Searches for BSM Higgs at the CMS experiment

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On behalf of the CMS Collaboration

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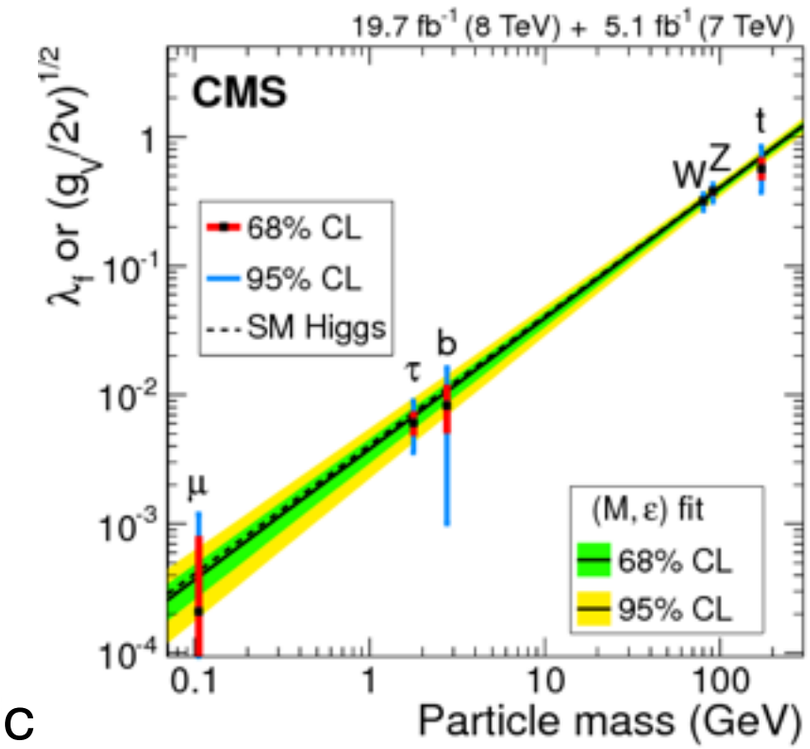
Outline

- A 125 GeV Higgs-like boson has been discovered:
  - → End or beginning of new discoveries?
  - → Extending the Higgs-sector:
    - → MSSM, NMSSM, 2HDM…
- The Compact Muon Solenoid (CMS)
- CMS searches on the extended-Higgs sector. Just a glimpse of few CMS results:
  - → Heavy Higgs searches
  - → Light Higgs searches
- Outlooks

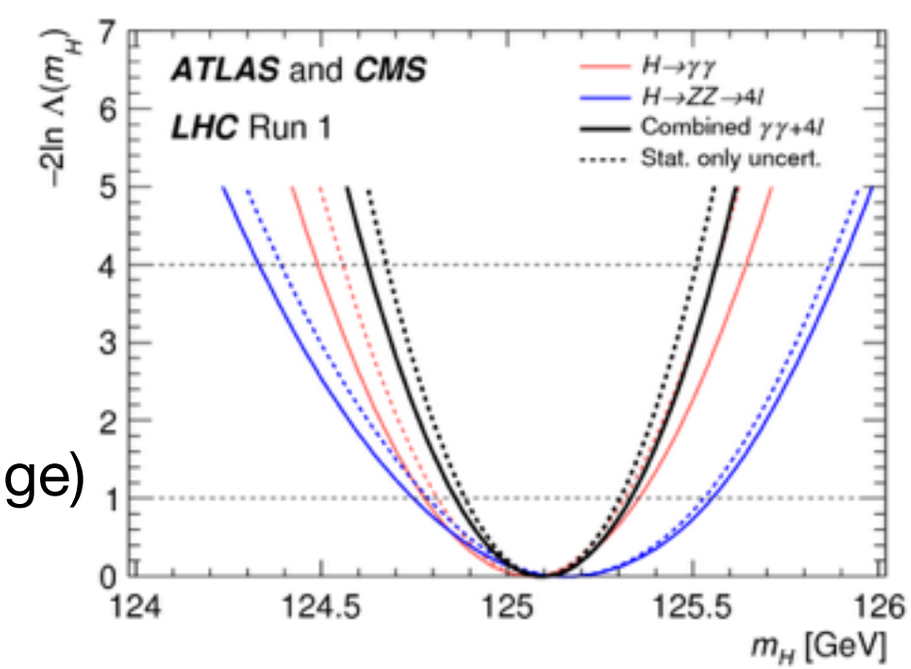
Extending the Higgs sector

- Higgs-like particle has been observed:
  - → $m_H = 125.09 \pm 0.21(\text{stat}) \pm 0.11(\text{syst})$
  - → $\Gamma_H < 26$ MeV (for $f_{\Lambda Q}=0$ at the 95% CL.)
  - → $J^{PC} = 0^{++}$

  (https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsHIG)



- No SUSY has been discovered so far, but:
  - → Still good to focus in naturalness
  - → General interest on sparticles with influence on quadratic term in Higgs potential
  - → See if newly found resonance is part of an extended Higgs sector is of primary importance!



- Higgs sector could result extended in many ways:
  - → MSSM (tension with current 125 GeV Higgs)
  - → NMSSM (add. superfield S singlet under the SM gauge)
  - → 2HDM (particularly simple extension of the SM)

Extending the Higgs sector

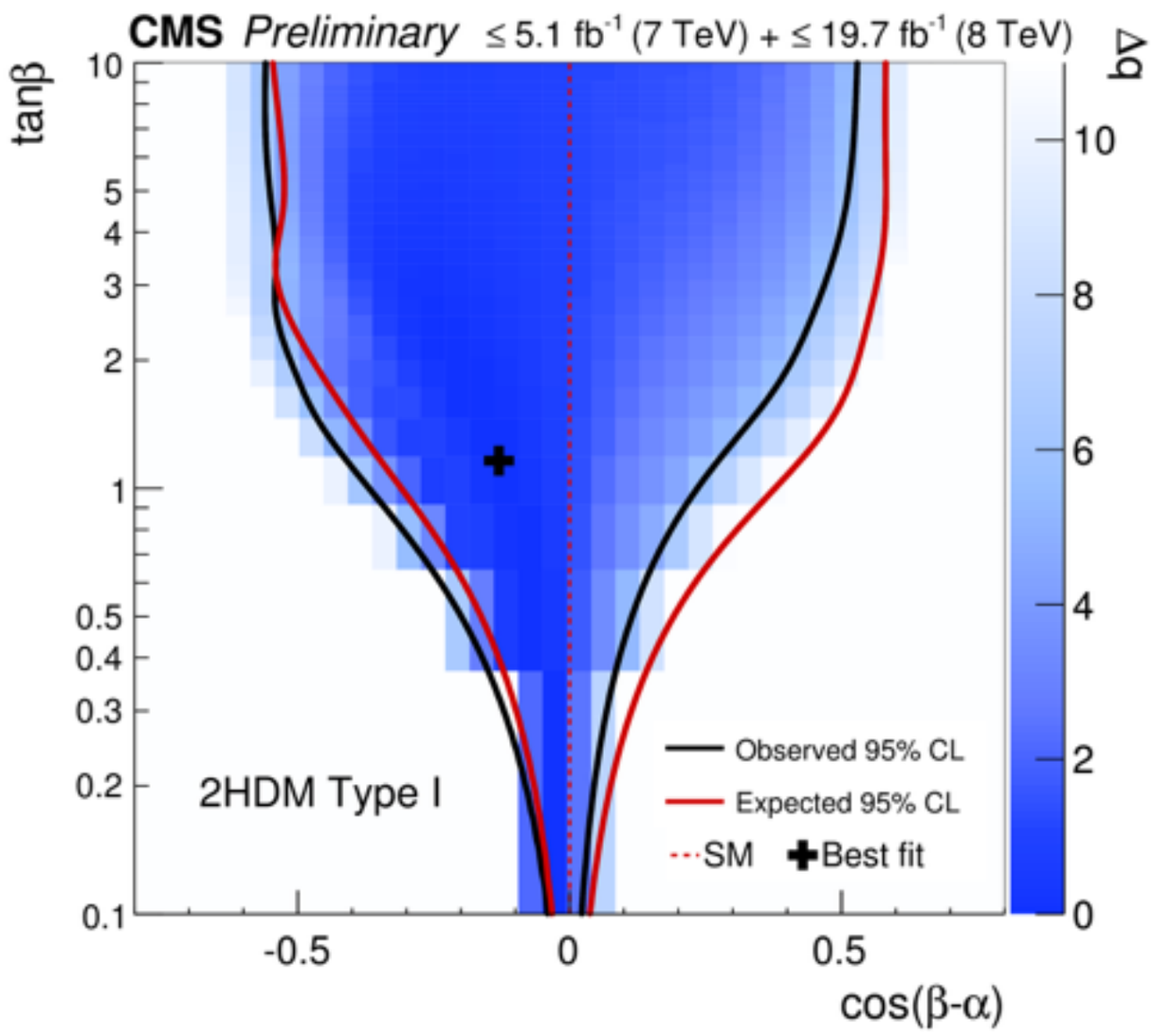
- Higgs sector could result extended in many ways.

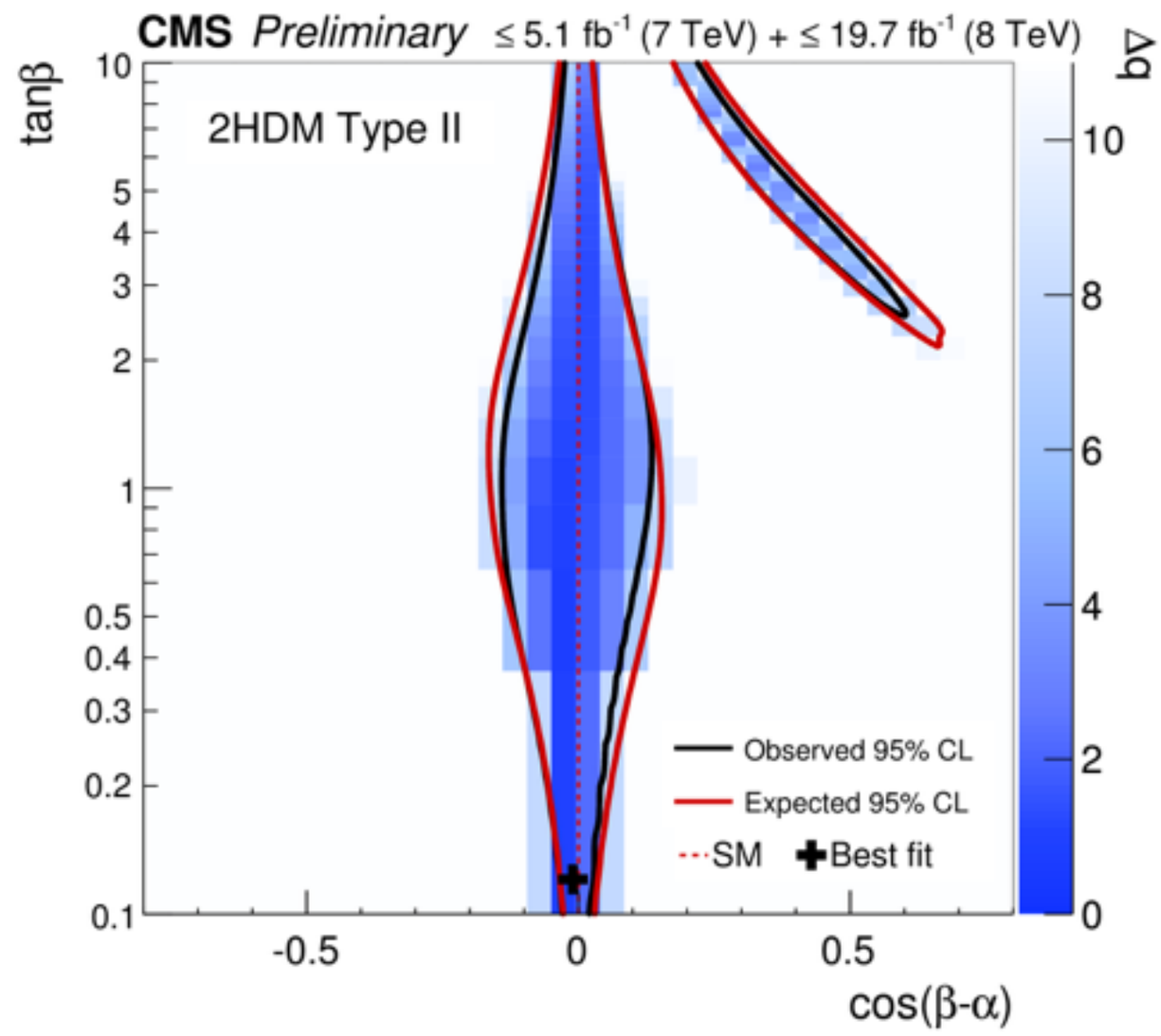
Model	Description	Higgs bosons
SM (one doublet of complex scalar fields)	3 d.o.f. give mass to $W^{\pm}$ and Z, Yukawa couplings generate fermion mass	h
SM + real singlet	Used in the context of EWK baryogenesis, DM…	h, H
2HDM (contains a second doublet)	Prerequisite for SUSY, natural in GUT, DM originating from 2HDM	h, H, A, $H^{\pm}$
2HDM + complex singlet (e.g. NMSSM)	Solve the mu-problem in MSSM (where H(125) is unnaturally heavy)	h_1, h_2, h_3, a_1, a_2, $H^{\pm}$
SM + triplet	Natural explanation for small neutrino masses	h, H, A, $H^{\pm}$, $H^{\pm\pm}$

Constrain from h(125) observation

- 2HDM is constrained from H(125) properties:
  Preventing FCNC leave only two free parameters in the Higgs sector
  → tanβ: ration of vev's associated with the doublets
  → α: mixing between the fields associated with the doublets

$$q(\lambda_{du}, \lambda_{Vu}, \kappa_{uu}) = -2\ln\left(\frac{\mathcal{L}(\text{data}|\lambda_{du}, \lambda_{Vu}, \kappa_{uu})}{\mathcal{L}(\text{data}|\hat{\lambda}_{du}, \hat{\lambda}_{Vu}, \hat{\kappa}_{uu})}\right)$$



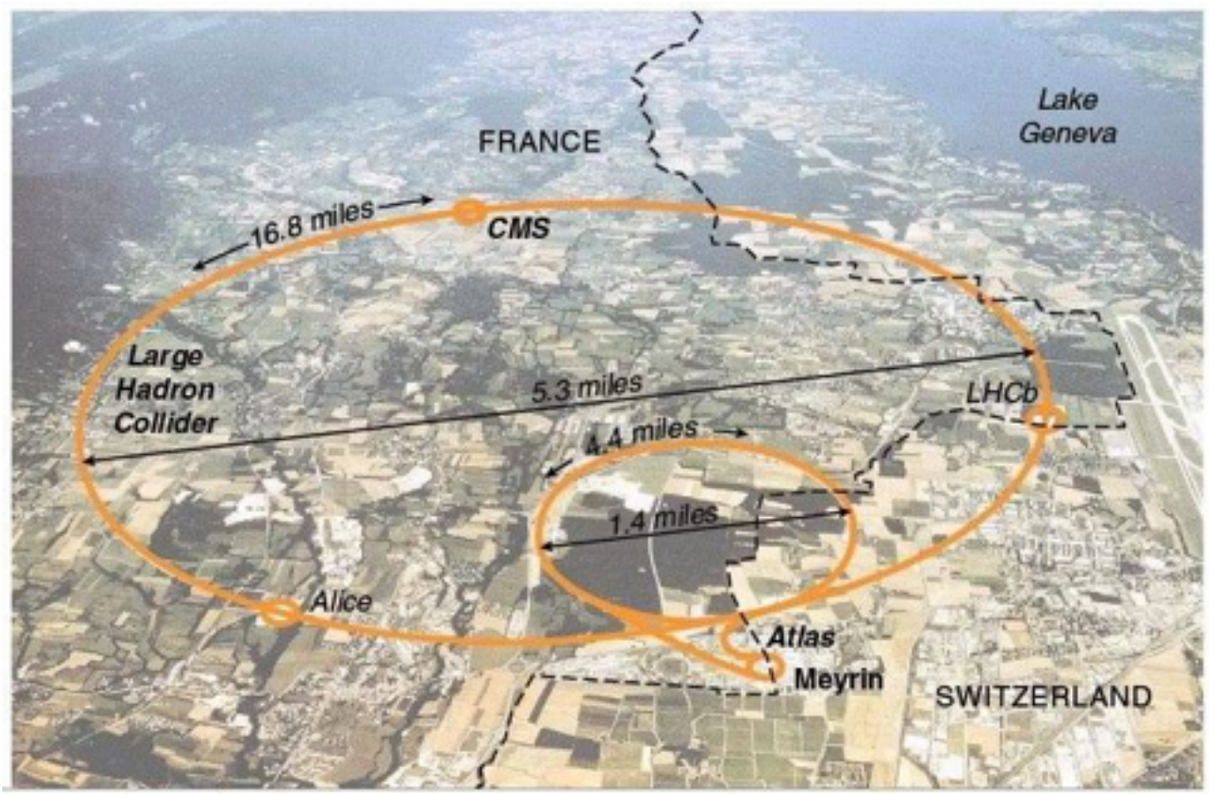


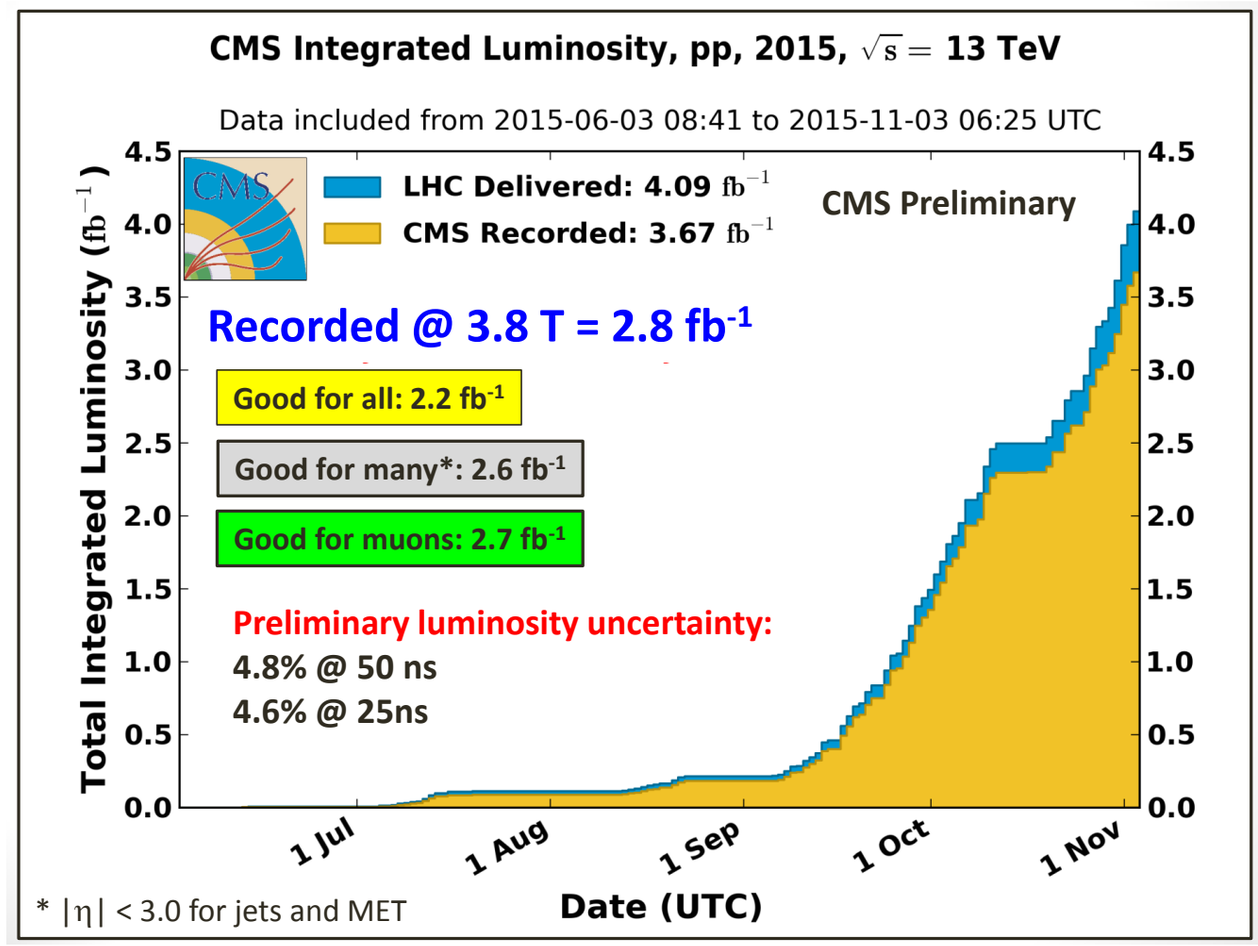
The Large Hadron Collider

- Run 2 is officially started!
  → About 3 fb^{-1} collected in 2015
  → 20 fb^{-1} by the end of 2016

- Comparison with 8 TeV:

- 160% larger collision energy → $\sqrt{s}$=13 TeV
- 200% larger number of bunches → 2800 bunches
- 200% larger pileup → 40 interactions/crossing
- 33% smaller β^* → 40 cm
- 170-220% larger peak Lumi. → (13-17)x10^{33} $cm^{-2}s^{-1}$





Heavy Higgs searches

Heavy Higgs searches in Run 1

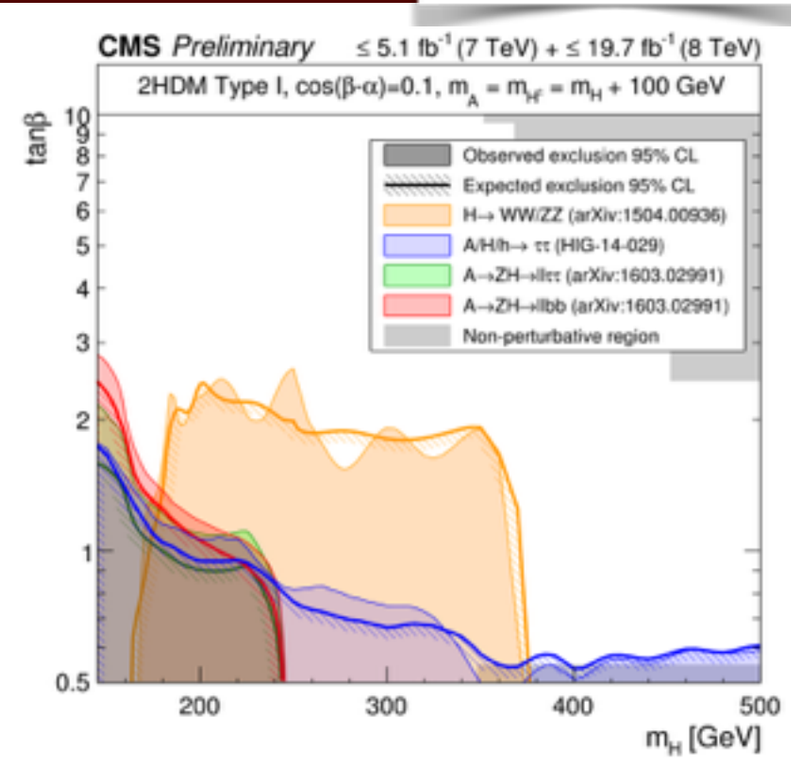
- Several analysis considered:
  - → H → WW/ZZ (145<m<1000 GeV), 55 event categories in WW(2l2ν), WW(2l2q), ZZ(4l), ZZ(2l2ν), ZZ(2l2q).
  - → A/H/h → ττ (90<m<1000 GeV), sensitive variable is $m_{\tau\tau}$. ($\tau_\mu\tau_\mu$, $\tau_e\tau_\mu$, $\tau_\mu\tau_h$, $\tau_e\tau_h$ and $\tau_h\tau_h$) and → μμ (115<m<300 GeV). Most sensitive CMS search to all three neutral Higgs bosons in the MSSM.
  - → $H^\pm$ → τν-tb (τν dominates sensitivity). Divided in low and high mass region.
  - → A/H → bb (100<m<900 GeV). Prod. in assoc. with b-jets. Discriminant variable: invariant mass of the 2 leading b-jets.
  - → A → ZH (140<m<1000 GeV). Z goes into leptons, H into b-quarks or τ. In the llbb final state discriminating variables are m(bb) and m(llbb) (2-dimensional shape analysis). The decay A → ZH is 2HDM specific. In MSSM it is kinematically not allowed (A and H are degenerate in mass, with $m_H \geq m_A$)

- Two ways to obtain limits:
  - → Templates for the full signal prediction for each value in the exclusion plane of the considered scenario (m_A-tanβ for MSSM; m_H-tanβ for 2HDM).
  - → 95% CL limits on σ·Br of a single, narrow-width resonance (except for H → WW ZZ analysis). Limits translated into the exclusion plane.

https://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/HIG-16-007/

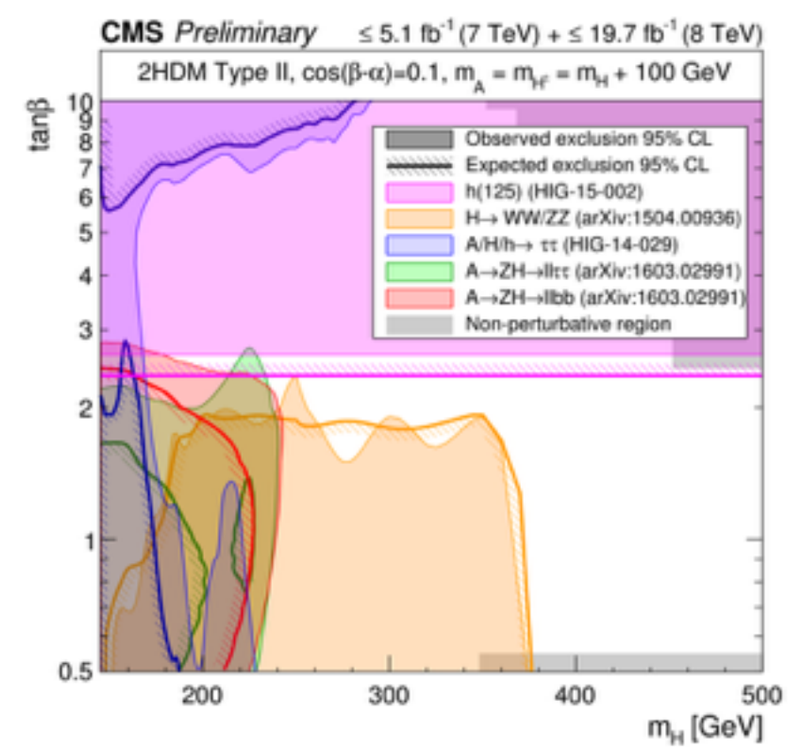
Heavy Higgs searches in Run 1

- By definition the whole parameter space that is displayed is mostly compatible with the constraints imposed by the couplings of the Higgs.
  - → Observed exclusion: transparently filled areas
  - → Expected exclusion: slightly darker shade (with hatching)
  - → The gray shaded areas: non-perturbative or unstable.



- Lower boundary in m_H marks the kinematically allowed region for WW/ZZ. Upper boundary coincides with the opening of the decay into top-quarks.

- A→ZH analysis sharp edge at m_H ~ 240 GeV coincides with opening of the decay of the A into top-quarks.
  Final state llbb shows the larger expected exclusion range.



- A/H/h → ττ: for type-I the dominant contribution to the exclusion originates from the production via gluon fusion.

https://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/HIG-16-007/

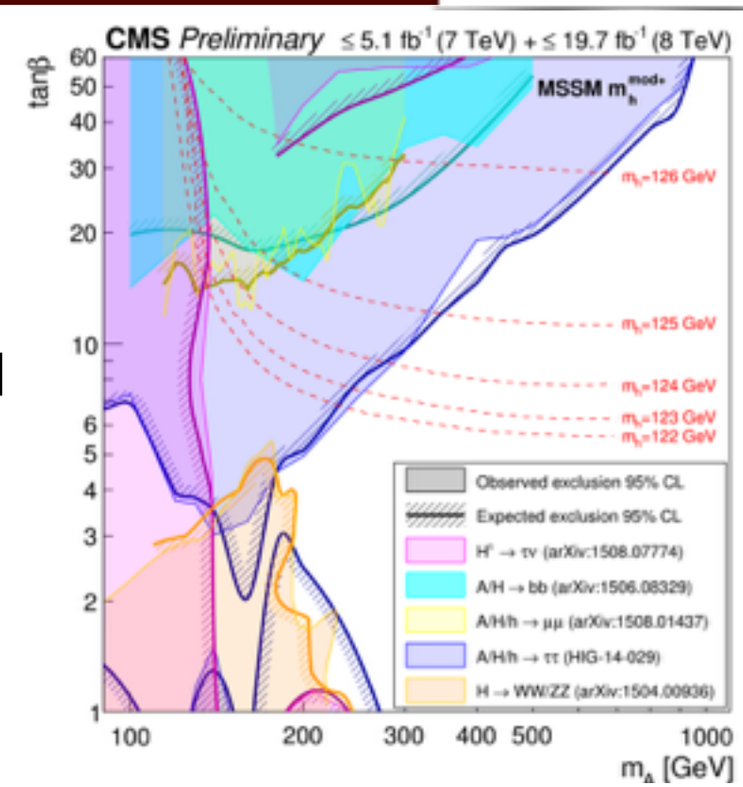
Heavy Higgs searches in Run 1

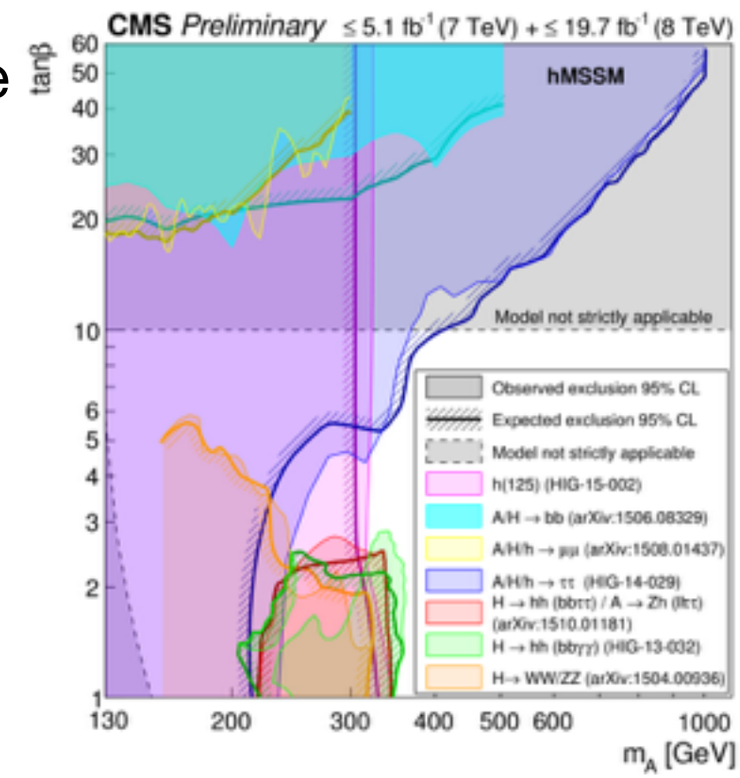
- Exclusion up to tan β ≈ 60 for masses up to m_A=1 TeV. For larger values of tanβ predictions in turn unstable.

- Most sensitive search: A/H/h → ττ (unable to separate S and B due to the presence of Z → ττ events with $m_Z \approx m_A$). The strongest exclusion sensitivity for high values of m_A and tanβ.

- Supported by the A/H → bb and A/H/h → μμ searches. Note: coupling of the Higgs bosons being proportional to the mass of the final state particle + difficulty to distinguish the signal from the large background from QCD multi-jet (in the case of b-quarks).

- H → WW/ZZ search leads to an exclusion for low values of m_A and tan β, where the H-coupling to vector bosons allows for a significant branching fraction in the m^{mod+}_h.

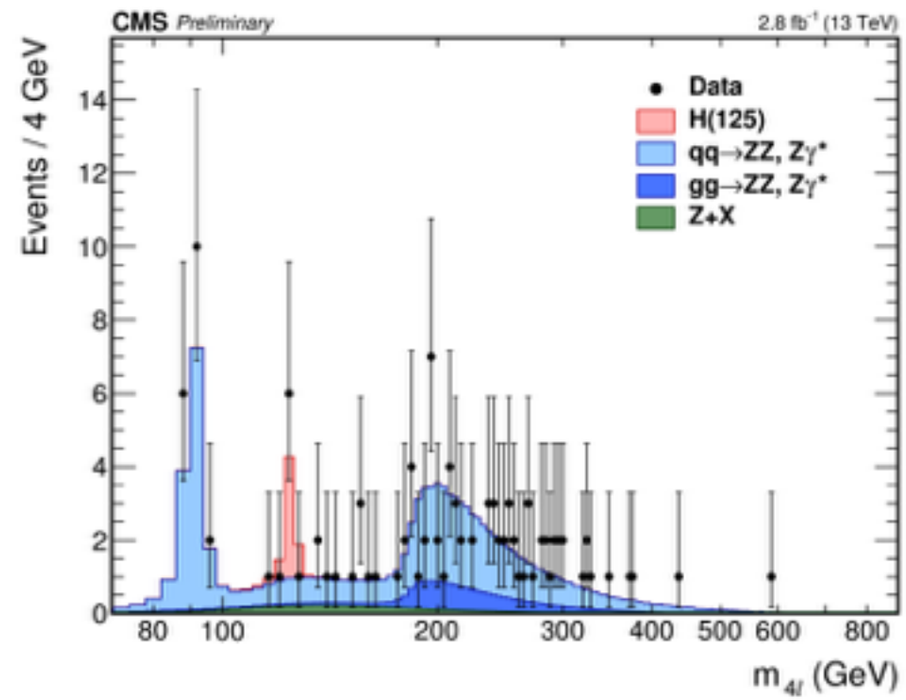




https://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/HIG-16-007/

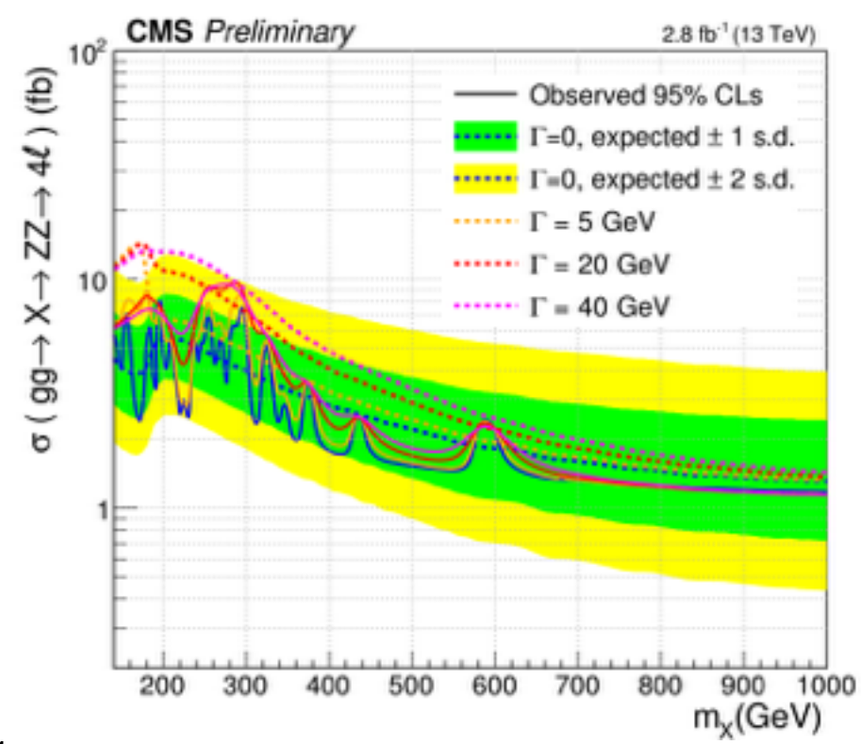
H→ZZ→4l @13 TeV

- Signal:
  - → H → ZZ → 4l (l = e,μ): analysis measures both SM-H and limits on additional resonances.
  - → Significance for SM-H: 2.5σ



- Backgrounds:
  - → ZZ (irreducible): estimated by simulation
  - → Z+jets, tt, Zγ + jets, WW+jets, WZ + jets (reducible): estimated by two independent control regions

- Search for add. narrow resonance, width less than 1% of m_H (dominated by the resolution)
  - → Acceptance and efficiency modeled using gluon fusion production for masses 120 - 850 GeV



- Few systematic uncertainties treated as shape (EWK correction). Fit to derive a 95% on σ × BR

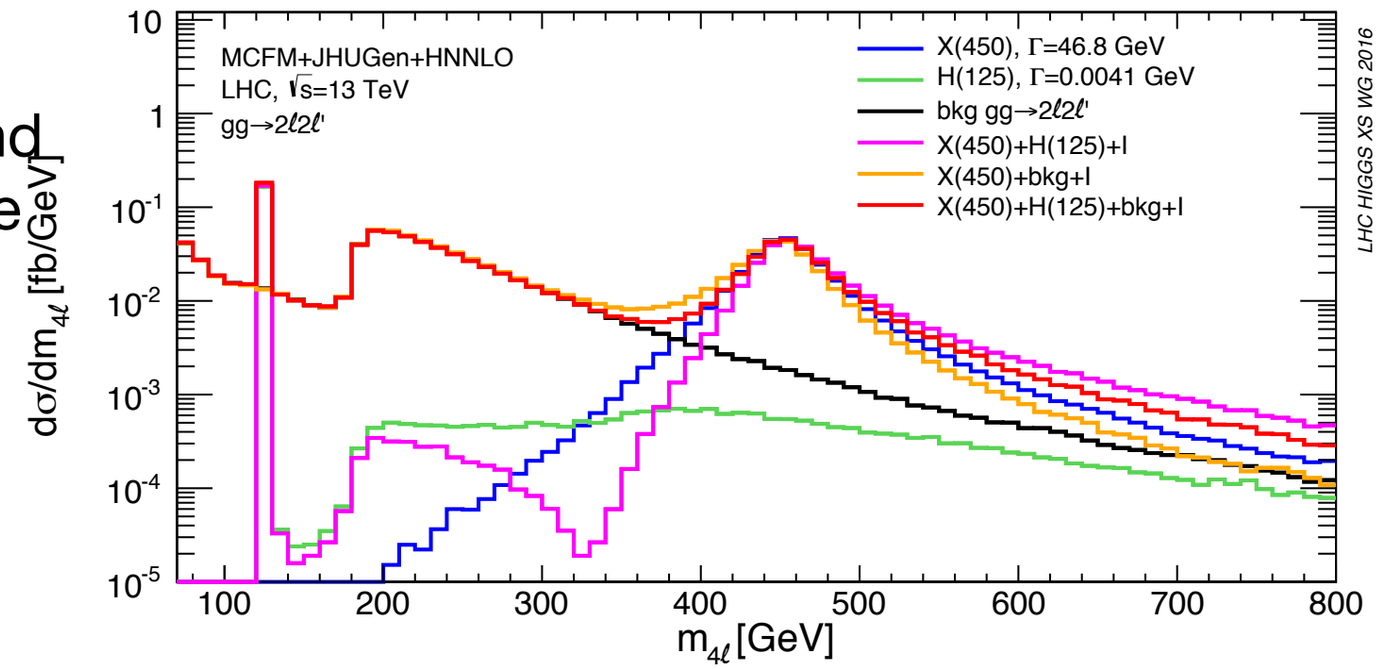
https://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/HIG-15-004

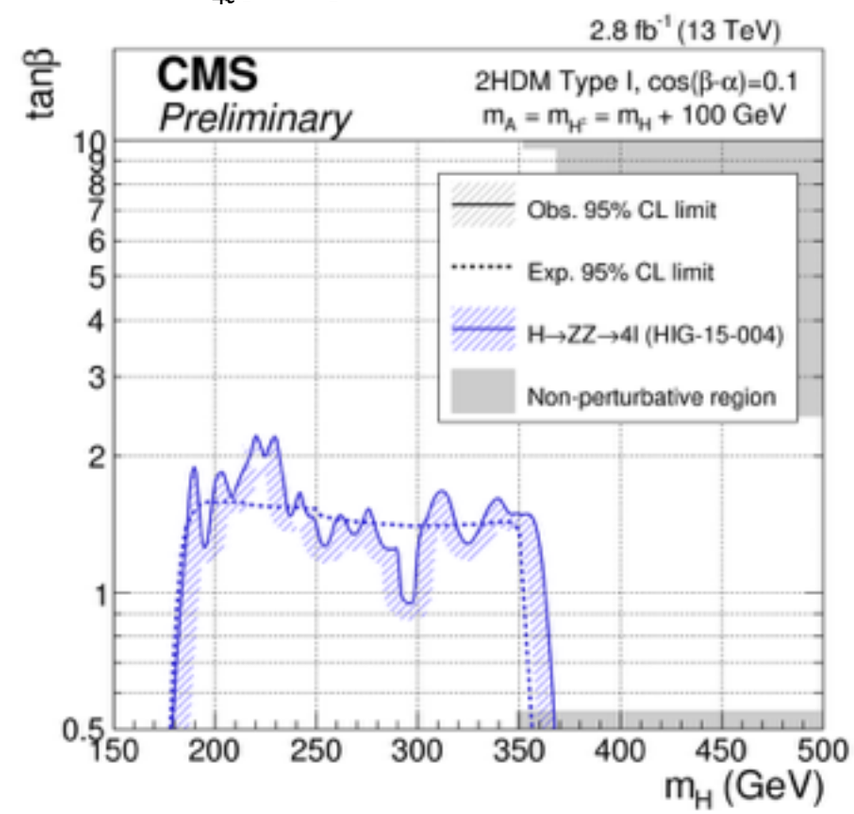
H→ZZ→4l @13 TeV

- Search for any resonance is of high priority. Recent hints of an excess around $m_{\gamma\gamma} \sim 750$ GeV make this task even more urgent.

- Production mechanism at high mass is predominantly gluon fusion with substantial contribution from VBF (here only gluon fusion).

- Treated as one process in gg-fusion:
  - → $P(m_{4l}, m_X, \Gamma_X, \sigma_X)$ for the gg →bkg + H(125)*+ X(mX) → 4l allows inclusion of interference, including off-shell tail of H(125)
  - → m_H, Γ_H, m_X, Γ_X are also included as general parameters of the model
  - → Limits at the 95% CL on $\sigma \cdot Br$ for several values of Γ_X



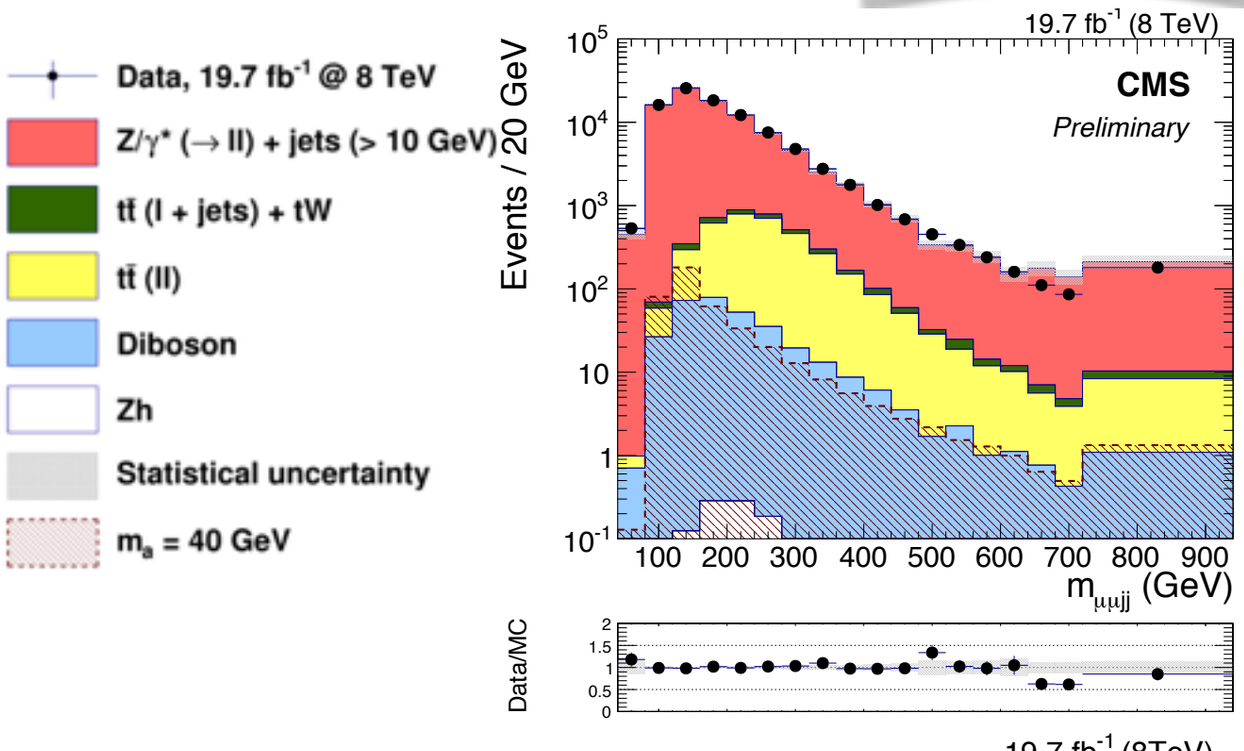


https://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/HIG-15-004

Light Higgs searches

H(125) → aa → μμbb

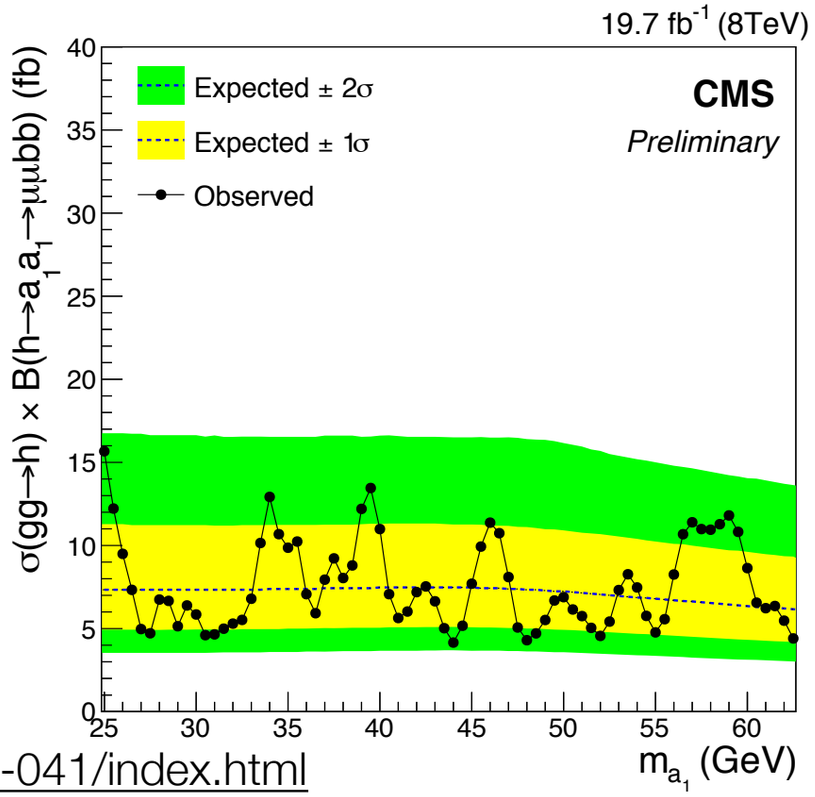
- Signal:
  - → SM Higgs decaying to 2 light bosons a (foreseen by in NMSSM or 2HDM)
  - → Only the gluon fusion production mechanism considered
  - → Here: m(a) ~ [25,65] GeV



- Selection:
  - → 2 muons with p_T > 24 and 9 GeV
  - → 2 jets with p_T >15 GeV (b-tagged)
  - → |m(μμbb)-125| < 25 GeV

- Main background:
  - → Z + jets, tt

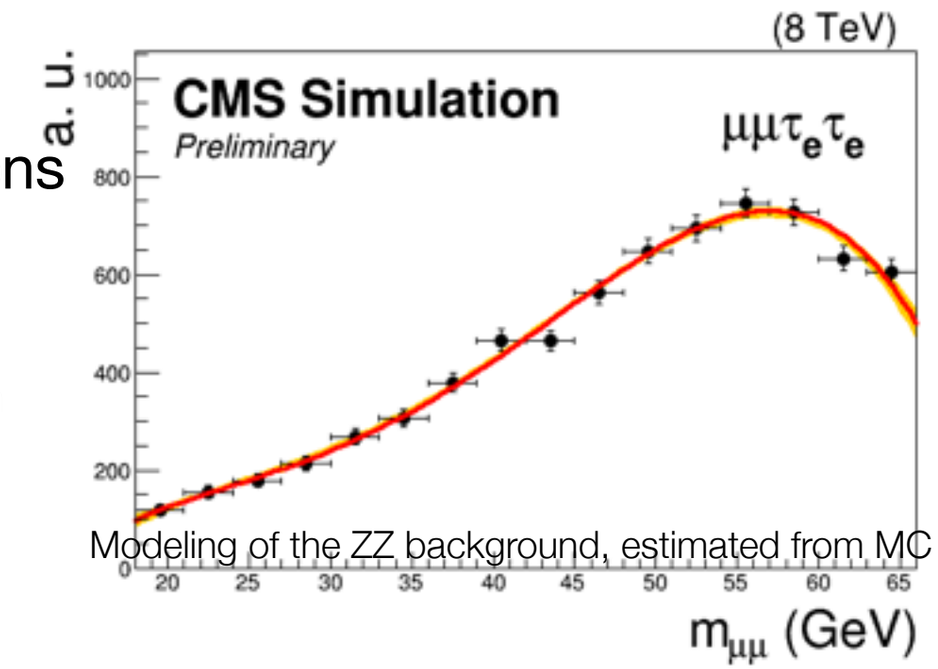
- Sensitivity extracted using a fit to m(μμ) distribution:
  - → Limits on the production rate times B.R.



https://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/HIG-14-041/index.html

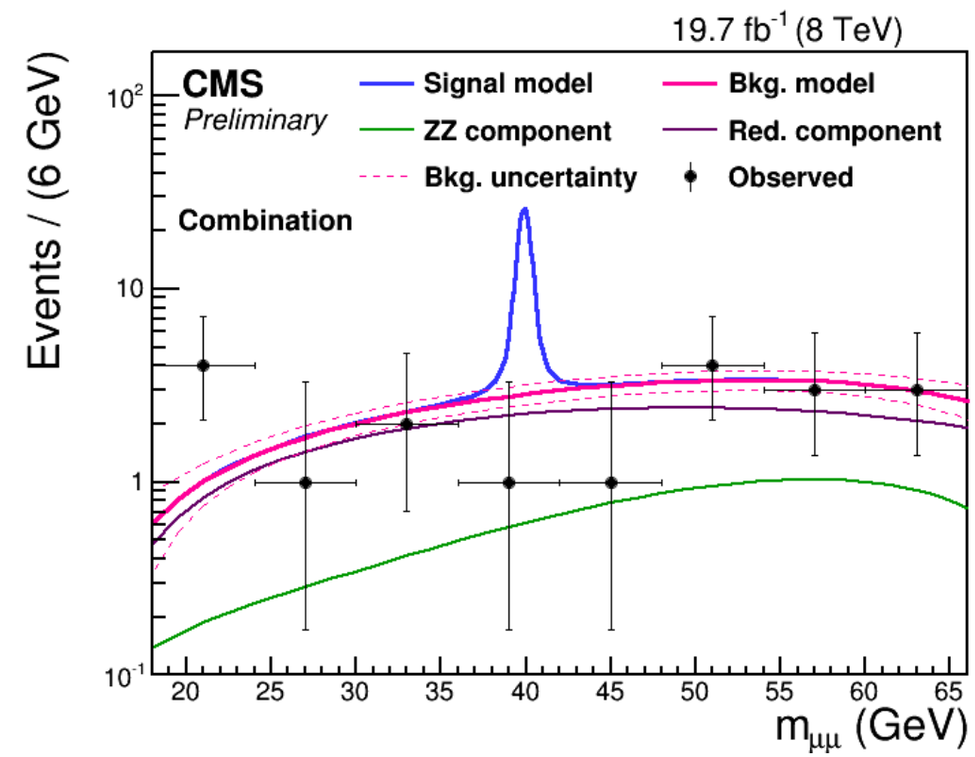
H(125) → aa → μμττ

- Signal:
  - → SM Higgs decaying to 2 light pseudoscalar bosons (foreseen by 2HDM or 2HDM+S)
  - → m_a ~ [20,63] GeV
  - → Considering: $\mu\mu\tau_e\tau_h$, $\mu\mu\tau_\mu\tau_h$, $\mu\mu\tau_\mu\tau_e$, $\mu\mu\tau_e\tau_e$, $\mu\mu\tau_h\tau_h$ ($\mu\mu\tau_\mu\tau_\mu$: ambiguities in pairing muons)



Modeling of the ZZ background, estimated from MC

- Selection:
  - → Two μ with p_T > 18/9 GeV
  - → p_T > 5,7,15 GeV for τ_μ, τ_e and τ_h
  - → |m(μμττ)-125| < 25 GeV
  - → |m(μμ)-m(ττ)| < 0.8 m(μμ)



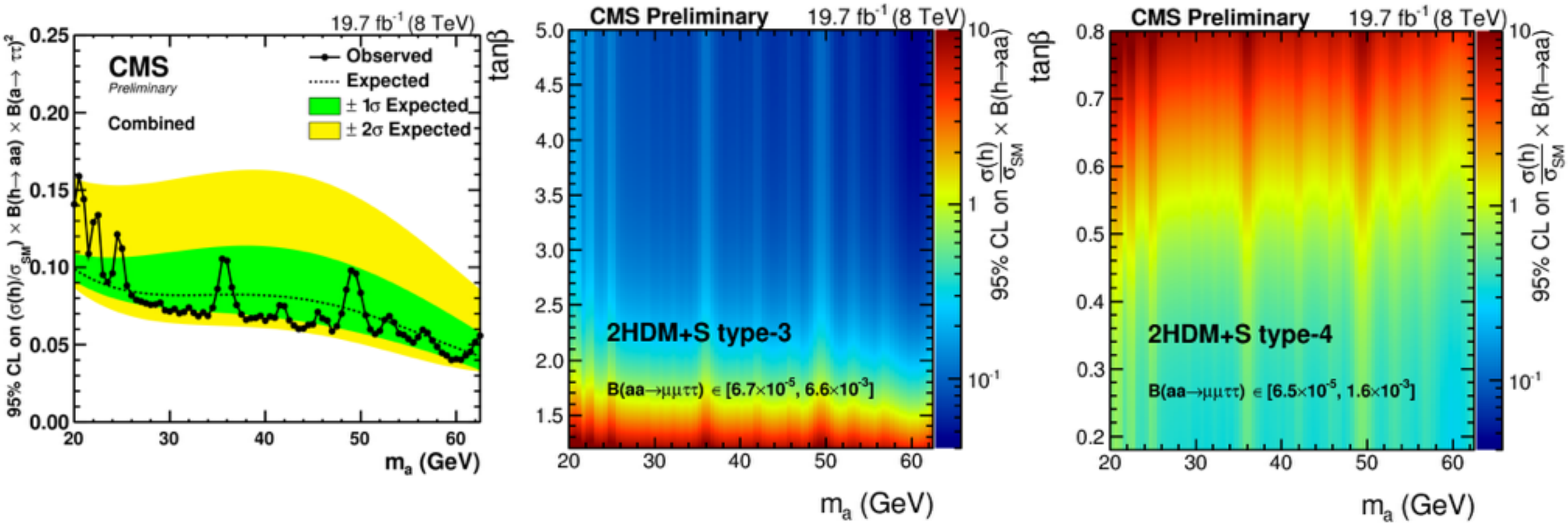
- Main background:
  - → Irreducible ZZ production
  - → Reducible processes with at least one jet misidentified (Z+jets and WZ+jets).

https://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/HIG-15-011/index.html

H(125) → aa → μμττ

- Upper limits on h→aa production relative to the SM h production, scaled by B(a → ττ)^2
  - → Data comparable with background-only hypothesis (No excess exceed 2σ glob. significance)
  - → Set 95% C.L. upper limits on signal event rate
  - → Limits in the context of 2 HDM+S models

$$\frac{\Gamma(a \to \mu\mu)}{\Gamma(a \to \tau\tau)} = \frac{m_\mu^2\sqrt{1-(2m_\mu/m_a)^2}}{m_\tau^2\sqrt{1-(2m_\tau/m_a)^2}}$$



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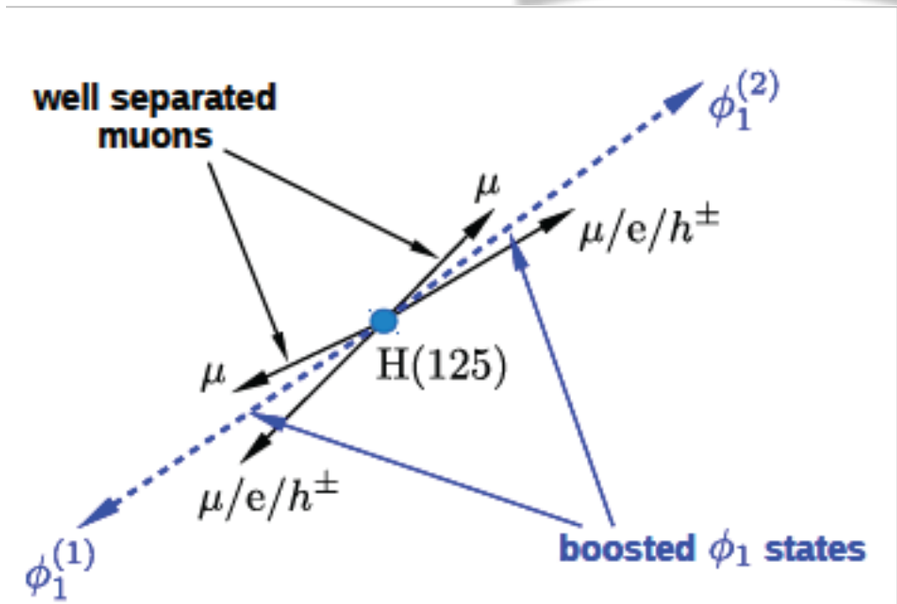
H(125) → aa → ττττ

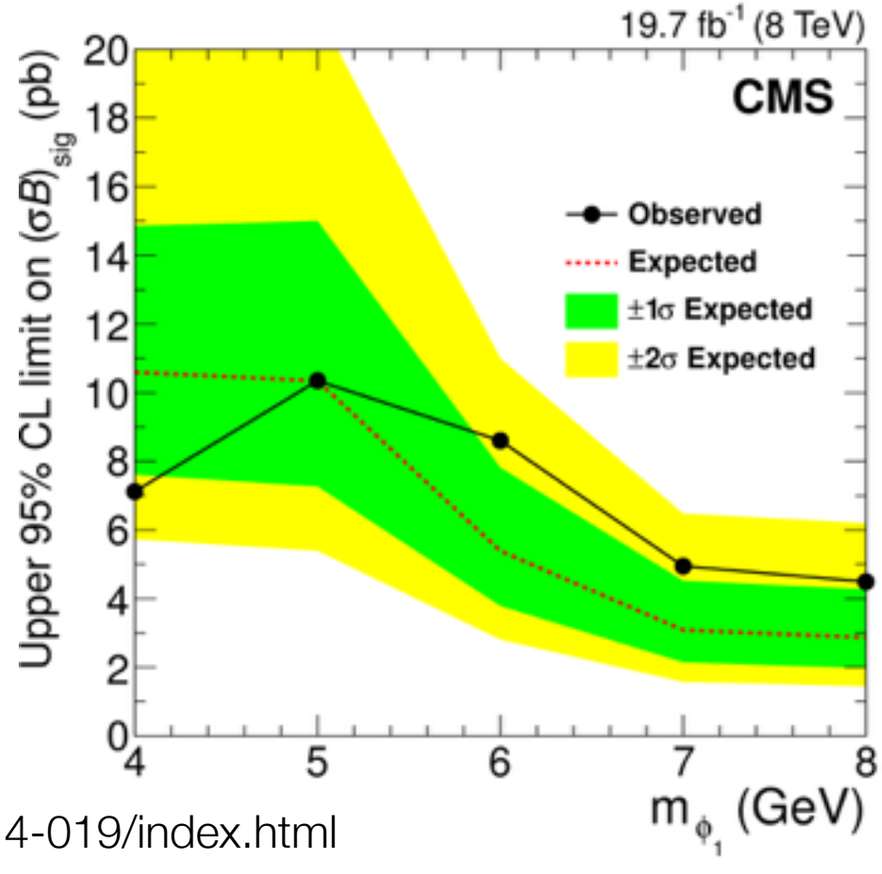
- Signal:
  - → SM-Higgs decaying into 2 light bosons Φ_1 (=a_1,h_1) (foreseen by NMSSM)
  - → SM-H corresponds to:
    - → h_2 and decays into $h_2 \rightarrow 2h_1$
    - → h_2 and decays into $h_2 \rightarrow 2a_1$ ($2m_\tau < m(a_1) < 2m_b$)
    - → h_1 and decays into $h_1 \rightarrow 2a_1$



- Selection:
  - → One τ goes to μ and other to one-prong mode
  - → Two same sign μ with p_T>17/10 GeV and |η|<2.1
  - → One opp. sign track with p_T>2.5 GeV and |η|<2.4

- Main background: QCD multijet events

- 95% C.L. upper limit set on the production rate of signal events



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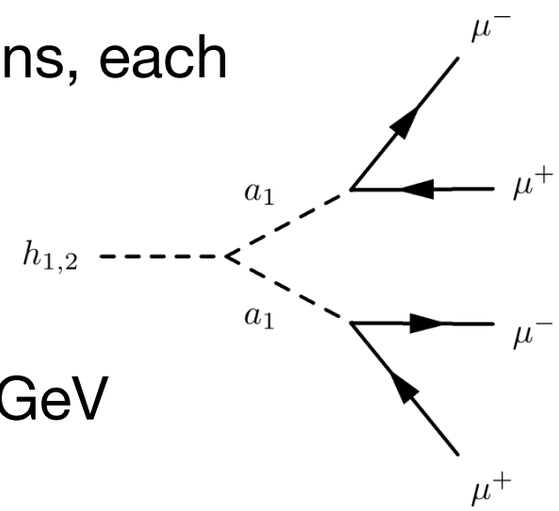
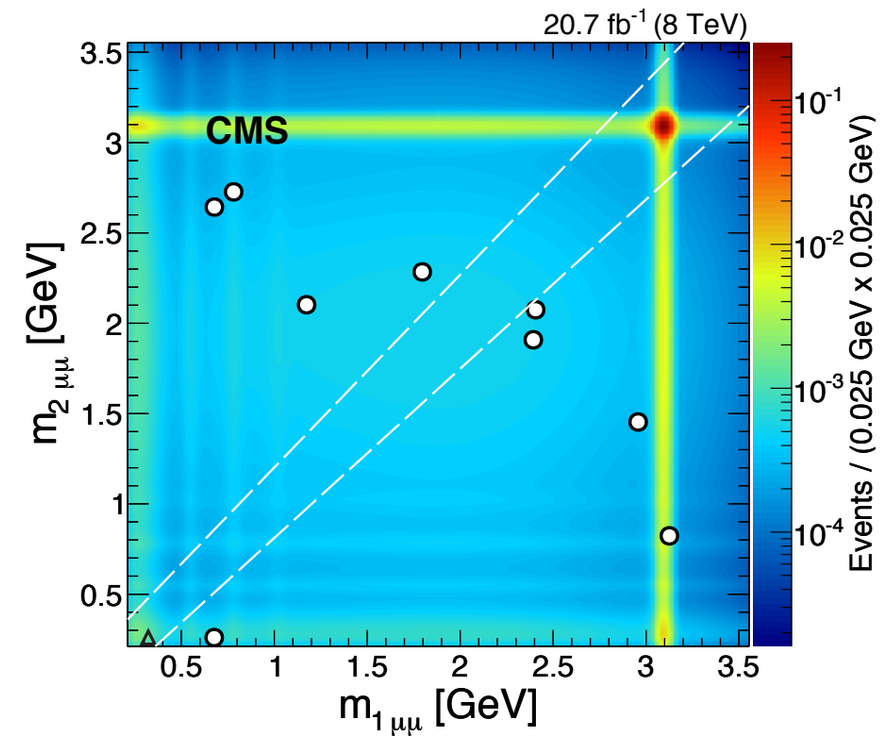
Search for H→aa→μμμμ

- Signal:
  → Pair production of new light bosons, each decaying into a pair of muons

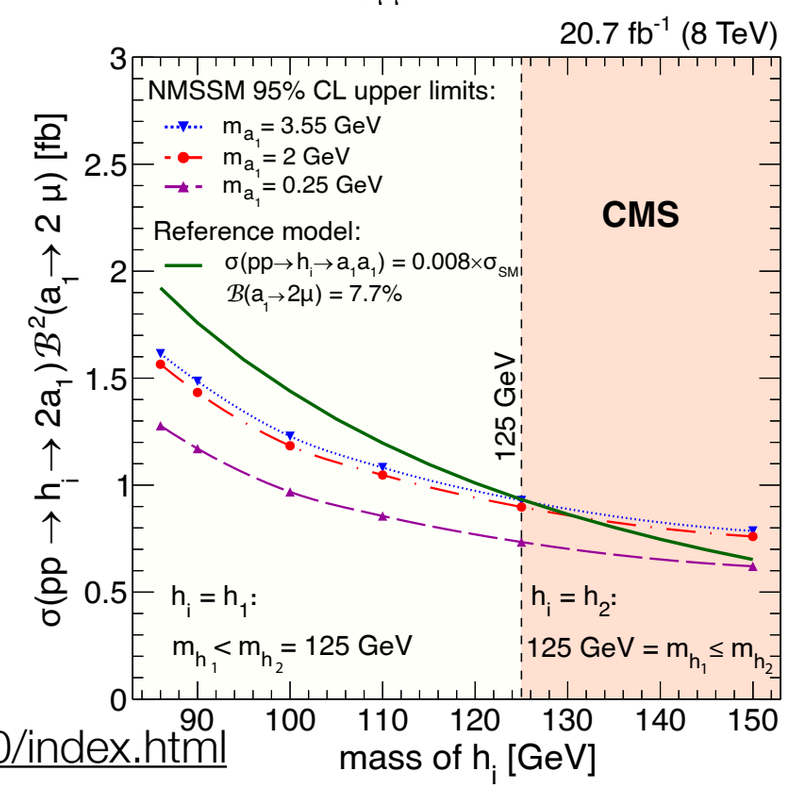




- Selection:
  → P_{T1}>17 GeV; $|\eta_1|$ <0.9; $P_{T2,3,4}$ > 8 GeV
  → $|z_{1\mu\mu} - z_{2\mu\mu}|$ < 1 mm

- Main background:
  → $b\bar{b}$, double J/Ψ (SPS and DPS)

- Excess searched on the diagonal:
  $|m_{1\mu\mu}-m_{2\mu\mu}| < 0.13$ GeV + $0.065(m_{1\mu\mu} + m_{2\mu\mu})/2$
  → Model independent search, benchmark model is NMSSM
  → Assume SM-like production σ for $h_{1,2}$ to simplify interpretation



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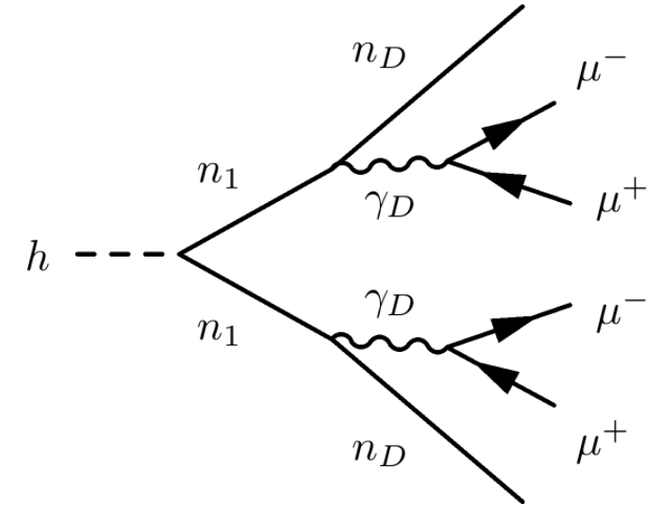
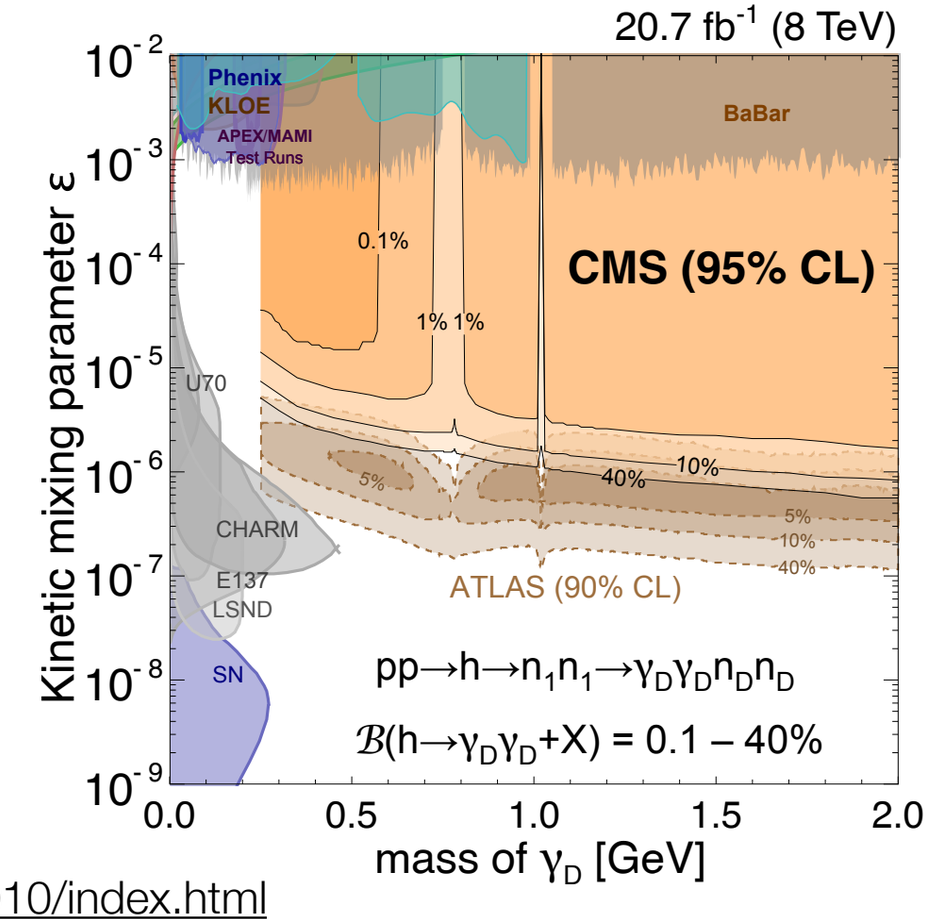
Search for H→aa→μμμμ

- Additional Benchmark: Dark SUSY
  $h \rightarrow n_1 n_1 \rightarrow n_D n_D \gamma_D \gamma_D + X$
  - → Dark photons could have an appreciable life-time before decay
  - → Dark photons are generated with m(γ) in the range 0.25–2.0 GeV and a decay length in the range of 0–20 mm



- 95% CL limit on H boson production σ·B.R.
  - → The limit set in the [m(γ_D),ε] plane.
  - → Implies model dependence when comparing to low energy results
  - → Nice complementarity with ATLAS analysis searching for decays far from the interaction point



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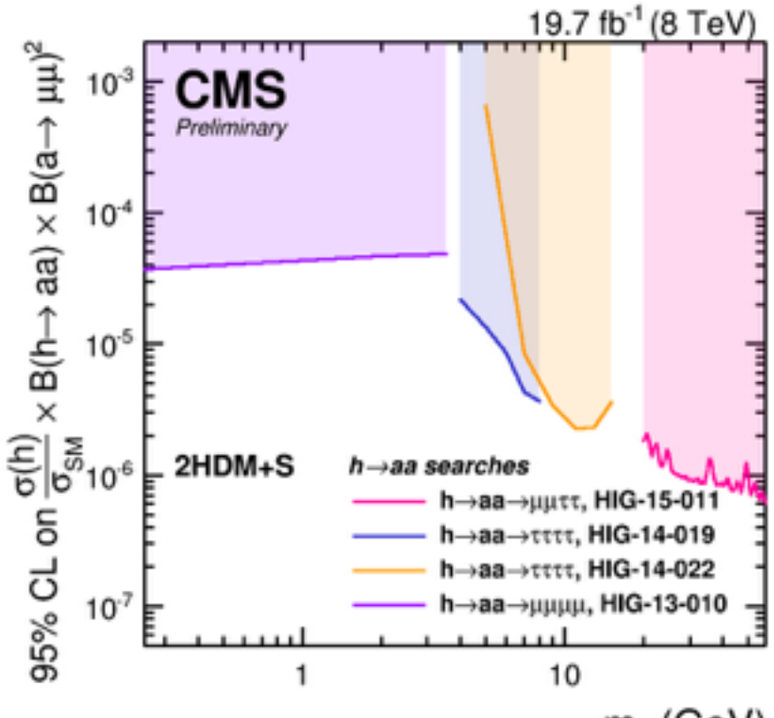
Conclusions

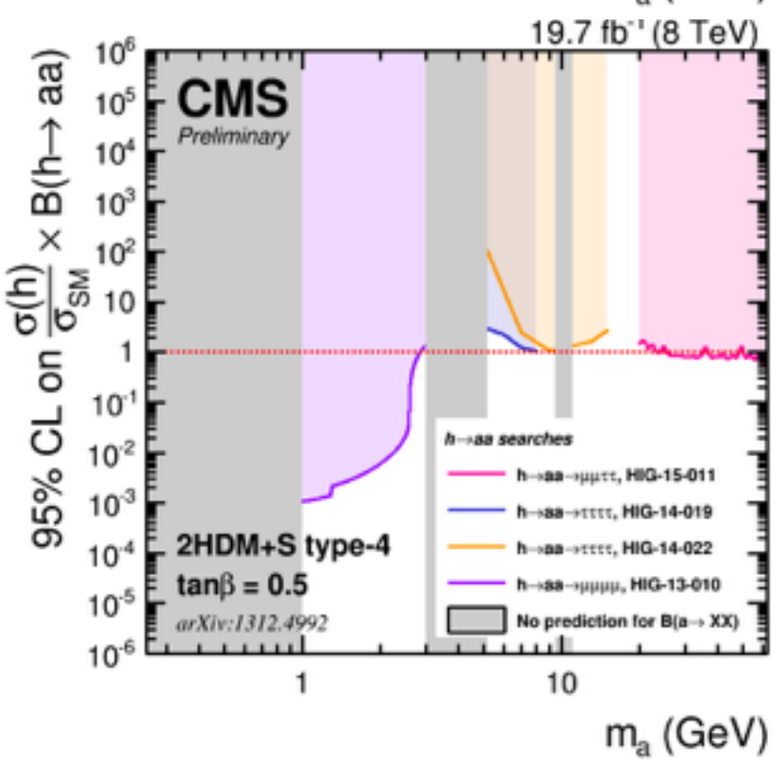
- Studies on the Higgs sector are moving towards the era of precision measurements:
  - → Kinematic
  - → Properties
  - → Production cross-sections

- So far the 13 TeV data are consistent with 7 and 8 TeV data

- Just few examples of searches for extended Higgs sector have been presented:
  - → Combination is in progress

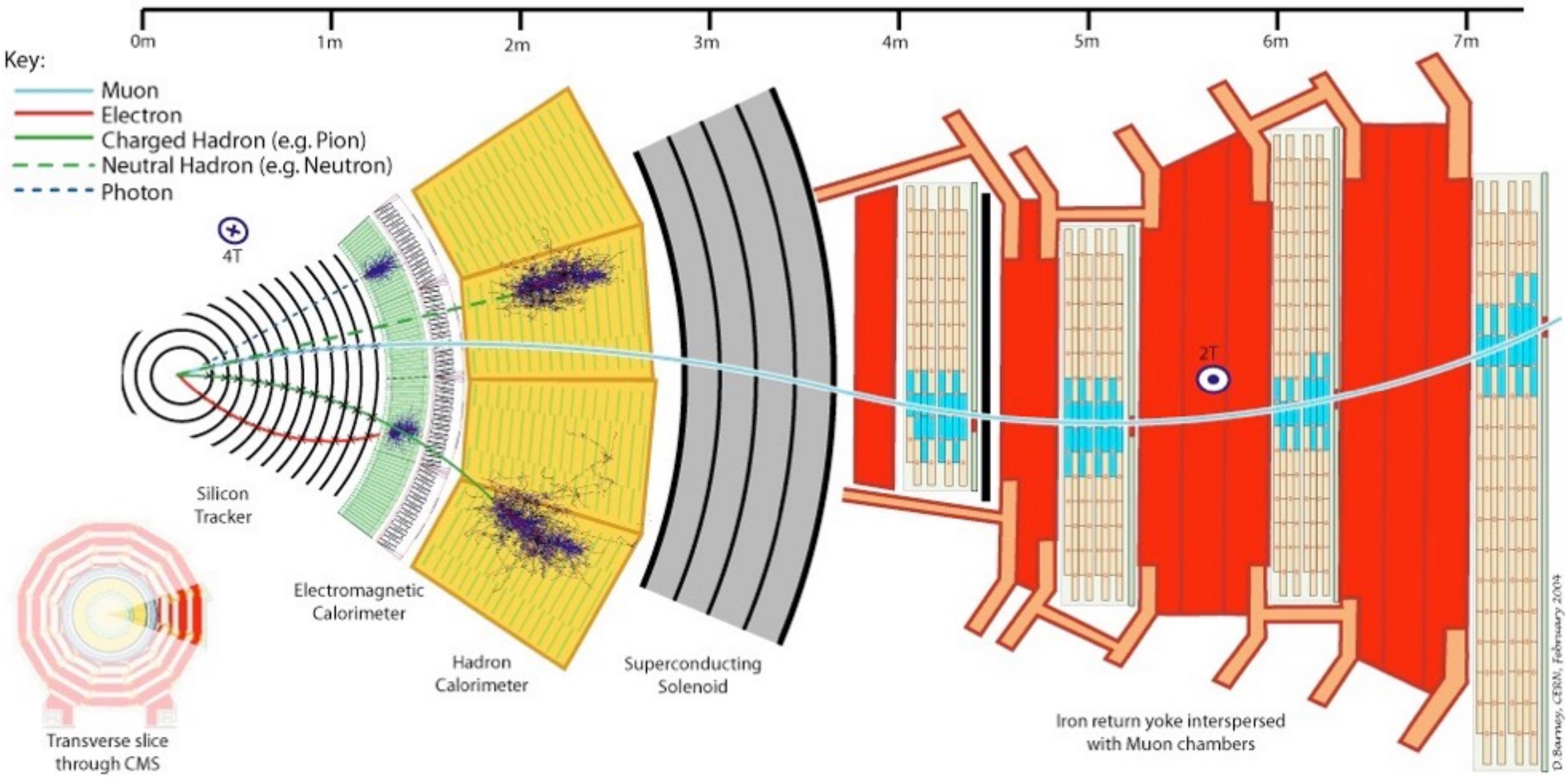
- Exciting news foreseen during this year:
  - → Expected 20 fb^{-1} by the end of the 2016





Backup

The Compact Muon Solenoid



Heavy Higgs searches in Run 1