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Search for additional Higgs bosons at low mass with CMS

S Gascon-Shotkin

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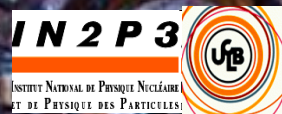
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New!

Searches for additional Higgs bosons at low mass with CMS



Suzanne GASCON-SHOTKIN
IP2i Lyon (IN2P3-CNRS)/Université Claude Bernard Lyon 1
on behalf of the CMS Collaboration

Rencontres de Moriond EW 2023

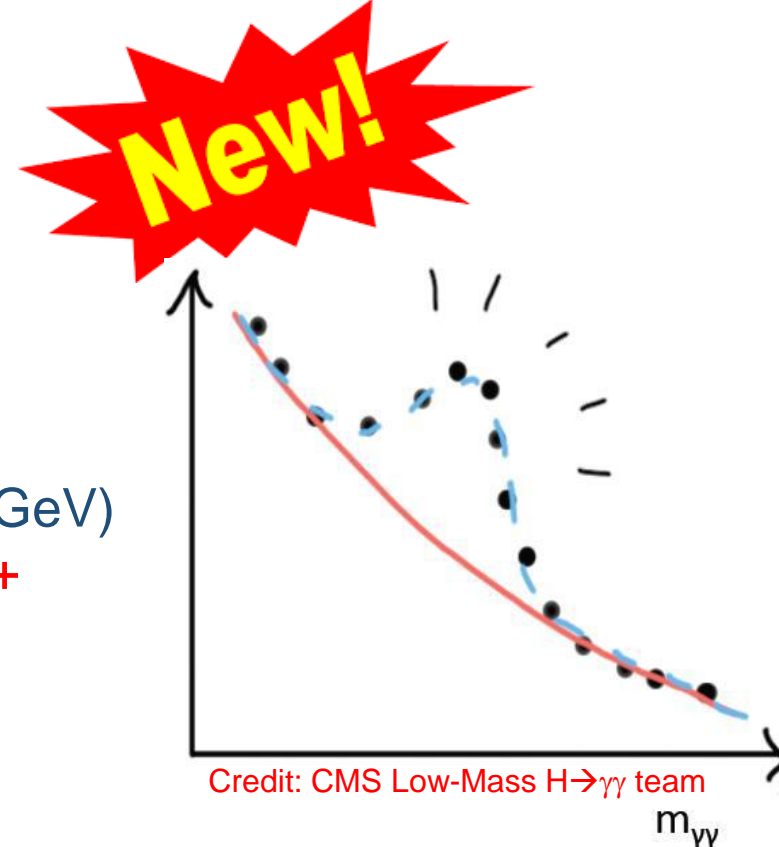
March 23, 2023 Hotel Planibel, LA THUILE (IT)





Outline

- Three new CMS searches for additional low-mass Higgs bosons presented here for the first time!
- All using full LHC Run 2 data!
 - Exotic SM-like $H_{125} \rightarrow a_1 a_1 \rightarrow \mu\mu bb$ or $\tau\tau bb$ ($12 \text{ GeV} < m_{a_1} < 62.5 \text{ GeV}$)
CMS-PAS-HIG-22-007 (includes CMS-PAS-HIG-21-021 ($\mu\mu bb$) + combination) Motivated by significant BR in 2HDM + S models
<http://cds.cern.ch/record/2853298?ln=en>
 - SM-like $H \rightarrow \gamma\gamma$ ($70 \text{ GeV} < m_H < 110 \text{ GeV}$)
CMS-PAS-HIG-20-002 Allowed in many BSM models
<http://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/HIG-20-002/>
 - LFV SM (H_{125}) or SM-like Exotic $X \rightarrow e\mu$ ($110 \text{ GeV} < m_X < 160 \text{ GeV}$)
CMS-PAS-HIG-22-002 Exotic case with $m_X < 2m_W$ motivated by potential constraints on Type III 2HDM
<http://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/HIG-22-002/index.html>
- Conclusion and perspectives
- Acknowledgements





Exotic SM-like $H_{125} \rightarrow a_1 a_1 \rightarrow \mu\mu bb$ or $\tau\tau bb$ ($12 \text{ GeV} < m_{a_1} < 62.5 \text{ GeV}$)

<http://cds.cern.ch/record/2853298?ln=en>

CMS-PAS-HIG-22-007

- Principal backgrounds: DY, ttbar, single t, dibosons
- $H \rightarrow a_1 a_1 \rightarrow \mu\mu bb$ (CMS-PAS-HIG-21-021)

- Exploit $\chi_{bb} = \frac{(m_{bb} - m_{\mu\mu})}{\sigma_{bb}}$, and $\chi_H = \frac{(m_{\mu\mu bb} - 125)}{\sigma_H}$

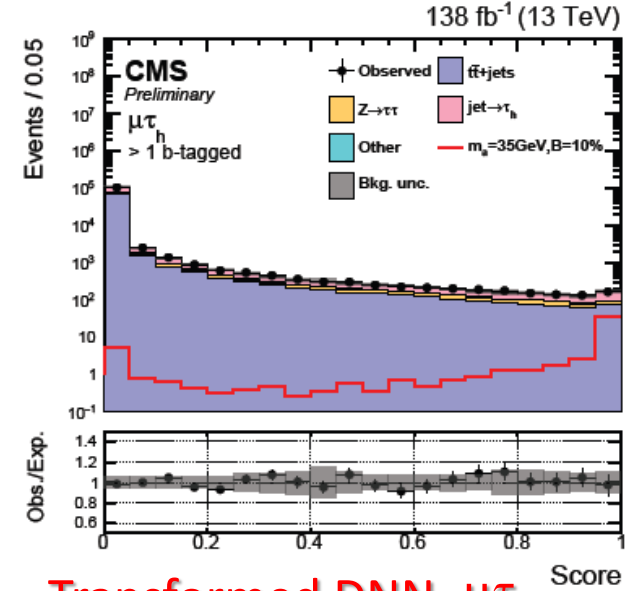
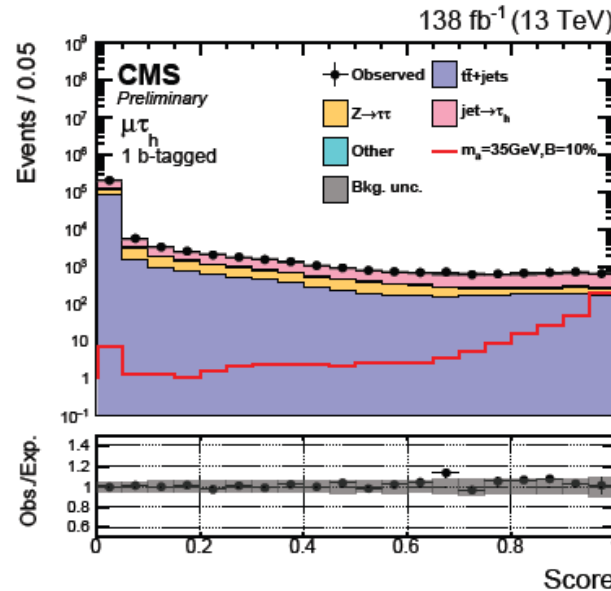
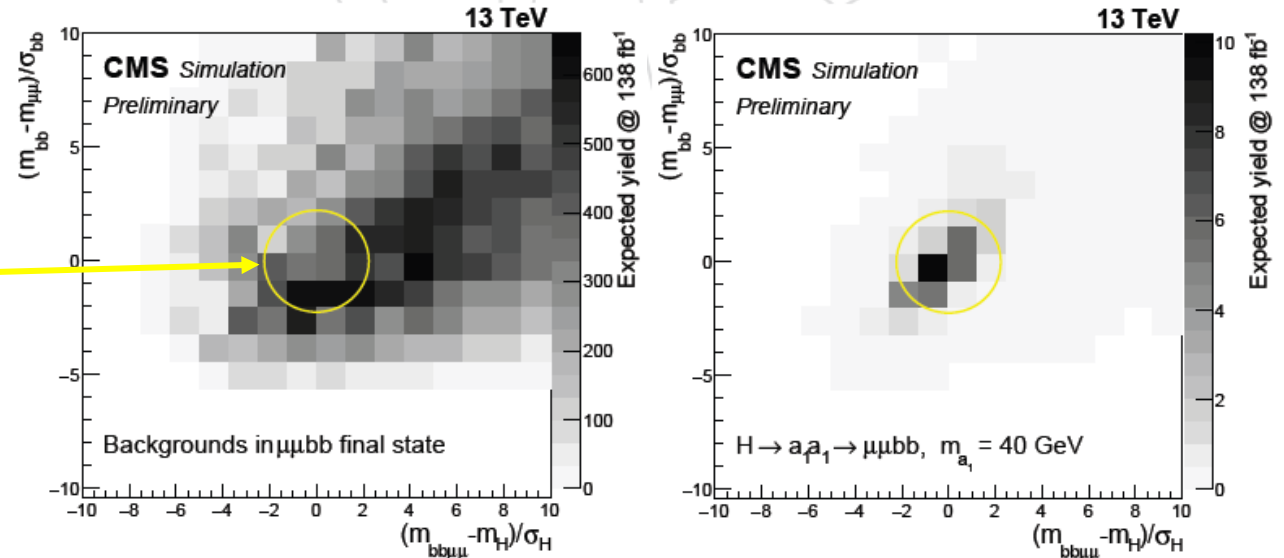
with requirement on $\chi_{tot}^2 = \chi_{bb}^2 + \chi_H^2$

- 5 event categories based on jet p_T , b-tag scores, additional jet activity
- Data-driven background modeling
- Unbinned ML fit to $m_{\mu\mu}$ distribution



- $H \rightarrow a_1 a_1 \rightarrow \tau\tau bb$ with $\mu\tau_h$, $e\tau_h$, $e\mu$ channels

- Exploit DNNs with important discriminating variables: $m_{b\tau\tau}$, transverse mass (ℓ , p_{Tmiss}) (both smaller for signal), $D_\zeta \equiv p_\zeta - 0.85 p_\zeta^{vis}$ where ζ is bisector of directions of visible τ decay products transverse to beam (small for DY, large for ttbar),
- 14 event categories based on 1, >1 b-jets, DNN
- Mostly data-driven background modeling
- Binned ML fit to $m_{\tau\tau}$ distribution



Transformed DNN $\mu\tau_h$



Exotic SM-like $H_{125} \rightarrow a_1 a_1 \rightarrow \mu\mu bb$ or $\tau\tau bb$ ($12 \text{ GeV} < m_{a_1} < 62.5 \text{ GeV}$)

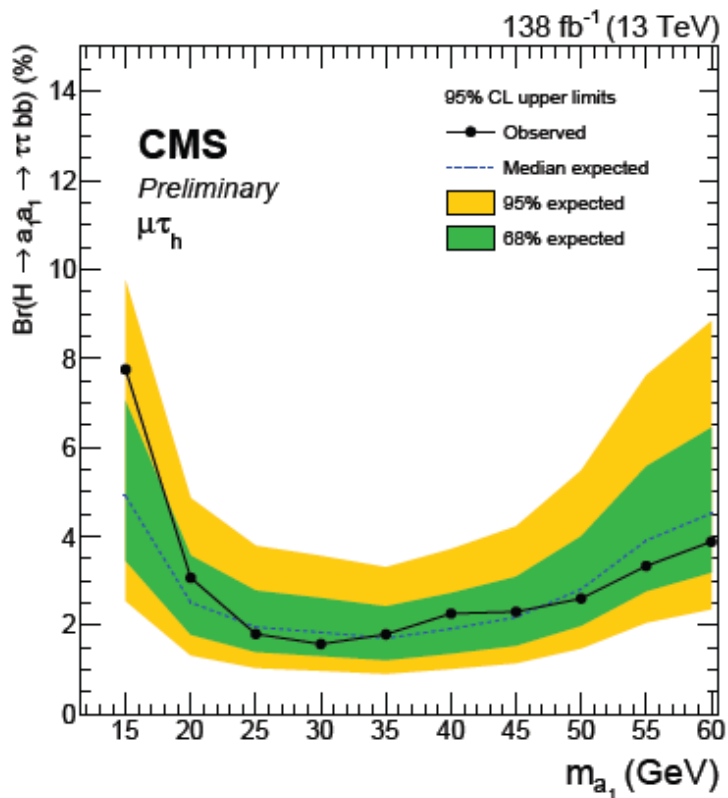
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CMS-PAS-HIG-22-007

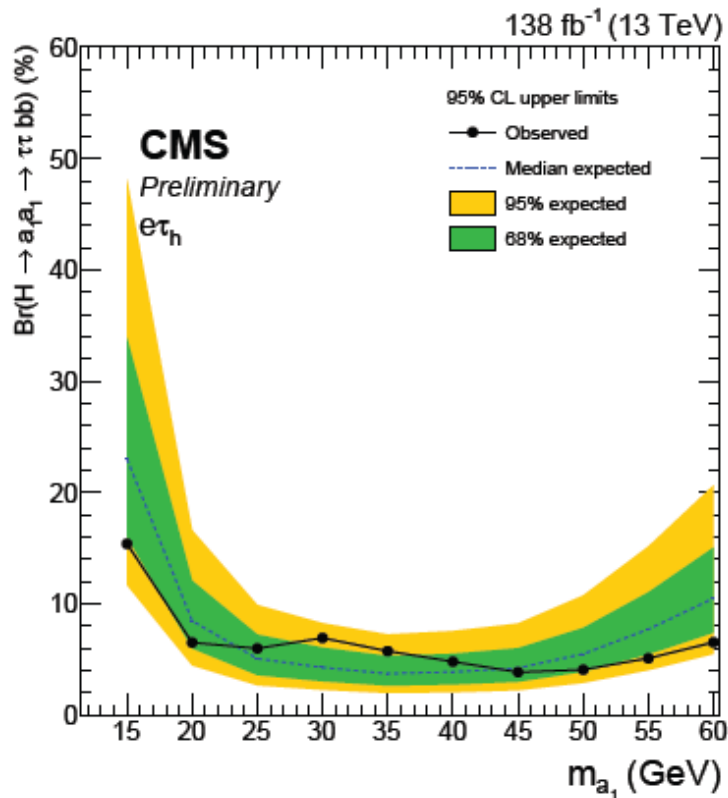


- 95% CL UL on $B(H \rightarrow a_1 a_1 \rightarrow \tau\tau bb)$

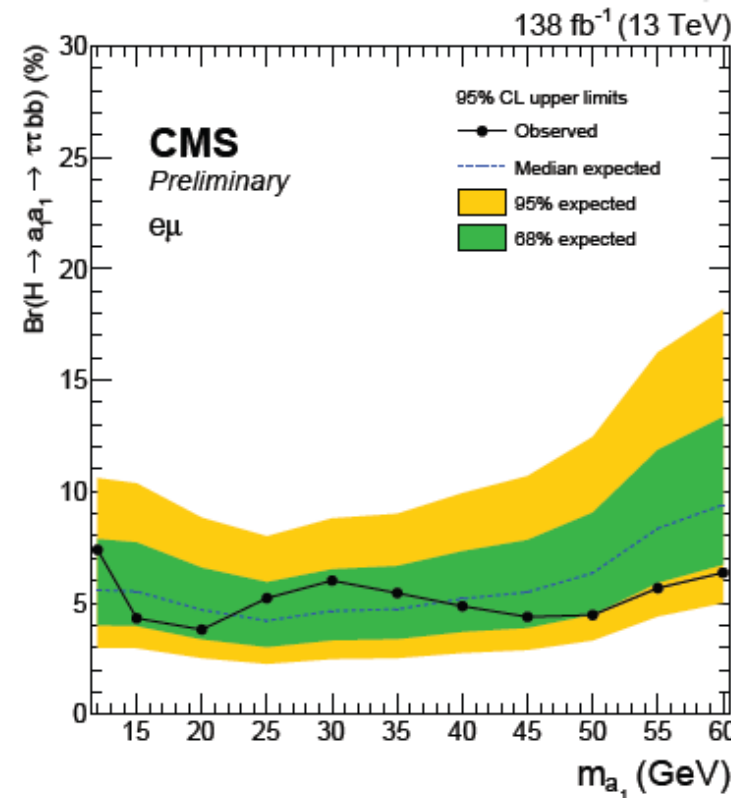
$\mu\tau_h$



$e\tau_h$



$e\mu$



- Most sensitive channel, limits as low as 1.4%

- Only channel providing sensitivity down to $m_{a_1} = 12 \text{ GeV}$



Exotic SM-like $H_{125} \rightarrow a_1 a_1 \rightarrow \mu\mu bb$ or $\tau\tau bb$ ($12 \text{ GeV} < m_{a_1} < 62.5 \text{ GeV}$)

<http://cds.cern.ch/record/2853298?ln=en>

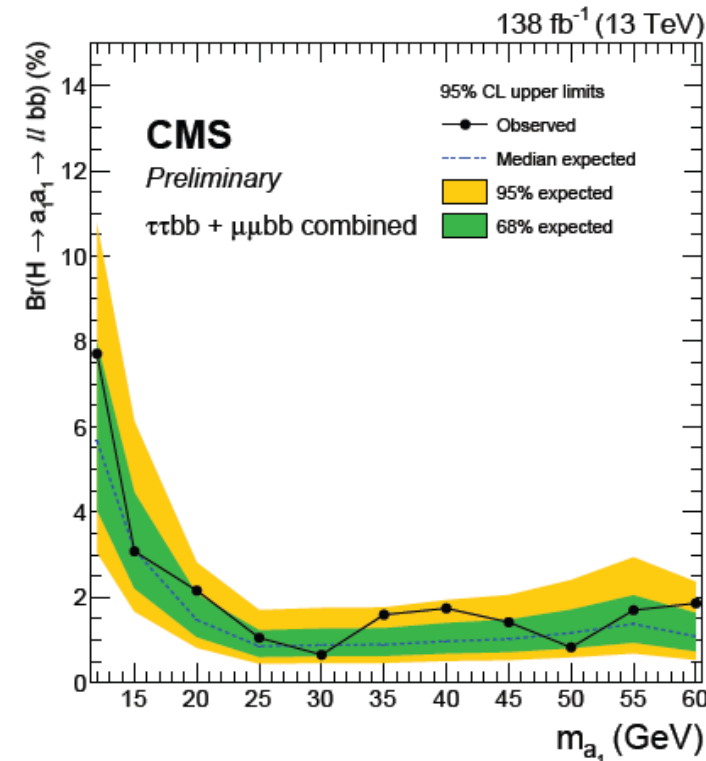
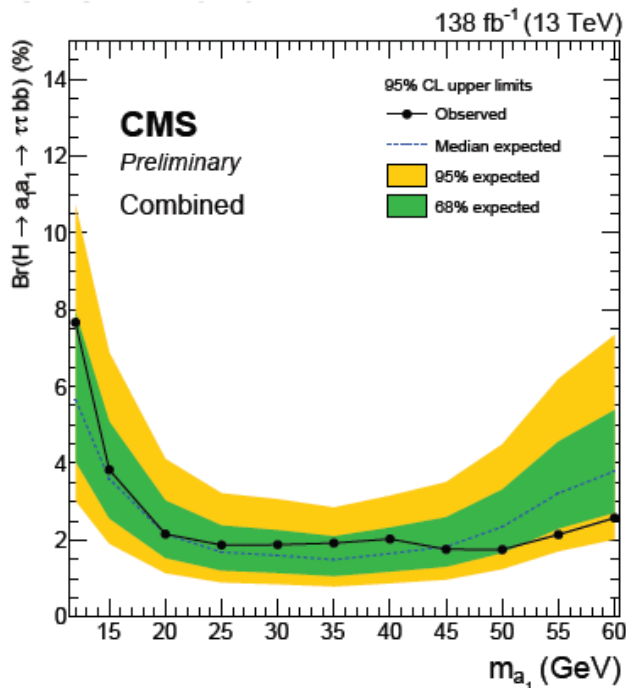
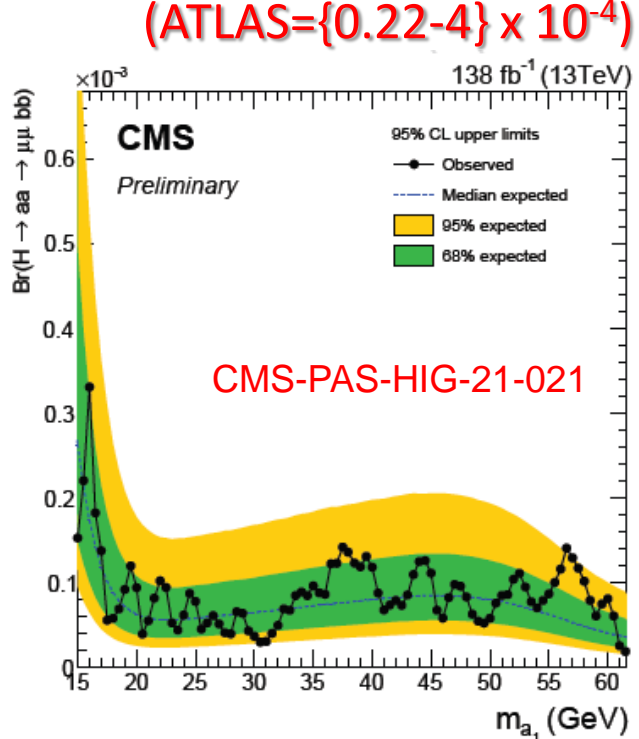


CMS-PAS-HIG-22-007

- 95% CL UL on : $B(H \rightarrow a_1 a_1 \rightarrow \mu\mu bb)$
 $= \{0.17-3.3\} \times 10^{-4}$
 (ATLAS = $\{0.22-4\} \times 10^{-4}$)

- $B(H \rightarrow a_1 a_1 \rightarrow \tau\tau bb)$
 $= \{1.7-7.6\} \times 10^{-2}$

- $B(H \rightarrow a_1 a_1 \rightarrow \ell\ell bb)$ combination
 $= \{0.7-7.7\} \times 10^{-2}$



Principal systematic uncertainties

Source	Uncertainty on best-fit signal strength [%]
JES variation in $\mu\mu bb$ signal samples	11
Signal theoretical uncertainty	6
QCD normalization in $\tau\tau bb$ channel in 2017	3
QCD normalization in $\tau\tau bb$ channel in 2018	3
$t\bar{t}$ +jets cross section normalization in $\tau\tau bb$ channel	3

- Limits improved wrt expectation from lumi increase: Improvements to χ^2 method for $\mu\mu bb$ and use of DNN for $\tau\tau bb$
- First $H_{125} \rightarrow a_1 a_1 \rightarrow \mu\mu(\tau\tau)bb$ results with Full Run 2!

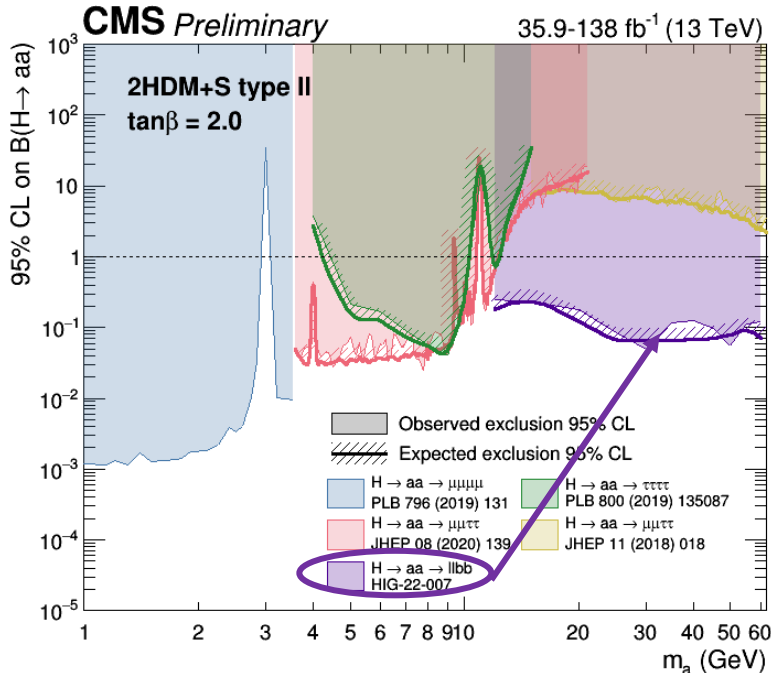


Exotic SM-like $H_{125} \rightarrow a_1 a_1 \rightarrow \mu\mu bb$ or $\tau\tau bb$ ($12 \text{ GeV} < m_{a_1} < 62.5 \text{ GeV}$)

<http://cds.cern.ch/record/2853298?ln=en> CMS-PAS-HIG-22-007

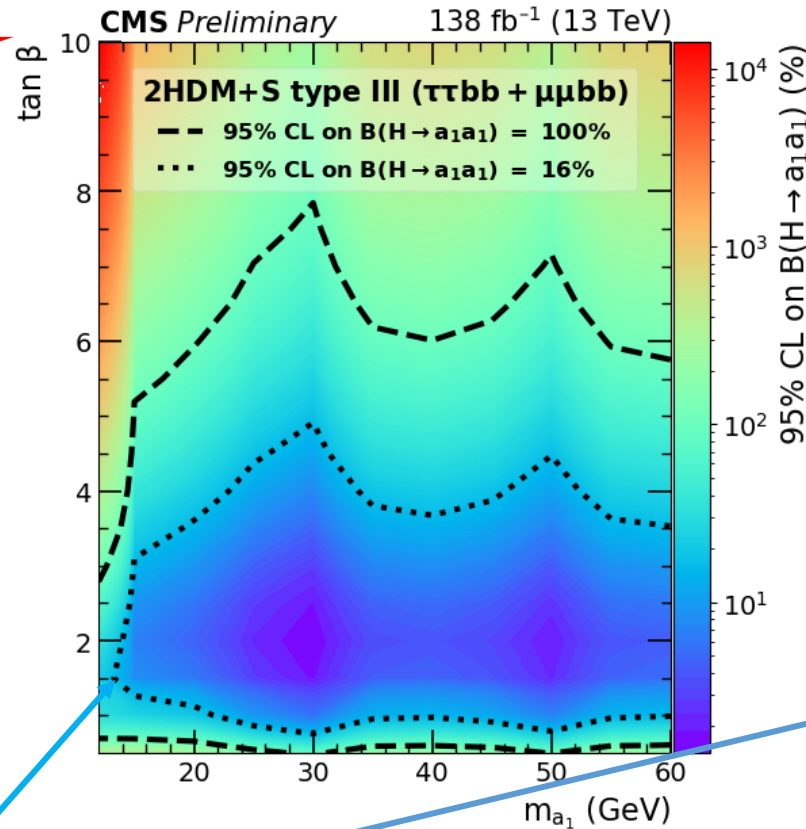
- Interpretations in 2HDM +S : **95% CL UL on $B(H \rightarrow a_1 a_1 \rightarrow \ell bb)$ with $\ell = \{\mu, \tau\}$ in $(\tan\beta, m_{a_1})$ plane**

- **Type II : $B(H \rightarrow a_1 a_1) > 0.23$ excluded @95% CL**

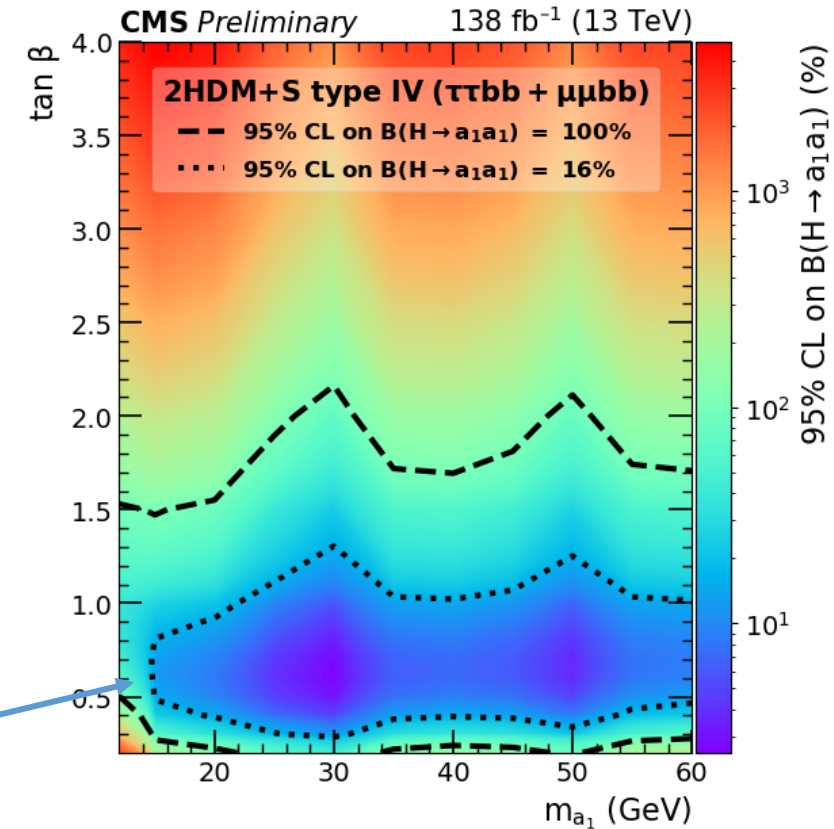


<https://twiki.cern.ch/twiki/bin/view/CMSPublic/Summary2HDMRun2>

- **Types III and IV: 95% UL on $B(H \rightarrow a_1 a_1)$: contours@16%: combined upper limit on $H_{125} \rightarrow BSM$ in Run 2 (Nature 607 (jul, 2022) 60–68)**



- **Type III with tan β =2.0: 95% UL on $B(H \rightarrow a_1 a_1)$ between 0.07 and 0.01**



- **Type IV with tan β =0.6: 95% UL on $B(H \rightarrow a_1 a_1)$ between 0.23 and 0.05**



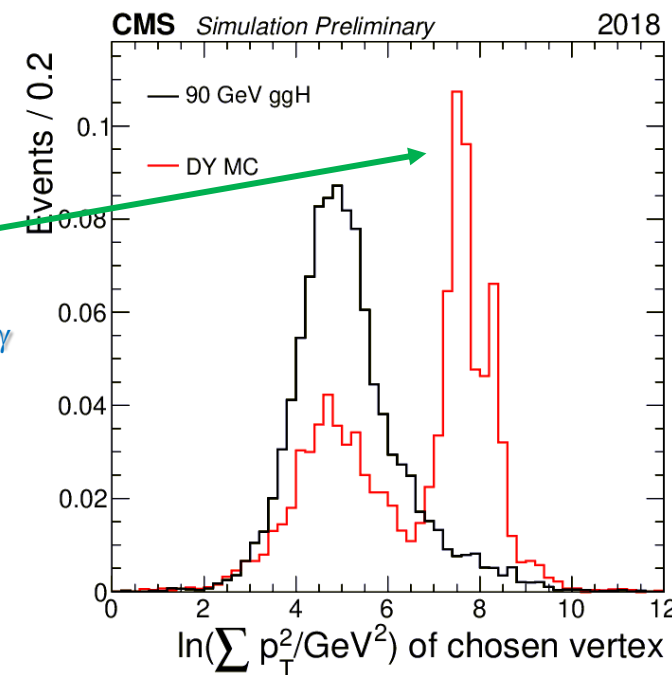
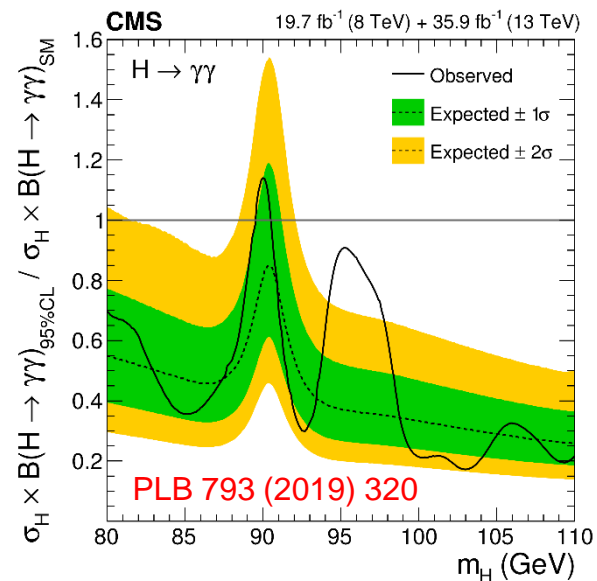
New!

SM-like $H \rightarrow \gamma\gamma$ ($70 \text{ GeV} < m_H < 110 \text{ GeV}$)

<http://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/HIG-20-002/>

CMS-PAS-HIG-20-002

- Search for narrow signal peak over smoothly-falling background (direct $\gamma\gamma$, reducible $\gamma + \text{jet}$, jet+jet processes) except for relic $Z \rightarrow ee$
- Event reconstruction/selection, γ ID techniques (BDTs), signal and data-driven background modeling with discrete profiling method inherited from SM $H \rightarrow \gamma\gamma$ analysis
- Major changes wrt prior version (PLB 793 (2019) 320) (2012+2016 data):
 - Kinematic event selection BDT ($p_T/m_{\gamma\gamma}$, η , $\cos(\phi_1 - \phi_2)$, both PhotonID BDT outputs, mass resolution wrt correct and incorrect vertices, vertex probability) reoptimized and events categorized for low-mass case
 - Electron/relic $Z \rightarrow ee$ veto (based on pixel detector hits) reinforced with:
 - Rejection of photon candidates also reconstructed as electrons
 - Maximum value of $\ln(\sum p_T^2 / \text{GeV}^2)$ [tracks in chosen vertex] as function of $p_{T\gamma\gamma}$
 - 2017/18: Events with additional jets selected for class targeting VBF process
 - 2016: data reanalyzed with improved calibration
- Major systematic uncertainties: per-photon energy resolution <20%, renormalization and factorization scales <14%, UE modeling <27%, PS <16%, JES corrections (VBF class) <16%.





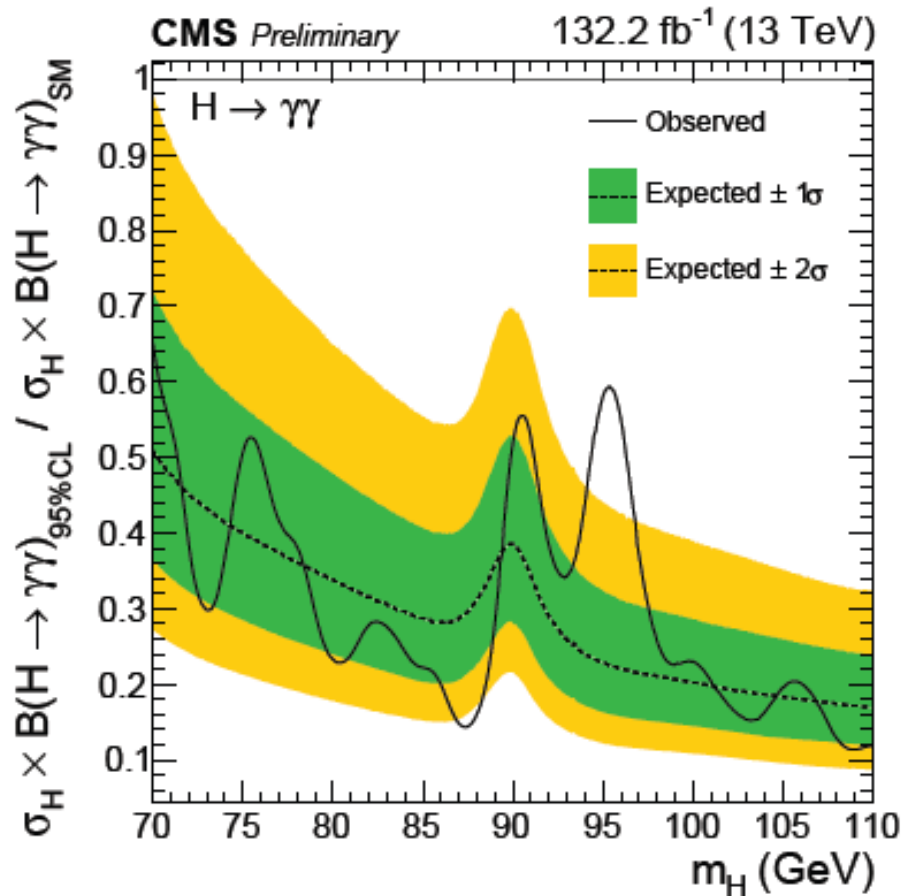
New!

SM-like $H \rightarrow \gamma\gamma$ ($70 \text{ GeV} < m_H < 110 \text{ GeV}$)

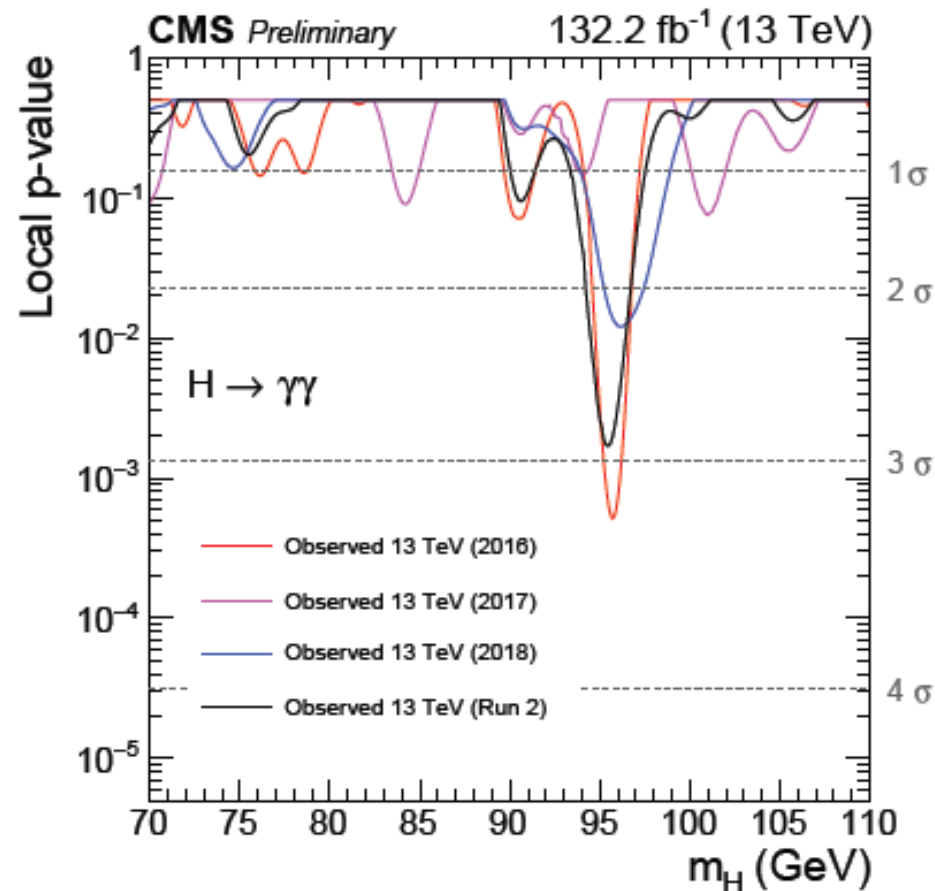
CMS-PAS-HIG-20-002

<http://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/HIG-20-002/>

- Observed and expected 95% CL UL on $\sigma \times B$ relative to SM-like expectation (production processes assumed in SM proportions)



- Observed local p-values for 2016, 2017, 2018 and combination



- Modest excess with $\sim 2.9\sigma$ local (1.3σ global) significance at $m_{\gamma\gamma} = 95.4 \text{ GeV}$, more data needed to conclude!

- Observed absolute 95% CL UL on $\sigma \times B$ between 15-73 fb

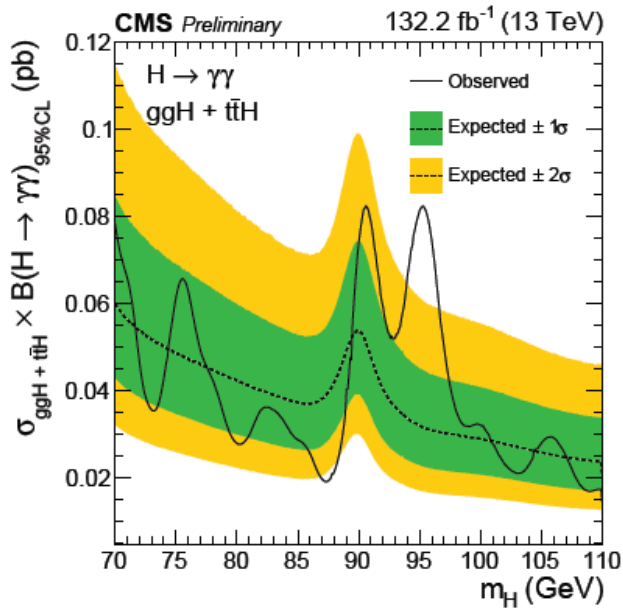


SM-like $H \rightarrow \gamma\gamma$ ($70 \text{ GeV} < m_H < 110 \text{ GeV}$)

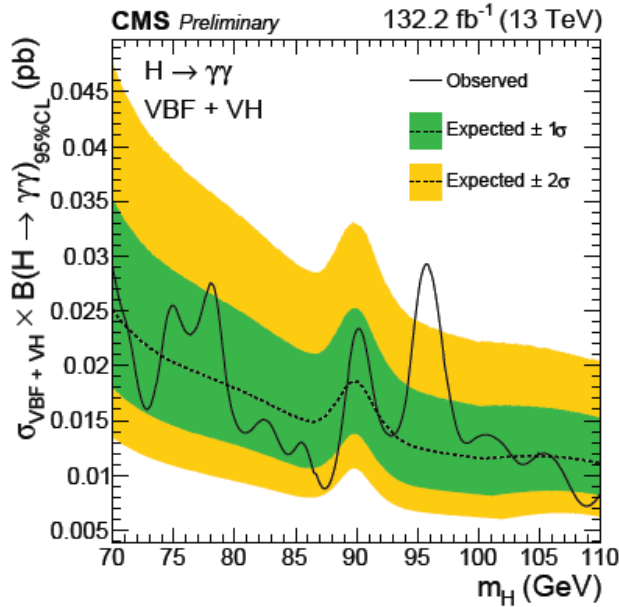
CMS-PAS-HIG-20-002

<http://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/HIG-20-002/>

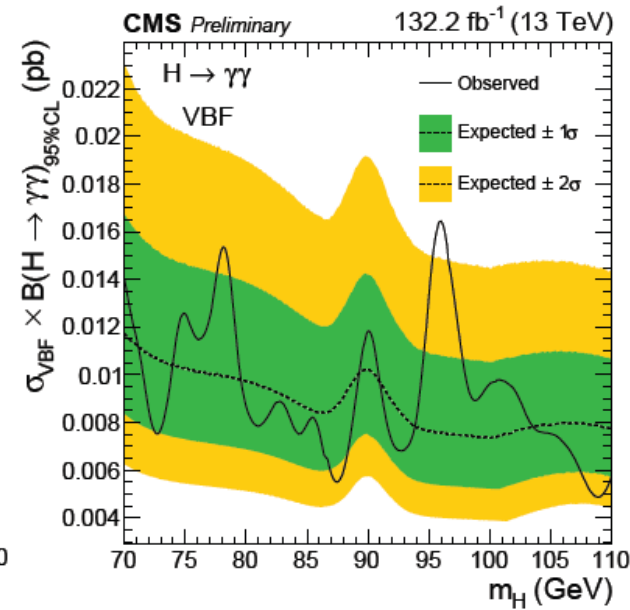
- Observed and expected 95% CL limits on $\sigma \times B$ by production process (integrated over all event classes)



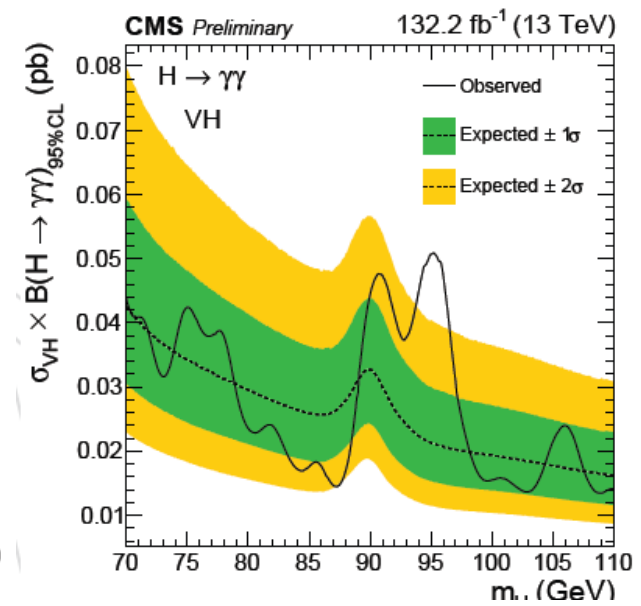
- 100% production via gluon-induced processes (ggH, $t\bar{t}H$ in SM proportions)



- 100% production via fermion-induced processes (VBF, VH in SM proportions)



- 100% production via VBF



- 100% production via VH



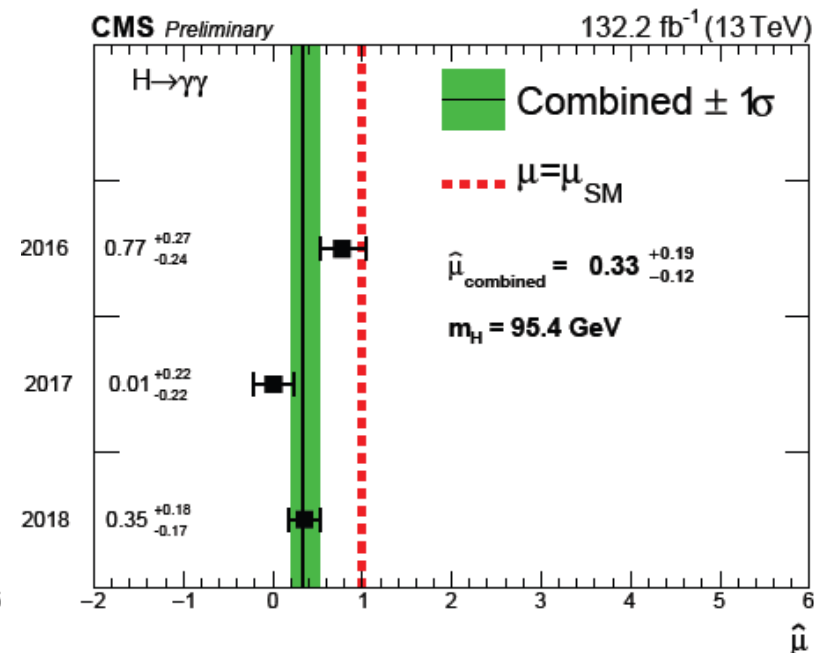
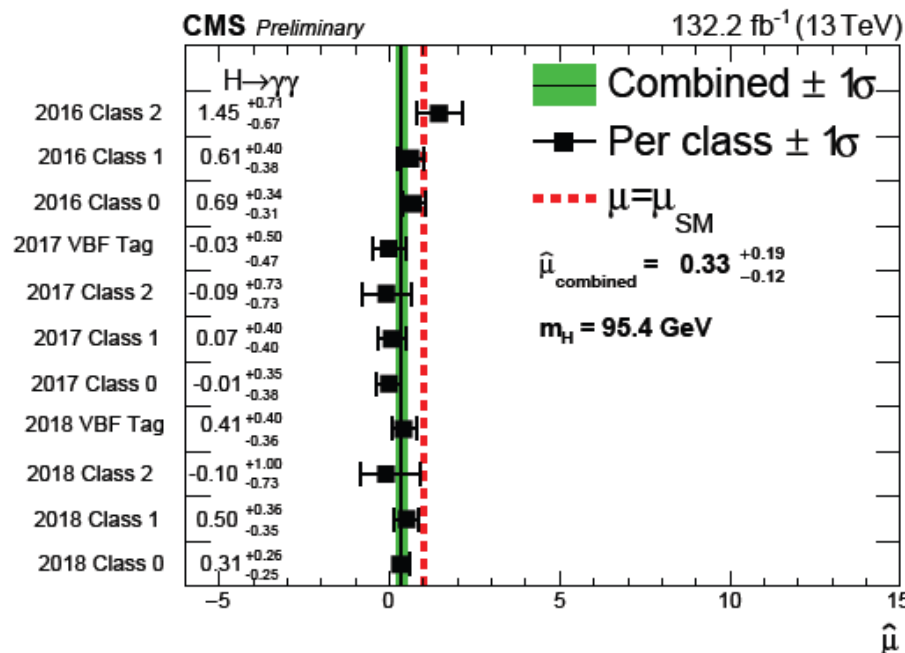
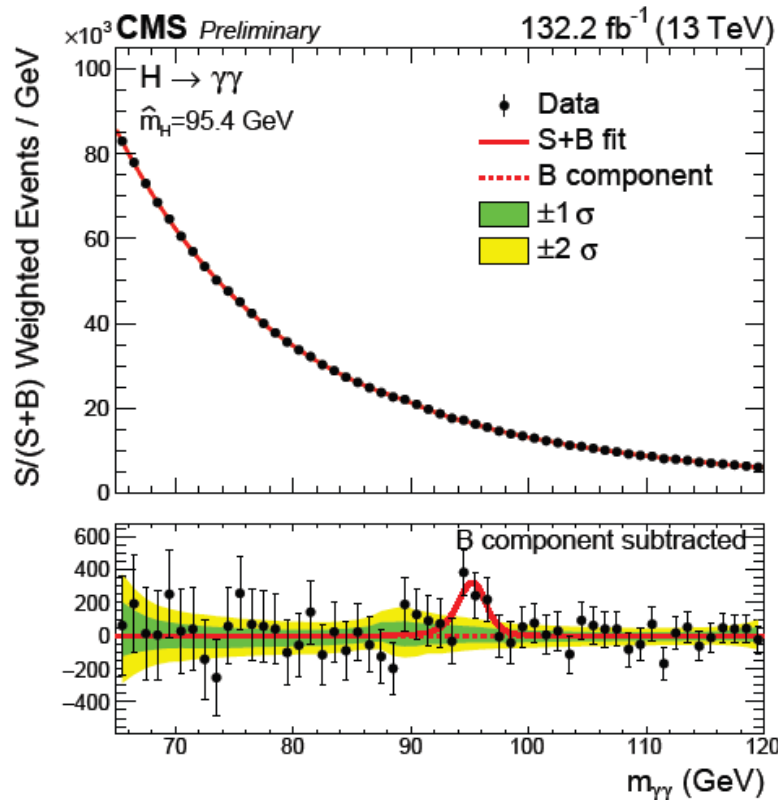
New!

SM-like $H \rightarrow \gamma\gamma$ ($70 \text{ GeV} < m_H < 110 \text{ GeV}$)

CMS-PAS-HIG-20-002

<http://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/HIG-20-002/>

- ‘Signal’ strengths μ fixing $m_H=95.4 \text{ GeV}$



- $S/(S+B)$ -weighted $m_{\gamma\gamma}$ distribution with $S+B$ fit for $m_H=95.4 \text{ GeV}$

- for the 11 event classes χ^2 compatibility probability: 68%
- First search for new diphoton resonances in this mass range with full LHC Run 2 data!

- for the 3 years χ^2 compatibility probability: 6%



LFV SM (H_{125}) or SM-like Exotic $X \rightarrow e\mu$ ($110 \text{ GeV} < m_H < 160 \text{ GeV}$)

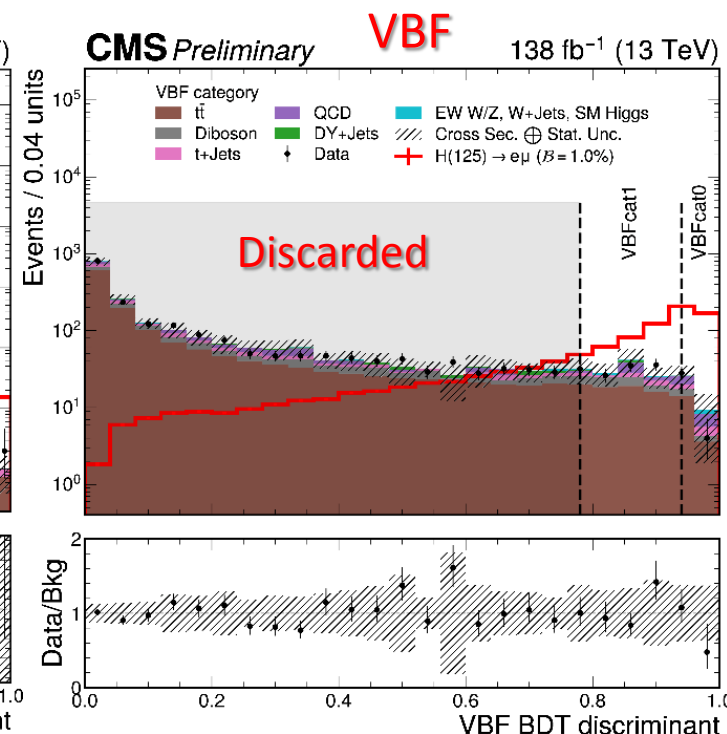
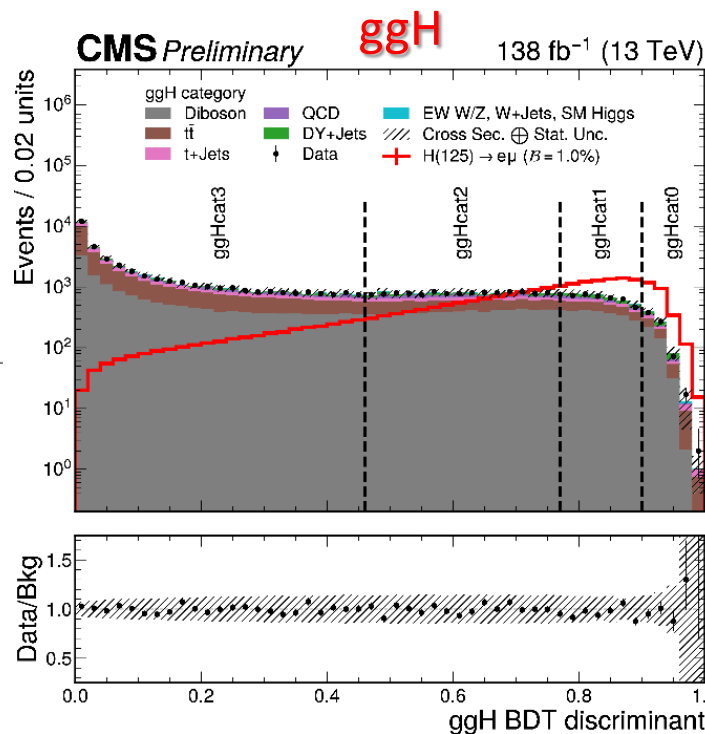
CMS-PAS-HIG-22-002

<http://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/HIG-22-002/index.html>



- Targets ggH and VBF production modes
- Principal backgrounds: $t\bar{t}$ or $WW \rightarrow$ leptons, DY with mis-id lepton
- Exploit BDTs with important input variables: $p_{T\text{miss}}$, p_T -centrality, p_T -balance ratio, jet-related variables, and Zeppenfeld variable for VBF:

$$\frac{\eta^{e\mu} - (\eta^{j_1} + \eta^{j_2})/2}{\Delta\eta(j_1, j_2)}$$
- 4 ggH, 2 VBF categories based on BDT scores
- Data-driven background modeling
- ML fit to $m_{e\mu}$ distribution



Principal systematic uncertainties

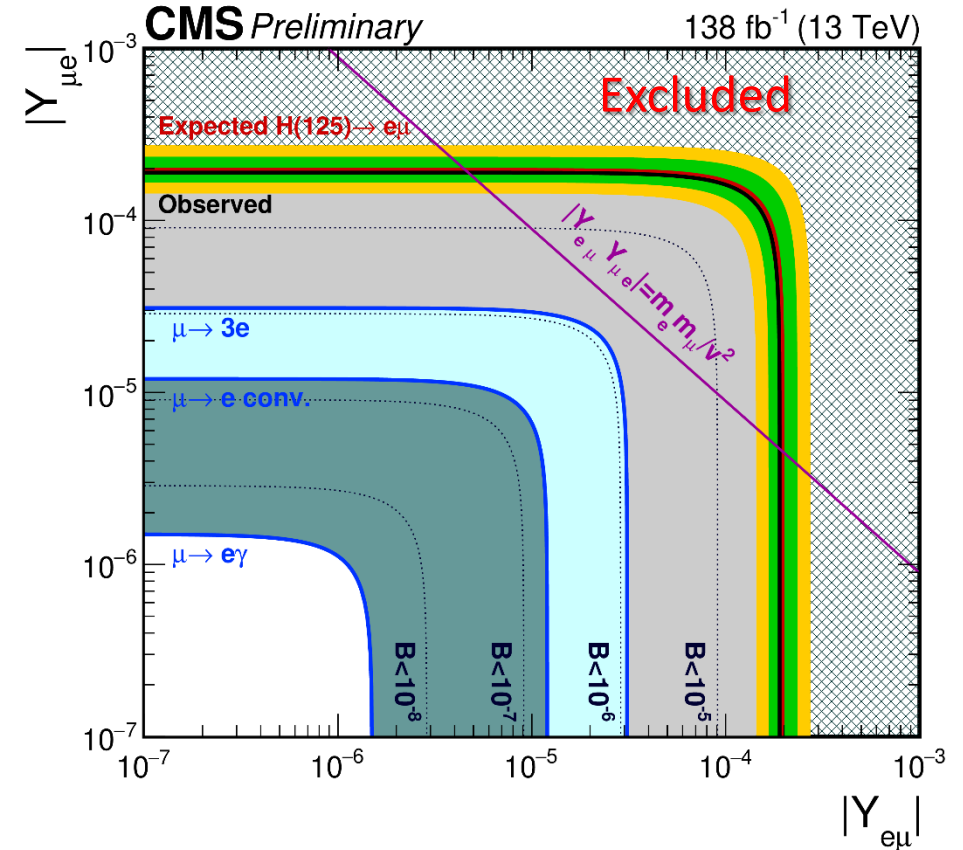
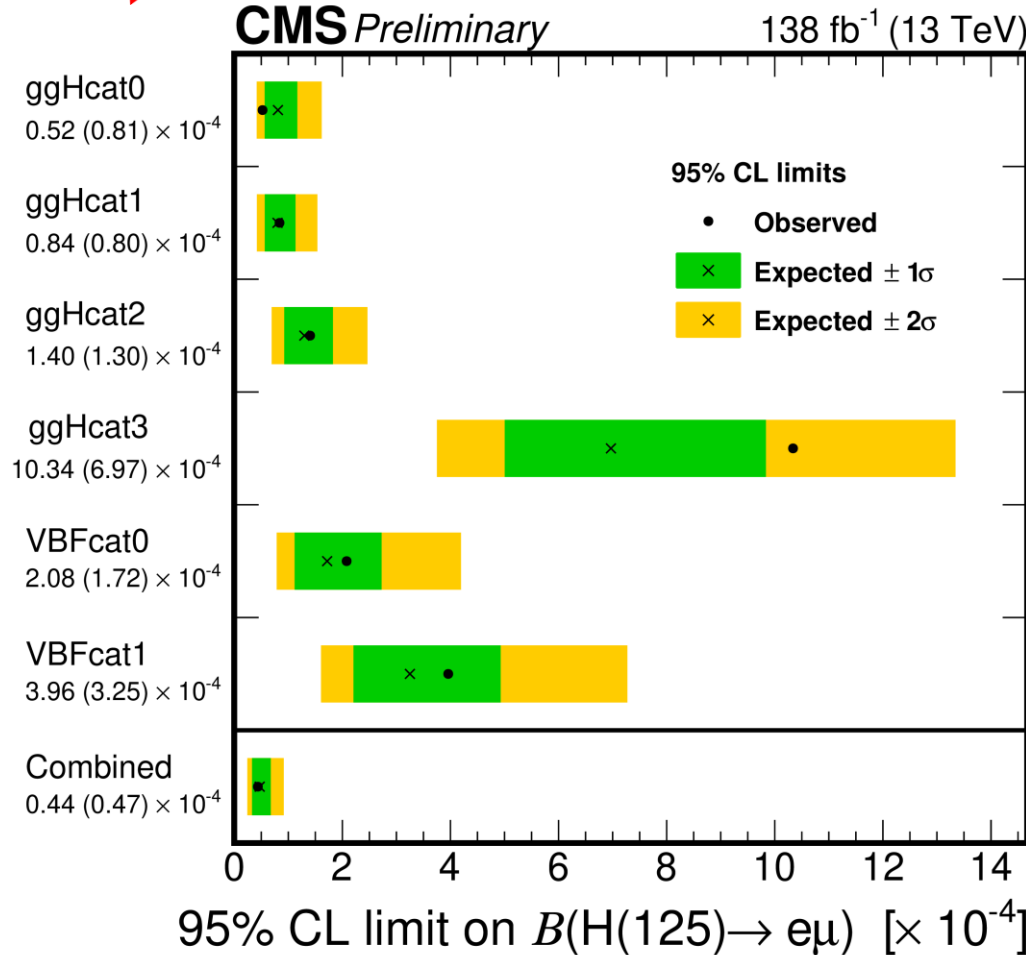
Systematic uncertainties	ggH mode (%)	VBF mode (%)
Muon identification, isolation, and trigger	< 1	< 1
Electron identification, isolation, and trigger	2	2
b tagging efficiency	< 1	< 1
Jet energy scale	1-8	1-3
Unclustered energy scale	2-6	1-6
Trigger timing inefficiency	< 1	< 1
Integrated luminosity	< 2	< 2
Pileup	< 2	< 2
Parton shower	-	3-11
Ren. and fact. scales	4	1
PDF + α_S	2	2
Effect of the ren. and fact. scales on the acceptance	1-10	< 2
Effect of the PDF + α_S on the acceptance	< 1	< 1



LFV SM (H_{125}) or SM-like Exotic $X \rightarrow e\mu$ ($110 \text{ GeV} < m_H < 160 \text{ GeV}$)

CMS-PAS-HIG-22-002

<http://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/HIG-22-002/index.html>



- Observed (expected) combined limit on B: 4.4(4.7) $\times 10^{-5}$
most stringent **direct** limit to-date!

- Constraints on LFV Yukawa couplings: $|Y_{e\mu}|, |Y_{\mu e}|$
Observed (expected) 95% CL UL:
 $\sqrt{|Y_{e\mu}|^2 + |Y_{\mu e}|^2} < 1.9(2.0) \times 10^{-4}$

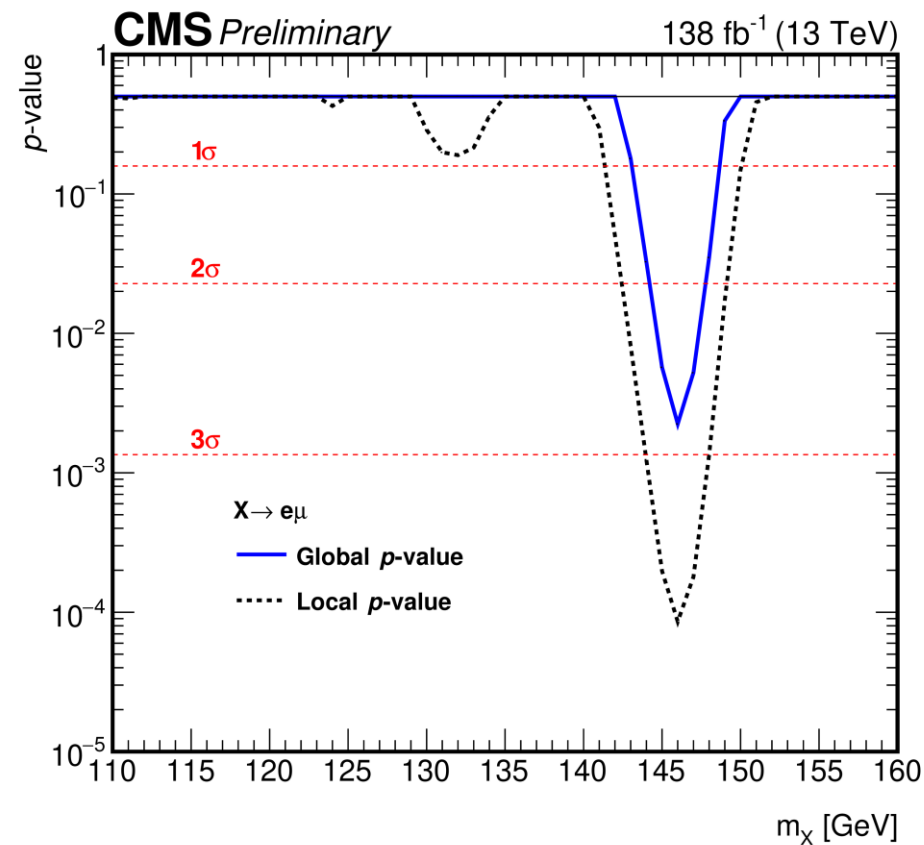
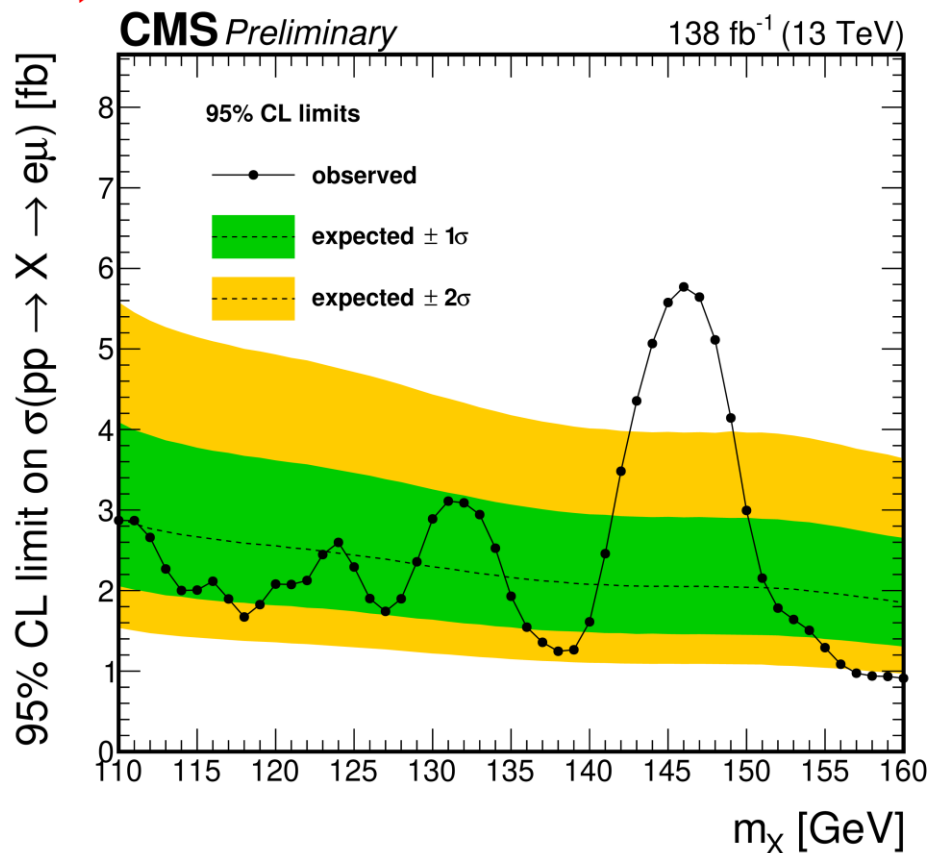


LFV SM (H_{125}) or SM-like Exotic $X \rightarrow e\mu$ ($110 \text{ GeV} < m_H < 160 \text{ GeV}$)

CMS-PAS-HIG-22-002

<http://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/HIG-22-002/index.html>

New!



- Observed & expected 95% CL UL on $\sigma (pp \rightarrow X \rightarrow e\mu)$

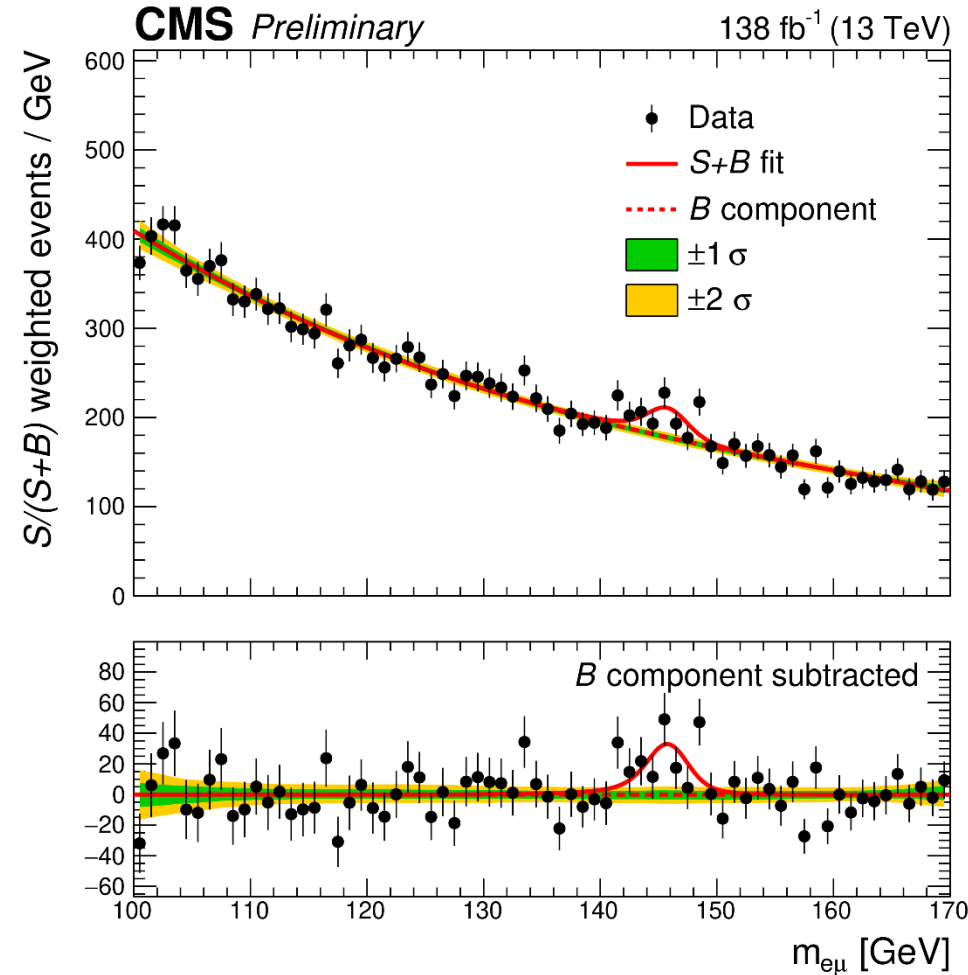
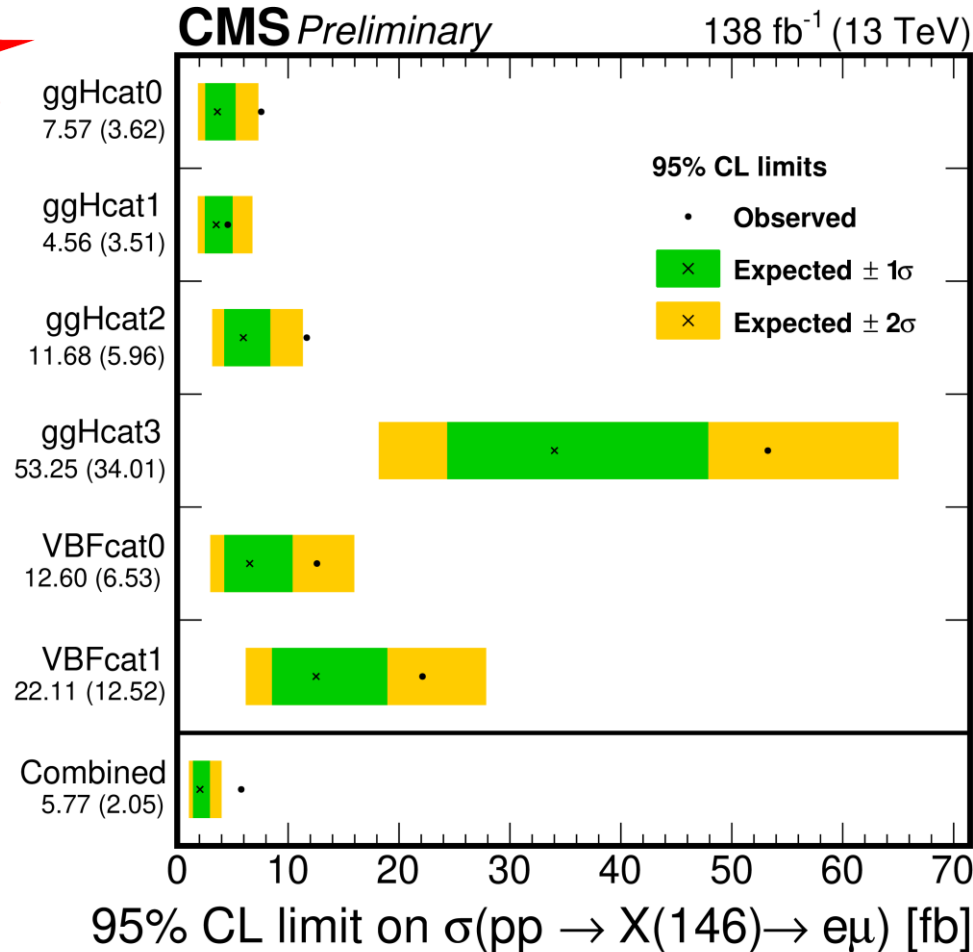
- Excess observed for $m_{e\mu} \sim 146$ GeV with global (2.8σ) and local (3.8σ) significances
- Not visible in ATLAS $m_{e\mu}$ spectrum (PLB 801 (2019) 135148), more data needed to conclude!



LFV SM (H_{125}) or SM-like Exotic $X \rightarrow e\mu$ ($110 \text{ GeV} < m_H < 160 \text{ GeV}$)

CMS-PAS-HIG-22-002

<http://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/HIG-22-002/index.html>



- Observed (expected) 95% CL UL on σ ($\text{pp} \rightarrow X(146) \rightarrow e\mu$) for each category and for their combination

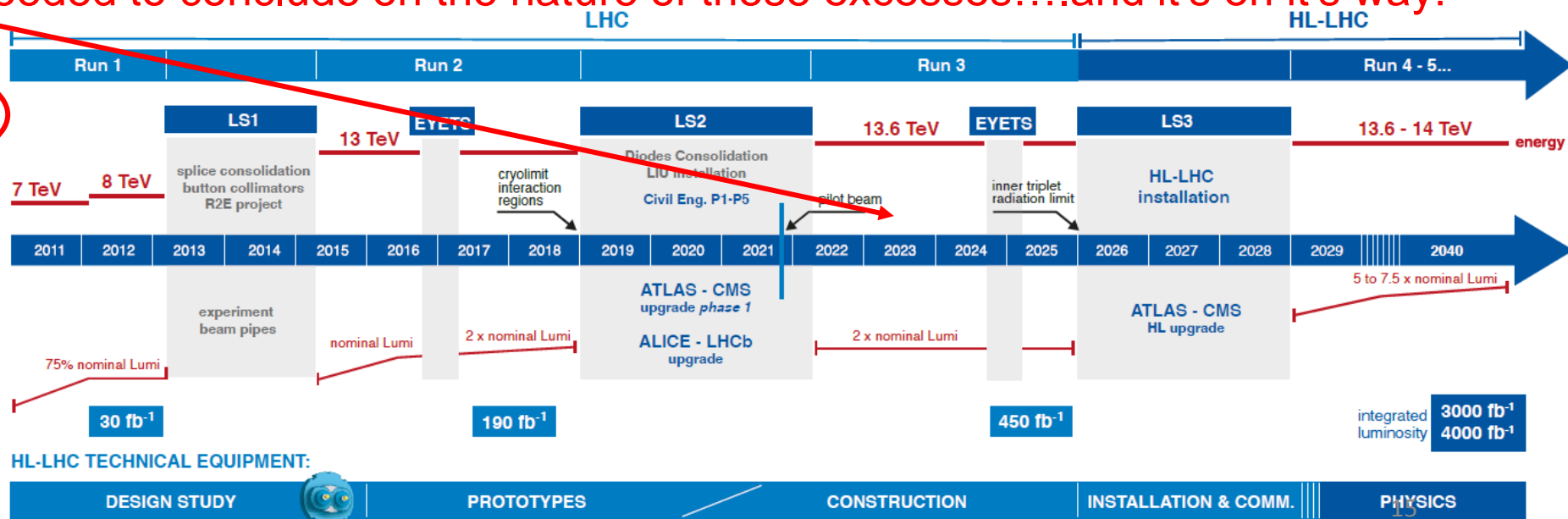
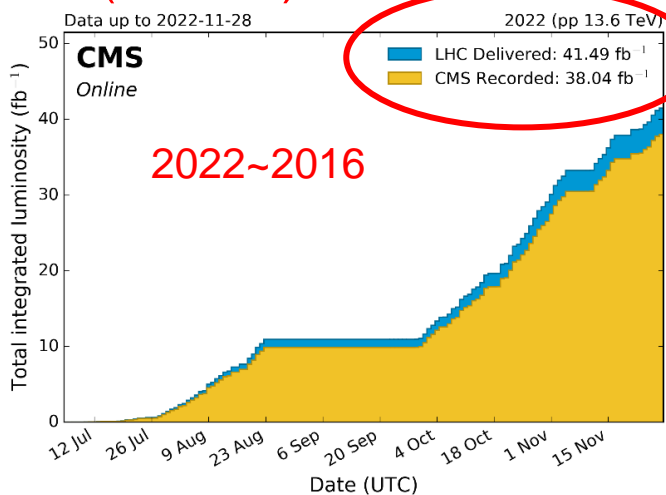
- $S/(S+B)$ -weighted $m_{e\mu}$ distribution with $S+B$ fit for $m_X = 146 \text{ GeV}$
- First direct search for extra Higgs with $m < 2m_W$



Conclusions and Perspectives

Presented three brand-new CMS searches for additional low-mass Higgs bosons using full LHC Run 2 data: No evidence for the existence of extra Higgs bosons has been found so far:

- Exotic SM-like $H_{125} \rightarrow a_1 a_1 \rightarrow \mu\mu bb$ or $\tau\tau bb$ ($12 \text{ GeV} < m_{a_1} < 62.5 \text{ GeV}$): **First results with Full Run 2! Stringent limits set in context of Types II, III and IV 2HDM+S**
- LFV SM (H_{125}) $\rightarrow e\mu$: **Most stringent direct limit to-date: $BR < 4.4 \times 10^{-5}$**
- LFV SM-like Exotic $X \rightarrow e\mu$ ($110 \text{ GeV} < m_X < 160 \text{ GeV}$): **First direct search in regime $m < 2m_W$. Excess at $m_{e\mu} \sim 146 \text{ GeV}$ with 3.8σ local (2.8σ global) significance**
- SM-like $H \rightarrow \gamma\gamma$ ($70 \text{ GeV} < m_H < 110 \text{ GeV}$): **Excess at $m_{\gamma\gamma} = 95.4 \text{ GeV}$ with 2.9σ local (1.3σ global) significance. First diphoton resonance search in this mass range with full LHC Run 2 data**
- More (Run 3) data is needed to conclude on the nature of these excesses....and it's on it's way! (250 fb^{-1})



Acknowledgements



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M. Lethuillier, H. Mei, M. Pierini, M. A.
Shahzad, J. Steggemann, J. Tao...

Thanks to the Moriond EW organization!



Backup



Exotic SM-like $H_{1,2,5} \rightarrow a_1 a_1 \rightarrow \mu\mu bb$ or $\tau\tau bb$ ($12 \text{ GeV} < m_{a_1} < 62.5 \text{ GeV}$)

CMS-PAS-HIG-22-007



- $\mu\mu bb$ category definitions

- $\tau\tau bb$ category definitions

Categories for selected events	
Low p_T	at least one b-jet with $p_T < 20 \text{ GeV}$
VBF	two add. jets with $p_T > 30 \text{ GeV}$, $ \eta < 4.7$, and $m_{jj} > 250 \text{ GeV}$
TL	looser b jet passes L but fails M
TM	looser b jet passes M but fails T
TT	looser b jet passes T

Table 5: Event categories and subregions for the $\tau\tau bb$ channel. The values correspond to the transformed DNN score used to define the signal (SRn) and control (CR) regions.

	Exactly one b jet				At least two b jets		
	SR1	SR2	SR3	CR	SR1	SR2	CR
$e\mu$ 2018	> 0.99	$\in [0.95, 0.99]$	$\in [0.85, 0.95]$	< 0.85	> 0.98	$\in [0.94, 0.98]$	< 0.94
$e\mu$ 2017	> 0.985	$\in [0.95, 0.985]$	$\in [0.85, 0.95]$	< 0.85	> 0.97	$\in [0.93, 0.97]$	< 0.93
$e\mu$ 2016	> 0.99	$\in [0.95, 0.99]$	$\in [0.85, 0.95]$	< 0.85	> 0.98	$\in [0.94, 0.98]$	< 0.94
	Exactly one b jet				At least two b jets		
	SR1	SR2	SR3	CR	SR1	SR2	CR
$e\tau_h$ 2018	> 0.97	$\in [0.945, 0.97]$	$\in [0.90, 0.945]$	< 0.90	> 0.96	NA	< 0.96
$e\tau_h$ 2017	> 0.985	$\in [0.965, 0.985]$	$\in [0.93, 0.965]$	< 0.93	> 0.985	NA	< 0.985
$e\tau_h$ 2016	> 0.985	$\in [0.965, 0.985]$	$\in [0.93, 0.965]$	< 0.93	> 0.96	NA	< 0.96
	Exactly one b jet				At least two b jets		
	SR1	SR2	SR3	CR	SR1	SR2	CR
$\mu\tau_h$ 2018	> 0.98	$\in [0.95, 0.98]$	$\in [0.90, 0.95]$	< 0.90	> 0.99	$\in [0.96, 0.99]$	< 0.96
$\mu\tau_h$ 2017	> 0.97	$\in [0.94, 0.97]$	$\in [0.90, 0.94]$	< 0.90	> 0.98	$\in [0.94, 0.98]$	< 0.94
$\mu\tau_h$ 2016	> 0.97	$\in [0.94, 0.97]$	$\in [0.89, 0.94]$	< 0.89	> 0.97	$\in [0.93, 0.97]$	< 0.93



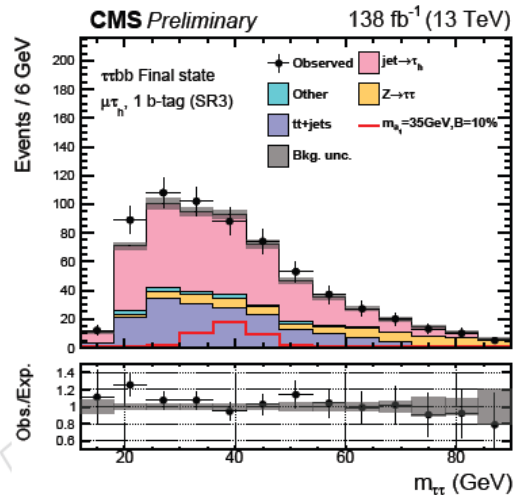
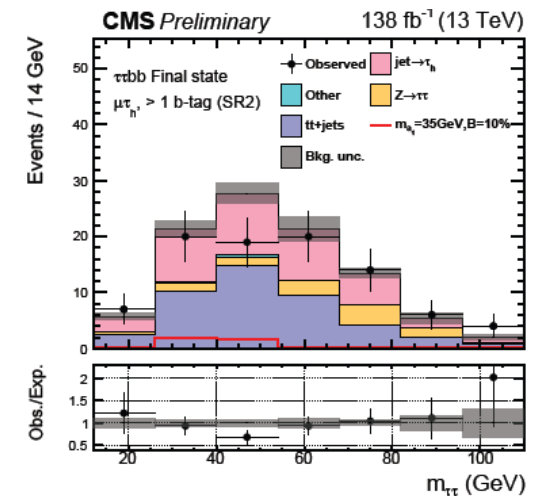
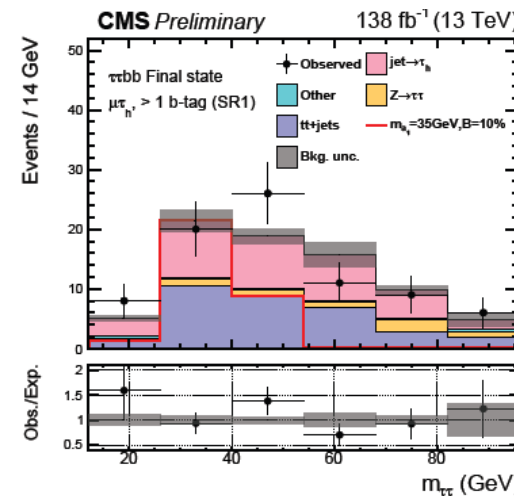
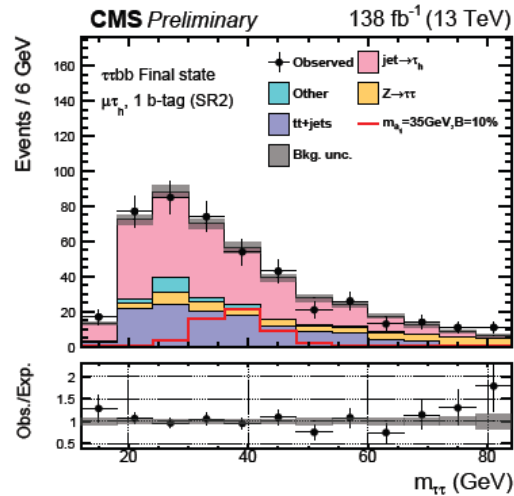
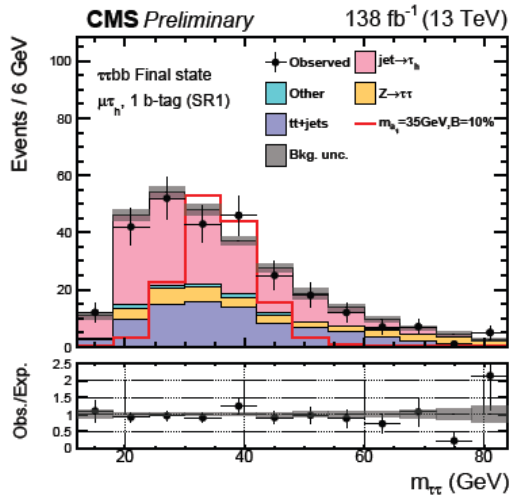
Exotic SM-like $H_{125} \rightarrow a_1 a_1 \rightarrow \mu\mu bb$ or $\tau\tau bb$ ($12 \text{ GeV} < m_{a_1} < 62.5 \text{ GeV}$)

CMS-PAS-HIG-22-007



- Post-fit $m_{\tau\tau}$ distributions, $\mu\tau_h$ final state 1 b-jet SR

Post-fit $m_{\tau\tau}$ distributions, $\mu\tau_h$ final state at least 2 b-jets SR





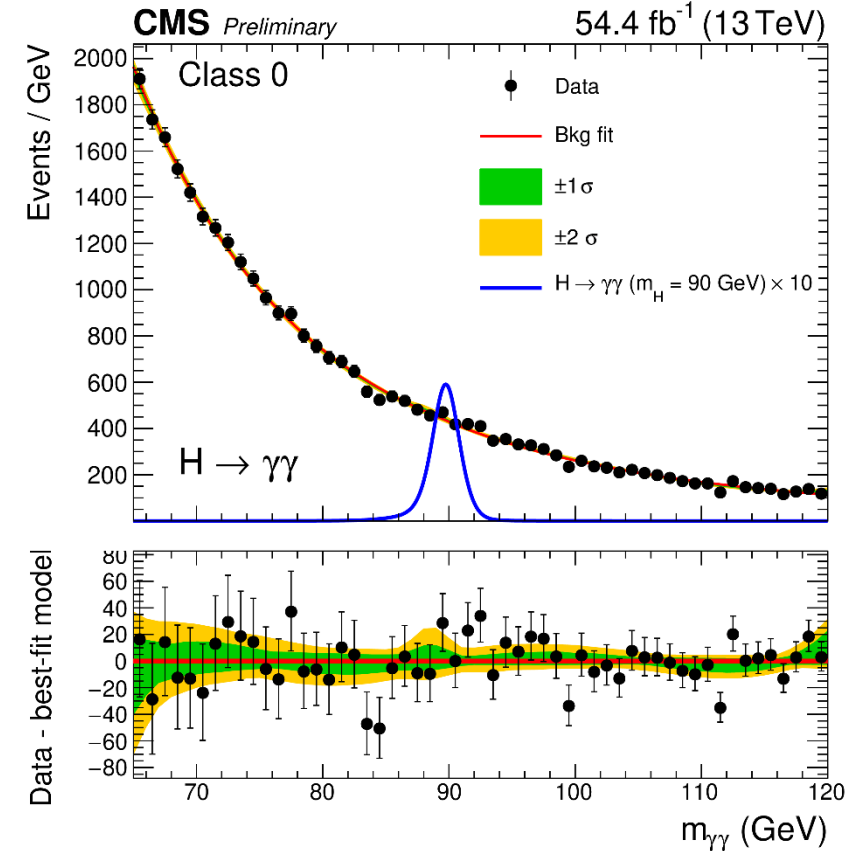
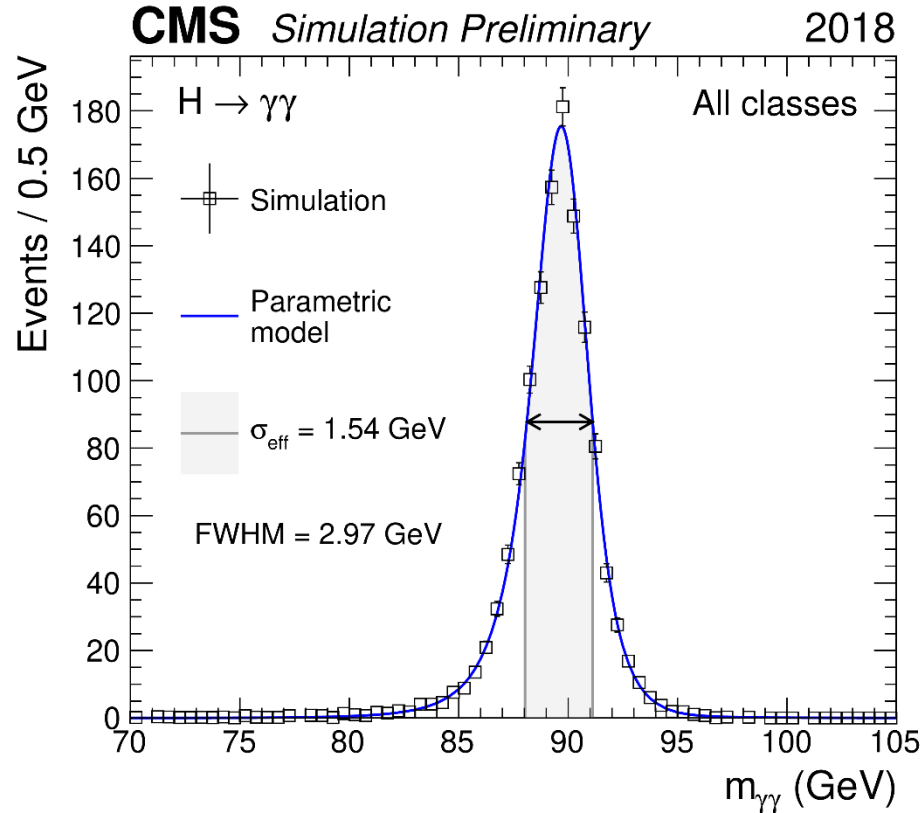
New!

SM-like $H \rightarrow \gamma\gamma$ ($70 \text{ GeV} < m_H < 110 \text{ GeV}$)

CMS-PAS-HIG-20-002

<http://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/HIG-20-002/>

- Signal modeling (sum of Gaussian functions), 2018
- Background model fit, stat.uncertainties only, 2018



- Families/orders of best-fit background functions with DCB+exponential fractions

Event class		0	1	2	VBF
2016	Family/Order	Power Law 1	Bernstein 4	Exponential 3	
	DCB + Exp. Fraction (%)	3.0	3.1	3.3	
2017	Family/Order	Bernstein 3	Exponential 3	Bernstein 4	Bernstein 3
	DCB + Exp. Fraction (%)	2.7	1.4	1.9	2.6
2018	Family/Order	Laurent 1	Bernstein 4	Exponential 3	Bernstein 2
	DCB + Exp. Fraction (%)	0.5	4.1	4.8	20.8



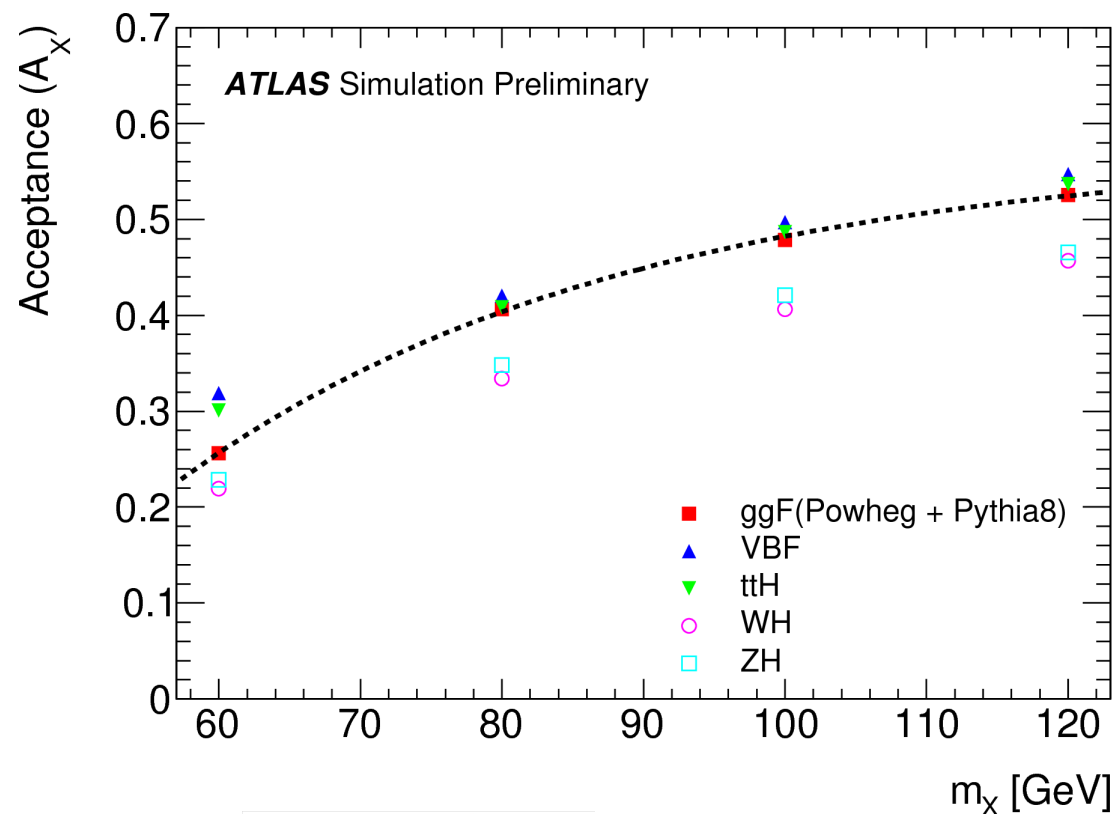
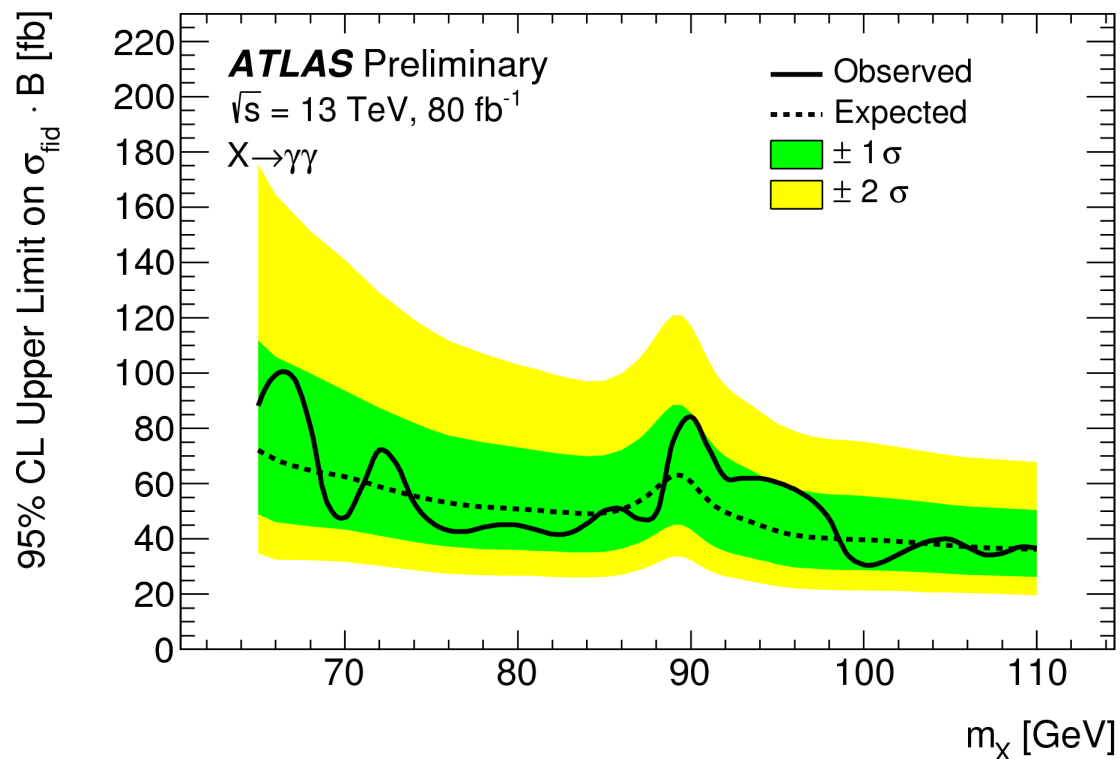
New!

SM-like $H \rightarrow \gamma\gamma$ ($70 \text{ GeV} < m_H < 110 \text{ GeV}$)

CMS-PAS-HIG-20-002

<http://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/HIG-20-002/>

- Most recent ATLAS results: ATLAS-CONF-2018-025



- Limit on fiducial $\sigma_X B$

$$\sigma_{\text{fid}} = A_X \sigma$$

$$A_X(m_X) = 0.57 - 2.07 e^{-3.13 m_X/100},$$



LFV SM (H_{125}) or SM-like Exotic $X \rightarrow e\mu$ ($110 \text{ GeV} < m_H < 160 \text{ GeV}$)

CMS-PAS-HIG-22-002

<http://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/HIG-22-002/index.html>

New!

• Category definitions and sensitivities

Analysis categories	BDT discriminant	σ_{eff} (GeV)	S	ggH mode fraction (%)	VBF mode fraction (%)	B	S/\sqrt{B}
ggH cat 0	0.89–1.00	1.7	22	94.2	5.8	79	2.5
ggH cat 1	0.77–0.89	2.1	55	96.4	3.6	399	2.8
ggH cat 2	0.46–0.77	2.4	60	96.0	4.0	1046	1.9
ggH cat 3	0.00–0.46	2.5	21	94.4	5.6	3755	0.3
VBF cat 0	0.94–1.00	1.9	2	23.7	76.3	1	2.2
VBF cat 1	0.78–0.94	2.2	2	42.2	57.8	10	0.8
VBF cat 2	0.00–0.78	2.4	2	61.8	38.2	161	0.2

• Observed (expected) limits on B by category: H_{125} case

Category	ggH cat 0	ggH cat 1	ggH cat 2	ggH cat 3	VBF cat 0	VBF cat 1	Combined
Observed limit (10^{-4})	< 0.52	< 0.84	< 1.40	< 10.34	< 2.08	< 3.96	< 0.44
Expected limit (10^{-4})	< 0.81	< 0.80	< 1.30	< 6.97	< 1.72	< 3.25	< 0.47

• Observed (expected) limits, best fit and local significances by category: case $X \rightarrow e\mu$

Category	ggH cat 0	ggH cat 1	ggH cat 2	ggH cat 3	VBF cat 0	VBF cat 1	Combined
Observed limit (fb)	< 7.57	< 4.56	< 11.68	< 53.25	< 12.60	< 22.11	< 5.77
Expected limit (fb)	< 3.62	< 3.51	< 5.96	< 34.01	< 6.53	< 12.52	< 2.05
Best fit (fb)	$4.11^{+2.02}_{-1.84}$	$1.29^{+1.81}_{-1.29}$	$6.50^{+3.11}_{-3.02}$	$23.13^{+11.87}_{-17.11}$	$5.34^{+3.91}_{-2.95}$	$8.87^{+7.35}_{-6.24}$	$3.82^{+1.16}_{-1.09}$
Local significance (σ)	2.3	0.7	2.2	1.4	2.1	1.5	3.8



LFV SM (H_{125}) or SM-like Exotic $X \rightarrow e\mu$ ($110 \text{ GeV} < m_H < 160 \text{ GeV}$)

CMS-PAS-HIG-22-002

<http://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/HIG-22-002/index.html>



- Signal modeling, ggH categories

- $p_{T^{\text{miss}}}$ distributions, ggH and VBF categories

