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Interpretations of the measurements of Higgs boson production and decay rates and differential cross-sections based on the Nature paper with ATLAS detector

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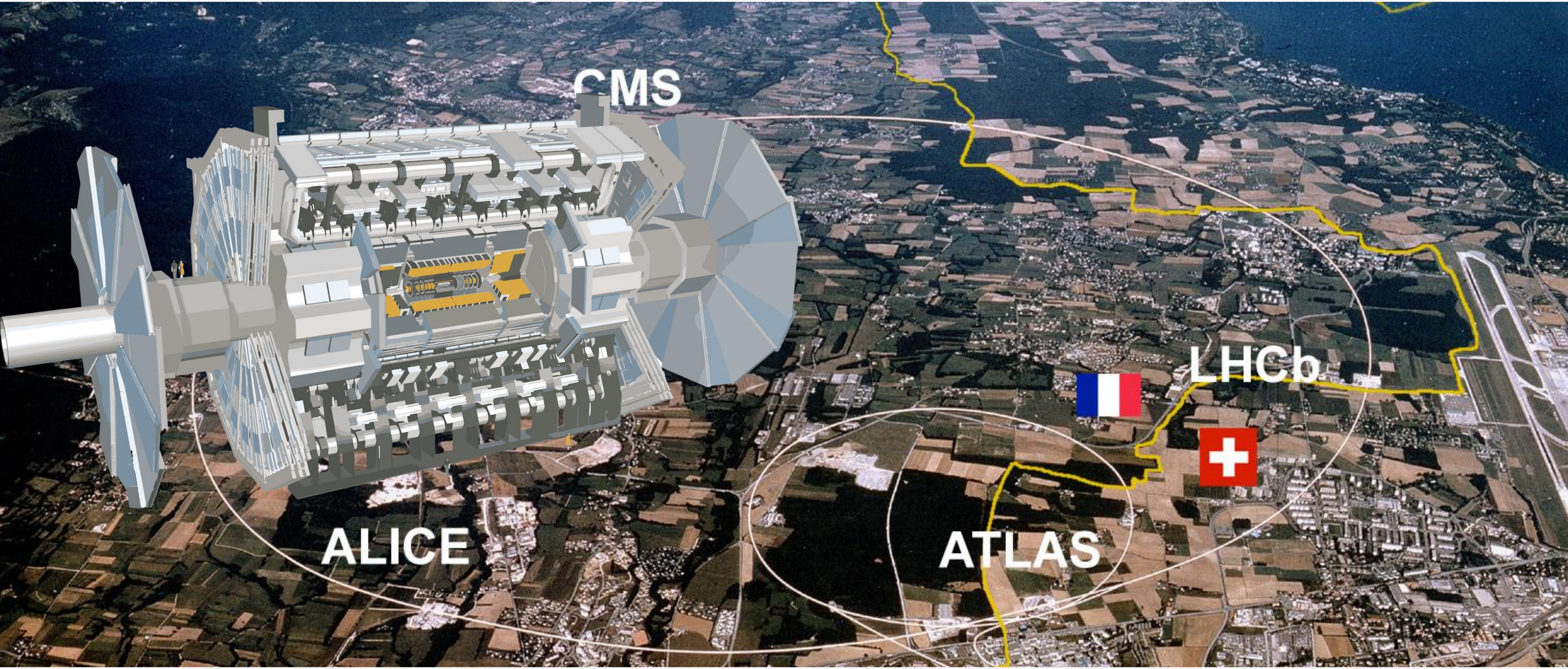
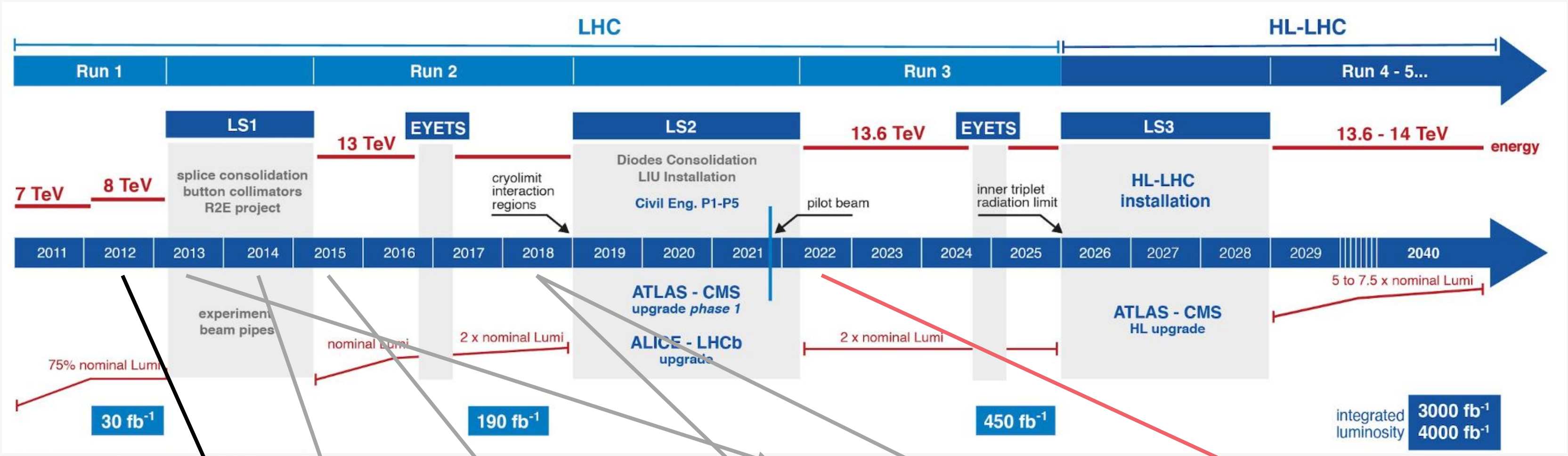
ATLAS EXPERIMENT

饮 水 思 源 · 爱 国 荣 校

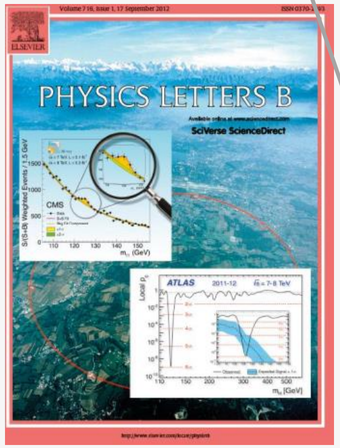
ATLAS Experiment



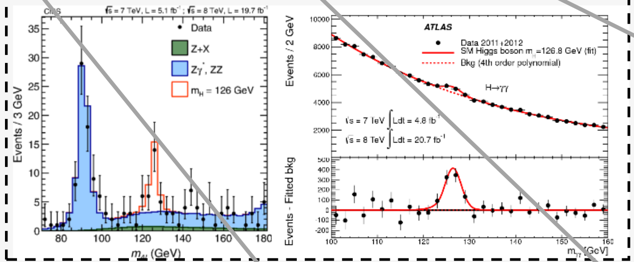
Higgs at ATLAS



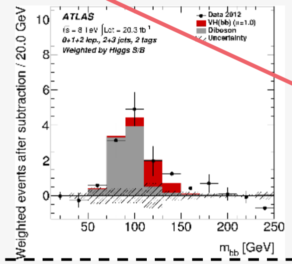
SM-like Higgs discovery
ggF→γγ+ZZ+WW



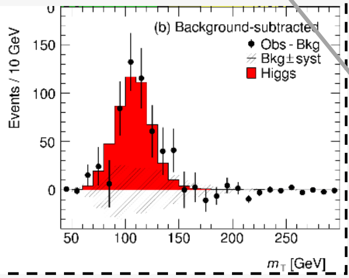
H→γγ, H→ZZ→4l observation



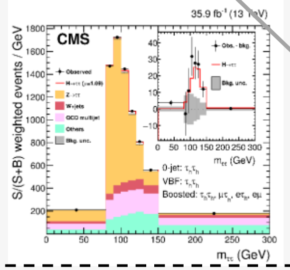
VH, H→bb observation



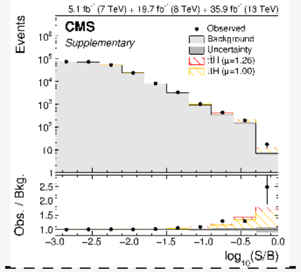
H→WW observation



VBF, H→ττ observation



ttH observation



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A detailed map of Higgs boson interactions by the ATLAS experiment ten years after the discovery

The ATLAS Collaboration

Nature 607, 52–59 (2022) | Cite this article

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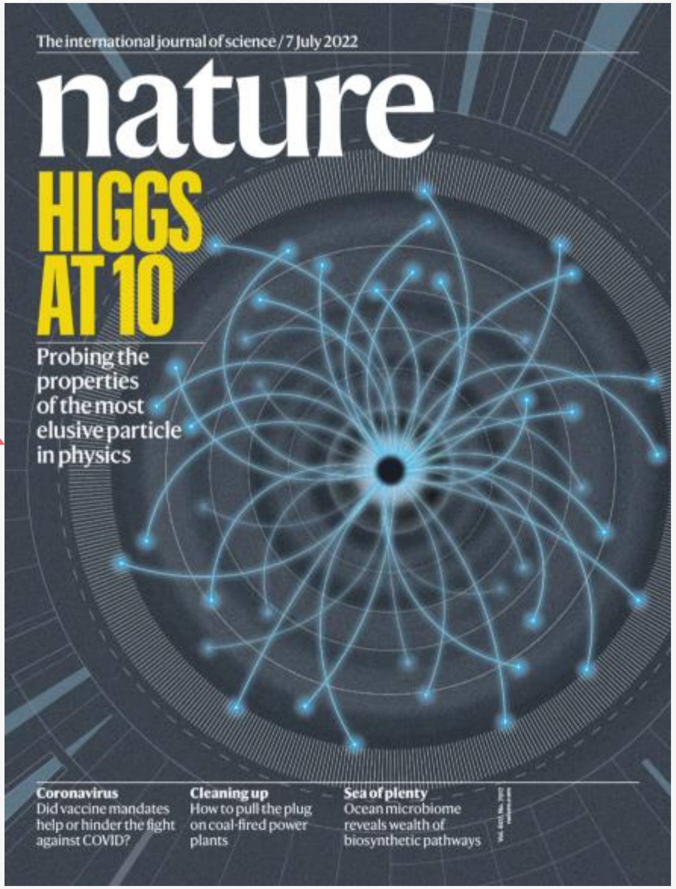
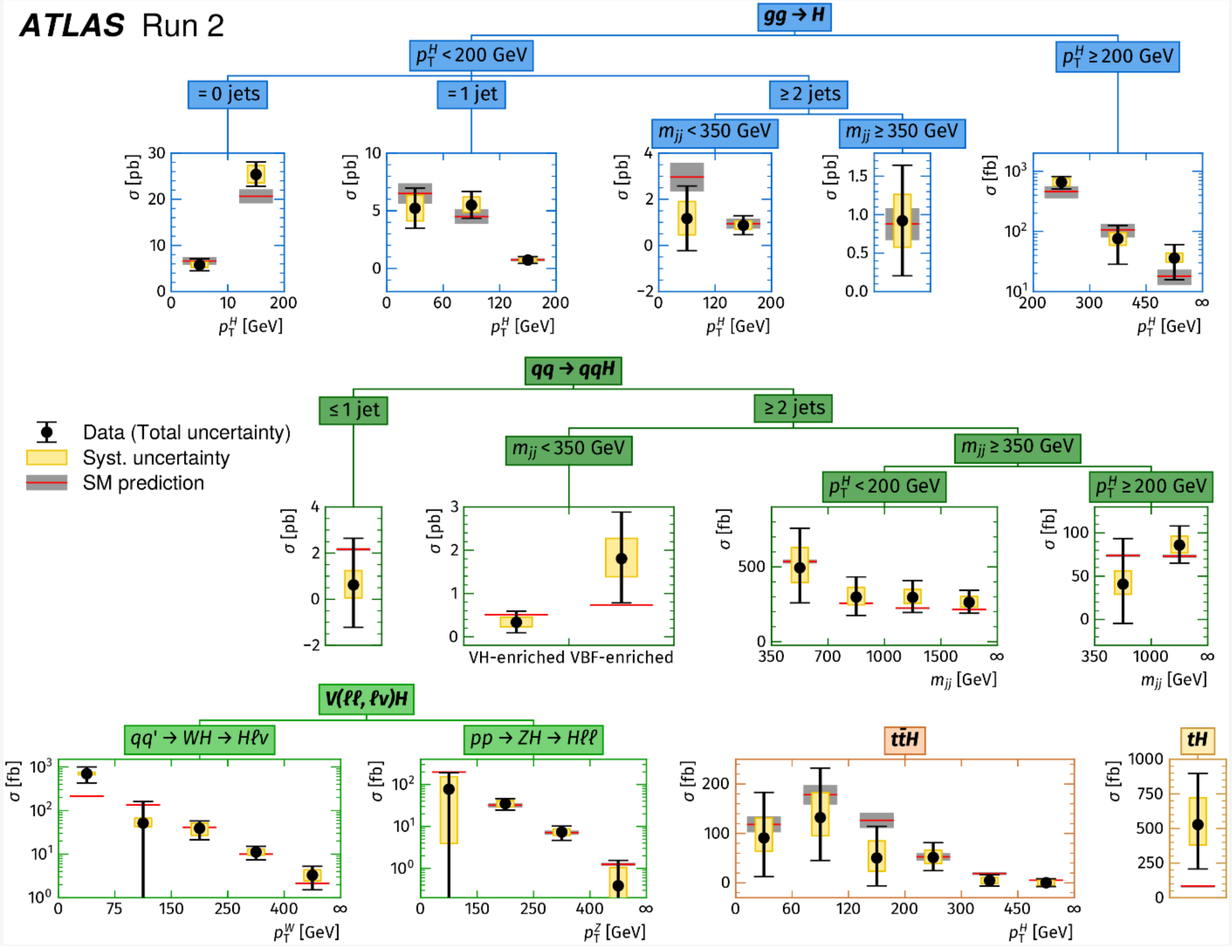


Standard model Higgs measurements



Higgs STXS measurements

- An unprecedented number of production and decay processes of the Higgs boson are combined to scrutinize its interactions with elementary particles
- Most precise measurements ever of interactions of Higgs boson with gluons, photons, and W and Z bosons—the carriers of the strong, electromagnetic and weak forces—are presented
- We reveal that the Higgs boson discovered ten years ago is remarkably consistent with the predictions of the theory

- **Based on these SM measurements, we will present BSM interpretations of Higgs bosons productions and decays**

Input Analyses

- All observed Higgs decays modes and two rare decays included

Decay channel	Analysis: Production mode	$\mathcal{L}$ [fb^{-1}]	Reference	Binning	SMEFT	2HDM and (h)MSSM
$H \to \gamma\gamma$	(ggF, VBF, WH, ZH, $t\bar{t}H$, tH)	139	[20]	STXS-1.2	✓	✓
			[18]	differential	✓(subset)	
$H \to ZZ^*$	($ZZ^* \to 4\ell$: ggF, VBF, $WH+ZH$, $t\bar{t}H+tH$)	139	[19]	STXS-1.2	✓	✓
			[17]	differential	✓(subset)	
	($ZZ^* \to \ell\ell\nu\bar{\nu}/\ell\ell q\bar{q}$: $t\bar{t}H$ multileptons)	36.1	[31]	STXS-0*		✓
$H \to \tau\tau$	(ggF, VBF, $WH+ZH$, $t\bar{t}H+tH$)	139	[26]	STXS-1.2	✓	✓
	($t\bar{t}H$ multileptons)	36.1	[31]	STXS-0*		✓
$H \to WW^*$	(ggF, VBF)	139	[27]	STXS-1.2	✓	✓
	(WH, ZH)	36.1	[41]	STXS-0*		✓
	($t\bar{t}H$ multileptons)	36.1	[31]	STXS-0*		✓
$H \to b\bar{b}$	(WH, ZH)	139	[21,22]	STXS-1.2	✓	✓
	(VBF)	126	[42]	STXS-1.2	✓	✓
	($t\bar{t}H+tH$)	139	[43]	STXS-1.2	✓	✓
	(boosted Higgs bosons: inclusive production)	139	[44]	STXS-1.2	✓	✓
$H \to Z\gamma$	(inclusive production)	139	[28]	STXS-0*	✓	✓
$H \to \mu\mu$	(ggF $+ t\bar{t}H + tH$, VBF $+ WH + ZH$)	139	[29]	STXS-0*	✓	✓

Input analyses

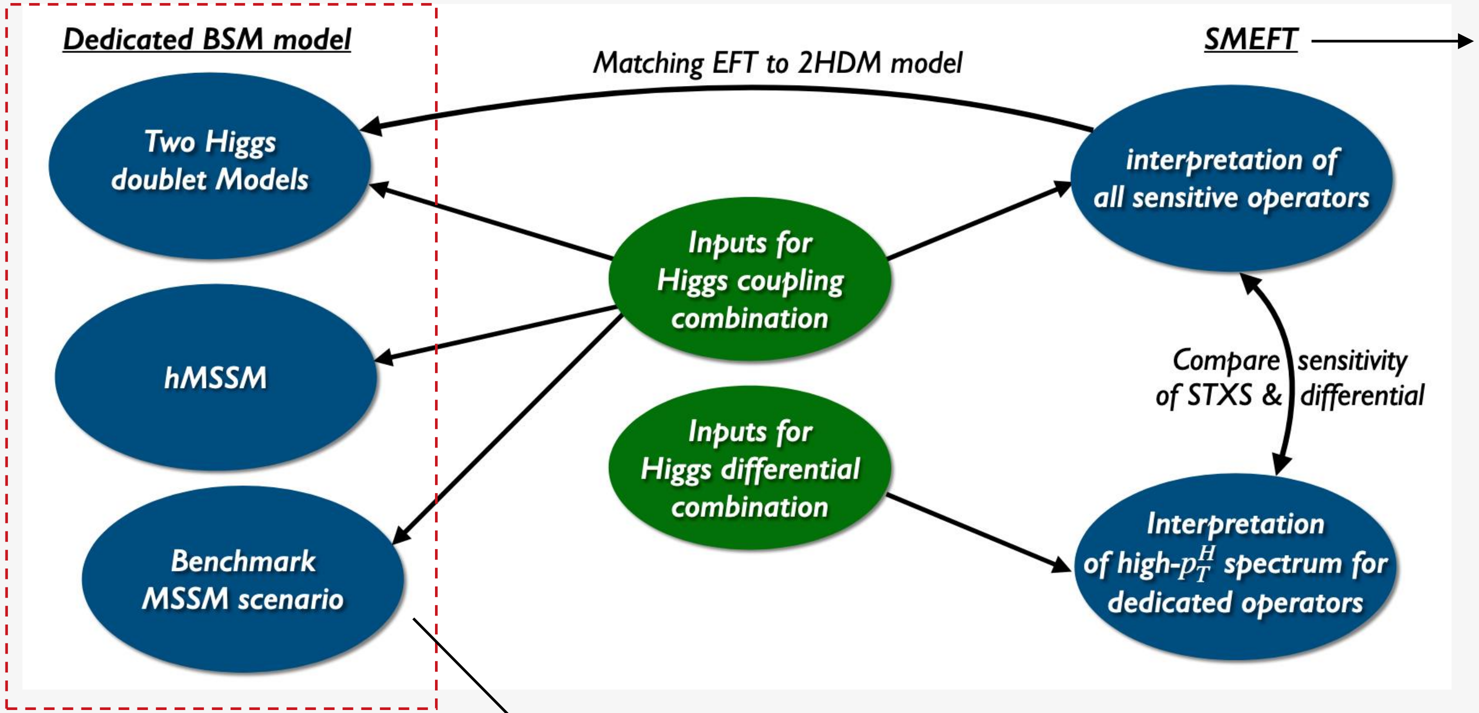
- What's new compared to HComb EFT and MSSM interpretations 2020?

Main decays modes:
- New productions included
- Full Run-2 results updated
- More analyses available in STXS
- tH production added

Rare decays:
- New H→Zγ
- H→μμ updated to 139fb^{-1}

Interpretation strategies

- Searches for physics beyond SM via multiple interpretations of Higgs boson measurements



- Interpretation based on the model-independent Effective Field Theory (EFT) framework with high dimensional operators

$$\mathcal{L}_{\mathrm{SMEFT}} = \mathcal{L}_{\mathrm{SM}} + \sum_{i}^{N_{d=6}} \frac{c_i}{\Lambda^2} O_i^{(6)} + \sum_{j}^{N_{d=8}} \frac{b_j}{\Lambda^4} O_j^{(8)} + \ldots,$$

- 2-Higgs-doublet model and supersymmetric model allow for direct search for additional Higgs bosons

EFT Interpretations of cross sections

- EFT provides an elegant language to encode the modifications of the Higgs boson properties induced by a wide class of BSM theories
- Within the mathematical language of the SMEFT, the effects of BSM dynamics at a high energy Λ=1TeV can be parametrized at low energies, E<<Λ, in terms of higher-dimensional operators built up from the Standard Model fields and respecting its symmetries such as gauge invariance. This yields an effective Lagrangian:

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_i^{N_{d=6}} \frac{c_i}{\Lambda^2} O_i^{(6)} + \sum_j^{N_{d=8}} \frac{b_j}{\Lambda^4} O_j^{(8)} + \ldots,$$

Wilson coefficients to be measured

$$\sigma_{\text{SMEFT}} = \sigma_{\text{SM}} + \sigma_{\text{int}} + \sigma_{\text{BSM}} = \sigma_{\text{SM}}^{((\text{N})\text{N})\text{NLO}} \times \left(1 + \frac{\sigma_{\text{int}}^{(\text{N})\text{LO}}}{\sigma_{\text{SM}}^{(\text{N})\text{LO}}} + \frac{\sigma_{\text{BSM}}^{(\text{N})\text{LO}}}{\sigma_{\text{SM}}^{(\text{N})\text{LO}}}\right).$$

consists of terms involving a single d = 6 SMEFT operator, suppressed by Λ^{-2}

consists of terms involving products of two d = 6 SMEFT operator, suppressed by Λ^{-4}

Linearized and quadratic models

- We further modified the Higgs productions and decays to reveal the impact of these SMEFT operators :

$$(\sigma\times B)^{i,k',H\to X}_{\mathrm{SMEFT}} = (\sigma\times B)^{i,k',H\to X}_{\mathrm{SM,(N(N))NLO}}\left(1+\frac{\sigma^{i,k'}_{\mathrm{int,(N)LO}}}{\sigma^{i,k'}_{\mathrm{SM,(N)LO}}}+\frac{\sigma^{i,k'}_{\mathrm{BSM,(N)LO}}}{\sigma^{i,k'}_{\mathrm{SM,(N)LO}}}\right)\left(\frac{1+\frac{\Gamma^{H\to X}_{\mathrm{int}}}{\Gamma^{H\to X}_{\mathrm{SM}}}+\frac{\Gamma^{H\to X}_{\mathrm{BSM}}}{\Gamma^{H\to X}_{\mathrm{SM}}}}{1+\frac{\Gamma^{H}_{\mathrm{int}}}{\Gamma^{H}_{\mathrm{SM}}}+\frac{\Gamma^{H}_{\mathrm{BSM}}}{\Gamma^{H}_{\mathrm{SM}}}}\right),$$

Consider this term only: **linearized model**

Consider both the terms: **quadratic model**

$$\frac{\sigma^{i,k'}_{\mathrm{int}}}{\sigma^{i,k'}_{\mathrm{SM}}} = \sum_j A_j^{\sigma_{i,k'}} c_j \qquad \frac{\sigma^{i,k'}_{\mathrm{BSM}}}{\sigma^{i,k'}_{\mathrm{SM}}} = \sum_{j,l\geq j} B_{jl}^{\sigma_{i,k'}} c_j c_l$$

$$\frac{\Gamma^{H\to X}_{\mathrm{int}}}{\Gamma^{H\to X}_{\mathrm{SM}}} = \sum_j A_j^{\Gamma^{H\to X}} c_j \qquad \frac{\Gamma^{H\to X}_{\mathrm{BSM}}}{\Gamma^{H\to X}_{\mathrm{SM}}} = \sum_{j,l\geq j} B_{jl}^{\Gamma^{H\to X}} c_j c_l$$

$$\frac{\Gamma^{H}_{\mathrm{int}}}{\Gamma^{H}_{\mathrm{SM}}} = \sum_j A_j^{\Gamma^{H}} c_j \qquad \frac{\Gamma^{H}_{\mathrm{BSM}}}{\Gamma^{H}_{\mathrm{SM}}} = \sum_{j,l\geq j} B_{jl}^{\Gamma^{H}} c_j c_l,$$

with

$$A_j^{\Gamma^H} = \frac{\sum_X \Gamma^{H\to X}_{\mathrm{SM}} A_j^{\Gamma^{H\to X}}}{\sum_X \Gamma^{H\to X}_{\mathrm{SM}}} \qquad B_{jl}^{\Gamma^H} = \frac{\sum_X \Gamma^{H\to X}_{\mathrm{SM}} B_{jl}^{\Gamma^{H\to X}}}{\sum_X \Gamma^{H\to X}_{\mathrm{SM}}}.$$

- The measurements are finally factorized using **Wilson coefficients c_i**
- A/B are derived from simulation, reflecting sensitivities of the processes to the EFT operators

Sensitivity estimate and choice of parameters

- Since the data samples are not capable of constraining all Wilson coefficients, we have to pick out sensitive ones or linear combinations of these parameters, based on the covariance matrices of data
  - A principal component analysis is done to identify sensitive directions

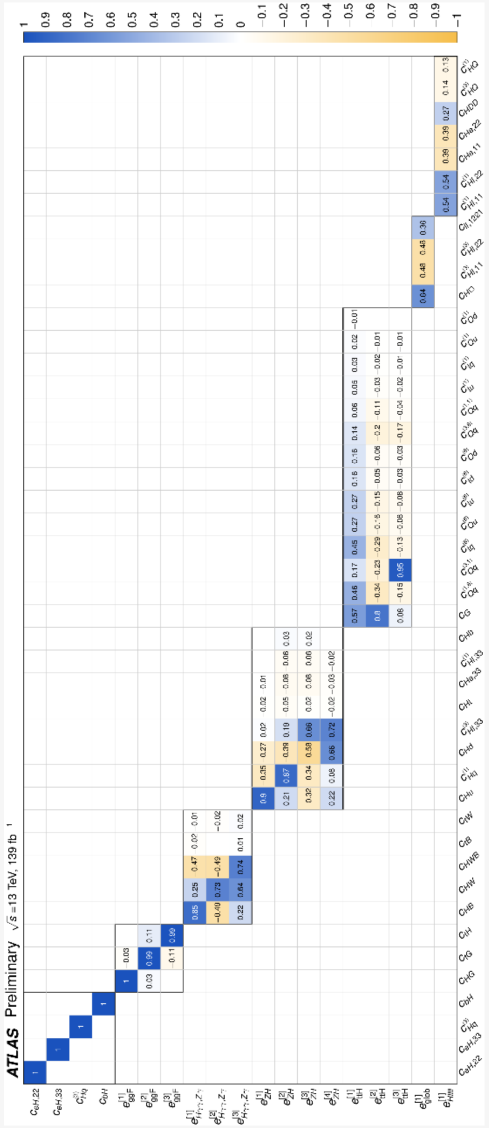
$$
\begin{aligned}
\boldsymbol{c} = &\{c_{eH,22}\} \cup \\
&\{c_{eH,33}\} \cup \\
&\{c_{Hq}^{(3)}\} \cup \\
&\{c_{bH}\} \cup \\
&\{c_{HG}, c_{tG}, c_{tH}\} \cup \\
&\{c_{HB}, c_{HW}, c_{HWB}, c_{tB}, c_{tW}\} \cup \\
&\{c_{Hu}, c_{Hq}^{(1)}, c_{Hd}, c_{Hl,33}^{(3)}, \\
&\qquad c_{Ht}, c_{He,33}, c_{Hl,33}^{(1)}, c_{Hb}\} \cup \\
&\{c_G, c_{Qq}^{(1,8)}, c_{Qq}^{(3,1)}, c_{tq}^{(8)}, c_{Qu}^{(8)}, c_{tu}^{(8)}, c_{td}^{(8)}, \\
&\qquad c_{Qd}^{(8)}, c_{Qq}^{(3,8)}, c_{Qq}^{(1,1)}, c_{tu}^{(1)}, c_{tq}^{(1)}, c_{Qu}^{(1)}, c_{Qd}^{(1)}\} \cup \\
&\{c_{H\Box}, c_{Hl,11}^{(3)}, c_{Hl,22}^{(3)}, c_{ll,1221}\} \cup \\
&\{c_{Hl,11}^{(1)}, c_{Hl,22}^{(1)}, c_{He,11}, c_{He,22}, c_{HDD}, c_{HQ}^{(3)}, c_{HQ}^{(1)}\}
\end{aligned}
$$

Original Wilson coefficients

$$
\begin{aligned}
\boldsymbol{c}' = &\{c_{eH,22}\} \cup \\
&\{c_{eH,33}\} \cup \\
&\{c_{Hq}^{(3)}\} \cup \\
&\{c_{bH}\} \cup \\
\rightarrow\ &\{e_{\mathrm{ggF}}^{[1]}, e_{\mathrm{ggF}}^{[2]}, e_{\mathrm{ggF}}^{[3]}\} \cup \\
\rightarrow\ &\{e_{H\gamma\gamma,Z\gamma}^{[1]}, e_{H\gamma\gamma,Z\gamma}^{[2]}, e_{H\gamma\gamma,Z\gamma}^{[3]}\} \cup \\
\rightarrow\ &\{e_{ZH}^{[1]}, e_{ZH}^{[2]}, e_{ZH}^{[3]}, e_{ZH}^{[4]}\} \cup \\
\rightarrow\ &\{e_{\mathrm{ttH}}^{[1]}, e_{\mathrm{ttH}}^{[2]}, e_{\mathrm{ttH}}^{[3]}\} \cup \\
\rightarrow\ &\{e_{\mathrm{glob}}^{[1]}\} \cup \\
\rightarrow\ &\{e_{Hllll}^{[1]}\}.
\end{aligned}
$$

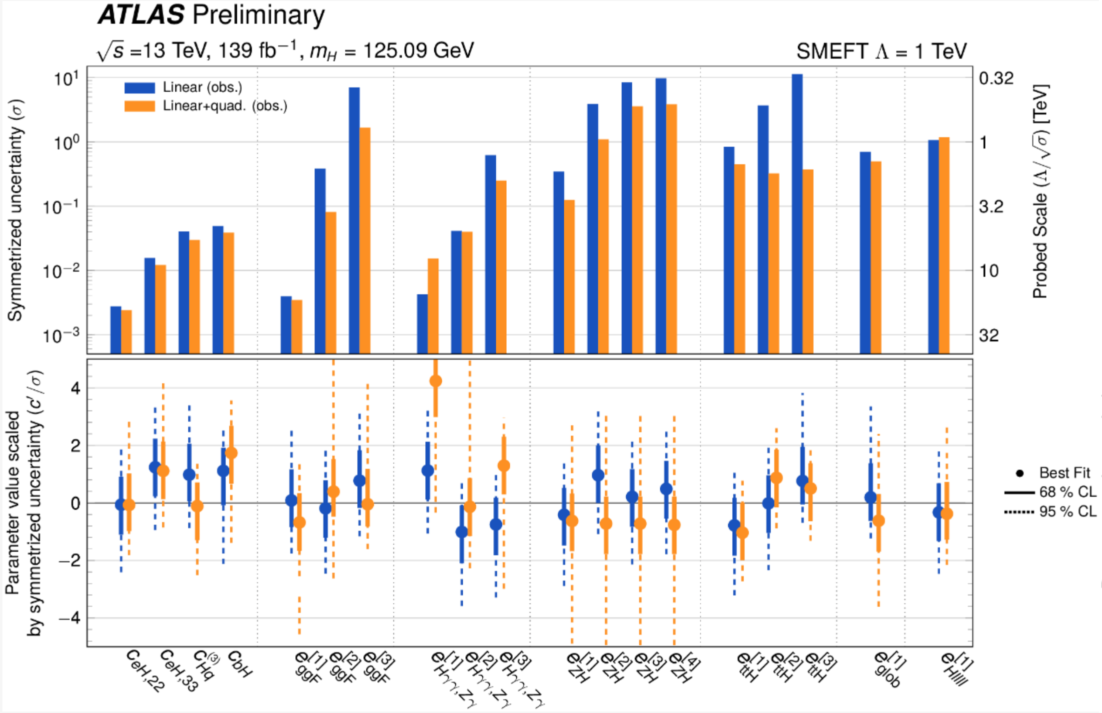
Coefficients measured in this analysis

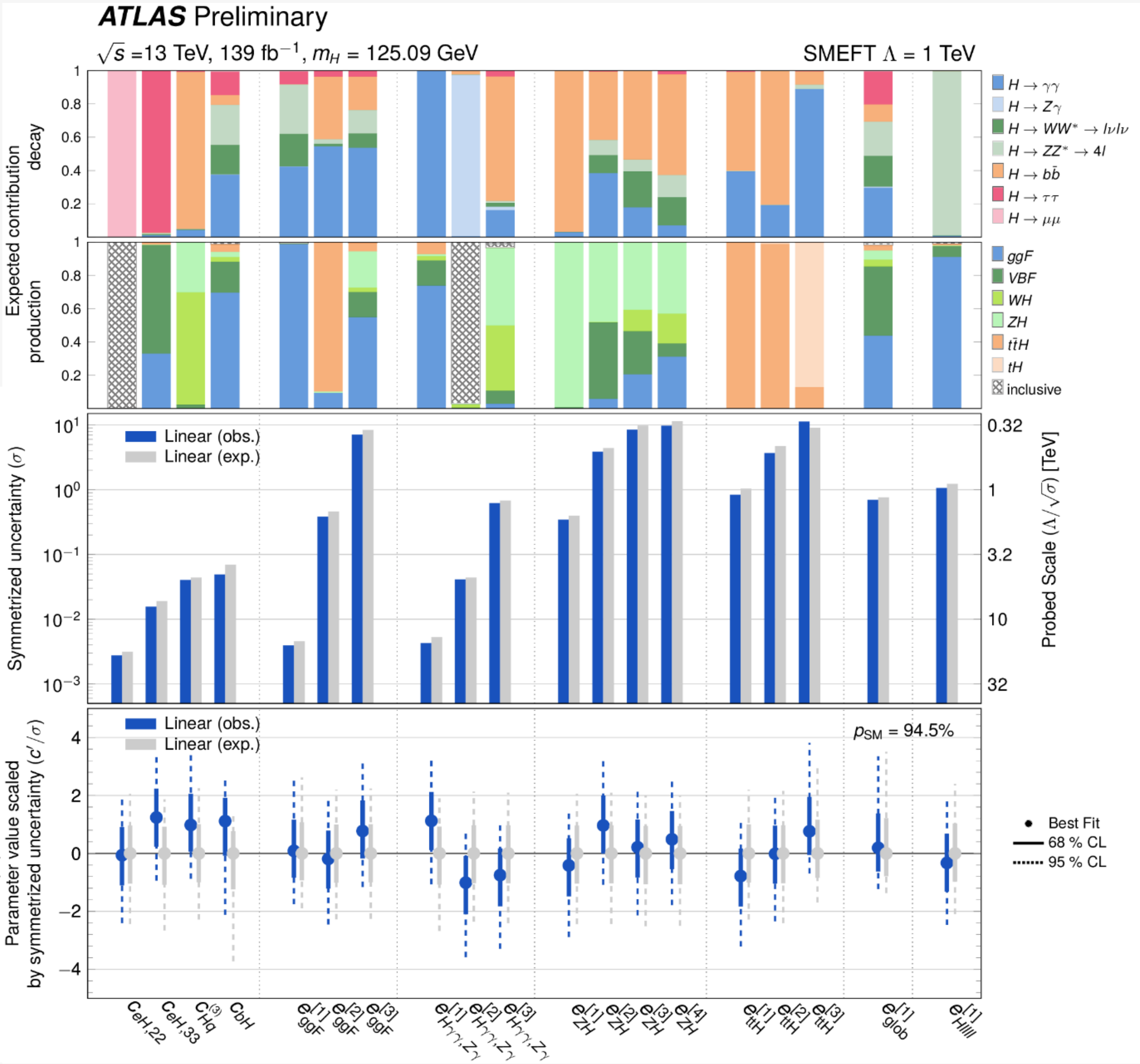
- H→μμ
- H→ττ
- VH, H→bb
- H→bb
- ggF/ttH production
- H→γγ, H→Zγ
- affect W/Z vertices with 3rd generation fermions & neutral current interactions with quarks
- tH, ttH
- shift in the Fermi constant/Higgs propagator correction
- anomalous HZee and HZμμ vertices



Results from EFT

- Right: Linearized model
  - Tightest constraints on EFT coefficients are observed for processes where the SM amplitudes are suppressed by factors that do not enter in SMEFT operators contributing to the same measured final states
- Bottom: Comparison of linearized and quadratic model



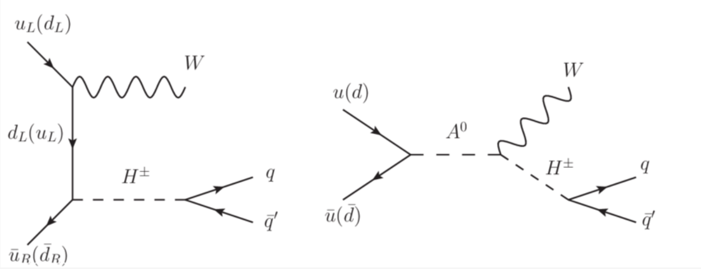


Constraints on two-Higgs-doublet models

- In two-Higgs-doublet models, the SM Higgs sector with one doublet of scalar complex fields Φ_1 is extended by introducing a second doublet Φ_2
- The vacuum-expectation-values $v_{1,2}$ of $\Phi_{1,2}$ that minimize V are related by $v_1^2+v_2^2=v^2$
- Electroweak symmetry breaking leads to five physical scalar Higgs fields: two neutral CP-even Higgs bosons h and H, one neutral CP-odd Higgs boson A, and two charged Higgs bosons $H^\pm$, where h is the observed Higgs

- Z_2 discrete symmetry forbids tree-level flavor-changing neutral currents(see S. L. Glashow and S. Weinberg, E. A. Paschos), which are strongly constrained by existing data, and implies that all fermions with the same quantum numbers couple to only one Higgs doublet
- Based on the couplings, 4 2HDM types are defined:

- Type I: All fermions couple to the same Higgs doublet.
- Type II: One Higgs doublet couples to up-type quarks while the other one couples to down-type quarks and charged leptons.
- Lepton-specific: One Higgs doublet couples to leptons while the other one couples to up- and down-type quarks.
- Flipped: One Higgs doublet couples to down-type quarks while the other one couples to up-type quarks and leptons.

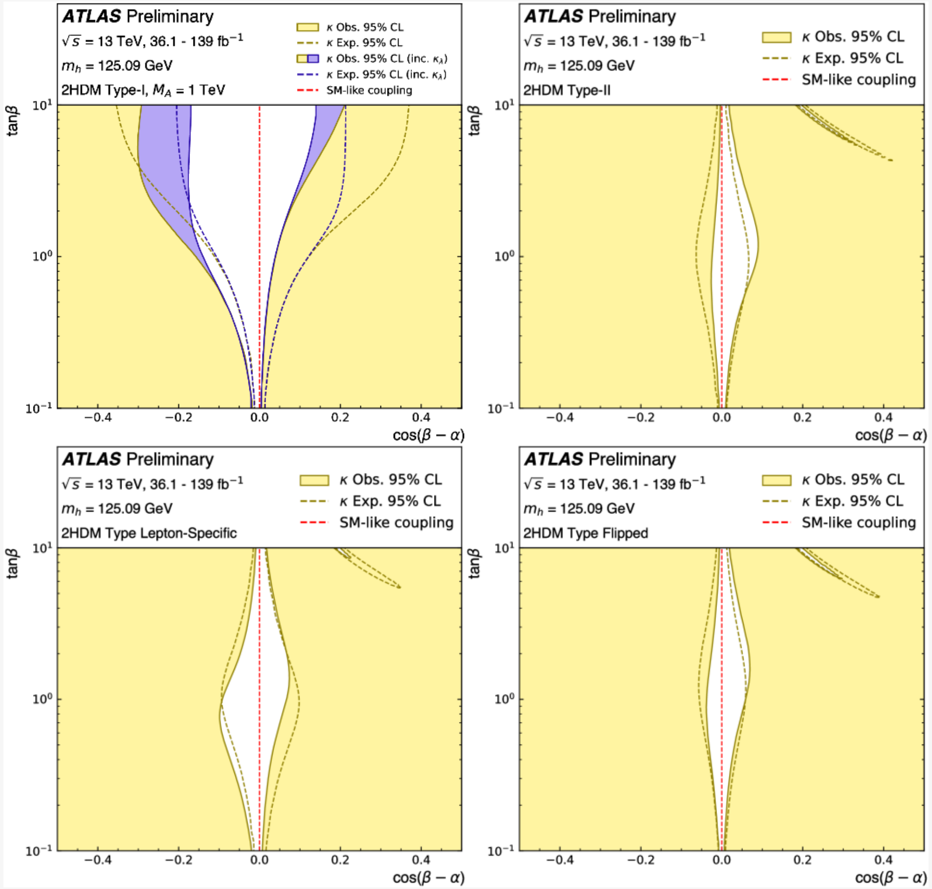


example of charged Higgs

Results based on κ-framework

- The measured signal strength μ is reparametrized using the mixing angle of the neutral CP-even Higgs sector **α**, and tan**β**=v_2/v_1:

$$\mu_k^{i,X} = \mu^{i,X}\left(\{\boldsymbol{\kappa}(\tan\beta, \cos(\beta-\alpha))\}\right)$$



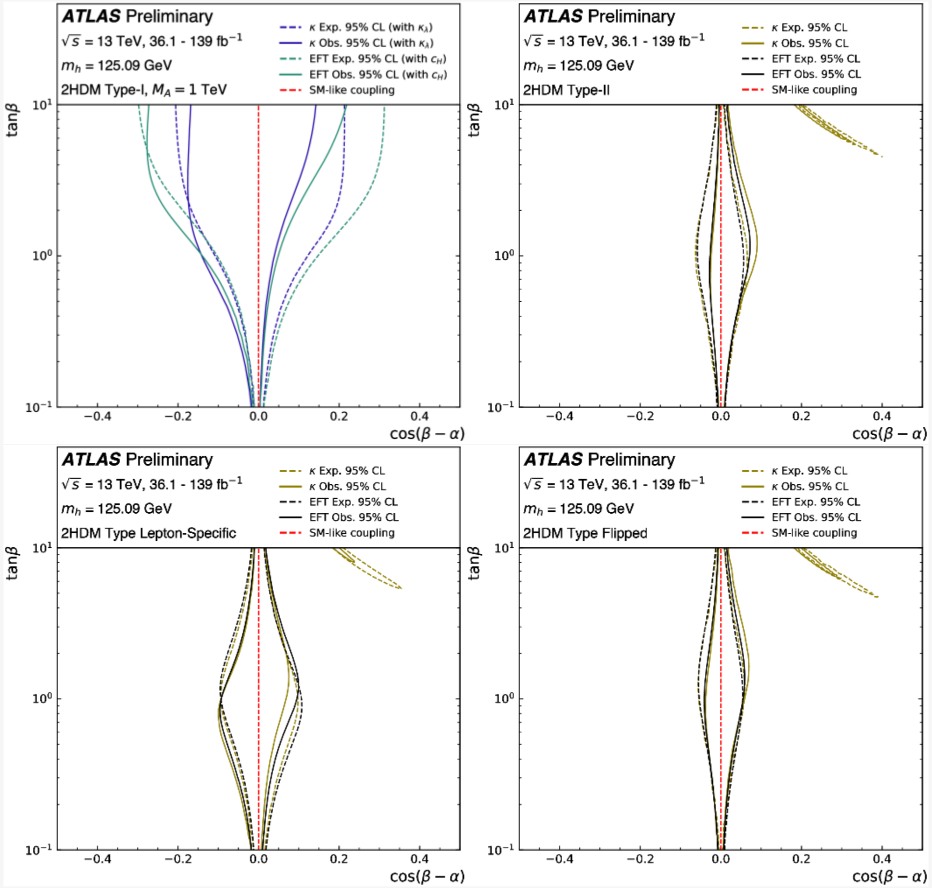
- All models exhibit similar exclusion regions in the (tanβ, cos(β−α)) plane at low values (<<1) of tanβ
- The interval of allowed values of cos(β−α) increases in size with tanβ, up to a total width of about 0.1–0.2 for tanβ=1

- A small allowed region in all types but Type-I corresponds to the fermion couplings that have same magnitude as in the SM but the opposite sign

Results based on EFT

- The modifications introduced in 2HDM could also be generated by EFT operators. E.g., the Wilson coefficients $c_{b/t/\tau H}$ could be matched to α & β as:

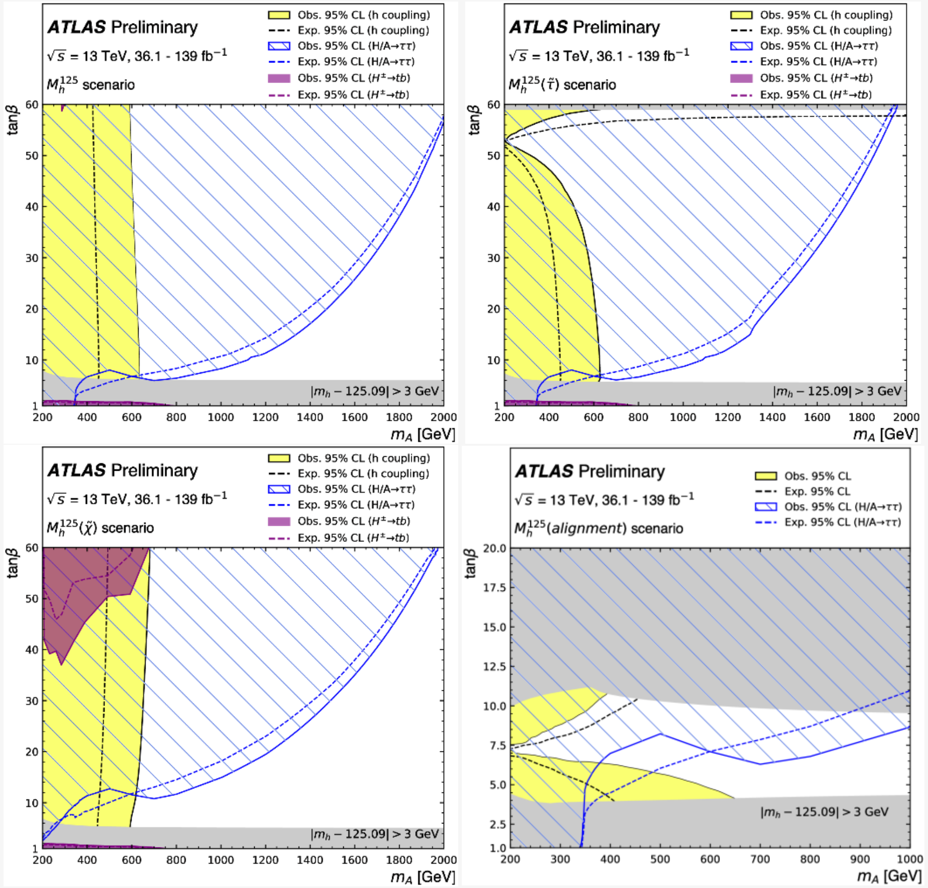
$$\frac{v^2 c_{iH}}{\Lambda^2} = -Y_i \eta_i \frac{\cos(\beta-\alpha)}{\tan\beta},$$



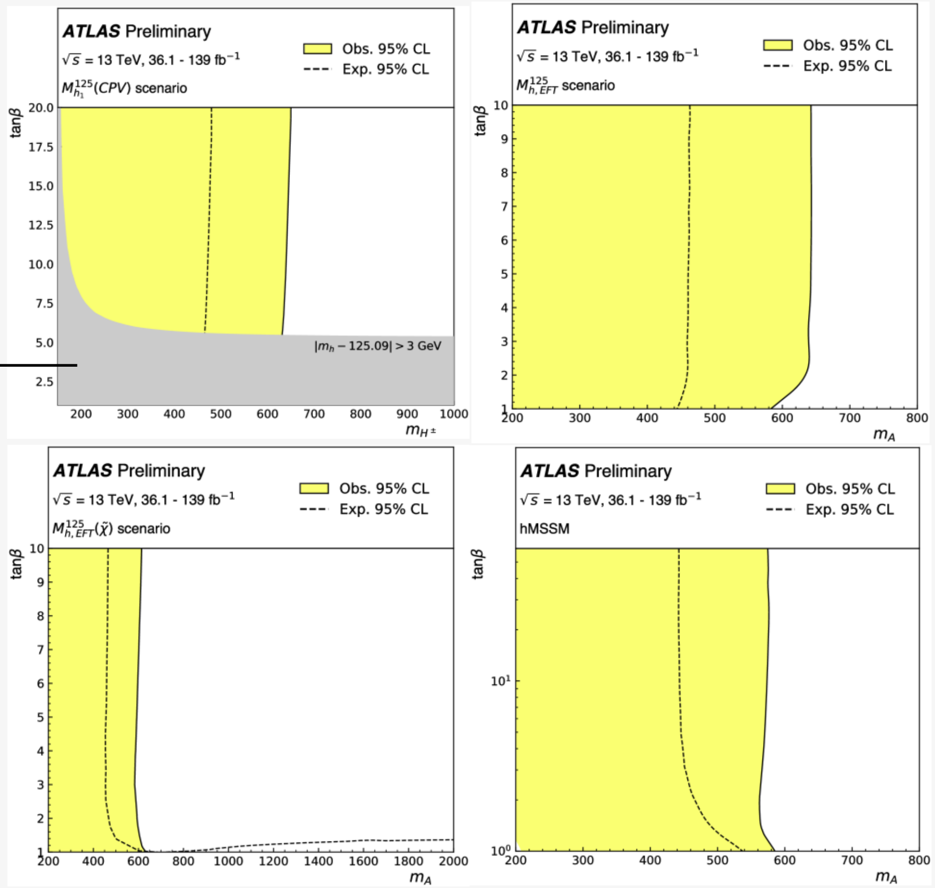
- Comparing the results from EFT interpretation and κ-framework, we found:
  - The exclusion regions are quite similar in general
  - In Type-I model, **EFT approach** leads to looser constrains due to not considering dimension-8 operators and higher level terms in Higgs self-coupling
  - The small allowed region disappear in other types because only dimesion-6 terms and linear expansions of Wilson coefficents are considered

Results of MSSM

- The minimal supersymmetric extension of the Standard Model, which introduces 7 benchmark scenarios plus a simplified one is also tested in our analysis
- These results exclude regime of pseudoscalar Higgs boson (m_A) for most of the scanned tan β range



Grey band:
excluded by the
requirement
|m_h-125.09GeV|



Conclusions

- We report novel interpretations of the recent ATLAS combined measurements of Higgs boson production and decays with new channels and updated luminosity

- The results based on the model-independent parametrization of SM Effective Field Theory show no deviations from SM, while considering all available terms suppressed by up to a factor Λ^{-4} do affect the measurements at Λ=1TeV level
- We also performed interpretations in the context of two-Higgs-doublet models and of eight benchmark scenarios of the minimal supersymmetric model, which are complementary to limits from direct searches for additional Higgs bosons

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Thank You

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