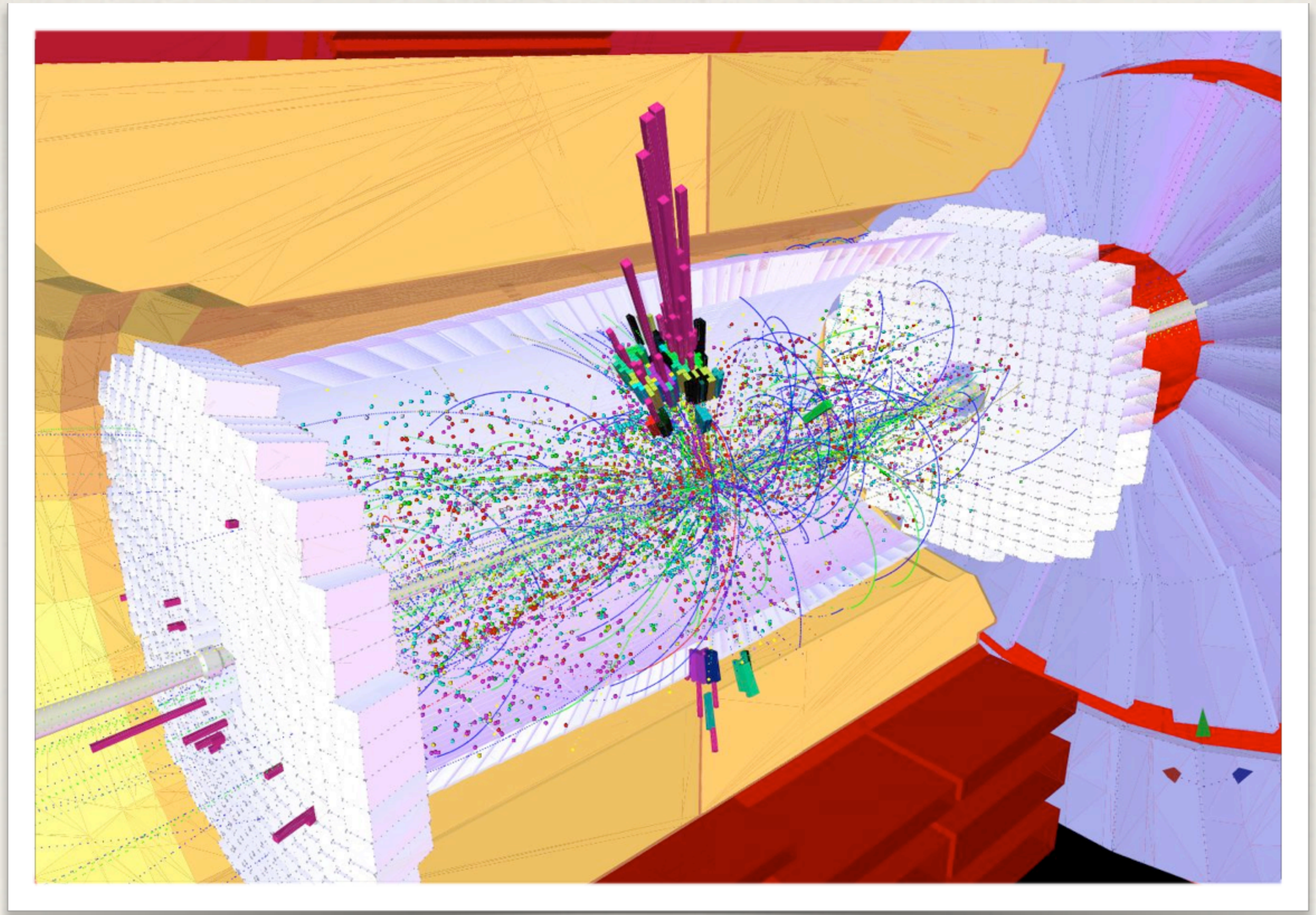


Jets and Jet Substructure at the LHC

David Krohn (Harvard)

LHC-TI Conference (BNL) 10/7/10

Image: http://cms.web.cern.ch/cms/Media/Images/EventDisplays/Simulations/index.html

Outline

1. Jet Algorithms
    - Jet Grooming
2. Jet Substructure
    - Unburied Higgs

Takeaway

- Hopefully, by the end of the talk you will be convinced that

1. When you perform a collider study, it's worthwhile to consider different jet algorithms.

    - This choice can make an appreciable difference in sensitivity.

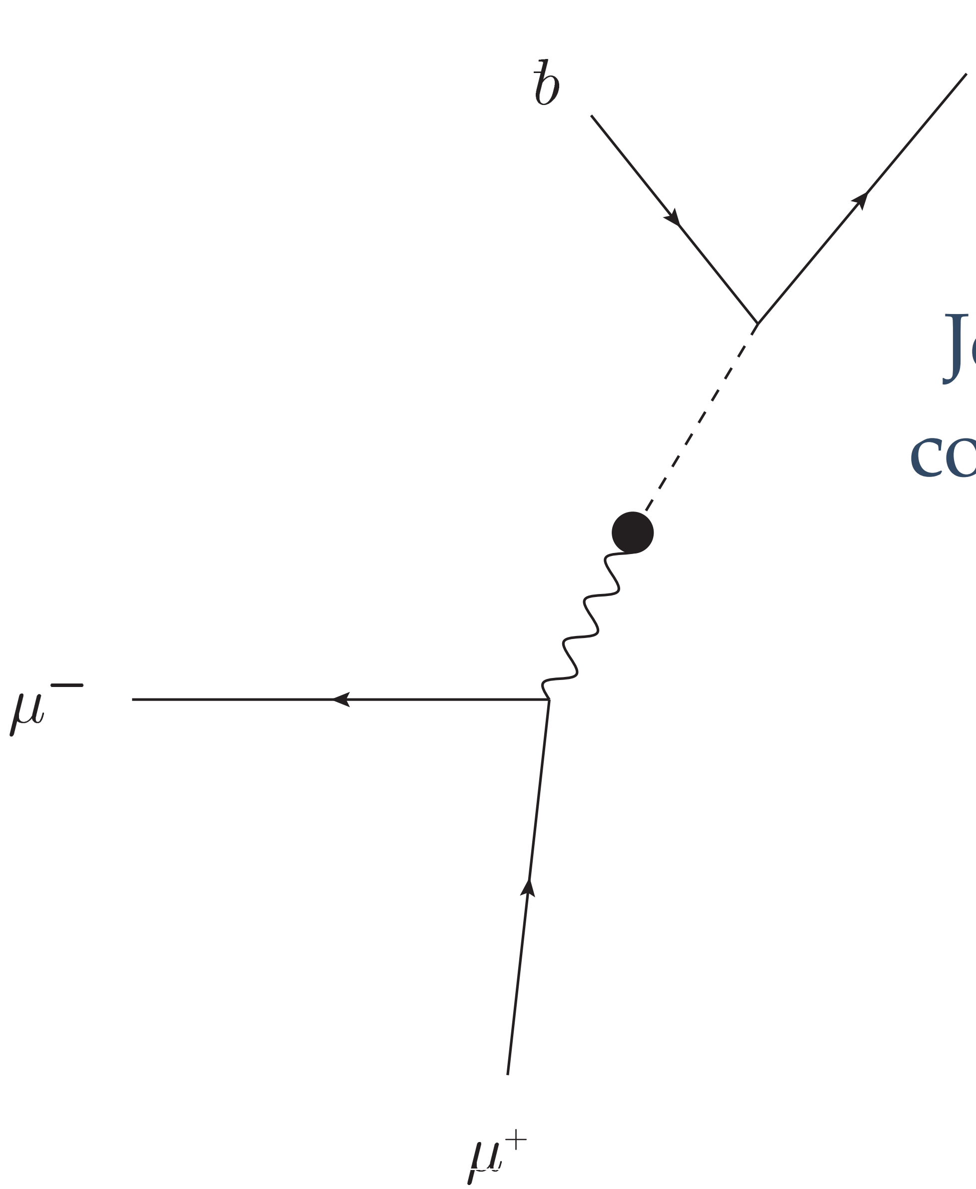
2. You should consider the boosted regime when designing a collider analysis.

    - Looking at boosted objects can simplify combinatorics, and give one access to new information (e.g. color structure).

Part I - Jets

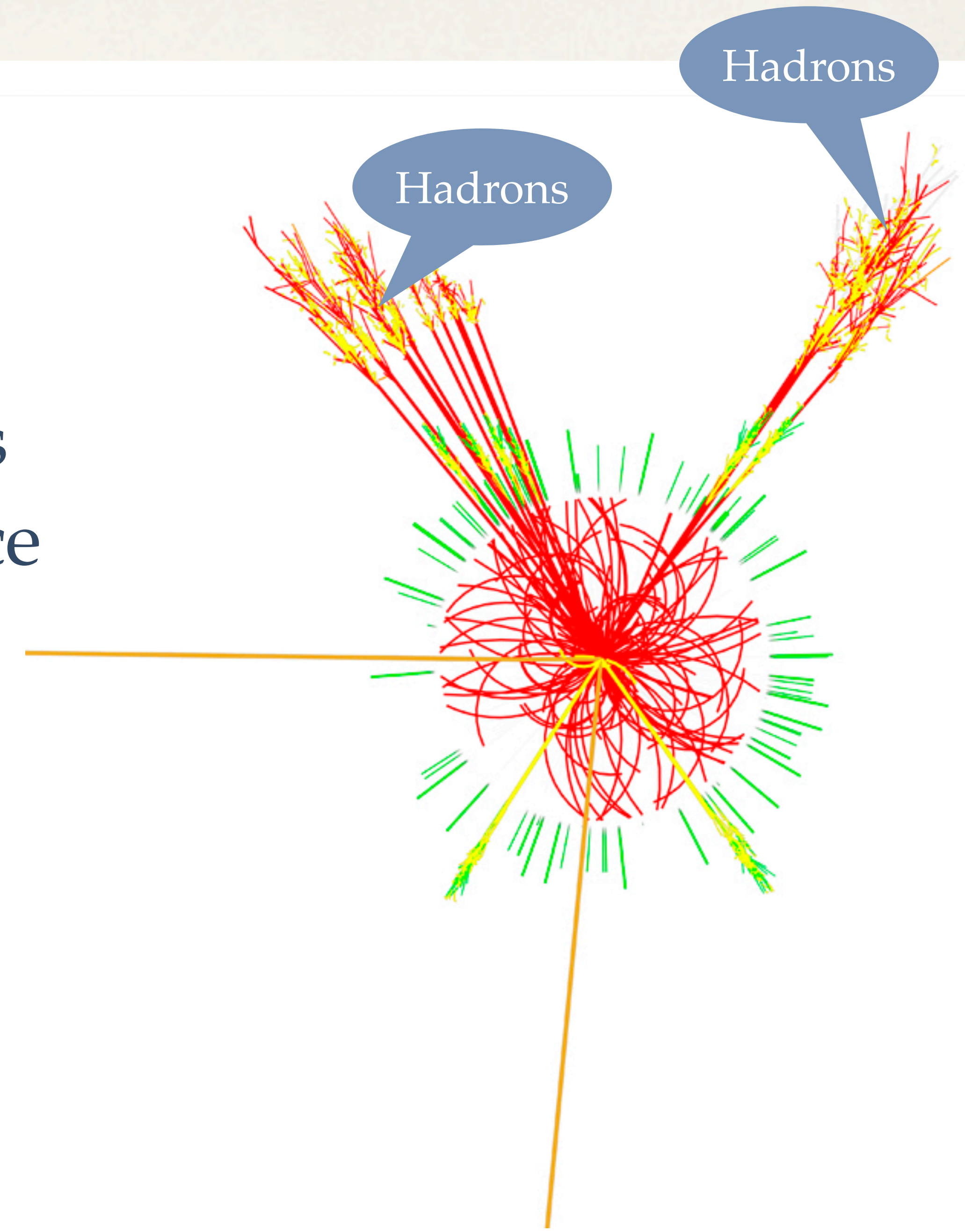
What is a Jet?

- A jet is a kinematical object we construct from collider data.
  - Specifically, jets are collections of hadronic four-vectors used to approximate the kinematics of the hard scattering in a collider event.
- They help us map things we cannot easily calculate (the exact energy distribution in the calorimeter) to things we can (perturbative Feynman amplitudes)



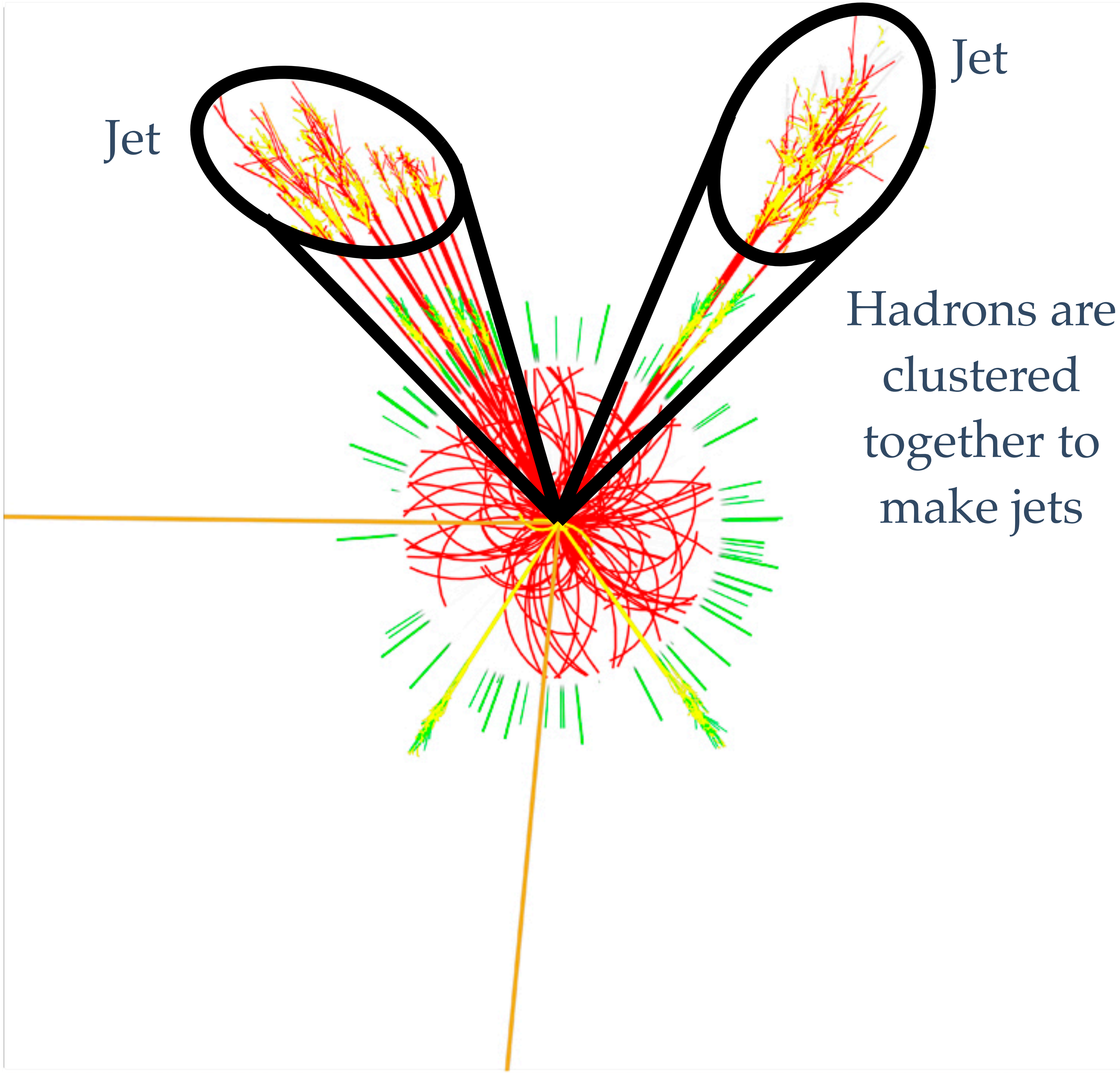
What we calculate

Jets make this correspondence



What we measure

Image: http://www.atlas.ch/photos/events-simulated-higgs-boson.html



Hadrons are clustered together to make jets

Image: http://www.atlas.ch/photos/events-simulated-higgs-boson.html

Jet Algorithms

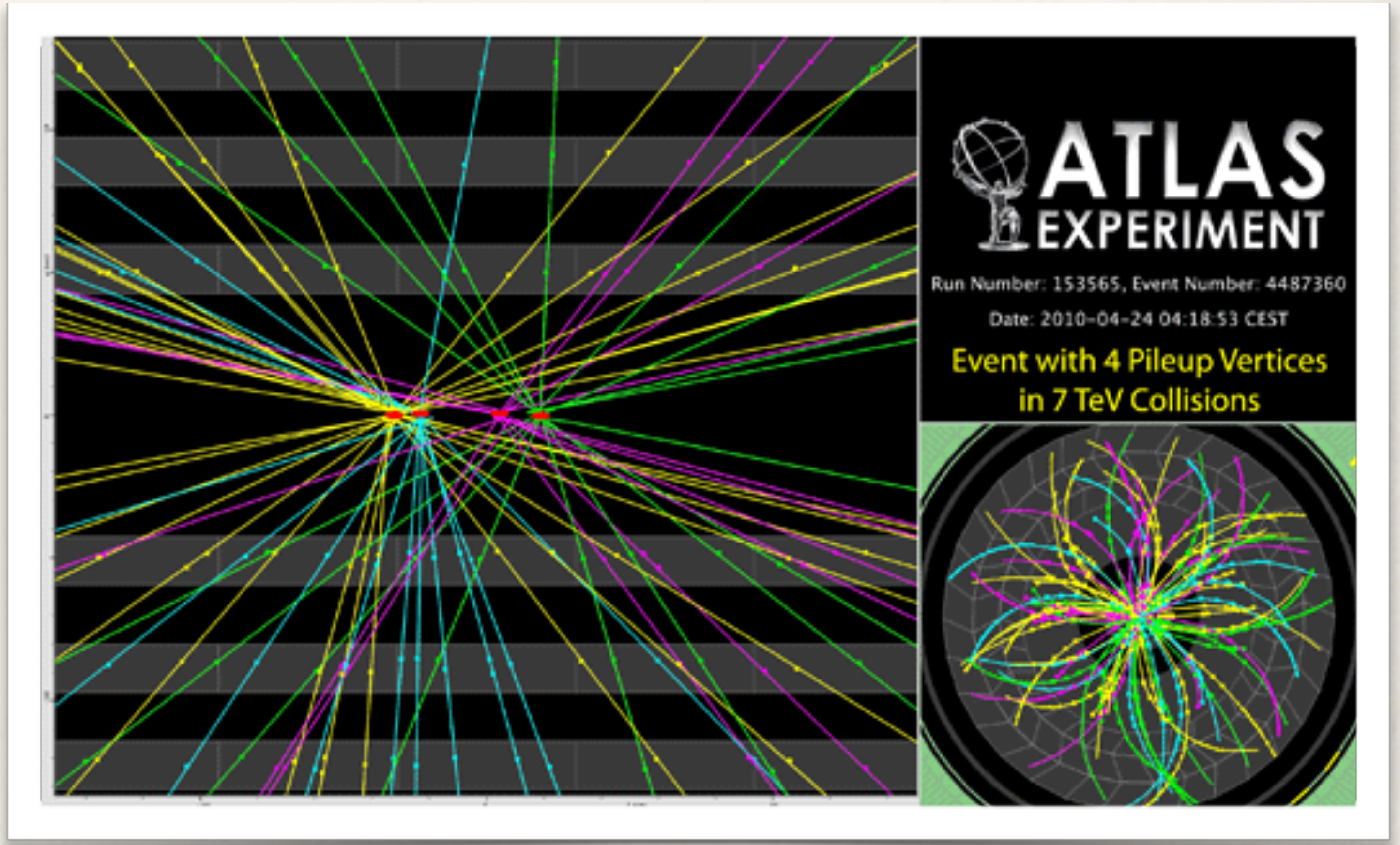
- Jet Algorithms are what we use to make jets from collider data.
- There has been a lot of recent activity in this subject.
- Here I'll discuss one particular jet algorithm - "Jet Trimming".

Jet Trimming

Source: DK, J. Thaler, and L. Wang, JHEP 1002 (2010) 084 [arXiv:0912.1342]

Messy Jets

- The LHC is a messy place.
- Contaminating radiation can always come from ISR and multiple interactions, but at the LHC a major source is pileup.
  - Pileup is when multiple scatterings take place in the same bunch-bunch crossing



Quantifying Contamination

- How much contamination is there?
- Contamination density in GeV/area:

$$\rho \sim \left(1 + \frac{N_{\rm PU}}{4}\right) \times (2 \leftrightarrow 3 \ \mathrm{GeV})$$

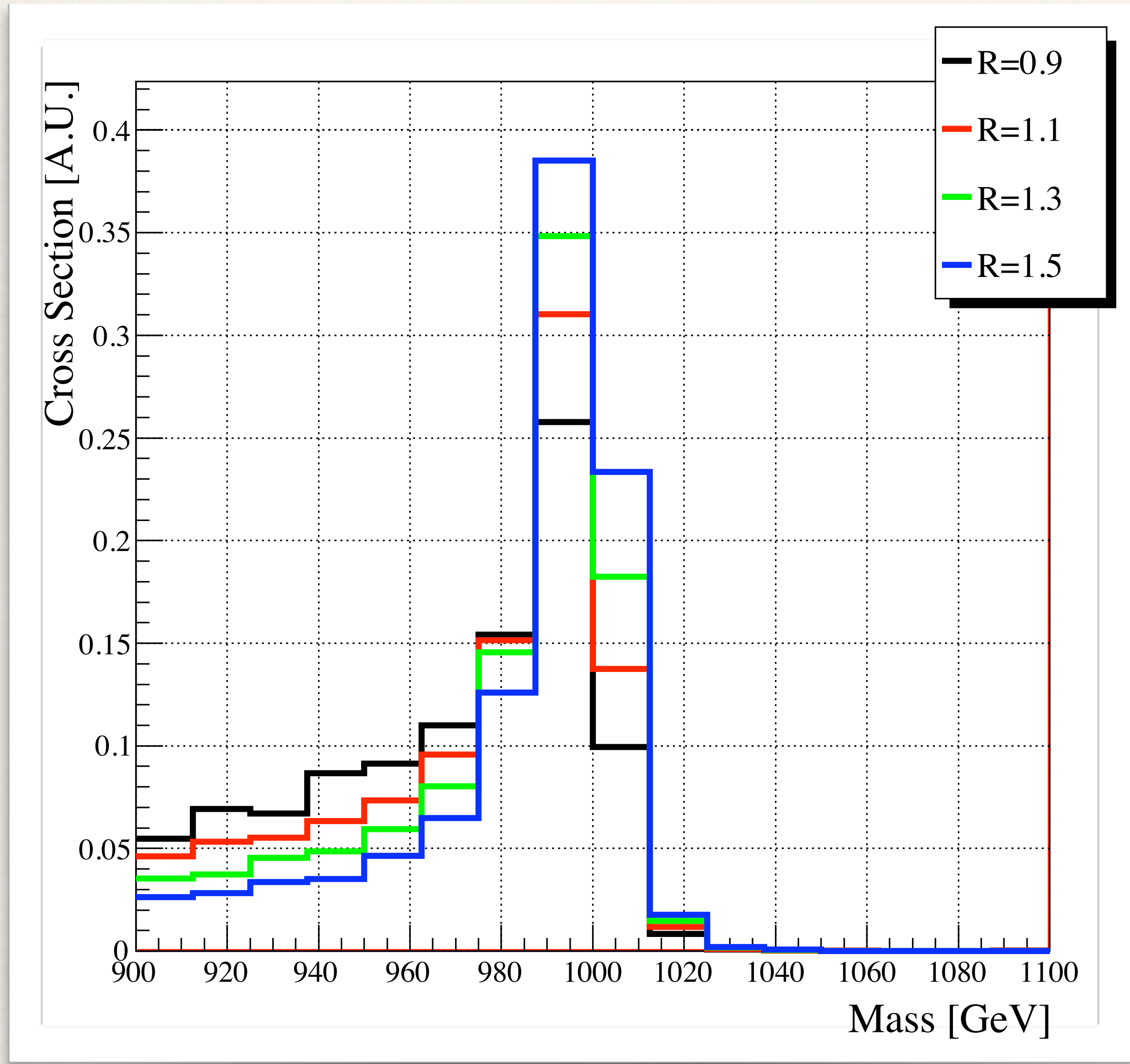
- The number of pileup events per crossing (N_{PU}) depends on the LHC running parameters. Roughly though, at 14 TeV we should start at ~20 and go to ~40.

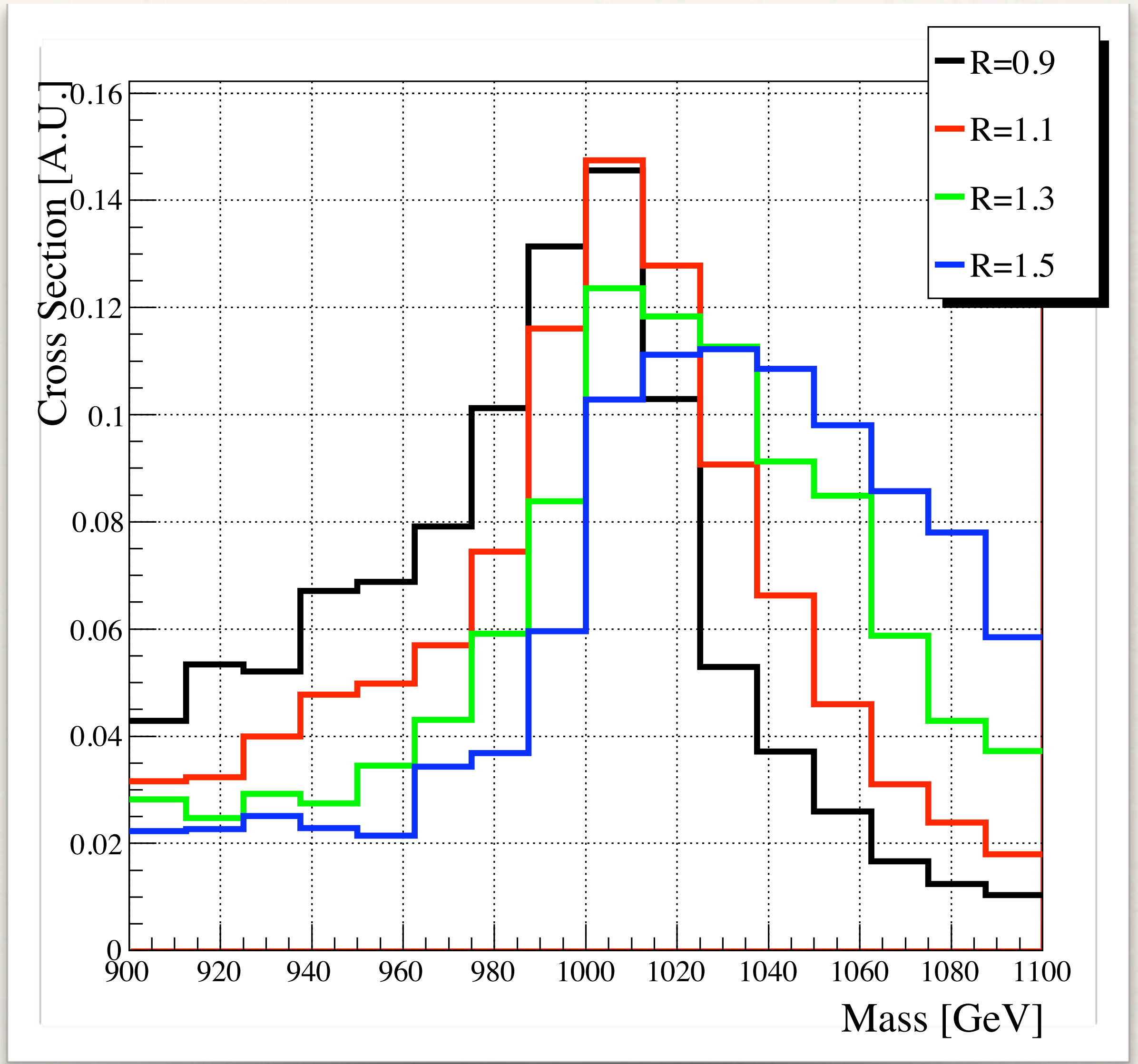
Source: M. Rubin [1002.4557]

Motivation for Trimming

- When we cluster jets there's inevitably a tradeoff:
  - Larger cones are less likely to miss radiation
  - But, they're also more susceptible to contamination

Contamination in Resonance Reconstruction





Contamination Off

Contamination On

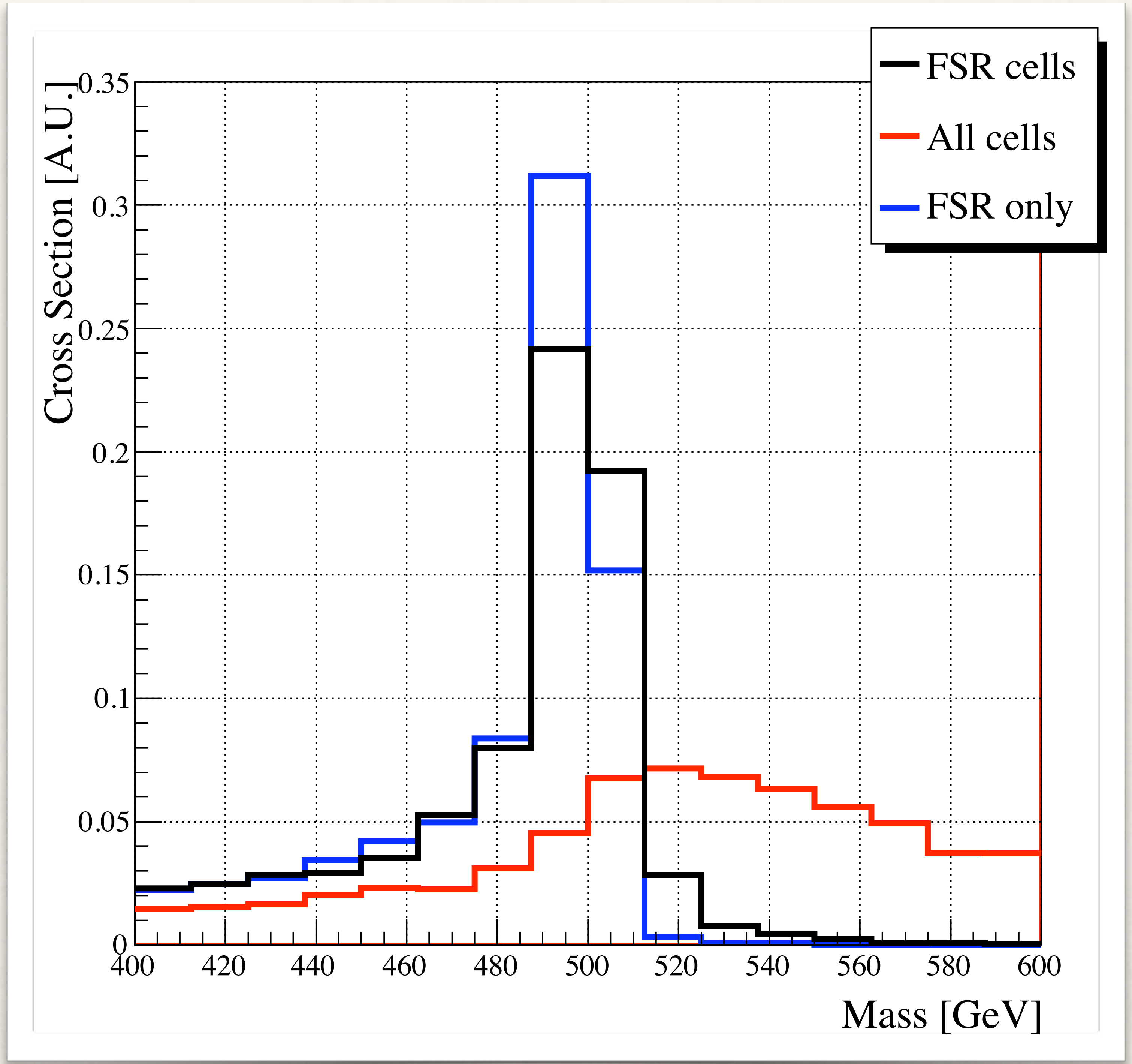
- In *Jet Trimming* we investigated ways to systematically remove jet contamination and improve reconstruction.

- There's a lot of room for reconstruction improvement.

- Irreducible contamination (we can't distinguish radiation in the same cell) is not a problem

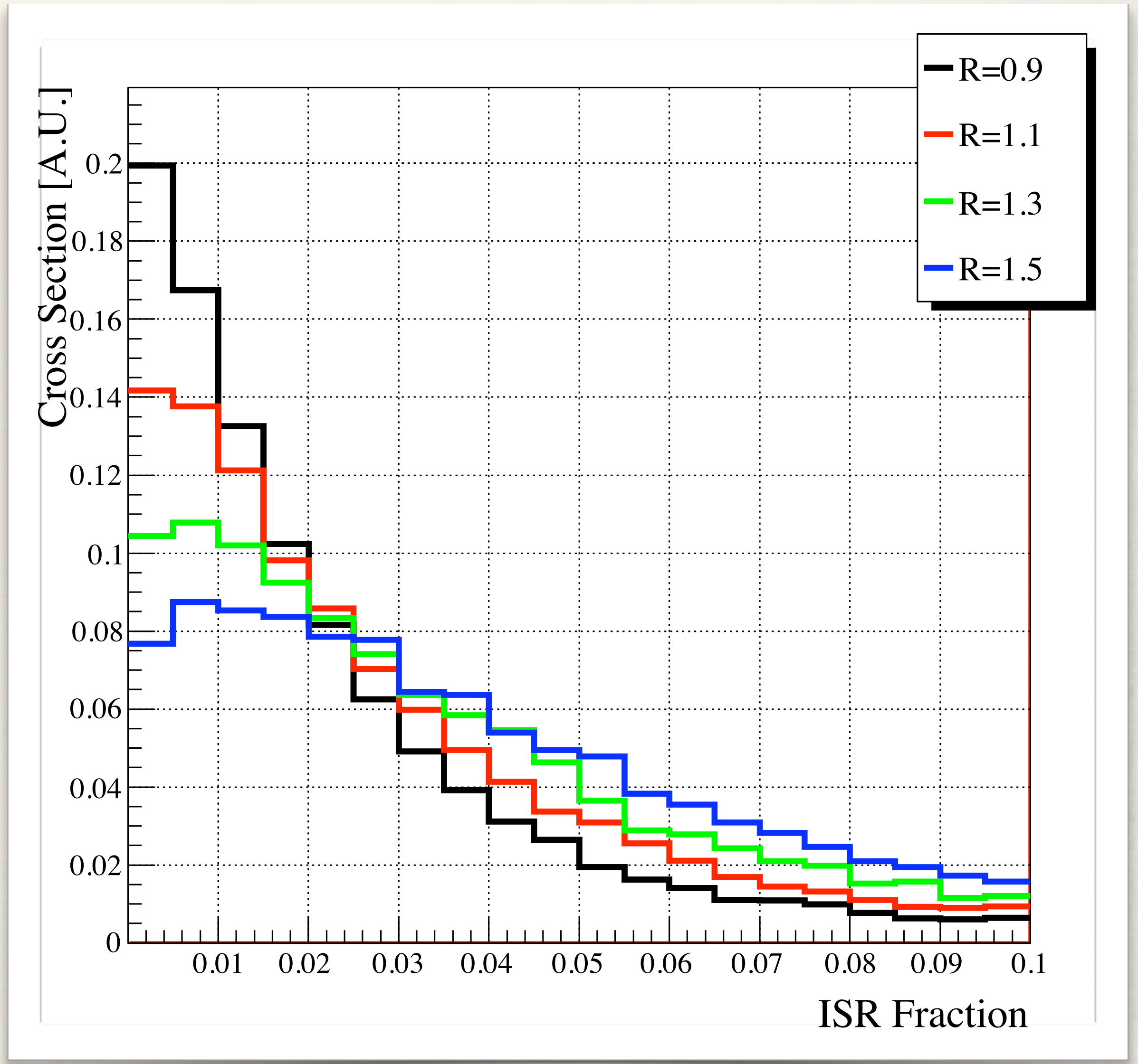
	Improvement	R_0	Γ [GeV]	M [GeV]
	$gg \to \phi \to gg$			
All cells	-	1.2	69	518
FSR cells	309%	1.5	15	501
	$q\bar{q} \to \phi \to q\bar{q}$			
All cells	-	0.8	31	505
FSR cells	189%	1.5	11	501

- If we knew what cells contained significant FSR, then we'd be able to remove everything else and nearly reproduce the distribution without contamination:



Trimming in Practice

- Contamination is usually quite soft (total ~5% of p_T).
- Use this to our advantage by only keeping the hard parts of a jet.



Implementation

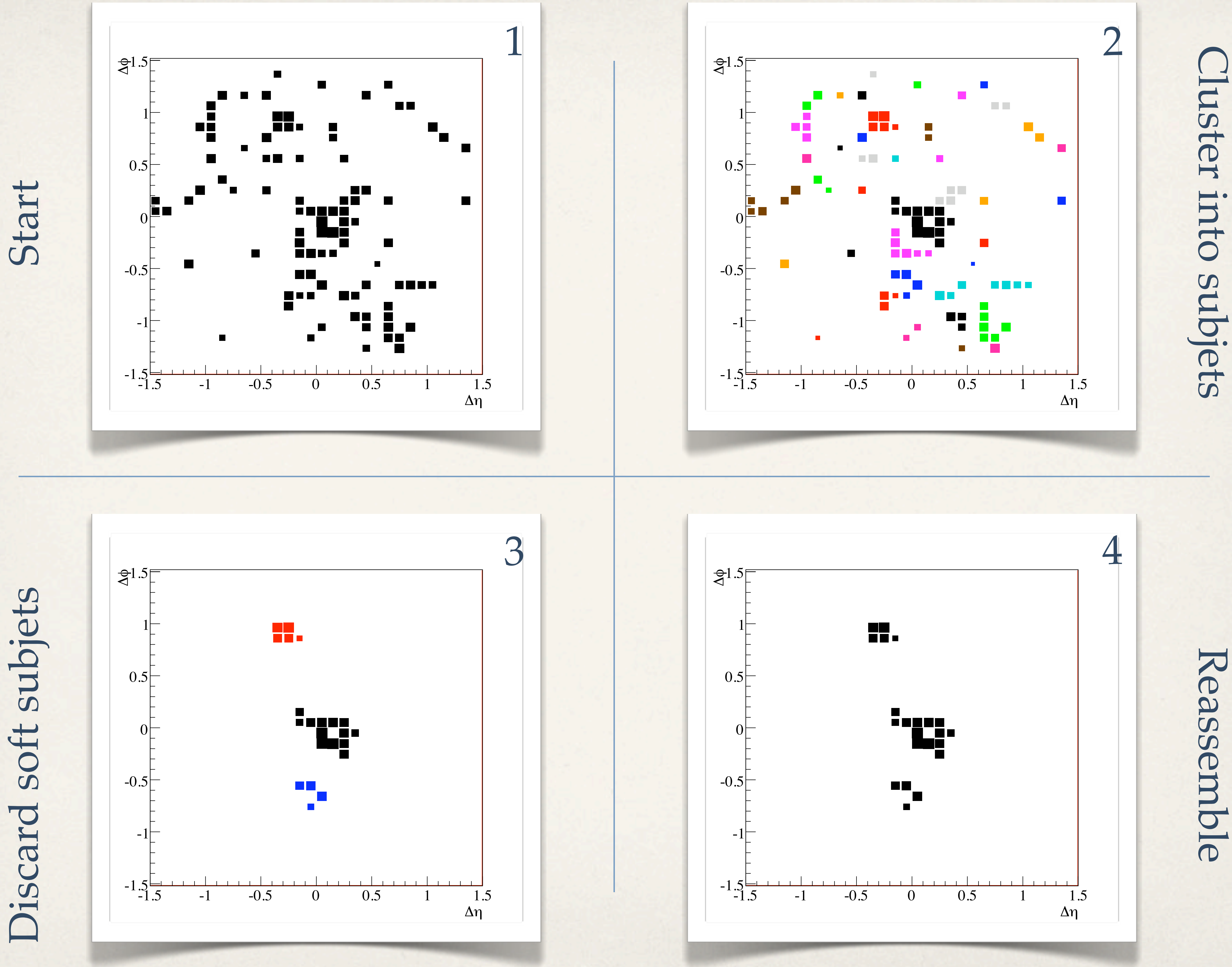
1. Cluster all calorimeter data using any algorithm

2. Take the constituents of each jet and recluster them using another, possibly different, algorithm (we advocate k_T) with smaller radius R_{sub} ($R_{sub} = 0.2$ seems to work well).

3. Discard the subjet i if

$$p_{Ti} < f_{\rm cut} \cdot \Lambda_{\rm hard}$$

4. Reassemble the remaining subjets into the trimmed jet

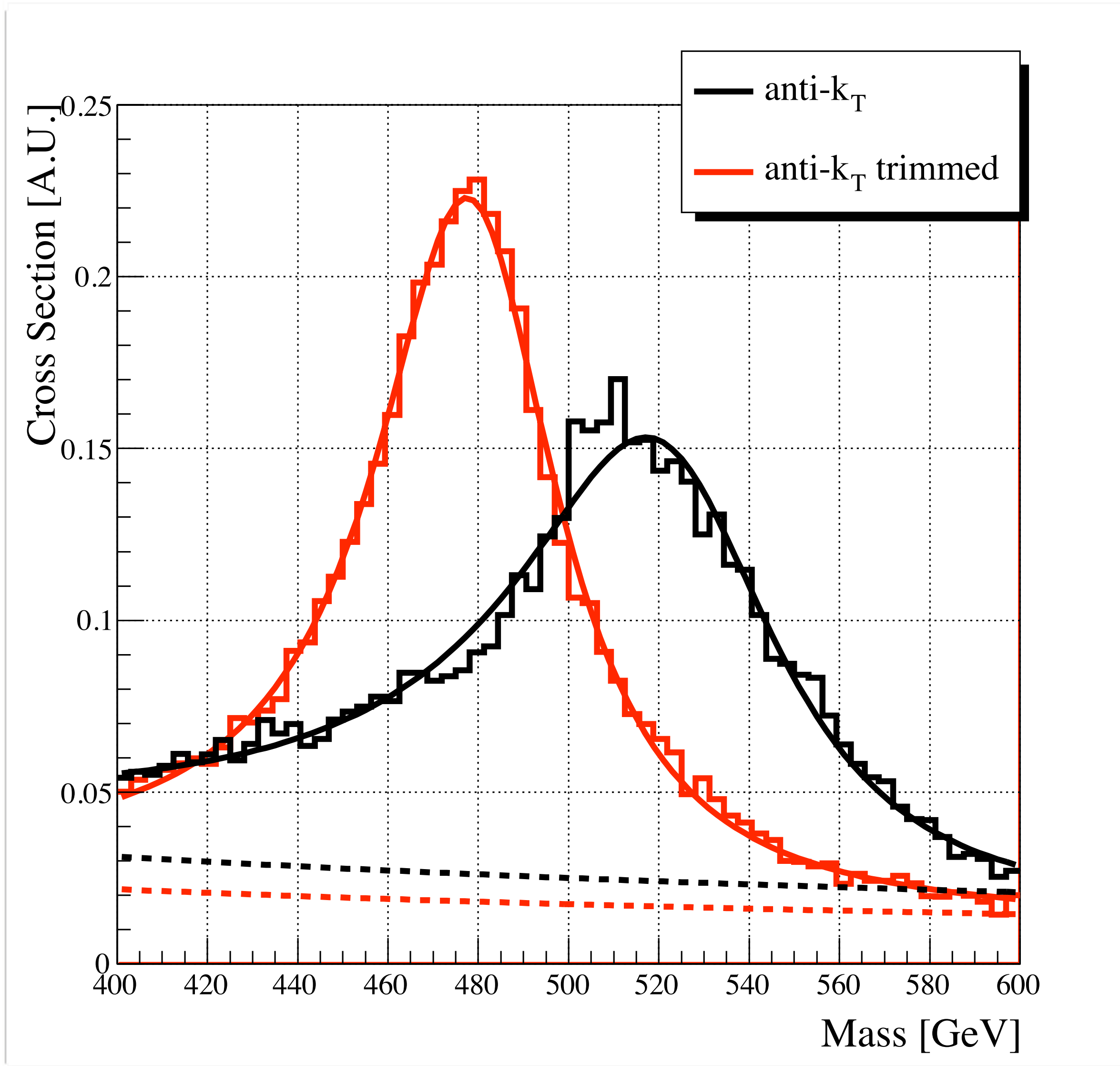

Start
Cluster into subjets
Discard soft subjets
Reassemble
1
2
3
4
Δφ
Δη

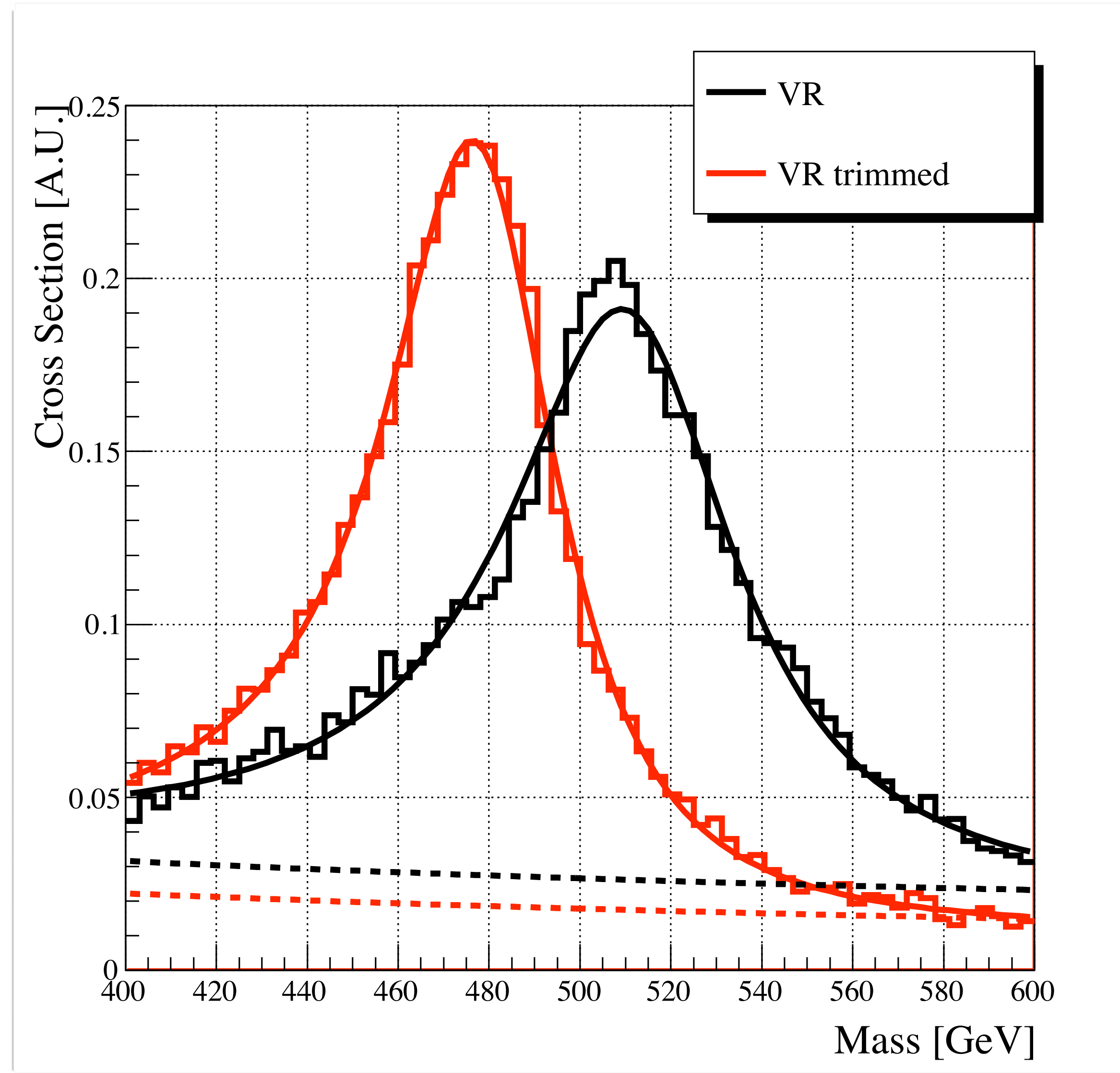
Results

- Find a significant improvement from using trimming to reconstruct a resonance decaying to dijets ($gg \to \phi \to gg$)

	Improvement	f_{cut}, N_{cut}	R_{sub}	R_0, ρ	Γ [GeV]	M [GeV]
anti-k_T	-	-	-	1.0^*	71	522
anti-k_T (N)	40%	5^*	0.2^*	1.5^*	62	499
anti-k_T $(f,\, p_T)$	59%	$3 \times 10^{-2*}$	0.2	1.5	52	475
anti-k_T $(f,\, H)$	61%	$1 \times 10^{-2*}$	0.2	1.5	50	478
VR	30%	-	-	200^* GeV	62	511
VR (N)	53%	5	0.2	275^* GeV	53	498
VR $(f,\, p_T)$	68%	3×10^{-2}	0.2	300^* GeV	49	475
VR $(f,\, H)$	73%	1×10^{-2}	0.2	300^* GeV	47	478
Filtering	27%	2	$R_0/2$	1.3^*	61	515

All histograms (those with and without trimming) are made using optimized parameters.



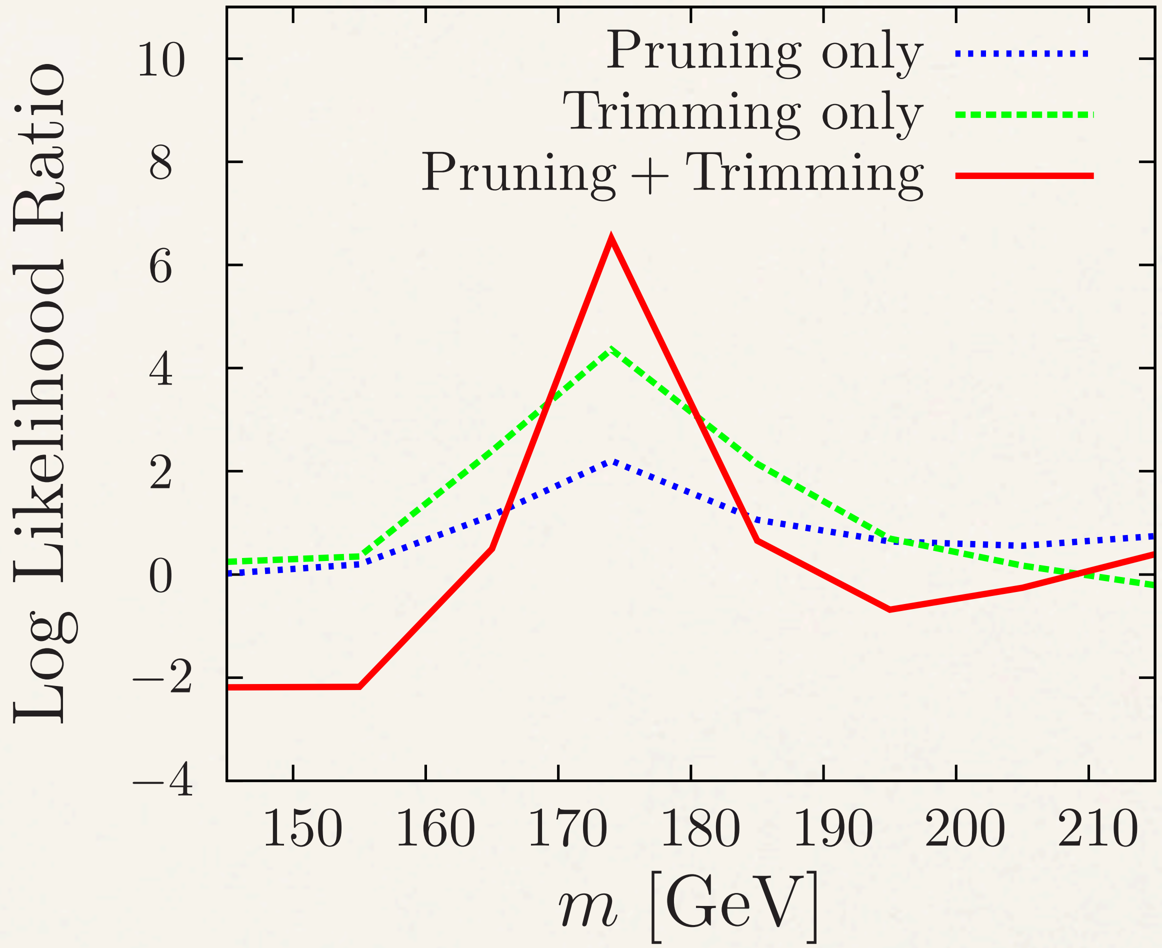


- Trimming was designed to clean up boosted “QCD Jets”. There are other approaches focused on cleaning up jets from boosted heavy objects

  1. Jet Pruning (Ellis, Vermilion, Walsh): 0903.5081, 0912.0033

  2. Filtering (Butterworth, Davison, Rubin, Salam): 0802.2470

- If you combine multiple algorithms together and statistically optimized you can do better:



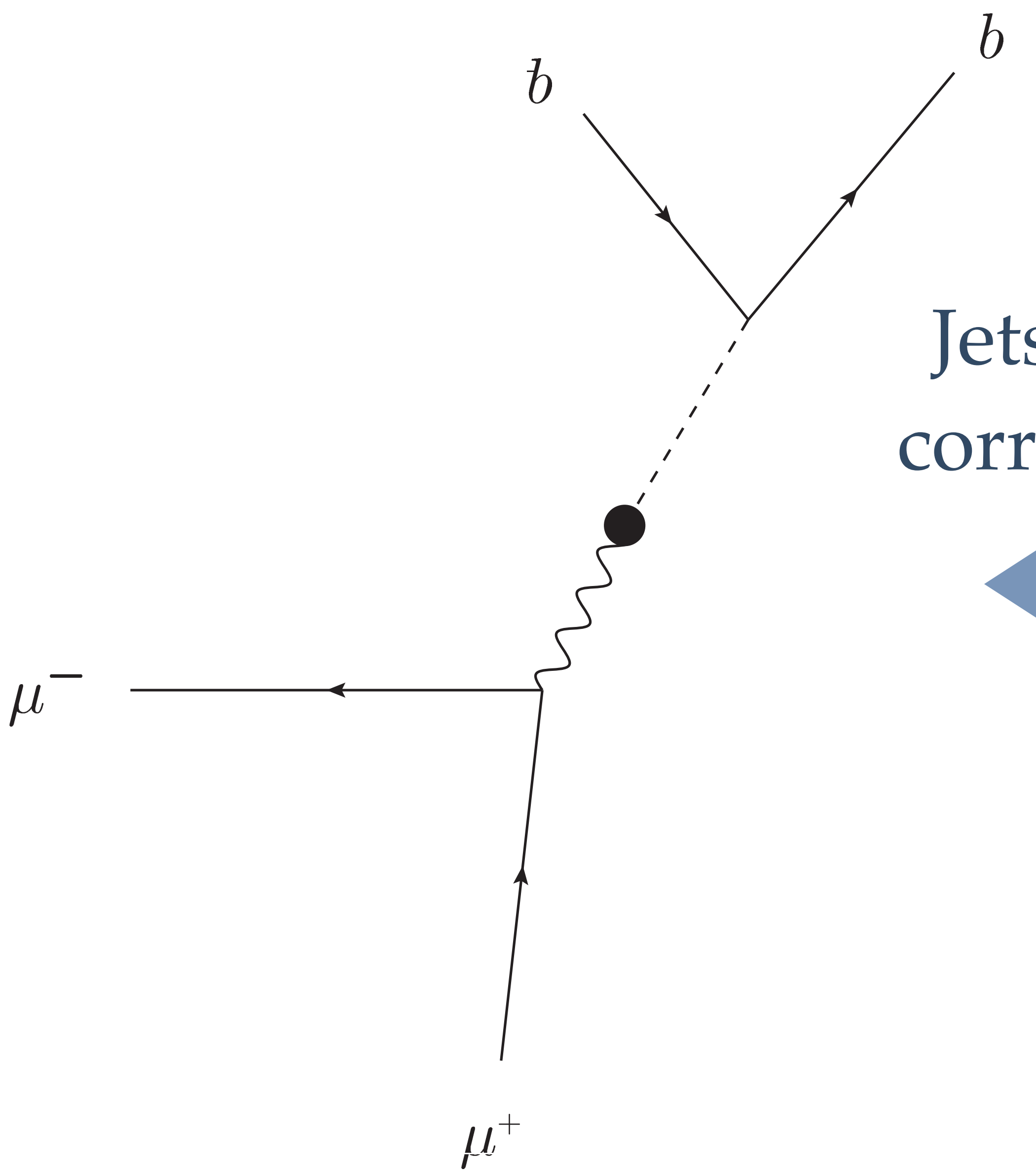
- Still a lot of room for improvement!

Figure source: Combining subjet algorithms to enhance ZH detection at the LHC, D. E. Soper, M. Spannowsky, [arXiv:1005.0417]

Part II - Jet Substructure

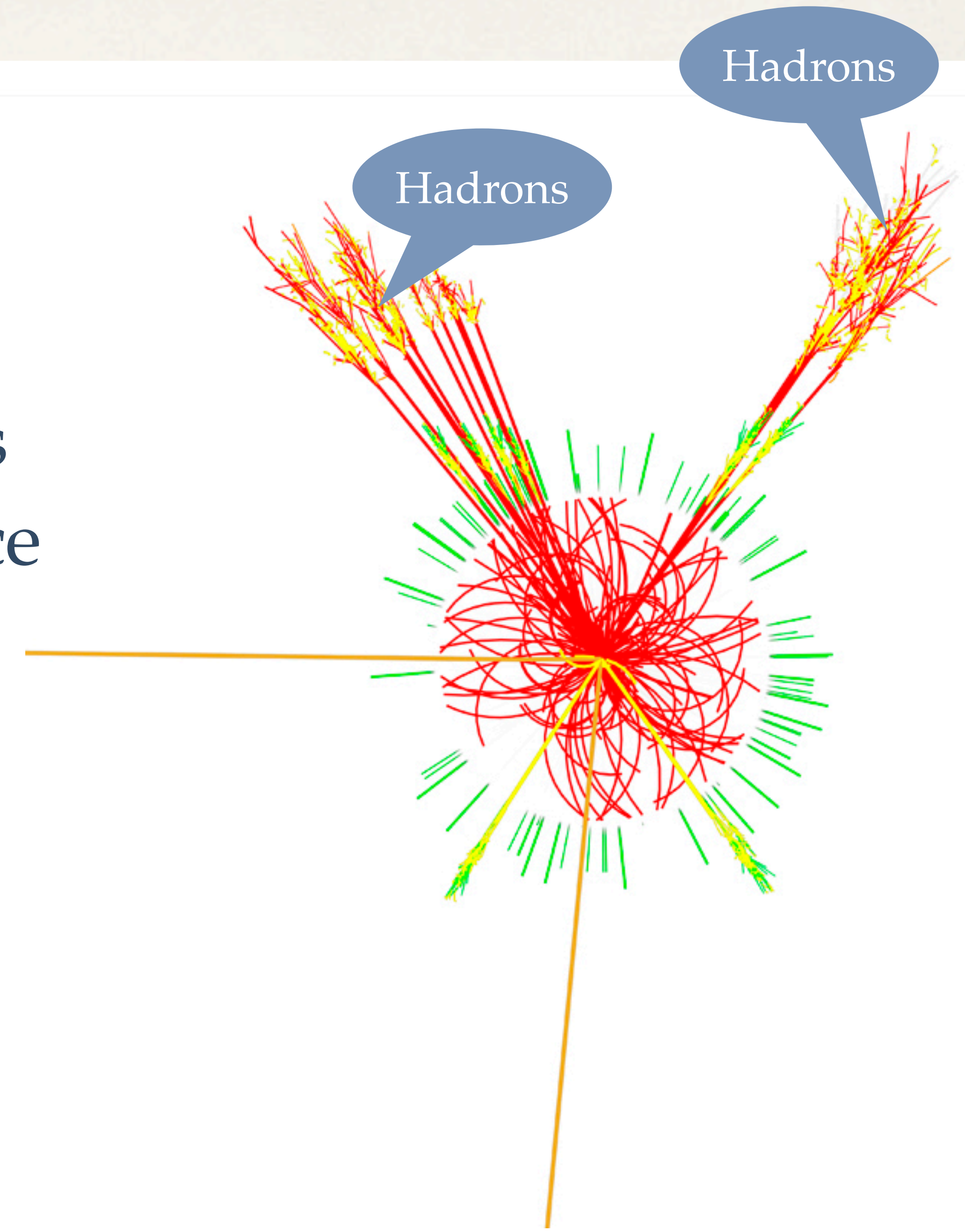
Jets

- We just discussed how jet algorithms operate.
  - They allow us to make the connection between what we calculate (feynman diagrams) and what we measure in the detector.
  - For instance, we'd expect to see two jets for each h->b bbar decay.



What we calculate

Jets make this correspondence



What we measure

Event picture from http://atlas.ch/photos/events.html

- However, this correspondence between jets and partons breaks down when things become collimated.

Kinematics of Boosted Particles

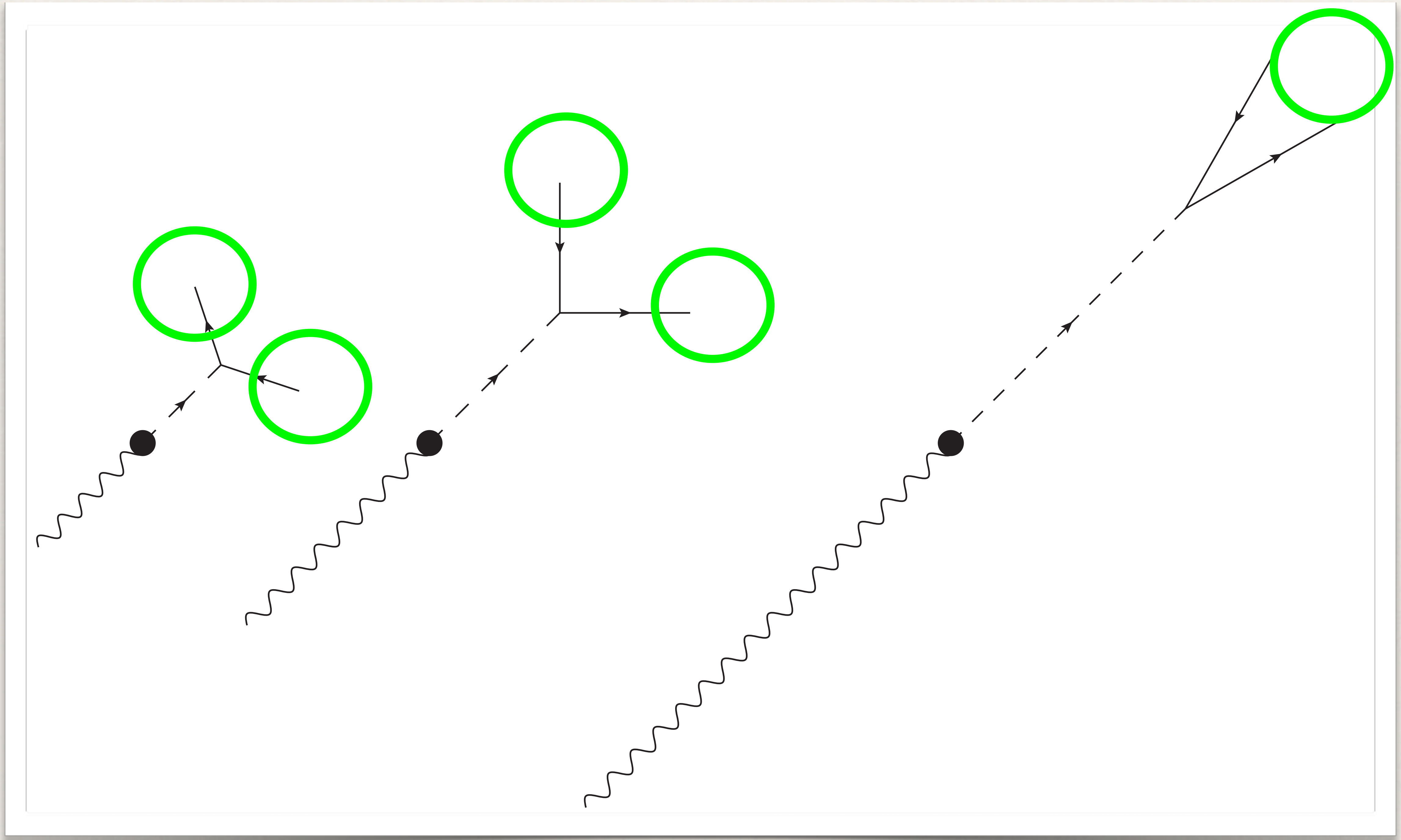
- The cone containing the decay products of a particle scales as

$$R \sim \frac{2m_X}{p_T}$$

- At LHC energies, even the heaviest particles we know of (Top, W, Z, Higgs) become can become collimated.

- When this happens we say that they're "boosted".

- So we find that EW scale particles are clustered as a single jet as soon as their p_T exceeds a few hundred GeV.



Here one can see the effect - as we boost more and more (i.e. go to higher pT), the particles become more collimated.

Boosted Collider Physics

- This can be a problem!
- Most new physics models include heavy states at the TeV scale
  - If these decay down to W/Z/t, what do we do if everything's collimated?
  - Traditional answer: use the leptonic decays to avoid this mess.
- Modern answer: look inside the jet and make use of QCD to see if the jet came from a boosted heavy object.

Tools

- QCD jets look really different than the jets of boosted heavy objects.
- QCD has soft/collinear singularities.
    - If we start with a high energy gluon/quark, it wants to emit soft/collinear gluons:

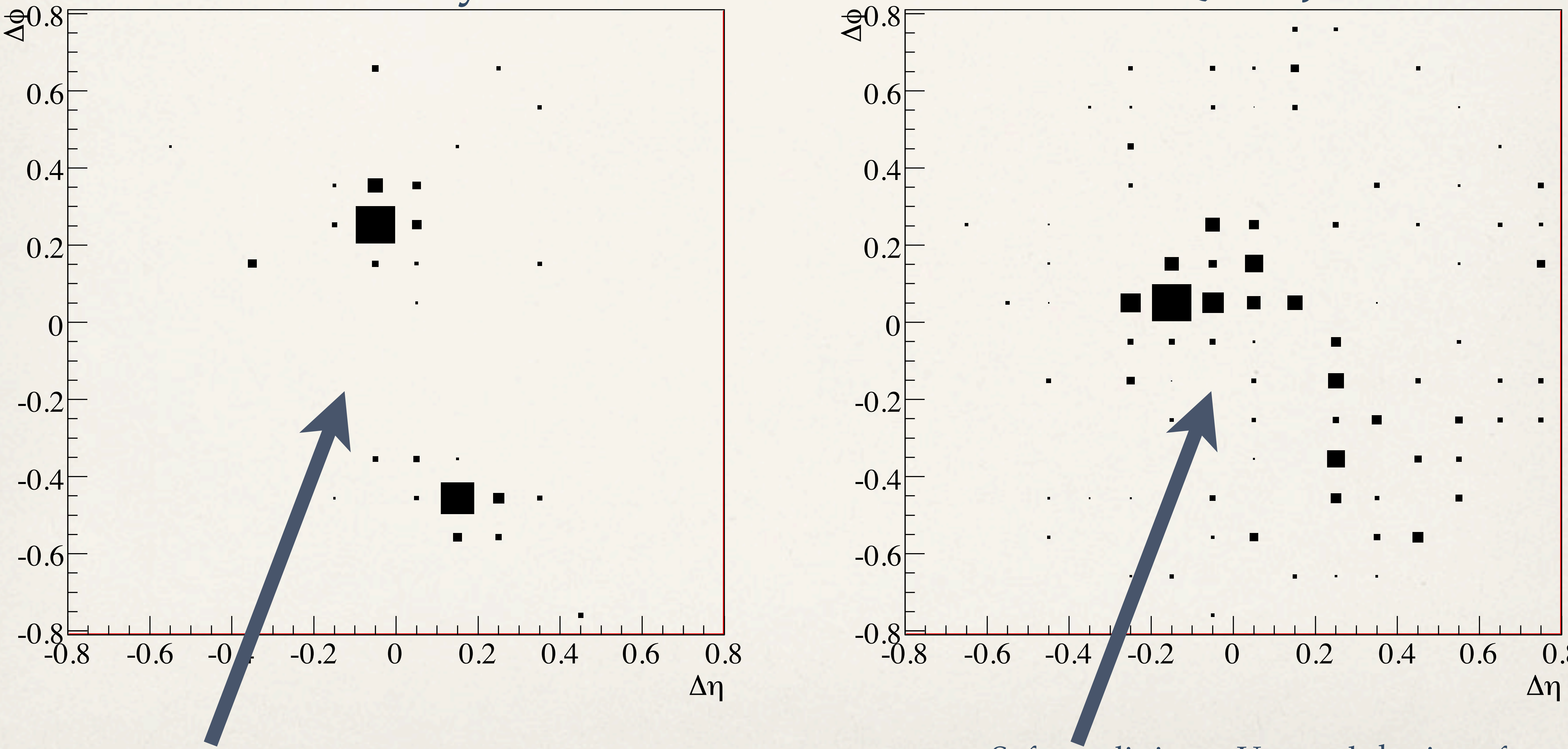
$$P_{q\to qg}(z) = C_F \frac{1+z^2}{1-z},$$
$$P_{g\to gg}(z) = C_A \left[\frac{1-z}{z} + \frac{z}{1-z} + z(1-z)\right]$$
$$P_{g\to q\bar{q}}(z) = T_R \left[z^2 + (1-z)^2\right],$$

    - Here P(z) measures how much a particle wants to emit another with energy fraction "z" (Altarelli-Parisi splitting fcns.).

- However, a high energy heavy particle (W/Z/t/h) just decays - it has no singularity.

Boosted Heavy Particle

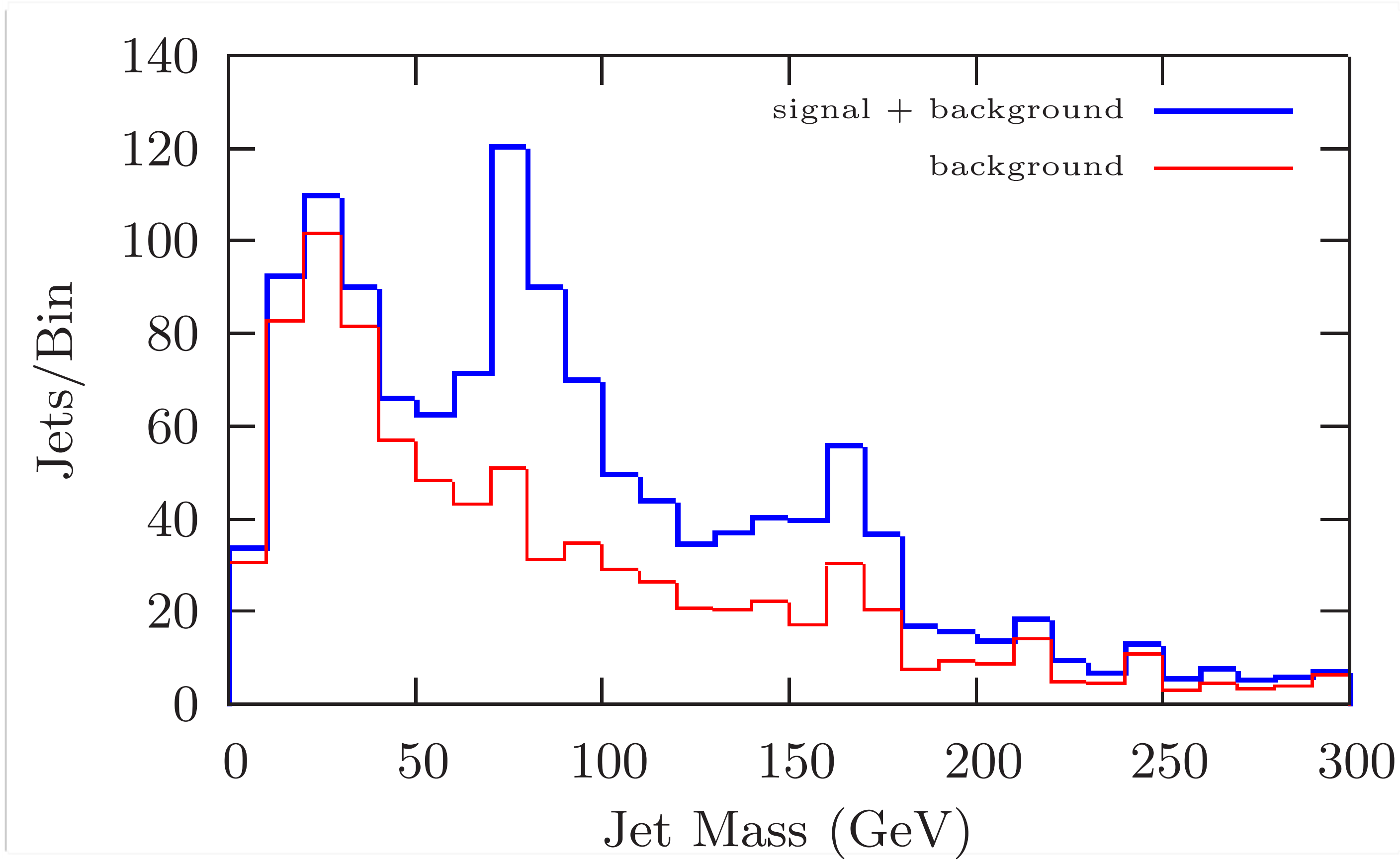
QCD Jet



Hard splitting, energy shared equally

Softer splittings. Unequal sharing of energy (note only one hard center)

- Moreover, QCD jets have a continuum mass distribution, while the jets of boosted heavy particles have a fixed mass.



- These will form our main tools.

1. Jet radiation distribution

2. Jet mass

Figure source: Using jet mass to discover vector quarks at the LHC, W. Skiba, D. Tucker-Smith, [hep-ph/0701247] Phys.Rev. D75 (2007) 115010

Application - Buried Higgs

Unburied Higgs

- The Buried Higgs model was created to yield an interesting phenomenology.
- Here the process h->*aa* can dominate the Higgs decay (*a* is a pseudoscalar)
- *a* will decay to gluons via a loop
- Thus the main decay mode of the Higgs can be (depending on the *a* mass)
    - h->aa->gggg

Unburied Higgs, A. Falkowski, D. Krohn, J. Shelton, A. Thalapillil, L. Wang, [arXiv:1006.1650]

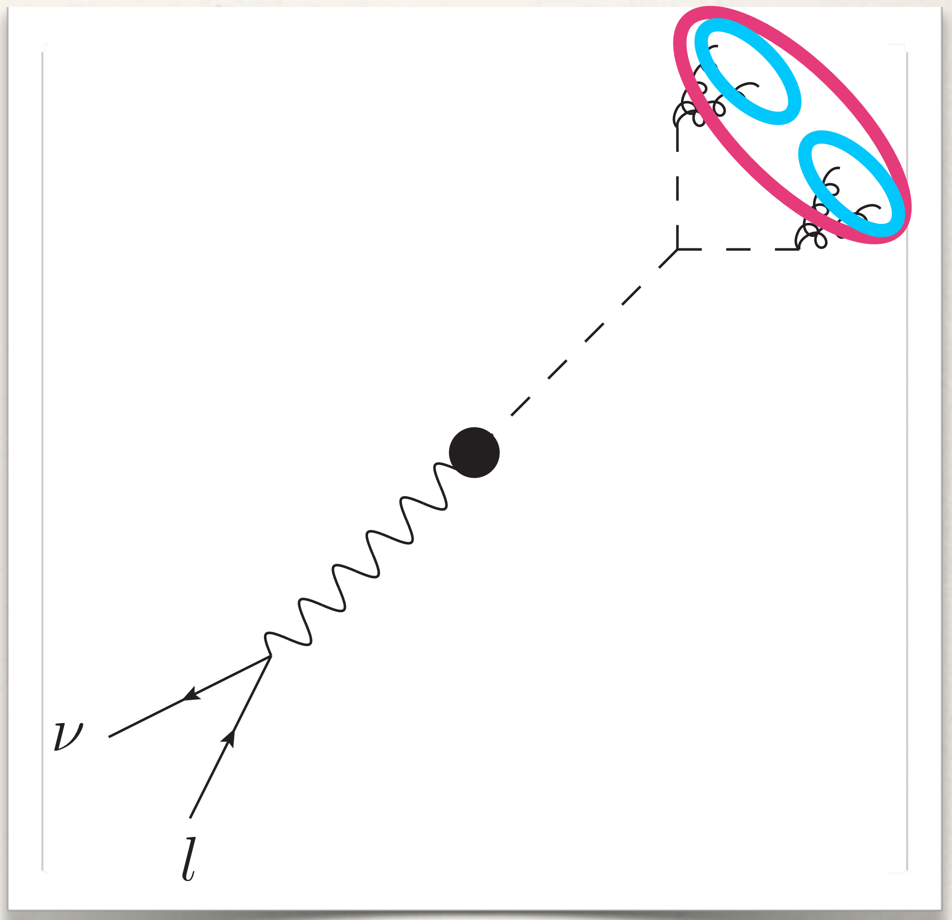
- The Buried Higgs model is very challenging to discover.
- Because the Higgs decays to gluons, it is “Buried” in the SM background.
- The trick to finding the Buried Higgs is to use substructure.

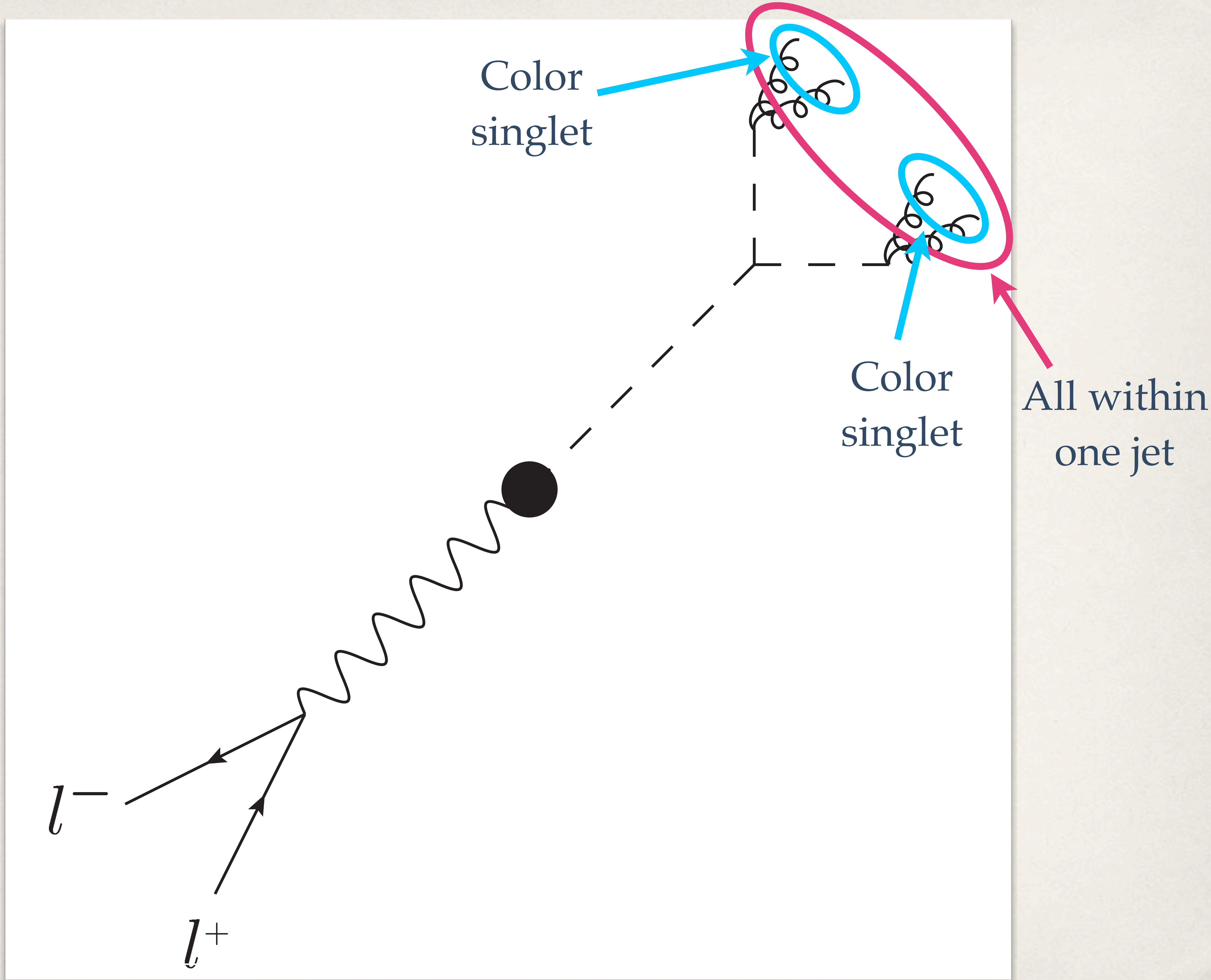
- A boosted Buried Higgs is distinguished in (at least) three ways

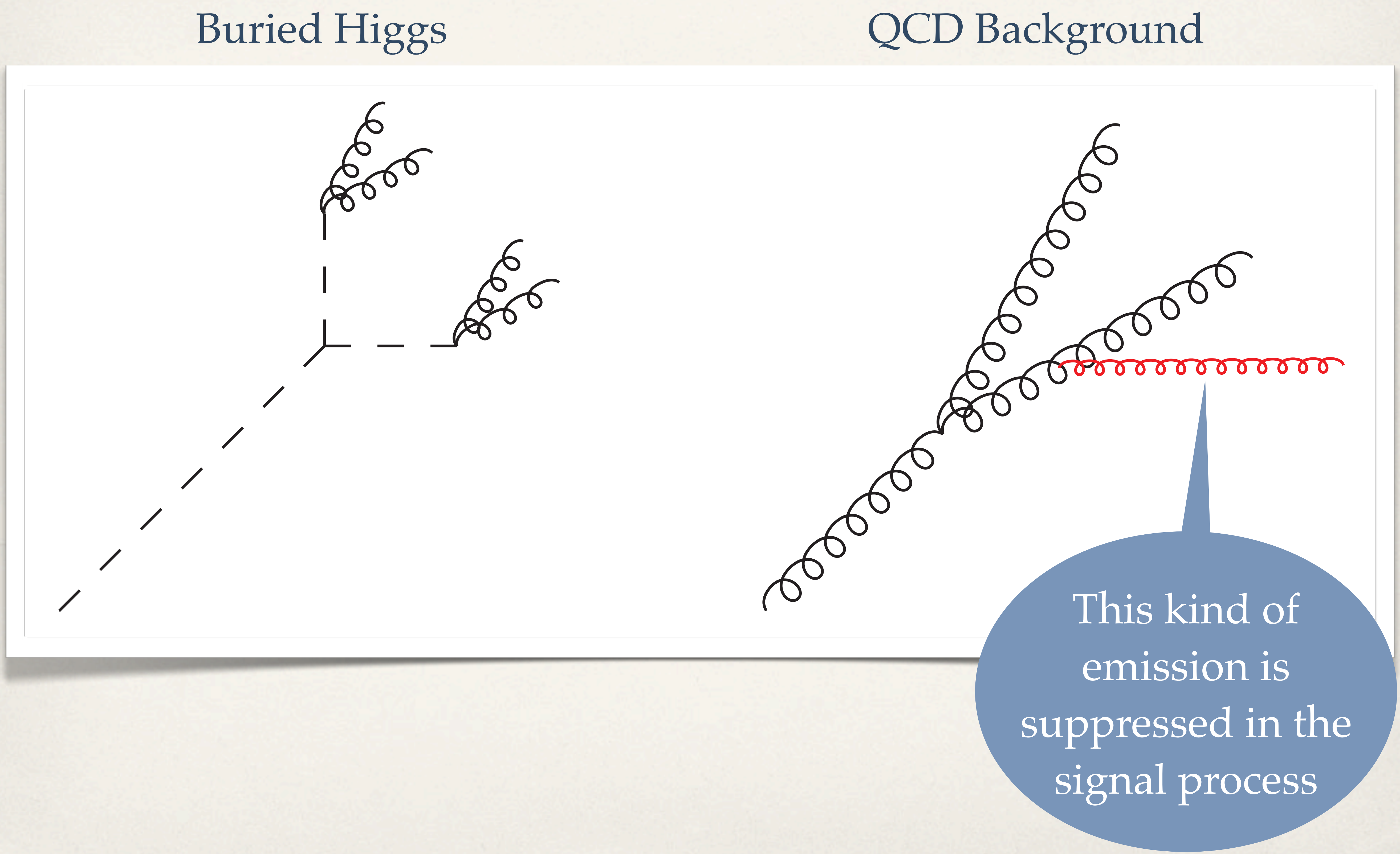
1. Each *a* subjet has a relatively *low* mass ($m_a < 2m_b$)

2. Each subjet inside the Higgs has roughly the *same* mass

3. Color is only resolved at the very end of the decay, at low mass and small angles.




Color singlet
Color singlet
All within one jet
l^-
l^+


Buried Higgs
QCD Background
This kind of emission is suppressed in the signal process

Observables

- Therefore we define three substructure observables sensitive to these characteristics

1. A subjet mass cut

$$\overline{m} \equiv \frac{m(j_1) + m(j_2)}{2} < 10 \text{ GeV}$$

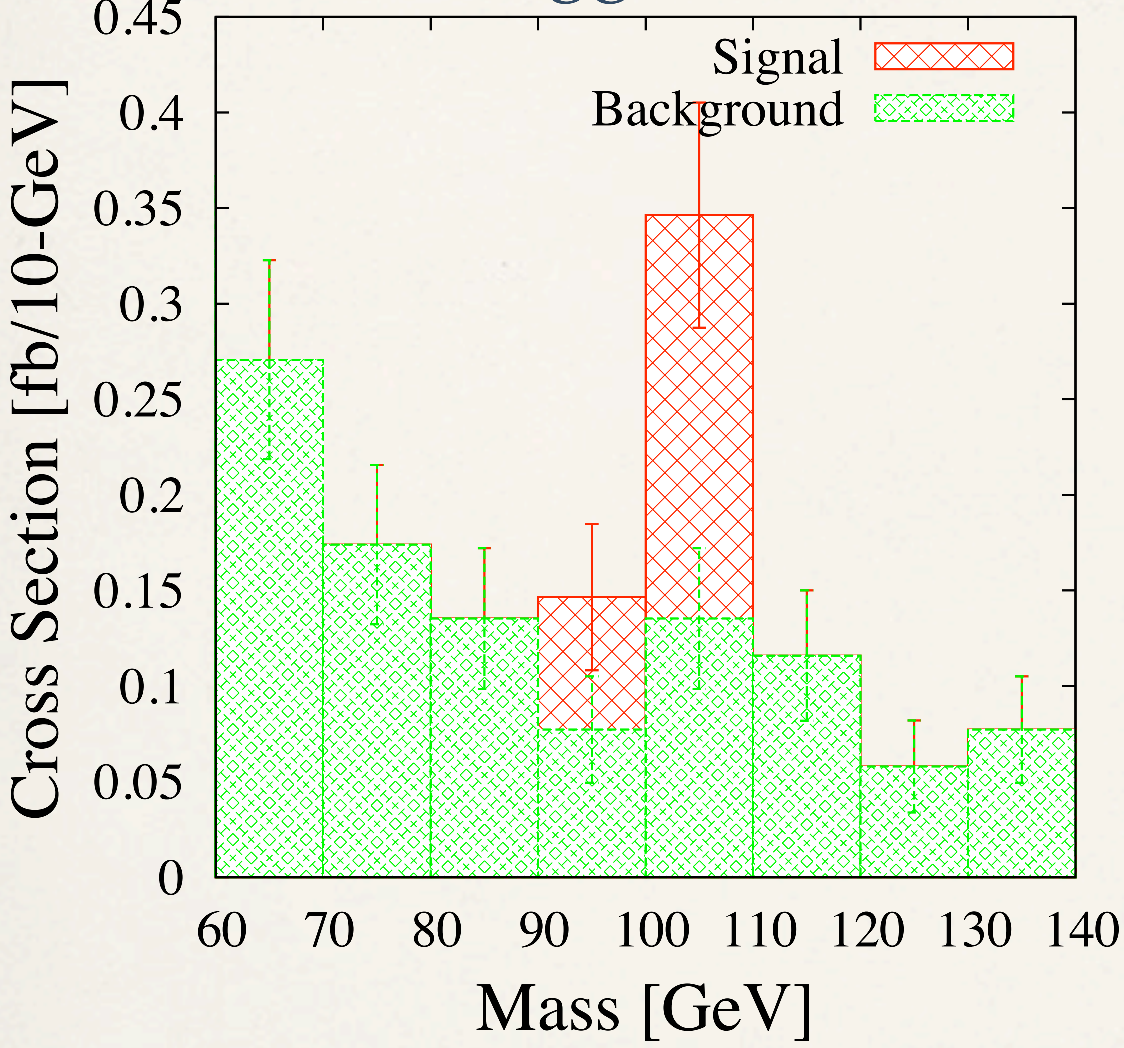
2. A mass democracy variable

$$\alpha = \min\left[\frac{m(j_1)}{m(j_2)}, \frac{m(j_2)}{m(j_1)}\right]$$

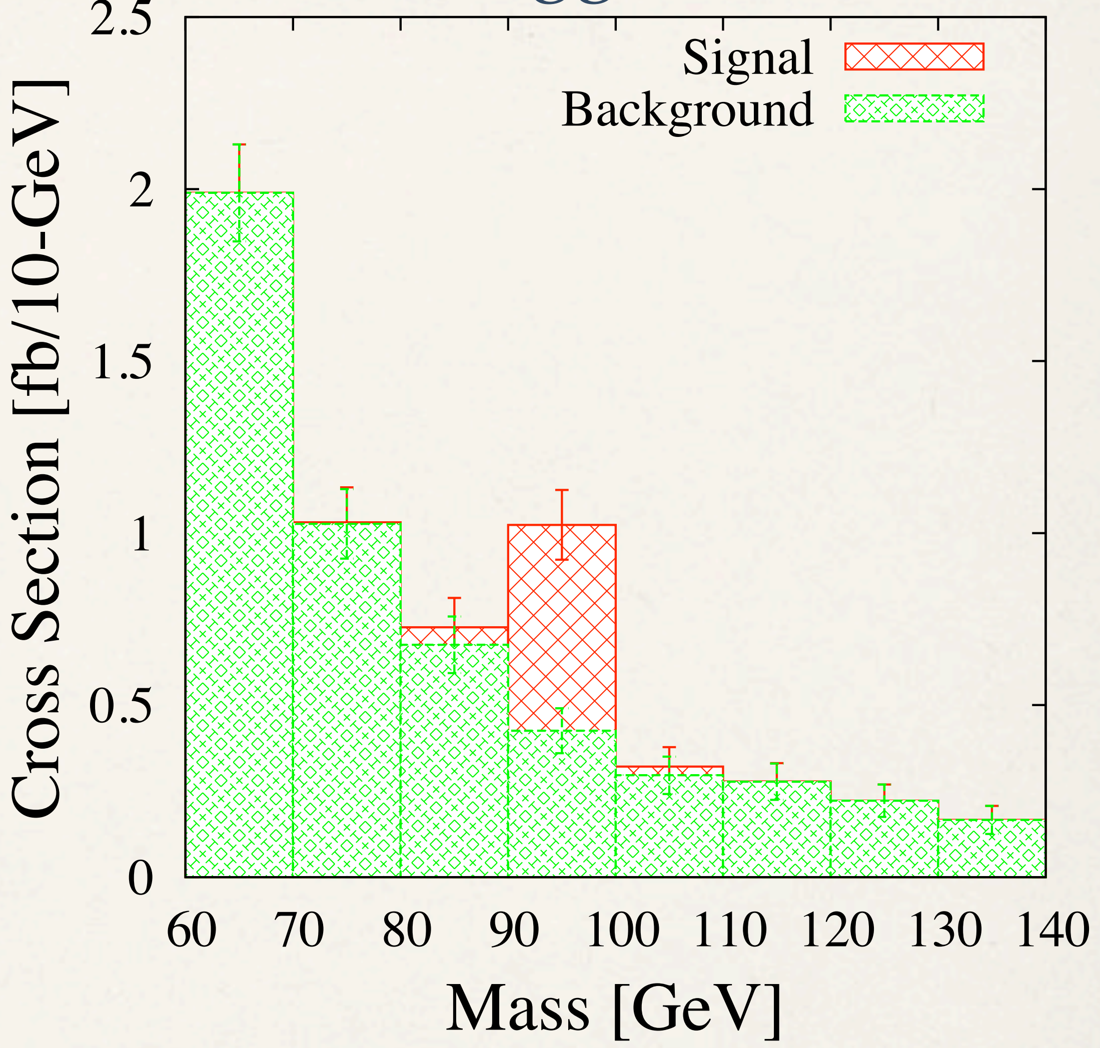
3. A color flow variable

$$\beta = \frac{p_T(j_3)}{p_T(j_1) + p_T(j_2)}$$

tt+h Higgs mass



W+h Higgs mass



Conclusions

- Jets and jet substructure constitute one of the most exciting recent developments in collider physics
- The choice of jet algorithm used in an analysis can make a big difference in its sensitivity
- Jet substructure helps to reduce combinatorics and gives one sensitivity to new information (e.g. color structure)
- Still a young field - much remains to be done.