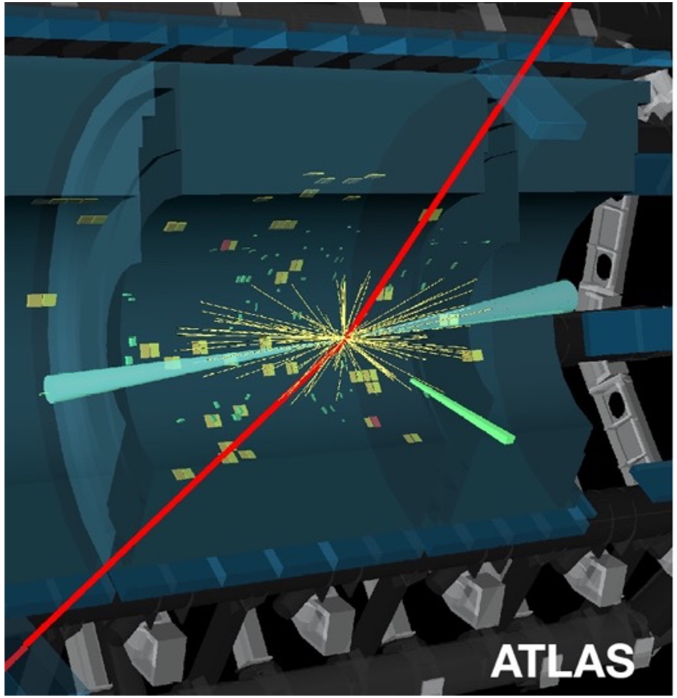
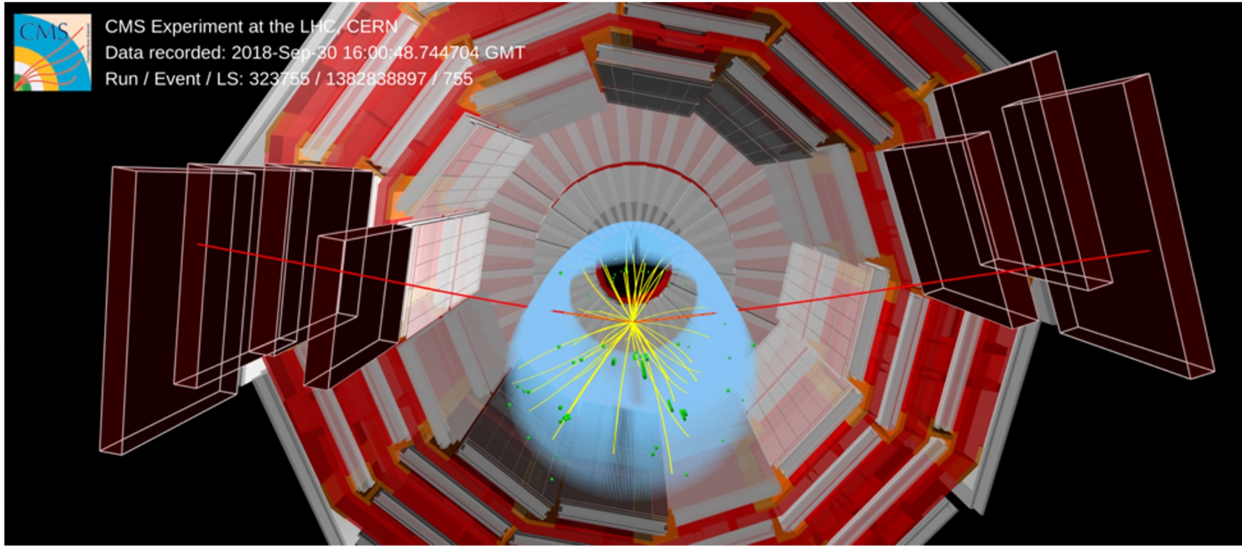
Rare processes and Searches for new Phenomena with **Higgs bosons**



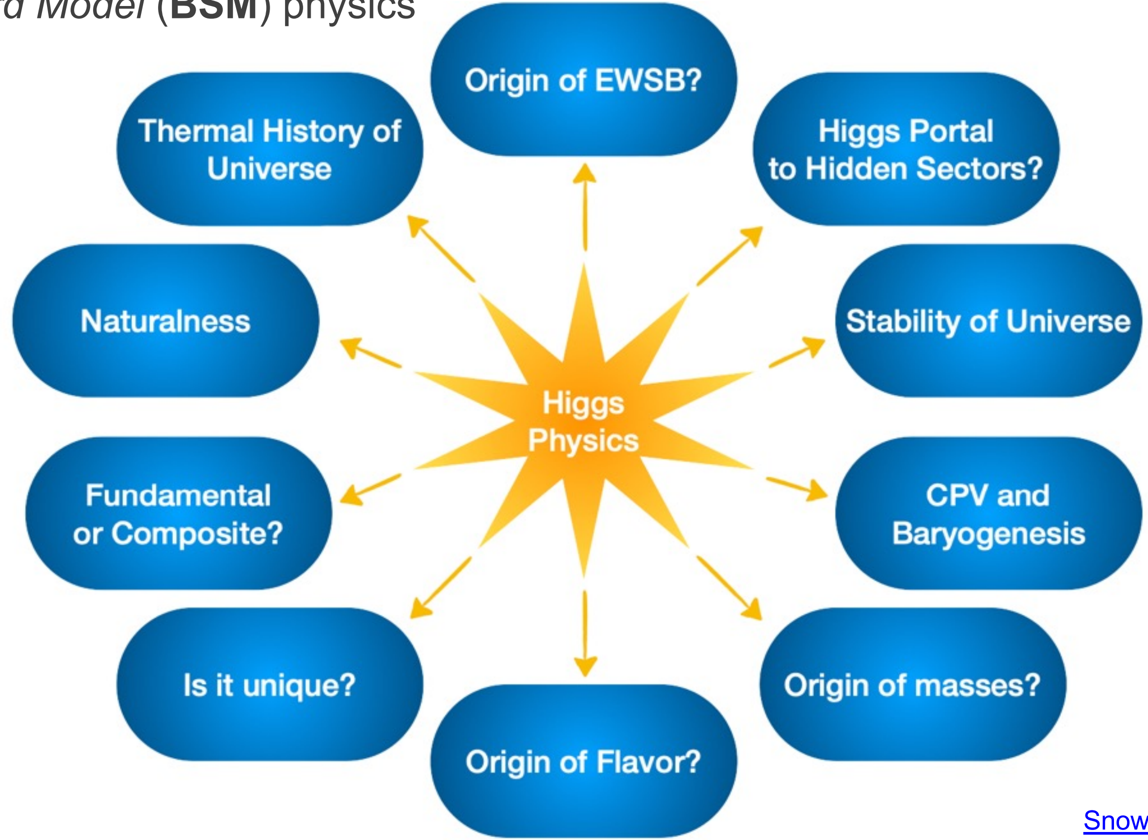


Bernd Stelzer for the ATLAS & CMS Collaboration

Physics in Collision Conference, Arica, Oct 10^{th}, 2023

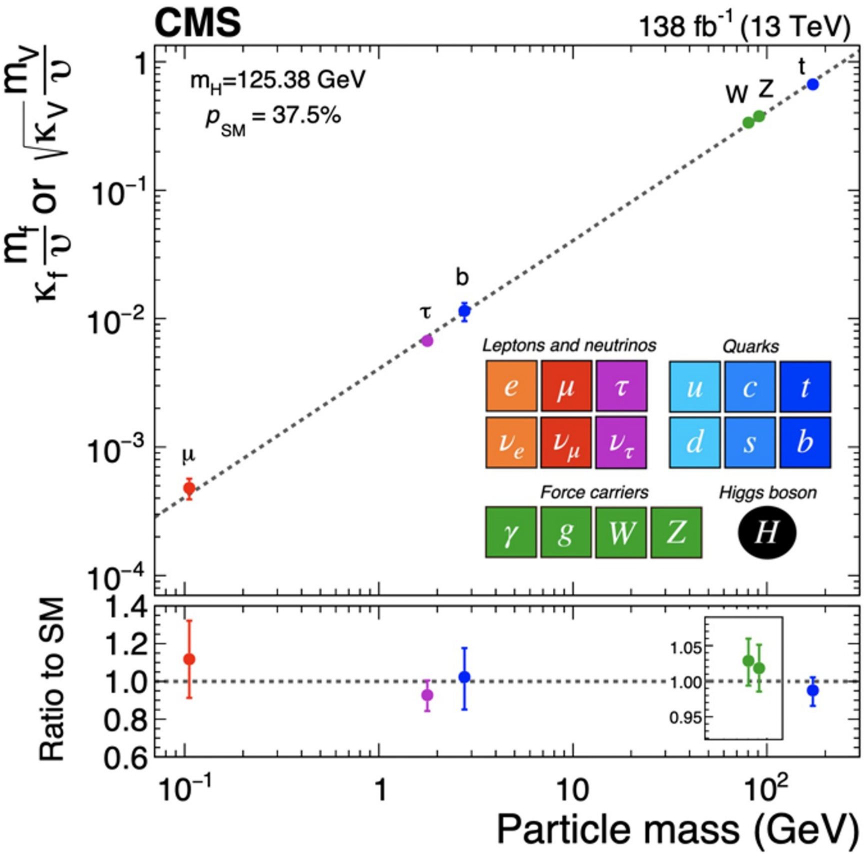
Introduction

The Higgs boson is **central** to **Standard Model** and *beyond Standard Model* (**BSM**) physics



Snowmass Higgs Report

Introduction

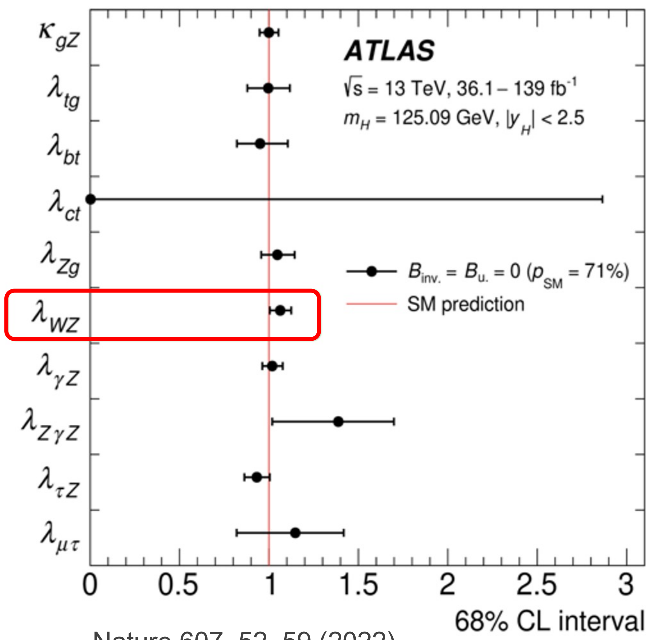


Nature 607, 52-68 (2022)

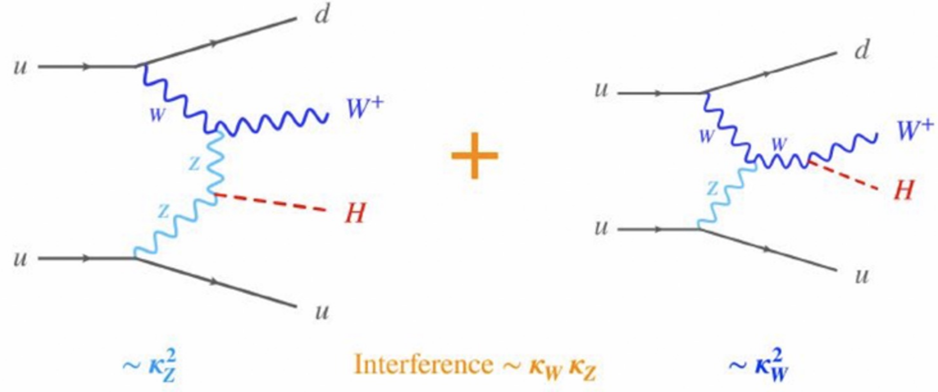
- In the past 11 years, since the **Higgs boson discovery**, we have learned a lot about its properties, coupling to bosons and 3rd generation fermions (*see previous talk*)
- Large LHC datasets can uncover **rare Higgs boson processes** e.g. *couplings to the 2nd generation* of fermions, processes with *destructive interference* and processes that are *not possible at tree level*
  - Physics Beyond the SM (**BSM**) could greatly enhance their rate, motivating these analyses
  - The Higgs boson could also directly couple to **BSM** phenomena

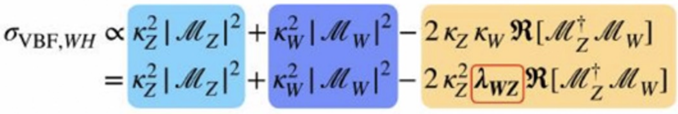
Rare Process, VBF HW

- Measuring the Higgs couplings to *W* and *Z* is essential for testing EWSB and custodial symmetry of the SM. Latest ATLAS result measure $\lambda_{WZ} = \kappa_W / \kappa_Z = 1.06 \pm 0.06$
- Currently *little* sensitivity to the **sign** of λ_{WZ}
- Destructive interference of VBF HW process leads to **rare Higgs process** in SM



Nature 607, 52–59 (2022)



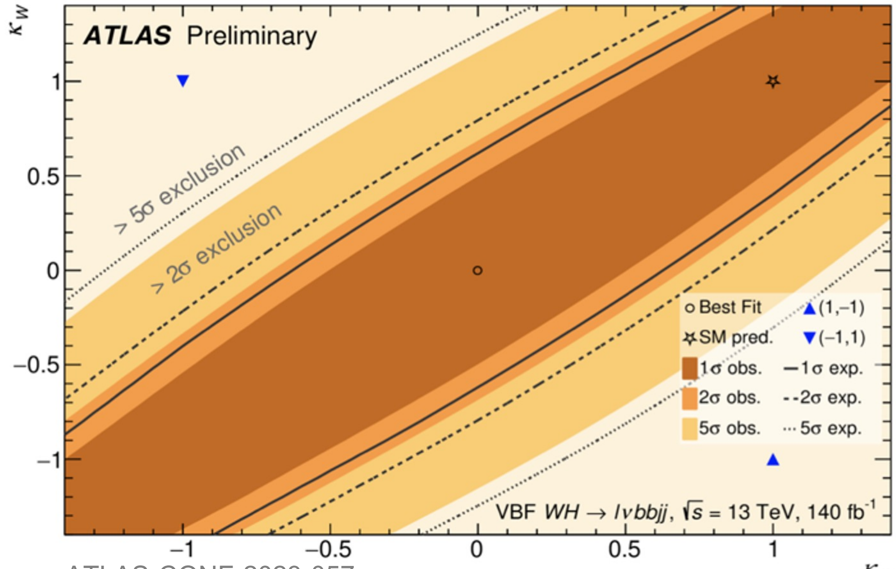


Interference is constructive if λ_{WZ} is negative

- Can determine the **sign** of λ_{WZ} by searching for *enhancement* of VBF WH.

Rare Process, VBF HW

- Negative λ_{WZ} signal would be easily separable from background based on kinematics
- ***No excess** is seen above SM prediction.*
- Opposite sign couplings for κ_W, κ_Z consistent with other Higgs measurements are **excluded** at > 8σ
  - *W*, *Z* couplings to Higgs have same sign



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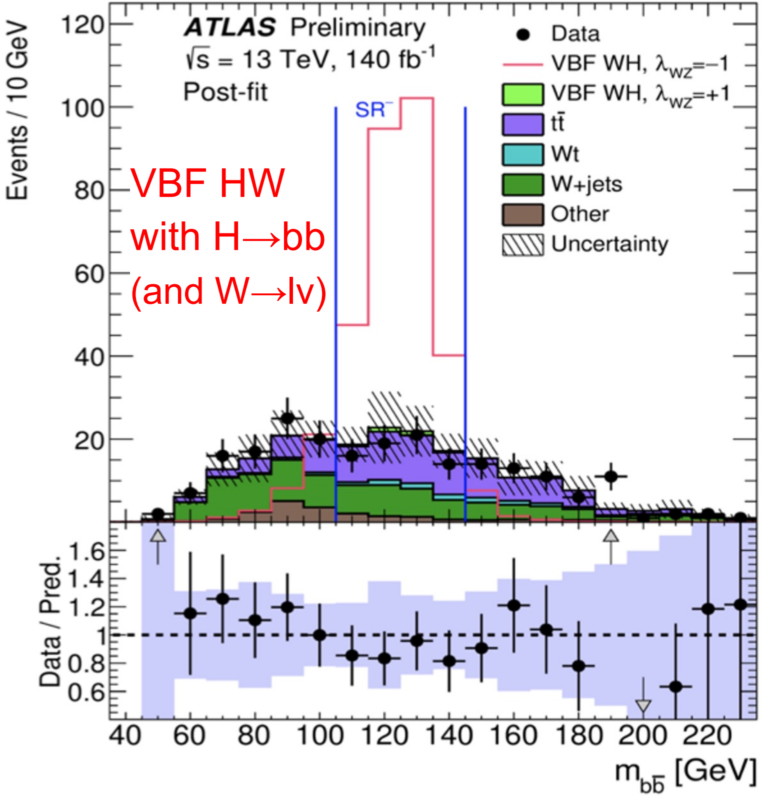
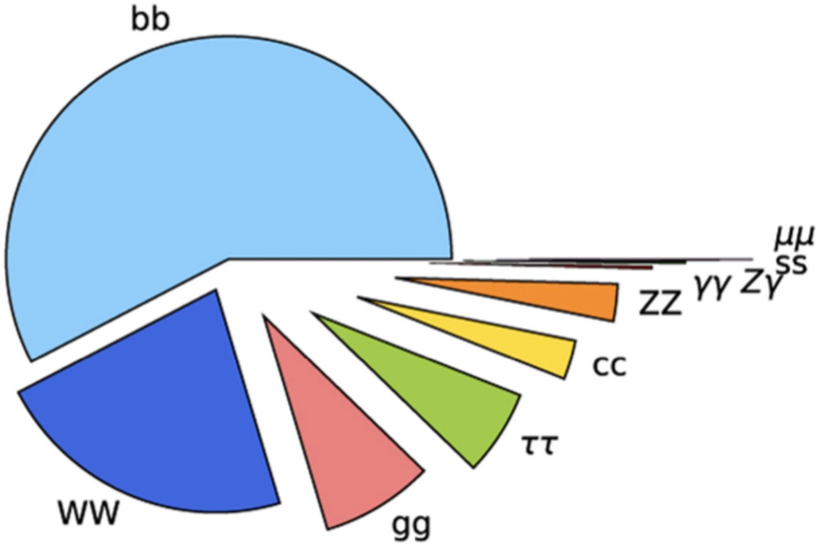


Higgs Rare Decays

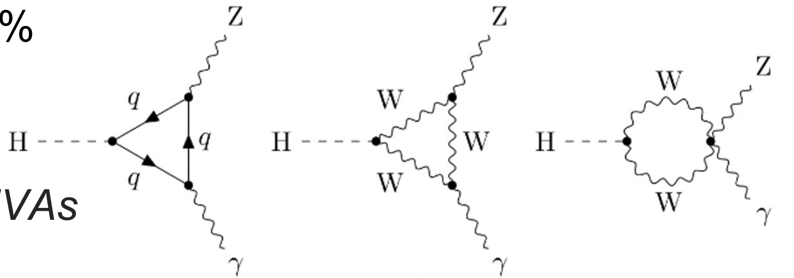
Decay channel	Branching fraction (%)	
bb	57.63	±0.70
WW	22.00	±0.33
gg	8.15	±0.42
ττ	6.21	±0.09
cc	2.86	±0.09
ZZ	2.71	±0.04
γγ	0.227	±0.005
Zγ	0.157	±0.009
ss	0.025	±0.001
μμ	0.0216	±0.0004



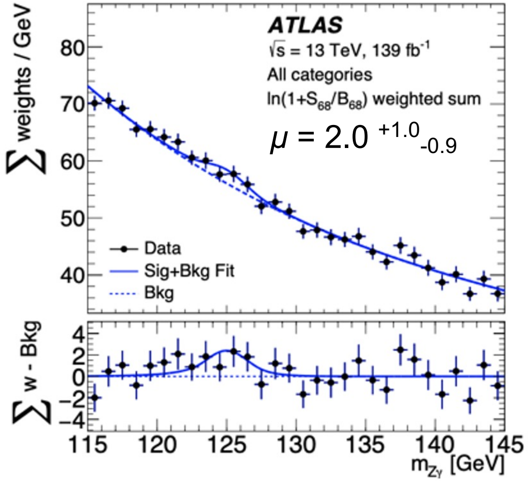
- Some rare processes also suffer from huge backgrounds, e.g. *H→cc* or *ss*
- Others searches depend on small BR of boson decay, e.g. *Z→ee*, *μμ* (BR=3.4%)

$H \to Z\gamma$ Decays

- Expect tiny signal from $\boldsymbol{H \to Z\gamma}$: BR($H \to Z\gamma$) =0.157%
  together with leptonic decay of Z boson
- Important for validating SM / BSM theories
- Fit ***narrow*** $m_{Z\gamma}$ in all production modes, *purify with MVAs*
- The combined fit to data from ATLAS and CMS results in the **first evidence** for $H \to Z\gamma$

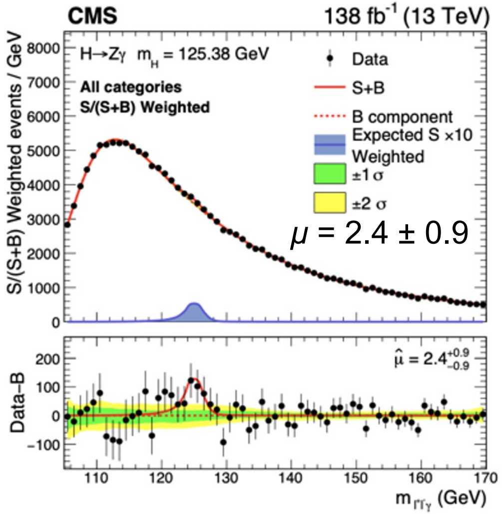


Local significance 2.2 (1.2) σ

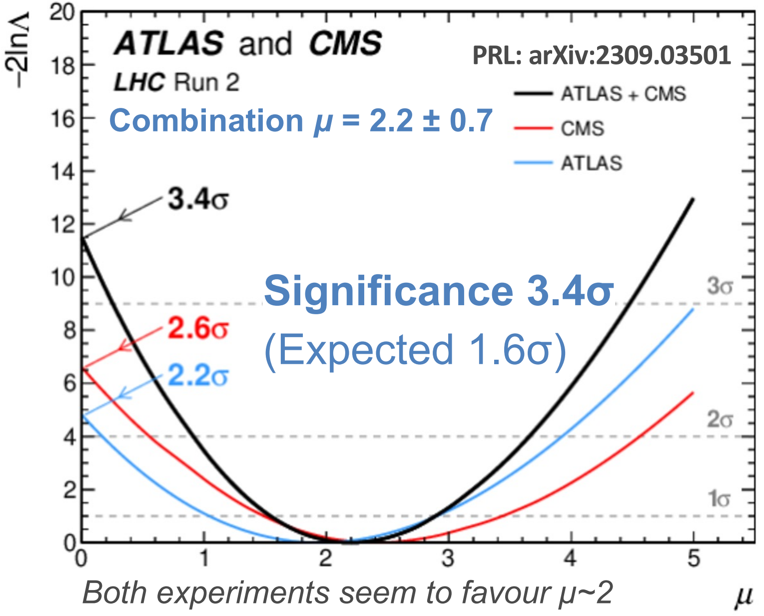


PLB 809 (2020) 135754

Local significance 2.7 (1.2) σ

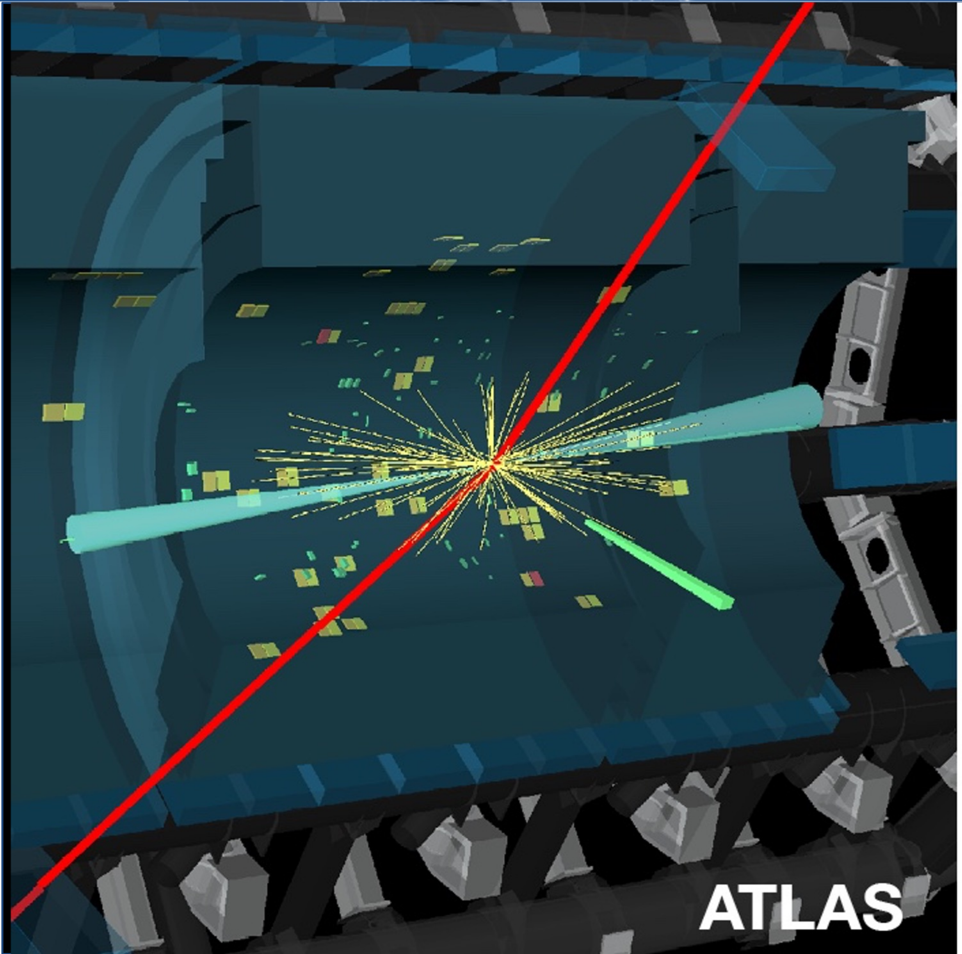


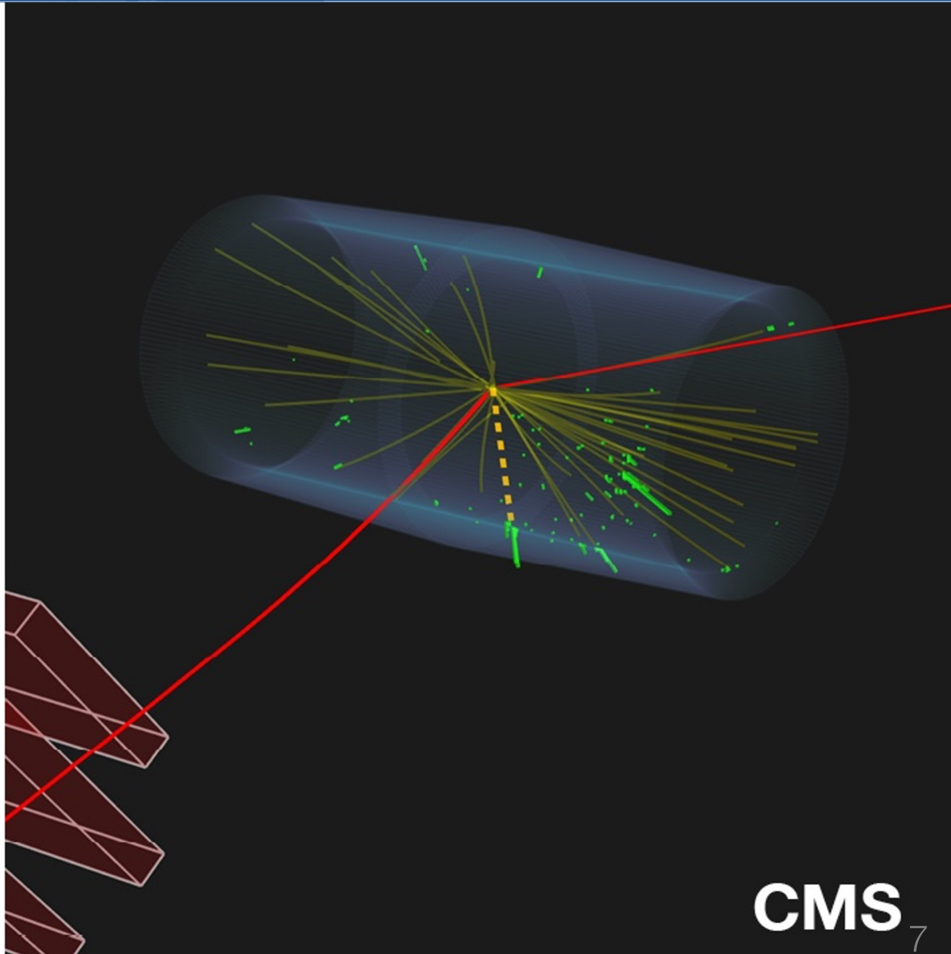
JHEP 05 (2023) 233



Both experiments seem to favour μ~2
Compatibility with SM is 1.9 σ

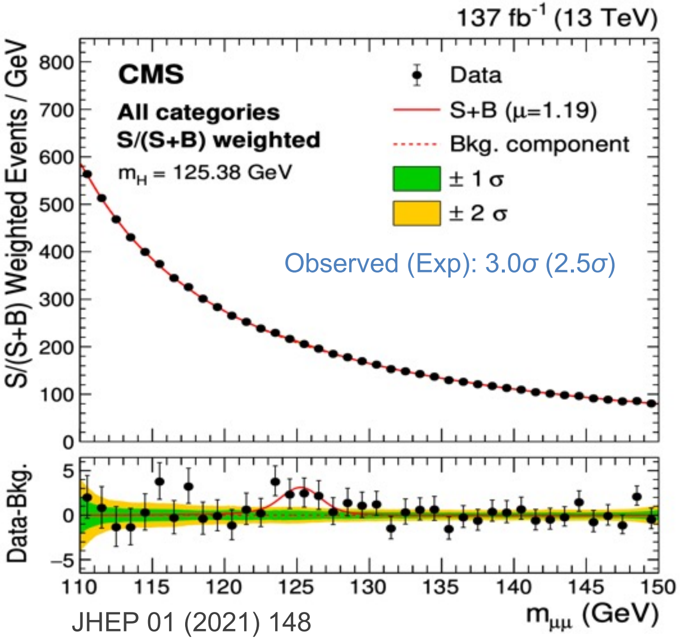
H→Zγ Decays





Higgs→μμ

- ***H→μμ*** is very **challenging**! BR($H \to \mu\mu$) = 0.0216%
- Search for ***narrow*** $m_{\mu\mu}$ in all production modes, *increase purity with MVAs*
- CMS first evidence with a **3σ signal significance**!



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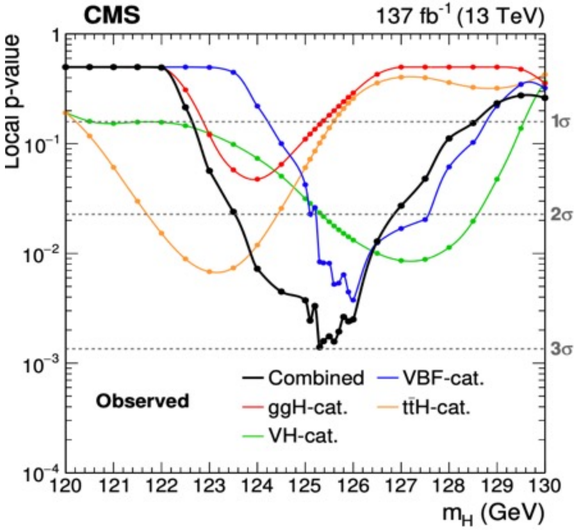

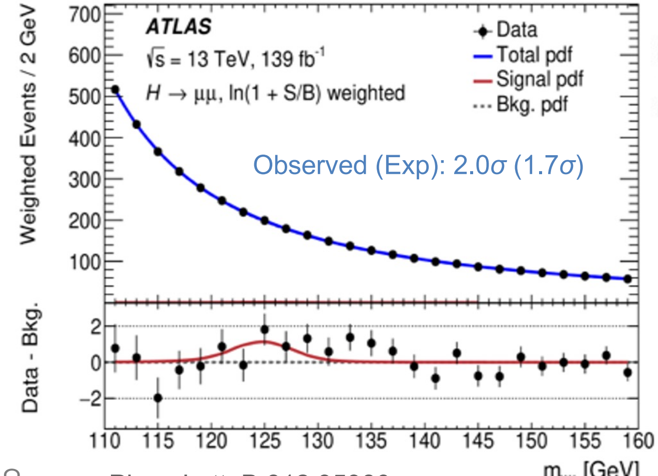

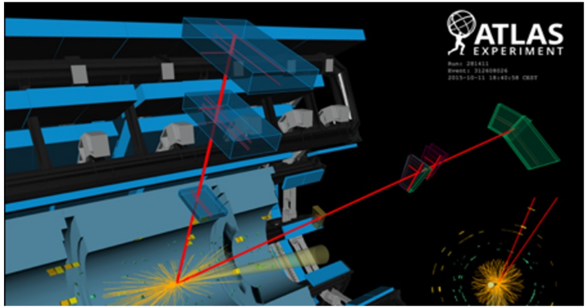

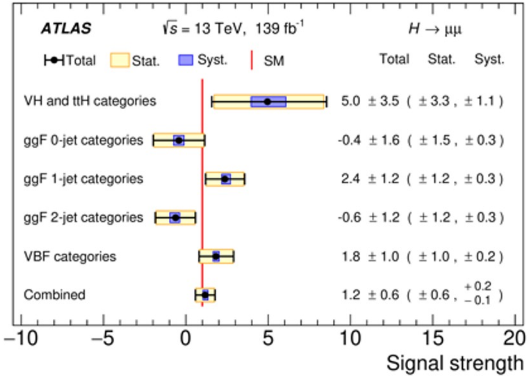

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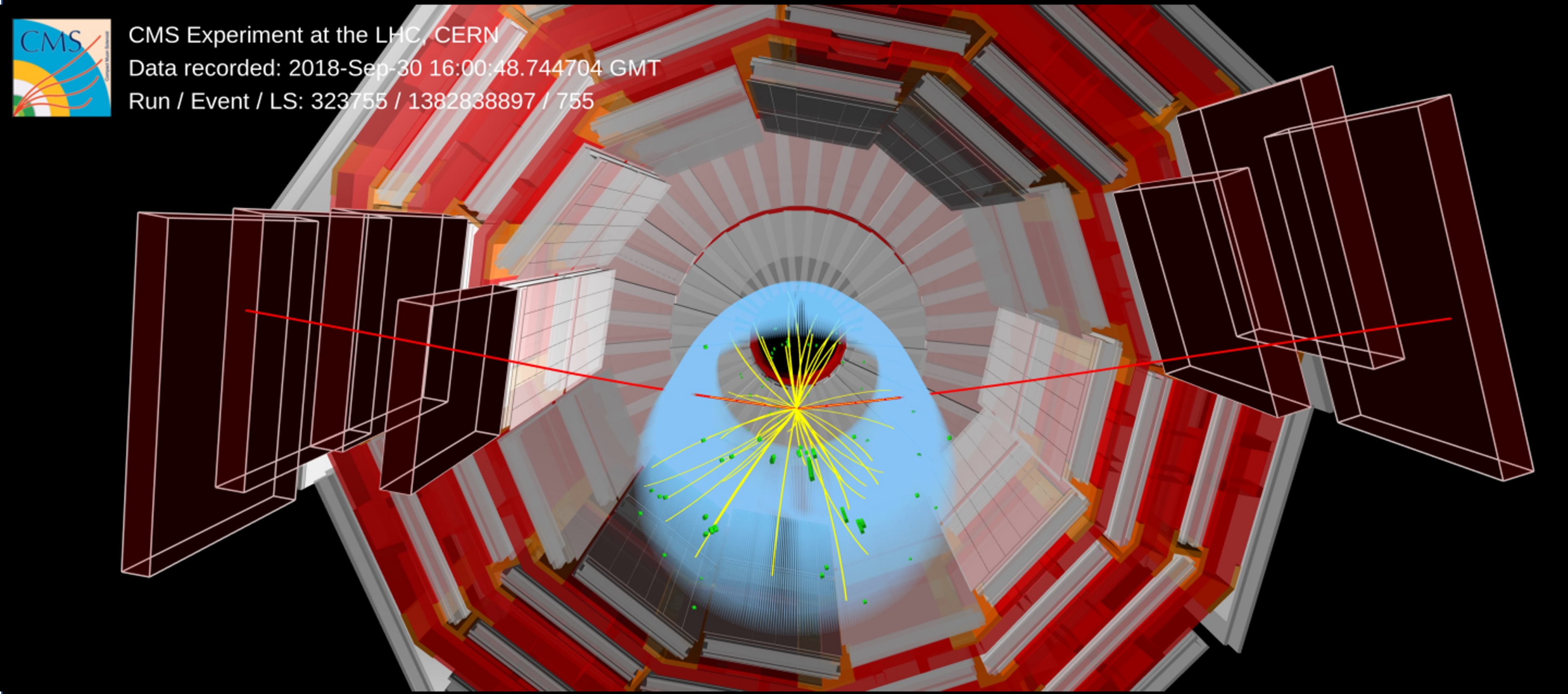
Higgs⟶μμ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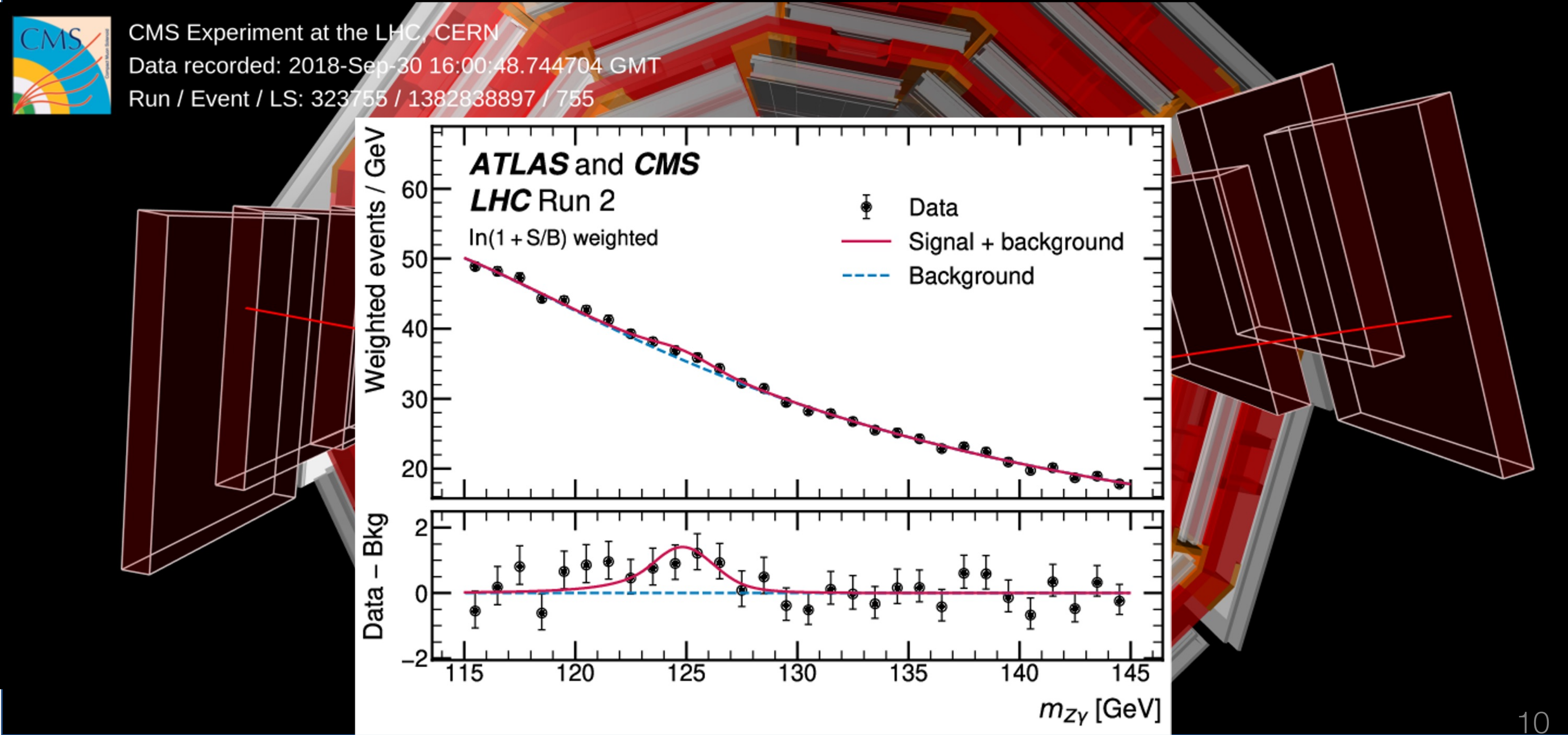
Run / Event / LS: 323755 / 1382838897 / 755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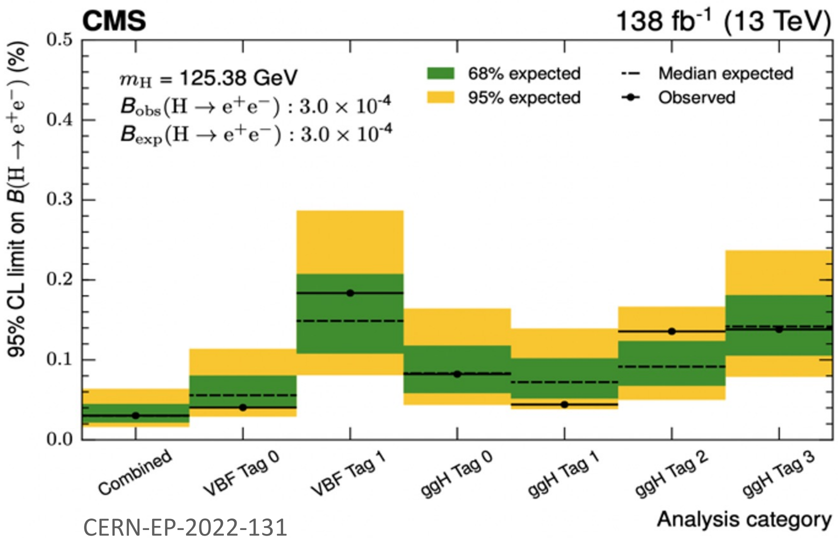
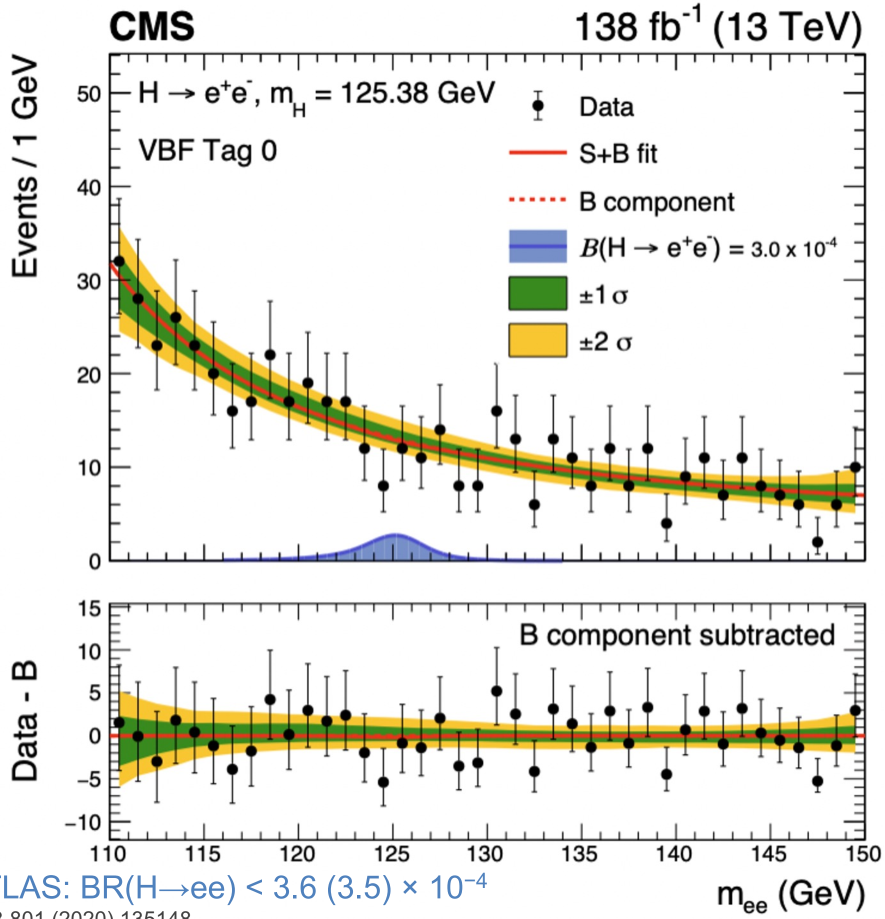
ATLAS and CMS
LHC Run 2
ln(1 + S/B) weighted
Data
Signal + background
Background
Weighted events / GeV
Data – Bkg
$m_{Z\gamma}$ [GeV]
115
120
125
130
135
140
145
60
50
40
30
20
2
0
−2

- **Higgs decay to electron pairs** has tiny BR(H → *ee*) = 0.0000005%
- **Could be enhanced** in BSM scenarios
- Search for *narrow* m_{ee} resonance in all production modes and *BDT purified "tag regions"*
- BR(H→ee) < 3.0 × 10^{-4} at 95%CL (exp and obs)



CERN-EP-2022-131

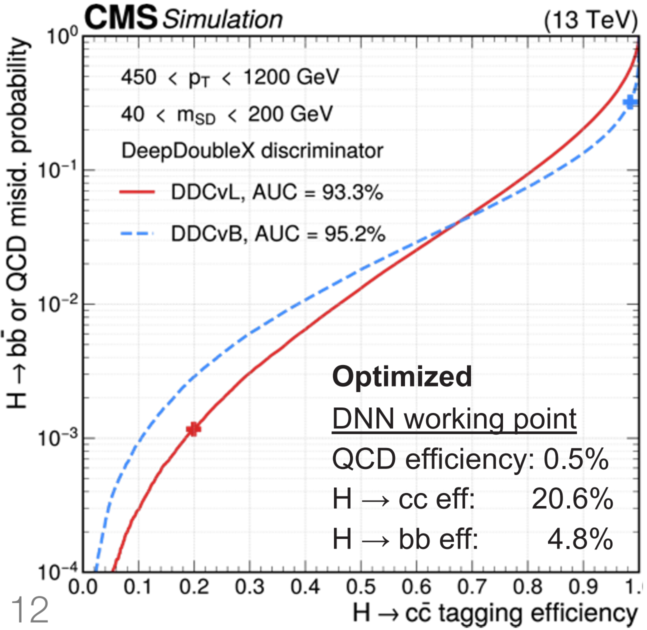


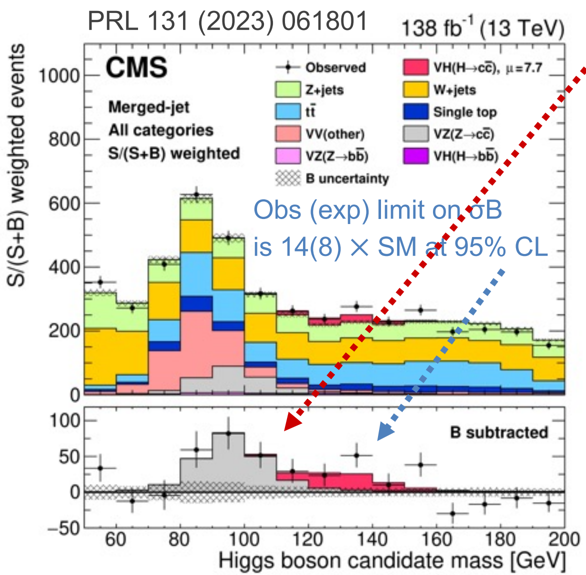
ATLAS: BR(H→ee) < 3.6 (3.5) × 10^{-4}

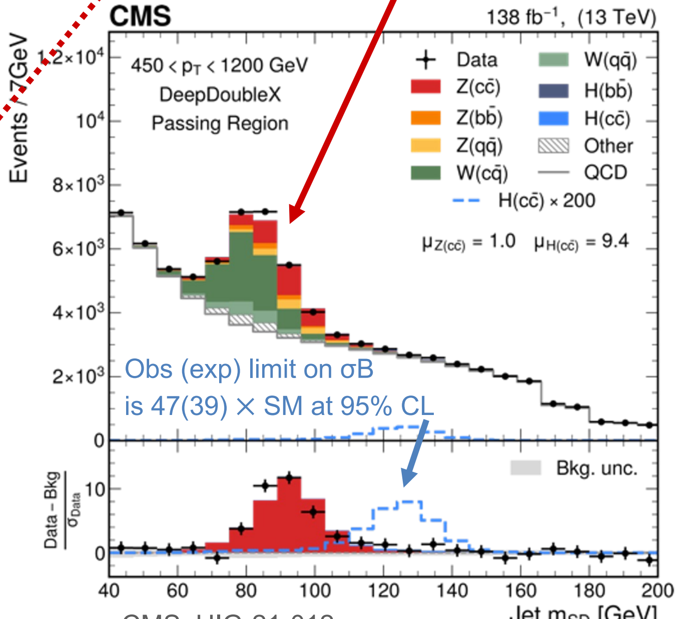
PLB 801 (2020) 135148

Higgs → cc

- **Higgs→cc (charm) is a very challenging** signature
  - *Small branching* ratio of 2.9% and difficulty of *c*-quark tagging given **huge background** rate
  - Search for ZH (*H* →*cc*) ***and*** boosted *H* → *cc* events, reconstructed as a single large-radius jet
  - Use of *Z*→*cc* data to validate the method yields a **first observation** of *Z*→*cc* ***and*** *Z*→*cc* + high p_T jets!
  - Use of Deep Neural Network **charm-tagging** technique essential!



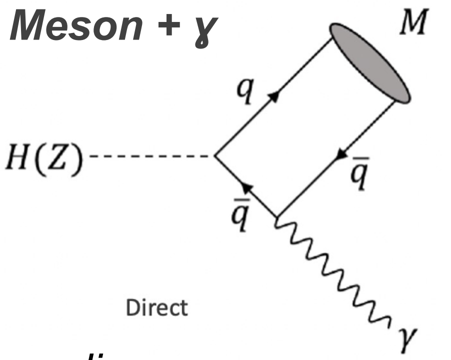


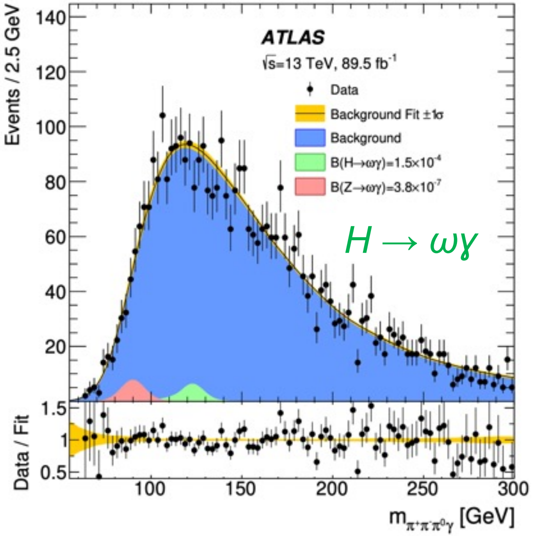


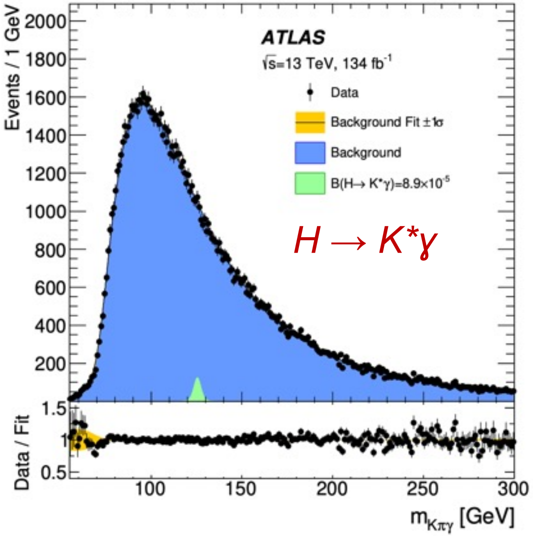
CMS: HIG-21-012

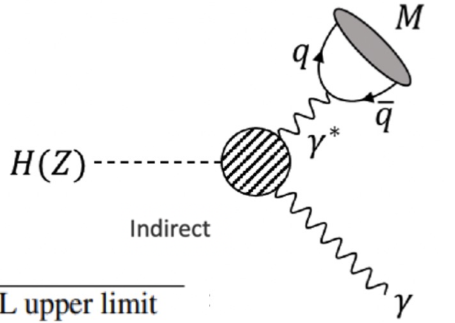
$H \to$ Meson + γ

- Probe Higgs boson coupling to **1st and 2nd generation** fermions in ***H* → *Meson* + γ**
- Test **Flavour conserving** coupling to *u* and *d* quarks ($H \to \omega\gamma$)
  Flavour violating coupling to *d* and *s* quarks ($H \to K^*\gamma$)
- Standard Model prediction are driven by two contributions:
  - **Direct interaction**: Scales with Yukawa coupling
  - **Indirect interaction**: $H \to \gamma^* \to M\gamma$ (M=meson)
- ***Destructive interference** yields* (BR ~10^{-5} – 10^{-10}), *sensitive to sign of coupling*









No excess

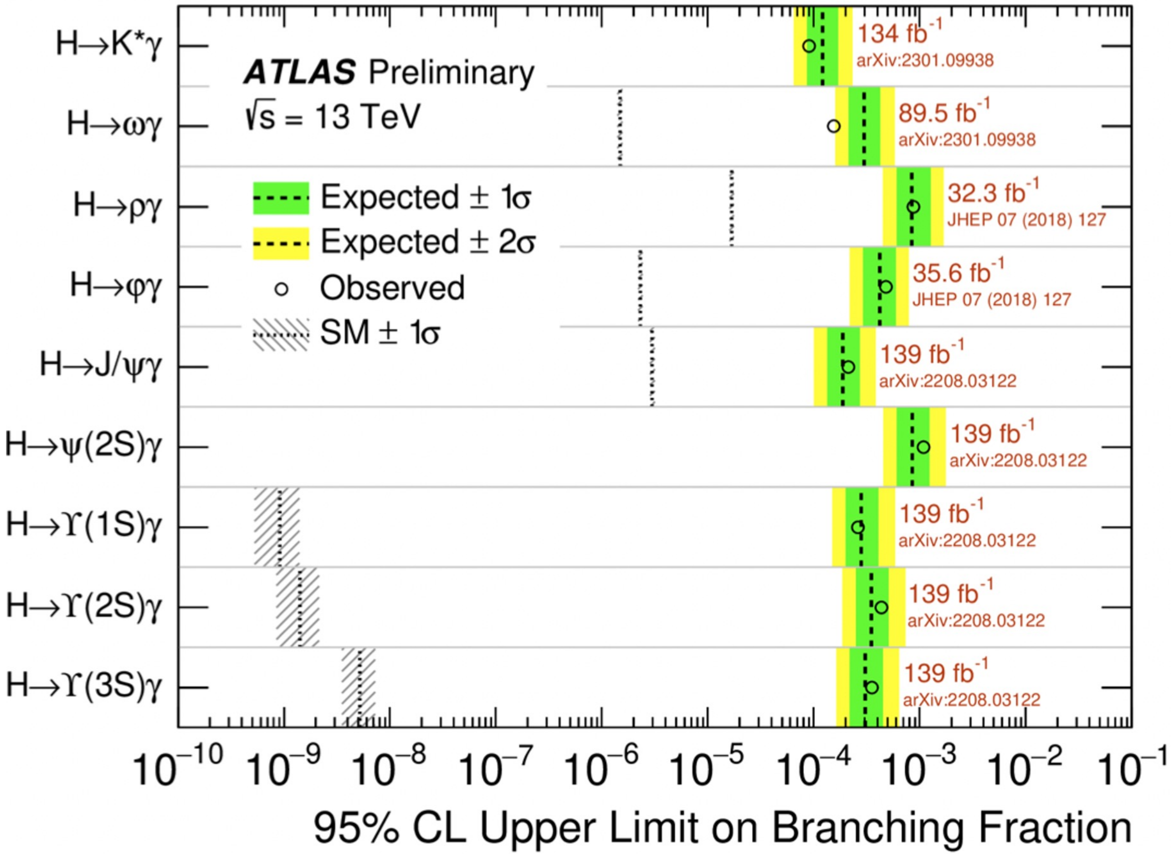
Observed limits:

Channel	95% CL upper limit	
	Expected	Observed
$H \to \omega\gamma\ [10^{-4}]$	$3.0^{+1.2}_{-0.8}$	1.5
$H \to K^*\gamma\ [10^{-5}]$	$12.2^{+4.9}_{-3.4}$	8.9

CERN-EP-2022-288, arXiv:2301.09938

$H \rightarrow$ Meson + γ

- **Summary of searches** using full Run-2 datasets:
  - b/c mesons: *J/ψ, ψ(2S), Υ(1S, 2S, 3S)*
  - Light/strange mesons: *K** and *ω*



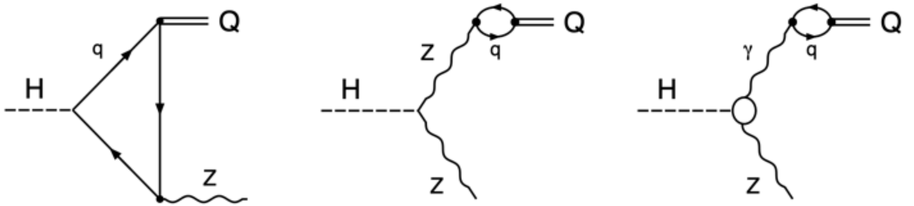
- **No significant excess**, *but many stringent limits!*

- All results are statistically limited!
- Will make excellent use of larger Run-3 and HL-LHC datasets

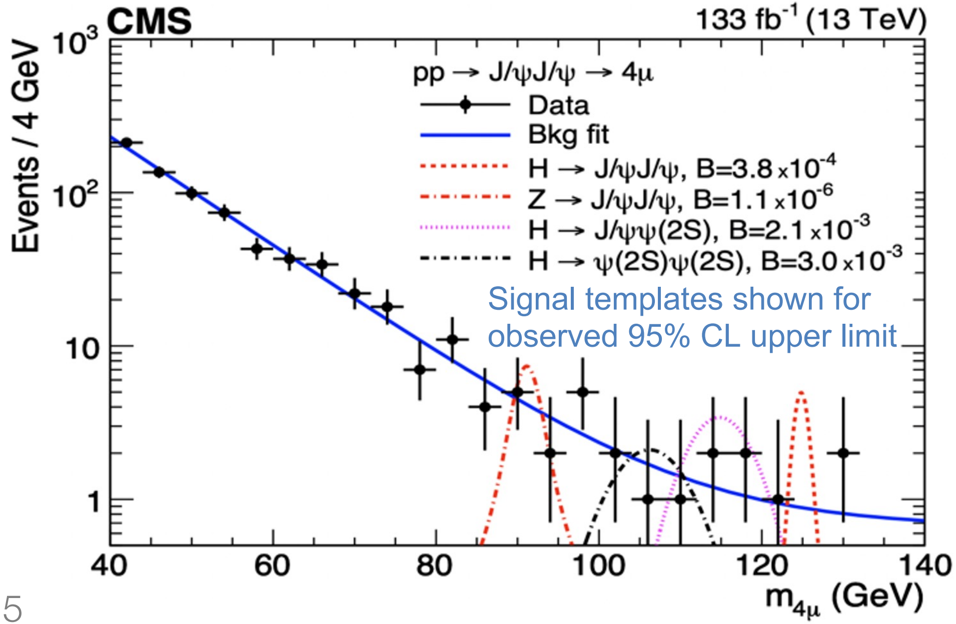
CERN-EP-2022-131

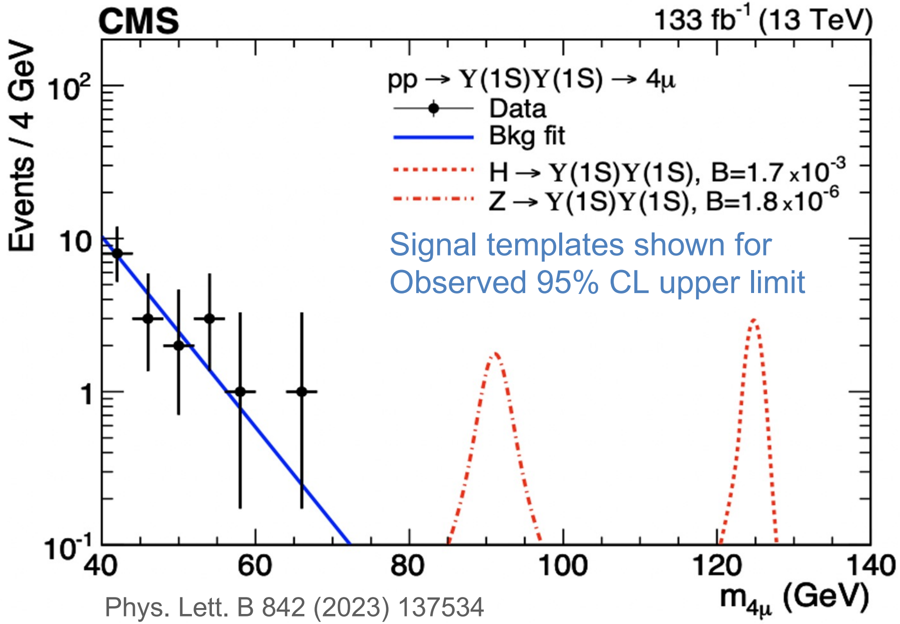
Higgs → Quarkonia

- **Higgs** → *vector* **Quarkonia** can be searched for in *experimentally clean* four-muon final state
- Tiny expected SM branching fractions ~10^{-9} several orders of magnitude *below* sensitivity
- An **observation would indicate BSM**



No evidence for anomalously large BRs

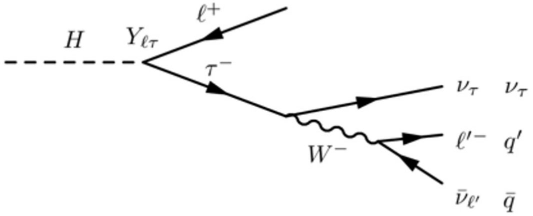




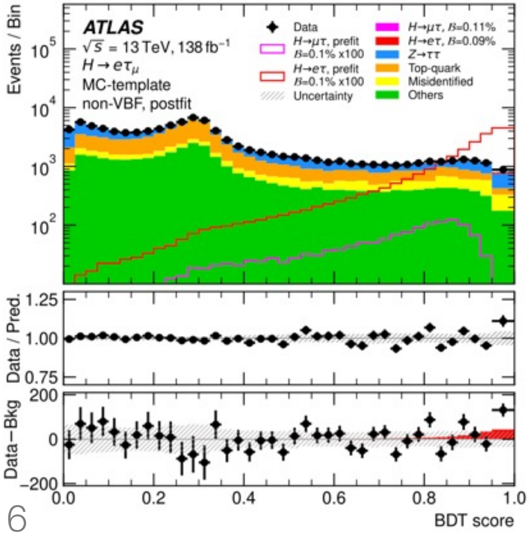
Phys. Lett. B 842 (2023) 137534

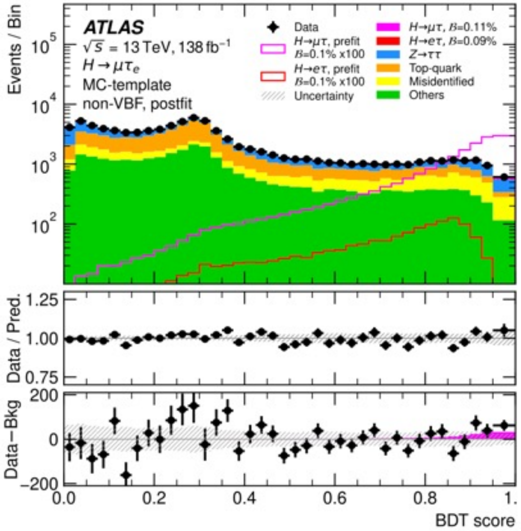
LFV Higgs → $e\tau$, $\mu\tau$

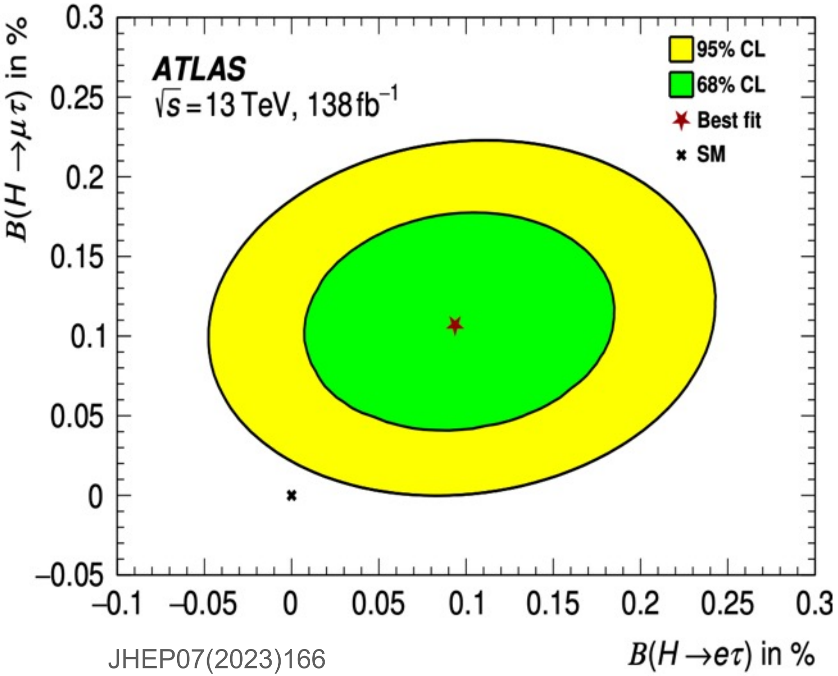
- Search for **Lepton Flavour Violating** (LFV) decay of Higgs boson, with $H \to e\tau$ and $H \to \mu\tau$ decay modes
- No significant excess is observed and limits are obtained:
- The simultaneous fit is **in tension with the SM at the 2.1σ** level



	Obs. (Exp.) 95% Upper Limit
$e\tau$	0.193% (0.114%)
$\mu\tau$	0.183% (0.087%)



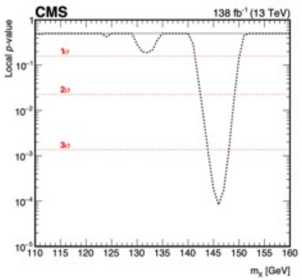


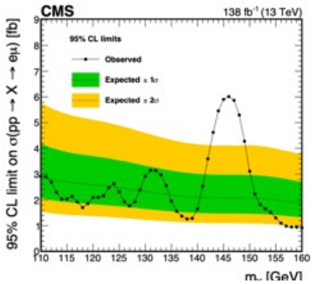


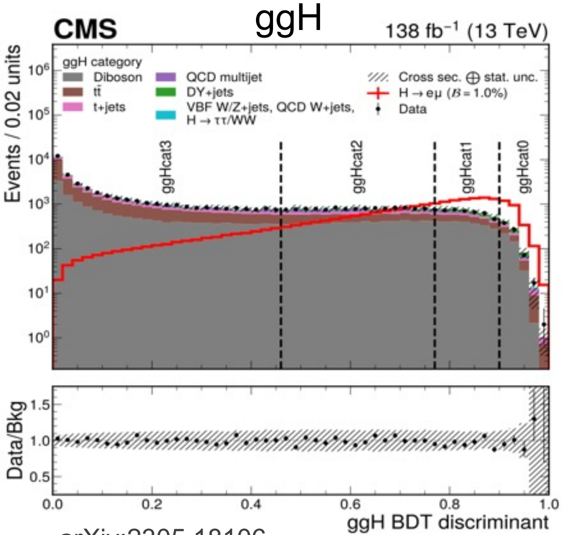
JHEP07(2023)166

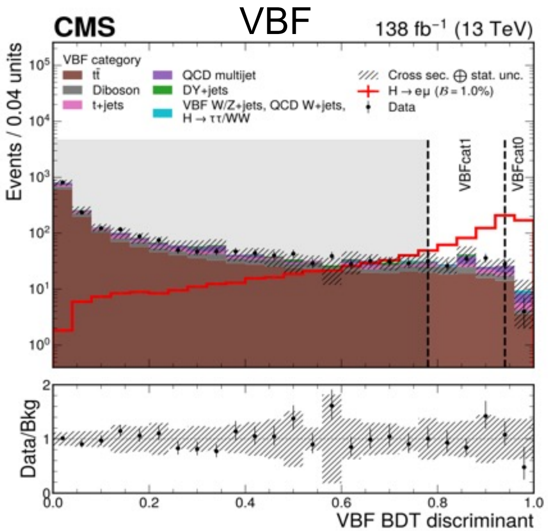
LFV Higgs → eμ

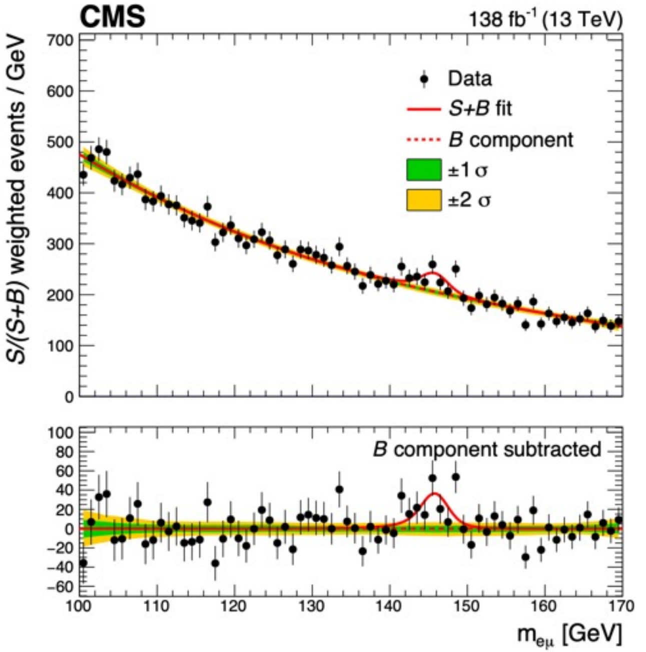
- Search for **LFV Decay $H \to e\mu$**
- Perform fit to $m_{e\mu}$ distribution across production categories (ggH and VBF) *purified by BDT categories*
- *BR(H→eμ)* < 4.4 (4.7) × 10^{-5} at 95%CL observed (exp)
- Scan for BSM Higgs boson: Modest excess in $m_{e\mu}$ *distribution* at 146 GeV: **3.8σ (local)**, **2.8σ (global)** significance.







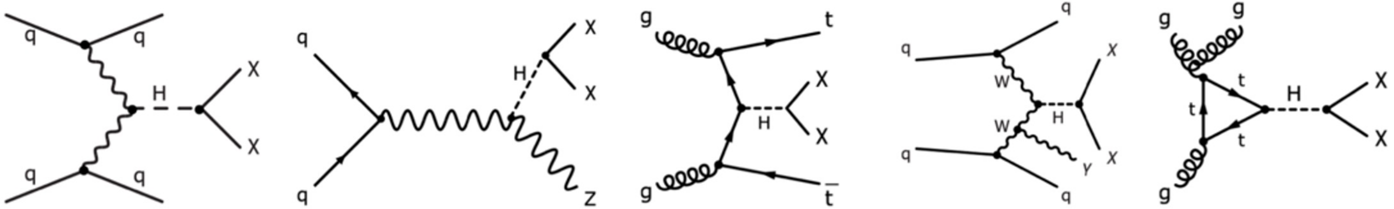




arXiv:2305.18106

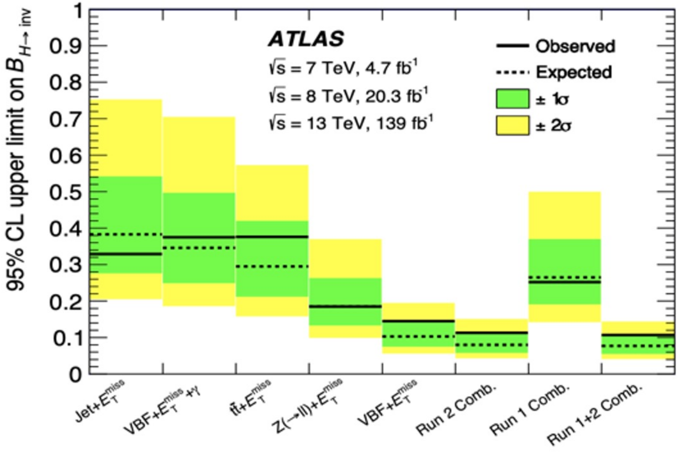
Higgs to Invisible

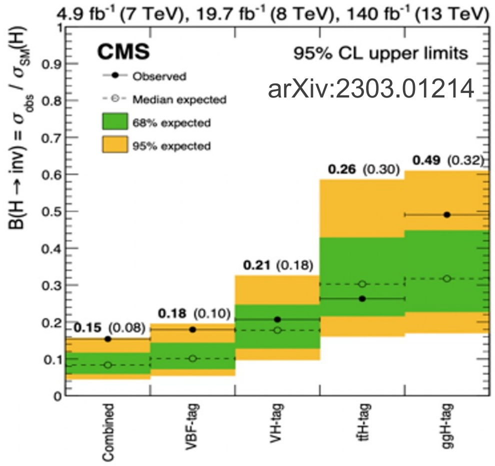
- Higgs-portal models to Dark Sector (e.g. Wilczek, Patt)
- Within the SM, **Higgs** → invisible decay is only H → ZZ* → 4ν (BR ~ 0.1%)
- Searches for **invisible Higgs decays**, leading to **missing p_T + X**



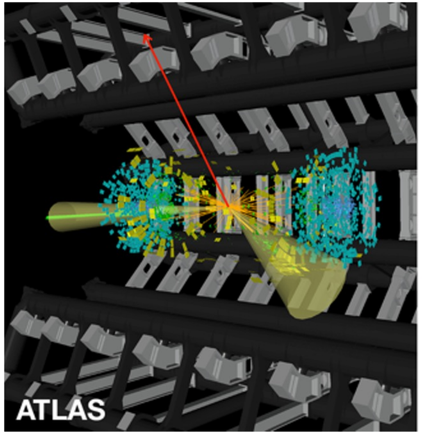
(a) VBF topology (b) $Z + H$ topology (c) $t\bar{t}H$ topology (d) VBF + photon topology (e) H+jet topology

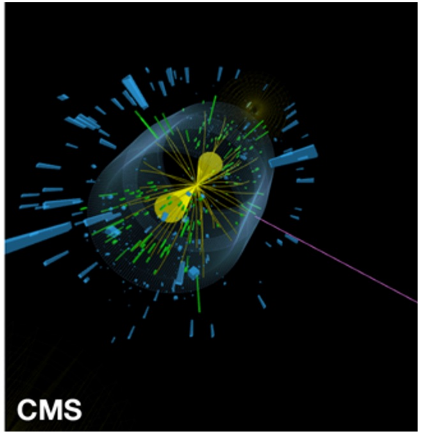
PLB 842 (2023) 137963





VBF + "missing p_T"





Combined ggH, VBF, VH, ttH; **CMS**: Br(H→inv) < 0.15 (0.08); **ATLAS**: Br(H→inv) < 0.107 (0.077) at 95% CL

Higgs to Invisible

- Higgs-portal models to Dark Sector (e.g. Wilczek, Patt)
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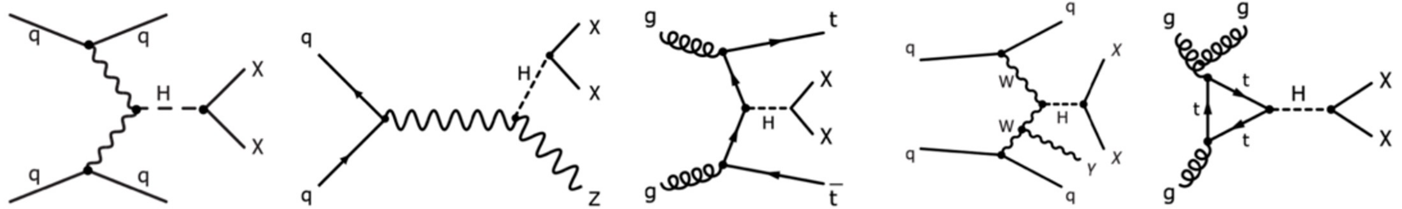
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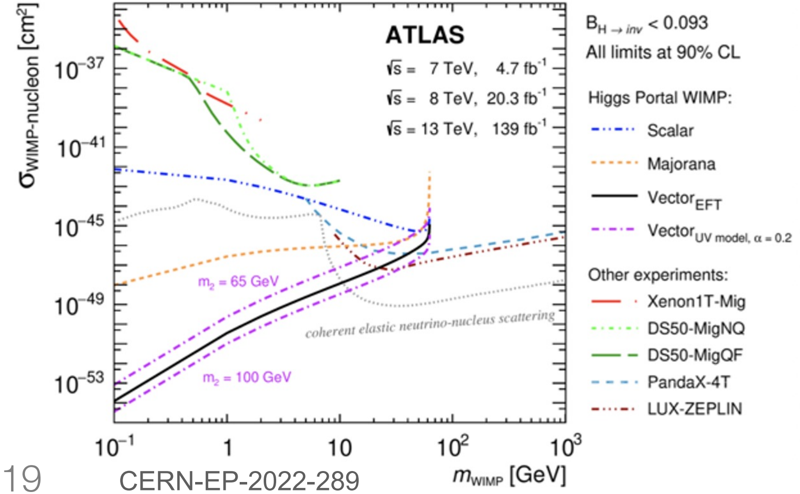
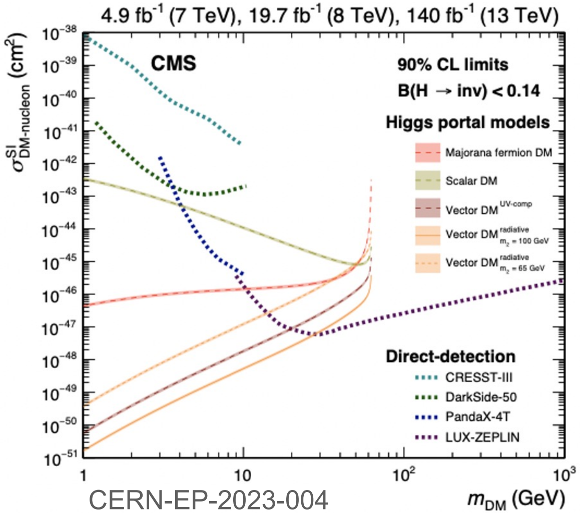
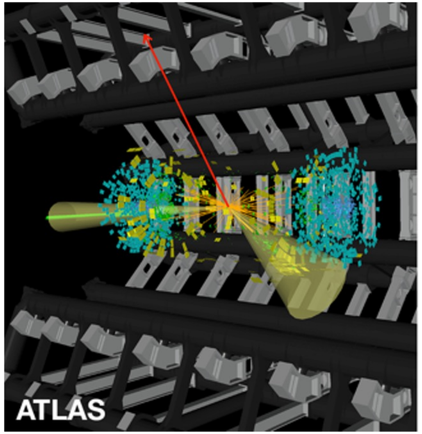
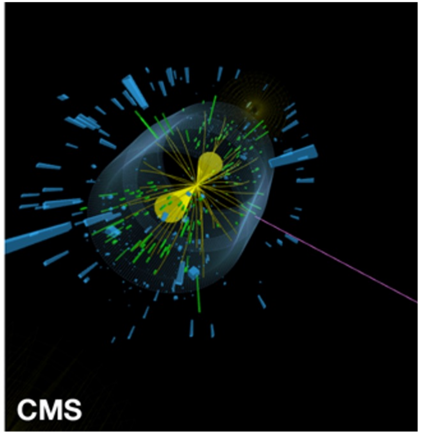


CERN-EP-2022-289



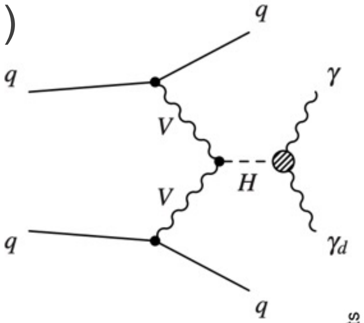
CERN-EP-2023-004

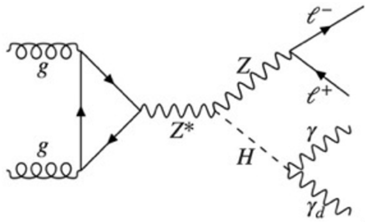


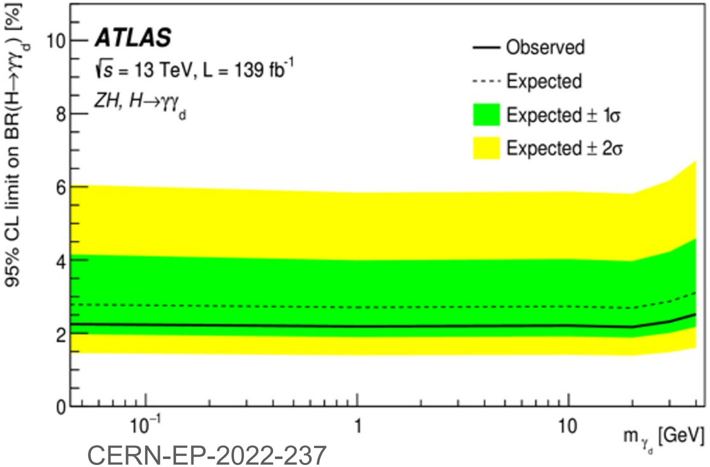


Dark Photon, $H \to \gamma\gamma_d$

- Search for Higgs boson decaying into a (mixed) photon and a **dark photon** (γ_d)
- Search in *ZH* production mode:
  - Leptonic Z →ll decay for clean signature
  - BDT to **enhance purity** in signal region
- Search in *VBF* production mode:
  - Scan Higgs mass m_H instead of $m\gamma_d$
- **No excess of events** above the SM expectation







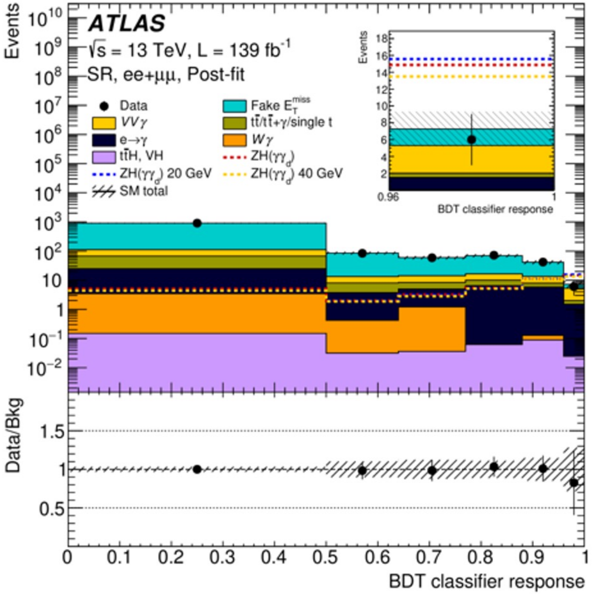
CERN-EP-2022-237

Observed (exp) **upper limit** on BR($H \to \gamma\gamma_d$) at 95% CL:

- Massless γ_d: 2.28% (2.82%)
- Massive γ_d: [2.19% - 2.52%]

For mass range from [1-40] *GeV*

VBF (m_H=125 GeV) upper limit on BR($H \to \gamma\gamma_d$) of 1.8% (1.7%)



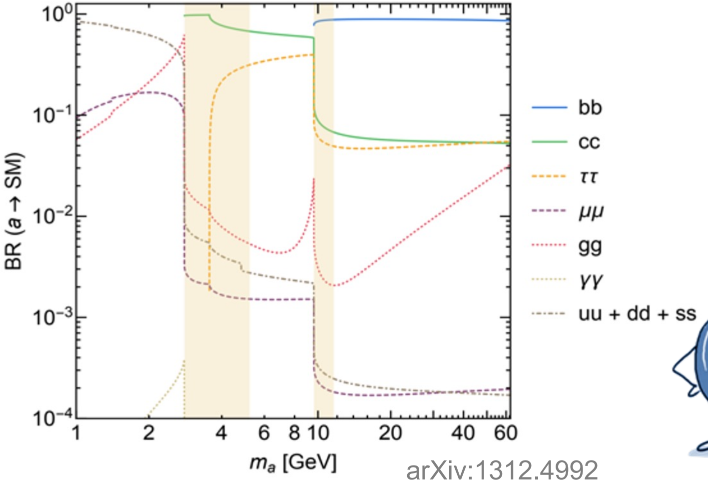
$H \rightarrow$BSM Scalars

SM Higgs boson measurements are not the only part of LHC Higgs physics program

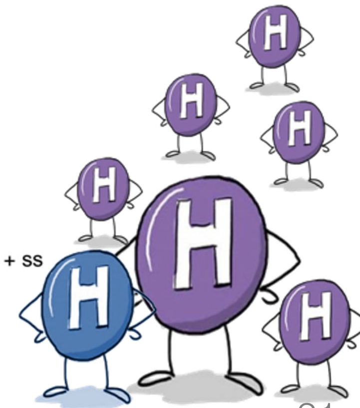
- Many **BSM theories** predict extended Higgs sector with **additional scalars**
- *Allowed branching ratio to exotic decays O(10%)*
- 2HDM is the simplest extension of the SM with: $H^{\pm}$, A(CP-odd), H and h (CP-even)
- Includes axion like particles (solution to strong CP problem Peccei–Quinn)
- Other extensions are considered e.g. MSSM, NMSSM, TRSM, 2HDM+S, g2HDM, …

Example: 2HDM+S: 2 Higgs doublets models extended with one gauge singlet S

- Predicts 7 physical Higgs states:
  - 3 Neutral scalars: **h1 (SM like)** h2, h3
  - 2 Charged Higgs: $H^{\pm}$
  - 2 pseudoscalars Higgs: A, a
- The branching ratios *depend on*
  - 4 Model types (I-IV) of fermion couplings
  - m_a (mass of the pseudoscalar)
  - tan β (ratio of the VEVs of the two doublets)

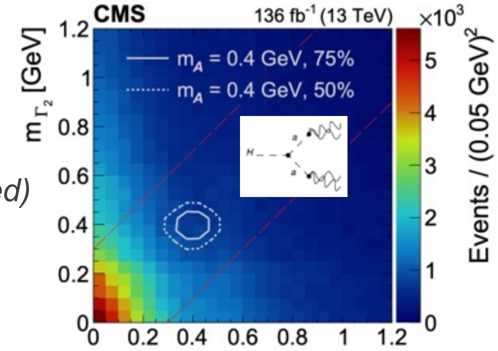


arXiv:1312.4992

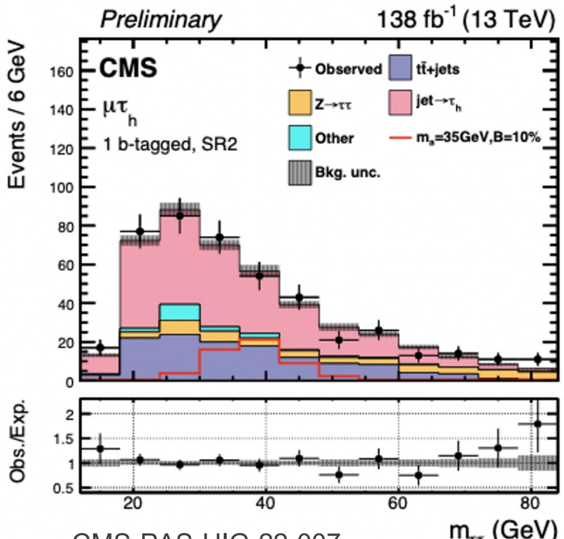


Higgs in 2HDM+S

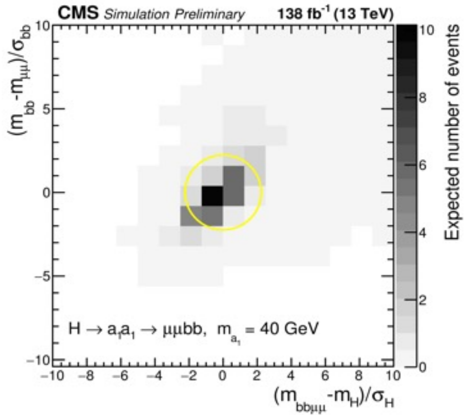
- Light pseudoscalar a is searched for via exotic SM Higgs decay *H → aa in* **2HDM+S model**
- Comprehensive search:
  - H→aa→ *4τ, 4μ*
  - H→aa→ *4γ, 2μ2τ* *(boosted & resolved)*
  - H→aa→ *2τ2b, 2μ2b; (llbb)*

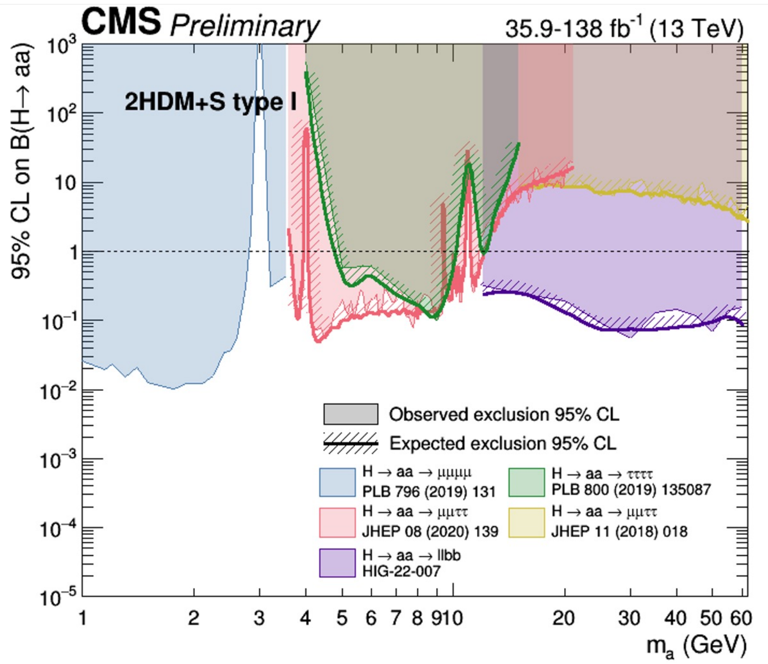


PRL131 (2023)



CMS-PAS-HIG-22-007



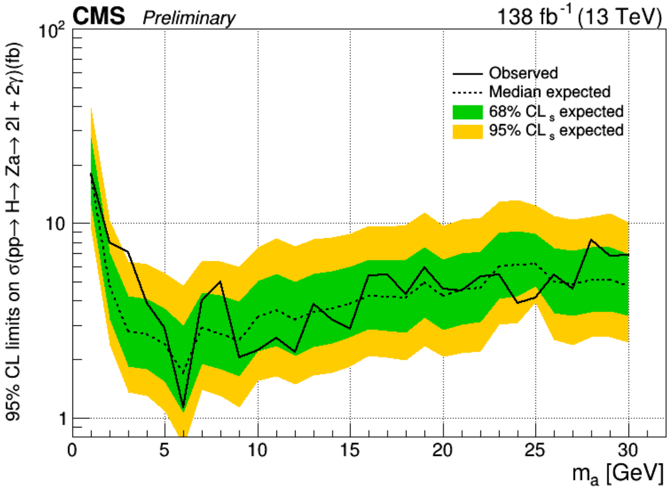


https://twiki.cern.ch/twiki/bin/view/CMSPublic/ Summary2HDMSRun2

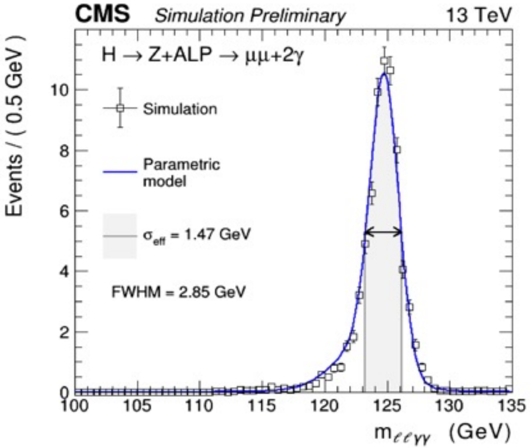
No signal, but many scenarios to be explored and relax assumptions

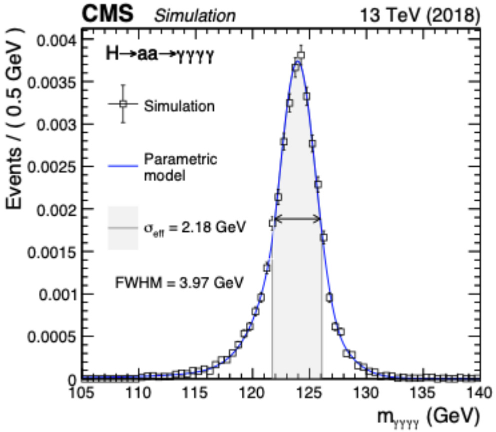
$H \rightarrow Za \rightarrow ll\gamma\gamma$

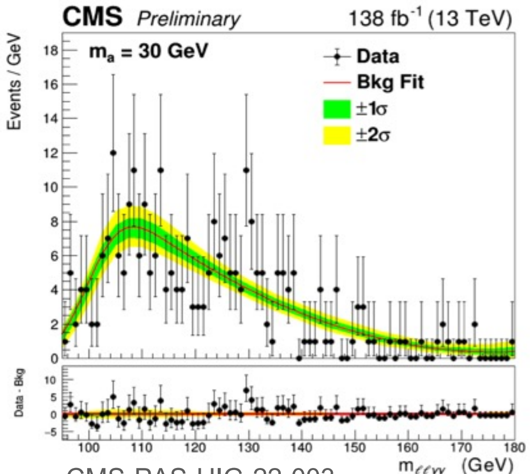
- Dedicated serach for $H \rightarrow Za \rightarrow ll\gamma\gamma$ ***and*** $\gamma\gamma\gamma\gamma$
- Use **high-resolution** 4-body invariant mass $m_{ll\gamma\gamma}$ ***and*** $m_{\gamma\gamma\gamma\gamma}$
- Sensitivity optimized using **BDTs** for *ee* and *μμ* channel



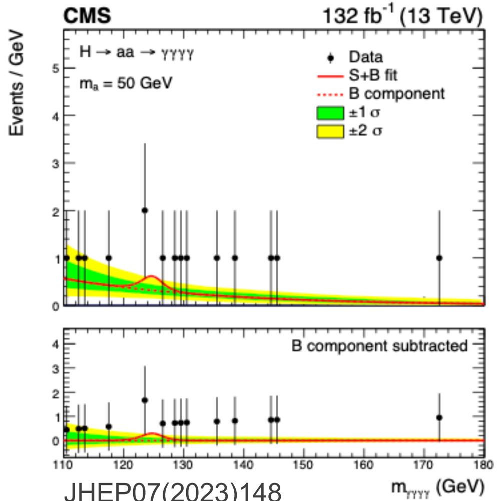
No significant excess observed







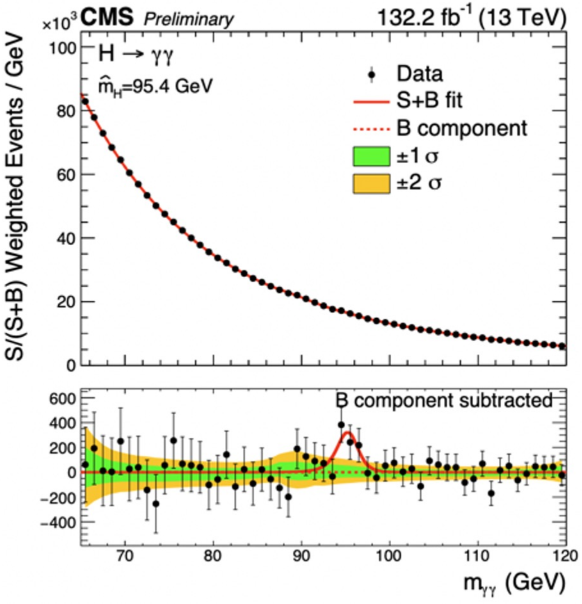
CMS-PAS-HIG-22-003

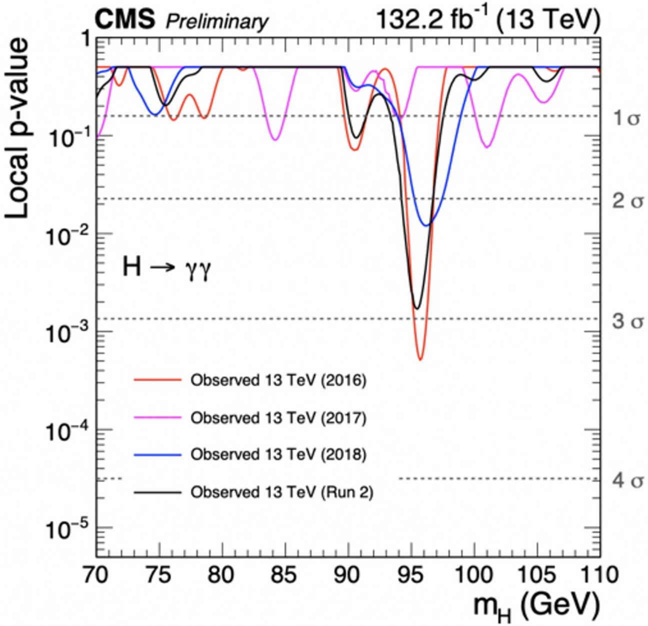


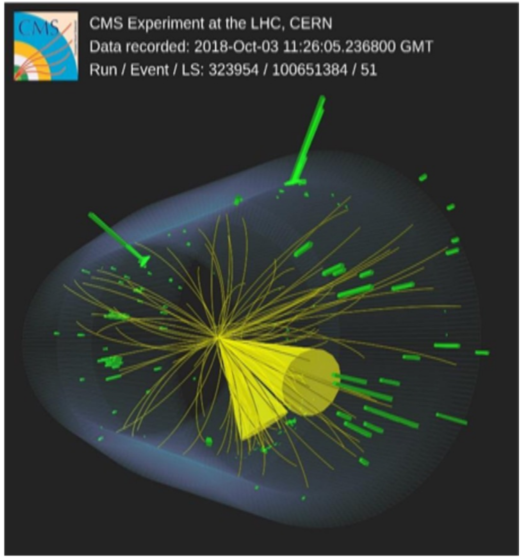
JHEP07(2023)148

Low Mass Higgs Boson?

- CMS performed a diphoton resonance search for a **standard model-like Higgs boson** in the mass range between **70 and 110 GeV** with full LHC Run 2 data.
- Modest excess at **$m_{\gamma\gamma}$ = 95.4 GeV** with **2.9σ local** (**1.3σ global**) significance.
- Large “**look elsewhere effect**” in high-resolution di-photon channel



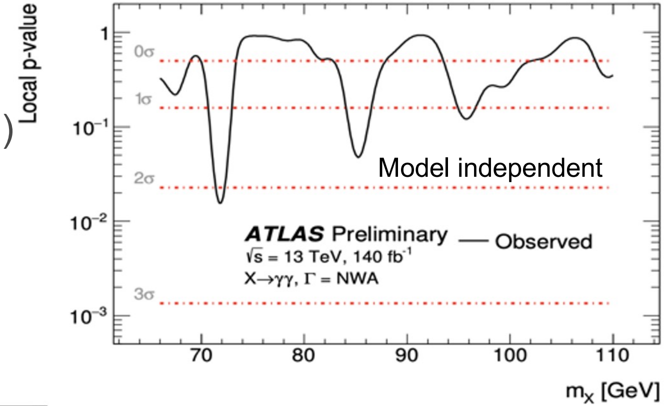


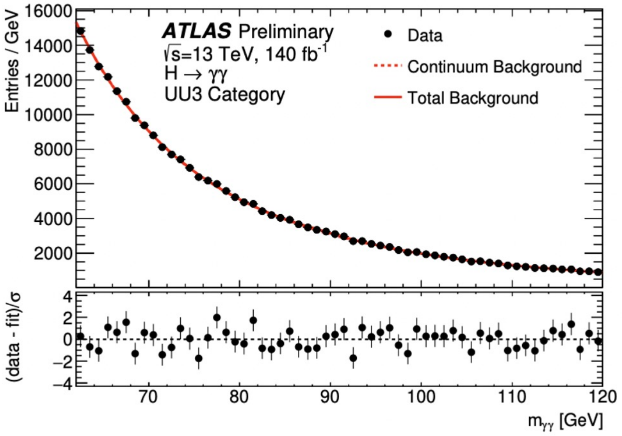


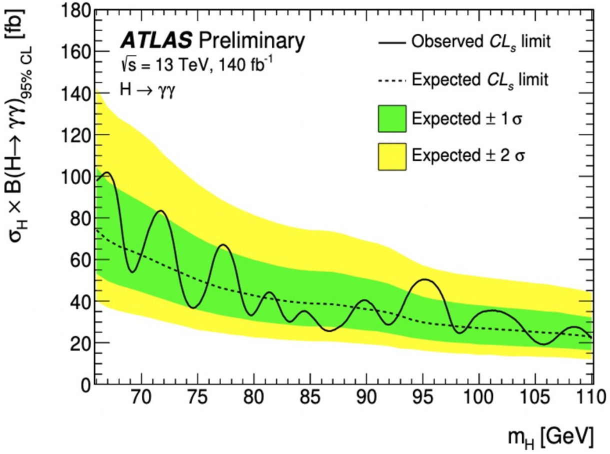
CMS-PAS-HIG-20-002

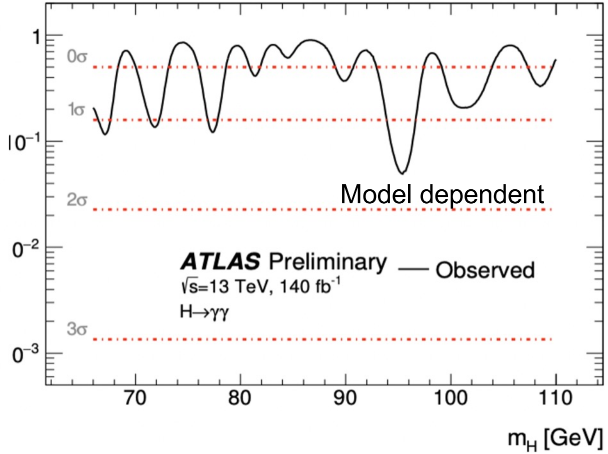
Low Mass Higgs Boson

- ATLAS performed recently a similar analysis in range between **$m_{\gamma\gamma}$ = 66 and 110 GeV**
- **Perform two searches:**
  - **Model independent** search for spin-0 particle (NWA) (three categories based on photon conversion, UU, UC, CC)
  - **Model dependent** search for light SM-like particle (additionally use three BDT categories to purify sample)
- **No significant excess** observed in full Run-2 dataset
- Will update with more data..





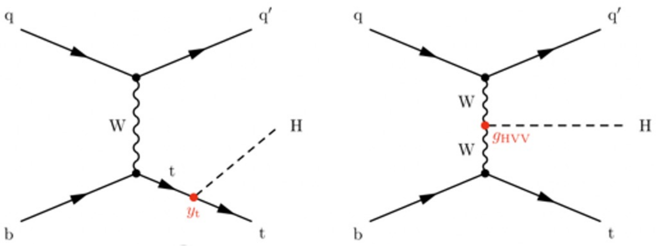


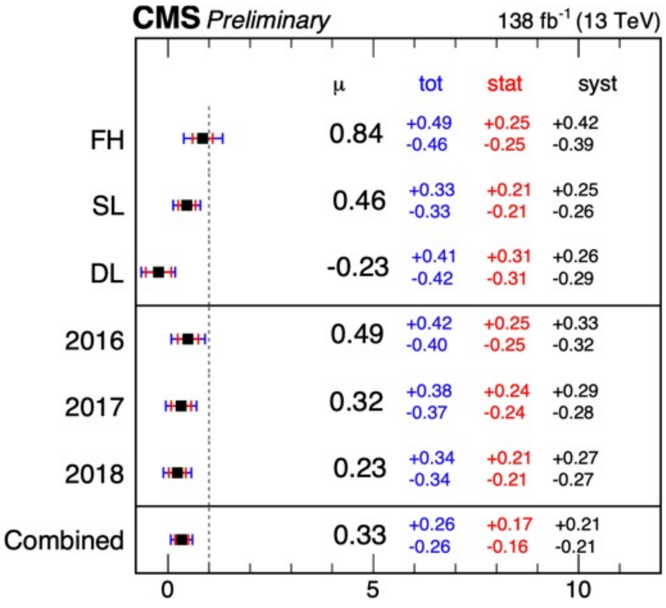


ATLAS-CONF-2023-035

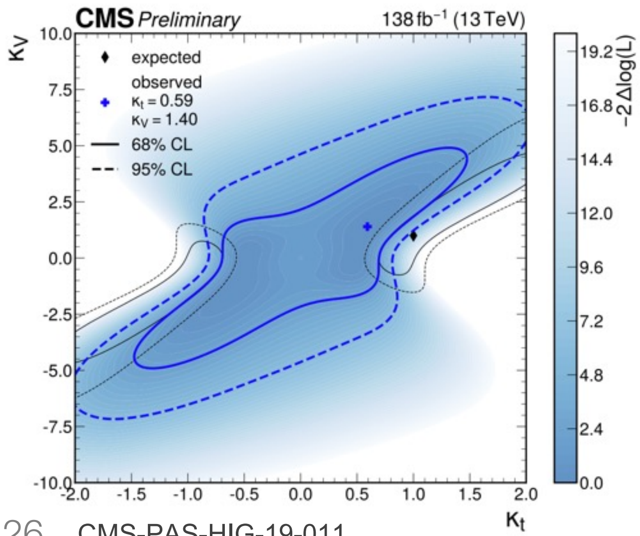
Single Top + Higgs

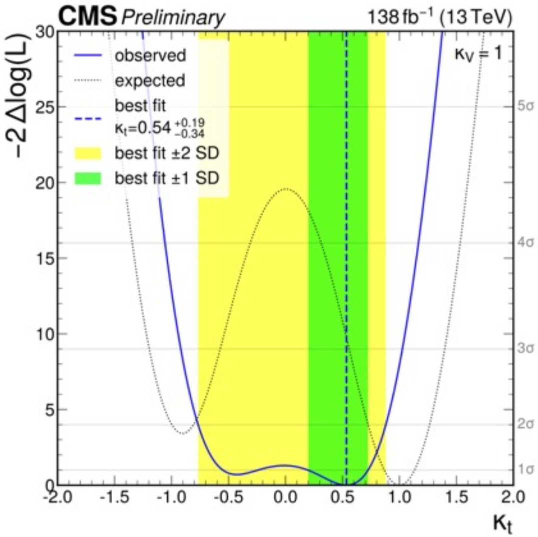
- Single Top + Higgs is a **rare process** due to destructive interference in SM
- Sensitive to absolute value of the top Yukawa coupling, the Higgs boson coupling to vector bosons and their **relative sign**
- New CMS result on search for tH production with H→bb
- Sensitivity optimized using **ANNs**





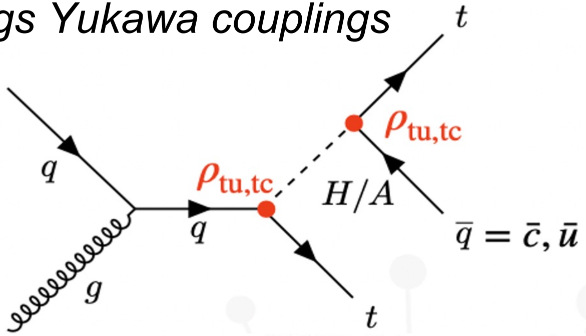
ATLAS: $\mu_{t\bar{t}H} = 0.35^{+0.36}_{-0.34}$

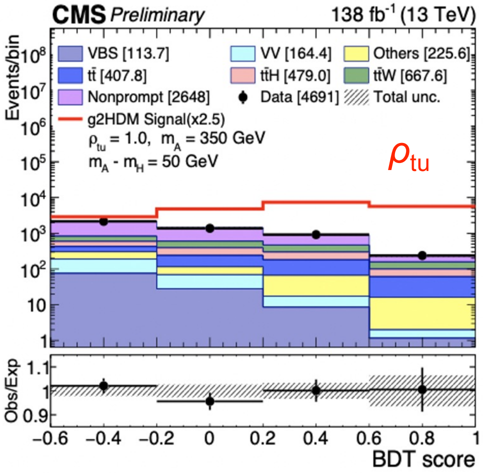


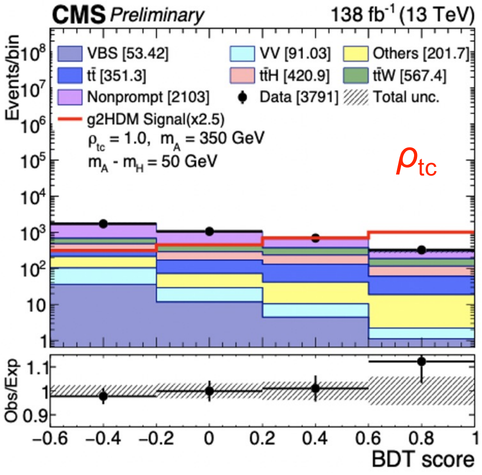


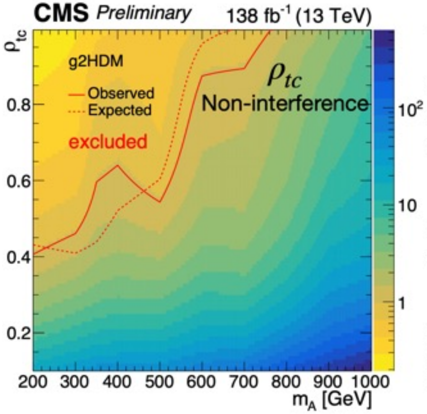
CMS-PAS-HIG-19-011

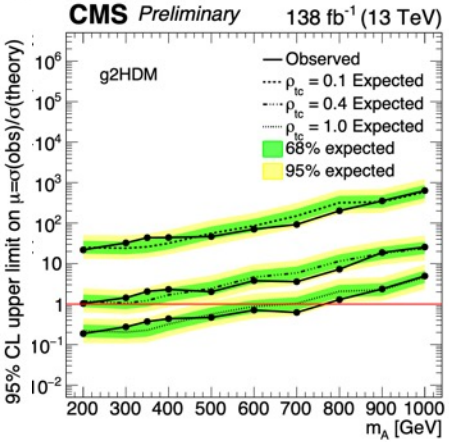
- Search for new couplings ρ_{tu}, ρ_{tc} in Higgs decays in **same-sign tt final states**
- Possible explanations for the *electroweak baryogenesis* and muon *anomalous magnetic moment* in the generalized 2HDM model with *FCNC H/A Higgs Yukawa couplings*
- Analysis optimized for top-pair final state (BDT)
  - Search same sign dilepton final states ($e^{\pm}e^{\pm}$, $\mu^{\pm}\mu^{\pm}$, $e^{\pm}\mu^{\pm}$)
  - No significant excess observed







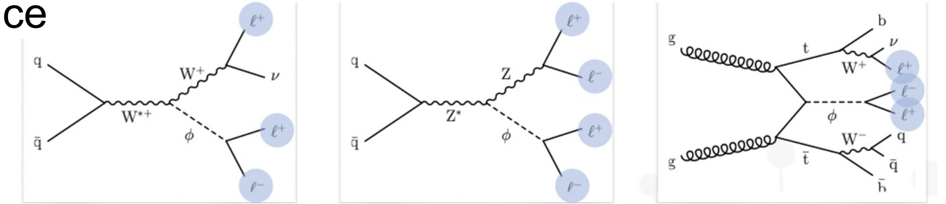


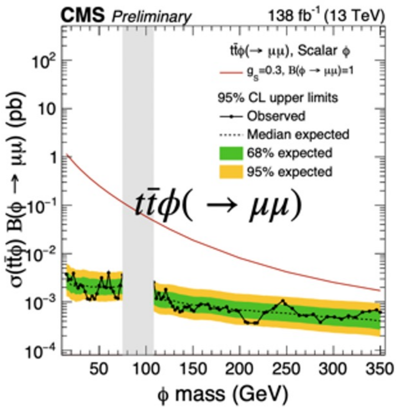


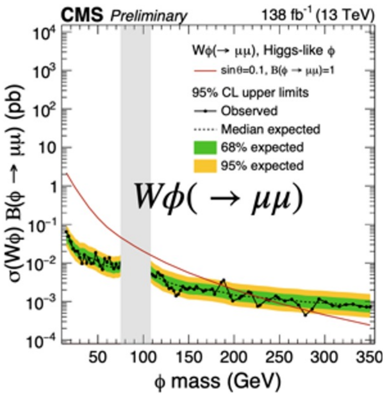
 CMS PAS TOP-22-010

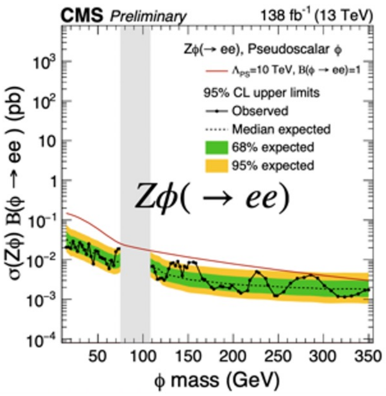
$V\phi$ / $tt\phi \rightarrow \ell\ell$

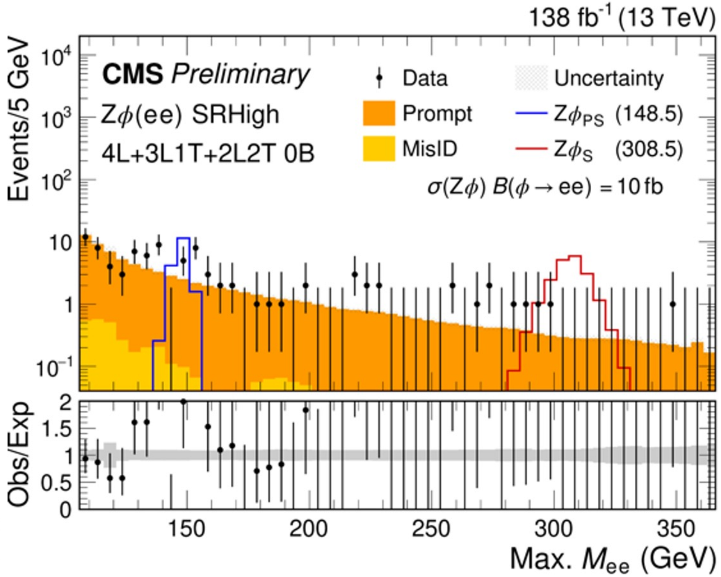
- First search for a **BSM spin-0 scalar ϕ resonance in association** with bosons (*V=W,Z*) or tops (*tt*)
- Target **multilepton** final state with $\phi \rightarrow$*dilepton*
  Considering decays into all lepton flavors
- Largest excess: 2.9σ (local) 1.4σ (global) significance at ~150 GeV in $Z\phi(\rightarrow ee)$









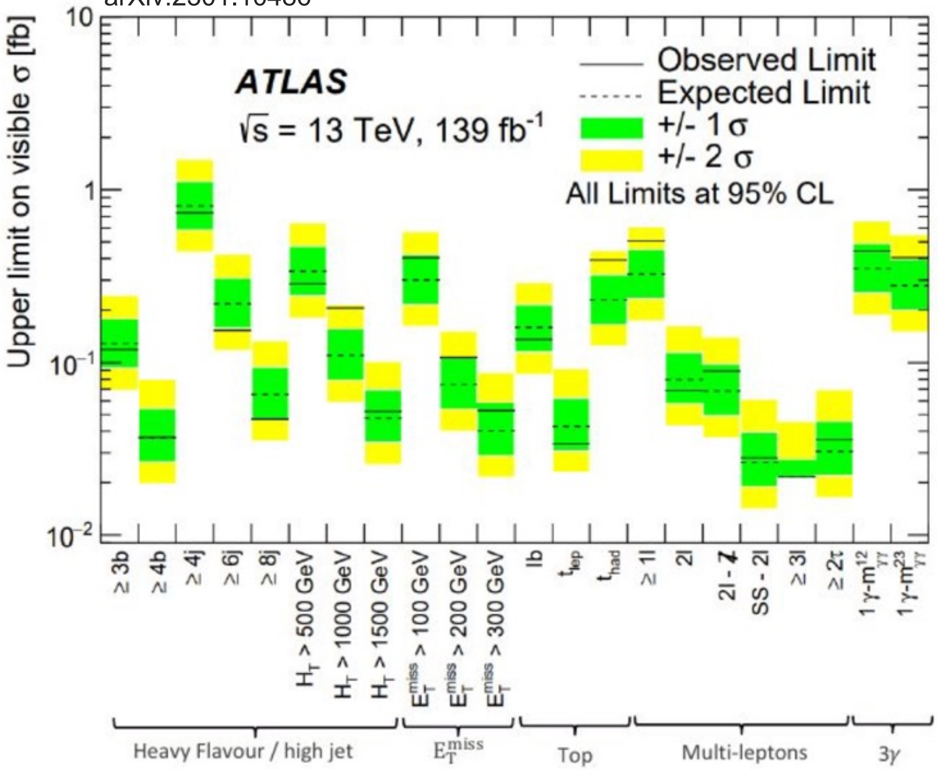


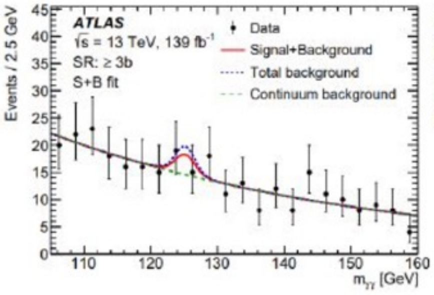
CMS-PAS-EXO-21-018

Higgs + Anything…

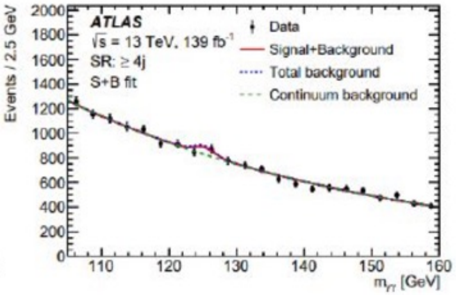
- Explores Higgs produced with additional objects to probe BSM in **model independent** way
  - →I.e. **Signature-based** search for 125 GeV **Higgs** → ***γγ*** produced *<u>with</u> additional objects*

arXiv:2301.10486

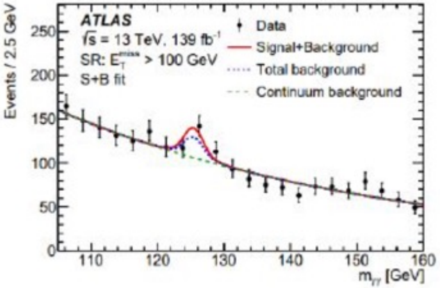




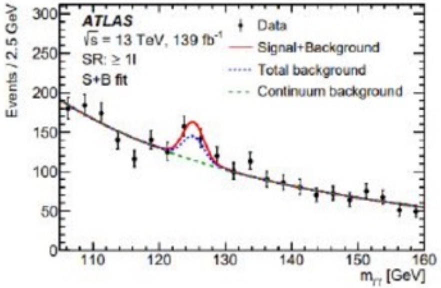
≥3b-jet SR



≥4 multi-jet SR



$E_T^{miss} > 100$ GeV SR



≥1ℓ SR

Effective Field Theory (EFT)

- To maximize *sensitivity to* possible **BSM effects** in Higgs measurements, **ATLAS and CMS** target *well-defined kinematic regions*, split by production and decay mode
  The set of ***σB** results* are used in **EFT interpretations**
- Expand the SM Lagrangian with higher dimensional operators, to parameterize BSM effects

$$\mathscr{L}_{SMEFT} = \mathscr{L}_{SM} + \sum_i \frac{c_i^{d=6}}{\Lambda^2}\mathcal{O}^{d=6} + \sum_i \frac{c_i^{d=8}}{\Lambda^4}\mathcal{O}^{d=8} + \ldots$$

- Deviation from SM quantified by d=6 **Wilson coefficients**

$$\sigma \propto \left| \mathcal{M}_{\rm SM} + \sum_i \frac{c_i^{(6)}}{\Lambda^2}\mathcal{M}_i^{(6)} + \sum_i \frac{c_i^{(8)}}{\Lambda^4}\mathcal{M}_i^{(8)} \right|^2$$

$$= |\mathcal{M}_{\rm SM}|^2 + \sum_i 2Re\left(\mathcal{M}_{\rm SM}^*\mathcal{M}_i^{(6)}\right)\frac{c_i^{(6)}}{\Lambda^2} + \sum_{ij} 2Re\left(\mathcal{M}_i^{(6)*}\mathcal{M}_j^{(6)}\right)\frac{c_i^{(6)}c_j^{(6)}}{\Lambda^4}$$

Linear term (interference with SM) | Quadratic term (purely BSM effect)

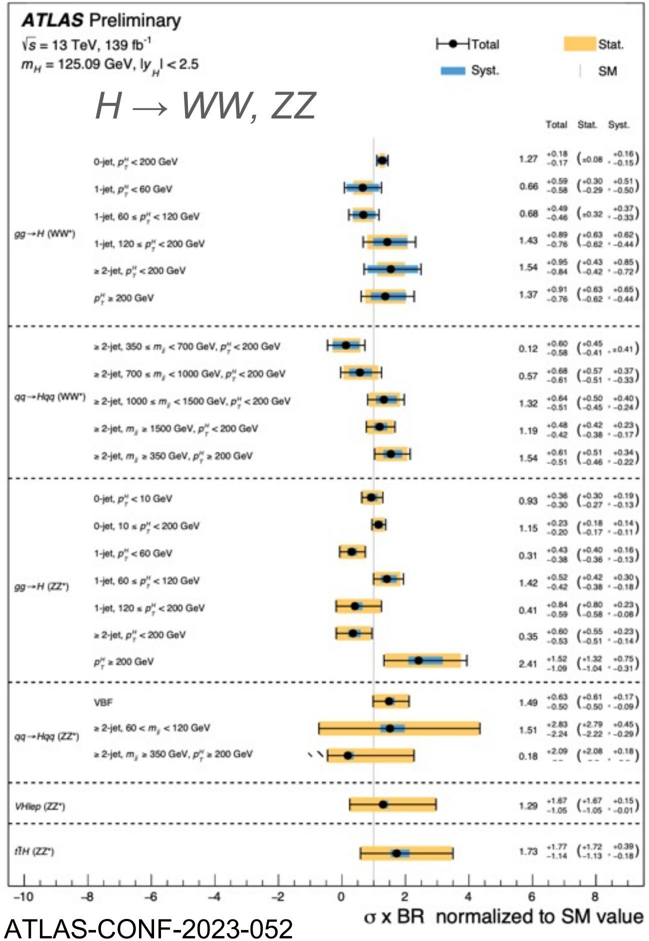
$$+O\left(\frac{1}{\Lambda^6}\right)$$

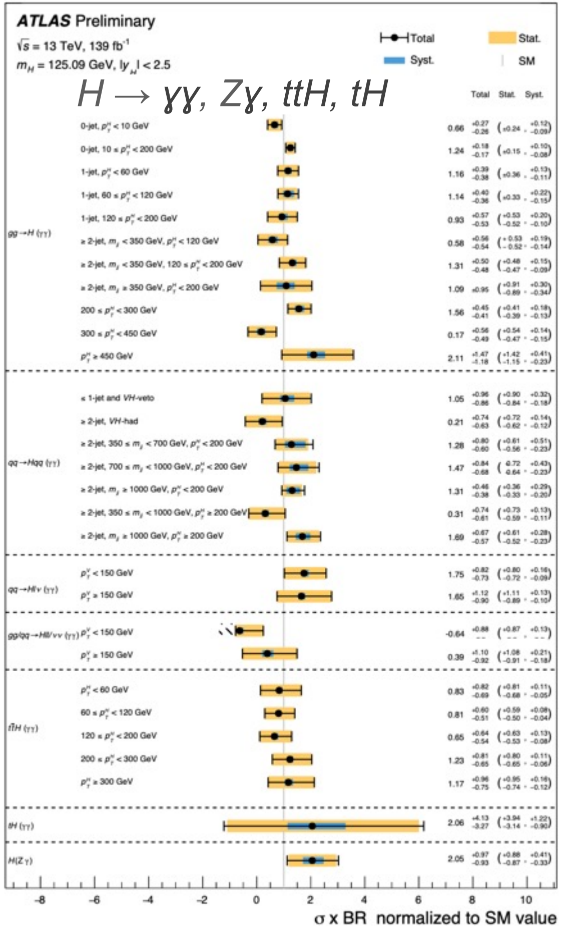
Neglect linear d=8 term, and model-dependent truncation

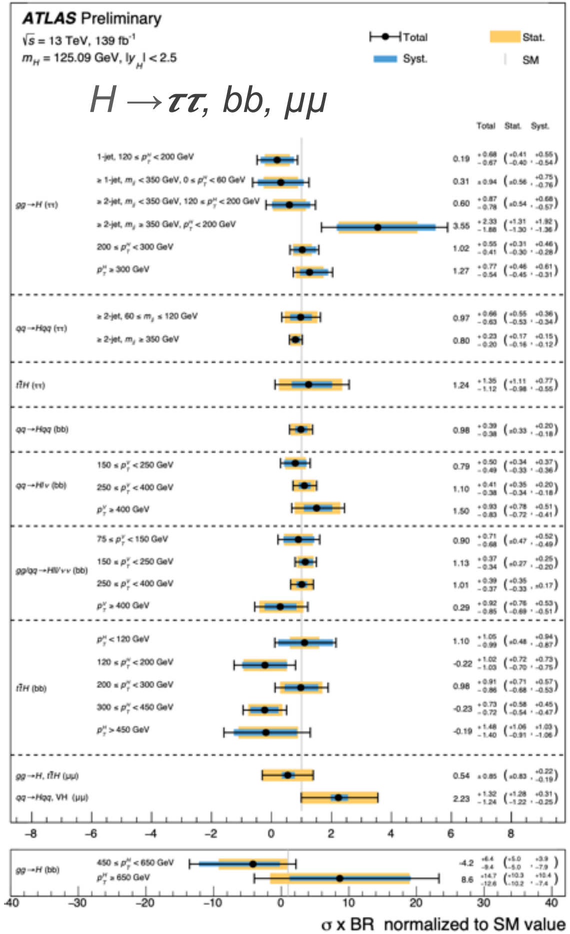
Wilson coefficient	Operator
c_H	$(H^\dagger H)^3$
$c_{H\Box}$	$(H^\dagger H)\Box(H^\dagger H)$
c_G	$f^{abc}G_\mu^{a\nu}G_\nu^{b\rho}G_\rho^{c\mu}$
c_W	$\epsilon^{IJK}W_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu}$
c_{HDD}	$(H^\dagger D^\mu H)^*(H^\dagger D_\mu H)$
c_{HG}	$H^\dagger H\, G_{\mu\nu}^A G^{A\mu\nu}$
c_{HB}	$H^\dagger H\, B_{\mu\nu}B^{\mu\nu}$
c_{HW}	$H^\dagger H\, W_{\mu\nu}^I W^{I\mu\nu}$
c_{HWB}	$H^\dagger\tau^I H\, W_{\mu\nu}^I B^{\mu\nu}$
$c_{Hl,11}^{(1)}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{l}_1\gamma^\mu l_1)$
$c_{Hl,22}^{(1)}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{l}_2\gamma^\mu l_2)$
$c_{Hl,33}^{(1)}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{l}_3\gamma^\mu l_3)$
$c_{Hl,11}^{(3)}$	$(H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar{l}_1\tau^I\gamma^\mu l_1)$
$c_{Hl,22}^{(3)}$	$(H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar{l}_2\tau^I\gamma^\mu l_2)$
$c_{Hl,33}^{(3)}$	$(H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar{l}_3\tau^I\gamma^\mu l_3)$
$c_{He,11}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{e}_1\gamma^\mu e_1)$
$c_{He,22}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{e}_2\gamma^\mu e_2)$
$c_{He,33}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{e}_3\gamma^\mu e_3)$
$c_{Hq}^{(1)}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{q}\gamma^\mu q)$
$c_{Hq}^{(3)}$	$(H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar{q}\tau^I\gamma^\mu q)$
c_{Hu}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{u}_p\gamma^\mu u_r)$
c_{Hd}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{d}_p\gamma^\mu d_r)$
$c_{HQ}^{(1)}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{Q}\gamma^\mu Q)$
$c_{HQ}^{(3)}$	$(H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar{Q}\tau^I\gamma^\mu Q)$
c_{Ht}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{t}\gamma^\mu t)$
c_{Hb}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{b}\gamma^\mu b)$

Wilson coefficient	Operator
$c_{Qq}^{(1,1)}$	$(\bar{Q}\gamma_\mu Q)(\bar{q}\gamma^\mu q)$
$c_{Qq}^{(1,8)}$	$(\bar{Q}T^a\gamma_\mu Q)(\bar{q}T^a\gamma^\mu q)$
$c_{Qq}^{(3,1)}$	$(\bar{Q}\sigma^i\gamma_\mu Q)(\bar{q}\sigma^i\gamma^\mu q)$
$c_{Qq}^{(3,8)}$	$(\bar{Q}\sigma^i T^a\gamma_\mu Q)(\bar{q}\sigma^i T^a\gamma^\mu q)$
$c_{qq}^{(3,1)}$	$(\bar{q}\sigma^i\gamma_\mu q)(\bar{q}\sigma^i\gamma^\mu q)$
$c_{tu}^{(1)}$	$(\bar{t}\gamma_\mu t)(\bar{u}\gamma^\mu u)$
$c_{tu}^{(8)}$	$(\bar{t}T^a\gamma_\mu t)(\bar{u}T^a\gamma^\mu u)$
$c_{td}^{(1)}$	$(\bar{t}\gamma_\mu t)(\bar{d}\gamma^\mu d)$
$c_{td}^{(8)}$	$(\bar{t}T^a\gamma_\mu t)(\bar{d}T^a\gamma^\mu d)$
$c_{Qu}^{(1)}$	$(\bar{Q}\gamma_\mu Q)(\bar{u}\gamma^\mu u)$
$c_{Qu}^{(8)}$	$(\bar{Q}T^a\gamma_\mu Q)(\bar{u}T^a\gamma^\mu u)$
$c_{Qd}^{(1)}$	$(\bar{Q}\gamma_\mu Q)(\bar{d}\gamma^\mu d)$
$c_{Qd}^{(8)}$	$(\bar{Q}T^a\gamma_\mu Q)(\bar{d}T^a\gamma^\mu d)$
$c_{tq}^{(1)}$	$(\bar{q}\gamma_\mu q)(\bar{t}\gamma^\mu t)$
$c_{tq}^{(8)}$	$(\bar{q}T^a\gamma_\mu q)(\bar{t}T^a\gamma^\mu t)$
$c_{eH,22}$	$(H^\dagger H)(\bar{l}_2 e_2 H)$
$c_{eH,33}$	$(H^\dagger H)(\bar{l}_3 e_3 H)$
c_{uH}	$(H^\dagger H)(\bar{q}Y_u^\dagger u\widetilde{H})$
c_{tH}	$(H^\dagger H)(\bar{Q}\widetilde{H}t)$
c_{bH}	$(H^\dagger H)(\bar{Q}Hb)$
c_{tG}	$(\bar{Q}\sigma^{\mu\nu}T^A t)\widetilde{H}\,G_{\mu\nu}^A$
c_{tW}	$(\bar{Q}\sigma^{\mu\nu}t)\tau^I\widetilde{H}\,W_{\mu\nu}^I$
c_{tB}	$(\bar{Q}\sigma^{\mu\nu}t)\widetilde{H}\,B_{\mu\nu}$
$c_{ll,1221}$	$(\bar{l}_1\gamma_\mu l_2)(\bar{l}_2\gamma^\mu l_1)$

Effective Field Theory







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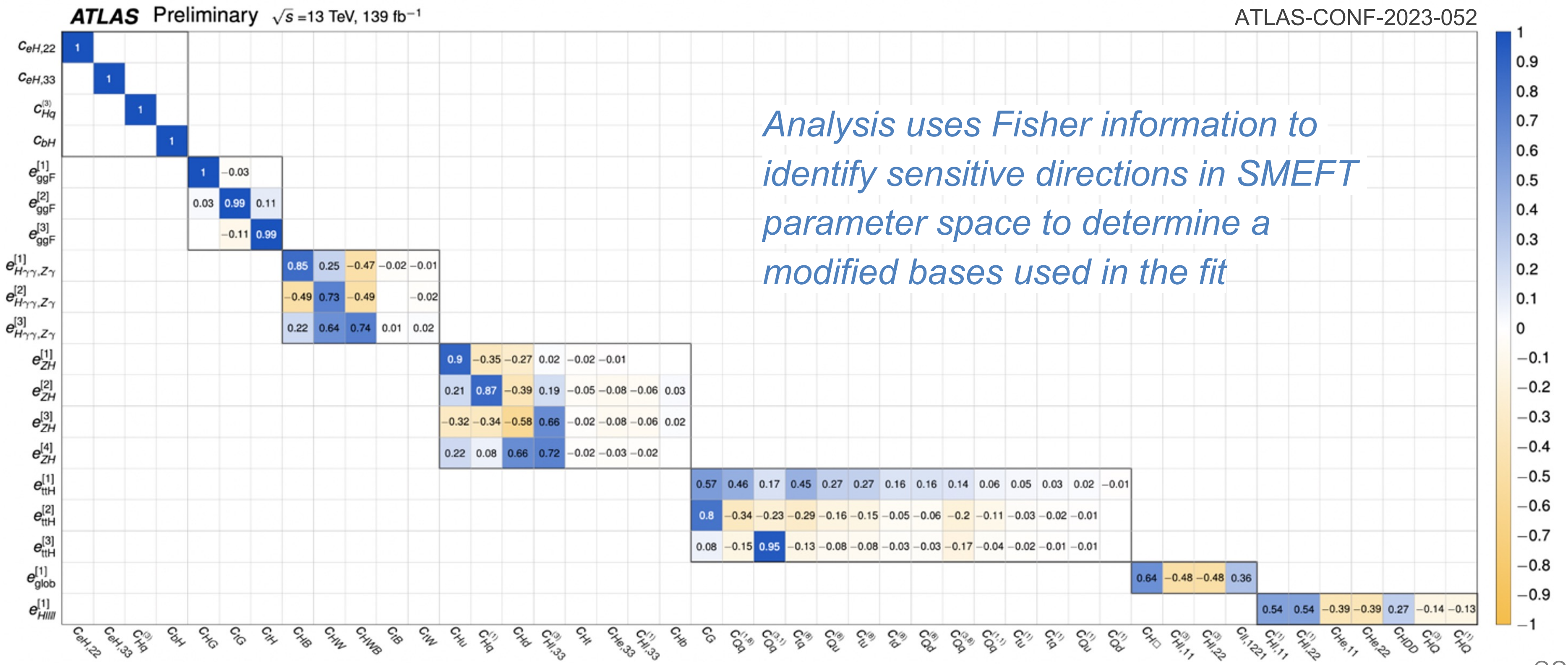
Effective Field Theory

Data is currently insufficient to constrain all Wilson Coefficients simultaneously!

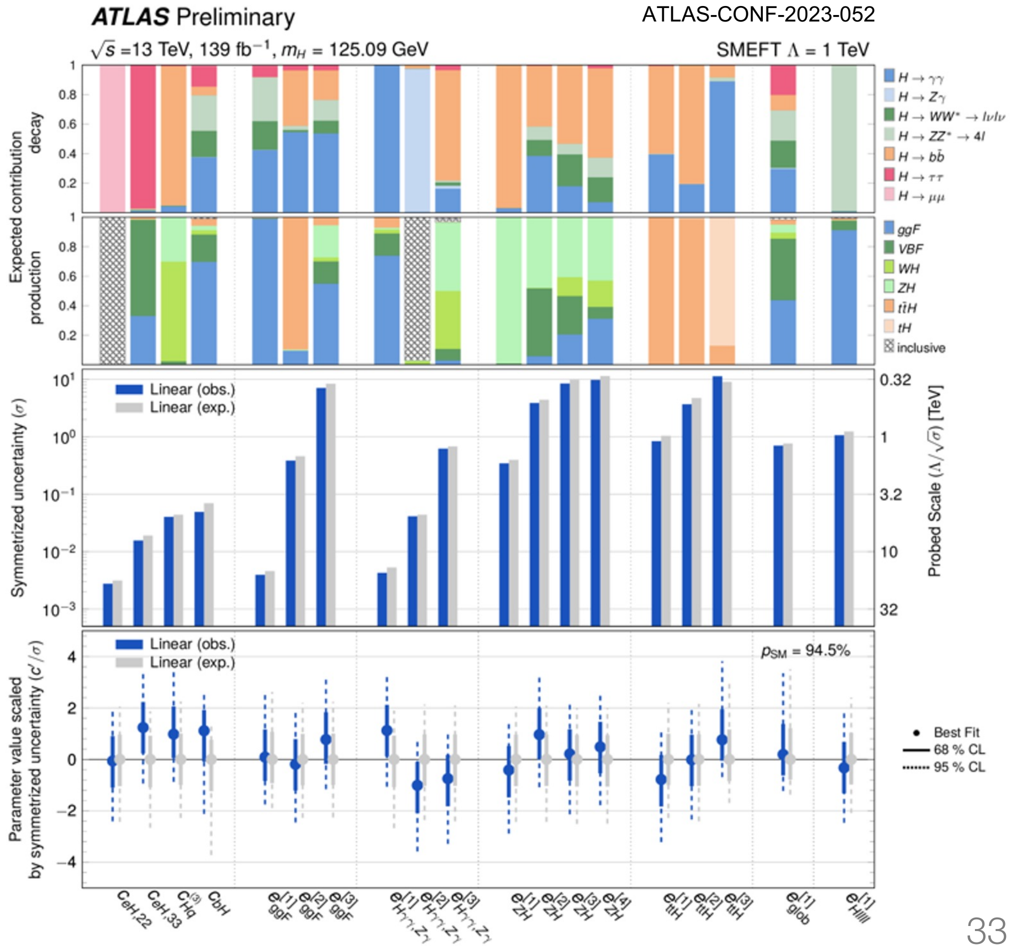
→ *Motivate a modified basis reducing the number of free parameters in the fit (39→19 shown here)*



Analysis uses Fisher information to identify sensitive directions in SMEFT parameter space to determine a modified bases used in the fit

Effective Field Theory

The production and decay channels contributing to the sensitivity →



The fit is performed with 19 free parameters profiled simultaneously! →

No significant deviation from SM

Summary and Outlook

- Rare Higgs boson processes offer fruitful ways to test the SM and search for BSM physics in a complementary way to the more *established* Higgs processes.
- Many results available with Run-2 dataset of ~140 fb^{-1} at 13 TeV (not all could be shown)
  - **ATLAS**: https://twiki.cern.ch/twiki/bin/view/AtlasPublic/HiggsPublicResults
  - **CMS**: https://cms.cern/physics/cms-higgs-results
- In many cases, improved sensitivity leads to tighter constraints beyond simple luminosity scaling, thanks to advanced analysis techniques
- Possible BSM physics is being constrained in Effective Field Theory Interpretations using Higgs boson data from ATLAS and CMS
- Run 3 physics program has just started!
- Much larger dataset will be available soon and beyond (HL-LHC)
- Rare Higgs processes promise to become even more interesting as the luminosity increases and observation comes within reach.
- New Physics could appear in the coming years…

CERN 10 years HIGGS boson discovery

Backup

Effective Field Theory

Demonstrate applicability of constraints using 2HDM benchmark