Search for Non-SM Higgs Boson Decays Using Collimated Muon Pairs at the CMS

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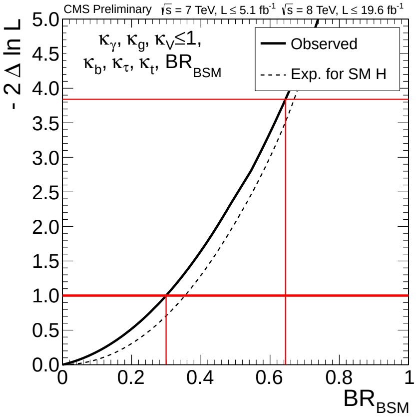
Introduction (1/2)

- Higgs-like particle with mass of 125.7 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 non-SM decays of SM-like Higgs:
  - In case of observation: this is non-SM Higgs!
  - In case of no signal: restrict broad class of scenarios beyond the SM



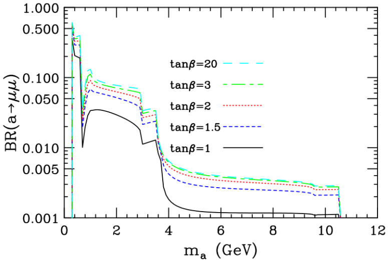
* CMS-PAS-HIG-13-005

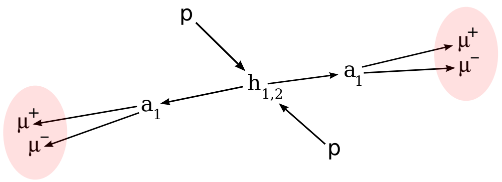
Introduction (2/2)

- Search for non-SM Higgs decays to a pair of new light bosons, each of which decays to boosted and isolated muon pairs (dimuons): $h \to 2a \to 4\mu$
  - 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
- 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: $h_{1,2} \to 2a_1$
  - a_1 weakly couples to SM particles due to its mostly singlet nature
  - Can have a substantial $\mathcal{B}(a_1 \to \mu\mu)$ when $2m_\mu < m_{a_1} < 2m_\tau$

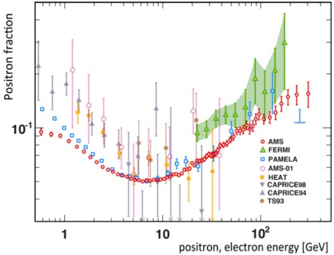




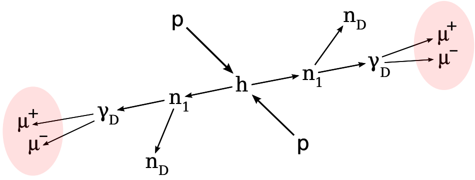
* Phys. Rev. D 81, 075003 (2010): significant structures on the left figure due to variations in $\mathcal{B}(a_1 \to gg)$

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

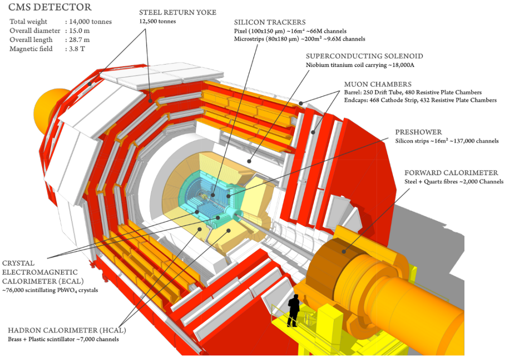


Phys. Rev. Lett. 110, 141102 (2013)



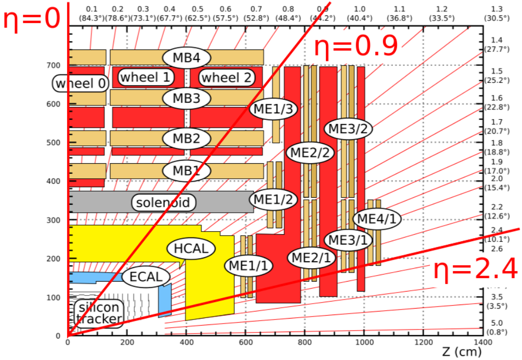
Experimental Apparatus

- CMS experiment at the LHC
  - Excellent ability of CMS detector to reconstruct muons
  - Efficient and well understood muon trigger
- Analysis Datasets:
  - 2010 year with $\int L \sim 35\ \text{pb}^{-1}$ (10.1007/JHEP07(2011)098)
  - 2011 year with $\int L \sim 5.3\ \text{fb}^{-1}$ (submitted to PLB: arxiv:1210.7619)
  - 2012 year with $\int L \sim 20.65\ \text{fb}^{-1}$ (THIS TALK)



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** $\Delta R_{\mu\mu} < 0.01$)



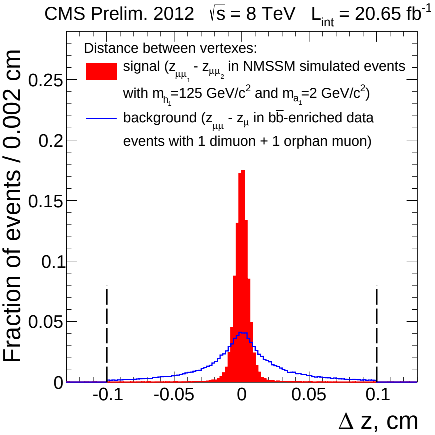
Event Selection (1/2)

- Further consider events with exactly two dimuons (there is no limit on number of unpaired muons)

- Reconstruct dimuon vertices: project dimuon's momentum vector to the beamline, find a point of the closest approach to the beamline in xy-plane
- Require dimuons to be produced in the same pp collision:

  $$|\Delta z| = |z_{\mu\mu_1} - z_{\mu\mu_2}| < 0.1 \text{ cm}$$

- Loose and safe requirement



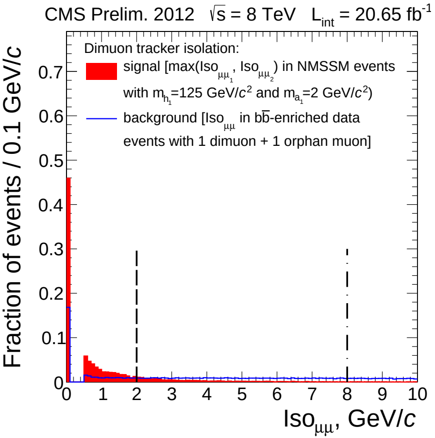
Event Selection (2/2)

- Apply isolation requirement to dimuons: supresses background by a factor of 50, reject about 20% of signal

$$Iso_{\mu\mu} = \sum_{tracks} p_T(track) < 2 \text{ GeV}$$

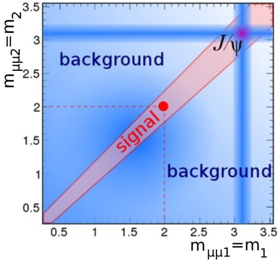
- $p_T(track) > 0.5$ GeV
- $\Delta R(track, \mu\mu) < 0.4$
- $|z_{track} - z_{\mu\mu}| < 0.1$ cm
- tracks of muons forming the dimuon are excluded

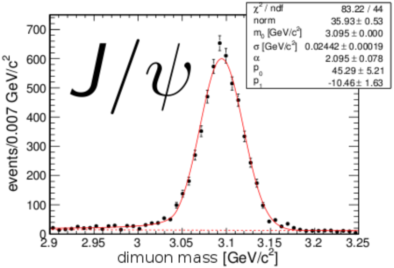
Relative isolation instead of absolute: introduces unnecessary p_T-dependence (more model-dependency)



Signal Region

- Target events where dimuons are produced in decays of new light bosons with the same mass
- Signal region: reconstructed 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'
  - $\sigma(m) \sim 0.026 + 0.013 \cdot m$

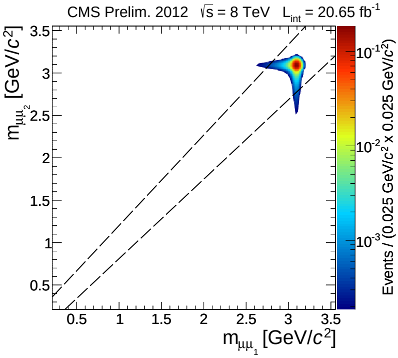


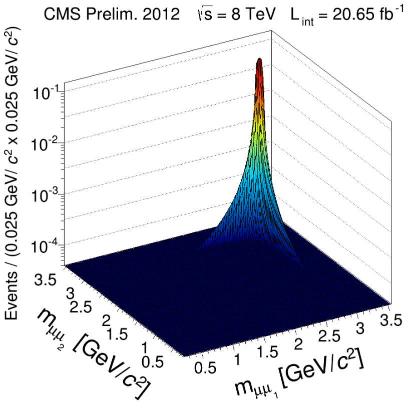


SM Background: Prompt Double J/ψ Production

Main SM background contributions:

- $b\bar{b}$ (next several slides)
- prompt double J/ψ production
  - 2D Crystal Ball template normalized to data
  - 2.0 ± 2.0 prompt double J/ψ events expected in the signal region

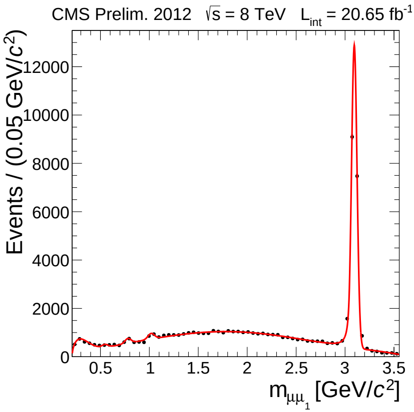




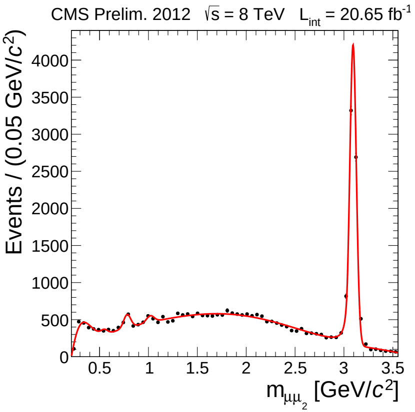
SM Background: $b\bar{b}$ (1/4)

2D background template $B_{17+8} \times B_{8+8}$ obtained from $b\bar{b}$ enriched data: events with one dimuon and one muon (no isolation requirement)

B_{17+8}

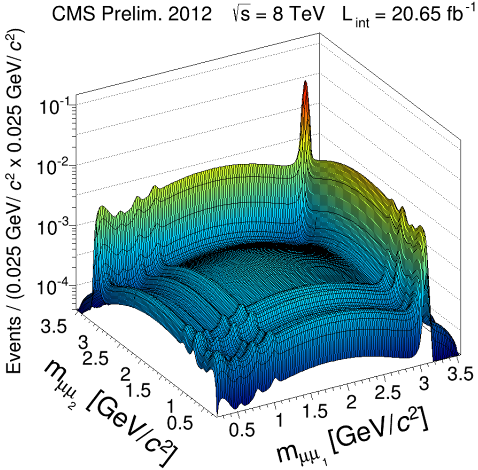


B_{8+8}



SM Background: $b\bar{b}$ (2/4)

2D background template $B_{17+8} \times B_{8+8}$ obtained from $b\bar{b}$ enriched data: events with one dimuon and one muon (no isolation requirement)

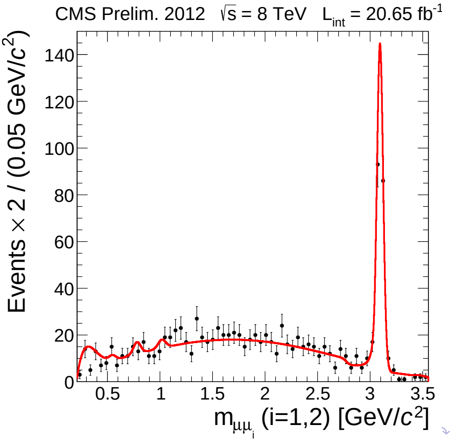


SM Background: $b\bar{b}$ (3/4)

- Use data sample with two dimuons
- Drop dimuon isolation requirement
- Keep diagonal region (signal region) blinded

Validation of $b\bar{b}$ 2D shape:

- Sum up 1D projections onto $m_{\mu\mu_1}$ and $m_{\mu\mu_2}$ in data
- Repeat the same for $b\bar{b}$ 2D shape
- Normalize $b\bar{b}$ 1D shape to data and check if the shape describes data well
- Good agreement observed

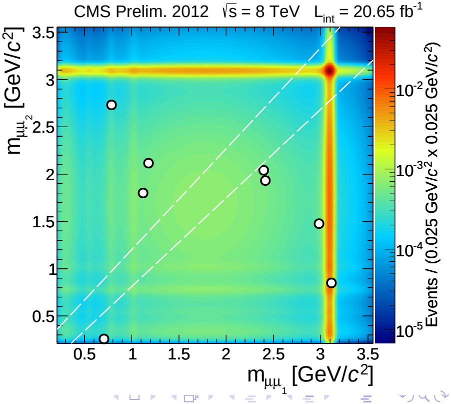


SM Background: $b\bar{b}$ (4/4)

- Now apply isolation requirement to dimuons
- Keep diagonal region (signal region) blinded
- Off-diagonal region is dominated by $b\bar{b}$ events

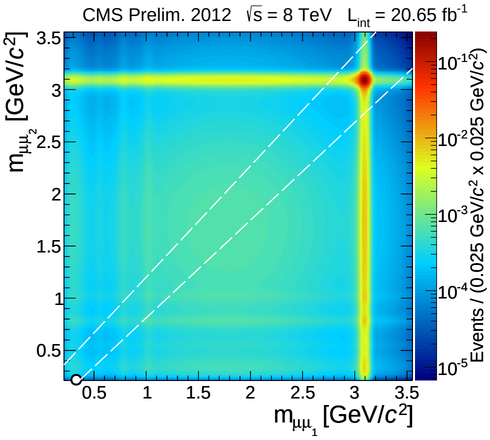
- Off-diagonal part of $b\bar{b}$ 2D shape is normalized to 8 events observed in off-diagonal region
- Ratio of areas under diagonal and off-diagonal parts of $b\bar{b}$ 2D shape: 0.18/0.82
- Number of $b\bar{b}$ events expected in the signal region:

$$(8 \pm \sqrt{8}) \cdot \frac{0.18}{0.82} = 1.8 \pm 0.6$$



Looking into the Signal Region

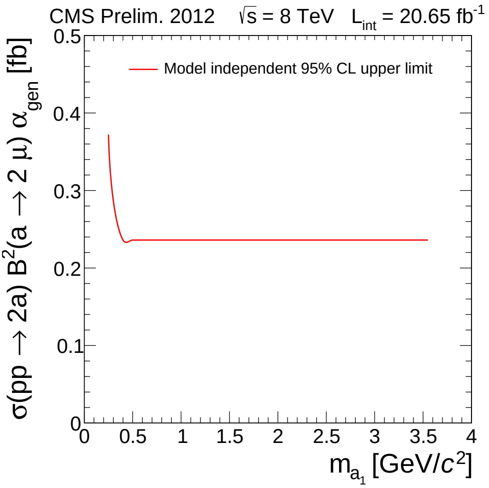
- Unblind the signal region (diagonal region)
- One event is observed in the signal region
- 3.8 ± 2.1 background events expected in the signal region (1.8 ± 0.6 $b\bar{b}$, 2.0 ± 2.0 double J/ψ)



Model Independent Limit

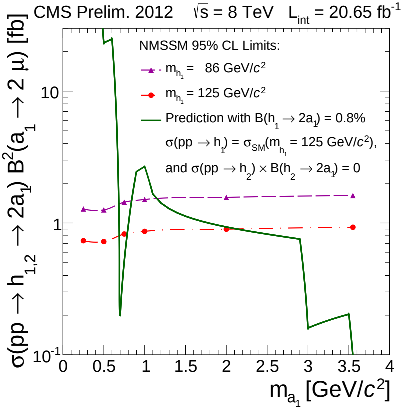
95% CL limit on $\sigma(pp \to h \to 2a) \times \mathcal{B}^2(a \to 2\mu) \times \alpha_{gen}$

- α_{gen} — kinematic and geometric acceptance on generator level
- We use flat $\frac{\epsilon_{full}}{\alpha_{gen}} = 0.63 \pm 0.05$ observed in all MC samples we used
- 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 and spatially separated



Bechmark Scenarios: NMSSM

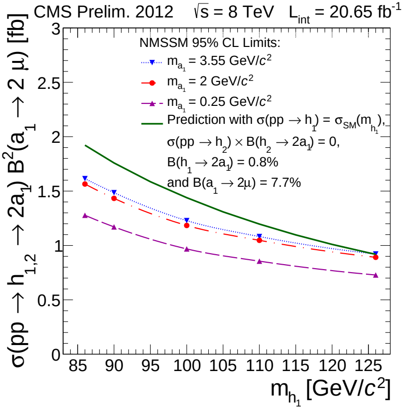
- 95% CL limit on $\sigma(pp \to h \to 2a)\mathcal{B}^2(a \to 2\mu)$ vs m_a
  - Exclusion region is above limit curves

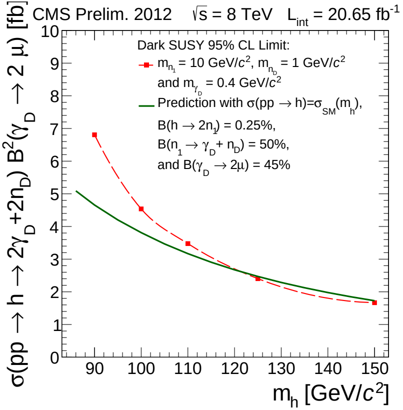


* significant structures on both figures are due to variations in $\mathcal{B}(a_1 \to gg)$ when m_{a_1} crosses internal quark loop thresholds

Benchmark Scenarios: NMSSM and Dark SUSY

- 95% CL limit on $\sigma(pp \to h \to 2a)\mathcal{B}^2(a \to 2\mu)$ vs m_h
  - Exclusion region is above limit curves
  - For $\sigma(pp \to h) = \sigma_{SM}(m_h = 125 GeV)$:
    $\mathcal{B}(h \to 4\mu) \lesssim 1.3 \cdot 10^{-4}$ (Dark SUSY), $\mathcal{B}(h \to 4\mu) \lesssim 5 \cdot 10^{-5}$ (NMSSM)
    much smaller than current 95% CL limit $\mathcal{B}_{BSM} < 0.64$





Conclusions

- Search for non-SM Higgs (h) decays to a pair of new light bosons (a), which decay to boosted and isolated muon pairs: $h \to 2a \to 4\mu$ $(2m_\mu \lesssim m_a \lesssim 2m_\tau)$
  - One event is observed in the signal region with 20.65 fb^{-1} of data collected at CMS experiment in 2012 at $\sqrt{s} = 8$ TeV
  - 95% CL model independent limit is set
    - Results are applicable to a broad spectrum of non-SM scenarios predicting the same signature
    - Recipe is provided
  - Interpreted in the context of NMSSM and Dark SUSY:
    - m_a or m_{γ_D} in range 0.25–3.55 GeV
    - m_{h_1} or $m_h > 86$ GeV

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%
  - provided by the CMS Luminosity Working Group in March 2012
- ✓ 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 × 0.2%
  - scale factor is 1.002 (AN-11-141) — syst. uncert. of 0.2% per muon
- ✓ Overlapping in the Tracker — 2 × 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 × 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	0.997
Muon HLT	0.985
Di-muon isolation	0.984
Di-muon common vertex fitting	1.002

- ✓ Muon ID — $4 \times 1\%$
- ✓ Muon HLT — 1.5%
- ✓ Dimuon isolation — $2 \times 0.13\%$
- ✓ Dimuon common vertex fitting — $2 \times 0.3\%$

Total uncertainty: 8.0%