New Tools to hunt for Multi-jet resonances

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QCD@LHC 2019, Buffalo

Based on: EXO-17-030 (10.1103/PhysRevD.99.012010)

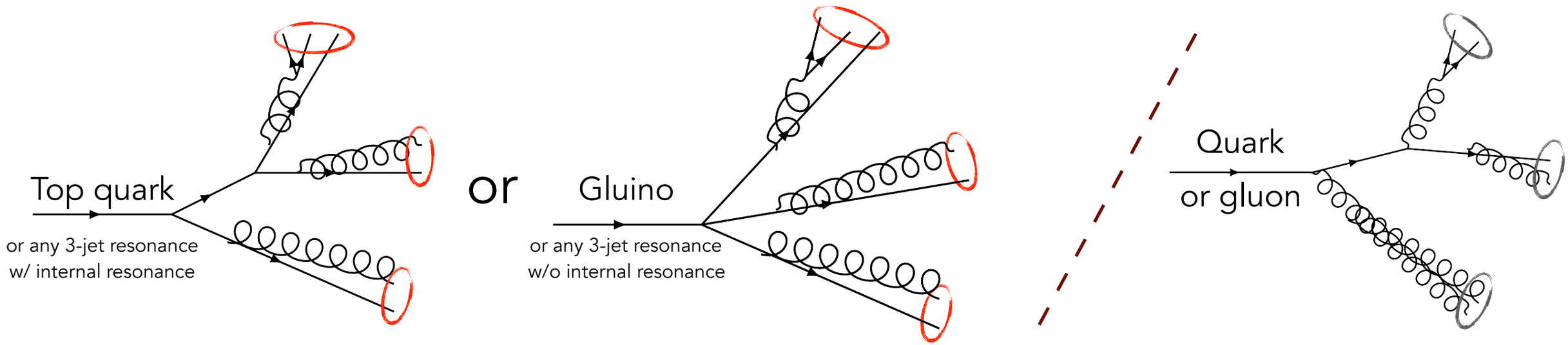
and work in progress with Scott Thomas, Amit Lath

Introduction

- Multi-jets is a very interesting final state !
- It is predicted by particle decays from various BSM models
  - RPV SUSY
  - Exotic Higgs decays
  - Colorons
  - Leptoquarks
  - And many more . . .
- But at LHC, QCD multi jets is a dominating background !
- Aim of this talk : Explore methods, techniques and new ideas to discriminate background (QCD multi jets) to look for these BSM multi jet signatures

Multijet resonances

- Lets take a look at the 3-jet resonances
- How do we tell differences between these ?



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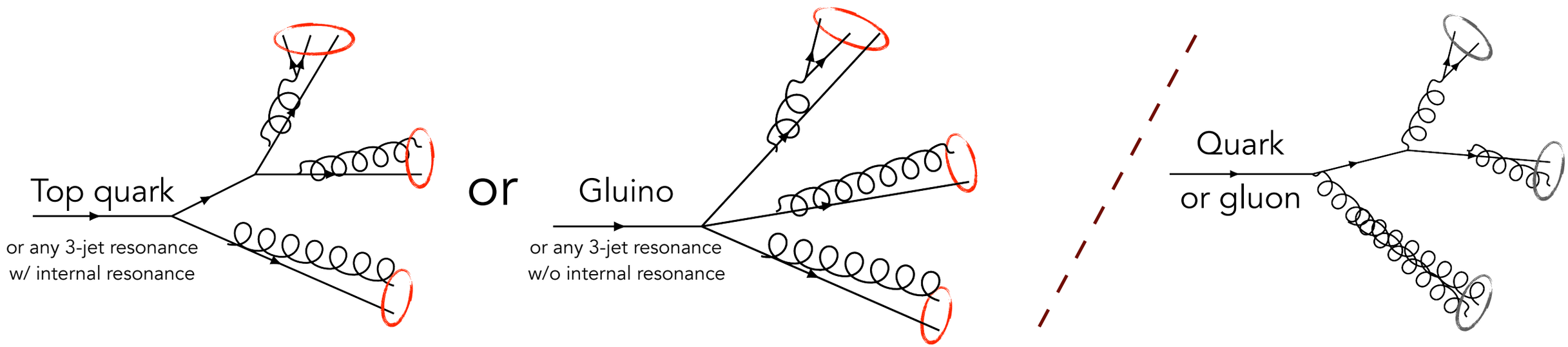
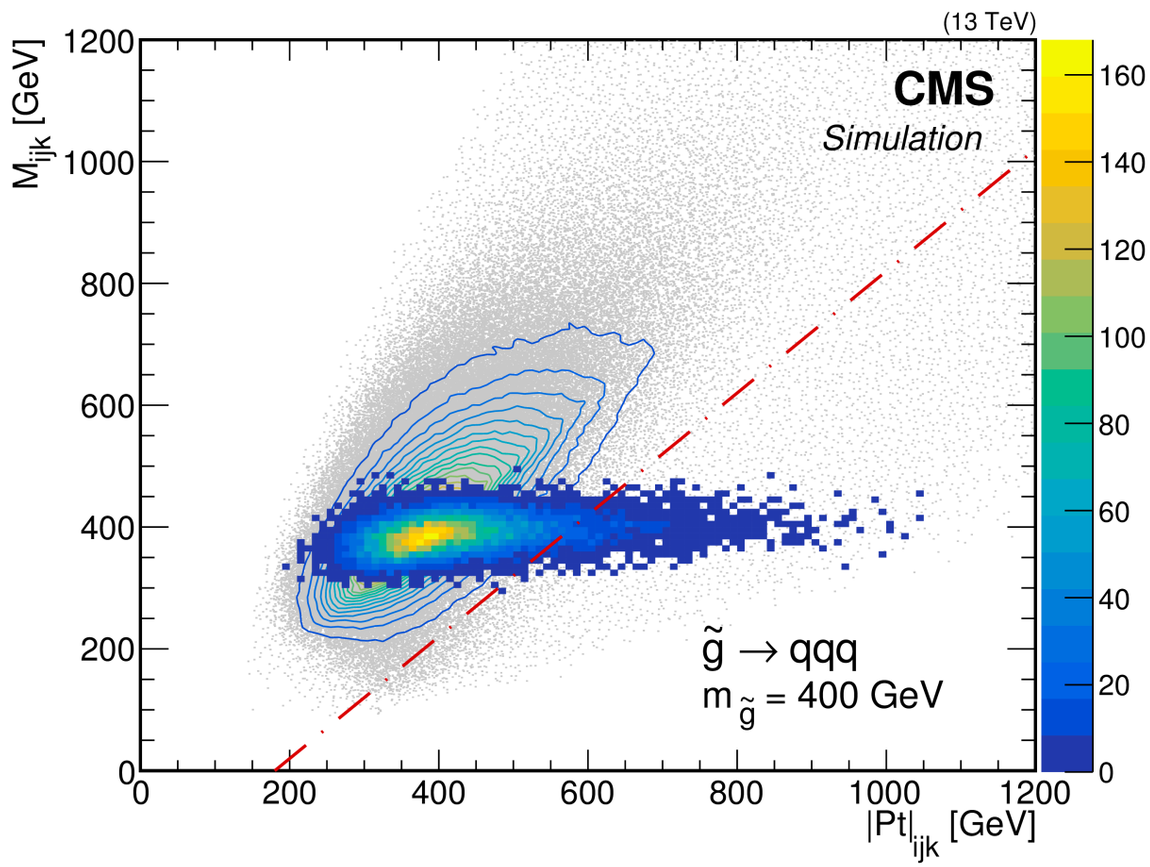


- Multi jet resonances have constant invariant mass
  - Delta cut, a triplet macro level variable exploits this

The Delta cut

- Invariant mass of 3-jet resonances is constant
- For QCD trijets there is a linear correlation of mass w.r.t pt
- Delta cut captures this feature



- Defined as : $|Pt_{ijk}| - M_{ijk} > \Delta$
- It's an offset in trijet Pt and mass space

- This can be used in the case of any multi-jet resonance
  - Used in the search of paired dijet resonances
- For current BSM searches this may not be efficient by itself.

[1]: EXO-17-030, 10.1103/PhysRevD.99.012010

Multijet resonances

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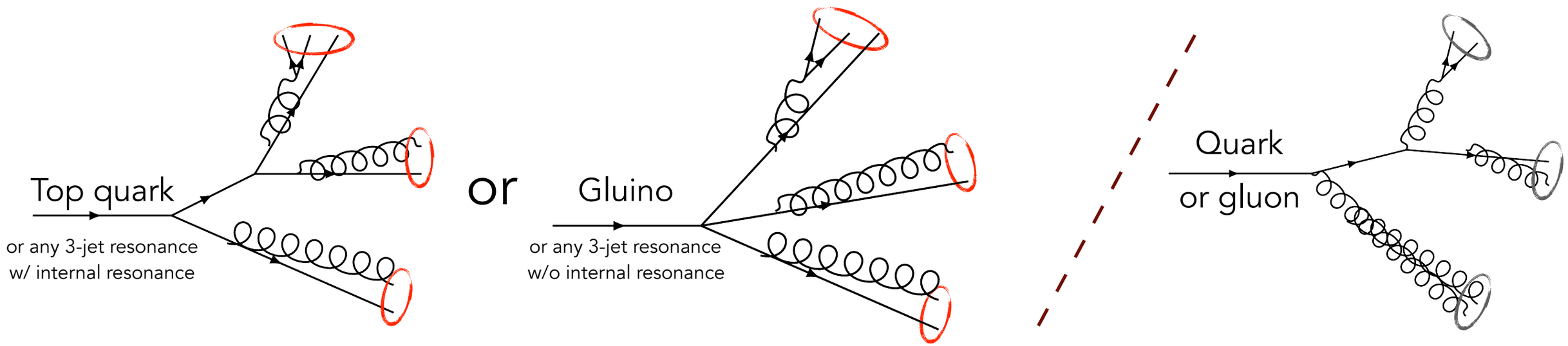
- How do we tell differences between these signatures?



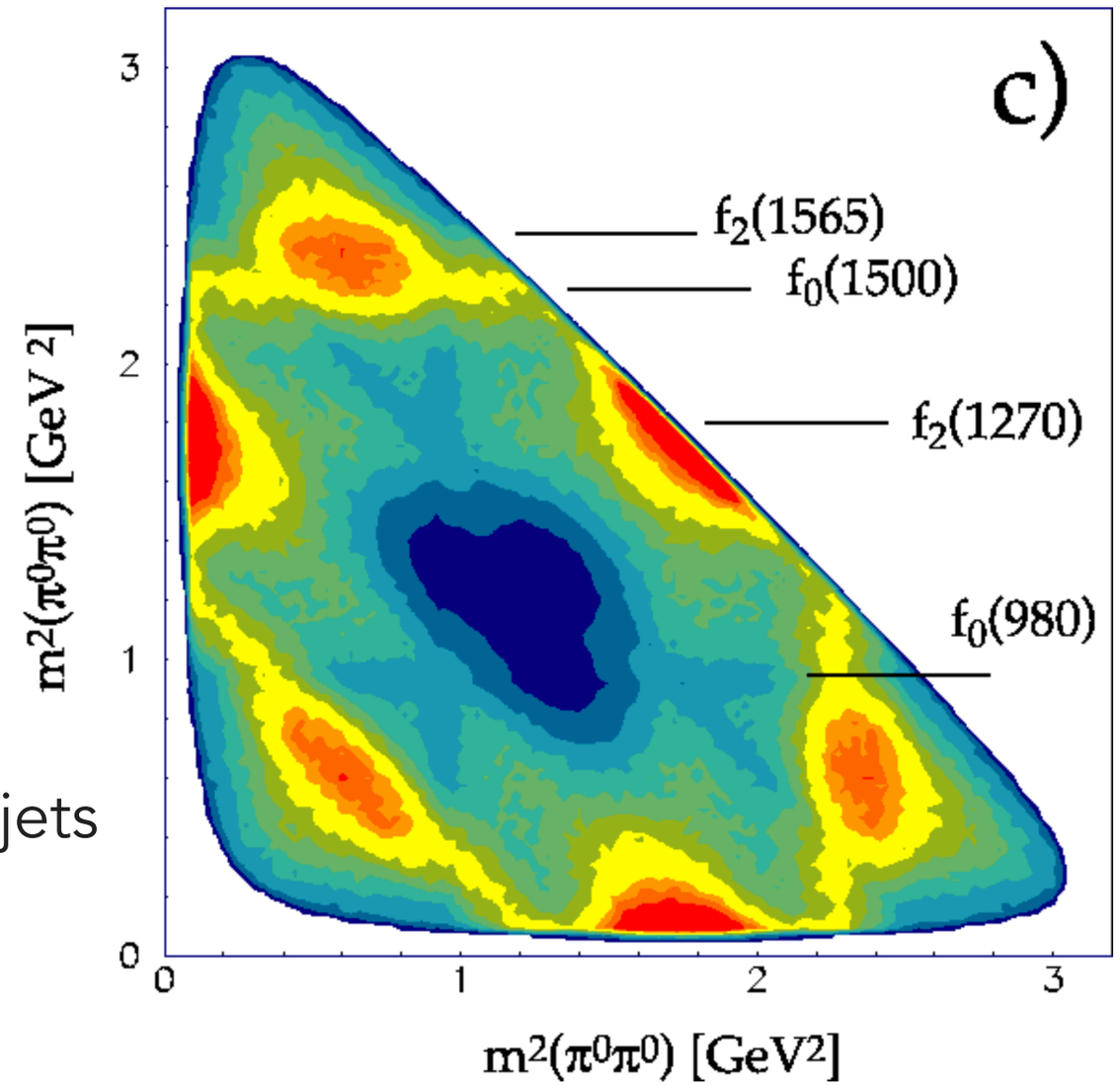
- Multi jet resonances have constant invariant mass
  - Delta cut helps, but not good enough by itself, especially at high masses
- What more can we use from these decays?
  - There is an interesting decay topology.
  - Use theses features to distinguish them.

Trijet internal dynamics - Dalitz plots

- A well known method to study the internal dynamics of a three-body decay is through "**Dalitz Plots**"
  - Used to study the decay of "τ-meson"
- Typically, for a Decay of a particle M → abc
  - We use:

$$x = m_{ab}^2 \quad \text{and} \quad y = m_{ac}^2$$

- Here we have Dalitz plot for $p\bar{p} \to \pi^0\pi^0\pi^0$
- Here to make Dalitz plots, we plots Invariant mass vs Invariant mass of pair of objets in three-body decay
  - We look at 'ab' vs 'ac' correlation, is there more information to gain by adding information of 'bc' ?
  - Can we use dimension less variables to construct this ?



[2]: Phys. Lett. B**355**, 425, (1995),
[3]: arXiv:hep-ex/9708025

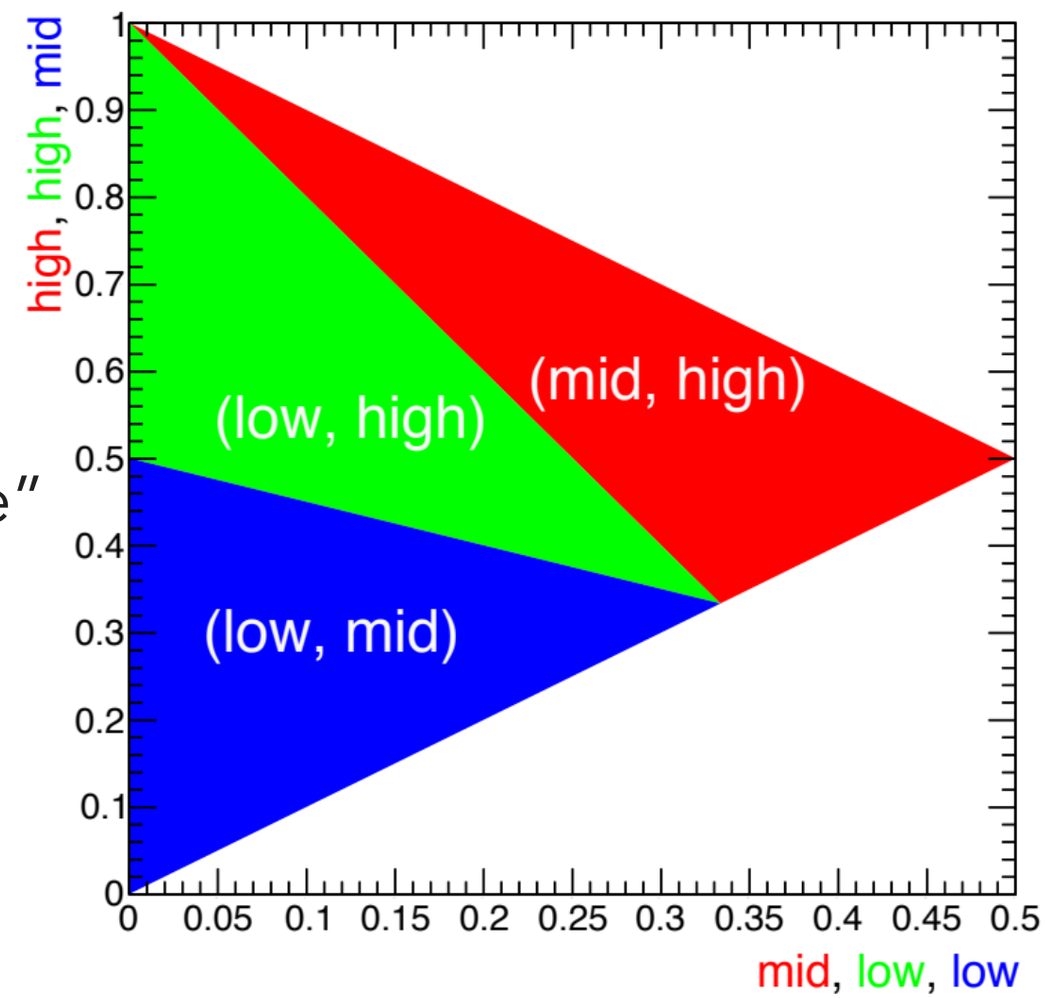
Dalitz variables

- We construct the Dimensionless Dalitz variables for trijets by
  - Take the invariant mass of pairs of jets in trijets, normalize them
  - Dalitz variables are defined as:

$$\hat{m}(3,2)^2_{ij} = \frac{m^2_{ij}}{m^2_{ijk} + m^2_i + m^2_j + m^2_k} \quad \text{where } i, j, k = 1,2,3$$

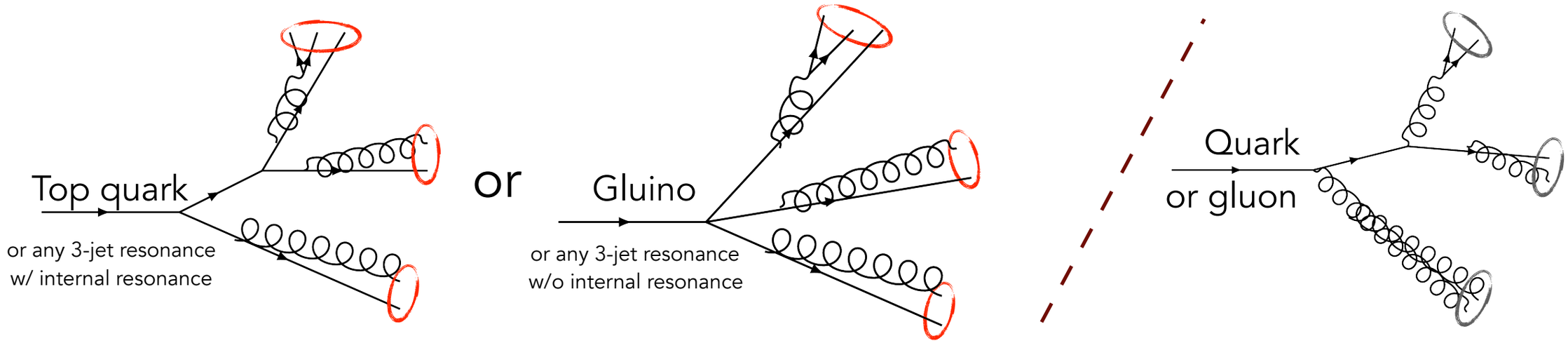
  - For a given triplet, we have: $\hat{m}^2_{12}$, $\hat{m}^2_{13}$, $\hat{m}^2_{23}$
- Arranging these variables in ascending order, we have: $\hat{m}^2_{\text{low}}$, $\hat{m}^2_{\text{mid}}$, $\hat{m}^2_{\text{high}}$
- To project to the information from "Dalitz-plane" in this 3-D space, we plot:

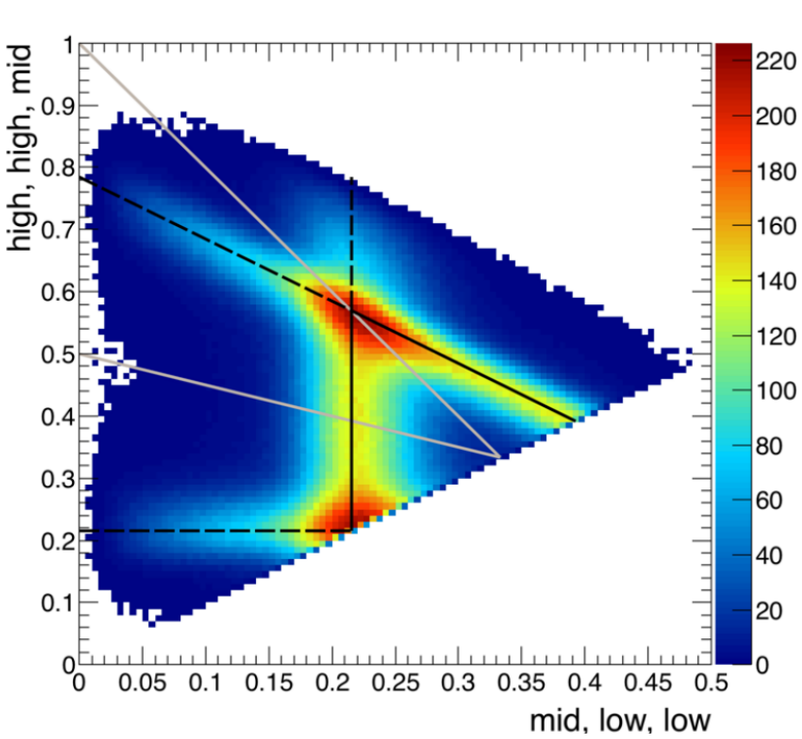
  $\hat{m}^2_{\text{low}}$ vs $\hat{m}^2_{\text{mid}}$, $\hat{m}^2_{\text{mid}}$ vs $\hat{m}^2_{\text{high}}$, $\hat{m}^2_{\text{low}}$ vs $\hat{m}^2_{\text{high}}$
- This is a new way to make Dalitz plots

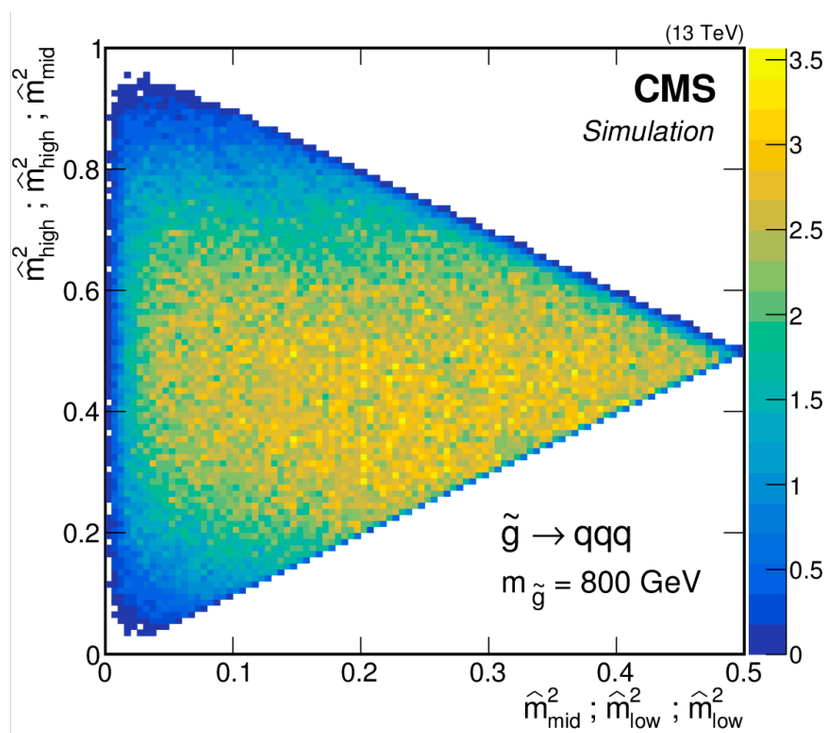


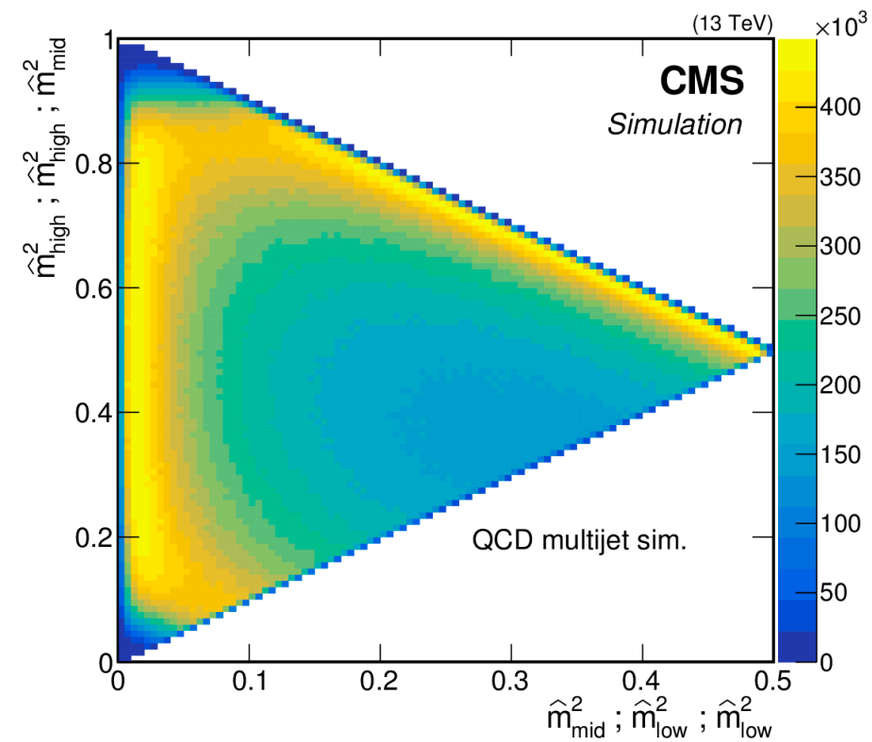
Dalitz plane

- How do our three cases of trijet decays look in this plane ?







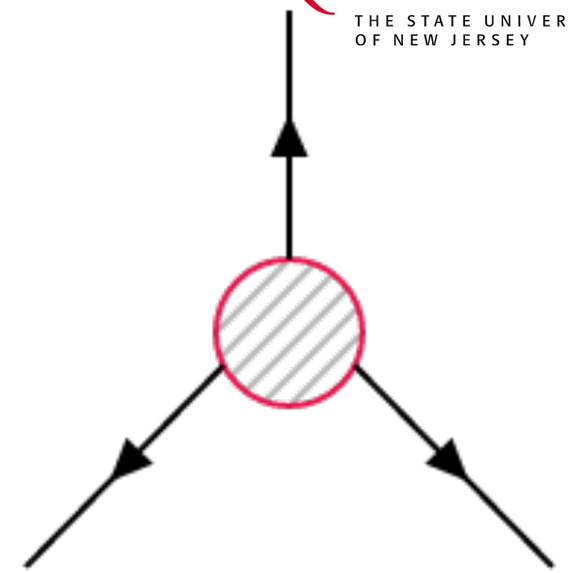


- In the Dalitz plot for top decay, we see the resonance lines indicating $m_{\mathrm{W}}^2/m_{\mathrm{top}}^2 \sim 0.21$!

[1]: EXO-17-030, 10.1103/PhysRevD.99.012010

Mass Distance Variables

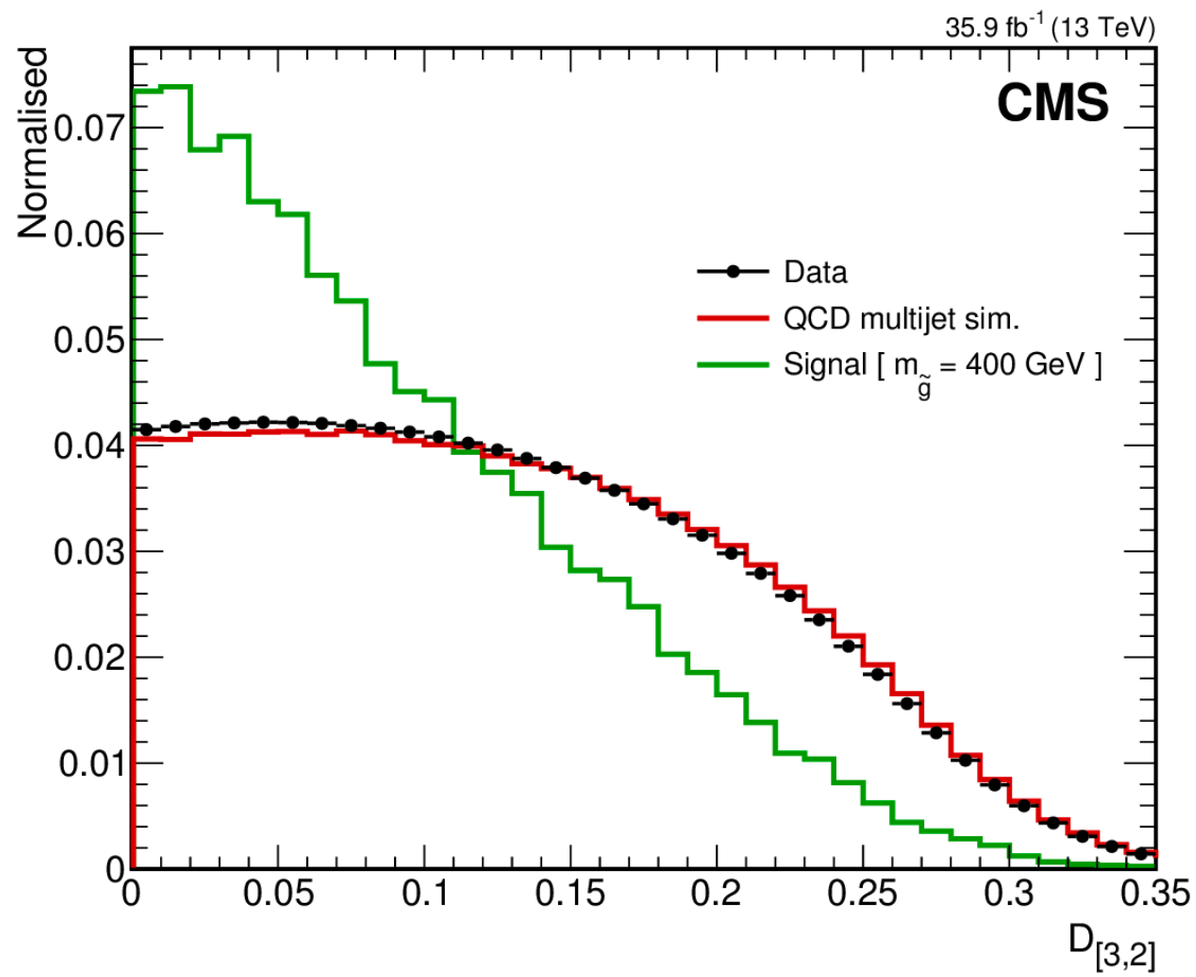
- In the rest frame of gluino, the decay is very symmetric
  - We need a 'Distance measure', which tells how symmetric is the decay to trijets



- For a symmetric decay, we have $\implies \hat{m}_{ij}^2 \sim \frac{1}{3}$
- Using this feature , we create a variable"Mass Distance Squared"
- It is defined as :

$$D^2_{[3,2]} = \sum_{i>j} \left(\hat{m}_{ij} - \frac{1}{\sqrt{3}} \right)^2$$

- This gives great signal/bkg discrimination from QCD multi jets
- It can used to identify the right three-jet combination in a multi-jet event



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Going beyond trijets

- The idea of Dalitz variables can be easily extended to identify features of multi-jet decays, beyond three jets.
- In a "n-jet" decay, we can look at a "m-jet" object
- For this we construct the Dalitz variables,

$$\hat{m}(n,m)^2_{i_1,i_2\ldots i_m} = \frac{m^2_{i_1,i_2\ldots i_m}}{C_1 m^2_{i_1,i_2\ldots i_n} + C_2 \sum_{i=1}^{n} m_i^2}$$

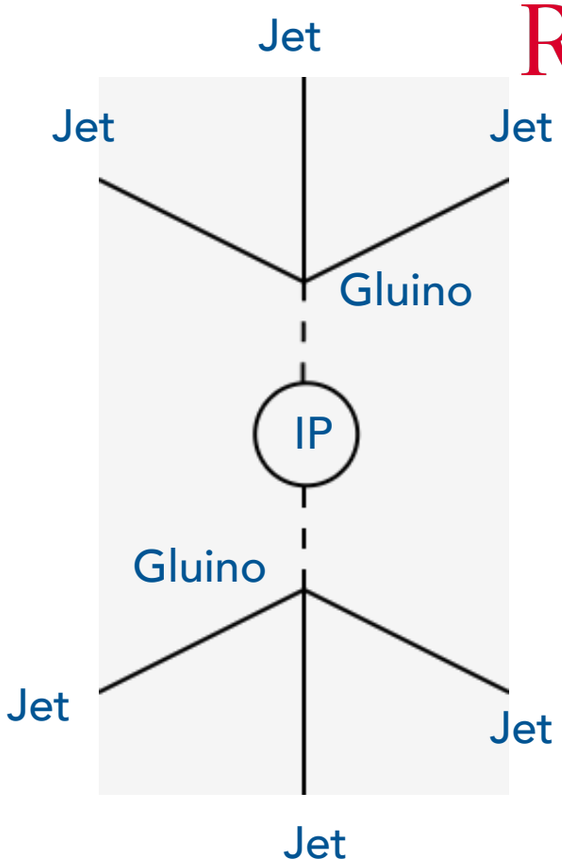
- If these "m-jet" objects in this "n-jet" decay are evenly distributed (or close to), we can define a distant measure

$$D^2_{[n,m]} = \sum_{i_1>i_2>\ldots i_m} \left(\hat{m}(n,m)_{i_1,i_2\ldots i_m} - \sqrt{\binom{n}{m}^{-1}} \right)^2$$

- These tools can used to identify certain decay topologies,
  - we can make custom distance measures, by mixing $D^2_{[n,m]}$ and $\hat{m}(n,m)^2_{i_1,i_2\ldots i_m}$

Building event level variables

- Lets take the Case of pair produced gluinos
- Features of this decay topology
  - Six jets from Gluino decay are more spread out than six jets from QCD
  - Any combination of three jets from this six jets are more likely to be symmetric than in QCD



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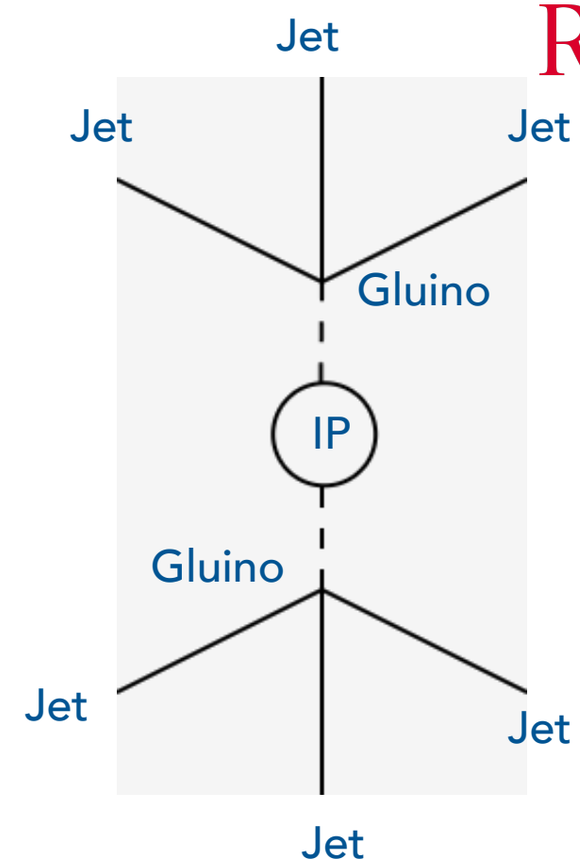
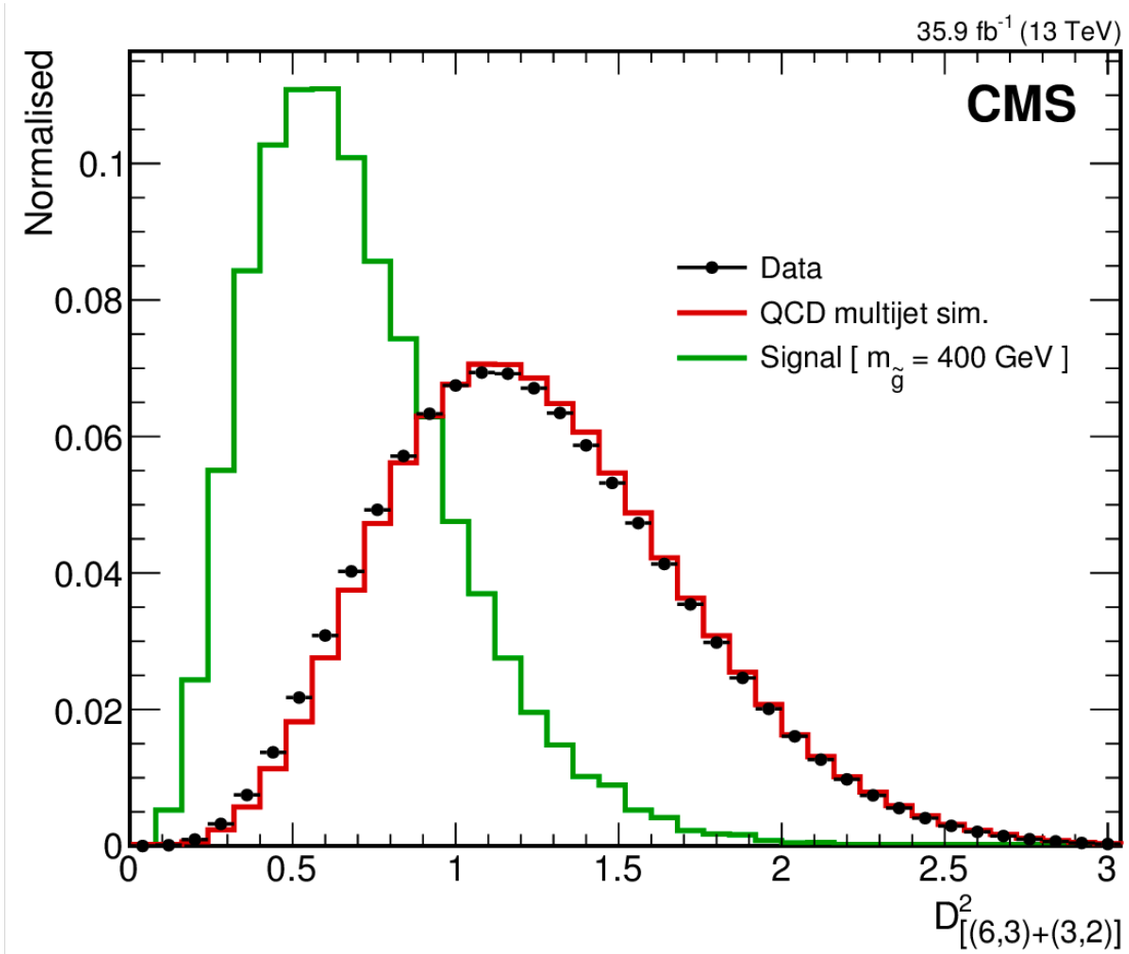
$$D^2_{[(6,3)+(3,2)]} = \sum_{i>j>k} \left(\sqrt{m(\hat{6},3)^2_{ijk} + D^2_{[3,2],ijk}} - \frac{1}{\sqrt{20}} \right)^2$$





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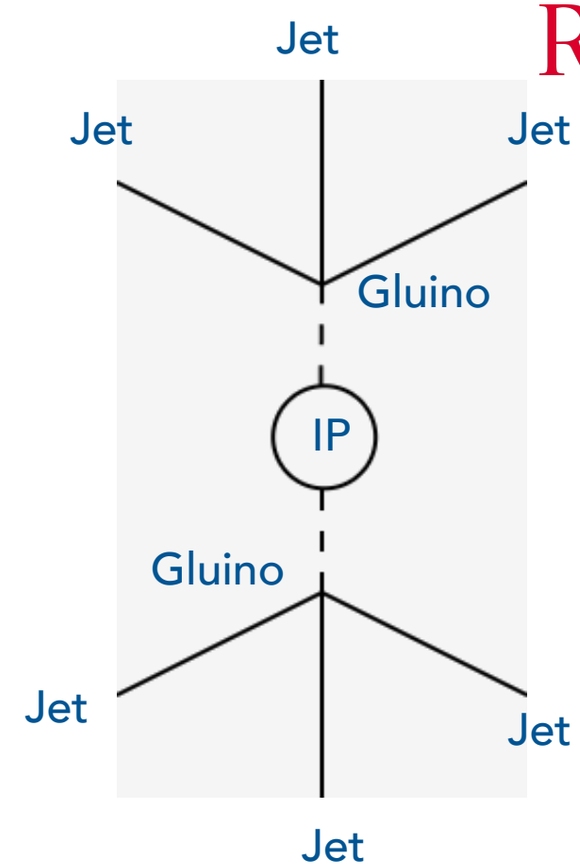

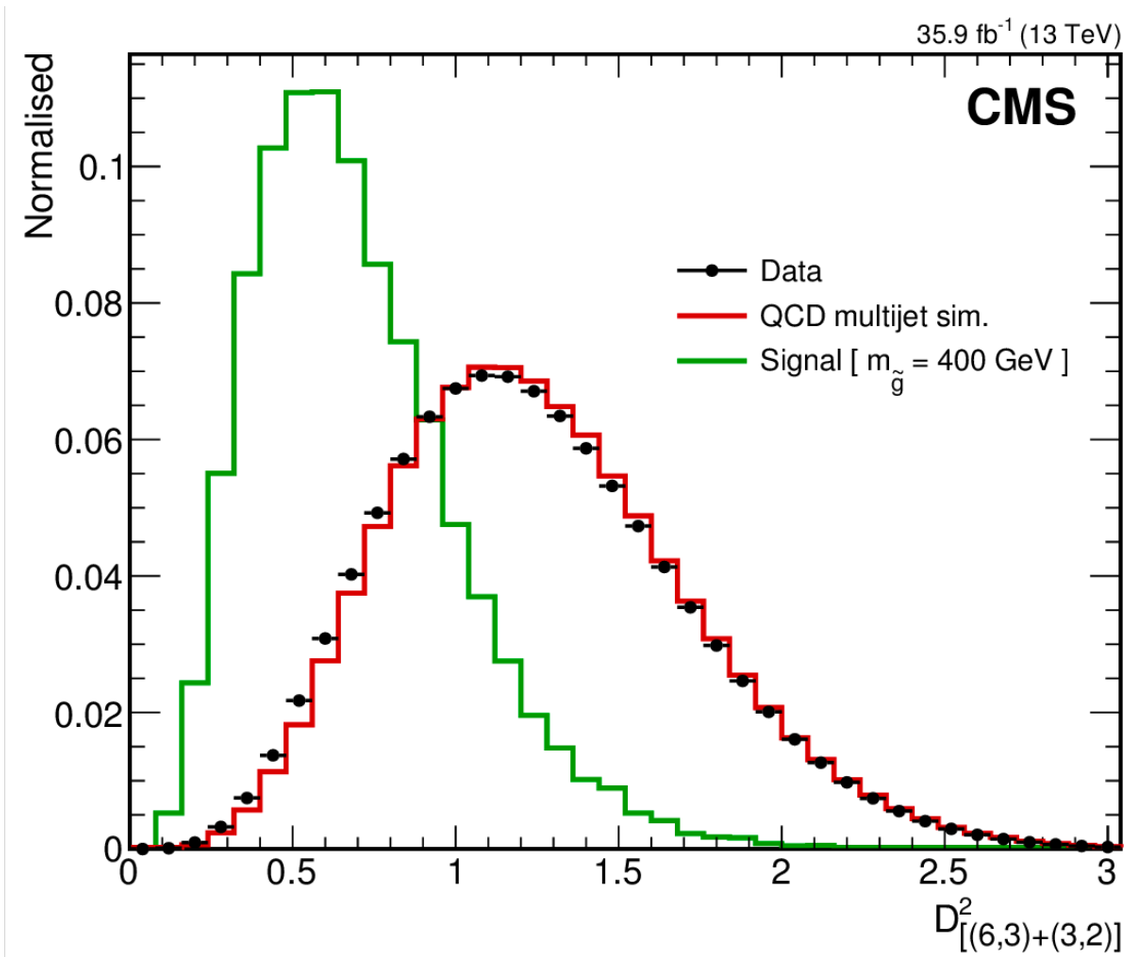

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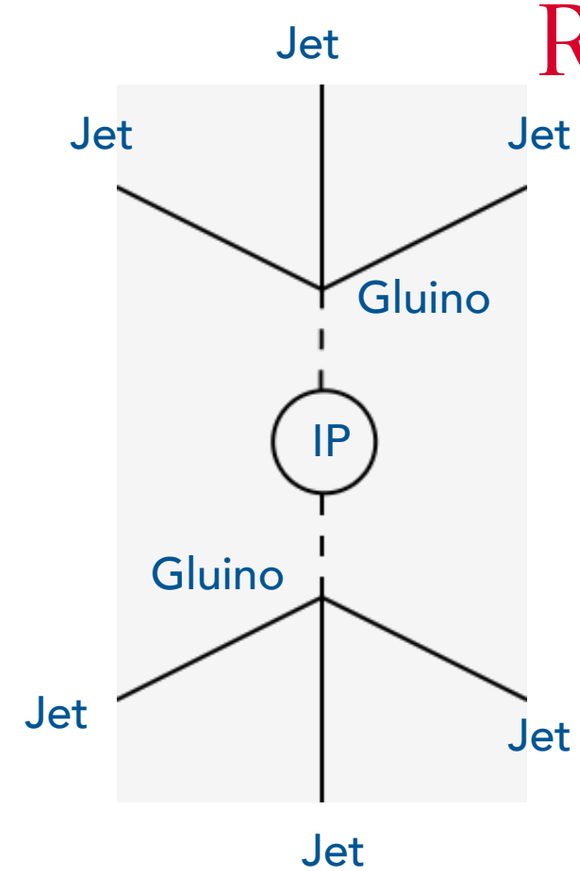
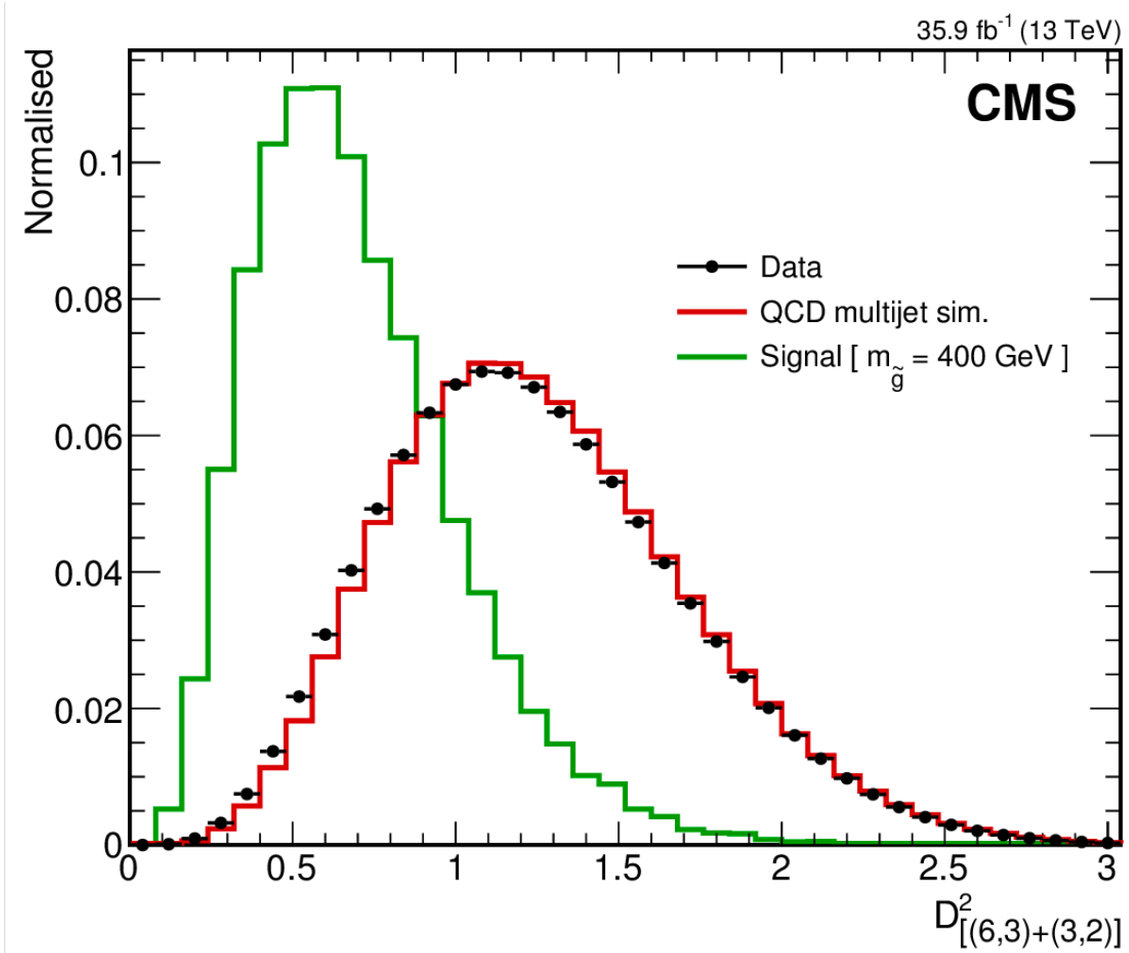
- Gives us a tool to identify event level decay topology
- We see a very close agreement with the data





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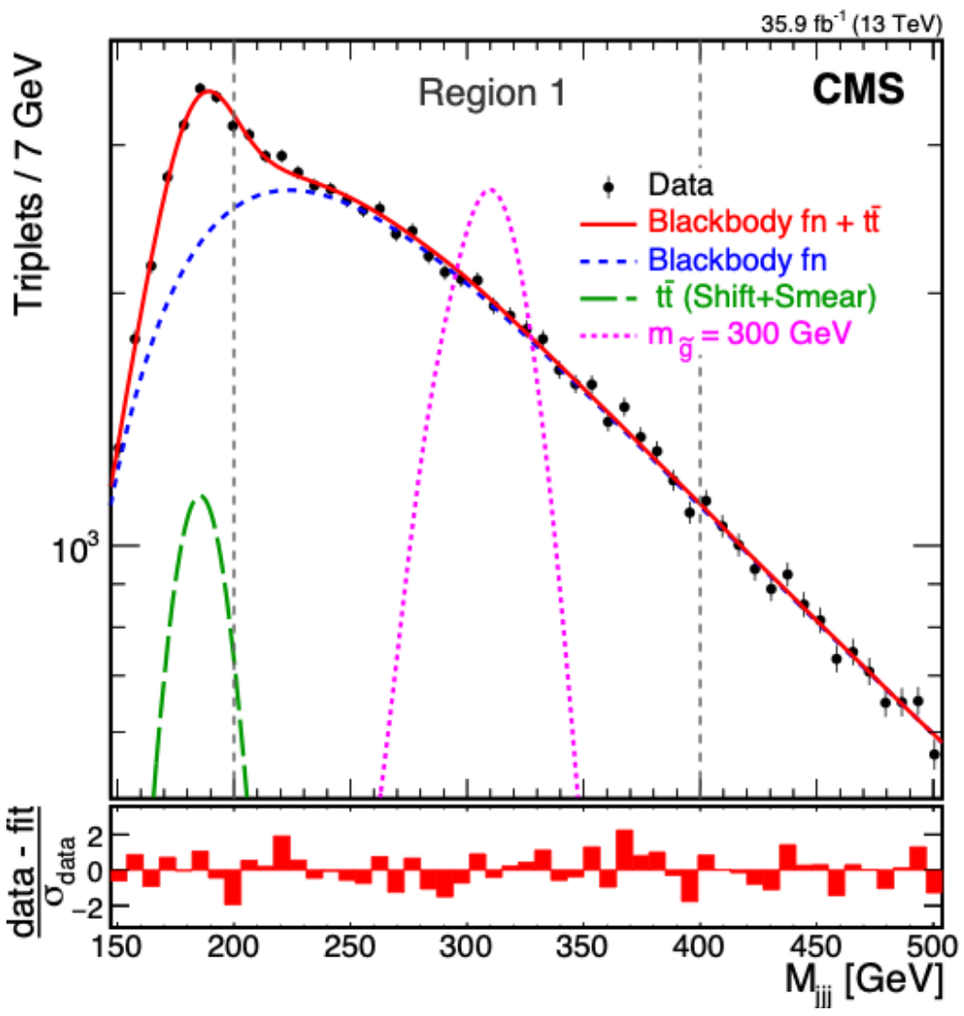
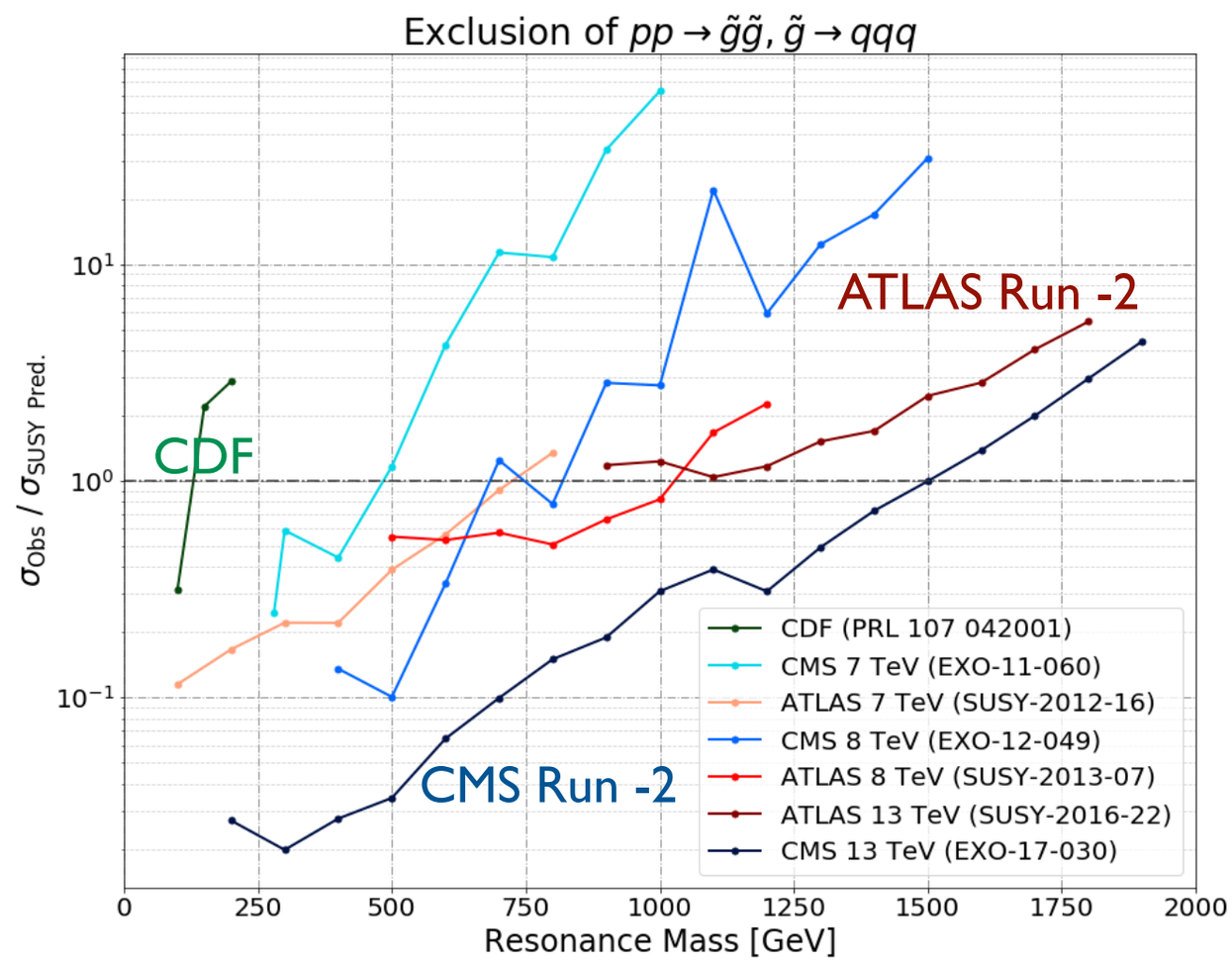
How do they perform ?

- These techniques were used in the search for "Pair-produced three jet resonance search" done at CMS
  - This search used events collected from the trigger using data scouting techniques (PF Scouting)
- These techniques, along with PF Scouting enabled us to see hadronic top decay with no-btag, lepton or MET requirement
- Allowed us to set some of the most stringent limits on gluino pair production





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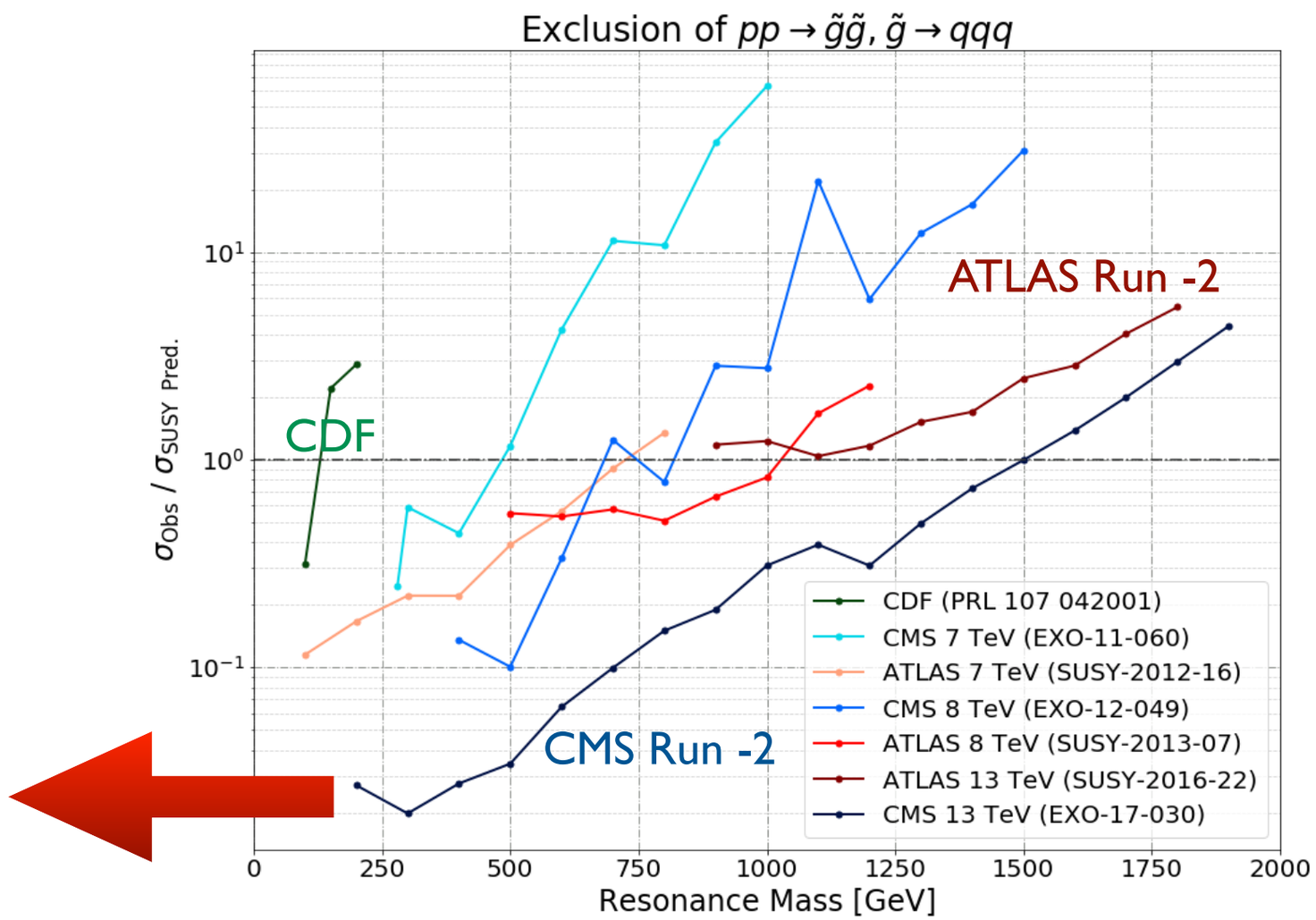
Low mass multi-jet resonances

- All the above techniques described are very good for observing multi-jet resonances
- How do we explore the low mass region ?



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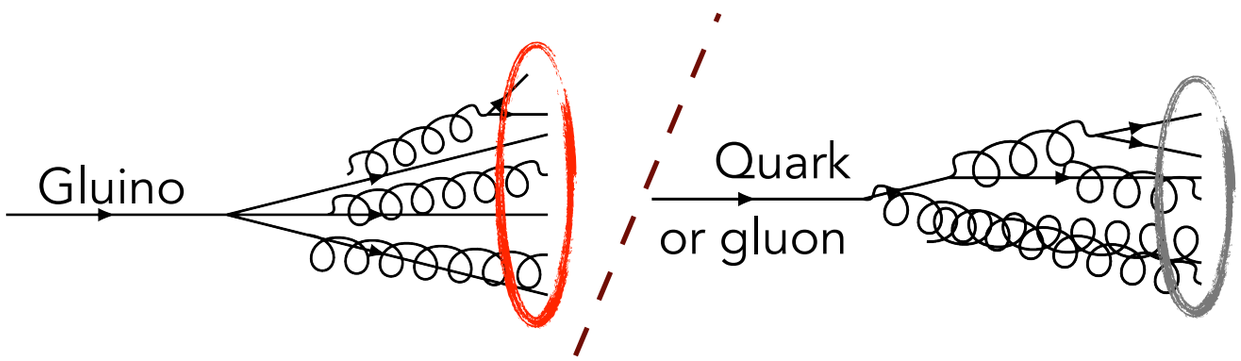
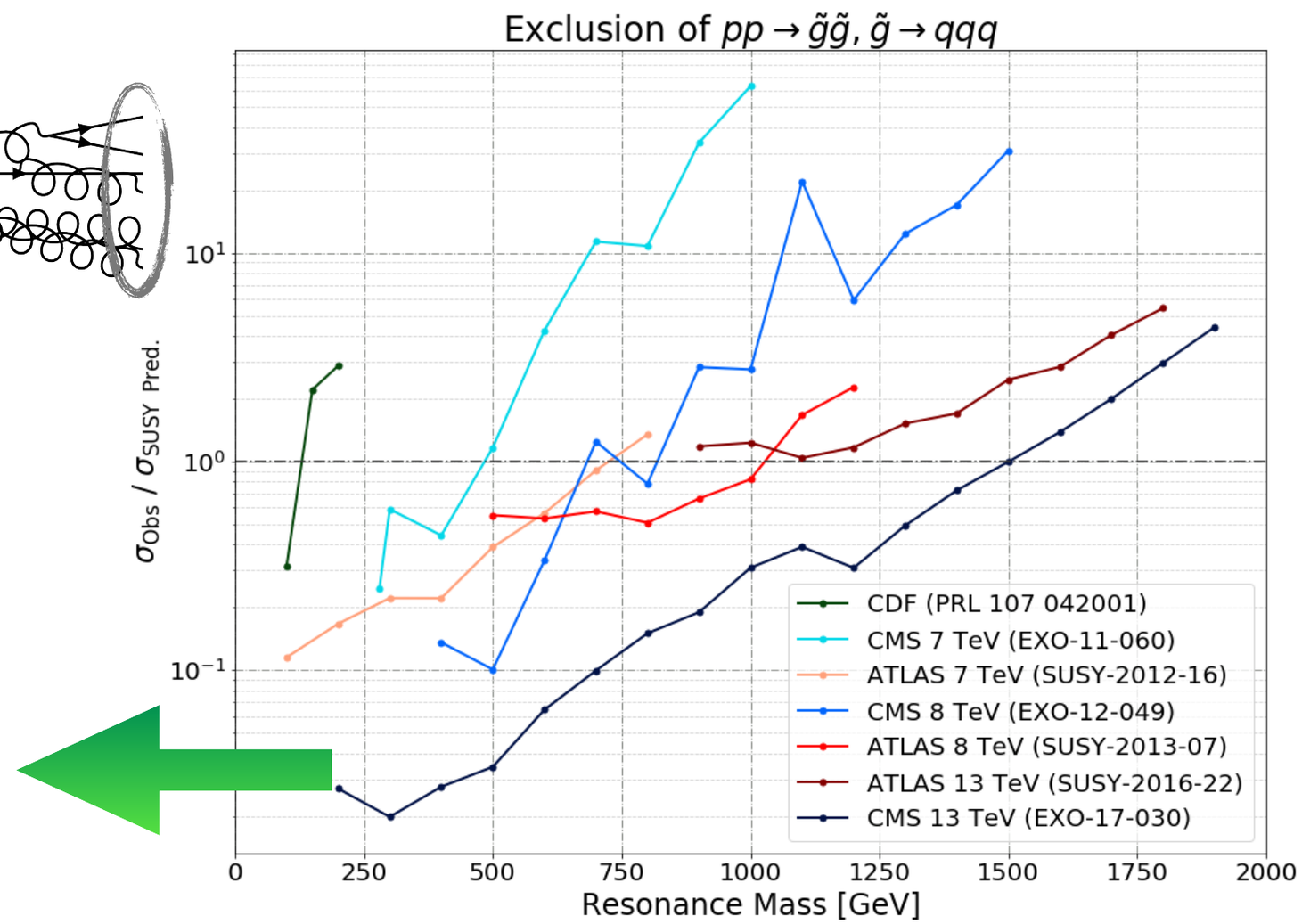
  - Due to current trigger trigger thresholds at LHC, way to go forward is to use boosted objects





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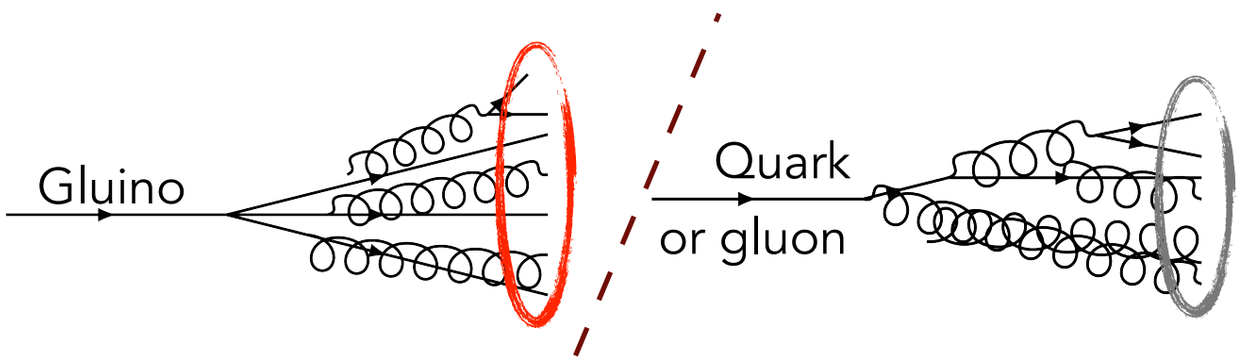
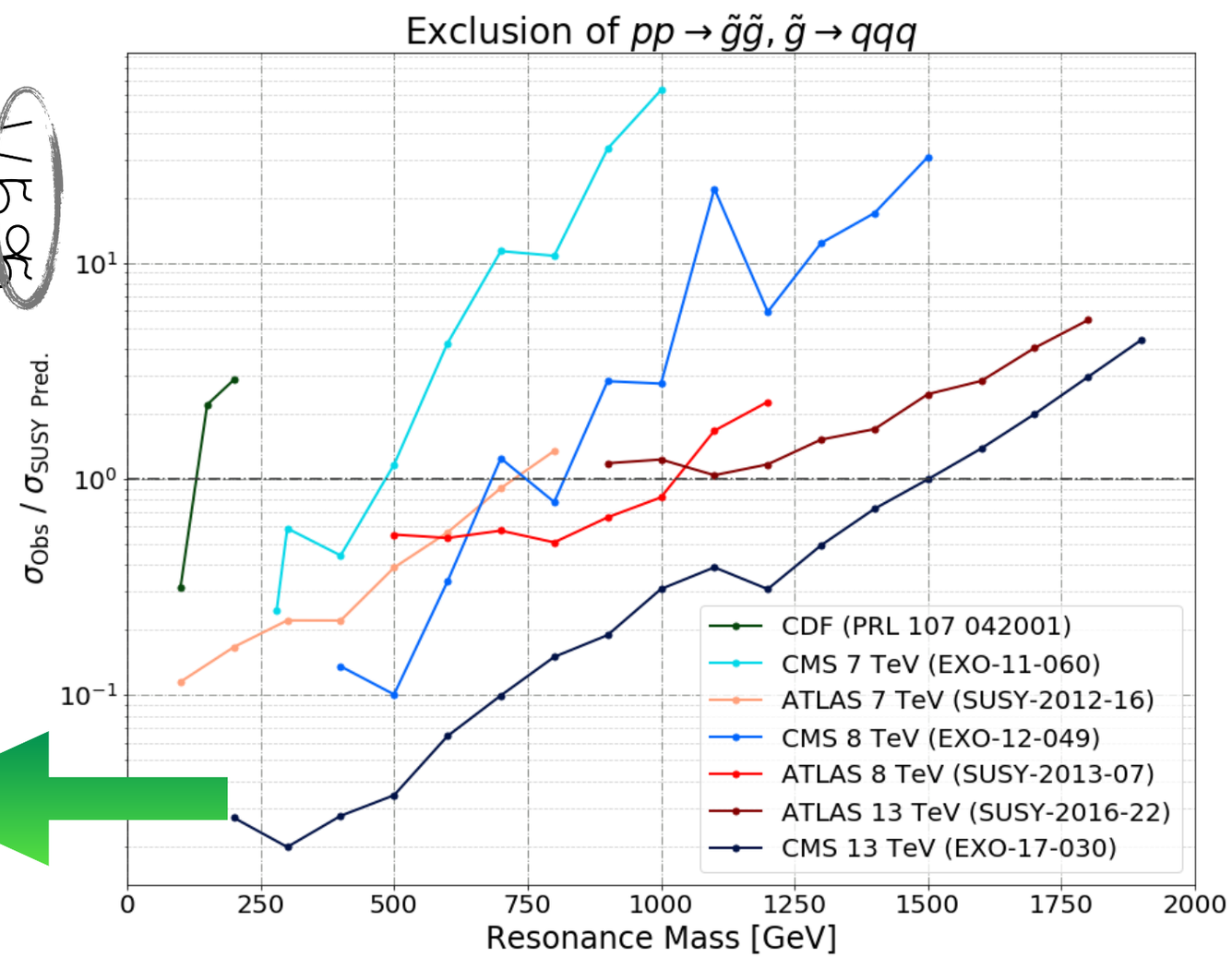


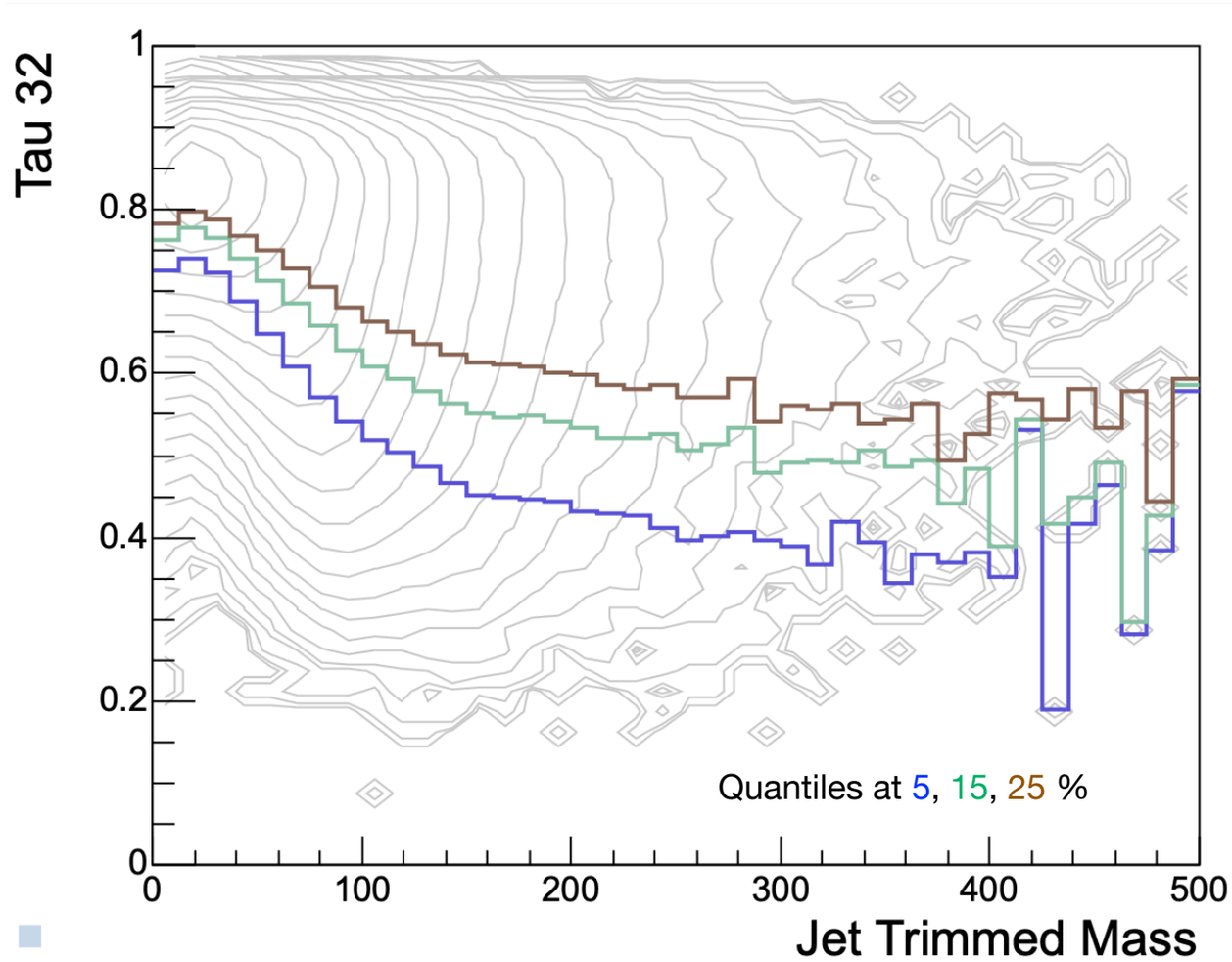


- To identify the multi pronged boosted objects, sub-structure techniques should be employed
  - Currently we use "τ" or "ECF" variables to do this

Sub-structure techniques

(work in progress)

- To identify a boosted three pronged object, we use "τ_{32}"
- But the tau variables are correlated with mass



- To get avoid problem, we have to decorrelate this !
  - Or get around by using new techniques

Dalitz based Sub-structure techniques (work in progress)

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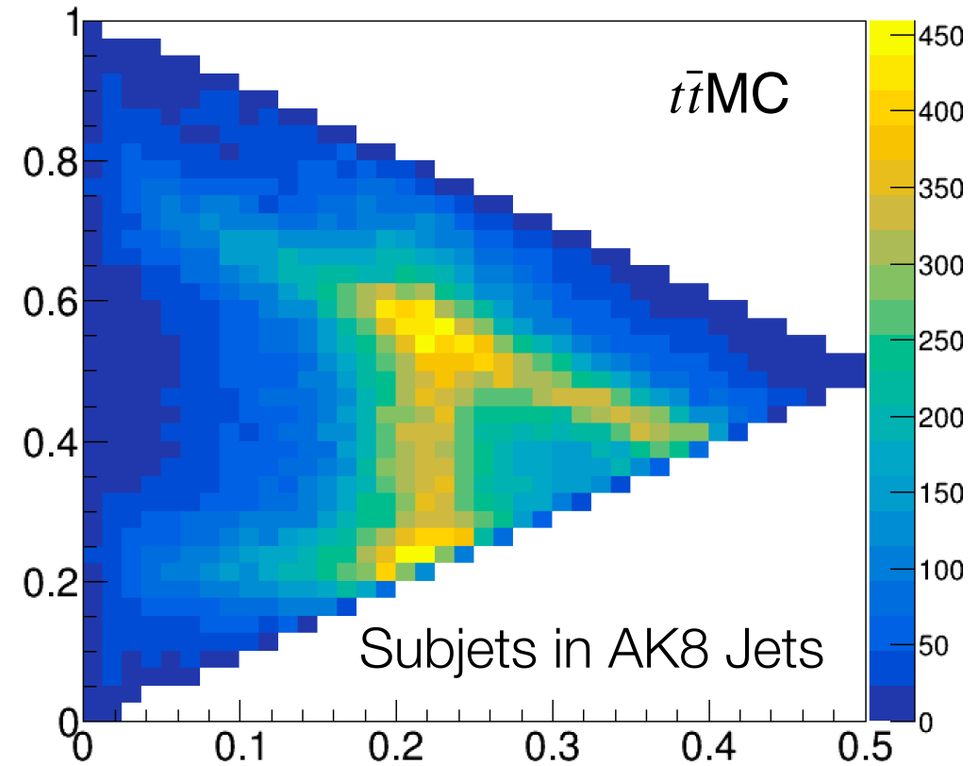
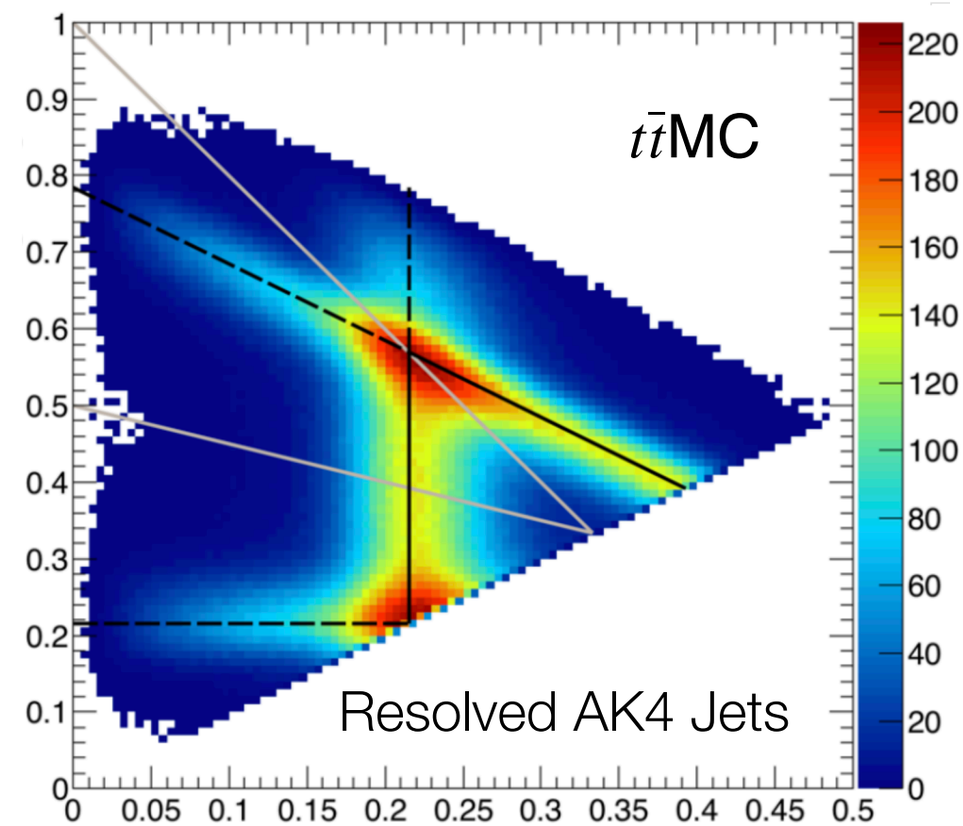
- How to do this:
  - Take a fat-jet, de-cluster the jets to make subjets
    - We currently re-cluster using KT clustering tree
  - Make Dalitz plane using these subjets,
  - Use the appropriate distance measure
- How does it look for merged top decay ?

Dalitz based Sub-structure techniques (work in progress)

- How to do this:
  - Take a fat-jet, de-cluster the jets to make subjets
    - We currently re-cluster using KT clustering tree
  - Make Dalitz plane using these subjets,
  - Use the appropriate distance measure
- How does it look for merged top decay ?
  - We clearly observe the W resonance line at $m_{\mathrm{W}}^2/m_{\mathrm{top}}^2 \sim 0.21$
- This is a promising result, we are working on perfecting it
- We can also use other distance measure to identify boosted objects with different prongs



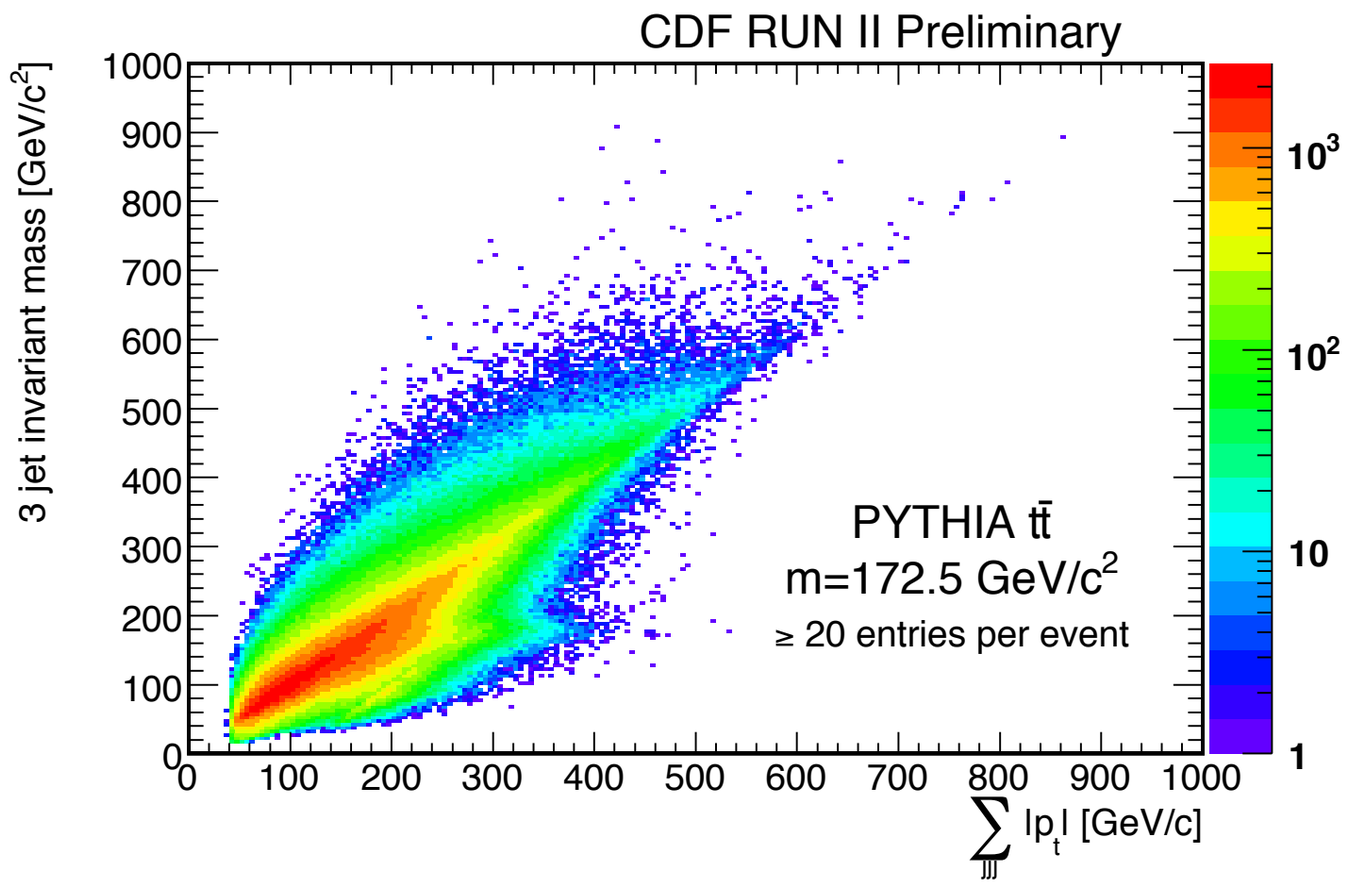


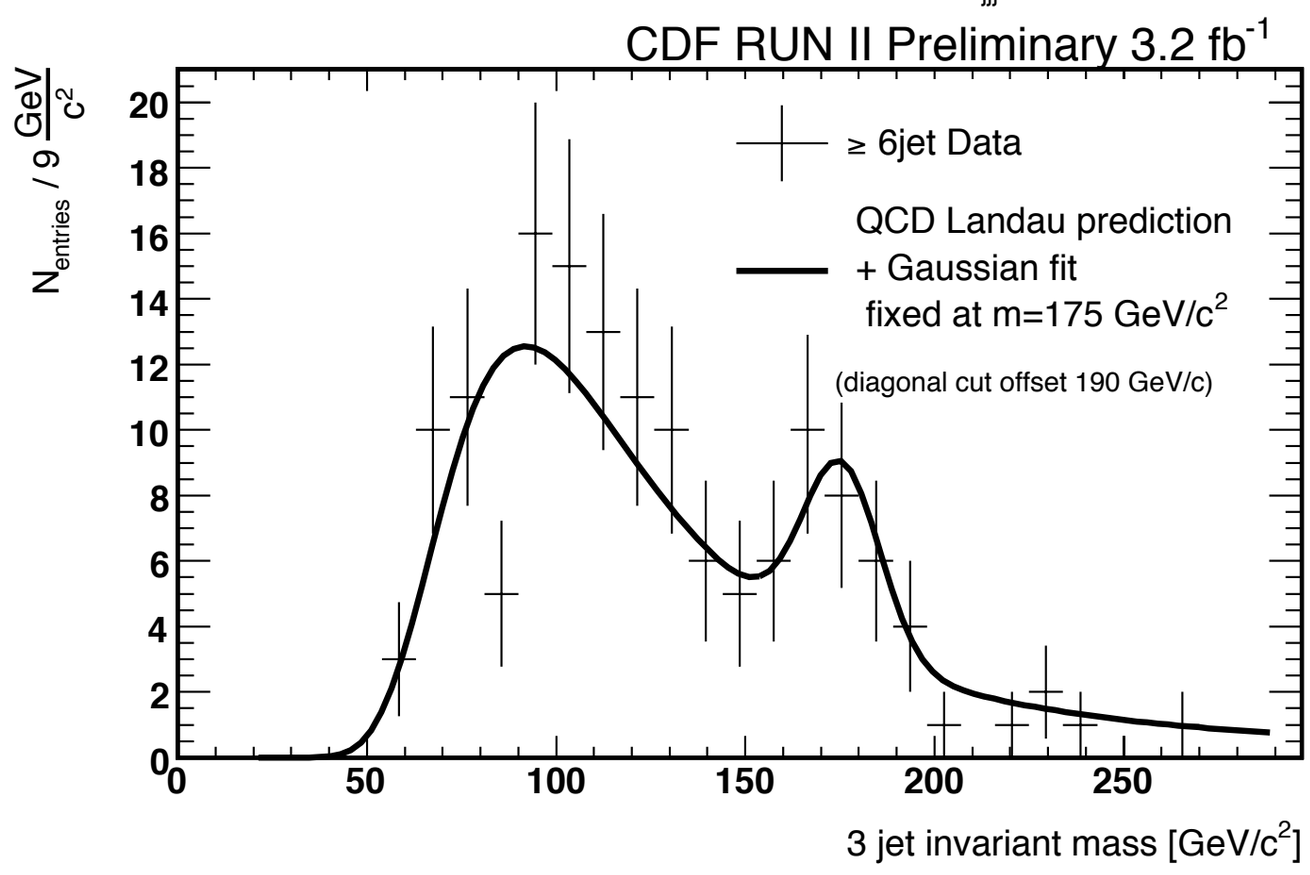
Summary

- Multi-jets is an very interesting final state, predicted by particle decays from various BSM models
  - This is often hard to probe due to the huge QCD multi jet background
  - Delta cuts works very well, but it's not effective just by itself
- Dalitz techniques give us a great tool to study the internal dynamic of a multi jet decay
- Dimensionless Dalitz variables can be used to define various distance measures to identify specific decay topologies
  - They can be used to find the right combination of jets
  - Gives us event-level discriminators
  - Works great when used in searches, to give great results
- Dalitz techniques can even be used to identify substructure inside a boosted object

Back up

Delta Plots from CDF





[4]: PRL 107 042001

Data Scouting

- Triggering is constrained by the CPU time and memory bandwidth available
- CMS records ~ 1kHz of events for physics analysis
- Forces triggers to have high thresholds, making CMS blind to physics at low masses
- Solution : Data Scouting
  - Make physics objets, online at HLT
  - Store only the required information:
    - Four vectors, etc . . .
  - Reduces event sizes (100x smaller)
  - Results in lower triggering thresholds