Search for a low-mass Higgs boson-like resonance in diphotons with ATLAS and CMS

based on: CMS-PAS-HIG-20-002 ATLAS-CONF-2023-035

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Seminar, Imperial College London IPPP (UK)

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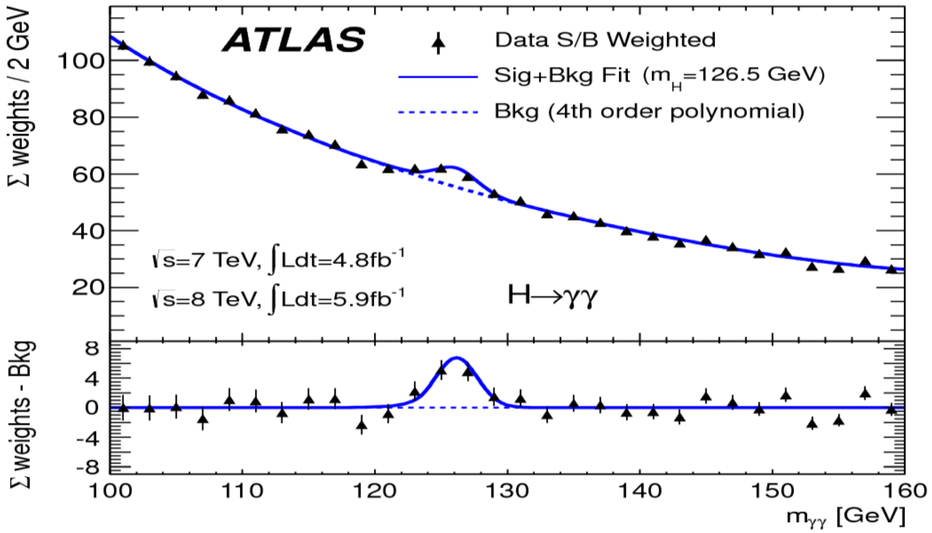
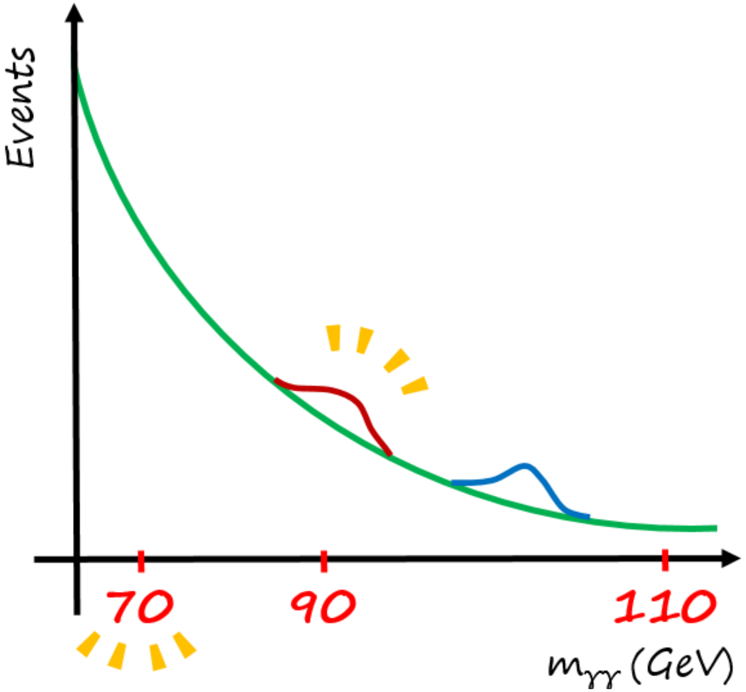
Introduction

- We found one Higgs (-Englert-Brout) boson in 2012….
- For the moment, compatible, within uncertainties, with that of the Standard Model…
- Why should we look for others?
- A second Higgs boson➔

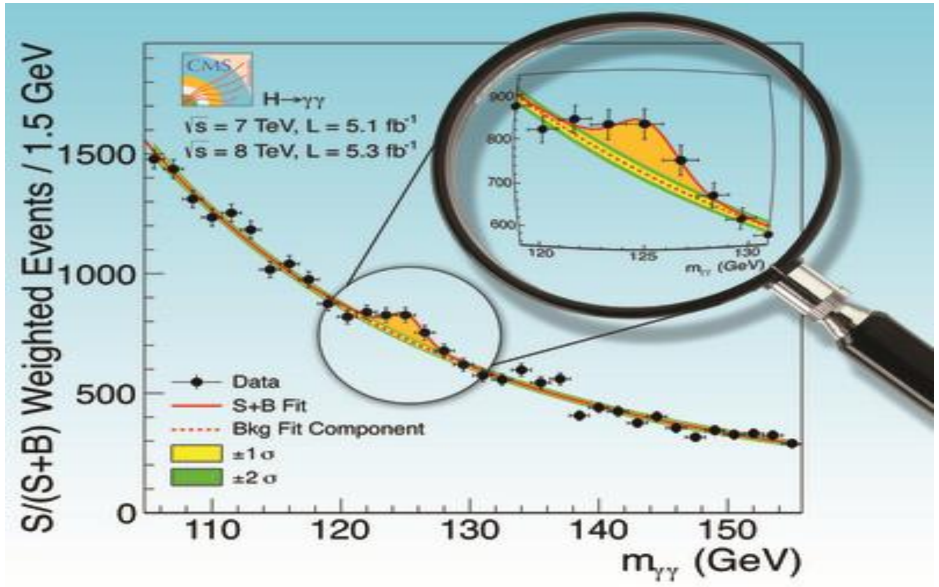
Evidence for physics beyond the Standard Model!



Phys. Lett. B 716 (2012)



Cartoon credit: L. Finco



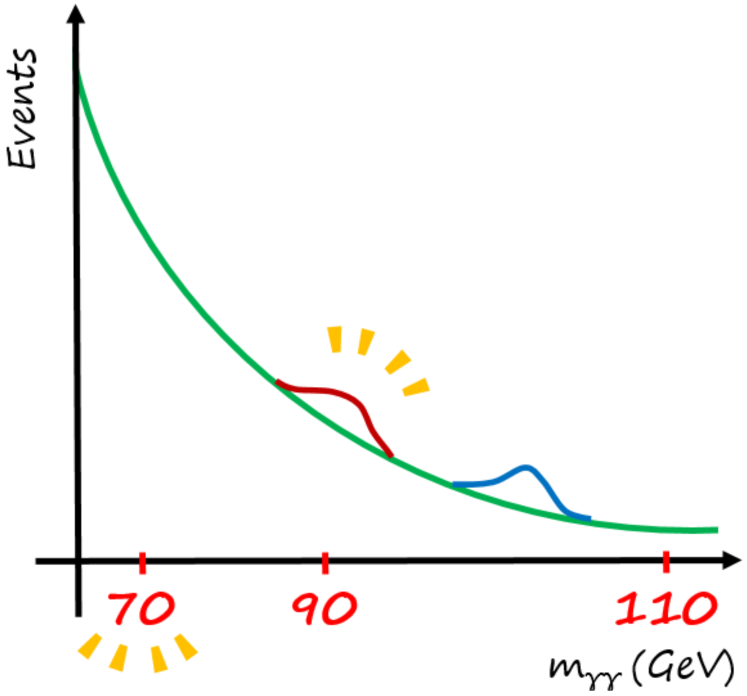
Outline

- Based on recent searches for additional low-mass (m<125 GeV) Higgs boson-like resonances in diphotons from the ATLAS and CMS collaborations at the CERN LHC:

  CMS-PAS-HIG-20-002 http://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/HIG-20-002/ (March 2023)

  ATLAS-CONF-2023-035 https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2023-035/ (June 2023)

- Motivations and detectors
- General analysis strategy
- Presentation of Results: ATLAS vs. CMS
- Triggering and search zone
- Photon Identification
- Event selection & Classification
- Signal modeling
- Background Modeling
- Systematic Uncertainties
- Results
- Summary/Conclusions
- Acknowledgements



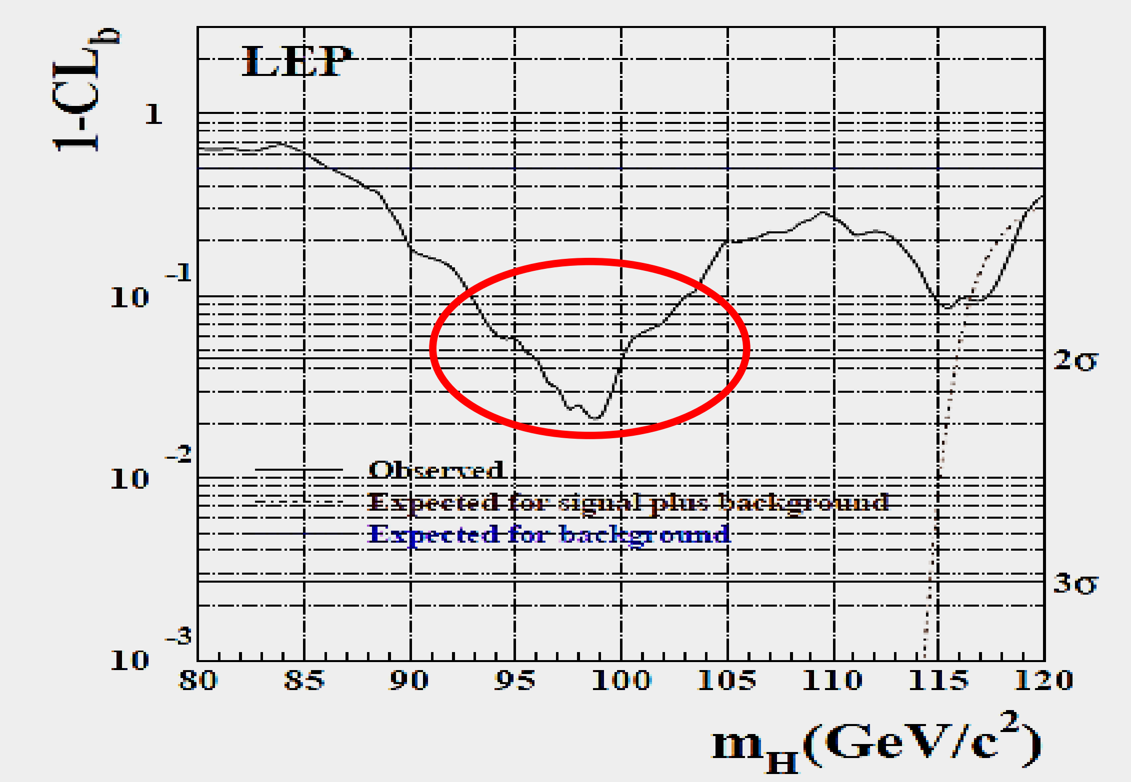
Cartoon credit: L. Finco

Motivation for low-mass diphoton searches

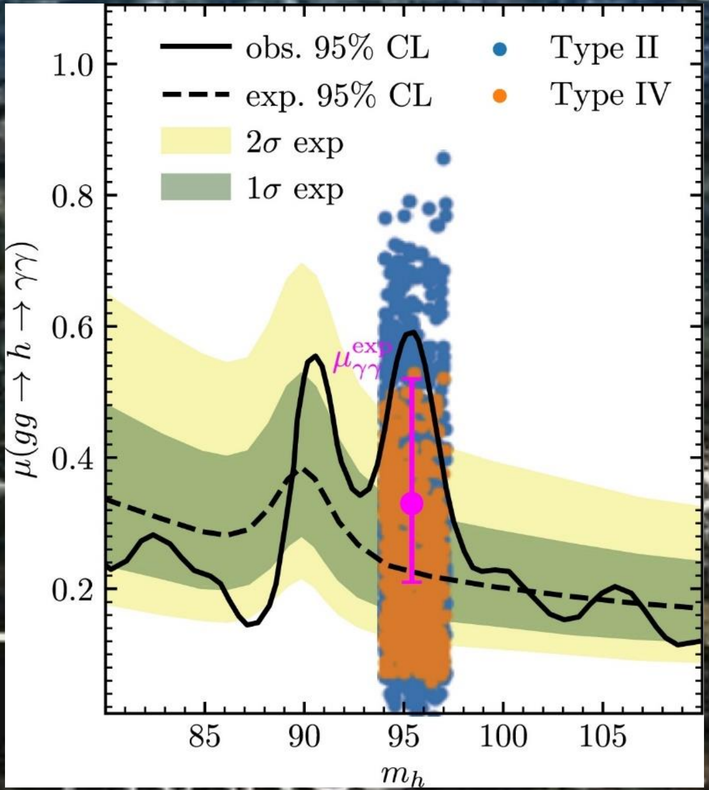
- Final LEP SM Higgs boson search results: >2σ excess at mH= 98 GeV. Has contributed to sustained interest by both theorests and experimentalists in the possibility of additional low-mass (pseudo-) scalars

- Many BSM models allow a resonance with m<125 GeV coexisting with the Higgs boson discovered in 2012 GeV (generalized 2HDM, NMSSM, 2HDM+S, Vector Dark Matter, Minimal Dilaton, Scotogenic …)

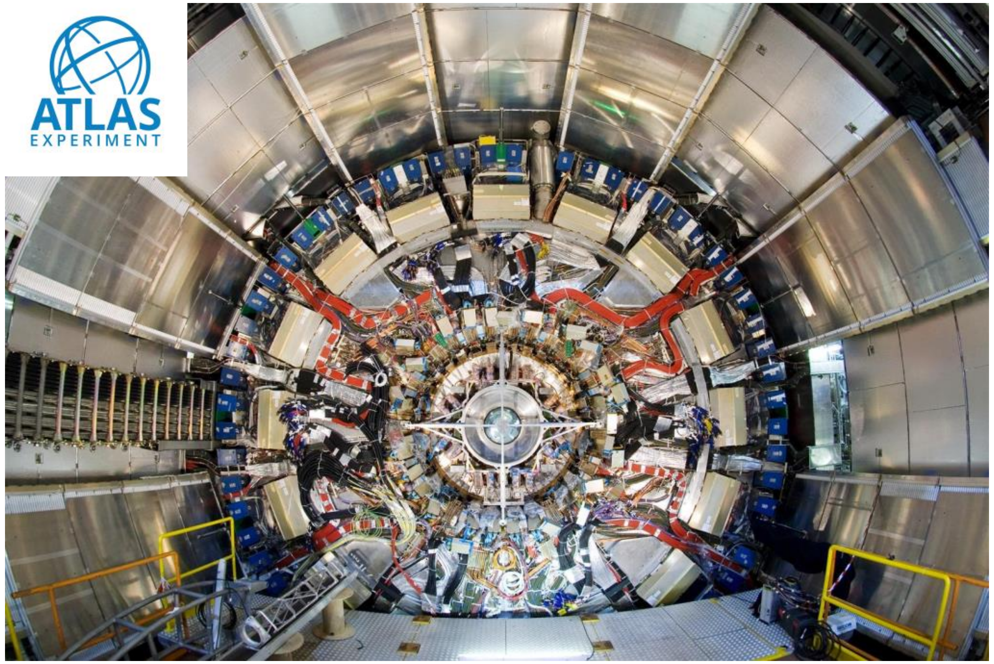
LEPHWG, Phys. Lett. B565:61-75,2003

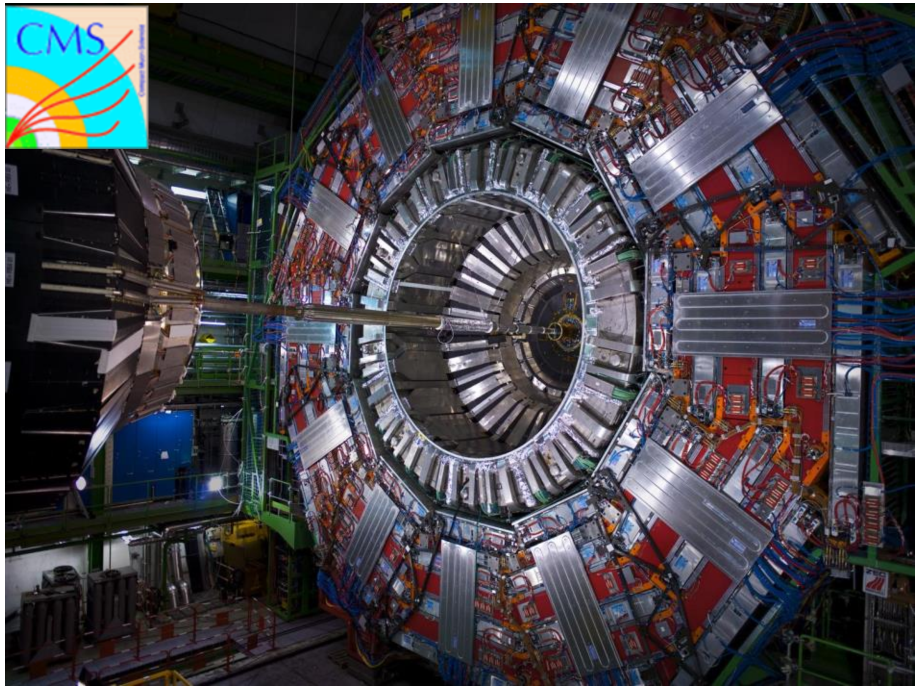


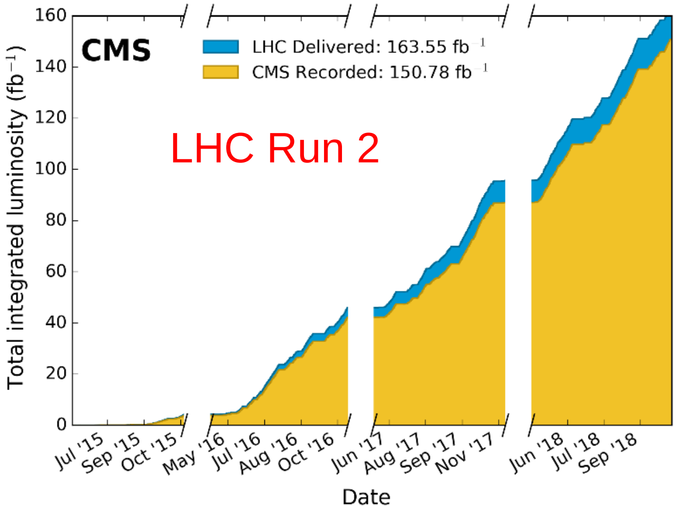
Biekoetter, Heinemeyer, Weiglein PLB 846 (2023) 138217



Detectors and data….

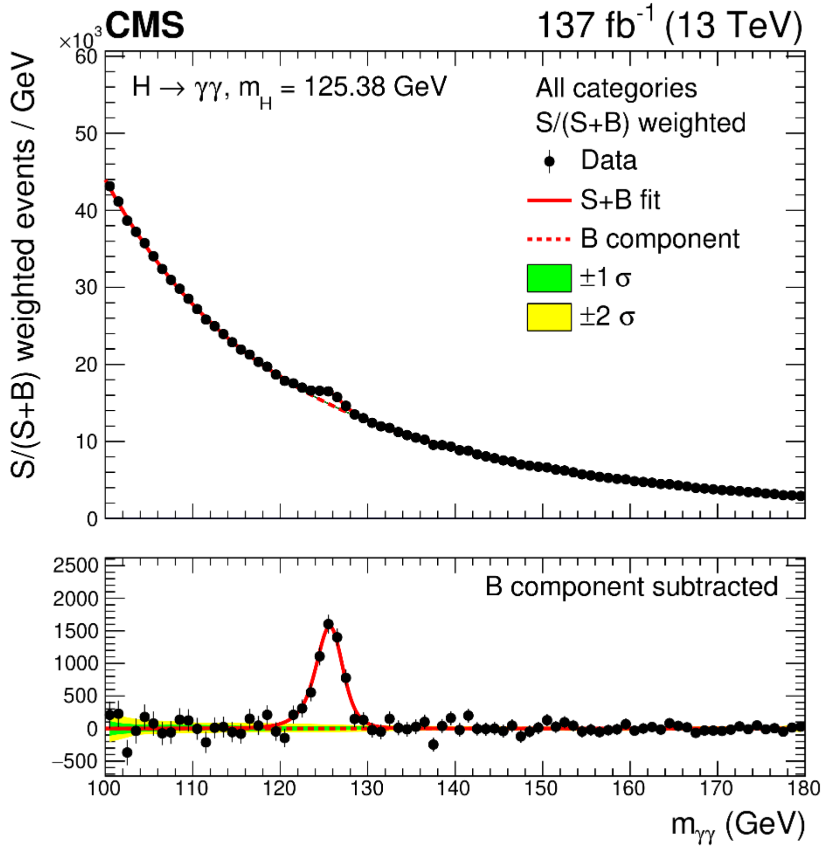


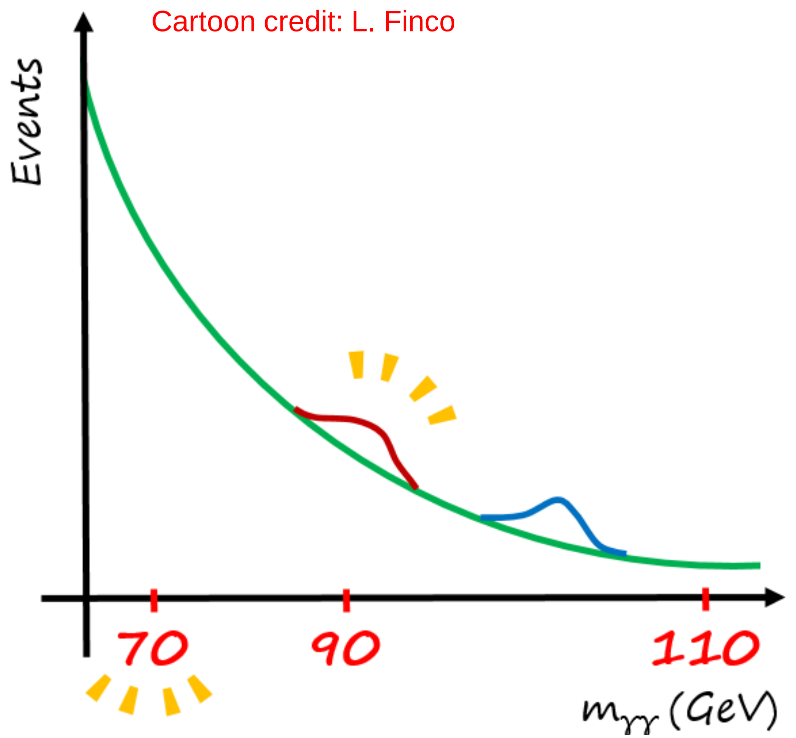




General Analysis Strategy: Std. vs low-mass H→γγ analysis

JHEP 07 (2021) 027





- Search for a narrow signal peak over a smoothly-falling background
- Lower limit of search range limited by triggering capabilities
- Relic dielectron→diphoton background from Z→ee, decreased sensitivity around m_Z
- Inherit many analysis elements from standard H→γγ analysis (photon and event reconstruction/selection, signal modeling and part of background modeling techniques..)

Presentation of Results

CMS-PAS-HIG-20-002

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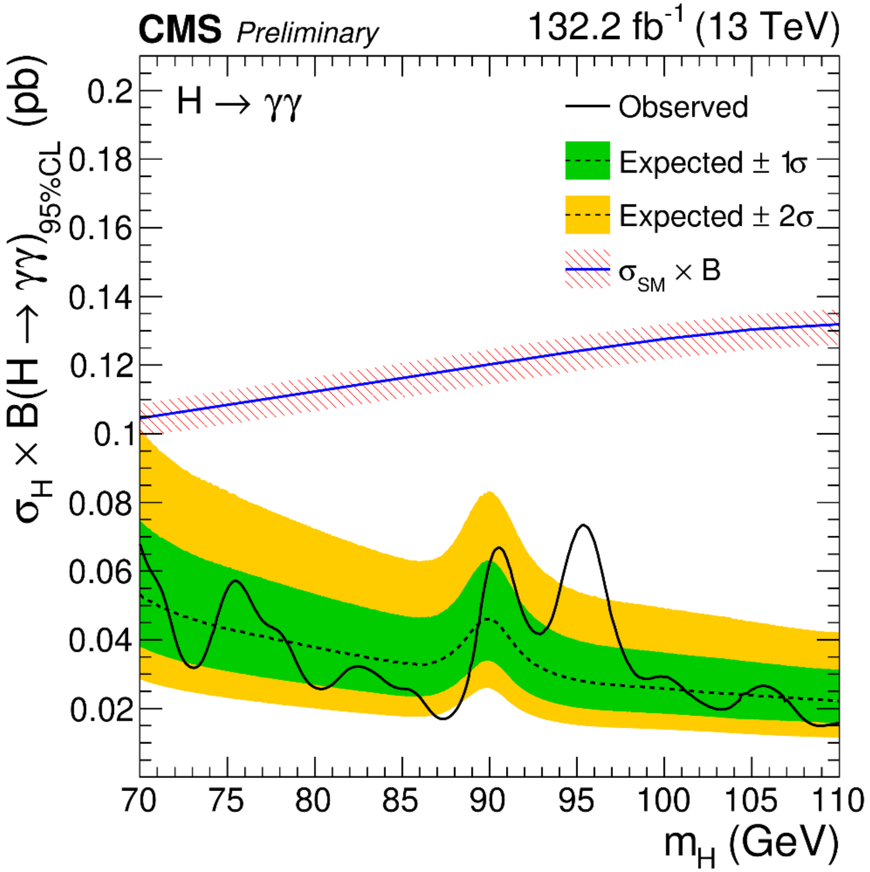
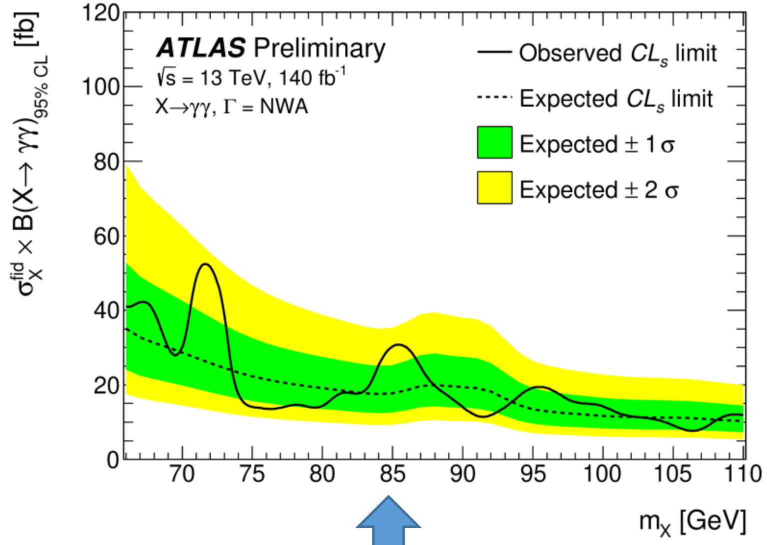
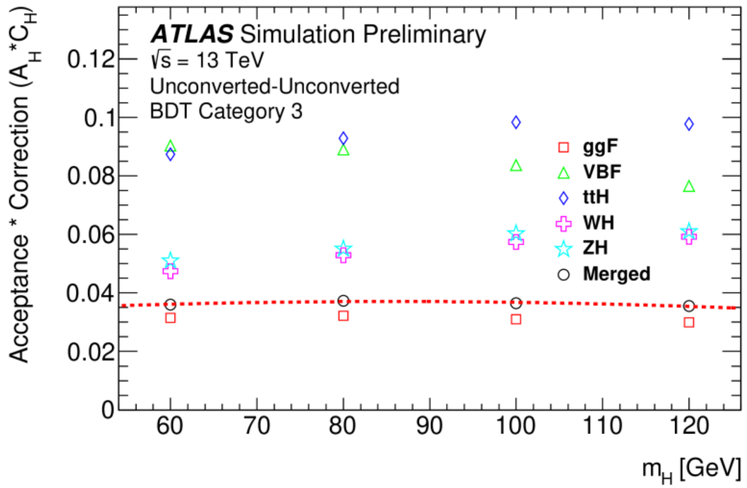




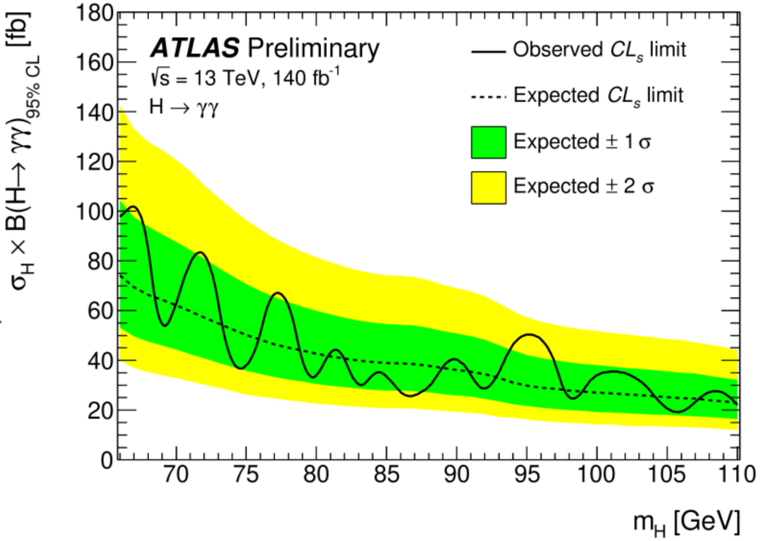


- "Model-independent": Limits on σ_{fid} X B with ggF nominal signal, uncertainty envelopes from other processes

$A_H\ C_H$ between 0.13→0.2

- "Model-dependent": Limits on σ_H X B, obtained from σ_{fid} via

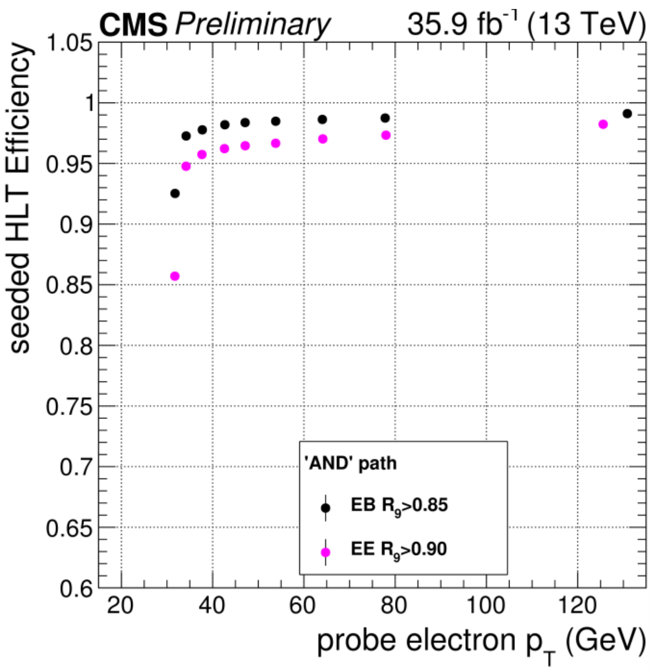
$$\sigma_H \cdot \mathcal{B} = \frac{N_S}{A_H C_H \mathcal{L}}$$

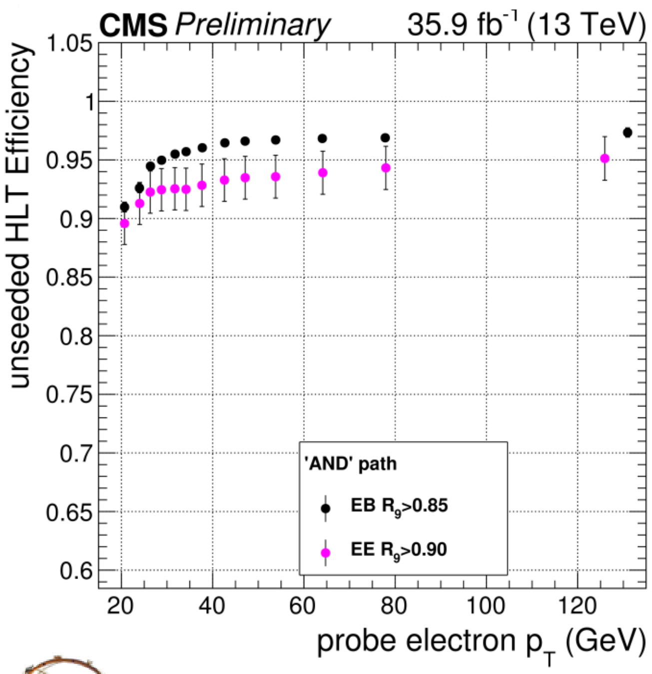


- CMS: Limits on total σ_H X B with production modes combined as in SM
- Also assuming 100% production via certain (groups of) processes

Triggering and search zone

CMS-PAS-HIG-20-002





- $p_{T\gamma}$ >{30,18} GeV, requirements on ratio of hadronic/electromagnetic energy, veto if hits in pixel detector (except 2018), EM shower shape and isolation energy requirements, $m_{\gamma\gamma}$ >55 GeV (except 2018)➔search zone: 70 GeV<m_h<110 GeV

CMS PAS HIG-17-013

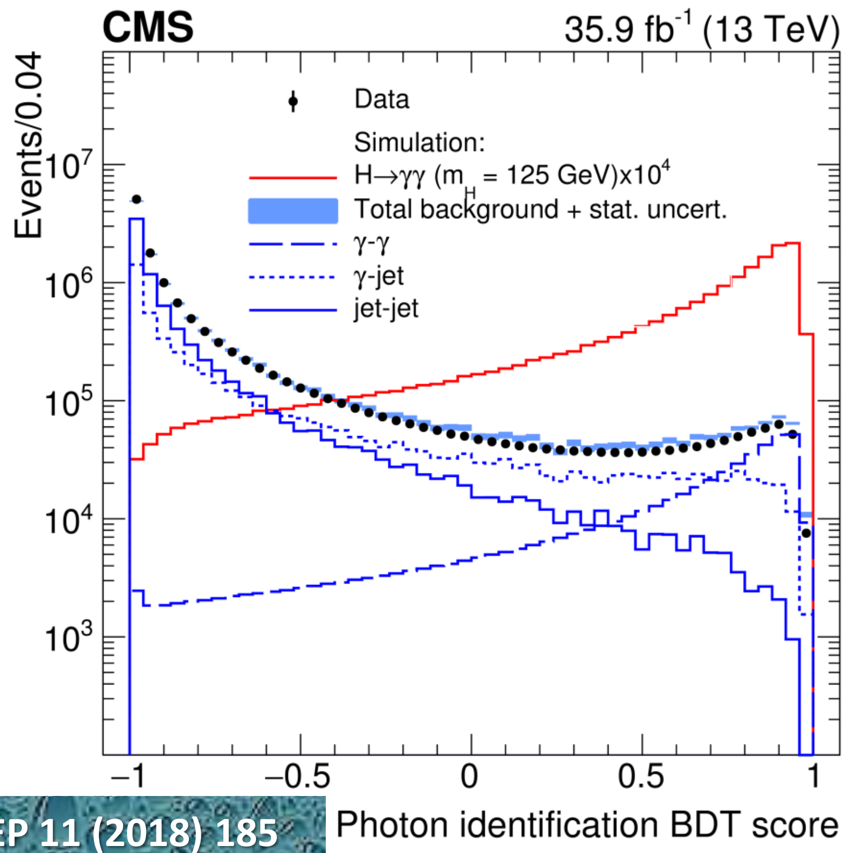
ATLAS-CONF-2023-035

- 2016-2017: $p_{T\gamma}$ >{20,20} then >{22,22} then >{20,20} GeV
- Requirements on EM shower shape, then isolation energy (2017)
- Search zone: 66 GeV<m_h <110 GeV

Photon Identification

CMS-PAS-HIG-20-002

- Fight reducible background, mostly from π^0
- Photon ID BDT: shower shape, 'particle flow' isolation sums (photon, charged hadron), energy-density coeff. ρ, η
- Minimum score required, otherwise score input to diphoton BDT (next slide)
- Veto photon candidates associated with at least 2 pixel detector hits



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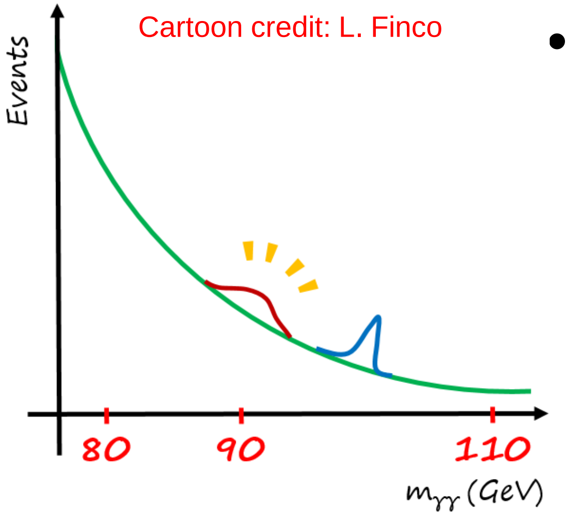
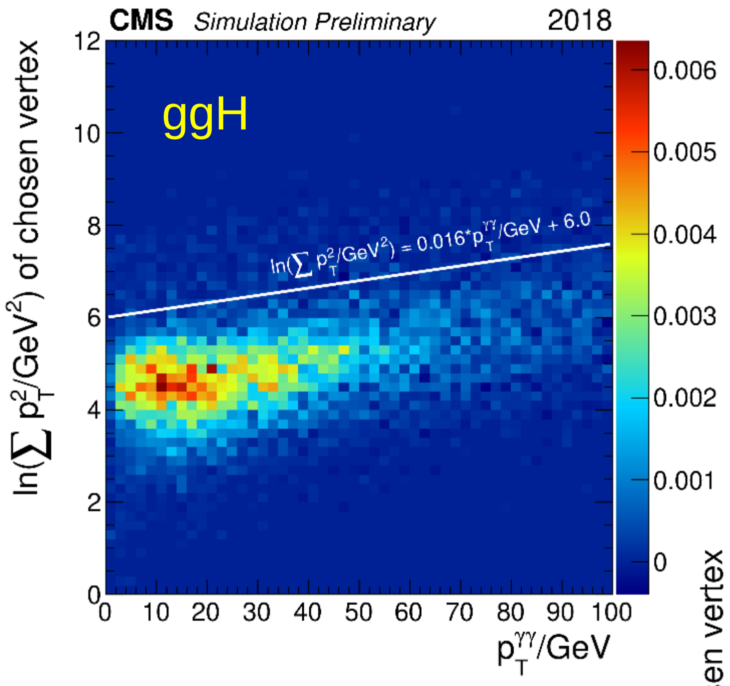
- Cut-based shower shape criteria
- Cut-based calorimeter and tracking isolation sum criteria
- Photon conversion identification: Association with 2 conversion-compatible tracks or 1 track with no hit in innermost layer of inner tracking detector

- Both experiments correct isolation sums for pileup and underlying-event contributions.

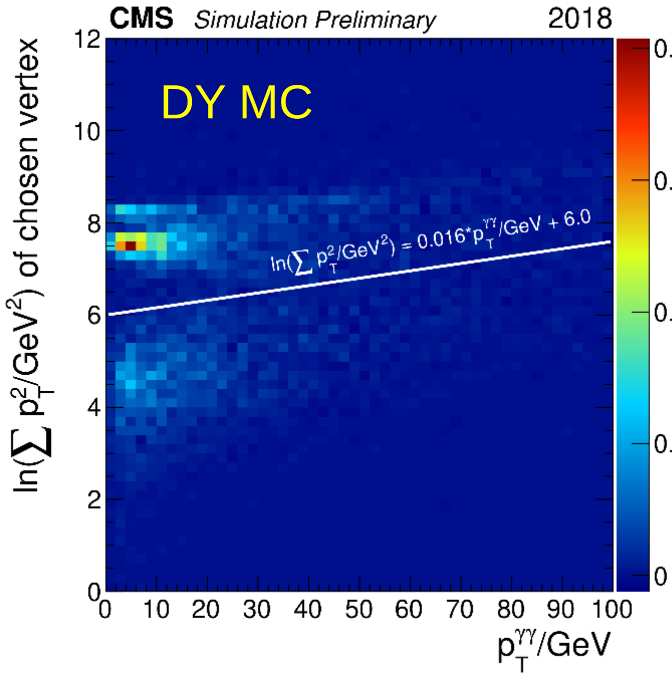
Fighting the relic Z→ee background.....

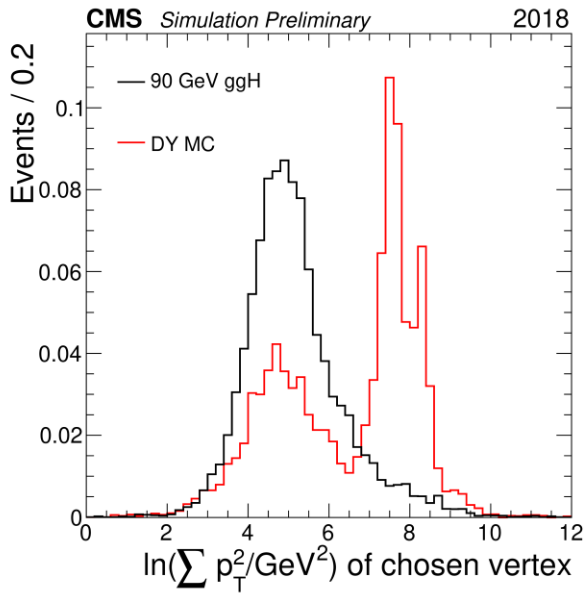


- Biggest challenge: misidentified Z→ee pairs



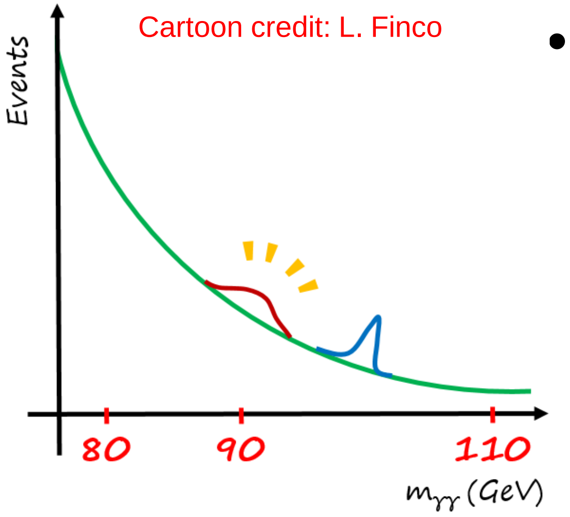
$$\ln(\Sigma p_T^2/\,\mathrm{GeV}^2) < 0.016 p_T^{\gamma\gamma}/\,\mathrm{GeV} + 6.0$$





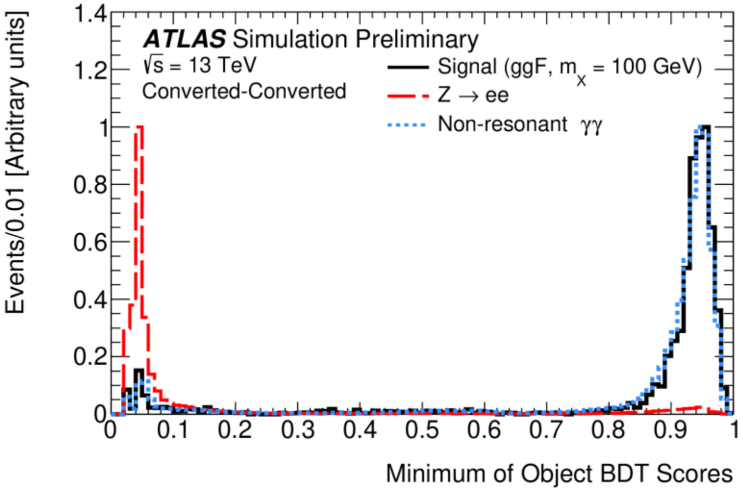
- Veto γ candidates also reconstructed as e (single hit in 1st pixel layer)
- Veto tracks late or missed by pixel detector, but spare boosted events

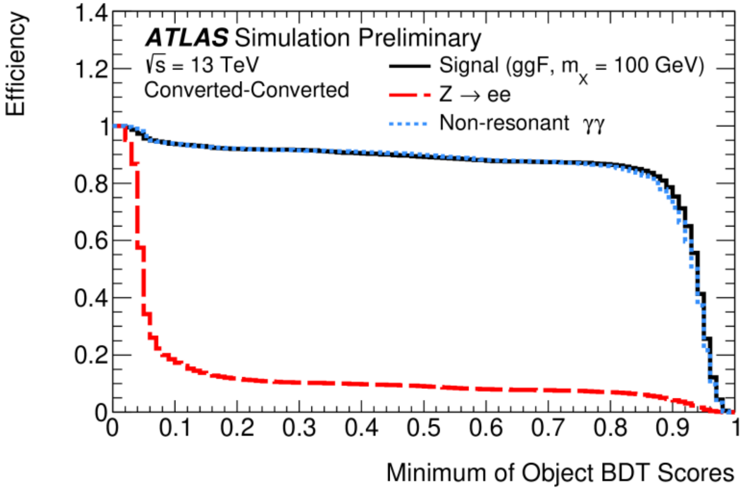
Fighting the relic Z→ee background…



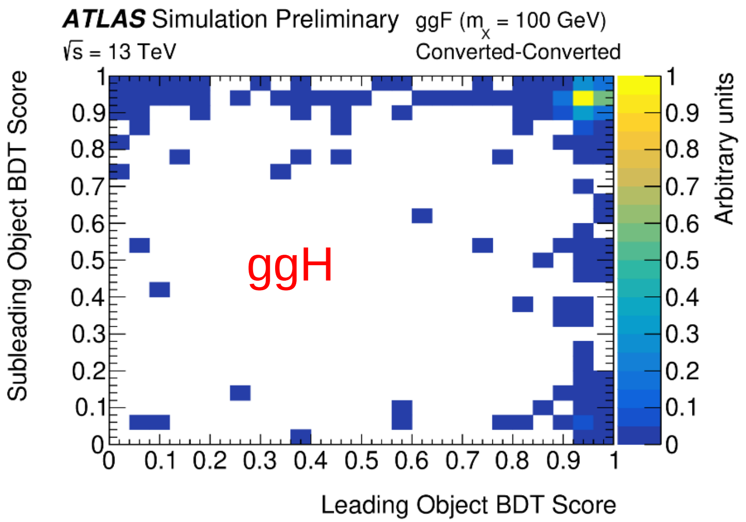
- Biggest challenge: misidentified Z→ee pairs

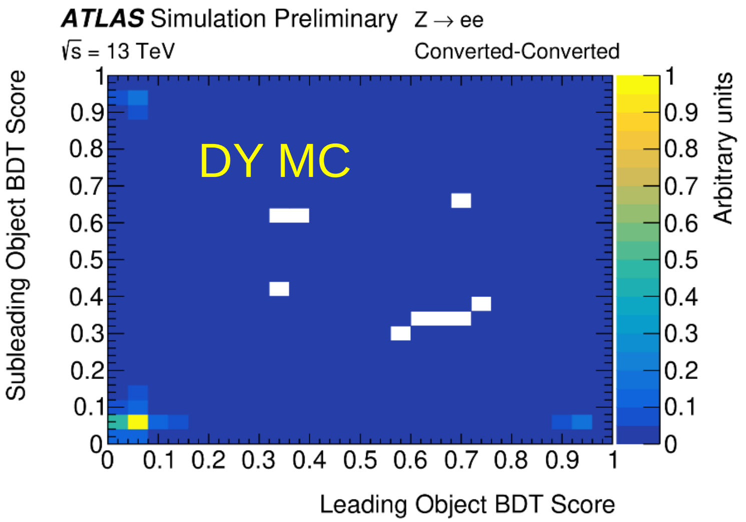
- Kinematical object BDT w/ track and conversion variables (if also reconstructed as e)





- Object BDT score>0.2 for both candidates, targets CC case in particular
- Model-dependent case:
  Also object BDT→ category BDT

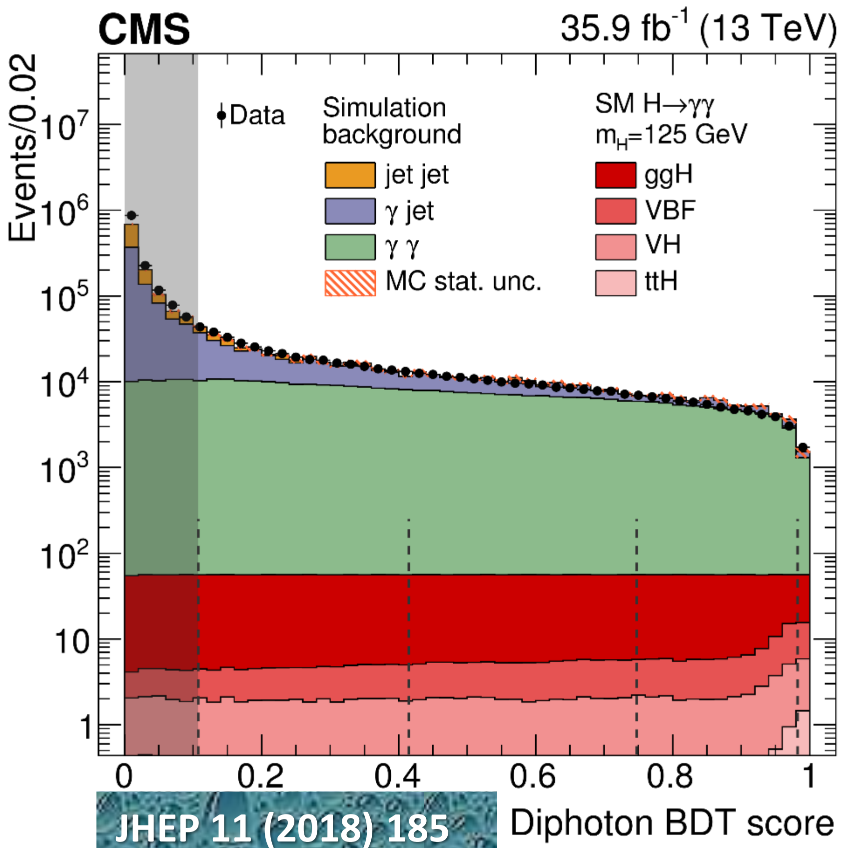




Event selection & Classification

CMS-PAS-HIG-20-002

- Diphoton BDT: $p_t/m_{\gamma\gamma}$, η , $\cos(\phi1-\phi2)$, both PhotonID BDT outputs, mass resolution wrt correct and incorrect vertices, vertex probability



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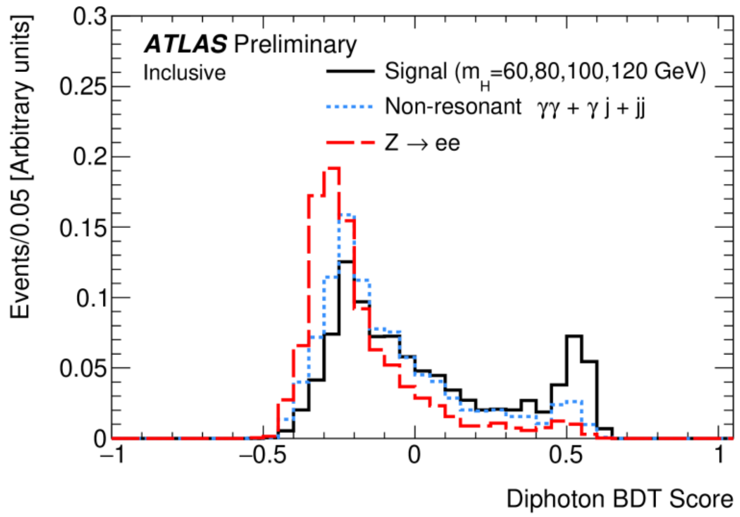

- Model-independent case: 3 classes, conversion status (UU,UC,CC)
- Model-dependent case: object BDT→ category BDT, most 'CMS' variables + minimum and both objectBDT scores
- {UU,UC, CC}X{category BDT}→6 classes

- 3 inclusive classes in diphotonBDT + 1 'VBF' class (2017-2018) for events w/additional jets, via combinedBDT, inputs: "dijet" BDT, diphotonBDT, $p_T/m_{\gamma\gamma}$

Signal modeling

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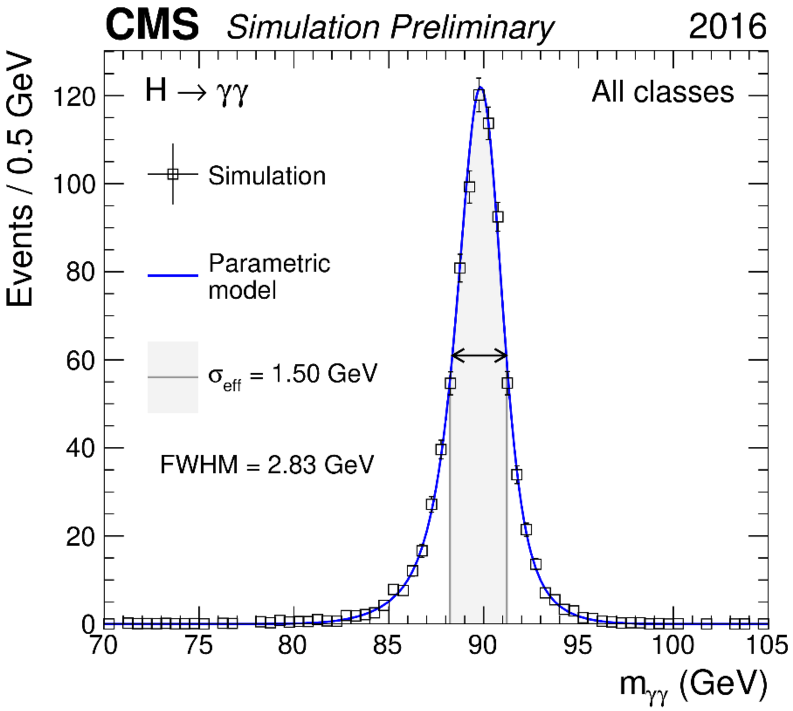
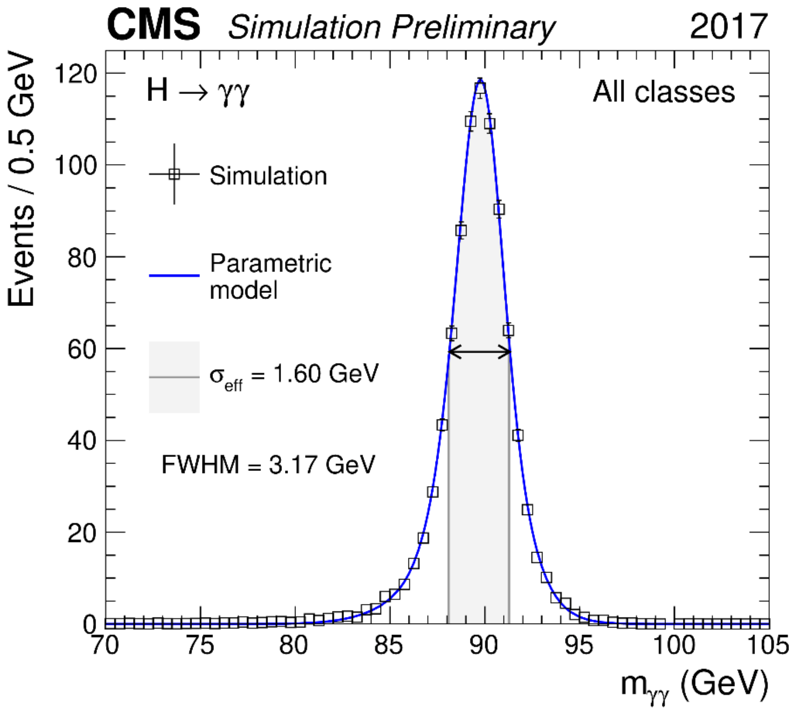
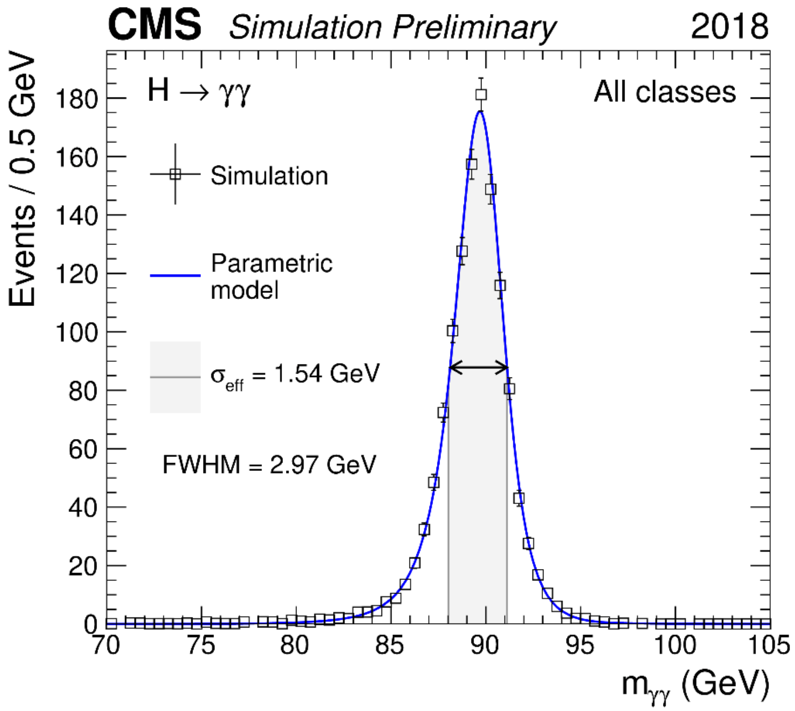


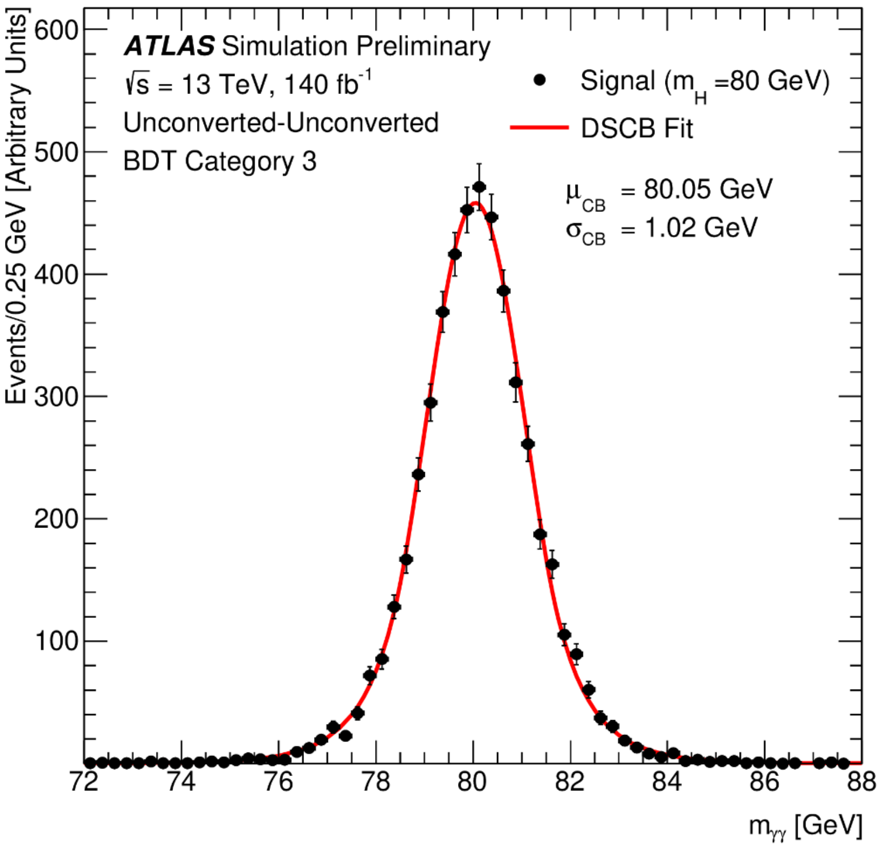


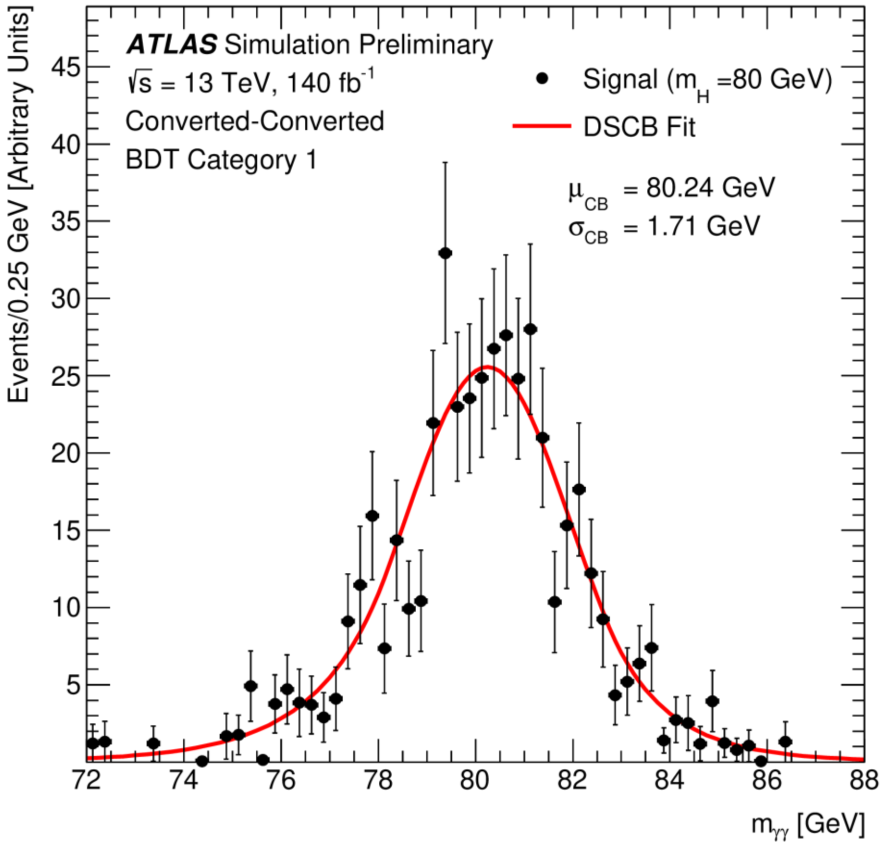


- Signal model: Sums of Gaussian functions
- MC ggH, ttbarH, VBF, VH production processes present in SM proportions, 'SM-like' σ from LHC Higgs WG

Signal modeling

ATLAS-CONF-2023-035



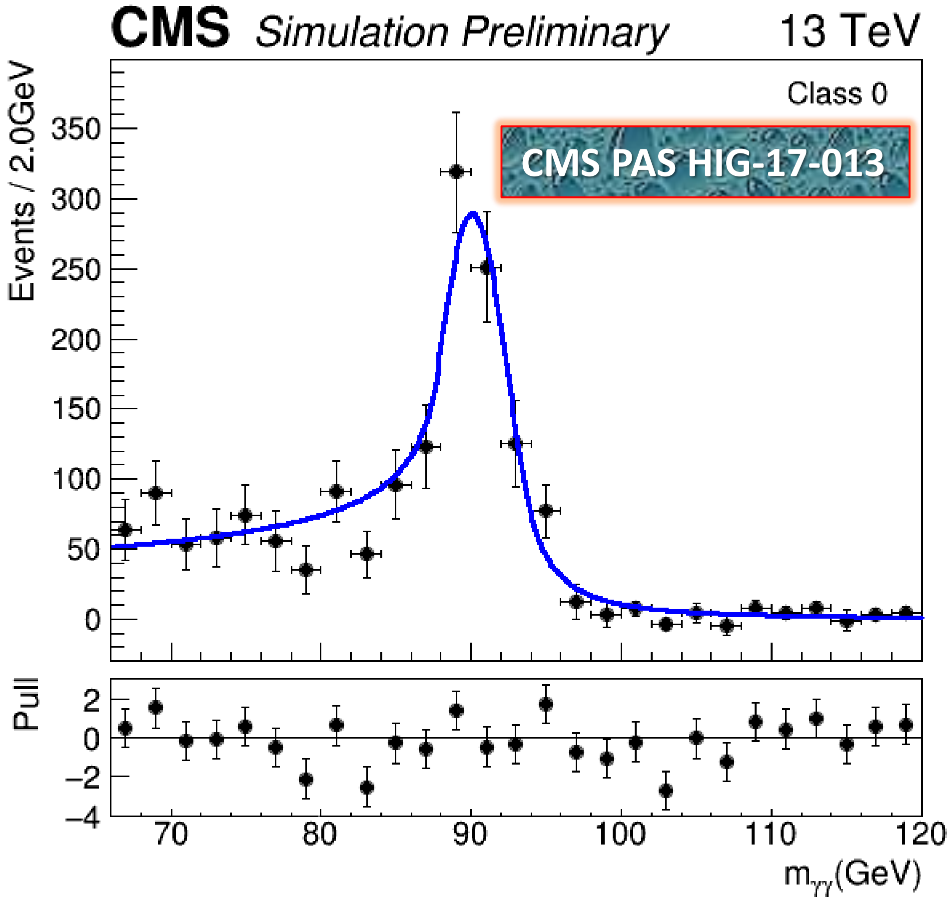


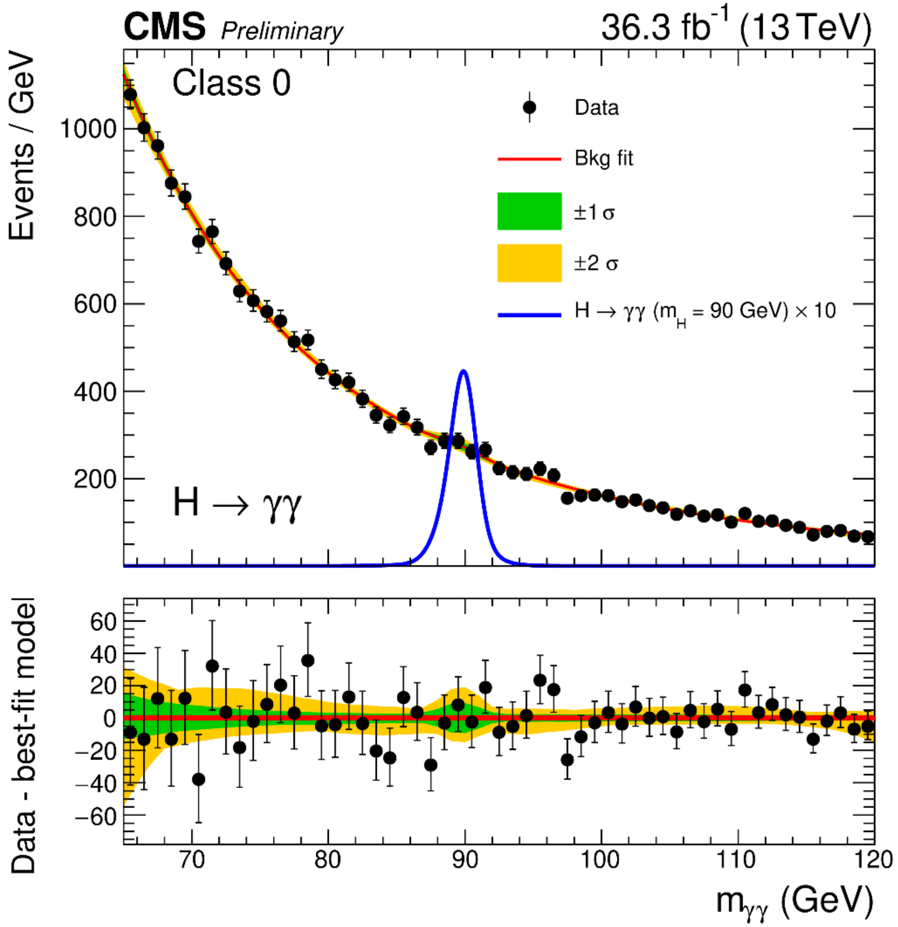
- Signal model: Double Crystal Ball (DCB) function (UU, CC shown)
- MC ggH production process nominal, ttbarH, VBF, VH processes used for systematic uncertainty estimation

CMS-PAS-HIG-20-002

Background Modeling

- Background Model: Sum of polynomial (chosen from 4 families) + double Crystal Ball (DCB) + exponential function for relic Z→ee
- DCB: shape parameters from MC 'double-fake' events, syst. uncertainty from 'single-fake' events, normalization floating





- Chosen polynomials:

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

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CMS-PAS-HIG-20-002

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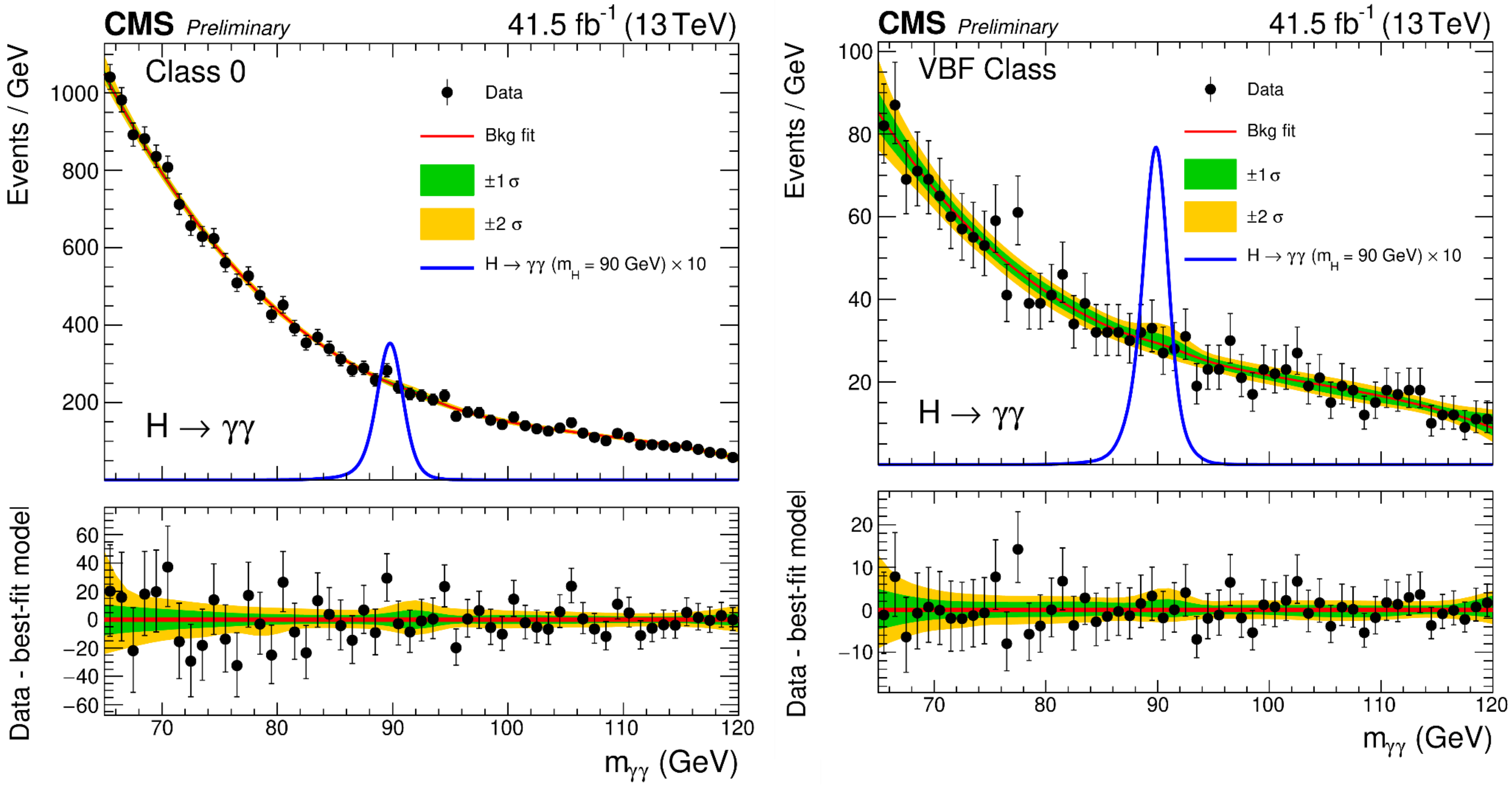

- Choice of background function is discrete parameter in lh fit to data, systematic error associated with each possible choice (discrete profiling or 'envelope' method)

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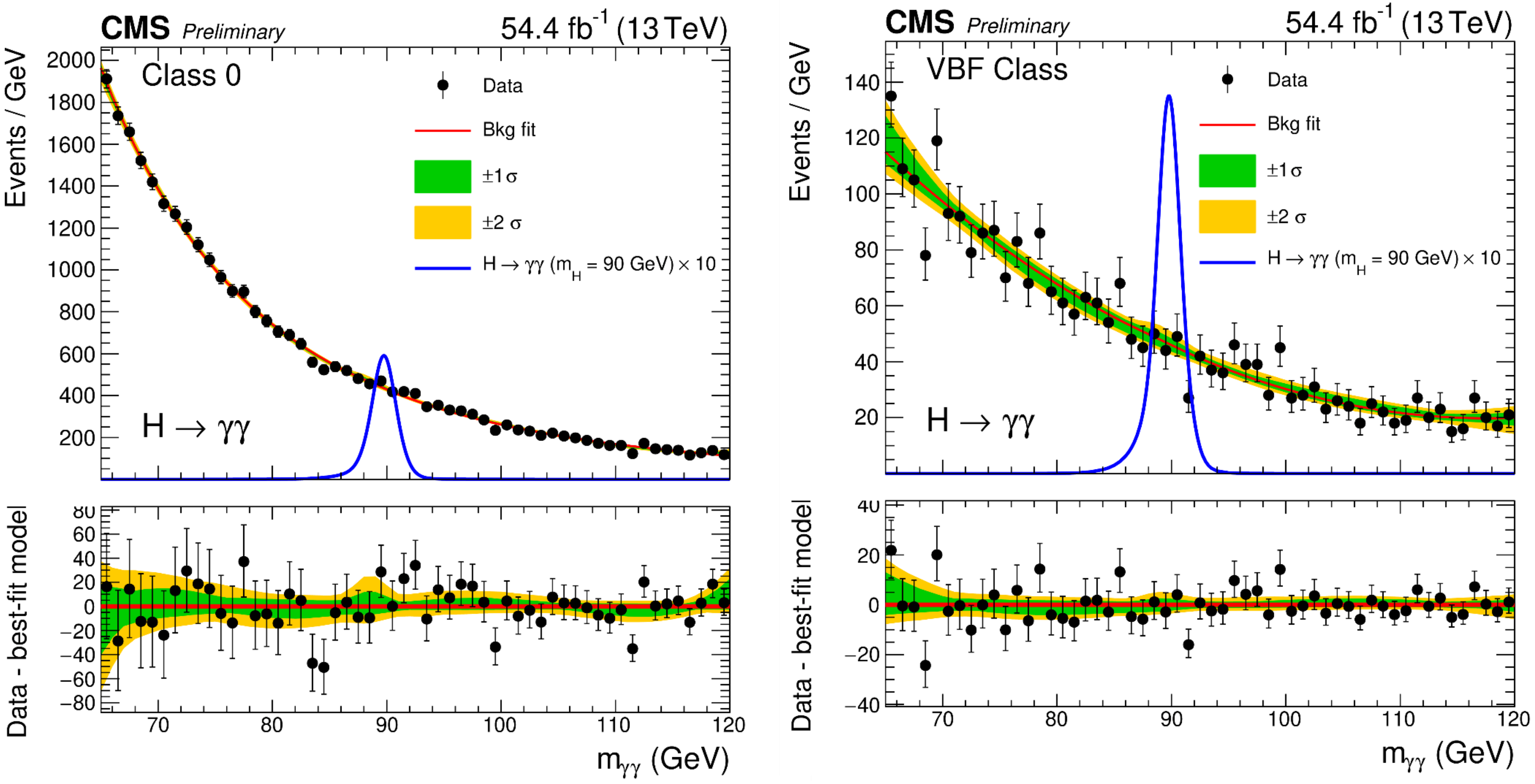

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Background Modeling

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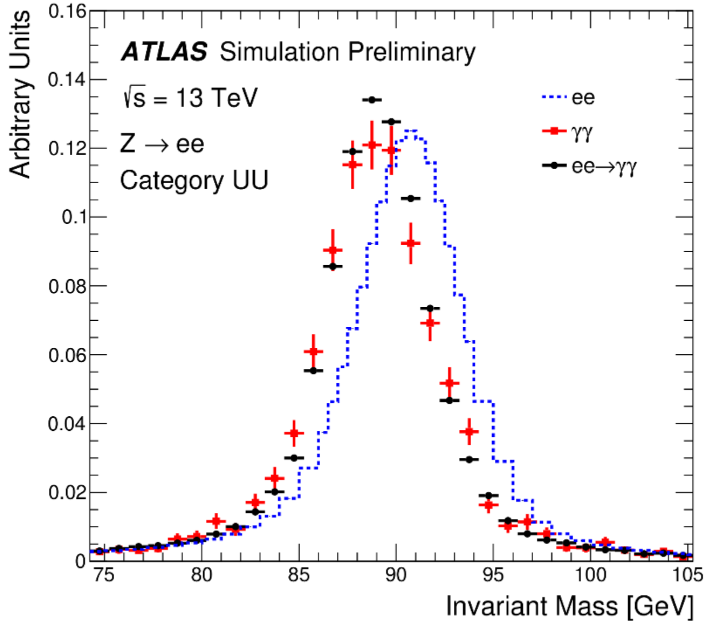
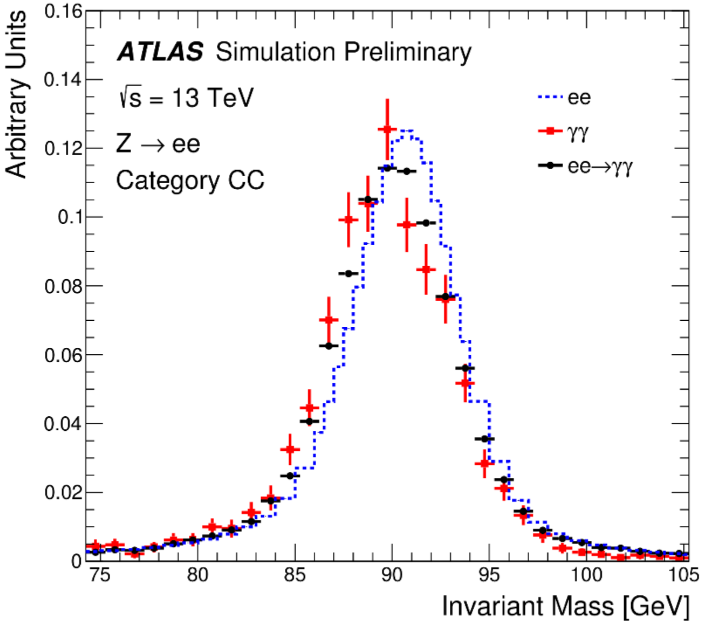
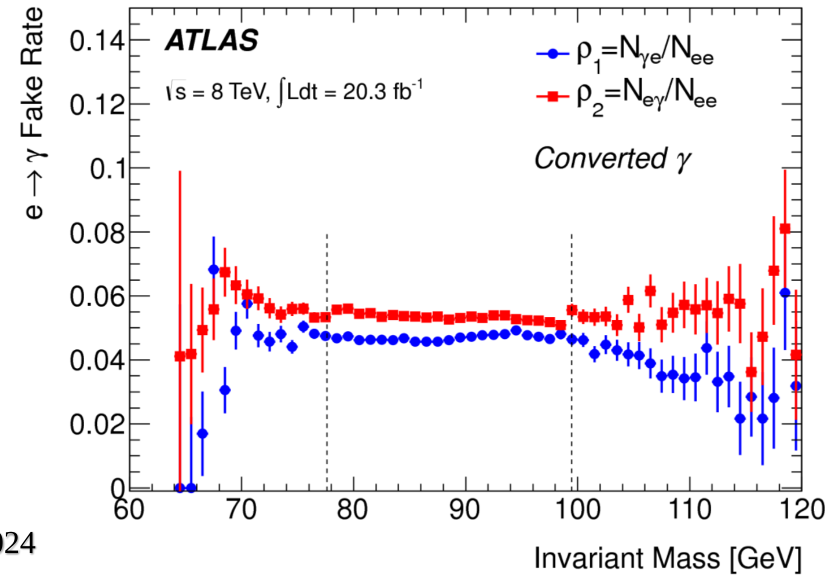
- Background Model: polynomial (chosen from Bernstein and exponentials of polynomials) + double Crystal Ball (DCB) function for relic Z→ee component
- DCB shape: Transformation (Smirnov on m_{ee}) applied to generic Zee MC events→match ‘double-fake MC events, resulting template fit to Zee data to extract shape parameters
- DCB normalization fixed from fake rates (eγ/ee pairs) in Zee data for $\gamma_{1,2}$ in each class, reactualized for Run 2







PRL 113 171801 (2014)

Background Modeling

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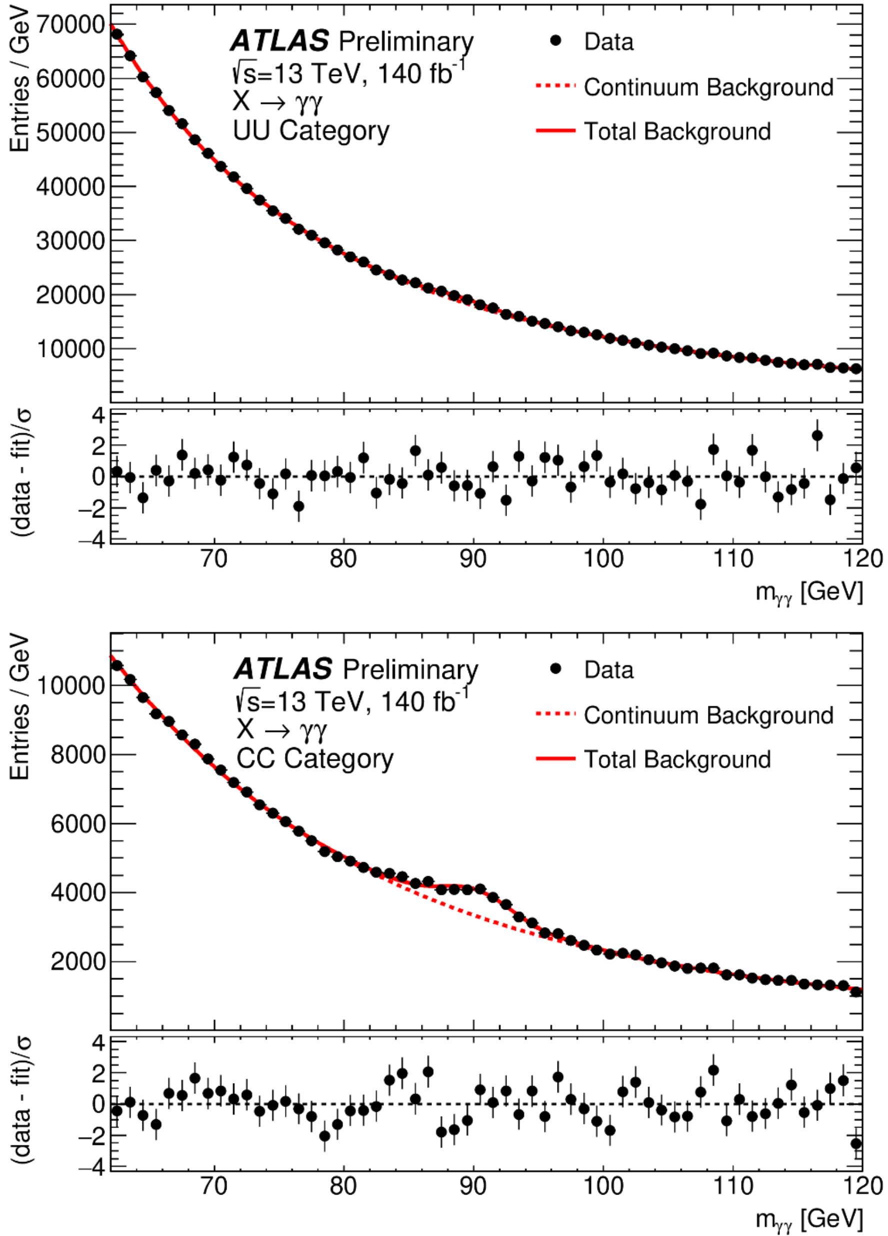
- Background Model: polynomial (chosen from Bernstein and exponentials of polynomials) + double Crystal Ball (DCB) function for relic Z→ee component
- Chosen polynomials: Exponential of 3d or 4th-order polynomial except for model-independent UC (6th order Bernstein) , fitted on data with normalization and function parameters free

BDT Category	Component	UU		UC		CC	
		Events	[%]	Events	[%]	Events	[%]
Bin 1	$\gamma\gamma$	423746	71.5	331118	67.0	64521	57.3
	γj	124037	20.9	118863	24.1	33610	29.9
	jj	40357	6.8	35958	7.2	9217	8.2
	DY	4263	0.7	8289	1.7	5255	4.6
Bin 2	$\gamma\gamma$	379797	74.7	279785	69.7	55632	64.5
	γj	102841	20.2	96895	24.1	23029	26.7
	jj	24437	4.8	22205	5.5	6037	7.0
	DY	1473	0.3	2761	0.7	1577	1.8
Bin 3	$\gamma\gamma$	205134	80.3	153411	73.5	30061	66.6
	γj	42662	16.7	45750	21.9	11808	26.2
	jj	6897	2.7	8395	4.0	2479	5.5
	DY	486	0.2	1160	0.6	758	1.7

- Choose model with smallest spurious signal in signal+background fit to build background-only template with components from MC; fractions determined from a 2D sideband method (developed for diphoton xs measurements), Gaussian process regression smoothing to limit fluctuations



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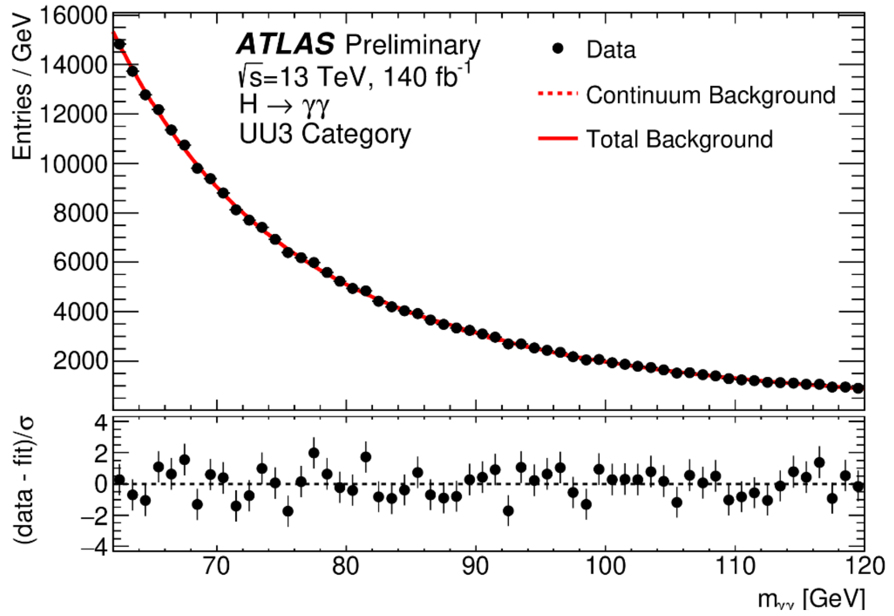

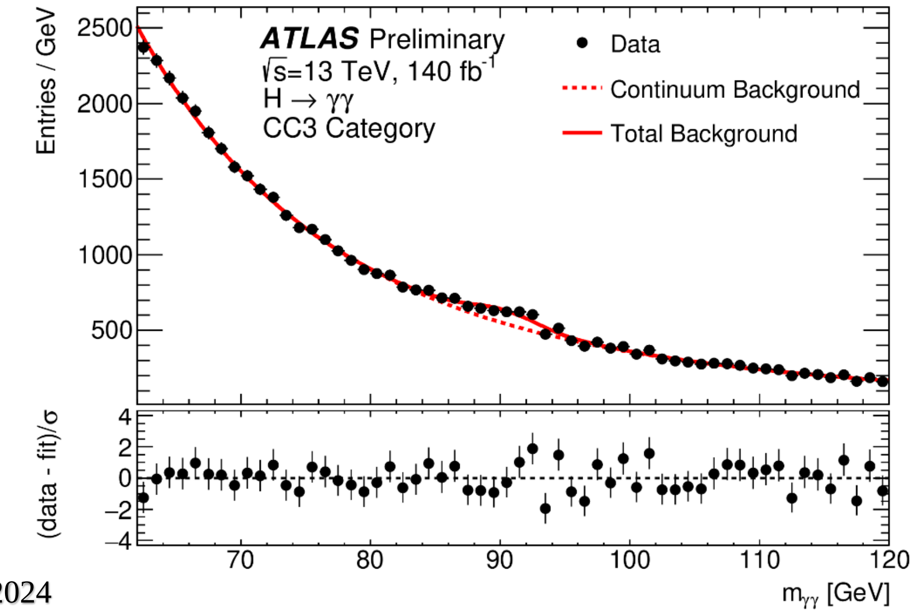

Systematic Uncertainties

ATLAS-CONF-2023-035

Source	Uncertainty [%]	Remarks
Signal yield		
Luminosity	± 0.83	
Trigger efficiency	$\pm 1.0-1.5$	m_X-dependent
Photon identification efficiency	$\pm 1.8-3.0$	m_X-dependent
Photon isolation efficiency	$\pm 1.6-2.4$	m_X-dependent
Photon energy scale	$\pm 0.1-0.3$	m_X-dependent
Photon energy resolution	$\pm 0.1-0.15$	m_X-dependent
Pile-up	$\pm 1.6-5.0$	m_X-dependent
Production mode	$\pm 4.3-29$	m_X-dependent (model-independent only)
Signal modeling		
Photon energy scale	$\pm 0.3-0.5$	m_X- and category–dependent
Photon energy resolution	$\pm 3-10$	m_X- and category-dependent
Migration between categories		
Material	$-2.0/+1.0/+4.1$	category-dependent
Non-resonant Background		
Spurious Signal	$20-50$	category-dependent
DY Background modeling		
Peak position	$\pm 0.1-0.2$	category-dependent
Peak width	$\pm 1.2-2.3$	category-dependent
Normalization	$\pm 6.1-9.0$	category-dependent

- DY systematics dominated by normalization uncertainty (6-9%), was 21%, big improvement from better material modeling/calibration for m_H measurement
- Spurious signal systematic dominant except in nbd of m_Z, (20-50%) reduced by 50% thanks to Gaussian smoothing+increased MC statistics
- Signal yield unc. from production mode: 4.3-29% (model-independent only)

CMS-PAS-HIG-20-002

- Major systematic uncertainties: per-photon energy resolution <20%, renormalization and factorization scales<14%, UE modeling <27%, PS<16%, JES corrections (VBF class) <16%.

Results: Expected numbers of events

ATLAS-CONF-2023-035
(Model-dependent case)

BDT Category	SM-like Higgs boson (m_H = 90 GeV) Total	ggF [%]	VBF [%]	WH [%]	ZH [%]	ttH [%]	Background Total [GeV^{-1}]	DY [GeV^{-1}]
1	741	97.1	1.2	1.0	0.6	0.1	18877	2179
2	942	93.4	2.9	2.1	1.2	0.4	14014	713
3	1187	72.4	13.5	6.7	4.0	3.4	6522	294
Total	2870	85.7	6.8	3.7	2.2	1.6	39413	3186

- Signal and background events per category (most sensitive category: 0 for CMS, 3 for ATLAS !)

Event classes		Expected SM-like Higgs boson signal yield (m_H = 90 GeV) Total	ggH (%)	VBF (%)	WH (%)	ZH (%)	$t\bar{t}H$ (%)	σ_{eff} (GeV)	σ_{HM} (GeV)	Bkg. (GeV^{-1})	DY Bkg. (GeV^{-1})
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

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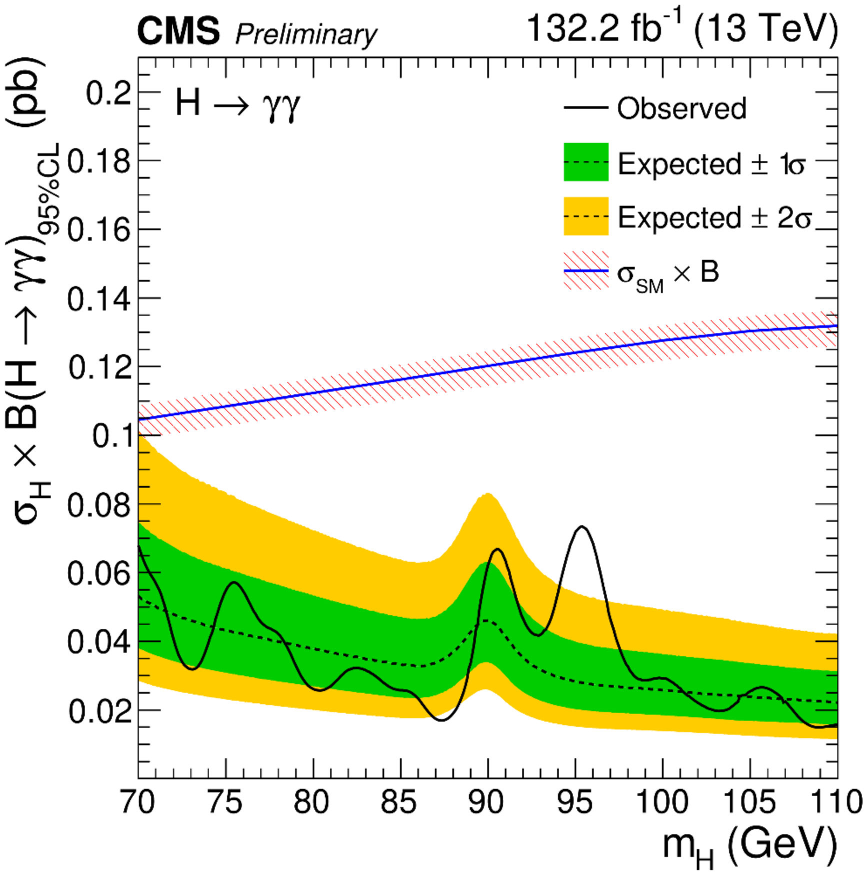
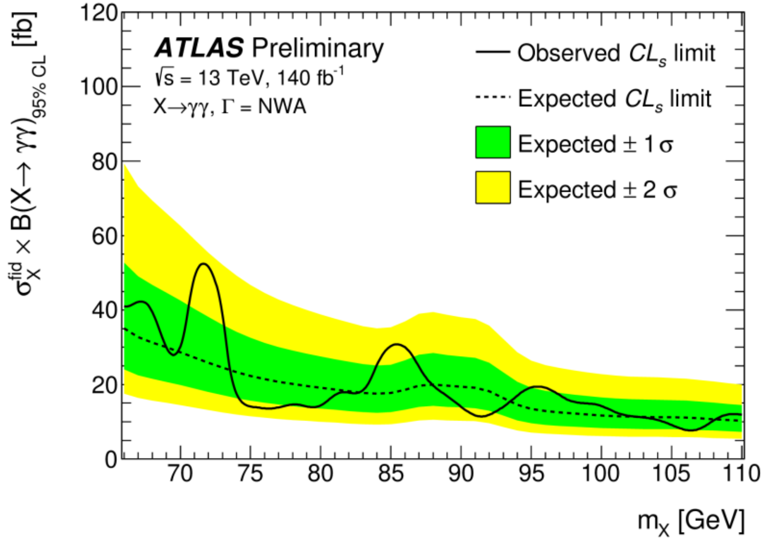
Results: Limits on $\sigma \times B$

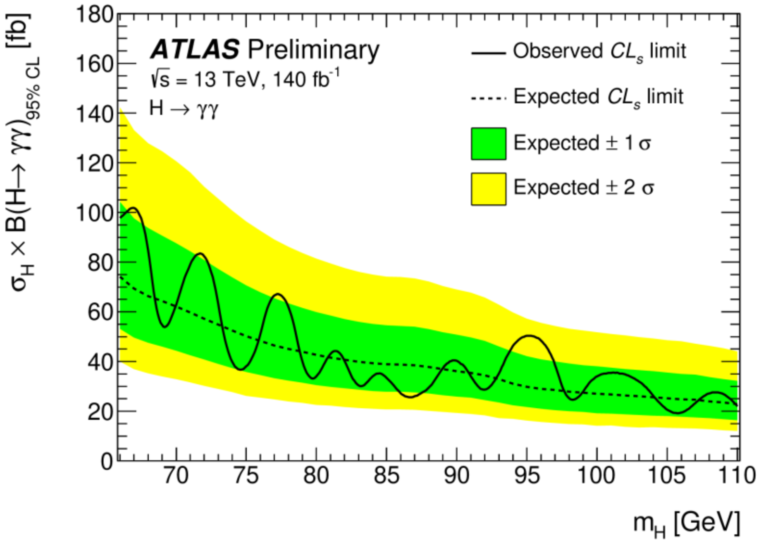
ATLAS-CONF-2023-035

CMS-PAS-HIG-20-002

- Model-dependent (σ_H):







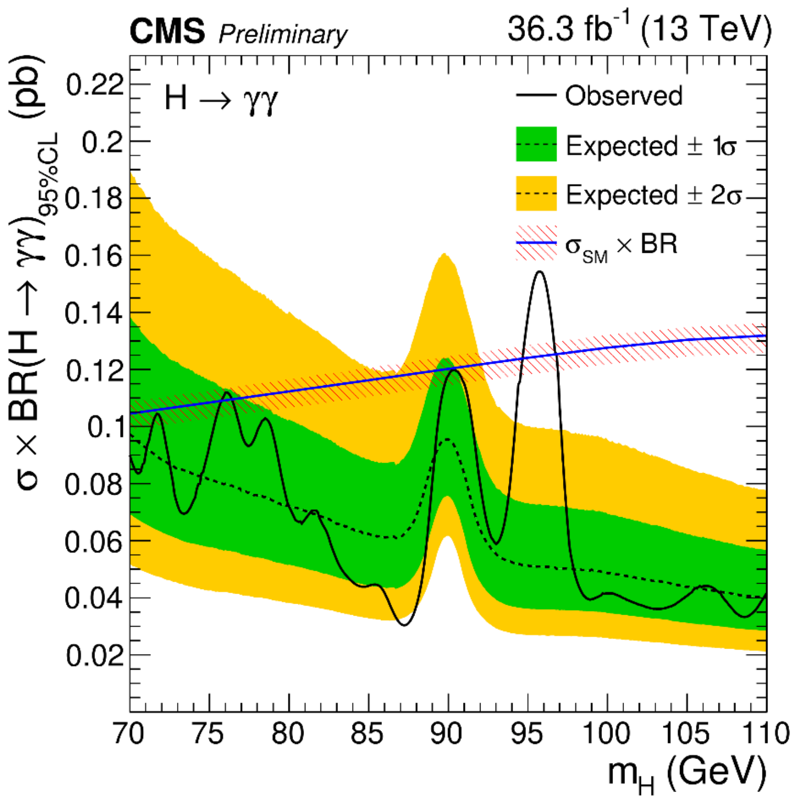
- Model-independent: 95% CL UL on σ_{fid} X B: 8-53 fb

- Model-dependent

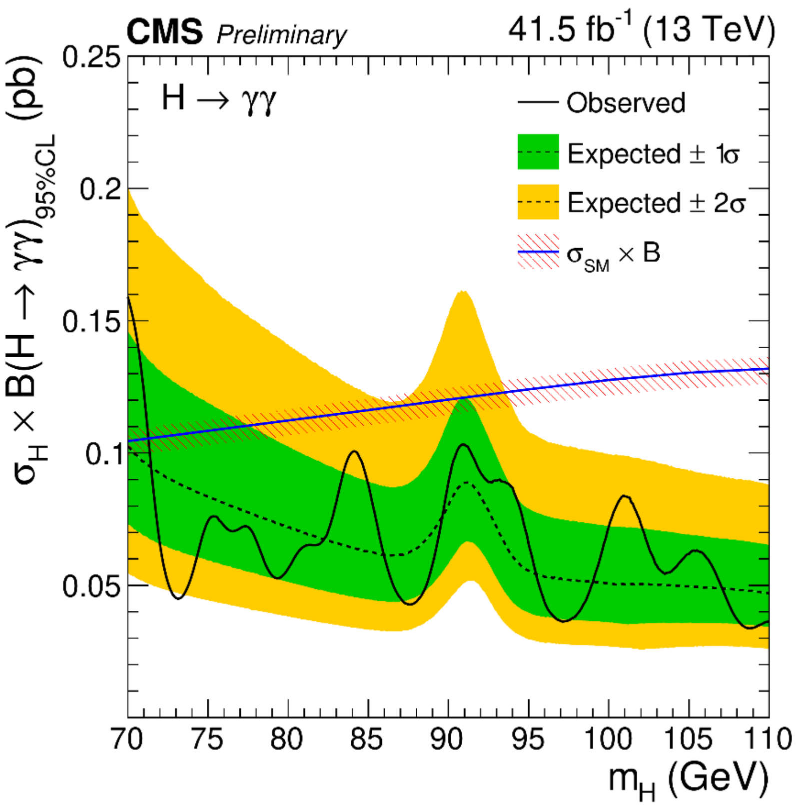
- 95% CL UL on σ X B between 15-73 fb ⇔
- 95% CL UL on σ_H X B: 8-53 fb

Results: Limits on σ x B by year

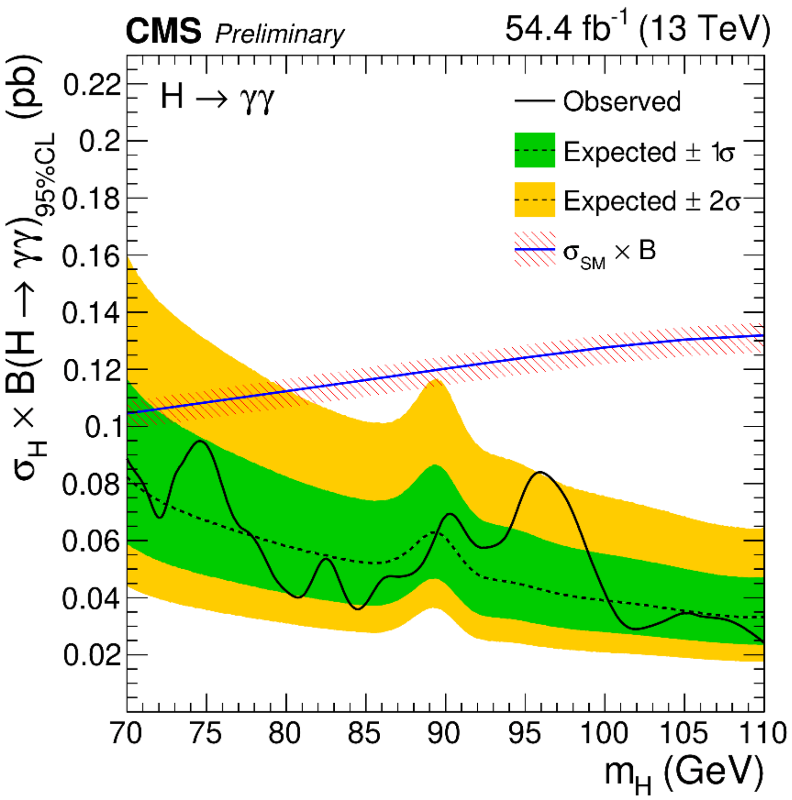
CMS-PAS-HIG-20-002



- 2016



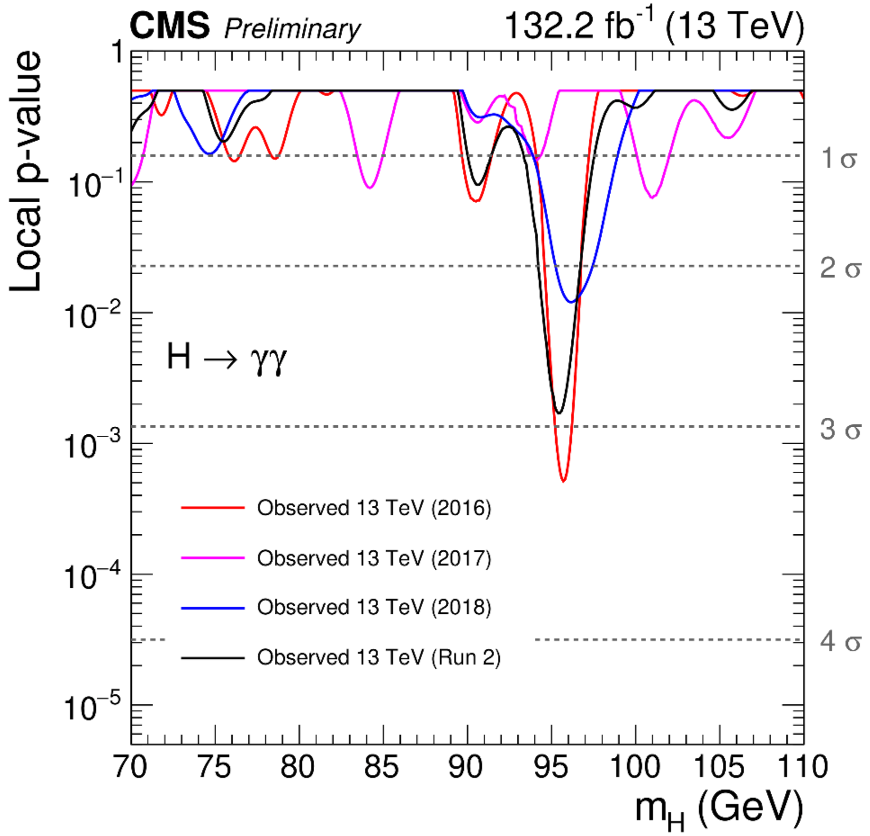
- 2017



- 2018

Results: p-values

CMS-PAS-HIG-20-002



- Modest excess: ~2.9σ local (1.3σ global) significance at $m_{\gamma\gamma}$=95.4 GeV

⇔

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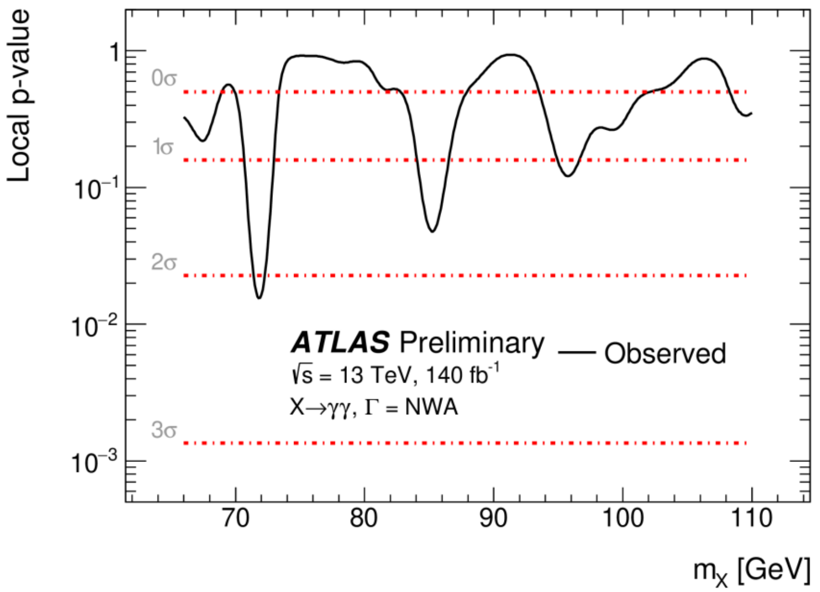

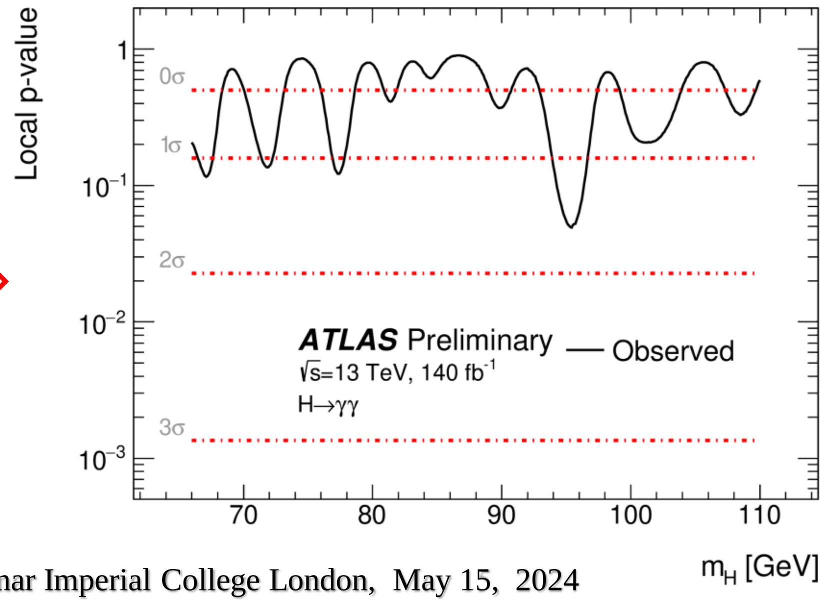

- **Model-independent:** Mild excess: ~2.2σ local significance at $m_{\gamma\gamma}$=71.8 GeV

- **Model-dependent:** Largest deviation: ~1.7σ local significance at $m_{\gamma\gamma}$=95.4 GeV

Results: p-values by category

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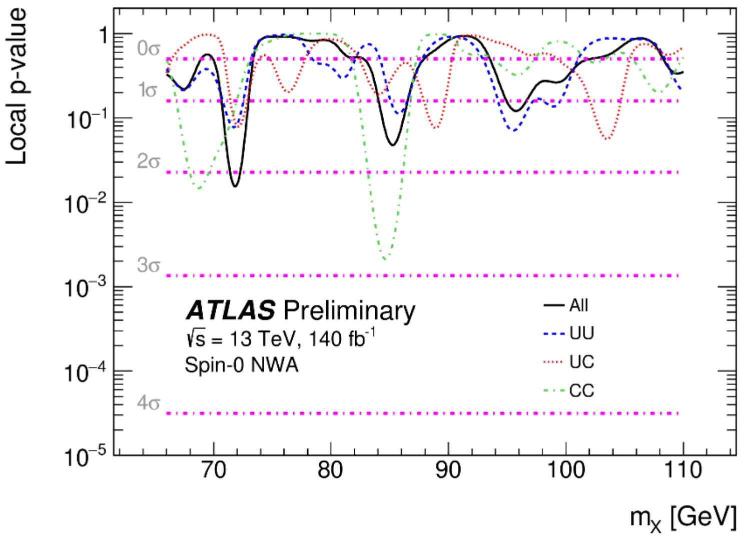
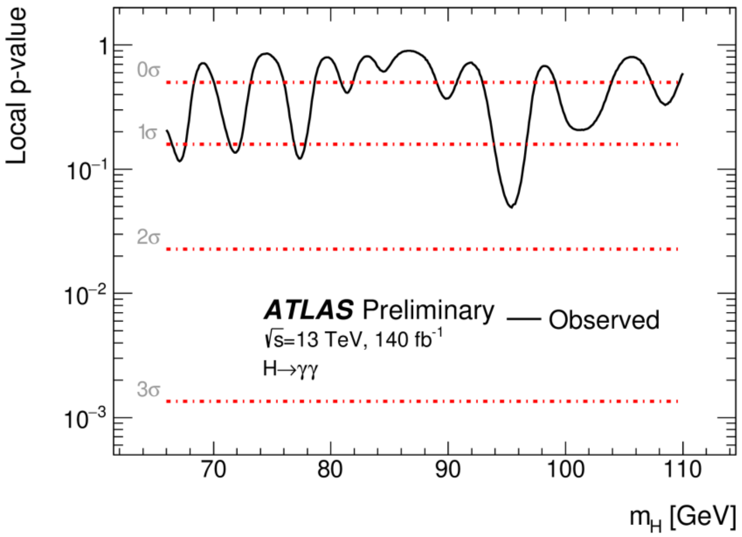
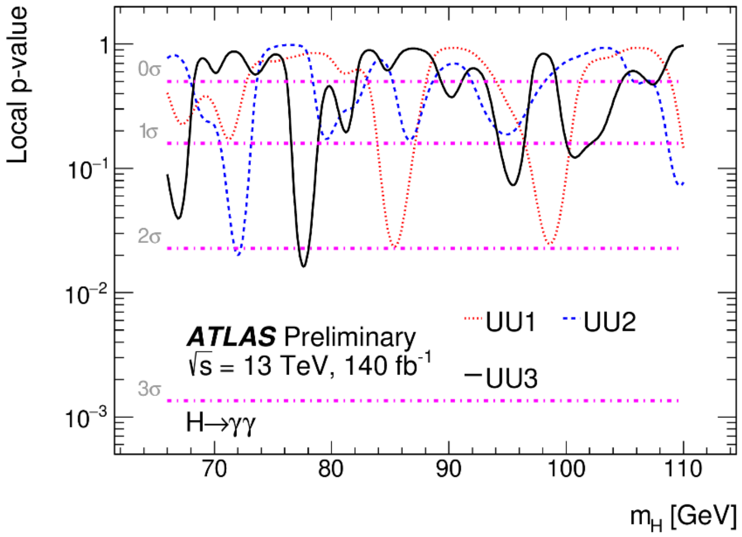
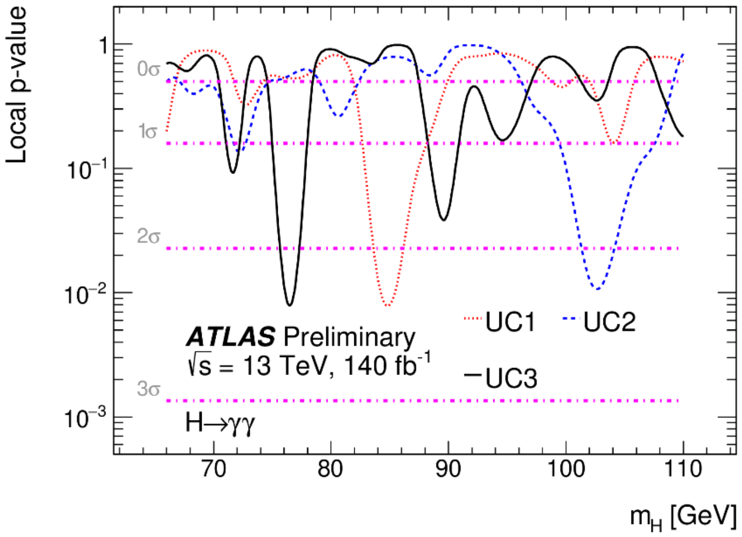
- Model-independent

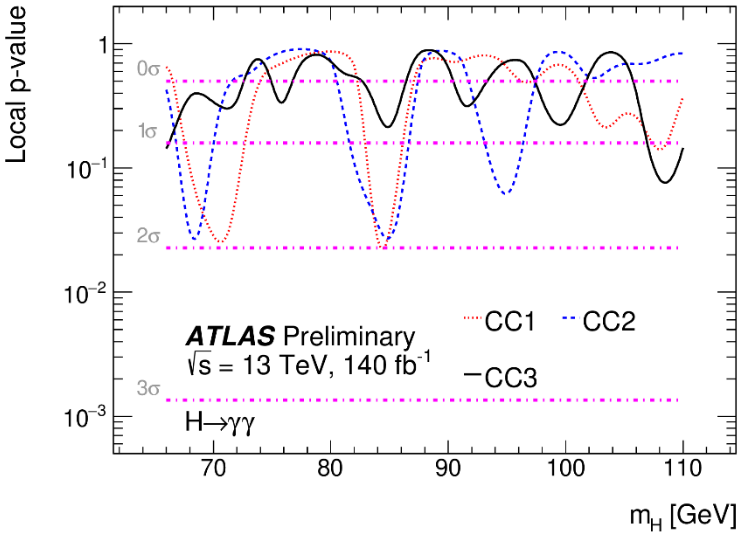




- Model-dependent:

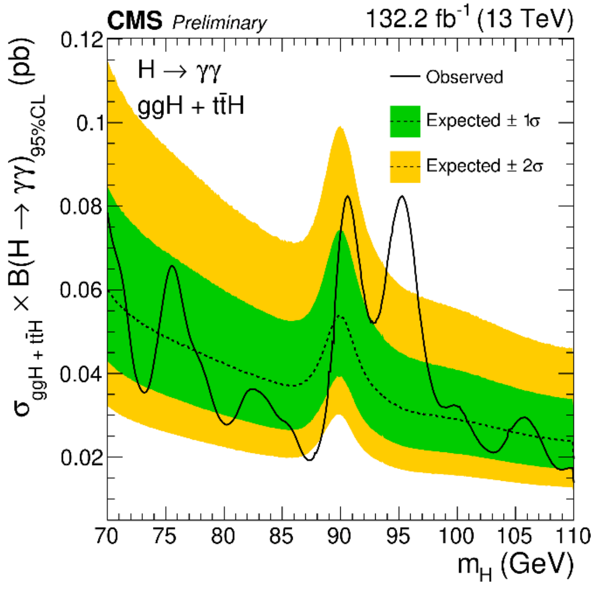


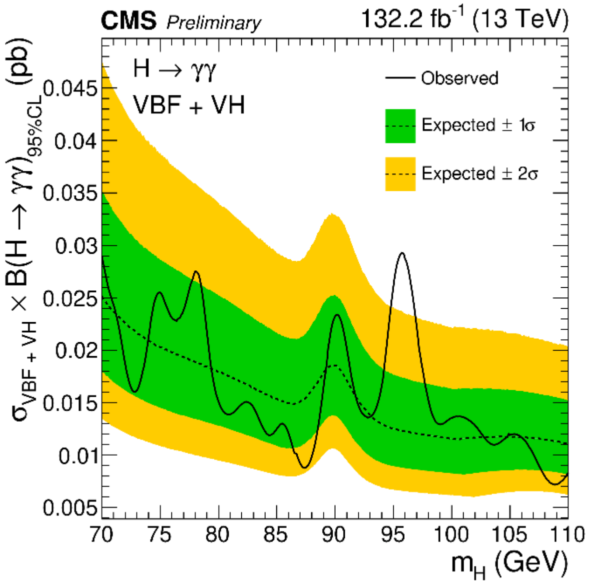


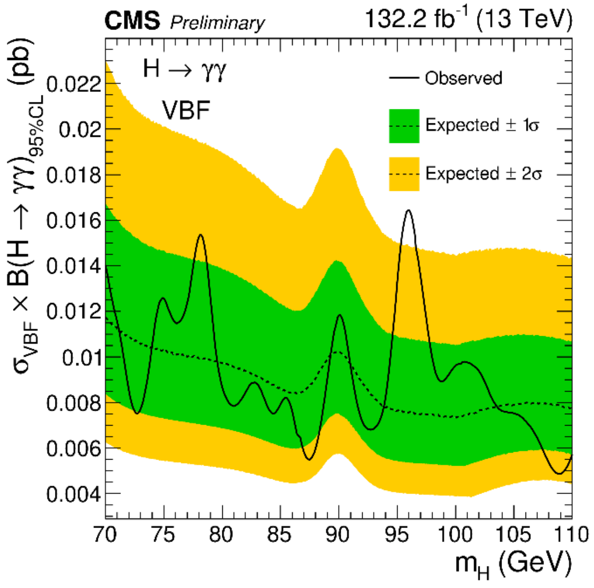


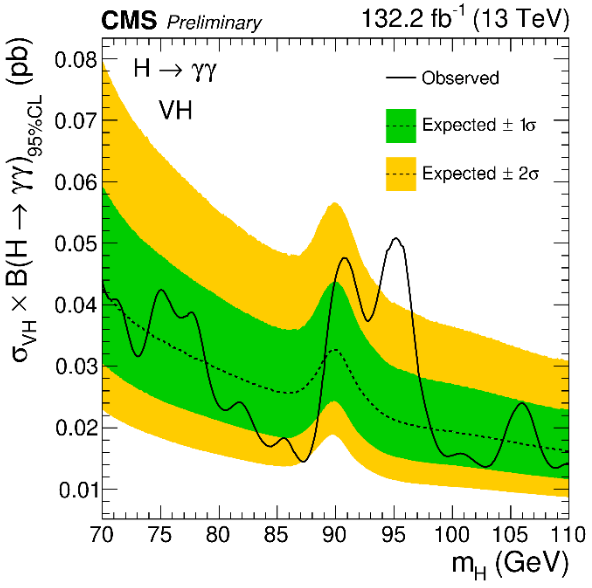
Results: Limits on σ x B by production process

- 95% CL limits on σ X B by production process (integrated over all experimental event classes)





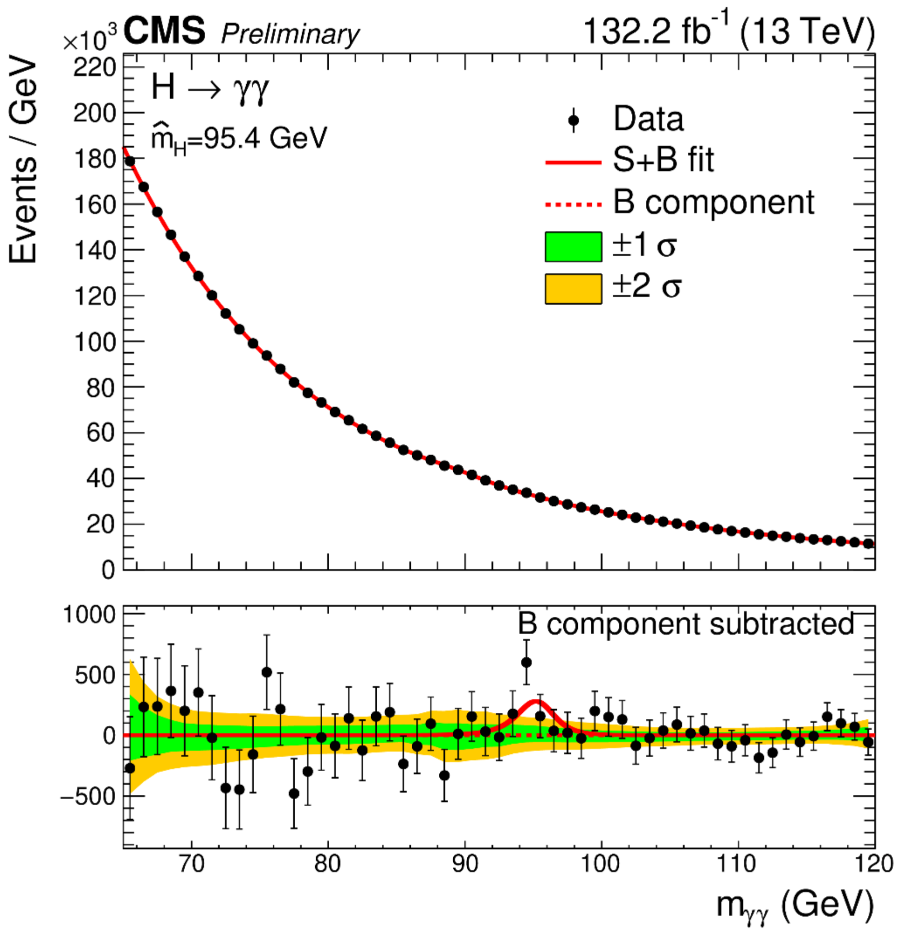


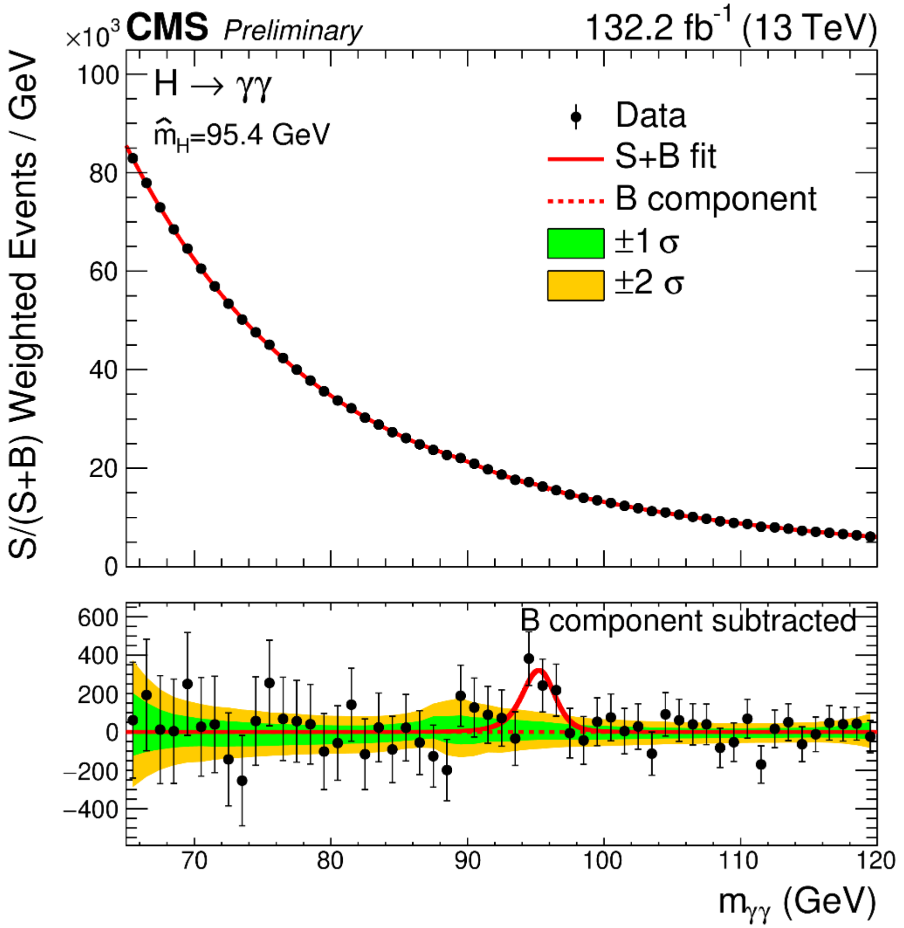


- 100% production via fermion-coupled processes (ggH, ttbarH in SM proportions)
- 100% production via vector boson-coupled processes (VBF, VH in SM proportions)
- 100% production via VBF
- 100% production via VH

Results: Signal +Background Fits

CMS-PAS-HIG-20-002

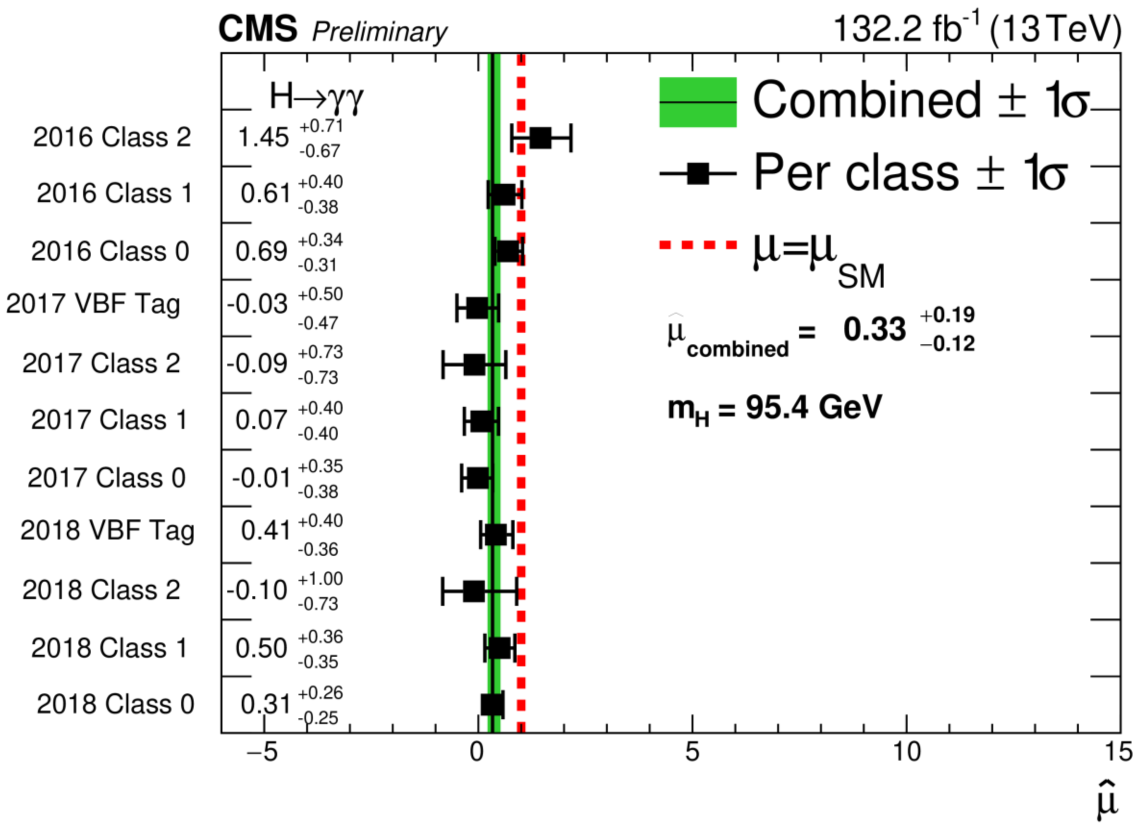


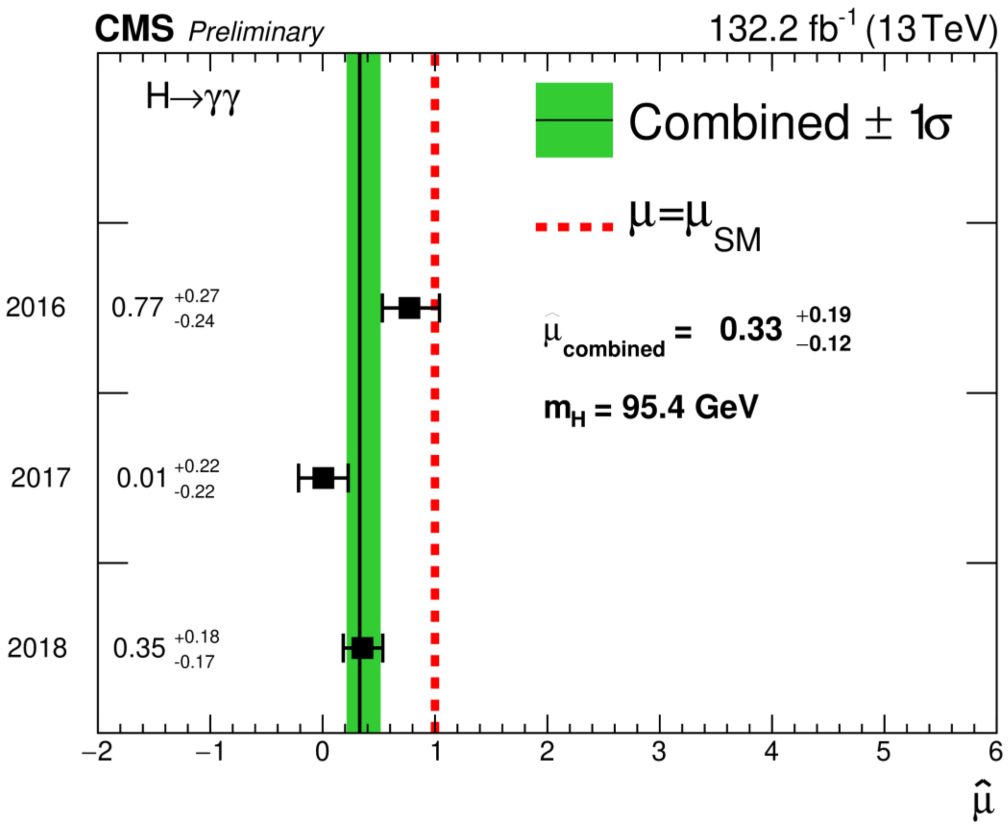


- Fits of S+B model over all event classes, for best-fit m=95.4 GeV
- Bands include uncertainties on fit function choice/fitted parameters (from toys).
- Left: unweighted, Right: each event weighted by the ratio S/(S+B) for its event class

Results: 'Signal' strengths μ fixing m_H=95.4 GeV

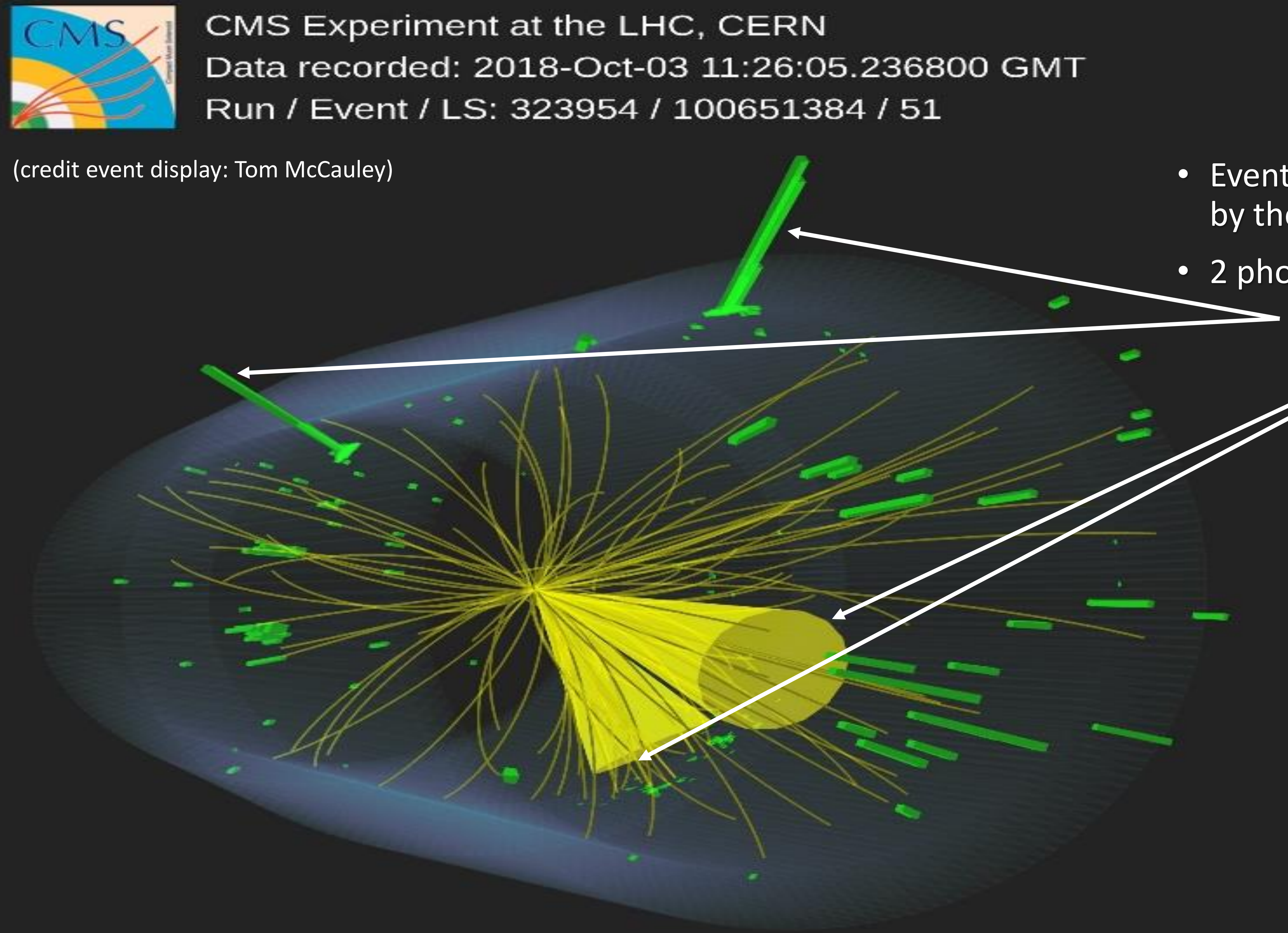
CMS-PAS-HIG-20-002





- for the 11 event classes
  χ^2 compatibility probability: 68%

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



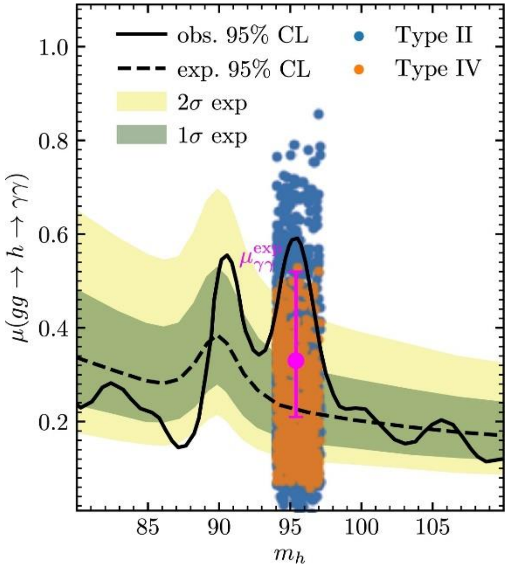
(credit event display: Tom McCauley)

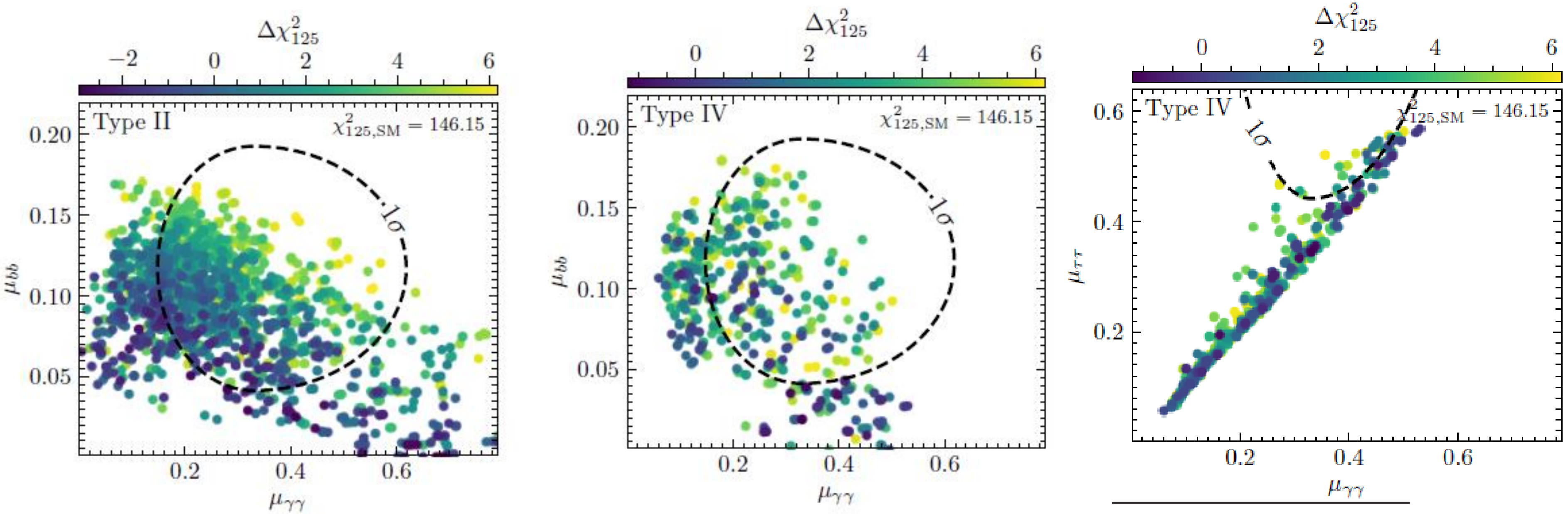
- Event recorded in 2018 selected by the analysis
- 2 photons and 2 jets

Example of theoretical interpretation

Interpretation of CMS-PAS-HIG-20-002: Biekoetter, Heinemeyer, Weiglein, Phys.Lett.B 846 (2023) 138217

- 2HDM + complex singlet model (S2HDM) compatible with excesses at ~95 GeV for $m_{\gamma\gamma}$ and m_{bb} (LEP) for Types II and IV, also with $m_{\tau\tau}$ (CMS, JHEP 07 (2023) 073) for Type IV (points in agreement with all experimental and theoretical bounds)
- Model contains 3 CP-even (**h_1**, h_2, h_3), 1 CP-odd (A) neutral, 2 charged (H^{+-}) and 1 DM (χ) scalars



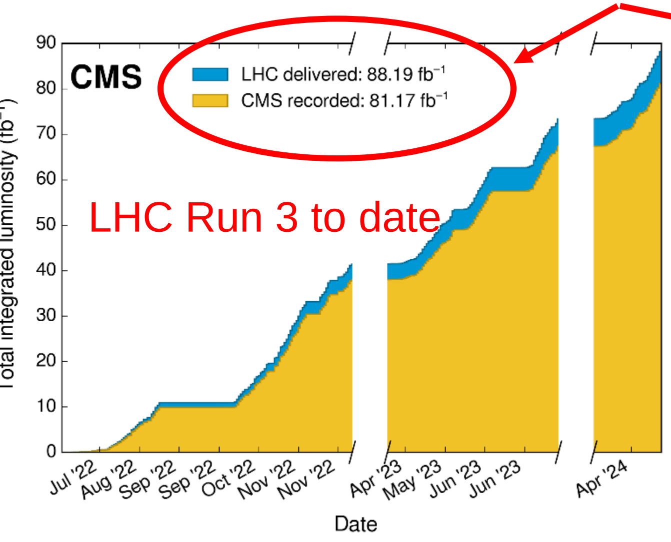


- Model types similar to those in 2HDM

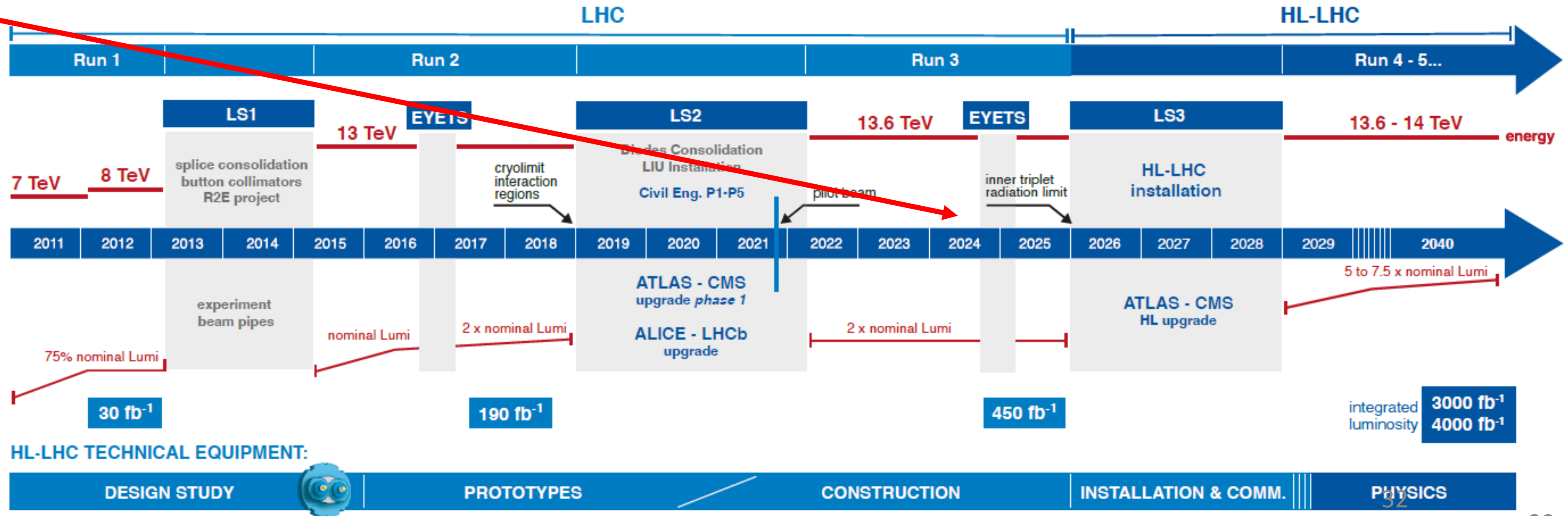
	u-type	d-type	leptons
type I	Φ_2	Φ_2	Φ_2
type II	Φ_2	Φ_1	Φ_1
type III (lepton-specific)	Φ_2	Φ_2	Φ_1
type IV (flipped)	Φ_2	Φ_1	Φ_2

Conclusions and Perspectives

- Presented new CMS and ATLAS searches for additional low-mass SM-like $H \rightarrow \gamma\gamma$ (70 GeV<mH<110 GeV) using full LHC Run 2 data: No evidence for the existence of extra Higgs bosons found so far
- CMS: Modest excess at $m_{\gamma\gamma}$=95.4 GeV with 2.9σ local (1.3σ global) significance.
- ATLAS: Mild excess: ~2.2σ local significance at $m_{\gamma\gamma}$=71.8 GeV (model-independent) and 1.7σ local significance deviation at $m_{\gamma\gamma}$=95.4 GeV (model-dependent)
- More (Run 3) data is needed to conclude ….and it's on it's way! (~250fb^{-1}) ➔Double the discovery possibilities!
- HL-LHC: Starts ~2029, expect 3ab-1



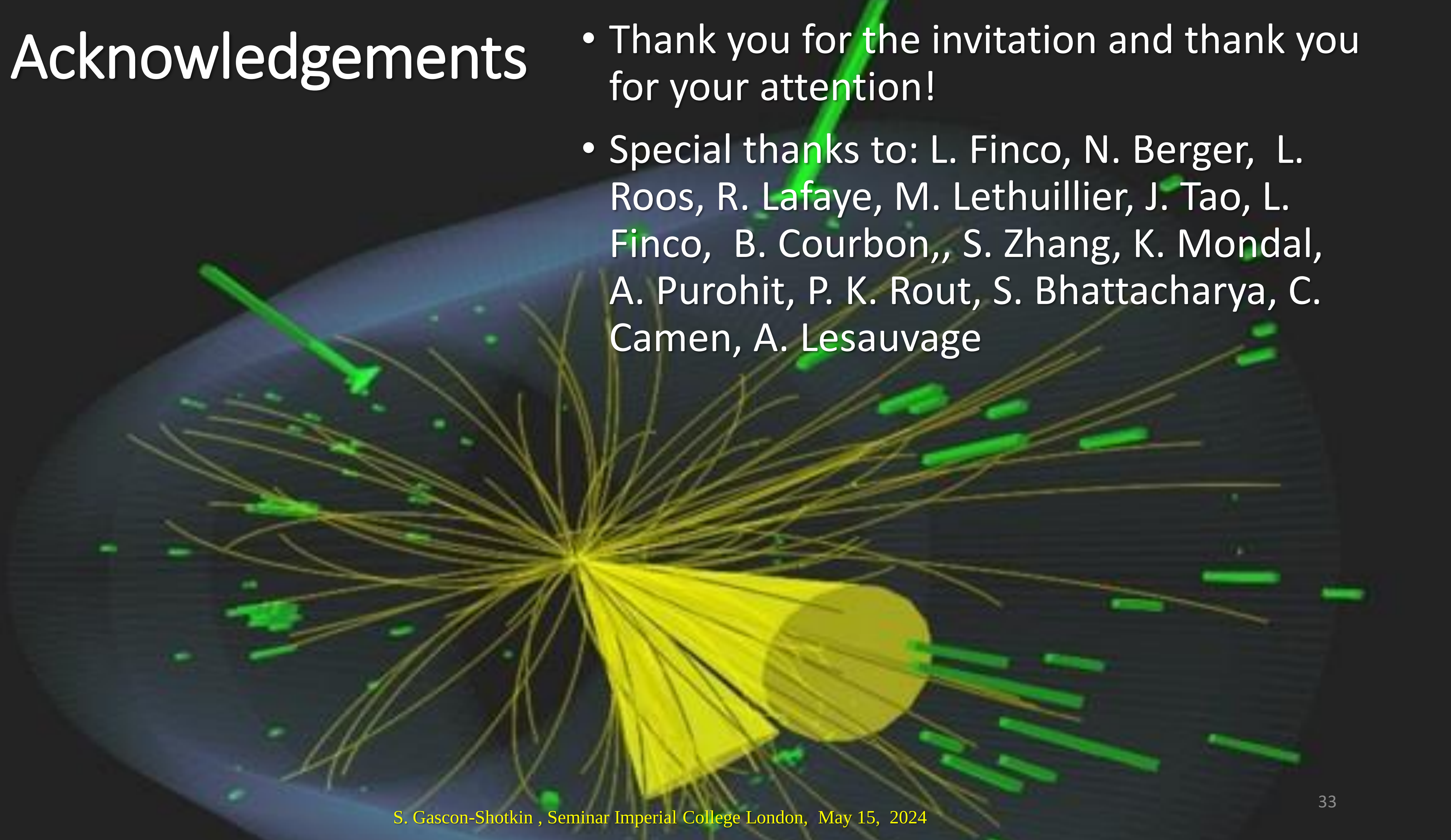
https://twiki.cern.ch/twiki/bin/view/CMSPublic/LumiPublicResults



https://hilumilhc.web.cern.ch/content/hl-lhc-project Feb 2022

Acknowledgements

- Thank you for the invitation and thank you for your attention!
- Special thanks to: L. Finco, N. Berger, L. Roos, R. Lafaye, M. Lethuillier, J. Tao, L. Finco, B. Courbon,, S. Zhang, K. Mondal, A. Purohit, P. K. Rout, S. Bhattacharya, C. Camen, A. Lesauvage



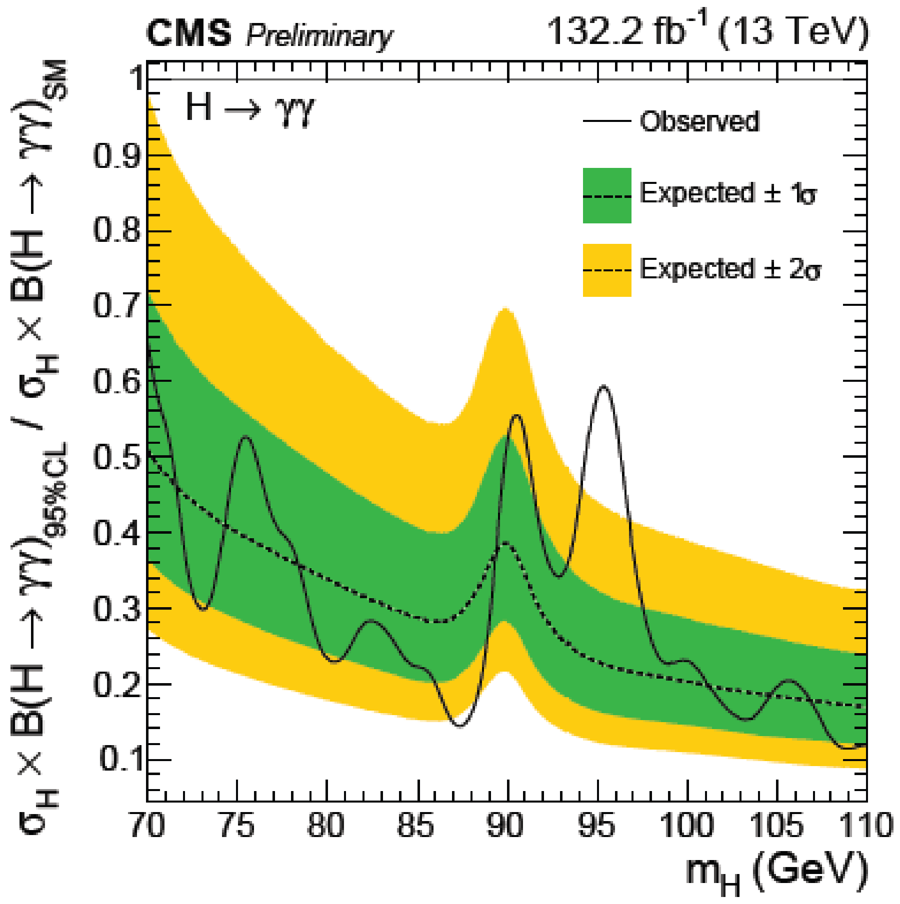
Backup

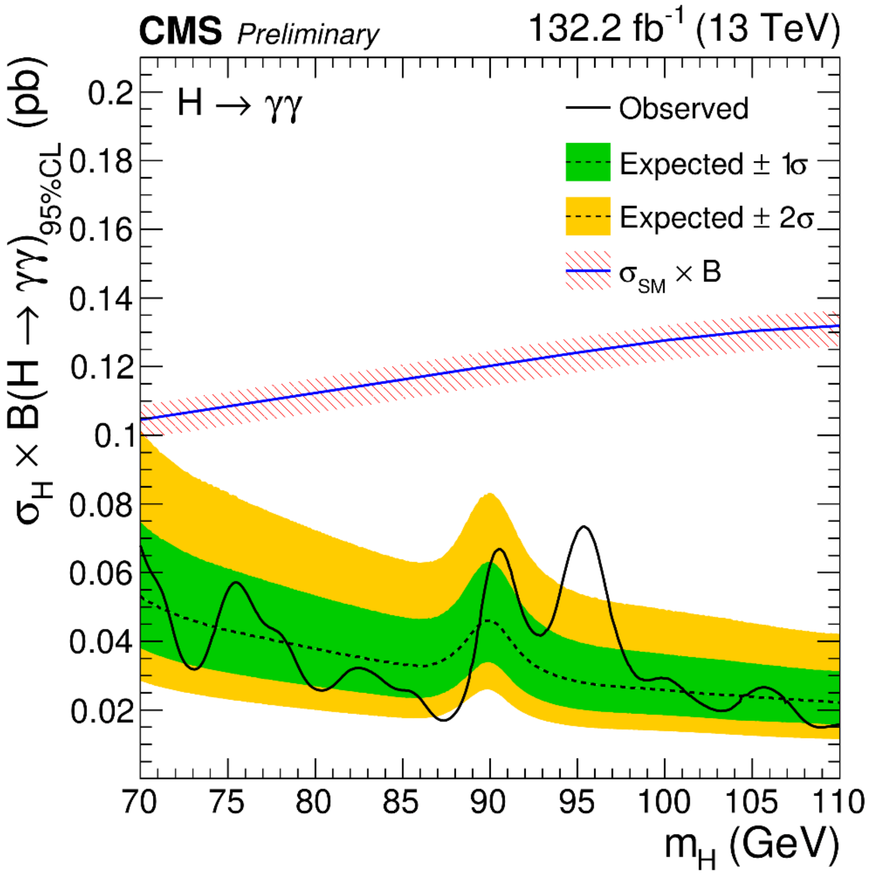
SM-like H→γγ (70 GeV<m_H<110 GeV)

CMS-PAS-HIG-20-002

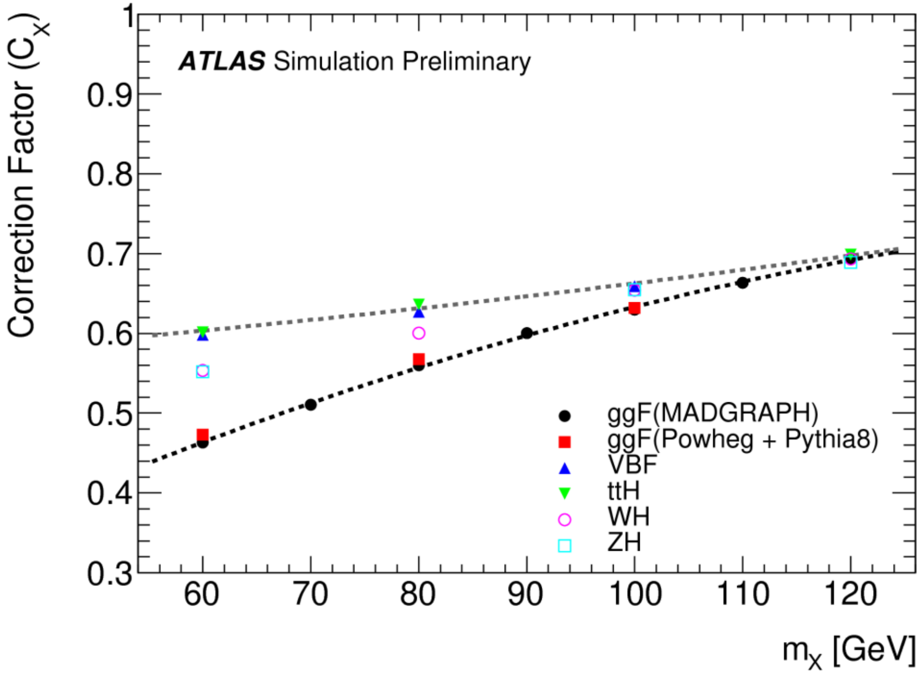
http://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/HIG-20-002/

- Observed and expected 95% CL UL on σ X B relative to SM-like expectation (production processes assumed in SM proportions)
- Observed absolute 95% CL UL on σ X B between 15-73 fb





ATLAS-CONF-2018-025



Source	Uncertainty [%]	Remarks
Signal yield		
Luminosity	±2	
Trigger eff.	±1.4 – 1.7	m_X-dependent
Photon identification eff.	±1.5 – 2.3	m_X-dependent
Isolation eff.	±4	
Photon energy scale	±0.13 – 0.49	m_X-dependent
Photon energy resolution	±0.053 – 0.28	m_X-dependent
Pile-up	±1.8 – 4.1	m_X-dependent
Production mode	±2.4 – 25	m_X-dependent
Signal modeling		
Photon energy scale	±0.3 – 0.5	m_X- and category–dependent
Photon energy resolution	±2 – 8	m_X- and category-dependent
Migration between categories		
Material	−2.0 / +1.0 / +4.1	category-dependent (UU/CU/CC)
Non-resonant Background		
Spurious Signal	128 / 104 / 79 (604 / 496 / 181 events)	ratio to the expected spurious signal uncertainty (category-dependent)
DY Background modeling		
Peak position	±0.1 – 0.2	category-dependent
Peak width	±2 – 3	category-dependent
Normalization	±9 – 21	category-dependent