Search for Non-Standard-Model Higgs Boson Decays Using Boosted Muon Pairs at the LHC

Aysen Tatarinov for CMS Collaboration

Texas A&M University

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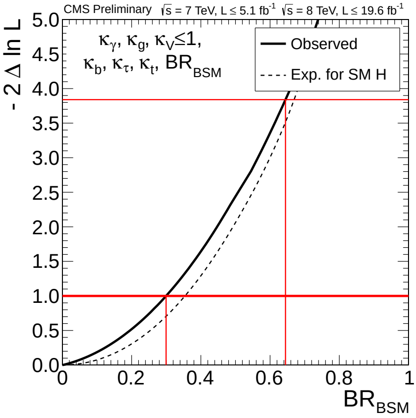
Introduction (1/2)

- Higgs-like particle with mass ∼125 GeV was observed at LHC
- Critical question: is it the SM Higgs boson?

- (1) Precise measurements of its branching ratios:
  - This may take many years
  - Current 95% CL limit: $\mathcal{B}_{BSM} \leq 0.64$
- (2) Direct searches for SM-like non-SM Higgs boson:
  - In case of observation: this is non-SM Higgs!
  - In case of no signal: restrict broad class of scenarios beyond the SM



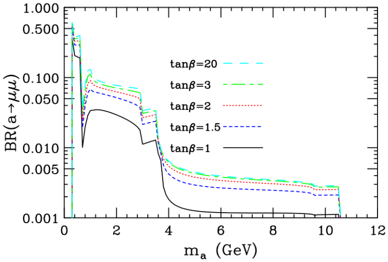
CMS-PAS-HIG-13-005

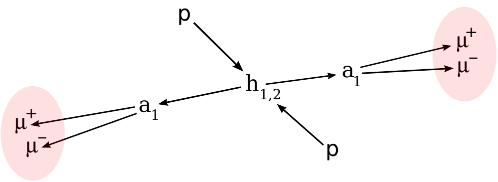
Introduction (2/2)

- Search for non-SM Higgs decays to a pair of new light bosons, which decay to boosted and isolated muon pairs: $h \to 2a \to 4\mu$
  - m_a within the range 0.25–3.55 GeV (roughly between $2m_\mu$ and $2m_\tau$)
- Analysis is designed to remain model independent
  - Allows easy reinterpretation in the context of any scenario with the same signature
- Wide class of scenarios beyond Standard Model predicts new light bosons, which may decay to boosted muon pairs (dimuons)
- Two specific benchmark scenarios (more details on next two slides)
  - Next-to-Minimal Sypersymmetric Standard Model (NMSSM)
  - SUSY + hidden dark sector (Dark SUSY)

Benchmark Scenario I: NMSSM

- Modified superpotential:
  - MSSM: $\mu H_u H_d$
  - NMSSM: $\lambda S H_u H_d + \frac{1}{3}\kappa S^3$
- Requires less fine tuning and solves μ-problem:
  - μ is generated by singlet field VEV and naturally has EW scale
- More complex Higgs sector:
  - 3 CP-even Higgses $h_{1,2,3}$ and 2 CP-odd Higgses $a_{1,2}$
  - Higgs-to-Higgs decay: $h_{1,2} \rightarrow 2a_1$
  - a_1 weakly couples to SM particles due to its mostly singlet nature
  - Can have a substantial $\mathcal{B}(a_1 \rightarrow \mu\mu)$ when $2m_\mu < m_{a_1} < 2m_\tau$

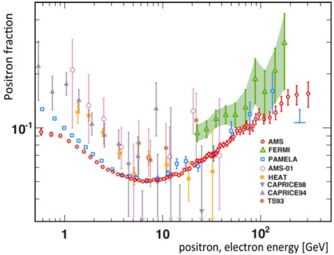




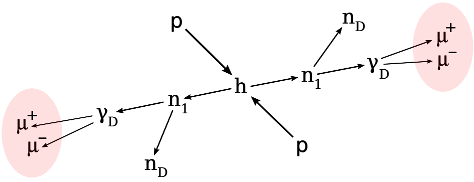
* Phys. Rev. D 81, 075003 (2010): significant structures on the left figure due to variations in $\mathcal{B}(a_1 \rightarrow gg)$

Benchmark Scenario II: Dark SUSY

- Recent observation of rising positron fraction at high energies by satellite experiments
- Dark matter annihilation: new light γ_D as an attractive long-distance force between slow moving WIMPs
- Simplified implementation of dark sector (for simulation only):
  - dark neutralino n_D (new LSP) + dark photon γ_D
- if $m_{n_1} < \frac{m_h}{2}$: $h \to 2n_1$
- n_1 decays into dark sector particles: $n_1 \to n_D \gamma_D$
- γ_D weakly couples to SM via kinetic mixing with photon

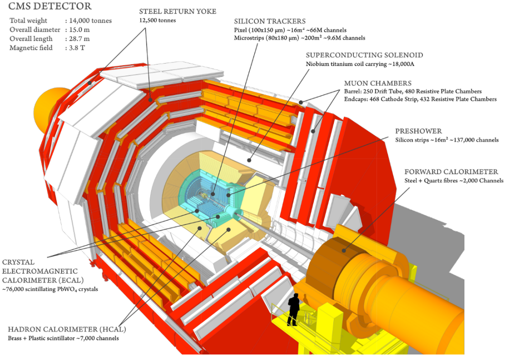


Phys. Rev. Lett. 110, 141102 (2013)



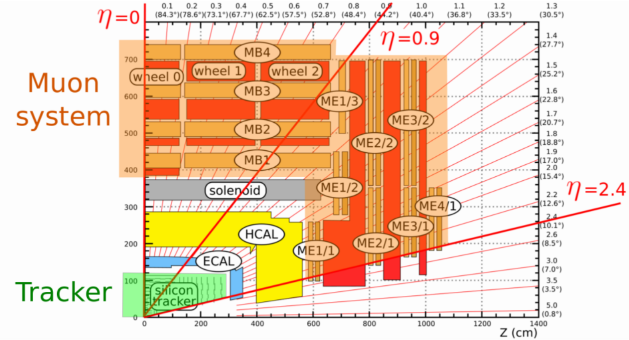
Experimental Apparatus

- CMS experiment at the LHC
  - Excellent ability of CMS detector to reconstruct muons
  - Efficient and well understood muon trigger
- Analysis Datasets:
  - 2010 year with $\int L \sim 35\ \mathrm{pb}^{-1}$ (10.1007/JHEP07(2011)098)
  - 2011 year with $\int L \sim 5.3\ \mathrm{fb}^{-1}$ (submitted to PLB: arxiv:1210.7619) THIS TALK
  - 2012 year with $\int L \sim 20.7\ \mathrm{fb}^{-1}$ (on the way to internal approval)



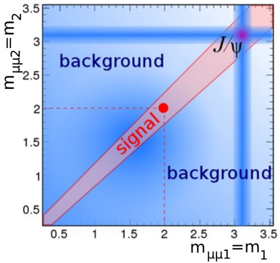
Analysis Selection

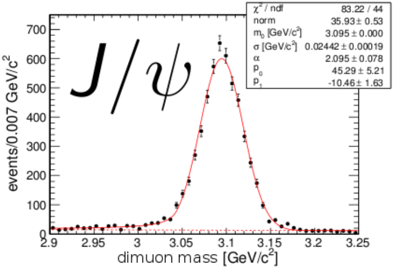
- At least four muons: $p_T > 8$ GeV/c, $|\eta| < 2.4$, good track quality
- To ensure constant efficiency of double muon trigger
  - At least one good quality muon with $p_T > 17$ GeV/c, $|\eta| < 0.9$
- Assign two opposite-sign muons to a dimuon
  - $m_{\mu\mu} < 5$ GeV/c^2 **and** (good common vertex **or** $\Delta R_{\mu\mu} < 0.01$)



Event Selection / Signal Region

- Events with two dimuons (no limit on number of unpaired muons)
- Require dimuons to be isolated
  - Supresses background by a factor of 40, rejects less than 10% of signal
- Signal region: dimuon masses consistent with each other:
  - $|m_1 - m_2| \leq 5 \cdot \sigma(\frac{m_1+m_2}{2})$ (where $\sigma(m)$ — dimuon mass resolution)
- Study of dimuon mass resolution:
  - Use narrow SM resonances in data: ω, ϕ, J/ψ, ψ'
  - $\sigma(m) \sim 0.026 + 0.013 \cdot m$

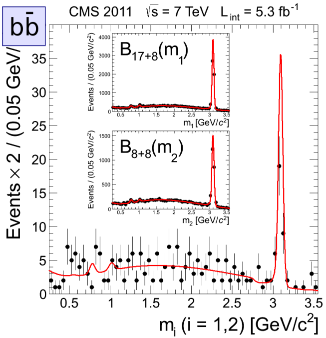


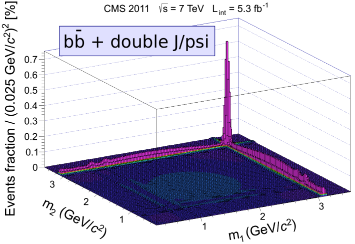


Modeling Background Shape

Main SM background contributions: $b\bar{b}$ and direct double J/ψ production

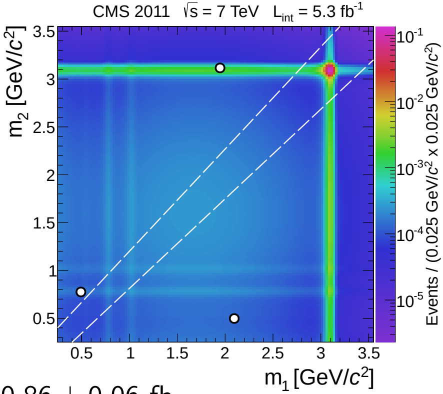
- $b\bar{b}$:
  - 2D background template $B_{17+8} \times B_{8+8}$ obtained from $b\bar{b}$ enriched data with 3 muons and no isolation requirement and normalized to data
  - Validated in control region (off-diagonal region with no isolation requirement)
- Direct double J/ψ production:
  - 2D Crystal Ball template normalized to data





Looking into the Signal Region

- No events in the signal region observed with data collected at CMS in 2011
  - 1.0 ± 0.5 background events expected in the signal region (0.7 ± 0.4 $b\bar{b}$, 0.3 ± 0.3 double J/ψ)
- Three events observed in off-diagonal region
- Model independent 95% CL limit:



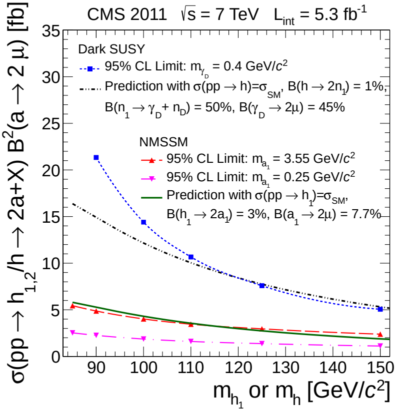
$$\sigma(pp \to h \to 2a)\mathcal{B}^2(a \to 2\mu) \times \alpha_{gen} < 0.86 \pm 0.06 \text{ fb}$$

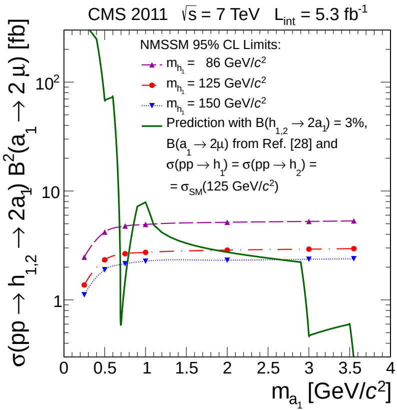
- α_{gen} — kinematic and geometric acceptance on generator level

Applicable to models with 4μ coming from new light bosons with mass in range 0.25–3.55 GeV, where new light bosons typically isolated, spatially separated, the light boson's decay vertex within $\sim$ 4cm from the beamline

Results: Benchmark Scenarios

- 95% CL. limit on $\sigma(pp \to h \to 2a)\mathcal{B}^2(a \to 2\mu)$ vs m_h and m_a
  - Exclusion region is above limit curves
  - $\mathcal{B}(h \to 4\mu) \lesssim 4{\cdot}10^{-4}$ (Dark SUSY), $\mathcal{B}(h \to 4\mu) \lesssim 1.5{\cdot}10^{-4}$ (NMSSM) much smaller than current 95% CL limit $\mathcal{B}_{BSM} < 0.64$





* significant structures on the right figure due to variations in $\mathcal{B}(a_1 \to gg)$ when m_{a_1} crosses internal quark loop thresholds

Conclusions

- Search for non-SM Higgs (h) decays to a pair of new light bosons (a), which decay to boosted and isolated muon pairs: $h \to 2a \to 4\mu$ ($2m_\mu \lesssim m_a \lesssim 2m_\tau$) with data collected at CMS experiment in 2011
  - No excess over SM background is observed
  - 95% CL model independent limit: $\sigma(pp \to h \to 2a)\mathcal{B}^2(a \to 2\mu) \times \alpha_{gen} < 0.86 \pm 0.06$ fb
  - Interpreted in the context of NMSSM and Dark SUSY:
    - m_{h_1} or m_h in range 86–130 GeV
    - m_a in range 0.25–3.55 GeV
- Analysis with data collected at CMS in 2012 is coming soon!
- Stay tuned!

BACKUP SLIDES

Model Independent Result

✓ The result of the analysis is the 95% C.L. upper limit on the production rate

$$\sigma(pp \to 2a + X) \times Br^2(a \to 2\mu) \times \epsilon_{full} < \frac{N_B}{\mathcal{L}}$$

where ϵ_{full} - is event selection efficiency

✓ The analysis selection requirements are designed to keep ratio $r = \frac{\epsilon_{full}}{\alpha_{gen}} = 0.67 \pm 0.05$ constant

- α_{gen} is the geometric and kinematic acceptance calculated using generator level information only
- flatness of the ratio is checked for several benchmark samples

✓ The generic model independent result:

$$\sigma(pp \to 2a + X) \times Br^2(a \to 2\mu) \times \alpha_{gen} < \frac{N_B}{\mathcal{L} \cdot r}$$

- easily applicable to an arbitrary non-SM scenario predicting the signature of two boosted isolated dimuons with consistent masses

Systematic Uncertainties (1/3)

- ✓ Integrated luminosity — 4%
  - currently recommended by CMS Luminosity Working Group
- ✓ PDF and α_s — 3%
  - parameterization varied within CTEQ6.6 family
  - compared with other PDF sets
  - follow the PDF4LHC recommendations
    - CERN-2011-002, arxiv:1101.0593
- ✓ QCD renormalization and factorization scales — negligible
  - μ_R and μ_F varied by a factor of two up and down
  - follow the study in H -> ZZ* -> 4l CMS note (AN-11-387)

Systematic Uncertainties (2/3)

- ✓ Tracking efficiency — $4 \times 0.2\%$
  - scale factor is 1.002 (AN-11-141) — syst. uncert. of 0.2% per muon
- ✓ Overlapping in the Tracker — $2 \times 1.2\%$
  - measure tracking efficiency for di-muons with pt from 0 to 100 GeV
  - compare the efficiency for a given di-muon mass and transverse momenta p_T and $(1 \pm 0.2) \times p_T$, effectively size of clusters changed by 20% (follow our previous analysis AN-10-462)
- ✓ Overlapping in the Muon system — $2 \times 1.3\%$
  - difference in single muon efficiency between the crossing and non-crossing cases, applied to muons in endcap
  - follow our previous analysis AN-10-462
- ✓ Dimuon mass consistency — 1.5%
  - the efficiency is driven by radiative tail simulation
  - signal shape parameters varied within uncertainties from the fit

Systematic Uncertainties (3/3)

- ✓ Account for difference between data and MC simulations:
  Scale factors from T&P studies from $Z \to \mu\mu$ and $J/\psi \to \mu\mu$

Source of Uncertainty	Scale factor
Muon ID	0.991
Muon HLT	0.982
Di-muon isolation	0.985
Di-muon common vertex fitting	1.00

- ✓ Muon ID — $4 \times 1.4\%$
- ✓ Muon HLT — 1.4%
- ✓ Dimuon isolation — $2 \times 0.13\%$
- ✓ Dimuon common vertex fitting — $2 \times 0.3\%$

Total uncertainty: 9.0%