The Multi-lepton Anomalies at the LHC and implications

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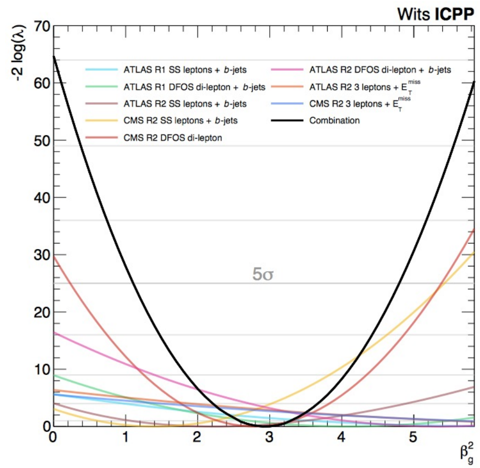
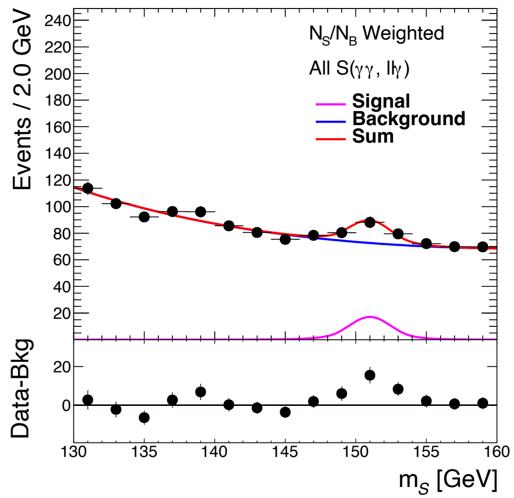
Higgs Potential 2022, 26/07/22

Outline

- ❑The simplified model
- ❑The multilepton anomalies
  - ❑Methodology
  - ❑The anatomy
- ❑Impact on Higgs physics
- ❑A possible candidate of S



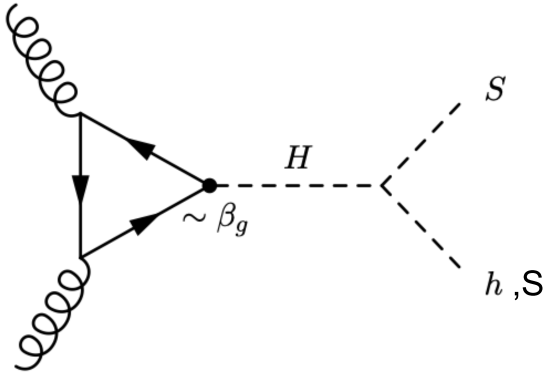


The Simplified Model and 2HDM+S

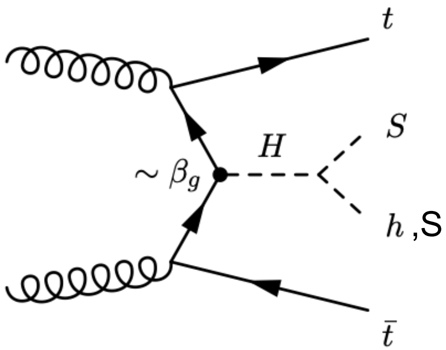
Eur. Phys. J. C (2016) 76:580

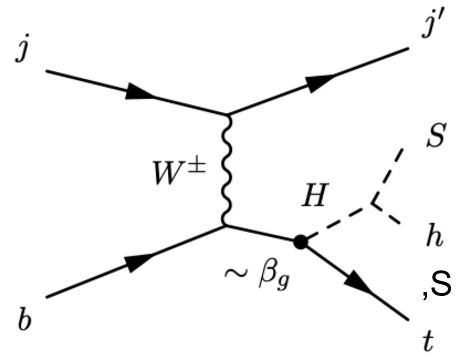
The simplified Model (from Run I)

1. **The starting point of the hypothesis is the existence of a boson, H, that contains Higgs-like interactions, with a mass in the range 250-280 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).





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

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

The Decays of H

- 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

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

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

Dominant decays

Diboson decay

$$H \to h(+X), S(+X)$$

The 2HDM+S

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

Introduce singlet real scalar, S.

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

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

2HDM+S potential

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

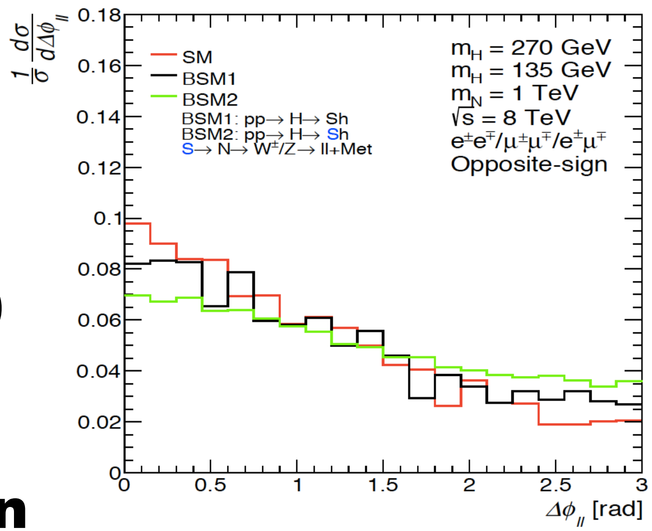
Out of considerations of simplicity, assume S to be Higgs-like, which is not too far fetched.

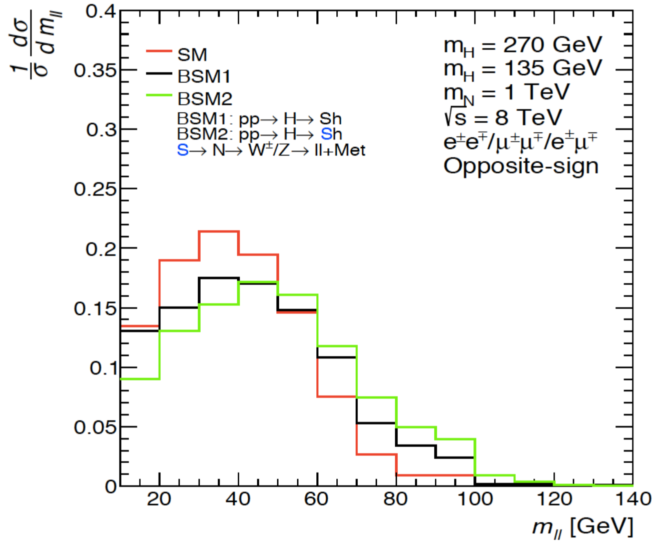
Multi-lepton final states

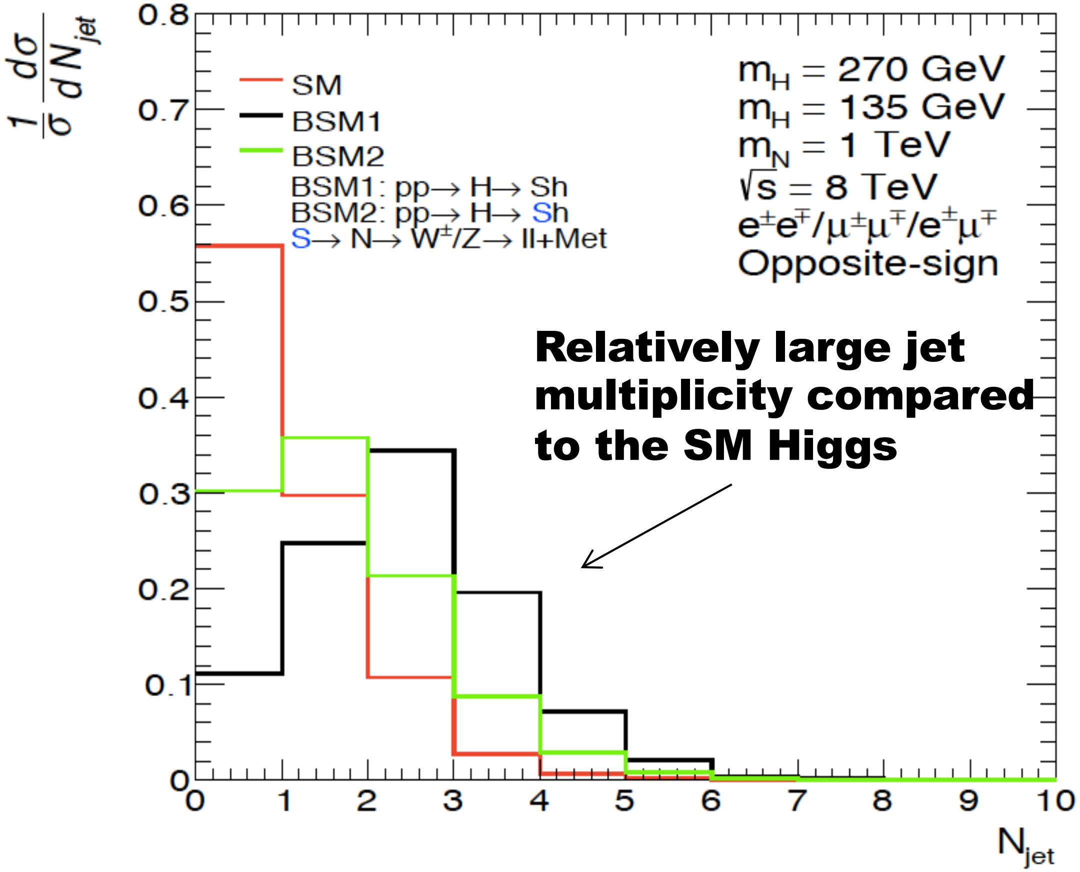
It is paramount to remark that the excesses are seen in final states that were predicted 2015/2016 on the basis of a simplified model and not the result of scan of the available phase-space. Additionally, the parameters of the model where fixed then leaving only one degree of freedom: normalization Thus, no look-elsewhere effects in parameter or phase-space

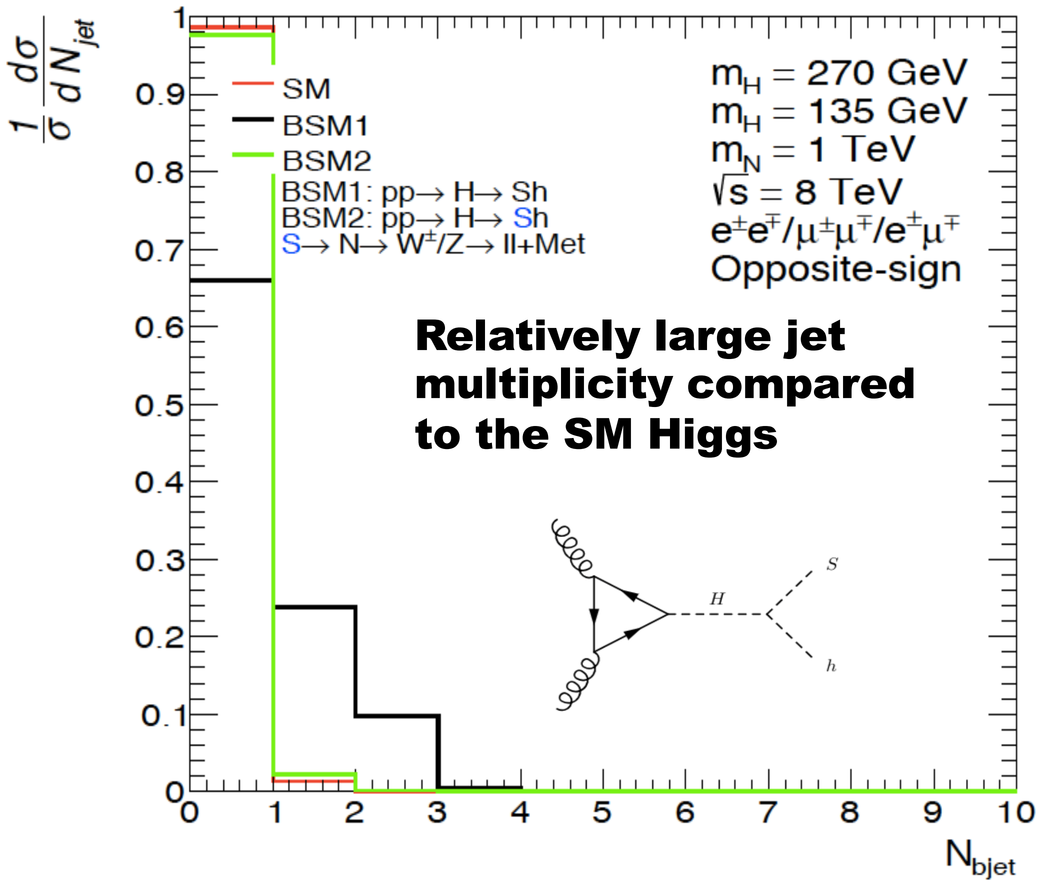
$$pp \to H \to Sh$$
$$\to \ell^+\ell^- + X$$

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

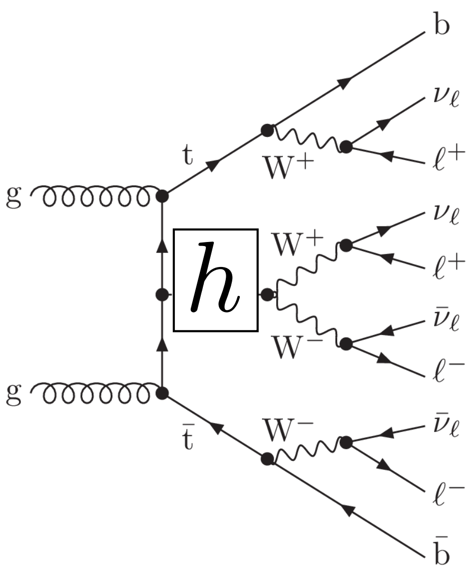


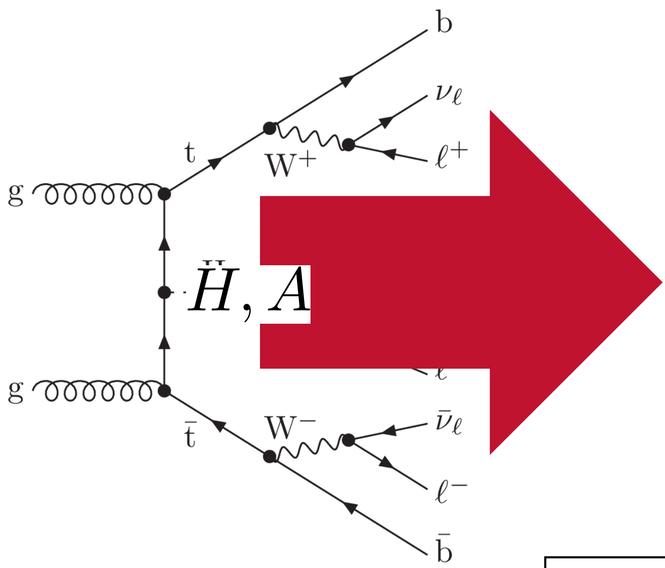






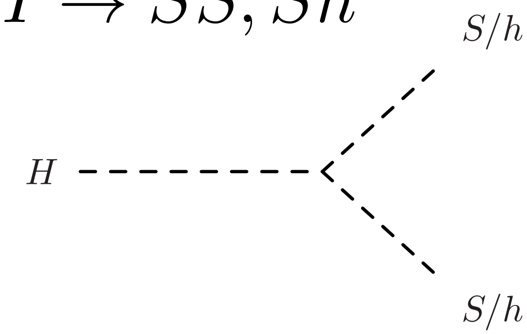
Top associated Higgs production
(Multi-lepton final states)





$A \to t\bar{t}, ZH$

$H \to SS, Sh$



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

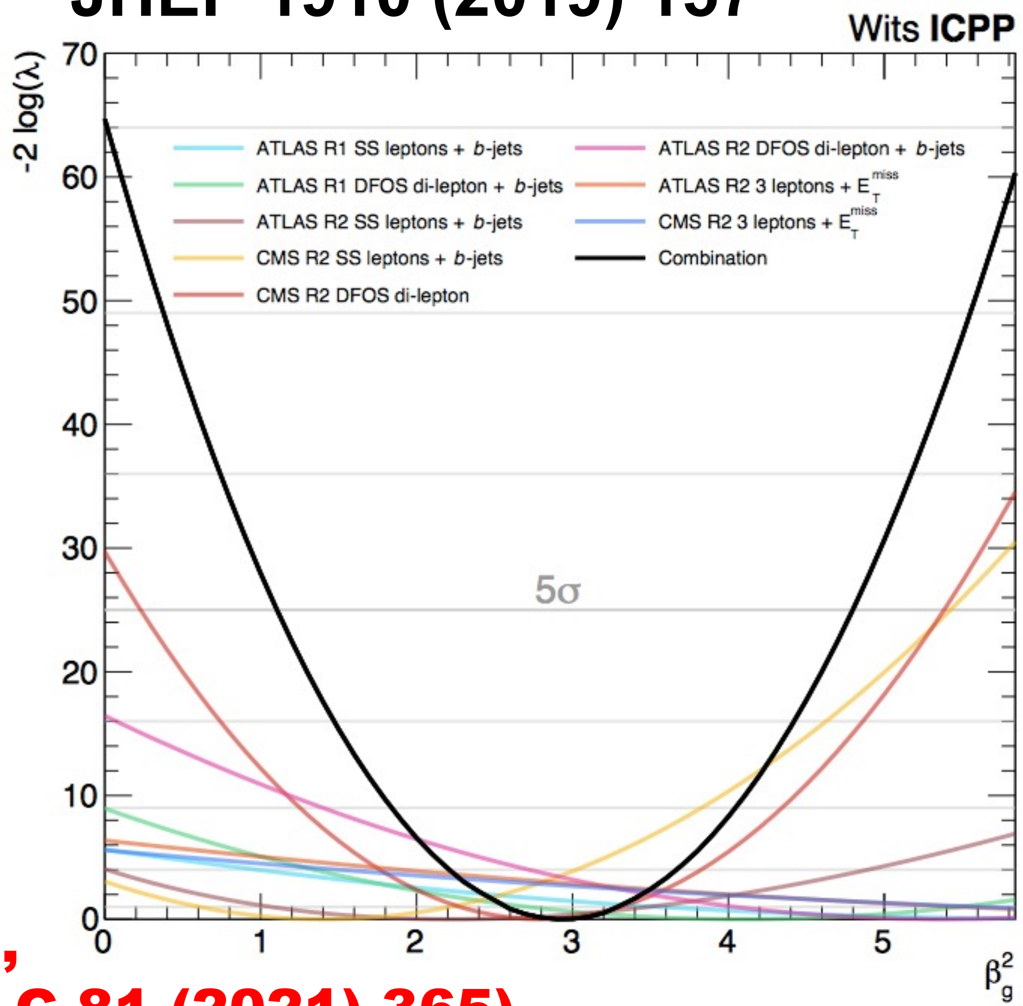
Combination of fit results (2019)

- **Simultaneous fit for all measurements:**
- **To the right: (-2 log) profile likelihood ratio for each individual result and the combination of them all**
- **The significance for each fit is calculated as**

$$\sqrt{-2\log\lambda(0)}$$

- **Best-fit: β_g^2 = 2.92 ± 0.35**
- **Corresponds to 8.04σ**

JHEP 1910 (2019) 157



Excesses have been growing since, and new have emerged (Eur.Phys.J.C 81 (2021) 365)

Interpretation: Measure of the inability of current MC tools to describe multiple-lepton data and how a simplified model with H→Sh is able to capture the effect with one parameter

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)	4.2σ
$Z(\rightarrow l^+l^-)+l$	p_{TZ}<100 GeV	ZW	>3σ

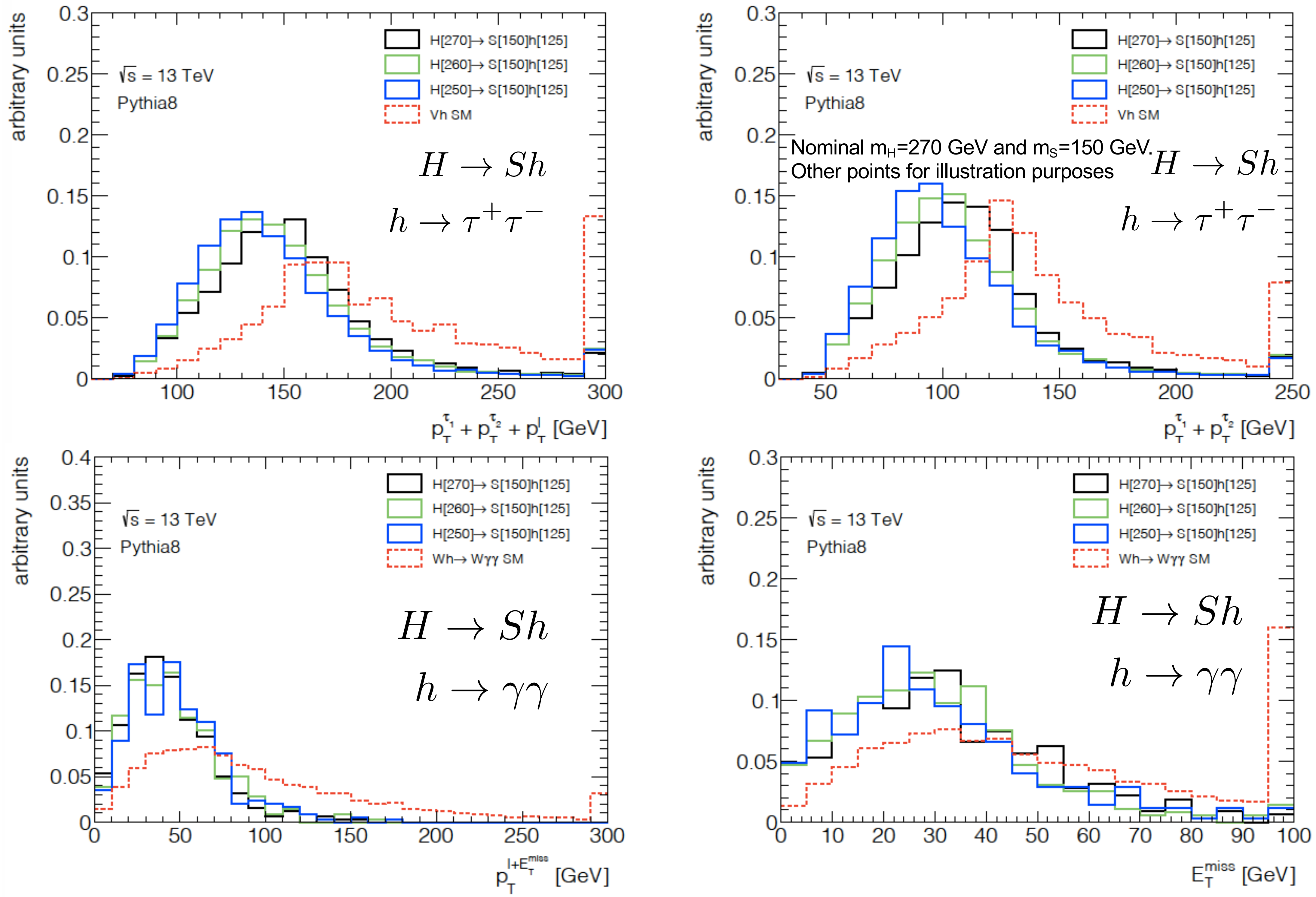
Anomalies cannot be explained by mismodelling of a particular process, e.g. ttbar production alone.

Impact on Higgs Physics

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

- ❑ **The presence of <u>extra leptons</u> 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]
Nominal m_H=270 GeV and m_S=150 GeV.
Other points for illustration purposes
$p_T^{\tau_1} + p_T^{\tau_2}$ [GeV]
Wh→ Wγγ SM
$h \to \gamma\gamma$
$p_T^{l+E_T^{miss}}$ [GeV]
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:

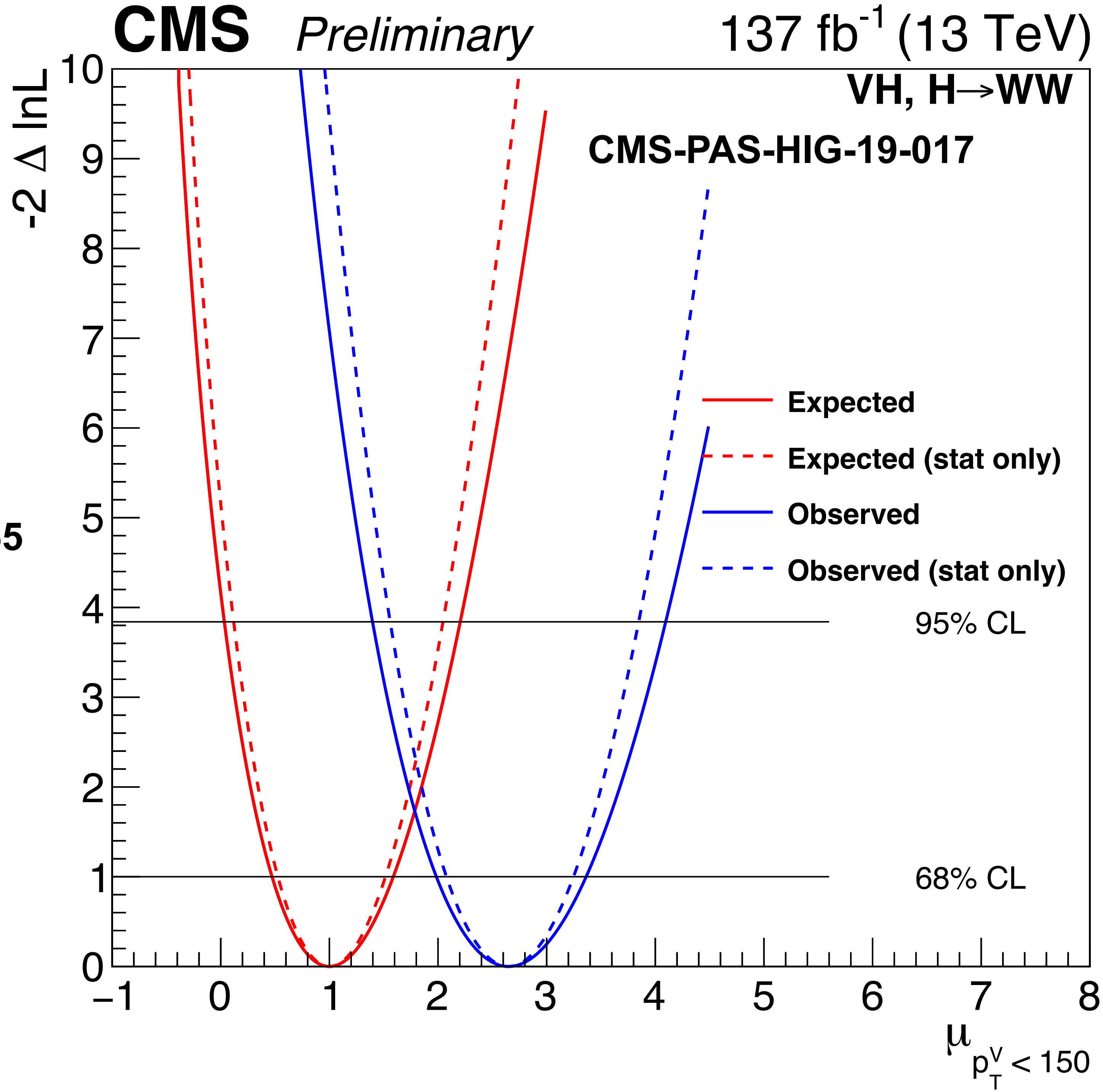
$$\mu(Wh) = 2.41 \pm 0.37$$

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%. Indicates that Br(H→SS) > Br(H→Sh)

Higgs decay	Ref.	Experiment	$\sqrt{s}$, $\mathcal{L}$ TeV, fb^{-1}	Final state	Category	μ	Used in combination	Comments
WW	[66]	ATLAS	7, 4.5; 8, 20.3	2ℓ	DFOS 2j	$2.2^{+2.0}_{-1.9}$	✓	
					SS 1j	$8.4^{+4.3}_{-3.8}$	✓	2ℓ combination: $\mu = 3.7^{+1.9}_{-1.5}$
					SS 2j	$7.6^{+6.0}_{-5.4}$	✓	
				3ℓ	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	3ℓ	1SFOS, 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	2ℓ	DFOS 2j	$0.39^{+1.97}_{-1.87}$	✓	Discrepancy at low $m_{\ell\ell}$
			8, 19.4	3ℓ	0+1SFOS	$0.56^{+1.27}_{-0.95}$	✓	
	[69]	CMS	13, 35.9	2ℓ	DFOS 2j	$3.92^{+1.32}_{-1.17}$	✓	Discrepancy at low $m_{\ell\ell}$
				3ℓ	0+1SFOS	$2.23^{+1.76}_{-1.53}$	✓	
$\tau\tau$	[70]	ATLAS	8, 20.3	1ℓ	$\ell + \tau_h\tau_h$	1.8 ± 3.1	✓	
				2ℓ	$e^\pm\mu^\pm + \tau_h$	1.3 ± 2.8	✓	
	[71]	CMS	7, 4.9	1ℓ	$\ell + \tau_h\tau_h$	-0.33 ± 1.02	x	BDT based on $p_T^{\tau_1} + p_T^{\tau_2}$
			8, 19.7	2ℓ	$e^\pm\mu^\pm + \tau_h$		x	Split $p_T^{\ell_1} + p_T^{\ell_2} + p_T^{\tau}$ at 130 GeV
	[72]	CMS	13, 35.9	1ℓ	$\ell + \tau_h\tau_h$	$3.39^{+1.68}_{-1.54}$	✓	
				2ℓ	$e^\pm\mu^\pm + \tau_h$			
$\gamma\gamma$	[73]	ATLAS	7, 5.4	$\ell\nu$	One-lepton			
				$\not\ell\nu, \nu\nu$	E_T^{miss}	1.0 ± 1.6	x	$E_T^{miss} > 70 - 100$ GeV
			8, 20.3	jj	Hadronic			$p_{Tt}^{\gamma\gamma} > 70$ GeV
	[74]	CMS	7, 5.1	$\ell\nu$	One-lepton			Split E_T^{miss} at 45 GeV
				$\not\ell\nu, \nu\nu$	E_T^{miss}	$-0.16^{+1.16}_{-0.79}$	x	$E_T^{miss} > 70$ GeV
			8, 19.7	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	$\ell\ell\ell\ell + \ell\nu$	Lep-enriched	$1.44^{+1.17}_{-0.93}$	x	Number of jets used in MVA
				$\ell\ell\ell\ell + q\bar{q}$	$2j$			m_{jj} used in MVA
	[79]	CMS	13, 137.1	$\ell\ell\ell\ell + \ell\nu$	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
				$\ell\ell\ell\ell + q\bar{q}$	$2j$	$0.57^{+1.20}_{-0.57}$	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



https://cds.cern.ch/record/2784454/files/HIG-19-014-pas.pdf

Available on the CERN CDS information server **CMS PAS HIG-19-014**

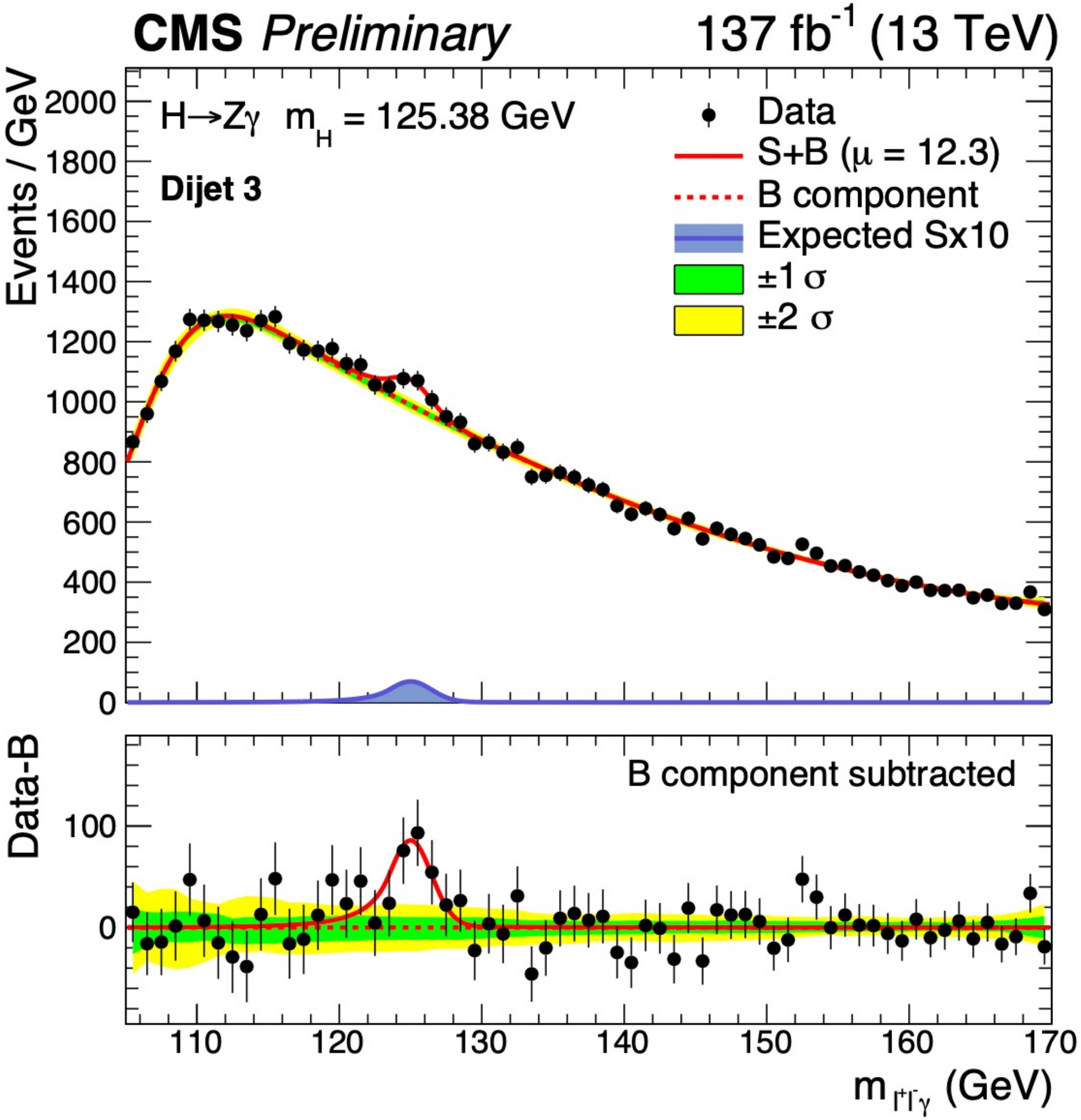
CMS Physics Analysis Summary

Contact: cms-pag-conveners-higgs@cern.ch 2021/10/19

Search for the Higgs boson decay to $Z\gamma$ in proton-proton collisions at $\sqrt{s} = 13$ TeV

The CMS Collaboration

CMS observes what appears to be an upward fluctuation of the $h \to Z\gamma$ in the di-jet bin optimized for the measurement of Wh production. The Signal strength deviates from unity by 3.2σ.

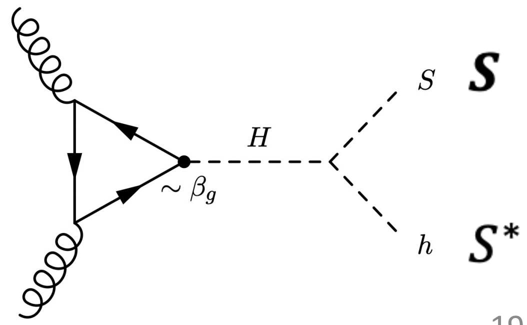


A possible candidate of S

Procedure

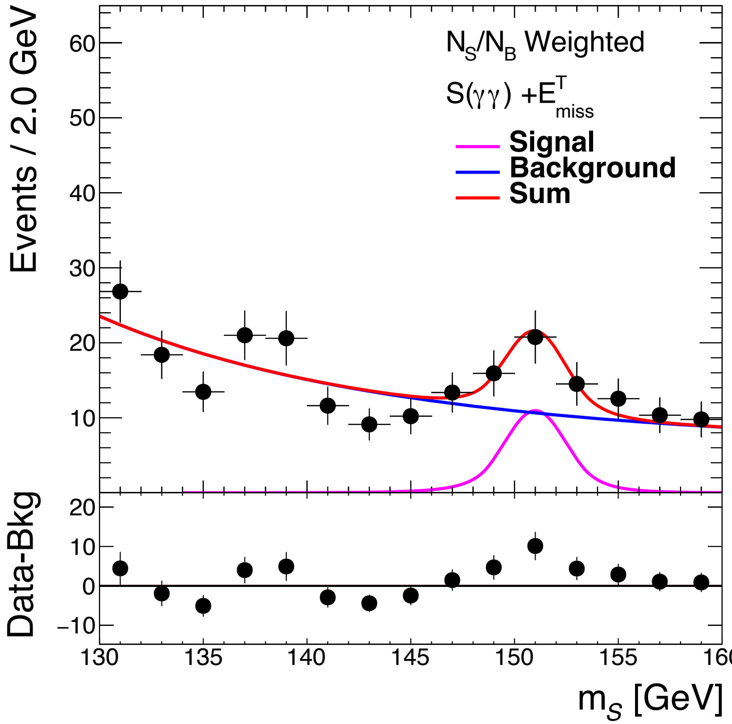
(avoiding “cherry picking”)

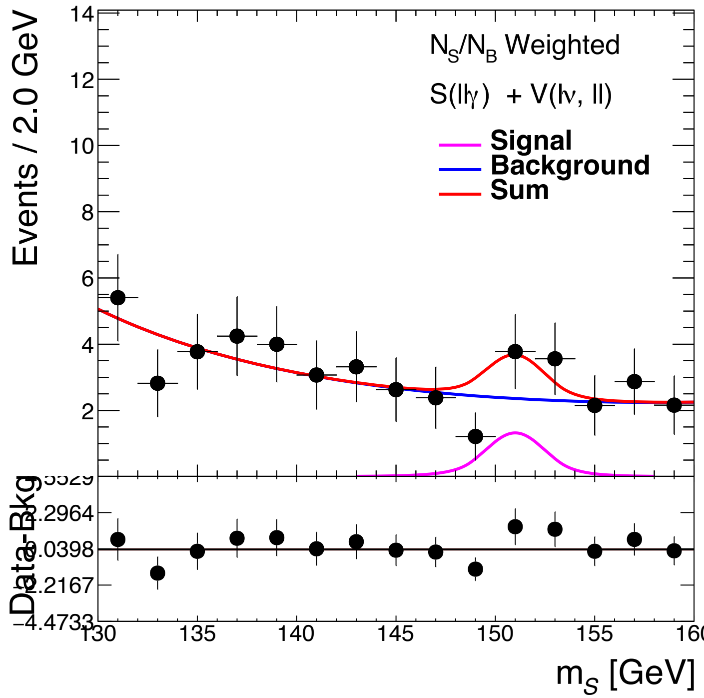
- ❑ **Setting a well-defined procedure is essential to the integrity of a search. Scanning nullifies significance**
- ❑ **From the di-lepton anomalies: $m_h < m_s < 170$ GeV**
  - ❑ **It is critical that search be localized and motivated**
- ❑ **Focus on $\gamma\gamma$ and $Z\gamma$ decays**
- ❑ **As per the model that described the multi-lepton anomalies, we select final state according to di-boson signatures. S is produced via the decay of something heavier and not directly**
  - ❑ **Re-use Higgs boson data**
  - ❑ **Remove VBF and boosted topologies**
    - **Related to direct production**

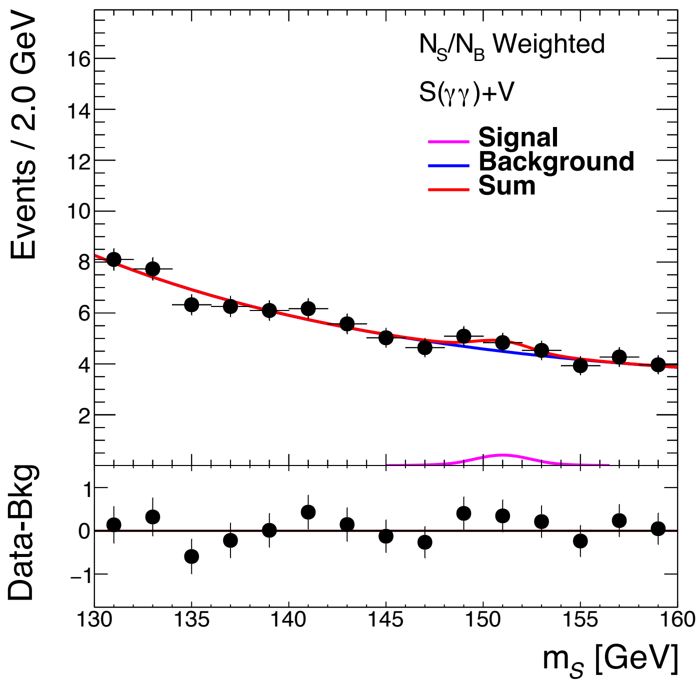


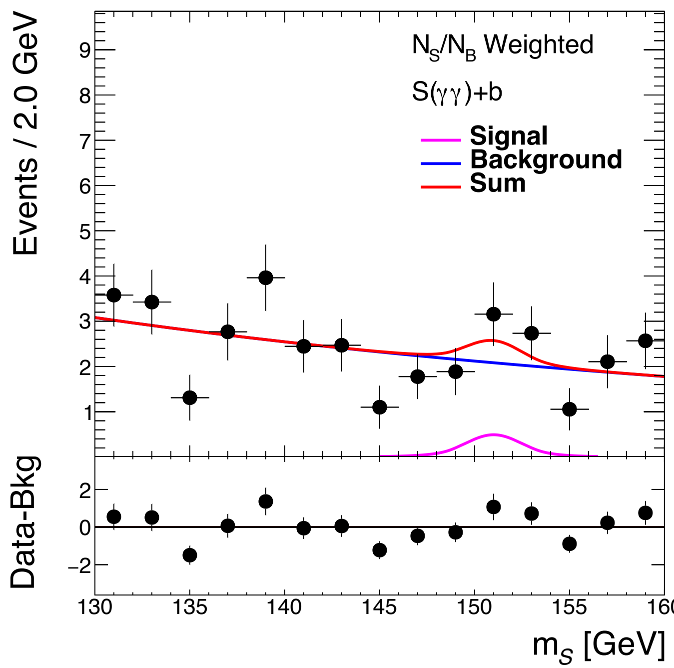
From Run 1 multi-lepton excesses model-dependent prediction of $m_s = 150 \pm 5$ GeV

A.Crivellin et al. https://arxiv.org/abs/2109.02650



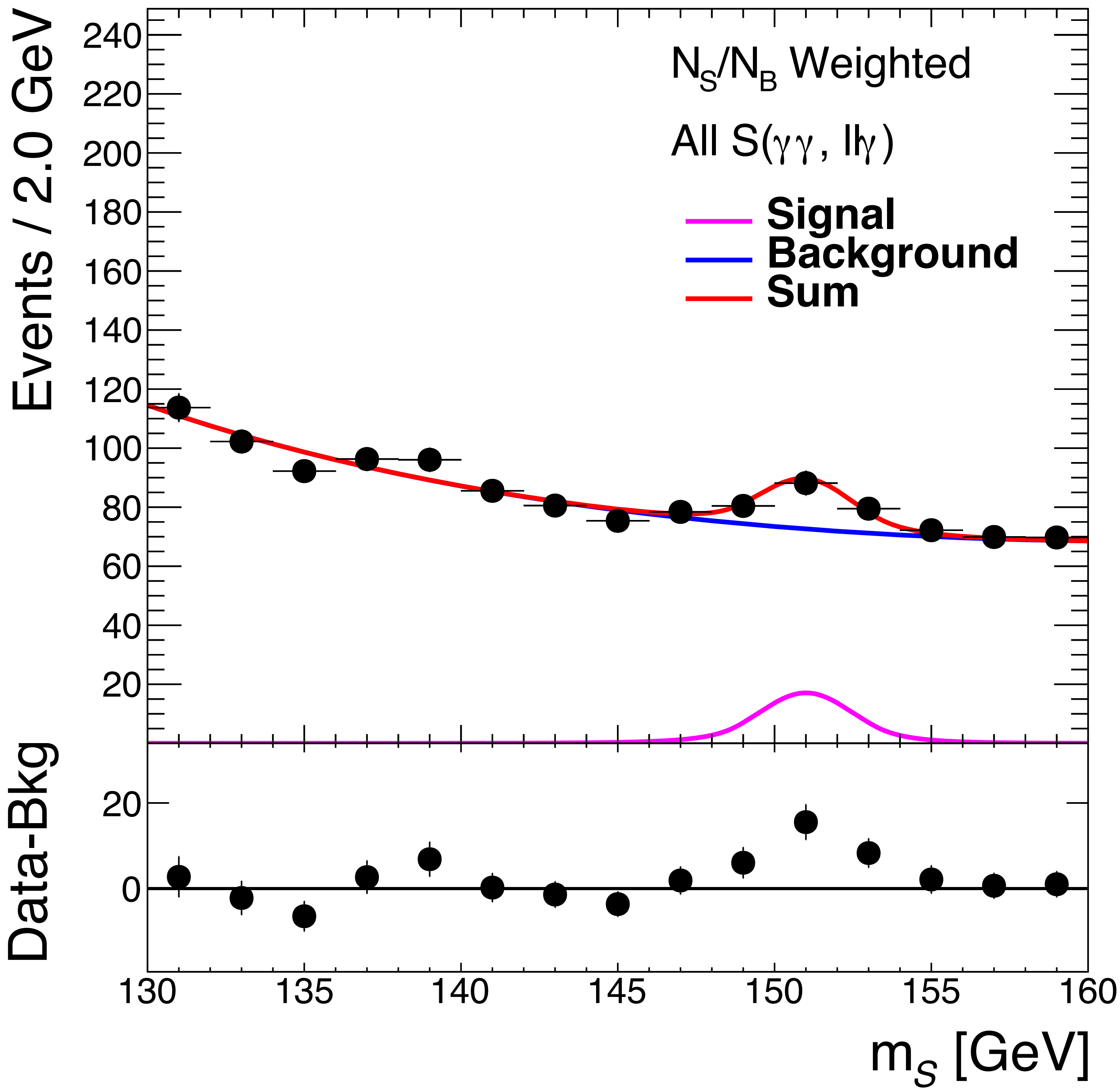




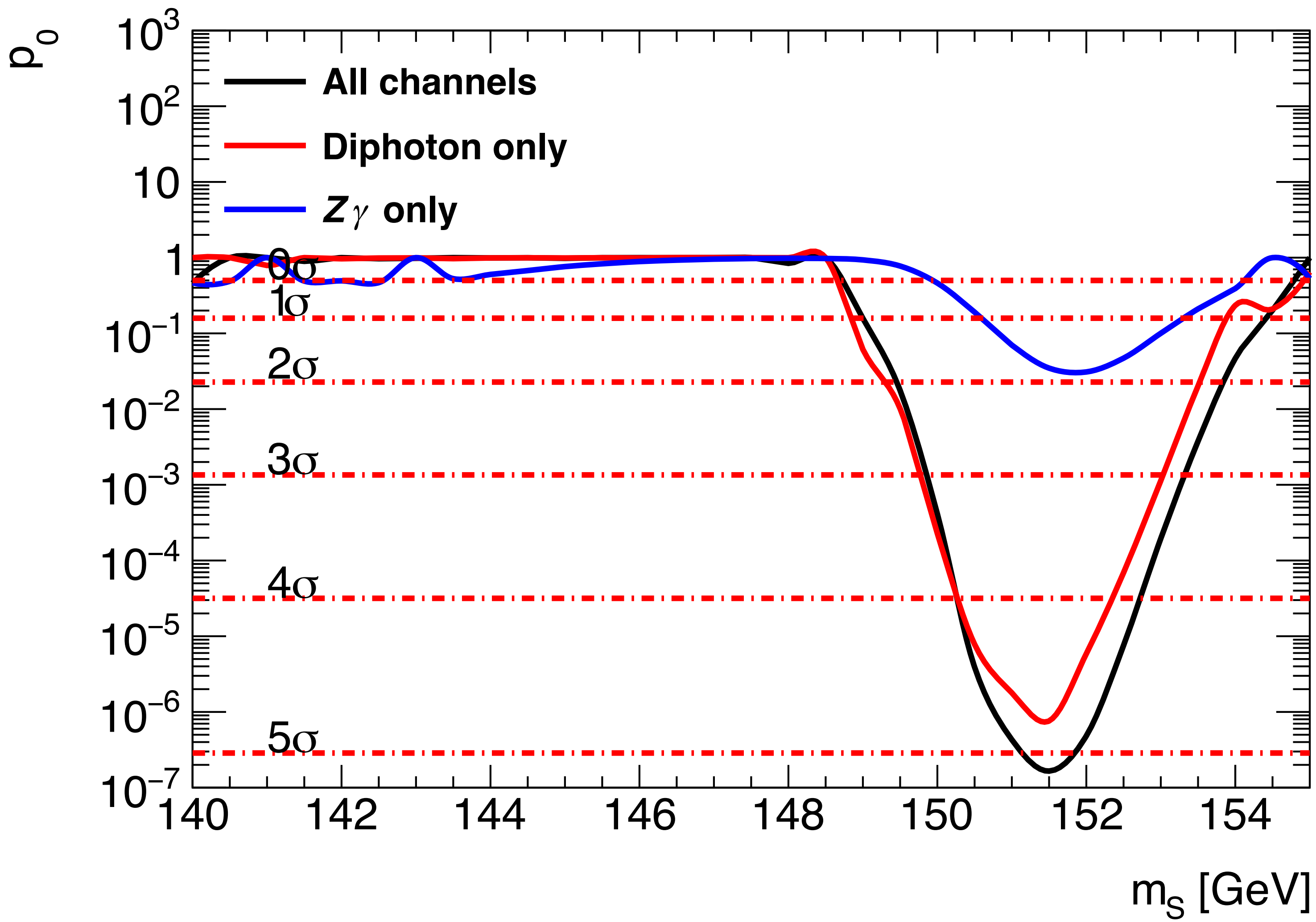


Analysis of publicly available di-photon and $Z\gamma$ spectra in associated production gives global 4.8σ excess around 151 GeV. Fiducial yields consistent with H→SS* hypothesis with m_H=270 GeV (see above)

Excess not seen in $S \rightarrow ZZ \rightarrow 4\ell, \ell = e, \mu$



Result is obtained with public results from the LHC experiments. Using a simplified model and two degrees of freedom global significance drops to ~4σ (under review).



CMS PAS HIG-20-013

CMS Physics Analysis Summary

https://cds.cern.ch/record/2803738/files/HIG-20-013-pas.pdf

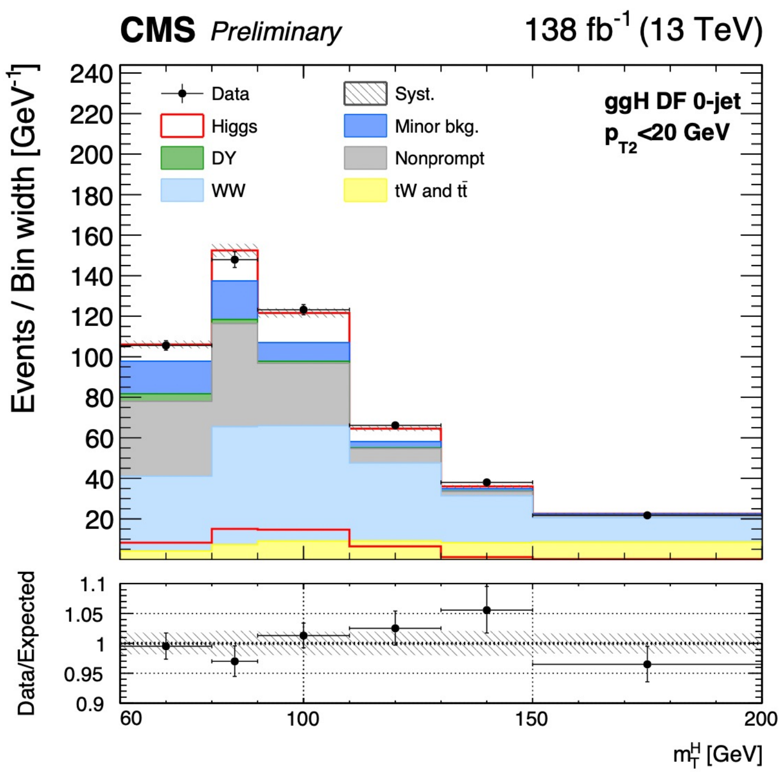
Contact: cms-pag-conveners-higgs@cern.ch

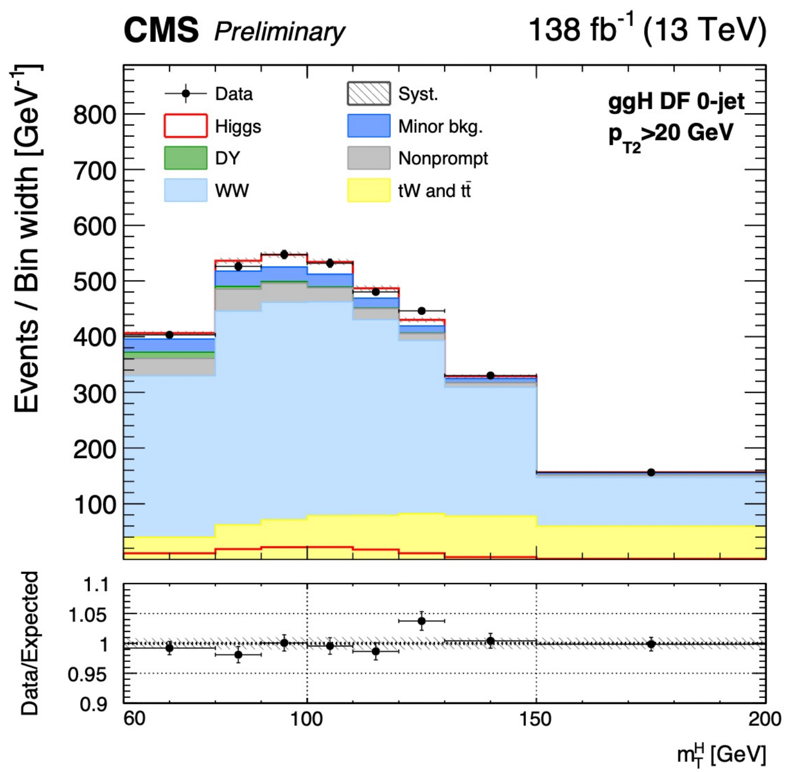
2022/03/11

Recent results with ll+MET not included above

Measurements of properties of the Higgs boson in the W boson pair decay channel in proton-proton collisions at $\sqrt{s} = 13$ TeV

The CMS Collaboration



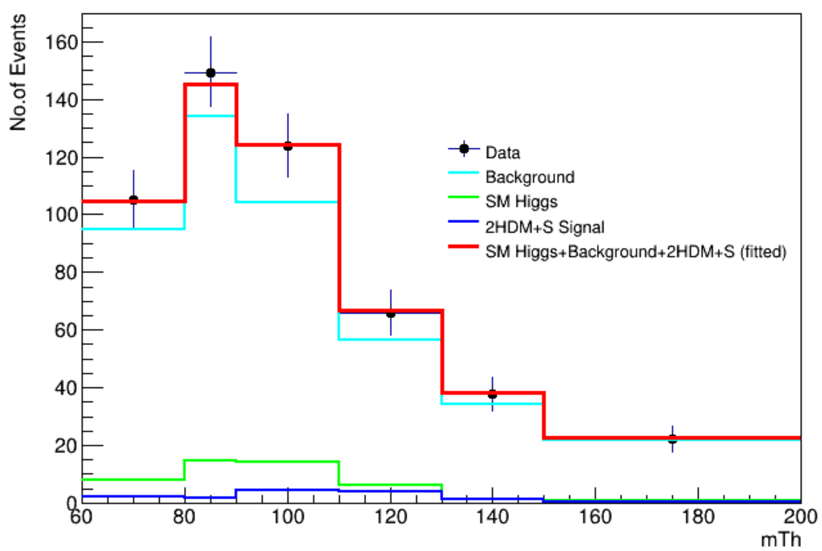


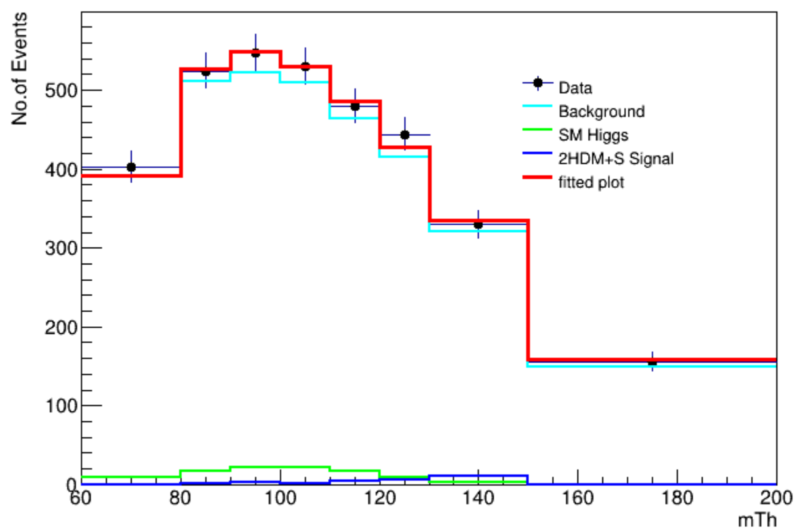
S.Bhattacharya

Contribution from a 2HDM+S signal is given by the dark blue histograms in the bottom two plots.

The BSM signal normalization of compatible for the two bins in p_{Tl2}.

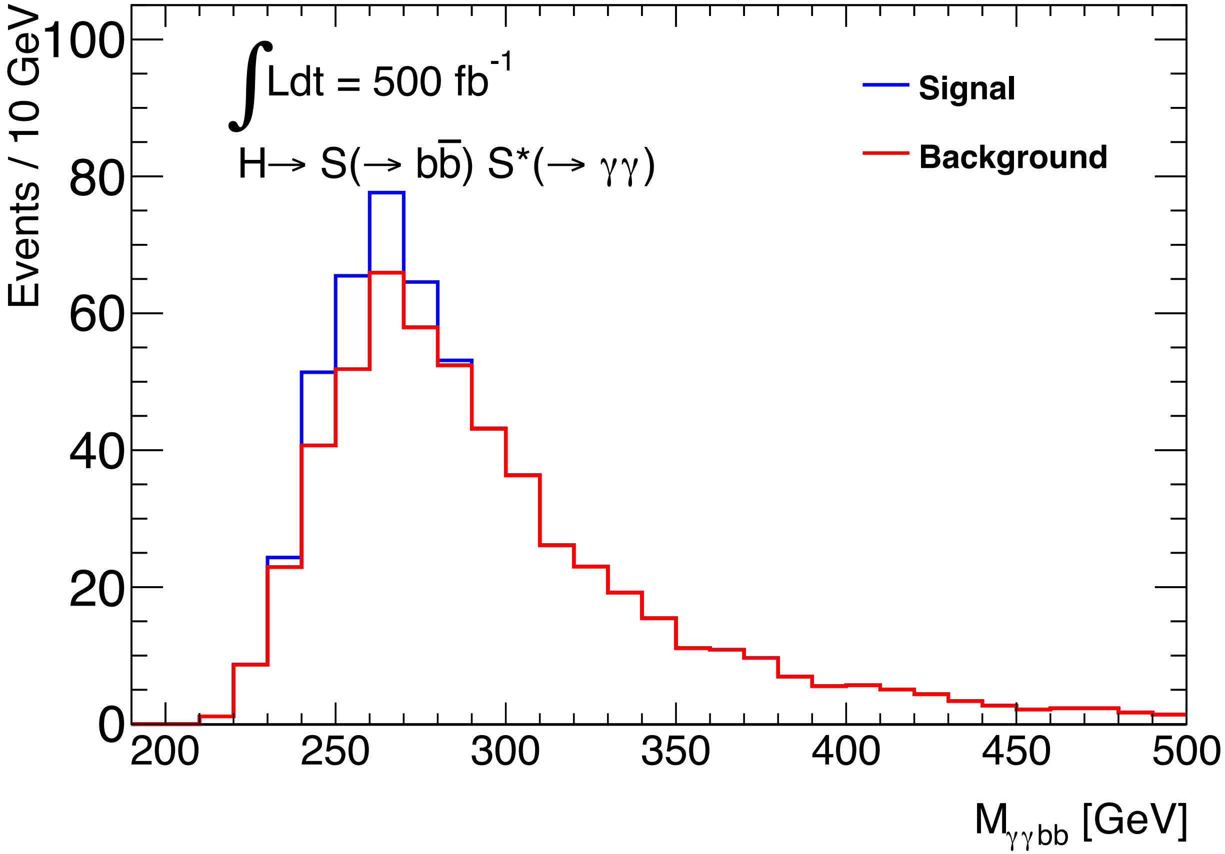
Signal extraction in the 1j bin and combination with other excesses in progress.

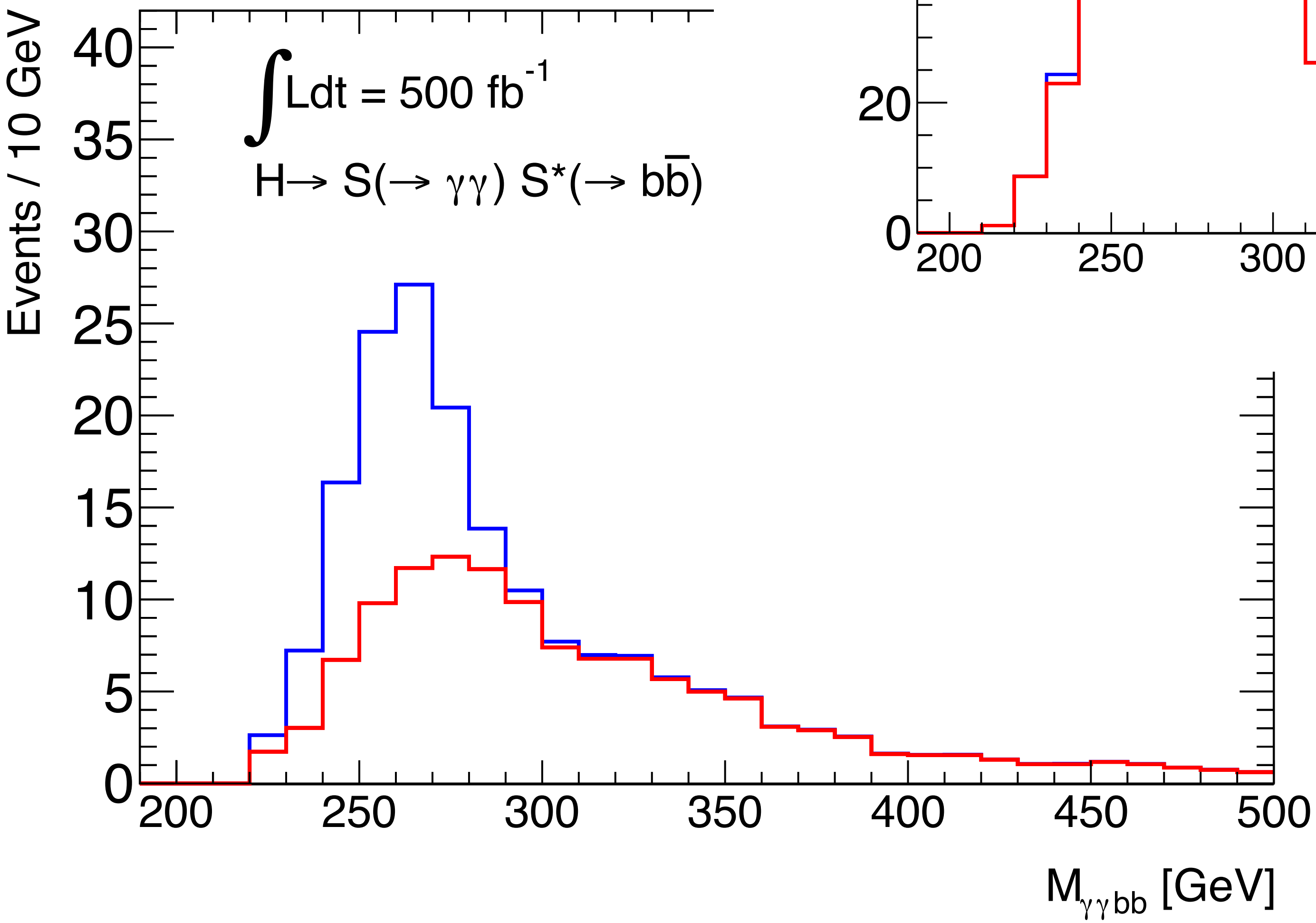




Data favors an admixture of a signal with m_S=150 GeV

Abovementioned excess further motivates searches for bosons in asymmetric $\gamma\gamma bb$ configurations not performed before at the LHC

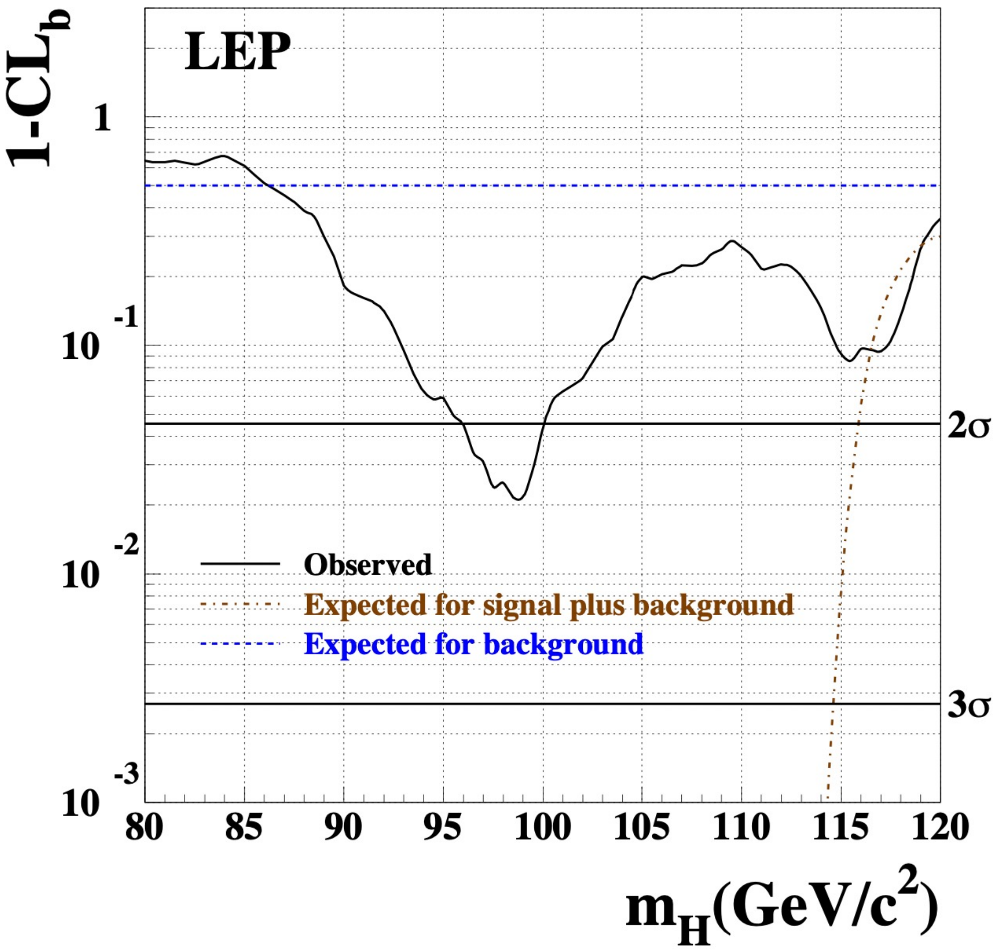




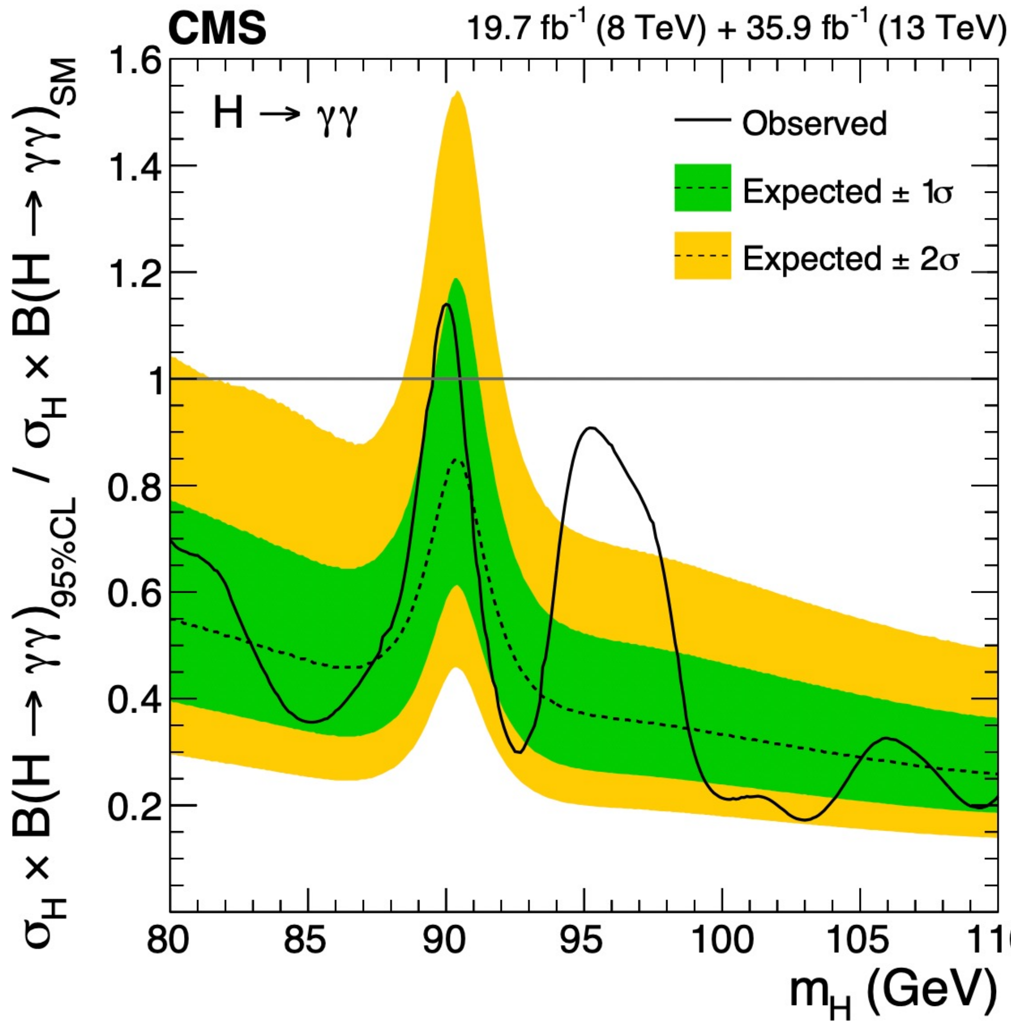
Expect more than 7σ significance for one experiment with the Run 2 + Run 3 data sets.

Some tantalizing results around 96 GeV from LEP and CMS, not contradicted by ATLAS. Interesting to see what the full Run 2 data set has to say. Further motivates asymmetric searches H→SS'…

LEP, Phys. Lett. B 565 (2003) 61–75



CMS, Phys. Lett. B 793 (2019) 320–347



Unveiling Hidden Physics at the LHC

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Outlook and Conclusions

- Discrepancies in multi-lepton final states at LHC w.r.t. current MCs are not statistical fluctuations
  - They appear in corners of the phase-space dominated by different processes (Wt/tt/4t, VV, ttV, Vh, WWW)
    - Hard to explain with MC mismodelling
  - Discrepancies interpreted with simplified model where H→SS, Sh is treated as SM Higgs-like and one parameter is floated
- Features of the Higgs data from LHC agree with predictions the simplified model used here
- Analysis of $\gamma\gamma$/Zγ spectra in associated production gives a large global excess around 151 GeV
  - Motivates H→SS*,Sh→$\gamma\gamma$bb searches, where asymmetric configurations play an important role