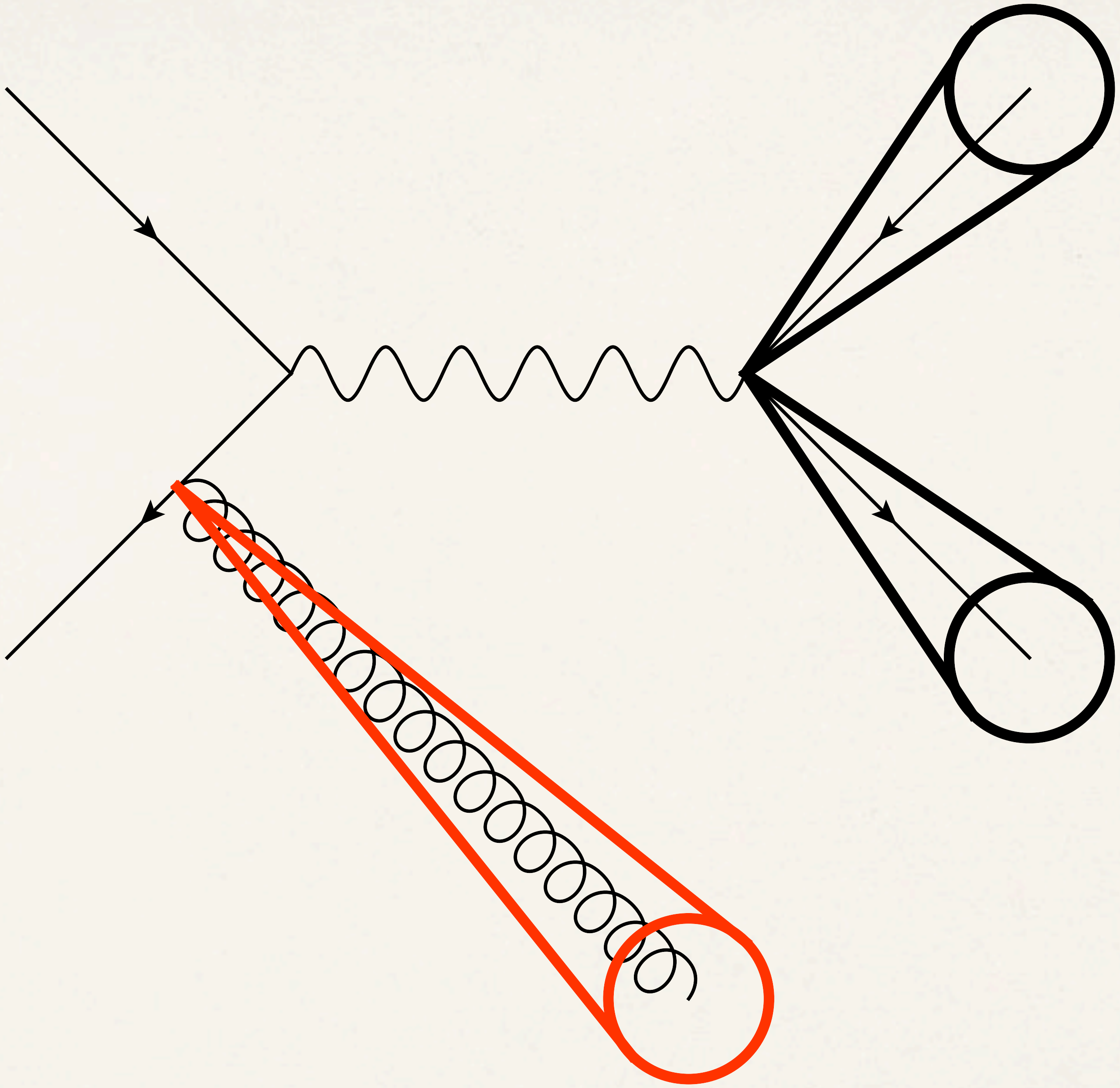


ISR Tagging

David Krohn (Harvard)

Cornell, 12/1/10

Based on work in progress with L. Randall and L.-T. Wang, as well as work with J. Thaler and L.-T. Wang

Some Upcoming Jet Conferences

- Boston Jet Physics Workshop [1/12-1/14]

  Goal: Bring together formal QCD theorists, BSM phenomenologists, and experimentalists.

  `http://jets.physics.harvard.edu`

- Boost 2011, Princeton [5/23-5/27]

  Goal: Study jets from boosted heavy objects, as well as exotic jets (lepton jets, etc.).

  `http://boost2011.org`

Outline

- Introduction to final/initial state radiation (FSR/ISR) and the parton shower
- Warmup - *Jet Trimming*
- What we can learn by tagging ISR jets
- Tagging example: SUSY disquarks
- Conclusion

Takeaway

- Initial state radiation (ISR) is normally a nuisance.
  - It can contaminate jets, and makes combinatorics hard.
- However,

1. New techniques (e.g. *Jet Trimming*) have been developed to reduce the effects of contamination (from ISR, as well as other sources).
2. Remarkably, by measuring the properties of ISR (i.e. through *ISR Tagging*) we can learn new things about an event.
   - Some of these measurements require calculations from QCD, others are more simple kinematic variables - in any case, there's a lot one can do.

Introduction & Motivations

Motivations

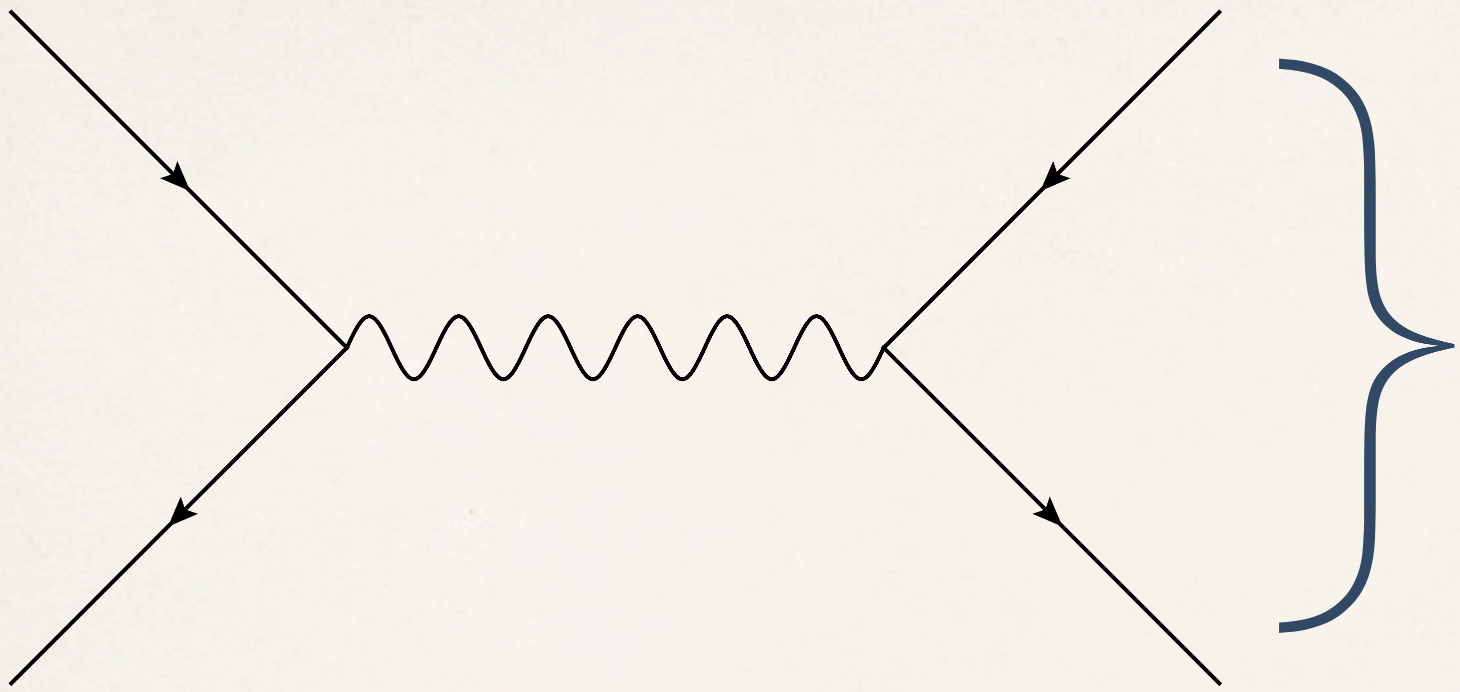
- The LHC will, hopefully, allow us to produce and study new physics particles.
- Usual collider study workflow:

1. Calculate spectrum/couplings for model
2. Calculate leading order processes for production/decay
3. Find useful observables
4. Determine backgrounds

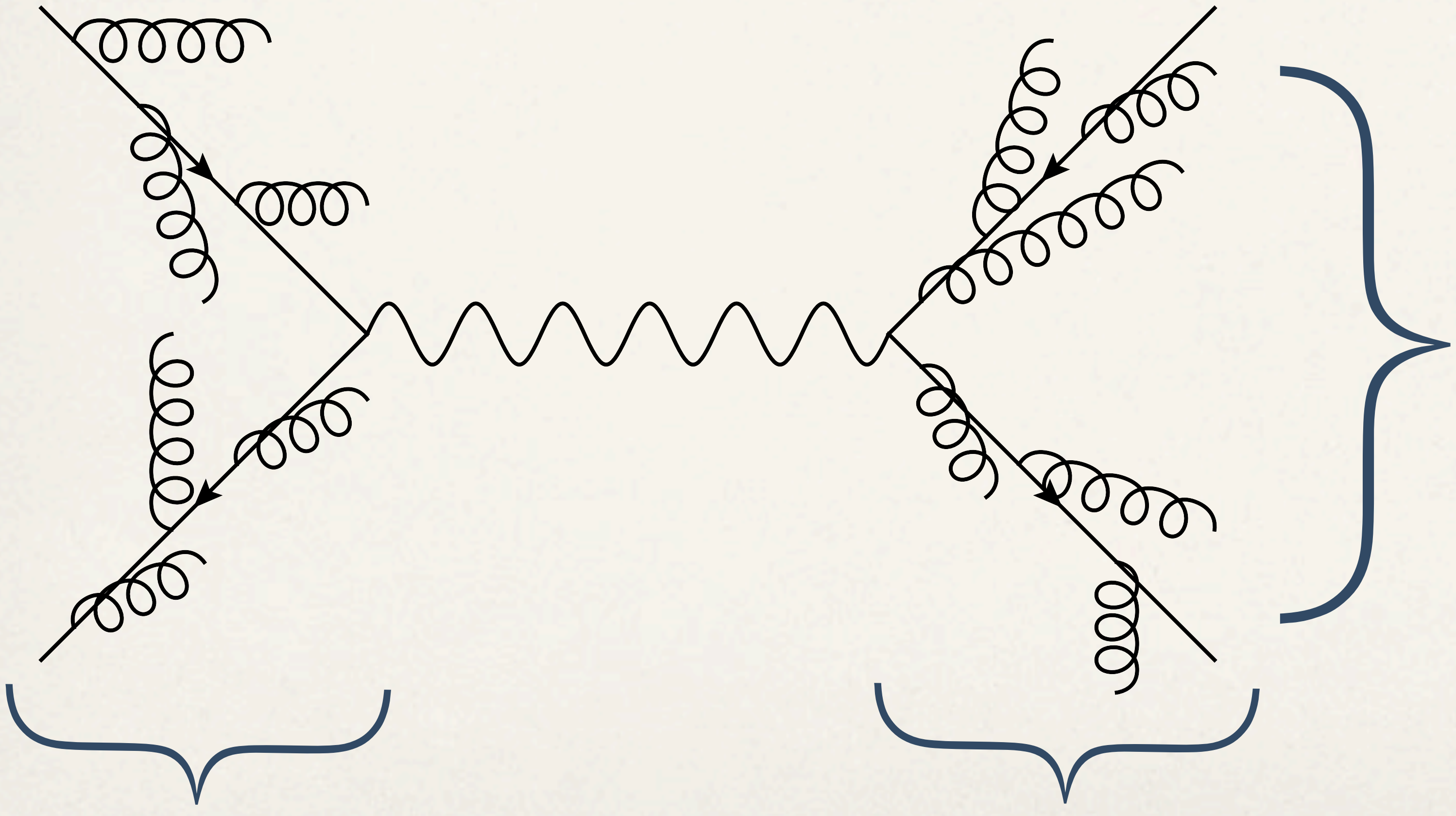
An iterative process

Initial & Final State Radiation (ISR/FSR)

- However, what we observe in the detector is more complicated than the leading tree level diagrams
- Final state particles will emit soft/collinear radiation (FSR)
  - These are resolved in jets - a spray of radiation in one direction
- Similarly, partons in the proton will emit soft/collinear radiation (ISR) before they scatter via the new physics states
  - We see these emissions as additional states in the detector.
  - Some emissions will contaminate jets, others will be assigned their own jets



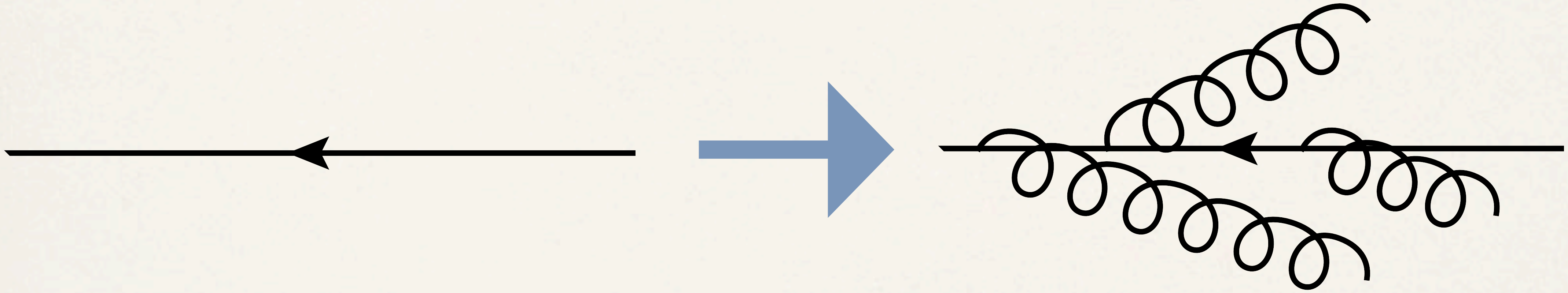
Lowest order diagram for the production and decay of a Z'



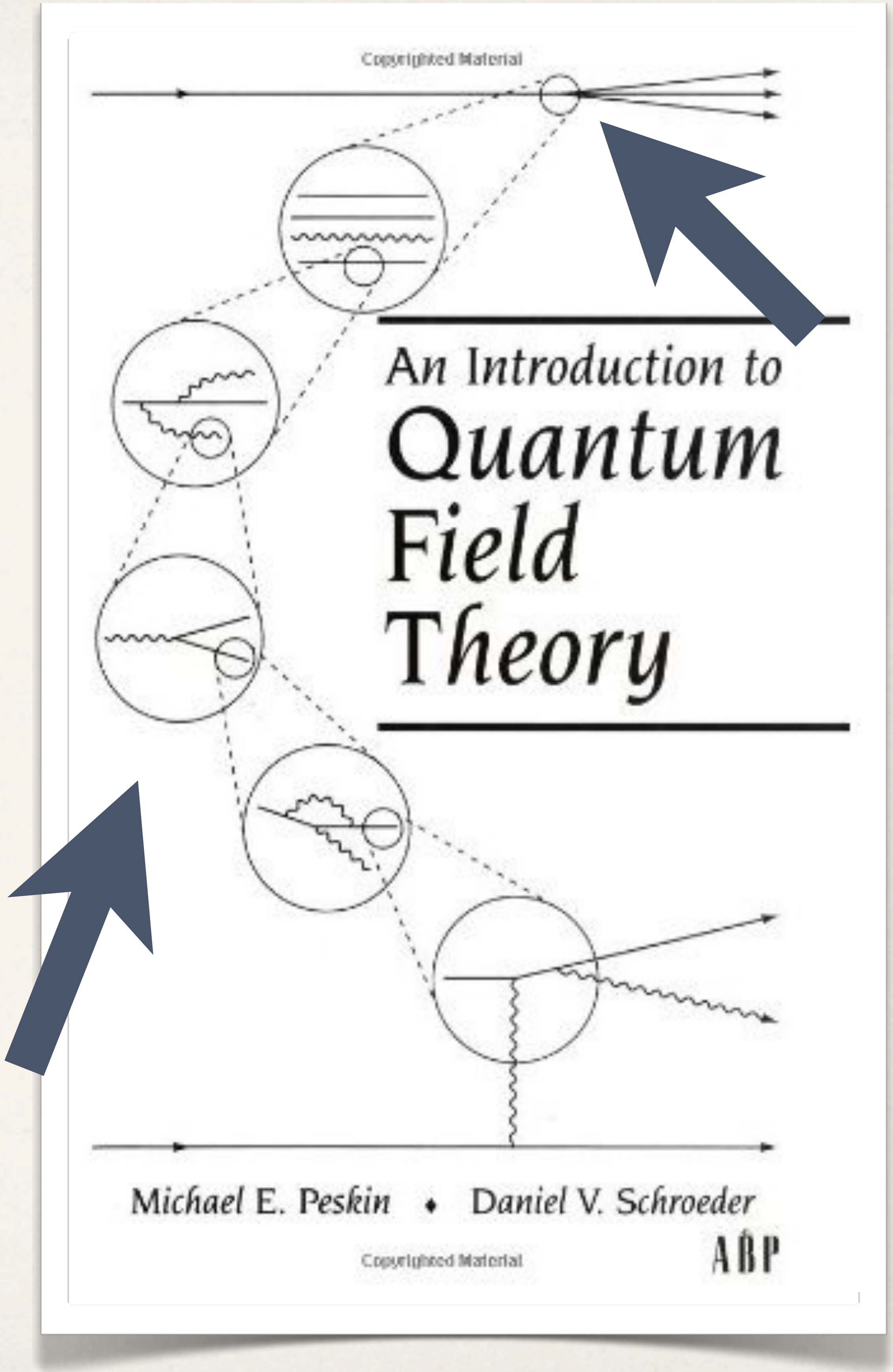
Production of Z' showing ISR/FSR

- Basically, this happens because the amplitude for a colored particle to emit a soft/and or collinear gluon diverges in the soft/collinear limit.

- So, if we have a Z' decaying to quarks, each quark will split into a quark with many gluons.



- Similarly, we can think of a proton as starting from two up quarks and a down, which then split and recombine into gluons, which then split again, into other quarks, etc.



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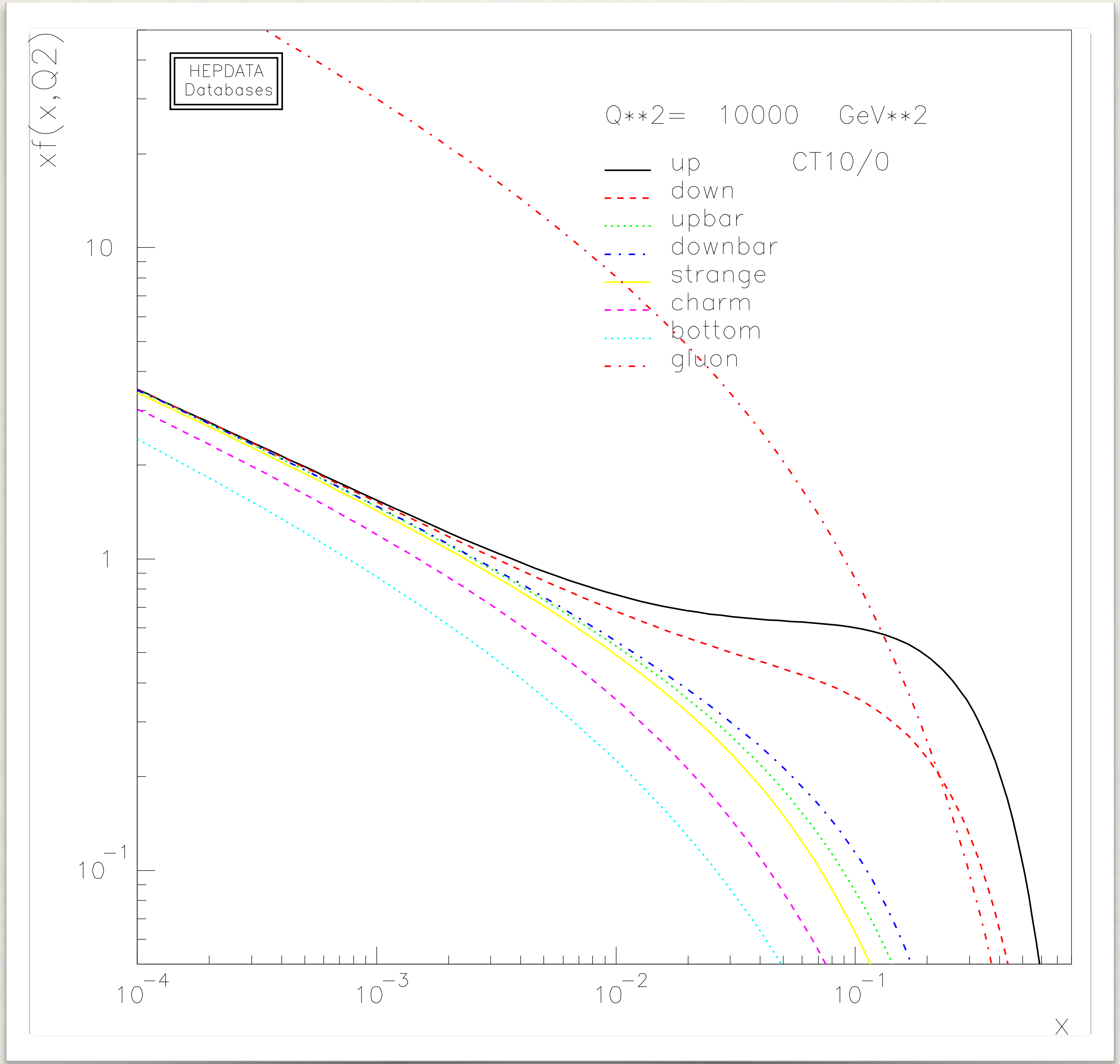
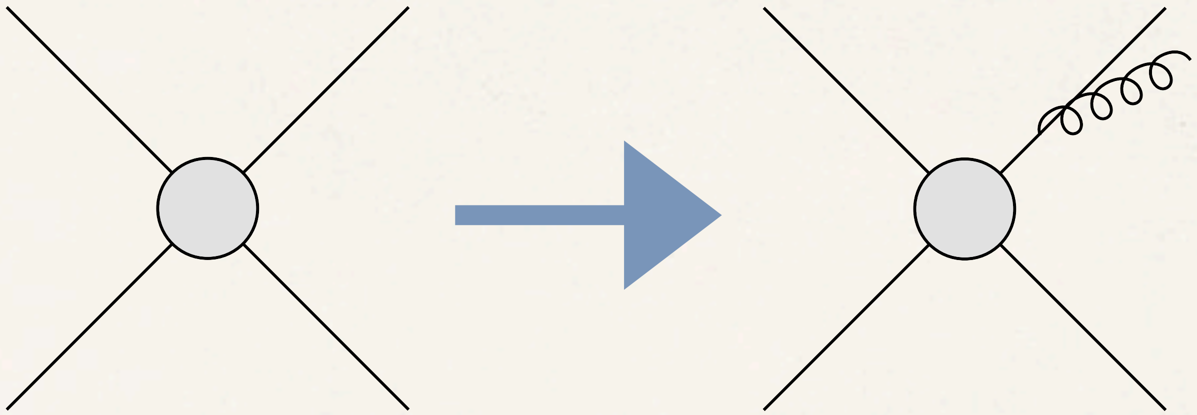
Parton Distribution Functions



This splitting gives us PDFs - it's why, for instance, we can think of the proton as being composed of charm/strange, etc.

PDF - http://hepdata.cedar.ac.uk/pdf/pdf3.html

- To see this in more detail, start with some amplitude, and its associated matrix element & cross section:



- When you take a final state and add on a soft and/or collinear particle the new amplitude factorizes into the lower-order amplitude times a new, potentially large, factor:

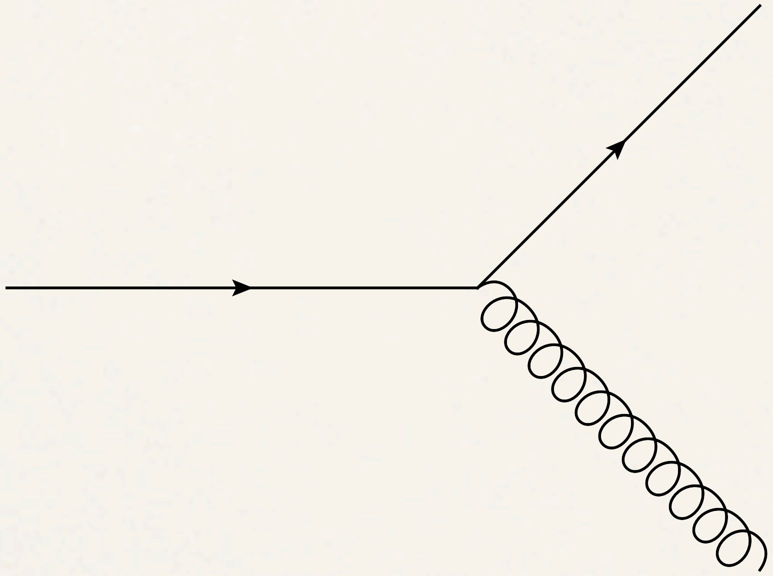
$$|\mathcal{M}_n|^2 \to \frac{4g^2}{t}\hat{P}(z)|\mathcal{M}_n|^2 \qquad d\sigma_{n+1} = \frac{\alpha}{2\pi} d\sigma_n \frac{dt}{t} dz \hat{P}(z)$$

- We make this approximation because while it's no longer exact at a given order, it allows us to handle emissions at very high orders.

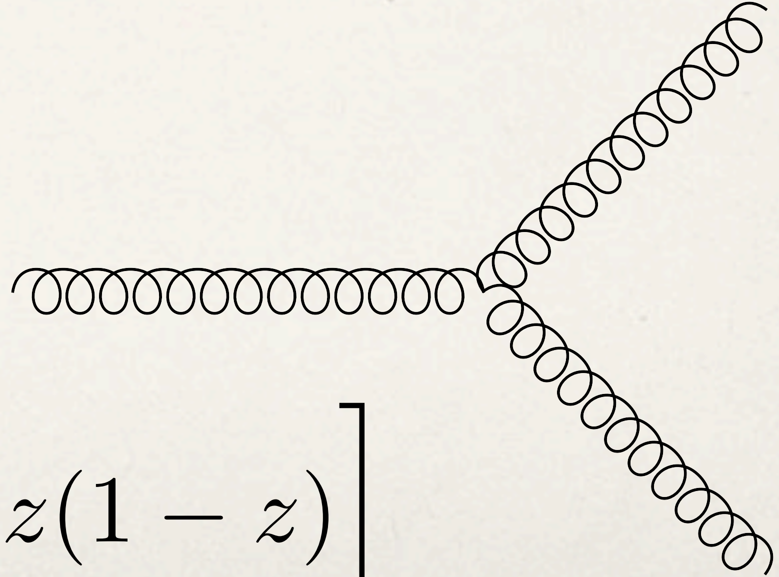
See R. K. Ellis, W. J. Stirling, and B. R. Webber, *QCD and Collider Physics*.

The Splitting Functions

$$a \to b + c, \;\; z = \frac{E_b}{E_a} \qquad d\sigma_{n+1} = \frac{\alpha}{2\pi} d\sigma_n \frac{dt}{t} dz \hat{P}(z)$$



$$\hat{P}_{q\to qg}(z) = C_F \frac{1+z^2}{1-z}$$



$$\hat{P}_{g\to gg}(z) = C_A \left[\frac{1-z}{z} + \frac{z}{1-z} + z(1-z) \right]$$

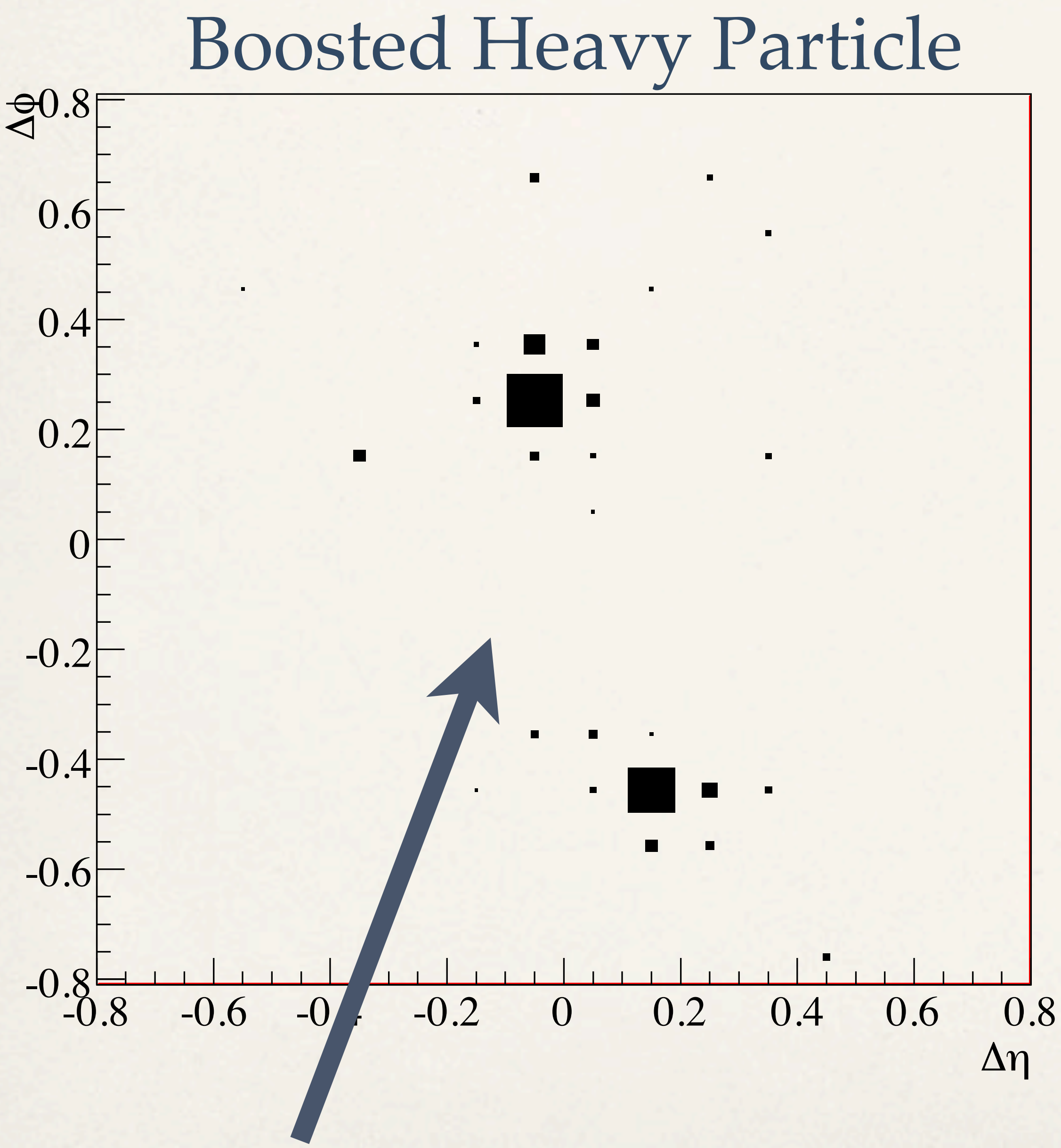
Divergences

- The probability of emitting a soft/collinear emission diverges in the soft/collinear limit (consider z->0).
  - We know that the divergence gets cancelled by loops, but there's still an large finite enhancement for soft/collinear emissions.
  - This means we expect to see lots of soft emissions as we let ourselves resolve softer/more collinear objects
- This is handled via the parton shower formalism:

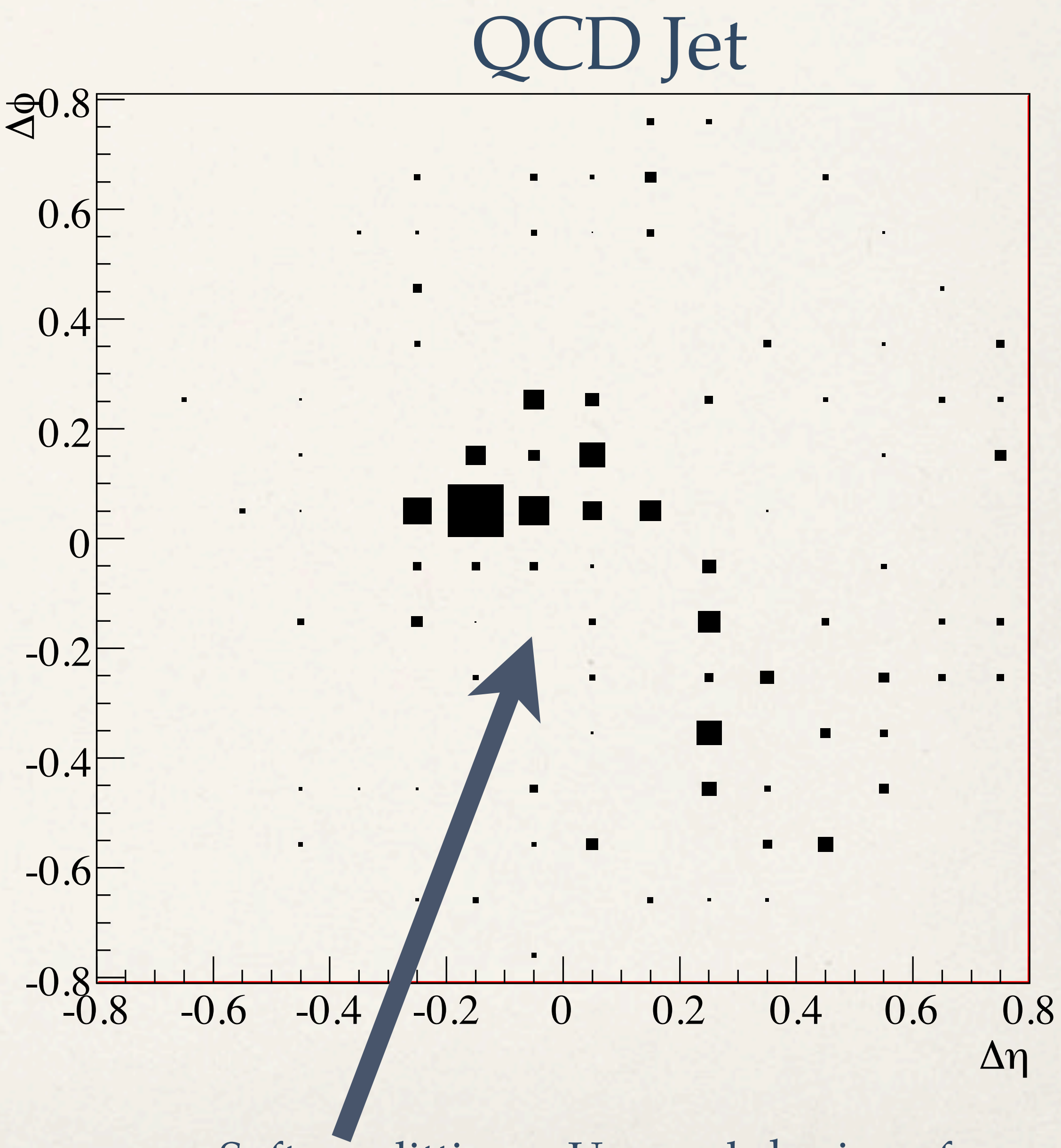
$$\left.\mathcal{P}(t_1, t_2) = \exp\left(- \int_{t_1}^{t_2} \frac{dt}{t} \int dz \frac{\alpha_S}{2\pi} \hat{P}(z) \right) \quad \right\}$$

Write evolution equation. Find probability of "no emission" between two scales

Here's what the results look like (jets):



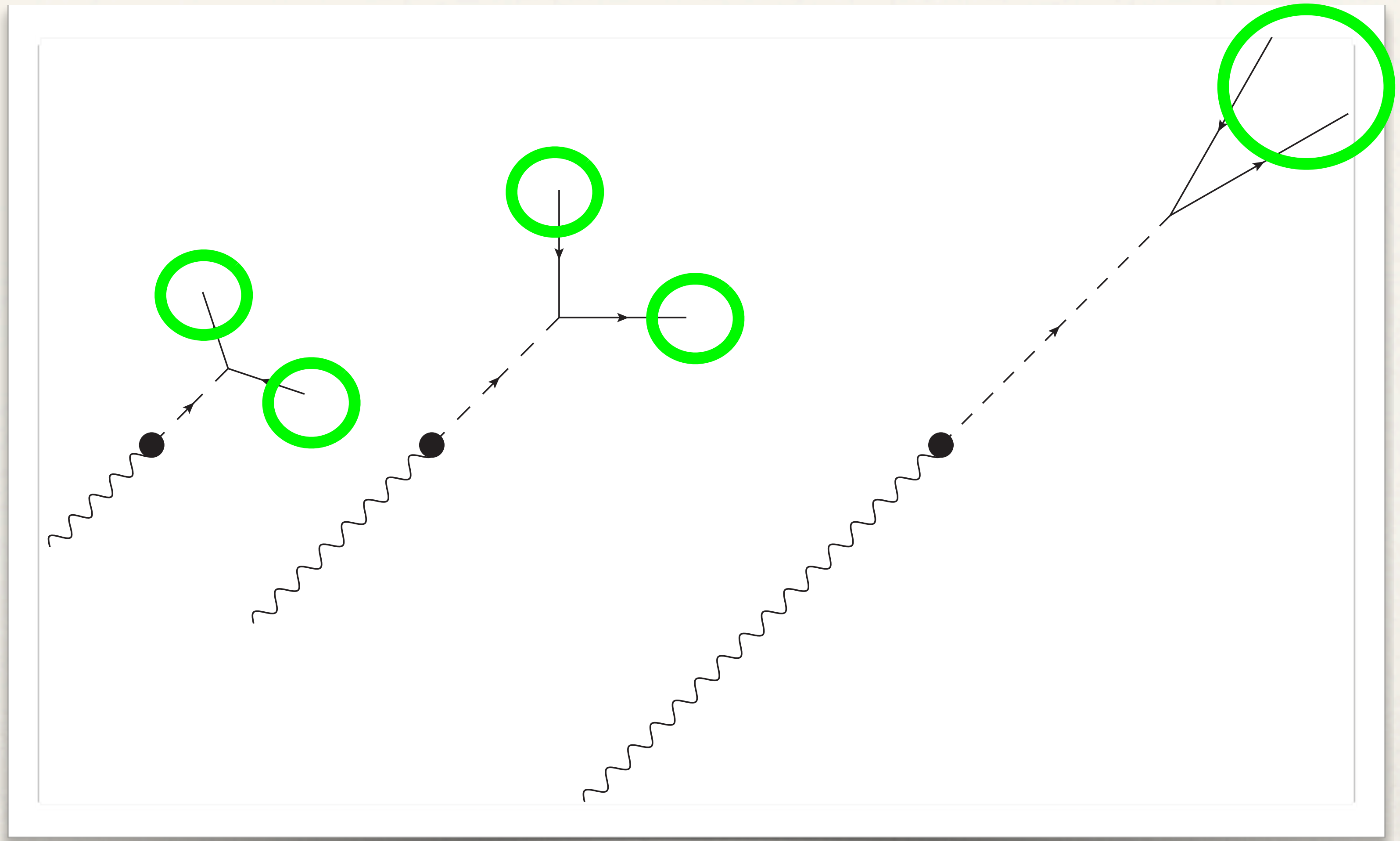
Hard splitting, energy shared equally



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

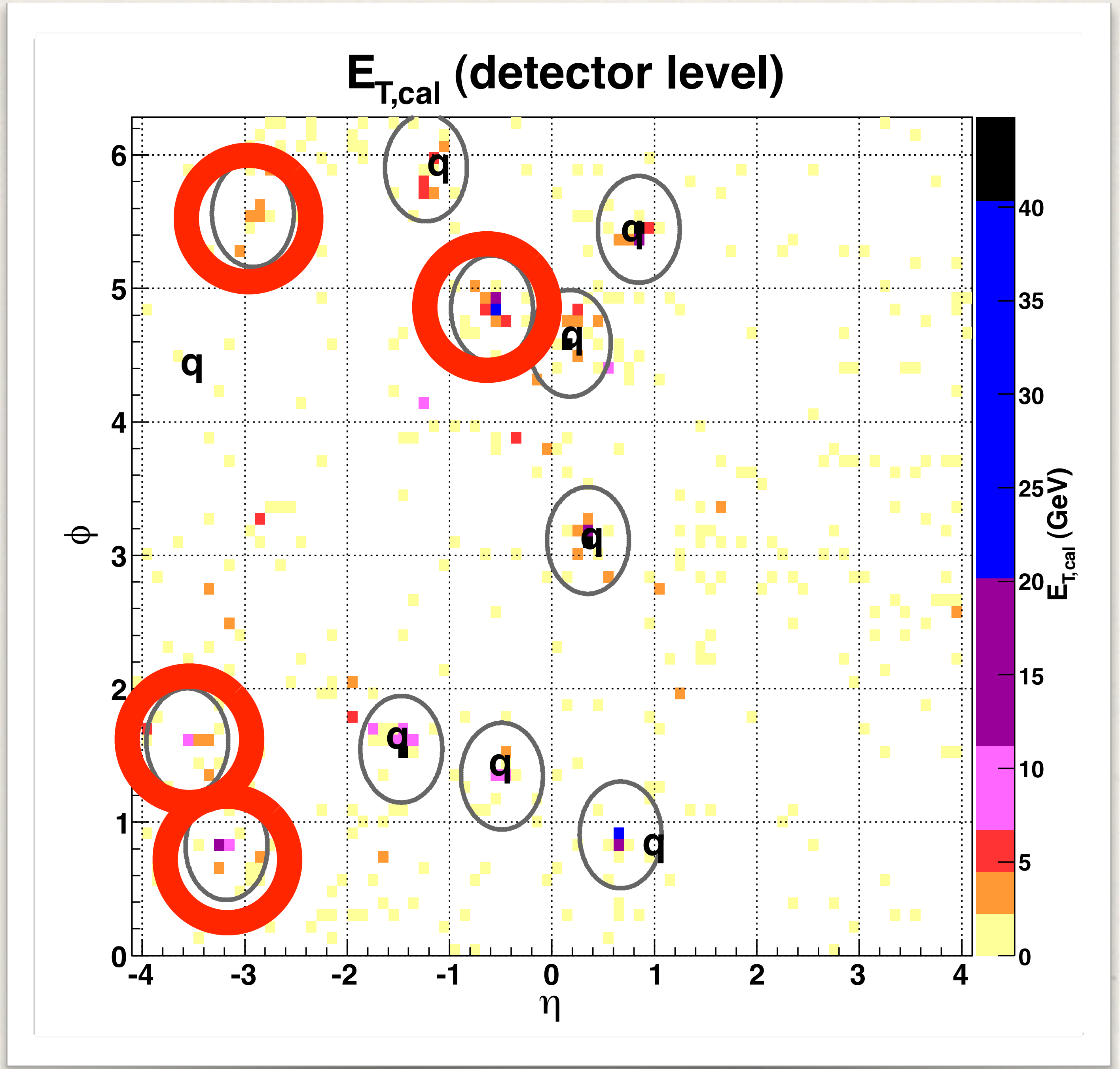
Aside: Substructure

- Looking for the presence/absence of these divergences can help us distinguish normal "QCD Jets" from the jets of from the collimated decay of heavy particles (e.g. Higgses)



ISR Introduces New Difficulties

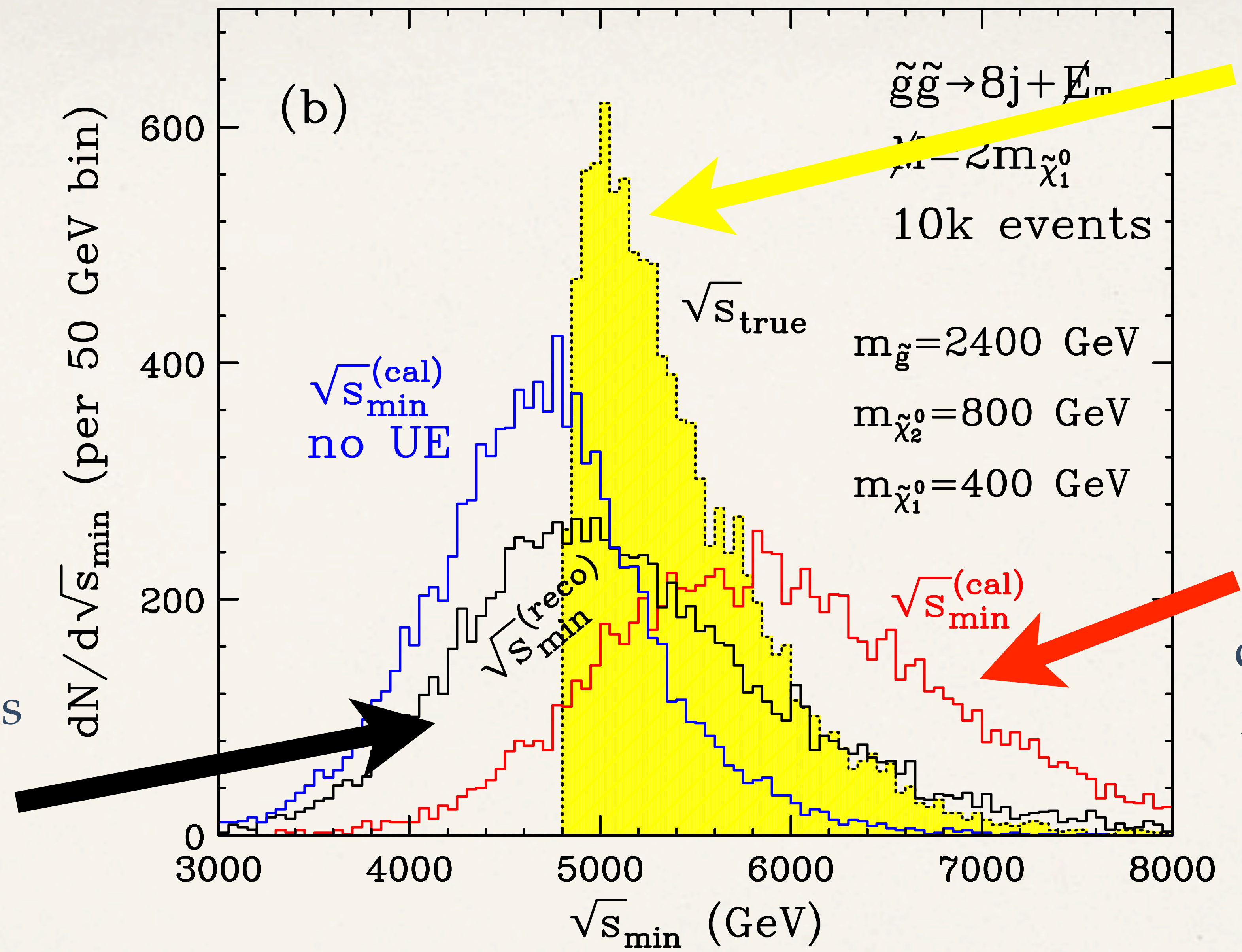
- ISR, comes from the showering of the incoming particles. At least for hadron colliders, is normally a nuisance.
- There are more jets in the final state - identifying FSR jets to construct kinematic variables becomes more challenging.
  - Combinatorics becomes difficult.
  - Event becomes “messy” - ISR will pollute the jets coming from new physics.
  - Events are no longer balanced - hard to use MT2



Pair production of gluinos, with each going to four jets and an LSP

○ = ISR Jet

Source: 1006.0653



The yellow curve is the one we want to measure

The red curve is the observable suffering from contamination

The black curve is the observable suffering from combinatorics

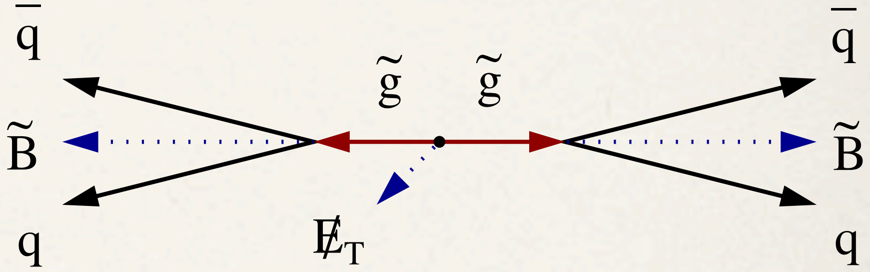
Here we can plainly see the effects of contamination and the combinatoric difficulties arising from ISR. The particular observable here doesn't matter.

$$\sqrt{s}_{min}(\not{M}) \equiv \sqrt{E^2 - P_z^2} + \sqrt{\not{M}^2 + \not{P}_T^2}$$

Source: 1006.0653

However, ISR is Not Always Bad

- ISR jets can be used to trigger on difficult BSM processes
  - Monojet searches (e.g. looking for DM)
  - Squeezed spectra [0803.0019,0809.3264]
    - Can increase missing energy, add another jet



Source: 0803.0019

- More intriguingly, its characteristics give us information about the “hard process” we’re interested in
  - Some recent studies have studied ISRs effect on inclusive variables [0903.2013, 1004.4762]

- End of introduction/motivations.
- Two main ideas ahead:

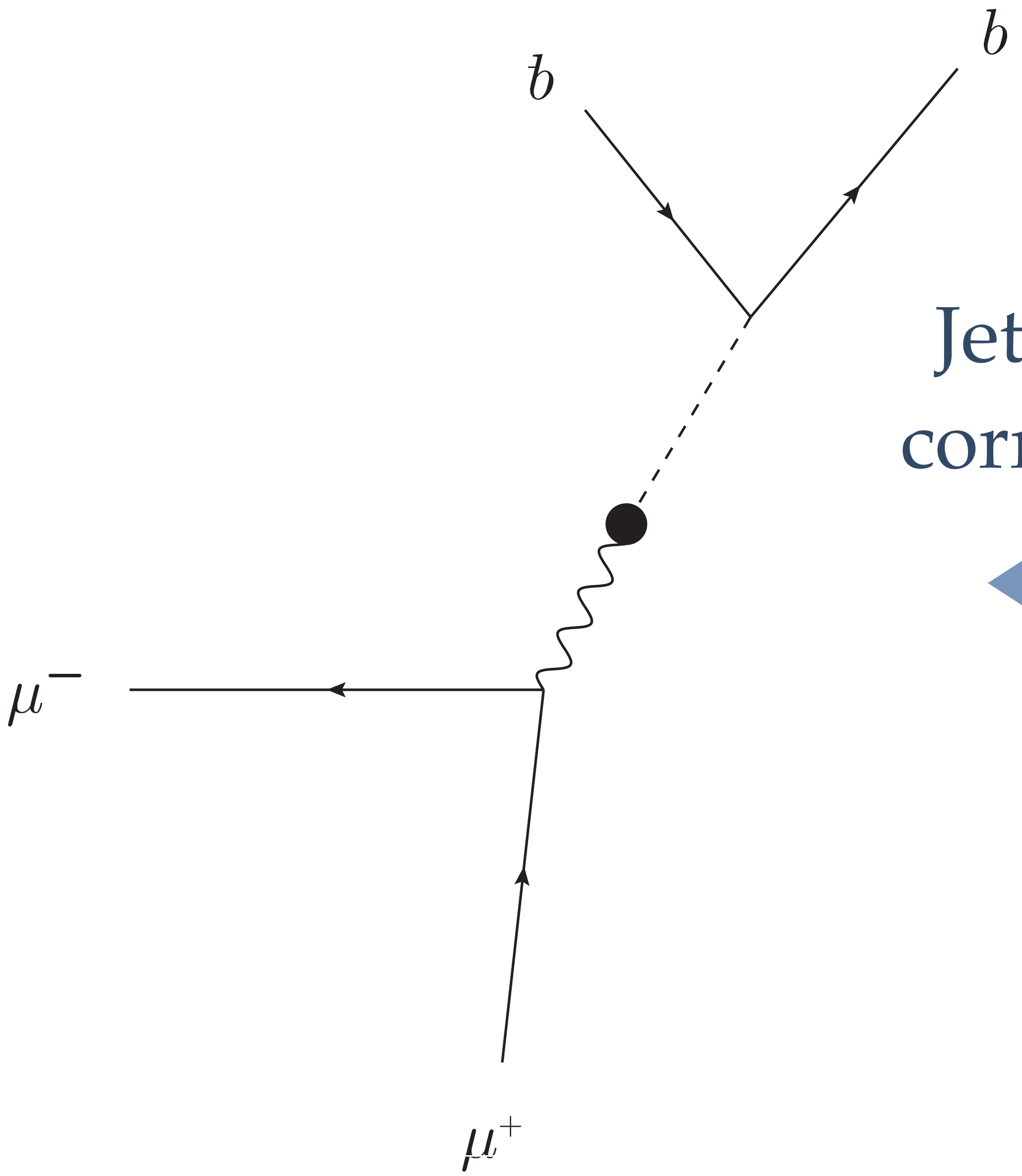
1. ISR contamination can be removed from jets
2. We can, on a jet by jet basis, identify ISR with a high degree of certainty.
    - This allows us to do even more than the inclusive observables mentioned before.

Jet Trimming

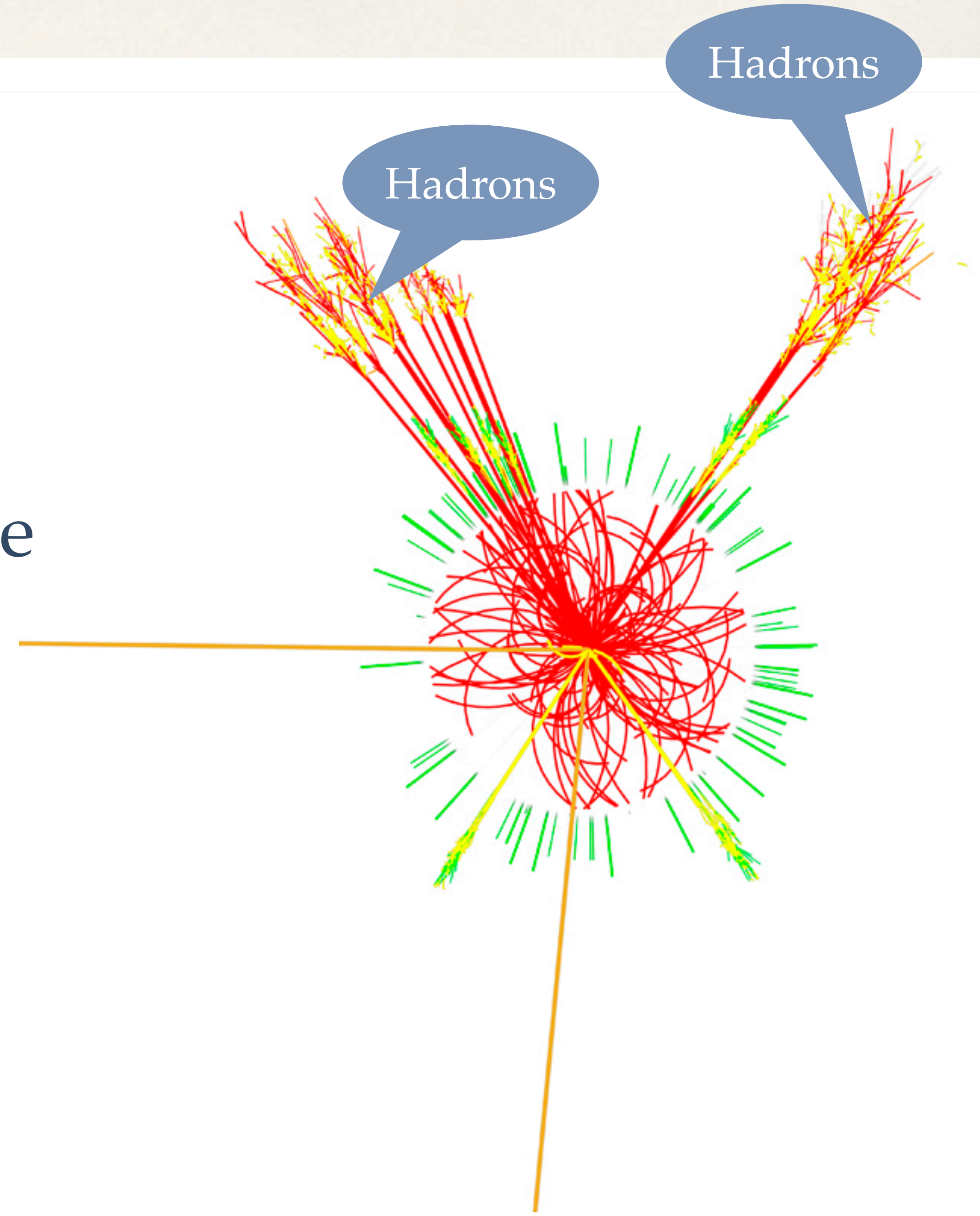
Source: DK, J. Thaler, and L. Wang, JHEP 1002 (2010) 084 [arXiv:0912.1342]

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 (i.e. jets should, ideally, correspond to FSR emissions).
- They help us map things we cannot easily calculate (the exact energy distribution in the calorimeter) to things we can (perturbative Feynman amplitudes)



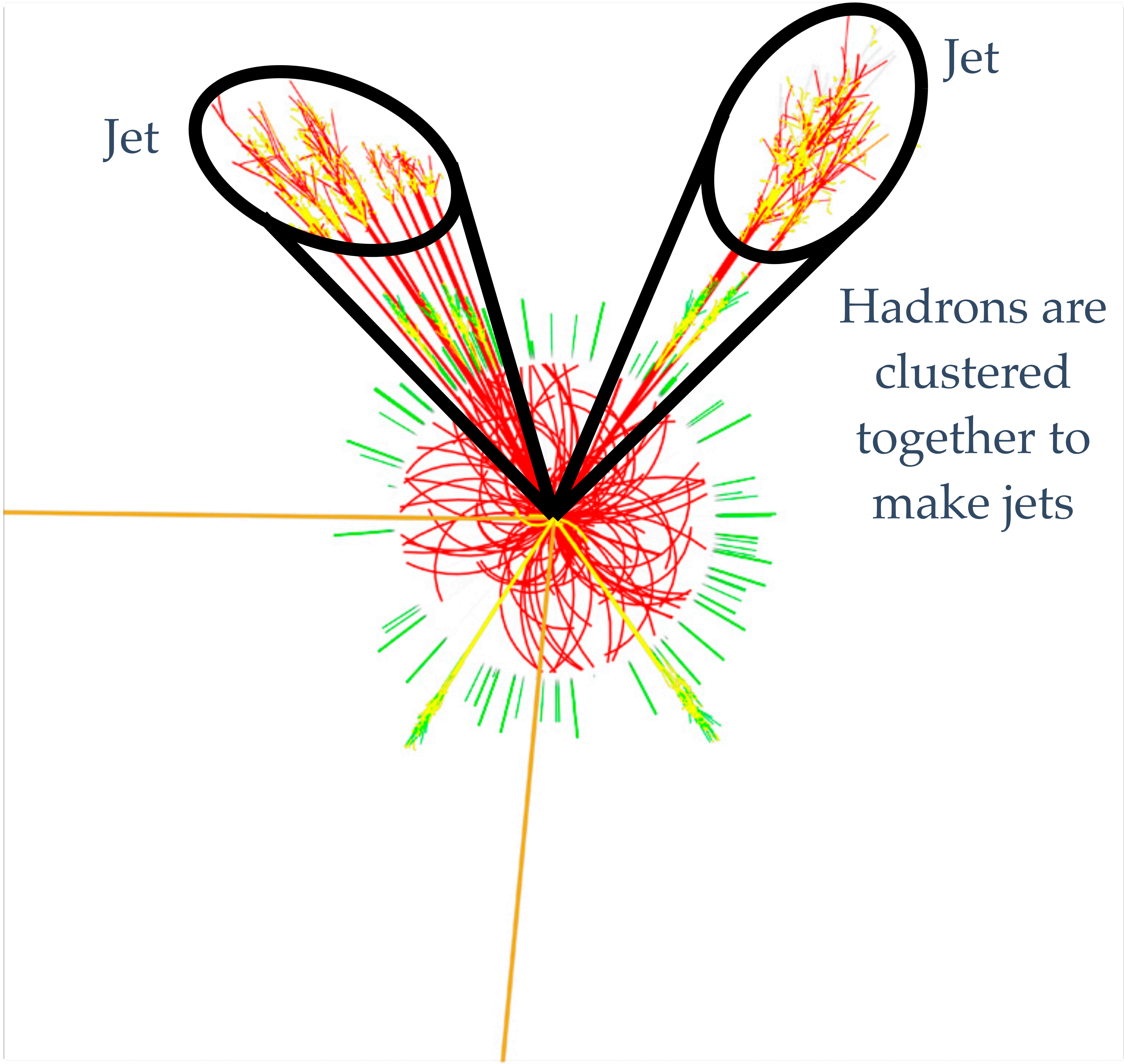
Jets make this correspondence



What we calculate

What we measure

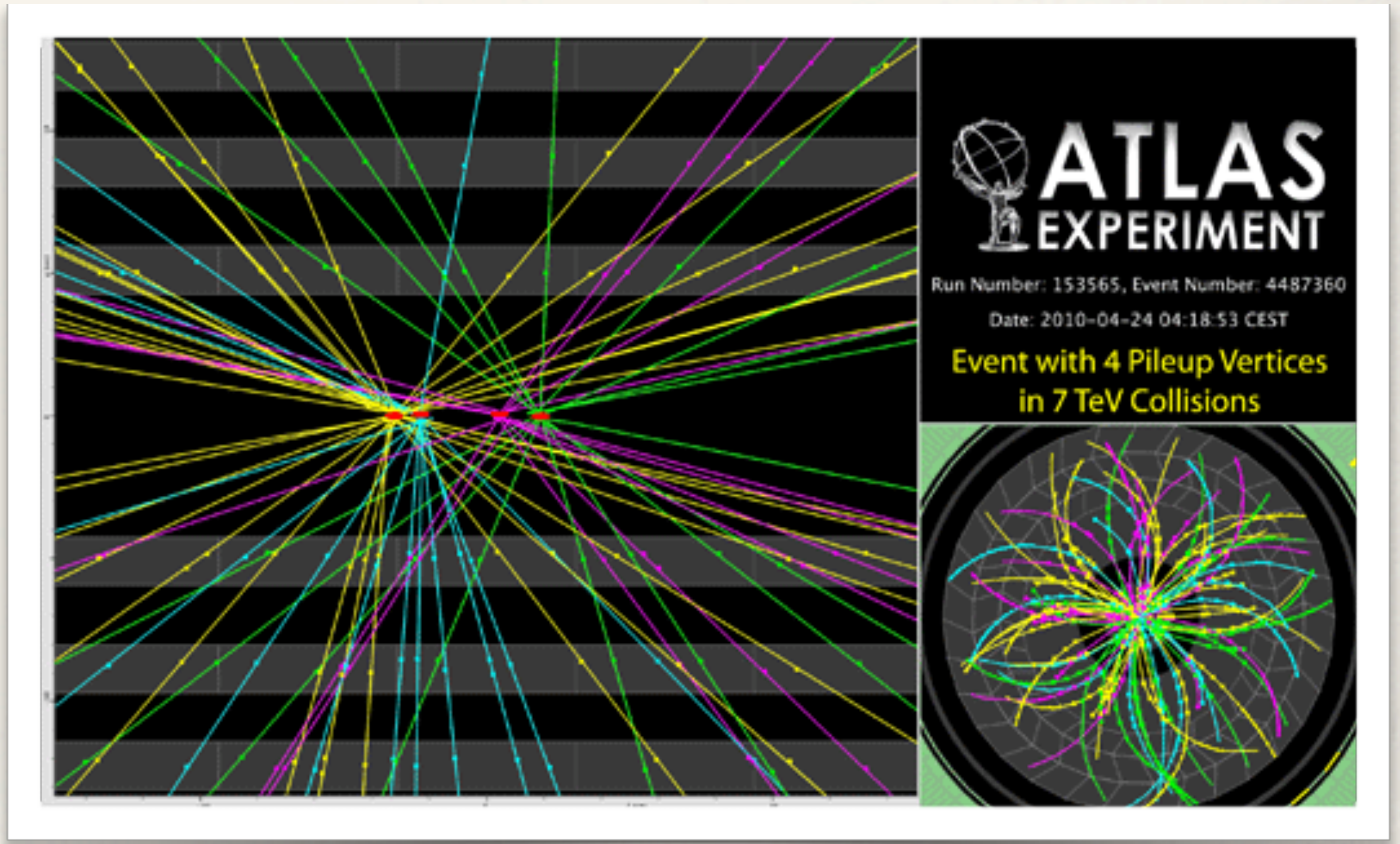
Event picture from http://atlas.ch/photos/events.html



Hadrons are clustered together to make jets

Messy Jets

- The LHC is a messy place.
- Contaminating radiation can always come from ISR and multiple interactions.
- Also, pileup can contaminate events



Quantifying Contamination

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

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

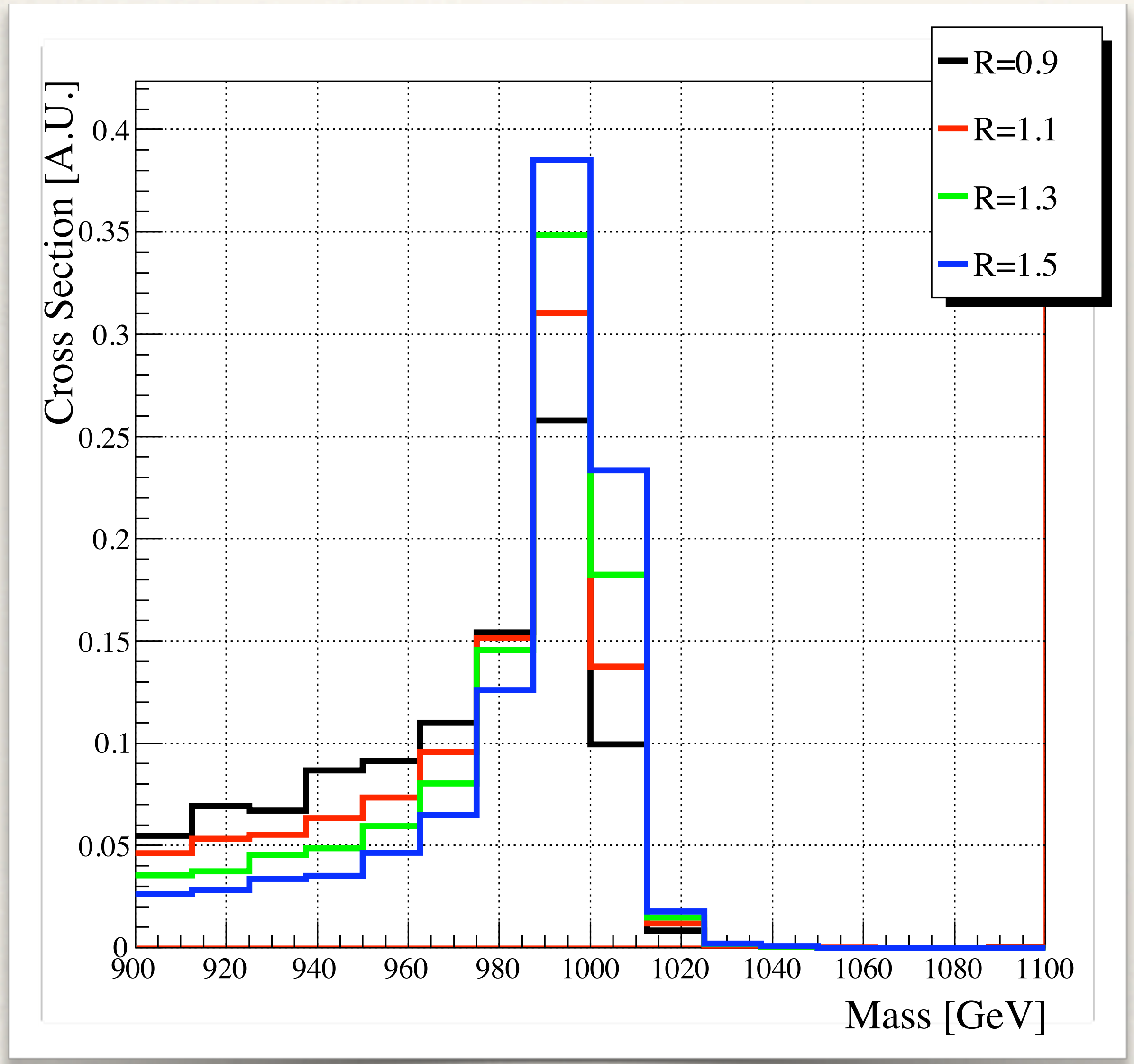
- The number of pileup events per crossing (N_{PU}) depends on the LHC running parameters. Roughly though, at 14 TeV we should start at ~20 and go to ~40.

Source: M.Rubin, 1002.4557

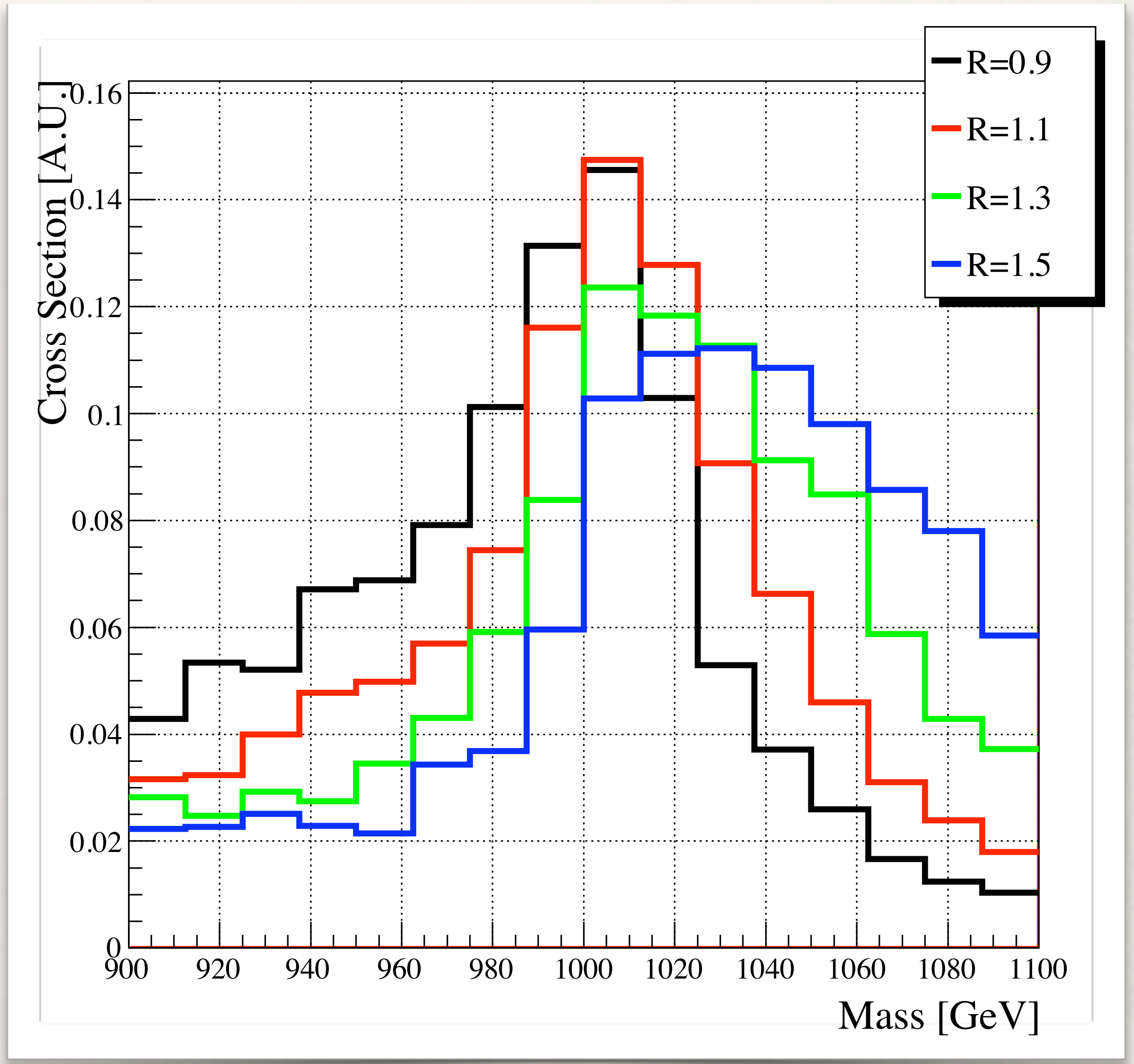
Unfortunate Tradeoff

- 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

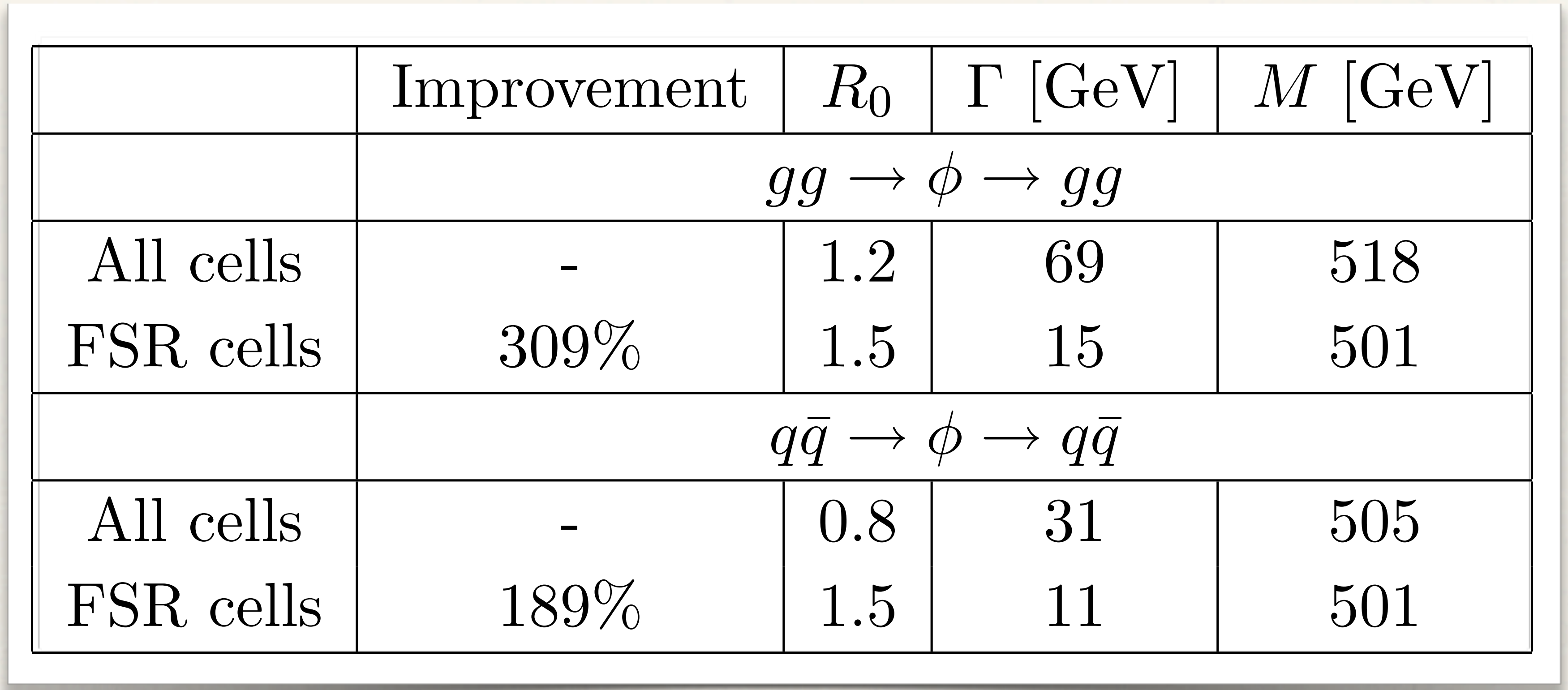


Contamination Off



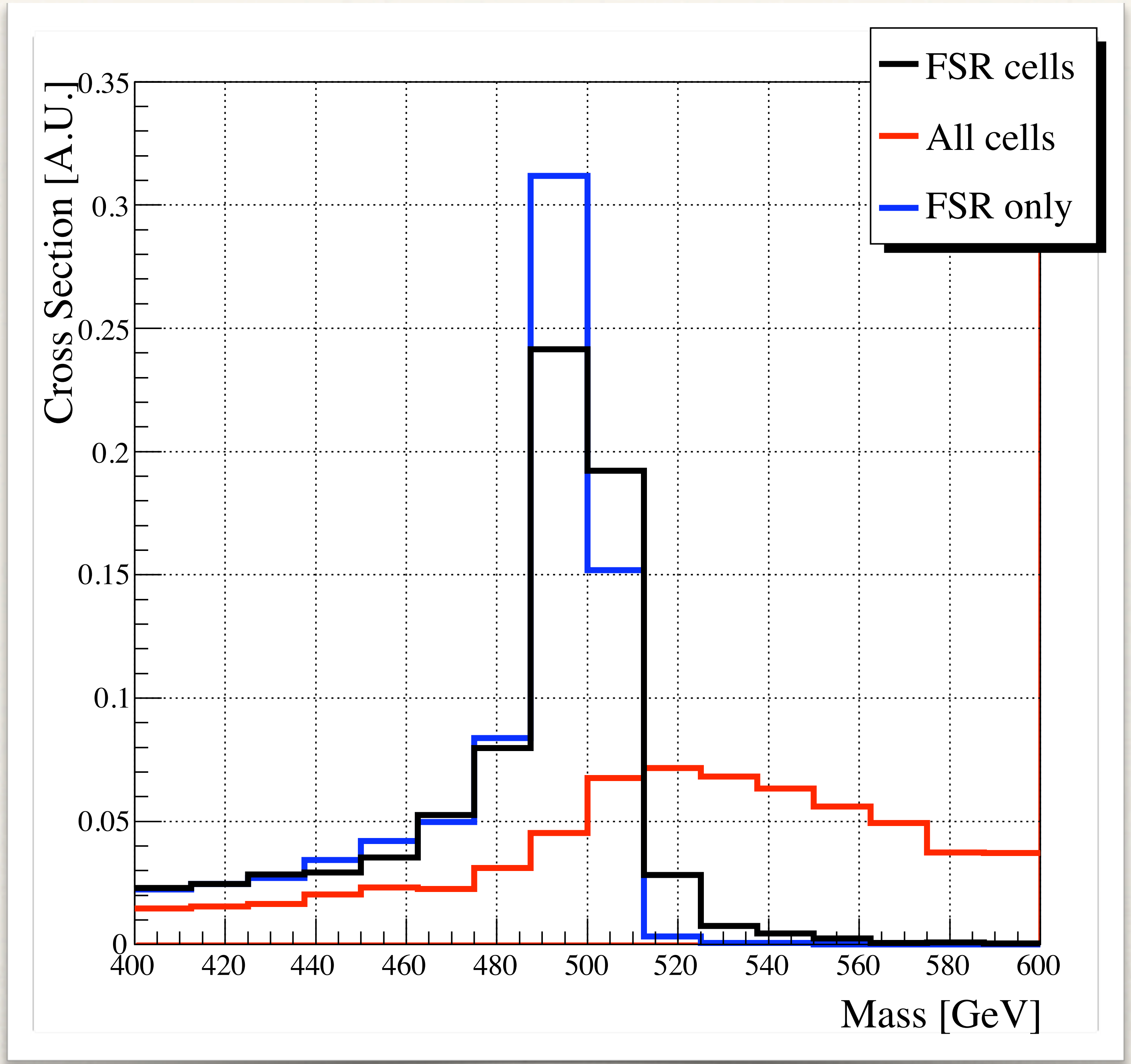
Contamination On

- 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



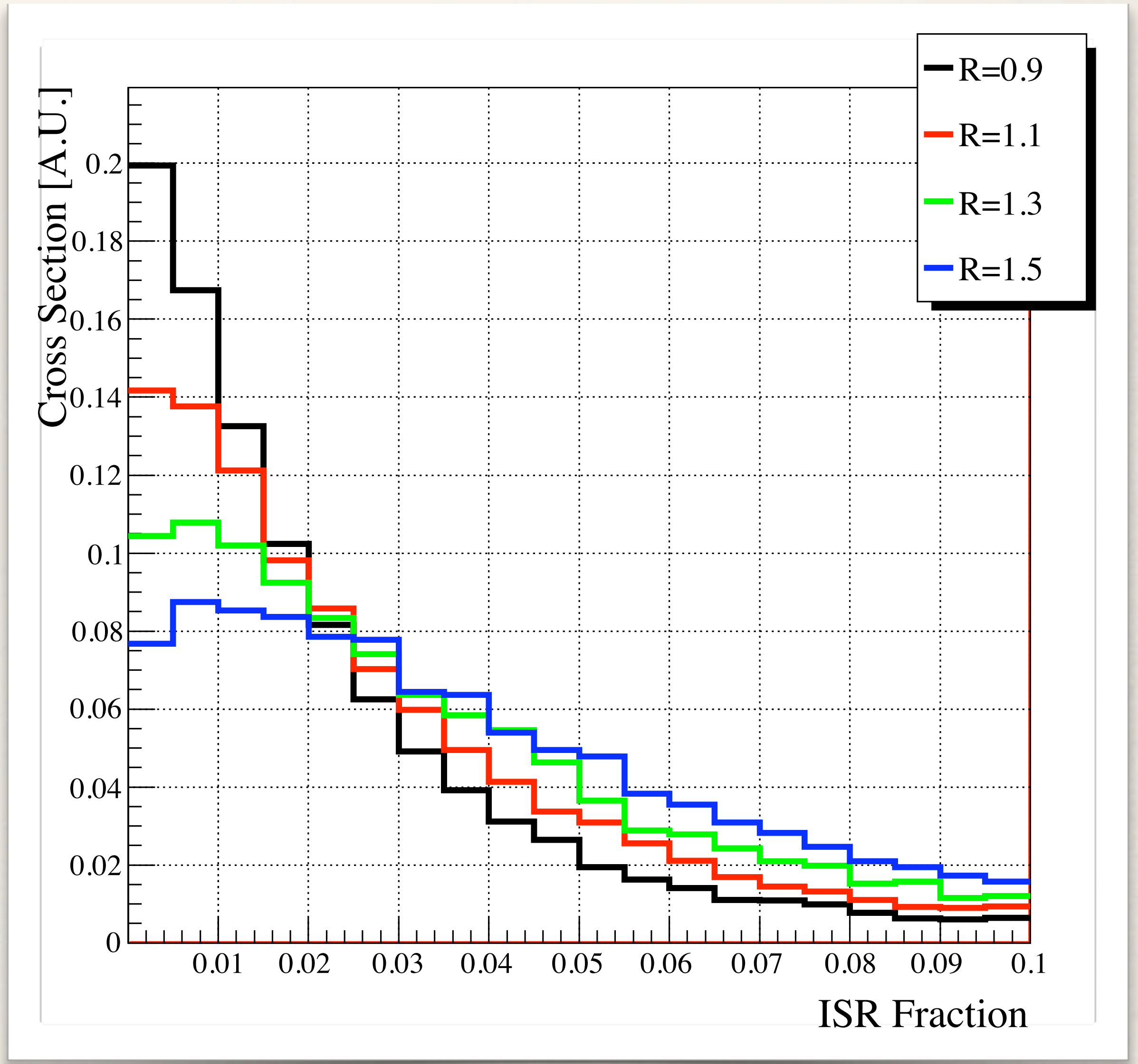
	Improvement	R_0	Γ [GeV]	M [GeV]
	$gg \to \phi \to gg$			
All cells	-	1.2	69	518
FSR cells	309%	1.5	15	501
	$q\bar{q} \to \phi \to q\bar{q}$			
All cells	-	0.8	31	505
FSR cells	189%	1.5	11	501

- 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

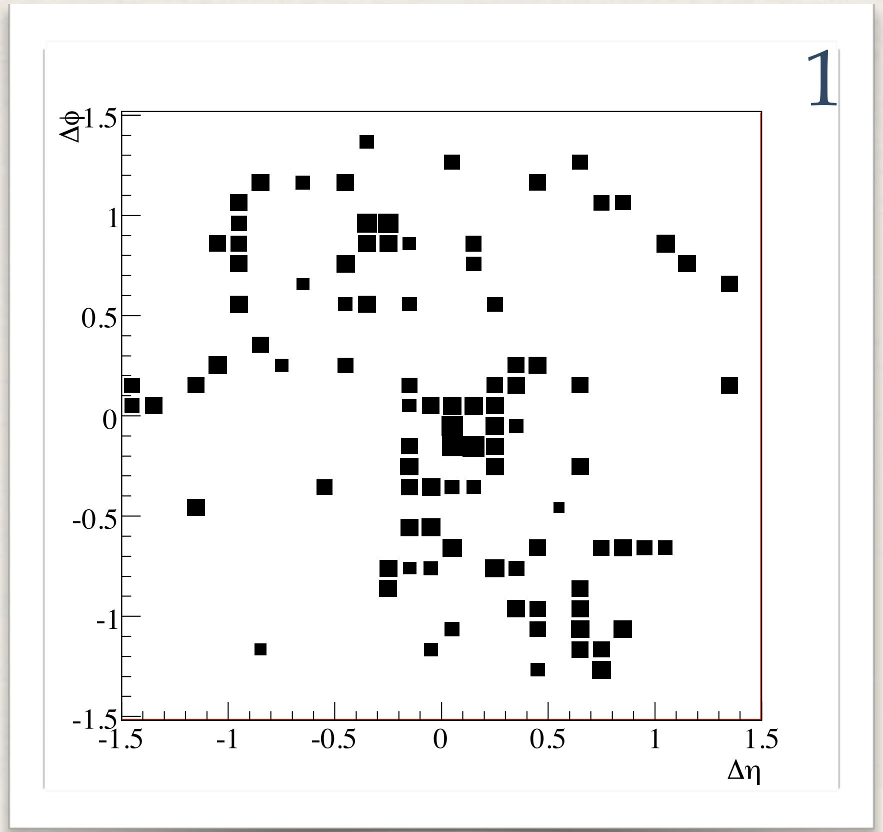
2. Take the constituents of each jet and recluster them using another, possibly different, algorithm (we advocate k_T) with smaller radius R_{sub} ($R_{sub} = 0.2$ seems to work well).

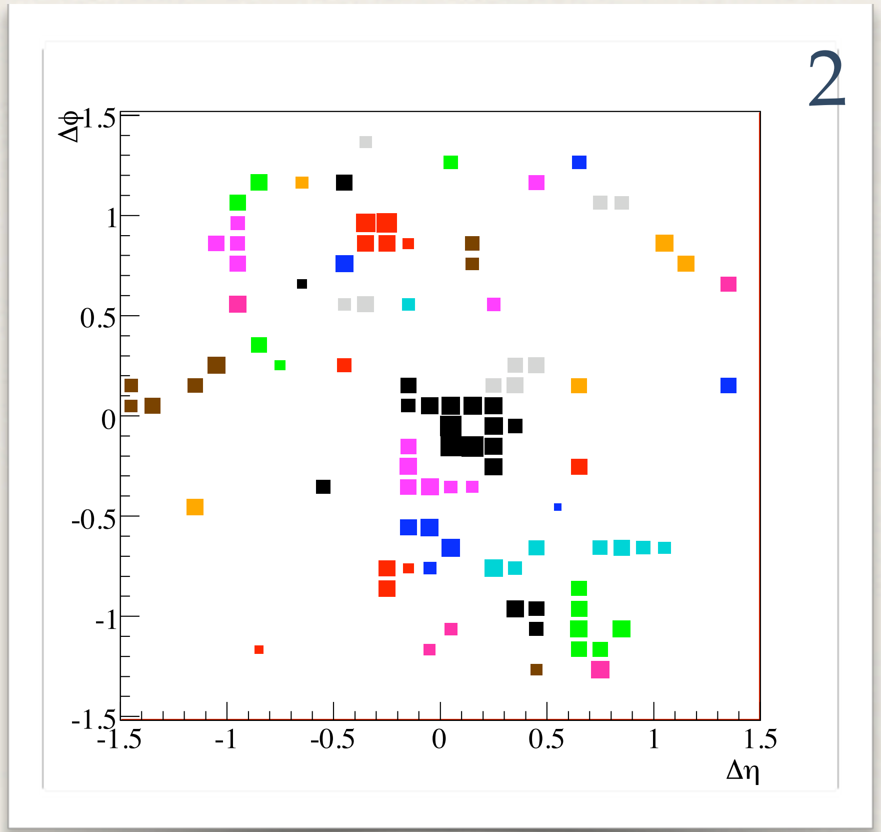
3. Discard the subjet *i* if

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

4. Reassemble the remaining subjets into the trimmed jet

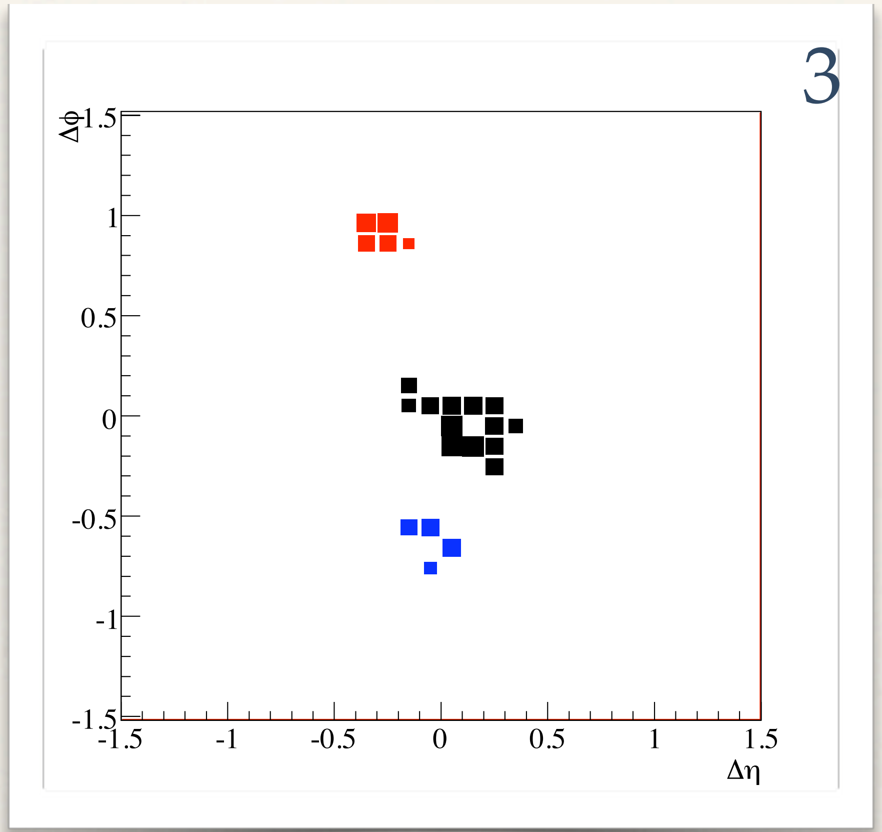
Start

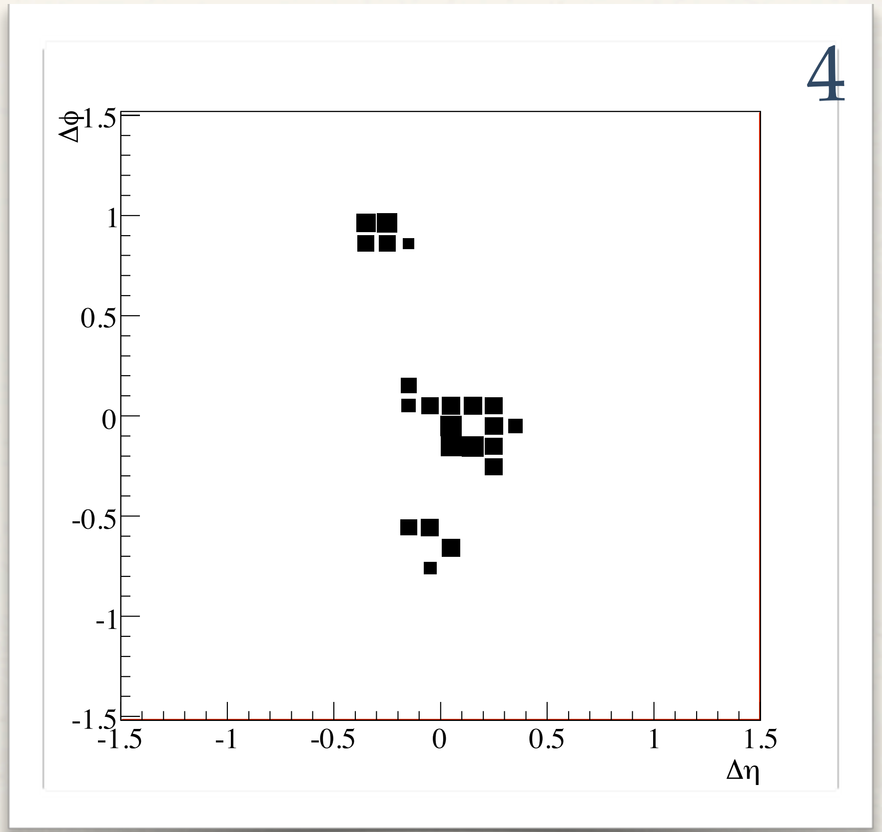




Cluster into subjets

Discard soft subjets

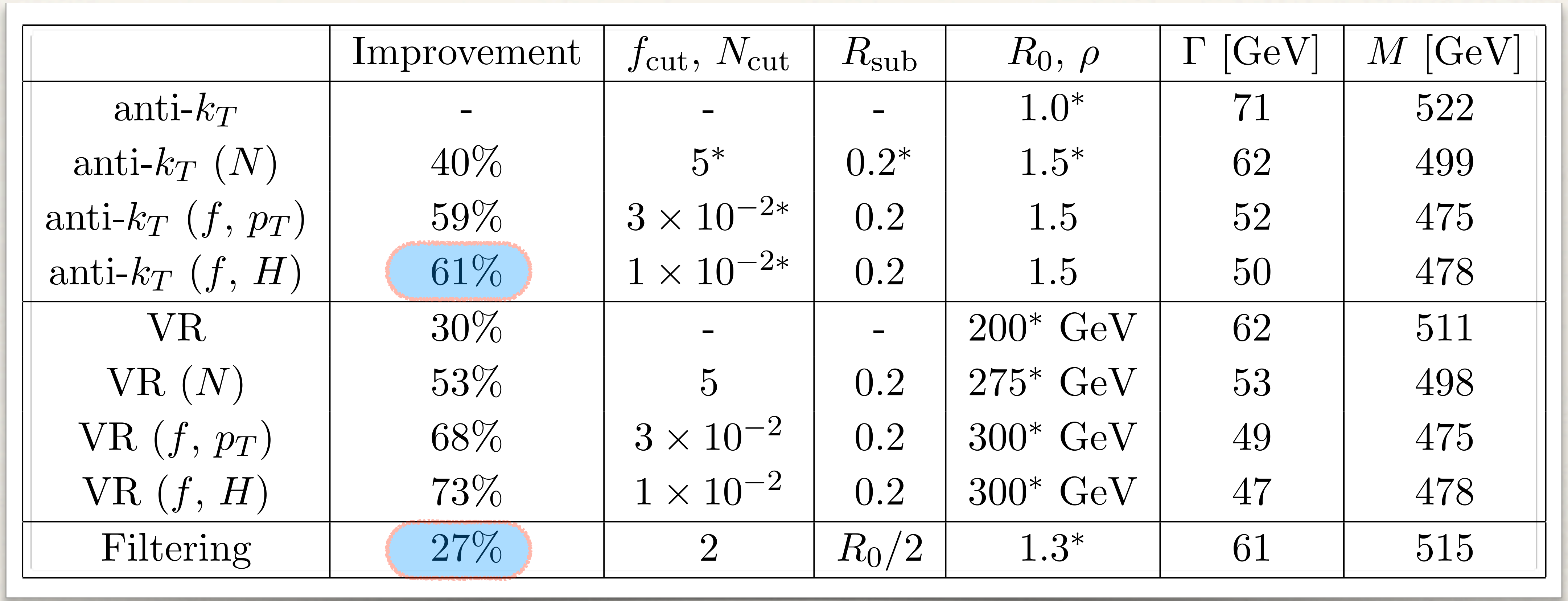




Reassemble

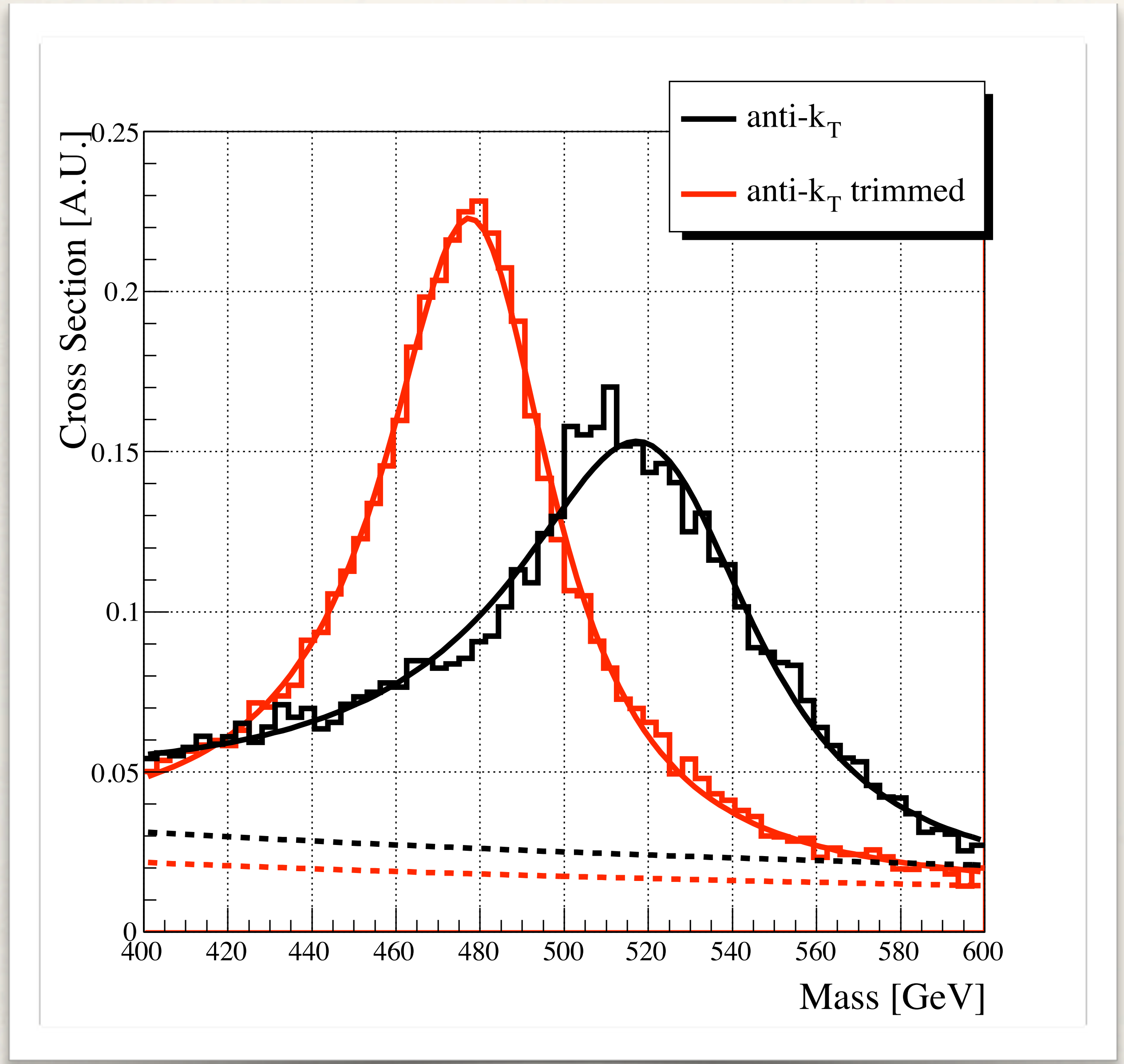
Results

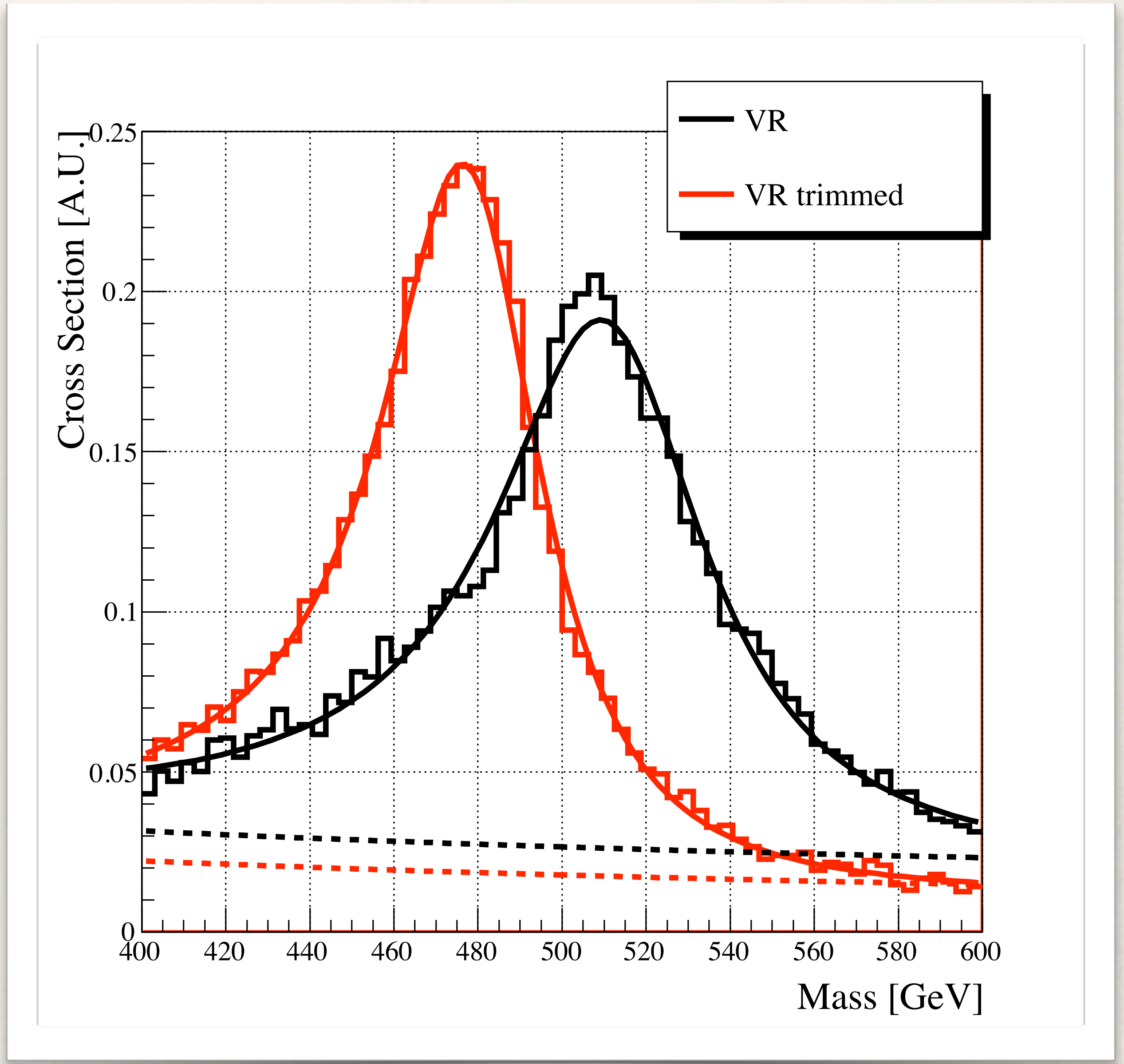
- Find a significant improvement from using trimming to reconstruct a resonance decaying to dijets (gg → ϕ → gg)



	Improvement	$f_{\mathrm{cut}},\ N_{\mathrm{cut}}$	R_{sub}	$R_0,\ \rho$	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.





Jet Topiary

- 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

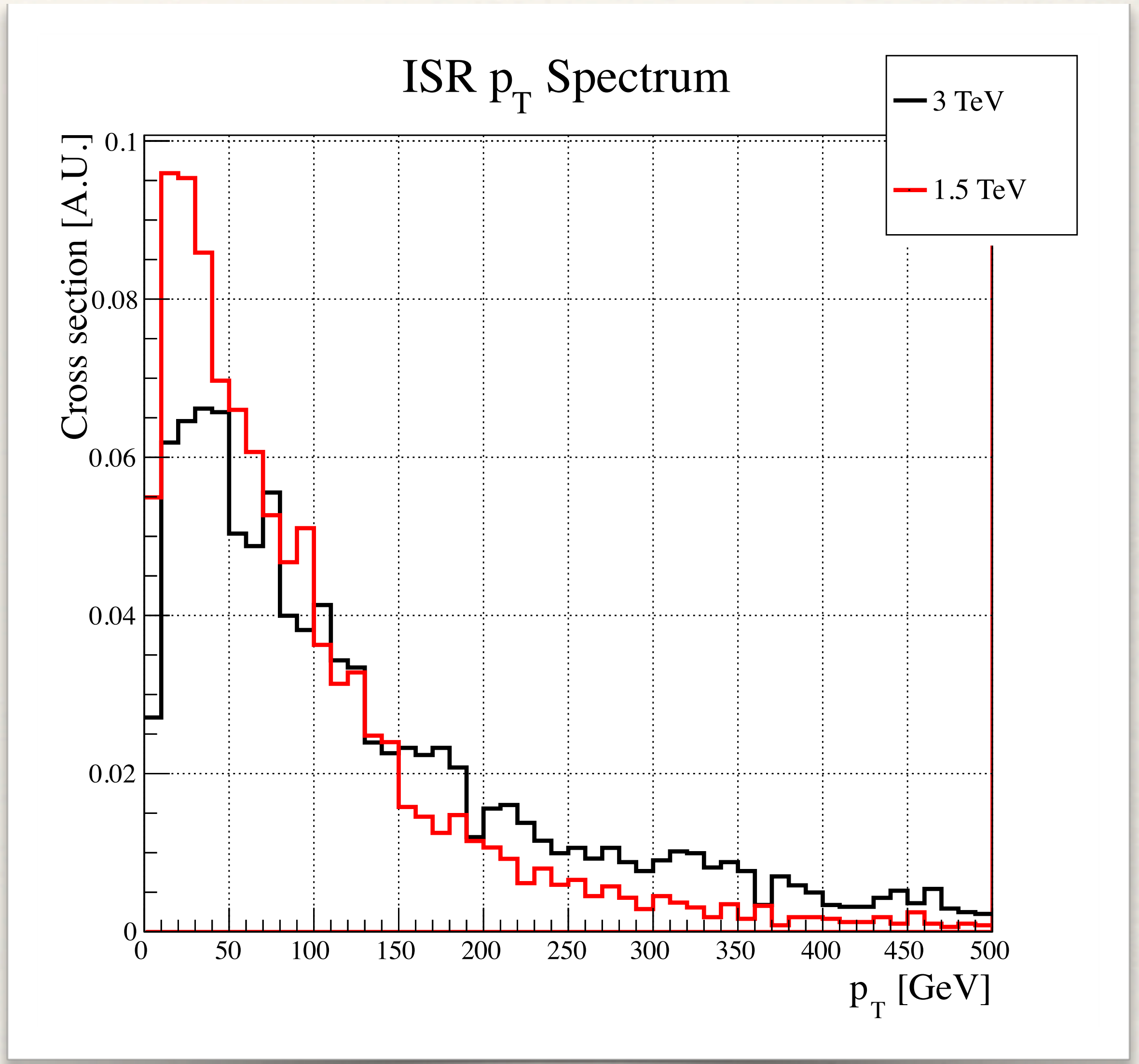
2. Filtering (Butterworth, Davison, Rubin, Salam): 0802.2470

- We just saw how we can, to some extent, deal with ISR contaminating other jets.
- What about when an ISR emission forms a jet unto itself?

What can we hope to learn by tagging ISR?

Radiative measure of scale

- The spectrum of ISR emissions is governed by the scale of the event (usually the mass of the new physics states).
- By looking at the ISR spectrum over many events, we can recover information about this original scale



$$\mathcal{P}(t_1,t_2,x) = \exp\left(-\boxed{\int_{t_1}^{t_2}\frac{dt}{t}}\int\frac{dz}{z}\frac{\alpha_S}{2\pi}\hat{P}(z)\frac{f(x/z,t)}{f(x,t)}\right)\Bigg\}\begin{matrix}\text{ISR}\\\text{Sudakov}\end{matrix}$$

Initial State Partons

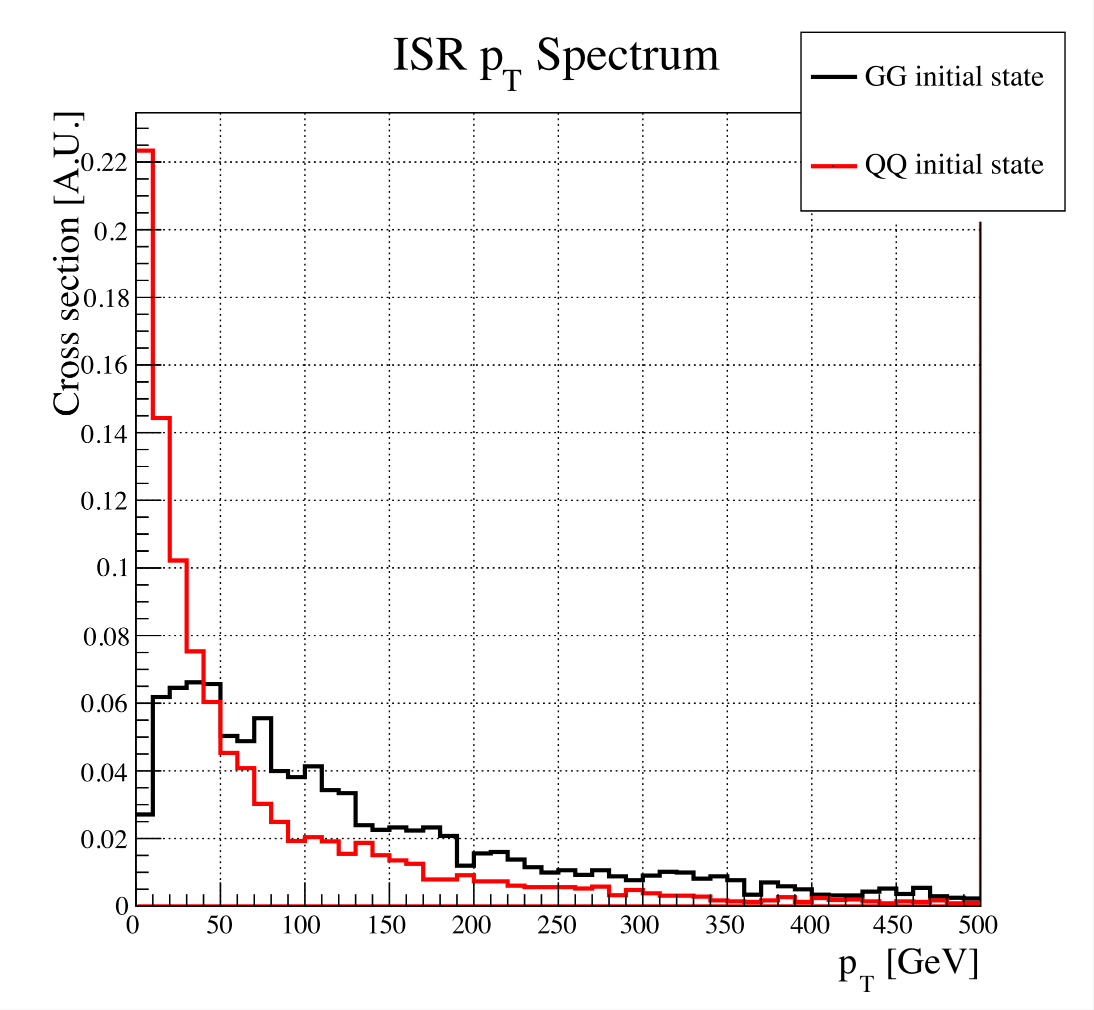
- The ISR spectrum also depends on the identity of the initial state because

1. The splitting functions are different

$$\hat{P}_{q\to qg}(z) = C_F\frac{1+z^2}{1-z}$$

$$\hat{P}_{g\to gg}(z) = C_A\left[\frac{1-z}{z}+\frac{z}{1-z}+z(1-z)\right]$$

2. The PDFs are different



$$\left.\mathcal{P}(t_1,t_2,x) = \exp\left(-\int_{t_1}^{t_2}\frac{dt}{t}\int\frac{dz}{z}\frac{\alpha_S}{2\pi}\overset{\text{PDFs}}{\boxed{\hat{P}(z)\frac{f(x/z,t)}{f(x,t)}}}\right)\right\}\begin{array}{c}\text{ISR}\\\text{Sudakov}\end{array}$$

Kinematic Measure of Scale

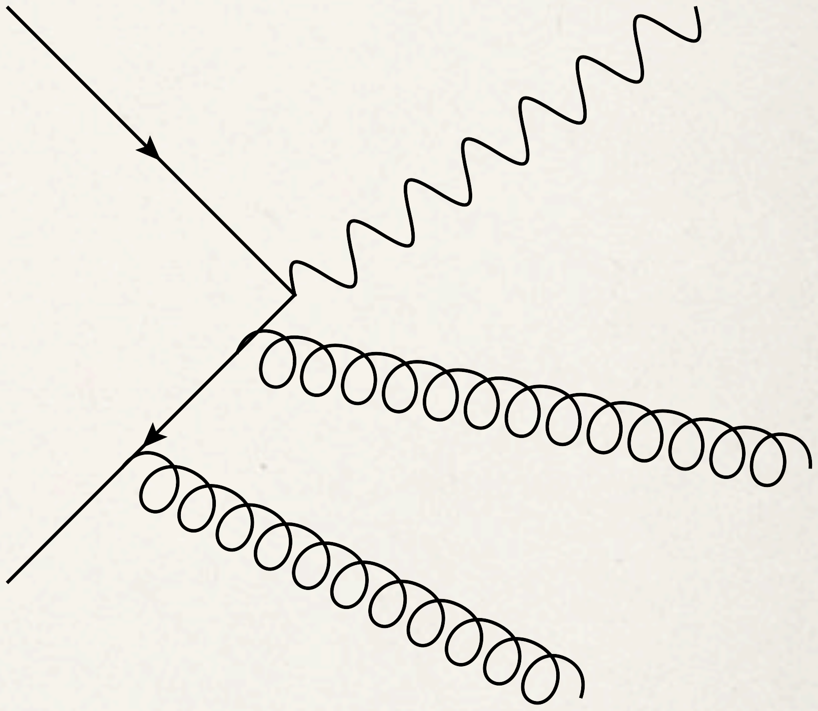
- To preserve momentum, new physics objects must recoil against ISR.
- This is especially useful in studying processes with invisible particles.
  - We get to see how the system reacts against a “push” of known pT
  - Another measure of scale - perhaps less sensitive to QCD corrections.

Background reduction

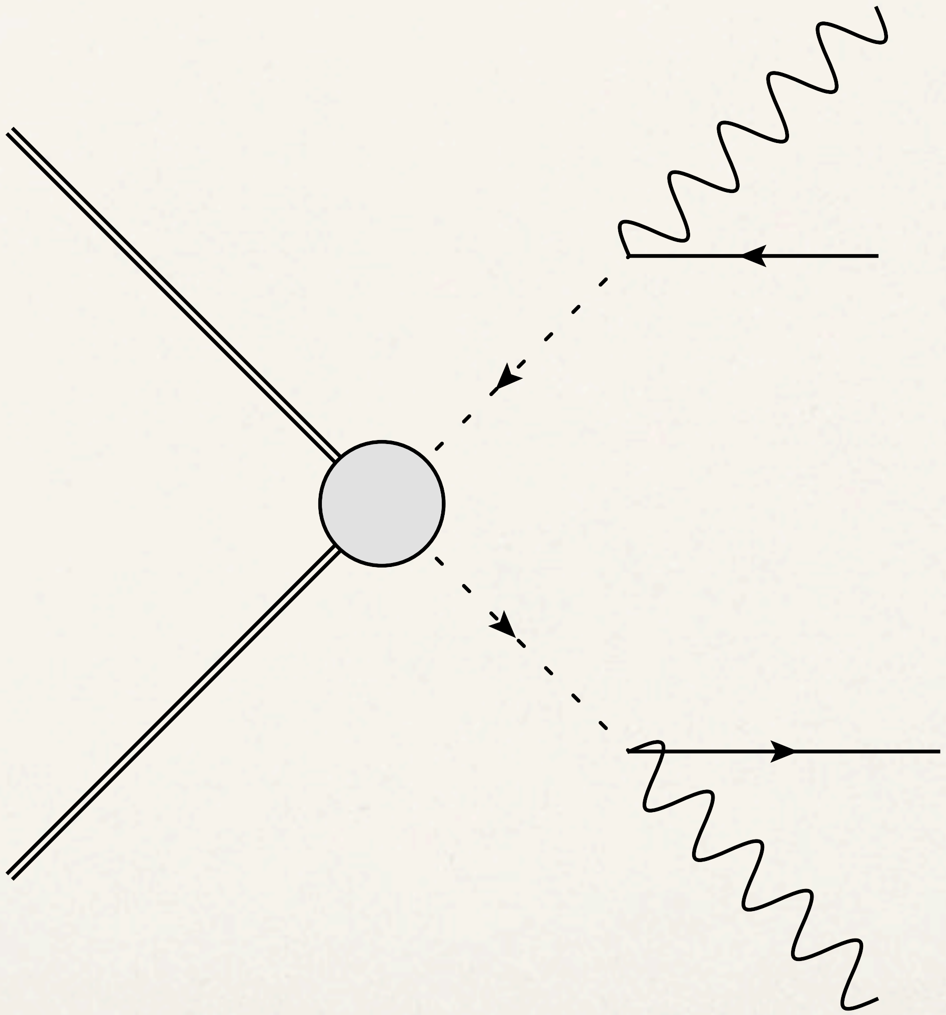
- ISR is well defined for new physics processes through narrow width resonances

- However, in a SM process like Z+jets, it's no longer well defined (why is one jet in Z+jets more "ISR"-like than another? - it's not).

- A lot of the qualities we look for to tag ISR jets aren't present in SM events.
  - ISR tagging can serve as a nice cut.



Example: Disquark production



Tagging Procedure

- **Tag**
  - Take three hardest jets. Look for those

    1. Distinguished in pT

OR

    2. Distinguished in rapidity

OR

    3. Distinguished in m/pT

- **Check**
  - Require the candidate ISR jet

    1. Not be central

AND

    2. Remain somewhat isolated in rapidity

  - And, require that the implicit FSR jets be

    1. Close in pT

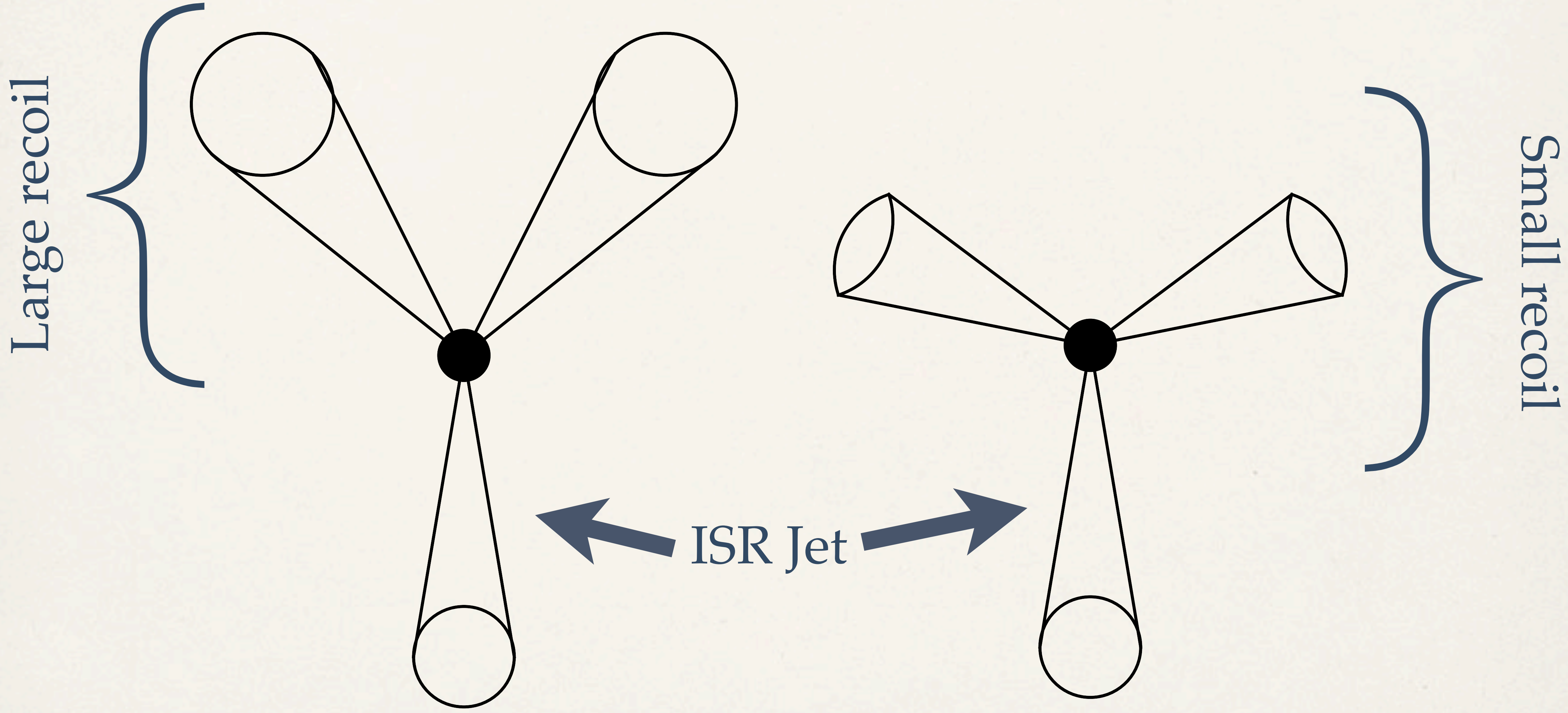
Efficiencies

The efficiencies are remarkably stable across a wide range of spectra

Squark mass [GeV]	LSP Mass [GeV]	Tagging Efficiency [%]	Fake Rate [%]
1000	900	46	12
1000	500	42	14
1000	100	40	11

- So we can identify the ISR jet in an event with ~90% certainty
  - This is surprising, because it works even when there is missing energy and no real energy scale difference between ISR and FSR.
- Let's now see what we can use it for. Can we measure the squark mass by looking at the system's recoil?

Moral of the story:



In our system there is missing energy - the above picture is only true on average

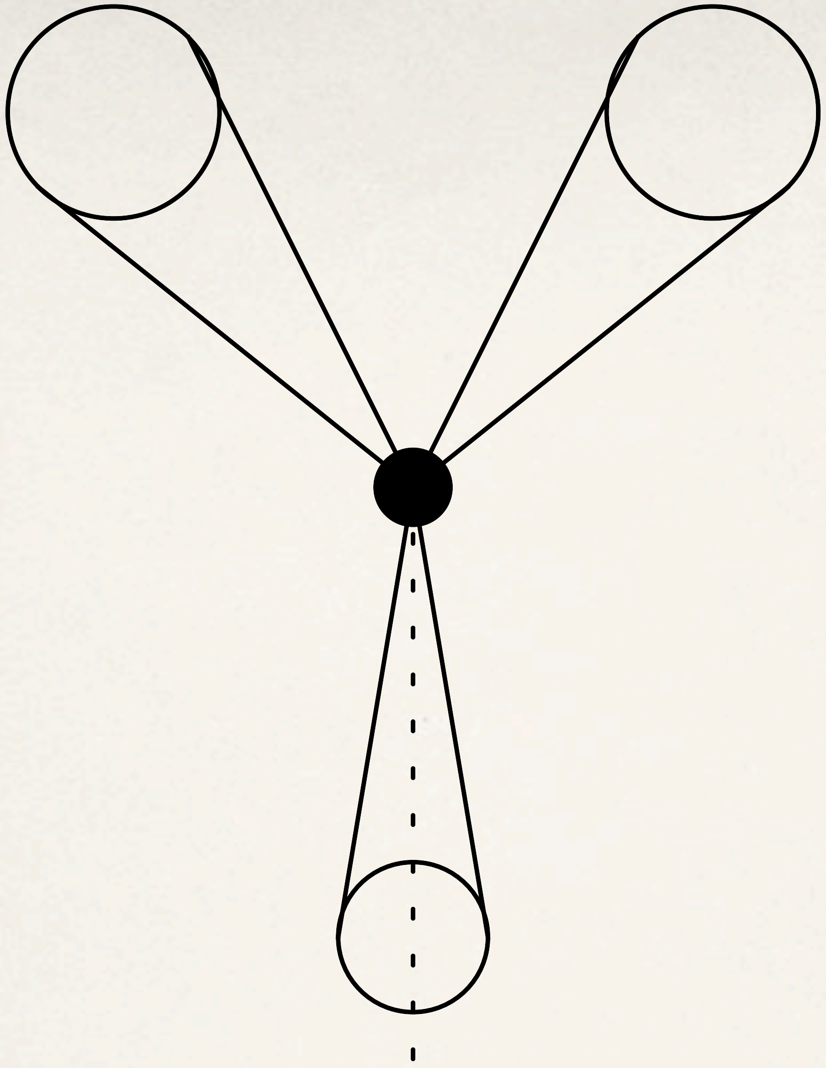
Boosting Procedure

- Let's see how we can use the recoil of the system to probe the new physics scale.

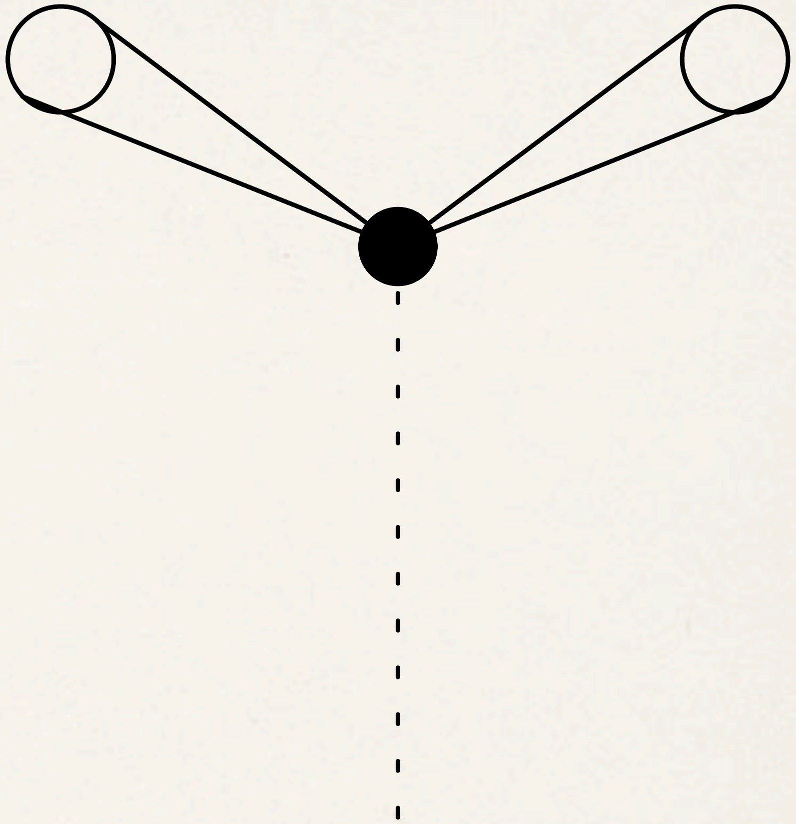
1. Boost both FSR jets along the z-direction so they're z-momenta are balanced

2. Boost along transverse direction to compensate for ISR. This requires an assumption of the system's mass.

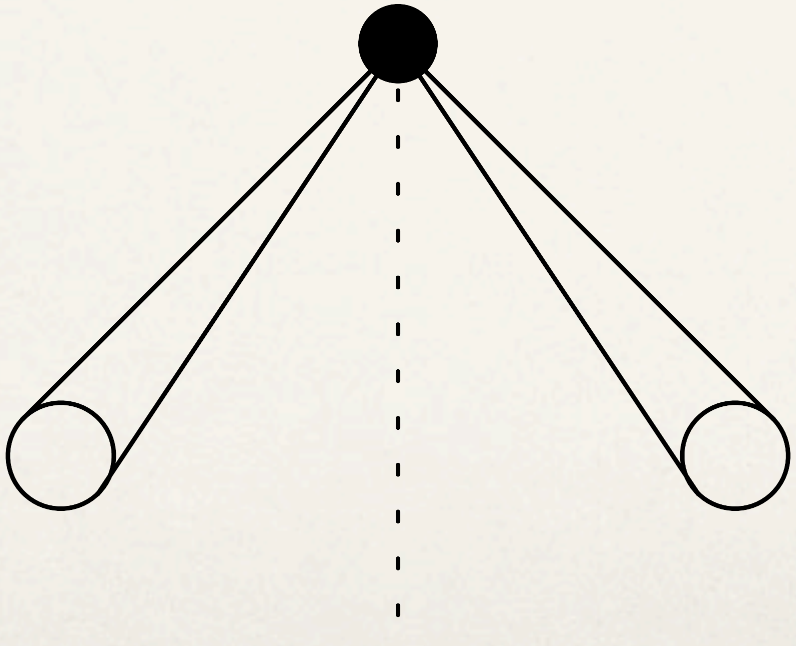
3. Measure the projection of the FSR along the ISR's direction. If the boost has been performed "correctly" there should be no net projection.



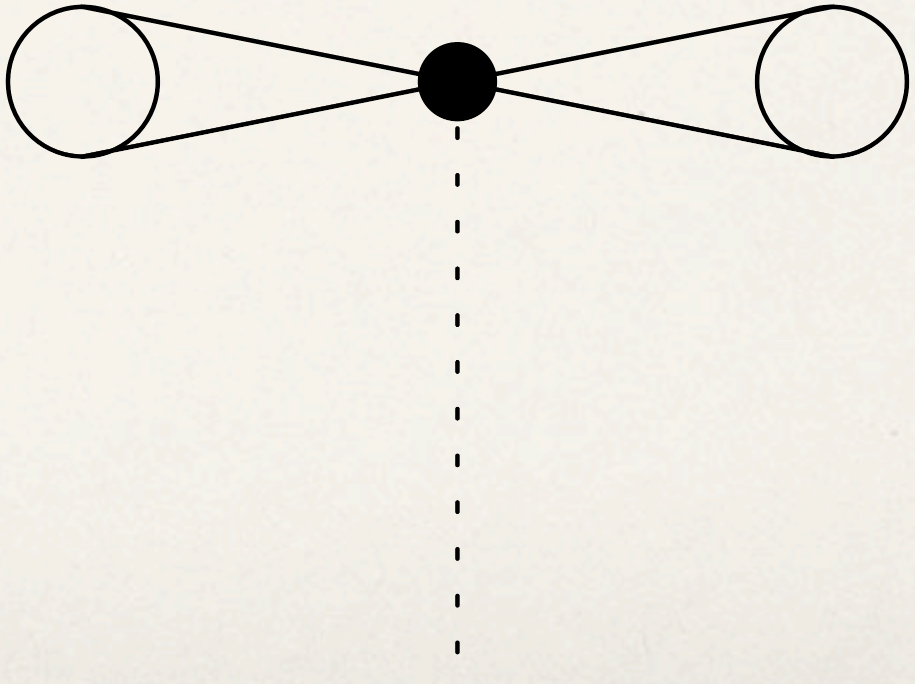
Pre-boost



Under boost

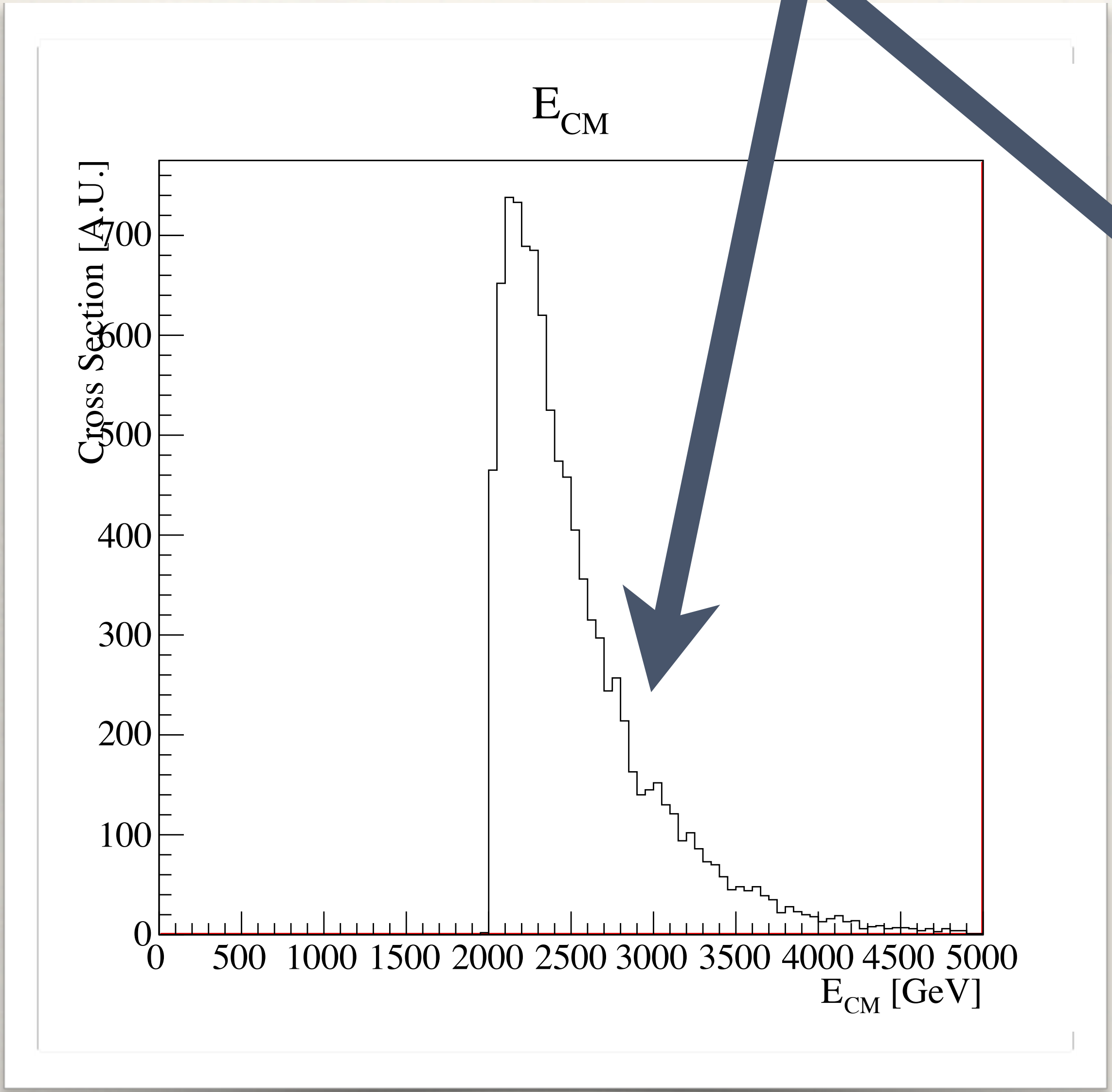


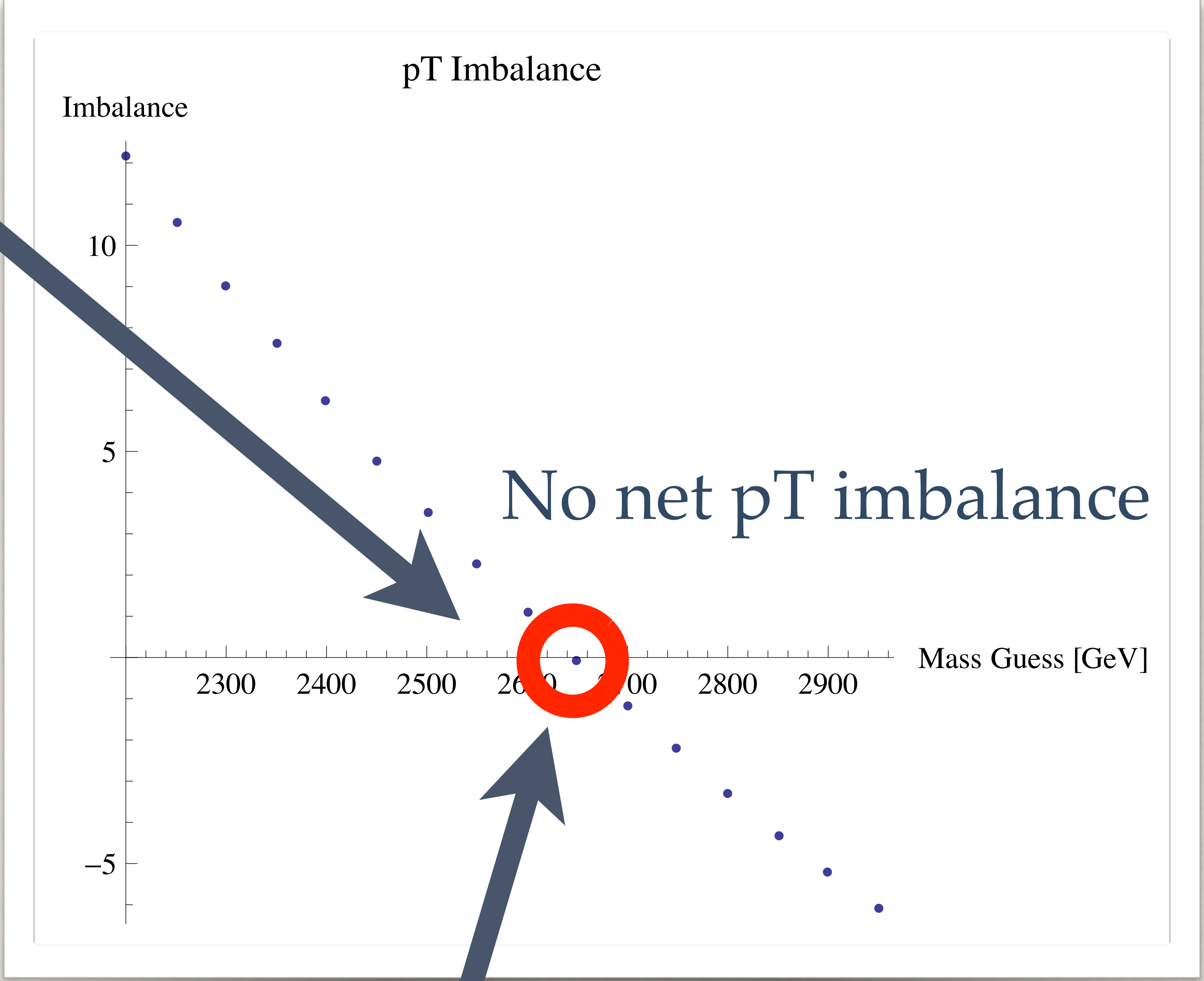
Over boost



Correct boost

Characteristic E_{CM} near 2.5 TeV for 1 TeV squark pairs





No net pT imbalance

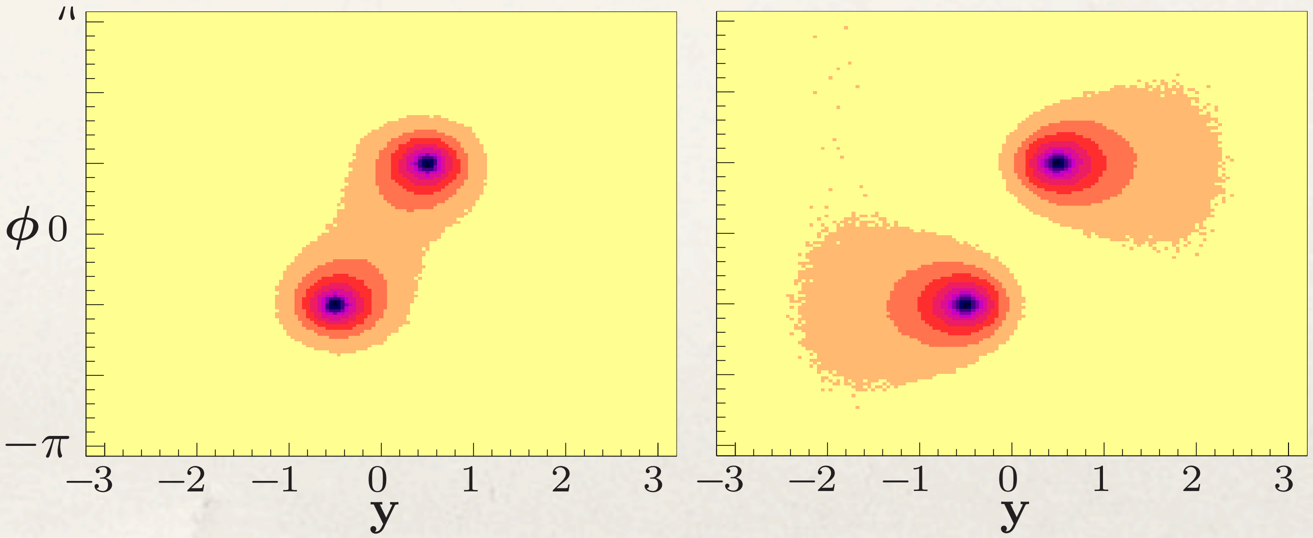
Center-of-mass energy distribution ~ $2m_{squark}$

Reconstructed characteristic center-of-mass energy

Future Directions

- Using jet substructure/superstructure
  - Distinguish, at least statistically, quark from gluon jets
  - Measure jet production “scale” - should see similarity between two jets
  - Look for color connections [1001.5027]

The radiation pattern between jets can tell us something about the color connections



Source: 1001.5027

Future Directions (contd.)

- Other ISR observables:
    - ISR rapidity as a probe of valence/sea parton couplings
- Develop taggers for other scenarios of new physics.
    - Add flavor information: tops, b-jets
- How well can we improve, say, MT2, by reducing combinatorics?

Conclusions

- In looking for new physics at the LHC, we'll have to contend with initial state radiation (ISR).
- We're used to thinking of ISR as an annoying fact of life, but recent advancements (e.g. Jet Trimming) have helped to mitigate its effects.
- Perhaps more interestingly, ISR can even be helpful
    - By tagging jets as being from ISR we can learn new things about an event.

`jets.physics.harvard.edu`

`boost2011.org`