Higher orders, jets and the interplay between them

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CDF Collaboration Meeting,
Jussieu, Paris, 1 June 2007

Outline

- Progress in higher order calculations
  - NLO wish list — new results, work in progress
  - NLO + parton showers — MC@NLO & POWHEG
  - NNLO news

- Jet algorithms
  - Infrared & Collinear Safety
  - Varying their parameters to probe higher orders & non-perturbative physics
  - Using them to measure underlying event
  - Jets & flavour

NLO Wish lists (2005)

Experimenters' priorities

Les Houches

1. pp → W W + jet
2. pp → H + 2 jets
   - Background to VBF Higgs production
3. pp → $t\bar{t}b\bar{b}$
4. pp → $t\bar{t}$ + 2 jets
   - Background to $t\bar{t}$H
5. pp → W W $b\bar{b}$
6. pp → V V + 2 jets
   - Background to $W\,W \to H \to W\,W$
7. pp → V + 3 jets
   - General background to new physics
8. pp → V V V + jet
   - Background to SUSY trilepton

Currently available

NLOJET++, MCFM, PHOX, ...

`http://www.cedar.ac.uk/hepcode/`

Theorist's list (G. Heinrich)

- 2 → 3 (OK for a good student!)
  - pp → W W + jet
  - pp → V V V
  - pp → H + 2 jets
- 2 → 4 (Beyond today's means)
  - pp → 4 jets
  - pp → $t\bar{t}$ + 2 jets
  - pp → $t\bar{t}b\bar{b}$
  - pp → V + 3 jets
  - pp → V V + 2 jets
  - pp → V V V + jet
  - pp → W W $b\bar{b}$

NLO Wish lists (2005)

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5. pp → $WW\ b\bar{b}$
6. pp → VV + 2 jets
   - Background to $WW \to H \to WW$
7. pp → V + 3 jets
   - General background to new physics
8. pp → VVV + jet
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  - pp → 4 jets
  - pp → $t\bar{t}$ + 2 jets
  - pp → $t\bar{t}b\bar{b}$
  - pp → V + 3 jets
  - pp → VV + 2 jets
  - pp → VVV + jet
  - pp → $WW\ b\bar{b}$

NLO Wish lists (2005)

Experimenters' priorities

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NLO Wish lists (2007)

Experimenters' priorities

1. pp → W W + jet   Les Houches
2. pp → H + 2 jets   CEZ '06
   - Background to VBF Higgs production
3. pp → $t\bar{t}b\bar{b}$
4. pp → $t\bar{t}$ + 2 jets   DUW '07
   - Background to $t\bar{t}$H
5. pp → W W $b\bar{b}$
6. pp → V V + 2 jets
   - Background to $WW \to H \to WW$
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Currently available

NLOJET++, MCFM, PHOX, ...

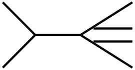
`http://www.cedar.ac.uk/hepcode/`

Theorist's list (G. Heinrich)

- 2 → 3 (some results)
  - pp → W W + jet
  - pp → V V V   LMP '07
  - pp → H + 2 jets   CEZ '06
- 2 → 4 (some progress)
  - pp → 4 jets
  - pp → $t\bar{t}$ + 2 jets
  - pp → $t\bar{t}b\bar{b}$
  - pp → V + 3 jets
  - pp → V V + 2 jets
  - pp → V V V + jet
  - pp → W W $b\bar{b}$

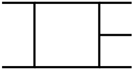
NLO bottleneck

2 → 3 @ NLO ~



2 → 4 @ Tree

+



2 → 3 @ 1−loop

+ **Tricks to cancel divergences**

(dipole subtraction)

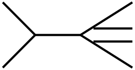
The issue is carrying out the 1-loop calculation for many different processes.

Two approaches:

- automate it
- understand underlying symmetries, recursions, etc, so as to simplify the problem.

NLO bottleneck

2 → 3 @ NLO ~



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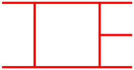

2 → 3 @ 1−loop

Bottleneck

+

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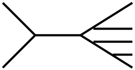
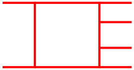
NLO bottleneck

2 → 4 @ NLO ~



2 → 5 @ Tree

+



2 → 4 @ 1−loop

+ **Tricks to cancel divergences**

(dipole subtraction)

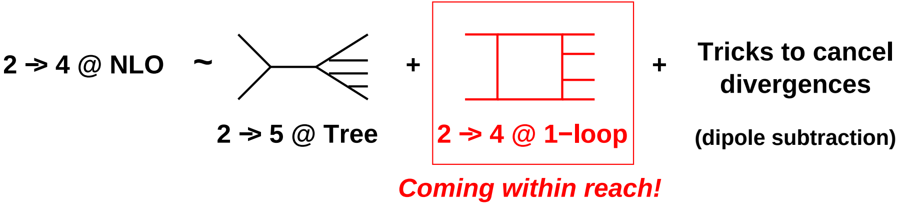
Coming within reach!

The issue is carrying out the 1-loop calculation for many different processes.

Two approaches:

- automate it
- understand underlying symmetries, recursions, etc, so as to simplify the problem.

NLO bottleneck



2 → 4 @ NLO ~ 2 → 5 @ Tree + 2 → 4 @ 1−loop + Tricks to cancel divergences (dipole subtraction)

Coming within reach!

The issue is carrying out the 1-loop calculation for many different processes.

Two approaches:

- automate it
- understand underlying symmetries, recursions, etc, so as to simplify the problem.

$2 \longrightarrow 3$ progress

Automation playing a big role (Feynman graph generation, reduction of loop integrals to known forms, producing Fortran code)

Semi-numerical: $H + 2$jets

Campbell, Ellis & Zanderighi '06
Ellis, Giele &Zanderighi '05

- reduction of integrals to known results done recursively for each momentum configuration
- part of MCFM

Automated analytical: $t\bar{t}$+jet

Dittmaier, Uwer & Weinzierl '07

- see next page...

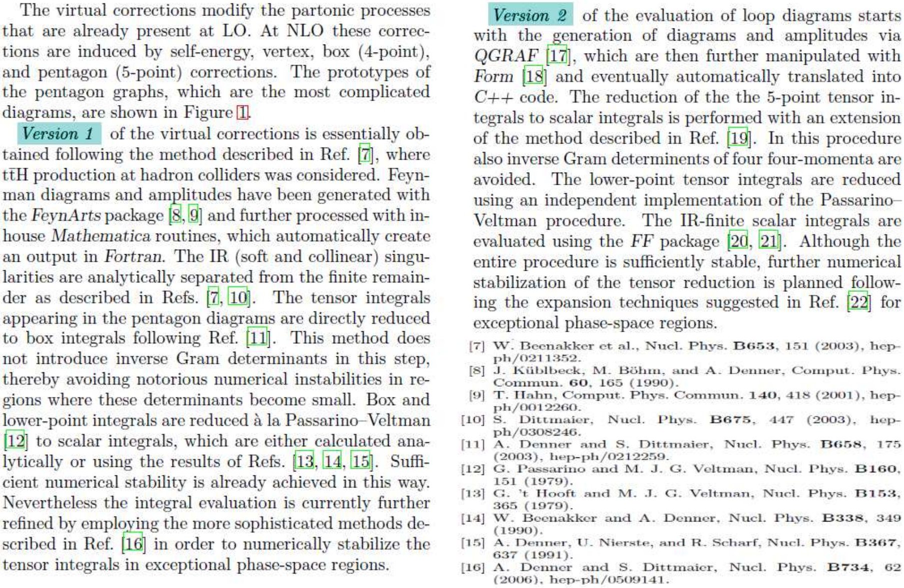
Sector decomposition: VVV

Lazopoulos, Melnikov & Petriello '07

- uses same method for combining real and virtual as NNLO Higgs.

NB: several other 'less technological' calculations
also carried out in past year or two

Extract from D. U. & W. ($t\bar{t}$+ jet)



The virtual corrections modify the partonic processes that are already present at LO. At NLO these corrections are induced by self-energy, vertex, box (4-point), and pentagon (5-point) corrections. The prototypes of the pentagon graphs, which are the most complicated diagrams, are shown in Figure 1.

Version 1 of the virtual corrections is essentially obtained following the method described in Ref. [7], where $t\bar{t}H$ production at hadron colliders was considered. Feynman diagrams and amplitudes have been generated with the *FeynArts* package [8, 9] and further processed with in-house *Mathematica* routines, which automatically create an output in *Fortran*. The IR (soft and collinear) singularities are analytically separated from the finite remainder as described in Refs. [7, 10]. The tensor integrals appearing in the pentagon diagrams are directly reduced to box integrals following Ref. [11]. This method does not introduce inverse Gram determinants in this step, thereby avoiding notorious numerical instabilities in regions where these determinants become small. Box and lower-point integrals are reduced à la Passarino–Veltman [12] to scalar integrals, which are either calculated analytically or using the results of Refs. [13, 14, 15]. Sufficient numerical stability is already achieved in this way. Nevertheless the integral evaluation is currently further refined by employing the more sophisticated methods described in Ref. [16] in order to numerically stabilize the tensor integrals in exceptional phase-space regions.

Version 2 of the evaluation of loop diagrams starts with the generation of diagrams and amplitudes via *QGRAF* [17], which are then further manipulated with *Form* [18] and eventually automatically translated into *C++* code. The reduction of the the 5-point tensor integrals to scalar integrals is performed with an extension of the method described in Ref. [19]. In this procedure also inverse Gram determinents of four four-momenta are avoided. The lower-point tensor integrals are reduced using an independent implementation of the Passarino–Veltman procedure. The IR-finite scalar integrals are evaluated using the *FF* package [20, 21]. Although the entire procedure is sufficiently stable, further numerical stabilization of the tensor reduction is planned following the expansion techniques suggested in Ref. [22] for exceptional phase-space regions.

[7] W. Beenakker et al., Nucl. Phys. **B653**, 151 (2003), hep-ph/0211352.
[8] J. Küblbeck, M. Böhm, and A. Denner, Comput. Phys. Commun. **60**, 165 (1990).
[9] T. Hahn, Comput. Phys. Commun. **140**, 418 (2001), hep-ph/0012260.
[10] S. Dittmaier, Nucl. Phys. **B675**, 447 (2003), hep-ph/0308246.
[11] A. Denner and S. Dittmaier, Nucl. Phys. **B658**, 175 (2003), hep-ph/0212259.
[12] G. Passarino and M. J. G. Veltman, Nucl. Phys. **B160**, 151 (1979).
[13] G. 't Hooft and M. J. G. Veltman, Nucl. Phys. **B153**, 365 (1979).
[14] W. Beenakker and A. Denner, Nucl. Phys. **B338**, 349 (1990).
[15] A. Denner, U. Nierste, and R. Scharf, Nucl. Phys. **B367**, 637 (1991).
[16] A. Denner and S. Dittmaier, Nucl. Phys. **B734**, 62 (2006), hep-ph/0509141.

Towards 6 legs at 1-loop

Most remaining wish-list process need 6-leg 1-loop calculation.

Major results:

- All helicity structures now known for 6-gluon amplitude

Numerically: Ellis, Giele & Zanderighi '06
Analytical/Recursion: Britto, Feng & Mastrolia '06; Xiao, Yang & Zhu '06
MHV n-gluon: Berger, Bern, Dixon, Forde & Kosower '06
+ many others before them

- Progress now being made on recursion for $H + n$-gluons

ϕnite: Berger, Del Duca & Dixon '06
MHV: Badger, Glover & Risager '07

Still some way from a full phenomenological $2 \to 4$ prediction.

e.g. for 4-jets, need $q\bar{q} + 4g$, $q\bar{q}q\bar{q} + 2g$, $q\bar{q}q\bar{q}q\bar{q}$
+ assembly into full NLO program is 'straightforward' but not easy

Parton showers (PS) + higher orders

Frixione–Webber (MC@NLO)

- ► Calculate NLO already present in parton shower
- ► Subtract it from true NLO and add remainder to shower
- ► Processes: $pp \to H, VV, Q\bar{Q}, t + X, \ell^+\ell^-, H + W/Z$
- ► New in 2006/07: NLO + spin-correlations @ LO

Frixione, Laenen, Motylinski & Webber '07

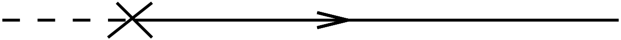
- ✗ Requires deep understanding of PS for each new process & MC
- ✗ So far worked out for Herwig
- ✓ But many processes available

Nason (POWHEG)

- ► Do 'hardest emission' according to NLO (virtuals → Sudakov exponent)
- ► Carry out a truncated parton shower to get remaining emissions
- ► Applied to: $pp \to ZZ$ Nason & Ridolfi '06
- ✓ Needs little detailed understanding of MC PS
- ✗ Requires small modification of PS (truncation)
- ✗ So far only one process implemented

POWHEG method

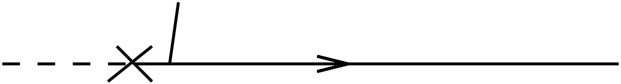
Normal
Ang. Ordered
Parton Showed



Method with
POWHEG

POWHEG method

Normal
Ang. Ordered
Parton Showed



Method with
POWHEG

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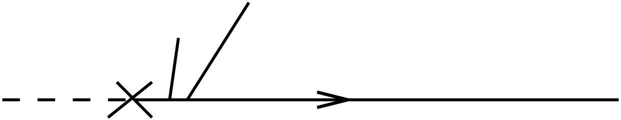

Method with
POWHEG

POWHEG method

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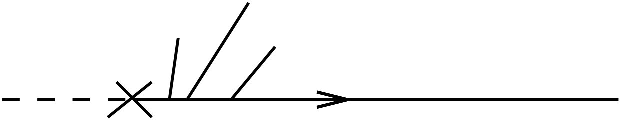

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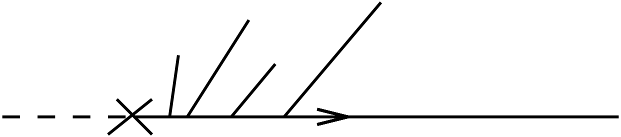

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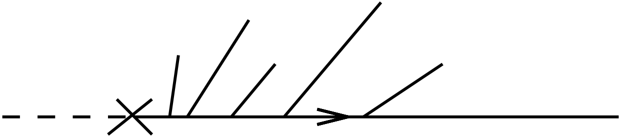

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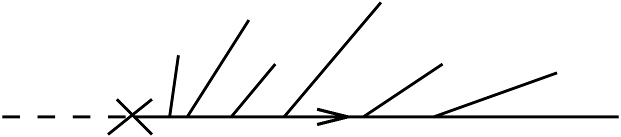

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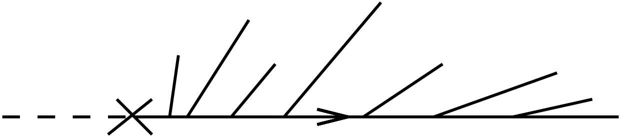

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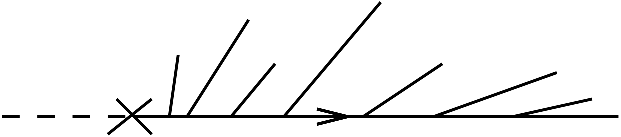

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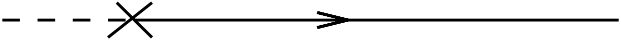

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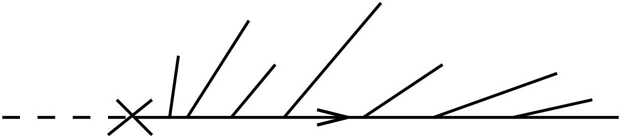

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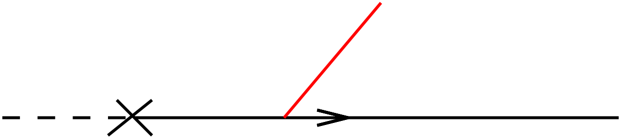

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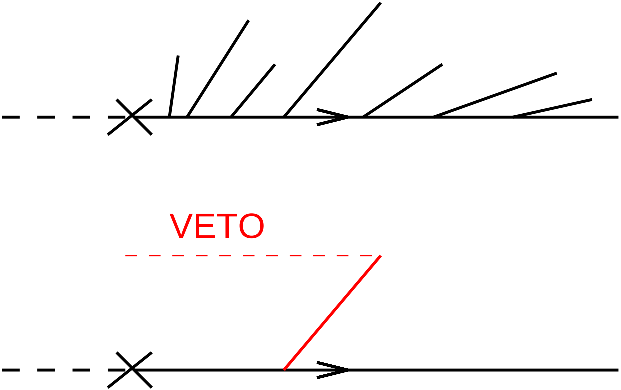

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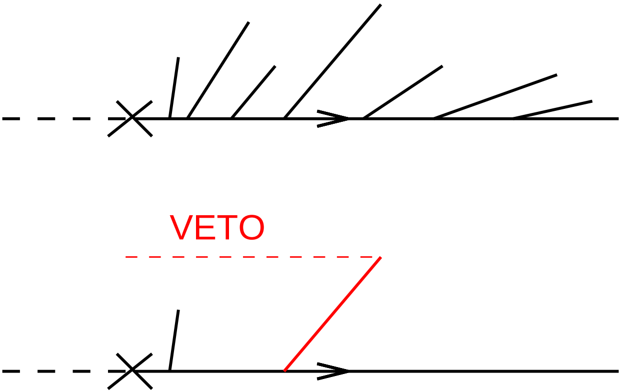
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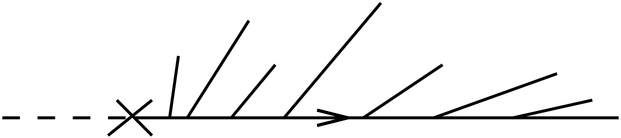

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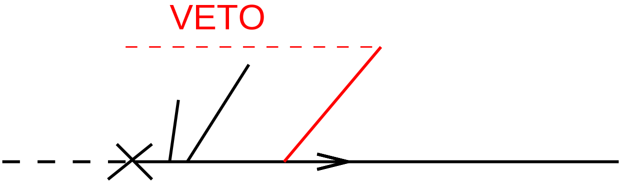

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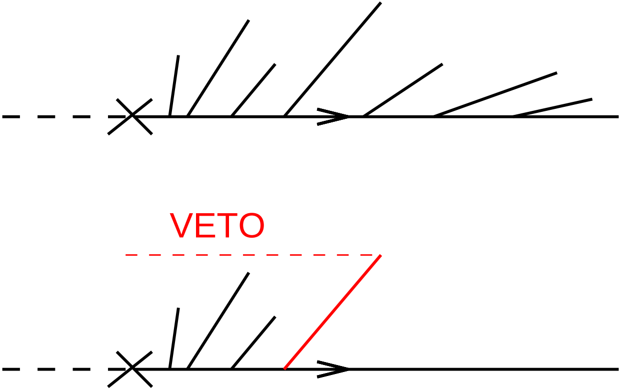

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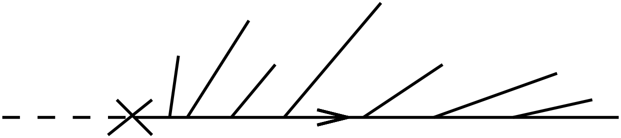

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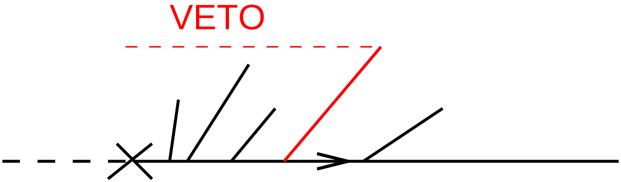

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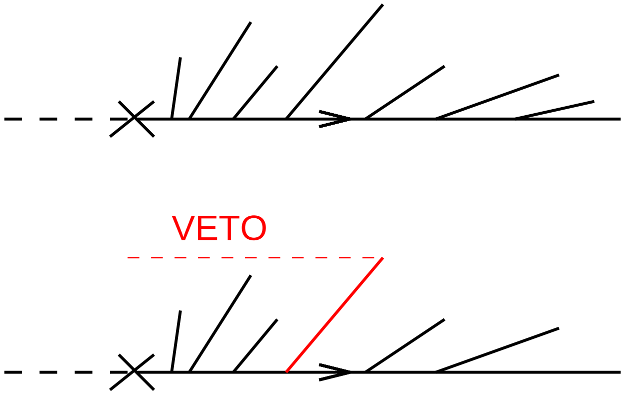

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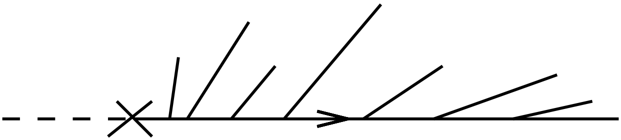
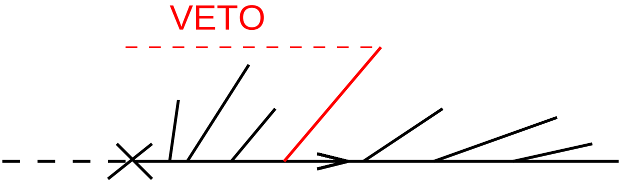
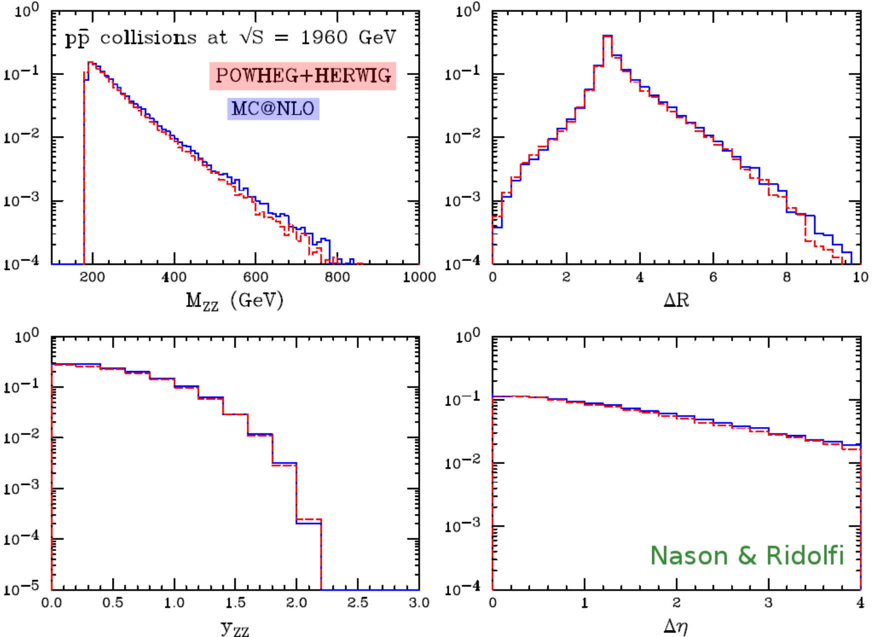




Method with
POWHEG

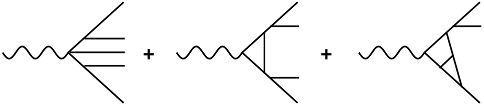
POWHEG v. MC@NLO



Nason & Ridolfi

News @ NNLO (with jets)

The current target is $e^+e^- \to 3$ jets:



1 -> 3 @ NNLO ~ [1 -> 5 @ Tree] + [1 -> 4 @ 1−loop] + [1 -> 3 @ 2−loop] + Tricks to cancel divergences

2004: $\alpha_s^3 C_F^3$ factor calculated — Gehrmann-de Ridder, Gehrmann, Glover (G^3)
2005: general (antenna) subtraction scheme — G^3
2006: sector-decomposition for part of $\alpha_s^3 C_F^3$ — Heinrich
2006: alternative subtraction scheme — Somogyi, Trocsanyi & Del Duca
2007: **prelim results for all colour factors** — G^3 + Heinrich

2006: outline of antenna sub. at NNLO for pp — Daleo, Gehrmann & Maitre

News @ NNLO (with jets)

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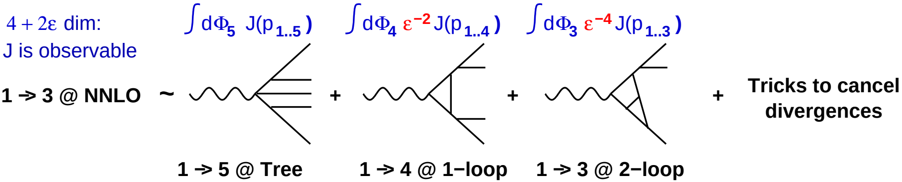

$4+2\varepsilon$ dim:
J is observable

1 -> 3 @ NNLO ~ $\int d\Phi_5\ J(p_{1..5})$ + $\int d\Phi_4\ \varepsilon^{-2}\ J(p_{1..4})$ + $\int d\Phi_3\ \varepsilon^{-4}\ J(p_{1..3})$ + **Tricks to cancel divergences**

1 -> 5 @ Tree **1 -> 4 @ 1−loop** **1 -> 3 @ 2−loop**

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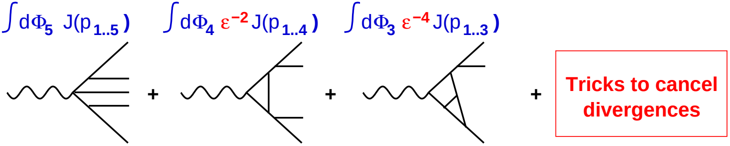

$4+2\varepsilon$ dim:
J is observable

1 -> 3 @ NNLO $\sim$ $\int d\Phi_5\ J(p_{1..5})$ + $\int d\Phi_4\ \varepsilon^{-2} J(p_{1..4})$ + $\int d\Phi_3\ \varepsilon^{-4} J(p_{1..3})$ + **Tricks to cancel divergences**

1 -> 5 @ Tree **1 -> 4 @ 1−loop** **1 -> 3 @ 2−loop** **Bottleneck**

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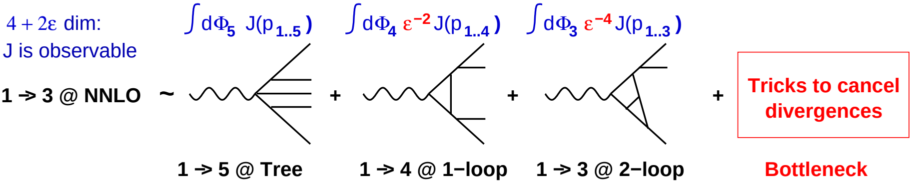

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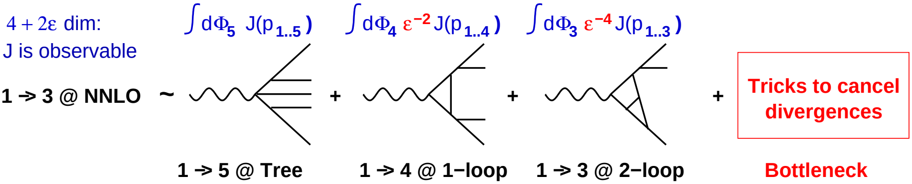

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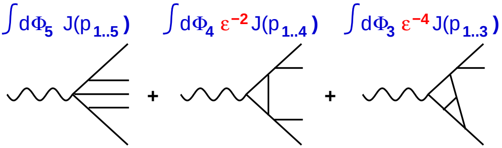

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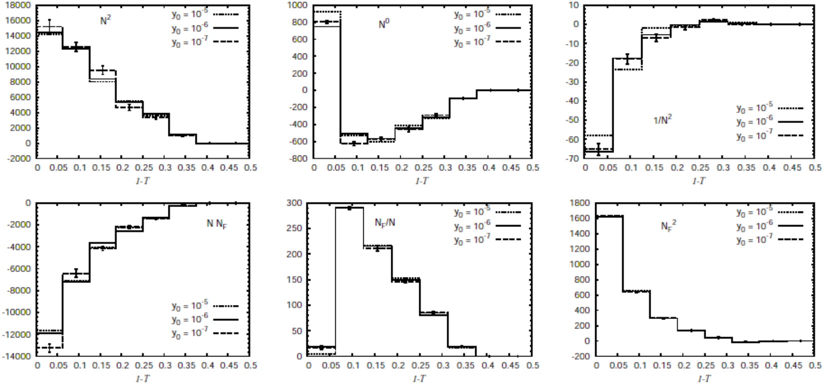
Results

NNLO coefficient $C(T)$ of thrust (preliminary)

T. Gehrmann, E.W.N. Glover, G. Heinrich, AG



What about what's poorly calculated / uncalculable?

- Non-perturbative effects — Underlying event, 'hadronisation'
- Higher orders that are missing
- Higher orders that are approximated (Monte Carlo)

  or combinations of above two
- Cases where perturbation theory converges slowly — E.g. for *b*-jets

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- Hadron-level contains far more information than is useful (e.g. much to do with non-perturbative fragmentation)
- Perturbative QCD calculations contain some unphysical information (divergences), and neglect many higher-order diagrams

Jets algorithms extract the physical information from each, and allow one to discuss the two on the same footing

Like a camera, they allow us to capture the essence of an event

Jets are one of the most basic tools in our field

1) Some are "better" than others
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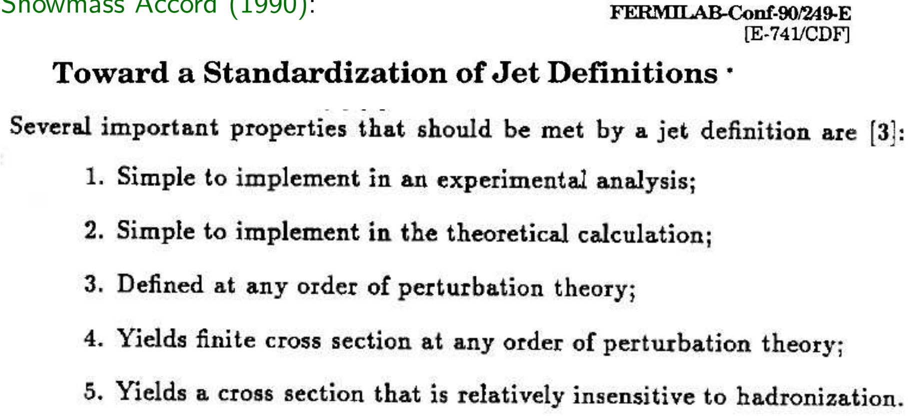
Some jet topics

- Infrared & Collinear Safety
- Varying their parameters to probe higher orders & non-perturbative physics
- Using them to measure underlying event
- Jets & flavour

1990 “standards”

Snowmass Accord (1990):



FERMILAB-Conf-90/249-E
[E-741/CDF]

Toward a Standardization of Jet Definitions *

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

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

Property 4 $\equiv$ Infrared and Collinear (IRC) Safety. It helps ensure:

- Non-perturbative effects are suppressed by powers of Λ_{QCD}/p_t
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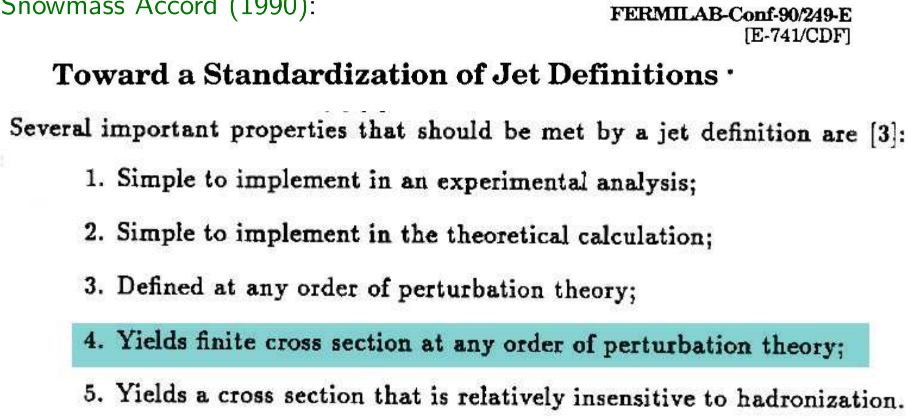

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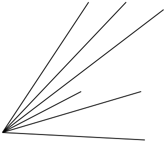
Cone basics

Modern cone algs have two main steps:

- Find some/all stable cones

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

  By running a 'split–merge' procedure



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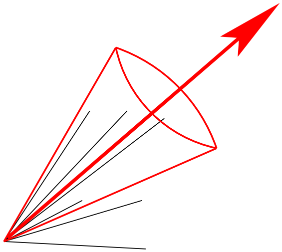

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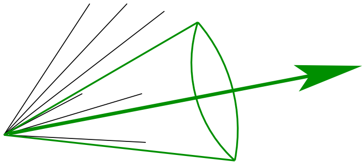

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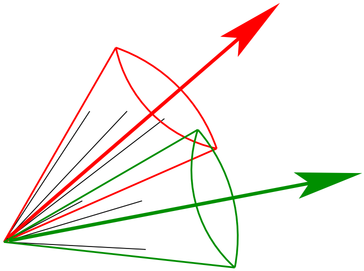

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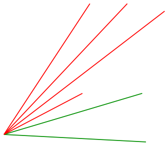

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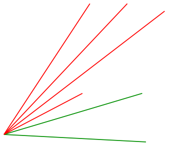
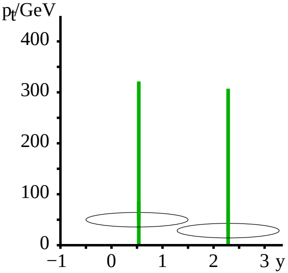
Qu: How do you find the stable cones?

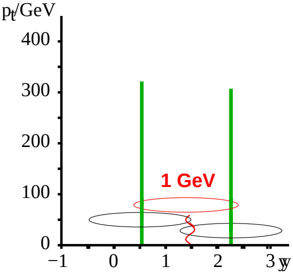
All experiments use iterative methods:

- use each particle as a starting direction for cone; use sum of contents as new starting direction; repeat.



JetClu IR problem





Stable cones with jetclu:	{1} & {2}	{1} & {1,2} & {2}
Jets with jetclu ($f = 0.5$)	{1} & {2}	{1,2}

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

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Or collinear unsafe with a seed threshold
Fix: add midpoint seeds between stable cones

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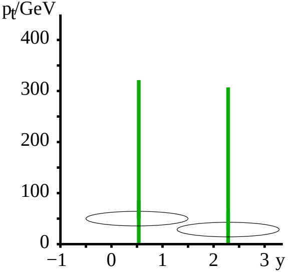

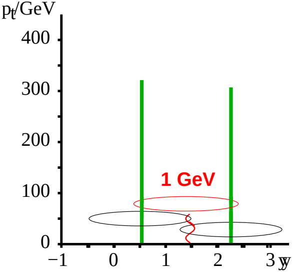

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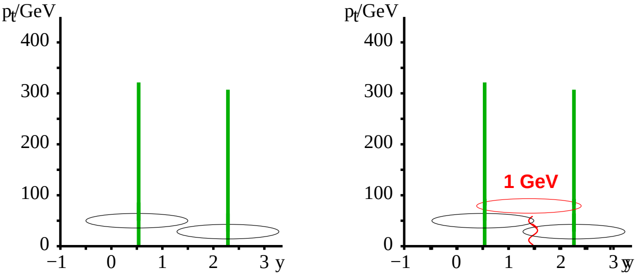

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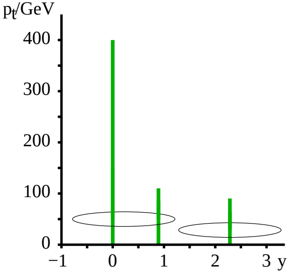

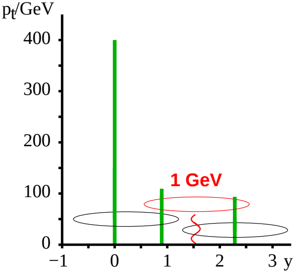

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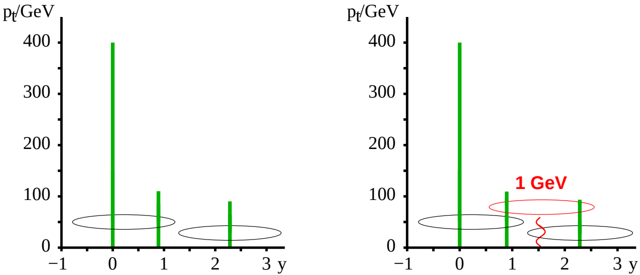

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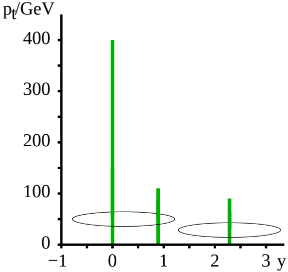

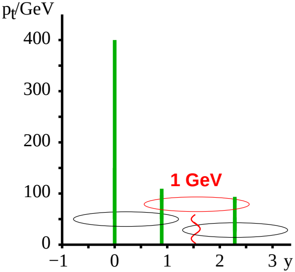

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IR unsafety? Who cares?

IR/Collinear unsafety is a serious problem for theorists!

- Invalidates theorems that ensure finiteness of perturbative QCD

  Cancellation of real & virtual divergences

  Makes results inherently non-perturbative

- 'Pragmatically:' limits accuracy to which it makes sense to calculate

  Higher orders no longer form convergent series

Process	*Last meaningful order*		
	JetClu/Searchcone	MidPoint	
Inclusive jets	LO	NLO	[NNLO being worked on]
$W/Z + 1$ jet	LO	NLO	
3 jets	**none**	LO	[NLO in `nlojet++`]
$W/Z + 2$ jets	**none**	LO	[NLO in `MCFM`]
jet masses in $2j + X$	**none**	**none**	[LO in `madgraph` etc.]

IRC safety FAQ

1. *I tried replacing [JetClu → Midpoint], effect was small, so maybe IR safety doesn't matter?*

   a) Effect can be small in one place (e.g. inclusive jet spectra), but big elsewhere; b) It still breaks partonic calculations (so theorists will use your competitors' results instead of yours)

2. *Now that we have MC@NLO we don't need parton-level theory and all its infinities*

   MC@NLO is a powerful tool, but still misses many processes (and will do for a while): $2j$, $3j$, $V+j$, $H+j$, $V+2j$, $H+2j$, $Q\bar{Q}+j$, NLO t-decay in single top, NLO t-decay in $t\bar{t}$, many SUSY ones…

3. *I'm searching for XYZ & only ever use data and Pythia — there, at hadron level, [JetClu]'s answer is well defined*

   It's well defined but not robust: a 1 GeV particle can change your 200 GeV jets. a) Do you really want your analysis to be that random and b) do you really trust Pythia's modeling of 1 GeV particles?

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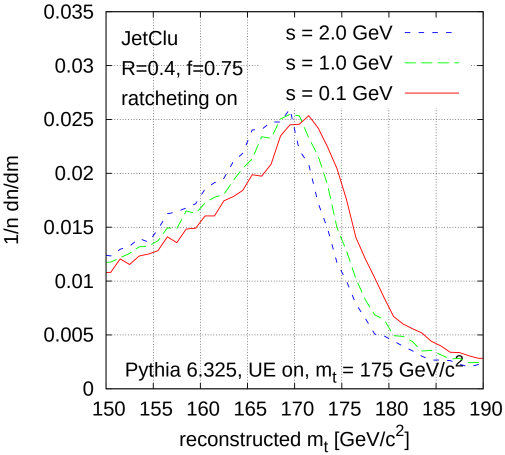

JetClu & MidPoint use a seed threshold (s).

Seeds should just be a trick to speed up jet-finding, with no effect on physics.

IRC unsafety → physical effect

E.g. top mass peak: shifts by 3 GeV for $0.1 < s < 2$ GeV.

Or height by 25% for $R = 0.8$

Accounted for in simulations: **but to what extent to you trust Pythia (e.g. UE) and detector details at 1 GeV level?**

e.g. event-by-event correlations between soft particles and jets

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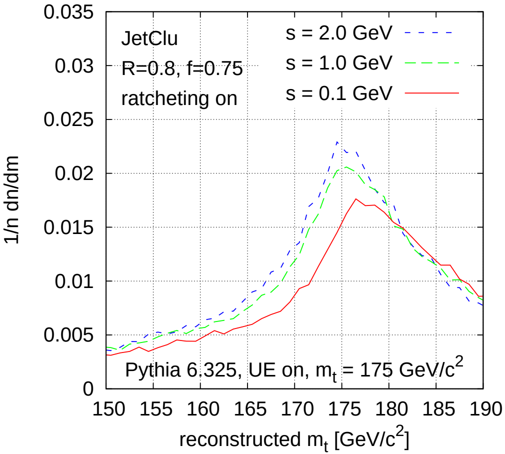

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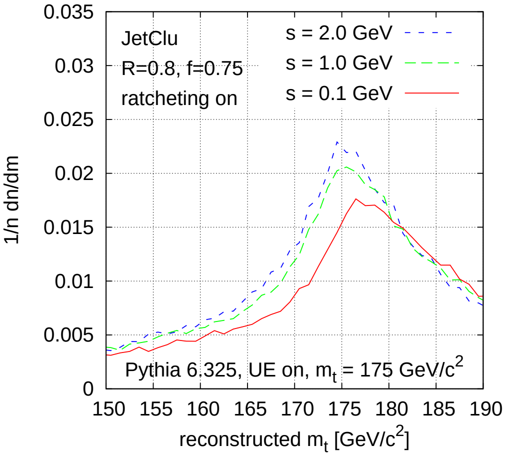

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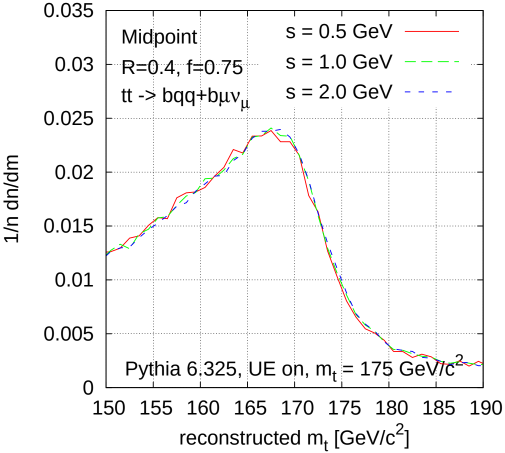

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The less you have to correct for, the better off you are.

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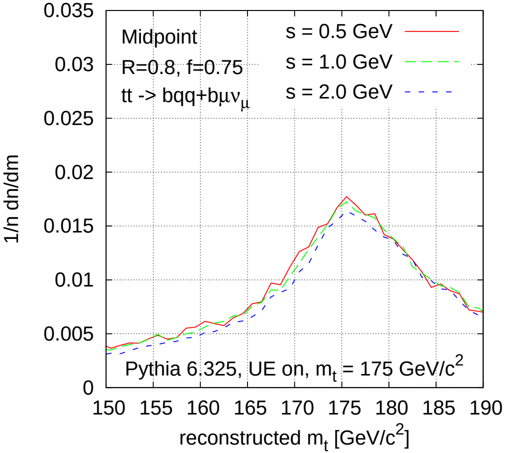

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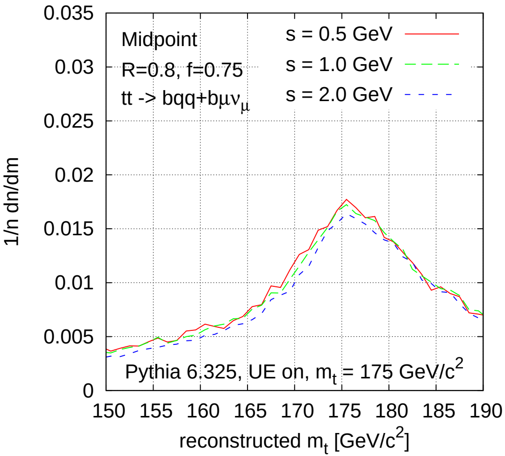
The less you have to correct for, the better off you are.

MidPoint's seed threshold dependence



JetClu & MidPoint use a seed threshold (s).

Seeds should just be a trick to speed up jet-finding, with no effect on physics.

IRC unsafety → physical effect

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Rather than define the cone alg. through the *procedure* you use to find cones, define it by the *result you want:*

A cone algorithm should find **all** stable cones

First advocated: Kidonakis, Oderda & Sterman '97

Guarantees IR safety of the set of stable cones

Only issue: you still need to find the stable cones in practice.

One known exact approach:

- Take each possible subset of particles and see if it forms a stable cone.

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Transform into geometrical problem

Cones are just *circles* in the $y - \phi$ plane. To find all stable cones:

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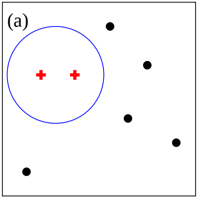
Finding all distinct circular enclosures of a set of points is *geometry:*



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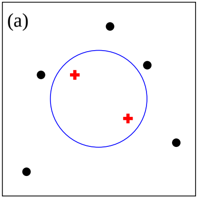

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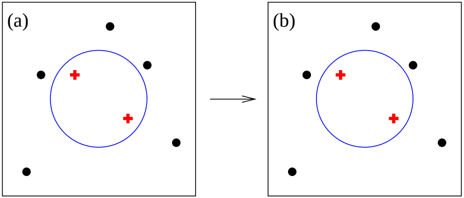

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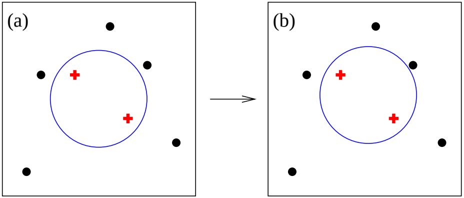

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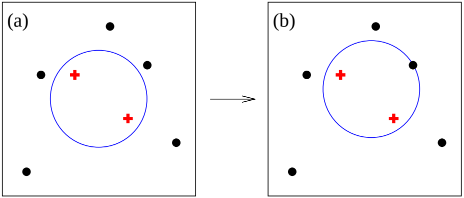

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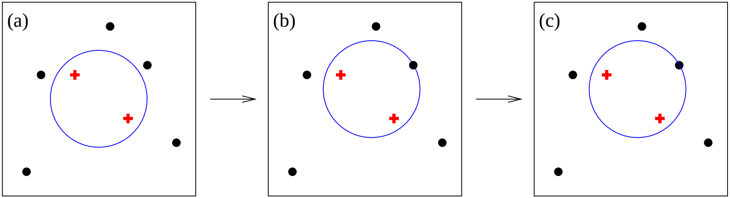

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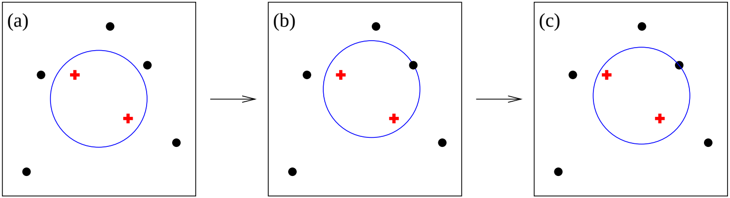

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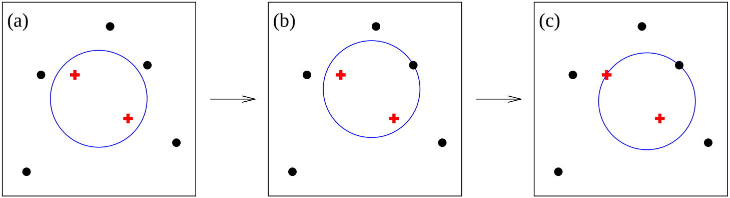

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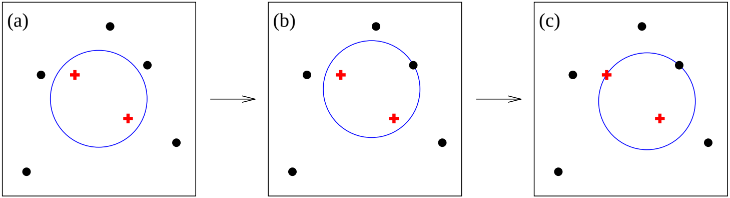

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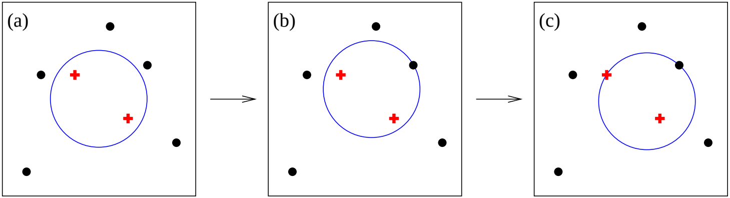

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- Generate event with $2 < N < 10$ hard particles, find jets
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Unsafety level	failure rate
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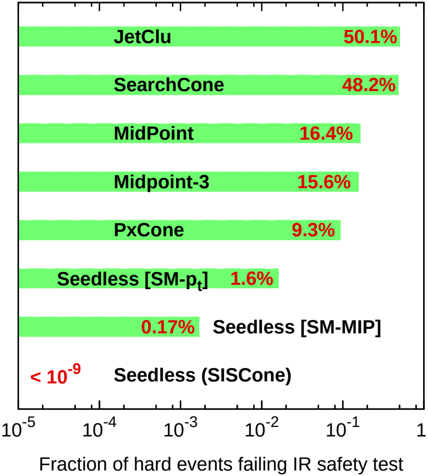

Two classes of jet algorithm

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

Sequential recombination

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

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

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

Example clustering with k_t algorithm, $R = 0.7$

ϕ assumed 0 for all towers

In QCD events, *d_{ij} is related to divergences for branching* — clustering attempts inverse branching.

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Tracks half the divergences

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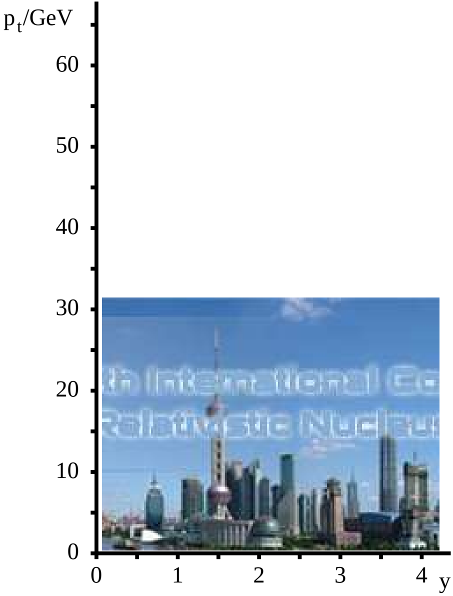

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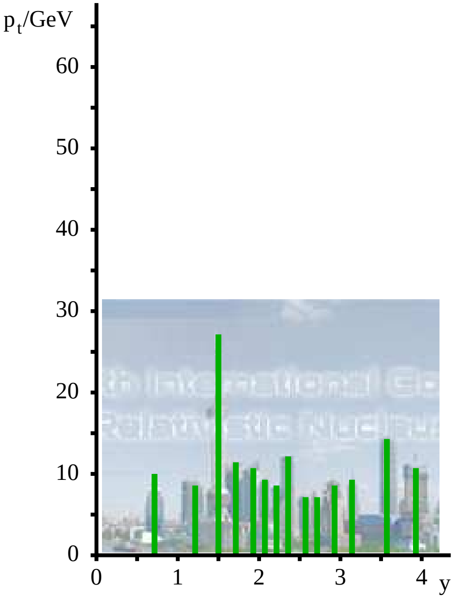

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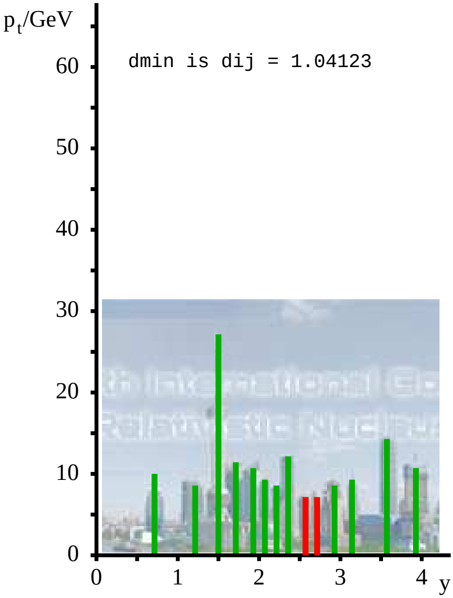

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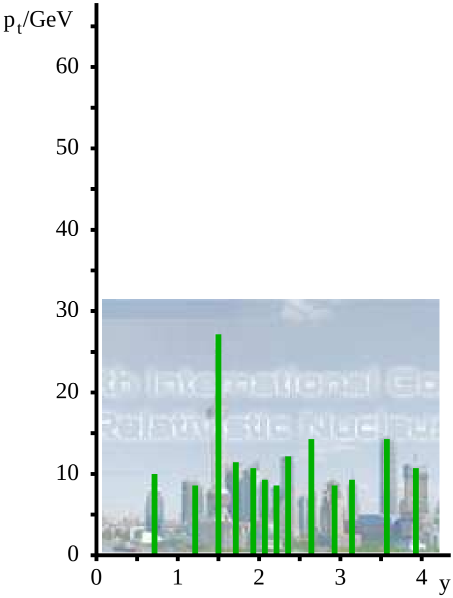

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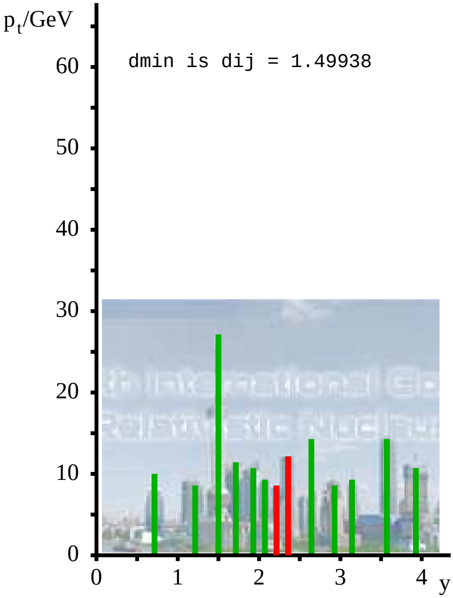

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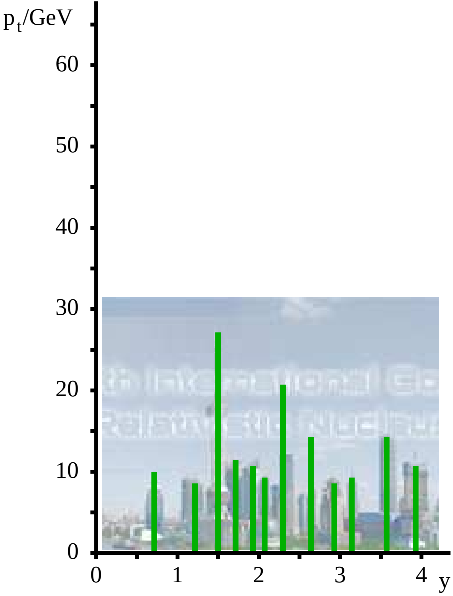

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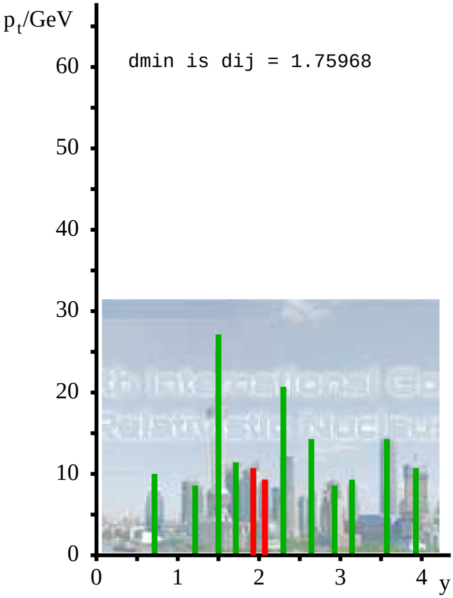

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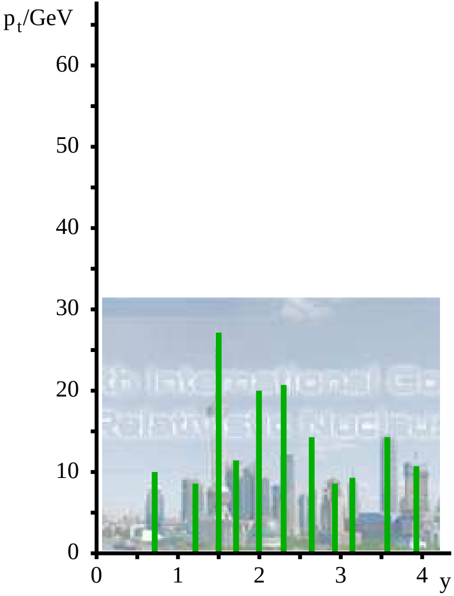

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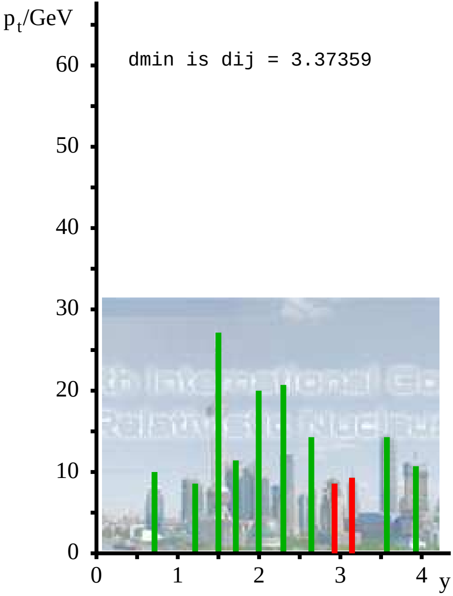

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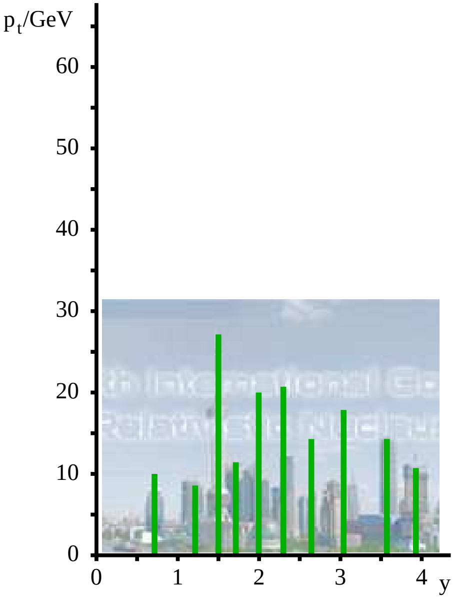

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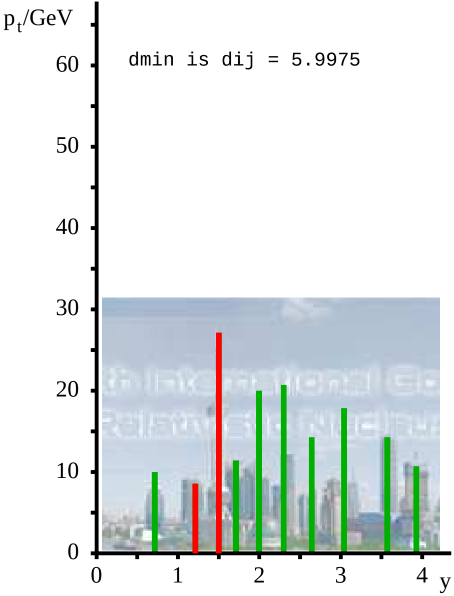

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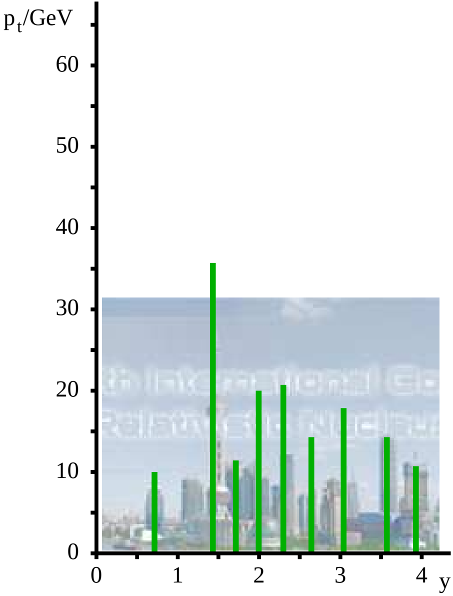

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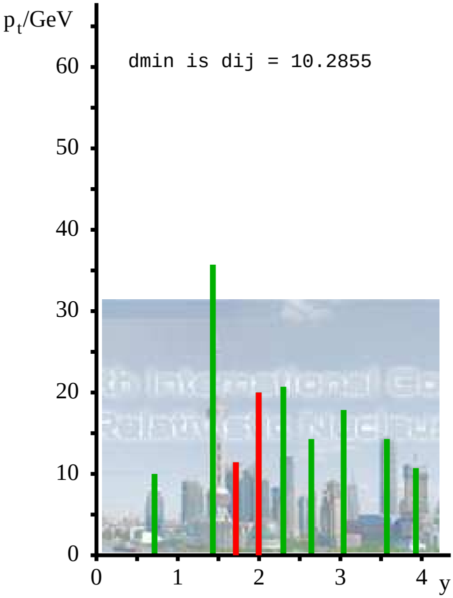

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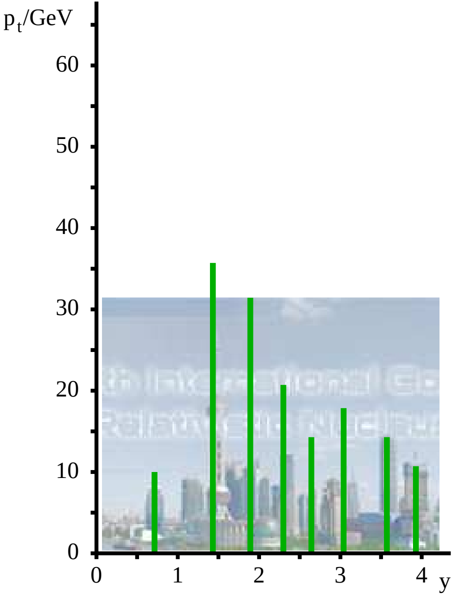

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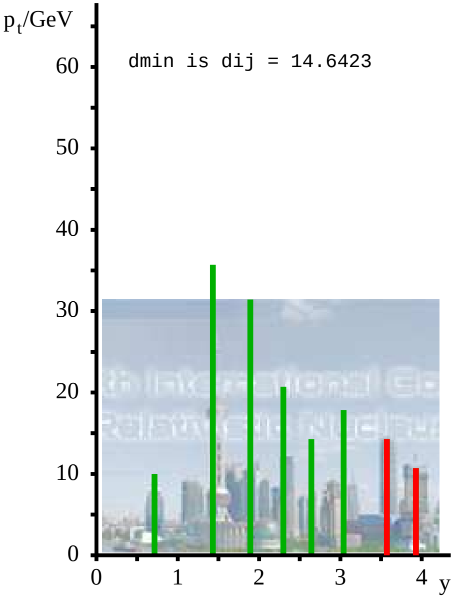

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Example clustering with k_t algorithm, $R = 0.7$

ϕ assumed 0 for all towers

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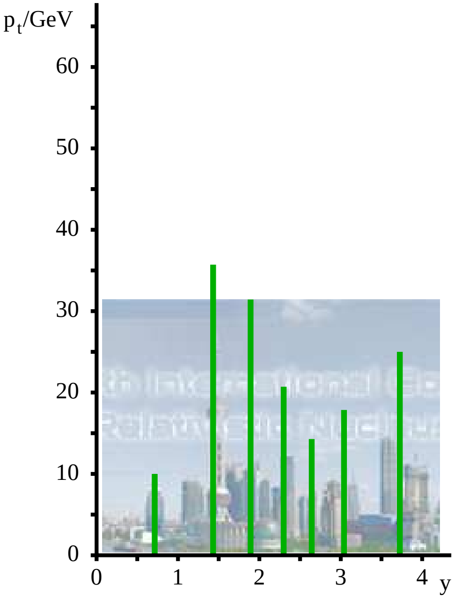

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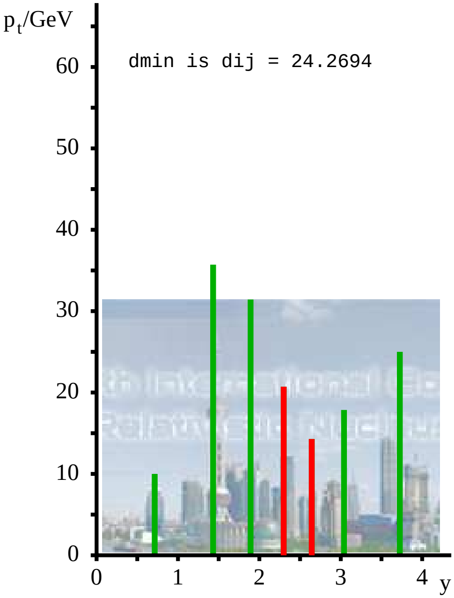

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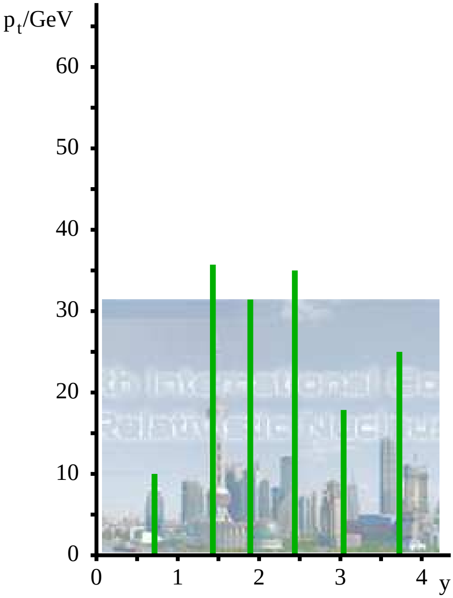

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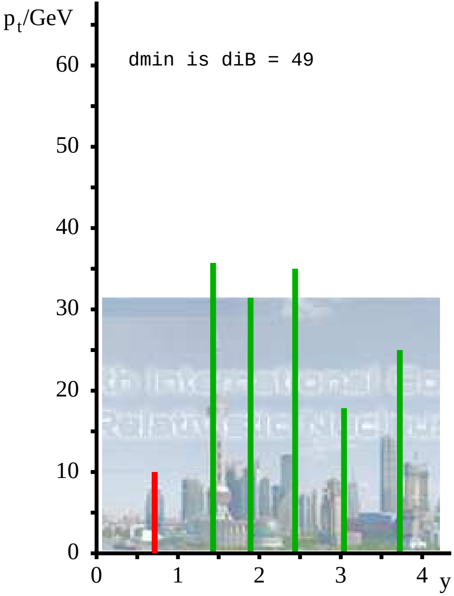

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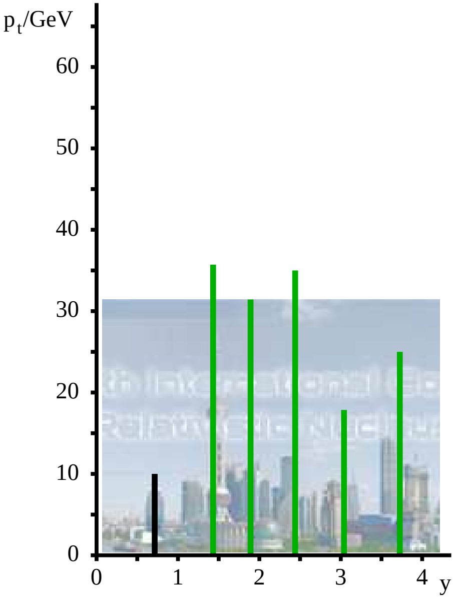

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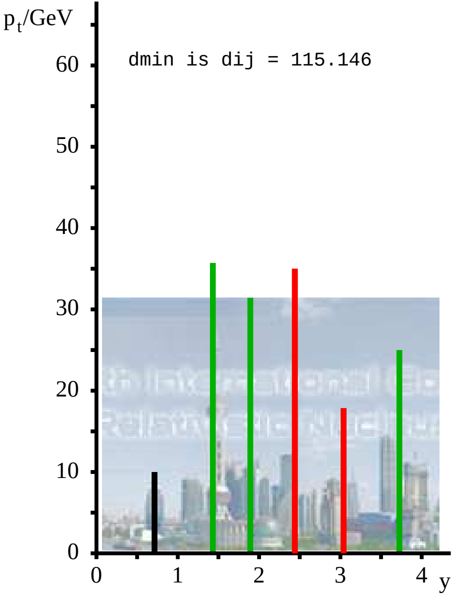

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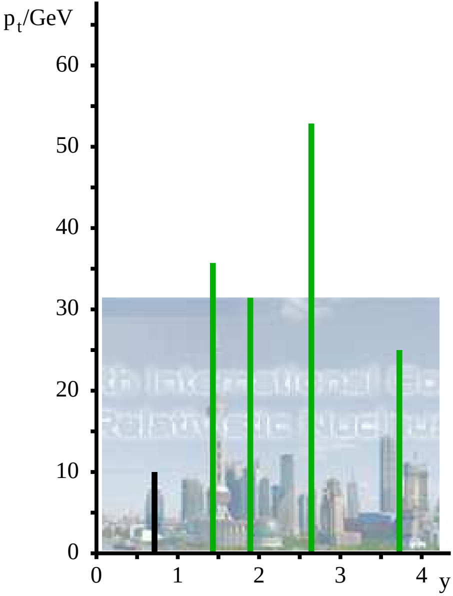

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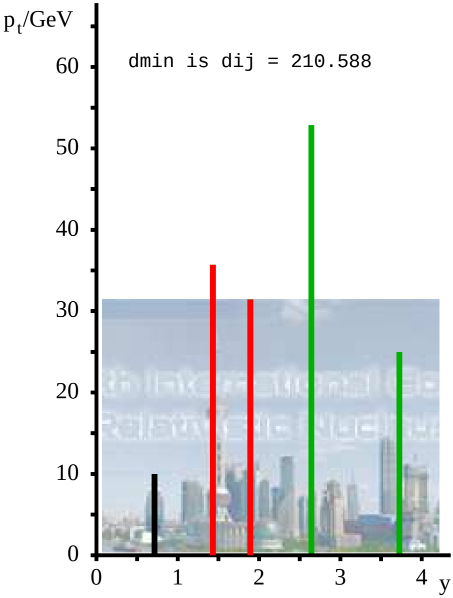

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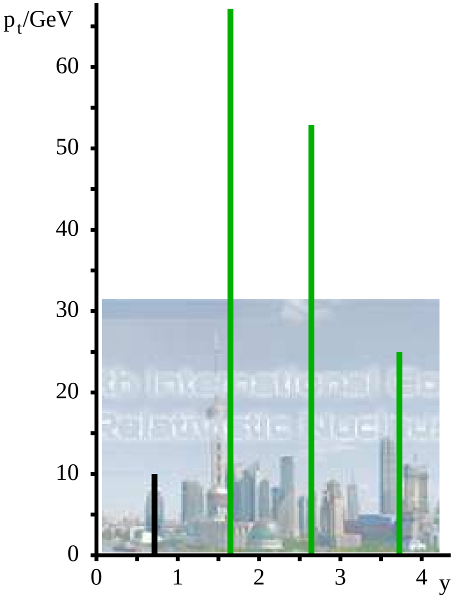

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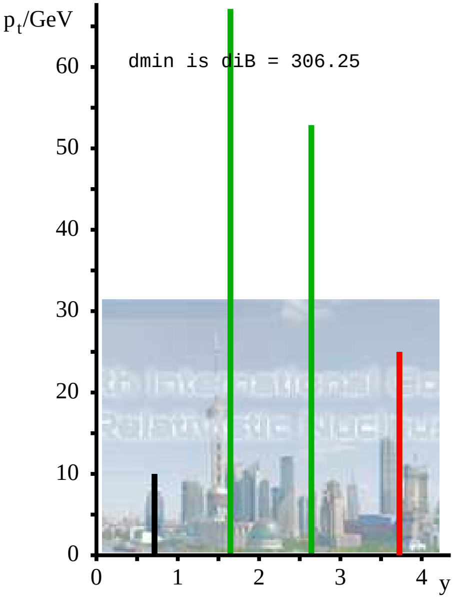

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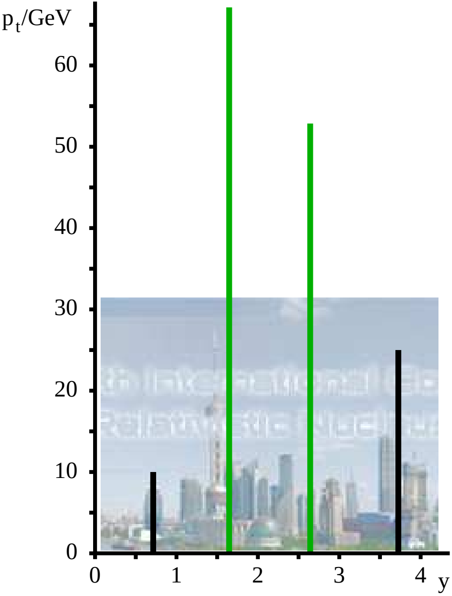

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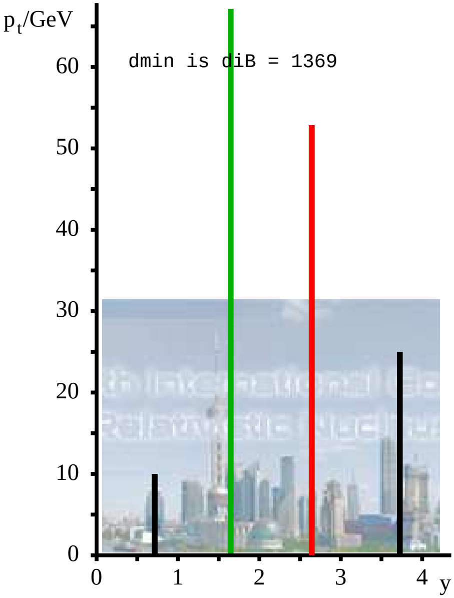

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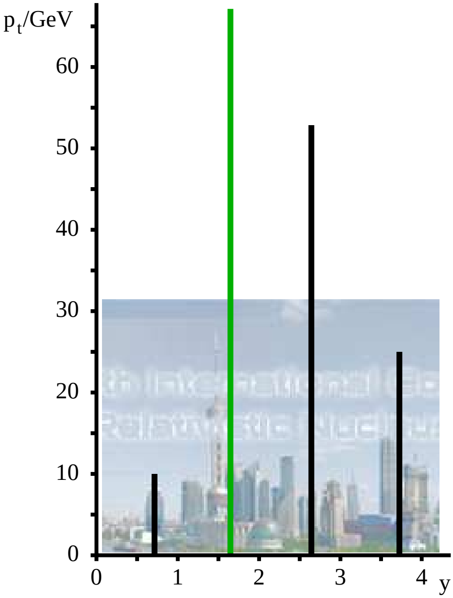

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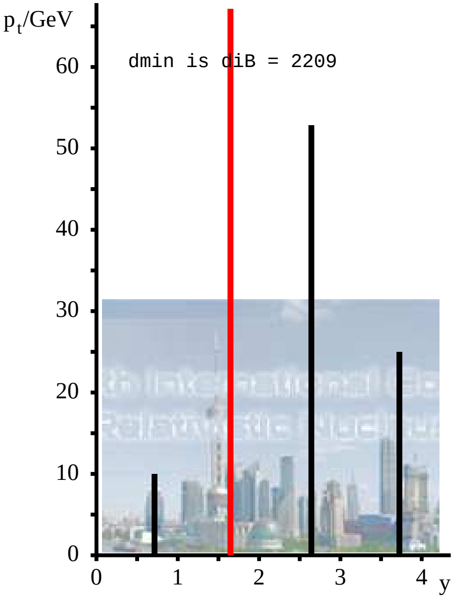

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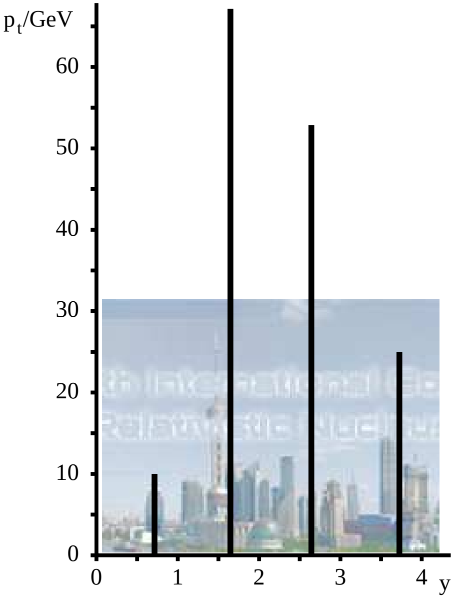

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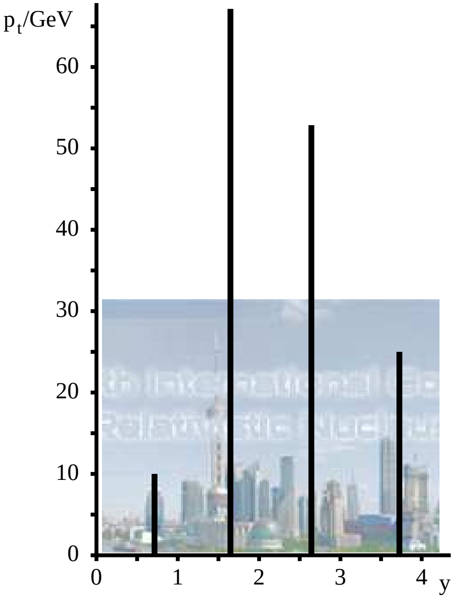

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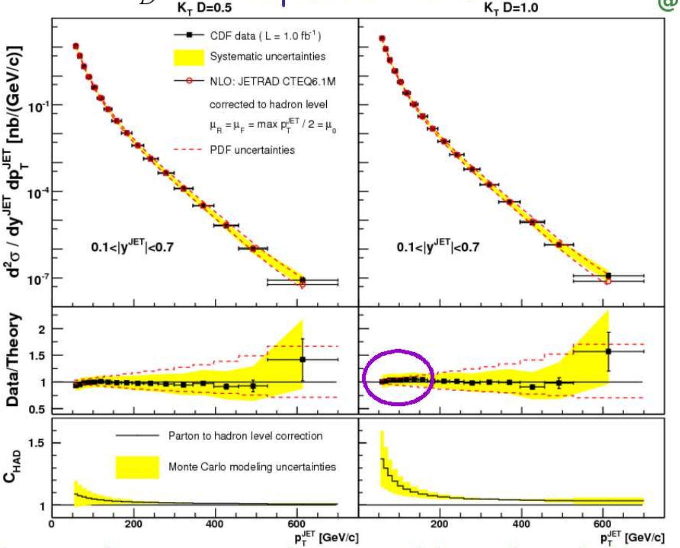
$$d_{ij} = \min(P^2_{T,i}, P^2_{T,j}) \frac{\Delta R^2}{D^2}$$

k_T Jets vs D

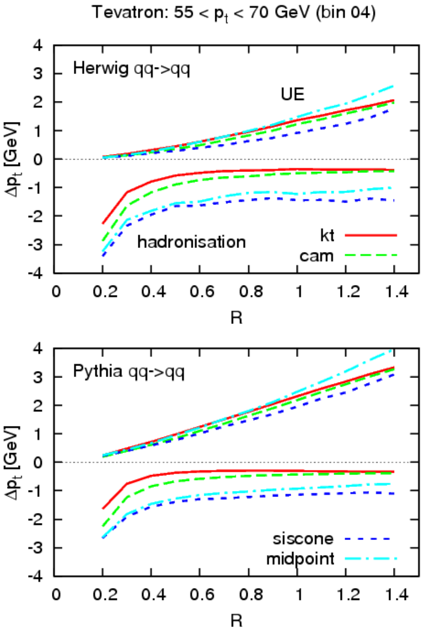
Norniella for CDF coll.
@ Moriond 07



As D increase the measurement is more sensitive to the underlying event contribution (important at low p_T).

The results show that the non-perturbative effect corrections are under control

Non-pert physics v. R



How do non-perturbative effects shift the p_t of a jet, as a function of R? Pert. goes as $\alpha_s p_t \ln R$ e.g. de Florian & Vogelsang '07

In a simple approx. (1-gluon) all algs. identical.

- Underlying event $\sim R^2 + \mathcal{O}\left(R^4\right)$
- Hadronisation $\sim -1/R + \mathcal{O}\left(R\right)$

Cacciari, Dasgupta, Magnea & GPS in prep.

"Reality:" algs. not identical, but scaling does mostly hold.

0.5 GeV for hadronisation is just what you expect from e^+e^- thrust.

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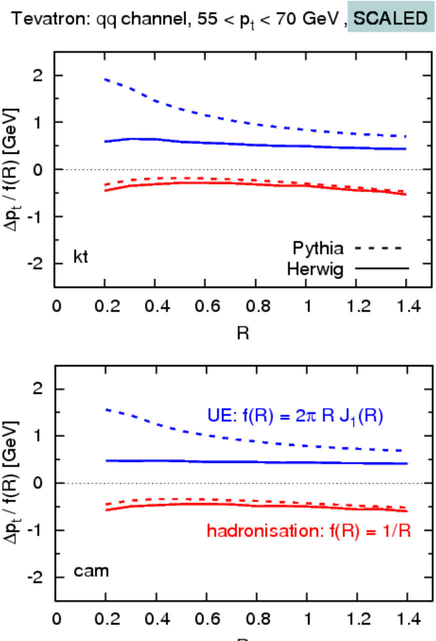

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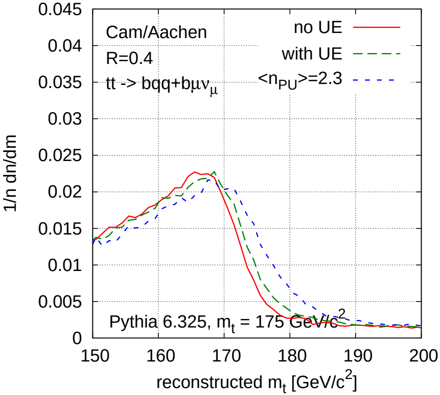

At small R, -7 GeV mass shift + spread — due in large part to hadronisation.

Do you trust Pythia's hadronisation of a $t \to b + W$?

Without UE, $R = 1$ is privileged: distribution peaks at m_t.

With UE $R = 1$ is too contaminated; with pileup (PU) it's even worse.

Best R is the one that minimizes both hadronisation and UE — but you can also check systematic errors by varying R around it.

Varying R, e.g. also Sullivan '04

Changing algorithm, e.g. Seymour & Tevlin '06

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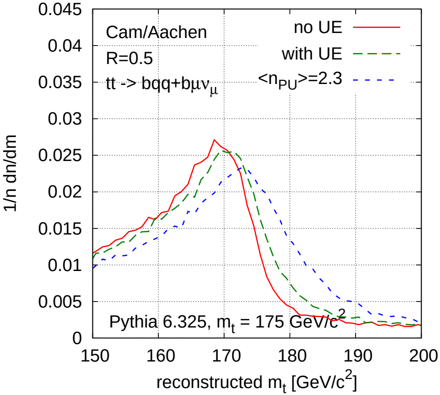

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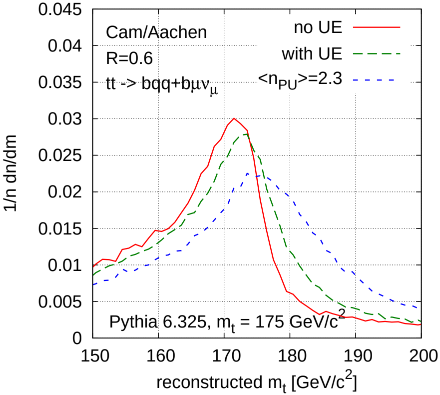

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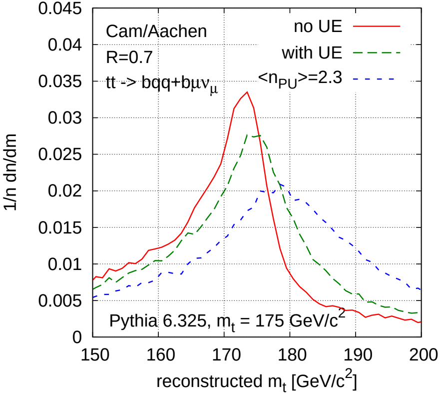

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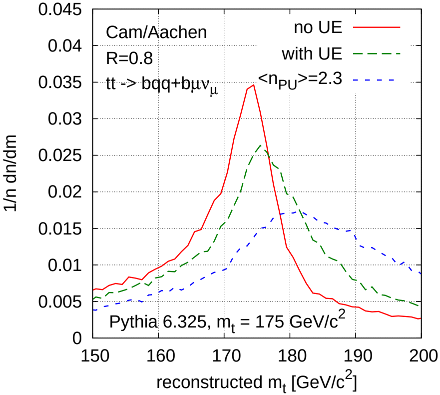

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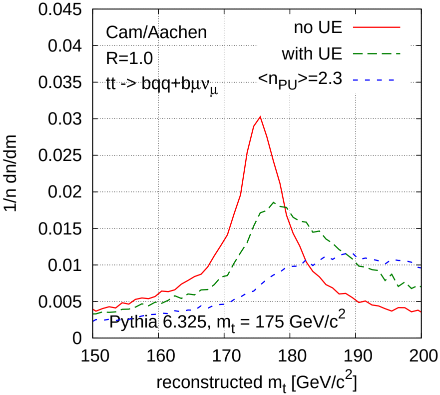

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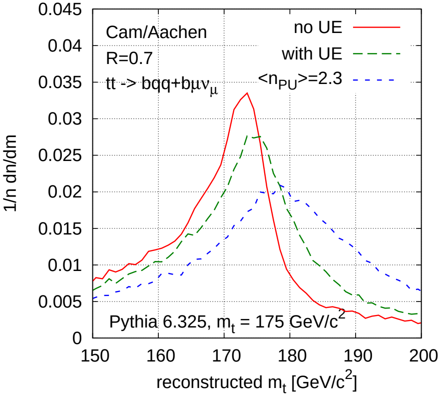

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Can we do better?

At LHC (high-lumi) pileup will be a huge effect, so work is ongoing to understand how to subtract it, jet-by-jet.

Basic method:

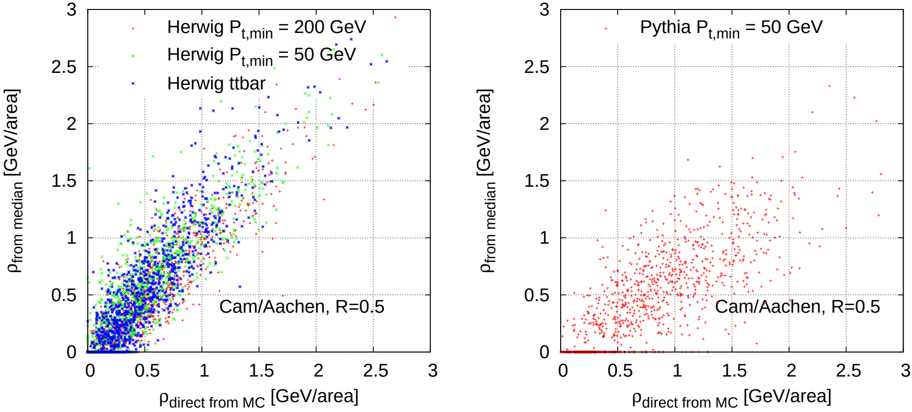
- Measure area A_j of each jet j Cacciari, GPS & Soyez, in prep.
- There are $\sim 50 - 100$ minijets — establish a distribution of p_{tj}/A_j.
- The median of that distribution tells you ρ the level of UE+pileup activity in the event (per unit area)
- Correct each jet with an area-based subtraction:

$$p_{tj} \to p_{tj}^{\text{sub}} = p_{tj} - \rho A_j$$

Cacciari & GPS, in prep.

Method is most impressive at high-lumi LHC, but might it work also at Tevatron?

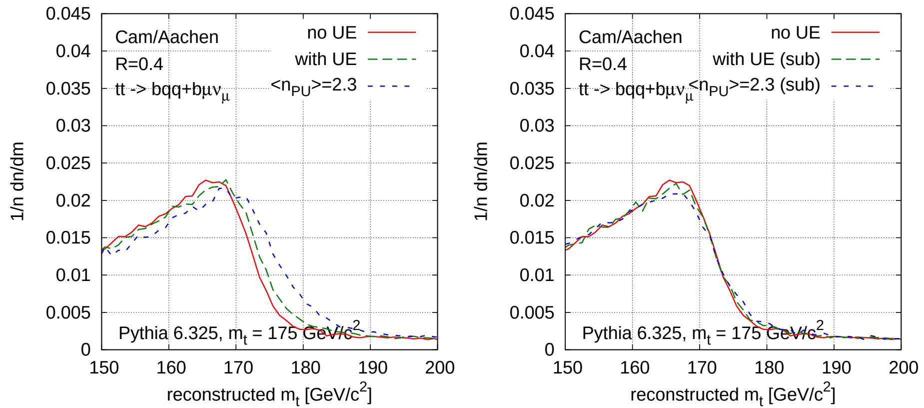
Measuring UE — event-by-event



Significant correlation between measured ρ and total p_t (per unit area) that Herwig/Pythia actually put in for UE.

Less correlation in Pythia, because method measures diffuse UE and Pythia's UE has an additional point-like component

Subtraction for $t\bar{t}$ @ Tevatron?

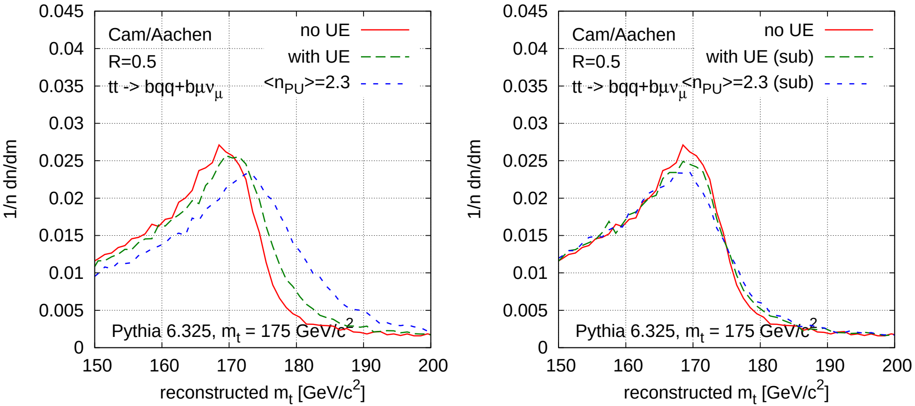


Subtraction correctly removes most of UE and pileup — **without any input from Monte Carlo**

Resolution for UE a bit disappointing

Because UE still fluctuates from point to point

Subtraction for $t\bar{t}$ @ Tevatron?



Subtraction correctly removes most of UE and pileup — **without any input from Monte Carlo**

Resolution for UE a bit disappointing

Because UE still fluctuates from point to point

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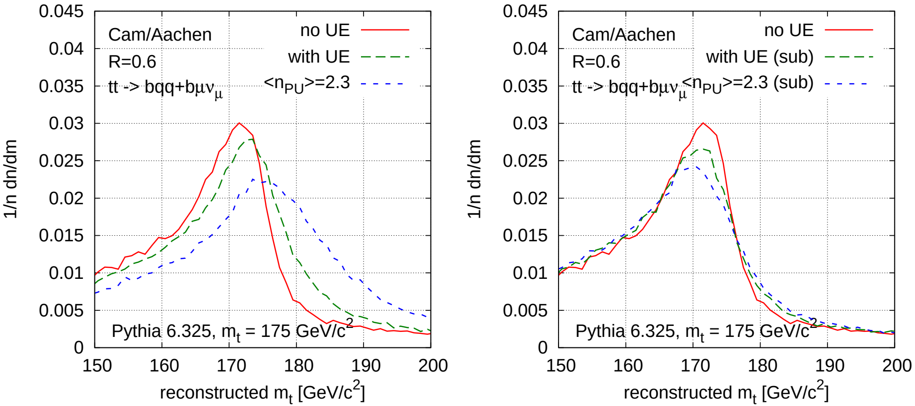

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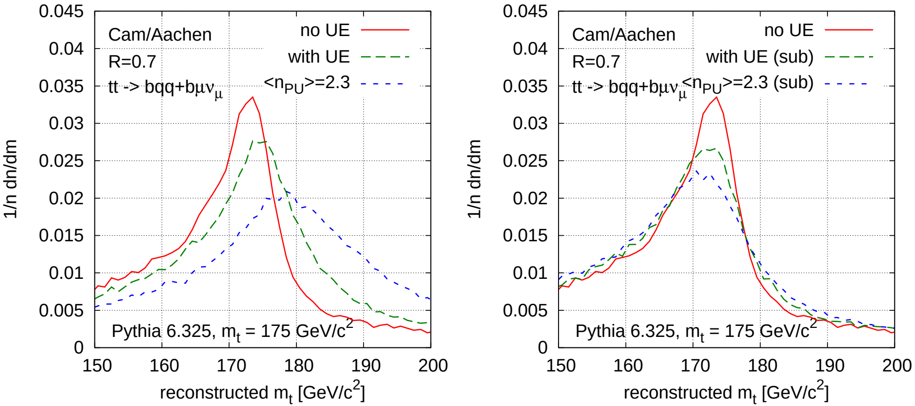

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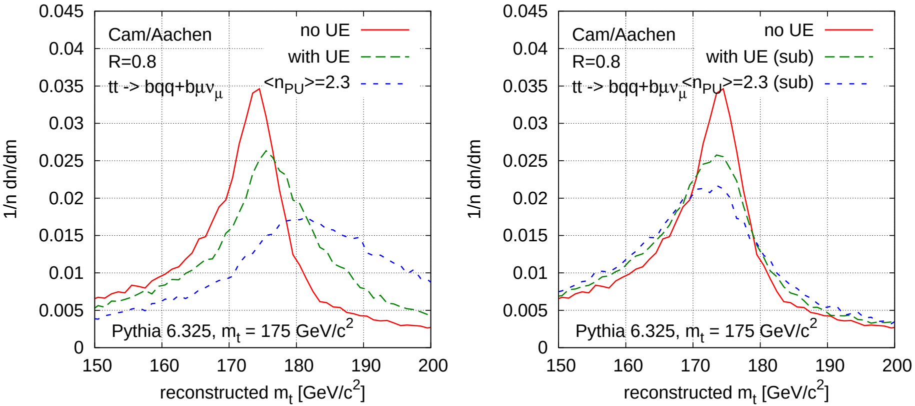

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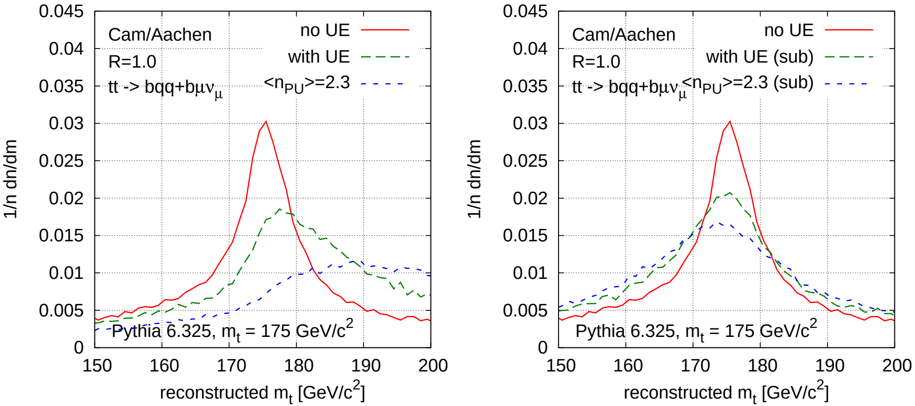

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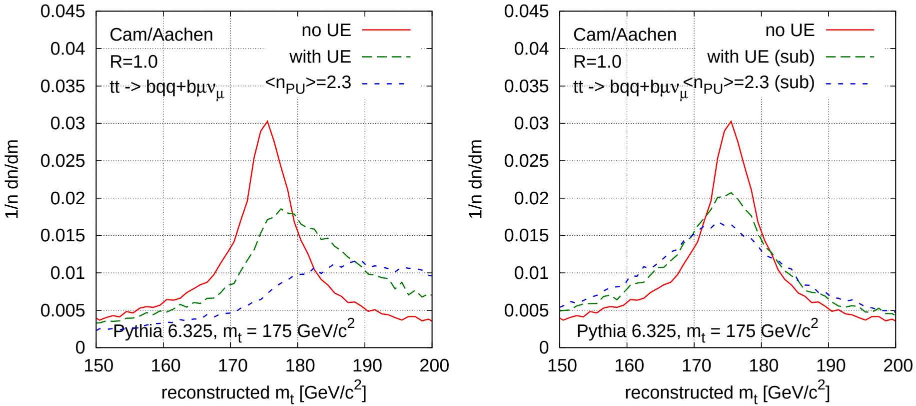

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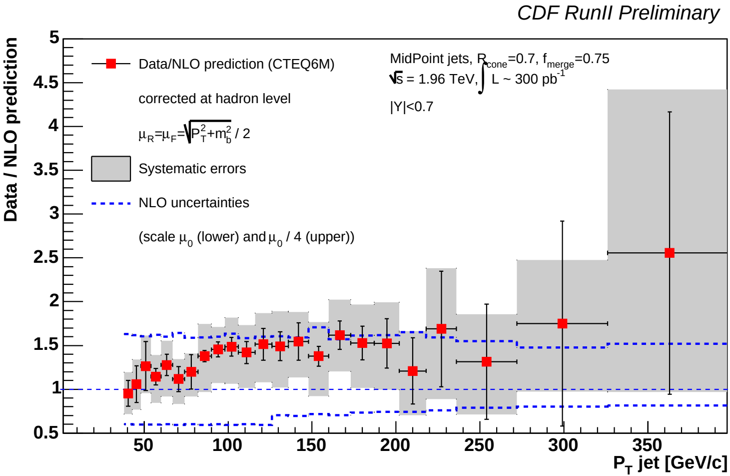
Where is NLO theory at its worst?



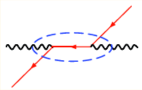
Inclusive *b*-jet spectrum is embarassingly poorly predicted (despite having NLO): 40 – 60% uncertainties.

true even with MC@NLO

NLO heavy quark production mechanisms

At LO:

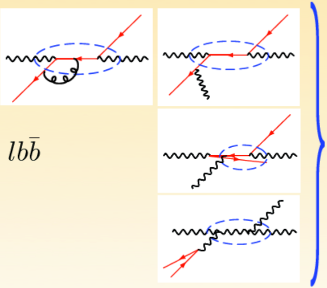
- flavour creation (FC): $ll \to b\bar{b}$



$\mathcal{O}(\alpha_s^2)$

At NLO:

- flavour creation (FC): $ll \to (b \to bl)\bar{b}$
- flavour excitation (FEX): $l(l \to b\bar{b}) \to lb\bar{b}$
- gluon splitting (GSP): $ll \to l(l \to b\bar{b})$

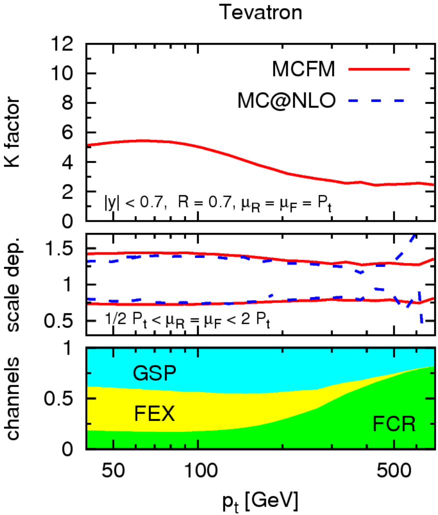


$\mathcal{O}(\alpha_s^3)$

⇒ two new channels open up at NLO

How important are those contributions?

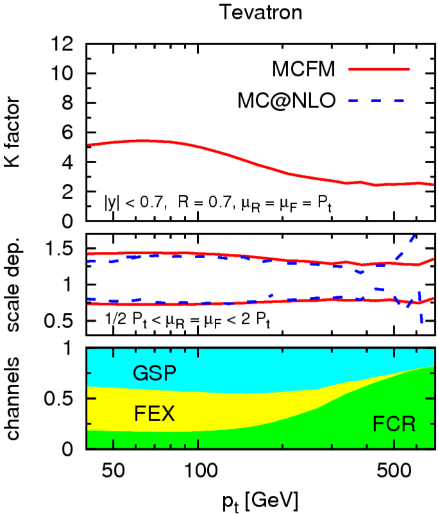
Origin of *n*-jet problems



LO channel (FCR) nearly always smaller than NLO channels (GSP and FEX). Because GSP and FEX enhanced by ln p_t/m_b

Large K-factors and uncertainties both with MCFM and MC@NLO.

Origin of *n*-jet problems



LO channel (FCR) nearly always smaller than NLO channels (GSP and FEX). Because GSP and FEX enhanced by $\ln p_t/m_b$

Large K-factors and uncertainties both with MCFM and MC@NLO.

Suppose we *redefine* *b*-jets:

- A jet with b and $\bar{b}$ inside is *not* a b-jet

cf. CDF 5-flavour tagging?
Kills GSP

- We use a flavour-k_t algorithm, aware of different divergences soft gluons and soft quarks:

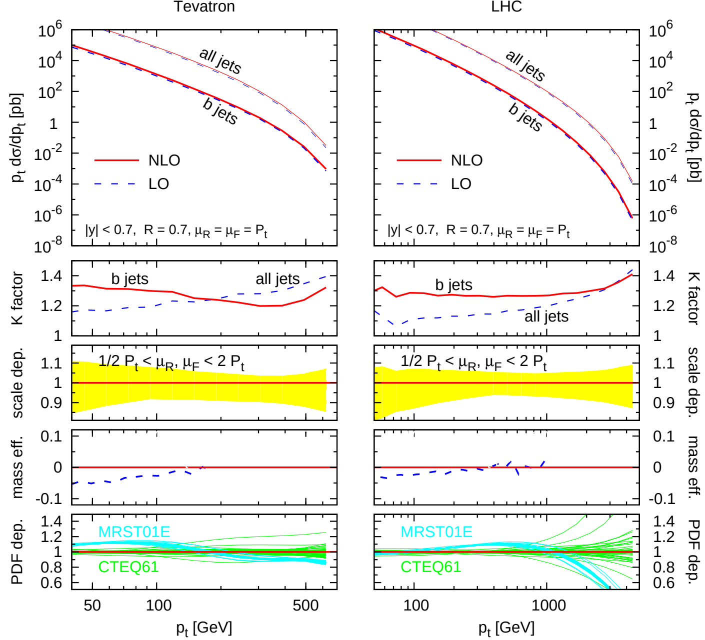
$$d_{ij}^{(F)} = \frac{\Delta R^2}{R^2} \times \begin{cases} \max(k_{ti}, k_{tj})^2 \min(k_{ti}, k_{tj})^2 \,, & \text{softer of } i,j \text{ is flavoured,} \\ \min(k_{ti}^2, k_{tj}^2)\,, & \text{softer of } i,j \text{ is flavourless,} \end{cases}$$

$+$ mod of d_{iB} also; Banfi, GPS & Zanderighi '06

Then *flavour becomes infrared safe*, we can neglect the b-quark mass and do a light-quark calculation (e.g. with NLOJET++)

FEX resummed in b-pdf

Gain factor 3 in accuracy



Conclusions

- QCD higher-order predictions are making progress, but it is an arduous task.
- JetClu (and to lesser extent MidPoint) are IRC unsafe. Use a seedless alternative (SISCone) — or Cambridge/Aachen, k_t, ...

  Otherwise part of theory effort goes to waste
- Some (e.g. non-perturbative) things are going to be very hard to predict. Varying R and changing jet alg. gives you a non-MC handle on them.

  CDF has shown measurements with other algorithms and R are possible
- Can we develop and use tools that will help us constrain (or better predict) poorly understood quantities — e.g. UE, flavour.

  Not just in theory talks but also in experiment!

Thanks to: Andrea Banfi, Matteo Cacciari, Mrinal Dasgupta, Lorenzo Magnea, Gregory Soyez, Giulia Zanderighi.

Some tools from: `http://www.lpthe.jussieu.fr/~salam/fastjet`

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EXTRA SLIDES

SISCone timing

Naive implementation of geometrical idea would run in N^3 time.

N^2 pairs of points, pay N for each pair to check stability

N^3 is also time taken by midpoint codes (smaller coeff.)

With some thought, this reduces to $\mathbf{N^2 \ln N}$ time.

Traversal order, stability check

checkxor

- Much faster than midpoint with no seed threshold

IR unsafe

- Same speed as midpoint codes with seeds > 1 GeV

Collinear unsafe

NB kt & Cam/Aachen (seq. recomb.) algs are much faster

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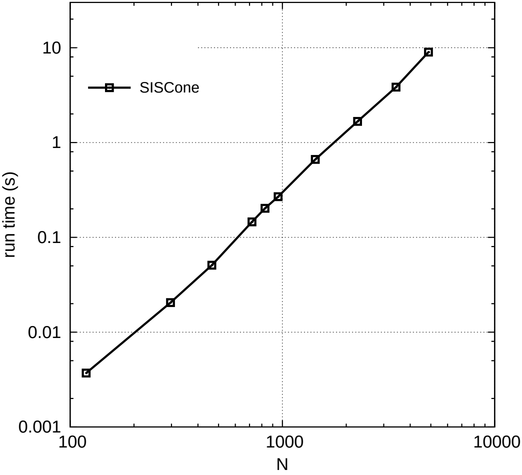

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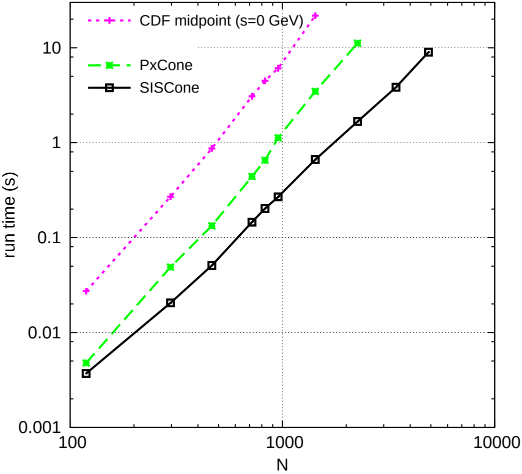

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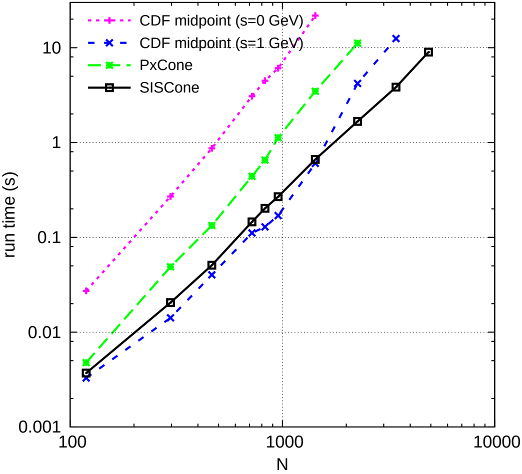

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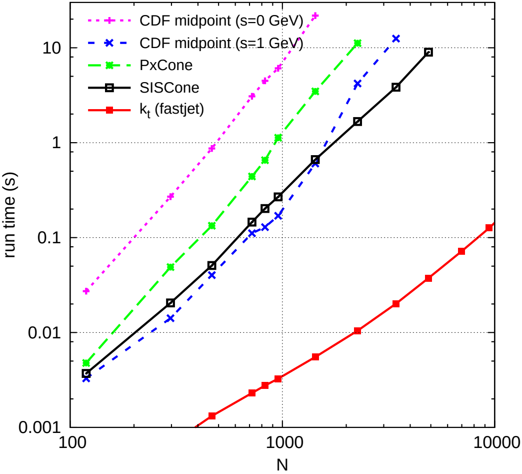


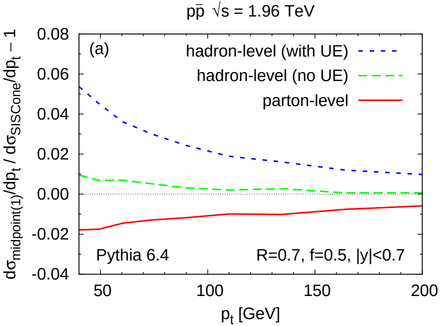
How much does IR safety *really* matter?

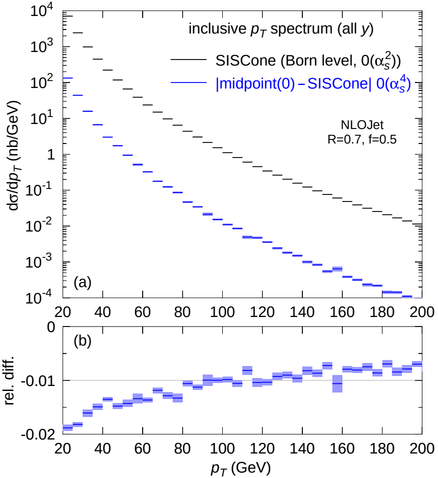
Compare midpoint and SISCone

Result depends on observable:

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

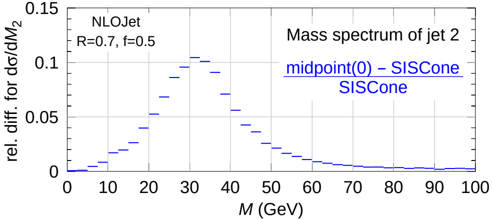
seedless reduces UE effect





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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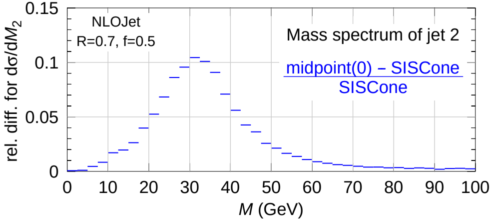

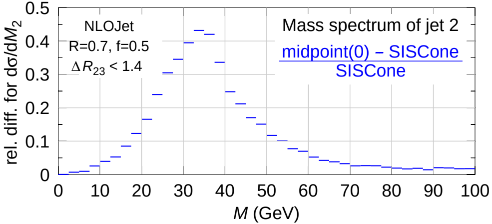

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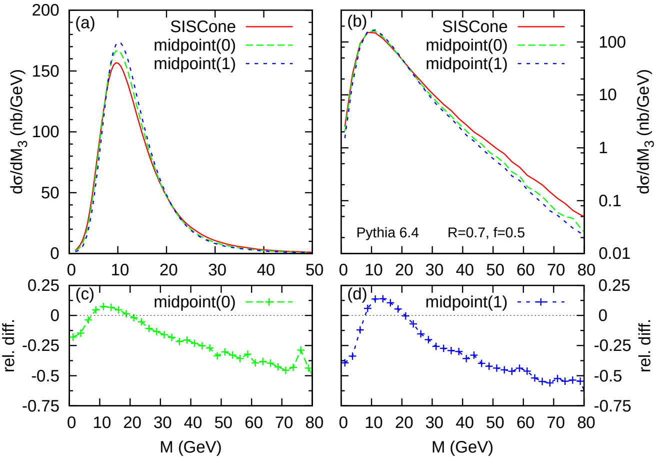
Multi-jet observables: after showering

Showering puts in many extra seeds: missing stable cones (in midpoint) should be less important?

Look at 3rd jet mass distribution (no ΔR_{23} cut):



Missing stable cones → 50% effects even after showering

Algorithm 1: SISCone as a whole

```
Put the set of current particles equal to the set of all particles in the event.
repeat
    Find all stable cones of radius $R$ for the current set of particles, e.g. using algorithm 2.
    For each stable cone, create a protojet from the current particles contained in the cone, and add it to the list of protojets.
    Remove all particles that are in stable cones from the list of current particles.
until No new stable cones are found, or one has gone around the loop $N_{\rm pass}$ times.
Run a Tevatron Run-II type split–merge procedure, algorithm 3, on the full list of protojets, with overlap parameter $f$ and transverse momentum threshold $p_{t,\rm min}$.
```

Algorithm 2: finding stable cones

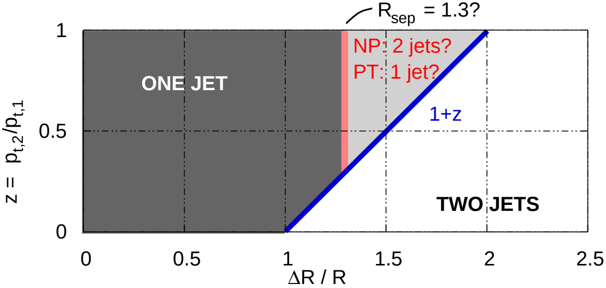
```
For any group of collinear particles, merge them into a single particle.
for particle $i = 1 \dots N$ do
  Find all particles $j$ within a distance $2R$ of $i$. If there are no such particles, $i$ forms a stable cone of its own.
  Otherwise for each $j$ identify the two circles for which $i$ and $j$ lie on the circumference. For each circle, compute the angle of its centre $C$ relative to $i$, $\zeta = \arctan \frac{\Delta\phi_{iC}}{\Delta y_{iC}}$.
  Sort the circles into increasing angle $\zeta$.
  Take the first circle in this order, and call it the current circle. Calculate the total momentum and checkxor for the cones that it defines. Consider all 4 permutations of edge points being included or excluded. Call these the "current cones".
  repeat
    for each of the 4 current cones do
      If this cone has not yet been found, add it to the list of distinct cones.
      If this cone has not yet been labelled as unstable, establish if the in/out status of the edge particles (with respect to the cone momentum axis) is the same as when defining the cone; if it is not, label the cone as unstable.
    end for
    Move to the next circle in order. It differs from the previous one either by a particle entering the circle, or one leaving the circle. Calculate the momentum for the new circle and corresponding new current cones by adding (or removing) the momentum of the particle that has entered (left); the checkxor can be updated by XORing with the label of that particle.
  until all circles considered.
end for
for each of the cones not labelled as unstable do
  Explicitly check its stability, and if it is stable, add it to the list of stable cones (protojets).
end for
```

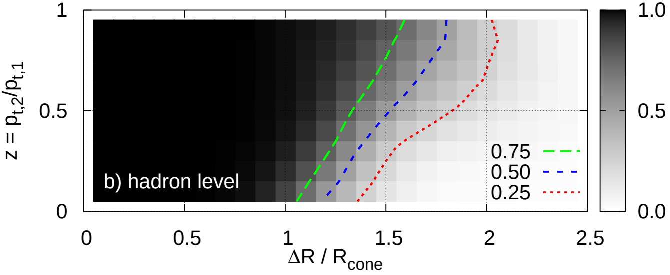
Algorithm 3: split–merge

```
 1: repeat
        Remove all protojets with $p_t < p_{t,\min}$.
        Identify the protojet ($i$) with the highest $\tilde{p}_t$ ($\tilde{p}_{t,\mathrm{jet}} = \sum_{i \in \mathrm{jet}} |p_{t,i}|$).
        Among the remaining protojets identify the one ($j$) with highest $\tilde{p}_t$ that shares
        particles (overlaps) with $i$.
 5:     if there is such an overlapping jet then
 6:         Determine the total $\tilde{p}_{t,\mathrm{shared}} = \sum_{k \in i \& j} |p_{t,k}|$ of the particles shared between $i$
            and $j$.
 7:         if $\tilde{p}_{t,\mathrm{shared}} < f \tilde{p}_{t,j}$ then
                Each particle that is shared between the two protojets is assigned to the one
                to whose axis it is closest. The protojet momenta are then recalculated.
 9:         else
                Merge the two protojets into a single new protojet (added to the list of protojets, while the two original ones are removed).
11:         end if
12:         If steps 7–11 produced a protojet that coincides with an existing one, maintain
            the new protojet as distinct from the existing copy(ies).
13:     else
            Add $i$ to the list of final jets, and remove it from the list of protojets.
15:     end if
16: until no protojets are left.
```

R_{sep}

When do two partons (separated by ΔR, with $z = p_{t2}/p_{t1}$) recombine?





Top mass issues

- Which mass ($\overline{\mathrm{MS}}$, pole?) does the Pythia top mass correspond to?

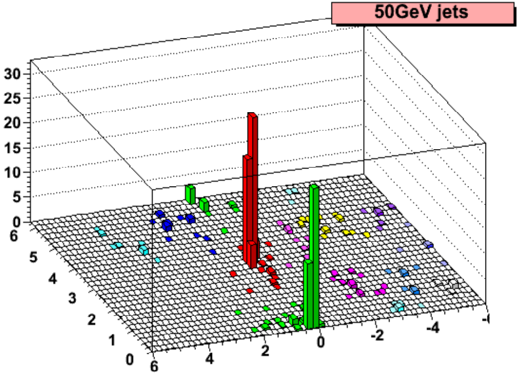
  Pythia is LO — question has limited sense

  But some form of pole/on-shell mass likey
- Pythia approximates radiation from top, b, (and $W \to q\bar{q}'$?)
- MC@NLO gives exact $\mathcal{O}(\alpha_s)$ radiation from top (as if it were stable)

  But radiation from b (and $W \to q\bar{q}'$?) is still approx.
- Partonic calculation by Bernreuther et al. (2001) has exact radiation (and full NLO) for t & b.
- But all above ignore how top *width* affects radiation?

  Relevant for $E \sim \Gamma \sim 1$ GeV

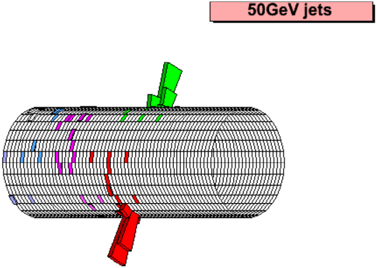
What is speed good for?



‘Standard hard’ event
Two well isolated jets

$\sim$ 200 particles

Easy even with old methods



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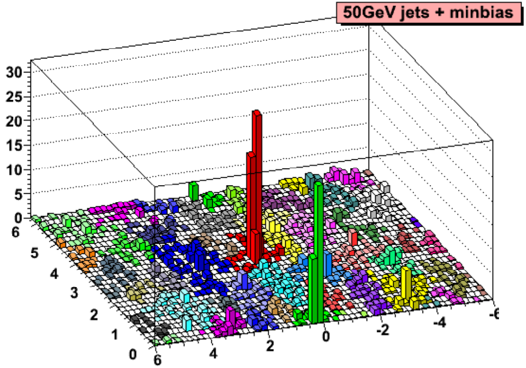
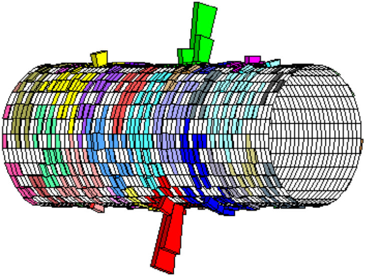


Add 10 min-bias events (moderately high lumi)

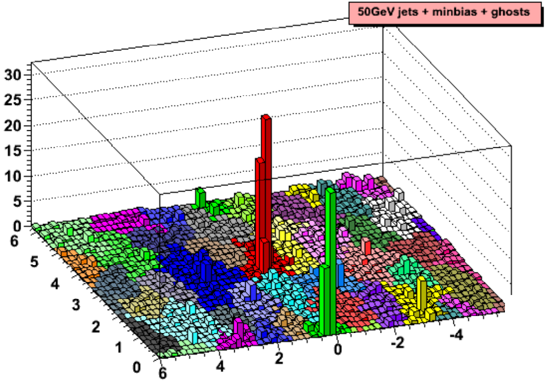


∼ 2000 particles

Clustering takes $\mathcal{O}(10s)$ with old methods.

20ms with `FastJet`.

What is speed good for?



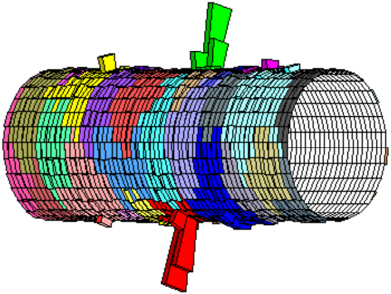
Add dense coverage of infinitely soft *"ghosts"*

See how many end up in jet to measure jet area

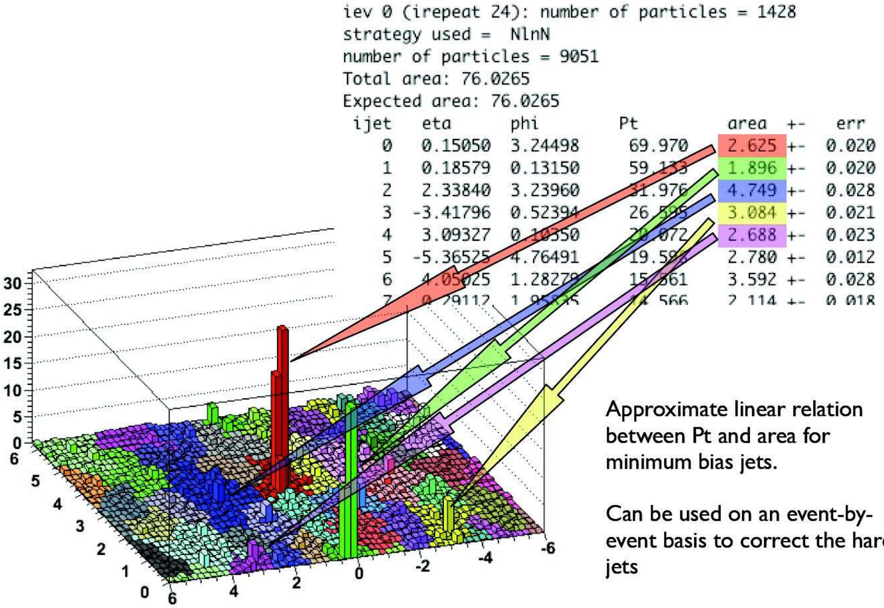
∼ 10000 particles

Clustering takes ∼ 20 minutes with old methods.

0.6s with `FastJet`.



Jet areas

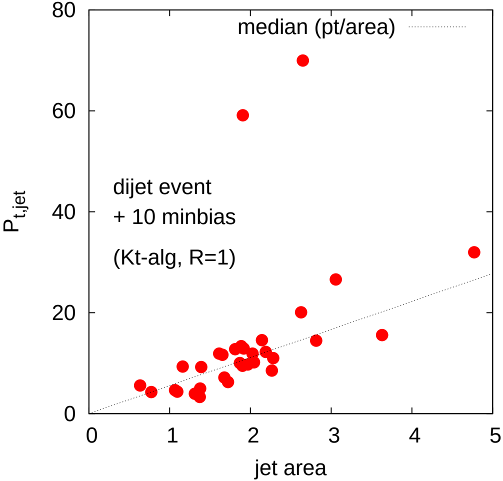


```
iev 0 (irepeat 24): number of particles = 1428
strategy used =  NlnN
number of particles = 9051
Total area: 76.0265
Expected area: 76.0265
 ijet    eta       phi          Pt         area  +-   err
    0   0.15050  3.24498      69.970      2.625 +-  0.020
    1   0.18579  0.13150      59.133      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

Jet areas



Jet areas in k_t algorithm are quite varied

Because k_t-alg adapts to the jet structure

- Contamination from min-bias $\sim$ area

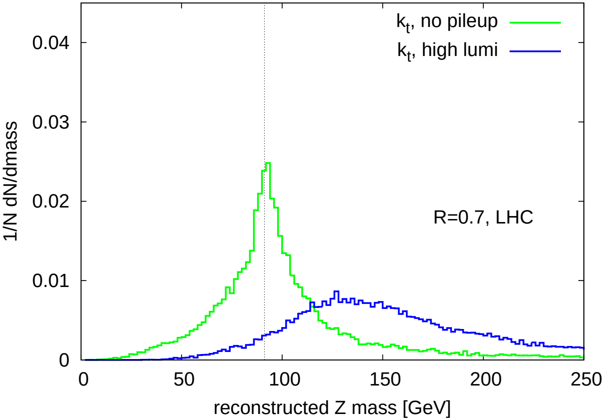
Complicates corrections: min-bias subtraction is different for each jet.

Cone supposedly simpler
Area $= \pi R^2$?

Z mass: k_t v. cone (uncorrected)

Try reconstructing M_Z from $Z \to 2$ jets [Use inv. mass of two hardest jets]

On same events, compare uncorrected k_t v. ILCA (midpoint) cone



k_t allegedly more sensitive to min-bias.
Is this true?

ILCA with standard parameters ($f_{overlap} = 0.5$) fares *very poorly*

ILCA with modified params. is no better than k_t.

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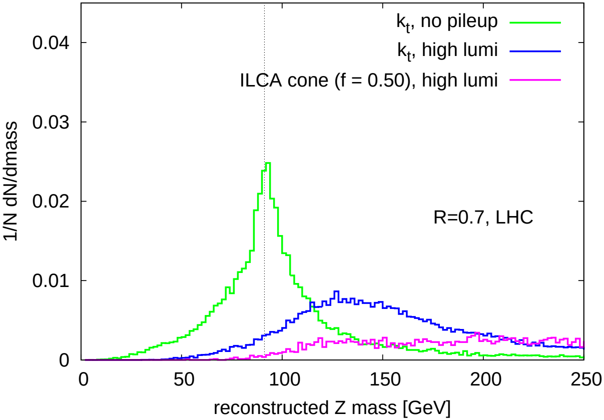

k_t allegedly more sensitive to min-bias.
Is this true?

ILCA with standard parameters ($f_{overlap} = 0.5$) fares *very poorly*

ILCA with modified params. is no better than k_t.

Z mass: k_t v. cone (uncorrected)

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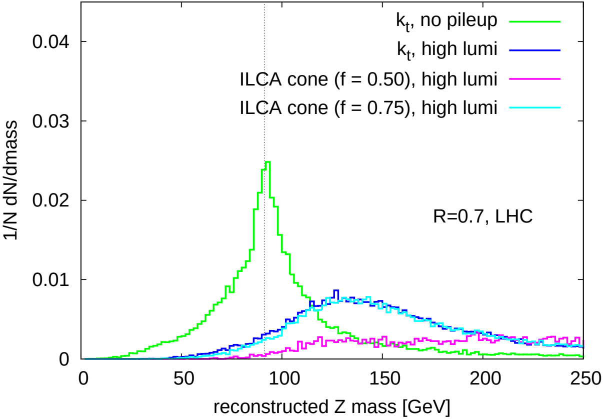

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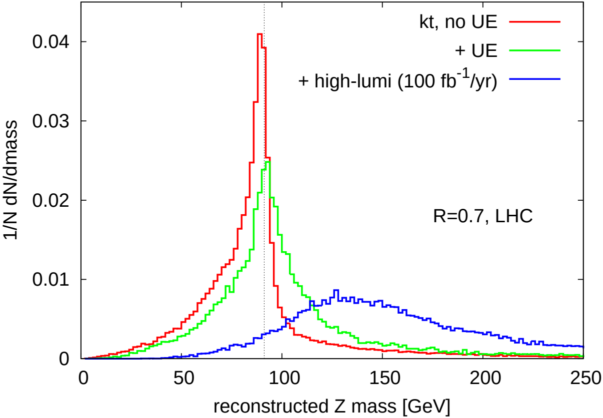
Use jet areas to correct jet kinematics



Correction procedure:

Measure area A of each jet

Find median $p_t/A = Q_0$

Subtract $\Delta p_t = A \times Q_0$ from each jet.

NB: cone much harder to correct this way — too slow to add 10^4 ghosts

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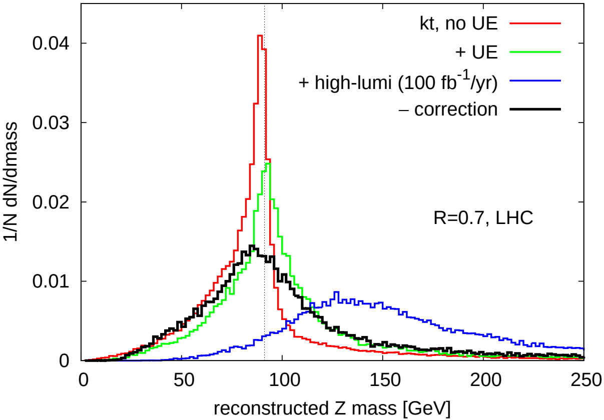

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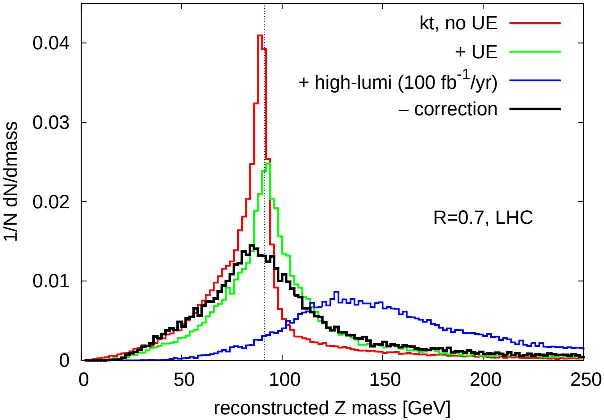

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Analytical results for mean areas

Suppose incoming partons (colour charge C_i) and outgoing jets (col. charge $= C_o$) are not colour connected.

Mean outgoing jet area $\langle A \rangle$ depends on jet P_t as follows:

$$\langle A \rangle = R^2 \left(\pi + (a_0 C_o + a_2 C_i R^2) \frac{\alpha_s}{\pi} \ln \frac{P_t^2}{Q_0^2} + \mathcal{O}\left(\alpha_s, \alpha_s^2 L^2\right) \right)$$

GPS & Cacciari, prelim.

	a_0	a_2	comment
k_t	$+1.771$	$+0.325$	significant, positive
ILCA (cone)	-0.200	-0.325	small, negative
Cam / Aachen	$+0.249$	0	small, positive

For $Q_0 \sim 10$ GeV, $P_t \sim 100 - 1000$ GeV, $\frac{\alpha_s}{\pi} \ln P_t^2/Q_0^2 \sim 0.2 - 0.4$

Cambridge / Aachen algorithm? Like k_t with but $d_{ij} = R_{ij}^2/R^2$ and $d_{iB} = 1$.

Dokshitzer, Leder, Moretti & Webber '97; Wobisch '00