Jets

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Lecture 1 $\longrightarrow$ 2

In lecture 1, we saw

- sequential recombination (k_t, etc.) algorithms
- the first of a series of cone-algorithms, those with "progressive removal" (xC-PR)
- and ran into collinear safety issues (from ordering of "seeds" for cone direction)

Today

- see the other series of cone-algorithms (with split–merge, xC-SM)
- look more at the physics of jet algs.

Cone algorithms today

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
Seedless (SC)		SISCone	

† JetClu also has "ratcheting"

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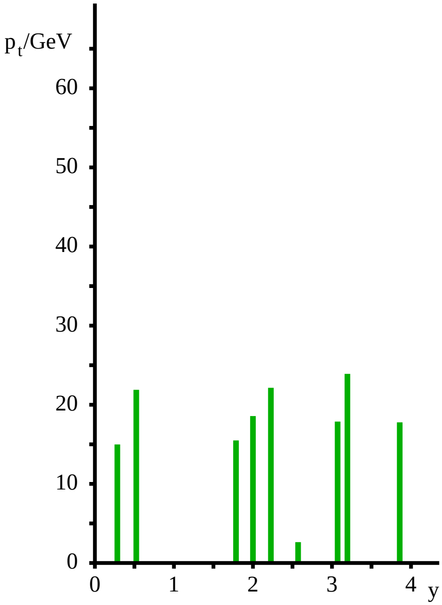

Avoid ordering seeds (coll. unsafe)

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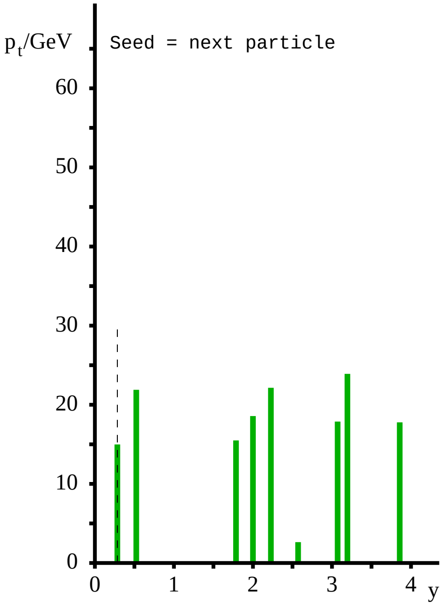

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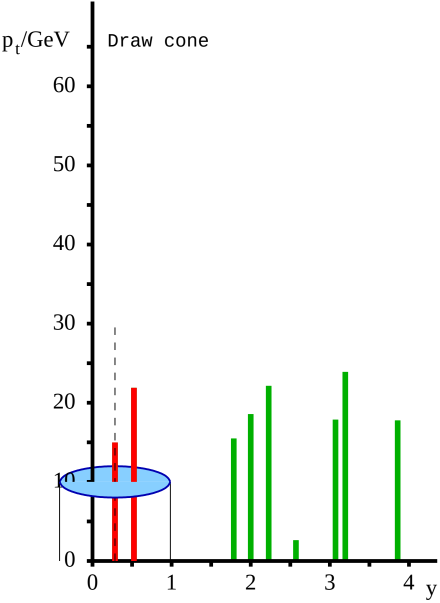

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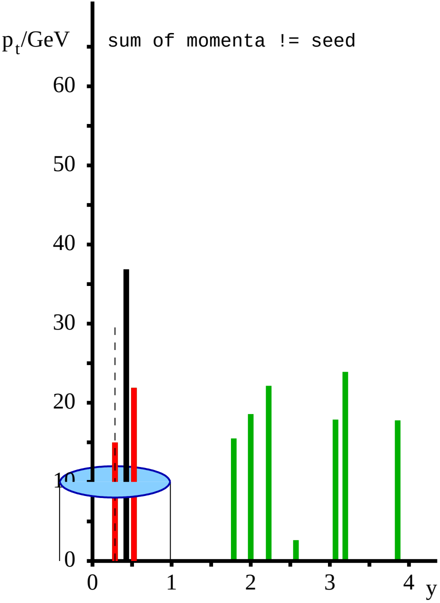

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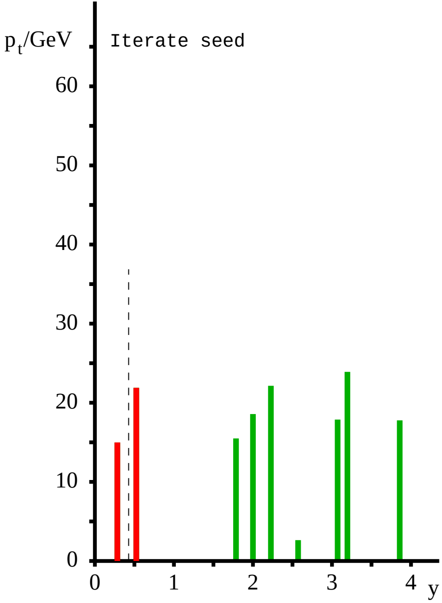

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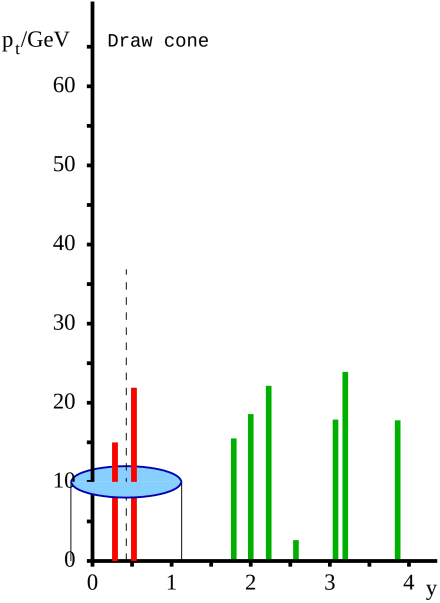

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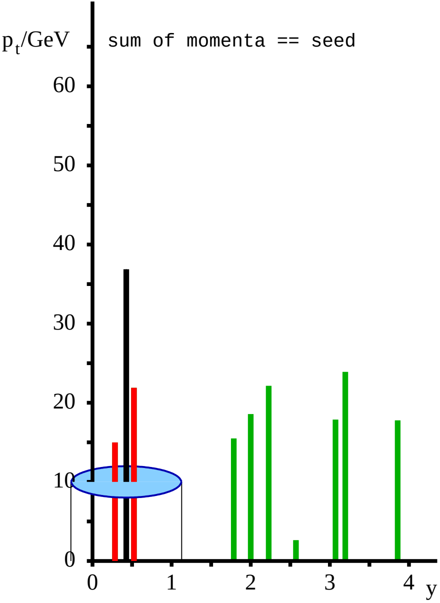

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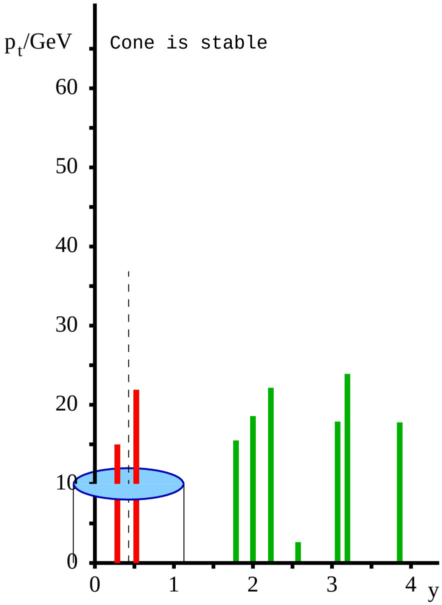

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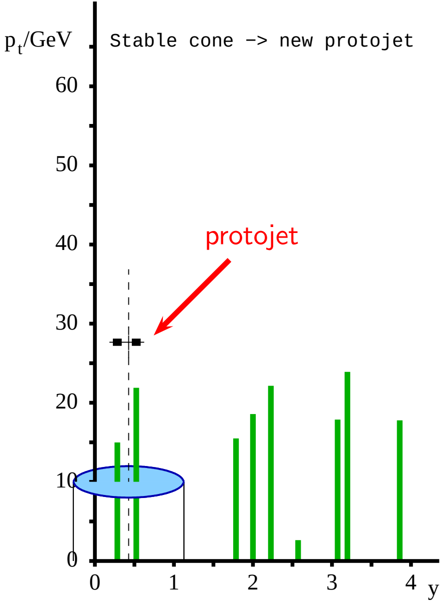

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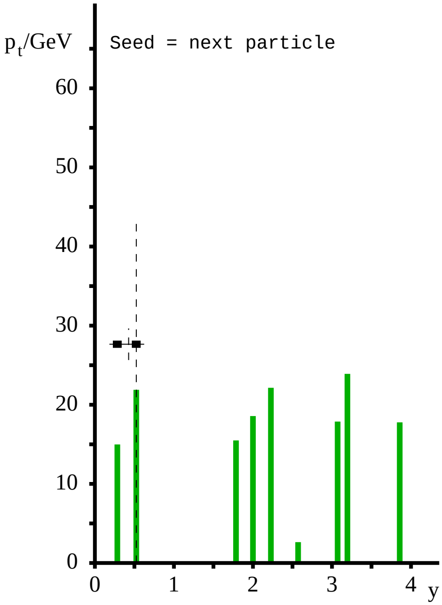

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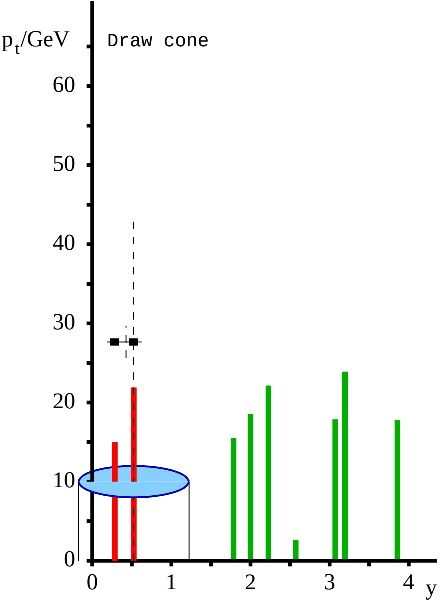

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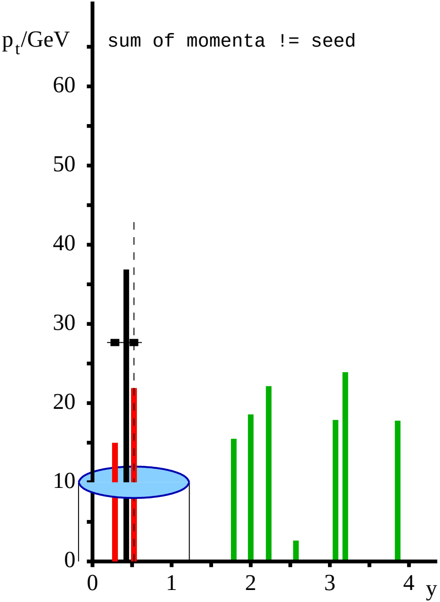

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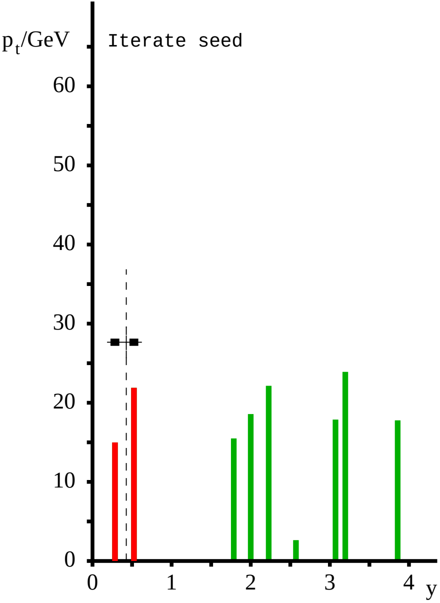

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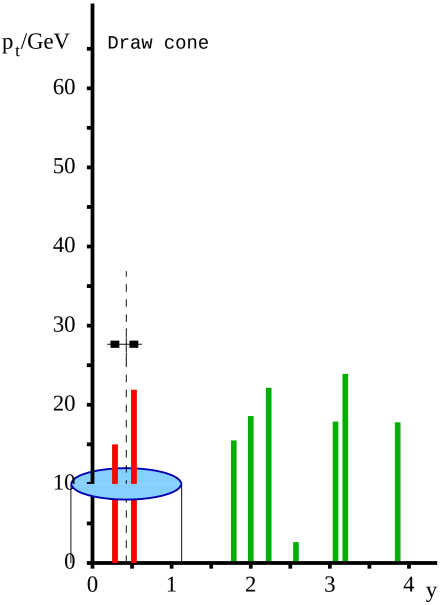

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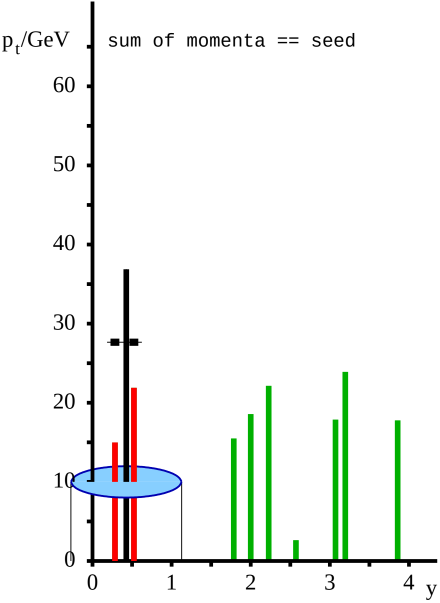

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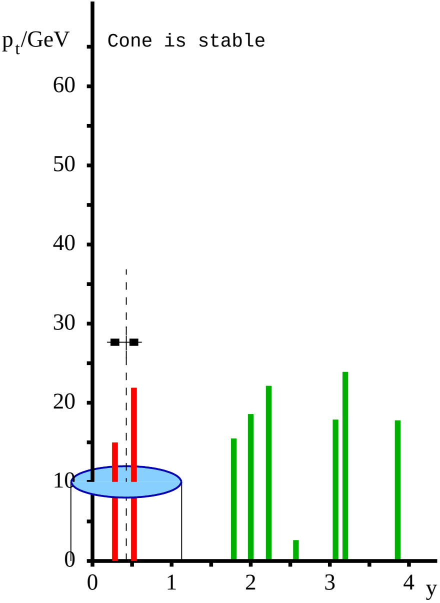

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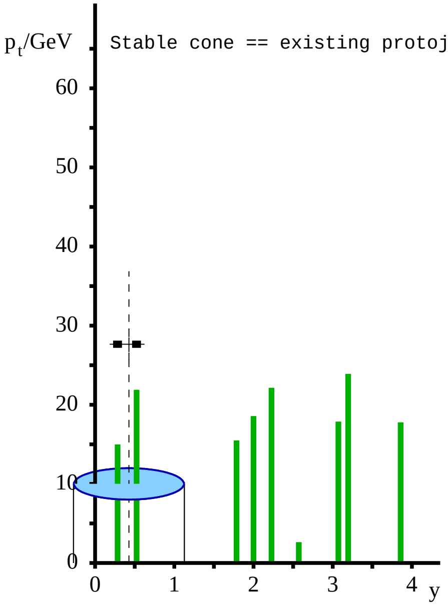

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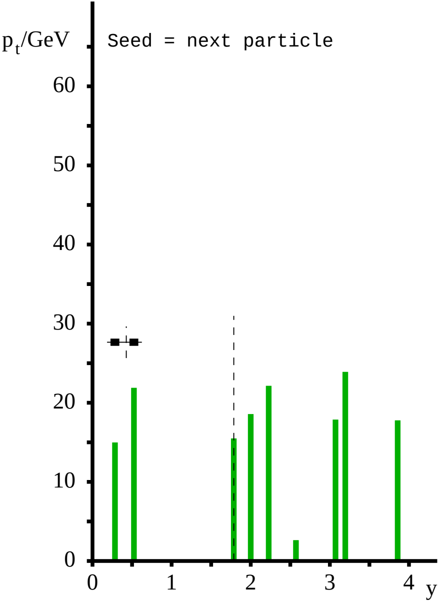

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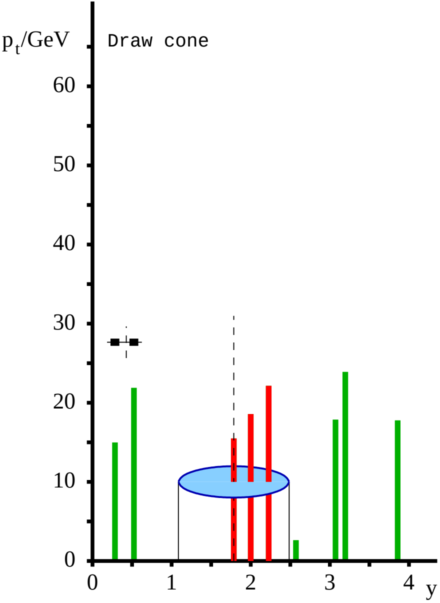

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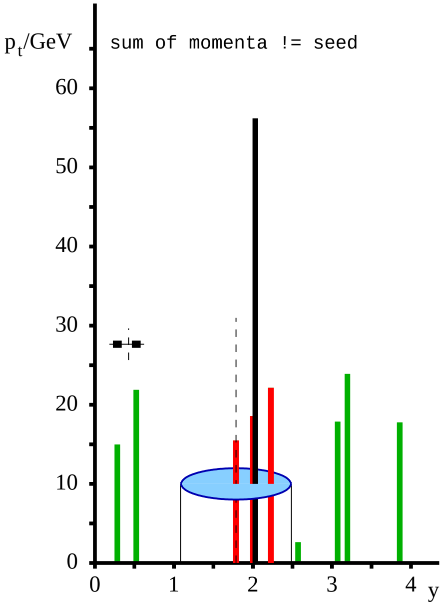

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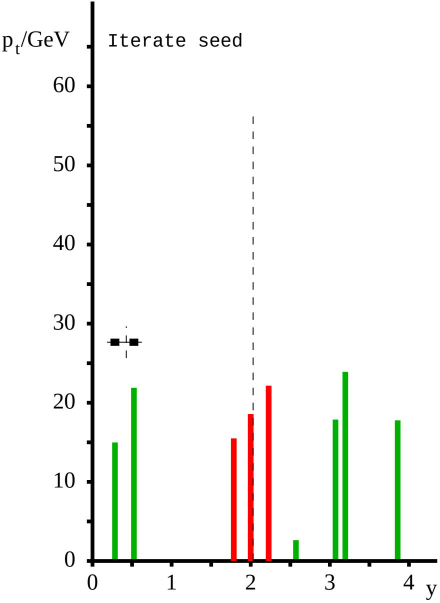

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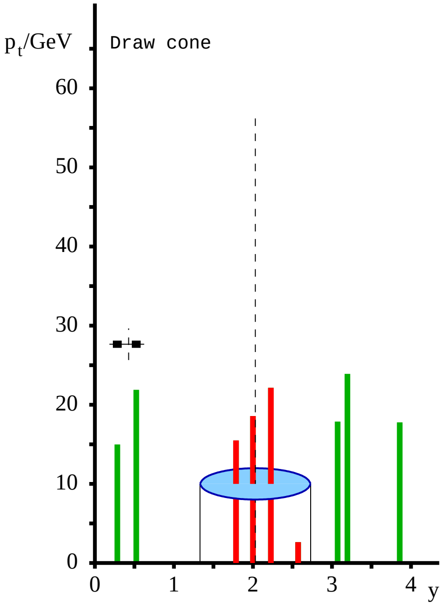

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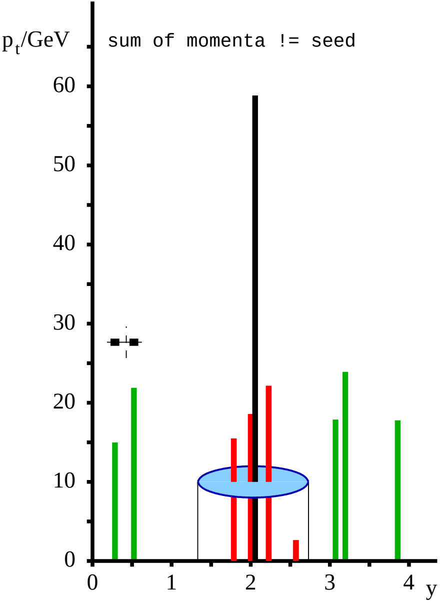

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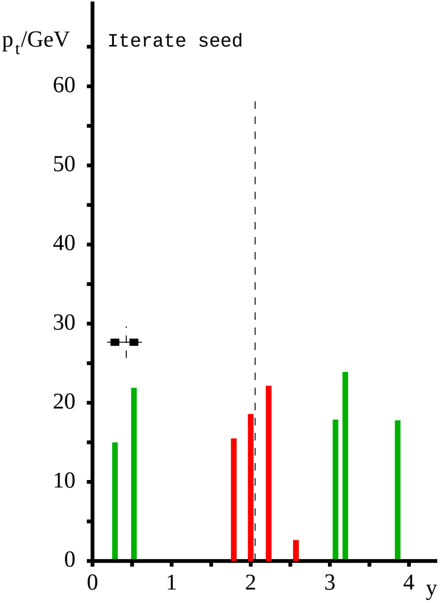

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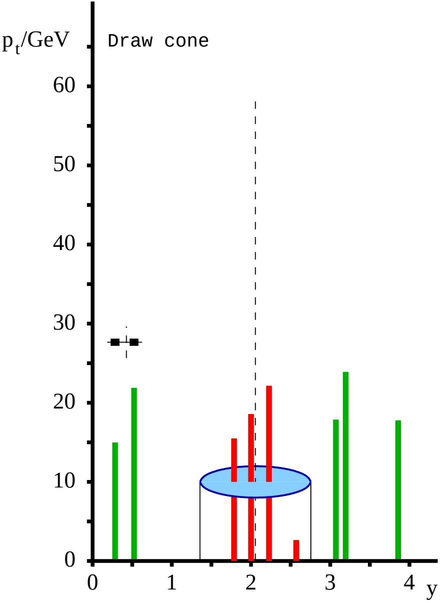

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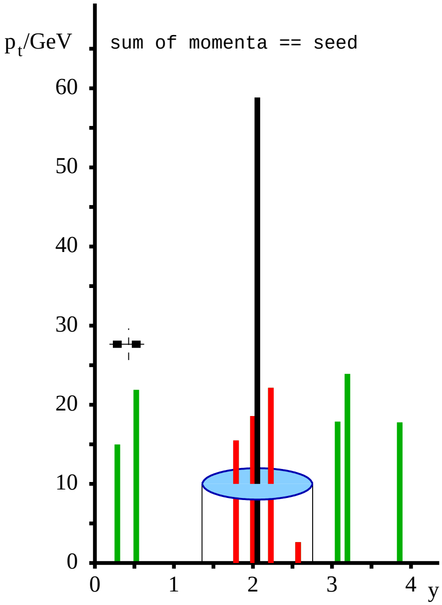

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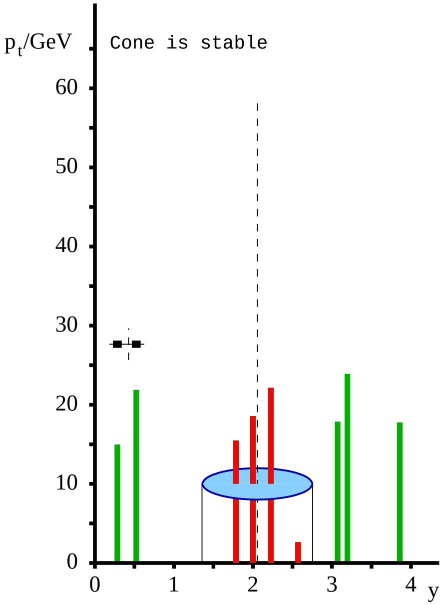

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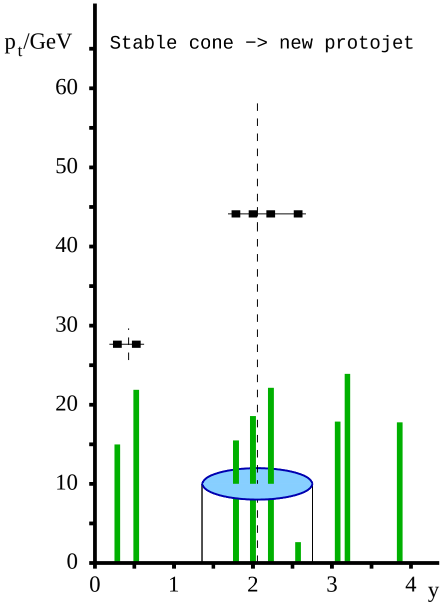

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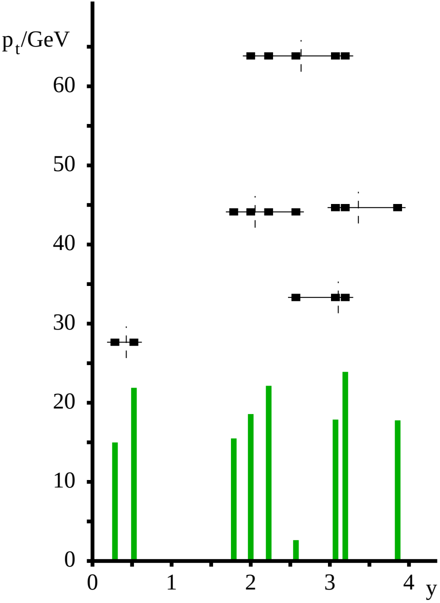

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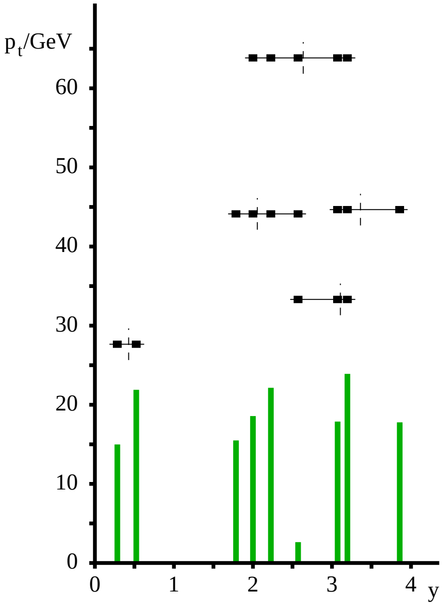

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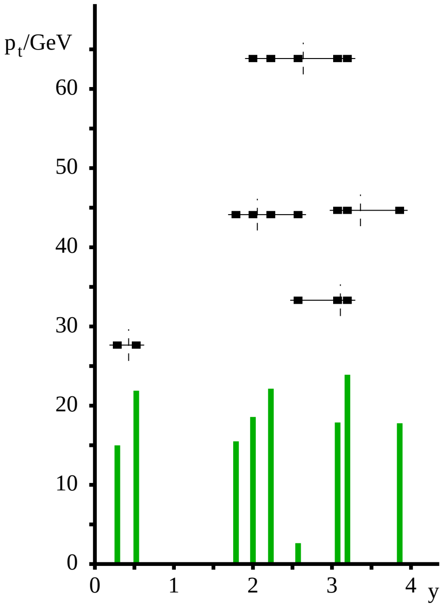

SM in Tevatron Run II formulation

but common to most xC-SM

Introduce overlap threshold f

- Identify hardest protojet (PJ), p_1
- Find hardest PJ that overlaps with it, p_2
- Calculated overlap, $O = p_{t,shared} / p_{t,2}$
  - if $O < f$, split along axis at center of two PJs
  - if $O > f$ merge the two PJs
- If there is no overlap, PJ $\rightarrow$ jet.
- repeat. . .

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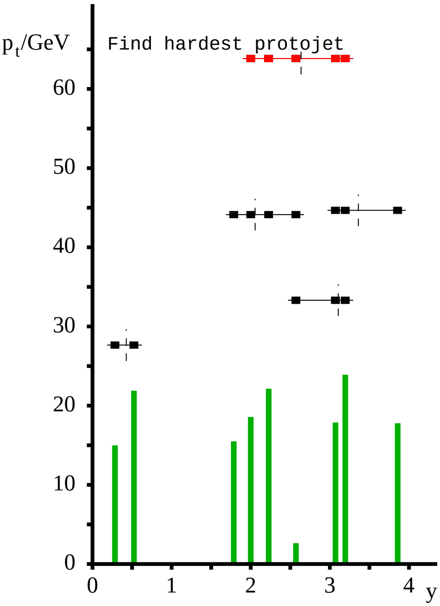

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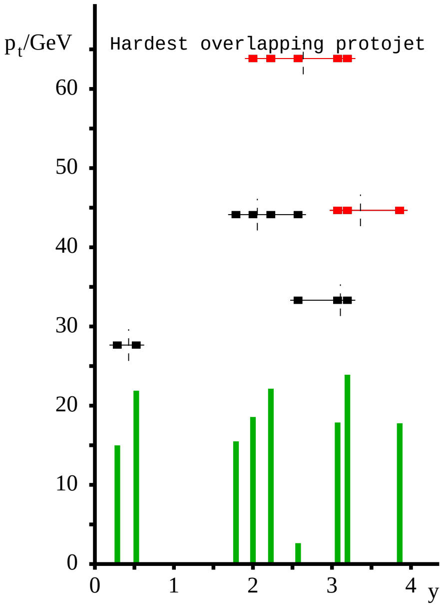

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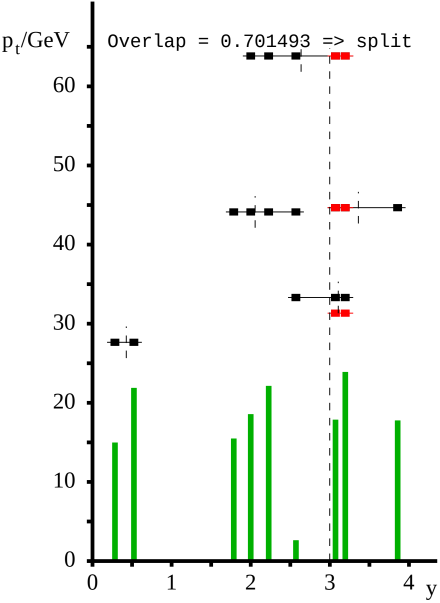
IC-SM: split–merge part



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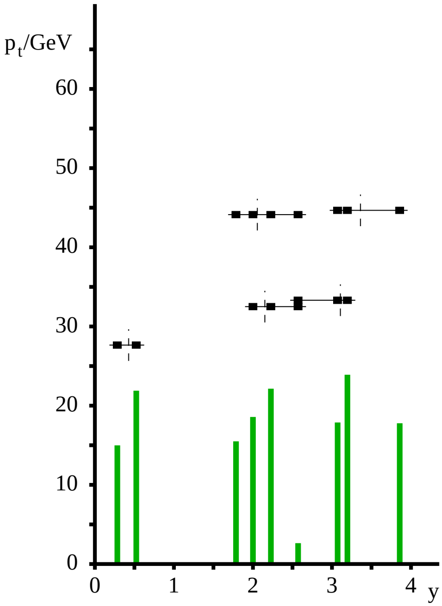

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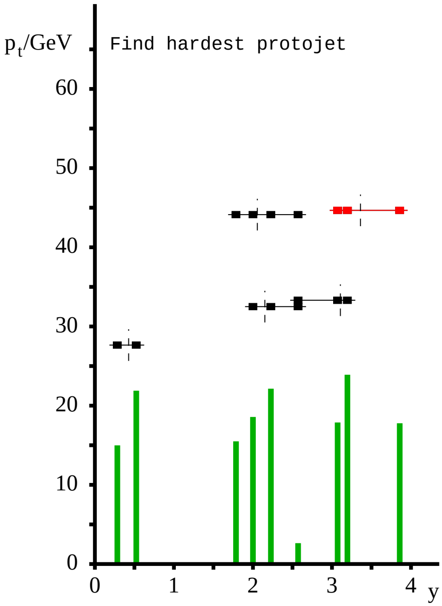

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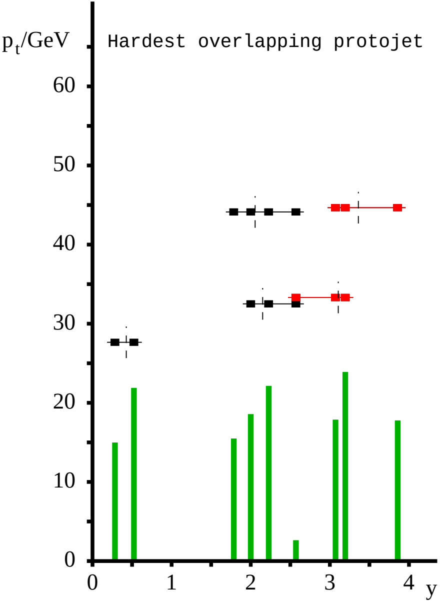

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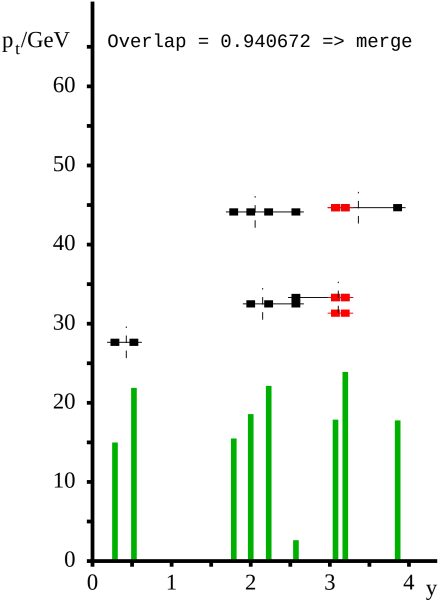

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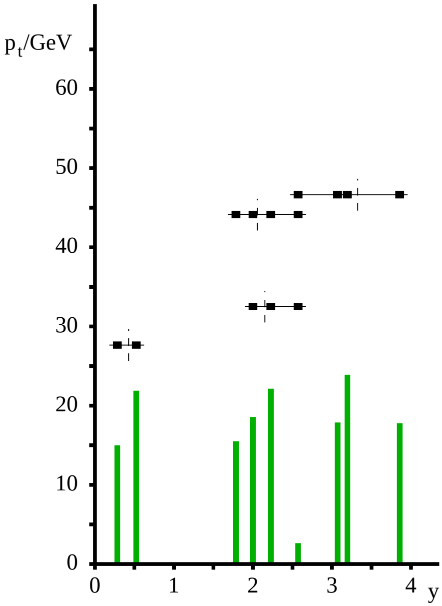

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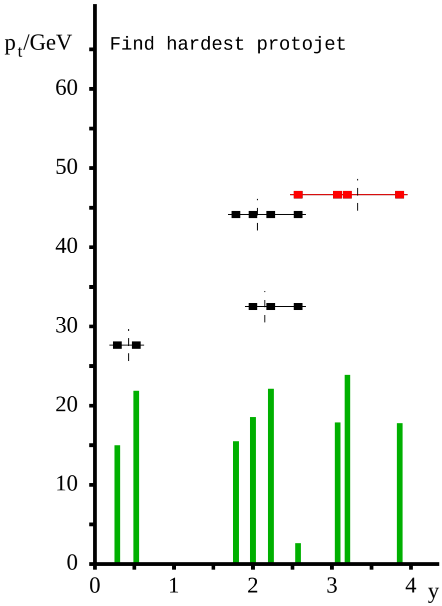

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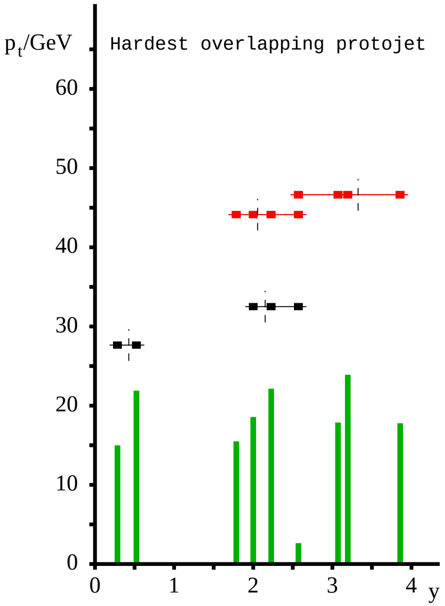

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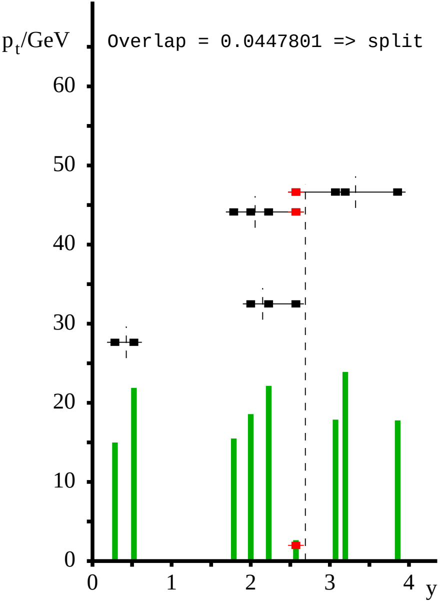

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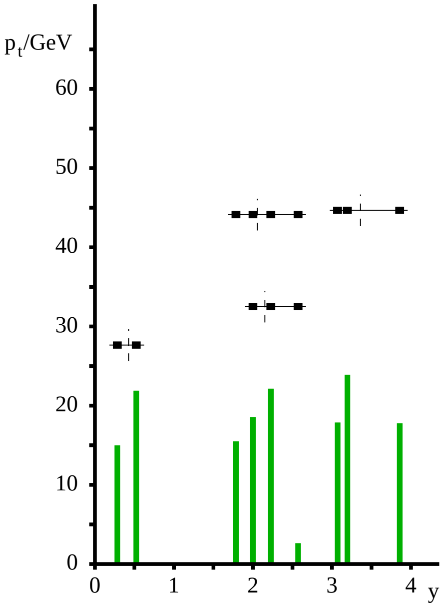

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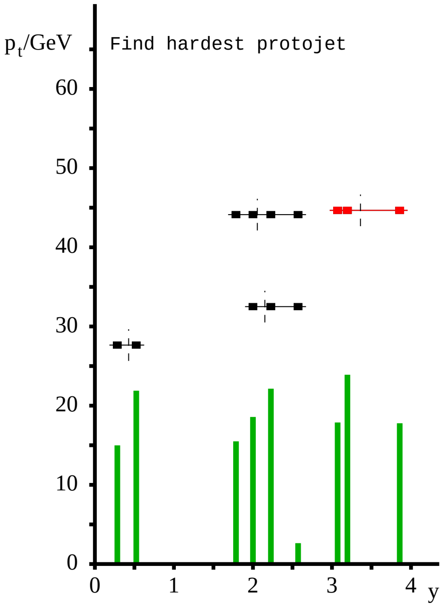

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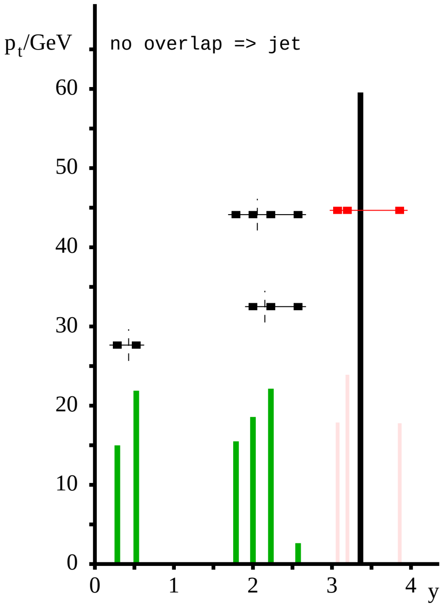

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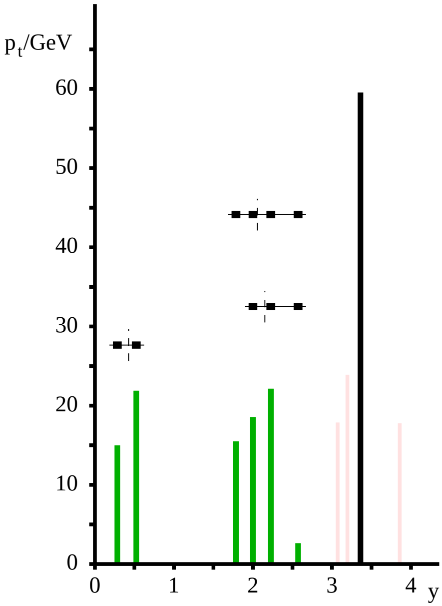

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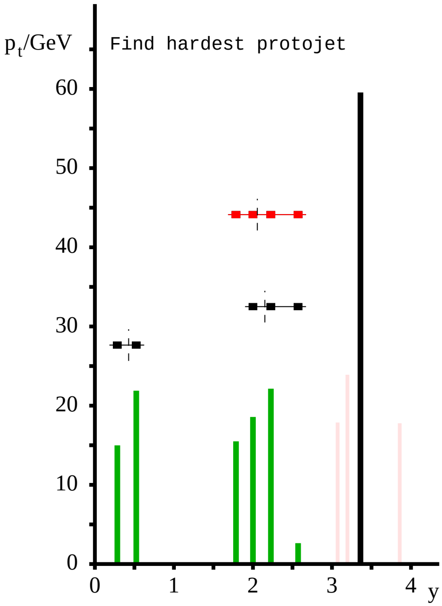

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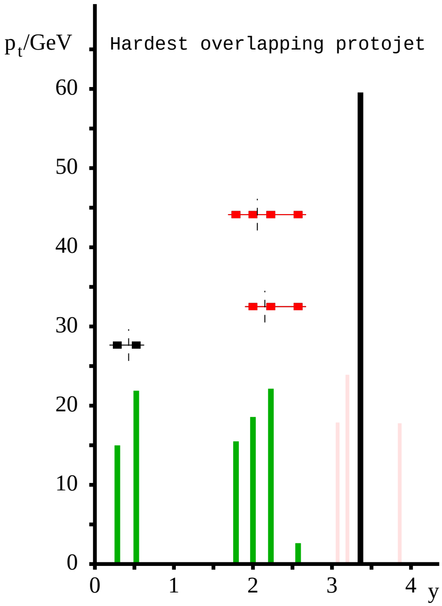

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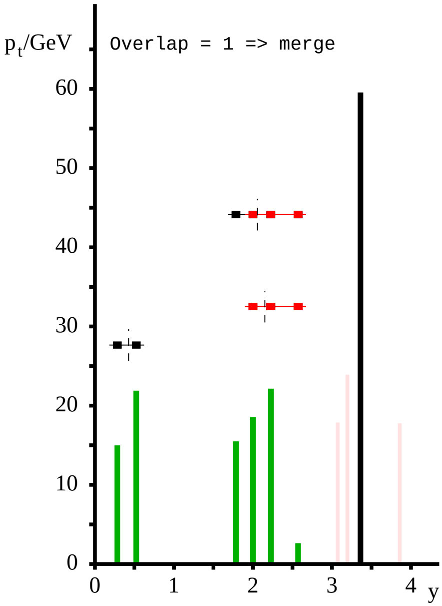

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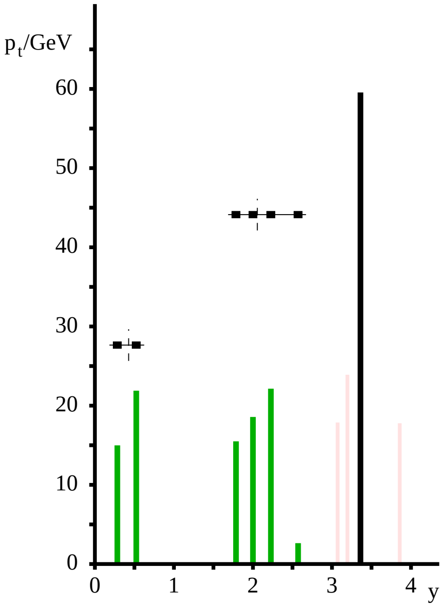

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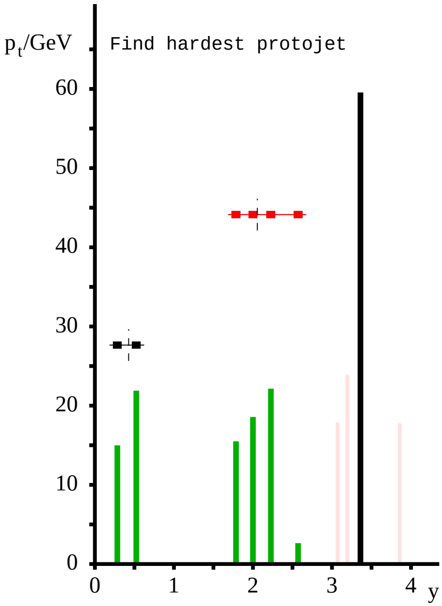

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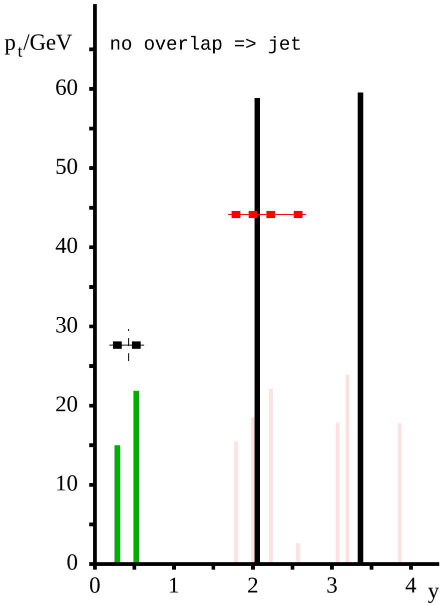

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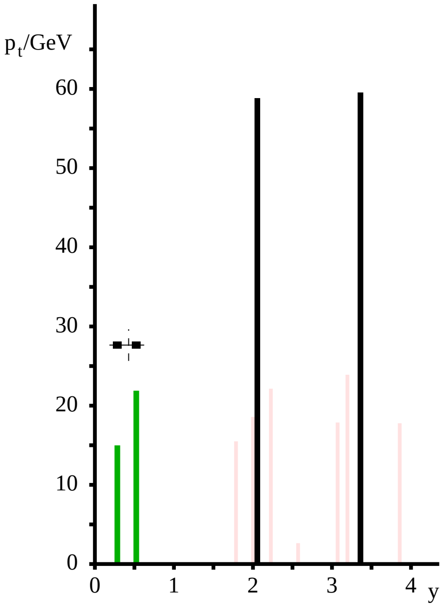

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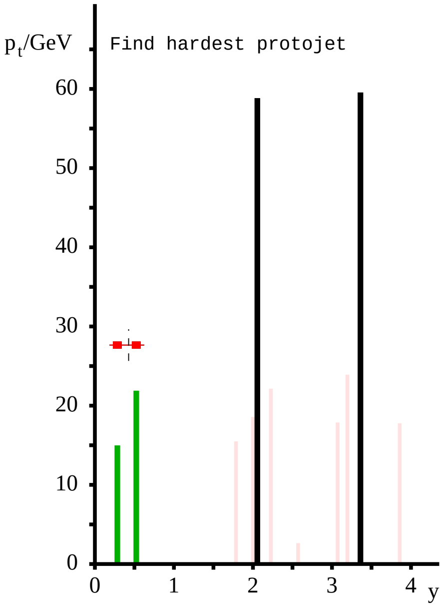

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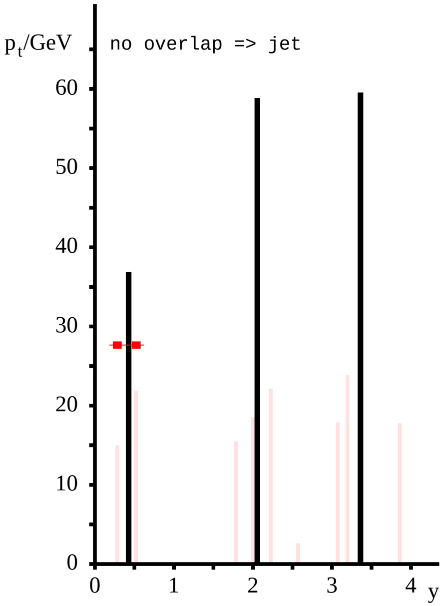

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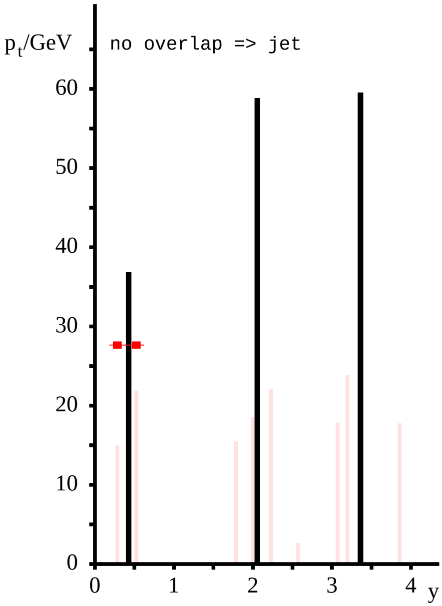

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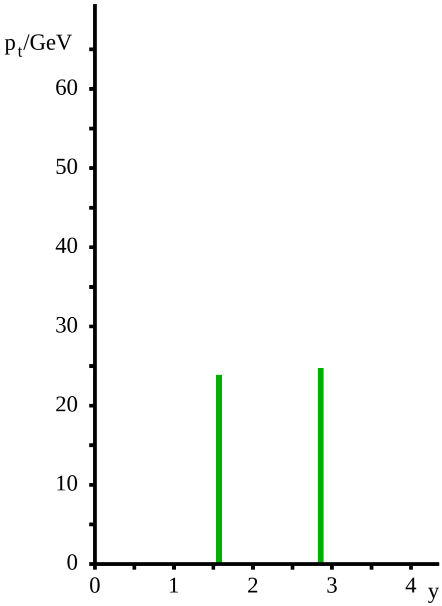

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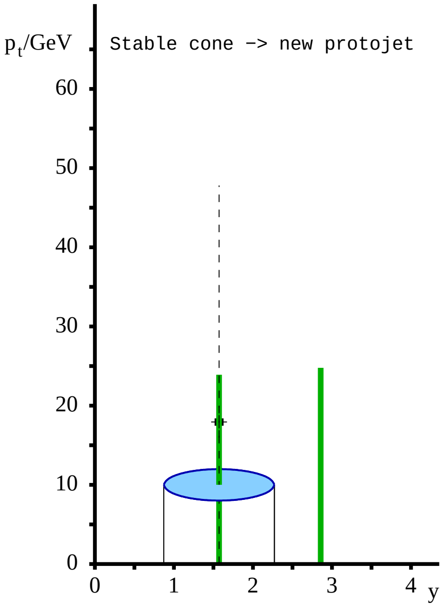

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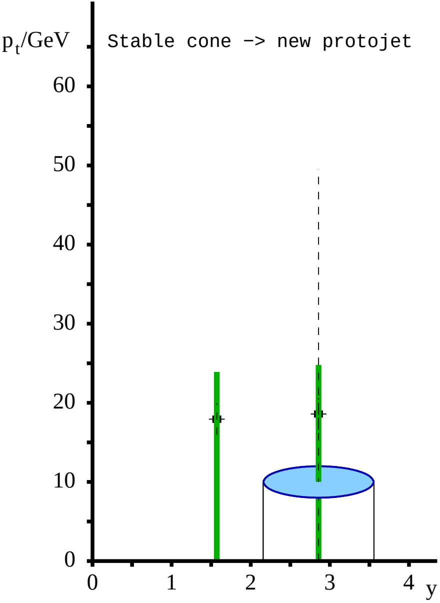

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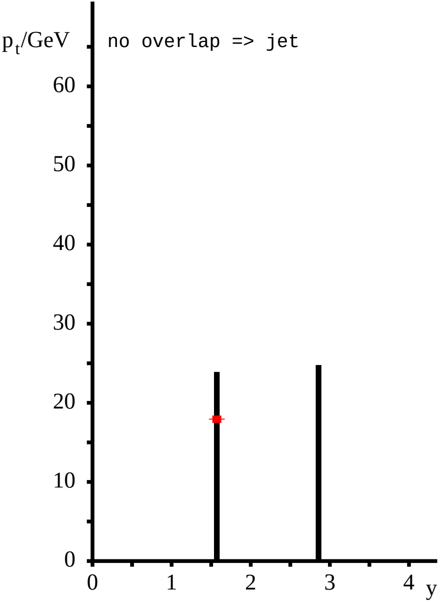

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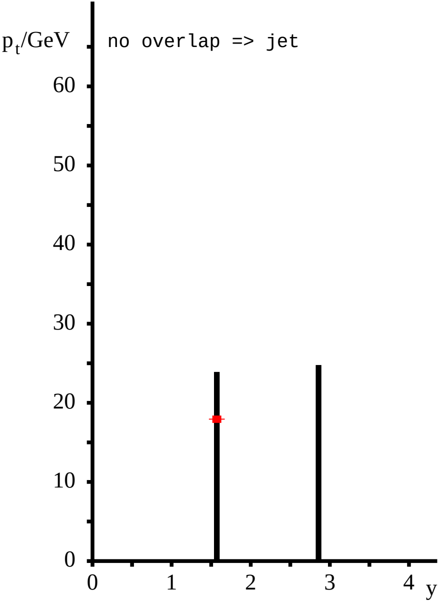

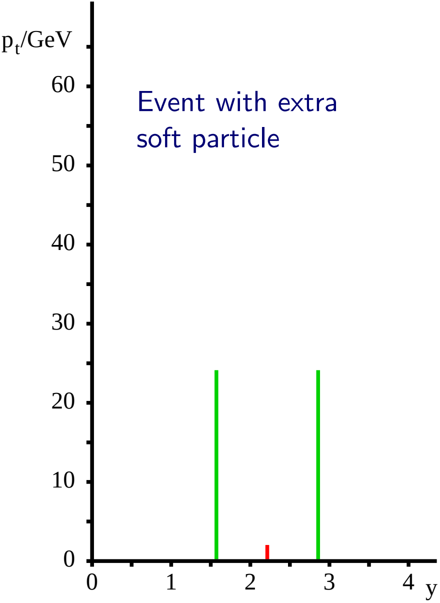

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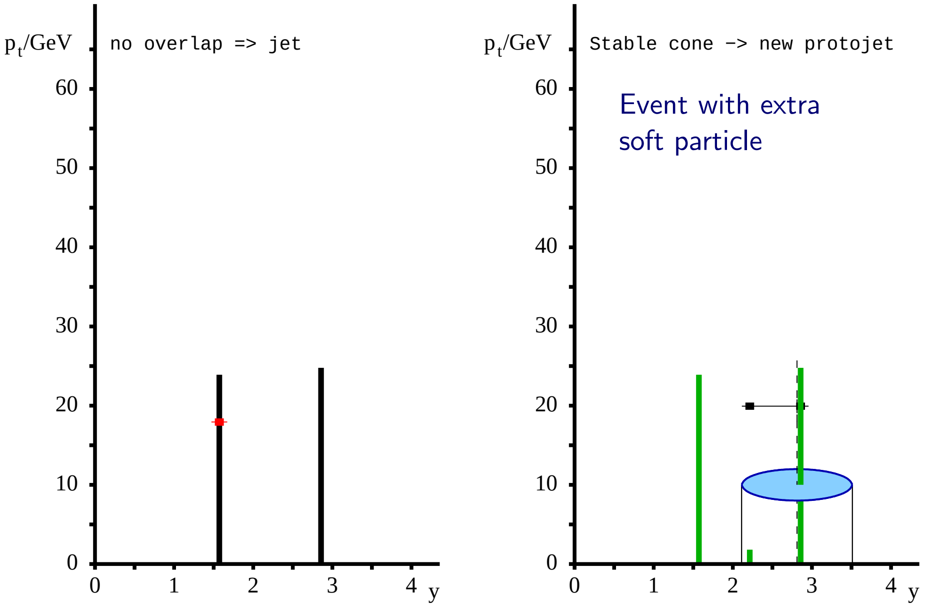

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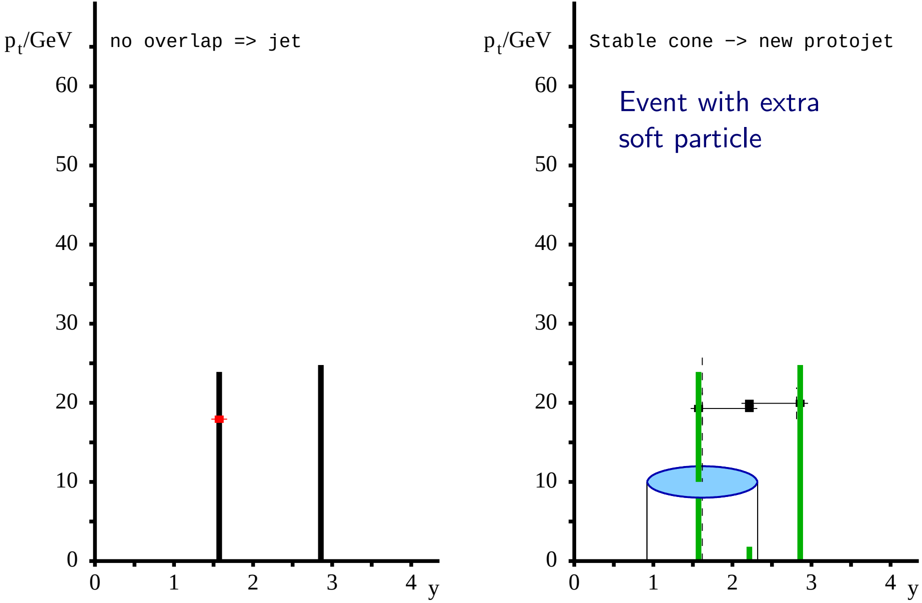

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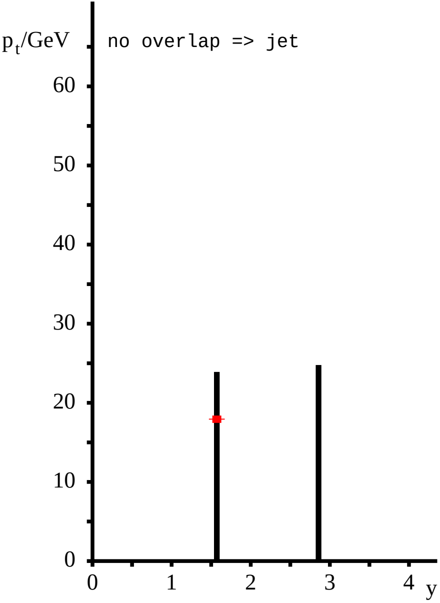

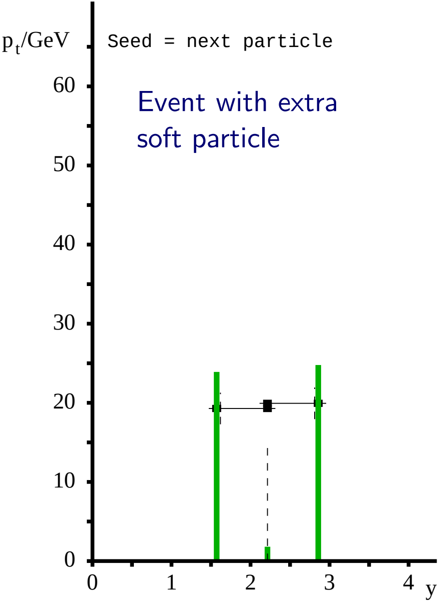

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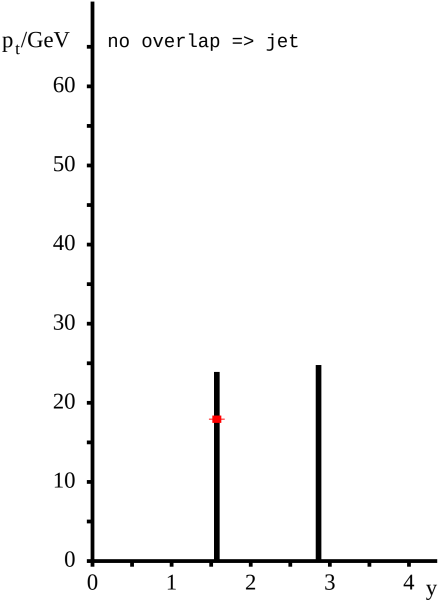

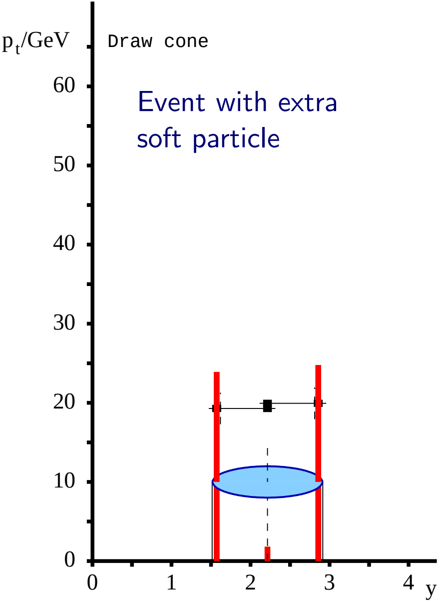

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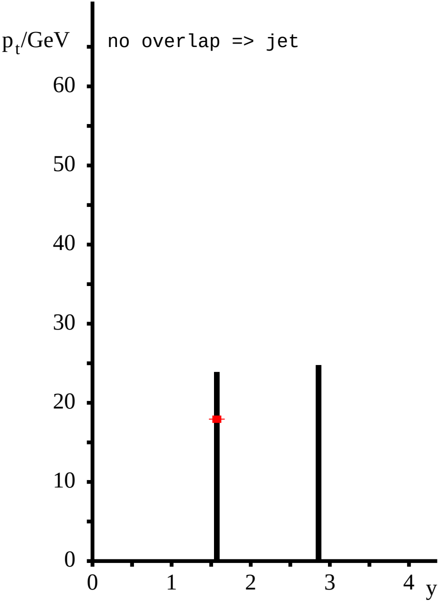

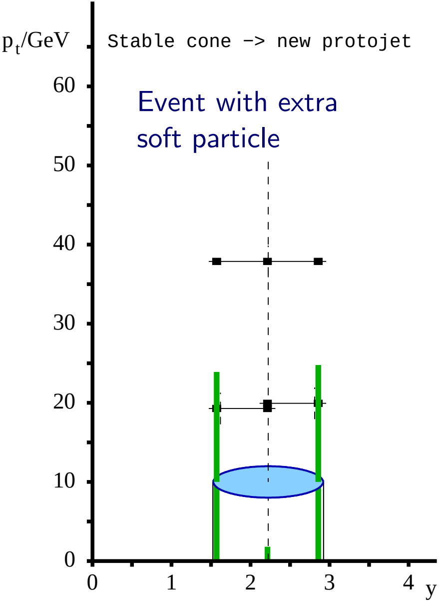

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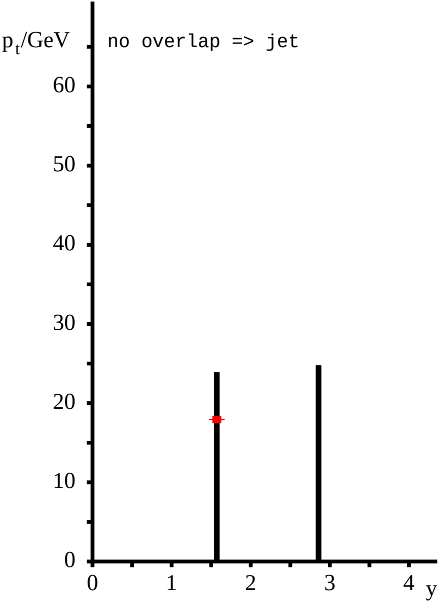

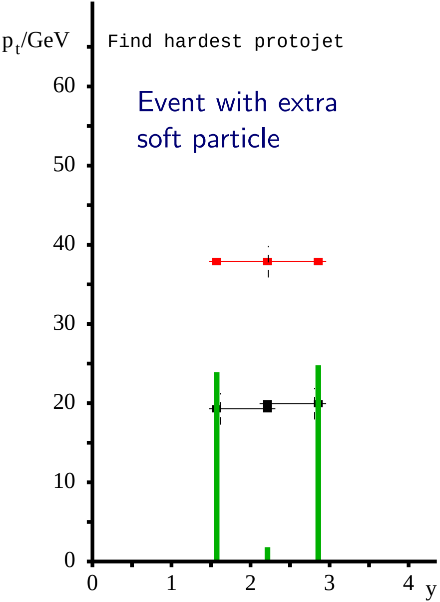

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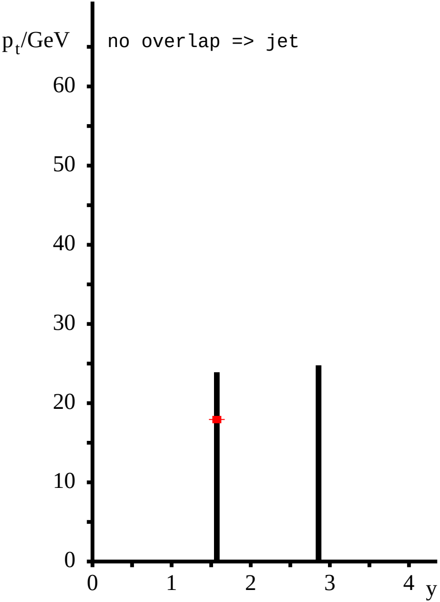

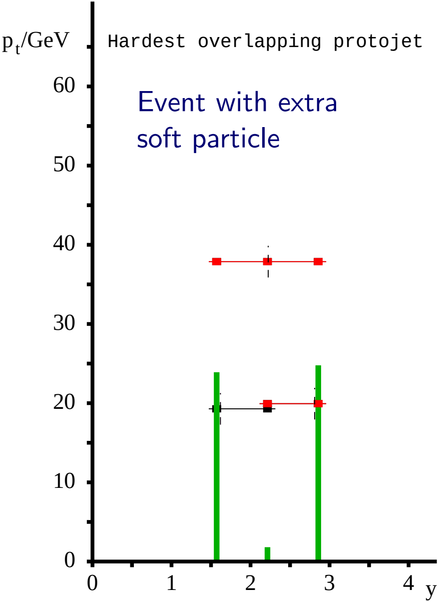

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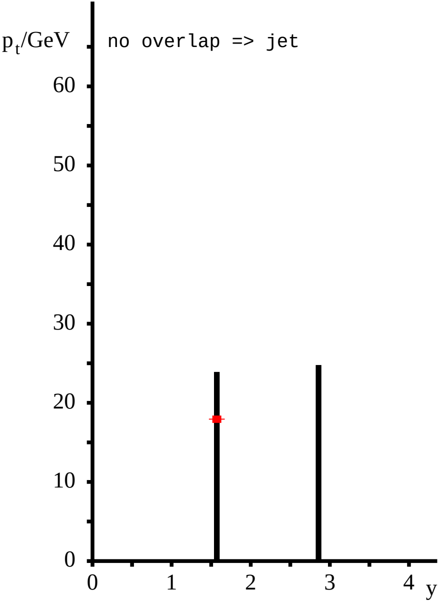

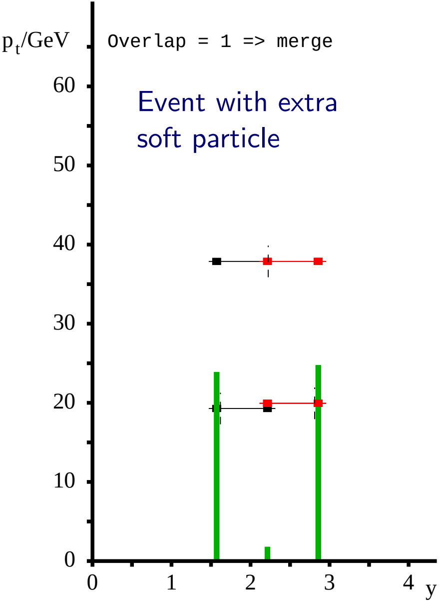

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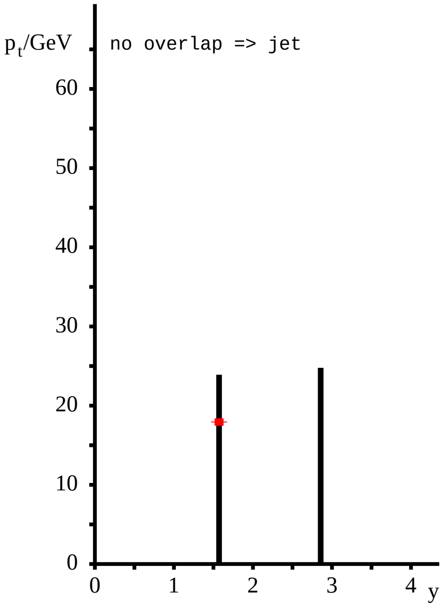

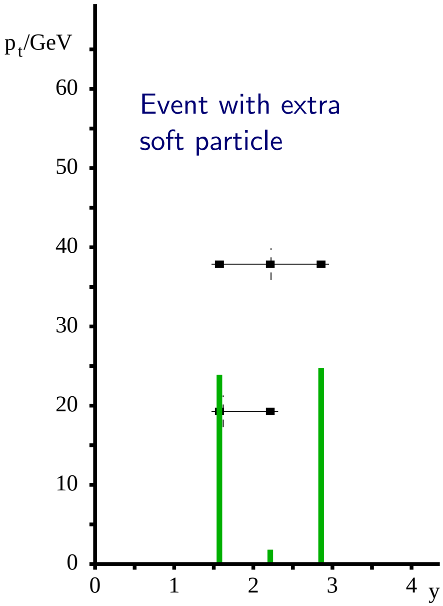

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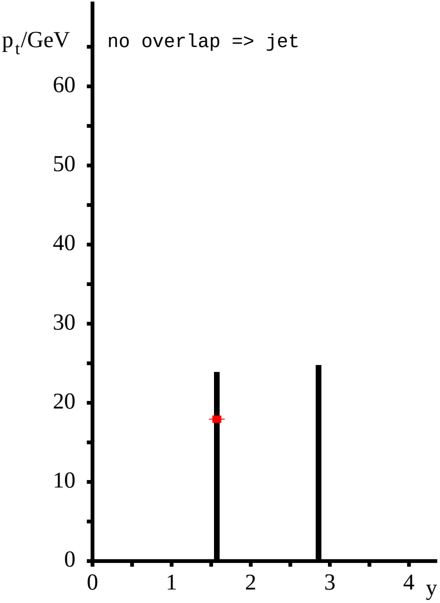

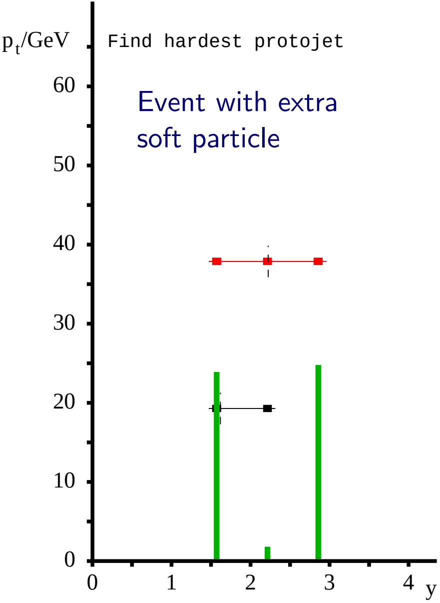

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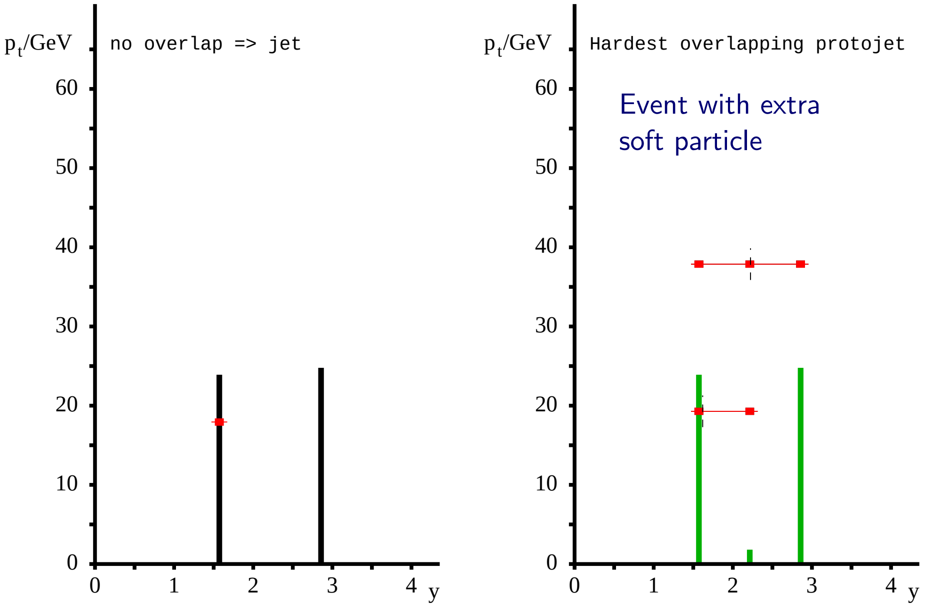

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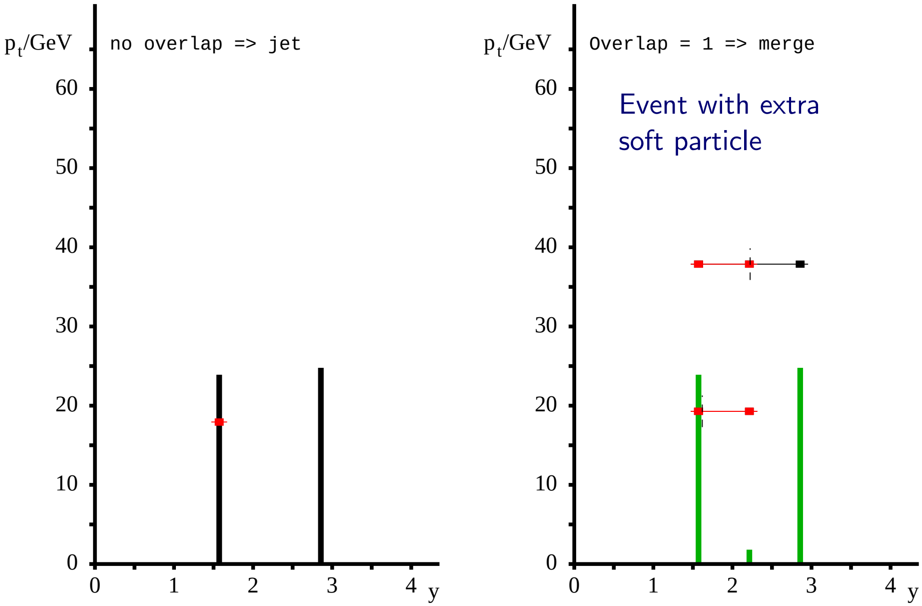

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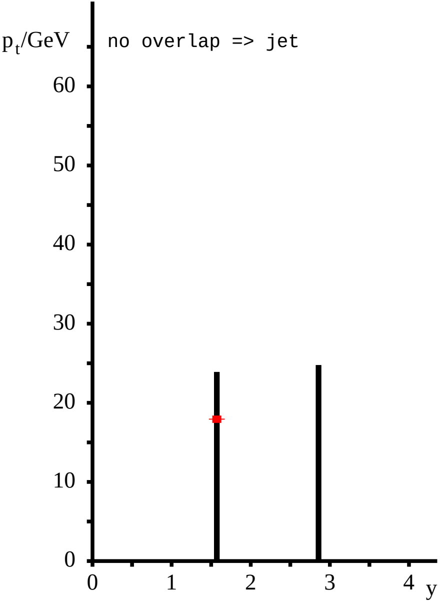

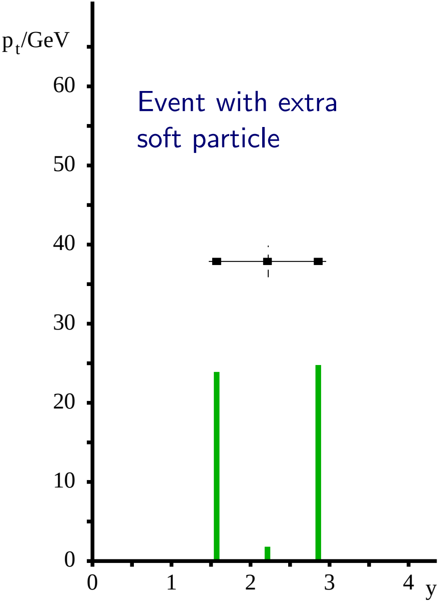

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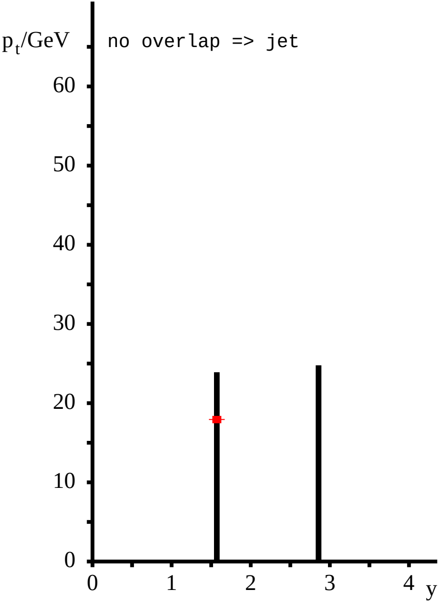

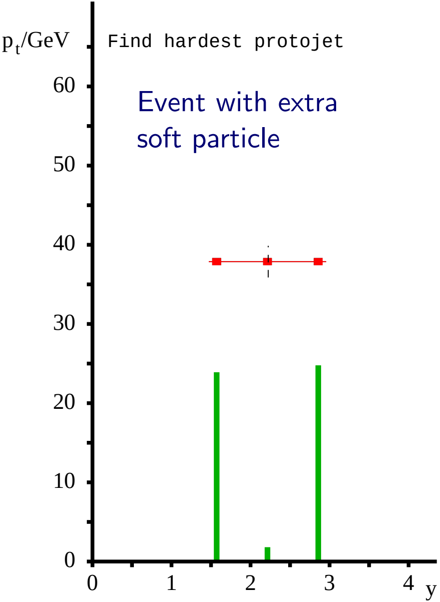

Event with extra soft particle

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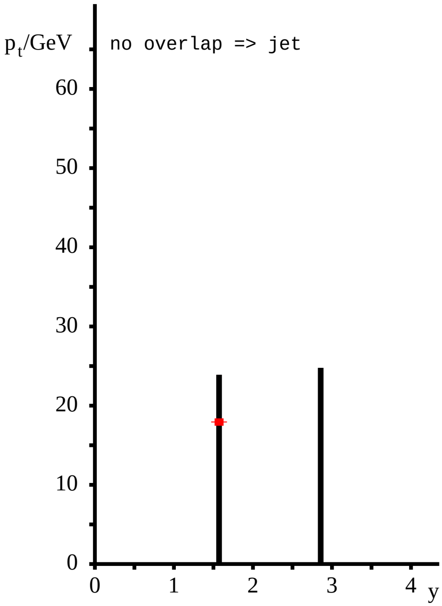
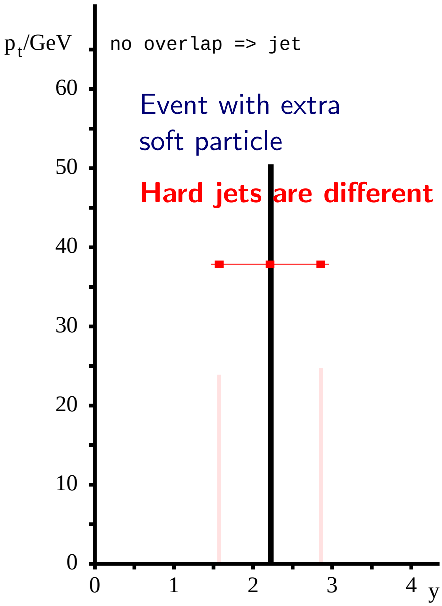




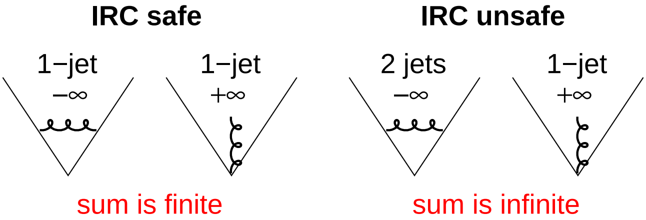
Event with extra soft particle

Hard jets are different

IRC safety crucial for theory

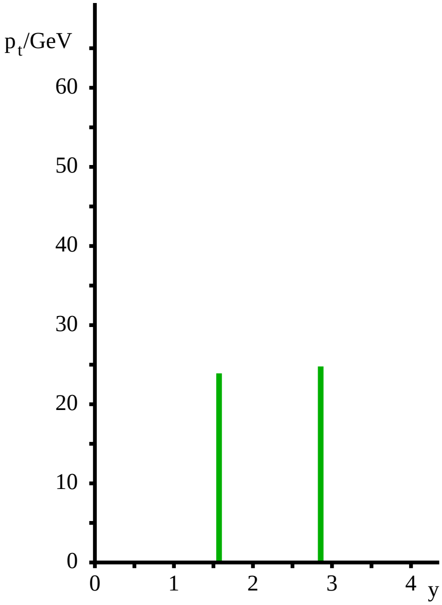
Soft emission, collinear splitting are both **infinite** in pert. QCD.

Infinities **cancel** with loop diagrams if jet-alg IRC safe



Some calculations simply become **meaningless**

Midpoint algorithm (IC_{mp}-SM)



Looking for stable cones $\simeq$ finding local minima of a potential.

Problem: set of iterative solution depends on set of starting points.

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This solves problem for 2-hard-particle configs.

[But it persists for 3-hard]

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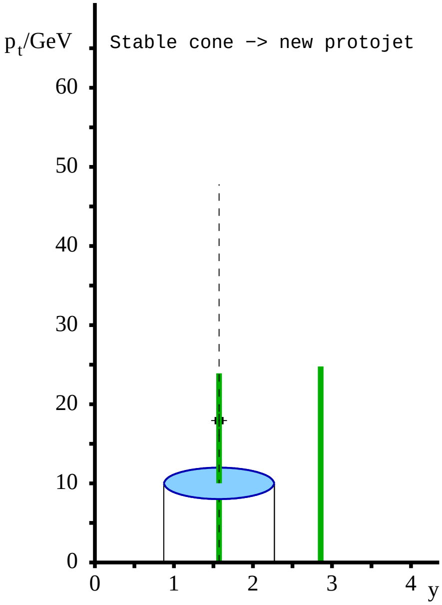

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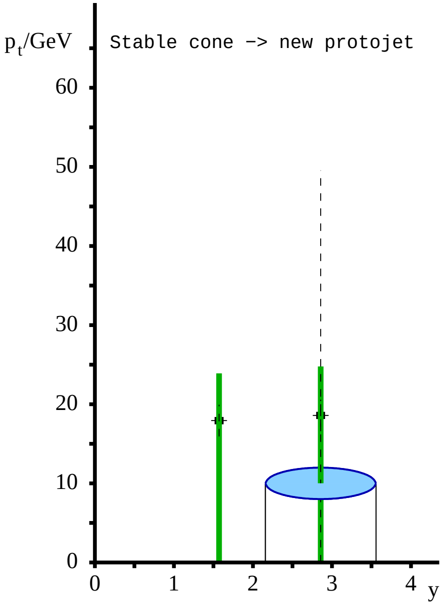

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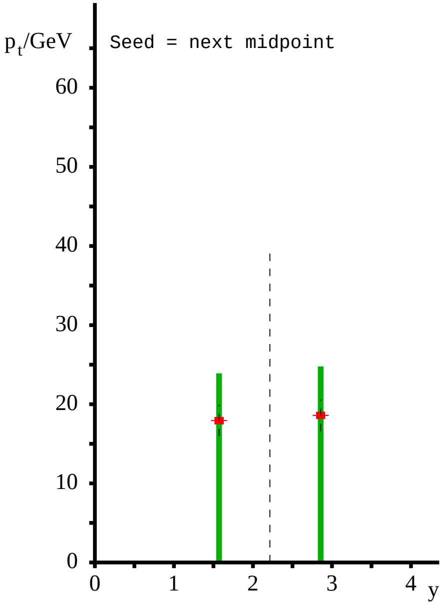

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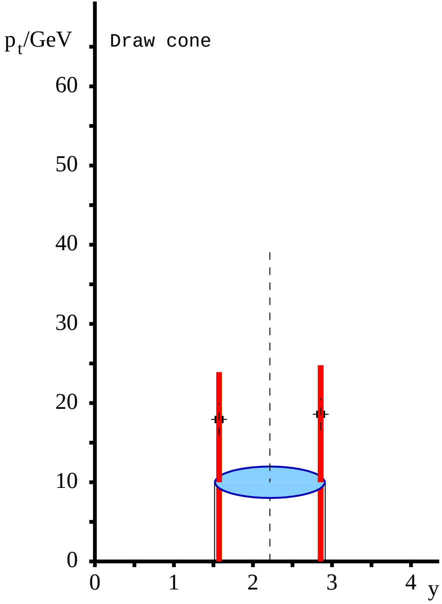

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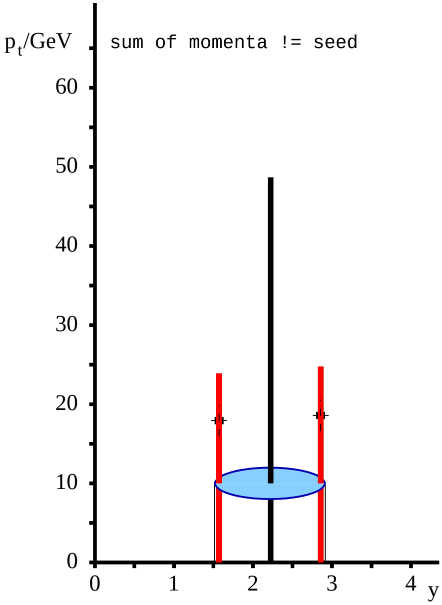

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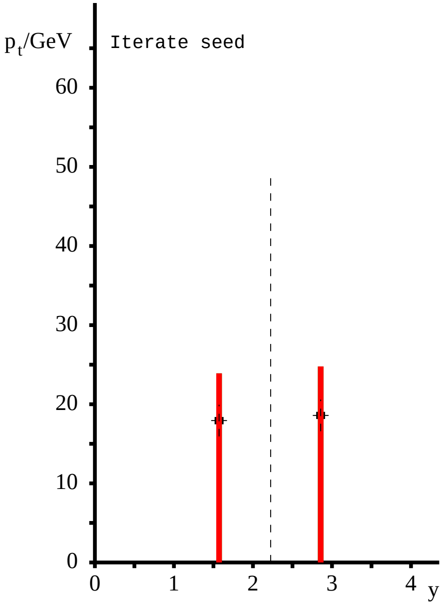

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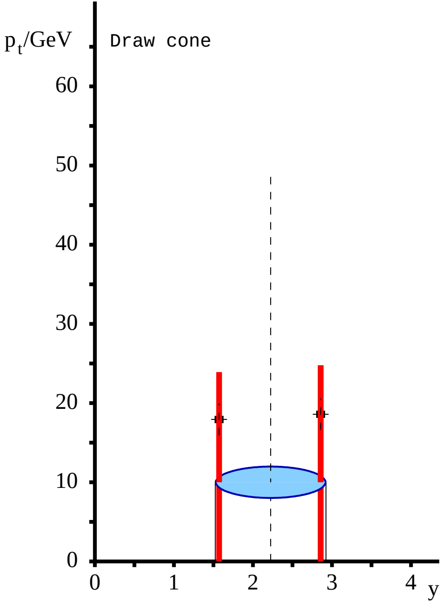

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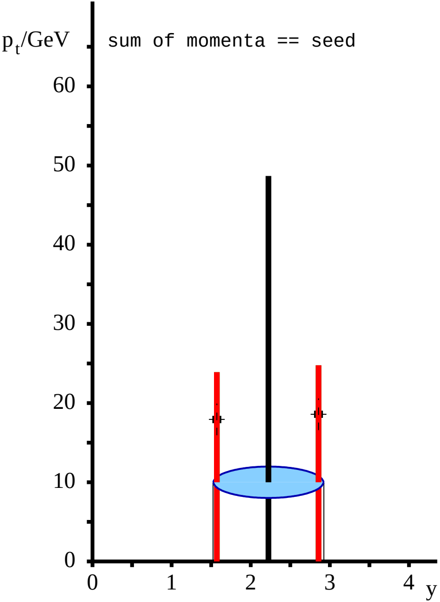

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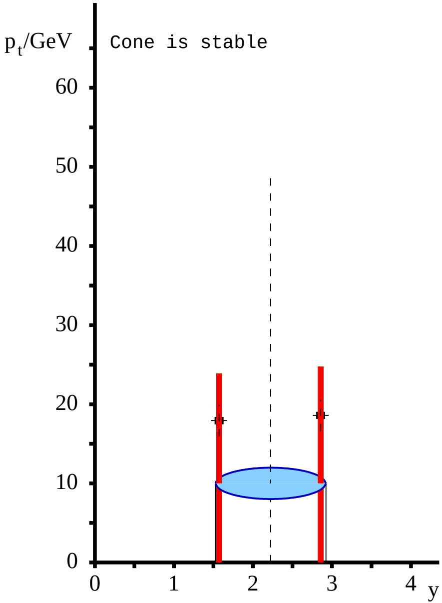

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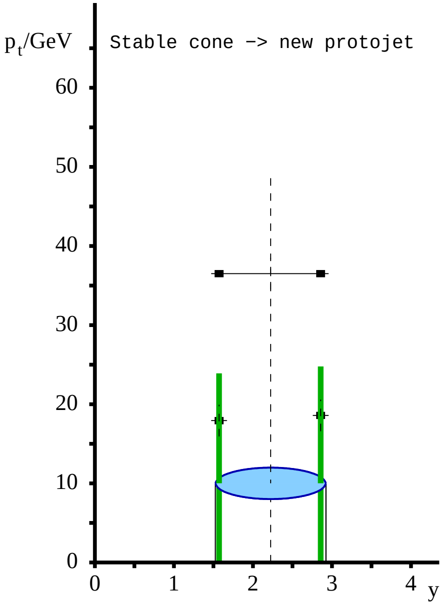

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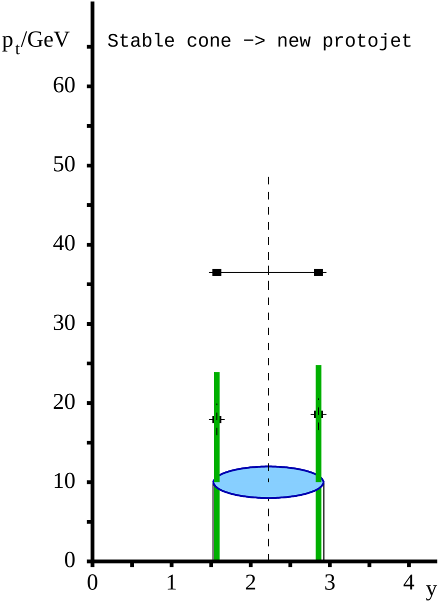

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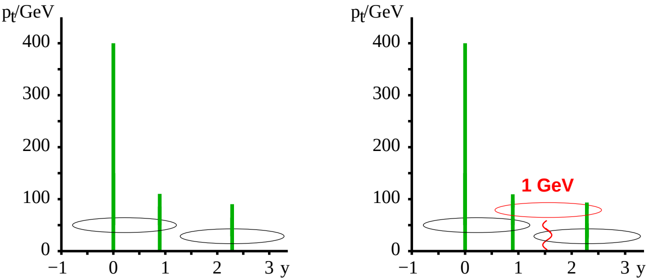

Stable cones with midpoint: {1,2} & {3} {1,2} & {2,3} & {3}

Jets with midpoint ($f = 0.5$) {1,2} & {3} {1,2,3}

Midpoint cone alg. misses some stable cones; extra soft particle → extra starting point → extra stable cone found

MIDPOINT IS INFRARED UNSAFE

Or collinear unsafe with seed threshold

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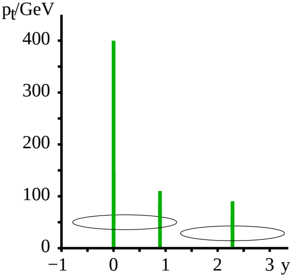

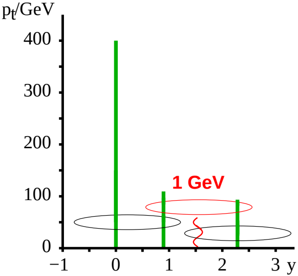

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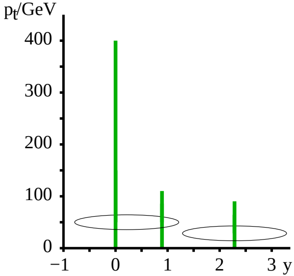

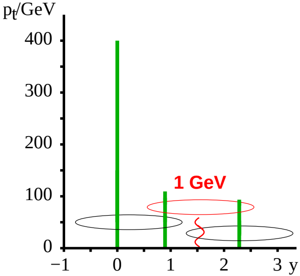

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Does IRC safety really matter?

IRC safety & real-life

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

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

Among consequences of IR unsafety:

	Last meaningful order			
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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**	LO

NB: \$30 – 50M 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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IRC safety not just for theory

1. Detectors play tricks with soft particles

calorimeter thresholds
magnetic fields acting on charged particles
calorimeter noise

2. Detectors split/merge collinear particles

Two particles into single calo-tower
One particles showers into two calo-towers

3. High lumi adds lots of extra soft seeds

IRC safety provides resilience to these effects
1 & 3 shift energy scale, but don't change overall jet-structure

If jet-algorithm is not IRC safe, fine-details of detector effects have potentially significant impact

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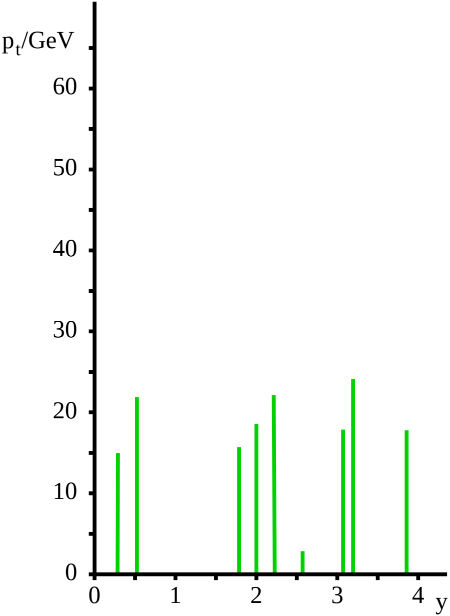
Can we cure this IR safety problem?

Seedless [Infrared Safe] cones (SC-SM)



Aim to identify *all* stable cones, independently of any seeds

Procedure in 1 dimension (y):

- find all distinct enclosures of radius R by repeatedly sliding a cone sideways until edge touches a particle
- check each for stability
- then run usual split–merge

In 2 dimensions (y,ϕ) can design analogous procedure **SISCone**
GPS & Soyez '07

This gives an IRC safe cone alg.

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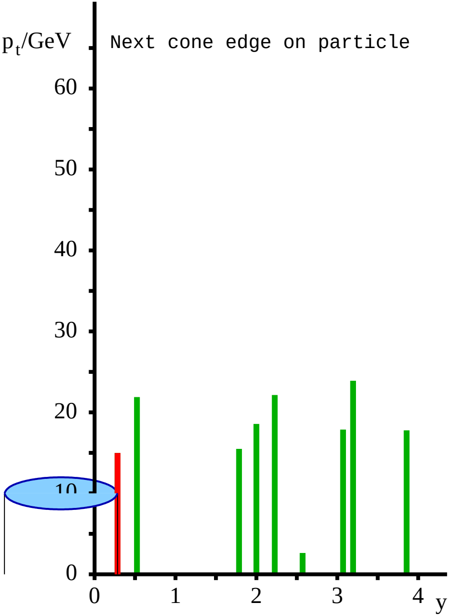

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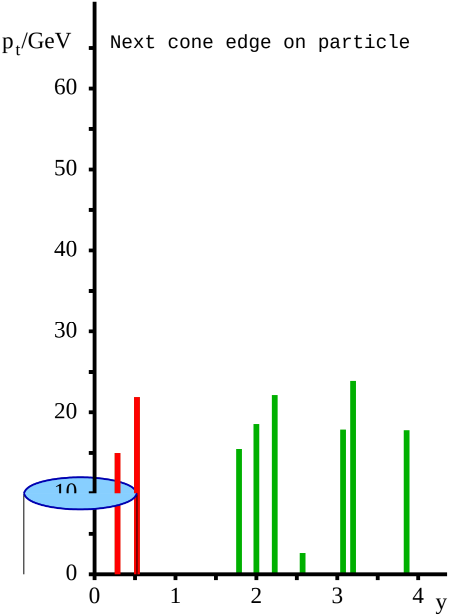

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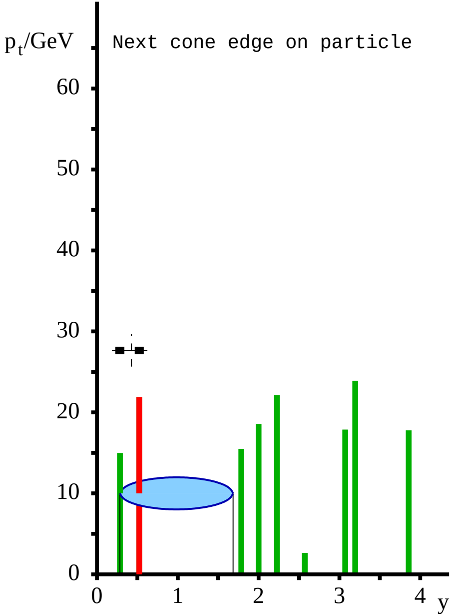

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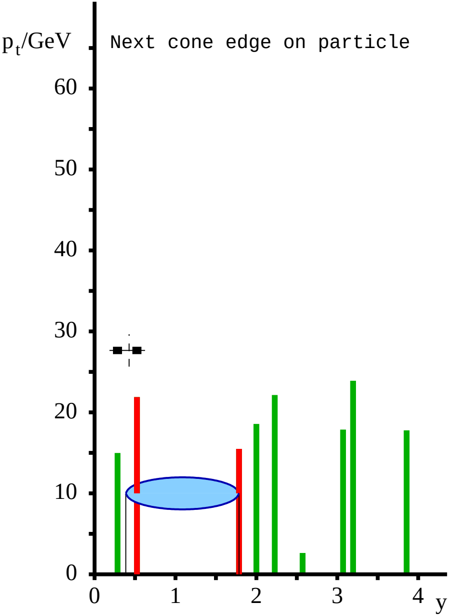

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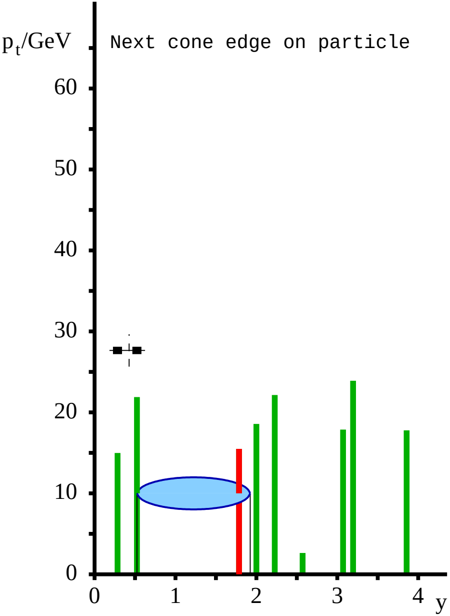

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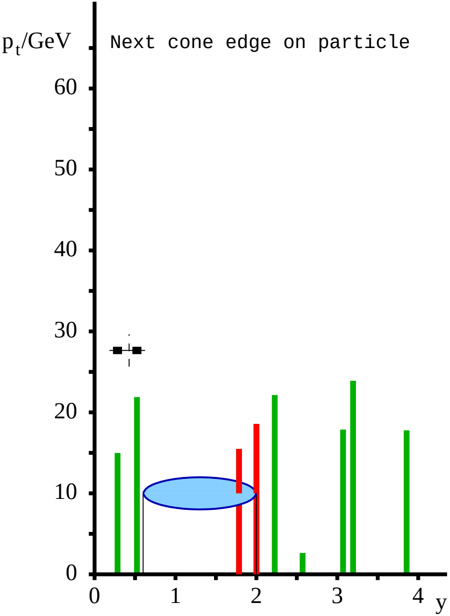

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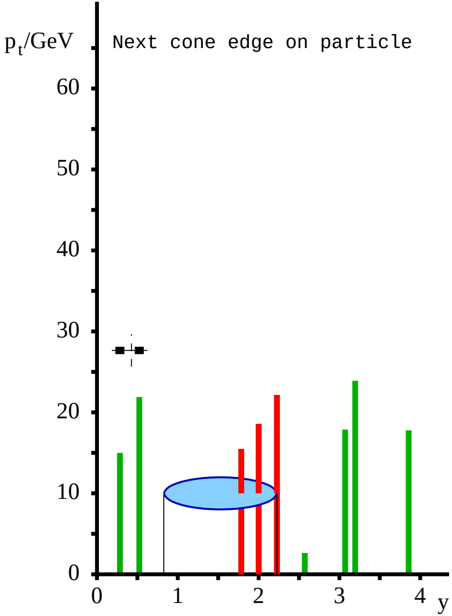

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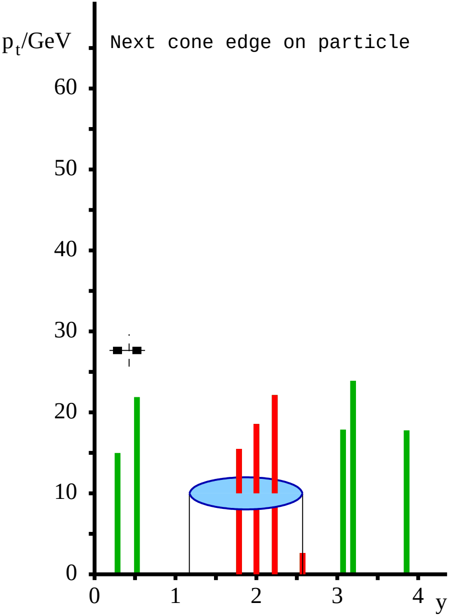

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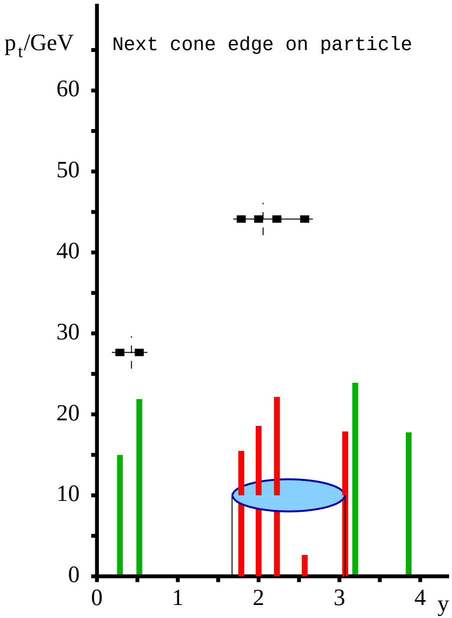

Aim to identify *all* stable cones, independently of any seeds

Procedure in 1 dimension (y):

- find all distinct enclosures of radius R by repeatedly sliding a cone sideways until edge touches a particle
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In 2 dimensions (y,ϕ) can design analogous procedure **SISCone**

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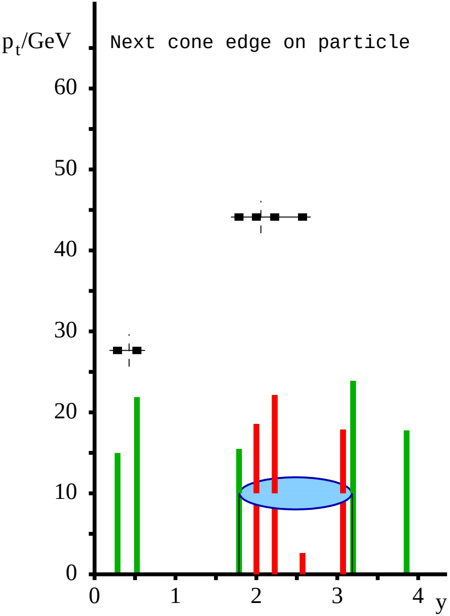

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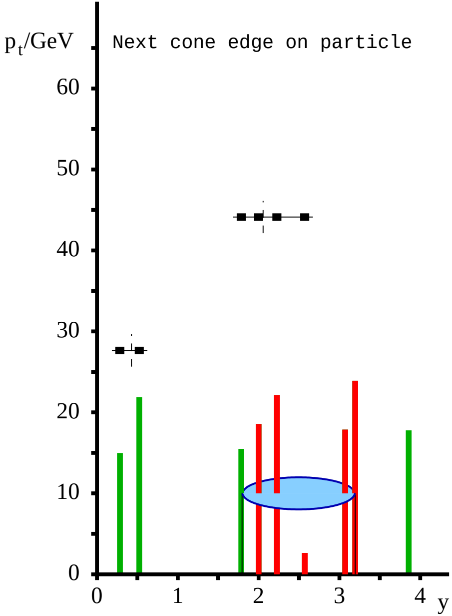

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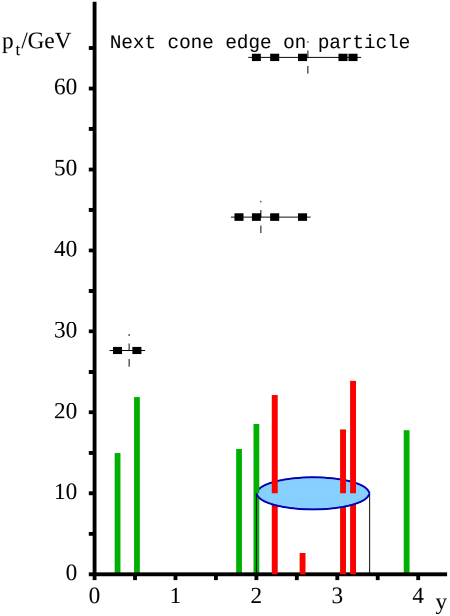

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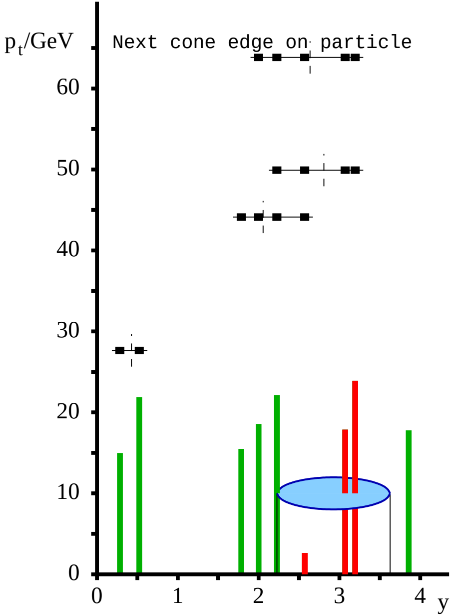

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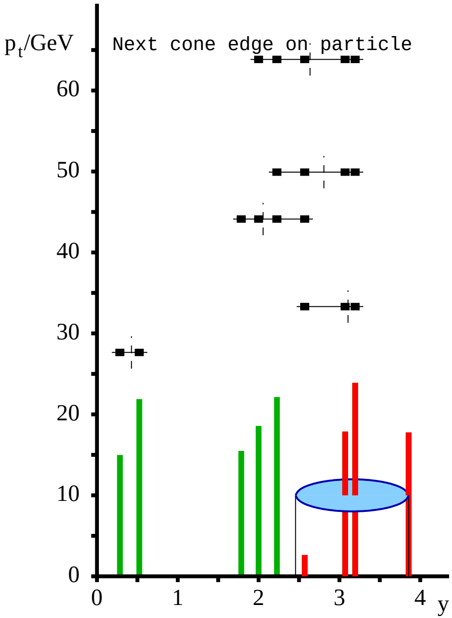

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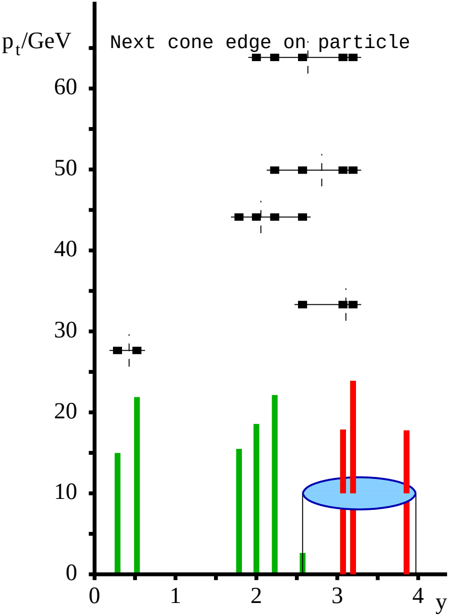

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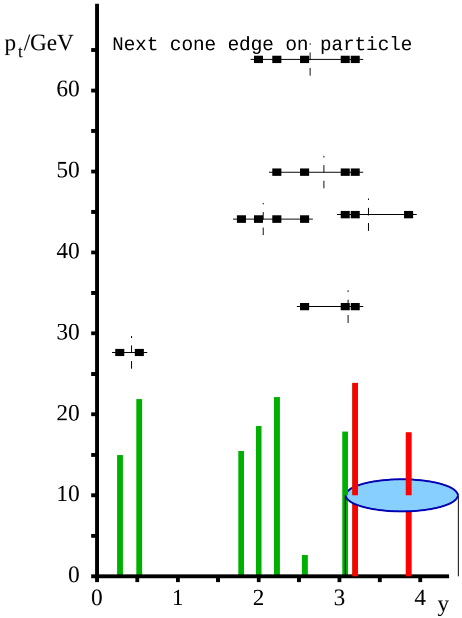

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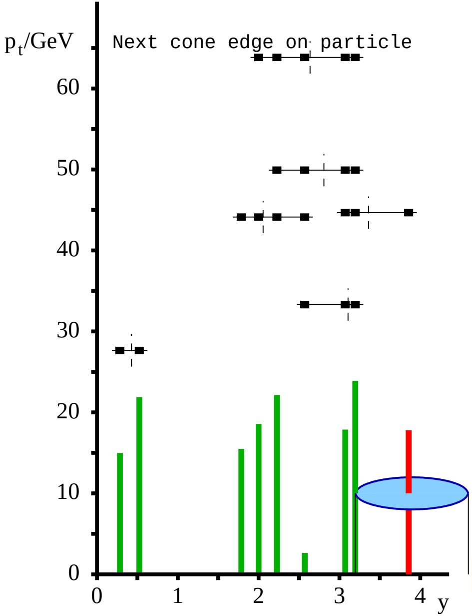

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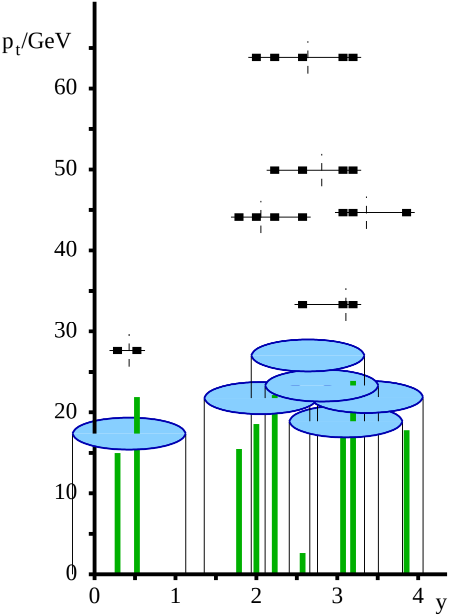

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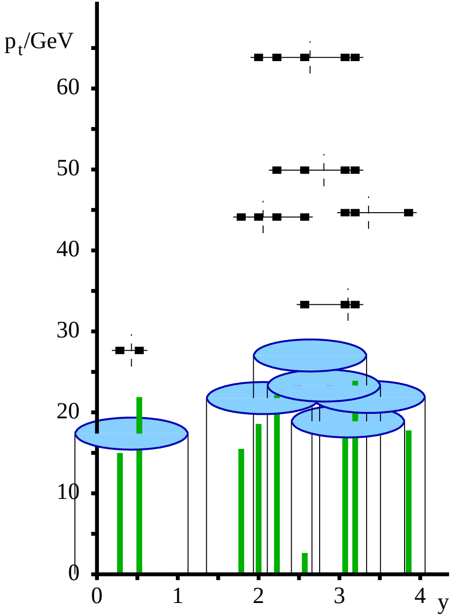

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Is it truly IR safe?

- Generate event with $2 < N < 10$ hard particles, find jets
- Add $1 < N_{soft} < 5$ soft particles, find jets again [repeatedly]
- If the jets are different, algorithm is IR unsafe.

Unsafety level	failure rate
2 hard + 1 soft	$\sim 50\%$
3 hard + 1 soft	$\sim 15\%$
SISCone	IR safe !

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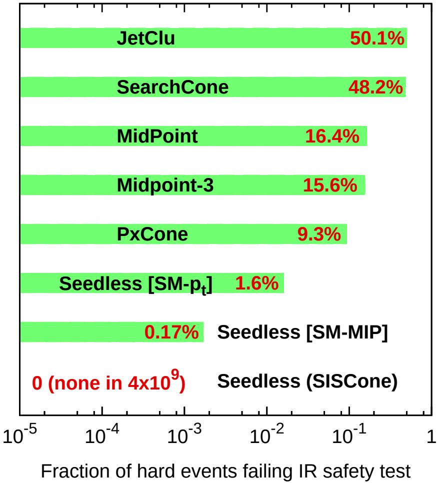


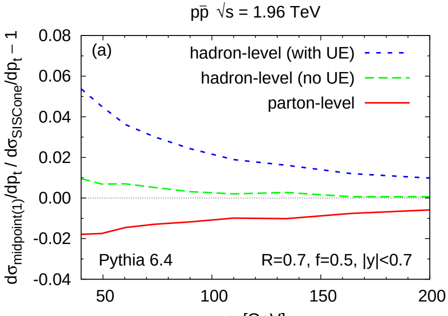
How much does IR safety *really* matter?

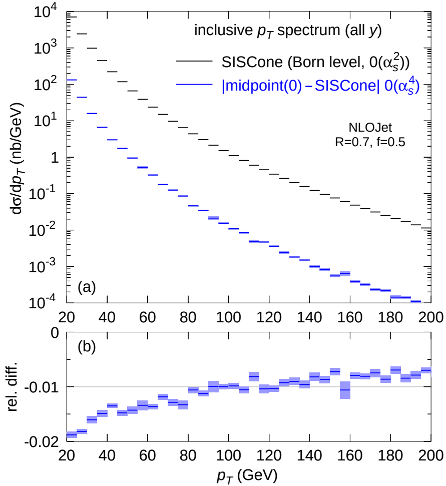
Compare midpoint and SISCone

Result depends on observable:

- inclusive jet spectrum is the least sensitive (affected at NNLO)
- larger differences (5 – 10%) at hadron level

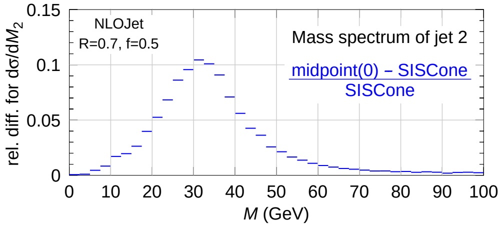
seedless reduces UE effect





IR safety & multi-jet observables

Look at jet masses in multijet events. NB: Jet masses reconstruct boosted $W/Z/H/top$ in BSM searches



Select 3-jet events

$$p_{t1,2,3} > \{120, 60, 20\} \text{ GeV},$$

Calculate LO jet-mass spectrum for jet 2, compare midpoint with SISCone.

- 10% differences by default
- **40% differences** with extra cut $\Delta R_{2,3} < 1.4$

  e.g. for jets from common decay chain

In complex events, IR safety matters

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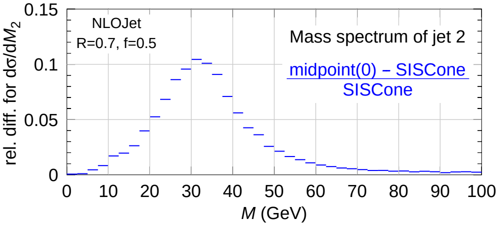

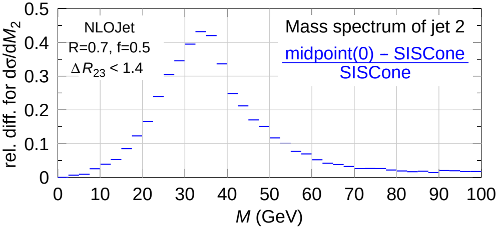

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Bottom line on IR safety

- IR safety often matters less in *inclusive* quantities
- It matters more in multi-jet cases

- ATLAS cone, JetClu (IC-SM) are *very bad*
- CMS cone (IC-PR), Midpoint (IC_{mp}-SM) *moderately bad*

- An IRC safe cone algorithm exists (SISCone)
- **Avoid trouble later: use IR-safe algs from the start**

cf. CDF W+jets

What jet definition should I use?

[jet def. $\equiv$ jet alg., R, (f)]

A full set of IRC-safe jet algorithms

Generalise inclusive-type sequential recombination with

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

	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.

Compromise between having a limited set of algs.
and a good range of complementary properties

COMMERCIAL BREAK

Use FastJet — it's free!

One place to stop for all your jet-finding needs:

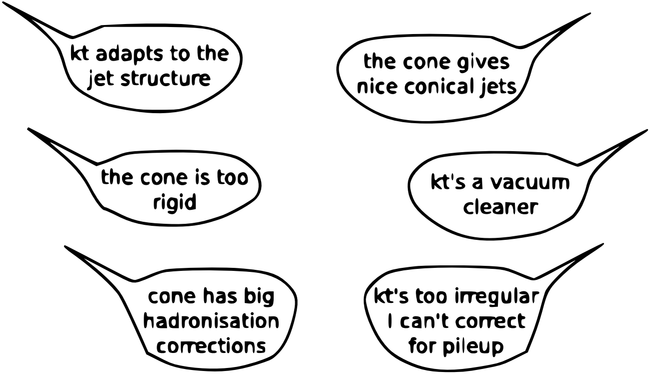
FASTJET

http://www.lpthe.jussieu.fr/~salam/fastjet
Cacciari, GPS & Soyez '05–07

- Fast, native, computational-geometry methods for k_t, Cam/Aachen
  Cacciari & GPS '05-06
- Plugins for SISCone (plus some other, deprecated cones)
- Many other features too, e.g. jet areas

Jet Folklore

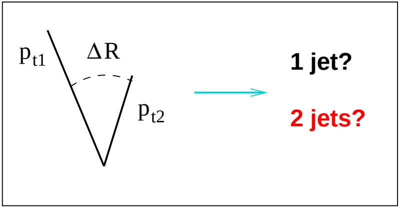
Jet discussions: often polarised, driven by unquantified statements



- Rigorous approach is to quantify similarities & differences
- Bottom line: grains of truth in the qualitative statements

  So want good cone algorithms too [NB: recall, two variants xC-SM & xC-PR]

the *reach* of jet algorithms



SISCone (xC-SM) reaches further for hard radiation than other algs

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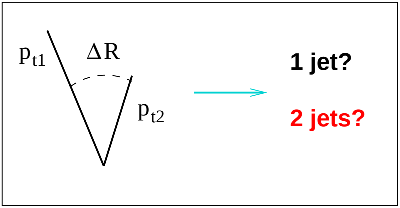

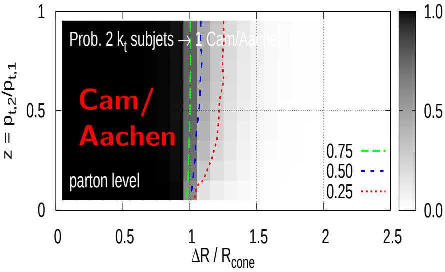

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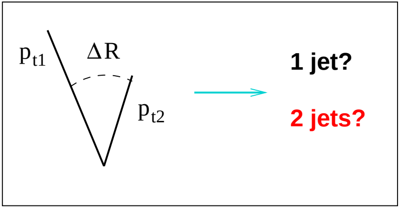

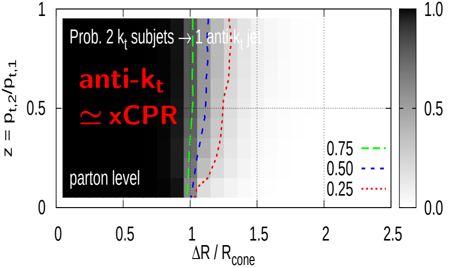

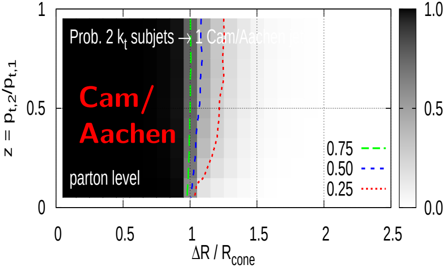

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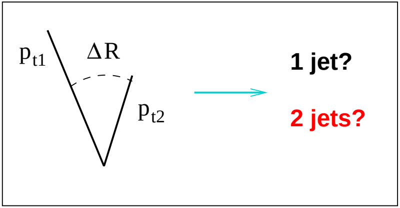

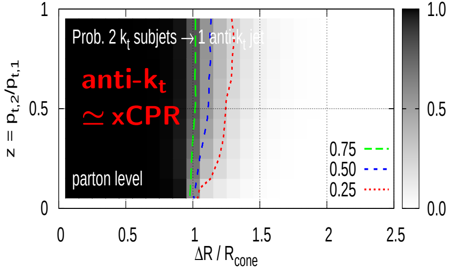

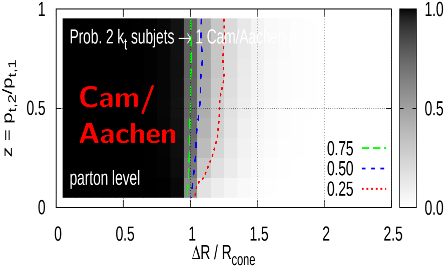

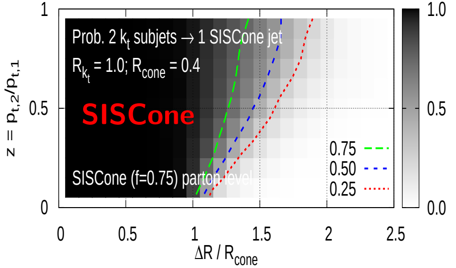

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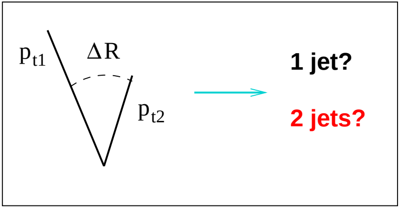

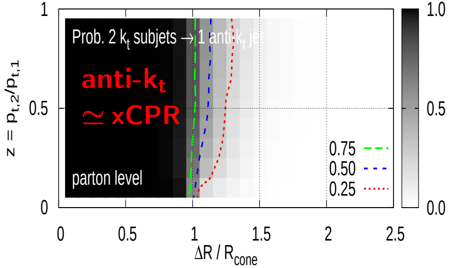

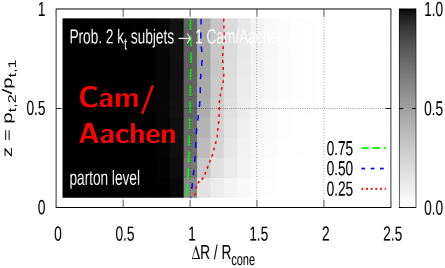

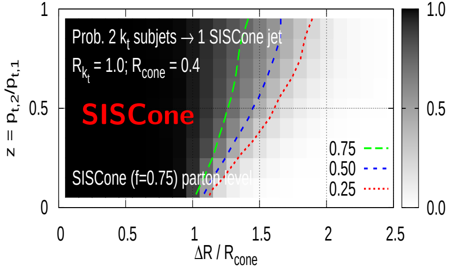

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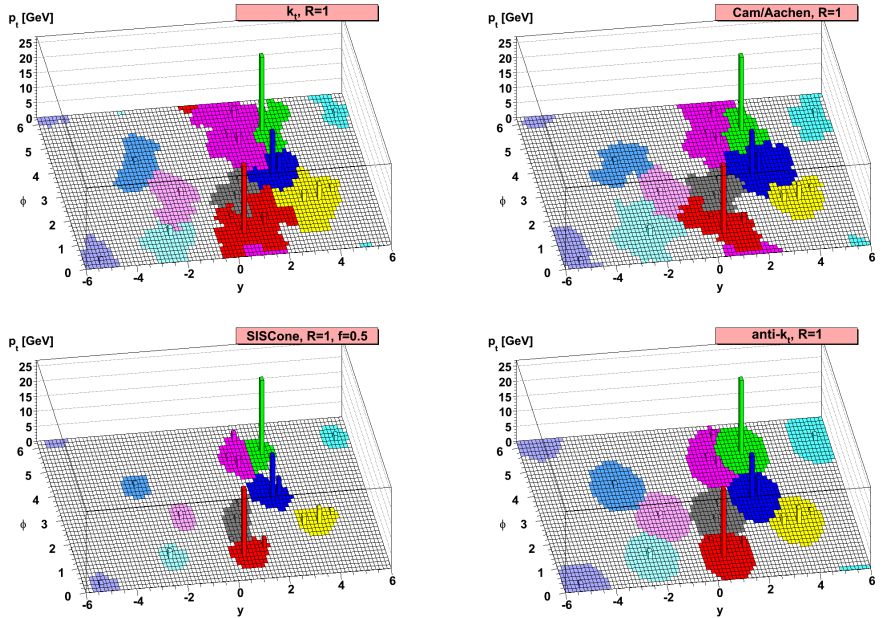
Jet contours – visualised



To first approx:
various algs. moderately different;
but **R** can matter a lot more

4-way tension in many measurements:

Prefer small R	prefer large R
resolve many jets (e.g. $t\bar{t}$)	minimize QCD radiation loss
limit UE & pileup	limit hadronisation

Jets v. R

Parton $p_t \to$ jet p_t

Ill-defined: MC "parton"

PT radiation:

$$q: \quad \Delta p_t \simeq \frac{\alpha_s C_F}{\pi} p_t \ln R$$

$$g: \quad \Delta p_t \simeq \frac{\alpha_s C_A}{\pi} p_t \ln R$$

Hadronisation:

$$q: \quad \Delta p_t \simeq \frac{C_F}{R} \cdot 0.4 \text{ GeV}$$

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Underlying event:

$$q, g: \quad \Delta p_t \simeq \frac{R^2}{2} \cdot 2.5\text{–}15 \text{ GeV}$$

crude analytical estimates
cf. Dasgupta, Magnea & GPS '07

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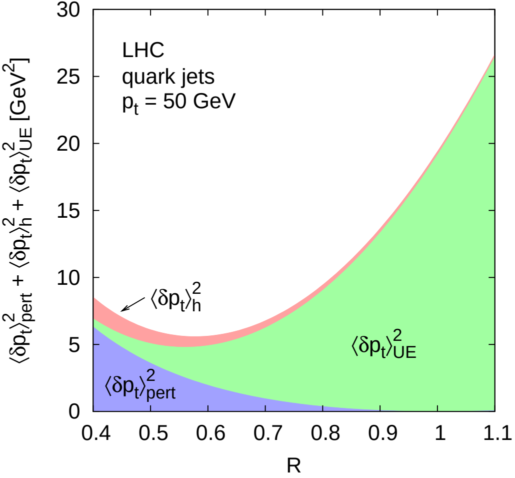

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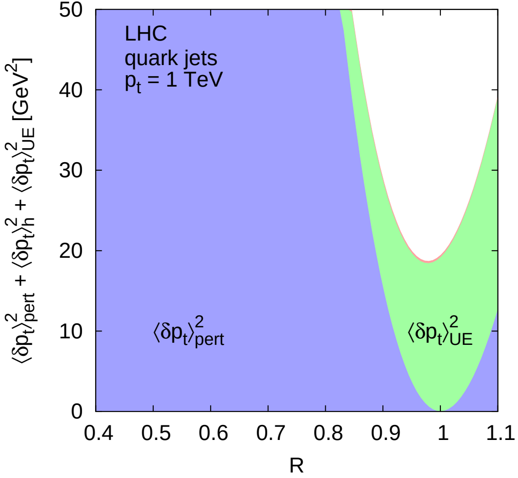

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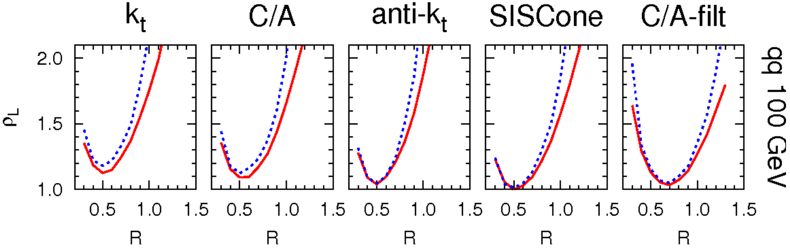
Relative peak quality (lumi ratios ρ_L), LHC



PRELIMINARY

Cacciari, Rojo, GPS & Soyez '08

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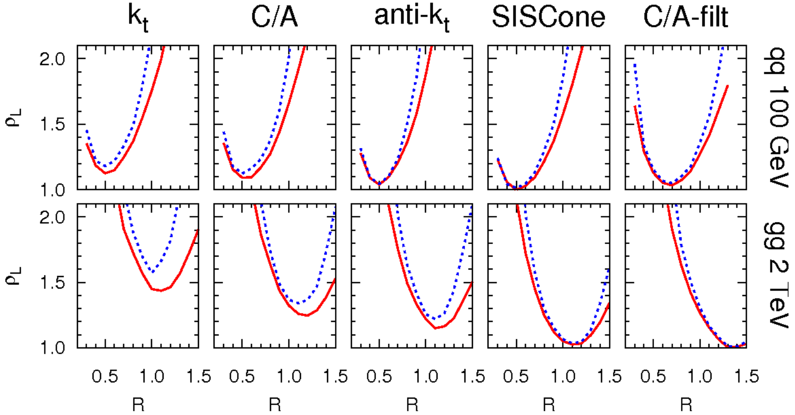

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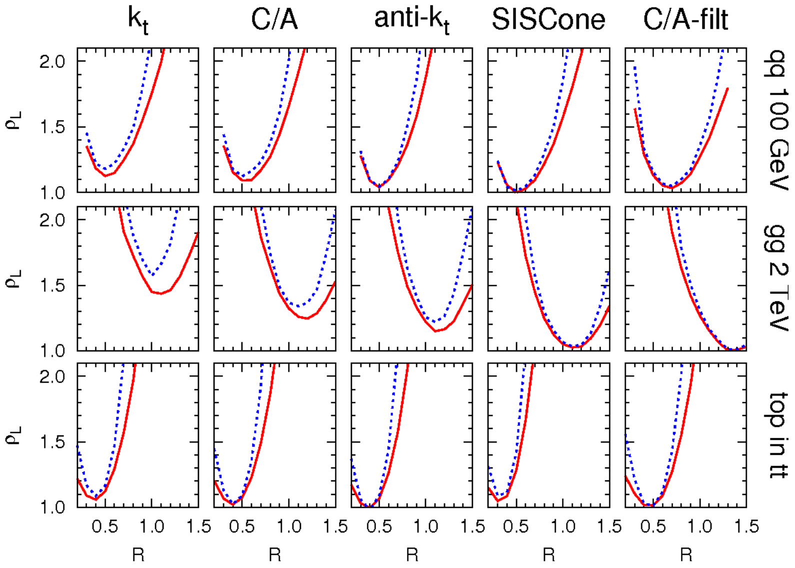

PRELIMINARY

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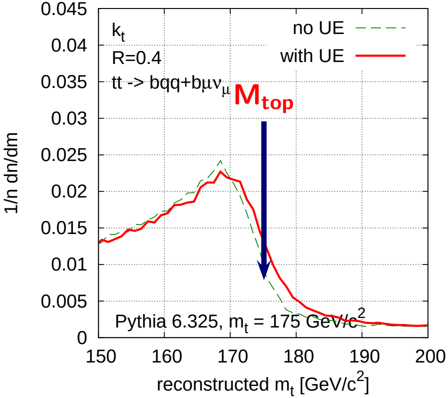
Robustness: M_{top} varies with R?



<u>Game: measure top mass to 1 GeV</u>

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?

Powerful cross-check of systematic effects

cf. Seymour & Tevlin '06

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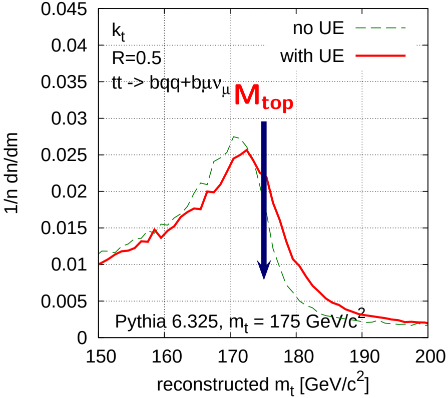

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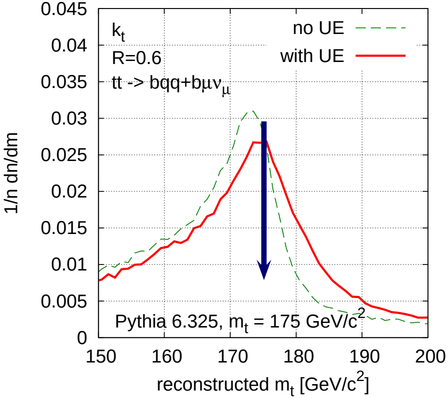

Game: measure top mass to 1 GeV

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?

Powerful cross-check of systematic effects

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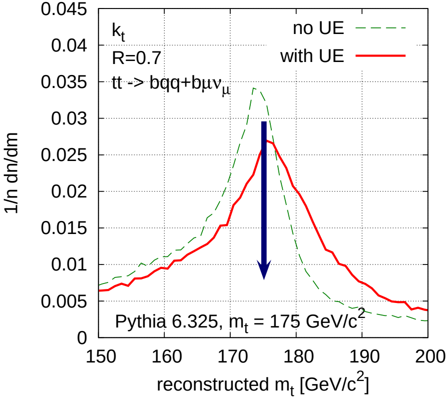

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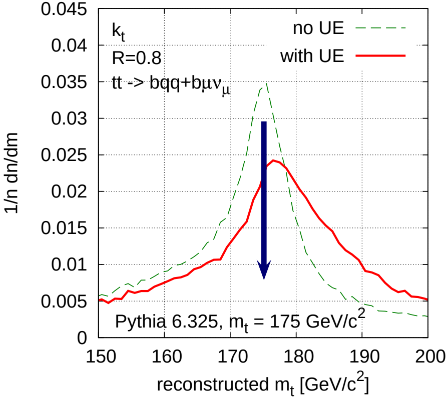

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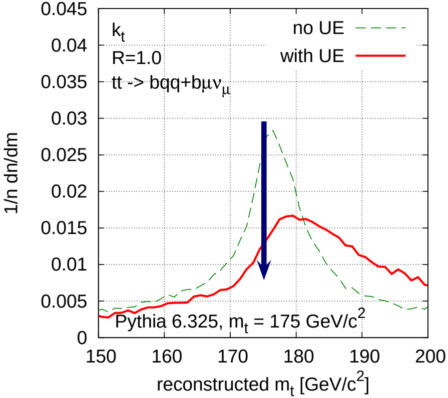

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Jets without hard partons:

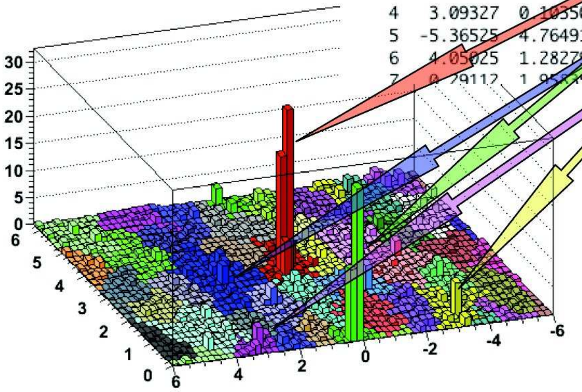
Most jet algorithms give you $\sim 50 - 100$ "jets," mostly not hard.

provide window on UE and min-bias

Making use of *all* jets

```
iev 0 (irepeat 24): number of particles = 1428
strategy used =  NlnN
number of particles = 9051
Total area: 76.0265
Expected area: 76.0265
```

ijet	eta	phi	Pt	area	+-	err
0	0.15050	3.24498	69.970	2.625	+-	0.020
1	0.18579	0.13150	59.133	1.896	+-	0.020
2	2.33840	3.23960	31.976	4.749	+-	0.028
3	-3.41796	0.52394	26.595	3.084	+-	0.021
4	3.09327	0.10350	20.072	2.688	+-	0.023
5	-5.36525	4.76491	19.593	2.780	+-	0.012
6	4.05025	1.28279	15.561	3.592	+-	0.028
7	0.29112	1.95835	14.566	2.114	+-	0.018



Approximate linear relation between Pt and area for minimum bias jets.

Can be used on an event-by-event basis to correct the hard jets

Pushing jets to their limit:

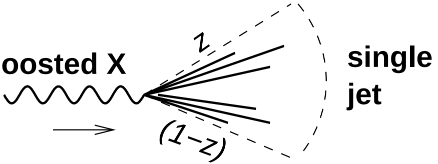
when a W, Z, H or a top $\longrightarrow$ a single jet

Not unusual at LHC: $m_W, m_t \ll 14$ TeV

EW bosons at @ high p_t

Illustrate LHC challenges with a recently widely discussed class of problems:

Can you identify hadronically decaying EW bosons when they're produced at high p_t?



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

Significant discussion over years: **heavy new things decay to EW states**

- Seymour '94 [Higgs $\to WW \to \nu\ell$jets]
- Butterworth, Cox & Forshaw '02 [$WW \to WW \to \nu\ell$jets]
- Agashe et al. '06 [KK excitation of gluon $\to t\bar{t}$]
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ETC.

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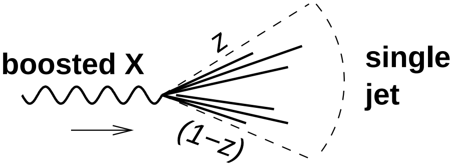

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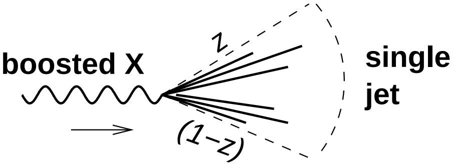

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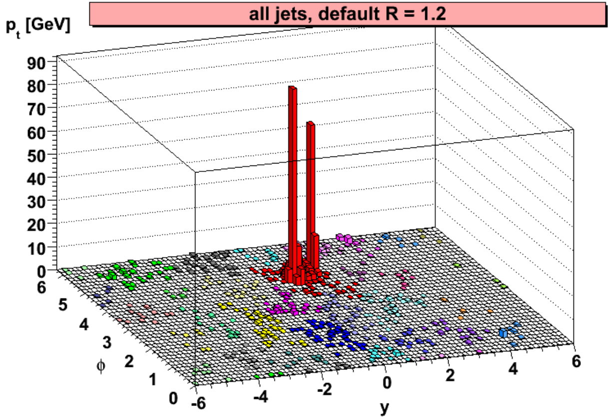
ETC.

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



[Herwig 6.5 + Jimmy 4.31 + FastJet Cam/Aa R=1.2]
Butterworth, Davison, Rubin & GPS '08

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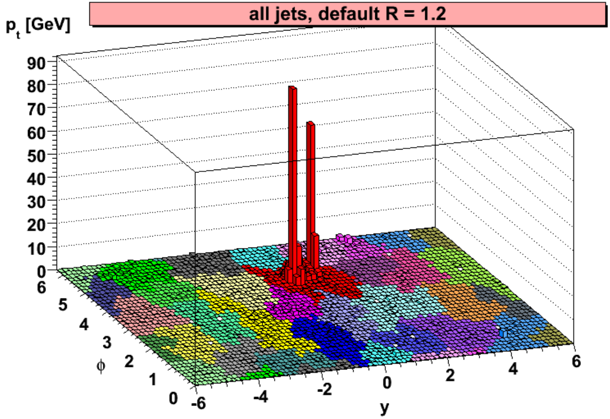

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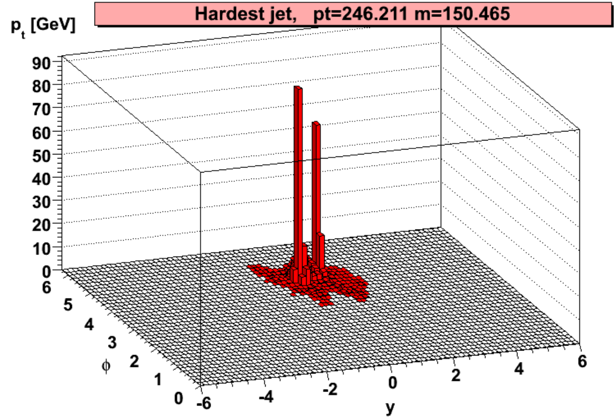

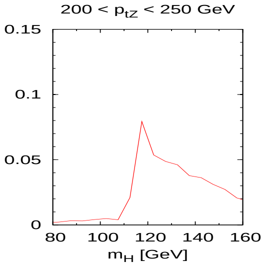

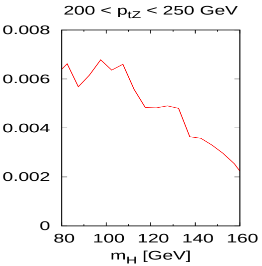

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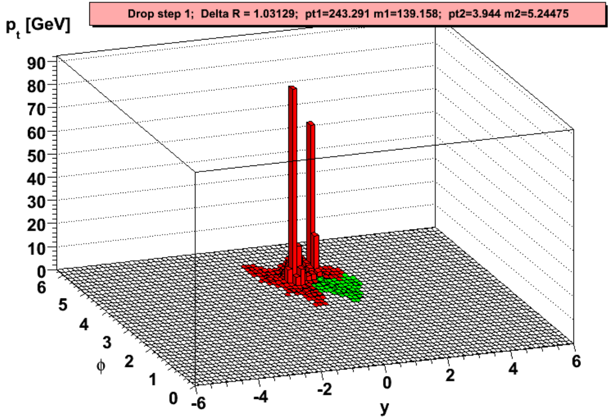
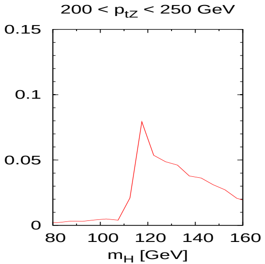
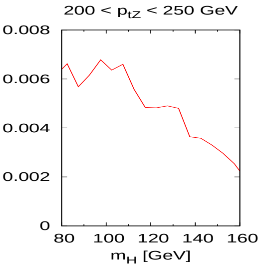


SIGNAL



Zbb BACKGROUND



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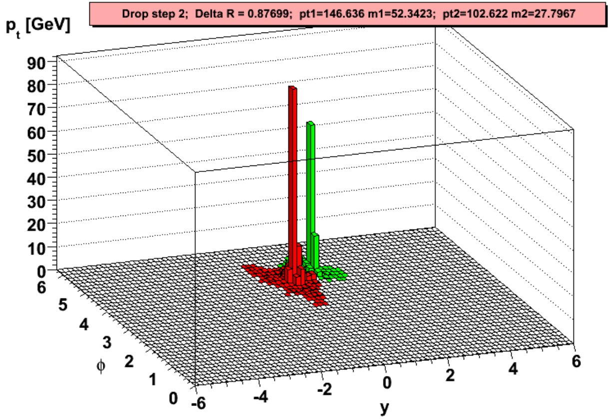

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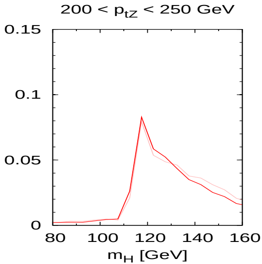

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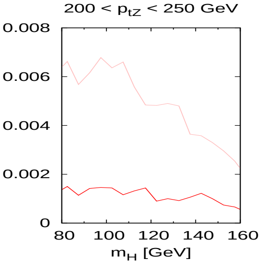

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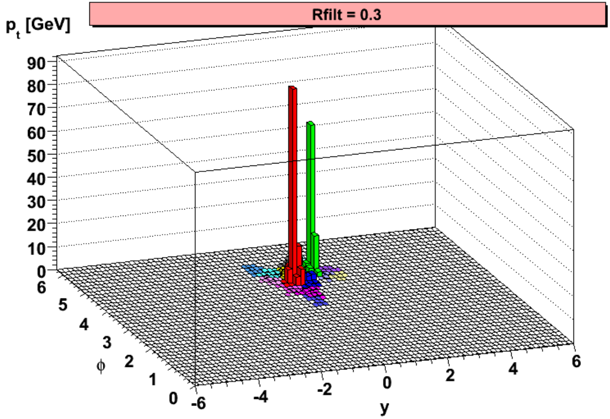

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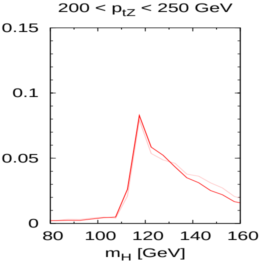

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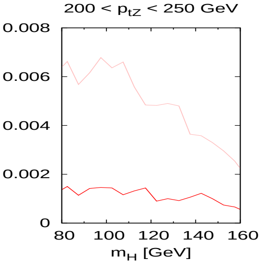

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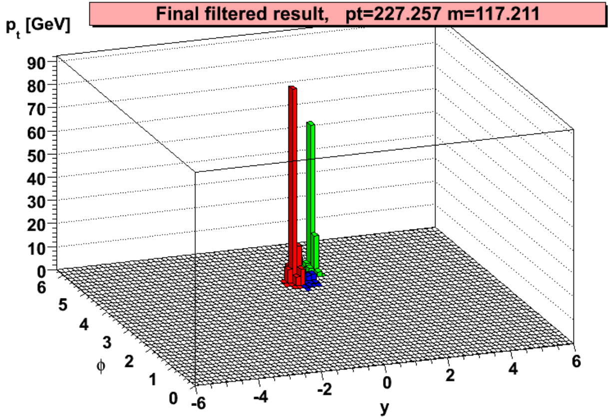

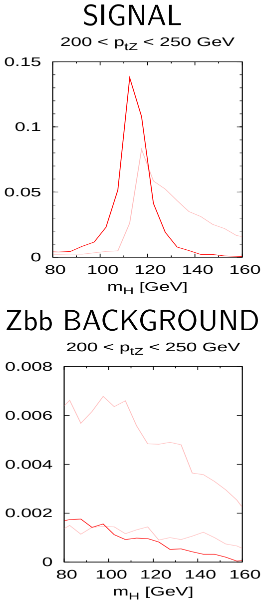

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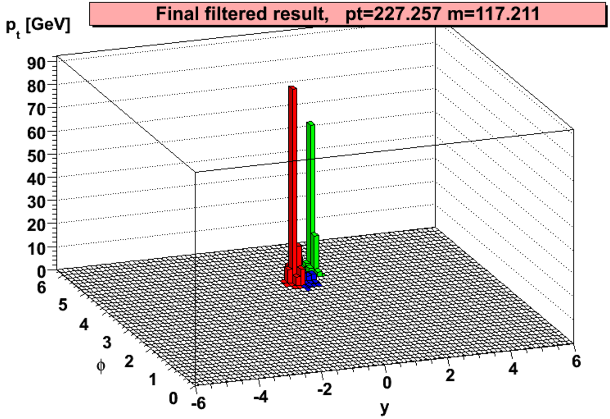

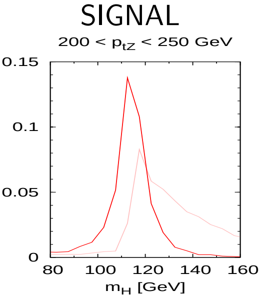

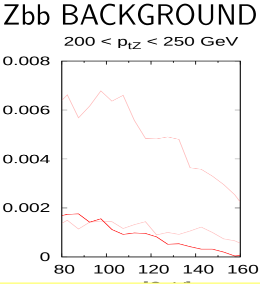

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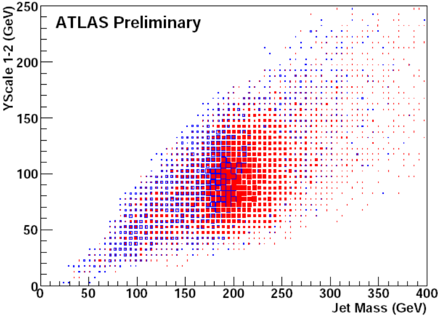
Much to be learnt still about extracting boosted W/H/Z/top?

High-p_t top $\longrightarrow b q \bar{q}'$

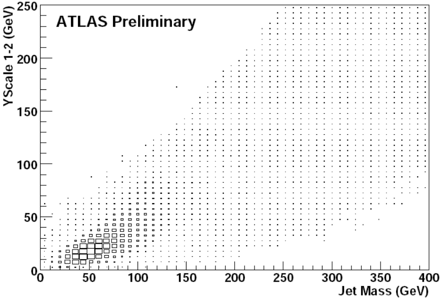
Brooijmans '08 ATL-PHYS-CONF-2008-008, based on k_t algorithm
+ Thaler & Wang '08; Almeida et al. '08 (k_t, jet-shapes)
+ Kaplan et al '08 (C/A decomposition)

Use subjet relative transverse-momentum scale ("'y-scale") & correlation with jet mass to pick out top quarks from background

top quarks $p_t \sim 1$ TeV



normal jets



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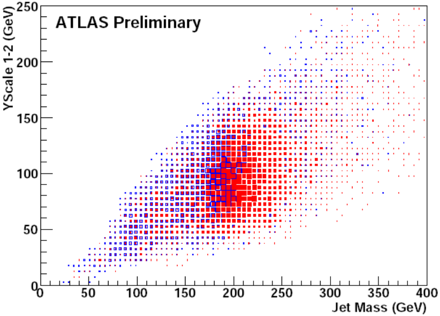
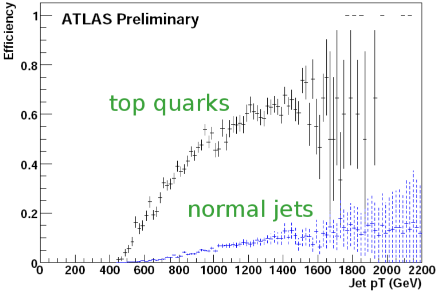


efficiencies



Conclusions

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- A jet is not a parton: it's (sort of) what you choose it to be.
- It's easier to think in terms of partons (LO, NLO pQCD) with IR/Collinear safe jet algorithms. And gives sense to pQCD predictions
- ∃ many cones algs. Not equivalent. Many are IR/Coll unsafe.
  xC-SM → SISCone; xC-PR → anti-k_t
- "The best" jet definition *does not exist*
- To get the most out of jet-algs.,
  - Understand the interplay of physical scales high $p_t \rightarrow$ larger R
  - Try out different combinations of algorithm & R
  - Check Variations of alg. & R don't change extracted physical quantities
- Special cases (e.g. boosted W/t/...) benefit from special techniques
  e.g. seq. recomb. "jet-decomposition" is a powerful tool