

Searches for extended Higgs sectors with the CMS experiment

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On behalf of the CMS Collaboration

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- ❖ 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



Extended H-sector ?

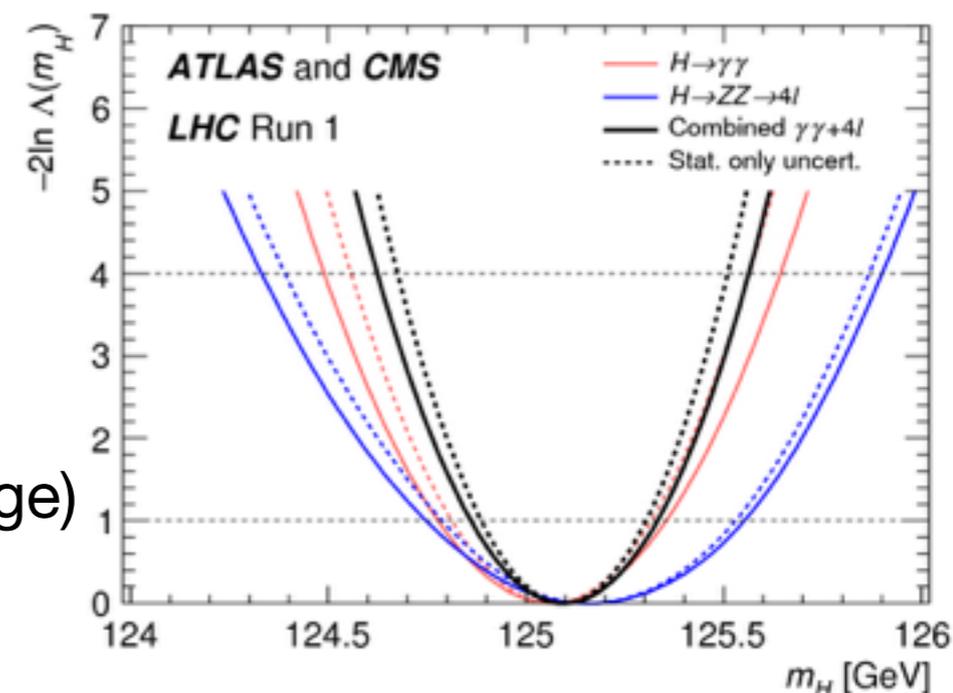
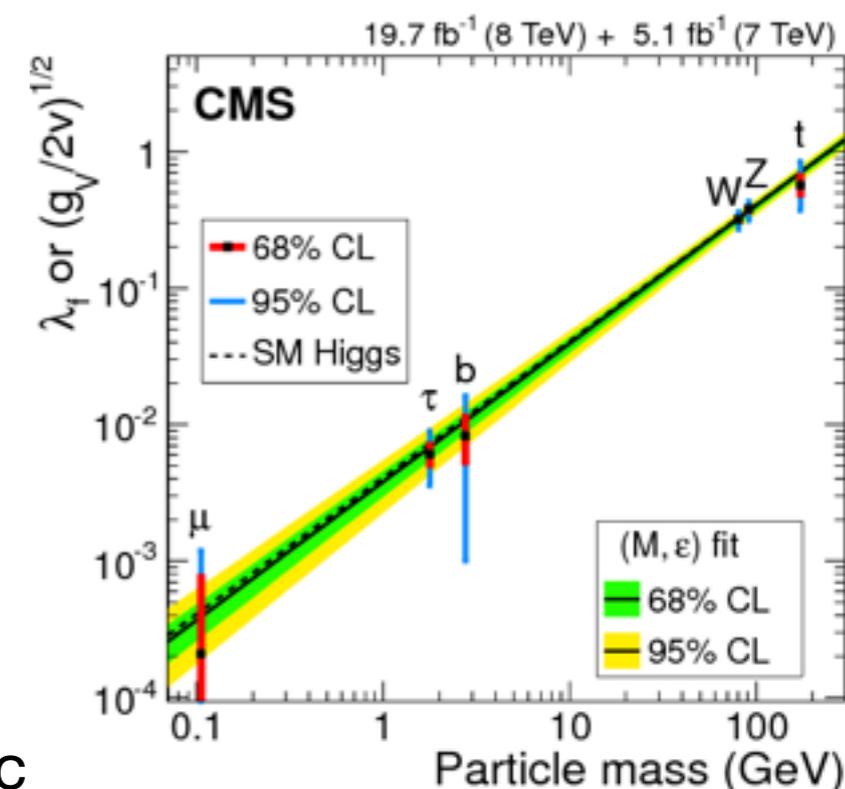
SM-like H

- ❖ Higgs-like particle has been observed:
 - $m_H = 125.09 \pm 0.21(\text{stat}) \pm 0.11(\text{syst})$
 - $\Gamma_H < 26 \text{ MeV}$ (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)

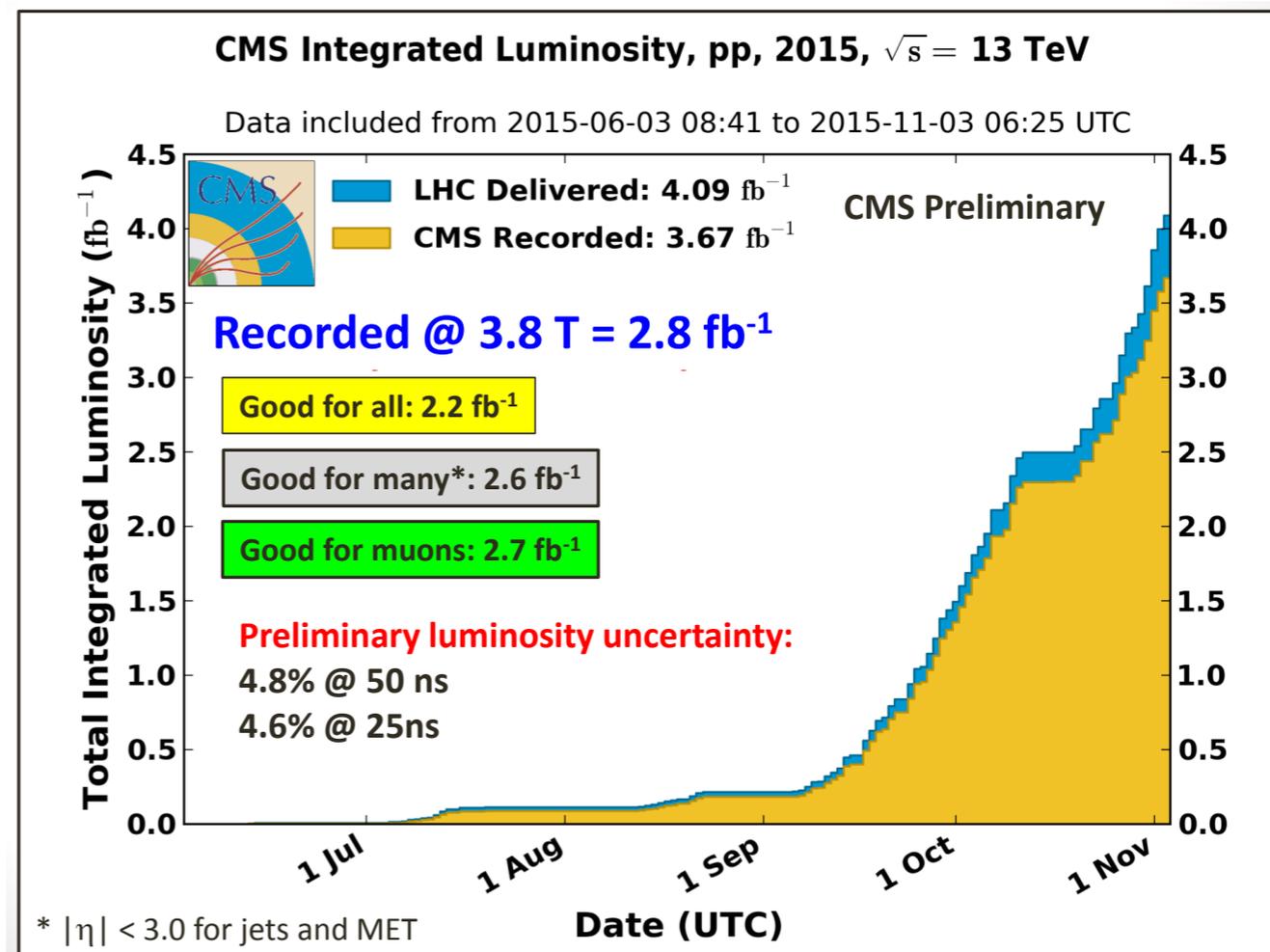
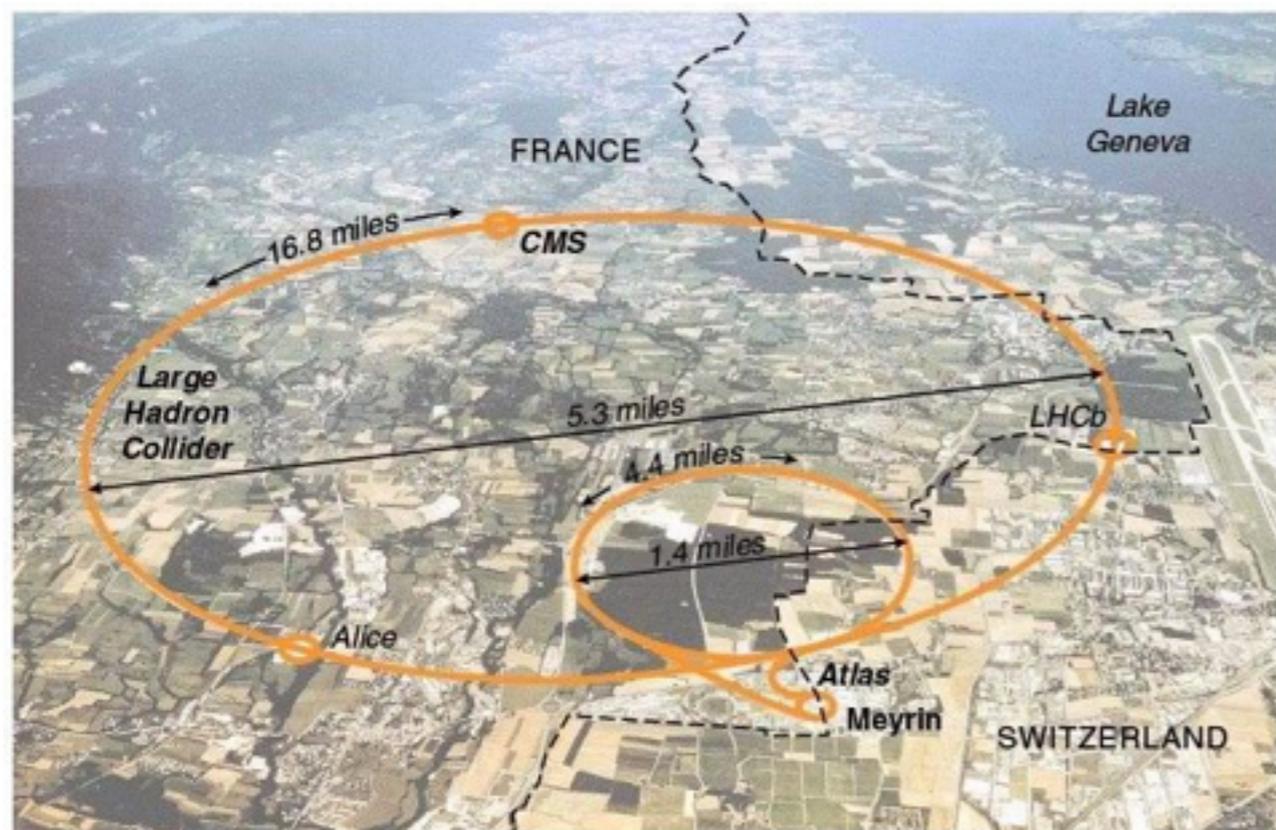


The Large Hadron Collider

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

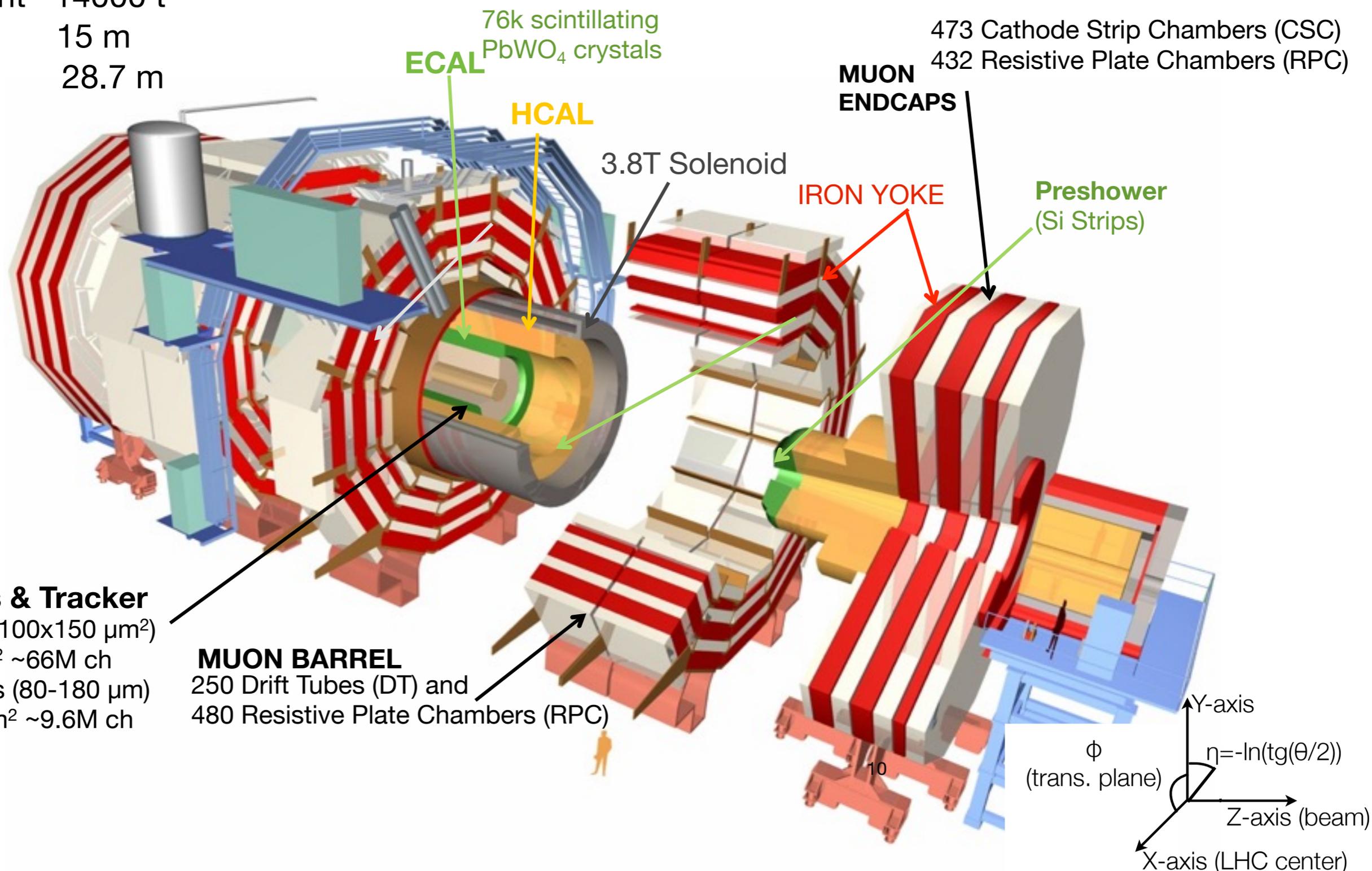
- ❖ Comparison with 8 TeV:

- 160% larger collision energy → $\sqrt{s}=13 \text{ TeV}$
- 200% larger number of bunches → 2800 bunches
- 200% larger pileup → 40 interactions/crossing
- 33% smaller β^* → 40 cm
- 170-220% larger peak Lumi. → $(13-17) \times 10^{33} \text{ cm}^{-2}\text{s}^{-1}$



The Compact Muon Solenoid

Total weight 14000 t
 Diameter 15 m
 Length 28.7 m



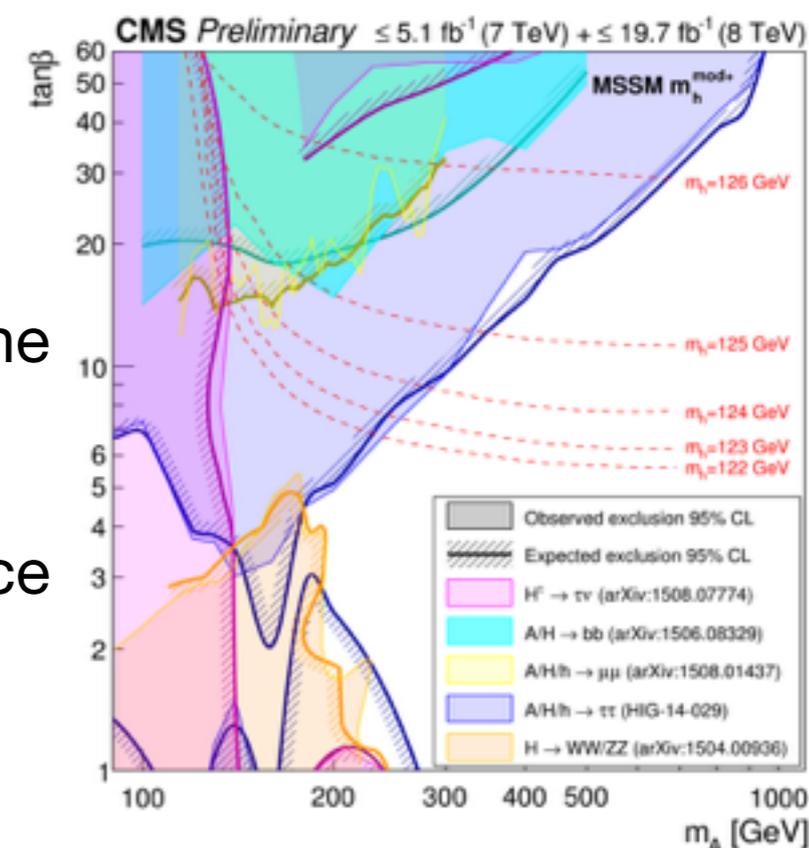
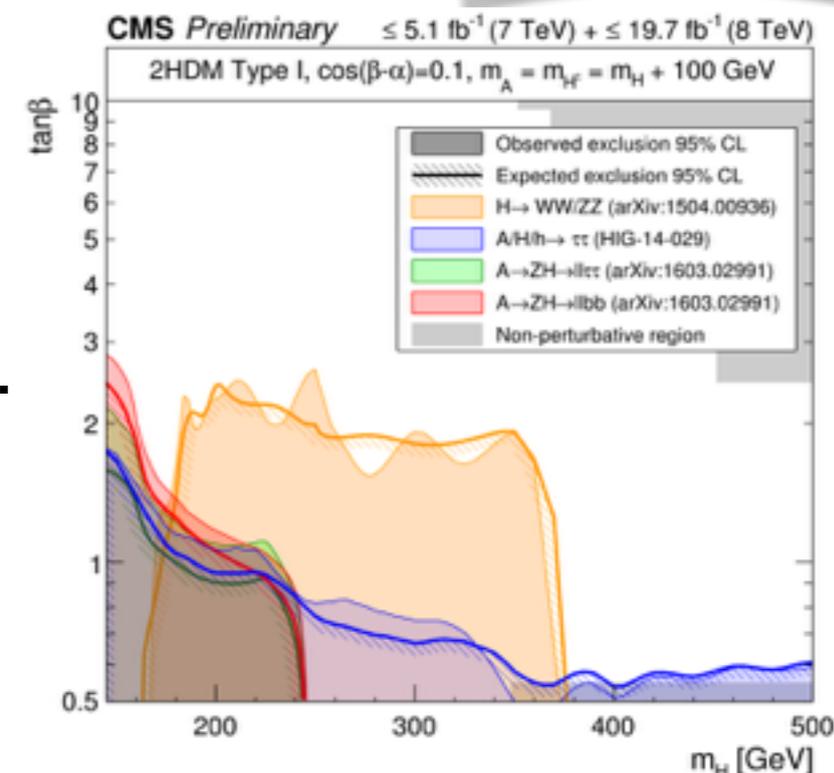
Heavy Higgs searches

❖ Several analysis considered:

- $H \rightarrow WW/ZZ$ ($145 < m < 1000$ GeV), 55 event categories in $WW(2l2\nu)$, $WW(2l2q)$, $ZZ(4l)$, $ZZ(2l2\nu)$, $ZZ(2l2q)$.
- $A/H/h \rightarrow \tau\tau$ ($90 < m < 1000$ 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 $\rightarrow \mu\mu$ ($115 < m < 300$ GeV).
- $H^\pm \rightarrow \tau\nu$ - tb ($\tau\nu$ dominates sensitivity). Divided in low and high mass region.
- $A/H \rightarrow bb$ ($100 < m < 900$ GeV). Prod. in assoc. with b-jets. Discr. variable: invariant mass of the 2 leading b-jets.
- $A \rightarrow ZH$ ($140 < m < 1000$ GeV). Z goes into leptons, H into b-quarks or τ .

❖ Two ways to obtain limits:

- Templates for the full signal prediction for each value in the exclusion plane of the considered scenario. (m_A - $\tan\beta$ for MSSM; m_H - $\tan\beta$ for 2HDM)
- 95% CL limits on $\sigma \cdot Br$ of a single, narrow-width resonance (except for $H \rightarrow WW/ZZ$ analysis). Limits translated into the exclusion plane.



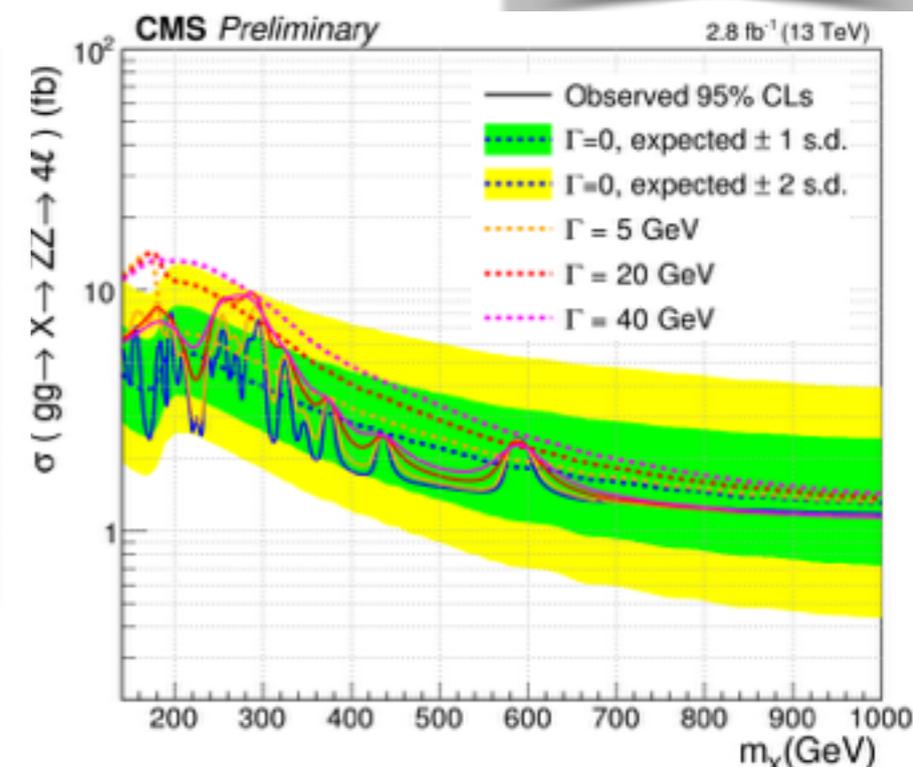
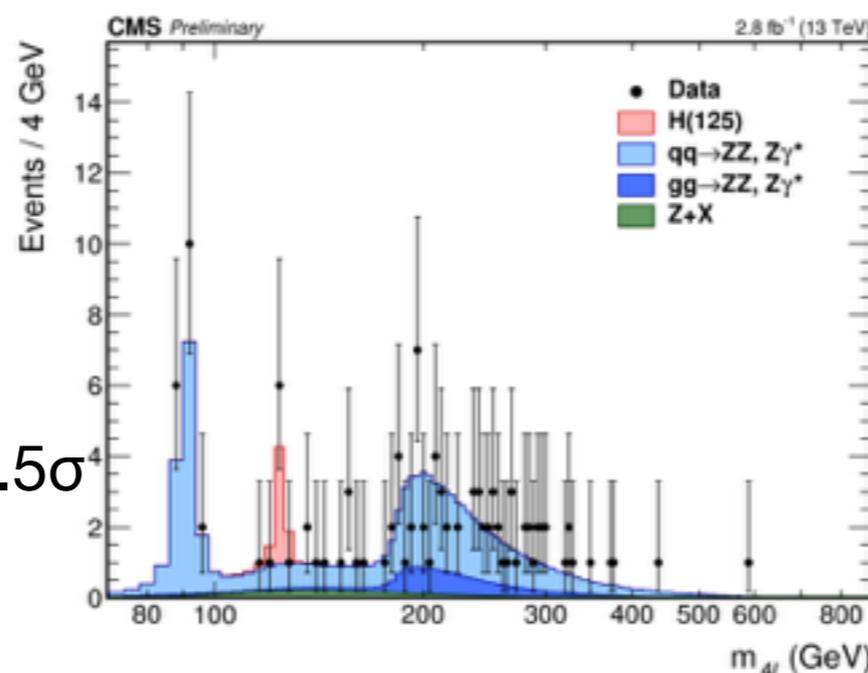
H → ZZ → 4l @13 TeV

❖ Signal:

→ H → ZZ → 4l (l = e, μ)

Analysis measures both SM-H and limits on additional resonances

→ Significance for SM-H: 2.5σ



❖ Backgrounds:

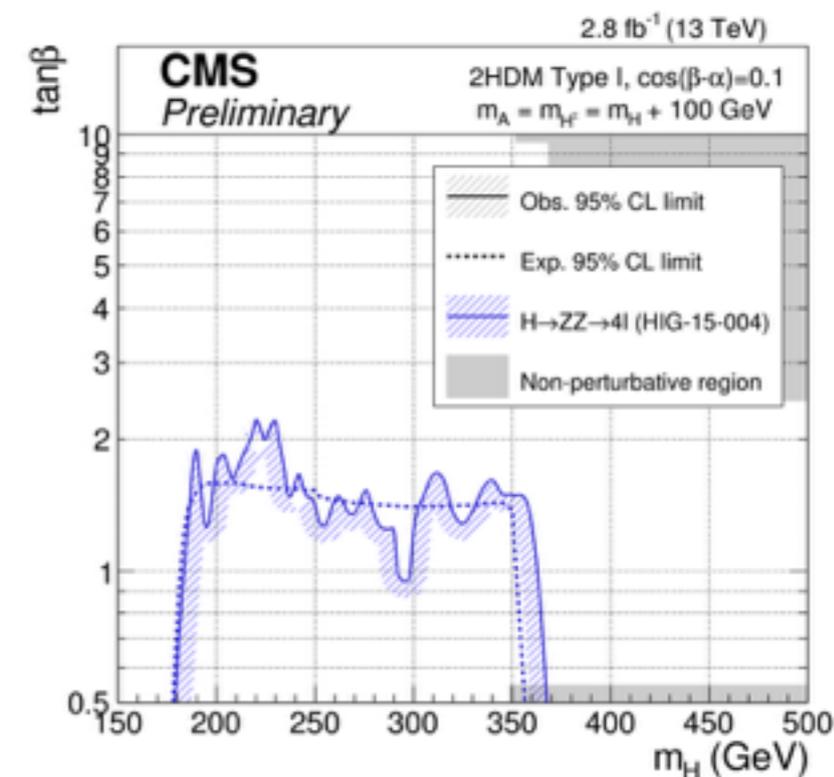
→ ZZ (irreducible): estimated by simulation

→ Z+jets, tt, Zγ + jets, WW+jets, WZ + jets (reducible): estimated by two independent control regions

❖ SM-H and bkg. treated as one process in gg-fusion:

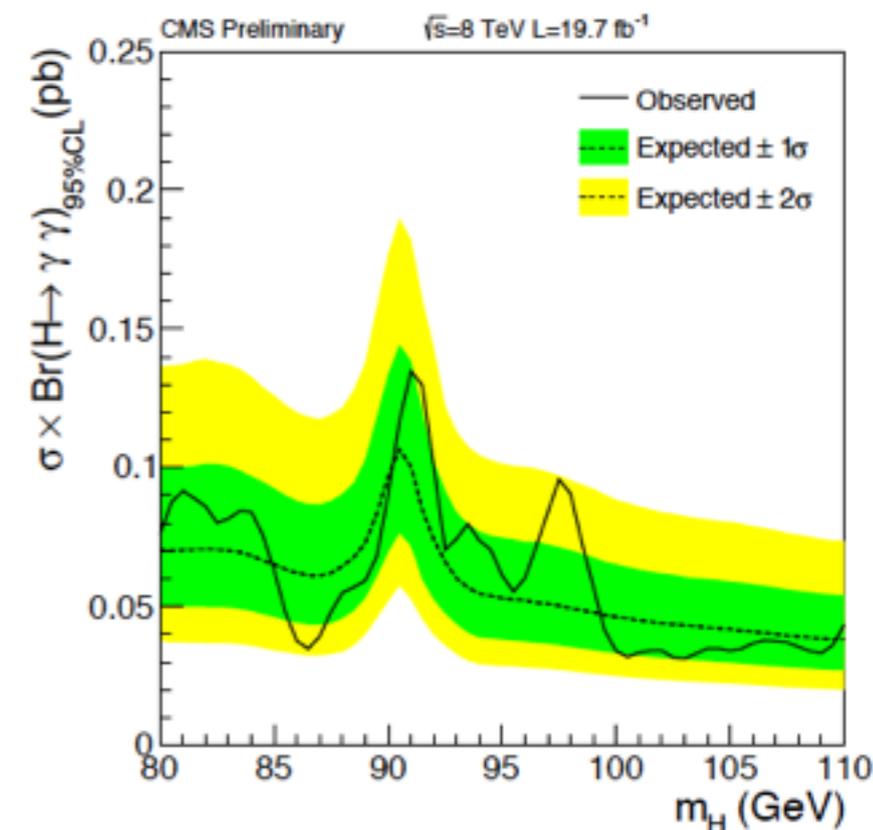
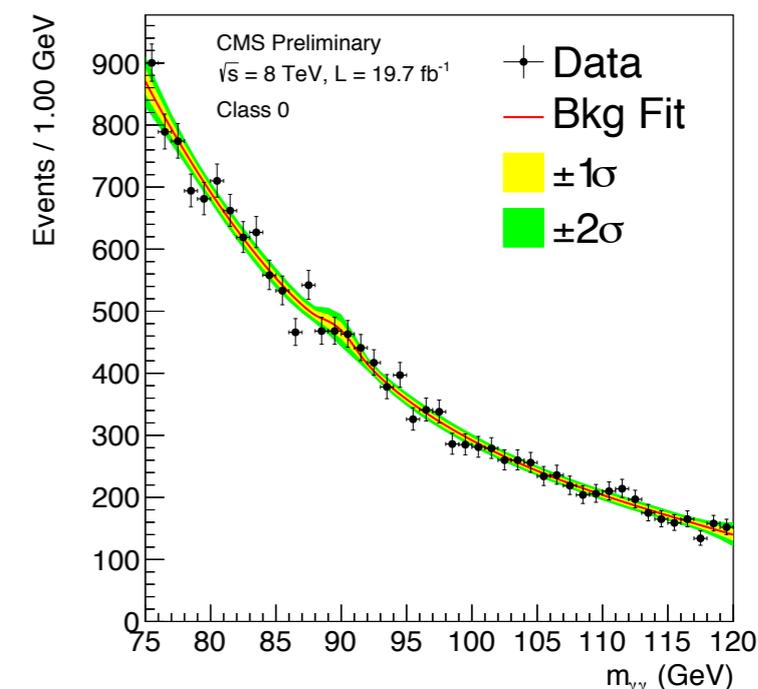
→ P(m_{4l}, m_X, Γ_X, σ_X) for the gg → bkg + H(125)* + X(m_X) → 4l allows inclusion of interference, including off-shell tail of H(125)

→ Limits at the 95% CL on σ · Br for several values of Γ_X



Low mass $H \rightarrow \gamma\gamma$

- ❖ Signal:
 - A new resonance decaying into two photons in 80-100 GeV range (in NMSSM or 2HDM a lighter Higgs is expected, if h_2 is the observed one)
- ❖ Selection: $p_{T1}/m(\gamma\gamma) > 28/80$; $p_{T2}/m(\gamma\gamma) > 20/80$
- ❖ Main background:
 - Irreducible direct di-photon production
 - Reducible γ/Z + jets
- ❖ 4 classes depending on η and R_9 variables
- ❖ Results:
 - No excess has been found in the 80-110 GeV mass range.
 - 95% C.L. upper limit has been set on the $\sigma \cdot B.R.$



Light Higgs searches

$H(125) \rightarrow aa \rightarrow \mu\mu bb$

❖ Signal:

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

❖ Selection:

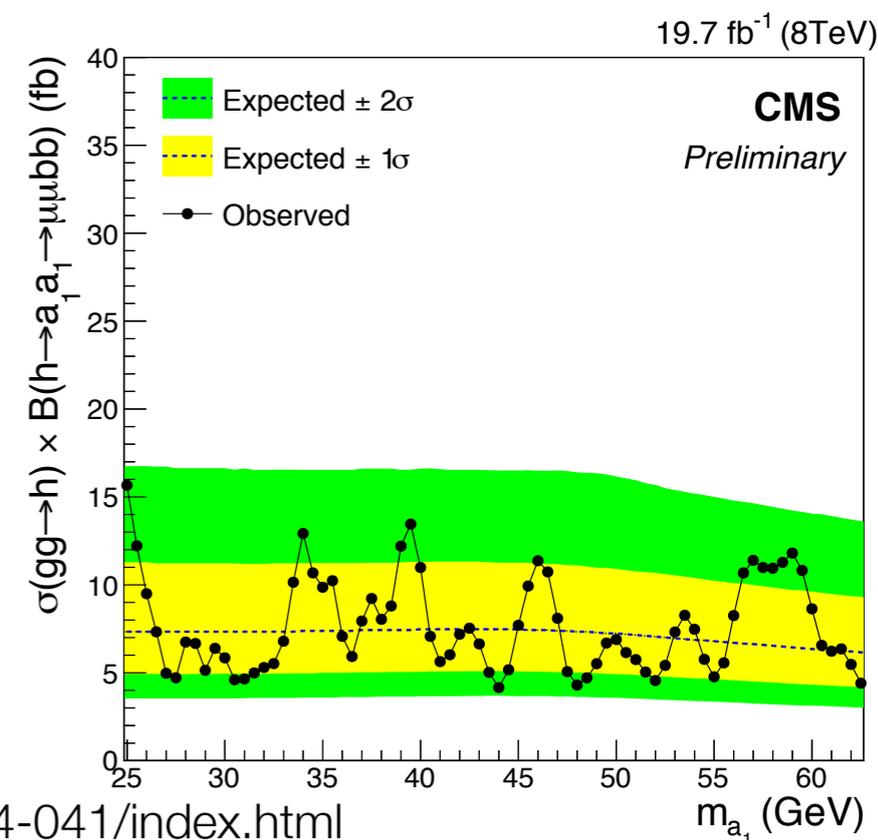
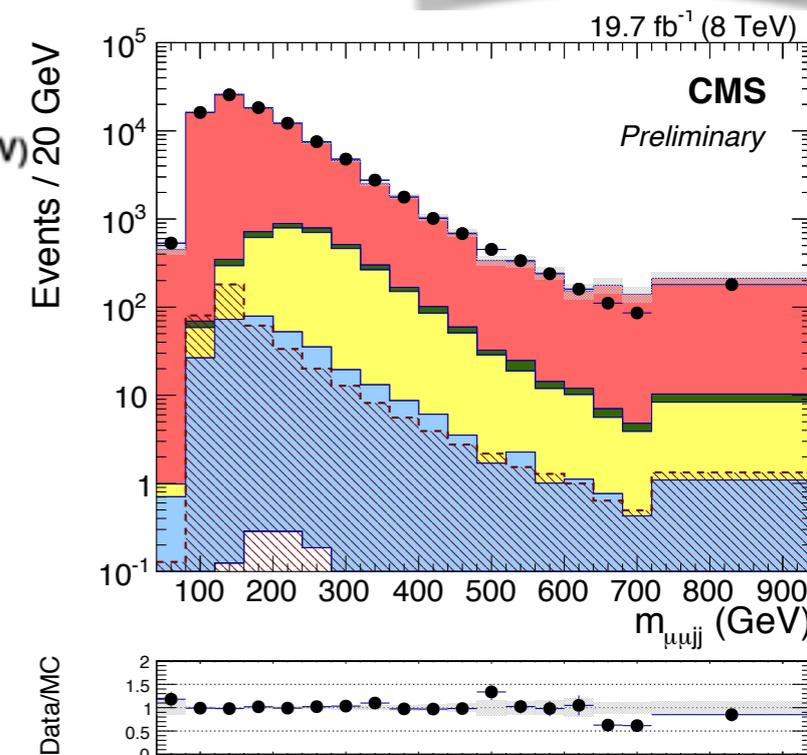
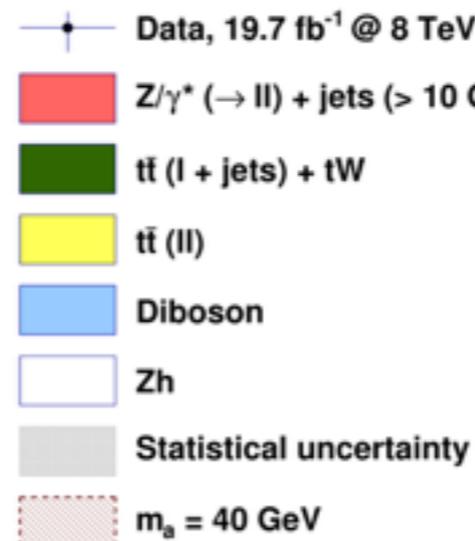
- 2 muons with $p_T > 24$ and 9 GeV
- 2 jets with $p_T > 15$ GeV (b-tagged)
- $|m(\mu\mu bb) - 125| < 25$ GeV

❖ Main background:

- Z + jets, tt

❖ Sensitivity extracted using a fit to $m(\mu\mu)$ distribution:

- Limits on the production rate times B.R.



$H(125) \rightarrow aa \rightarrow \mu\mu\tau\tau$

❖ Signal:

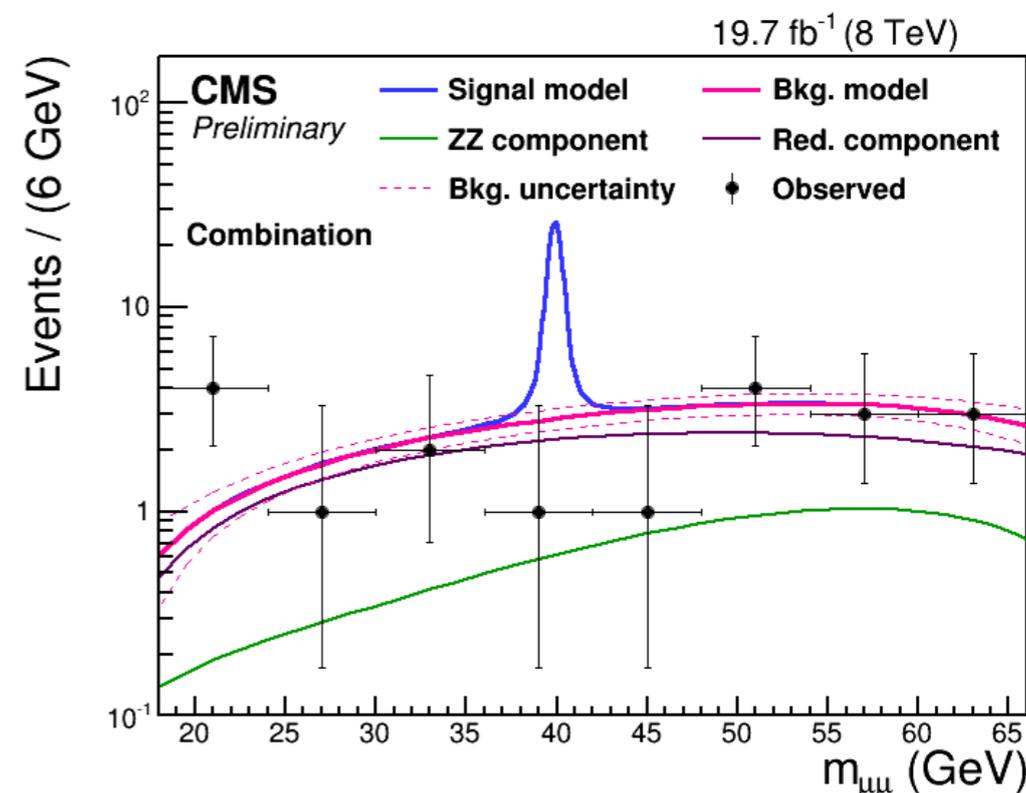
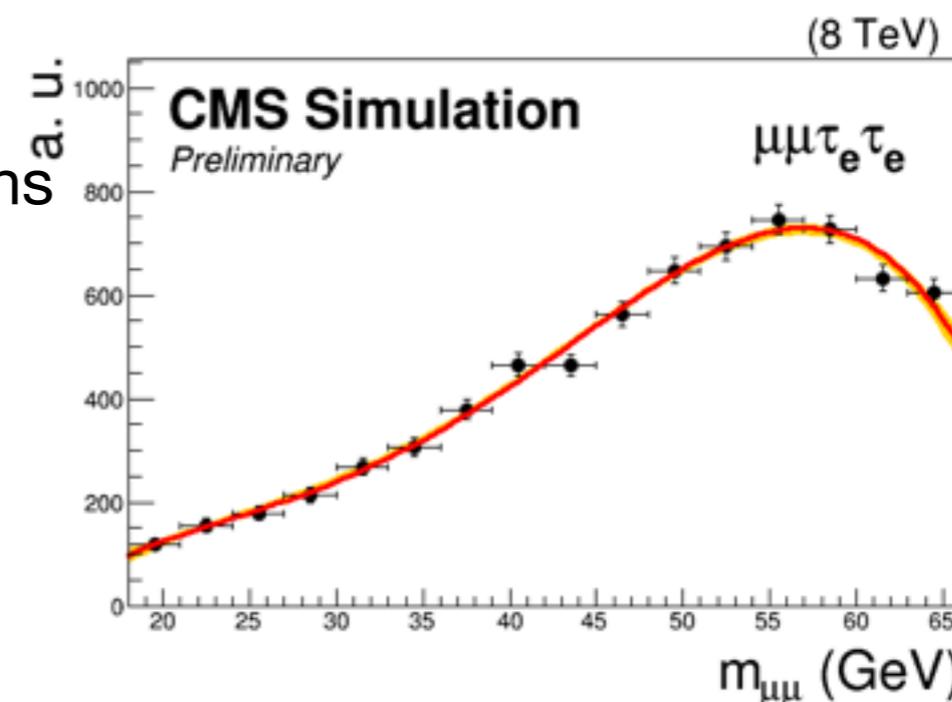
- SM Higgs decaying to 2 light pseudoscalar bosons (foreseen by 2HDM or 2HDM+S)
- $m(a) \sim [20,63]$ GeV
- Considering: $\mu\mu\tau_e\tau_h$, $\mu\mu\tau_\mu\tau_h$, $\mu\mu\tau_\mu\tau_e$, $\mu\mu\tau_e\tau_e$, $\mu\mu\tau_h\tau_h$ ($\mu\mu\tau_\mu\tau_\mu$: ambiguities in pairing muons)

❖ Selection:

- Two μ with $p_T > 18/9$ GeV
- $p_T > 5,7,15$ GeV for τ_μ , τ_e and τ_h
- $|m(\mu\mu\tau\tau) - 125| < 25$ GeV
- $|m(\mu\mu) - m(\tau\tau)| < 0.8 m(\mu\mu)$

❖ Main background:

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

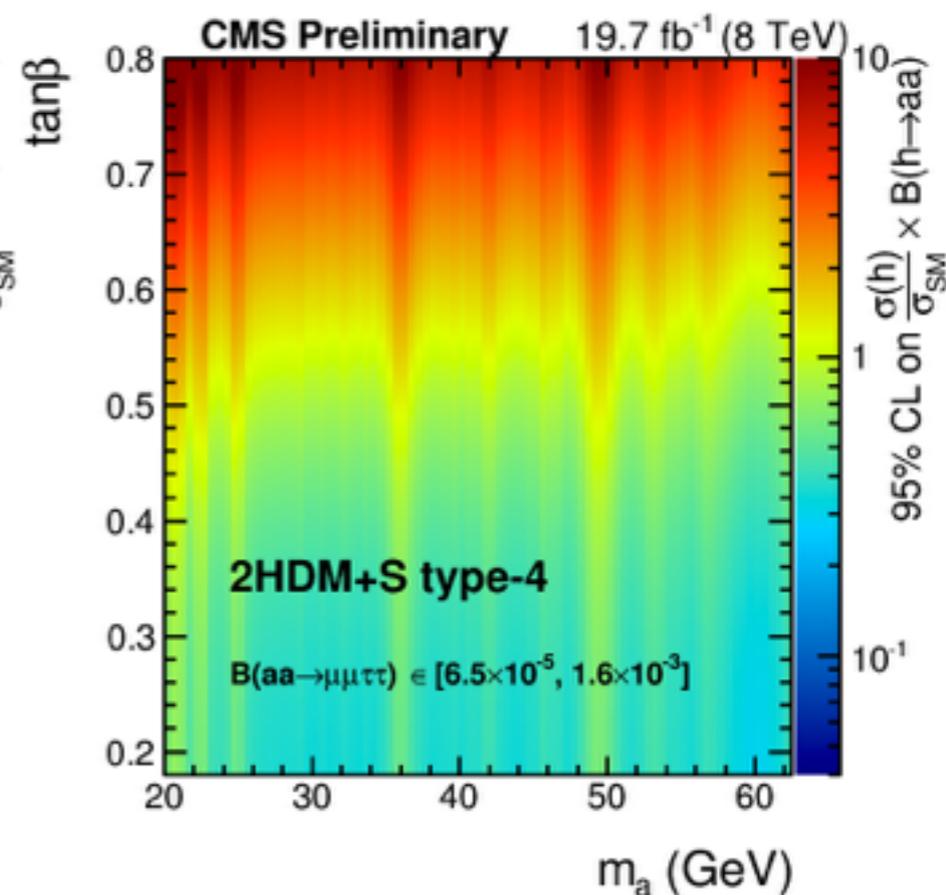
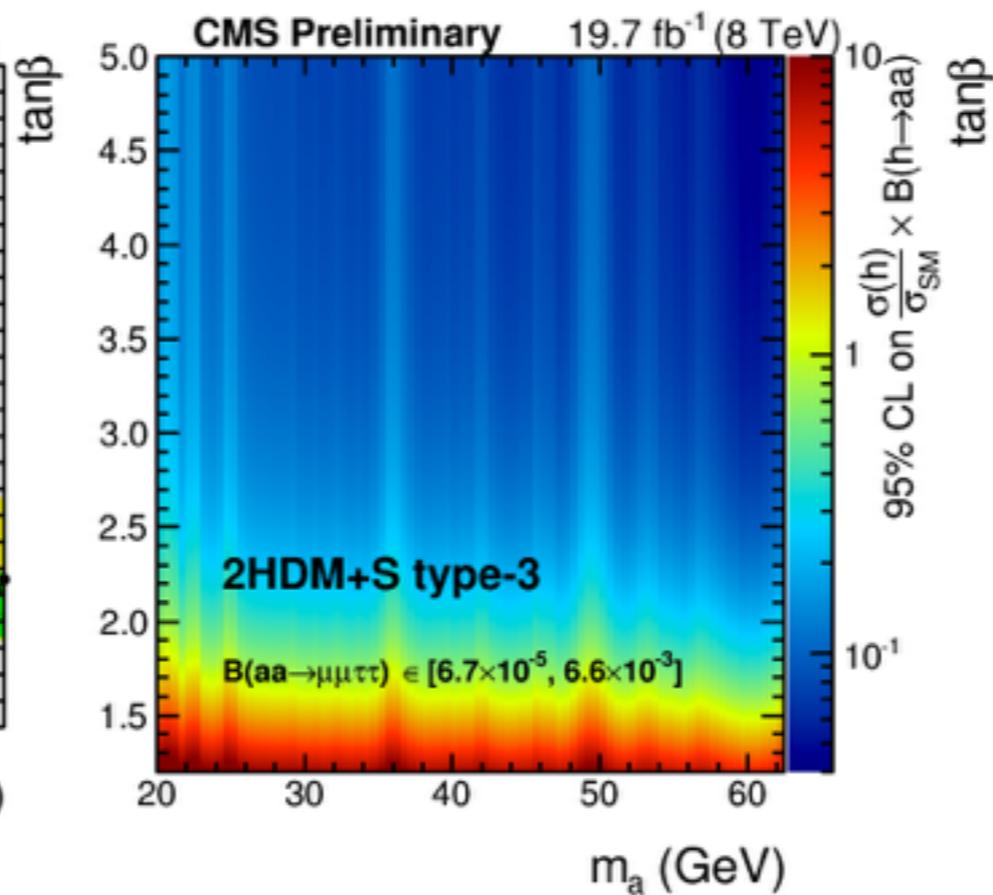
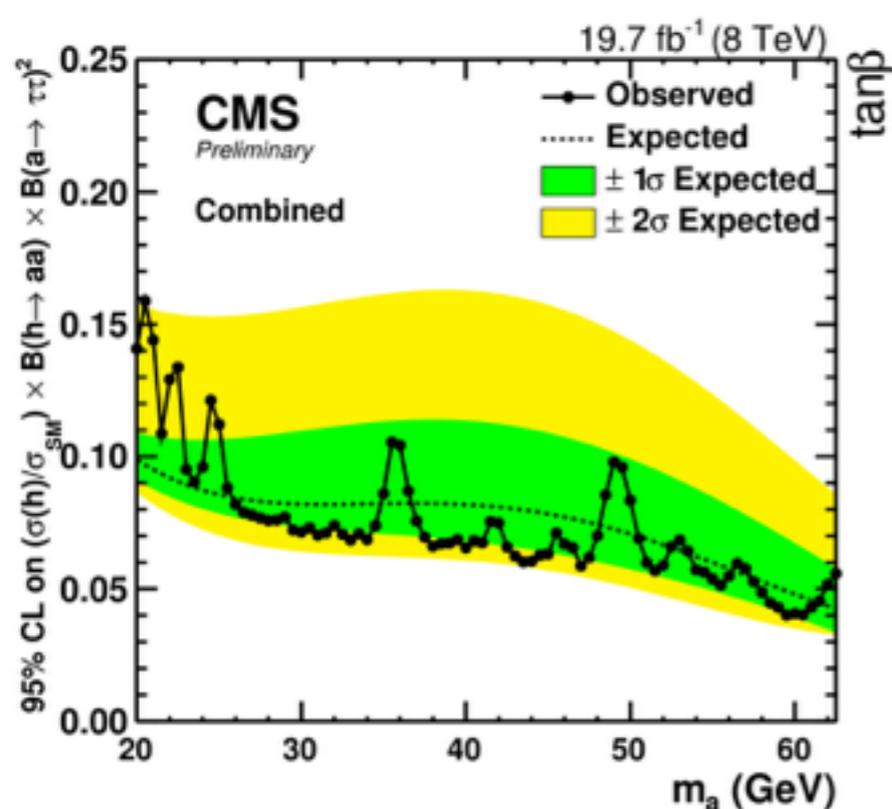


H(125) \rightarrow aa \rightarrow $\mu\mu\tau\tau$

Upper limits on $h \rightarrow aa$ production relative to the SM h production, scaled by $B(a \rightarrow \tau\tau)^2$

- 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

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



H(125) → aa → τττ

❖ Signal:

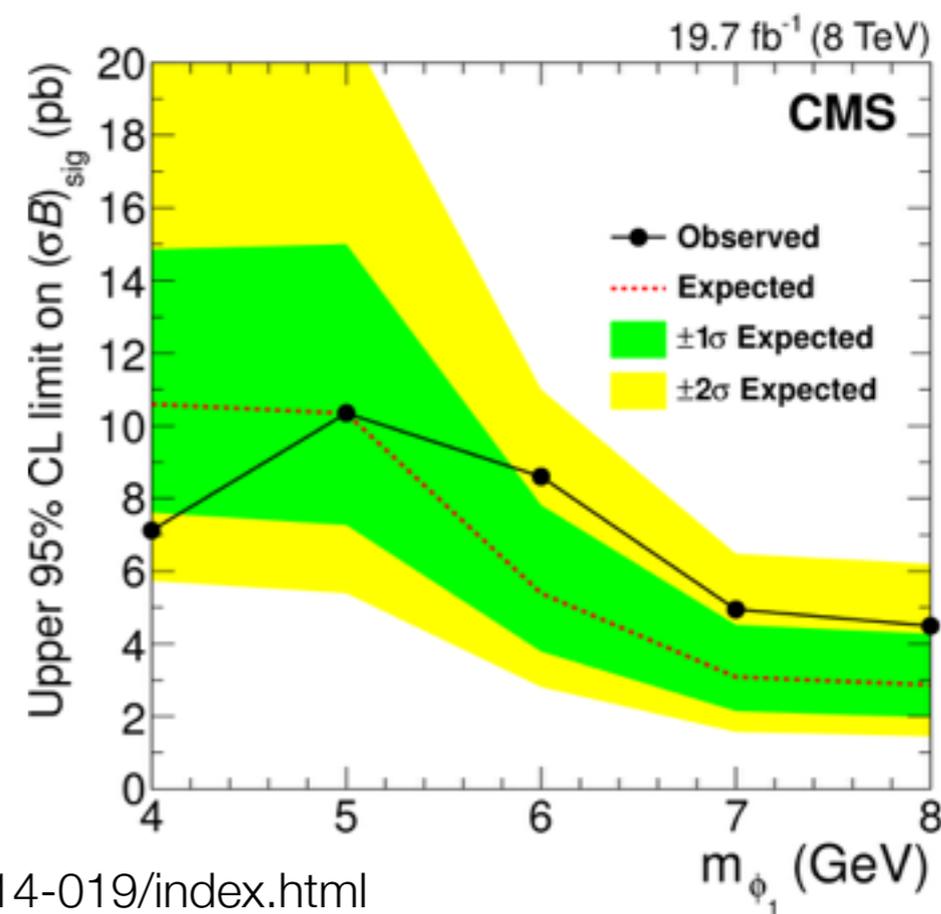
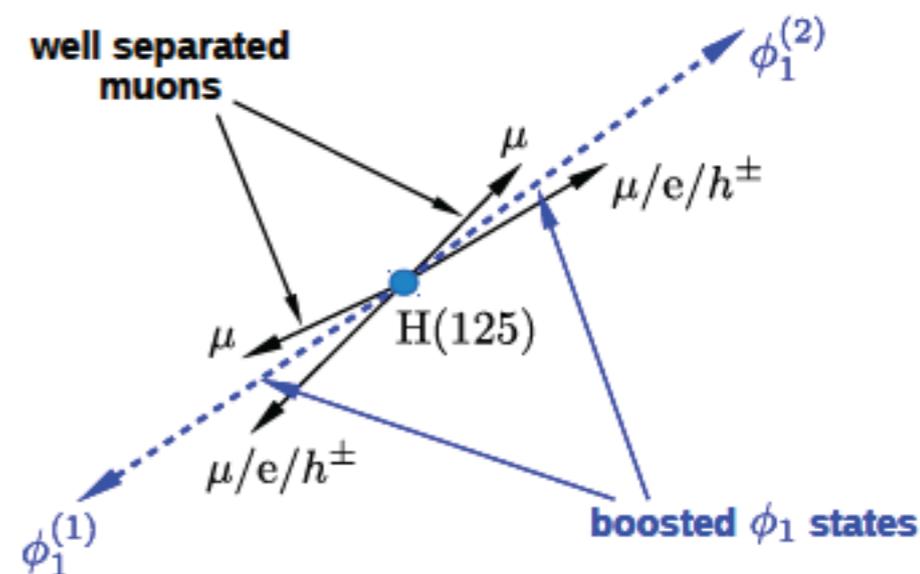
- SM-Higgs decaying into 2 light bosons $\Phi_1 (=a_1, h_1)$ (foreseen by NMSSM)
- SM-H corresponds to:
 - h_2 and decays into $h_2 \rightarrow 2h_1$
 - h_2 and decays into $h_2 \rightarrow 2a_1$ ($2m_\tau < m(a_1) < 2m_b$)
 - h_1 and decays into $h_1 \rightarrow 2a_1$

❖ Selection:

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

❖ Main background: QCD multijet events

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

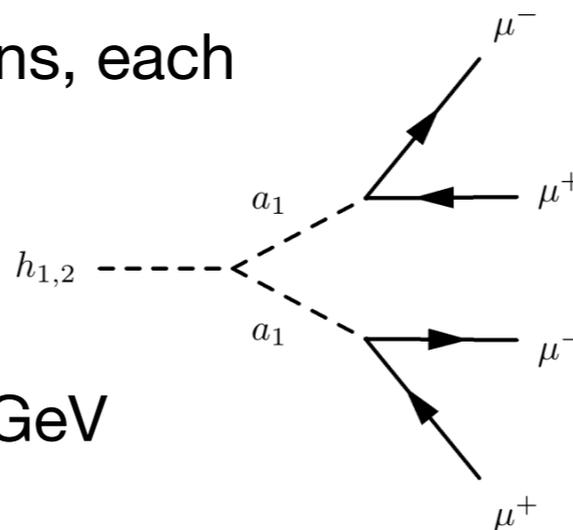


<https://cms-results.web.cern.ch/cms-results/public-results/publications/HIG-14-019/index.html>

Search for $H \rightarrow aa \rightarrow \mu\mu\mu\mu$

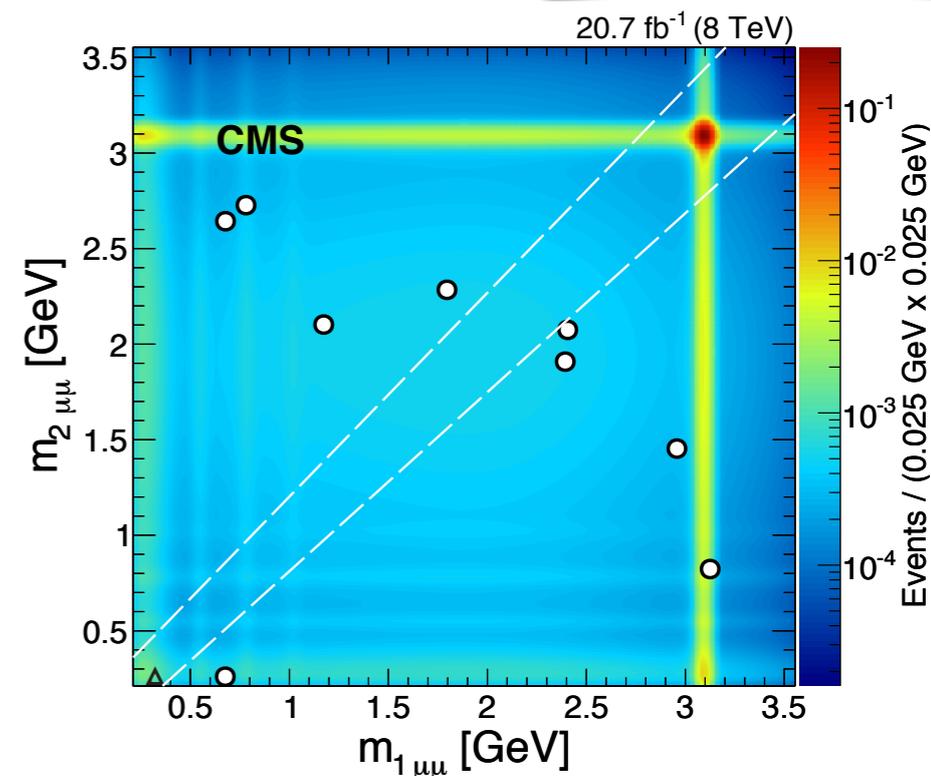
❖ Signal:

→ 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

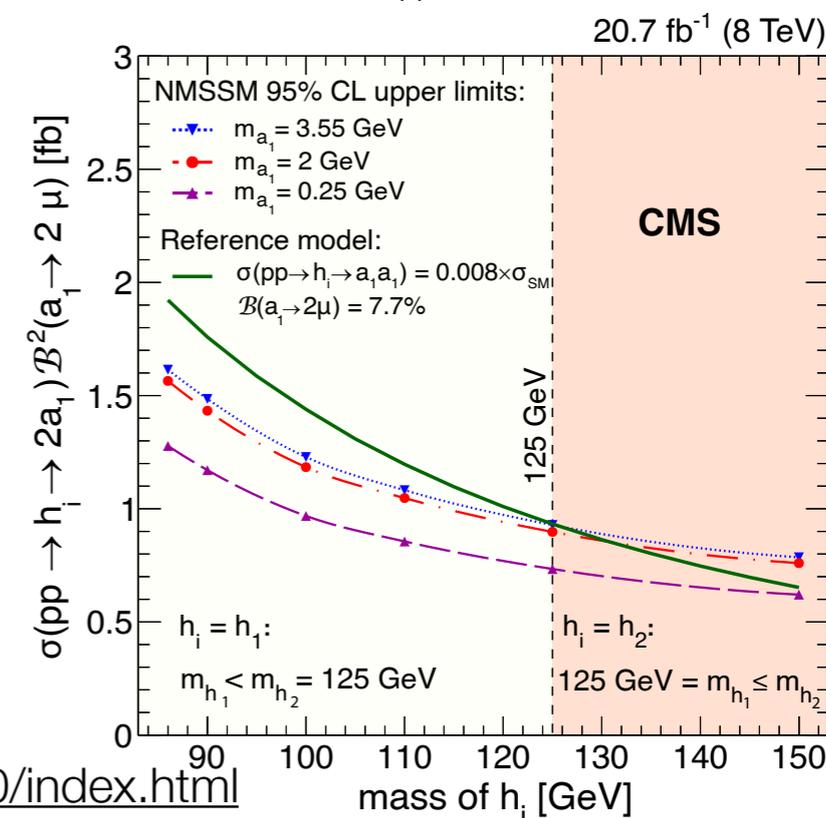


❖ Main background:

→ $b\bar{b}$, 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

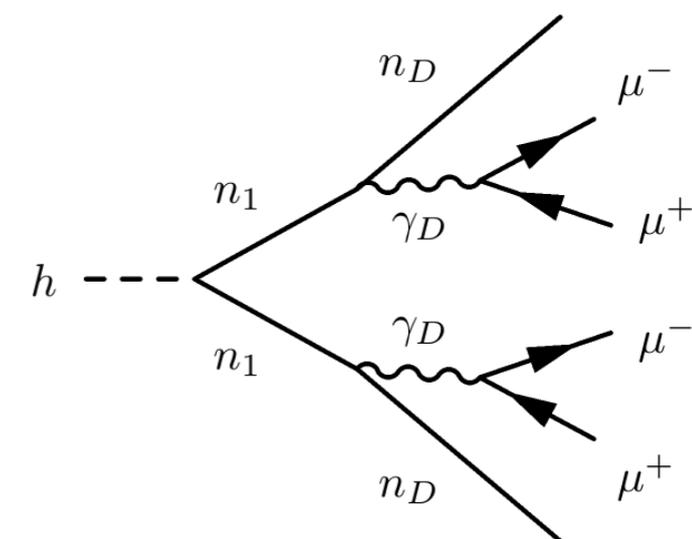


❖ Additional Benchmark: Dark SUSY

$$h \rightarrow n_1 n_1 \rightarrow n_D n_D \gamma_D \gamma_D + X$$

→ Dark photons could have an appreciable life-time before decay

→ Dark photons are generated with $m(\gamma)$ in the range 0.25–2.0 GeV and a decay length in the range of 0–20 mm

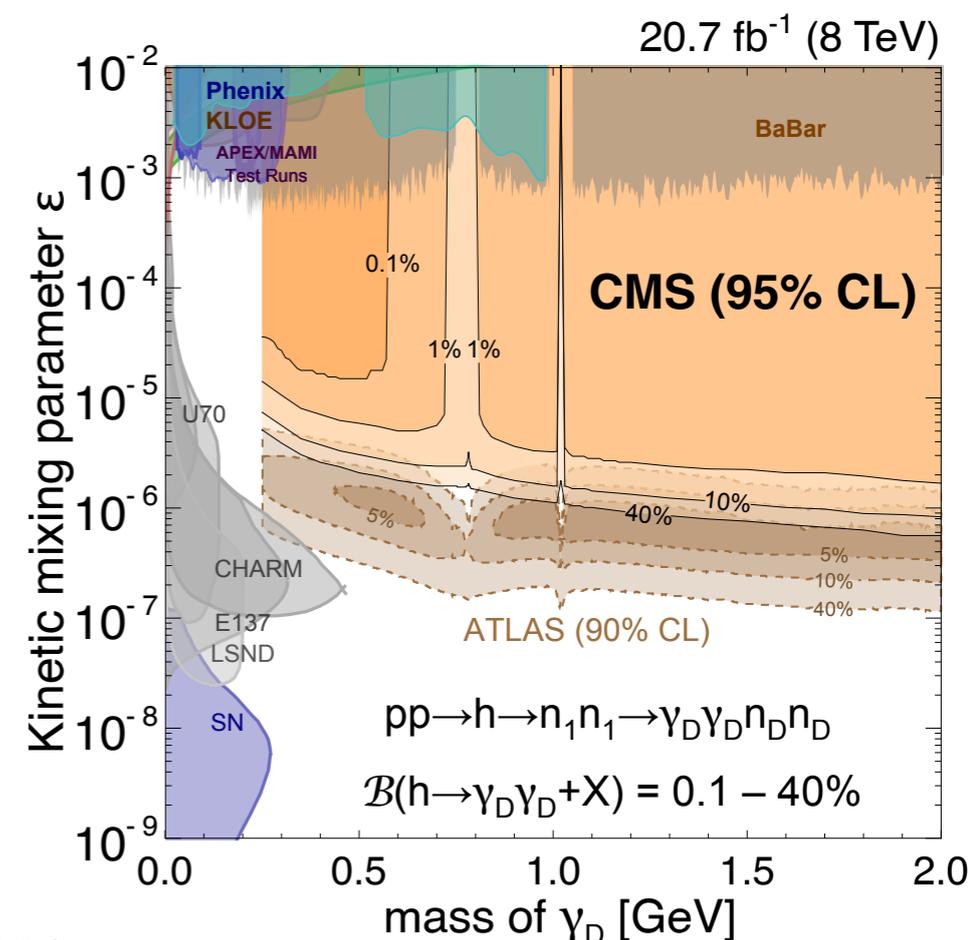


❖ 95% CL limit on H boson production $\sigma \cdot B.R.$

→ The limit set in the $[m(\gamma_D), \epsilon]$ plane.

→ Implies model dependence when comparing to low energy results

→ Nice complementarity with ATLAS analysis searching for decays far from the interaction point

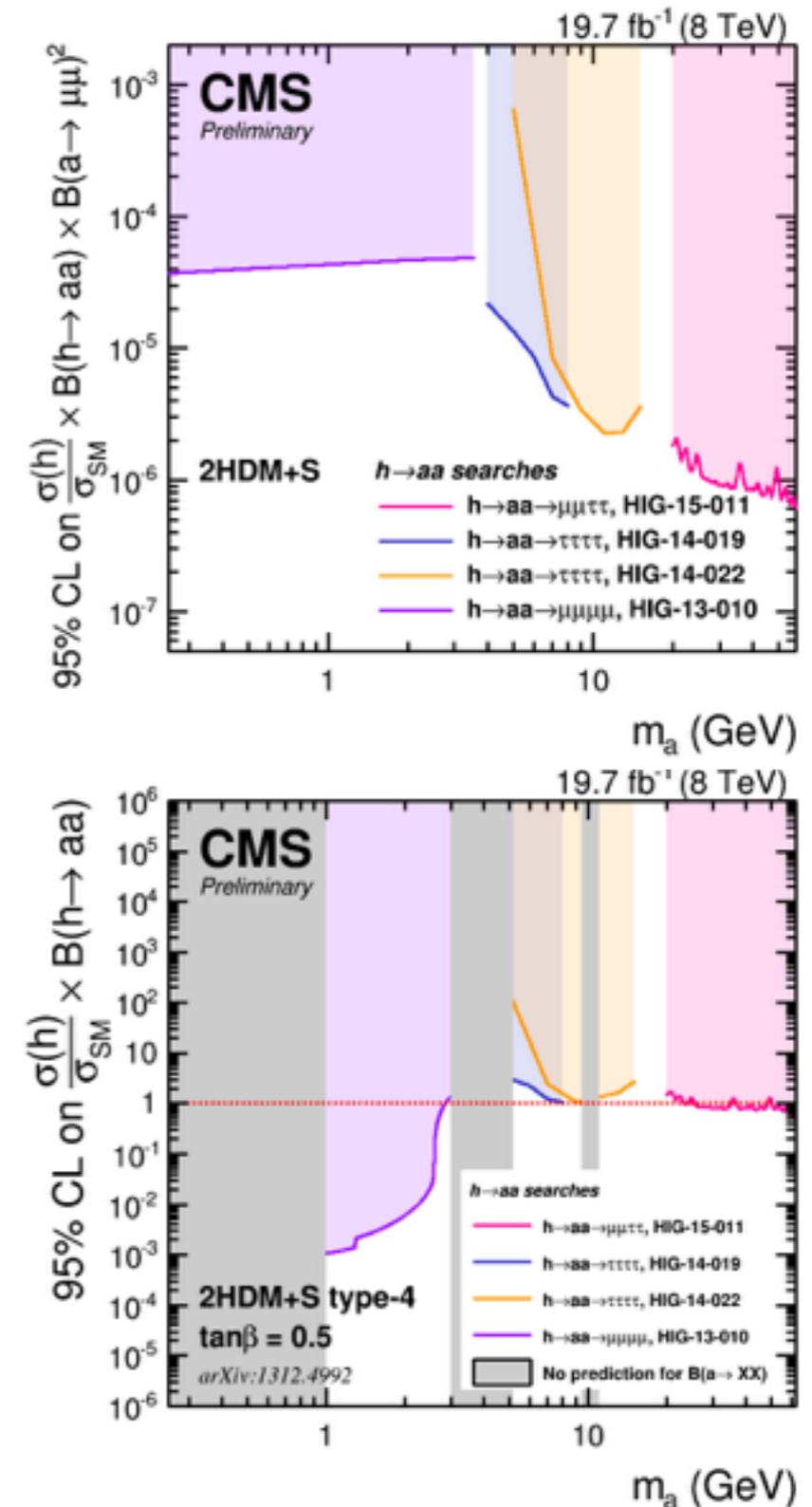


- ❖ Studies on the Higgs sector are moving towards the era of precision measurements:
 - Kinematic
 - Properties
 - Production cross-sections

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

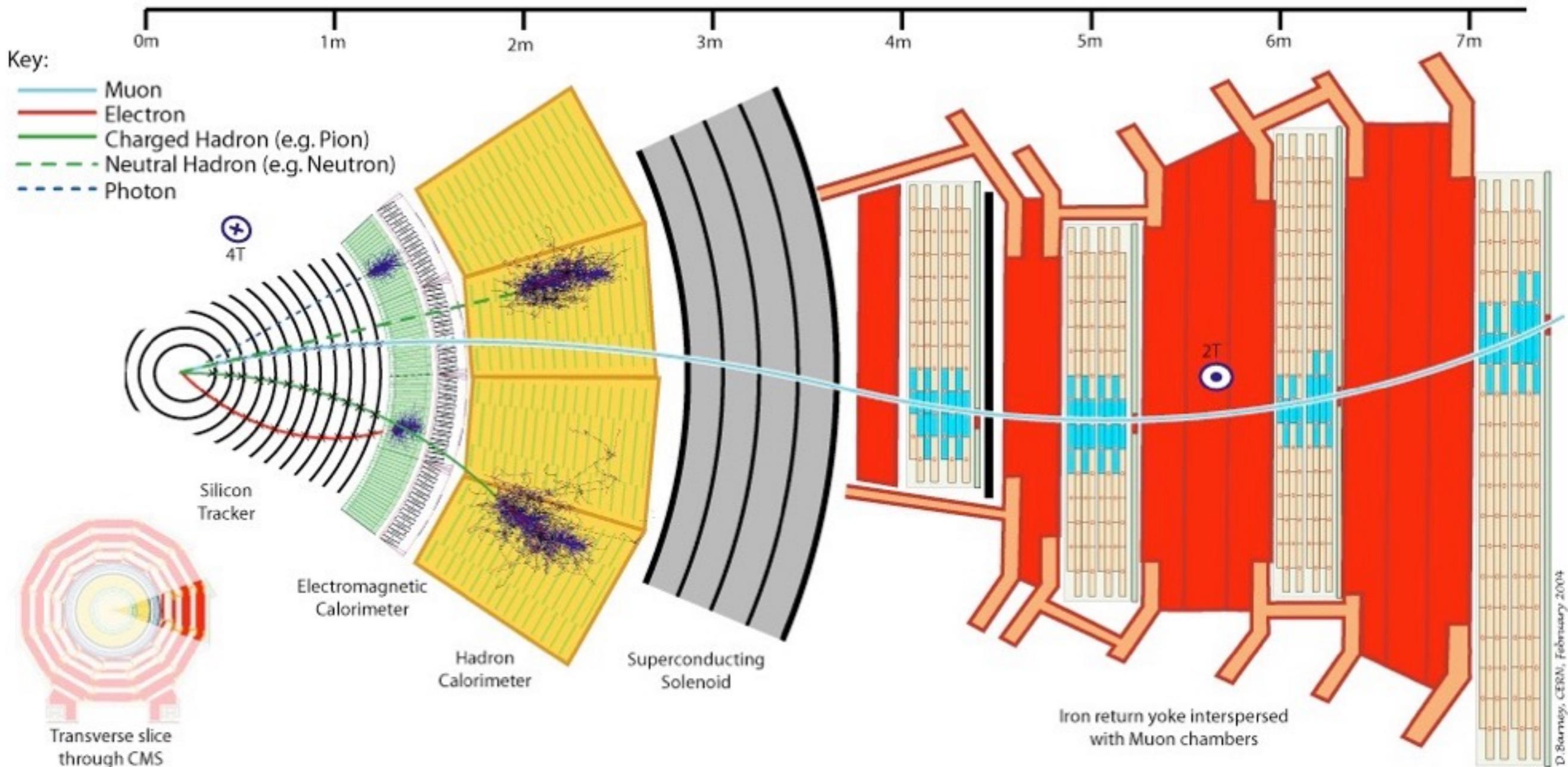
- ❖ Just few examples of searches for extended Higgs sector have been presented:
 - Combination is in progress

- ❖ Exciting news foreseen during this year:
 - Expected 30 fb⁻¹ by the end of the 2016



Backup

The Compact Muon Solenoid



Heavy Higgs searches in Run 1

