Recent results from BSM Higgs searches and searches for new light bosons decaying into muon pairs with the CMS detector

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• Discovered Higgs boson at LHC via mass peaks in multiple decay channels, via several production mechanisms

• Minimal Higgs model very predictive: $m_H$ only free parameter
  • From this can predict production cross section, decay widths, etc
  • Increasingly precise measurements of mass, spin, parity, and coupling strengths
Experimental checklist

☑ Find Higgs boson

☑ Determine if it’s the SM Higgs
  ☑ Measure couplings: 3rd gen fermions, \( W/Z \), associated production
  ☑ Measure properties

☑ Find other Higgs-like particles
  ☑ Part of spectrum? Many models propose additional bosons (NMSSM, 2-Higgs doublets, little Higgs...)

☑ Use Higgs as a portal to new physics
  ☑ Exotic production modes: High mass particles decaying to Higgs pairs (\( X \rightarrow HH \))
  ☑ Exotic decay modes: \( H \rightarrow \text{invisible}, H \rightarrow aa \rightarrow 4\mu \)
Higgs couplings: $tHq, H \rightarrow WW$

- Very sensitive probe of top-Higgs coupling $C_t$
  - Higgs typically irradiated from heavier legs
- Strong interference between two diagrams
- Cross section enhanced for negative couplings
- Multivariate discriminant
- Combined limit of $6.7 \times \sigma_{C_t} = -1$ (expected 5.0)
Exotic production: $X \rightarrow HH \rightarrow 4b$

- Model independent search for narrow resonance decaying to Higgs pair
  - 4b final state most sensitive to high-mass resonance
  - Search performed for spin-0, spin-2 signals

- Non-resonant HH production in SM too small in Run 1
  - $\sigma_{NNLO}(pp \rightarrow HH) = 10$ fb

arXiv: 1503.04114
Extended Higgs sectors: $\text{NMSSM} \ H \rightarrow b \bar{b}$

- Search for light neutral Higgs decaying to $b$-quark pair plus 2 jets and large MET
- NMSSM Higgs sector: Two complex Higgs doublets and one additional singlet
  - Lightest scalars can be lighter than $H$ at 125 GeV
- Limits interpreted for single resonant Higgs-like structure with $m_{h_1}$ and in context of NMSSM
Extended Higgs sectors: Heavy $H$ in mass range 145—1000 GeV

- Other SM extensions predict additional neutral or charged scalars
  - SM with heavy EWK singlet: Predicts high-mass scalar that contributes to symmetry breaking

- Combination search for heavy Higgs in $H \to WW$ and $H \to ZZ$ decay channels
  - Multiple final states, production modes considered
  - Upper limits determined for heavy Higgs contribution to EWK symmetry breaking $C'^2$ for various contributions to the width of non-SM decays $B_{\text{new}}$

arXiv: 1504.00936
Exotic decays: VBF $H \rightarrow$ invisible

- Invisible decays probe of new physics coupling to Higgs sector
  - Decays to neutralinos (SUSY), graviscalars (extra dimensions), and DM (Higgs-portal interactions)

- Indirect constraint on undetected decay modes via visible modes
  - $\Gamma_{tot}$ from measured Higgs production rates

- Observed (expected) 95% CL upper limit on invisible BR for $m_H = 125$ GeV is 0.57 (0.40)
Benchmark: NMSSM

- NMSSM—well motivated minimal extension of MSSM
  - More complex Higgs sector: 3 CP-even states ($h_1, h_2, h_3$), 2 CP-odd states ($a_1, a_2$)
  - Inclusion of $a_1$ changes Higgs phenomenology: $h_1 \rightarrow a_1a_1$ can have significant BR
- Benchmark model: $h_1 \rightarrow a_1a_1 \rightarrow 4\mu$
  - $0.25 < m_{a_1} < 3.55$ GeV
    ($2m_\mu < m_{a_1} < 2m_\tau$)
  - $BR(a_1 \rightarrow \mu\mu) \sim 7.7\%$ at $m_{a_1} = 2$ GeV

Benchmark: Dark SUSY

- Motivation from satellite experiments (PAMELA, Fermi)
  - Higher fraction of positrons at high energy; from dark matter annihilation in galactic halo?
    - Posit “light dark boson” $\gamma_D$ to provide attractive long-distance force to slow-moving WIMPs
    - $\gamma_D$ couples weakly to SM
    - $m_{\gamma_D} \lesssim 1$ GeV (decays to $p\bar{p}$ forbidden)

- Benchmark model:
  - $0.25 < m_{\gamma_D} < 3.55$ GeV
  - $90 < m_{h_1} < 150$ GeV
  - $BR(\gamma_D \rightarrow \mu\mu) \sim 45\%$ at $m_{\gamma_D} = 0.4$ GeV

JHEP 1005:077,2010
$H \rightarrow aa \rightarrow 4\mu$: Data selection

- Require 4 muons
  - $p_T(\mu) > 8$ GeV, $|\eta(\mu)| < 2.4$
  - At least 1 mu with $|\eta| < 0.9$, $p_T > 17$ GeV
    - High trigger efficiency
- Group oppositely charged muons into dimuons
  - If pairwise invariant mass $< 5$ GeV and
    - Either probability of common vertex $P > 1\%$ or
    - Two muon tracks satisfy $\Delta R < 0.01$
  - Muons can be shared among several dimuons
    - Select events with exactly two dimuons not sharing any common muons
    - No restriction on orphaned muons
- Event selection, diagonal signal region
**Background estimation**

- Dominant background contributions to $4\mu$ from SM:
  - $b\bar{b}$ events with $b$-quark decays to $\mu\mu + X$ via semileptonic decays, resonances
  - Shape of dimuon invariant mass distribution measured independently for two dimuons via orthogonal sample with one dimuon and one orphan muon
  - 2D template constructed as Cartesian product of 1D templates
  - Prompt double $J/\psi$ events
    - Estimated from normalizing MC prediction to data

![CMS 2011 $\sqrt{s} = 7$ TeV $L_{\text{int}} = 5.3$ fb$^{-1}$](image1.png)

![Phys.Lett.B726(2013)564](image2.png)

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Model independent limit: \( \sigma(pp \rightarrow 2a + X) \times BR^2(a \rightarrow 2\mu) \times \alpha_{gen} < 0.77 \text{ fb} \)

- 95% CL upper limit on production rate

- Determine exclusion limits on Higgs production in NMSSM and dark SUSY models as function of \( m_{h_1} \)
$H \rightarrow aa \rightarrow 4\mu$: Results

- Search for nonstandard decay modes of CP-even Higgs to new light boson ($a_1$ or $\gamma_D$) in 4$\mu$ final state
  - Specifically explore NMSSM and dark SUSY models
  - Examined mass ranges $86 < m_{h_{1,2}} < 150$ GeV and $0.25 < m_{a_1} < 3.55$ GeV

- Compute 95% CL upper limits as function of $m_{a_1}$
Conclusions

• Extensive program of BSM Higgs production and decay modes from Run 1
  • Several strong limits on new physics, but many decay modes still largely unconstrained by 8 TeV data

• Many well-motivated possible extensions to Higgs sector
  • Large phase space probed in Run 1

• Expect Run 2 to significantly improve reach
  • Run 1 sensitivity reached with ~ 10/fb at 13 TeV
  • Increasing precision on Higgs properties constrains BSM models
  • Scalar searches benefit from high statistics
Backup slides
Pseudoscalar $A \rightarrow Z h \rightarrow l l b b$

- Search for decays of pseudoscalar $A$ to a $Z$ and a light scalar $h$
  - $Z$ decays to a pair of opposite-charge electrons or muons
  - $h$ decays to $b \bar{b}$
- Limits interpreted in context of 2-Higgs doublet model
• Search for high mass scalar decaying to $Z$ and photon
• Require opposite-sign electron or muon pairs
• Observed limits between 0.2 and 1.4 fb as function of scalar mass
$H \rightarrow aa \rightarrow 4\mu$: Systematic uncertainties

- Integrated luminosity: 2.2%
- PDF and $\alpha_s$: 3%
- QCD renormalization and factorization scales: $\sim$ 0%
- Tracking efficiency: 4 * 0.2%
- Overlapping in the tracker: 2 * 1.2%
- Overlapping in the muon system: 2 * 1.3%
- Dimuon mass consistency: 1.5%
- Data/MC scale factors for muon ID, isolation, vertex: ...
- Total uncertainty: 8.0%