# BSM resonance search in $H \rightarrow SS/Sh$ at the LHC

Yaquan Fang (IHEP)
in Collaboration with Bruce Mellado (WIS/ICPP, South Africa) et al.

北京大学高能物理中心

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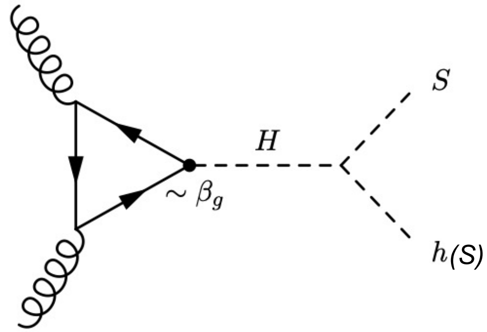
# Outline

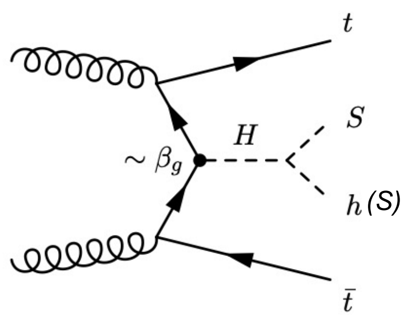
- The 2HDM+S model
- H→Sh searches done so far
  - H→SS → WW*WW*→2l,3l,4l（ATLAS）
  - H→ Sh → $\tau\tau$bb（CMS）
- Excesses on di-photon, Z-$\gamma$ final states in association with leptons, b-jets, etc.
- The "multi-lepton anomalies”
- Proposal for further searches
- Impact on the search in future e+e- colliders
- Outlook and Conclusions

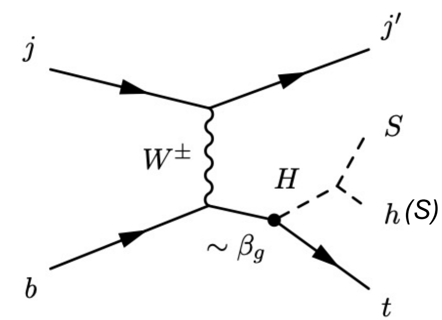
# The simplified Model (from Run I)

1. The hypothesis is the existence of a boson, H, that contains Higgs-like interactions, with a mass in the range 240-280 GeV
2. In order to avoid large quartic couplings, incorporate a mediator scalar, S, that interacts with the SM and Dark Matter.
3. Dominance of H→Sh,SS decay over other decays




(a) Gluon fusion ($ggF$).




$$\mathcal{L}_{\rm int} \supset -\beta_g \frac{m_t}{v} t\bar{t}H + \beta_V \frac{m_V^2}{v} g_{\mu\nu}\, V^\mu V^\nu H$$

$$\mathcal{L}_{HhS} = -\frac{1}{2}\, v\Big[\lambda_{hhS}hhS + \lambda_{hSS}hSS + \lambda_{HHS}HHS + \lambda_{HSS}HSS + \lambda_{HhS}HhS\Big],$$

*Eur. Phys. J. C (2016) 76:580*

# The 2HDM+S

**Introduce singlet real scalar, S.**

**2HDM potential,** $\mathscr{V}(\Phi_1, \Phi_2)$

$$
\begin{aligned}
&= m_1^2 \Phi_1^\dagger \Phi_1 + m_2^2 \Phi_2^\dagger \Phi_2 - m_{12}^2 \left( \Phi_1^\dagger \Phi_2 + \text{h.c.} \right) \\
&+ \frac{1}{2}\lambda_1 \left( \Phi_1^\dagger \Phi_1 \right)^2 + \frac{1}{2}\lambda_2 \left( \Phi_2^\dagger \Phi_2 \right)^2 \\
&+ \lambda_3 \left( \Phi_1^\dagger \Phi_1 \right) \left( \Phi_2^\dagger \Phi_2 \right) + \lambda_4 \left| \Phi_1^\dagger \Phi_2 \right|^2 \\
&+ \frac{1}{2}\lambda_5 \left[ \left( \Phi_1^\dagger \Phi_2 \right)^2 + \text{h.c.} \right] \\
&+ \left\{ \left[ \lambda_6 \left( \Phi_1^\dagger \Phi_1 \right) + \lambda_7 \left( \Phi_2^\dagger \Phi_2 \right) \right] \Phi_1^\dagger \Phi_2 + \text{h.c.} \right\}
\end{aligned}
$$

**2HDM+S potential**

$$
\begin{aligned}
&\mathscr{V}(\Phi_1, \Phi_2) + \frac{1}{2} m_{S_0}^2 S^2 + \frac{\lambda_{S_1}}{2} \Phi_1^\dagger \Phi_1 S^2 \\
&+ \frac{\lambda_{S_2}}{2} \Phi_2^\dagger \Phi_2 S^2 + \frac{\lambda_{S_3}}{4} (\Phi_1^\dagger \Phi_2 + \text{h.c}) S^2 \\
&+ \frac{\lambda_{S_4}}{4!} S^4 + \mu_1 \Phi_1^\dagger \Phi_1 S + \mu_2 \Phi_2^\dagger \Phi_2 S \\
&+ \mu_3 \left[ \Phi_1^\dagger \Phi_2 + \text{h.c} \right] S + \mu_S S^3 .
\end{aligned}
$$

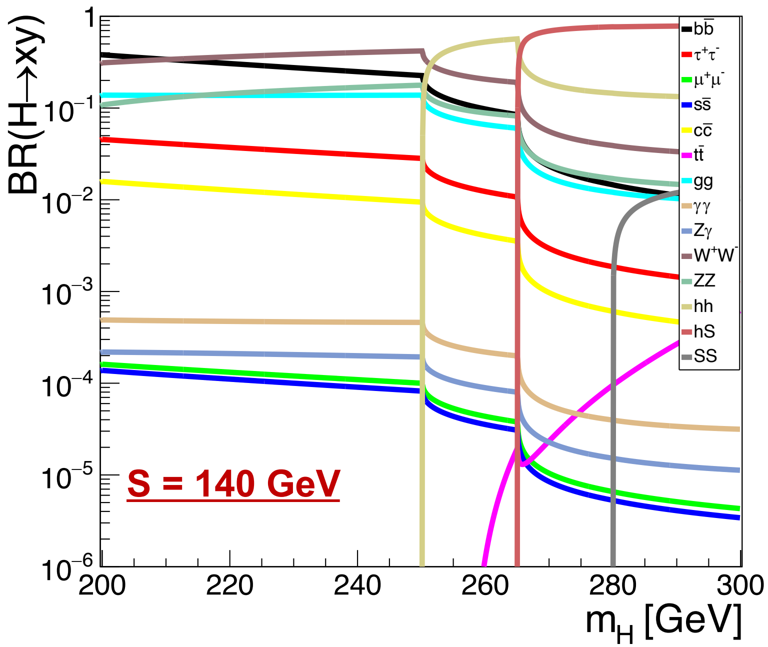
**Out of considerations of simplicity, assume S to be Higgs-like, which is not too far fetched.**

# The Decays of H and S

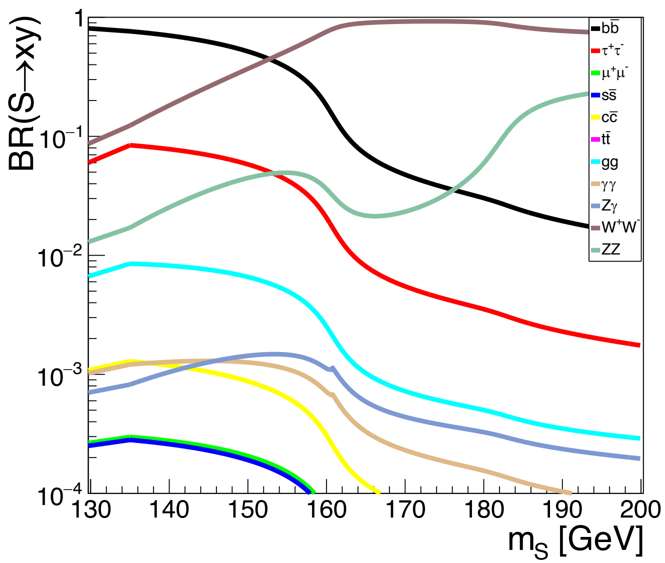
- **In the general case, H can have couplings as those displayed by a Higgs boson in addition to decays involving the intermediate scalar and Dark Matter**

$$H \to WW, ZZ, q\bar{q}, gg, Z\gamma, \gamma\gamma, \chi\chi$$

$$+ \quad H \to SS, Sh, hh$$




**For simplicity we will assume that S decays like the SM Higgs boson**



# Interesting final states : Multilepton, di-photon

| S. No. | Scalars | Decay modes |
|---|---|---|
| D.1 | $h$ | $b\bar{b}$, $\tau^+\tau^-$, $\mu^+\mu^-$, $s\bar{s}$, $c\bar{c}$, $gg$, $\gamma\gamma$, $Z\gamma$, $W^+W^-$, $ZZ$ |
| D.2 | $H$ | D.1, $hh$, $SS$, $Sh$ |
| D.3 | $A$ | D.1, $t\bar{t}$, $Zh$, $ZH$, $ZS$, $W^{\pm}H^{\mp}$ |
| D.4 | $H^{\pm}$ | $W^{\pm}h$, $W^{\pm}H$, $W^{\pm}S$ |
| D.5 | $S$ | D.1, $\chi\chi$ |

Eur. Phys. J. C (2016) 76:580

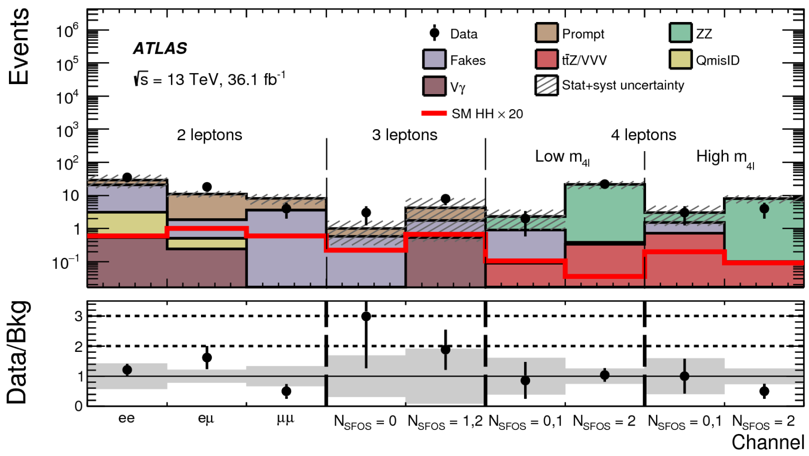
| Scalar | Production mode | Search channels |
|---|---|---|
| $H$ | $gg \to H, Hjj$ (ggF and VBF) | Direct SM decays as in Table 1<br>$\to SS/Sh \to 4W \to 4\ell + E_T^{miss}$<br>$\to hh \to \gamma\gamma b\bar{b}$, $b\bar{b}\tau\tau$, $4b$, $\gamma\gamma WW$ etc.<br>$\to Sh$ where $S \to \chi\chi \implies \gamma\gamma$, $b\bar{b}$, $4\ell + E_T^{miss}$ |
| | $pp \to Z(W^{\pm})H$ $(H \to SS/Sh)$ | $\to 6(5)l + E_T^{miss}$<br>$\to 4(3)l + 2j + E_T^{miss}$<br>$\to 2(1)l + 4j + E_T^{miss}$ |
| | $pp \to t\bar{t}H, (t+\bar{t})H$ $(H \to SS/Sh)$ | $\to 2W + 2Z + E_T^{miss}$ and $b$-jets<br>$\to 6W \to 3$ same sign leptons + jets and $E_T^{miss}$ |
| $H^{\pm}$ | $pp \to tH^{\pm}$ $(H^{\pm} \to W^{\pm}H)$ | $\to 6W \to 3$ same sign leptons + jets and $E_T^{miss}$ |
| | $pp \to tbH^{\pm}$ $(H^{\pm} \to W^{\pm}H)$ | Same as above with extra $b$-jet |
| | $pp \to H^{\pm}H^{\mp}$ $(H^{\pm} \to HW^{\pm})$ | $\to 6W \to 3$ same sign leptons + jets and $E_T^{miss}$ |
| | $pp \to H^{\pm}W^{\pm}$ $(H^{\pm} \to HW^{\pm})$ | $\to 6W \to 3$ same sign leptons + jets and $E_T^{miss}$ |
| $A$ | $gg \to A$ (ggF) | $\to t\bar{t}$<br>$\to \gamma\gamma$ |
| | $gg \to A \to ZH$ $(H \to SS/Sh)$ | Same as $pp \to ZH$ above, but with resonance structure over final state objects |
| | $gg \to A \to W^{\pm}H^{\mp}(H^{\mp} \to W^{\mp}H)$ | $6W$ signature with resonance structure over final state objects |

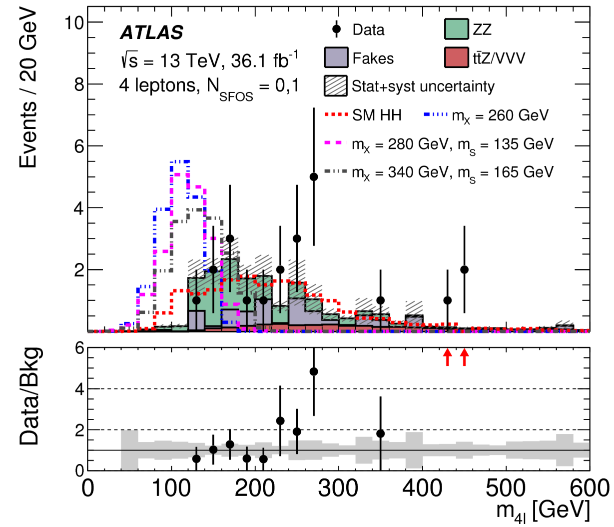
$S \to \gamma\gamma/VV$ $h \to bb/\gamma\gamma$ etc..

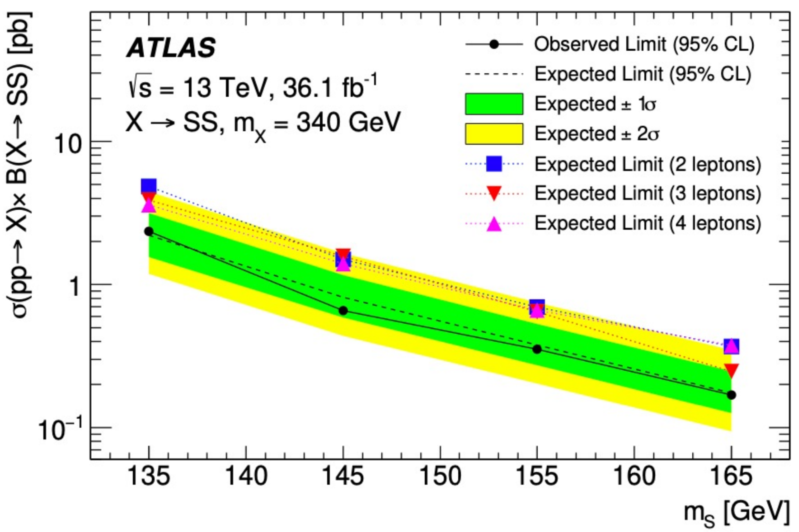
**ATLAS/CMS H→SS/Sh searches performed**

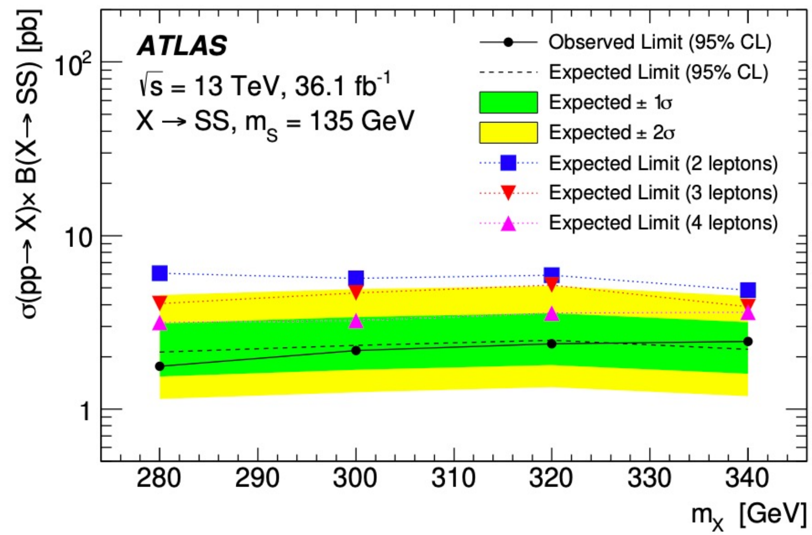
# Search for H→SS in ATLAS

*JHEP 05 (2019) 124*



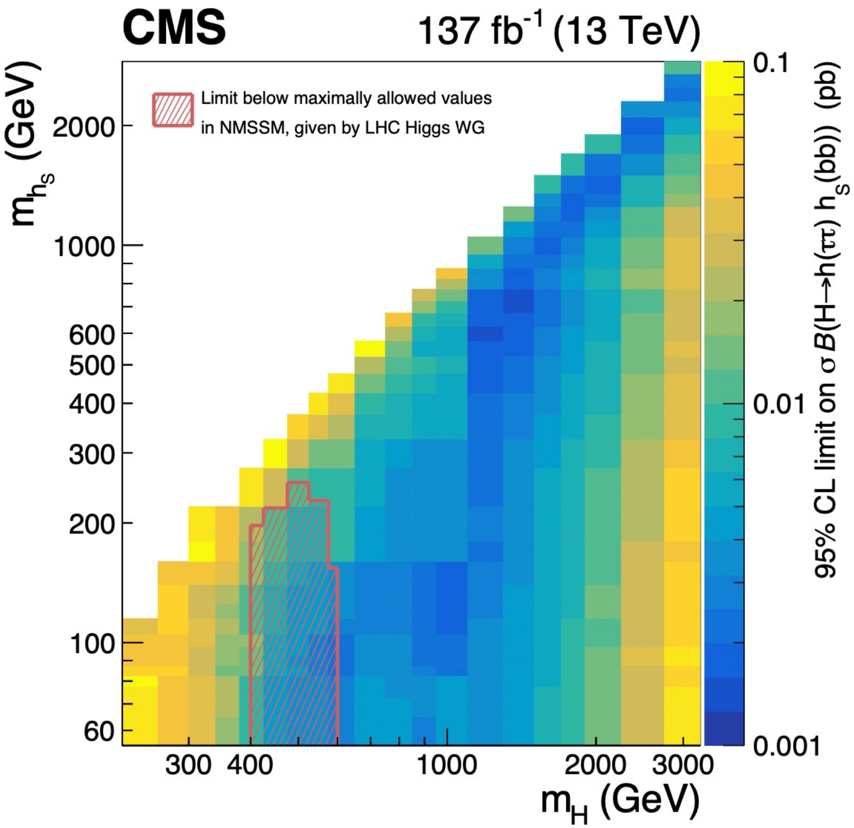



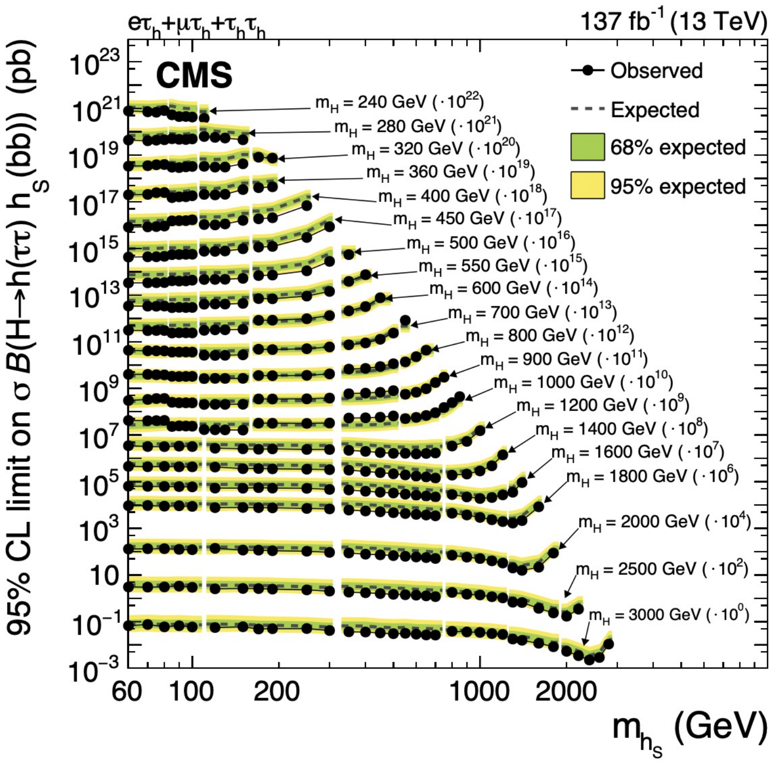




✓ **ATLAS H→SS was performed together with BSM H → hh search with 4W multi-lepton final states and some benchmark mass points were chosen.**

# Search for H→Sh in CMS

*2106.10361*

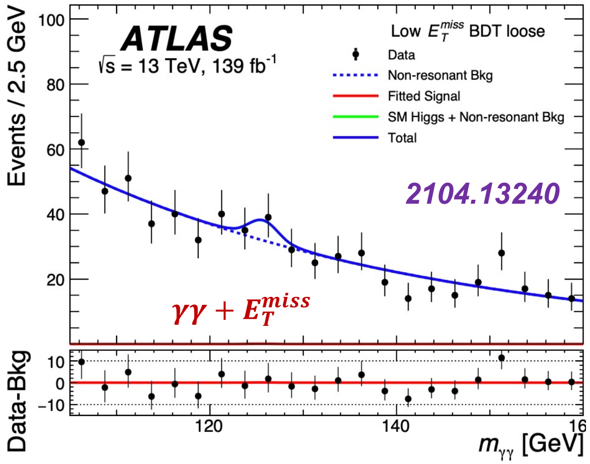


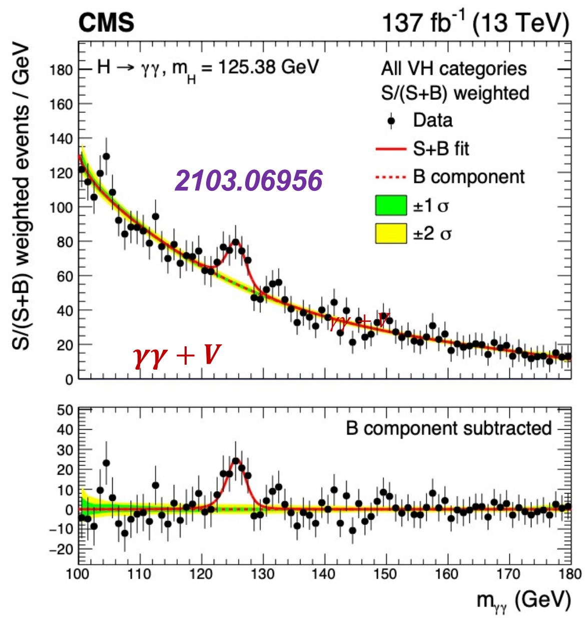



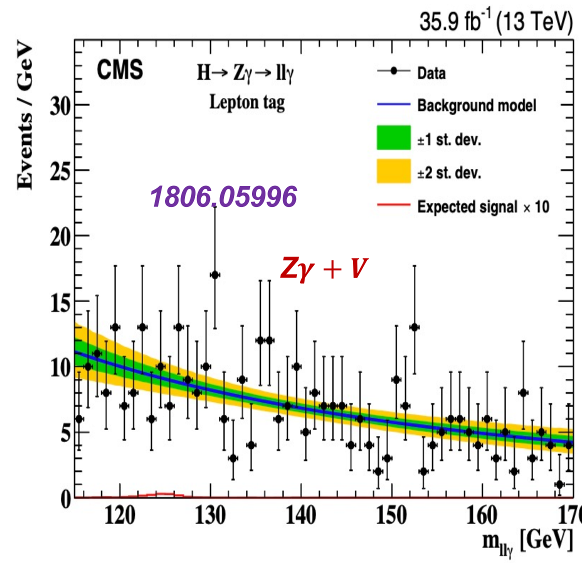

- ✓ **Very recently, CMS showed the X→S(→*bb*)h(→ττ) search with a grid of mass points X and S.**
- ✓ **No excess has been observed.**

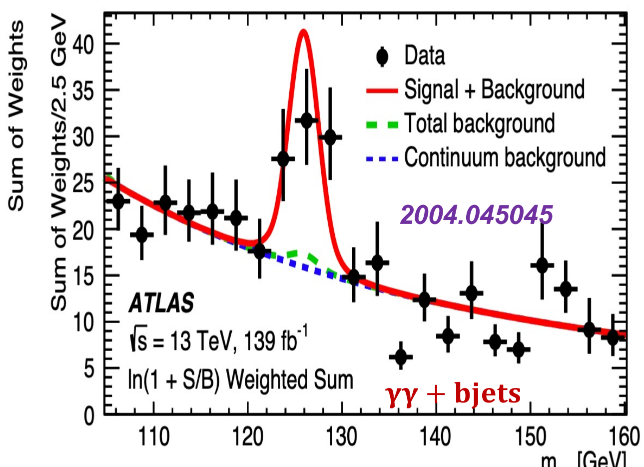
**Photon related $H \rightarrow SS, Sh$ searches performed so far at the LHC**

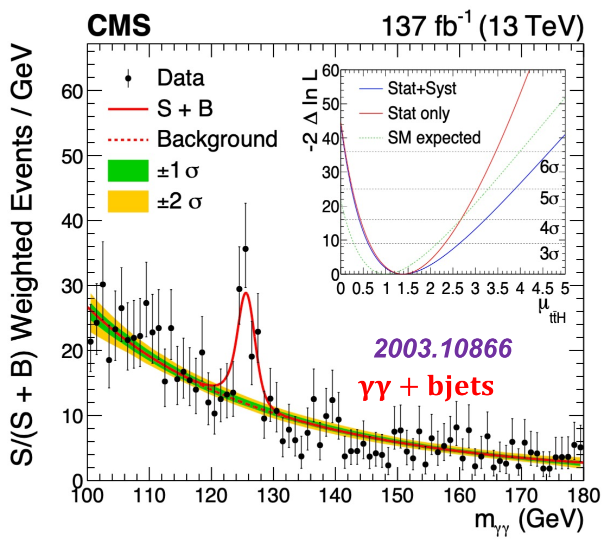
# Excesses for di-photon, zγ final states associated with leptons, missing energy, b-jets

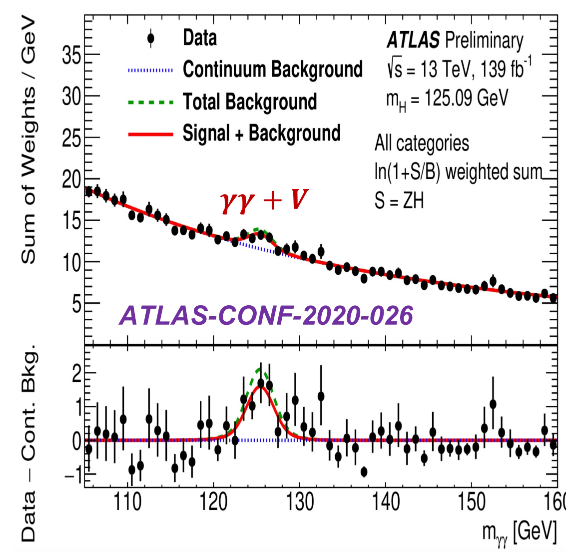


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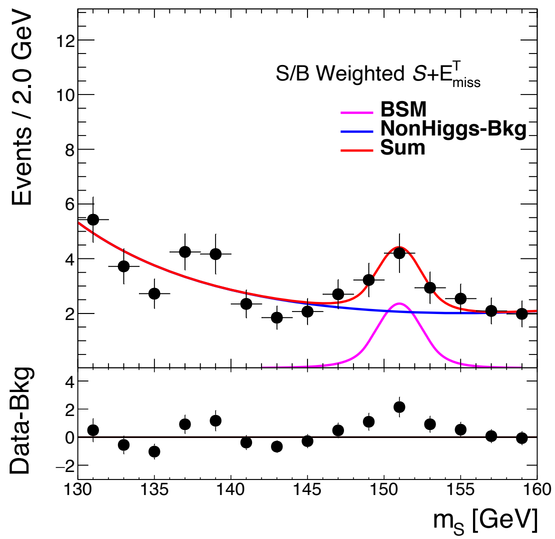


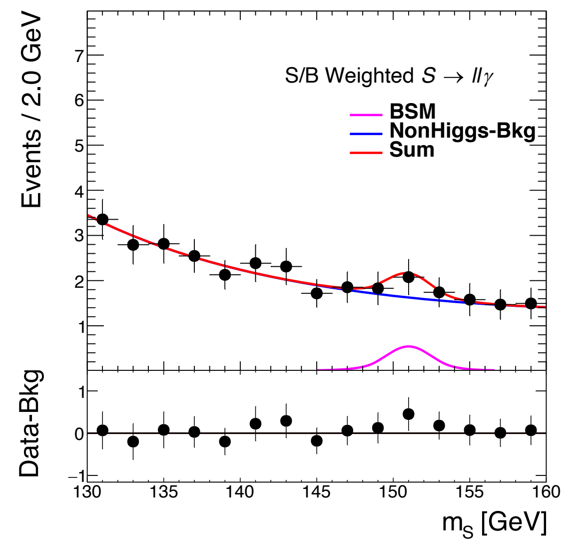


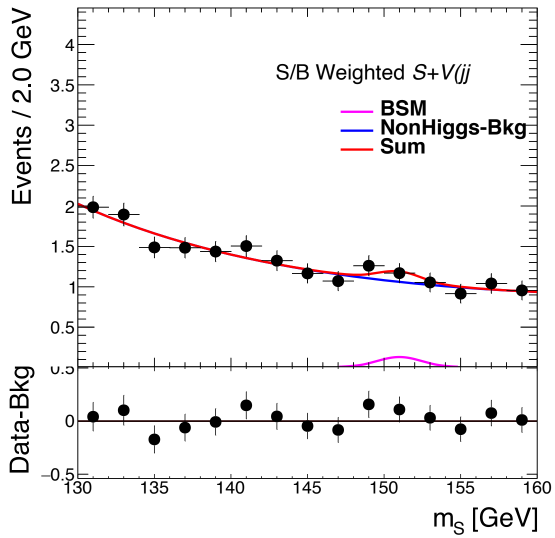


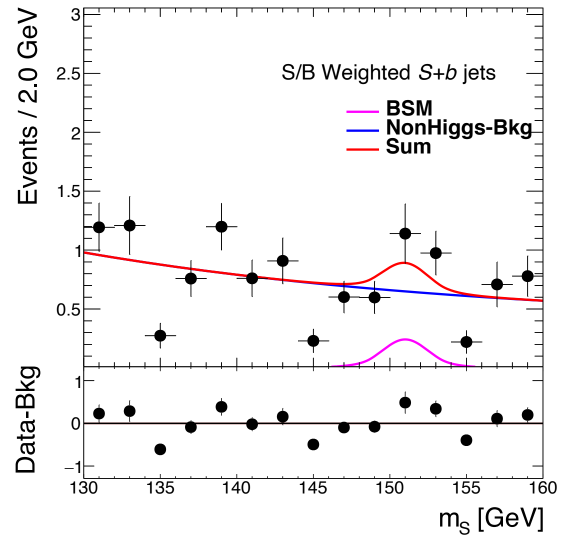

# Excess for ATLAS/CMS di-photon/Zγ related results

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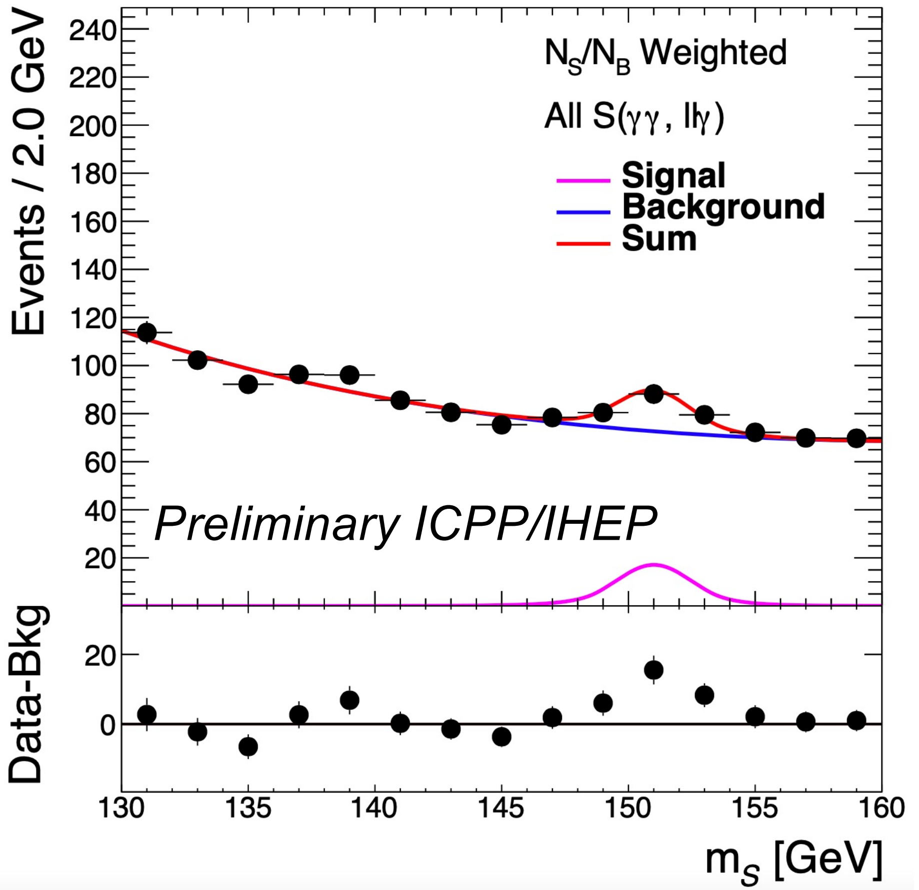
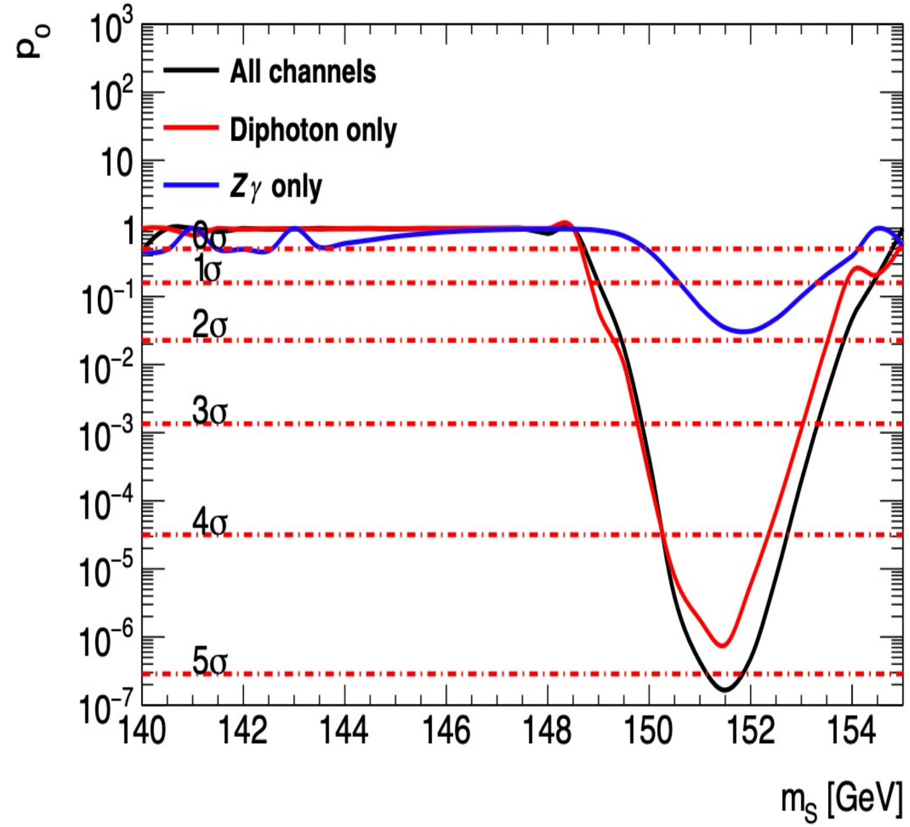


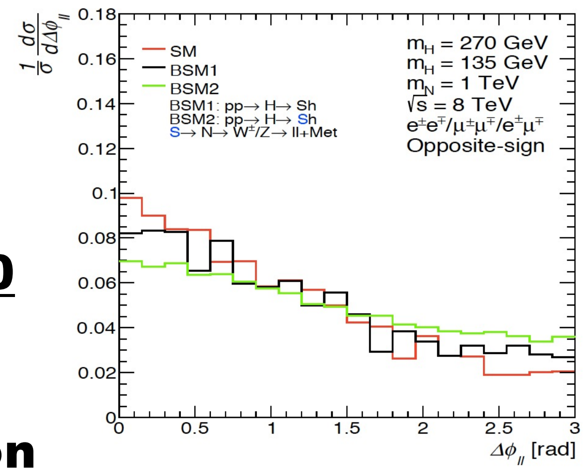



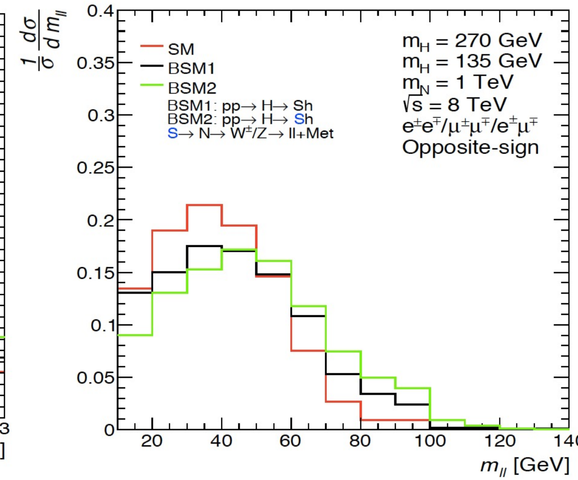

- Using public ATLAS/CMS results with di-photon and Zγ results, we can extract the excess around 151 GeV with 5.1σ and 4.8σ considering Look-Else-Where effect.
  - ✓ Most contribution from di-photon.
- Consistent with H →SS* hypothesis with $m_H$=270 GeV

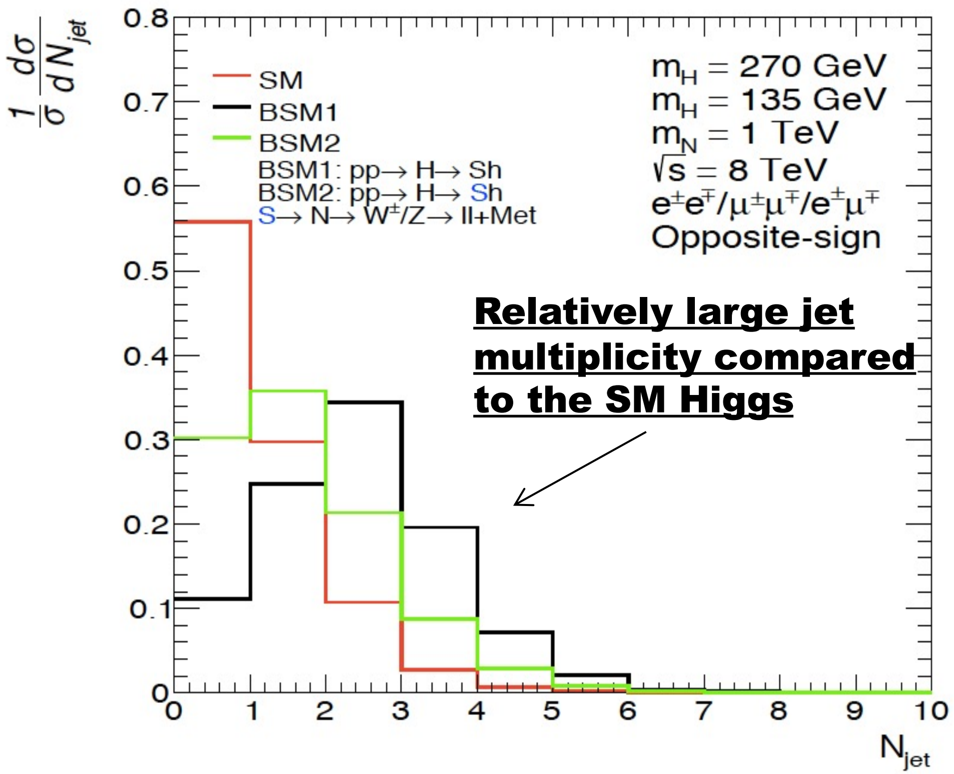
# Multi-lepton final states

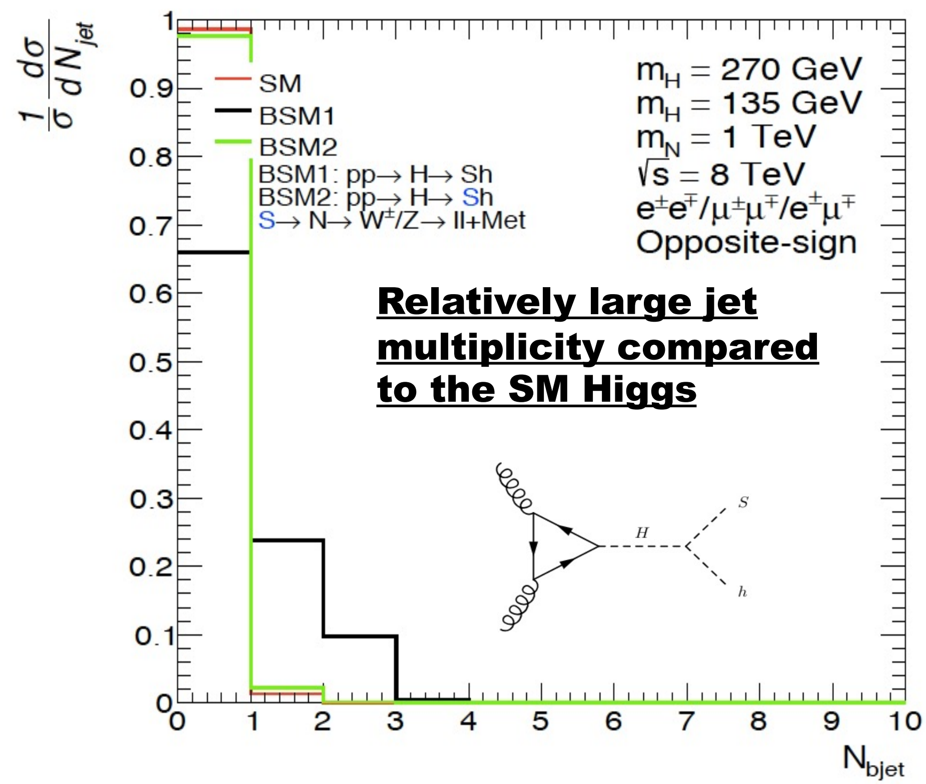
$$pp \to H \to Sh$$
$$\to \ell^+ \ell^- + X$$

**<u>Expect di-leptons ($m_{ll}$<100 GeV) with jets and b-jets with rates comparable to that of the SM Higgs boson</u>**

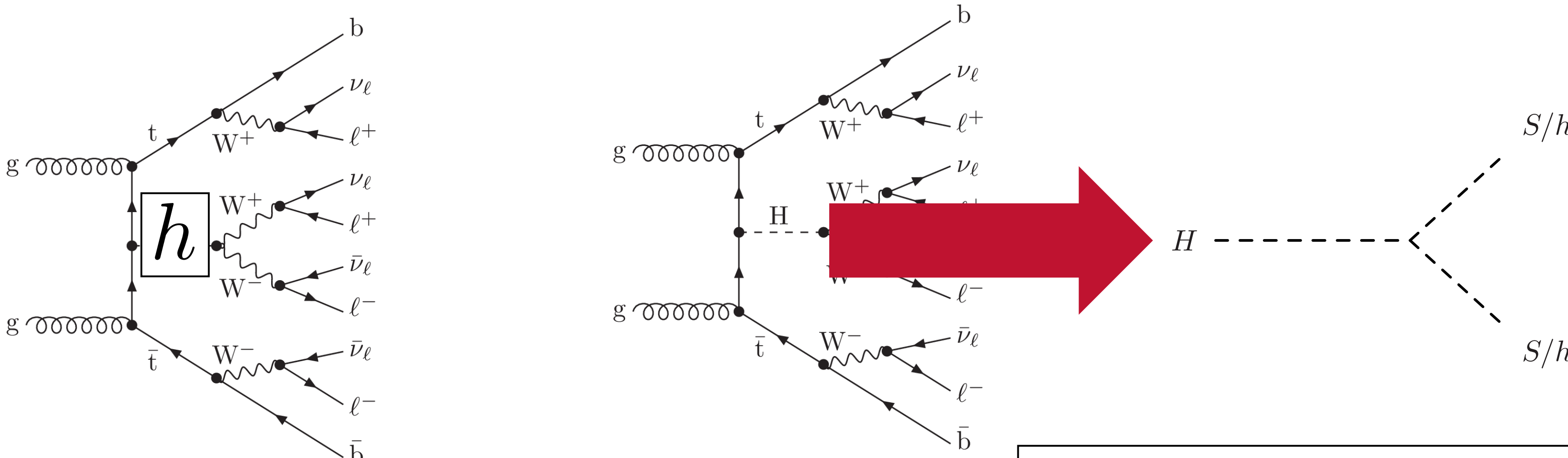


# Top associated Higgs production
## (Multi-lepton final states)




**Reduced cross-section of ttH+tH is compensated by di-boson, (SS, Sh) decay and large Br(S→WW). Production of same sign leptons, three leptons is enhanced. Enhanced tH cross-section**

**Produces SS 2l, 3l with b-jets, including 3 b-jets**

**Explains anomalously large ttW+tth+4t cross-sections seen by ATLAS and CMS**

# Methodology

**(to avoid biases and look-else-where effects)**

Based Higgs $p_T$, hh, tth, VV in Run 1
Eur. Phys. J. C (2016) 76:580

Model defined and predictions made for multilepton excesses

Multi-lepton excesses in Run 1 and few Run 2 results available in 2017

J.Phys.G 45 (2018) 11, 115003

Model parameters fixed in 2017 with $m_H$=270 GeV, $m_S$=150 GeV, S treated as SM Higgs-like, dominance of H→Sh,SS

Fixed final states and phase-space defined by fixed model parameters. NO tuning, NO scanning

Update same final states with more data in Run 2

Study new final states where excesses predicted and data available in Run 1 and Run 2 (e.g., SS0b, 3l0b, ZW0b)

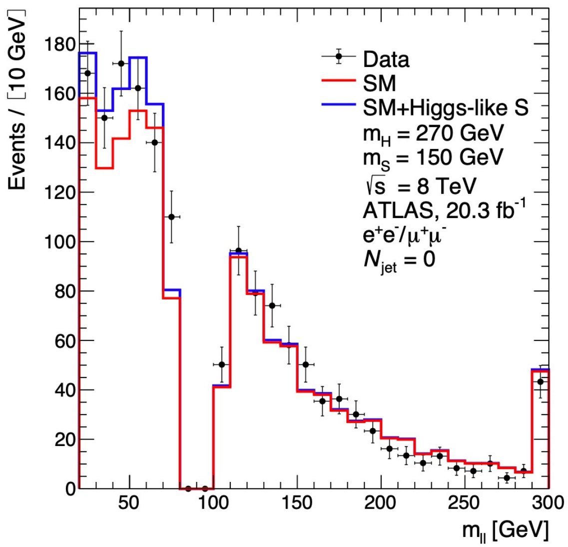
J.Phys. G46 (2019) no.11, 115001
JHEP 1910 (2019) 157
Chin.Phys.C 44 (2020) 6, 063103
Physics Letters B 811 (2020) 135964
Eur.Phys.J.C 81 (2021) 365

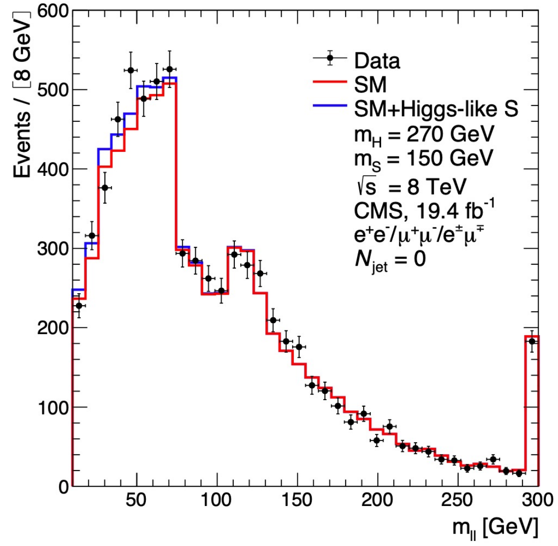
# Anatomy of the multi-lepton anomalies

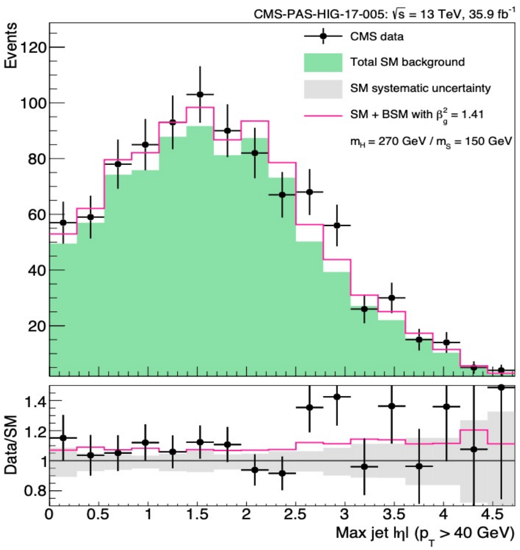
| Final state | Characteristic | Dominant SM process | Significance |
|---|---|---|---|
| $l^+l^-$ + jets, b-jets | $m_{ll}$<100 GeV, dominated by 0b-jet and 1b-jet | tt+Wt | >5σ |
| $l^+l^-$ + full-jet veto | $m_{ll}$<100 GeV | WW | ~3σ |
| $l^\pm l^\pm$ & $l^\pm l^\pm l$ + b-jets | Moderate $H_T$ | ttW, 4t | >3σ |
| $l^\pm l^\pm$ & $l^\pm l^\pm l$ et al., no b-jets | In association with h | Wh, WWW | ~4.5σ |
| $Z(\rightarrow l^+l^-)+l$ | $p_{TZ}$<100 GeV | ZW | >3σ |

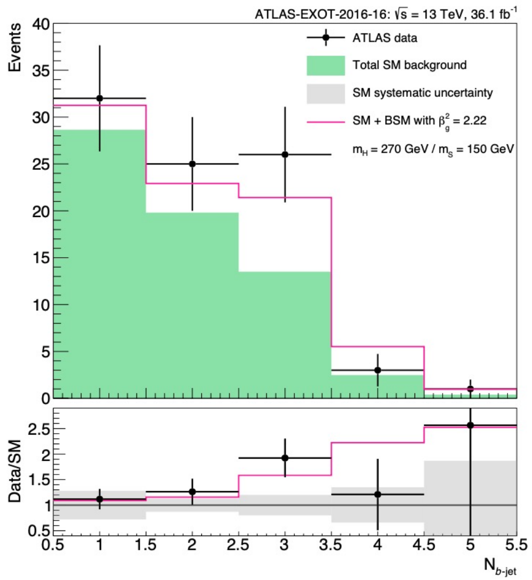
**Anomalies cannot be explained by mismodelling of a particular process, e.g. ttbar production alone.**

# Examples


Data
SM
SM+Higgs-like S
$m_H$ = 270 GeV
$m_S$ = 150 GeV
$\sqrt{s}$ = 8 TeV
ATLAS, 20.3 fb$^{-1}$
$e^+e^-/\mu^+\mu^-$
$N_{jet}$ = 0
Events / [10 GeV]
$m_{ll}$ [GeV]


Data
SM
SM+Higgs-like S
$m_H$ = 270 GeV
$m_S$ = 150 GeV
$\sqrt{s}$ = 8 TeV
CMS, 19.4 fb$^{-1}$
$e^+e^-/\mu^+\mu^-/e^\pm\mu^\mp$
$N_{jet}$ = 0
Events / [8 GeV]
$m_{ll}$ [GeV]


CMS-PAS-HIG-17-005: $\sqrt{s}$ = 13 TeV, 35.9 fb$^{-1}$
CMS data
Total SM background
SM systematic uncertainty
SM + BSM with $\beta_g^2$ = 1.41
$m_H$ = 270 GeV / $m_S$ = 150 GeV
Events
Data/SM
Max jet |η| ($p_T$ > 40 GeV)

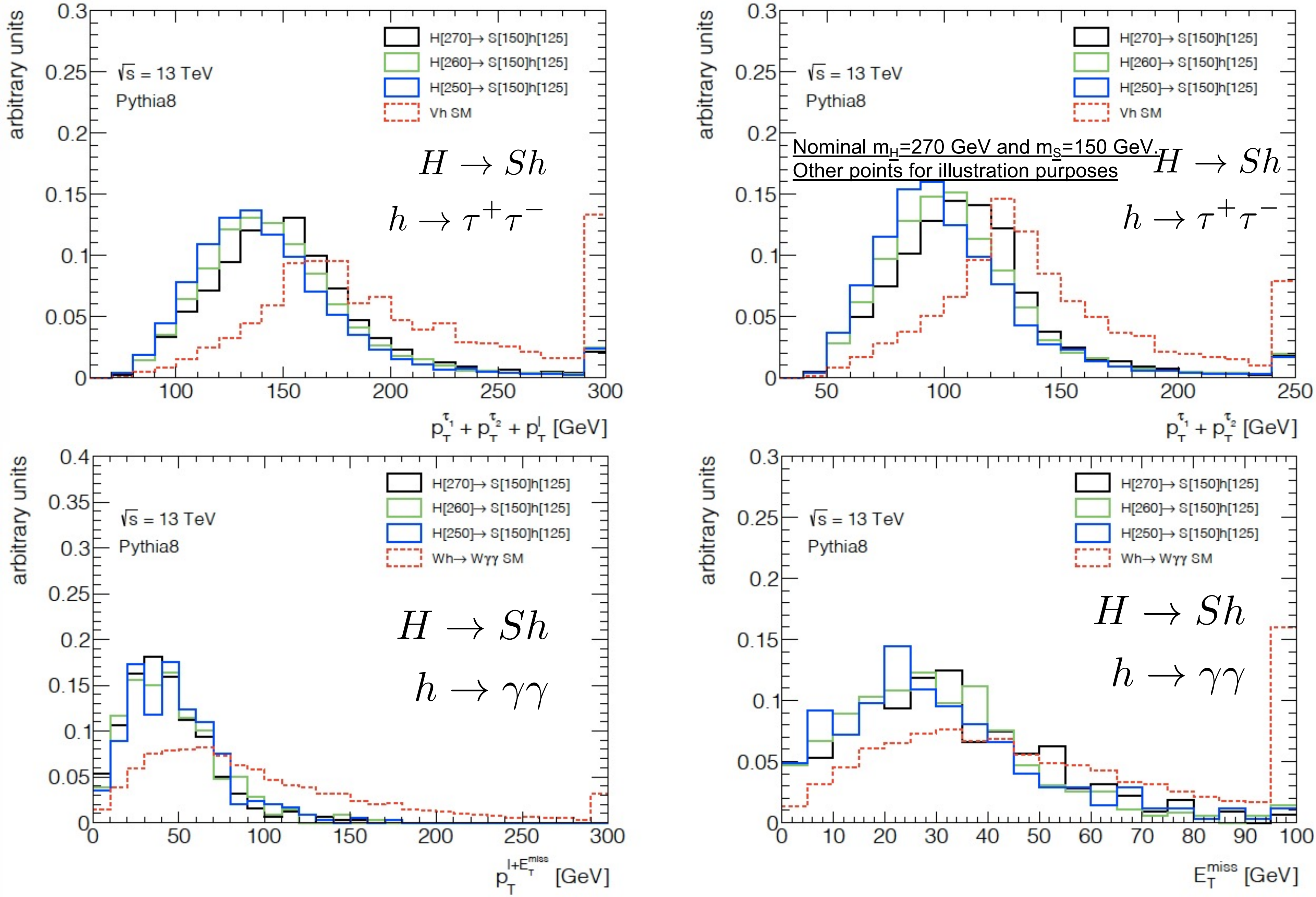

ATLAS-EXOT-2016-16: $\sqrt{s}$ = 13 TeV, 36.1 fb$^{-1}$
ATLAS data
Total SM background
SM systematic uncertainty
SM + BSM with $\beta_g^2$ = 2.22
$m_H$ = 270 GeV / $m_S$ = 150 GeV
Events
Data/SM
$N_{b\text{-jet}}$

# Impact on Higgs Physics

The presence of a BSM signal of the type H→Sh would lead to:

- ❑ The presence of extra leptons in association with h.
- ❑ Affects the Wh measurement (*Eur.Phys.J.C 81 (2021) 365*)
- ❑ Distortion of Higgs $p_T$ and rapidity (under study)

**No tuning of model parameters performed. Look at fixed corners of the phase-space fixed with parameters of 2017.**



arbitrary units
$\sqrt{s}$ = 13 TeV
Pythia8
H[270]→ S[150]h[125]
H[260]→ S[150]h[125]
H[250]→ S[150]h[125]
Vh SM
$H \to Sh$
$h \to \tau^+\tau^-$
$p_T^{\tau_1} + p_T^{\tau_2} + p_T^{l}$ [GeV]
arbitrary units
$\sqrt{s}$ = 13 TeV
Pythia8
H[270]→ S[150]h[125]
H[260]→ S[150]h[125]
H[250]→ S[150]h[125]
Vh SM
Nominal $m_H$=270 GeV and $m_S$=150 GeV.
Other points for illustration purposes
$H \to Sh$
$h \to \tau^+\tau^-$
$p_T^{\tau_1} + p_T^{\tau_2}$ [GeV]
arbitrary units
$\sqrt{s}$ = 13 TeV
Pythia8
H[270]→ S[150]h[125]
H[260]→ S[150]h[125]
H[250]→ S[150]h[125]
Wh→ Wγγ SM
$H \to Sh$
$h \to \gamma\gamma$
$p_T^{l+E_T^{miss}}$ [GeV]
arbitrary units
$\sqrt{s}$ = 13 TeV
Pythia8
H[270]→ S[150]h[125]
H[260]→ S[150]h[125]
H[250]→ S[150]h[125]
Wh→ Wγγ SM
$H \to Sh$
$h \to \gamma\gamma$
$E_T^{miss}$ [GeV]

- Survey of LHC results on Vh (V=W,Z) production (*Eur.Phys.J.C 81 (2021) 365*)
- **The BSM (H→Sh) signal appears at low $p_{Th}$** and the SM signal is prevalent at larger $p_{Th}$ **(no tuning of parameters)**
- Include those results from ATLAS and CMS where no requirements on $p_{Th}$ (or correlated observables) is not done or used in an MVA.
- Those results where the final state is treated more "inclusively" display elevated signal strengths for Wh production:

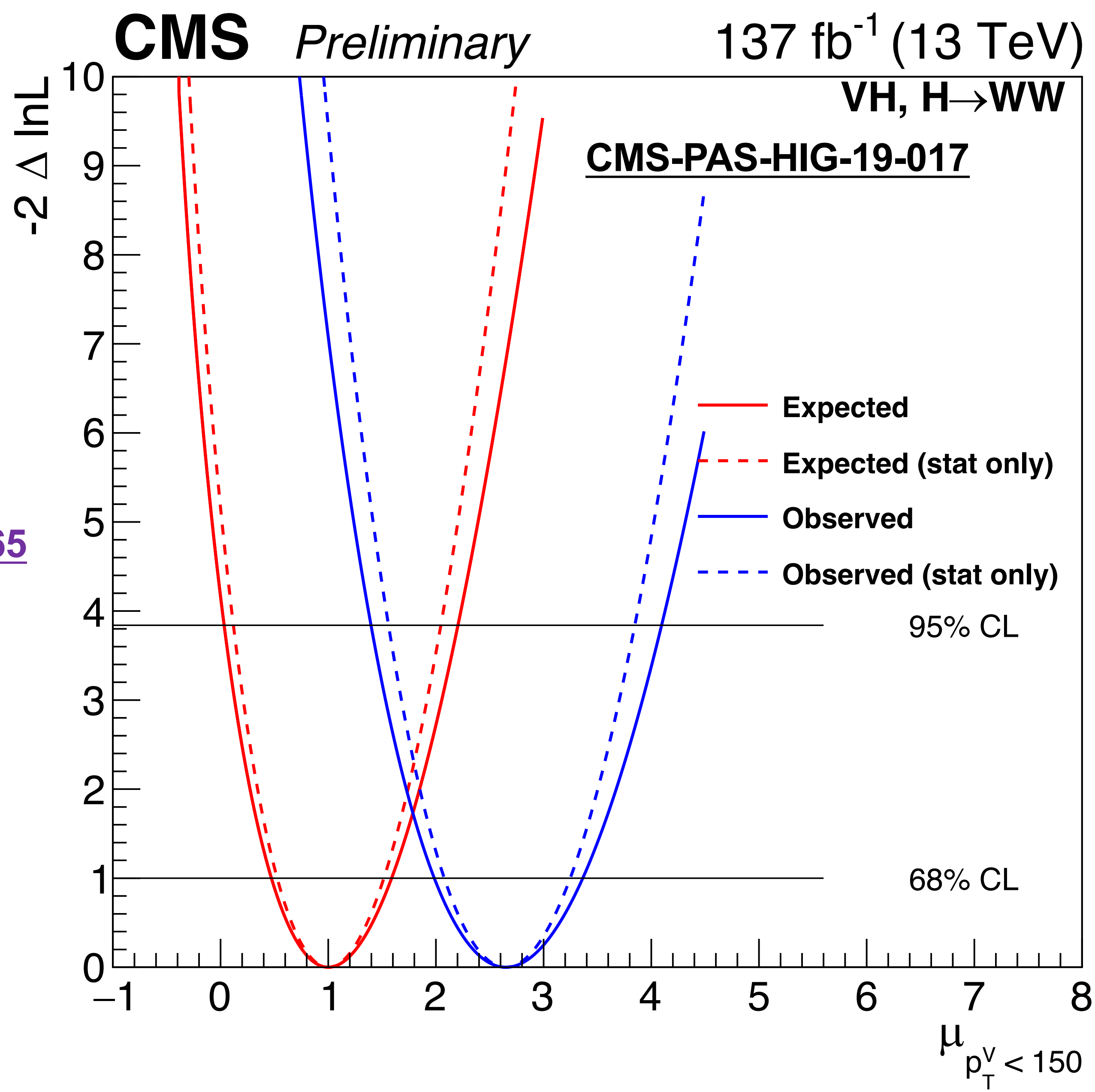
$$\mu(Wh) = 2.41 \pm 0.37$$

- This represents a **3.8σ deviation** from the SM value of 1.
  - BSM signal normalization less than expected from multilepton excesses assuming Br(H→Sh)=100%.

| Higgs decay | Ref. | Experiment | $\sqrt{s}$, $\mathcal{L}$ TeV, $fb^{-1}$ | Final state | Category | $\mu$ | Used in combination | Comments |
|---|---|---|---|---|---|---|---|---|
| $WW$ | [66] | ATLAS | 7, 4.5<br>8, 20.3 | $2\ell$ | DFOS 2j | $2.2^{+2.0}_{-1.9}$ | ✓ | |
| | | | | | SS 1j | $8.4^{+4.3}_{-3.8}$ | ✓ | $2\ell$ combination: $\mu = 3.7^{+1.9}_{-1.5}$ |
| | | | | | SS 2j | $7.6^{+6.0}_{-5.4}$ | ✓ | |
| | | | | $3\ell$ | 1SFOS | $-2.9^{+2.7}_{-2.1}$ | x | $m_{\ell_0\ell_2}$ used as input BDT discriminating variable |
| | | | | | 0SFOS | $1.7^{+1.9}_{-1.4}$ | ✓ | |
| | [67] | ATLAS | 13, 36.1 | $3\ell$ | 1SFOS<br>0SFOS | $2.3^{+1.2}_{-1.0}$ | ✓ | 1SFOS channel uses $m_{\ell_0\ell_2}$ in the BDT but excess driven by 0SFOS |
| | [68] | CMS | 7, 4.9 | $2\ell$ | DFOS 2j | $0.39^{+1.97}_{-1.87}$ | ✓ | Discrepancy at low $m_{\ell\ell}$ |
| | | | 8, 19.4 | $3\ell$ | 0+1SFOS | $0.56^{+1.27}_{-0.95}$ | ✓ | |
| | [69] | CMS | 13, 35.9 | $2\ell$ | DFOS 2j | $3.92^{+1.32}_{-1.17}$ | ✓ | Discrepancy at low $m_{\ell\ell}$ |
| | | | | $3\ell$ | 0+1SFOS | $2.23^{+1.76}_{-1.53}$ | ✓ | |
| $\tau\tau$ | [70] | ATLAS | 8, 20.3 | $1\ell$ | $\ell + \tau_h\tau_h$ | $1.8 \pm 3.1$ | ✓ | |
| | | | | $2\ell$ | $e^\pm\mu^\pm + \tau_h$ | $1.3 \pm 2.8$ | ✓ | |
| | [71] | CMS | 7, 4.9 | $1\ell$ | $\ell + \tau_h\tau_h$ | $-0.33 \pm 1.02$ | x | BDT based on $p_T^{\tau_1} + p_T^{\tau_2}$ |
| | | | 8, 19.7 | $2\ell$ | $e^\pm\mu^\pm + \tau_h$ | | x | Split $p_T^{\ell_1} + p_T^{\ell_2} + p_T^{\tau}$ at 130 GeV |
| | [72] | CMS | 13, 35.9 | $1\ell$ | $\ell + \tau_h\tau_h$ | $3.39^{+1.68}_{-1.54}$ | ✓ | |
| | | | | $2\ell$ | $e^\pm\mu^\pm + \tau_h$ | | | |
| $\gamma\gamma$ | [73] | ATLAS | 7, 5.4<br>8, 20.3 | $\ell\nu$ | One-lepton | $1.0 \pm 1.6$ | x | |
| | | | | $\not{\ell}\nu, \nu\nu$ | $E_T^{miss}$ | | | $E_T^{miss} > 70 - 100$ GeV |
| | | | | $jj$ | Hadronic | | | $p_{Tt}^{\gamma\gamma} > 70$ GeV |
| | [74] | CMS | 7, 5.1<br>8, 19.7 | $\ell\nu$ | One-lepton | $-0.16^{+1.16}_{-0.79}$ | x | Split $E_T^{miss}$ at 45 GeV |
| | | | | $\not{\ell}\nu, \nu\nu$ | $E_T^{miss}$ | | | $E_T^{miss} > 70$ GeV |
| | | | | $jj$ | Hadronic | | | $p_T^{\gamma\gamma} > 13m_{\gamma\gamma}/12$ |
| | [75] | ATLAS | 13, 139 | $\ell\nu$ | One-lepton | $2.41^{+0.71}_{-0.70}$ | ✓ | $p_T^{\ell+E_T^{miss}} < 150$ GeV |
| | | | | | | $2.64^{+1.16}_{-0.99}$ | x | $p_T^{\ell+E_T^{miss}} > 150$ GeV |
| | | | | $\not{\ell}\nu, \nu\nu$ | $E_T^{miss}$ | - | x | $E_T^{miss} > 75$ GeV |
| | | | | $jj$ | Hadronic | $0.76^{+0.95}_{-0.83}$ | x | $60 < m_{jj} < 120$ GeV |
| | | | | | | $3.16^{+1.84}_{-1.72}$ | ✓ | $m_{jj} \in [0, 60] \| [120, 350]$ GeV |
| | [76] | CMS | 13, 35.6 | $\ell\nu$ | One-lepton | $3.0^{+1.5}_{-1.3}$ | x | Superseeded by full Run 2 result |
| | | | | $\not{\ell}\nu, \nu\nu$ | $E_T^{miss}$ | - | x | $E_T^{miss} > 85$ GeV |
| | | | | $jj$ | Hadronic | $5.1^{+2.5}_{-2.3}$ | ✓ | $p_T^{\gamma\gamma}/m_{\gamma\gamma}$ not used |
| | [77] | CMS | 13, 137 | $\ell\nu$ | One-lepton | $1.31^{+1.42}_{-1.12}$ | ✓ | $p_T^V < 75$ GeV |
| | | | | $jj$ | Hadronic | $0.89^{+0.89}_{-0.91}$ | x | $p_T^{\gamma\gamma}/m_{\gamma\gamma}$ used in BDT |
| ZZ | [78] | ATLAS | 13, 139 | $\ell\ell\ell + \ell\nu$ | Lep-enriched | $1.44^{+1.17}_{-0.93}$ | x | Number of jets used in MVA |
| | | | | $\ell\ell\ell + q\bar{q}$ | $2j$ | | | $m_{jj}$ used in MVA |
| | [79] | CMS | 13, 137.1 | $\ell\ell\ell + \ell\nu$ | Lep-low $p_T^h$ | $3.21^{+2.49}_{-1.85}$ | ✓ | $p_T^h$ <150 GeV |
| | | | | | Lep-high $p_T^h$ | $0.00^{+1.57}_{-0.00}$ | x | $p_T^h$ >150 GeV |
| | | | | $\ell\ell\ell + q\bar{q}$ | $2j$ | $0.57^{+1.20}_{-0.57}$ | x | $60 < m_{jj} < 120$ GeV |

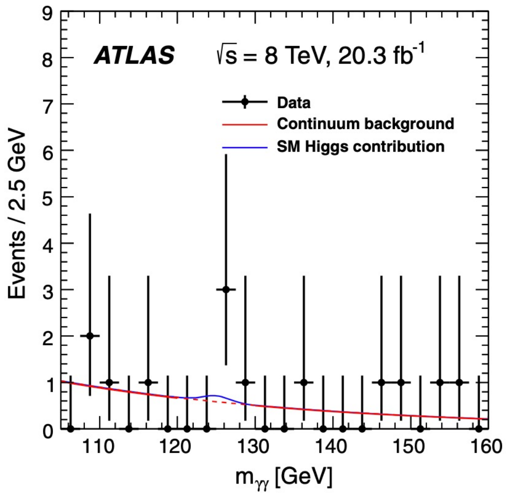
New results from CMS in the measurement of Vh, h→WW add to the anomalies reported in Eur.Phys.J.C 81 (2021) 365

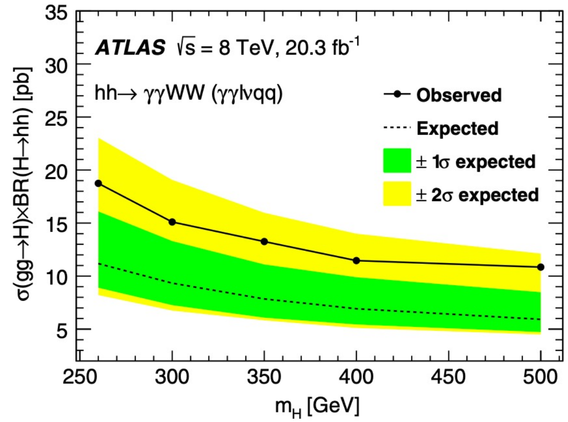
Deviation from the SM becomes stronger with $p_{TV}$<150 Gev

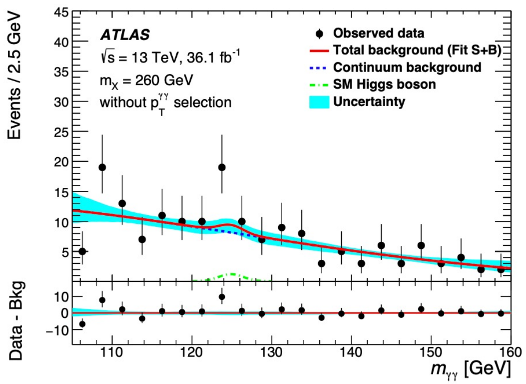


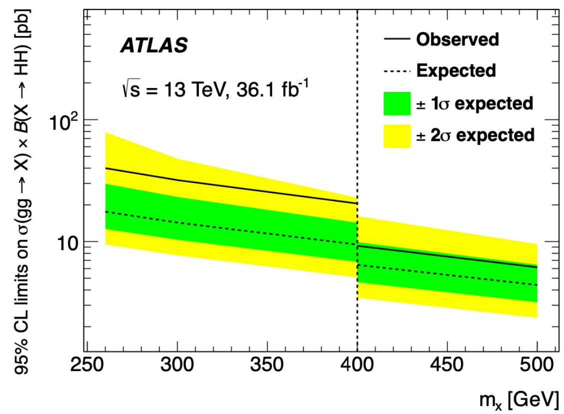
# Proposed further studies at the LHC/CEPC

# ATLAS γγ+1Lepton/2Letpon analysis under $h(\rightarrow \gamma\gamma)h(\rightarrow WW^{*})$



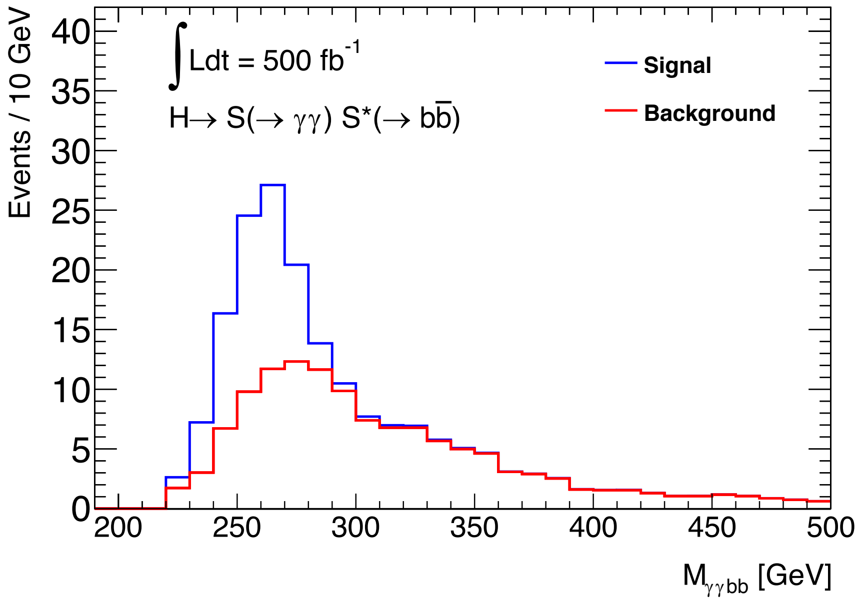



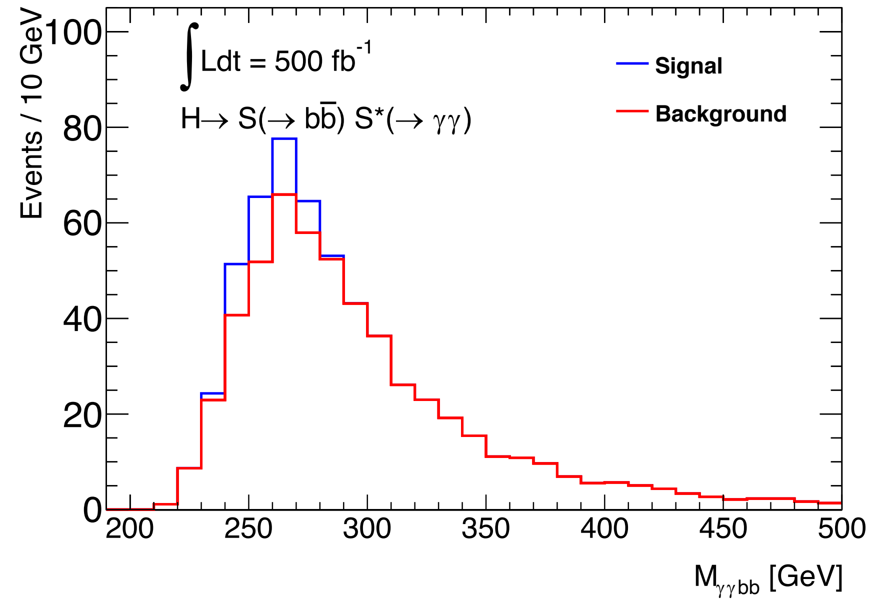




- ✓ The signal can also be produced by $h(\rightarrow \gamma\gamma)S(151.5)(\rightarrow WW^{*})$.
- ✓ ATLAS shows the analyses of γγ+Leptons under the frame of $h(\rightarrow \gamma\gamma)h(\rightarrow WW)$ with Run1 and Run2 analysis.
- ✓ From the di-photon peak around 125 GeV and with the subtract the SM Higgs contribution, one can extract the contribution from $h(\rightarrow \gamma\gamma)S(151.5)(\rightarrow WW^{*})$.

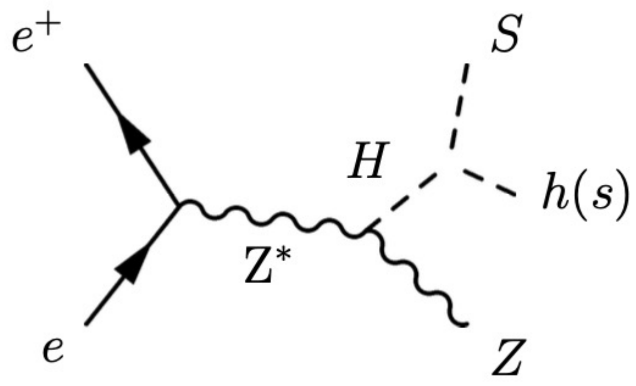
# H→SS*→γγ+bb analysis

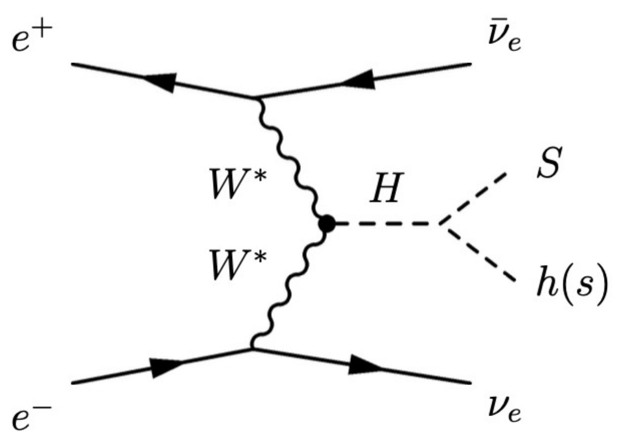


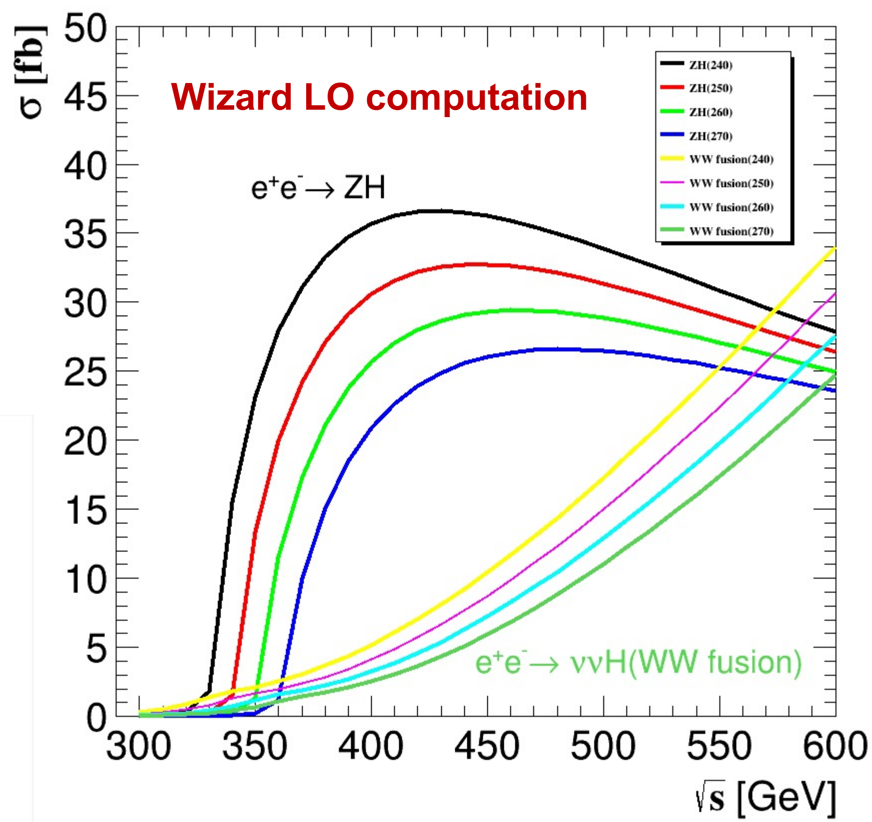




- ✓ **The search for H→SS* can also be performed with asymmetrical configuration of γγ+bb.**
- ✓ **One can expect to achieve 7σ according to current excess with Run2+3 data.**
- ✓ **In addition *H→SS*→ bb* ττ can also be exploited.**

# H→SS,Sh in future $e^+e^-$ colliders




- ✓ **Considering that the S is around 151 GeV, H 240-270 GeV, future $e^+e^-$ colliders can be a idea place to do the study.**
  - ✓ **in particular for upgradable run (>360 GeV)**
  - ✓ **With higher order computation, the xsection peak can shift a bit to the left (need inputs from you theorists)**

# Outlook and Conclusions

- Searches for $H\rightarrow SS^*/Sh$ remain unexplored for the most part at the LHC
- Possible candidates for S with masses around 151.5 GeV and observed excess is ~5$\sigma$
  - Further motivate $\gamma\gamma$bb searches in asymmetric configurations at the LHC
  - $h(\rightarrow\gamma\gamma)S(\rightarrow WW^*)$ can be exploited as well.
- These produce final states with multiple leptons in different topologies that include OS 2l, SS 2l, 3l, 4l, with and without b-quarks
  - Seem to describe reasonably well the multi-lepton anomalies at the LHC
- Future High energy run for $e^+e^-$ colliders can be a good machine to further exploit this.

# backup Slides

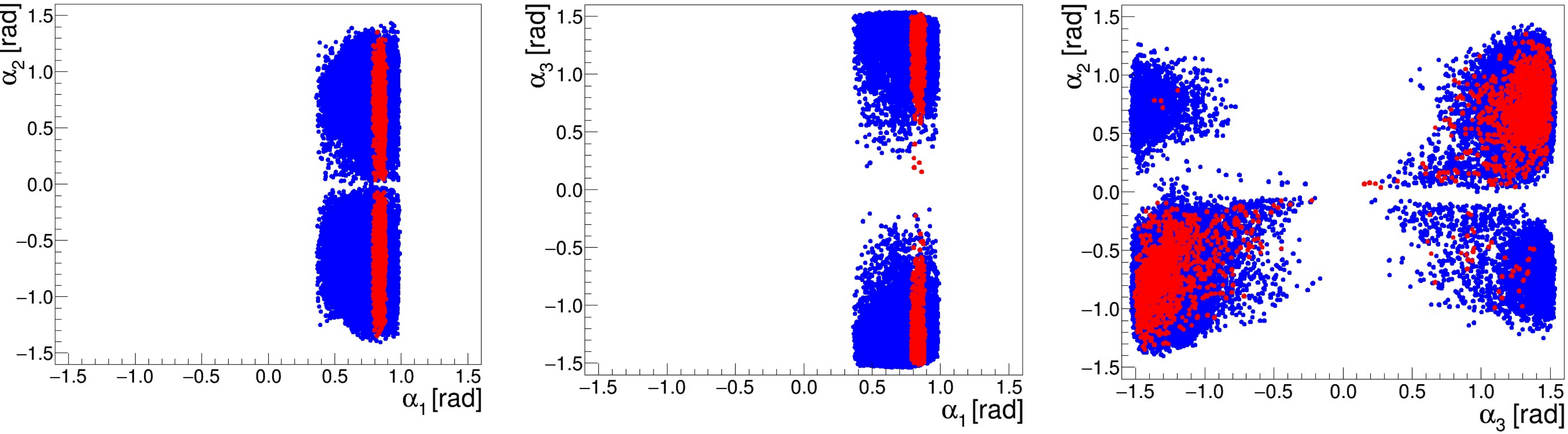
# Masses in the 2HDM+S

$$\begin{pmatrix} H_1 \\ H_2 \\ H_3 \end{pmatrix} = \mathbb{R} \begin{pmatrix} \rho_1 \\ \rho_2 \\ \rho_S \end{pmatrix},$$

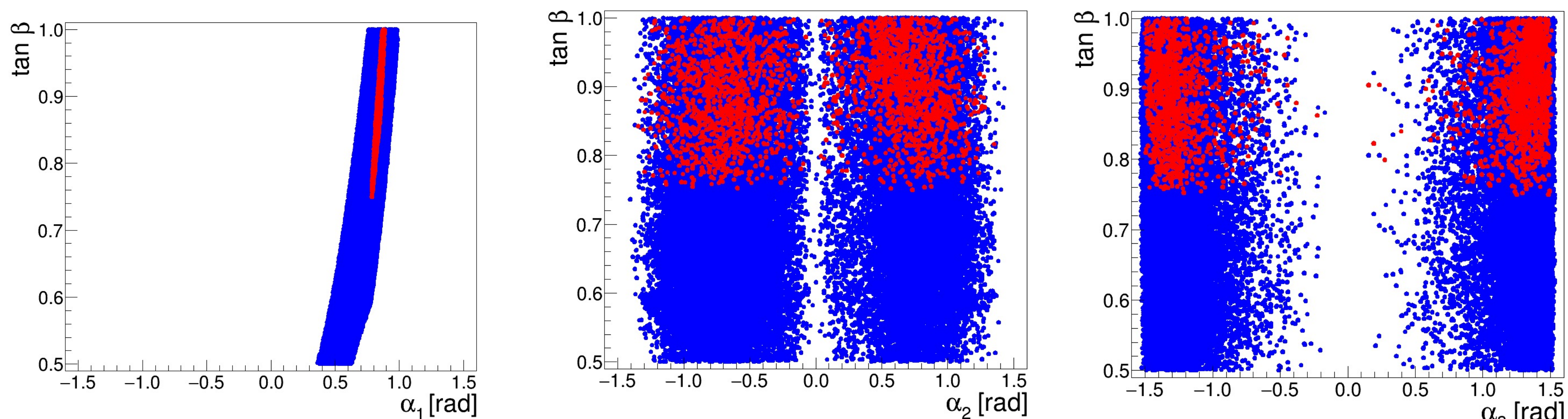
**Mass-matrix for the CP-even scalar sector will modified with respect to 2HDM and that needs a 3 x3 matrix (three mixing angles). Couplings are modified.**

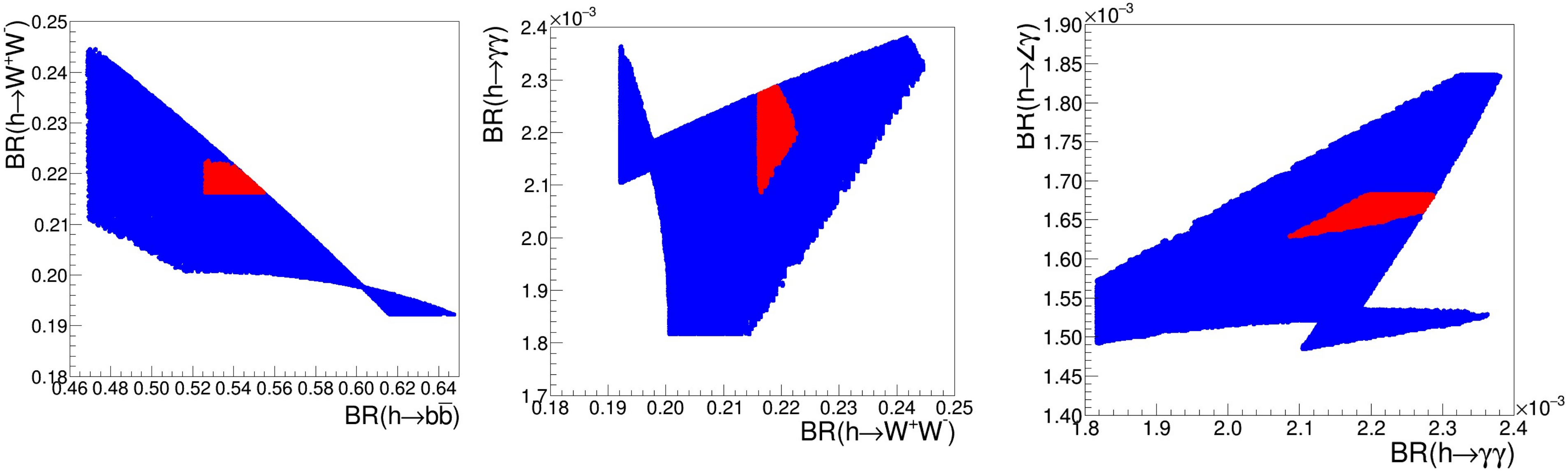
$$\mathbb{R} = \begin{pmatrix} c_{\alpha_1} c_{\alpha_2} & s_{\alpha_1} c_{\alpha_2} & s_{\alpha_2} \\ -\left(c_{\alpha_1} s_{\alpha_2} s_{\alpha_3} + s_{\alpha_1} c_{\alpha_3}\right) & c_{\alpha_1} c_{\alpha_3} - s_{\alpha_1} s_{\alpha_2} s_{\alpha_3} & c_{\alpha_2} s_{\alpha_3} \\ -c_{\alpha_1} s_{\alpha_2} s_{\alpha_3} + s_{\alpha_1} s_{\alpha_3} & -\left(c_{\alpha_1} s_{\alpha_3} + s_{\alpha_1} s_{\alpha_2} c_{\alpha_3}\right) & c_{\alpha_2} c_{\alpha_3} \end{pmatrix}$$

$$M^2_{\mathrm{CP-even}} = \begin{pmatrix} 2\lambda_1 v_1^2 - m_{12}\frac{v_2}{v_1} & m_{12} + \lambda_{345} v_1 v_2 & 2\kappa_1 v_1 v_S \\ m_{12} + \lambda_{345} v_1 v_2 & -m_{12}\frac{v_2}{v_1} + 2\lambda_2 v_2^2 & 2\kappa_2 v_2 v_S \\ 2\kappa_1 v_1 v_S & 2\kappa_2 v_2 v_S & \frac{1}{3}\lambda_S v_S^2 \end{pmatrix}$$




**Correlation plots for the three mixing angles and tanβ. Blue (red) points correspond to Br(h→SM) within 10% (20%) of the SM h values** (J.Phys. G46 (2019) no.11, 115001 )






## Results using N2HDECAY (arXiv:1612.01309) for one benchmark point