Improving Heavy Dijet Resonance Searches Using Jet Substructure at the LHC

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Anomalies 2020

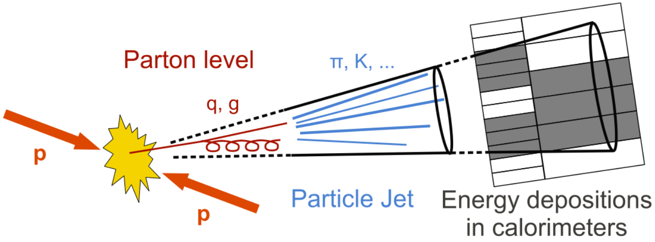
Outline

- Motivation
- Jet and Jet Substructure observables
- Quark vs. Gluon tagging
- Dijet resonance searches
- Results
- Summary

Motivation

- Resonance search is perhaps the most simple and direct ways to find new particles at a collider.
- LHC is running at 13 TeV. This can produce heavy resonances up to 4-5 TeV.
- Being a hadron collider, heavy strongly interacting particles can be produced at the LHC easily.
- Now, we have better understanding of Jet and its substructure.
- Current dijet resonance search strategies do not use Jet substructure technique.
- Will Jet substructure help us to probe heavy resonances?

Jets at Collider



A **Jet** is a collection of four momenta resulting from Jet Clustering Algorithm.

Jet algorithms: C/A, kt, anti-kt.

Fig: cms.cern

Jet Substructure Observables

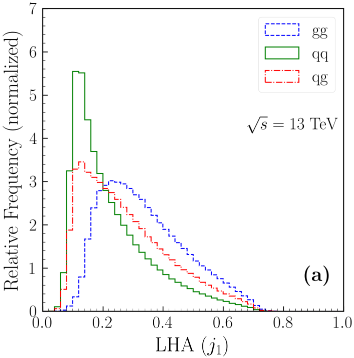
Jet substructure (JSS) observables are variables constructed from the constituents of the jet.

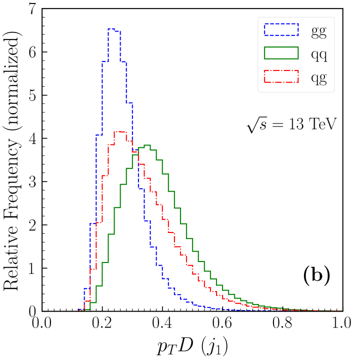
Examples:

- Particle and track multiplicity inside a jet.
- Les Houches Angularity: $\mathrm{LHA} = \sum_{i \in J} \cdot \frac{p_{T_i}}{p_{T_J}} \sqrt{\frac{\Delta R(i,J)}{R}}$.
- Width: $w = \sum_{i \in J} \frac{p_{T_i}}{p_{T_J}} \left(\frac{\Delta R(i,J)}{R} \right)$.
- Two-point energy correlation variables: $e_\beta = \sum_{i > j \in J} \frac{p_{T_i} p_{T_j}}{p_{T_J}^2} \left(\frac{\Delta R(i,j)}{R} \right)^\beta$.
- p_T^2 weighted jet minor axis (σ_2) with respect to the jet axis in $\eta - \phi$ plane.
- $p_T D = \frac{\sqrt{\sum_{i \in J} p_{T_i}^2}}{\sum_{i \in J} p_{T_i}}$.

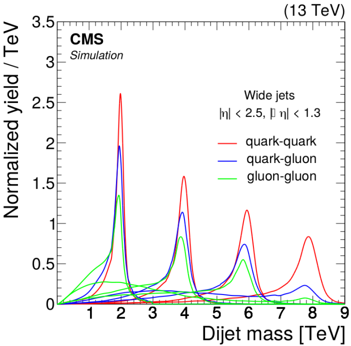
quark vs. gluon tagging

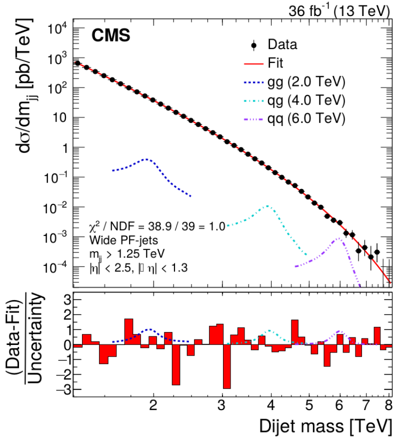
- The distributions of jet substructure observables constructed from quark-initiated jets differs from those of gluon-initiated jets.
- This helps us to tag quark and gluon jet to some extent.





CMS dijet resonance searches





gg	*qg*	*qq*
297 fb	167 fb	108 fb

Table: 95% C.L. upper limit on $\sigma \times A$ at $M = 2$ TeV

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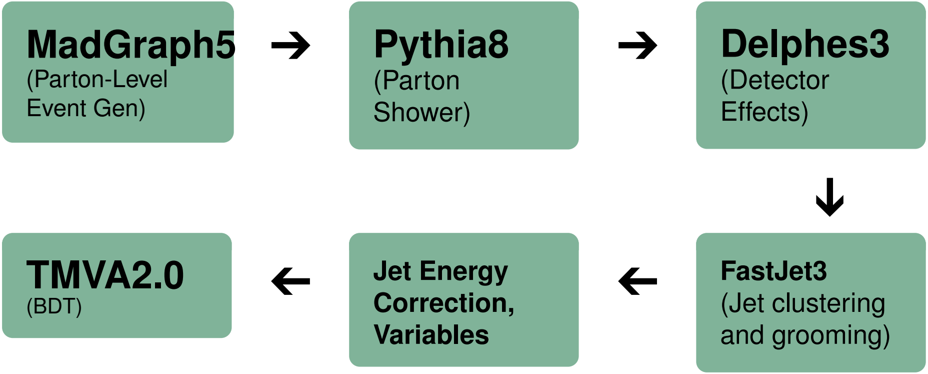
Models

Signals	Lagrangian	Parameters Values	σ_{total} [fb]
gg	$g_s \frac{f_s}{\Lambda} d_{abc}\, \phi^a\, G^{b\,\mu\nu} G^c_{\mu\nu}$	$\frac{f_s}{\Lambda} = 5.8 \times 10^{-2}$ TeV^{-1}	493.9
qq	$g_s f_s\, G'^{a}_{\mu}\, \bar{u}\gamma^\mu T_a u$	$f_s = 0.09$	122.0
qg	$g_s \frac{f_s}{2\Lambda} \bar{U}^* [\gamma^\mu, \gamma^\nu] T_a u\, G^a_{\mu\nu}$	$\frac{f_s}{\Lambda} = 1.5 \times 10^{-2}$ TeV^{-1}	219.4

Table: Cross section is calculated at 13 TeV LHC for $M = 2$ TeV.

MadGraph5 (Parton-Level Event Gen) → **Pythia8** (Parton Shower) → **Delphes3** (Detector Effects) → **FastJet3** (Jet clustering and grooming) → **Jet Energy Correction, Variables**

Variables	Cuts
$p_T(j_{1,2})$	$>$ 700 GeV
$\lvert\eta(j_{1,2})\rvert$	$<$ 2.15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Jet Energy
Correction,
Variables
TMVA2.0
(BDT)

Variables and their importance in BDT

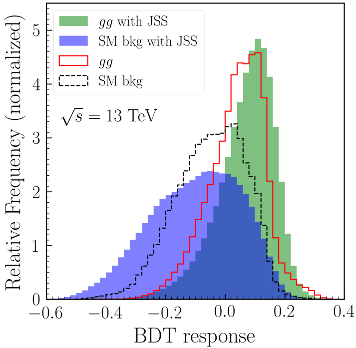
$$1.58 \text{ TeV} < m_{jj} < 2.1 \text{ TeV}$$

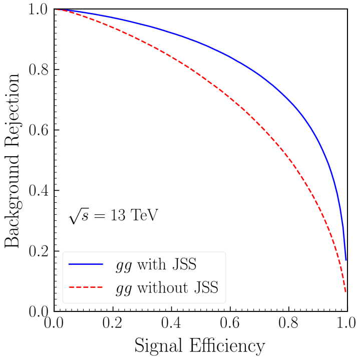
Variables		Variable Importance (in %) *gg* Jet 1	Jet 2	
Event Variables	m_{jj}	7.377		51.16%
	$\Delta R(j_1, j_2)$	9.161		
	$\lvert\Delta\eta(j_1, j_2)\rvert$	5.338		
	p_T	5.704	4.871	
	Energy	5.119	5.090	
	η	4.472	4.030	
JSS Variables	Particle Multiplicity	11.98	9.226	48.84%
	$p_T D$	6.196	4.870	
	LHA	5.333	4.861	
	σ_2	3.111	3.259	

BDT Response and ROC

The analysis is done in two stages.

- Analysis with Event variables only – ‘without JSS’.
- Analysis with Event variables plus JSS observables – ‘with JSS’.



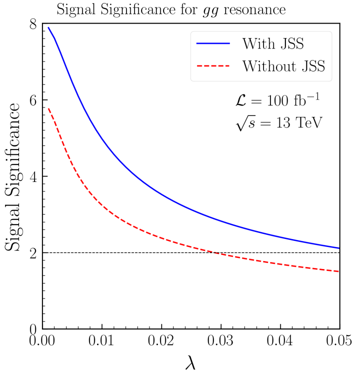


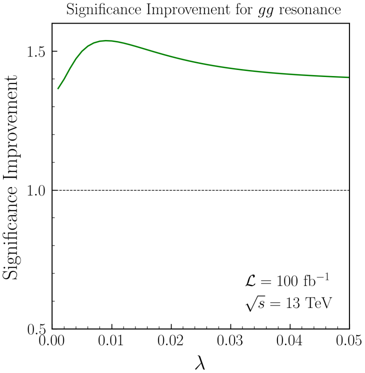
Signal Significance and Improvements

`RooStats` package is used to calculate significance by Profile Likelihood method.

Significance Improvement

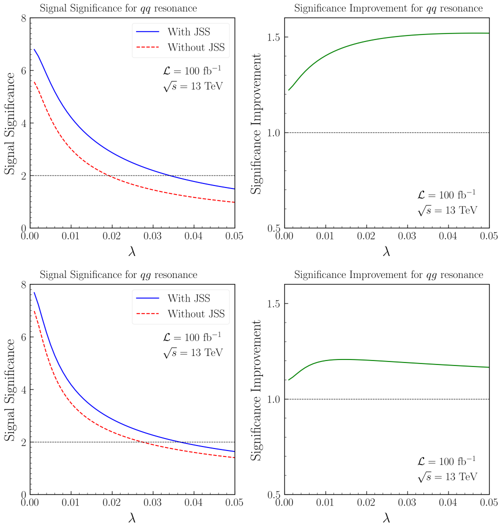
$$= \frac{\text{significance with JSS}}{\text{significance without JSS}}$$



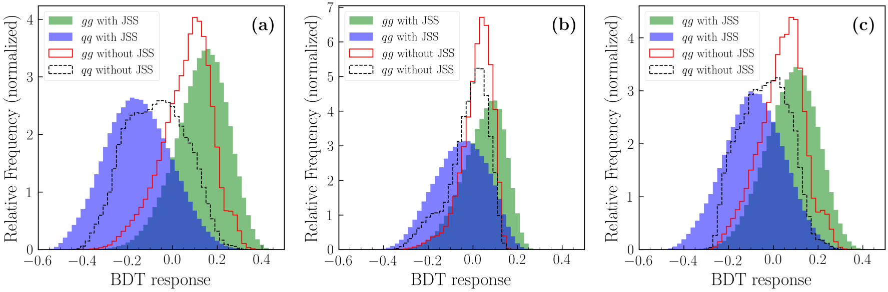


λ = relative systematic uncertainty.

Signal Significance and Improvements



Discrimination among different types of resonances



$$\langle S^2 \rangle = \frac{1}{2} \int dx \frac{(p(x) - q(x))^2}{p(x) + q(x)}$$

	$\langle S^2 \rangle$ (w/o JSS)	$\langle S^2 \rangle$ (with JSS)	Percentage Improvement
gg vs. *qq*	23.77%	58.04%	244.17%
gg vs. *qg*	5.71%	17.79%	311.56%
qg vs. *qq*	11.41%	32.19%	282.12%

Summary and Outlook

- Jet substructure technique is a useful way to get more information from collider events.
- Study of jet substructure can help improving significance of heavy dijet resonance searches.
- Jet substructure observables can potentially be used to discriminate between different types of resonances.
- Although the analysis is done at 13 TeV, the same technique can also be effectively applied to proposed future high energy machines.

Thank you