Jets in QCD, an introduction

Gavin P. Salam
LPTHE, UPMC Paris 6 & CNRS

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Drawing on work with M. Cacciari, J. Rojo & G. Soyez

Jets in Heavy-Ion Collisions?

Jets are the most direct of all hard probes of the medium.

As close as you can get to the original quark or gluon near its time of creation

What might you want to do with them? cf. talks by Wiedemann, Arleo

- Look back in time to before the parton traversed the medium

  And so get the parton's energy near start of fragmentation

  e.g. to normalise fragmentation functions
- Then scan forwards "time" to see what happened to it as it went through the medium
- And to identify "where its energy went"

This talk

- Some background about jets in usual collider contexts
- Some thoughts on jets in heavy-ion collisions

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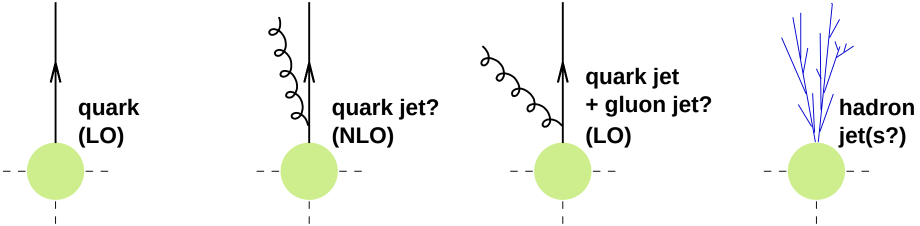
Partons v. Jets?

Partons (quarks, gluons) are not trouble-free concepts...



- Partons split into further partons
- Jets are a a way of thinking of the 'original parton'
- A 'jet' is a fundamentally ambiguous concept (e.g. requires a resolution)

Jets are only meaningful once you've got a **jet definition**

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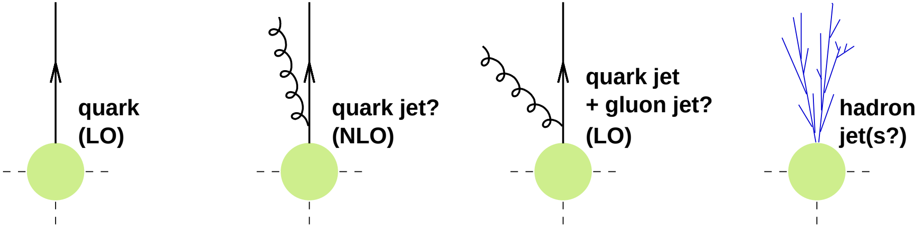

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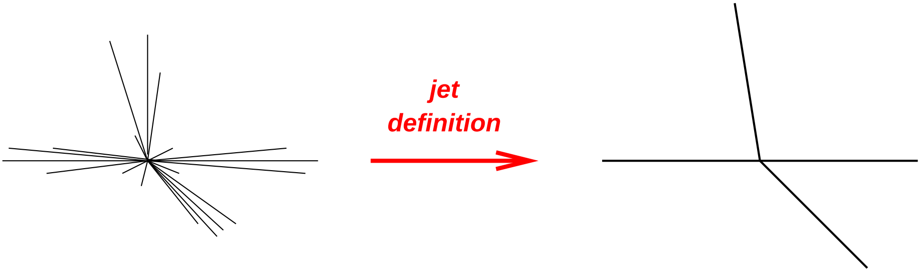
Jet definition / algorithm

A jet definition is a systematic procedure that **projects away the multiparticle dynamics**, so as to leave a simple picture of what happened in an event:



Jets are *as close as we can get to a physical single hard quark or gluon:* with good definitions their properties (multiplicity, energies, [flavour]) are

- finite at any order of perturbation theory
- insensitive to the parton $\rightarrow$ hadron transition

NB: finiteness $\longleftrightarrow$ set of jets depends on jet def.

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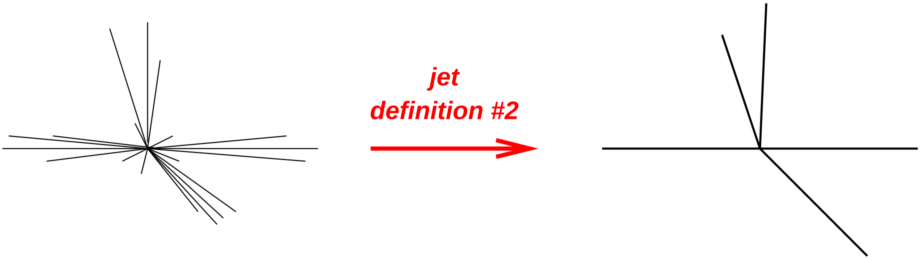

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Two broad classes of jet algorithm

Sequential recombination (SR)	**Cone**
k_t, Jade, Cam/Aachen, ...	UA1, JetClu, Midpoint, ...
Bottom-up: Cluster 'closest' particles repeatedly until few left → jets.	Top-down: Find coarse regions of energy flow (cones), and call them jets.
Works because of mapping: *closeness* ⇔ *QCD divergence*	Works because *QCD only modifies energy flow on small scales*
Loved by e^+e^-, ep (& theorists)	Loved by pp (& fewer theorists)

2005-2008: Major progress in bridging gulf between SR & cone advocates

Driven by LHC's arrival [and Tevatron's mixed record]

- Let's see how each type works
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Sequential recombination (e.g. k_t) algorithms

Catani et al '91-93, Ellis & Soper '93

The favourite in e^+e^- and DIS

Much loved by QCD theorists

Long disfavoured in *pp*

Sequential recombination algorithms

k_t algorithm

- Find smallest of all $d_{ij} = \min(k_{ti}^2, k_{tj}^2)\Delta R_{ij}^2/R^2$ and $d_{iB} = k_i^2$
- Recombine i, j (if iB: $i \to$ jet)
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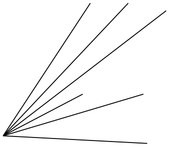

'Trivial' computational issue:

- for N particles: N^2 d_{ij} searched through N times $= N^3$
- 4000 particles (or calo cells): 1 minute

NB: often study $10^7 - 10^8$ events

Advance #1: factorise momentum and geometry

Borrow methods & tools from Computational Geometry:

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Time reduced to Nn or $N \ln N$: 25ms for N=4000. Cacciari & GPS '05

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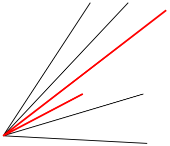

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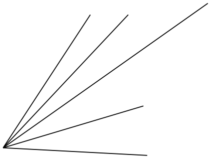

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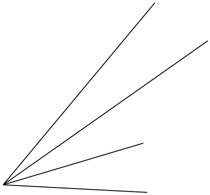

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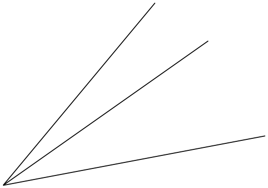

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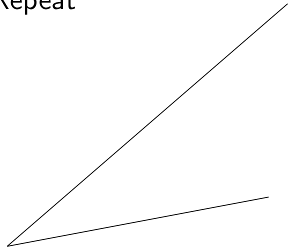

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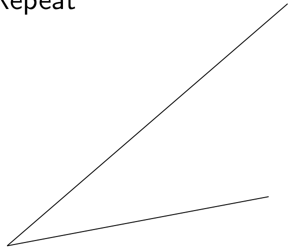

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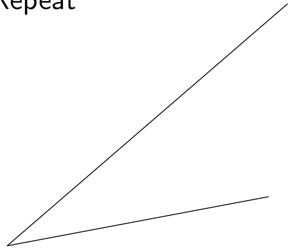

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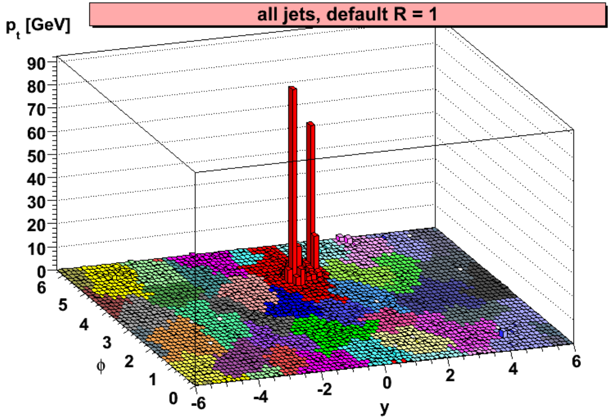
An event clustered with k_t



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often quoted as a difficulty in experimental calibration ✗

- A consequence of hierarchical nature

Which gives window on substructure ✓

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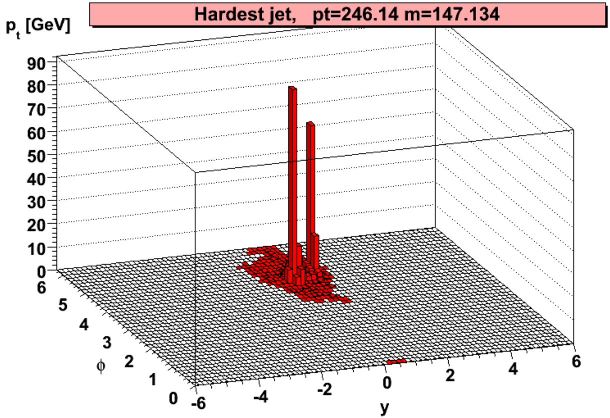

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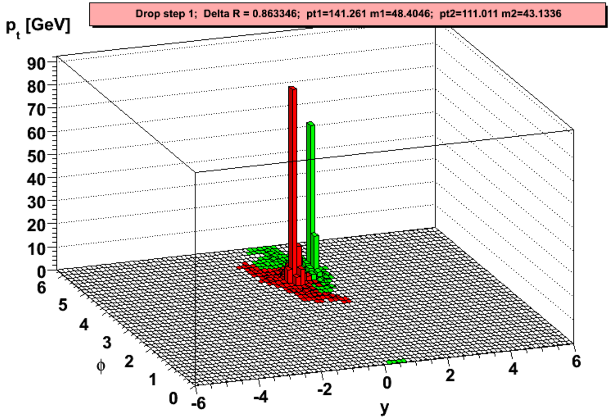

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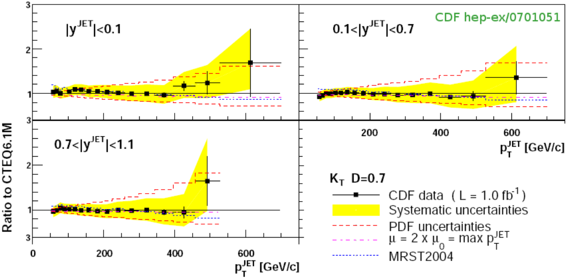
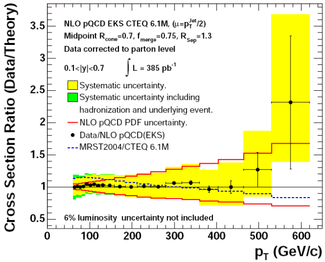
Advance #1b: non-Cone algs **do** work in *pp*

CDF hep-ex/0512062 & hep-ex/0701051 inclusive-jet results show irregularity of k_t jets does not prevent a good measurement.





This, and k_t's theoretical simplicity have spurred inclusion of k_t algorithm in standard LHC experiments' "panoply" of jets

Cone algorithms

Sterman & Weinberg '77, UAx '80s, Tevatron '90s

Widely used at pp colliders

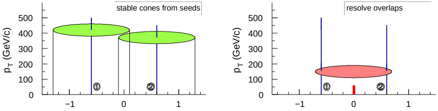
Range from simple to very complex

Plagued by infrared and collinear safety issues

Health warning

Much work in past years: help LHC avoid previous pp colliders' deficiencies

infrared unsafety



When a soft particle changes the jets

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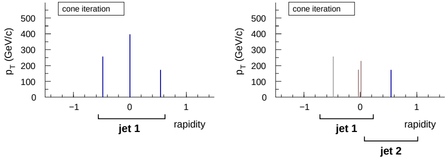

When a collinear splitting changes the jets

Historically, all practical cone algs had these problems

Because they used **"seed particles"**

- Cause perturbative QCD to give divergent answers → meaningless
- Issue exarcerbated in complex environments [e.g. multijet BSM signatures]
- **HIC are a complex environment too!** IR & Coll. safety are important there too

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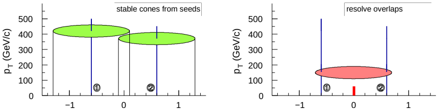

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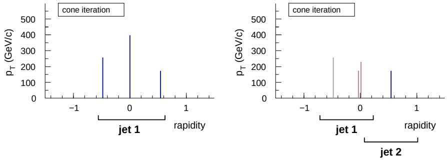

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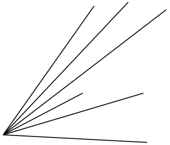
Tevatron & ATLAS cone algs have two main steps:

- Find some/all stable cones

  ≡ cone pointing in same direction as the momentum of its contents

- Resolve cases of overlapping stable cones

  By running a 'split–merge' procedure



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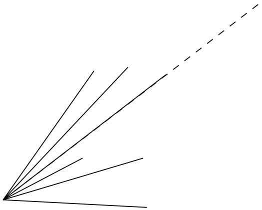

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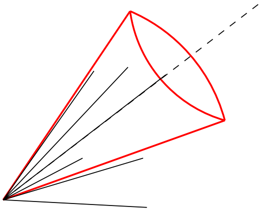

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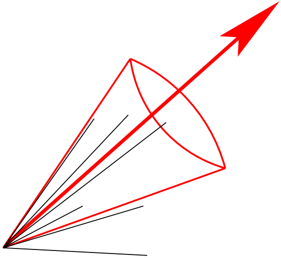

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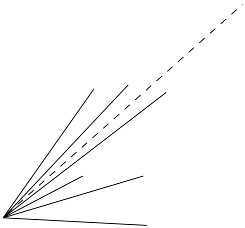

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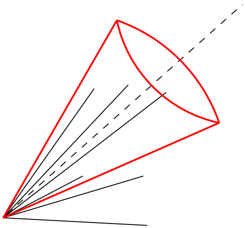

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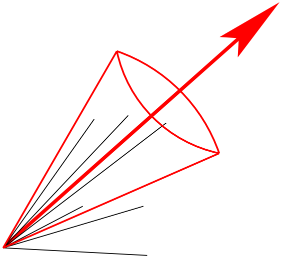

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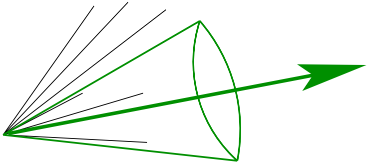

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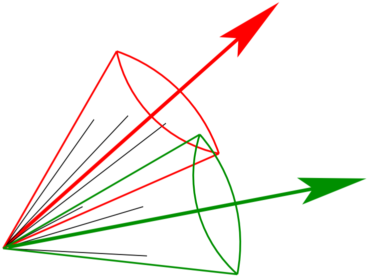

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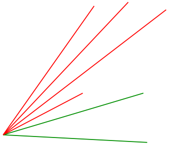

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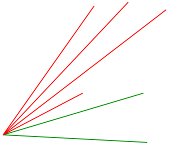

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  Done originally, very IR unsafe, N^2 [JetClu, Atlas]
- Iterate from 'midpoints' between cones from seeds — Midpoint cone, less IR unsafe, N^3
- Seedless: try all subsets of particles — IR safe, $N2^N$

  100 particles: 10^{17} **years**

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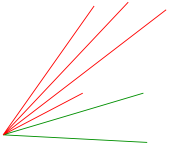

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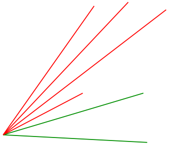
- Find some/all stable cones

  ≡ cone pointing in same direction as the momentum of its contents
- Resolve cases of overlapping stable cones

  By running a 'split–merge' procedure



How do you find the stable cones?

- Iterate from 'seed' particles

  Done originally, very IR unsafe, N^2 [JetClu, Atlas]
- Iterate from 'midpoints' between cones from seeds — Midpoint cone, less IR unsafe, N^3
- Seedless: try all subsets of particles — IR safe, $N2^N$

  100 particles: 10^{17} years

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$\equiv$ cone pointing in same direction as the momentum of its contents

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How do you find the stable cones?

- Iterate from 'seed' particles

Done originally, very IR unsafe, N^2 [JetClu, Atlas]

Advance #2: IR safe seedless cone (SM) separate mom. and geometry

New comp. geometry techniques: 2D all distinct circular enclosures

Then for each check whether $\longrightarrow$ stable cone

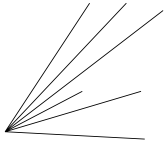
Time reduced from $N2^N$ to $\mathbf{N^2 \ln N}$: 6s for N=4000. GPS & Soyez '07

"SISCone"

Cone basics II: IC-PR

Other cones avoid split-merge:

- Find one stable cone — E.g. by iterating from hardest seed particle
- Call it a jet;remove its particles from the event; repeat



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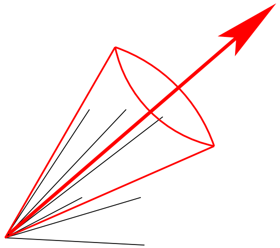

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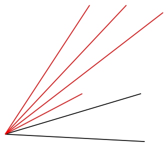

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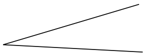

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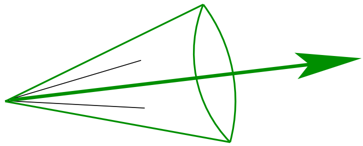

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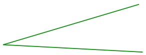

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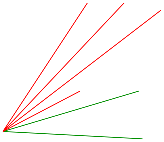

- This is not the same algorithm
- Many physics aspects differ

Iterative Cone with Progressive Removal (IC-PR)

Collinear unsafe [$\leftarrow$ hardest seed]

e.g. CMS it. cone, [Pythia Cone, GetJet]

Cone basics II: IC-PR

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- Find one stable cone — E.g. by iterating from hardest seed particle
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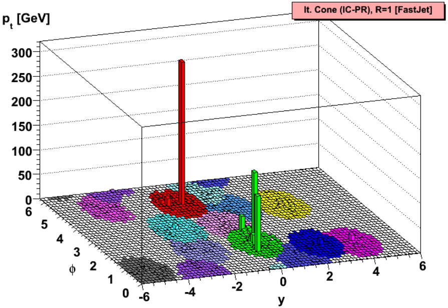
Iterative Cone with Progressive Removal (IC-PR)

Collinear unsafe [← hardest seed]

Advance #3: anti-k_t algorithm — GPS, Cacciari & Soyez '08

Seq. Rec.: find smallest of d_{ij}, d_{iB}: $d_{ij} = \min(p_{ti}^{-2}, p_{tj}^{-2})\Delta R_{ij}^2/R^2$, $d_{iB} = p_{ti}^{-2}$

- Grows outwards from hard "seeds," but in collinear safe way
- Has **circular jet "area,"** just like IC-PR & same @ NLO (incl.jets)
- Fast: Nn or $Nn^{1/2}$, 25ms for 4000 particles



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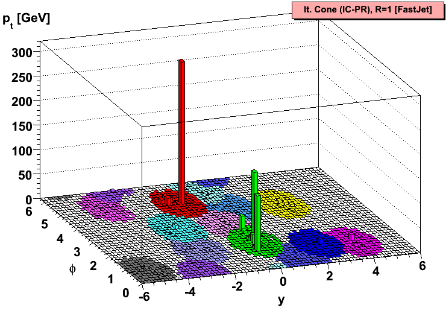
  But collinear unsafe

- So does anti-k_t

  safe from theory point of view

- Cones with split-merge (SISCone) **shrink** to remove soft junk



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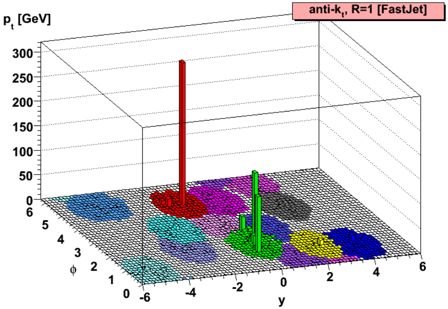

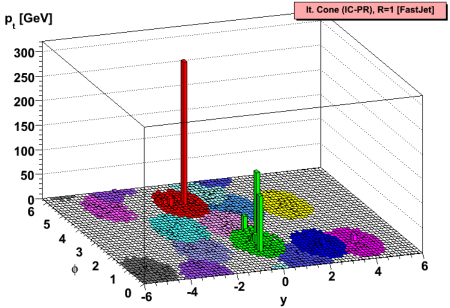

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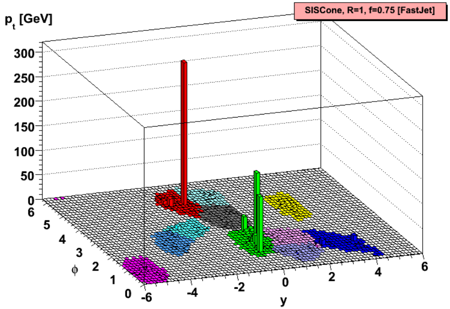

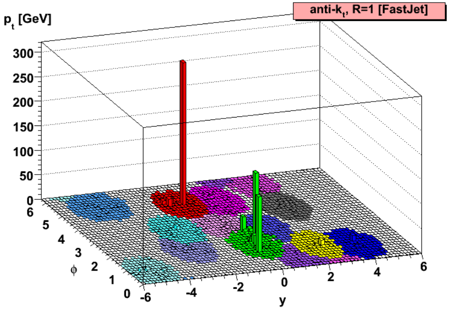

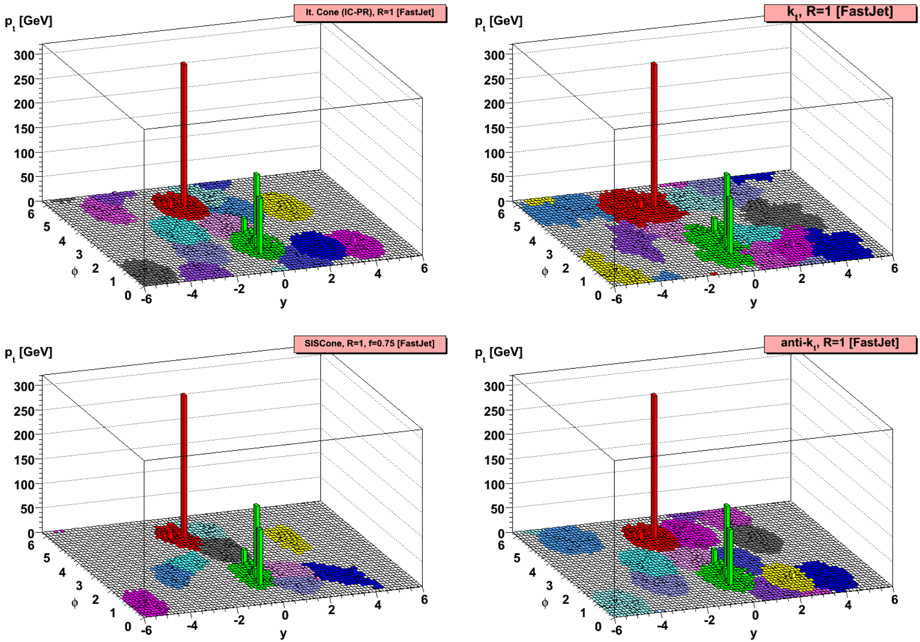

It. Cone (IC-PR), R=1 [FastJet]
k_t, R=1 [FastJet]
SISCone, R=1, f=0.75 [FastJet]
anti-k_t, R=1 [FastJet]
p_t [GeV]
ϕ
y

A set of 4 jet algorithms

k_t SR, $d_{ij} = \min(k_{ti}^2, k_{tj}^2)\Delta R_{ij}^2/R^2$ hierarchical in rel $\perp$ momenta	Cambridge/Aachen SR, $d_{ij} = \Delta R_{ij}^2/R^2$ hierarchical in angle
anti-k_t SR, $d_{ij} = \min(k_{ti}^{-2}, k_{tj}^{-2})\Delta R_{ij}^2/R^2$ gives perfectly conical jets	SISCone Seedless Infrared Safe cone +SM gives "economical" jets

All share 1 main parameter: R, the angular reach

differ in details of shape, substructure, NLO corrections

[and all accessible through FastJet: Cacciari, GPS & Soyez, '05-08]

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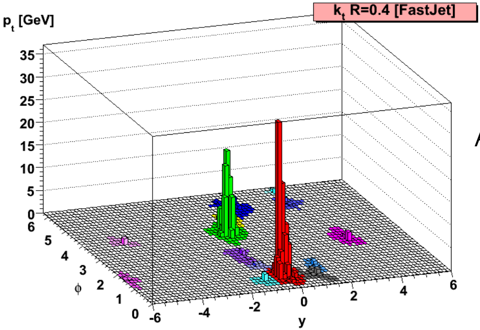
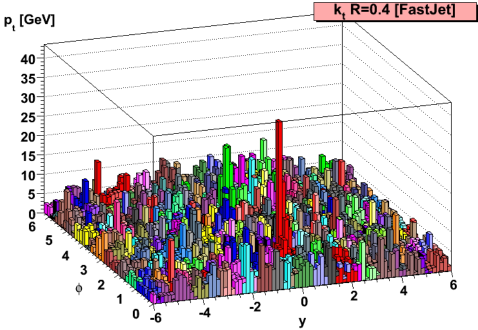
Jets in HIC



An example hard event

$p_t \sim 100$ GeV

Generated with Pythia



Mixed into LHC HI environment

HydJet, $dN_{ch}/dy \simeq 1600$

Jets in HIC: the issues

- Huge soft background in each event ~ 200 GeV per unit area in ϕ, η
- Modelling very uncertain; we're not too sure how medium affects
  - distribution of hadron momenta so dangerous to place p_t cutoffs?
  - multiplicities
  - angular distribution of energy flow so want to study different angular scales
- Full programme of what we/you want to do with jets in HIC not yet clear?
  - provide reference momentum, e.g. to get hadron fragementation functions
  - look inside them, to learn about how medium changes energy flow
- Technical issues: multiplicity of $30k$ particles [without cutoff]

  Solved for all algs, except SISCone (but could pre-cluster)

Extracting jets from the medium flow

Guiding principles

- Be detector independent, as far as possible

  Enable direct comparisons between collaborations

- Ensure continuity with *pp*

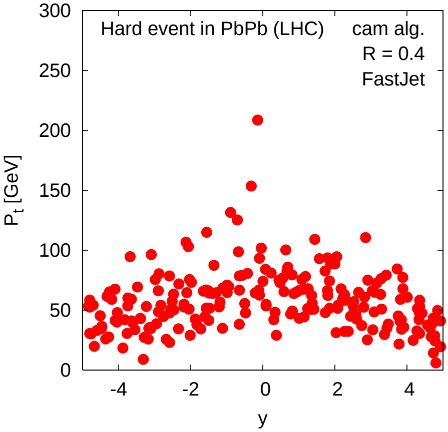
  pp has “underlying event” noise, & will have much pileup at LHC

- Be aware of inherent systematics in the procedure & quantify them

  All methods have some systematics

Elements in jet extraction [1]

1. *Estimate the transverse momentum density from the collective flow*



Example

Cacciari & GPS '07
Cacciari, GPS & Soyez'08
+ talk by J. Rojo tomorrow

- For each jet look at p_t/A
- Extract resulting $\rho(y)$ (or $\rho(y, \phi)$)
  locally, globally
  removing "hard" jets
- $p_t \to p_t - \rho A$

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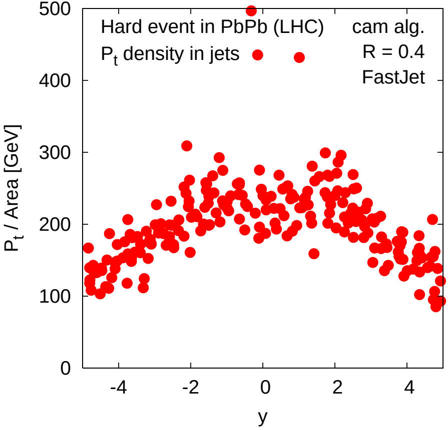

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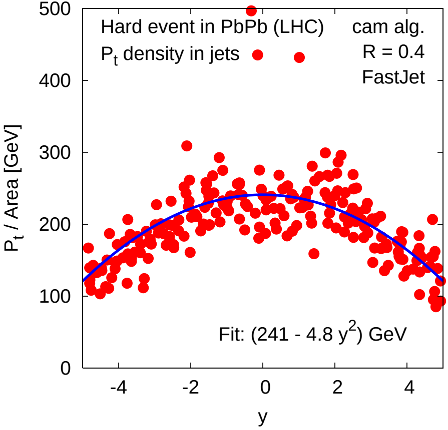

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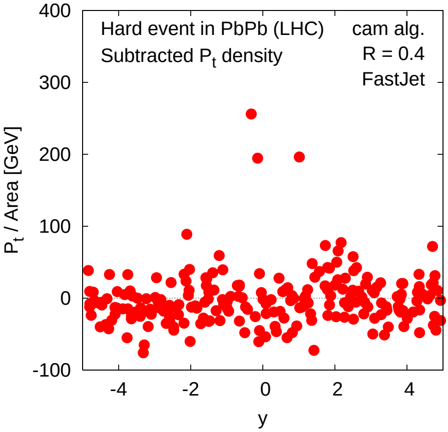
  $-$ve p_t jets $\to$ resolution
  hard jets "stick out" clearly

Elements in jet extraction [2]

2. Subtract the collective flow from jets (either before or after clustering)



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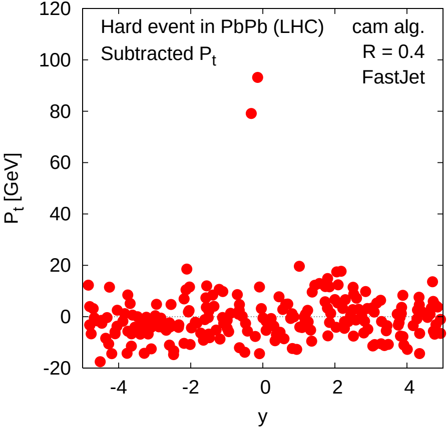

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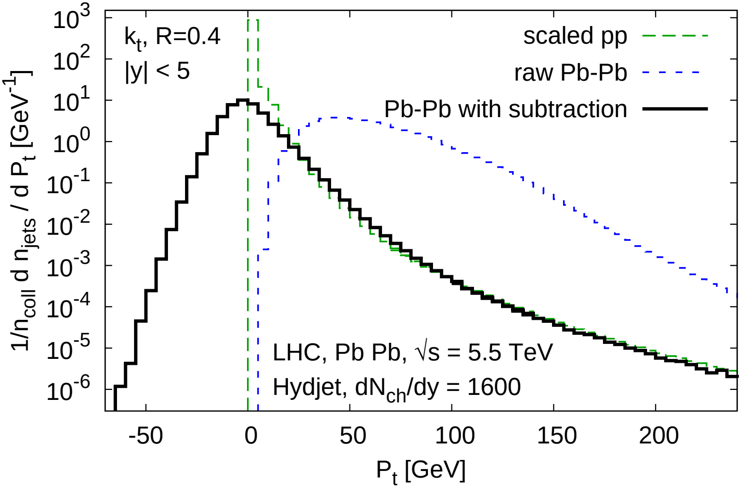
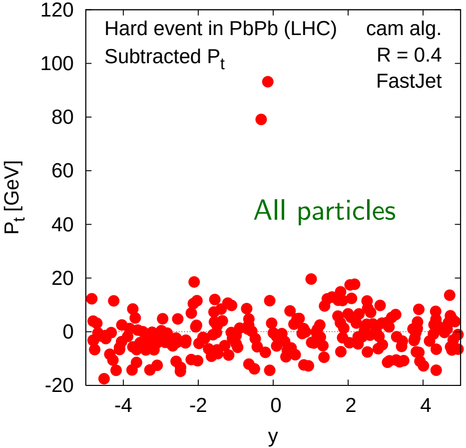
Subtraction in action



the inclusive jet spectrum — a basic measurement
[here shown unquenched]

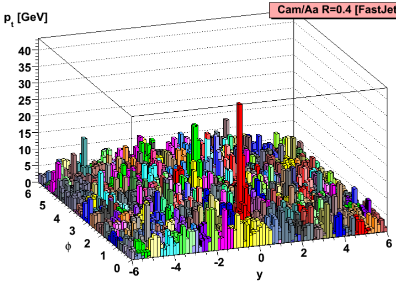
Noise reduction



Events are noisy. One approach: apply p_t cut on particles.

cf. STAR talk?

But quenching can change p_t distribution of particles in jets. . .



Understand systematics of "noise"

$$\langle \Delta p_t^2 \rangle \simeq \langle A_{JA,R} \rangle \langle \sigma^2 \rangle + \langle \Delta p_t^2 \rangle_{BR}$$

Low jet-areas good; Back-reaction?

Better understanding → better algs

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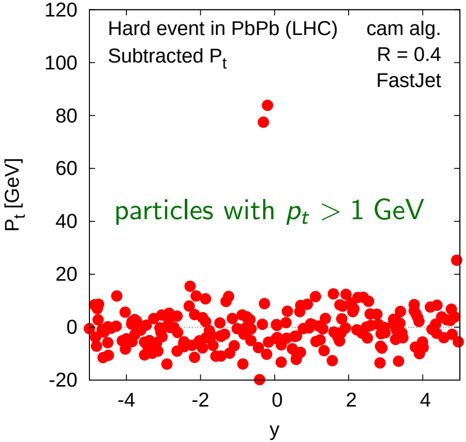

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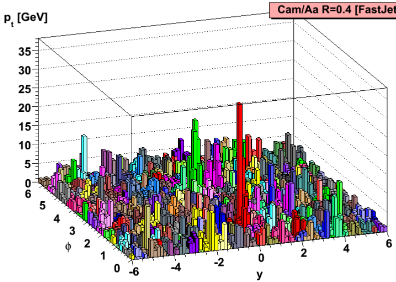

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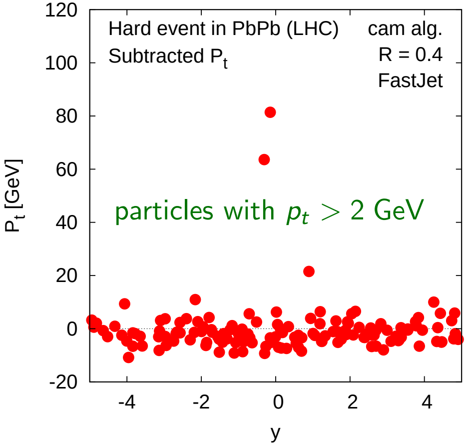

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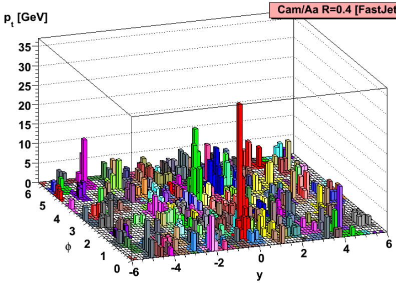

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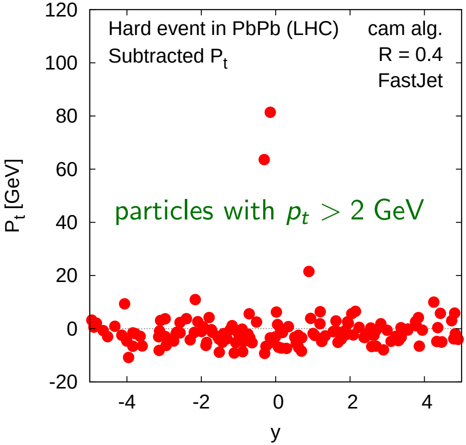

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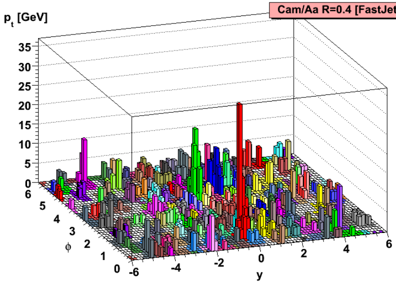

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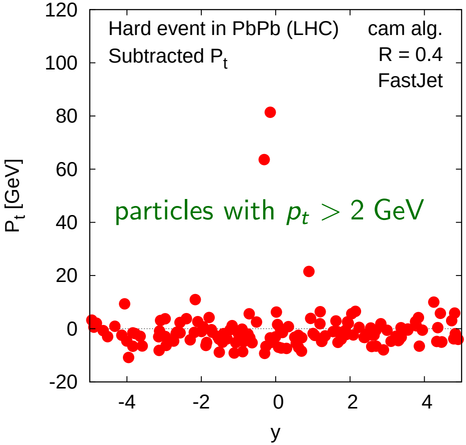

particles with $p_t > 2$ GeV

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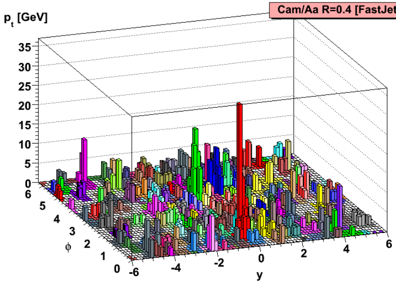

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Low jet-areas good; Back-reaction?

Better understanding → better algs

Example of unclear issues

"Background" may not be uniform

- Ridge
- Mach cone

When estimating background (globally, locally), are you affected by this?

➥Importance of using complementary methods within each experiment

Are these structures part of background, or part of jet?

What goes into the jet is ultimately your choice

➥Should jet algorithms be designed to include them?

Outlook

Jets are just now becoming a reality in Heavy-Ion Collisions

STAR, & in not so long LHC

It's important to start on a good footing

Infrared & Collinear safe algorithms

E.g.: k_t, Cam/Aachen, anti-k_t & SISCone [all in FastJet]

Exciting new territory, in terms of how we study it...

Exploit flexibility in approaches to separating jets & background

and in how we use the jets

And in terms of what it will teach us!

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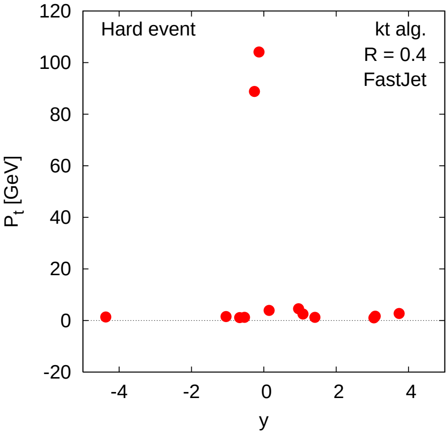
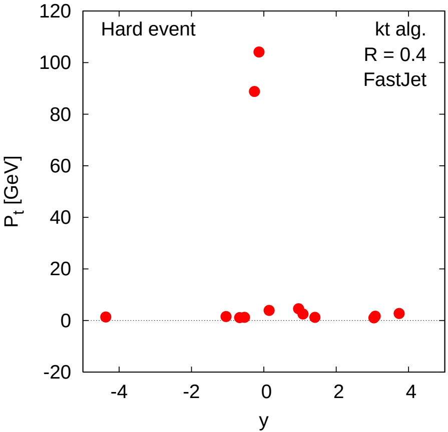
EXTRAS

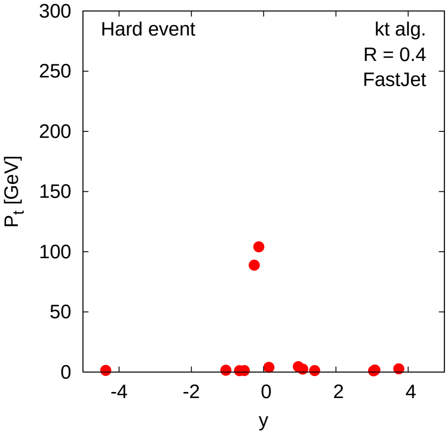
Background subtraction in HI event



Start with a hard dijet event

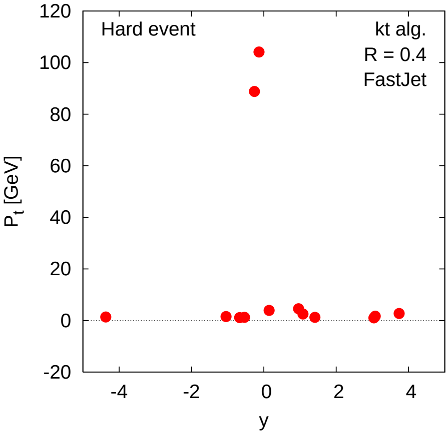
Background subtraction in HI event

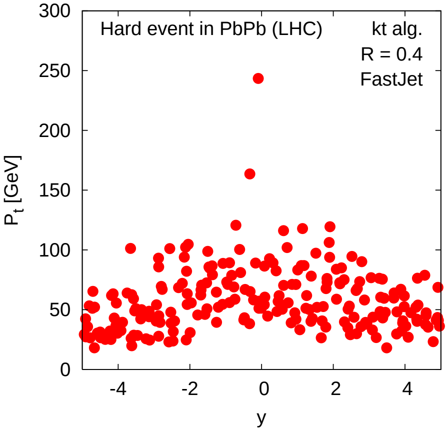




Same event on a different scale

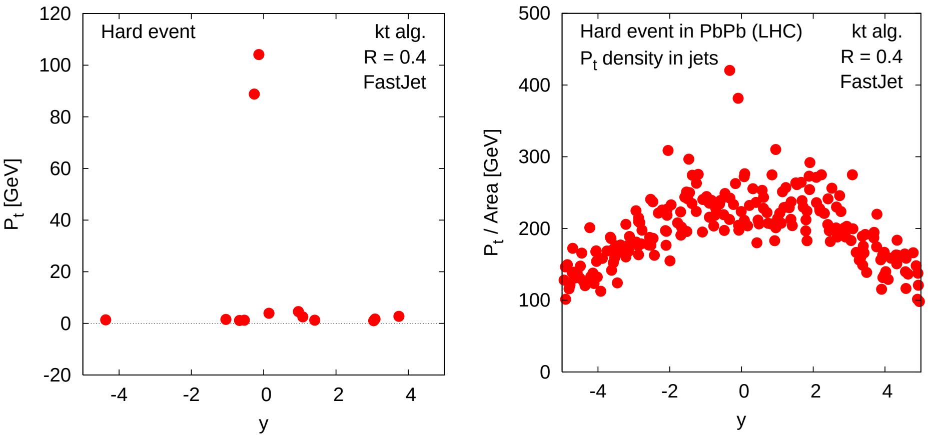
Background subtraction in HI event





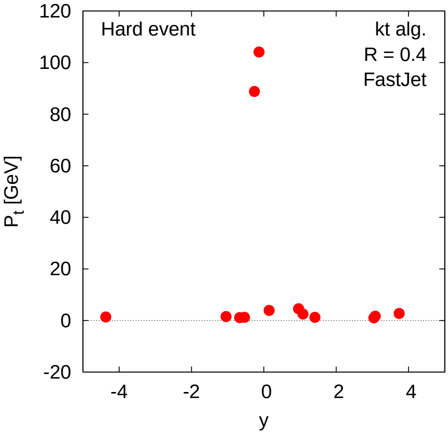
Embed it into a central Hydjet Pb Pb event

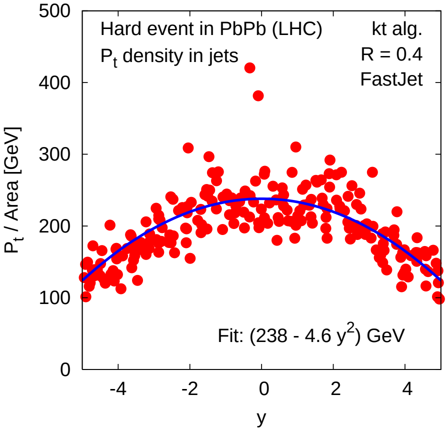
Background subtraction in HI event



Look at P_t/Area for each jet

Background subtraction in HI event

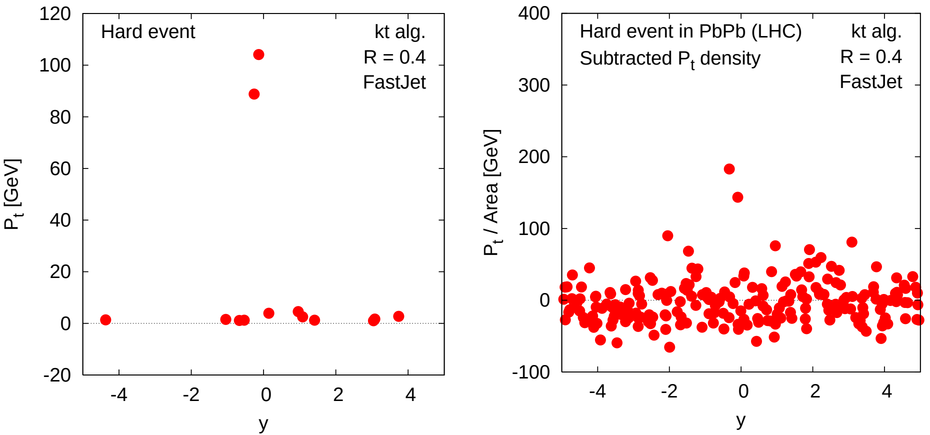




Fit the background $\rho(y)$

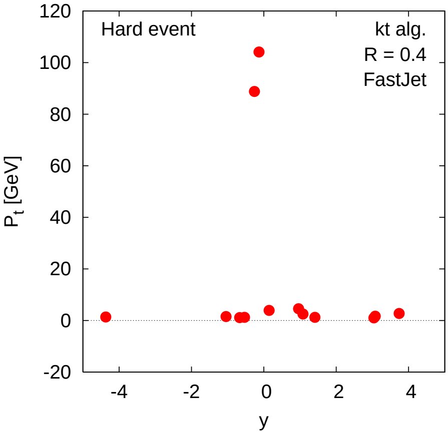
[NB: more general functional form needs investigating]

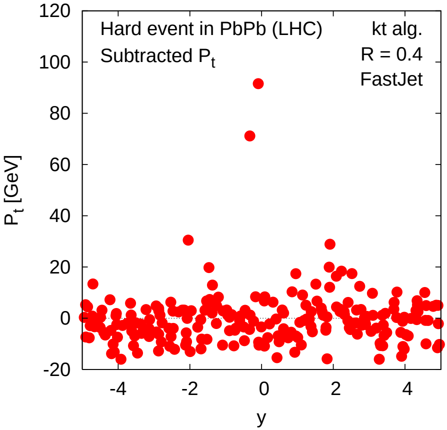
Background subtraction in HI event



Subtract $\rho(y)$ from P_t/Area for each jet

Background subtraction in HI event

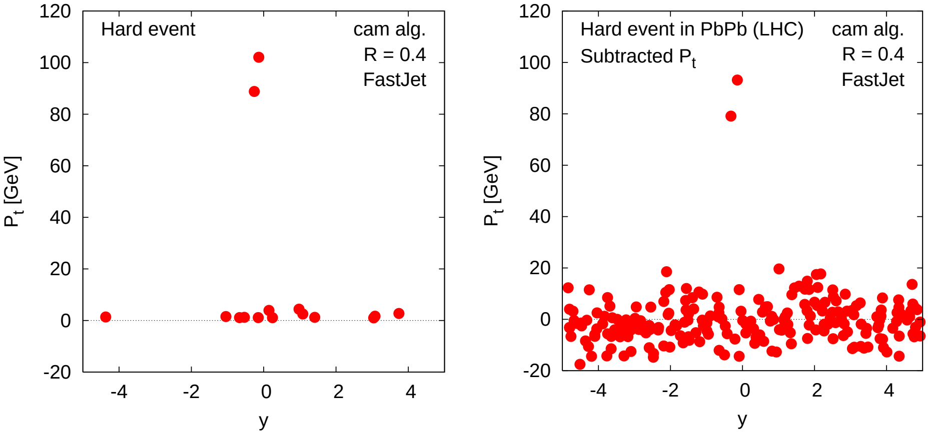




Look at resulting corrected $P_t = P_{t,orig} - \rho(y) \times \mathrm{Area}$

Hard jets with roughly correct P_t and y emerge clearly!

Background subtraction in HI event



Try with Cambridge/Aachen instead of k_t to check robustness!