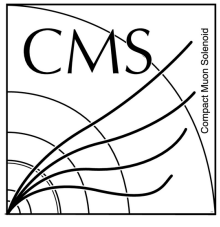
FCPPL18, 22th May, 2018

# Search for low mass Higgs-boson like resonances with $m_h < 125$ GeV in the diphoton final state with the CMS experiment

S. Zhang

On behalf of CMS collaboration

May 22, 2018



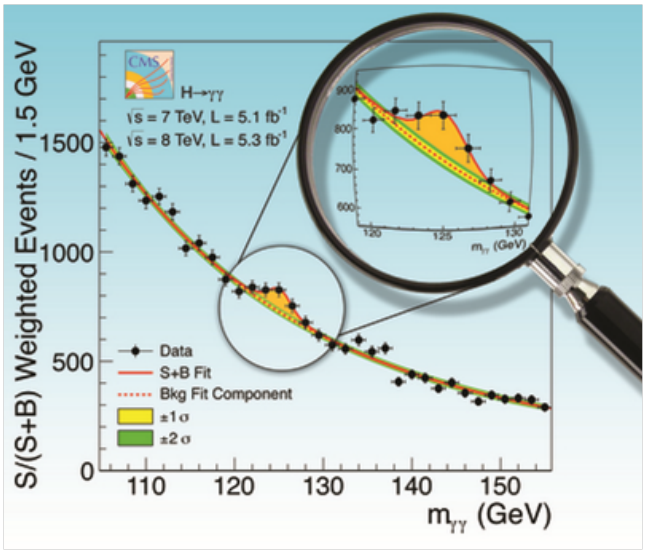


# Outline

- Motivation:
  - ⋆ BSM models including NMSSM (Lightest scalar h1$\rightarrow \gamma\gamma$)
  - ⋆ BSM models including 2HDM (Lightest scalar h(a)$\rightarrow \gamma\gamma$)
- Search results with the CMS experiment:
  - ⋆ Result of 13 TeV data
  - ⋆ Combined result(8 TeV and 13 TeV)
- Summary

# Motivation - introduction

• Is the observed 125 GeV scalar at the LHC really the SM Higgs boson?




→ Still room for BSM!

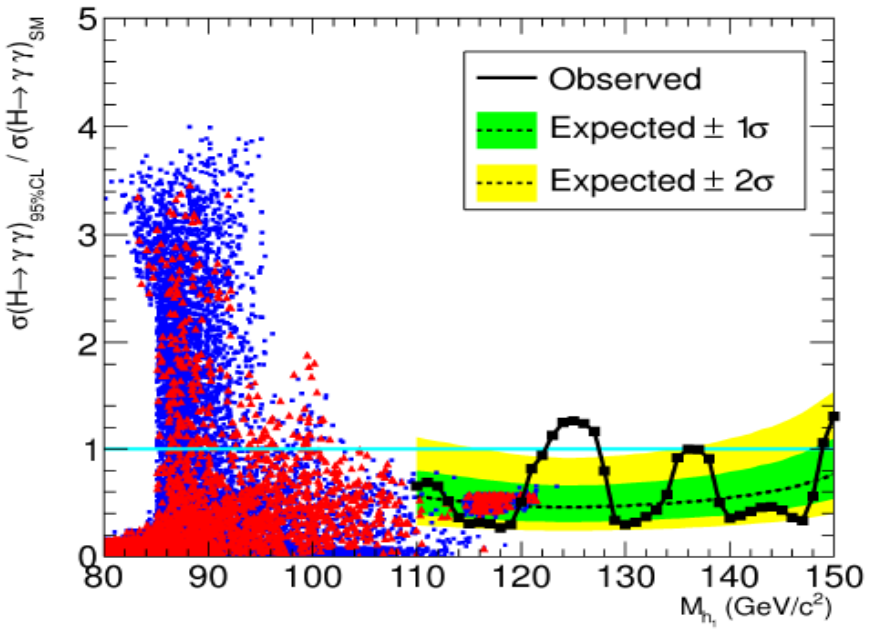
# Motivation - Beyond-Standard-Models

• Some BSM theories predict modified and extended Higgs sectors, possibly with additional low-mass($< 125$GeV) scalars/pseudoscalars.

→ General Two Higgs Doublet Model (2HDM):
- ⋆ 2 Higgs doublets(h, H, a, $H^{\pm}$)
- ⋆ 4 types of models($tan\beta$, $\alpha$)
- ⋆ compatible with a 125 GeV SM-like scalar (h or H) + a lighter Higgs Boson (a or h) in the "alignment limit".

→ Next-to-Minimal Supersymmetric Standard Model (NMSSM):
- ⋆ 2 Higgs doublets & 1 singlet superfields($h_1$, $h_2$, $h_3$, $a_1$, $a_2$, $H^{\pm}$)
- ⋆ solves the known "$\mu$-problem" of MSSM;
- ⋆ compatible with a 125 GeV SM-like scalar ($h_1$ or $h_2$) & a mostly "singlet-like" lighter Higgs Boson ($a_1$ or $h_1$).

# Example of Motivation: Lightest scalar $h_1$ in NMSSM




*J. Fan, J. Tao, Y. Shen, G. Chen, H. Chen, S. Gascon, M. Lethuillier Chin. Phys. C 38 (2014): 073101*

Relic density("WMAP" window):

- $\star \Omega_{h2} < 0.1102$
- $\star 0.1102 < \Omega_{h2} < 0.1272$

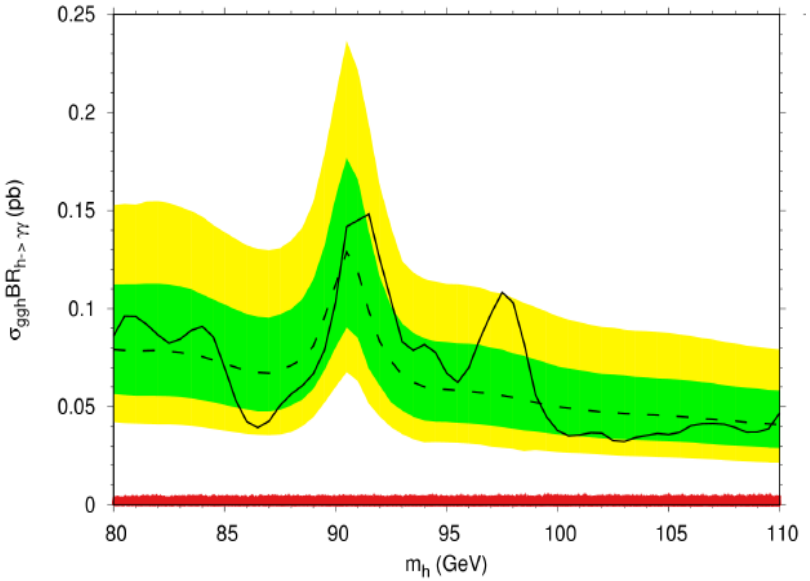
• Assume the next-to-lightest scalar $h_2$ corresponds to the observed 125 GeV Higgs in LHC, then focus on the lightest Higgs boson h1;

• Scans with NMSSMTools(U. Ellwanger, C. Hugonie) and the constraints from HiggsBounds and HiggsSignal(P. Bechtle et al.) on $h_2$, and other constraints;

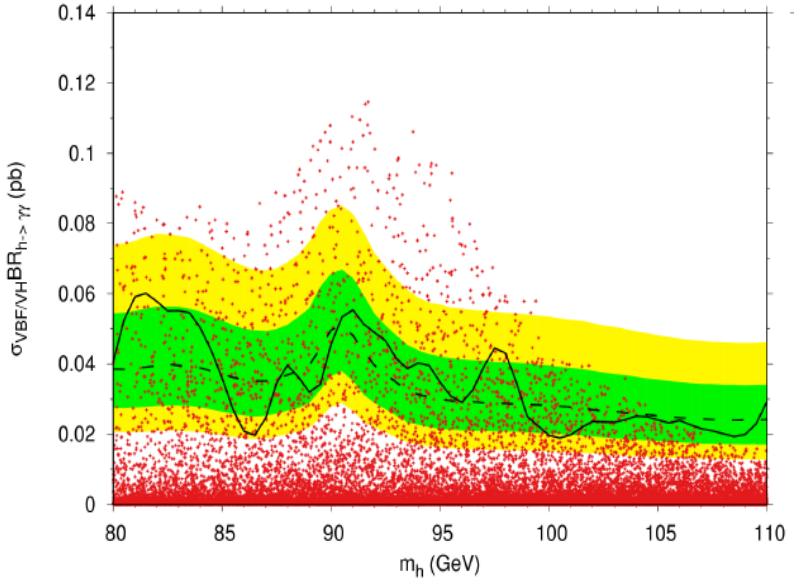
• The lightest Higgs $h_1$ signal strength could be enhanced by a factor up to $\sim$3.5 compared to the SM predictions in the mass range of [85,95] GeV.

# Example of Motivation: Lightest scalar in 2HDM

$\sigma_{gg\to h}$ x $BR_{h\to\gamma\gamma}$




$\sigma_{VBF/VH\to h}$ x $BR_{h\to\gamma\gamma}$




*G. Cacciapagliaa, A. Deandrea, S. Gascon, S. Le Corre, M. Lethuillier and J. Tao JHEP12(2016)068*

- Interpretation of CMS Run1 low-mass H $\to \gamma\gamma$ results (from HIG-14-037);
- Work done jointly with IPN Lyon theory group;
- No sensitivity in the gluon fusion production channel;
- Red points passing the indirect, LEP and LHC Run1 constraints;
- Many points are above the CMS observed limit in the VBF/VH production mode for $m_h$ <105 GeV.
- The region of parameter space probed:

| $m_h$(GeV) | $m_H$(GeV) | $m_A$(GeV) | $m_{H^\pm}$(GeV) | $sin(\beta-\alpha)$ | $tan\beta$ | $m_{12}^2$ |
|---|---|---|---|---|---|---|
| [80,110] | 125 | [60,650] | [60,630] | [-0.3,-0.05] | [2,12] | $[-(100)^2,+(100)^2]$ |

# CMS Experimental Search: With 2016 13TeV data

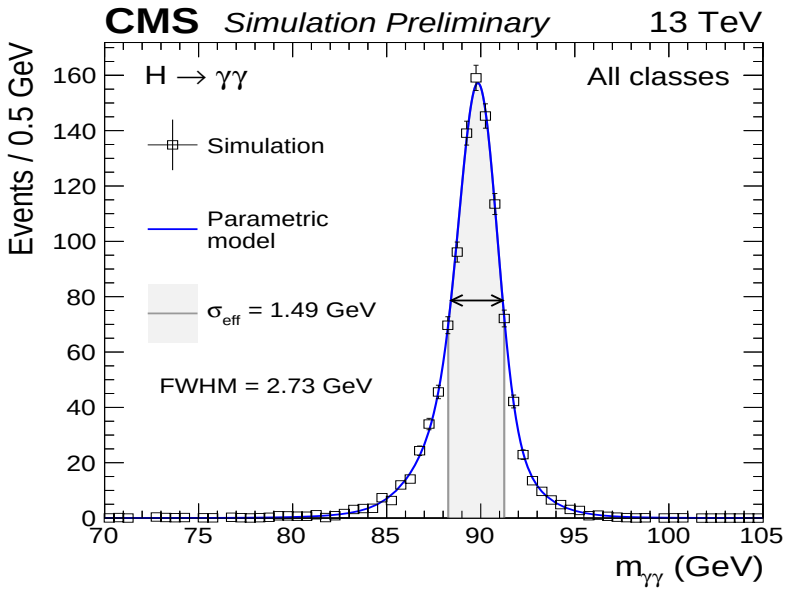
*CMS-HIG-17-013*

• Dedicated Run2 "low-mass" diphoton triggers: Cope with increased rate with stricter isolation/shower shape requirements + reject endcap photons compatible with conversions;

• Enables extension of lower limit of search zone : [80, 110] GeV $\rightarrow$ [70, 110] GeV;

• As in Run 1, inherit photon and event reconstruction/selection techniques from standard H$\rightarrow \gamma\gamma$ analysis (photon ID and kinematic event selection BDTs. . .);

• 3 inclusive event classes based on DiPhoton BDT scores.




⋆ Entire 2016 dataset (35.9 $fb^{-1}$) analyzed

⋆ Signal modelling: Sums of Gaussian functions (same as Run1)

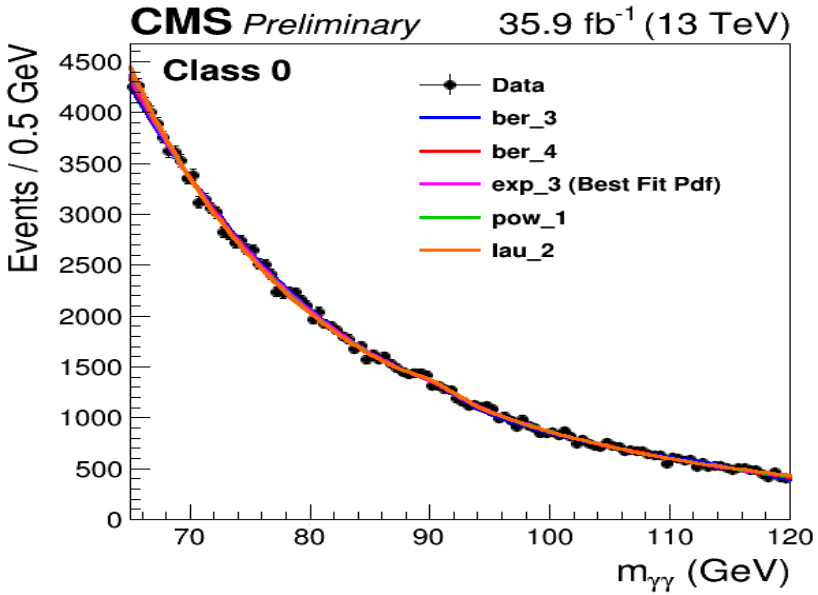
# Background modelling

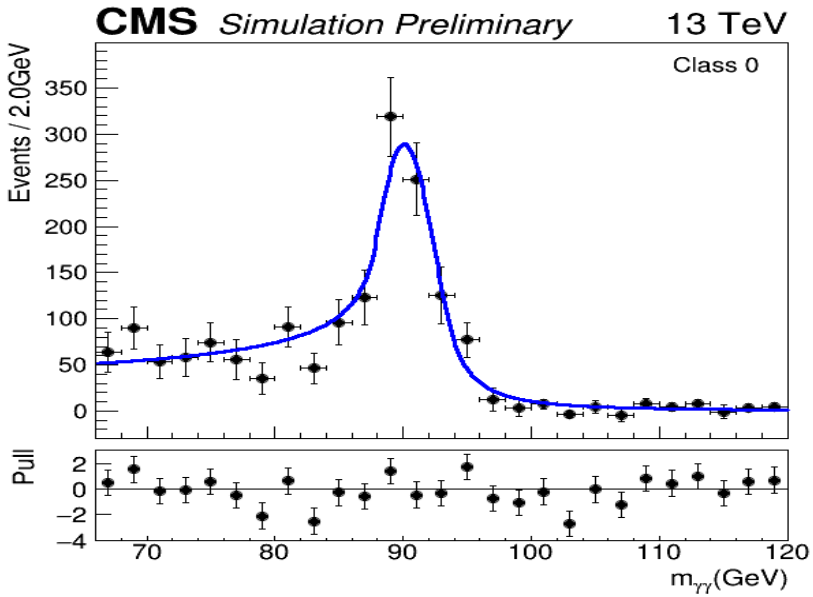
*CMS-HIG-17-013*

• Background Model(data driven): Sum of polynomial(chosen from 4 families) + Double-sided Crystal Ball (DCB) functions for relic Z→ee component;

• Chosen polynomials: 3d-order sum of exponentials (classes 0,2), 1st-order power law (class1);

• DCB: shape parameters from MC "double-fake" events, syst. uncertainty from "single-fake" events, normalization floating;



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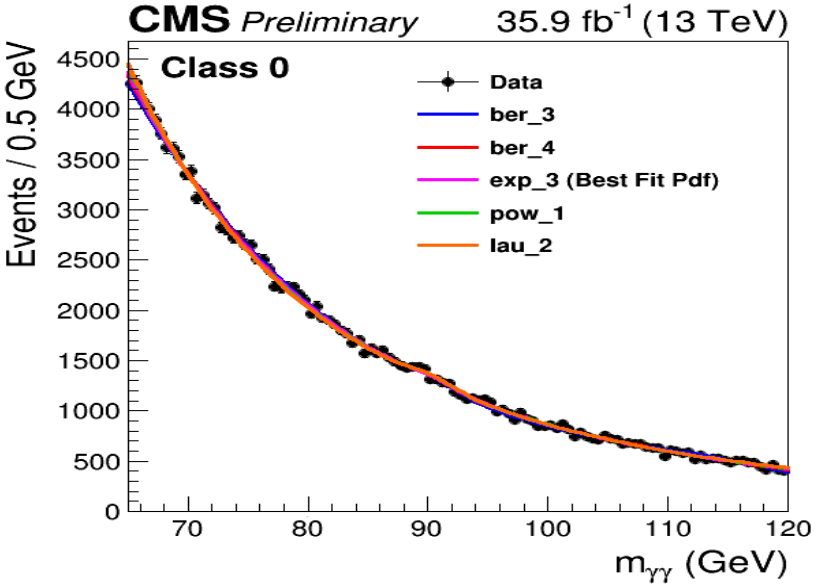
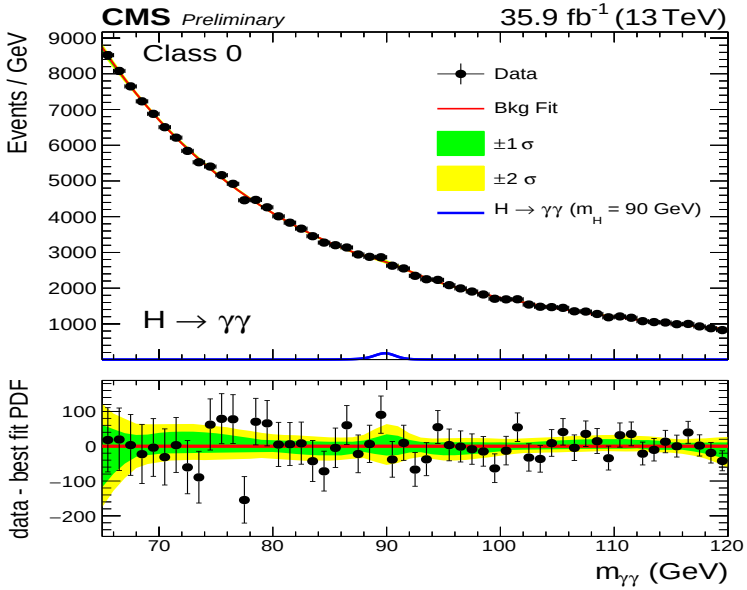
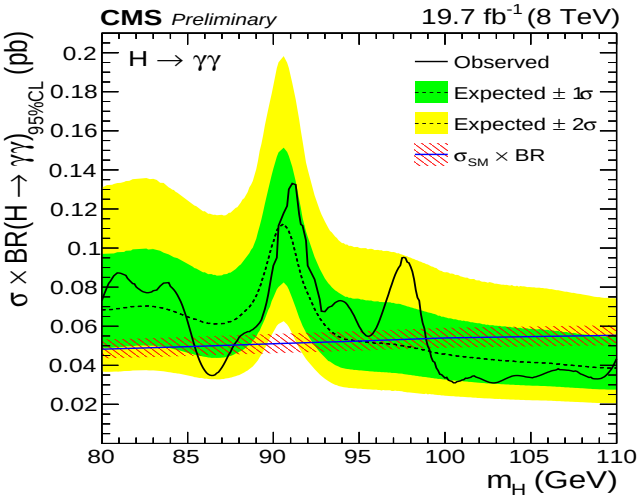


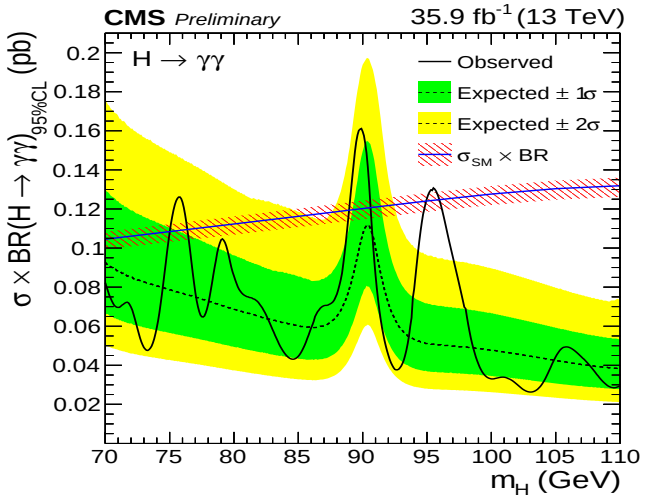




• Choice of background function discrete parameter in lh fit to data, systematic error associated with each possible choice (discrete profiling or "envelope" method).

# CMS Experimental Search: Upper limits on $\sigma$ x Br

*CMS-HIG-17-013*



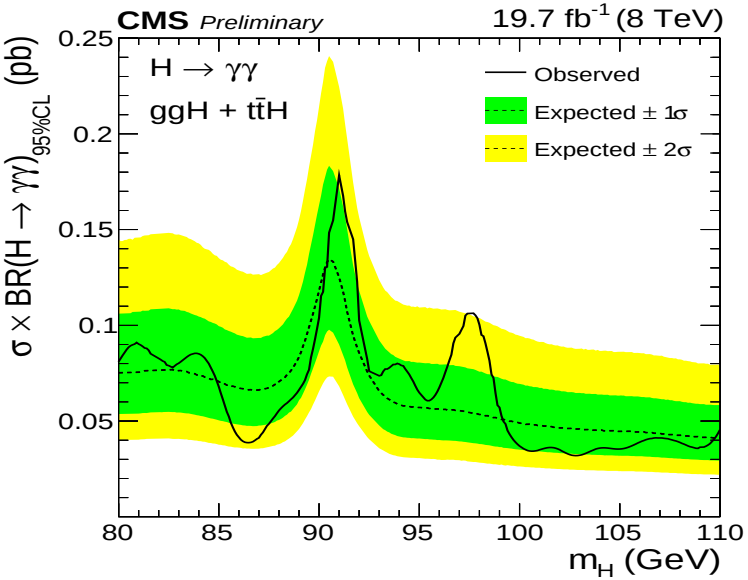



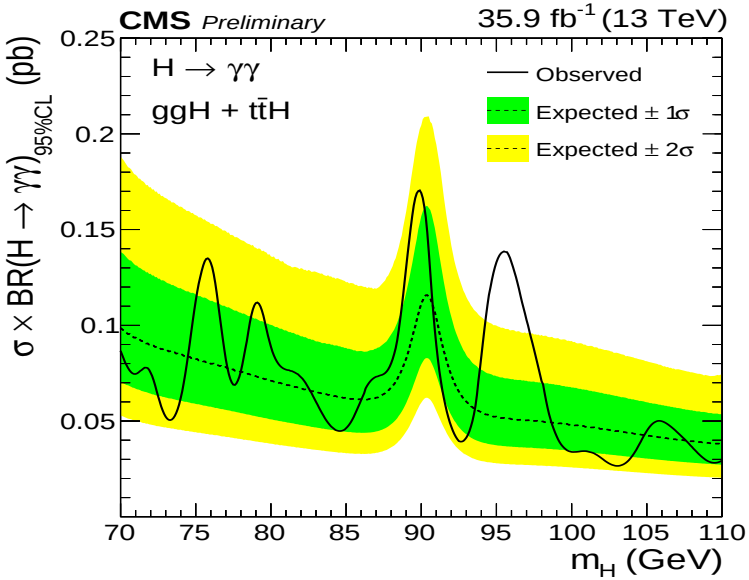

→ 8 TeV: minimum(maximum) limit on $\sigma$ x Br : 31(133) fb at m=102.8(91.1)GeV
→ 13 TeV: minimum(maximum) limit on $\sigma$ x Br : 26(161) fb at m=103.0(89.9)GeV

- Production processes assumed in SM proportions.

# CMS Experimental Search: Upper limits on $\sigma$ x Br(ggH+ttH)

*CMS-HIG-17-013*

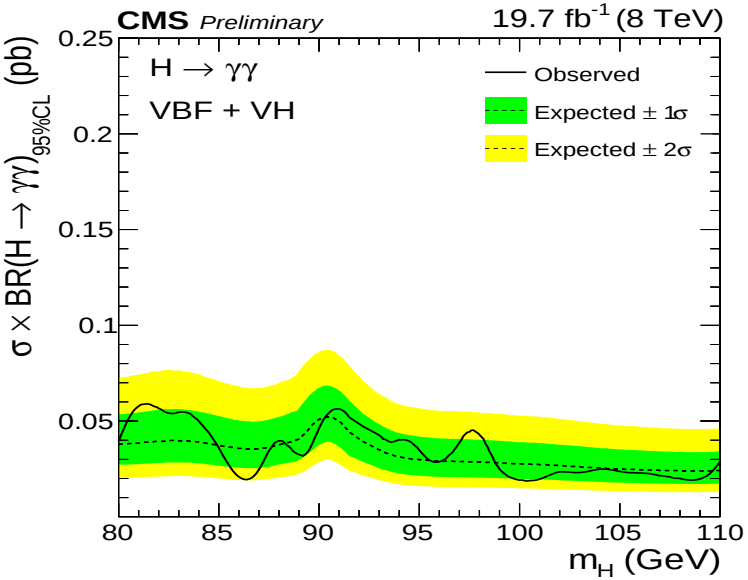


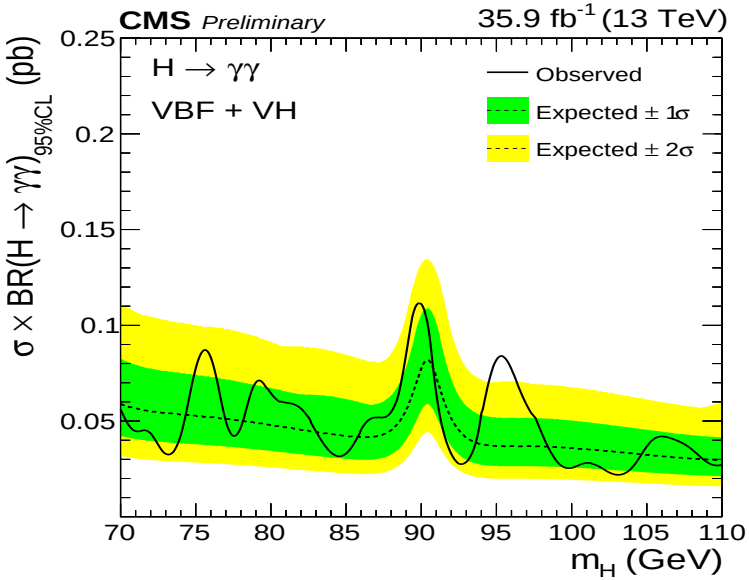




• Per-process limits on $\sigma$ x Br assuming 100% gluon-induced processes (ggH, ttbarH in SM proportions)

# CMS Experimental Search: Upper limits on $\sigma$ x Br(VBF+VH)

*CMS-HIG-17-013*



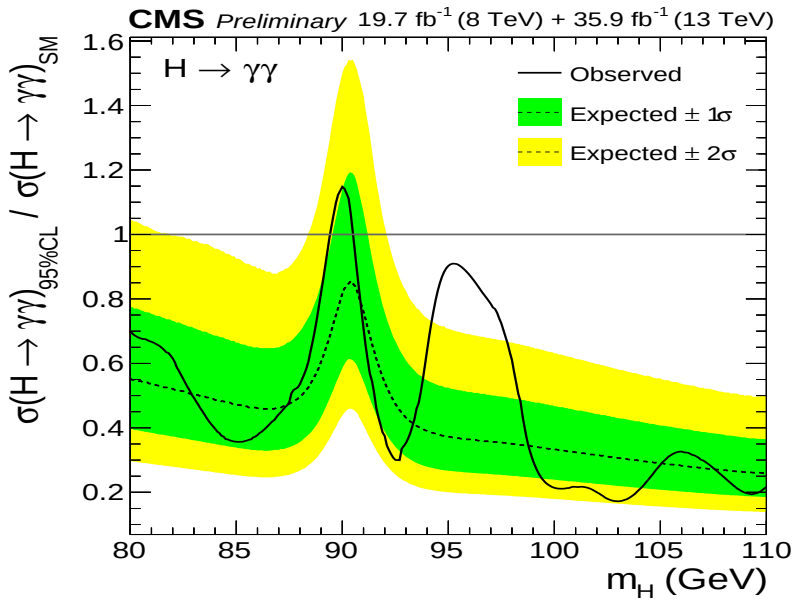




• Per-process limits on $\sigma$ x Br assuming 100% fermion-induced processes (VBF, VH in SM proportions)

# CMS Experimental Search: Upper limits on $\sigma$ x Br

*CMS-HIG-17-013*

- Combined results from 2012 (8 TeV) and 2016 (13 TeV) data

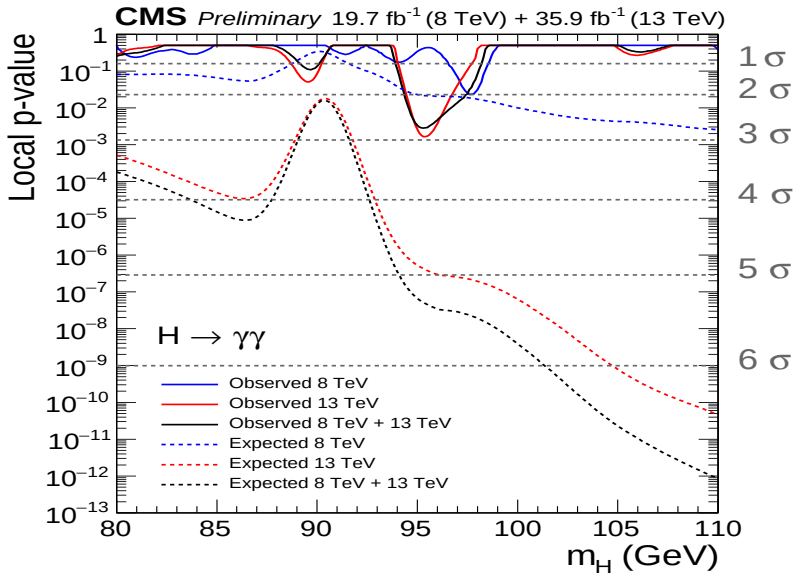



$\rightarrow$ minimum(maximum) limit on ($\sigma$ x Br)/($\sigma$ x Br)$_{SM}$ : 0.17(1.15) at m = 103.0(90.0)GeV

- $\sigma$ x Br limit normalized to SM expectation (production processes assumed in SM proportions).

# CMS Experimental Search: Local p-value

→ Run1(2012), Run2(2016) and their Combination




• Expected and observed local p-values for 8 TeV, 13 TeV and their combination

*CMS-HIG-17-013*

→ 8 TeV: Excess with 2.0$\sigma$ local significance at m=97.6 GeV

→ 13 TeV: Excess with 2.9$\sigma$ local (1.47$\sigma$ global) significance at m=95.3 GeV

→ 8TeV+13 TeV: Excess with 2.8$\sigma$ local (1.3$\sigma$ global) significance at m=95.3 GeV

→ More data are required to ascertain the origin of this excess.

# Summary

• From NMSSM, signal strength of the lightest scalar $h_1$ over that of SM goes up to 3.5 within the mass range of [85, 95]GeV;

• CMS run1(8 TeV): Modest excess with maximum local significance $2.0\sigma$ at $m_H$=97.6GeV;

• CMS run2(13 TeV 2016 data): Modest excess with maximum local significance $2.9\sigma$ at $m_H$=95.3GeV;

• Combination results(run1 and run2): Modest excess with maximum local significance $2.8\sigma$ at $m_H$=95.3GeV;

$\star\star$ Looking forward to the results of *13TeV 2017 data !*

# BackUp

# $\mu$ problem

- MSSM:
  $\rightarrow$ 2 Higgs doublets(2 CP-even, 1 CP-odd and 2 charged Higgs bosons)
  $\rightarrow$ $\mu$ problem: There's a mass term $\mu$ in the low energy Higgs which seems unrelated to the electroweak scale;

- Solution of $\mu$ problem in NMSSM:
  $\rightarrow$ NMSSM introduces a new gauge singlet superfield which only couples to the Higgs sector in a similar way as the Yukawa coupling and give rise to a effective $\mu$-term to solve the "$\mu$ problem";
  $\rightarrow$ The nwe siglet adds additional degrees of freedom to the NMSSM particle spectrum.
  $\rightarrow$ 2 Higgs doublets(3 CP-even, 2 CP-odd and 2 charged Higgs bosons)

# NMSSM scans

- Assume the next-to-lightest scalar Higgs boson h2 corresponds to the observed 125 GeV Higgs in LHC, then focus on the lightest Higgs boson h1

- Scans with NMSSMTools and the constraints from HiggsBounds and HiggsSignal on h2, and other constraints

- Parameter ranges by theoretical and experimental considerations

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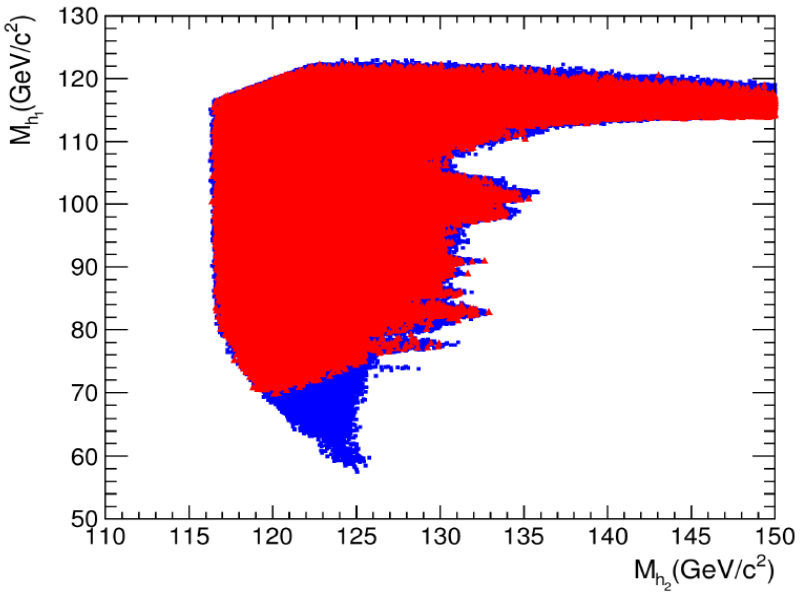


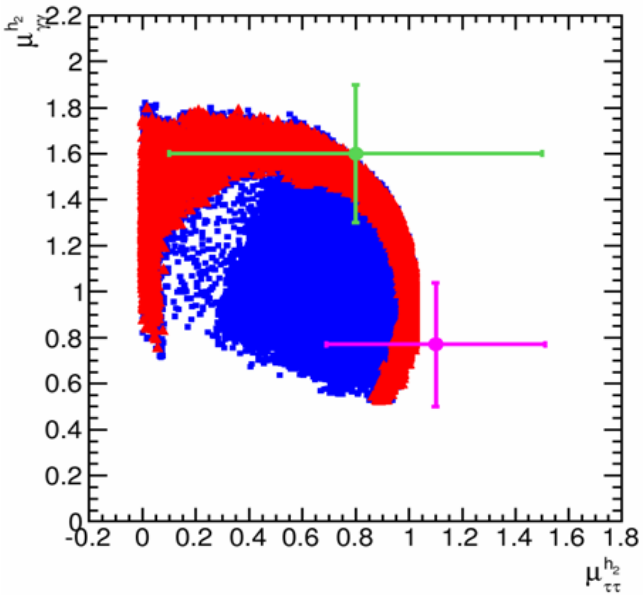

$0.1102 < \Omega h^2 < 0.1272$("WMAP" window)

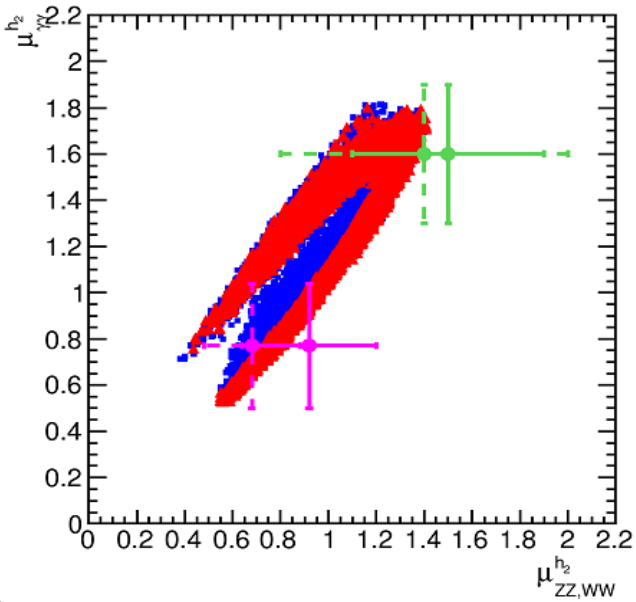
**Before constraint on h2** from Higgs Bounds and Higgs Signal

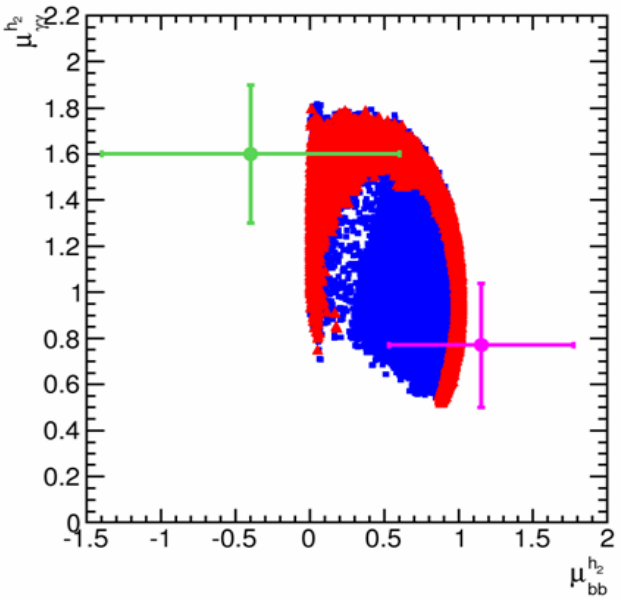
# h2 compared with LHC experiments

• Compare the h2 signal strength in $\gamma\gamma$, ZZ, WW, $\tau\tau$ and bb decay modes with the ATLAS and CMS results: magenta cross for CMS and green for ATLAS in 2013.

NMSSM h2 is compatible with the LHC-discovered Higgs boson




J. Fan, JT, G. Chen et al. Chin. Phys. C 38 (2014): 073101

# Interpretation with 2HDM

Is CMS 8 TeV h $\rightarrow \gamma\gamma$ result sensitive to a lighter Higgs in 2HDM?

- Reminder: Two doublets($\Phi_1$ and $\Phi_2$), 5 Higgses(h, H, A, $H^{\pm}$)
- Parameters in the physical basis($m_H$=125 GeV in our case):

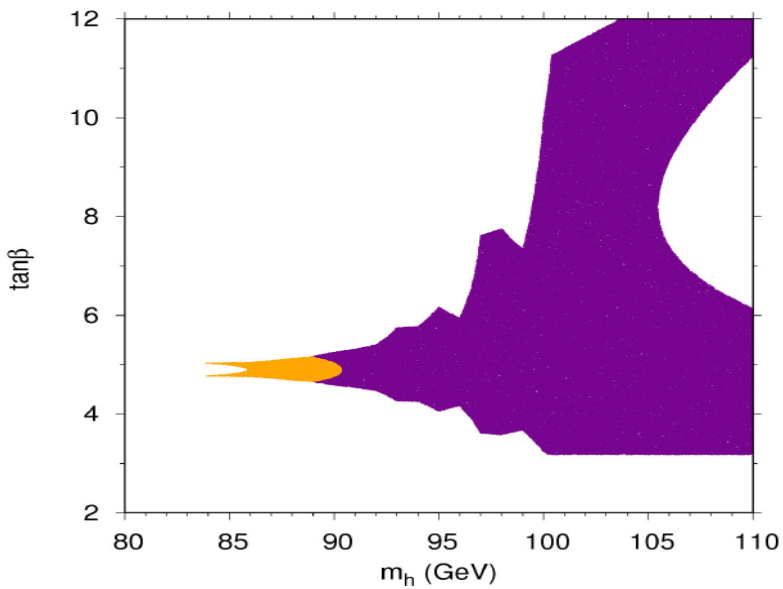
$$m_h,\ m_H,\ m_A,\ m_{H^{\pm}},\ sin(\beta-\alpha),\ \nu,\ m_{12}^2$$

- 4 types of 2HDM: different ways to couple $\Phi_1$ and $\Phi_2$ to fermions : focus on Type I
- Extension of 2HDM predictions from gluon fusion and bb production modes in SusHi+2HDMC : VBF/VH production;
- First comparison of 2HDM with the LHC (CMS) low mass diphoton analysis at 8 TeV.

| | Type I | Type II | Flipped(Type Y) | Lepton Specific(Type X) |
|---|---|---|---|---|
| Up-type quark | $\Phi_2$ | $\Phi_2$ | $\Phi_2$ | $\Phi_2$ |
| Down-type quark | $\Phi_2$ | $\Phi_1$ | $\Phi_1$ | $\Phi_2$ |
| Leptons | $\Phi_2$ | $\Phi_1$ | $\Phi_2$ | $\Phi_1$ |

# A lighter scalar Higgs : Constraints

- An exclusion zone in the plane $tan\beta$ vs $m_h$ in the particular case
- Violet points passing the indirect, LEP and LHC Run1 constraints
- Orange points are excluded by the CMS low mass di-photon analysis at 95% C.L..
- But the exclusion zone depends on the value of the different free parameters.




$m_H$ = 125 GeV, $m_A = m_{H_\pm}$ = 80 GeV

$sin(\beta - \alpha)$ =-0.2 and $m_{12}$ = 30 GeV

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# A lighter pseudo-scalar Higgs

- Similar kinematic behavior of the two photons coming from a pseudo-scalar particle and a scalar particle
- So can directly apply the CMS study as for the scalar case to constrain a possible light pseudo-scalar
- Restrict ourselves to Type I only in the gluon fusion production channel
- No sensitivity to a light pseudo-scalar at the LHC Run 1 in the di-photon final state

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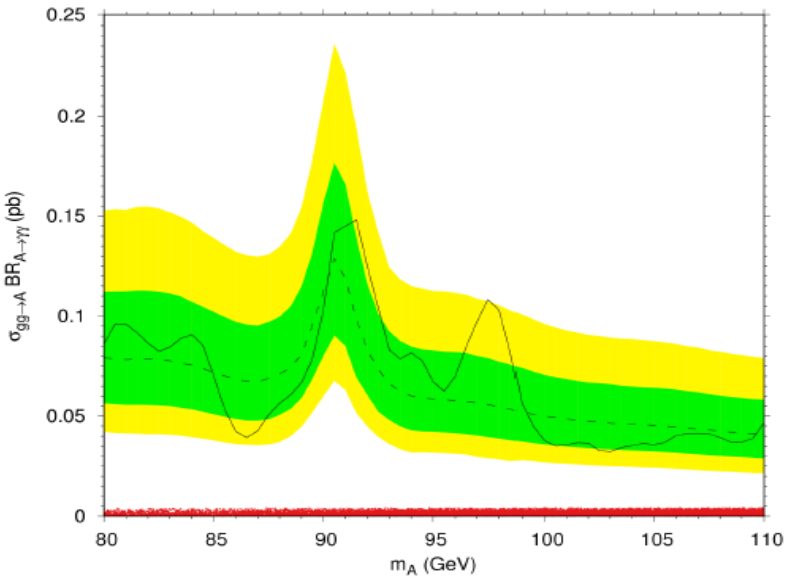
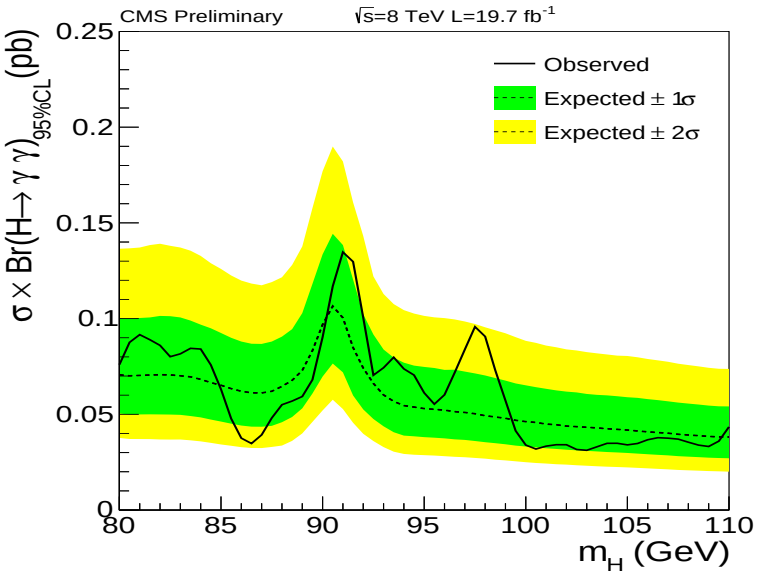



Red points passing the indirect, LEP and LHC Run1 constraints

# 8TeV results: Upper limits on $\sigma$ x BR



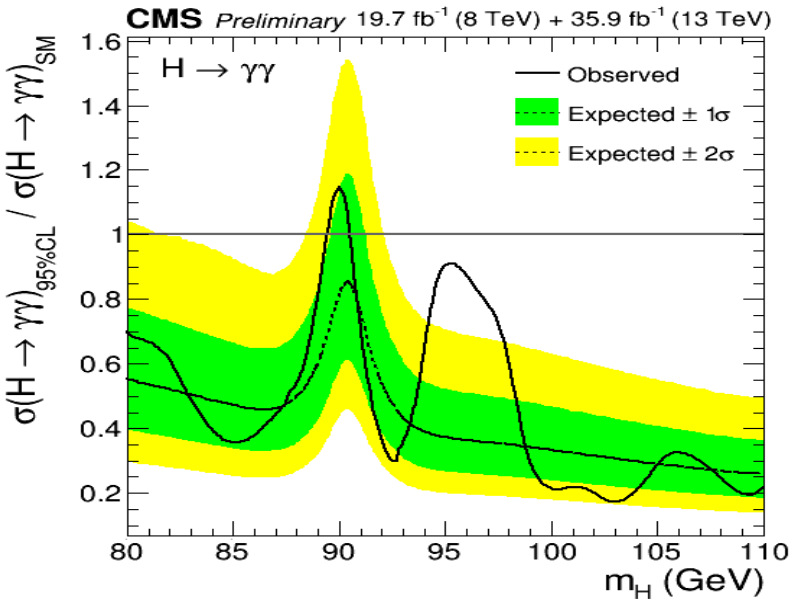

*CMS-HIG-14-037*

- Observed limit range of [40,75] fb.
- Statistical treatment for extraction of limits and p-values is the same as that used by all CMS Higgs boson search channels as well as for the combination of channels.

# Run1+Run2: Combined results

CMS-HIG-17-013

All experimental + theoretical systematic uncertainties assumed uncorrelated except for those on signal acceptance due to scale variations + those on production cross sections (assumed 100% correlated).

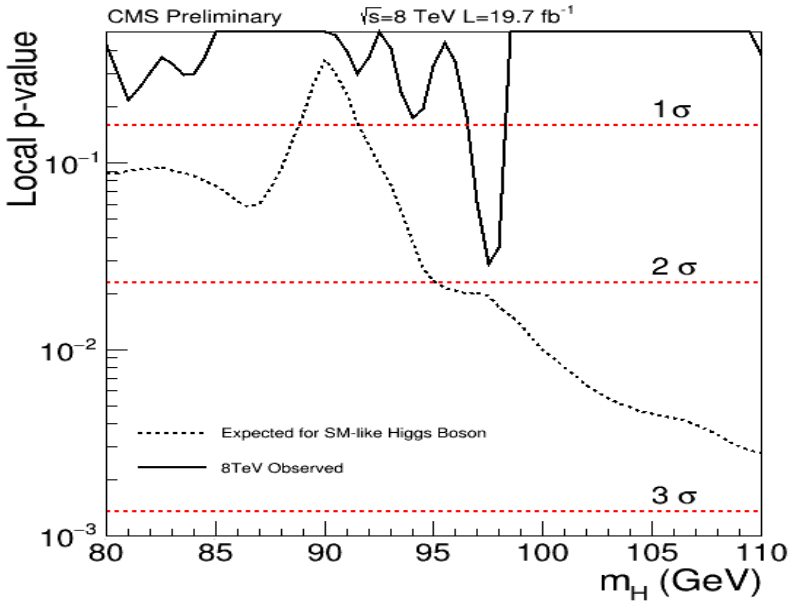



→ 8 TeV+13TeV: minimum(maximum) limit on ($\sigma$ X Br)/ ($\sigma$ X Br)$_{SM}$ : 0.17(1.15) at m=103.0(90.0)GeV

• Combined 8 TeV+13 TeV s X BR limit normalized to SM expectation (production processes assumed in SM proportions ). No significant excess with respect to

# The result with 8TeV data: Local p-value

CMS PAS HIG-14-037




- Maximum significance: $\sim 1.9\sigma$ at $m_H = 97.5$ GeV