Angular Correlations in High Energy Collisions

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1104.1646, ????

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What Defines QCD?

- Approximately scale-invariant non-Abelian gauge theory at high energies

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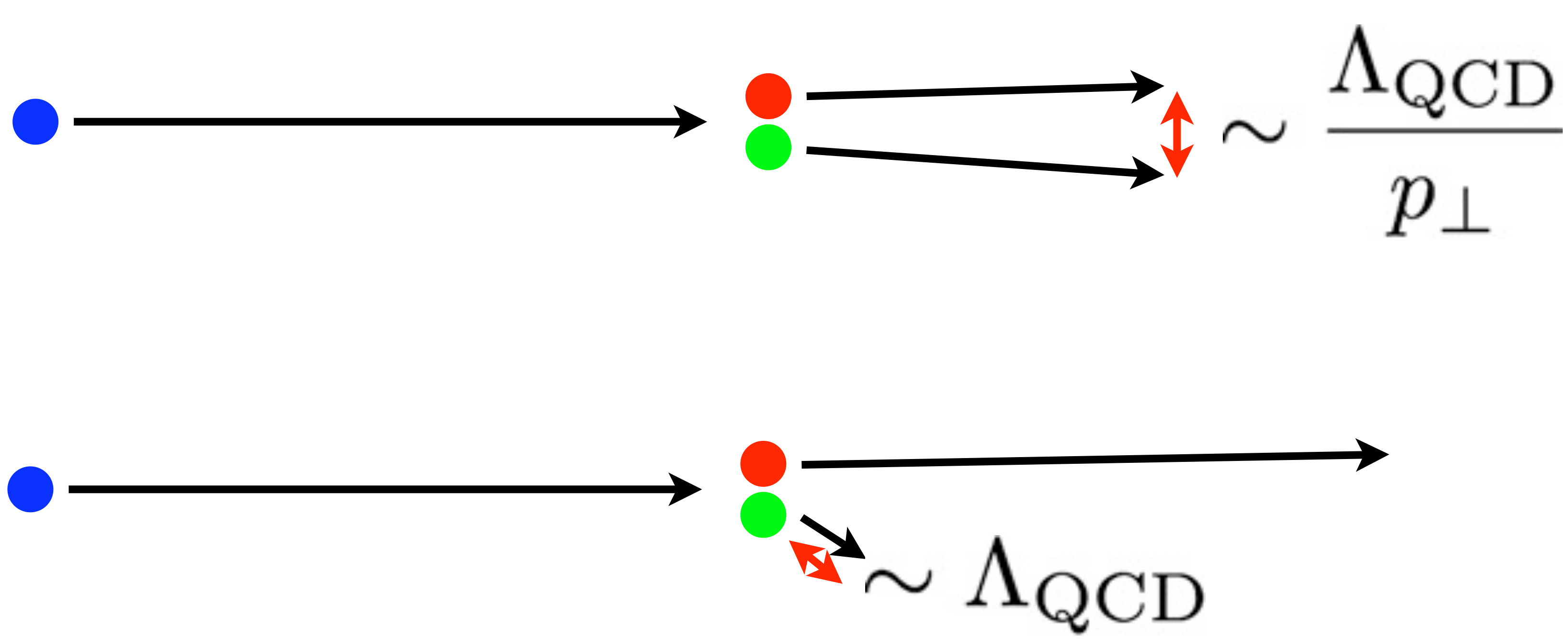
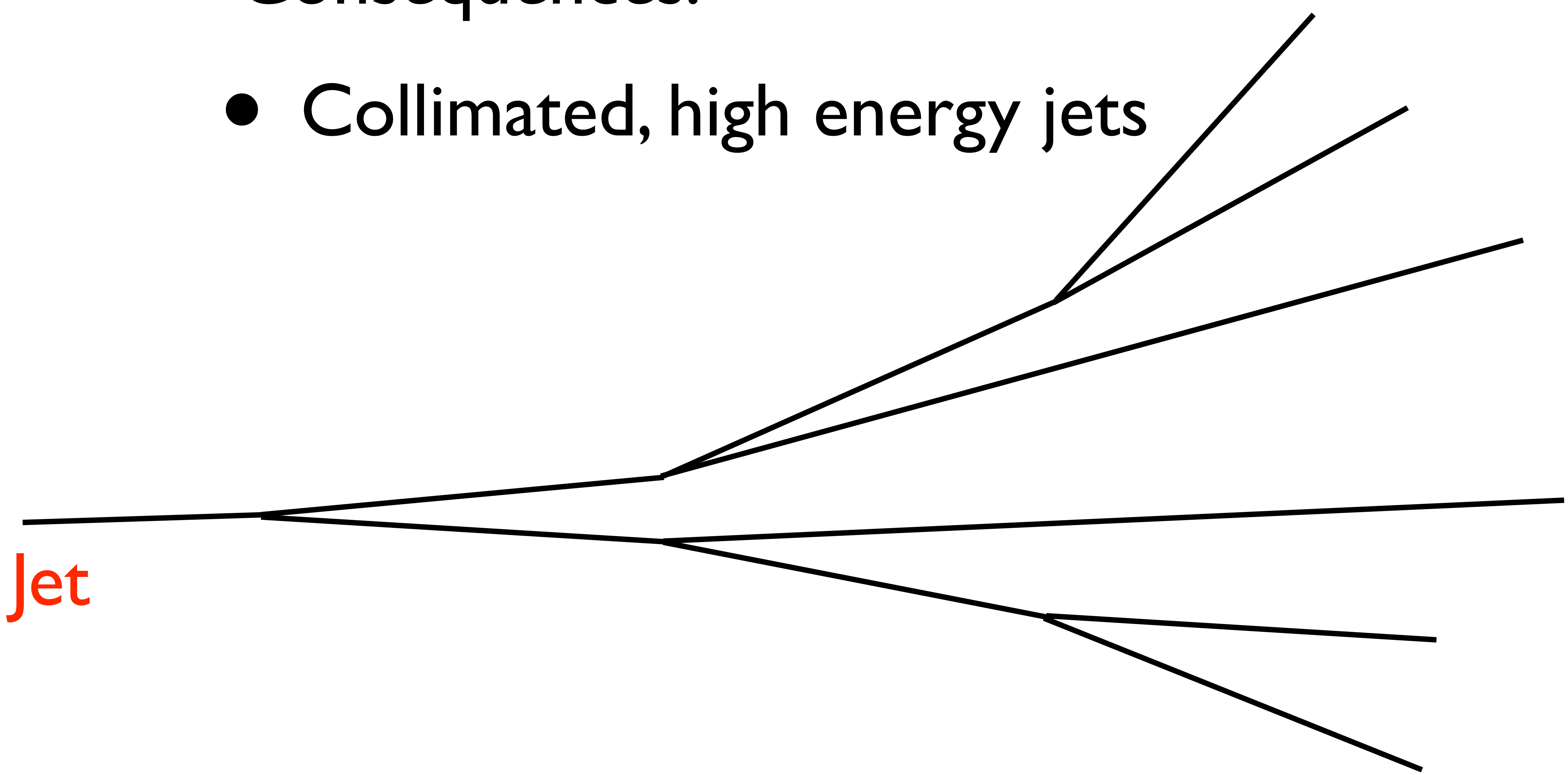
- Approximately scale-invariant non-Abelian gauge theory at high energies
  - Consequences:
    - Soft & Collinear singularities



What Defines QCD?

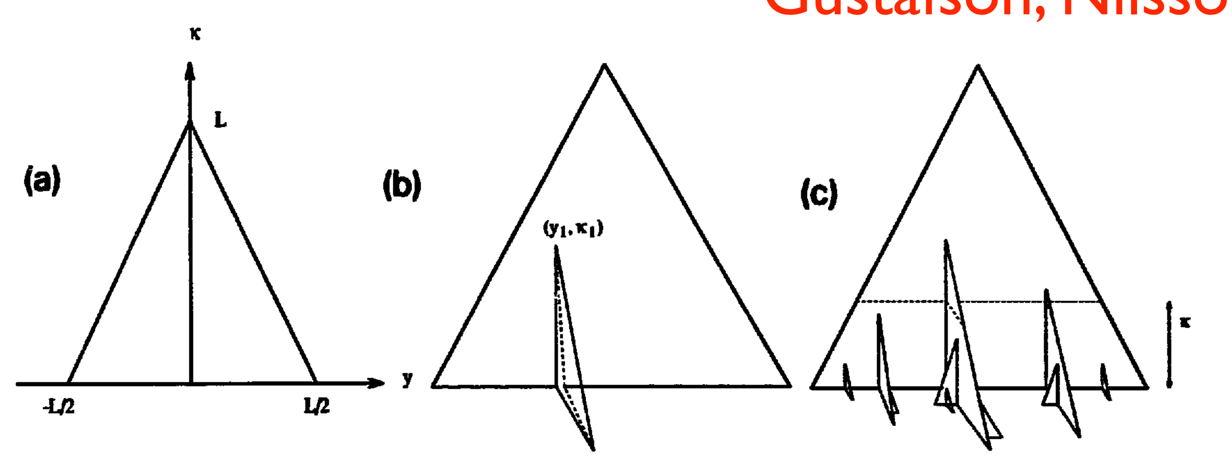
- Approximately scale-invariant non-Abelian gauge theory at high energies
  - Consequences:
    - Collimated, high energy jets



What Defines QCD?

- Approximately scale-invariant non-Abelian gauge theory at high energies
  - Consequences:
    - Anomalous dimensions
      - "Textbook": $\langle\psi(x)\psi(0)\rangle \sim \frac{1}{|x|^D}$
      - "Fractal Phase Space"

Gustafson, Nilsson 1991; Bjorken 1992

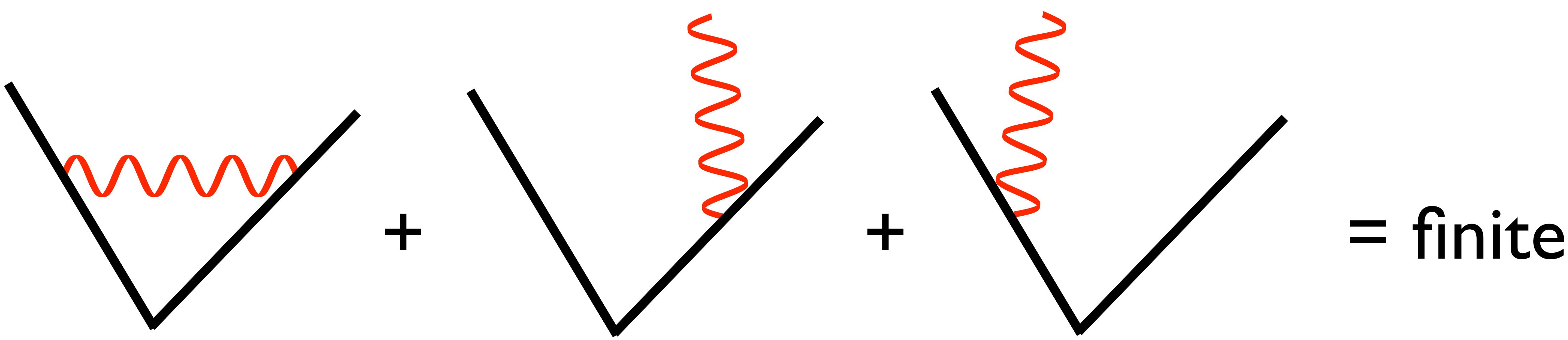


What Defines QCD?

- Our Goal: Define an observable that can distinguish between approximately scale invariant objects and objects that have an intrinsic, high energy scale
  - This observable will be a function which quantifies the scaling properties of the system
  - The argument of the function is a resolution parameter

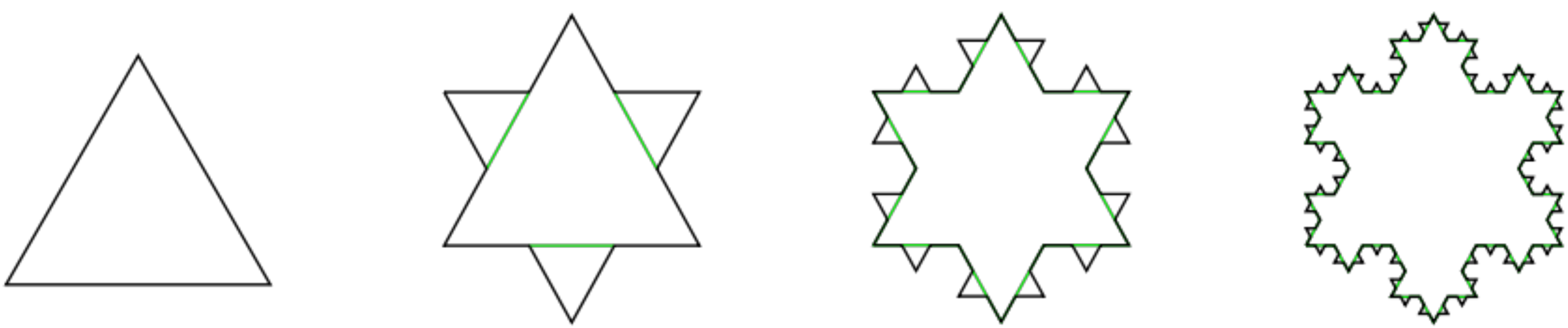
Defining an Observable

- Requirements from theory:
  - Infrared and Collinear safety
    - Want to compute in pert. theory



Defining an Observable

- Requirements from theory:
  - Scale invariant ~ constant
    - Want to extract a dimension
    - Can do this by defining an angular correlation between constituents



Increasing resolution ⟶

Defining an Observable

- Requirements from theory:
  - Correlation should be *z*-boost invariant
    - Jet mass!

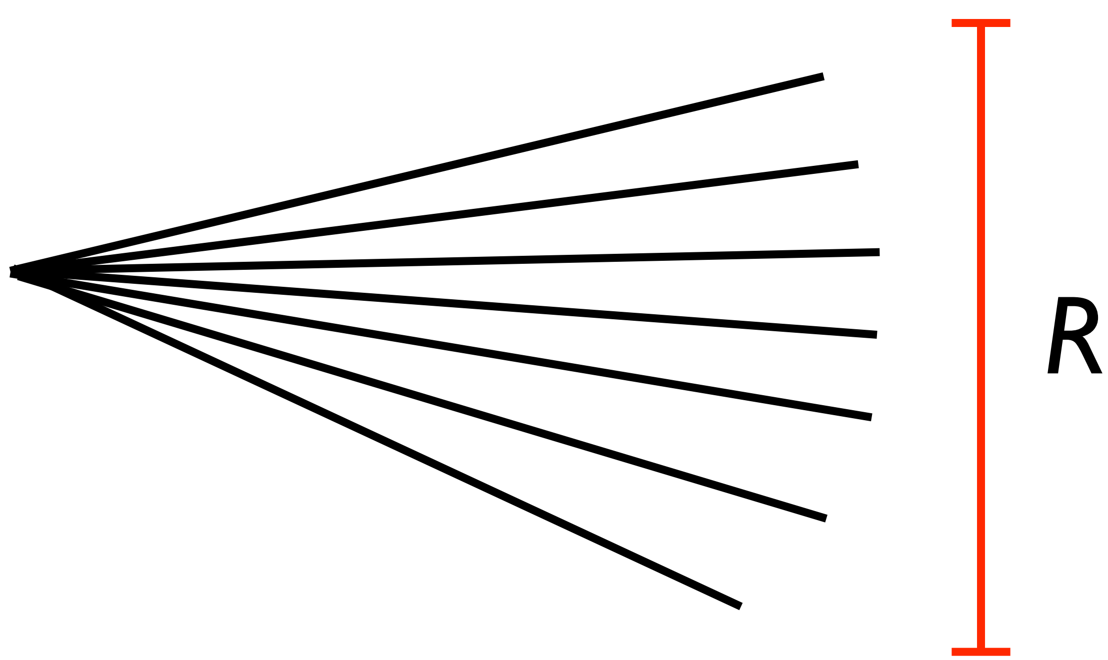
$$\mathcal{G}(R) \equiv \sum_{i \neq j} p_{\perp i} p_{\perp j} \Delta R_{ij}^2 \Theta[R - \Delta R_{ij}]$$

$$\Delta R_{ij}^2 = (\eta_i - \eta_j)^2 + (\phi_i - \phi_j)^2$$

- Angular Correlation Function (ACF)

Angular Correlation Function

- Expectations
  - ACF in QCD ~ R^2



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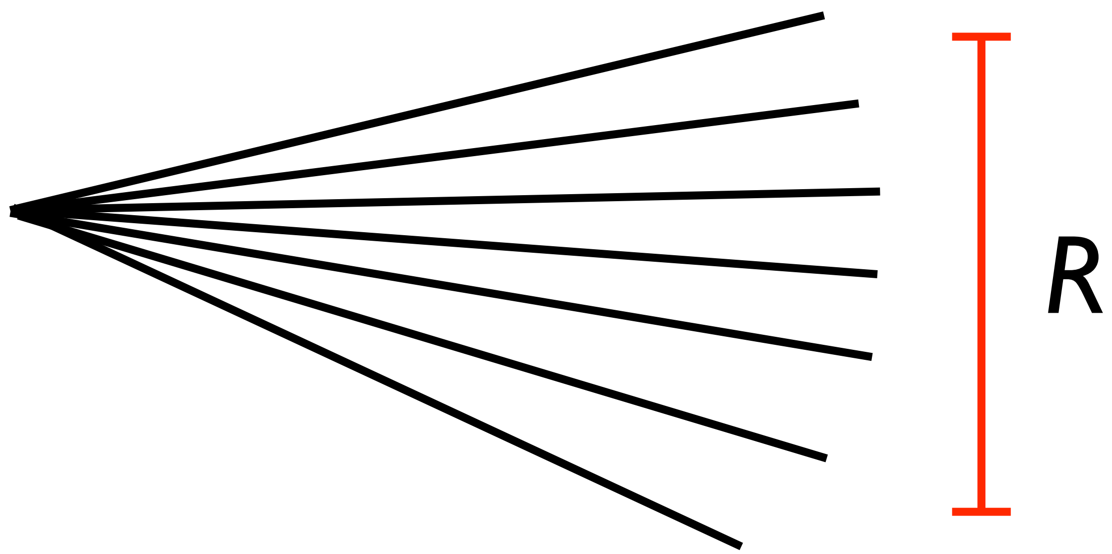

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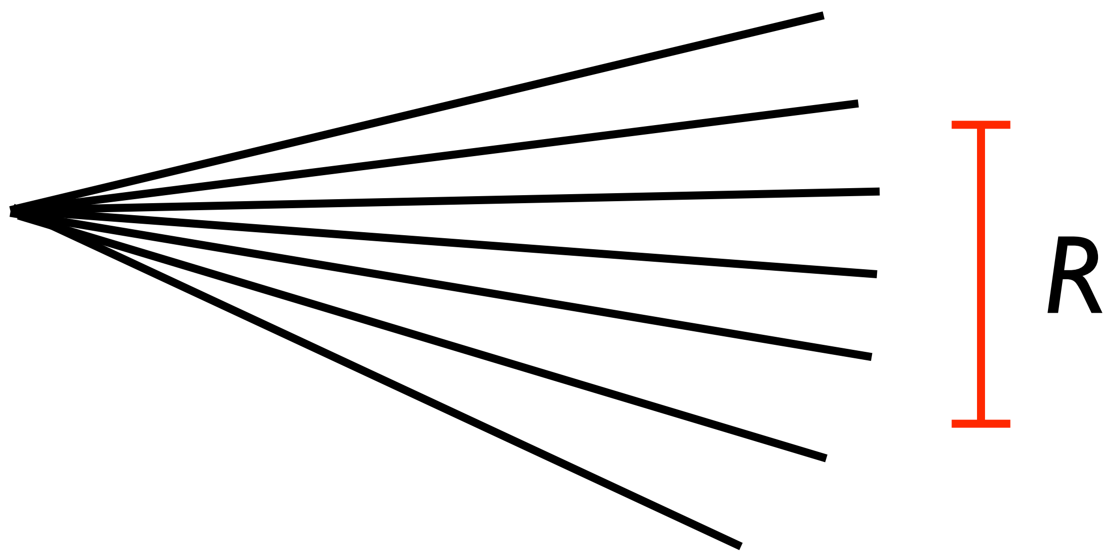
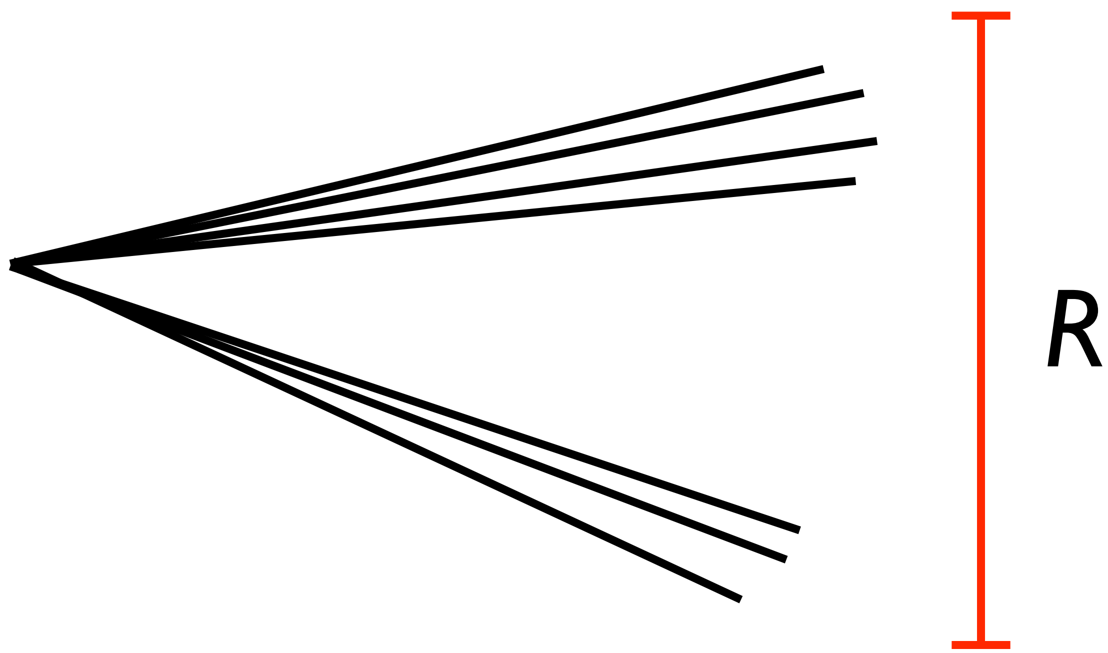


Angular Correlation Function

- Expectations
  - ACF for heavy particle jet will have “cliffs” at characteristic values of R



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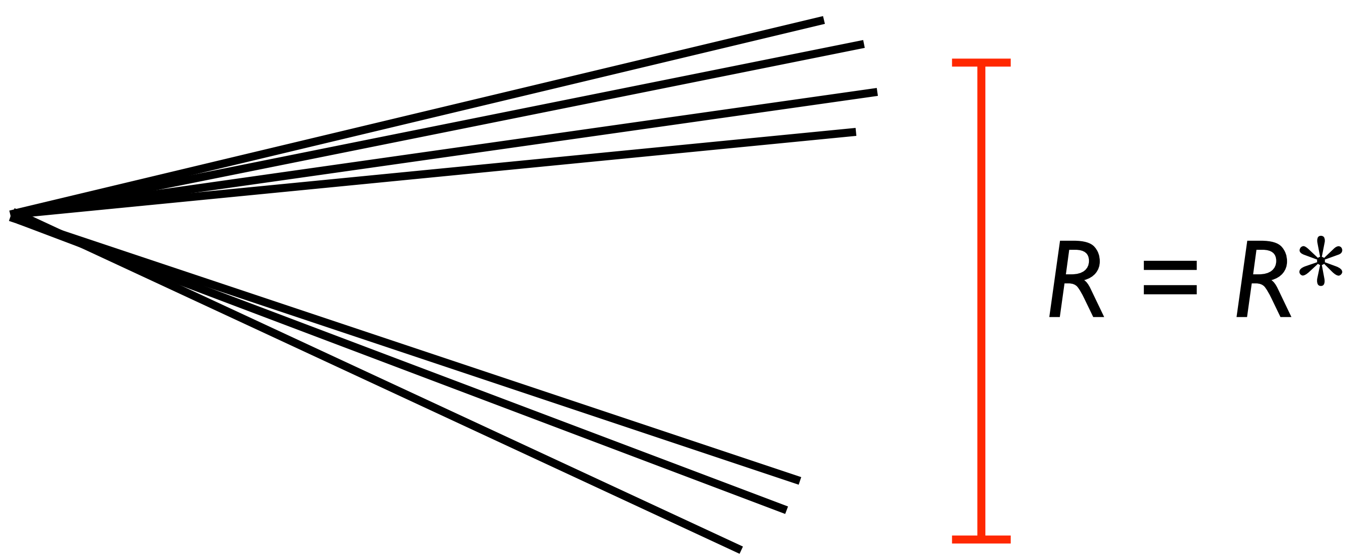

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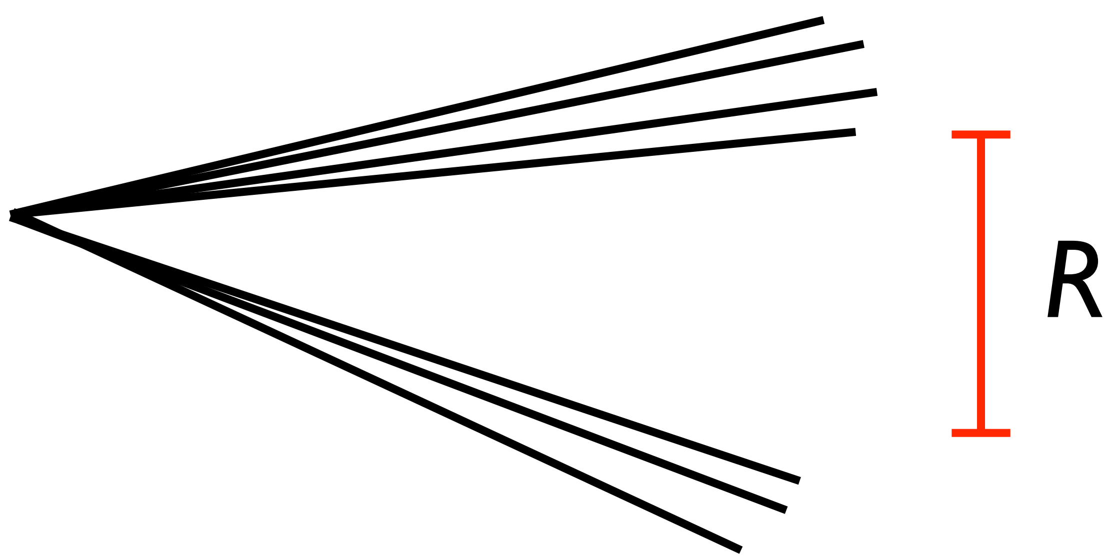


Angular Structure Function

- How to extract a dimension:
  - "Standard way":

$$D = \lim_{R \to 0} \frac{\log \mathcal{G}(R)}{\log R}$$

  - Problems: limiting procedure, only defined in unphysical/unreachable limit
  - No simple way to see structure

Angular Structure Function

- How to extract a dimension:
  - Better: take a derivative

$$D = \frac{d \log \mathcal{G}(R)}{d \log R}$$

  - Benefits: Defined for all R, cliffs in ACF manifest themselves as peaks in derivative

Angular Structure Function

- Define angular structure function (ASF):

$$\Delta\mathcal{G}(R) \equiv \frac{d\log\mathcal{G}(R)}{d\log R} = R\frac{\sum_{i\neq j} p_{\perp i}p_{\perp j}\Delta R_{ij}^2\,\delta[R-\Delta R_{ij}]}{\sum_{i\neq j} p_{\perp i}p_{\perp j}\Delta R_{ij}^2\,\Theta[R-\Delta R_{ij}]}$$

- Structure in ASF is ~uniform in R for QCD

Angular Structure Function

- Delta-function is noisy in finite data
- Smooth ASF by replacing:

$$\Delta\mathcal{G}(R) = R\frac{\sum_{i\neq j} p_{\perp i}p_{\perp j}\Delta R_{ij}^2 K[R-\Delta R_{ij}]}{\sum_{i\neq j} p_{\perp i}p_{\perp j}\Delta R_{ij}^2 \Theta[R-\Delta R_{ij}]}$$

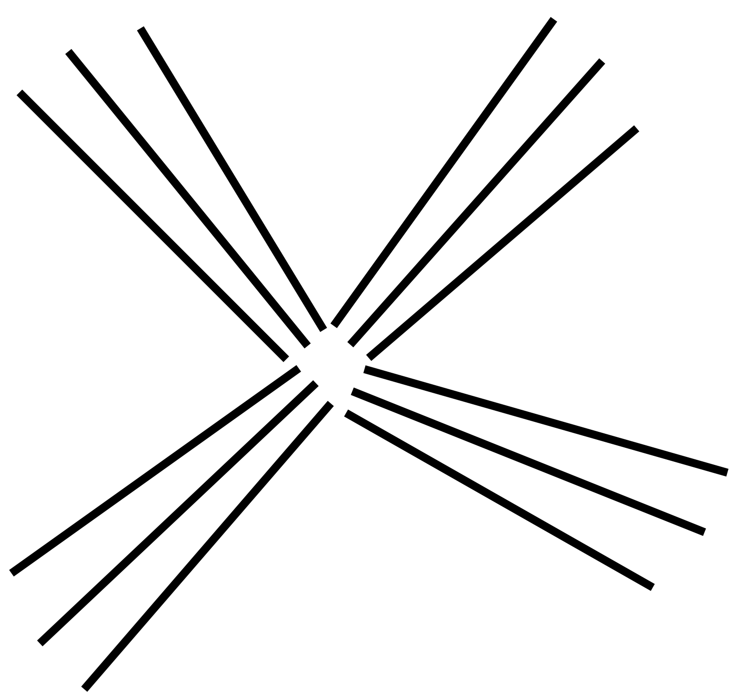
- *K* is taken to be a smooth gaussian kernel:

$$\delta(R-\Delta R_{ij}) \simeq \frac{e^{-\frac{(R-\Delta R_{ij})^2}{2dR^2}}}{dR\sqrt{2\pi}}$$

Top Tagging

Jet Substructure

- Problem: Boosted stuff at LHC doesn't necessarily lead to distinct jets as it did in lower energy experiments



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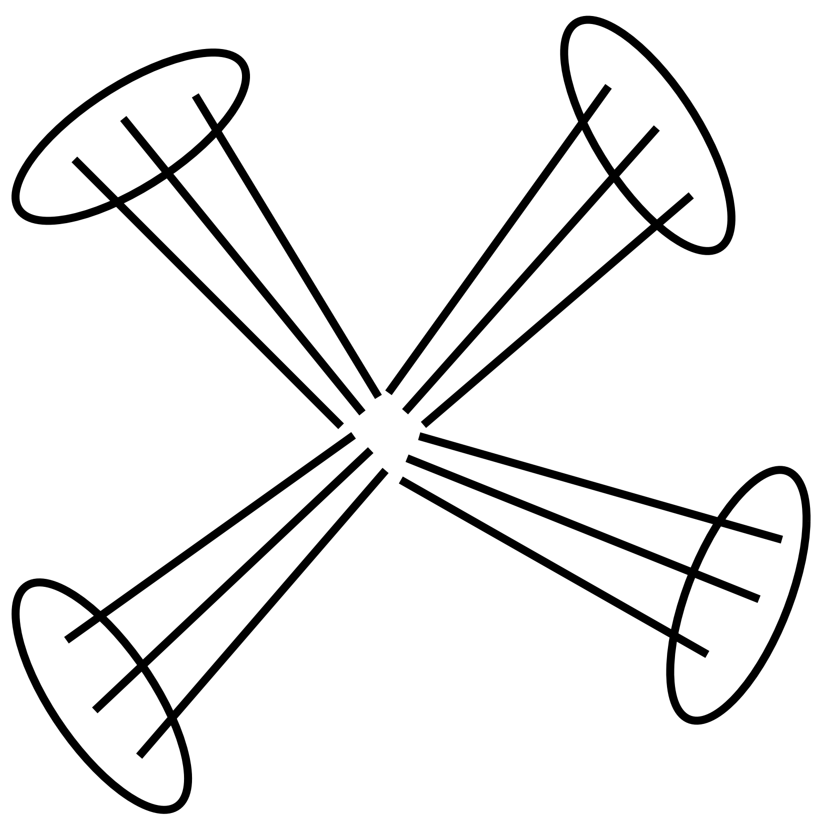

4 well-separated jets

Jet Substructure

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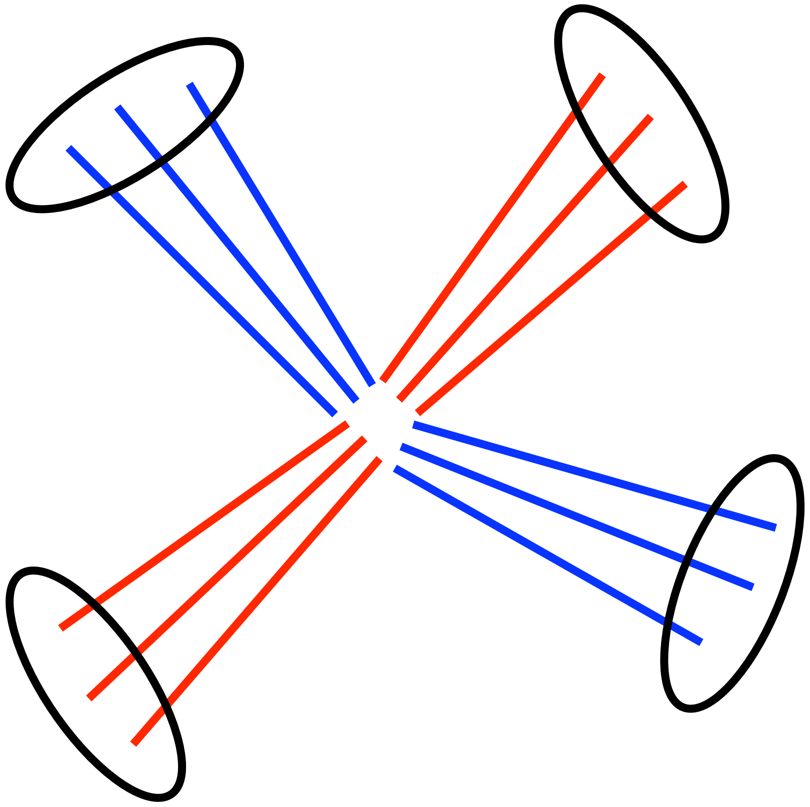

Combinatoric problem: how to pair them?

Jet Substructure

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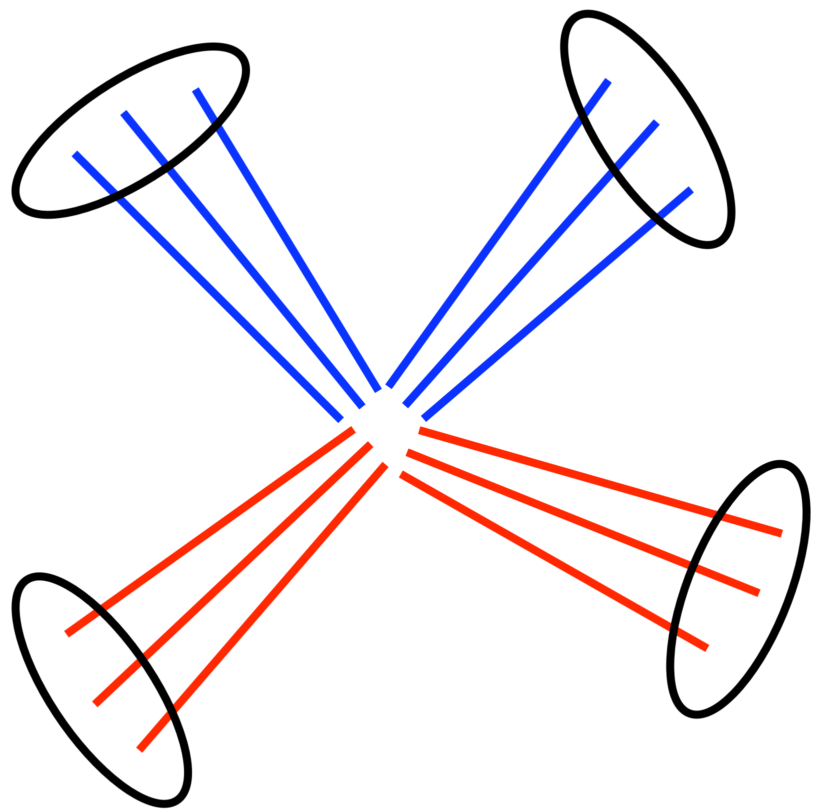

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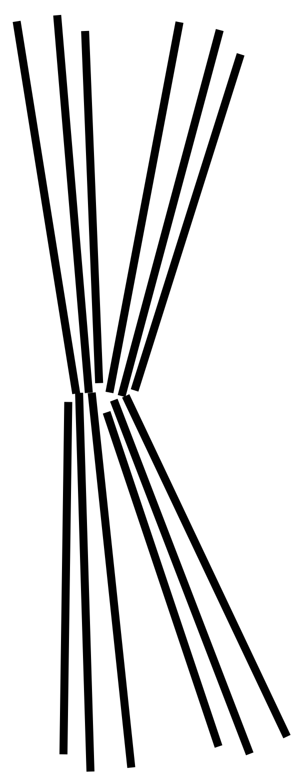

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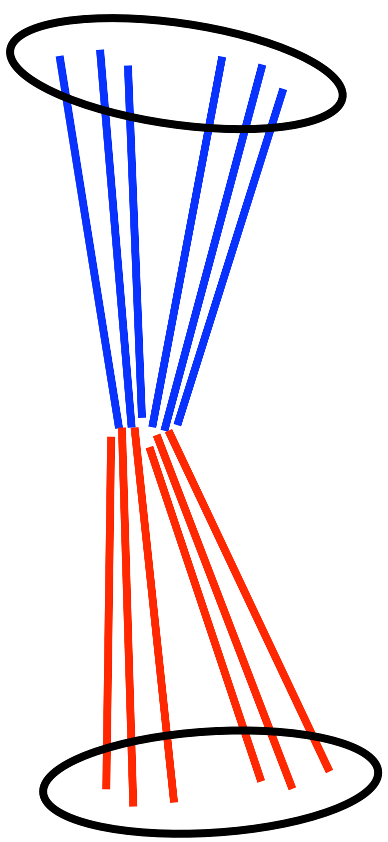
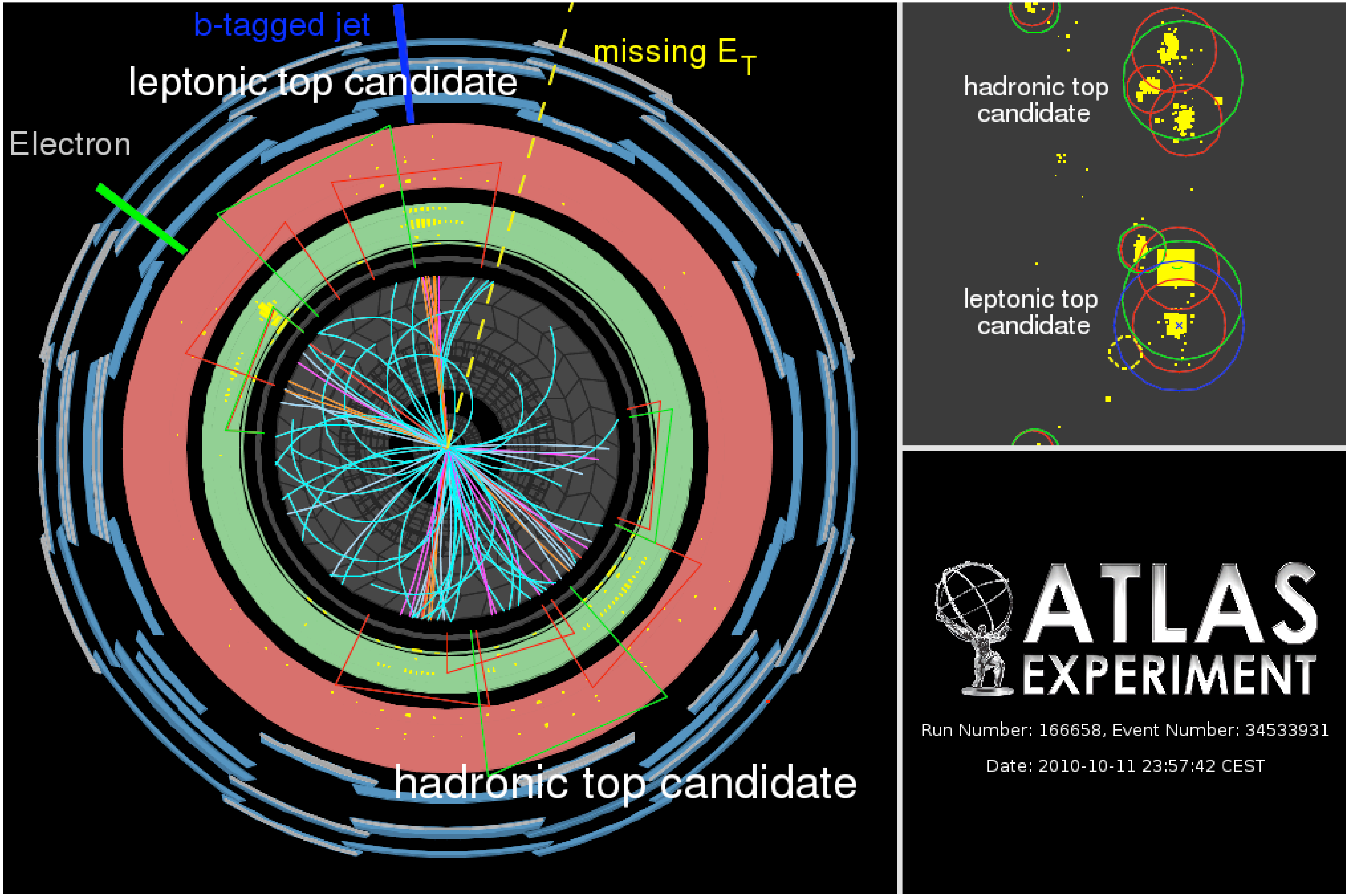


- Boost removes combinatoric problem
- Jets are no longer widely separated
- Study inside of "fat" jets

Jet Substructure



Jet Substructure

- Declustering
  - Define a branching tree with a sequential jet algorithm
- *kT*-type sequential jet algorithm

Ellis, Soper
Catani, *et al.*

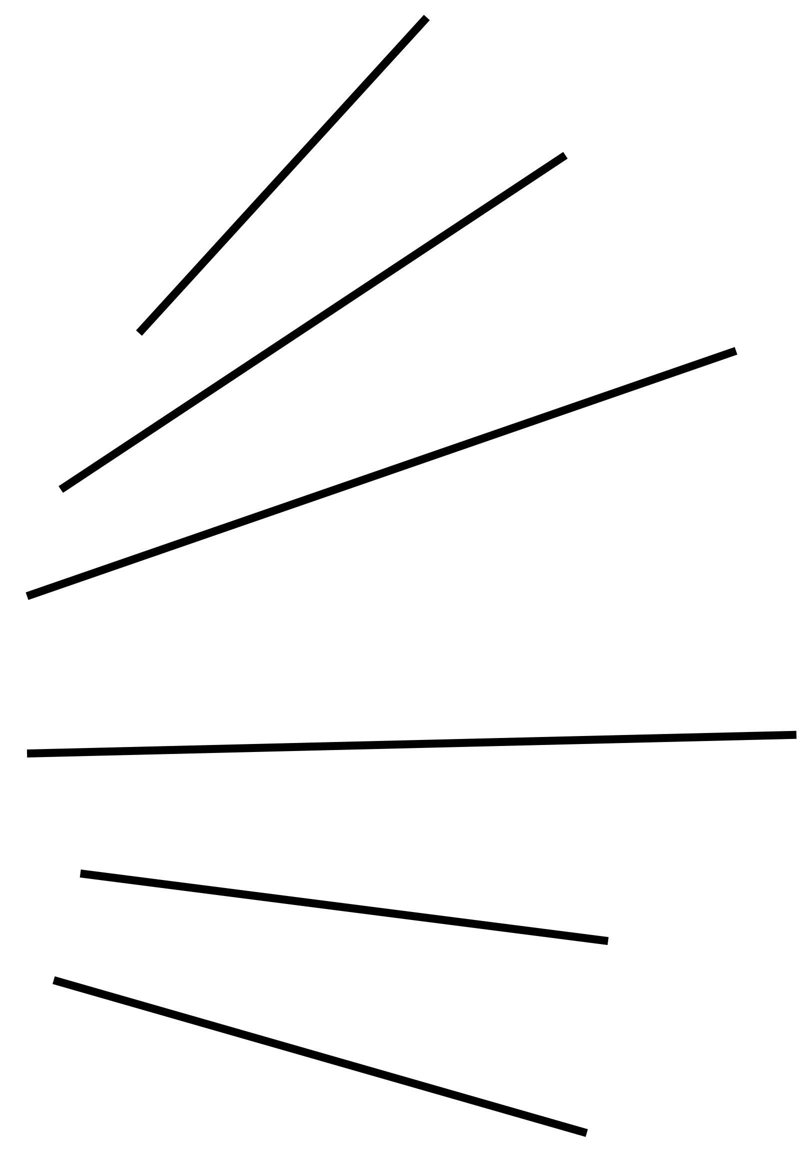
  - 1) Compute $d_{ij} = \min[p_{T,i}^{2n}, p_{T,j}^{2n}] \frac{\Delta R_{ij}^2}{R^2}$

$$\Delta R_{ij}^2 = (\eta_i - \eta_j)^2 + (\phi_i - \phi_j)^2$$

  - n = 1: kT
  - n = 0: Cambridge-Aachen
  - n = -1: anti-kT

Jet Substructure

- *kT*-type sequential jet algorithm
  - 2) Merge closest pair of particles



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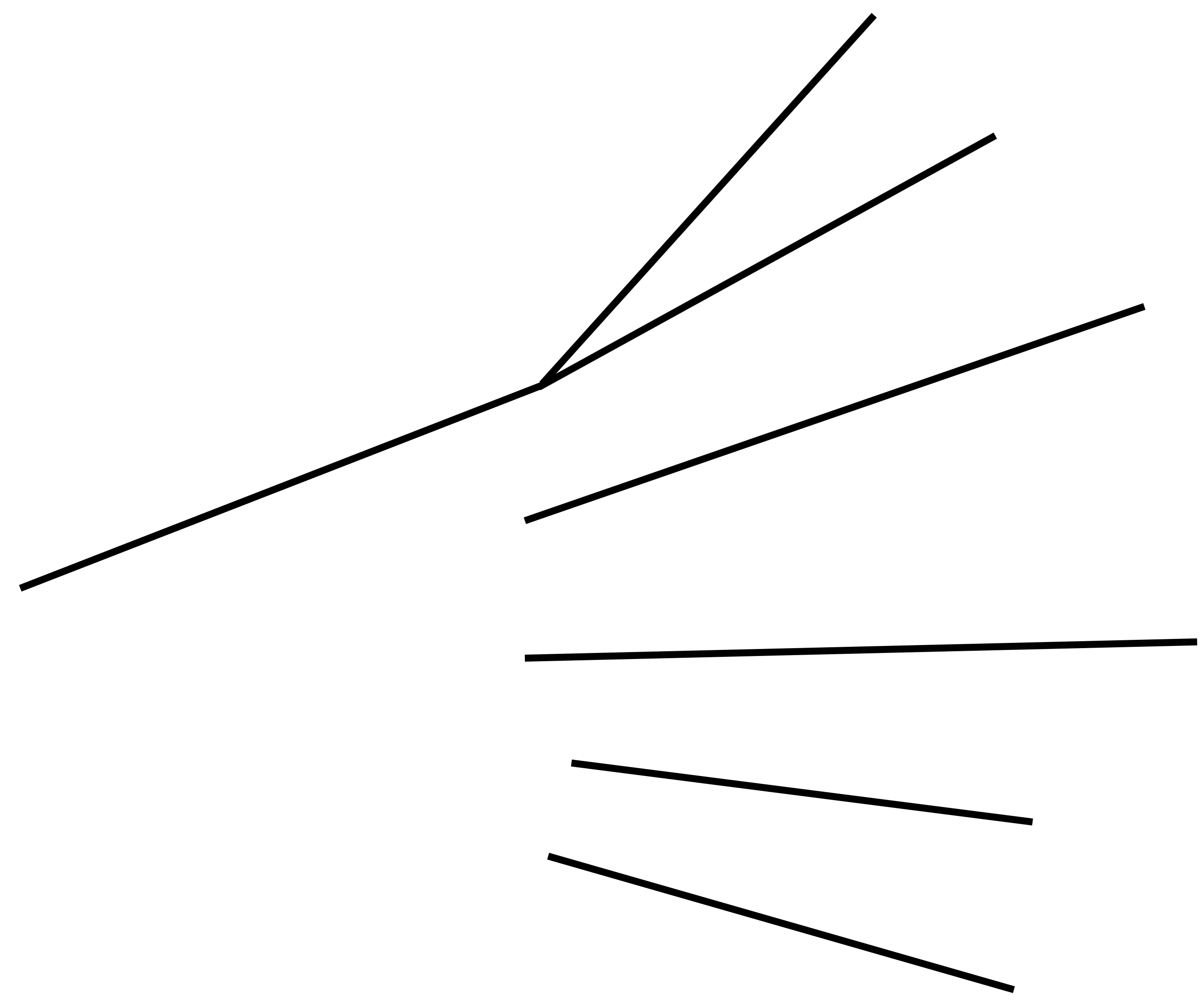

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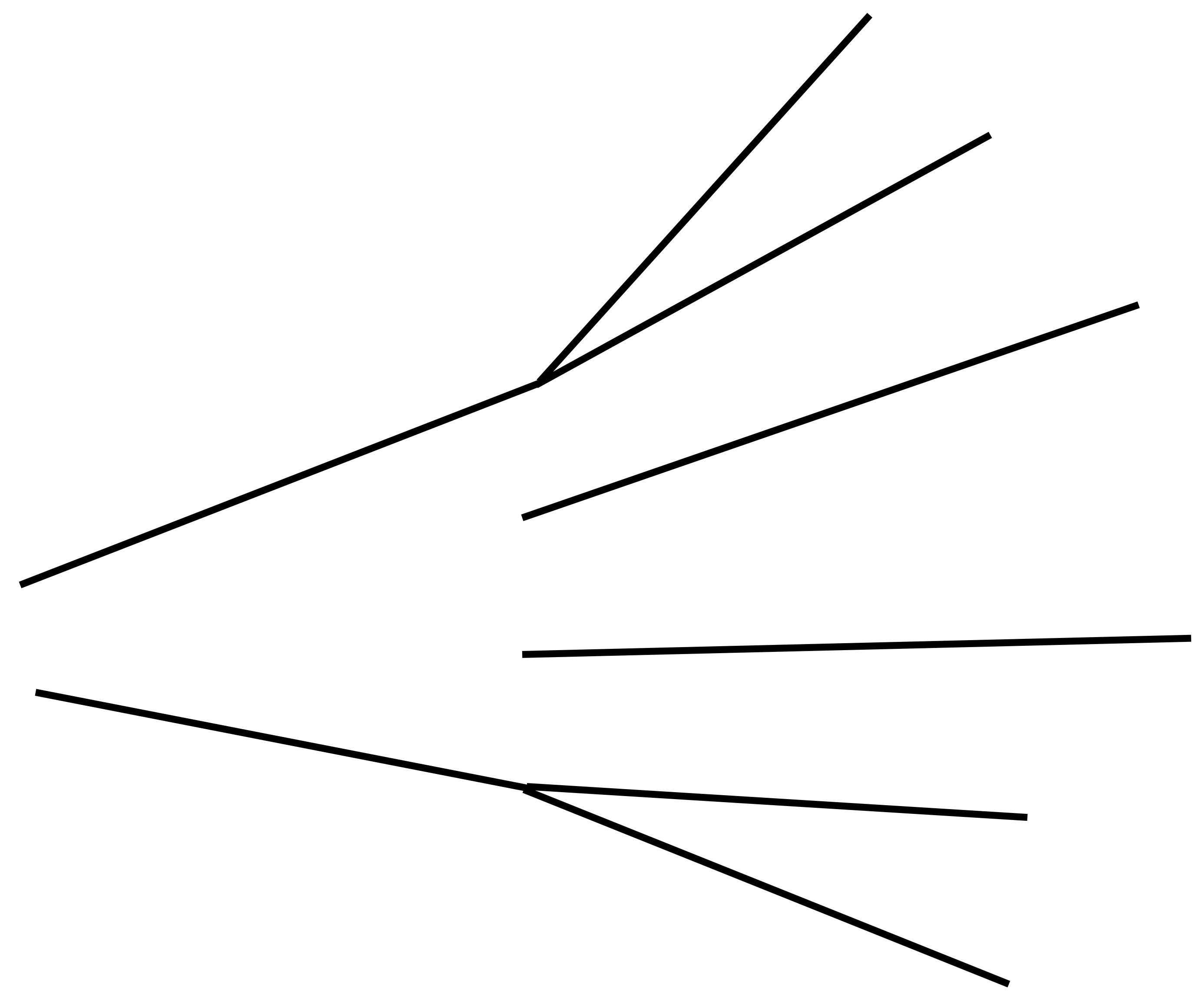

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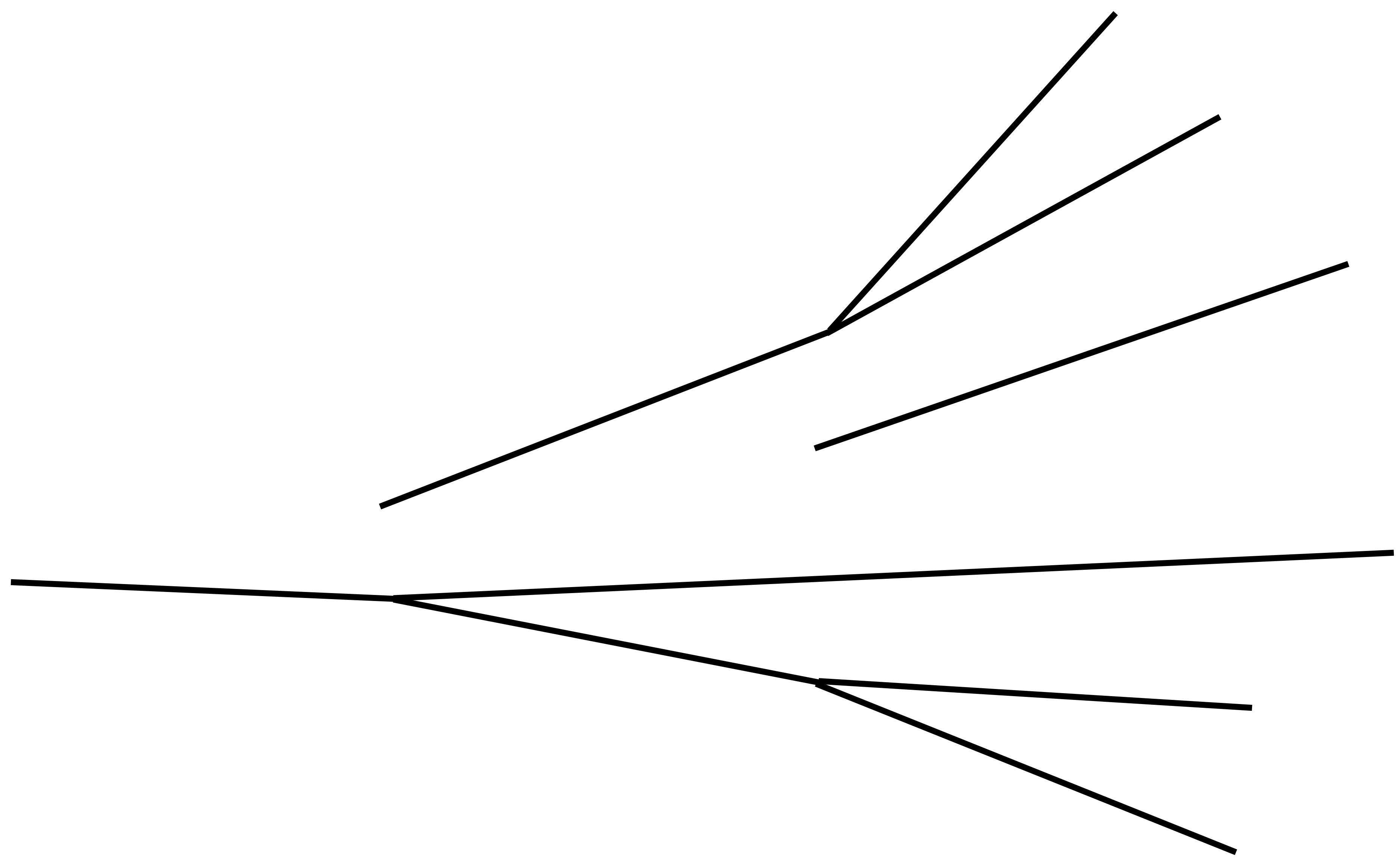

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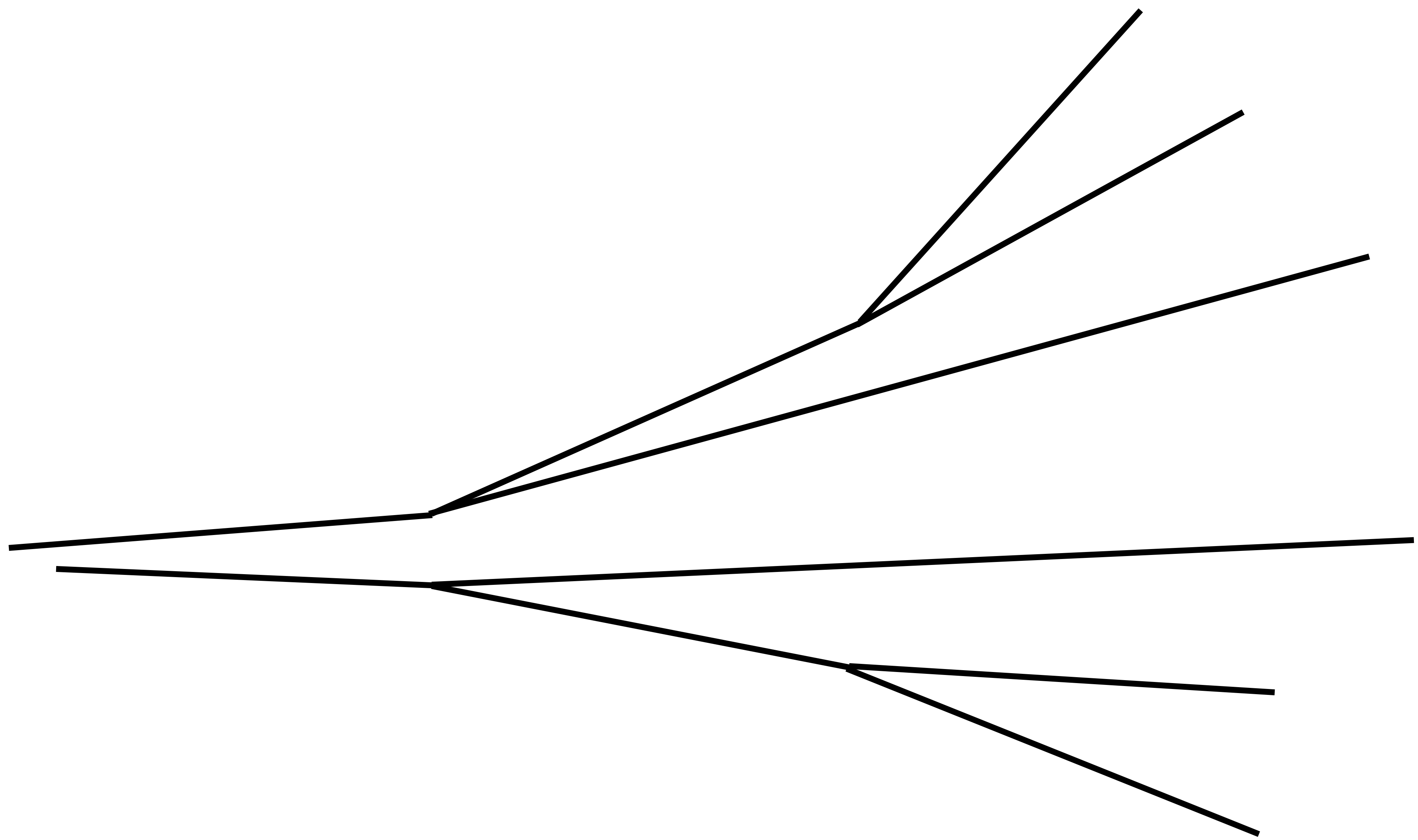
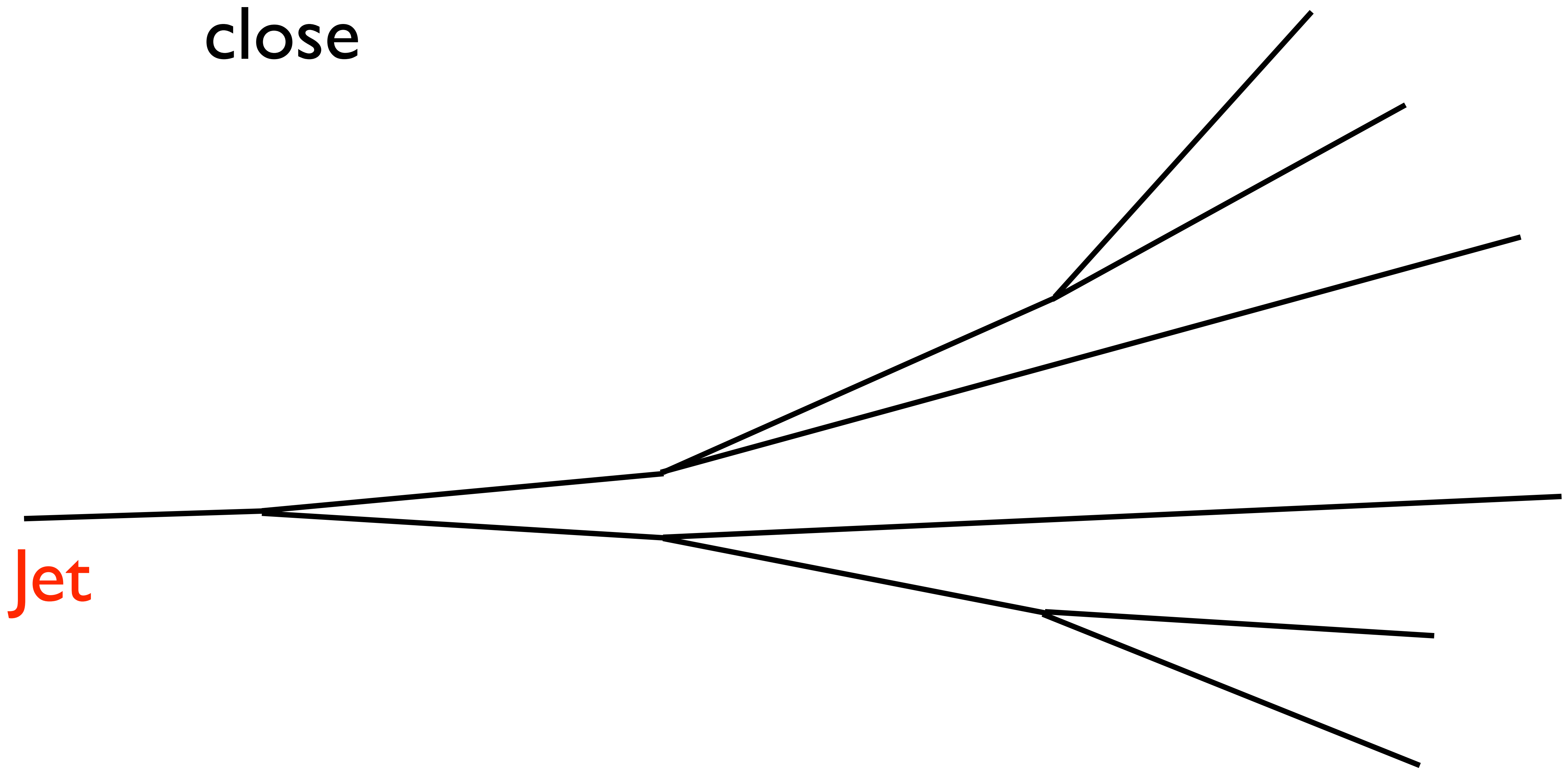


Jet Substructure

- *kT*-type sequential jet algorithm
  - 3) Continue until no pair of particles is close



Jet Substructure

- Idea: Clustering procedure defines a branching tree!

Jet Substructure

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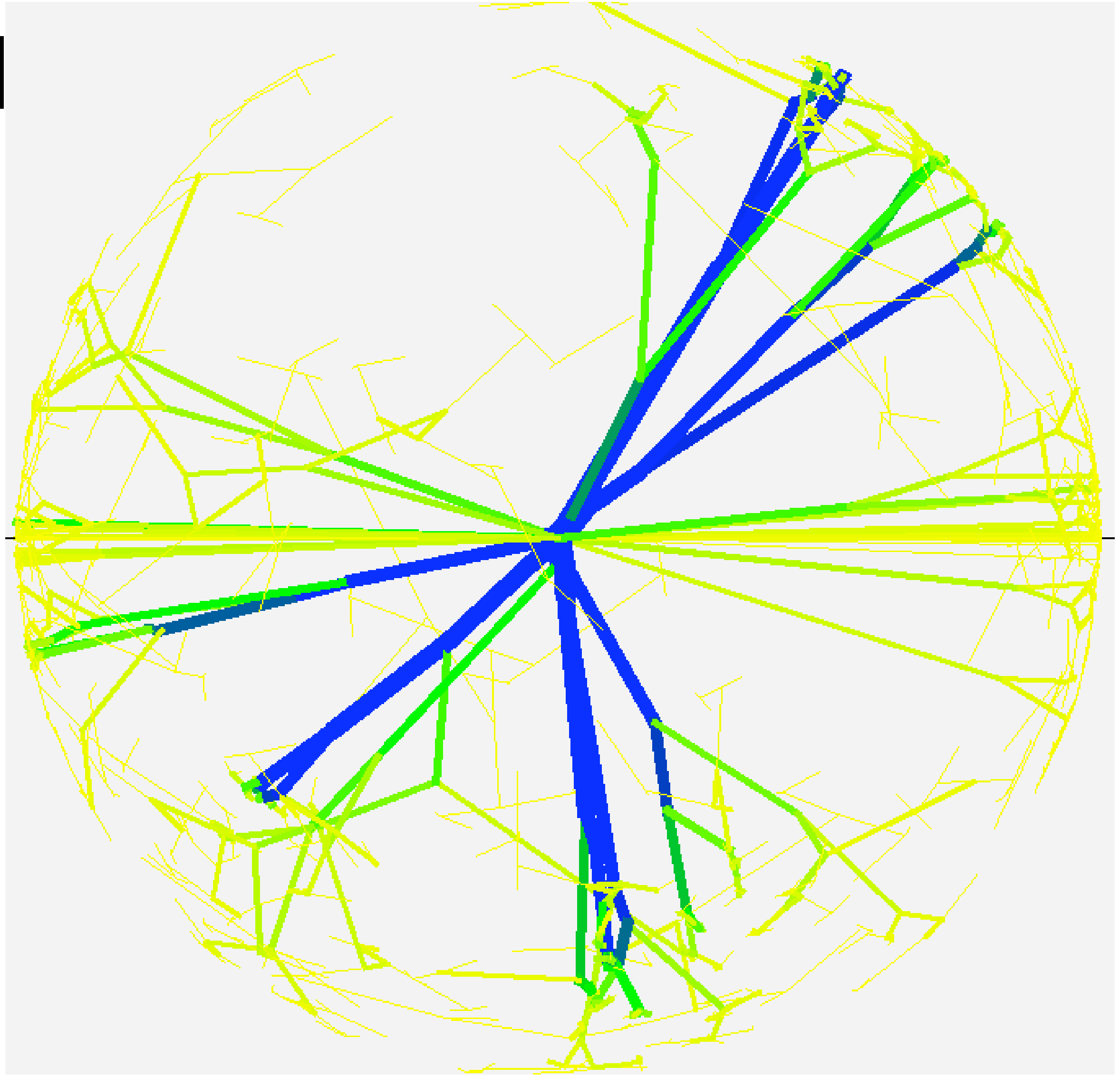
- QCD: branches of small mass, small angle, low energy

- Heavy particle: some branches with large mass, large energy

- Isolate/remove QCD branches



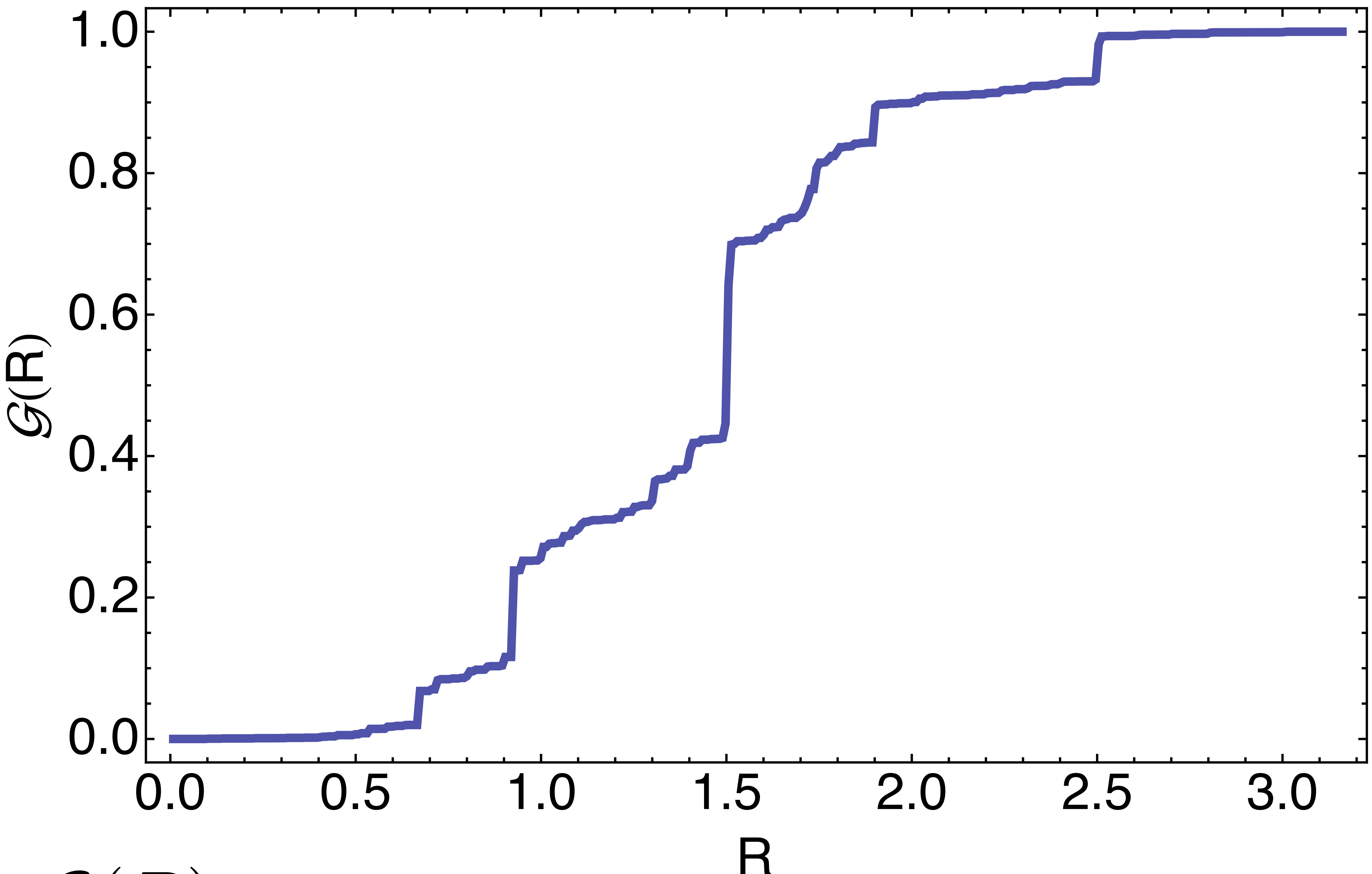
Courtesy Jon Walsh

“Jet Substructure Without Trees”

- Use ACF and ASF to extract angular and mass scales directly from constituents without reference to any clustering tree

Why the ASF?

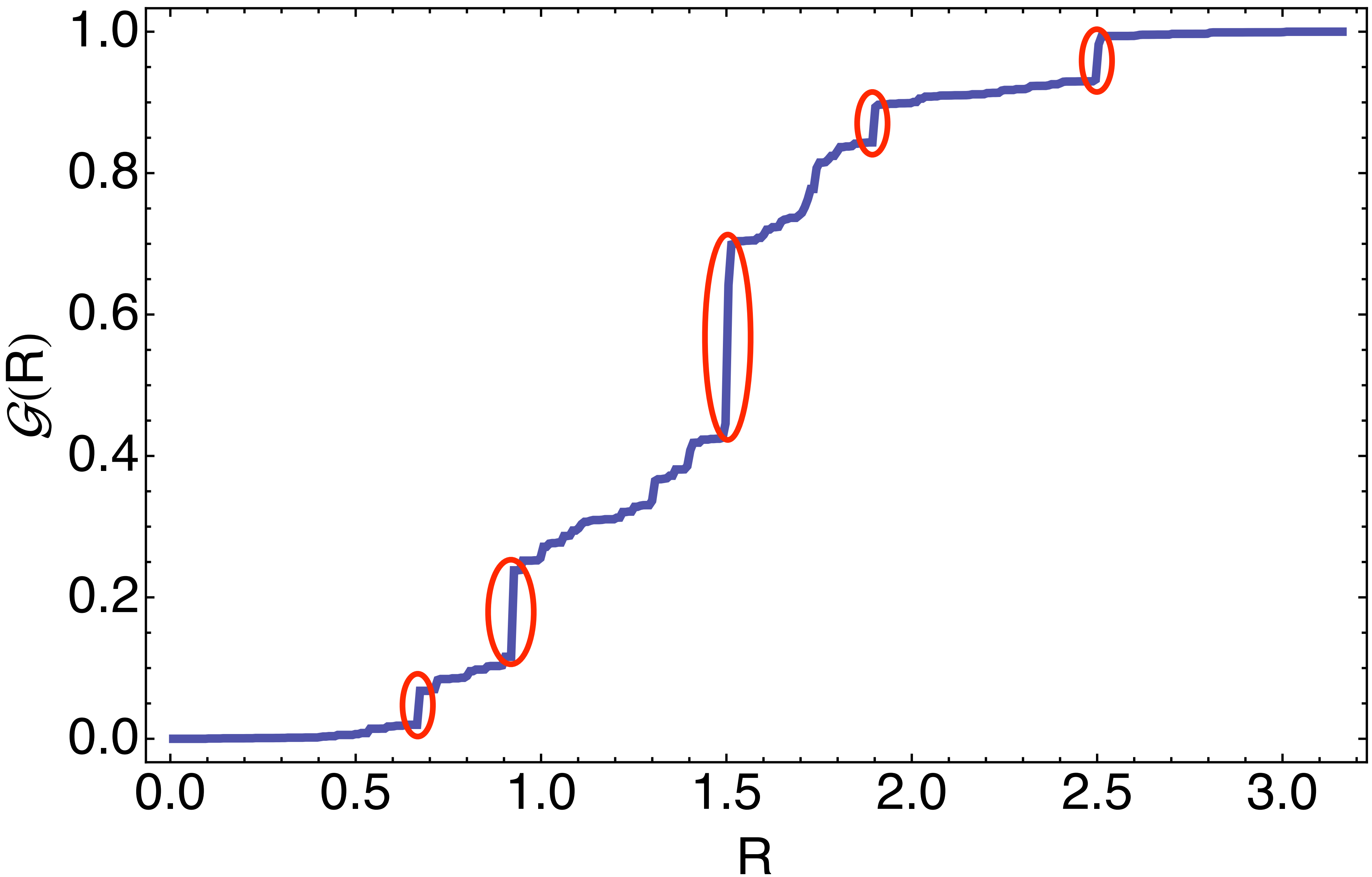
- Cliffs in $\mathcal{G}(R)$ = separation of hard subjets



- $\mathcal{G}(R)$ for a top quark jet

Why the ASF?

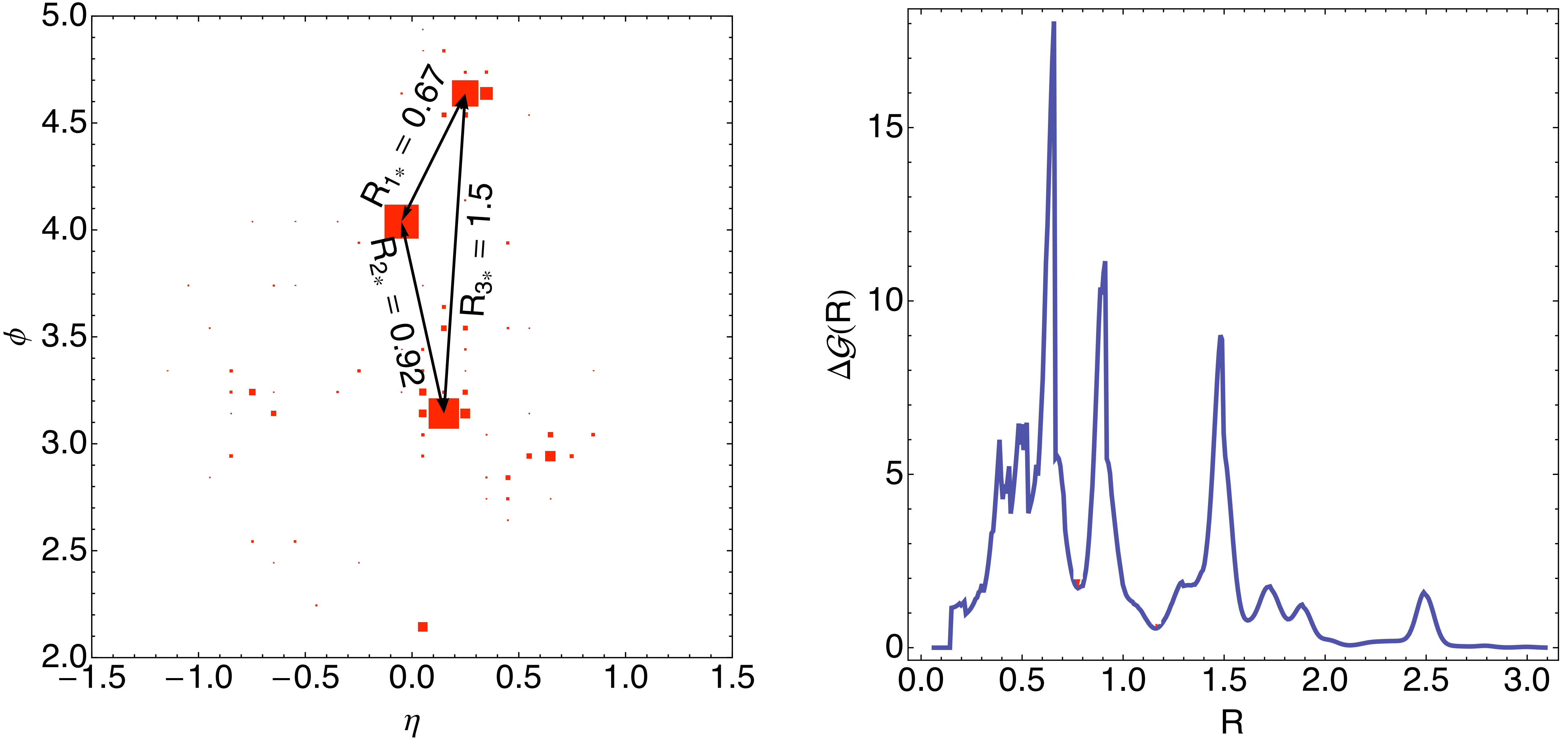
- Cliffs in $\mathcal{G}(R)$ = separation of hard subjets



- Which correspond to something physical?

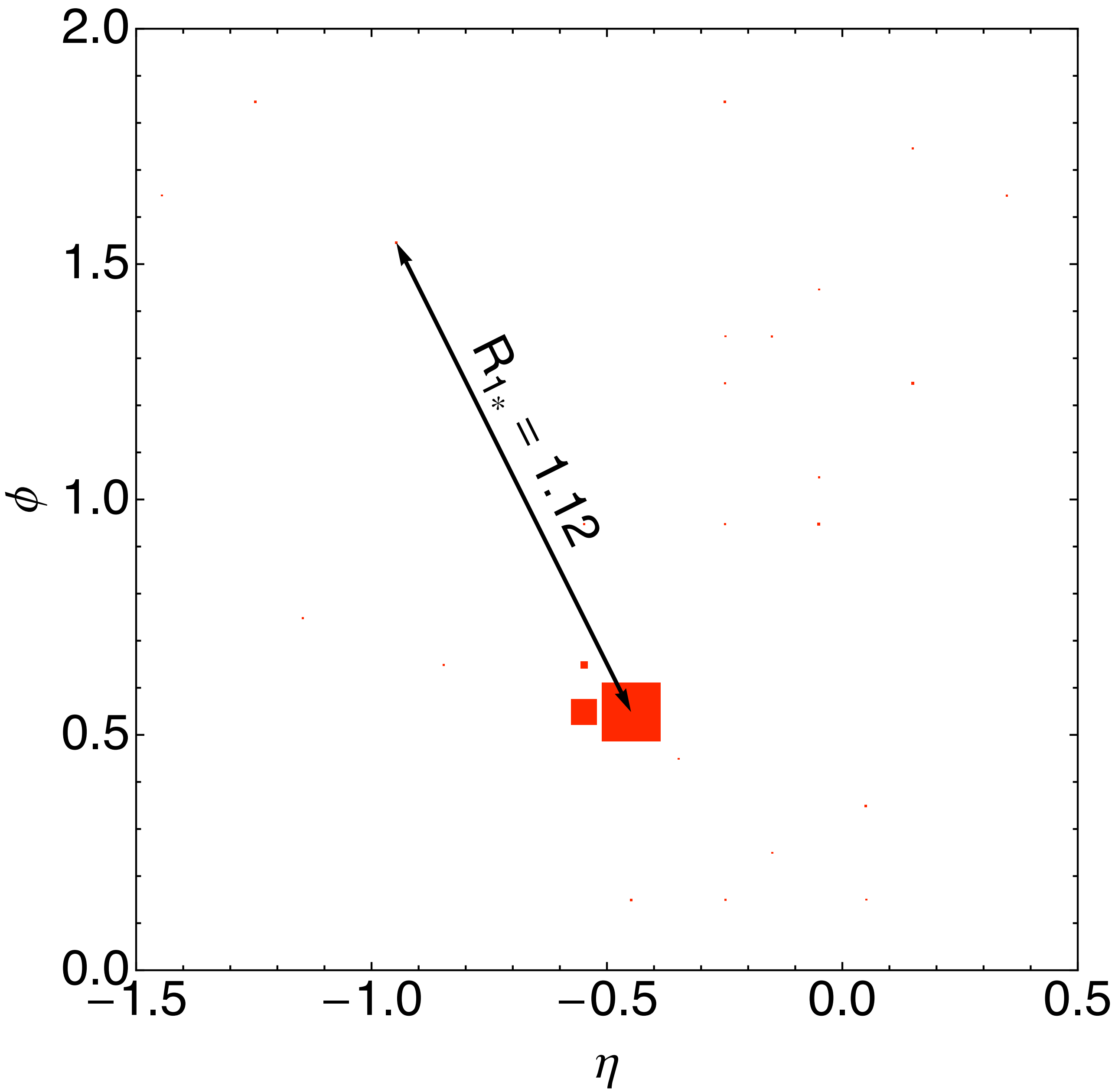
Why the ASF?

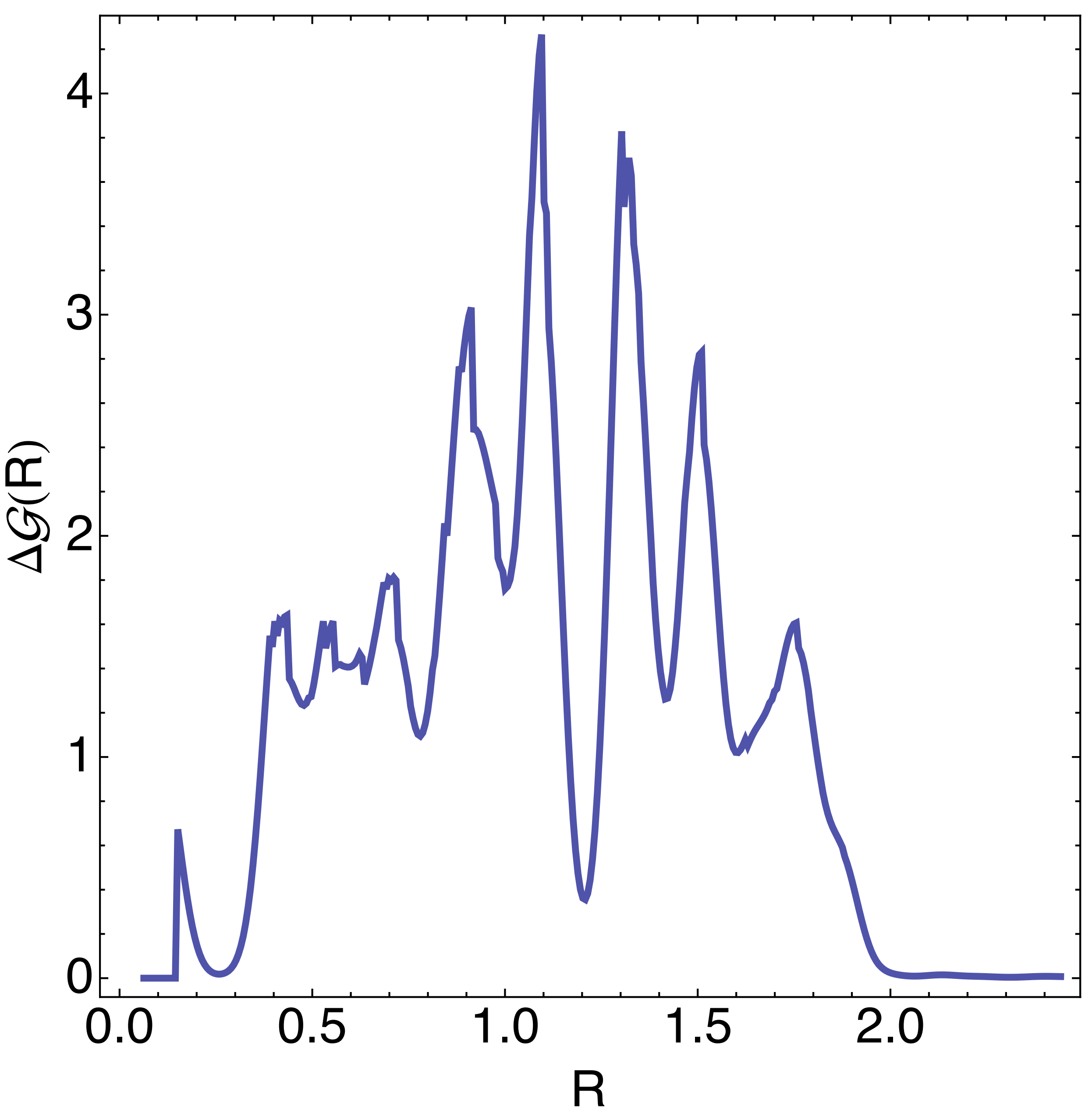
Top Jet



Why the ASF?

QCD Jet

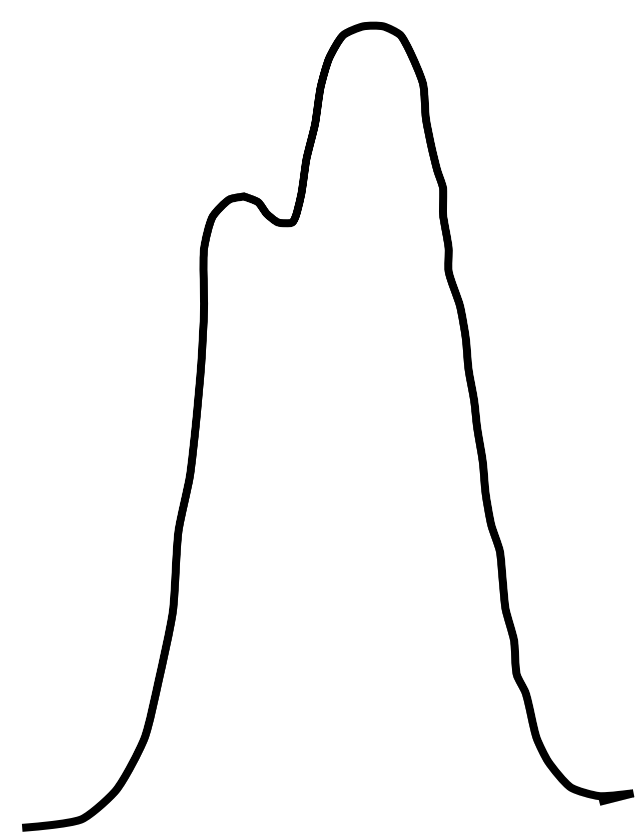




Prominence

- $\Delta\mathcal{G}(R)$ picks out physical peaks beautifully!
- How do we define interesting peaks?
  - By height? Why?

Is the little bump interesting?



Prominence

- Disclaimer: The following slides were made for an audience in the US. I haven't been able to find an analogy for Europeans.

Prominence

- Quiz: What is the highest mountain in the contiguous US?

Prominence

- Quiz: What is the highest mountain in the contiguous US?
  - Mt. Whitney, CA
- What is the most *prominent* mountain in the contiguous US?

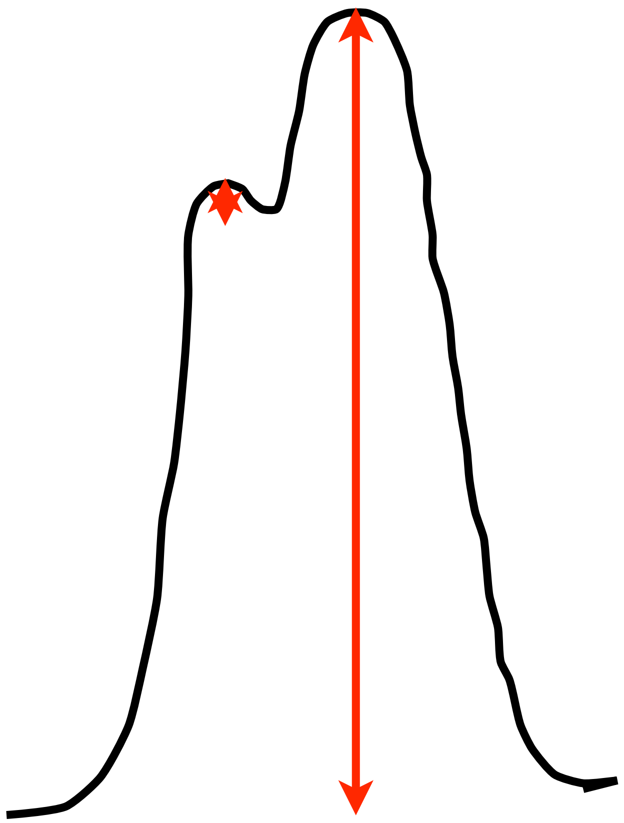
Prominence

- Quiz: What is the highest mountain in the contiguous US?
  - Mt. Whitney, CA
- What is the most *prominent* mountain in the contiguous US?
  - Mt. Rainier, WA

Prominence

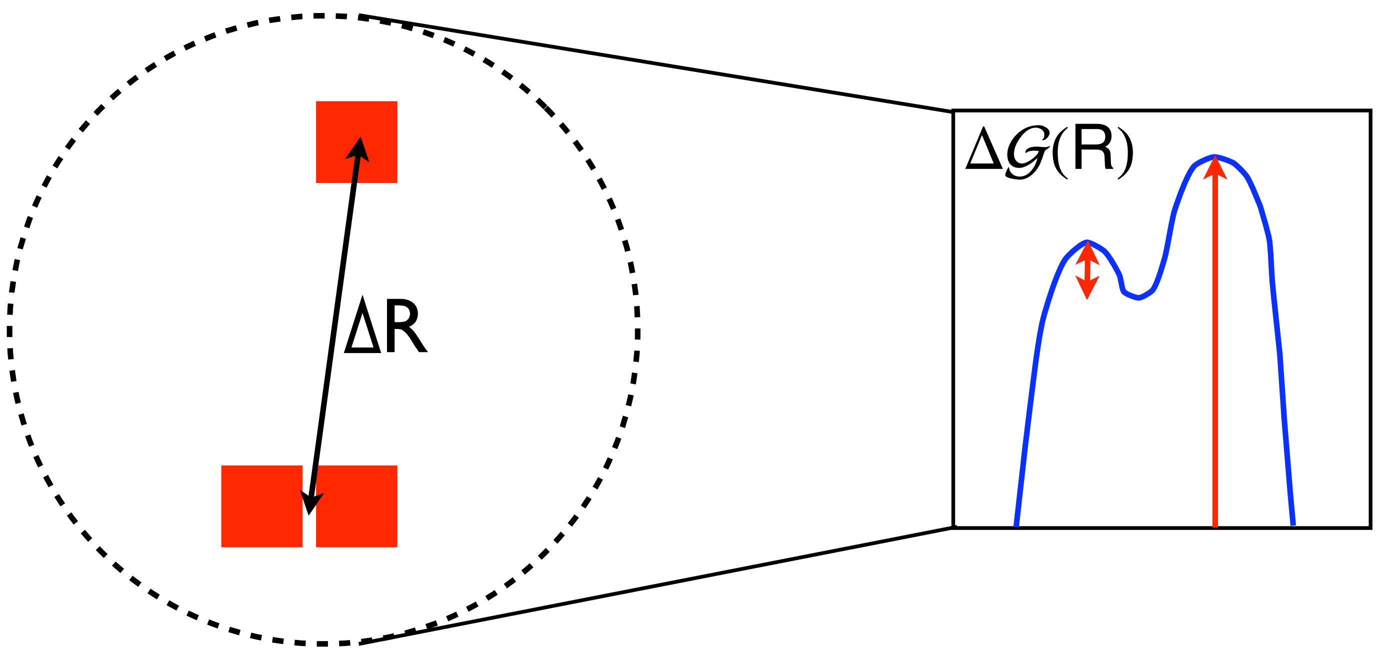
- Proposition: Define peaks by their *prominence*
- Prominence = amount peak sticks out above ambient background

Prominence of little bump is tiny!



Prominence

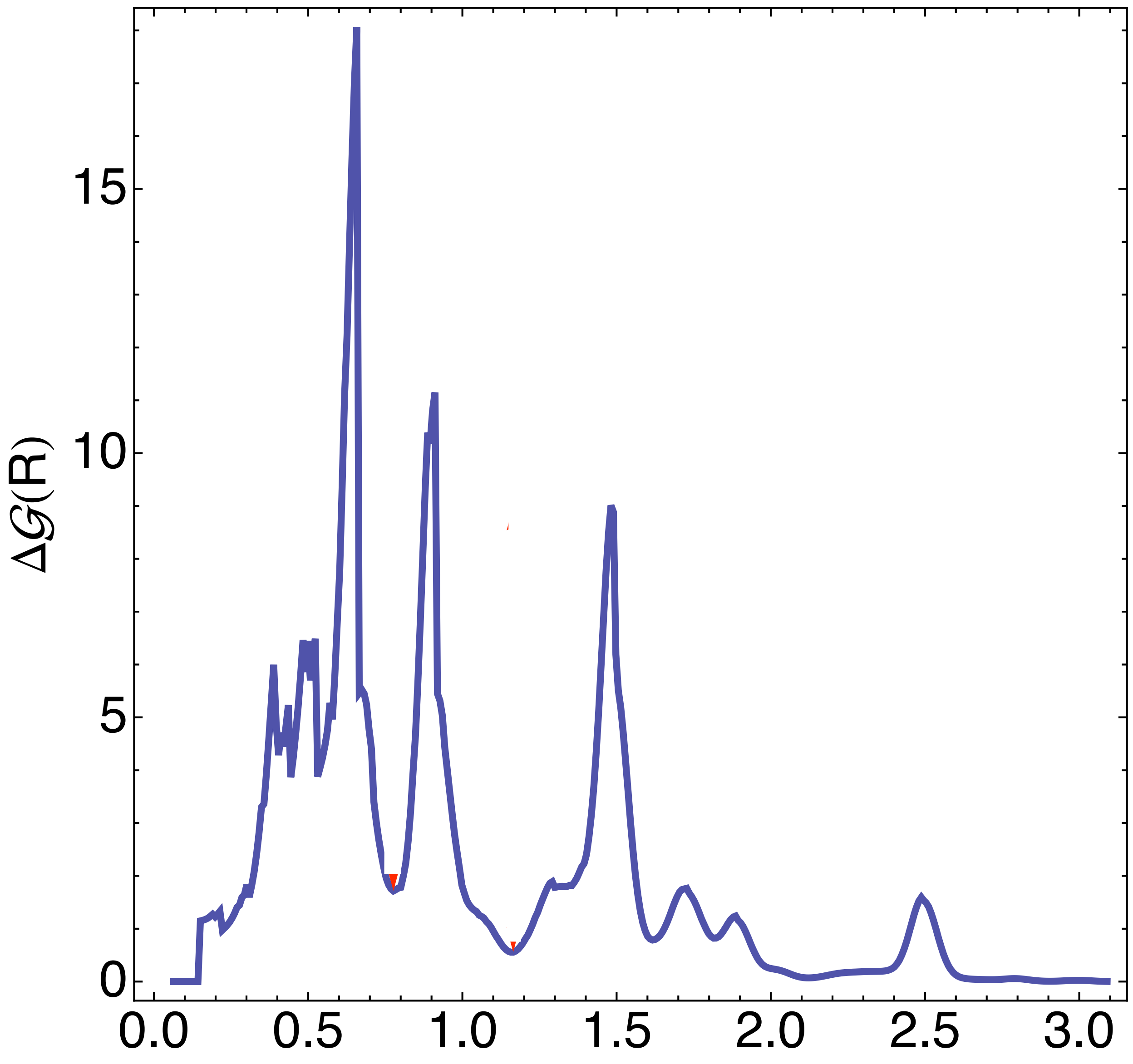
- Possible double counting of angular scales



- Defining interesting peaks by prominence removes double counting ambiguity

Defining Observables

- IRC safe observables from $\Delta\mathcal{G}(R)$:



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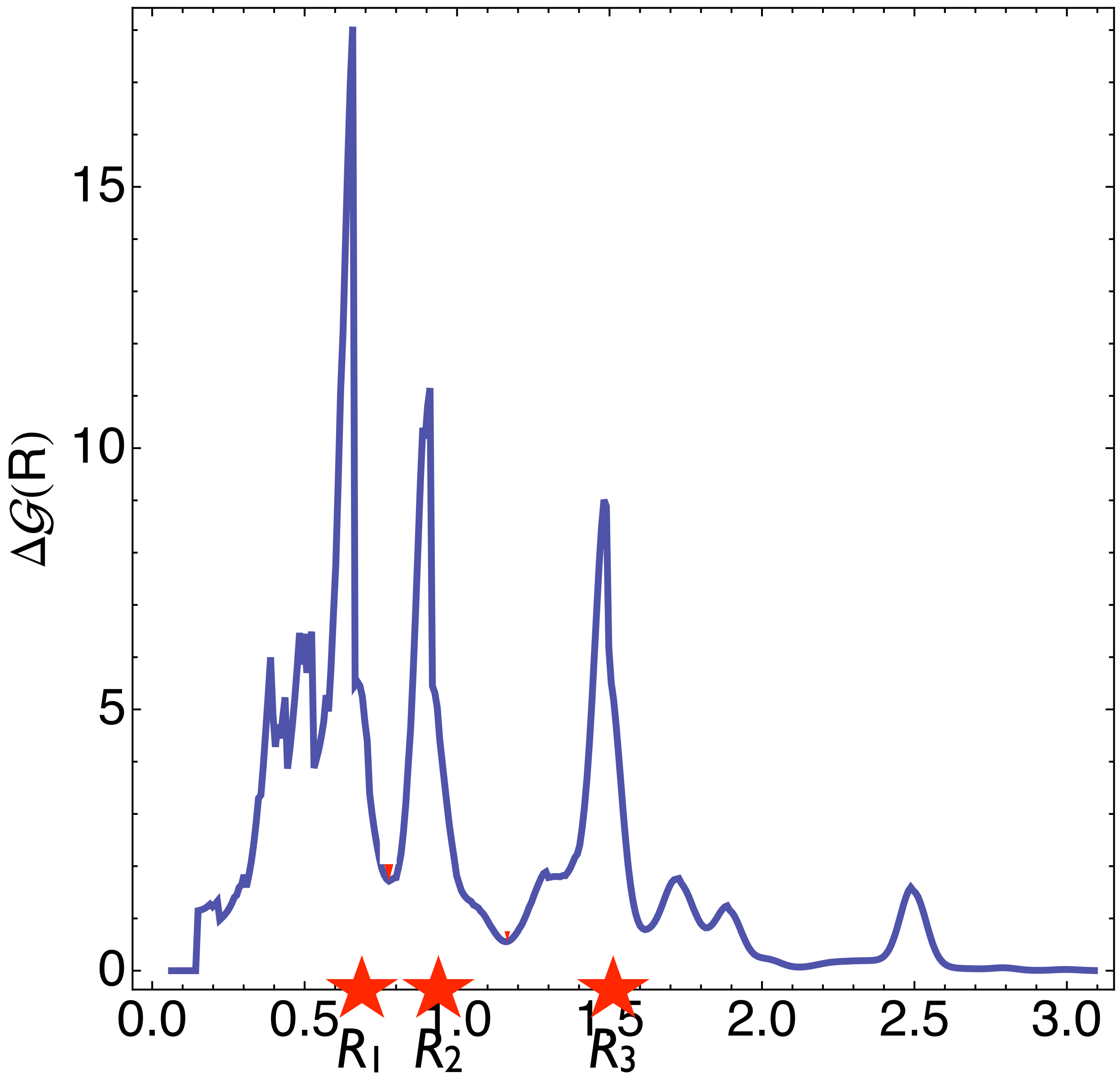

- Entire curve is IRC safe
- Location of peaks in *R*

Defining Observables

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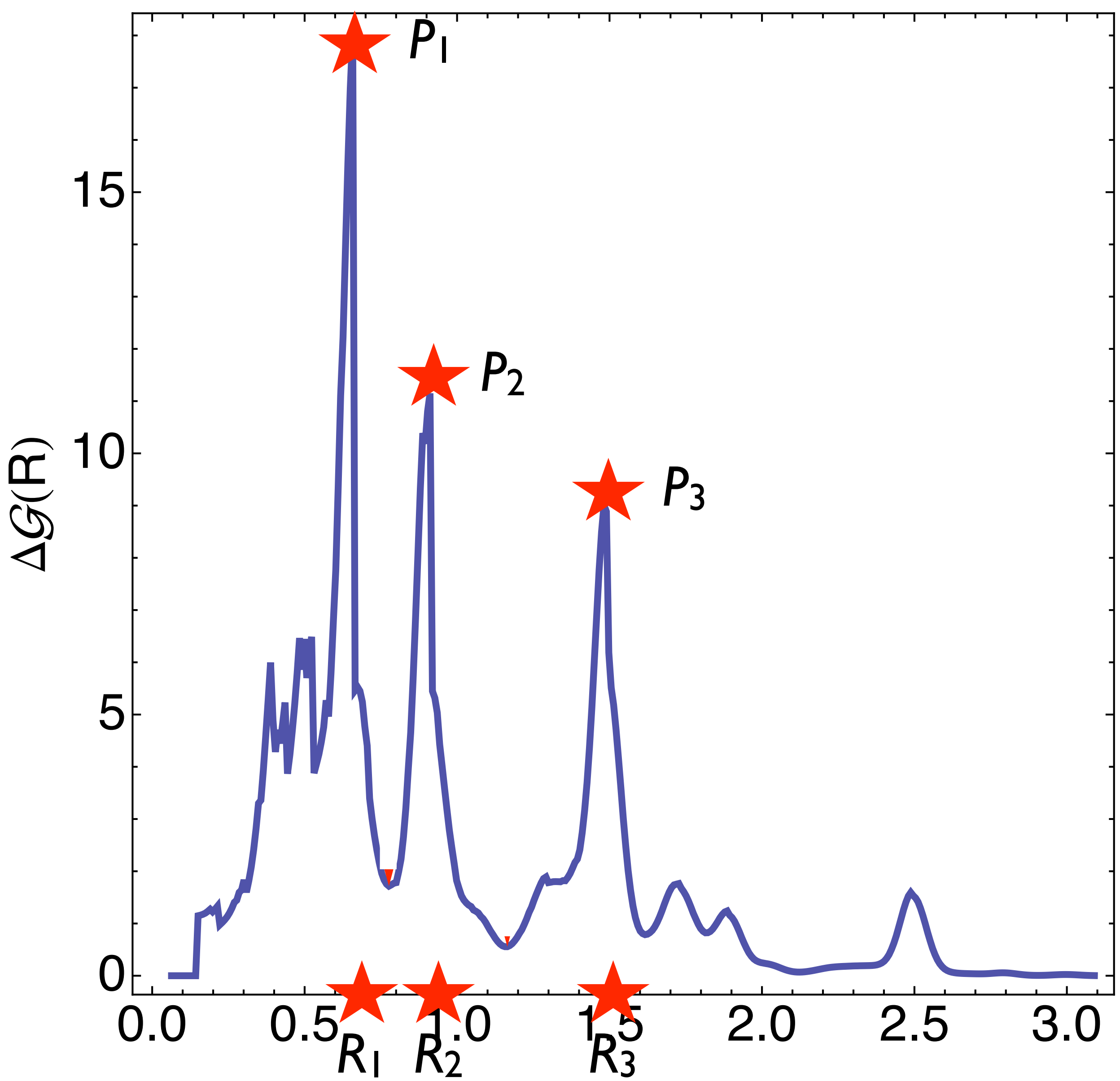

- Location of peaks in R
- Height of peaks

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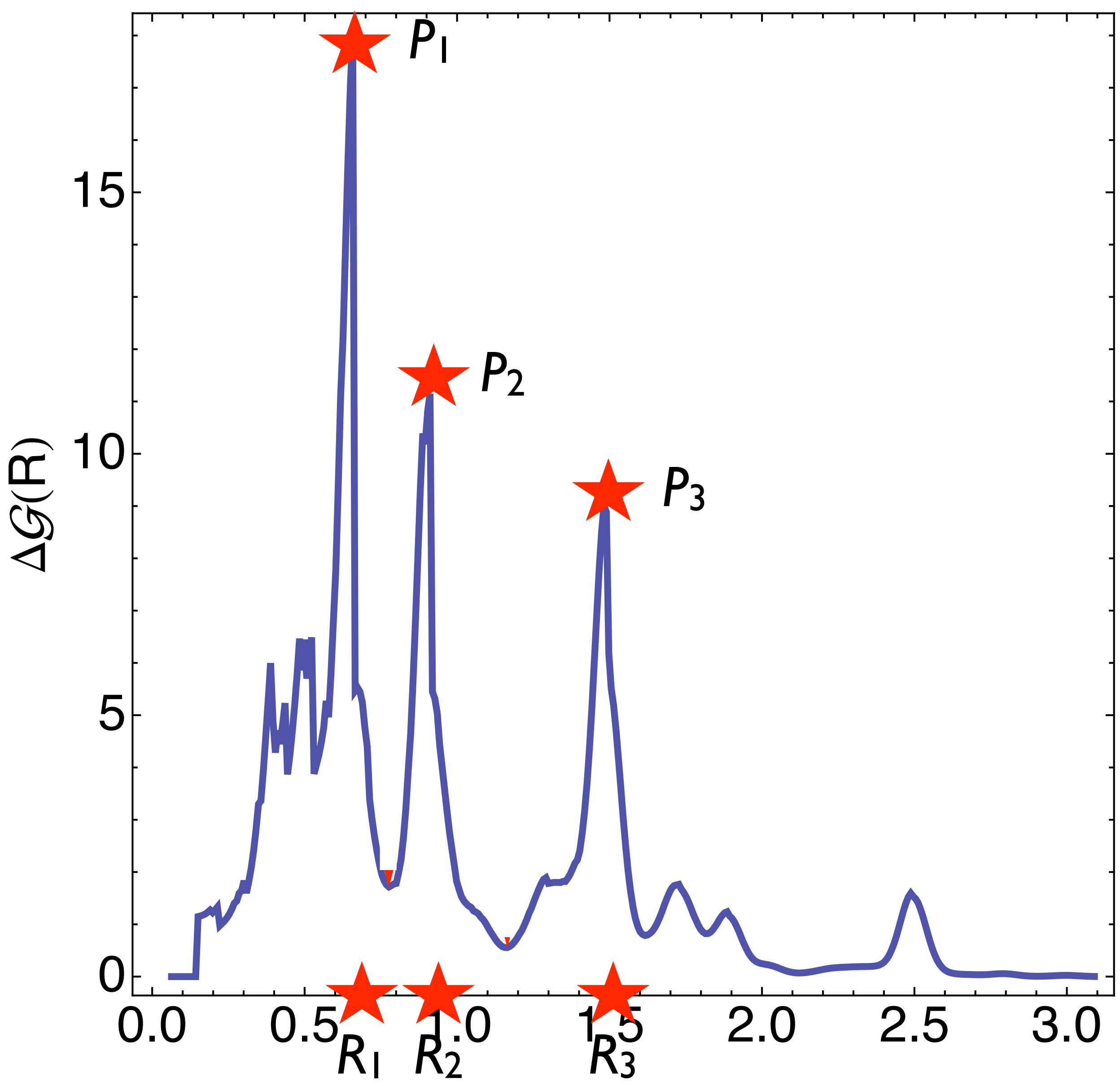
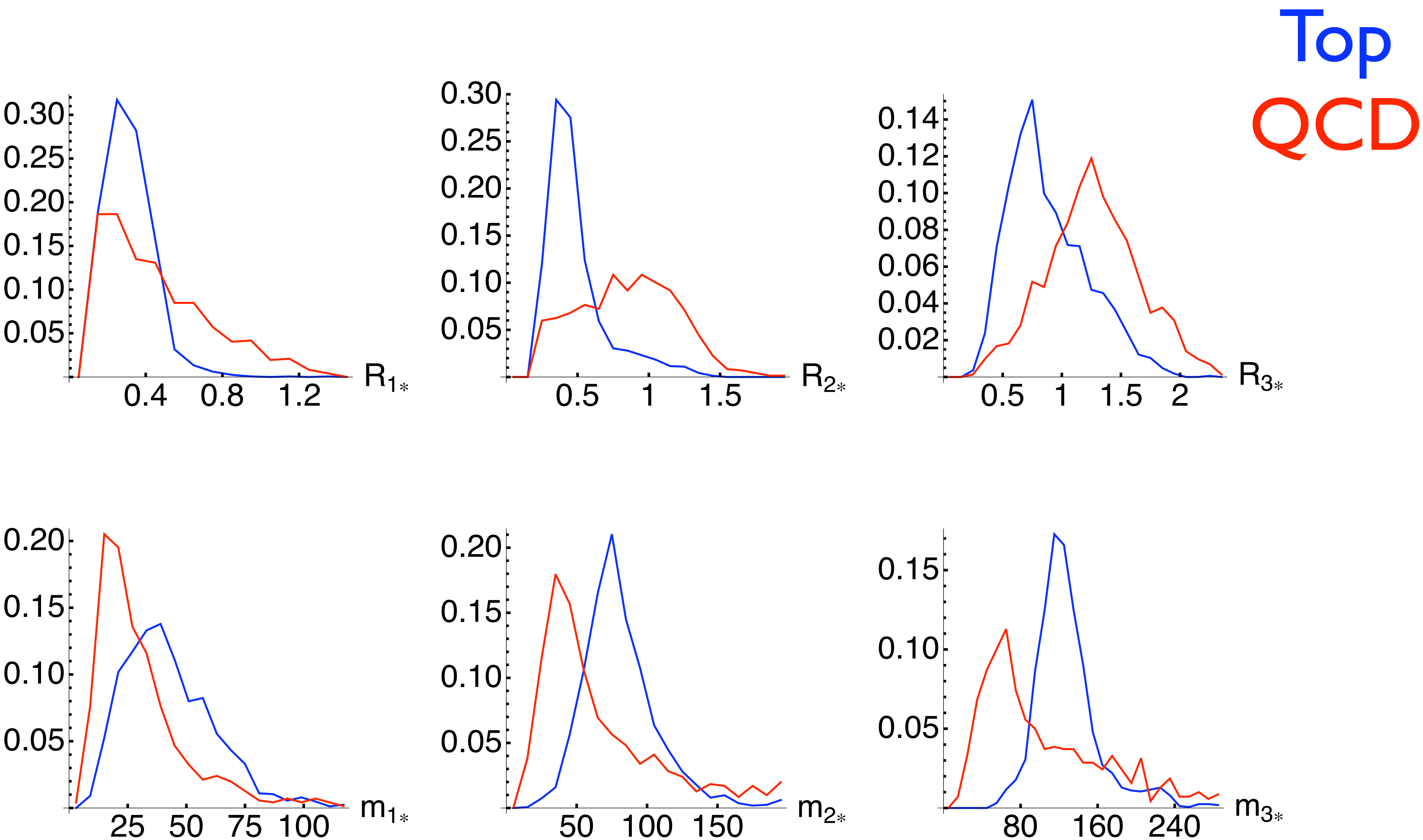


- Location of peaks in R
- Height of peaks
- Number of peaks

Top Tagger

- Observables for dR = 0.06, min prom = 4.0, npeaks = 3



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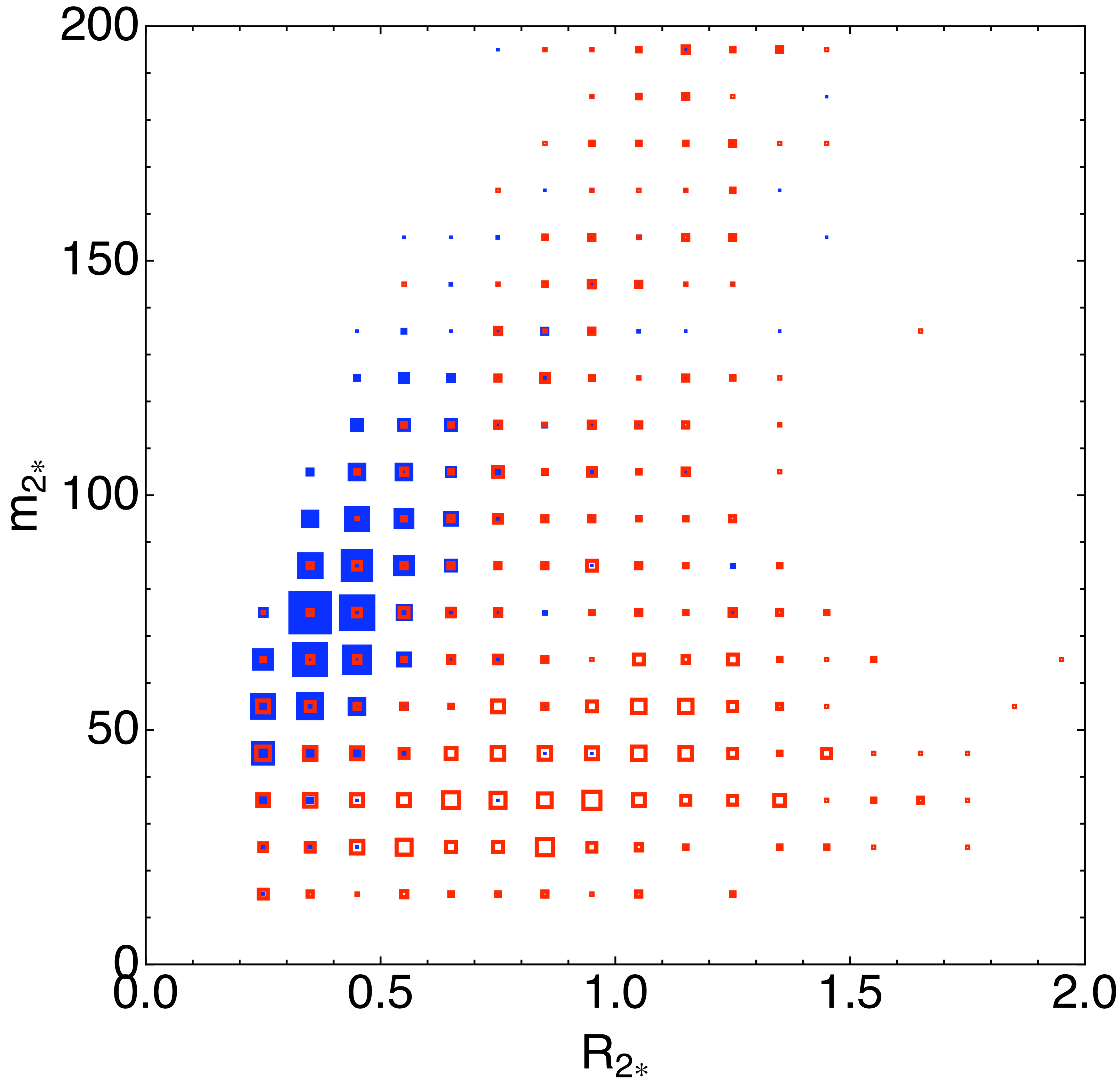

Top
QCD

- Correlation of separation of subjets and their invariant mass
- Top: m ~ R
- QCD: m, R uncorrelated

Top Tagger

- Comparison to other top taggers