

Global fit of 2HDM with future collider results

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- (EF04) EW Precision Physics and constraining new physics
- (EF08) BSM: Model specific explorations
- (TF07) Collider phenomenology

Abstract

In this work, we summarize a global fit study of Type-II two Higgs doublet models (2HDM), and explore the impact of future SM-like Higgs and Z -pole precision measurements on the allowed parameter space. The work is based on the study results of a global fit of 2HDMs with the tool **GAMBIT**, utilising various current constraints including theoretical constraints (unitarity, perturbativity and vacuum stability), Higgs searches at colliders, electroweak physics and flavour constraints. We further investigate the ability of future facilities, such as the HL-LHC, CEPC, ILC and FCC-ee to explore the 2HDM parameter space.

1 Introduction

The discovery of a Standard Model (SM)-like Higgs boson at the Large Hadron Collider (LHC) set a milestone for high energy physics, confirming the self-consistency of the SM. At

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the same time there are also various unsolved mysteries, such as the source of dark matter, the origin of the baryon asymmetry of the universe, and the muon $g-2$ anomaly. Models with extended Higgs sectors provide promising solutions to these problems.

As one of the simplest such frameworks, the Two Higgs Doublet Model (2HDM) is embedded in various models with extended Higgs sectors, such as the Minimal Supersymmetric Standard Model, and gauge extensions (such as the Left-Right symmetric model). After electroweak symmetry breaking (EWSB), the general CP-conserving 2HDM can generate five physical eigenstates: the observed 125 GeV CP-even neutral scalar h , an additional CP-even neutral scalar H , one CP-odd Higgs boson A , and a pair of charged Higgs bosons H^\pm [1]. Exploring the properties of 2HDMs with various experimental constraints can help us understand the new physics potential of a broad class of BSM scenarios.

In this paper, we present preliminary results of a forthcoming global fit of the Z_2 -Yukawa symmetric, Type-II 2HDM [2]. This analysis is carried out using the open-source tool **GAMBIT** [3] (Global and Modular beyond-Standard Model Inference Tool) **GAMBIT** is compatible with both the Bayesian and frequentist statistical frameworks, and we here focus on frequentist results obtained with the **Diver** [4] implementation of the differential evolution algorithm. We investigate the effect of theoretical constraints (unitarity, perturbativity and vacuum stability), Higgs searches at colliders, electroweak physics and flavour constraints individually, as well as displaying the final results with all constraints. We also investigate the impact on the allowed parameter space of a series of future collider measurements, by reweighting the likelihoods of the **GAMBIT** samples outside of the **GAMBIT** framework

Our paper is organised as follows. Section 2 provides the details of our assumed future collider measurements. Section 3 summarises the general 2HDM and our results are presented in Section 4.

2 Higgs precision measurements at future lepton colliders

At future lepton colliders, the dominant channel to measure the properties of the Higgs boson is the Higgsstrahlung process, $e^+e^- \rightarrow hZ$, at center of mass energies (\sqrt{s}) of around 240–250 GeV. Due to the nature of lepton colliders, both the inclusive cross section, $\sigma(hZ)$, and the exclusive $\sigma(hZ) \times \text{BR}$ values for different Higgs decay modes, can be measured with remarkable precision. The invisible decay width of the Higgs can also be very well constrained. In addition, the cross section for a Higgs production via the WW fusion process grows with energy. While it cannot be measured very well at 240–250 GeV, at higher center of mass energies (in particular, at linear colliders), such a fusion process becomes significantly more important and can provide crucial complementary information. For $\sqrt{s} > 500$ GeV, tth production can also be investigated.

When investigating the impact of future facilities, our study makes use of the following scenarios of various machines (in terms of the center of mass energy and the corresponding integrated luminosity), as well as the estimated precision of relevant Higgs measurements:

- **CEPC** According to the preCDR [10], CEPC plans to collect 5 ab^{-1} data points at 240 GeV. The estimated precision of measurements for the Higgsstrahlung process $e^+e^- \rightarrow hZ$ with various final states, as well as the WW fusion process with Higgs

collider	CEPC	FCC-ee			ILC				
\sqrt{s}	240 GeV	240 GeV	365 GeV		250 GeV	350 GeV		500 GeV	
$\int \mathcal{L} dt$	5.6 ab ⁻¹	5 ab ⁻¹	1.5 ab ⁻¹		2 ab ⁻¹	200 fb ⁻¹		4 ab ⁻¹	
production	Zh	Zh	Zh	$\nu\bar{\nu}h$	Zh	Zh	$\nu\bar{\nu}h$	Zh	$\nu\bar{\nu}h$
$\Delta\sigma/\sigma$	0.5%	0.5%	0.9%	–	0.71%	2.0%	–	1.05	–
decay	$\Delta(\sigma \cdot BR)/(\sigma \cdot BR)$								
$h \rightarrow b\bar{b}$	0.27%	0.3%	0.5%	0.9%	0.46%	1.7%	2.0%	0.63%	0.23%
$h \rightarrow c\bar{c}$	3.3%	2.2%	6.5%	10%	2.9%	12.3%	21.2%	4.5%	2.2%
$h \rightarrow gg$	1.3%	1.9%	3.5%	4.5%	2.5%	9.4%	8.6%	3.8%	1.5%
$h \rightarrow WW^*$	1.0%	1.2%	2.6%	3.0%	1.6%	6.3%	6.4%	1.9%	0.85%
$h \rightarrow \tau^+\tau^-$	0.8%	0.9%	1.8%	8.0%	1.1%	4.5%	17.9%	1.5%	2.5%
$h \rightarrow ZZ^*$	5.1%	4.4%	12%	10%	6.4%	28.0%	22.4%	8.8%	3.0%
$h \rightarrow \gamma\gamma$	6.8%	9.0%	18%	22%	12.0%	43.6%	50.3%	12.0%	6.8%
$h \rightarrow \mu^+\mu^-$	17%	19%	40%	–	25.5%	97.3%	178.9%	30.0%	25.0%
$(\nu\bar{\nu})h \rightarrow b\bar{b}$	2.8%	3.1%	–	–	3.7%	–	–	–	–

Table 1: Estimated statistical precisions for Higgs measurements obtained at the proposed CEPC program with 5.6 ab⁻¹ integrated luminosity [5, 6], FCC-ee program with 5 ab⁻¹ integrated luminosity [7, 8], and ILC with various center-of-mass energies [9].

decaying to bottom pairs ($e^+e^- \rightarrow \nu\bar{\nu}h$, $h \rightarrow b\bar{b}$) are summarized in Table 1. As systematic uncertainties of the Higgs measurements can be reduced using Z -pole calibration, they are assumed to be much smaller than the statistical uncertainties and are therefore neglected.

- **FCC-ee** The FCC-ee CDR is finished in 2018 [7, 8, 11]. At the current moment, the white paper proposes total luminosities of 5 ab⁻¹ at 240 GeV and 1.5ab⁻¹ at 350 GeV. The estimated precision of $e^+e^- \rightarrow hZ$ measurements at 240 GeV, as well as $h \rightarrow b\bar{b}$ channel in WW fusion are listed in Table 1. In addition, the cross sections of vector boson fusion processes for the Higgs production ($WW, ZZ \rightarrow h$) grow with the center of mass energy logarithmically. While their rates are still rather small at 240-250 GeV, at higher energies such as 350 GeV, such fusion processes become significantly more important and can provide crucial complementary information.
- **ILC** The proposed run scenarios in the ILC TDR [12] have been updated in recent documents [13, 14], which suggested that the ILC could collect 2ab⁻¹ data points at 250 GeV, 200fb⁻¹ at 350 GeV, and 4ab⁻¹ at 500 GeV. However, the estimation of signal strengths, as summarized in Ref. [14], are only available for smaller benchmark luminosities for which the full detector studies are performed. We take these estimations and scale them up to the current run scenarios, assuming statistical uncertainties dominate [15]; these are summarized in Table 1. Such scaling provides a reasonable approximation as long as the luminosities are not excessively large and the systematic uncertainties are under control.

With large center of mass energies up to 3 TeV, CLIC is also able to measure the Higgs properties very well through the WW fusion process [16, 17]. On the other hand, with

its extensive coverage of energy scales, the primary goal of CLIC is to directly search for new particles, in particular, the ones coupled to SM particles only through electroweak interactions. A comprehensive study of the CLIC physics potential including both the direct and indirect searches of new physics is beyond the scope of this paper.

In our global fit to the Higgs measurements, we only include the rate information for the Higgsstrahlung as well as the WW fusion process. Electroweak (EW) precision measurements at the Z -pole also impose strong constraints on new physics [18, 19]. The current constraints from the Large Electron Positron (LEP) collider can be significantly improved by a Z -pole run at any of the future lepton colliders. While these constraints are not explicitly considered in our study, we do restrict ourselves to models with suppressed EW precision corrections (*e.g.*, by imposing custodial symmetries) such that these constraints are automatically satisfied.

It is also important to study the reach of the future High Luminosity LHC (HL-LHC) [20–22]. Current LHC Higgs measurements are included via the GAMBIT interfaces to HiggsBounds-5.3.2 [23, 24] and HiggsSignals-2.2.3 [25]. For the future HL-LHC, we take their designed precision measurements to construct likelihood, which will be introduced in detail later.

Based on these analyses, we propose a global fit study of the 2HDM with hypothetical data from Higgs and Z pole precision measurements at future HL-LHC and Higgs factories.

3 2HDM and study strategy

The general 2HDM has two $SU(2)_L$ scalar doublets Φ_i ($i = 1, 2$) with hyper-charge $Y = +1/2$,

$$\Phi_i = \begin{pmatrix} \phi_i^+ \\ (v_i + \phi_i^0 + iG_i)/\sqrt{2} \end{pmatrix}, \quad (1)$$

where v_i ($i = 1, 2$) are the vacuum expectation values (VEVs) of the two doublets after EWSB with $v_1^2 + v_2^2 = v^2 = (246 \text{ GeV})^2$ and $\tan \beta = v_2/v_1$.

The 2HDM Lagrangian for the Higgs sector can be written as

$$\mathcal{L} = \sum_i |D_\mu \Phi_i|^2 - V(\Phi_1, \Phi_2) + \mathcal{L}_{\text{Yuk}}, \quad (2)$$

with a Higgs potential of

$$\begin{aligned} V(\Phi_1, \Phi_2) = & m_{11}^2 \Phi_1^\dagger \Phi_1 + m_{22}^2 \Phi_2^\dagger \Phi_2 - m_{12}^2 (\Phi_1^\dagger \Phi_2 + h.c.) + \frac{\lambda_1}{2} (\Phi_1^\dagger \Phi_1)^2 + \frac{\lambda_2}{2} (\Phi_2^\dagger \Phi_2)^2 \\ & + \lambda_3 (\Phi_1^\dagger \Phi_1) (\Phi_2^\dagger \Phi_2) + \lambda_4 (\Phi_1^\dagger \Phi_2) (\Phi_2^\dagger \Phi_1) + \frac{\lambda_5}{2} \left[(\Phi_1^\dagger \Phi_2)^2 + h.c. \right], \end{aligned} \quad (3)$$

where we have assumed CP conservation and a soft \mathbb{Z}_2 symmetry breaking term m_{12}^2 . The physical degrees of freedom after EWSB are a pair of singly-charged Higgs bosons H^\pm , a CP-odd Higgs boson A and two CP-even Higgs bosons h and H . Here we take h as the observed Higgs boson with a mass of 125 GeV. Our current study focuses on the Type-II 2HDM, where one Higgs doublet couples to up-type quarks, and the other Higgs doublet couples to down-type quarks and leptons.

	Current ($1.7 \times 10^7 Z$'s)			CEPC ($10^{10} Z$'s)			FCC-ee ($7 \times 10^{11} Z$'s)			ILC ($10^9 Z$'s)						
	σ	correlation			σ (10^{-2})	correlation			σ (10^{-2})	correlation			σ (10^{-2})	correlation		
		S	T	U		S	T	U		S	T	U		S	T	U
S	0.04 ± 0.11	1	0.92	-0.68	2.46	1	0.862	-0.373	0.67	1	0.812	0.001	3.53	1	0.988	-0.879
T	0.09 ± 0.14	-	1	-0.87	2.55	-	1	-0.735	0.53	-	1	-0.097	4.89	-	1	-0.909
U	-0.02 ± 0.11	-	-	1	2.08	-	-	1	2.40	-	-	1	3.76	-	-	1

Table 2: Estimated S , T , and U parameter ranges and correlation matrices ρ_{ij} from Z -pole precision measurements, mostly from LEP-I [28] and future lepton colliders such as CEPC [10], FCC-ee [29] and ILC [15]. Gfitter package [30] is used to obtain these constraints.

	λ_1	λ_2	λ_3	λ_4	λ_5
Region	(0, 5.5)	(0, 1)	(-1.8, 1.5)	(-2, 2)	(-1.4, 1.2)

Table 3: Allowed region in the generic basis λ_{1-5} at the 95% confidence level.

For the study of current constraints, we refer to the forthcoming work of the GAMBIT collaboration [2], which includes the latest theoretical constraints (unitarity, perturbativity and vacuum stability), Higgs searches at colliders, electroweak physics and flavour constraints. To further investigate the precise measurement constrains of future colliders, such as HL-LHC, CEPC, ILC and FCC-ee, we define new likelihoods for the proposed Higgs factories as

$$-2 \ln \mathcal{L}_{\text{Future}} = \frac{(m_h - m_h^{\text{obs}})^2}{\delta_{m_h}^2} + \sum_i \frac{(\mu_i - \mu_i^{\text{obs}})^2}{\sigma_{\mu_i}^2} + \sum_{ij} (X_i - \hat{X}_i)(\sigma^2)_{ij}^{-1}(X_j - \hat{X}_j), \quad (4)$$

Here $\mu_i^{\text{BSM}} \equiv (\sigma \cdot \text{BR})_{\text{BSM}} / (\sigma \cdot \text{BR})_{\text{SM}}$ for various Higgs search channels, σ_{μ_i} is the experimental precision on a particular channel, and the index i runs over all the Higgs search channels in Table 1. For the future μ_i^{obs} , we take them to 1. For the future δ_{m_h} , since the present experimental uncertainty, $\sigma_{m_h}^{\text{exp}} = 0.17$ GeV [26], we suppose that δ_{m_h} will be dominated by the theoretical uncertainty, to be 1 GeV.* For the Z -pole observables, $X_i = (\Delta S, \Delta T, \Delta U)_{2\text{HDM}}$ are the 2HDM predicted values, and $\hat{X}_i = (\Delta S, \Delta T, \Delta U)$ are the best-fit central values for current measurements (or zero for future measurements)[†]. The σ_{ij} are the components of the error matrix, $\sigma_{ij}^2 \equiv \sigma_i \rho_{ij} \sigma_j$ where σ_i and the correlation matrix components ρ_{ij} are given in Table 2.

4 Study results

In Fig. 1, we show the 1D and 2D profile likelihood distributions for the couplings in the generic basis, with marked boundaries for the 1σ , 2σ and 3σ confidence regions. These results include all of the latest relevant constraints, including theoretical constraints (unitarity, perturbativity and vacuum stability), Higgs searches at colliders based on latest version of HiggsBounds-5.3.2 [23, 24] and HiggsSignals-2.2.3 [25], electroweak physics and flavour constraints. A more detailed description will be provided in the forthcoming GAMBIT paper [2].

*Our study results show a small difference between $\delta_{m_h} = 1$ GeV and 3 GeV.

[†]Here we only consider effects of S, T and U parameters. There are other paramters discussed such U, V, W [27] are not included in our study.

Generally speaking, there are still large allowed regions in the general basis as summarized in Table 3, and the regions change little after including hypothetical future results.

In Fig. 2, we show the global fit results in the m_H - m_A plane (top), m_H - m_{H^\pm} plane (middle) and m_H - $\tan\beta$ plane (bottom). The left panels show the global fit results with current data and theoretical constraints. Generally speaking, there are lower limits on the heavy scalar masses of approximately 400 GeV, which mainly comes from the Z -pole precision measurements and flavour physics. There is also a lower limit on $\tan\beta$ that arises mainly from flavor physics. The right panels compare the current 2σ confidence regions (black) with those arising from the inclusion of future precision measurements, including those from the HL-LHC (orange), HL-LHC + CEPC (red), HL-LHC + ILC (blue), and HL-LHC + FCC-ee (green). The inclusion of HL-LHC precision measurements pushes the lower limit on the scalar mass up to 500 GeV, and these rise further up to 700 GeV after including constraints from future lepton colliders.

Finally in Fig. 3, we show the 1σ and 2σ regions allowed by current measurements and theoretical constraints in the plane of $\Delta m_A = m_A - m_H$ vs $\Delta m_C = m_{H^\pm} - m_H$ (left panel). The right panel compares the 2σ region (black) with those arising from the inclusion of future precision measurements including those from the HL-LHC (orange), HL-LHC + CEPC (red), HL-LHC + ILC (blue), and HL-LHC + FCC-ee (green). At present, Δm_A and Δm_C are limited to the range $(-200, 150)$ GeV and $(-200, 250)$ GeV respectively, both of which will be reduced to $(-200, 100)$ GeV in the future.

We also notice that the expected limit from the FCC-ee proposal is a little stronger than those arising from the ILC and CEPC proposals. This is mainly because the currently proposed FCC-ee will have a larger luminosity around 250 GeV, which is about 2 times that of CEPC. At the same time, it will also produce more Z bosons than the other two lepton colliders.

To summarise, after comparing global fit results with current and hypothetical future data, we find that:

1. In the generic coupling basis, there is not much ability to constrain λ_{1-5} from future Higgs mass, coupling, and Z -pole precision measurements.
2. The same is not true when considering the physical masses of the heavy scalars. Currently, the masses m_{H,A,H^\pm} have a lower limit of approximately 400 GeV, which is increased to 500 and 700 GeV after including hypothetical results from the HL-LHC and HL-LHC + lepton colliders.
3. There are strong constraints on the mass splittings $\Delta m_A = m_A - m_H$ and $\Delta m_C = m_{H^\pm} - m_H$ from Higgs and Z -pole precision measurements, which are currently limited to the ranges $(-200, 150)$ GeV and $(-200, 250)$ GeV. Future precision measurements will shrink the allowed range on Δm_C to $(-200, 100)$ GeV.

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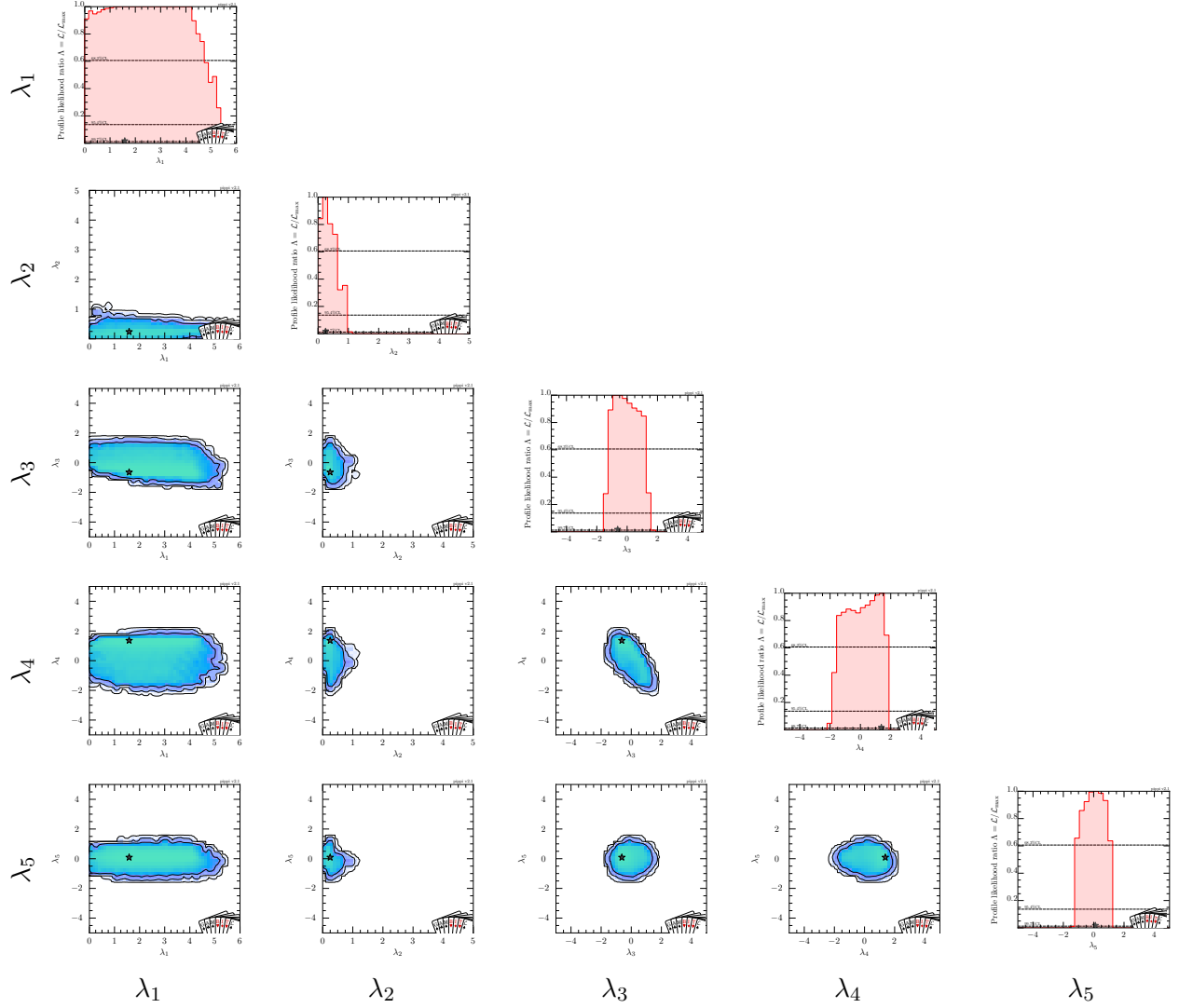


Figure 1: Combined 1D and 2D profile likelihood distributions for the couplings in the generic basis, with marked boundaries for the 1σ , 2σ and 3σ confidence regions. The global fit includes theoretical constraints and current collider Higgs, electroweak precision and flavour constraints.

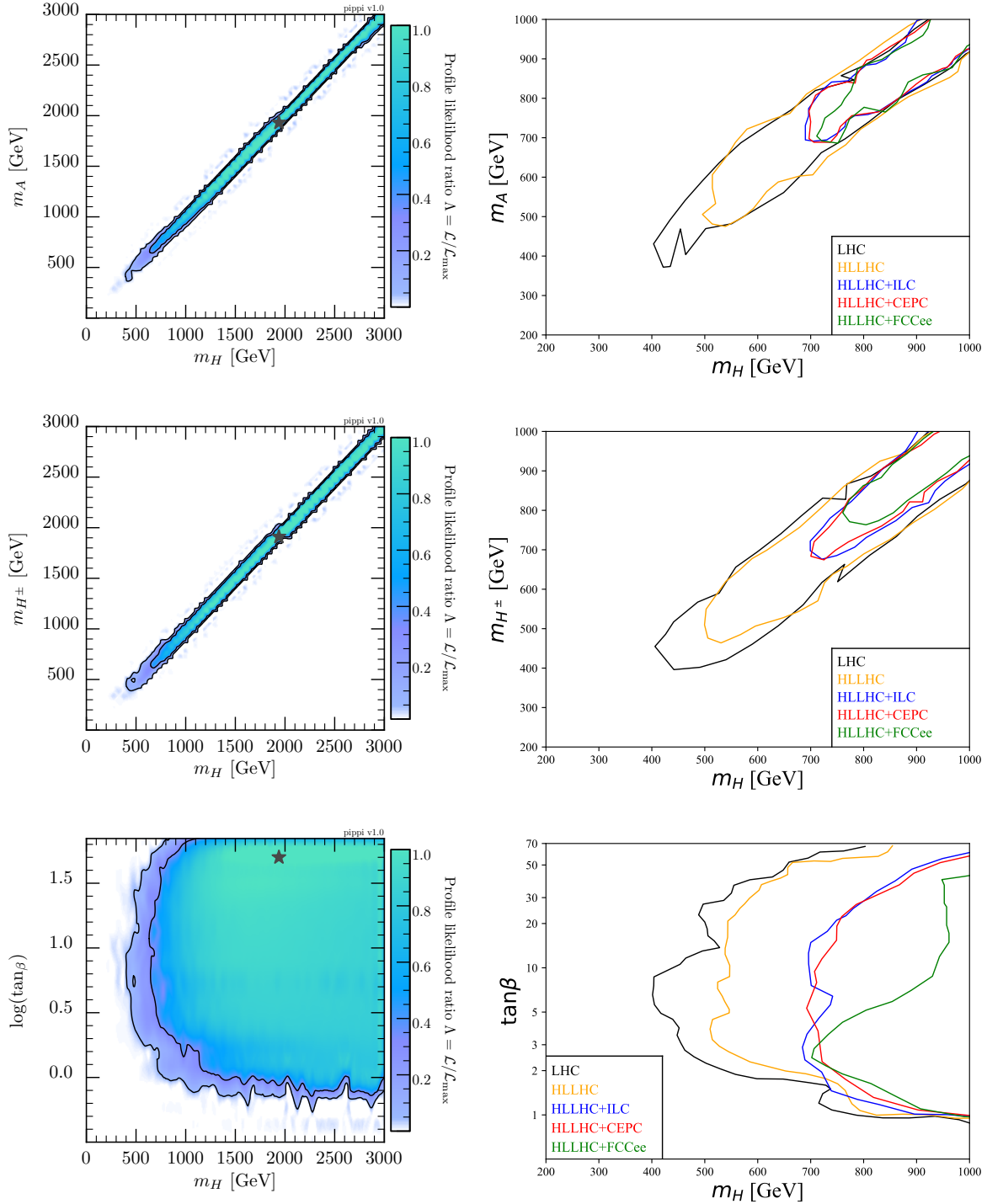


Figure 2: Left panel: Global fit results showing the 1σ and 2σ regions in the m_H - m_A plane (top), m_H - m_{H^\pm} plane (middle) and m_H - $\tan\beta$ plane (bottom) based on current measurements and theoretical constraints. Right panel: Comparison of current 2σ constraints (black) with those arising from the inclusion of future precision measurements, including those from the HL-LHC (orange), HL-LHC + CEPC (red), HL-LHC + ILC (blue), and HL-LHC + FCC-ee (green).

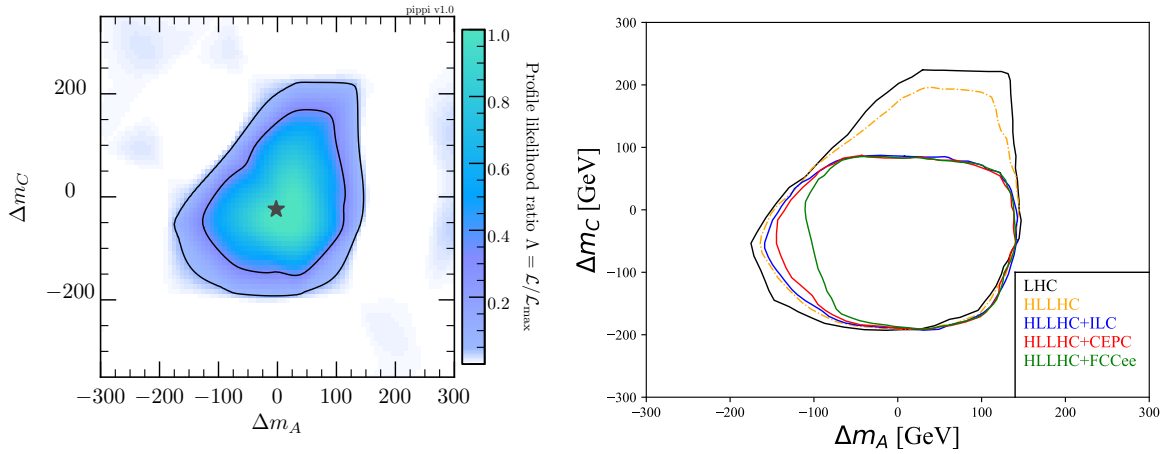


Figure 3: Left panel: The 1σ and 2σ allowed regions in $\Delta m_A - \Delta m_C$ plane, based on current measurements and theoretical constraints. Right panel: Comparison of the 2σ region allowed by current constraints (black) with those arising from the inclusion of future precision measurements, including those from the HL-LHC (orange), HL-LHC+CEPC (red), HL-LHC + ILC (blue), and HL-LHC + FCC-ee (green).