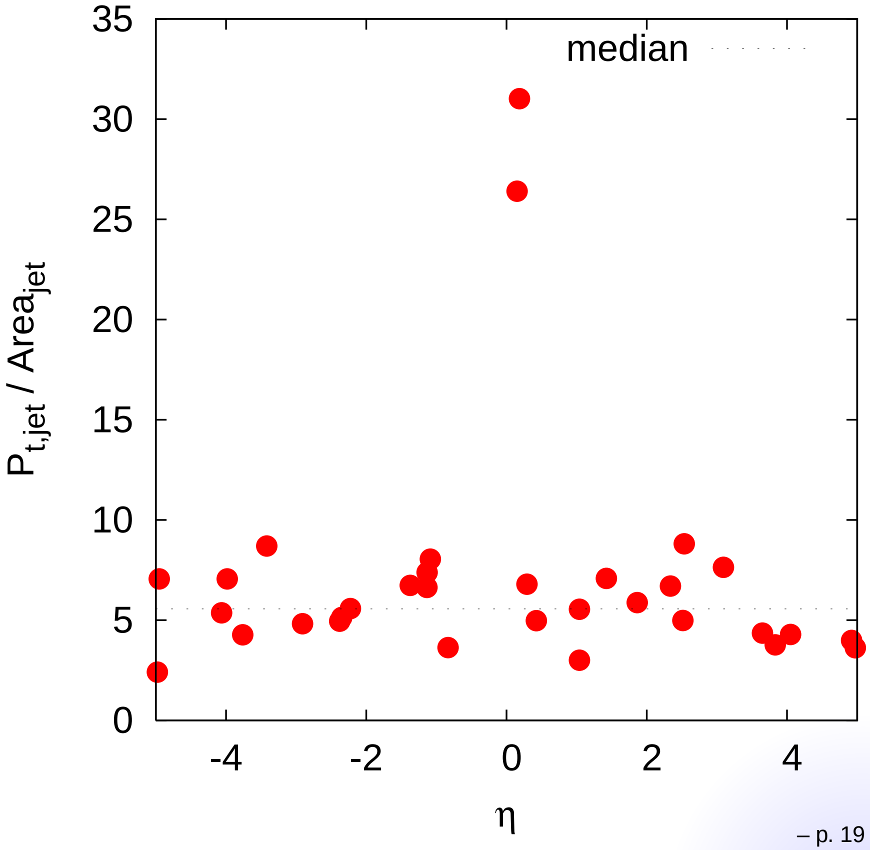
Basic idea: [M.Cacciari, G.Salam, 08]

$$p_{t,\mathrm{subtracted}} = p_{t,\mathrm{jet}} - \rho_{\mathrm{pileup}} \times \mathrm{Area}_{\mathrm{jet}}$$

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

- Pileup density per unit area: ρ_{pileup}

e.g. estimated from the median of $p_{t,\mathrm{jet}}/\mathrm{Area}_{\mathrm{jet}}$



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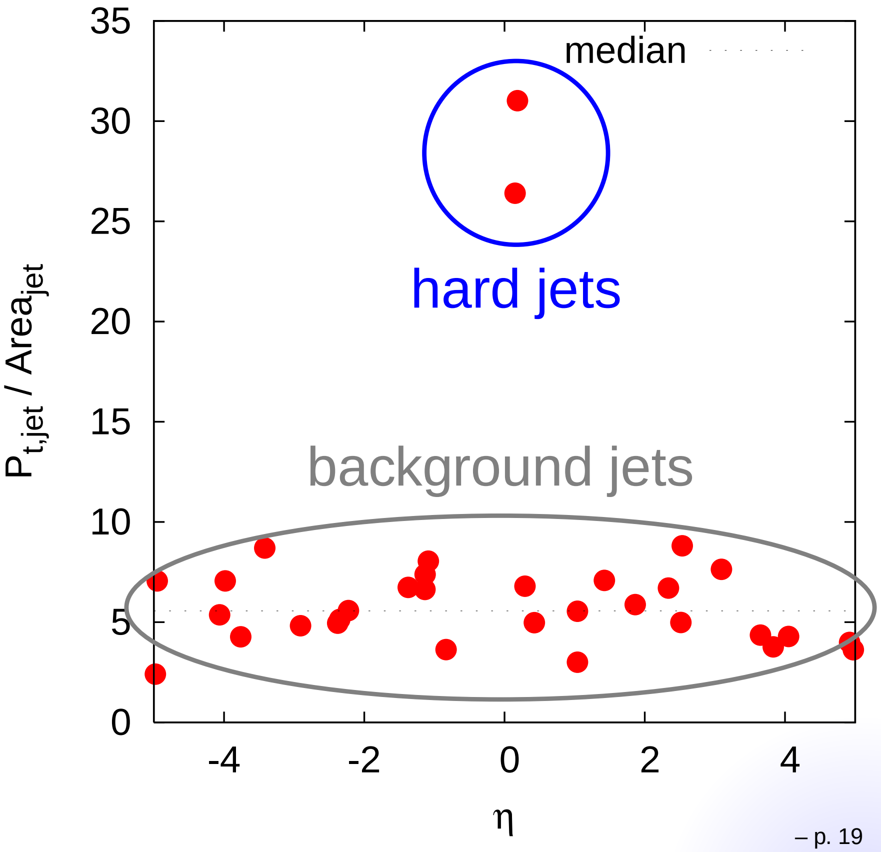

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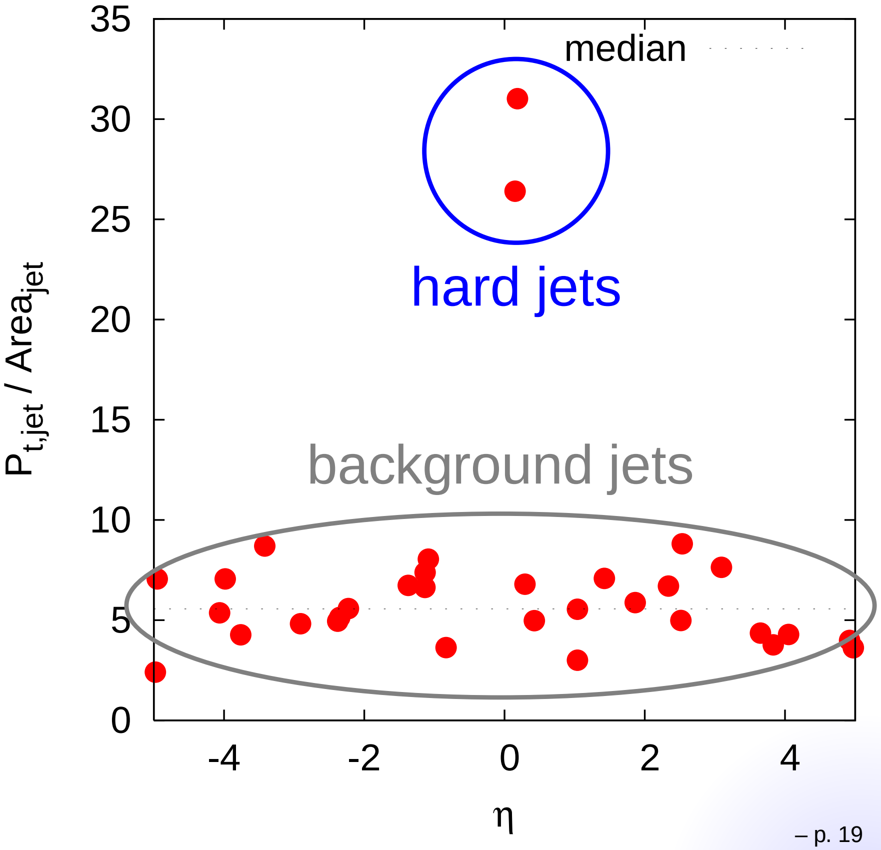
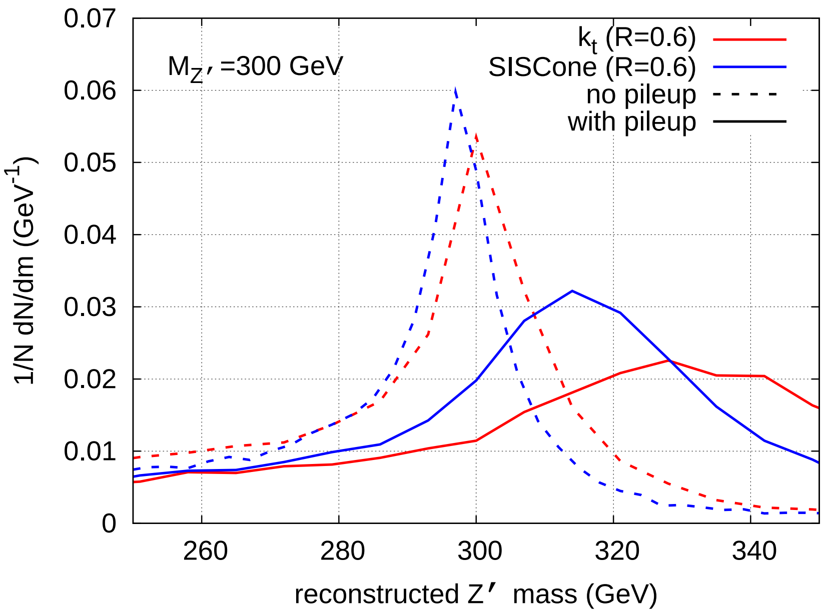
  e.g. estimated from the median of $p_{t,\text{jet}}/\text{Area}_{\text{jet}}$

implemented in FastJet
on an event-by-event basis



Our example: subtracting pileup

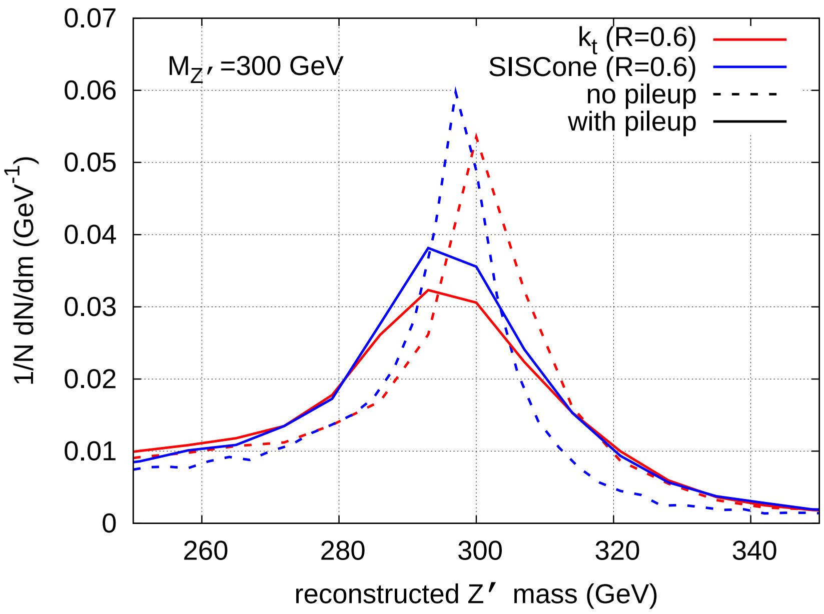
Pileup unsubtracted



width = 29.5 GeV

width = 21.0 GeV

pileup subtracted



width = 21.0 GeV

width = 17.7 GeV

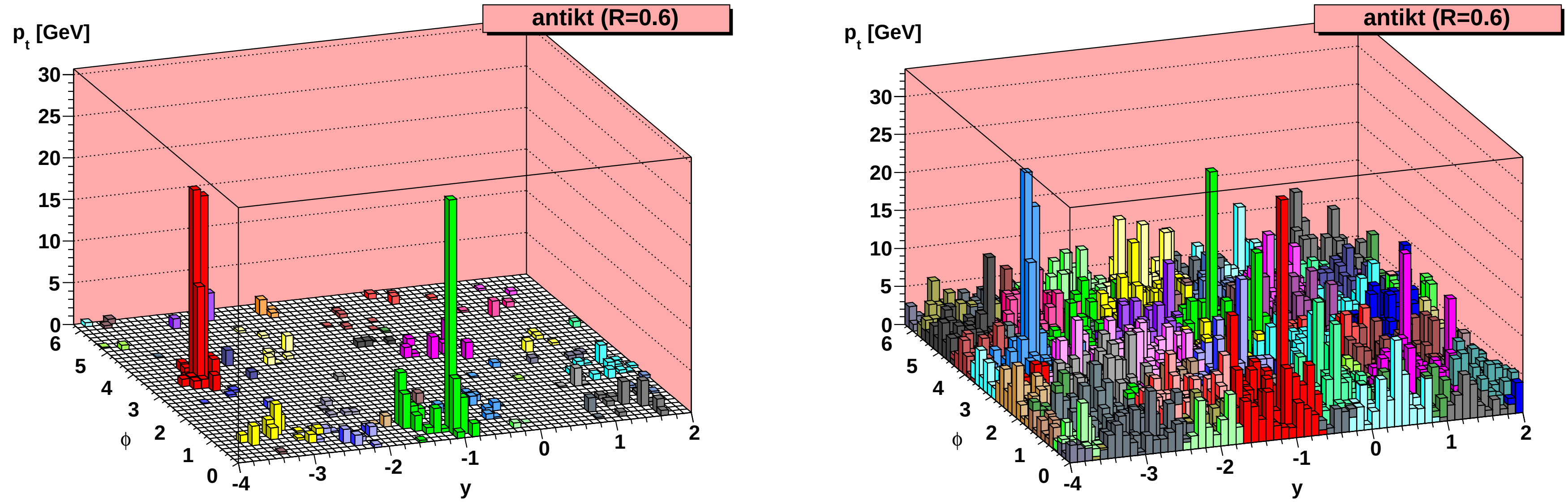
✓ position reasonnable

✓ dispersion reduced

Part 4

AA: more background!

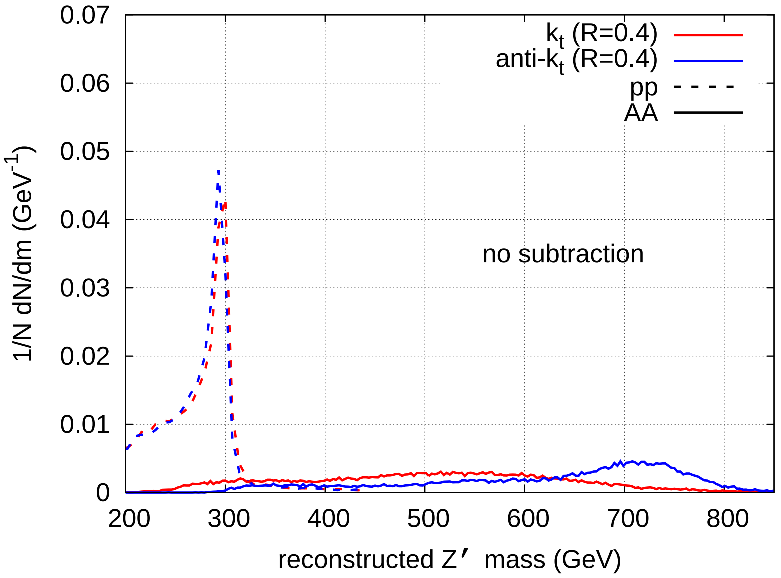
pp AA

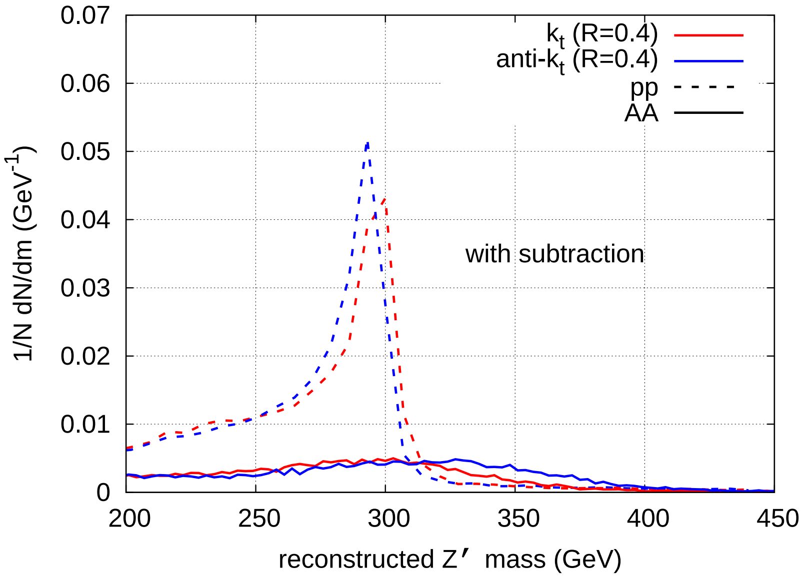


Complications

Problem:

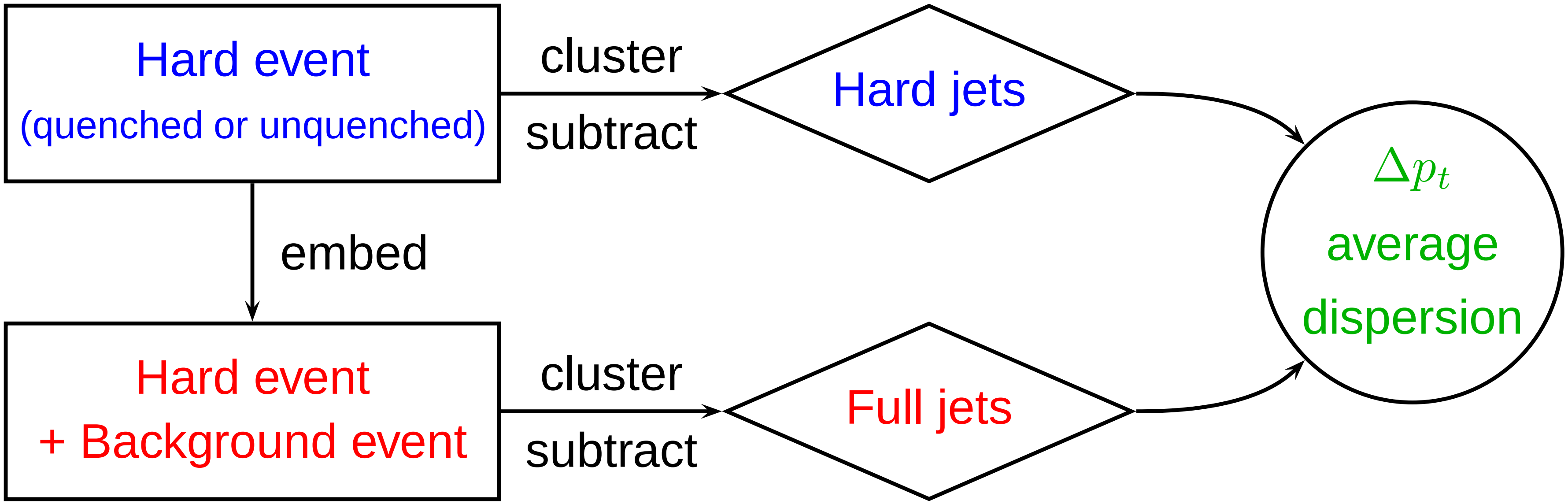
- Much larger background ($\sim$100 GeV/unit area at RHIC,
  $\sim$250 GeV/unit area at the LHC)
- With large fluctuations





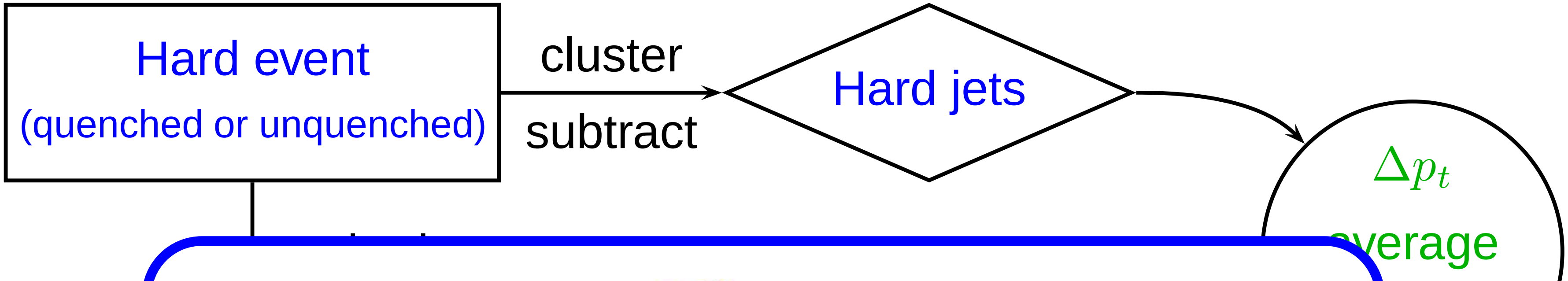
Question: how well can we measure the “hard jet” (quenched or not) in the heavy-ion background?

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 Δp_t shift, smallest Δp_t dispersion
- Note: in what follows, R fixed to 0.4

Framework for study



- Generic trends under control
- Final numbers may change

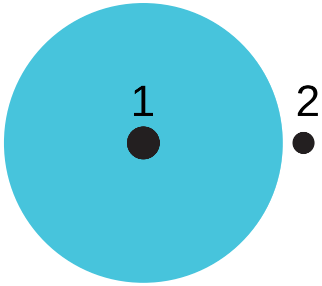
[M.Cacciari, J.Rojo, G.Salam, GS, in prep.]

- H
- B
- Analysis: FastJet(v2.4)
  Ideally: smallest Δp_t shift, smallest Δp_t dispersion
- Note: in what follows, R fixed to 0.4

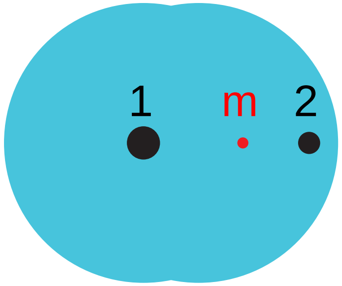
A technical point: Back-reaction

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:

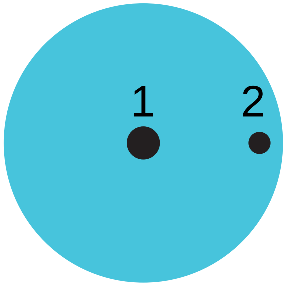


no medium: $p_t = p_{t1}$

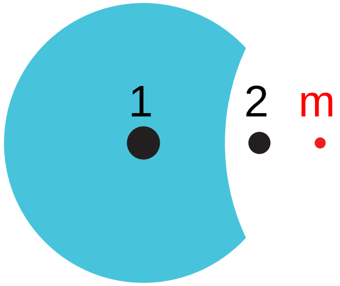


medium: $p_t = p_{t1} + p_{t2} + p_{tm}$

  - loss:



no medium: $p_t = p_{t1} + p_{t2}$

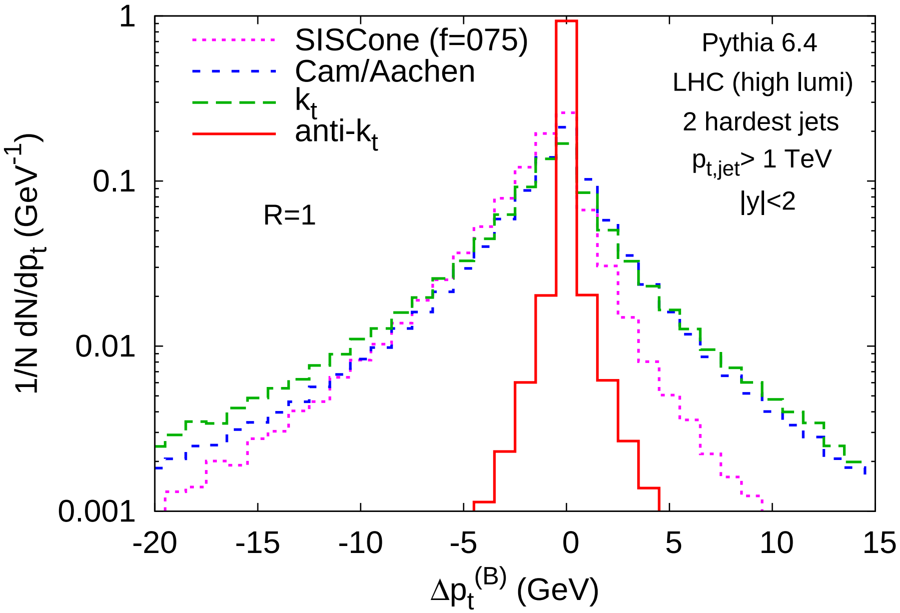


medium: $p_t = p_{t1} + p_{tm}$

A technical point: Back-reaction

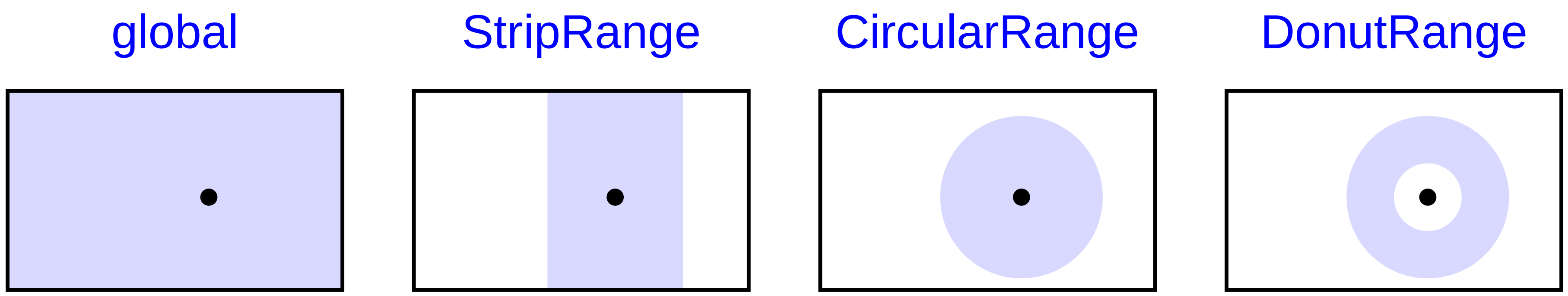
Additional soft background has 2 effects:

- 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 > SISCone $\gg$ anti-k_t



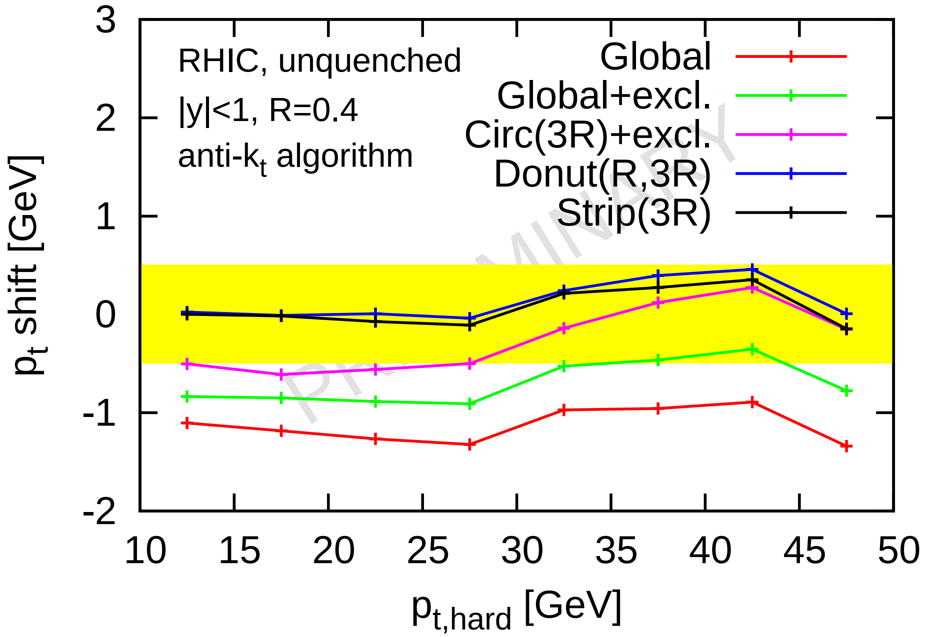
Idea #1: use a local range to compute ρ_{bkg}

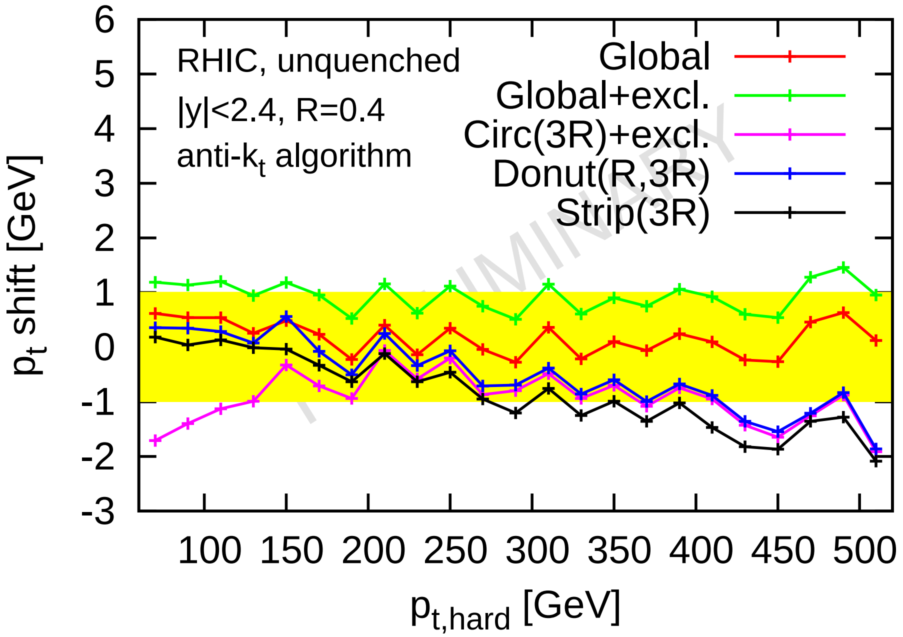
- Fluctuating background
  $\longrightarrow$ determine the background density ρ_{bkg}
  from jets in the vicinity of the jet we want to subtract



- Exclude the hardest jets from the determination of ρ_{bkg}
  $\Rightarrow$ reduce the bias in the computation median

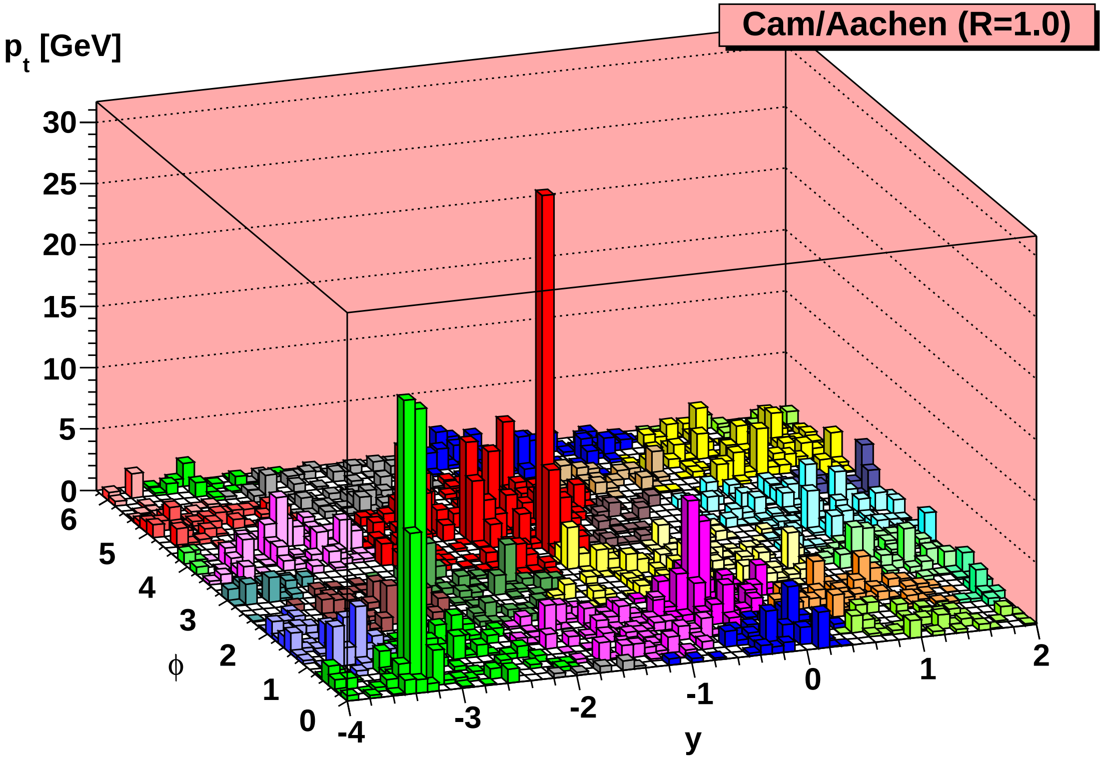
Effect of choosing a local range





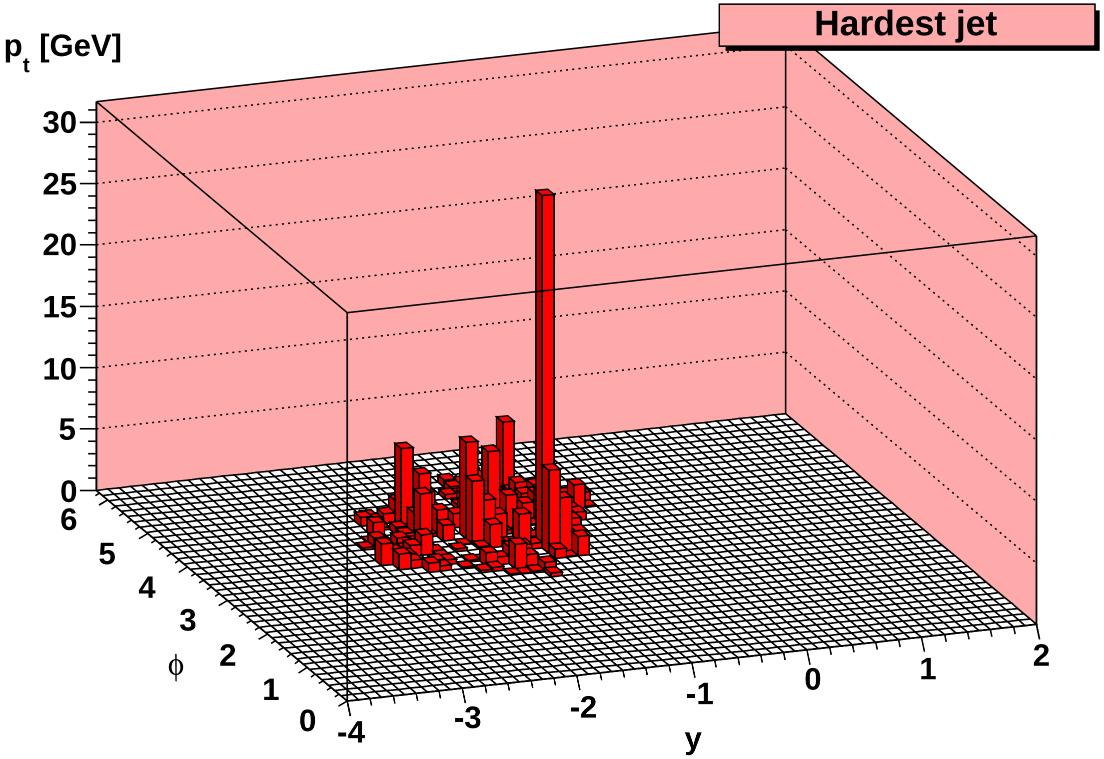
- effect $\sim$ 0.5-1 GeV
- differences between local ranges $\longrightarrow$ uncertainty
- for limited acceptance, global range $\approx$ local range
- analytic control would be nice

Idea #2: use filtering



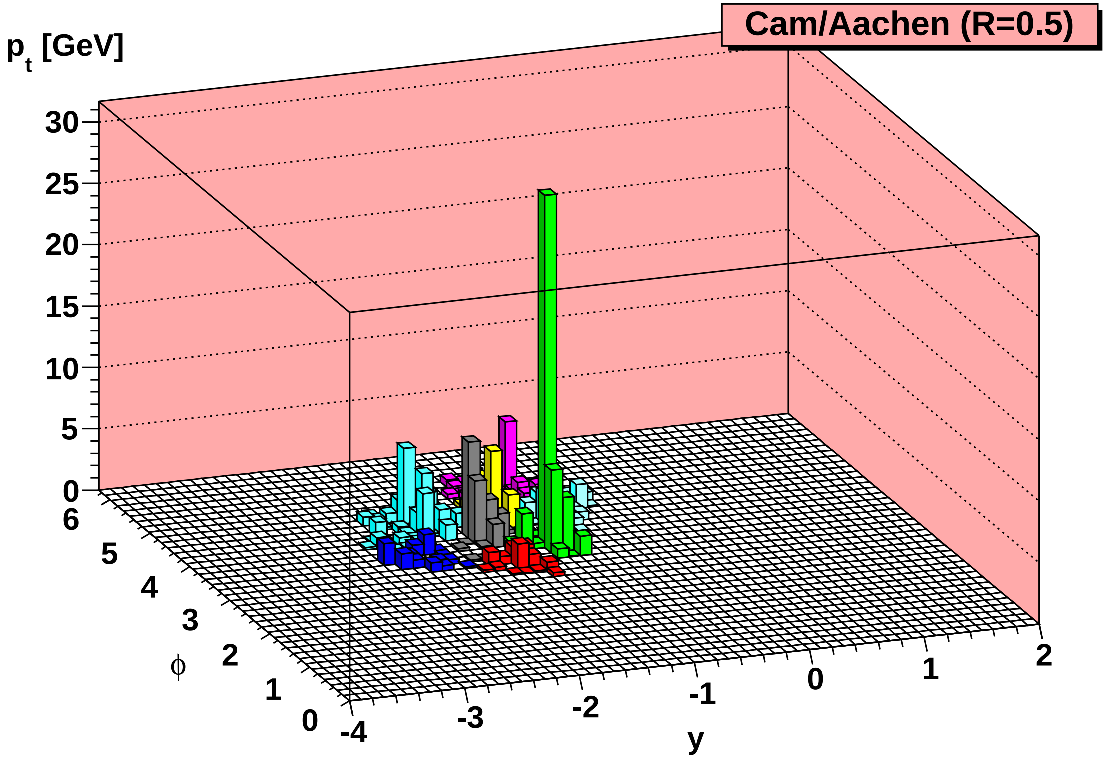
- cluster with Cambridge/Aachen(R)

Idea #2: use filtering



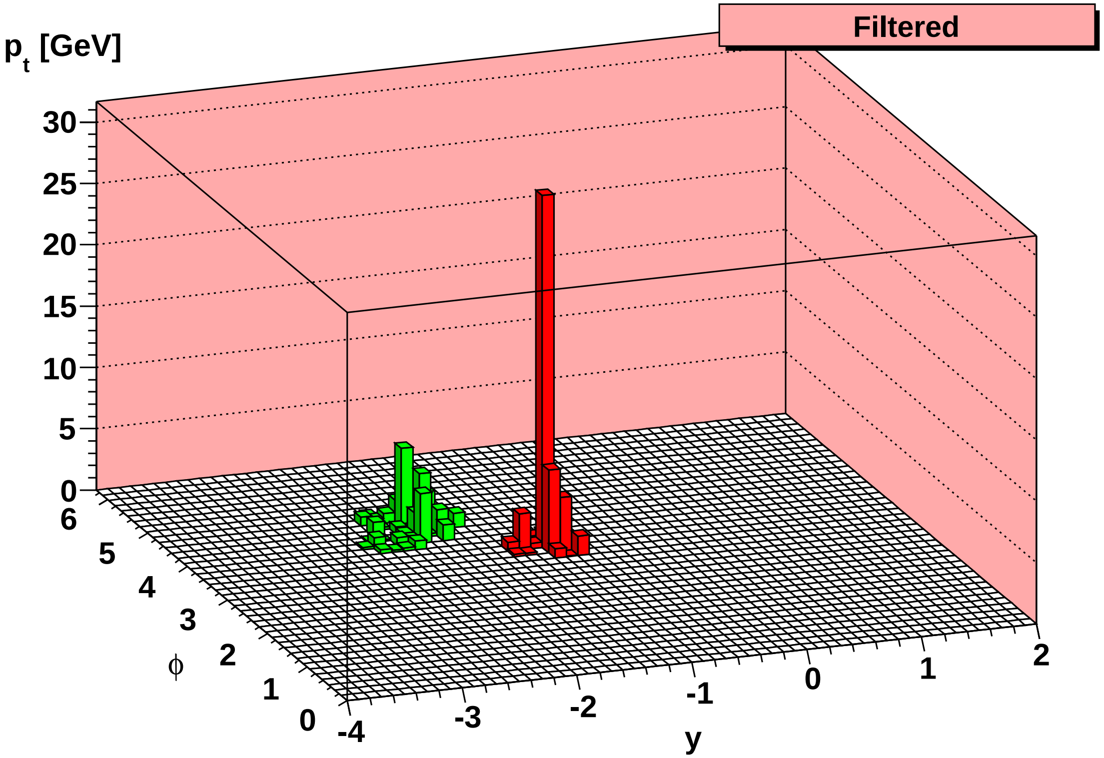
- cluster with Cambridge/Aachen(R)
- for each jet

Idea #2: use filtering



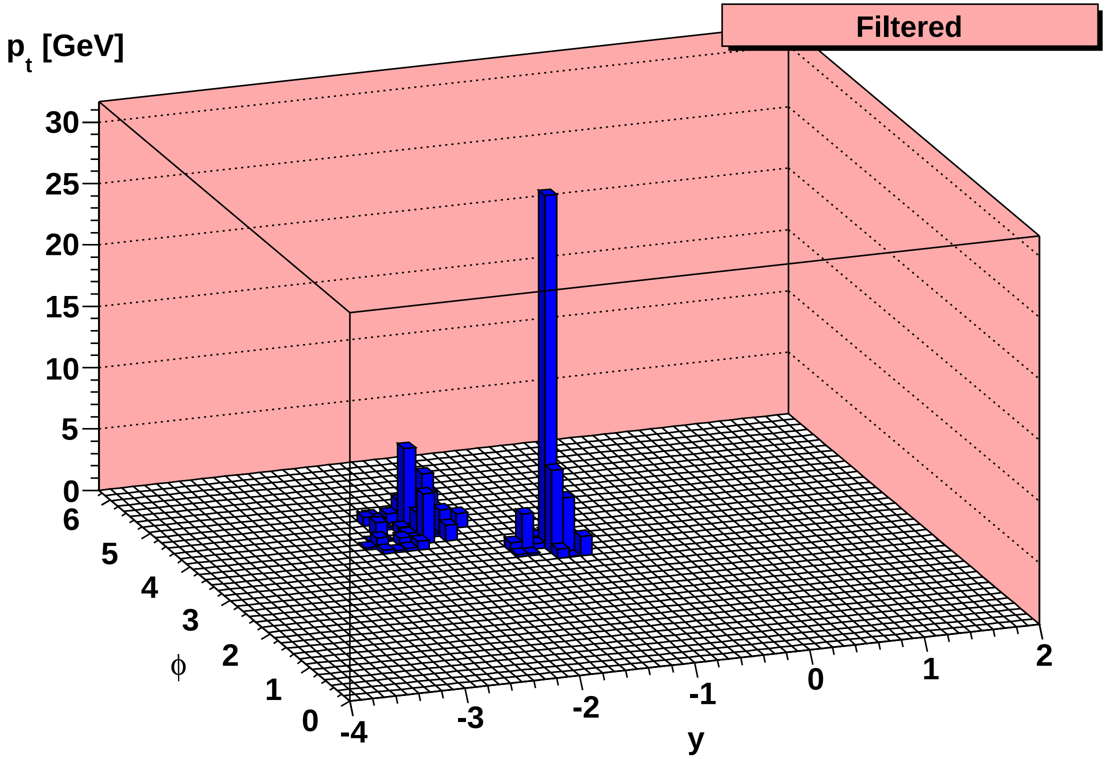
- cluster with Cambridge/Aachen(R)
- for each jet
  - recluster with Cambridge/Aachen(R/2)

Idea #2: use filtering



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

Idea #2: use 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

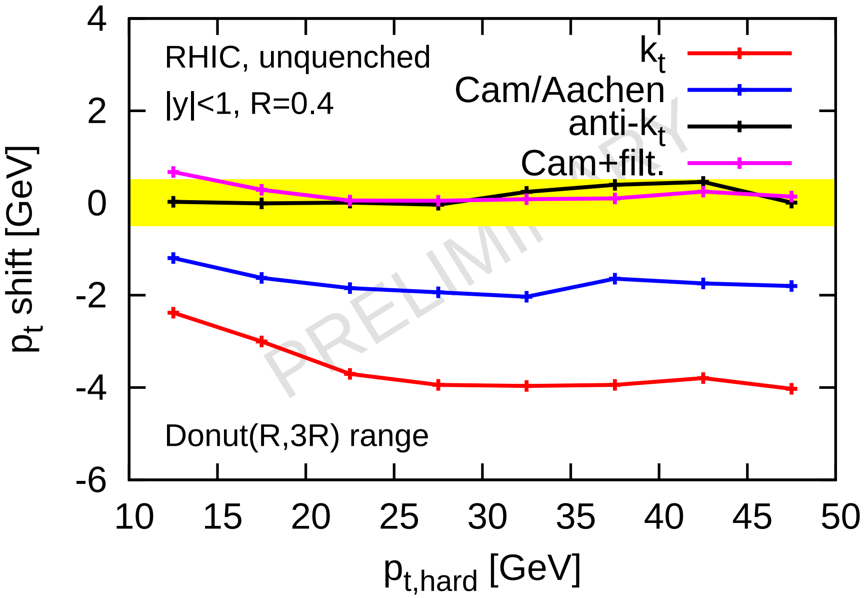
- Proven useful for boosted jet $H \to b\bar{b}$ tagging

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

- Proven useful for kinematic reconstructions

[M.Cacciari, J.Rojo, G.Salam, GS, 08]

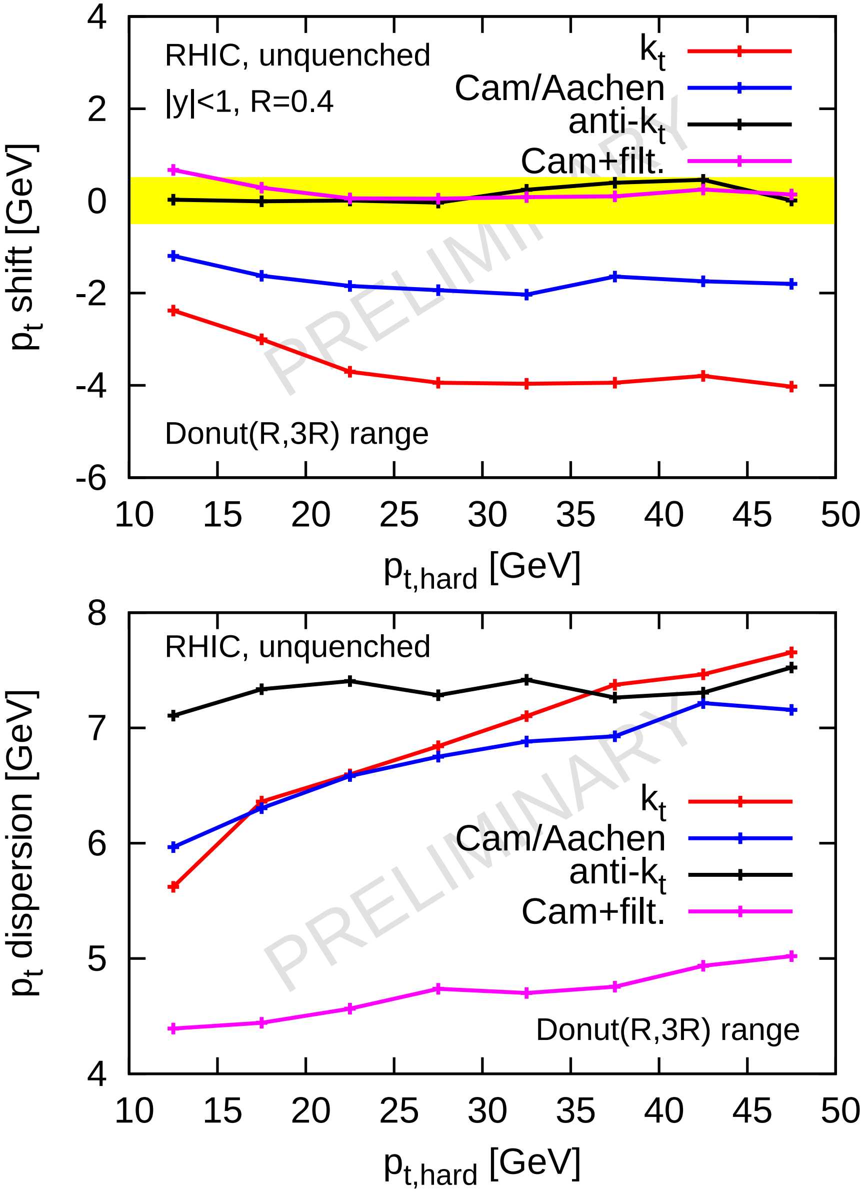
Results: RHIC kinematics



- average p_t shift:

  anti-k_t and C/A+filt. Ok

Results: RHIC kinematics



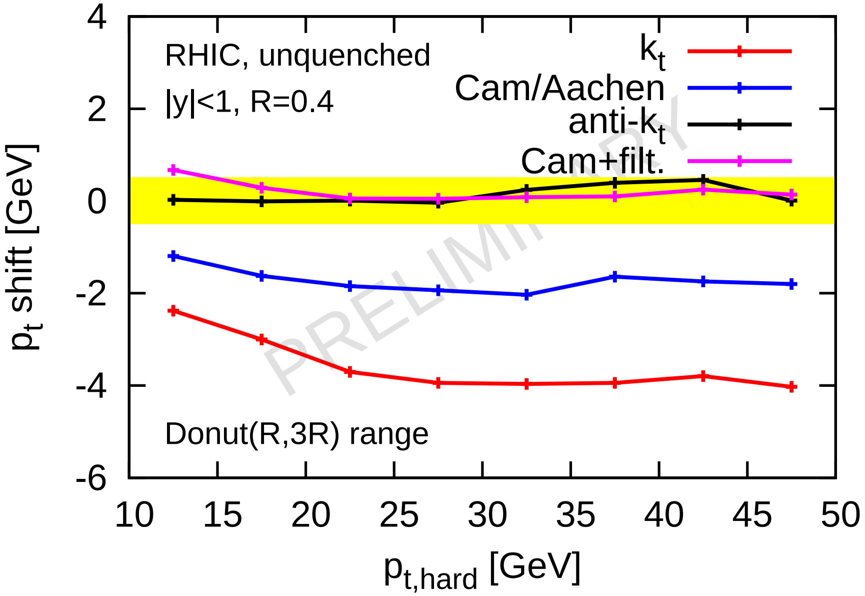
- average p_t shift:

  anti-k_t and C/A+filt. Ok

- p_t shift dispersion:

  C/A+filt. better

Results: RHIC kinematics



- average p_t shift:

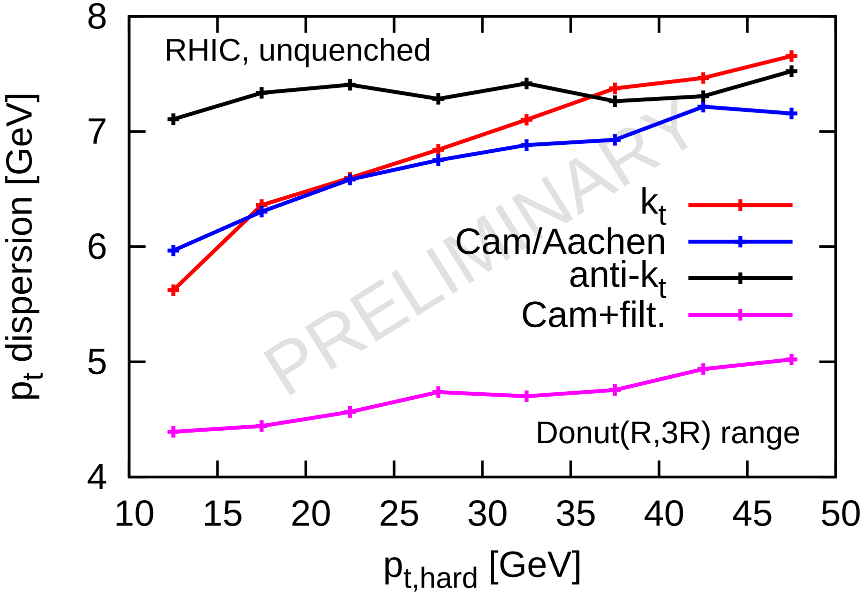
  anti-k_t and C/A+filt. Ok

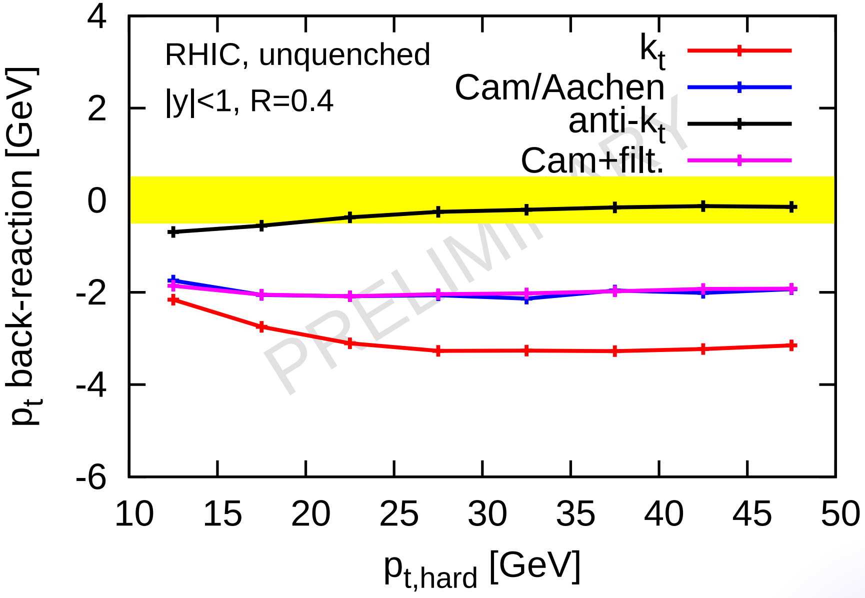
- p_t shift dispersion:

  C/A+filt. better

- watch out C/A+filt. average:

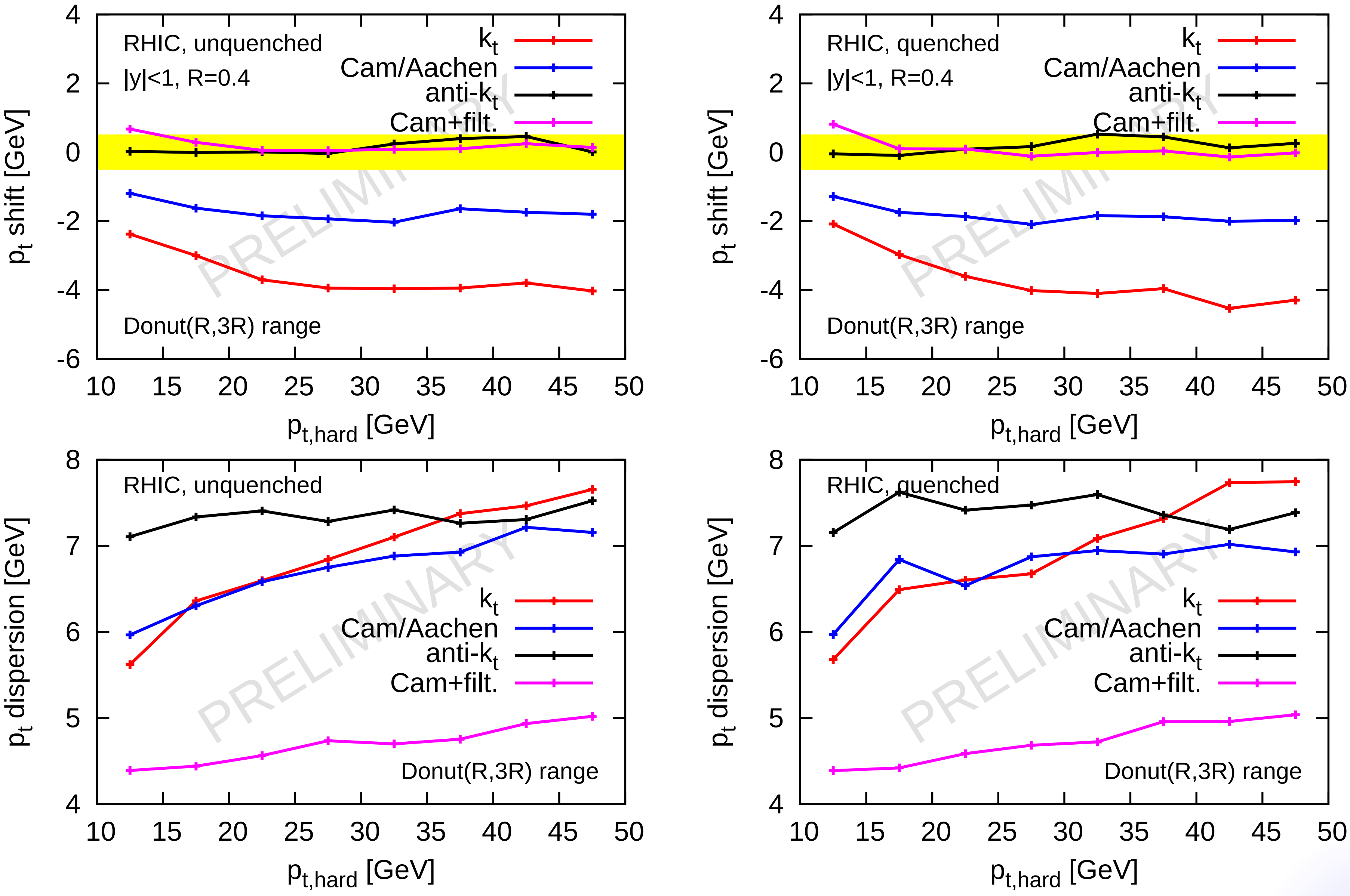
  back-reaction compensated



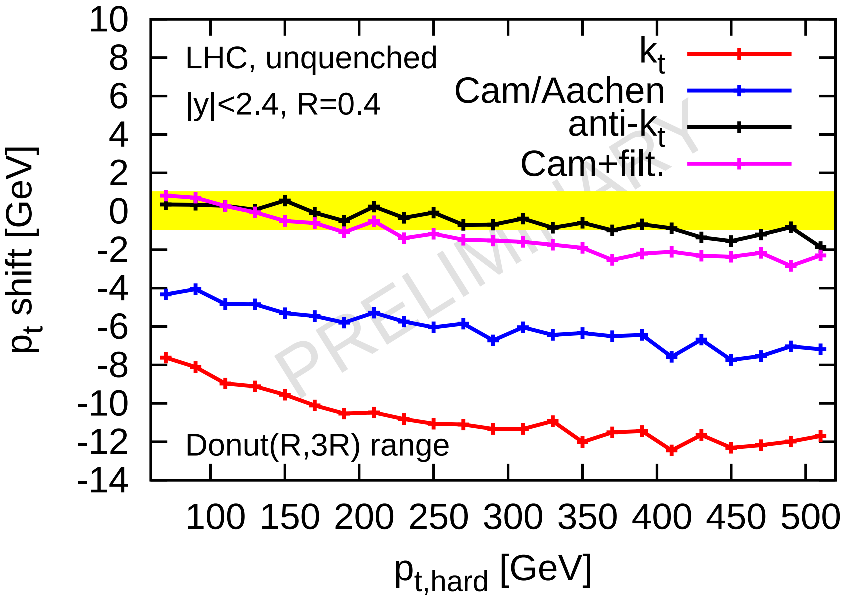


Results: RHIC kinematics – quenching

Performances not much affected by quenching (need more models)

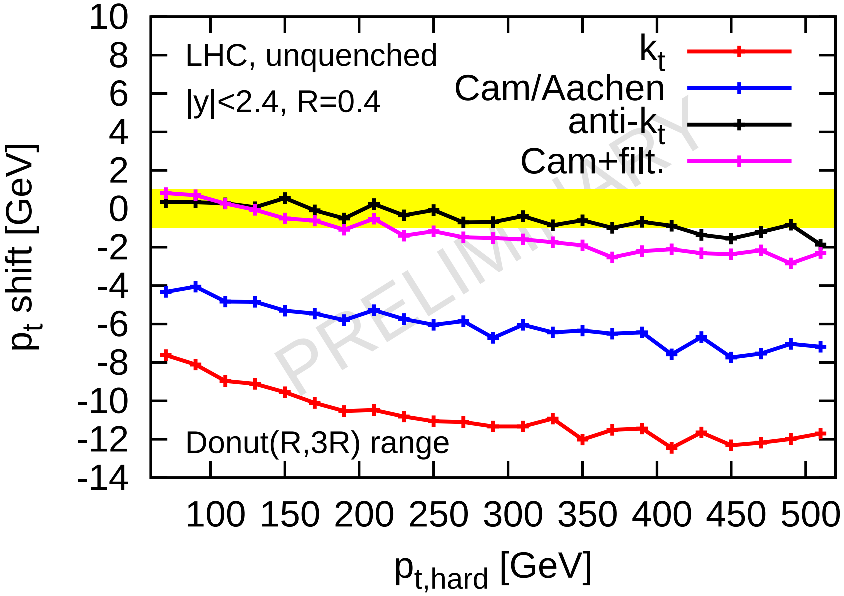


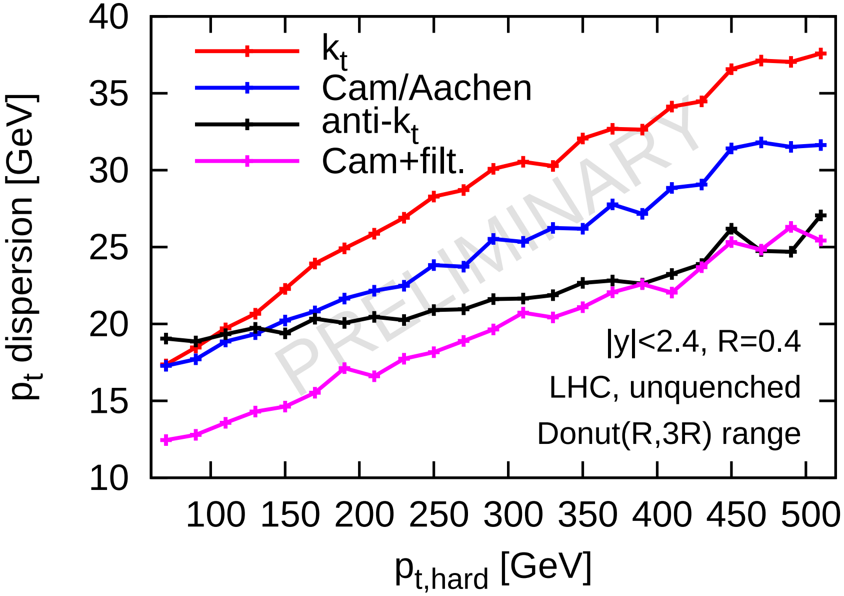
Results: LHC kinematics



- 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

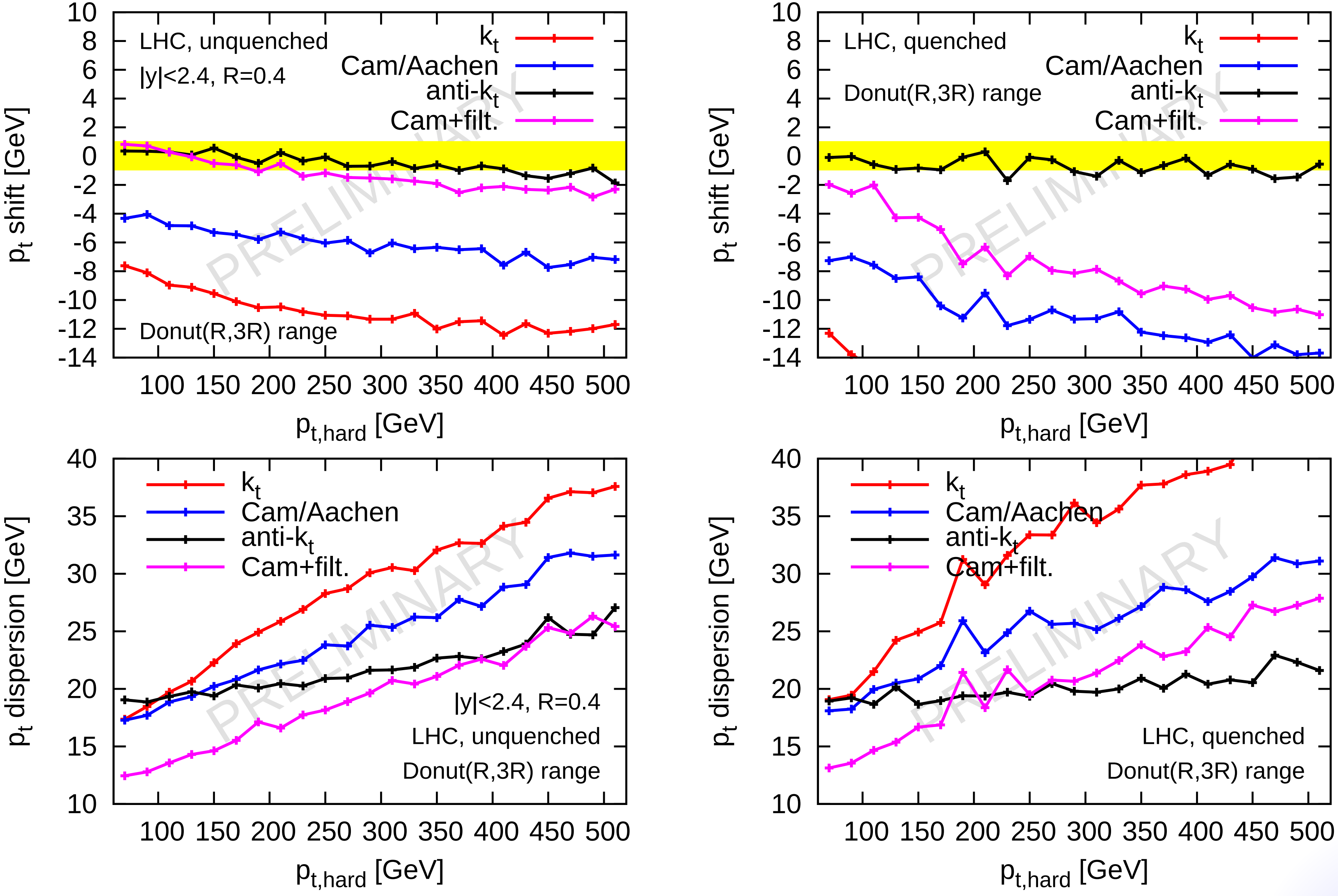
- p_t shift dispersion:

  C/A+filt. better

  anti-k_t Ok

Results: LHC kinematics – quenching

Large quenching effect but anti-k_t's rigidity plays for it



Conclusions

- Cone algorithm: use and infrared-and-collinear-safe one

ATLAS Cone
CDF/D0 MidPoint } → SISCone √ fast √ safe

CMS It. Cone → anti-k_t √ fast √ safe

- Background subtraction: use jet areas
  - properly defined, under analytic control
  - simple and generic subtraction method
- More refined techniques: use local ranges and filtering techniques
  - decrease sensitivity to the background and its fluctuations
  - RHIC and LHC may behave differently
  - Try BOTH anti-k_t (reliable because of its rigidity)
    AND Cambridge/Aachen+filtering (many nice features)