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

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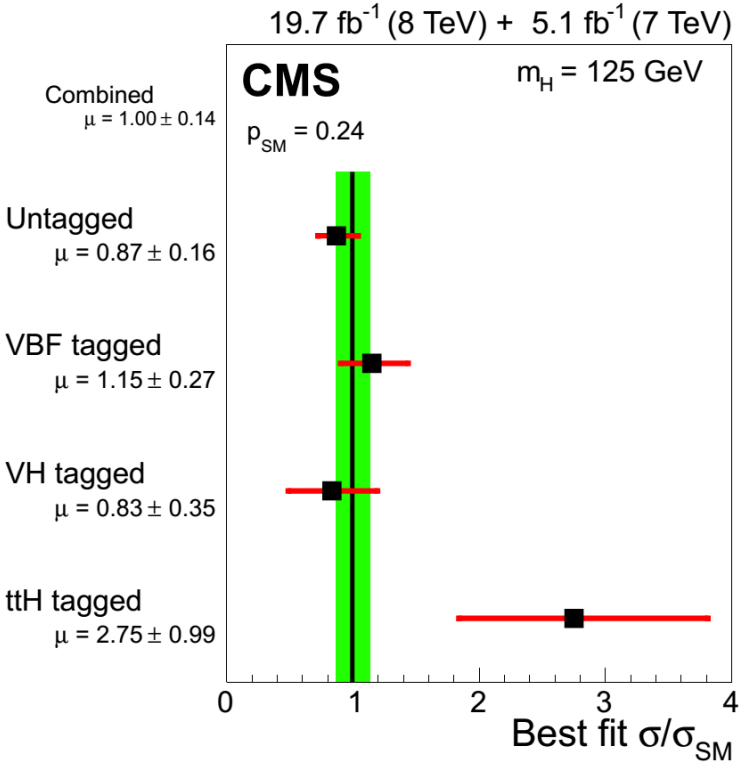
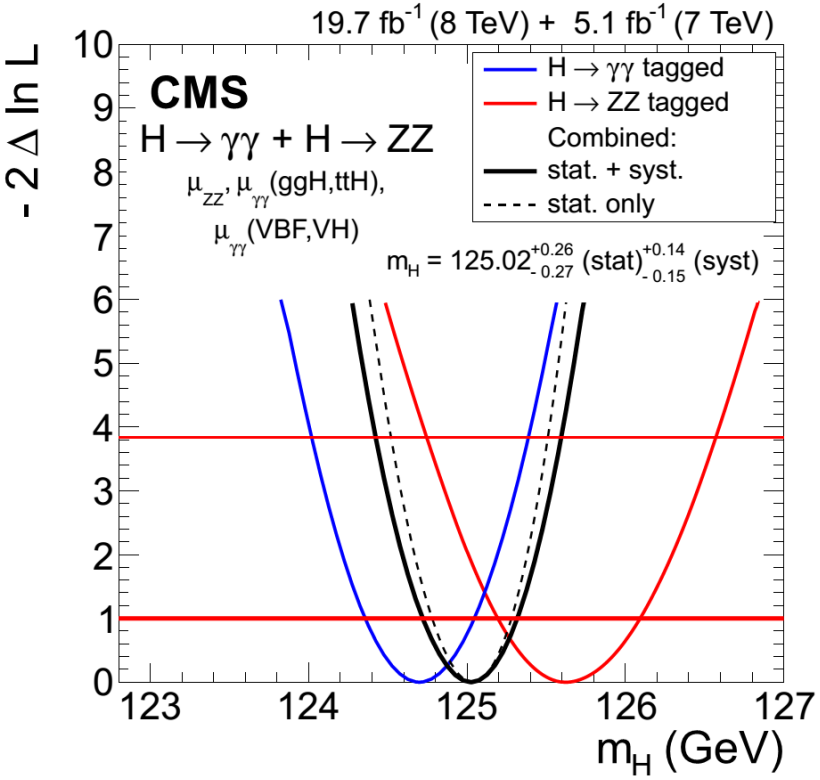
Higgs physics at CMS

- 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



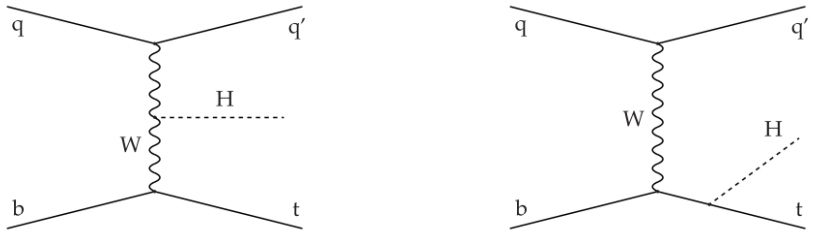


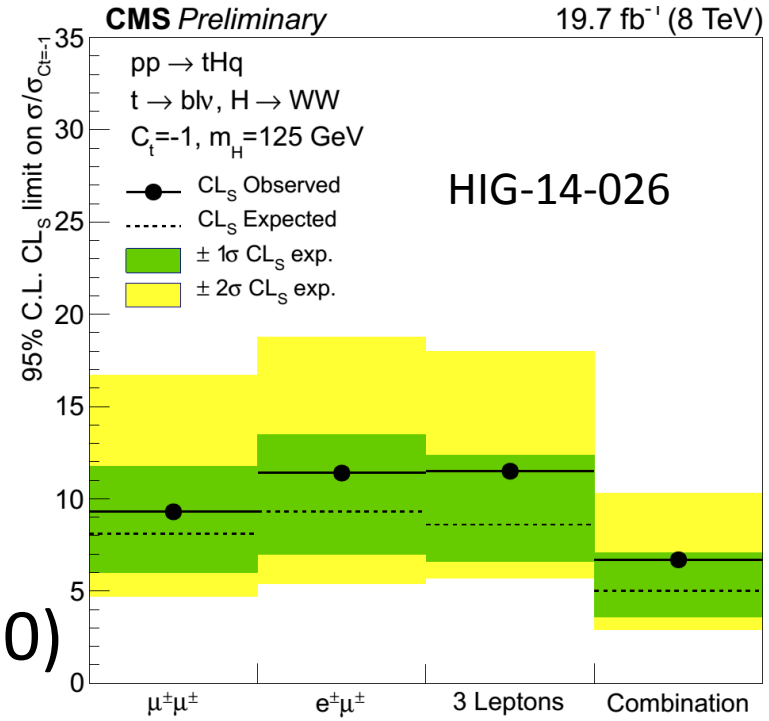
Experimental checklist

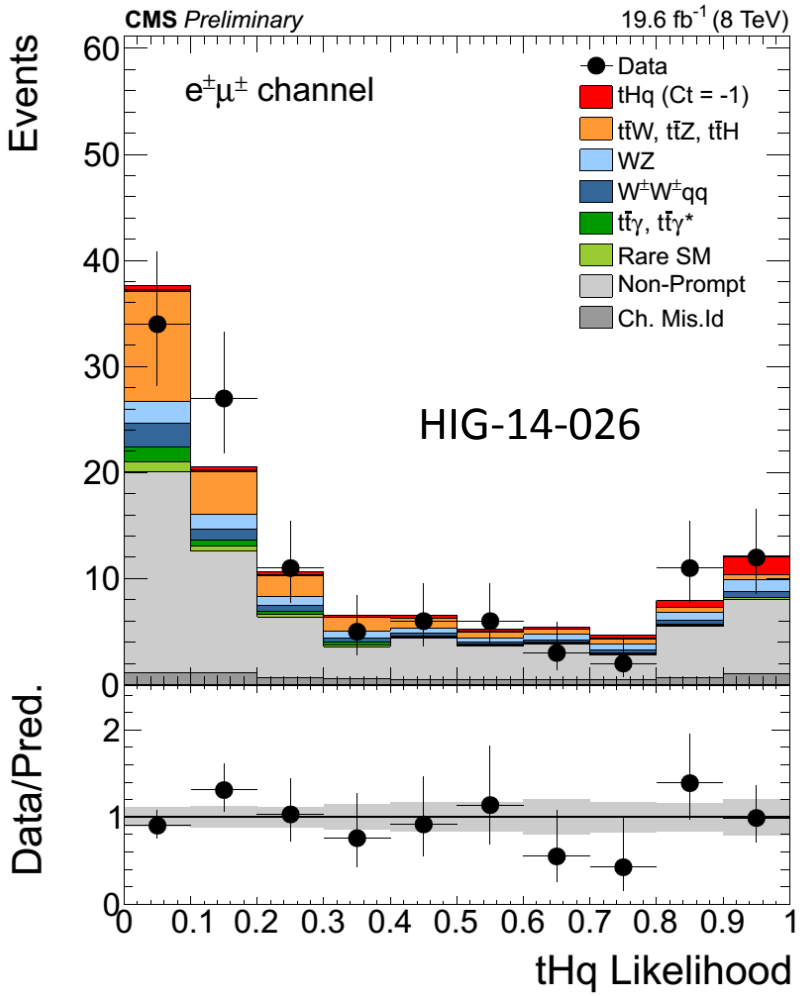
- ☑ Find Higgs boson
- ❑ Determine if it's the SM Higgs
  - ❑ Measure couplings: 3rd gen fermions, W/Z, associated production
  - ❑ Measure properties
- ❑ Find other Higgs-like particles
  - ❑ Part of spectrum? Many models propose additional bosons (NMSSM, 2-Higgs doublets, little Higgs…)
- ❑ Use Higgs as a portal to new physics
  - ❑ Exotic production modes: High mass particles decaying to Higgs pairs ($X \to HH$)
  - ❑ Exotic decay modes: $H \to$ invisible, $H \to aa \to 4\mu$

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)

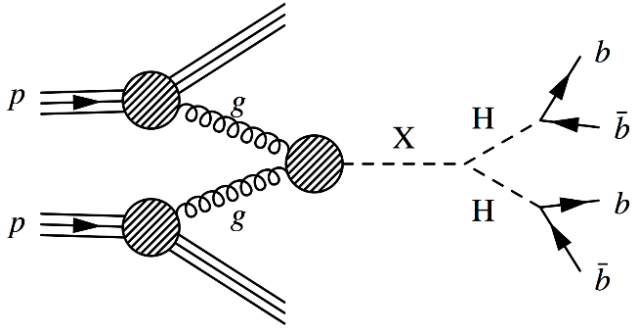




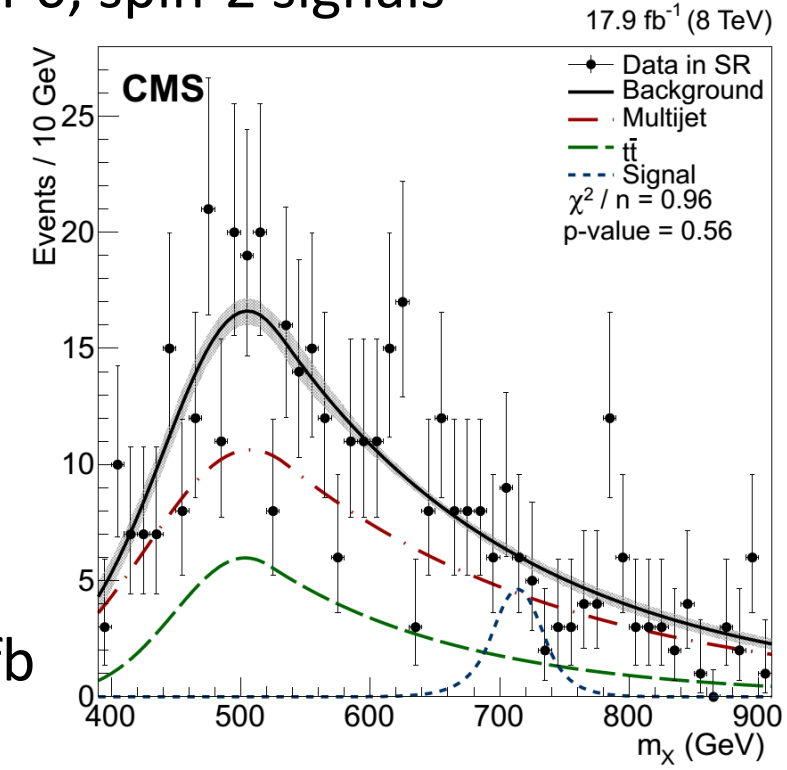


Exotic production: $X \rightarrow HH \rightarrow 4b$

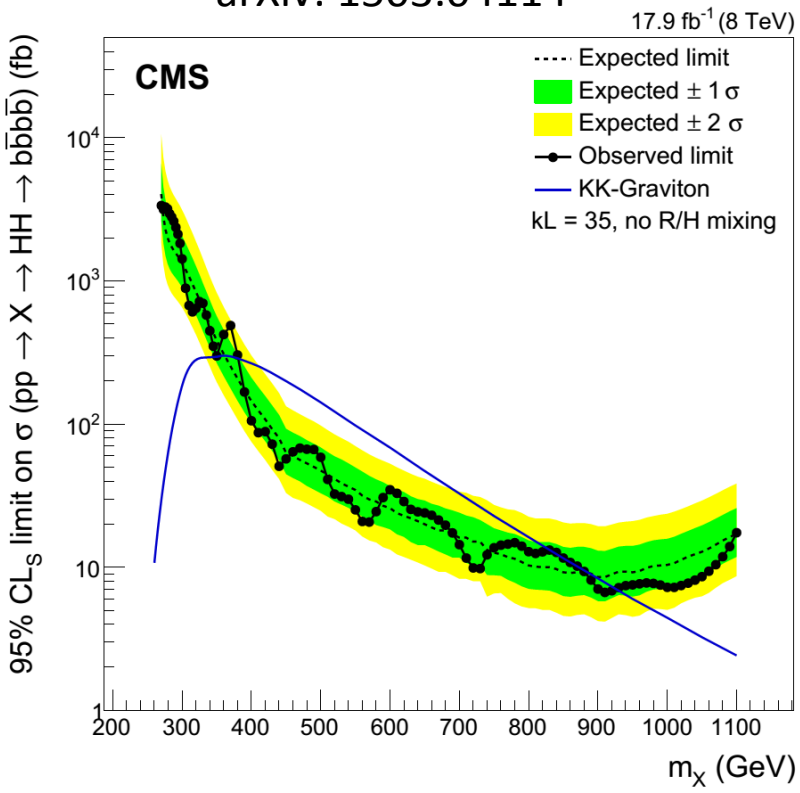
- Model independent search for narrow resonance decaying to Higgs pair
  - 4b final state most sensitive to high-mass resonance
  - Search performed for spin-0, spin-2 signals



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

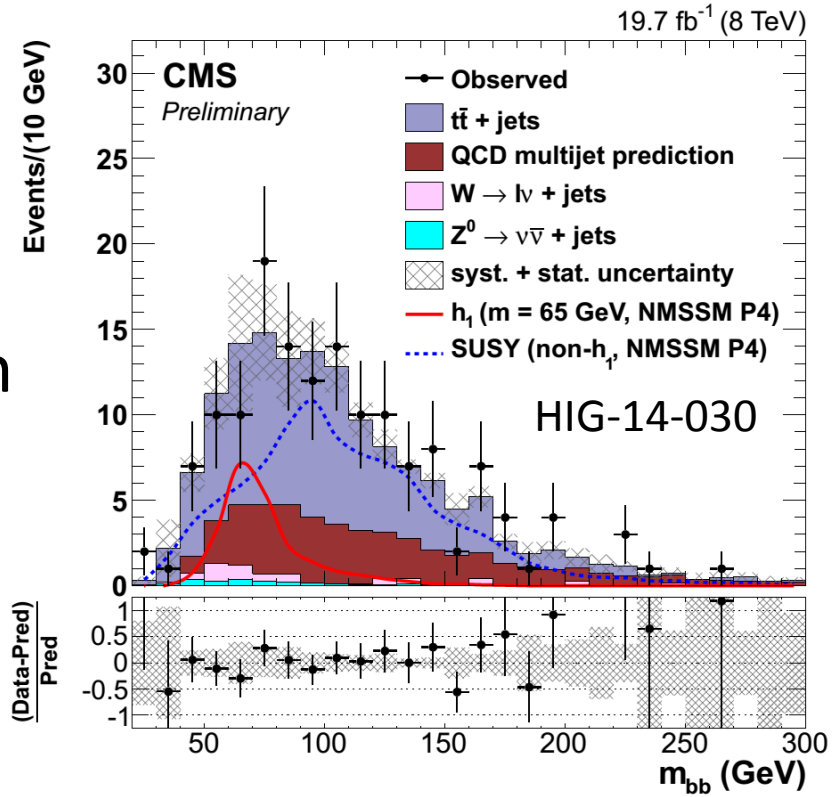


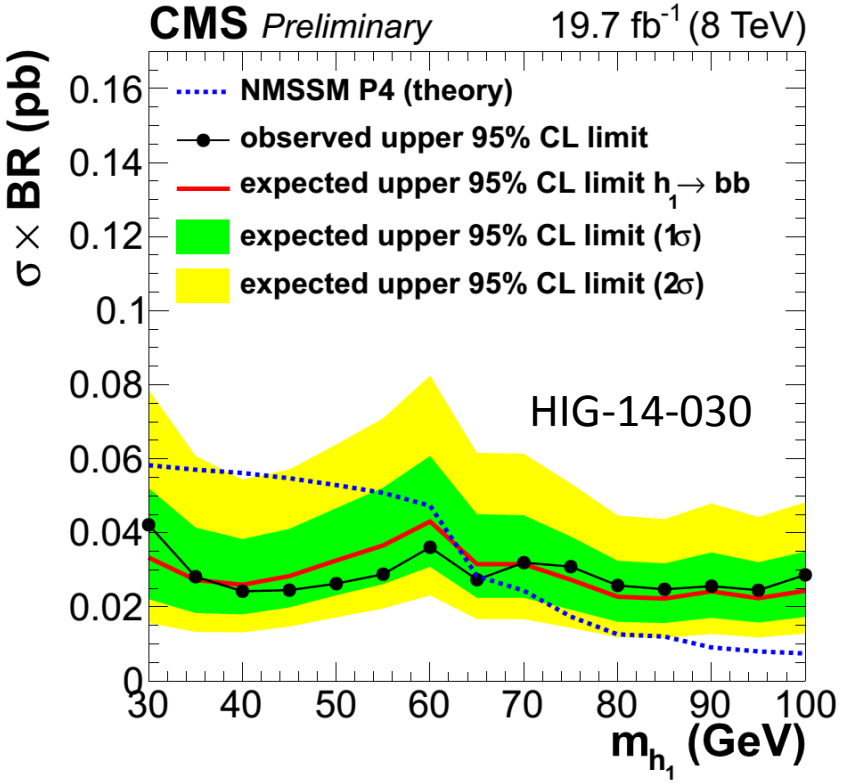
arXiv: 1503.04114



Extended Higgs sectors: 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

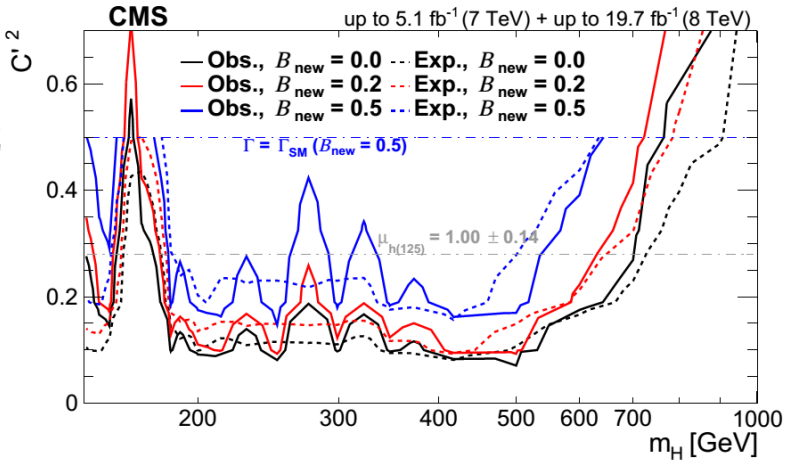


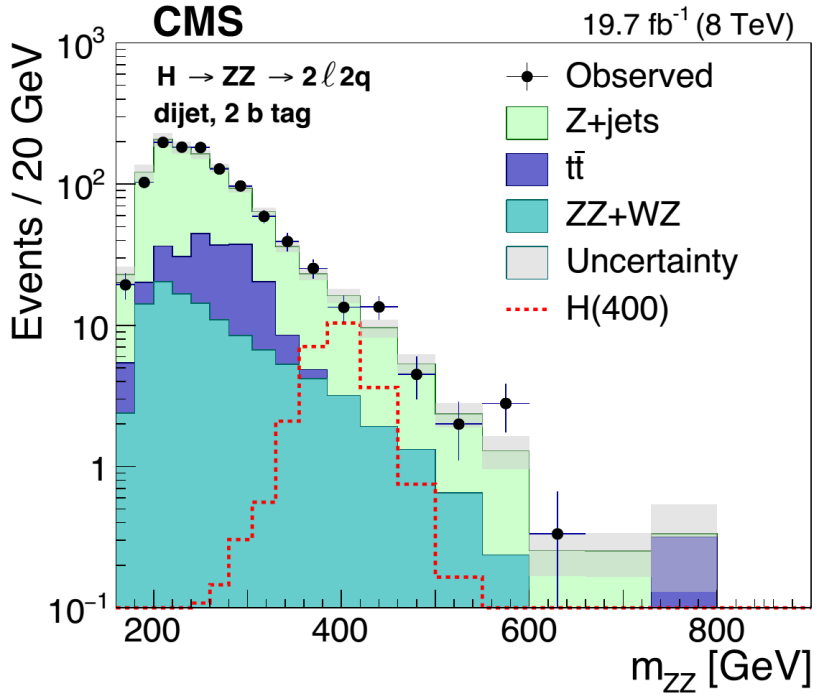


Extended Higgs sectors: Heavy H in mass range 145—1000 GeV

- 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_{new}

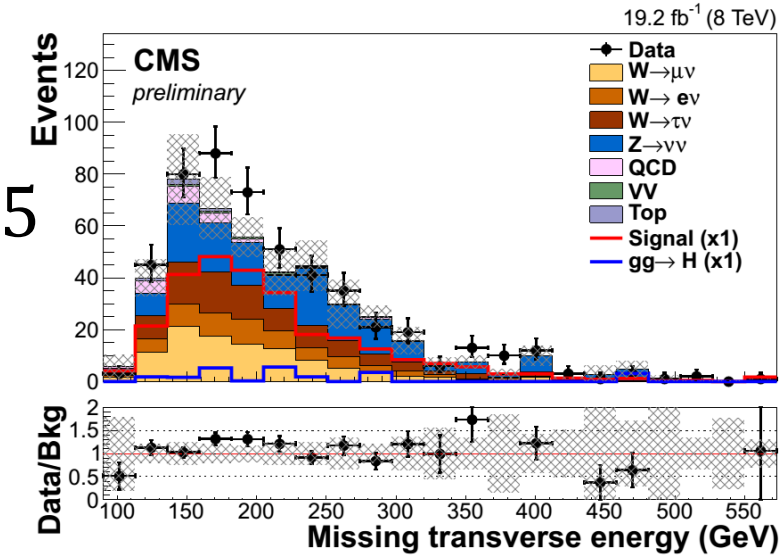
arXiv: 1504.00936





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
  - Γ_{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)



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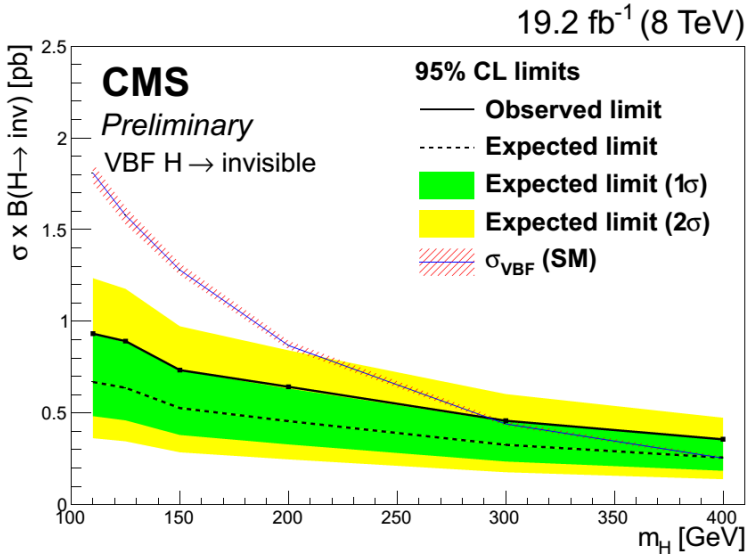
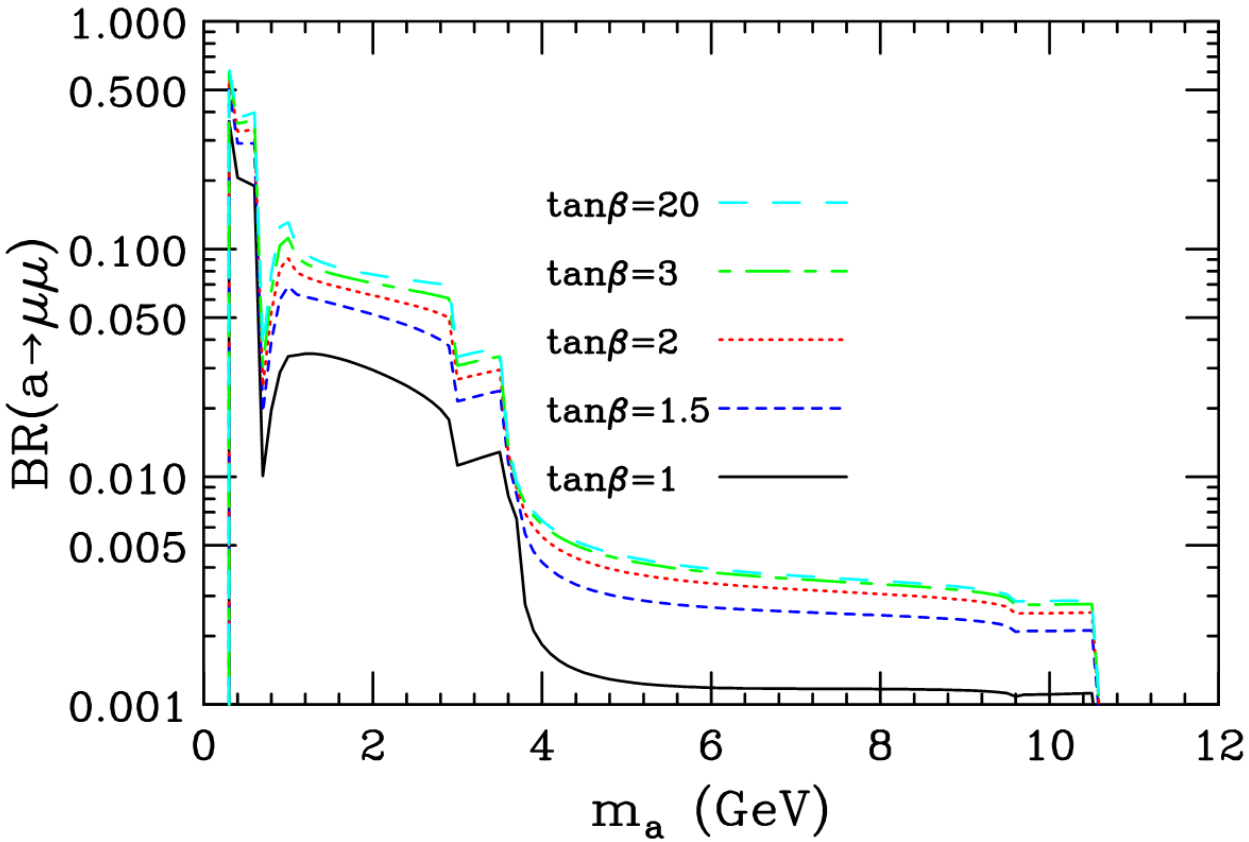


Benchmark: NMSSM

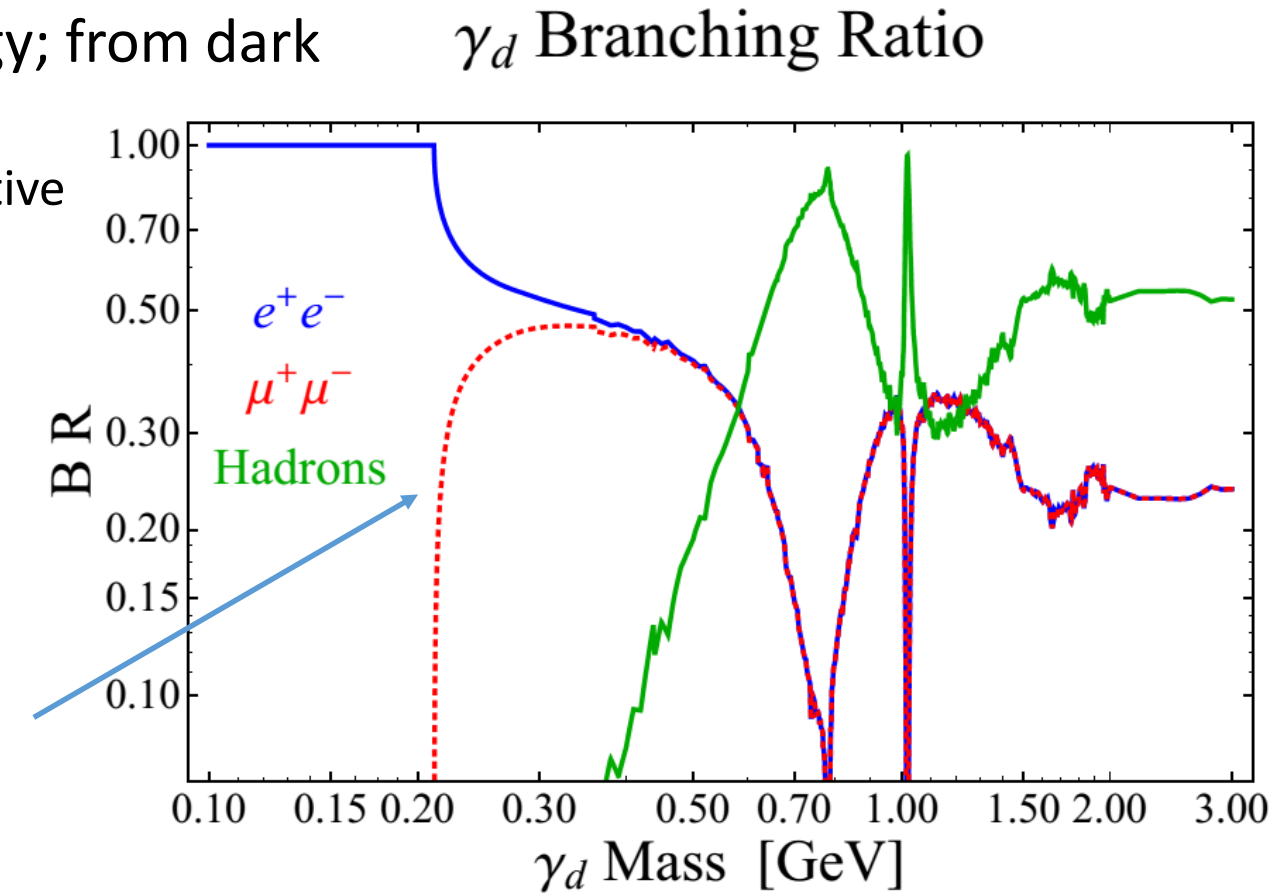
- NMSSM—well motivated minimal extension of MSSM
  - More complex Higgs sector: 3 CP-even states (h_1, h_2, h_3), 2 CP-odd states (a_1, a_2)
  - Inclusion of a_1 changes Higgs phenomenology: $h_1 \rightarrow a_1 a_1$ can have significant BR
- Benchmark model: $h_1 \rightarrow a_1 a_1 \rightarrow 4\mu$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

Phys.Rev.D81:075003,2010



Benchmark: Dark SUSY

- Motivation from satellite experiments (PAMELA, Fermi) JHEP 1005:077,2010
  - Higher fraction of positrons at high energy; from dark matter annihilation in galactic halo?
    - Posit "light dark boson" γ_D to provide attractive long-distance force to slow-moving WIMPs
    - γ_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
  - $BR(\gamma_D \to \mu\mu) \sim 45\%$ at $m_{\gamma_D} = 0.4$ GeV

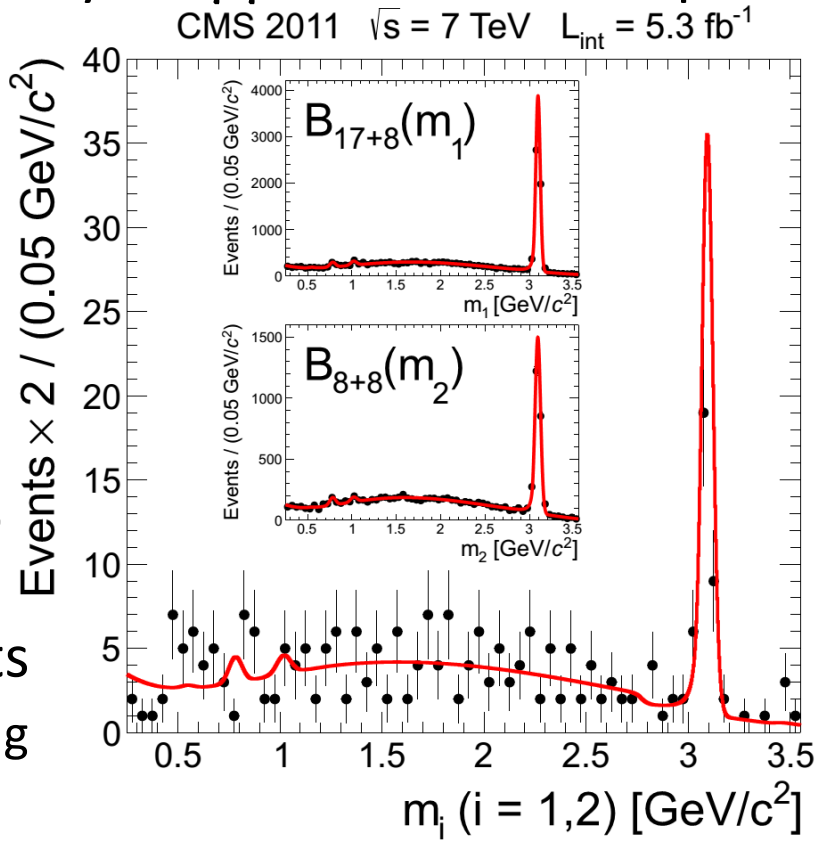


$H \to aa \to 4\mu$: Data selection

- Require 4 muons
  - pT(mu) > 8 GeV, |eta(mu)| < 2.4
  - At least 1 mu with |eta| < 0.9, pT > 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

$H \to aa \to 4\mu$: Background estimation

- Dominant background contributions to 4 muons 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/ψ events
    - Estimated from normalizing MC prediction to data



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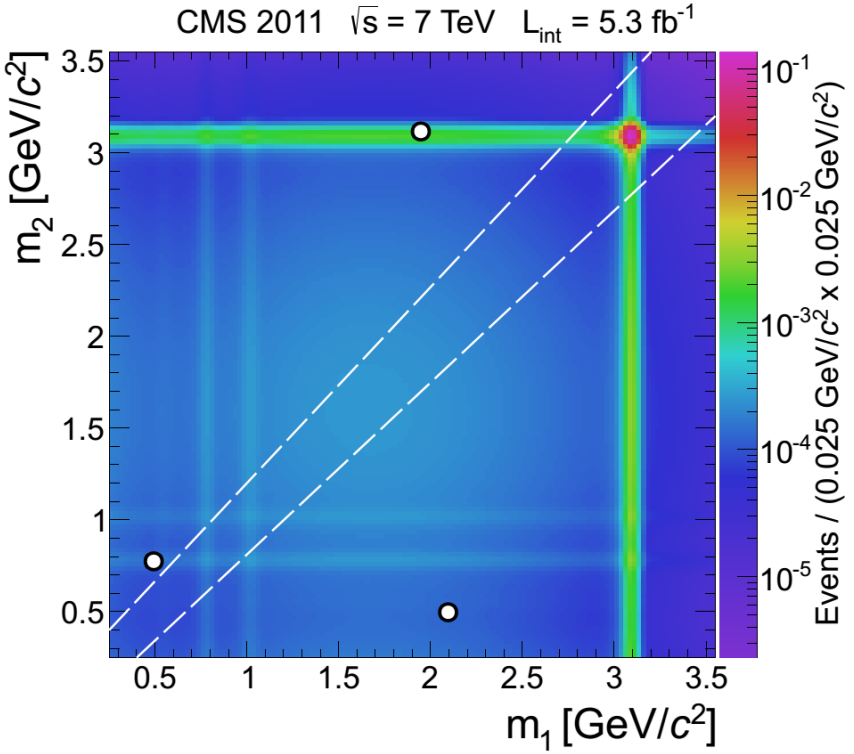
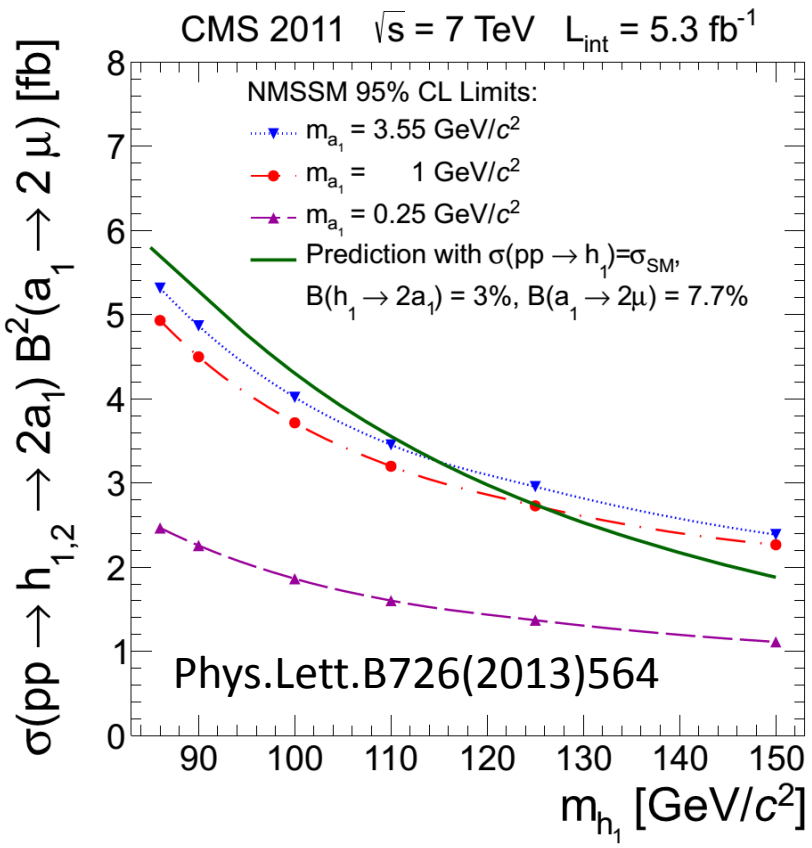
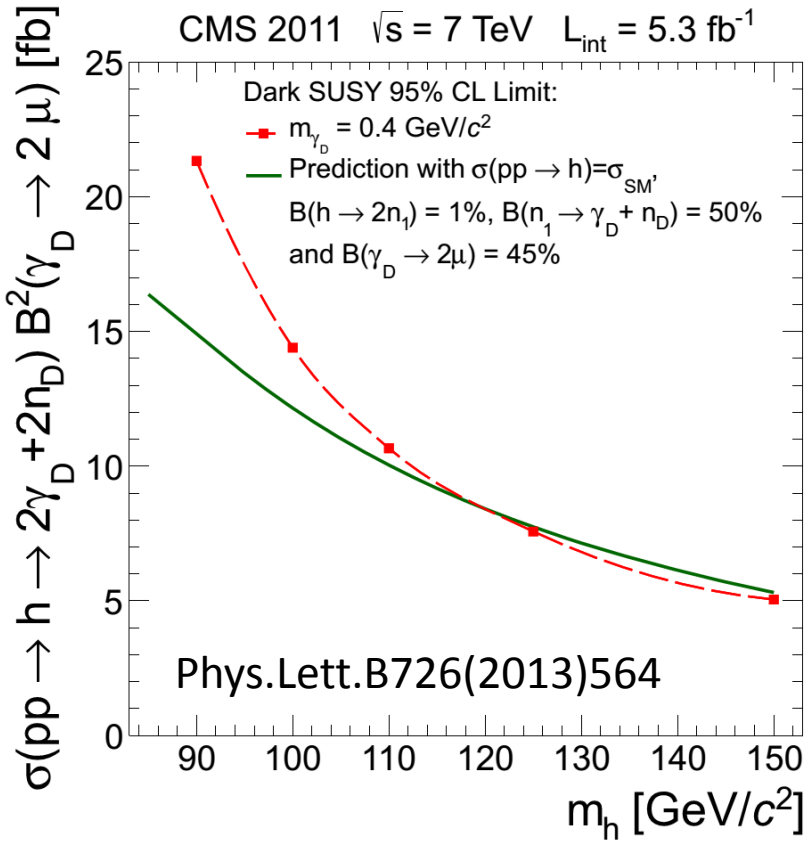


$H \to aa \to 4\mu$: Results

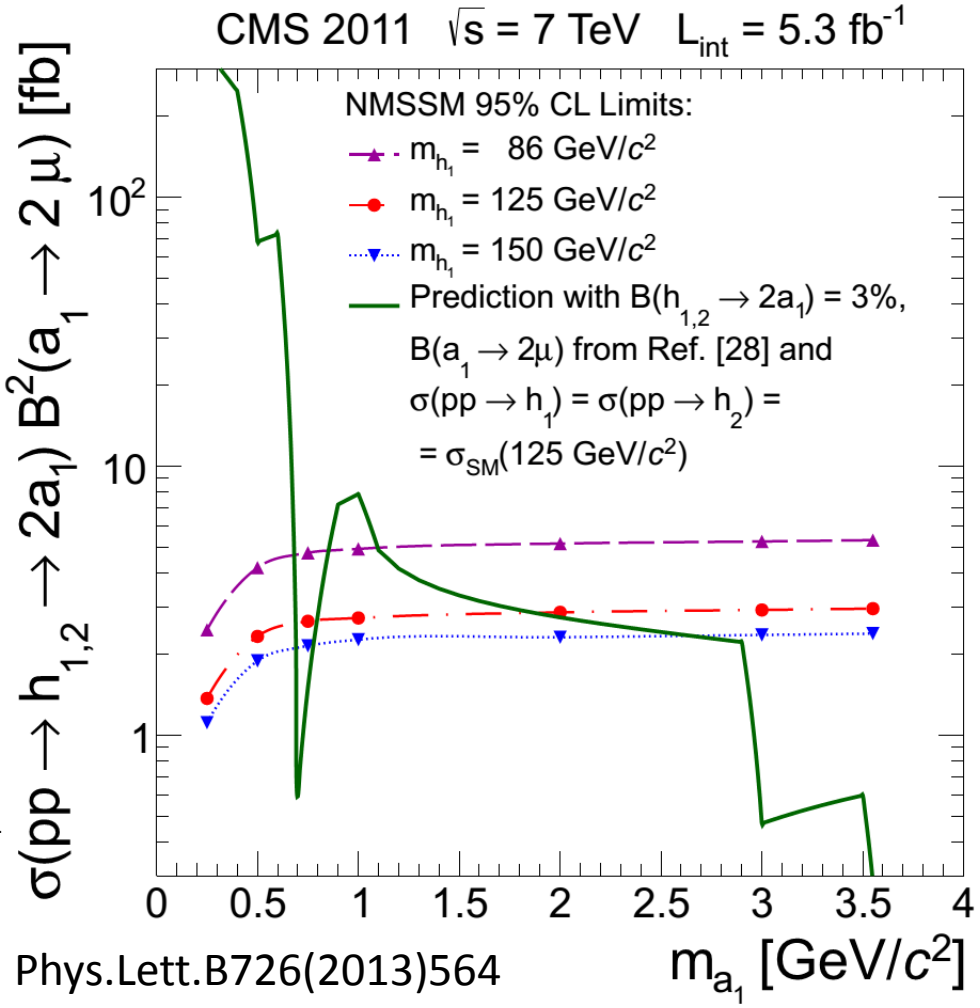
- Model independent limit: $\sigma(pp \to 2a + X) \times BR^2(a \to 2\mu) \times \alpha_{gen} < 0.77$ fb
  - 95% CL upper limit on production rate
- Determine exclusion limits on Higgs production in NMSSM and dark SUSY models as function of m_{h_1}





$H \to aa \to 4\mu$: Results

- Search for nonstandard decay modes of CP-even Higgs to new light boson (a_1 or γ_D) in 4μ 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}



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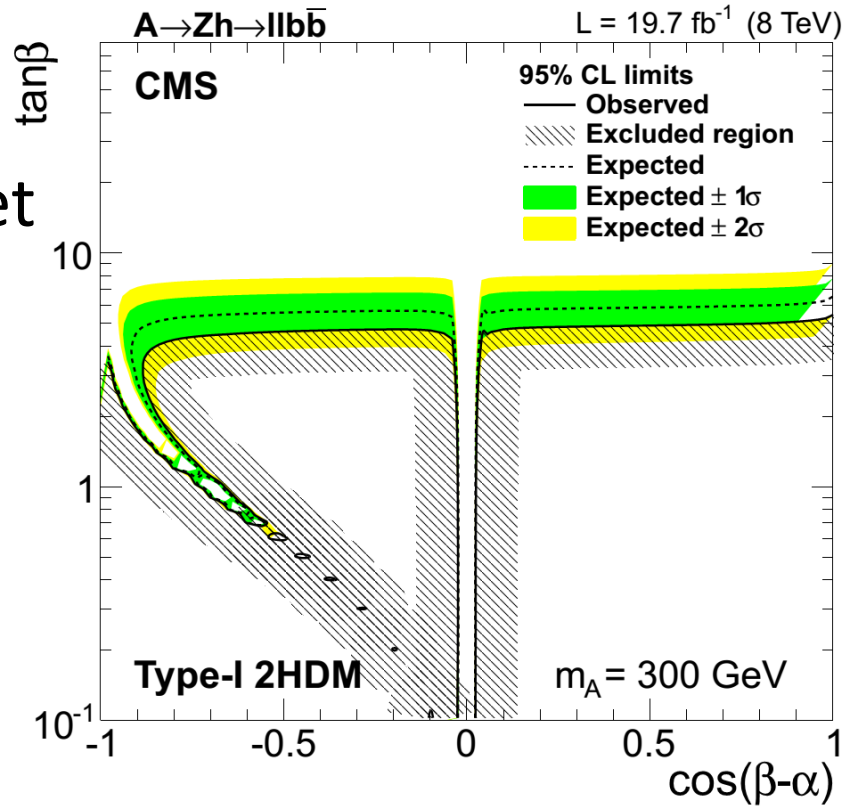
Conclusions

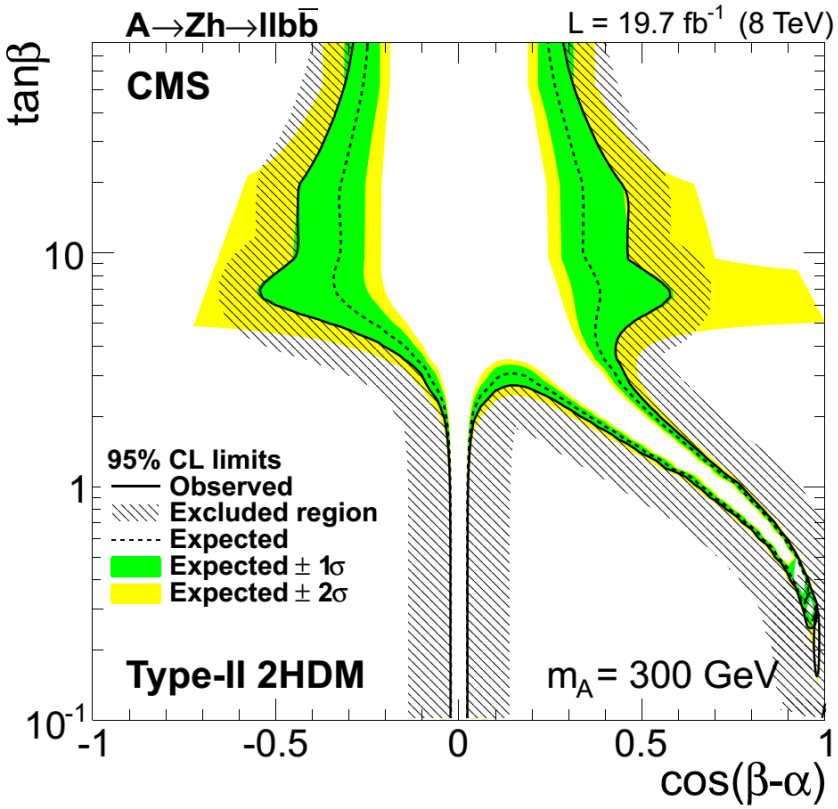
- Extensive program of BSM Higgs production and decay modes from Run 1
  - Several strong limits on new physics, but many decay modes still largely unconstrained by 8 TeV data
- Many well-motivated possible extensions to Higgs sector
  - Large phase space probed in Run 1
- Expect Run 2 to significantly 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 $A \rightarrow Zh \rightarrow llbb$

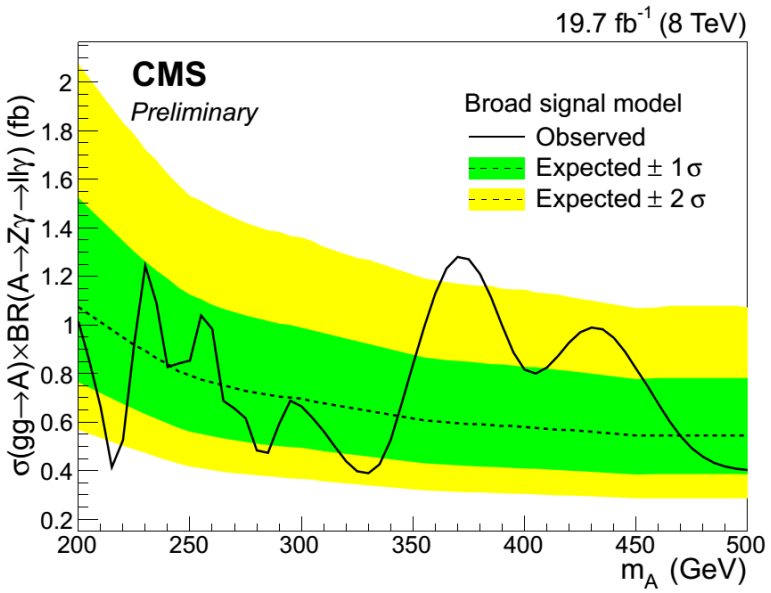
- Search for decays of pseudoscalar A to a Z and a light scalar h
  - Z decays to a pair of opposite-charge electrons or muons
  - h decays to $b\bar{b}$
- Limits interpreted in context of 2-Higgs doublet model

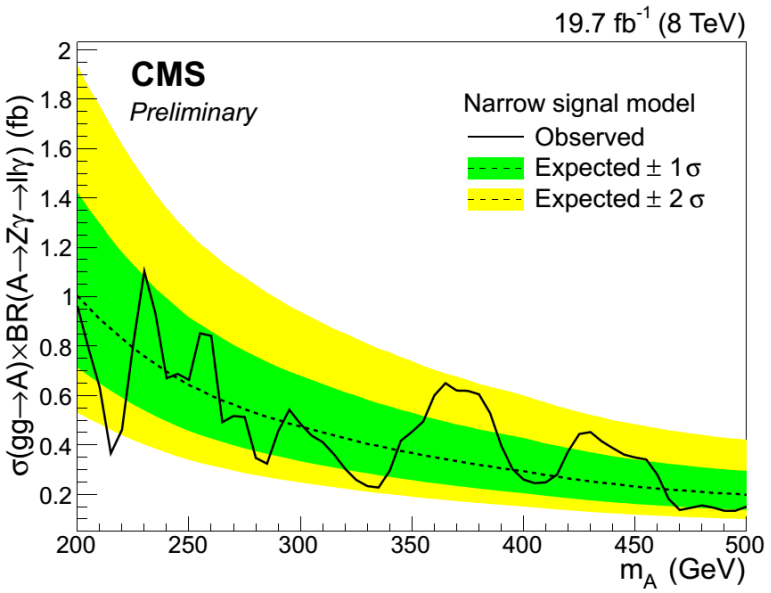




$A \rightarrow Zg$ at high mass

- 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: ~ 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%