A History of defining jets

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V^e rencontre SPP/IPhT — CEA/Saclay — November 17 2009

Plan

- The past/present: Jet algorithms and jet definitions
  - basic ideas: why jets? recombinations and cones
  - failures of the 20^{th}-century cone algorithms
  - new algorithms in the 21^{st}-century without the failures

- The present/future: how to better use the tools we have?
  - UE sensitivity

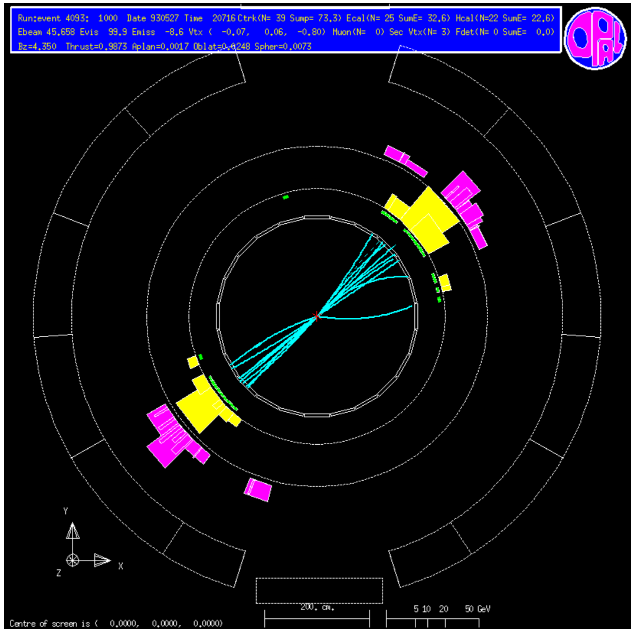
    keywords: *jet areas, subtraction, filtering*
  - boosted taggers (Higgs, top)

    keywords: *same as above* + *subjets*

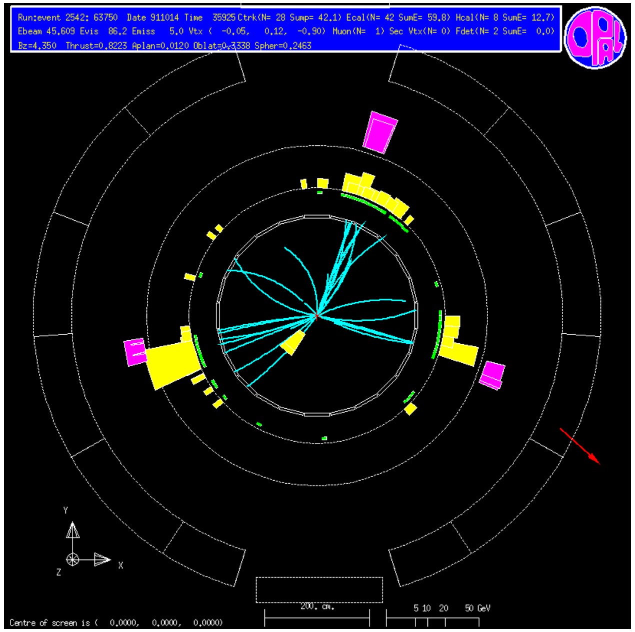
Motivation: why jets

Collinear divergence $\Rightarrow$ QCD produces “jetty” showers

Example: LEP (OPAL) events



2 jets



3 jets

“Jets” $\equiv$ bunch of collimated particles $\cong$ hard partons

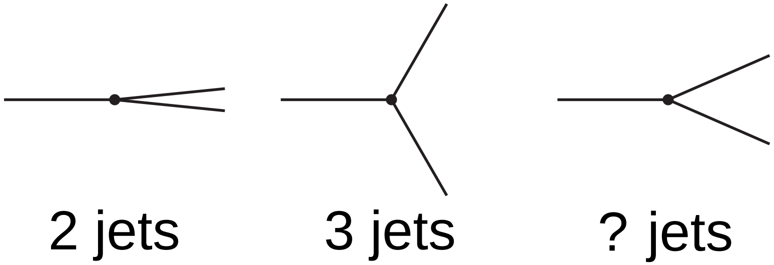
Motivation: why jets

Collinear divergence $\Rightarrow$ QCD produces “jetty” showers

“Jets” $\equiv$ bunch of collimated particles $\cong$ hard partons

BUT

- a “parton” is an ambiguous concept (NLO)
- “collinear” has some arbitraryness



Motivation: why jets

Collinear divergence ⇒ QCD produces “jetty” showers

“Jets” $\equiv$ bunch of collimated particles $\cong$ hard partons

BUT

- a
- “c

In practice: use of a jet definition

$$\text{particles } \{p_i\} \xrightarrow[\text{definition}]{\text{jet}} \text{jets } \{j_k\}$$

Jet algorithm: the recipe (insufficient!)

Jet definition: algorithm + the parameters

20th century jet algorithms

Recombination:

- k_t algorithm
- Cambridge/Aachen alg.

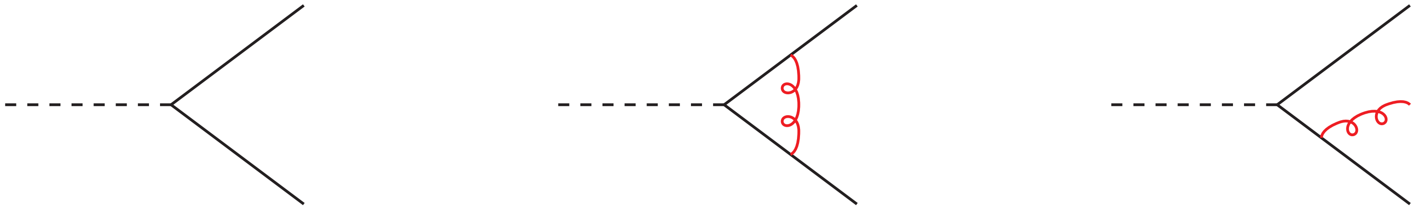
Cone:

- CDF JetClu
- CDF MidPoint
- D0 (run II) Cone
- PxCone
- ATLAS Cone
- CMS Iterative Cone
- PyCell/CellJet
- GetJet

How has that list changed recently?

IR-Coll safety for jets

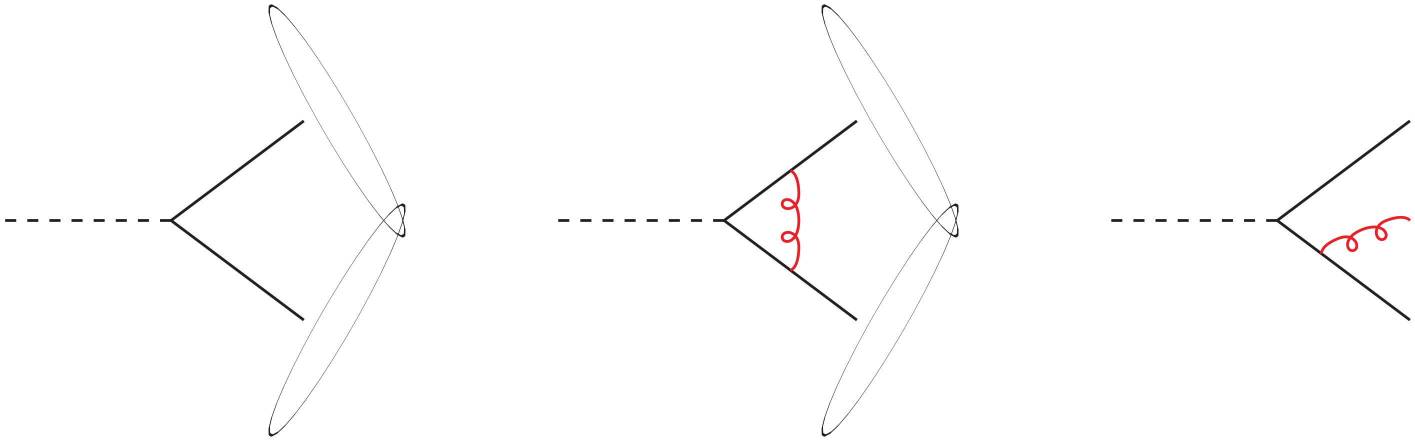
Ingredient: QCD soft and collinear divergencies



- ∞ (from soft gluons) cancel (inclusive x-section)

IR-Coll safety for jets

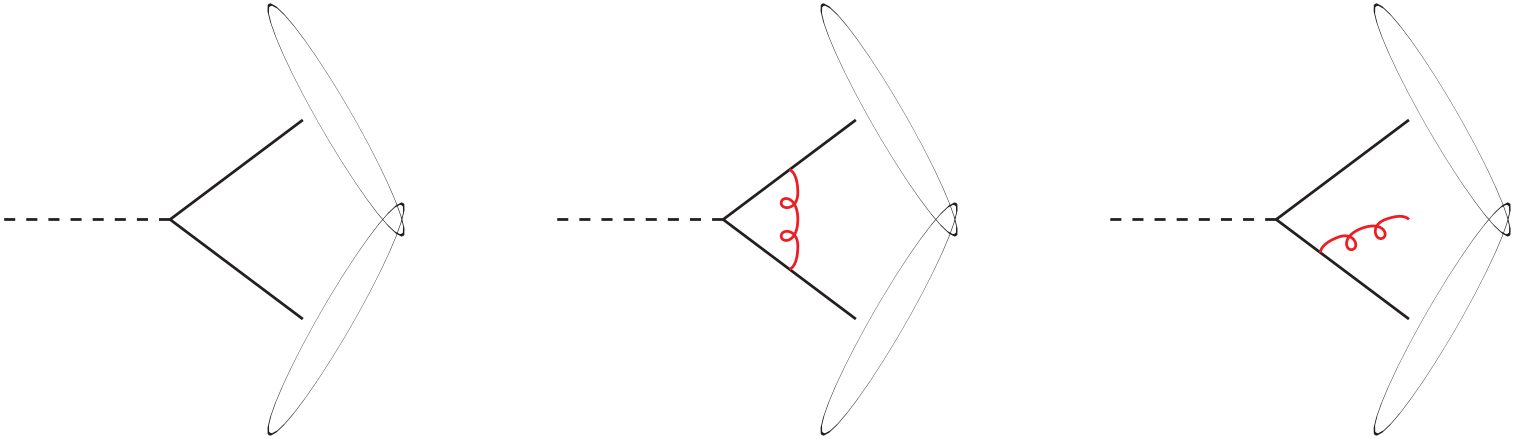
Ingredient: QCD soft and collinear divergencies



- Consider an extra (NLO) soft gluon
- Assume LO gives 2 jets $\Rightarrow$ NLO(virt) gives 2 jets

IR-Coll safety for jets

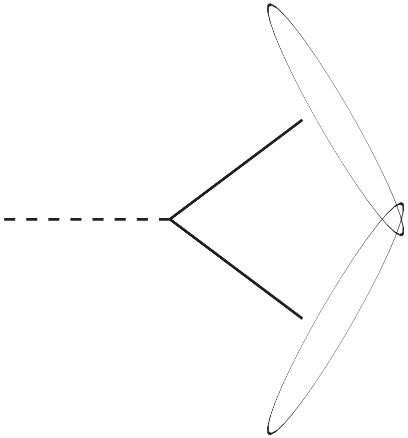
Ingredient: QCD soft and collinear divergencies



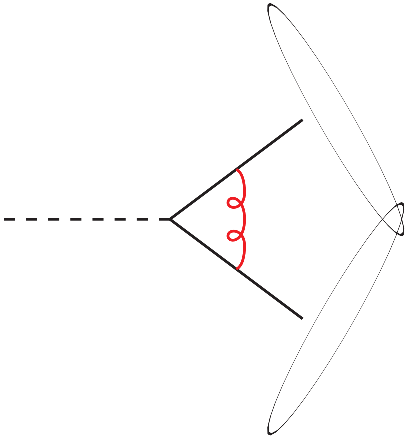
- Consider an extra (NLO) soft gluon
- Assume LO gives 2 jets ⇒ NLO(virt) gives 2 jets
- NLO(real) gives 2 jets ⇒ ∞ cancel ⇒ finite jet cross-section

IR-Coll safety for jets

Ingredient: QCD soft and collinear divergencies

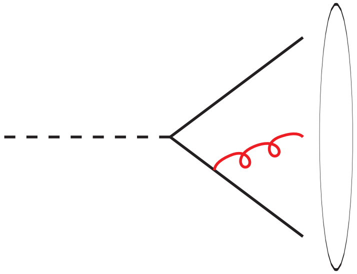


LO



NLO(virt)

∞



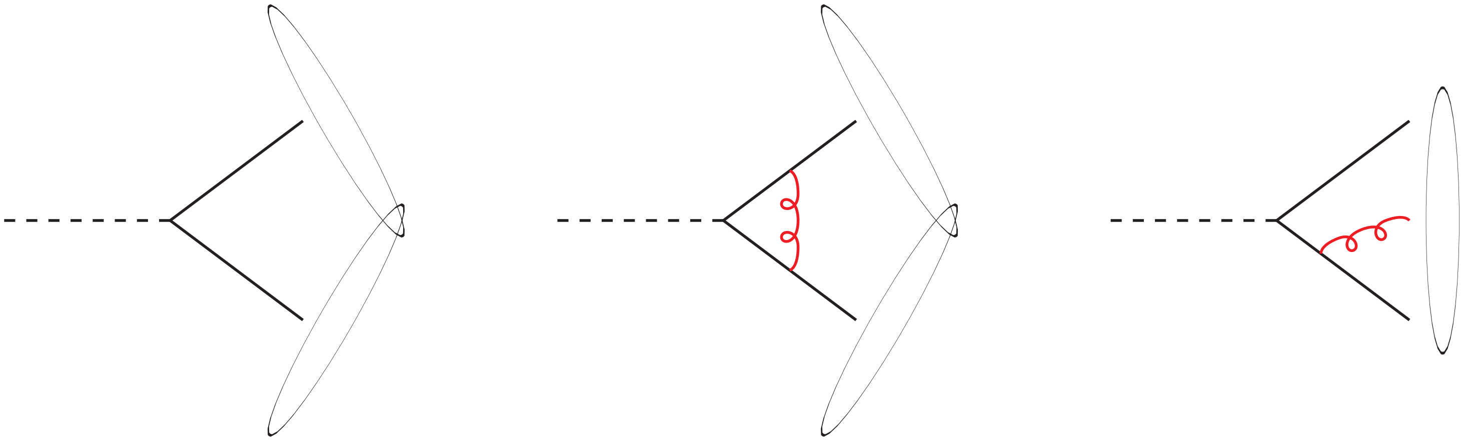
NLO(real)

∞

- Consider an extra (NLO) soft gluon
- Assume LO gives 2 jets $\Rightarrow$ NLO(virt) gives 2 jets
- NLO(real) gives 2 jets $\Rightarrow$ ∞ cancel $\Rightarrow$ finite jet cross-section
  NLO(real) gives 1 jets $\Rightarrow$ ∞ do not cancel $\Rightarrow$ infinite jet x-section

IR-Coll safety for jets

Ingredient: QCD soft and collinear divergencies

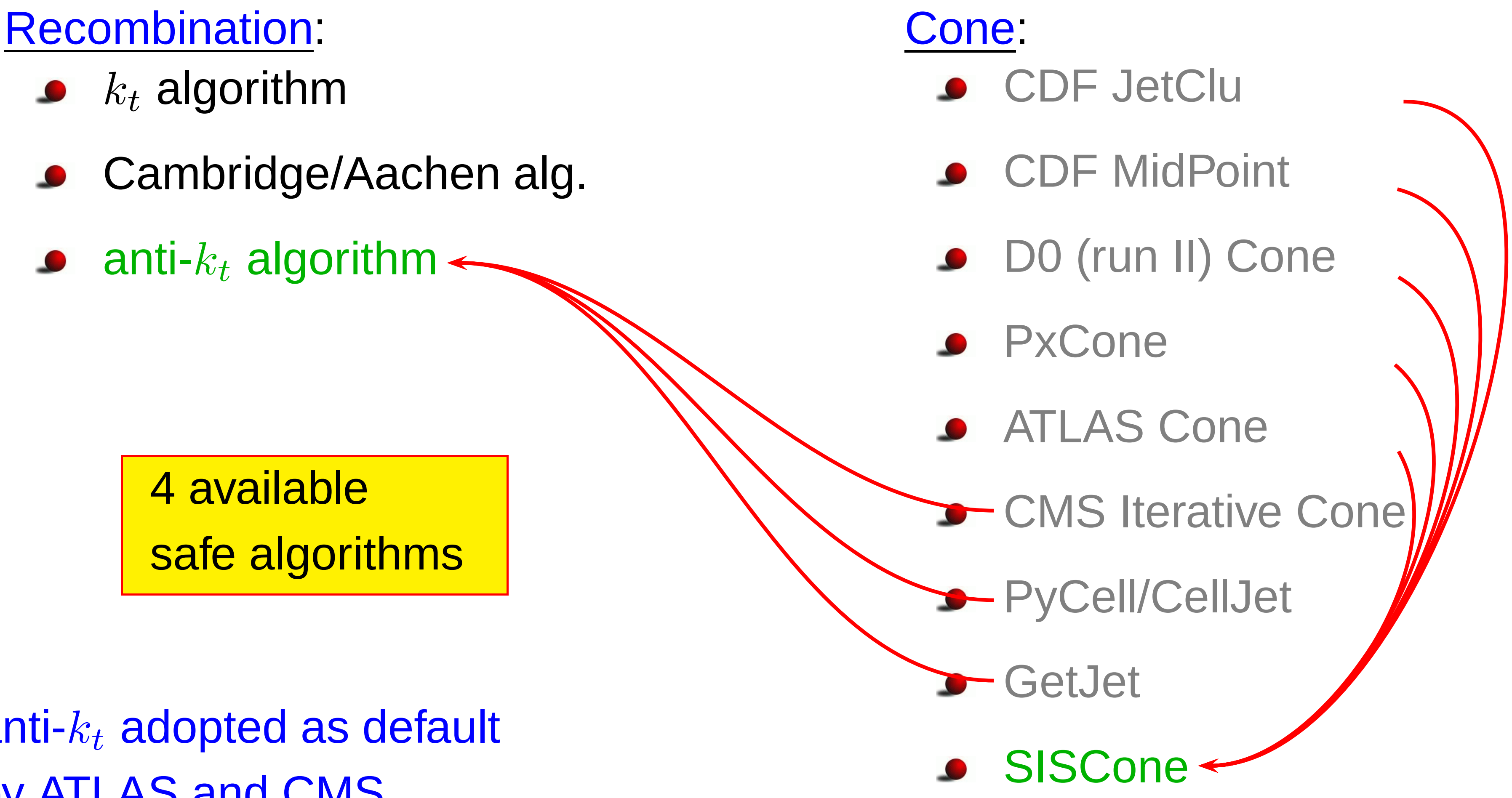


For pQCD to make sense, the (hard) jets should not change when

- one has a soft emission *i.e.* adds a very soft gluon
- one has a collinear splitting
  i.e. replaces one parton by two at the same place (η, ϕ)

[SNOWMASS Accords, Fermilab, 1990]

21st century jet algorithms



Recombination:

- k_t algorithm
- Cambridge/Aachen alg.
- anti-k_t algorithm

Cone:

- CDF JetClu
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- D0 (run II) Cone
- PxCone
- ATLAS Cone
- CMS Iterative Cone
- PyCell/CellJet
- GetJet
- SISCone

4 available
safe algorithms

anti-k_t adopted as default
by ATLAS and CMS

[G.Salam, GS, 07]

[M.Cacciari, G.Salam, GS, 08]

Inside the black box

- Recombination: recombine closest pair until $d > R$

$$d_{ij} = \min\left(k_{t,i}^{2p}, k_{t,j}^{2p}\right)\left(\Delta y_{ij}^2 + \Delta\phi_{ij}^2\right)$$

  - k_t ($p = 1$): the closest to QCD
    matches the soft and collinear divergences of QCD
  - Cambridge/Aachem ($p = 0$): the simplest
    close to k_t in many respects
  - anti-k_t ($p = -1$): gives circular/rigid hard jets
    calibration advantages, a safe CMS iterative cone

- Cone: find a direction of energy flow stable cone $\equiv$ the total momentum points towards the centre of the cone + split–merge for the overlap
  - SISCone: reduced sensitivity to the UE
    a safe CDF JetClu/Midpoint, D0 MidPoint, ATLAS Cone

Inside the black box

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```
#--------------------------------------------------------------------------
#                          FastJet release 2.4
#         Written by M. Cacciari, G.P. Salam and G. Soyez
#                         http://www.fastjet.fr
#--------------------------------------------------------------------------
```

All those algorithms (and much more) implemented (efficiently) in FastJet

- ntum
points towards the centre of the cone + split–merge for the overlap

  - SISCone: reduced sensitivity to the UE
    a safe CDF JetClu/Midpoint, D0 MidPoint, ATLAS Cone

We (finally) have a good set of tools

Can we do better?

A growing list

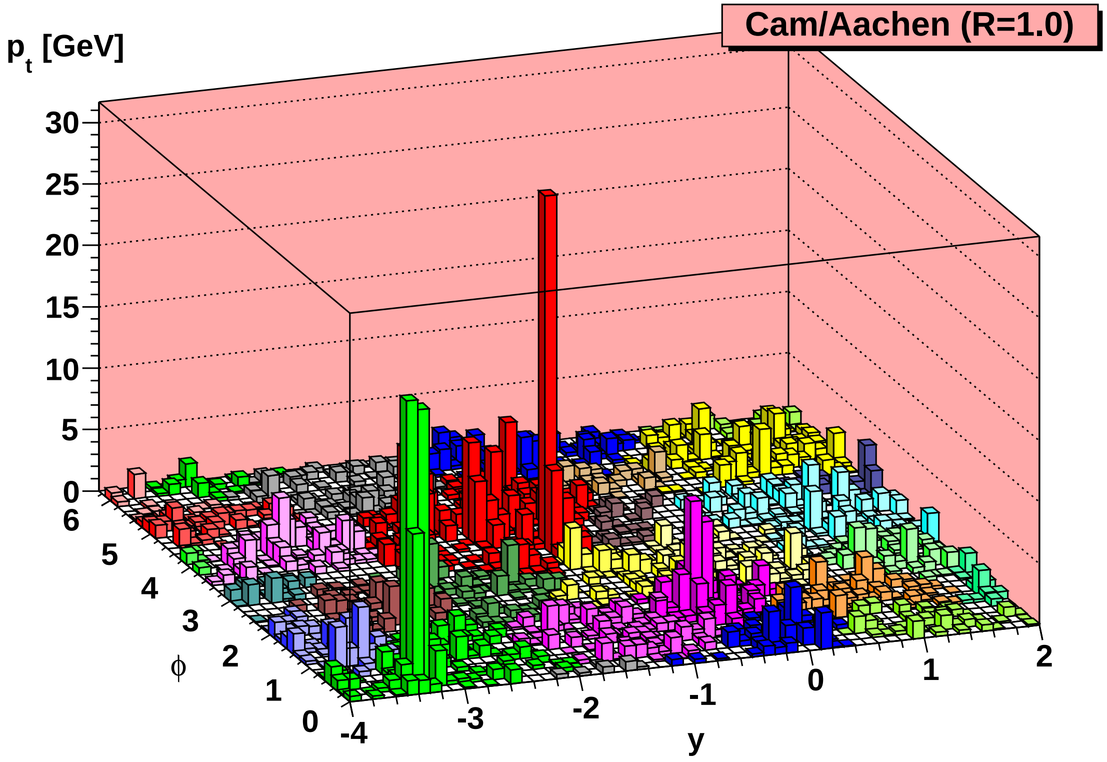
Many ideas and applications:

- Handle soft backgrounds
  - ✓ tune the algorithm, filter
    $\longrightarrow$ ex.: kinematic dijet reconstruction
  - ✓ jet areas and background subtraction
    $\longrightarrow$ UE, pileup, heavy-ion background subtraction
- Tag boosted objects (mostly for discovery purposes)
  - ✓ subjet analysis
    $\longrightarrow H \to b\bar{b},\ t \to bq\bar{q},\ \tilde{\chi}_0^1 \to qqq,\ \ldots$

I will only give a brief overview of what can be done

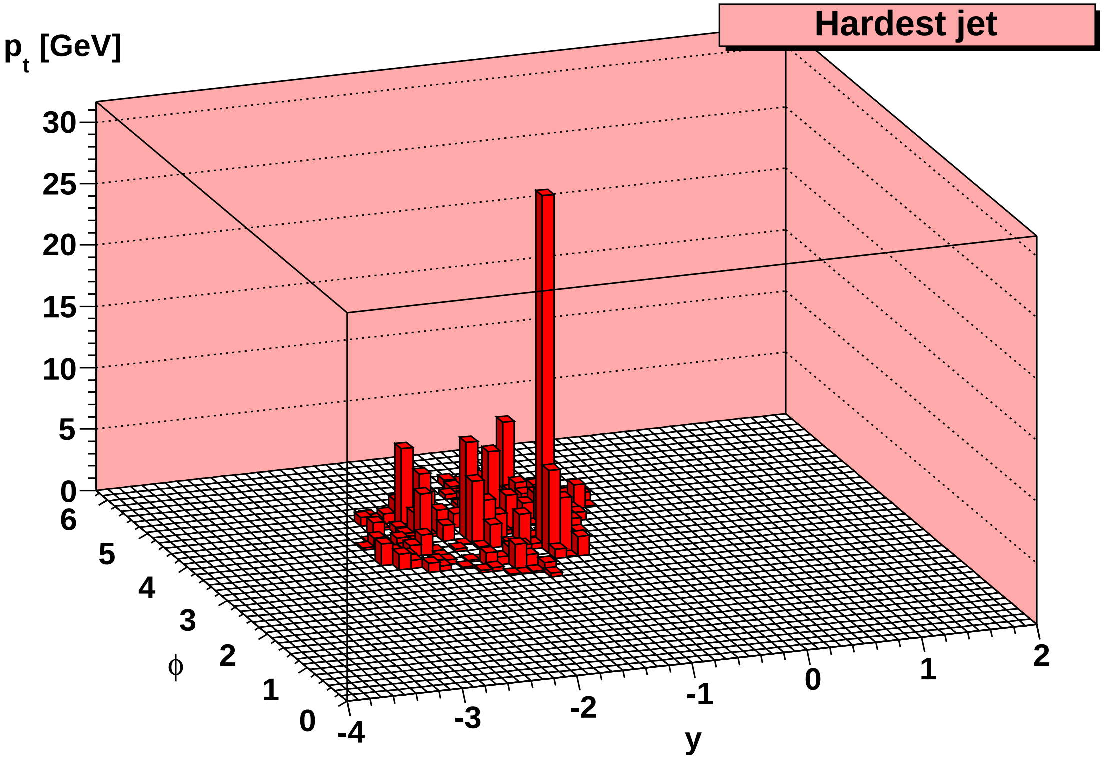
New idea #1: filtering

Filtering



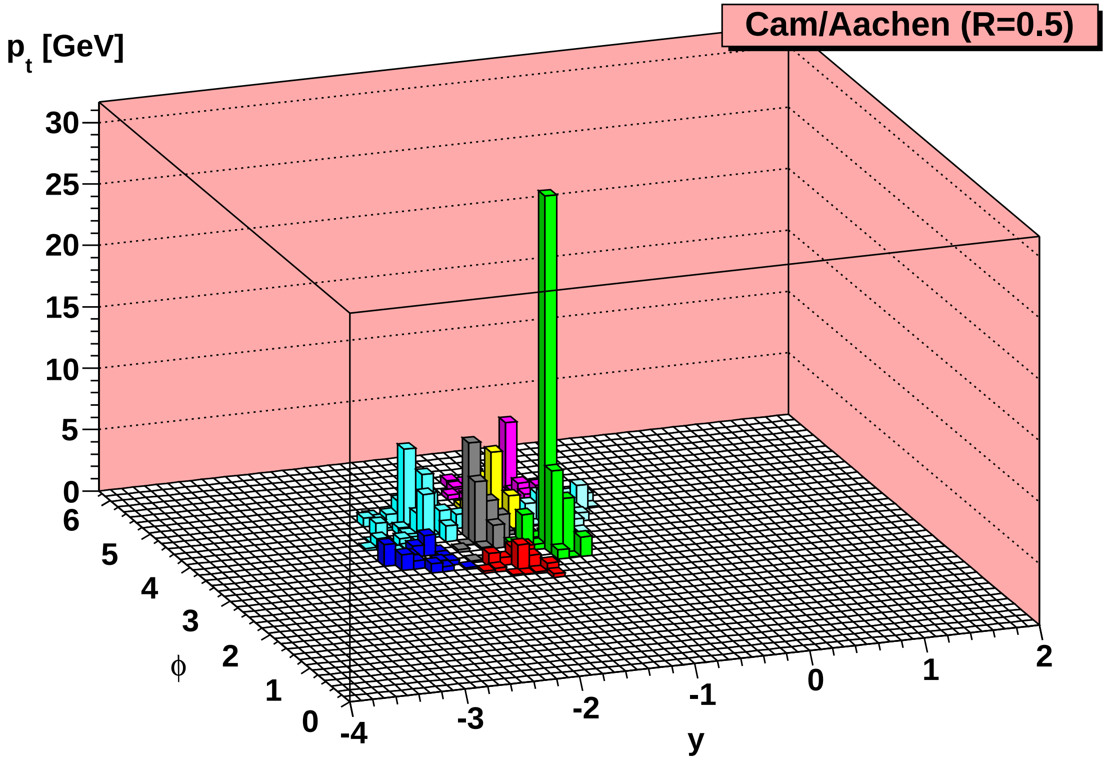
- cluster with Cambridge/Aachen(R)

Filtering



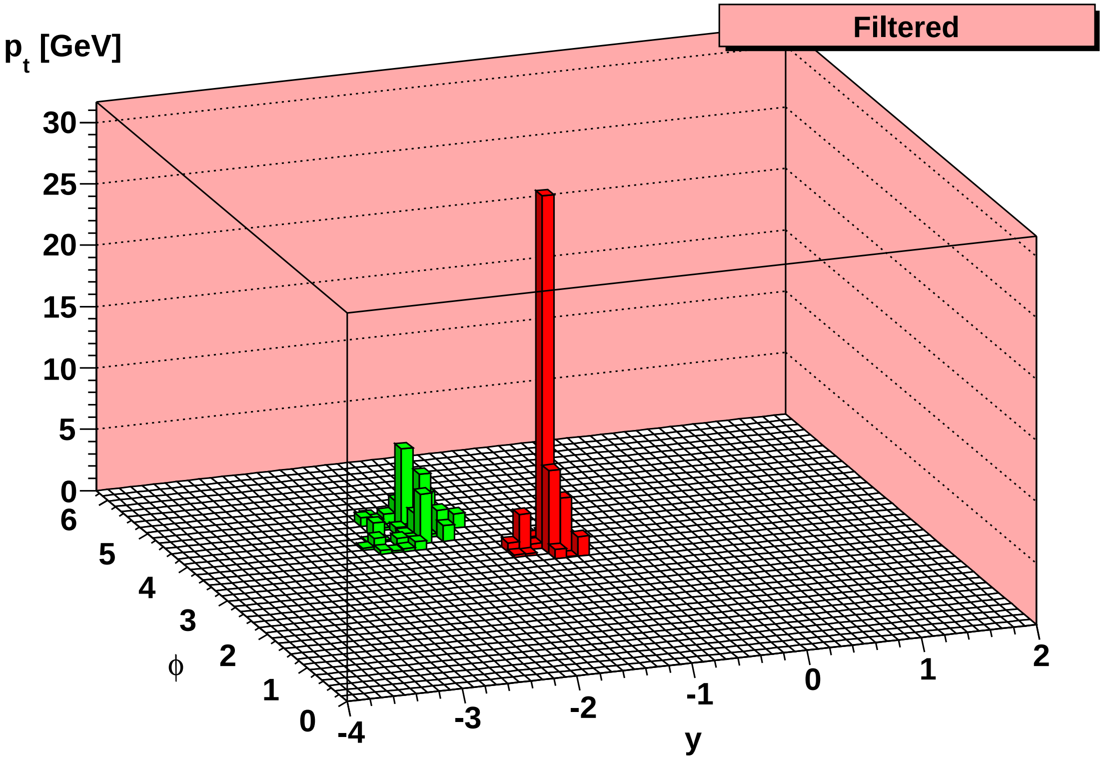
- cluster with Cambridge/Aachen(R)
- for each jet

Filtering



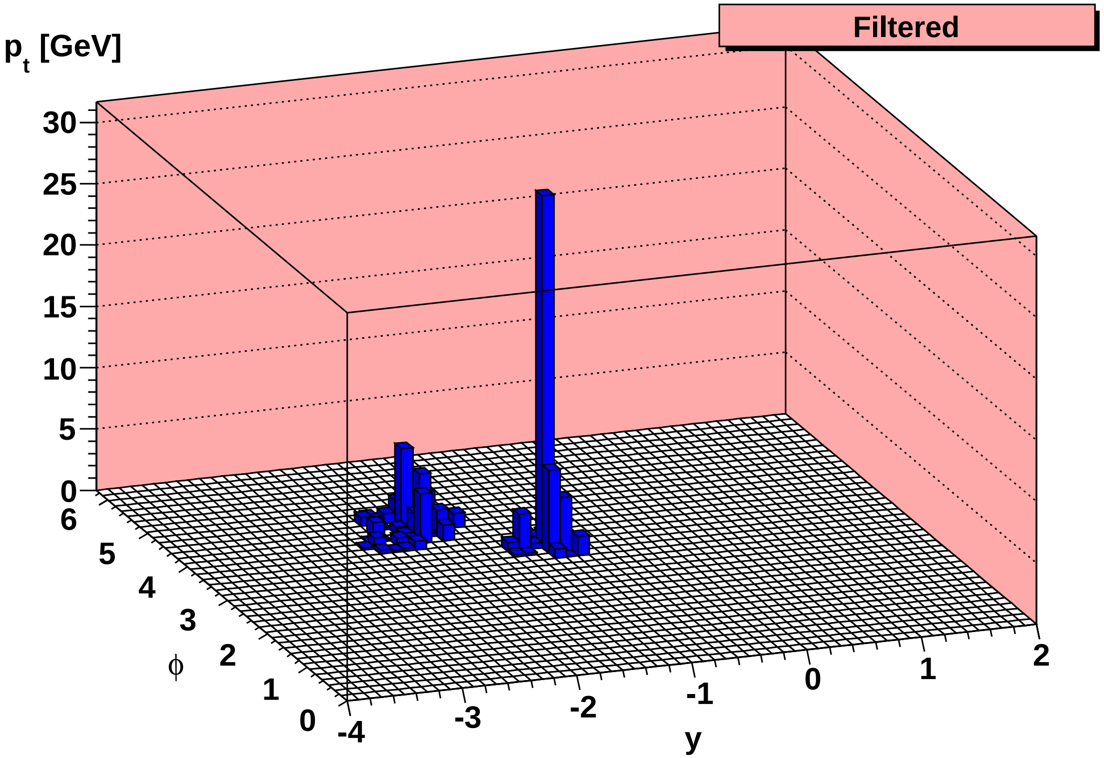
- cluster with Cambridge/Aachen(R)
- for each jet
  - recluster with Cambridge/Aachen(R/2)

Filtering



- cluster with Cambridge/Aachen(R)
- for each jet
  - recluster with Cambridge/Aachen(R/2)
  - keep the 2 hardest subjets

Filtering



- cluster with Cambridge/Aachen(R)
- for each jet
  - recluster with Cambridge/Aachen(R/2)
  - keep the 2 hardest subjets

Idea:

✓ keep perturb. radiation

✓ remove UE

- Proven useful for boosted jet $H \to b\bar{b}$ tagging

  [J.Butterworth, A.Davison, M.Rubin, G.Salam, 08]

- Proven useful for kinematic reconstructions

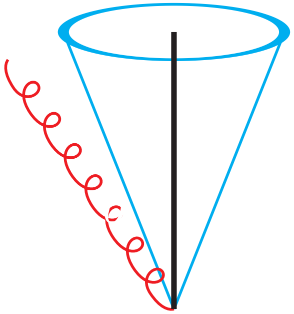
  [M.Cacciari, J.Rojo, G.Salam, GS, 08]

Application:
optimise dijet kinematic reconstruction

The pQCD-vs-UE paradox

Competition between

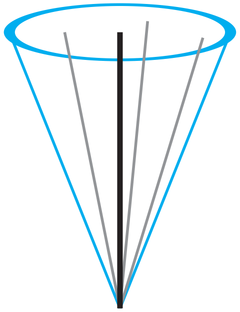
- catching perturbative radiation



Out-of-cone radiation:

$$\langle \delta p_t \rangle \propto -\int_R \frac{d\theta}{\theta} \sim -\log(1/R)$$

- not catching soft background radiation (underlying event)



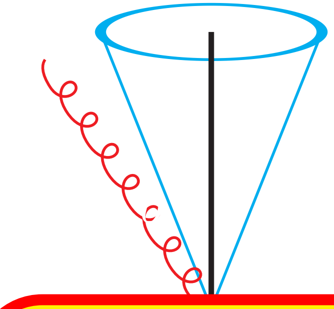
$\langle \delta p_t \rangle \sim$ Soft contents $\propto$ jet area $\sim R^2$

the coefficients depend on the algorithm

The pQCD-vs-UE paradox

Competition between

- catching perturbative radiation

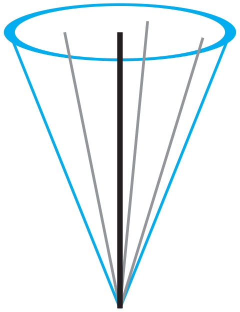


Out-of-cone radiation:

$$\langle \delta p_t \rangle \propto -\int_R \frac{d\theta}{\theta} \sim -\log(1/R)$$

What is the optimal jet definition (algo+R!)?

- not [illegible]



$$\langle \delta p_t \rangle \sim \text{Soft contents} \propto \text{jet area} \sim R^2$$

the coefficients depend on the algorithm

Optimisation: dijet reconstruction

Example process to illustrate various effects:

$$Z' \to q\bar{q} \to 2 \text{ jets}$$

- $M_{Z'}$ can be varied (between 100 GeV and 4 TeV)
- Also valid for $H \to gg$ to study gluon jets
- Reconstruction method:
  - get the 2 hardest jets: j_1 and j_2
  - reconstruct the Z': $m_{Z'} = (j_1 + j_2)^2$

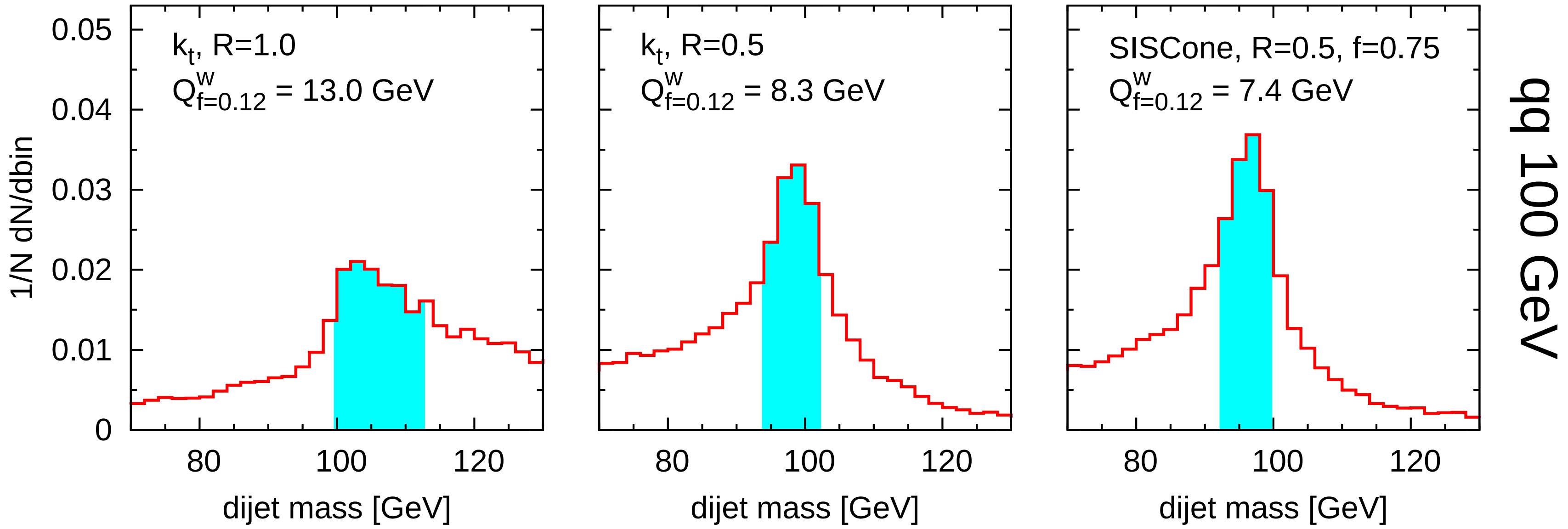
  Look how the mass peak is reconstructed
- Also $t\bar{t}$ with full hadronic decay for multijet tests

Optimisation: quality measure

Measure of the jet reconstruction efficiency:

- Forget about measures related to parton-jet matching
- Forget about fits depending on the shape of the peak

$\Rightarrow$ maximise the signal over background ratio ($S/\sqrt{B}$)
a narrower peak is better.

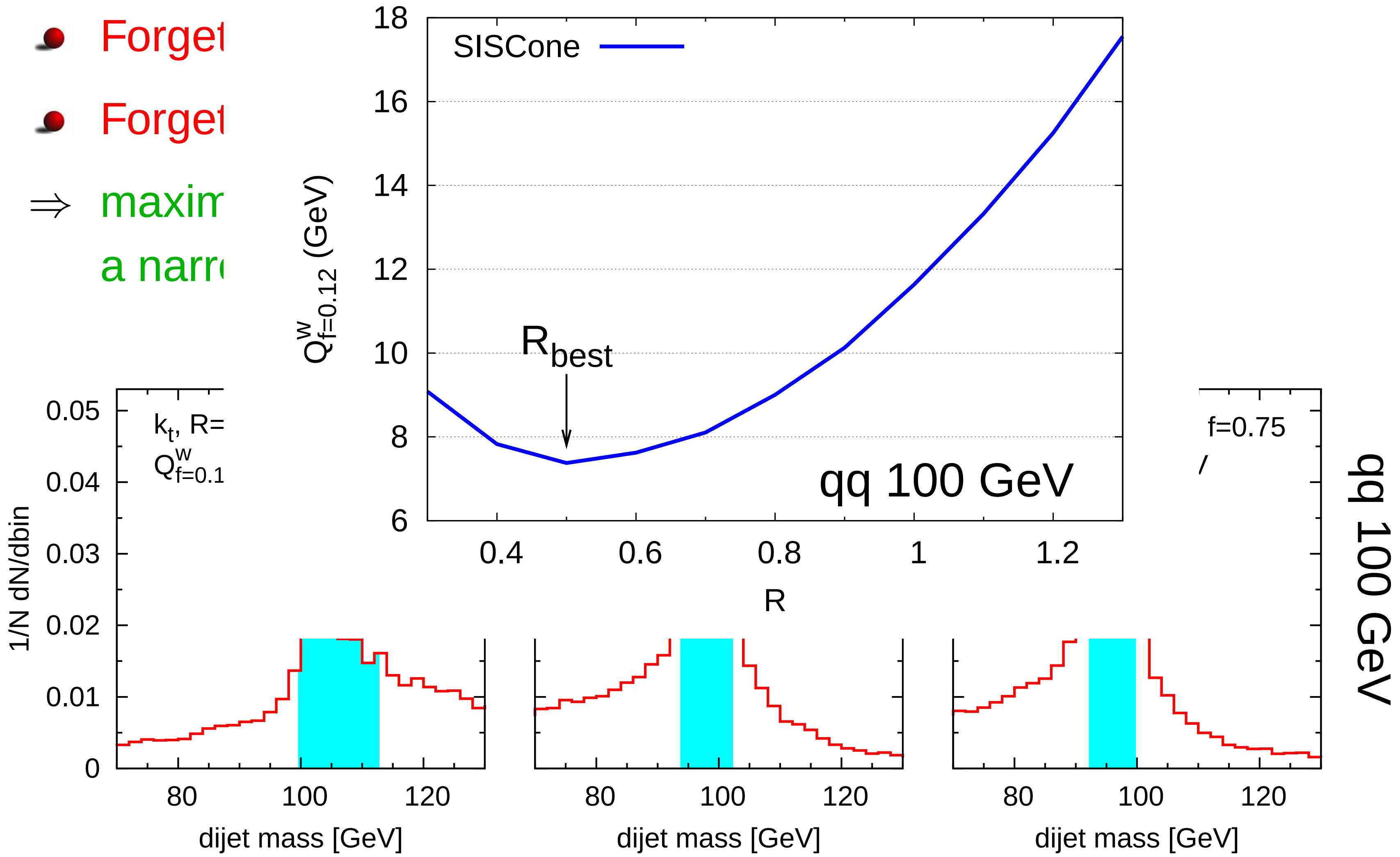


Optimisation: quality measure

Measure of the jet reconstruction efficiency:

- Forget
- Forget

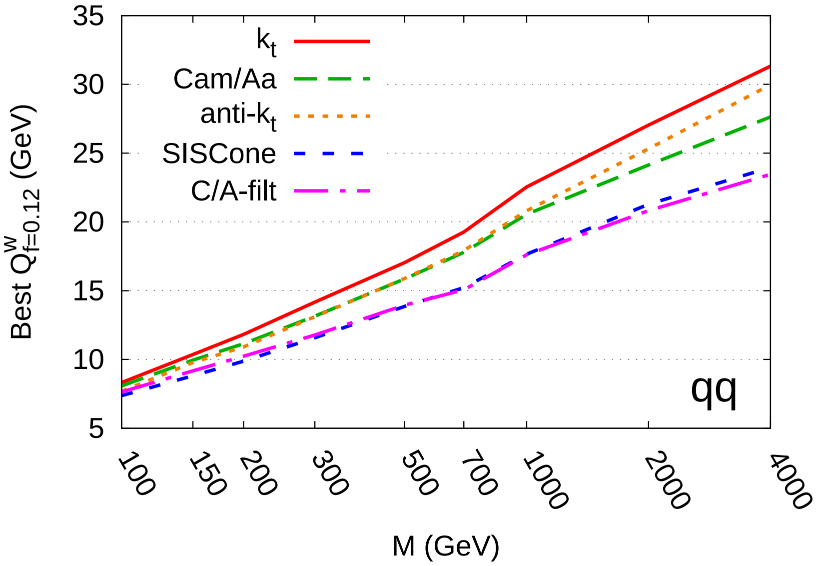
⇒ maxim
a narr

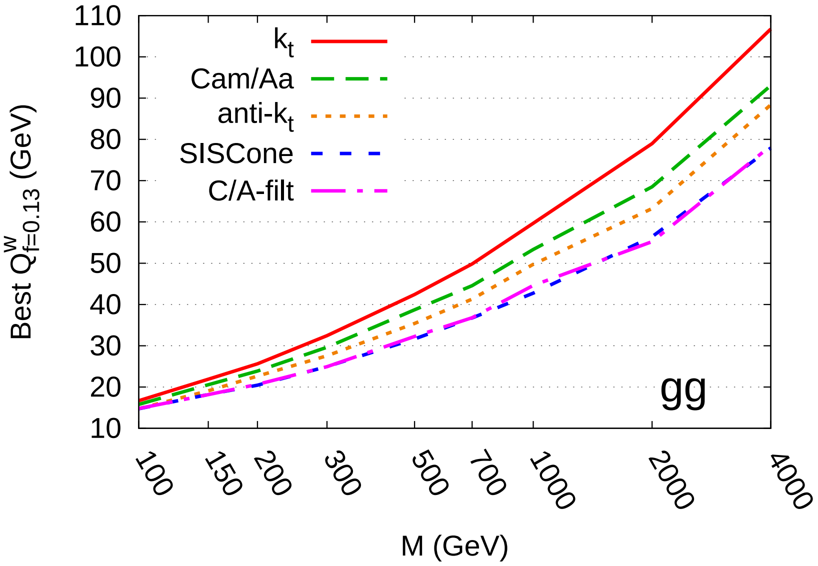


Optimisation: best definition

[M.Cacciari, J.Rojo, G.Salam, GS, 08]

- SISCone and C/A+filt. do slightly better than k_t, C/A or anti-k_t





Optimisation: best definition

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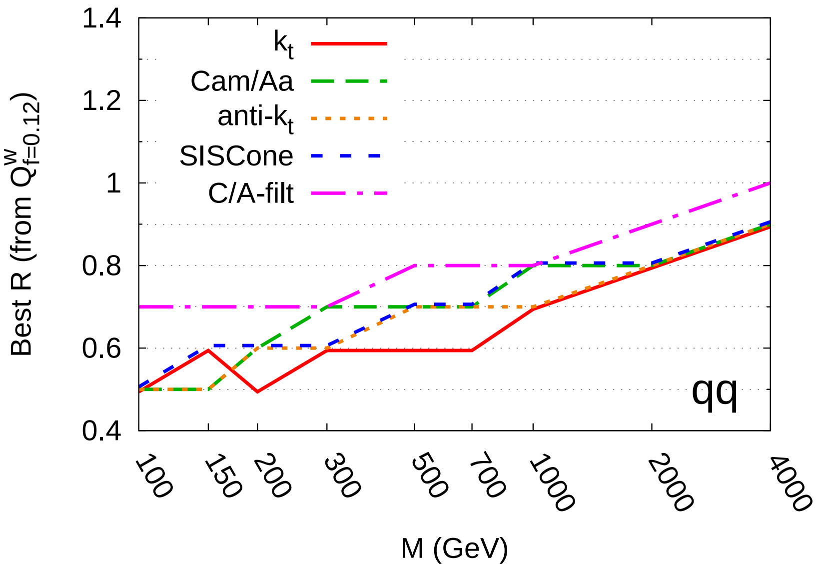
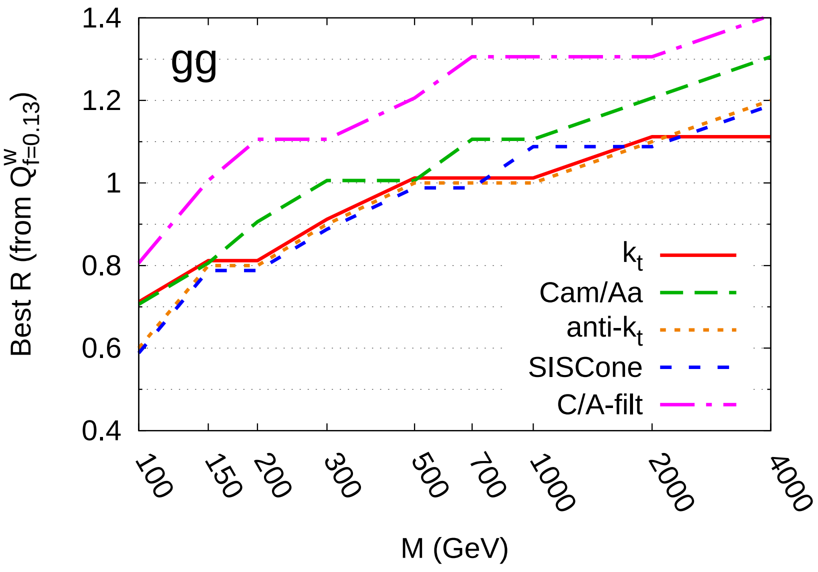
- SISCone and C/A+filt. do slightly better than k_t, C/A or anti-k_t

- $M \nearrow \Rightarrow R_{\text{best}} \nearrow$ (and $R_{\text{best}}(g) > R_{\text{best}}(q)$)





Optimisation: quality measure $\sim$ luminosity

Assuming a constant background,

quality measure $\longrightarrow$ effective luminosity ratio

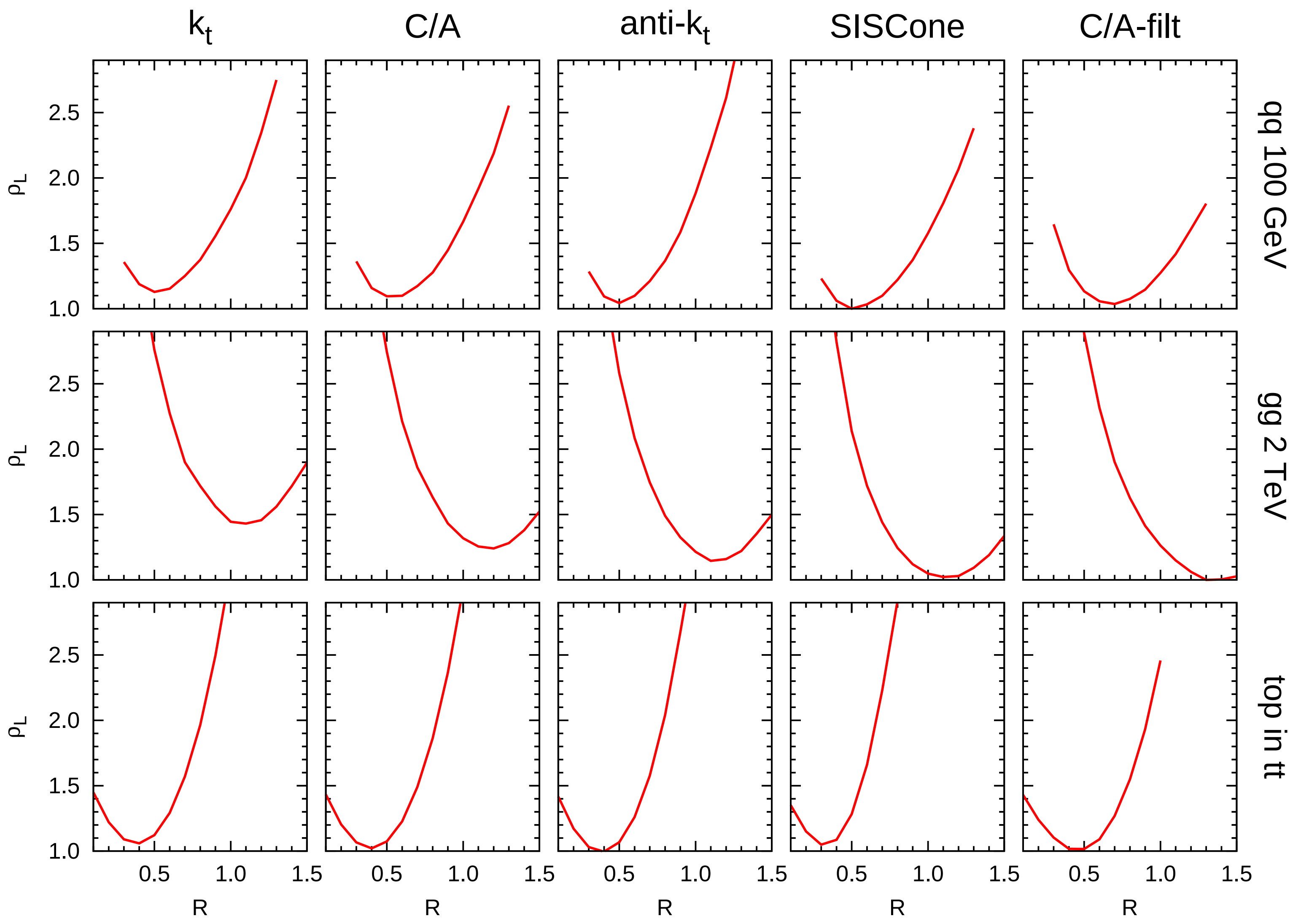
$$\rho_{\mathcal{L}}(\mathrm{JD}_2/\mathrm{JD}_1) = \frac{\mathcal{L}\text{ needed with }\mathrm{JD}_2}{\mathcal{L}\text{ needed with }\mathrm{JD}_1} = \frac{Q^w_{f=z}(\mathrm{JD}_2)}{Q^w_{f=z}(\mathrm{JD}_1)}$$

e.g. $\rho_{\mathcal{L}}(\mathrm{JD}_2/\mathrm{JD}_1) = 2$

$\Leftrightarrow$ JD_2 requires 2 times the integrated luminosity of JD_1
to achieve the same discriminative power.

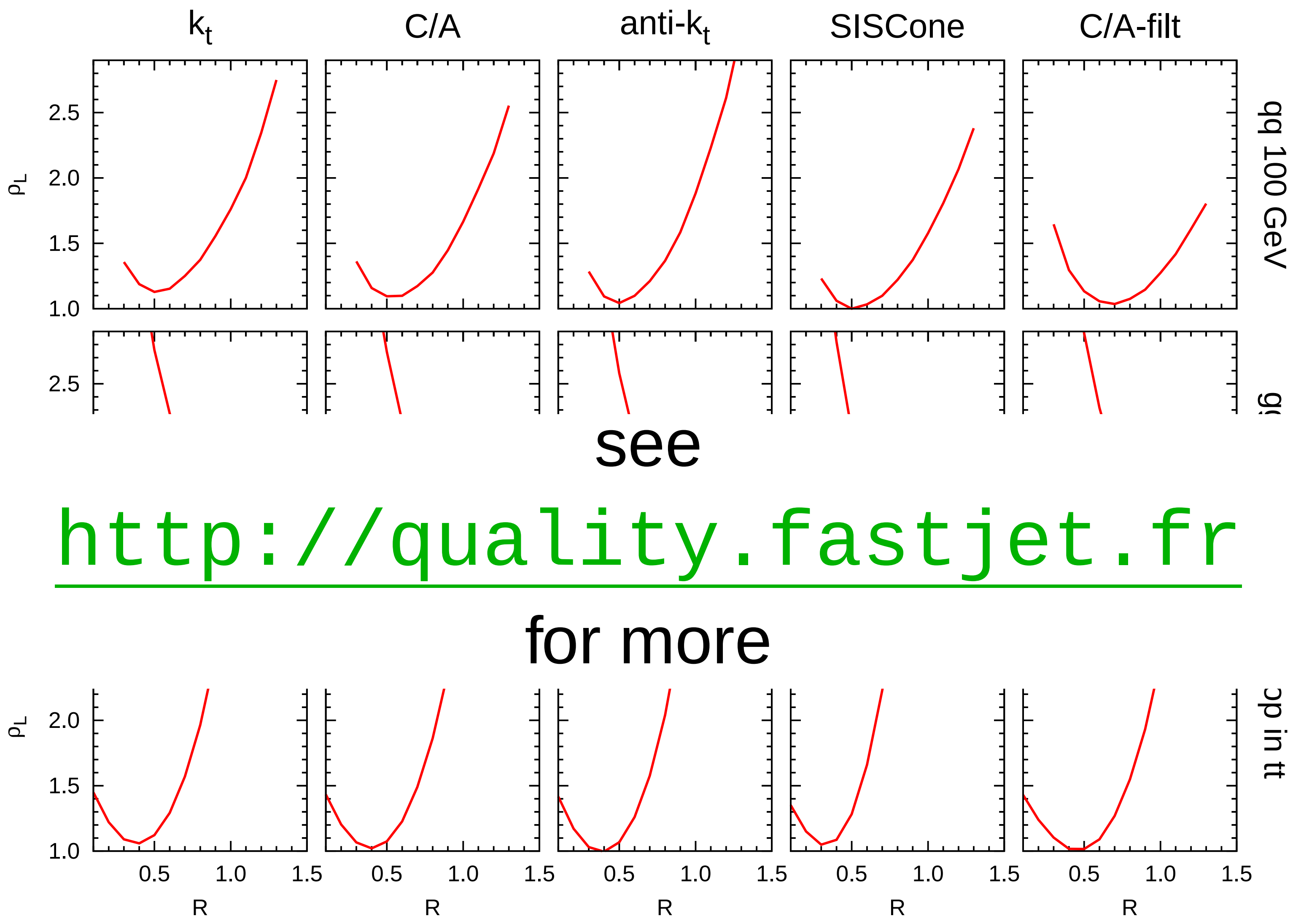
Note: results cross-checked with 2 different definitions of the quality measure

Optimisation: consequences



Using a single jet definition for all processes
may cost a factor ~ 2 in time for early discoveries at the LHC

Optimisation: consequences



see

http://quality.fastjet.fr

for more

Using a single jet definition for all processes

may cost a factor ~ 2 in time for early discoveries at the LHC

New idea #2: jet area and soft background subtraction

Jet areas

[M.Cacciari, G.Salam, GS, 08]

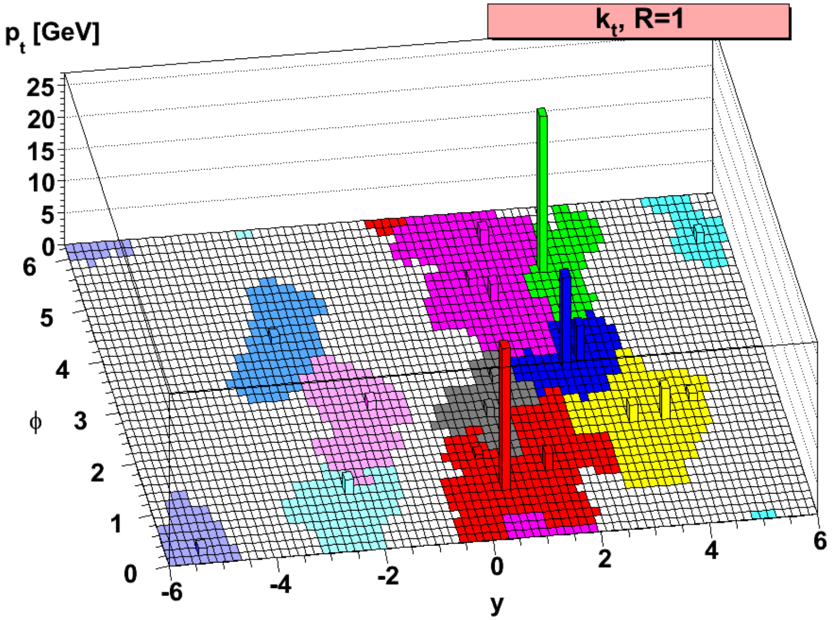
Area $\equiv$ region where the jet catches soft particles

- Recipe: add infinitely soft particles (aka *ghosts*)
  and see in which jet they are clustered
- 2 methods:
  - Passive area: add one ghost at a time and repeat many times
  - Active area: add a set of ghosts and cluster once
- Idea: ghost $\approx$ background particle
  $\Rightarrow$ active area $\approx$ uniform background
  passive area $\approx$ pointlike background
- Notes:
  - passive = active for large multiplicities
  - require an IR-safe algorithm!
  - generic/universal definition (*e.g.* independent of a calorimeter)

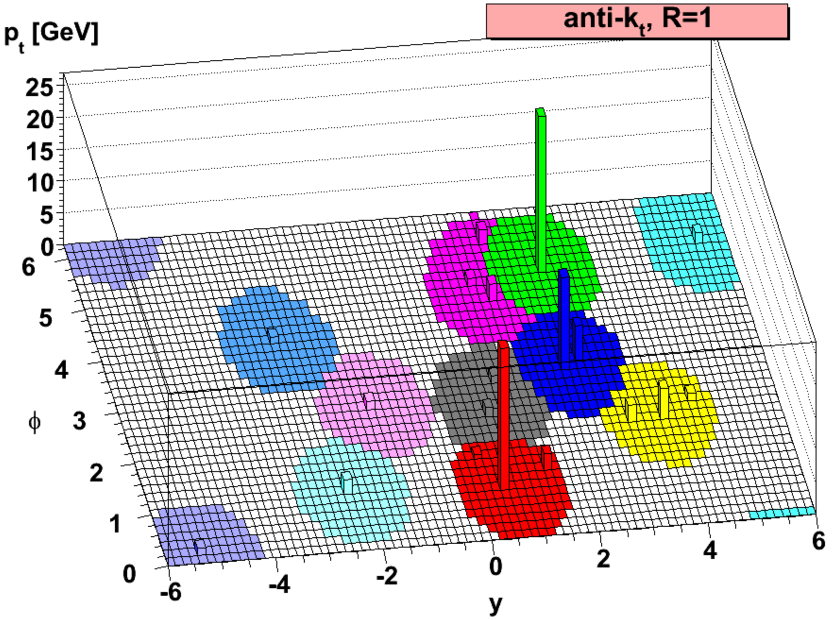
Jet area: examples

Example 1: active area for a simple event

k_t



anti-k_t



Note: analytic control

Example 2: perturbative expansion of areas (at order α_s)

$$\langle \mathcal{A}(p_t, R) \rangle = \mathcal{A}_0 + \frac{C_{F,A}}{b_0 \pi} \pi R^2 \, d \, \log \left(\frac{\alpha_s(Q_0)}{\alpha_s(R p_t)} \right)$$

- area $\neq \pi R^2$, area $\neq$ const.
- coefficients computable

	$\mathcal{A}_0/(\pi R^2)$		d	
	passive	active	passive	active
k_t	1	0.81	0.56	0.52
Cam/Aachen	1	0.81	0.08	0.08
anti-k_t	1	1	0	0
SISCone	1	1/4	-0.06	0.12

- $Q_0 \equiv$ IR regulator $\propto$ background density

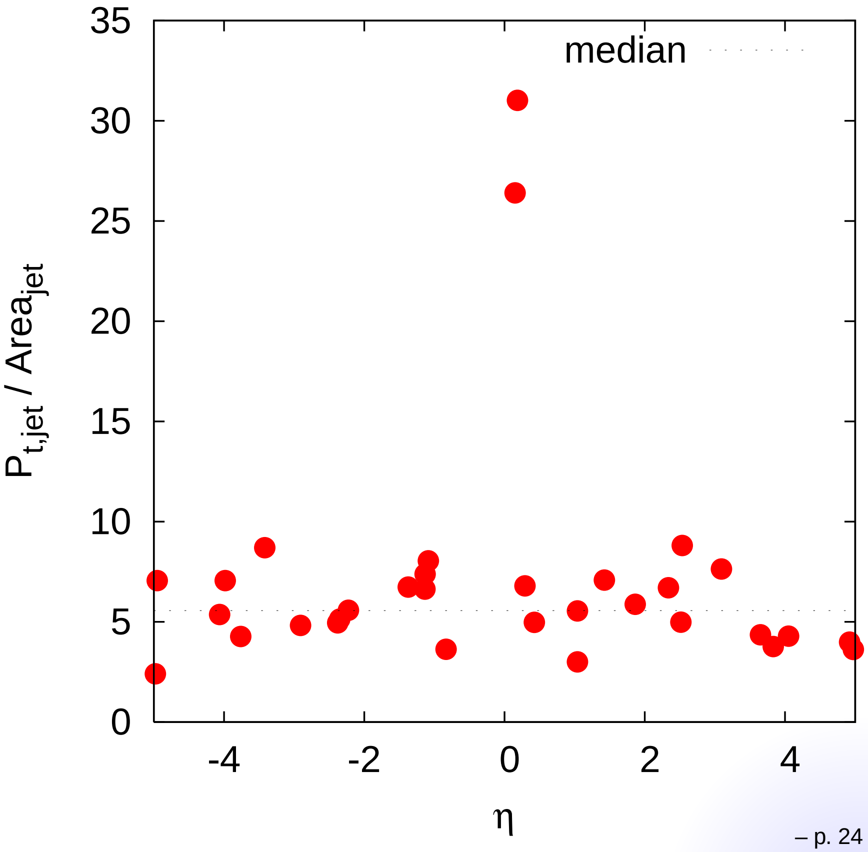
Pileup subtraction *(for uniform backgrounds)*

Basic idea: [M.Cacciari, G.Salam, 08]

$$p_{t,\mathrm{subtracted}} = p_{t,\mathrm{jet}} - \rho_{\mathrm{pileup}} \times \mathrm{Area}_{\mathrm{jet}}$$

- Jet area: [M.Cacciari, G.Salam, G.S., 08]
  - region where the jet catches infinitely soft particles (active/passive)
  - analytic control and understanding in pQCD
- Pileup density per unit area: ρ_{pileup}

  e.g. estimated from the median of $p_{t,\mathrm{jet}}/\mathrm{Area}_{\mathrm{jet}}$



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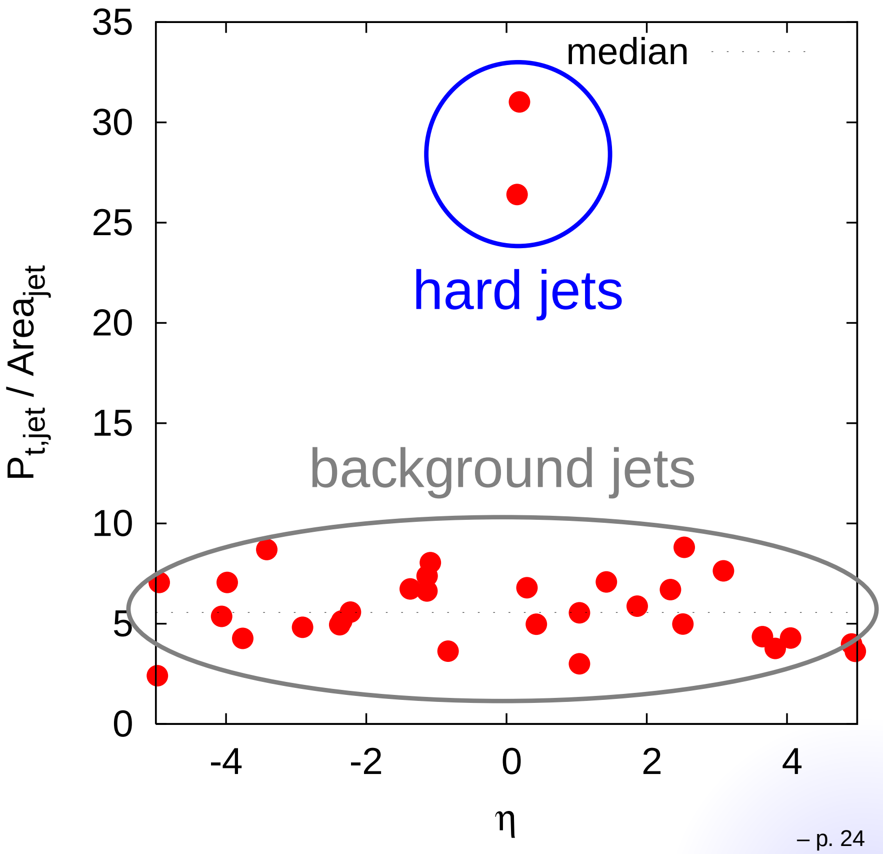

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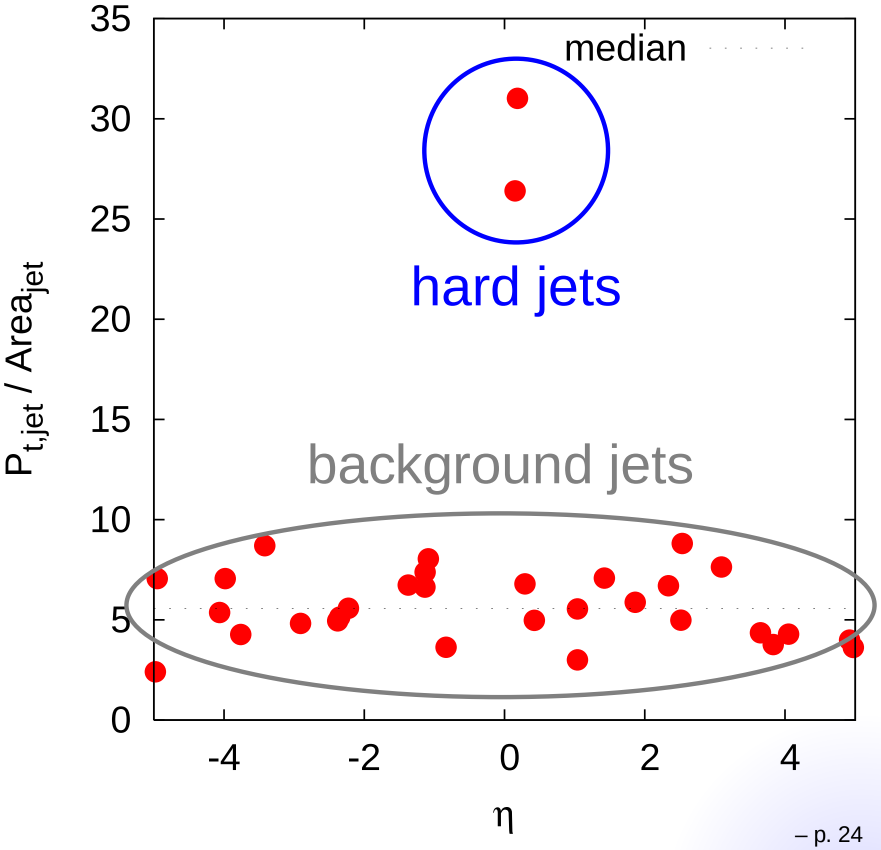
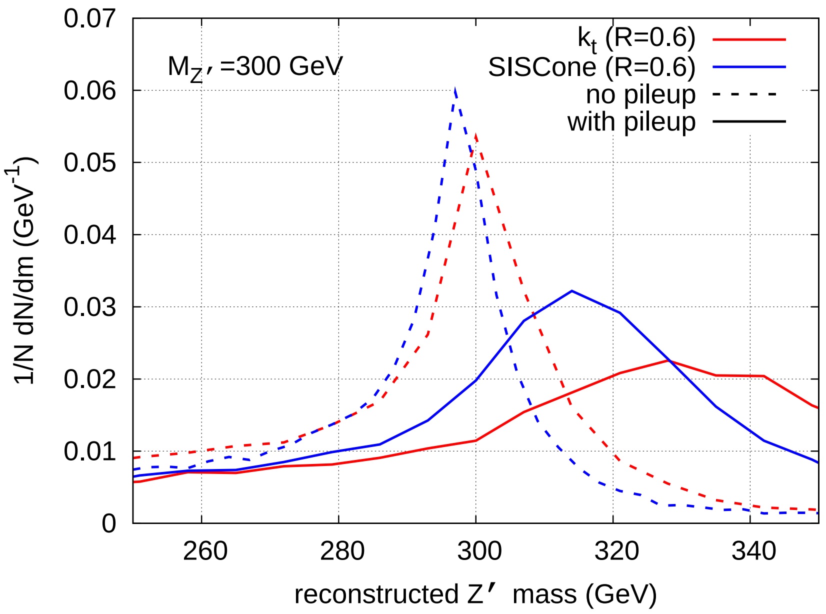
implemented in FastJet
on an event-by-event basis



Effect on dijet reconstruction

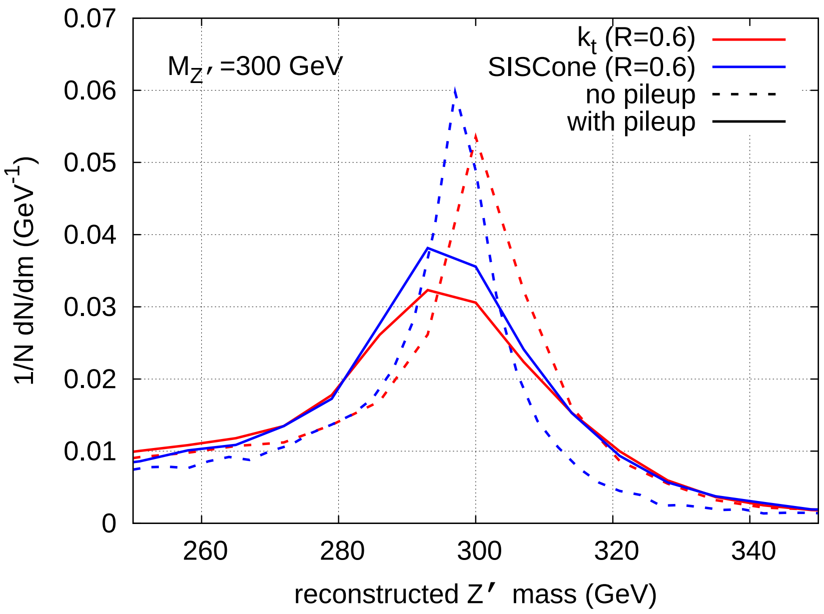
Pileup unsubtracted



width = 29.5 GeV

width = 21.0 GeV

pileup subtracted



width = 21.0 GeV

width = 17.7 GeV

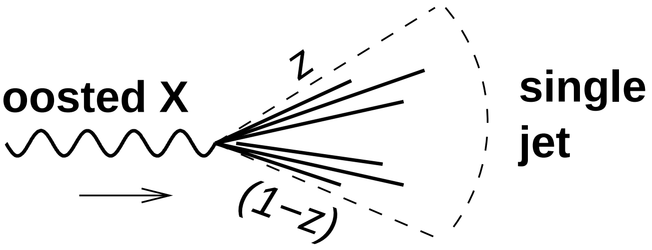
- ✓ position reasonnable
- ✓ dispersion reduced (thanks to the event-by-event approach)
- ✓ used by STAR for the first jet analysis in heavy-ions

New idea #3:
Subjets help tagging boosted objects

Example: boosted Higgs

[J.Butterworth, A.Davison, M.Rubin, G.Salam,08]

- $H \to b\bar{b}$: dominant decay for small M_H but large backgrounds
- boosted H (HW, HZ): many advantages (*e.g.* no $t\bar{t}$ background),
  main problem: small cross-section
- boosted particle: decay products in the same jet



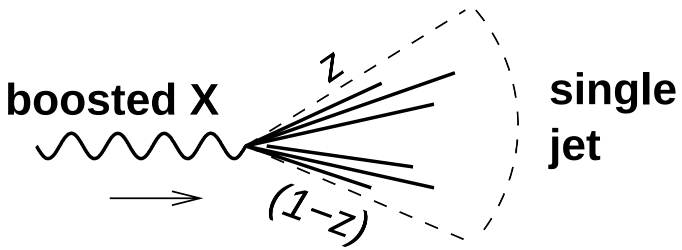
$$R \gtrsim \frac{m}{p_t}\frac{1}{\sqrt{z(1-z)}}$$

Note: other similar examples:

- boosted top
- $t\bar{t}H$
- $\tilde{\chi}^0 \to qqq$

Example: boosted Higgs

[J.Butterworth, A.Davison, M.Rubin, G.Salam,08]



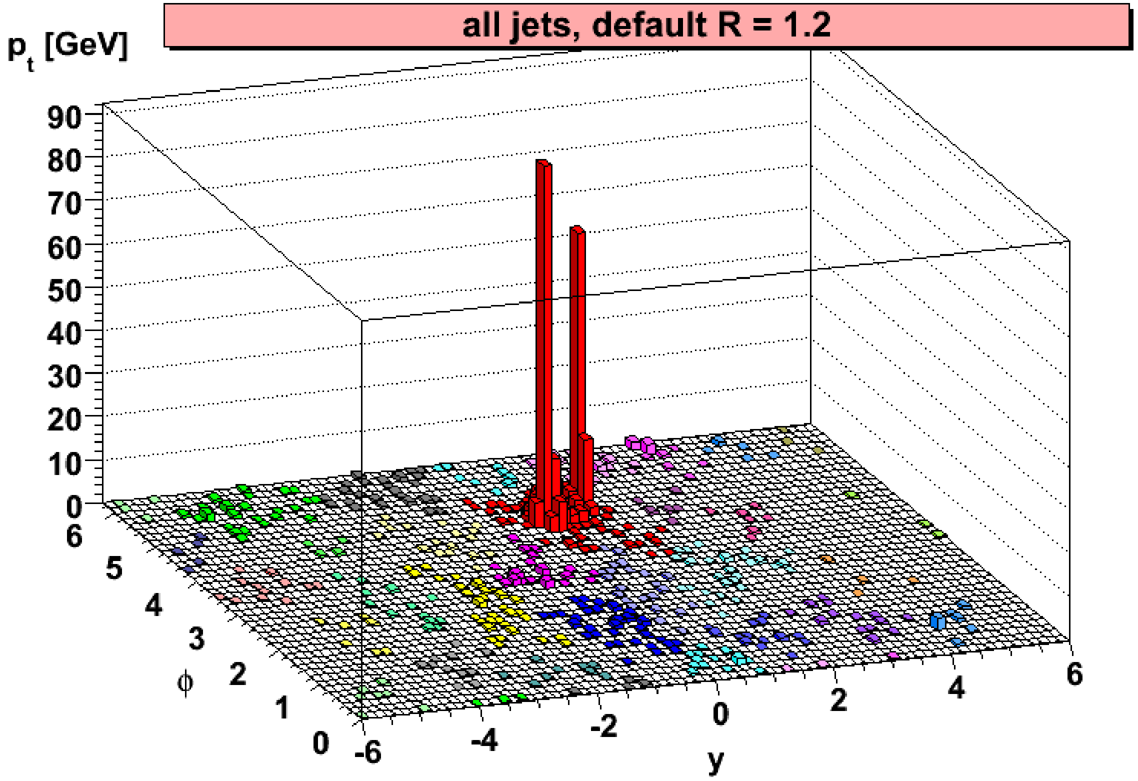
$$R \gtrsim \frac{m}{p_t} \frac{1}{\sqrt{z(1-z)}}$$

Method: start with a hard (C/A, radius R) jet j

1. Undo the last clustering $\rightarrow j_1, j_2$
2. If $\max(m_1, m_2) < 0.67m$, we have a mass drop, else back to 1
   idea: find the 2 b-jets, dynamically find R_{bb}
3. Require symmetric splitting $y_{12} \approx \frac{\min(z_1,z_2)}{\max(z_1,z_2)} > 0.09$, else go to 1
   idea: remove QCD asymmetric splittings
4. Require 2 b taggings
5. Filter *i.e.* uncluster down to $R_{\text{filt}} = R/3$, keep the 3 hardest subjets
   idea: keep “hard” QCD radiations, reduce UE

Boosted Higgs: one event, effects on S/B

Herwig 6.510 + Jimmy 4.31 + FastJet 2.3



Cluster C/A, R=1.2

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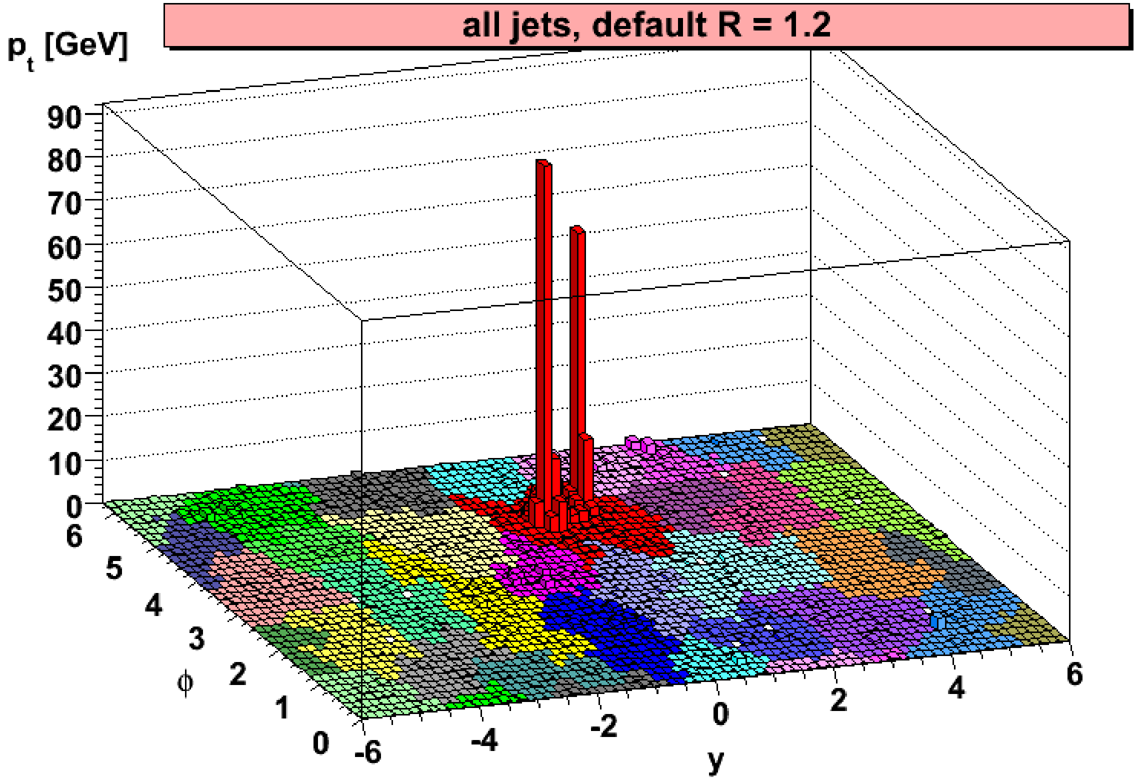

Show jets more clearly

Boosted Higgs: one event, effects on S/B

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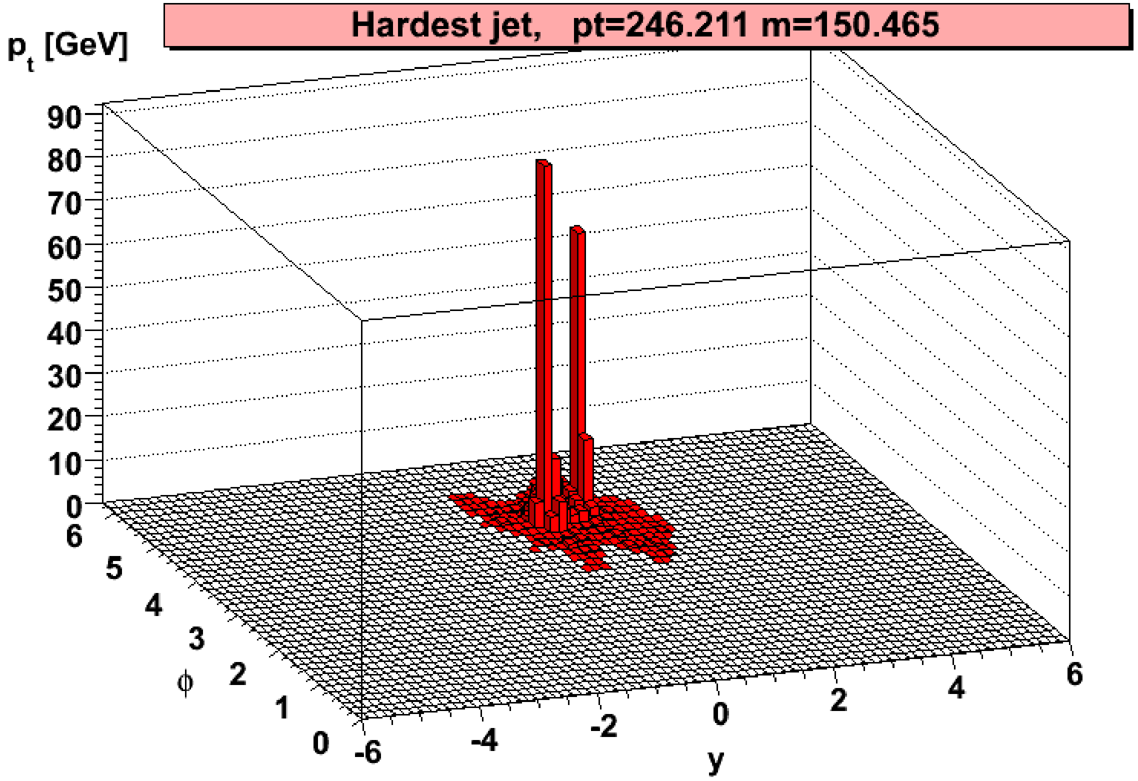
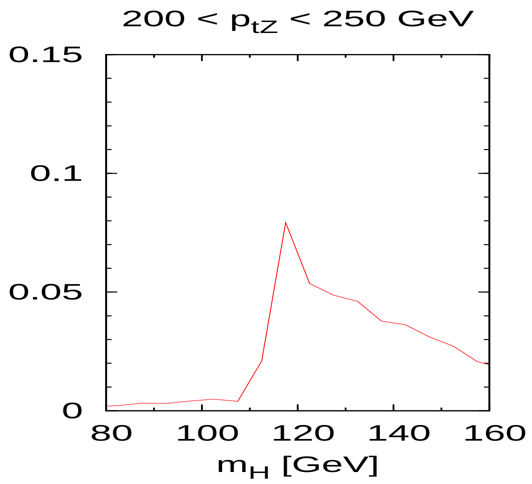
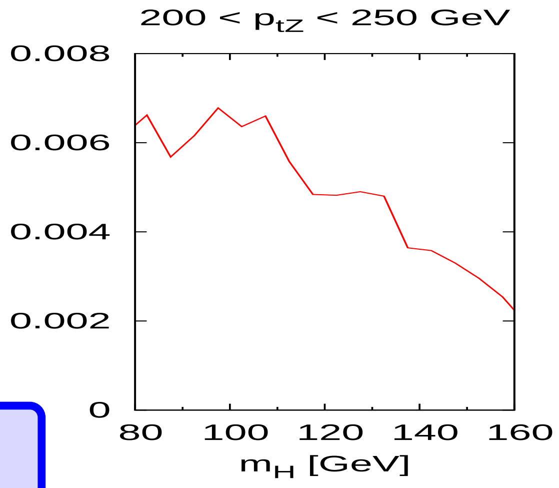


HZ Signal



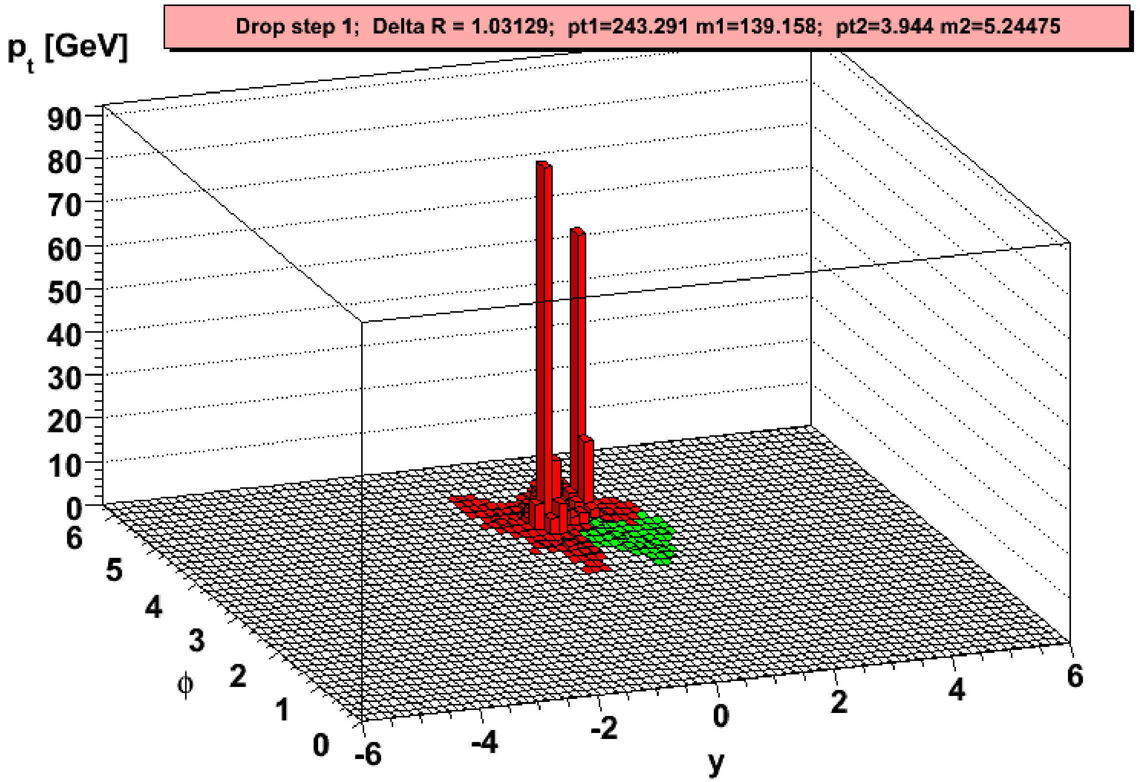
Zbb Background



Hardest jet ($m = 150$ GeV)

Boosted Higgs: one event, effects on S/B

Herwig 6.510 + Jimmy 4.31 + FastJet 2.3



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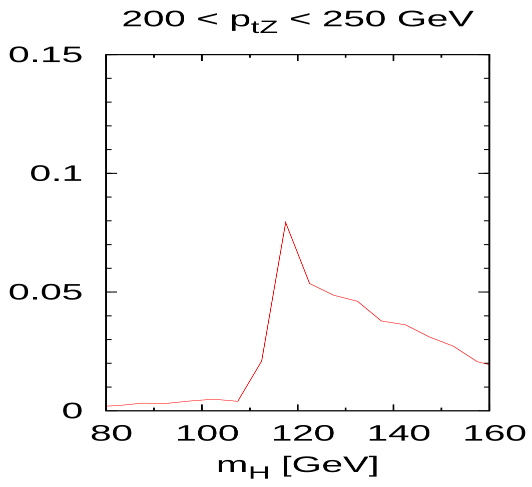

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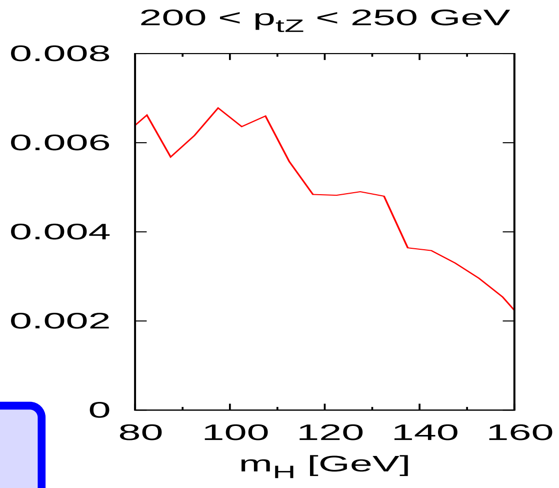
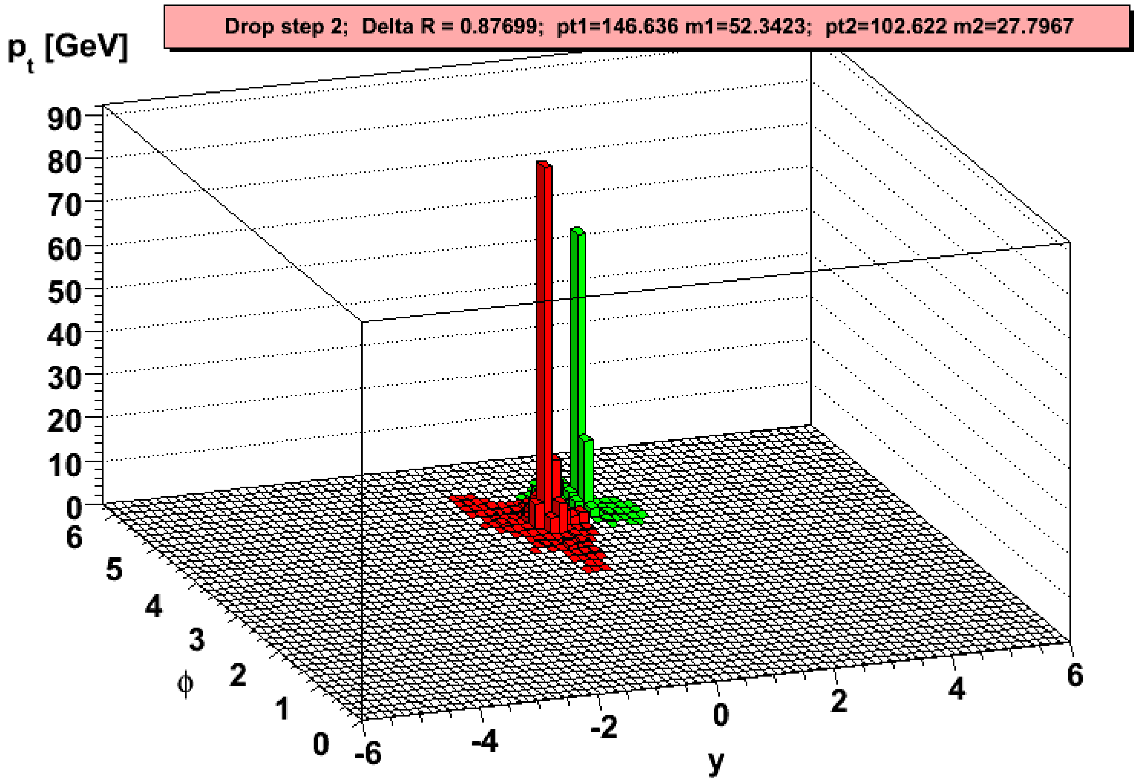


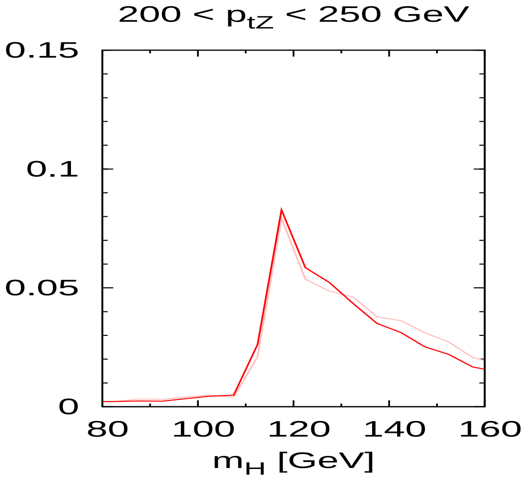
Split: $\frac{\max(m_1,m_2)}{m} = 0.92$, repeat ($m = 150$ GeV)

Boosted Higgs: one event, effects on S/B

Herwig 6.510 + Jimmy 4.31 + FastJet 2.3



HZ Signal



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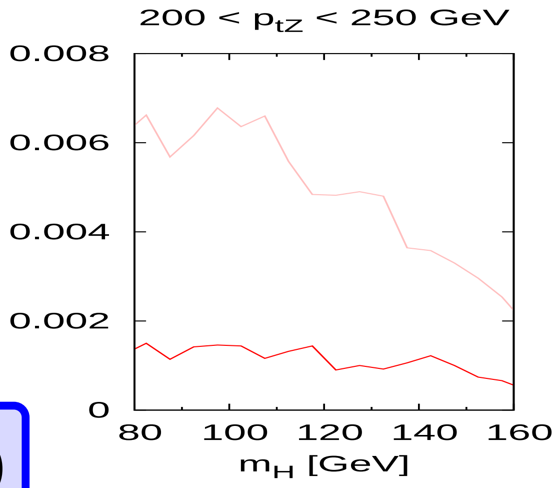
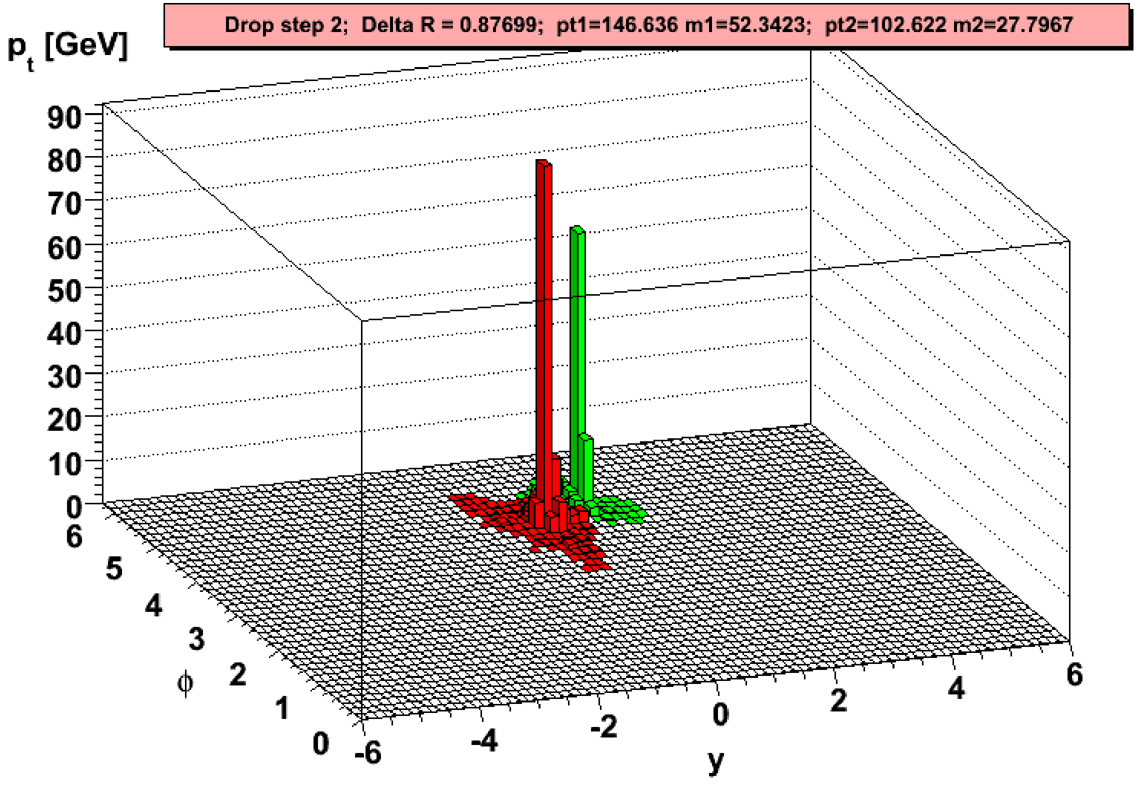


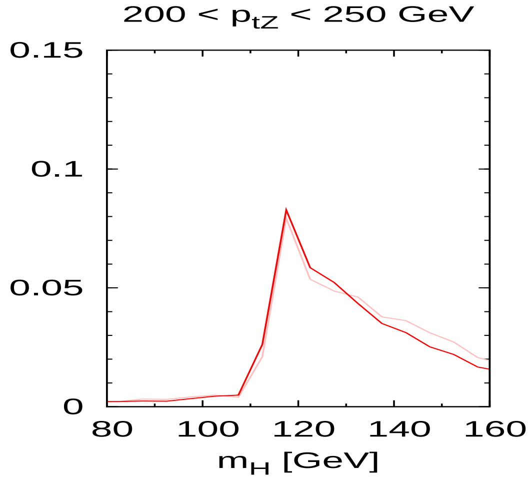
Split: $\frac{\max(m_1,m_2)}{m} = 0.37$, mass drop ($m = 139$ GeV)

Boosted Higgs: one event, effects on S/B

Herwig 6.510 + Jimmy 4.31 + FastJet 2.3



HZ Signal



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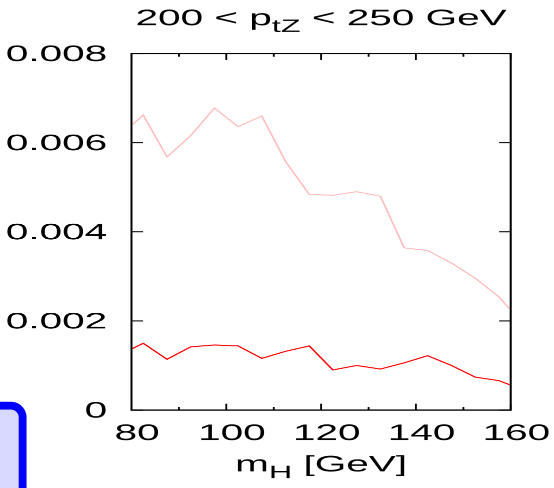
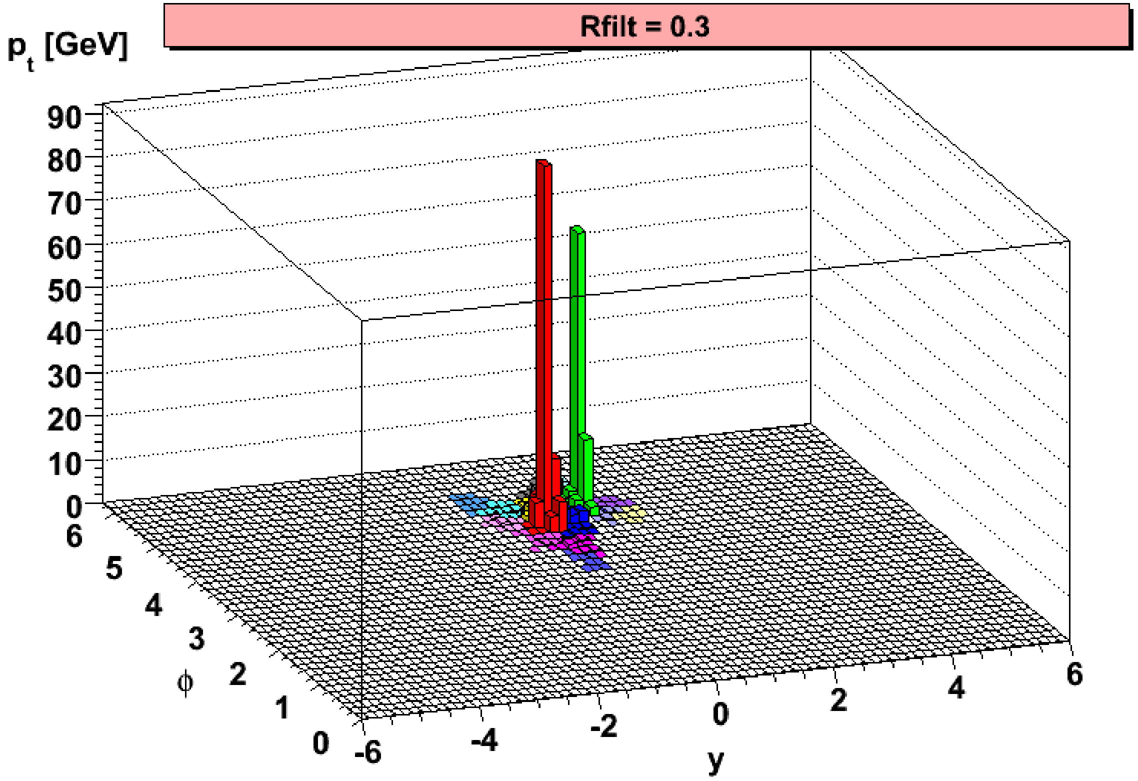


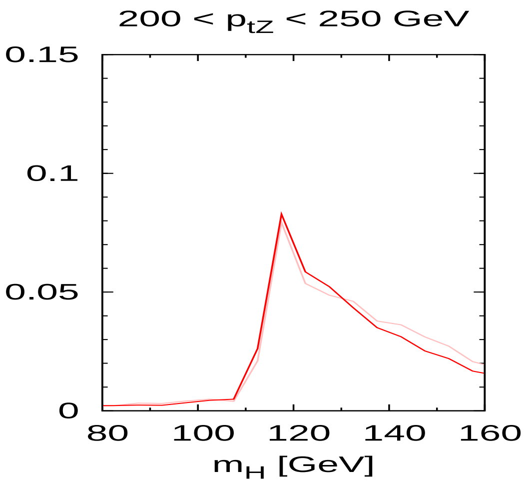
Split: $y_{12} = 0.7$, 2 b tags $\Rightarrow$ OK ($m = 139$ GeV)

Boosted Higgs: one event, effects on S/B

Herwig 6.510 + Jimmy 4.31 + FastJet 2.3



HZ Signal



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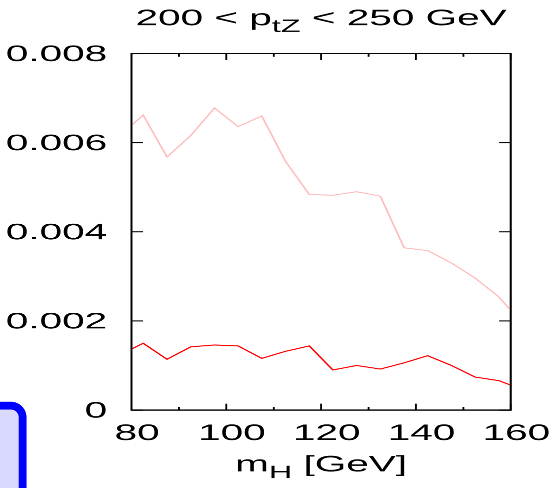
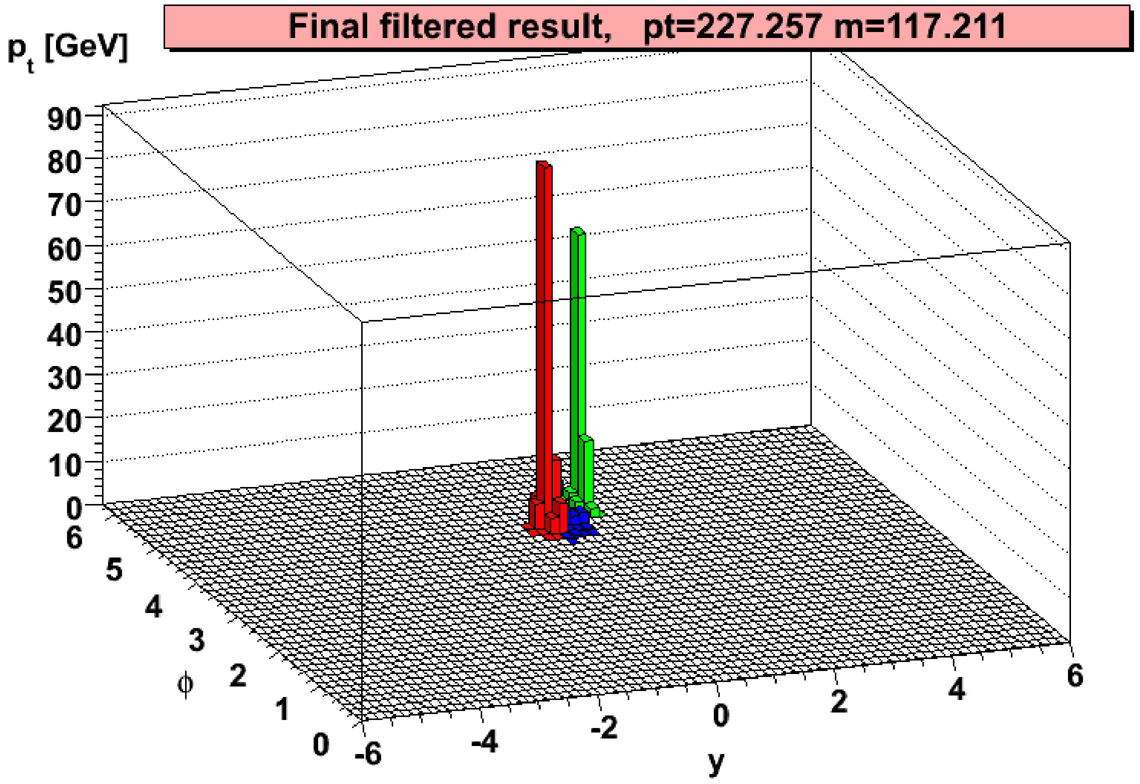


Re-cluster: $R_{\text{filt}} = 0.3$

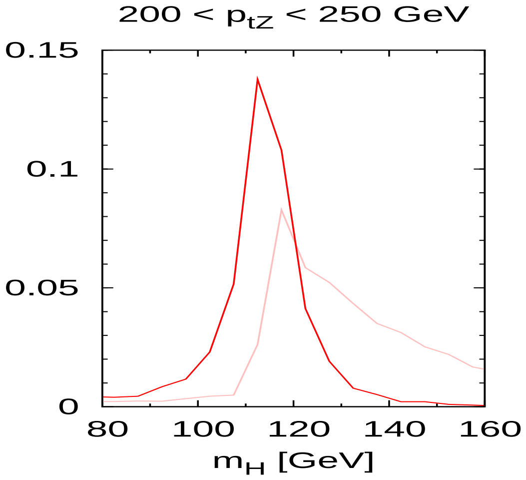
Boosted Higgs: one event, effects on S/B

Herwig 6.510 + Jimmy 4.31 + FastJet 2.3

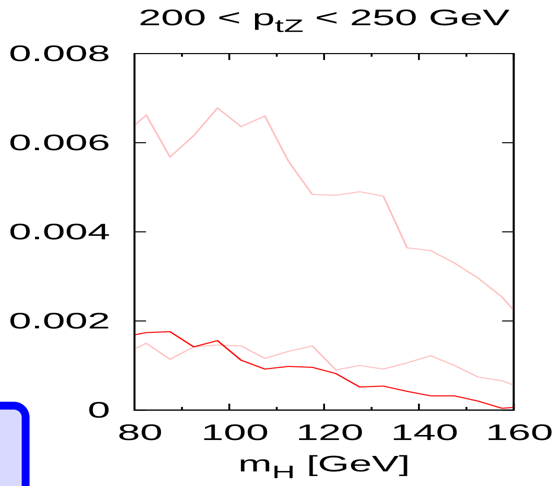


Filter: keep 3 hardets ($m = 117$ GeV)

HZ Signal

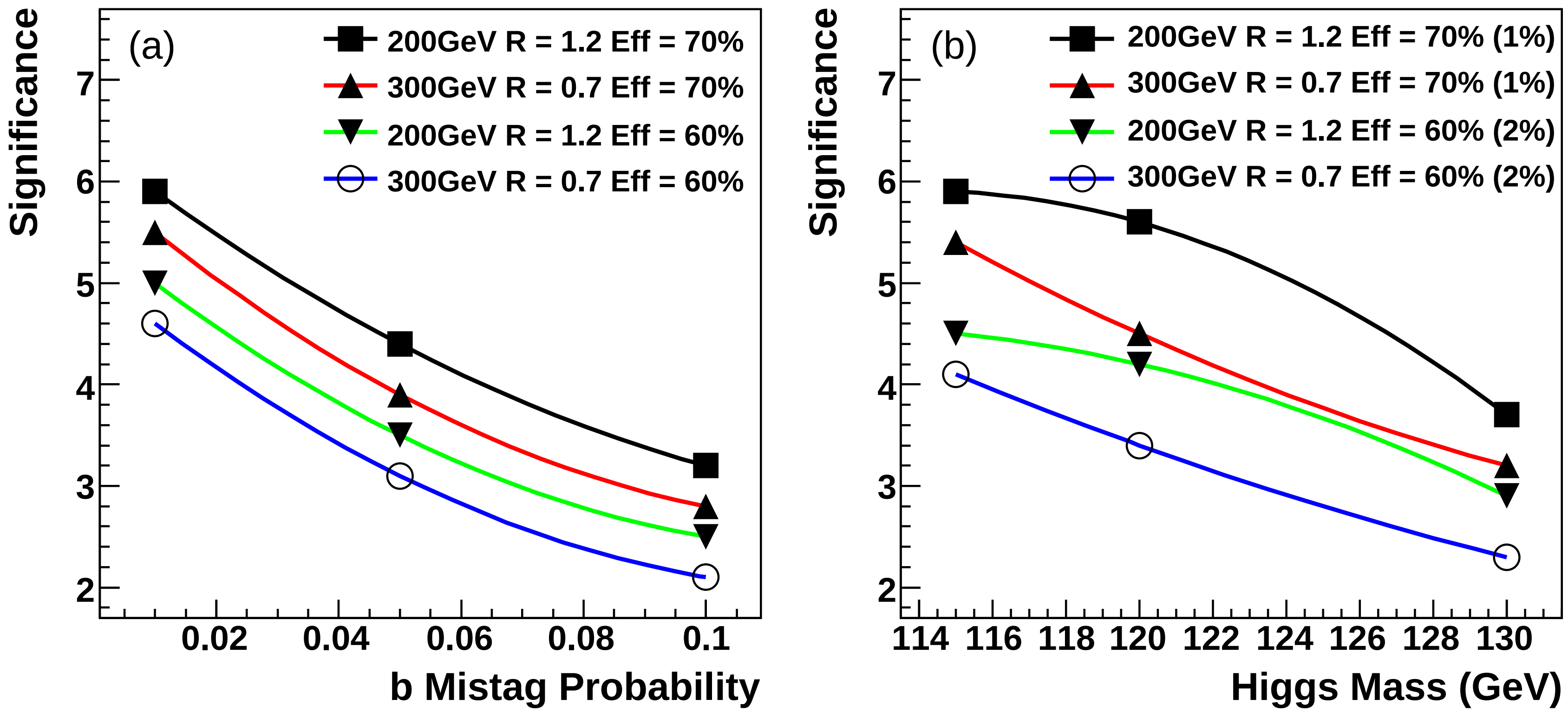


Zbb Background



Boosted Higgs: one event, effects on S/B

Hc



More than 3σ for most scenarios (30 fb^{-1})

Filter: keep 3 hardest ($m = 117$ GeV)

Summary (1)

Message #1:

Use infrared-and-collinear-safe algorithms

ATLAS Cone
CDF/D0 MidPoint
} → SISCone
$\surd$ fast
$\surd$ safe

CMS It. Cone → anti-k_t
$\surd$ fast
$\surd$ safe

Mandatory to benefit fully from pQCD multileg/loop calculations at the LHC

Summary (2)

Message #2:

correct tools ⇒ new ideas, new concepts
⇒ new generation of jet definitions

- jet areas ⟶ pileup and HI background subtraction
- jet substructure improves reconstruction (Higgs, top, SUSY, ...)

Message #3:

keep some flexibility in the jet definition choice

- optimisation ⟶ luminosity gains for LHC searches

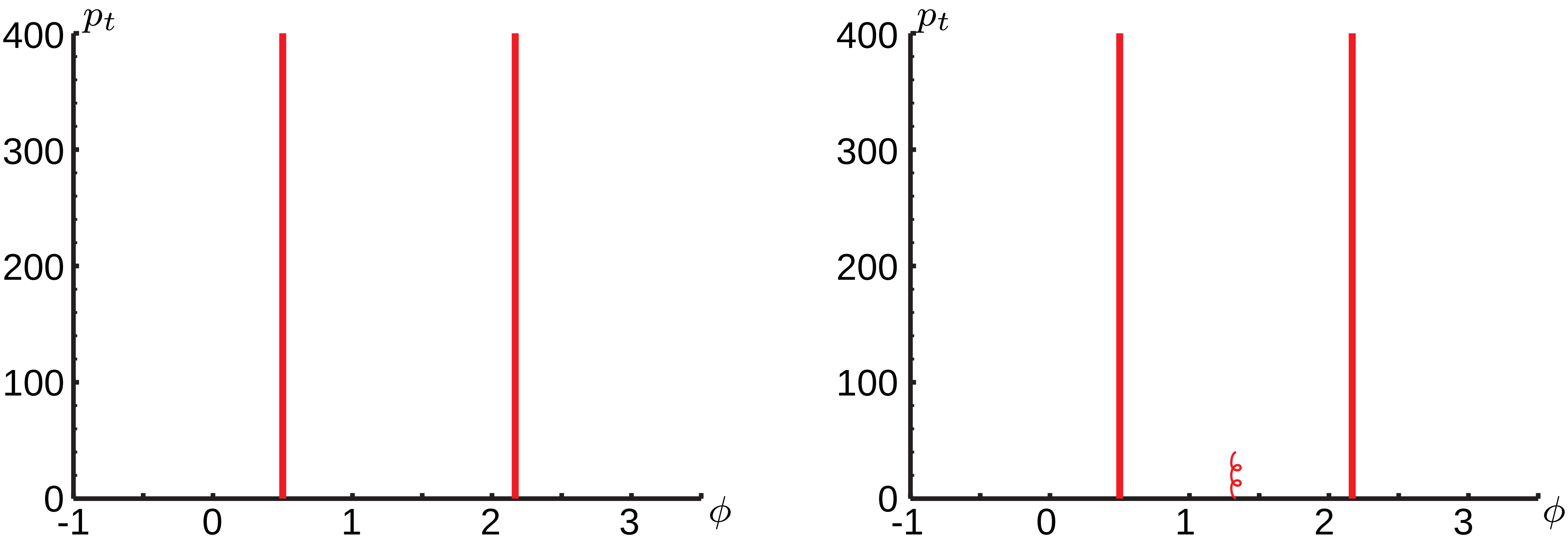
Future perspectives

This is not the end of the story:

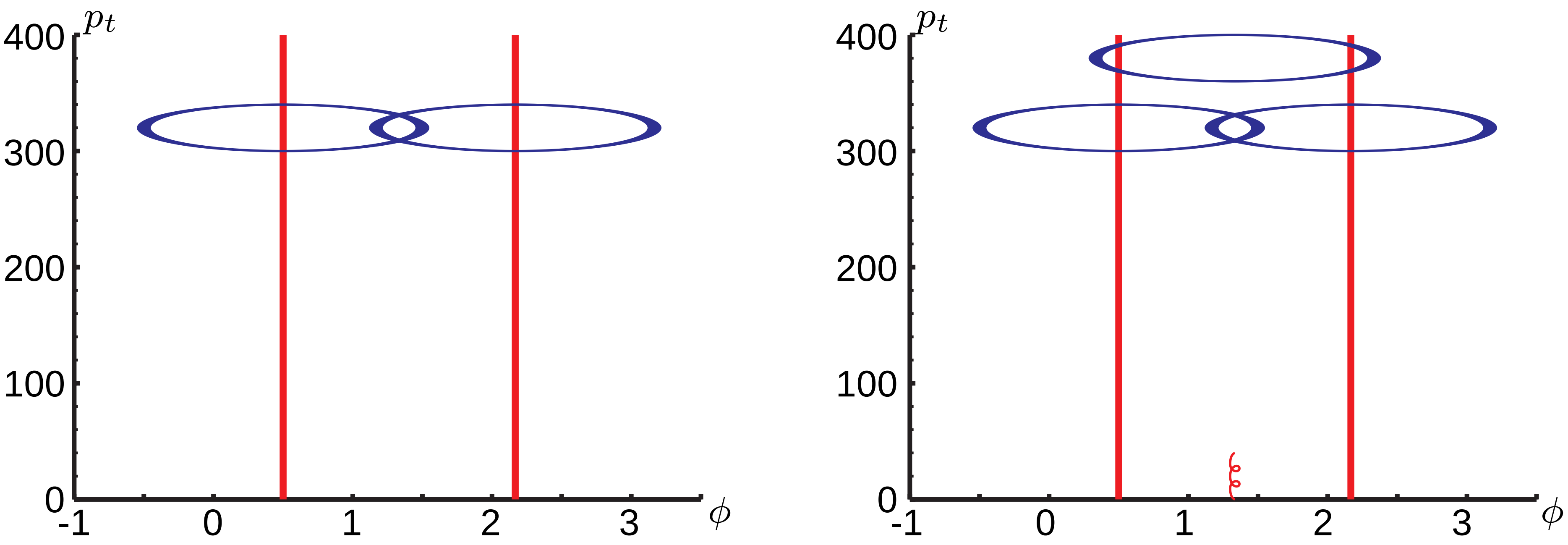
- Study the parameters used when filtering
- Analytic understanding of the optimisation of R
- Optimisation for other processes

backup slides

IR (un)safety? JetClu and Atlas Cone

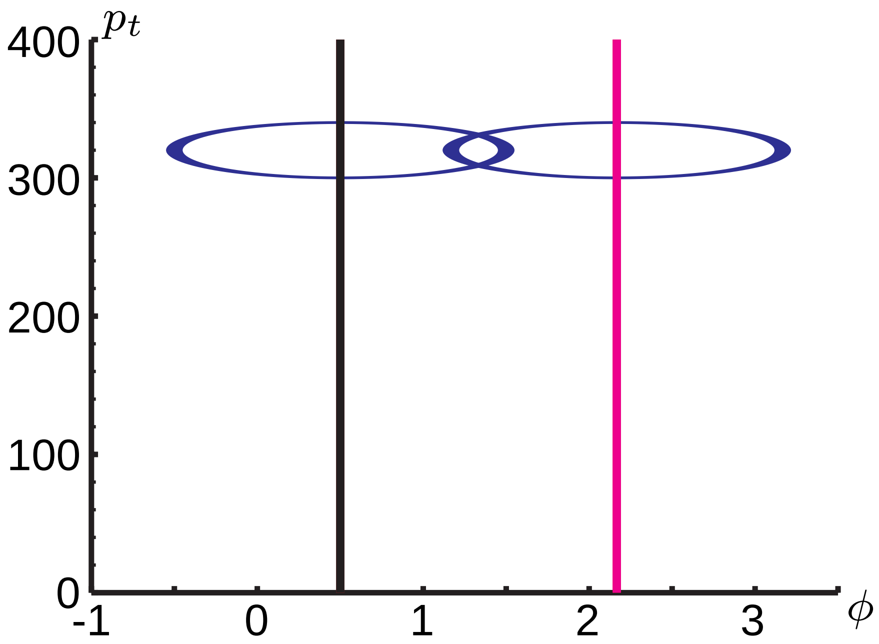


IR (un)safety? JetClu and Atlas Cone

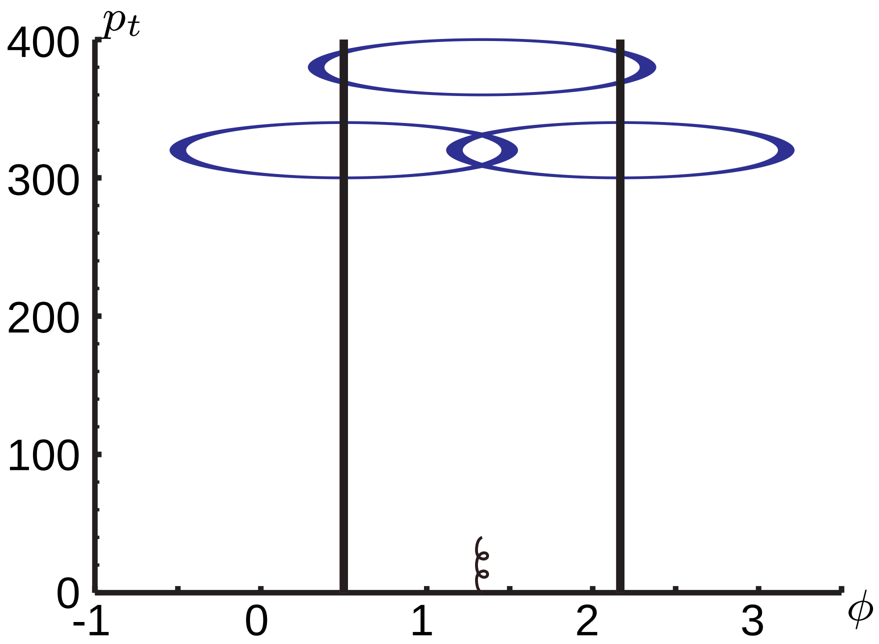


Stable cones found

IR (un)safety? JetClu and Atlas Cone



2 jets

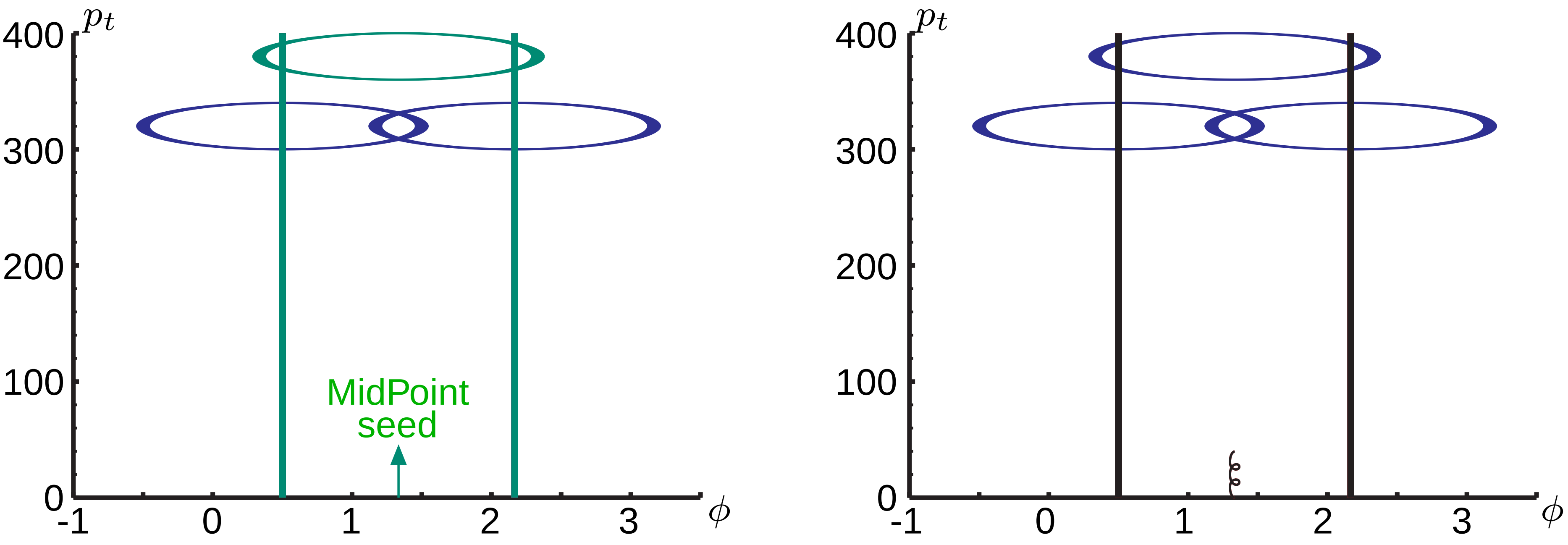


1 jet

A soft gluon changed the number of jets

$\Rightarrow$ IR unsafety of JetClu and the ATLAS Cone

IR (un)safety? JetClu and Atlas Cone



2 jets

1 jet

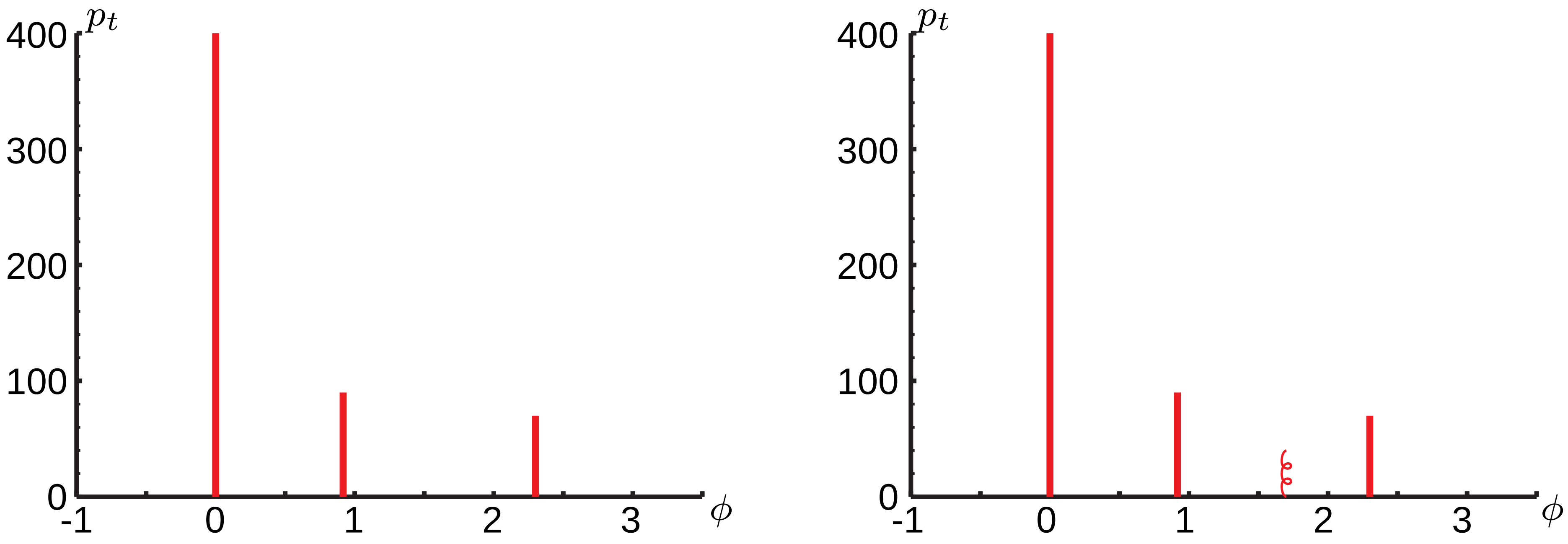
A soft gluon changed the number of jets

⇒ IR unsafety of JetClu and the ATLAS Cone

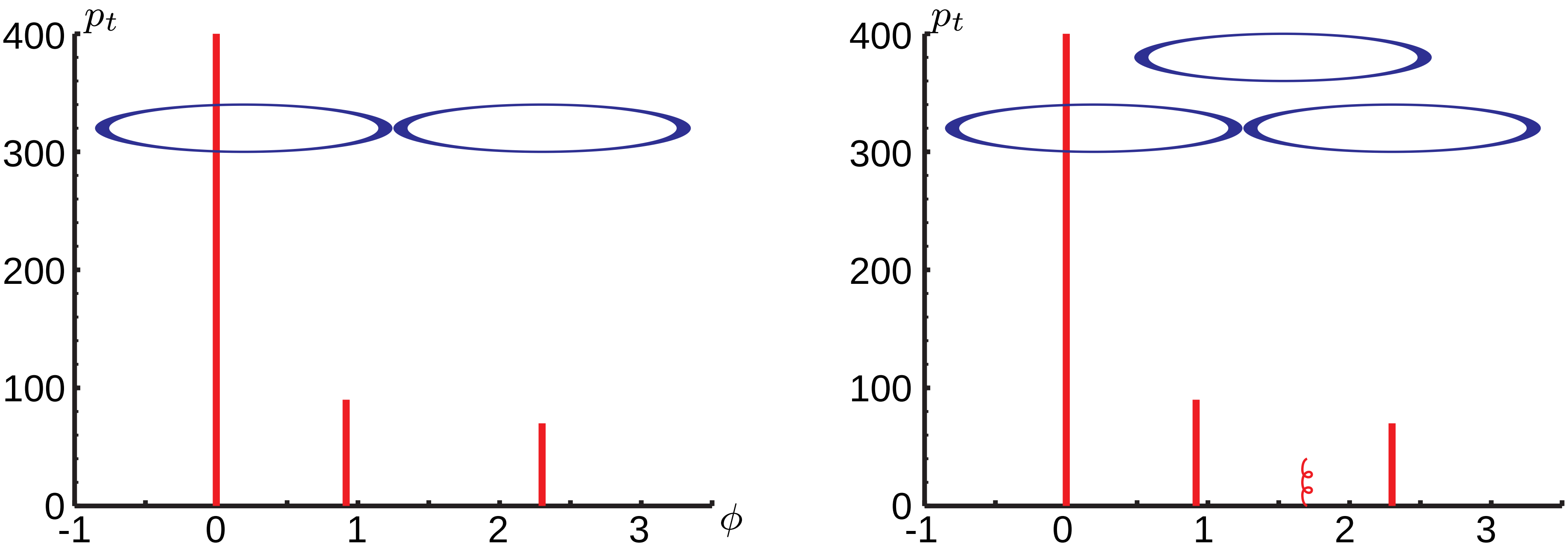
Fixed by MidPoint

[Blazey *et al.*, 00]

IR (un)safety? MidPoint

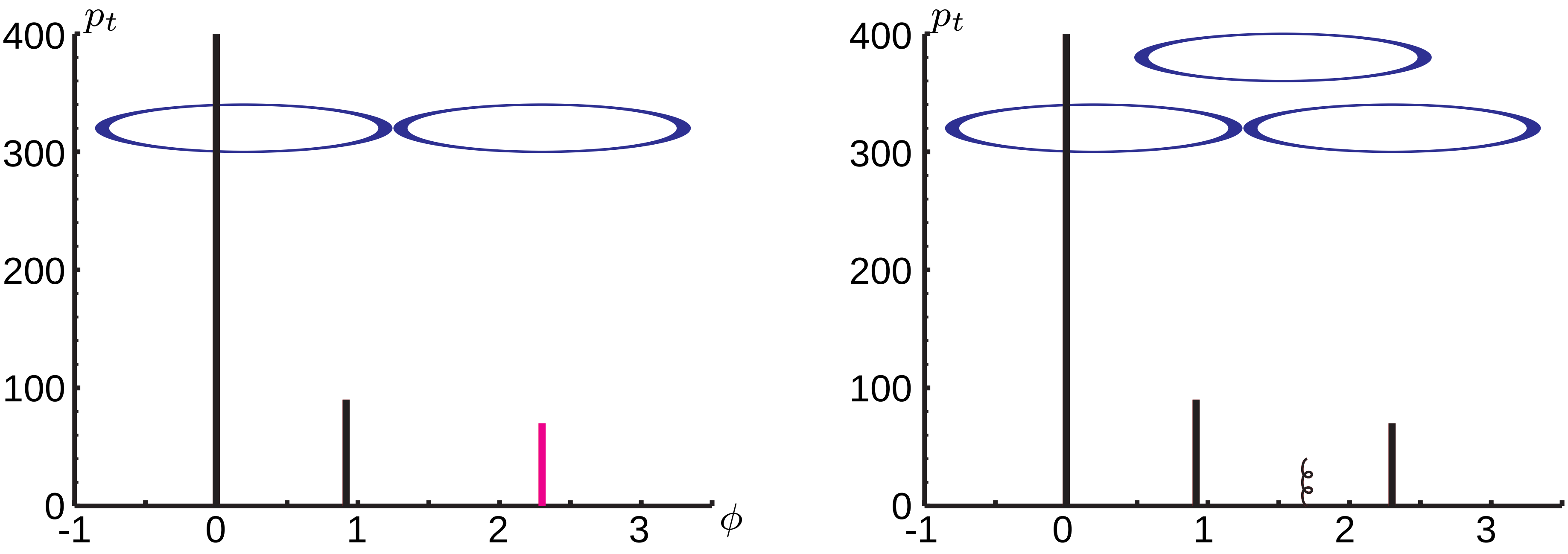


IR (un)safety? MidPoint



Stable cones found

IR (un)safety? MidPoint



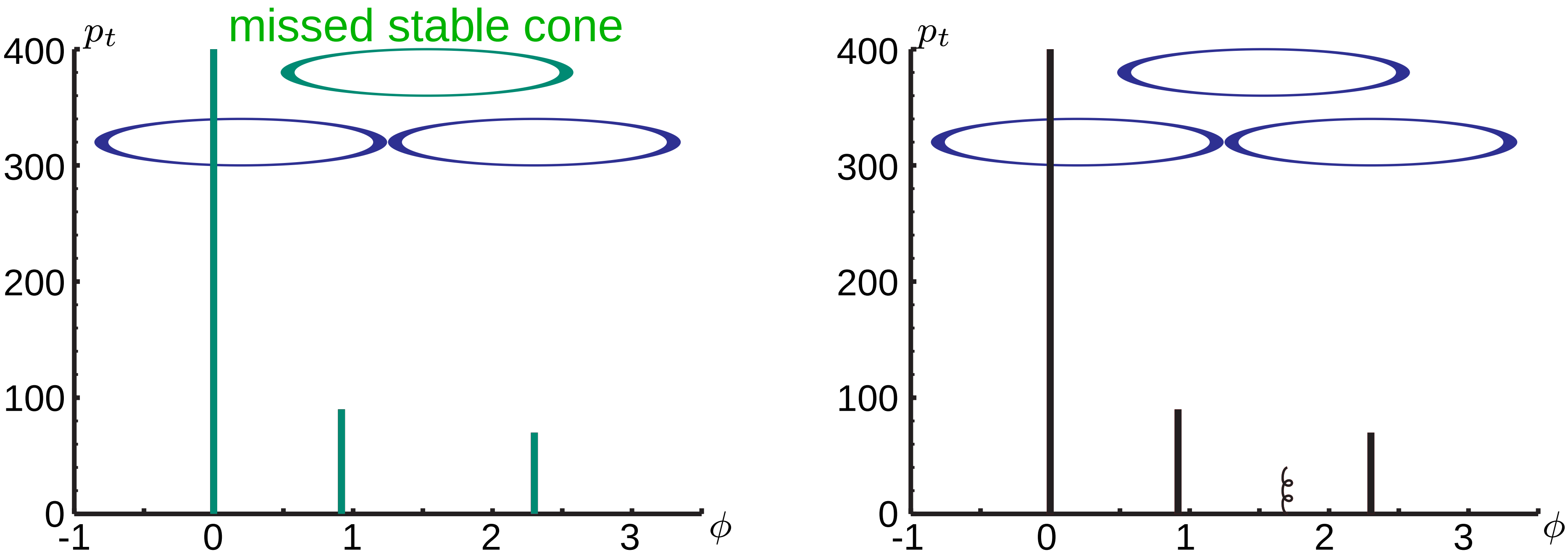
2 jets

1 jet

A soft gluon changed the number of jets

$\Rightarrow$ IR unsafety of MidPoint (1 order in α_s later than JetClu)

IR (un)safety? MidPoint



2 jets

1 jet

Solution: be sure to find **all** stable cones

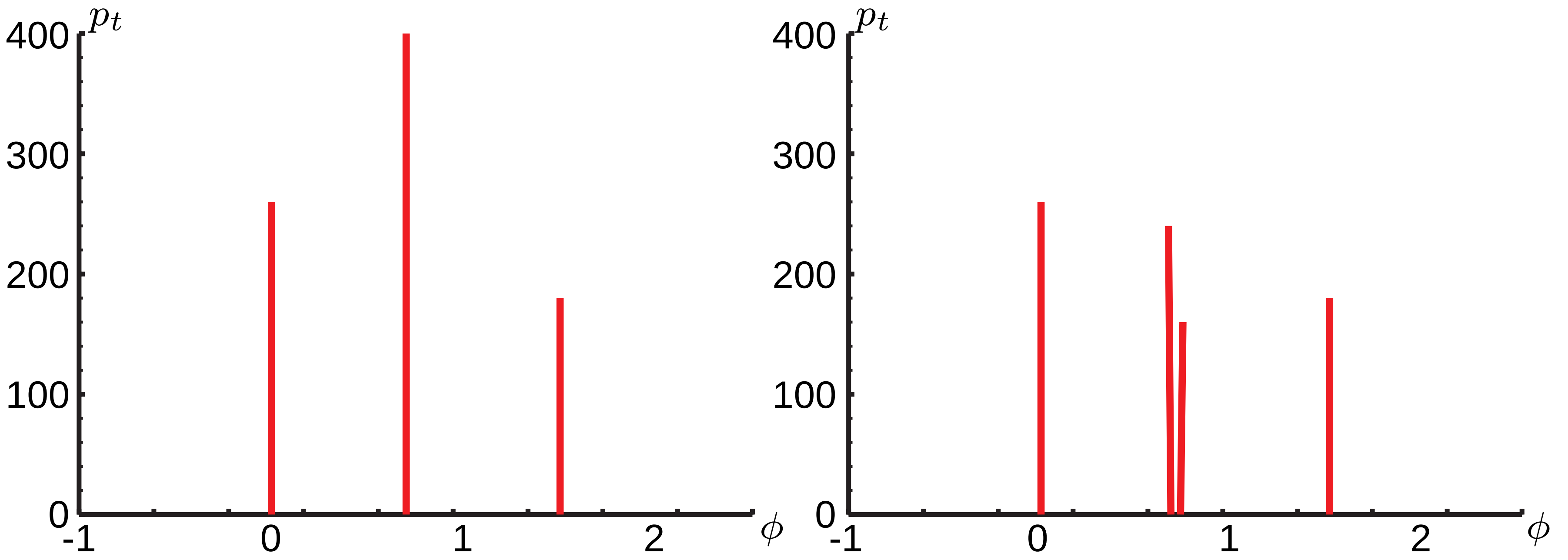
SISCone: Seedless Infrared-Safe Cone algorithm

`http://projects.hepforge.org/siscone`

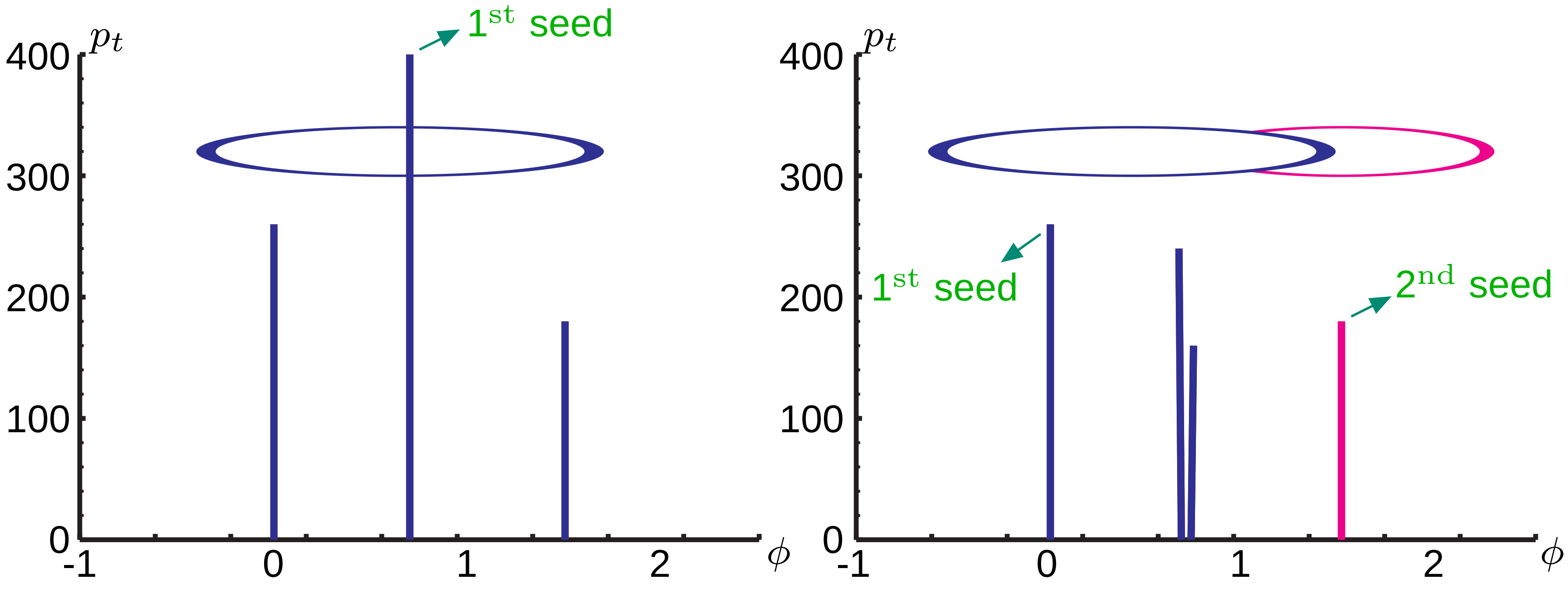
[G.Salam, G.S., 07]

Idea: enumerate enclosures by enumerating pairs of particles

Collinear (un)safety? the CMS iterative cone



Collinear (un)safety? the CMS iterative cone



1 jet

2 jets

A colinear splitting changed the number of jets

⇒ Collinear unsafety of the CMS iterative cone

Anti-k_t

Come back to recombination-type algorithms:

$$d_{ij} = \min(k_{t,i}^{2p}, k_{t,j}^{2p})\ \left(\Delta\phi_{ij}^2 + \Delta\eta_{ij}^2\right)$$

- $p = 1$: k_t algorithm
- $p = 0$: Aachen/Cambridge algorithm

Anti-k_t

Come back to recombination-type algorithms:

$$d_{ij} = \min(k_{t,i}^{2p}, k_{t,j}^{2p})\ (\Delta\phi_{ij}^2 + \Delta\eta_{ij}^2)$$

- $p = 1$: k_t algorithm
- $p = 0$: Aachen/Cambridge algorithm
- $p = -1$: anti-k_t algorithm [M.Cacciari, G.Salam, G.S., 08]

Why should that be related to the iterative cone ?!?

- “large $k_t \Rightarrow$ small distance”
  i.e. hard partons “eat” everything up to a distance R
  i.e. circular/regular jets, jet borders unmodified by soft radiation
- infrared and collinear safe

When does IRC safety matters?

Take *e.g.* the MidPoint cone

$$\overbrace{\alpha_s^2 \times \ldots}^{\text{2 particles}} + \overbrace{\alpha_s^3 \times \ldots}^{\text{3 particles}} + \overbrace{\alpha_s^4 \times \ldots}^{\text{4 particles}} + \overbrace{\alpha_s^5 \times \qquad\qquad\qquad \ldots}^{\text{4 particles + 1 soft}} + \ldots$$

- QCD expansion (one α_s can be replaced by α_{EW})

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Take *e.g.* the MidPoint cone

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- QCD expansion (one α_s can be replaced by α_{EW})
- IRC unsafety (regulated at the hadronic scale $\sim \Lambda_{\mathrm{QCD}}$)
- $\alpha_s \log(p_t/\Lambda_{\mathrm{QCD}}) \sim 1$
- **last meaningful order =** $\alpha_{\mathbf{s}}^{\mathbf{3}}$ **or** $\alpha_{\mathrm{EW}}\alpha_{\mathbf{s}}^{\mathbf{2}}$

When does IRC safety matters?

Take *e.g.* the MidPoint cone

$$\overbrace{\alpha_s^2 \times \ldots}^{\text{2 particles}} + \overbrace{\alpha_s^3 \times \ldots}^{\text{3 particles}} + \underbrace{\overbrace{\alpha_s^4 \times \ldots}^{\text{4 particles}} + \overbrace{\alpha_s^5 \times \log(p_t/\Lambda_{\mathrm{QCD}}) \ldots}^{\text{4 particles + 1 soft}} + \ldots}_{\text{cannot be trusted}}$$

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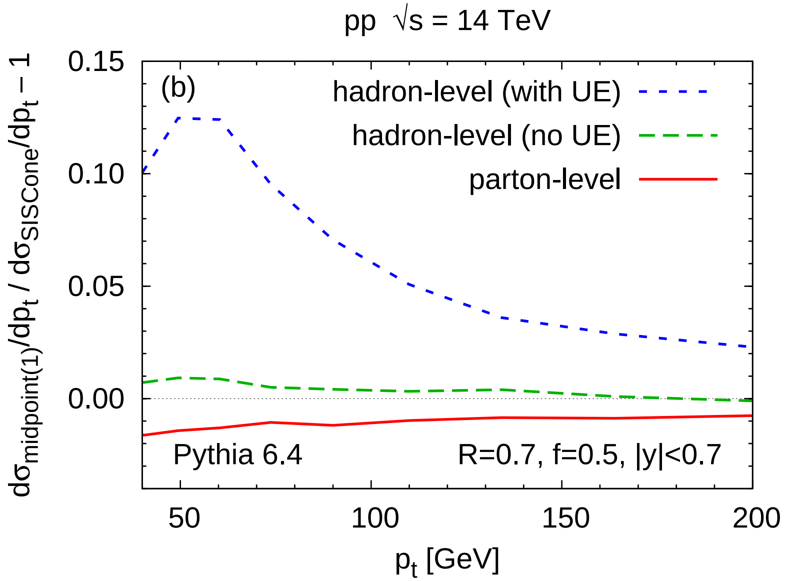
- $\alpha_s \log(p_t/\Lambda_{\mathrm{QCD}}) \sim 1$
- **last meaningful order = $\alpha_{\mathbf{s}}^{\mathbf{3}}$ or $\alpha_{\mathrm{EW}}\alpha_{\mathbf{s}}^{\mathbf{2}}$**
- same argument for the Iterative Cone
- 1 order worse for JetClu or the ATLAS cone

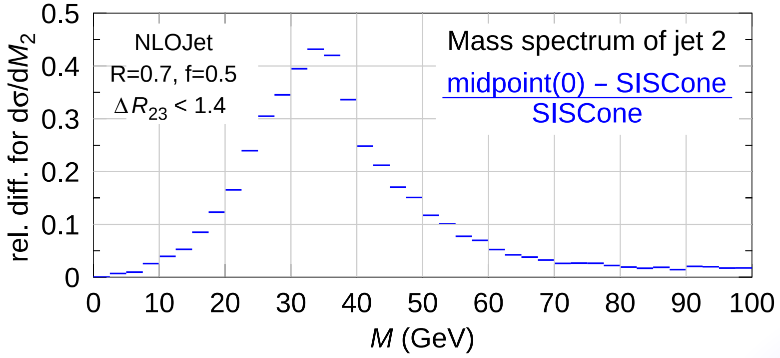
Physical impact

	Last meaningful order	
Observable	MidPoint/CMS	JetClu/ATLAS
Inclusive jet cross sect.	NLO	LO (NLOJet: NLO)
3 jet cross section	LO	none (NLOJet: NLO)
$W/Z/H$ + 2 jet x-sect.	LO	none (MCFM: NLO)
jet masses in 3 jets	none	none (NLOJet: LO)

Example: (Midpoint-SISCone)/SISCone



- Incl. cross-section: a few %
- Masses in 3-jet events: $\sim 45\%$



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$W/Z/H$ + 2 jet x-sect.	LO	none (MCFM: NLO)
jet masses in 3 jets	none	none (NLOJet: LO)

⚠ Huge effort (~ 50 M€) to compute processes in pQCD

The SISCone search for stable cones

- Solution: use a seedless approach, find ALL stable cones
- Naive approach: check stability of each subset of particle

The SISCone search for stable cones

- Solution: use a seedless approach, find ALL stable cones

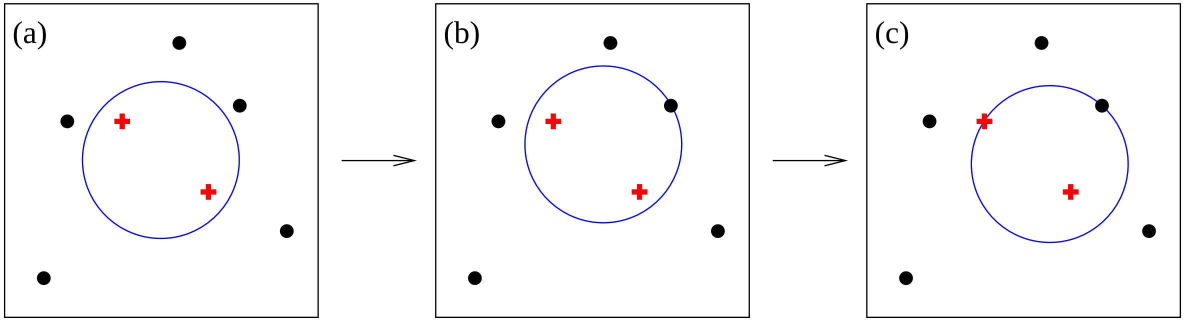
- Naive approach: check stability of each subset of particle
  Complexity is $\mathcal{O}\left(N2^N\right)$
  $\Rightarrow$ definitely unrealistic: 10^{17} years for $N = 100$

- Midpoint complexity: $\mathcal{O}\left(N^3\right)$

The SISCone search for stable cones

- Solution: use a seedless approach, find ALL stable cones
- Midpoint complexity: $\mathcal{O}\left(N^3\right)$

Idea: use geometric arguments



- Each enclosure can be moved (in any dir.) until it touches a point
- ... then rotated until it touches a second one

$\Rightarrow$ Enumerate all pairs of particles
with 2 circle orientations and 4 possible inclusion/exclusion
$\longrightarrow$ find all enclosures

The SISCone search for stable cones

- Solution: use a seedless approach, find ALL stable cones
- Midpoint complexity: $\mathcal{O}\left(N^3\right)$

Idea: use geometric arguments

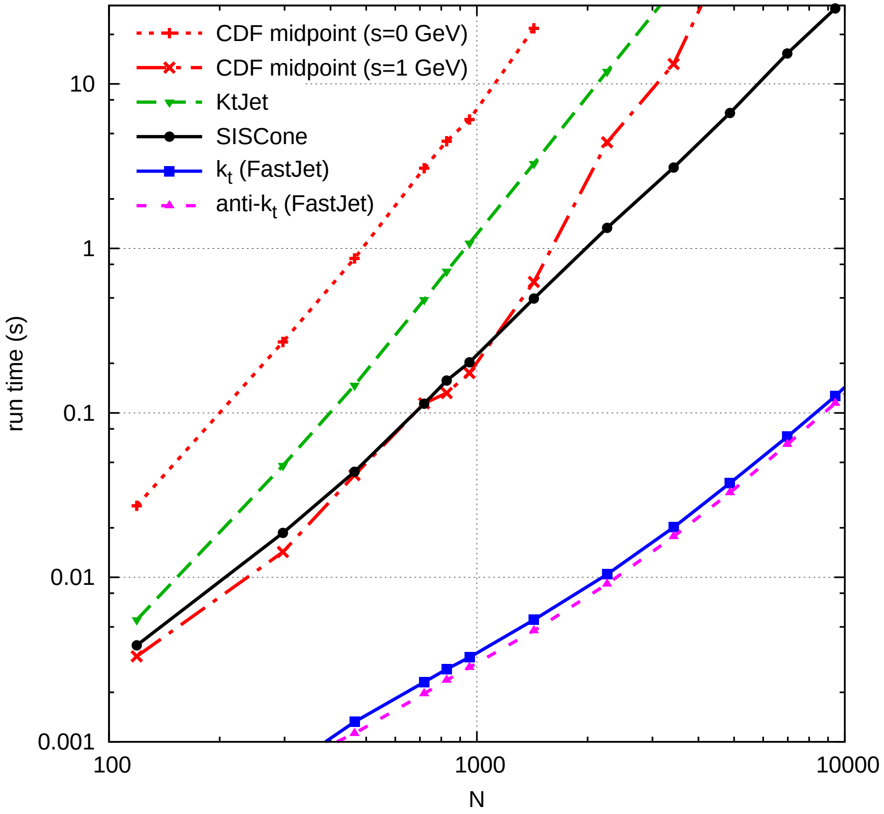
$\Rightarrow$ Enumerate all pairs of particles
with 2 circle orientations and 4 possible inclusion/exclusion
$\longrightarrow$ find all enclosures

- Complexity: $\mathcal{O}\left(N^3\right)$, with improvements: $\mathcal{O}\left(N^2 \log(N)\right)$

$\longrightarrow$ C++ implementation: Seedless Infrared-Safe Cone algorithm (SISCone)
G.Salam, G.S., JHEP 04 (2007) 086; http://projects.hepforge.org/siscone

NB.: also available from FastJet
[M.Cacciari, G.Salam, G.S.]; http://www.fastjet.fr

Algorithm timings



- Recombination algorithms very fast

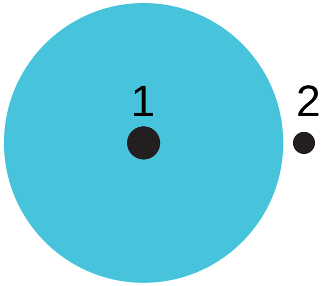
[M. Cacciari, G. Salam, 06]

- SISCone not slower than Midpoint (even with a 1 GeV seed threshold)

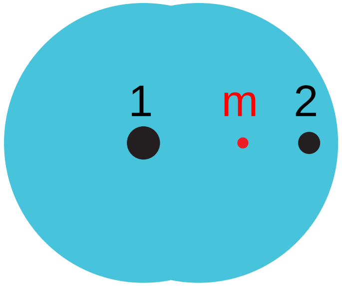
A technical point: Back-reaction

Additional soft background has 2 effects:

- Throw soft particles in the hard jet: dealt with by subtraction
- Modify the hard scattering (back-reaction)
  - can be pointlike or diffuse
  - gain:

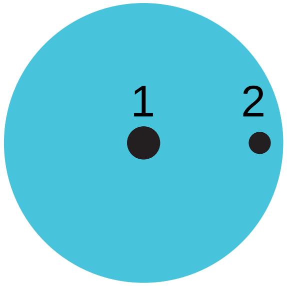


no medium: $p_t = p_{t1}$

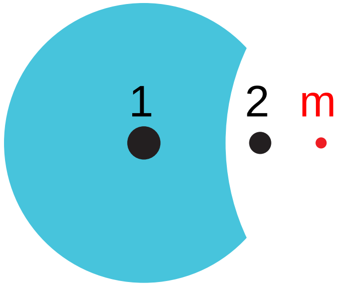


medium: $p_t = p_{t1} + p_{t2} + p_{tm}$

  - loss:



no medium: $p_t = p_{t1} + p_{t2}$



medium: $p_t = p_{t1} + p_{tm}$

A technical point: Back-reaction

Additional soft background has 2 effects:

- Throw soft particles in the hard jet: dealt with by subtraction
- Modify the hard scattering (back-reaction)
  - can be pointlike or diffuse
  - tractable analytically (similar to areas)
  - $k_t \gtrsim$ Cambridge > SISCone $\gg$ anti-k_t