Exotic searches by ATLAS and CMS

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5th International Conference on Particle Physics and Astrophysics

October 5-9, 2020
Introduction

- ATLAS and CMS are two multipurpose detectors at the LHC ring resulted in the discovery of Higgs Boson in 2012.
- With successful data taking during Run-II and having several upgrades for implementing fast electronics, ATLAS and CMS has recorded up to \(~139 \text{ fb}^{-1}\) of data at 13 TeV.
- This would help in looking at several model predictions falling in beyond standard model sector.
- Will answer many unanswered questions like matter-antimatter asymmetry, existence of dark matter and so on....
Why do we need to look Beyond Standard Model?

- Standard model successfully explains the structure of matter and the forces acting between them. Still, it fails to answer many important questions:
  - Inclusion of the fourth fundamental force i.e. gravitational force
  - Why only 5% of matter made of ordinary SM particles?
  - Why there are only three families of quarks and leptons?
  - Is there a more fundamental theory of which the Standard Model is a low energy approximation?

To answer such questions, new models beyond standard model have evolved with time and predicts "new phenomena" at the "TeV" scale.
What do we expect Beyond Standard Model?

- New resonance?
- Dark matter?
- Long lived particles?
- New quarks?
Resonances

**Focus on very recent or brand new results!**
Di-Jet resonance search

- Considered "wide" jets to combine close-by jets: reduce analysis sensitivity to final state radiation
- Parametric fit to signal region data for $1.5 < m_{jj} < 2.4$ TeV
- New "ratio method" for $m_{jj} > 2.4$ TeV: using control regions with larger $\Delta\eta$ values and MC-to-data transfer factors

For broad resonances, the ratio method provides significantly enhanced sensitivity compared to the fit method.

Limits set for qq, qg and gg final states, with narrow and broad widths (up to 30% of resonance mass).
Di-Jet resonance search

- To get sensitivity at low masses:
  - Data collected with different technique known as “Data scouting” is analyzed
- 3-jet events are recorded and reconstructed using only calorimeter-based information with lower $p_T$ thresholds
- Backgrounds estimated using parametric fit to data

![CMS: PhysLettB(2020)135448]

![Graph showing dijet mass vs. cross section]
FULLY-HADRONIC TOP-PAIR RESONANCES

- Fully hadronic top decaying to large-radius jets (R = 1.0)
- Jets are DNN top-tagged
- b-tagging using variable-radius track-jets: two signal regions with 1 or 2 b-tagged jets

No significant deviation from the background prediction is observed.

Thr $Z'$ boson masses below 3.9 and 4.7 TeV are excluded at 95% confidence level for the decay widths of 1% and 3% respectively.

Improved analysis techniques lead to 65% improvement in exp. limits at 4 TeV.
diboson resonance search

- Targeting O(100 GeV) to multi-TeV resonances (radions, gravitons, new vector bosons, extended Higgs sector) in different BSM scenarios:
- Warped extra-dimensions, composite Higgs, technicolor, …

Highlights

- All possible production modes are targeted
- Improved tagging algorithms for high $p_T$
  $V \to qq, H \to bb, H \to \tau\tau$ decays:
- Dense environment: critical to combine calorimeter with superior angular resolution of trackers
- Novel analysis methods: 3D likelihood fits and anomaly detection techniques for broadening scope of the searches
VH resonances

- **Fully-hadronic final state:** two large-radius jets, jet substructure, track multiplicity and b-tagging to identify H->bb and V-> qq candidates

- **Semi-leptonic final state:** 0 lepton and 2 lepton channels considered
  - Resolved: 2 small-R(0.4) calo jets
  - Marged: 1 large-R TCC calo jet with at least 1 associated b-tagged VR track jet

New: Variable-radius track-jets for b-tagging: pT-dependent radius to resolve highly boosted bb pairs from Higgs boson decay

Multijet Background estimated from region with 0-tag: BDT trained on control region data to estimate extrapolation corrections to 1 and 2-tag
ZH resonances

- Search for spin 1 resonances in the boosted regime for $m_X > 800$ GeV
  - $\Rightarrow$ 0 lepton (large $p_{T\text{miss}}$) and 2 lepton channels considered
    - Including VBF production for the first time!
  - Major backgrounds V+jets, ttbar and VV

- The $m_X$ (or $m_{TX}$) distributions are estimated using the data in the jet mass sidebands
- A function is defined as the ratio of the two functions describing the $m_X$ shape in the signal and sideband range of the V+jets background

$Z'$ with mass below 3.5 TeV and 3.7 TeV is excluded
Leptoquarks and vector like-quarks

- LQ appears in many BSM models to answer the question: **Why same number of generation for leptons and quarks**
- Leptoquarks carry both lepton and baryon number
  - Decay in lepton-jet
- Motivated by models such as grand unified theories, technicolor models, compositeness scenario and R-parity violating supersymmetry

Vector-like quarks

- Heavy quarks for which left- and right- handed chirality components transform the same under SU(2)
- Predicted in many theories (extra- dimensions, Higgs compositeness, ….) to solve hierarchy problem
- Strong production of pairs, electroweak single production
Search for leptoquarks

- Events having one light lepton and at least one $\tau_h$, or at least two light lepton with two or more jets with at least one to be arising from the fragmentation of b-hadron

**Scalar leptoquarks decaying exclusively into $t\tau$ are excluded up to masses of 1.43 TeV**

- Events having a top quark and either an electron or a muon
- targets heavy leptoquarks having top quark decaying to single high $p_T$ wide jet

limits are set at 1.48 TeV and 1.47 TeV for the $e$ and $\mu$ channels
Search for leptoquarks

- The leptoquark (LQ) may couple to a top quark plus a τ lepton (tτ) or a bottom quark plus a neutrino (bν, scalar LQ), or else to τν or bτ (vector LQ), leading to the final states tτb and tτν
- high $p_T^{miss}$, high $H_T$, one hadronic top candidate and one hadronic τ

Lower limits at 95% CL are set on the LQ mass in the range 0.98-1.73 TeV, depending on the LQ spin and the LQ-lepton-quark vertex coupling $\lambda$, and assuming equal branching fractions for the two LQ decay modes considered.

Major backgrounds: real top production checked in control region and backgrounds from misidentified τ from data.
Dark matter

- Pair production at LHC
- DM candidates escape the detector (weakly interacting)
- Large missing energy distribution is the key variable

- Simplified S-channel model: **Mediator that couples to SM and to Dark Sector particles**
- **low mass mediator searches:** triggering on an associated object or performing analysis at the “trigger level”

- More complete models:
  - 2HDM + a:
    - Mediator that couples to Higgs, SM and Dark Sector → typically: mediator + 2HDM in alignment limit
    - Higgs coupling to new particles

Parallel talk by: Nikolina Ilic [Link]
Search for Dark matter

- On-shell production of charged Higgs boson leads to a resonance enhancement of $tW + \text{MET}$ signal
- $tW + \text{MET} \ 1L$: shape fit on $E_{\text{T}}^{\text{miss}}$, $tW + \text{MET} \ 2L$: single-bin SR
- Major backgrounds: $t\overline{t}$bar and $W$+jets (normalized in CRs)

- Cross-section increases with the mass of the charged Higgs
  - $tj + \text{MET} \ 1L$: shape fit on BDT score using $E_{\text{T}}^{\text{miss}}$, transverse mass $m_T^{\ell\ell}$, number of forward jets, $\Delta\phi(\ell\ell, b\text{jet}1)$
  - Major backgrounds: $t\overline{t}$bar and $W$+jets (normalized in CRs)

No significant excess is found with respect to Standard Model predictions
Search for Dark matter

- Events having jets and large missing transverse energy
- Considered models: pair-produced weakly interacting dark-matter candidates, large extra spatial dimensions, supersymmetric particles, axion-like particles, and new scalar particles in dark-energy inspired models

Model-independent 95% confidence level limits on visible cross sections obtained in the range between 861 fb and 0.3 fb
Search for Dark matter

- Search is performed for DM particles produced in association with a Dark Higgs boson 's' decaying to $VV$ where $VV = W^\pm, Z$

**FIRST RESULTS!**

$S \to V(q\bar{q})V(q\bar{q})$ decays are reconstructed with ‘Track Assisted Reclustered’ (TAR) jets technique using reclustered jets with a cone parameter $R=0.8$ based on $R=0.4$ calorimeter jets and tracking information.

No significant excess over the predicted background is found and sets exclusion for $m_s > 160$ GeV
• The signal topology consists of two forward high-$p_T$ jets consistent with VBF production (large $\Delta \eta$ and $m_{jj} > 500$ GeV), large $p_T^{\text{miss}}$ and an isolated high $p_T$ photon.

**Fit to the $m_T$ distribution ($p_T^{\text{miss}} + \text{photon}$)**

Combining with similar CMS ZH search the observed (expected) upper limits at 95% confidence level at $m_H = 125$ GeV on $B(H \rightarrow \text{invisible} + \gamma)$ is 2.9 (2.1) %

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Amandeep Kaur (CMS) (ICPPA-2020)  
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Search for long lived particles

• Long-lived and unconventional exotic particles with striking signatures predicted by many extensions of the SM

• Examples:
  • Heavy, long-lived, charged particles (R-hadrons, Sleptons)
    Particles can decay in the detector after few cm
  • neutralinos in GMSB, mass-degenerate gauginos, particles of an Hidden sector

Challenging from the experimental point of view:

• Non-standard reconstruction
• Displacements, timing and ionization
  • Dedicated triggers
• Non-standard background is a challenge
  • Detector noise, cosmic rays, reconstruction failures
  • Usually estimated from data
Search for long lived particles

- Distinctive topology: pair of jets originating at a secondary vertex
- Models targeted: LLP decaying to q-qbar, Exotic decays of Higgs: \( gg \rightarrow H \rightarrow 2S, S \rightarrow q\overline{q} \) (\( c\tau \sim 1\text{mm} \) to 3mm)

CMS excludes top squark masses up to 1.6 TeV for \( c\tau \) between 3 and 340 mm
Neutrino oscillation experiments have demonstrated that Lepton Flavour Conservation is violated in nature.

Searching $Z$ boson decaying into a $\tau$-lepton and another lepton of different flavour ($e$ or $\mu$) with opposite charge, superseding the otherwise best limits set by the LEP experiments.
Conclusion

• Searching for exotics is both challenging and exciting, with developing new techniques and considering possible final states

• With increasing efficiency with using increased analysis techniques and improved object performance, sensitivity is increased leading to improved exclusion limits

• Many full run-2 results are still to come. Stay tuned!
Conclusion

- Searching for exotics is both challenging and exciting, with developing new techniques and considering possible final states.
- With increasing efficiency with using increased analysis techniques and improved object performance, sensitivity is increased leading to improved exclusion limits.
- Many full run-2 results are still to come. Stay tuned!

Thank You
Additional Slides
Search for leptoquarks

• events with two electrons or two muons and two or more jets, including jets identified as arising from the fragmentation of c- or b-quarks

Leptoquarks with masses below 1.8 TeV and 1.7 TeV are excluded in the electron and muon channels

A branching ratio into a charged lepton and a quark is assumed to be 100%, with minimal dependence on the quark flavor
Di-Jet resonance search

- Inclusive result with events with 1 or 2 b-jets
- Jets close in $\Delta y$ (to reject background)
- Background from sliding-window fit to data
- Exclusions on several benchmarks: e.g. excited quarks, chiral excitation of the W, leptophobic $Z'$ DM mediator
- For reinterpretation: 95% CL cross-section limits on gaussian-shaped signals of various widths (up to 15%) as a function of the mass