Jets at Hadron Colliders (2)

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CERN Academic Training Lectures
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Generalise inclusive-type sequential recombination with

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

	Alg. name	Comment	time
$p = 1$	k_t CDOSTW '91-93; ES '93	Hierarchical in rel. k_t	$N \ln N$ exp.
$p = 0$	Cambridge/Aachen Dok, Leder, Moretti, Webber '97 Wengler, Wobisch '98	Hierarchical in angle Scan multiple R at once $\leftrightarrow$ QCD angular ordering	$N \ln N$
$p = -1$	anti-k_t Cacciari, GPS, Soyez '08 $\sim$ reverse-k_t Delsart	Hierarchy meaningless, jets like CMS cone (IC-PR)	$N^{3/2}$
SC-SM	SISCone GPS Soyez '07 + Tevatron run II '00	Replaces JetClu, ATLAS MidPoint (xC-SM) cones	$N^2 \ln N$ exp.

All these algorithms [& much more] coded in (efficient) `C++` at
`http://fastjet.fr/` (Cacciari, GPS & Soyez '05-'11)

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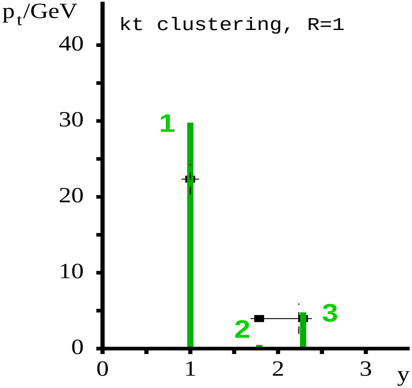

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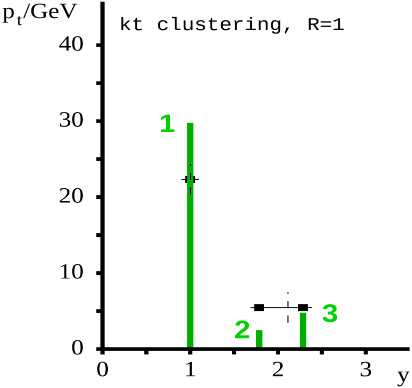

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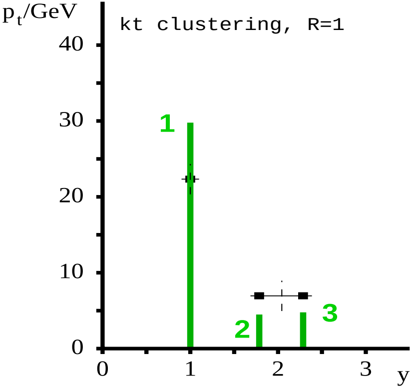

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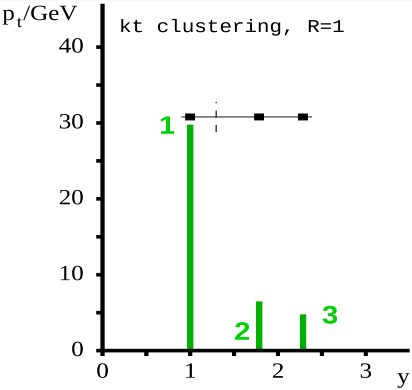

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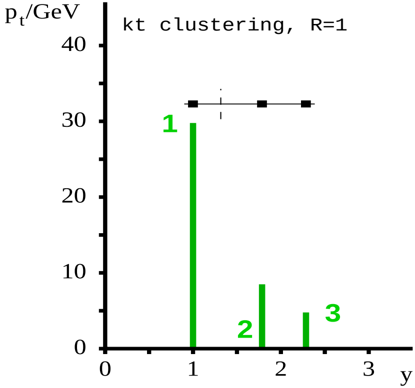

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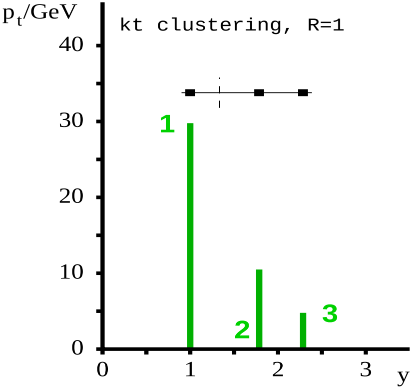

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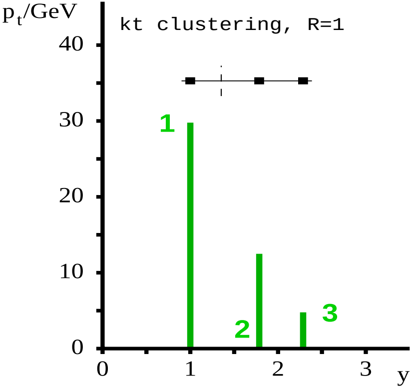

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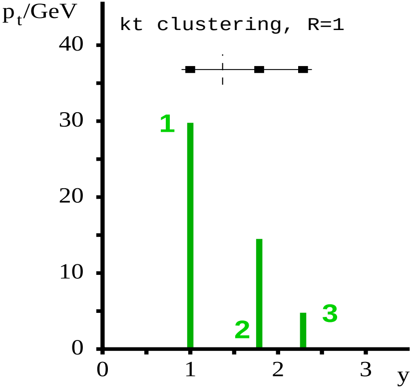

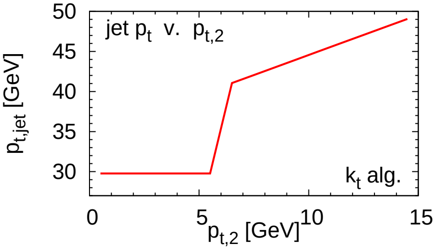

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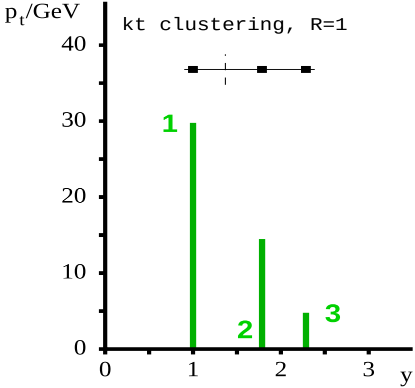

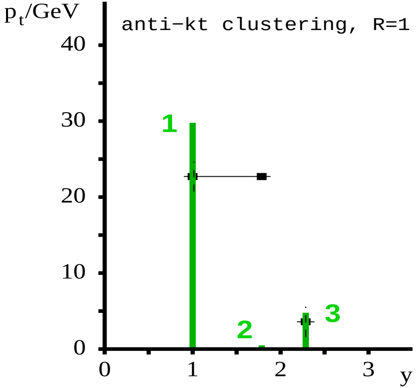

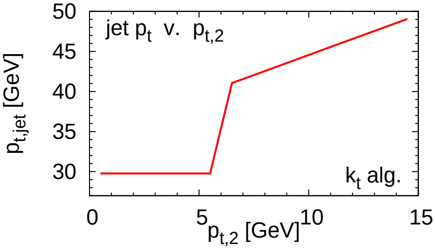

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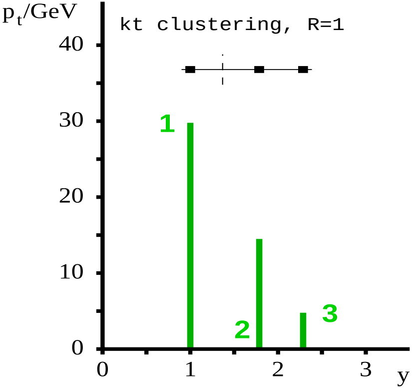

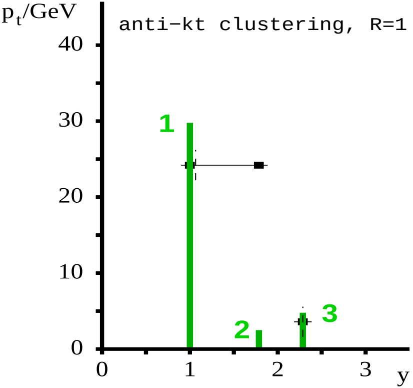

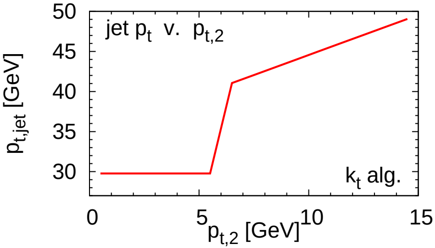

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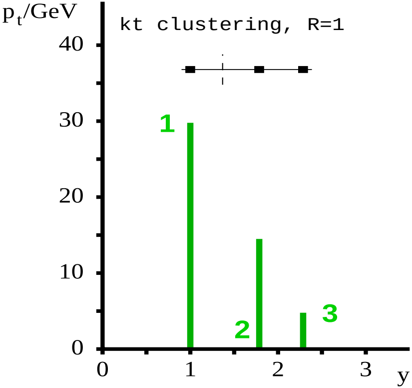

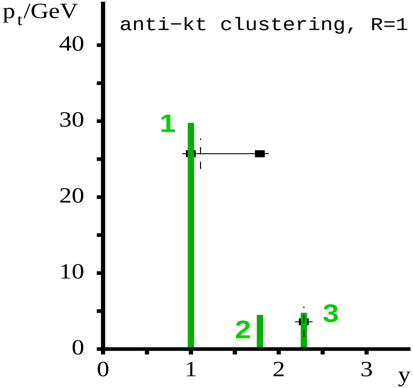

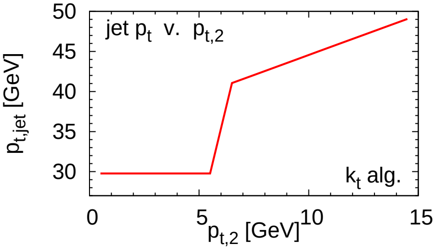

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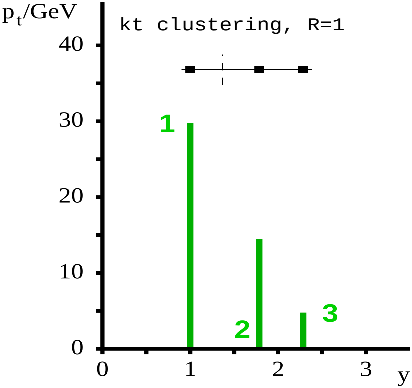

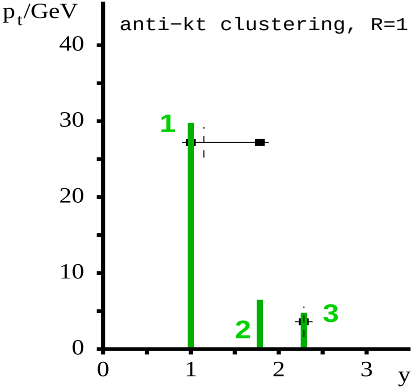

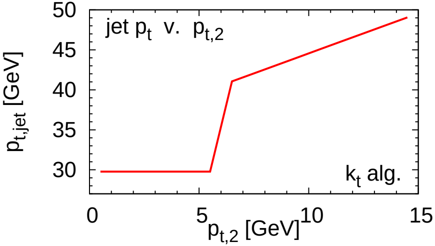

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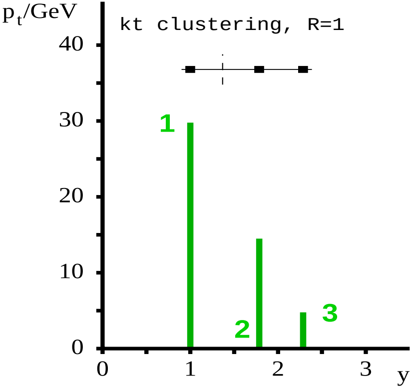

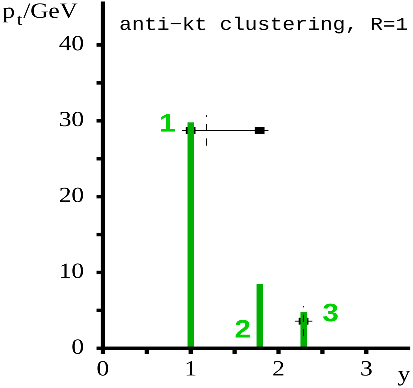

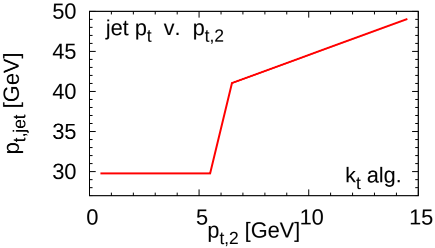

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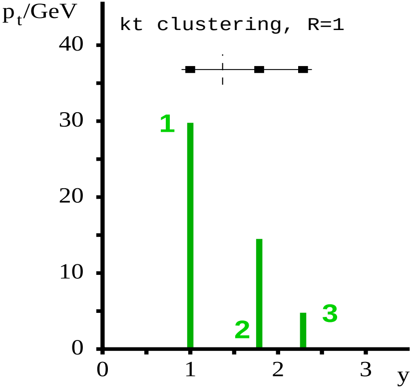

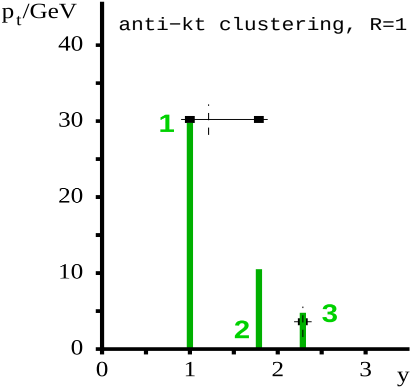

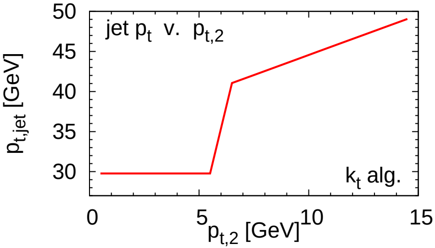

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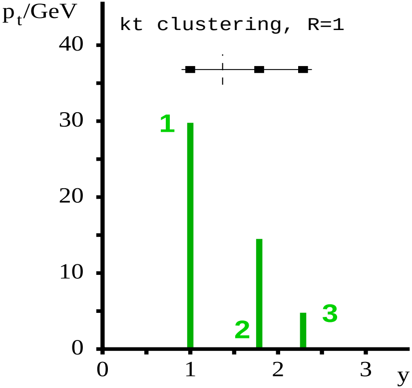

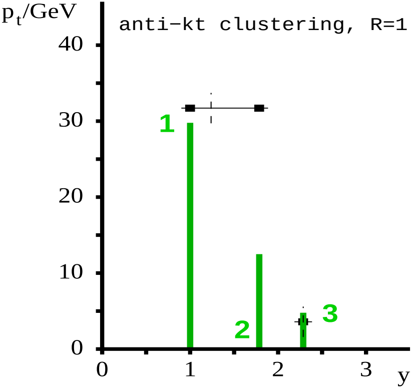

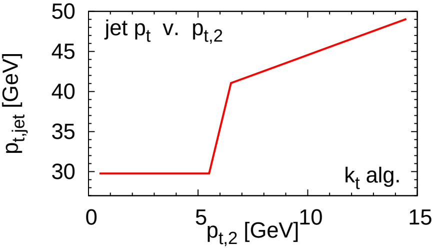

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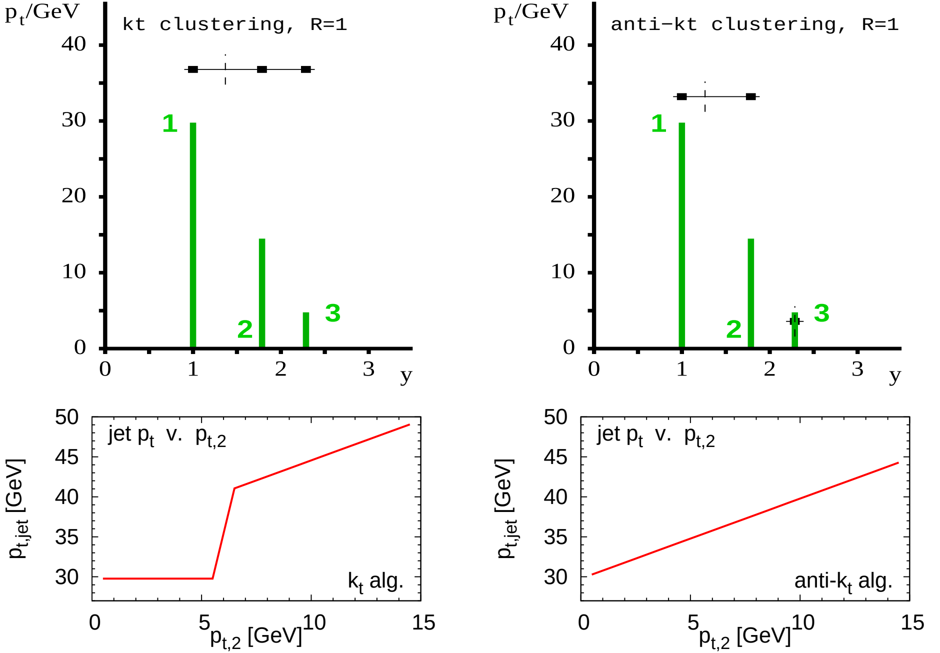

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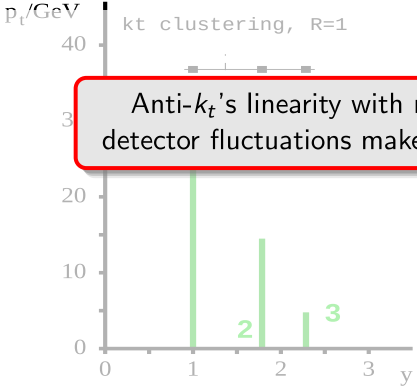
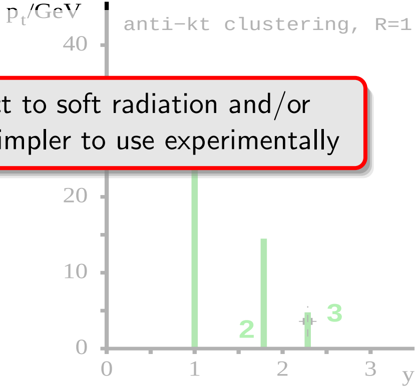
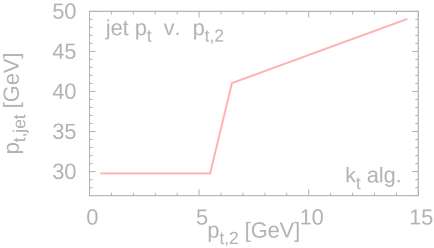
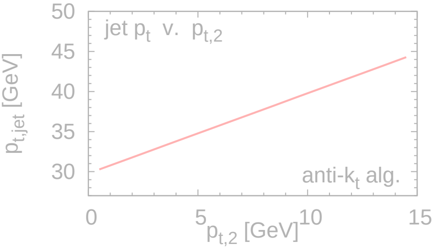




Anti-k_t's linearity with respect to soft radiation and/or detector fluctuations makes it simpler to use experimentally





Comparing theory and experiment

The full cross section that you measure in experiment should correspond to an expression looking roughly as follows:

$$\sigma^{full} = \sigma_{LO}\left(1 + \alpha_s c_1 + \alpha_s^2 c_2 + \alpha_s^3 c_3 + \ldots + \mathcal{O}\left(\frac{\Lambda_{QCD}}{p_t}\right)\right)$$

A perturbative series

plus a non-perturbative contribution, suppressed by a power of Λ_{QCD}/p_t

We don't have the technology to calculate the full series or the non-perturbative part. Typically, one might "just" calculate next-to-leading order

$$\sigma^{NLO} = \sigma_{LO}(1 + \alpha_s c_1)$$

The point to perturbation theory is that the $c_2\alpha_s^2$, etc. terms are small compared to the ones you have calculated — *hence (e.g.) NLO should be a good approximation.*

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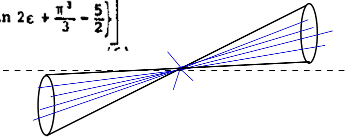
What happens with an infrared or collinear unsafe algorithm?

Cone Origins

First 'jet algorithm' dates back to Sterman and Weinberg (1977) — the original infrared-safe cross section:

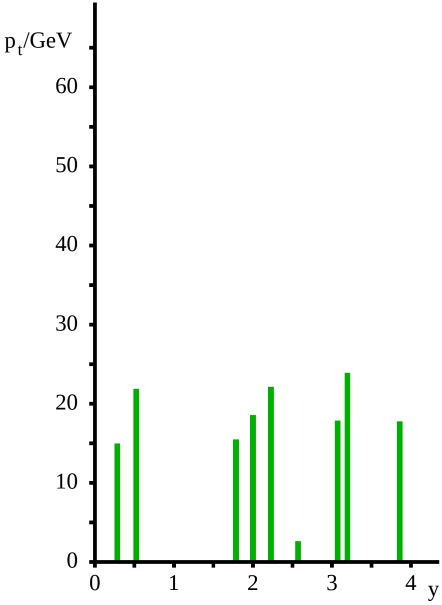
To study jets, we consider the partial cross section $\sigma(E,\theta,\Omega,\epsilon,\delta)$ for e^+e^- hadron production events, in which all but a fraction $\epsilon \ll 1$ of the total e^+e^- energy E is emitted within some pair of oppositely directed cones of half-angle $\delta \ll 1$, lying within two fixed cones of solid angle Ω (with $\pi\delta^2 \ll \Omega \ll 1$) at an angle θ to the e^+e^- beam line. We expect this to be measur-

$$\sigma(E,\theta,\Omega,\epsilon,\delta) = (d\sigma/d\Omega)_0\,\Omega\left[1 - (g_E^2/3\pi^2)\left\{3\ln\delta + 4\ln\delta\,\ln 2\epsilon + \frac{\pi^3}{3} - \frac{5}{2}\right\}\right]$$



Groundbreaking; good for 2 jets in e^+e^-
but generalisations to hadron colliders often had problems

Iterative Cone, Prog Removal (IC-PR)



One of the simplest of the cone algs

e.g. CMS iterative cone

- Take hardest particle as seed for cone axis
- Draw cone around seed
- Sum the momenta use as new seed direction, iterate until stable
- Convert contents into a "jet" and remove from event

Notes

- "Hardest particle" is collinear unsafe more right away...

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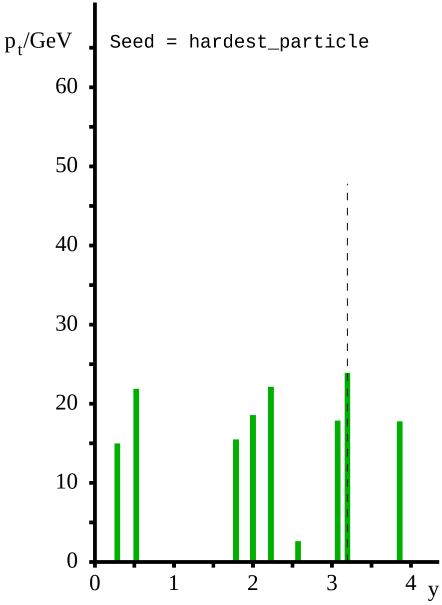

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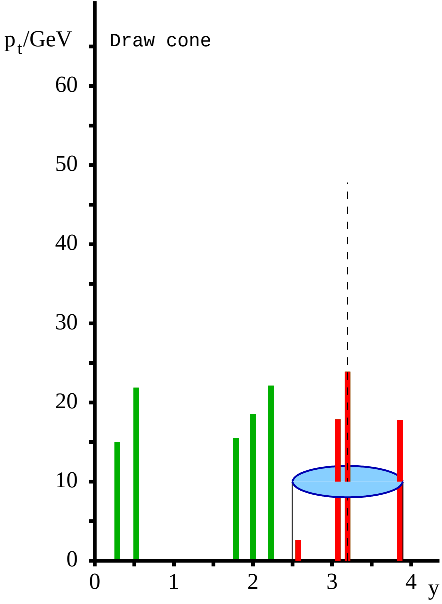

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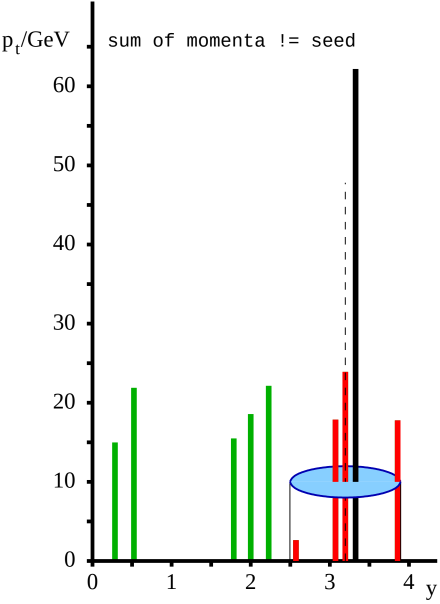

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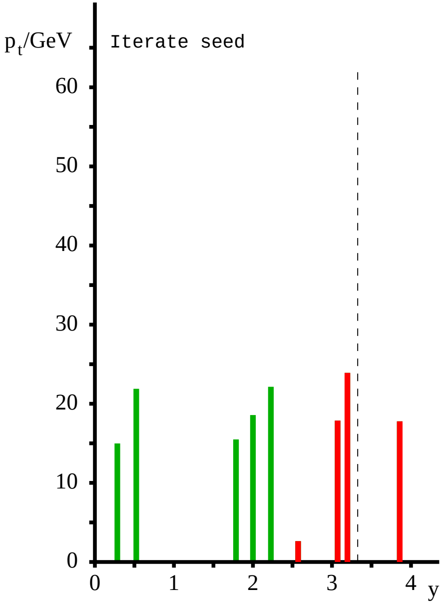

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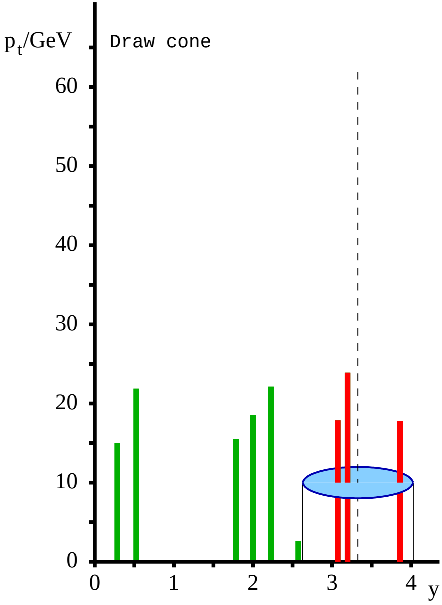

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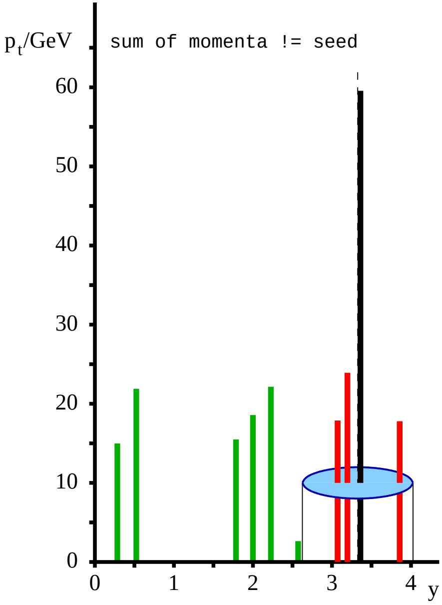

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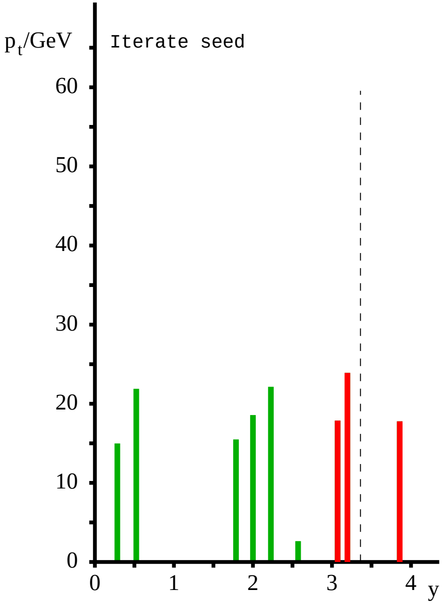

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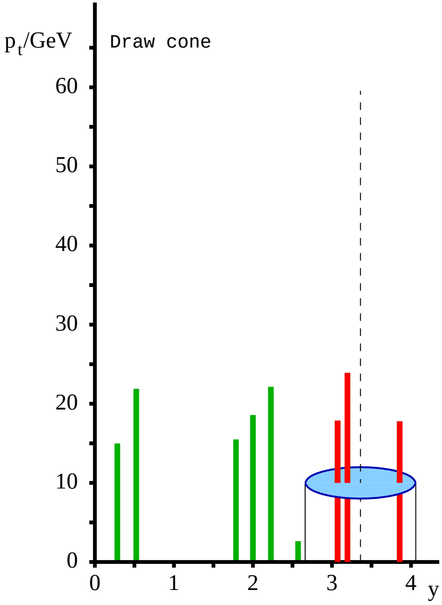

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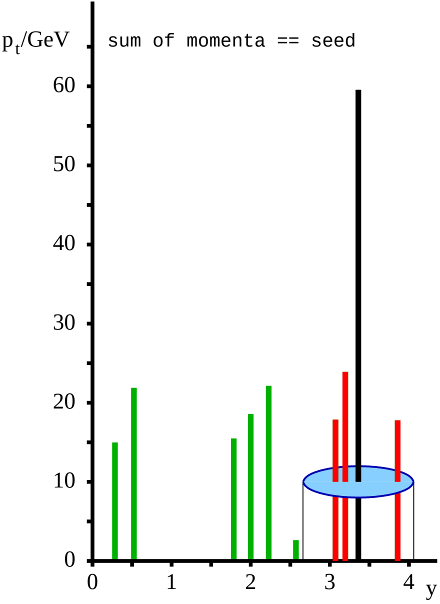

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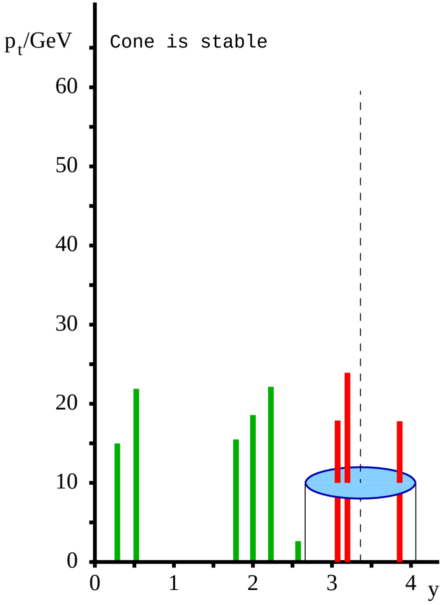

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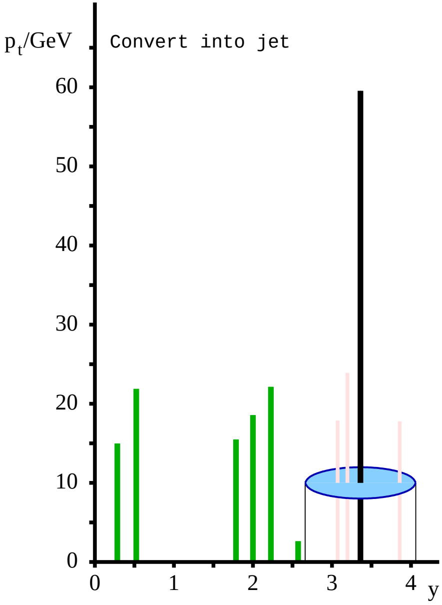

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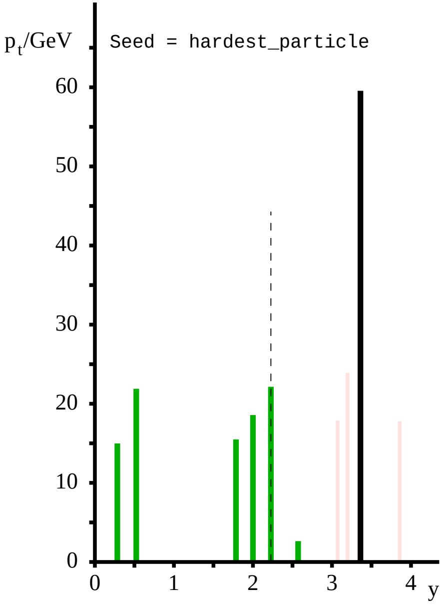

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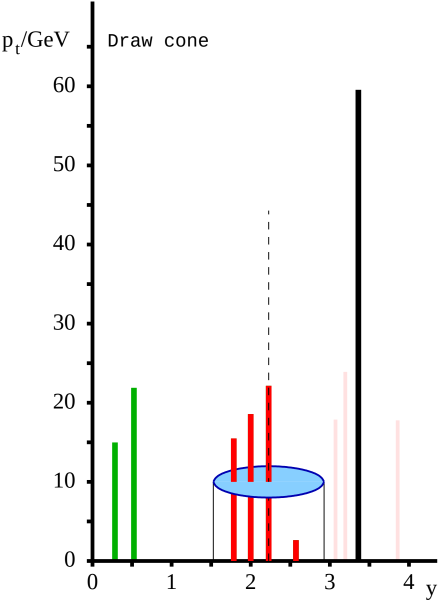

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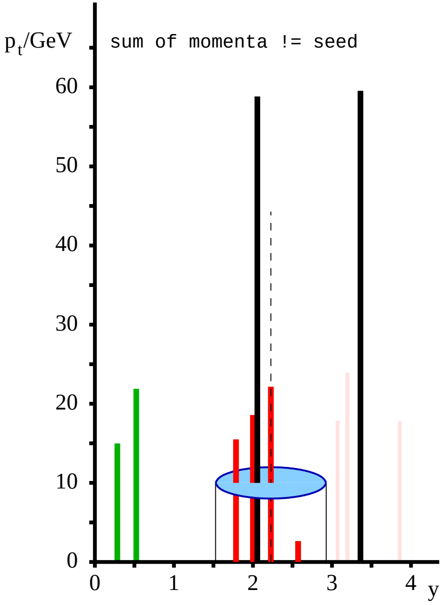

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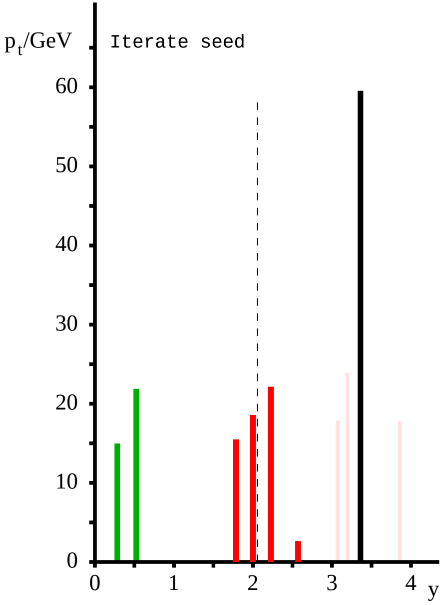

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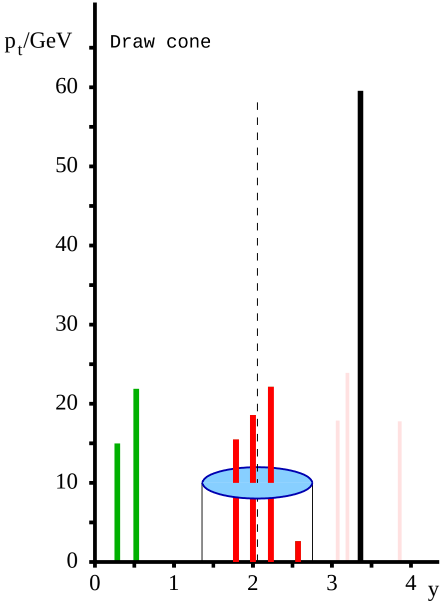

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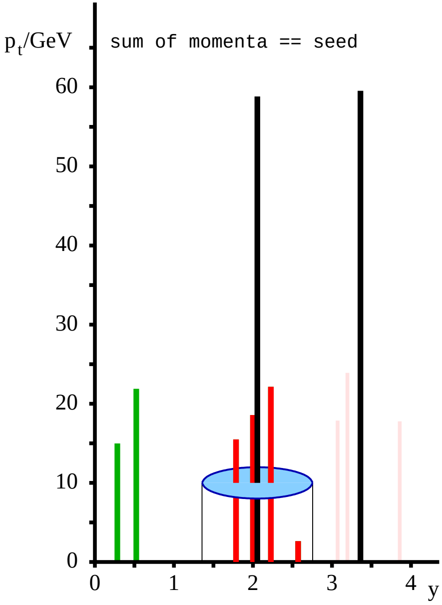

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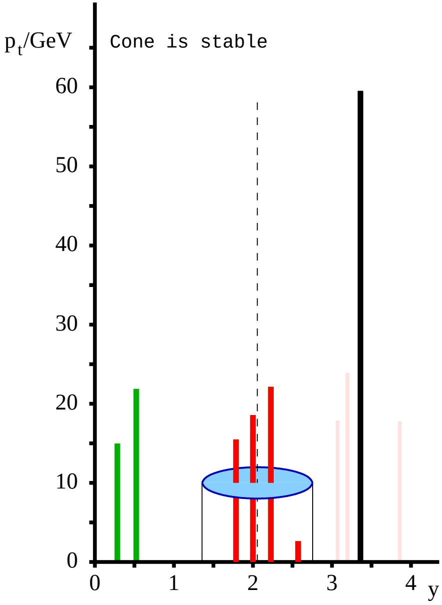

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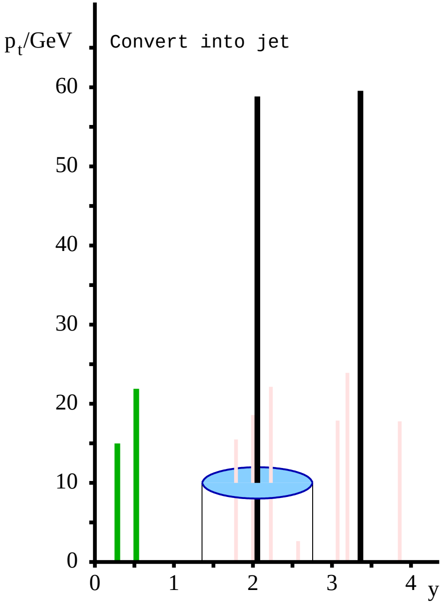

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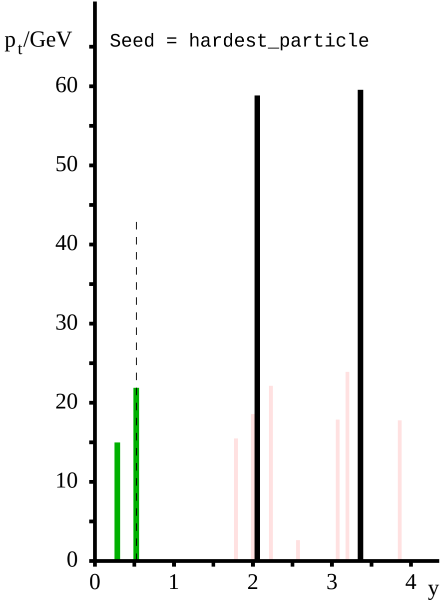

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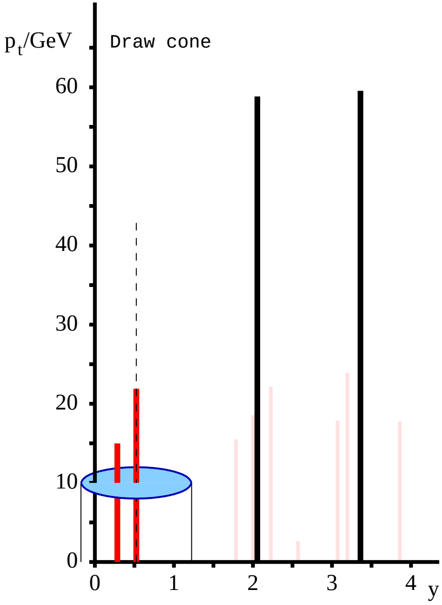

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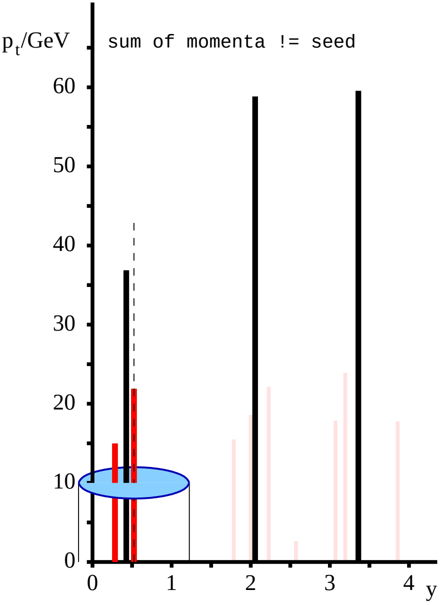

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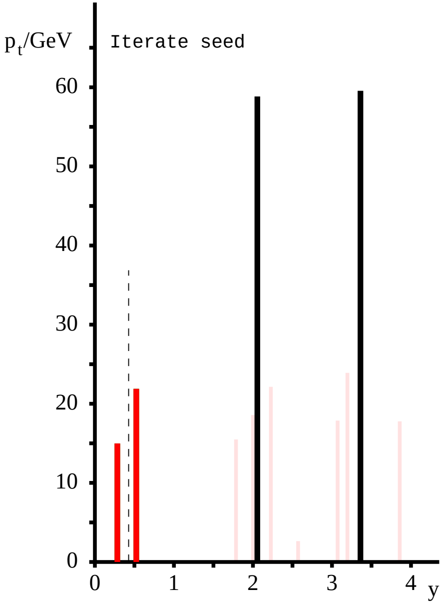

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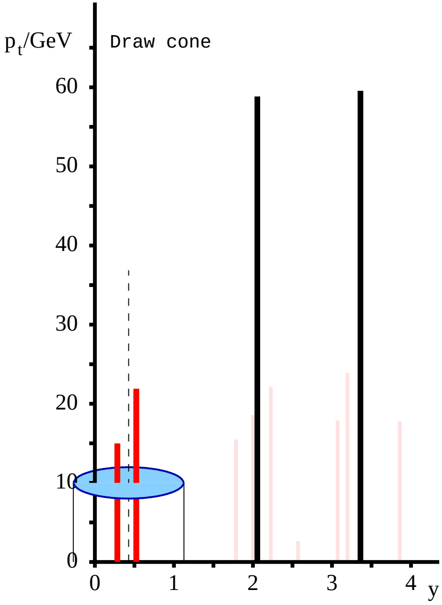

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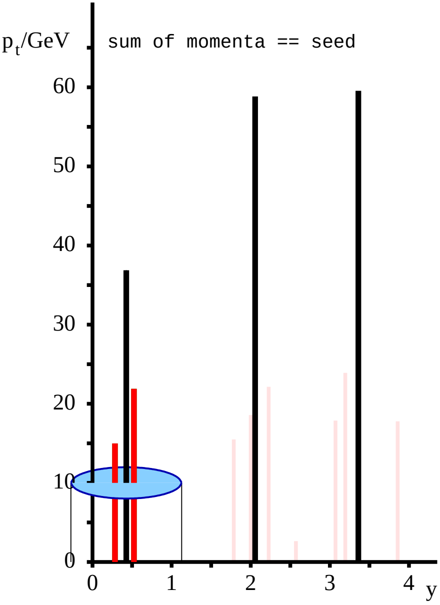

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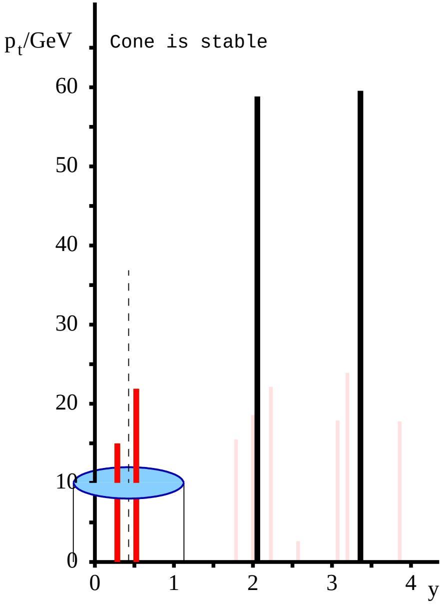

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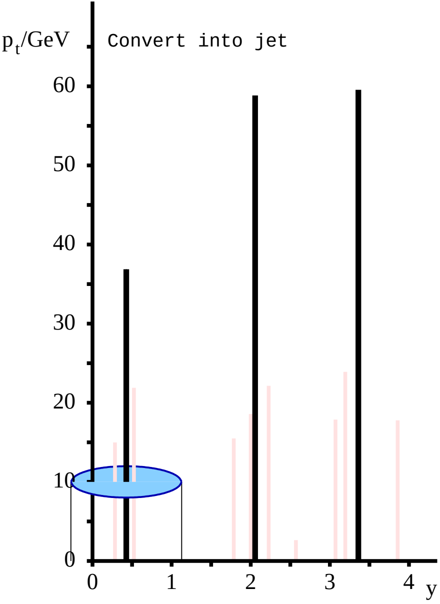

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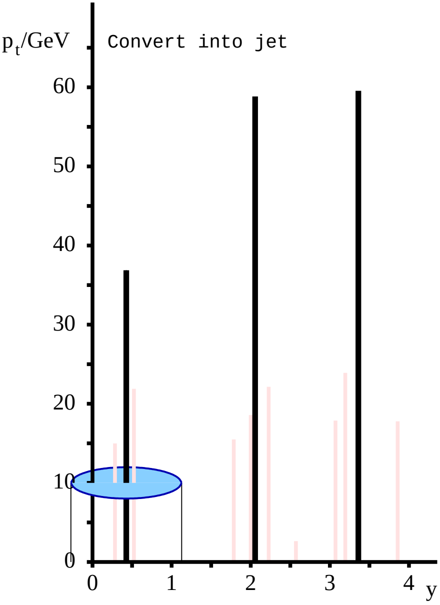

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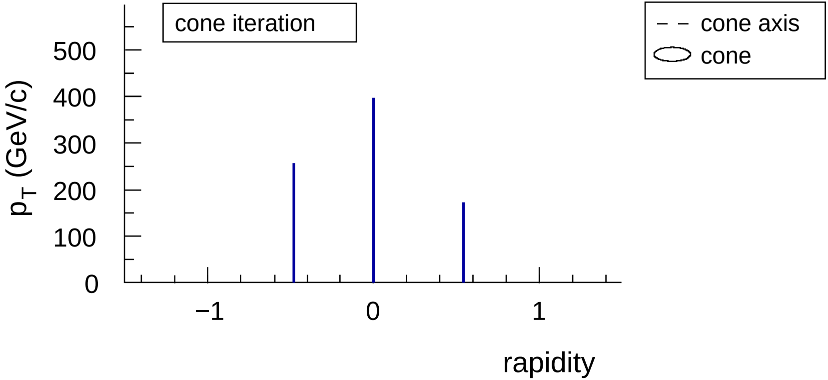

Collinear splitting can modify the hard jets: ICPR algorithms are collinear unsafe $\Longrightarrow$ perturbative calculations give ∞

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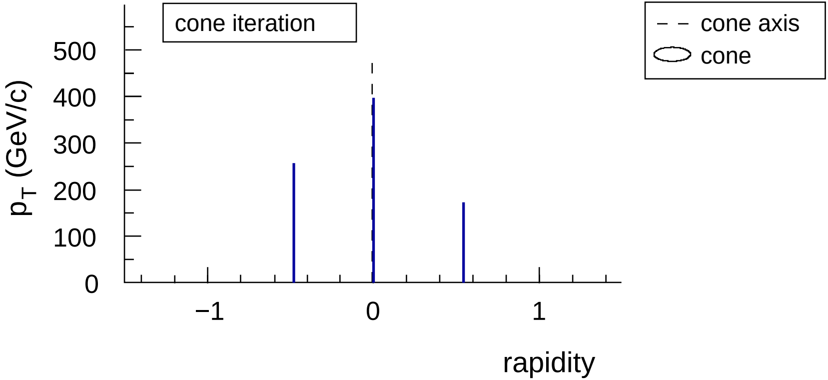

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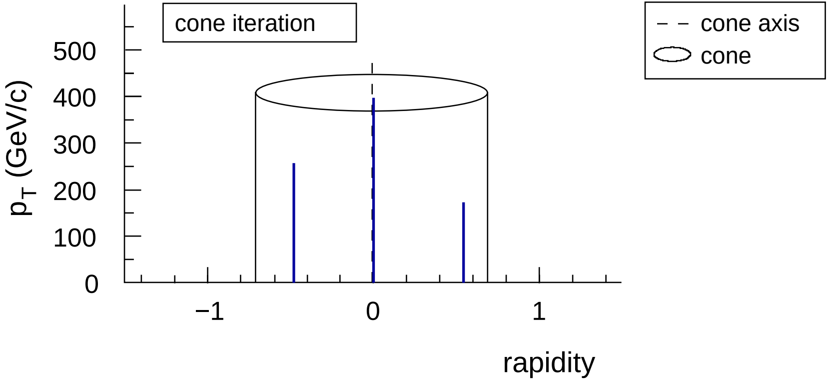

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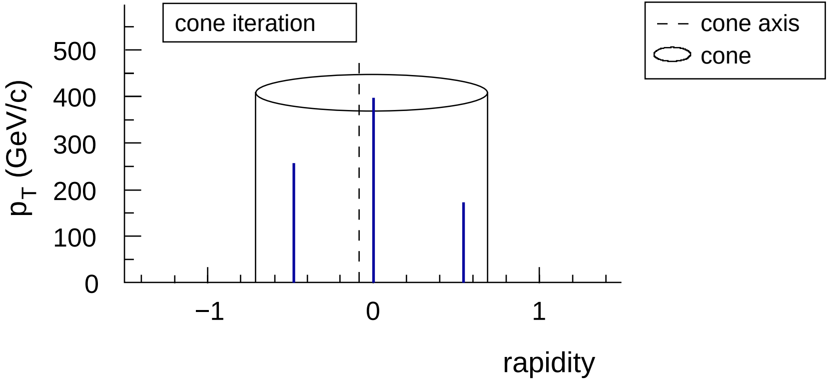

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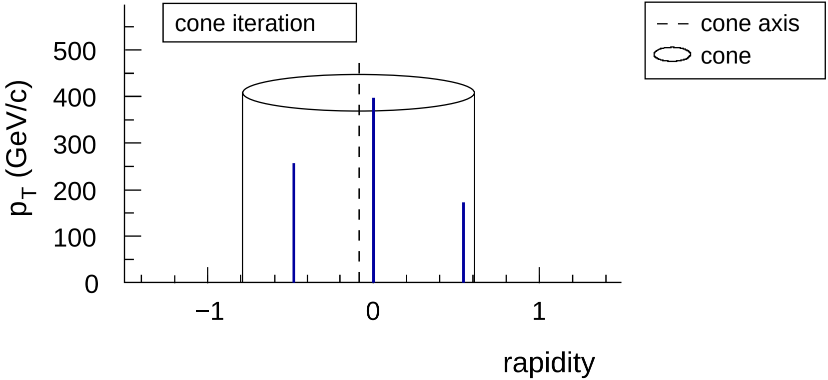

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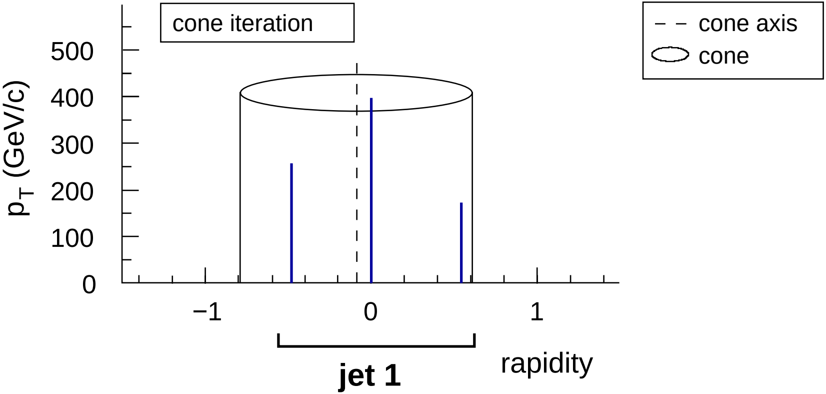

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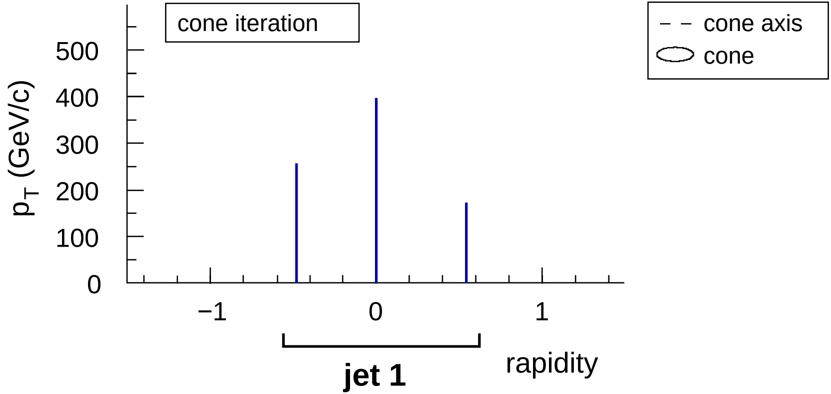

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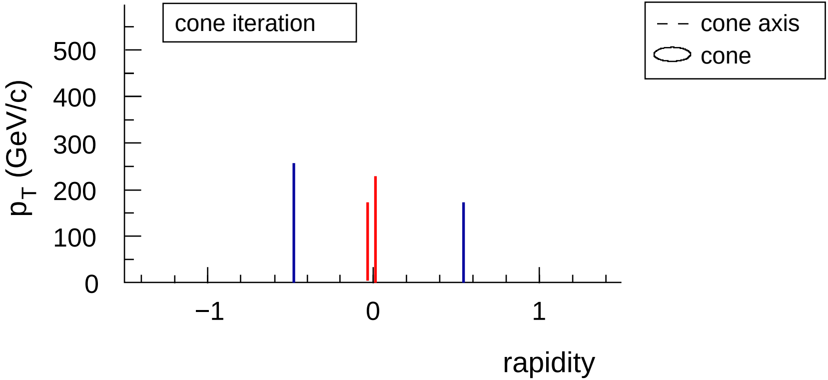

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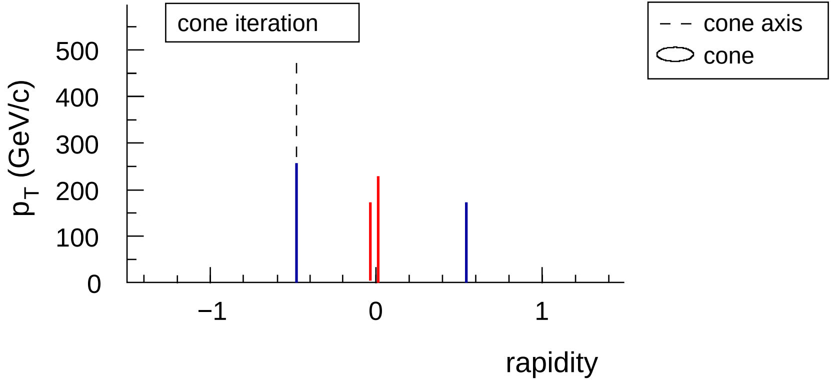

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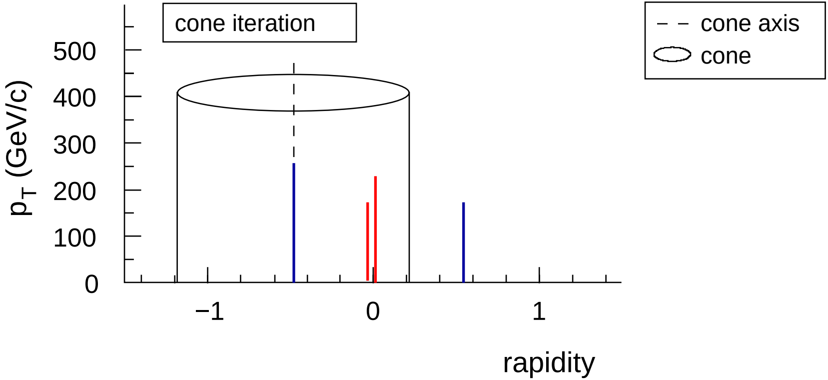

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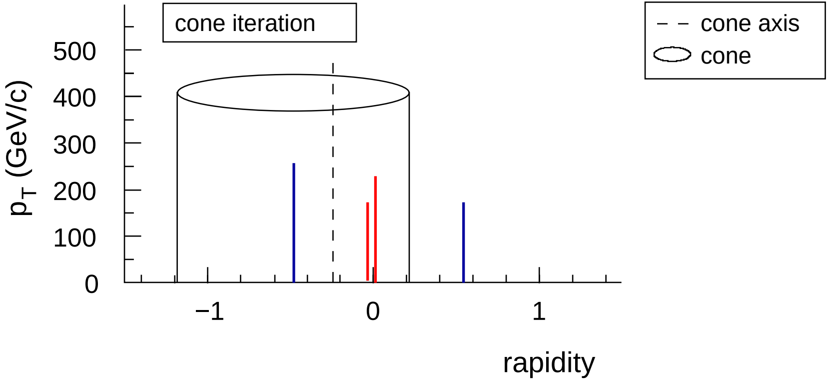

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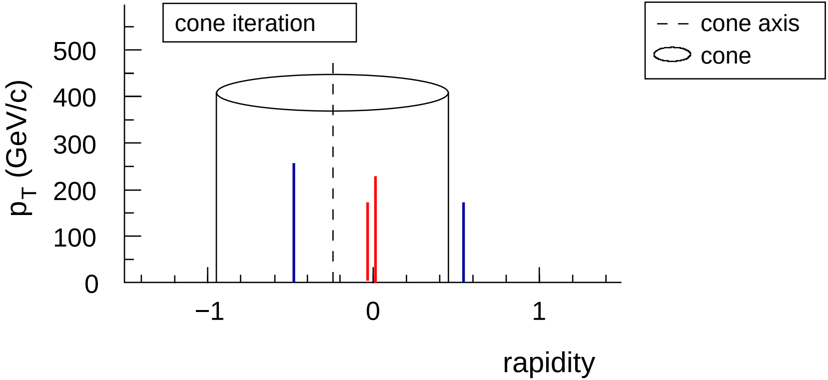

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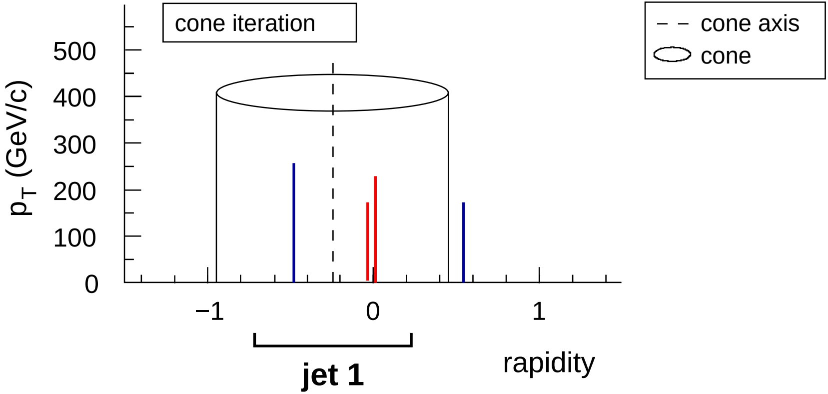

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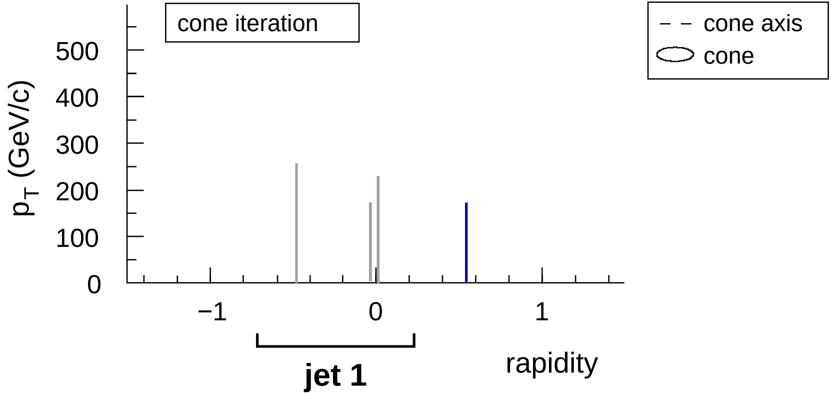

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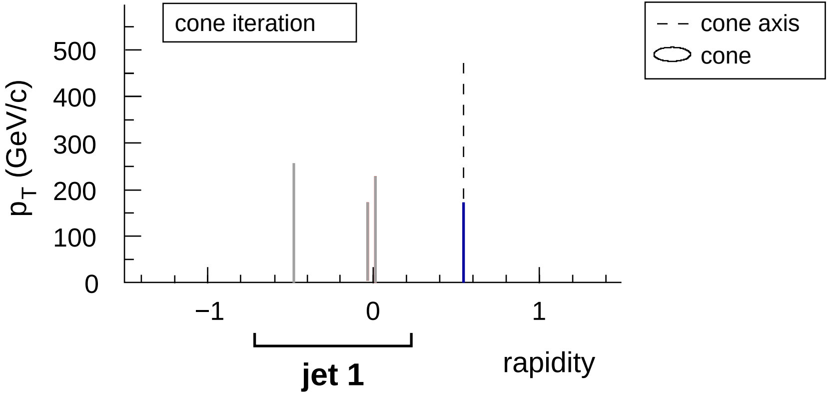

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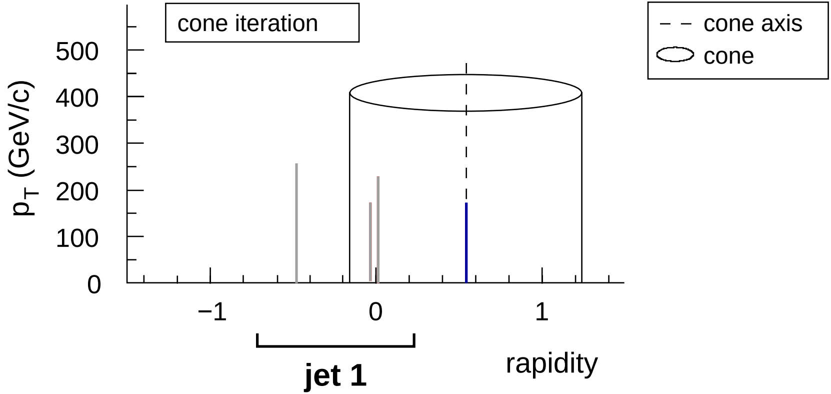

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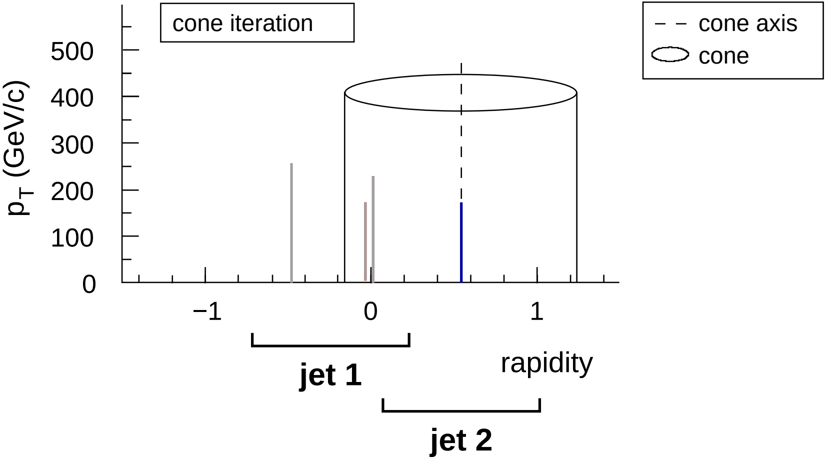

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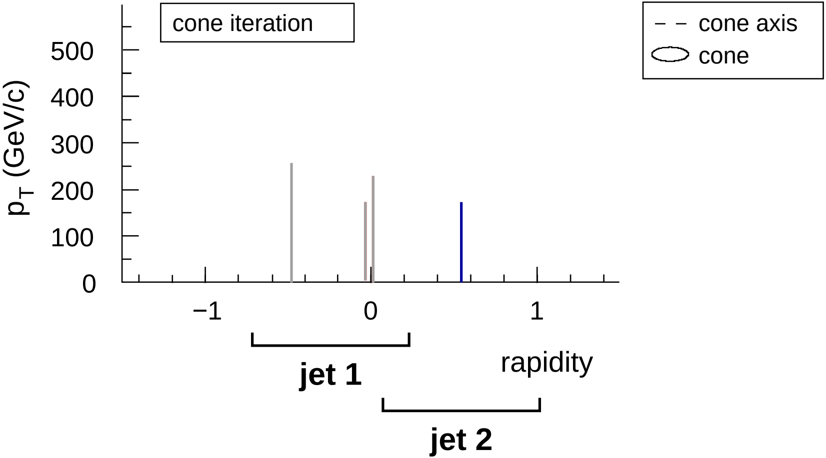

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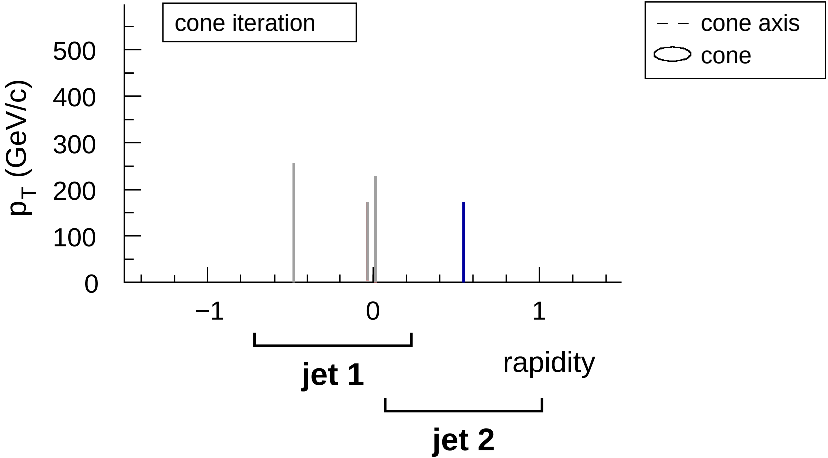

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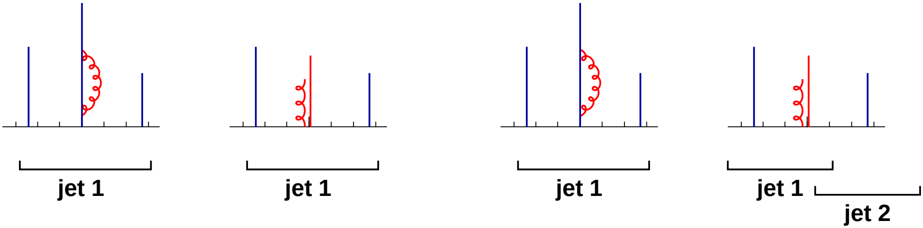
Consequences of collinear unsafety

Collinear Safe | Collinear Unsafe



$\alpha_s^n \times (-\infty)$ $\alpha_s^n \times (+\infty)$ $\alpha_s^n \times (-\infty)$ $\alpha_s^n \times (+\infty)$

Infinities cancel | **Infinities do not cancel**

Invalidates perturbation theory

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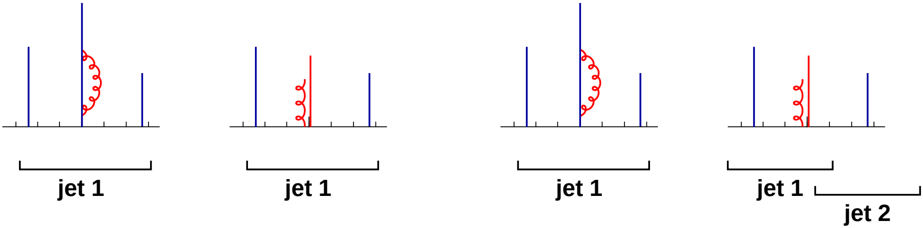

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IRC safety & real-life

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

$$\alpha_s^2 + \alpha_s^3 + \alpha_s^4 \times \infty \rightarrow \alpha_s^2 + \alpha_s^3 + \alpha_s^4 \times \ln p_t/\Lambda \rightarrow \alpha_s^2 + \underbrace{\alpha_s^3 + \alpha_s^3}_{\text{BOTH WASTED}}$$

Among consequences of IR unsafety:

	Last meaningful order			
	JetClu, ATLAS cone [IC-SM]	MidPoint [IC$_{mp}$-SM]	CMS it. cone [IC-PR]	Known at
Inclusive jets	LO	NLO	NLO	NLO ($\rightarrow$ NNLO)
$W/Z + 1$ jet	LO	NLO	NLO	NLO
3 jets	**none**	LO	LO	NLO [nlojet++]
$W/Z + 2$ jets	**none**	LO	LO	NLO [MCFM]
m_{jet} in $2j + X$	**none**	**none**	**none**	NLO [Blackhat/Rocket/...]

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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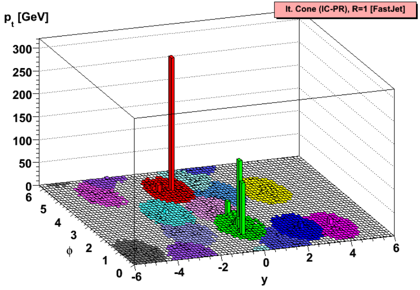
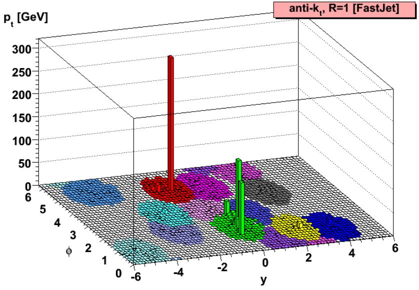
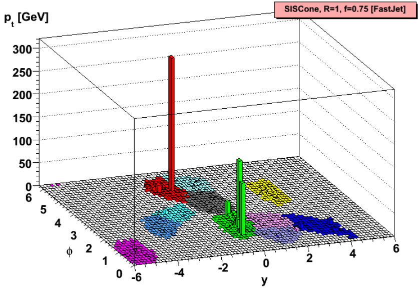
Cones v. anti-k_t







ICPR type cone can straightforwardly be replaced by anti-k_t.

Another class of cones — those with split-merge steps (Tevatron, old ATLAS cone), can be replaced with the *Seedless Infrared Safe Cone (SISCone)*.

Towards an understanding of jets

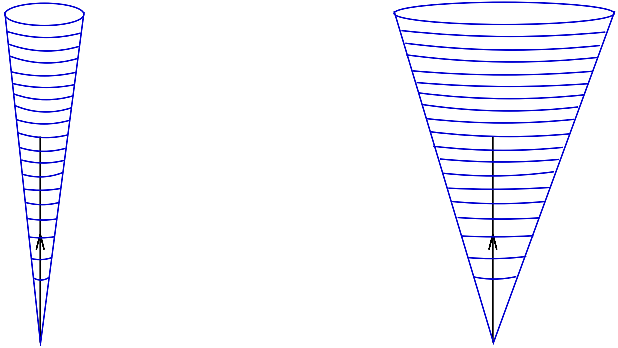
How a jet is and isn't like a parton —
quantitatively

And how this relationship is affected by the jet
radius

Small v. large jet radius (R) $\equiv$ HSBC

Small jet radius

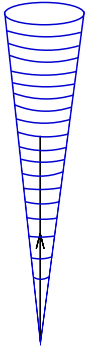
Large jet radius



single parton @ LO: **jet radius irrelevant**

Small v. large jet radius (R) ≡ HSBC

Small jet radius **Large jet radius**



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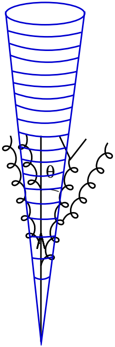
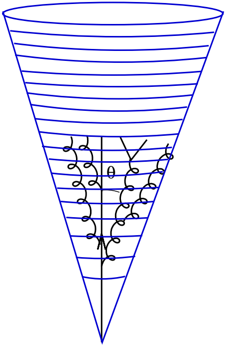


Large jet radius



perturbative fragmentation: **large jet radius better**
(it captures more)

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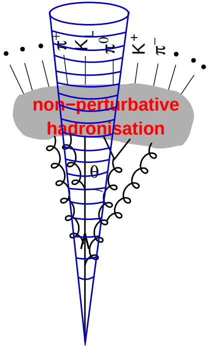

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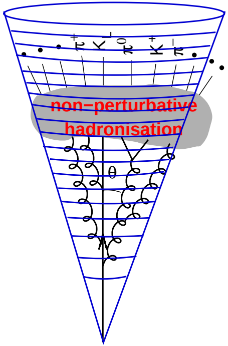

non-perturbative fragmentation: **large jet radius better**
(it captures more)

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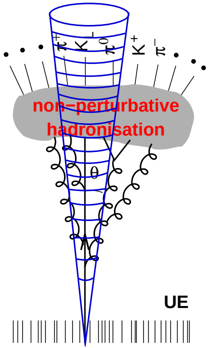
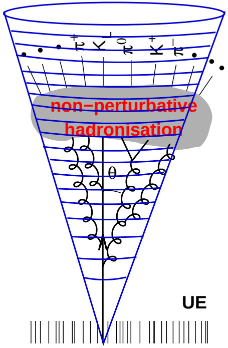
Small jet radius



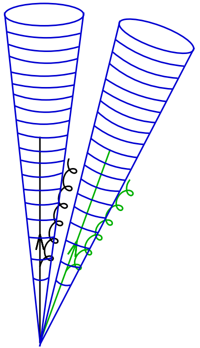
Large jet radius



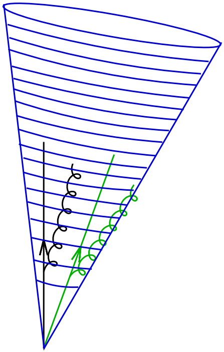
underlying ev. & pileup "noise": **small jet radius better**
(it captures less)

Small v. large jet radius (R) $\equiv$ HSBC

Small jet radius

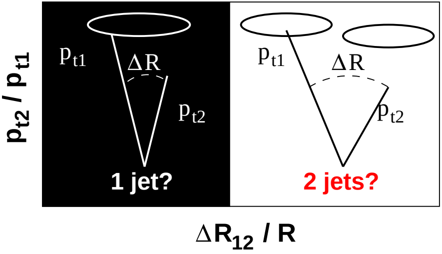


Large jet radius



multi-hard-parton events: **small jet radius better**
(it resolves partons more effectively)

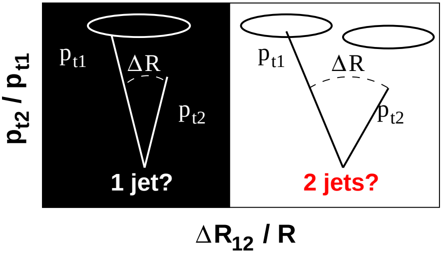
the *reach* of jet algorithms

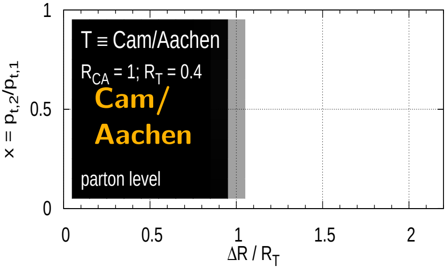


Most algs reach as far as R for radiation

SISCone (xC-SM) reaches further for hard radiation

the *reach* of jet algorithms





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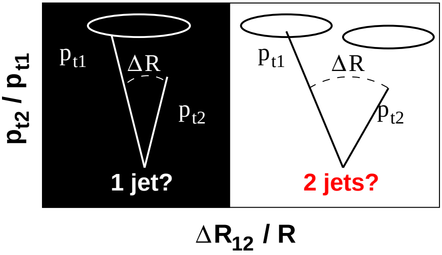

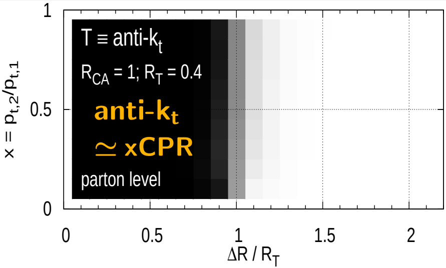

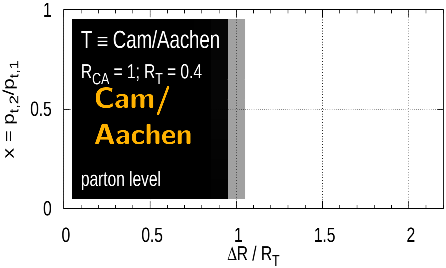

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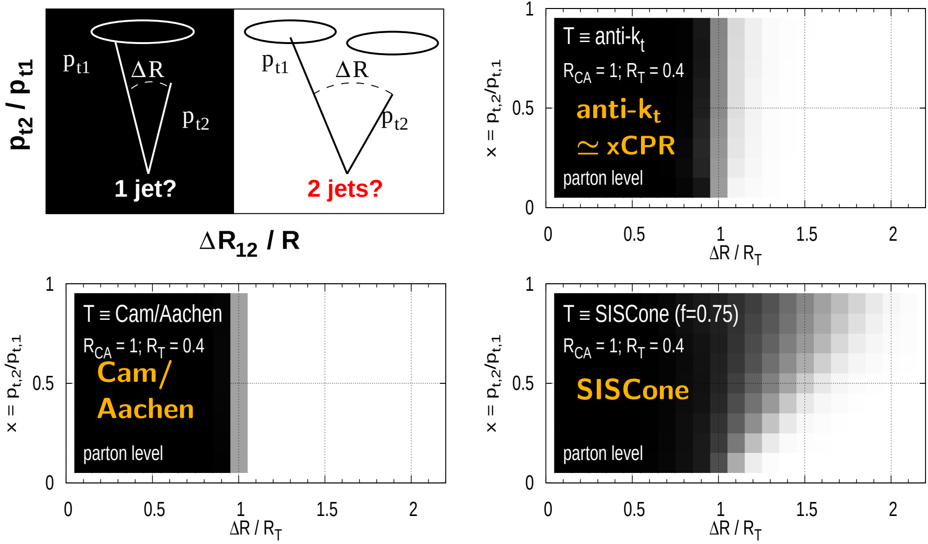

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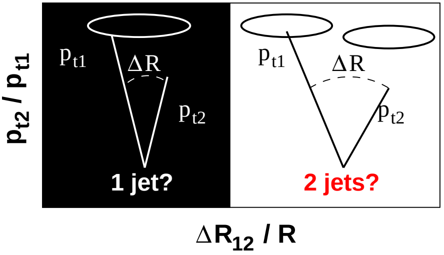

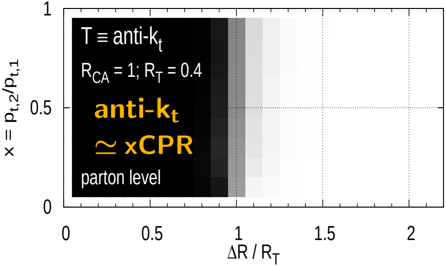

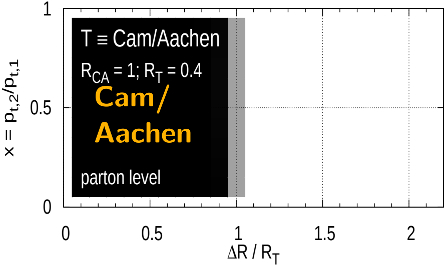

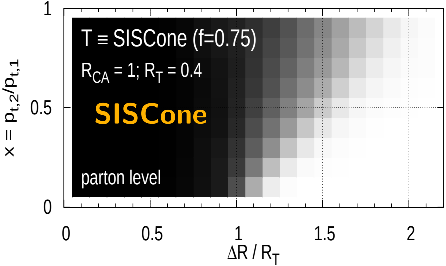

Most algs reach as far as *R* for radiation

SISCone (xC-SM) reaches further for hard radiation

Parton p_t v. jet p_t

3 physical effects:

1. Gluon radiation from the parton
2. Hadronisation
3. Underlying Event

One important consideration:

Whether the parton is a quark or a gluon

[quarks radiate with colour factor $C_F = 4/3$
gluons radiate with colour factor $C_A = 3$]

Jet p_t v. parton p_t: perturbatively?

The question's dangerous: a "parton" is an ambiguous concept

Three limits can help you:

- Threshold limit — e.g. de Florian & Vogelsang '07
- Parton from color-neutral object decay (Z')
- Small-R (radius) limit for jet

One simple result (small-R limit)

$$\frac{\langle p_{t,jet} - p_{t,parton}\rangle}{p_t} = \frac{\alpha_s}{\pi} \ln R \times \begin{cases} 1.01 C_F & \textit{quarks} \\ 0.94 C_A + 0.07 n_f & \textit{gluons} \end{cases} + \mathcal{O}\left(\alpha_s\right)$$

only $\mathcal{O}\left(\alpha_s\right)$ depends on algorithm & process
cf. Dasgupta, Magnea & GPS '07

Jet p_t v. parton p_t: hadronisation?

Hadronisation: the "parton-shower" $\rightarrow$ hadrons transition

Method:

- "infrared finite α_s" — à la Dokshitzer & Webber '95
- **prediction** based on e^+e^- event shape data
- could have been deduced from old work — Korchemsky & Sterman '95, Seymour '97

Main result

$$\langle p_{t,jet} - p_{t,parton-shower} \rangle \simeq -\frac{0.4\ \text{GeV}}{R} \times \begin{cases} C_F & quarks \\ C_A & gluons \end{cases}$$

cf. Dasgupta, Magnea & GPS '07

coefficient holds for anti-k_t; see Dasgupta & Delenda '09 for k_t alg.

Underlying Event (UE)

"Naive" prediction (UE $\simeq$ colour dipole between pp):

$$\Delta p_t \simeq 0.4\text{ GeV} \times \frac{R^2}{2} \times \begin{cases} C_F & q\bar{q}\text{ dipole} \\ C_A & \text{gluon dipole} \end{cases}$$

Modern Monte Carlo tunes tell you ($\sqrt{s} = 7$ TeV):

$$\Delta p_t \simeq \mathbf{8\text{ GeV}} \times \frac{R^2}{2} \simeq 1.2\text{ GeV} \times (\pi R^2)$$

This big coefficient motivates special effort to understand interplay between jet algorithm and UE: "jet areas"

How does coefficient depend on algorithm?

How does it depend on jet p_t? How does it fluctuate?

cf. Cacciari, GPS & Soyez '08

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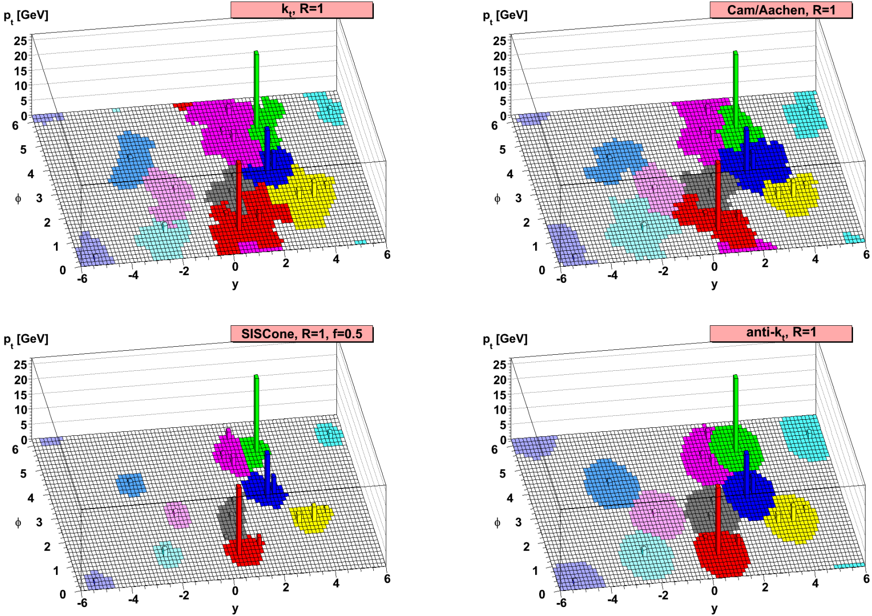
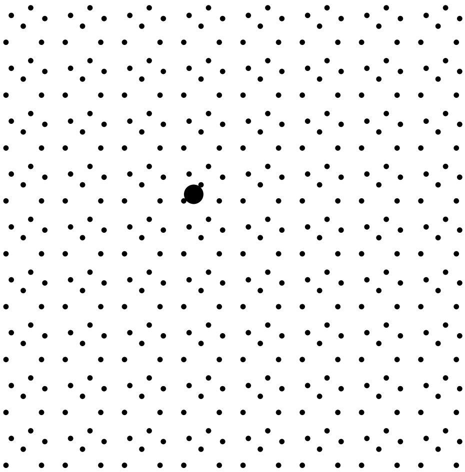
Jet contours – visualised



E.g. SISCone jet area

1. One hard particle, many soft



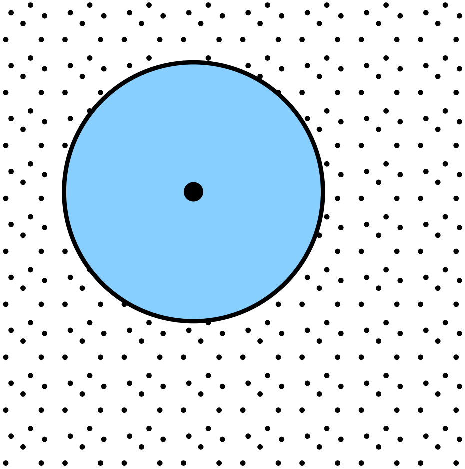
SISCone, any R, $f \gtrsim 0.391$

Jet area =
Measure of jet's susceptibility to uniform soft radiation

Depends on details of an algorithm's clustering dynamics.

E.g. SISCone jet area

2. One hard stable cone, area $= \pi R^2$



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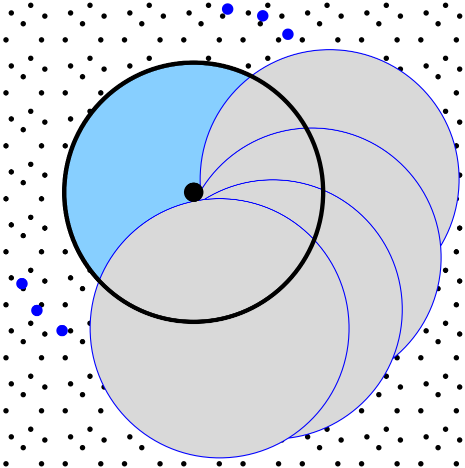
Jet area =

Measure of jet's susceptibility to uniform soft radiation

Depends on details of an algorithm's clustering dynamics.

E.g. SISCone jet area

3. Overlapping "soft" stable cones



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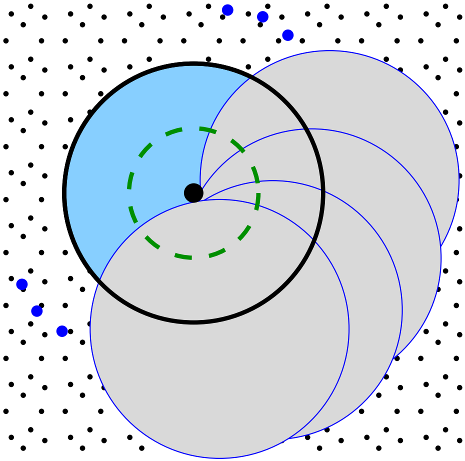
Measure of jet's susceptibility to uniform soft radiation

Depends on details of an algorithm's clustering dynamics.

E.g. SISCone jet area

4. "Split" the overlapping parts



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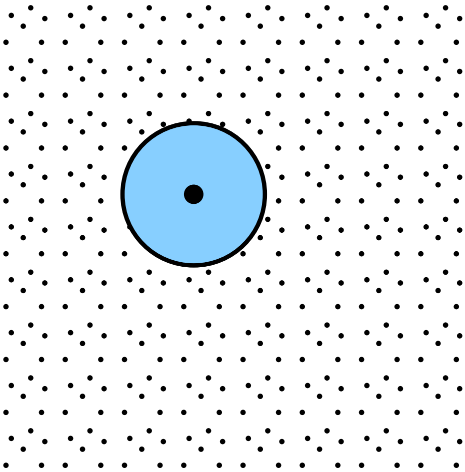
Jet area =
Measure of jet's susceptibility to uniform soft radiation

Depends on details of an algorithm's clustering dynamics.

E.g. SISCone jet area

5. Final hard jet (reduced area)



SISCone, any R, $f \gtrsim 0.391$

Jet area =
Measure of jet's susceptibility to uniform soft radiation

Depends on details of an algorithm's clustering dynamics.

SISCone's area (1 hard particle)
$$= \frac{1}{4}\pi R^2$$

Small area ≡
low sensitivity to UE & pileup

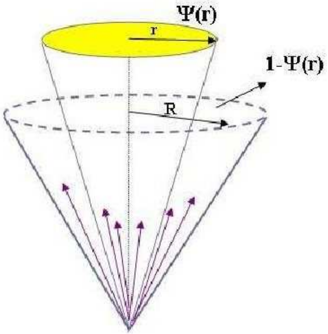
Jet algorithm properties: summary

	k_t	Cam/Aachen	anti-k_t	SISCone
reach	R	R	R	$(1+\frac{p_{t2}}{p_{t1}})R$
$\Delta p_{t,PT} \simeq \frac{\alpha_s C_i}{\pi} \times$	$\ln R$	$\ln R$	$\ln R$	$\ln 1.35R$
$\Delta p_{t,hadr} \simeq -\frac{0.4\,\text{GeV}\, C_i}{R} \times$	0.7	?	1	?
area $= \pi R^2 \times$	0.81 ± 0.28	0.81 ± 0.26	1	0.25
$+\pi R^2 \frac{C_i}{\pi b_0} \ln \frac{\alpha_s(Q_0)}{\alpha_s(Rp_t)} \times$	0.52 ± 0.41	0.08 ± 0.19	0	0.12 ± 0.07

In words:

- k_t: area fluctuates a lot, depends on p_t (bad for UE)
- Cam/Aachen: area fluctuates somewhat, depends less on p_t
- anti-k_t: area is constant (circular jets)
- SISCone: reaches far for hard radiation (good for resolution, bad for multijets), area is smaller (good for UE)

Where does radiation go? Look at jet "shapes"



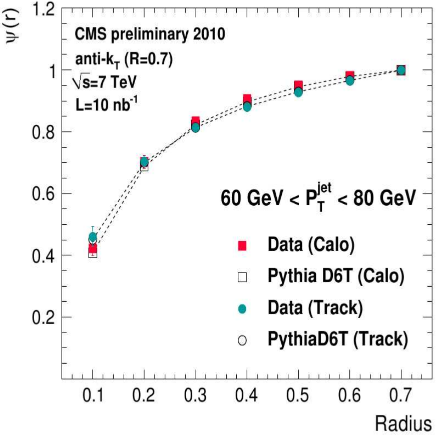
Jet Shape:

$$\Psi(r) = \int_0^r \frac{p_t(r')}{p_t(jet)} dr'$$

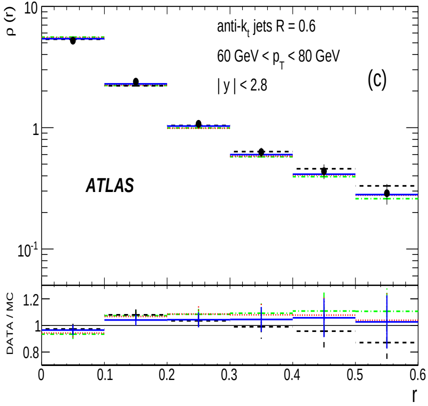
Fraction of energy inside a sub-cone of size r

Jet shape results from LHC

Integrated Jet Shape $\Psi(r)$ v. r

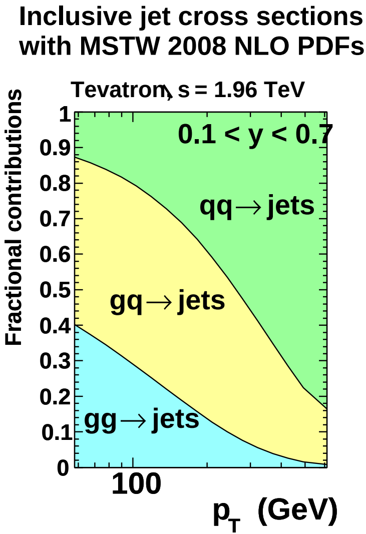


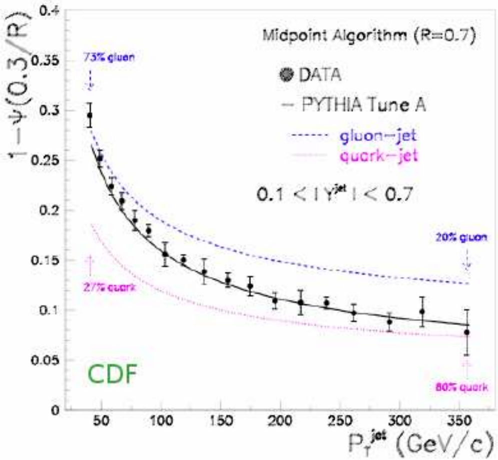
Differential Jet Shape $\rho(r) = d/dr\Psi(r)$



50% of energy concentrated in cone of $\sim$ 0.1

Jet shape results from Tevatron

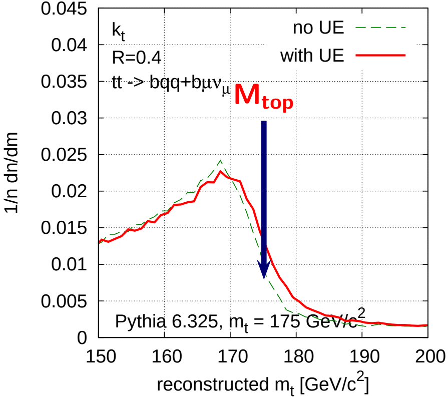




see clear sign of quark to gluon ratio evolving

A qualitative example: top reconstruction

Robustness: M_{top} varies with R?



Game: measure top mass to 1 GeV

example for Tevatron

$m_t = 175$ GeV

- Small R: lose 6 GeV to PT radiation and hadronisation, UE and pileup irrelevant
- Large R: hadronisation and PT radiation leave mass at ~ 175 GeV, UE adds $2-4$ GeV.

Is the final top mass (after W jet-energy-scale and Monte Carlo unfolding) independent of R used to measure jets?

Flexibility in jet finding gives powerful cross-check of systematic effects

cf. Seymour & Tevlin '06

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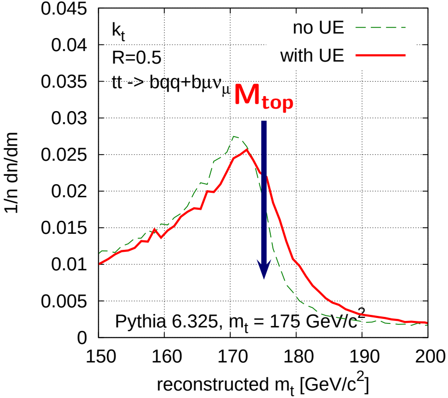

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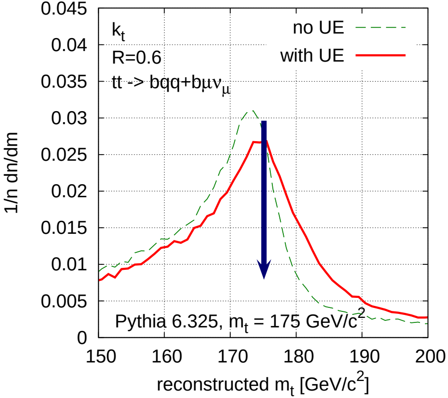

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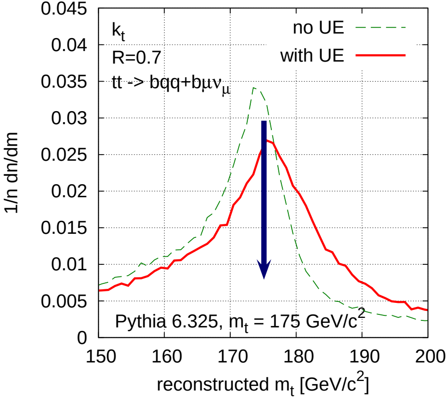

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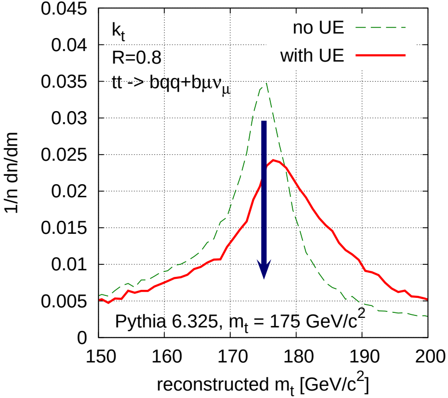

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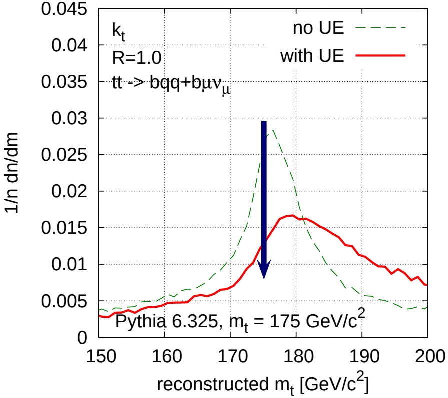

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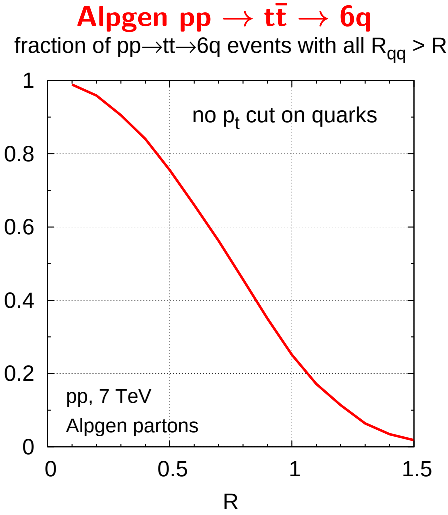
6 partons v. 6 jets?



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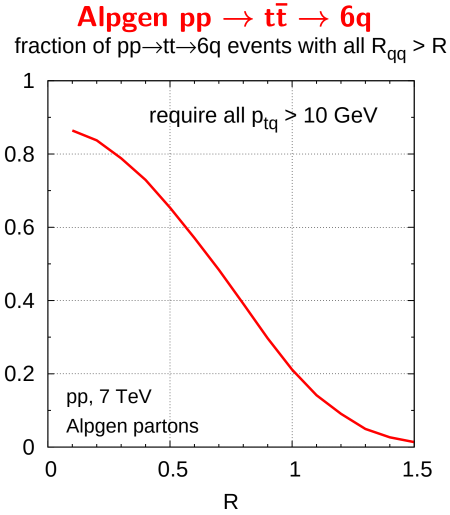

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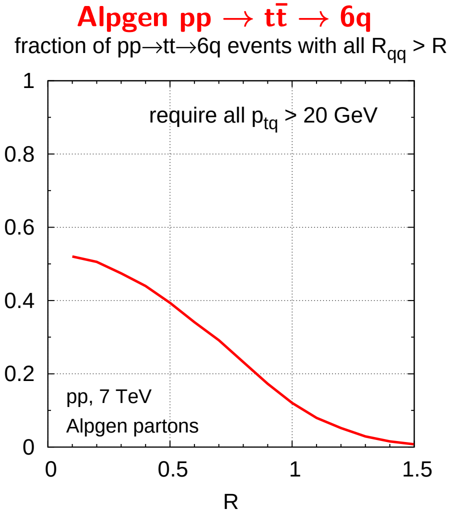

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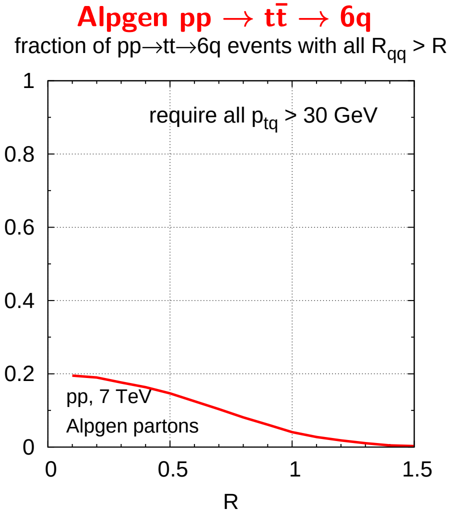
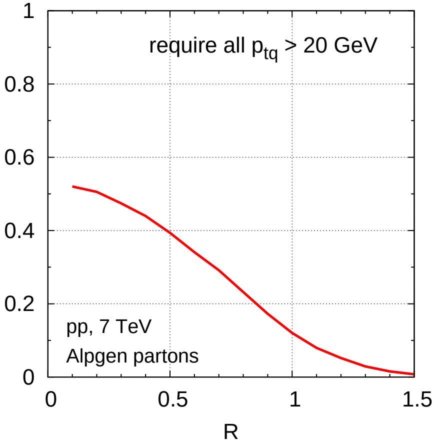


6 partons v. 6 jets?

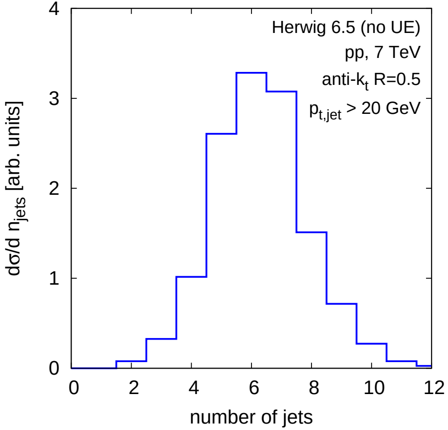
Alpgen pp → $t\bar{t}$ → 6q

fraction of pp→tt→6q events with all R_{qq} > R



Herwig pp → $t\bar{t}$ → hadrons

Distribution of number of jets



Some points to take home

Experiment-theory correspondence relies on infrared and collinear safety

Relation between a parton and a jet is ambiguous (because "partons" are ambiguous)

But many rule-of-thumb relations can be derived, e.g. for R-dependence from different physics contributions
[perturbative radiation, hadronisation, underlying event]