New tools in jet physics:

SISCone (new cone algorithm) - jet areas (new concept)

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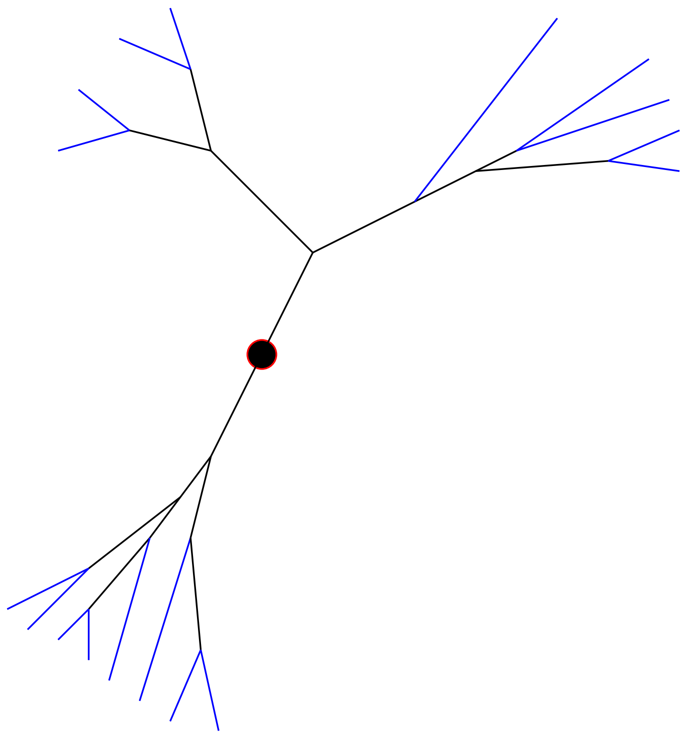
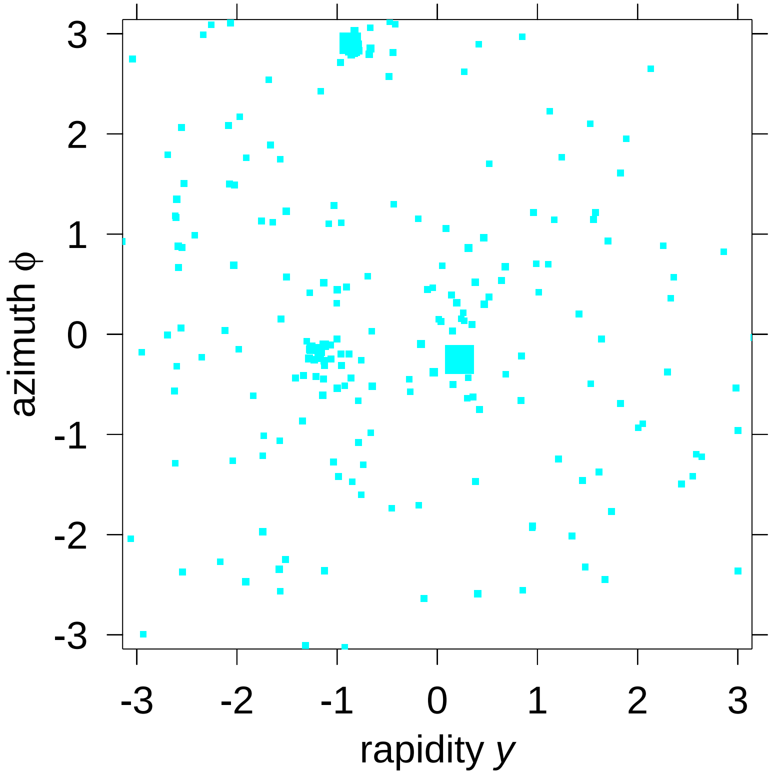
- In collaboration with Gavin Salam
- paper available as JHEP 05 (2007) 086 [arXiv:0704.0292]
- code available at `http://projects.hepforge.org/siscone`
  FastJet plugin: `http://www.lpthe.jussieu.fr/~salam/fastjet`
- Paper with Matteo Cacciari and Gavin Salam in preparation

Outline

- Introduction: jet algorithms in general
- Infrared-Safety issues:
  - Why is this mandatory?
  - IR unsafety of the JetClu and midpoint algorithms
- SISCone: a practical solution
- Physical consequences:
  - Algorithm speed
  - Inclusive jet spectrum
  - Jet mass spectrum in multi-jet events
- Area of a jet
  - Definition and properties
  - Applications

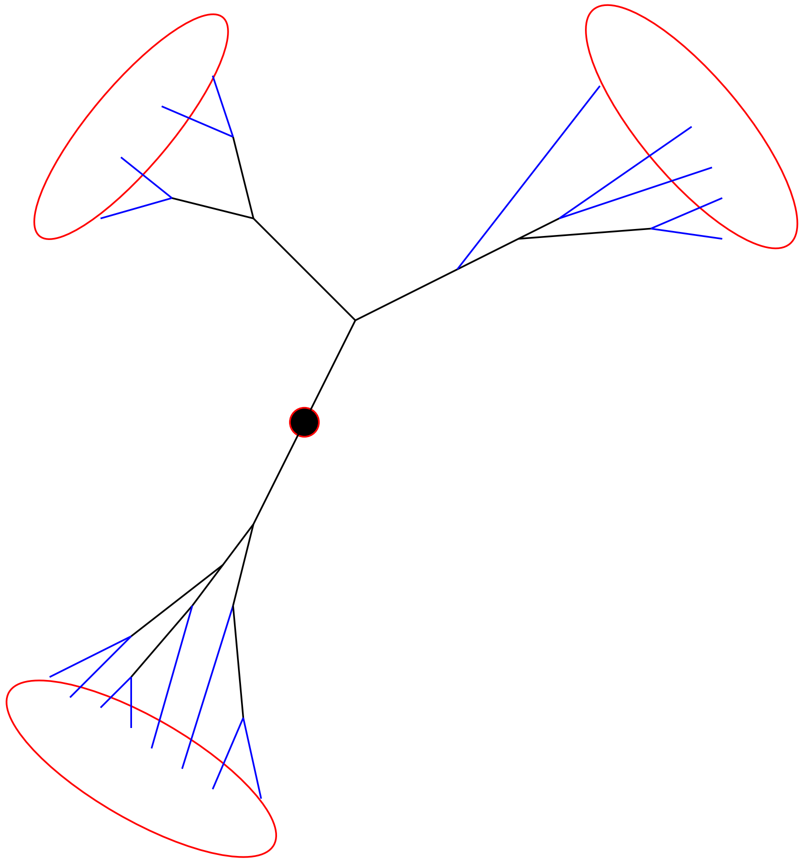
- Given: set of N particles with their 4-momentum

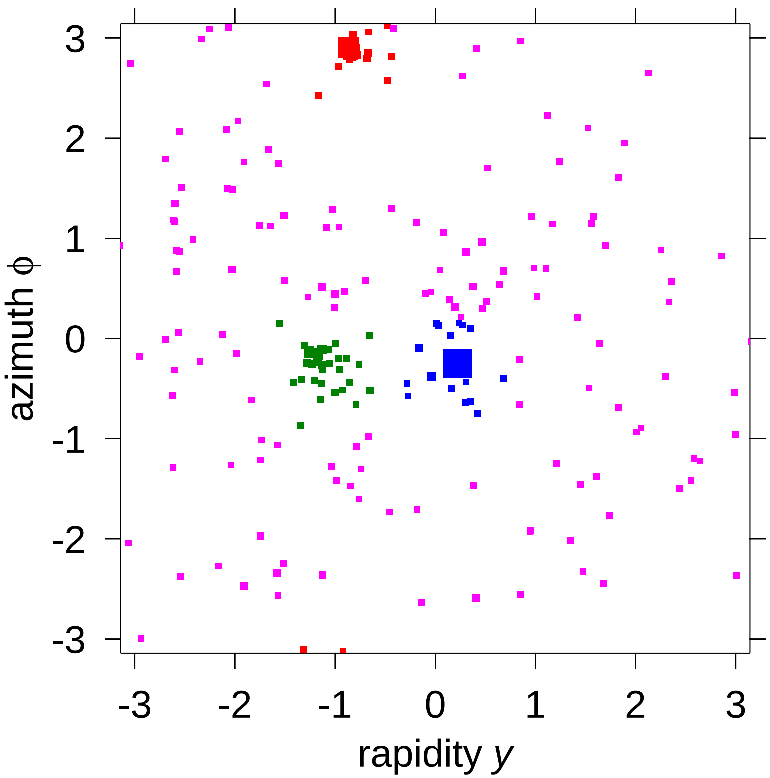




Why jet algorithms?

- Given: set of N particles with their 4-momentum
- Quest: clustering those particles into jets

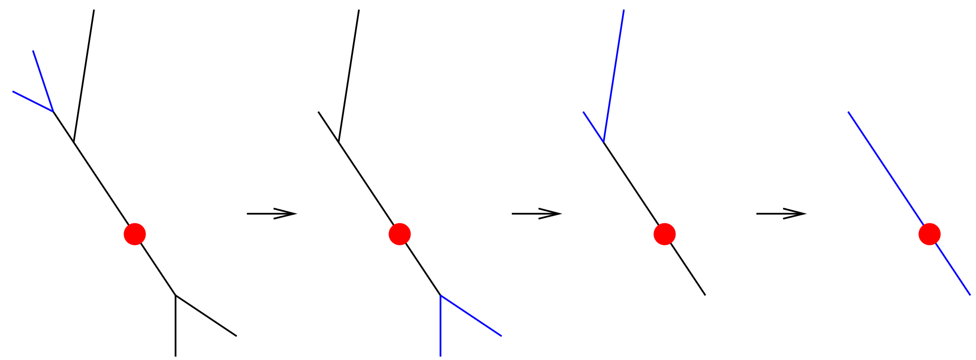




⇒ understand the original particle-level process

Class 1: recombination

Successive recombinations of the "closest" pair of particle



- Distance:

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

$$\text{Aachen/Cam.}: \quad d_{i,j} = \Delta\phi_{i,j}^2 + \Delta y_{i,j}^2$$

- stop when $d_{\text{min}} > R$

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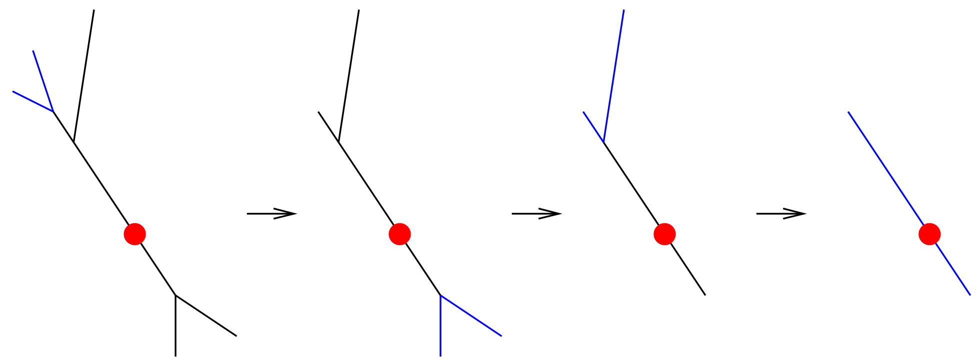

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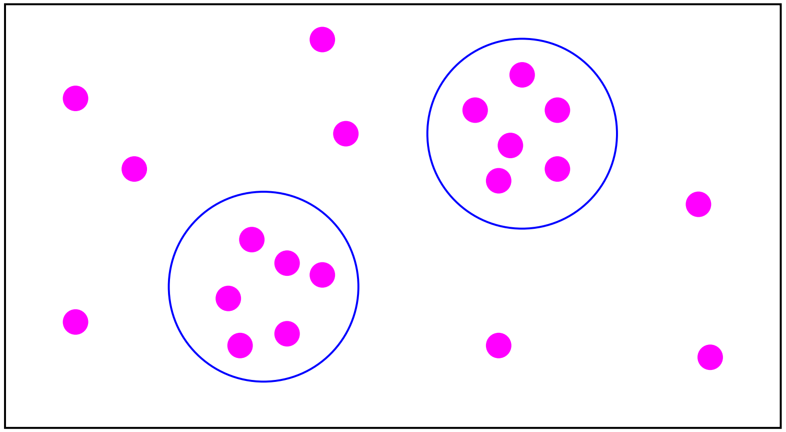
- stop when $d_{\text{min}} > R$
- Often used for $e^{\pm}e^{\pm}$ or $e^{\pm}p$
- `FastJet` : a fast implementation of those algorithms
  `www.lpthe.jussieu.fr/~salam/fastjet/` (M. Cacciari, G. Salam)

Two classes of algorithms

Class 2: cone

Find directions of dominant energy flow



for a cone of radius R in the (y, ϕ) plane, **stable cones** are such that:

centre of the cone $\equiv$ direction of the total momentum of its particle contents

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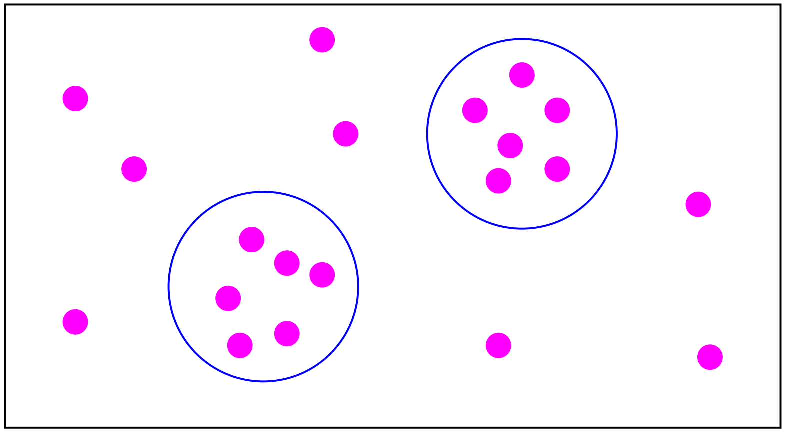

for a cone of radius R in the (y, ϕ) plane, **stable cones** are such that:
centre of the cone $\equiv$ direction of the total momentum of its particle contents

- Often used for pp
- Many cone algorithms: Snowmass, JetClu, PxCone, CDF Midpoint, ...
- BUT none satisfies 1990's requirements

Cone requirements

- Snowmass Accord (FERMILAB, 1990):
  any jet algorithm must satisfy

  1. Can be practically used in experimental analysis
  2. Can be practically used in theoretical computations
  3. Can be defined at any order of the perturbation theory
  4. Yields finite cross-sections at any order
  5. Has a small sensitivity to hadronisation corrections

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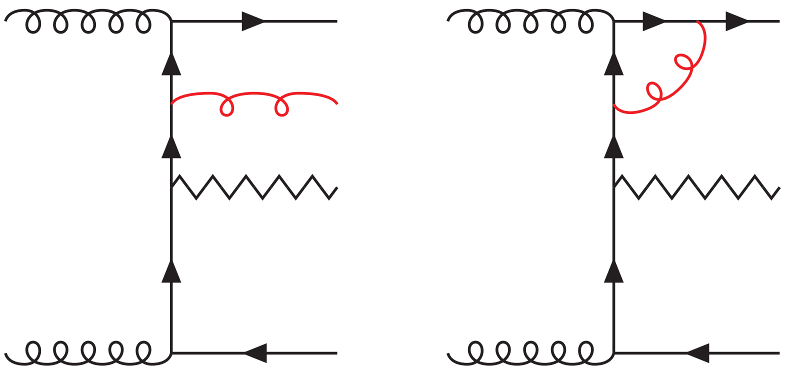
- Previous cone algorithms:
  - 1, 2 and 4 never satisfied together
  - 5 is unclear (Underlying event and $R_{\rm sep}$ issues discussed later)
- This talk shows how to satisfy all these.

Ellipsis: IR safety, i.e. stability upon emission of soft particles,
is required for perturbative computations to make sense!

Cancellation of IR divergences between real and virtual emissions of SOFT gluons in QCD



- IF Jet clustering is different in both cases, THEN the cancellation is not done and the result is not consistent with pQCD

  $\Rightarrow$ Stable cones must not change upon addition of soft particles

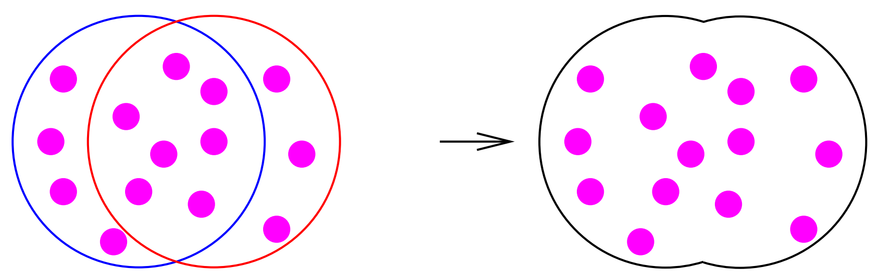
- Note: 100 GeV jet cannot change by adding a 1 GeV particle
  This would break parton/hadron correspondence

Modern cone jet algorithm

Modern cone jet algorithm (Tevatron Run II type):

- Step 1: find ALL stable cones of radius R
- Step 1': if some of the particles are not in stable cones, rerun Step 1 with the remaining ones.
- Step 2: run a split-merge procedure with overlap f to deal with overlapping stable cones

$\tilde{p}_{t,\text{shared}} > f\,\tilde{p}_{t,\text{min}}$



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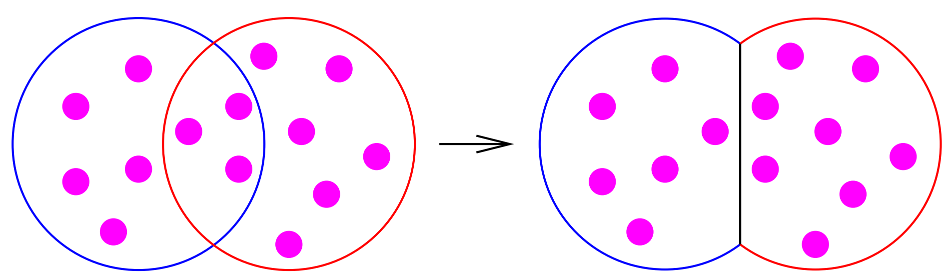

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- Standard parameters: cone radius R, overlap parameter f
- Additional controls: number of passes n_{pass}, stable cone $p_{t,\text{min}}$ cut-off

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This talk: Why finding all stable cones and how.

$\longrightarrow$ C++ implementation: Seedless Infrared-Safe Cone algorithm (SISCone)

Typical cone: Midpoint algorithm

Usual seeded method to search stable cones: midpoint cone algorithm

- For an initial seed
  1. sum the momenta of all particles within the cone centred on the seed
  2. use the direction of that momentum as new seed
  3. repeat 1 & 2 until stable state cone reached

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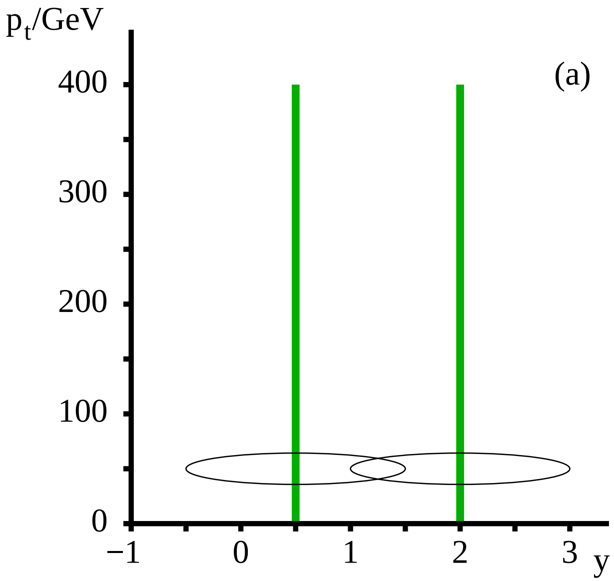
Problems:

- the p_t threshold s is collinear unsafe
- seeded approach $\Rightarrow$ stable cones missed $\Rightarrow$ infrared unsafety
- NB.: addition of soft particles does not modify the set of stable cone,

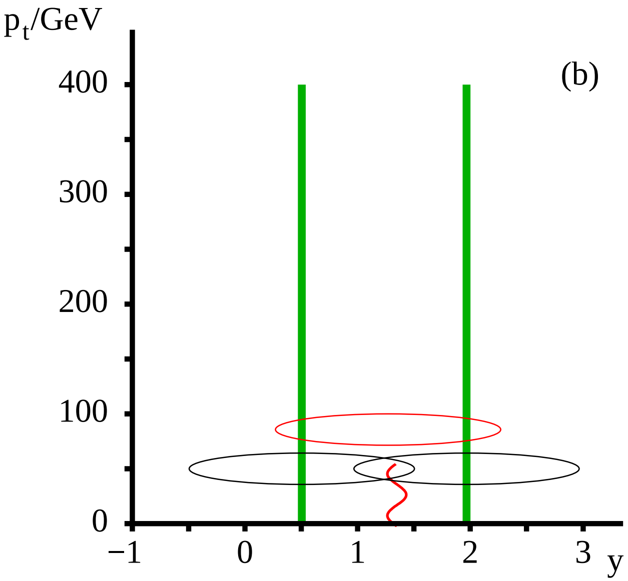
  the question is “does our algorithm find all of them”?

JetClu IR Unsafety (R=1)

Hard event



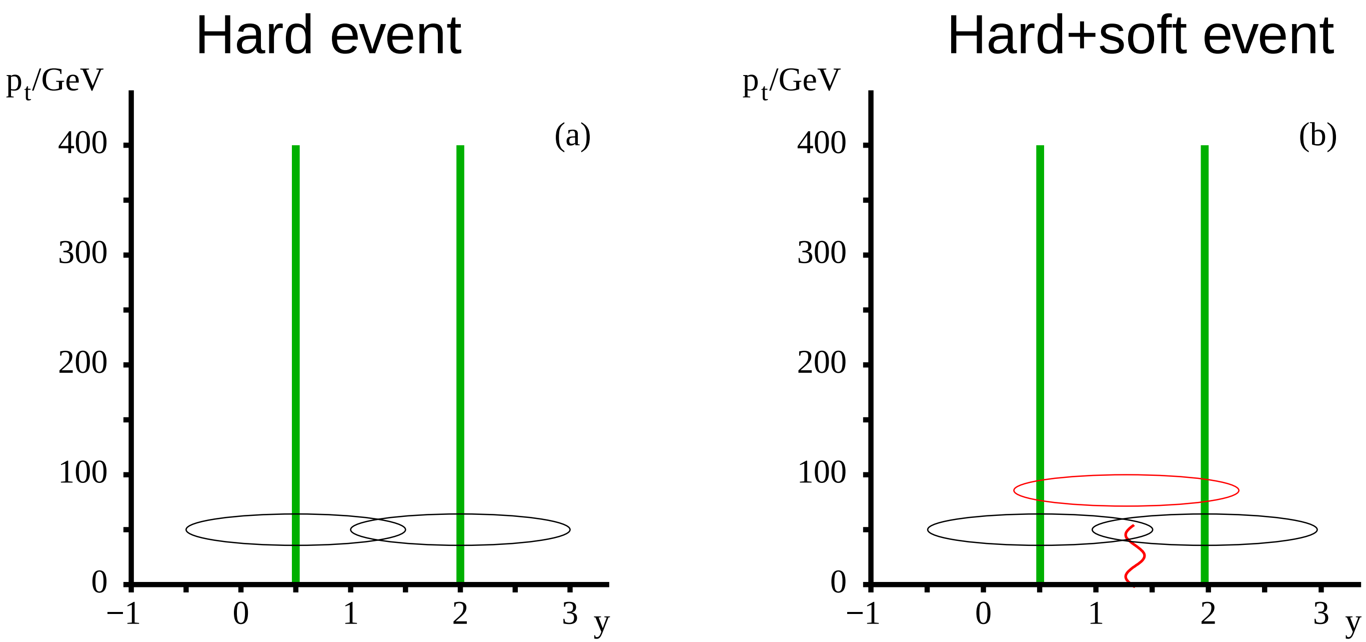
Hard+soft event



Stable cones:

JetClu: {1} & {2} | {1} & {2} & {1,2}

JetClu IR Unsafety (R=1)



Stable cones:

	Hard event	Hard+soft event
JetClu:	{1} & {2}	{1} & {2} & {1,2}

Jets: ($f = 0.5$)

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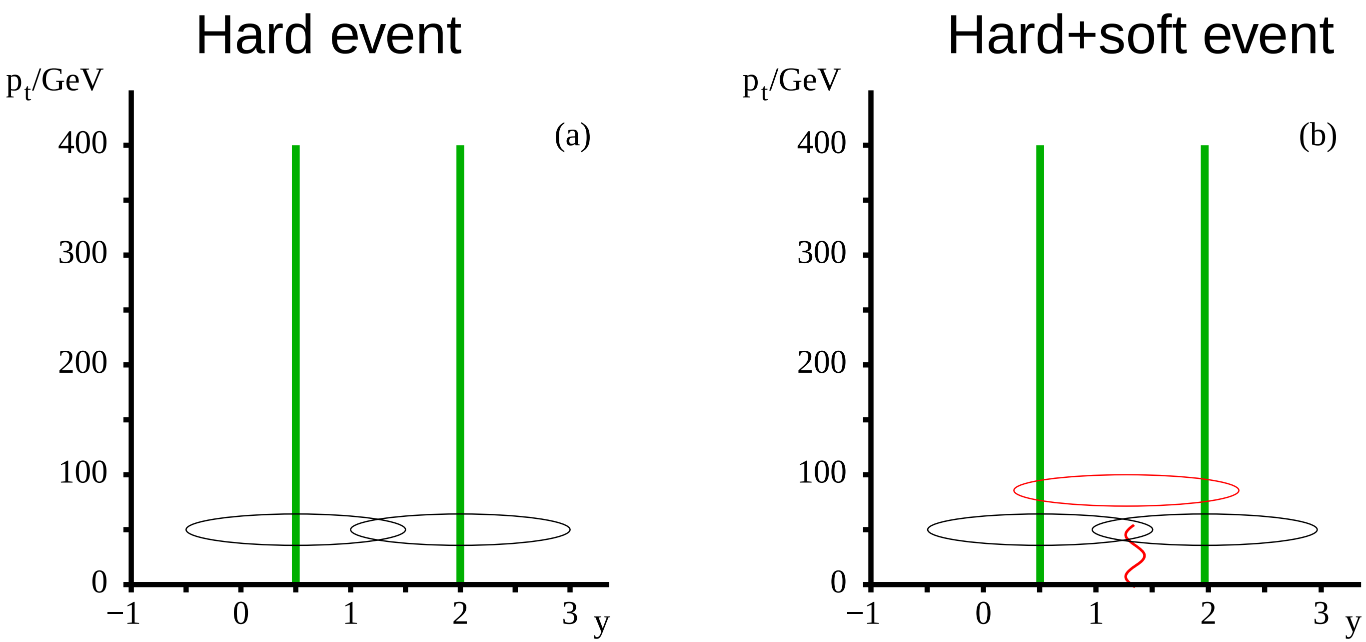

Stable cones:

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JetClu:	{1} & {2}	{1} & {2} & {1,2}
Midpoint:	{1} & {2} & {1,2}	{1} & {2} & {1,2}

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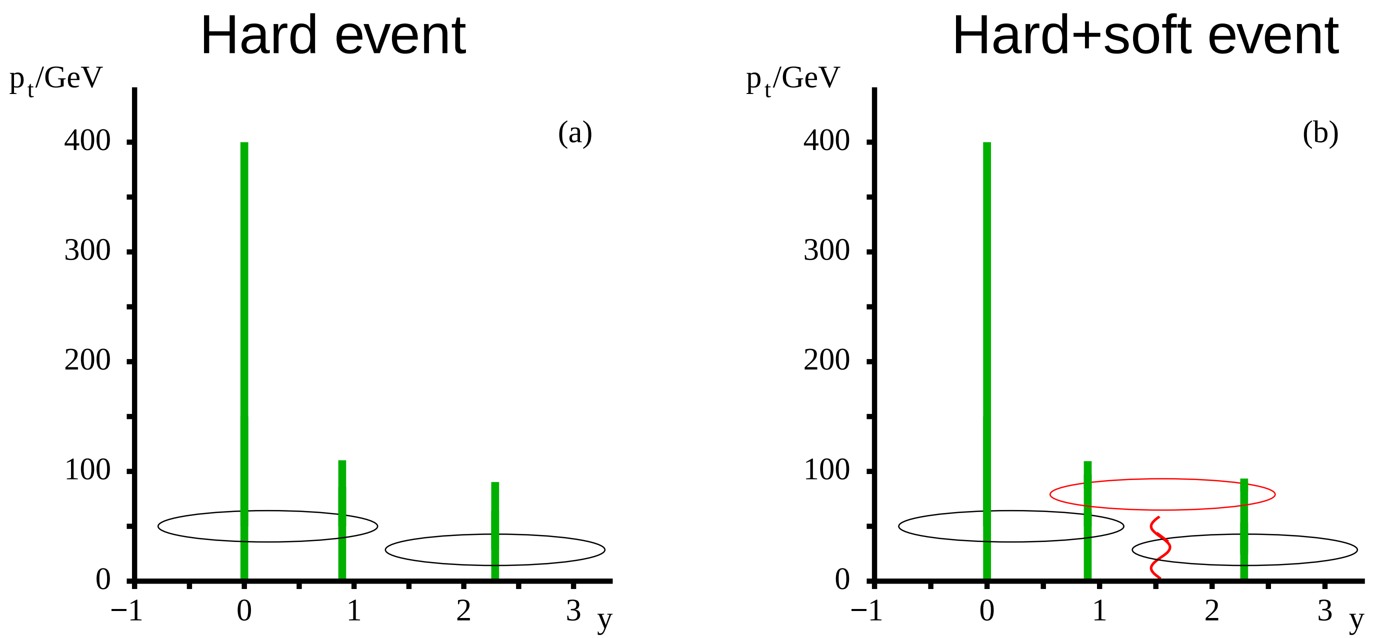
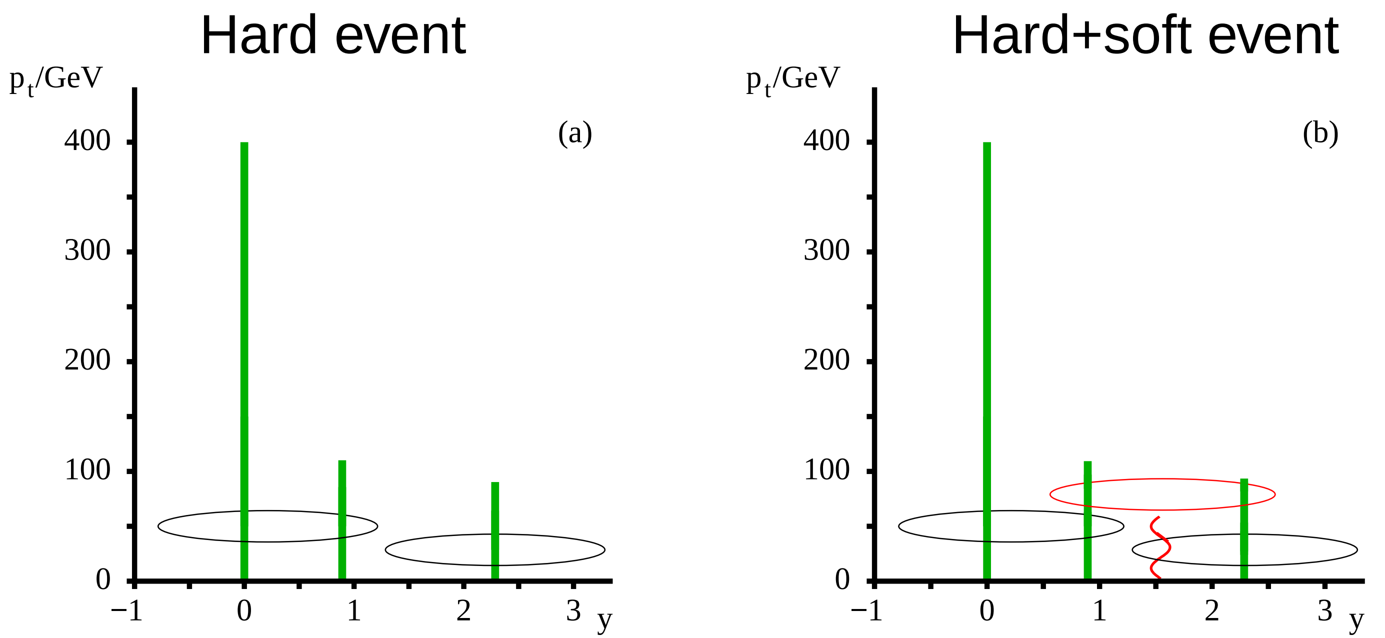
Midpoint IR Unsafety (R=1)



Stable cones:

Midpoint: {1,2} & {3} — {1,2} & {3} & {2,3}

Midpoint IR Unsafety (R=1)



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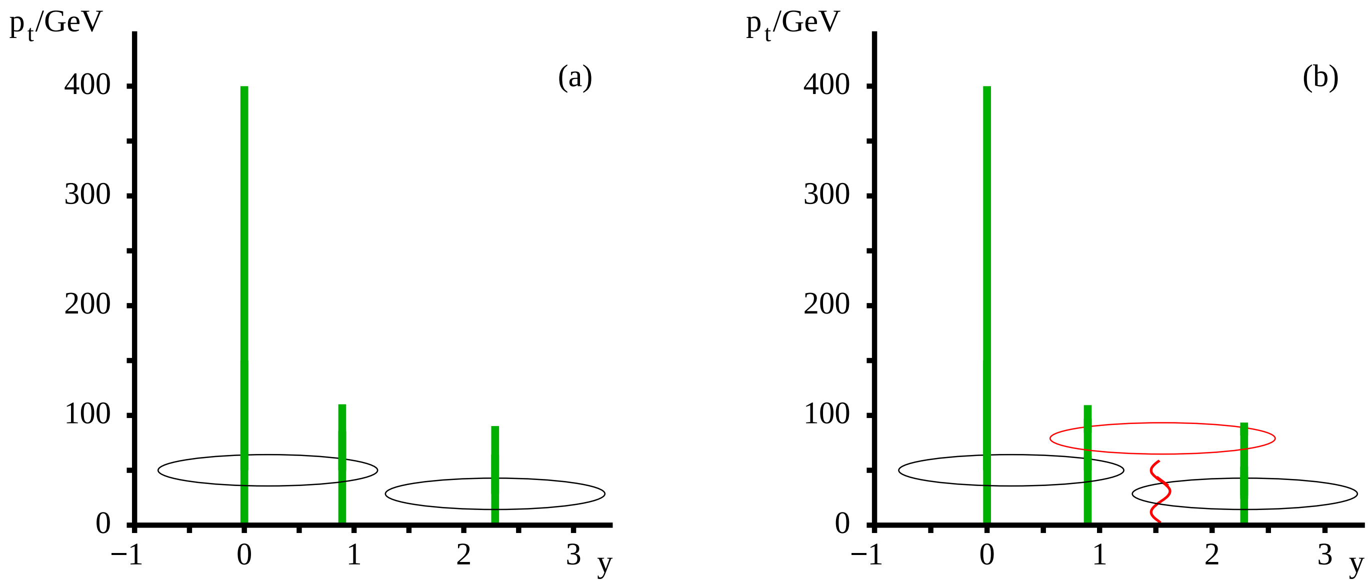
Stable cone missed ⟶ IR unsafety of the midpoint algorithm

Hard event — Hard+soft event



	Hard event	Hard+soft event
Stable cones:		
Midpoint:	{1,2} & {3}	{1,2} & {3} & {2,3}
Seedless:	{1,2} & {3} & {2,3}	{1,2} & {3} & {2,3}
Jets: ($f = 0.5$)		
Midpoint:	{1,2} & {3}	{1,2,3}
Seedless:	{1,2,3}	{1,2,3}

Stable cone missed $\longrightarrow$ IR unsafety of the midpoint algorithm

is a seedless solution practical?

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  Complexity is $\mathcal{O}\left(N2^N\right)$
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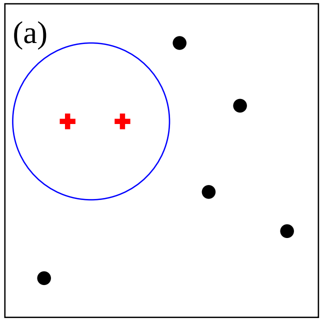
- Midpoint complexity:
  - For 1 seed: build and check cone content is $\mathcal{O}\left(N\right)$
  - initially N seeds $\Rightarrow \mathcal{O}\left(N\right)$ stable cones
    $\Rightarrow \mathcal{O}\left(Nn\right)$ new, midpoint, seeds
    $\Rightarrow$ midpoint complexity is $\mathcal{O}\left(N^2 n\right)$
  - with $n \sim N$ the number of points in a circle of radius R
  - Note: the number of stable cones is $\mathcal{O}\left(N\right)$

SISCone: seedless solution

Idea: use geometric arguments



- Enumerate enclosures and check if they are stable

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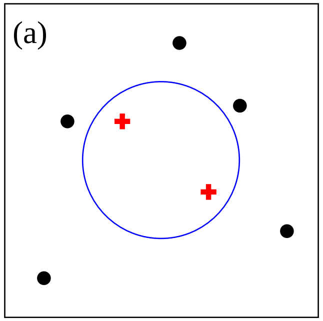

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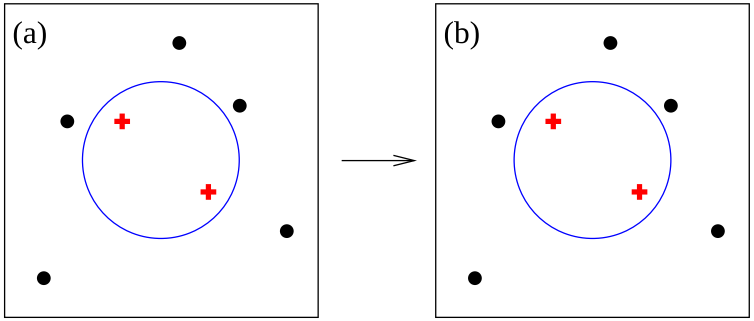

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- Each enclosure can be moved (in any direction) to touch a point

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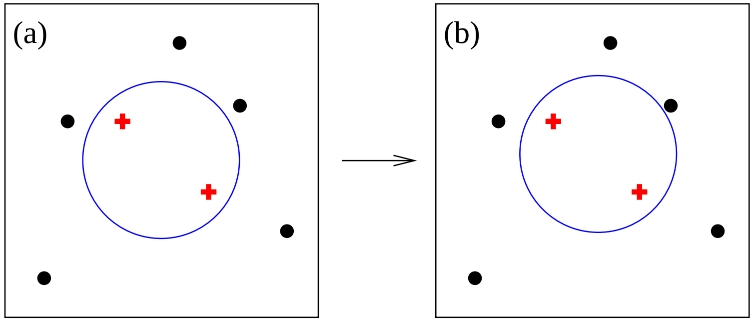

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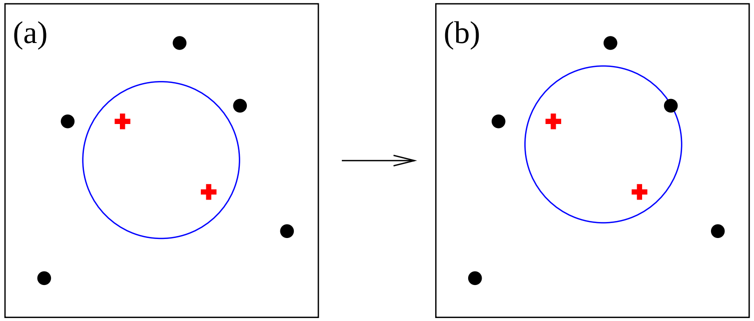

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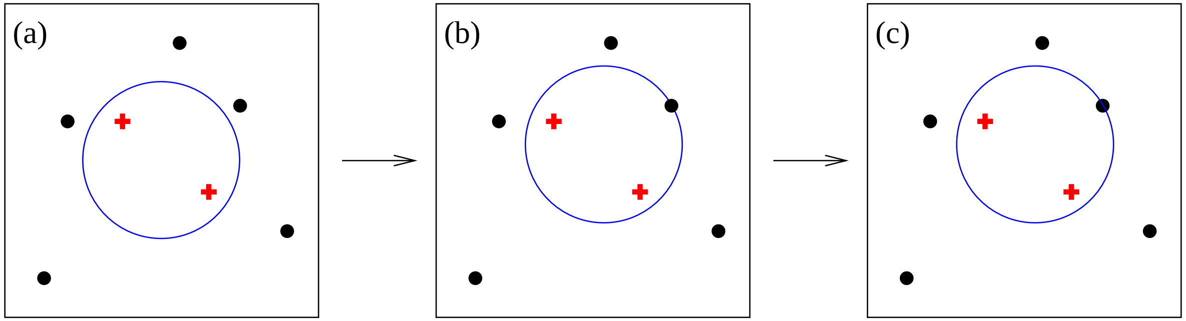

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- Each enclosure can be moved (in any direction) to touch a point
- ... then rotated to touch a second one

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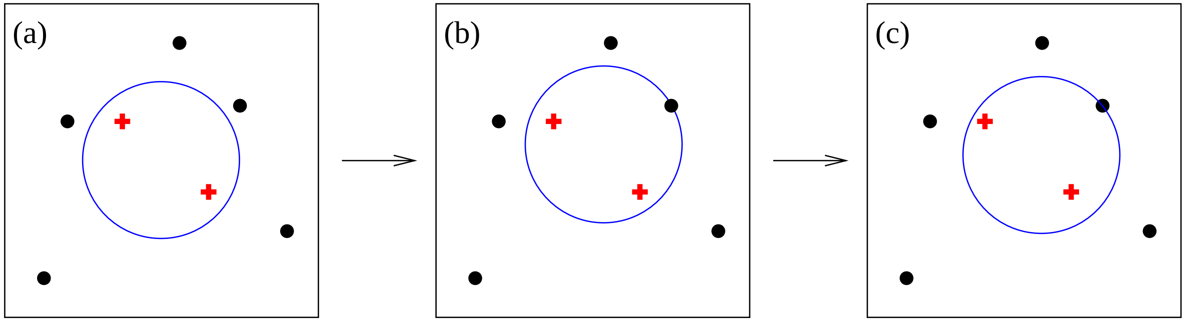

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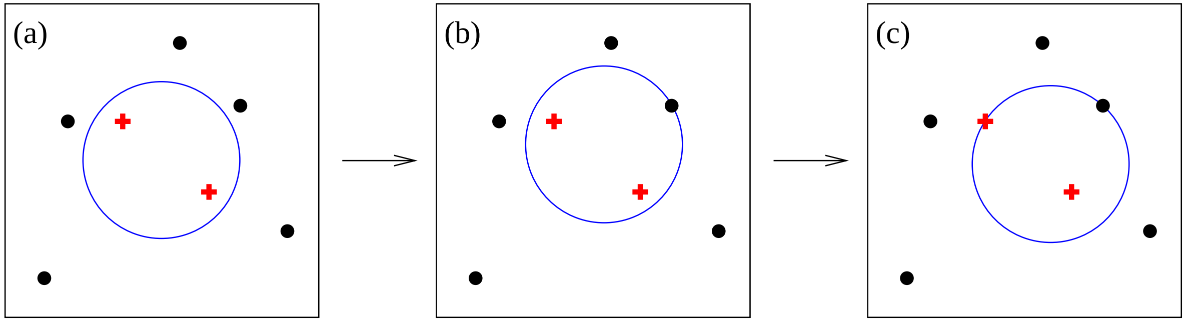

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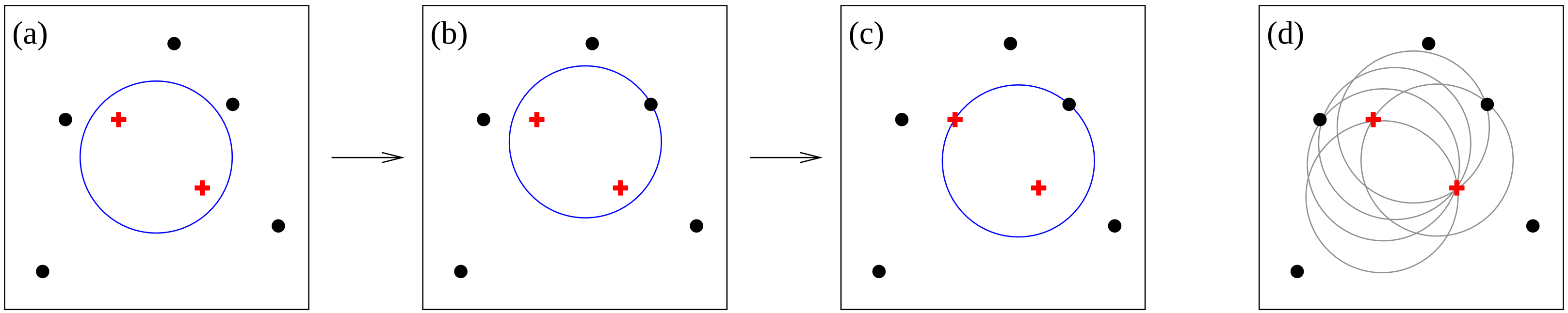

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$\Rightarrow$ Enumerate all pairs of particles
with 2 circle orientations and 4 possible inclusion/exclusion
$\longrightarrow$ find all enclosures

SISCone: seedless solution

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Complexity?

- Enumerate all pairs of particles: $\mathcal{O}(Nn)$
- For each, build content and check stability
  $\Rightarrow \mathcal{O}(N^2 n)$

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Complexity?

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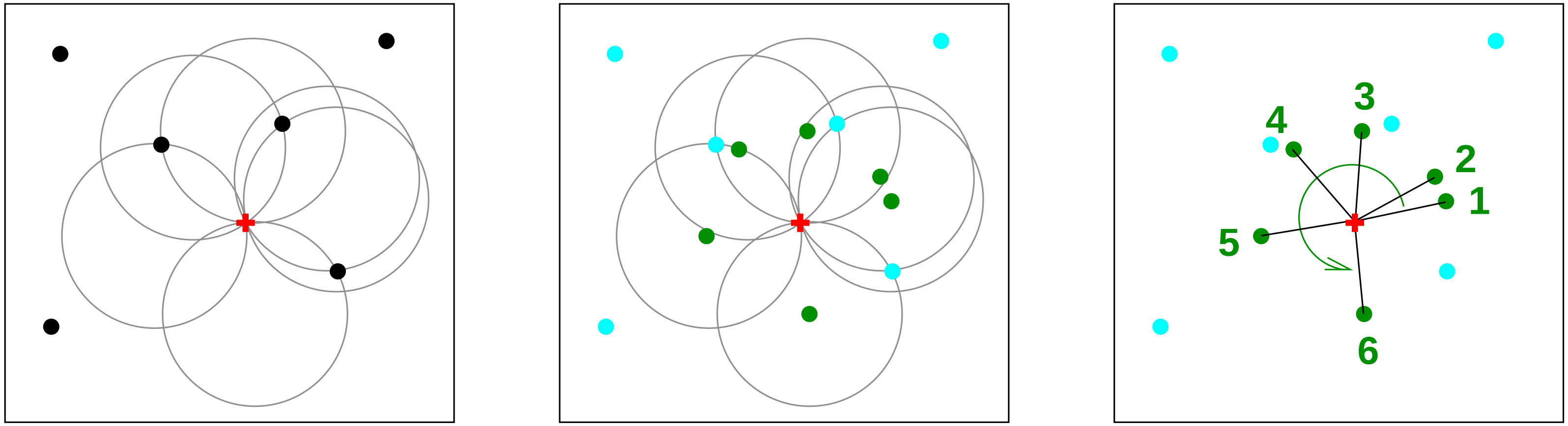
- For each, build content and check stability
  $\Rightarrow \mathcal{O}(N^2 n)$

Same as midpoint... but we'll use more tricks:

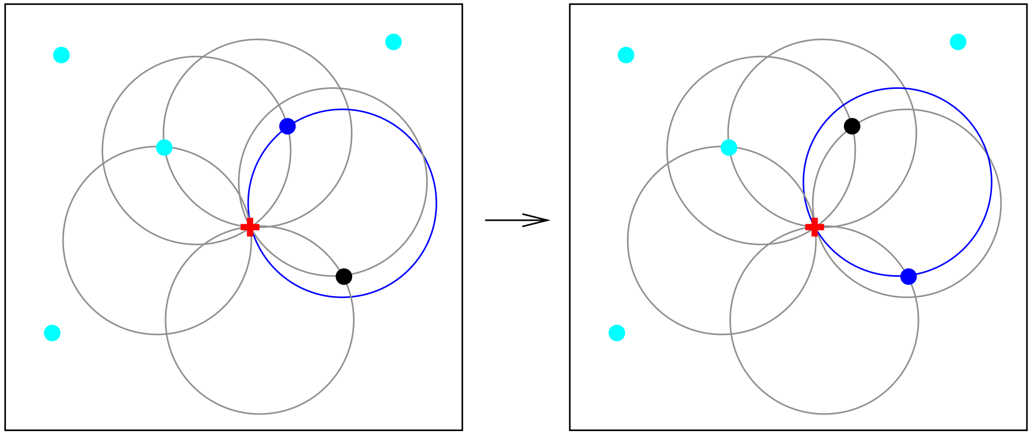
- avoid systematic recomputation of cone contents
- limit complete tests of cone stability

Tricks:

- For all enclosures around a particle, introduce a traversal order



From one cone to the next one, contents only changed by "border" particles



$\Rightarrow$ avoids recomputing the cone contents at each step

Tricks:

- For all enclosures around a particle, introduce a traversal order
  $\Rightarrow$ avoids recomputing the cone contents at each step
- Label the particles using a q-bit tag
  $\Rightarrow$ checkxor to identify distinct cones
  Introduces a potential “collision” problem

$$q = 96 \qquad \Rightarrow \qquad P(\text{collision}) = 10^{-18}$$

Tricks:

- For all enclosures around a particle, introduce a traversal order
  $\Rightarrow$ avoids recomputing the cone contents at each step

- Label the particles using a q-bit tag
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- Only test "border particles" for stability (cost $\mathcal{O}(1)$)
  $\Rightarrow$ limits the number of full stability test to $\mathcal{O}(N)$
  checkxor $\longrightarrow$ keep trace of stability tests

The SISCone stable-cone search

How to efficiently determine all stable cones:

- For each particle i
  - get “partners” and associated cone centres
  - order them by angle
  - build the first candidate cone contents
  - for all those candidates
    - check stability w.r.t. border particles
      4 possible $\in$ or $\notin$ & keep track of tested cones
    - move to the next cone
- Full stability test for the $\mathcal{O}(N)$ not-yet-unstable candidated

The SISCone stable-cone search

How to efficiently determine all stable cones:

- For each particle i
  - get “partners” and associated cone centres $\mathcal{O}(N)$
  - order them by angle $\mathcal{O}(n\log(n))$
  - build the first candidate cone contents $\mathcal{O}(n)$
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How to efficiently determine all stable cones:

- For each particle i — overall $\mathcal{O}\left(Nn\log(n)\right)$
  - get "partners" and associated cone centres $\mathcal{O}\left(N\right)$
  - order them by angle $\mathcal{O}\left(n\log(n)\right)$
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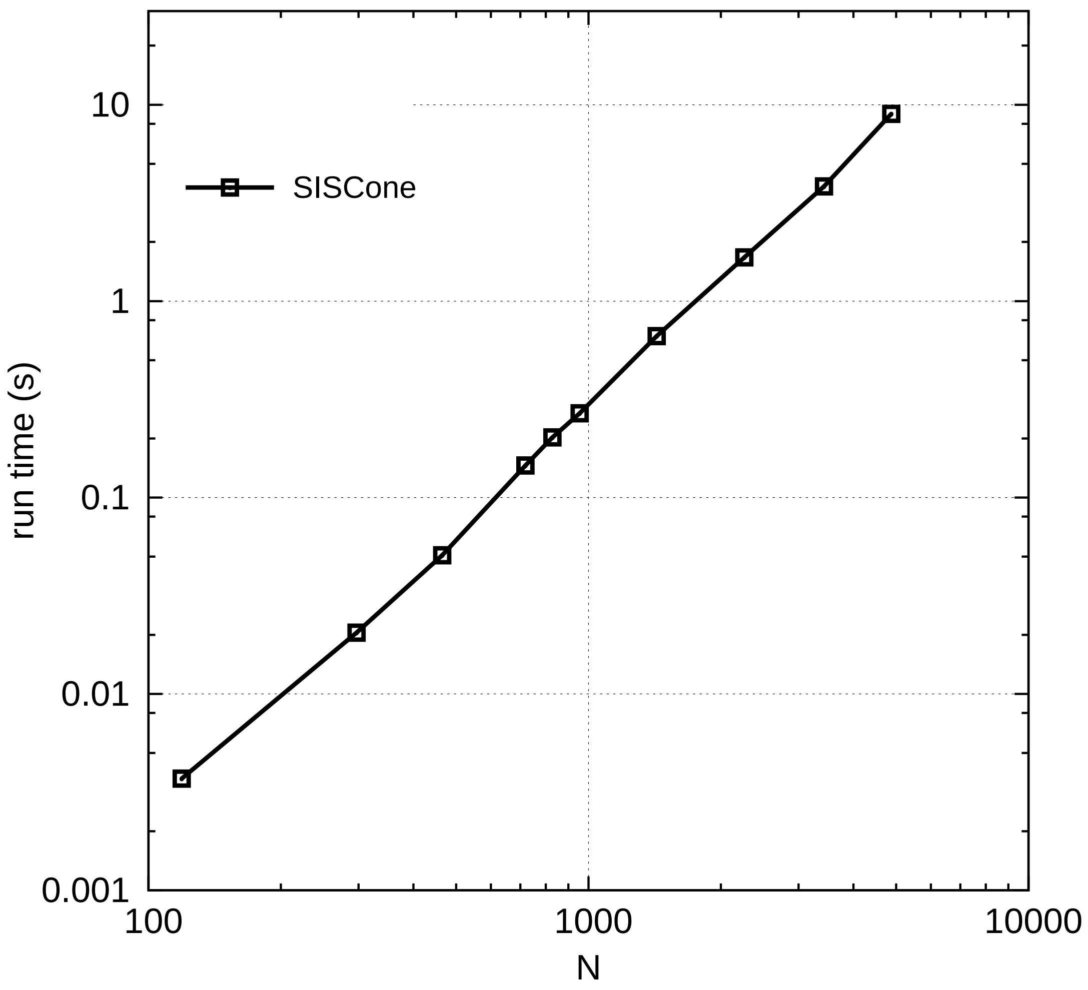
    - move to the next cone $\mathcal{O}\left(1\right)$
- Full stability test for the $\mathcal{O}\left(N\right)$ not-yet-unstable candidated $\mathcal{O}\left(N^2\right)$

All stable cones found in $\mathcal{O}\left(Nn\log(n)\right)$

SISCone vs. other cone algorithms

implications of a seedless cone

Speed



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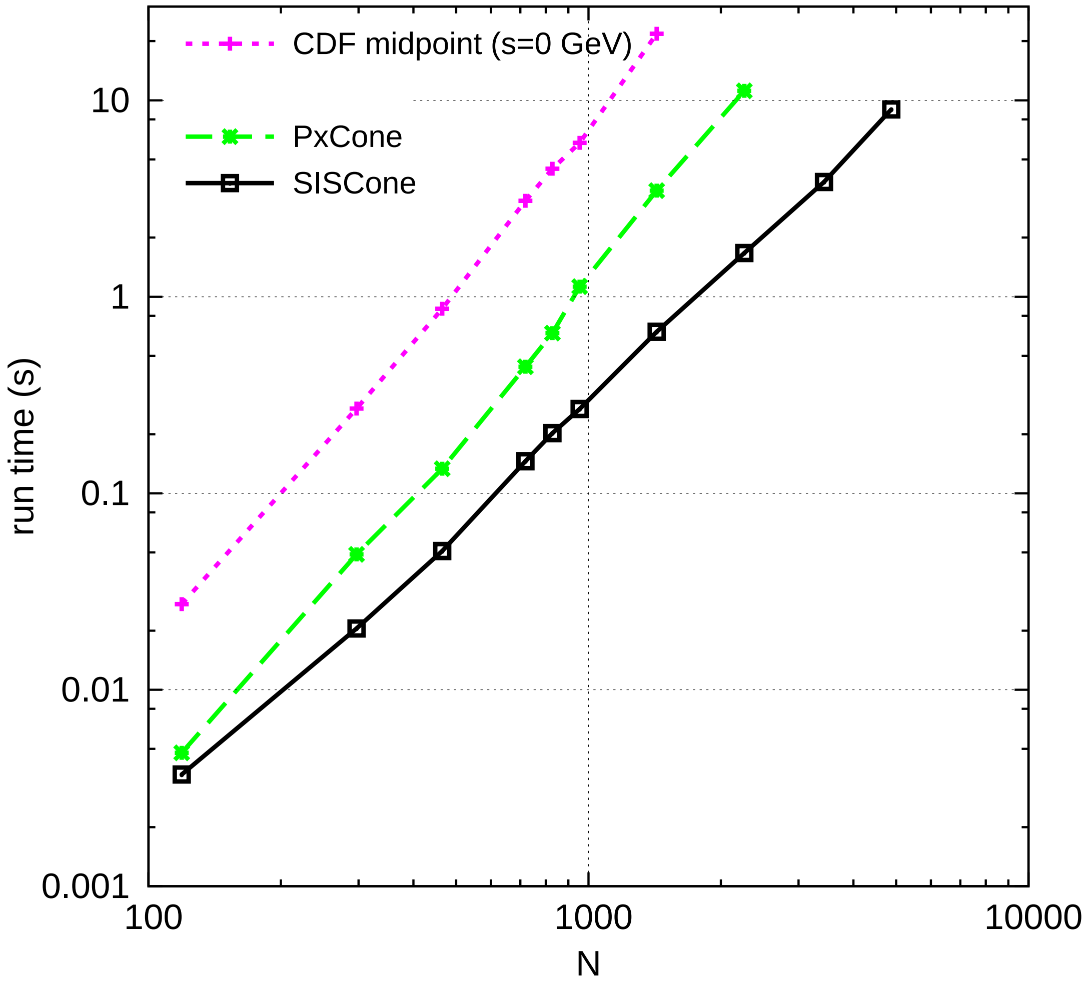
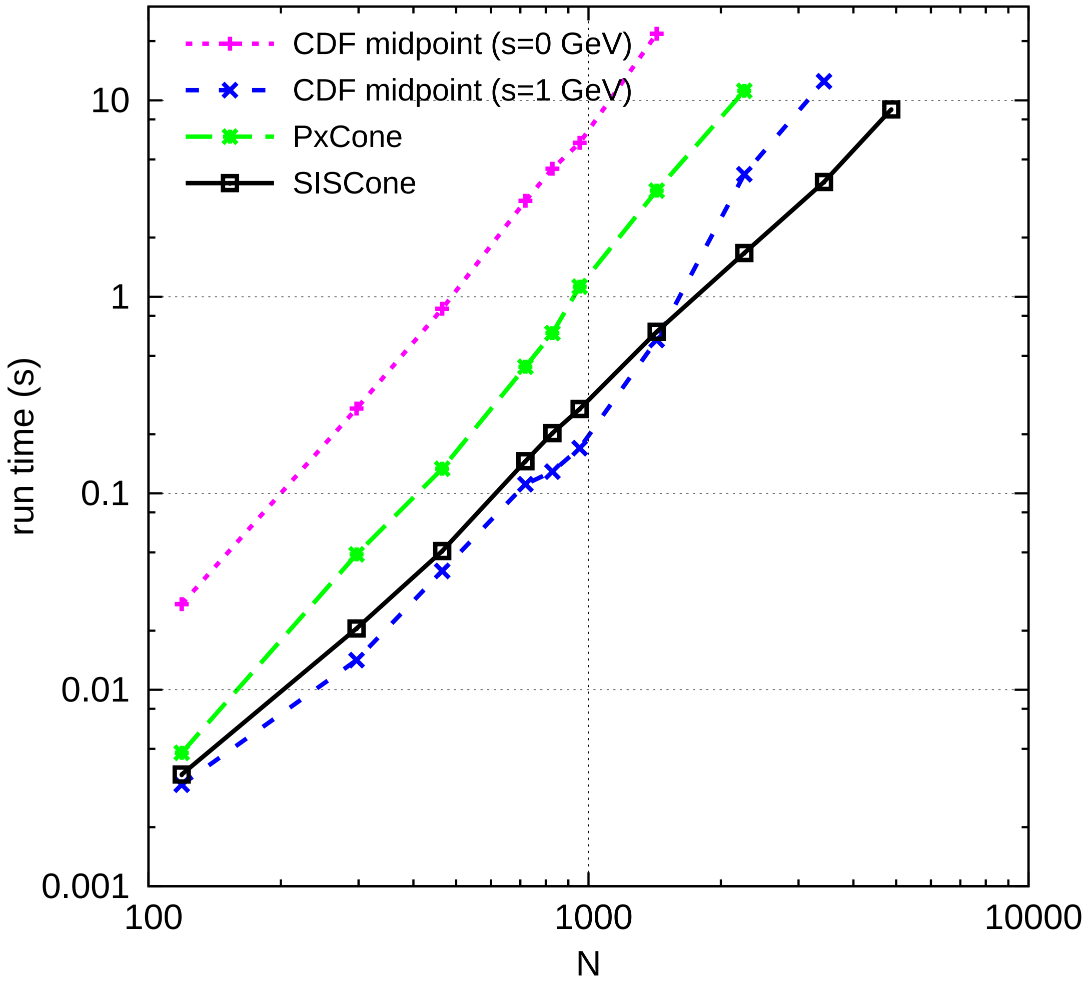
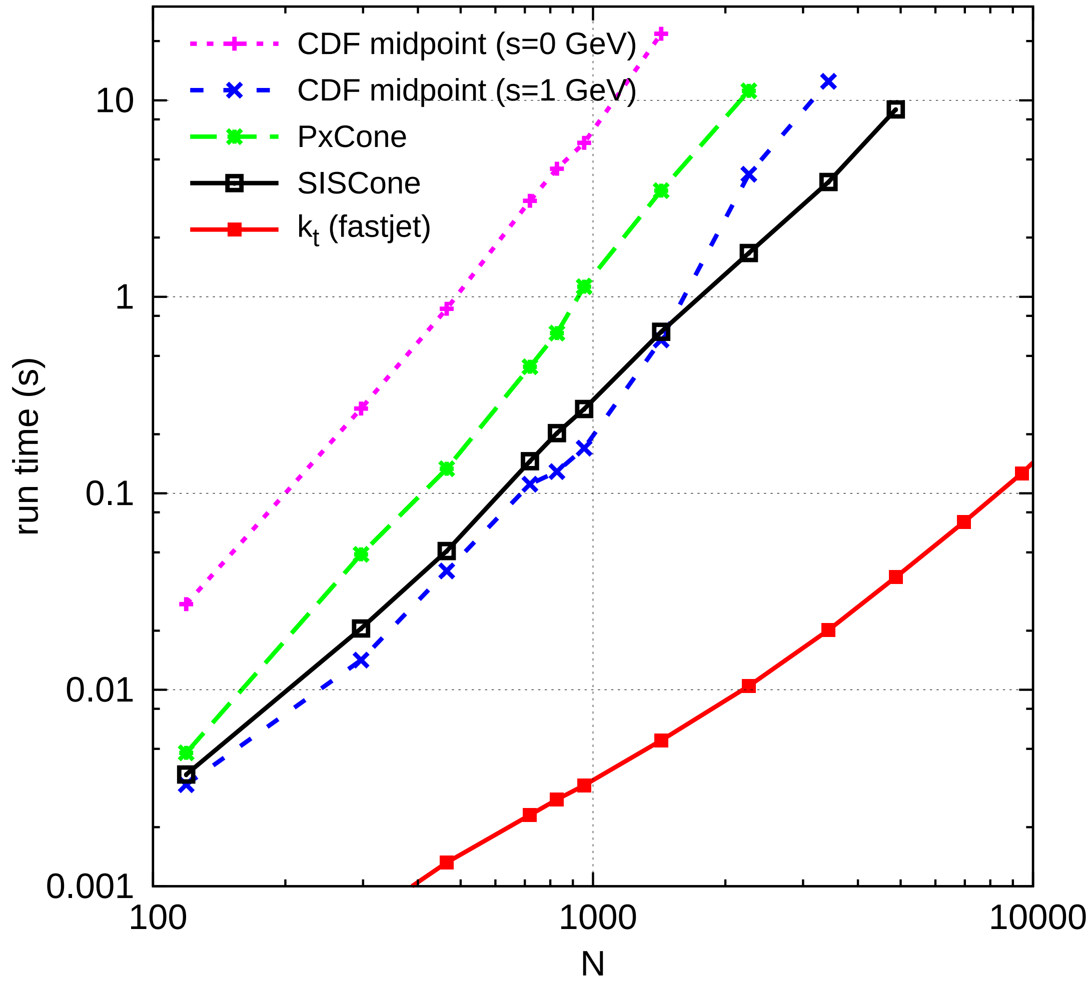


- faster than midpoint with no seed threshold and IR safe



- faster than midpoint with no seed threshold and IR safe
- same as midpoint with 1 GeV seed and collinear safe

Speed



- faster than midpoint with no seed threshold and IR safe
- same as midpoint with 1 GeV seed and collinear safe
- slower that k_t/FastJet affordable for practical usage e.g. at the LHC

IR Unsafety failure rates

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- Soft add-on: 1-5 particles
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  - many “hard+soft” trials
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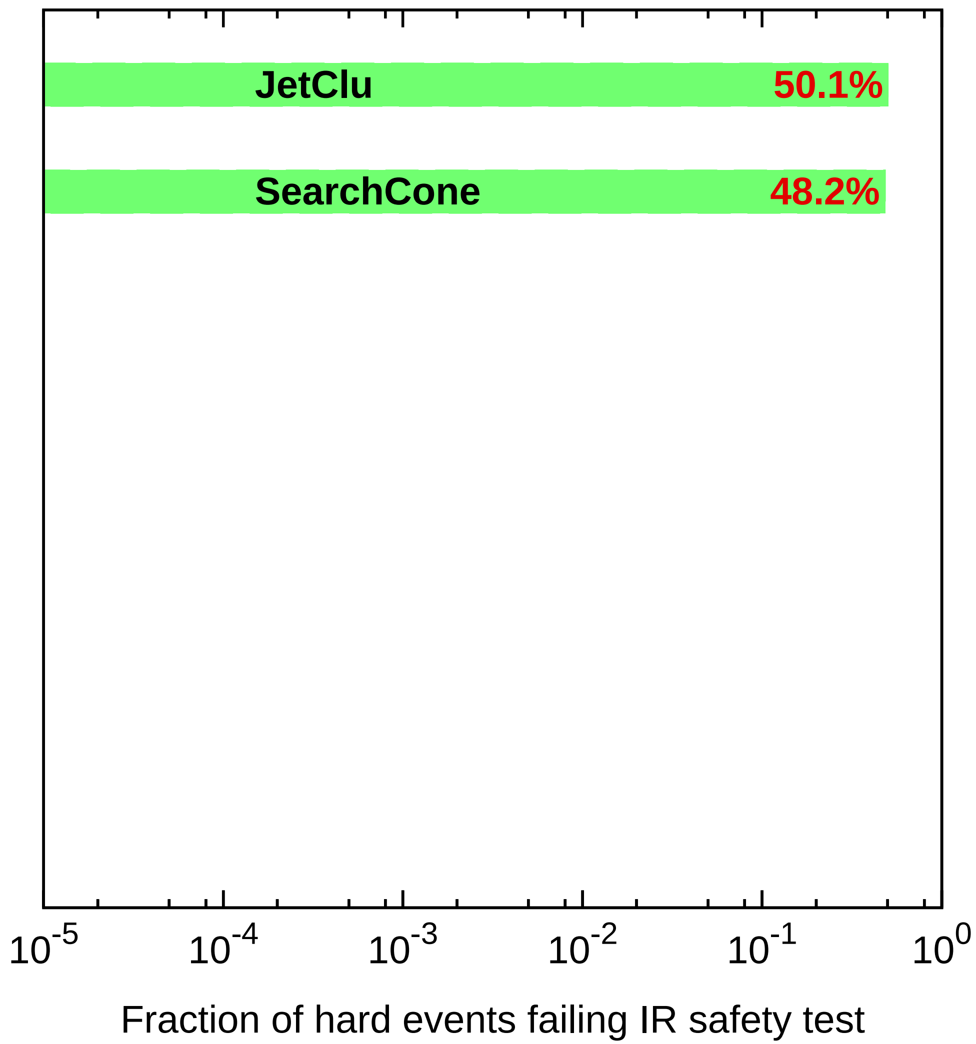

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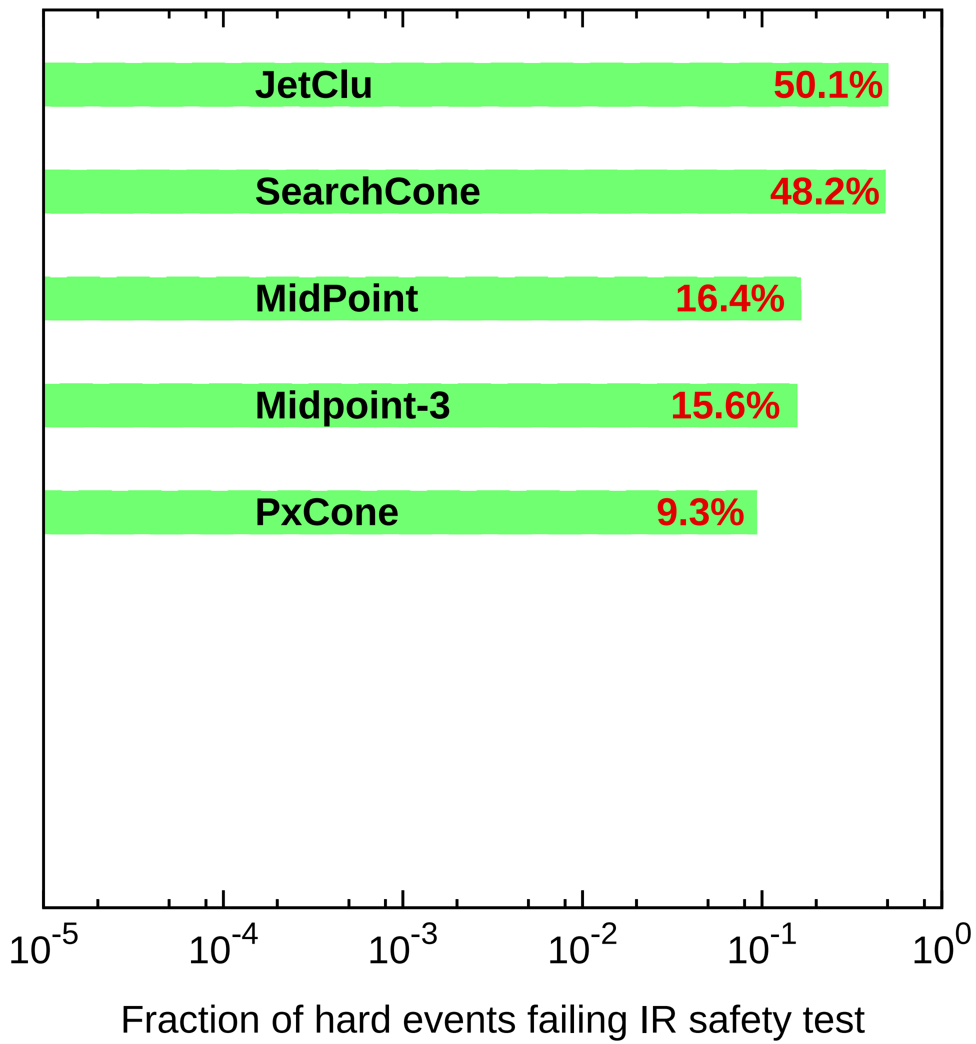

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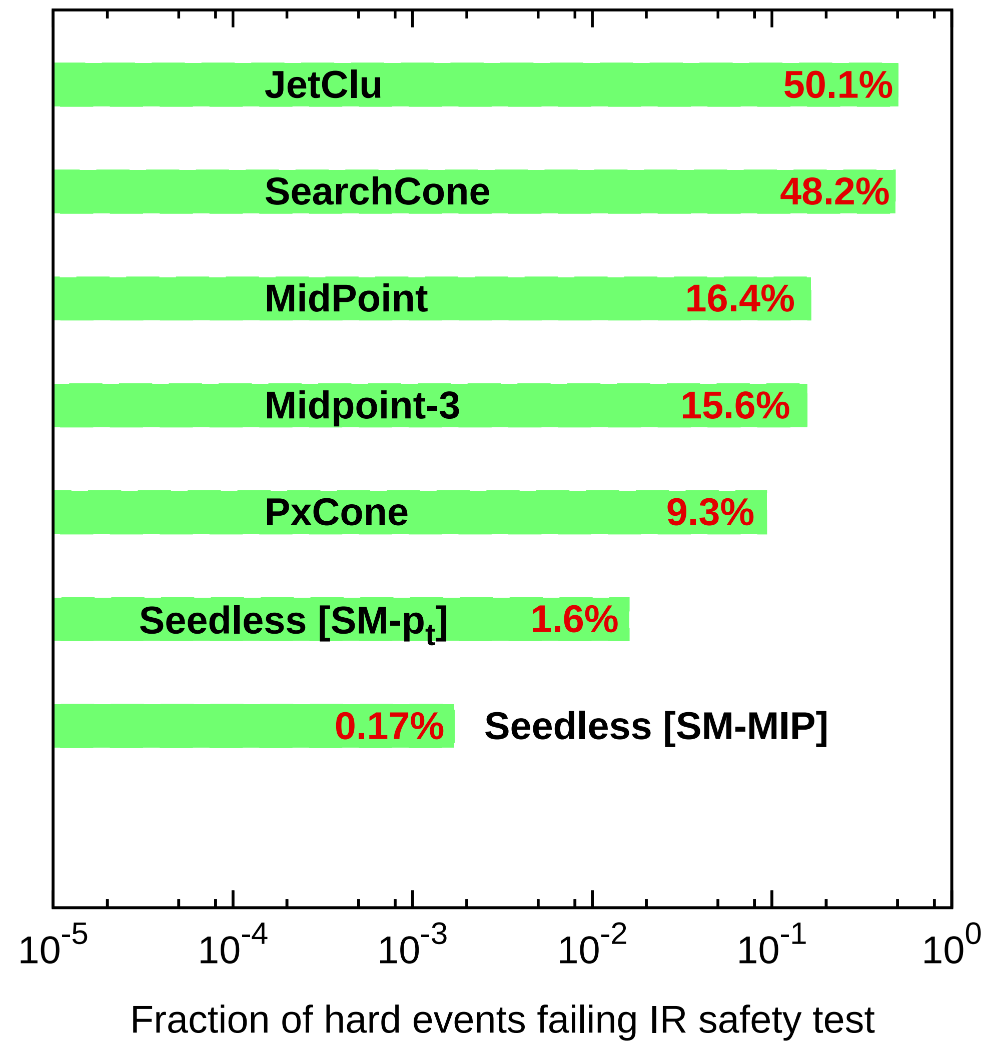

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SISCone	IR safe !

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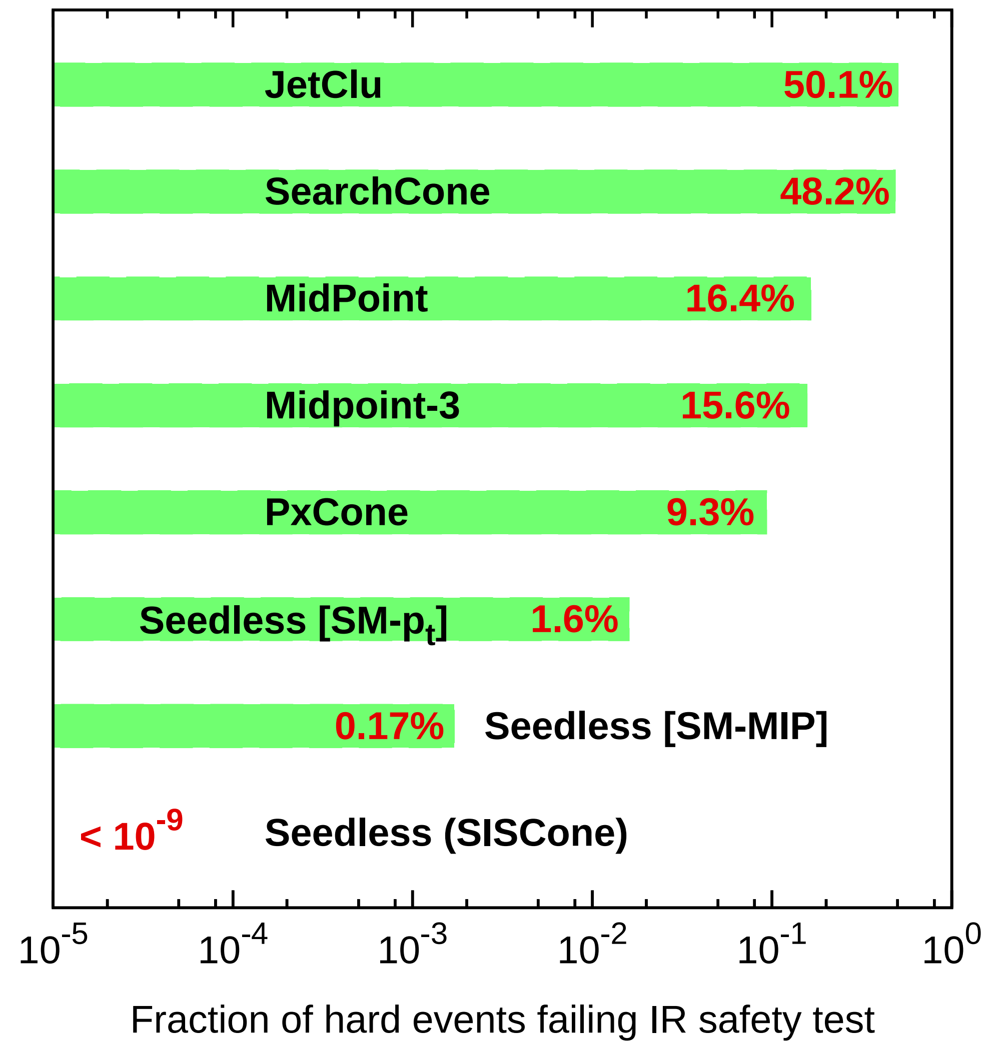

Physical impact: SISCone vs. midpoint(s) ?

IR unsafety of midpoint: 3 particles in the same vicinity + 1 to balance p_t
$\Rightarrow$ starts at the $2 \to 4$ level ($\mathcal{O}\left(\alpha_s^4\right)$)

Observable	1st miss cones at	Last meaningful order
Inclusive jet cross section	NNLO	NLO
$W/Z/H$ + 1 jet cross section	NNLO	NLO
3 jet cross section	NLO	LO
$W/Z/H$ + 2 jet cross section	NLO	LO
jet masses in 3 jets	LO	none
masses in $W/Z/H + 2$ jets	LO	none

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The IR-unsafety issue will matter at LHC

SISCone vs. midpoint(s) in inclusive jet spectrum?

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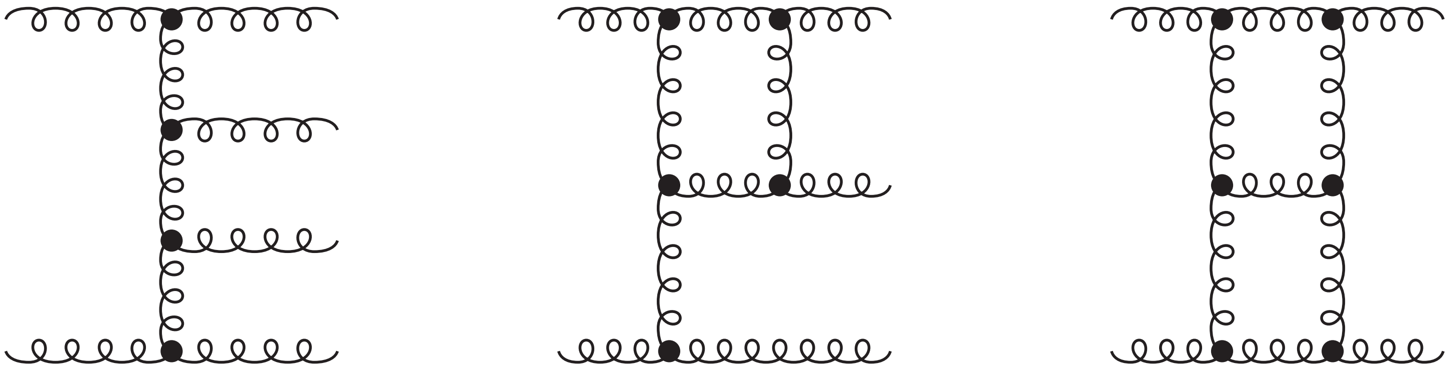

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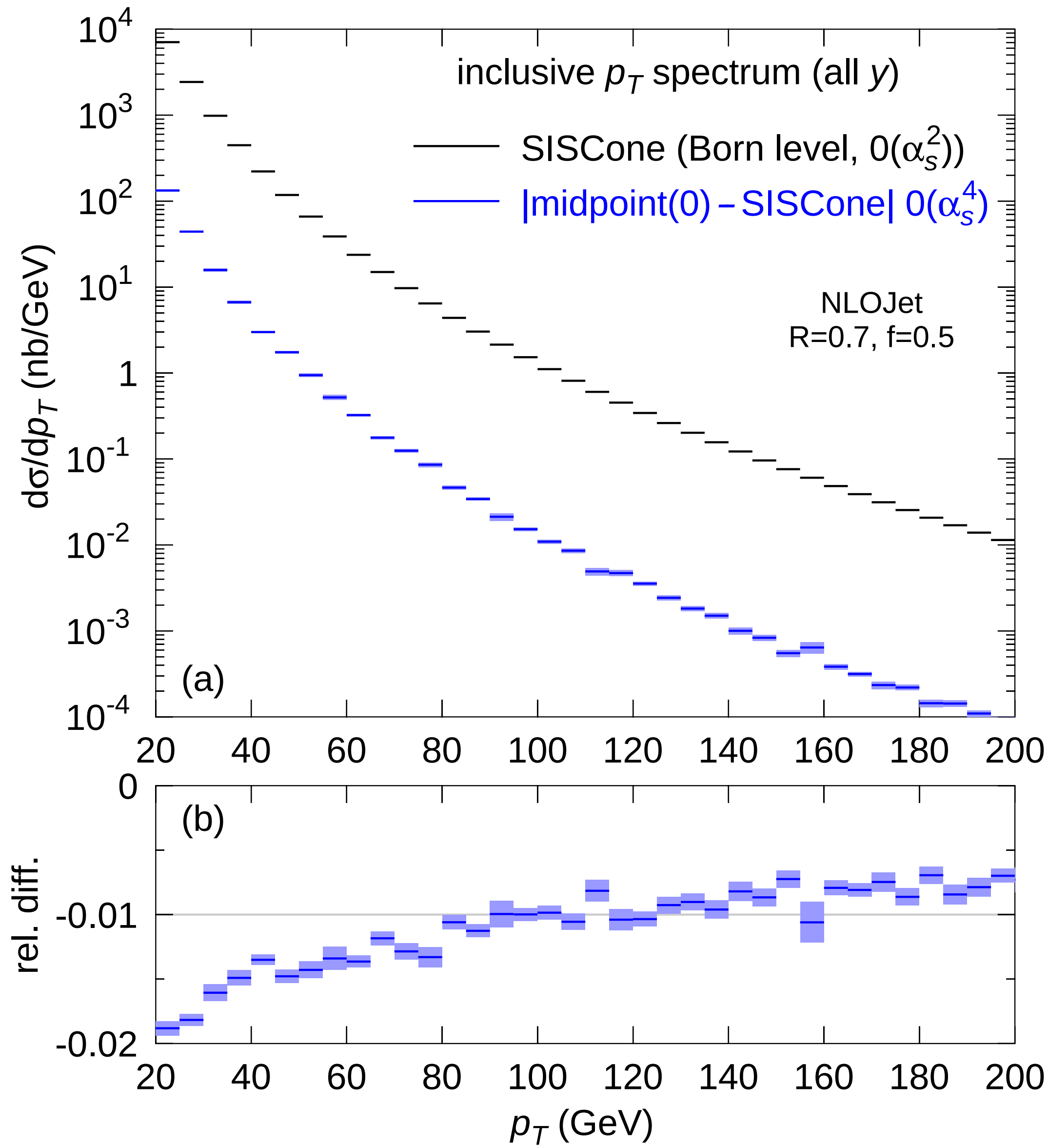
- $2 \to 4$ at LO is IR divergent
  BUT the <u>difference</u> between SISCone and midpoint(s) in finite since it is 0 at the $2 \to 2$ and $2 \to 3$ levels

$\Rightarrow$ compute $|$SISCone-midpoint$(s)|$ for $2 \to 4$ diagrams

- Compare with the $2 \to 2$ (LO) spectrum to estimate effect

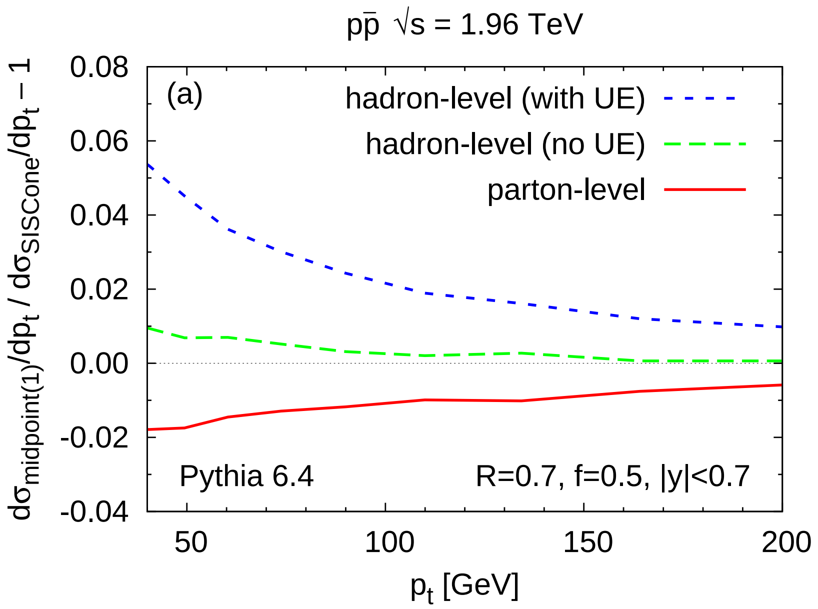
Inclusive jet spectrum: perturbative exp.



Differences of order 1-2 %

Including parton shower, hadronic corrections and/or underlying event:

Ratio midpoint/SISCone-1:



Inclusive jet spectrum: hadron level

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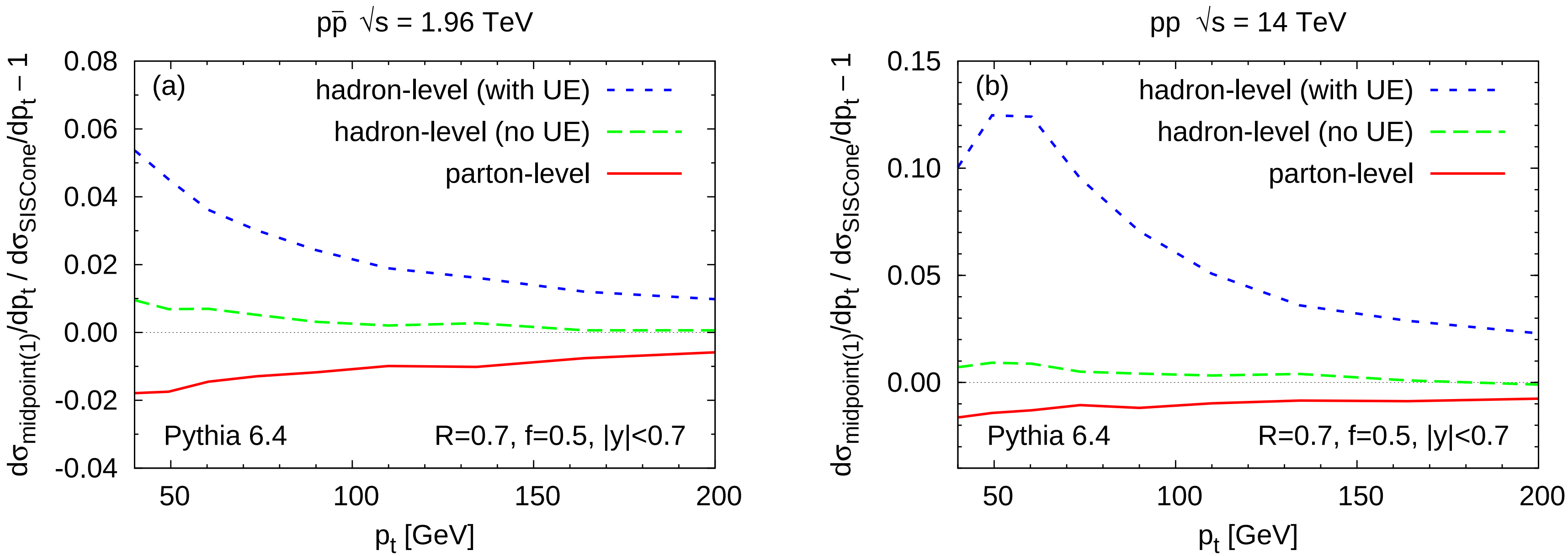

- Differences up to 5% (with a change of sign)
- Raise up to 10% at LHC energy!

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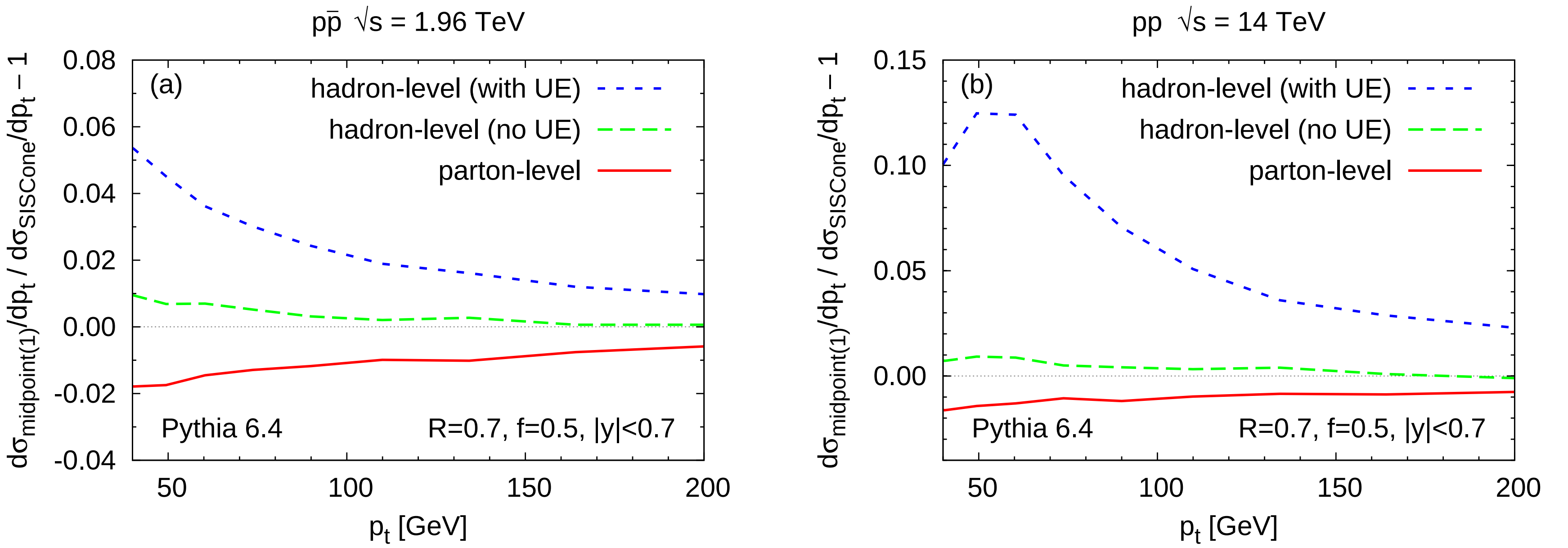


- Differences up to 5% (with a change of sign)
- Raise up to 10% at LHC energy!
- Less effect from underlying event in SISCone (i.e. better agreement with parton level)

Jet mass spectrum

Inclusive jet spectrum

$\rightarrow$ effect at NNLO i.e. $\mathcal{O}\left(\alpha_s^2\right)$ w.r.t. LO

$\Rightarrow$ want to look at more exclusive processes

Example: mass spectrum in 3-jet events (or W/Z/H+2j)

$2 \rightarrow 2$ has only 2 jets
$2 \rightarrow 3$ has zero masses
$\Bigg\} \Rightarrow$ first contribution from $2 \rightarrow 4$

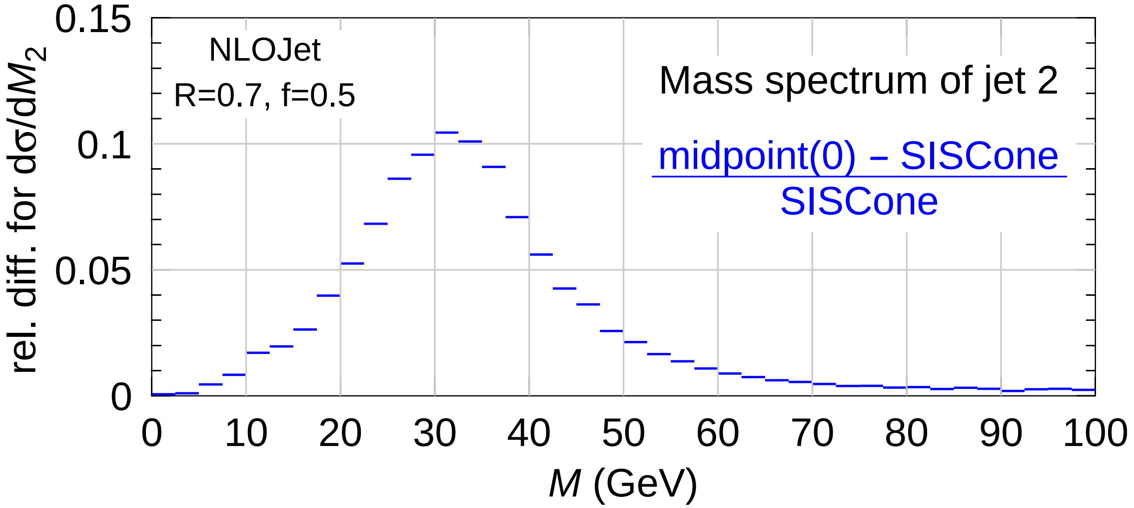
$\Rightarrow$ Expect modifications at LO!

Ratio $\frac{\text{midpoint}-\text{SISCone}}{\text{SISCone}}$ for masses spectra in 3-jet events

cuts: $p_{t,1} \geq 120$ GeV, $p_{t,2} \geq 80$ GeV, $p_{t,3} \geq 40$ GeV

Jet mass spectrum: perturbative level

1. Fixed order computation (NLOJet, LO, $2 \to 4$)



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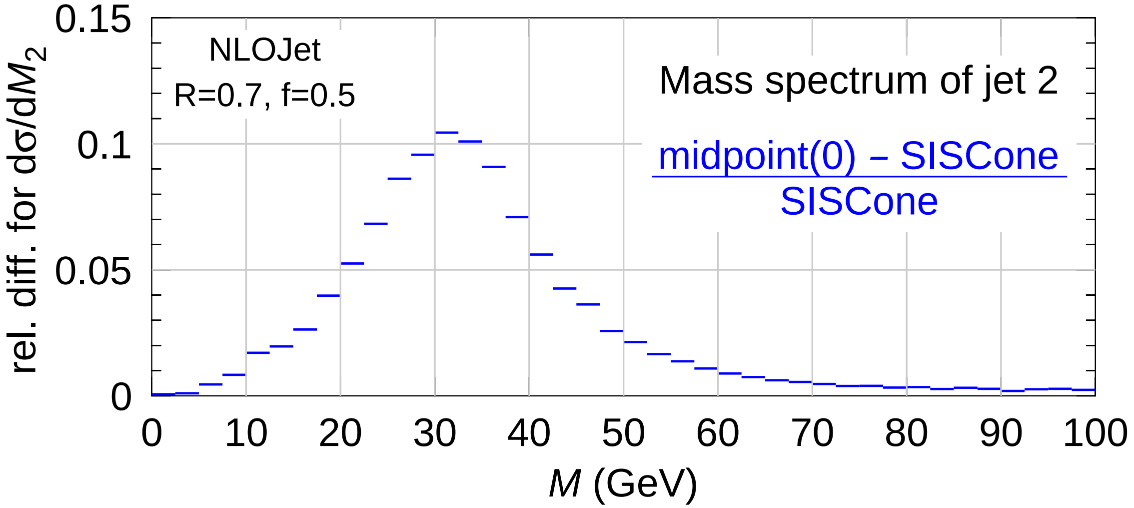
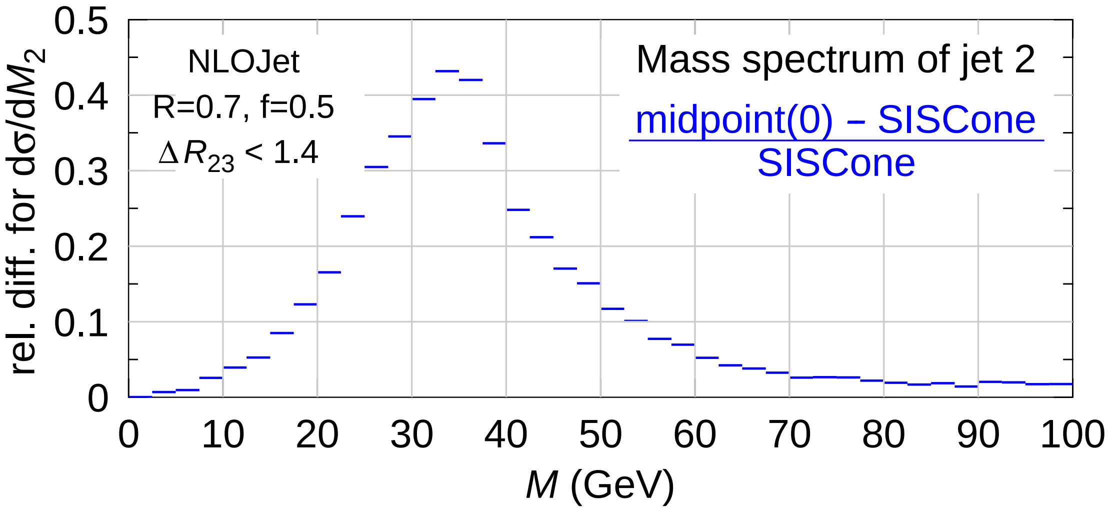


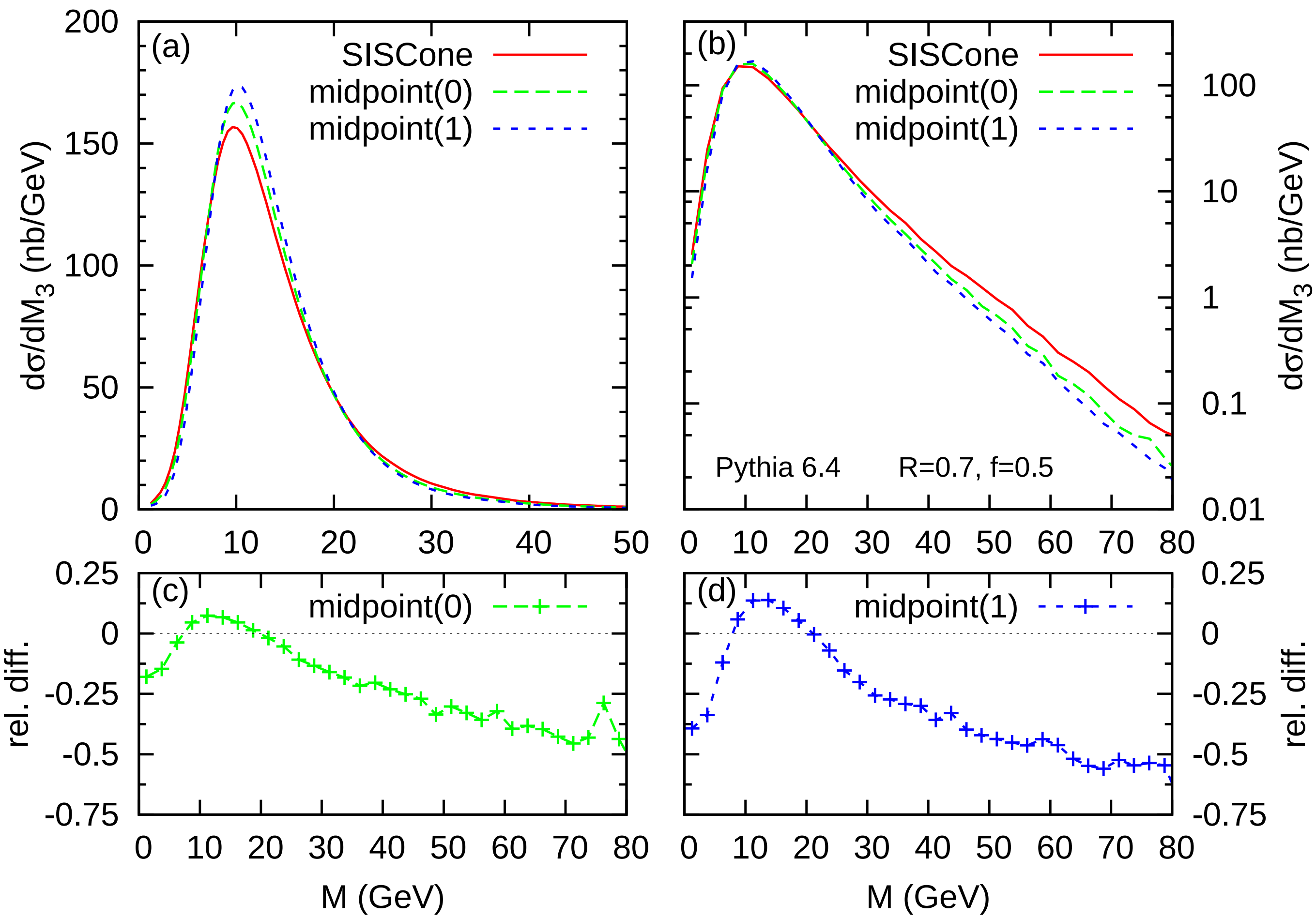
Differences up to 10 %

2. Also require jets 2 and 3 within distance $\leq 2R$



Differences up to 40 %

3. At hadron level (PYTHIA)



- ▷ Differences of order 10 %
- ▷ Larger effects in the tail
- ▷ seed threshold even worse

SISCone conclusions

- Jets are present everywhere: k_t and cone are widely used
- seeded implementations are IR unsafe (sometimes collinear unsafe)
  IR safety is a prerequisite for perturbative QCD to make sense

We propose a new cone algorithm (SISCone):

- IR safe (and collinear safe)
- as fast as available cone implementations
- has 10% impact on jet mass spectra (can be up to 40%)
- is less affected by underlying events

Jet area

Everyone has an idea of what a jet area is

but can we define that properly?

[M. Cacciari, G. Salam, G.S., in preparation]

[M. Cacciari, G. Salam, arXiv:0707.1378]

Area definition

- Idea: add soft particle (ghosts)
  - with IR-safe algorithms such as k_t, Aachen/Cambridge and SISCone, clustering is unchanged
  - look in which jets added particles are catched

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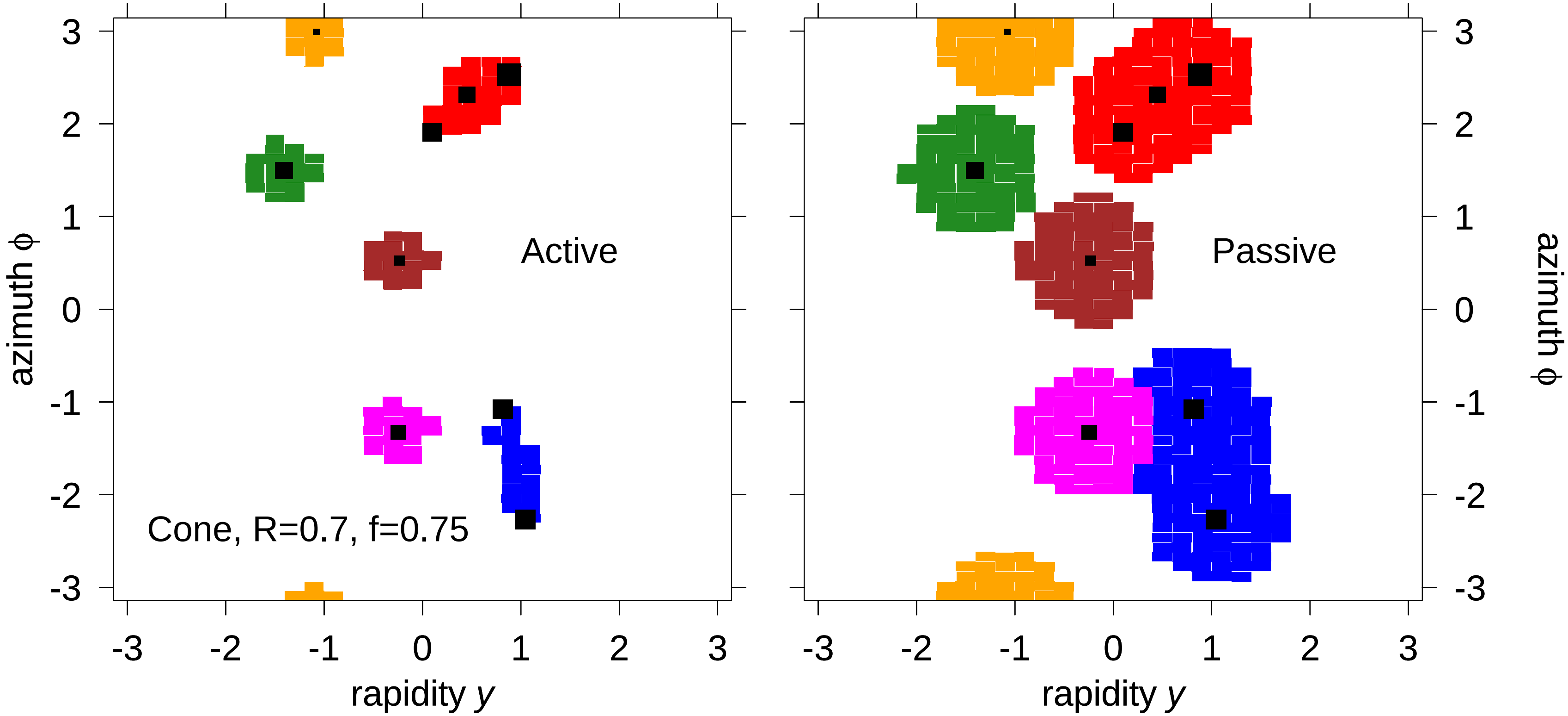
- Voronoi area

  $\sim$ Area of the Voronoi cells

Area definition

- Small N: active area is usually smaller than passive area (especially for the cone)



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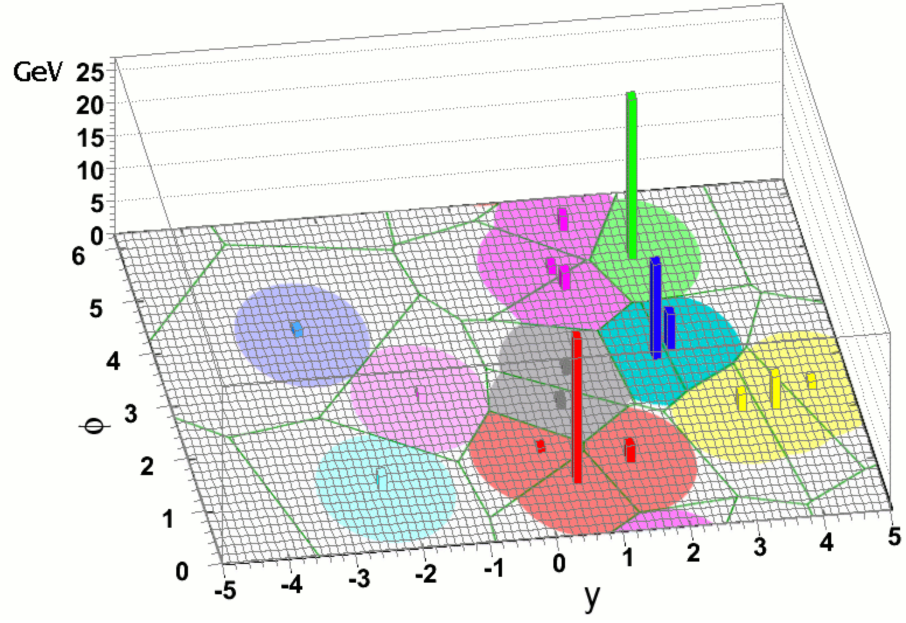

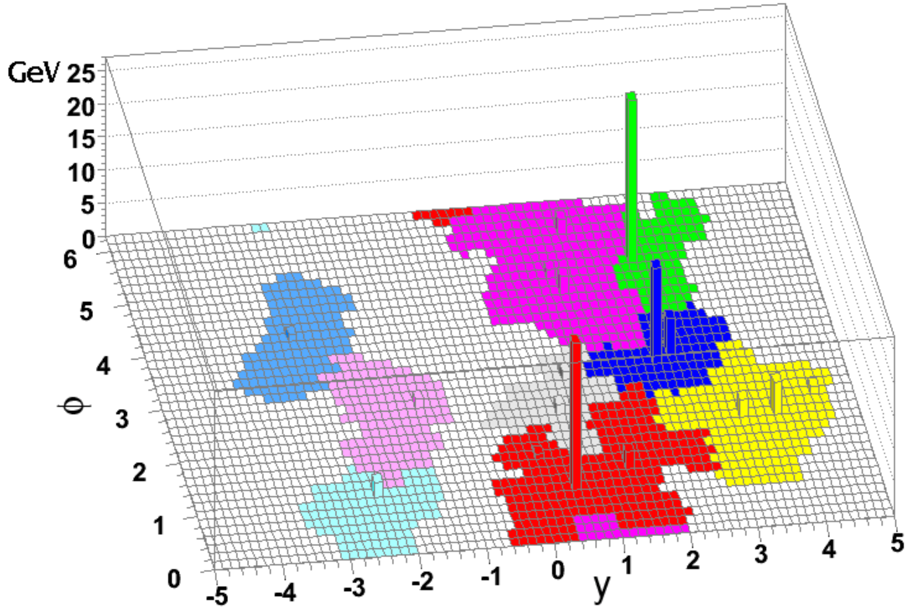

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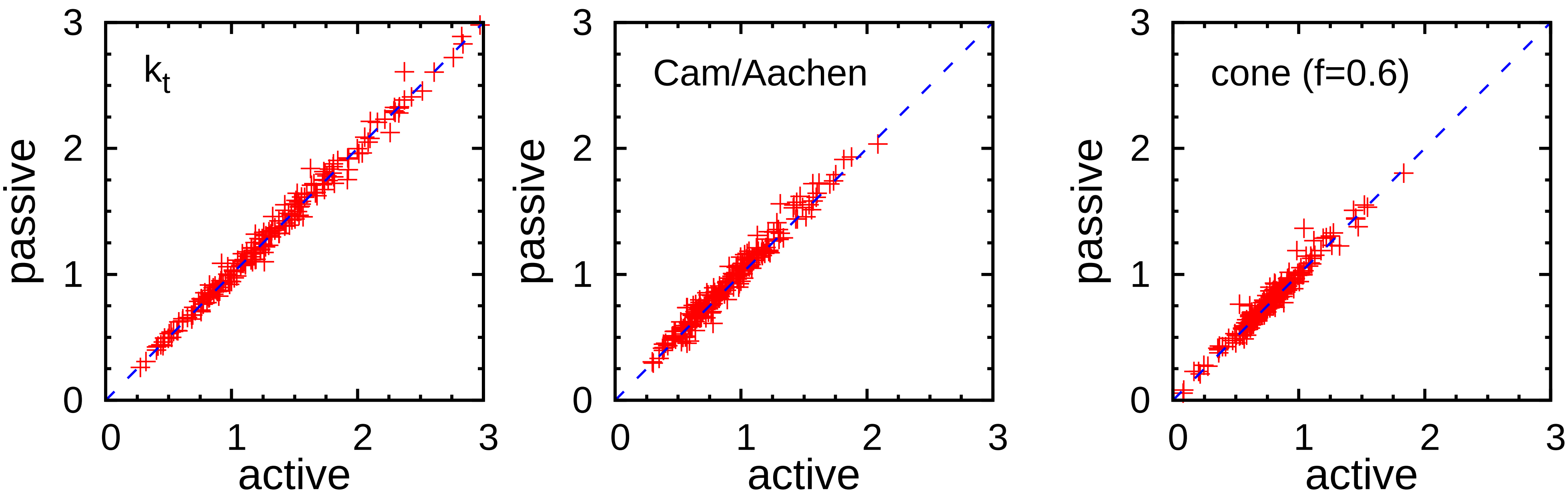

Examples: 1-particle cases

	k_t	Aac/Cam	cone
Passive			
Active			

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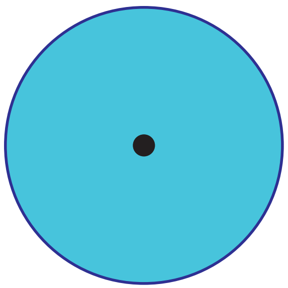
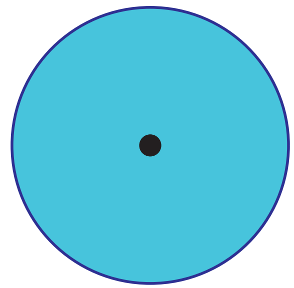
Passive	 πR^2	 πR^2	
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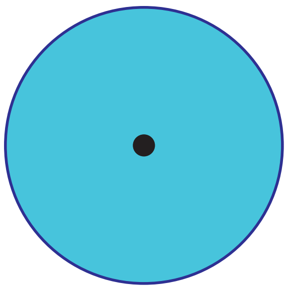
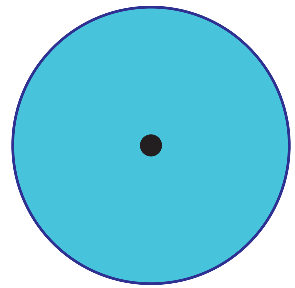
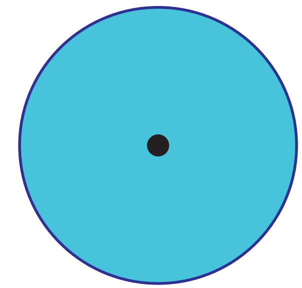
Passive	 πR^2	 πR^2	 πR^2
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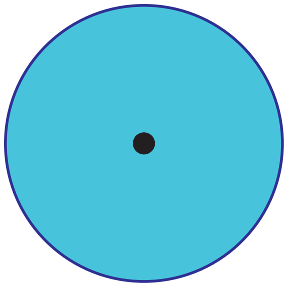
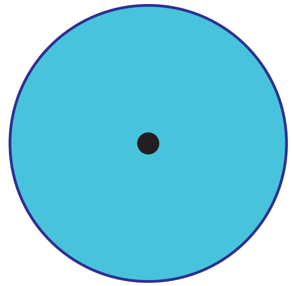
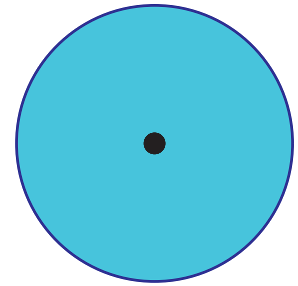
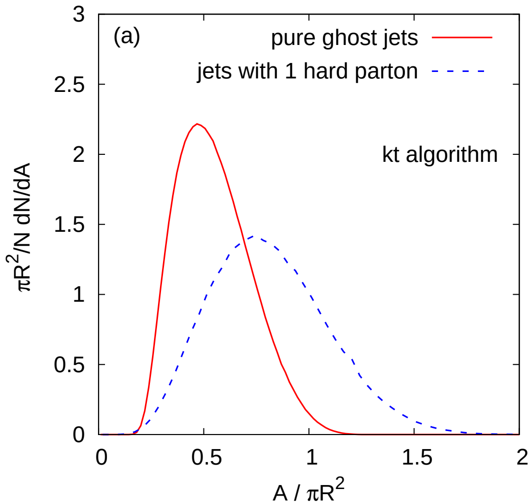
<tr><th></th><th>k_t</th><th>Aac/Cam</th><th>cone</th></tr>
<tr><td>Passive</td><td> πR^2</td><td> πR^2</td><td> πR^2</td></tr>
<tr><td>Active</td><td>

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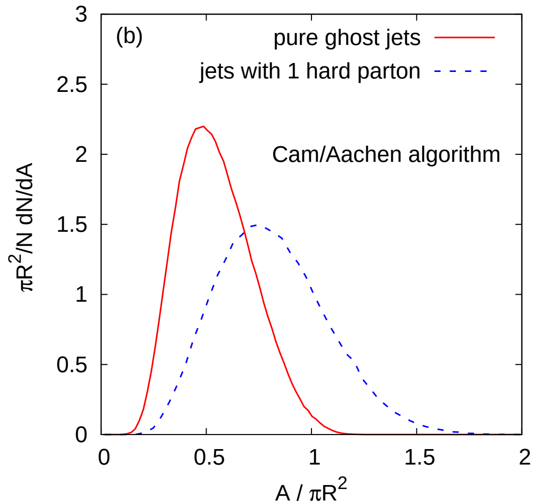
$\frac{A_{\text{ghost}}}{\pi R^2} \approx 0.554 \pm 0.174$</td><td>

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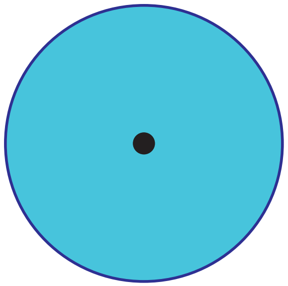
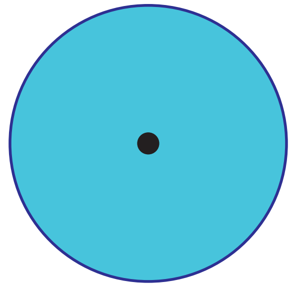
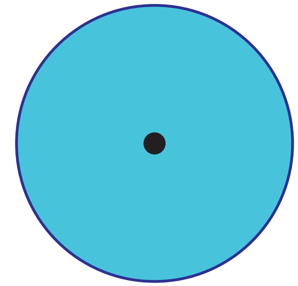
<td> πR^2</td>
<td> πR^2</td>
<td> πR^2</td></tr>
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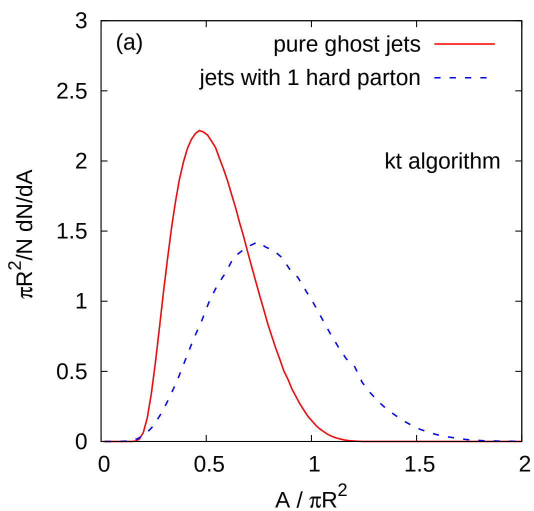
<td>

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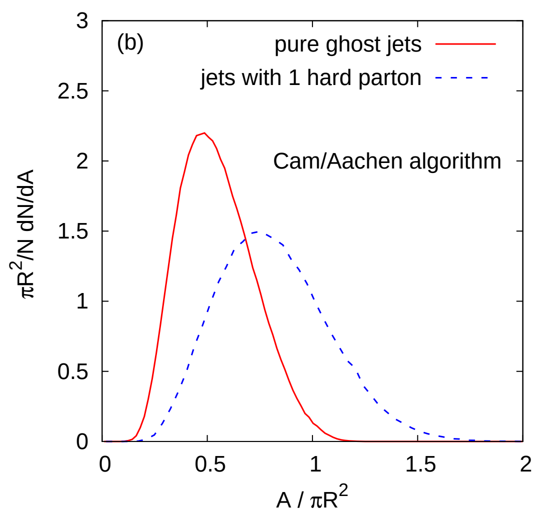
<td>

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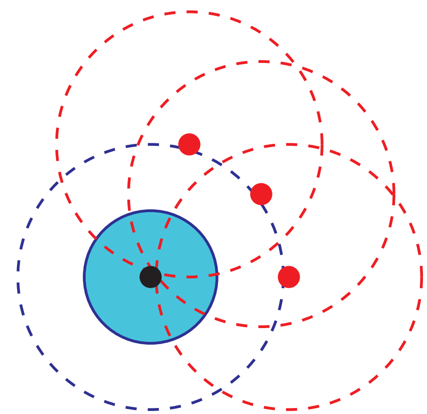
<td>
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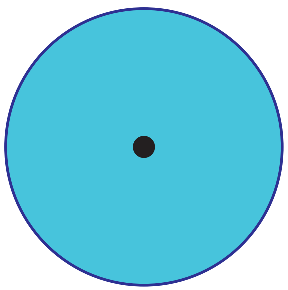
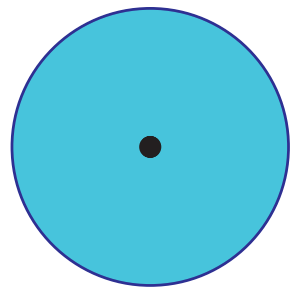
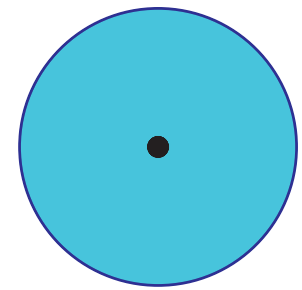
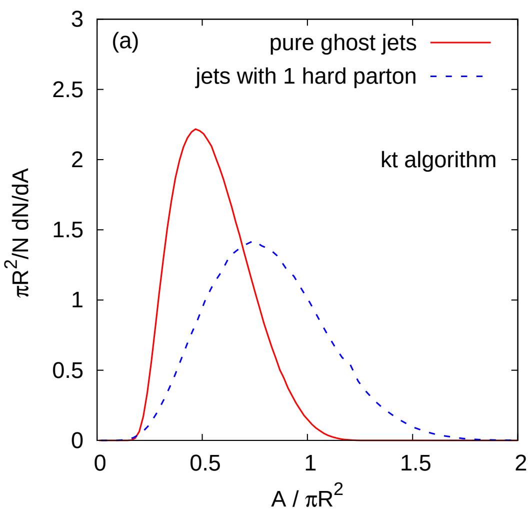
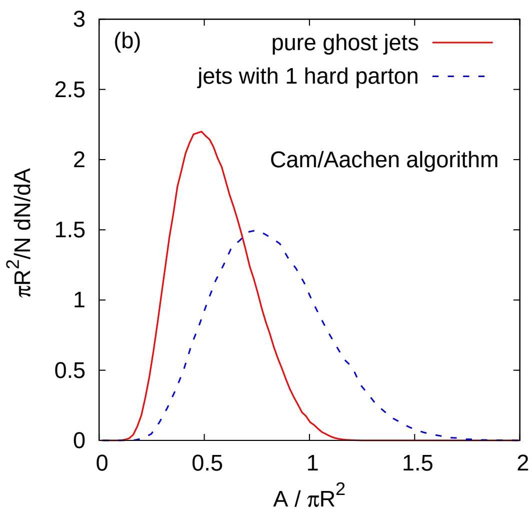
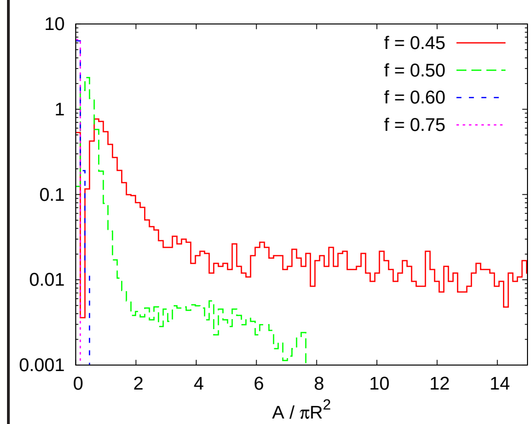
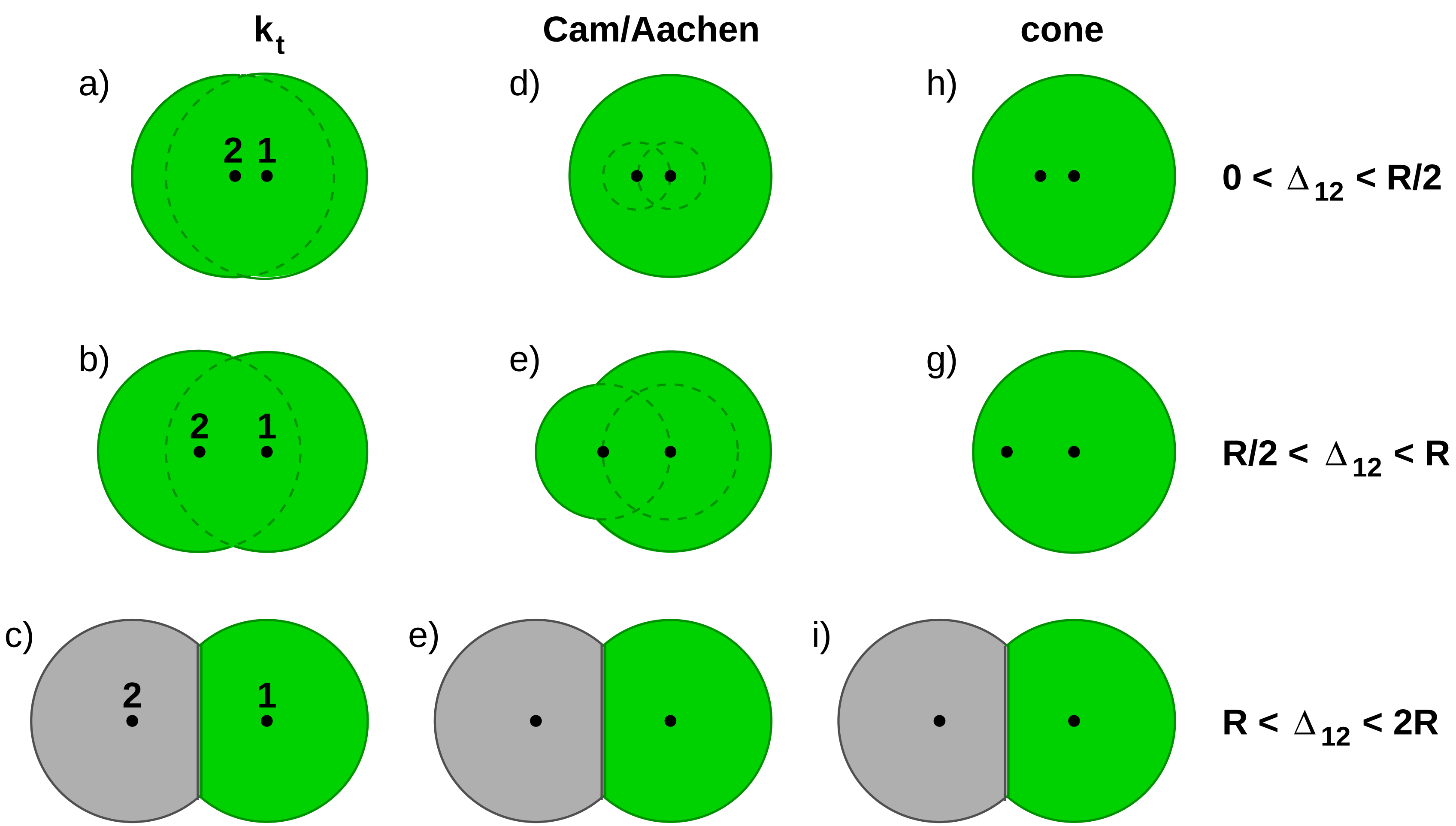
Passive	 πR^2	 πR^2	 πR^2
Active	 $\frac{\mathcal{A}_{\text{hard}}}{\pi R^2} \approx 0.812 \pm 0.277$ $\frac{\mathcal{A}_{\text{ghost}}}{\pi R^2} \approx 0.554 \pm 0.174$	 $\frac{\mathcal{A}_{\text{hard}}}{\pi R^2} \approx 0.814 \pm 0.261$ $\frac{\mathcal{A}_{\text{ghost}}}{\pi R^2} \approx 0.551 \pm 0.176$	 $\frac{\mathcal{A}_{\text{hard}}}{\pi R^2} = 0.25$ $\mathcal{A}_{\text{ghost}}$ depends on f possible monster jets!

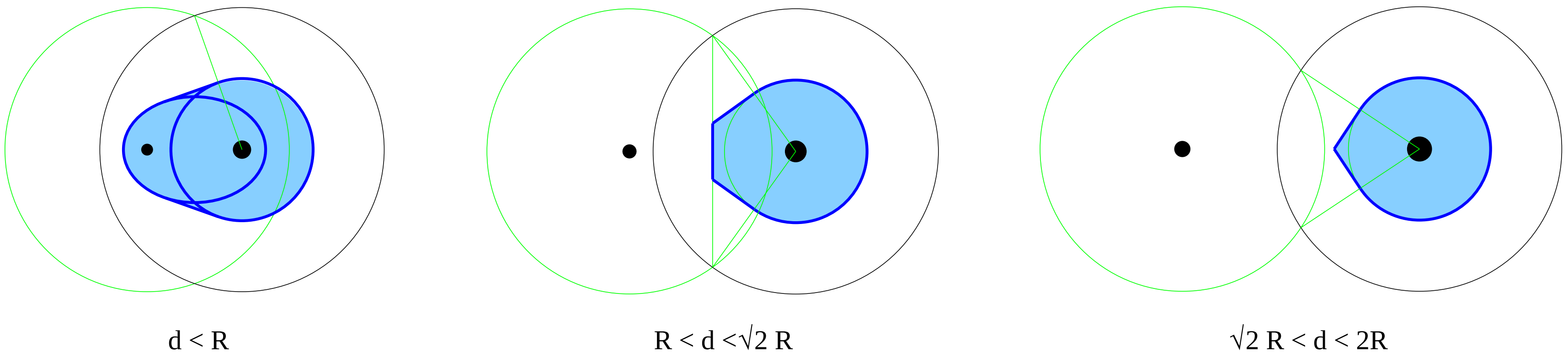
2-particle cases

Passive area: 1 hard particle + 1 soft



2-particle cases

Active area: 1 hard particle + 1 soft: analytic result for cone only



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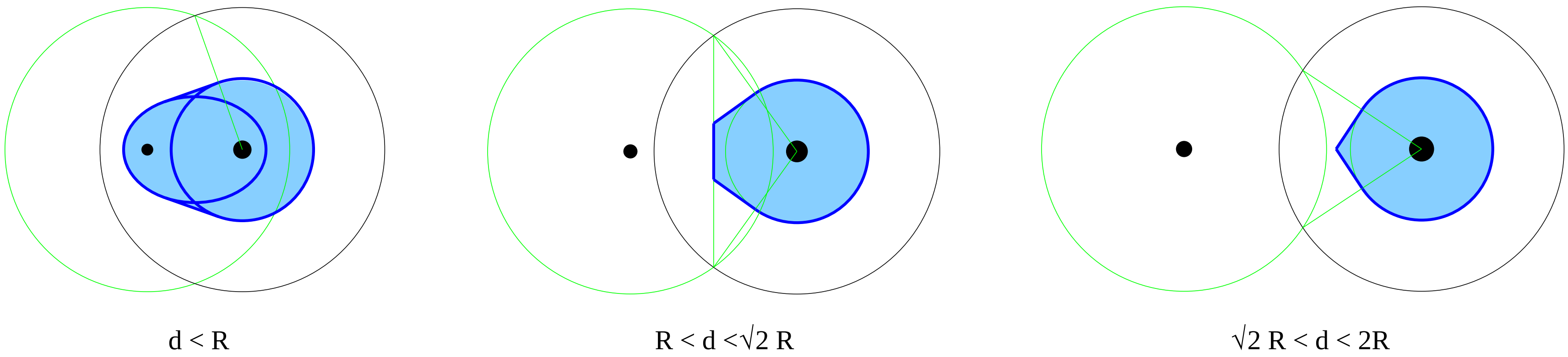
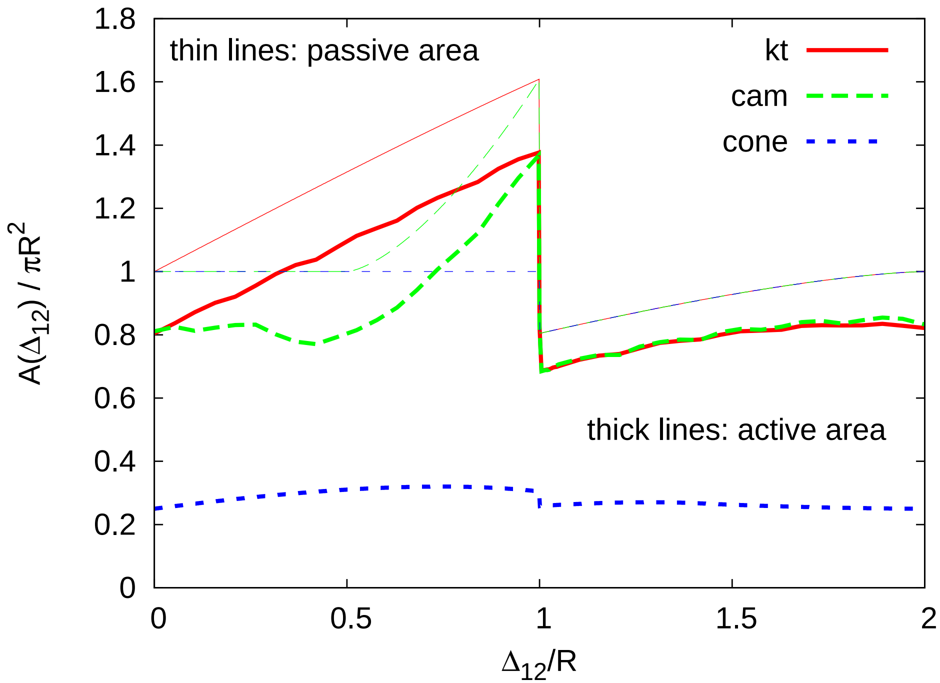


Alltogether, we have:

- Area $\neq$ cst. πR^2
- Δ_{12} dependence under control



Area scaling violations

QCD probability of emitting a small-angle soft gluon:

$$\frac{dP}{d\Delta_{12}dp_{t,2}} = C_{F,A}\frac{2\alpha_s}{\pi}\frac{1}{\Delta_{12}}\frac{1}{p_{t,2}}$$

Hence the average area is

$$\langle \mathcal{A}(p_{t,1}, R)\rangle \quad = \quad \mathcal{A}_{\text{1hard}}(R) + \int d\Delta\, dp_{t,2}\,\frac{dP}{d\Delta_{12}dp_{t,2}}\left[\mathcal{A}_{\text{hard+1 soft}}(\Delta, R) - \pi R^2\right]$$

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$$\frac{dP}{d\Delta_{12}dp_{t,2}} = C_{F,A}\frac{2\alpha_s}{\pi}\frac{1}{\Delta_{12}}\frac{1}{p_{t,2}}$$

Hence the average area is

$$\begin{aligned}\langle\mathcal{A}(p_{t,1},R)\rangle &= \mathcal{A}_{\text{1hard}}(R) + \int d\Delta\, dp_{t,2}\,\frac{dP}{d\Delta_{12}dp_{t,2}}\left[\mathcal{A}_{\text{hard+1 soft}}(\Delta,R) - \pi R^2\right] \\ &= \frac{C_{F,A}}{\pi b_0}\log\left(\frac{\alpha_s(\Lambda}{\alpha_s(Rp_t)}\right)\pi R^2\, d\end{aligned}$$

- Scaling viloation
- gluon > quark

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- Scaling viloation
- gluon > quark
- with know LO anomalous dimension

d	passive	active
k_t	0.5638	0.519
Cam	0.07918	0.0865
Cone	-0.06378	0.1246

“Real-life” anomalous dimension

Herwig simulations of qq or gg processes at hadron level with underlying event: area vs. p_t of the jet

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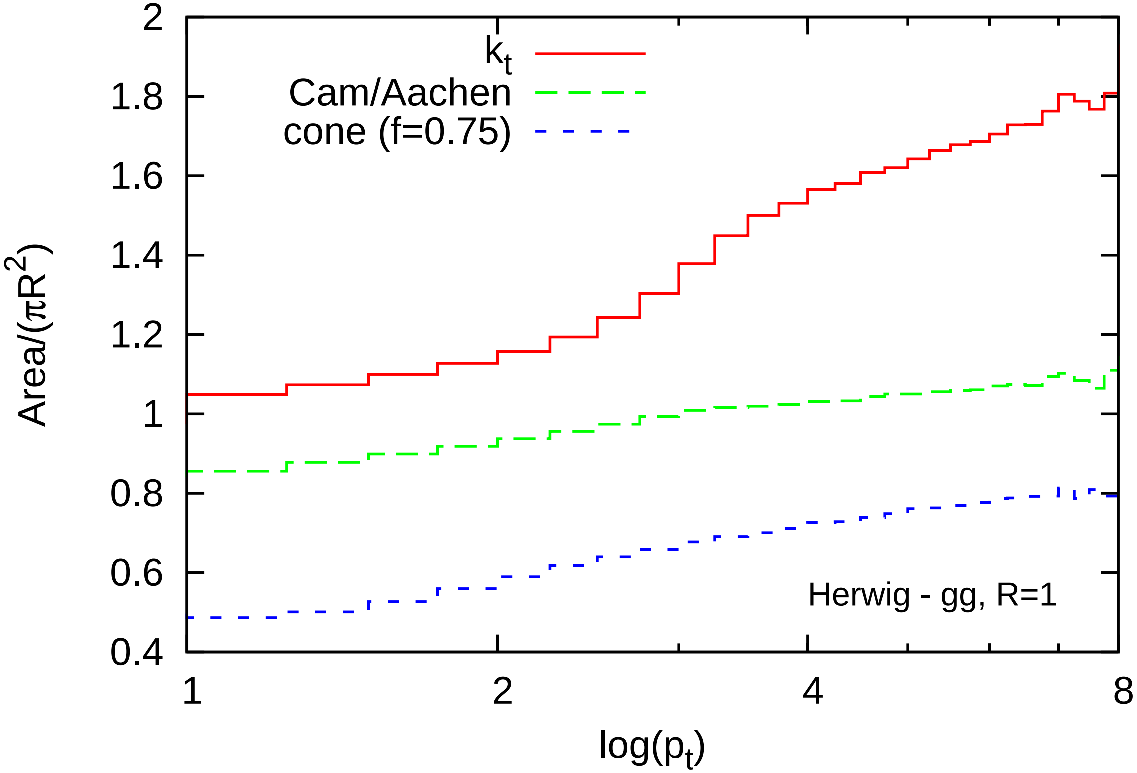

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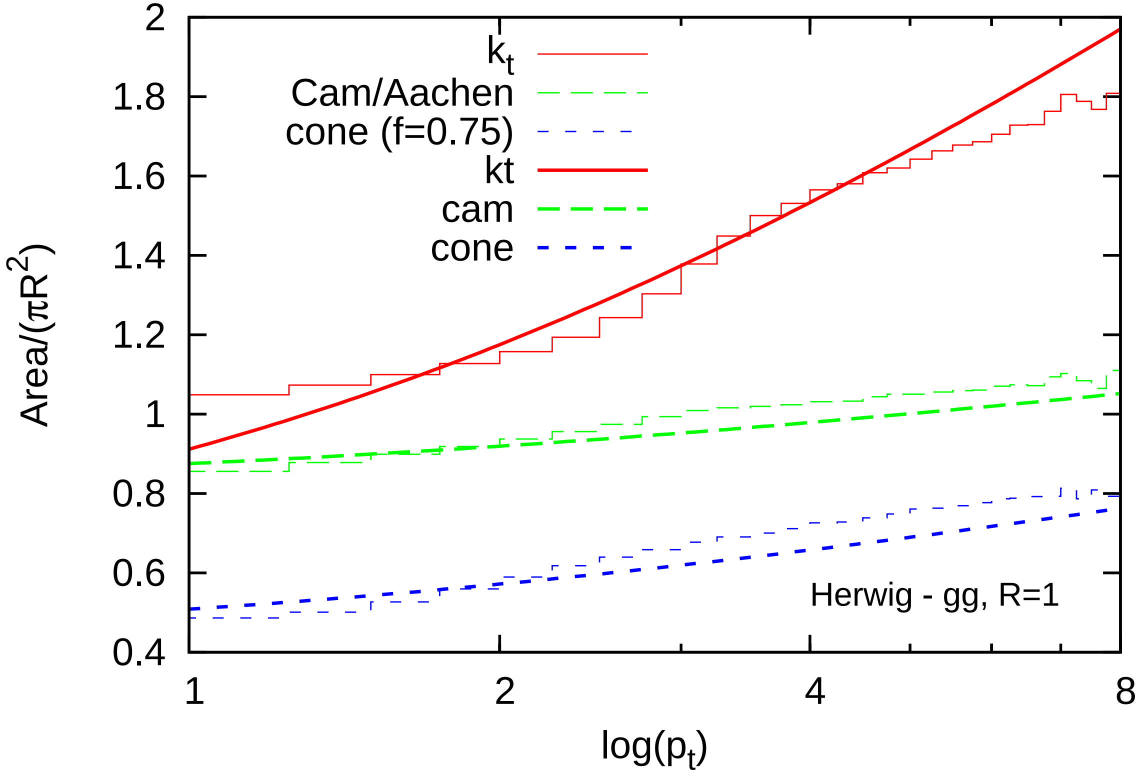
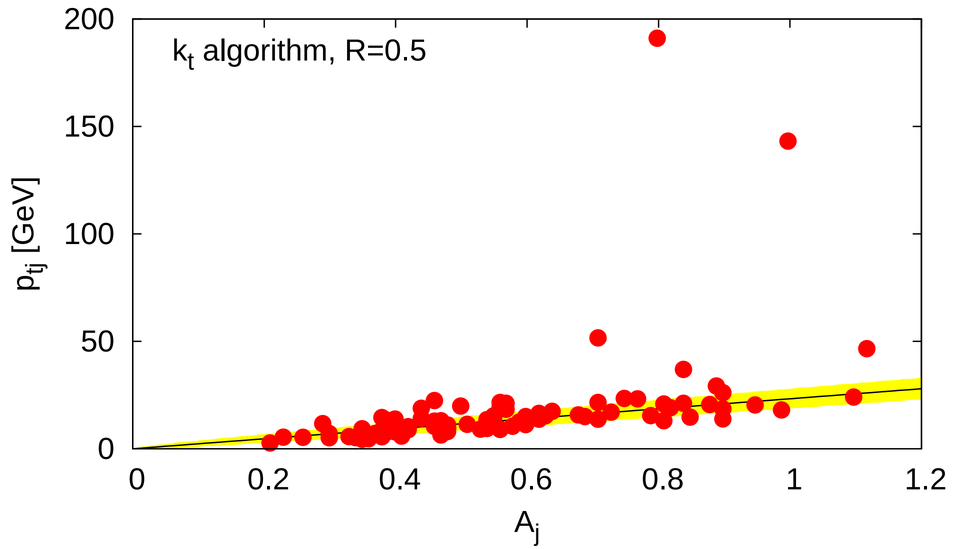


- good agreement with LO predictions
- k_t bigger $\Rightarrow$ NLO?

What can area be used for?

Dense event with pile-up:



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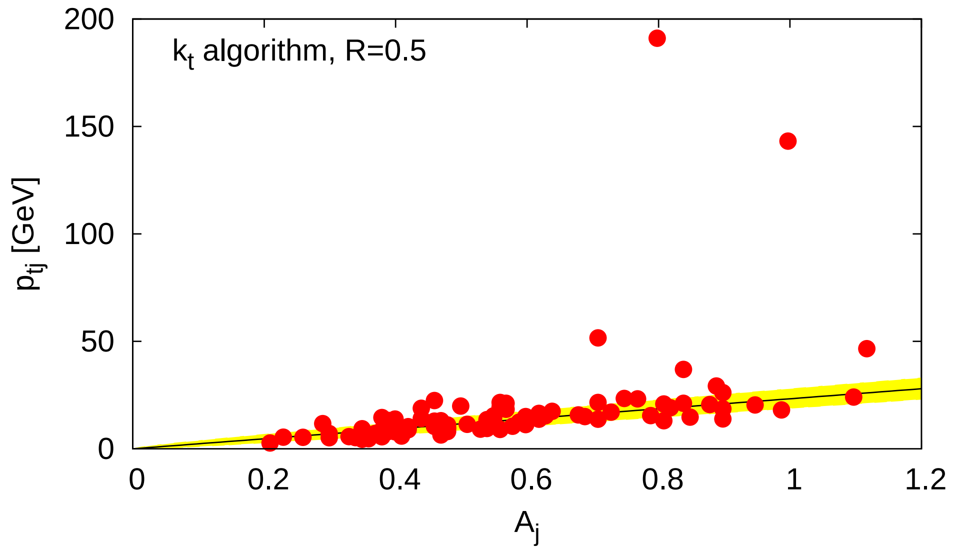

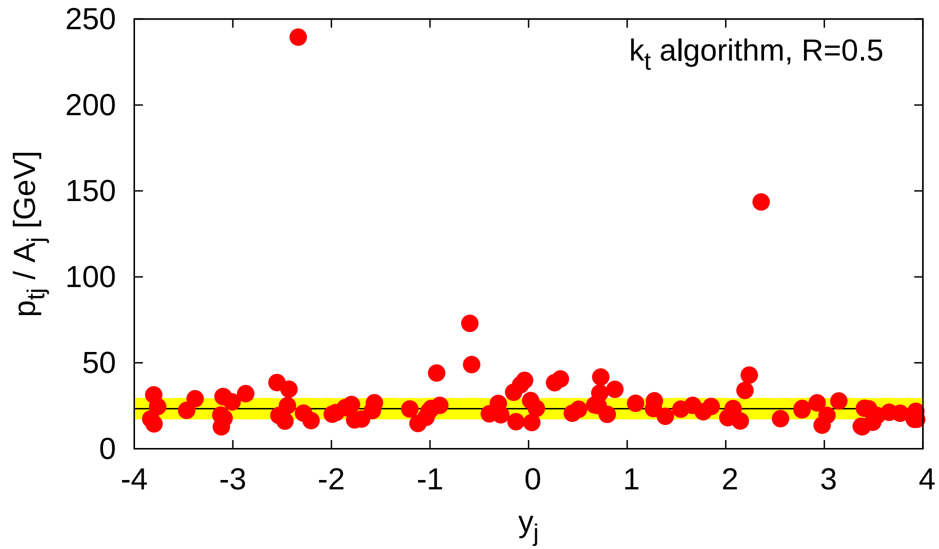

- Area $\propto p_t$ of the jet
- p_t/area is constant $\rightarrow \rho$ = median p_t/area

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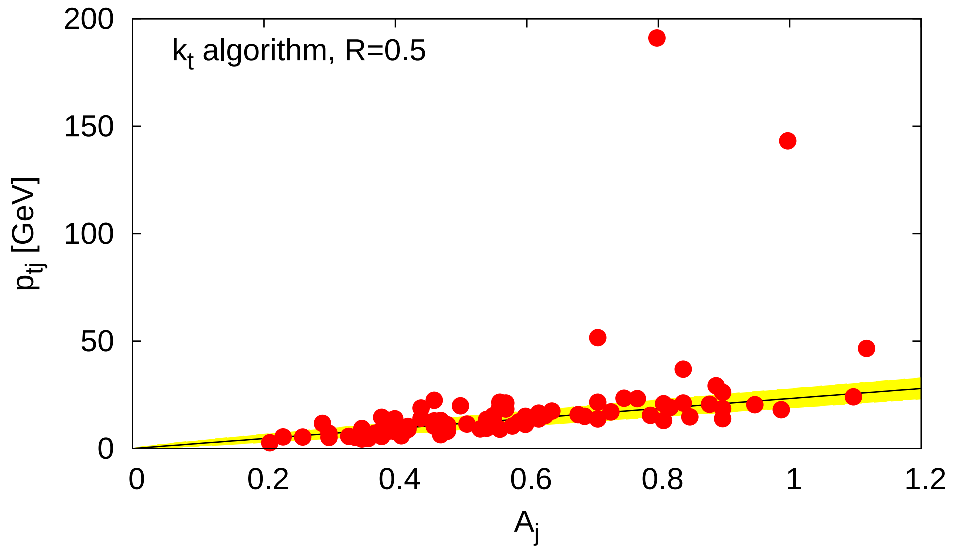

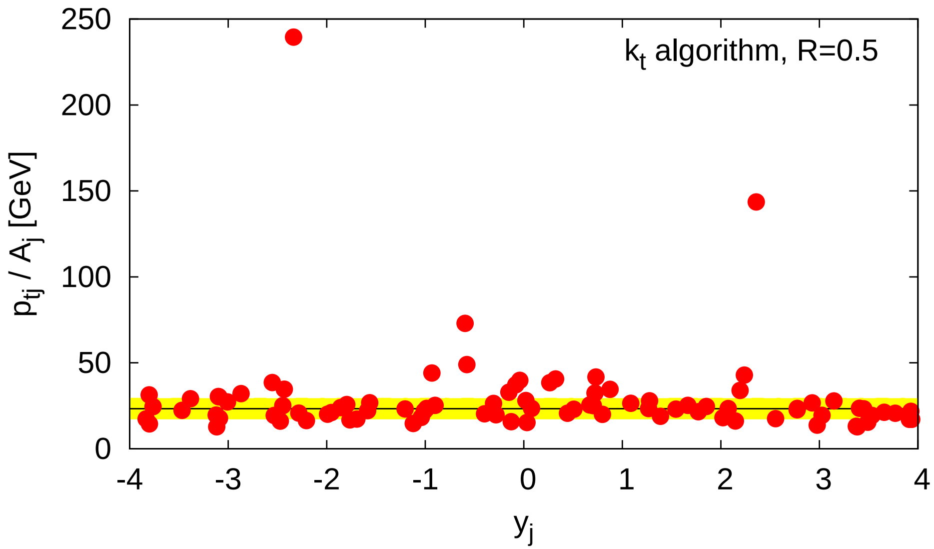

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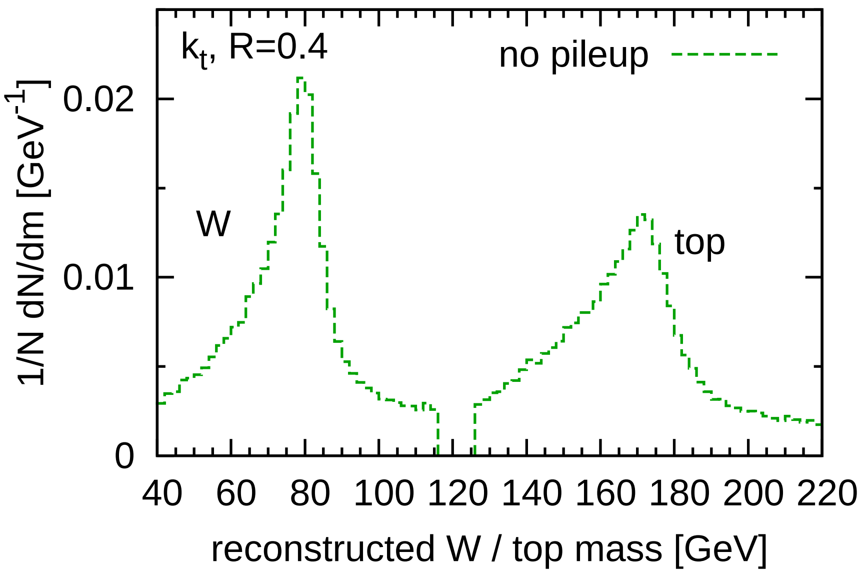
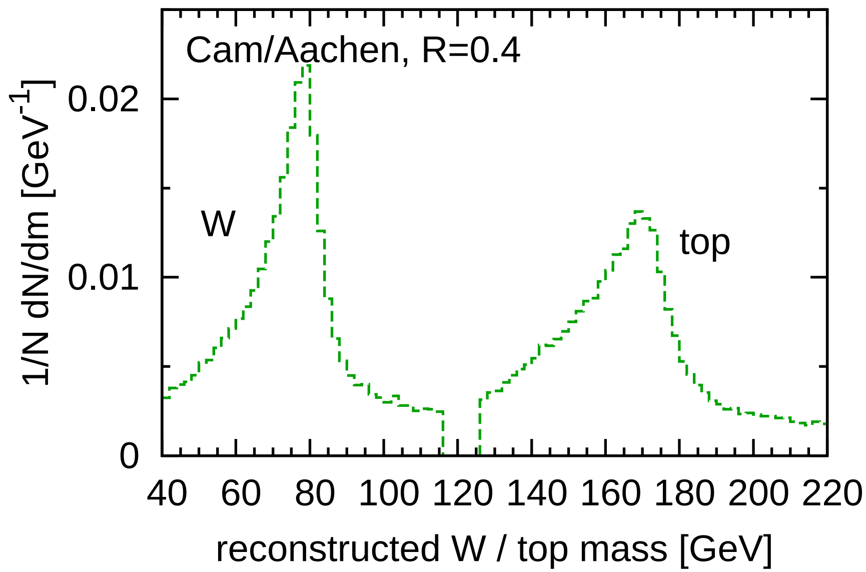
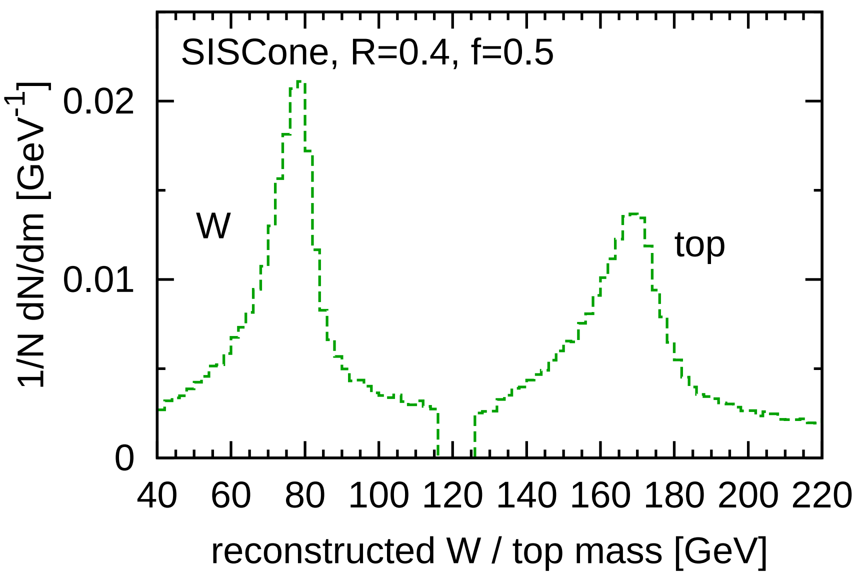
Area can be used to remove pileup pollution
e.g. by removing ρ.area

Subtraction in action

$t\bar{t} + W$ $\quad (t\bar{t} \to \ell^+ \nu_\ell b + q\bar{q}\bar{b}) \quad (W \to q\bar{q})$







LHC at high lumi

no pileup $\Rightarrow$ good result

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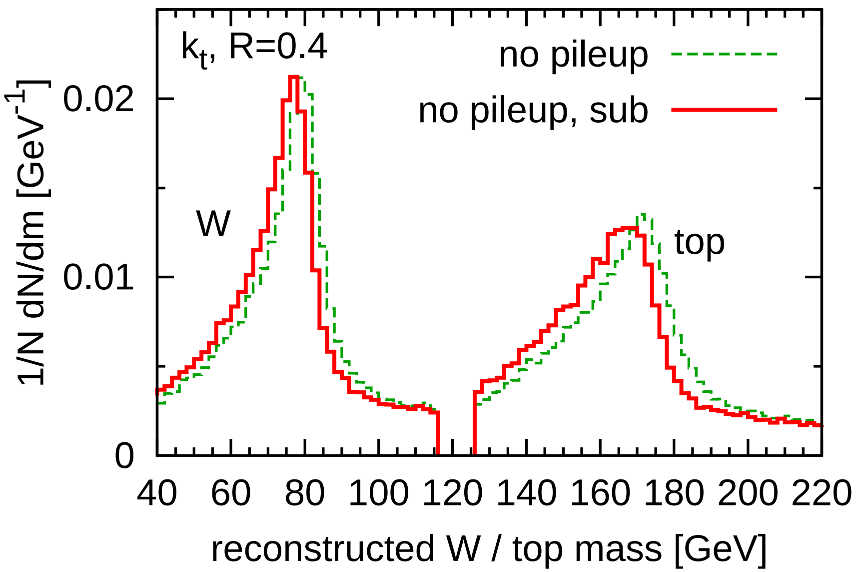

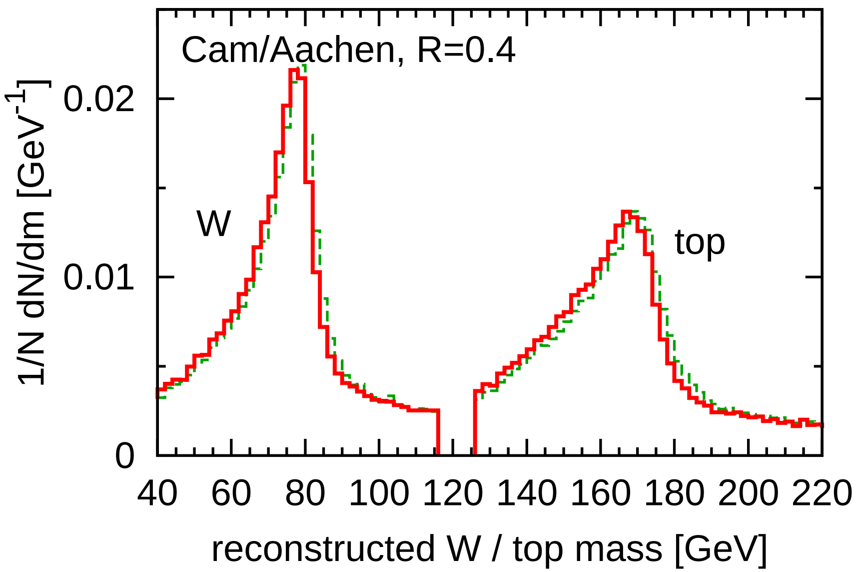

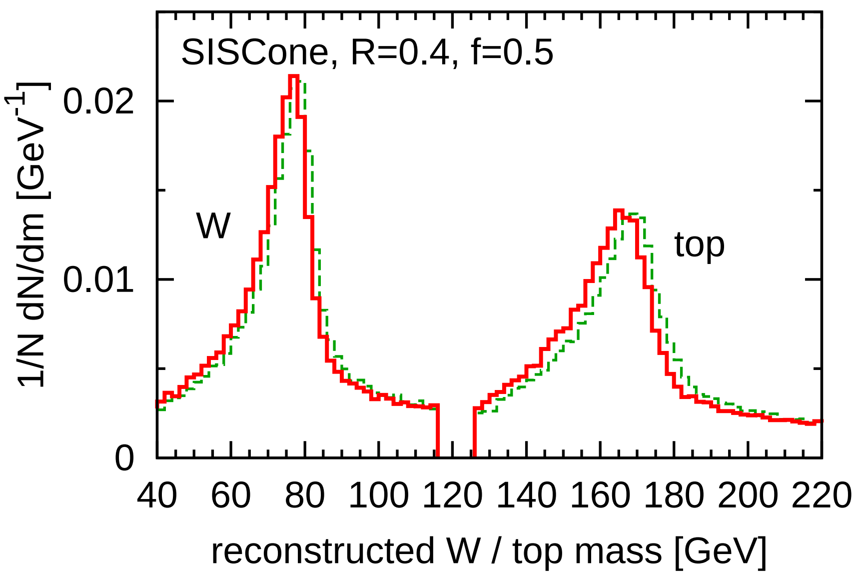

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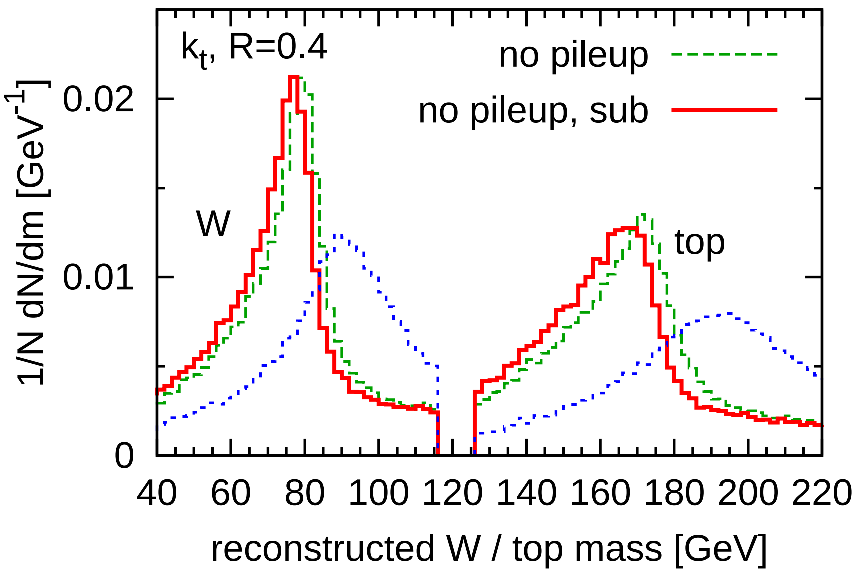

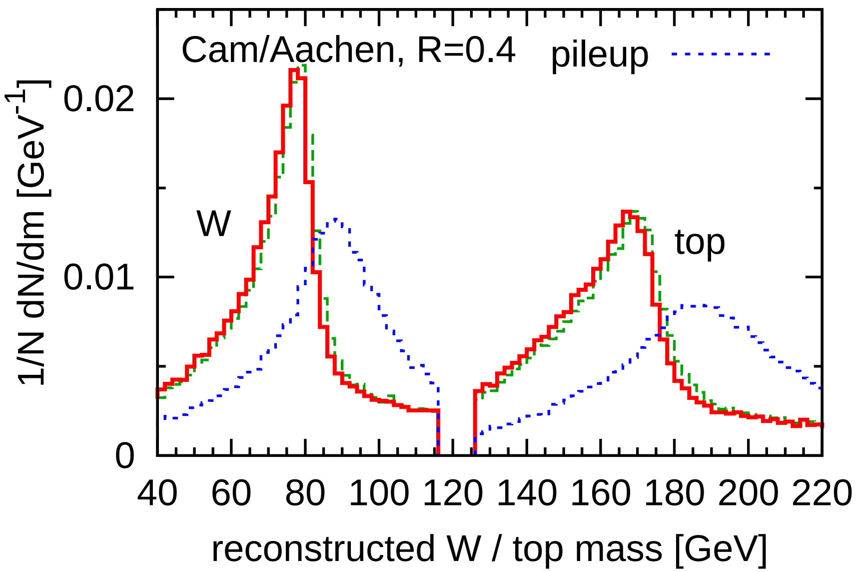

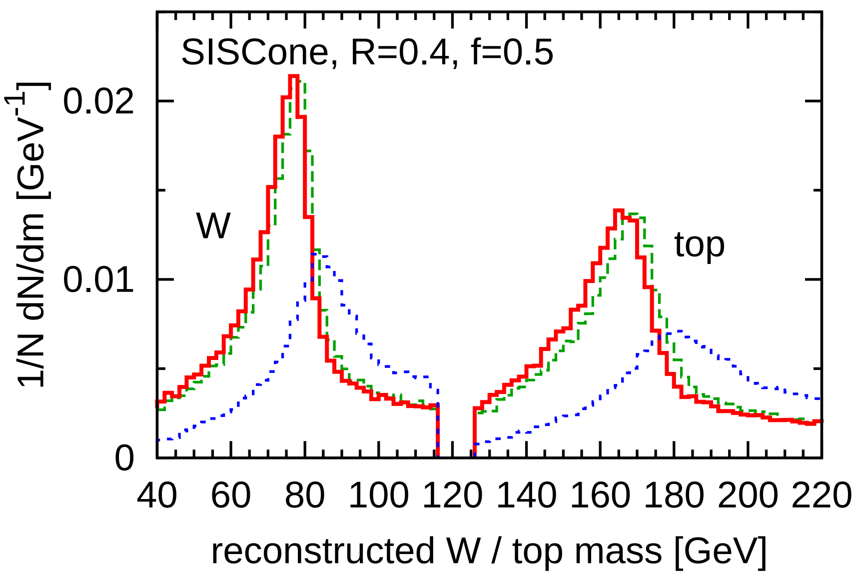

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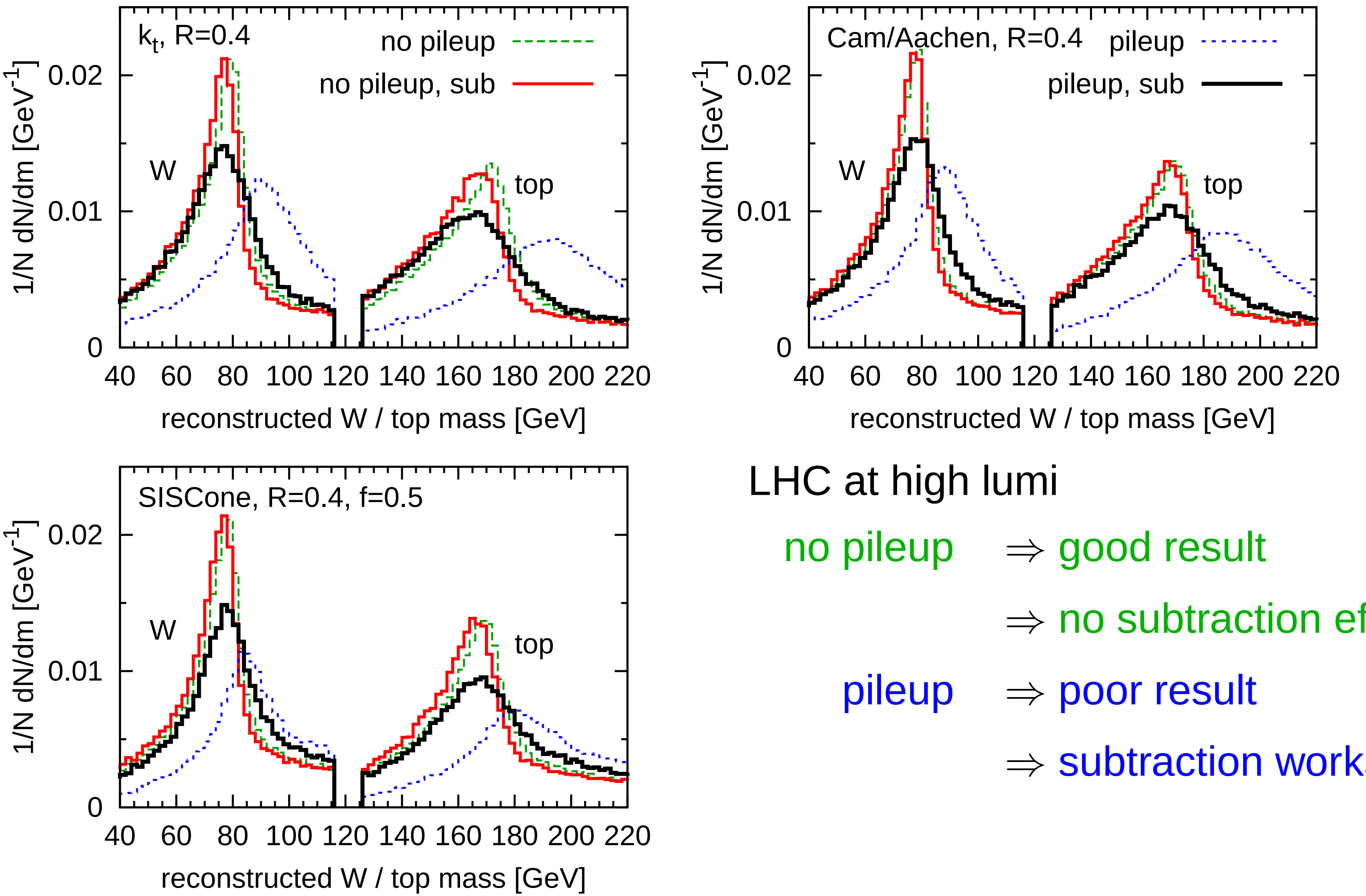

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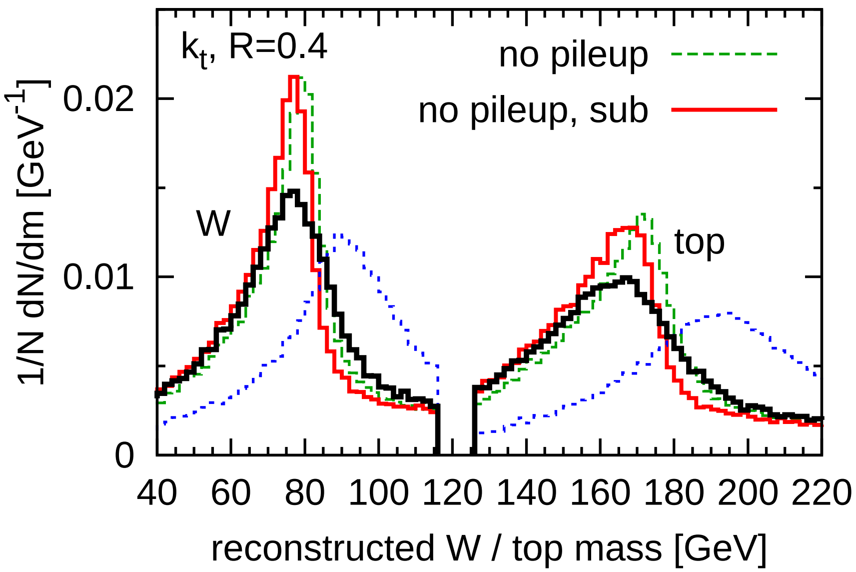

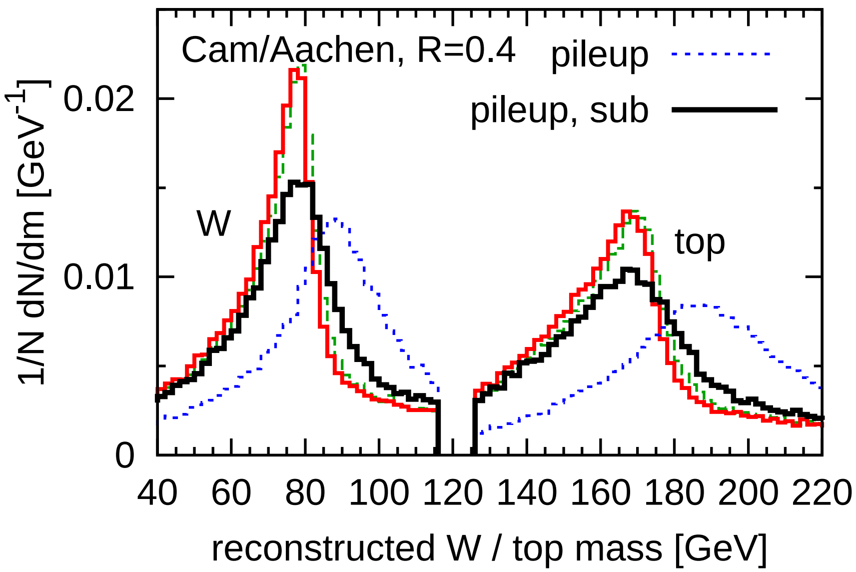

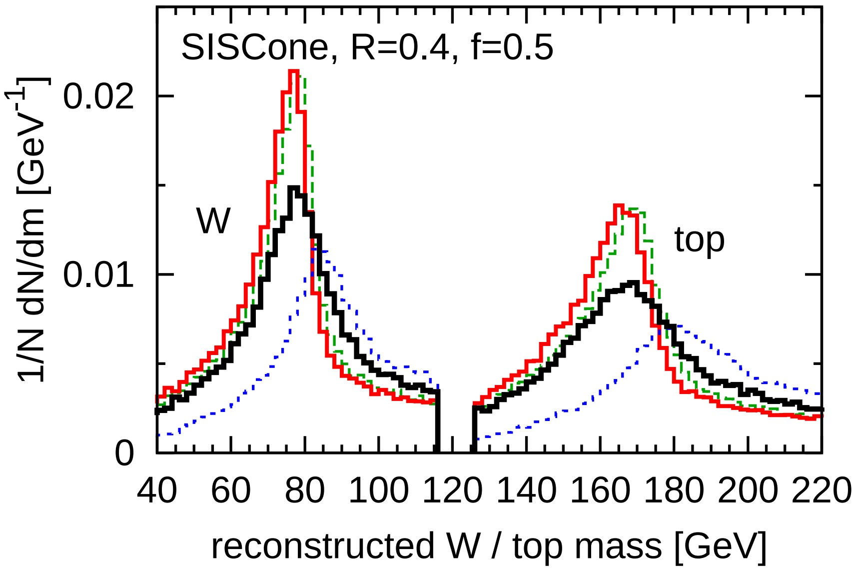

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Background suppresion in heavy ions!

Conclusions

- SISCone: a new cone jet algorithm
  - first to satisfy requirements of the 90's!
  - mandatory for LHC
  - Get it at http://projects.hepforge.org/siscone or http://www.lpthe.jussieu.fr/~salam/fastjet

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- TODO:
  - anomalous dimension resummation
  - only the beginning...