BSM searches with Jets at CMS

Niki Saoulidou,
National and Kapodistrian University of Athens, Greece

On Behalf of the CMS Collaboration

DISCRETE 2018, Vienna, Austria
6th to the 30th of November 2018.
Outline

• Introduction

• Brief overview of the CMS Experiment

• Particle Flow Jets, Jet Substructure and Jet Mass in CMS

• Selected new physics searches with jets

• Summary and Outlook

N. Saoulidou (Univ. of Athens, Greece)
SM is incomplete

Theoretical point of view

- **Quantum Gravity**: SM describes three of the four fundamental interactions at the quantum level (microscopically) BUT gravity is only treated classically.

- **Hierarchy Problem**: Why is $M_{Pl}/M_{EW} \sim 10^{15}$
  What is the mechanism of cancelation of quadratic divergencies?

- **Unification of Gauge couplings**: Why couplings are so different?

- **Origin of generations**: Why three?
SM is incomplete

Experimental point of view

- **Dark matter – Dark Energy**: What is 95% of the Universe made off?

- **Cosmological constant**: Why is vacuum energy so small?
  \[ \rho_{\text{VAC}} = M_{\text{Pl}}^4 = 10^{120} \rho_{\text{VAC}}^{\text{obs}} \] (!!!)

- **CP Violation**: Why are we here? OR What is the source of the dramatic matter-antimatter asymmetry in the Universe?

- **Neutrino masses and mixings**: What is the Origin of neutrino masses, what is the nature of neutrino, why are \( \nu \) mixings so different than quark ones?
The CMS Detector

3.8 T

Pixels
\( \sigma/pT \sim 1.5 \cdot 10^{-4} pT(\text{GeV}) \oplus 0.005 \)

Electromagnetic Calorimeter
\( \sigma E/E \approx 2.9\%/\sqrt{E(\text{GeV})} \oplus 0.5\% \oplus 0.13\text{GeV/E} \)

Hadronic Calorimeter
\( \sigma E/E \approx 120\%/\sqrt{E(\text{GeV})} \oplus 6.9\% \)

Muon Spectrometer
\( \sigma pT/pT \approx 1\% \text{ for low } pT \text{ muons} \)
\( \sigma pT/pT \approx 5\% \text{ for 1 TeV muons} \)

N. Saoulidou (Univ. of Athens, Greece)
Jet Reconstruction

- Particle Flow Algorithm combines all information from several sub-detector systems.
- Individual particles are reconstructed with Particle Flow Algorithm and then clustered into jets.

**Anti-kt clustering algorithm**: with $R = 0.4$ and $0.8$ for CMS. It is infrared and collinear safe, geometrically well defined, and tends to cluster around the hard energy deposits.

N. Saoulidou (Univ. of Athens, Greece)
Jet Calibration

\[
E_{\text{corrected}} = (E_{\text{uncorrected}} - E_{\text{offset}}) \times C_{\text{rel}}(\eta, p_T'') \times C_{\text{Abs}}(p_T')
\]

where \( p_T'' \) is the transverse momentum of the jet corrected for offset and \( p_T'' = p_T \times C_{\text{Rel}}(\eta, p''T) \)

Data driven methods used for the residual corrections

Dijet asymmetry

N. Saoulioudou (Univ. of Athens, Greece)
Jet Calibration

**Response very close to unity for PF jets.**

**Uncertainties <1% for pT>100 GeV**

N. Saoulidou (Univ. of Athens, Greece)
Jet Resolution

JINST 6 (2011)

\[ A = \frac{p_T^{\text{Jet1}} - p_T^{\text{Jet2}}}{p_T^{\text{Jet1}} + p_T^{\text{Jet2}}} \]

\[ \sigma_A^2 = \left| \frac{\partial A}{\partial p_T^{\text{Jet1}}} \right|^2 \cdot \sigma^2(p_T^{\text{Jet1}}) + \left| \frac{\partial A}{\partial p_T^{\text{Jet2}}} \right|^2 \cdot \sigma^2(p_T^{\text{Jet2}}) \]

\[ \frac{\sigma(p_T)}{p_T} = \sqrt{2} \sigma_A \]

Better than 10% (5%) resolution above 100GeV (1TeV).

N. Saoulidou (Univ. of Athens, Greece)
Jet Substructure

- Main discriminating variables between a "uniform" jet and one experiencing inner "sub-structure" are the N-subjetiness ones [JHEP 1103:015,2011].

$$\tau_N = \frac{1}{d_0} \sum_k p_{T,k} \min \{\Delta R_{1,k}, \Delta R_{2,k}, \cdots, \Delta R_{N,k}\}$$

![Diagram showing subjetiness comparison between different jets](https://example.com/jet_diagram.png)

New Physics Searches with Jets

• Dark Matter (\textit{mono-X}, dijet, trijet)
• Compositeness (dijets)
• Flavour difference (dijets)
• Extra dimensions (dijets, \textit{multijets})
• Fourth generation (dijets)
• RPV SUSY (multijets)
• Lepto-quarks (dijet+X pair production, jet+X single-production) \textit{Talk by Norbert Neumeister}
• Majorana Neutrinos (dijet+X)
• Long-lived particles (displaced, delayed, disappearing, emerging jets) \textit{Talk by Alberto Escalante Del Valle}
Dijets with/without ISR, Boosted or Resolved

Access a broad range of new physics hypothesis

- Decay Products can be:
  - Highly boosted, merged in one jet: Access low X masses and utilize jet substructure techniques
  - Produced at medium or low boost: Access higher X masses and utilized resolved jets and scouting techniques.

- Triggers can be satisfied by final state particles or initial (final) state radiation (ISR and FSR) jets or photons

N. Saoulidou (Univ. of Athens, Greece)
Resolved dijet in a nutshell

q, q, g

q, q, g

q, q, g

SM Backgrounds

q, q, g

QCD

- Reconstructed objects
  - Particle Flow Jets, Calorimeter Jets

- Physics observables
  - M(jj) → Resonance Mass
  - Δη(jj) → Resonance Spin

(X rest frame)

Δη_{12} = |η_{jet1} - η_{jet2}| = \ln \frac{1 + |\cos θ^*|}{1 - |\cos θ^*|}

N. Saoulidou (Univ. of Athens, Greece)
• New data driven background estimation technique:
  ➢ Ratio Method uses data in the control region at high $|\Delta \eta|$ to estimate the background in the signal region at low $|\Delta \eta|$.
  ➢ Robust technique, complementary to the standard fit method, with less dependence on arbitrary parameterizations.
• Data in the signal region extends to a new high dijet mass value of 8 TeV.

N. Saoulidou (Univ. of Athens, Greece)
• Highest dijet mass event at 8 TeV has unusual 4-jet topology.
  - Wide jets each have a mass of 1.8 TeV.
  - Probability of getting such a 4-jet event from QCD is approximately $10^{-4}$.
    [arXiv:1810.09429]

• Possible candidate for a massive resonance decaying to pairs of dijet resonances.
Data is well modeled by both ratio method and the background fit.

- No evidence for dijet resonances.

- We set limits on 10 different models of dijet resonances including those of a DM mediators.

  - Expected limits have improved by 0.2-0.3 TeV

N. Saouilidou (Univ. of Athens, Greece)
Boosted dijet in a Nutshell

• Search for $Z'$ resonance produced in association with a jet ($m_{SD}:50-450$ GeV).

• Uses **ISR jet** to overcome trigger requirements.

• Uses **jet substructure** techniques to identify 2 prong-signal.

• Background is estimated from data by inverting substructure requirement.

• Use **soft-drop mass** distribution to look for signal.
• The W and Z peaks clearly visible in an all hadronic final state.

• Sensitivity of search extended significantly to lower Z’ masses
Boosted dijet limits

Z’ limits in a previously unexplored region.

N. Saoulioudou (Univ. of Athens, Greece)
Boosted b-tagged dijet in a Nutshell

- Search for Φ resonance decaying to a bbbar pair produced in association with a jet using two jet cone-sizes (AK8 0.8 and CA1.5) to probe lower and higher resonance masses.

- Use ISR jet to overcome trigger requirements.

- Use jet substructure and soft-drop mass techniques to identify 2 prong-signal.

- Background is estimated from data by inverting the b-tagging requirement.

- Use double b-tagging and single b-tagging of subjets.

N. Saoulidou (Univ. of Athens, Greece)
• The Z peak clearly visible in an all hadronic final state with b-tagged jets.

• Sensitivity of search extended significantly to medium Z’ masses

N. Saoulidou (Univ. of Athens, Greece)
Boosted b-tagged dijet limits

First constraints from the LHC on exotic bottom quark-antiquark resonances with masses below 325 GeV

N. Saoulidou (Univ. of Athens, Greece)
Dijet $x$ Distributions

$\chi = e^{\mid y_1 - y_2 \mid} \approx \frac{1 + \mid \cos \theta^* \mid}{1 - \mid \cos \theta^* \mid}$

- $\chi$ chosen since main QCD background is flat.

- Experimental uncertainties dominated by jet resolution and relative ($\eta$) JES (absolute cancels)

- Theoretical uncertainties dominated by non-perturbative corrections and renormalization scale.

N. Saoulidou (Univ. of Athens, Greece)
• Unique analysis with coupling limits extending to higher DM mediator masses and larger DM mediator widths.

• Additional limits are placed to a variety of new physics models like quark contact interactions, extra spatial dimensions, quantum black holes.
Where we stand, What is next

- Jets are a unique tool to search for new physics at the LHC.

- Recent significant improvements in:
  - Analysis methodologies
  - Substructure techniques
  - Triggering
  - Heavy flavor tagging

  allow us to probe lower particle masses and larger widths, thus significantly enhancing our physics discovery potential.

- There are many more results in the pipeline aiming at legacy publications with the full 2016+2017+2018 dataset so stay tuned!

N. Saoulidou (Univ. of Athens, Greece)
N. Saoulidou (Univ. of Athens, Greece)
• There is plenty of evidence for the existence of Dark Matter which we have only seen so far gravitationally, and there are several ways to search for it.

• **Direct Dark Matter searches**: Detect interactions of DM particle (or particles) with terrestrial detectors

• **Indirect Dark Matter searches**: Detect DM-DM interactions in the cosmos, i.e. DM-DM interactions at the centre of the galaxy

• **Collider Searches**: Produce DM and DM mediators in the Lab

N. Saoulidou (Univ. of Athens, Greece)
Dark Matter Searches: Simplified Models

\[ \Gamma_{\text{tot}}^{\text{AV}} = \Gamma_{\text{AV}}^{\chi\bar{\chi}} + 3 \times \sum_{q=u,d,s,c,b,t} \Gamma_{\text{AV}}^{\bar{q}q} \]

\[ \Gamma_{\text{axial-vector}}^{\bar{q}q} = \frac{g_q^2 M_{\text{med}}}{4\pi} (1 - 4z_q)^{3/2} \]

\[ \Gamma_{\text{vector}}^{\bar{q}q} = \frac{g_q^2 M_{\text{med}}}{4\pi} (1 - 4z_q)^{1/2} (1 + 2z_q) \]

\[ z_i = \frac{m_i^2}{M_{\text{med}}^2} \]

- DM-nucleon scattering cross section:

  - Vector: \[ \sigma_{\text{SI}} \simeq 6.9 \times 10^{-41} \text{ cm}^2 \cdot \left( \frac{g_q g_{\text{DM}}}{0.25} \right)^2 \left( \frac{1 \text{ TeV}}{M_{\text{med}}} \right)^4 \left( \frac{\mu_{\chi N}}{1 \text{ GeV}} \right)^2 \]

  - Axial-vector: \[ \sigma^{\text{SD}} \simeq 2.4 \times 10^{-42} \text{ cm}^2 \cdot \left( \frac{g_q g_{\text{DM}}}{0.25} \right)^2 \left( \frac{1 \text{ TeV}}{M_{\text{med}}} \right)^4 \left( \frac{\mu_{\chi N}}{1 \text{ GeV}} \right)^2 \]

N. Saoulidou (Univ. of Athens, Greece)
Dark Matter Searches:

$g_q$ Coupling summary plot

CMS Preliminary

LHCP 2018

95% CL exclusions

- Observed
- Expected

$\Gamma_{Z'}/M_{Z'} < \sim 100\%$

Dijet $\chi$ [EXO-16-046]
35.9 fb$^{-1}$, 13 TeV

$\Gamma_{Z'}/M_{Z'} < \sim 30\%$

Broad Dijet [arXiv:1806.00843]
35.9 fb$^{-1}$, 13 TeV

$\Gamma_{Z'}/M_{Z'} < \sim 10\%$

Dijet [arXiv:1806.00843]
35.9 fb$^{-1}$, 13 TeV
Dijet [arXiv:1604.08907]
19.7 fb$^{-1}$, 8 TeV
Boosted Dijet [arXiv:1710.00159]
35.9 fb$^{-1}$, 13 TeV
Dijet b-tagged [arXiv:1802.06149]
19.7 fb$^{-1}$, 8 TeV

N. Saoulidou (Univ. of Athens, Greece)
DATA SCOUTING

- Technique of data scouting
  - Reconstruct/save only necessary information to perform analysis → record more events
- "PF Scouting" limited by CPU time: allows us to get down to $H_T > 450$ GeV
- "Calo Scouting" allows us to get down to $H_T > 250$ GeV (L1 trigger limited)
Model-less Motivation

Robert Harris (2006)

- **Theoretical Motivation**
  - The many models of dijet resonances are ample theoretical motivation.
  - But experimentalists should not be biased by theoretical motivations . . .

- **Experimental Motivation**
  - The LHC collides partons (quarks, antiquarks and gluons).
    - LHC is a parton-parton resonance factory in a previously unexplored region
    - Motivation to search for dijet resonances and contact interactions is obvious
      - We must do it.
  - We search for generic dijet resonances, not specific models.
    - Nature may surprise us with unexpected new particles.
    - One search encompasses ALL narrow dijet resonances.
  - We search for deviations in dijet angular distributions vs. dijet mass
    - Now the search is focused on a model of quark contact interactions.
    - It will also be applicable for generic parton contact interactions.
    - And essential for confirming and understanding any resonances seen.