Recent Exotics/BSM Results

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On behalf of ATLAS and CMS Collaboration

New methods and ideas at the frontiers of particle physics
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Triumph of the standard model

• So far, the standard model predicts pretty much everything we observed...
Quest for new physics

• The standard model is a low-energy approximation theory, and we were hopeful to find new physics early from the start of the new energy frontier
  • Dark matter candidate?
    • SUSY, Higgs $\rightarrow$ inv
  • What makes Higgs boson light?
    • SUSY, Vector-like quarks
  • Origin of neutrino masses?
    • Heavy neutrinos
  • Flavor anomalies, g-2, CKM...
    • LQs, $Z'/W'$, vector-like leptons
• New fermions/scalars, new interactions
New methods and ideas at the frontier

New Physics
Focus of this talk: new ideas in BSM

• Capitalize on full hardware and data analysis capabilities of the detectors
  • Advancement of data analysis tools allows expanding the sensitivity to experimentally challenging processes (DNN, graph CNN)

• Both ATLAS and CMS has a vibrant physics program with a lot of new results
  • Too many to present during this short talk. Here is a quick links to public results from the ATLAS and CMS
    • ATLAS public results
    • CMS public results: papers and preliminary results

• Here, I will focus mainly on recent results that use new techniques and ideas to search for new physics
Search for $H \rightarrow AA \rightarrow 4\gamma$

- Motivated by various extensions of the Higgs sector
  - $A \rightarrow \ell\ell$ has been investigated in the past, but $A \rightarrow \gamma\gamma$ has a clear experimental signature, and if $A$ is fermiophobic, diphoton final state is the only process where $A$ can be discovered
    - Higher mass pseudoscalar searches (above 10 GeV):
      - ATLAS: Run 1 3\gamma + X search EXOT-2013-24
      - CMS: Run 2 4\gamma CMS-HIG-21-003
  - No evidence for light resonance with masses above 10 GeV Limits are set at around 1 – 0.3 /fb for 15 – 60 GeV masses of $A @ 95\% CL$

- Very low mass is unique as photon merge into a single shower
  - Could be impossible to separate from the vanilla $H \rightarrow \gamma\gamma$ process without a dedicated reconstruction
- New search in the boosted final state CMS-HIG-21-016
How do we reconstruct boosted $\gamma \gamma$?

- Most of energy for higher mass resonance is deposited in a single crystal!

  $m_A = 1.0$ GeV
  $\gamma_L \approx 60$

  $m_A = 0.1$ GeV
  $\gamma_L \approx 600$

- Develop a dedicated ResNet convolutional NN to reconstruct the mass of the diphoton candidate based on the energy deposition in the $\eta - \phi$ space
  - Validate on data by reconstructing $\pi^0$ candidates
Reconstruction of $\pi^0$ with CNN @ CMS

- Excellent performance of the CNN in data
Search for $H \rightarrow AA \rightarrow 4\gamma$

- Use 2D candidate mass (leading $p_T$ vs. sub-leading $p_T$ diphoton candidate)

- Assumptions: identical mass hypothesis and prompt $A \rightarrow \gamma\gamma$ decay

- Use maximum likelihood estimation to determine the compatibility of observed template with signal and background models
  - Signal region: $110 \text{ GeV} < m_A < 140 \text{ GeV}$
  - Signal template: 2D diagonal using simulation
  - Background template: binned 2D template from data and SM $H \rightarrow 2\gamma$ simulation in sidebands of diphoton invariant mass and 2D distributions
Search for $H \rightarrow AA \rightarrow 4\gamma$

- No evidence for a resonant structure

CMS Preliminary 136 fb$^{-1}$ (13 TeV)

$\text{Obs. events / 0.05 GeV}$

$\text{Obs. / Bkg.}$

$\text{m}_{T,1}$ [GeV]

$\text{m}_{T,2}$ [GeV]

$\text{Events / 0.05 GeV}^2$

$\text{Obs. events / (0.05 GeV)}$

$\text{Obs. / Bkg.}$

$\text{m}_{T,2}$ [GeV]

$\text{Obs. events / 0.05 GeV}^2$

$\text{Obs. / Bkg.}$

$\text{m}_{T,2}$ [GeV]

$\text{Obs. events / (0.05 GeV)}$

$\text{Obs. / Bkg.}$
Search for $H \rightarrow AA \rightarrow 4\gamma$

- No evidence for a resonant structure

- Improves indirect constraints from $\text{Br}(H \rightarrow \gamma\gamma)$
- First CMS limits below $A \rightarrow \mu\mu$ threshold
- Future: adapt CNN to look for di-electron resonance; look at GNN
Search for new heavy H/A → t¯t

- Search for SM-like boson predicted by MSSM, **axion models, 2HDM**
  - Dominant decay mode to a pair of top quarks: inclusive production has a negative interference with \( gg \rightarrow t\bar{t} \): search in \( t\bar{t}H/A \) associative production instead
  - Final state: at least 6 jets, \( \geq 2 \) of which are b-tagged; \( H_T > 500 \) GeV
  - Sequential **XGBoost** BDT classifiers to separate
    - 4t final state from other backgrounds
    - SM 4t from signal (mass-parameterized BDT)
Search for dark matter in $tW$

- Search for a DM candidate within the 2HDM
  - Complements the t+MET+X ATLAS analysis with Run 2 data and t/ttbar+MET CMS analysis with 2016 dataset
- Consider final states with 0 or 1 e/µ + at least one b-jet (DNN DL1r), high jet multiplicity, and significant MET due to $\chi s$
  - Backgrounds (V+jets, ttbar, tt+Z, single top) are estimated from data using CR
- Results are combined with the previous ATLAS analysis with two leptons in the final state

M. Bauer et al, 1701.07427
Search for resonant $WZ \rightarrow \ell\nu\ell'\ell'$

- Interpretation within a Georgi-Machacek **model** (VBF production) and a Heavy Vector Triplet (HVT) $W'$ (both Drell-Yan and VBF)
  - Use **Keras** ANN to categorize events as coming from a VBF process or background
  - Use dedicated control regions to validate major backgrounds: $WZ$ and $ZZ$
  - Final discriminant in all signal regions is the mass of the $WZ$ system

- Interpretation of this and all previous heavy Higgs boson searches within GM model is documented as a separate note **ATL-PHYS-PUB-2022-008**
Search for VV → jets

- Target heavy mass resonant production of WW, ZZ, WZ, WH, and ZH in DY/gg and VBF production
  - RS R/G, W' and Z' from composite/little Higgs models, HVT
  - Boosted regime: two “fat” AK8 jets (+2 jets for VBF)
    - Significant improvement wrt to previous results due to DeepAK8 to separate W/Z/H from gluon or quark jets
- 10 categories (VBF/ggH, high and low purity)
- 3D bump hunt in m_{jet1}, m_{jet2}, m_{jets}
- Mild 3.6σ (local) 2.3σ (global) excess at around 2.1 and 2.9 TeV
Search for cross-generation LQs

- Traditional LQ searches focused on scalars and decaying to the same generation leptons and quarks
  - Two charged leptons in the final state are easier

- Cross-generation vector LQs could accommodate both $g-2$ and existing $B \to K\ell\ell$ and $B \to D\tau\nu$ anomalies

- Dedicated search for pairs of CG LQs with all possible decays to $3^{rd}$ generation quarks (t, b) and $1^{st}/2^{nd}$ generation leptons (e, $\mu$, $\nu$) final state
  - Focus on single lepton (e, $\mu$) final state; vector LQ optimization
  - One e or $\mu$, high MET, at least 4 jets
  - Dedicated NNs to separate signal and backgrounds (tt, W+jets, single top) are trained on the orthogonal control regions in data

Search for cross-generational LQs

- Data-background prediction for W+jets, single-top and low-NN (dominated by tt-bar) regions
  \[ LQ_{mix}^Y \rightarrow b\mu/t\nu \] with \( B = 0.5 \)

- Data-background prediction for signal regions

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Yuri Maravin – Recent Exotics/BSM Results  
Aspen 2022: New Methods and Ideas at the frontier of particle physics
Search for cross-generational LQs

- No significant excess observed. Limits at around 1.4 – 1.9 TeV were set on scalar and vector LQs for eight different models.

- Limits on the vector leptoquarks that could be responsible to B-anomalies are between 1.7 and 1.9 TeV depending on the coupling scenario.

![Graph showing search for cross-generational LQs](image-url)

<table>
<thead>
<tr>
<th>LQ</th>
<th>Theoretical Limit</th>
<th>Observed Limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$LQ^u_{mix}$</td>
<td>1440+60</td>
<td>1460</td>
</tr>
<tr>
<td>$LQ^d_{mix}$</td>
<td>1440+60</td>
<td>1440</td>
</tr>
<tr>
<td>$LQ^e_{mix}$</td>
<td>1380+50</td>
<td>1370</td>
</tr>
<tr>
<td>$LQ^\tau_{mix}$</td>
<td>1410+60</td>
<td>1390</td>
</tr>
<tr>
<td>$vLQ^u_{SM}$</td>
<td>1930+50</td>
<td>1980</td>
</tr>
<tr>
<td>$vLQ^d_{SM}$</td>
<td>1930+50</td>
<td>1900</td>
</tr>
<tr>
<td>$vLQ^e_{SM}$</td>
<td>1660+50</td>
<td>1710</td>
</tr>
<tr>
<td>$vLQ^\tau_{SM}$</td>
<td>1650+50</td>
<td>1620</td>
</tr>
</tbody>
</table>
Search for vector-like leptons

- 4321 model extending the SM sector provides a leptoquark for the source of the LFV and new families of vector-like fermions
  - Leptoquark $U$ primarily decays to third generation leptons and quarks
  - The final state has at least 4 $b$-jets and various numbers of tau leptons, neutrinos and light jets from top quark decays

<table>
<thead>
<tr>
<th>tau multiplicity</th>
<th>production + decay mode</th>
<th>final state</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 $\tau$</td>
<td>$EE \rightarrow b(t\nu_\tau)b(t\nu_\tau)$, $EN \rightarrow b(t\nu_\tau)t(t\nu_\tau)$, $NN \rightarrow t(t\nu_\tau)t(t\nu_\tau)$</td>
<td>$4b + 4j + 2\nu_\tau$, $4b + 6j + 2\nu_\tau$, $4b + 8j + 2\nu_\tau$</td>
</tr>
<tr>
<td>1 $\tau$</td>
<td>$EE \rightarrow b(b\tau)b(t\nu_\tau)$, $EN \rightarrow b(t\nu_\tau)t(b\tau)$, $EN \rightarrow b(b\tau)t(t\nu_\tau)$, $NN \rightarrow t(b\tau)t(t\nu_\tau)$</td>
<td>$4b + 2j + \tau + \nu_\tau$, $4b + 4j + \tau + \nu_\tau$, $4b + 4j + \tau + \nu_\tau$, $4b + 6j + \tau + \nu_\tau$</td>
</tr>
<tr>
<td>2 $\tau$</td>
<td>$EE \rightarrow b(b\tau)b(b\tau)$, $EN \rightarrow b(b\tau)t(b\tau)$, $NN \rightarrow t(b\tau)t(b\tau)$</td>
<td>$4b + 2\tau$, $4b + 2j + 2\tau$, $4b + 4j + 2\tau$</td>
</tr>
</tbody>
</table>
Machine learning tools: deep tau ID

- Deep convolutional neural network for identification of tau leptons
  - About 100k input features used in training

- Significant improvement in suppression of backgrounds

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Search for vector-like leptons

- In addition to deep tau ID, use DeepCSV for b-jet identification at trigger level, DeepJET for offline selection
- ABCNet graph neural network is used to set up deep neural network classifiers to reject major QCD multijet and tt-bar backgrounds using dedicated control regions
  - Final fit is over number of jets, tau leptons, and DNN_{tt} classifier

- 2.8σ for signal ~600 GeV with 2016+2017 data only
Search for $Y \rightarrow XX \rightarrow (jj)(jj)$

- Resolved jets final state: sensitivity to high mass X and Y
  - Interpretation: RPV SUSY or heavy di-quark that decays to vector-like quarks
- Final state: four highest-$p_T$ jets paired to dijet pair
  - Minimize the sum $\Delta R_i - 0.8$
  - Reduce QCD by imposing $\Delta R_i < 2$ and $\Delta \eta_{12} < 2$
  - Assume same X mass hypothesis $\frac{|m_1 - m_2|}{m_1 + m_2} < 0.1$
- Search over $M_{4j}$ and average dijet mass $m_{jj}$
  - Background is estimated from a fit to ModDijet-3p function
    - Two other empirical functions were used to estimate systematic uncertainties

CMS EXO-21-010

Evans et al, 1209.0764

Dobrescu et al, 1810.09429
Search for $Y \rightarrow XX \rightarrow (jj)(jj)$

3.6σ Local
2.5σ Global

3.9σ Local
1.6σ Global
• Impressive number of new results with Run 2 data
  • Several very intriguing results!

• ATLAS and CMS collected about 138 /fb of integrated luminosity, and this is only about 5% of the expected luminosity from the LHC
Backup