New Horizons in Jet Substructure and Boosted Physics
@LHC

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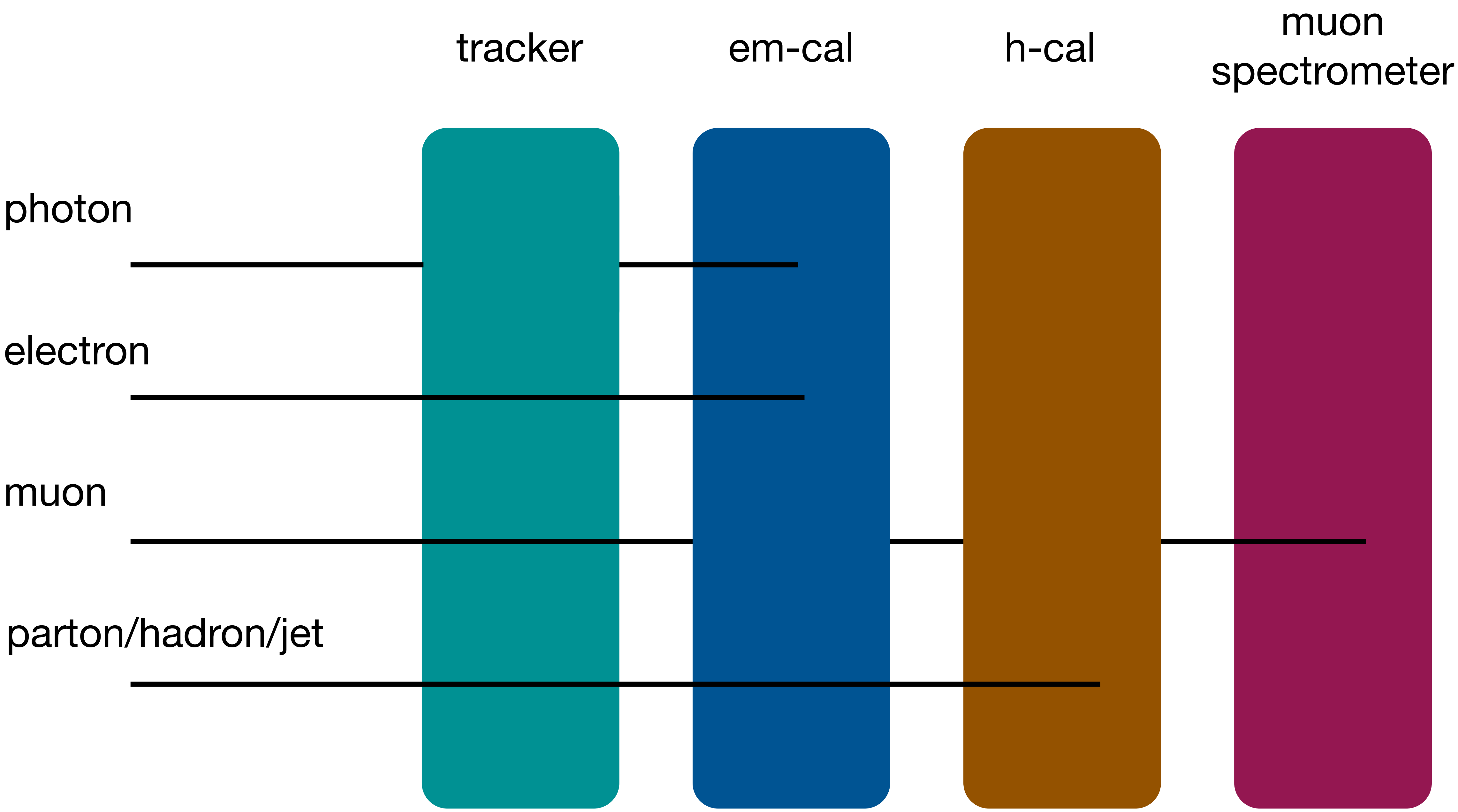
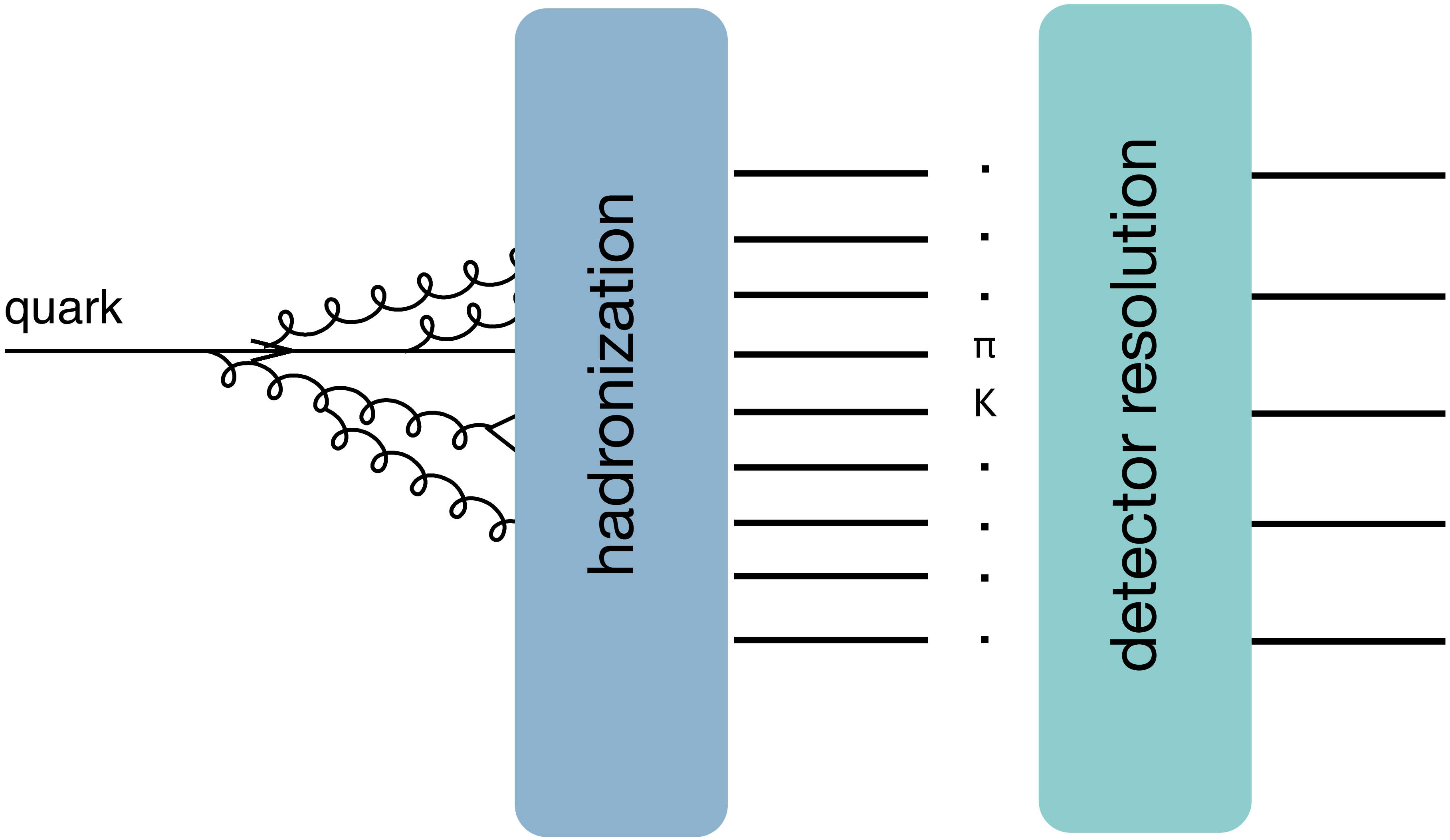
University of Washington

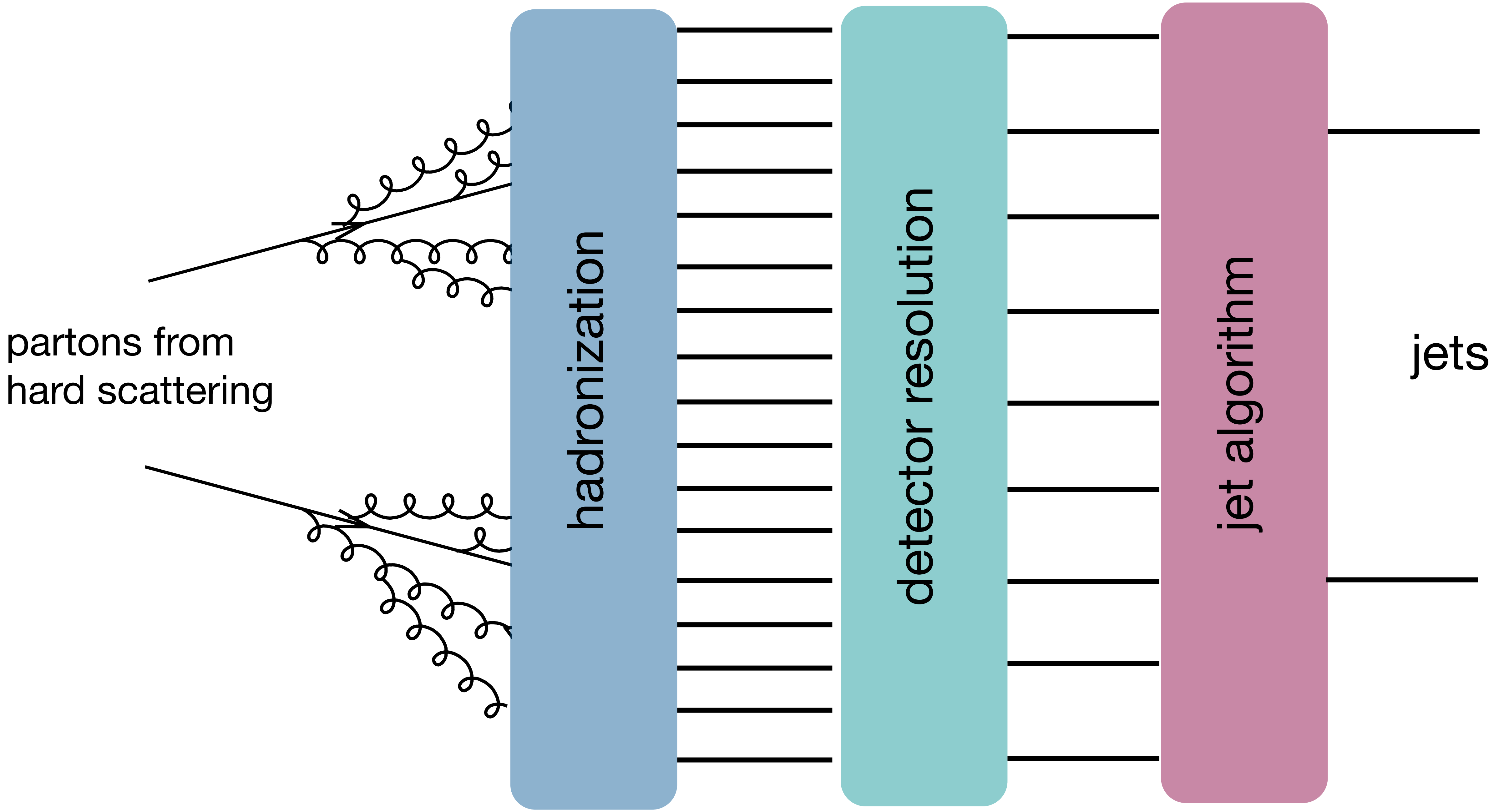
Theorist's view of a detector



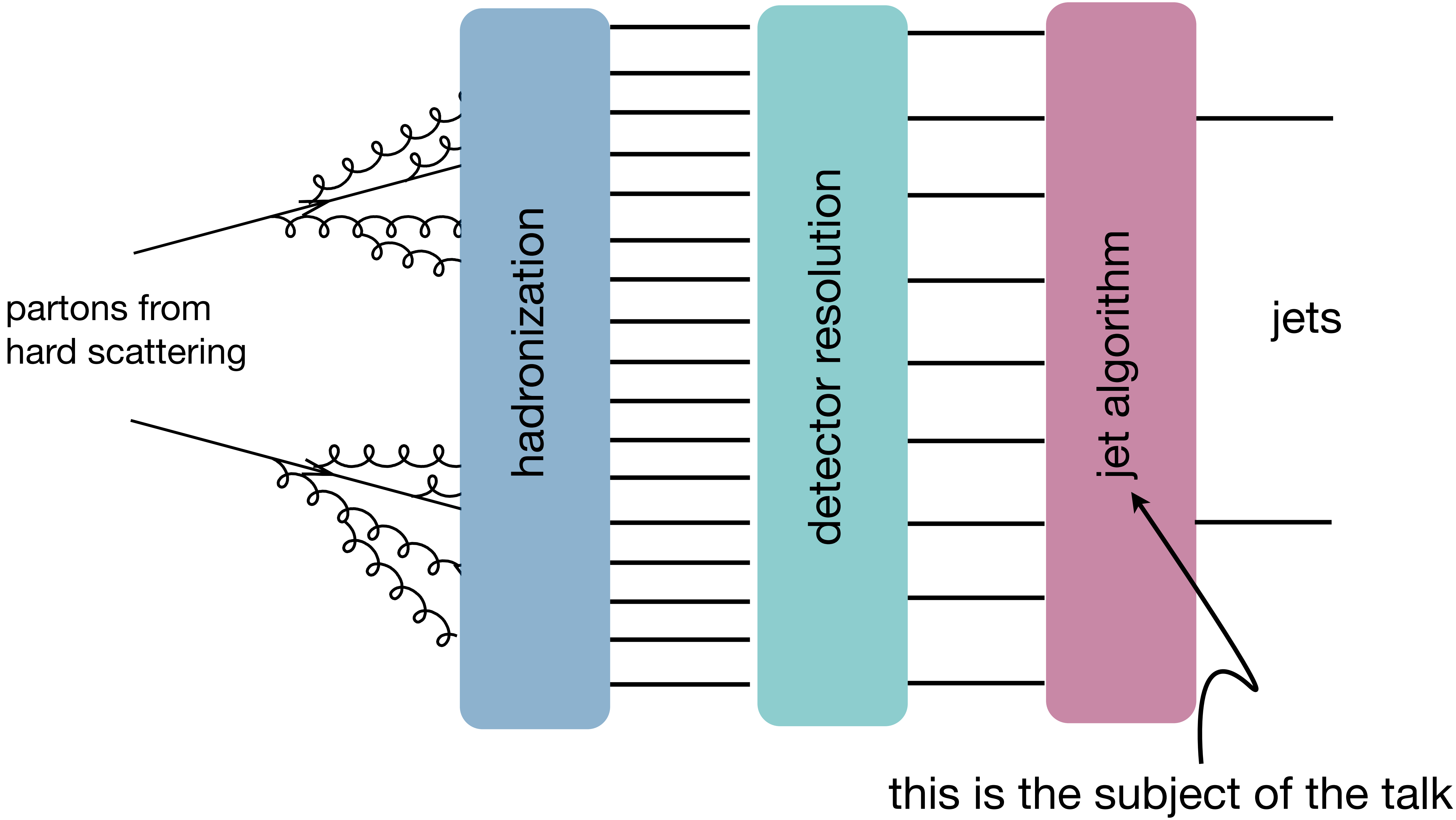
Heuristic understanding of parton/jet



Heuristic understanding of parton/jet



Heuristic understanding of parton/jet



Outline

Jet Clustering Algorithm

- Standard Use of Jets

Boosted Jets and Substructure Analysis

- Applications in Higgs Search

QClustering: a non-deterministic jet clustering algorithm

- Clustering vs. QClustering
  - Applications in noise removal

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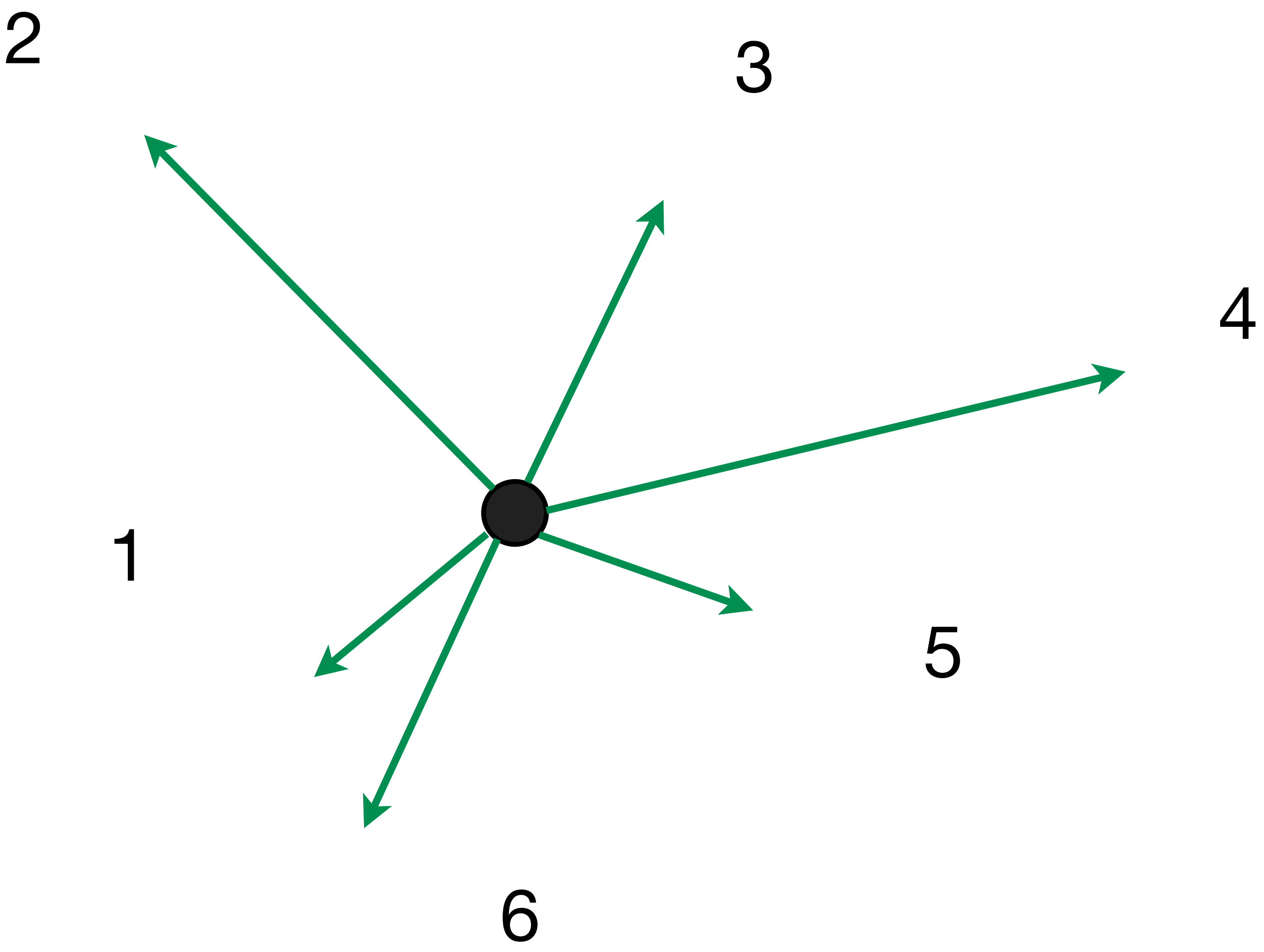
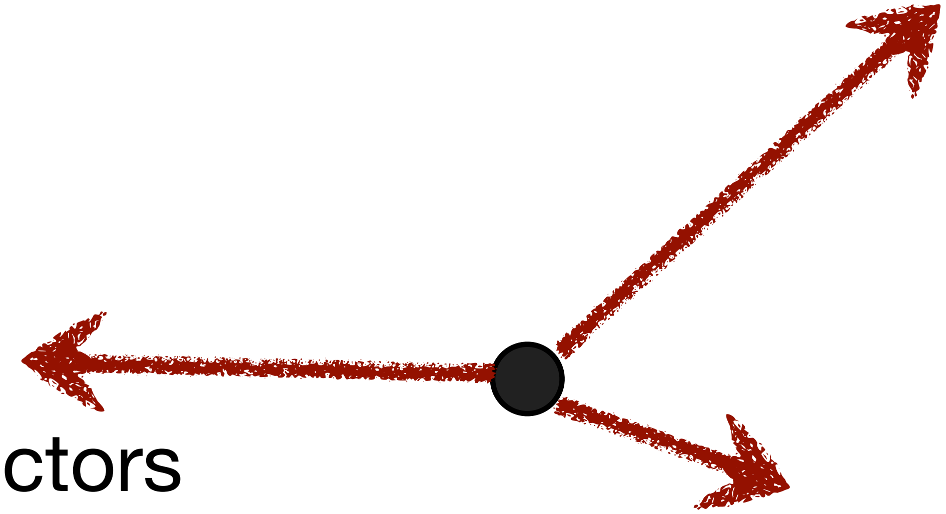
Jet Clustering Algorithm



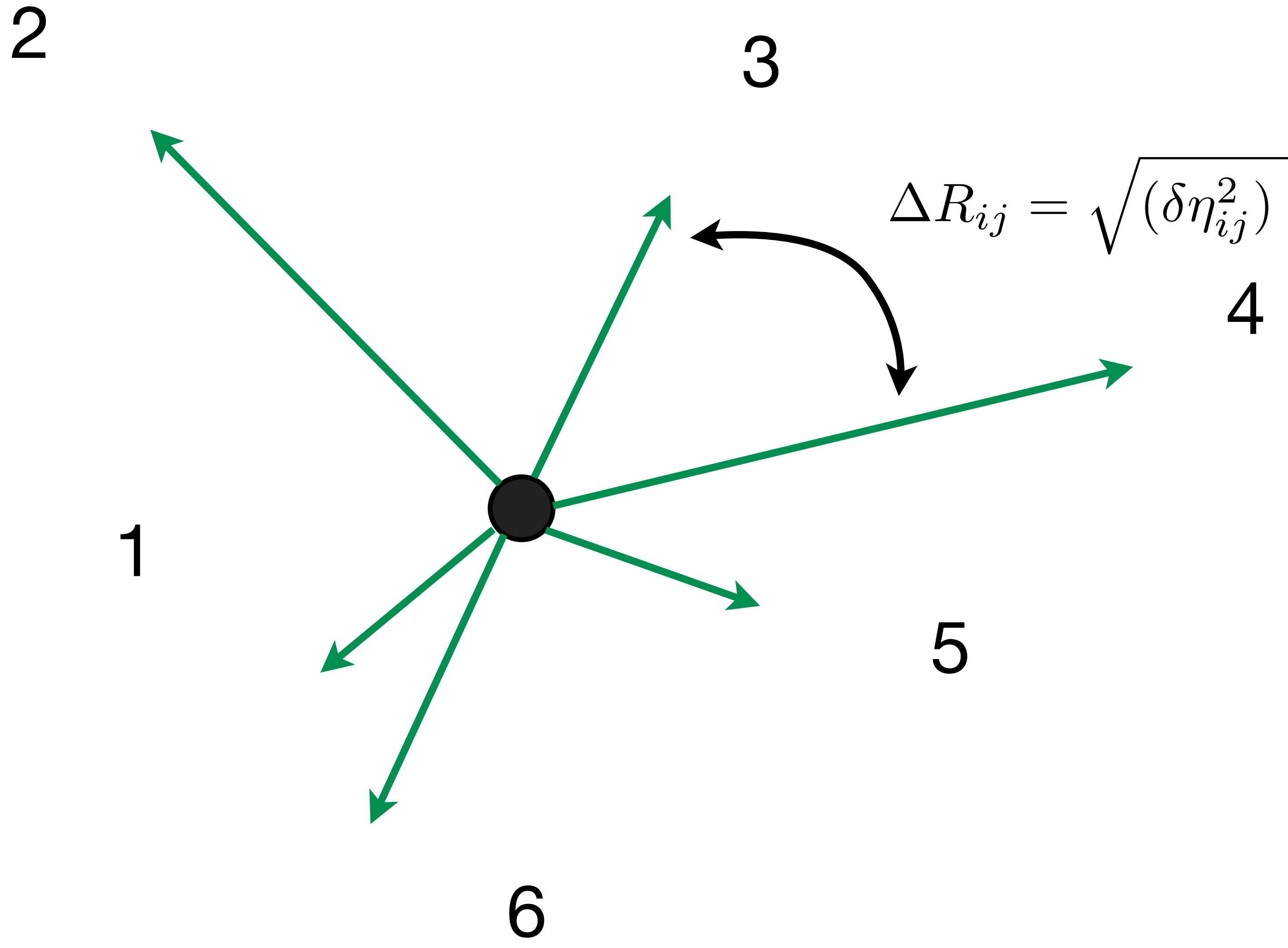
four-vectors representing calorimeter cells

jet clustering algorithm

four-vectors representing jets



Jet Clustering Algorithm



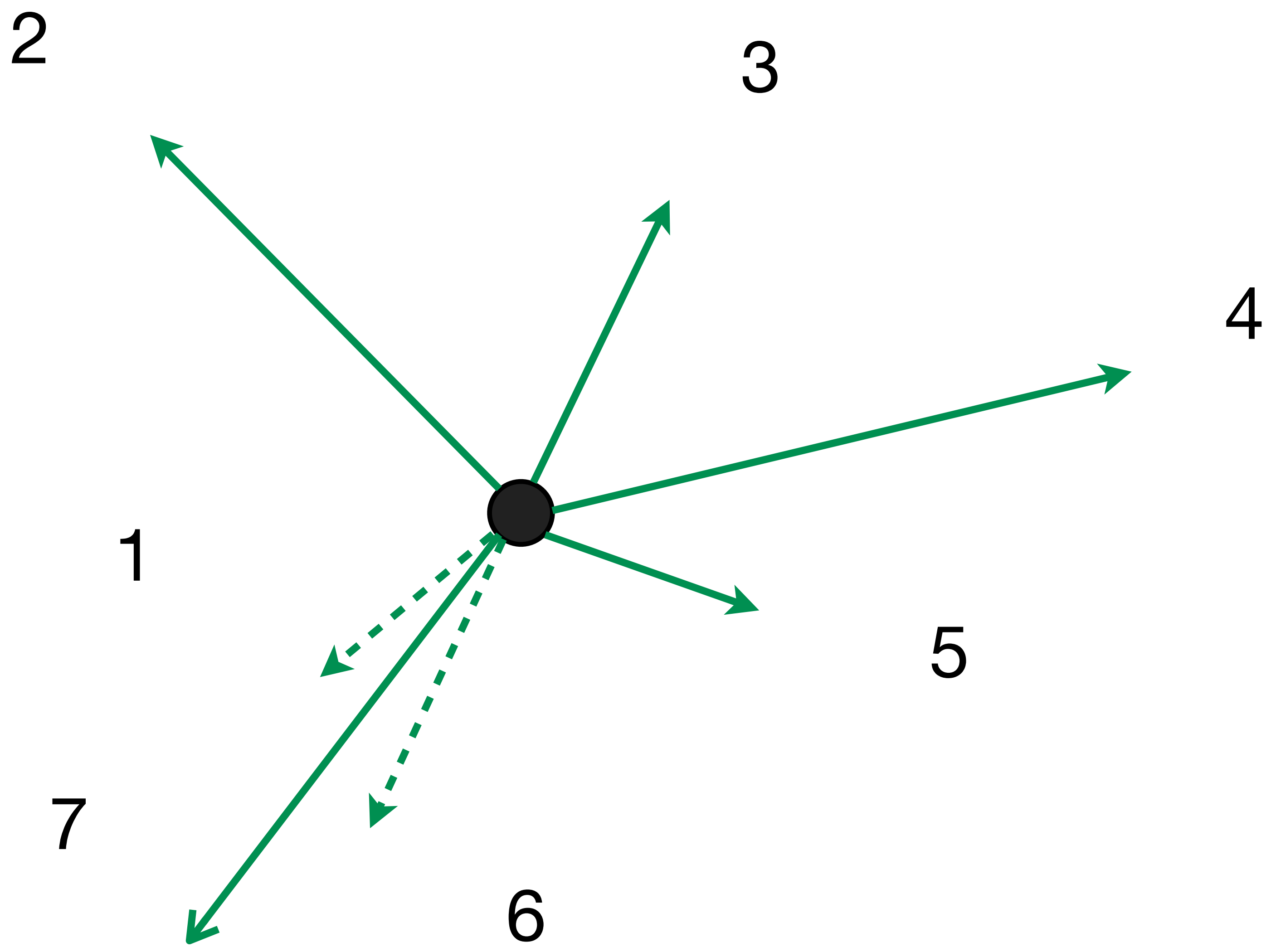
$$\Delta R_{ij} = \sqrt{(\delta\eta_{ij}^2) + (\delta\phi_{ij})^2}$$

calculate

$$d_{ij} = \min\left(p_{ti}^{2n},\ p_{tj}^{2n}\right)\Delta R_{ij}^2/R^2$$

$$d_i = p_{ti}^{2n}$$

Jet Clustering Algorithm

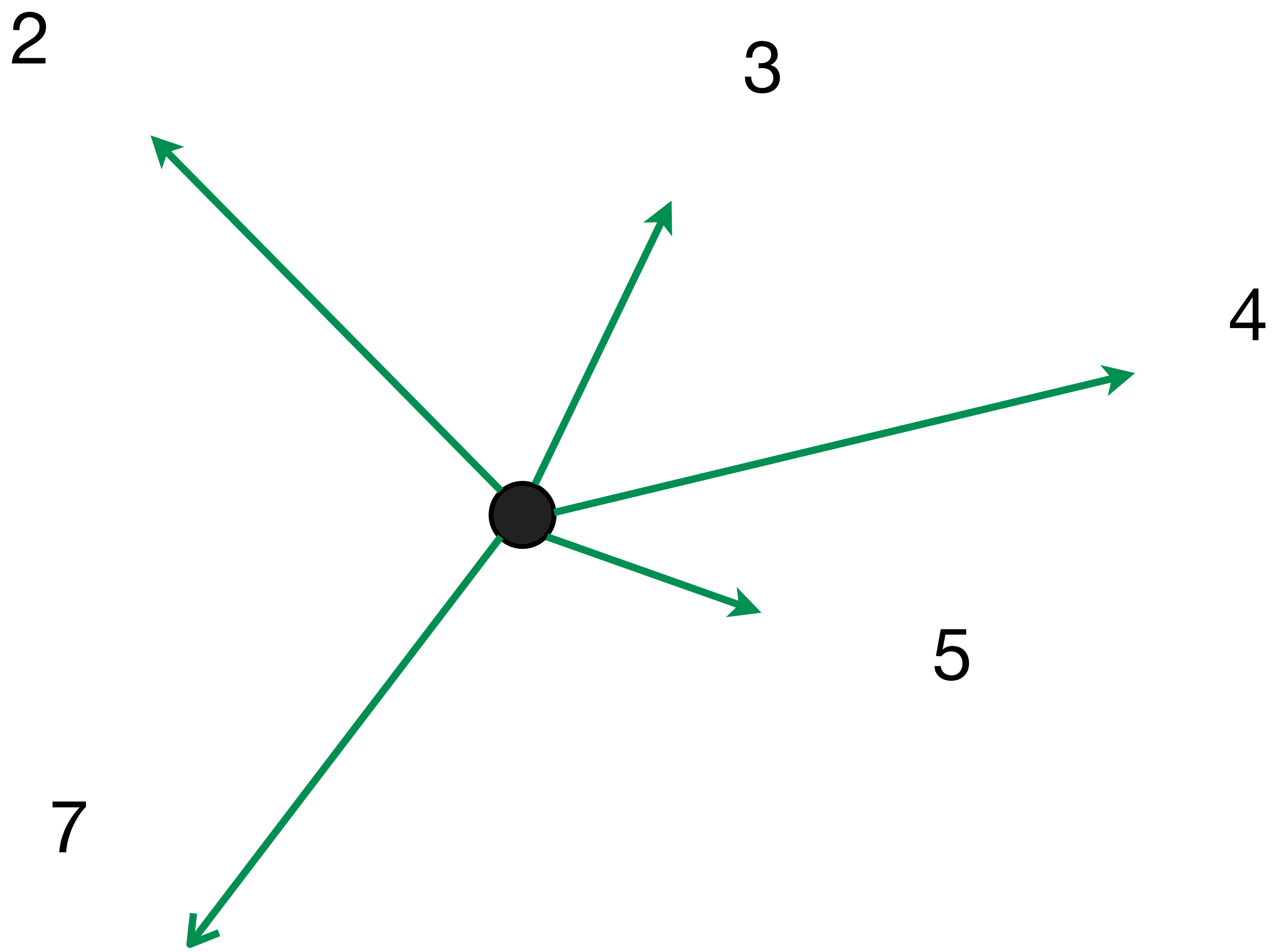


example:

$$\min\left(d_{ij}, d_i\right) \;=\; d_{1\ 6}$$

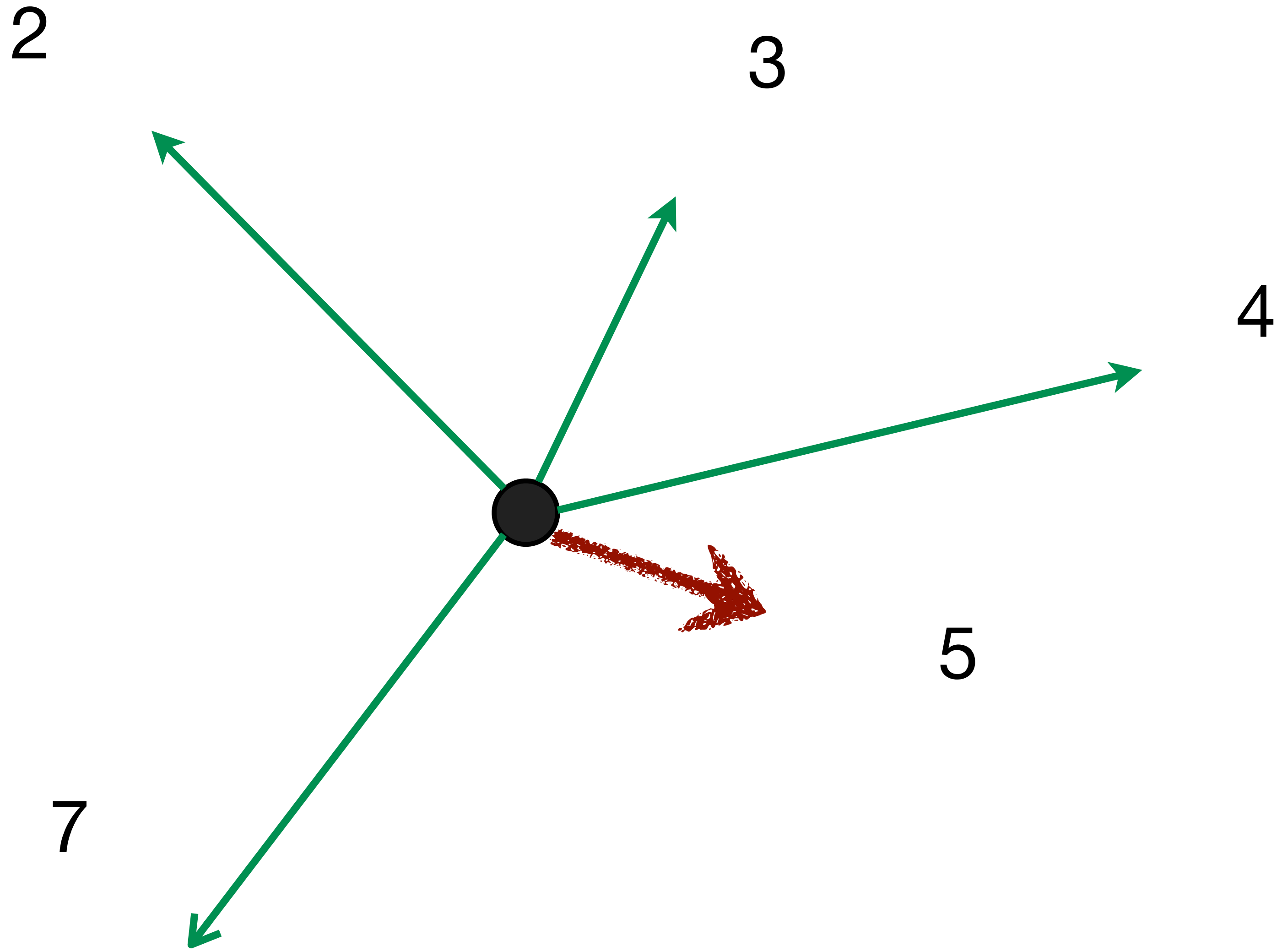
combine 1 and 6 into 7
and remove 1 and 6

Jet Clustering Algorithm



calculate again $\min\left(d_{ij}, d_i\right)$

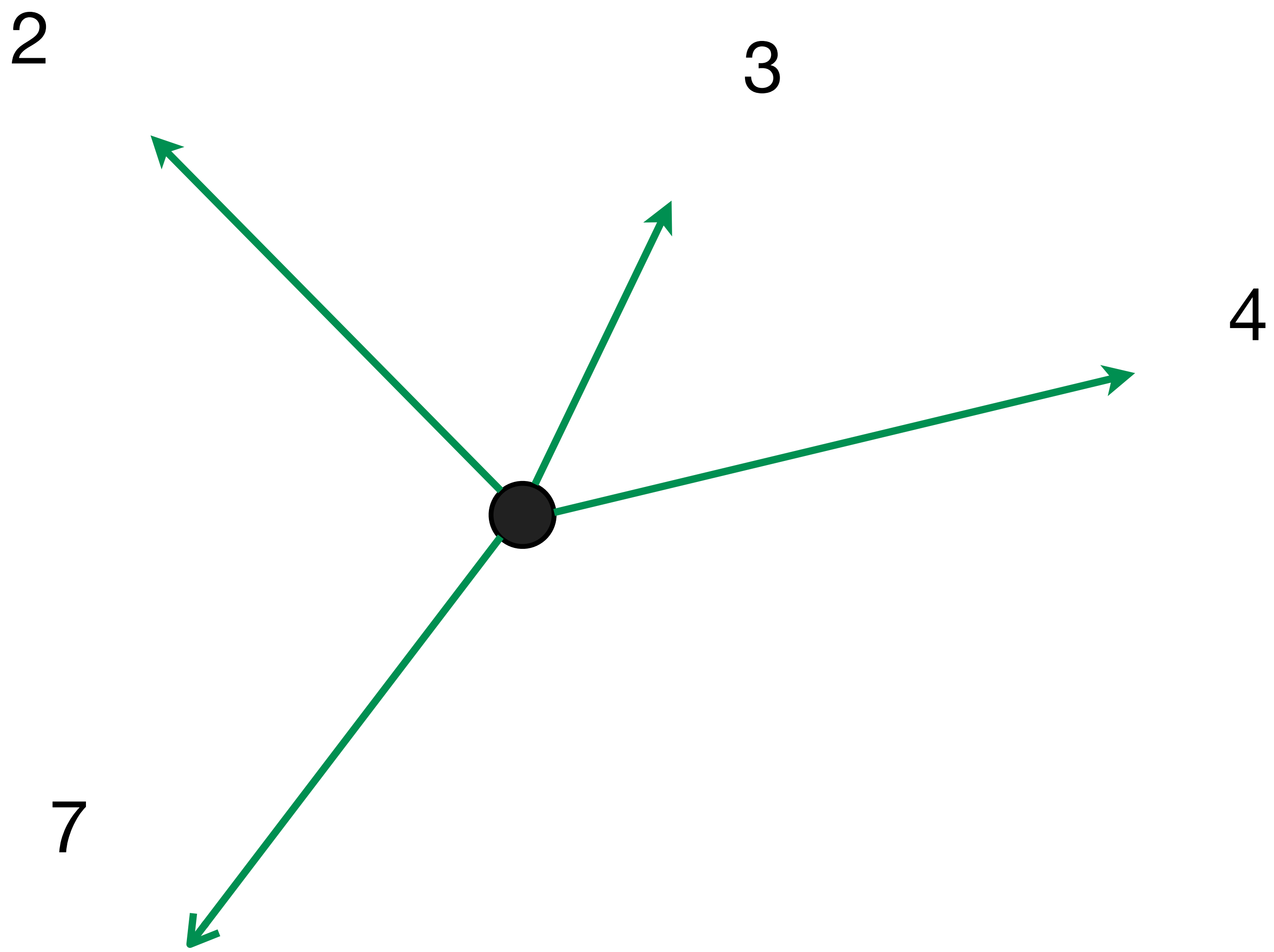
Jet Clustering Algorithm



$$\min\left(d_{ij}, d_i\right) \;=\; d_5$$

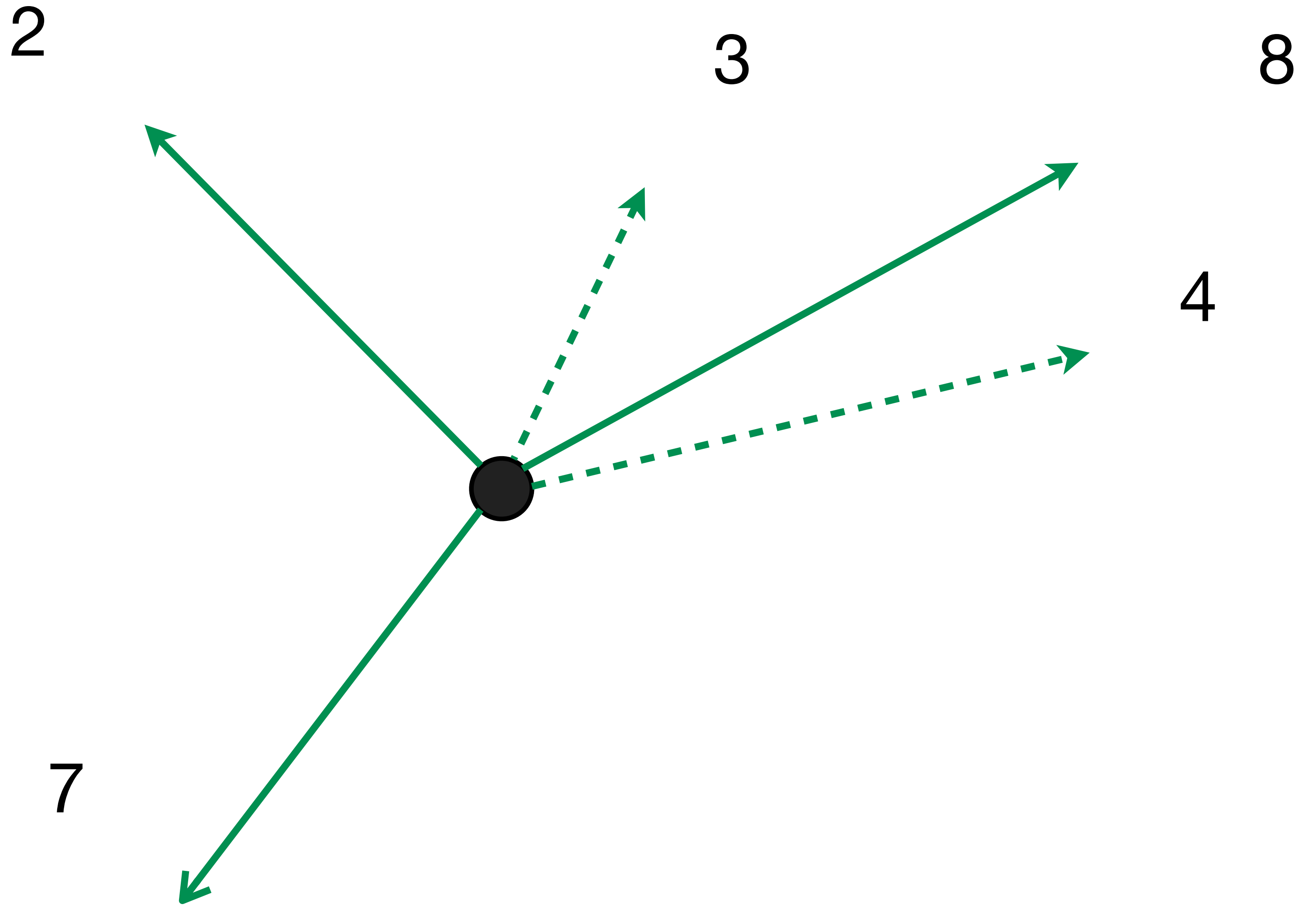
promote 5 to jet and remove

Jet Clustering Algorithm



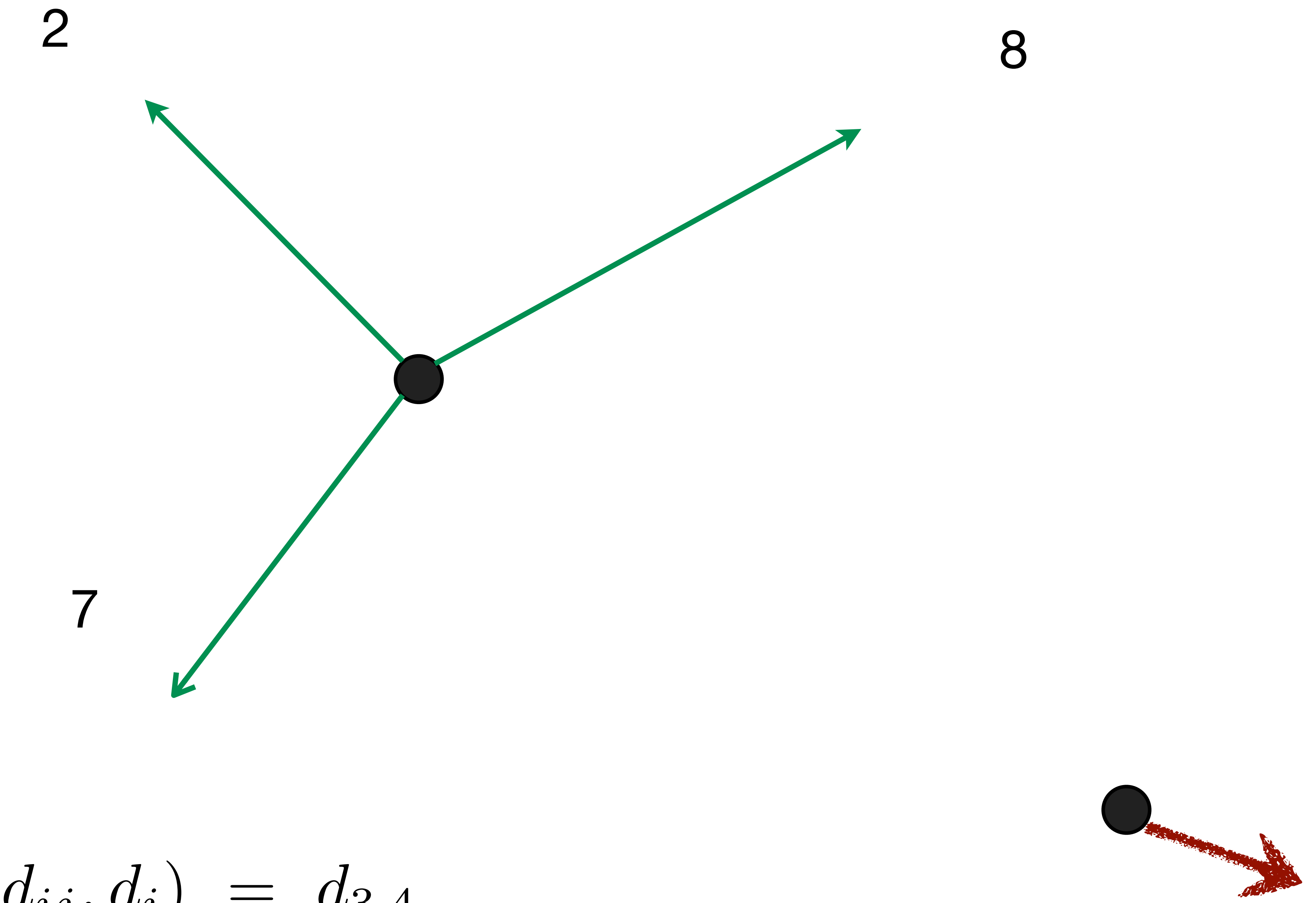
calculate again all
d_{ij} and d_i

Jet Clustering Algorithm



$$\min\left(d_{ij}, d_i\right) \;=\; d_{3\;4}$$

Jet Clustering Algorithm



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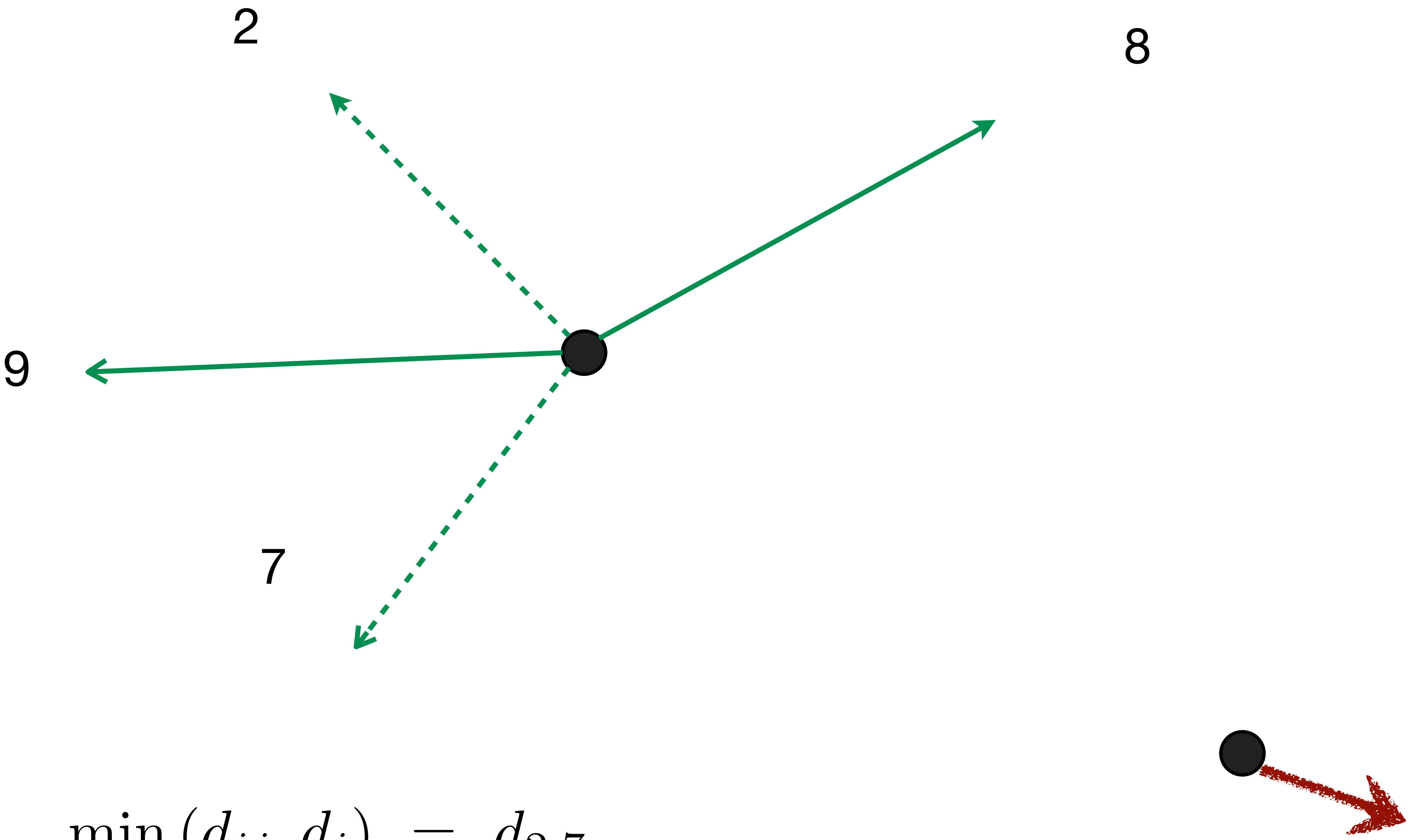
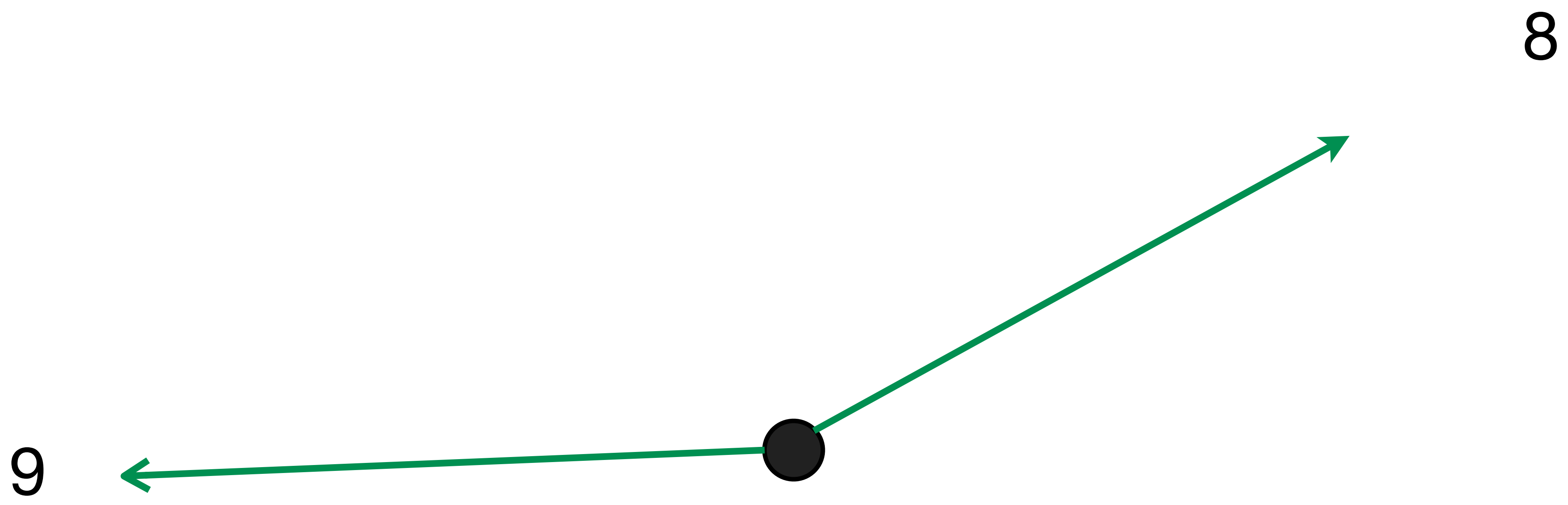


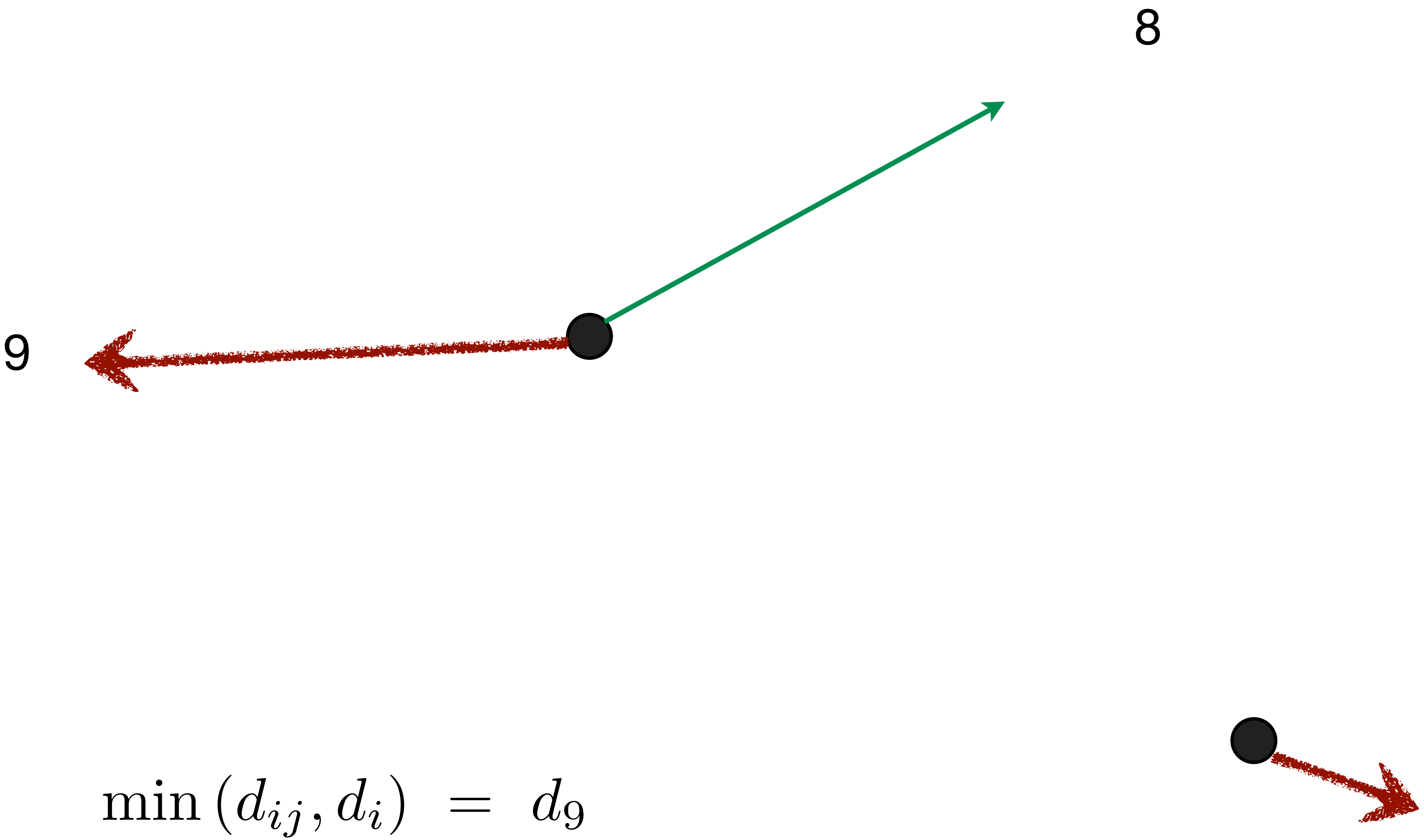
$$\min\left(d_{ij}, d_i\right) \;=\; d_{2\,7}$$

Jet Clustering Algorithm



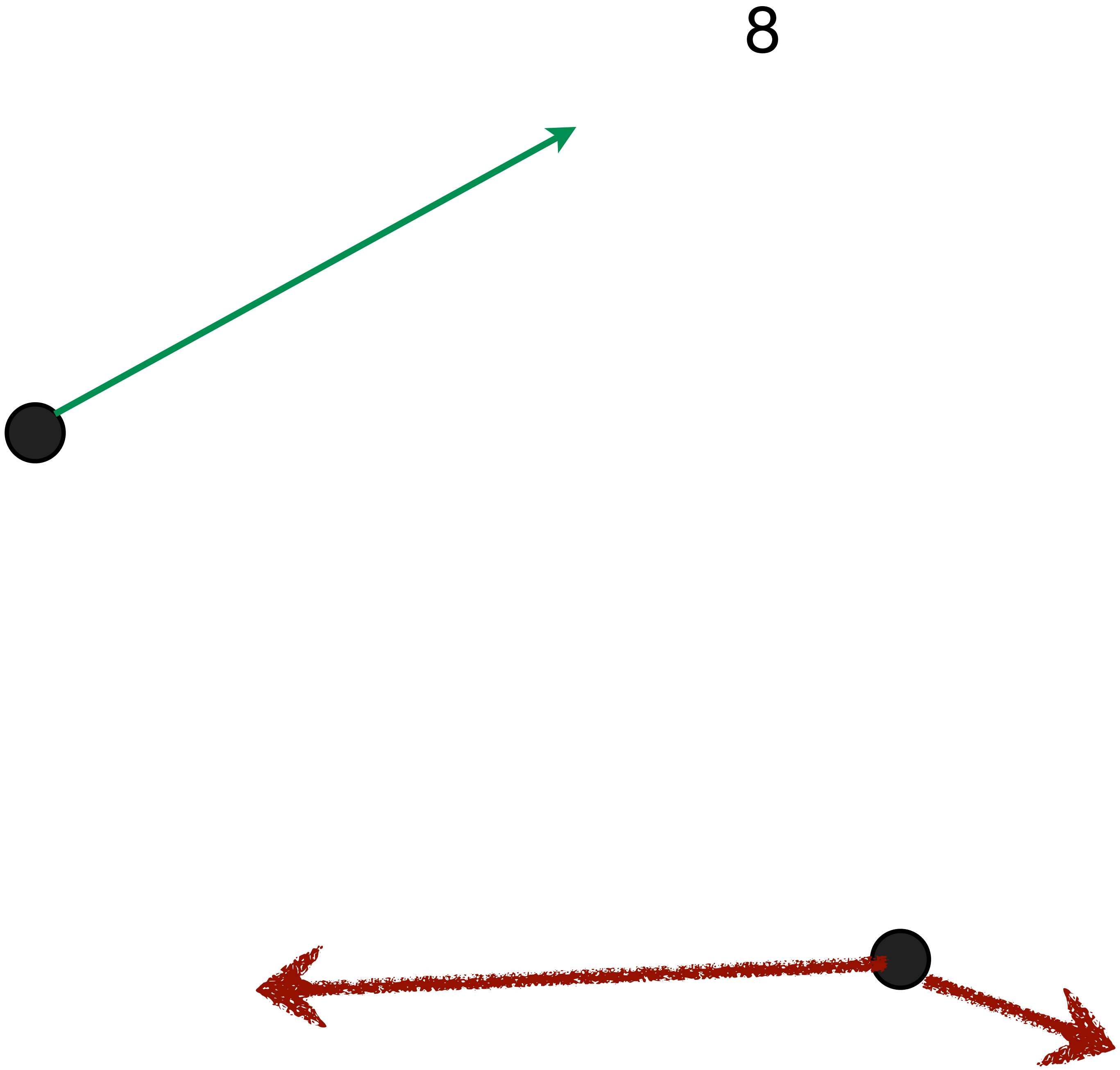
$$\min\left(d_{ij}, d_i\right) \ = \ d_{2\ 7}$$

Jet Clustering Algorithm

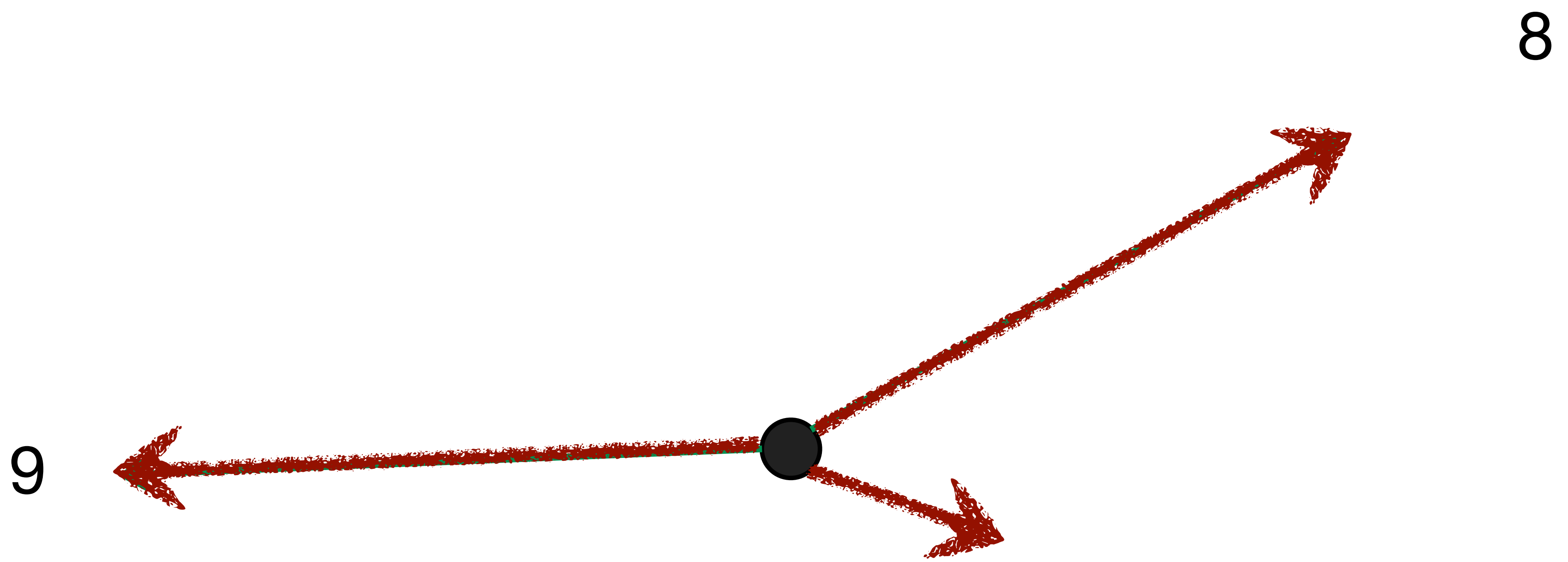


$$\min\left(d_{ij}, d_i\right) \;=\; d_9$$

Jet Clustering Algorithm

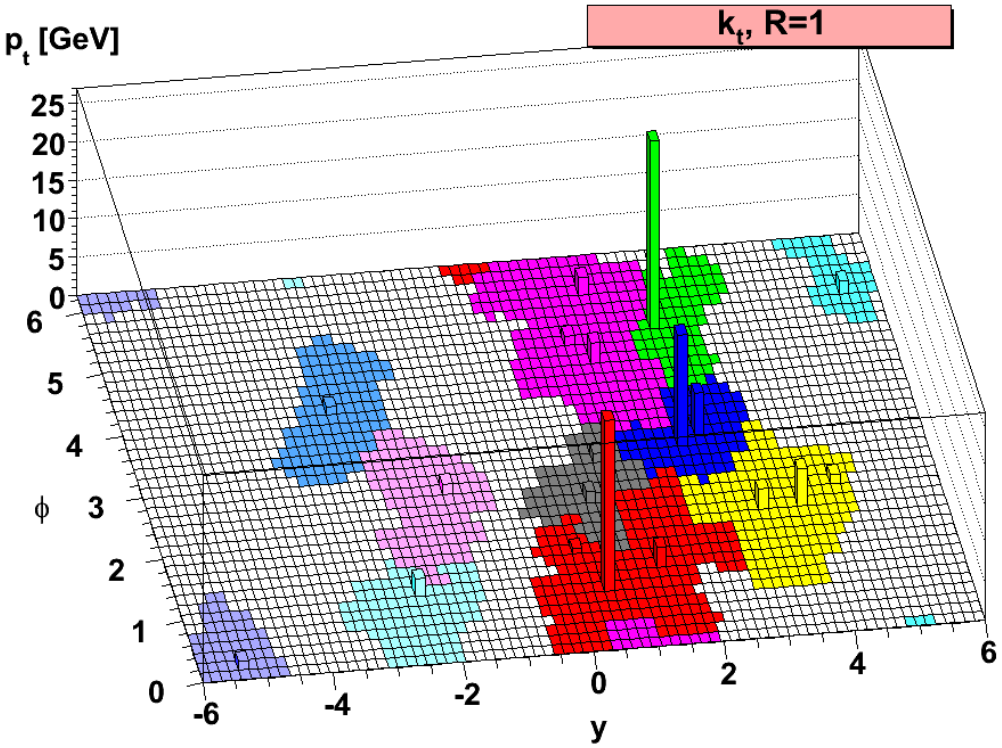


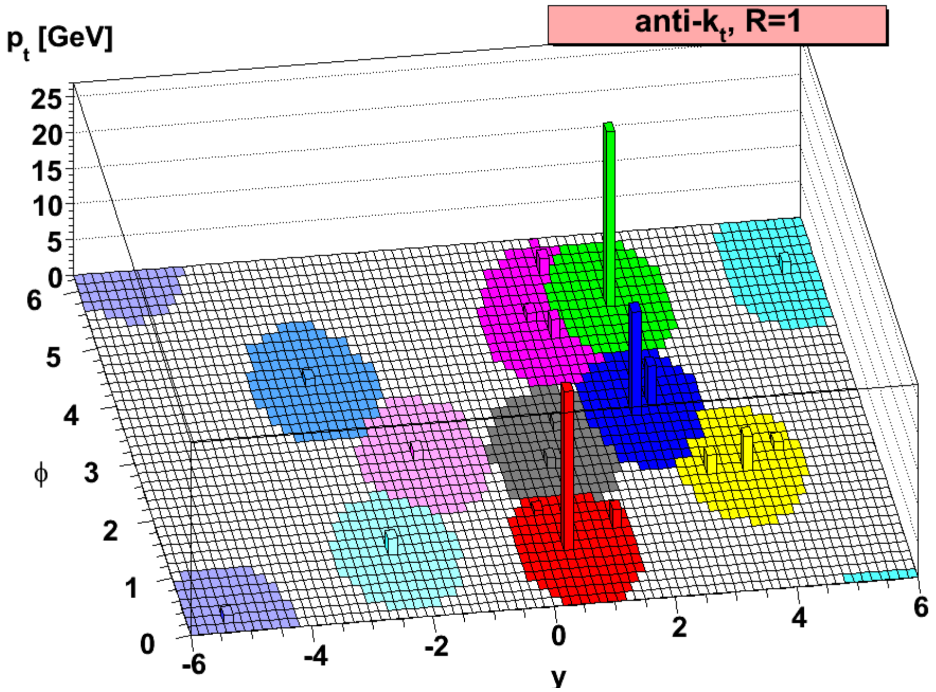
Jet Clustering Algorithm



final list of jets

Jet Clustering Algorithm

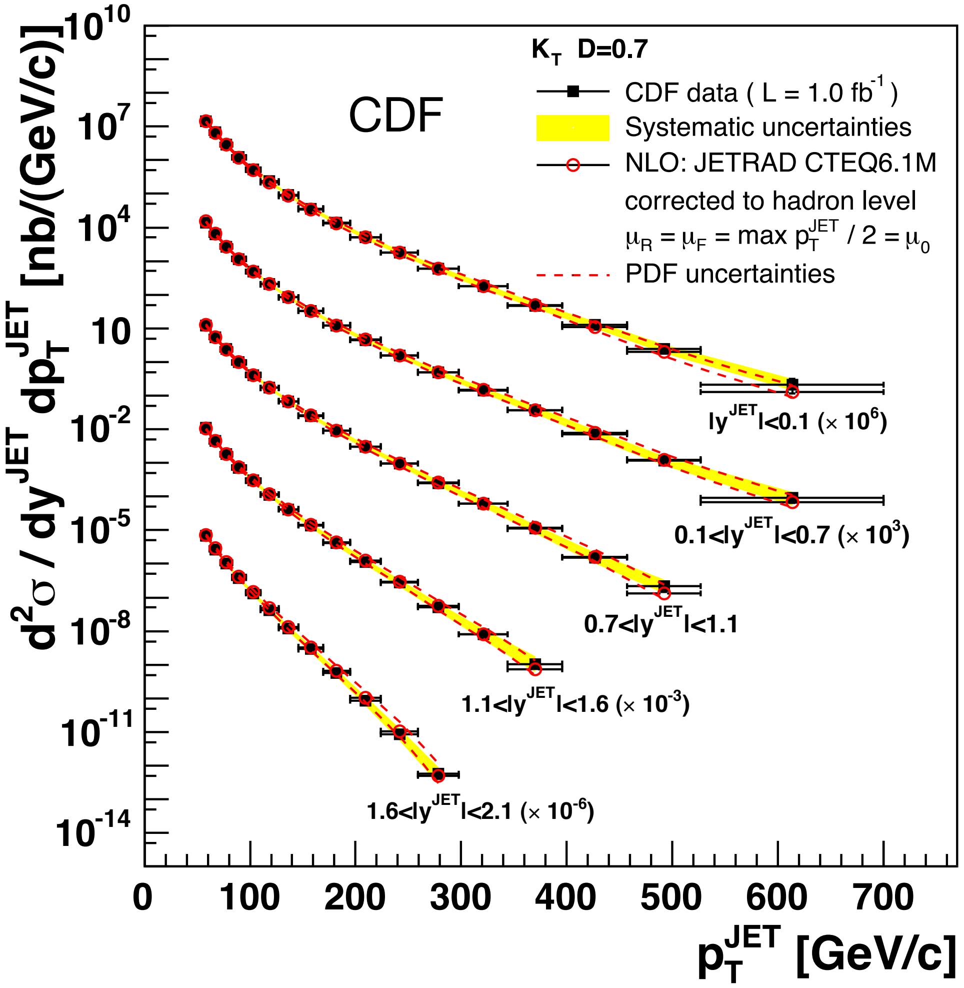


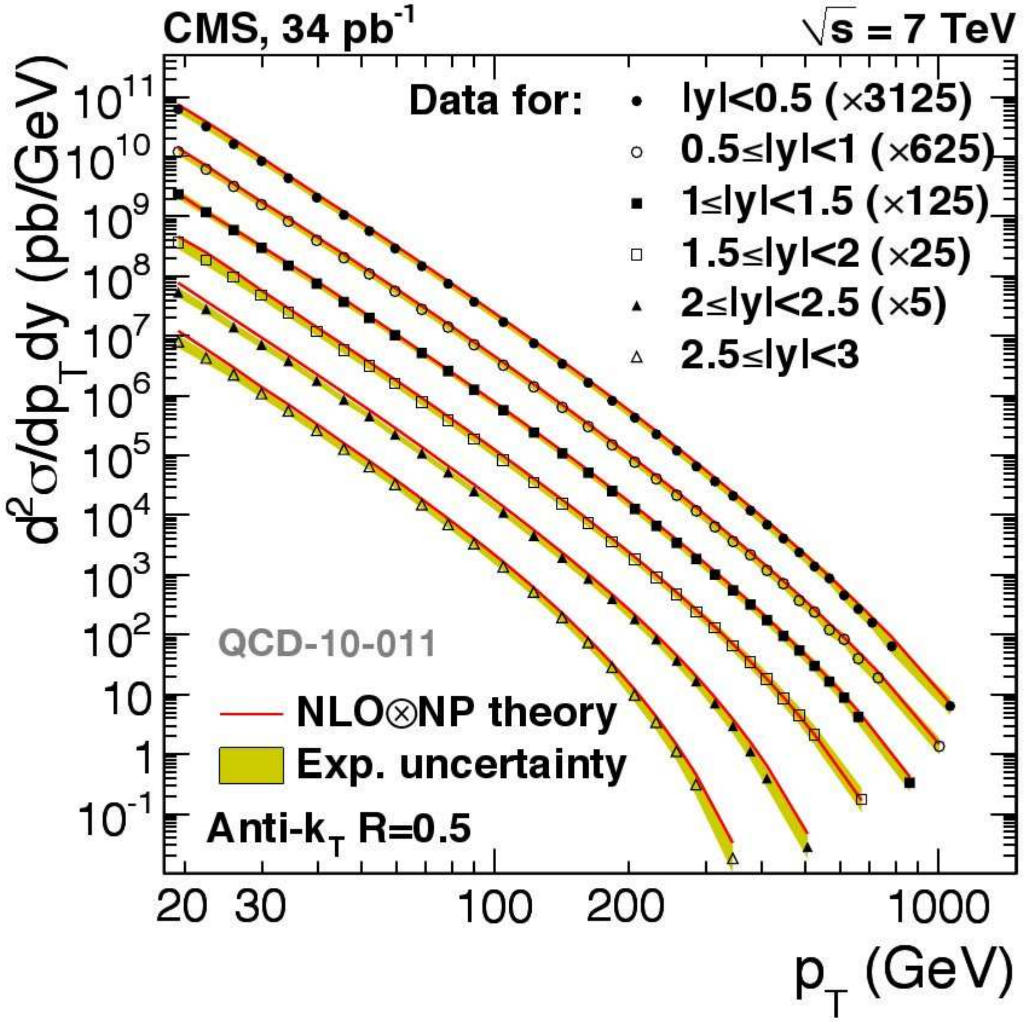


visualization of
jets and its
elements

Jet Clustering Algorithm

Jets are well understood and theoretically well controlled



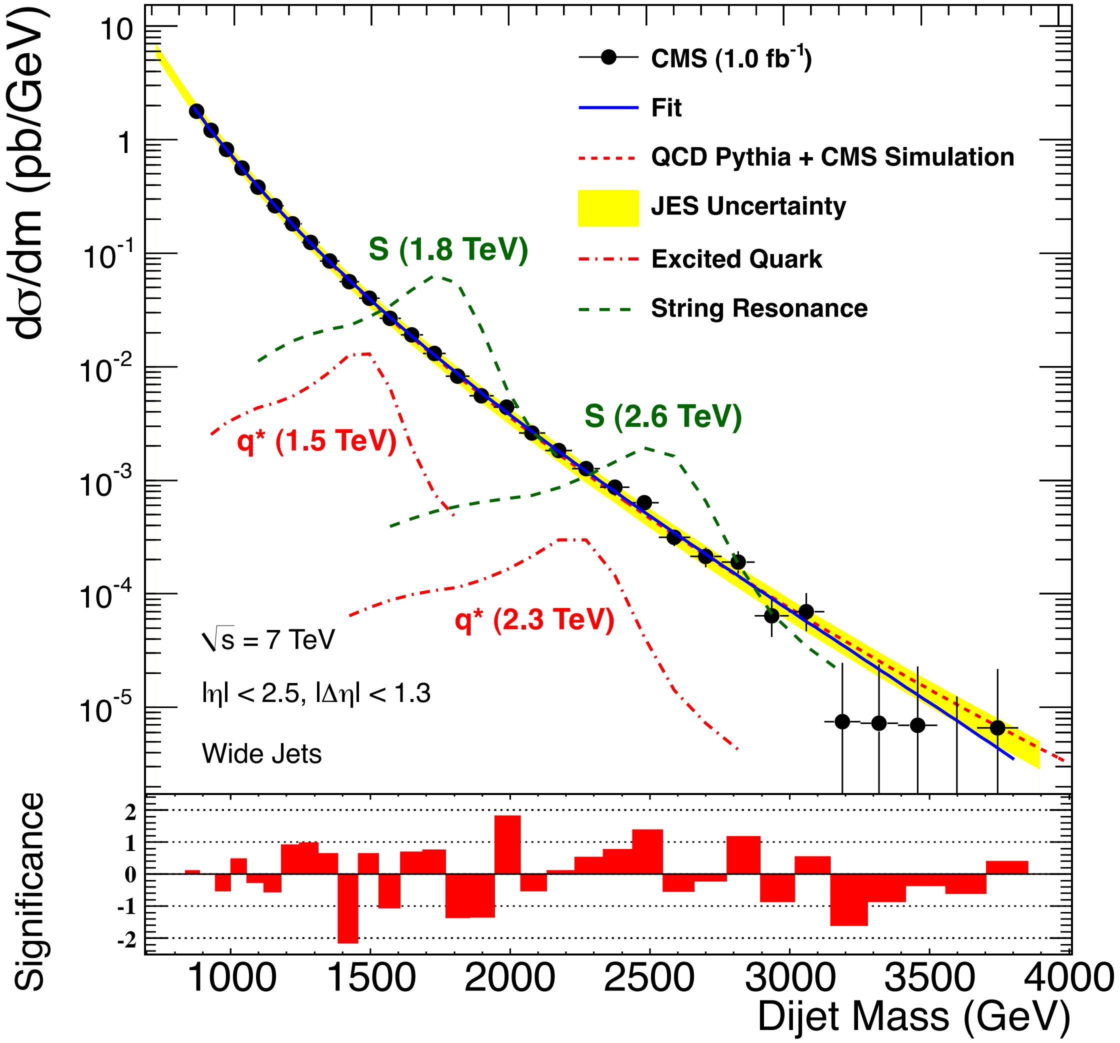


Data and theory agree with many orders of magnitude

Jet Clustering Algorithm

Data and theory agree with many orders of magnitude

Such theoretical control on jet-observables allows us to probe the highest scales available



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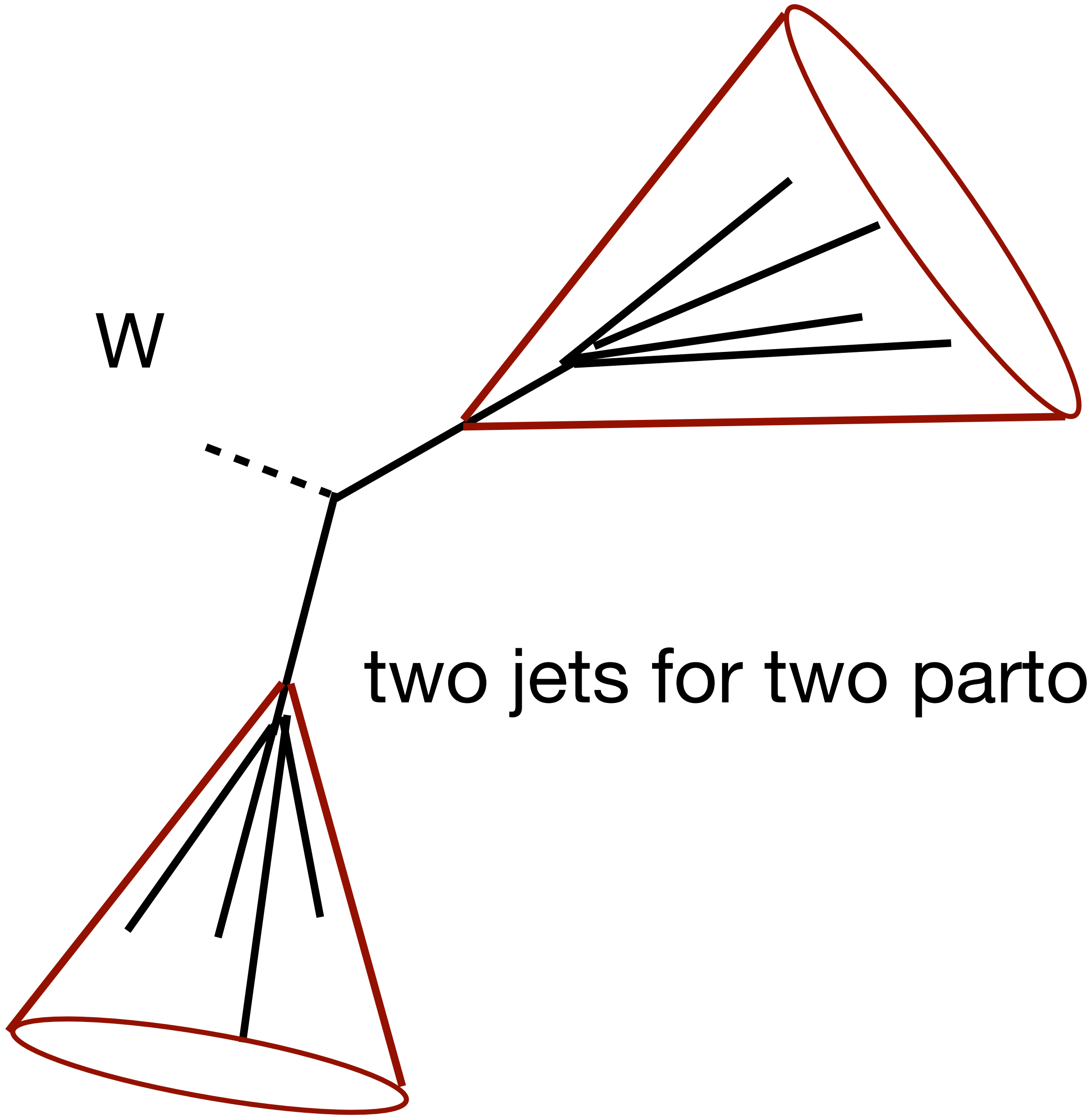
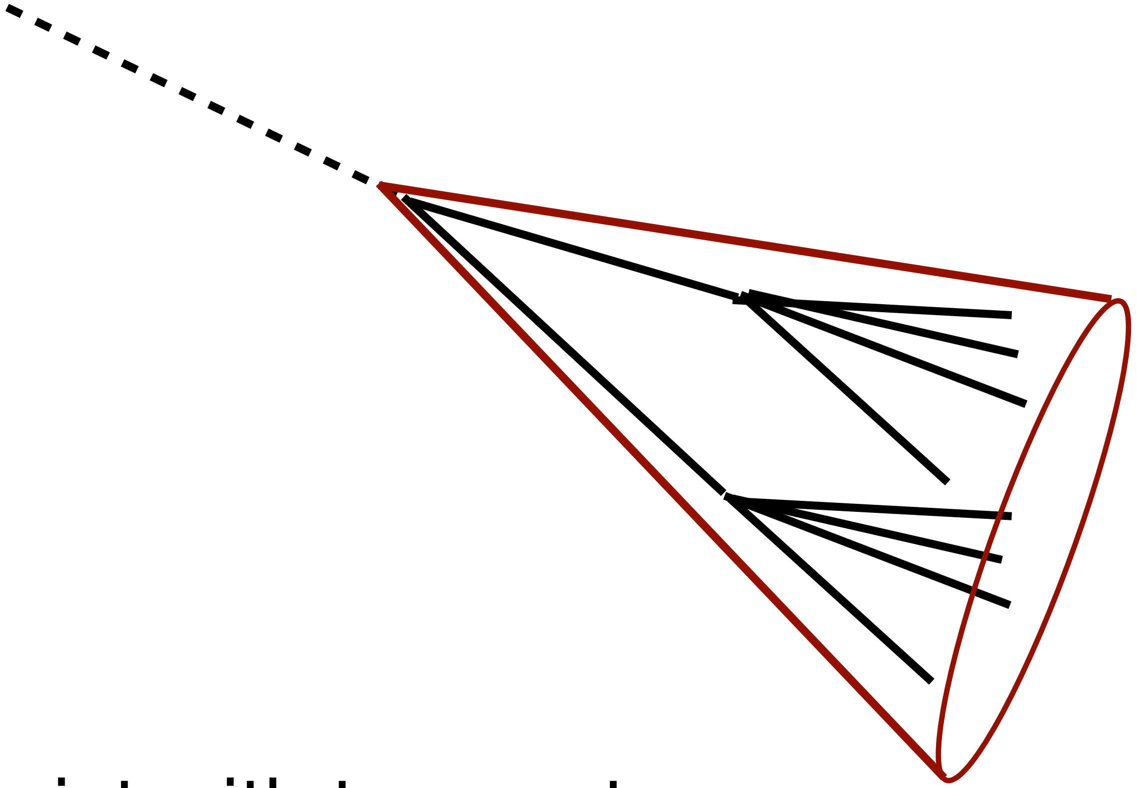
Boosted Jets and Substructure

take a hadronically decaying W



two jets for two partons

W with a large p_T



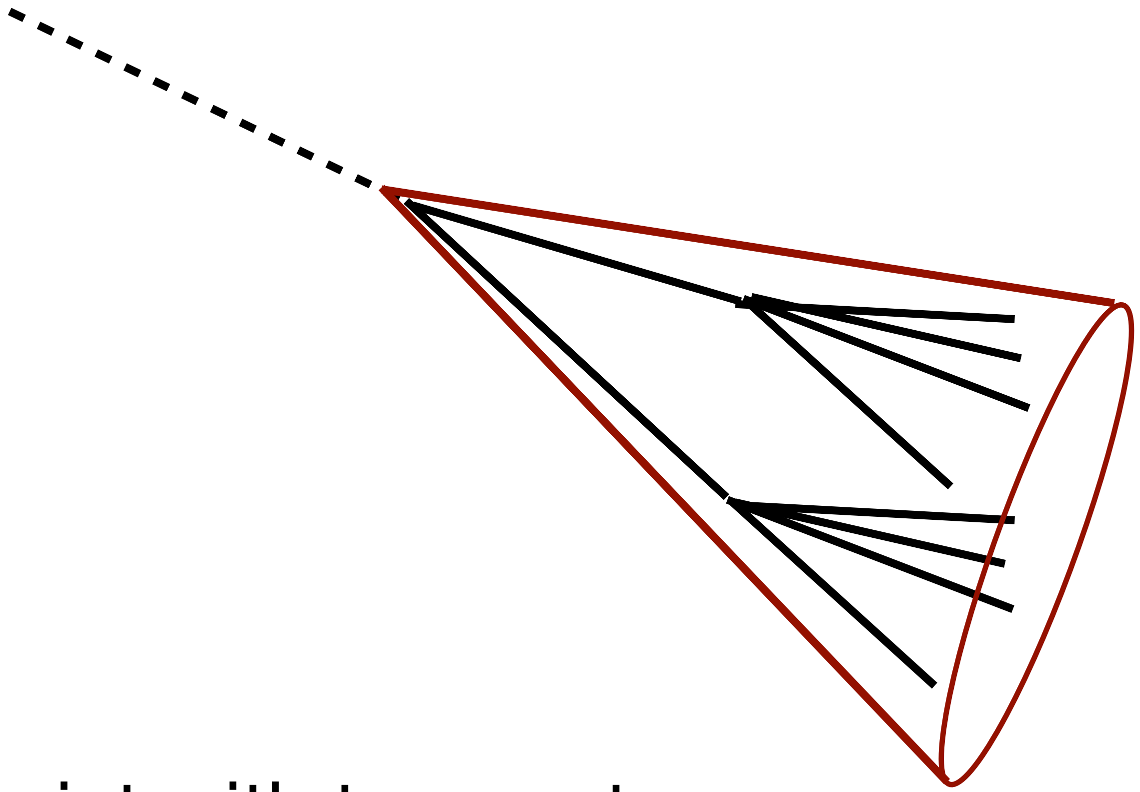
a jet with two partons

Boosted Jets and Substructure

take a hadronically decaying W

Jet substructure

- Use the characteristic kinematics of 1->2 splitting to reject background.
- Use different energy flows to reject background.
- Protect jet-mass resolution from pollutions due to underlying events and pile-up.



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a jet with two partons

Boosted Jets and Substructure

Jet substructure

- Use the characteristic kinematics of 1->2 splitting to reject background.
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mass-drop, angle between decay products,
masses of subjets etc.

Seymore'93
Butterworth, Cox, Forshaw'02
Butterworth, Davison, Rubin, Salam'08
Thaler, Wang'08
Kaplan, Rehermann, Schwartz, Tweedie'08

Boosted Jets and Substructure

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pull, Nsubjettiness, Boosted decision tree, Jet deconstruction, Template etc.

Gallicchio, Schwatrz ’10
Kim; Thaler, Tilburg ’10
Cui, Schwartz ’10
Jankowiak, Hook, Wacker ’10
Soper, Spannowaky ’10
Almeida et al. ’11
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Boosted Jets and Substructure

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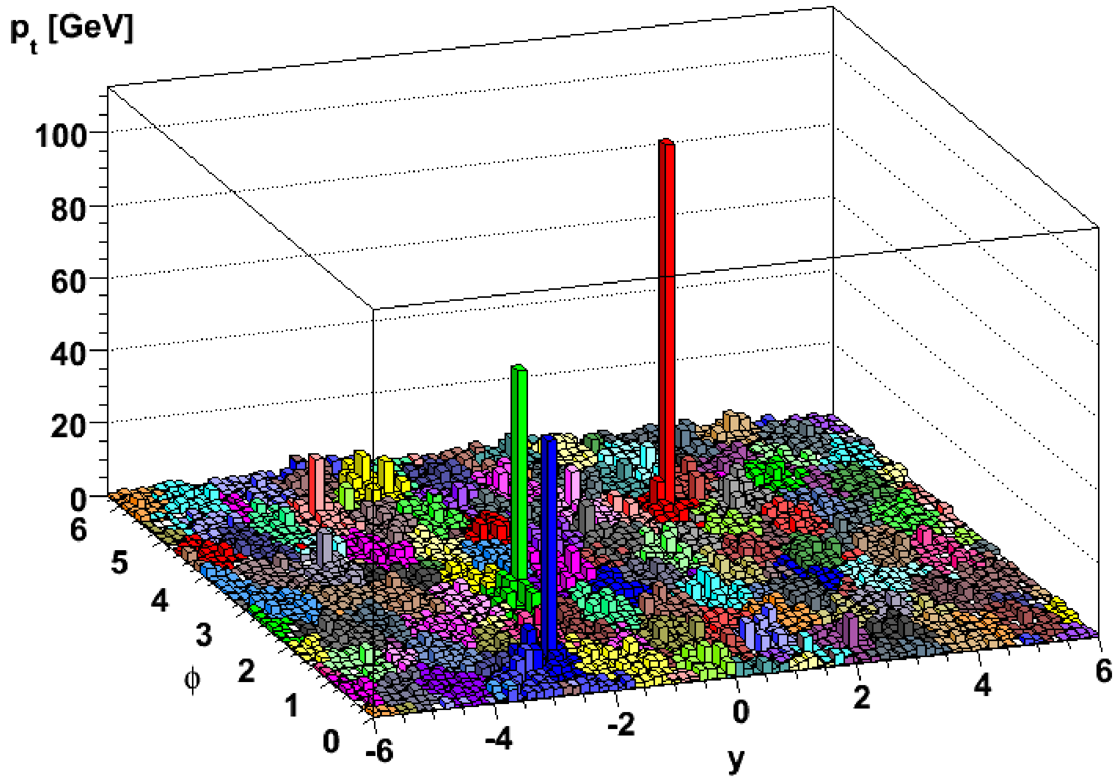


pythia event + ~10 pile-up

Boosted Jets and Substructure

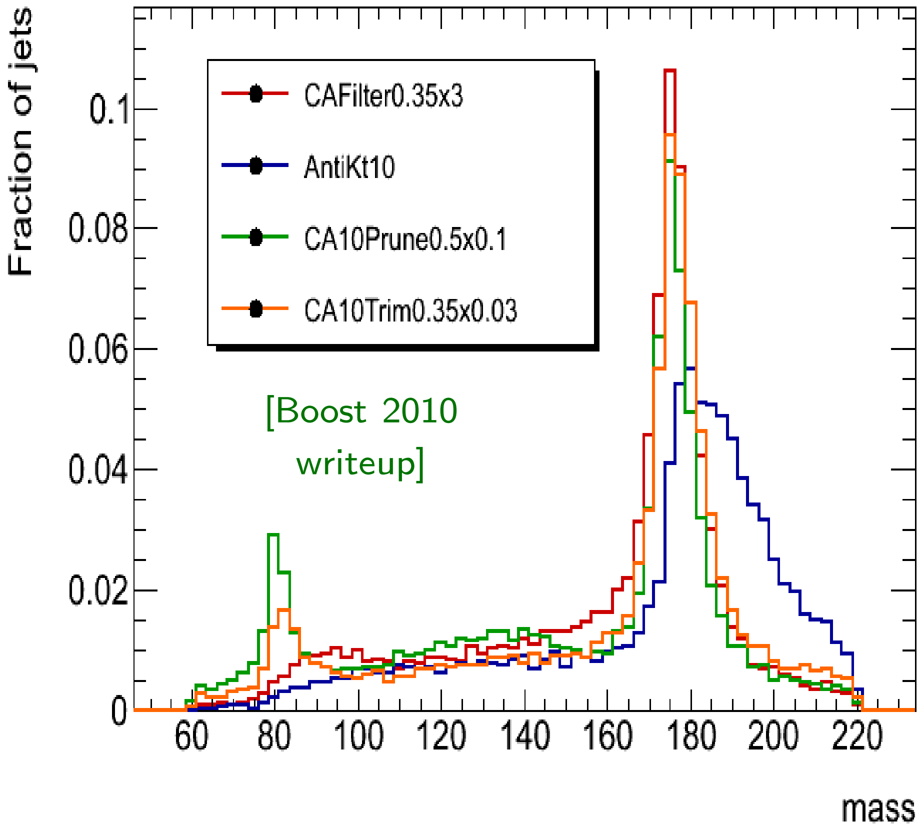
take a hadronically decaying W

- cleaning a jet involves guessing which components are not due to decay + FSR and getting rid of these

Jet substructure

- Use the characteristic kinematics of 1->2 splitting to reject background.
- Use different energy flows to reject background.
- Protect jet-mass resolution from pollutions due to underlying events and pile-up.

ex: filtering, pruning, trimming etc.



Boosted Jets and Substructure

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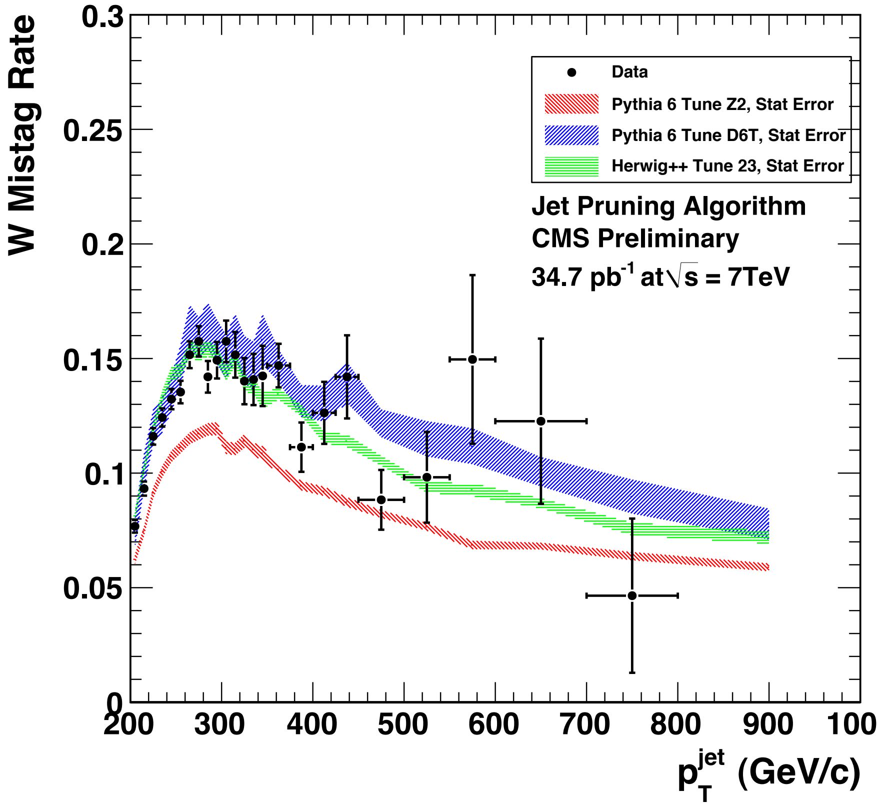

test of pruning with early CMS data

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LHC Higgs reach

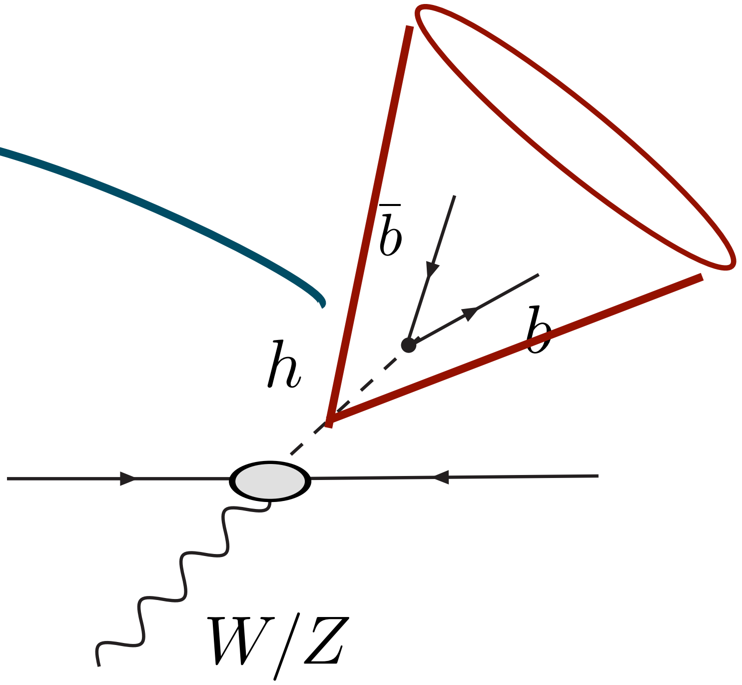
Butterworth, Davison, Rubin, Salam

0802.2470

Ex. $pp \to V\ h$

significance of 4.2 σ at $\mathcal{L} = 30\ \mathrm{fb}^{-1}$

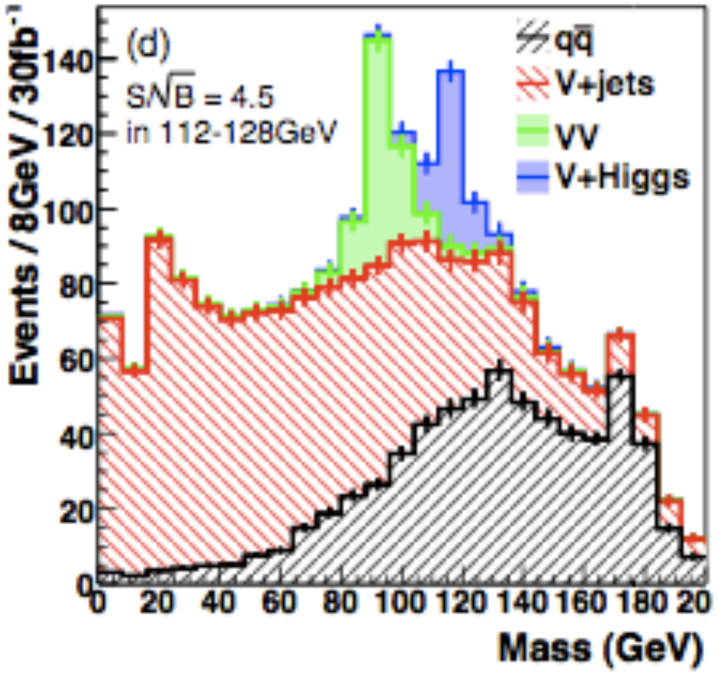
using jet-substructure for jets with $p_{T,h} > 200\ \mathrm{GeV}$



Jet with substructure

- subjets are significantly lighter than the jet
- splitting is not too asymmetric
- jet is double b-tagged

filtered



LHC Higgs reach

Kribs, Martin, Spannowsky, TSR

1006.1656

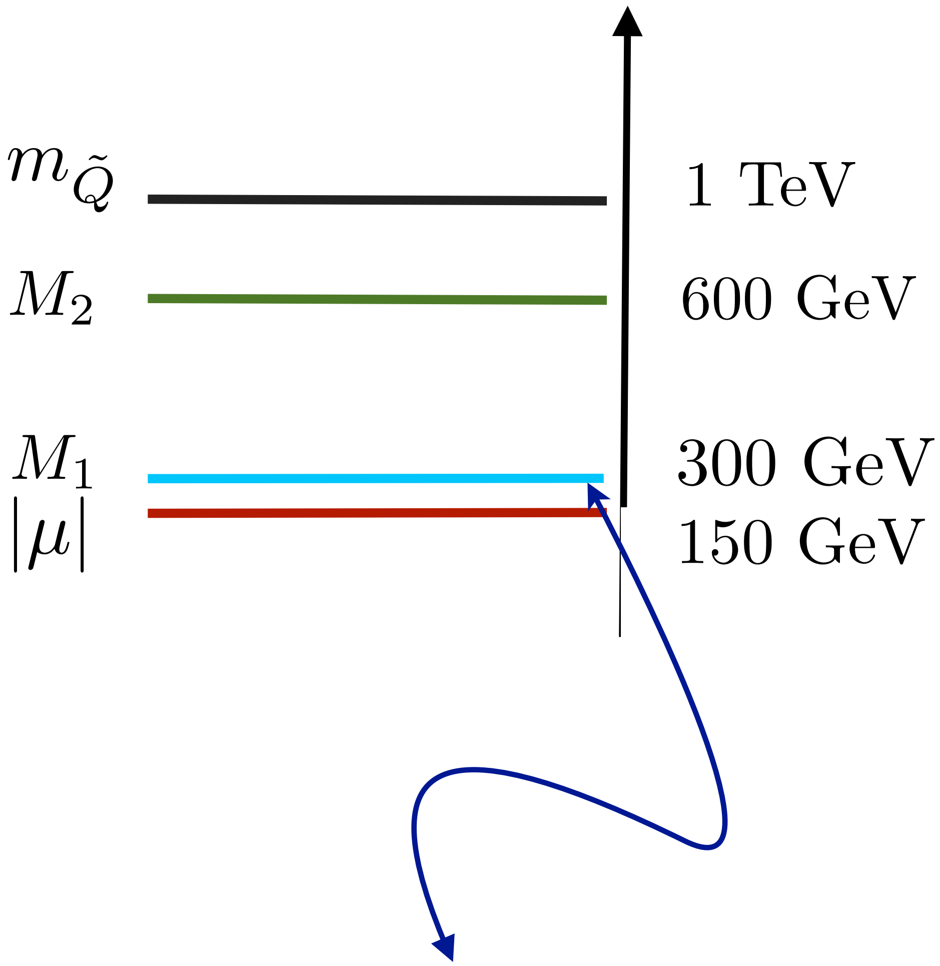
Ex. Higgs in supersymmetry

$\sqrt{s} = 14 \text{ TeV}, \mathcal{L} = 10 \text{ fb}^{-1}$

$\not{E}_T > 100 \text{ GeV}$, $H_T > 1 \text{ TeV}$

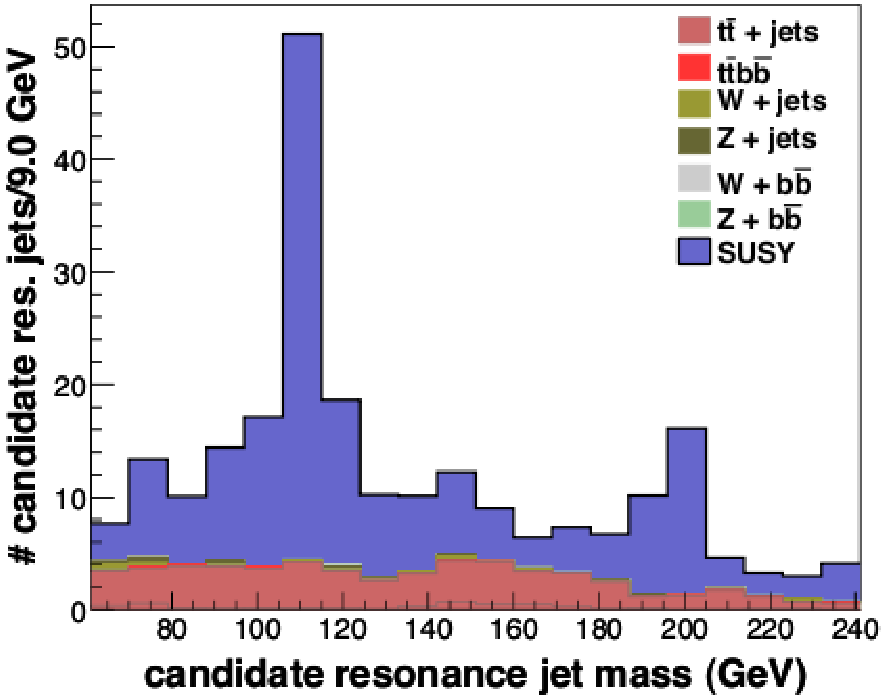
isolated lepton veto

2^+C/A jets with $R = 1.2$, $p_T > 200$ GeV



$m_A \ = \ 200 \text{ GeV}$

Jet with substructure + filtering



$S/\sqrt{B} = 8.2$

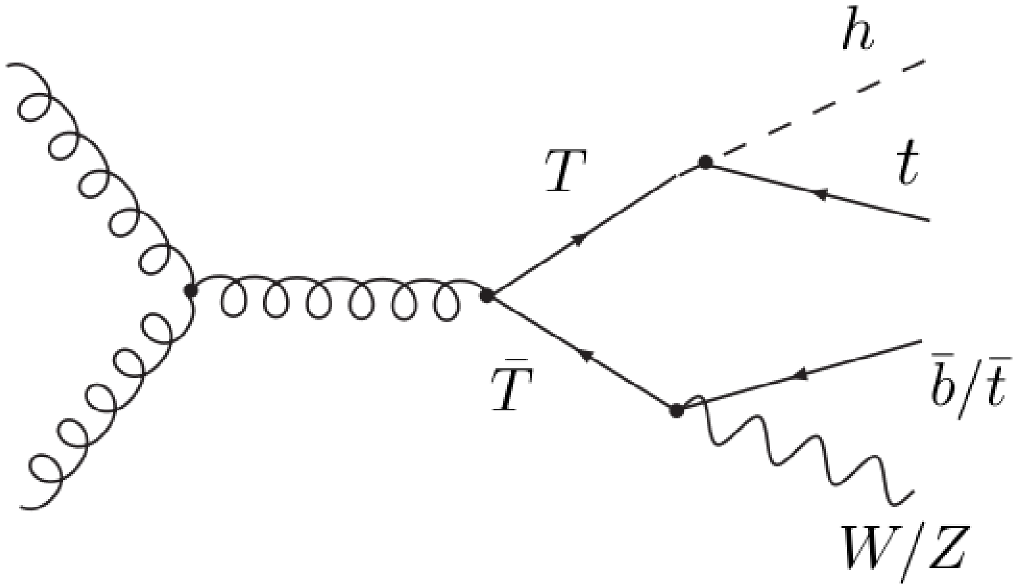
LHC Higgs reach

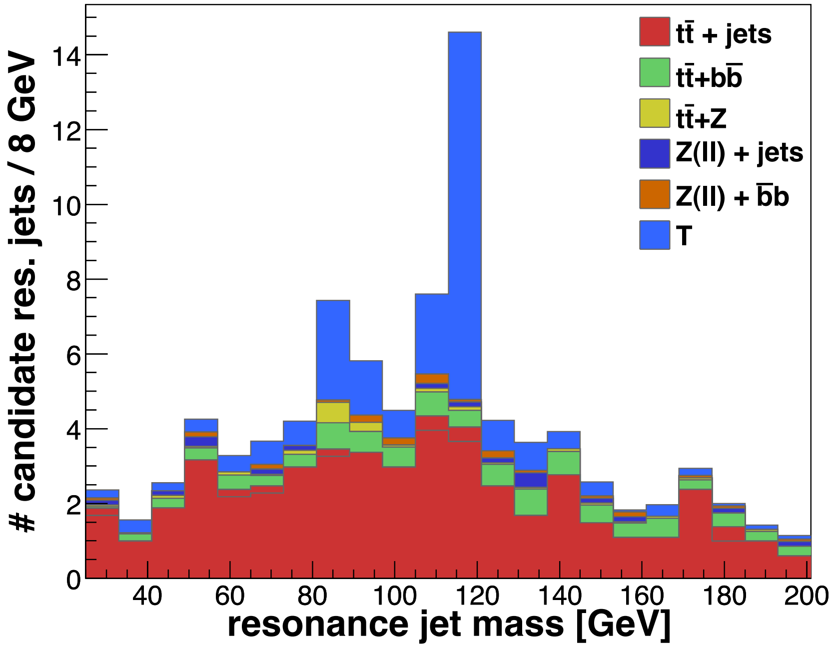
Kribs, Martin, TSR

1012.2866

Ex. Higgs from top partners

$$\sqrt{s} = 14\ \mathrm{TeV}, \mathcal{L} = 10\ \mathrm{fb}^{-1}$$





$$M_T = 800\ \mathrm{GeV}$$

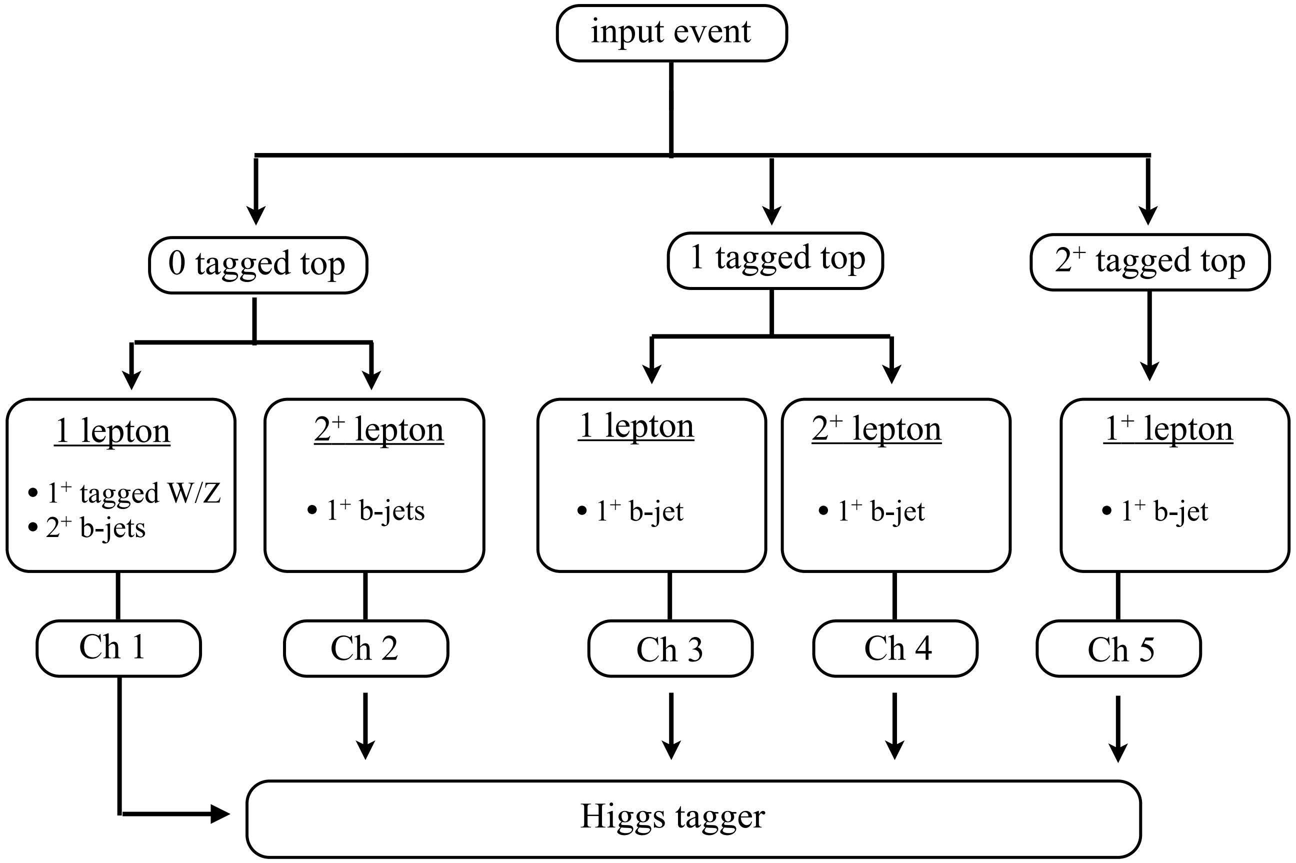
LHC Higgs reach

Kribs, Martin, TSR

1012.2866

Ex. Higgs from top partners

$$\sqrt{s} = 14 \text{ TeV}, \mathcal{L} = 10 \text{ fb}^{-1}$$



input event

0 tagged top

1 tagged top

2^+ tagged top

1 lepton
- 1^+ tagged W/Z
- 2^+ b-jets

2^+ lepton
- 1^+ b-jets

1 lepton
- 1^+ b-jet

2^+ lepton
- 1^+ b-jet

1^+ lepton
- 1^+ b-jet

Ch 1

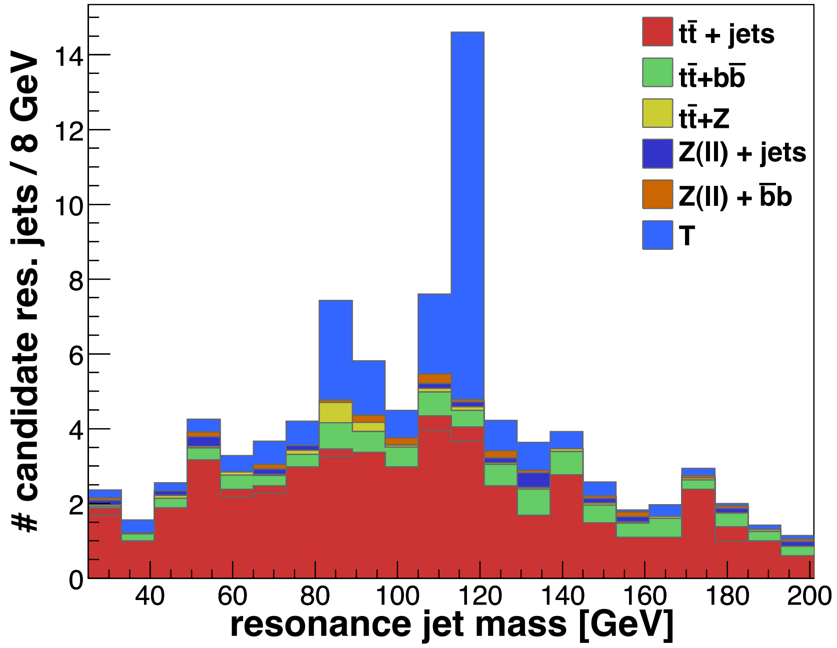
Ch 2

Ch 3

Ch 4

Ch 5

Higgs tagger



$$M_T = 800 \text{ GeV}$$

$$S/\sqrt{B} = 5.2$$

Boosted jets and substructure analysis

Butterworth, Davison, Rubin, Salam

0802.2470

Recipe for boosted resonance search:

(if you know what you are looking for)

- Look for “boosted” jets
- Identify “interesting” jets
- Clean jets

Boosted jets and substructure analysis

Recipe for boosted resonance search:

(if you don't know what you are looking for)

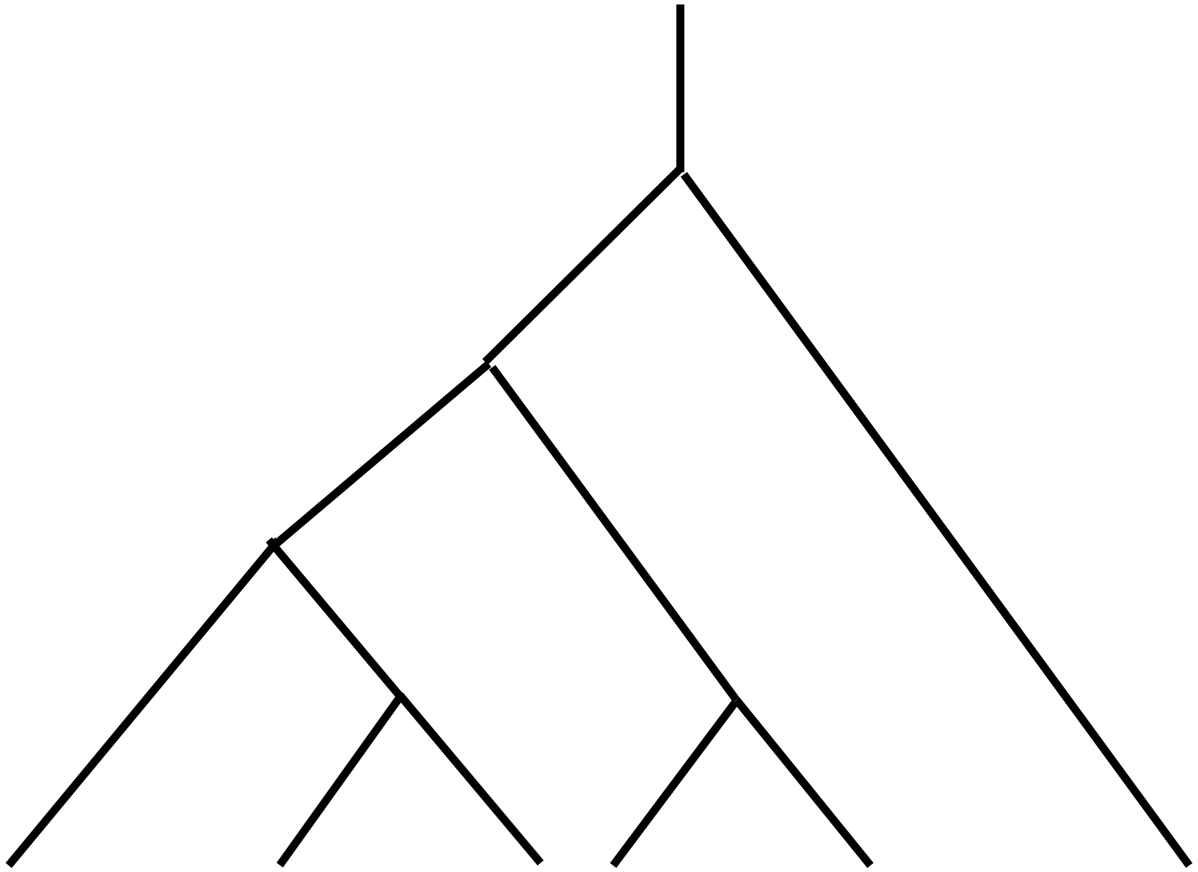
- Look for "boosted" jets
- ~~Identify "interesting" jets~~
- Clean jets

more important than ever

let me now show how exactly pruning works

Pruning

Start with the constituents of a given jet and rebuild the jet along C/A or k_T



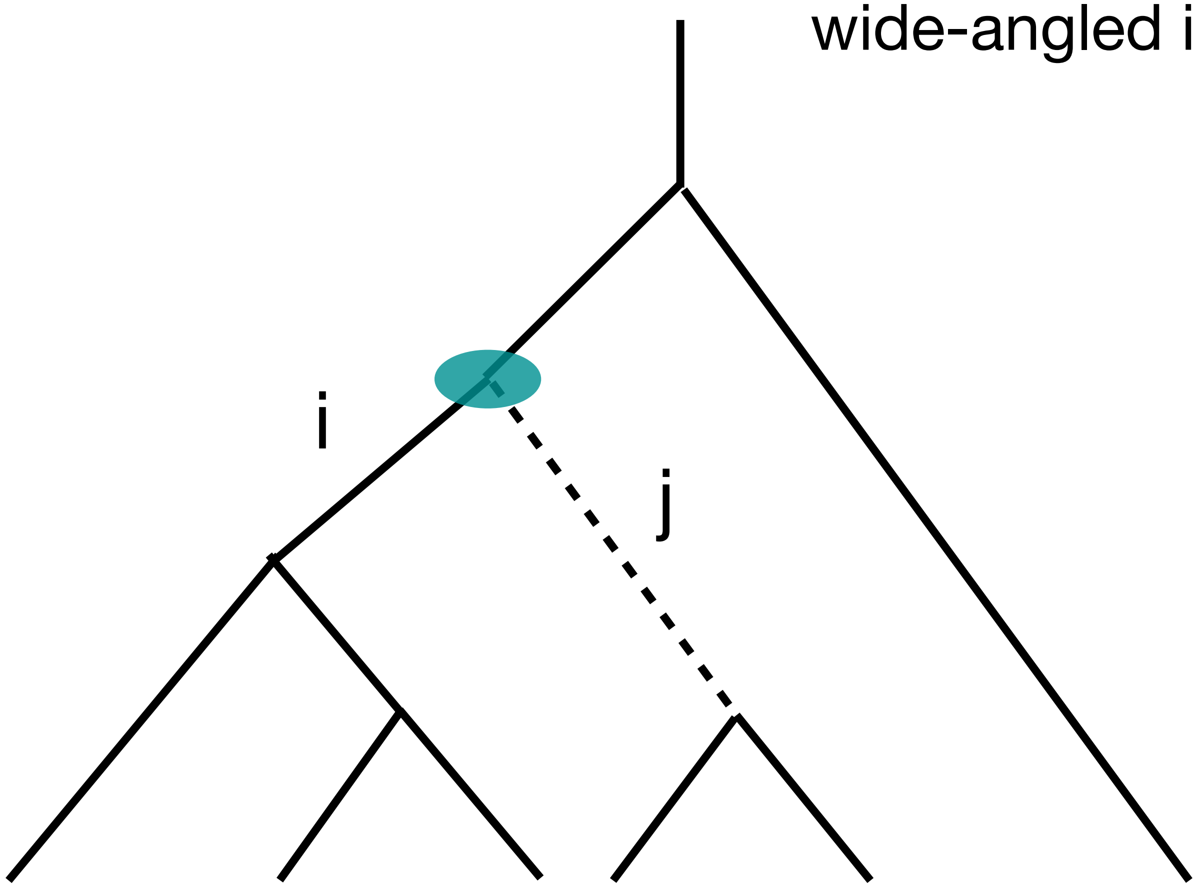
Pruning

At every step of clustering check whether the branch to be added is soft **and** wide angled.

- if yes discard the softer four-vector.

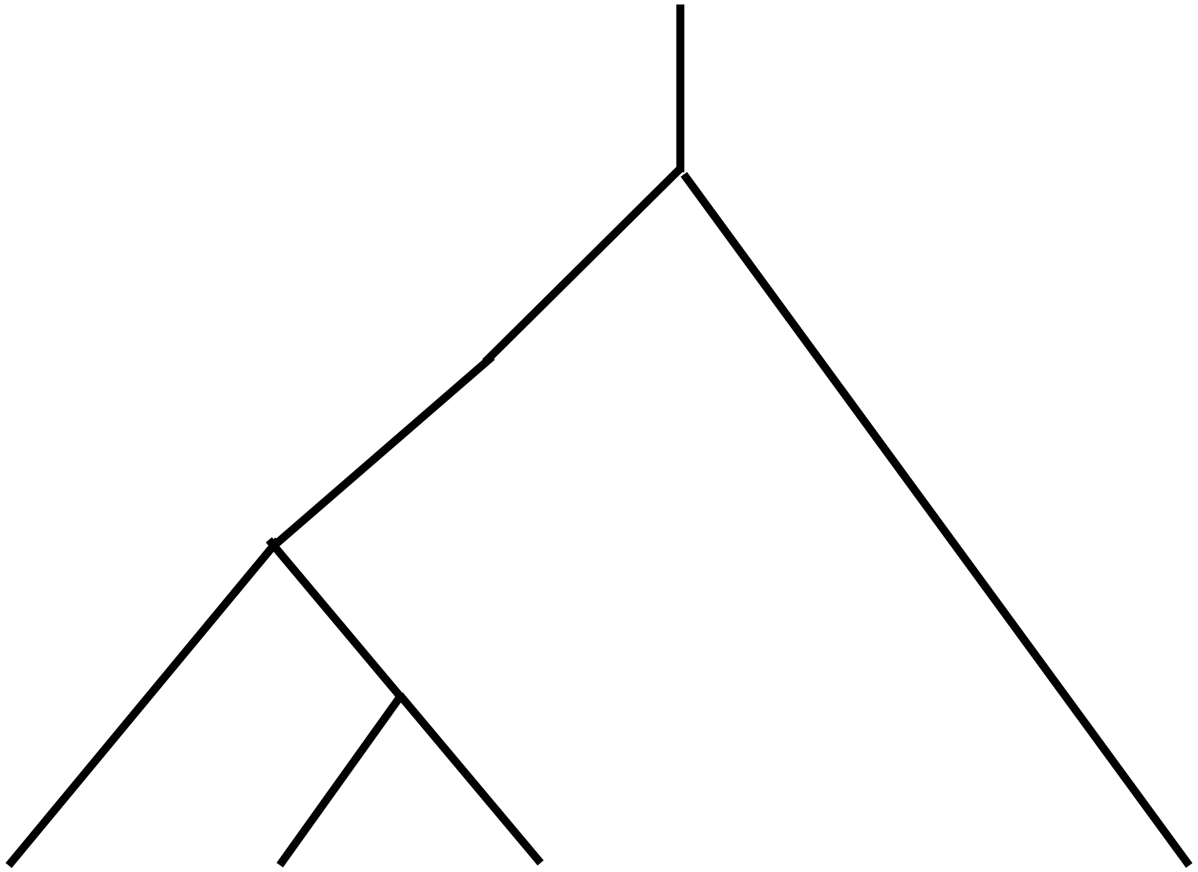
soft if: $\dfrac{\min\left(p_{T_i}, p_{T_j}\right)}{|\vec{p_{T_i}} + \vec{p_{T_j}}|} < z_{\rm cut}$

wide-angled if: $\Delta R_{ij} > D_{\rm cut}$



Pruning

Pruned Jet

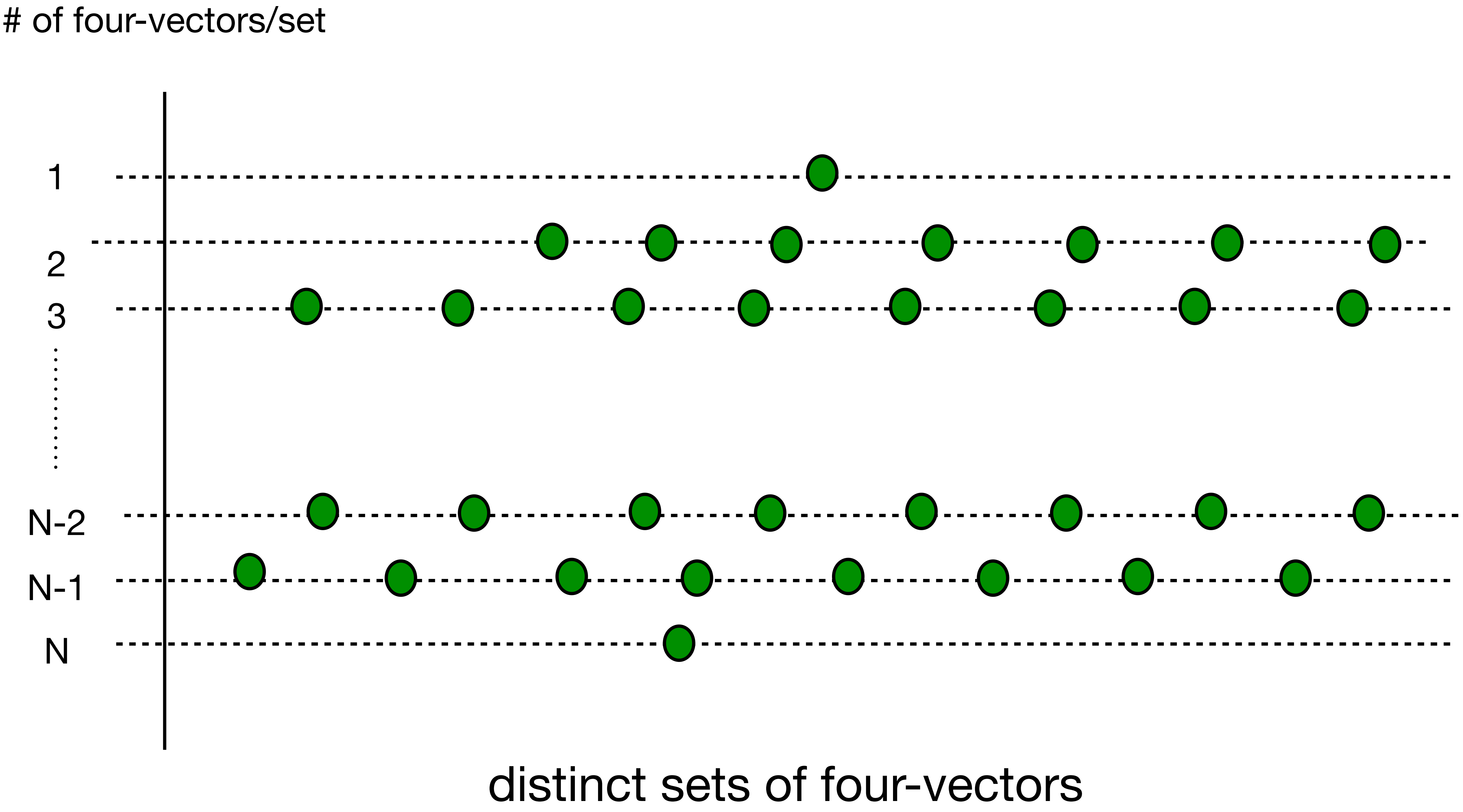


Pruning

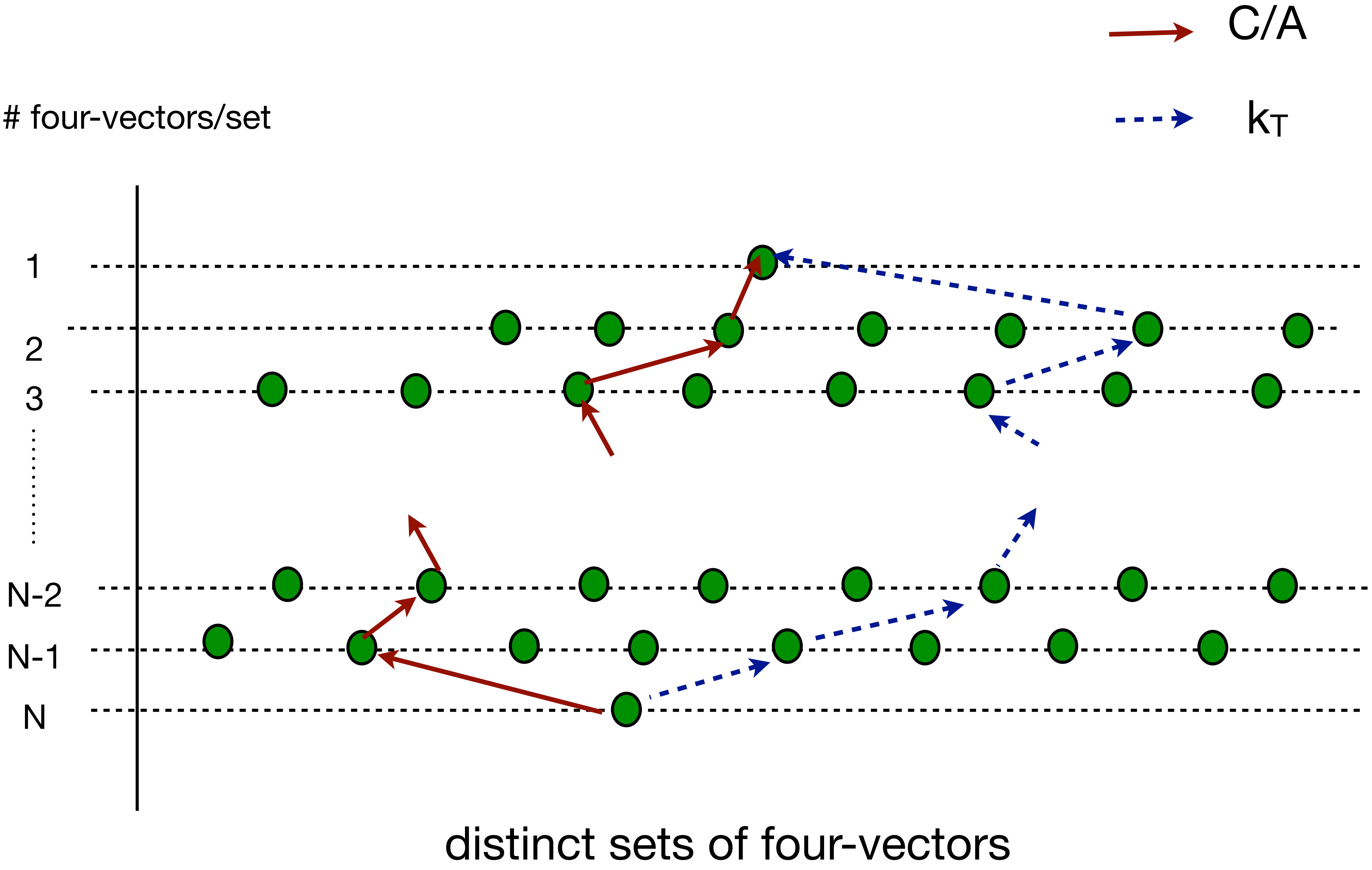
- Four-vectors that are pruned are actually branches of the tree.
- Pruned jets depend crucially on the tree-structure or the clustering algorithm used to construct the jet.

but who ordered the clustering algorithm?

Clustering

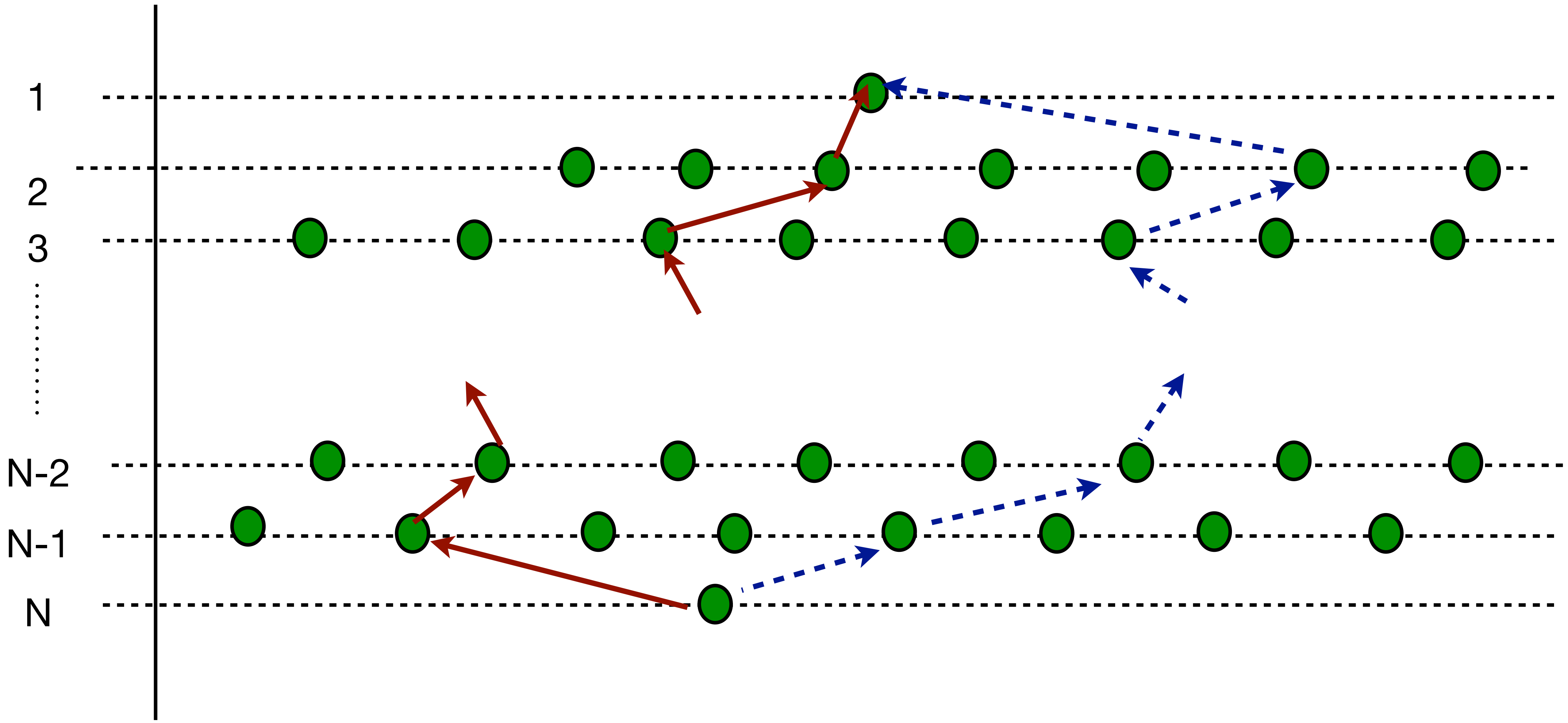


Clustering


C/A
k_T
four-vectors/set
1
2
3
N-2
N-1
N
distinct sets of four-vectors

Clustering

Many paths remain unexplored that are equally physically relevant



distinct sets of four-vectors

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Clustering

Many paths remain unexplored that can be equally physically relevant

A better formalism should explore all such paths

one needs to be clever since the total number of distinct trees is enormous

$$\frac{(2N)!}{2^N N!}$$

our prescription is QClustering

QClustering

with Steve Ellis, Andrew Hornig, David Krohn
and Matt Schwartz

As in a sequential recombination algorithm, assign every pair of four-vectors a distance measure d_{ij}.

However, unlike a normal sequential algorithm (where the pair with the smallest measure is clustered), here a given pair is randomly selected for merging with probability

$$\Omega_{ij} = \frac{1}{N}\exp\left(-\underset{\uparrow}{\alpha}\;\frac{d_{ij}}{d_{\min}}\right)$$

rigidity parameter

Repeat many (~100-1000) times, till the distribution stabilizes

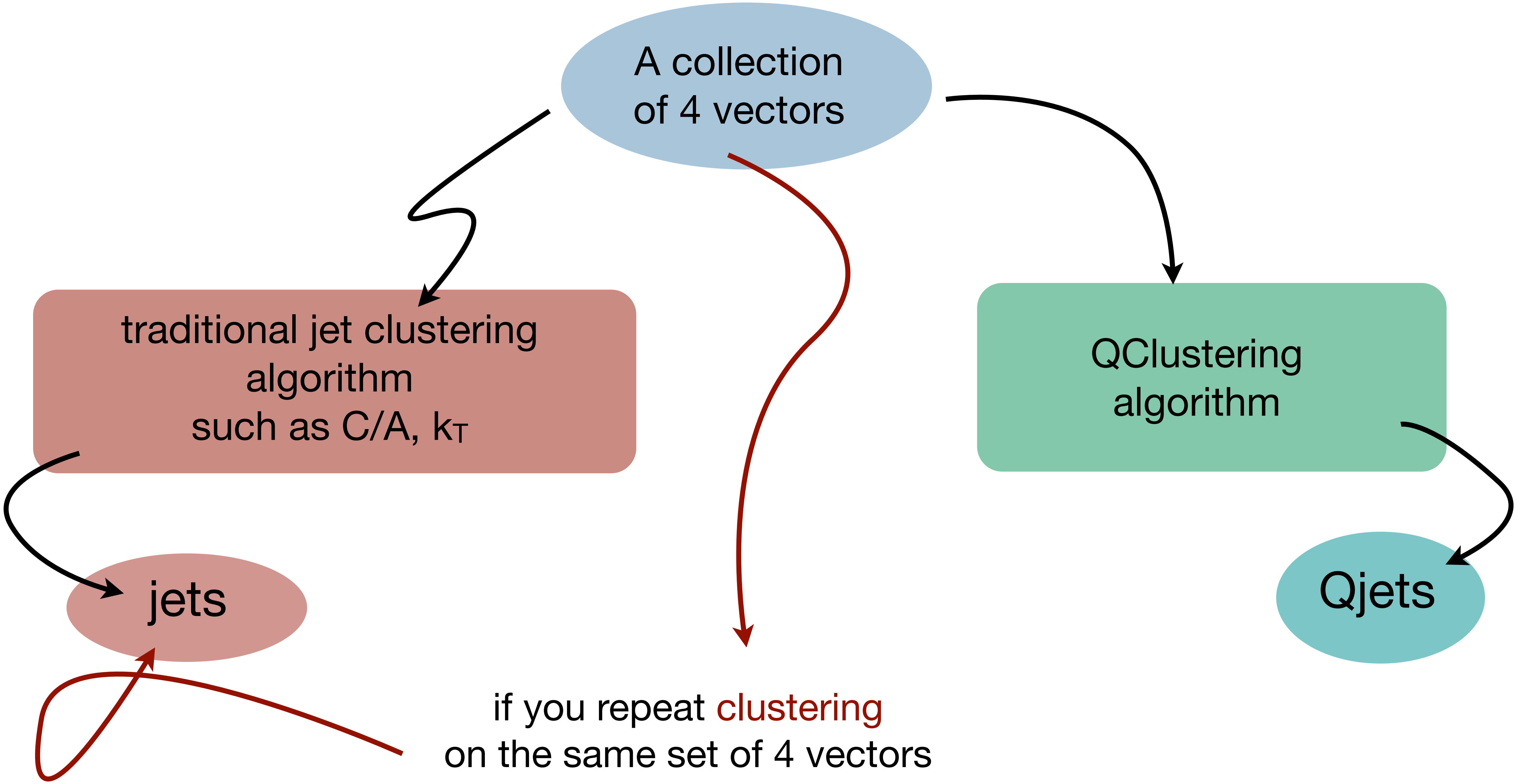
QClustering

$$\Omega_{ij} = \frac{1}{N} \exp\left(-\alpha \ \frac{d_{ij}}{d_{\min}} \right)$$

d_{ij} : we take C/A or kT measure

$\alpha \to \infty$	Classical regime: only path corresponding to $d_{\min}$ is selected
$\alpha > 0$	physical regime: physical paths are preferred
$\alpha \to 0$	democratic regime: all paths have same weight
$\alpha < 0$	unphysical regime: physical paths are de-weighted

QJets



A collection of 4 vectors

traditional jet clustering algorithm such as C/A, k_T

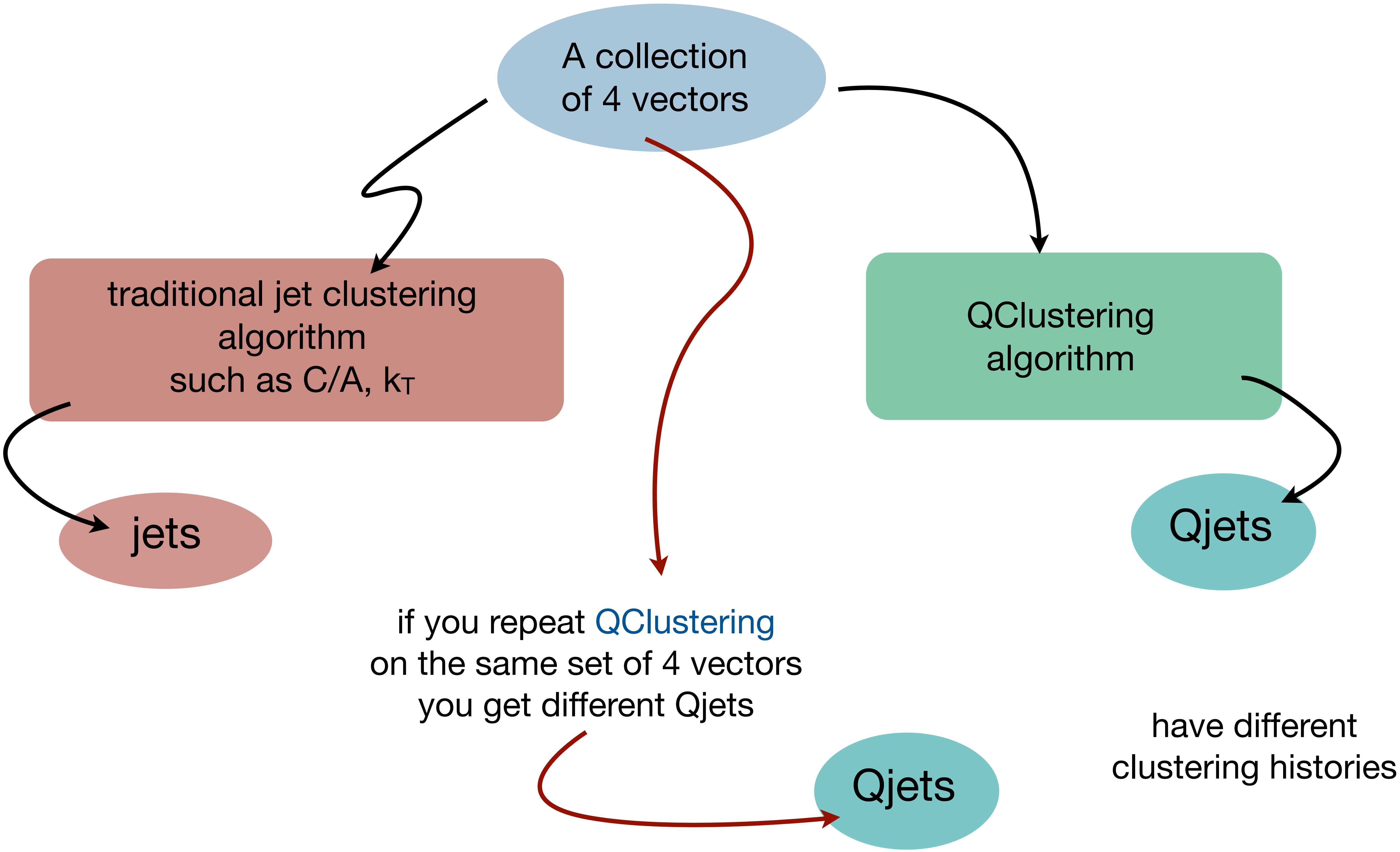
jets

QClustering algorithm

Qjets

if you repeat clustering on the same set of 4 vectors you get the same jets

QJets



A collection of 4 vectors

traditional jet clustering algorithm such as C/A, k_T

jets

QClustering algorithm

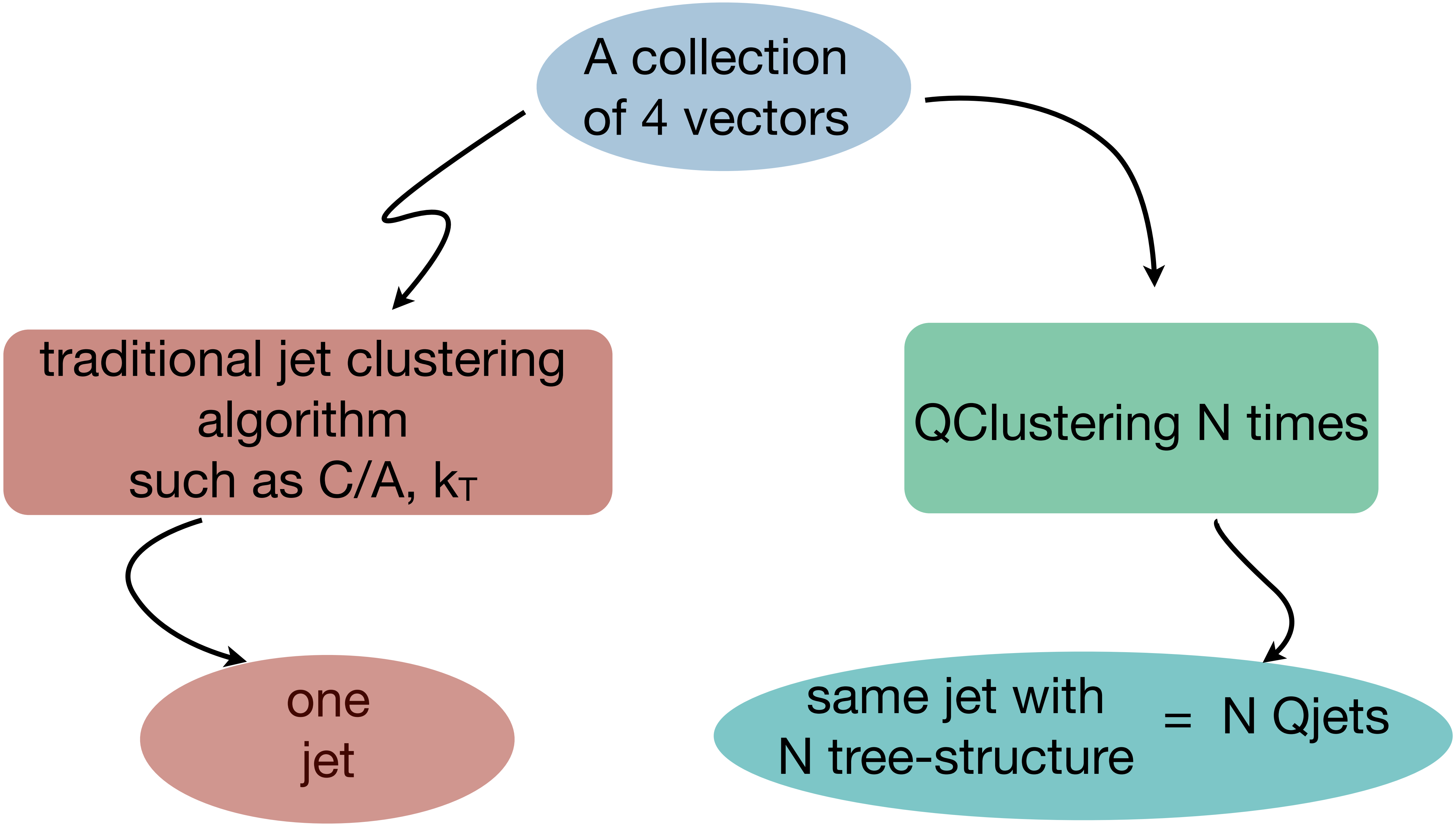
Qjets

if you repeat QClustering on the same set of 4 vectors you get different Qjets

Qjets

have different clustering histories

QClustering vs. Clustering



A collection of 4 vectors

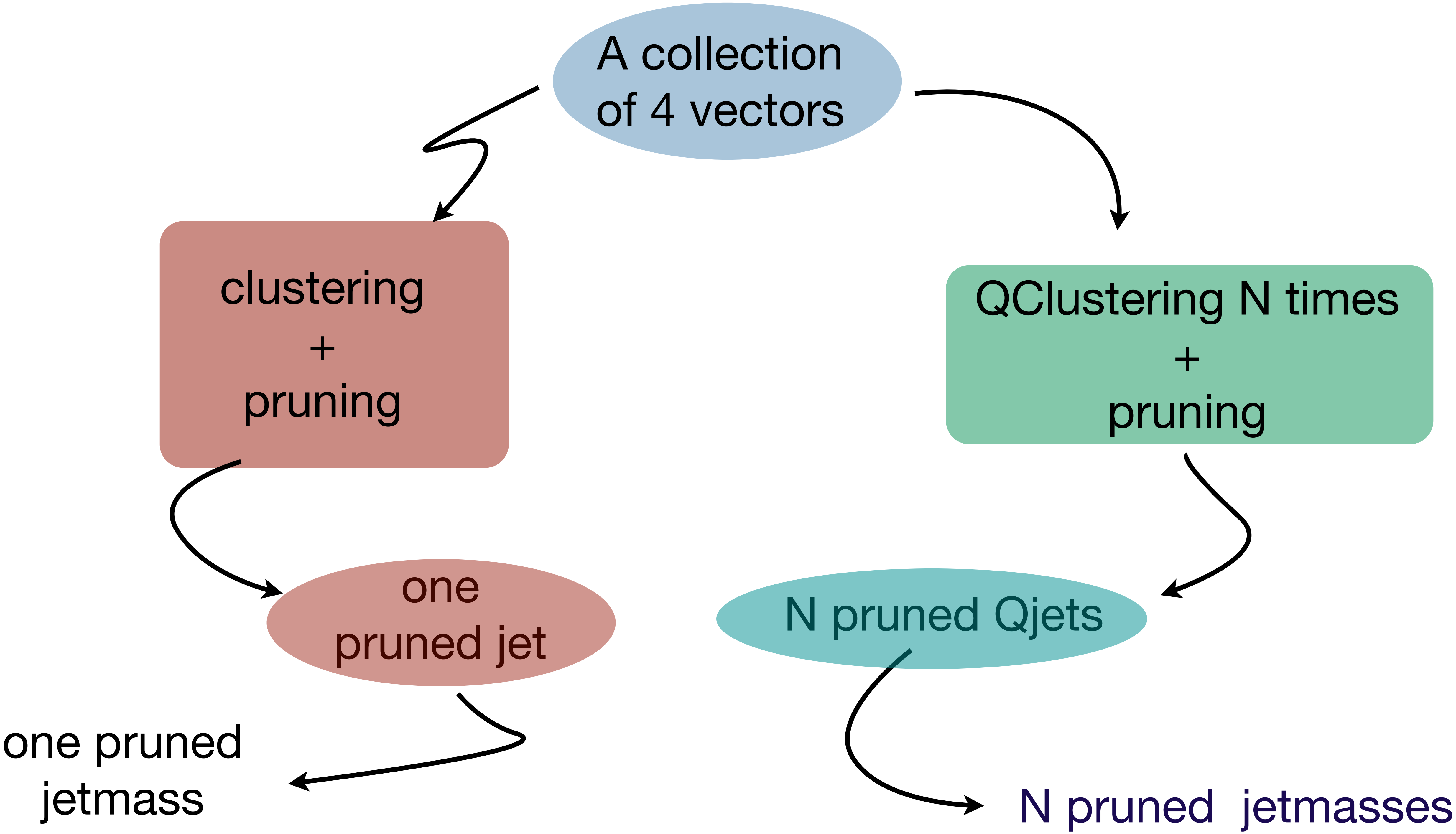
traditional jet clustering algorithm such as C/A, k_T

one jet

QClustering N times

same jet with N tree-structure = N Qjets

QClustering vs. Clustering



A collection of 4 vectors

clustering
+
pruning

one
pruned jet

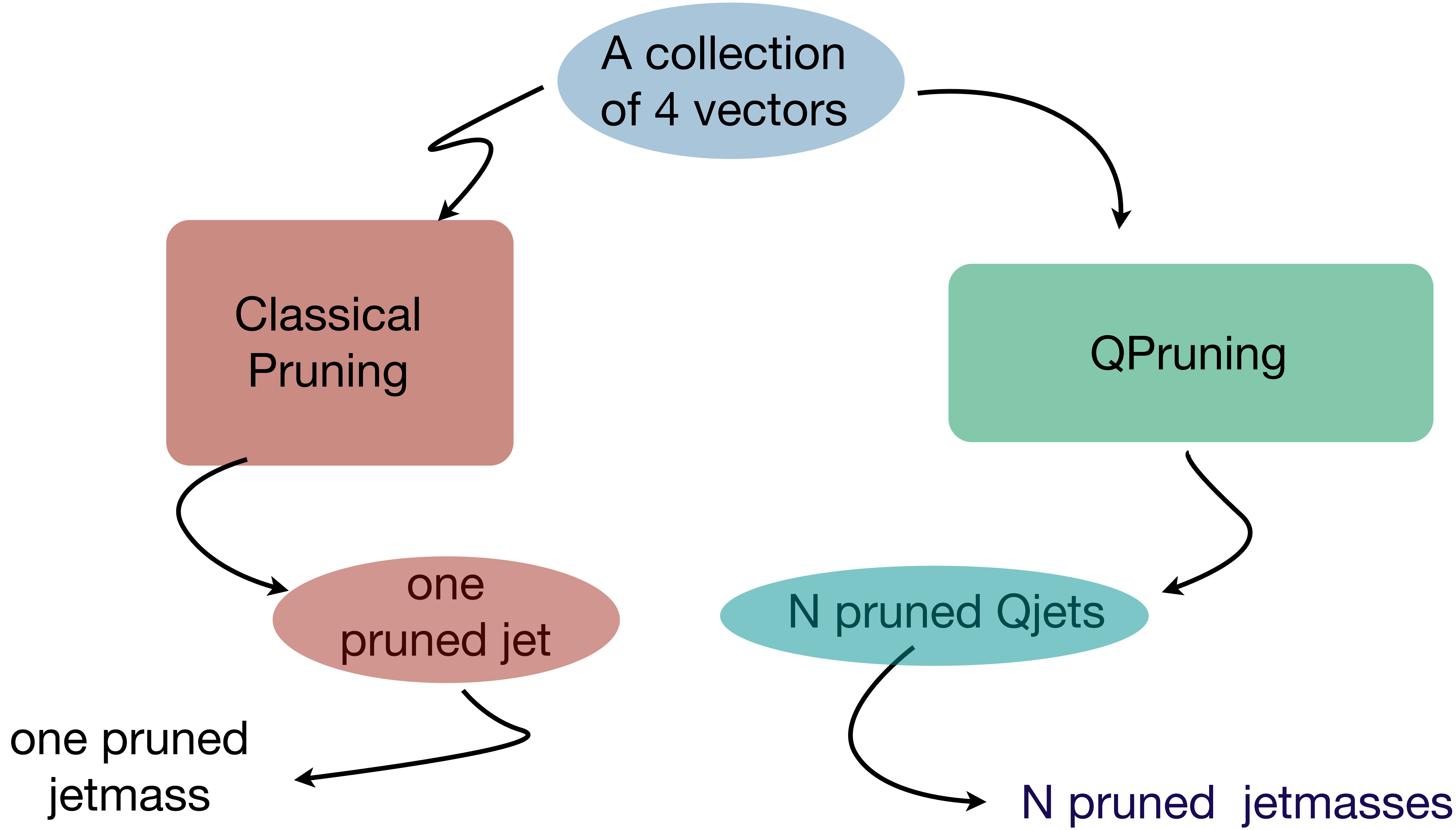
one pruned
jetmass

QClustering N times
+
pruning

N pruned Qjets

N pruned jetmasses

QClustering vs. Clustering



A collection of 4 vectors

Classical Pruning

one pruned jet

one pruned jetmass

QPruning

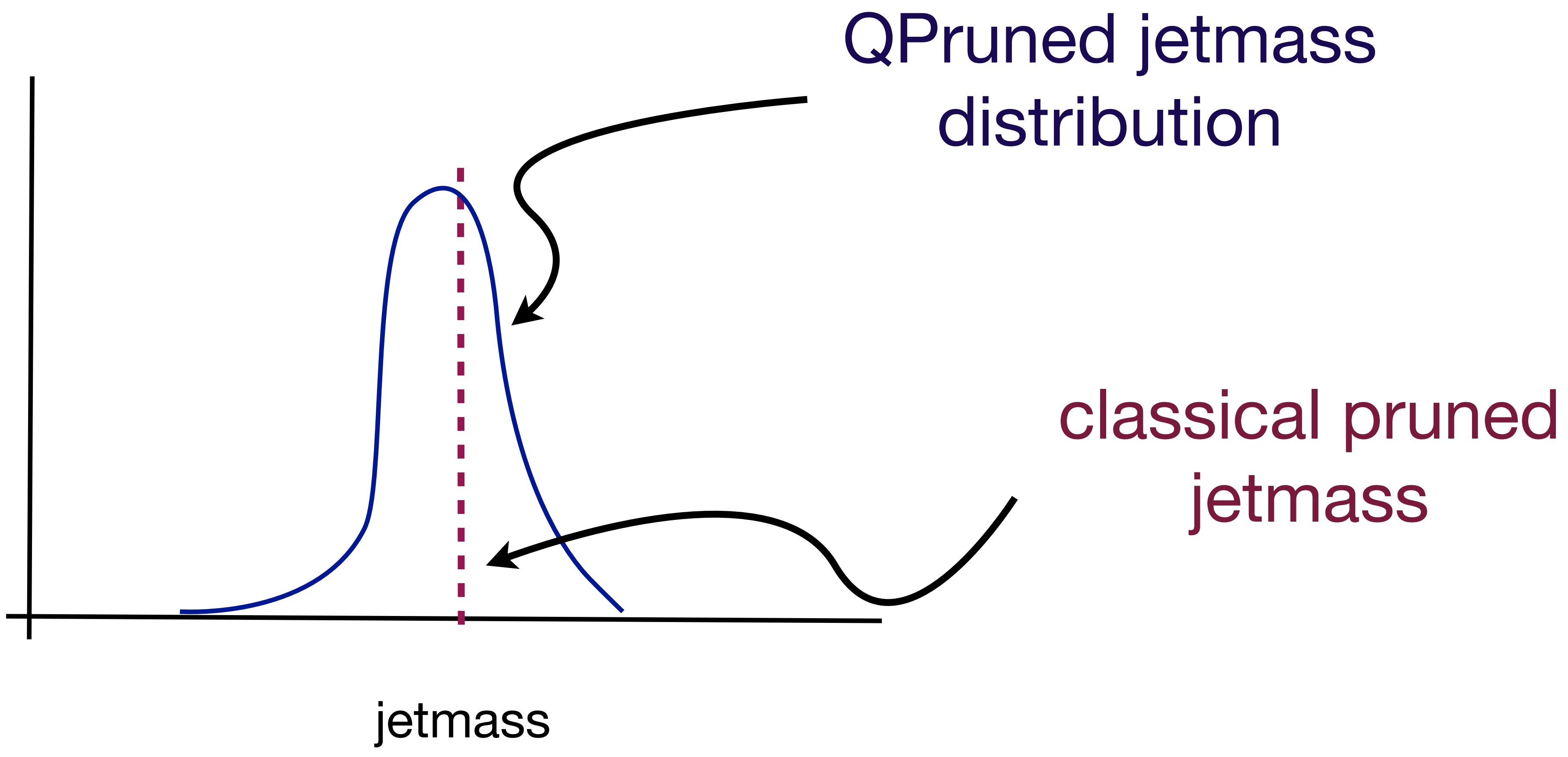
N pruned Qjets

N pruned jetmasses

QClustering + Pruning

Ex. a hadronic W jet from WW events

The original jet is made from C/A algorithm with R = 1.0 and pT > 200GeV



QPruned jetmass distribution

classical pruned jetmass

QClustering + Pruning = QPruning

Ex. a hadronic W jet from WW events

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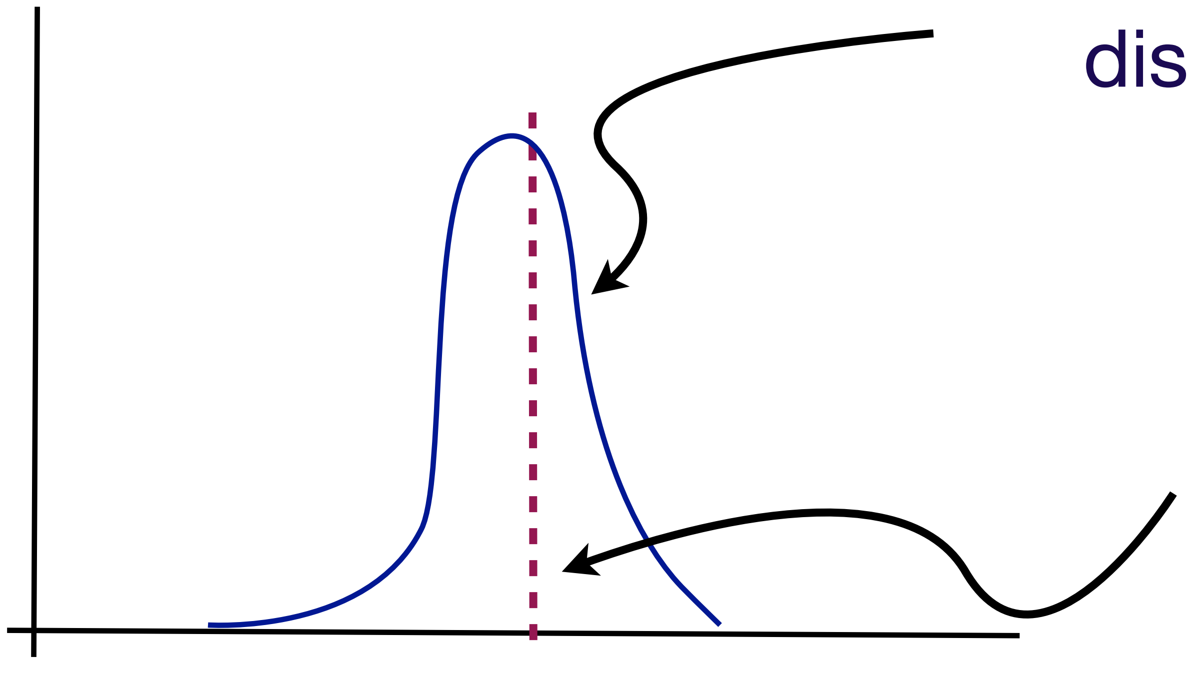


QPruned jetmass
distribution

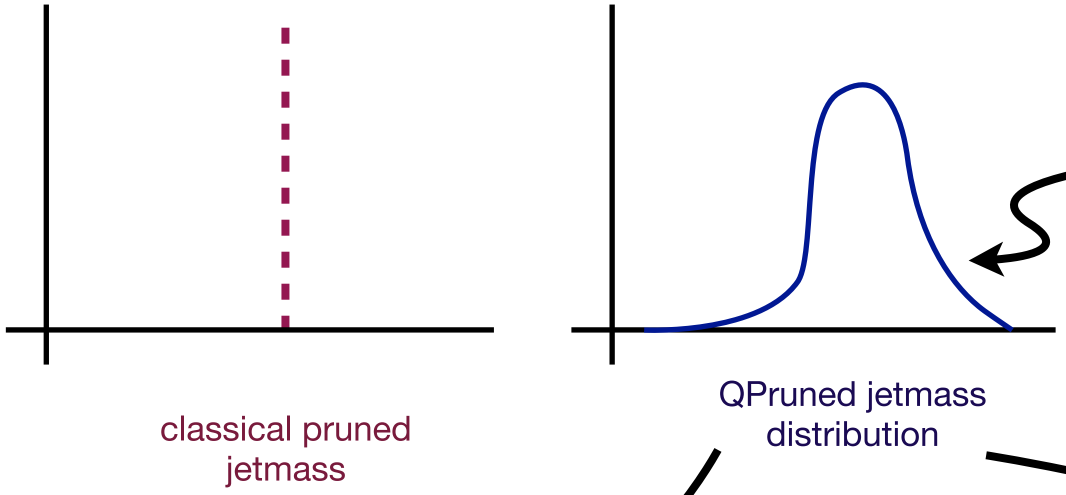
classical pruned
jetmass

jetmass

How can this distribution be used?

QPruning vs. Pruning

Let us take a sample jet



How can this distribution be used?

Simply use the shape of the distribution to discriminate signal from background

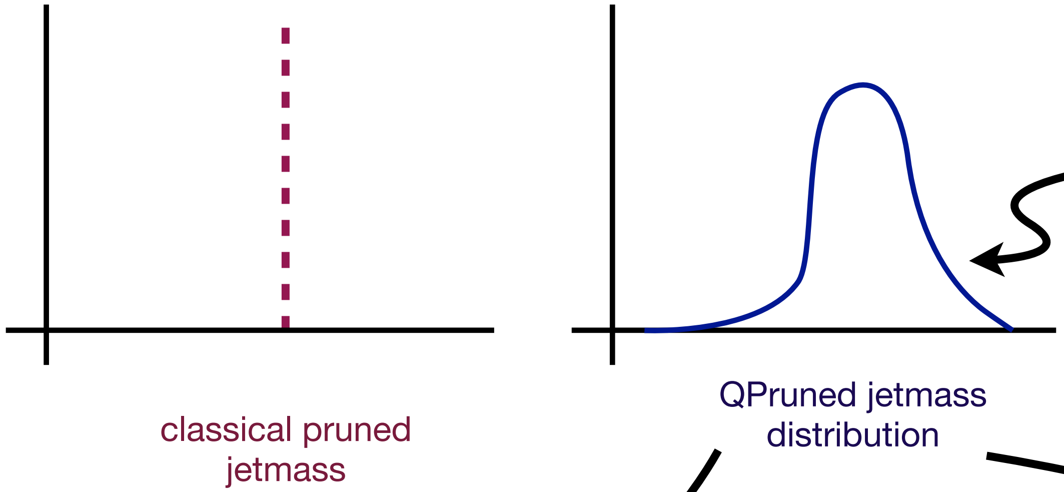
Use the distribution to reduce statistical fluctuations in measurements

Application in determination of cross-section, mass etc.

Application in signal discovery

QPruning vs. Pruning

Let us take a sample jet



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Application in determination of cross-section, mass etc.

Application 1: discovery of W

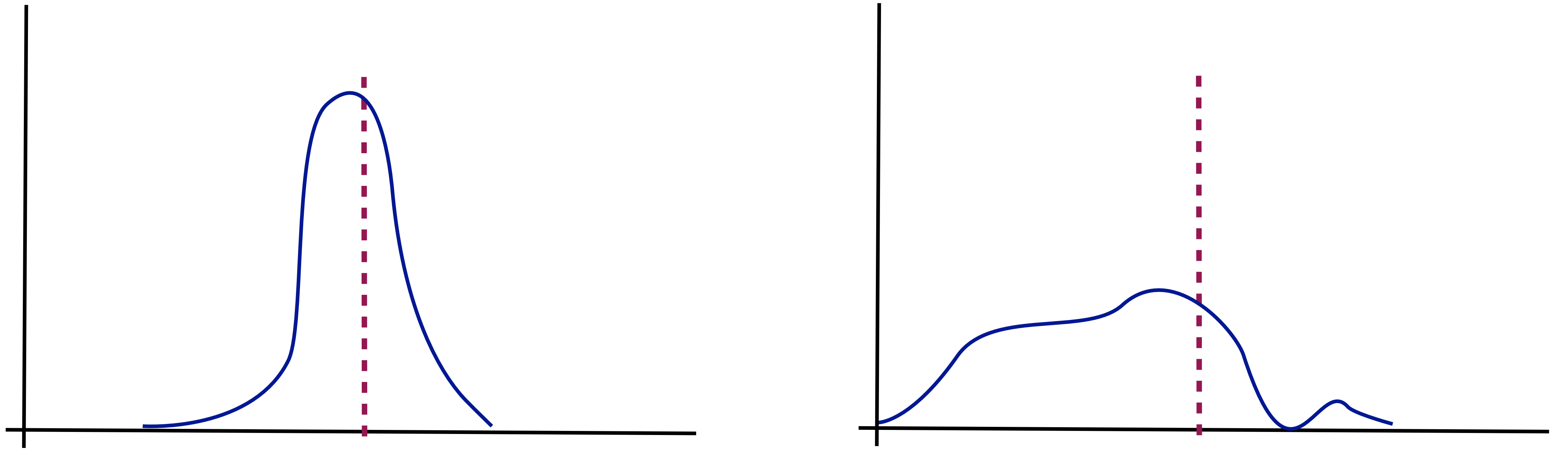
- When there is an intrinsic mass scale for a jet, the pruned jetmass is more or less robust under variation of paths.
- Signal jets with decay products of massive resonances have intrinsic mass scales.
- Even QCD jets with $m/p_T \sim 1$ have hard splittings and hence intrinsic mass scales.
- But background is dominantly due to QCD jets with $m/pt < 1/2$ - whose masses are highly volatile.

Application 1: discovery of W

When there is an intrinsic mass scale for a jet, the pruned jetmass is more of less robust under variation of paths.

W jet

QCD jet with $m/p_T < 1/2$

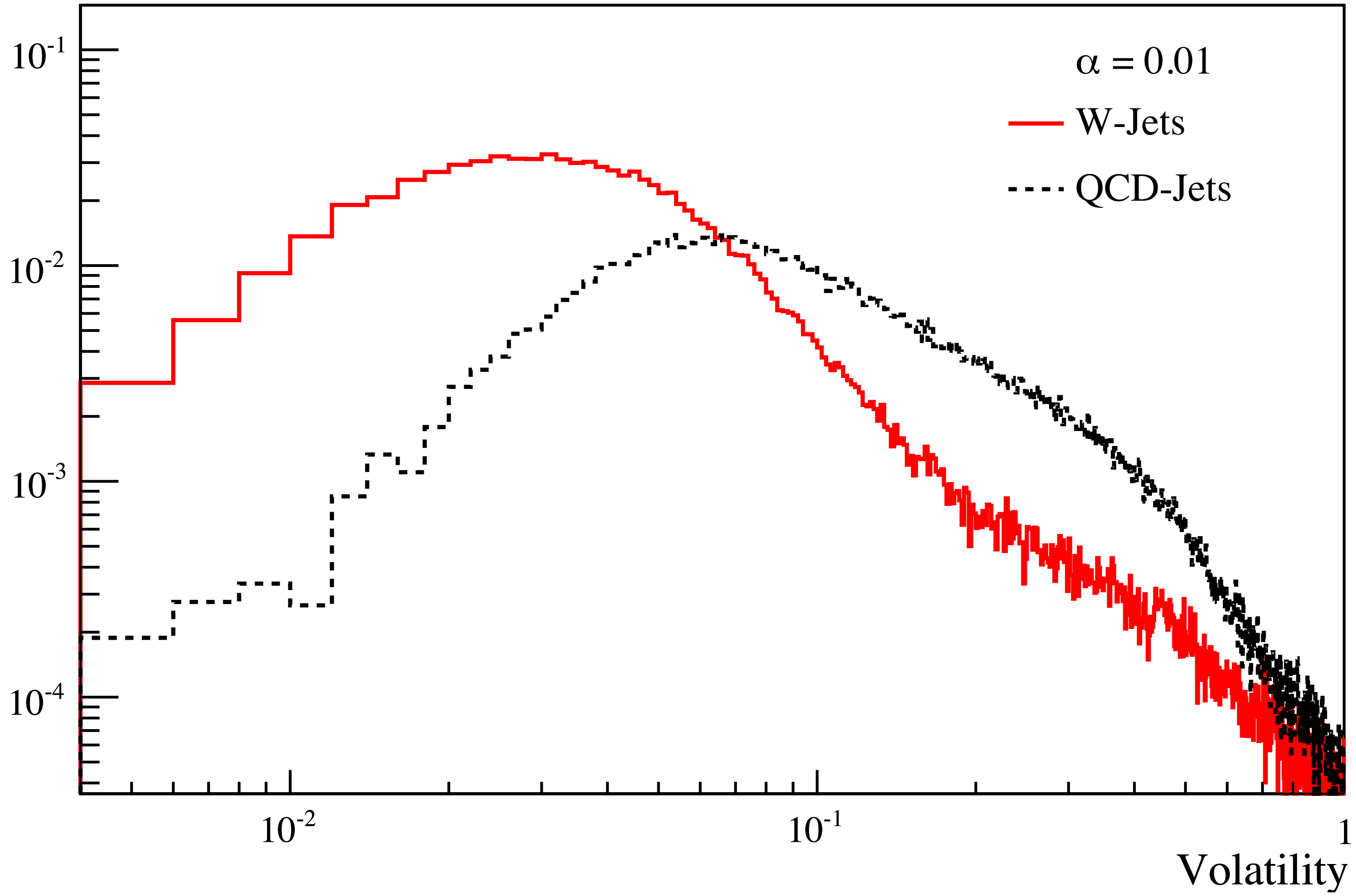


Application 1: discovery of W

volatility of a jet $\mathcal{V} = \frac{\omega_p}{m_p}$

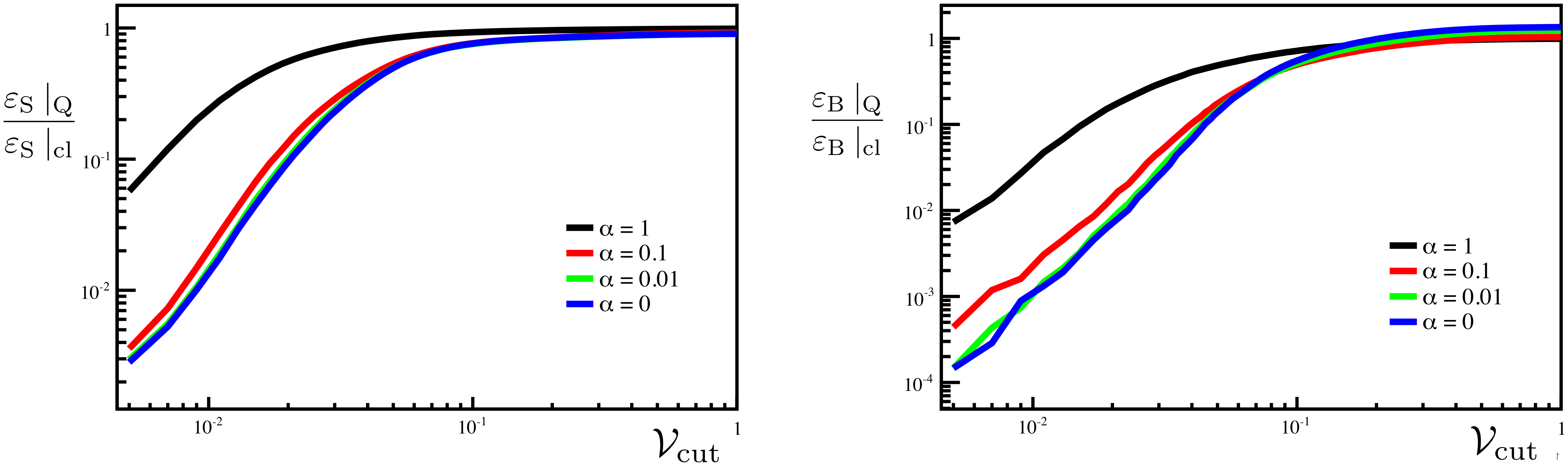
ω_p = width of jetmass distribution

m_p = averaged pruned jetmass



Application 1: discovery of $\mathcal{W}$

a cut on $\mathcal{V}$ decreases background significantly



Application 1: discovery of $\mathcal{W}$

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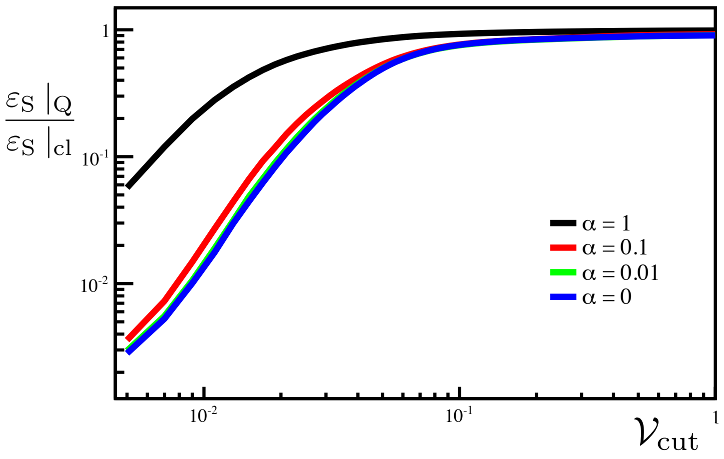
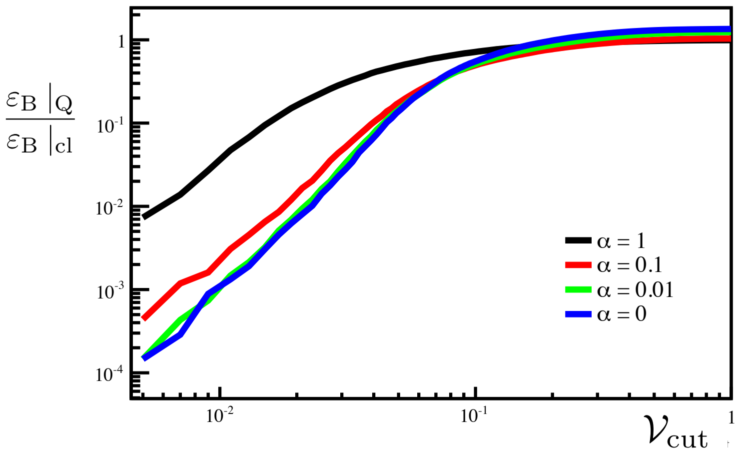
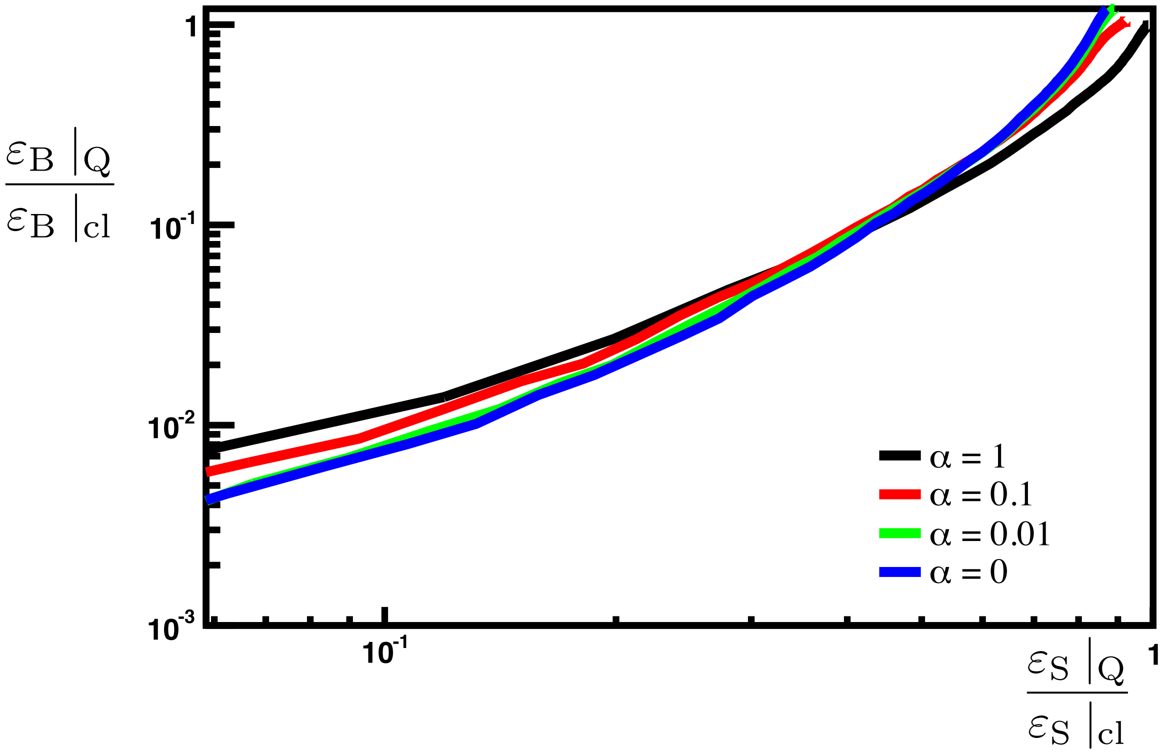
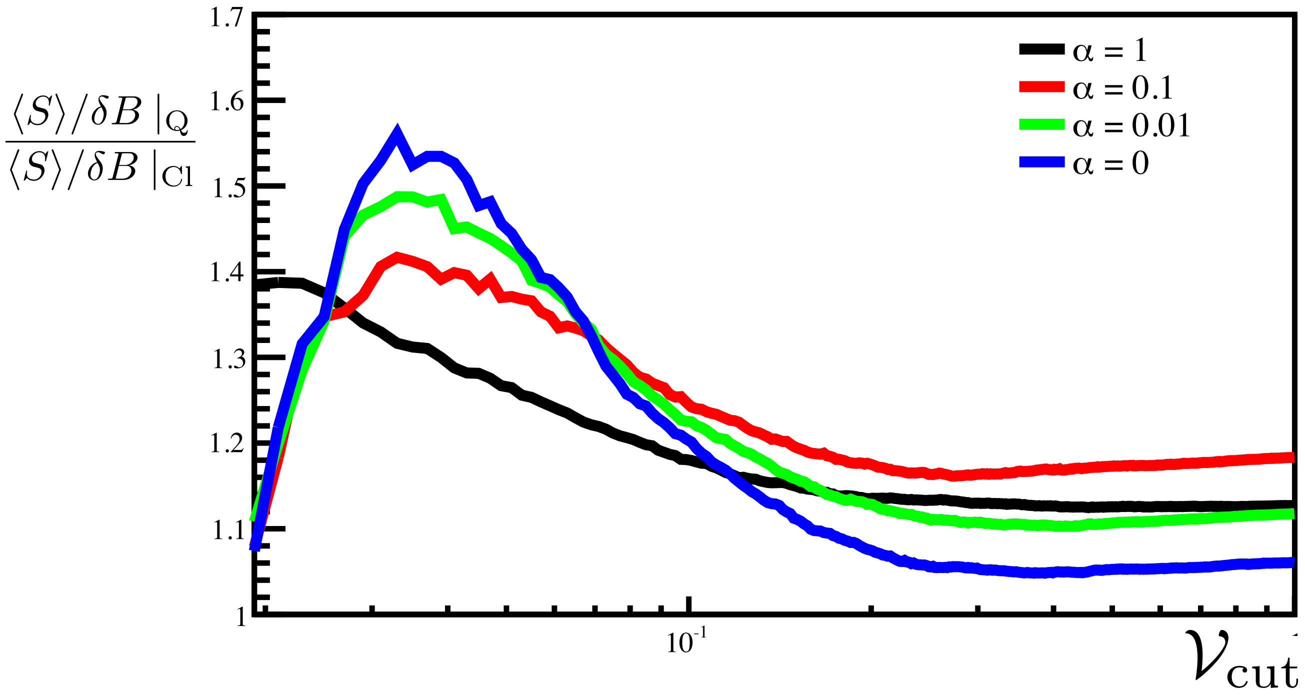


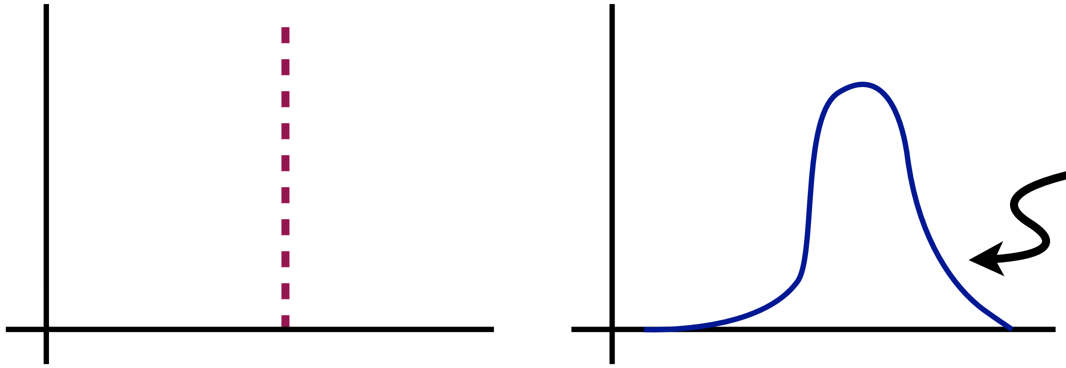






QPruning vs. Pruning

Let us take a sample jet



classical pruned jetmass

QPruned jetmass distribution

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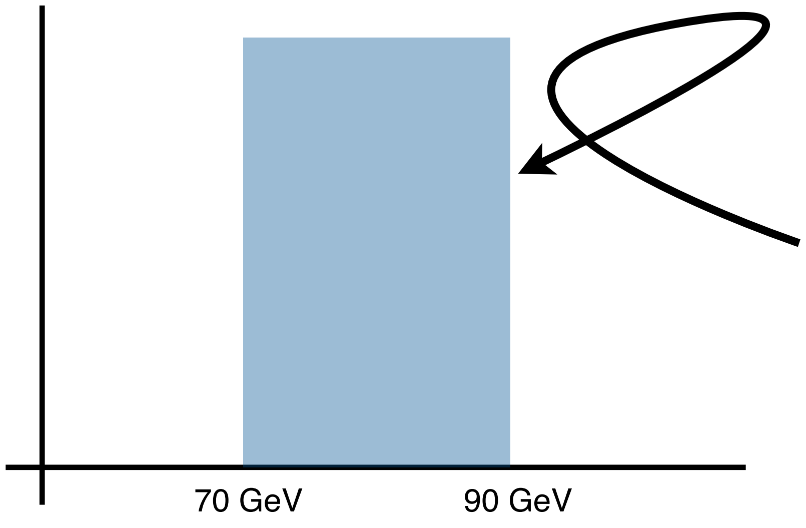
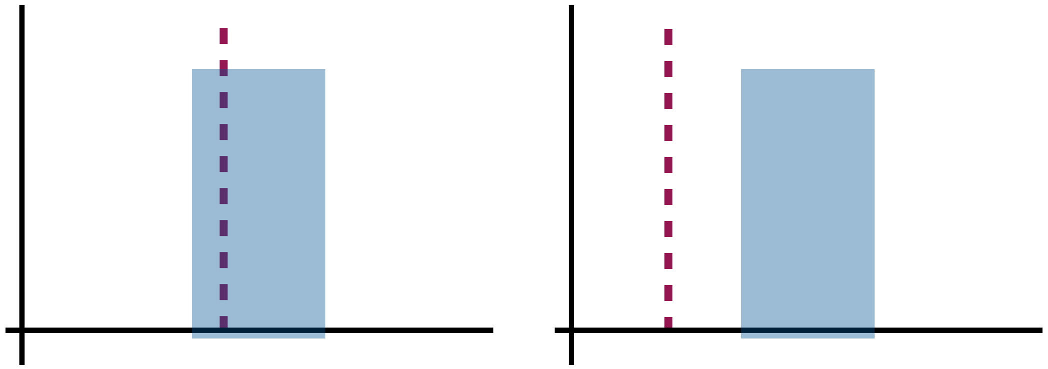
QPruning vs. Pruning

Consider candidates for a W jet



Mass window for W

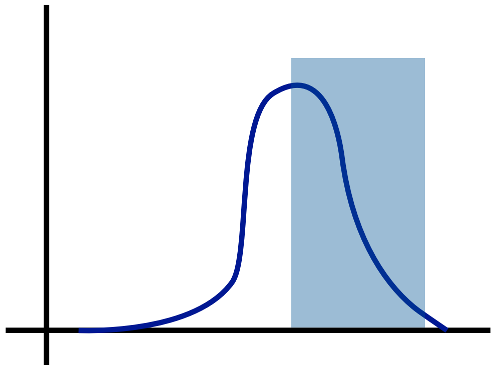
classical pruned jetmass



pruned mass is
either in or out of the bin

tagging efficiency is either 0 or 1

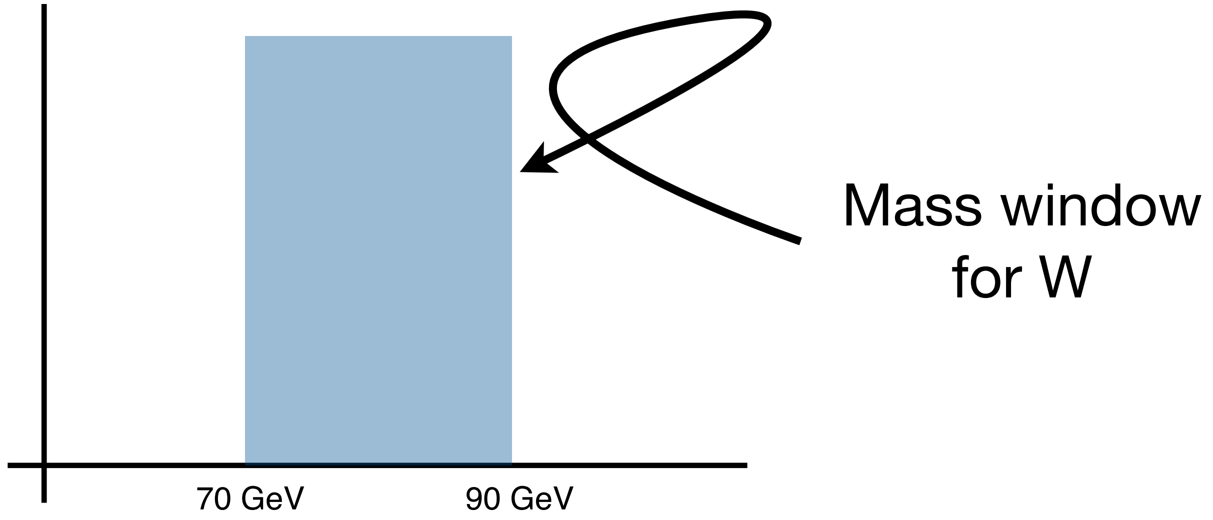
QPruned jetmass distribution



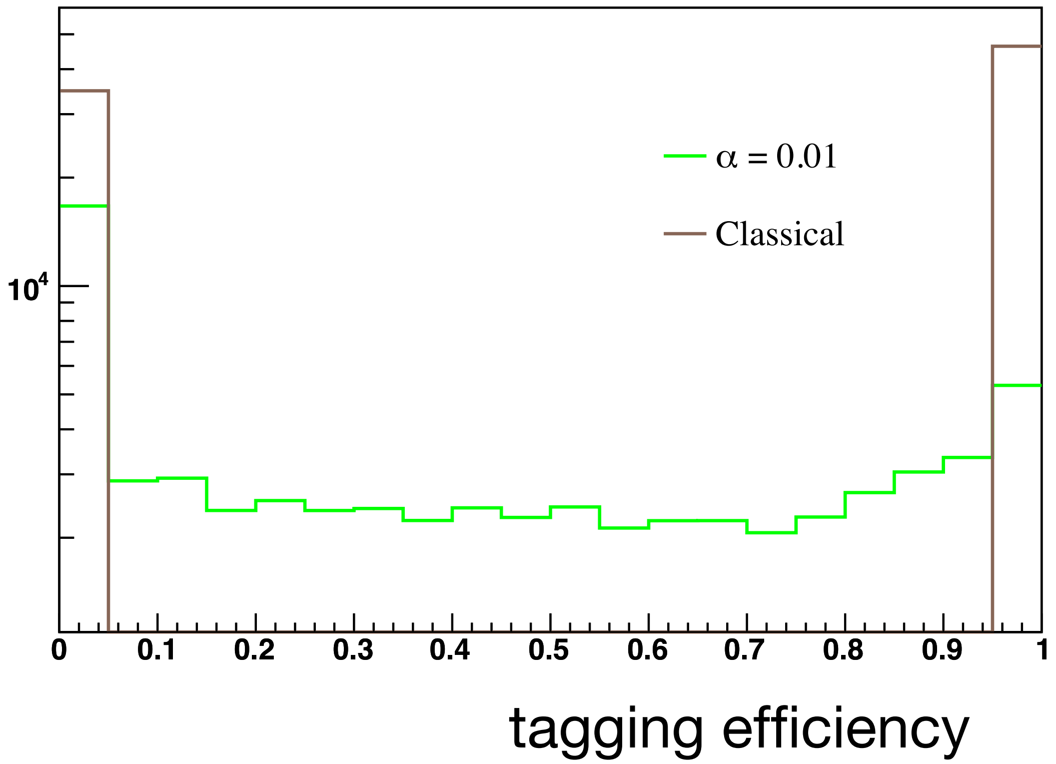
tagging efficiency is a number between 0 to 1

QPruning vs. Pruning

Consider candidates for a W jet



Mass window for W



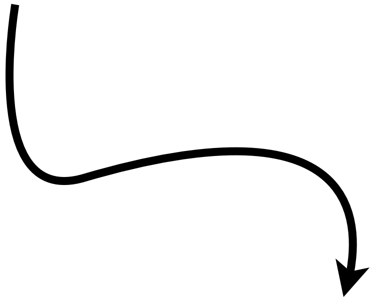
Pruning -> QPruning

A transition from a discrete (binomial distribution) to a continuous distribution

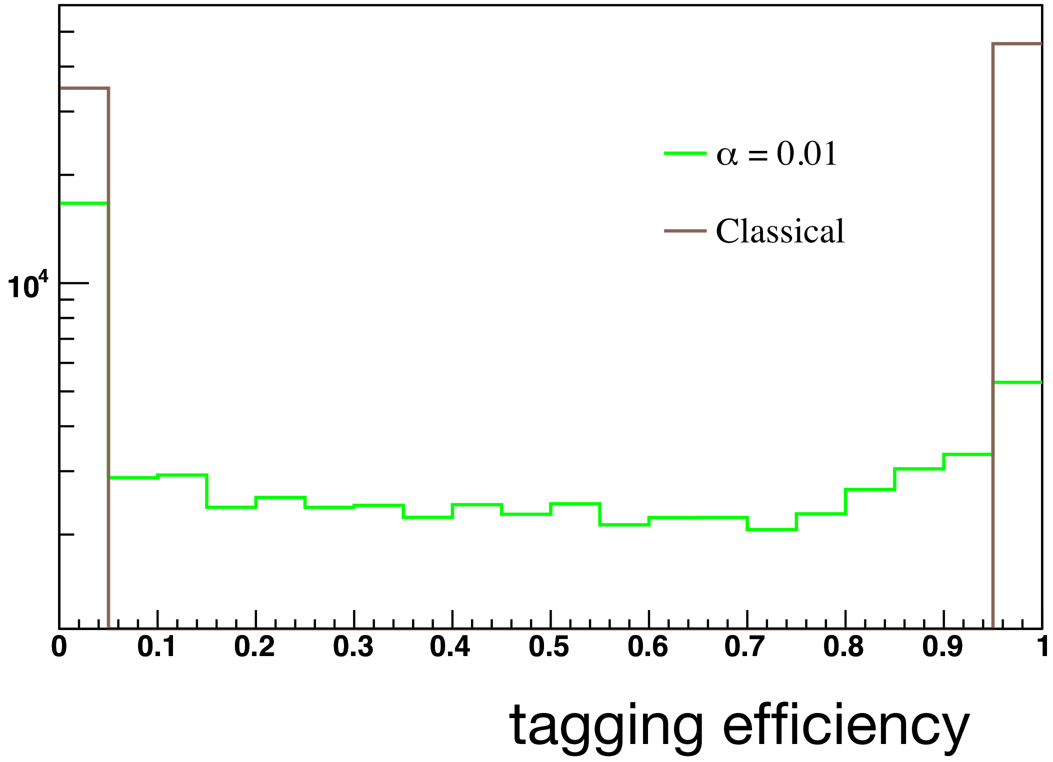
QPruning vs. Pruning

Pruning --> QPruning

A binomial distribution --> a continuous distribution



Use the distribution to reduce statistical fluctuations in measurements



Application 2: CS measurement

- As an example, take a sample of ~10 boosted QCD jets and ask for number of jets in a mass bin.
- The uncertainty associated with cross-section measurement decreases from classical pruning to QPruning
- Need half the luminosity to make a measurement of the same precision.

Algorithm	$\frac{\delta N}{\sqrt{N}}$	Relative luminosity required
prune with C/A	~1.0	1.0
QPrune	0.72	0.52

Application 3: mass measurement

- As an example, take a sample of ~10 boosted W jets and ask for average jet mass.
- The uncertainty associated with mass measurement decreases from classical pruning to QPruning
- Need less than half the luminosity to make a measurement of the same precision.

Algorithm	Mass uncertainty [GeV]	Relative luminosity required
prune with C/A	3.2	1.0
QPrune	2.4	0.58

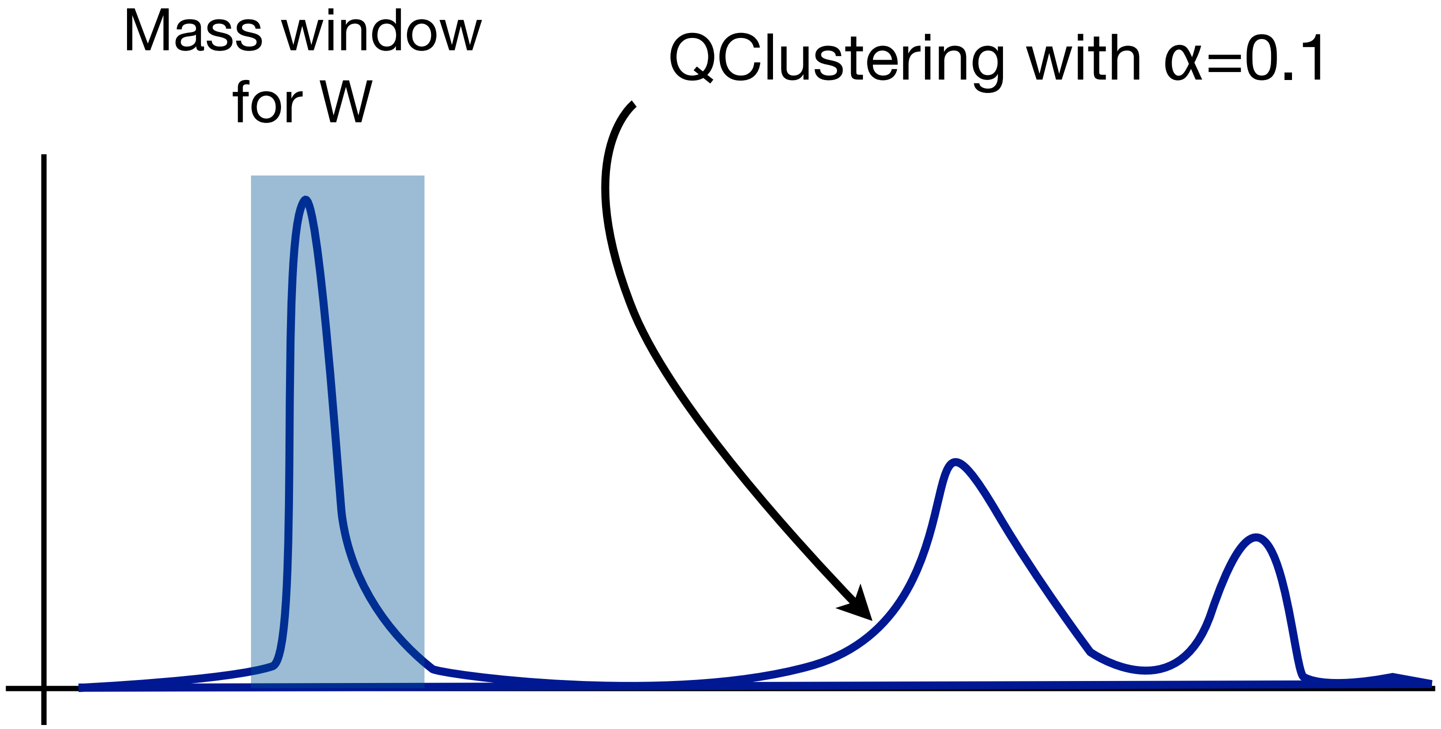
Future Directions

- In substructure physics, it still remains to be seen whether QClustering can be applied to other quantities such as mass-drop, Y_{23} etc.
- QClustering has been done on the elements of a jet. We intend to extend it to an entire event.
- We need to find a formalism towards analytical calculations.

Future Directions

- QClustering has been done on the elements of a jet. We intend to extend it to an entire event.

work in progress with Krohn, Schwartz and Dilani



all di-jet masses in a W+jet event

Conclusion

Jet substructure is an extremely interesting and active field.

- $\mathcal{O}(10)$ dedicated workshops in last 5 years, active experimentalists+theorists collaboration, there is a lot of creativity.

Grooming tools (pruning, trimming, filtering) even though designed for boosted search, are useful and essential for non-boosted cases.

We introduced QClustering: a non-deterministic jet clustering algorithm.

- QClustering lets us look inside a jet in a new way.
- QClustering + pruning renders stability to jet observables and provides new discriminants for the discovery of signal jets.
- This is only the beginning!