Search for heavy resonances in diboson final states at CMS

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Why…

Theoretical motivation

how can we explain the big difference between EW and gravitation?

\[ m^2_H = -2\mu^2 \sim 10^4 \text{ GeV}^2 \ll M^2_{Pl} \sim 10^{38} \text{ GeV}^2 \]

natural explanation

SM is extended by another theory at the TeV scale

warped extra dimensions
- Tentative solution of the hierarchy problem
- Radion (spin 0) and graviton (spin 2) can decay to HH

heavy vector triplet
- General Framework
- Include Little Higgs, Composite Higgs
- Introduction of spin-1 resonance
CMS performed an extensive multi-channel search

- Search for heavy resonances ($m_X \gtrsim 800$ GeV) decaying into 2 bosons
- Several combination and decaying mode considered

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<th>$V \rightarrow q\bar{q}$</th>
<th>$W \rightarrow l\nu$</th>
<th>$Z \rightarrow ll$</th>
<th>$Z \rightarrow \nu\bar{\nu}$</th>
<th>$H \rightarrow b\bar{b}$</th>
<th>$H \rightarrow \tau\tau$</th>
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<tbody>
<tr>
<td>$W \rightarrow l\nu$</td>
<td>B2G-16-029</td>
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<td>$Z \rightarrow ll$</td>
<td>B2G-17-013</td>
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<td>$Z \rightarrow \nu\bar{\nu}$</td>
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<td>$H \rightarrow \tau\tau$</td>
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How to detect these resonances at CMS

- Di-boson final states could help finding spin 0, 1 or 2 resonances
- Depending on model parameters, resonances may be narrow or wide
- Majority of analysis focus on narrow resonance
How to detect these resonances at CMS

- Bosons have been searched in all possible decay mode
  - W, Z in leptonic channels
  - W, Z in hadronic channels
  - Z invisible
  - H in $b\bar{b} e \tau^+\tau^-$

- For high mass resonances, bosons will be very energetic
  - Decay products are highly collimated

- Jets from partons are frequently merged
- Dedicated reconstruction algorithms needed for high-$p_T$ leptons
- Powerful τ-id needed
How…
How to trigger these resonances at CMS

All analysis use similar trigger strategies

• Single electron and single muon trigger if a lepton in the final state
  • Typically $p_T^{ele} > 50$ GeV with additional ID and isolation cuts and $p_T^{mu} > 50$ GeV

• Missing energy trigger or missing hadronic activity requests if neutrinos in the final state
  • $H_T^{mis}$ or $E_T^{mis} > 90, 110, 120$ or $170$ GeV depending on luminosity and pre-scaling of the trigger path

• Several combination of Jet and HT trigger when no $E_T^{mis}$ and no leptons in the final state
  • Jets from anti-$k_T$ algorithm with $R = 0.8$ and $p_T > 360$ GeV
  • Scalar sum of all jet $p_T$ above 650, 700 or 800 GeV depending on luminosity or additional requests on jets
How…
Objects reconstruction

• A Particle Flow (PF) event algorithm is used to reconstruct and identify each individual particle

• All leptons are reconstructed with standard CMS cuts trying to maximize efficiency
  • Acceptance range is typically $|\eta| < 2.4$ for electrons, $|\eta| < 2.5$ for muons and $|\eta| < 2.3$ for hadronic taus
  • Requirements on minimum $p_T$ for all leptons are applied
  • Isolation cuts as well as quality cuts are used to select only prompt leptons from bosons decays
  • A special reconstruction algorithm is used to identify hadronically decayed $\tau$ leptons
  • For leptonic decay of the Z boson, opposite charge is required

• Jets reconstruction uses anti-$k_T$ algorithm with $R=0.4$ and 0.8 (fat-jet)
  • Jets $p_T$ is corrected using the standard CMS energy scale (JES) prescription

• Missing transverse energy is calculated from all the PF particles
  • $E_T^{mis}$ is corrected for JES and electrons and muons momentum scale

• Pile-up (PU) mitigation techniques are applied
Merged jets techniques

- For **resonances above 1 TeV**, a significant fraction of bosons is reconstructed as a single jet
  - Using $R=0.8$ jets helps collecting the full boson decay within a fat jet
- **Mass of the jet** (corrected for soft radiation contribution) can be used to select jets from bosons
- **Jet grooming** remove soft and large angle radiation
  - Before grooming, PU is removed
  - Re-cluster iteratively particles in 2 sub-jet and remove softer contribution
  - Jet mass resolution is approximately 10%
  - No W/Z/H ambiguity after mass selection
How…
Merged jets techniques

• For **resonances above 1 TeV**, a significant fraction of bosons is reconstructed as a single jet
  • Using $R=0.8$ jets helps collecting the full boson decay within a fat jet
• **Jet pruning** was used till 2015 but **soft drop** more stable against PU and it is both infrared and collinear safe
• All 2016 analysis use soft-drop
• Control sample (high momentum $t\bar{t}$) are used to check data-simulation agreement
How…
Merged jets techniques

• For **resonances above 1 TeV**, a significant fraction of cases is reconstructed as a single jet
  • Using $R=0.8$ jets helps collecting the full decay within a fat jet
• **N-subjettiness** is another technique to identify a fat jet with more than one sub-jet
• If more than one parton contribute to the fat jet…
  • Energy-flow align along more than 1 momentum direction
• New variable (sub-jettiness ratio) used to discriminate 1-subjet to 2-subjets composition
  • Validation on data is needed
  • Uncertainties derived from $W \rightarrow q\bar{q}$ in $t\bar{t}$ enriched samples
How...

b-jets tagging

- Dedicated Higgs-tagger using double-b tagger applied to fat jets
  - Inputs based on observables from secondary vertices and tracks associated to each sub-jet axis
  - MVA algorithm gives a 80% (30%) Higgs-Jet tag efficiency for tight (loose) working point
- At the same signal efficiency, the mis-tag rate is lower by a factor of 2 compared to the sub-jet b tagging approach
  - Identify 2 sub-jet
  - b-tag each sub-jet
Resonances $ZZ - ZW - ZH$

Final state with $Z \rightarrow e^+ e^-, \mu^+ \mu^-$

- **Second boson decay**
  - 2q in 1 merged or 2 unmerged jets
  - 2 neutrinos
  - 1 fat jet from 2 merged b from the Higgs
- A bump search has been used in the 2q and 2b analysis
  - Low and high mass signal extracted separately for 2q
  - Mass limits on $W'$ and spin-2 graviton signal extracted for 2q
  - Mass limits on $Z'$, $W'$ and the 2 Higgs doublet model for 2b
- A Jacobian edge has been searched for the 2 neutrinos analysis
  - Data driven bkgd estimation from $\gamma$+jets events
  - Good sensitivity for resonance below 1.5 TeV
Resonances $WZ - WW - WH$

Final state with $W \rightarrow l\nu$

- **Second boson decay**
  - 2q in 1 merged jet from $Z$ or $W$
  - 1 fat jet from 2 merged $b$ from the Higgs
- The Higgs fat jet is required to have at least 1 $b$-tagged sub-jet
  - No significant deviation from the SM found
- Search in the 1.0 to 4.5 TeV range for $Z$ and $W$ as second boson
  - 4 categories depending on lepton flavor and sub-jettiness ratio
  - All distribution compatible with SM

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Resonances $HZ - HW - HH$

Final state with $H \rightarrow \tau^+\tau^-$

- Boosted taus in the final state
- Higgs searched as a single fat jet
- If 2-sub-jet in the fat jet $\rightarrow \tau$-id
  applied $\rightarrow$ 2 $\tau$-tagged sub-jet $\rightarrow$ event selected
- Event selected also if a Higgs candidate found in $e\tau_h$ or $\mu\tau_h$

**Second boson decay**
- Soft-drop algorithm & N-subjettiness
- $b$-Tag applied to identify the Higgs boson
Resonances $ZZ - ZW - ZH$

Final state with $Z \rightarrow \nu\bar{\nu}$

- Large missing energy or missing hadronic activity
- **Second boson decay**
  - Largest fat jet and $p_T > 200$ GeV
  - Soft-drop algorithm & N-subjettiness
  - $b$-Tag applied to identify the Higgs boson
- Transverse mass is used for the reconstruction of the $ZV - ZH$ candidate
  - $Z$ boson $\not p_T$ is set equal to $\not p_T^{miss}$
- Unbinned profile likelihood fit on the transverse mass diboson candidate
- No excess found with respect to SM predictions
Resonances $ZZ - ZW - WW$

Final state with $(q\bar{q})(q\bar{q})$

- Events with 2 fat jets are selected
  - Both fat jet with $p_T > 200$ GeV
  - Soft-drop algorithm & N-subjettiness
  - No high $p_T$ leptons

- Signal shape in di-jet invariant mass spectrum modelled with a Gaussian core and exponential tail

- Background modelled using smooth, parametrized, monotonically decreasing distribution

- Maximum likelihood fit performed on data, fixing the number of expected signal events to zero
Resonances $HZ - HW - HH$

Final state with $H \to b\bar{b}$

- **Second boson decay**
  - If $H \to b\bar{b}$, 2 fat jets with with $p_T > 300$ GeV, soft-drop algo and double b-tagger for both jets
  - If $V \to q\bar{q}$, 2 fat jets with with $p_T > 200$ GeV, soft-drop algo and double b-tagger for the Higgs candidate

- Several categories defined in all 3 channels depending on the $b$-Tag working points and the soft-drop mass
- Separated unbinned profile likelihood fit on the background and signal shape
**Limits**

Spin-2 bulk graviton

For the narrow width resonances with $\tilde{\kappa} = 0.5$, the masses below 800 GeV are excluded at 95% CL

$X \rightarrow ZZ \rightarrow ll\nu\bar{\nu}$

$W \bar{W}$ resonances with $\tilde{\kappa} = 0.5$, the masses below 1 TeV are excluded at 95% CL
Limits

$W'$ and $Z'$ resonances in the HVT model A/B

$W' \rightarrow WZ \rightarrow q\bar{q}νν\bar{ν}$

A $W'$ resonance below 3.2 TeV in model A and 3.5 TeV in model B is excluded at 95% CL

$Z' \rightarrow WW \rightarrow q\bar{q}q\bar{q}$

A $Z'$ resonance below 2.7 TeV is excluded at 95% CL
For the mass scale $\Lambda_R = 3$ TeV, a radion of mass between 970 and 1450 GeV is excluded at 95% CL.

Assuming $\Lambda_R = 1$ TeV, a radion resonance with mass lower than 2.5 TeV is excluded at 95% CL.
Limits
The other analysis...

- No SM deviation found...
- Process $W' \rightarrow WZ \rightarrow llqq$
- Process $V \rightarrow ZH \rightarrow llbb + lvbb + vvbb$
- Process $Z' \rightarrow ZH \rightarrow qqbb$

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Conclusions and the future…

- Wide program of di-bosons resonance search at CMS presented
  - We are probing many BSM theories
  - None till now has been found working…
  - But higher statistics is coming!
- CMS is ready to improve its searches
  - More work to better understand jets substructure
  - Non stop work to improve $b$-Tag and $\tau$-Tag techniques
  - Multi-dimensional fits to make best use of statistics

Well set up to make best use of full Run-2 data set
Bibliography

- **B2G-16-023** Search for diboson resonances in the 2l2ν final state
- **B2G-16-026** Search for heavy resonances decaying to a pair of Higgs bosons in the four b quark final state in proton-proton collisions at $s\sqrt{}=13$ TeV
- **B2G-16-029** Search for heavy resonances decaying to pairs of vector bosons in the l nu q qbar final state with the CMS detector in proton-proton collisions at sqrt s = 13 TeV
- **B2G-17-001** Search for massive resonances decaying into WW, WZ, ZZ, qW and qZ in the dijet final state at $\sqrt{s}=13$ TeV
- **B2G-17-002** Search for heavy resonances decaying into a vector boson and a Higgs boson in hadronic final states with 2016 data
- **B2G-17-004** Search for a heavy resonance decaying into a vector boson and a Higgs boson in semileptonic final states at $\sqrt{s} = 13$ TeV
- **B2G-17-005** Search for heavy resonances decaying into a Z boson and a vector boson in the vv qq̄ final state
- **B2G-17-006** Search for heavy resonances decaying into two Higgs bosons or into a Higgs and a vector boson in proton-proton collisions at 13 TeV
- **B2G-17-013** Search for new heavy resonances decaying into a Z boson and a massive vector boson in the 2ℓ2q final state at $s\sqrt{}=13$~TeV
- **LHC Seminar** Search for heavy resonances in diboson final states at CMS
Limits
Spin-2 bulk graviton

$X \rightarrow ZZ \rightarrow ll\nu\bar{\nu}$

For the narrow width resonances with $\tilde{k} = 0.5$, the masses below 800 GeV are excluded at 95% CL

$X \rightarrow WW \rightarrow l\nu q\bar{q}$

$WW$ resonances with $\tilde{k} = 0.5$, the masses below 1 TeV are excluded at 95% CL
Limits

$W'$ and $Z'$ resonances in the HVT model A/B

$W' \rightarrow WZ \rightarrow q\bar{q}v\bar{v}$

A $W'$ resonance below 3.2 TeV in model A and 3.5 TeV in model B is excluded at 95% CL

$Z' \rightarrow WW \rightarrow q\bar{q}q\bar{q}$

A $Z'$ resonance below 2.7 TeV is excluded at 95% CL
Jet grooming: soft drop algo

• The goal of jet grooming is to re-cluster the jet constituents while applying additional requirements that eliminate soft, large-angle QCD radiation that increases the jet mass compared to the initial V-boson, quark or gluon mass.

• **Soft drop is both infrared and collinear safe** in contrast the *jet pruning* algorithm used in 2015 CMS analysis, while providing similar discrimination power

• The soft-drop algorithm use from a Cambridge-Aachen jet clustered from the constituents of the original AK8 jet
Backup
N-subjettiness ratio

\[ \tau_N = \frac{1}{d_0} \sum_k p_{T,k} \min(\Delta R_{1,k}, \Delta R_{2,k}, \ldots, \Delta R_{N,k}) \]

- Low value of \( \tau_N \) → compatibility with the hypothesis of N axis
- Ratio \( \tau_2/\tau_1 \) has good discrimination power
CMS-PAS-BTV-15-002
Identification of double-b quark jets in boosted event topologies

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