Hands-on: QCD Jets

Developed by:
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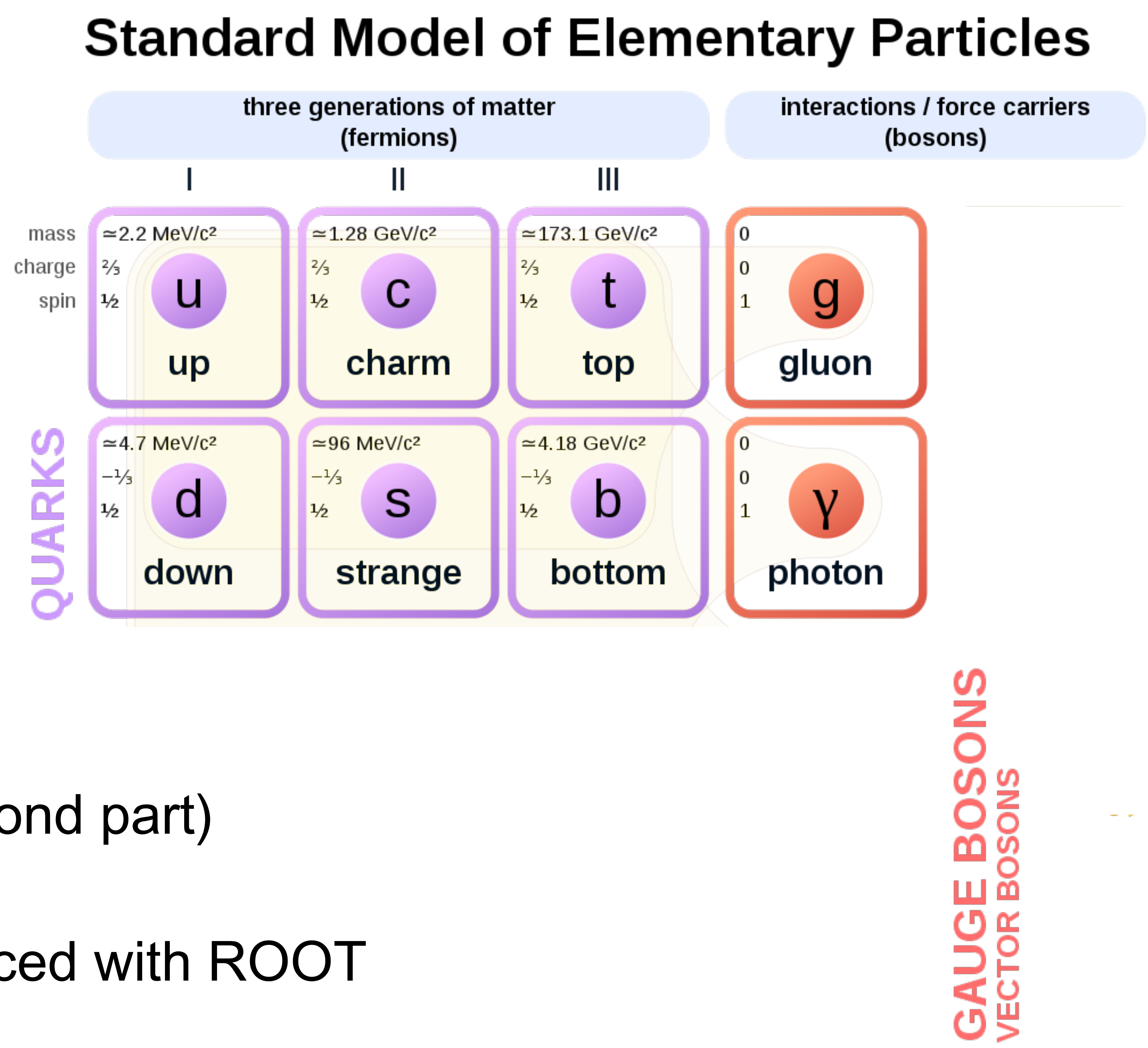
LIP

Hands on: QCD Jets

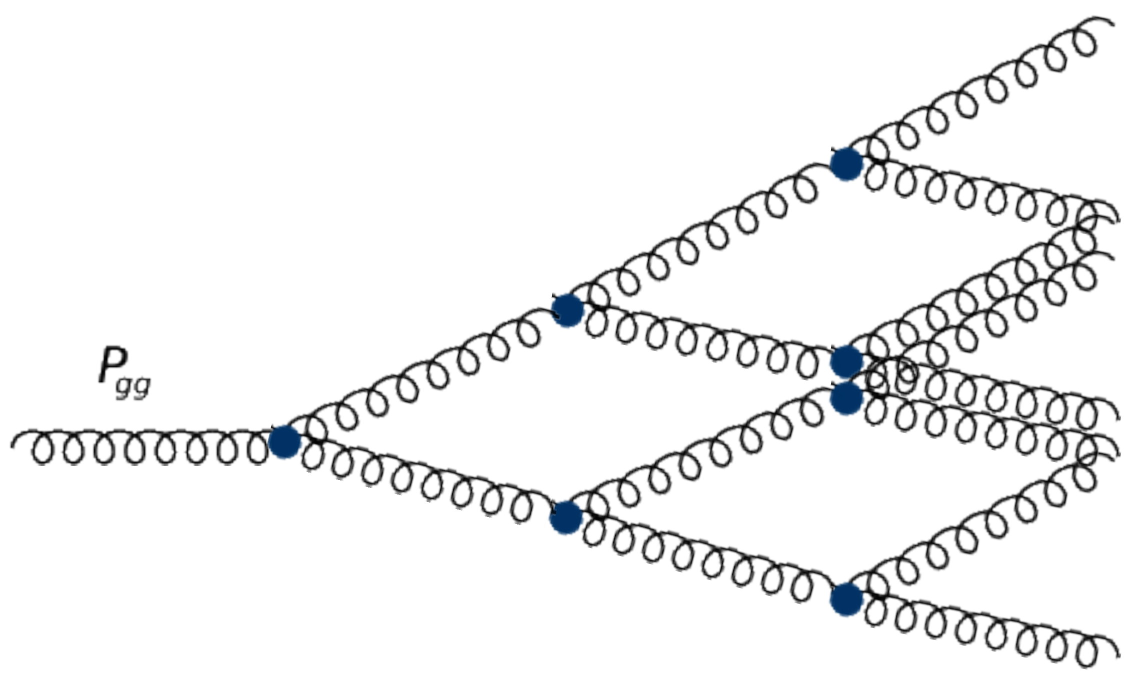
- What is this hands-on about:
  - Better understanding and visualisation of the Standard model sector:
    - Quantum Chromodynamics (QCD)



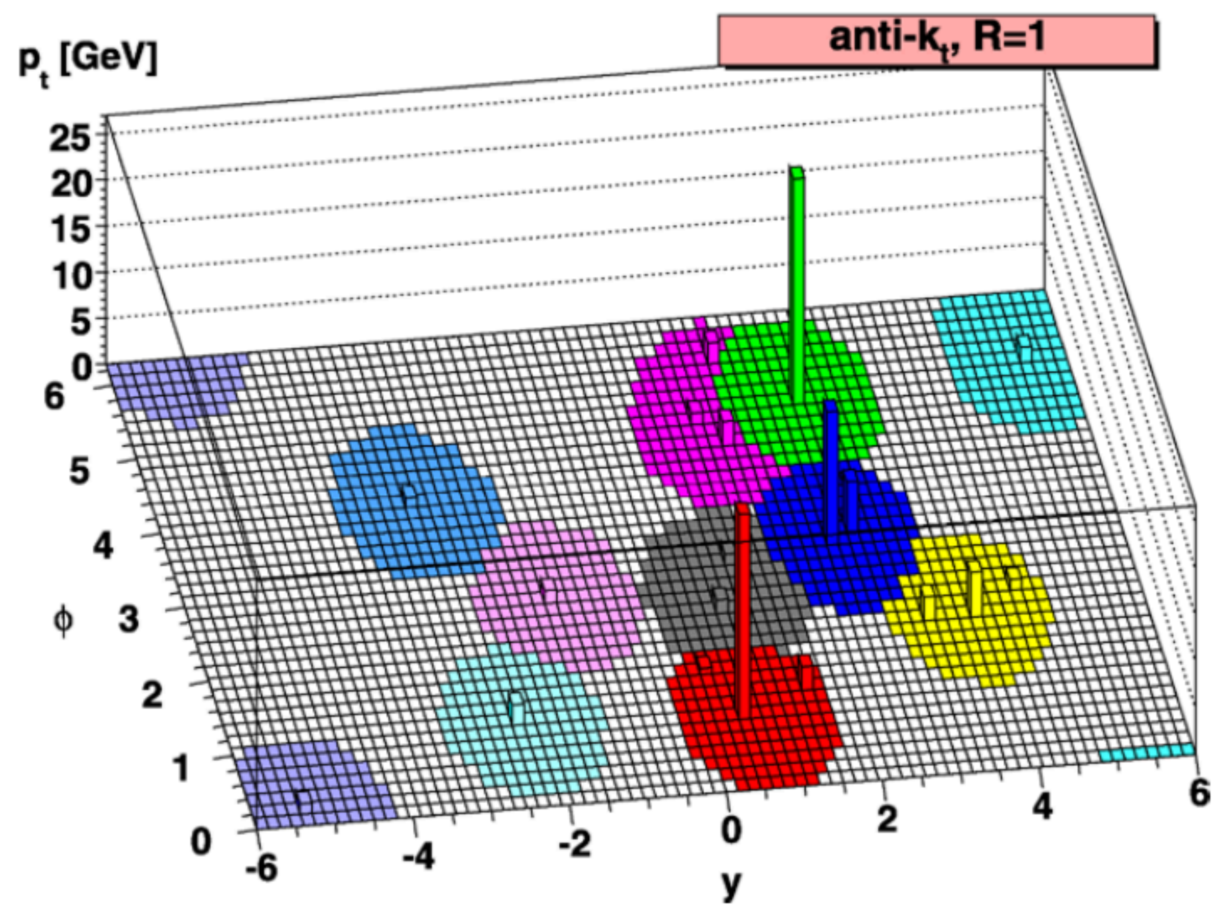
- What I will do:
  - Simple analytic exercises (first part) and a bit of coding (second part)
  - Requirements: C/C++ and ROOT installed or Python interfaced with ROOT

Questions to be answered

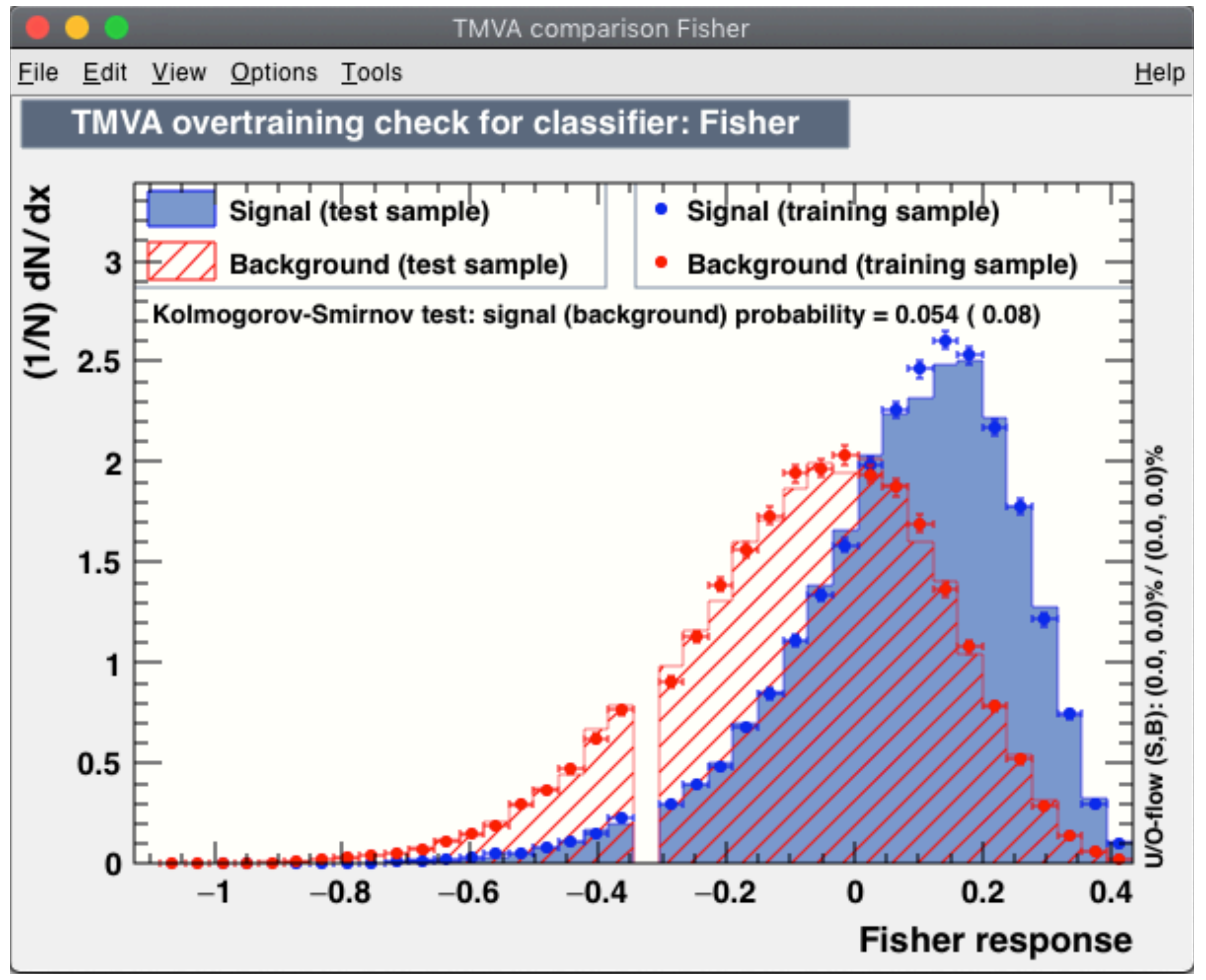
- What exactly is a jet?
  - Simple visualisation and analytic exercise to build a picture of a jet



- How can we reconstruct a jet?
  - Attempt to reconstruct and visualize a jet



- What can we do with jets?
  - Classification problem through multivariate algorithms (e.g: NN): Quark vs Gluon-initiated jets



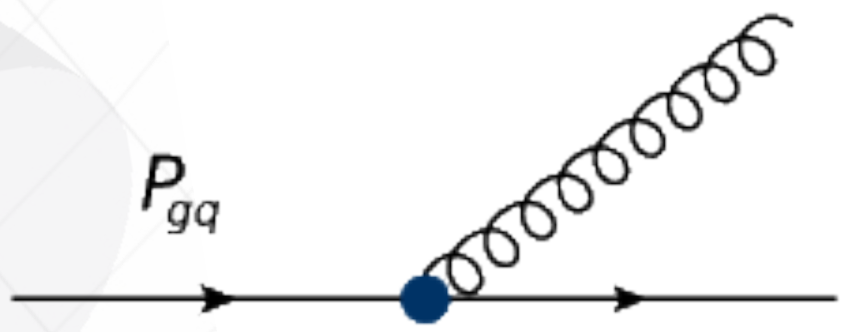
Preparing for Hands-On

- Have ROOT installed:
  - See https://lip.pt/~liliana/HandsOn_QCDJets_Guide.pdf
- For Part 2 and 3:
  - Download: https://lip.pt/~liliana/HandsOn_QCDJets_Code.tar.gz

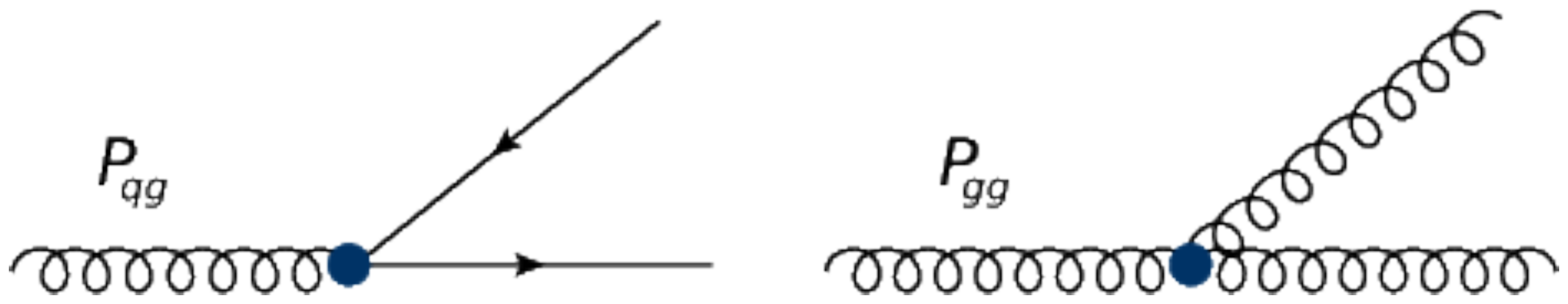
What is a jet?

Parton radiation

- Recall parton splitting processes 1—>2:
  - Quark:



  - Gluon:



Parton radiation

- Let's follow particles during some time… What is likely to happen?

Exercise

- Considering two subsequent splittings, find the two possible diagrams for a quark?

Parton radiation

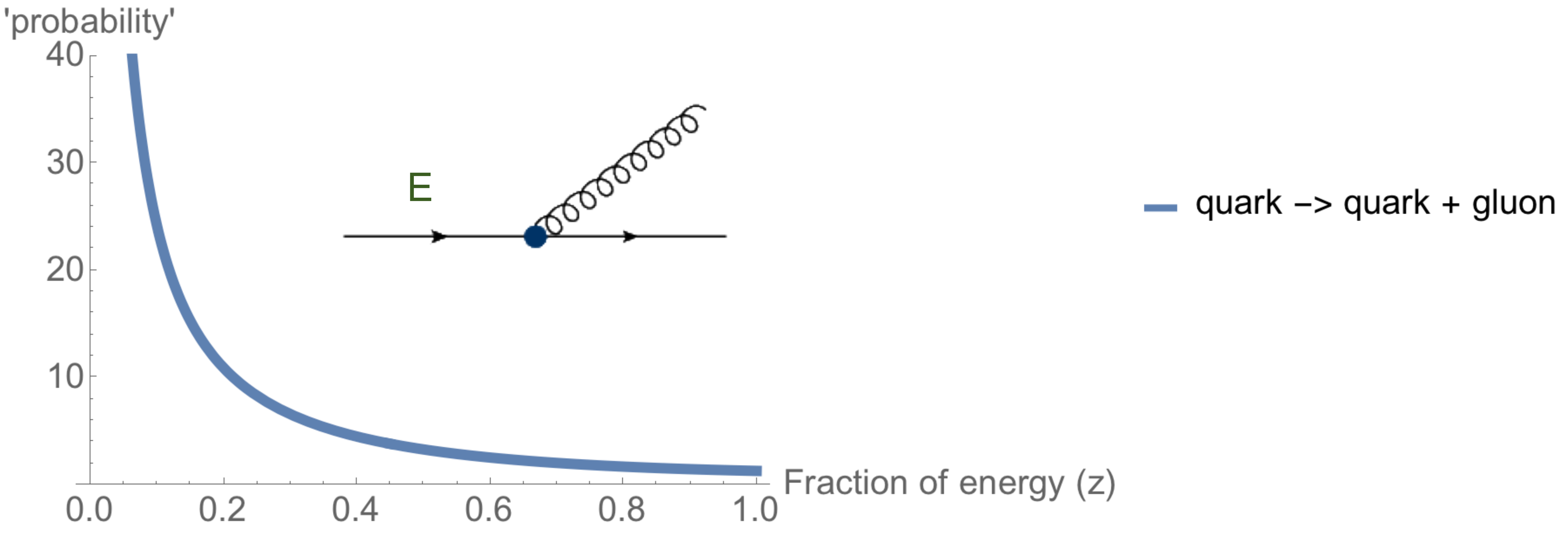
- Let's follow particles during some time… What is likely to happen?

Exercise

- Considering two subsequent splittings, find the four possible diagrams for a gluon?

Parton radiation

- What is likely to be the energy distribution of the particles at the end?
  - Let's look to the parton splitting functions:
    - The probability for a given parton (quark or gluon) to emit another parton (quark or gluon) with a fraction of energy (z):



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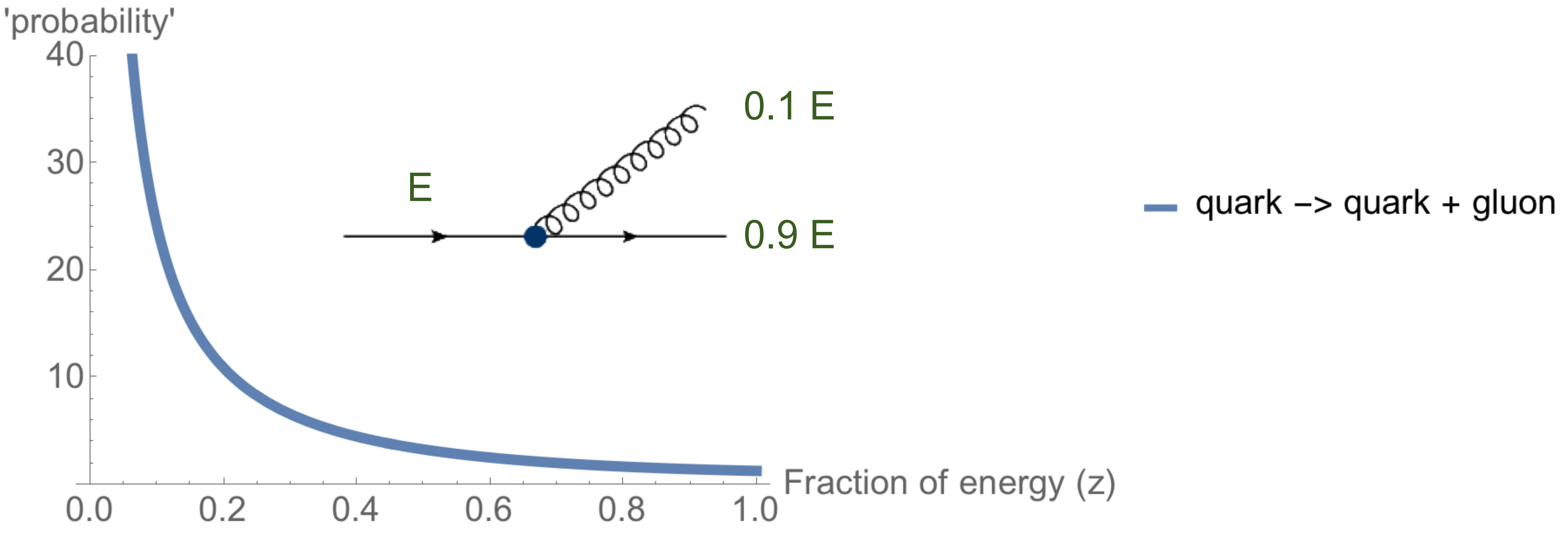

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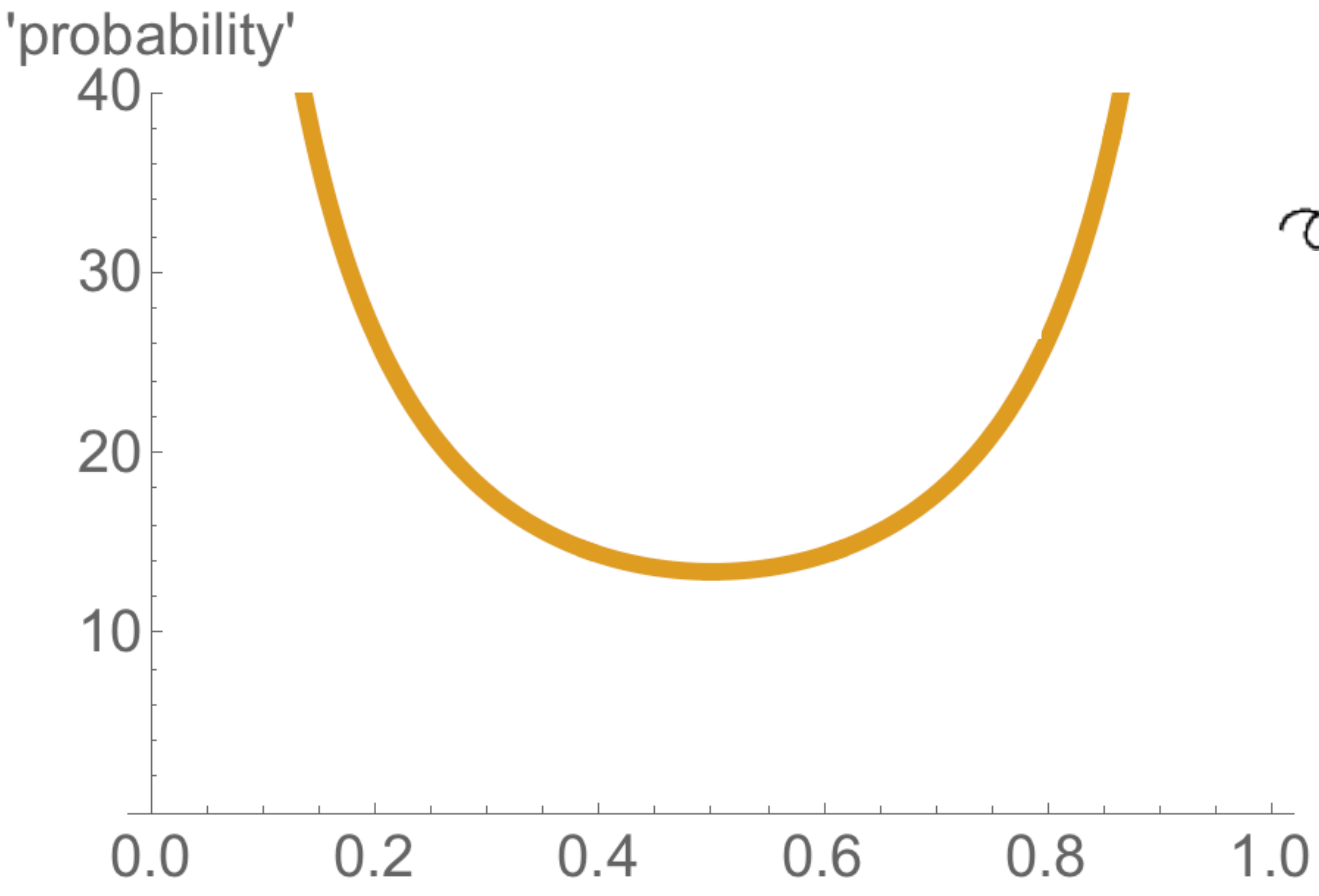

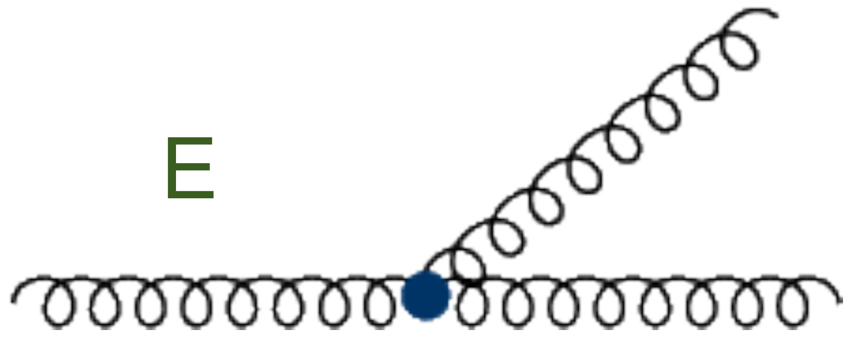

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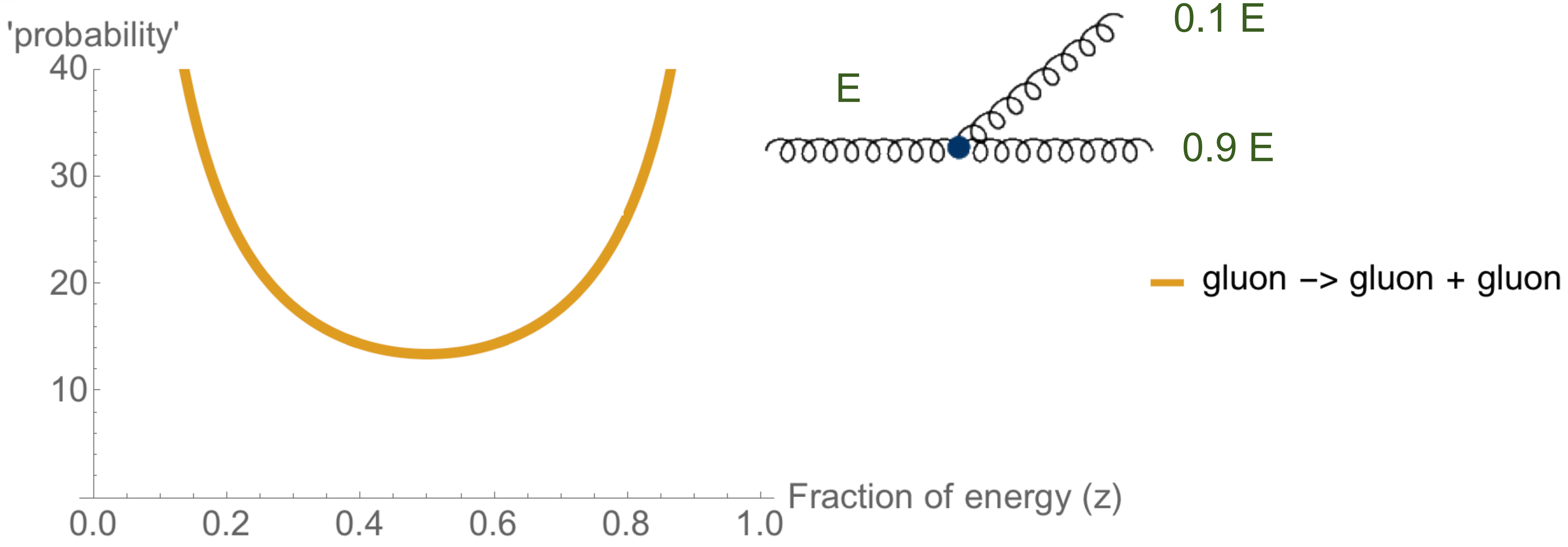

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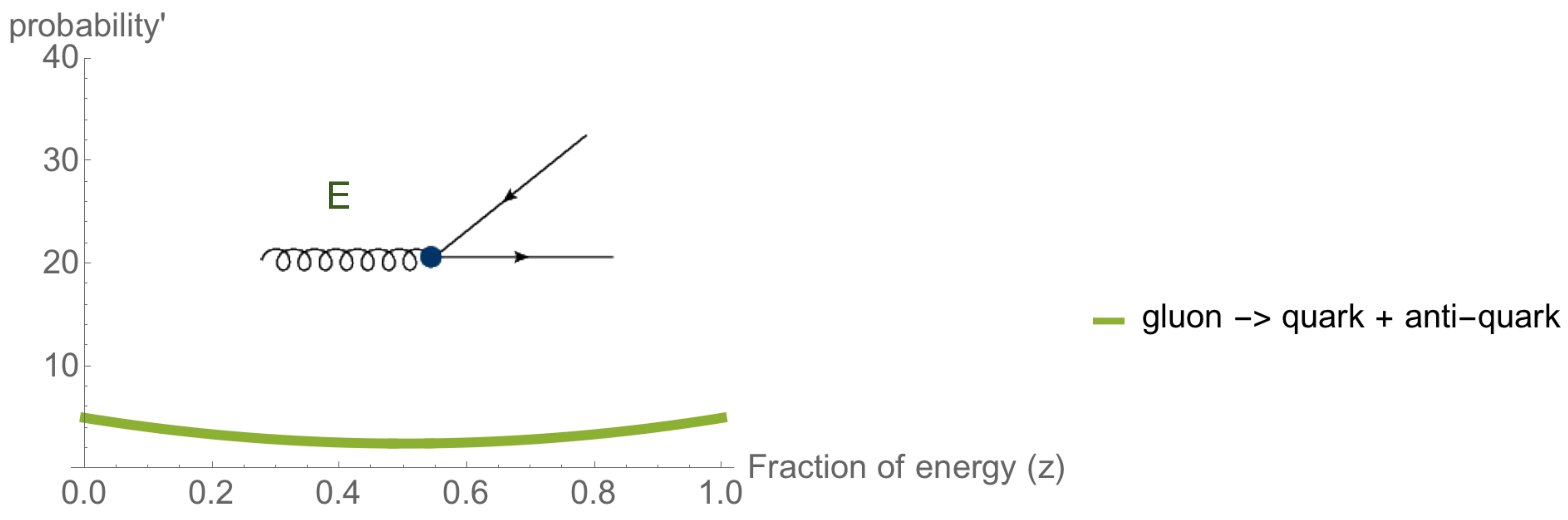

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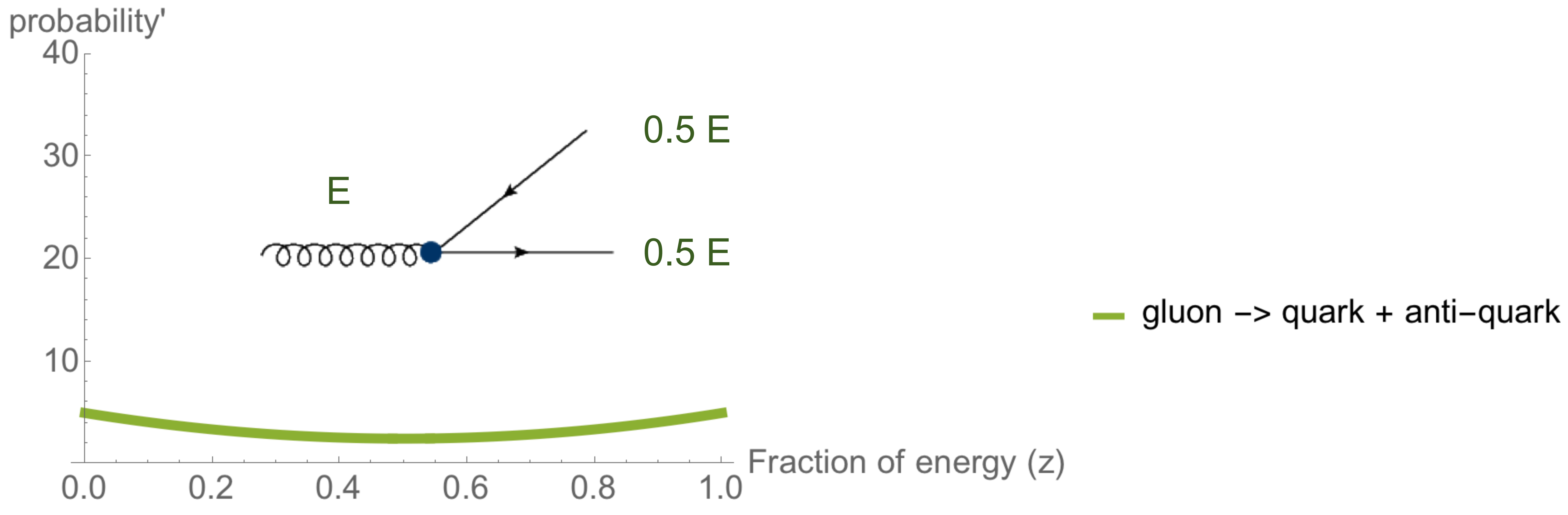

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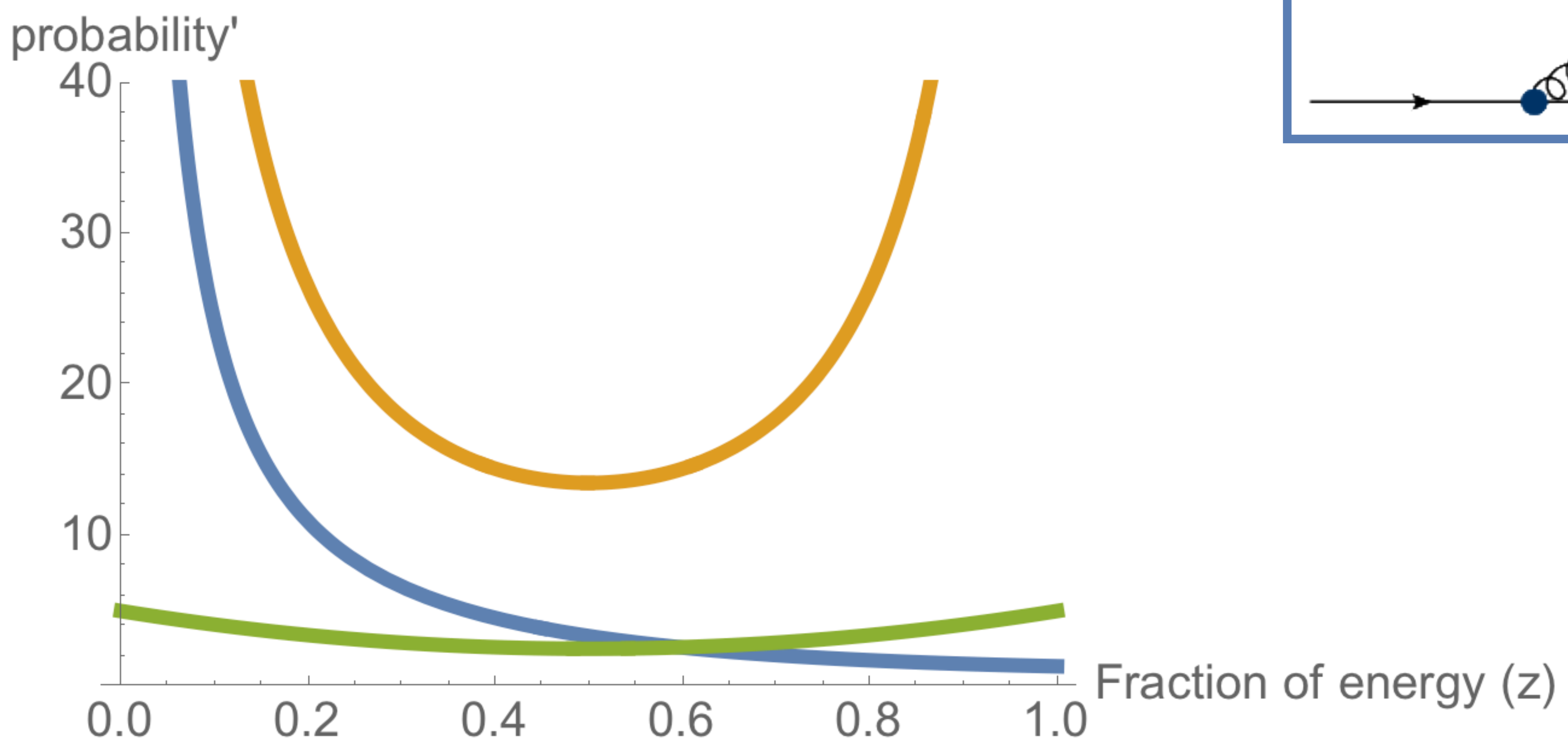
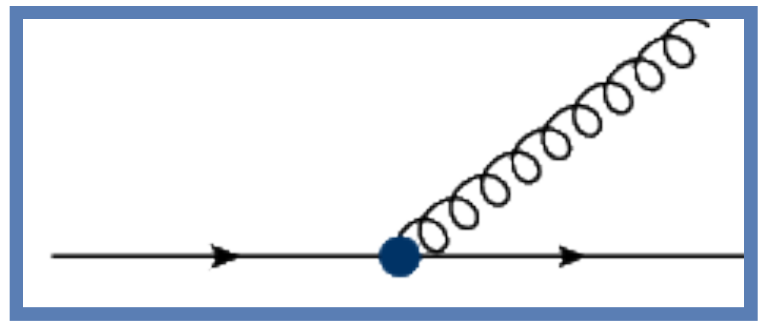
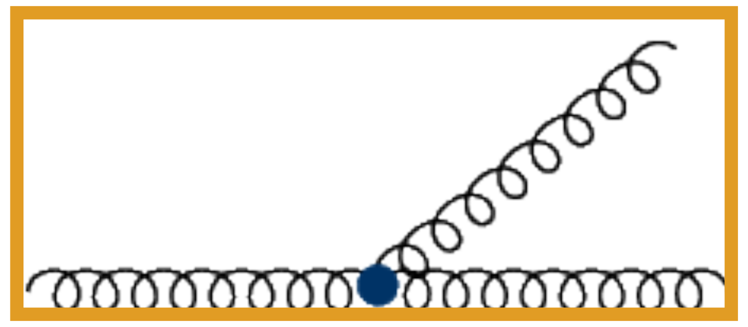
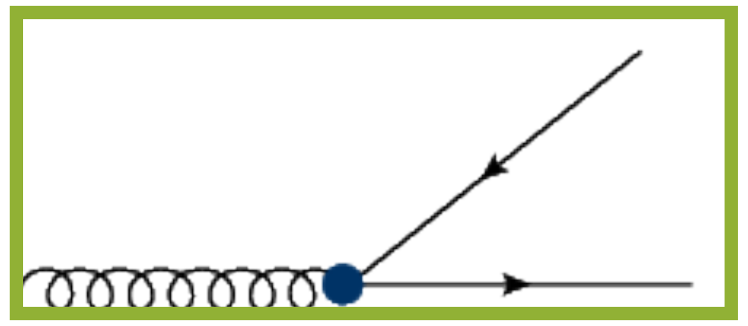




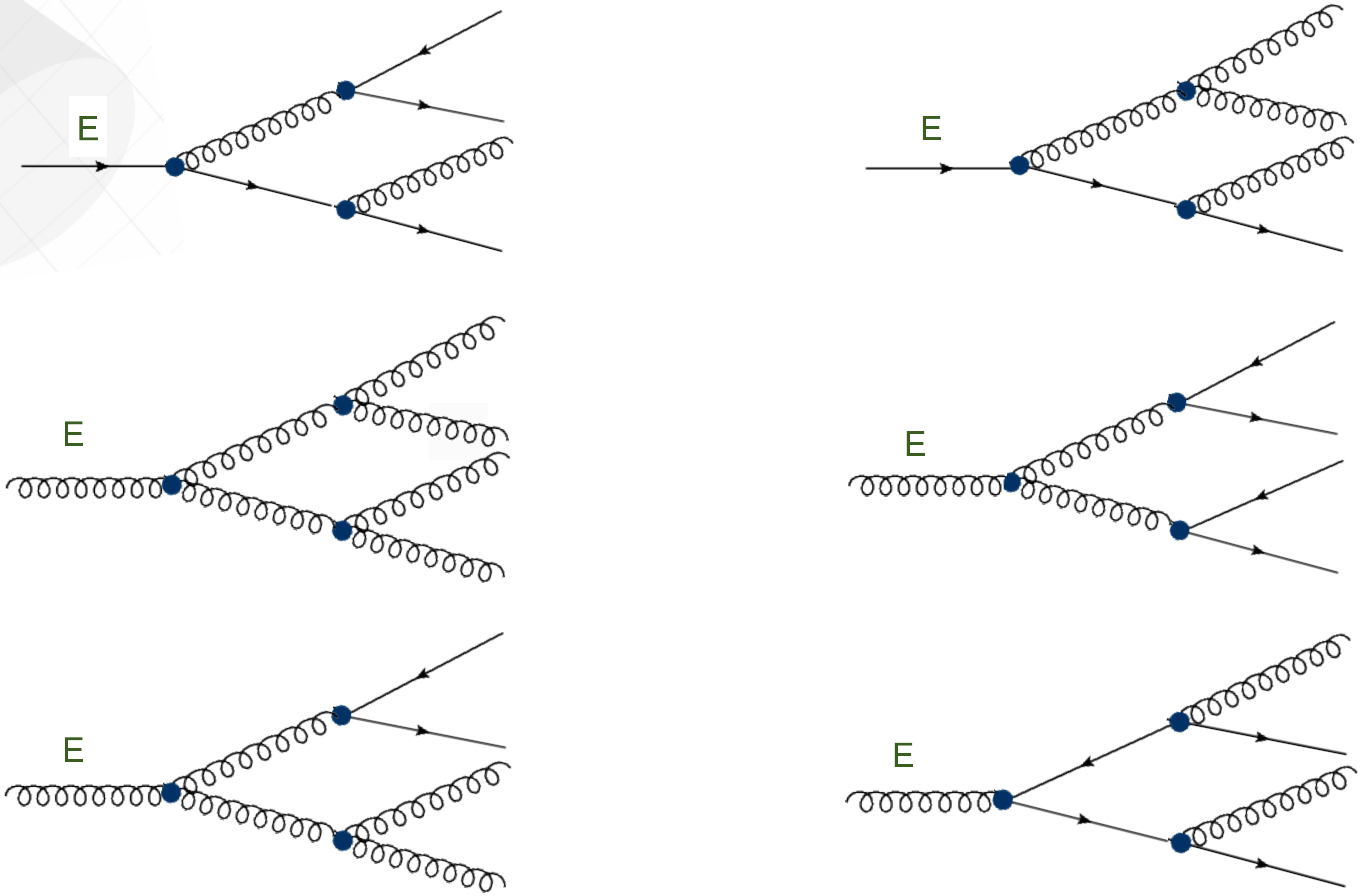




Parton radiation

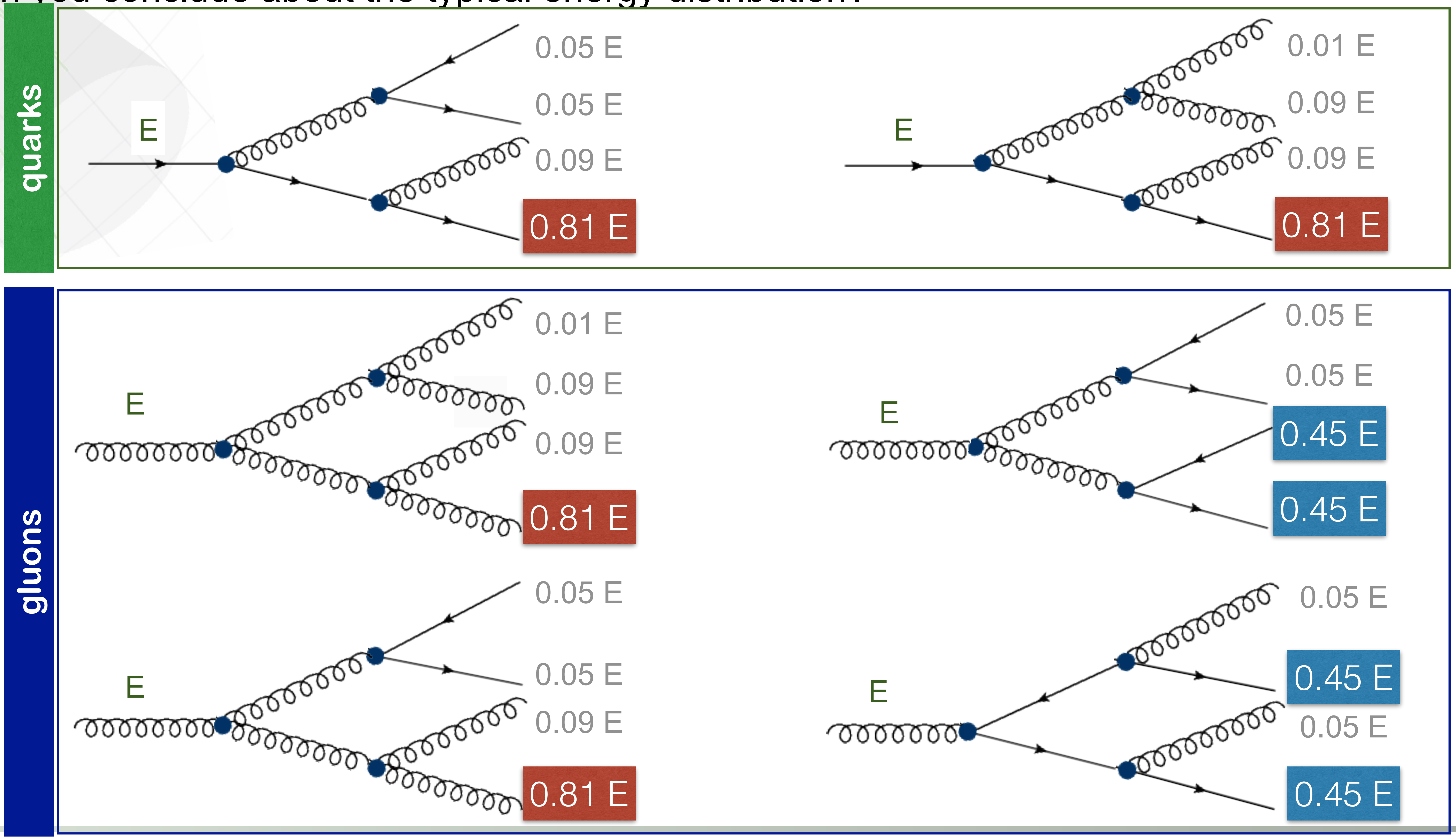
Exercise

- Find the energy of the final particles for these 6 configurations?



Parton radiation

- What can you conclude about the typical energy distribution?



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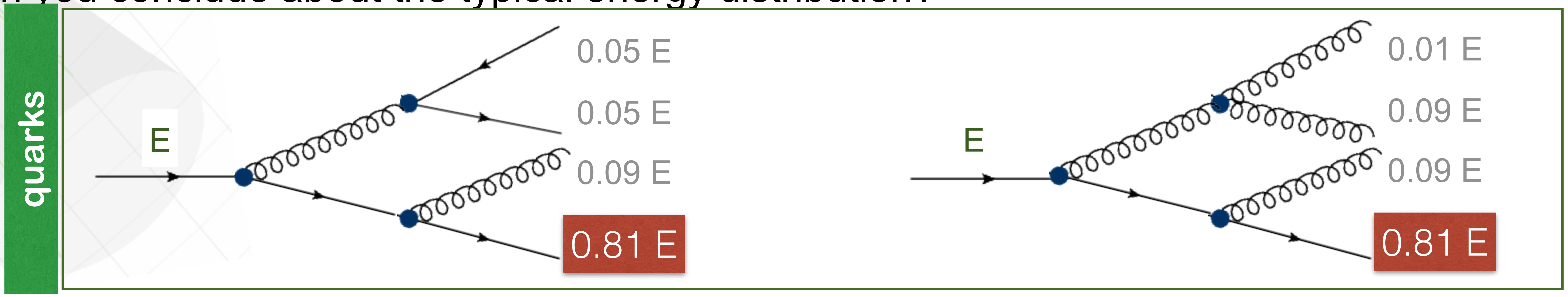
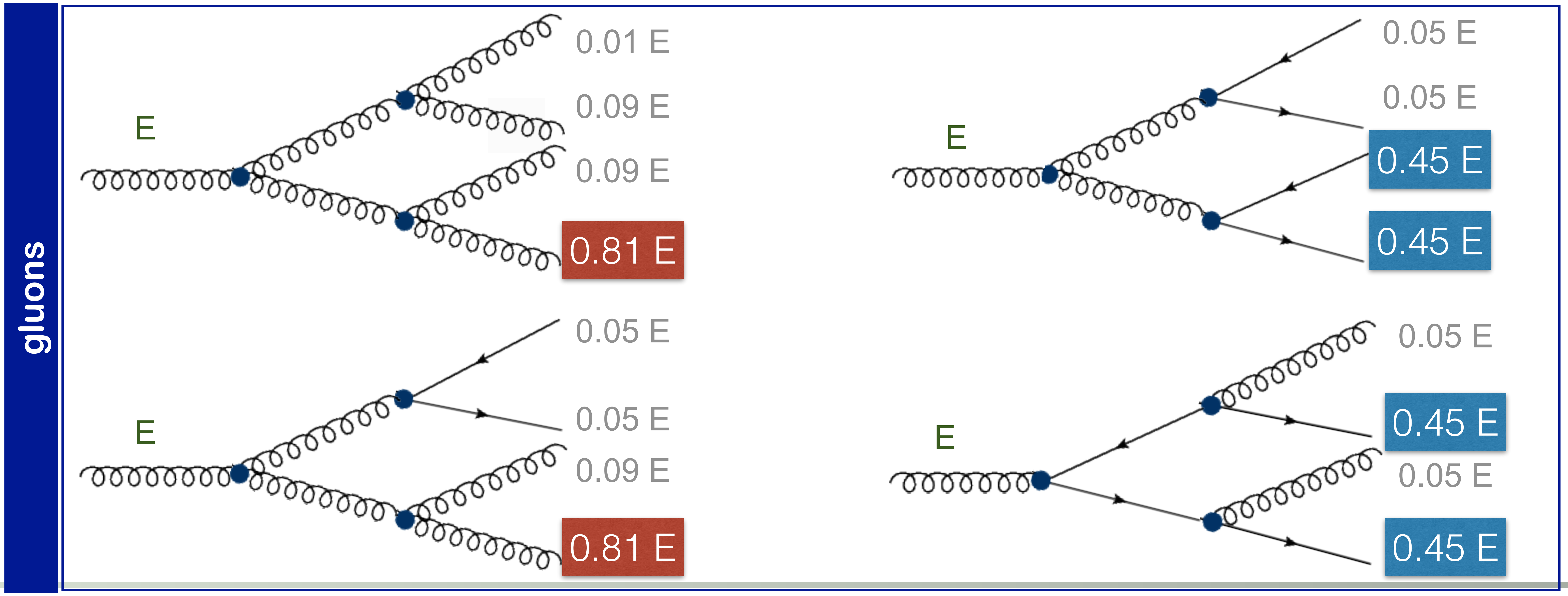


Source of collimated energy always present!

Parton radiation

- What can you conclude about the typical energy distribution?

There are channels that produce a more energy balance in the final list of particles



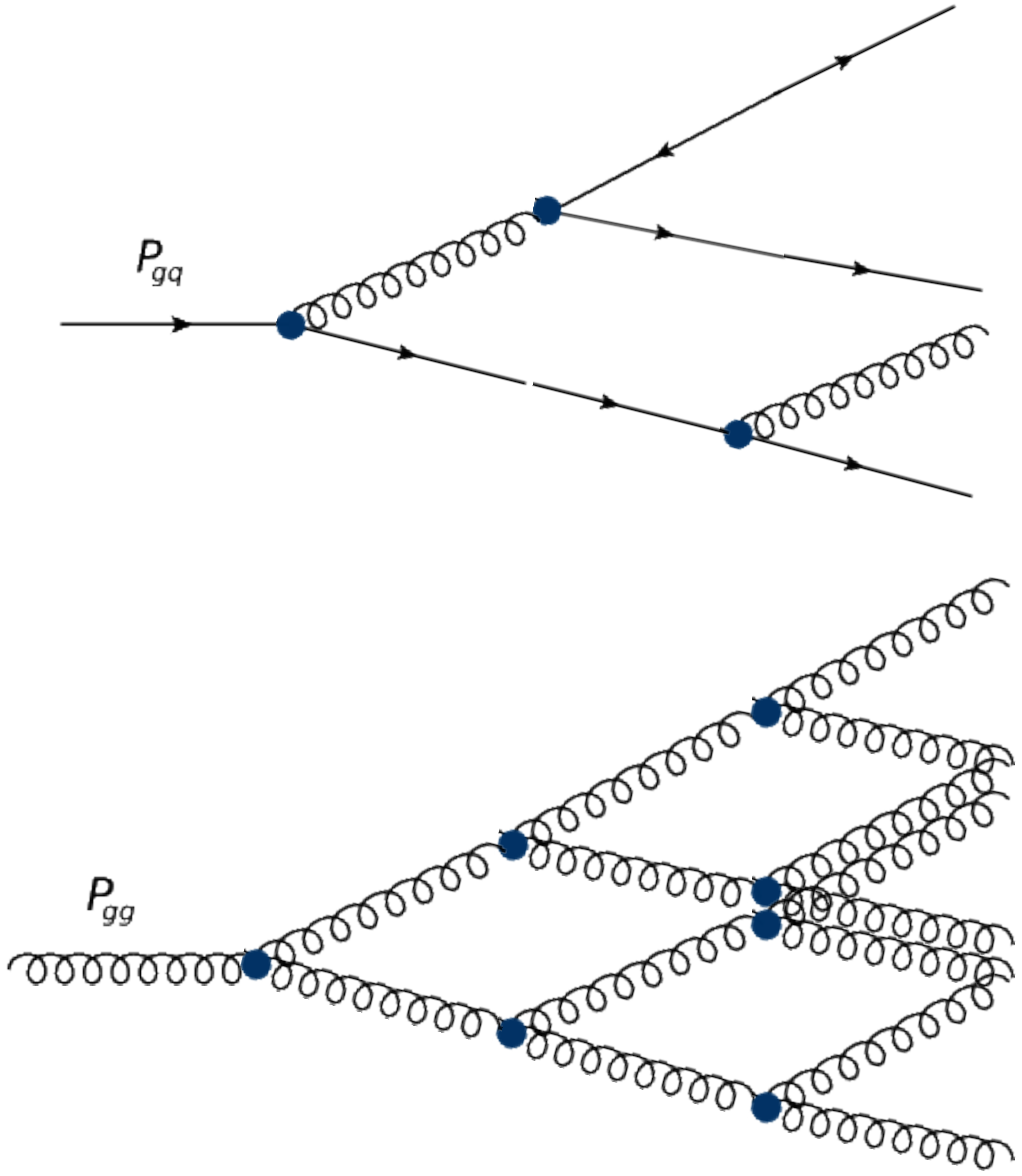
Parton radiation

- What can you conclude about the typical energy distribution?

Additional tip:

gluons radiate more than quarks

(~2x more!)



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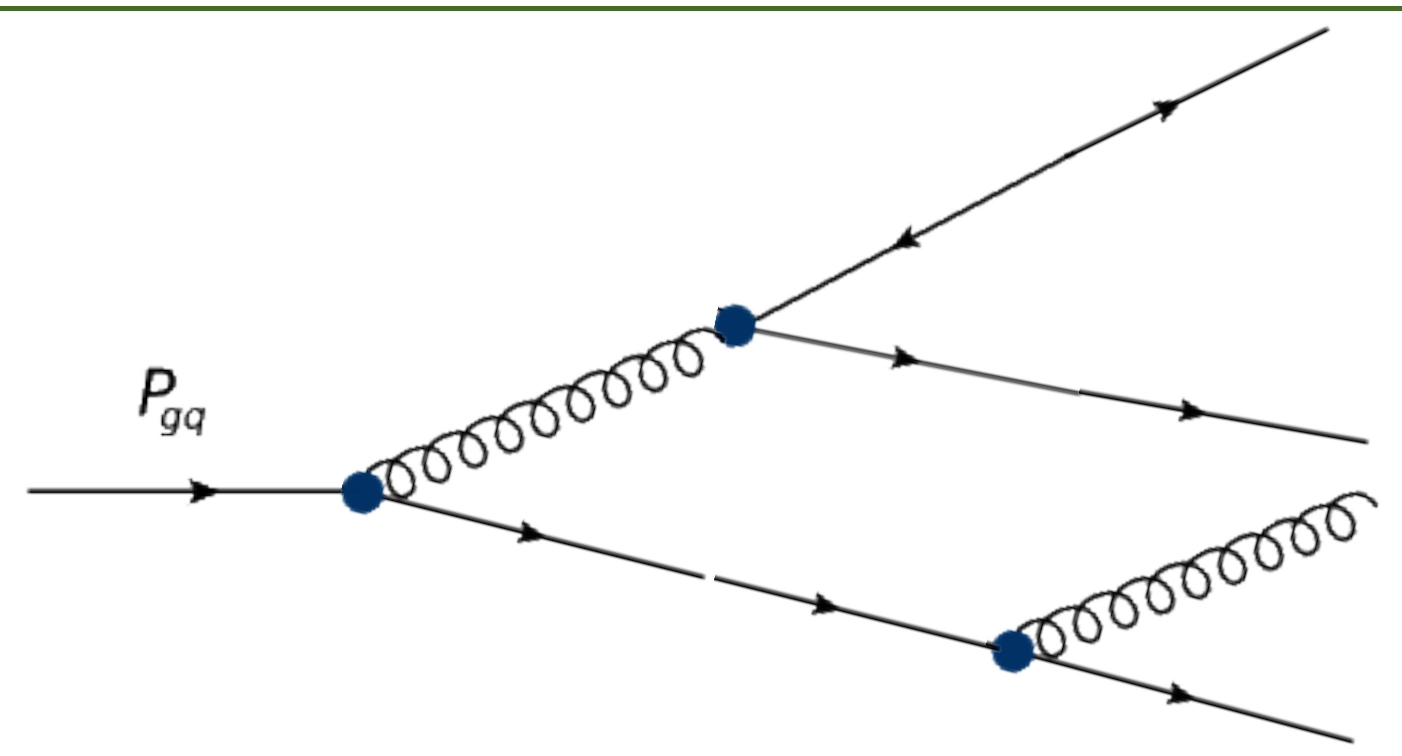
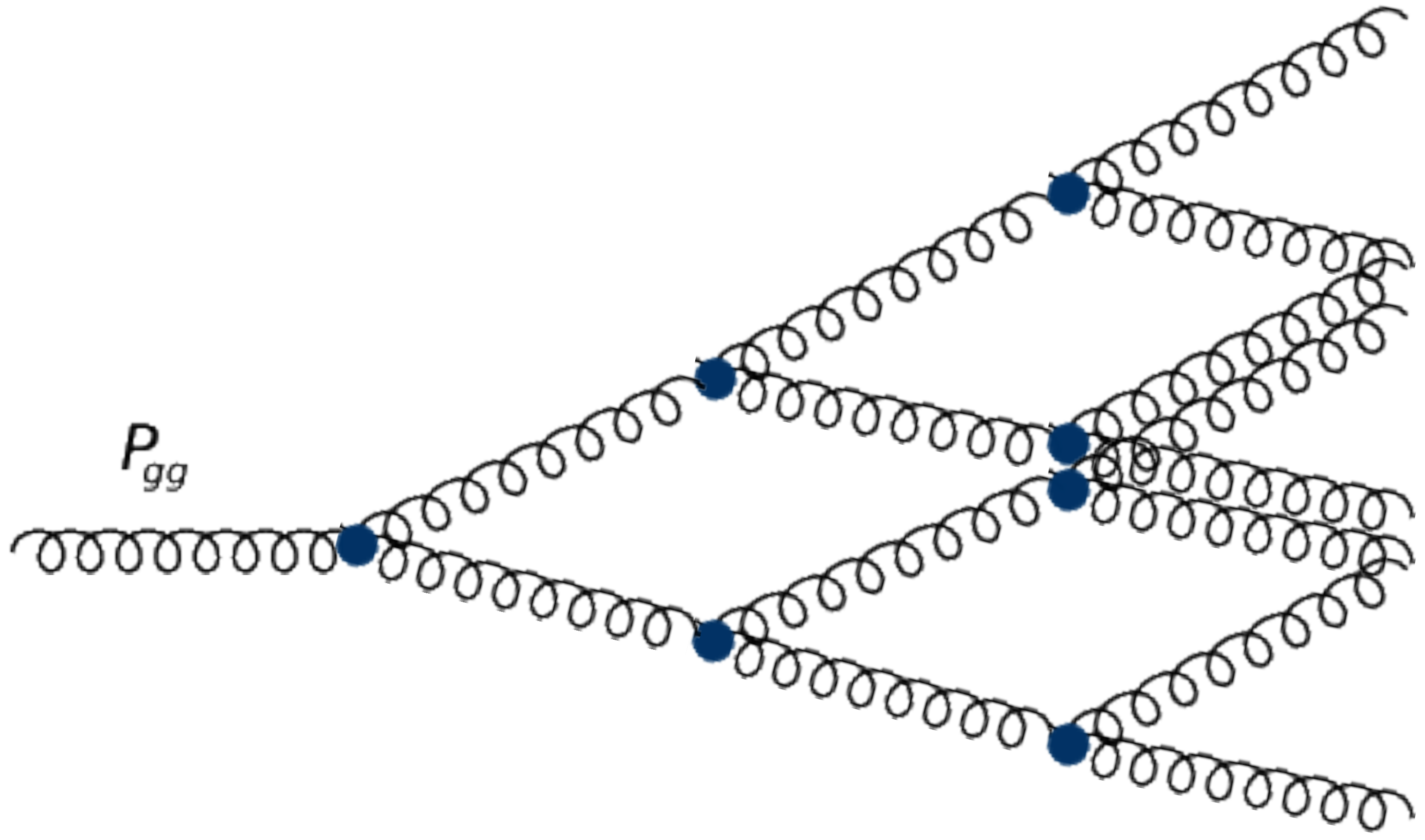


Small number of particles

Energy more collimated

gluons

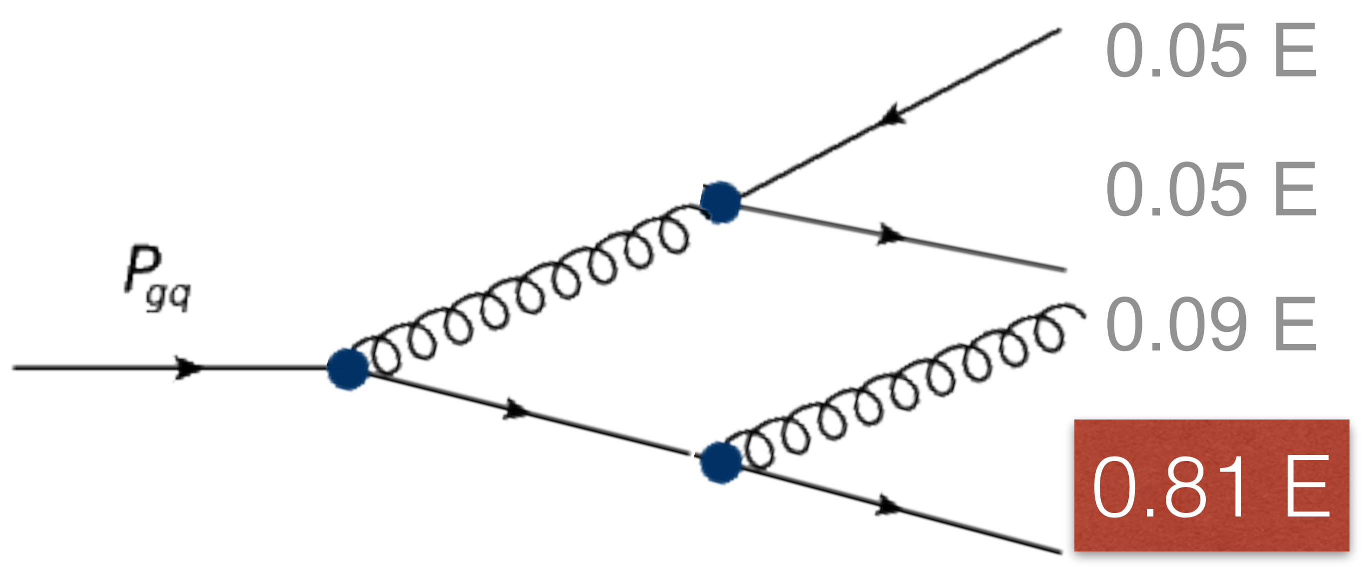


Larger number of particles

Energy less collimated

From partons to jets

- We measure only the final particles…
  - From energy and “distance” correlations, we can cluster the particles likely to come from the same original quark or gluon:



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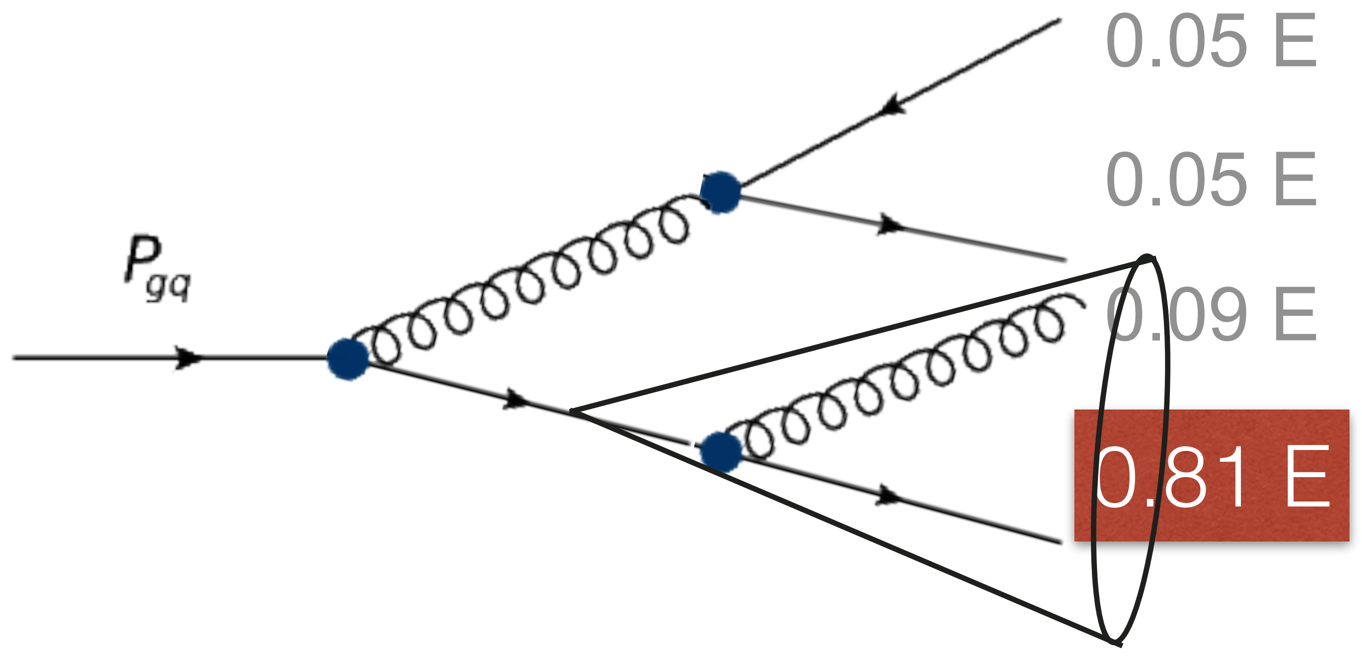

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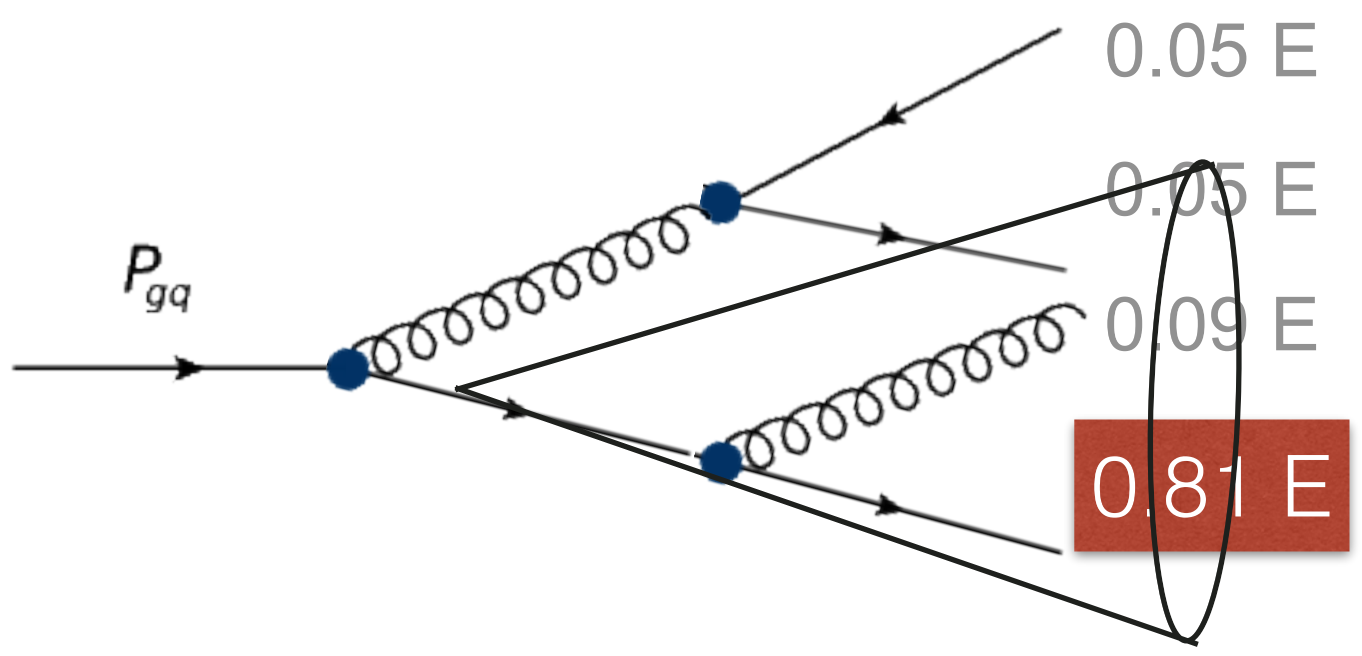

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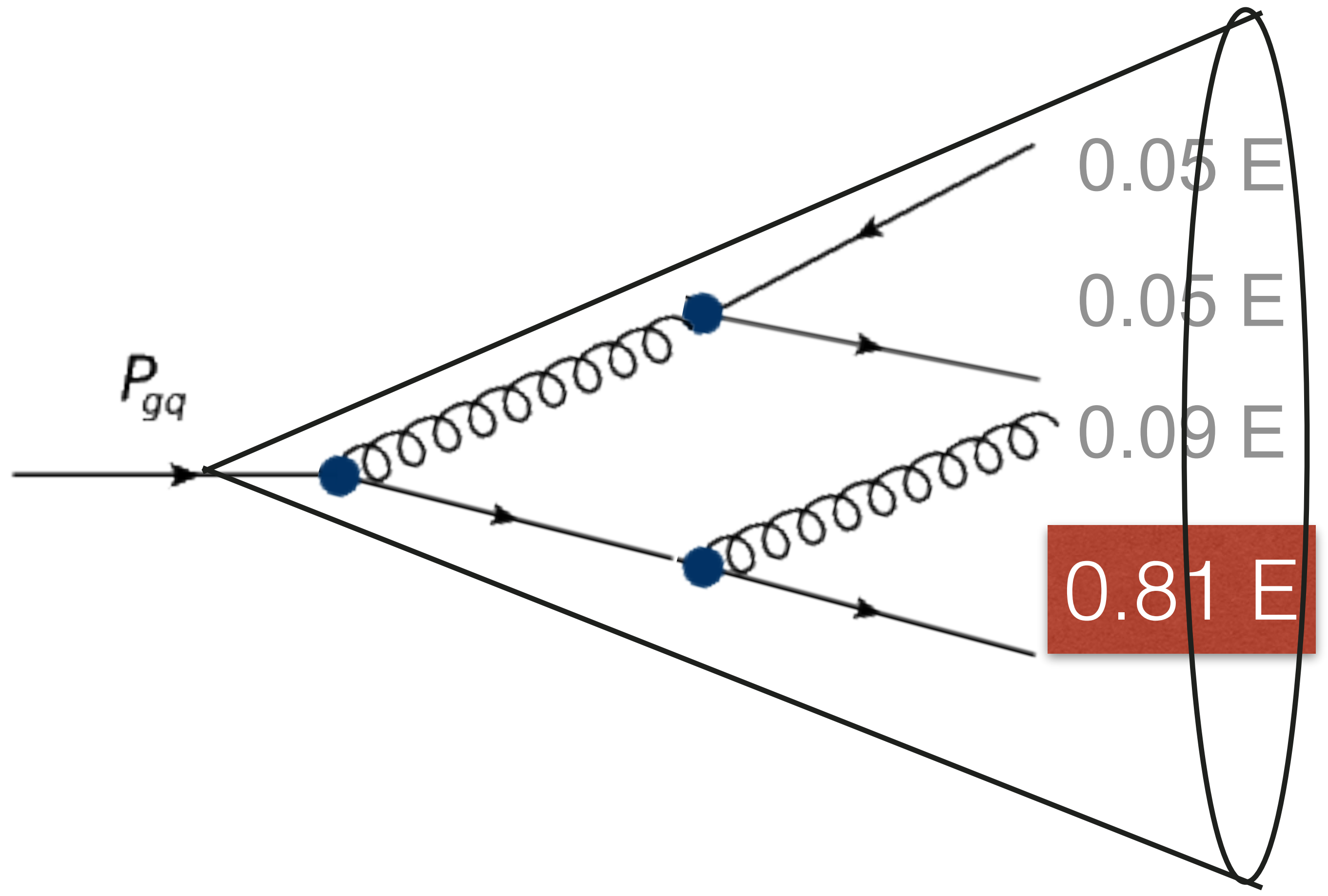

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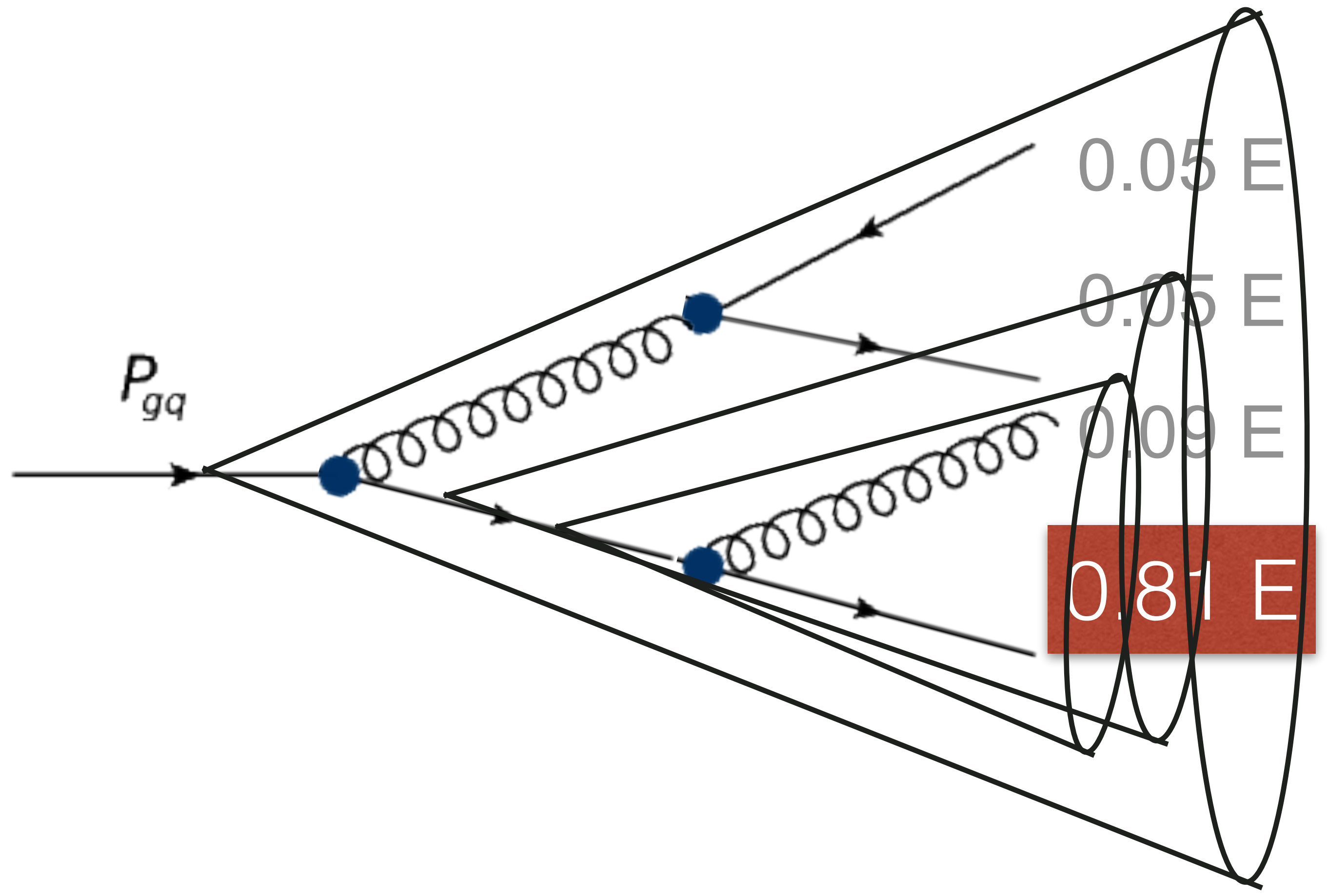
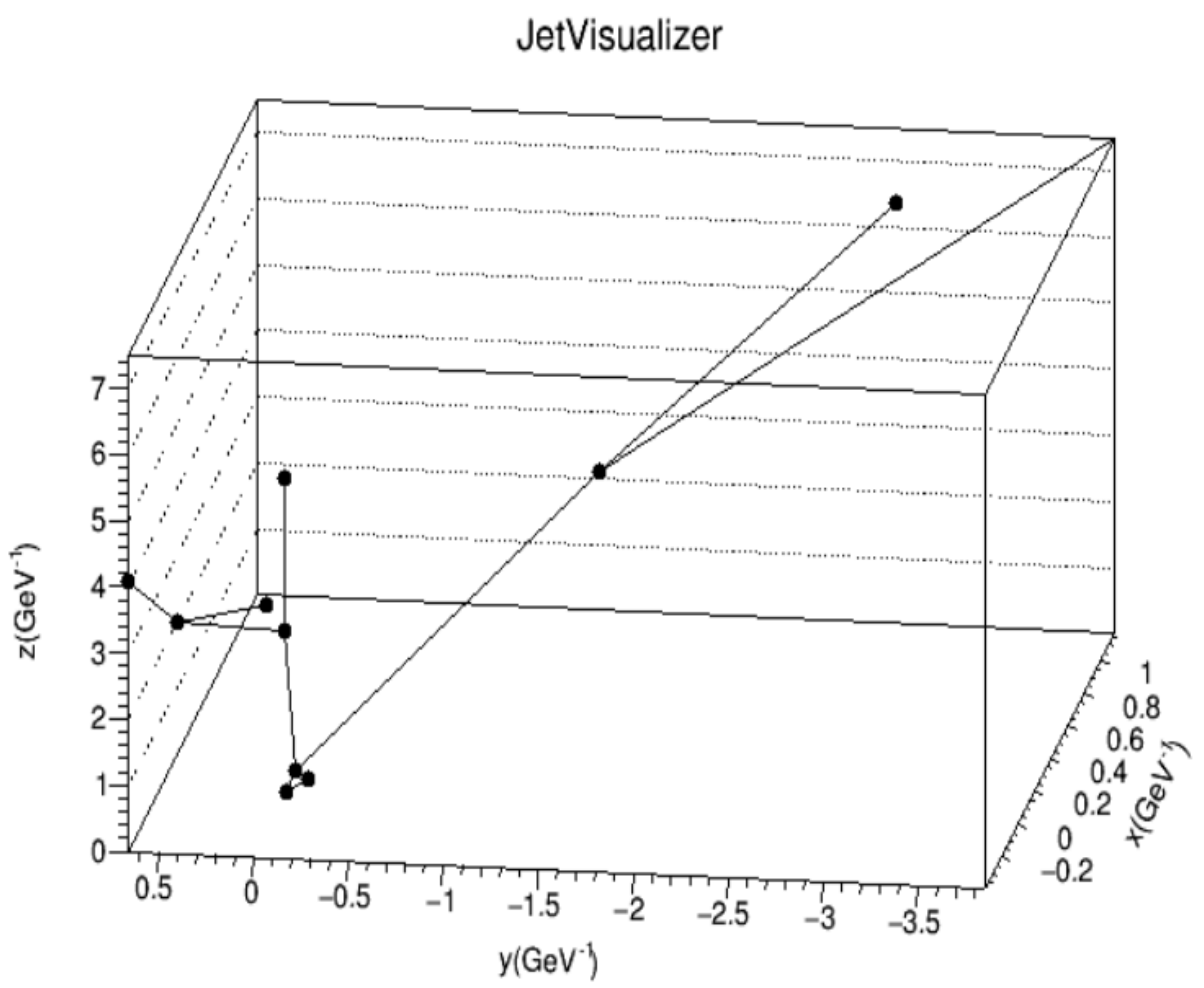


All these are suitable jets! We just need to specify:
- The size of the jet (R)
- The algorithm to cluster particles

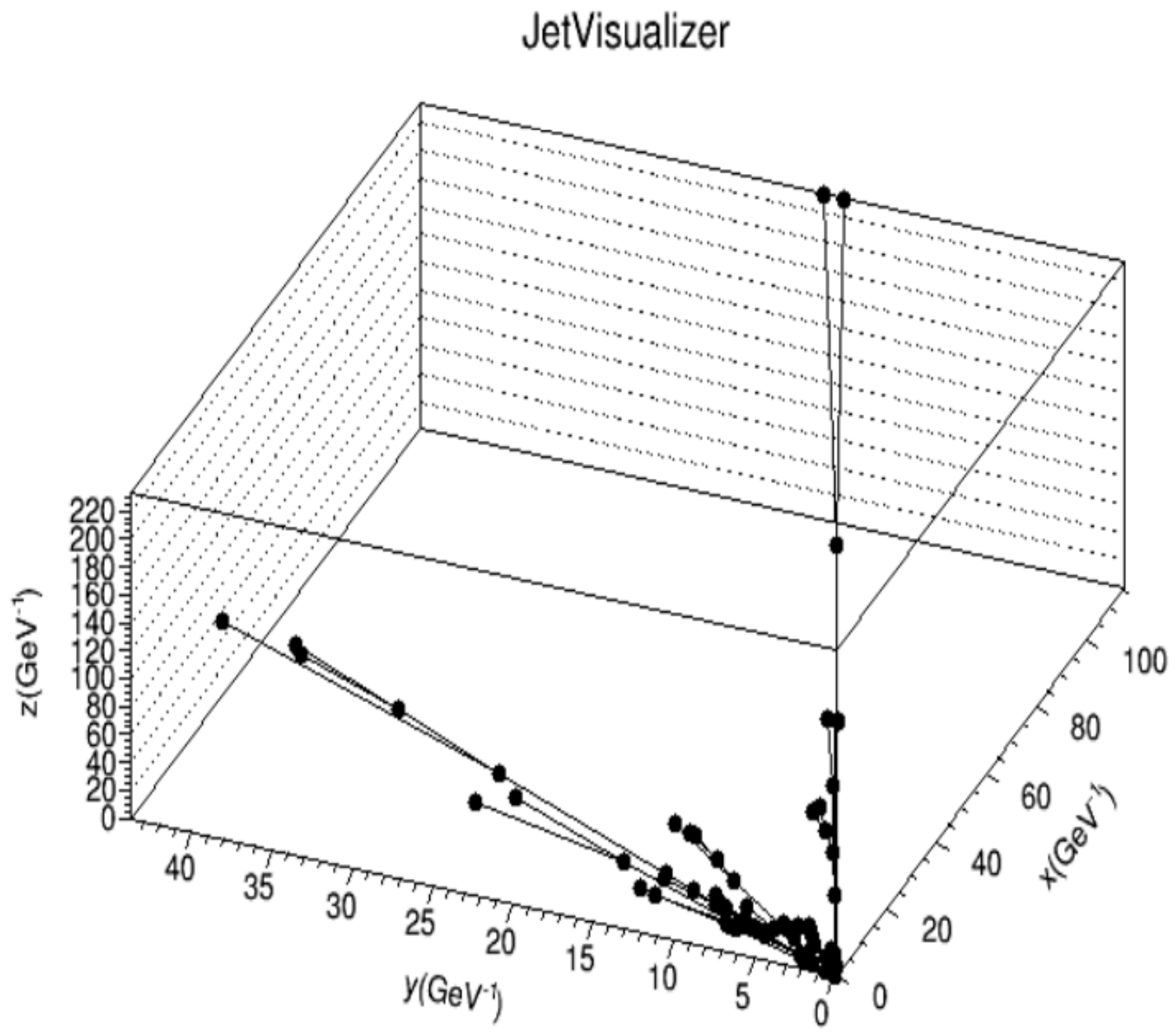
From partons to jets

- Special thanks to Sérgio Carrôlo and Íris Silva:
  - Build the first spatial jet visualizer!!

S. Carrôlo, I. Silva, "LIP Summer Internships 2010"



- Quark initiated jet — low multiplicity



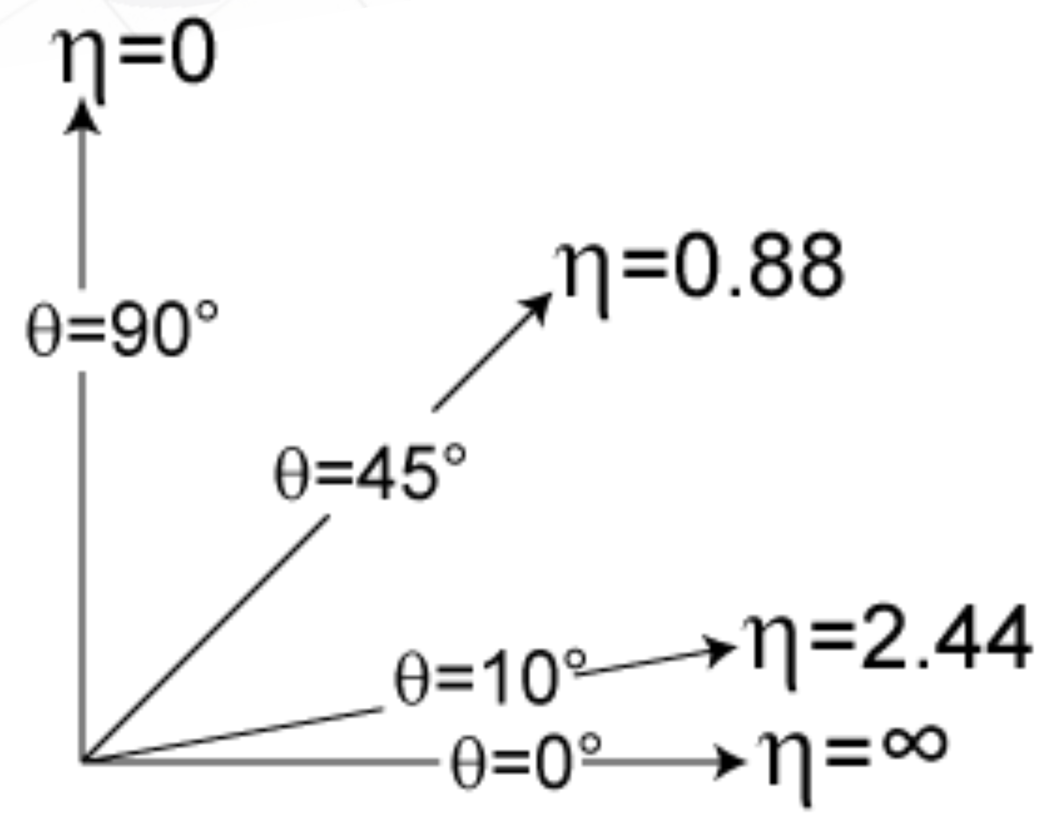
- Gluon initiated jet — high multiplicity

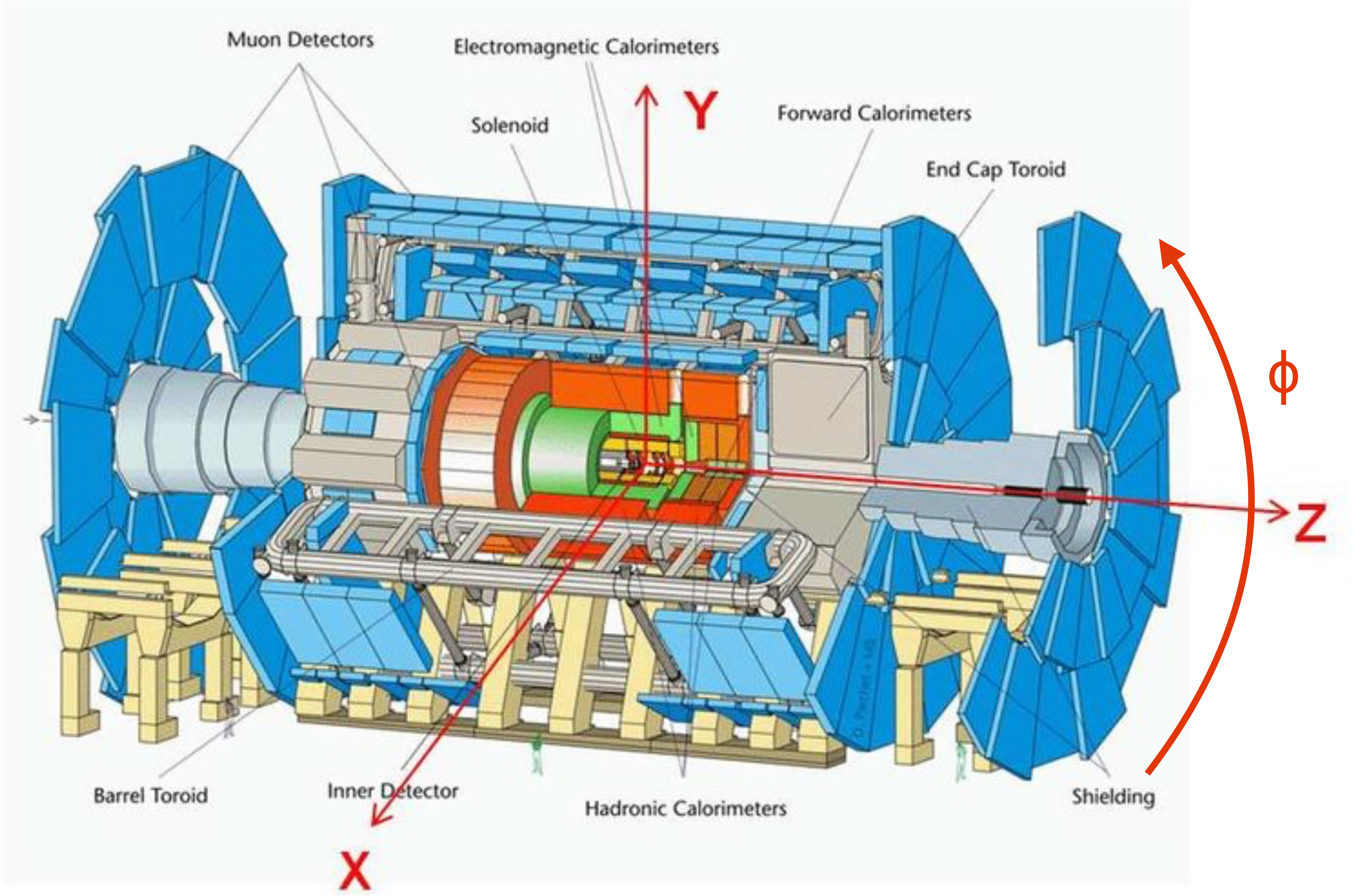

What is a jet ✓
How can we measure one?

Recap: what do we detect?

- What is the information that we get from the detector?

"Our" variables: (3D space) x, y, z ⟷ "Detector" variables: (2D plane) Azimuthal angle: ϕ Pseudo-rapidity: η

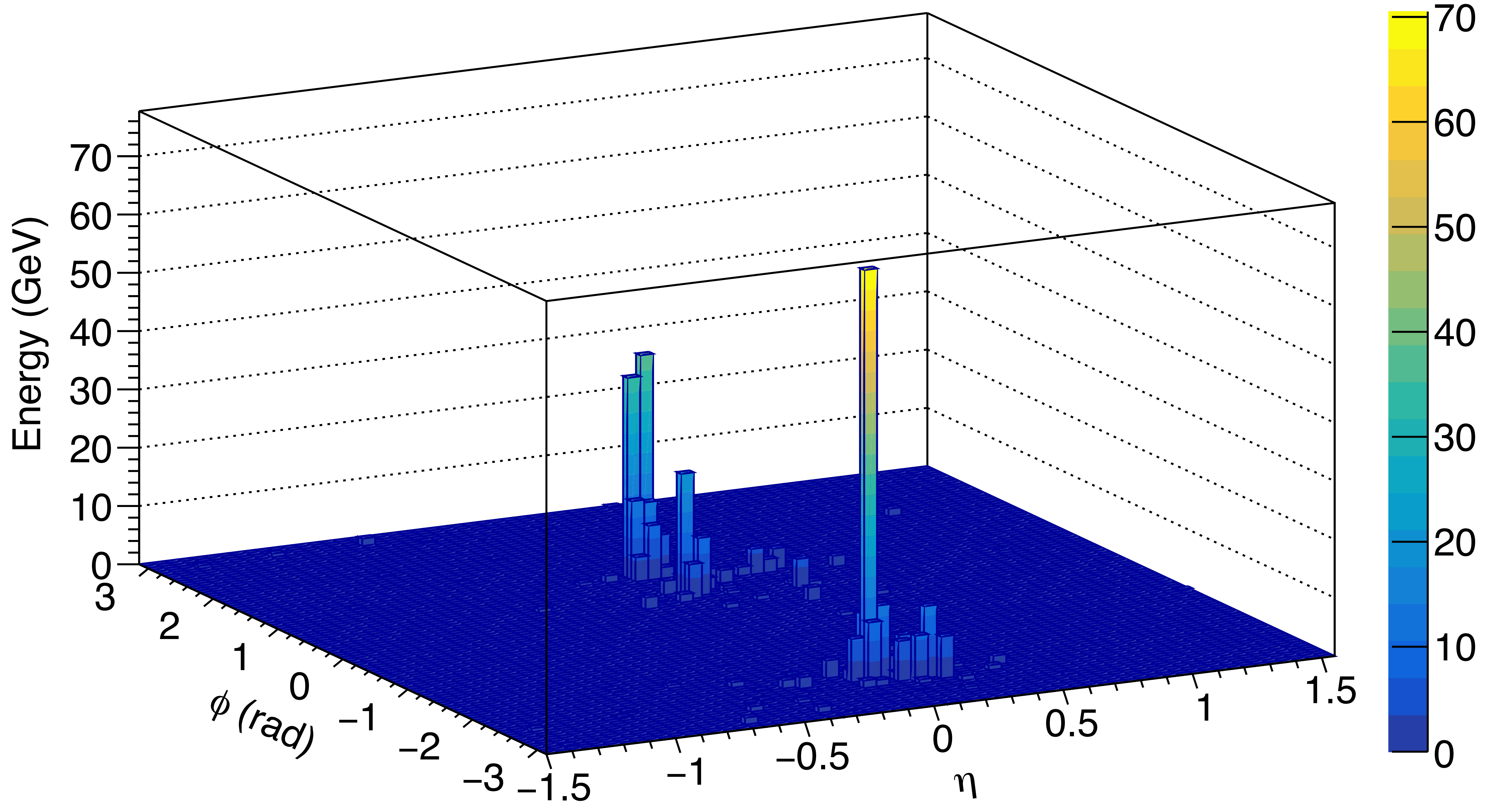




p_T: projection of momentum in the transverse (η ~0) direction

Identifying jets

- Now that we know what is a jet, how can we reconstruct it?
  - Simulated Proton-Proton event in detector coordinates:



Identified 2 likely jets
"by eye"

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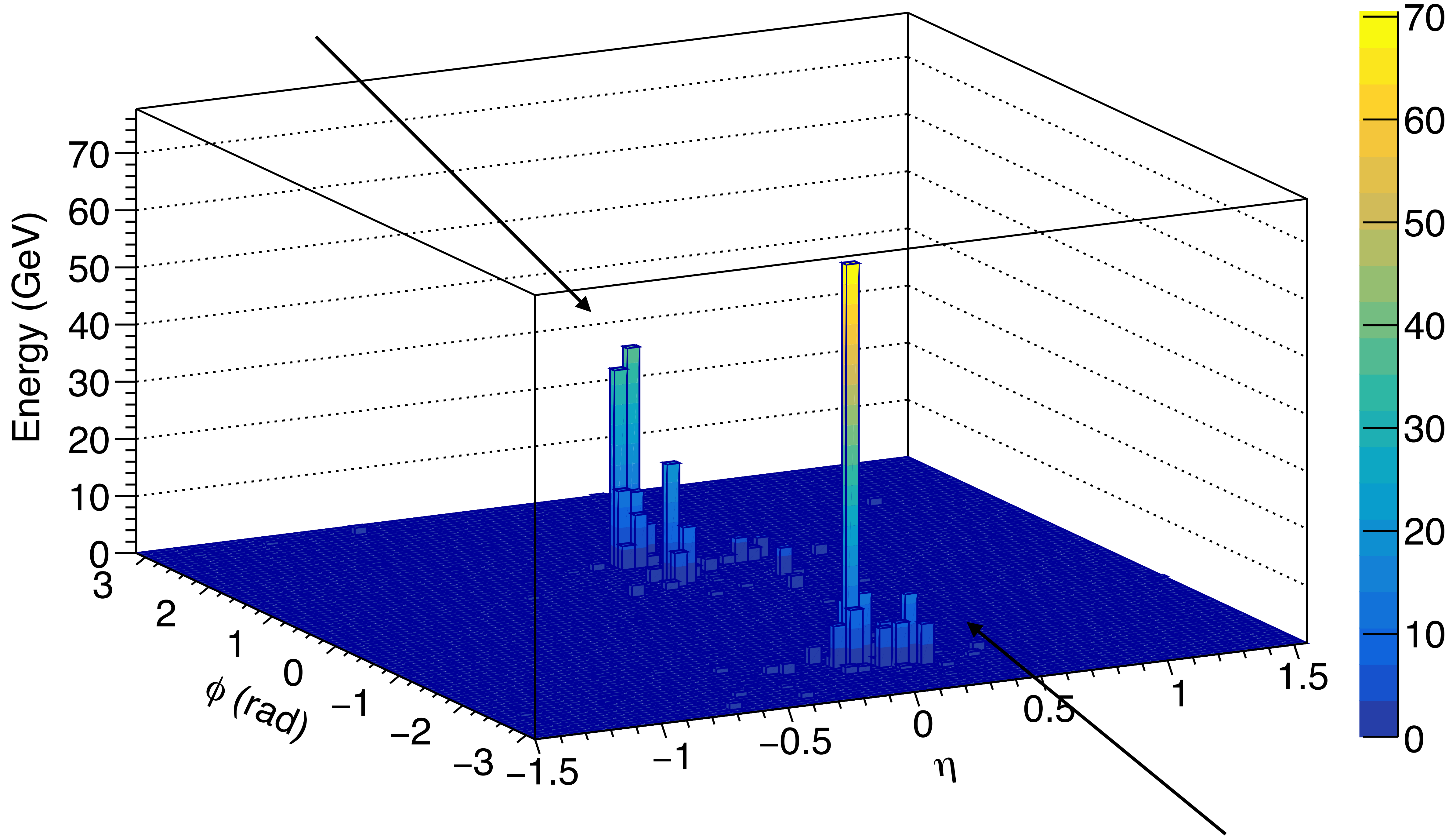

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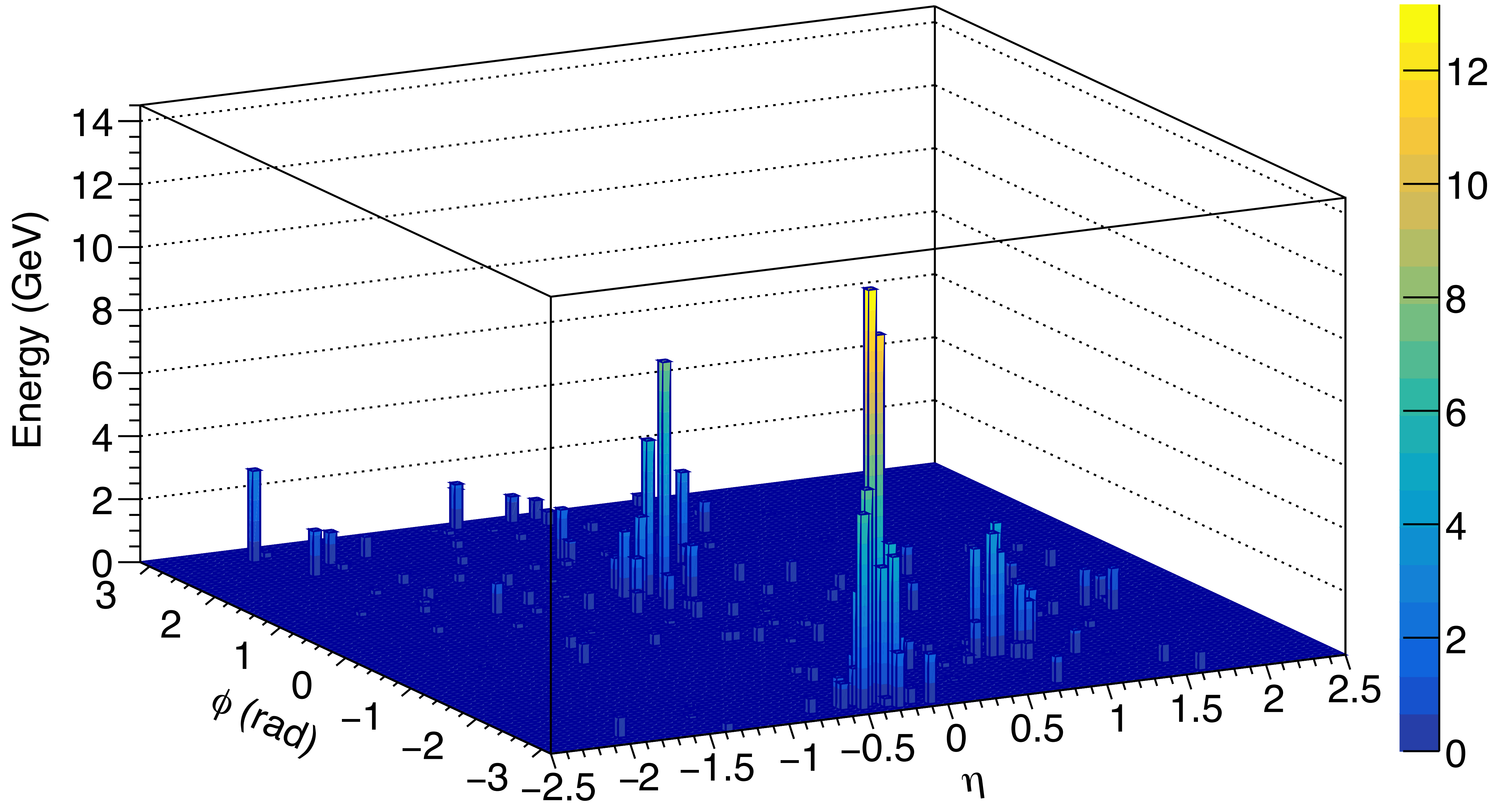

Identified 2 to 3 likely jets "by eye"

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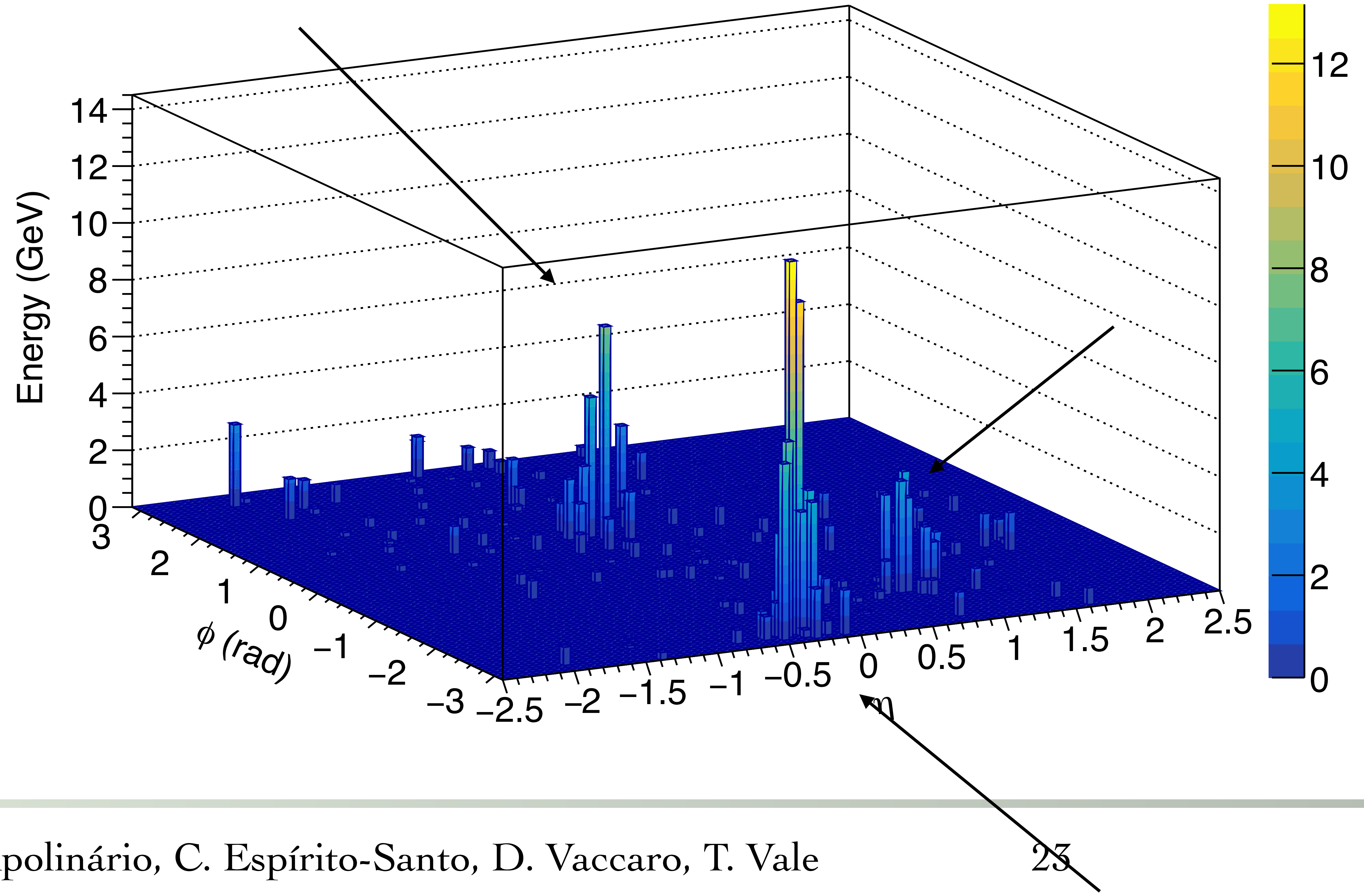
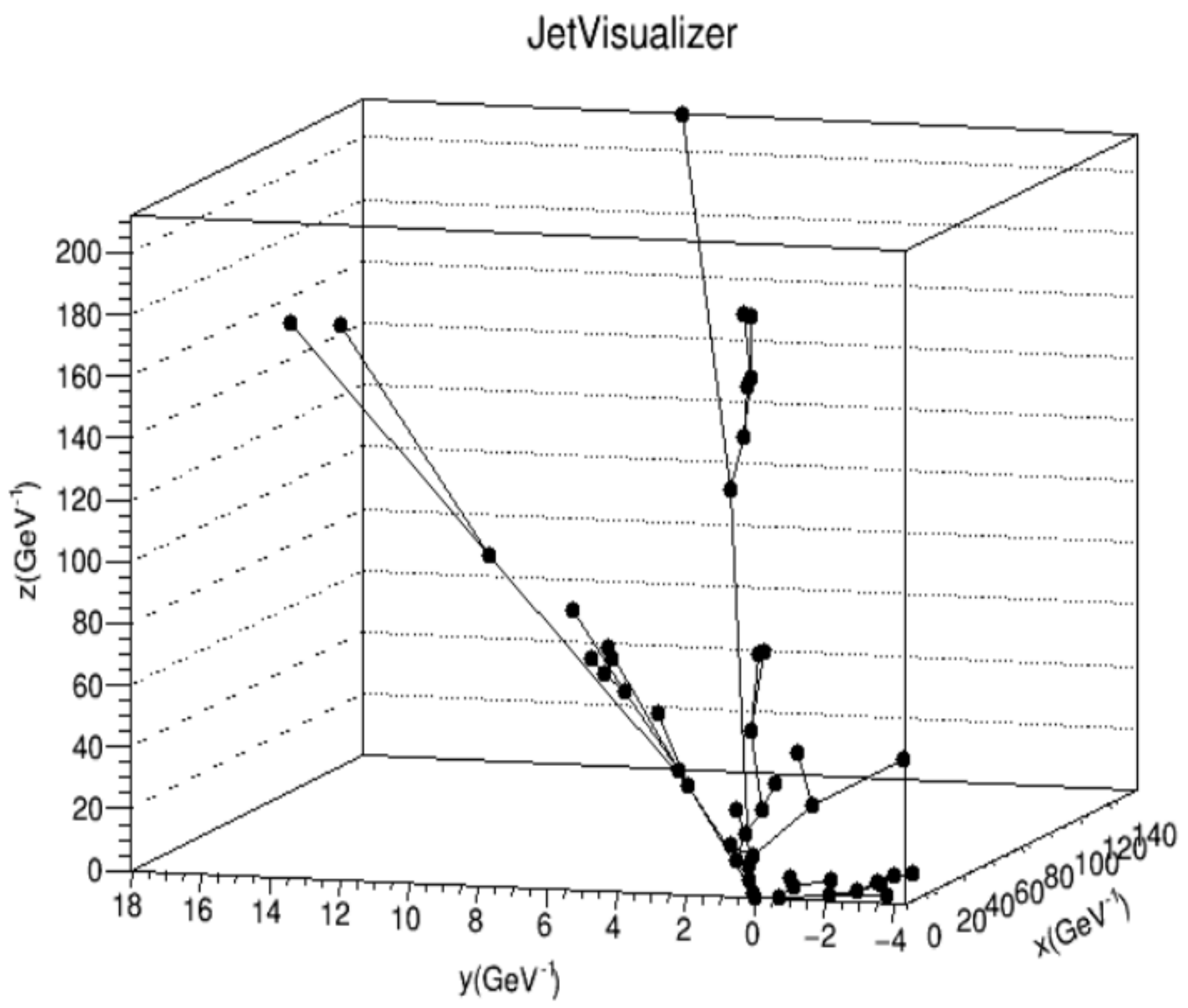


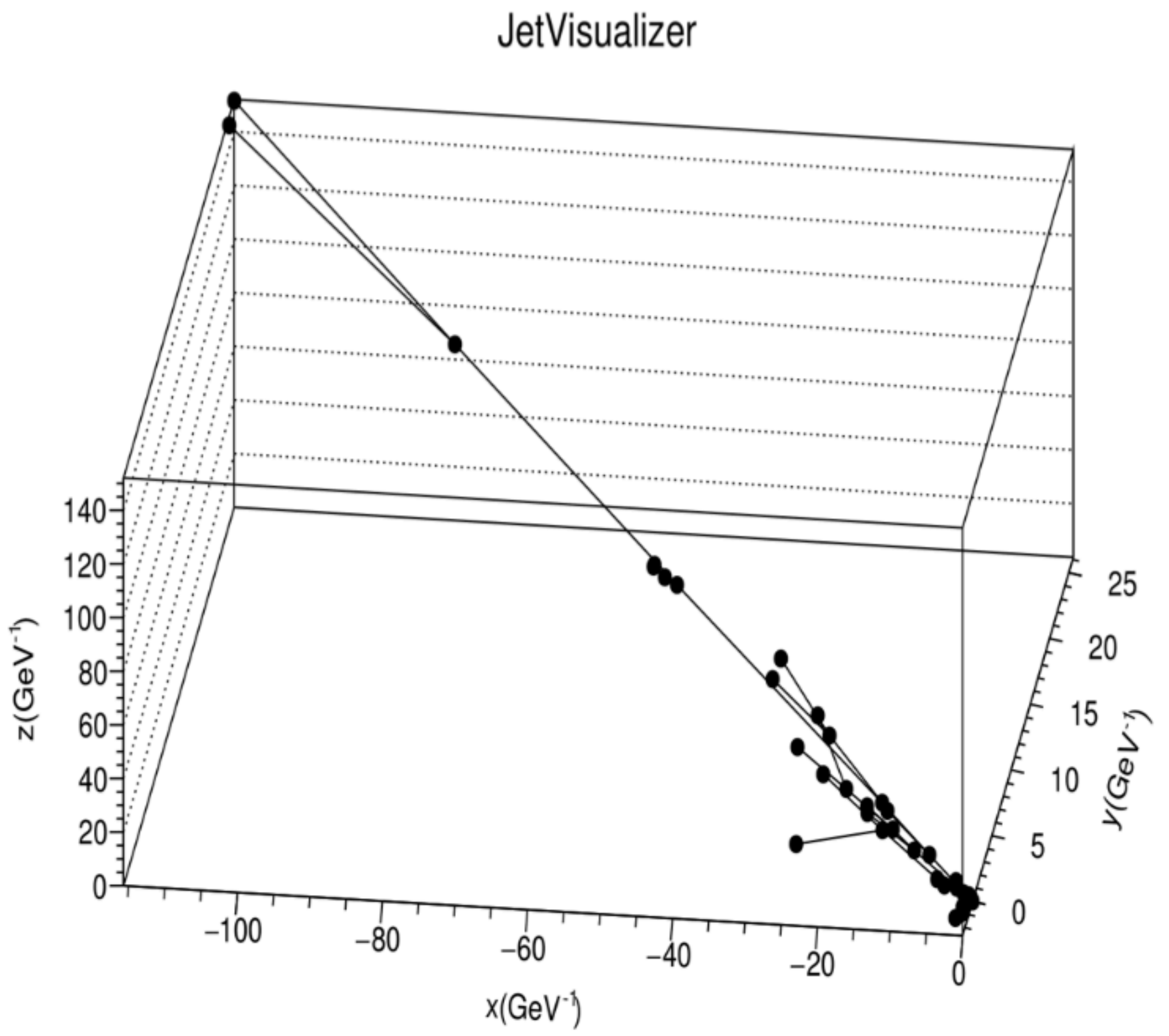
Identified 2 to 3 likely jets "by eye"

Identifying jets

- 3-jet like events can come from large angle splittings that share (approximately) the same energy fraction:



- Symmetric splitting function — two main branches



- Asymmetric splitting function — one main branch

S. Carrôlo, I. Silva, "LIP Summer Internships 2010"

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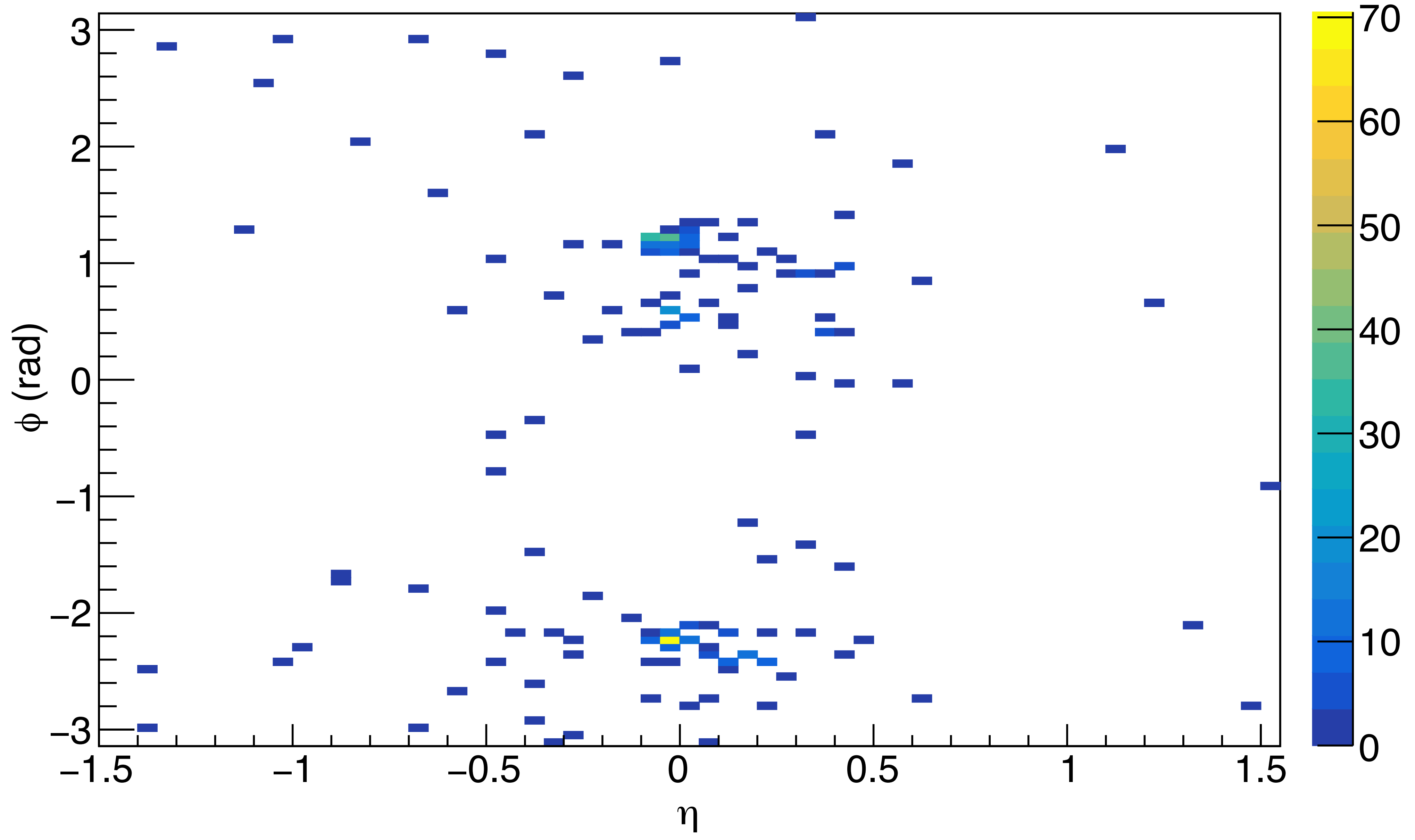
View from the top



But the details are not that simple…

Given a fixed size R, where are exactly my 2 jets in this event?

Identifying jets

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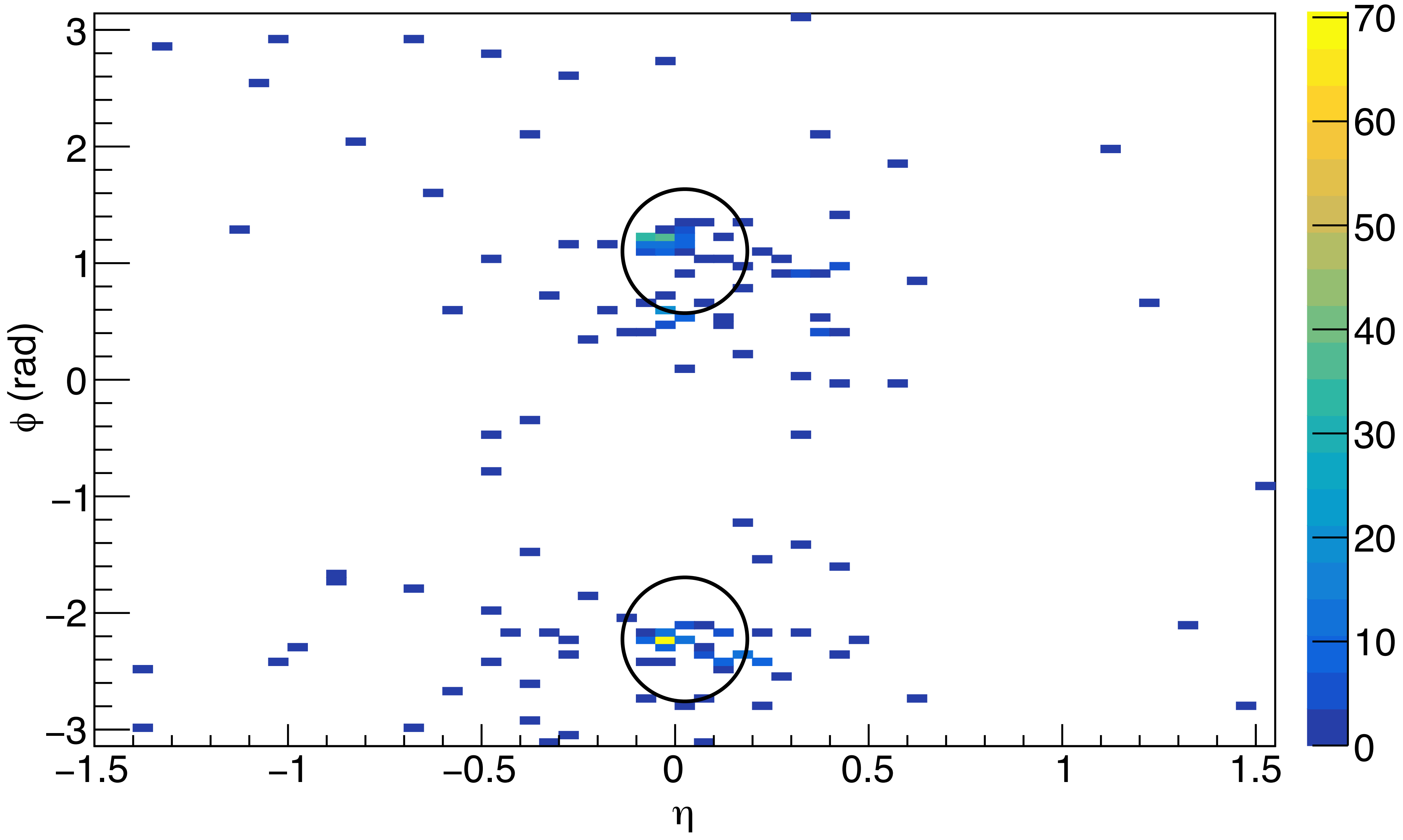

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Cluster the most energetic particles?

Identifying jets

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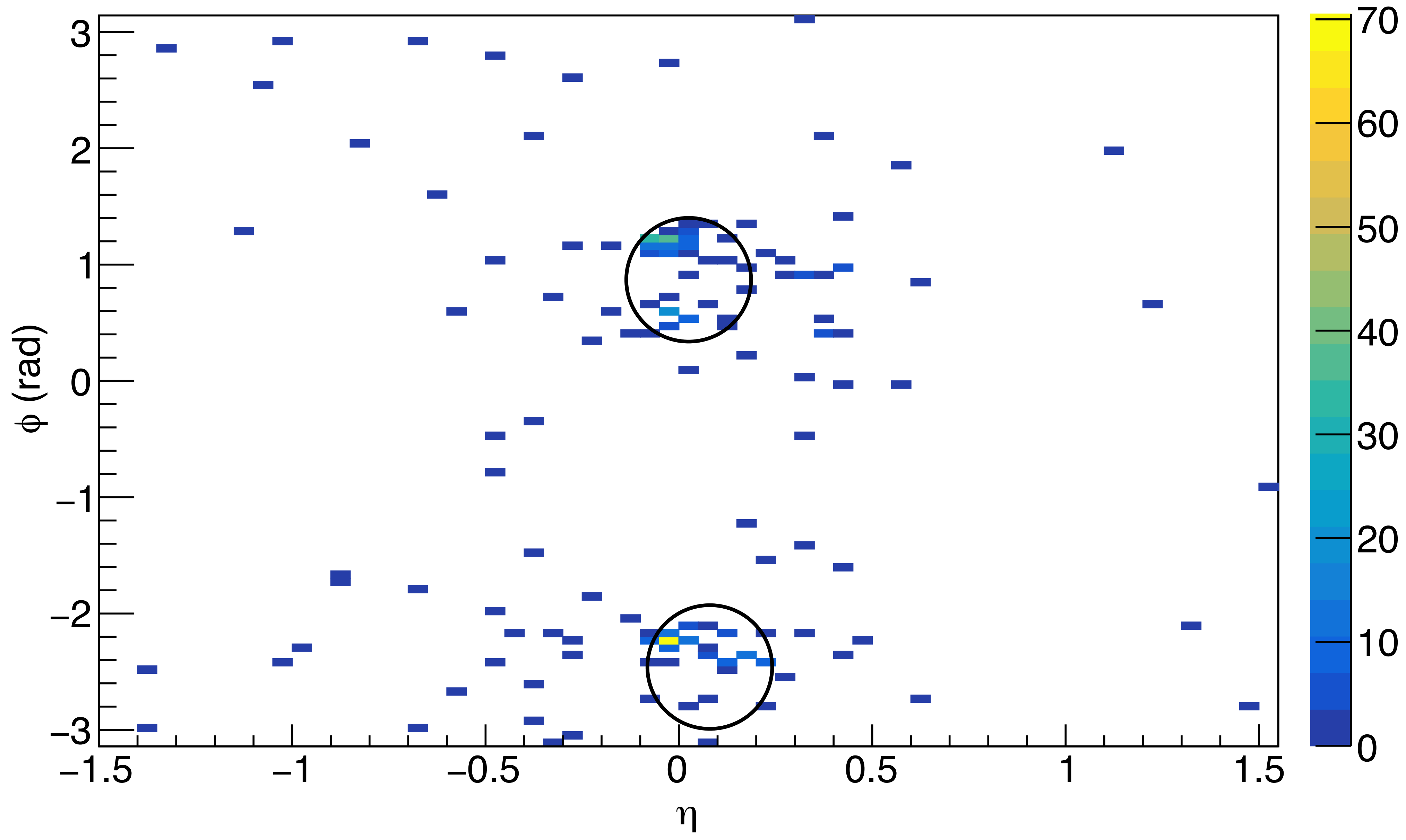

But the details are
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Given a fixed size R, where are
exactly my 2 jets in this event?

Cluster the largest amount of
energy/particles?

Identifying jets

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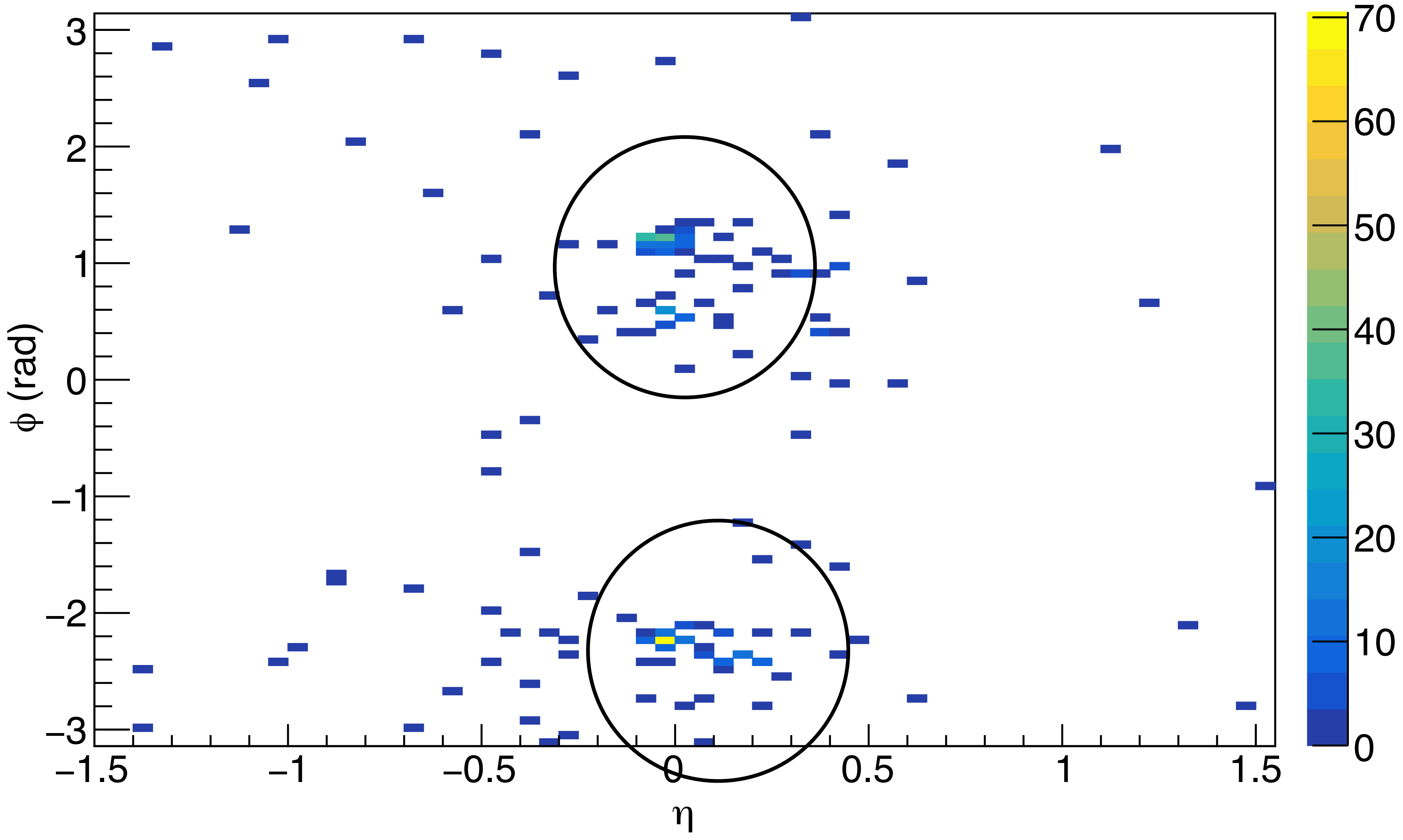

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Larger size jets will have the same problem

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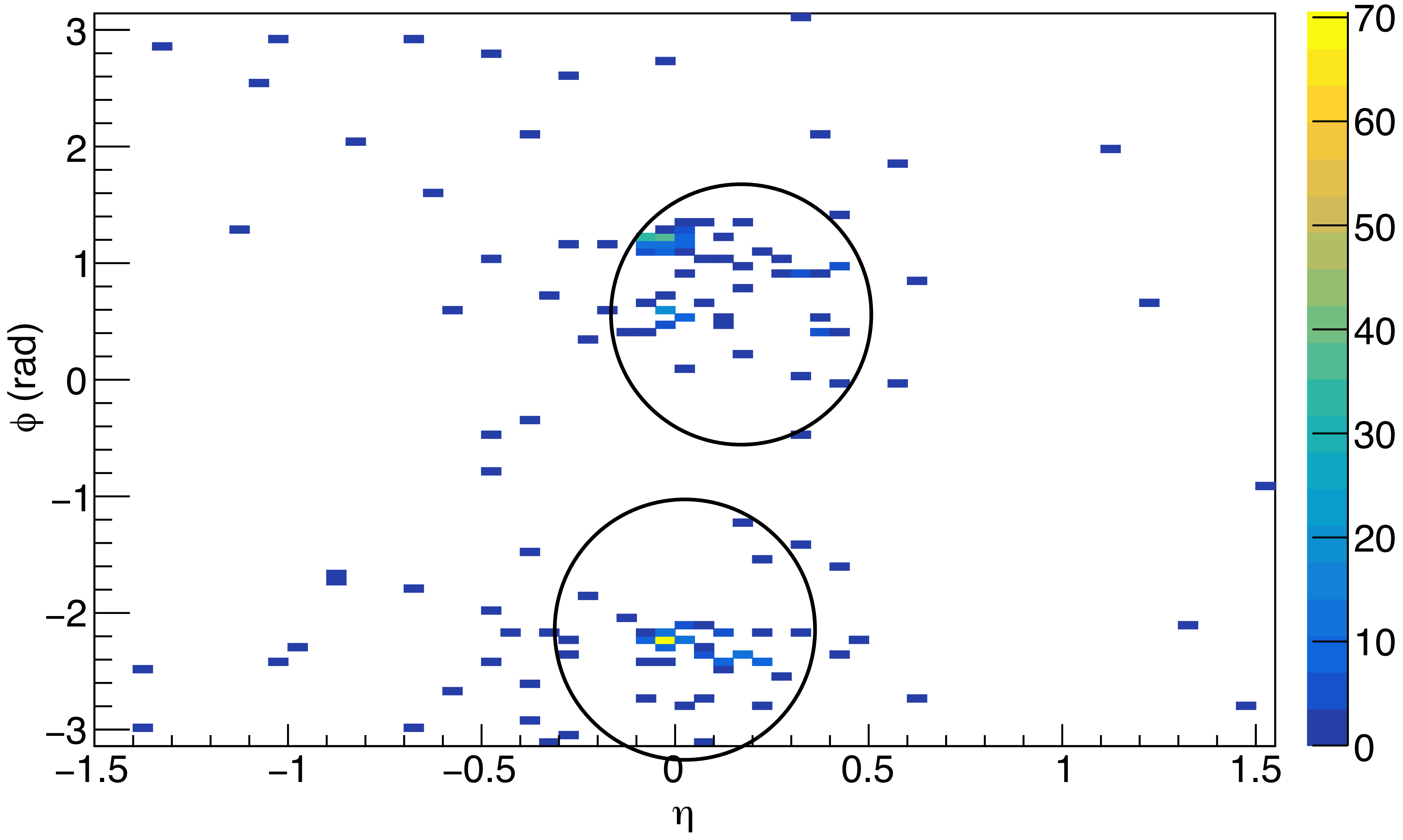

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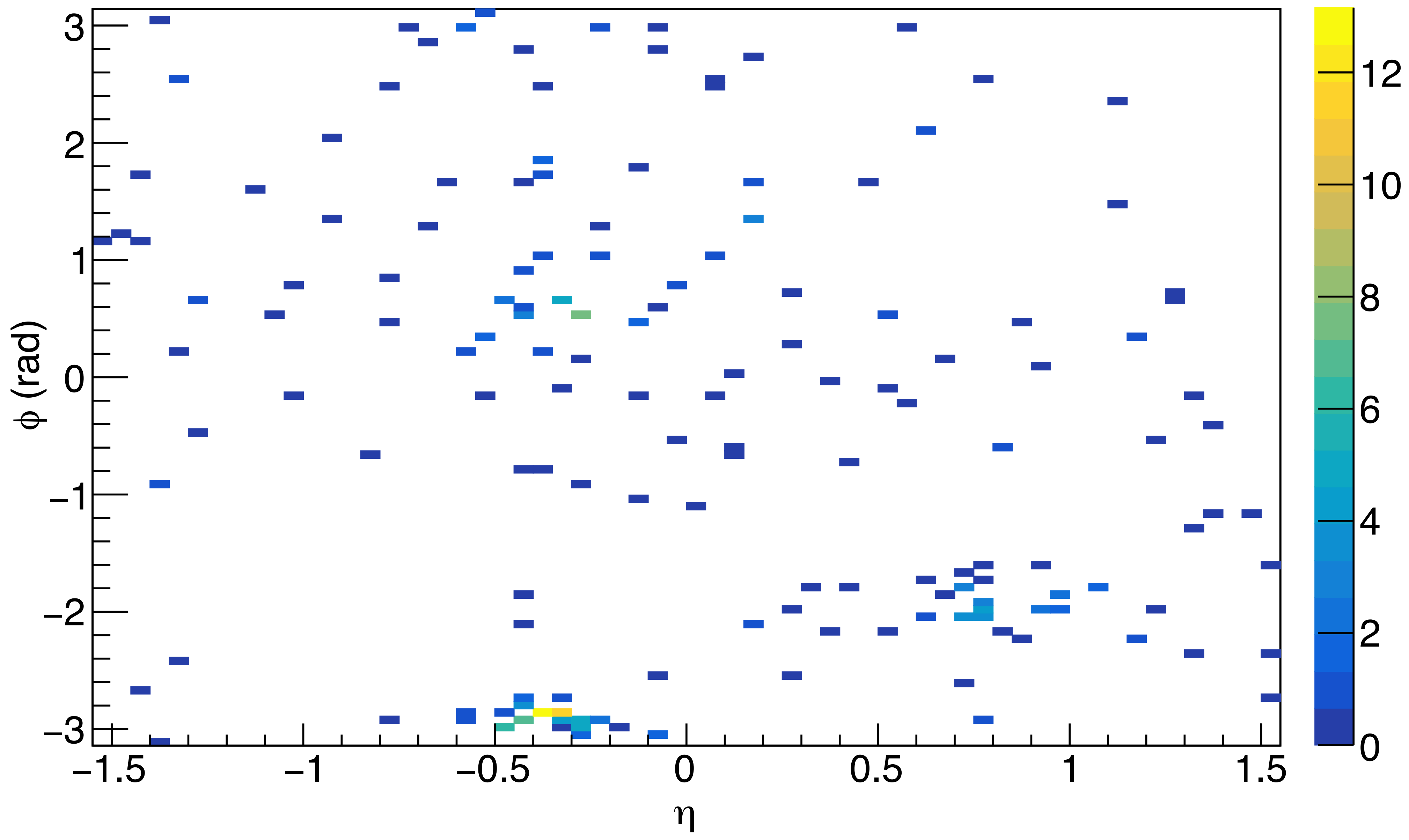


But the details are not that simple…

Seems like a 3-jet event

Are these particles still part of this jet?

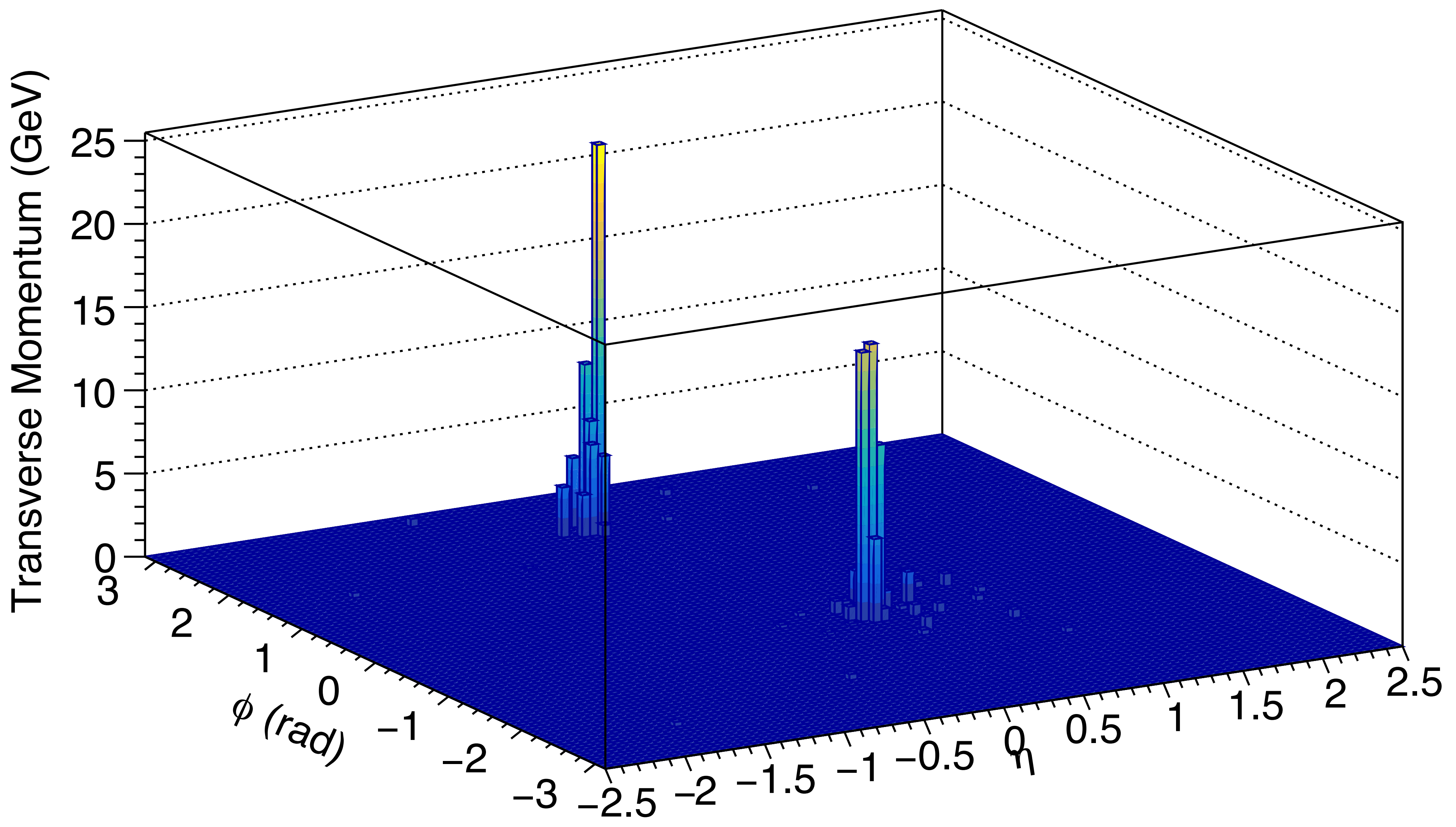
Identifying jets

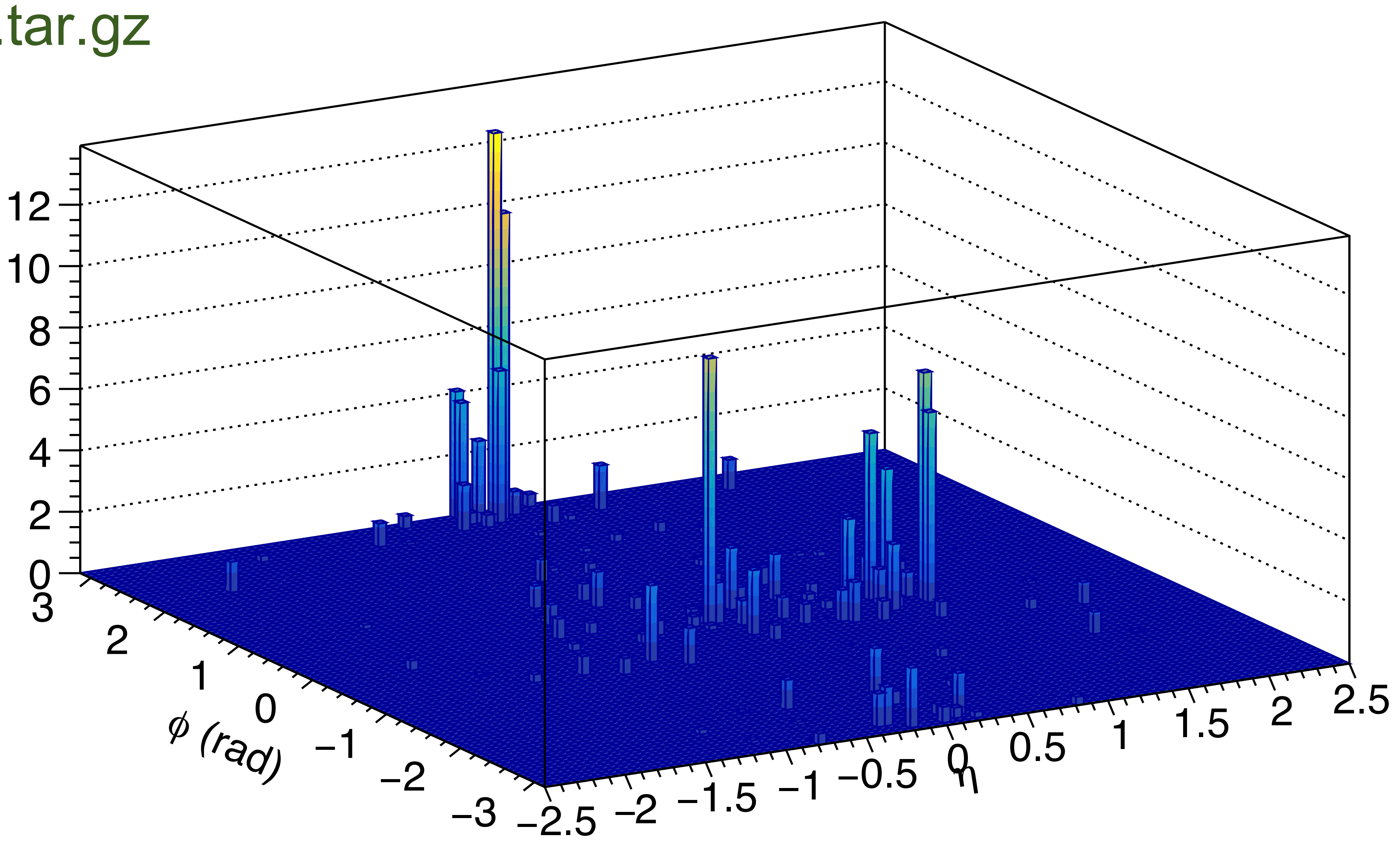
Exercise

- Try to devise a jet clustering algorithm to find the 2 jets with R = 0.4 with the largest transverse momentum in the following simulation sets:

Extract: tar -xzvf HandsOn_QCDJets_Code.tar.gz

- Open Part2 of the HandsOn_QCDJets_Code
- Some examples:





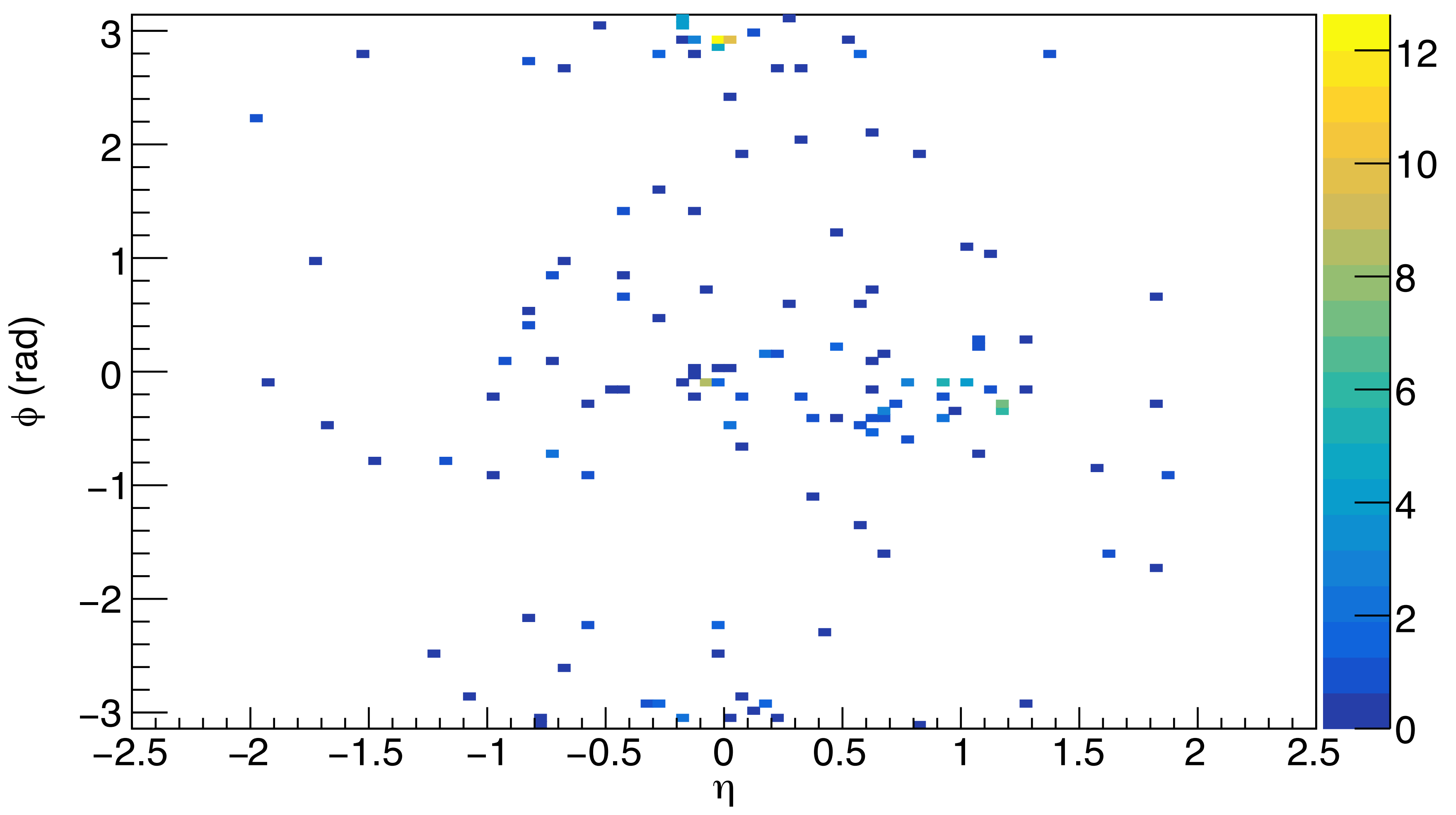
Identifying jets

Solution

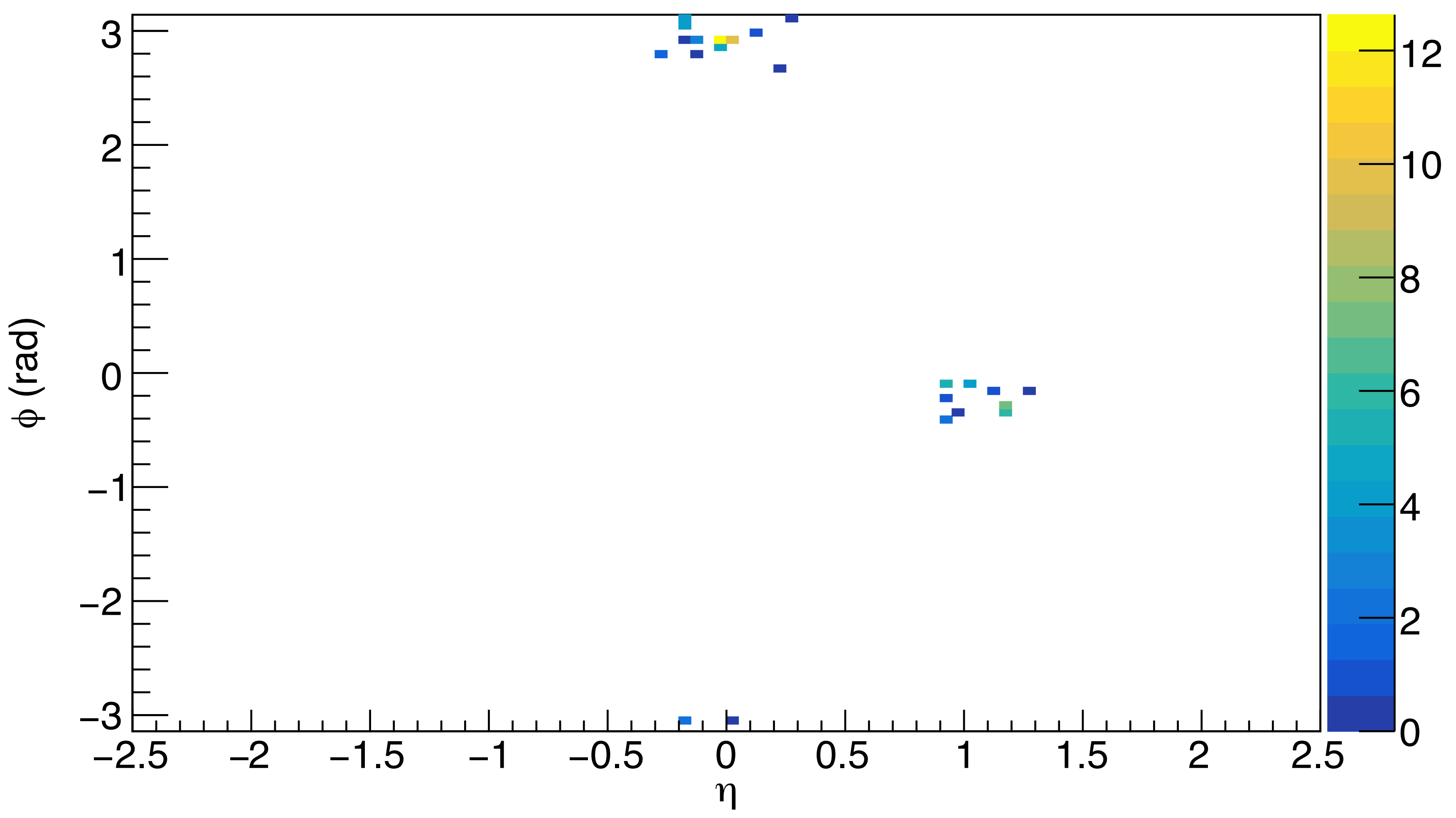
- Try to devise a jet clustering algorithm to find the 2 jets with R = 0.4 with the largest transverse momentum in the following simulation sets:

  - A possible solution: First event

Event



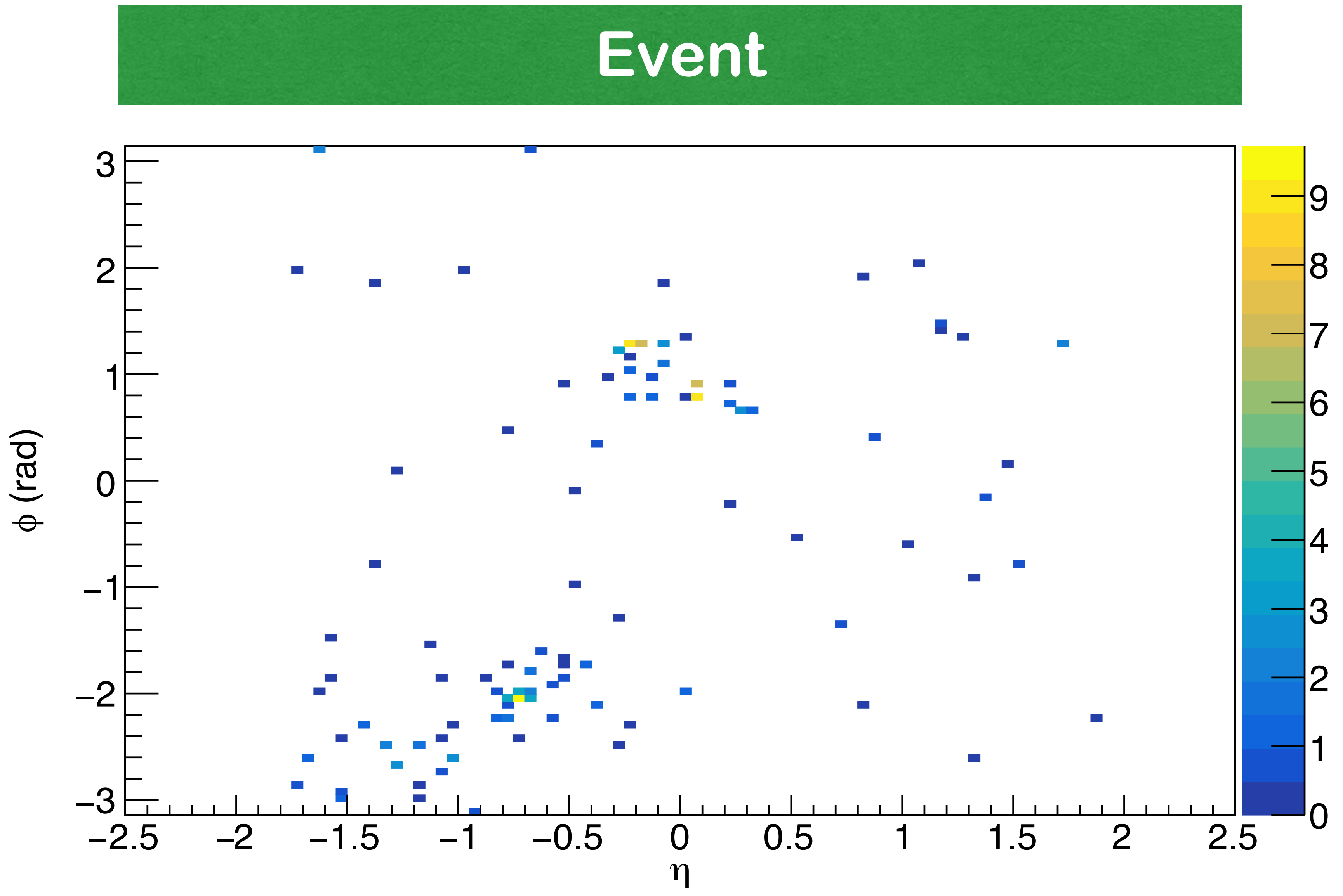
2 Jets

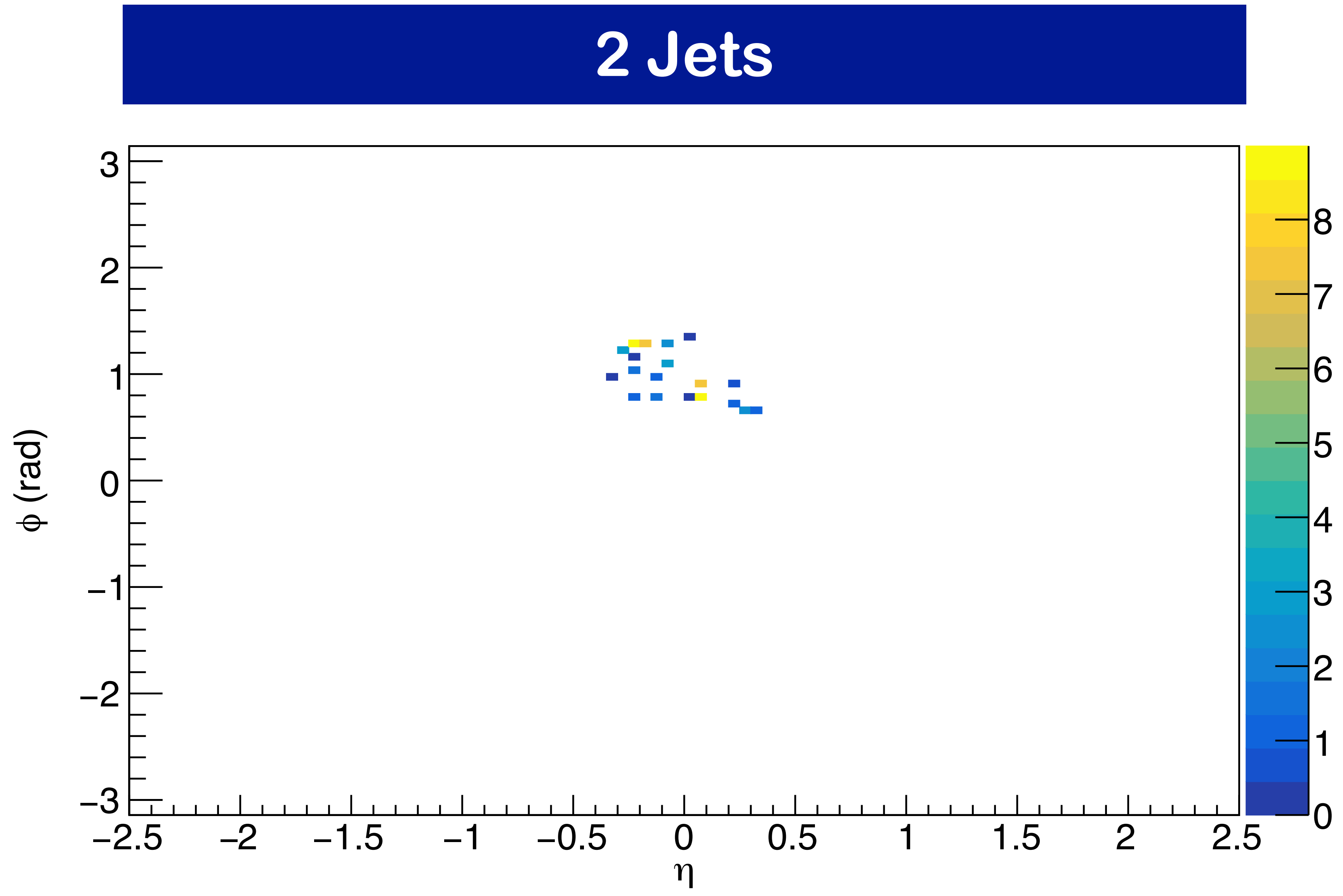


Identifying jets

Solution

- Try to devise a jet clustering algorithm to find the 2 jets with R = 0.4 with the largest transverse momentum in the following simulation sets:
  - A possible solution: Second event





Jet Clustering Algorithms

- First jet clustering algorithms were also based on a seed particle
  - Abandoned as likely to be biased…
- Nowadays only used sequential recombination algorithms:

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

$$d_{iB} = p_{ti}^{2p},$$

$$\Delta R_{ij}^2 = (y_i - y_j)^2 + (\phi_i - \phi_j)^2,$$

Family of jet clustering algorithms:

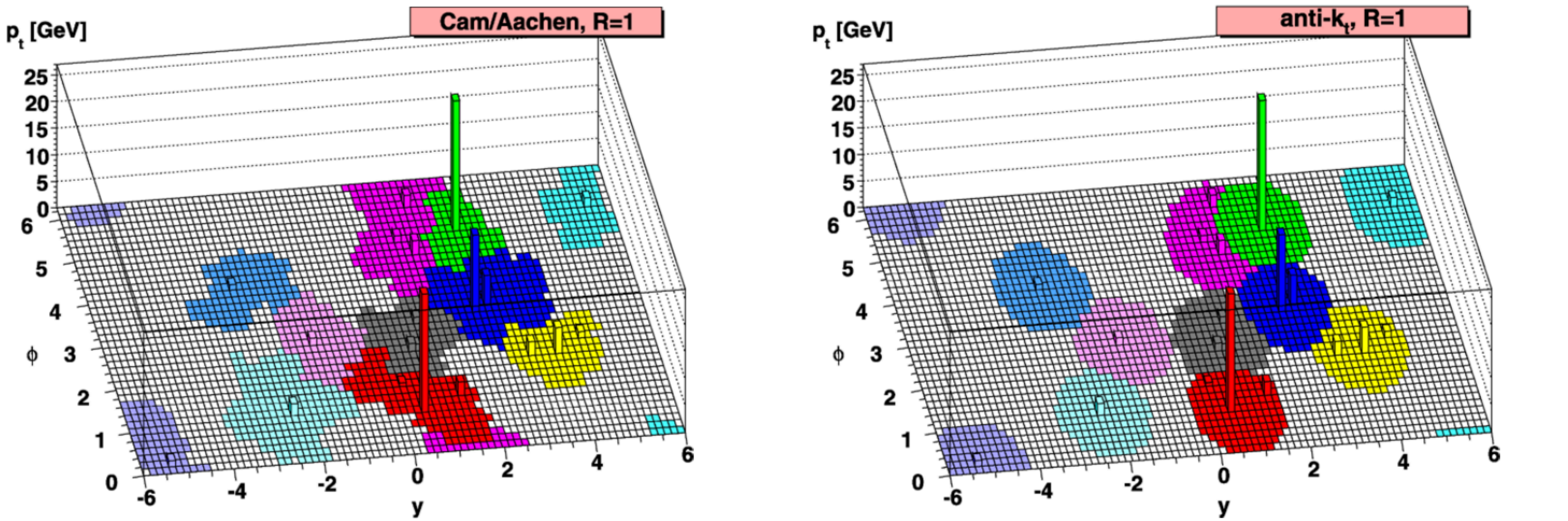
p = 1: kt

p = 0: Cambridge/Aachen

p = -1: anti-kt

Jet Clustering Algorithms

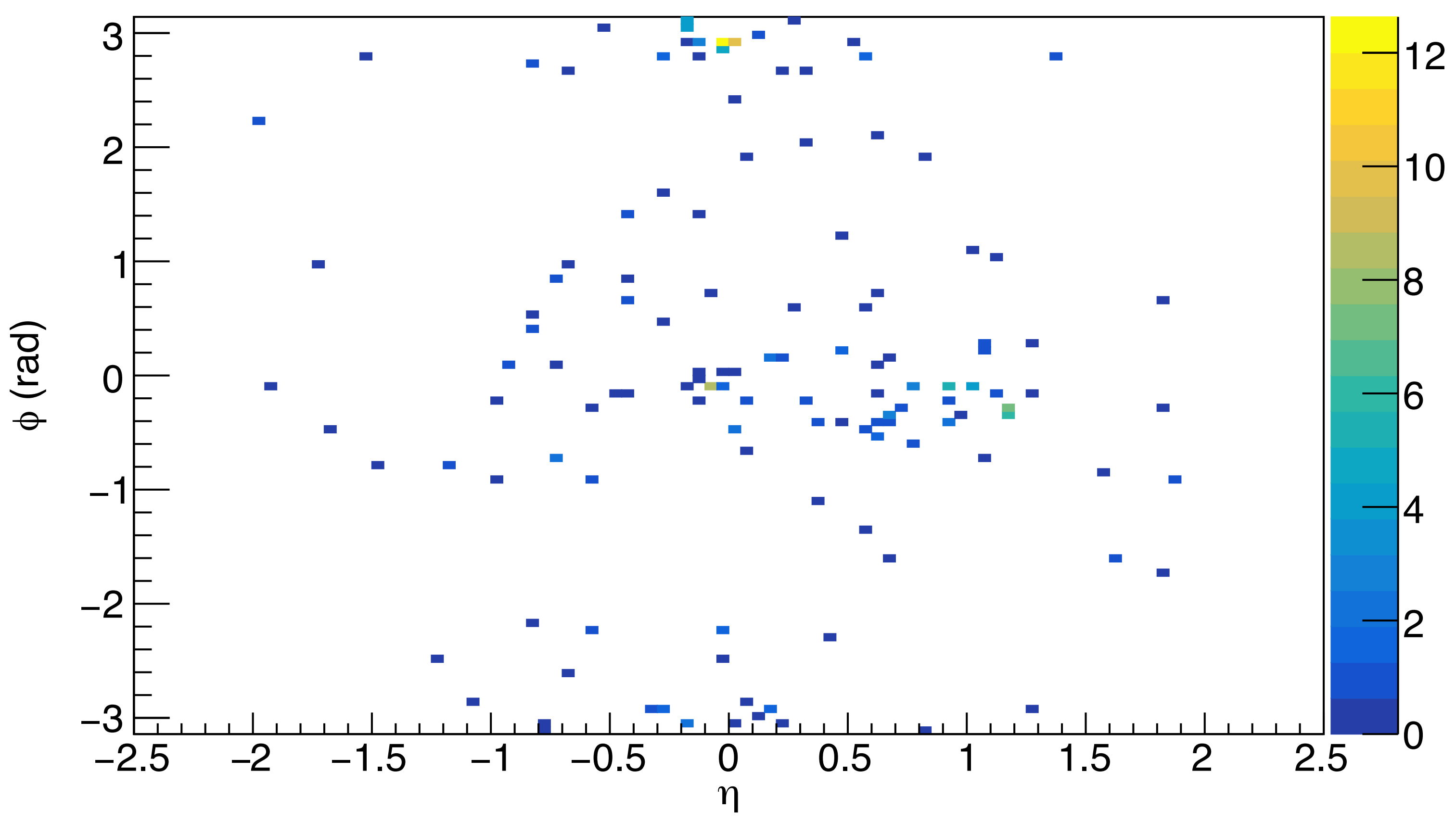
- Sequential Recombination algorithms:
    - For the same event, they will give different jets:



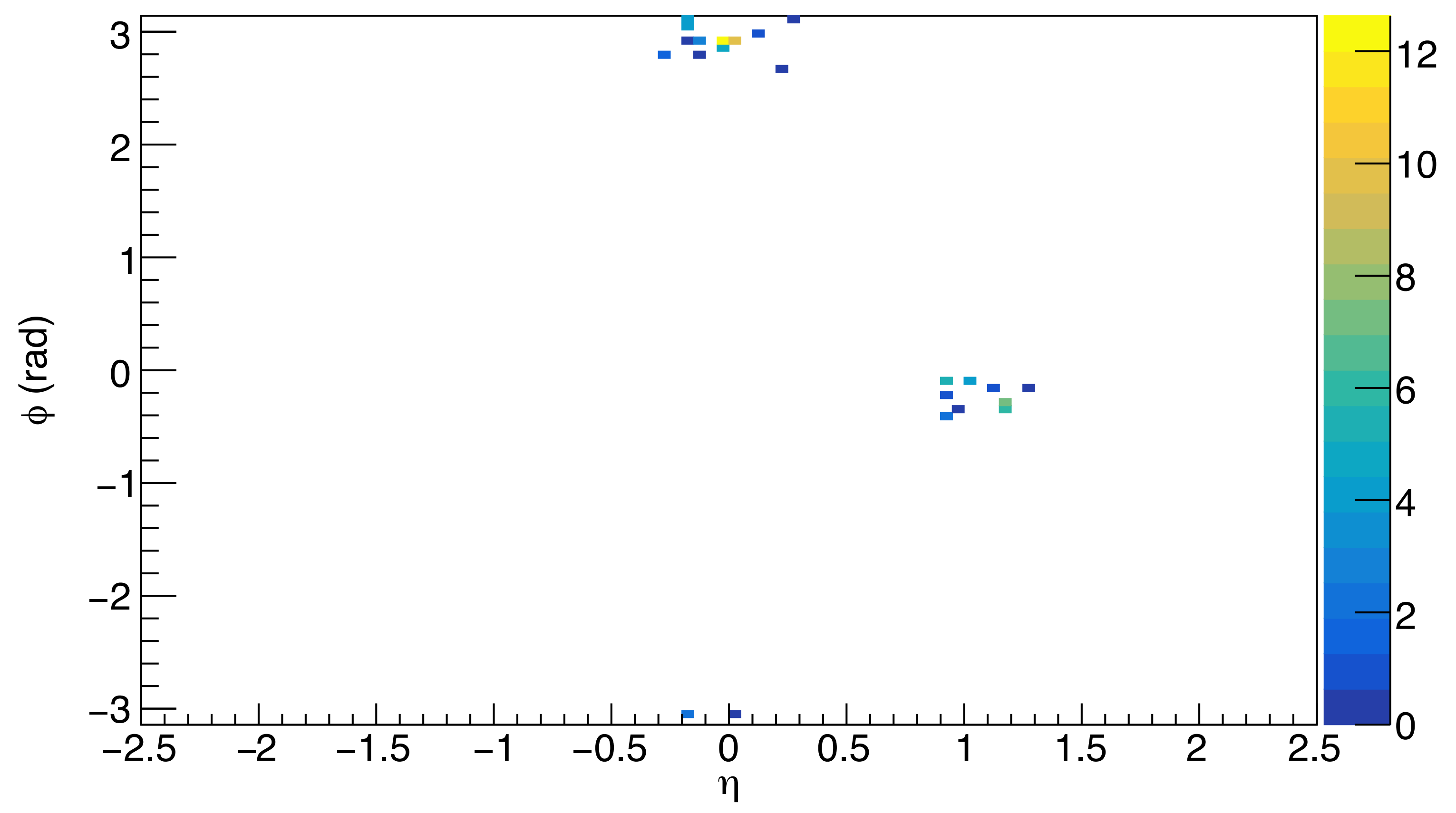
Jet Clustering Algorithms

- Let's compare its result agains ours:
  - From the previous solution: First event

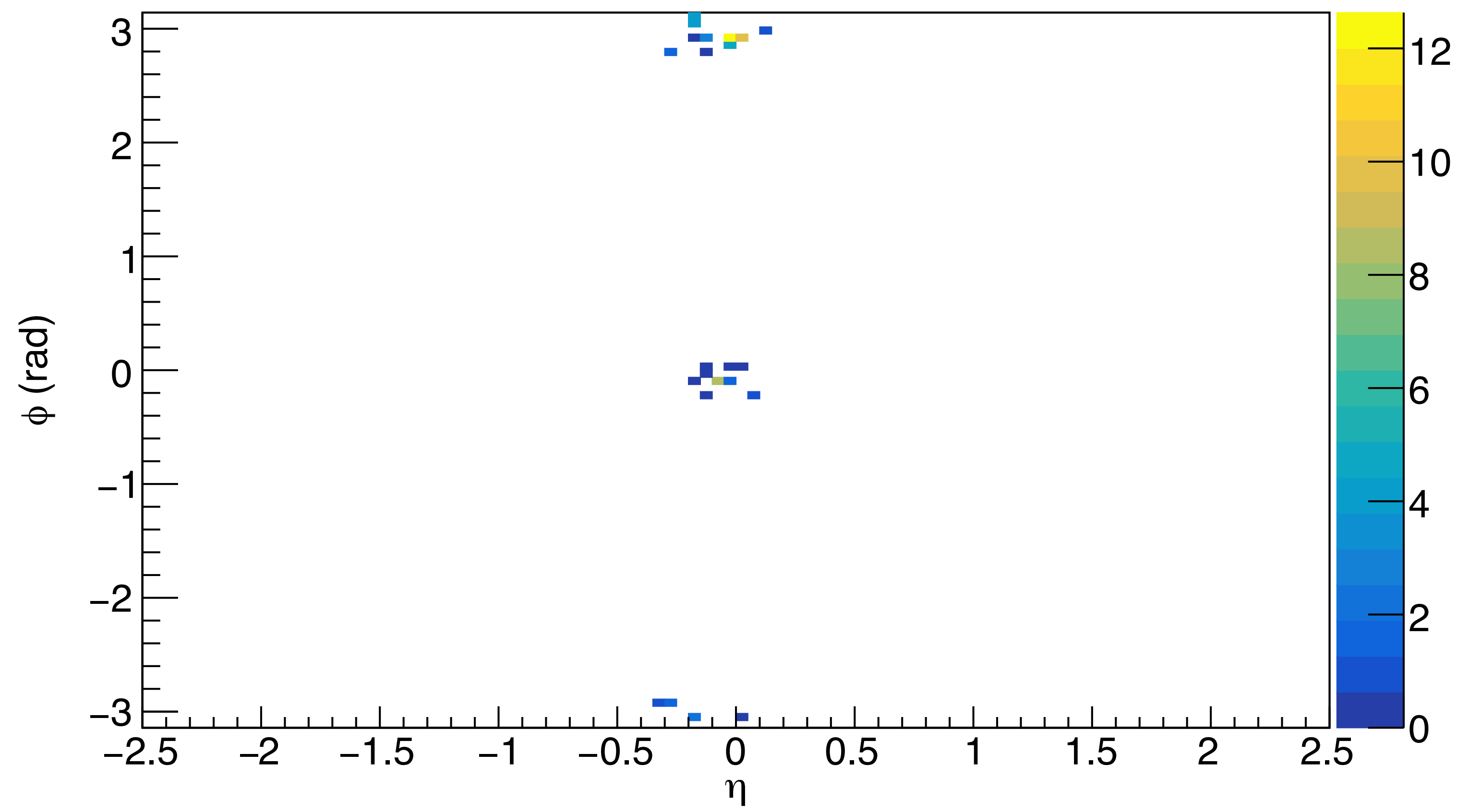
Event



My Algorithm



kt Algorithm



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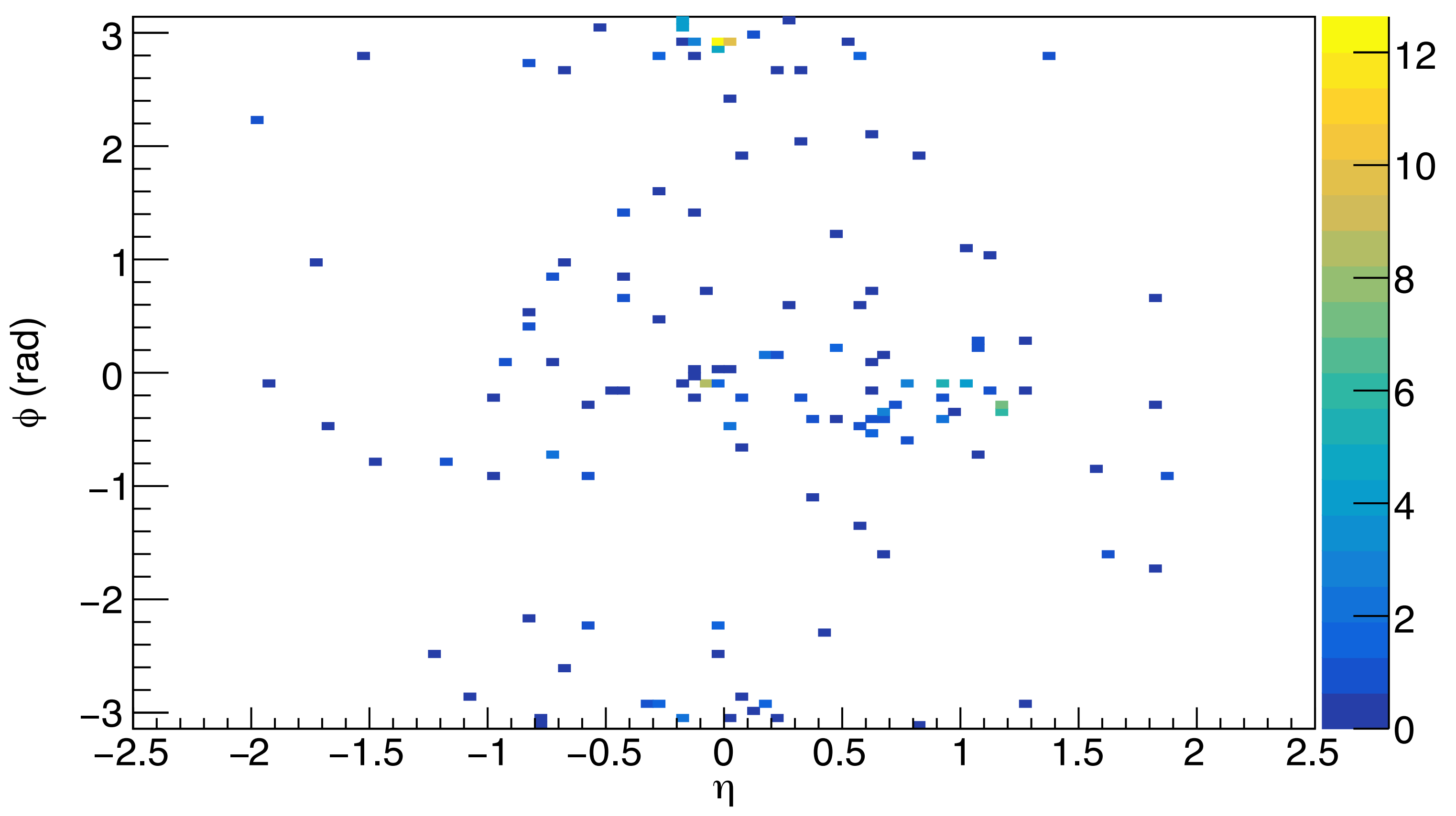

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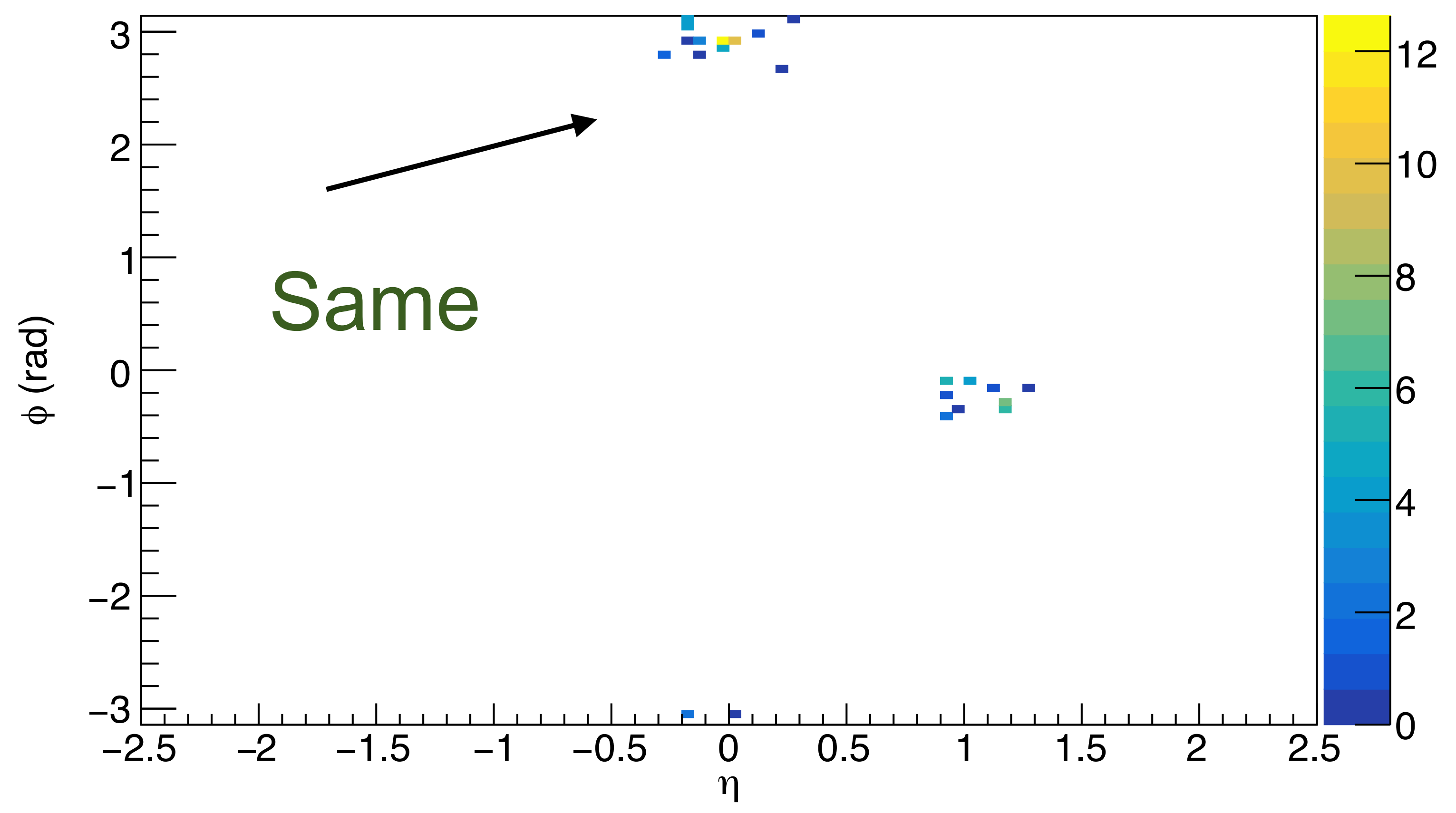

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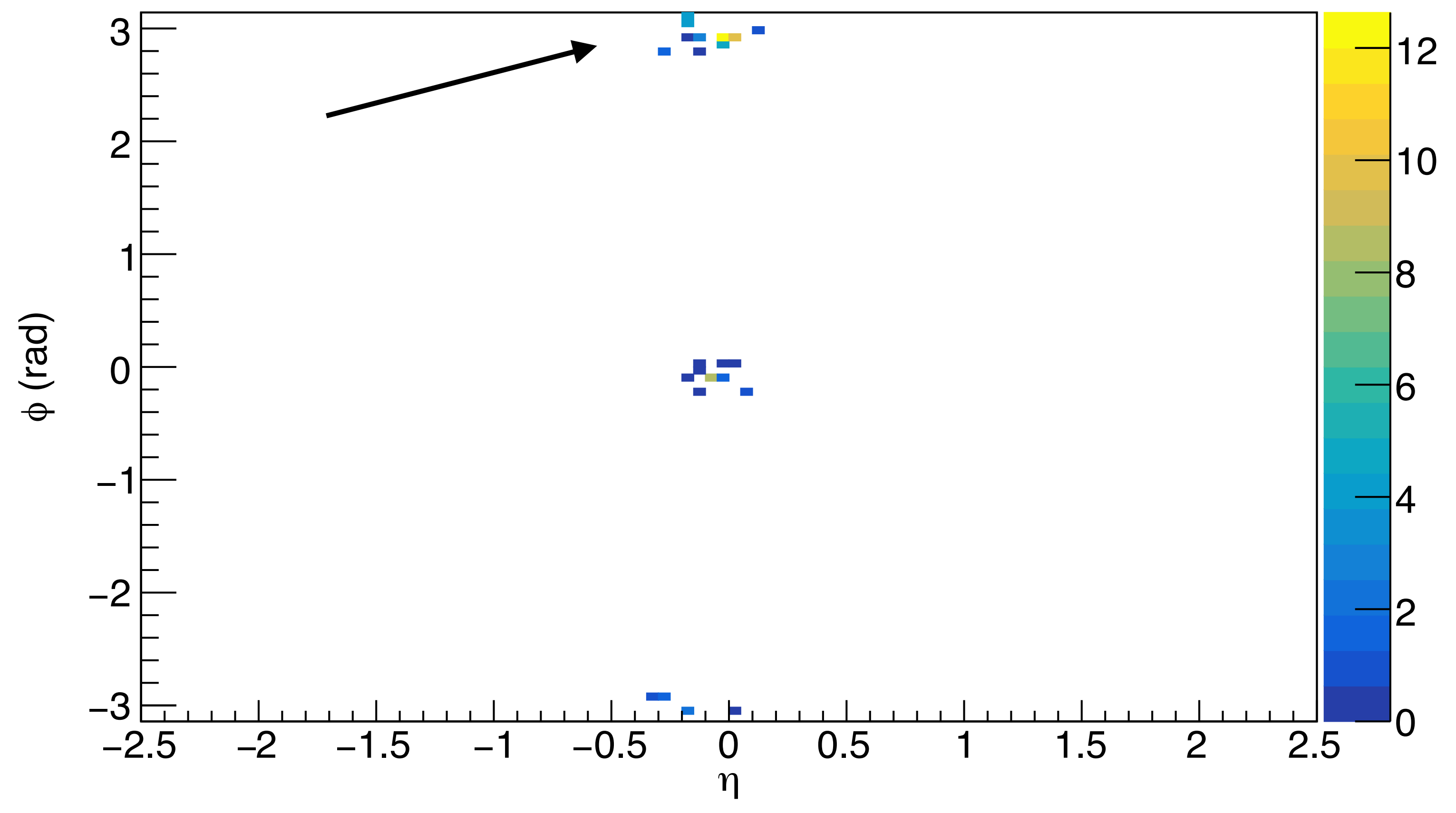

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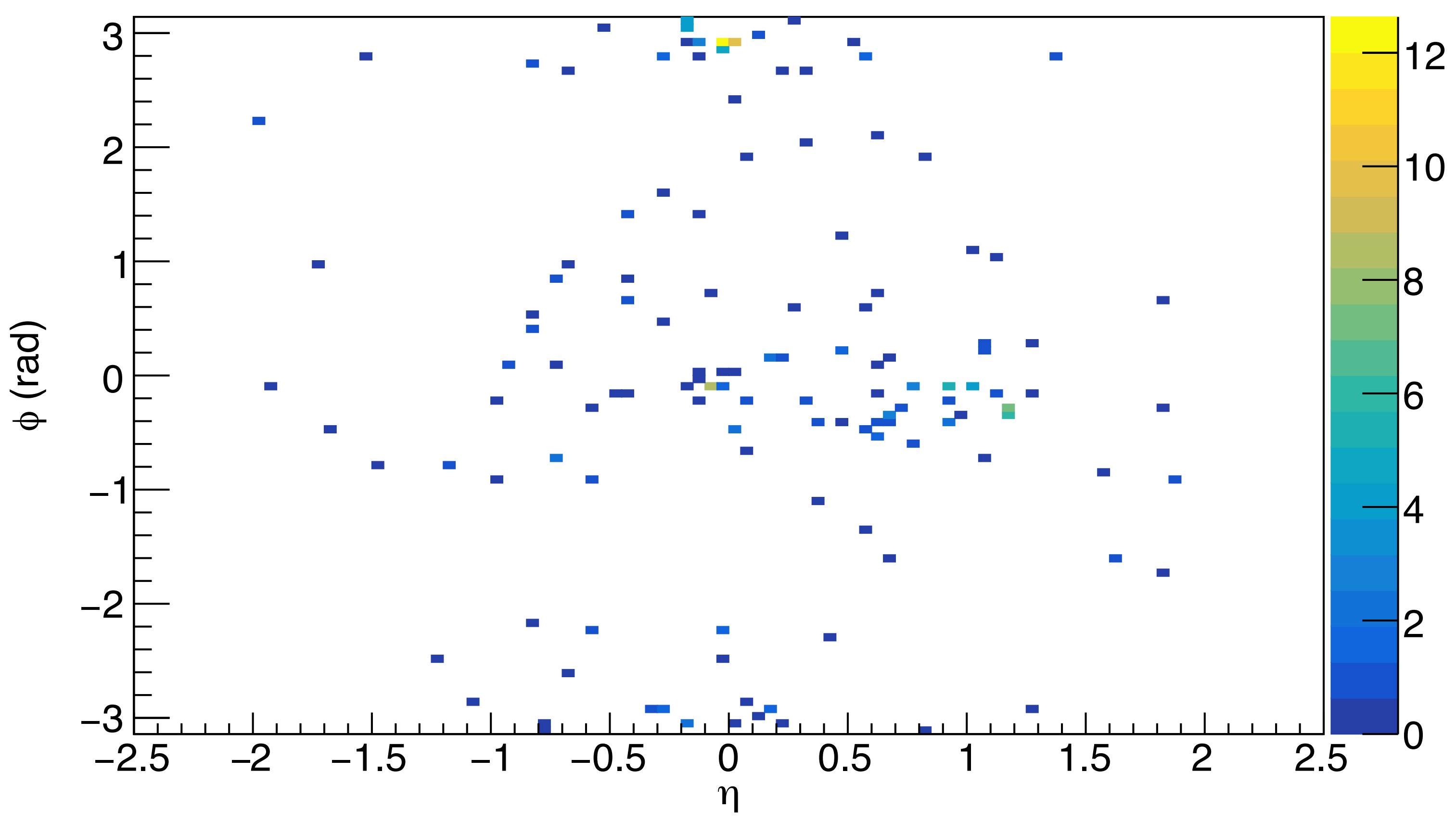

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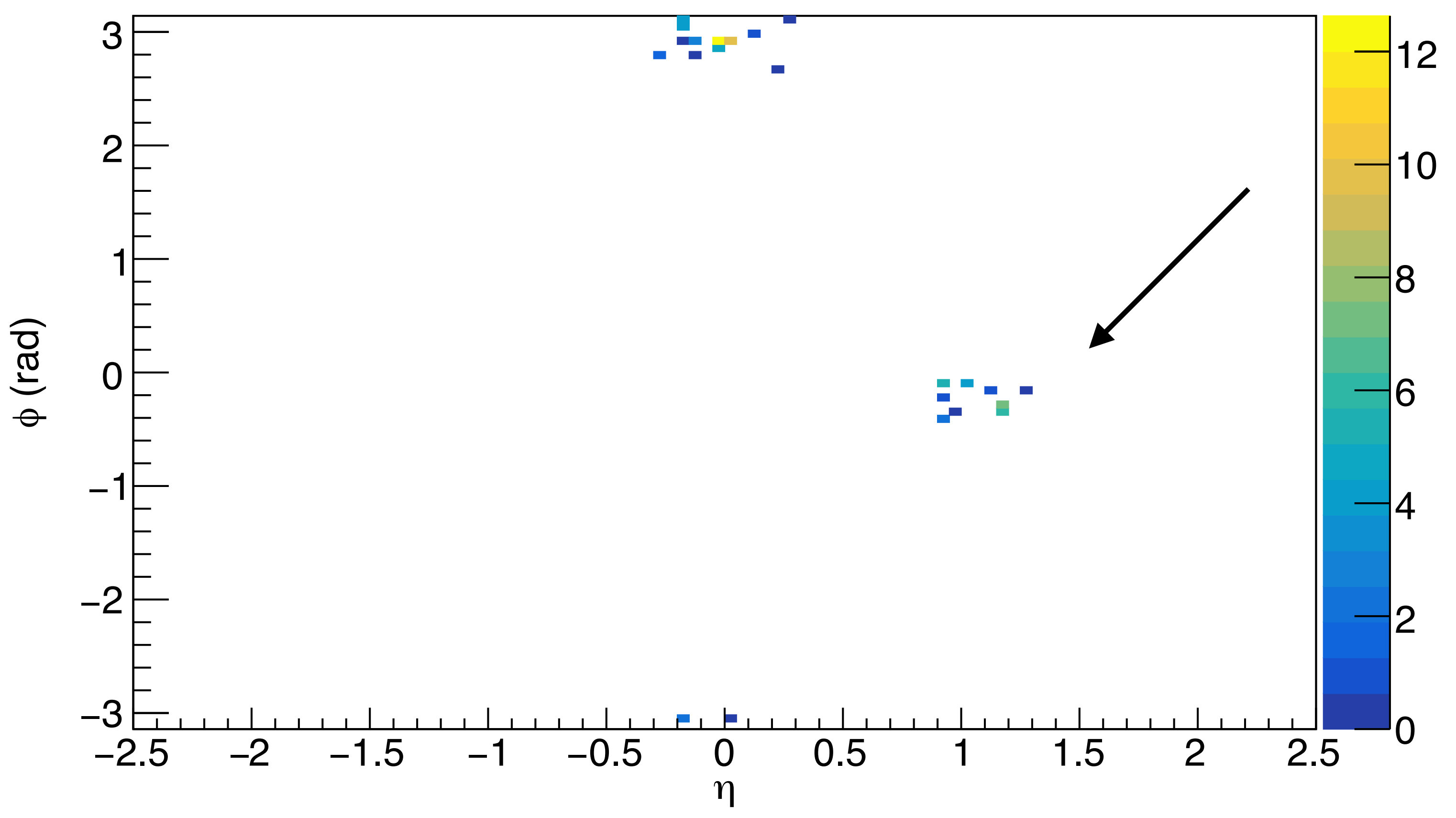

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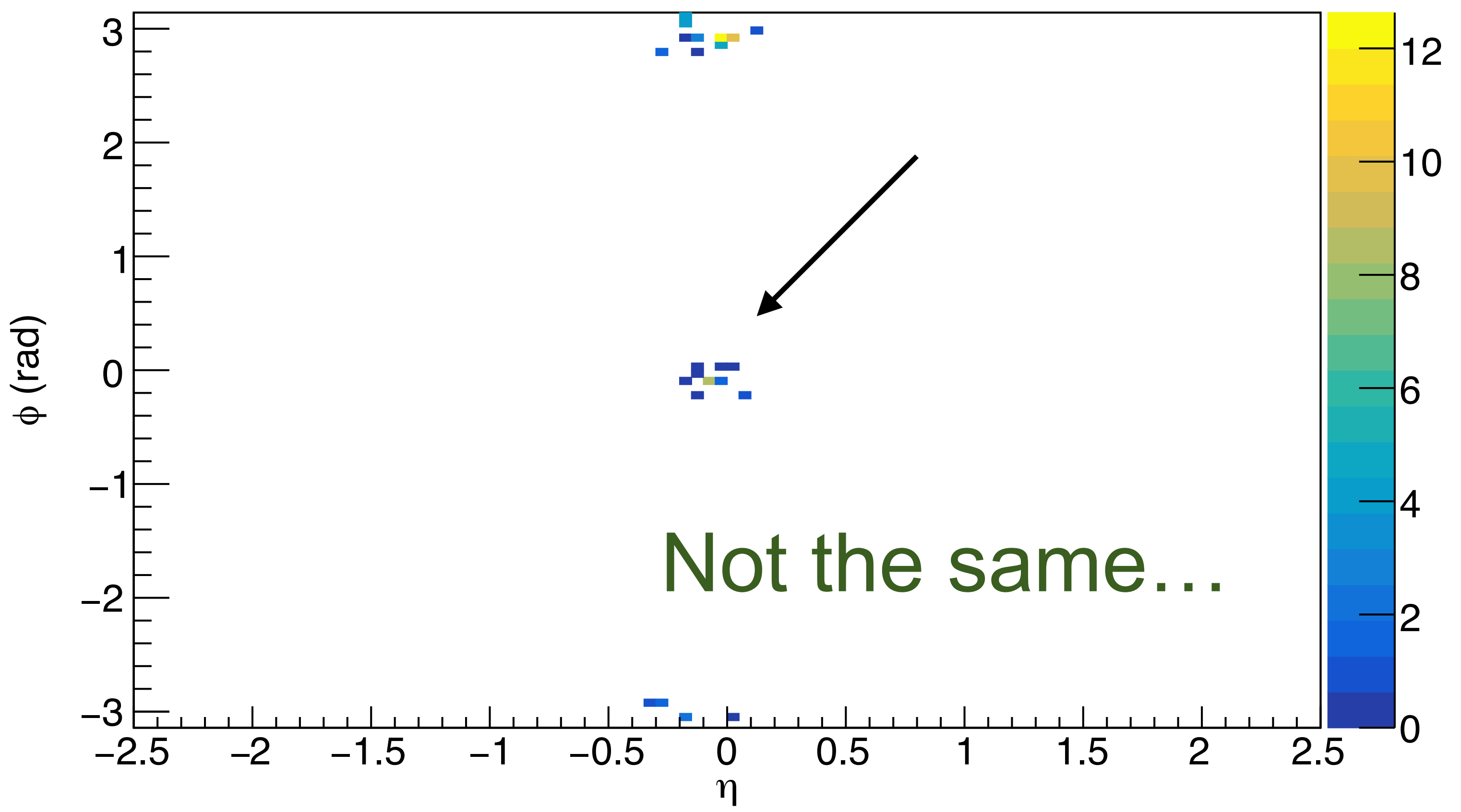

Jet Clustering Algorithms

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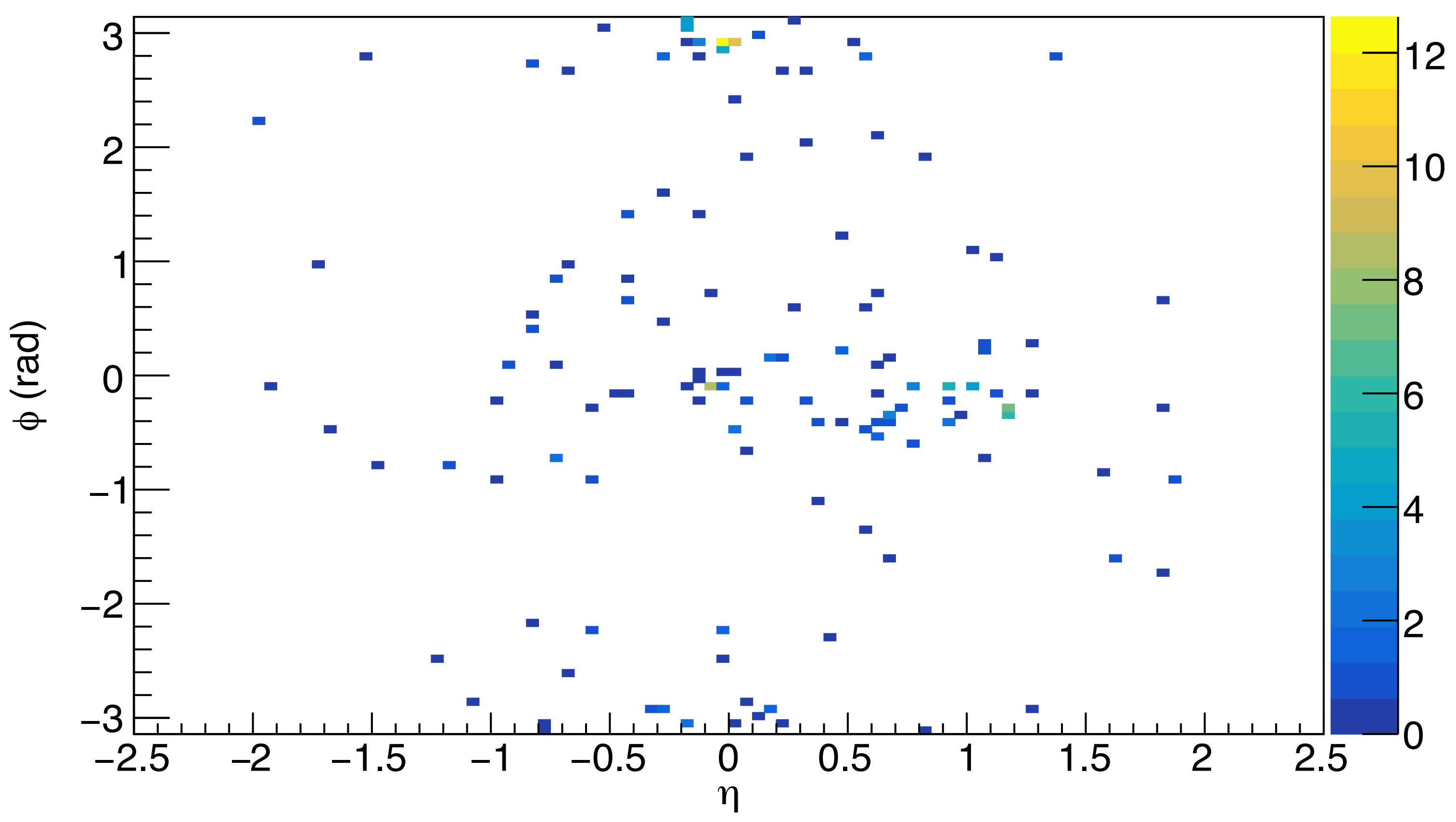
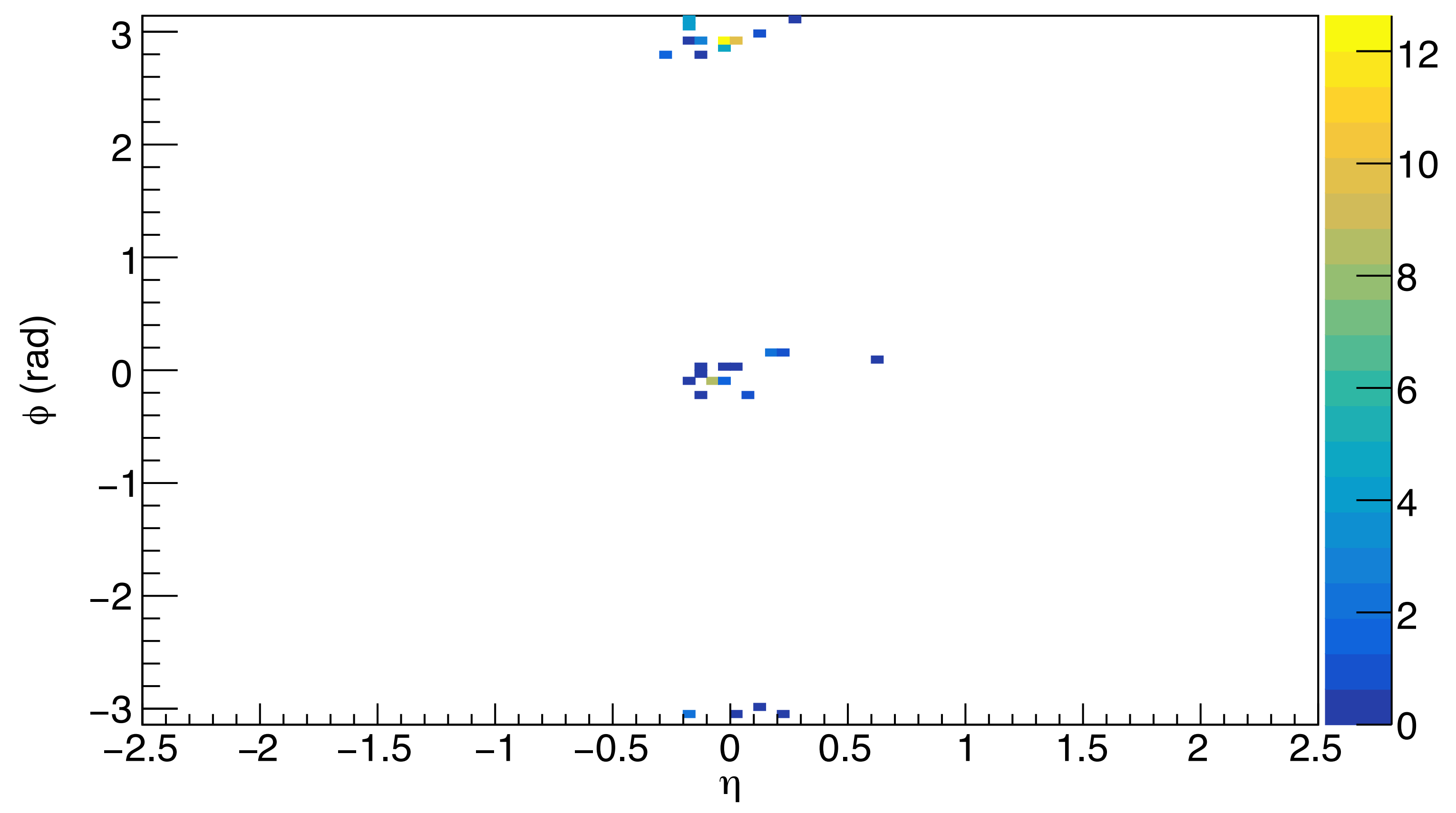
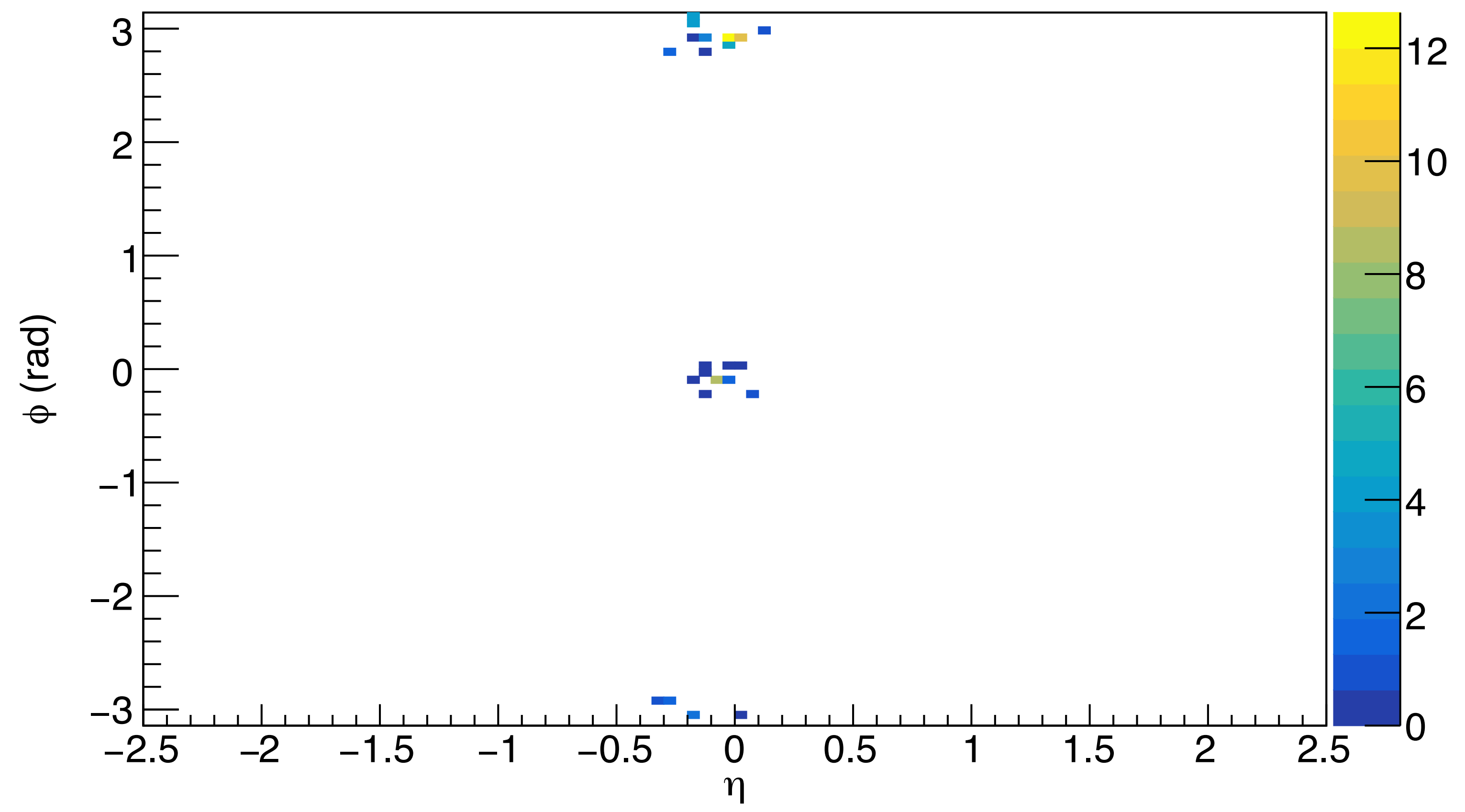


Anti-kt Algorithm



kt Algorithm



Jet Clustering Algorithms

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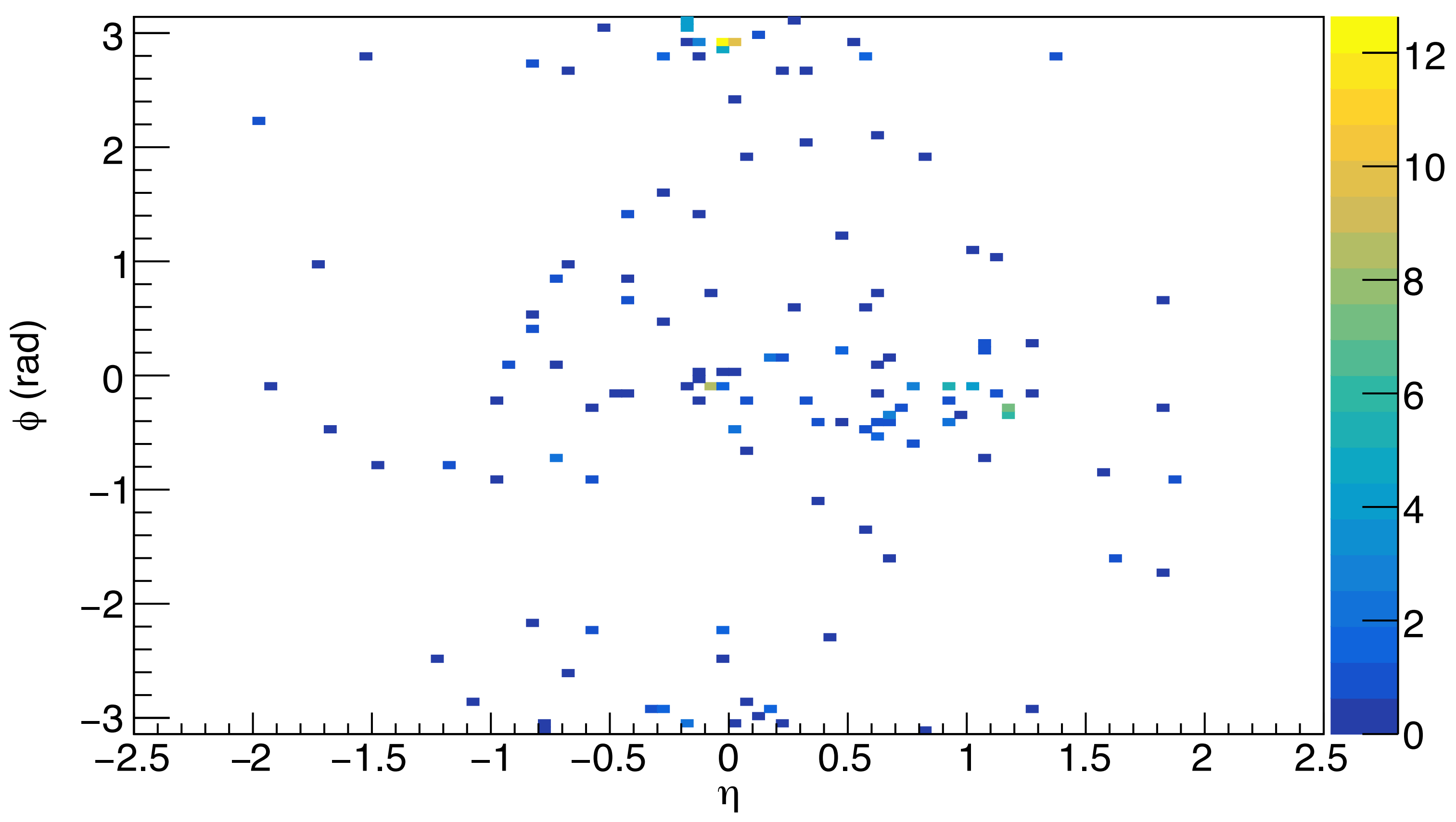
Event



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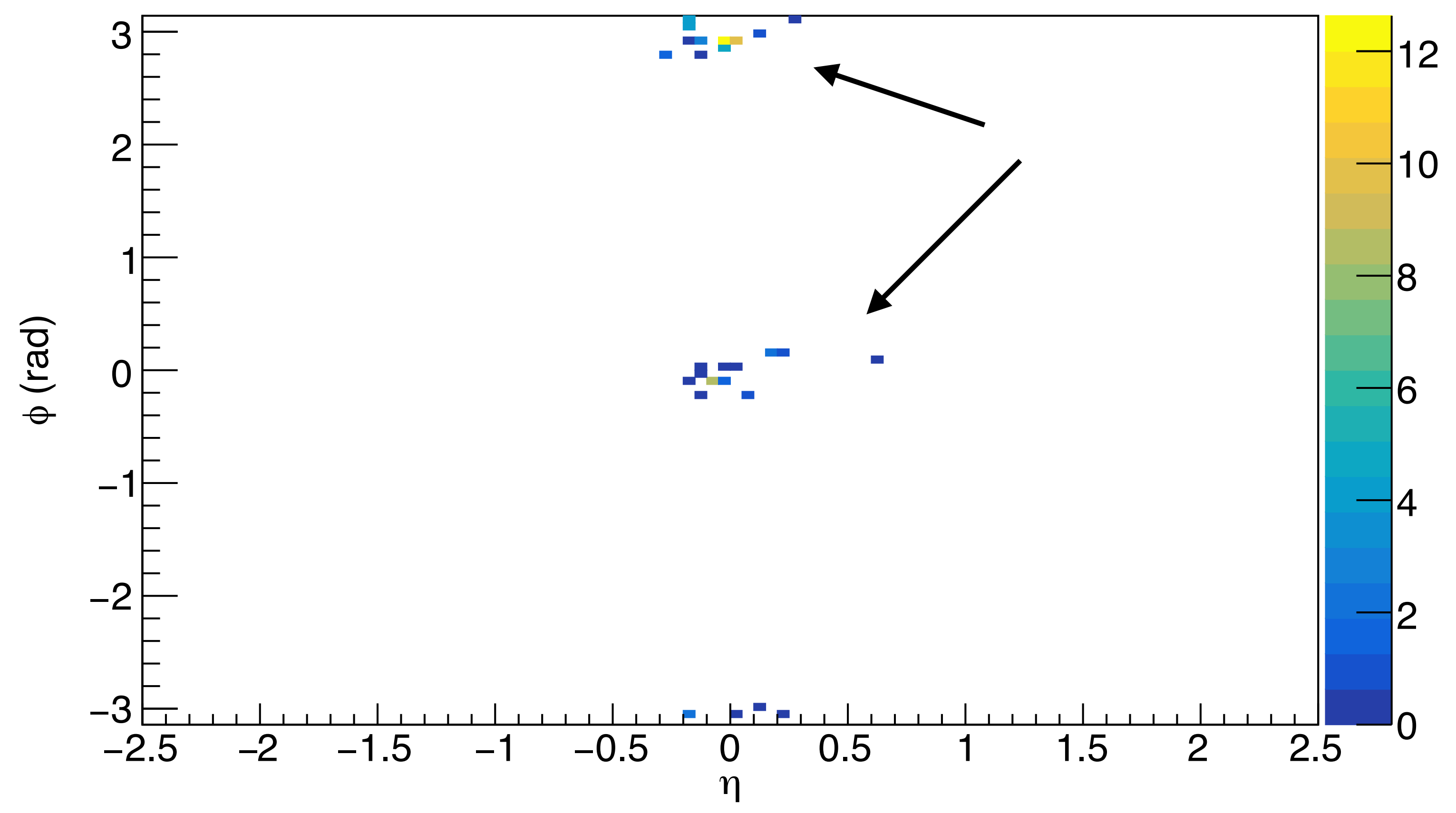

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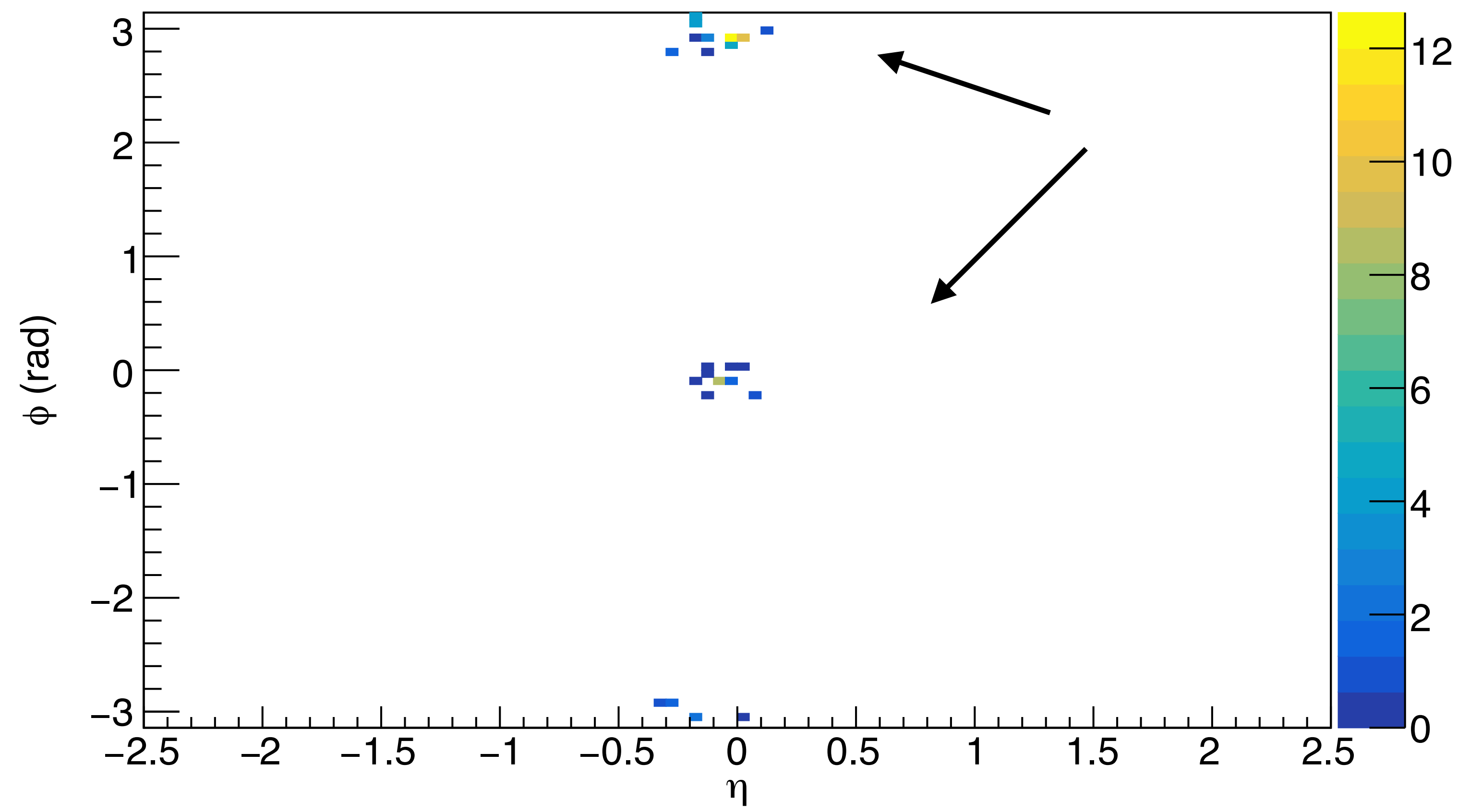

Small diferences among the three…

Jet Clustering Algorithms

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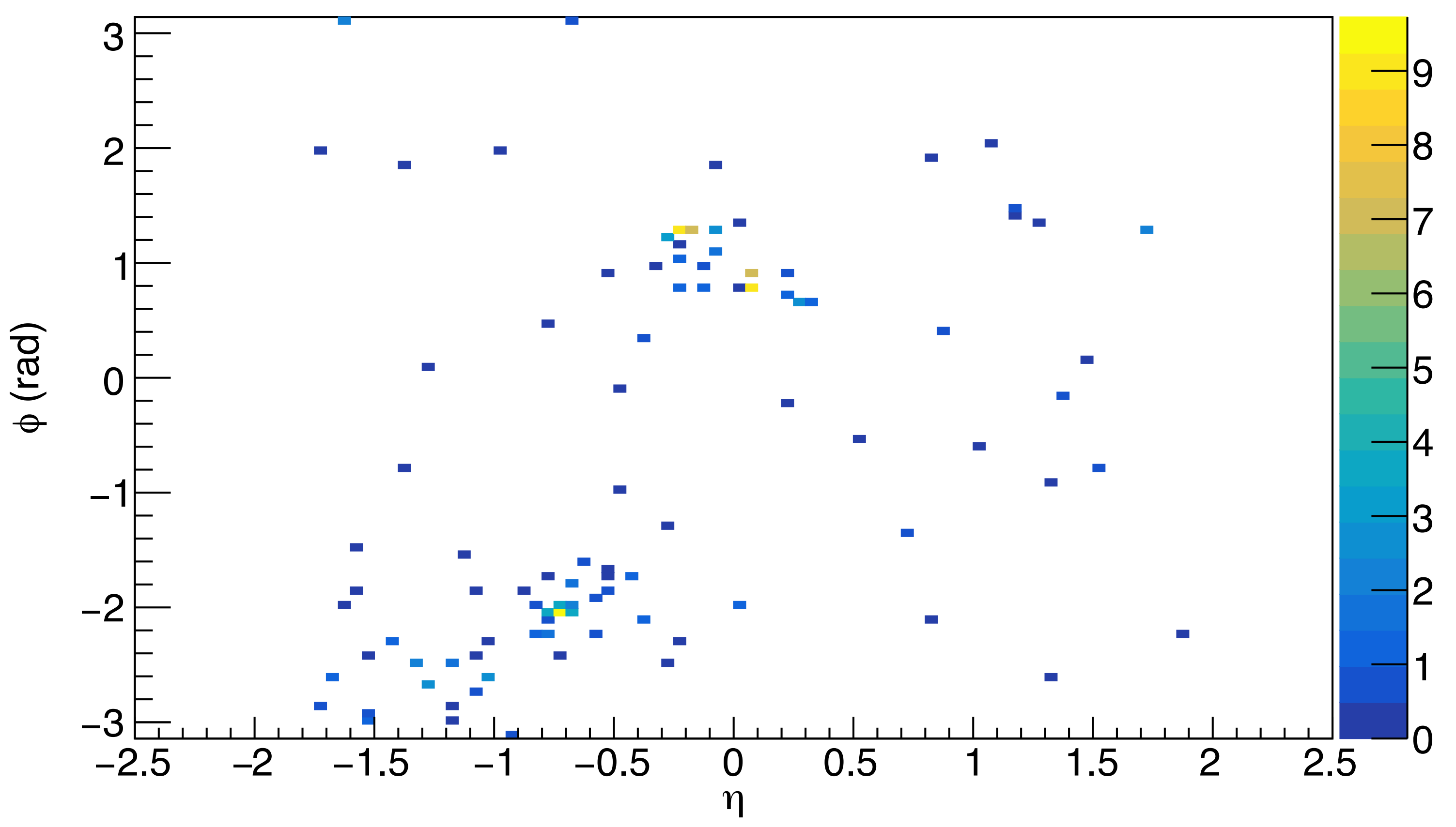
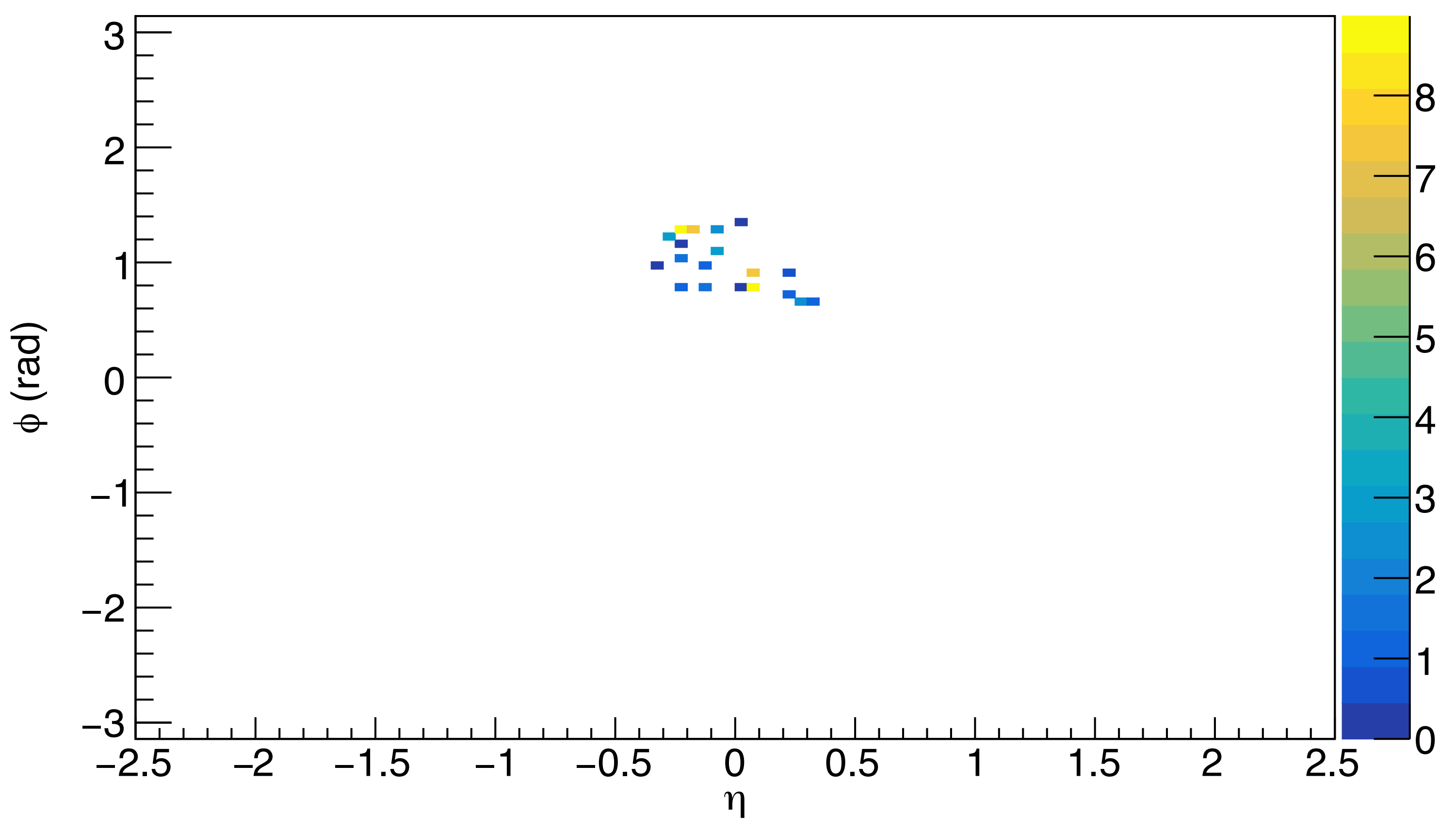
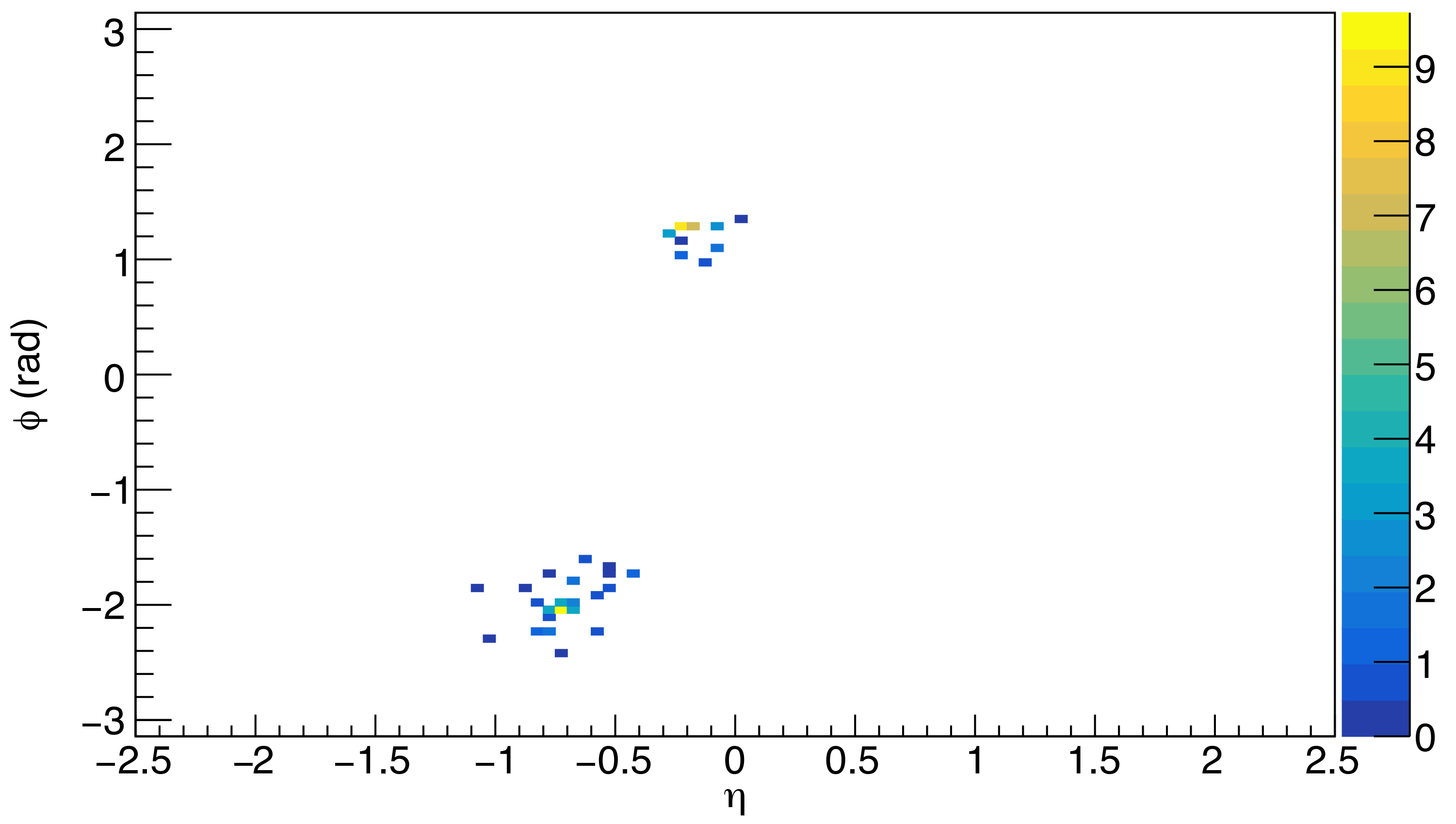
Event



My Algorithm



C/A Algorithm



Jet Clustering Algorithms

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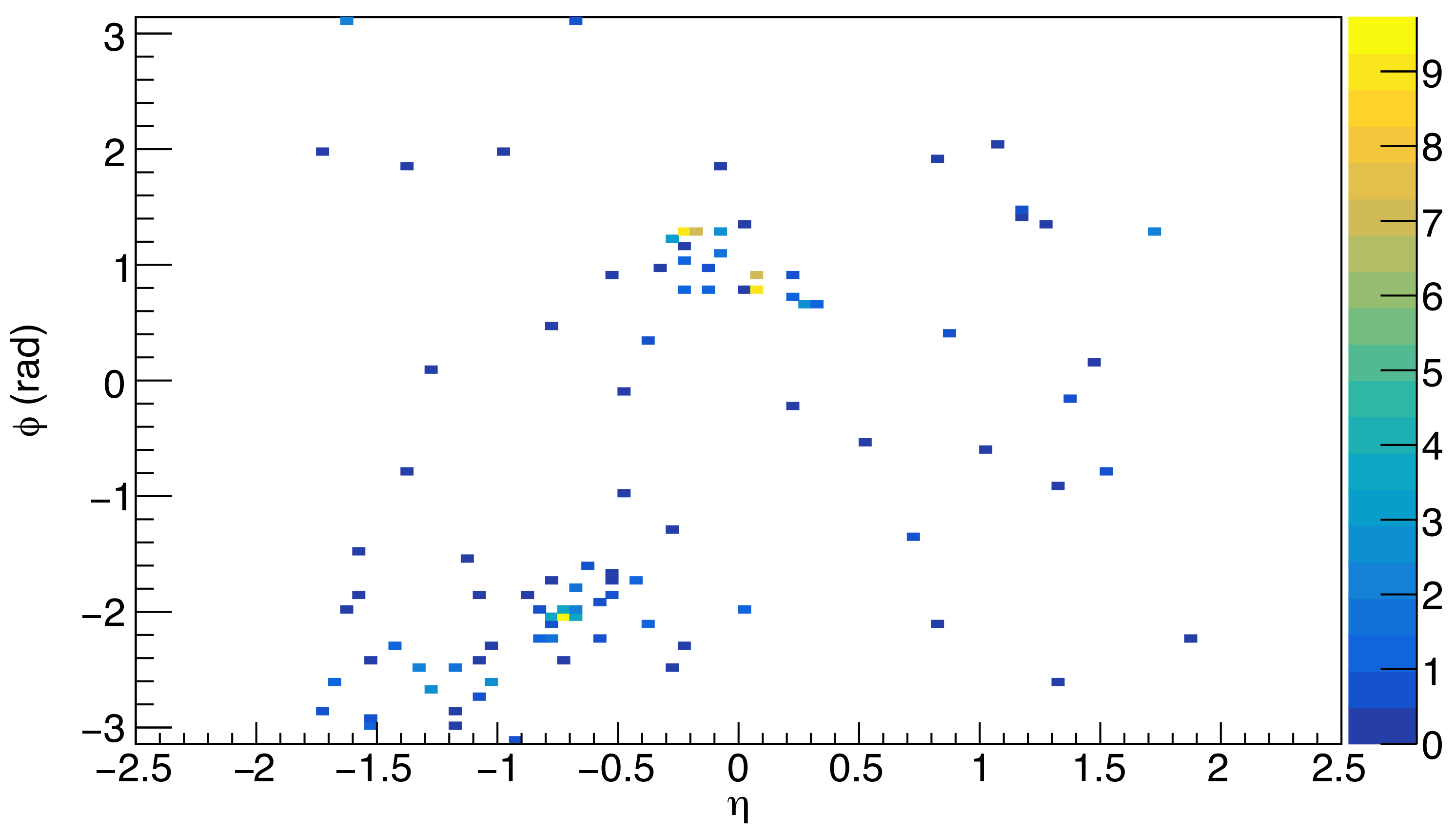

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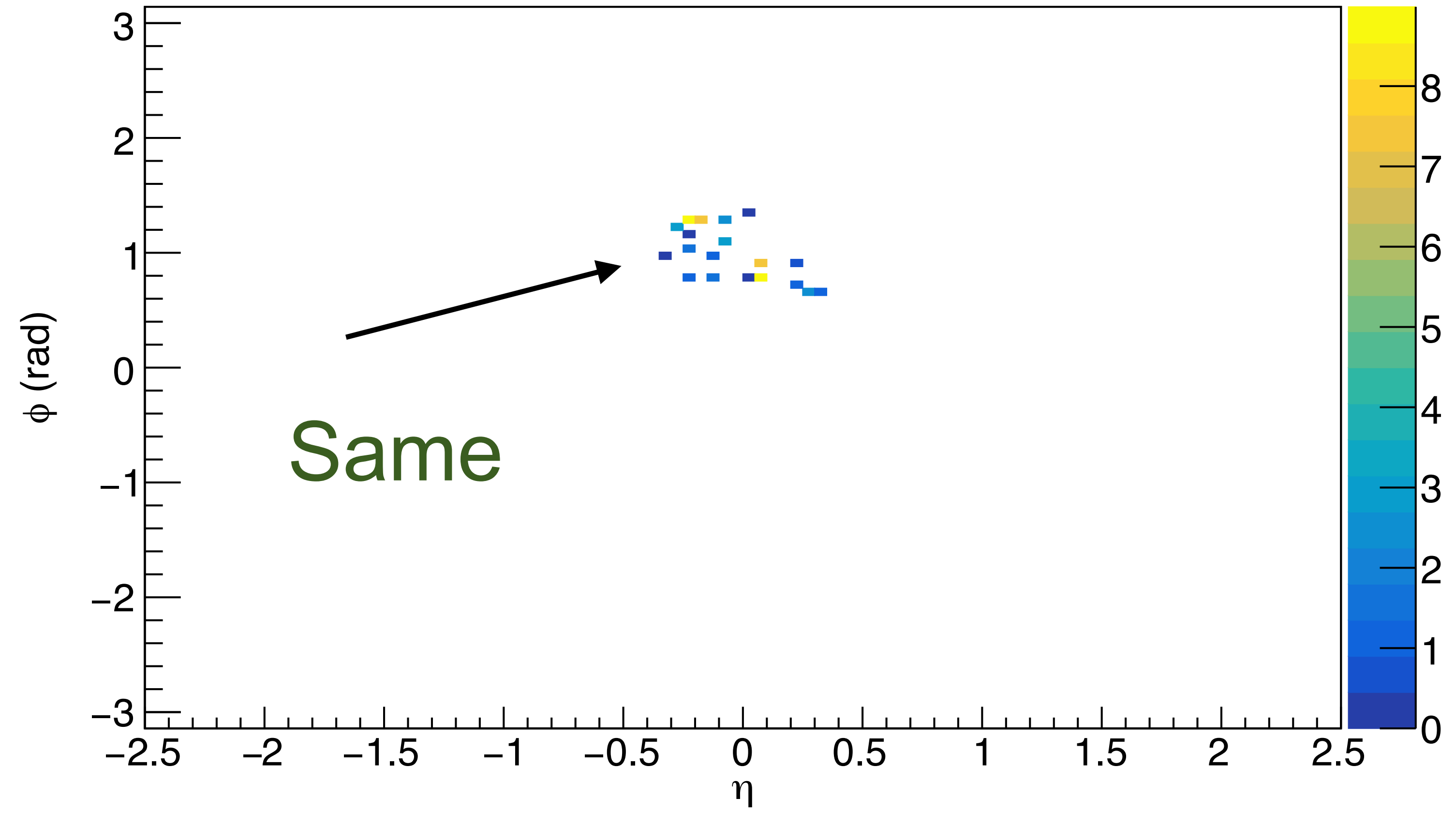

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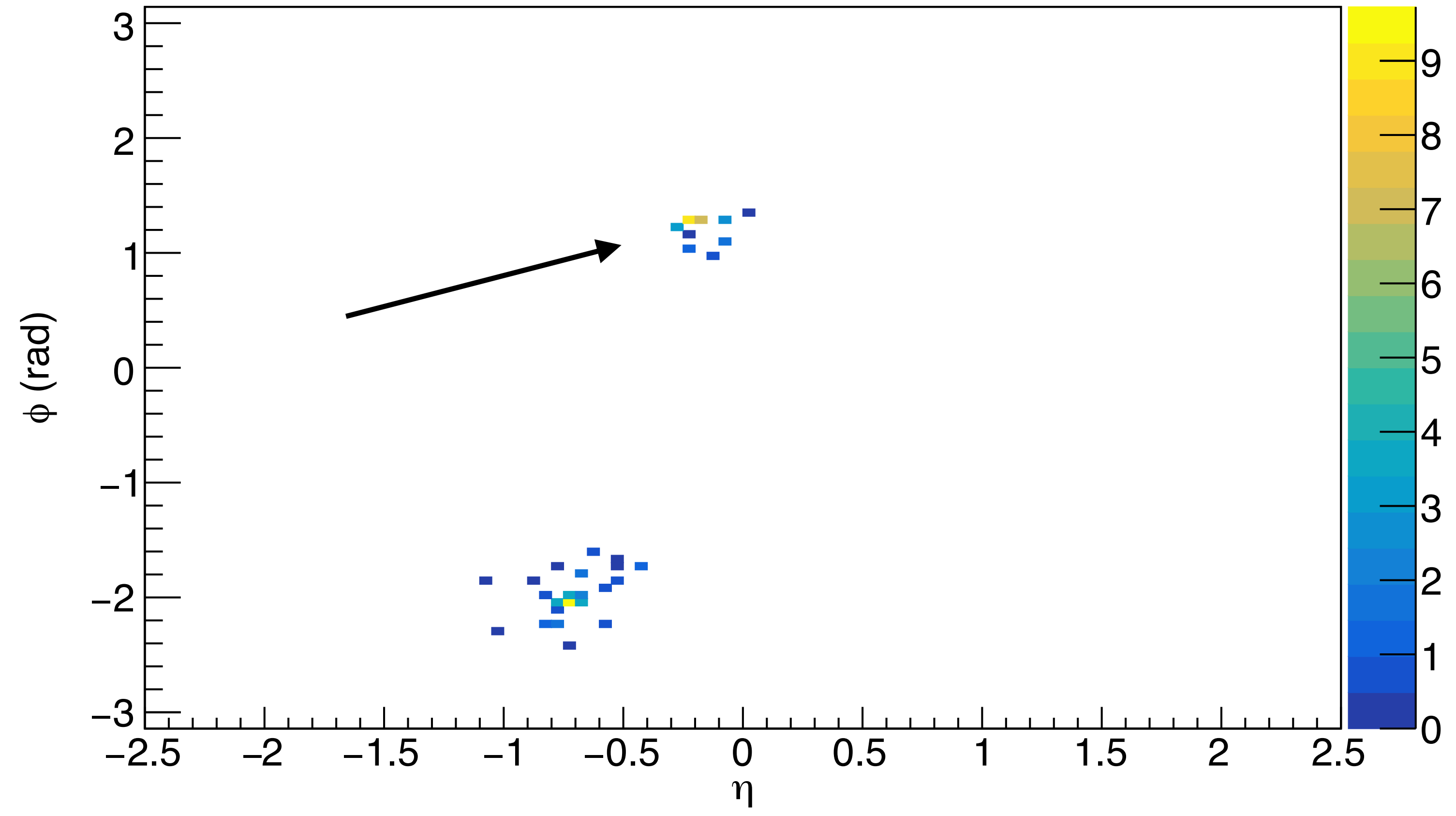

Jet Clustering Algorithms

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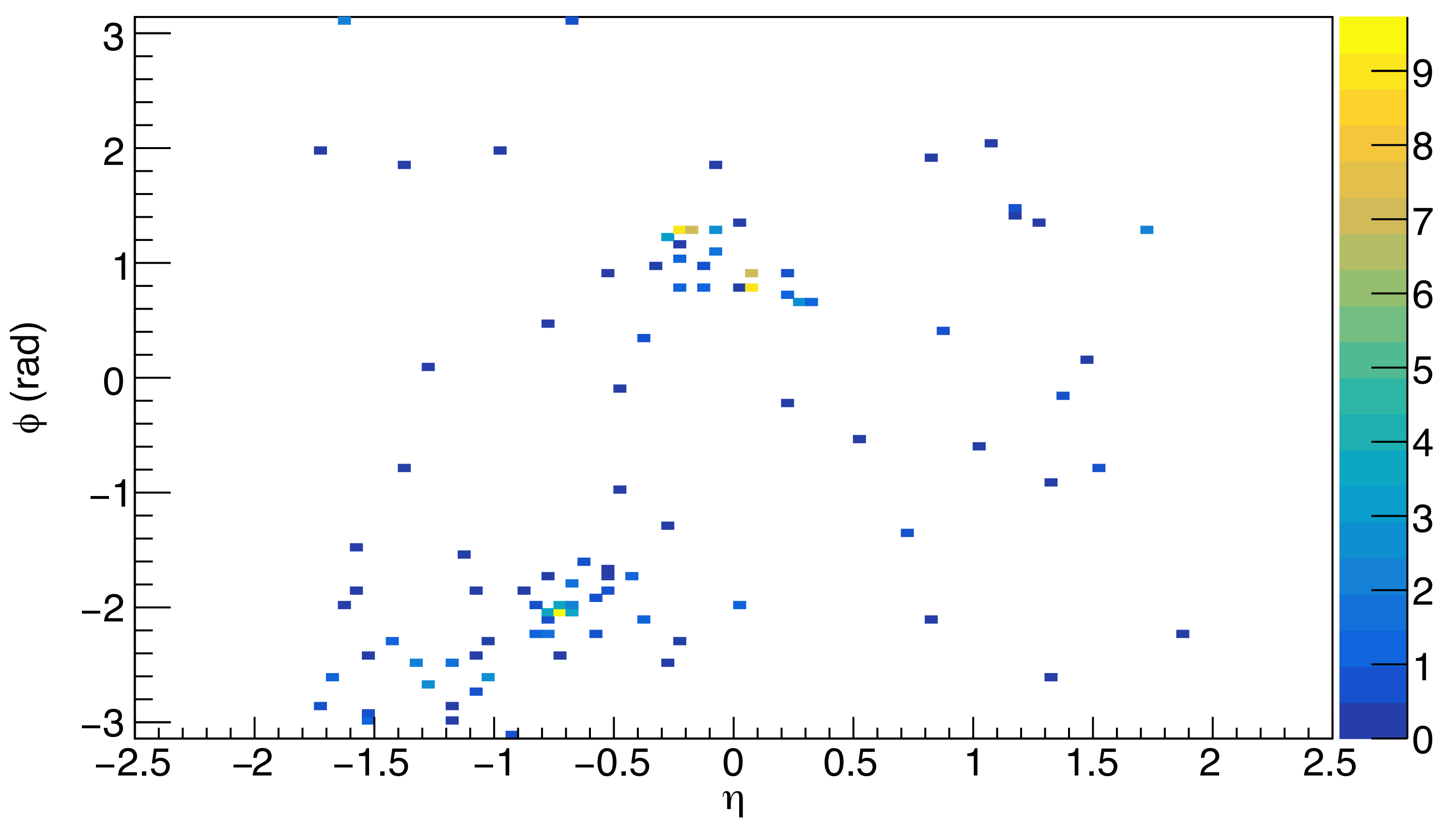
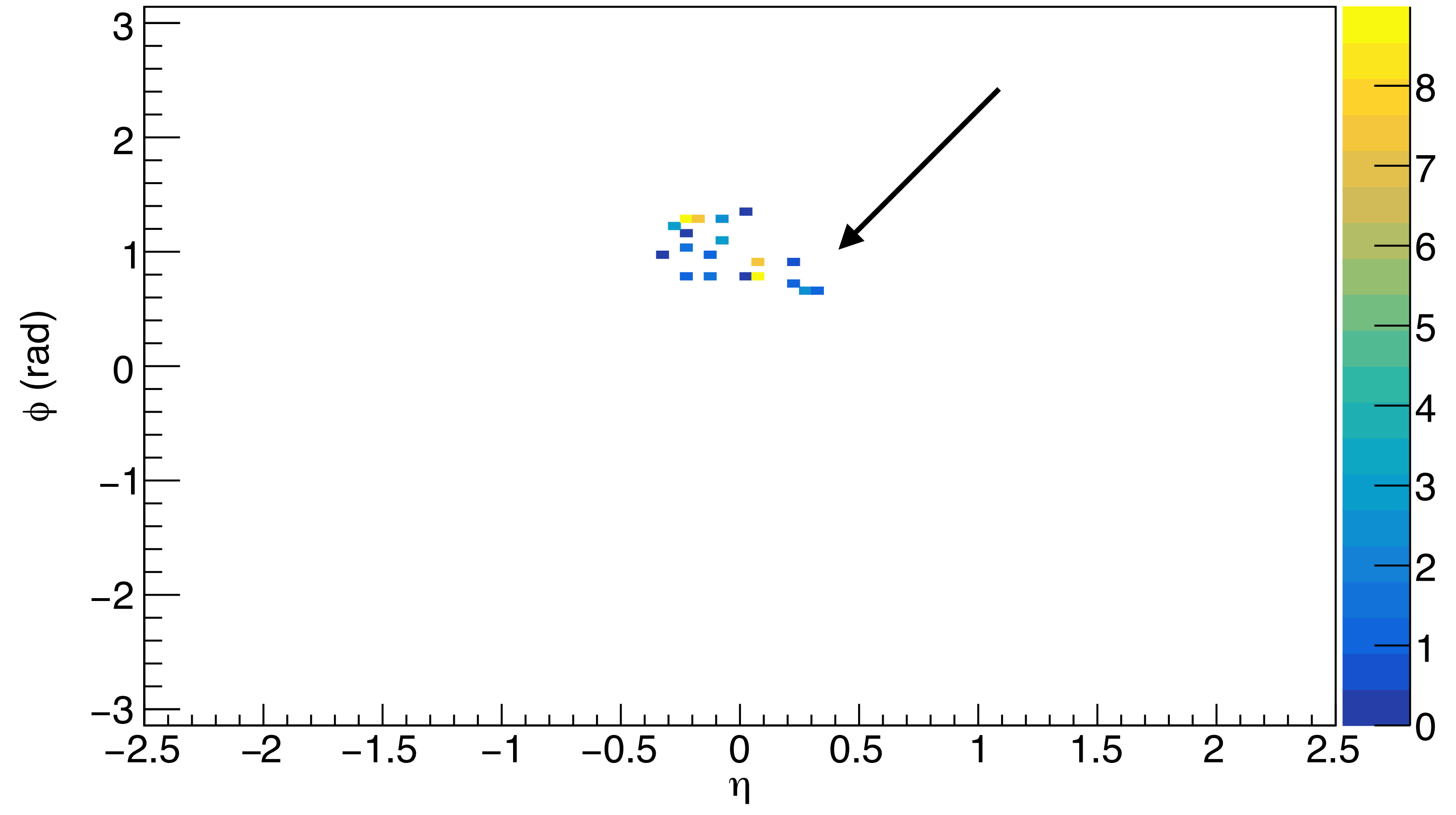


My Algorithm



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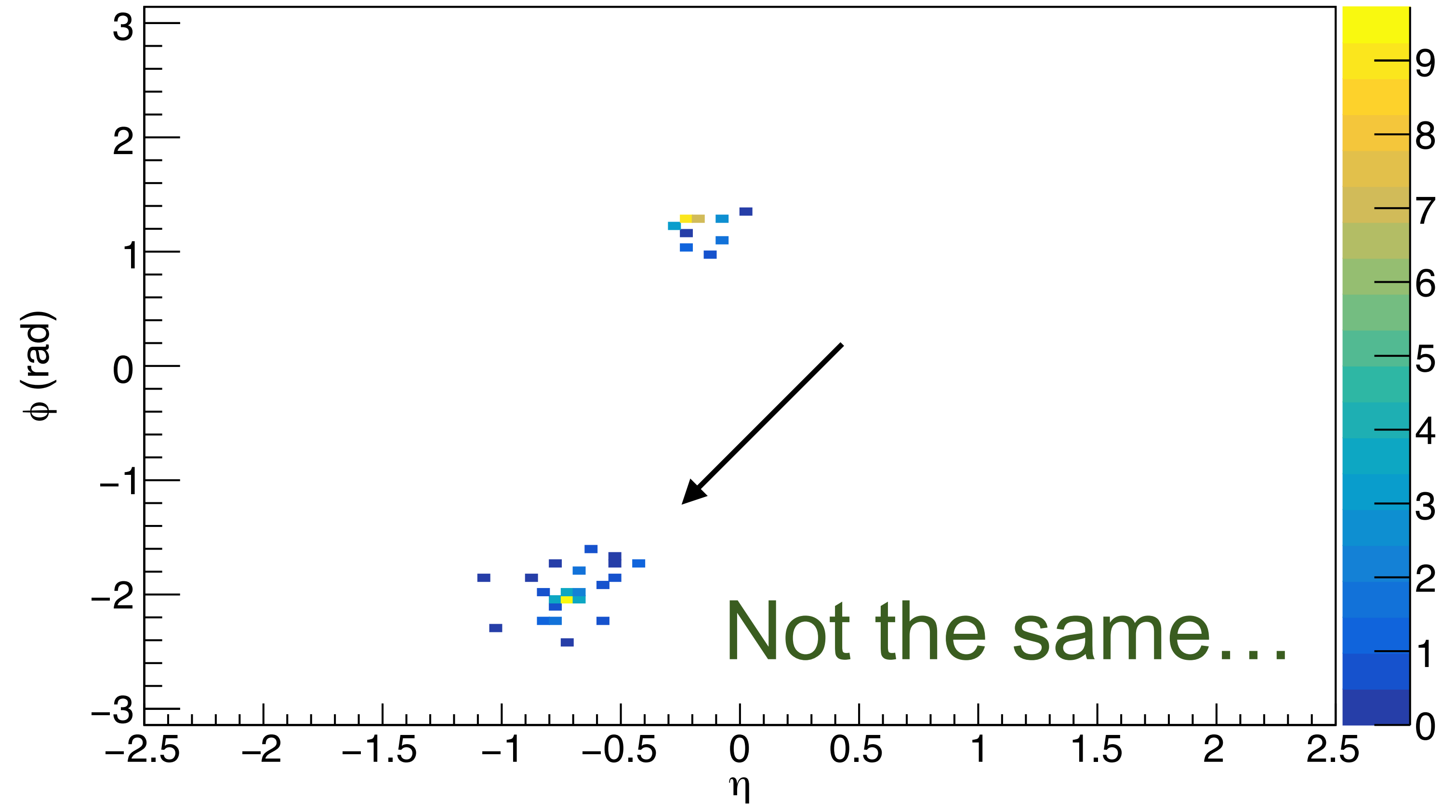

Jet Clustering Algorithms

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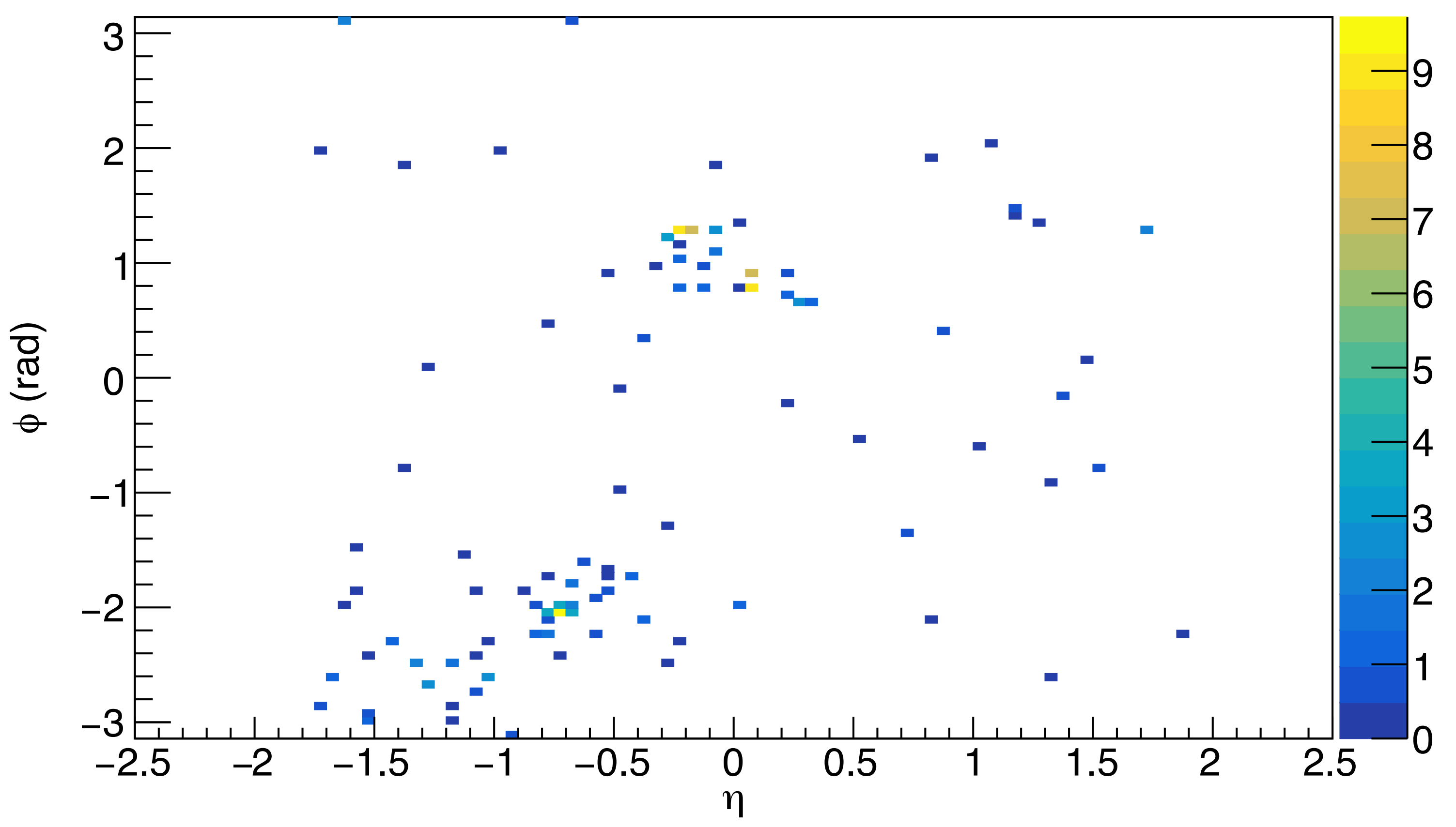
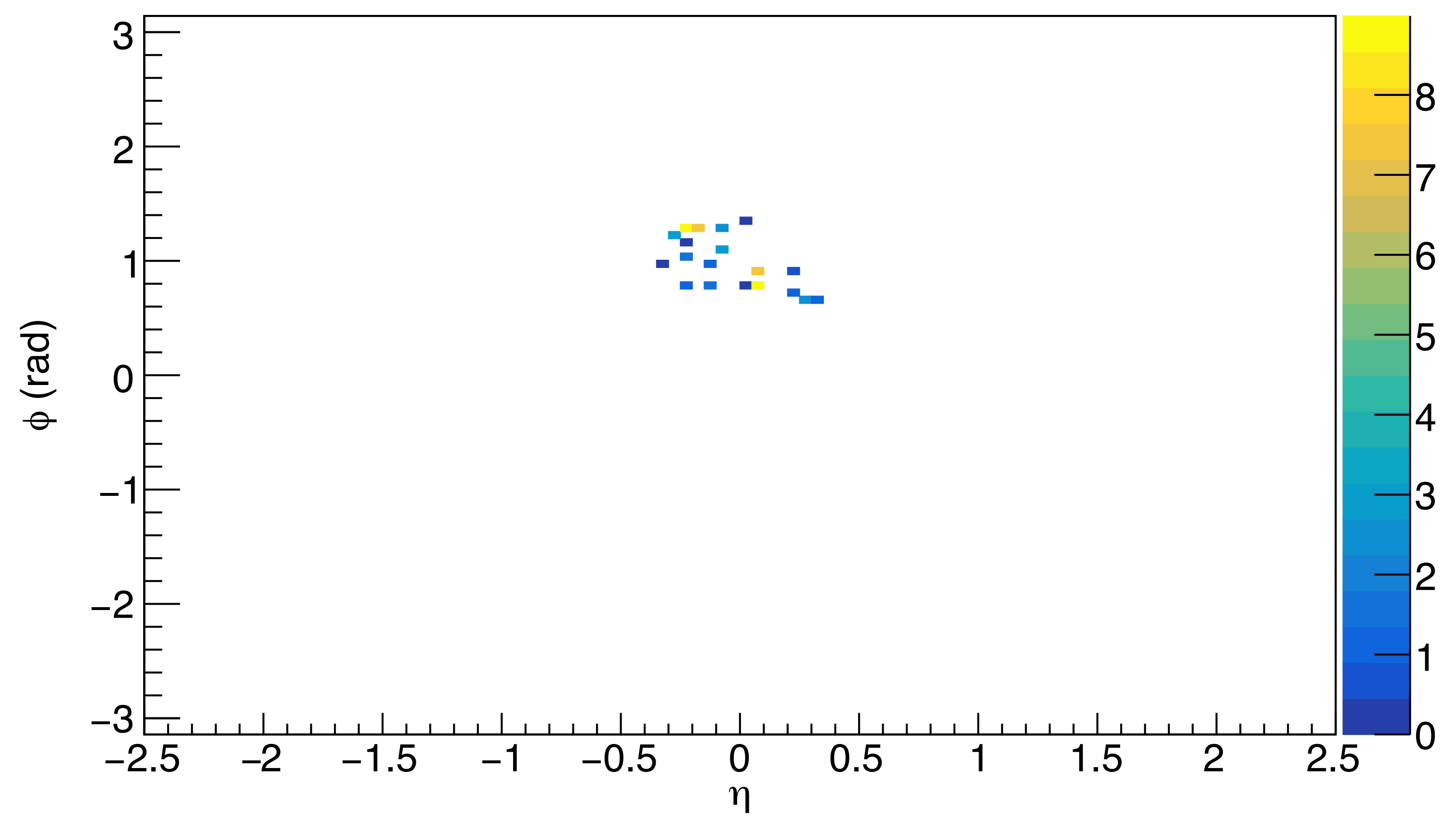


Our simple algorithm usually fails for the sub-leading jet…

My Algorithm



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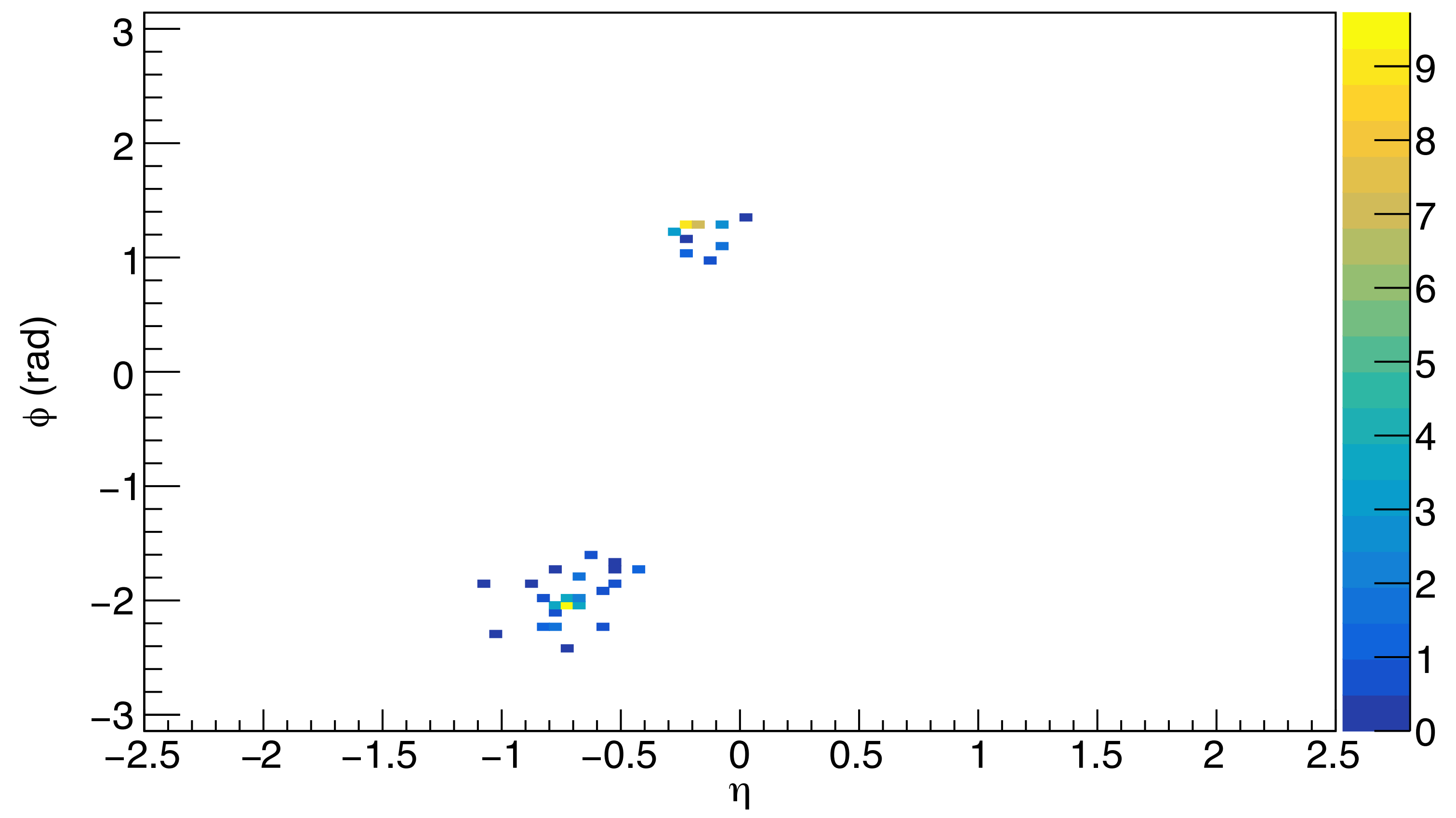

Jet Clustering Algorithms

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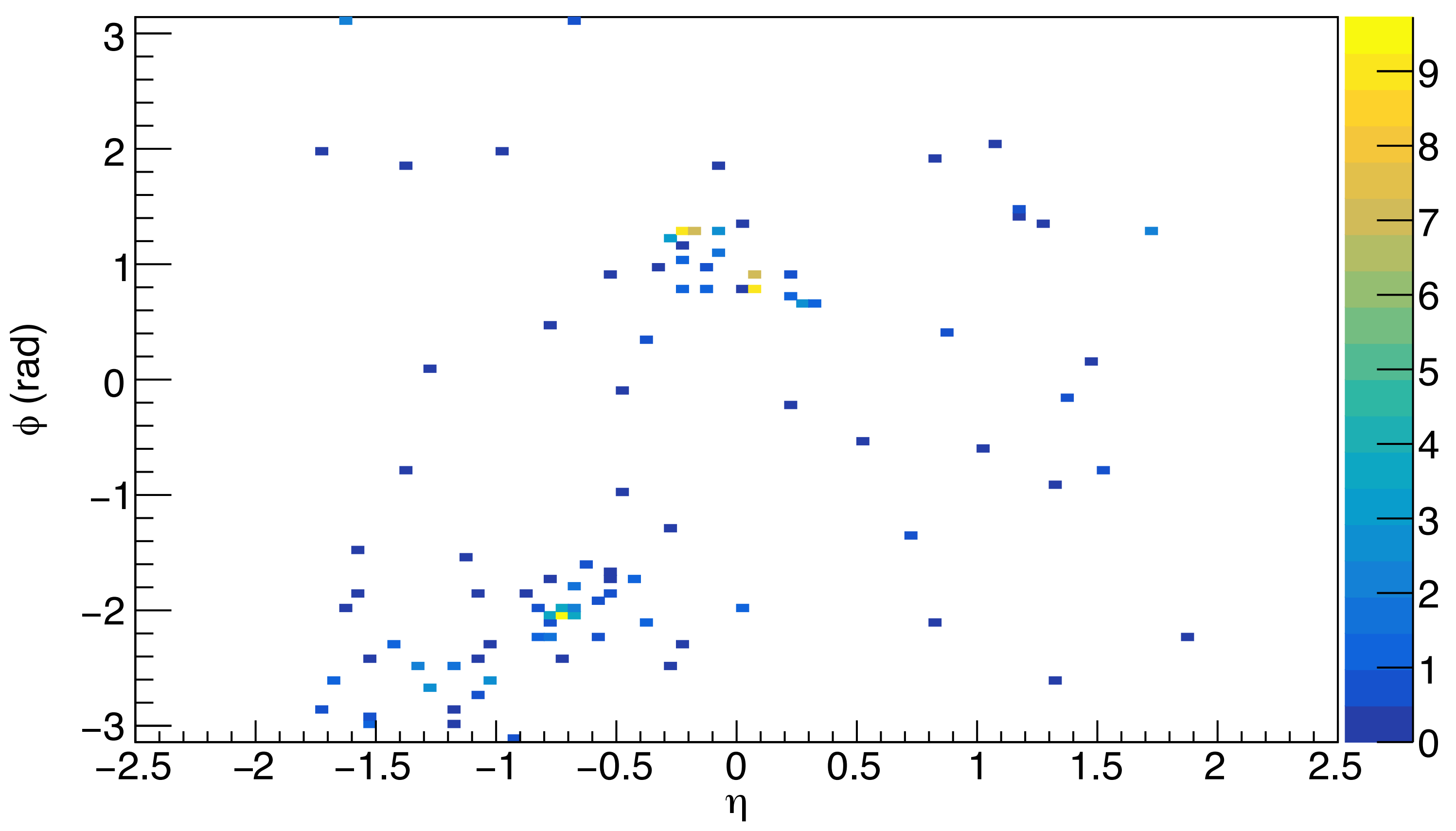
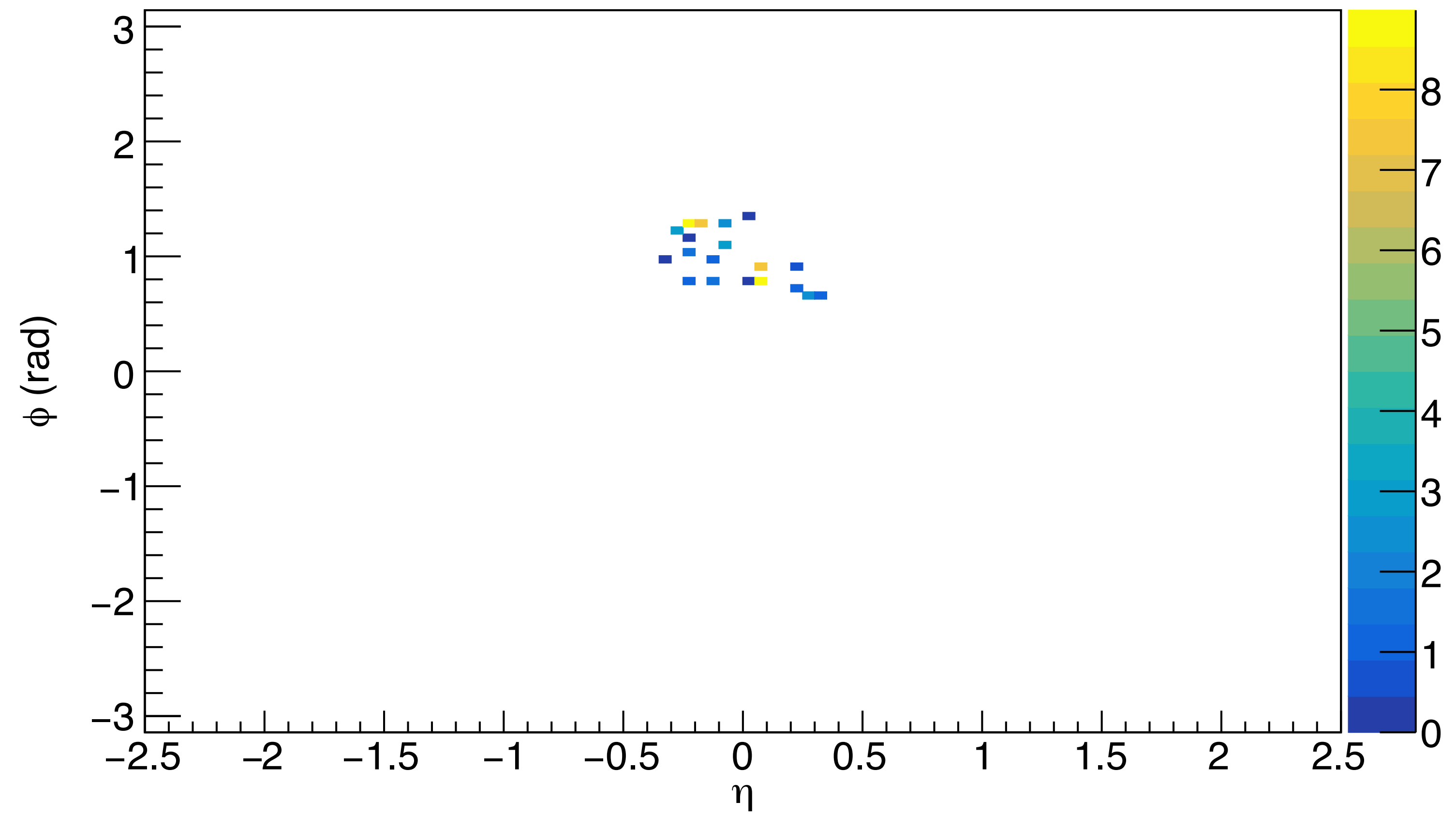


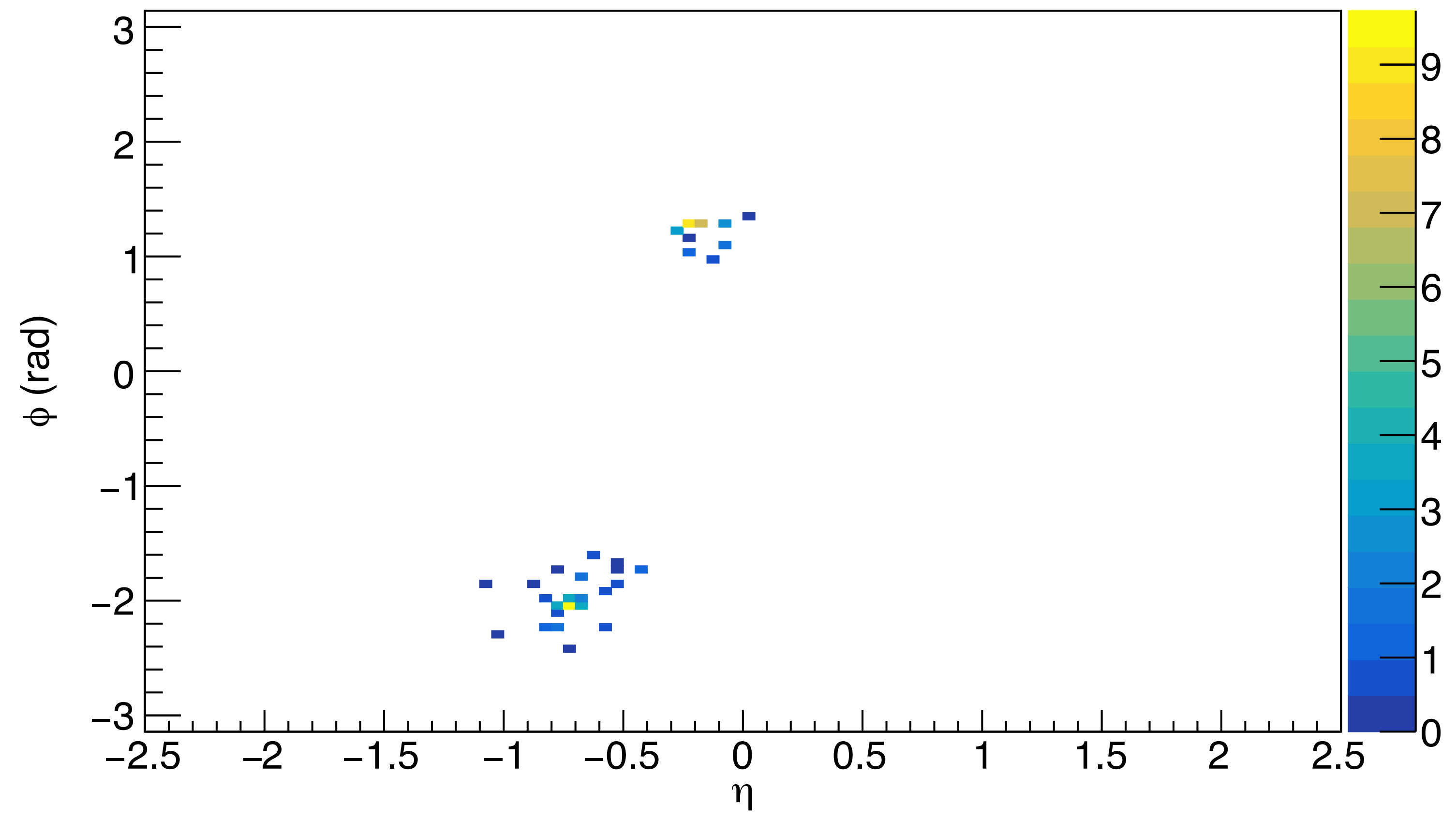
Our simple algorithm usually fails for the sub-leading jet…

While geometric considerations usually work, QCD-inspired jets are better at identifying jets that fragment more!

My Algorithm



C/A Algorithm



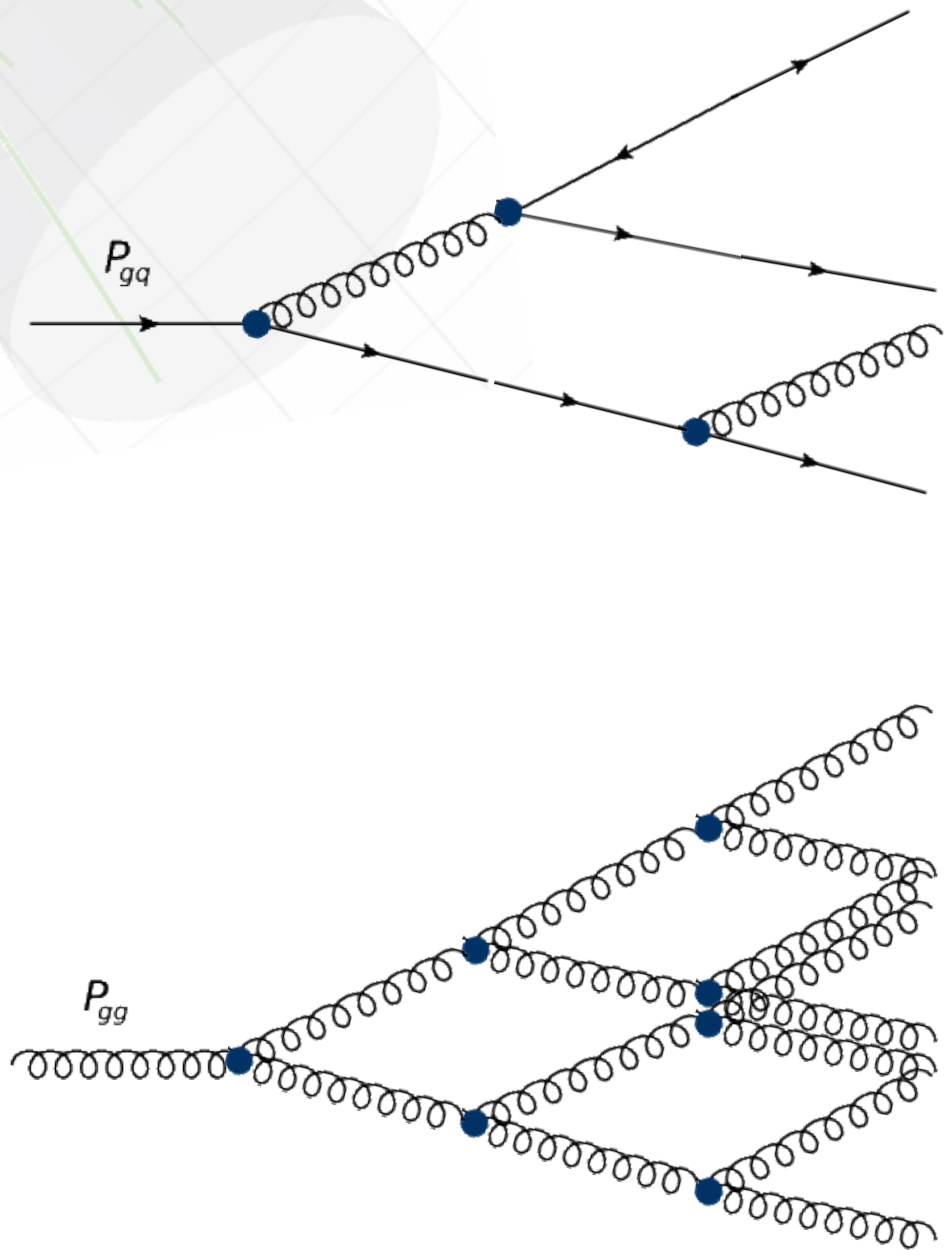
What is a jet ✓

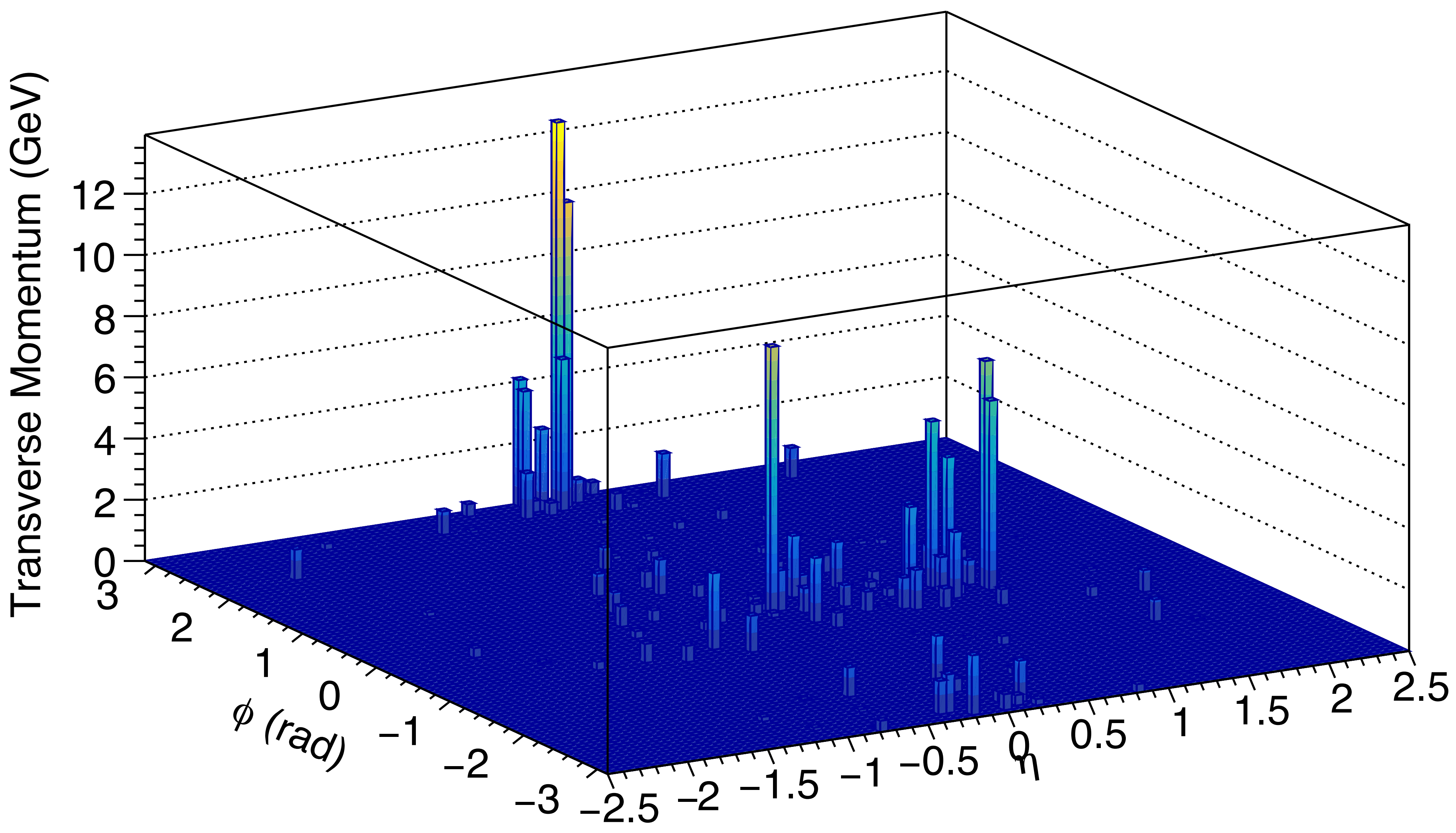
How can we measure one ✓

What can we do with jets?

Relating Experiment to QCD

- Reconstructed jets are proxies for the QCD parton shower:





Relating Experiment to QCD

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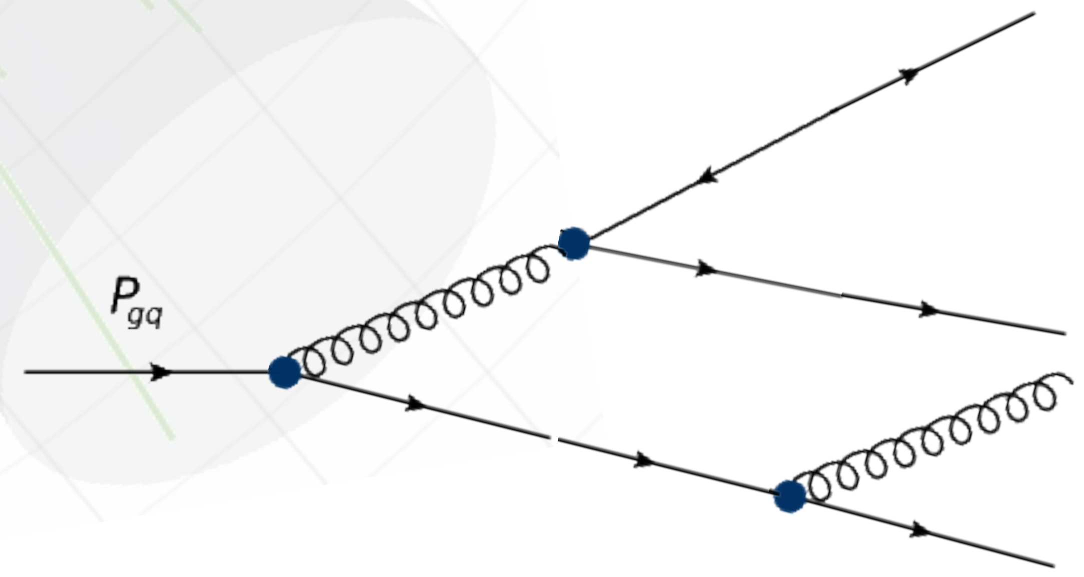

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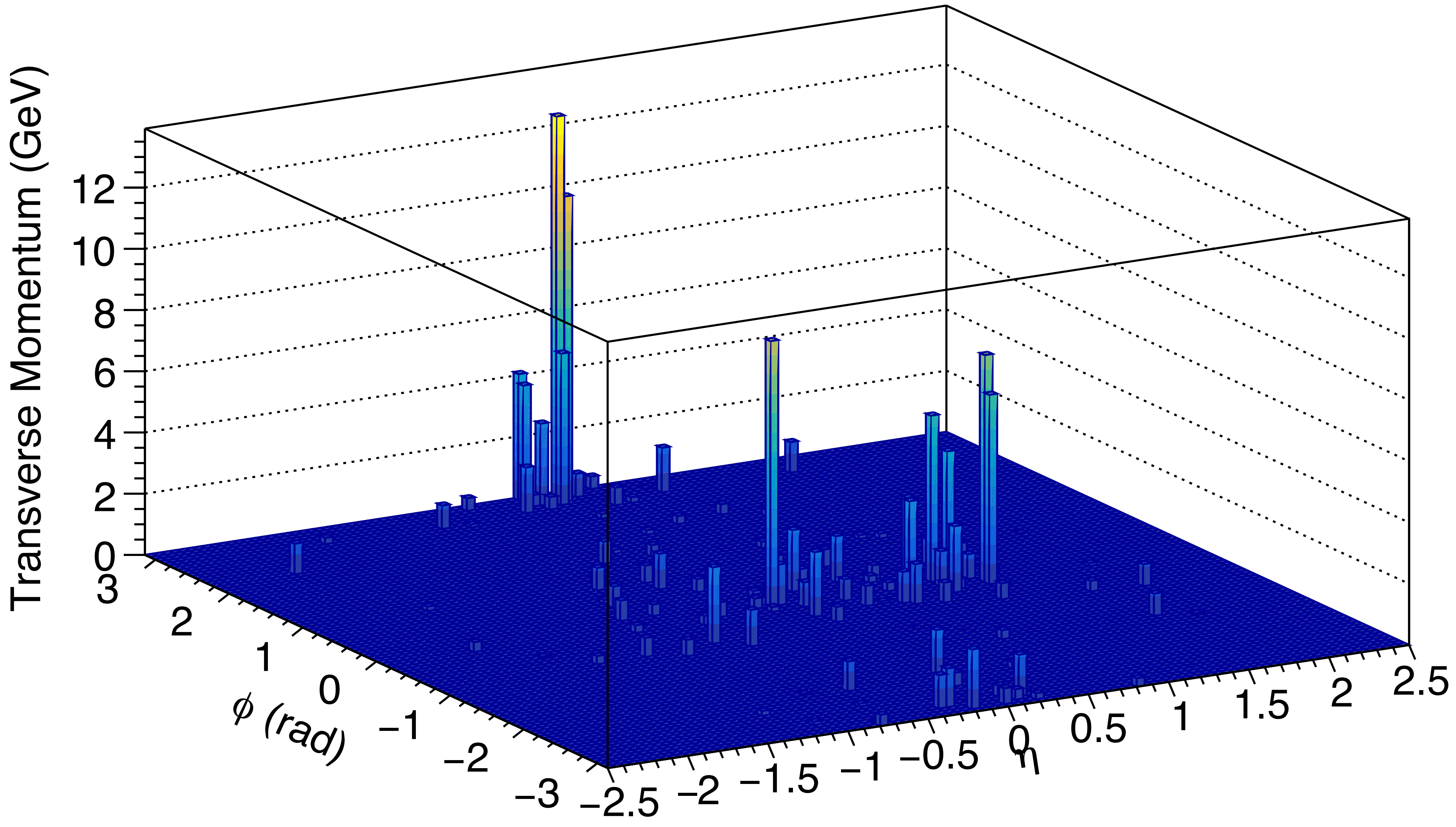

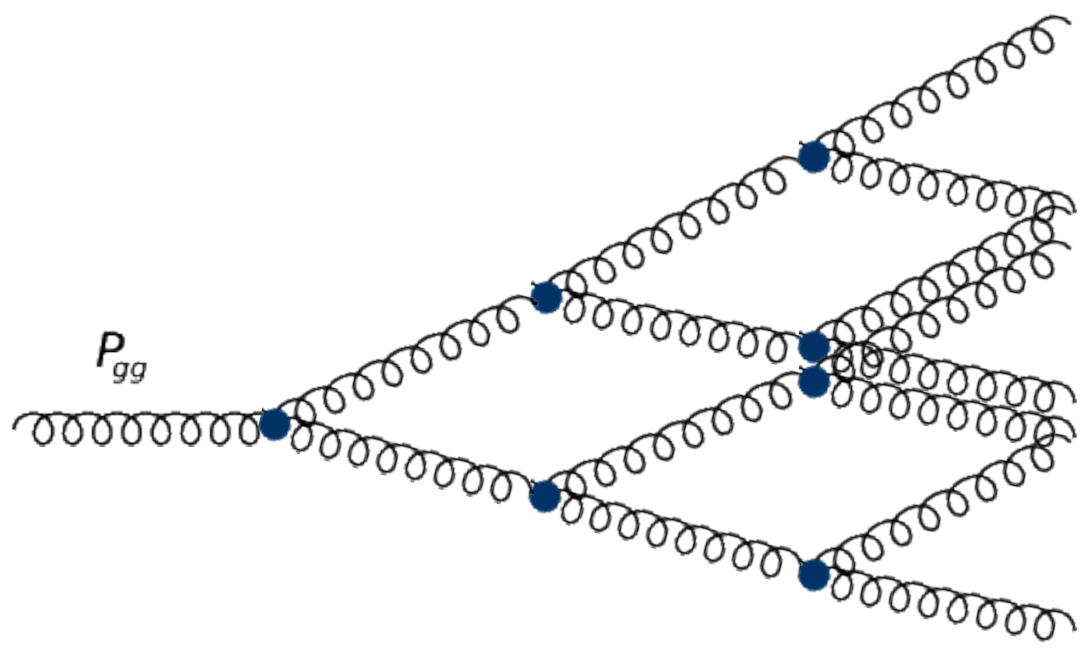

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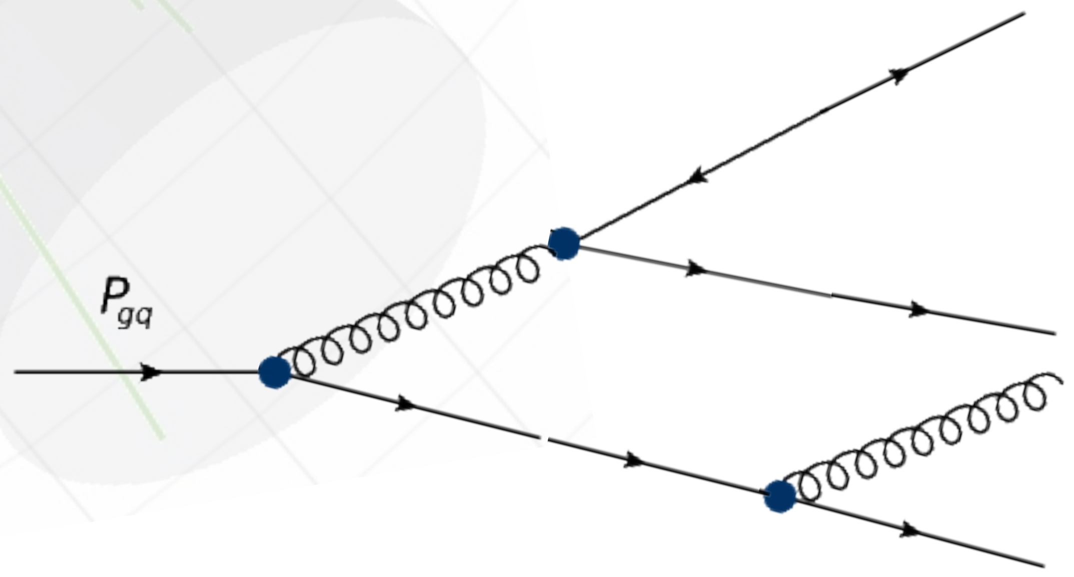

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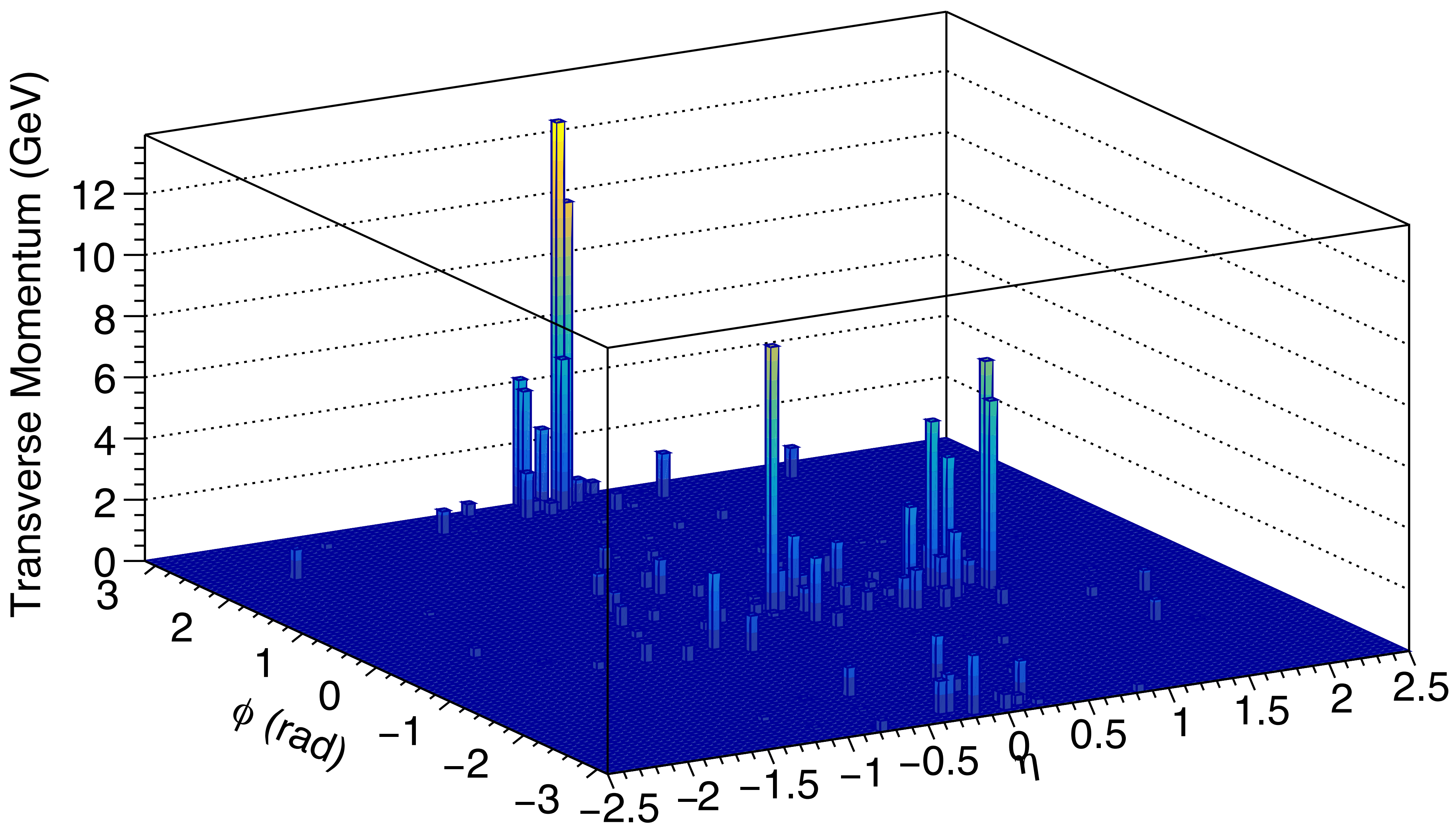
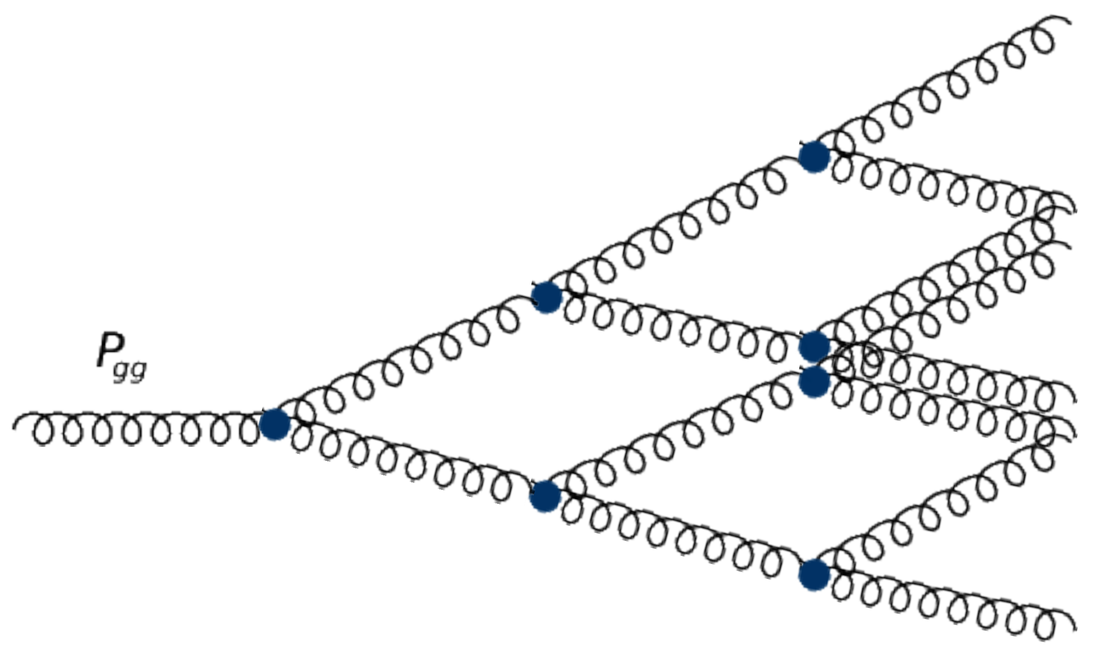




??

Can we identify if a jet was
initiated by a quark or a gluon?

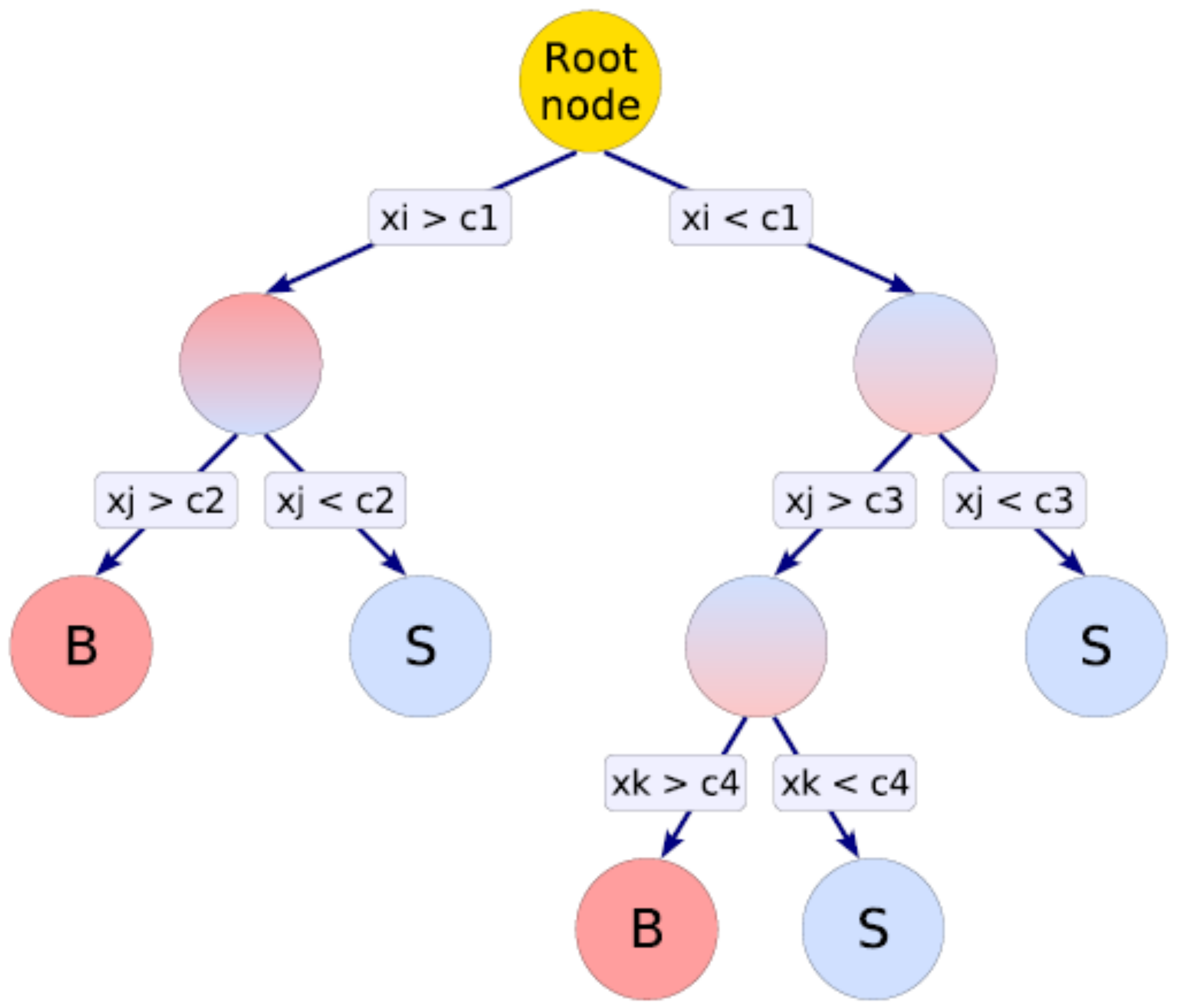
Quark vs Gluon jets

Exercise

- Try to Identify the best observable to discriminate between quark-initiated jets from gluon-initiated jets:
  - Code: Open Part3 from HandsOn_QCDJets_Code   Extract: tar -xzvf HandsOn_QCDJets_Code.tar.gz
  - Sample: sample_a.root
    - Observables: Jet transverse momentum (jetPt), Jet pseudo-rapidity (η, jetEta), Jet azimuthal angle (ϕ, jetPhi), Jet multiplicity(ntowers), energy of the highest momentum particle (towerE[0]),
    - Methods available: Boosted Decision Trees (BDT), Fisher and Multivariate Algorithm (MVA)

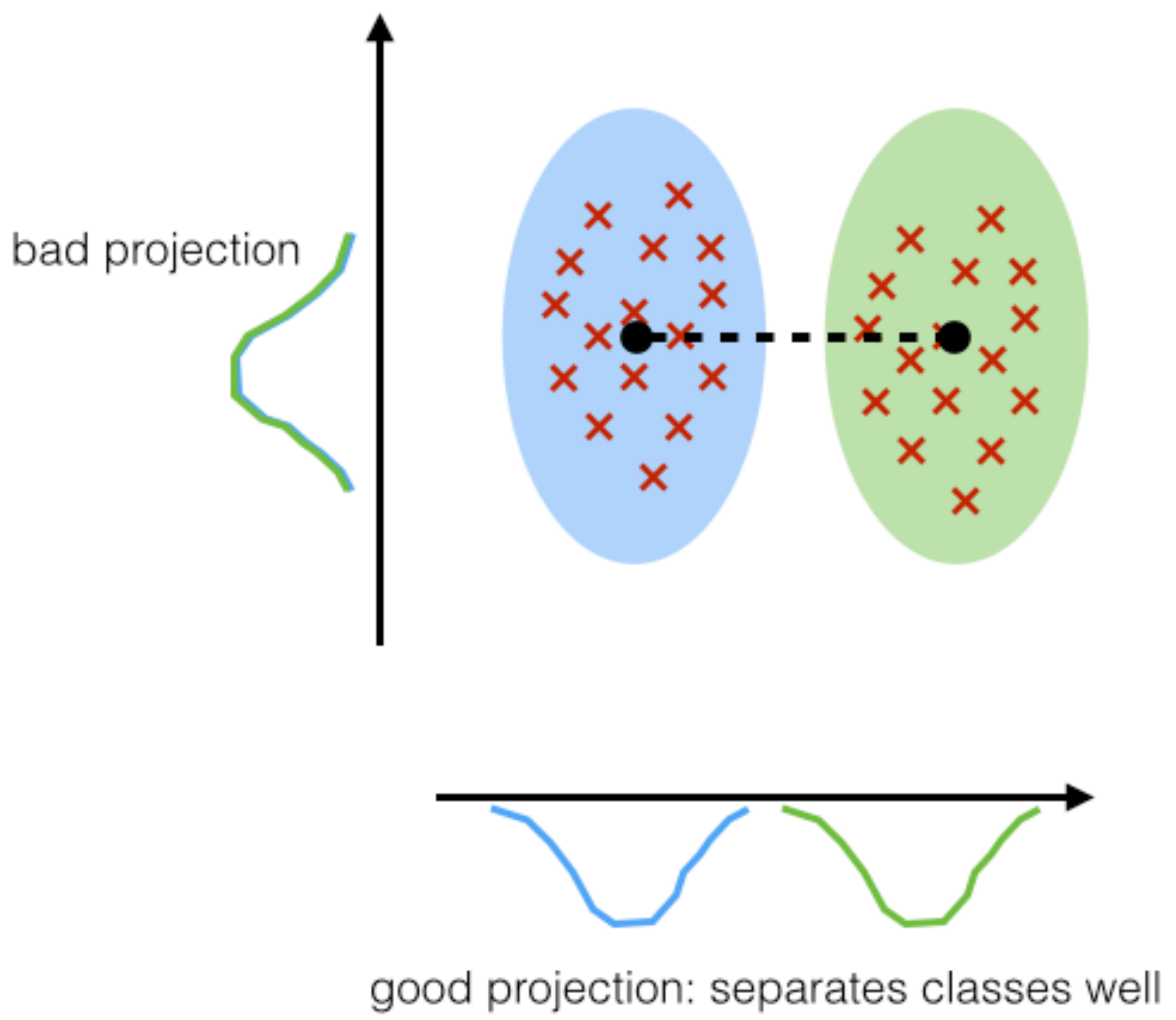
Boosted Decision Trees (BDT)

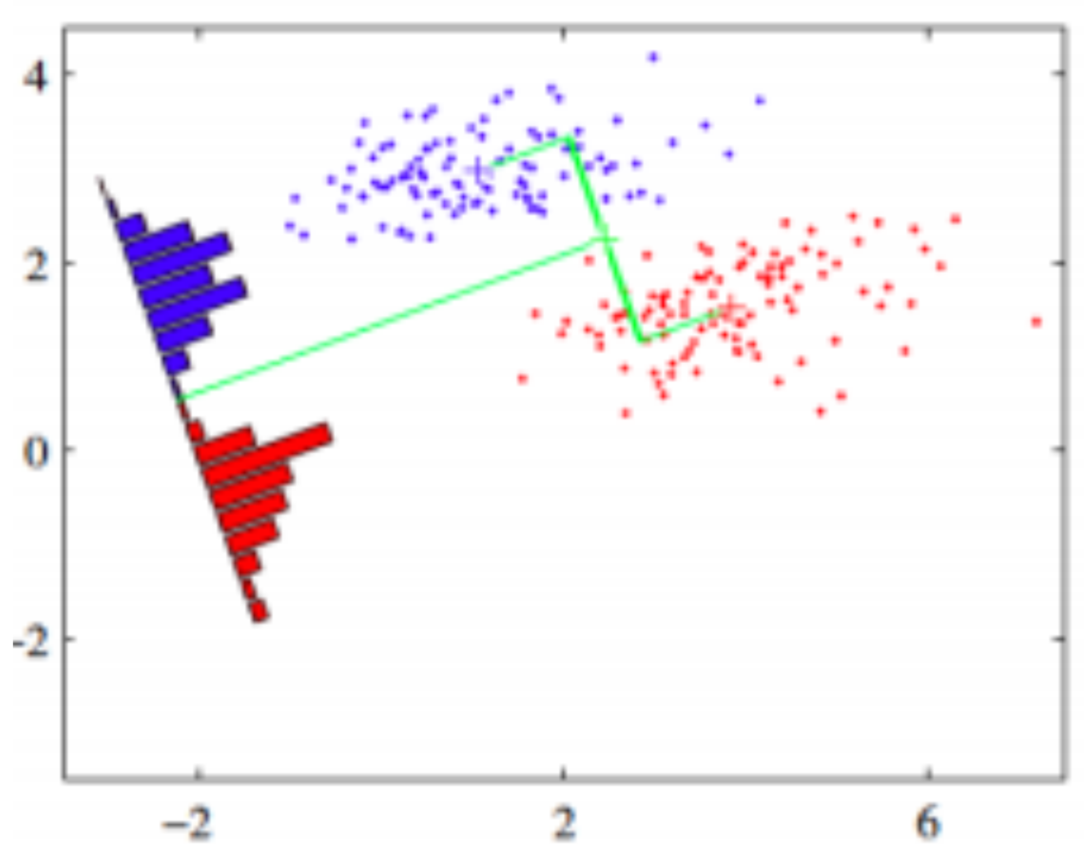
- Phase space is split into regions that are classified as signal or background.
- Each split uses the variable that gives the best separation between signal and background.
- The division is stopped once a certain node has reached a minimum number of events, or a given signal purity.
- Decision trees are insensitive to the inclusion of poorly discriminating input variables.



Fisher's linear discriminant

- Linear Discriminant Analysis:
  - Statistical Method to find a linear combination of features that separates two or more classes of objects or events:

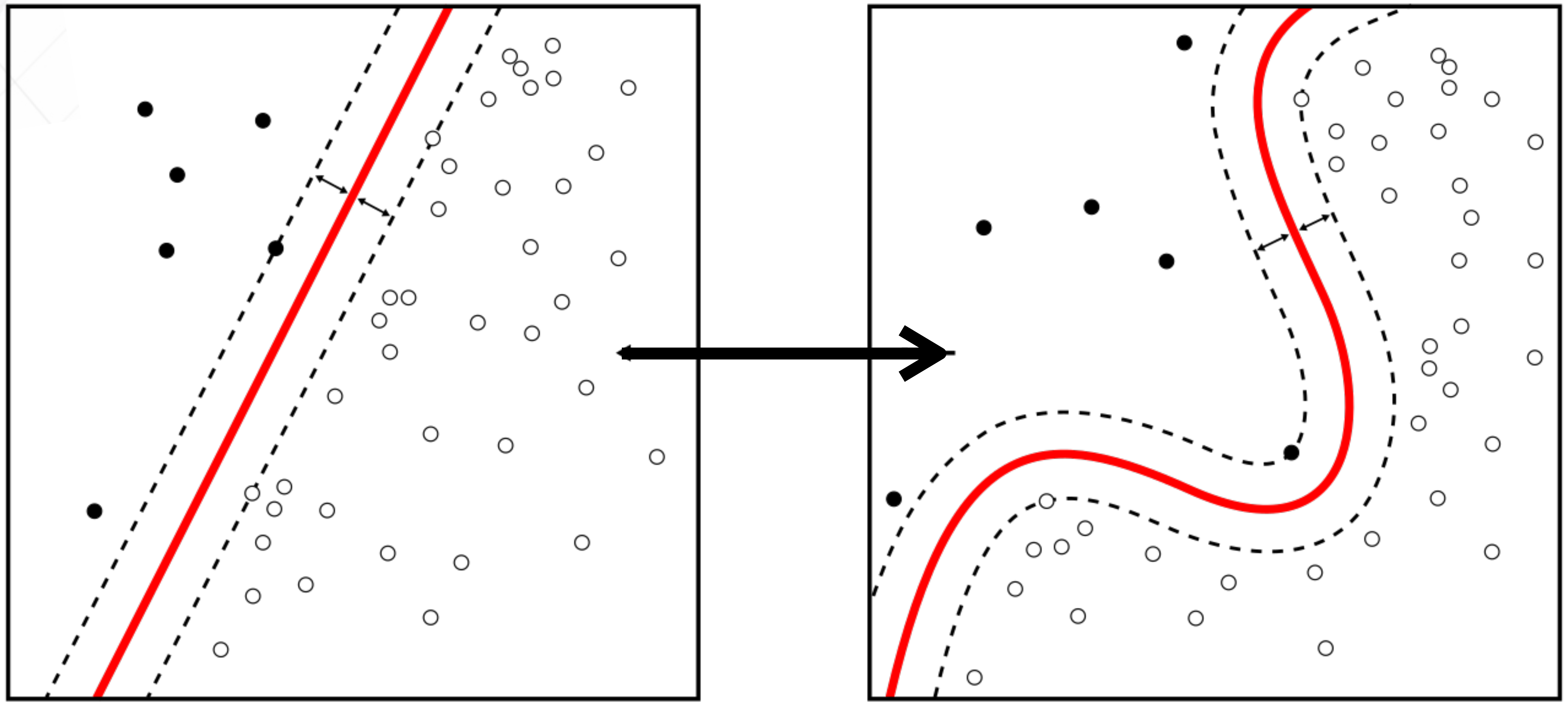




  - The resulting combination may be used as a linear classifier (in our case, to provide a cut to distinguish quarks from gluon-initiated jets)

Multilayer Perceptron (MLP)

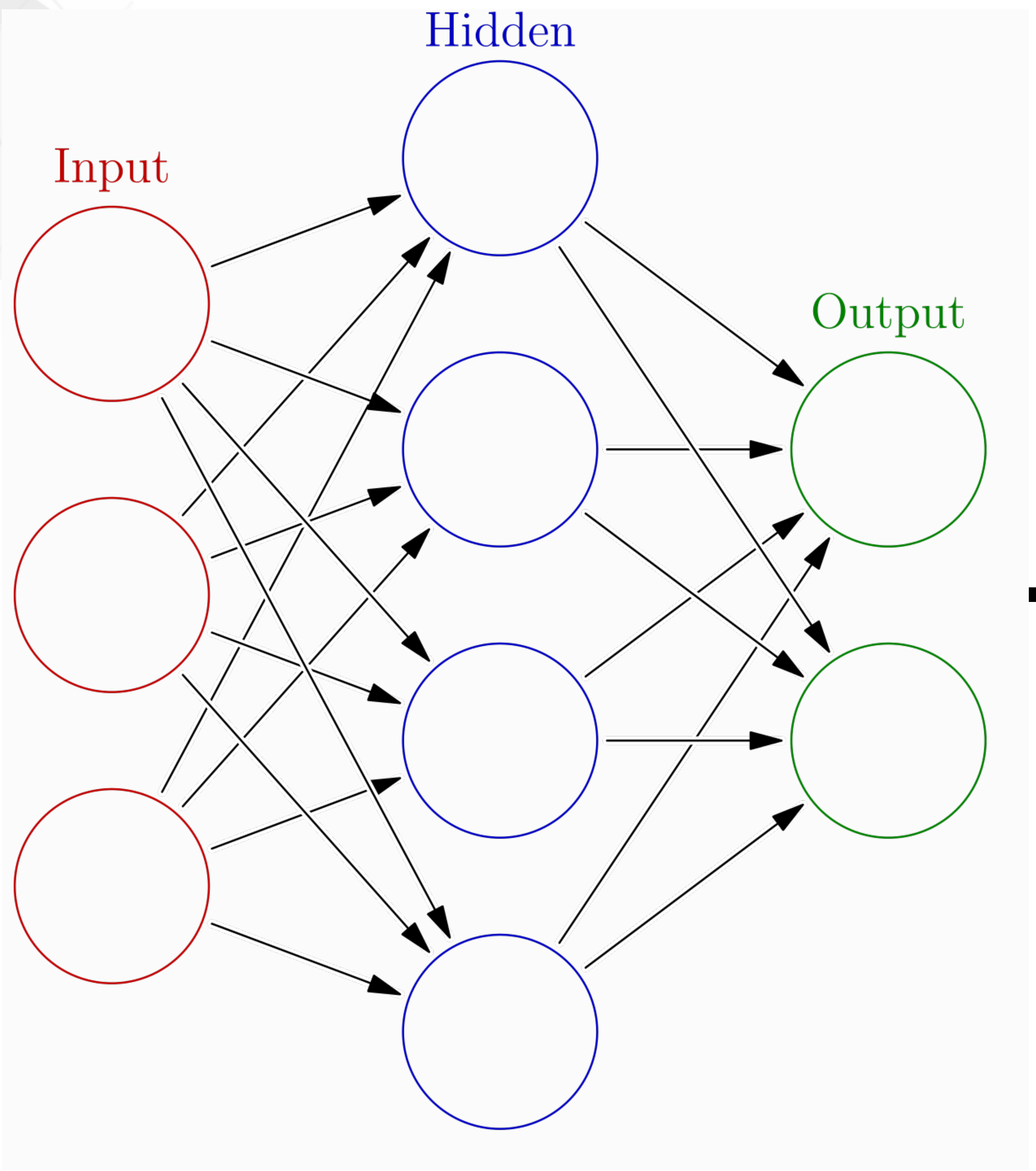
- Neural Network: Non-linear Discriminant analysis (identical to Fisher, but more flexible)

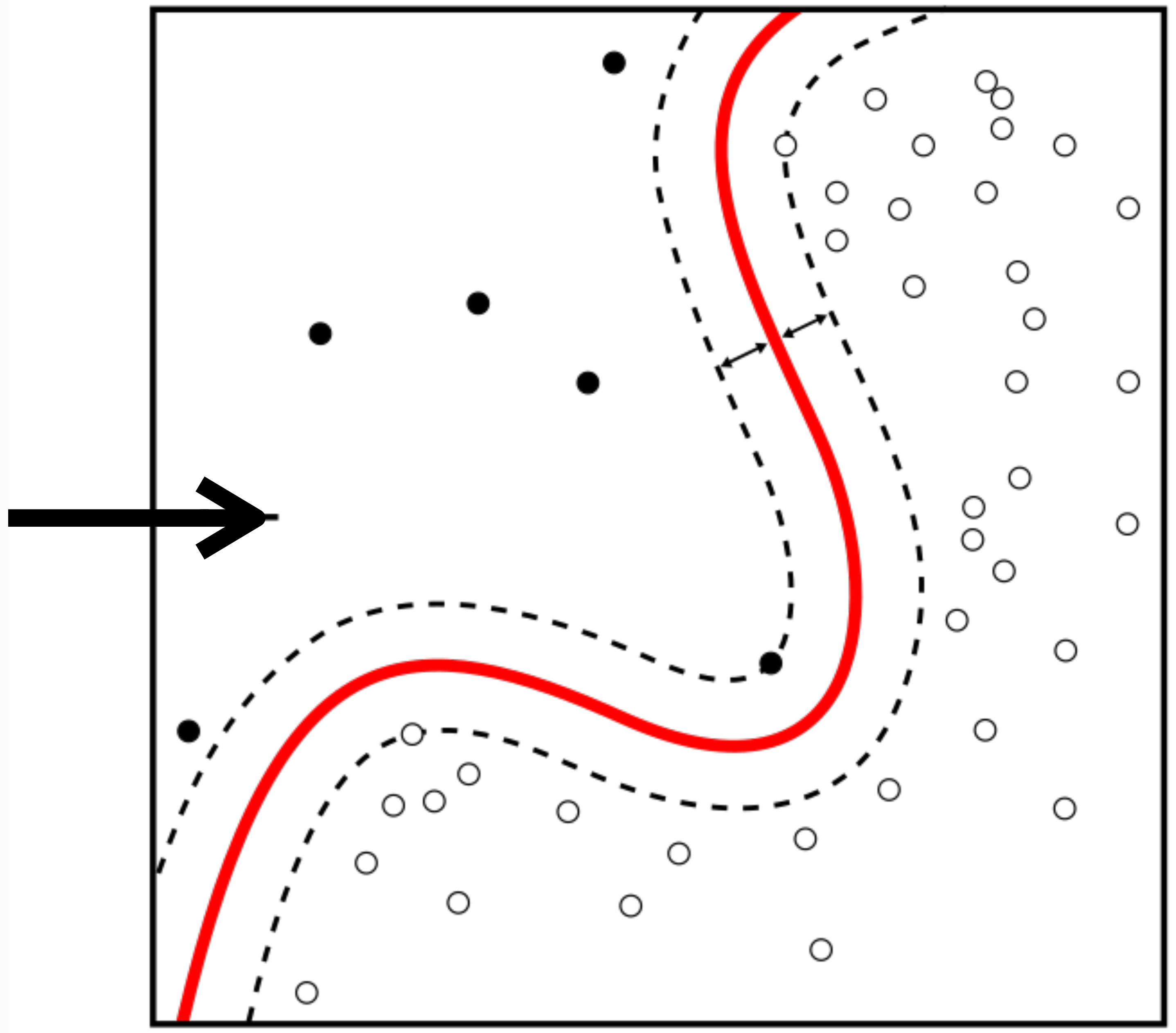


Fisher (linear discriminant) MVA (non-linear discriminant)

Multilayer Perceptron (MLP)

- Neural Network: Non-linear Discriminant analysis (identical to Fisher, but more flexible)





MVA (non-linear discriminant)

Quark vs Gluon jets

Exercise

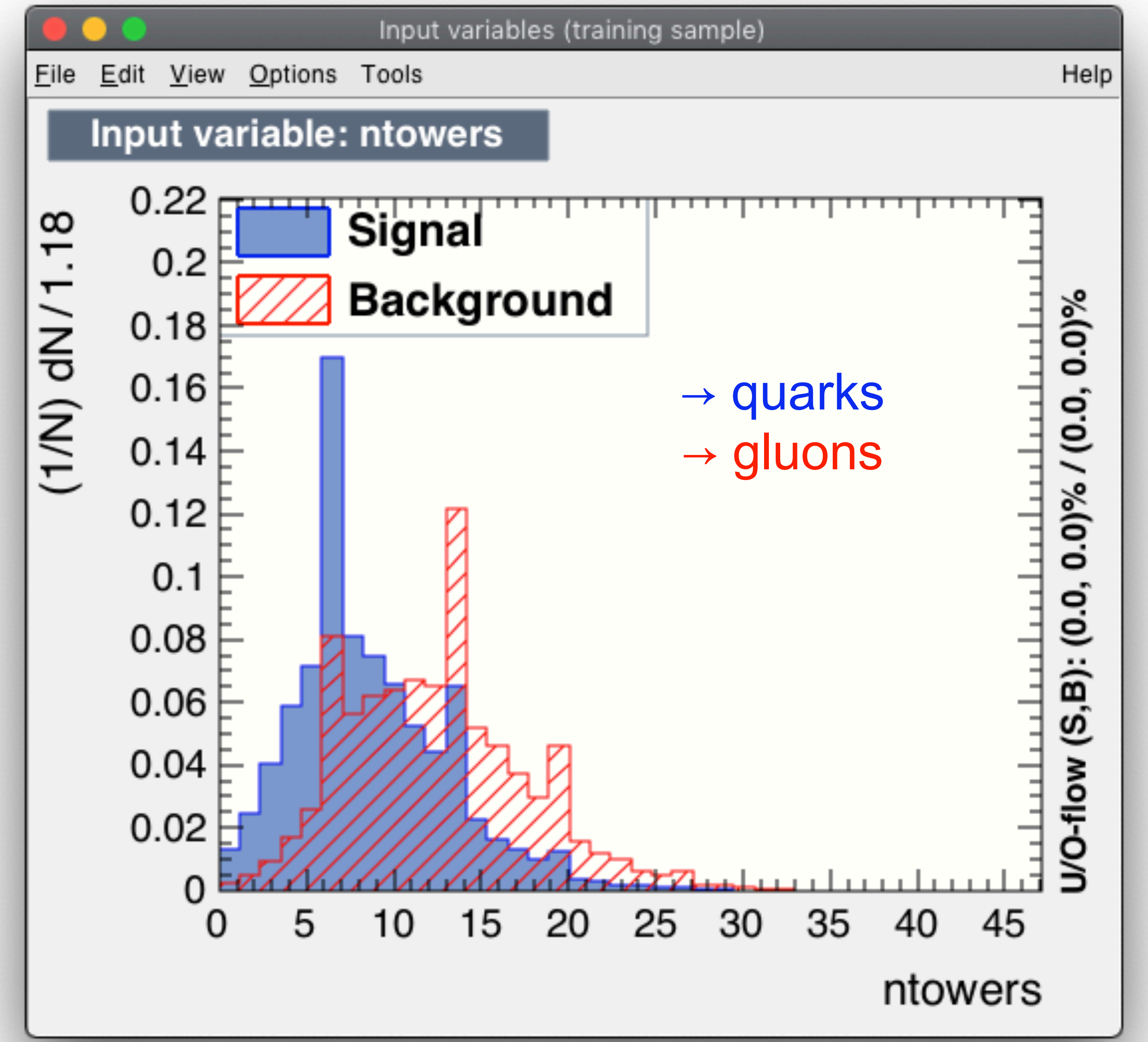
- Try to Identify the best observable to discriminate between quark-initiated jets from gluon-initiated jets:
    - Code: TMVA_Training.C (to train), TMVA_Application.C (to apply to an unknown sample) and TMVA_compare.C (to compare training with simulation)
    - Sample: sample_a.root
    - Observables: Jet transverse momentum (jetPt), Jet pseudo-rapidity (η, jetEta), Jet azimuthal angle (ϕ, jetPhi), Jet multiplicity(ntowers), energy of the highest momentum particle (towerE[0]),
        - Methods available: Boosted Decision Trees (BDT), Fisher and Multivariate Algorithm (MVA)

Quark vs Gluon jets

Solution

- Try to Identify the best observable to discriminate between quark-initiated jets from gluon-initiated jets:

    - An attempt: Jet Multiplicity (ntowers)



Quark vs Gluon jets

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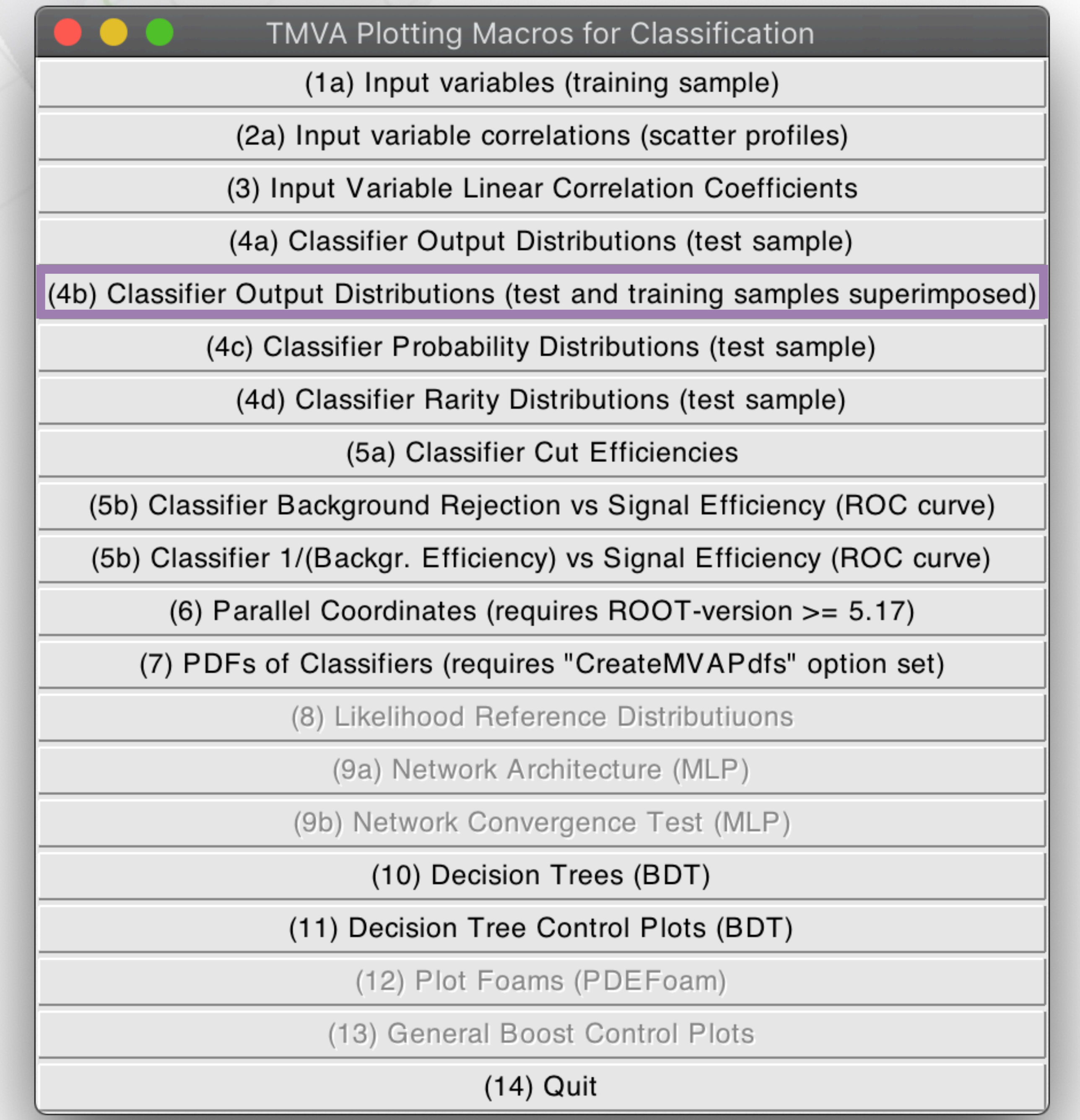
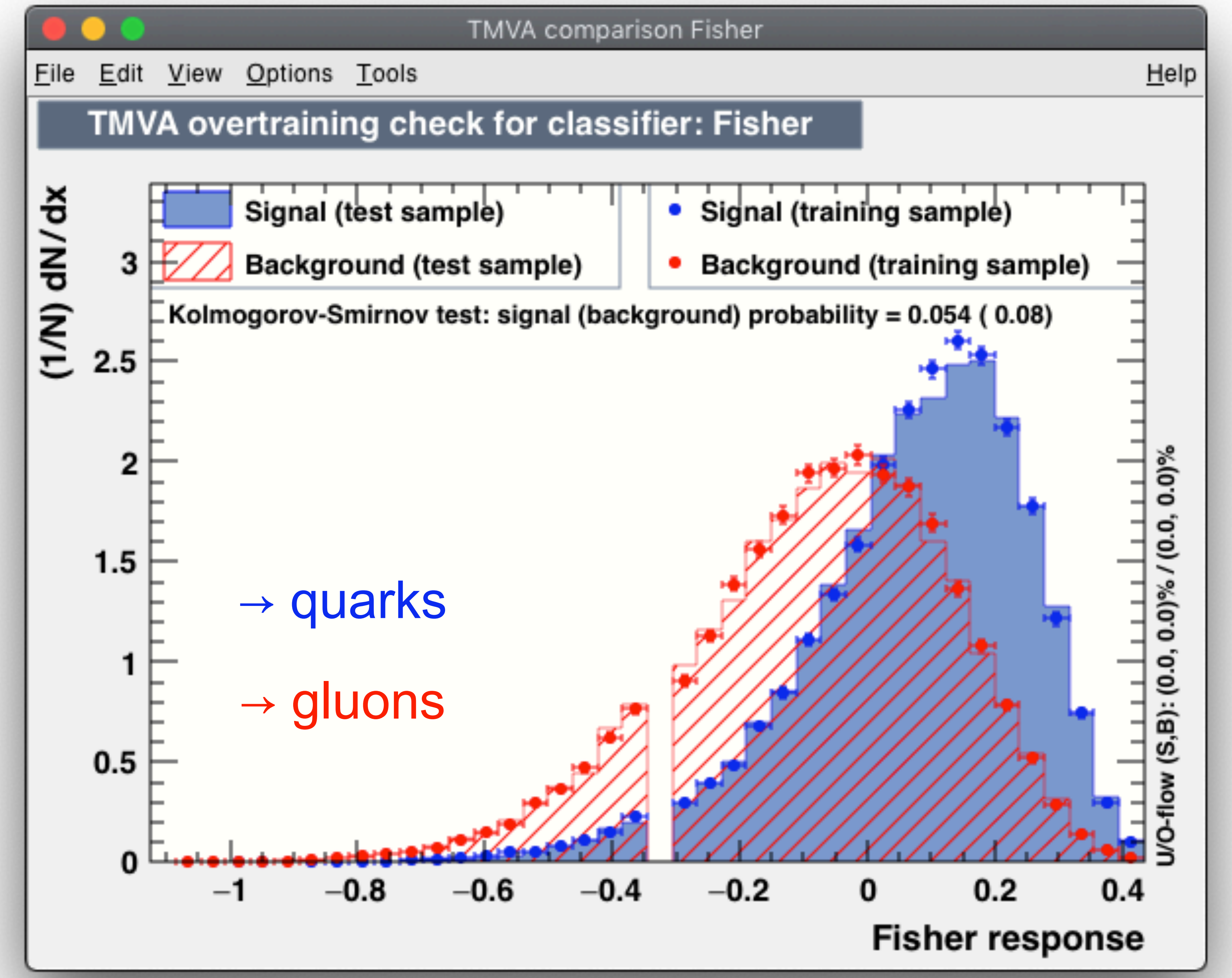


Cut at "0" seems to provide a reasonable separation



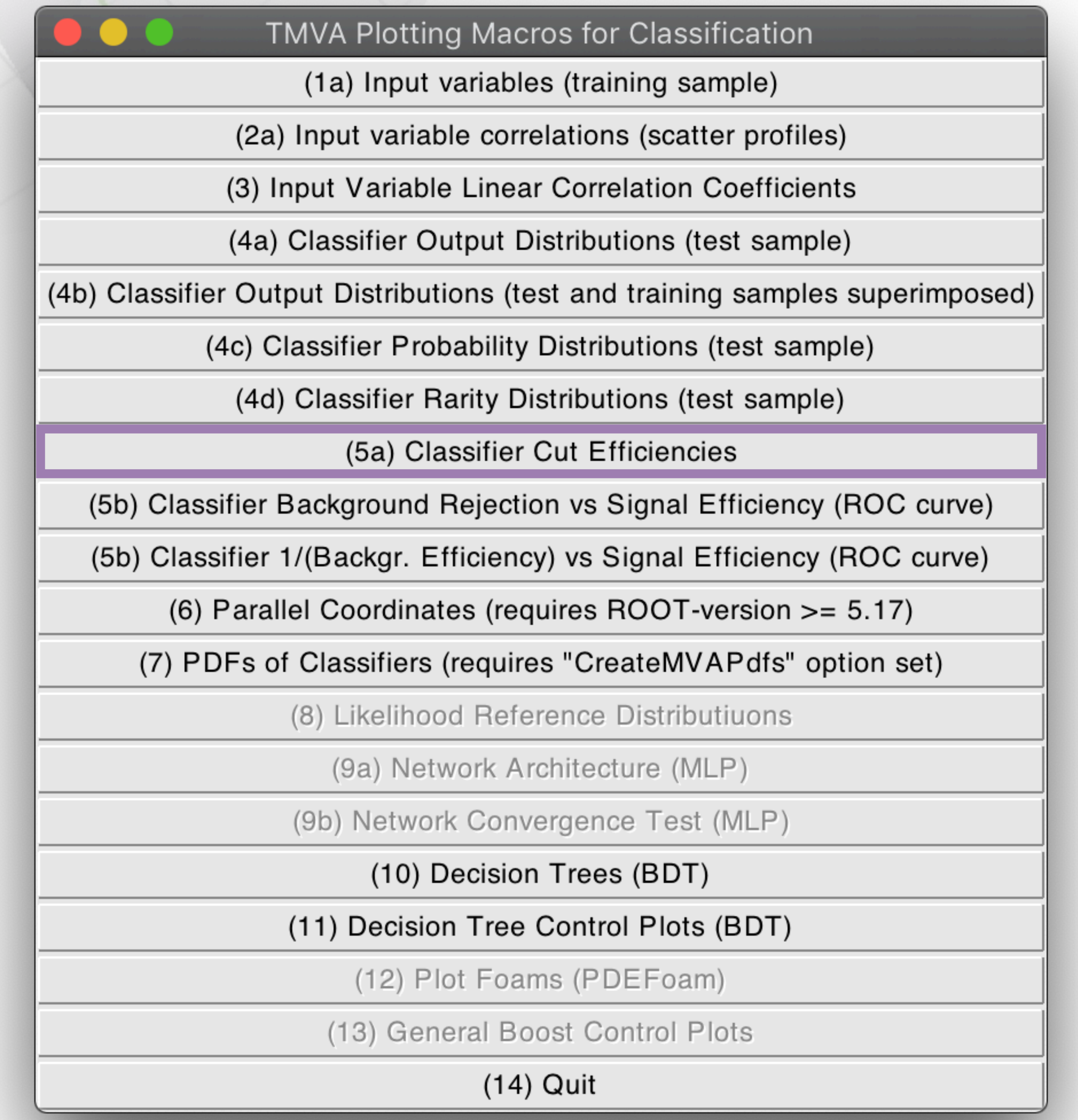
Quark vs Gluon jets

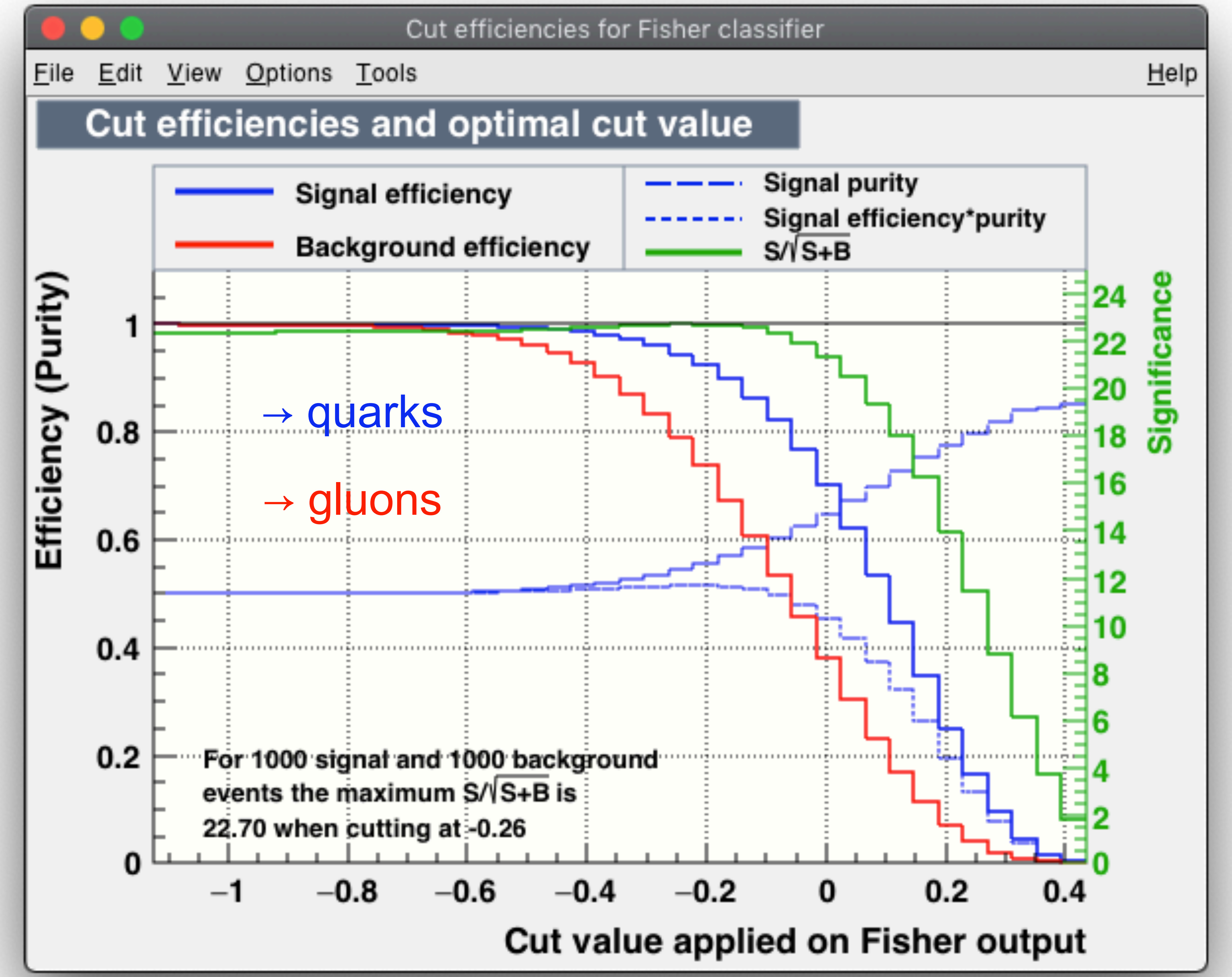
Solution

- Try to Identify the best observable to discriminate between quark-initiated jets from gluon-initiated jets:

  - An attempt: Jet Multiplicity (ntowers)

But “signal purity" increases with higher cut



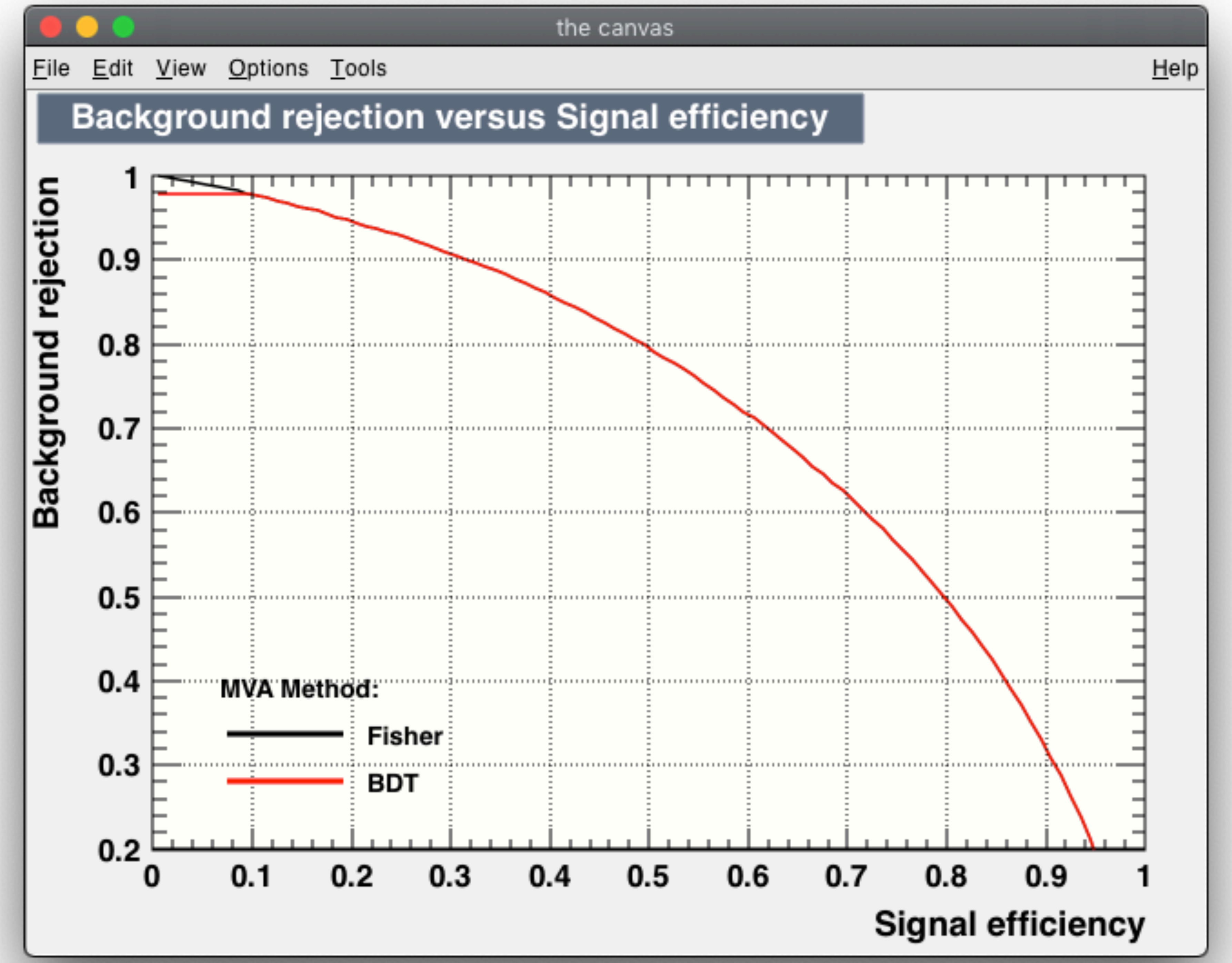


Quark vs Gluon jets

Solution

- Try to Identify the best observable to discriminate between quark-initiated jets from gluon-initiated jets:
  - An attempt: Jet Multiplicity (ntowers)

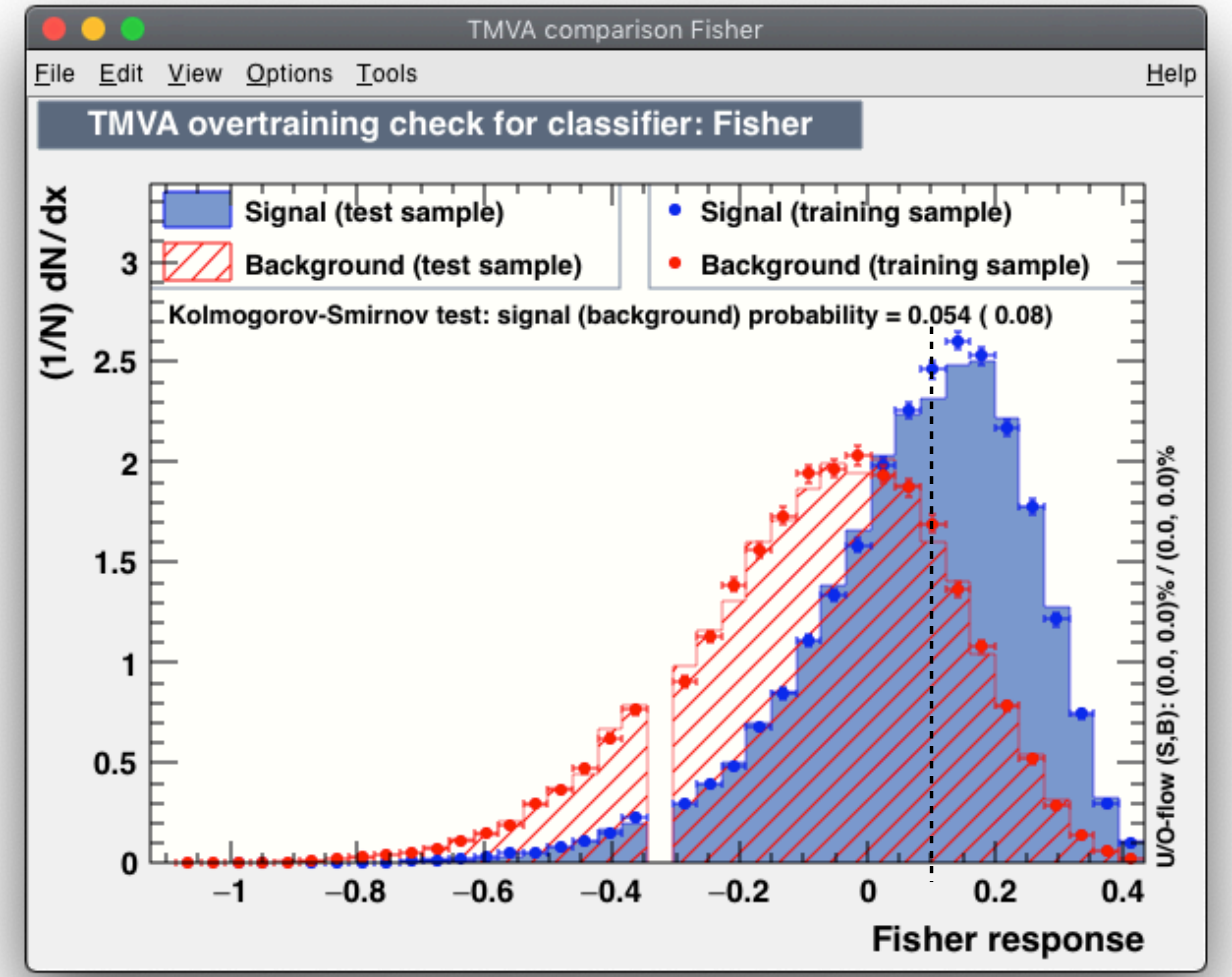
Both methods provide the same Background/Signal efficiency



Quark vs Gluon jets

Solution

- Try to Identify the best observable to discriminate between quark-initiated jets from gluon-initiated jets:
  - An attempt: Jet Multiplicity (ntowers)
    - Selection example: Fisher Algorithm with cut at “0.1”
    - Sample a:
      - 88 981 quark-jets
      - 121 483 gluon-jets



Quark vs Gluon jets

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- Try to Identify the best observable to discriminate between quark-initiated jets from gluon-initiated jets:
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Quark vs Gluon jets

Solution

- Try to Identify the best observable to discriminate between quark-initiated jets from gluon-initiated jets:
  - An attempt: Jet Multiplicity (ntowers)
    - Selection example: Fisher Algorithm with cut at “0.1”
    - Sample a:
      - 88 981 quark-jets
      - 121 483 gluon-jets

Real values:

123 015 quark-jets

87 449 gluon-jets

Quark vs Gluon jets

Solution

- Try to Identify the best observable to discriminate between quark-initiated jets from gluon-initiated jets:
  - An attempt: Jet Multiplicity (ntowers)
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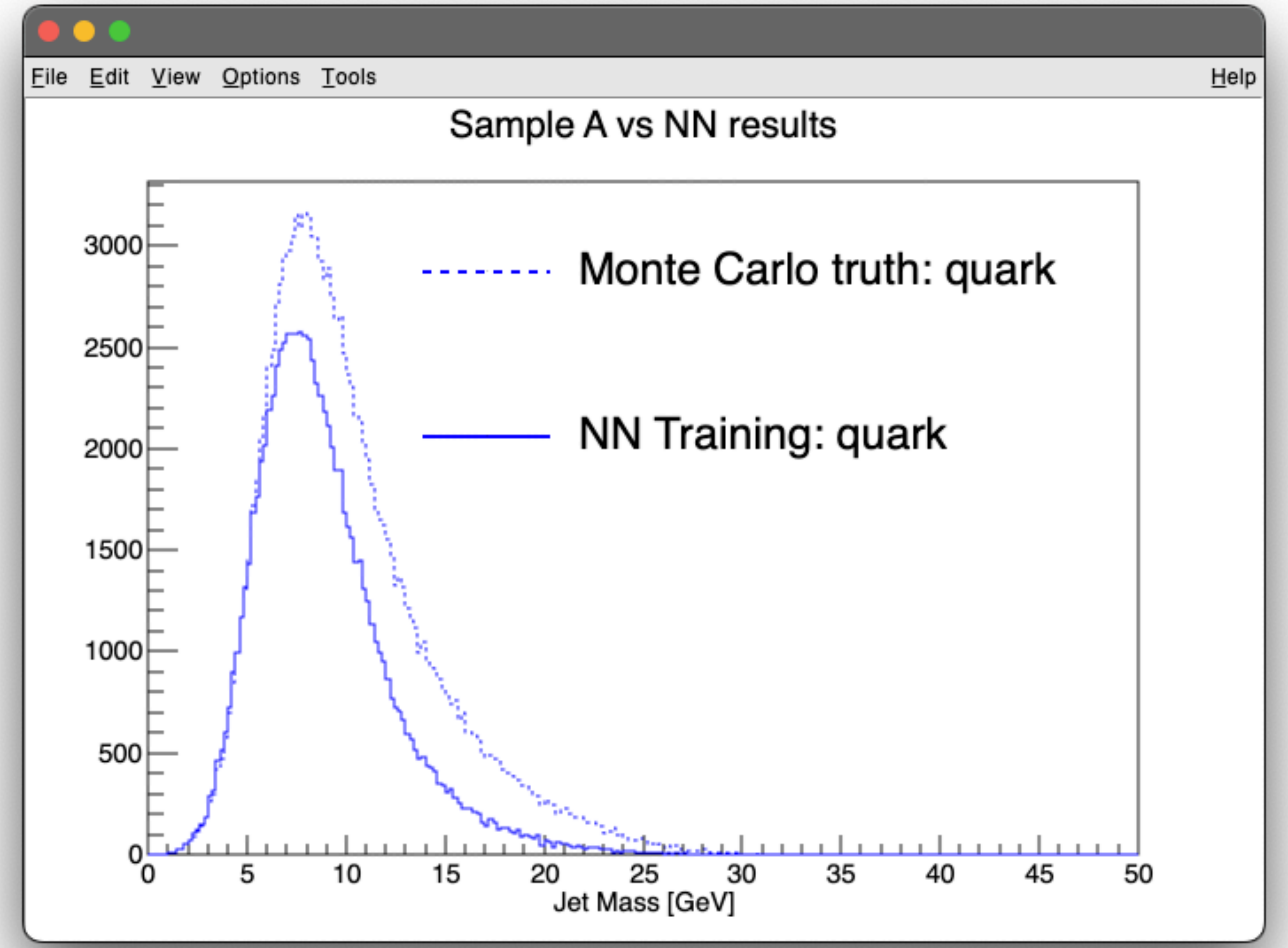
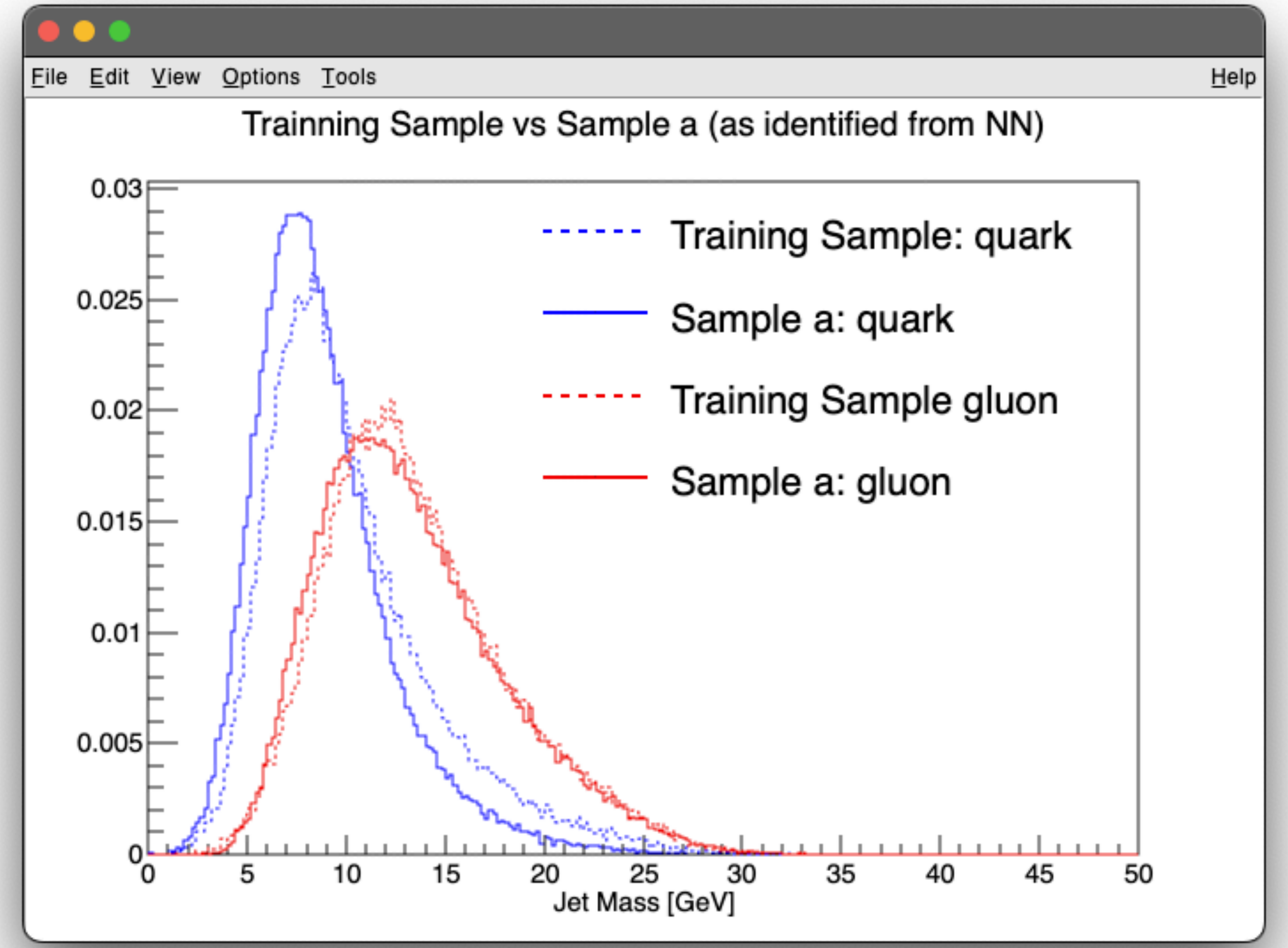


Quark vs Gluon jets

Solution

- Try to Identify the best observable to discriminate between quark-initiated jets from gluon-initiated jets:
  - An attempt: Jet Multiplicity (ntowers)
    - Selection example: Fisher Algorithm with cut at "0.1"
    - Checking how does it compare to the training sample:



Quark vs Gluon jets

Exercise

- Try to Identify the best observable to discriminate between quark-initiated jets from gluon-initiated jets:
  - Play with more than one observable and different methods:
    - a: “identical” samples

Quark vs Gluon jets

Exercise

- Try to Identify the best observable to discriminate between quark-initiated jets from gluon-initiated jets:
  - After finding the best combination of parameters use:
    - TMVA_Training.C (to train), TMVA_Application.C (to apply to an unknown sample) and TMVA_compare.C (to compare training with simulation)
    - In samples:
      - a: “identical” samples
      - b: gluon dominated
      - c: quark dominated

Quark vs Gluon jets

Exercise

- Try to Identify the best observable to discriminate between quark-initiated jets from gluon-initiated jets:
  - After finding the best combination of parameters use:
    - TMVA_Training.C (to train), TMVA_Application.C (to apply to an unknown sample) and TMVA_compare.C (to compare training with simulation)
    - In samples:
      - a: “identical” samples — 123 015 quark-jets vs 87 449 gluon-jets
      - b: gluon dominated — 4 697 quark-jets vs 87 449 gluon-jets
      - c: quark dominated — 118 363 quark-jets vs 5 922 gluon-jets