Defining jets at the LHC

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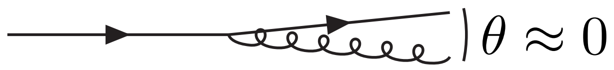
arXiv:0704:0292, arXiv:0802:1189, arXiv:0810.1304

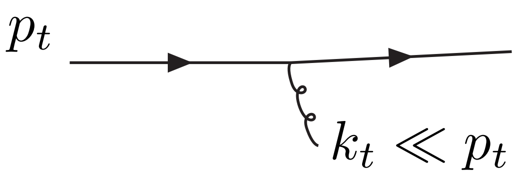
Unavoidable theory

QCD probability for gluon emission (angle θ and $\perp$-mom. k_t):

$$dP \propto \alpha_s \frac{d\theta}{\theta} \frac{dk_t}{k_t}$$

Two divergences:





collinear

soft

Divergences cancelled by virtual corrections

Motivation: why QCD?

Lot of QCD in the final-state at the LHC

- QCD studies: *e.g.* $t \to bq\bar{q}$
- new physics:
  - $H \to b\bar{b}$
  - $Z' \to q\bar{q}$
  - SUSY $\to$ QCD
- backgrounds: *e.g.* $gg \to b\bar{b}$, ...

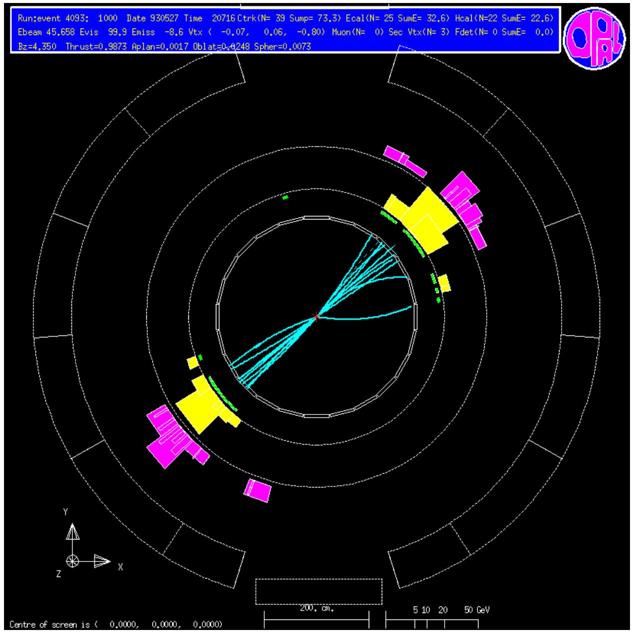
$\Rightarrow$ Huge effort to compute multileg/NLO processes in pQCD ($\sim$ 100 M$)

This talk: how to avoid wasting that effort, in the optimal way

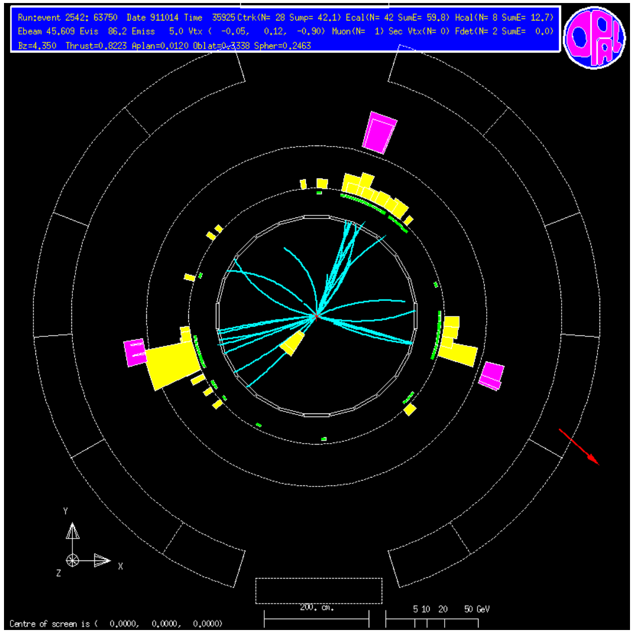
Motivation: why jets

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

Example: LEP (OPAL) events



2 jets



3 jets

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

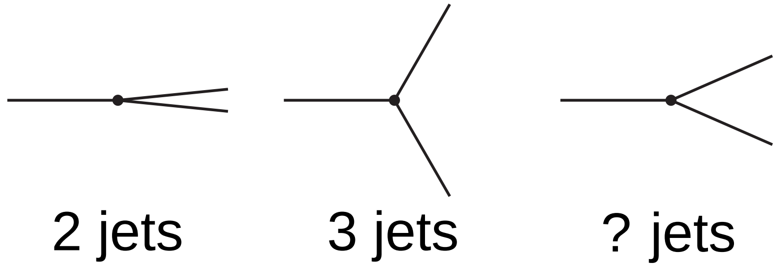
Motivation: why jets

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



$\Rightarrow$ Different jet definitions

20th century jet finders

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

20th century jet finders

Recombination:

- k_t algorithm
- Cambridge/Aachen alg.

Idea: undo the showering

Successively

- find the closest pair of particles
- recombine them

Distance:

k_t:

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

Cam/Aachen:

$$d_{i,j} = \Delta\phi_{i,j}^2 + \Delta y_{i,j}^2$$

stop at a distance R

20th century jet finders

Idea: dominant flow of energy

Stable cone (radius R):
sum of particles in the cone points towards the cone centre

All these are iterative cones:

- start from a seed
- iterate until stable

seeds = {particles, midpoints}

Jet $\equiv$ stable cone
modulo overlapping

Cone:

- CDF JetClu
- CDF MidPoint
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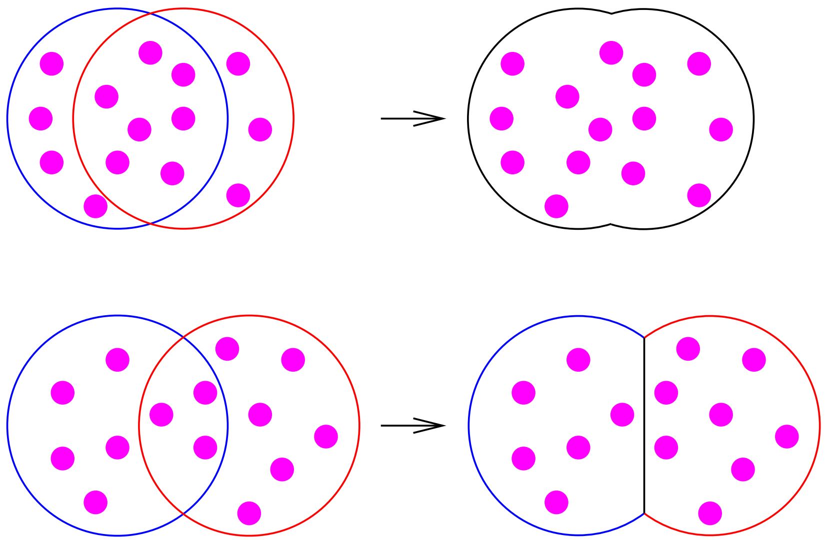
20th century jet finders

Cone with split-merge

Split/merge if the overlap is smaller/larger than a threshold f



Cone:

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20th century jet finders

Cone with progressive removal

Successively

- iterate from hardest particle
- call that a jet (remove particles)

Basic property:

hard circular jets

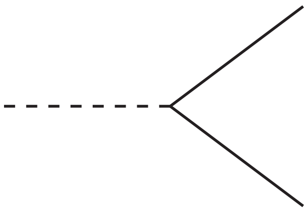
Cone:

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

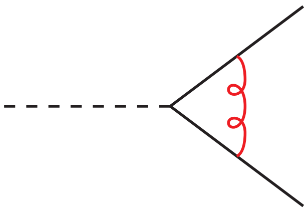
21st century: how does that picture change?

QCD divergences

Ingredient: QCD soft and collinear divergencies

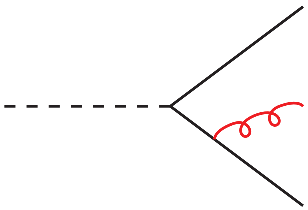


LO



NLO(virt)

∞



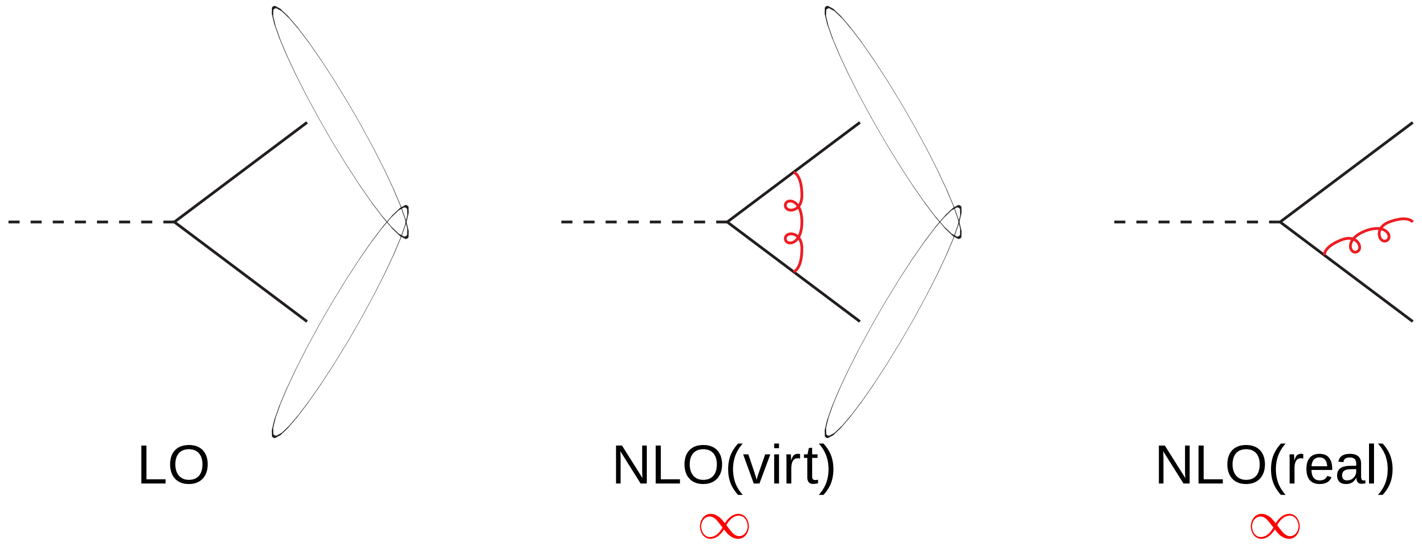
NLO(real)

∞

- ∞ (from soft gluons) cancel

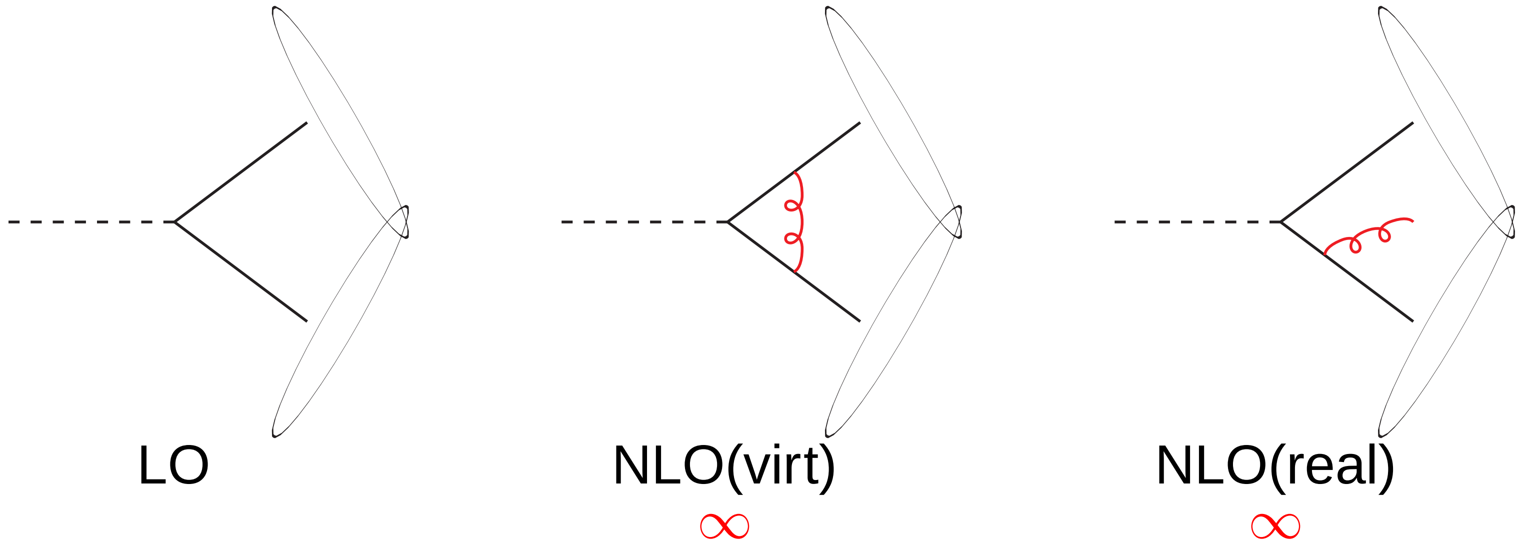
QCD divergences

Ingredient: QCD soft and collinear divergencies



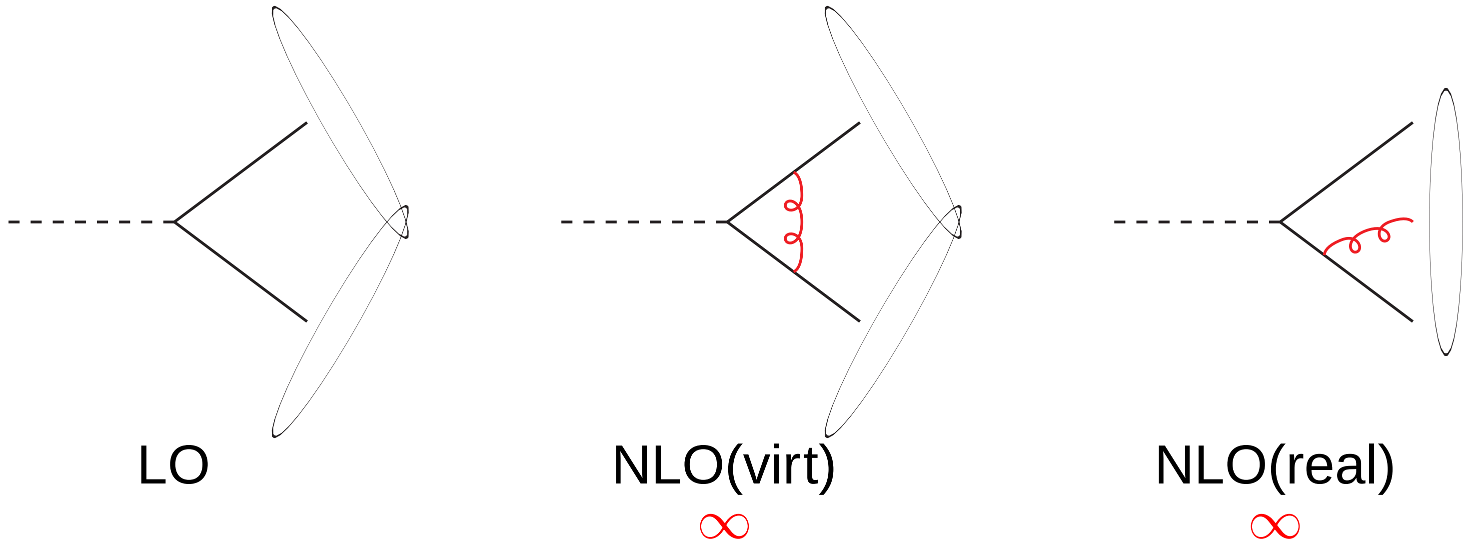
- Consider an extra (NLO) soft gluon
- Assume LO gives 2 jets $\Rightarrow$ NLO(virt) gives 2 jets

Ingredient: QCD soft and collinear divergencies



- Consider an extra (NLO) soft gluon
- Assume LO gives 2 jets $\Rightarrow$ NLO(virt) gives 2 jets
- NLO(real) gives 2 jets $\Rightarrow \infty$ cancel $\Rightarrow$ finite jet cross-section

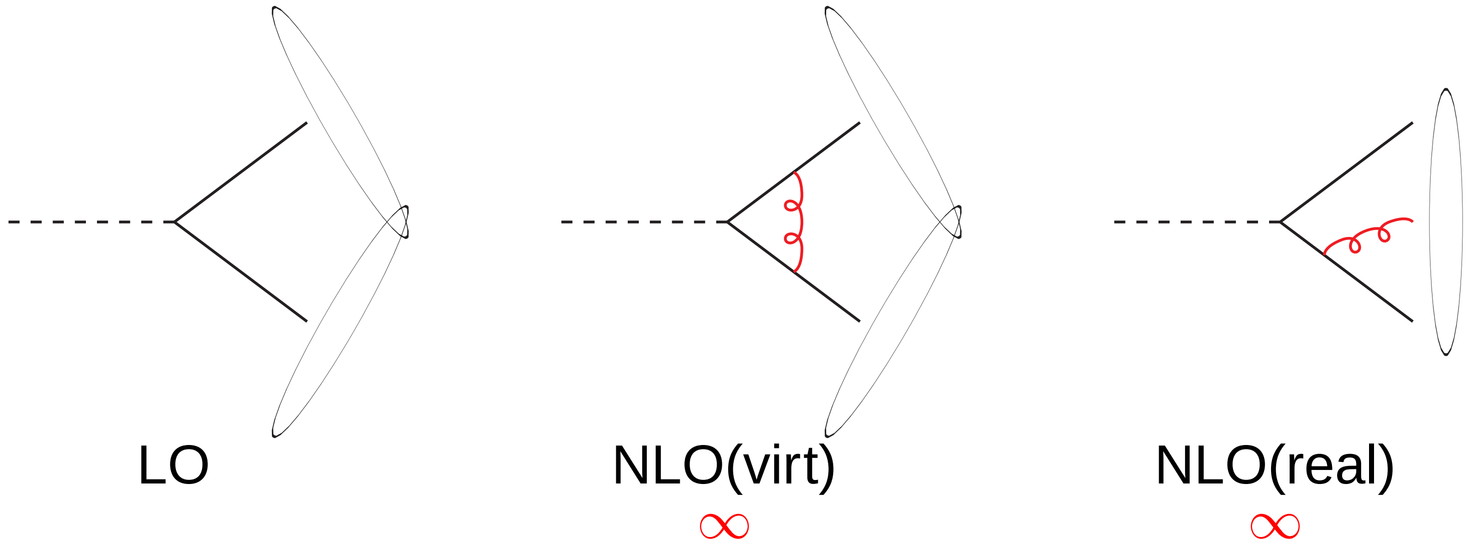
Ingredient: QCD soft and collinear divergencies



- 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 cross-section

QCD divergences

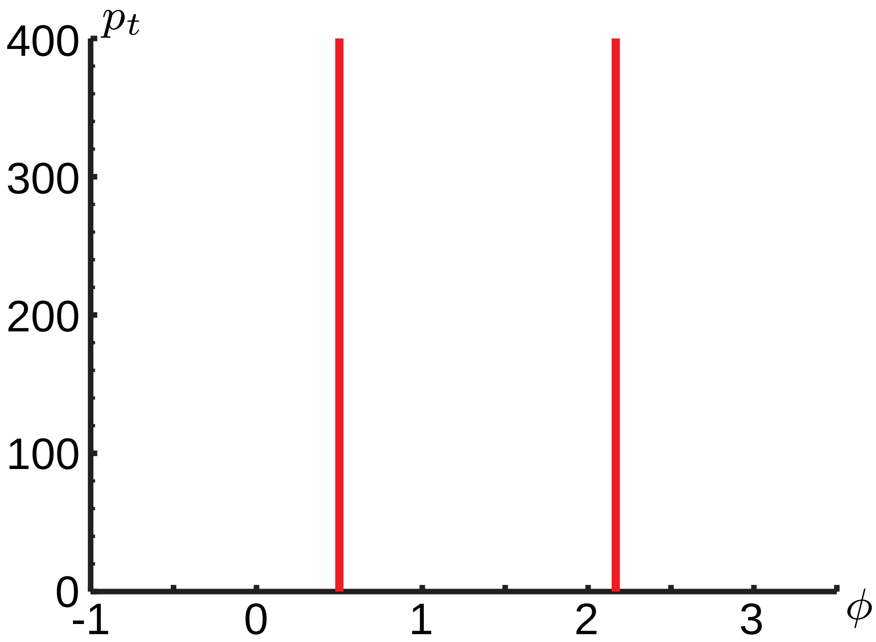
Ingredient: QCD soft and collinear divergencies

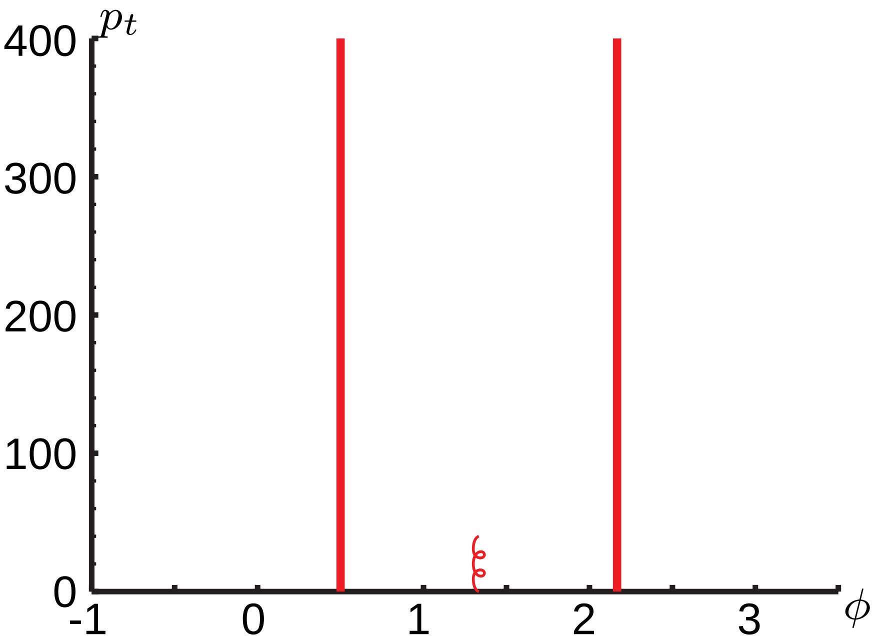


For pQCD to make sense, the (hard) jets should not change when

- 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)

IR (un)safety? JetClu and Atlas Cone





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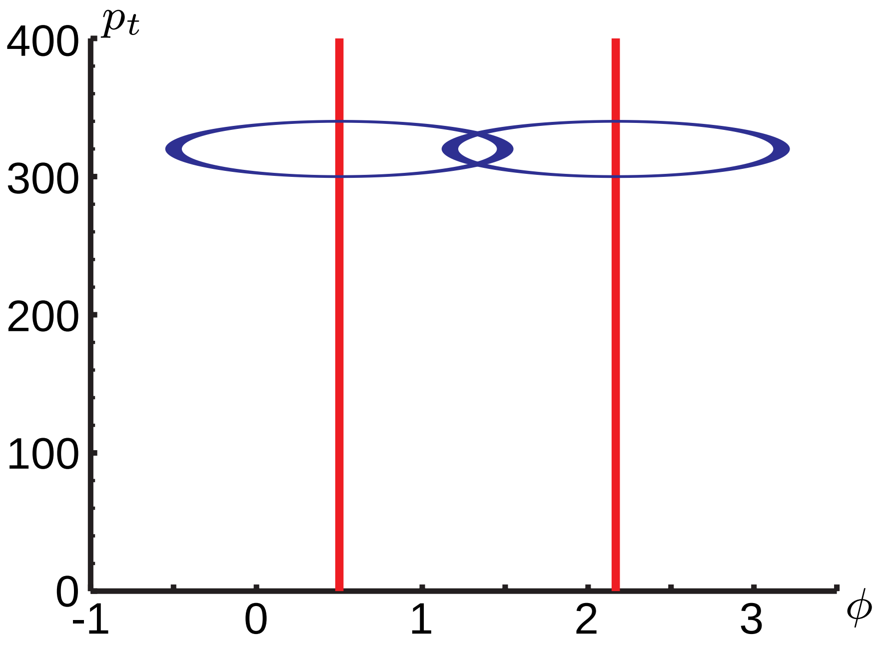
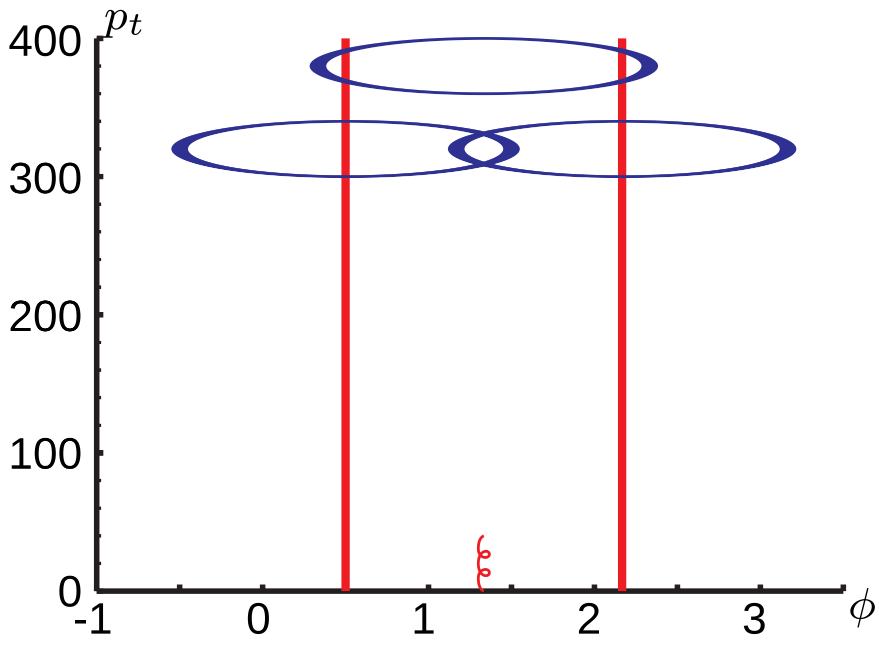
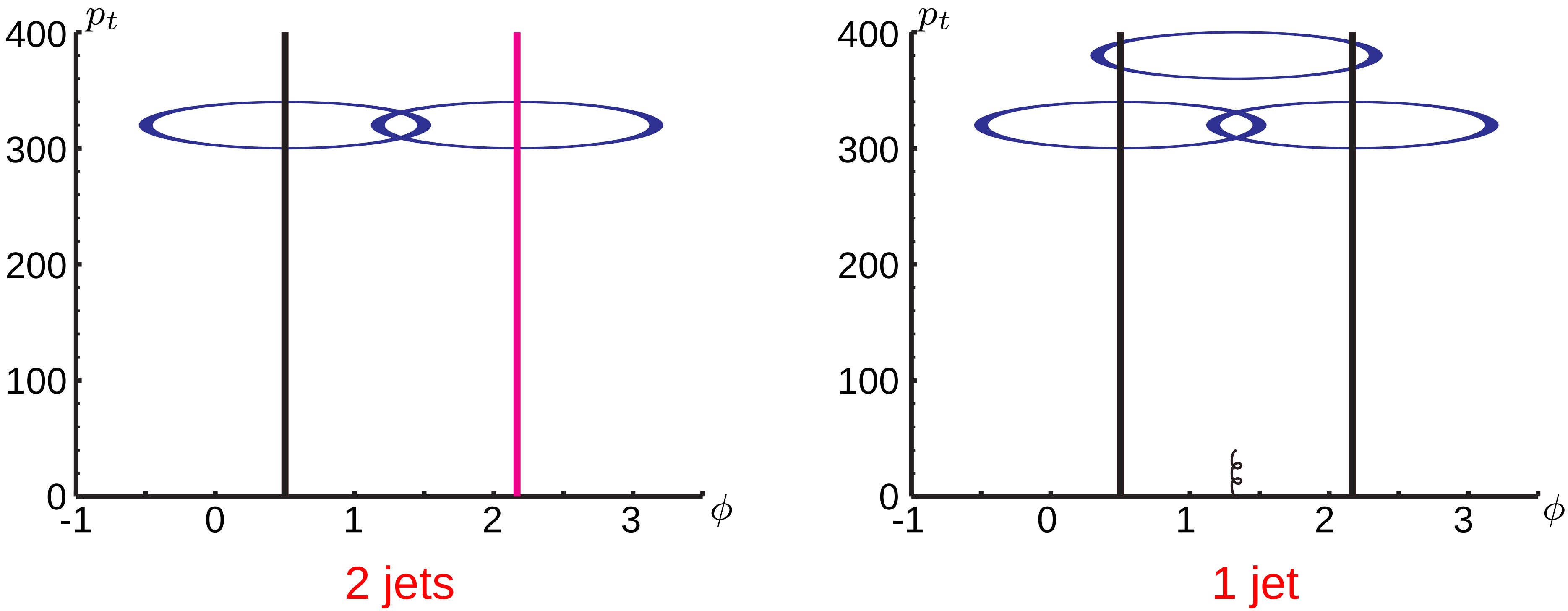




Stable cones found

IR (un)safety? JetClu and Atlas Cone



A soft gluon changed the number of jets

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

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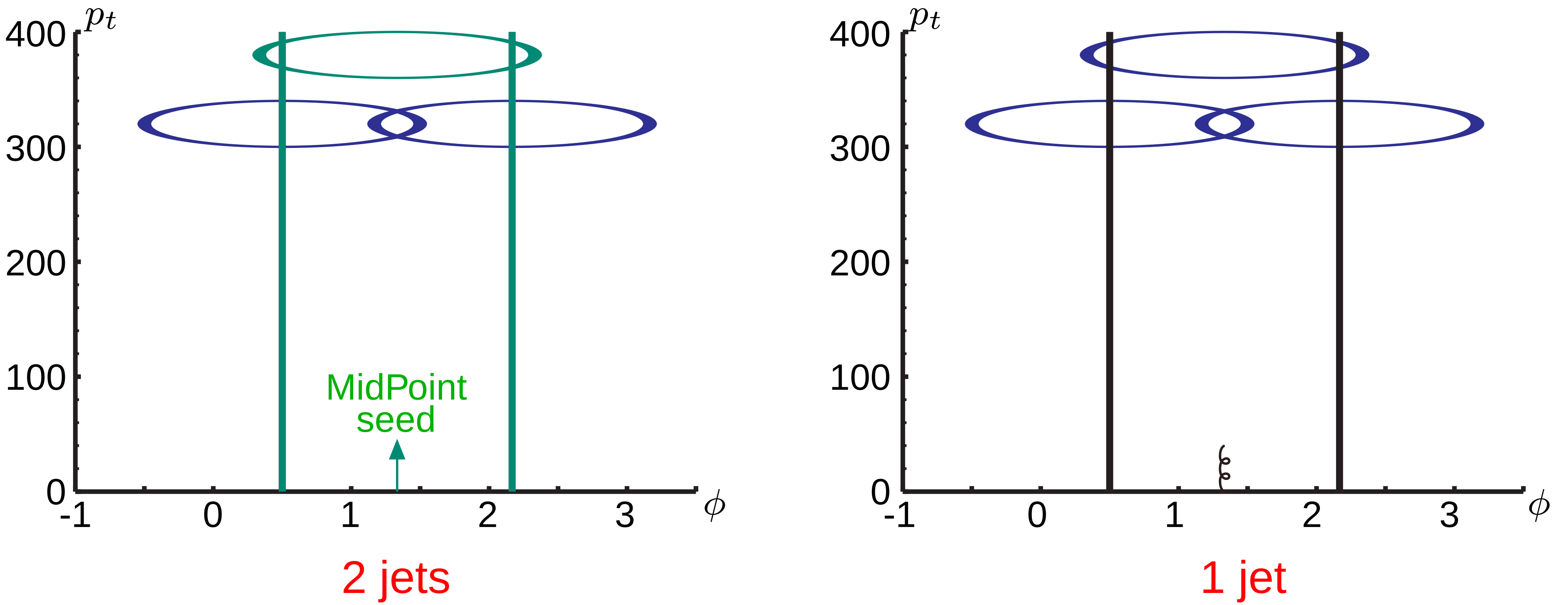

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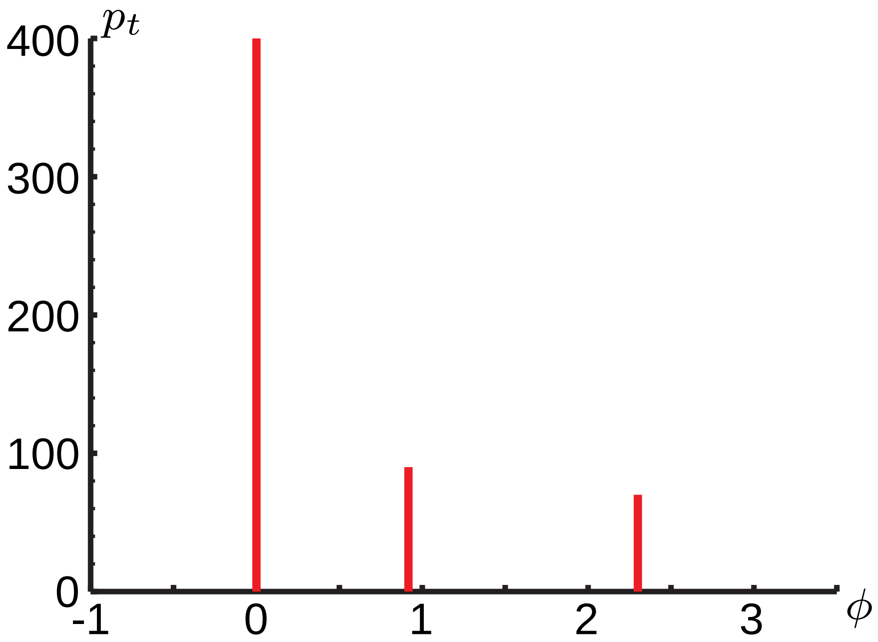
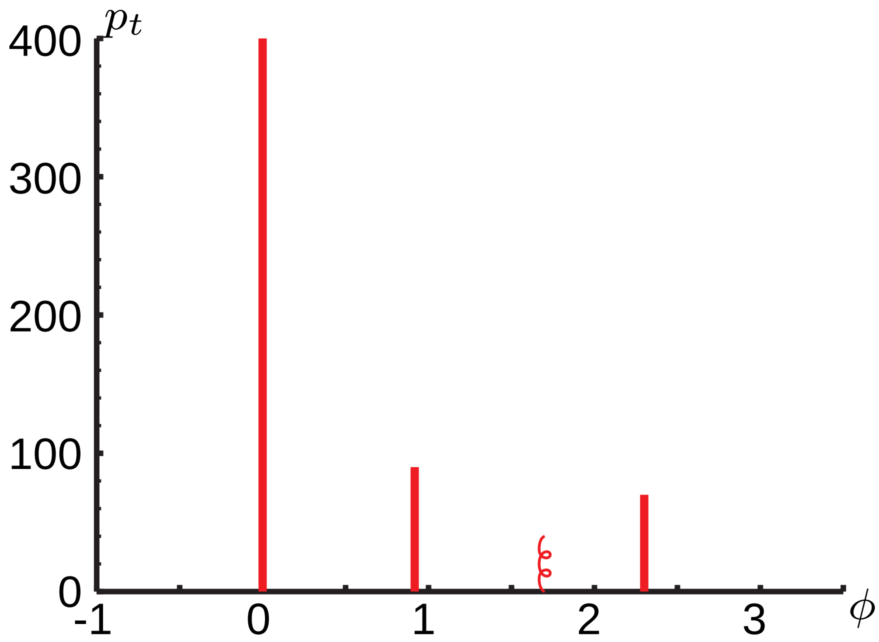
$\Rightarrow$ IR unsafety of JetClu and the ATLAS Cone

Fixed by MidPoint

[Blazey *et al.*, 00]

IR (un)safety? MidPoint





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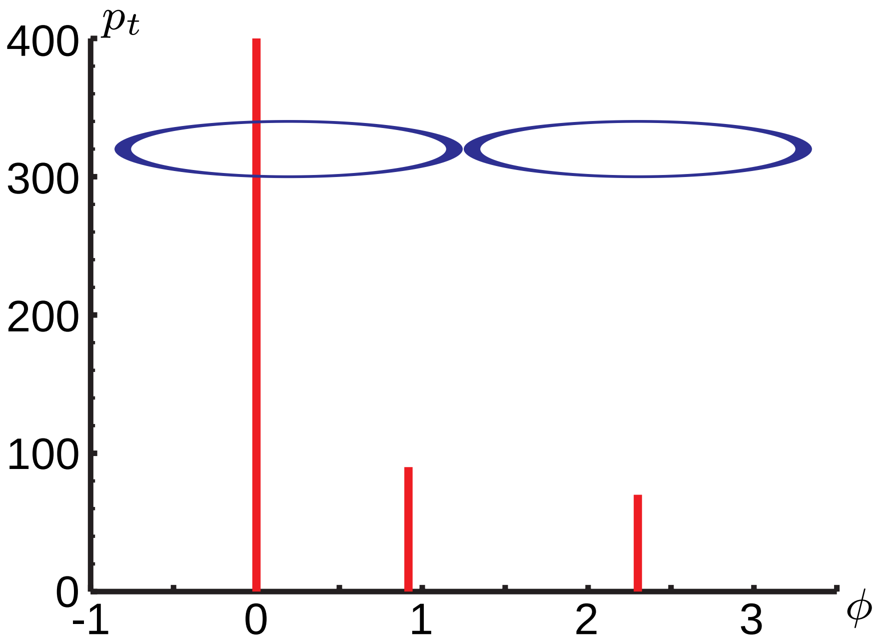
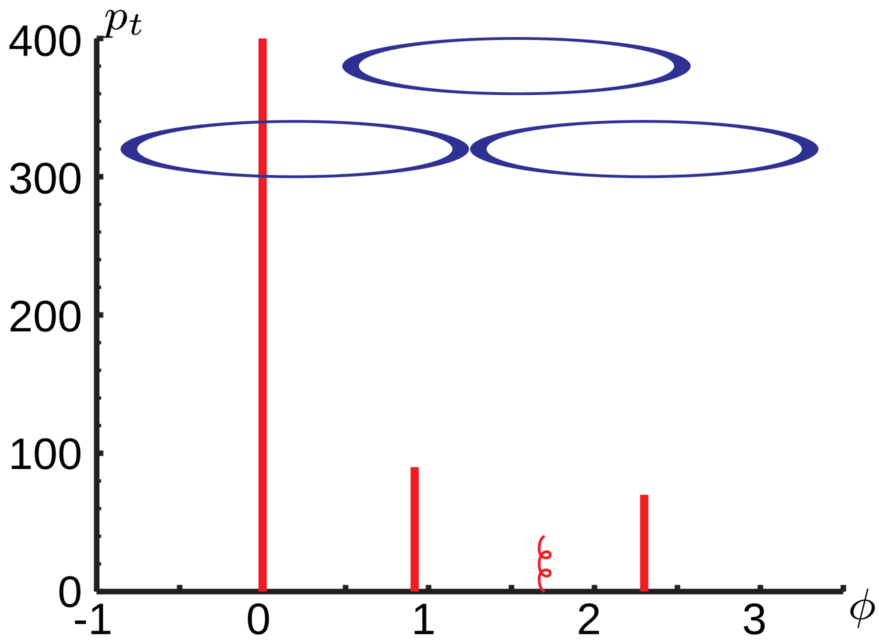
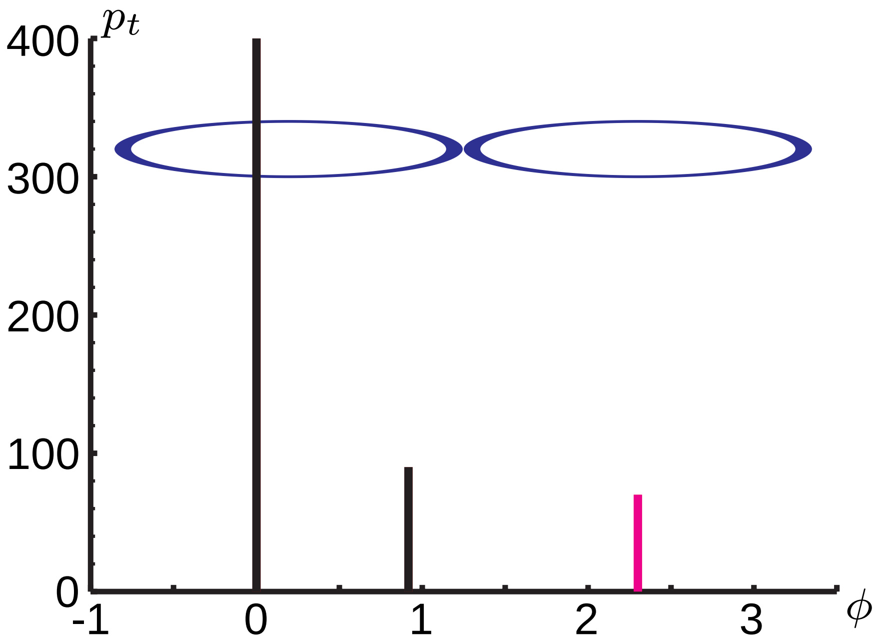


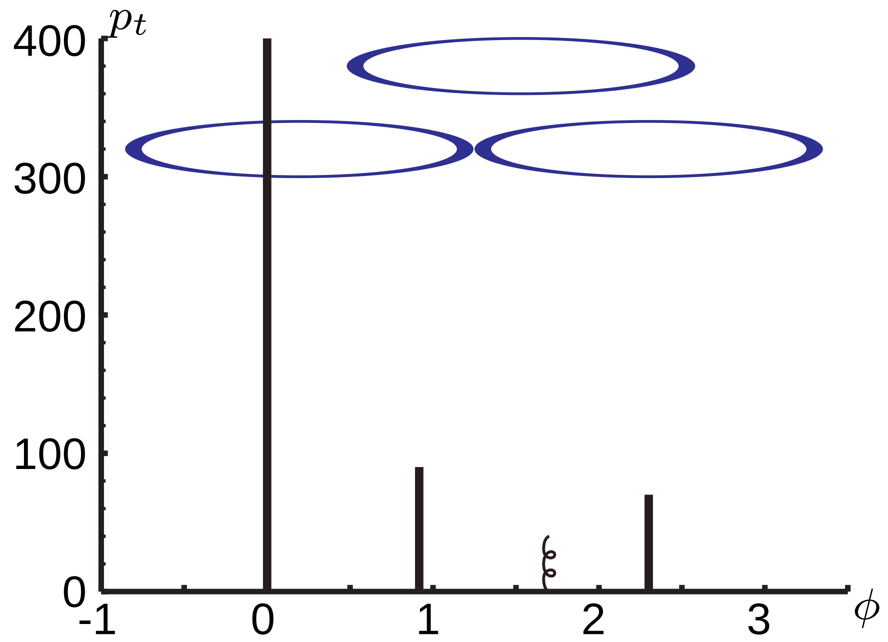


Stable cones found

IR (un)safety? MidPoint



2 jets

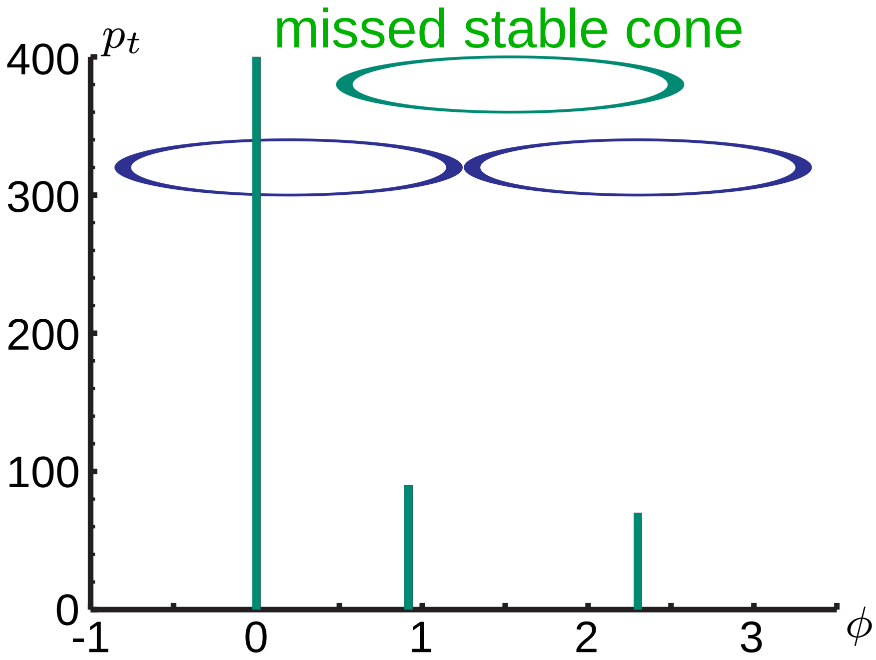


1 jet

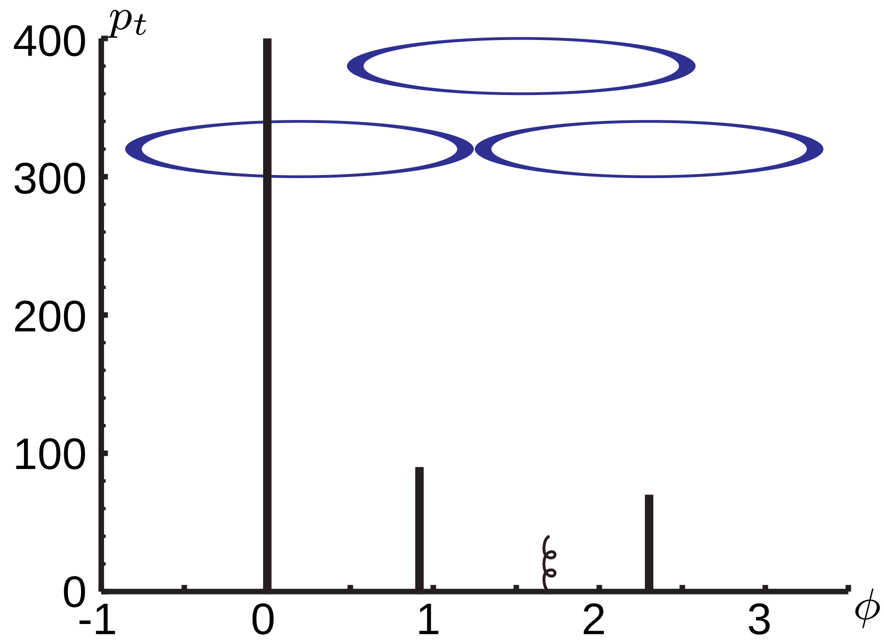
A soft gluon changed the number of jets

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

IR (un)safety? MidPoint



2 jets



1 jet

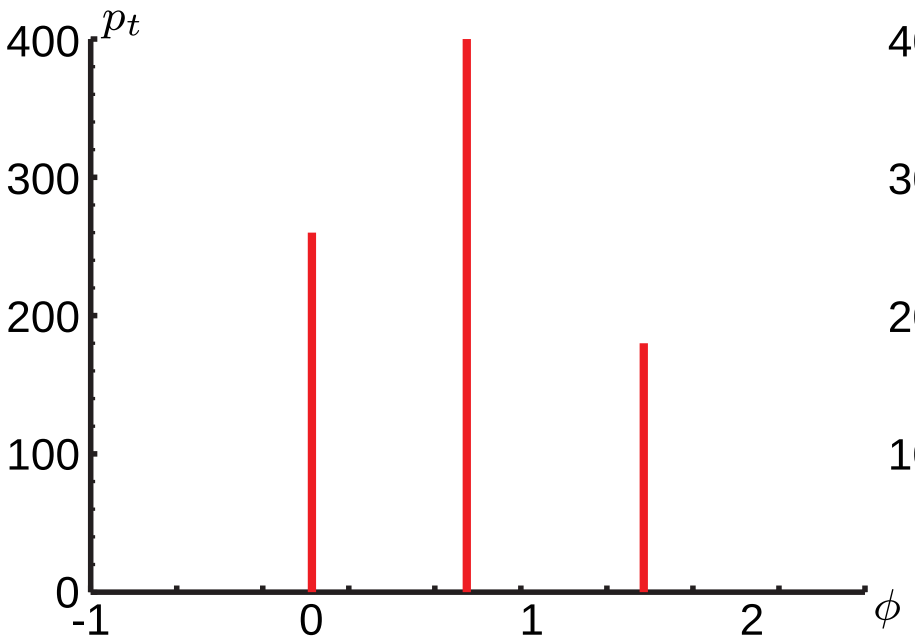
Solution: be sure to find **all** stable cones

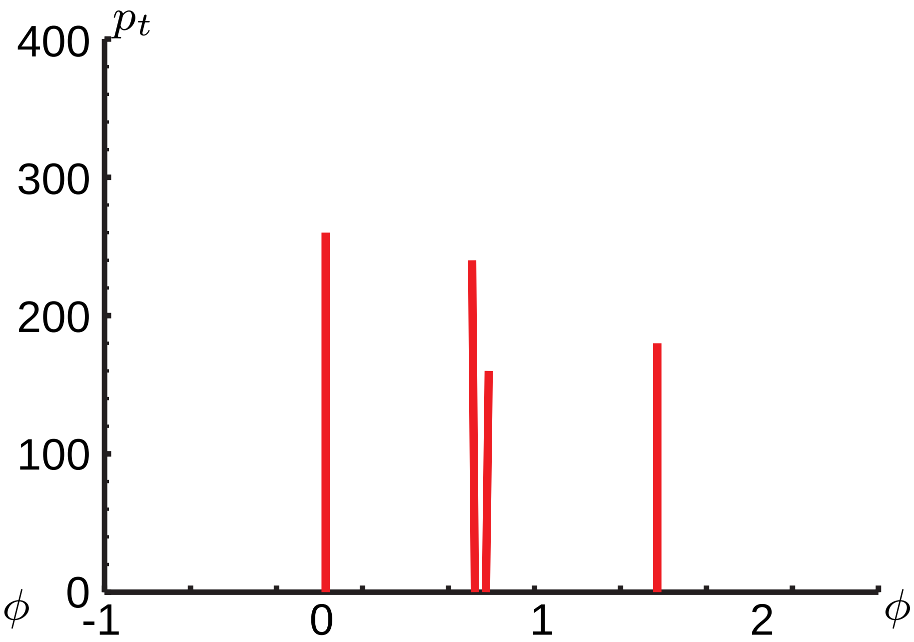
> SISCone: Seedless Infrared-Safe Cone algorithm
> `http://projects.hepforge.org/siscone`

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

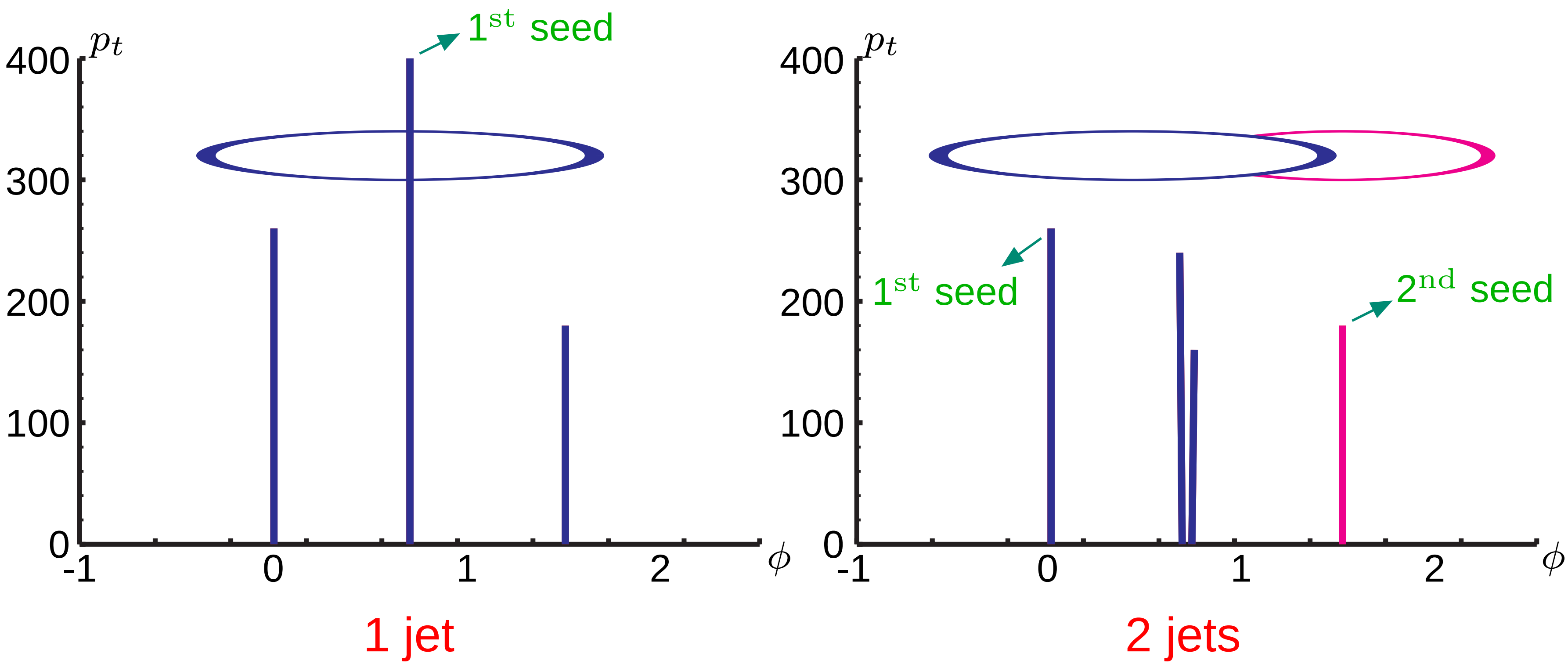
Idea: enumerate enclosures by enumerating pairs of particles

Collinear (un)safety? the CMS iterative cone





Collinear (un)safety? the CMS iterative cone



A colinear splitting changed the number of jets

$\Rightarrow$ 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
- $p = 0$: Cambridge/Aachen algorithm

Anti-k_t

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

21st century jet finders

Recombination:

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

Cone:

- CDF JetClu
- CDF MidPoint
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- PxCone
- ATLAS Cone
- CMS Iterative Cone
- PyCell/CellJet
- GetJet
- SISCone

4 available
safe algorithms

All accessible from **FastJet**

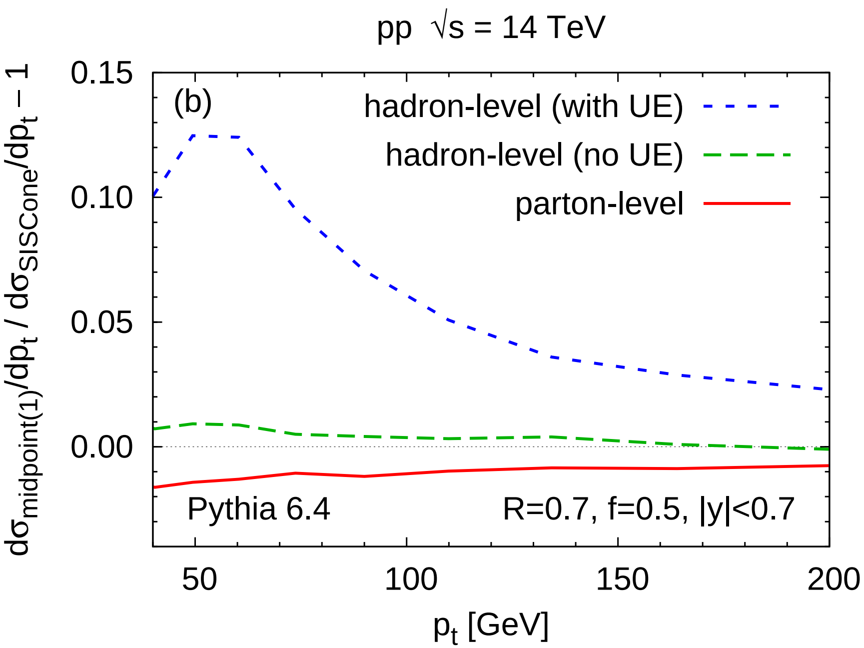
http://www.fastjet.fr [M.Cacciari, G.Salam, G.S.]

Physical impact

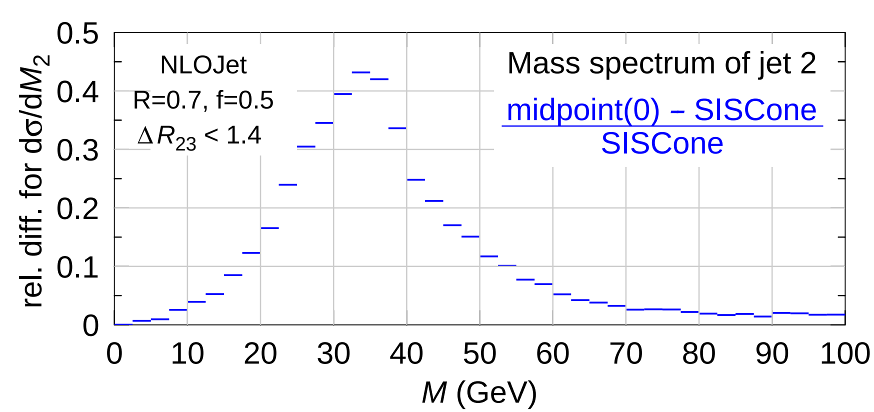
MidPoint/CMS iterative cone unsafe at $\mathcal{O}(\alpha_s^4)$ (or $\mathcal{O}(\alpha_{\rm ew}\alpha_s^3)$)

Physical observable	IRC-safe until		
	JetClu/ATLAS cone	MidPoint/CMS it. cone	SISCone/recomb.
Inclusive jet cross section	LO	NLO	any
3-jet cross section	**none**	LO	any
$W/Z/H$ + 2 jet cross sect.	**none**	LO	any
jet masses in 3 jets	**none**	**none**	any

Example: (Midpoint-SISCone)/SISCone



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



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jet masses in 3 jets	**none**	**none**	any

Huge theoretical effort to compute multileg/NLO processes

That can be wasted by using unappropriate tools.

Note:

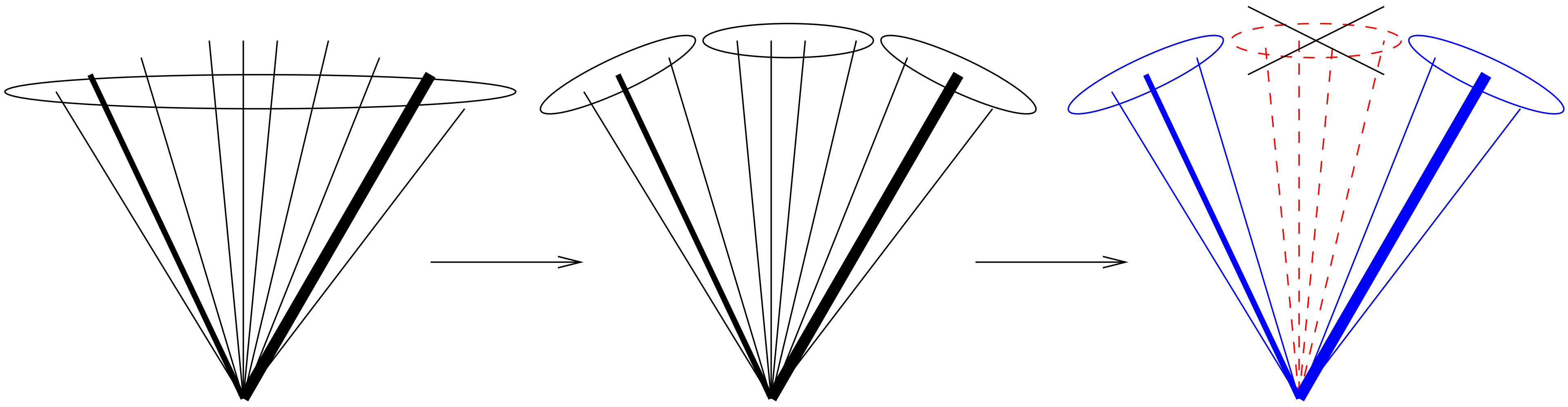
- arXiv:0903.0814: $W+2$ jets vs. LO QCD using CDF JetClu
- arXiv:0903.1748: $Z+2$ jets vs. NLO QCD using the D0runII cone
- arXiv:0903.1801: $Z+2$ jets vs. NLO QCD using the CMS iterative cone

Filtering using jet substructure

More refined clustering ("$3^{\rm rd}$ generation of algorithms")

Cambridge+Filtering algorithm:

- Cluster with Cambridge/Aachen and radius R
- For each jet, recluster it with Cambridge/Aachen and radius $R_{\rm sub}$ keep only $n_{\rm sub}$ hardest sub-jets of the initial jet



Filtering using jet substructure

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- For each jet, recluster it with Cambridge/Aachen and radius $R_{\rm sub}$
  keep only $n_{\rm sub}$ hardest sub-jets of the initial jet

Aim: remove the soft background

Properties:

- Proven to improve jet reconstruction, in $H \to b\bar{b}$
  [J.Butterworth, A.Davison, M.Rubin, G.Salam, 08]
- Additional parameters that deserve appropriate studies
- We will use the simplest choice: $R_{\rm sub} = R/2$, $n_{\rm sub} = 2$

jet definitions = algorithm + parameters

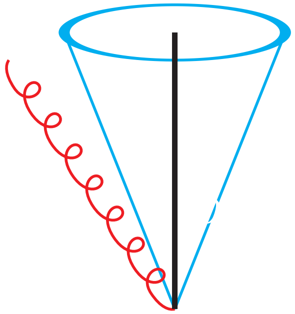
Algorithm: k_t***, Cam./Aachen, anti-***k_t***, SISCone, filtering?***
+ *parameters:* mainly R

Which one to choose?

Underlying idea

Competition between

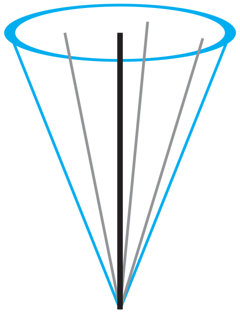
- catching perturbative radiation



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

Jet optimisation study

We analyse 3 processes typical of kinematic reconstructions:

- $Z' \to q\bar{q} \to$2 jets and $H \to gg \to$2 jets:

  simple environment: identify 2 jets and reconstruct $M_{Z',H}$
  source of monochromatic quark/gluon jets
  scale dependence: mass of the Z'/H varied between 100 GeV and 4 TeV
  ficticious narrow Z', H

- $t\bar{t} \to W^+bW^-\bar{b} \to q\bar{q}bq\bar{q}\bar{b} \to$6 jets:

  complex environment: identify 6 jets and reconstruct 2 top
  balance between reconstruction efficiency and identification

with

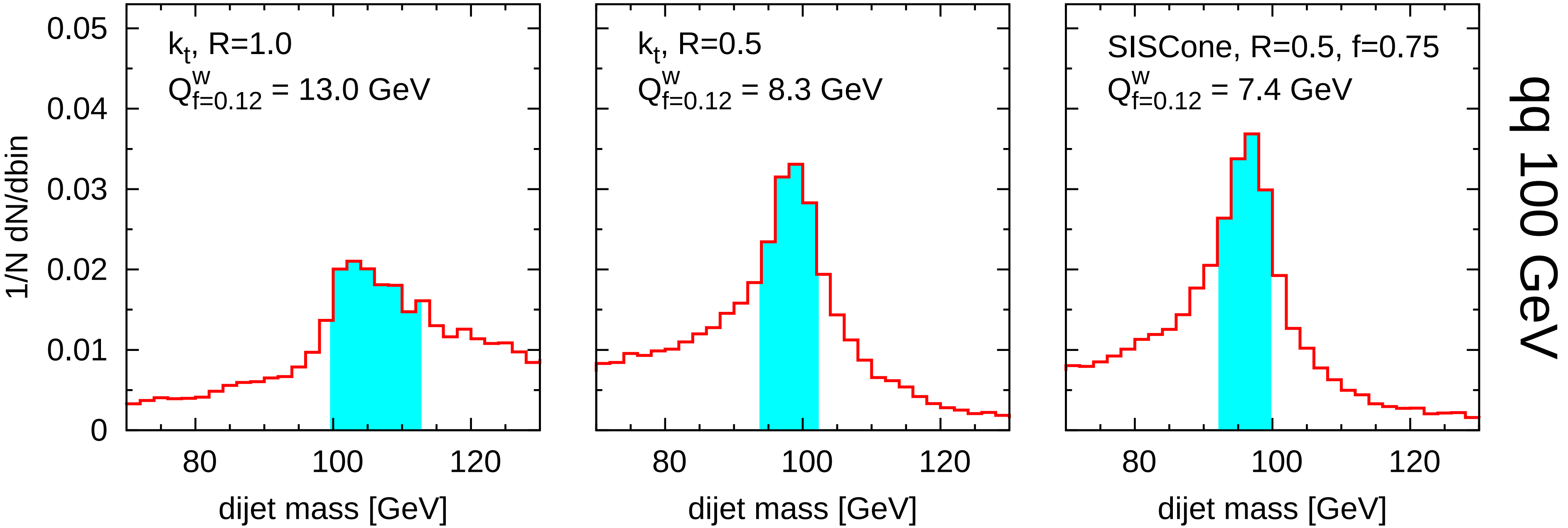
- the 5 IRC-safe algorithms: k_t, Cambridge, anti-k_t, SISCone, Cam+filtering
- jet radius varied between 0.1 and 1.5

Reconstruction quality (1)

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.



Reconstruction quality (2)

Assuming a constant background,

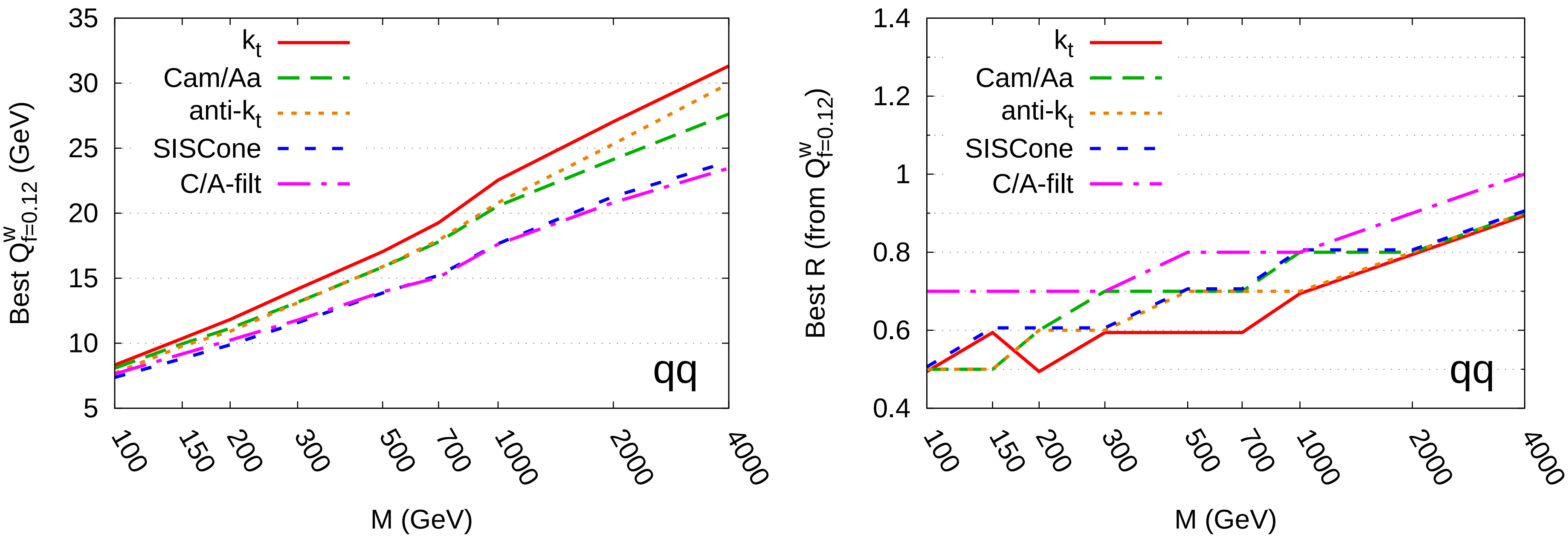
quality measure $\longrightarrow$ effective luminosity ratio

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

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

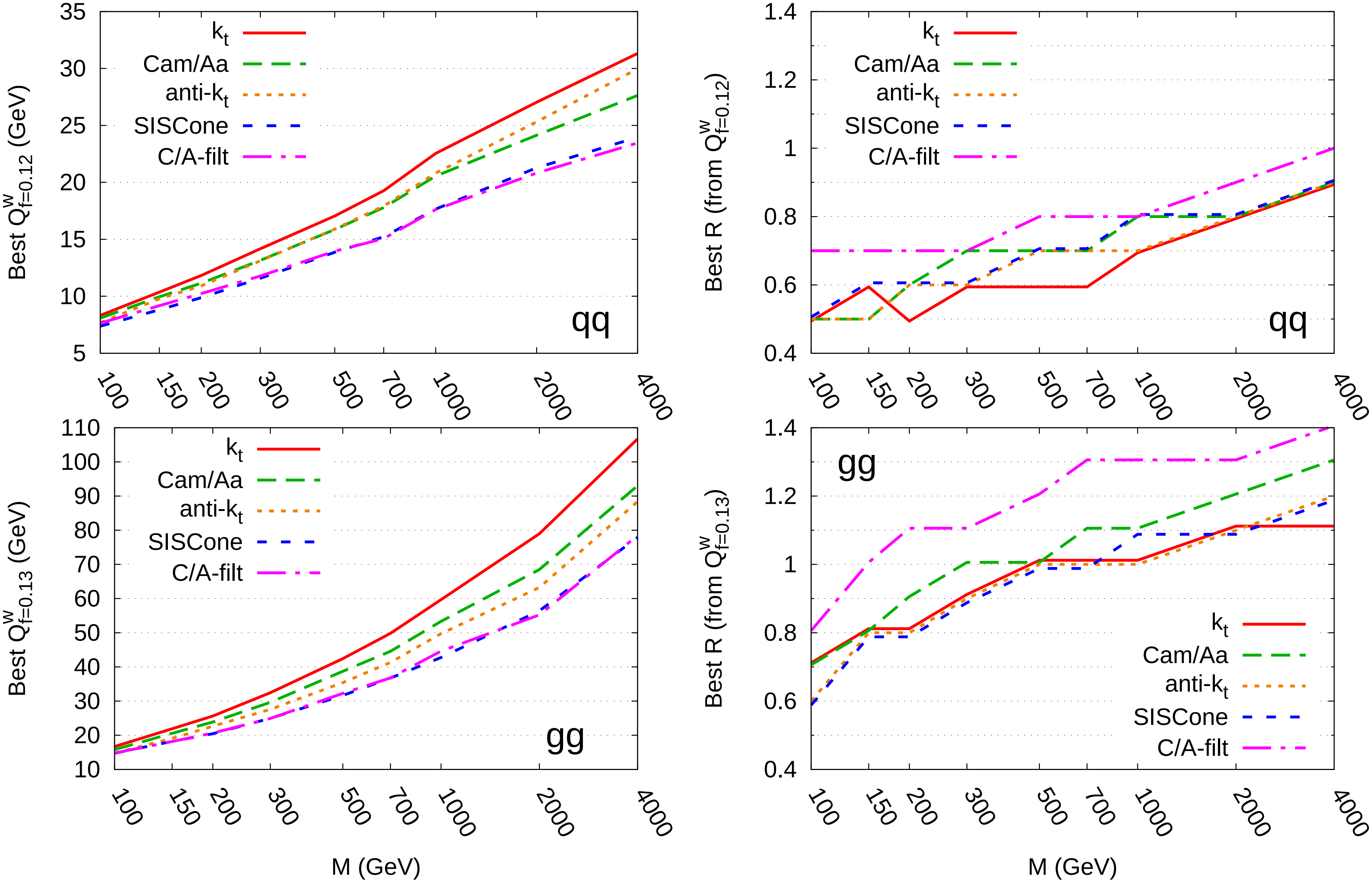
$\Leftrightarrow$ JD_2 requires 2 times the integrated luminosity of JD_1 to achieve the same discriminative power.

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



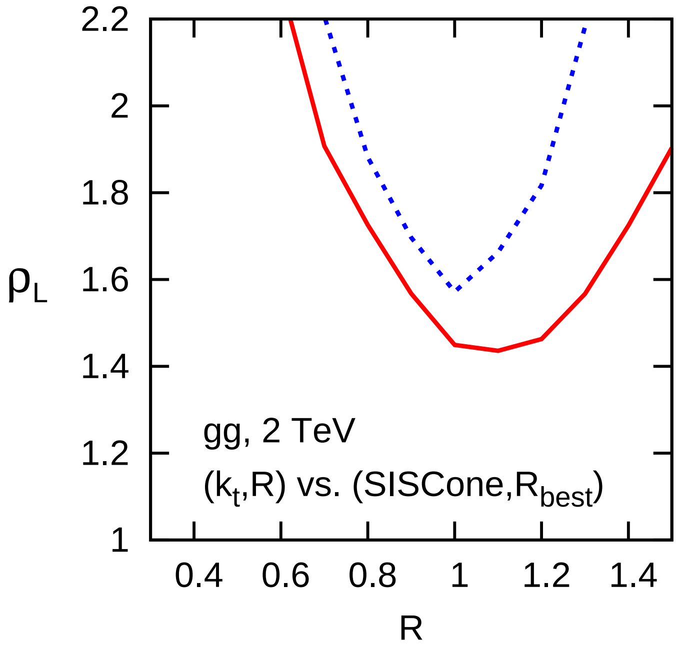
- SISCone and Cam+filtering perform better
- R_{best} strongly depends on the mass

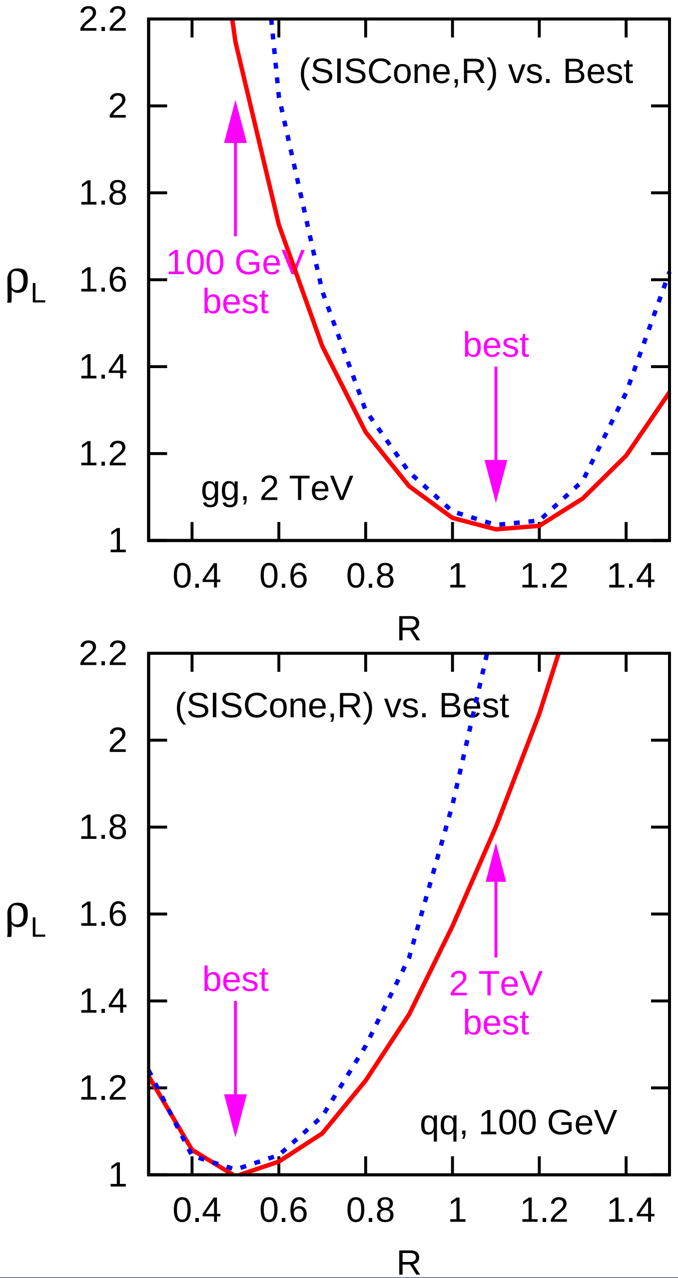
Quarks vs. gluons



Same conclusions for gluon jets with slightly larger R

Luminosity ratios





Mandatory at the LHC:
Not choosing the best alg.
AND R can be very costly
for new discoveries

Conclusions

- New jet algorithms available

  ~~JetClu~~, ~~ATLAS Cone~~, ~~MidPoint~~ → SISCone: ✓ as fast, ✓ IRC safe

  ~~Iterative Cone~~ → Anti-k_t: ✓ regular, ✓ IRC safe

  important for precision at the LHC!

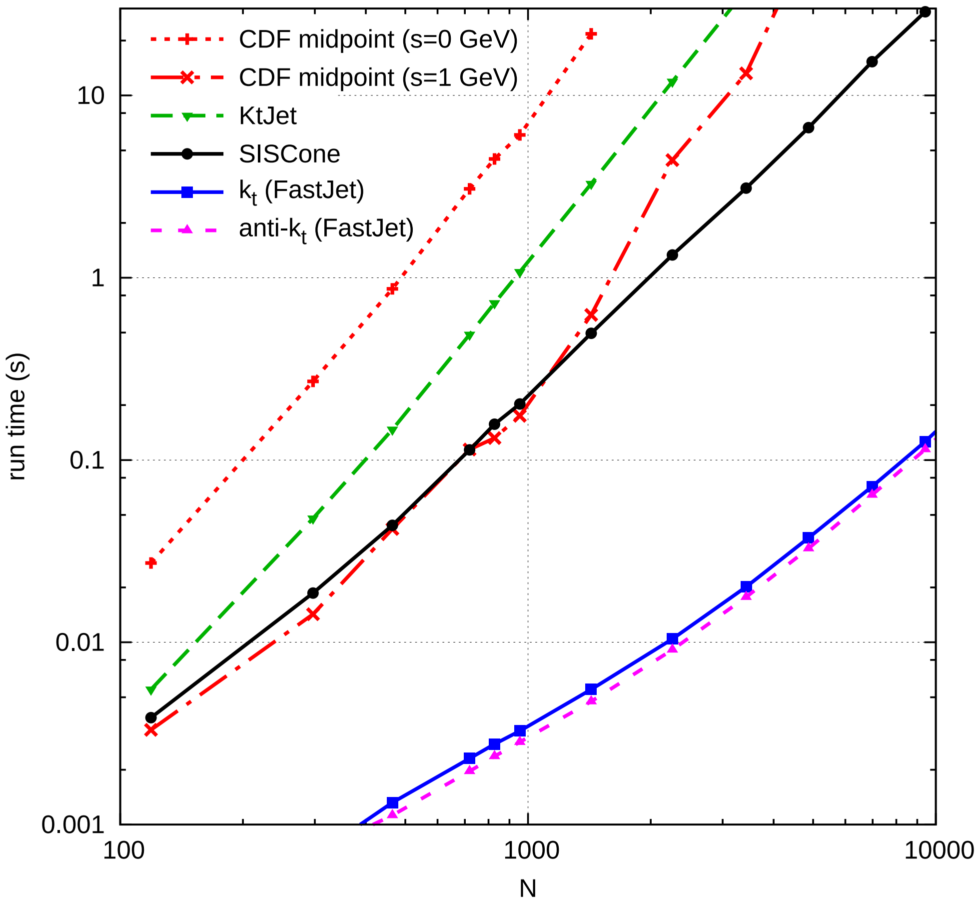
- Early discovery may rely on an optimal choice of a jet definition
  - SISCone and Camb/Aachen+filtering slightly preferred
  - Strong dependence on R: larger scales $\leftrightarrow$ larger R

Available from FastJet (or SpartyJet)

Check http://quality.fastjet.fr for interactive plots

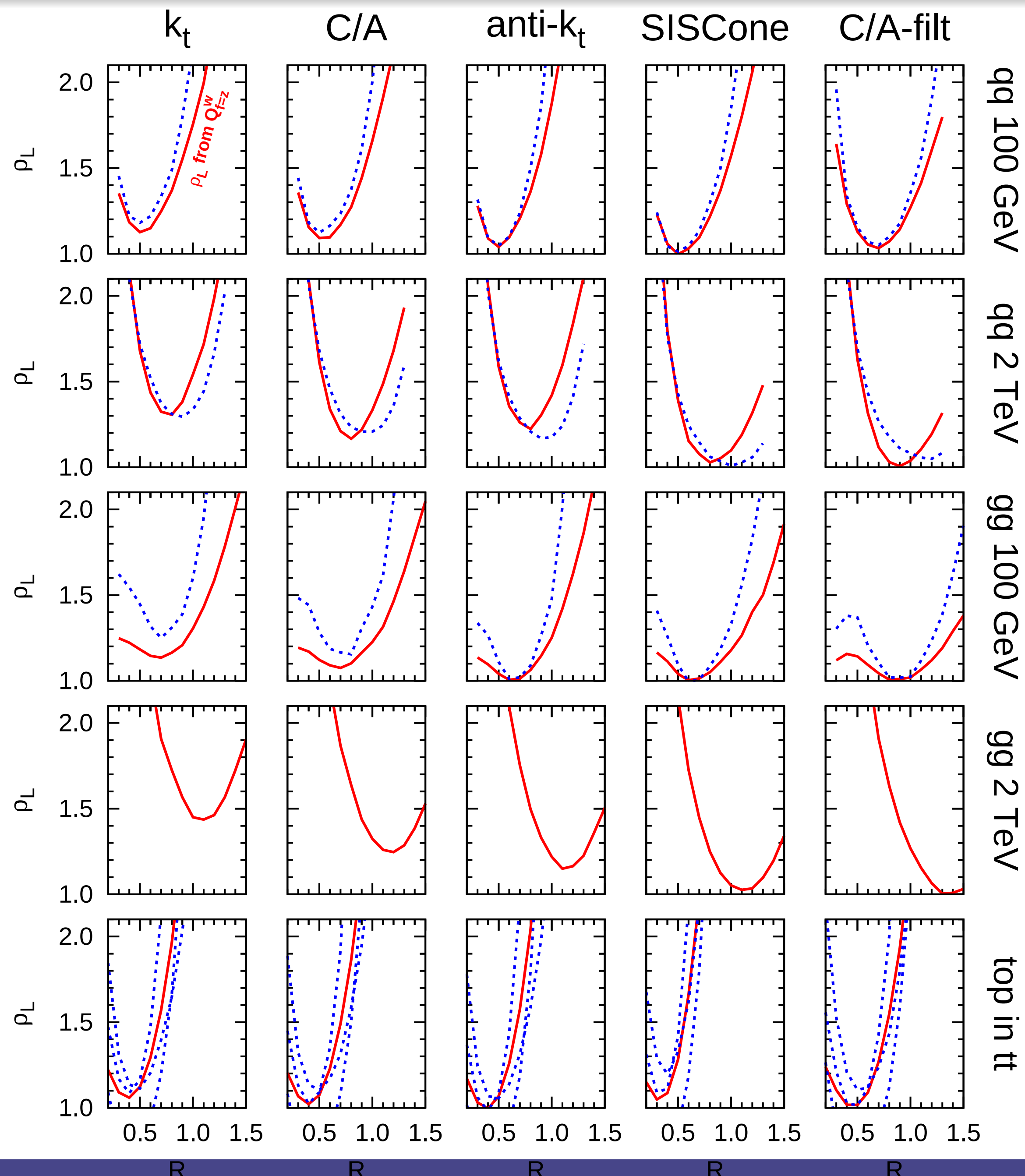
Backup slides

Speed



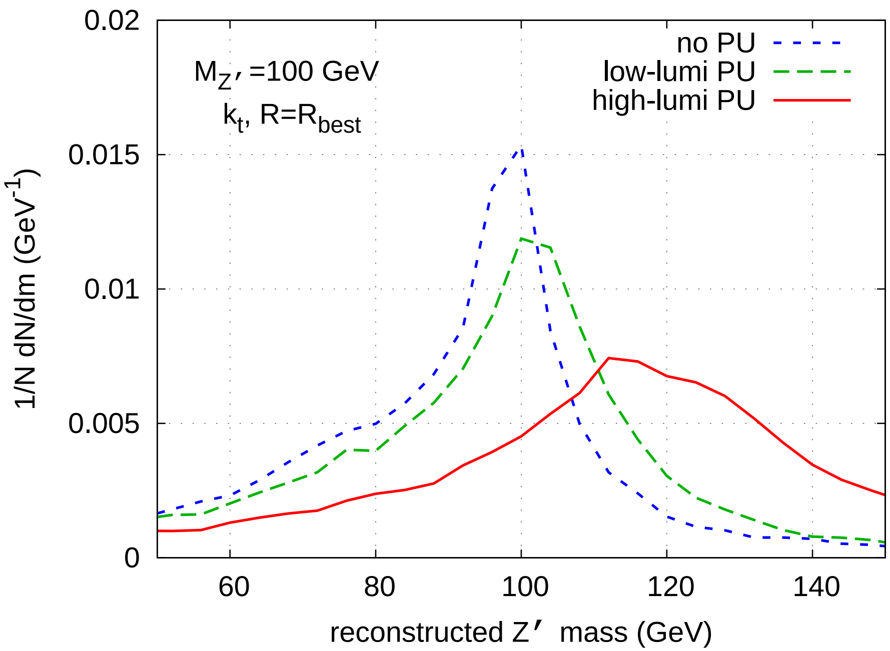
- Recombination algorithms very fast [M. Cacciari, G. Salam, 06]
- SISCone not slower than Midpoint (even with a 1 GeV seed threshold)

Optimisation - more results



Need for subtraction

Pileup $\approx$ uniform soft background that shifts jets to higher p_t



... that needs to be subtracted!

$\Rightarrow$ Using jet areas!

Pileup subtraction

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

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

Pileup subtraction

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

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

- Jet area: [M.Cacciari, G.Salam, G.S., 08]
  - region where the jet catches infinitely soft particles (active/passive)
  - tractable analytically in pQCD

    Example: area corrections from QCD radiation

$$\langle \mathcal{A}(p_{t,1}, R)\rangle = \mathcal{A}_{1\ \text{parton}}(R) + \frac{C_{F,A}}{\pi b_0} \log\left(\frac{\alpha_s(Q_0)}{\alpha_s(Rp_t)}\right) \pi R^2\, d$$

- area $\neq \pi R^2$
- area scaling violations

d	passive	active
k_t	0.5638	0.519
Cam	0.07918	0.0865
SISCone	-0.06378	0.1246
anti-k_t	0	0

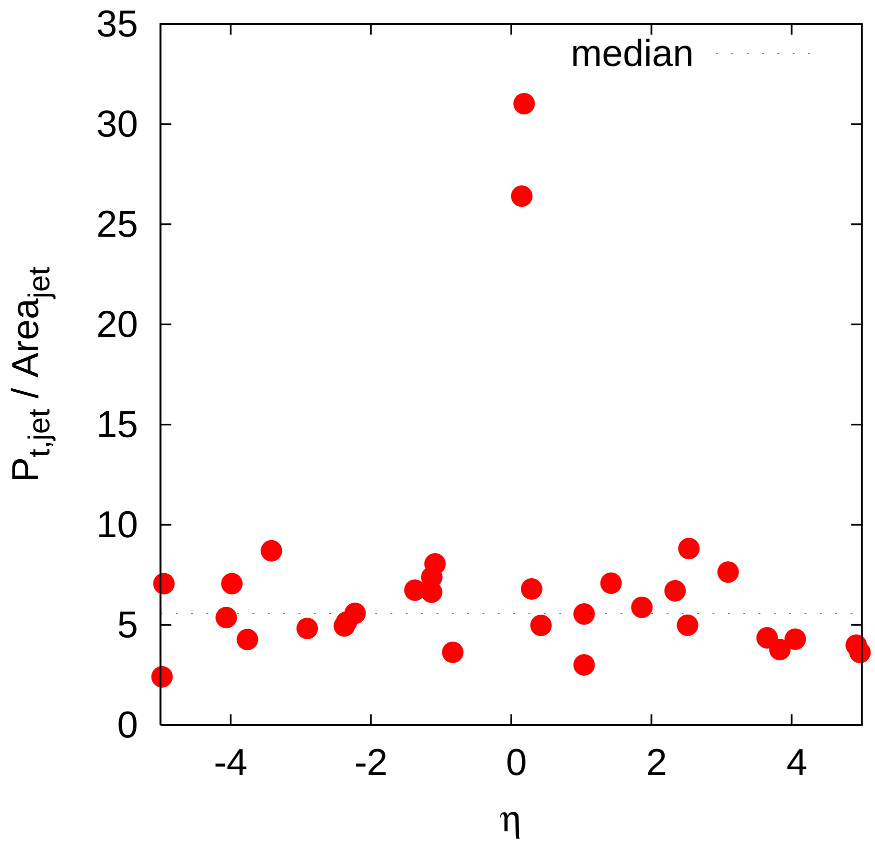
Pileup subtraction

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

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

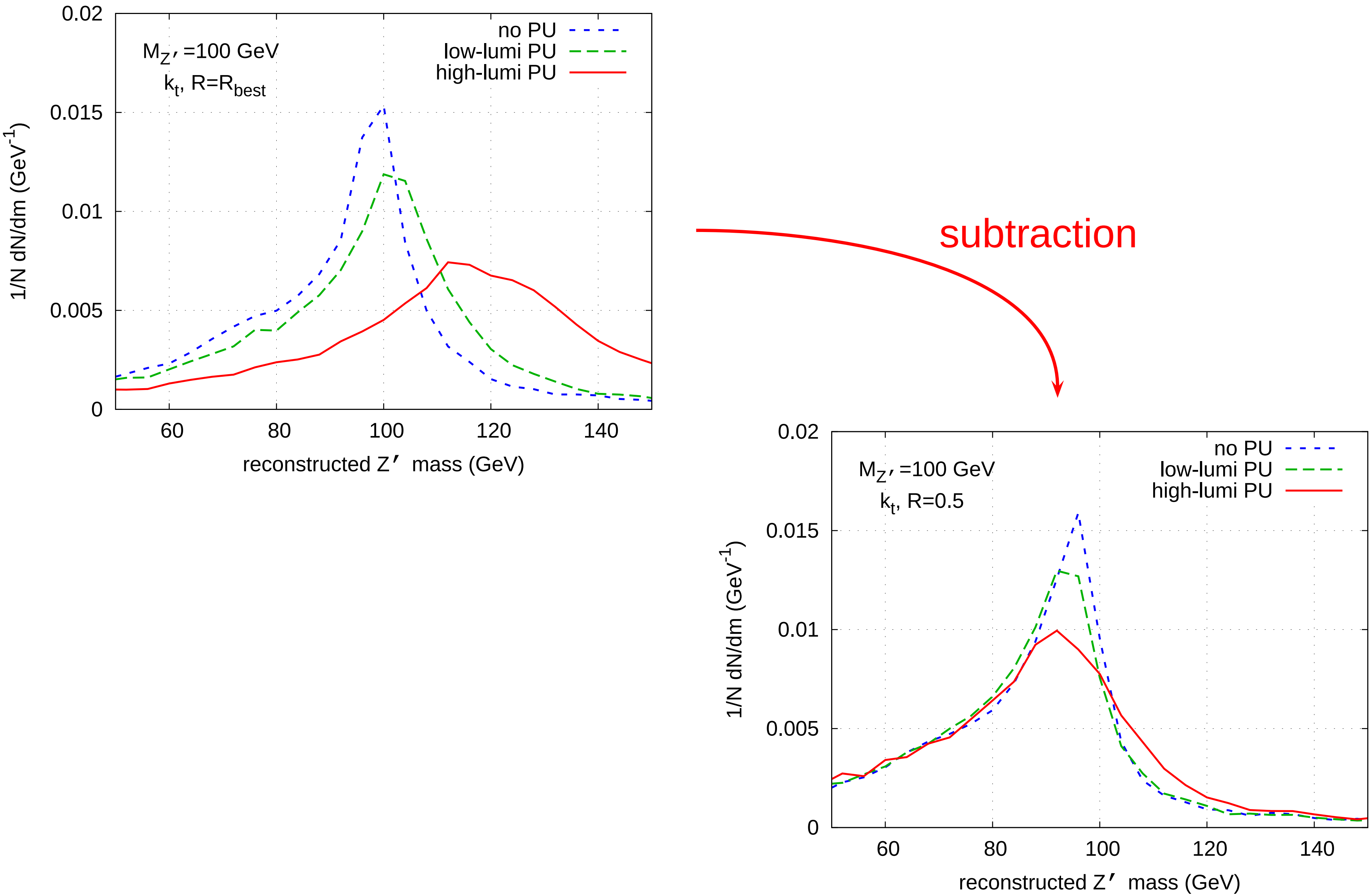
- Jet area: [M.Cacciari, G.Salam, G.S., 08]
  - region where the jet catches infinitely soft particles (active/passive)
  - tractable analytically in pQCD
- Pileup density per unit area: ρ_{pileup}

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



implemented in FastJet
on an event-by-event basis

Subtraction at work



Optimisation - pileup