Recent BSM Higgs Searches at CMS & ATLAS

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Higgs Status: This week @ LHCP!

- SM measurements: $\sigma$, Br, $\mu$, $\kappa$, ...
- BSM searches/theory: 2HDM(+S), Heavy, Light, EFT, ...

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Every problem of the SM originates from Higgs interactions

\[ L = \lambda H \bar{\psi} \psi + \mu^2 |H|^2 - \lambda |H|^4 - V_0 \]

↑

flavour  naturalness  stability  C.C.
Summary of Newest Results

- Low mass $H \rightarrow \gamma\gamma$
- $H \rightarrow$ invisible
- Heavy H
- Searches for HH or HS
- LFV $H \rightarrow \ell\tau$, $e\mu$
- Light pseudoscalars
- $H \rightarrow$ meson + $\gamma$

CMS
- ATLAS

CMS
- ATLAS

CMS
- ATLAS

CMS(2)
- ATLAS

Chertok BSM Higgs LHCP 2023
BSM Searches for $H \rightarrow \gamma\gamma$
CMS H → γγ Search

- Search for narrow-width SM-like Higgs in the diphoton channel, 70 < M(γγ) < 110 GeV
- Previous CMS result showed mild excess at 95 GeV, follow up with full Run 2 data!
- Primary challenges: sufficient trigger efficiency, Z → ee background rejection

- Diphoton trigger, with pT > 30,18 GeV
  - 2016 only: 2 paths: 1. Barrel only, 2. Barrel+Endcap, with additional shower shape requirements
- Trigger requirements limit search to M(γγ) > 70 GeV
- Reconstruction-level classes: VBF (2017 and 2018 only), Class 0, 1, 2. Class 0 has highest exp. sensitivity
CMS H → γγ Search

- Small excess seen in all production modes: ggH+ttH, VBF, VH

Local/global significance: 2.9σ/1.3σ @ 95.4 GeV

Previous CMS analysis: 2.8σ/1.3σ @ 95.3 GeV

Chertok BSM Higgs LHCP 2023
H → invisible final states
ATLAS H $\rightarrow$ Invisible

- Higgs $\rightarrow$ Dark Matter! Invisible ($\rightarrow$ MET), so measure and interpret accompanying visible particles
- New combination of results:
  - VBF + MET
  - $Z + $ MET
  - $tt + $ MET
  - VBF + MET + $\gamma$
  - Jet + MET

![Diagram of Higgs decaying to invisible particles and accompanying visible particles]

Also combined with Run 1 results
VBF+MET most sensitive channel. Slight excess observed: \( \text{Br} @ 95\% \text{ CL} < 0.145(0.103) \text{ obs(exp)} \)

Run 1+2 combined: 0.107 (0.077)

Higgs portal: \( m_2 = \text{dark Higgs mass} \)
CMS H → Invisible  \[ \text{arXiv:2303.01214v1} \]

- New: \(ttH+\text{MET}\), combine with previous (VH production)
  - BGs: \(Z\rightarrow \text{inv}\), EWK → lost leptons
- AK8 Jet mass (PUPPI PF with SD plus Deep AK8) separates high-pT t or V decays from q/g fragmentation
  - \(@ p_T > 400 \text{ GeV}\), t quark tag eff ~ 28% with 1% QCD mistag rate

\[ 4.9 \, \text{fb}^{-1} (7 \text{ TeV}), 19.7 \, \text{fb}^{-1} (8 \text{ TeV}), 140 \, \text{fb}^{-1} (13 \text{ TeV}) \]

Run 1+2 combined: 0.15 (0.08)  

Chertok BSM Higgs LHCP 2023
Heavy Higgs Searches
2HDM, baryogenesis: $M_A > M_H$
Consider mass ranges:
- $M_A > 800$ GeV
- $M_H > 2M_{\text{top}} = 350$ GeV
Channels:
- $tt\ell\ell$: leptons+b’s+jets
- $bb\nu\nu$: complementary, DM search for heavy $H \rightarrow bb$ + MET

bg only fits to data
upper: $tt\ell\ell$
lower: $bb\nu\nu$
Searches for HH Production
CMS HH Search

- Non-resonant: Study SM couplings and check for deviations
- HH $\rightarrow$ bb + WW
- Require at least one $W \rightarrow \ell \nu$
- Resonant production search for exotic heavy states
  - $250 < M_X < 900$ GeV, Spin 0, 2

Radion

Graviton
Search for heavy scalar X decaying to SM Higgs plus singlet (S)

Appearing in 2HDM+S, nMSSM

- X mass: 500 - 1500 GeV
- S mass: 200 - 500 GeV

Require:

- $H \rightarrow \tau \tau \rightarrow \tau_{\text{had}} \tau_{\text{had}}$
- $S \rightarrow VV \rightarrow 1 \text{ or } 2 \ell (=e, \mu)$

BDT uses kinematics to separate signal from BG

Fake $\tau_{\text{had}}$ measured from DD using CR techniques

resulting upper limits @ 95% CL
range: 72 - 542 fb
H $\rightarrow$ decays with LFV final states
ATLAS $H \rightarrow e\tau, \mu\tau$  

**Motivation:**  
- $\nu$ mixing, flavor anomalies  
- BSM: 2HDM, CHM, flavor symmetries, etc.  
- Include all tau decays  
- Independent BG methods:  
  - MC templates using DD normalization  
  - Flavor symmetry $e \leftrightarrow \mu$

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**Chertok BSM Higgs LHCP 2023**
Search considers both the “SM” Higgs and a BSM Higgs:

- $110 \text{ GeV} < M(H), M(X) < 160 \text{ GeV}$
- range below $2M_W$ important for constraining 2HDM Type-III models
- Look for peak over smoothly falling BG from tt, WW, Z+jets
CMS $H \rightarrow e^{\pm} \mu^{\mp}$ Search

$B(H_{125} \rightarrow e\mu) < 4.4 \text{ obs (4.7 exp) x } 10^{-5}$

Chertok BSM Higgs LHCP 2023
Searches for light pseudoscalar Higgs Bosons
ATLAS Searches for light pseudoscalars with ttbar

- Two searches:
  - tta production
  - tt with $t \rightarrow H^+ b$, $H^+ \rightarrow W^+ a$, $a \rightarrow \mu\mu$
- Light "a" motivation:
  - 2HDM+S, NMSSM,
  - Explain galactic $\gamma$ emission excess!? 
- $a \rightarrow \mu\mu$ provides clean signature
- Search probes:
  - $15 < m(a) < 72$ GeV
  - $120 < m(H^\pm) < 160$ GeV
CMS H → Za, with a → γγ

- Signature: Za → ℓℓγγ
- Consider 1 < m(a) < 30 GeV
- Apply to ALPs models

input to BDT, others include photon variables

BDT Output m(a) = 10 GeV

Chertok BSM Higgs LHCP 2023

ALPs coupling to ZH

CMS-PAS-HIG-22-003
CMS H → aa → μμbb, ττbb

- Yukawa couplings: a → bb maximal when kinematically allowed, a → ττ is next, ...

- 2HDM+S:
  - Type II: B(aa → ττbb) ~ 10%
  - Type IV: ~ 50%
- Di-tau decays: eμ, eτh, μτh
- τh reconstructed with HPS;
  - j → τh mis-id performed with DD methods.
- BGs: tt, DY, diboson
CMS H → aa → μμbb, ττbb

Chertok BSM Higgs LHCP 2023
$H \rightarrow \text{meson} + \gamma$

(a) Direct amplitude

(b) Indirect amplitude
Unique approach to study Higgs couplings to light flavor

Signatures:
  - $K\pi\gamma$, $3\pi\gamma$, $2\pi\gamma$, $KK\gamma$, $\mu\mu\gamma$ ...

SM predictions are tiny
Conclusions

- Large data sets at 13 TeV from Run 2 with excellent ATLAS and CMS detectors provide unprecedented search reach for BSM Higgs signals. 12 new results shown!
  - tl;dr: no BSM discoveries so far ;)
- The two collaborations have methodically improved search strategy and parameter space considered as the data sets have increased. Now ubiquitous:
  - Advanced and varied ML techniques
  - Combination of channels
- Observed bumps and wiggles will be vigorously probed with additional Run 3 data in advance of HL-LHC, which promises another 10X data at 14 TeV.