H → Zγ ATLAS+CMS Combination

Ying An, Mingshui Chen, Andrew Gilbert, Andrea Carlo Marini, Yajun Mao, Mingtao Zhang, Chen Zhou

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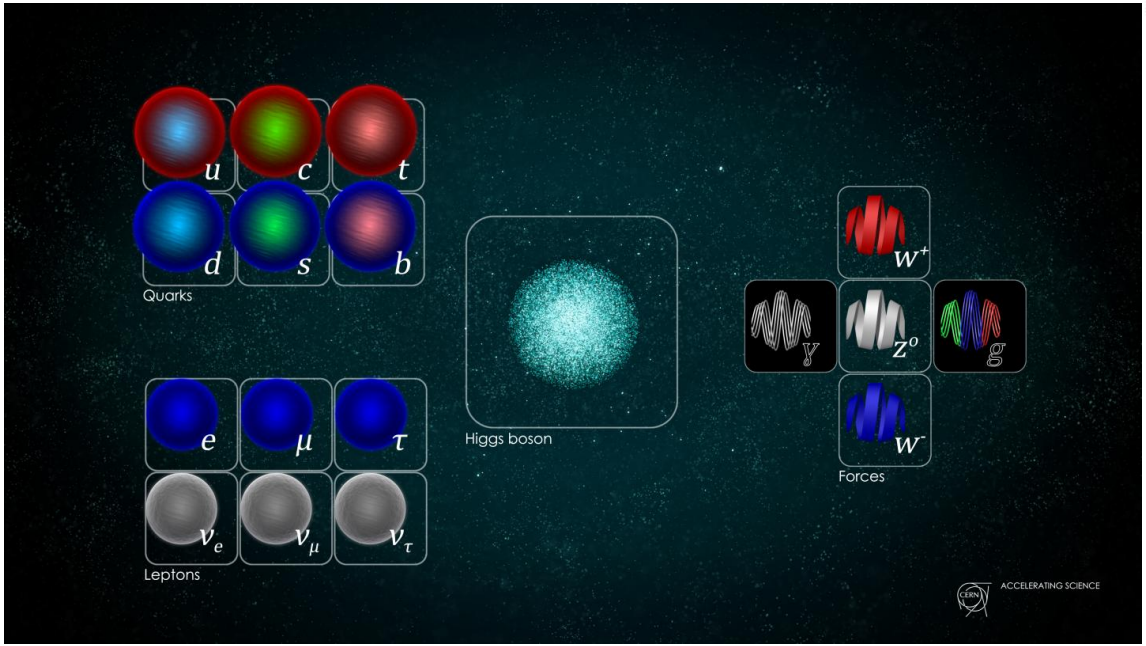
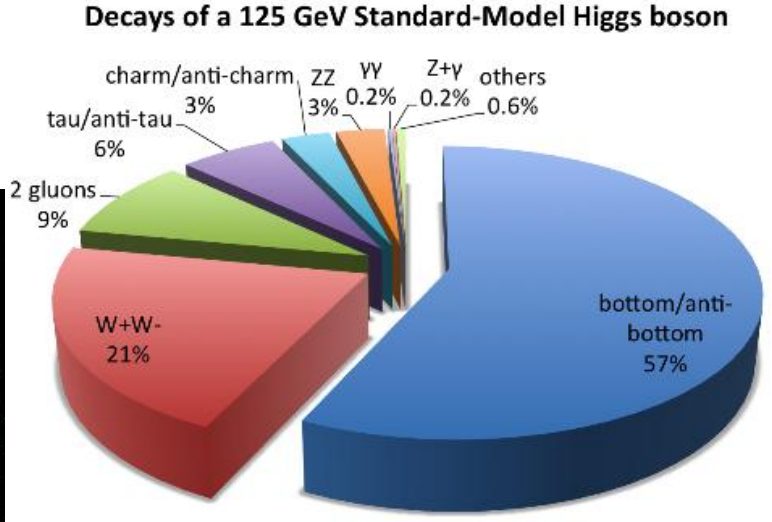
Introduction

- In 2012, the discovery of Higgs boson marked a significant milestone in particle physics.
- Many researches are carried out to investigate the propeties of Higgs boson.





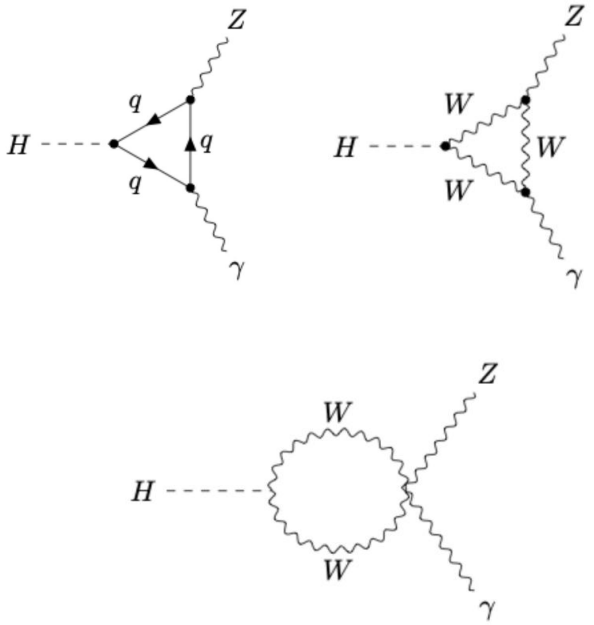
SM Branch ratio:

$B(H \rightarrow Z\gamma) = (1.54 \pm 0.09) \times 10^{-3}$ for 125.09GeV

$B(H \rightarrow Z\gamma) = (1.57 \pm 0.09) \times 10^{-3}$ for 125.38GeV

Introduction

- BSM couplings could be expected in the quantum loops, which result in the deviation of branching fractions from the SM.
- BSM particles could be present in the quantum loops. (Such as a composite Higgs boson[1], a pseudo Nambu-Goldstone boson[2], a neutral scalar from a different source[3-4], etc.)
- Difference between H → Zγ decay and H → γγ/ZZ decay sensitive to new physics.
- **Main bkg**: SM Zγ, Z+jets (Z→*ll*, BR~6.6%)



[1] Phys. Rev. D 88 (2013) 075019 [2] Phys. Lett. B 789 (2019) 233
[3] Phys. Rev. D 84 (2011) 035027 [4] Phys. Rev. D 86 (2012) 093012

Introduction -- Run2 analysis

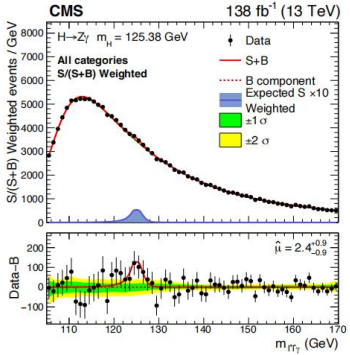
- **Run2 analysis:**

  CMS and ATLAS have searched for the H→Zγ decay using Run 2 data (138fb^{-1} for CMS and 139fb^{-1} for ATLAS), using the llγ final state, with $m_{ll} > 50$ GeV

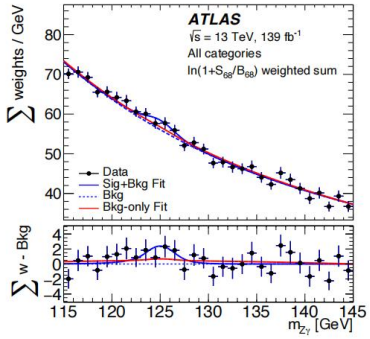
- **Similar strategies:**

  Categorise events to exploit production mode kinematics and fit to $m_{ll\gamma}$ distribution in each category

- The observed H→Zγ significance in full Run 2 result is 2.2σ/2.7σ (expected 1.2σ) for ATLAS/CMS



HIG-19-014 (Accepted by JHEP)



PLB 809 (2020) 135754

	CMS	ATLAS
No. categories	8	6
Prod modes	ggF, VBF, VH+ttH (lep)	ggF, VBF
Background uncertainty	Discrete profiling	Spurious signal
m_H	125.38 GeV	125.09 GeV
Signal strength	2.4 ± 0.9 (stat) ± 0.3 (syst)	2.0 ± 0.9 (stat) ± 0.4 (syst)
Significance Obs (Exp)	2.7 (1.2)	2.2 (1.2)

Introduction -- Combine procedure

- Similar to previous CMS-ATLAS Run 1 combination[1]
- ATLAS and CMS agreed to have a $H \rightarrow Z\gamma$ combined result in Run 2

- Workspaces exchanged between the collaborations, followed by technical checks that results are reproducible
  - CMS result reported only for $m_H = 125.38$ GeV[2] , ATLAS for only 125.09 GeV[3]
  - Both collaborations provided workspaces for 125.09 GeV and 125.38 GeV
  - Compromise solution: report results for both m_H values

- We will show the results for the combination of these workspaces

[1] Doi: 10.1007/JHEP08(2016)045
[2] Doi: 10.1016/j.physletb.2020.135425
[3] Doi: 10.1103/PhysRevLett.114.191803

Correlation of uncertainties

- The experimental uncertainties from ATLAS and CMS analyses are considered uncorrelated
- Reviewed all systematic uncertainties for consistency and a small number of modifications are made to facilitate the combination.
- **Outcome:**

➢ **Correlated:** Main theory production cross section and H→Zγ branching fraction uncertainties

➢ **Not correlated:** The other Higgs boson production modes, the choice of PDF, strong-force coupling constant, the modeling of the underlying event and parton shower

➢ The uncertainty of luminosity were investigated using approximate correlation strategies; they are found to have a negligible impact

➢ ATLAS include a Higgs mass uncertainty, but effect is very small (0.2%)

Category	ATLAS	CMS	Correlate
QCD scale ggF	TheorySig_QCDscale_ggF	THU_ggH_Mu	+
	TheorySig_QCDscale_ggF_pTt		
	TheorySig_QCDscale_ggF_relpT		
	TheorySig_QCDscale_ggF_vbf[2,3]j		
	TheorySig_QCDscale_ggF_VBFModel		
		THU_ggH_Res	
QCD scale others	TheorySig_QCDscale_ttH	THU_ttH_Yield	
	TheorySig_QCDscale_VBFH	THU_VBF_Yield	
	TheorySig_QCDscale_WH	QCDscale_WH	
	TheorySig_QCDscale_ZH	QCDscale_ZH	
PDF	TheorySig_PDF_[ttH,VBFH,WH,ZH]		
	TheorySig_PDF4LHC_NLO_30_EV[1-30]		
		pdf_Higgs_ttH	
		pdf_Higgs_qqbar	
		pdf_Higgs_gg	
QCD alphaS	TheorySig_QCDalphaS		
	TheorySig_QCDalphaS_[ttH,VBFH,WH,ZH]		
BR	TheorySig_BR_Zy	BR_hzg	+
UEPS	TheorySig_UEPS_ggH		
		UnderlyingEvent_norm	
		PartonShower_norm	
Higgs Mass	ATLAS_LHCmass		

Combination results (ATLAS+CMS)

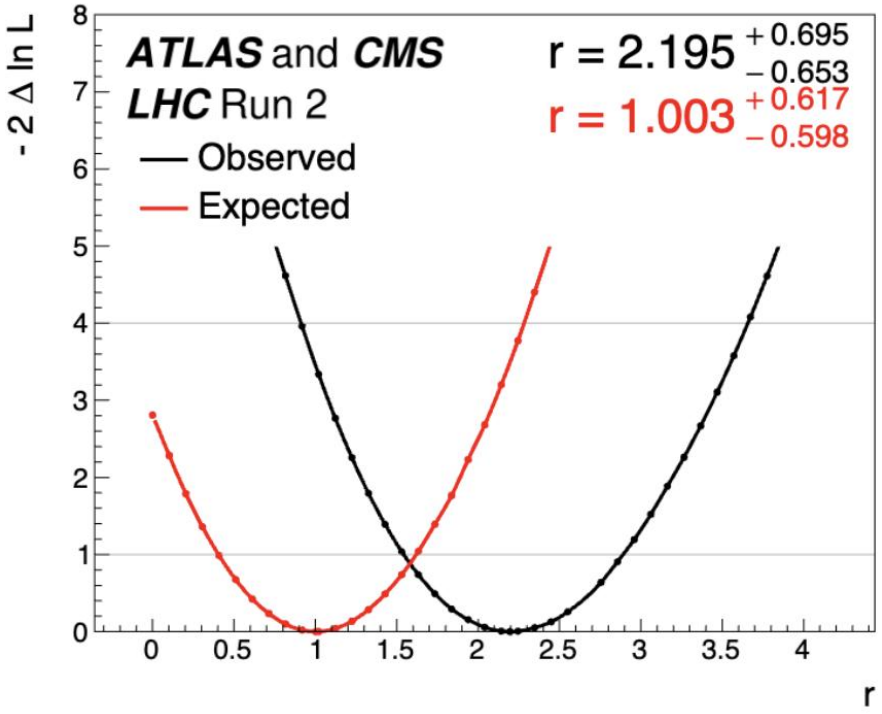
Combine results (m_H = 125.38 GeV)

Combining ATLAS125.38+CMS125.38

Expected Significance: 1.7σ (post-fit)

Observed Significance: 3.4σ

Signal Strength: 2.2 ± 0.7



The combined significance is close to the sum of square of two individual results.

Combine results (m_H = 125.09 GeV)

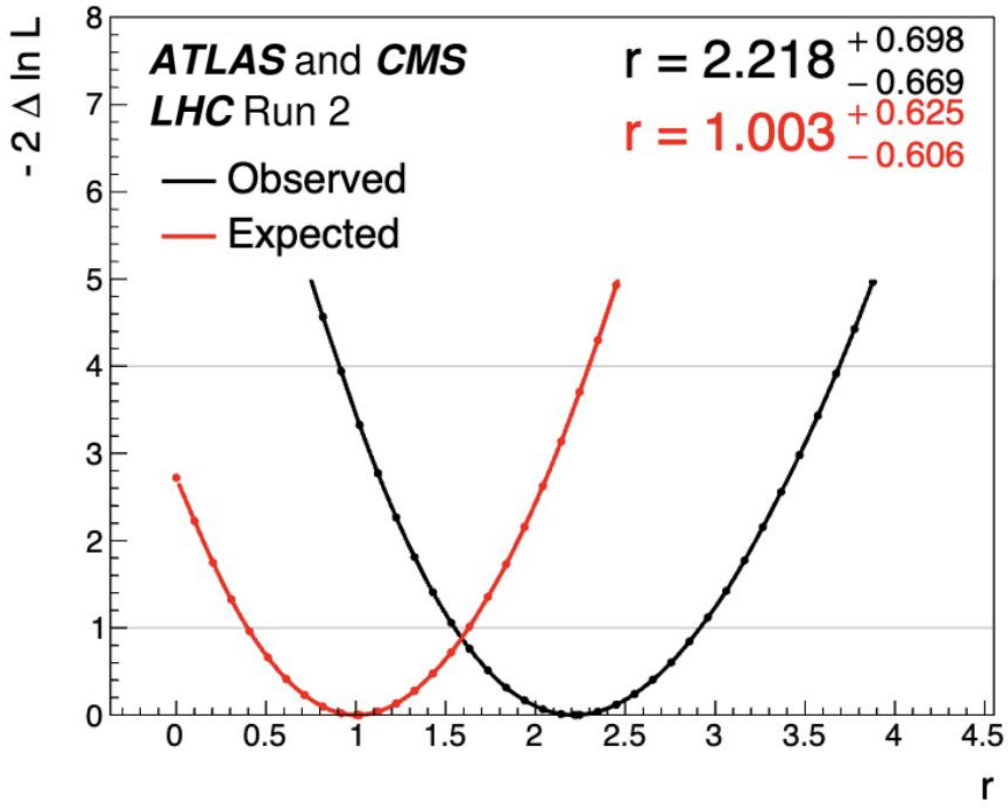
Combining ATLAS125.09+CMS125.09

Expected Significance: 1.6σ (post-fit)

Observed Significance: 3.4σ

Signal Strength: 2.2 ± 0.7

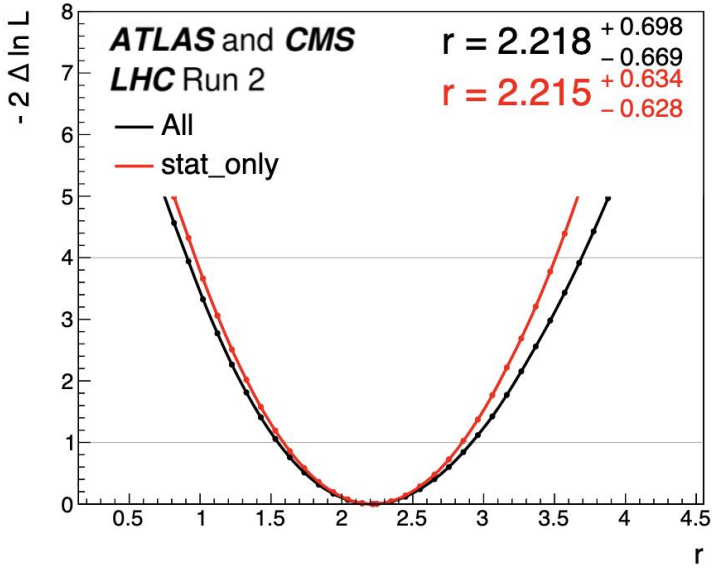
The effect of the Higgs mass is negligible.



Breakdown of uncertainties

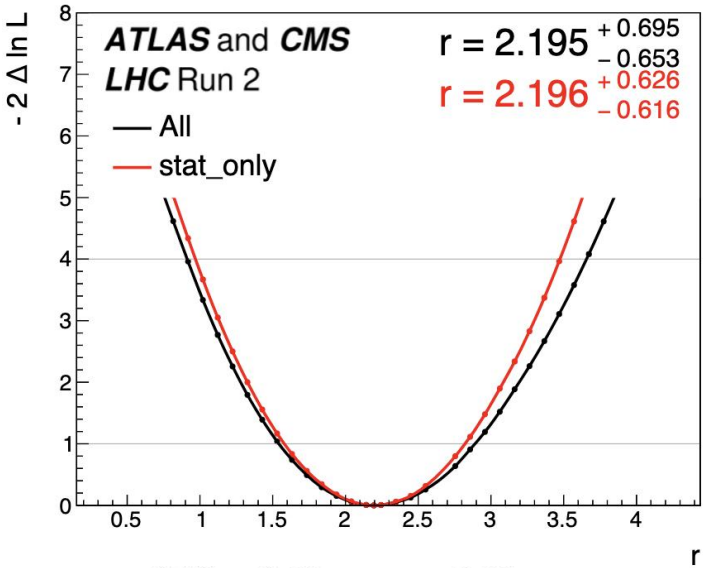
- The total uncertainty is divided into two parts: systematic uncertainty and statistical uncertainty. The systematic uncertainty is obtained from the subtraction in quadrature of red one from black one

$m_H = 125.09$ GeV



$\mu = 2.22^{+0.70}_{-0.67}\left(^{+0.63}_{-0.63}(\text{Stat})^{+0.30}_{-0.23}(\text{Syst})\right)$

$m_H = 125.38$ GeV



$2.20^{+0.70}_{-0.65}\left(^{+0.63}_{-0.62}(\text{Stat})^{+0.30}_{-0.22}(\text{Syst})\right)$

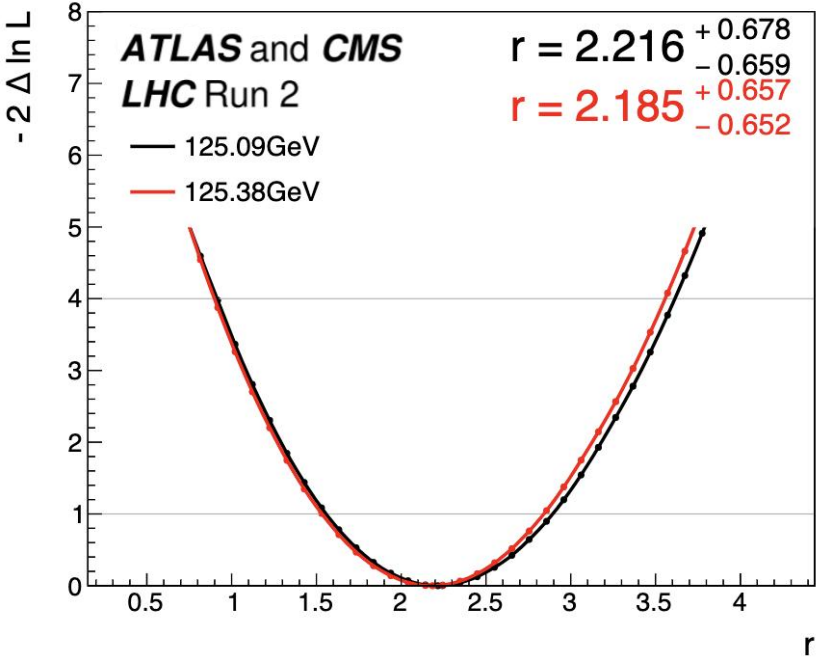
Branch ratio

- the signal strengths used to calculate the branching ratio of H→Zγ are obtained with freezing the uncertainties of branch ratio to zero.

$$\mu_{BR} = 2.2 \pm 0.7 \text{ for both mass}$$

This is corresponding to

$$B(H \to Z\gamma) = (3.4 \pm 1.1) \times 10^{-3} \text{ for both mass}$$



Compatibility with SM (r=1)

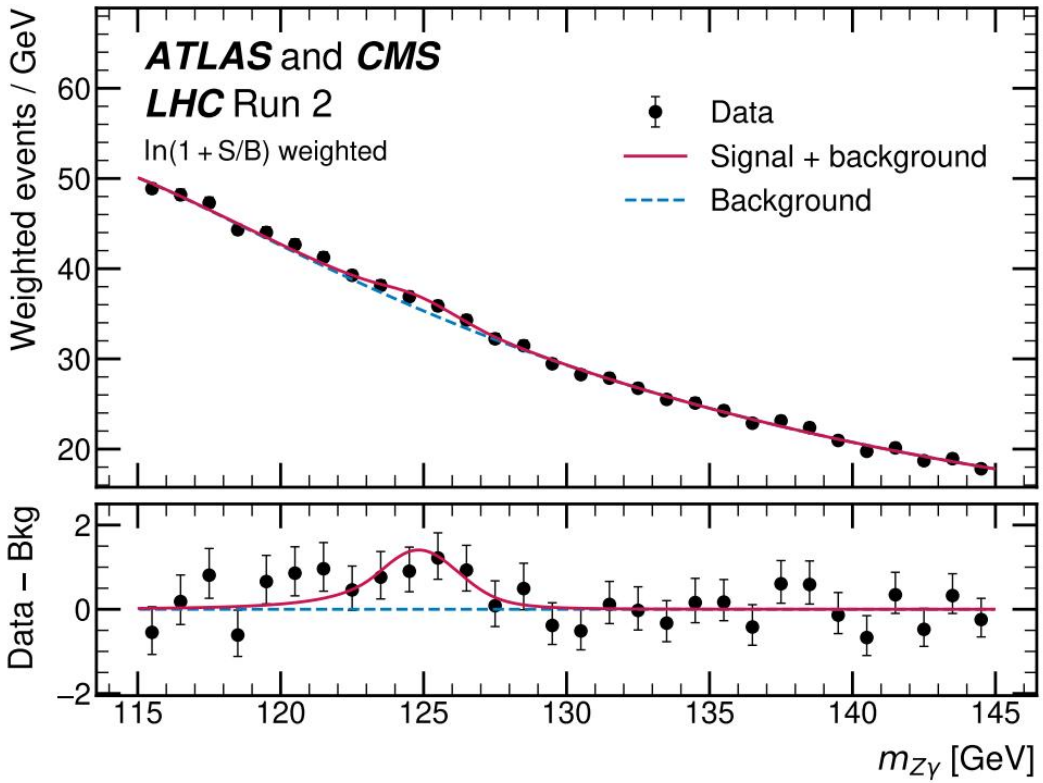
Likelihood scans for inclusive signal strength under different Higgs mass assumptions

	Compatibility	
Higgs mass	125.09 GeV	125.38 GeV
Standard Model (r = 1)	1.82σ	1.83σ

Compatibility with Standard Model is about 1.8σ

Spectrum of $m_{ll\gamma}$

- Visualisation of excess in $m_{ll\gamma}$
- Sum of events over a common mass window of 115-145 GeV, with each category weighted by ln(1+S/B)
- S and B are signal and background events in the 120-130 GeV range



Summary

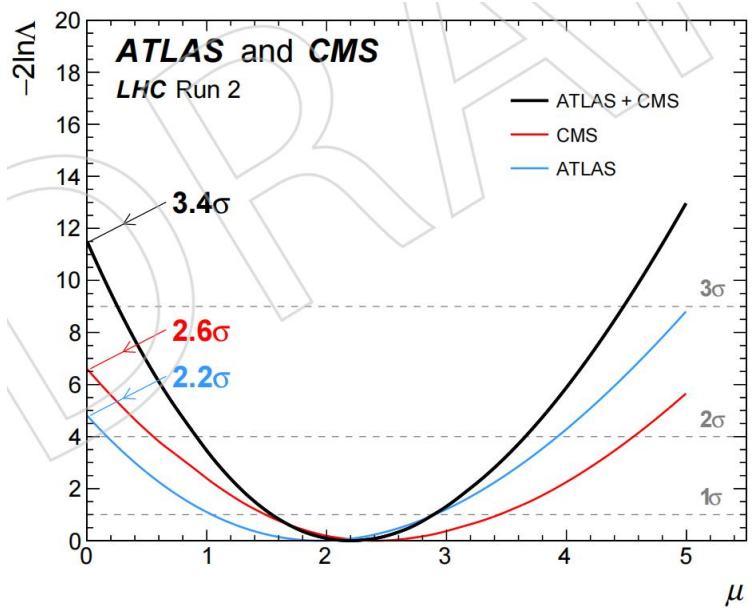
Summary

- First CMS-ATLAS Higgs combination in Run 2. Useful to exercise combination machinery in anticipation of full CMS+ATLAS Run 2 combination.
- **First evidence** of the $H \to Z\gamma$ decay: Observed significance is about 3.4σ, and signal strength is about 2.2 ± 0.7.
- This study is a powerful test of the Standard Model. The $H \to Z\gamma$ decay could provide indirect evidence of the existence of particles beyond those predicted by the Standard Model of particle physics.
- With the ongoing Run3 of the LHC and the future HL-LHC, we will be able to improve the precision of this test and probe ever rarer Higgs decays.

Combine results

- **Signal strength**: 2.2 ± 0.7, **significance**: 3.4σ
- To the relevant level of precision, results are independent of chosen m_H
- Compatible with SM expectation ($\mu = 1$) at: 1.8σ

Experiment	Dataset	Higgs Mass [GeV]	Signal strength	Significance
ATLAS	observed	125.09	$2.01^{+0.97}_{-0.91}$	2.24σ
		125.38	$1.95^{+0.96}_{-0.90}$	2.19σ
ATLAS	expected	125.09	$1.00^{+0.90}_{-0.86}$	1.17σ
		125.38	$1.00^{+0.89}_{-0.85}$	1.18σ
CMS	observed	125.09	$2.48^{+1.06}_{-0.94}$	2.56σ
		125.38	$2.41^{+1.03}_{-0.92}$	2.57σ
CMS	expected	125.09	$1.01^{+0.90}_{-0.87}$	1.14σ
		125.38	$1.01^{+0.88}_{-0.85}$	1.17σ
Combined	observed	125.09	$2.22^{+0.70}_{-0.67}$	3.40σ
		125.38	$2.20^{+0.70}_{-0.65}$	3.36σ
Combined	expected	125.09	$1.00^{+0.63}_{-0.61}$	1.64σ
		125.38	$1.00^{+0.62}_{-0.60}$	1.68σ



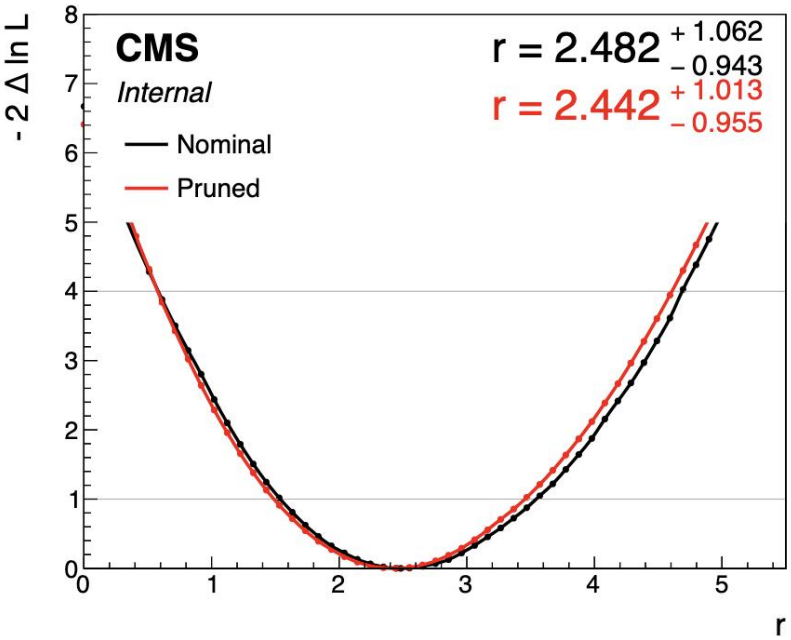
m_H	Obs	Exp
125.09 GeV	$2.22^{+0.70}_{-0.67}\,(^{+0.63}_{-0.63}\,(\text{Stat})^{+0.30}_{-0.23}\,(\text{Syst}))$	$1.00^{+0.63}_{-0.61}\,(\pm 0.59\,(\text{Stat})^{+0.20}_{-0.15}\,(\text{Syst}))$
125.38 GeV	$2.20^{+0.70}_{-0.65}\,(^{+0.63}_{-0.62}\,(\text{Stat})^{+0.30}_{-0.22}\,(\text{Syst}))$	$1.00^{+0.62}_{-0.60}\,(^{+0.59}_{-0.58}\,(\text{Stat})^{+0.20}_{-0.15}\,(\text{Syst}))$

Back up

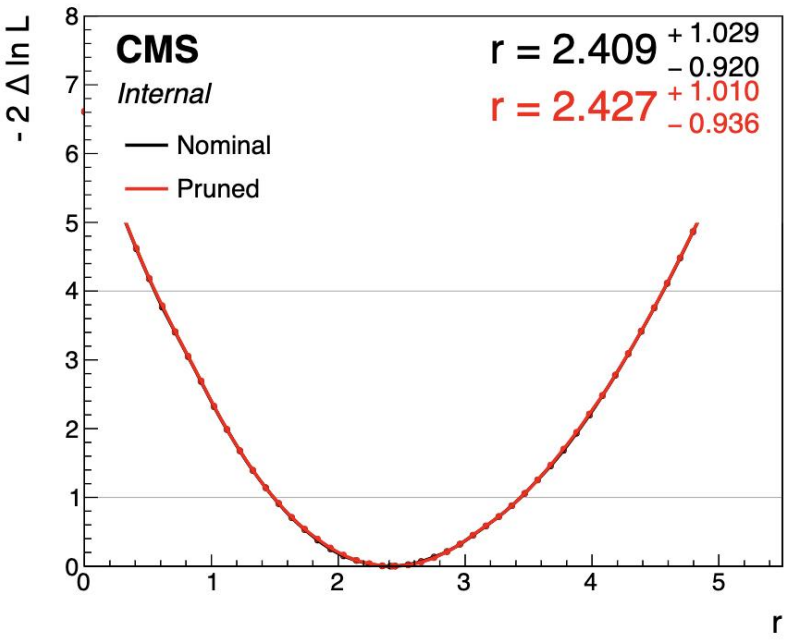
CMS only results

Comparison of full and pruned set of background functions

m_H =125.09GeV



m_H =125.38GeV



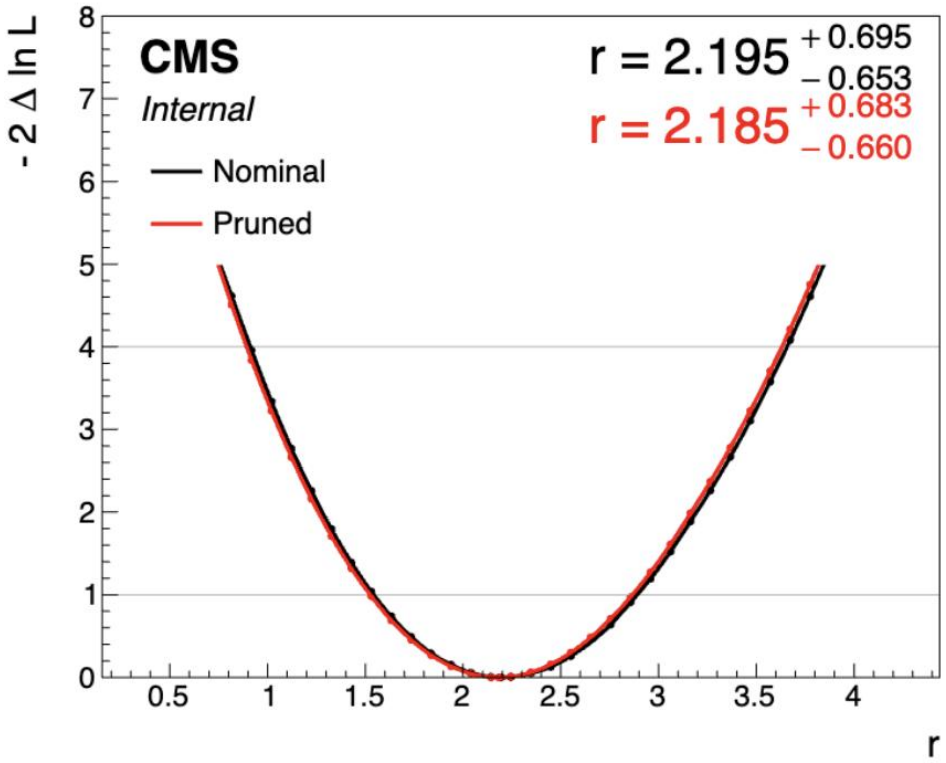
The results meet with the Run2 paper, which signal strength is 2.4 ± 0.9 [(10.1007/JHEP05(2023)233)]

Discrete nuisances on the comb

The effect of the discrete nuisances in the combination is reduced a lot.

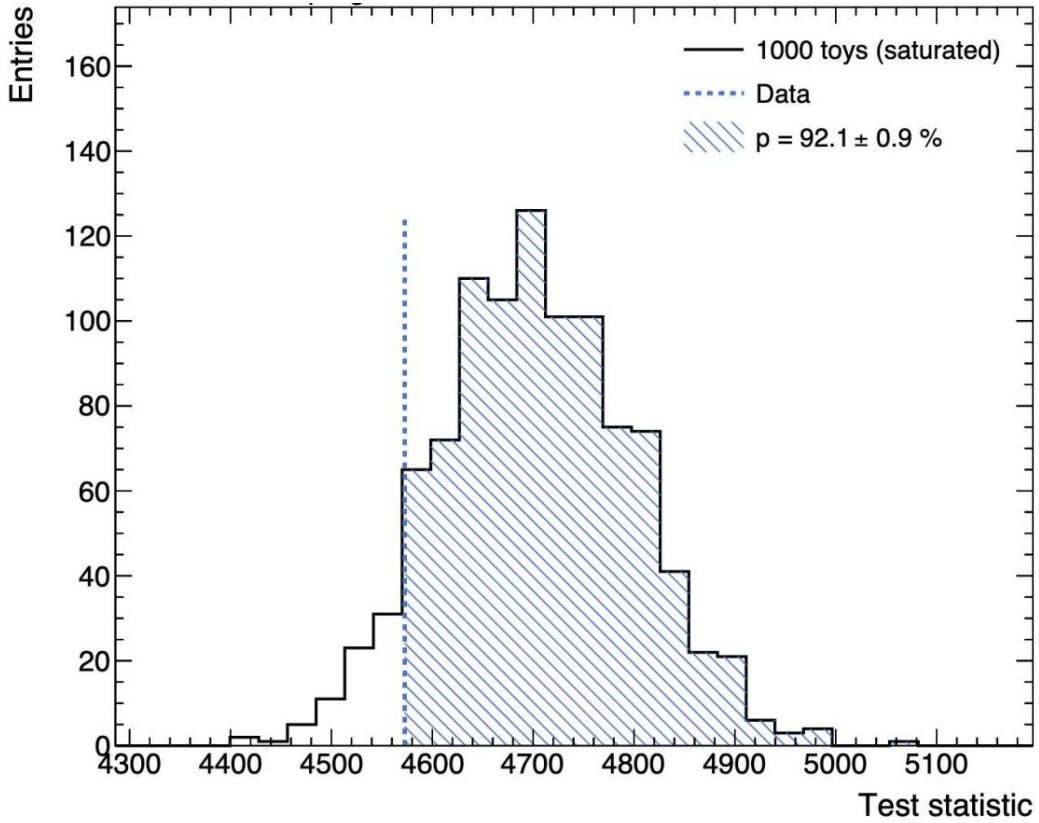
ATLAS125.09GeV + CMS125.38GeV

Identical at 1σ intervals.



Compatibility of the results

Goodness of Fit



Compatibility with SM (r=1)

Likelihood scans for signal strengths of 3 different production modes

-2 Δ lnL	mu_XS_VH	mu_XS_ggF	mu_XS_VBF
0	18.78	2.44	-1.48
8.20	1	1	1

Compatibility with Standard Model is about 1.73σ