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

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

Top quark or any 3-jet resonance w/ internal resonance

or

Gluino or any 3-jet resonance w/o internal resonance

Quark or gluon

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Multijet resonances

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

- 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: $|\text{Pt}_{ijk}| - M_{ijk} > \Delta$
- 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

- Let's take a look at the 3-jet resonances.
- How do we tell differences between these signatures?

- Multijet 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 \( p\bar{p} \rightarrow \pi^0\pi^0\pi^0 \)
  - Here to make Dalitz plots, we plots Invariant mass vs Invariant mass of pair of objects 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?

[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:
    \[
    \hat{m}(3,2)^2_{ij} = \frac{m_{ij}^2}{m_{ijk}^2 + m_i^2 + m_j^2 + m_k^2}
    \]
    where \(i, j, k = 1, 2, 3\)

- For a given triplet, we have: \(\hat{m}_{12}^2, \hat{m}_{13}^2, \hat{m}_{23}^2\)

- Arranging these variables in ascending order, we have: \(\hat{m}_{\text{low}}^2, \hat{m}_{\text{mid}}^2, \hat{m}_{\text{high}}^2\)

- To project to the information from “Dalitz-plane” in this 3-D space, we plot:
  \(\hat{m}_{\text{low}}^2 \text{ vs } \hat{m}_{\text{mid}}^2, \hat{m}_{\text{mid}}^2 \text{ vs } \hat{m}_{\text{high}}^2, \hat{m}_{\text{low}}^2 \text{ vs } \hat{m}_{\text{high}}^2\)

- 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 $m_w^2/m_{\text{top}}^2 \sim 0.21$!

[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 $\hat{m}_{ij}^2 \sim \frac{1}{3}$

- Using this feature, we create a variable “Mass Distance Squared”

- It is defined as:

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

- 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,

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

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

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

- These tools can be used to identify certain decay topologies,

- we can make custom distance measures, by mixing $D_{[n,m]}^2$ and $\hat{m}(n, m)_{i_1,i_2...i_m}$
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_6,3_{ijk}^2 + D^2_{[3,2],ijk}} - \frac{1}{\sqrt{20}} \right)^2
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  \[ D^2_{[(6,3)+(3,2)]} = \sum_{i\neq j\neq k} \left( \sqrt{m_{(6,3)}^2_{ijk} + D^2_{(3,2),ijk} - \frac{1}{\sqrt{20}}} \right)^2 \]
- Gives us a tool to identify event level decay topology
- We see a very close agreement with the data

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

[1]: EXO-17-030, 10.1103/PhysRevD.99.012010
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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Low mass multi-jet resonances

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- How do we explore the low mass region?
  - Due to current trigger thresholds at LHC, way to go forward is to use boosted objects

- To identify the multi pronged boosted objects, sub-structure techniques should be employed
  - Currently we use \( \tau \) or \( \text{ECF} \) variables to do this
Sub-structure techniques

• To identify a boosted three pronged object, we use \( \tau_{32} \)

• 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)

• 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)

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  - 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 \( \frac{m_W^2}{m_{\text{top}}^2} \sim 0.21 \)
  - 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

CDF RUN II Preliminary

PYTHIA $t\bar{t}$
$m=172.5$ GeV/$c^2$
$\geq 20$ entries per event

CDF RUN II Preliminary 3.2 fb$^{-1}$

$N_{\text{entries}} / 9 \text{ GeV}^2$

$\geq 6$jet Data
QCD Landau prediction
+ Gaussian fit
fixed at $m=175$ GeV/$c^2$
(diagonal cut offset 190 GeV/c)

[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 objects online at HLT.
- Store only the required information:
  - Four vectors, etc...
- Reduces event sizes (100x smaller).
- Results in lower triggering thresholds.