Search for a standard model-like Higgs boson in the mass range 70 to 110 GeV in the diphoton final state at CMS

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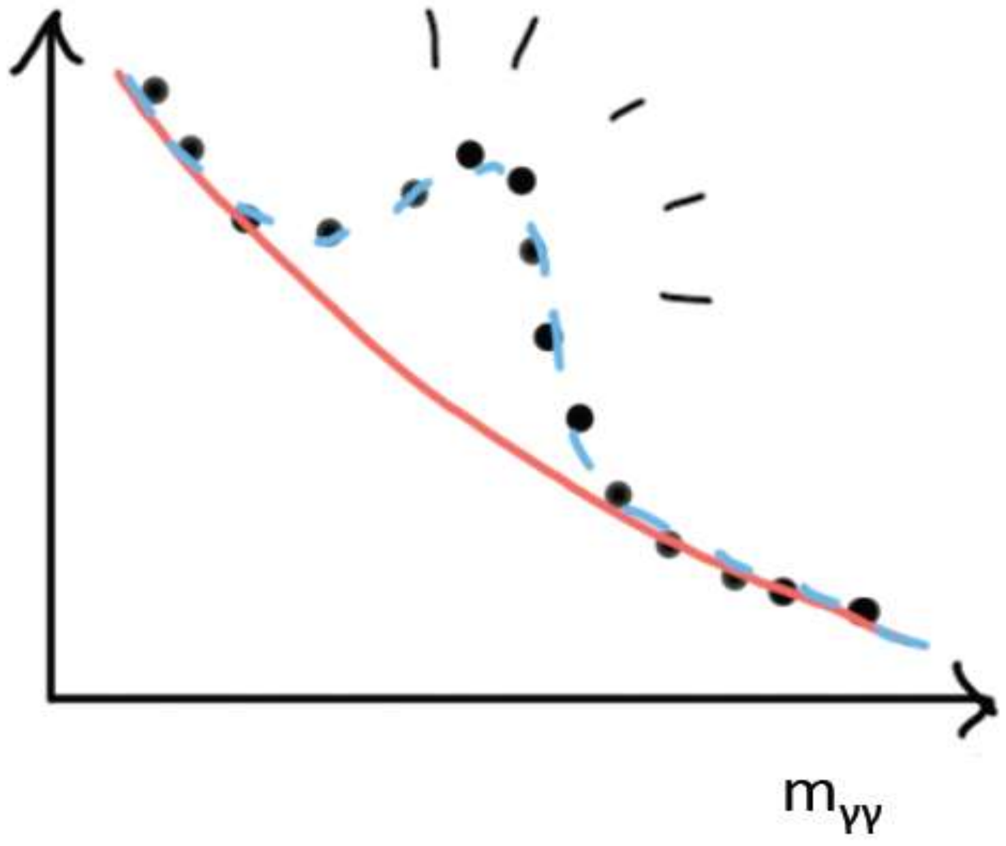
On behalf of the CMS Collaboration

Higgs 2023, 27 Nov. - 01 Dec.

Outline

Results are based on
CMS-PAS-HIG-20-002

- **Motivations and previous experimental searches (low-mass)**
- **Analysis strategy**
- **Signal and Background modelling**
- **Full Run 2 results**
- **Summary**



Motivations and previous experimental searches

- Many BSM theories (e.g. 2HDM, Composite Higgs) predict an extended sector with a boson mass < 125 GeV
- **A small excess of events (~2 σ) w.r.t. background was observed at LEP.**

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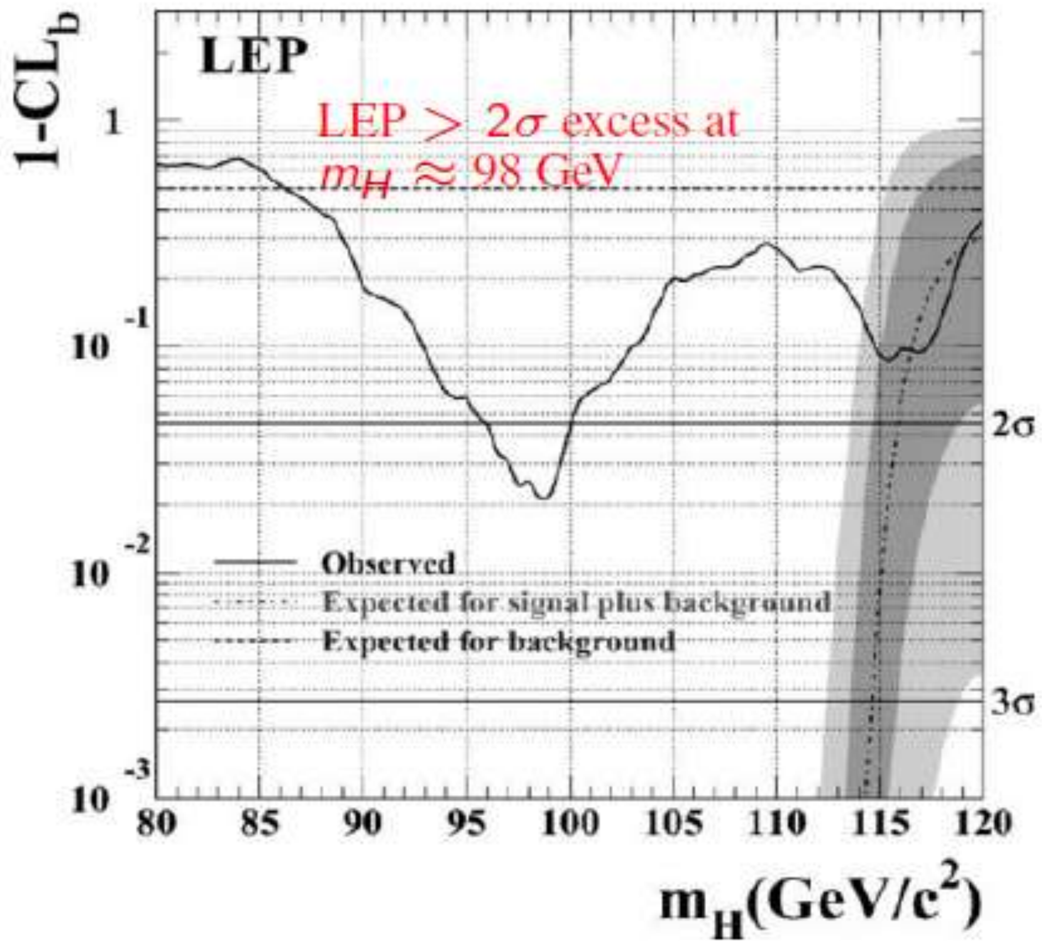
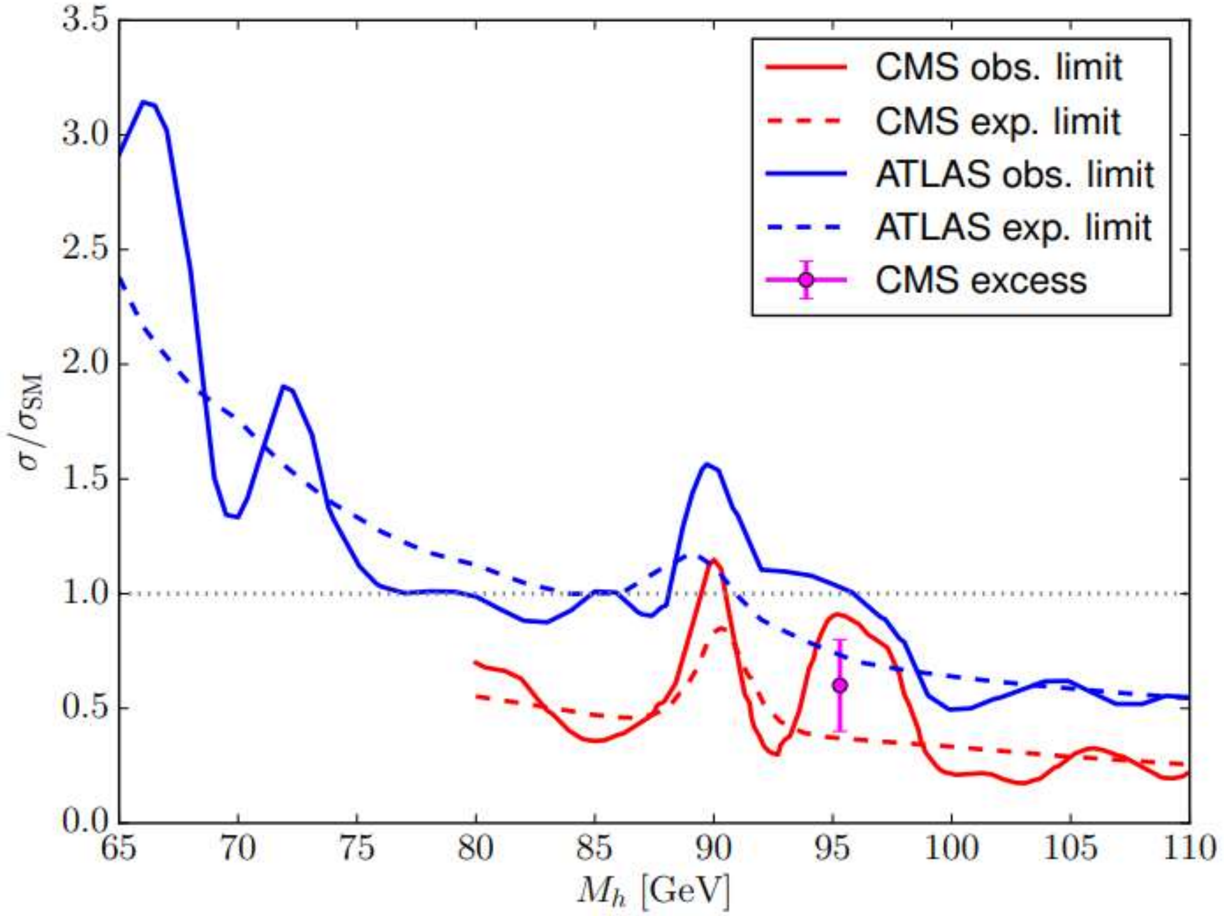
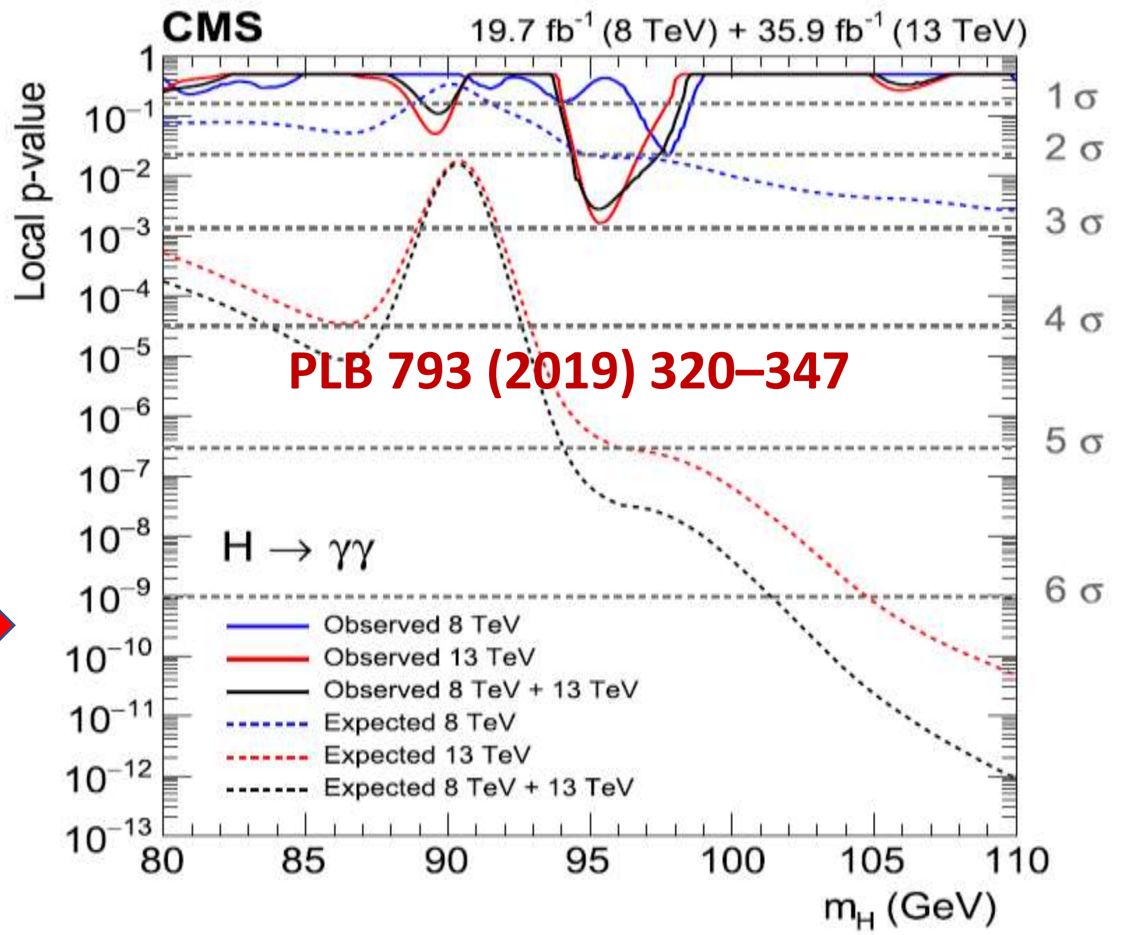


- We have performed LM Hγγ search since Run 1 at CMS
- 13 TeV 2016 (35.9 fb^{-1}) + 8 TeV 2012 (19.7 fb^{-1}): HIG-17-013
  - ✓ **8 TeV+13 TeV: 2.8σ** local (1.3σ global) significance at m=95.3 GeV





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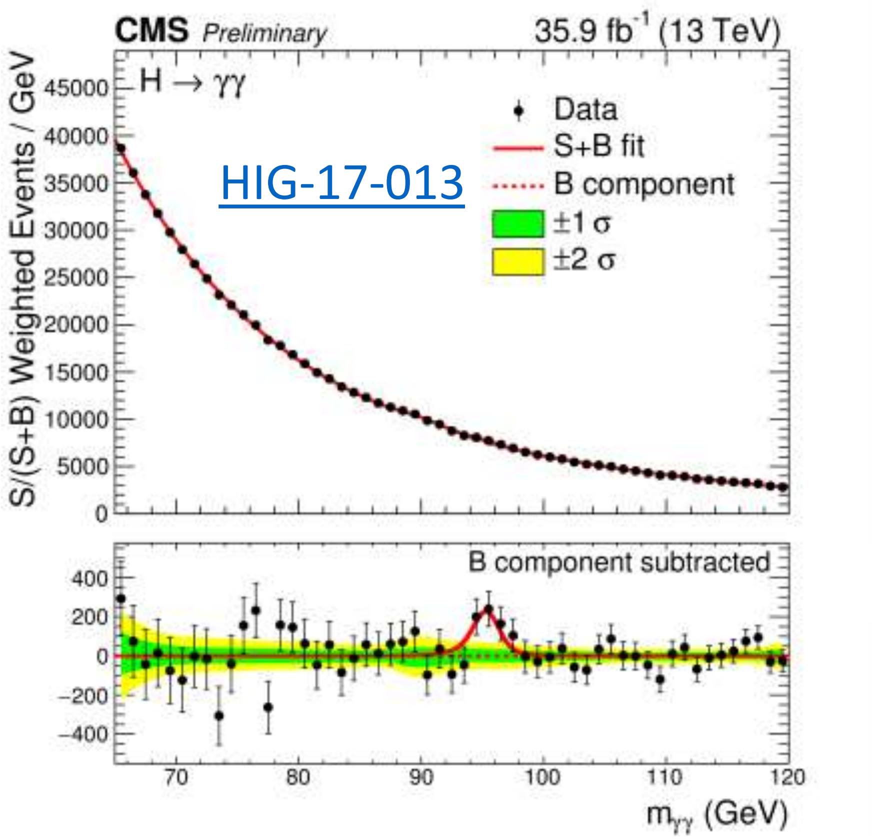
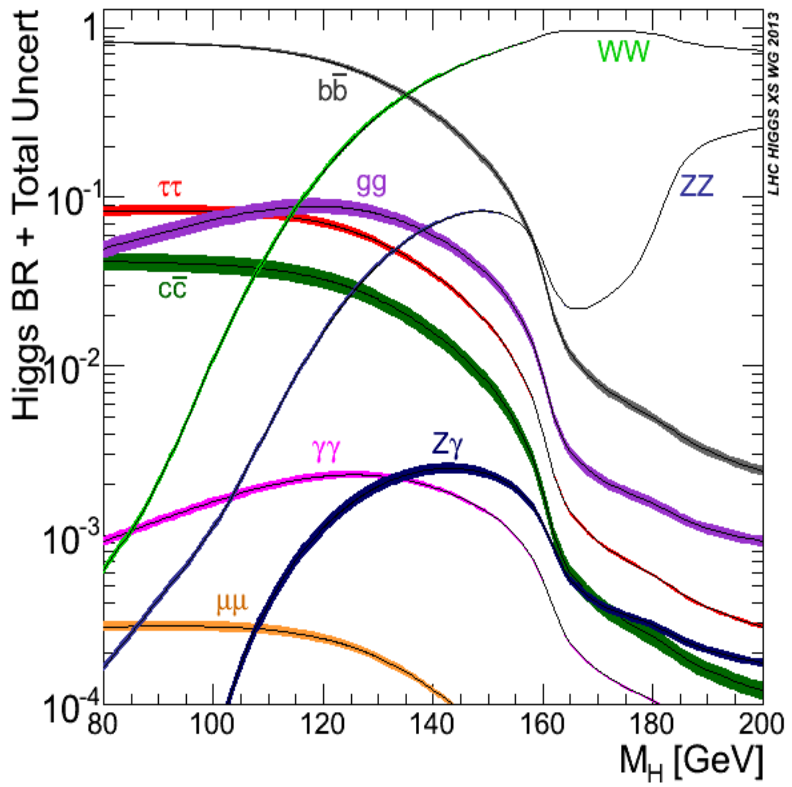
ATLAS-CONF-2018-025 (2016+2017)
CMS-HIG-17-013 (2012+2016)

SM-like low mass Hγγ search

- **Hγγ** decay channel provide a clean final-state topology which allows the mass of a Higgs boson to be reconstructed with High precision(1-2%)
  - ✓ Challenges: Significant background including continuum γγ (irreducible) and fakes from γ+jet and jet+jet (reducible) and relic Z→ee background
- **Production modes:** ggH, VBF, associated production with a W or Z boson (VH), ttH
- **Data samples:** 132.2 fb^{-1} Run 2 data
- **Signal search region:** 70-110 GeV and background fitting range 65-120 GeV





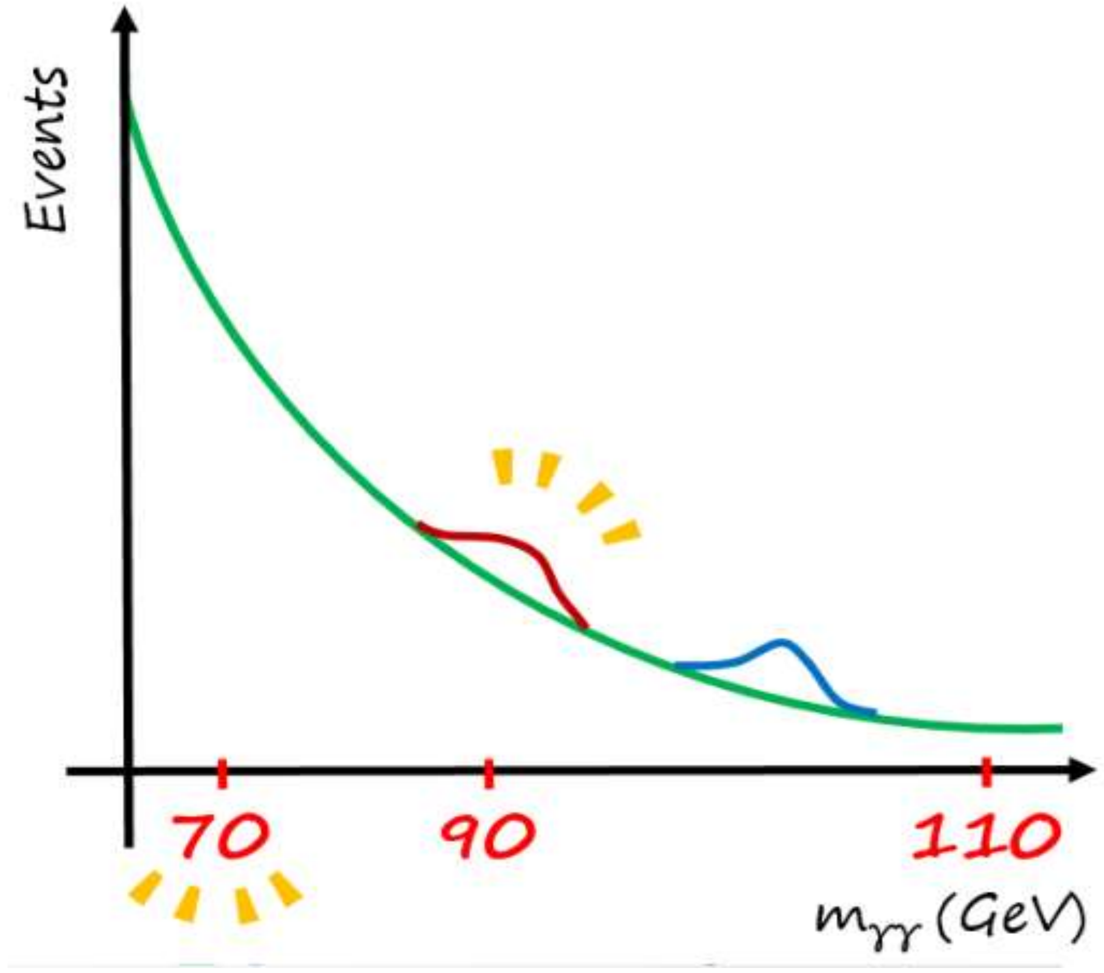
Analysis strategy

- **Strategy:** Extraction of signal peak through fit of di-photon invariant mass spectrum for each event class

- **Background components:** Irreducible direct QCD production, reducible γ+jet and jet+jet processes and $Z\rightarrow ee$ component

- **Analysis inherits many elements from the 125 GeV $H\rightarrow\gamma\gamma$ analysis:** Photon reconstruction and correction, Vertex ID, Signal and background modeling techniques

- **Dedicated updates and optimizations:** HLT paths, preselections, DY suppression strategy, retrained Photon ID MVA and di-photon BDT, **Dijet** and **Combined (**dijet+diphoton**) MVA's** retrained for VBF tagged events (**2017/2018)**

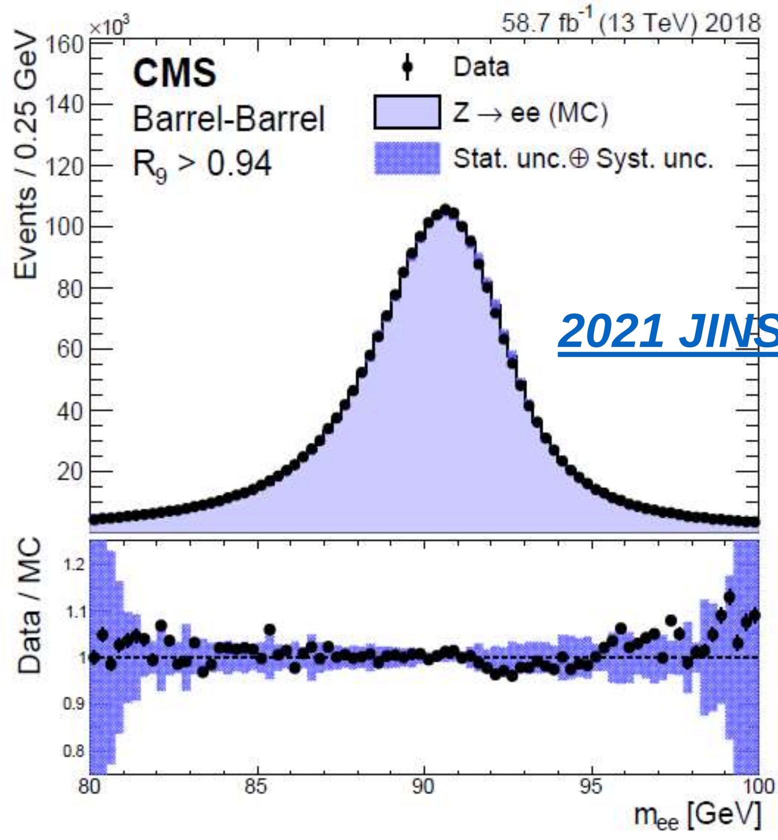


Analysis strategy (cont…)

- **Signal mass reconstruction:**
  - ✓ Reconstruct two photons with precise photon energy
  - ✓ MVA is used to select the vertex and to estimate the probability that it is the correct one (inherited from 125 GeV H$\gamma\gamma$ analysis)

- **Background suppression:** "Photon IDMVA" retrained with "LM samples" (γ+jets)
  - ✓ Validated with diphoton data/MC, $Z\rightarrow ee$, $Z\rightarrow \mu\mu\gamma$

- **Retrained Di-photon BDT:** based on LM samples and kinematics including mass resolution
  - ✓ validated with $Z\rightarrow$ ee, diphoton data/MC



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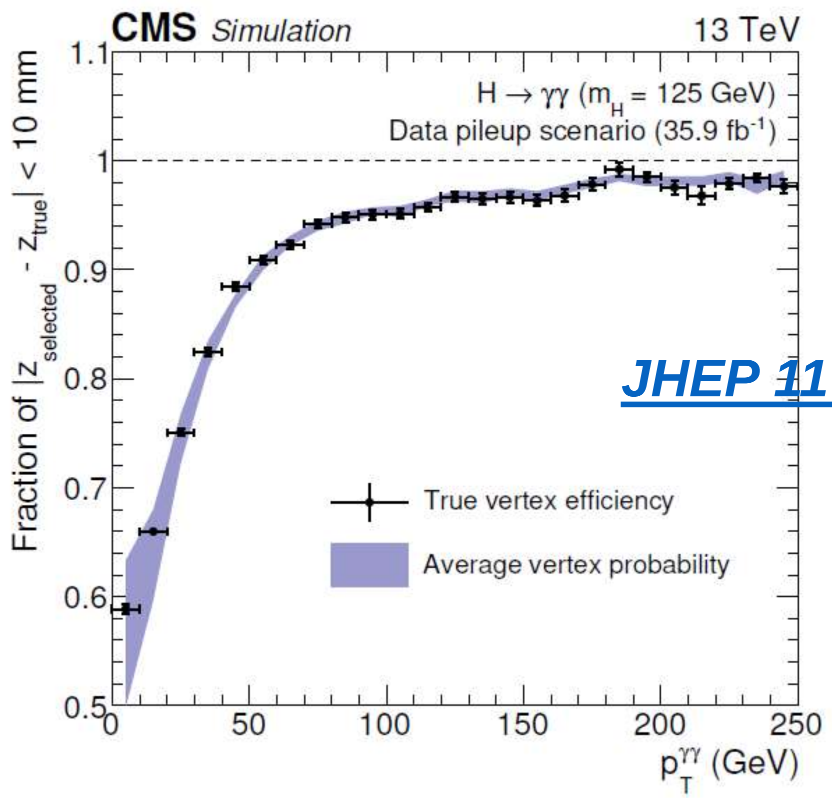

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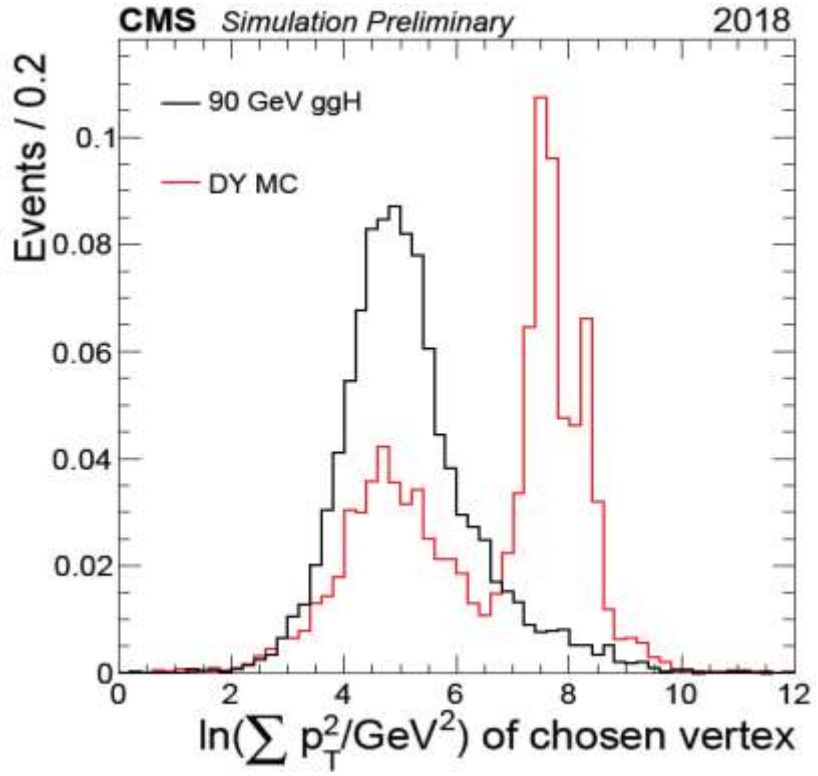
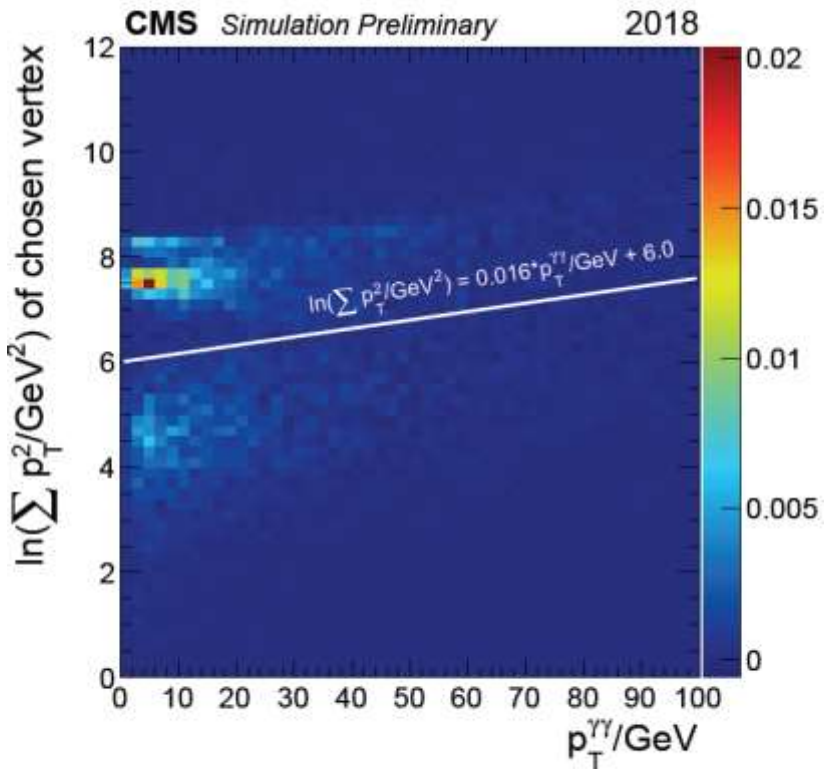
Analysis strategy (cont…)

- To deal with DY bkg., updated strategy is used
  - ✓ Electron-veto without pixel detector hits was used in previous published 2016+2012 paper
  - ✓ **$\ln(\Sigma p_T^2/\mathrm{GeV}^2)$** production as function of **$p_T^{\gamma\gamma}$ (GeV):** optimized cut with **$\ln(\Sigma p_T^2) < 0.016\, p_T^{\gamma\gamma} + 6$**



- Dijet and Combined (dijet + di-photon) MVA's were retrained with LM samples for VBF class, and validated with $Z\rightarrow ee$, di-photon data/MC

- Event categorization:
  - ✓ **2016:** 3 untagged event (re-categorized) classes based on LM retrained diphoton BDT with legacy data
  - ✓ **2017 & 2018:** 3 untagged event classes based on diphoton BDT, 1 VBF tagged event class based on the combined MVA



CMS-PAS-HIG-20-002 supplementary

Signal modeling

- A parametric model is used to describe the shape of the signal in each event class

- All production modes (ggH, VBF, WH, ZH, ttH) from 70 GeV to 110 GeV with a 5 GeV granularity are used

- The final parametrized signal shape for the combination of all production modes for all event classes, is weighted by their SM-like BSM cross sections

- Full parameterized signal shape, integrated over all event classes, in simulated signal events with m_H = 90 GeV

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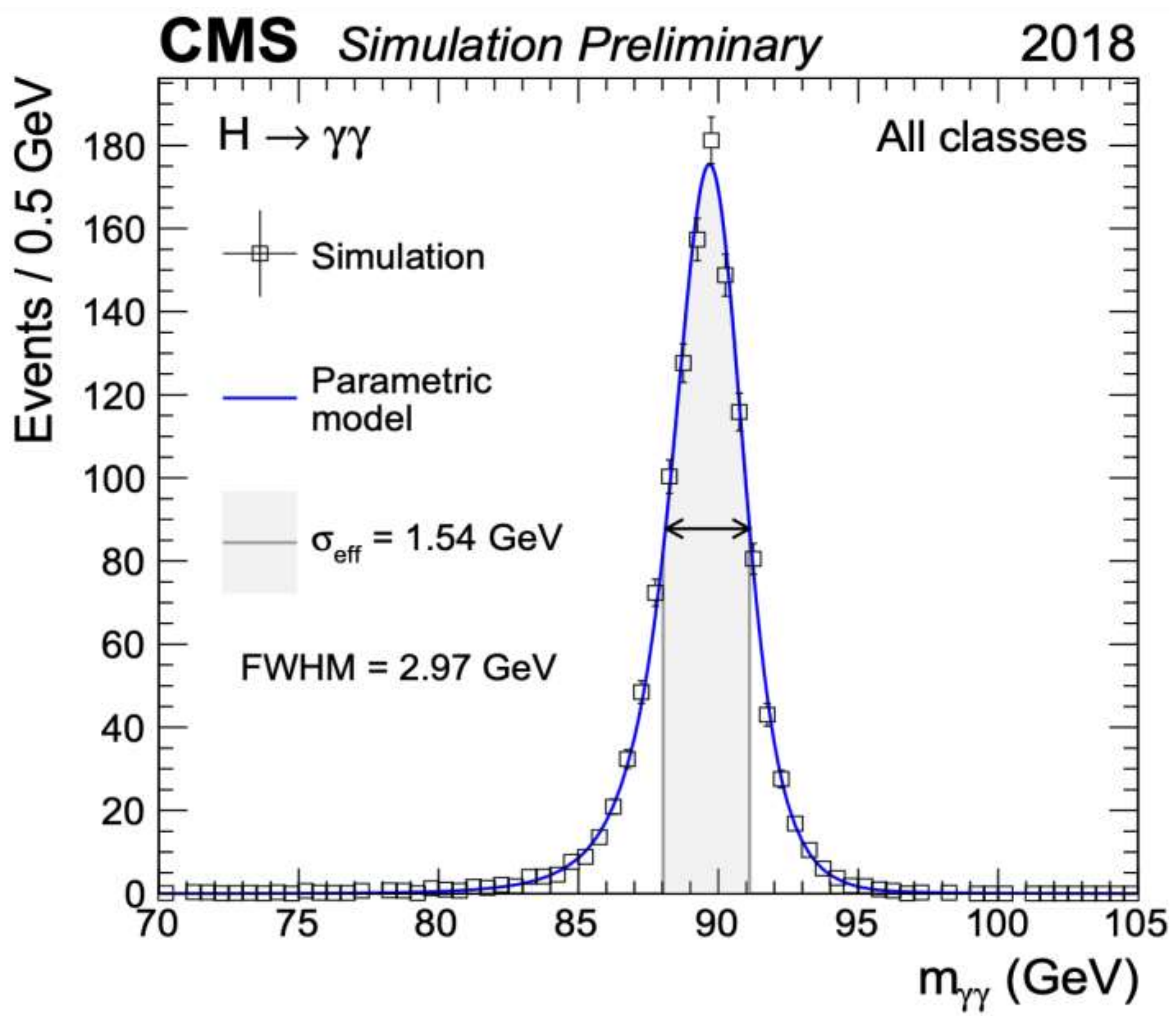

All classes combined

Background modeling

- ➢Relic DY contribution fitted by a **double-sided Crystal Ball (DCB) function + an exponential**: (1.0-frac)*DCB(x) + frac*exp(p1*x)

- ➢**Continuum background** using **Envelope** method (discrete profiling method) by performing fit with four analytic function families (**Power law, Exponential, Laurent, Bernstein)**

  - ✓Built directly from data using the diphoton mass spectrum (65-120GeV) in each event class

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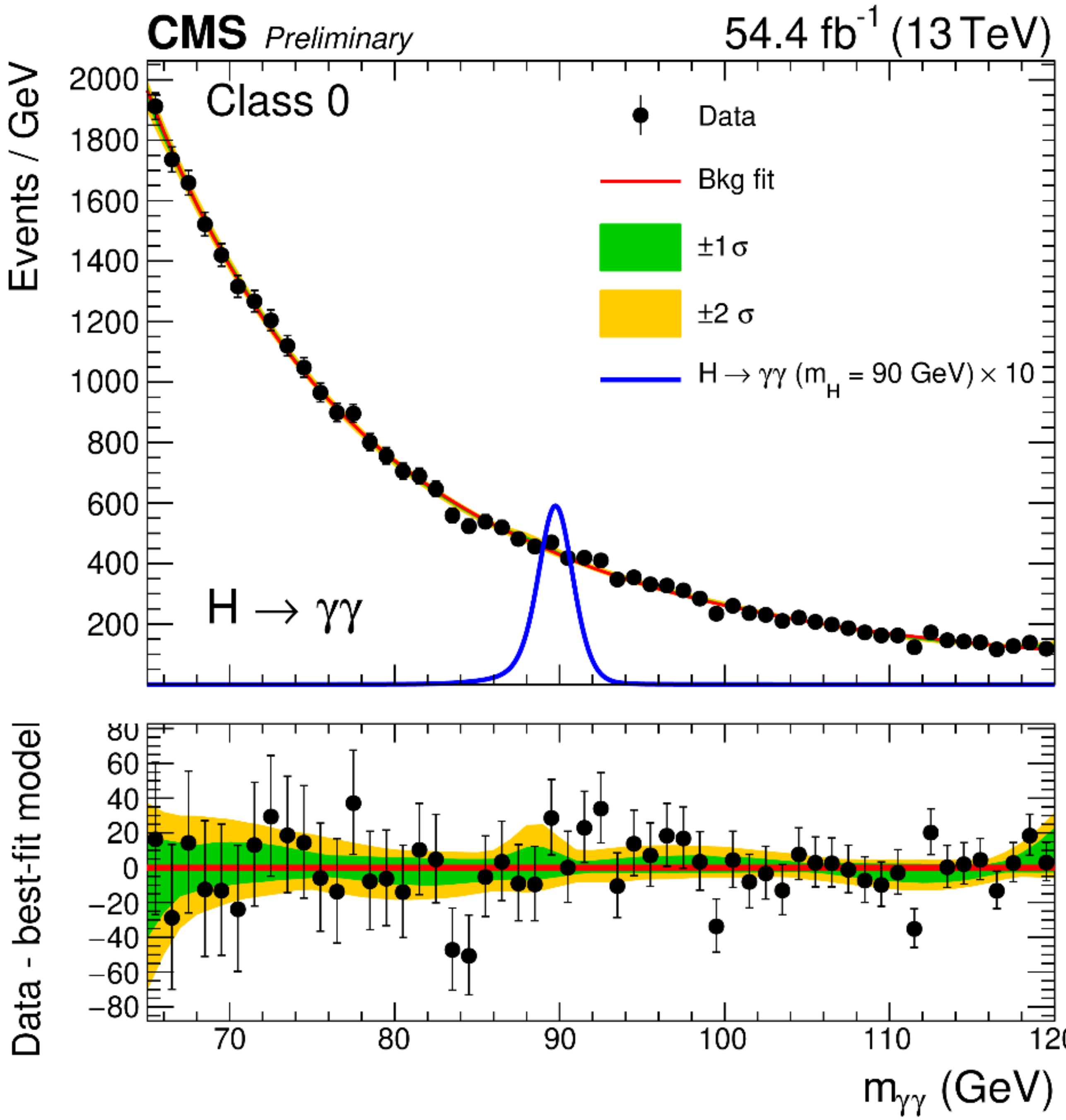
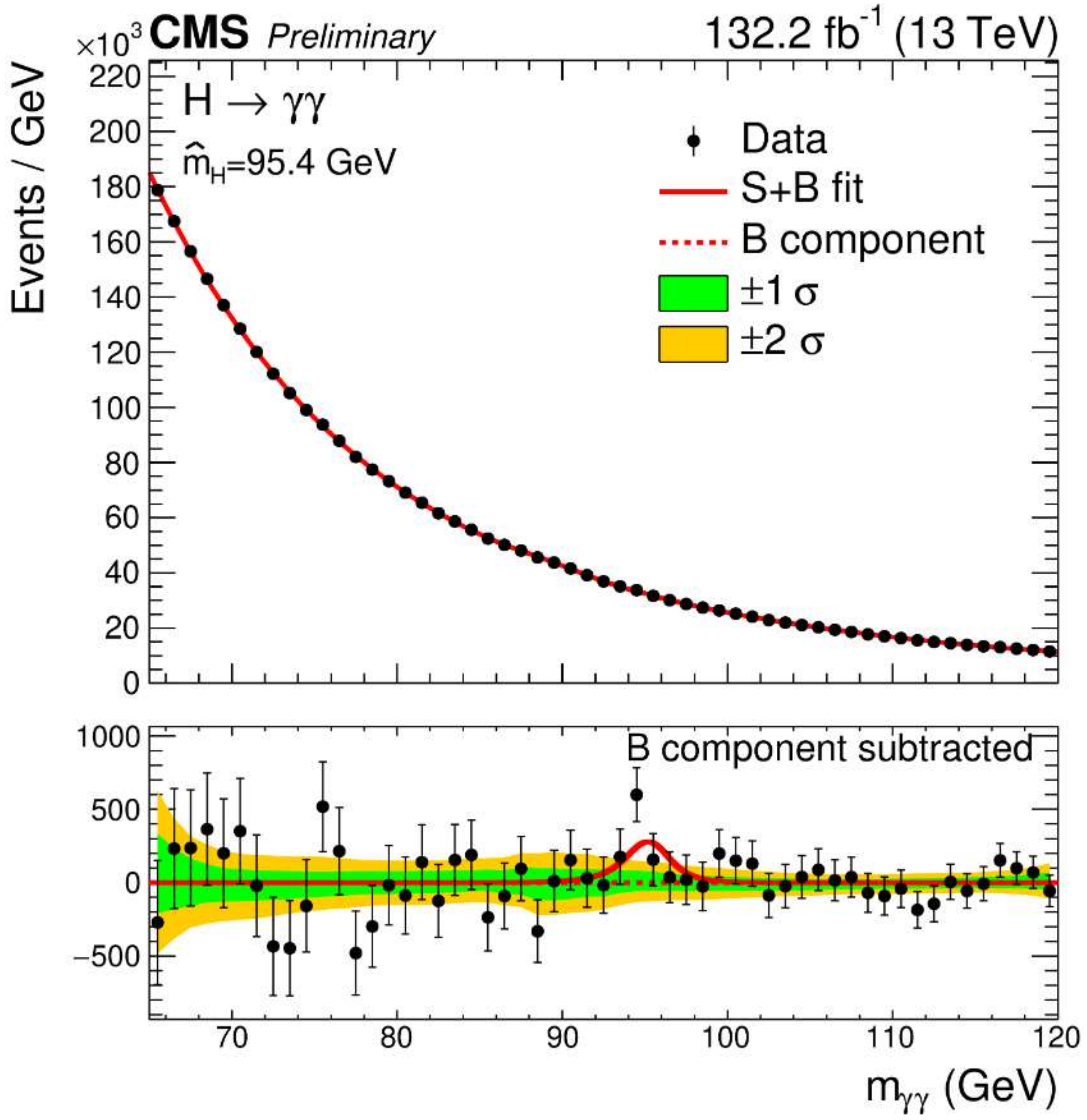


2018

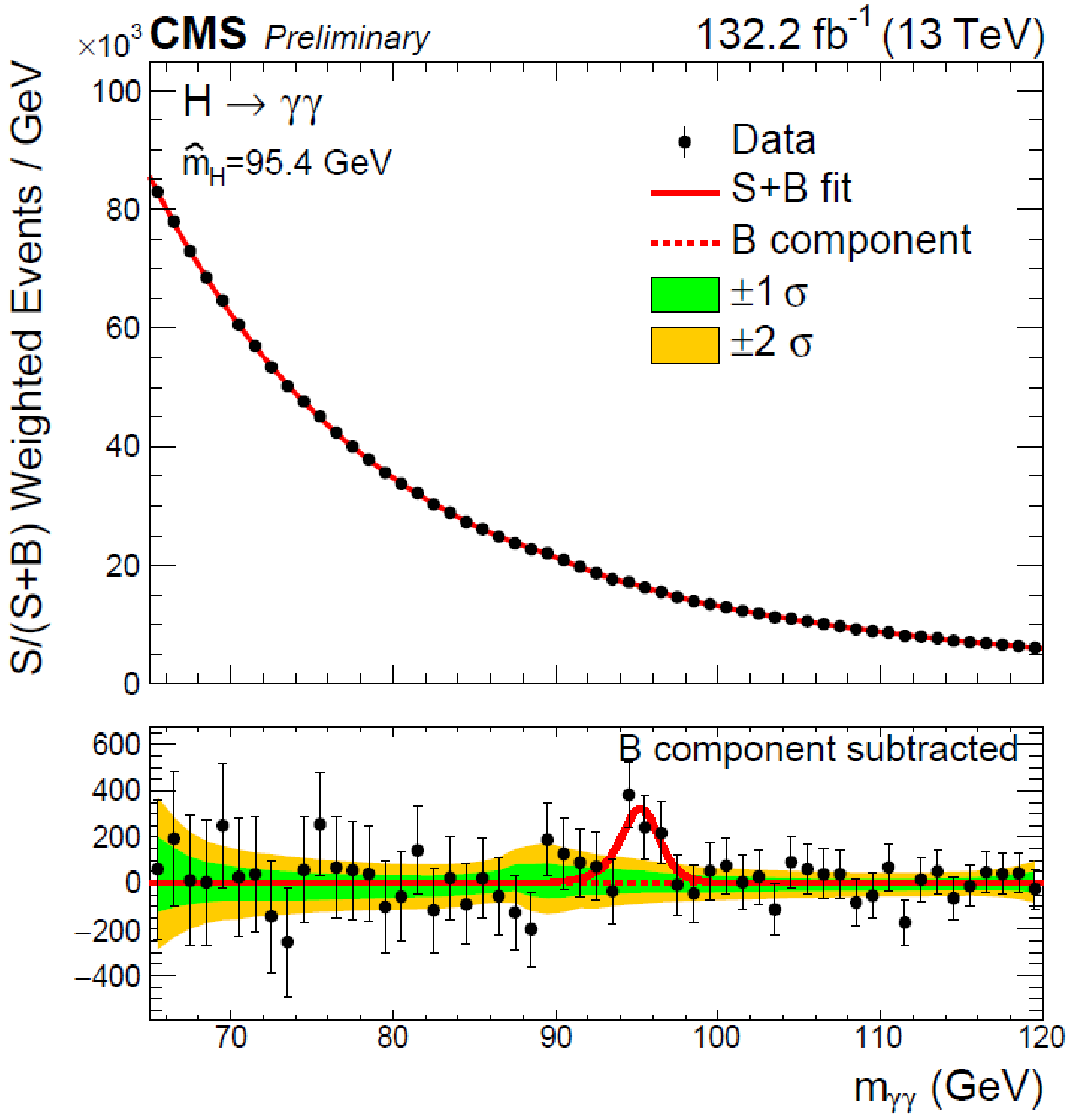
Mass distributions

- Events in all classes of the combined 13 TeV data set, S+B fit for m_H =95.4 GeV



[CMS-PAS-HIG-20-002](CMS-PAS-HIG-20-002) supplementary

- **S/(S+B)-weighted** diphoton mass distribution with S+B fit for m_H =95.4 GeV



[CMS-PAS-HIG-20-002](CMS-PAS-HIG-20-002)

Results: Inclusive Limits (Full Run 2)

- Observed absolute 95% CL UL on σ X B between 15-73 fb (22-53 fb expected)

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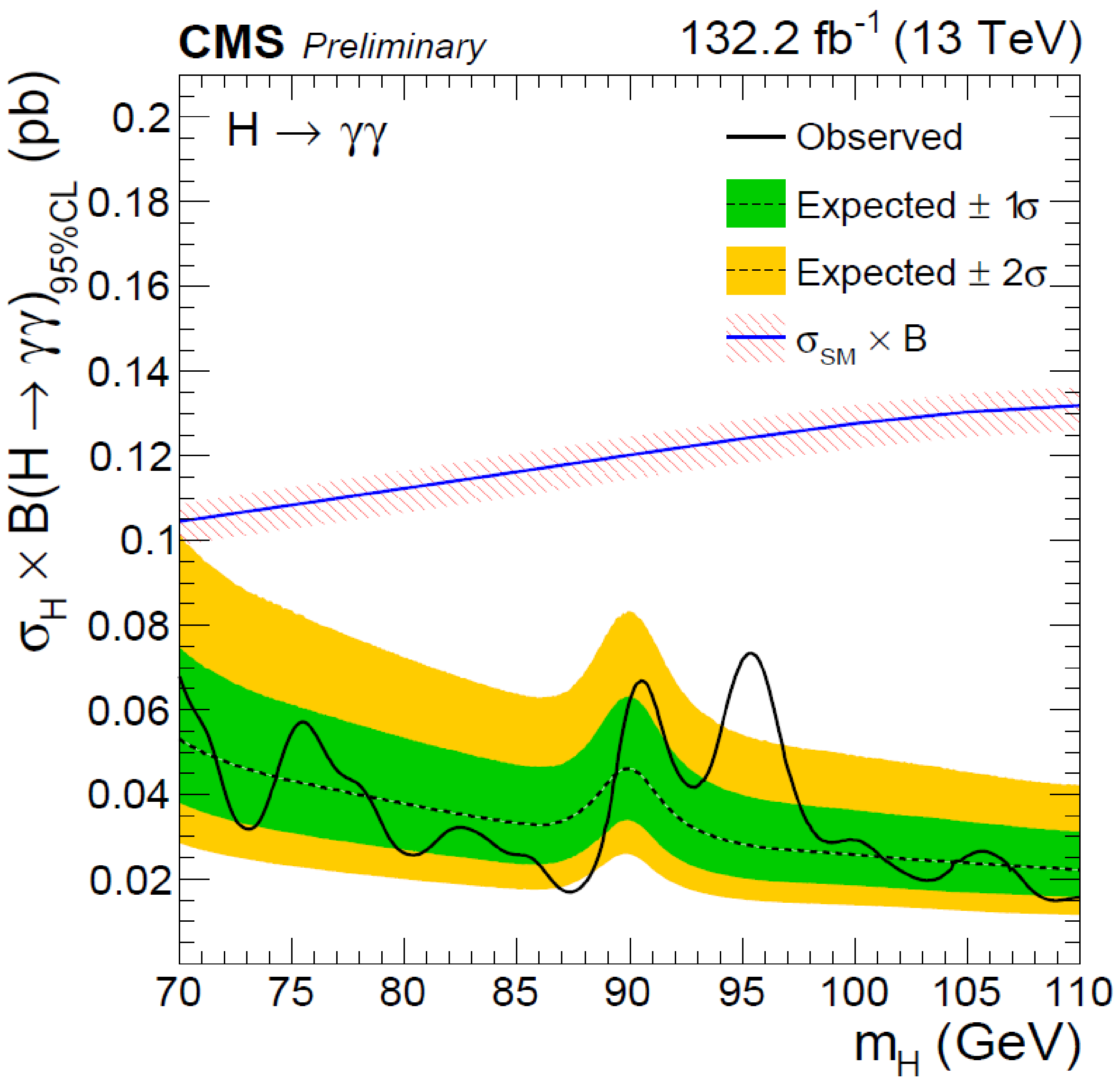
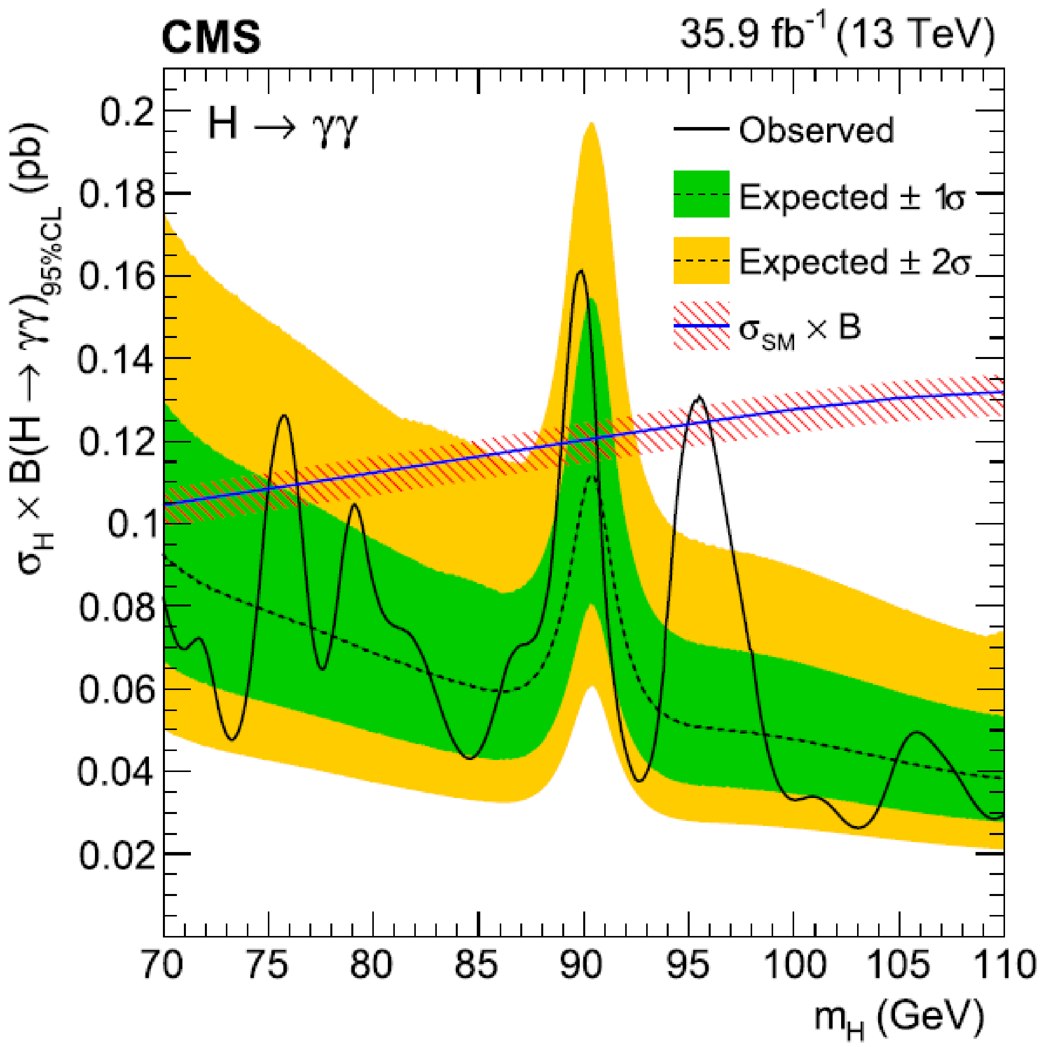


Observed:

Worst: 73 fb @ 95.4 GeV

Best: 15 fb @ 108.9 GeV

- **Previous 2016 results (HIG-17-013):** 26-161 fb (obs.) 37-110 fb(exp.)



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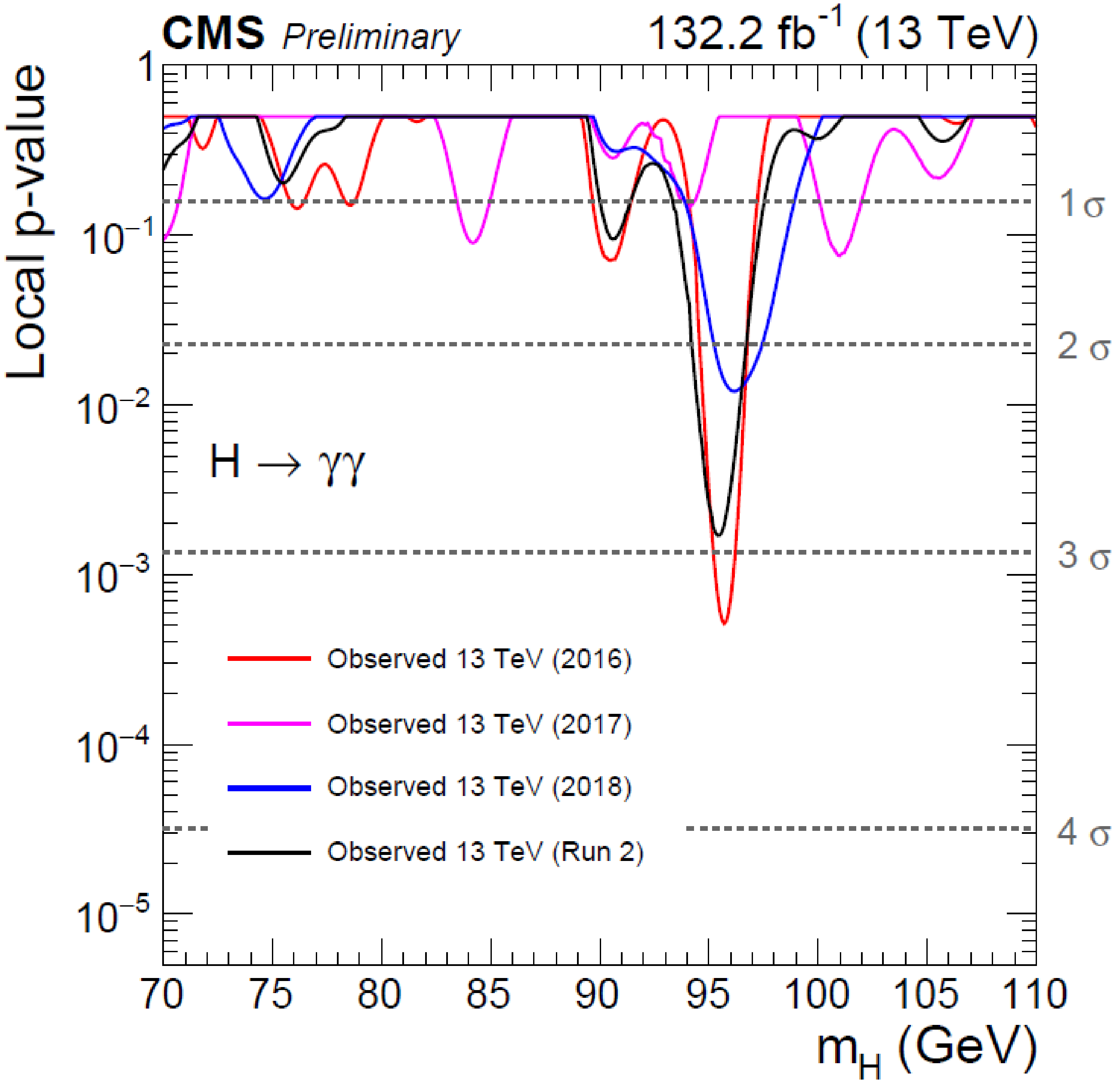
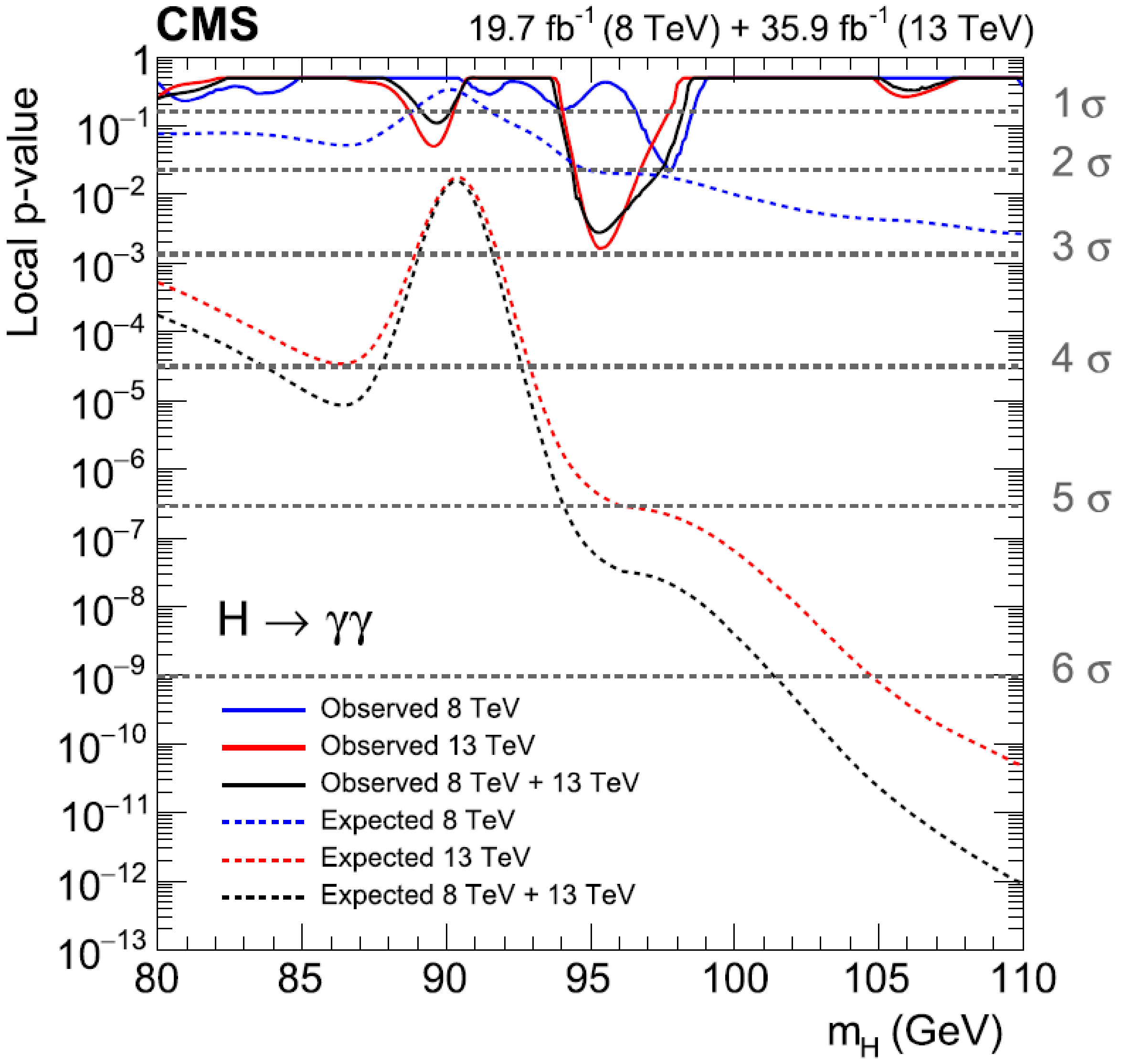
Results: P-values or Significances (Full Run 2)

- **Observed local p-values** for **2016/2017/2018** and their statistical combination

CMS-PAS-HIG-20-002



2012+2016 data



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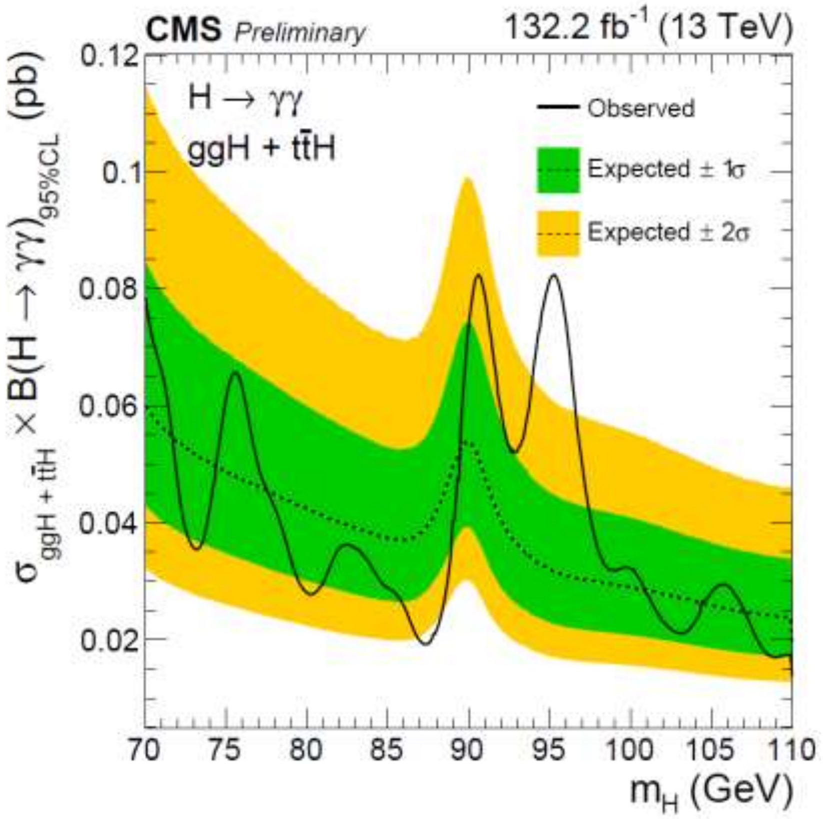
- Modest excess with ~2.9σ local (1.3σ global) significance at $m_{\gamma\gamma}$=95.4 GeV, need more data to conclude!

Results: Limits by production mode (Full Run 2)

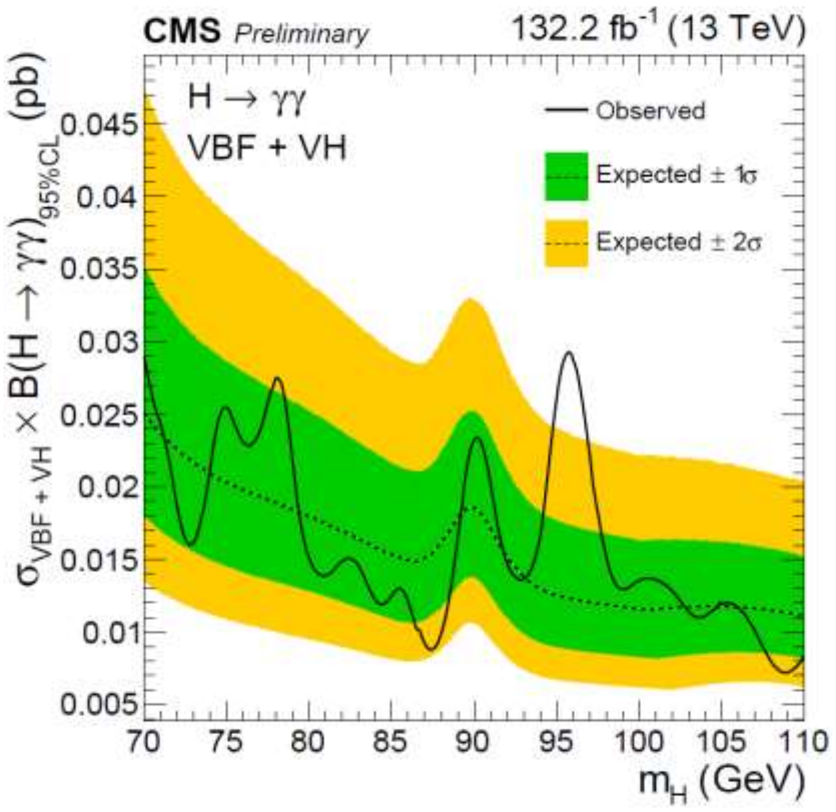
- Observed and expected 95% CL limits on σ X B by **production process** (all event classes combined)

ggH+ttH



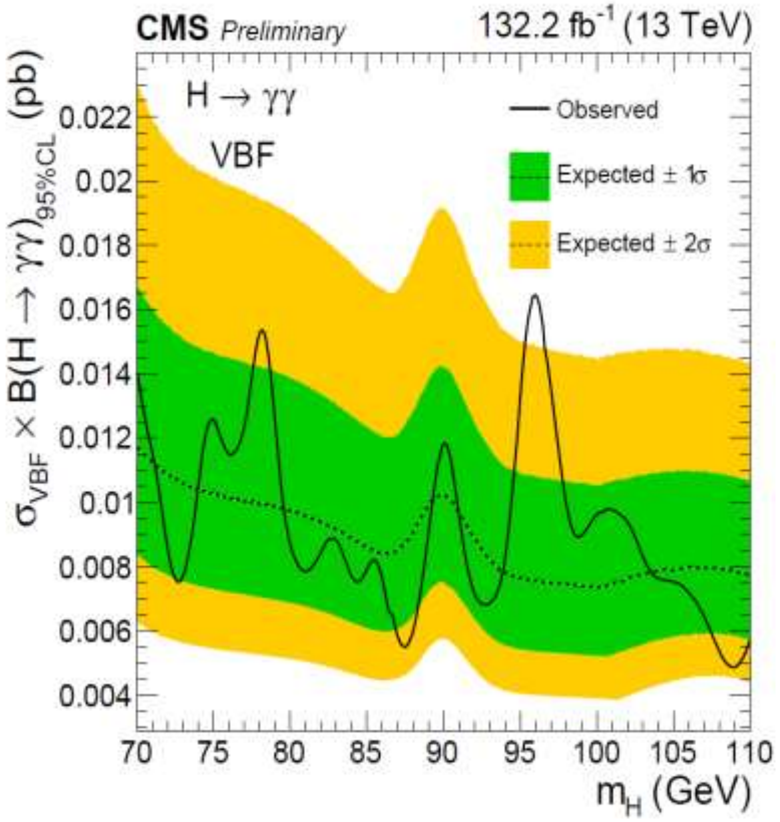
- ✓ 100% production via gluon-induced processes (**ggH, ttbarH** in SM proportions) 17-83 fb observed

VBF+VH



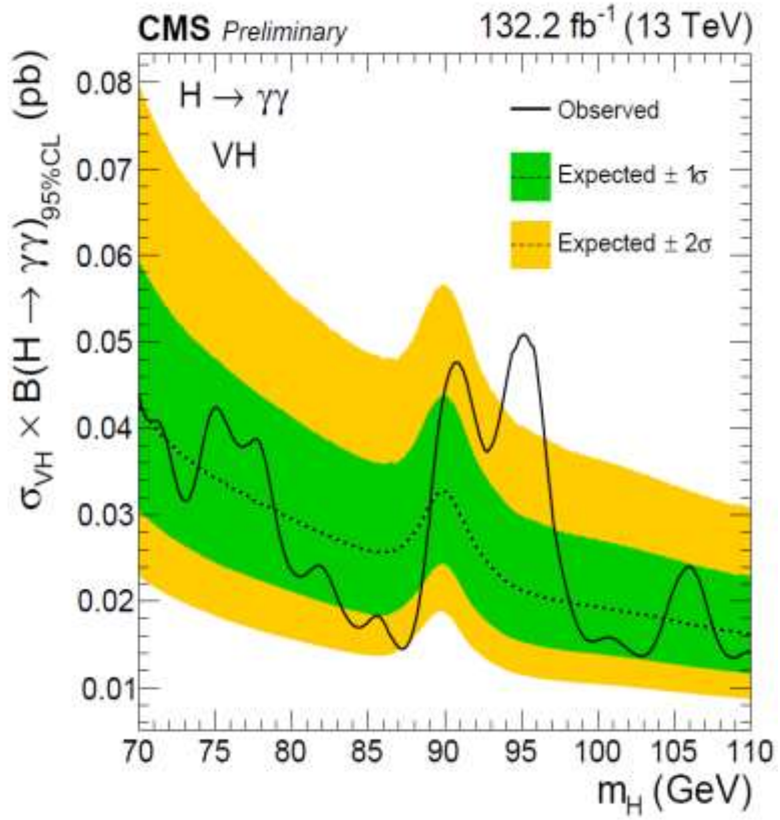
- ✓ 100% production via fermion-induced processes (**VBF, VH** in SM proportions) 7-29 fb observed

VBF



- 100% production via **VBF,** 5-17 fb observed

VH



- 100% production via **VH,** 13-51 fb observed

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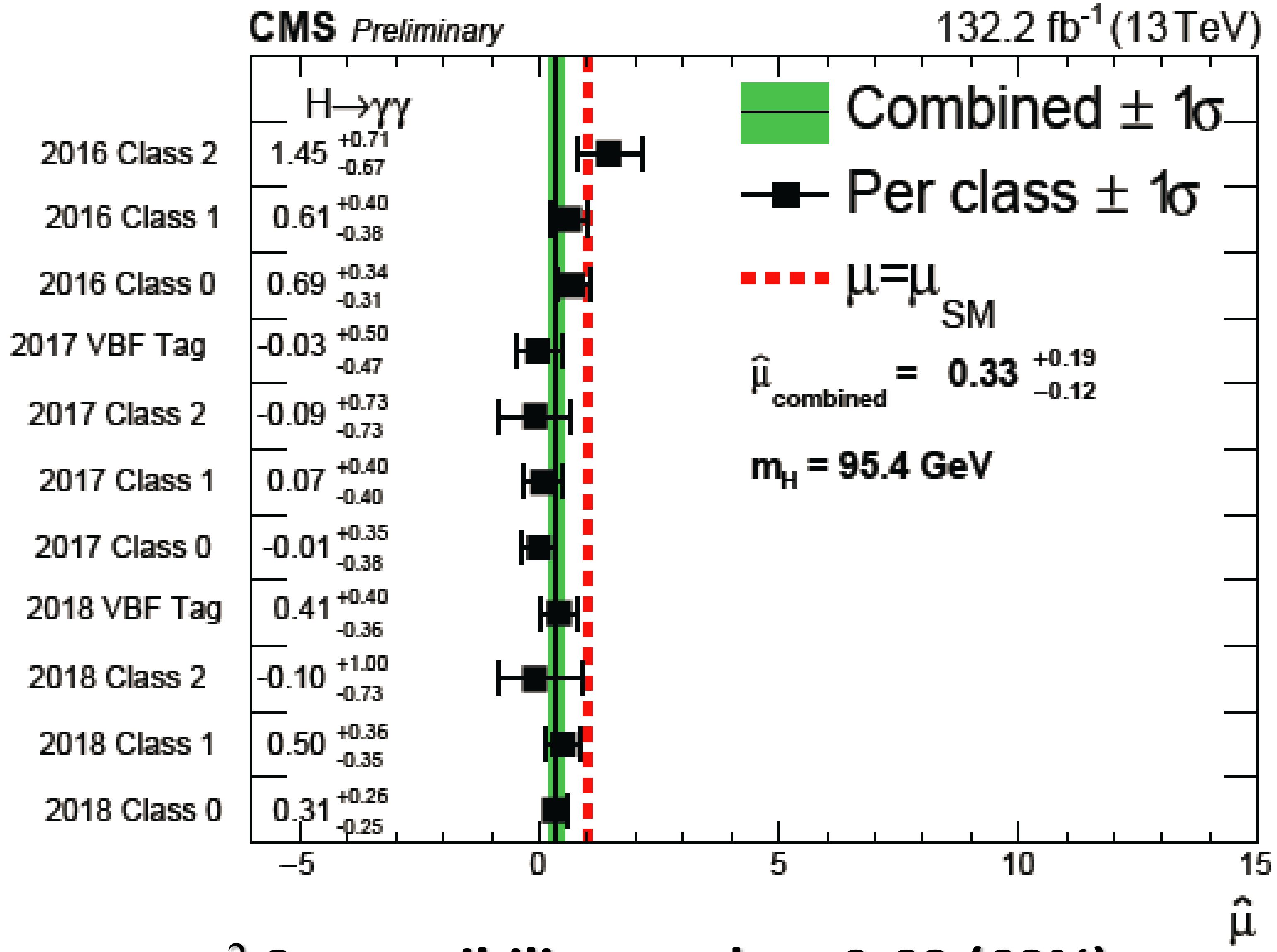
Signal Strengths (μ)

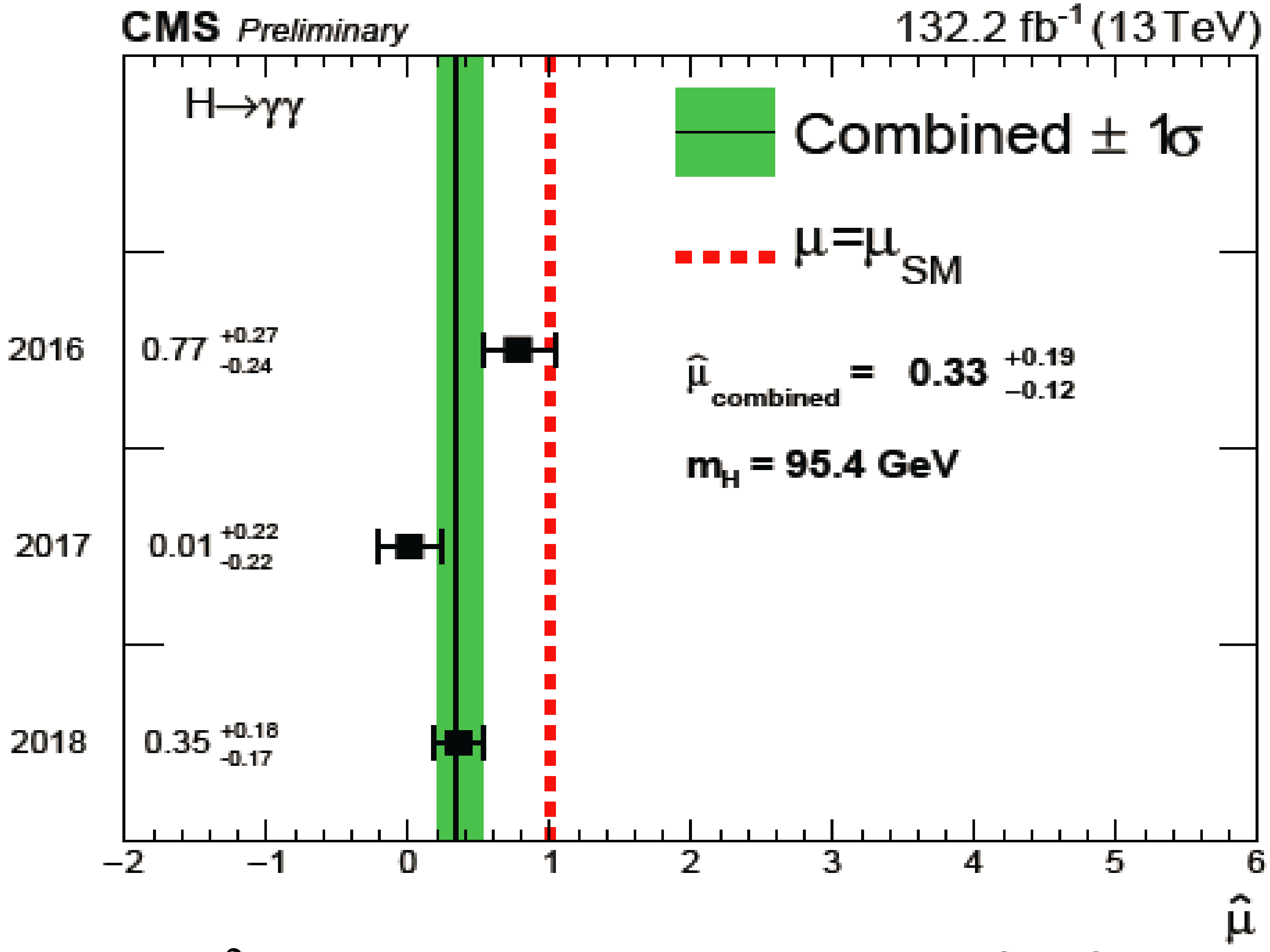
m_h fixed to max. significance value of 2016+2017+2018 (**95.4** GeV)

Channel compatibility 11 event class



χ^2 **Compatibility p-value: 0.68 (68%)**

Channel compatibility 3 year



χ^2 **Compatibility p-value: 0.06 (6%)**

[CMS-PAS-HIG-20-002](CMS-PAS-HIG-20-002) supplementary

Summary

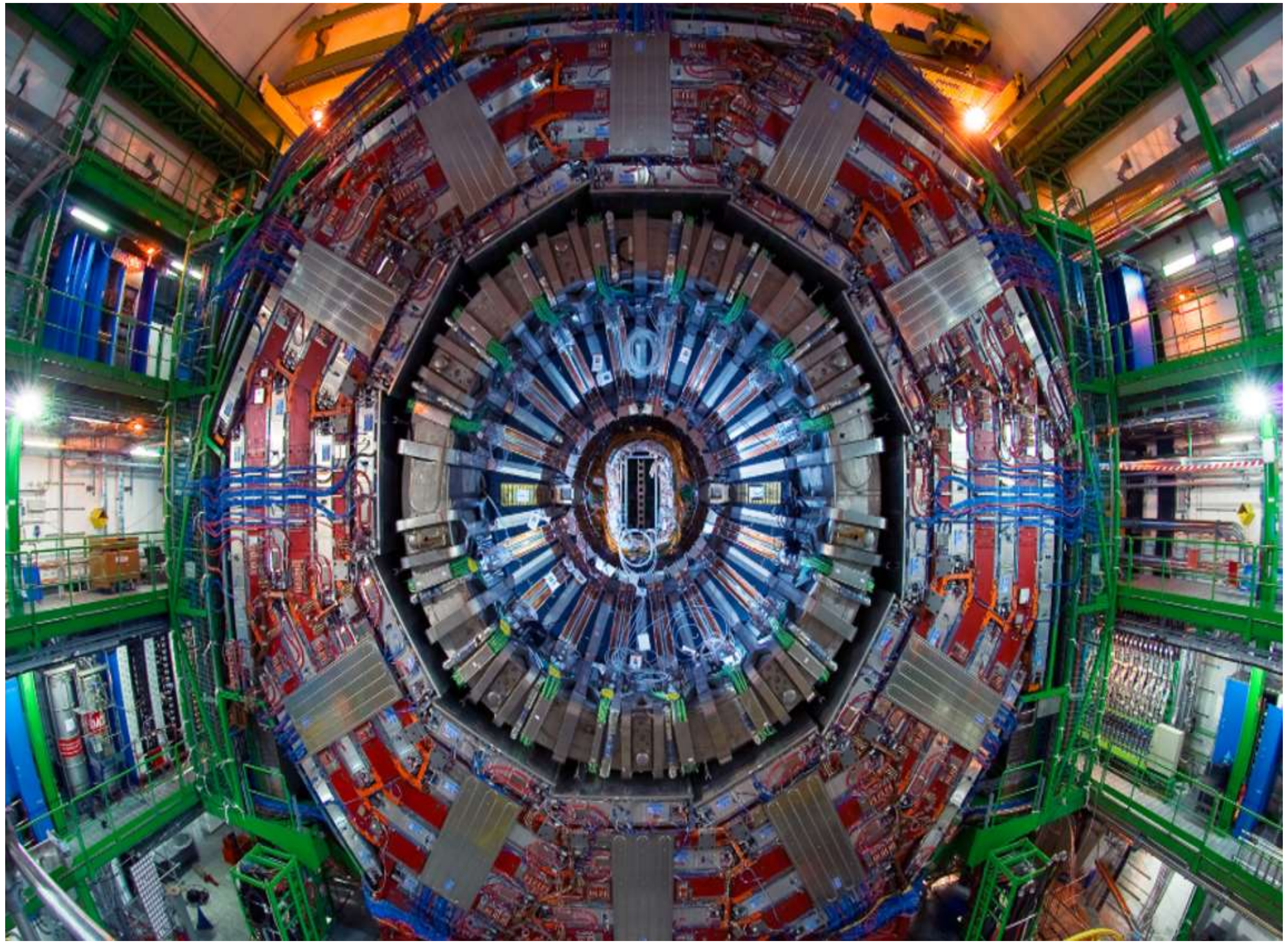
- **Results of search for a standard model-like Higgs boson in the mass range between 70 and 110 GeV in the diphoton final state at 13 TeV with full Run 2 data has been presented**

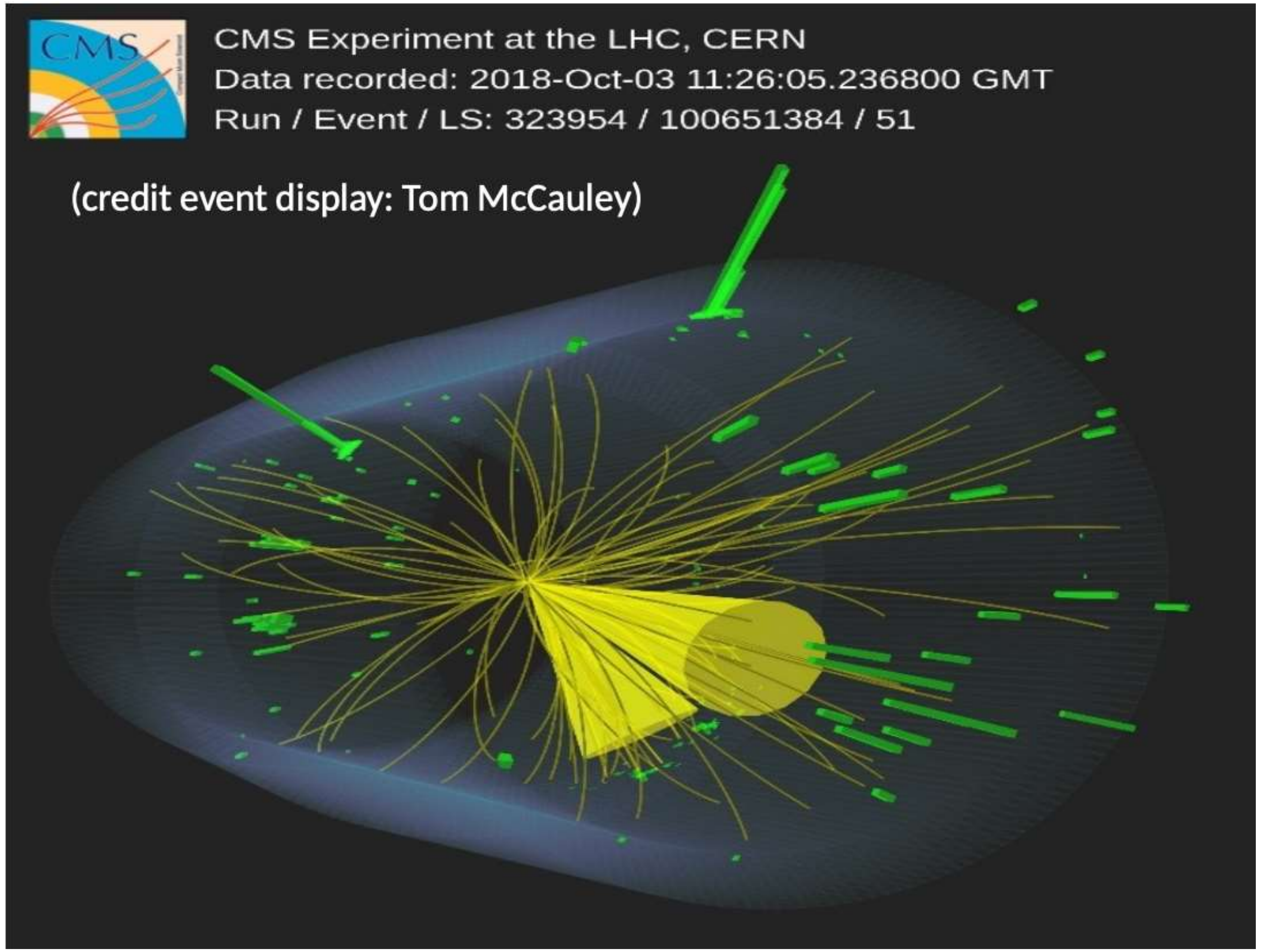
- **No hint for the existence of new Higgs boson so far.** The maximum local significance corresponds to 2.9σ at 95.4 GeV for all production mechanisms and event classes combined (1.3σ global significance)

- **Signal strengths at 95.4 GeV are compatible among 2016, 2017, 2018 and for all the event classes in 2016, 2017 and 2018.**

- **First search for a new diphoton resonance in this mass range with full Run 2 data**

- **More data is needed to conclude the nature of excess. Run 3 analysis is on its way. Stay tuned…!**

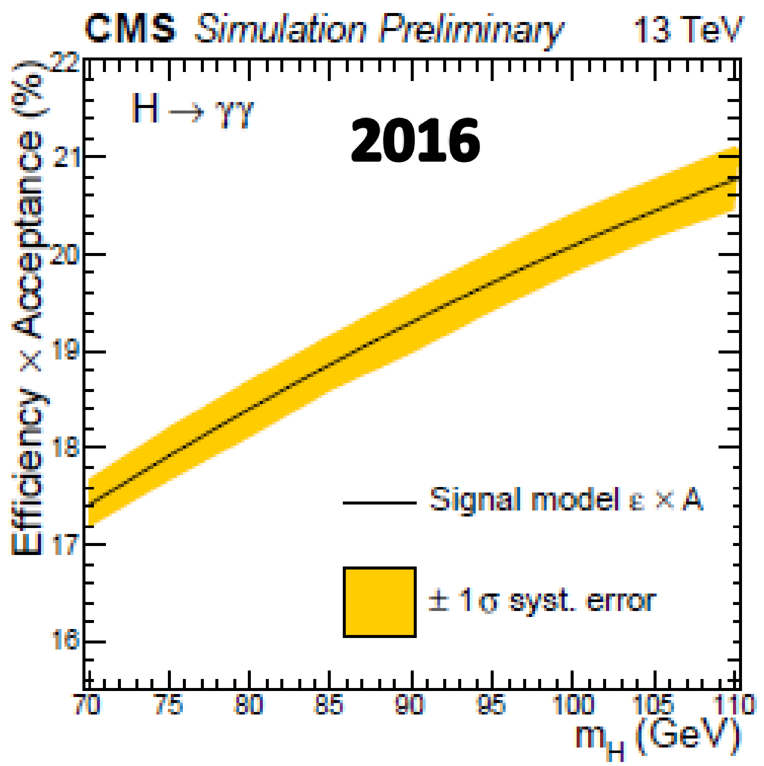


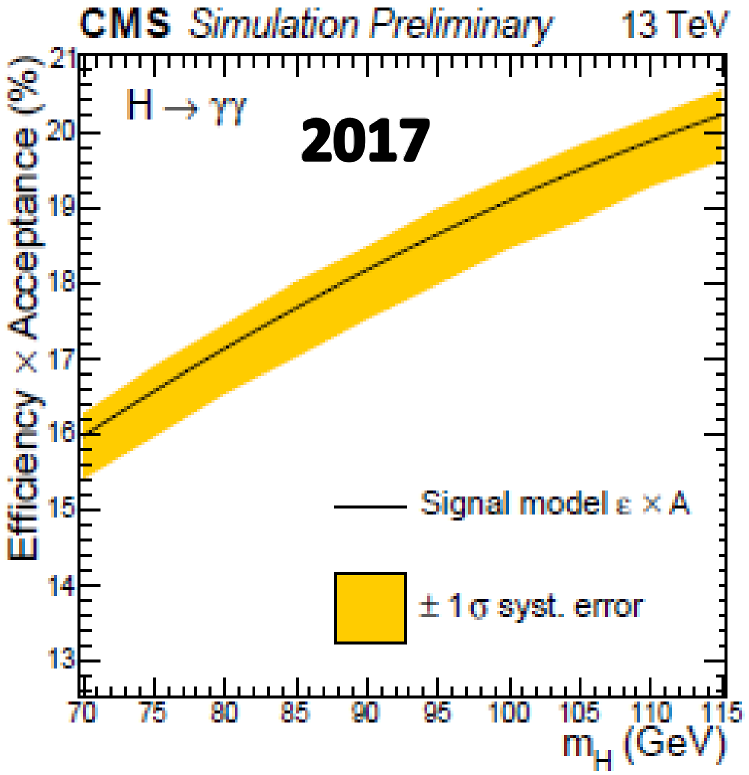


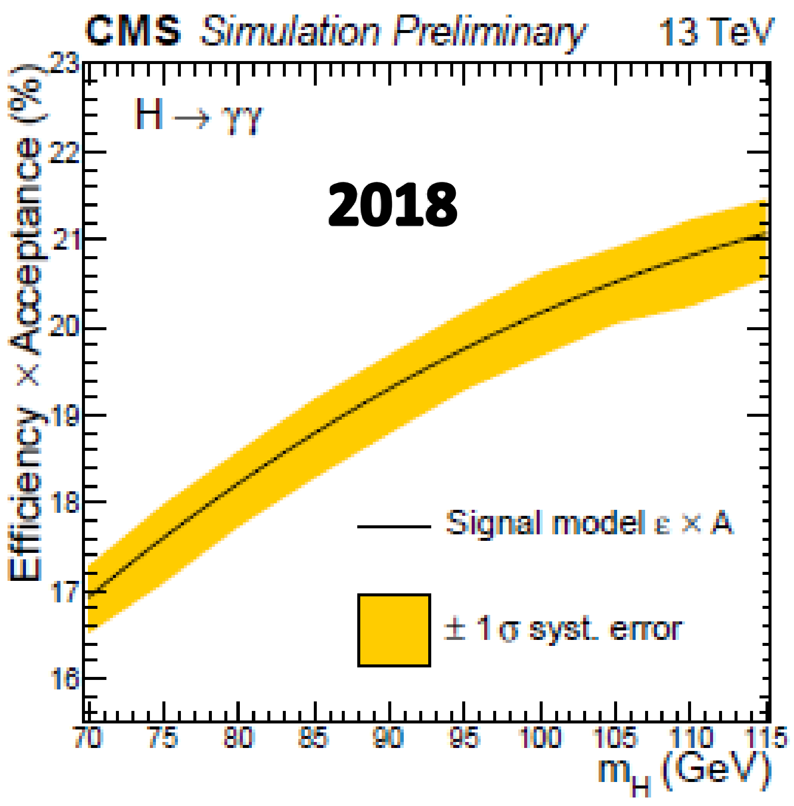
Thanks for your attention…!

Backup

Signal Modelling (Cont…)



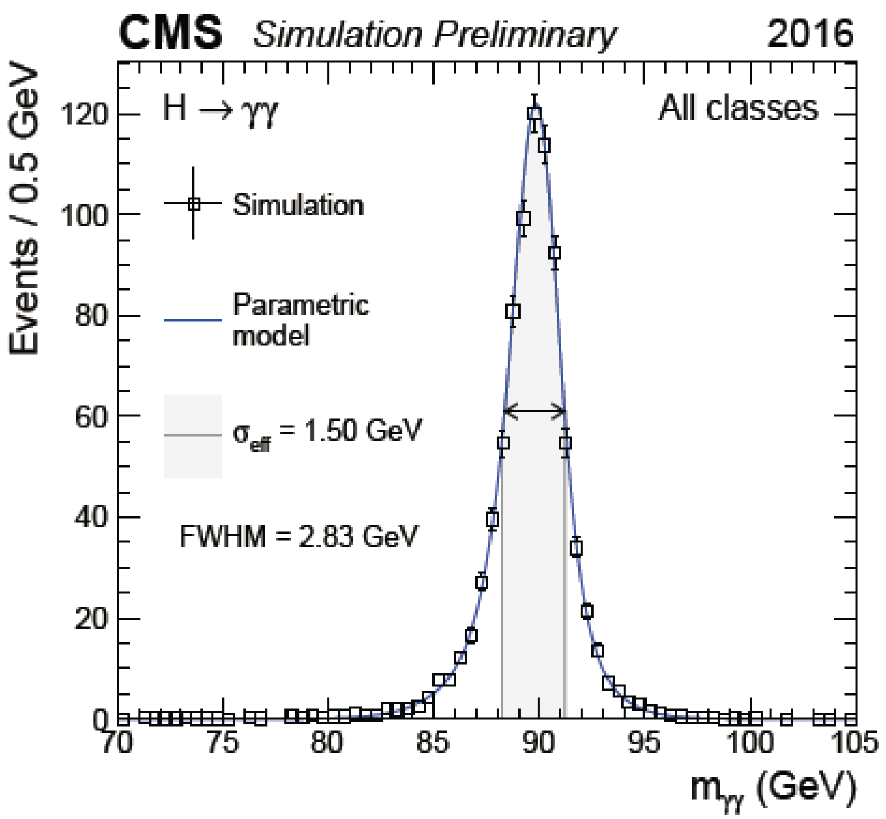


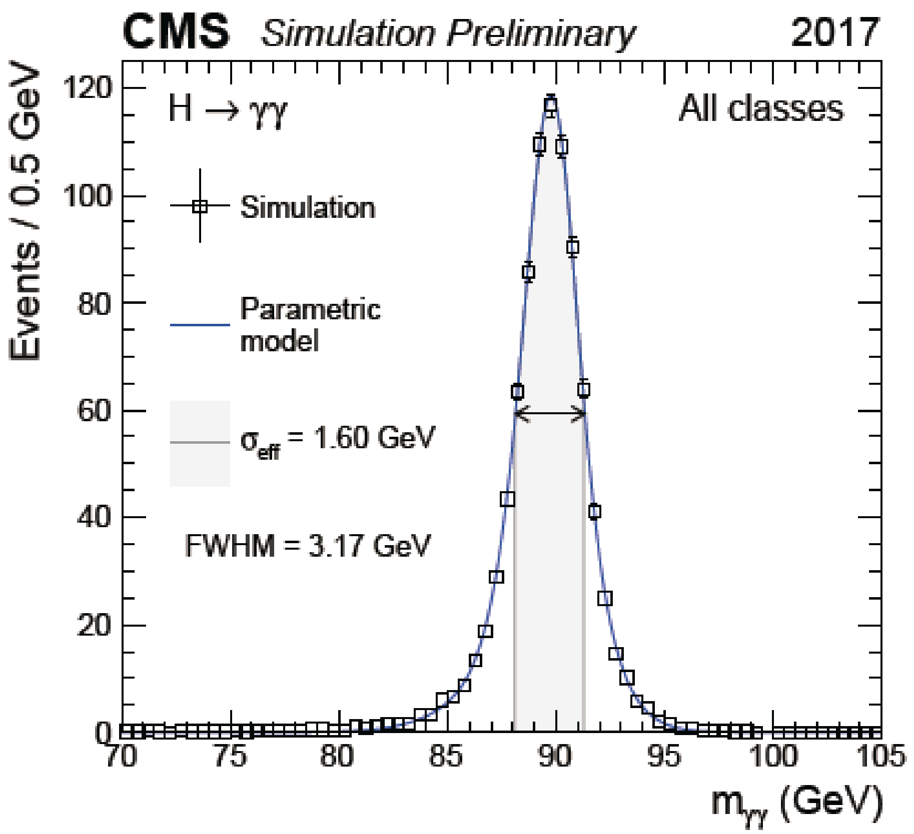


- The **final parametrized signal** shape for the combination of all production modes for all event classes, is weighted by their SM cross sections
- Signal efficiency x acceptance used for **signal normalization** ($\sigma \times$BR from SM hypothesis)
- Different selections for 3 years i.e. trigger, offline selections etc

Signal parametrization

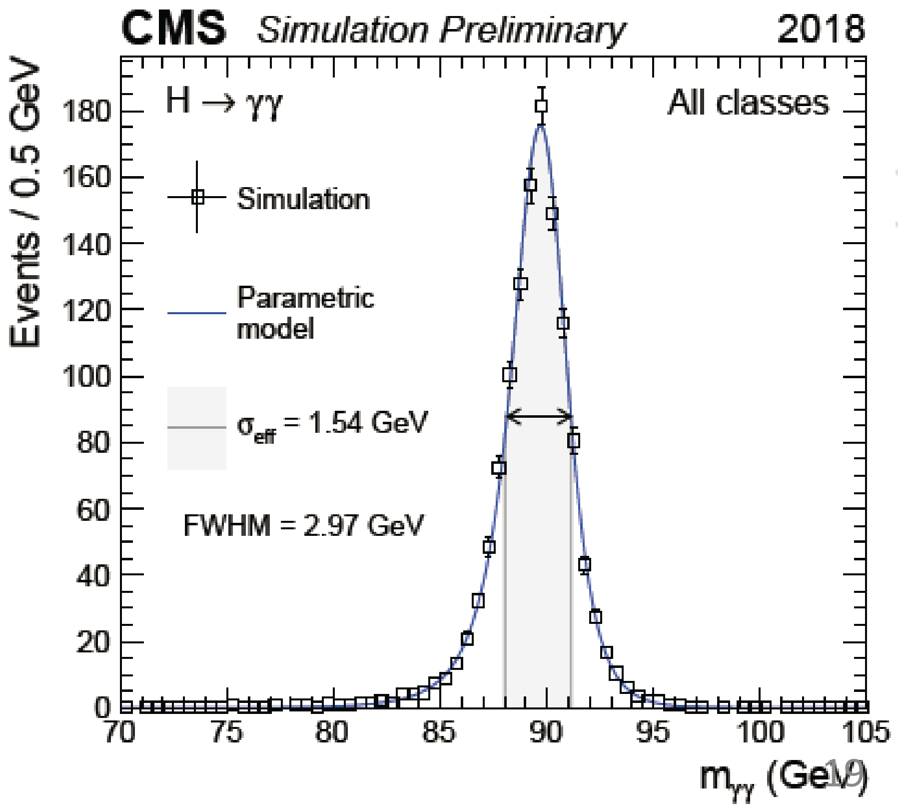
- A parametric model is used to describe the shape of the signal in each event class
- Same as the standard $H \rightarrow \gamma\gamma$ analysis method: Simultaneous Signal Fitting
- All production modes (ggH, VBF, WH, ZH, ttH) from 70 GeV to 110 GeV with a 5 GeV granularity are used
- The final parametrized signal shape for the combination of all production modes for all event classes, is weighted by their SM-like BSM cross sections
- Full parameterized signal shape, integrated over all event classes, in simulated signal events with m_H = 90 GeV





All classes combined

[CMS-PAS-HIG-20-002]



Background modeling

Best-fit functions: "DCB+exponential" fractions (0.5% - 4.8%) in 85 to 95 GeV mass range

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	0.8

Systematic uncertainties

- **Uncertainties evaluated at the per-event level:**
  - ✓ Total integrated luminosity
  - ✓ 2016 and 2017 pre-firing
  - ✓ Underlying event and parton shower
  - ✓ 2018 HEM issue
  - ✓ 2017 and 2018, VBF additional jet radiation issue
  - ✓ Linear cut SF
- **Uncertainties evaluated at the per-photon level:**
  - ✓ Shape of the photon identification BDT distribution
  - ✓ Photon energy scale and resolution
  - ✓ Trigger efficiencies SF
  - ✓ Preselection SF
  - ✓ Electron veto SF and $N_{MatchedEle}$=0 SF
  - ✓ Minimum photon identification BDT
  - ✓ Non-uniformity of light collection (FNUF)
  - ✓ Photon energy scale non-linearity
  - ✓ Vertex selection uncertainty
- **Dedicated systematics have been added for VBF class:**
  - ✓ jet energy correction and resolution,
  - ✓ PUJID
  - ✓ Tight Jet ID
- **Theoretical uncertainties:**
  - ✓ PDF uncertainty
  - ✓ QCD scale and strong coupling strength (α_s) uncertainty
  - ✓ Cross-section uncertainties (for normalized limit and p-value)
- Major systematic uncertainties: per-photon energy resolution <20%, renormalization and factorization scales<14%, UE modeling <27%, PS<16%, JES corrections (VBF class) <16%.

Signal yields and Bkg. events

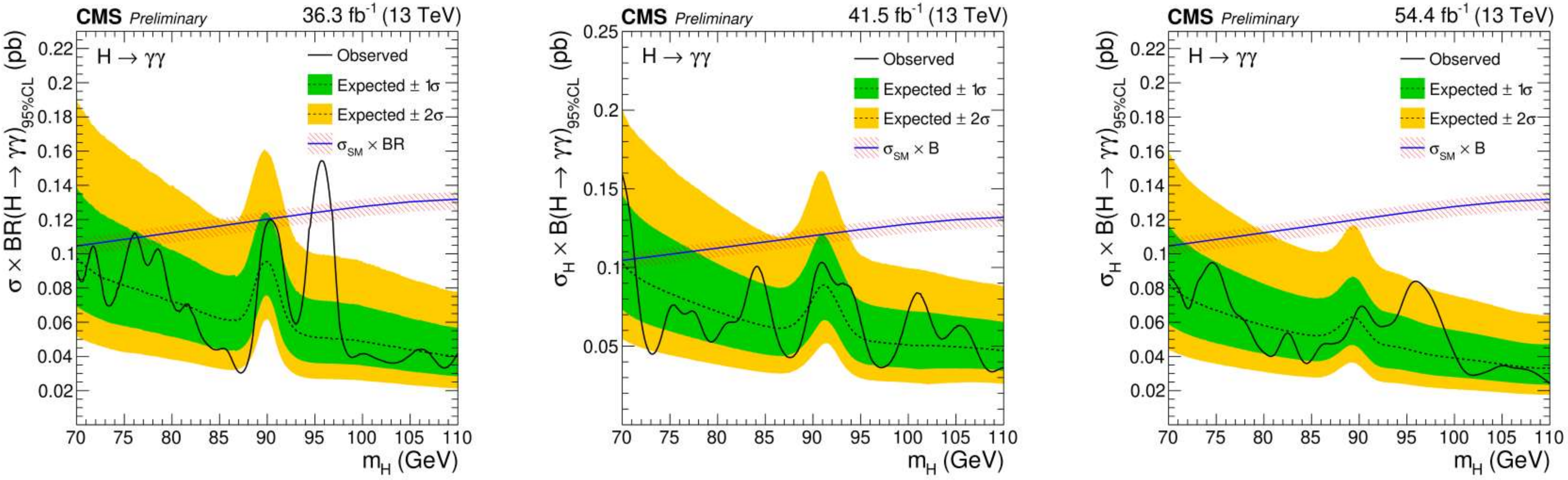
CMS-PAS-HIG-20-002

Table 2: The expected number of SM-like Higgs boson signal events ($m_H = 90\,\text{GeV}$) per event class and the corresponding percentage breakdown per production process, for the 2016, 2017 and 2018 data. The values of σ_{eff} and σ_{HM} are also shown, along with the number of background events ("Bkg.") per GeV estimated from the background-only fit to the data, that includes the number, shown separately, from the Drell–Yan process ("DY Bkg."), in a σ_{eff} window centered on $m_H = 90\,\text{GeV}$.

Event classes		Expected SM-like Higgs boson signal yield ($m_H = 90\,\text{GeV}$)								Bkg. (GeV^{-1})	DY Bkg. (GeV^{-1})
		Total	ggH (%)	VBF (%)	WH (%)	ZH (%)	$t\bar{t}$H (%)	σ_{eff} (GeV)	σ_{HM} (GeV)		
2016	0	130	71.9	15.6	6.2	3.6	2.6	1.12	1.00	271	12
36.3 fb^{-1}	1	304	87.4	6.6	3.6	2.1	0.3	1.25	1.07	3093	33
	2	407	94.7	2.5	1.7	1.0	0.1	1.87	1.51	9190	193
	Total	842	88.5	6.0	3.1	1.8	0.6	1.50	1.20	12 554	239
2017	0	104	73.4	11.6	7.5	4.3	3.2	1.27	1.13	248	7
41.5 fb^{-1}	1	347	88.5	5.6	3.5	2.1	0.3	1.40	1.24	3625	83
	2	413	94.4	2.6	1.9	1.1	0.1	1.91	1.64	8169	244
	VBF	26	45.6	51.8	1.0	0.5	1.0	1.33	1.15	29	1
	Total	890	88.2	6.2	3.1	1.8	0.6	1.60	1.35	12 071	338
2018	0	162	75.1	10.2	7.3	4.3	3.0	1.21	1.05	430	3
54.4 fb^{-1}	1	585	90.1	4.8	3.1	1.8	0.2	1.34	1.17	6445	378
	2	473	94.4	2.5	1.9	1.2	0.1	2.01	1.73	10 982	720
	VBF	38	45.4	51.9	1.1	0.6	1.0	1.21	1.03	46	1
	Total	1258	88.4	6.1	3.1	1.8	0.6	1.54	1.27	17 902	1104

Results: Limits each year

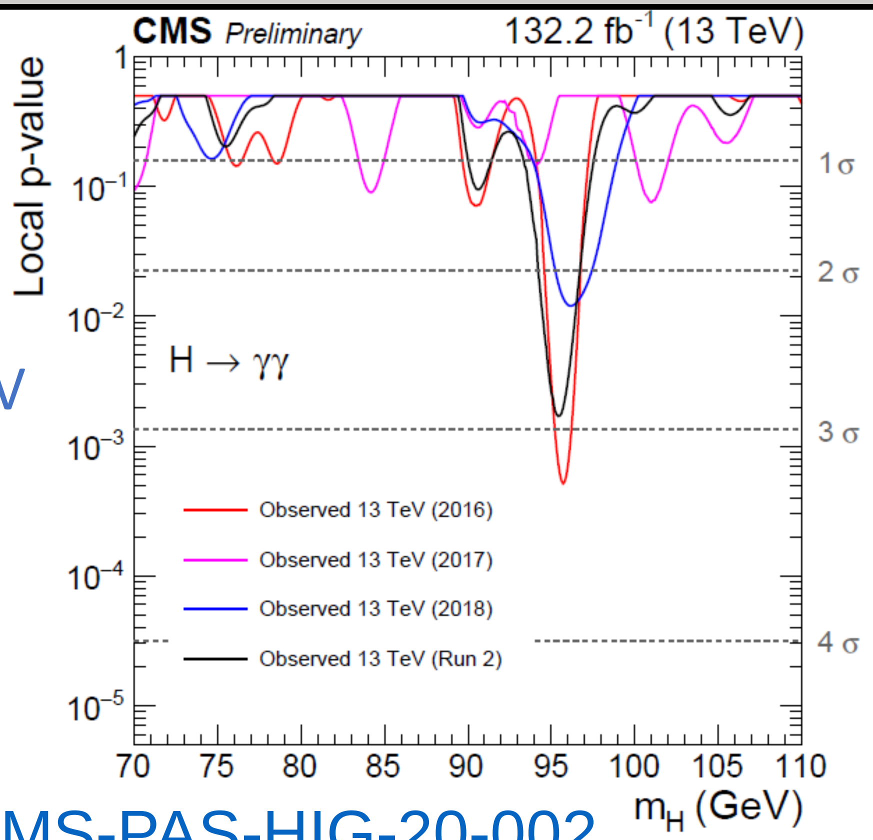
2016 | 2017 | 2018



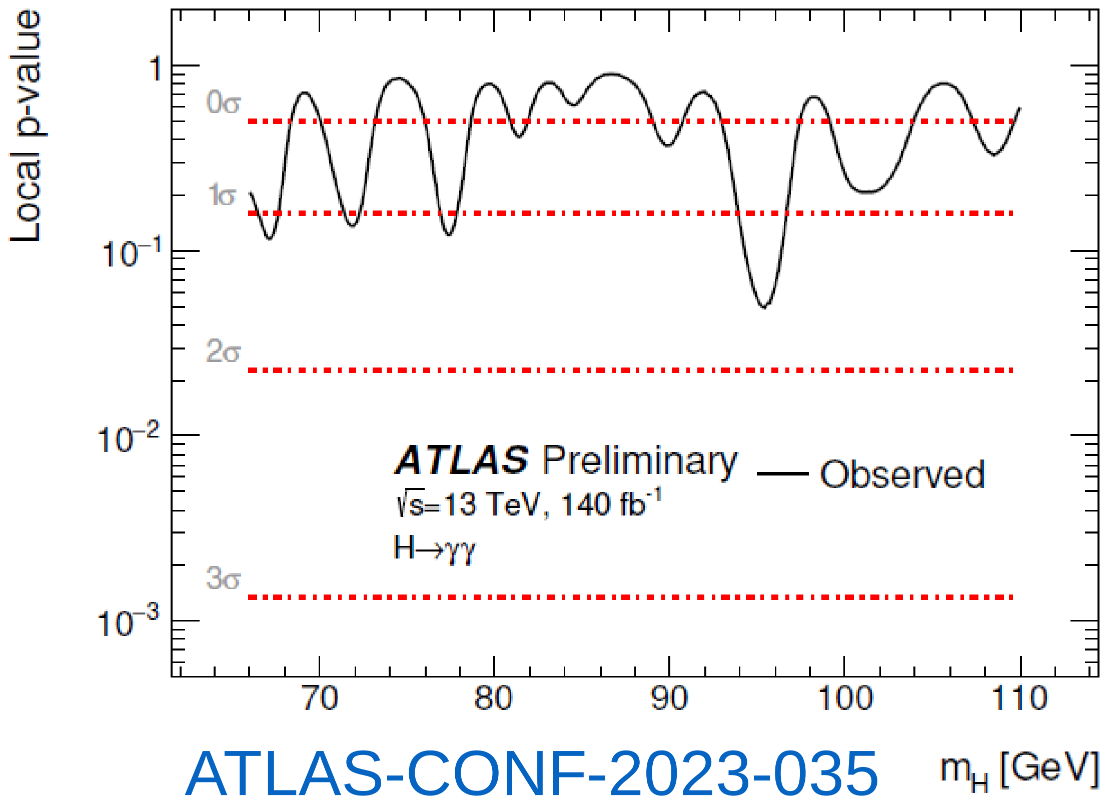
CMS-PAS-HIG-20-002 supplementary

Comparison with ATLAS

2.9σ @ 95.4 GeV



[CMS-PAS-HIG-20-002]

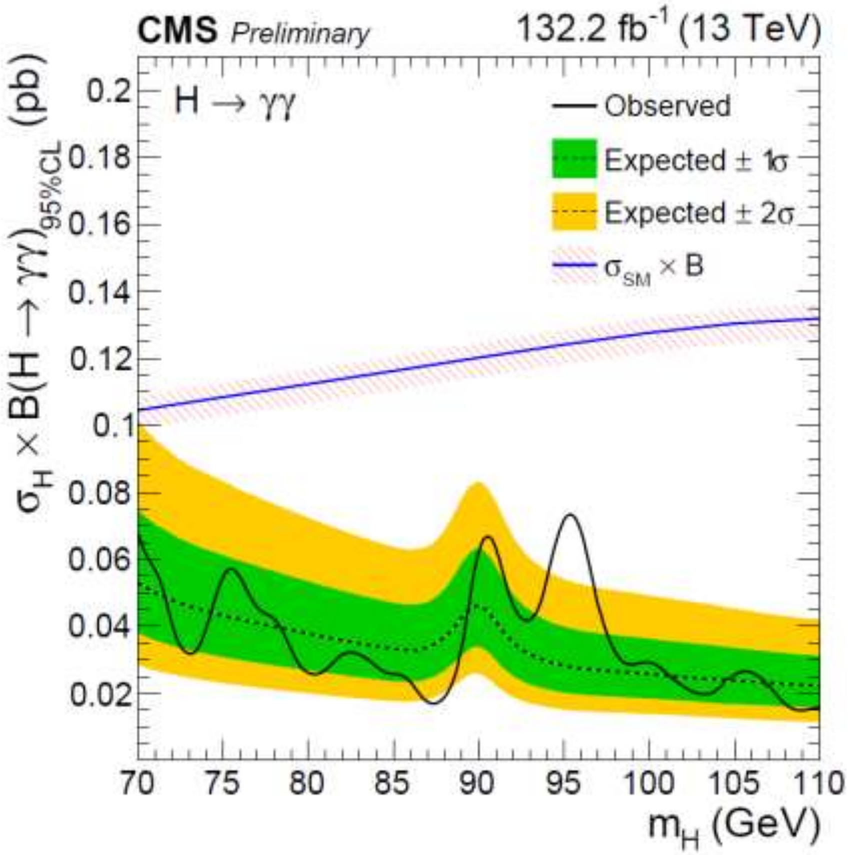


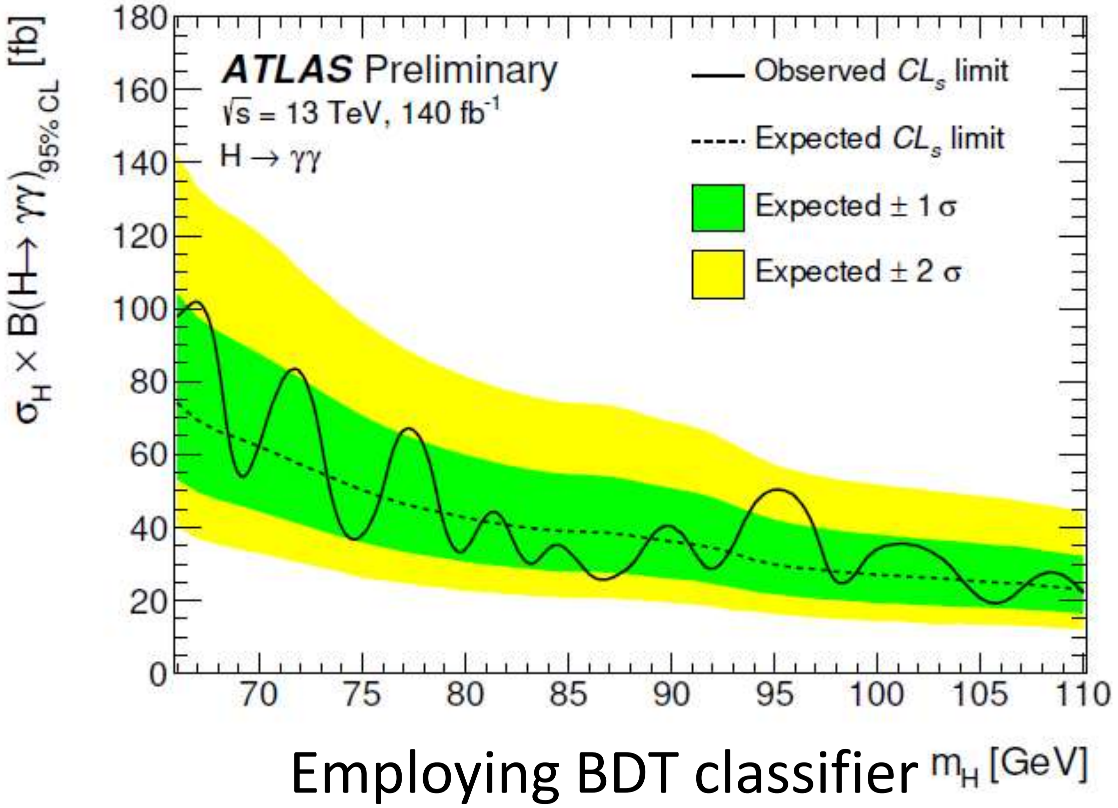
[ATLAS-CONF-2023-035]

1.7 σ @ 95.4 GeV

June 6, 2023

CMS still has better sensitivity than ATLAS





Employing BDT classifier