QCD (for LHC)
Lecture 4

1. Merging parton showers and fixed order
2. Jets

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- Tree-level (LO) gives decent description of multi-jet structure
- NLO gives good normalisation
- Parton-shower gives good behaviour in soft-collinear regions and fully exclusive final state.

Can we combine the advantages of all three?

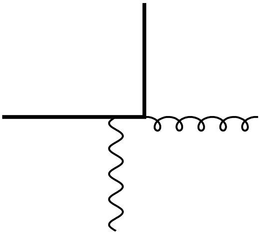
Difficulties in merging Tree-level(s) + PS?

Suppose you ask for Z+jet as your initial hard process in Pythia/Herwig.

- They contain the correct ME for Z+j.
- But you want Z+2j to be correct too.

Naive approach: you could also generate Z+2j events with Alpgen (or Madgraph, etc.) and run the shower from those configurations too.

Add Z+1jet, Z+2jet + shower



Z+parton

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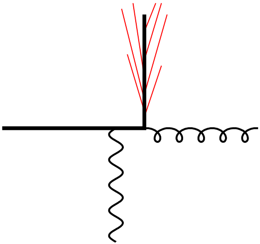

shower **Z+parton**

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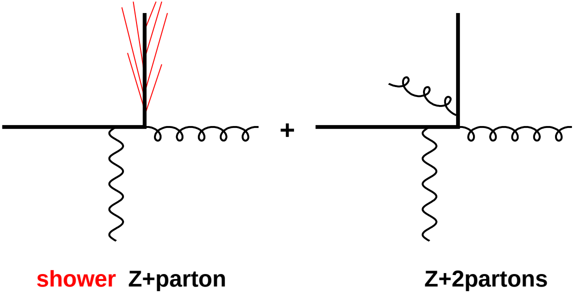

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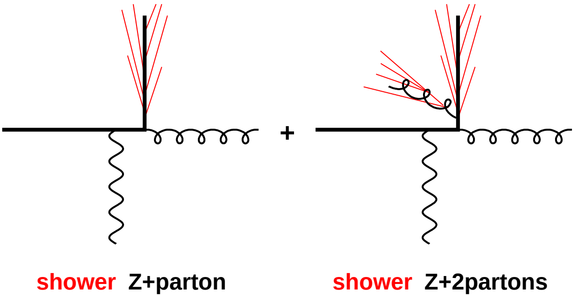

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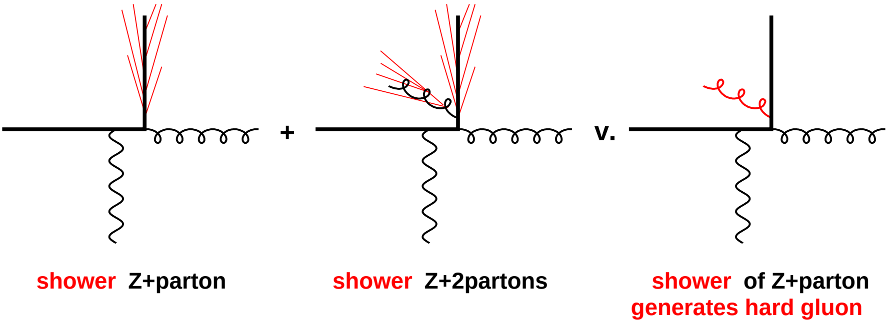

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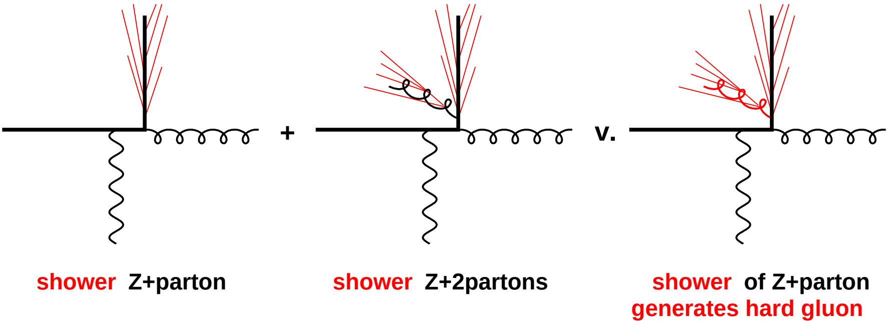

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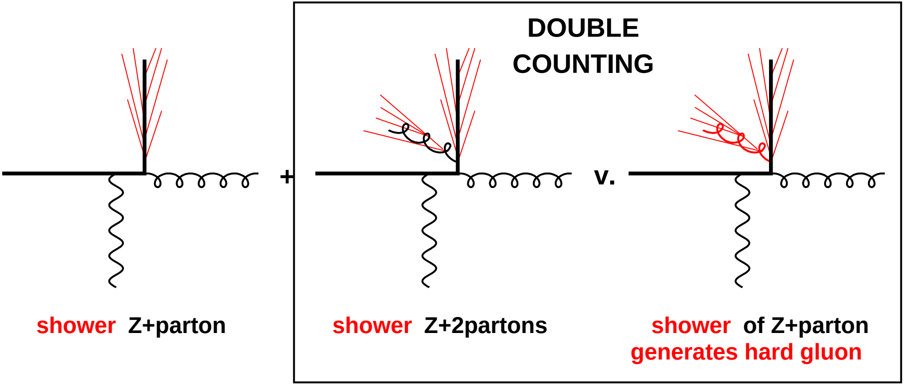


Double counting + associated issues with virtual corrections are the main problems when merging PS + ME

Merging procedures

ME + PS merging is an attempt to solve this. There are many variants. One common one is **"MLM matching"** — a summary of it is:

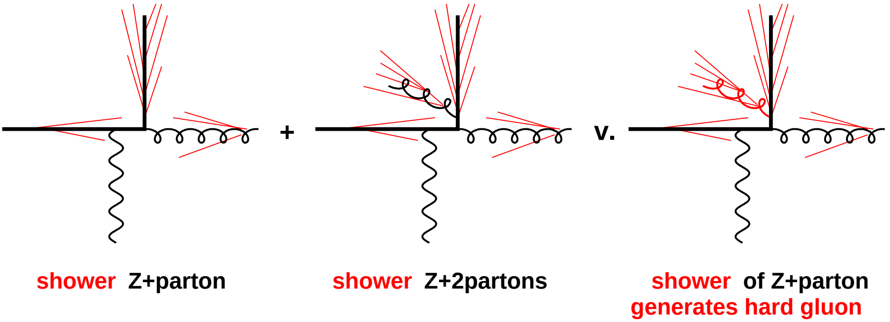
- Introduce a cutoff Q_{ME}
- Use the matrix elements to generate tree-level events for Z+1 parton, Z+2 partons, ... Z+N partons, where all partons must have $p_t > Q_{ME}$, and are separated from the others by some angle R_{ME}.

  Numbers of events are in proportion to their cross sections with these cuts
- Take one of these tree level events, say with n-partons.
- Shower it with your favourite Parton Shower program.
- Identify all jets that have $p_t > Q_{merge}$ (chosen $\gtrsim Q_{ME}$)
- If each parton corresponds to one of the jets ($\equiv$ is nearby in angle) and there are no extra jets above scale Q_{merge}, accept the event.

  [Replace $Q_{merge} \to p_{tn}$ if $n = N$]
- Otherwise reject it.

NB: MLM stands for Michelangelo L. Mangano

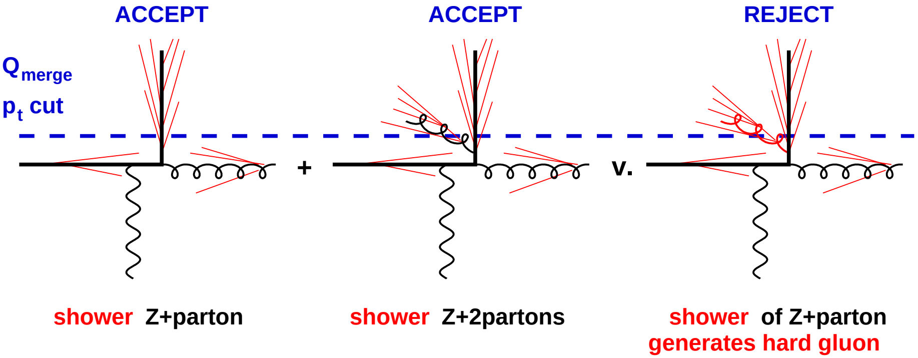
MLM example



- Hard jets above scale Q_{merge} have distributions given by tree-level ME
- Rejection procedure eliminates “double-counted” jets from parton shower
- Rejection generates Sudakov form factors between individual jet scales

How well? Depends on details of PS. One of the weaker points of MLM

MLM example



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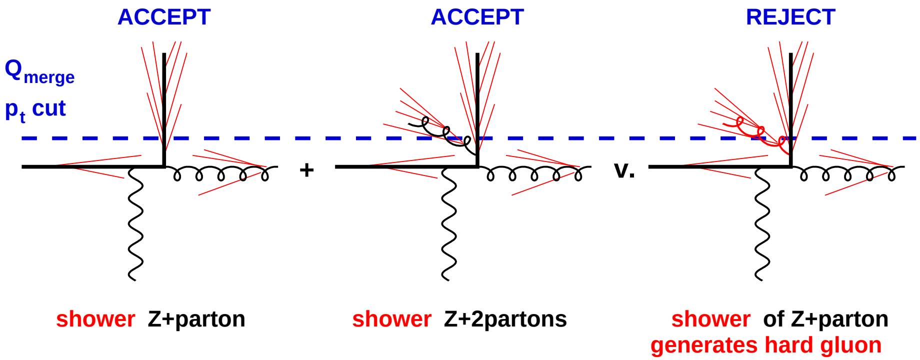

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Merging – other schemes

MLM is the standard merging available from Alpgen

There are several other merging procedures on the market

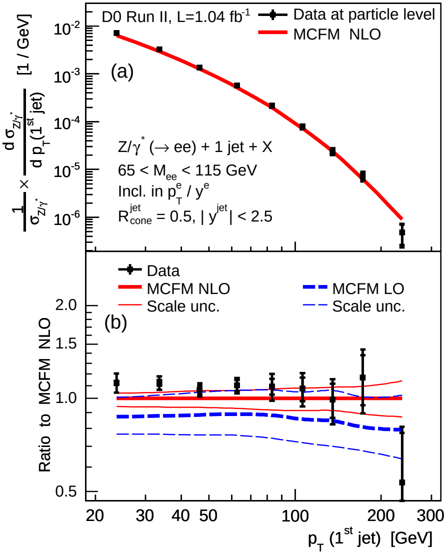
- MLM à la MadGraph — Mainly changes details of jet finding
- CKKW — e.g. in Sherpa
- CKKW-L — e.g. in Ariadne
- Pseudo Shower — by Mrenna

They vary essentially in whether/how they match partons & jets, the definitions of the jets, and some include analytic Sudakov form factors (e.g. CKKW).

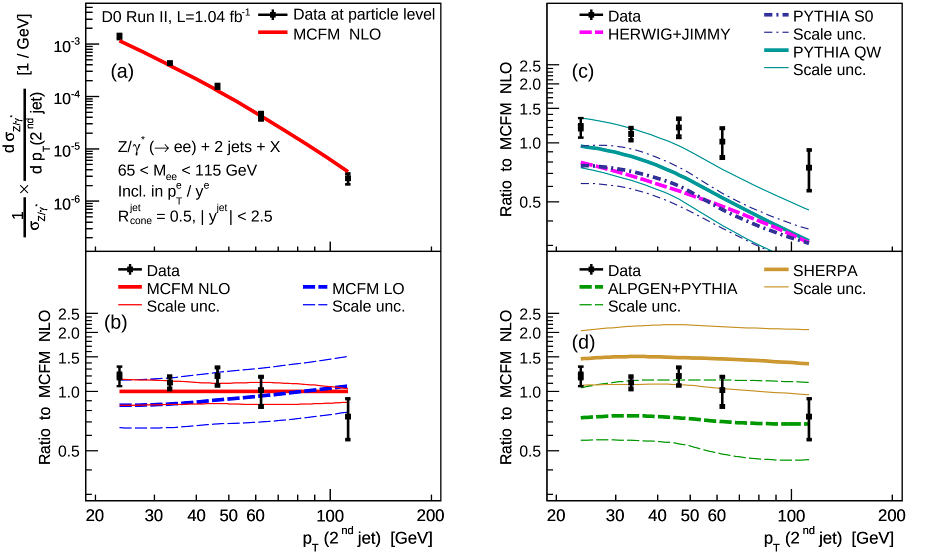
They all involve some implicit form of p_t cutoff.

Usually physics well above cutoff is independent of cutoff?

Z + 1 jet


D0 Run II, L=1.04 fb^{-1}
Data at particle level
MCFM NLO
(a)
Z/γ^* ($\rightarrow$ ee) + 1 jet + X
65 < M_{ee} < 115 GeV
Incl. in p_T^e / y^e
R_{cone}^{jet} = 0.5, | y^{jet}| < 2.5
$\frac{1}{\sigma_{Z/\gamma^*}} \times \frac{d\sigma_{Z/\gamma^*}}{d p_T(1^{st}\text{ jet})}$ [1 / GeV]
Data
MCFM NLO
Scale unc.
MCFM LO
Scale unc.
(b)
Ratio to MCFM NLO
Data
HERWIG+JIMMY
PYTHIA S0
Scale unc.
PYTHIA QW
Scale unc.
(c)
Data
ALPGEN+PYTHIA
Scale unc.
SHERPA
Scale unc.
(d)
p_T (1^{st} jet) [GeV]

Z + 2 jets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(b)
Data
MCFM NLO
Scale unc.
MCFM LO
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(c)
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HERWIG+JIMMY
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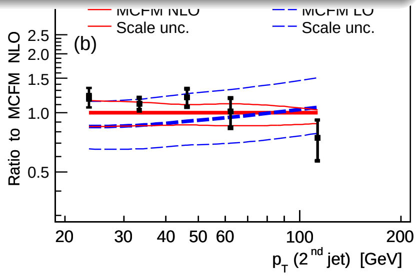
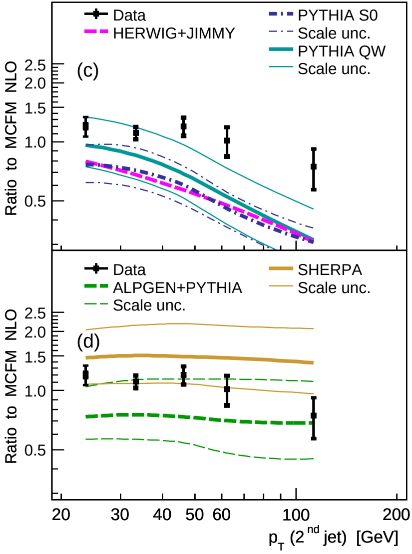
(d)
Data
ALPGEN+PYTHIA
Scale unc.
SHERPA
Scale unc.
Ratio to MCFM NLO
p_T (2^{nd} jet) [GeV]

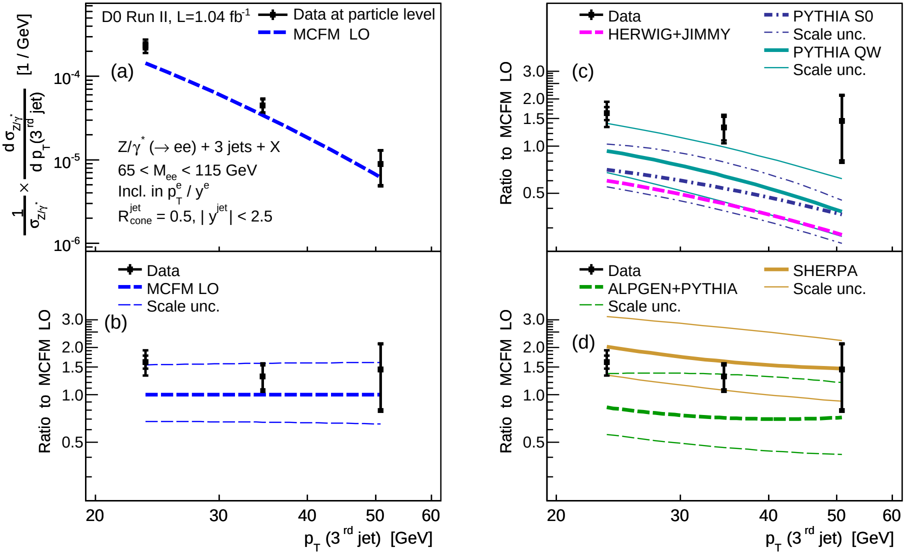
Z + 2 jets

- ME + PS merging helps get correct p_t dependence
- It works much better than plain parton showers
- Normalisation is still quite uncertain





Z + 3 jets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Data at particle level
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(a)
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Incl. in p_T^e / y^e
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$\frac{1}{\sigma_{Z/\gamma^*}} \times \frac{d\sigma_{Z/\gamma^*}}{d p_T (3^{rd} \text{ jet})}$ [1 / GeV]
(b)
Data
MCFM LO
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Ratio to MCFM LO
p_T (3^{rd} jet) [GeV]

Can we get parton-shower structure, with NLO accuracy (e.g. control of normalisation, pattern of radiation of extra parton)?

MC@NLO ideas

Frixione & Webber '02

- Expand your Monte Carlo branching to first order in α_s

  Rather non-trivial – requires deep understanding of MC
- Calculate differences wrt true $\mathcal{O}(\alpha_s)$

  both in real and virtual pieces
- If your Monte Carlo gives correct soft and/or collinear limits, those differences are **finite**
- Generate extra partonic configurations with phase-space distributions proportional to those differences and shower them

MC@NLO cont.

Let's imagine a problem with one phase-space dimension, e.g. E. Expand Monte Carlo cross section for emission with energy E:

$$\sigma^{MC} \equiv 1 \times \delta(E) + \alpha_s \sigma_{1R}^{MC}(E) + \alpha_s \sigma_{1V}^{MC} \delta(E) + \mathcal{O}\left(\alpha_s^2\right)$$

With true NLO real/virtual terms as $\alpha_s \sigma_{1R}(E)$ and $\alpha_s \sigma_{1V} \delta(E)$, define

$$\text{MC@NLO} = \text{MC} \times \left(1 + \alpha_s(\sigma_{1V} - \sigma_{1V}^{MC}) + \alpha_s \int dE(\sigma_{1R}(E) - \sigma_{1R}^{MC}(E))\right)$$

All weights finite, but can be ± 1

Processes include   Frixione, Laenen, Motylinski, Nason, Webber, White '02–'08

Higgs boson, single vector boson, vector boson pair, heavy quark pair, single top (with and without associated W), lepton pair and associated Higgs+W/Z

POWHEG

Aims to work around MC@NLO limitations — Nason '04

- the (small fraction of) negative weights
- the tight interconnection with a specific MC

Principle

- Write a simplified Monte Carlo that generates **just one emission** (the hardest one) which alone gives the correct NLO result.

  Essentially uses special Sudakov

  $\Delta(k_t) = \exp(-\int$ exact real-radition probability above $k_t)$
- Lets your default parton-shower do branchings below that k_t.

Processes include

$pp \to$ Heavy-quark pair, Higgs, single vector-boson

Alioli, Frixione, Nason, Oleari, Re '07–08

$pp \to W'$, $e^+e^- \to t\bar{t}$ — Papaefstathiou, Latunde-Dada

MC@NLO e.g.: $t\bar{t}$ p_t distribution for LHC

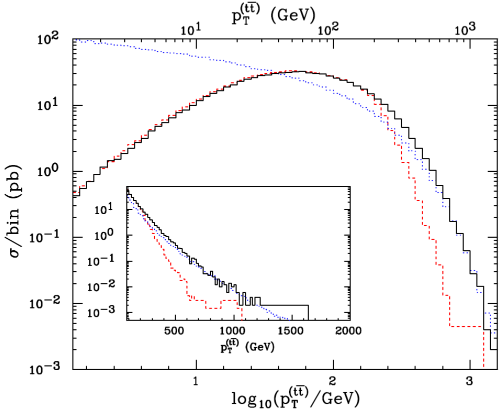


figure from talk by Frixione '04

Solid: MC@NLO

Dashed: HERWIG$\times\frac{\sigma_{NLO}}{\sigma_{LO}}$

Dotted: NLO

- MC@NLO gets right normalisation
- correct behaviour at low p_t ($\sim$ rescaled Herwig)
- correct behaviour at high p_t ($\sim$ NLO)

Summary of merging/matching

- You can merge many different tree-levels (Z+1, Z+2, Z+3, ...) with parton showering together into a consistent sample.

  Shapes should be OK, normalisation is rather uncertain

  Procedures are flexible and general — but not necessarily the final word

- You can merge NLO accuracy with parton showers for simple processes (at most one light jet — single top case)

  Two main methods: MC@NLO / POWHEG

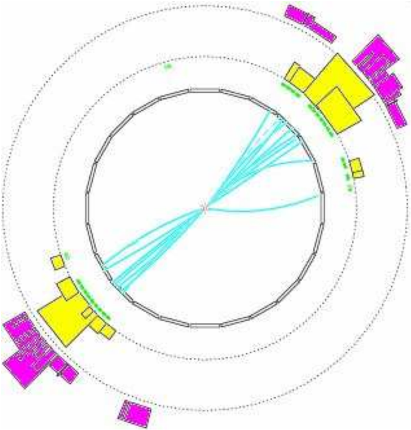
  It is hard theory work — must be done on a case by case basis

- Incorporation of different multiplicities (Z+1, Z+2, Z+3, ...) consistently at NLO for each multiplicity, together with parton showering, is a current research problem.

We've completed our tour of predictive methods in collider QCD
(LO, NLO, NNLO; parton showers; mergings and matchings)

The last topic of these lectures is **jets**
They've already arisen in various contexts; now look at them in detail

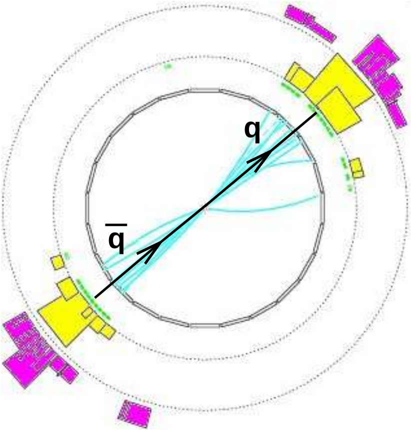
Seeing v. defining jets



Jets are what we see.
Clearly(?) 2 jets here

How many jets do you see?
Do you really want to ask yourself this question for 10^9 events?

Seeing v. defining jets



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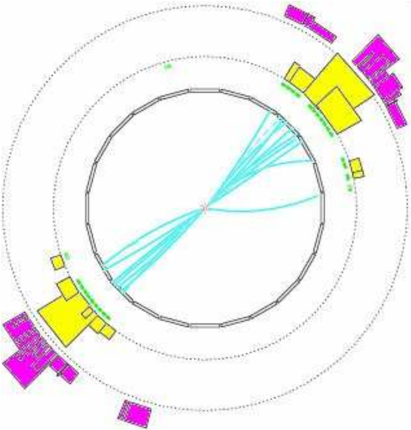

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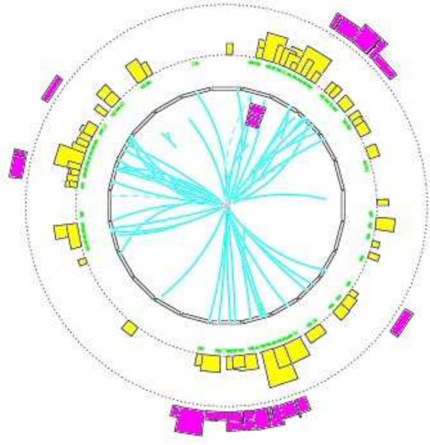

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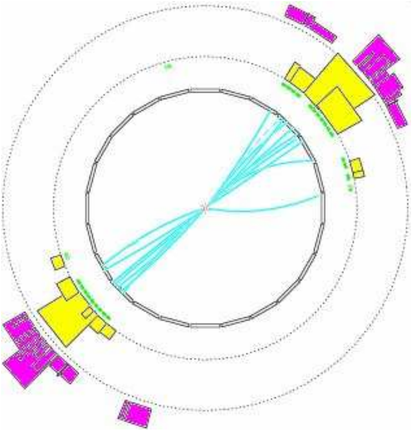

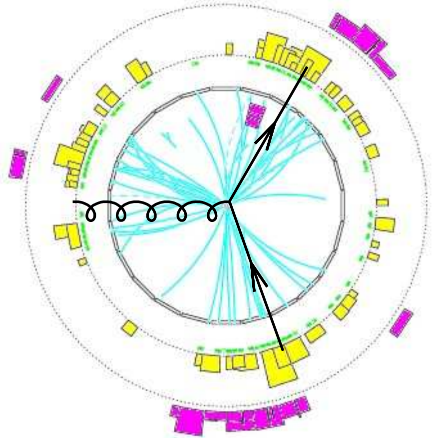

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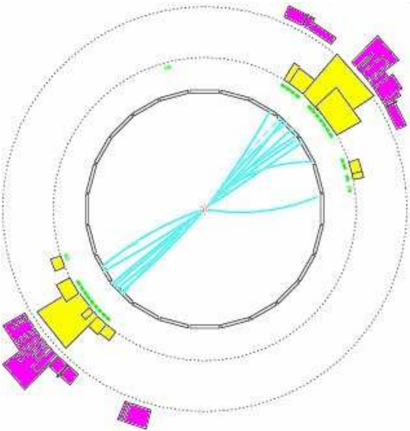

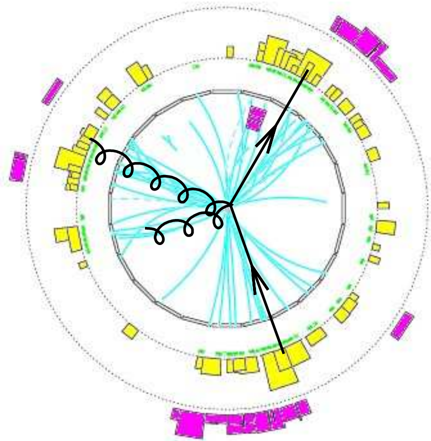

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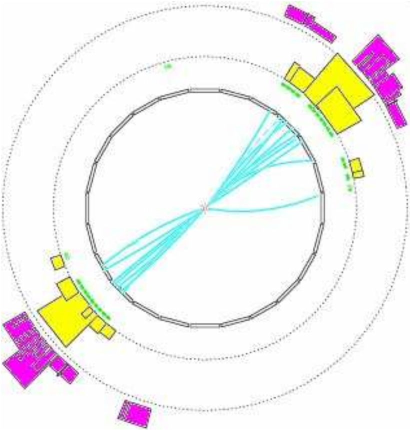

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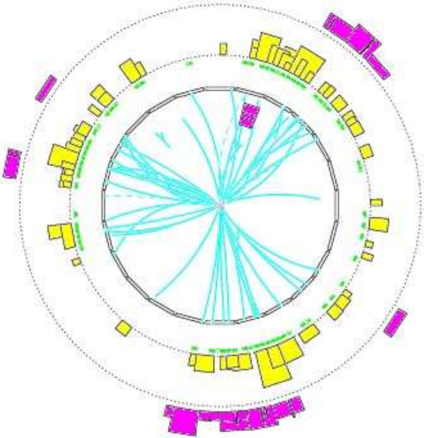

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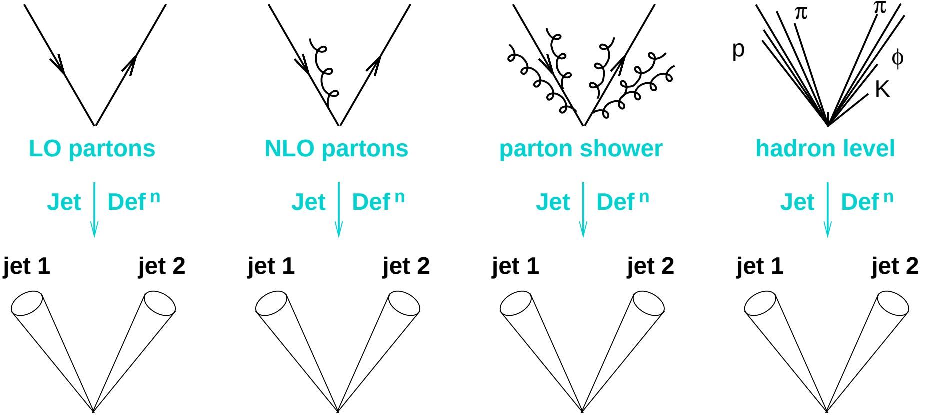
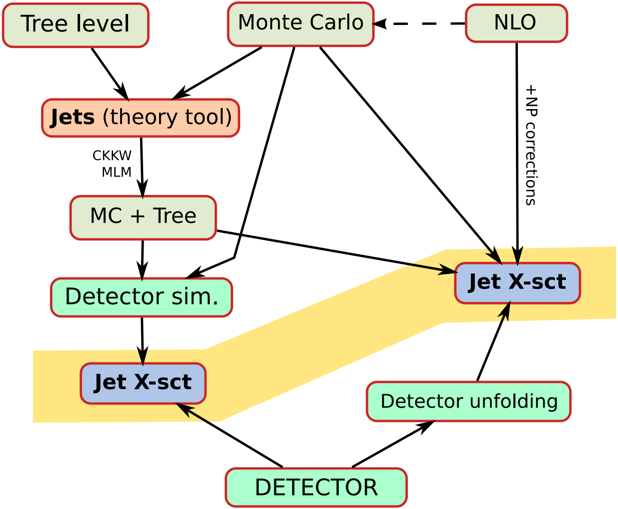
Jets as projections



Projection to jets provides "universal" view of event

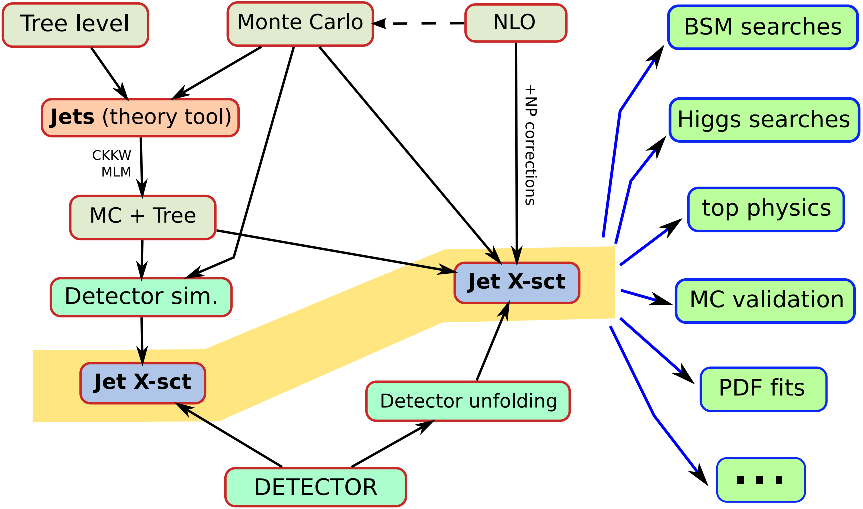
QCD jets flowchart



Jet (definitions) provide central link between expt., "theory" and theory

And jets are an input to almost all analyses

QCD jets flowchart



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There is no unique jet definition

The construction of a jet is unavoidably ambiguous. On at least two fronts:

1. which particles get put together into a common jet? — Jet algorithm
   + parameters, e.g. jet angular radius R
2. how do you combine their momenta? — Recombination scheme
   Most commonly used: direct 4-vector sums (E-scheme)

Taken together, these different elements specify a choice of jet definition — cf. Les Houches '07 nomenclature accord

**Ambiguity complicates life,
but gives flexibility in one's view of events
→ Jets non-trivial!**

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→ Jets non-trivial!

Two main classes of jet alg.

Sequential recombination (k_t, etc.)

- bottom-up
- successively undoes QCD branching

Cone

- top-down
- centred around idea of an 'invariant', directed energy flow

k_t/Durham algorithm

Majority of QCD branching is soft & collinear, with following divergences:

$$[dk_j]|M^2_{g\to g_i g_j}(k_j)| \simeq \frac{2\alpha_s C_A}{\pi} \frac{dE_j}{\min(E_i, E_j)} \frac{d\theta_{ij}}{\theta_{ij}}, \qquad (E_j \ll E_i\,,\ \theta_{ij} \ll 1)\,.$$

To invert branching process, take pair with strongest divergence between them — they're the most *likely* to belong together.

This is basis of **$\mathbf{k_t}$/Durham algorithm** (e^+e^-):

1. Calculate (or update) distances between all particles i and j:

$$y_{ij} = \frac{2\min(E_i^2, E_j^2)(1-\cos\theta_{ij})}{Q^2}$$

NB: relative k_t between particles

2. Find smallest of y_{ij}
   - If $> y_{cut}$, stop clustering
   - Otherwise recombine i and j, and repeat from step 1

Catani, Dokshitzer, Olsson, Turnock & Webber '91

k_t alg. at hadron colliders

inclusive k_t algorithm

- Introduce angular radius R (NB: dimensionless!)

$$d_{ij} = \min(p_{ti}^2, p_{tj}^2)\frac{\Delta R_{ij}^2}{R^2}\,, \qquad d_{iB} = p_{ti}^2 \qquad [\Delta R_{ij}^2 = (y_i - y_j)^2 + (\phi_i - \phi_j)^2]$$

- 1. Find smallest of d_{ij}, d_{iB}
  2. if ij, recombine them
  3. if iB, call i a jet and remove from list of particles
  4. repeat from step 1 until no particles left.

S.D. Ellis & Soper, '93; the simplest to use

Jets all separated by at least R on y, ϕ cylinder.

NB: number of jets not IR safe (soft jets near beam); number of jets above p_t cut **is** IR safe.

Sequential recombination

$\mathbf{k_t}$ alg.: Find smallest of

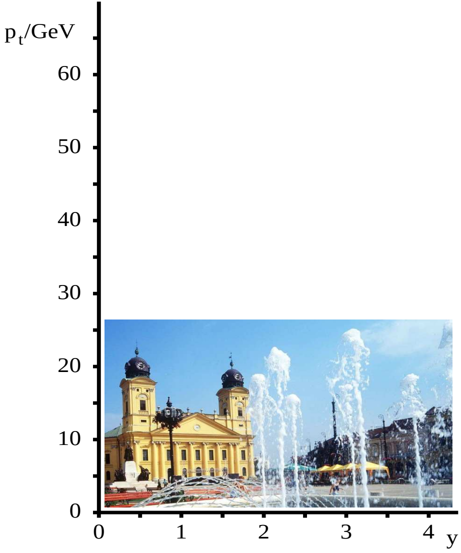
$$d_{ij} = \min(k_{ti}^2, k_{tj}^2)\Delta R_{ij}^2/R^2, \quad d_{iB} = k_{ti}^2$$

If d_{ij} recombine; if d_{iB}, i is a jet

Example clustering with k_t algorithm, $R = 0.7$

ϕ assumed 0 for all towers

Sequential recombination



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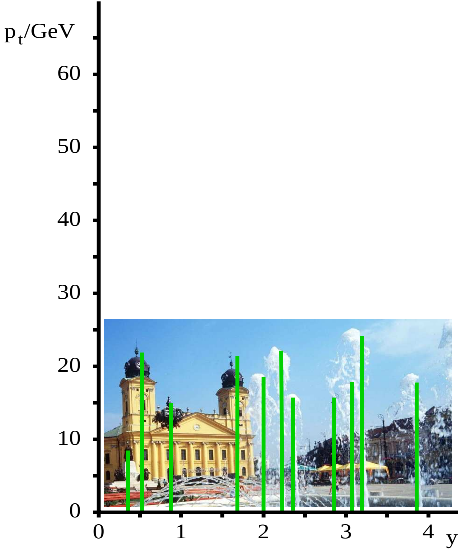

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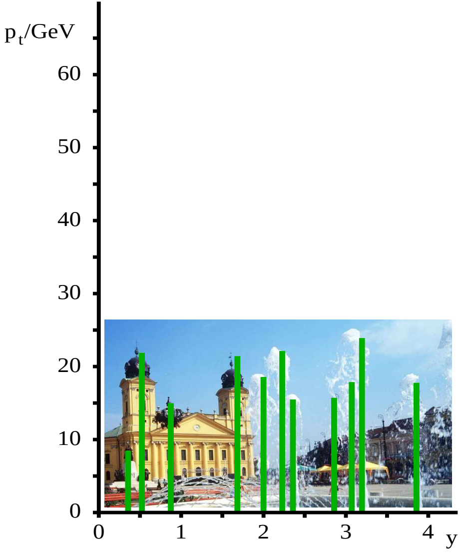

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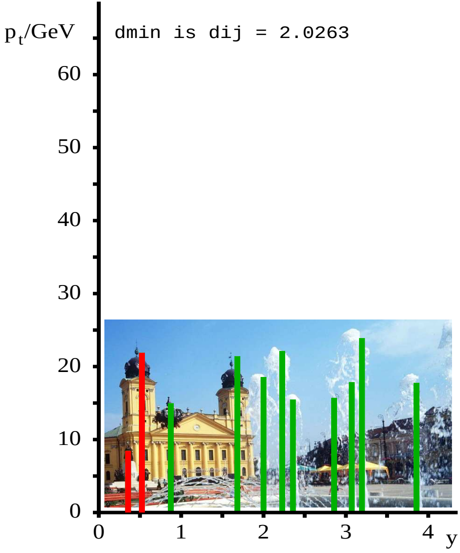

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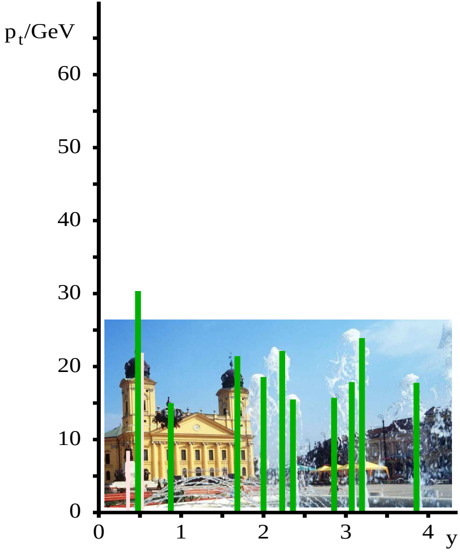

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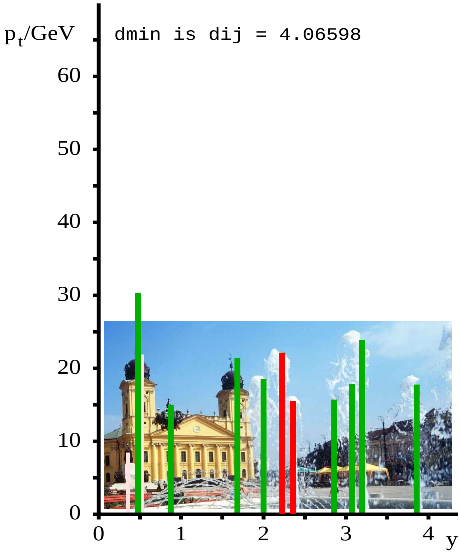

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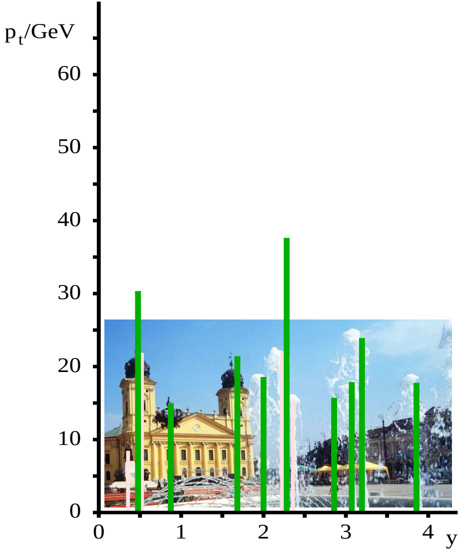

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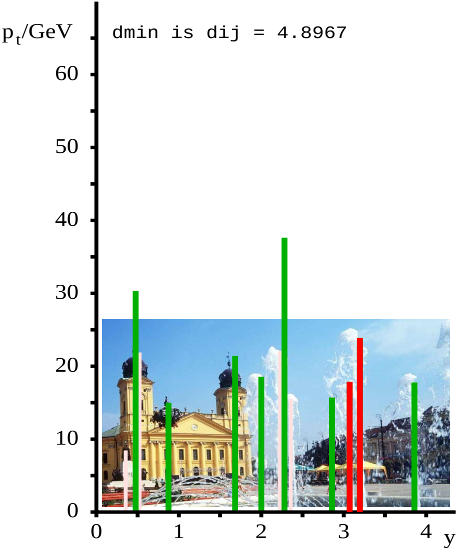

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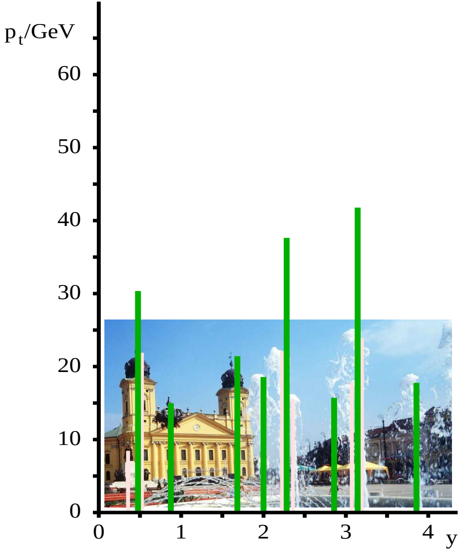

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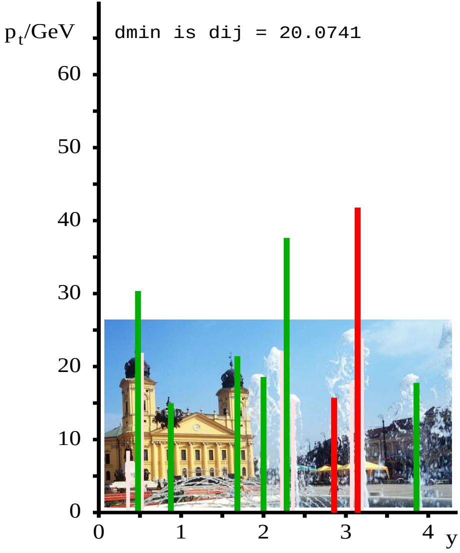

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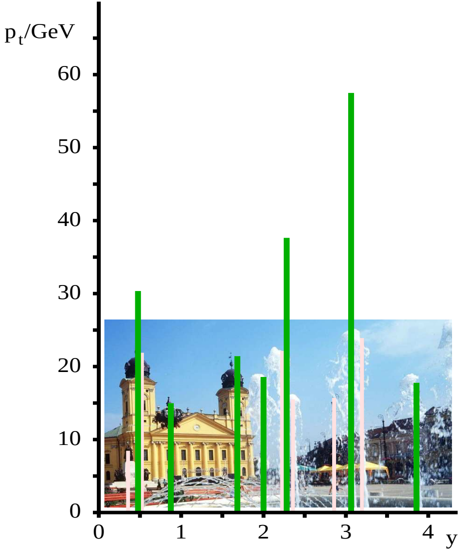

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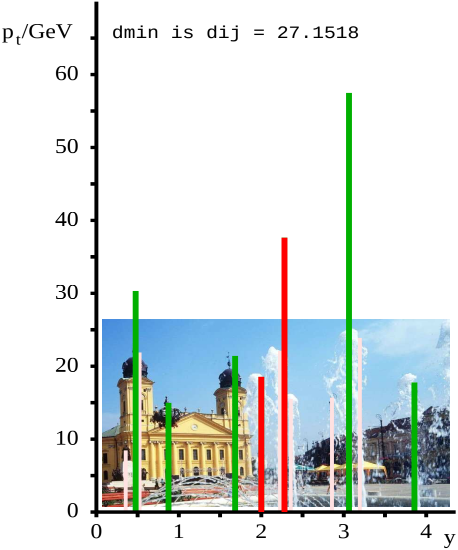

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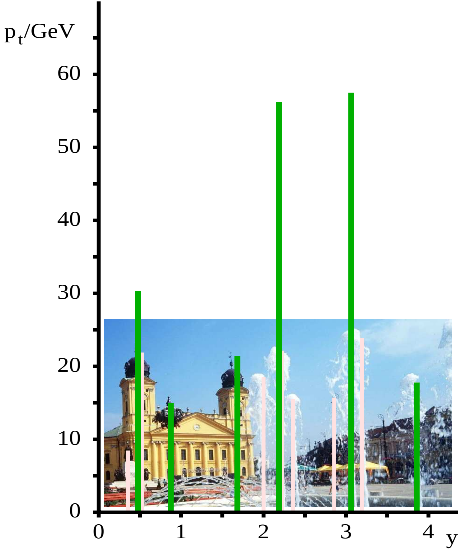

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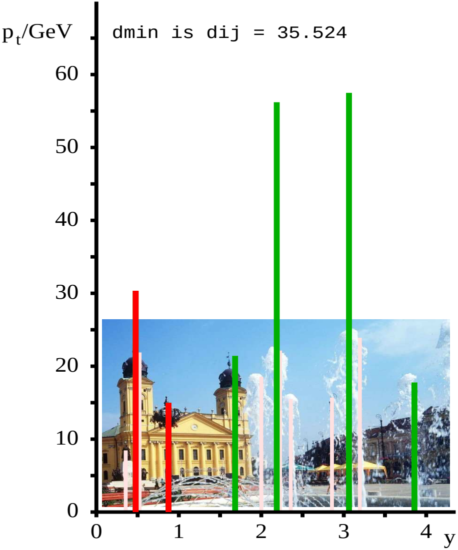

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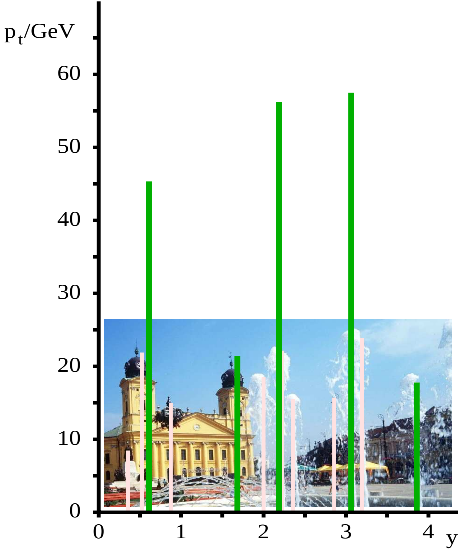

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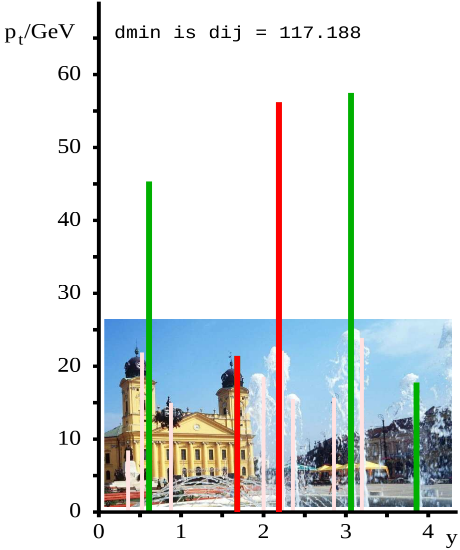

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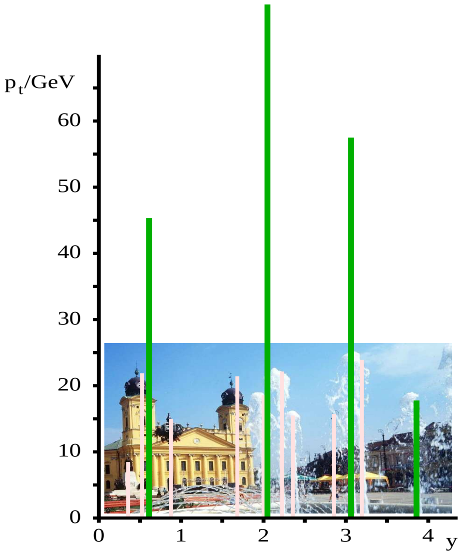

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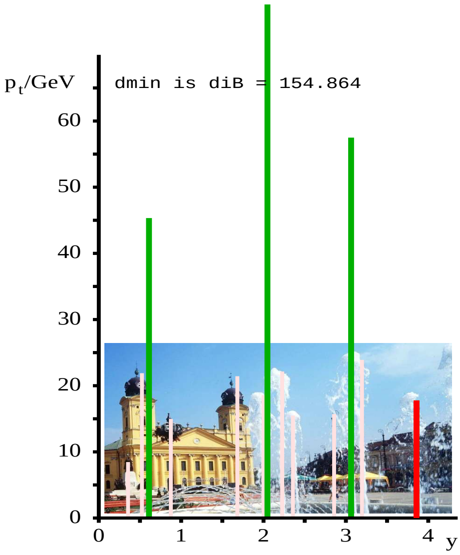

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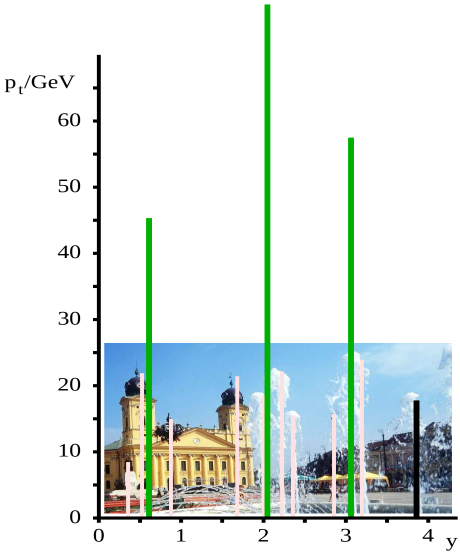

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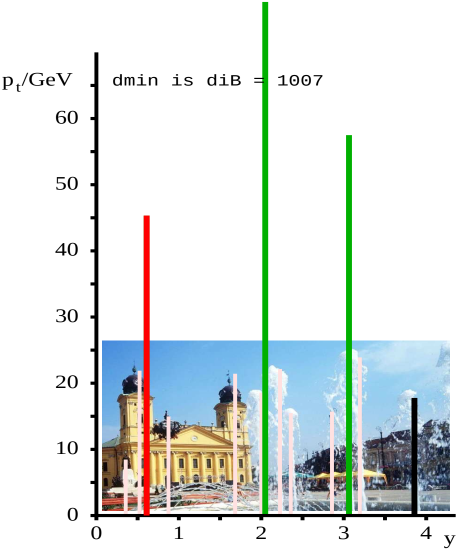

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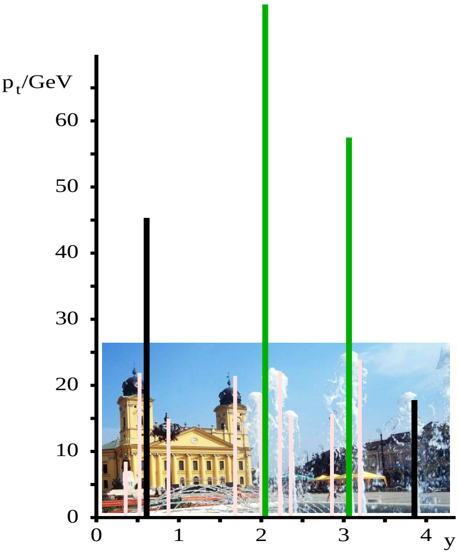

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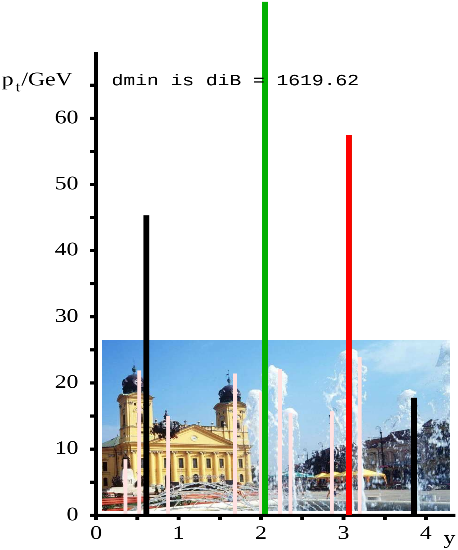

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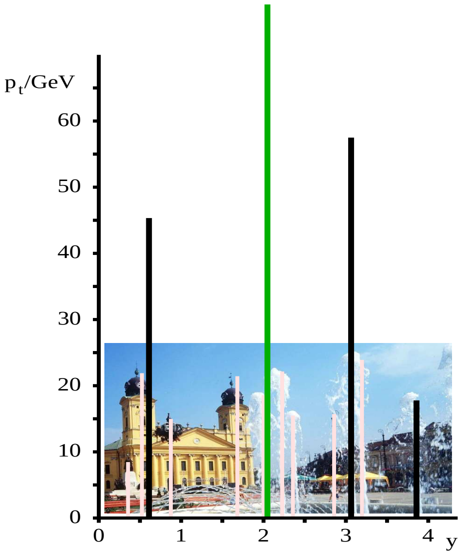

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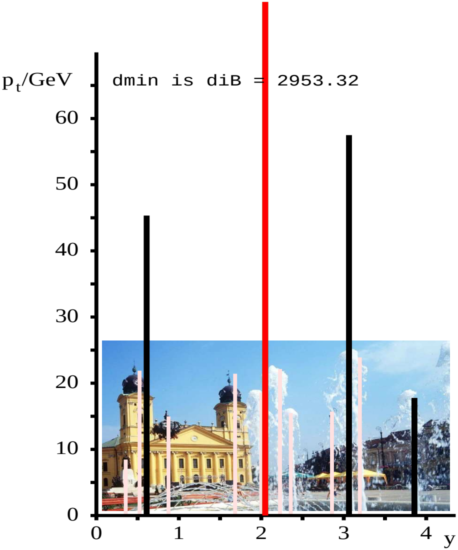

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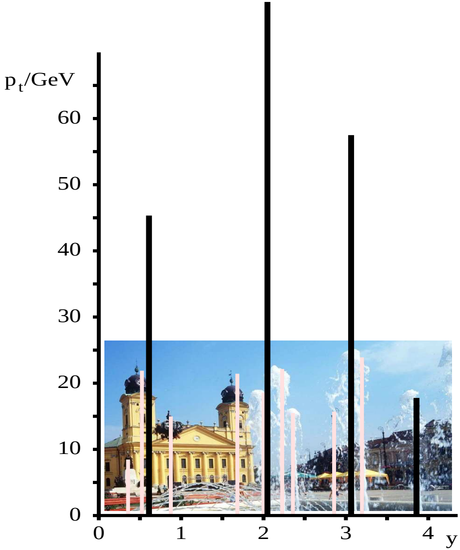

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Unifying idea: momentum flow within a cone only marginally modified by QCD branching

But cones come in many variants

Finding cones \ Processing	Progressive Removal	Split–Merge	Split–Drop
Seeded, Fixed (FC)	GetJet CellJet		
Seeded, Iterative (IC)	CMS Cone	JetClu (CDF)† ATLAS cone	
Seeded, It. + Midpoints (IC_{mp})		CDF MidPoint D0 Run II cone	PxCone
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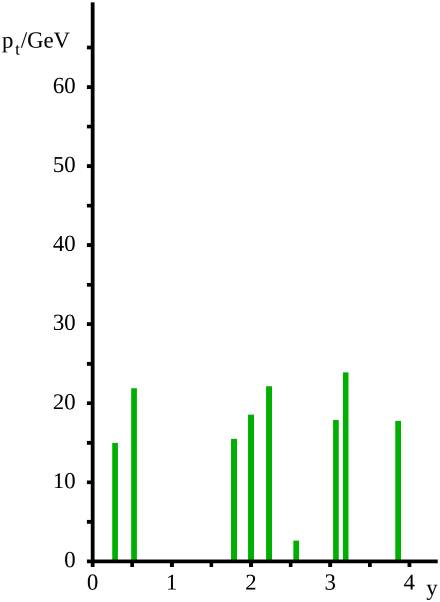

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e.g. CMS iterative cone

- Take hardest particle as seed for cone axis
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- "Hardest particle" is collinear unsafe more right away...

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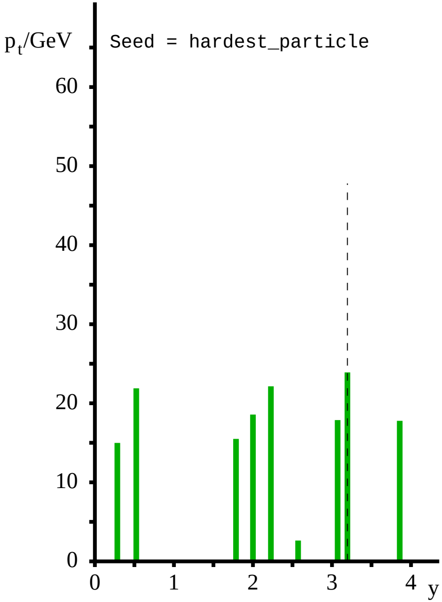

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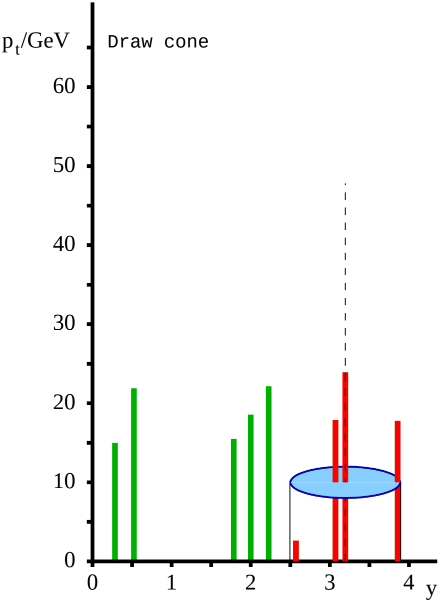

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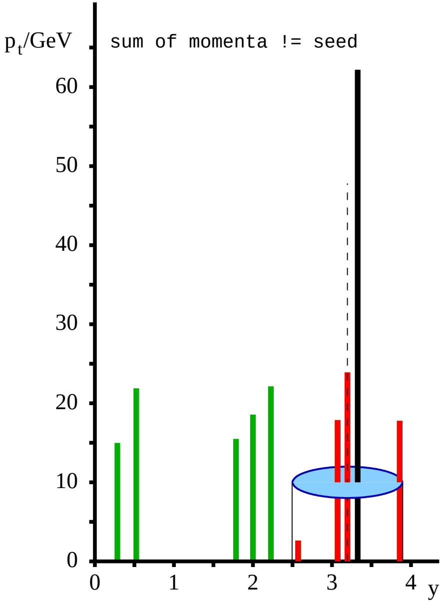

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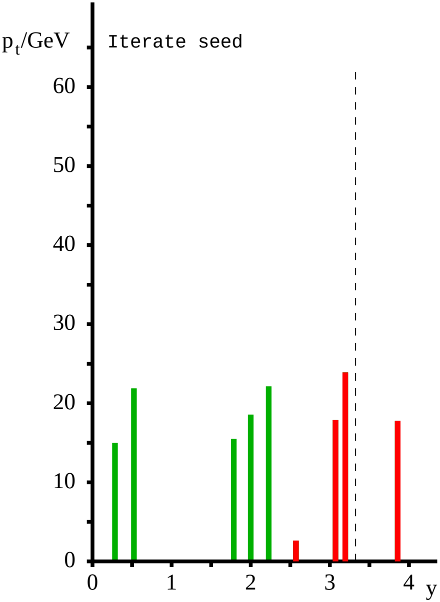

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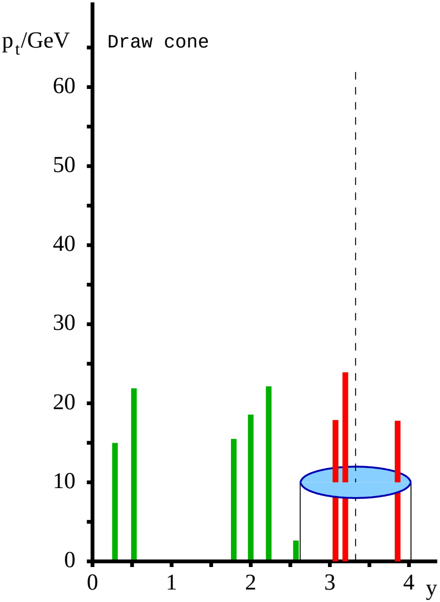

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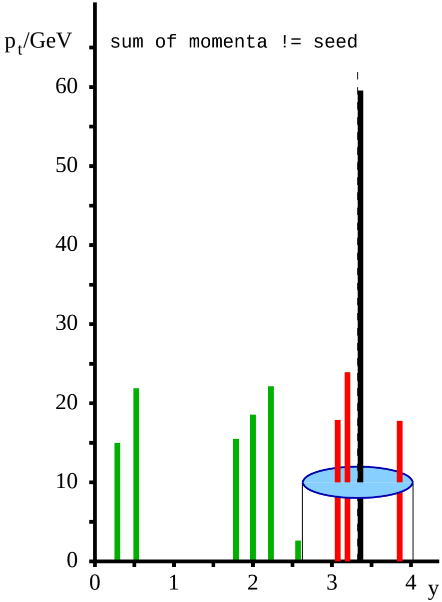

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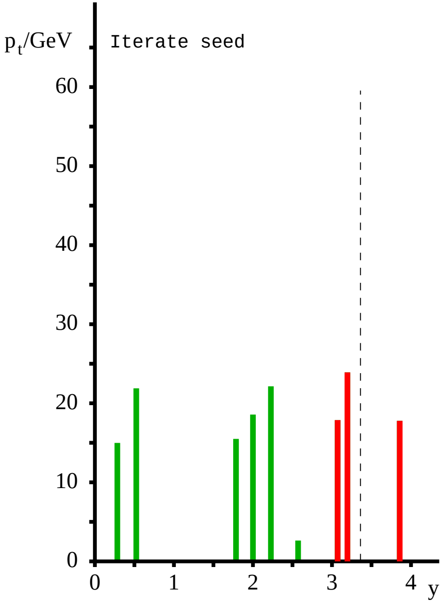

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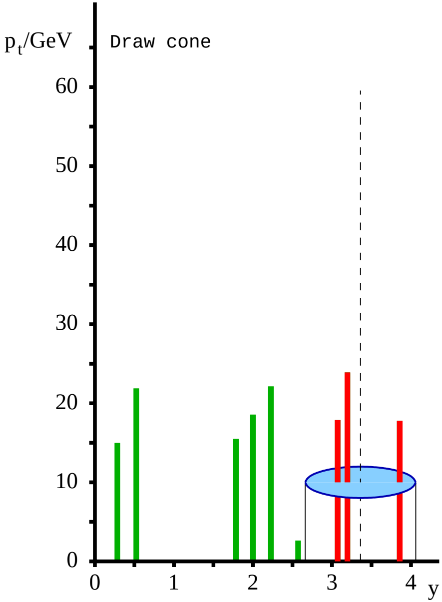

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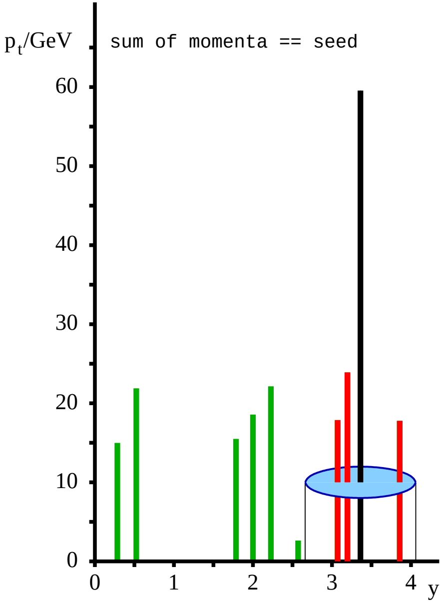

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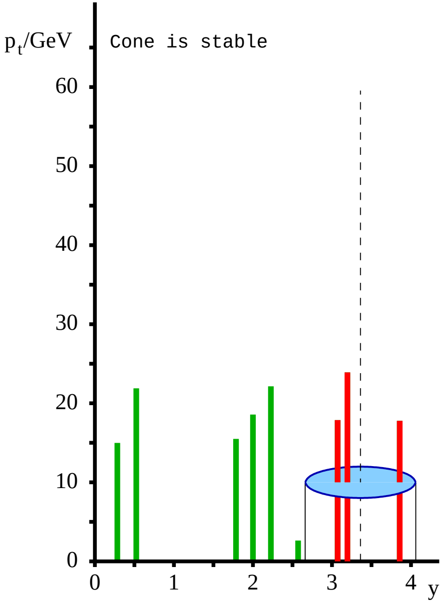

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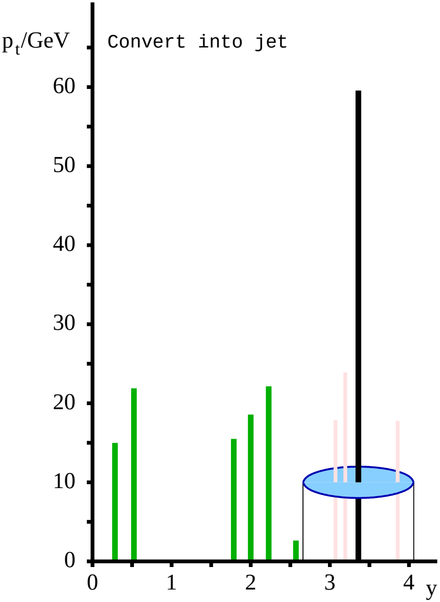

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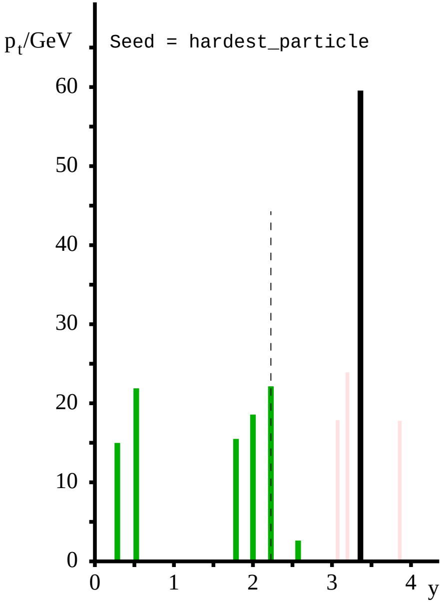

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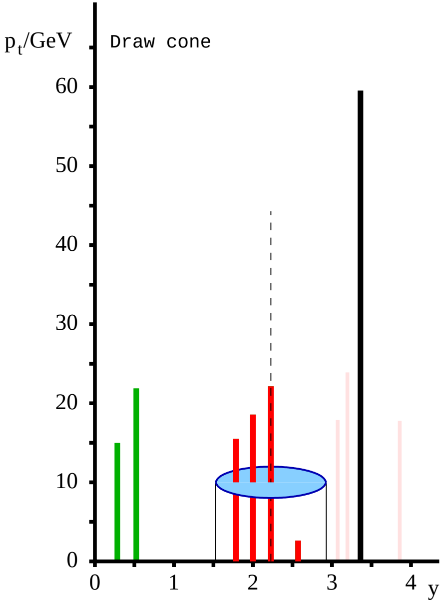

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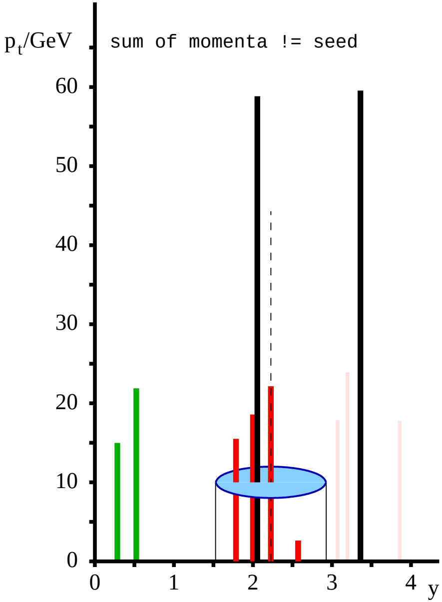

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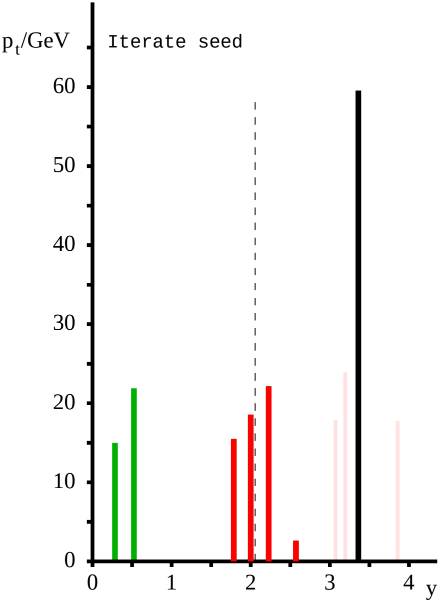

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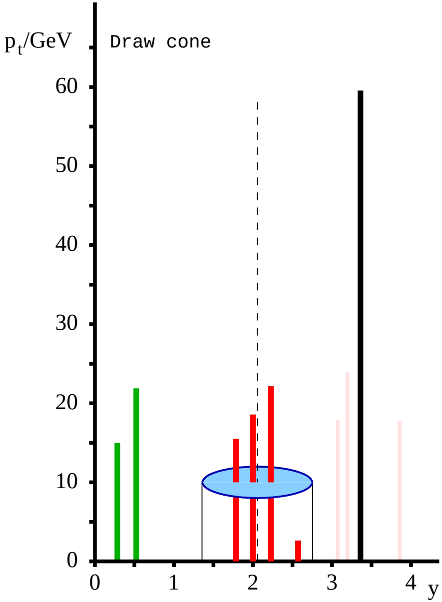

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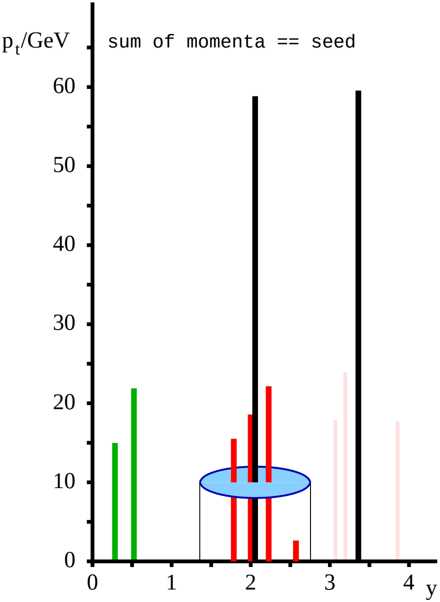

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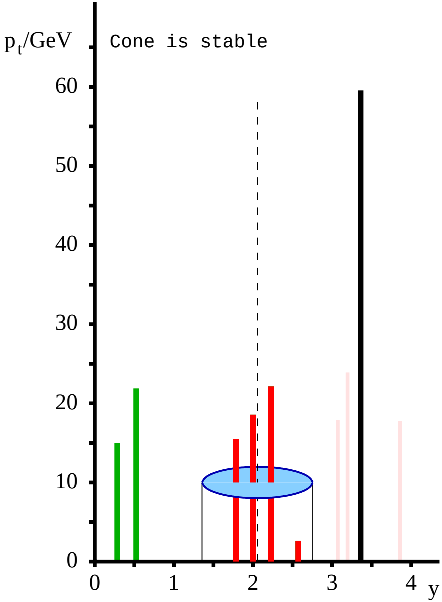

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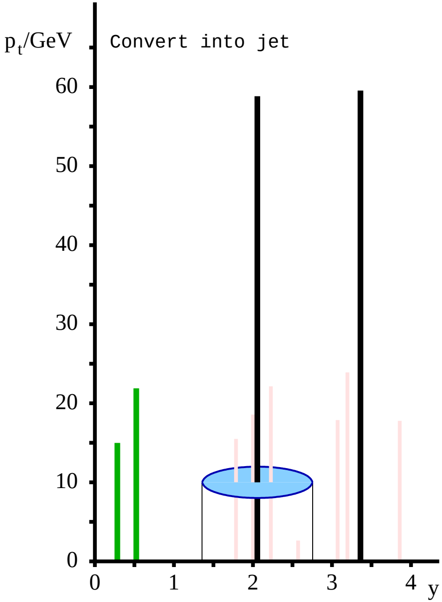

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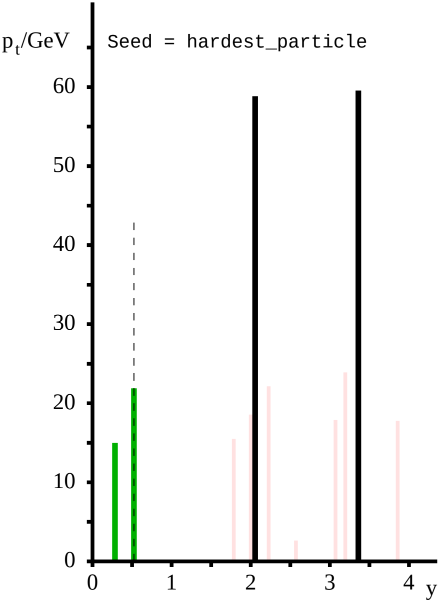

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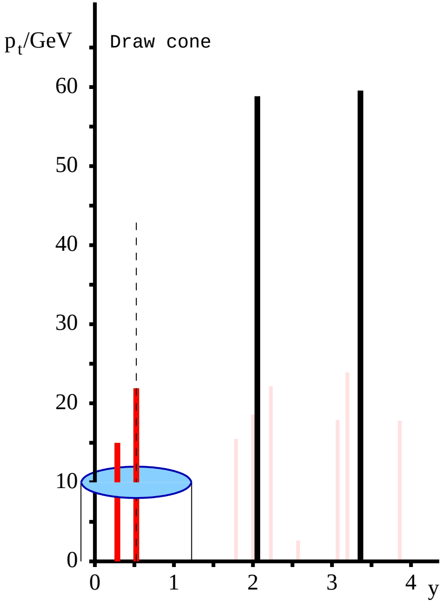

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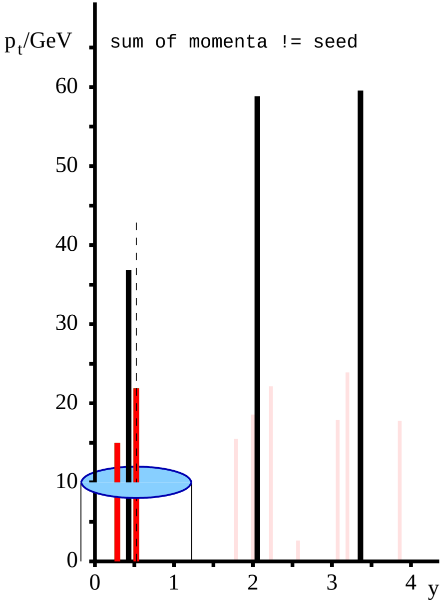

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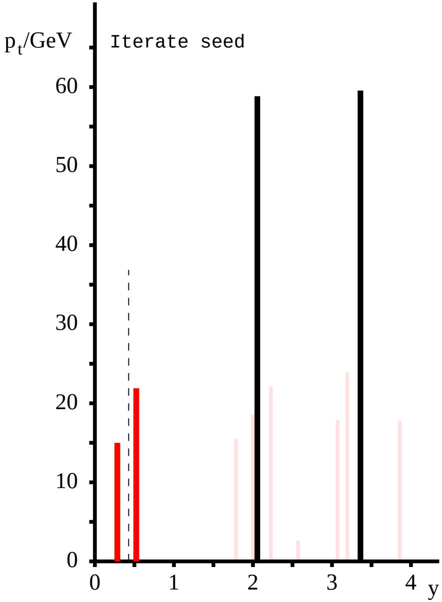

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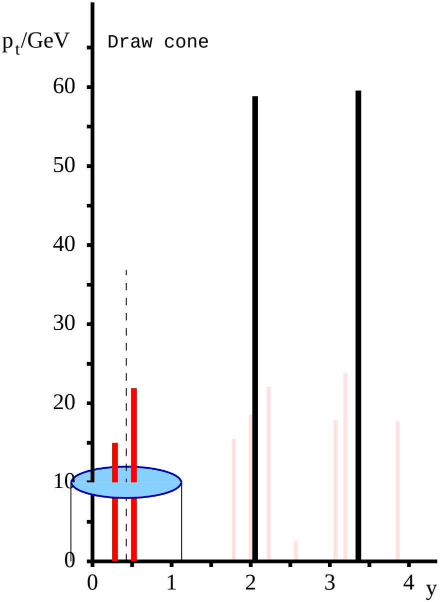

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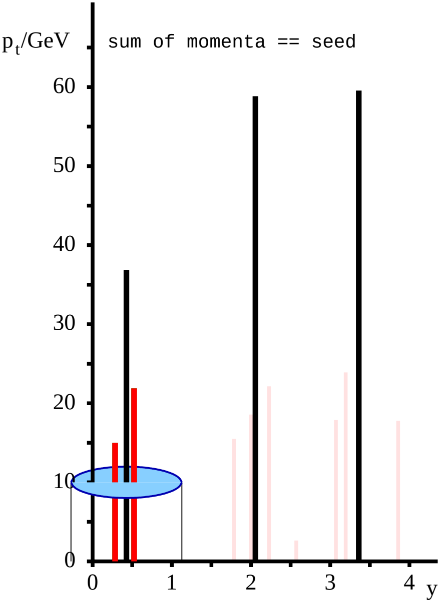

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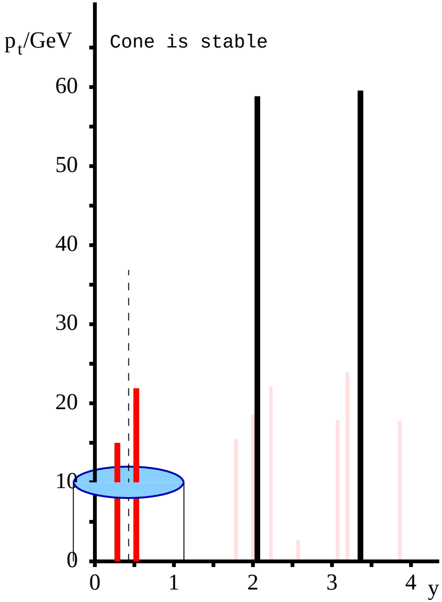

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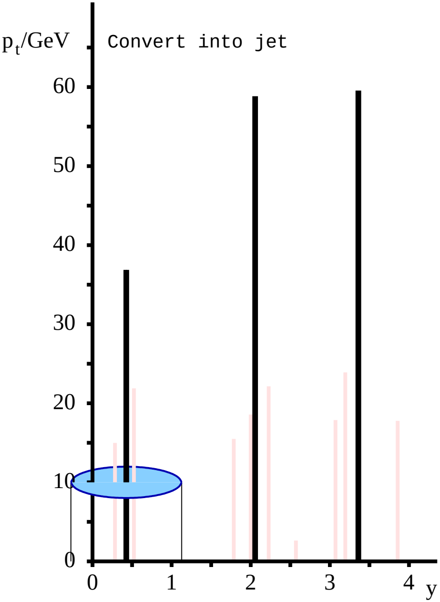

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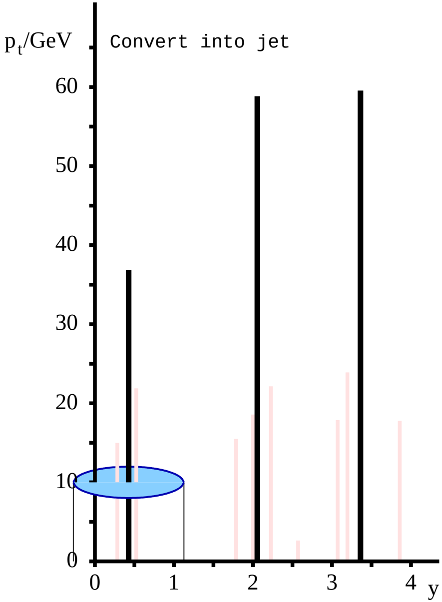

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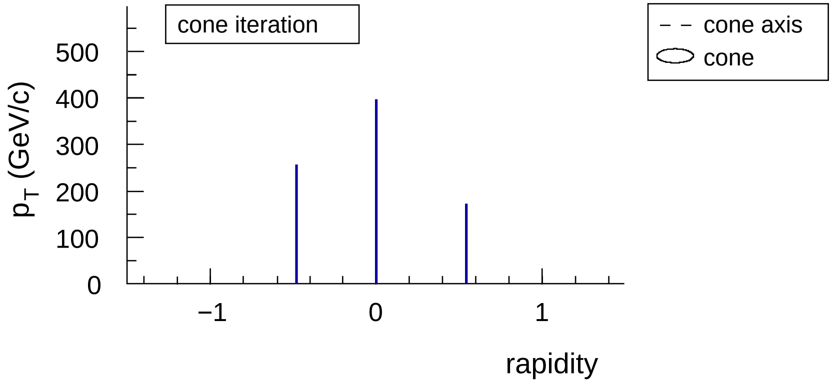

Collinear splitting can modify the hard jets: ICPR algorithms are collinear unsafe $\Longrightarrow$ perturbative calculations give ∞

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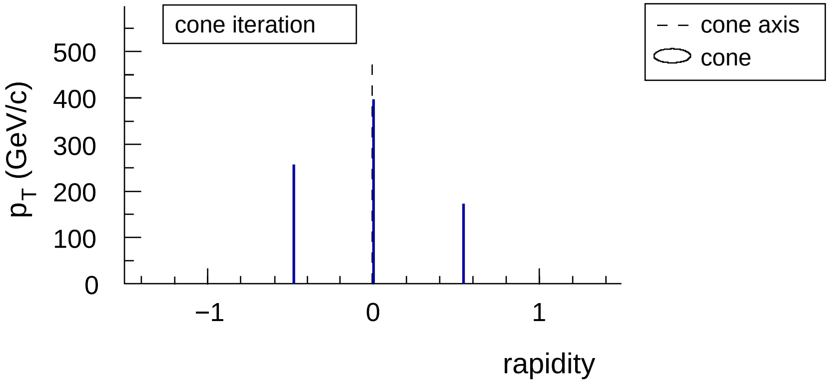

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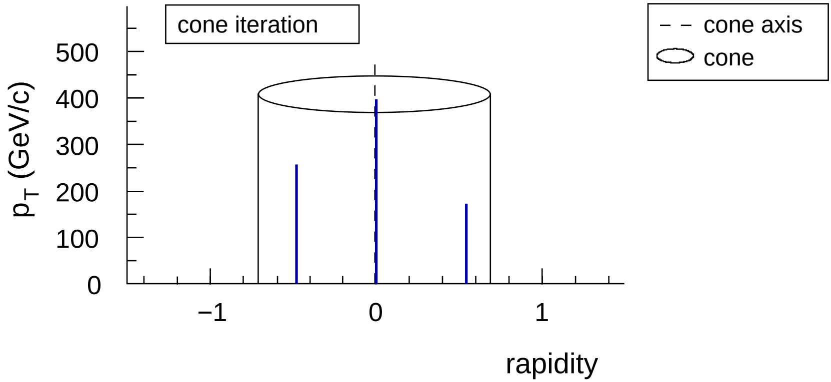

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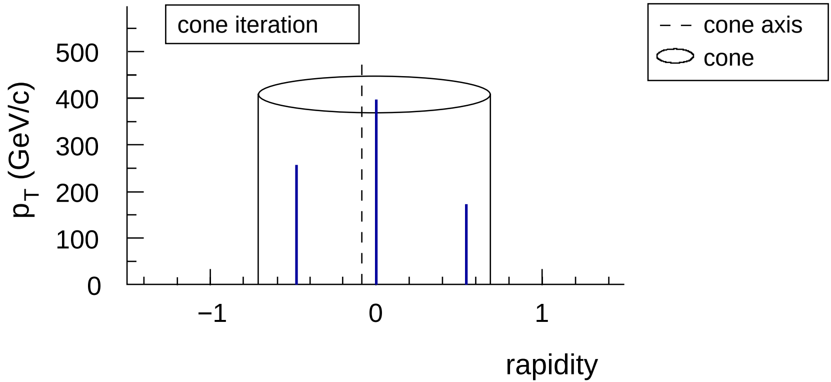

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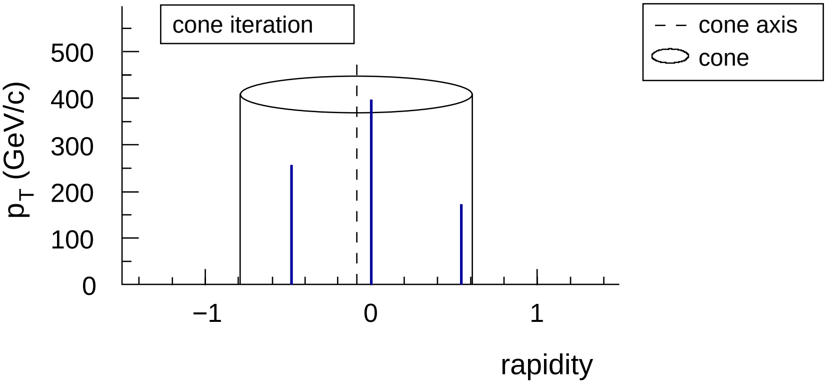

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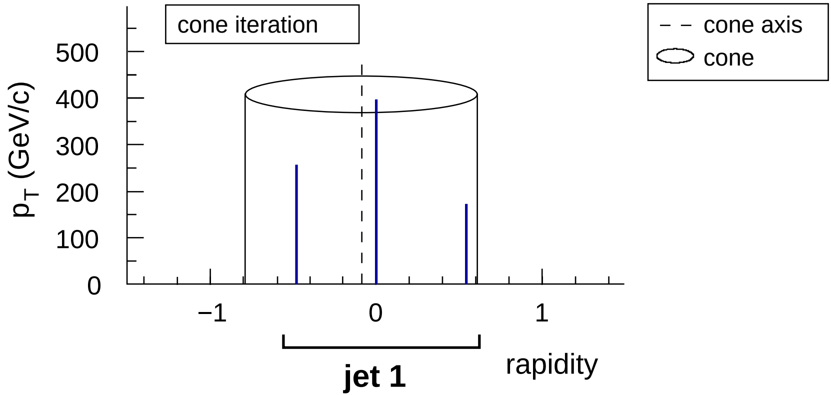

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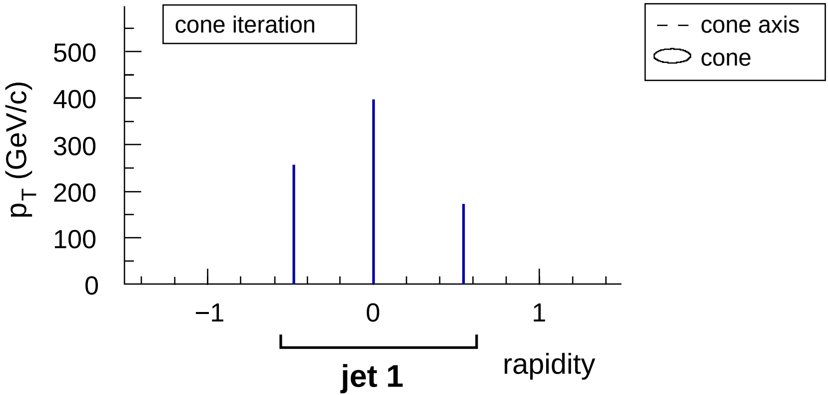

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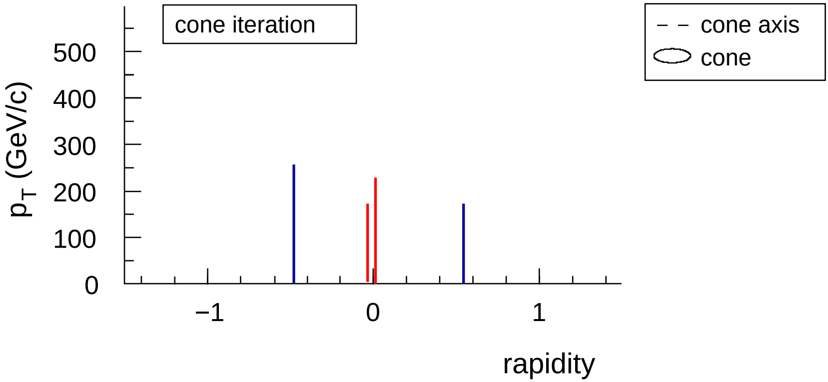

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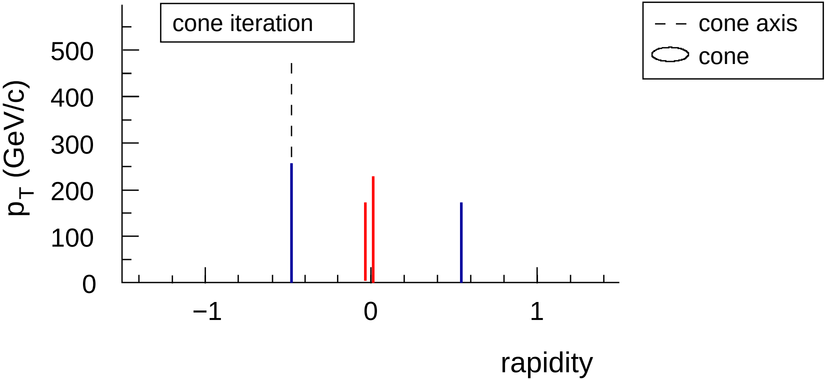

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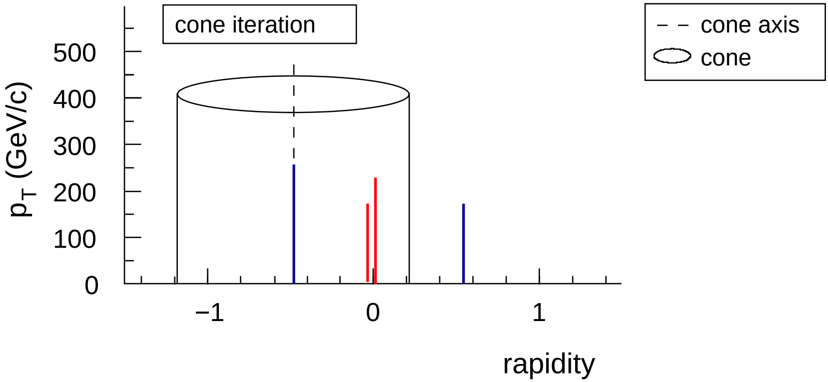

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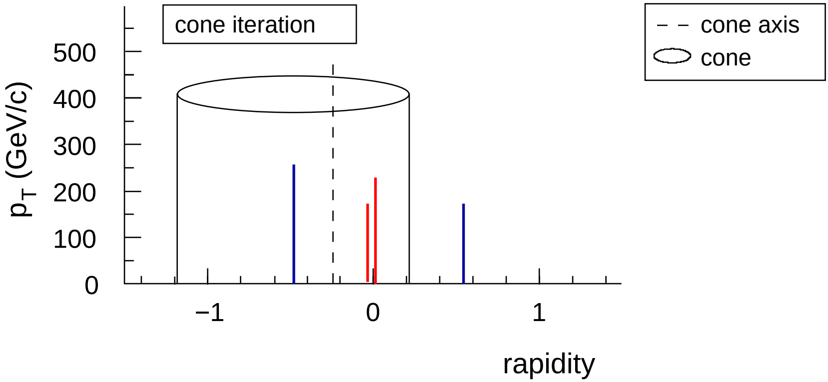

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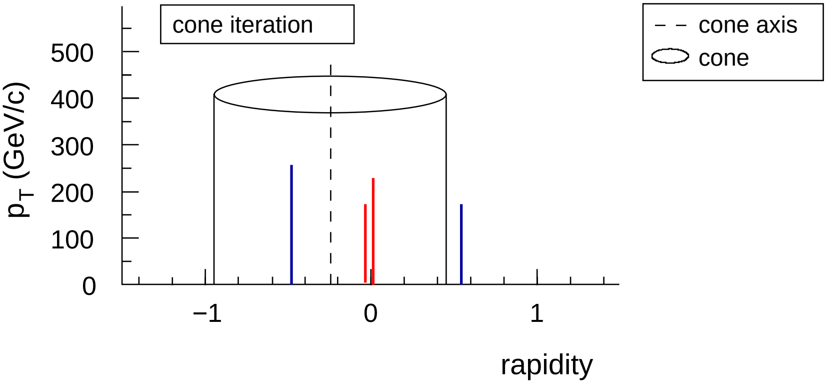

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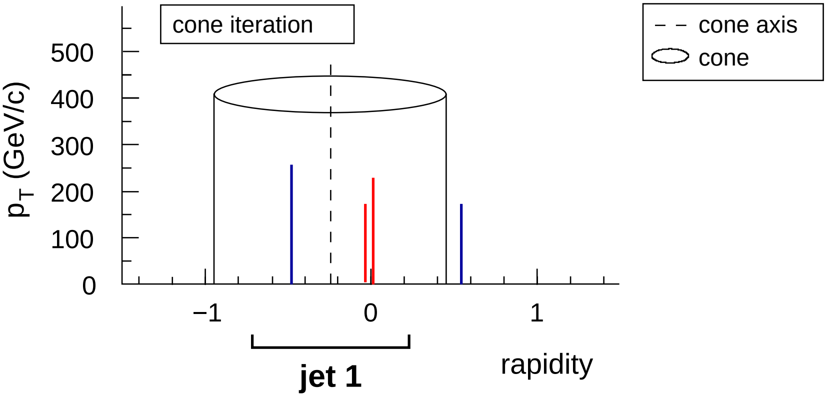

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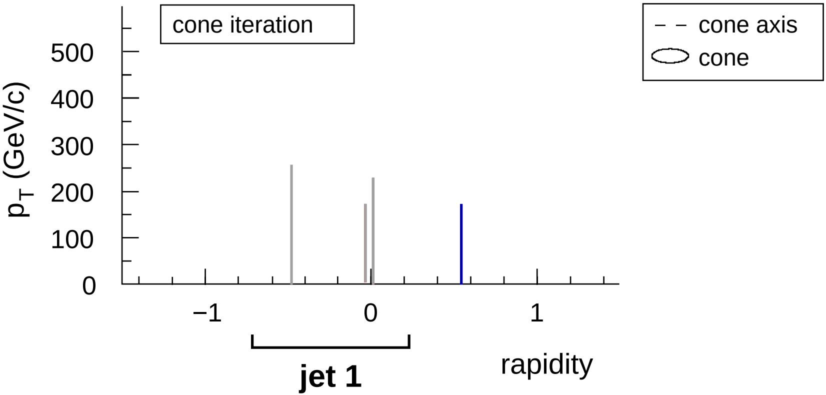

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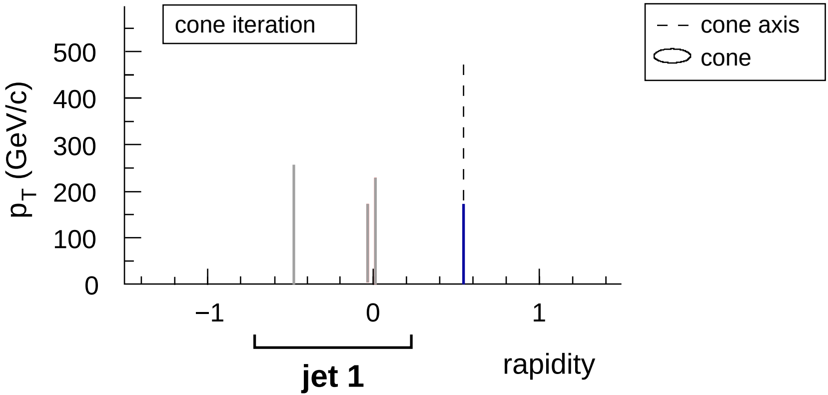

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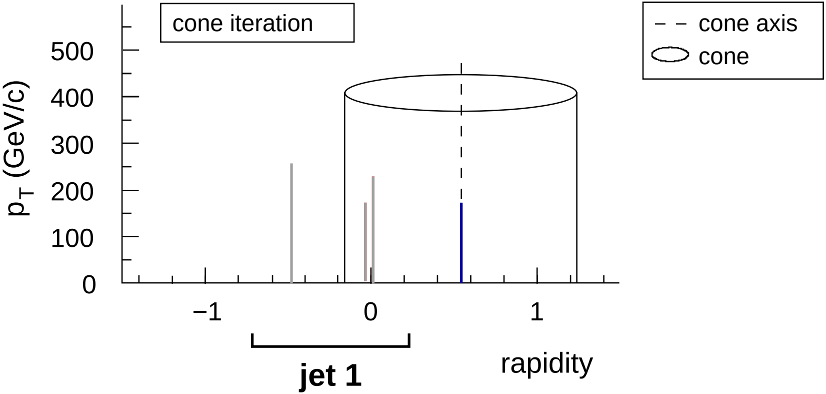

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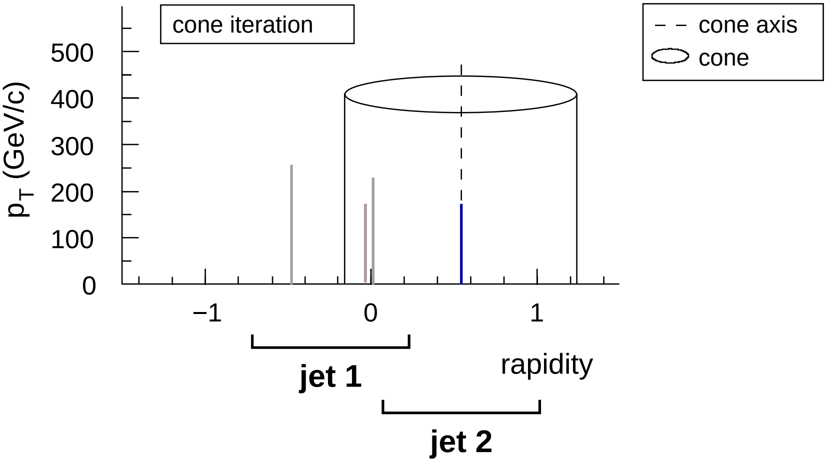

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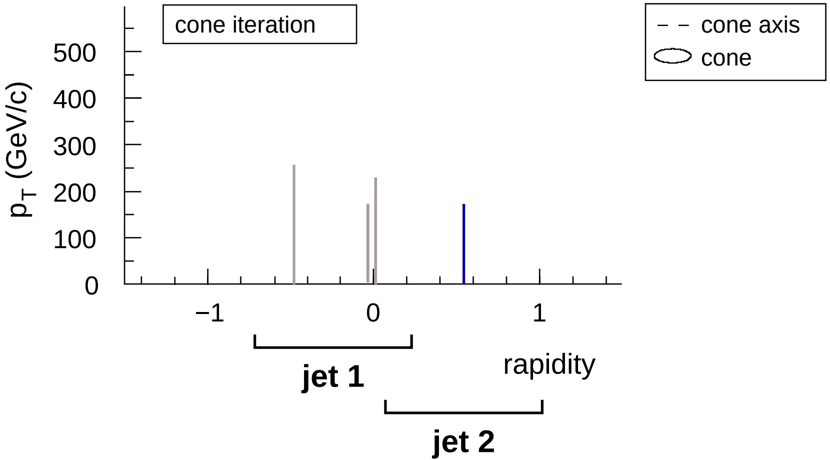

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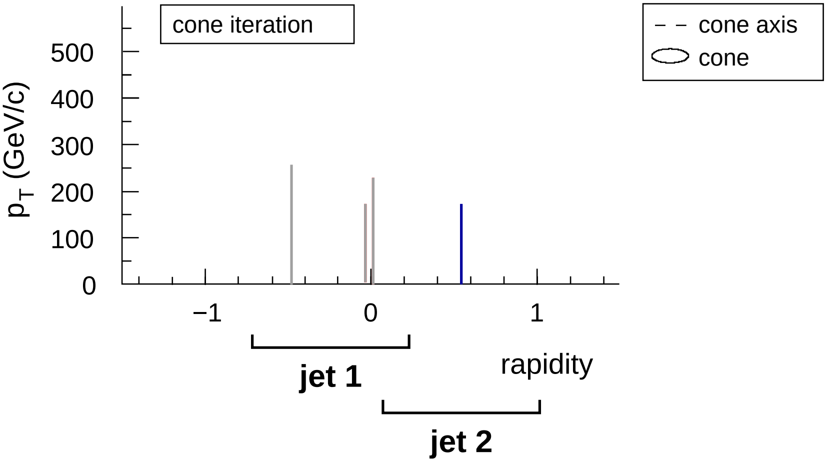

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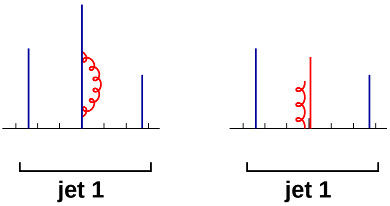

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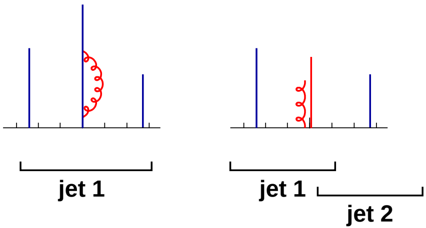

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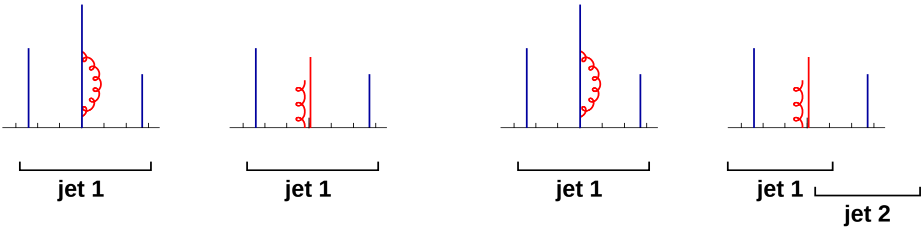

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IRC safety & real-life

Real life does not have infinities, but pert. infinity leaves a real-life trace

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Among consequences of IR unsafety:

	Last meaningful order			
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m_{jet} in $2j + X$	**none**	**none**	**none**	LO

NB: 50,000,000\$/£/CHF/€ investment in NLO

Multi-jet contexts much more sensitive: **ubiquitous at LHC**

And LHC will rely on QCD for background double-checks

extraction of cross sections, extraction of parameters

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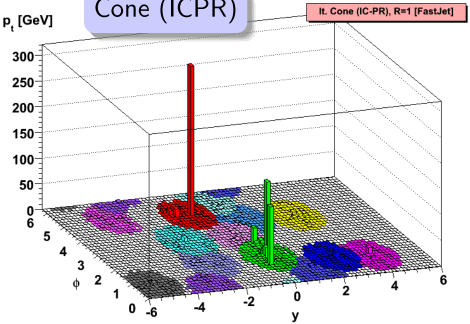
Essential characteristic of cones?

Cone (ICPR)



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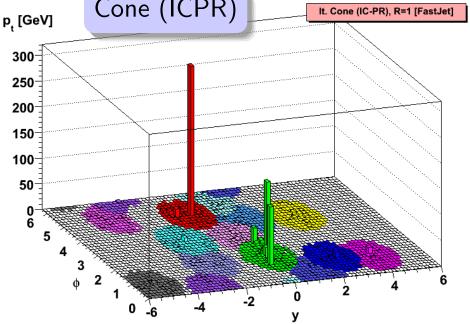

(Some) cone algorithms give **circular** jets in $y - \phi$ plane

Much appreciated by experiments e.g. for acceptance corrections

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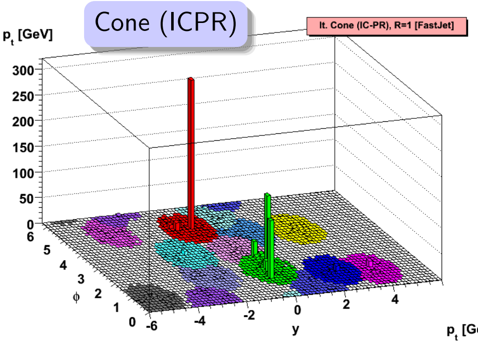

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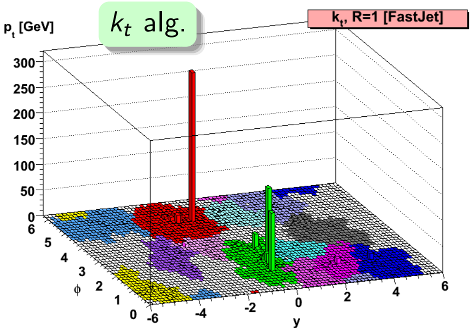

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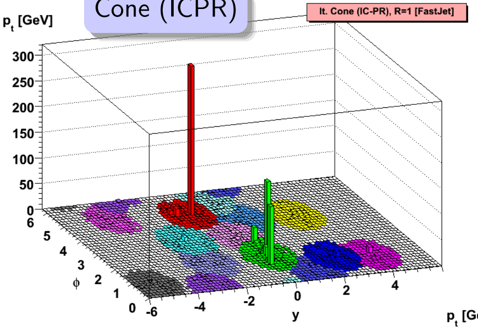

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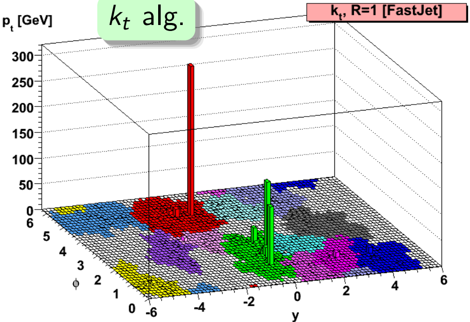
k_t alg.



k_t jets are **irregular**

Because soft junk clusters together first:

$$d_{ij} = \min(k_{ti}^2, k_{tj}^2)\Delta R_{ij}^2$$

Regularly held against k_t

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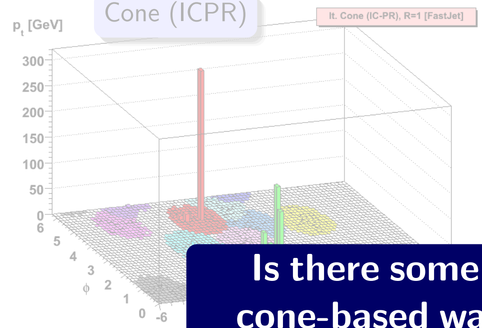

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Is there some other, non cone-based way of getting circular jets?

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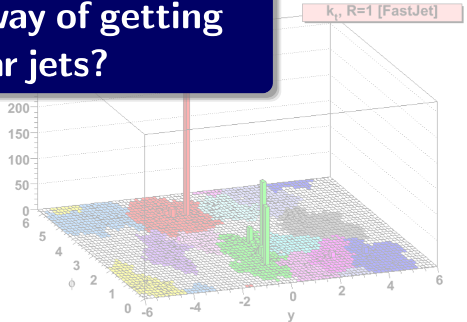

Two directions

How do we solve cone IR safety problems?

Fix stable-cone finding

↓

SISCone

GPS & Soyez '07

Same family as Tev. Run II alg

Invent "cone-like" alg.

↓

anti-kt

Cacciari, GPS & Soyez '08

Adapting seq. rec. to give circular jets

Soft stuff clusters with nearest neighbour

$$k_t\text{: } d_{ij} = \min(k_{ti}^2, k_{tj}^2)\Delta R_{ij}^2 \longrightarrow \textbf{anti-k}_\mathbf{t}\text{: } d_{ij} = \frac{\Delta R_{ij}^2}{\max(k_{ti}^2, k_{tj}^2)}$$

Hard stuff clusters with nearest neighbour

Privilege collinear divergence over soft divergence

Cacciari, GPS & Soyez '08

Adapting seq. rec. to give circular jets

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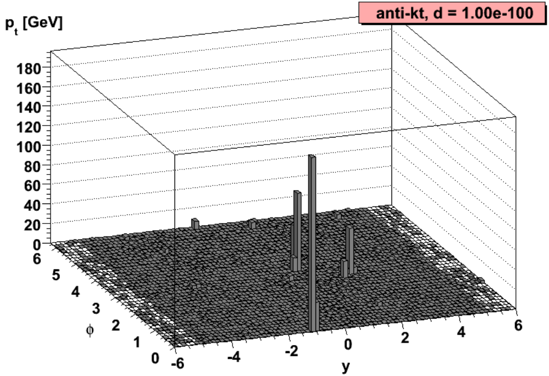
Hard stuff clusters with nearest neighbour

divergence over soft divergence

Cacciari, GPS & Soyez '08



Adapting seq. rec. to give circular jets

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divergence over soft divergence

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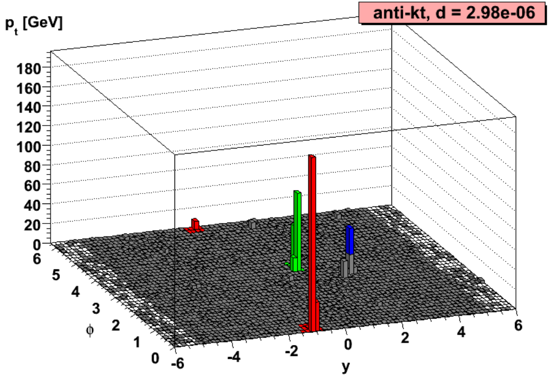

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divergence over soft divergence

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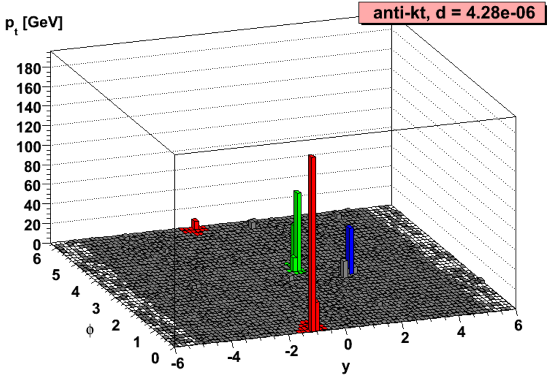

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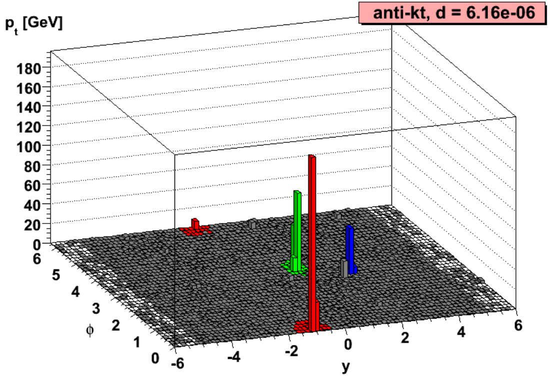
Cacciari, GPS & Soyez '08



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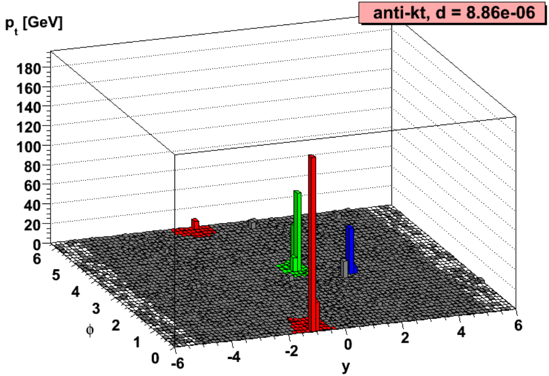

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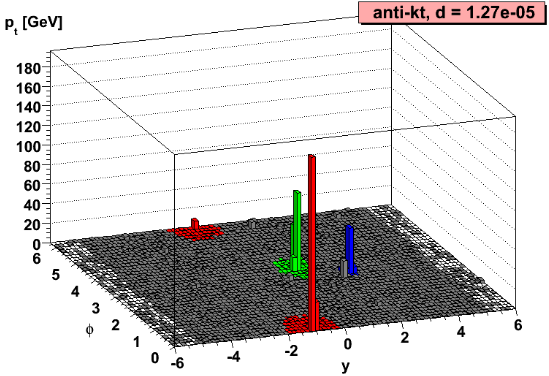

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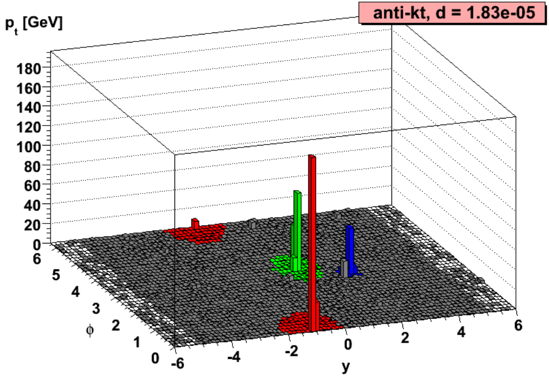

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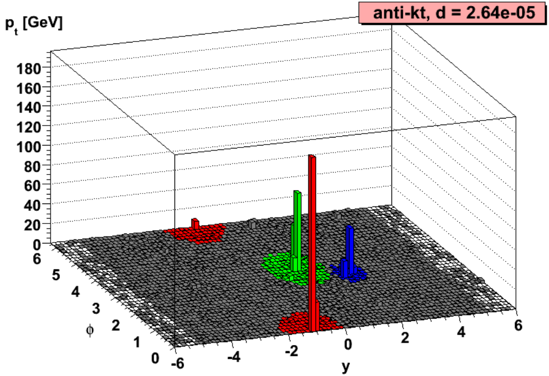

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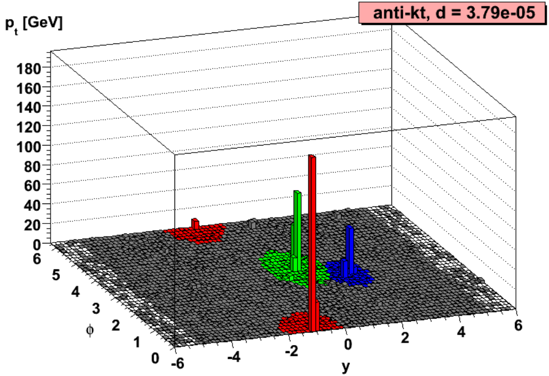

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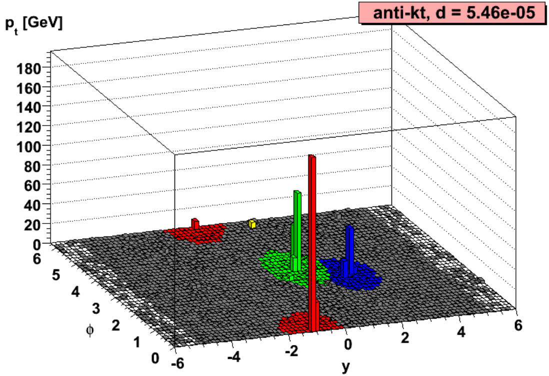

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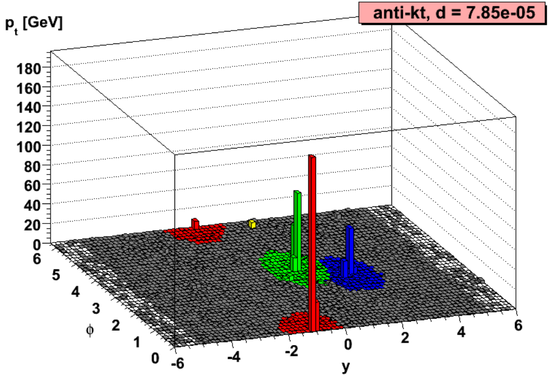

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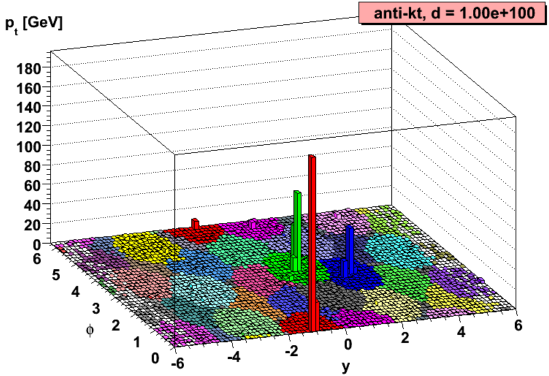


anti-k_t gives cone-like jets without using stable cones

There is plenty more choice for (IR safe) jet finding
(4 good algs are Cam/Aachen, anti-k_t, SISCone and k_t)

Do all you can to avoid IR unsafe jet algorithms
(ATLAS iterative cone, CMS iterative cone, etc.).

Think about the choice of parameters in your jet definition
(what radius for what problem?)

An example

Searching for high-p_t (boosted) heavy particles, such as a Higgs boson.

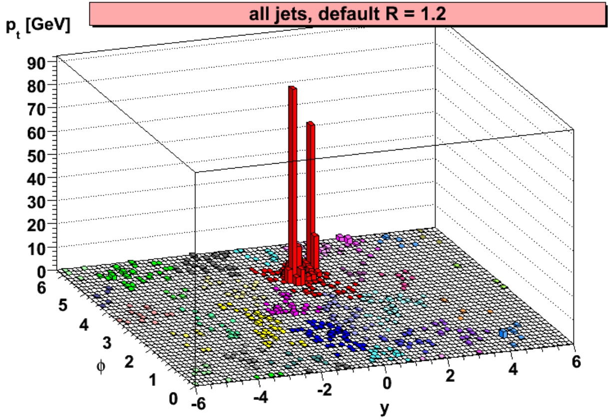
Because LHC will have $\sqrt{s} \gg m_H$, highly boosted Higgses, $p_{tH} \gg m_H$, are not so rare.

The boost factor collimates the Higgs decay into a single jet. Can we still identify it?

$pp \to ZH \to \nu\bar{\nu}b\bar{b}$, @14 TeV, $m_H = 115$ GeV

SIGNAL

Herwig 6.510 + Jimmy 4.31 + FastJet 2.3



Zbb BACKGROUND

Cluster event, C/A, R=1.2

arbitrary norm.

$pp \to ZH \to \nu\bar{\nu}b\bar{b}$, @14 TeV, $m_H = 115$ GeV

SIGNAL

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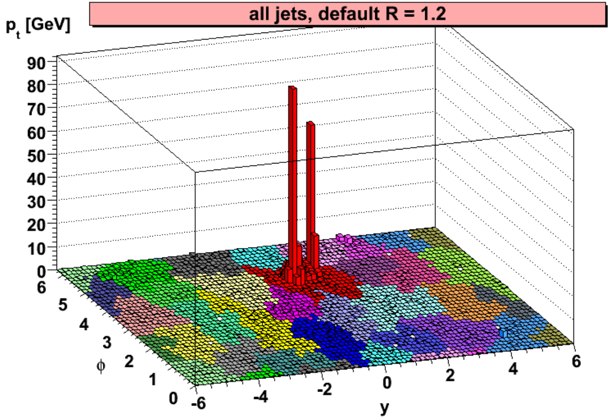


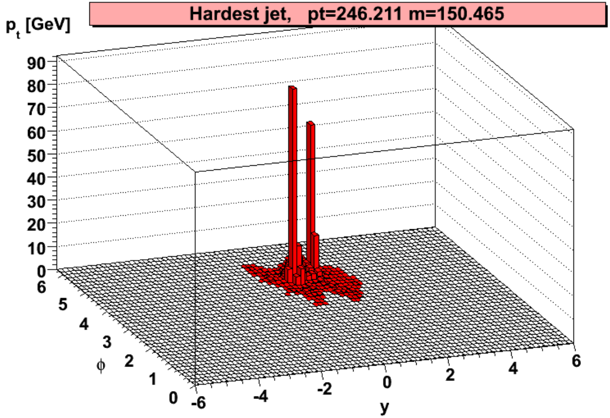
Zbb BACKGROUND

Fill it in, $\to$ show jets more clearly

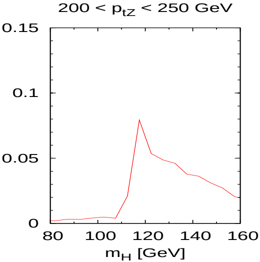
arbitrary norm.

$pp \to ZH \to \nu\bar{\nu}b\bar{b}$, @14 TeV, $m_H = 115$ GeV

Herwig 6.510 + Jimmy 4.31 + FastJet 2.3



SIGNAL



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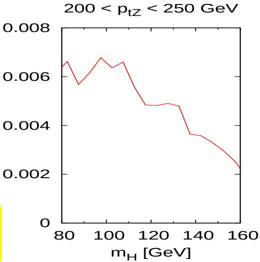
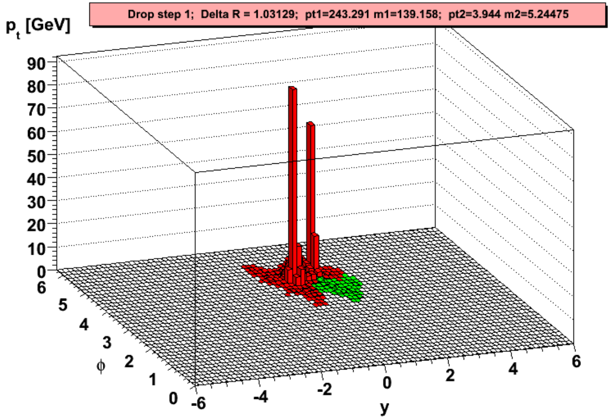


Consider hardest jet, $m = 150$ GeV

arbitrary norm.

$pp \to ZH \to \nu\bar{\nu}b\bar{b}$, @14 TeV, $m_H = 115$ GeV

Herwig 6.510 + Jimmy 4.31 + FastJet 2.3



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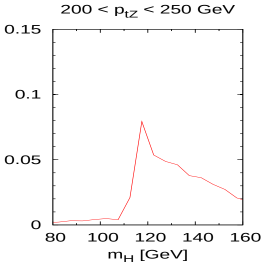

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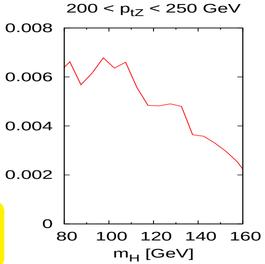
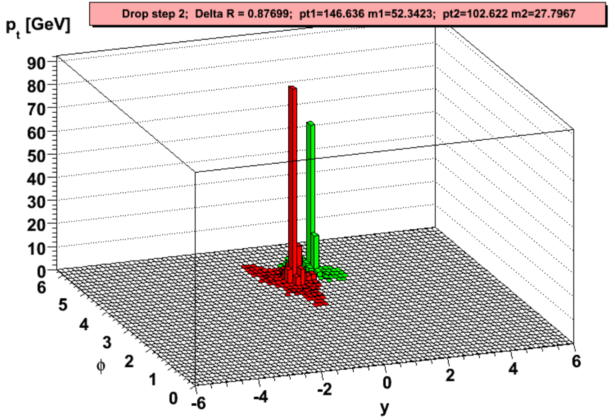


split: $m = 150$ GeV, $\frac{\max(m_1, m2)}{m} = 0.92 \to$ repeat

arbitrary norm.

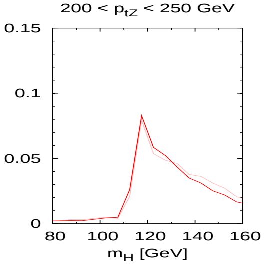
$pp \to ZH \to \nu\bar{\nu}b\bar{b}$, @14 TeV, $m_H = 115$ GeV

Herwig 6.510 + Jimmy 4.31 + FastJet 2.3



split: $m = 139$ GeV, $\frac{\max(m_1, m2)}{m} = 0.37 \to$ mass drop

SIGNAL



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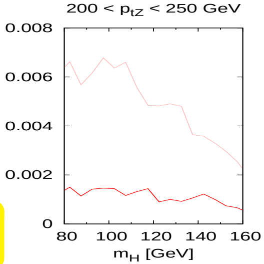

arbitrary norm.

$pp \to ZH \to \nu\bar{\nu}b\bar{b}$, @14 TeV, $m_H = 115$ GeV

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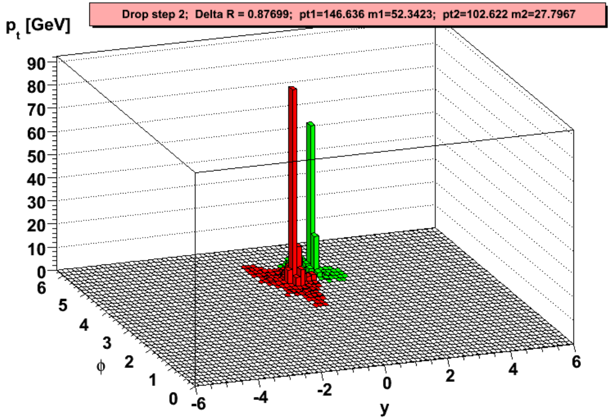

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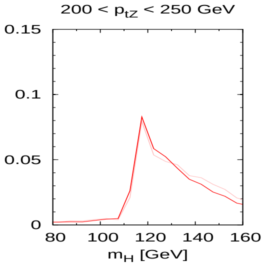

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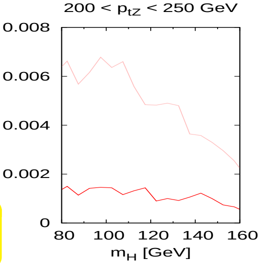
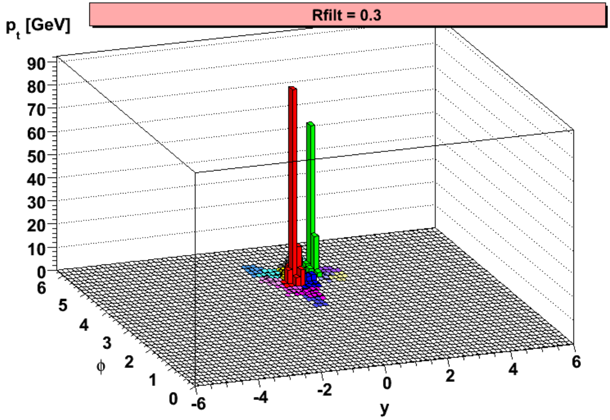


check: $y_{12} \simeq \frac{p_{t2}}{p_{t1}} \simeq 0.7 \to$ OK + 2 b-tags (anti-QCD)

arbitrary norm.

$pp \to ZH \to \nu\bar{\nu}b\bar{b}$, @14 TeV, $m_H = 115$ GeV

Herwig 6.510 + Jimmy 4.31 + FastJet 2.3



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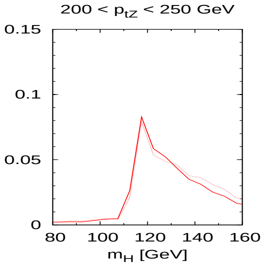

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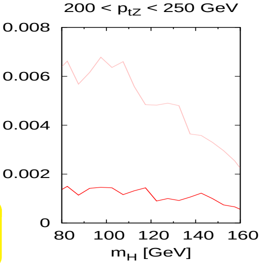
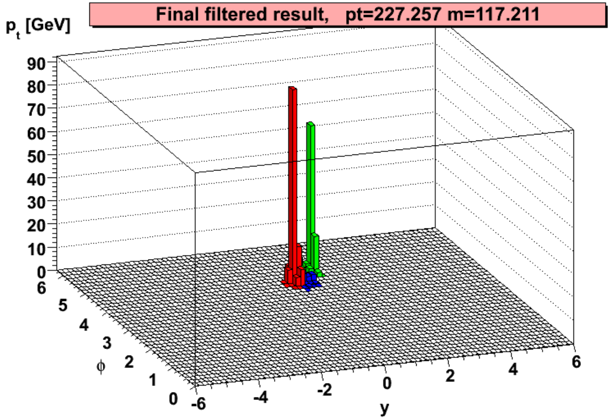


$R_{filt} = 0.3$

arbitrary norm.

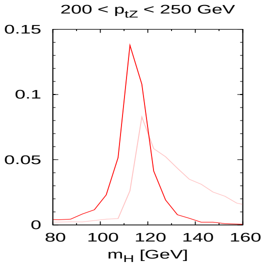
$pp \to ZH \to \nu\bar{\nu}b\bar{b}$, @14 TeV, $m_H = 115$ GeV

Herwig 6.510 + Jimmy 4.31 + FastJet 2.3



$R_{filt} = 0.3$: take 3 hardest, **m = 117 GeV**

SIGNAL



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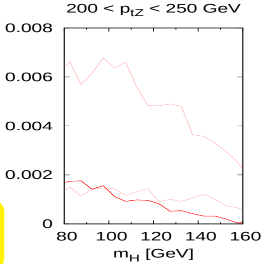
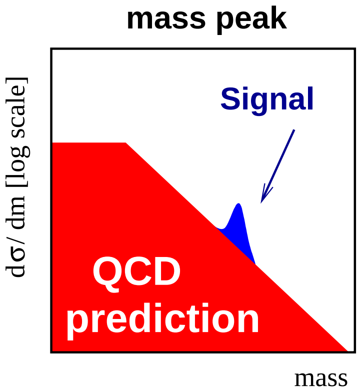


arbitrary norm.

To conclude

What kinds of searches?



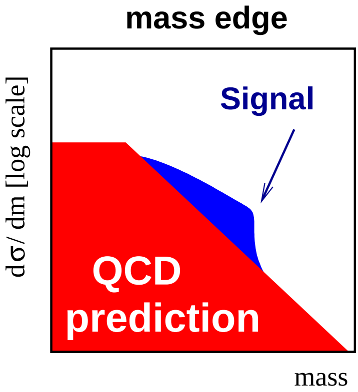
New resonance (e.g. Z') where you see all decay products and reconstruct an invariant mass

QCD may:

- swamp signal
- smear signal

leptonic case easy; hadronic case harder

What kinds of searches?



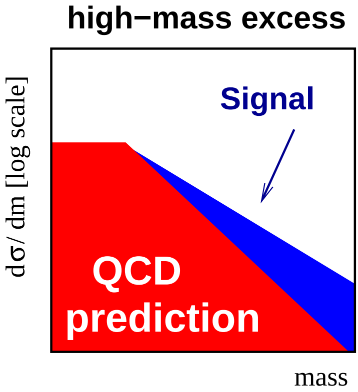
New resonance (e.g. R-parity conserving SUSY), where undetected new stable particle escapes detection.

Reconstruct only *part* of an invariant mass $\longrightarrow$ kinematic edge.

QCD may:

- swamp signal
- smear signal

What kinds of searches?



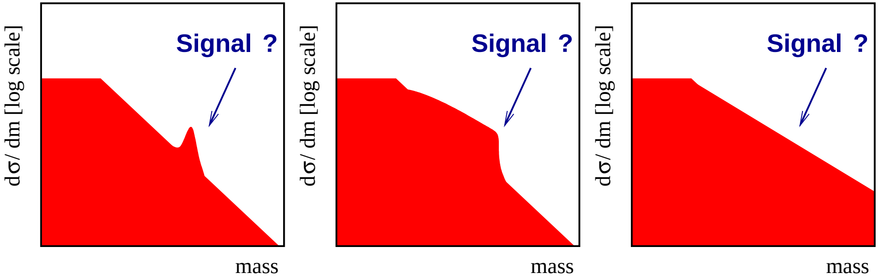
Unreconstructed SUSY cascade. Study *effective* mass (sum of all transverse momenta).

Broad excess at high mass scales.

Knowledge of backgrounds is crucial is declaring discovery.

QCD is *one way* of getting handle on background.

What kinds of searches?



If you want to find out more

Classic references

QCD and collider physics
Ellis, Stirling & Webber,
Cambridge University Press 1996

The Handbook of Perturbative QCD,
the CTEQ Collaboration
`http://www.phys.psu.edu/~cteq/`

Advanced topics

Monte Carlos, Matching, Heavy-quarks, Jets, PDFs, etc.
E.g.: transparencies from CTEQ-MCNet 2008 QCD school
`http://tr.im/oUWG`