Combined Higgs Boson Measurements and Their Interpretations with the ATLAS Experiment

Zhu Yifan

On behalf of ATLAS Experiment

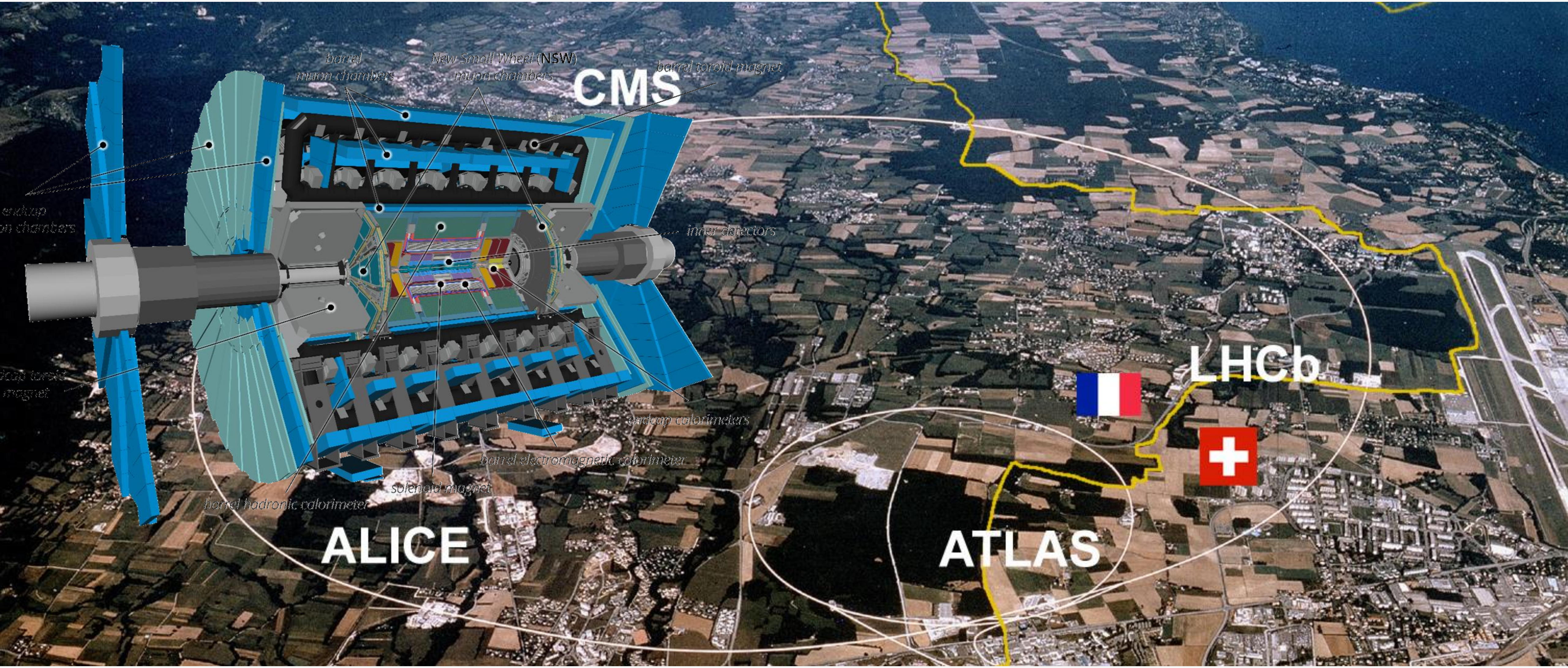
上海交通大學 SHANGHAI JIAO TONG UNIVERSITY
THE UNIVERSITY of EDINBURGH
ATLAS EXPERIMENT

饮 水 思 源 • 爱 国 荣 校

Outline

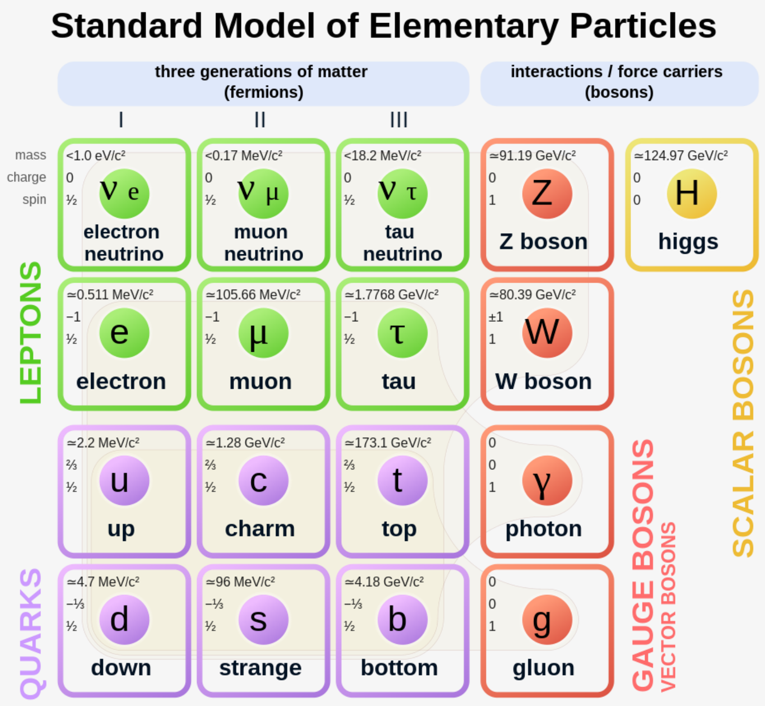
- **Higgs Combination for Couplings to Particles**
- **Higgs Combination for Self-Coupling**
- **Higgs BSM Interpretations**

LHC & ATLAS Experiment



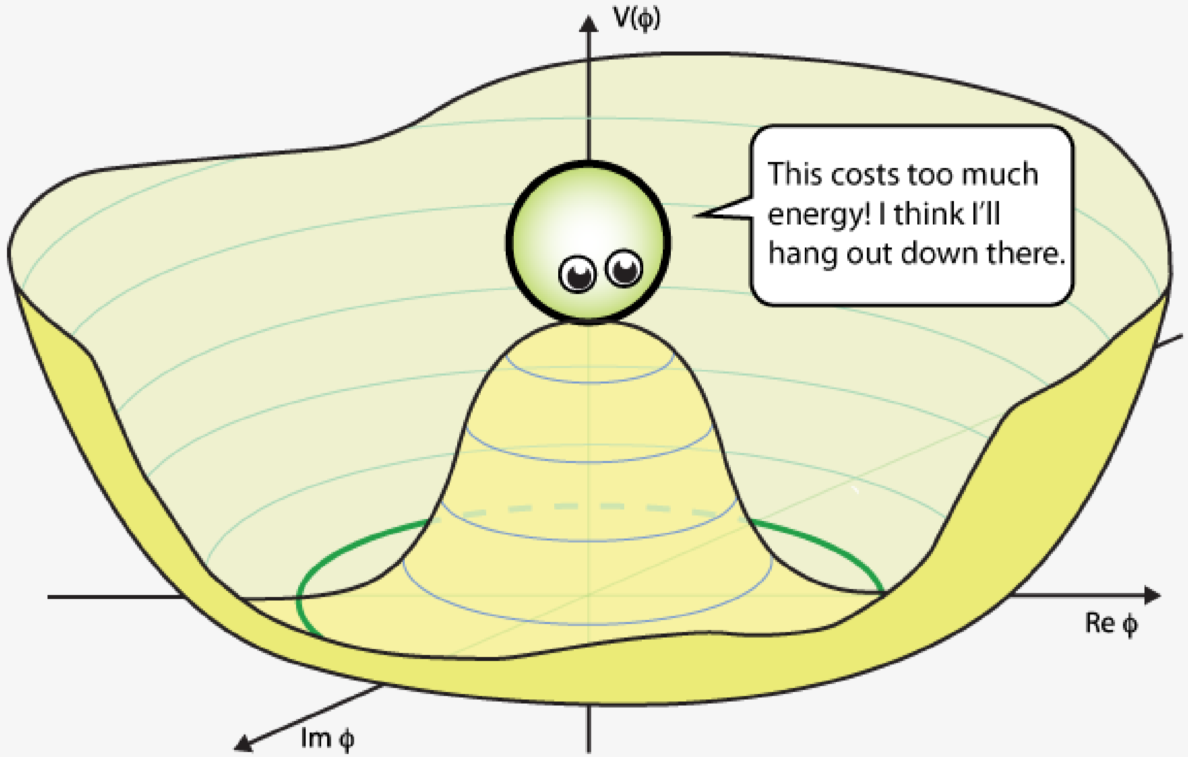
Standard Model and Brout–Englert–Higgs Mechanism

- Masses of all massive elementary particles rise from their couplings to Higgs boson
  - Vector boson masses → spontaneous symmetry breaking
  - Fermion masses → Yukawa couplings

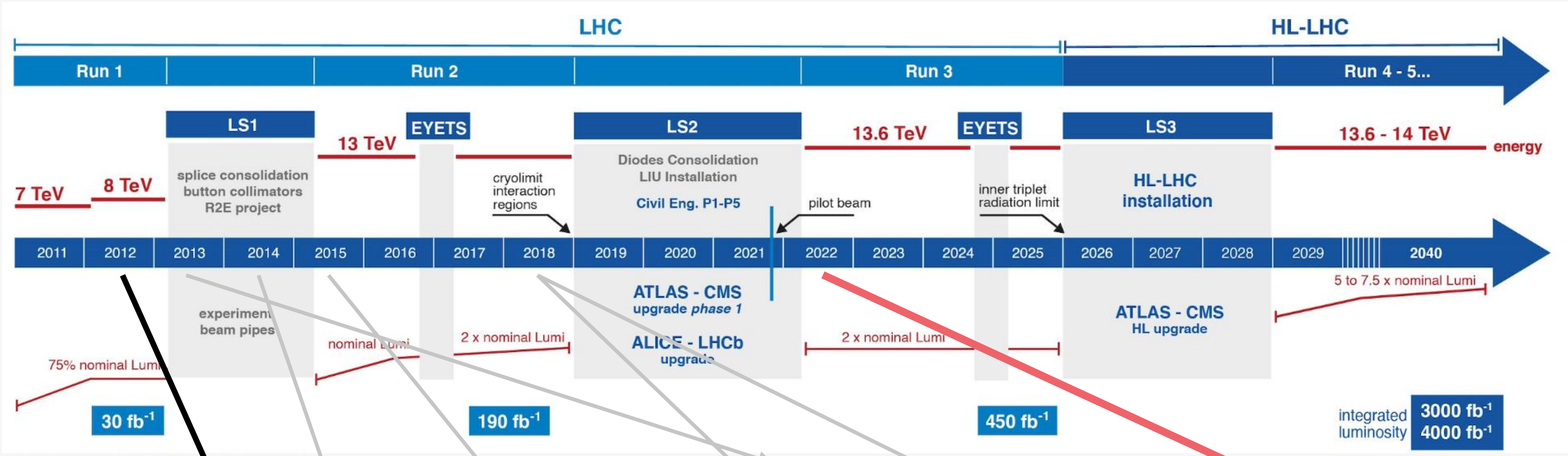


Standard Model of Elementary Particles

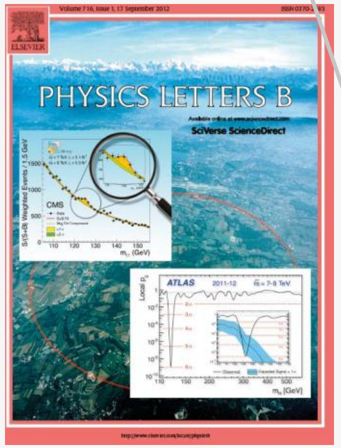
	three generations of matter (fermions) I	II	III	interactions / force carriers (bosons)	
mass charge spin	<1.0 eV/c^2 0 ½ ν_e electron neutrino	<0.17 MeV/c^2 0 ½ ν_μ muon neutrino	<18.2 MeV/c^2 0 ½ ν_τ tau neutrino	≈91.19 GeV/c^2 0 1 Z Z boson	≈124.97 GeV/c^2 0 0 H higgs
LEPTONS	≈0.511 MeV/c^2 −1 ½ e electron	≈105.66 MeV/c^2 −1 ½ μ muon	≈1.7768 GeV/c^2 −1 ½ τ tau	≈80.39 GeV/c^2 ±1 1 W W boson	SCALAR BOSONS
	≈2.2 MeV/c^2 ⅔ ½ u up	≈1.28 GeV/c^2 ⅔ ½ c charm	≈173.1 GeV/c^2 ⅔ ½ t top	0 0 1 γ photon	
QUARKS	≈4.7 MeV/c^2 −⅓ ½ d down	≈96 MeV/c^2 −⅓ ½ s strange	≈4.18 GeV/c^2 −⅓ ½ b bottom	0 0 1 g gluon GAUGE BOSONS VECTOR BOSONS	



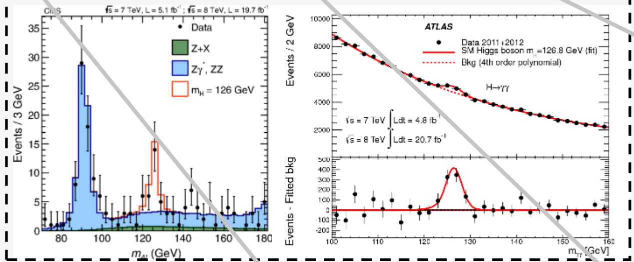
Higgs at LHC



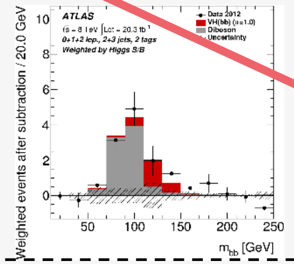
SM-like Higgs discovery
ggF→γγ+ZZ+WW



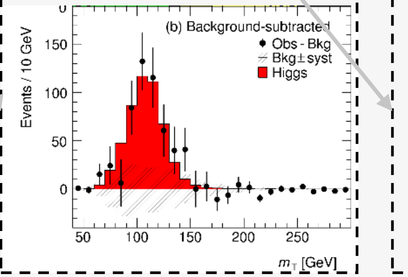
H→γγ, H→ZZ→4l observation



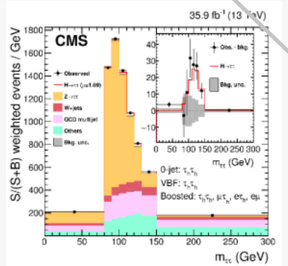
VH, H→bb observation



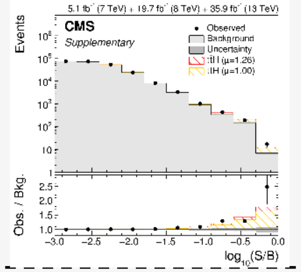
H→WW observation



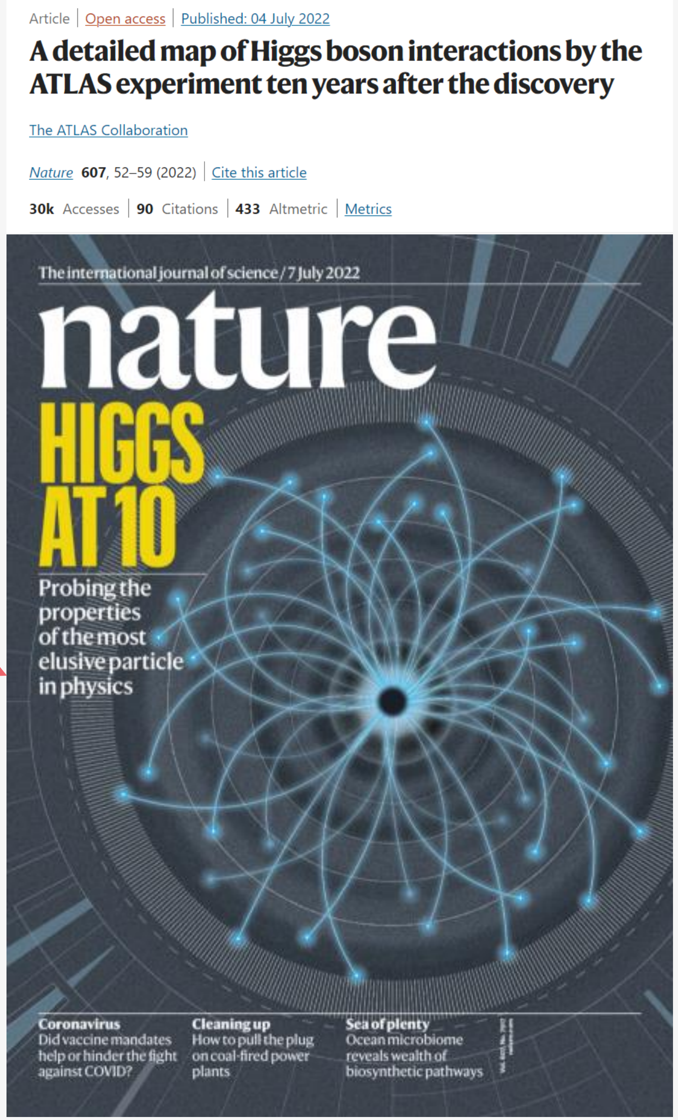
VBF, H→ττ observation



ttH observation



Nature 607, 52–59 (2022)



Article | Open access | Published: 04 July 2022

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

30k Accesses | **90** Citations | **433** Altmetric | Metrics

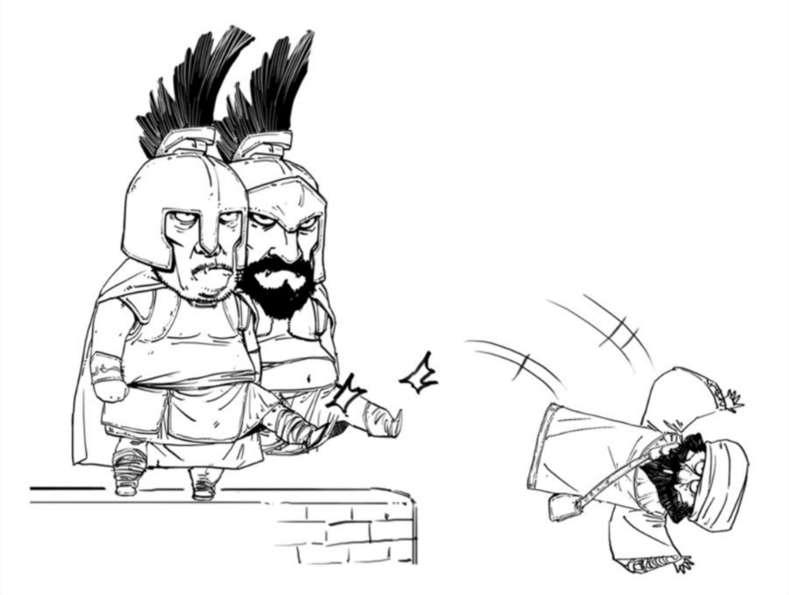
Motivation for Combination

- In LHC Run 2, **30x** more Higgs are recorded by the ATLAS detector than the discovery, which allows for precise measurements of **cross-sections**, **couplings and kinematic properties**, searches for **rare decay** modes and test phase space that hasn't been probed before

- A measurement based on a **combination** of **all major ATLAS Higgs analyses** can present **more sensitive** and **less model-dependent** results on Higgs, e.g.:
  - The combination of all measurements is necessary to constrain the couplings individually
  - Some analyses having higher sensitivity in certain kinematic regions

Athens

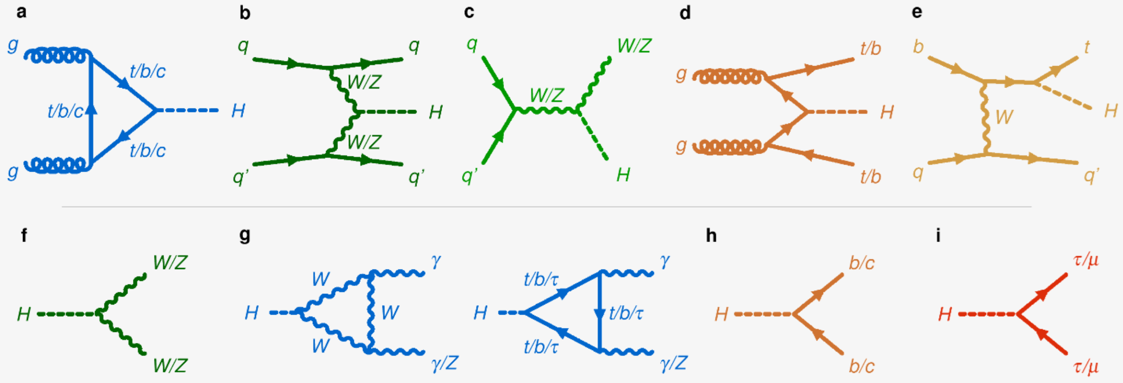
Sparta



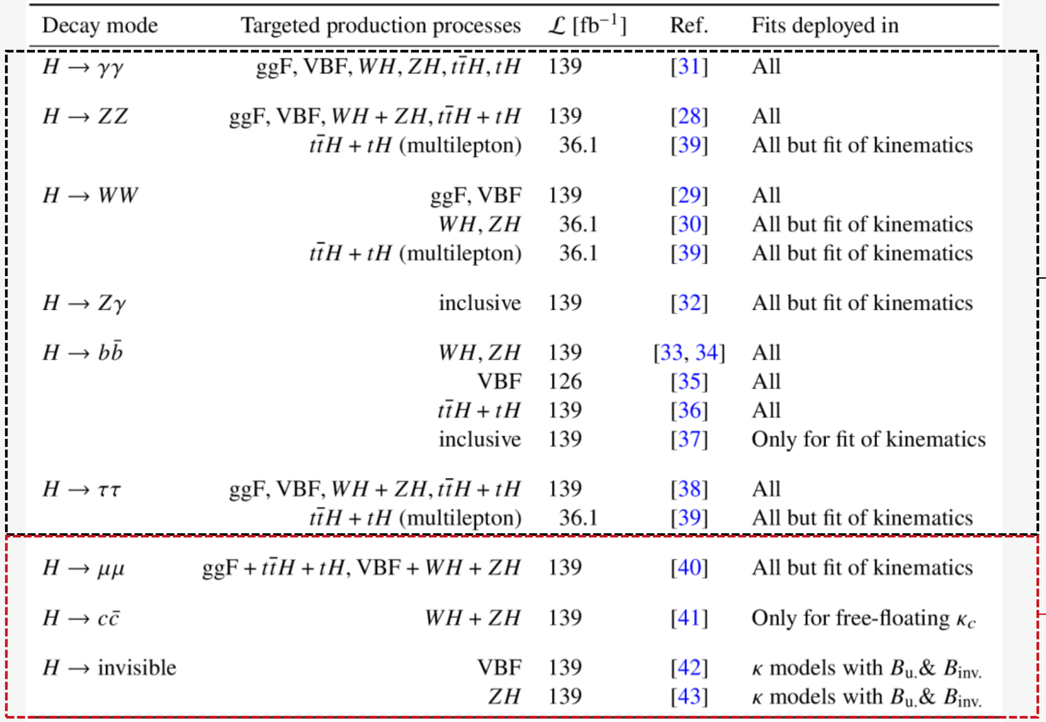
Greco-Persian Wars

source

Input Analyses



input analyses



Decay mode	Targeted production processes	$\mathcal{L}$ [fb^{-1}]	Ref.	Fits deployed in
$H \to \gamma\gamma$	ggF, VBF, WH, ZH, $t\bar{t}H$, tH	139	[31]	All
$H \to ZZ$	ggF, VBF, $WH + ZH$, $t\bar{t}H + tH$	139	[28]	All
	$t\bar{t}H + tH$ (multilepton)	36.1	[39]	All but fit of kinematics
$H \to WW$	ggF, VBF	139	[29]	All
	WH, ZH	36.1	[30]	All but fit of kinematics
	$t\bar{t}H + tH$ (multilepton)	36.1	[39]	All but fit of kinematics
$H \to Z\gamma$	inclusive	139	[32]	All but fit of kinematics
$H \to b\bar{b}$	WH, ZH	139	[33, 34]	All
	VBF	126	[35]	All
	$t\bar{t}H + tH$	139	[36]	All
	inclusive	139	[37]	Only for fit of kinematics
$H \to \tau\tau$	ggF, VBF, $WH + ZH$, $t\bar{t}H + tH$	139	[38]	All
	$t\bar{t}H + tH$ (multilepton)	36.1	[39]	All but fit of kinematics
$H \to \mu\mu$	ggF + $t\bar{t}H + tH$, VBF + $WH + ZH$	139	[40]	All but fit of kinematics
$H \to c\bar{c}$	$WH + ZH$	139	[41]	Only for free-floating κ_c
$H \to$ invisible	VBF	139	[42]	κ models with $B_{\text{u.}}$ & $B_{\text{inv.}}$
	ZH	139	[43]	κ models with $B_{\text{u.}}$ & $B_{\text{inv.}}$

- **All** observed production & decay modes on ATLAS experiment included

What's new w.r.t. combination in 2020?

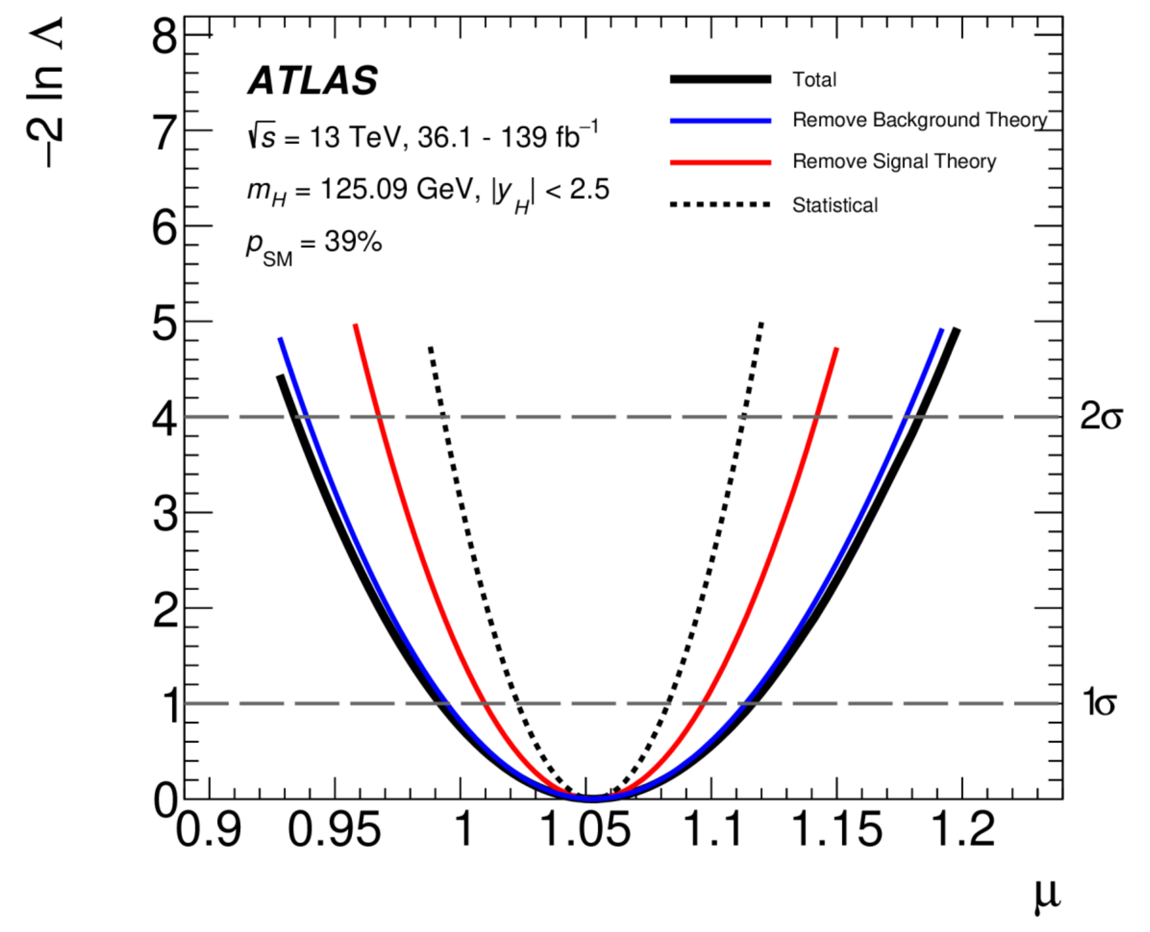
Main decay modes:

- New productions included
- More analyses updated to full Run-2
- More analyses available in the simplified template cross-section model
- Independent ttH and tH measurements

Rare decays:

- New H→Zγ/cc
- H→μμ updated to 139fb^{-1}

Global Signal Strength



- Considering all production and decay modes together

$$\mu = \frac{\sigma \times \mathrm{B}}{(\sigma \times \mathrm{B})_{\mathrm{SM}}}$$

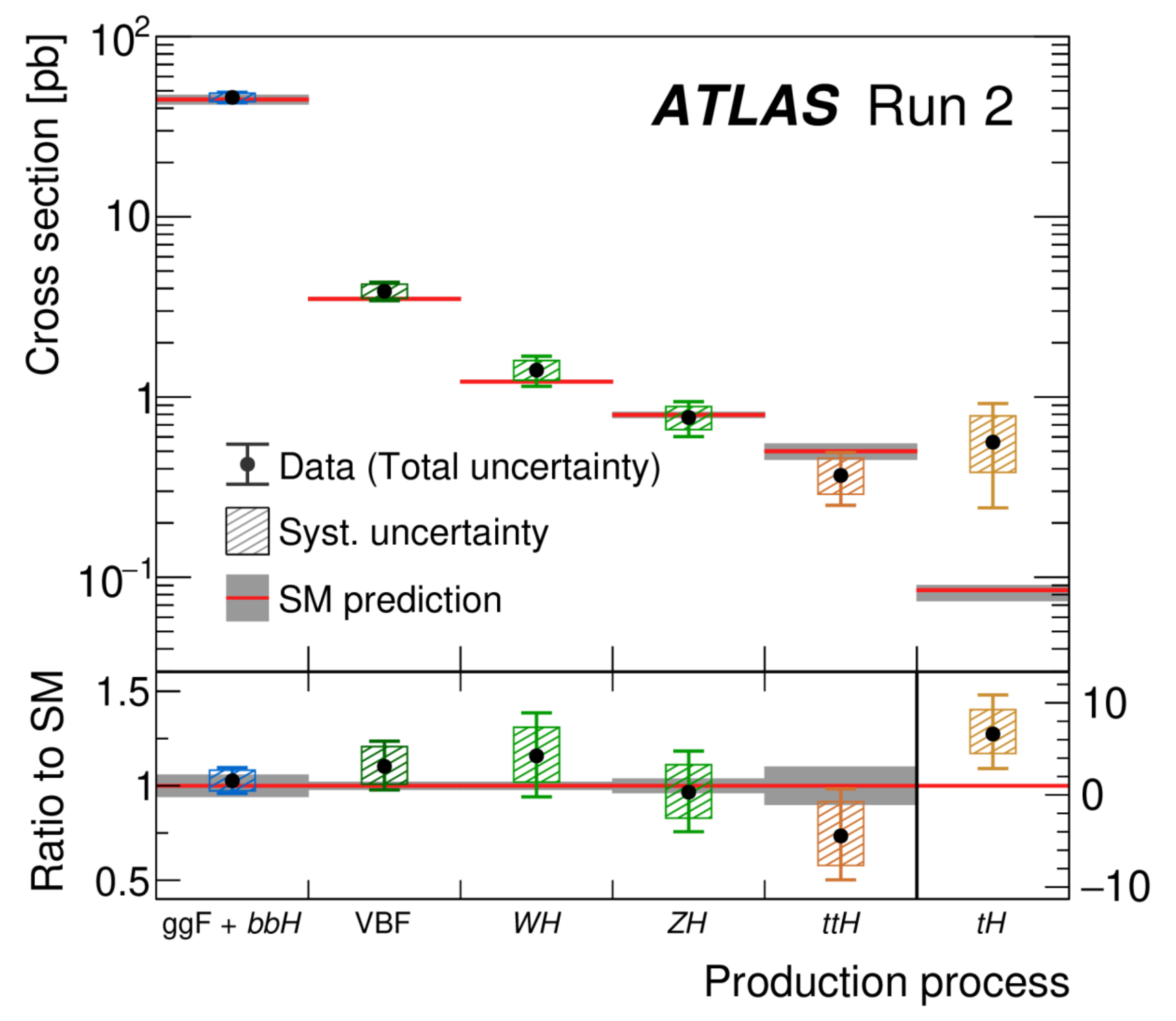
- Experimental and theory uncertainties reduced by a factor of 2 w.r.t. Run 1 result:

$\boldsymbol{\mu}$ **= 1.05 ± 0.06**
= 1.05 ± 0.03 (*stat.*) ± 0.03 (*exp.*)
± 0.04 (*sig. th.*) ± 0.02 (*bkg. th.*)

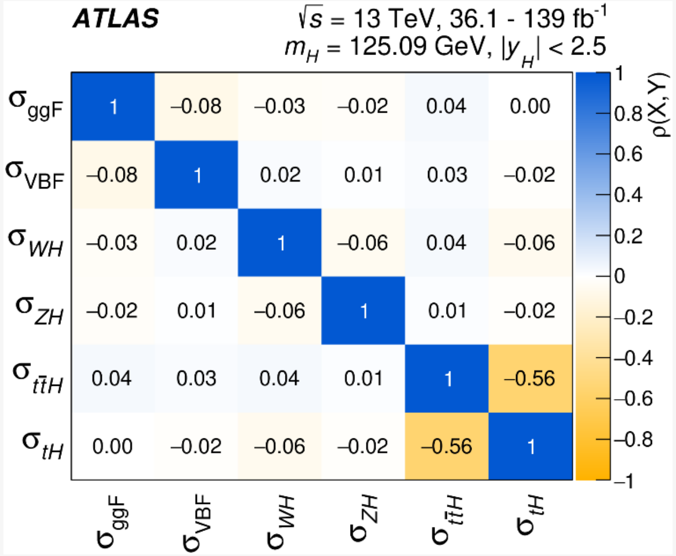
  - Theoretical uncertainties now dominate

- SM compatibility (p-value): 39%

Production Cross-Section



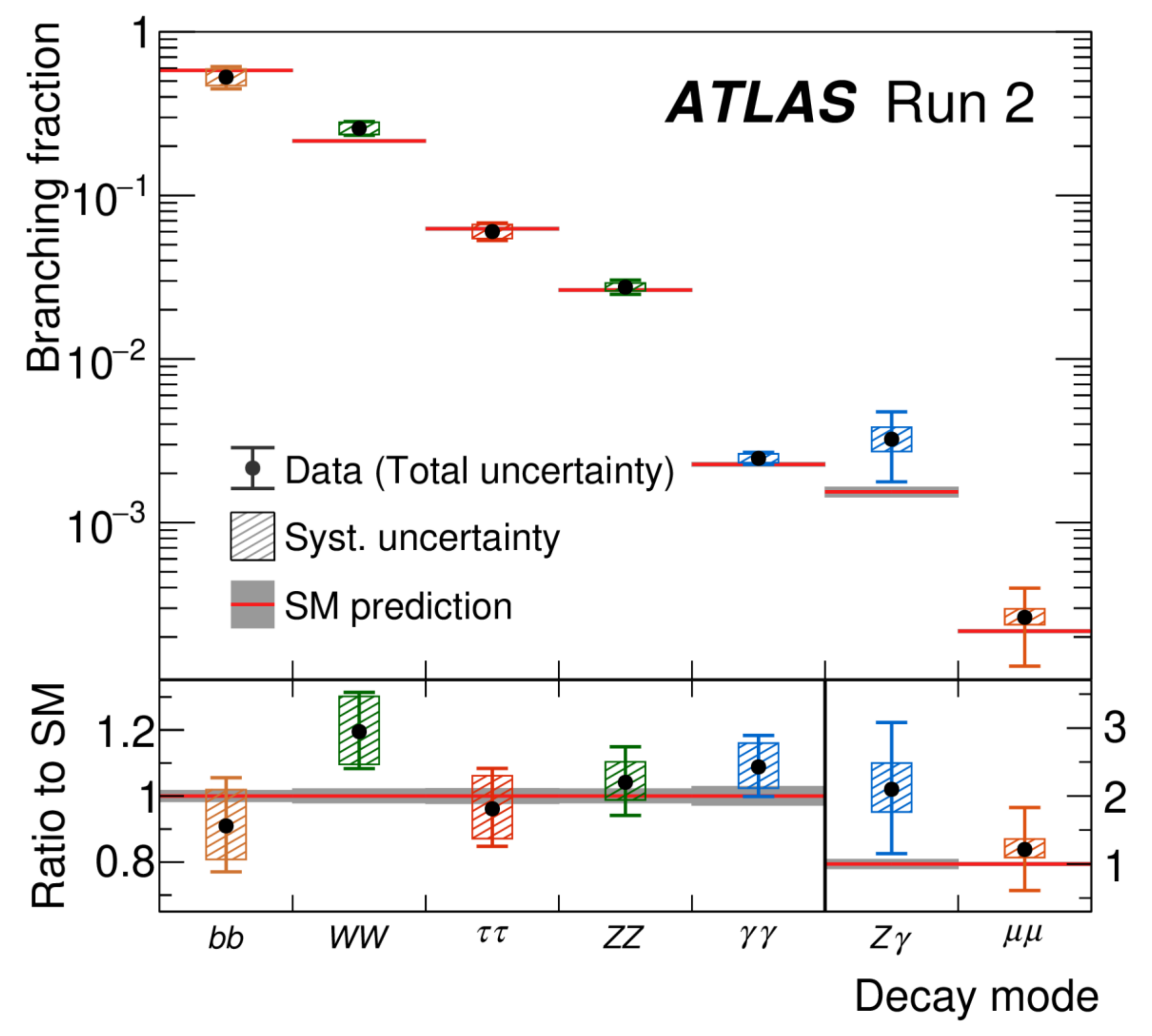
- Better precision:
  - ggF now at precision of 7%
  - VBF now at precision of 12%
- Evidence of rare production mode:
  - Upper limit on tH of 15(7) x SM at 95% C.L.
- SM compatibility (p-value): 65%



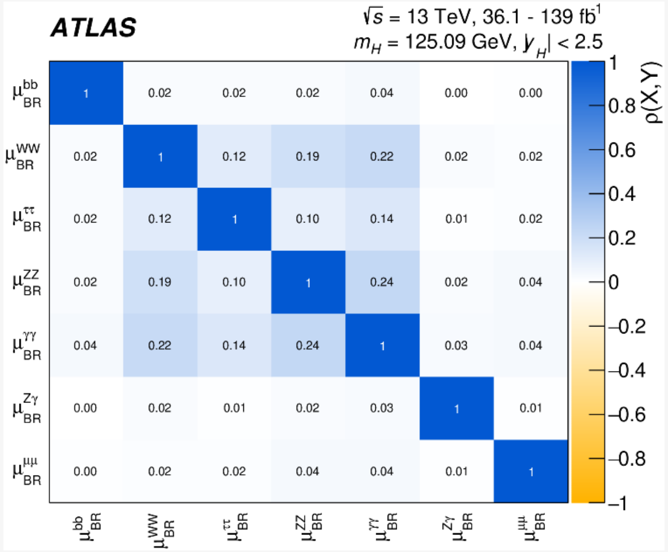
ATLAS $\sqrt{s}$ = 13 TeV, 36.1 - 139 fb^{-1}
m_H = 125.09 GeV, $|y_H| < 2.5$

	σ_{ggF}	σ_{VBF}	σ_{WH}	σ_{ZH}	$\sigma_{t\bar{t}H}$	σ_{tH}
σ_{ggF}	1	−0.08	−0.03	−0.02	0.04	0.00
σ_{VBF}	−0.08	1	0.02	0.01	0.03	−0.02
σ_{WH}	−0.03	0.02	1	−0.06	0.04	−0.06
σ_{ZH}	−0.02	0.01	−0.06	1	0.01	−0.02
$\sigma_{t\bar{t}H}$	0.04	0.03	0.04	0.01	1	−0.56
σ_{tH}	0.00	−0.02	−0.06	−0.02	−0.56	1

Decay Branching Ratio

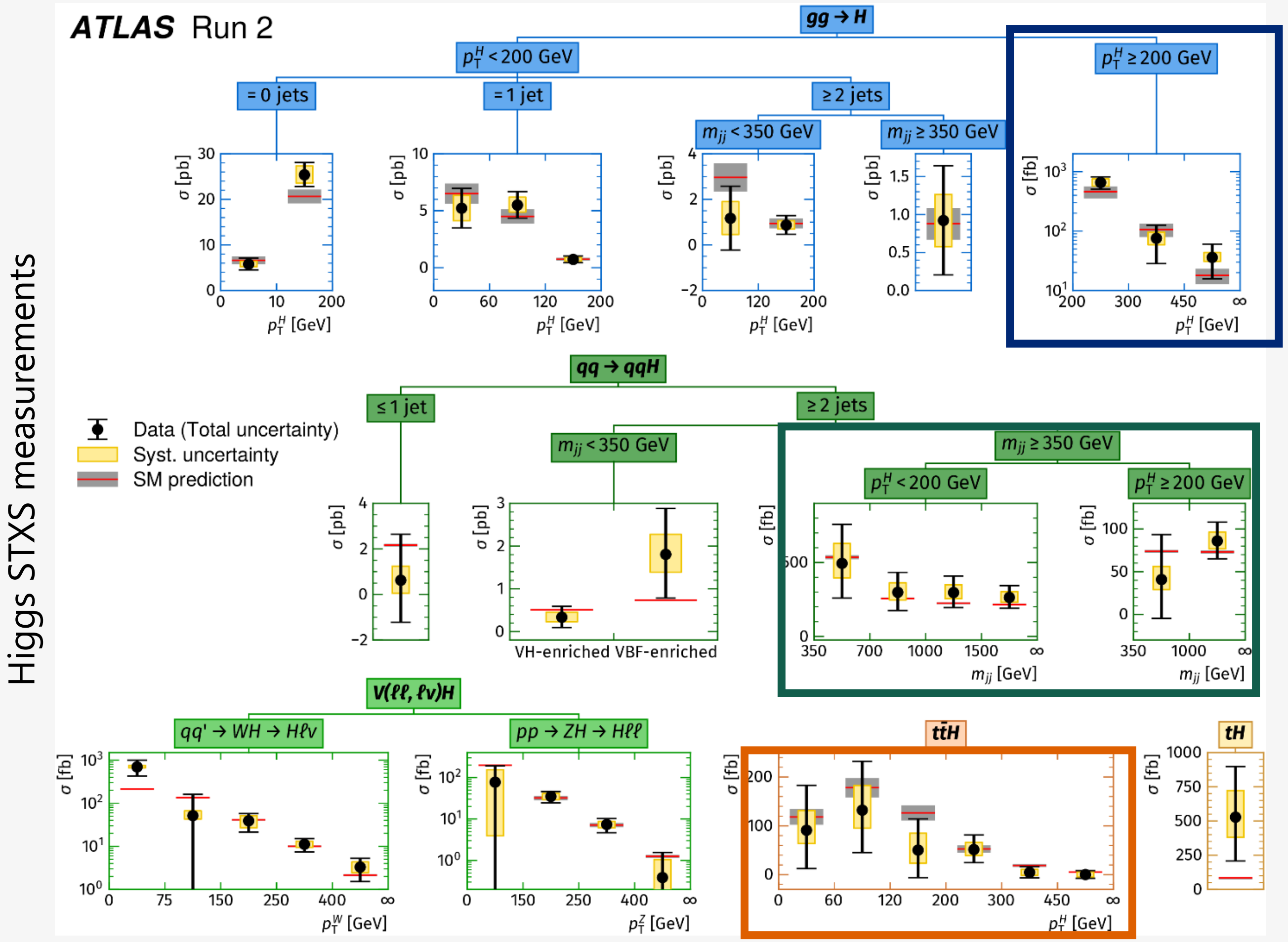


- Better precision:
  - H→γγ, ZZ, WW & ττ 10%~12%
- Evidence of rare decay modes:
  - H→μμ 2.0σ (1.7σ), Zγ 2.3σ (1.1σ)
- SM compatibility (p-value): 56%



	μ_{BR}^{bb}	μ_{BR}^{WW}	$\mu_{BR}^{\tau\tau}$	μ_{BR}^{ZZ}	$\mu_{BR}^{\gamma\gamma}$	$\mu_{BR}^{Z\gamma}$	$\mu_{BR}^{\mu\mu}$
μ_{BR}^{bb}	1	0.02	0.02	0.02	0.04	0.00	0.00
μ_{BR}^{WW}	0.02	1	0.12	0.19	0.22	0.02	0.02
$\mu_{BR}^{\tau\tau}$	0.02	0.12	1	0.10	0.14	0.01	0.02
μ_{BR}^{ZZ}	0.02	0.19	0.10	1	0.24	0.02	0.04
$\mu_{BR}^{\gamma\gamma}$	0.04	0.22	0.14	0.24	1	0.03	0.04
$\mu_{BR}^{Z\gamma}$	0.00	0.02	0.01	0.02	0.03	1	0.01
$\mu_{BR}^{\mu\mu}$	0.00	0.02	0.02	0.04	0.04	0.01	1

Simplified Template Cross-Section



- Split phase space of Higgs production processes into 36 kinematic regions
  - Defined by kinematics of Higgs Boson and of associated jets, W, Z bosons
- Goal
  - provide sensitivity to BSM effects
  - avoid large theory uncertainties in predictions
  - minimize model-dependence from acceptance extrapolations

- SM compatibility (p-value): 92%
- Highlights

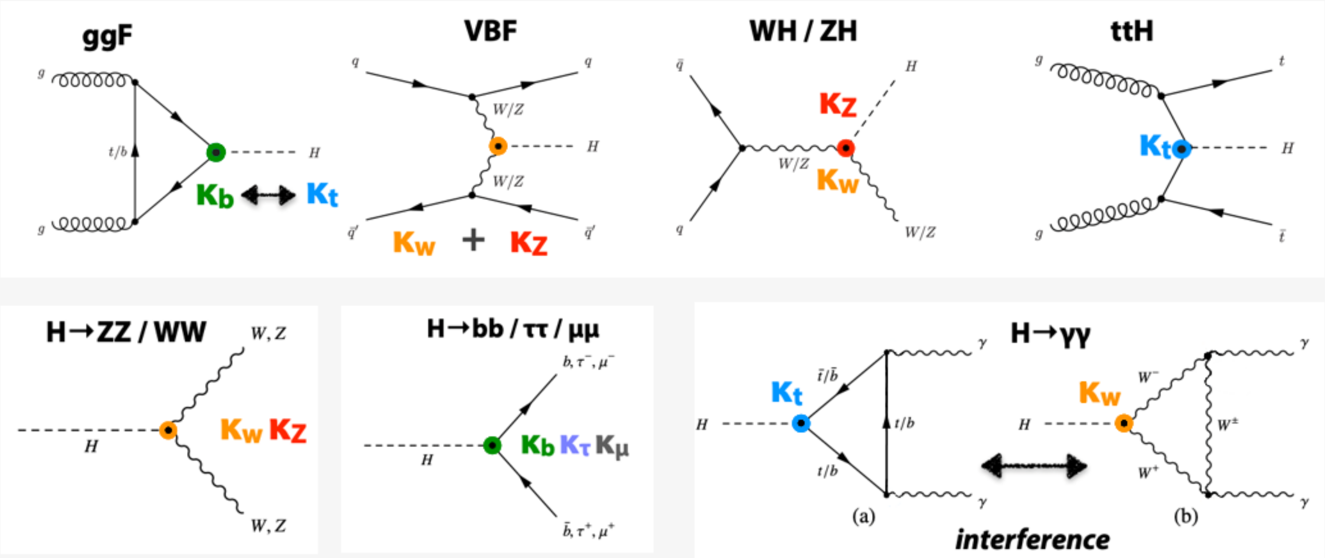
▯ ▯ ▯ new bins from updated analysis, high p_T bins have sensitivity to BSM

κ Framework

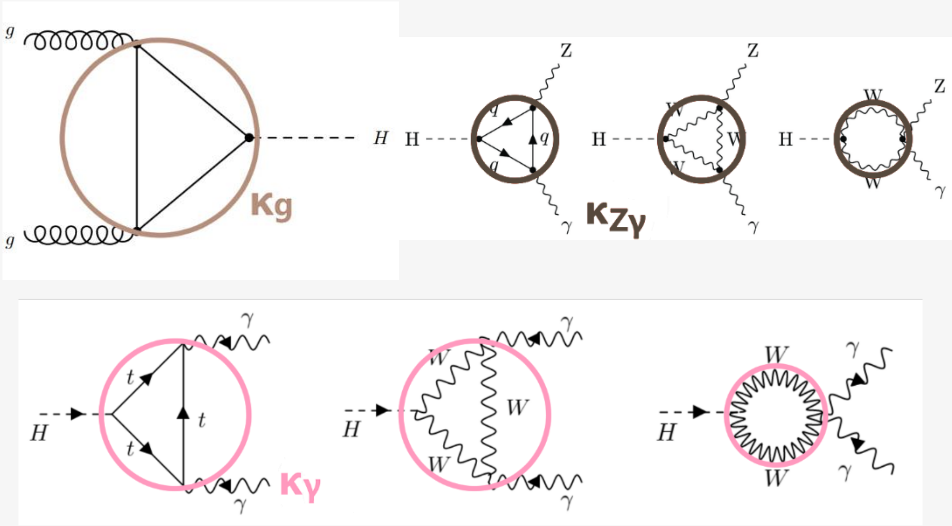
- A coupling modifier κ is introduced to probe into the structures of Higgs couplings to particles
  - Direct couplings: κ_b, κ_t, κ_W, κ_Z, κ_τ, κ_μ
  - Effective couplings: κ_γ, κ_g, $\kappa_{Z\gamma}$, etc

$$(\sigma \cdot BR)\,(i \to H \to f) \sim \frac{\sigma_i \cdot \Gamma_f}{\Gamma_H} = \frac{\sigma_i^{SM} \cdot \Gamma_f^{SM}}{\Gamma_H^{SM}} \cdot \left(\frac{\boldsymbol{\kappa}_i^2 \cdot \boldsymbol{\kappa}_f^2}{\boldsymbol{\kappa}_H^2}\right)$$

- Beyond Standard Model effects, e.g., undetected decays, can be parameterized within the Higgs total width $\Gamma_H{}^{SM}$

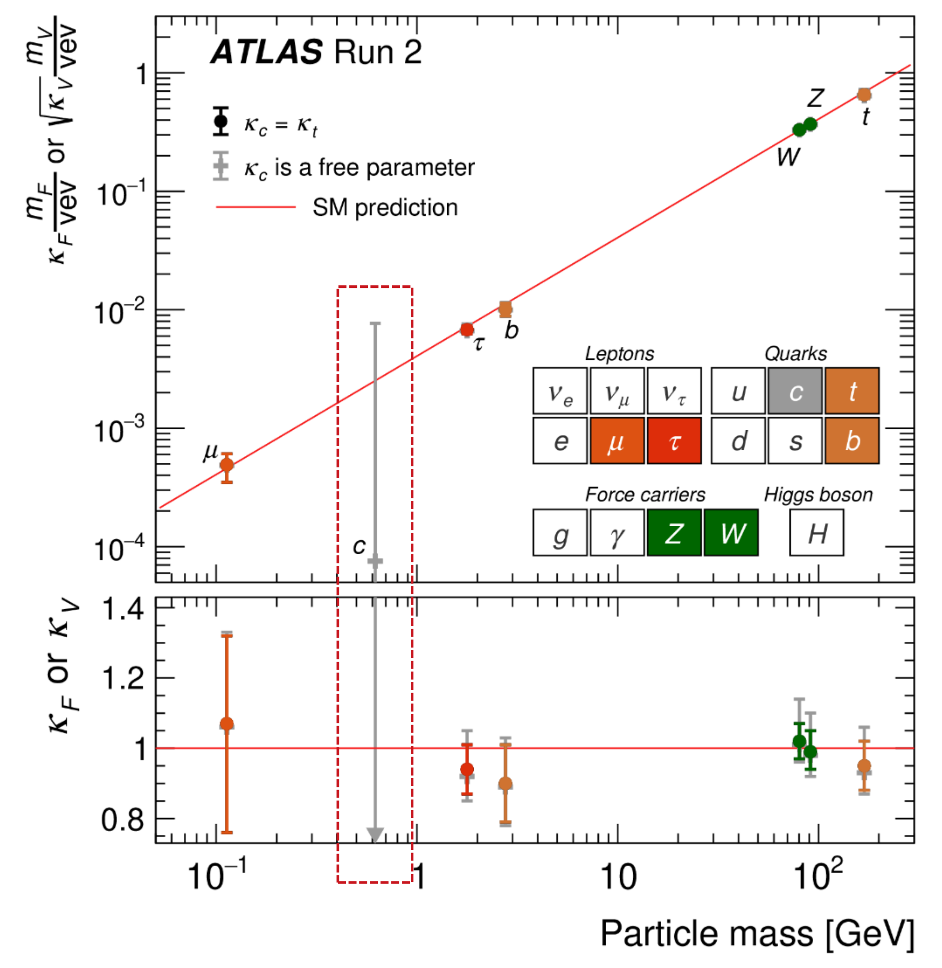


direct couplings

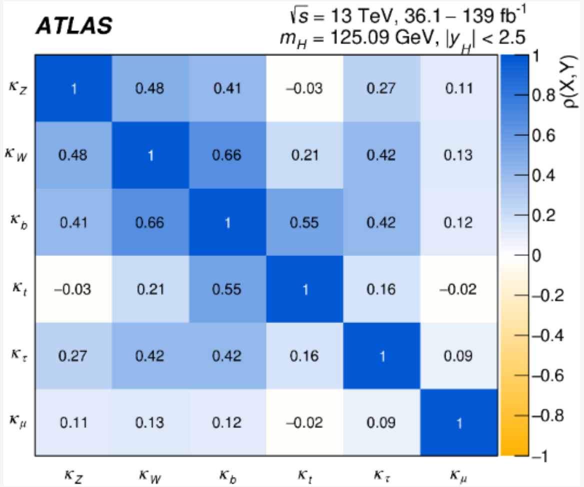


effective couplings

Higgs Couplings to Each Particle

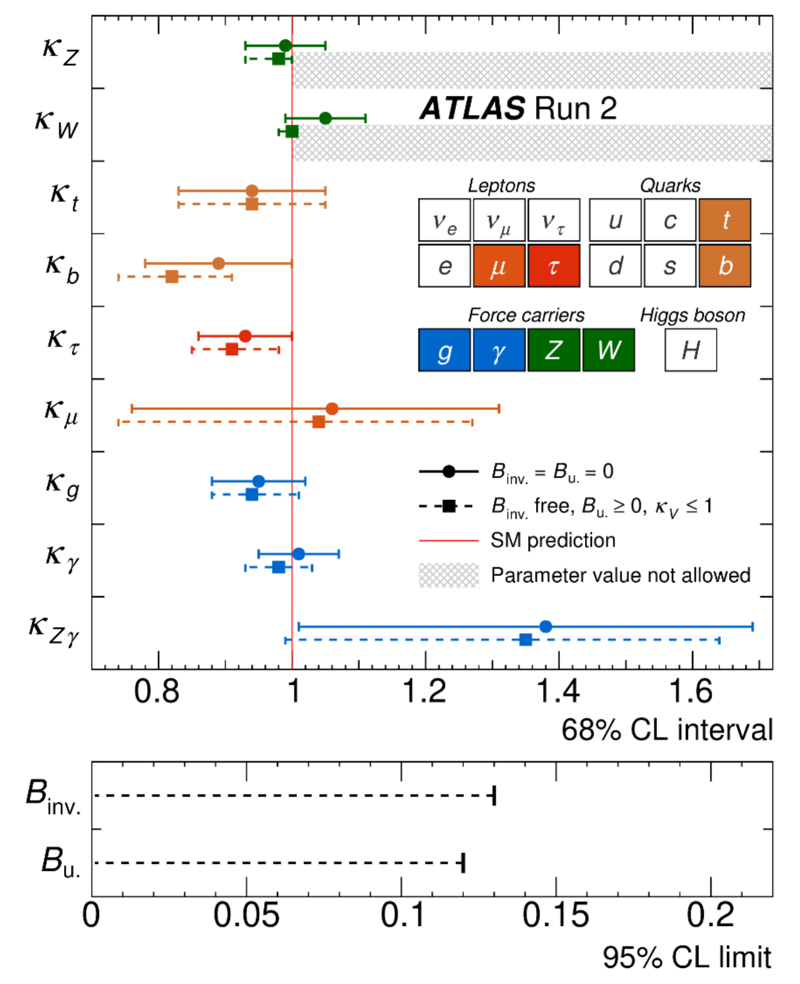


- All modifiers assumed to be positive
- Only **SM processes**
- Two scenarios: $\boldsymbol{\kappa_c = \kappa_t}$ and $\boldsymbol{\kappa_c}$ **free-floating**
  - Upper limit on κ_c of 5.7 (7.6) x SM at 95% CL
- Results
  - Fermions (t, b, τ): precision of 7%~12%
  - Vector bosons (W, Z): precision of 5%
  - SM compatibility (p-value): 56% ($\kappa_c = \kappa_t$) and 65% (κ_c free-floating)



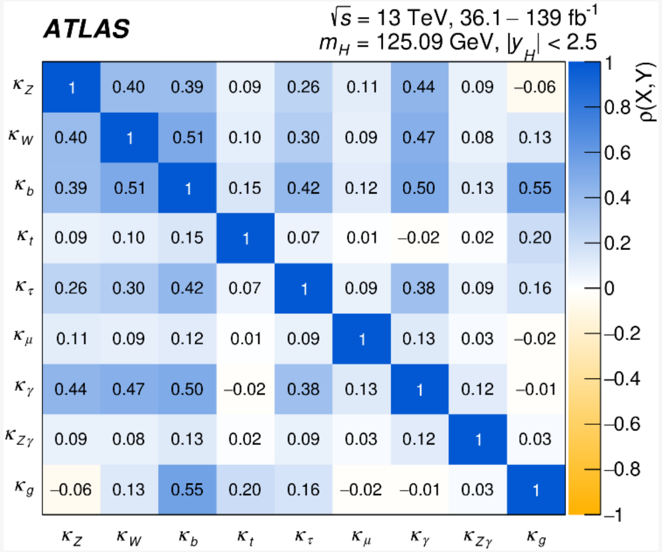
	κ_Z	κ_W	κ_b	κ_t	κ_τ	κ_μ
κ_Z	1	0.48	0.41	−0.03	0.27	0.11
κ_W	0.48	1	0.66	0.21	0.42	0.13
κ_b	0.41	0.66	1	0.55	0.42	0.12
κ_t	−0.03	0.21	0.55	1	0.16	−0.02
κ_τ	0.27	0.42	0.42	0.16	1	0.09
κ_μ	0.11	0.13	0.12	−0.02	0.09	1

Higgs Generic Couplings



- Allowing for **non-SM particles** in loop processes, with **effective coupling** strengths.

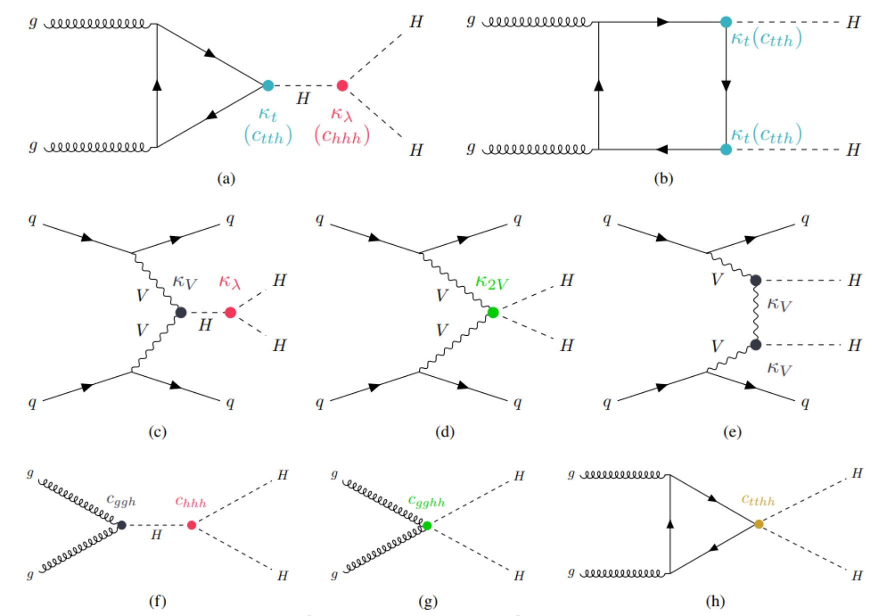
- Two scenarios: with and without invisible and undetected non-SM Higgs decays
- Results
  - SM compatibility (p-value): 61% ($B_{inv.} = B_{u.} = 0$)
  - Upper limits: $B_{inv.} < 0.13$ (0.08) and $B_{u.} < 0.12$ (0.21) at 95% CL



	κ_Z	κ_W	κ_b	κ_t	κ_τ	κ_μ	κ_γ	$\kappa_{Z\gamma}$	κ_g
κ_Z	1	0.40	0.39	0.09	0.26	0.11	0.44	0.09	−0.06
κ_W	0.40	1	0.51	0.10	0.30	0.09	0.47	0.08	0.13
κ_b	0.39	0.51	1	0.15	0.42	0.12	0.50	0.13	0.55
κ_t	0.09	0.10	0.15	1	0.07	0.01	−0.02	0.02	0.20
κ_τ	0.26	0.30	0.42	0.07	1	0.09	0.38	0.09	0.16
κ_μ	0.11	0.09	0.12	0.01	0.09	1	0.13	0.03	−0.02
κ_γ	0.44	0.47	0.50	−0.02	0.38	0.13	1	0.12	−0.01
$\kappa_{Z\gamma}$	0.09	0.08	0.13	0.02	0.09	0.03	0.12	1	0.03
κ_g	−0.06	0.13	0.55	0.20	0.16	−0.02	−0.01	0.03	1

Combination for Higgs Self-Coupling

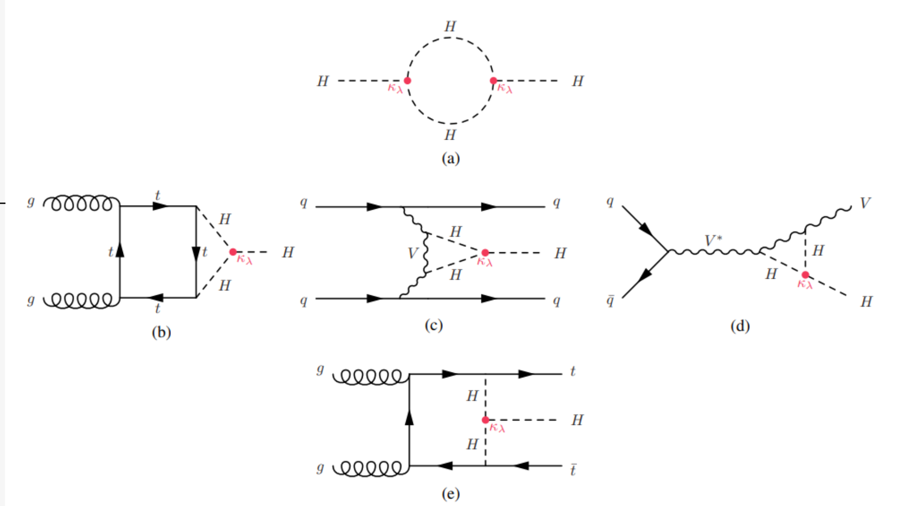
- Higgs has coupling to itself as well: Higgs self-coupling
- Higgs self-coupling plays an important role in
  - Understanding Higgs mechanism itself
  - Predicting the stability of the universe



di-Higgs productions

direct sensitivity

$$\mathcal{A}(\kappa_t,\kappa_\lambda)=\kappa_t^2\mathcal{A}_1+\kappa_t\kappa_\lambda\mathcal{A}_2,$$



single-Higgs productions

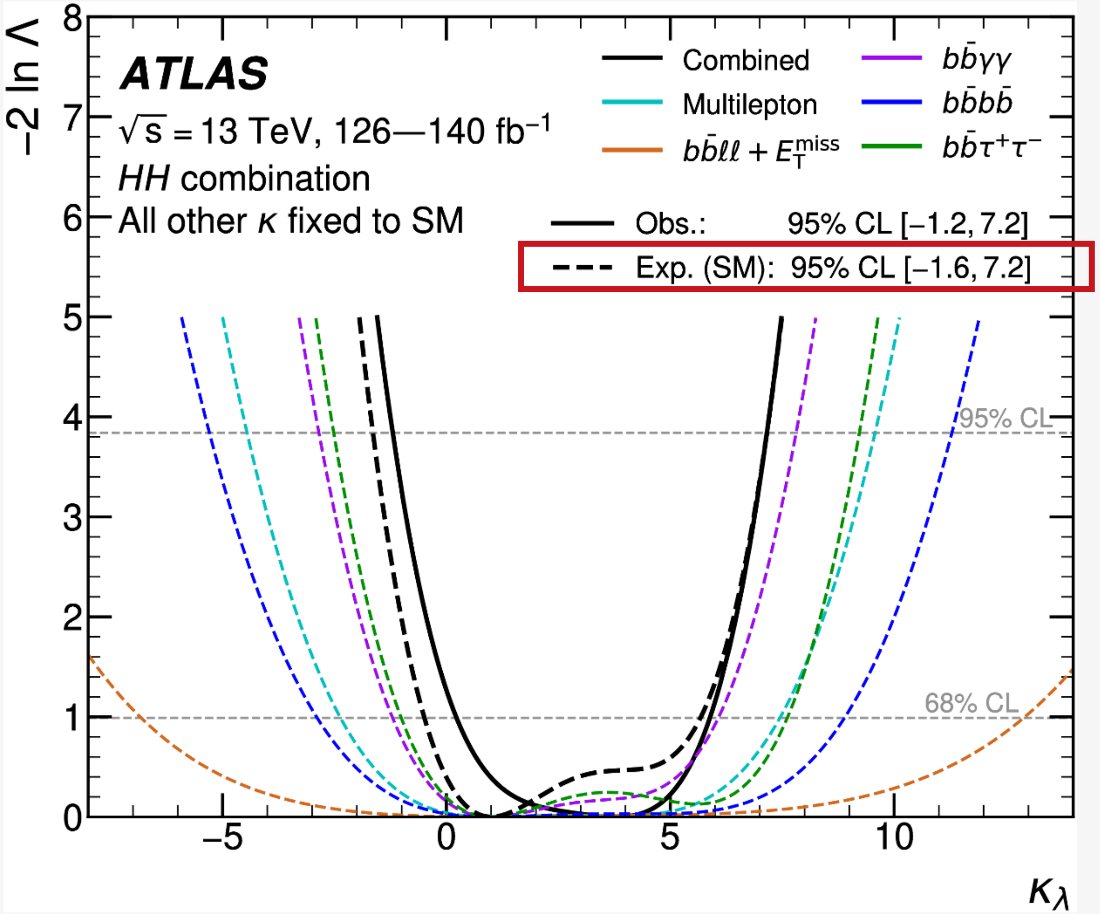
sensitivity through EW corrections

$$\mu_i(\kappa_\lambda,\kappa_i)=\frac{\sigma^{\mathrm{BSM}}}{\sigma^{\mathrm{SM}}}=Z_H^{\mathrm{BSM}}(\kappa_\lambda)\left[\kappa_i^2+\frac{(\kappa_\lambda-1)C_1^i}{K_{\mathrm{EW}}^i}\right],$$

Higgs Self-Coupling from Di-Higgs

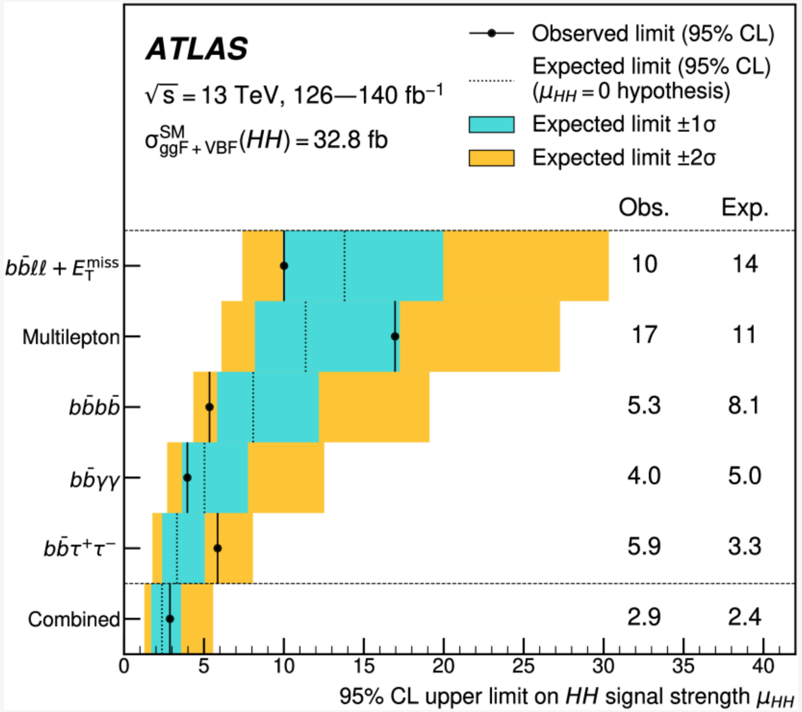
accepted by PRL

- Constraint on κ_λ from di-Higgs combination



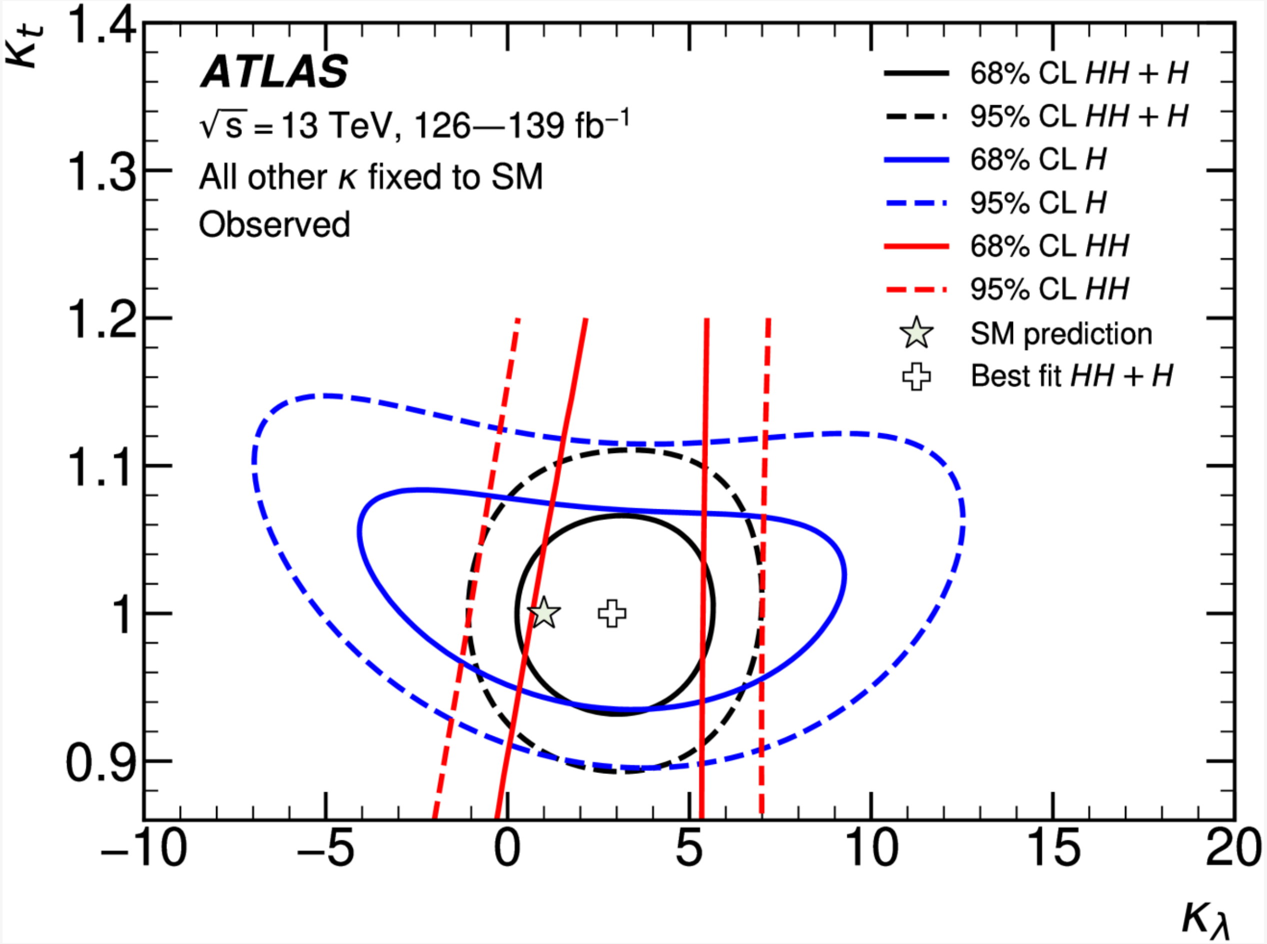
- Provides the **best expected sensitivities** to the di-Higgs production cross-section and the Higgs boson self-coupling.

- Di-Higgs production cross-section:



Higgs Self-Coupling vs Higgs to Top Coupling

Phys. Lett. B 843 (2023) 137745



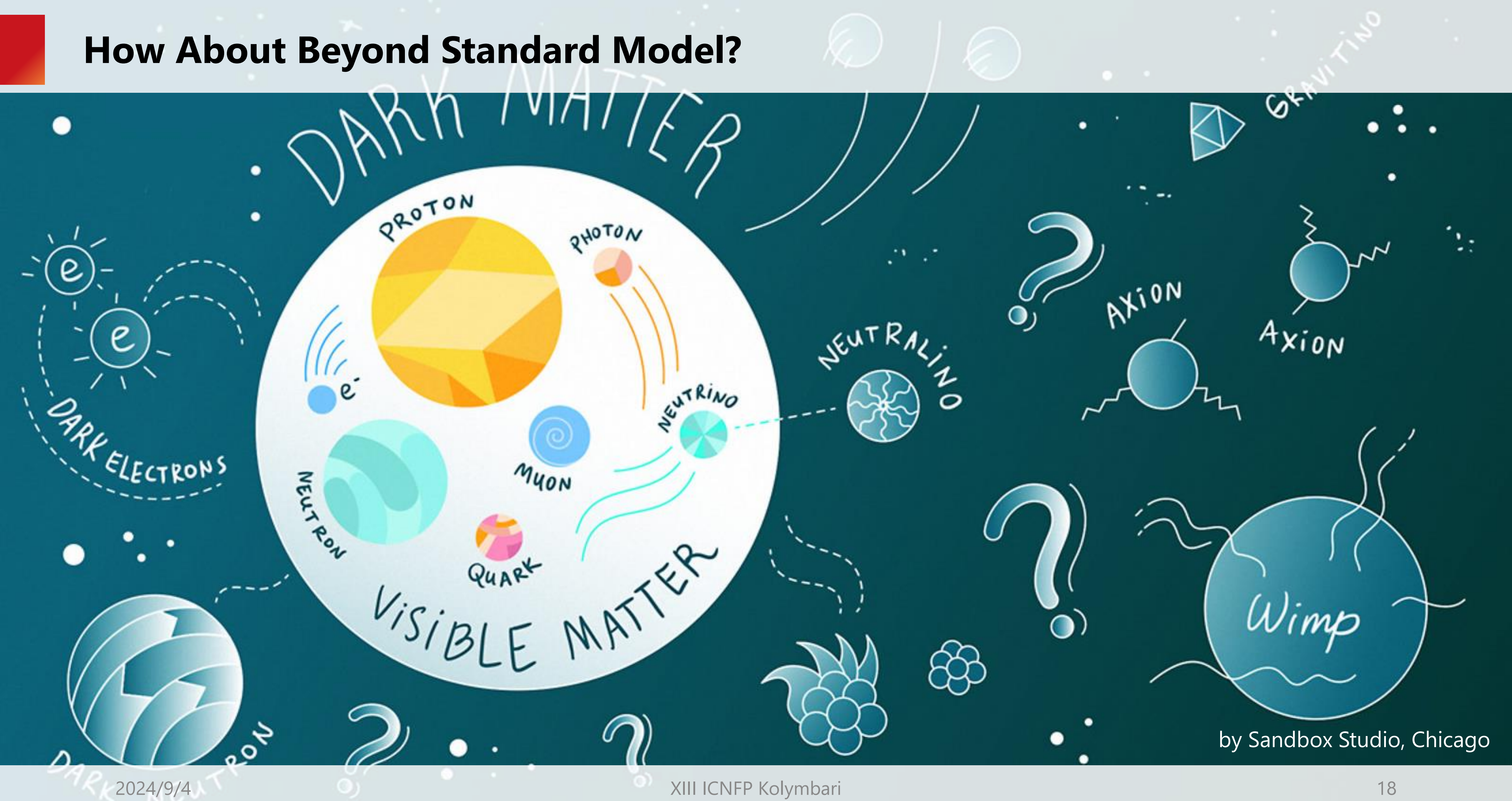
- **single-Higgs** processes help to relax assumptions about couplings to other SM particles, e.g., to top

- 95% CL:

  $$-2.2 < \kappa\lambda < 7.7 \text{ (exp)}$$

  - Constraints on κ_λ with floated κ_t are almost as strong as those with its value fixed to unity

How About Beyond Standard Model?

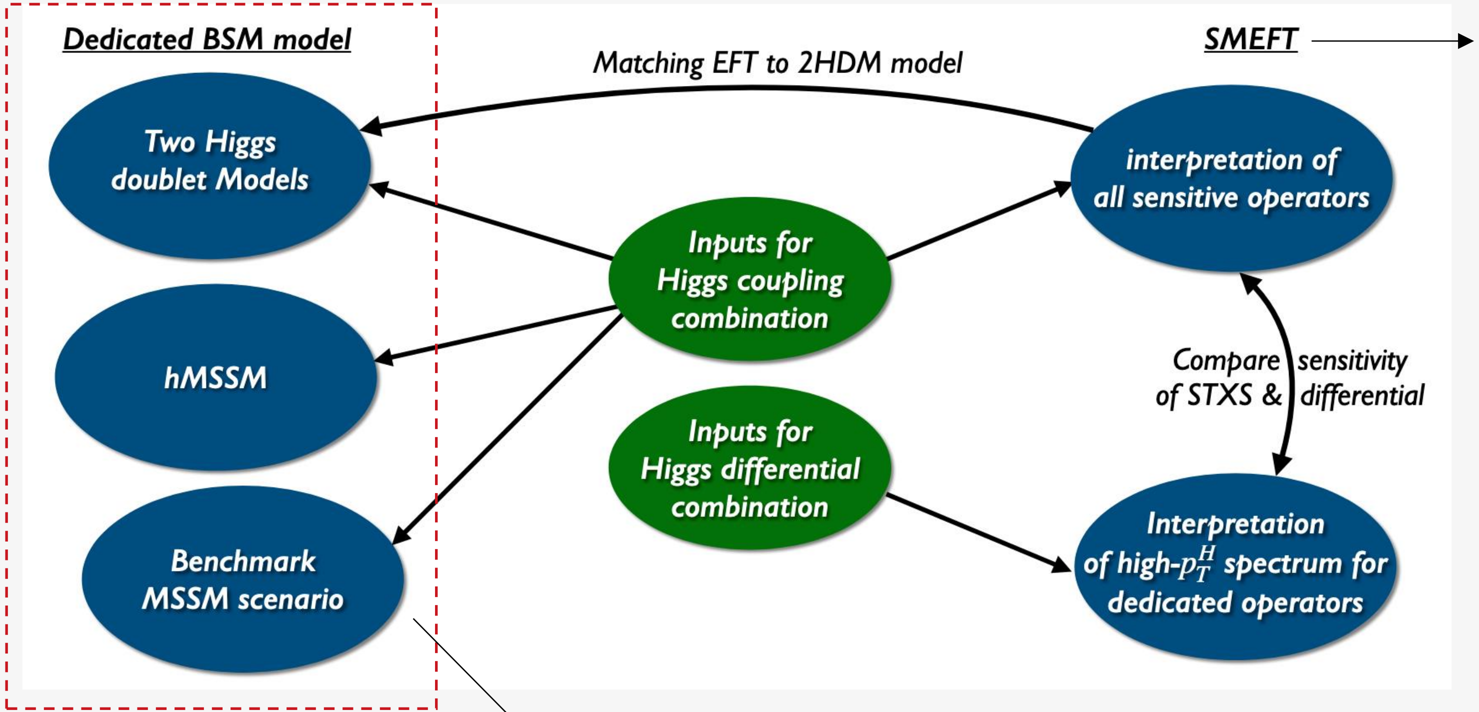


by Sandbox Studio, Chicago

Interpretation Strategies

Submitted to JHEP

- 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

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

- **2-Higgs-doublet model** and **supersymmetric model** allow for direct searches 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 language of the SMEFT, the effects of BSM dynamics at a high energy Λ = 1 TeV can be parametrized at low energies, E << Λ, in terms of higher-dimensional operators from the Standard Model fields and respecting its symmetries:

Wilson coefficients
to be measured

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

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

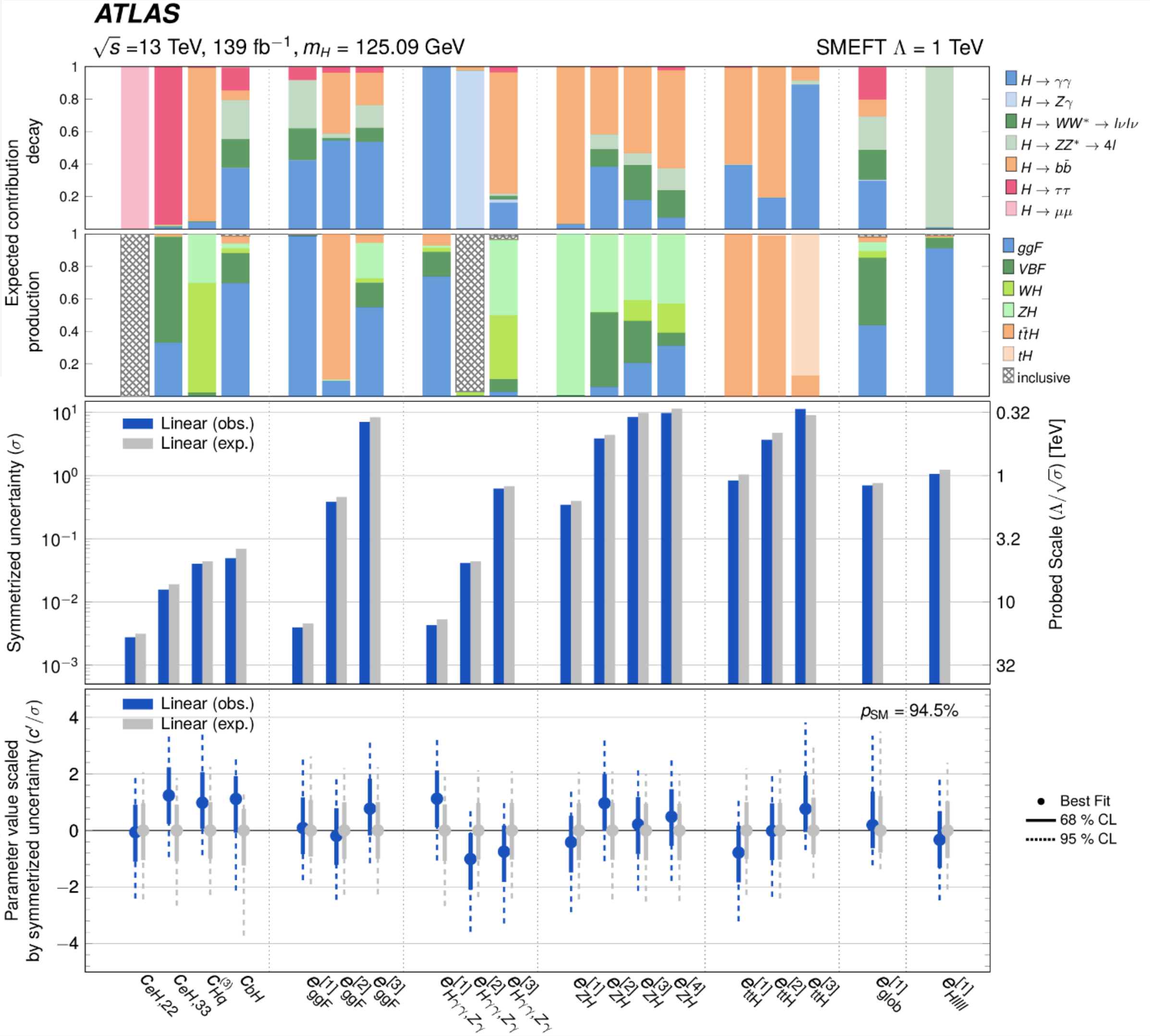
Linearized model: consists of terms involving a single d = 6 SMEFT operator, suppressed by Λ^{-2}

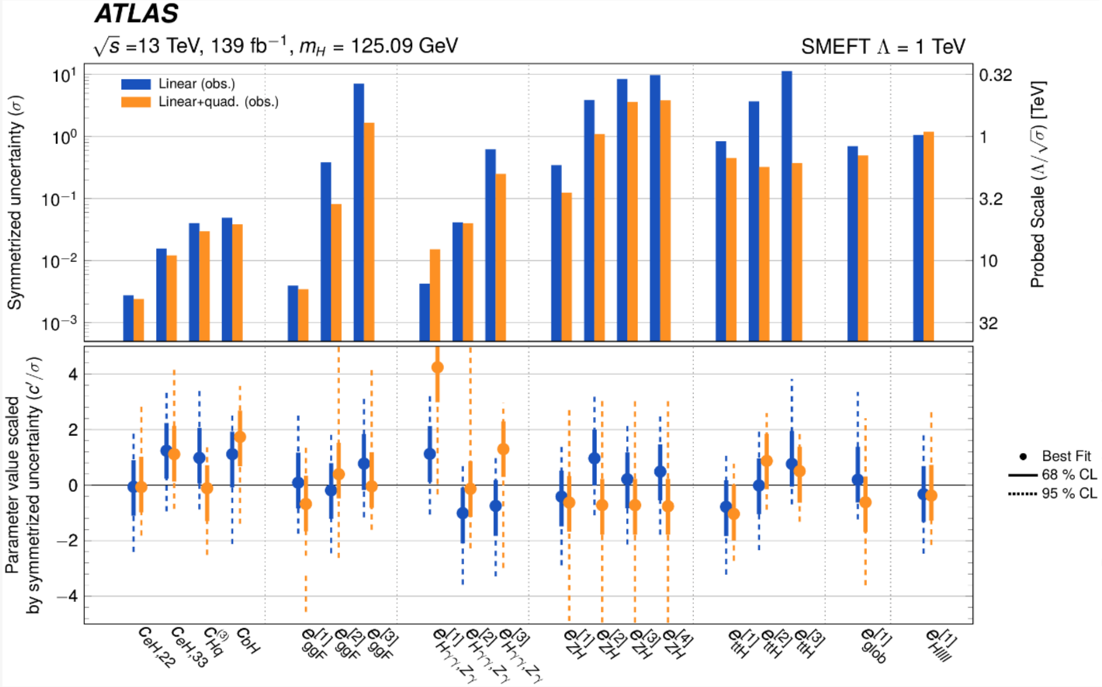
Quadratic model: consists of terms involving products of two d = 6 SMEFT operator, suppressed by Λ^{-4} as well

- Comparison between them helps to understand if the EFT expansion is valid

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 EFT operators contributing to the same measured final states
- Bottom left: comparison of linearized and quadratic model



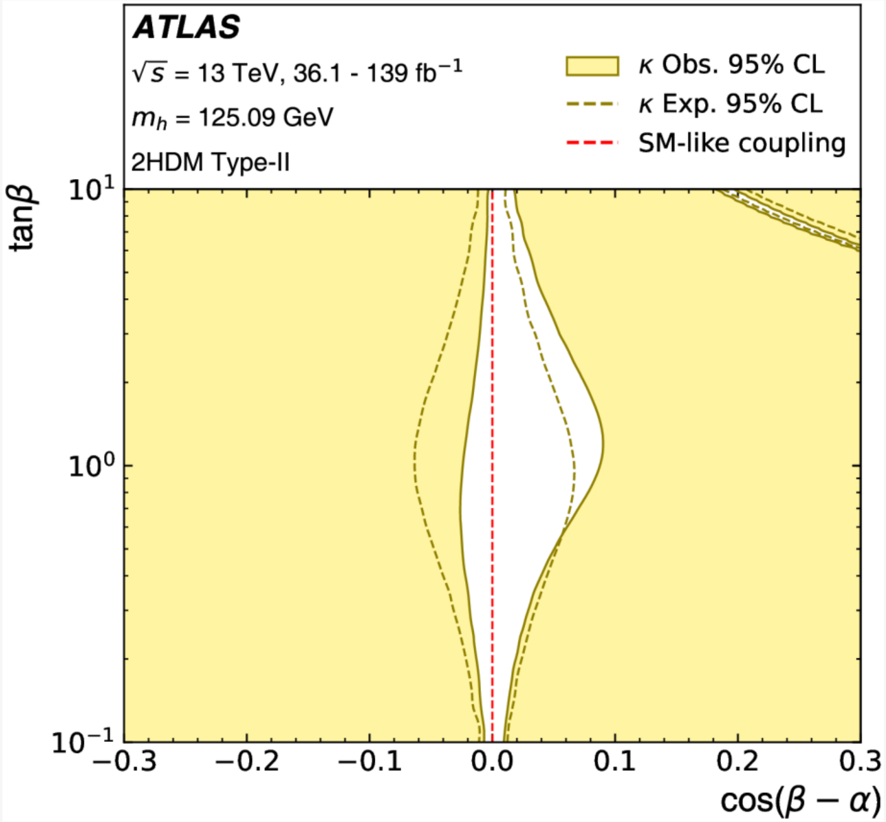


Two-Higgs-Doublet Models

- 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
- Four types of 2HDM models based on couplings

- Take Type-II model as an example
  - Φ_1 has coupling to down-type quarks while Φ_2 to up-type & leptons
  - Of great interest due to its resemblance with the SM in the quark sector

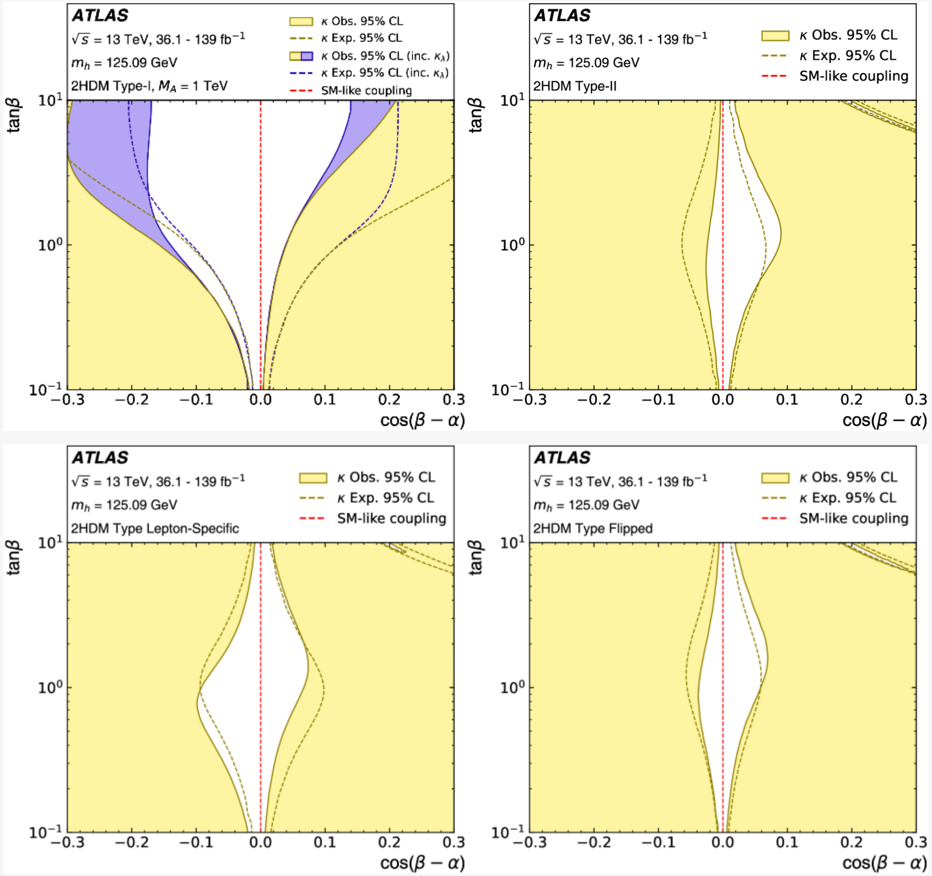
- Two parameters are measured in this analysis
  - tan**β**$=v_2/v_1$, $v_{1,2}$ are vacuum-expectation-values of the doublets
  - **α**: mixing angle of the CP even neutral Higgs bosons



Results of 2HDM

- The measured signal strength μ is reparametrized by using α & β:

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

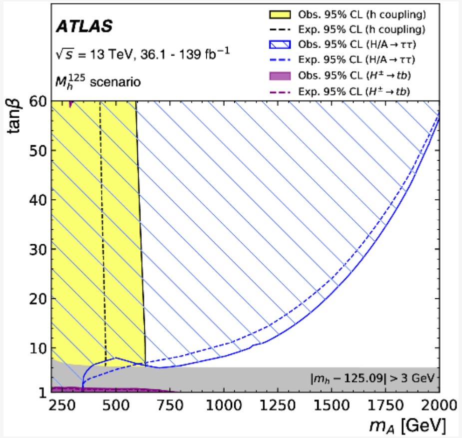


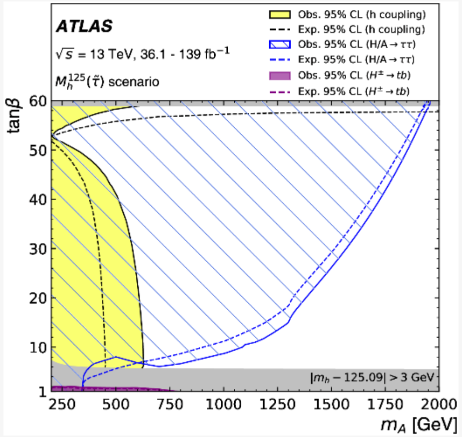
- All models exhibit similar exclusion regions in the (tanβ, cos(β−α)) plane at low values (<<1) of tanβ
- The interval of allowed values of cos(β−α) increases in size with tanβ, up to a total width of about 0.1–0.2 for tanβ=1

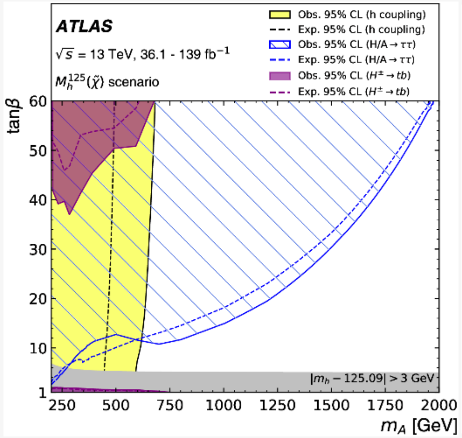
- A small allowed region in all types but Type-I corresponds to the fermion couplings that have same magnitude as in the SM but the opposite sign

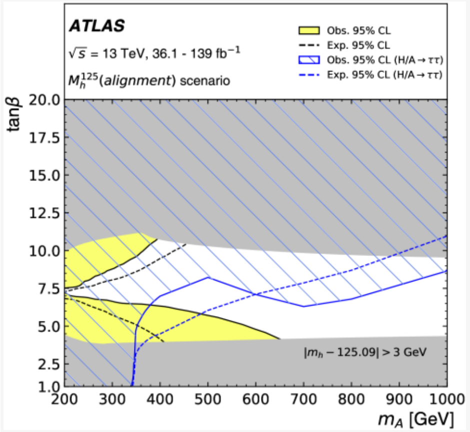
Results of MSSM Interpretation

- 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

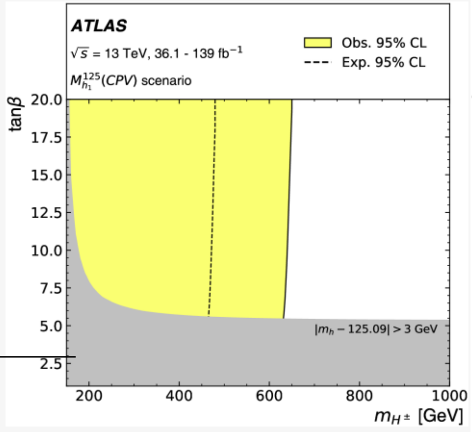


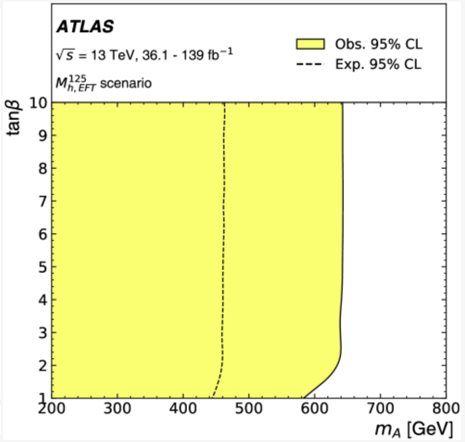


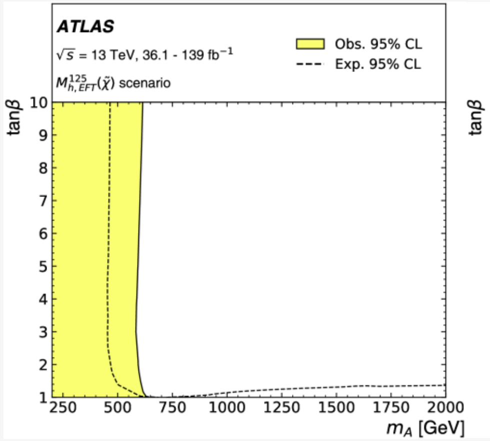


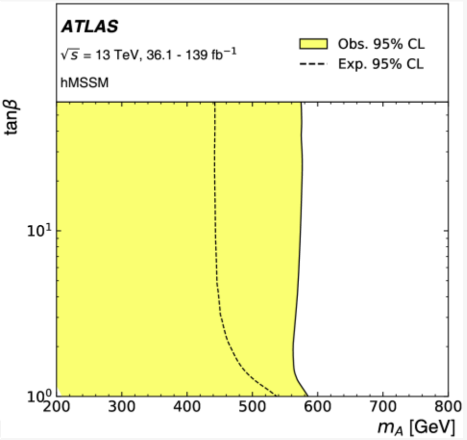


Grey band: excluded by the requirement $|m_h$-125.09GeV$|$









Summary

- In the tenth anniversary of Higgs discovery, ATLAS experiment presented combination measurements on its coupling and beyond Standard Model interpretations with unprecedented precision
  - All main production and decay modes are observed
  - Hints of rare Higgs decays have been seen
  - **Kinematic dependence of production cross sections** has been studied across a wide range of phase space
  - **Higgs couplings to other particles** are measured
  - **Higgs self-coupling** is constrained from single-Higgs and di-Higgs combination
  - **BSM searches** show no deviation
- All these results are in good agreement with SM

- What will we see in the next ten years?

上海交通大學

SHANGHAI JIAO TONG UNIVERSITY

Thank You!

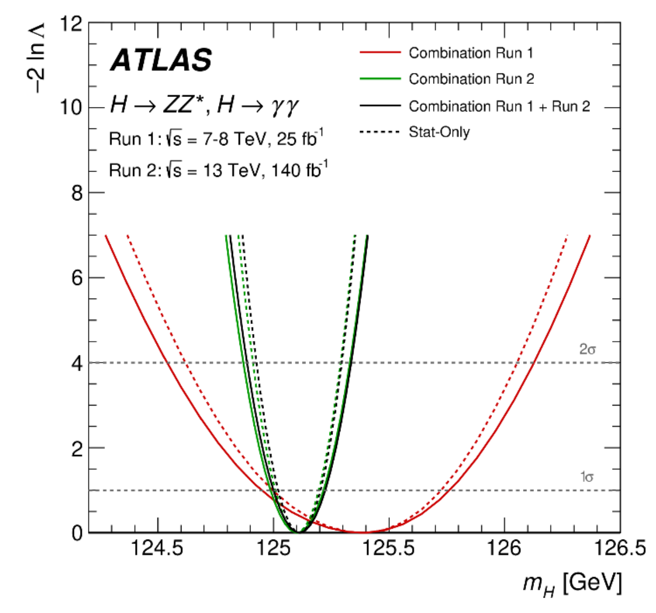
饮水思源 爱国荣校

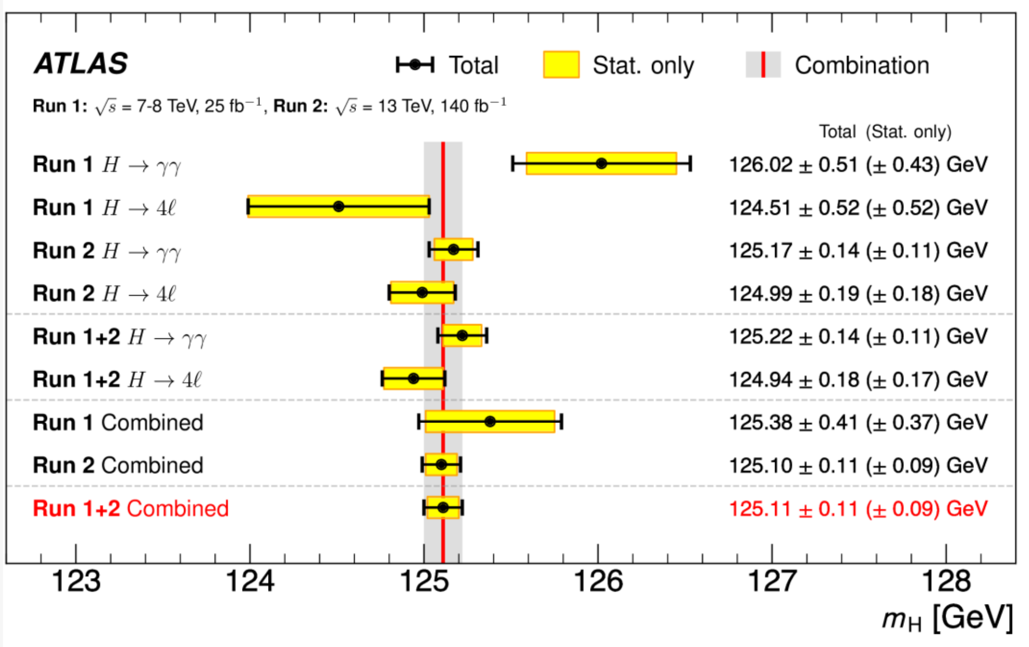
Higgs Mass Combination

Phys. Rev. Lett. 131 (2023) 251802

- A measurement of the mass of the Higgs boson combining the Run 1 and Run 2 **H→ZZ→4l** and **H→γγ** analyses
  - The most suitable processes to measure m_H at the LHC due to their excellent mass resolution

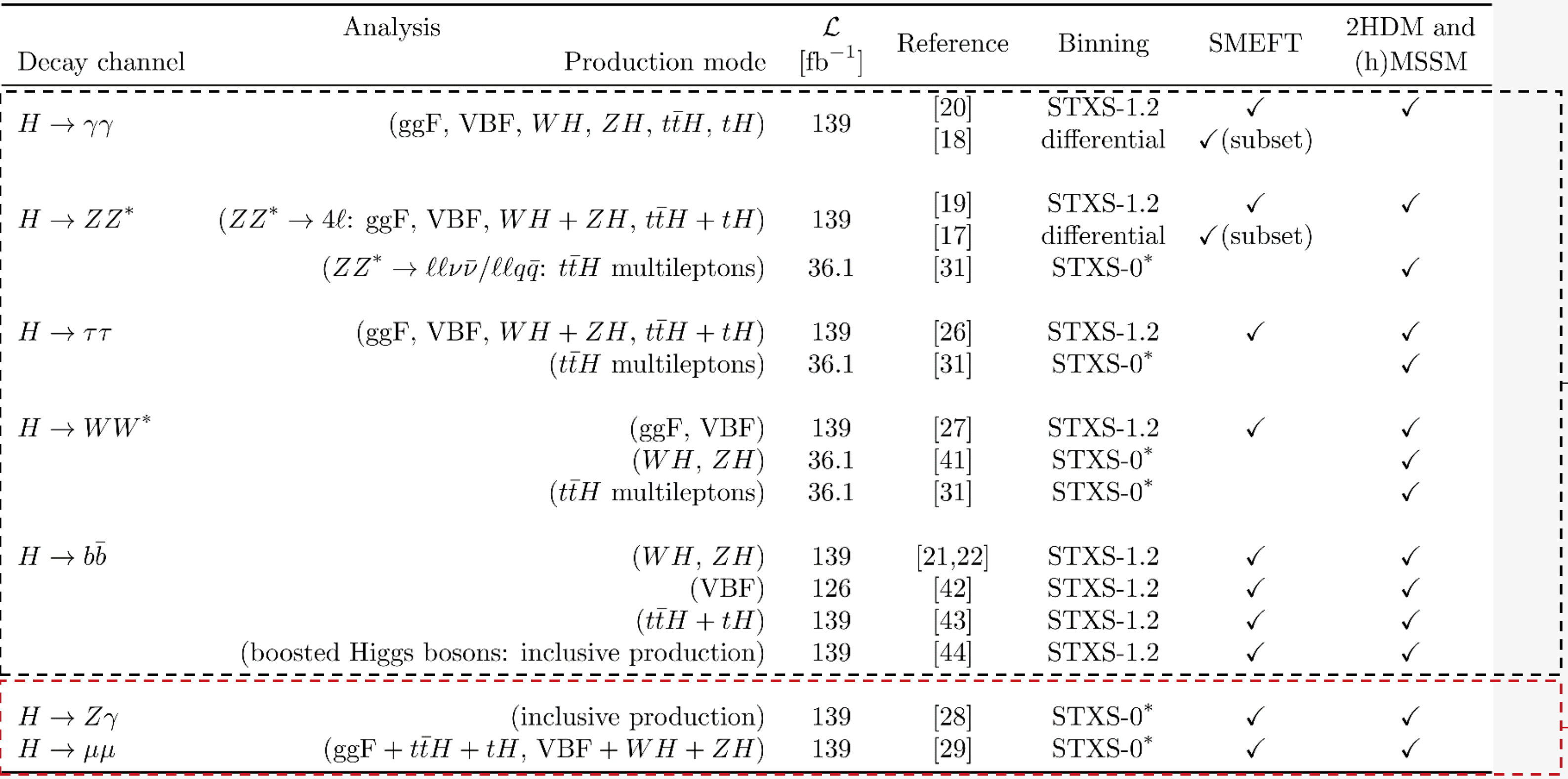
- Result **m_H = 125.11 ± 0.09 (stat.) ± 0.06 (syst.) GeV**
  - Most precise measurement of the Higgs boson mass, thanks to the improvement in object calibration and increase in data statistics





Input Analyses for the Interpretations

- All observed Higgs decay modes and two rare decays included



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

input analyses

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

Main decay modes:

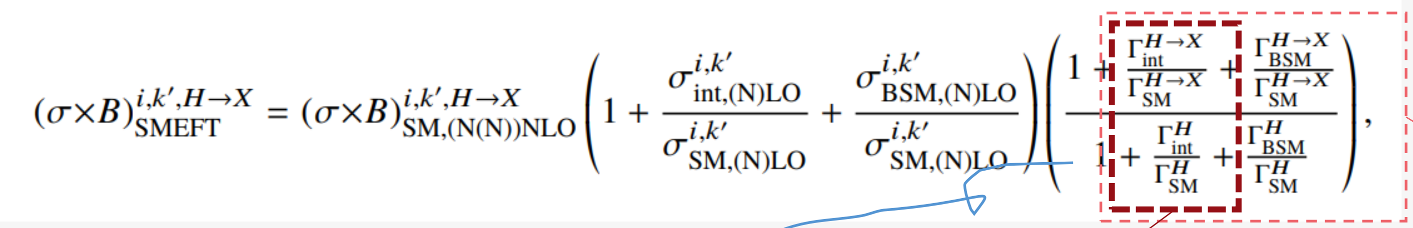
- **All** inputs from the coupling combination wherever STXS available

Rare decays:

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

Linearized and quadratic models

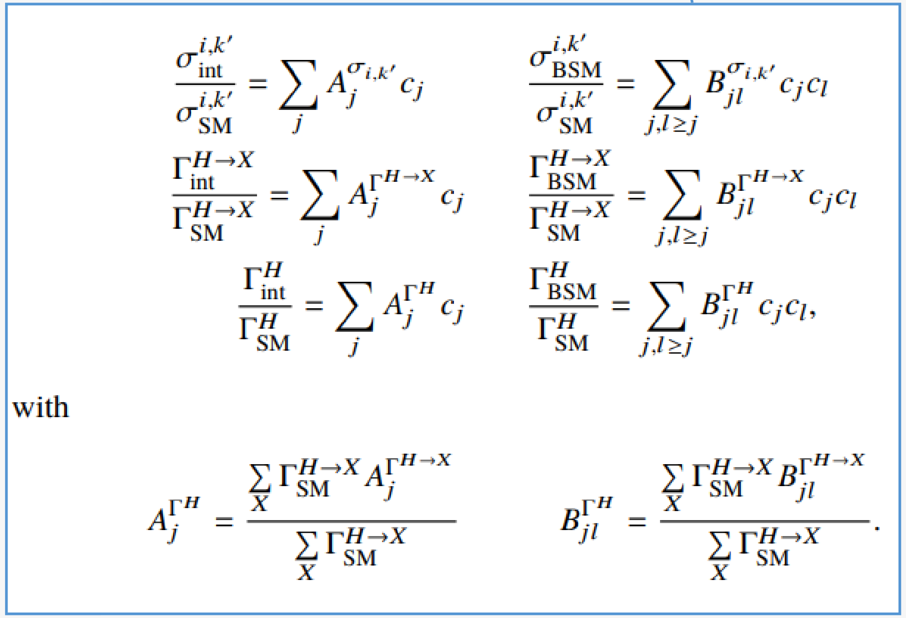
- We further modified the Higgs productions and decays to reveal the impact of these SMEFT operators :



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

Consider this term only: **linearized model**

Consider both the terms: **quadratic model**



$$\frac{\sigma^{i,k'}_{\text{int}}}{\sigma^{i,k'}_{\text{SM}}} = \sum_j A^{\sigma_{i,k'}}_j c_j \qquad \frac{\sigma^{i,k'}_{\text{BSM}}}{\sigma^{i,k'}_{\text{SM}}} = \sum_{j,l\geq j} B^{\sigma_{i,k'}}_{jl} c_j c_l$$

$$\frac{\Gamma^{H\to X}_{\text{int}}}{\Gamma^{H\to X}_{\text{SM}}} = \sum_j A^{\Gamma^{H\to X}}_j c_j \qquad \frac{\Gamma^{H\to X}_{\text{BSM}}}{\Gamma^{H\to X}_{\text{SM}}} = \sum_{j,l\geq j} B^{\Gamma^{H\to X}}_{jl} c_j c_l$$

$$\frac{\Gamma^{H}_{\text{int}}}{\Gamma^{H}_{\text{SM}}} = \sum_j A^{\Gamma^{H}}_j c_j \qquad \frac{\Gamma^{H}_{\text{BSM}}}{\Gamma^{H}_{\text{SM}}} = \sum_{j,l\geq j} B^{\Gamma^{H}}_{jl} c_j c_l,$$

with

$$A^{\Gamma^H}_j = \frac{\sum_X \Gamma^{H\to X}_{\text{SM}} A^{\Gamma^{H\to X}}_j}{\sum_X \Gamma^{H\to X}_{\text{SM}}} \qquad B^{\Gamma^H}_{jl} = \frac{\sum_X \Gamma^{H\to X}_{\text{SM}} B^{\Gamma^{H\to X}}_{jl}}{\sum_X \Gamma^{H\to X}_{\text{SM}}}.$$

- 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

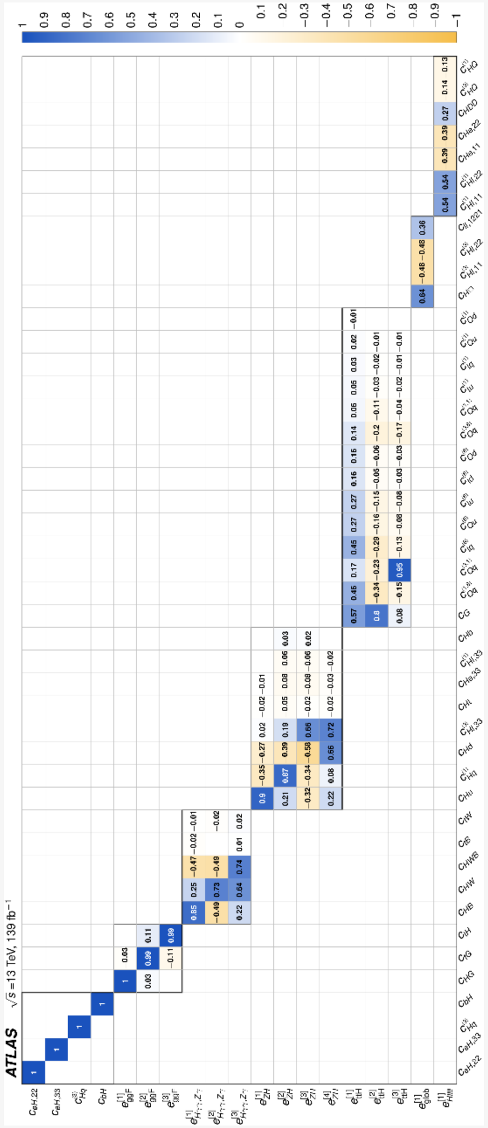
$$
\begin{aligned}
\boldsymbol{c} = \;& \{c_{eH,22}\} \cup \\
& \{c_{eH,33}\} \cup \\
& \{c_{Hq}^{(3)}\} \cup \\
& \{c_{bH}\} \cup \\
& \{c_{HG}, c_{tG}, c_{tH}\} \cup \\
& \{c_{HB}, c_{HW}, c_{HWB}, c_{tB}, c_{tW}\} \cup \\
& \{c_{Hu}, c_{Hq}^{(1)}, c_{Hd}, c_{Hl,33}^{(3)}, \\
& \qquad c_{Ht}, c_{He,33},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

Original Wilson coefficients

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

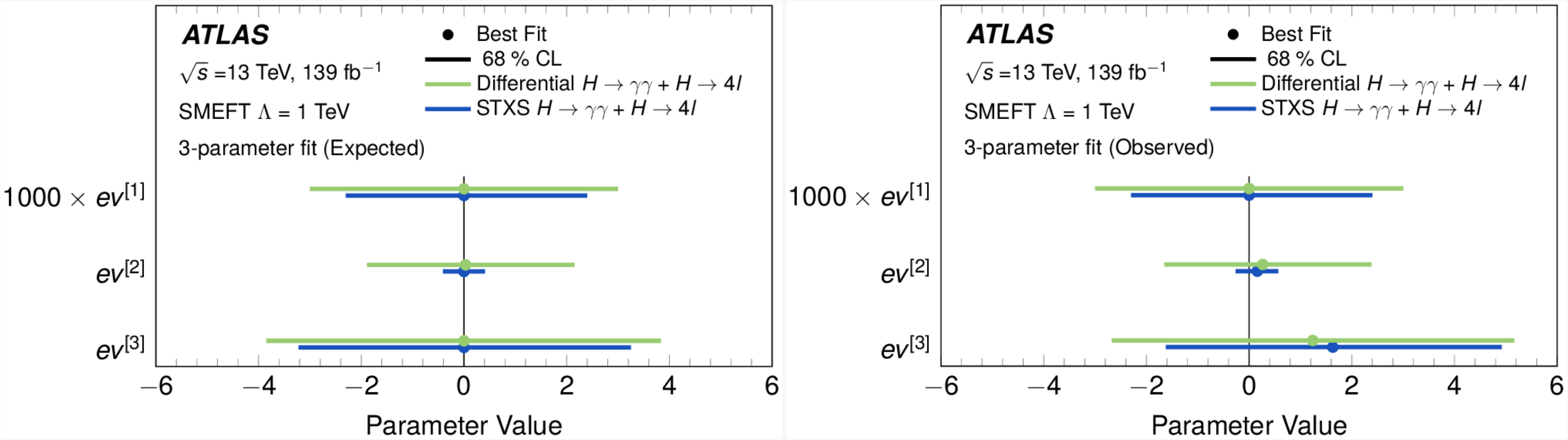
Coefficients measured in this analysis

- 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



EFT differential results

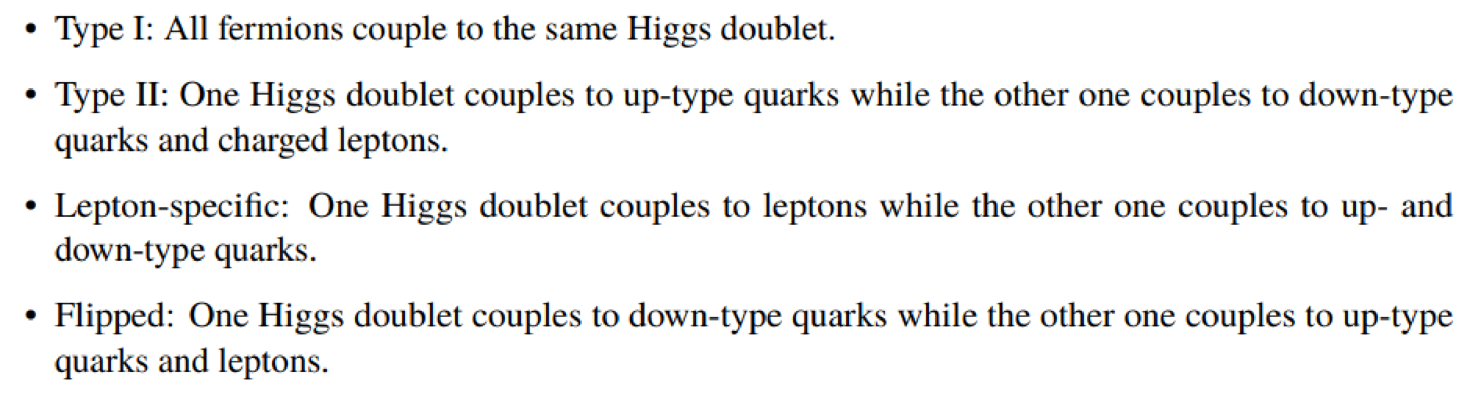
- Anomalous couplings of the Higgs boson to gluons and top quarks, as well as between gluons and top-quarks, can affect the total Higgs boson production cross-section and its dependence on the Higgs boson transverse momentum
- The expected deviations from the SM predictions due to these anomalous couplings can be relatively large in high Higgs boson pT regions, which are also characterized by a better signal-to-background ratio, making the $p^{H}{}_{\mathrm{T}}$-differential cross-section measurement more sensitive to these effects compared to a measurement of the inclusive rate



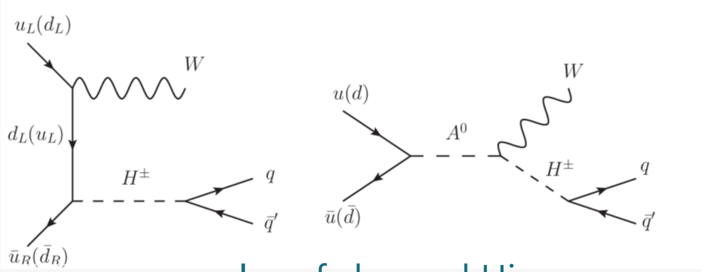
Two-Higgs-Doublet Models

- 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 $\Phi_{1,2}$ 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. Glashow and S. Weinberg, E. Paschos), which are strongly constrained by existing data, and implies that all fermions with the same quantum numbers couple to only one Higgs doublet



- 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.

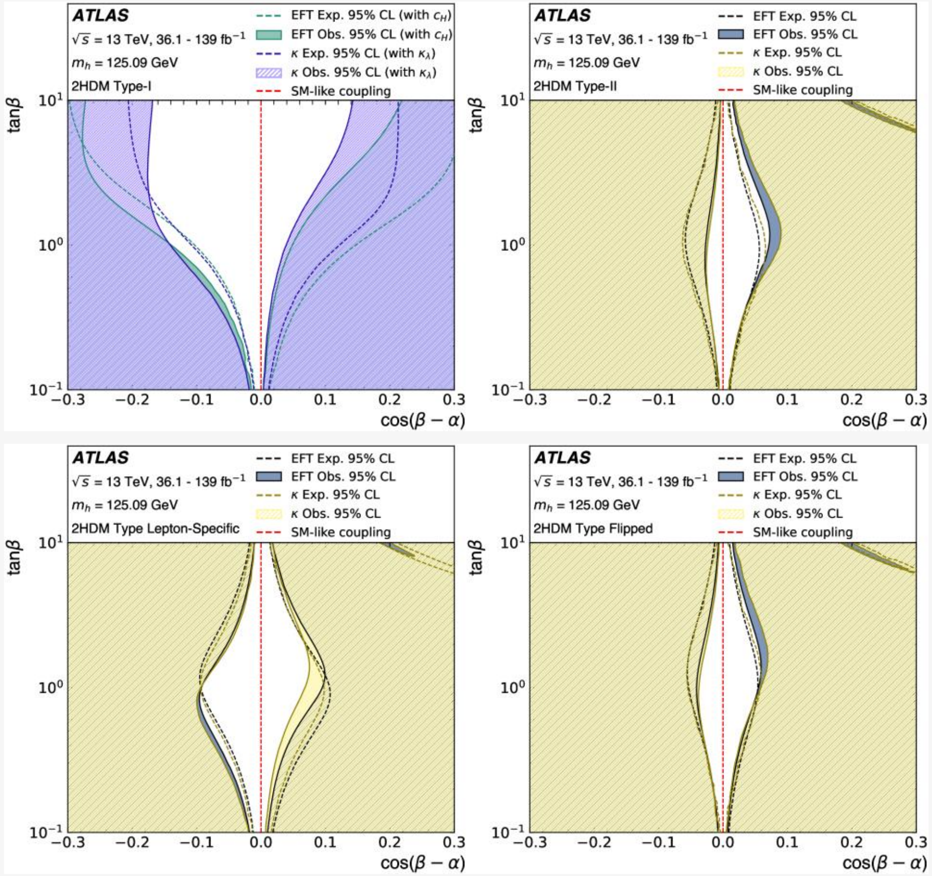


examples of charged Higgs

Results of 2HDM Based on κ-framework

- The modifications introduced in 2HDM could also be generated by using the κ-framework:

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



- 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 coefficients are considered