2025 第一期新物理冬季学校

Multi-Higgs Models
（2HDM…）

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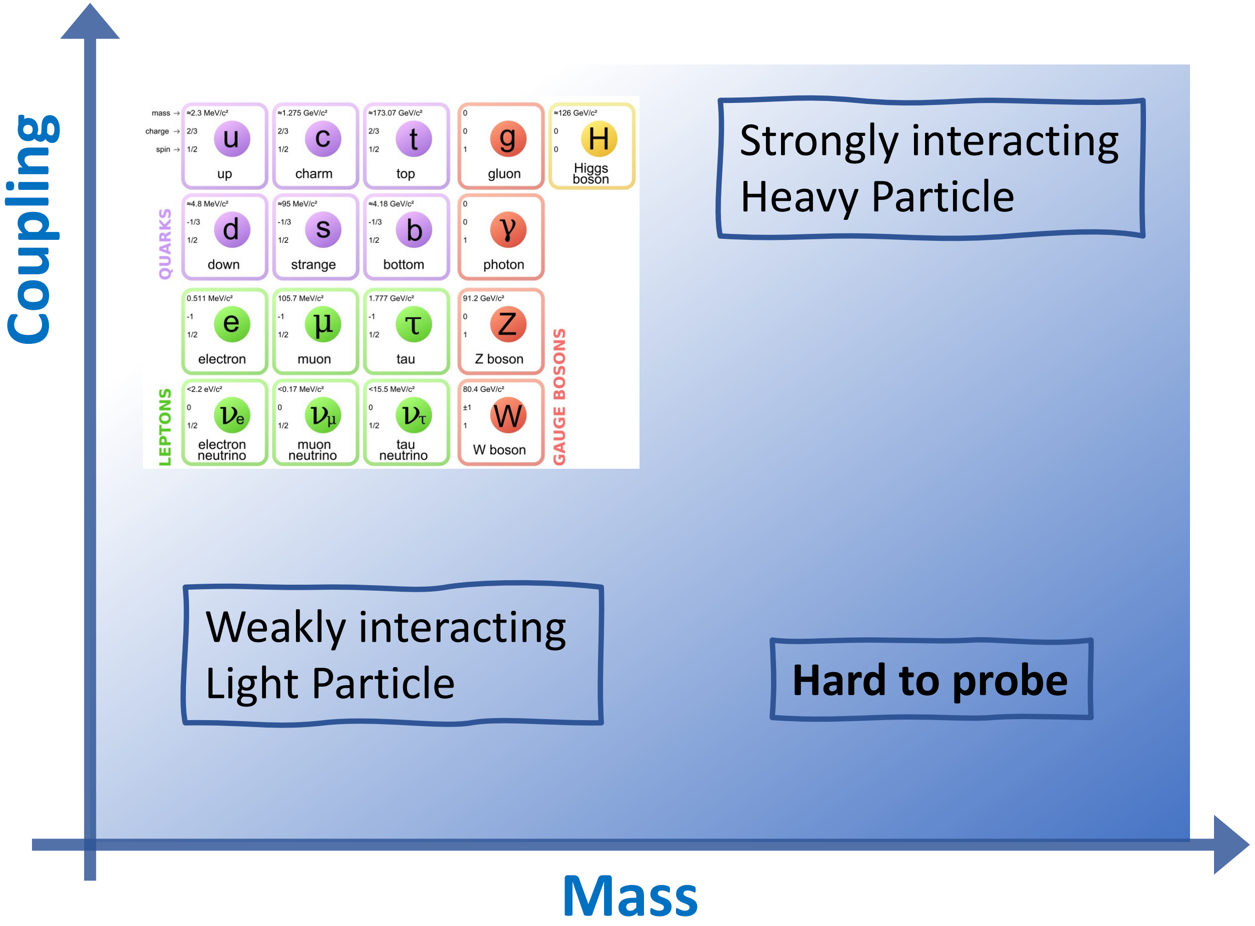
1924

Why BSM

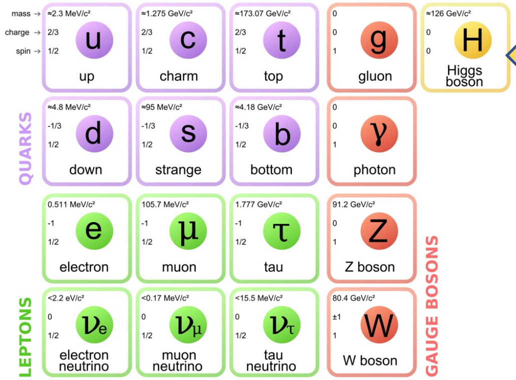


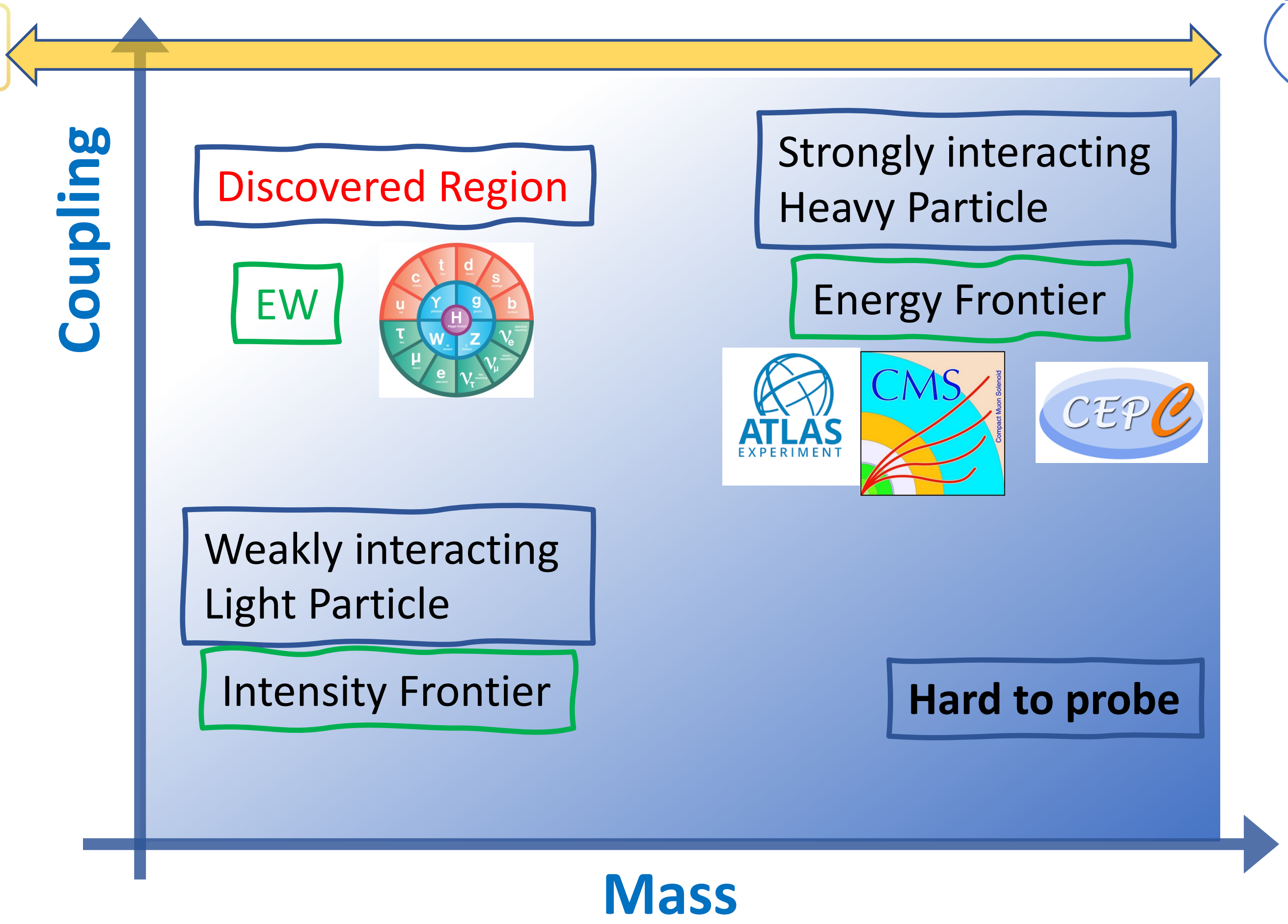
Strongly interacting
Heavy Particle

Weakly interacting
Light Particle

Hard to probe

Why BSM





Discovered Region

EW

Strongly interacting Heavy Particle

Energy Frontier

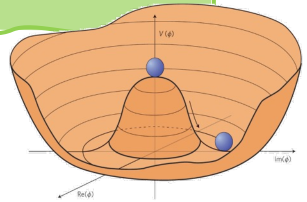
Weakly interacting Light Particle

Intensity Frontier

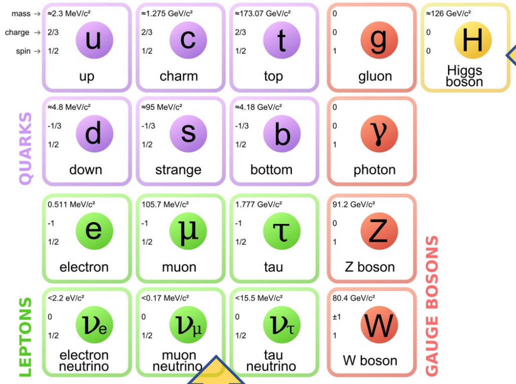
Hard to probe

$DM, Dark\ Photon$ …

- Naturalness
- Muon g-2
- Phase transition
- …



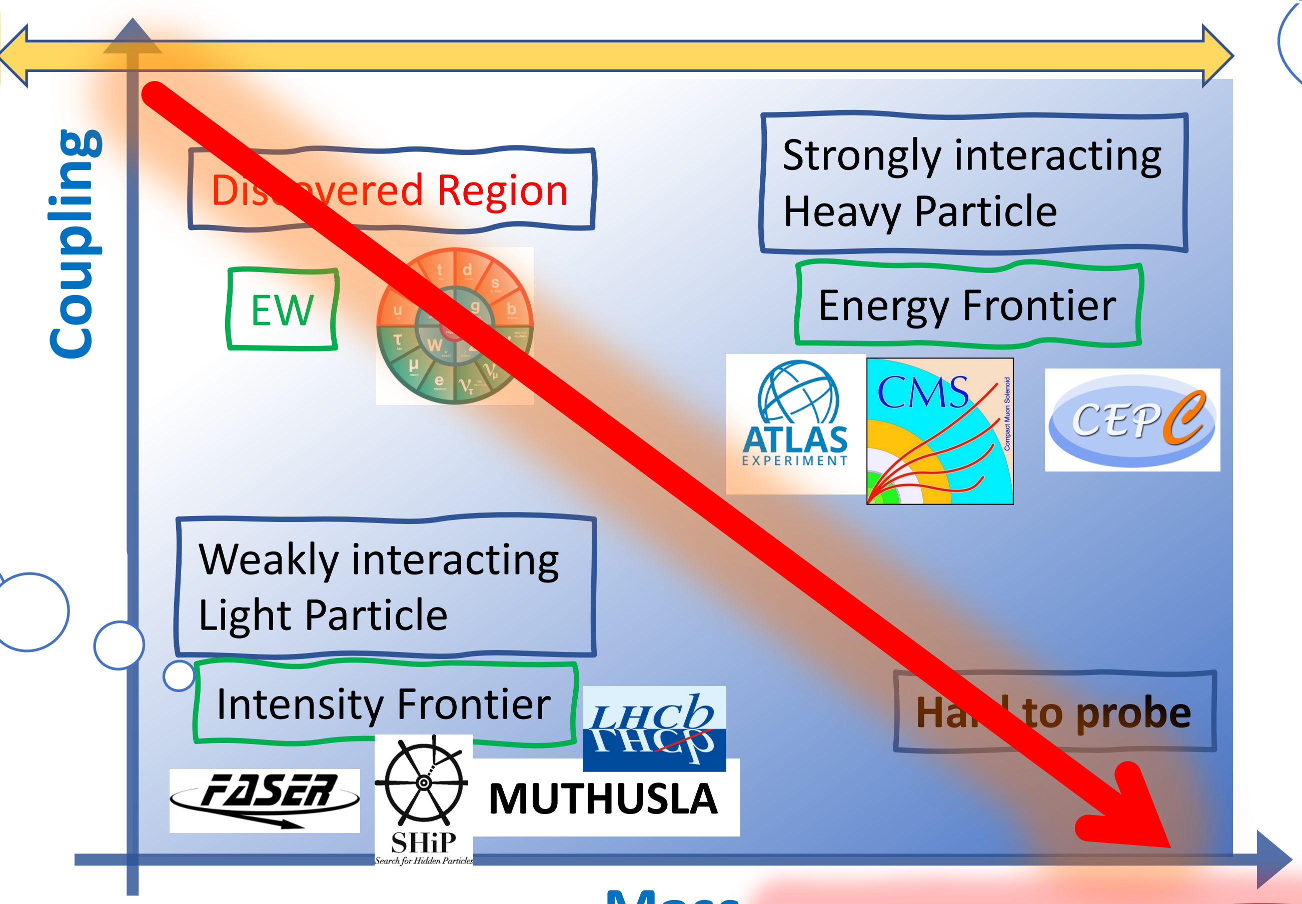
Why BSM



WIMP, Dark Photon ..

- Naturalness
- Muon g-2
- B anomaly
- …

$$R_{K^{(*)}} = \frac{\mathrm{BR}(B \to K^{(*)}\mu\mu)}{\mathrm{BR}(B \to K^{(*)}ee)}$$



Coupling

Discovered Region

EW

Strongly interacting Heavy Particle

Energy Frontier

Weakly interacting Light Particle

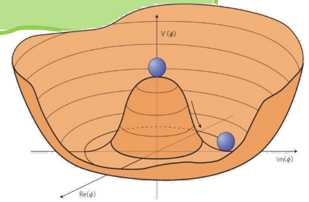
Intensity Frontier

Hard to probe

Mass

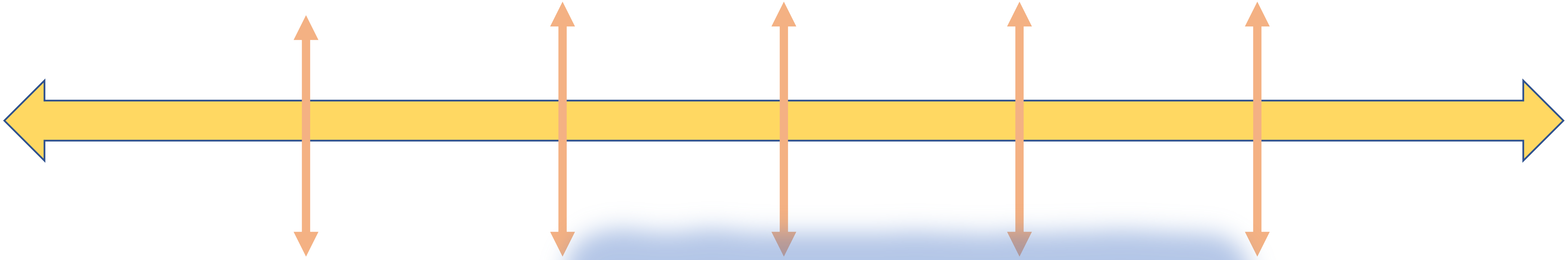
DM, Dark Photon …

- Naturalness
- Muon g-2
- Phase transition
- …



We are searching for BSM discovery

Scenarios



BSM
Mass hierarchy

- $m_{h_S} < 0.1$ GeV
- 0.1 GeV$< m_{h_S} < 10$ GeV
- 10 GeV $< m_{h_S} < 62.5$ GeV
- 62.5 GeV $< m_{h_S} < 1$ TeV
- 1 TeV $< m_{h_S} <$ 10TeV
- 10 TeV $< m_{h_S}$

Why BSM

Motivations for extended scalar sectors:

- Why not?
- Susy
- Sources of (spontaneous CP violation) for baryogenesis
- Inflation
- Mass hierarchy of SM fermions
- Strong CP problem - axions
- GUTs
- Dark matter relic abundance
- Vacuum stability

后续课程：

此次新物理冬季学校包含以下课程

基础课程：EW+QCD，BSM（CHM，SSM/2HDM，SUSY，EFT）

第一天：电弱相互作用3课时、CHM 2课时(张宏浩)，强相互作用3课时(刘晓辉)，

第二天：SSM+2HDM 2课时(苏伟)，SUSY 2课时（曹俊杰）， EFT4课时（顾嘉荫）

核心课程： 36课时，包含

暗物质(宋宁强、刘佐伟)、中微子(李玉峰，丁桂军)、AI（吴永成，刘炳萱）

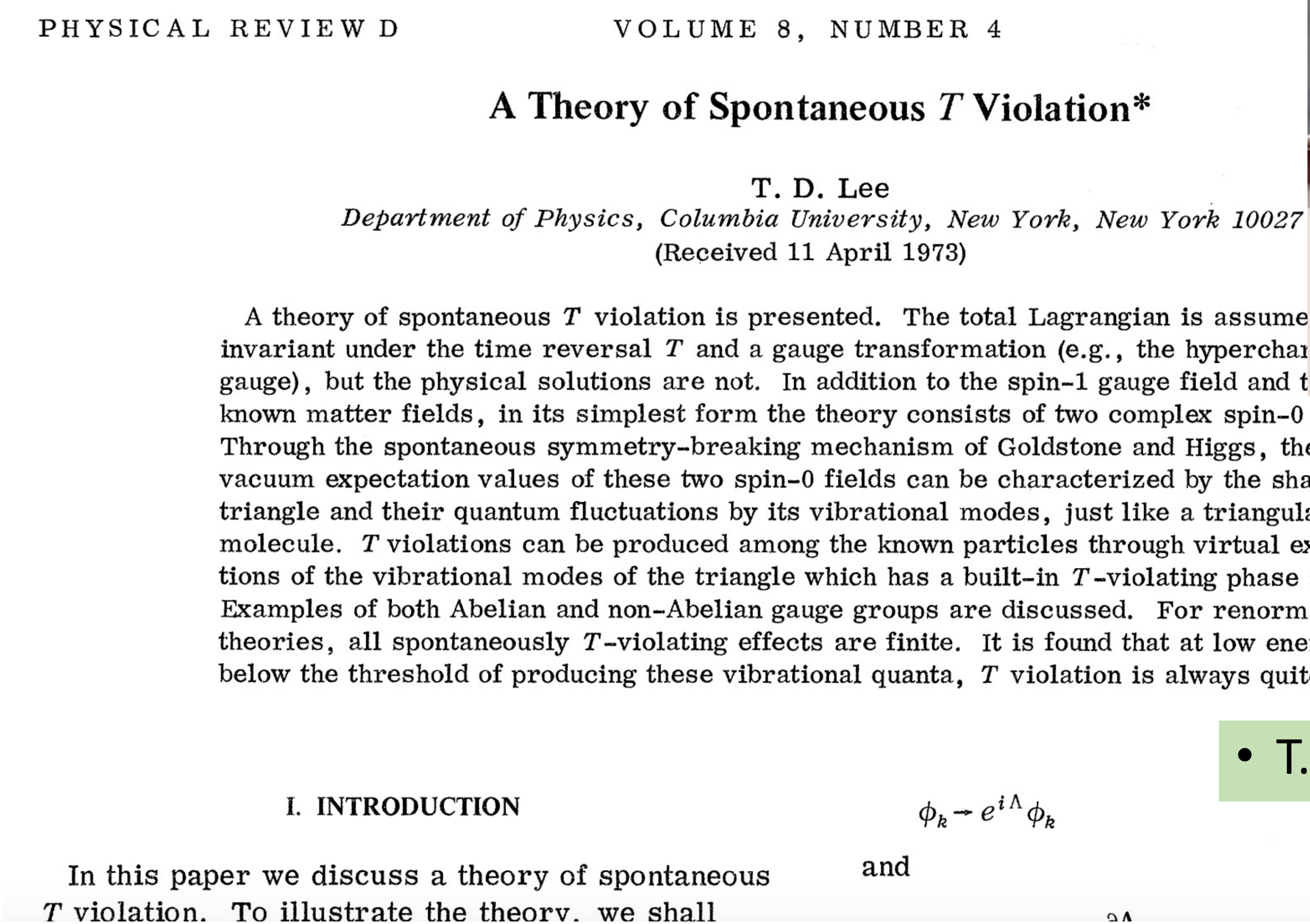
拓展课程：16课时，包含 对撞机物理 (岩斌，张昊)，相变 (边立功，张阳)

特邀报告：Tao Han， 杨金民，...

Outline

- 2HDM framework
- Higgs and Z-pole Precision Measurements
- Direct searches
- Study Results: Tree & one-loop Level
- Electroweak Phase Transition
- multi-Higg models / scenoris

The Two-Higgs doublet mo



PHYSICAL REVIEW D VOLUME 8, NUMBER 4

A Theory of Spontaneous *T* Violation*

T. D. Lee
Department of Physics, Columbia University, New York, New York 10027
(Received 11 April 1973)

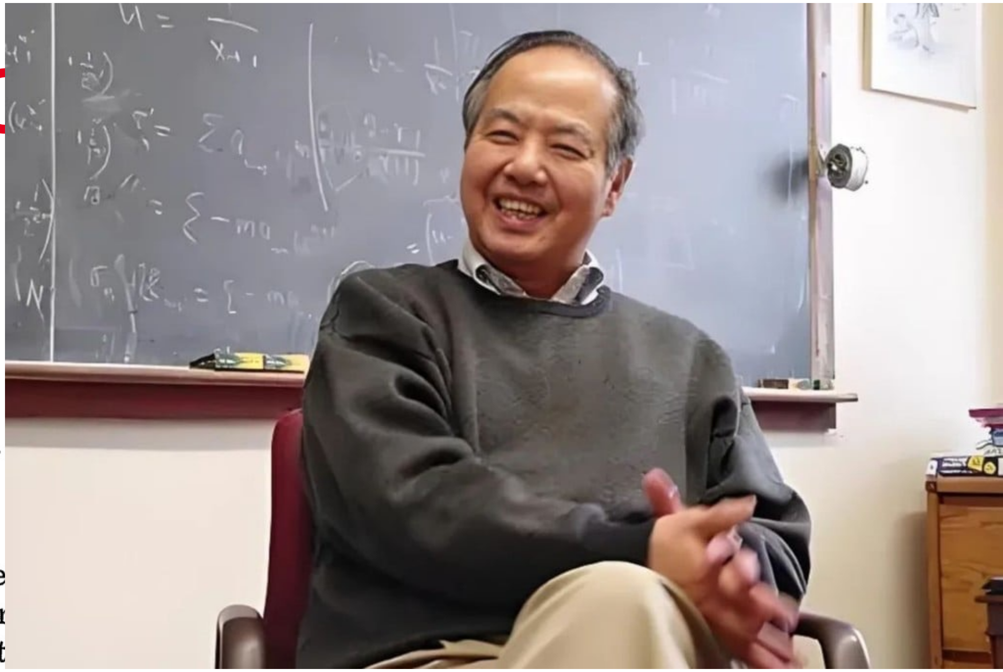
A theory of spontaneous *T* violation is presented. The total Lagrangian is assume invariant under the time reversal *T* and a gauge transformation (e.g., the hypercha gauge), but the physical solutions are not. In addition to the spin-1 gauge field and t known matter fields, in its simplest form the theory consists of two complex spin-0 fields. Through the spontaneous symmetry-breaking mechanism of Goldstone and Higgs, the vacuum expectation values of these two spin-0 fields can be characterized by the shape of a triangle and their quantum fluctuations by its vibrational modes, just like a triangular molecule. *T* violations can be produced among the known particles through virtual excitations of the vibrational modes of the triangle which has a built-in *T*-violating phase angle. Examples of both Abelian and non-Abelian gauge groups are discussed. For renormalizable theories, all spontaneously *T*-violating effects are finite. It is found that at low energy, below the threshold of producing these vibrational quanta, *T* violation is always quite small.

I. INTRODUCTION

In this paper we discuss a theory of spontaneous *T* violation. To illustrate the theory, we shall

$$\phi_k \to e^{i\Lambda}\phi_k \tag{1}$$

and



- T.D.Lee,Phys.Rev.D8(1973)1226

The Two-Higgs doublet model (2HDM)

The 2HDM, consists of two-complex hypercharge-one scalar doublets Φ_1 and Φ_2. Of the eight initial degrees of freedom, three are eaten and provide masses for the $W^{\pm}$ and Z, and the remaining five correspond to physical scalars: a charged Higgs pair, $H^{\pm}$, and three neutral scalars h_1, h_2 and h_3. In contrast to the SM, where the Higgs-sector is CP-conserving, the 2HDM allows for Higgs-mediated CP-violation.

If CP is conserved, the three scalars can be classified as two CP-even scalars, h and H (where $m_h < m_H$) and a CP-odd scalar A.

2HDM: Brief Introduction

- Two Higgs Doublet Model

Soft breaking of Z2

$$
\begin{aligned}
V(\Phi_1,\Phi_2) = \ & m_{11}^2\Phi_1^\dagger\Phi_1 + m_{22}^2\Phi_2^\dagger\Phi_2 - \boxed{m_{12}^2(\Phi_1^\dagger\Phi_2 + h.c.)} + \frac{\lambda_1}{2}(\Phi_1^\dagger\Phi_1)^2 + \frac{\lambda_2}{2}(\Phi_2^\dagger\Phi_2)^2 \\
& + \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) + \frac{1}{2}\left[\lambda_5(\Phi_1^\dagger\Phi_2)^2 + h.c.\right] \\
& \boxed{+\frac{1}{2}(\Phi_1^\dagger\Phi_2 + h.c.)(\lambda_6\Phi_1^\dagger\Phi_1 + \lambda_7\Phi_1^\dagger\Phi_1)}
\end{aligned}
$$

Hard breaking of Z2

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

$$
\Phi_1 \rightarrow \Phi_1\,,\ \ \Phi_2 \rightarrow -\Phi_2
$$

2HDM: Brief Introduction

- Two Higgs Doublet Model

Soft breaking of Z2

$$\begin{aligned} V(\Phi_1,\Phi_2) = \; & m_{11}^2\Phi_1^\dagger\Phi_1 + m_{22}^2\Phi_2^\dagger\Phi_2 - \boxed{m_{12}^2(\Phi_1^\dagger\Phi_2 + h.c.)} + \frac{\lambda_1}{2}(\Phi_1^\dagger\Phi_1)^2 + \frac{\lambda_2}{2}(\Phi_2^\dagger\Phi_2)^2 \\ & + \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) + \frac{1}{2}\left[\lambda_5(\Phi_1^\dagger\Phi_2)^2 + h.c.\right] \\ & \boxed{+\frac{1}{2}(\Phi_1^\dagger\Phi_2 + h.c.)(\lambda_6\Phi_1^\dagger\Phi_1 + \lambda_7\Phi_1^\dagger\Phi_1)} \end{aligned}$$

Hard breaking of Z2

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

$$\begin{aligned} v_u^2 + v_d^2 = v^2 = (246\mathrm{GeV})^2 \\ \tan\beta = v_u/v_d \end{aligned}$$

$$\begin{pmatrix} H^0 \\ h^0 \end{pmatrix} = \begin{pmatrix} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} \phi_1^0 \\ \phi_2^0 \end{pmatrix}, \qquad \begin{aligned} A &= -G_1\sin\beta + G_2\cos\beta \\ H^\pm &= -\phi_1^\pm\sin\beta + \phi_2^\pm\cos\beta \end{aligned}$$

2HDM: Brief Introduction

- Two Higgs Doublet Model

Soft breaking of Z2

$$\begin{aligned} V(\Phi_1,\Phi_2) = \; & m_{11}^2\Phi_1^\dagger\Phi_1 + m_{22}^2\Phi_2^\dagger\Phi_2 - \boxed{m_{12}^2(\Phi_1^\dagger\Phi_2 + h.c.)} + \frac{\lambda_1}{2}(\Phi_1^\dagger\Phi_1)^2 + \frac{\lambda_2}{2}(\Phi_2^\dagger\Phi_2)^2 \\ & + \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) + \frac{1}{2}\left[\lambda_5(\Phi_1^\dagger\Phi_2)^2 + h.c.\right] \\ & \boxed{\cancel{+\frac{1}{2}(\Phi_1^\dagger\Phi_2 + h.c.)(\lambda_6\Phi_1^\dagger\Phi_1 + \lambda_7\Phi_1^\dagger\Phi_1)}} \end{aligned}$$

Hard breaking of Z2

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

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2HDM: Brief Introduction

- Why is the Z2 symmetry demanded?

$$\mathcal{L}_Y \sim Y_f \Phi \bar{f}_i f_j \xrightarrow{\langle\Phi\rangle=v} M_{ij} = Y_f v \bar{f}_i f_j$$

$$\mathcal{L}_Y \sim Y_f^1 \Phi_1 \bar{f}_i f_j + Y_f^2 \Phi_2 \bar{f}_i f_j \xrightarrow[\langle\Phi_2\rangle=v_2]{\langle\Phi_1\rangle=v_1} M_{ij} = Y_f^1 v_1 \bar{f}_i f_j + Y_f^2 v_2 \bar{f}_i f_j$$

Z_2 symmetry avoids FCNC at tree level

2HDM: Brief Introduction

- Two Higgs Doublet Model

$$
\begin{aligned}
V(\Phi_1,\Phi_2) = \;& m_{11}^2\Phi_1^\dagger\Phi_1 + m_{22}^2\Phi_2^\dagger\Phi_2 - m_{12}^2(\Phi_1^\dagger\Phi_2 + h.c.) + \frac{\lambda_1}{2}(\Phi_1^\dagger\Phi_1)^2 + \frac{\lambda_2}{2}(\Phi_2^\dagger\Phi_2)^2 \\
& + \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) + \frac{1}{2}\left[\lambda_5(\Phi_1^\dagger\Phi_2)^2 + h.c.\right]
\end{aligned}
$$

- Parameters (CP-conserving, Flavor Limit, Z_2 Symmetry)

$$
\boxed{m_{11}^2, m_{22}^2, \lambda_1, \lambda_2, \lambda_3, \lambda_4, \lambda_5} \longrightarrow \boxed{\underset{\downarrow \; 246\ \mathrm{GeV}}{v}, \tan\beta\,, \alpha, \underset{\downarrow \; 125.\ \mathrm{GeV}}{m_h}, m_H, m_A, m_{H^\pm}}
$$

Soft Z_2 symmetry breaking: m_{12}^2

2HDM: Brief Introduction

- Two Higgs Doublet Model

$$V(\Phi_1,\Phi_2) = m_{11}^2\Phi_1^\dagger\Phi_1 + m_{22}^2\Phi_2^\dagger\Phi_2 - m_{12}^2(\Phi_1^\dagger\Phi_2 + h.c.) + \frac{\lambda_1}{2}(\Phi_1^\dagger\Phi_1)^2 + \frac{\lambda_2}{2}(\Phi_2^\dagger\Phi_2)^2 + \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) + \frac{1}{2}\left[\lambda_5(\Phi_1^\dagger\Phi_2)^2 + h.c.\right]$$

- Parameters (Alignment limit)

	Φ1	Φ2
Type I	u,d,l	
Type II	u	d,l
lepton-specific	u,d	l
flipped	u,l	d

$$\kappa_i = g_{hii}^{BSM} / g_{hii}^{SM}$$

Model	κ_V	κ_u	κ_d	κ_ℓ
2HDM-I	$\sin(\beta-\alpha)$	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$
2HDM-II	$\sin(\beta-\alpha)$	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$	$-\sin\alpha/\cos\beta$
2HDM-L	$\sin(\beta-\alpha)$	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$
2HDM-F	$\sin(\beta-\alpha)$	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$	$\cos\alpha/\sin\beta$

2HDM framework

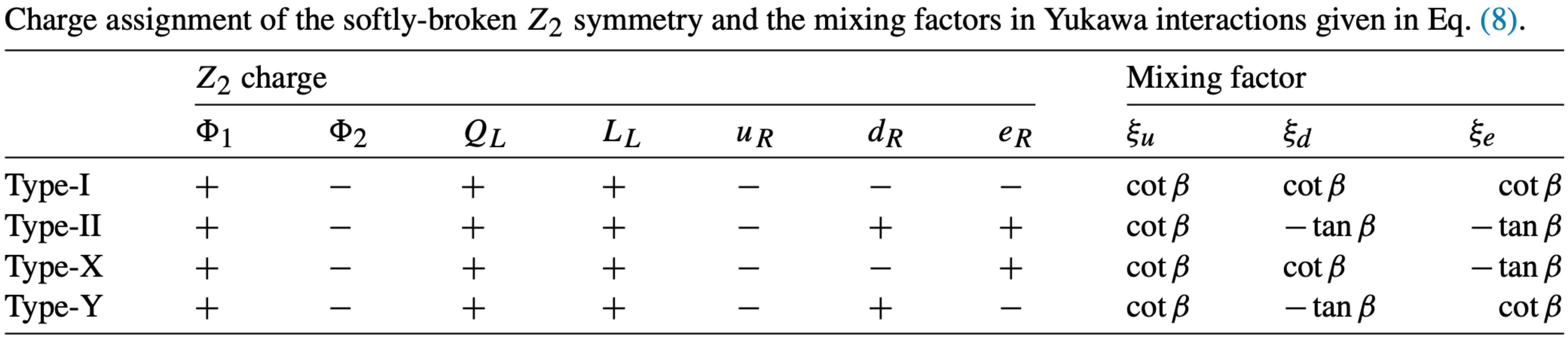
$$\mathcal{L}_{\text{kin}} = [\sin(\beta-\alpha)h + \cos(\beta-\alpha)H]\left(\frac{m_W^2}{v}W^{+\mu}W_\mu^- + \frac{m_Z^2}{2v}Z^\mu Z_\mu\right)$$
$$+ g_{\phi_1\phi_2 V}(\partial^\mu\phi_1\phi_2 - \phi_1\partial^\mu\phi_2)V_\mu + g_{\phi_1\phi_2 V_1 V_2}\phi_1\phi_2 V_1^\mu V_{2\mu},$$

$$-\mathcal{L}_Y = Y_u\overline{Q}_L i\sigma_2\Phi_u^* u_R + Y_d\overline{Q}_L\Phi_d d_R + Y_e\overline{L}_L\Phi_e e_R + \text{h.c.},$$

$$\text{-}\mathcal{L}_Y^{\text{int}} = \sum_{f=u,d,e}\frac{m_f}{v}\left(\xi_h^f\overline{f}fh + \xi_H^f\overline{f}fH - 2iI_f\xi_f\overline{f}\gamma_5 fA\right)$$
$$+ \frac{\sqrt{2}}{v}\left[V_{ud}\bar{u}\left(m_d\xi_d P_R - m_u\xi_u P_L\right)dH^+ + m_e\xi_e\bar{\nu}P_R eH^+ + \text{h.c.}\right],$$

$$\xi_h^f = \sin(\beta-\alpha) + \xi_f\cos(\beta-\alpha),$$
$$\xi_H^f = \cos(\beta-\alpha) - \xi_f\sin(\beta-\alpha),$$

2HDM framework

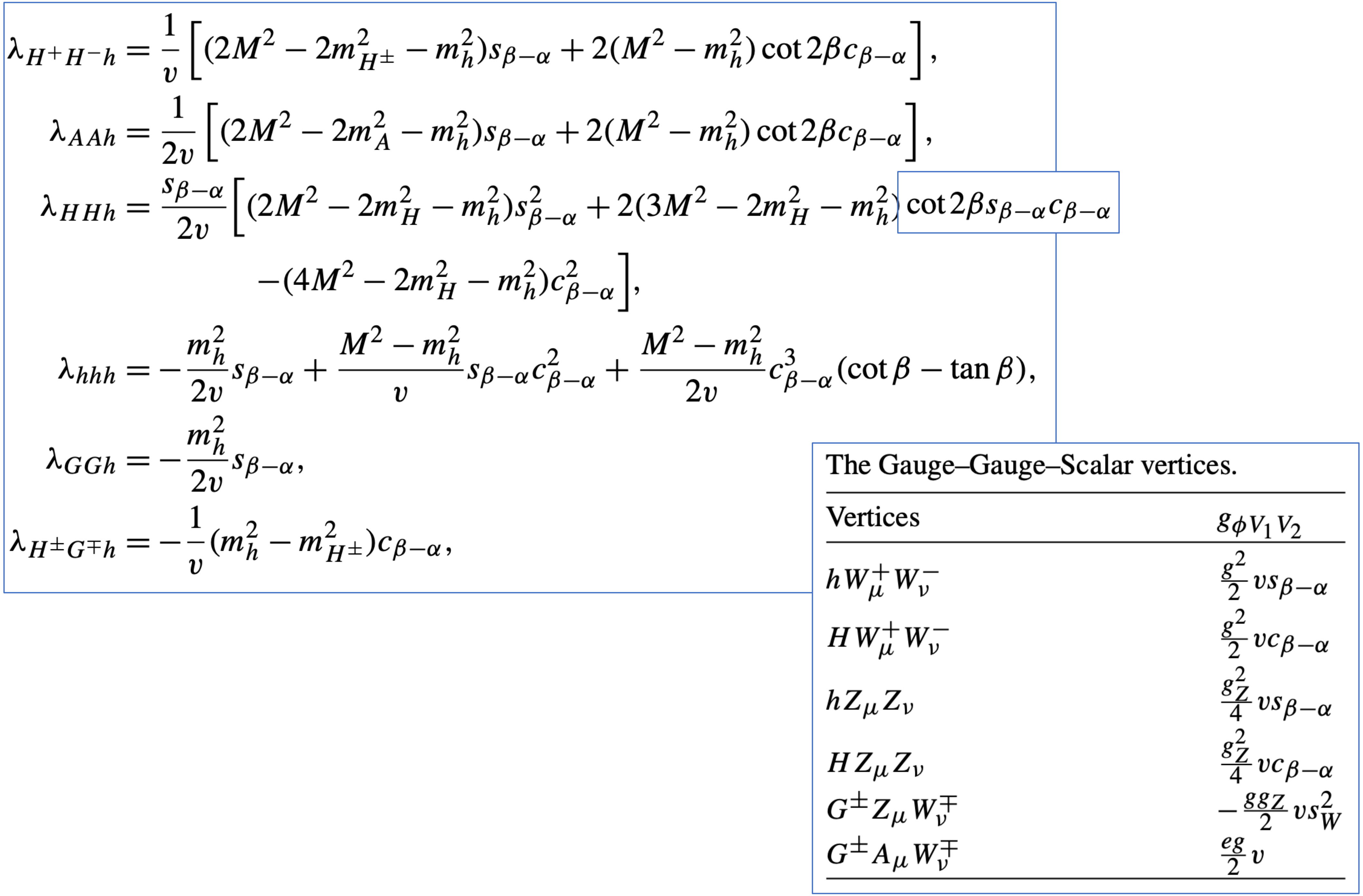


Charge assignment of the softly-broken Z_2 symmetry and the mixing factors in Yukawa interactions given in Eq. (8).

	Z_2 charge							Mixing factor		
	Φ_1	Φ_2	Q_L	L_L	u_R	d_R	e_R	ξ_u	ξ_d	ξ_e
Type-I	+	−	+	+	−	−	−	$\cot\beta$	$\cot\beta$	$\cot\beta$
Type-II	+	−	+	+	−	+	+	$\cot\beta$	$-\tan\beta$	$-\tan\beta$
Type-X	+	−	+	+	−	−	+	$\cot\beta$	$\cot\beta$	$-\tan\beta$
Type-Y	+	−	+	+	−	+	−	$\cot\beta$	$-\tan\beta$	$\cot\beta$

$$\begin{aligned}\mathcal{L} = &+g_{\phi V_1 V_2} g^{\mu\nu} \phi V_{1\mu} V_{2\nu} + g_{\phi_1 \phi_2 V}(\partial^\mu \phi_1 \phi_2 - \phi_1 \partial^\mu \phi_2) V_\mu \\ &+ g_{\phi_1 \phi_2 V_1 V_2} g^{\mu\nu} \phi_1 \phi_2 V_{1\mu} V_{2\nu} + \cdots .\end{aligned}$$

$$\mathcal{L} = +\lambda_{\phi_i \phi_j \phi_k} \phi_i \phi_j \phi_k + \lambda_{\phi_i \phi_j \phi_k \phi_l} \phi_i \phi_j \phi_k \phi_l + \cdots .$$



$$\lambda_{H^+H^-h} = \frac{1}{v}\left[(2M^2 - 2m_{H^\pm}^2 - m_h^2)s_{\beta-\alpha} + 2(M^2 - m_h^2)\cot 2\beta c_{\beta-\alpha}\right],$$

$$\lambda_{AAh} = \frac{1}{2v}\left[(2M^2 - 2m_A^2 - m_h^2)s_{\beta-\alpha} + 2(M^2 - m_h^2)\cot 2\beta c_{\beta-\alpha}\right],$$

$$\lambda_{HHh} = \frac{s_{\beta-\alpha}}{2v}\Big[(2M^2 - 2m_H^2 - m_h^2)s_{\beta-\alpha}^2 + 2(3M^2 - 2m_H^2 - m_h^2)\cot 2\beta s_{\beta-\alpha}c_{\beta-\alpha}$$

$$-(4M^2 - 2m_H^2 - m_h^2)c_{\beta-\alpha}^2\Big],$$

$$\lambda_{hhh} = -\frac{m_h^2}{2v}s_{\beta-\alpha} + \frac{M^2 - m_h^2}{v}s_{\beta-\alpha}c_{\beta-\alpha}^2 + \frac{M^2 - m_h^2}{2v}c_{\beta-\alpha}^3(\cot\beta - \tan\beta),$$

$$\lambda_{GGh} = -\frac{m_h^2}{2v}s_{\beta-\alpha},$$

$$\lambda_{H^\pm G^\mp h} = -\frac{1}{v}(m_h^2 - m_{H^\pm}^2)c_{\beta-\alpha},$$

The Gauge–Gauge–Scalar vertices.

Vertices	$g_{\phi V_1 V_2}$
$hW_\mu^+W_\nu^-$	$\frac{g^2}{2}vs_{\beta-\alpha}$
$HW_\mu^+W_\nu^-$	$\frac{g^2}{2}vc_{\beta-\alpha}$
$hZ_\mu Z_\nu$	$\frac{g_Z^2}{4}vs_{\beta-\alpha}$
$HZ_\mu Z_\nu$	$\frac{g_Z^2}{4}vc_{\beta-\alpha}$
$G^\pm Z_\mu W_\nu^\mp$	$-\frac{gg_Z}{2}vs_W^2$
$G^\pm A_\mu W_\nu^\mp$	$\frac{eg}{2}v$

The Scalar–Scalar–Gauge and Scalar–Scalar–Gauge–Gauge type vertices and those coefficients.

Vertices	$g_{\phi_1\phi_2 V}$
$hG^{\pm}W^{\mp}_{\mu}$	$\mp i\,\frac{g}{2}s_{\beta-\alpha}$
$HG^{\pm}W^{\mp}_{\mu}$	$\mp i\,\frac{g}{2}c_{\beta-\alpha}$
$G^0G^{\pm}W^{\mp}_{\mu}$	$-\frac{g}{2}$
$hH^{\pm}W^{\mp}_{\mu}$	$\mp i\,\frac{g}{2}c_{\beta-\alpha}$
$HH^{\pm}W^{\mp}_{\mu}$	$\pm i\,\frac{g}{2}s_{\beta-\alpha}$
$AH^{\pm}W^{\mp}_{\mu}$	$-\frac{g}{2}$
$G^+G^-Z_{\mu}$	$i\,\frac{g_Z}{2}c_{2W}$
$H^+H^-Z_{\mu}$	$i\,\frac{g_Z}{2}c_{2W}$
hG^0Z_{μ}	$-\frac{g_Z}{2}s_{\beta-\alpha}$
hAZ_{μ}	$-\frac{g_Z}{2}c_{\beta-\alpha}$
HG^0Z_{μ}	$-\frac{g_Z}{2}c_{\beta-\alpha}$
HAZ_{μ}	$\frac{g_Z}{2}s_{\beta-\alpha}$
$G^+G^-A_{\mu}$	ie
$H^+H^-A_{\mu}$	ie

Vertices	$g_{\phi_1\phi_2 V_1 V_2}$	Vertices	$g_{\phi_1\phi_2 V_1 V_2}$
$hhW^+_{\mu}W^-_{\nu}$	$\frac{g^2}{4}$	$G^{\pm}G^0W^{\mp}_{\mu}Z_{\nu}$	$\pm i\,\frac{gg_Z}{2}s_W^2$
$HHW^+_{\mu}W^-_{\nu}$	$\frac{g^2}{4}$	$H^{\pm}AW^{\mp}_{\mu}Z_{\nu}$	$\pm i\,\frac{gg_Z}{2}s_W^2$
$AAW^+_{\mu}W^-_{\nu}$	$\frac{g^2}{4}$	$G^{\pm}HW^{\mp}_{\mu}Z_{\nu}$	$-\frac{gg_Z}{2}s_W^2c_{\beta-\alpha}$
$G^0G^0W^+_{\mu}W^-_{\nu}$	$\frac{g^2}{4}$	$H^{\pm}hW^{\mp}_{\mu}Z_{\nu}$	$-\frac{gg_Z}{2}s_W^2c_{\beta-\alpha}$
$G^+G^-W^+_{\mu}W^-_{\nu}$	$\frac{g^2}{2}$	$G^{\pm}hW^{\mp}_{\mu}Z_{\nu}$	$-\frac{gg_Z}{2}s_W^2s_{\beta-\alpha}$
$H^+H^-W^+_{\mu}W^-_{\nu}$	$\frac{g^2}{2}$	$H^{\pm}HW^{\mp}_{\mu}Z_{\nu}$	$\frac{gg_Z}{2}s_W^2s_{\beta-\alpha}$
$hhZ_{\mu}Z_{\nu}$	$\frac{g_Z^2}{8}$	$H^{\pm}AW^{\mp}_{\mu}A_{\nu}$	$\mp\frac{eg}{2}$
$HHZ_{\mu}Z_{\nu}$	$\frac{g_Z^2}{8}$	$G^{\pm}G^0W^{\mp}_{\mu}A_{\nu}$	$\mp\frac{eg}{2}$
$AAZ_{\mu}Z_{\nu}$	$\frac{g_Z^2}{8}$	$H^{\pm}hW^{\mp}_{\mu}A_{\nu}$	$\frac{eg}{2}c_{\beta-\alpha}$
$G^0G^0Z_{\mu}Z_{\nu}$	$\frac{g_Z^2}{8}$	$G^{\pm}HW^{\mp}_{\mu}A_{\nu}$	$\frac{eg}{2}c_{\beta-\alpha}$
$G^+G^-Z_{\mu}Z_{\nu}$	$\frac{g_Z^2}{4}c_{2W}^2$	$G^+G^-A_{\mu}Z_{\nu}$	eg_Zc_{2W}
$H^+H^-Z_{\mu}Z_{\nu}$	$\frac{g_Z^2}{4}c_{2W}^2$	$H^+H^-A_{\mu}Z_{\nu}$	eg_Zc_{2W}
$G^+G^-A_{\mu}A_{\nu}$	e^2	$G^{\pm}hW^{\mp}_{\mu}A_{\nu}$	$\frac{eg}{2}s_{\beta-\alpha}$
$H^+H^-A_{\mu}A_{\nu}$	e^2	$H^{\pm}HW^{\mp}_{\mu}A_{\nu}$	$-\frac{eg}{2}s_{\beta-\alpha}$

Higgs Basis

It is convenient to define new Higgs doublet fields:

$$H_1 = \begin{pmatrix} H_1^+ \\ H_1^0 \end{pmatrix} \equiv \frac{v_1^*\Phi_1 + v_2^*\Phi_2}{v}, \qquad H_2 = \begin{pmatrix} H_2^+ \\ H_2^0 \end{pmatrix} \equiv \frac{-v_2\Phi_1 + v_1\Phi_2}{v}.$$

$\langle H_1^0 \rangle = v/\sqrt{2}$ and $\langle H_2^0 \rangle = 0$

$$H_2 \to e^{i\chi} H_2$$

$$\begin{aligned}\mathcal{V} = {} & Y_1 H_1^\dagger H_1 + Y_2 H_2^\dagger H_2 + [Y_3 H_1^\dagger H_2 + \text{h.c.}] + \tfrac{1}{2} Z_1 (H_1^\dagger H_1)^2 \\ & + \tfrac{1}{2} Z_2 (H_2^\dagger H_2)^2 + Z_3 (H_1^\dagger H_1)(H_2^\dagger H_2) + Z_4 (H_1^\dagger H_2)(H_2^\dagger H_1) \\ & + \left\{ \tfrac{1}{2} Z_5 (H_1^\dagger H_2)^2 + \left[Z_6 (H_1^\dagger H_1) + Z_7 (H_2^\dagger H_2) \right] H_1^\dagger H_2 + \text{h.c.} \right\},\end{aligned}$$

The gauge boson–Higgs boson interactions

$$\mathscr{L}_{VVH} = \left(g m_W W^+_\mu W^{\mu\,-} + \frac{g}{2c_W} m_Z Z_\mu Z^\mu\right) \mathrm{Re}(q_{k1}) h_k + e m_W A^\mu (W^+_\mu G^- + W^-_\mu G^+)$$

$$- g m_Z s_W^2 Z^\mu (W^+_\mu G^- + W^-_\mu G^+)\,,$$

$$\mathscr{L}_{VVHH} = \left[\tfrac{1}{4} g^2 W^+_\mu W^{\mu\,-} + \frac{g^2}{8c_W^2} Z_\mu Z^\mu\right] \mathrm{Re}(q^*_{j1} q_{k1} + q^*_{j2} q_{k2})\, h_j h_k$$

$$+ \left[\tfrac{1}{2} g^2 W^+_\mu W^{\mu\,-} + e^2 A_\mu A^\mu + \frac{g^2}{c_W^2}\left(\tfrac{1}{2} - s_W^2\right)^2 Z_\mu Z^\mu + \frac{2ge}{c_W}\left(\tfrac{1}{2} - s_W^2\right) A_\mu Z^\mu\right] (G^+ G^- + H^+ H^-)$$

$$+ \left\{\left(\tfrac{1}{2} e g A^\mu W^+_\mu - \frac{g^2 s_W^2}{2c_W} Z^\mu W^+_\mu\right) (q_{k1} G^- + q_{k2} H^-) h_k + \text{h.c.}\right\},$$

$$\mathscr{L}_{VHH} = \frac{g}{4c_W} \mathrm{Im}(q_{j1} q^*_{k1} + q_{j2} q^*_{k2}) Z^\mu h_j \overleftrightarrow{\partial}_\mu h_k - \tfrac{1}{2} g \left\{ i W^+_\mu \left[q_{k1} G^- \overleftrightarrow{\partial}^\mu h_k + q_{k2} H^- \overleftrightarrow{\partial}^\mu h_k\right] + \text{h.c.}\right\}$$

$$+ \left[ie A^\mu + \frac{ig}{c_W}\left(\tfrac{1}{2} - s_W^2\right) Z^\mu\right] (G^+ \overleftrightarrow{\partial}_\mu G^- + H^+ \overleftrightarrow{\partial}_\mu H^-)\,,$$

where $s_W \equiv \sin\theta_W$ and $c_W \equiv \cos\theta_W$.

How to test it?

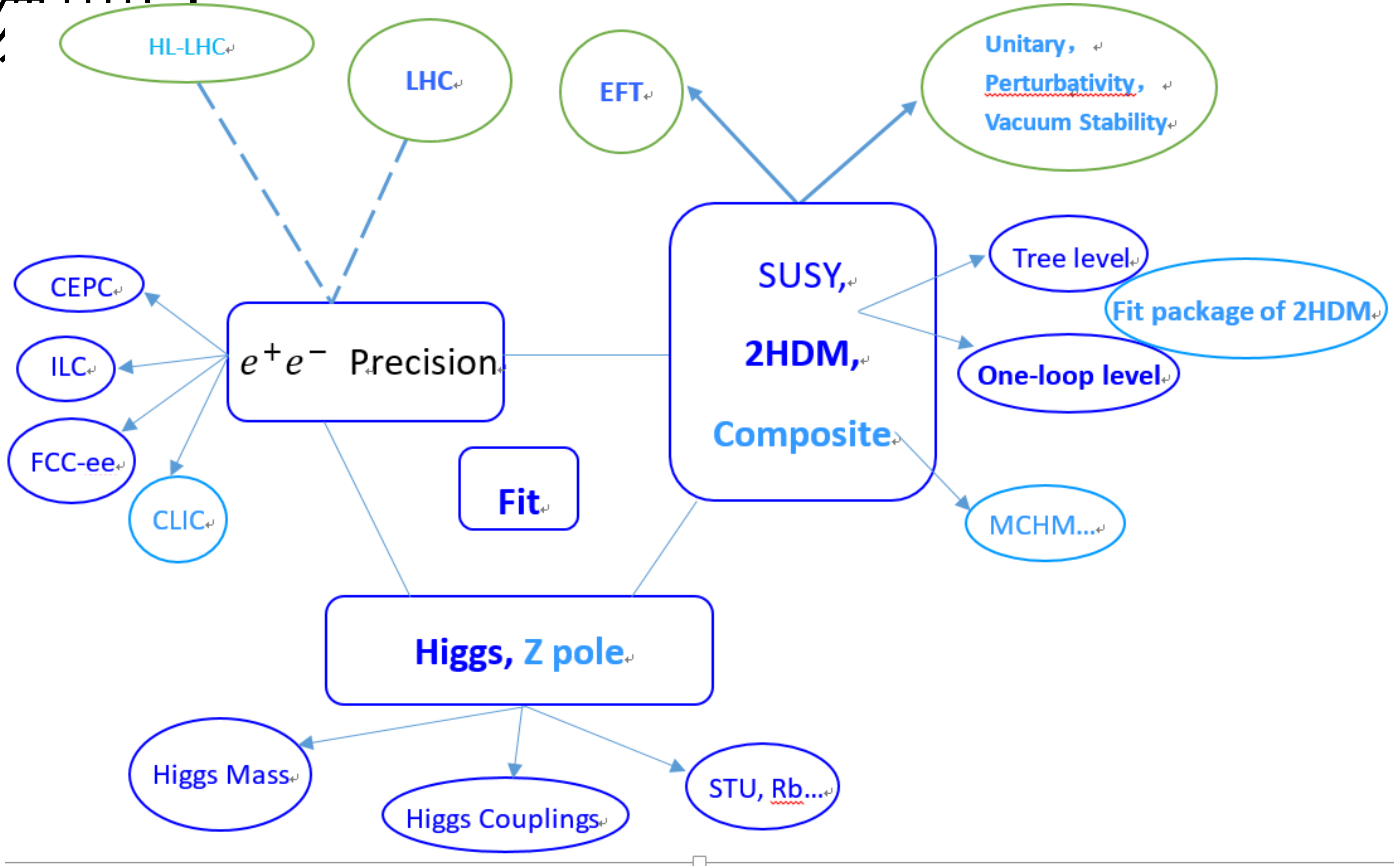
Various constraints have to be taken into account:

- Flavour physics observables
- Electroweak precision observables
- Collider searches
- SM Higgs-boson mass and signal strengths
- $Zb\bar{b}$ vertex corrections

Constraints from theoretical considerations:

- Stability of the vacuum
- Perturbativity
- Perturbative unitarity

新物理：



HL-LHC

LHC

EFT

Unitary，

Perturbativity，

Vacuum Stability

CEPC

ILC

FCC-ee

CLIC

e^+e^- Precision

SUSY,

2HDM,

Composite

Tree level

Fit package of 2HDM

One-loop level

MCHM…

Fit

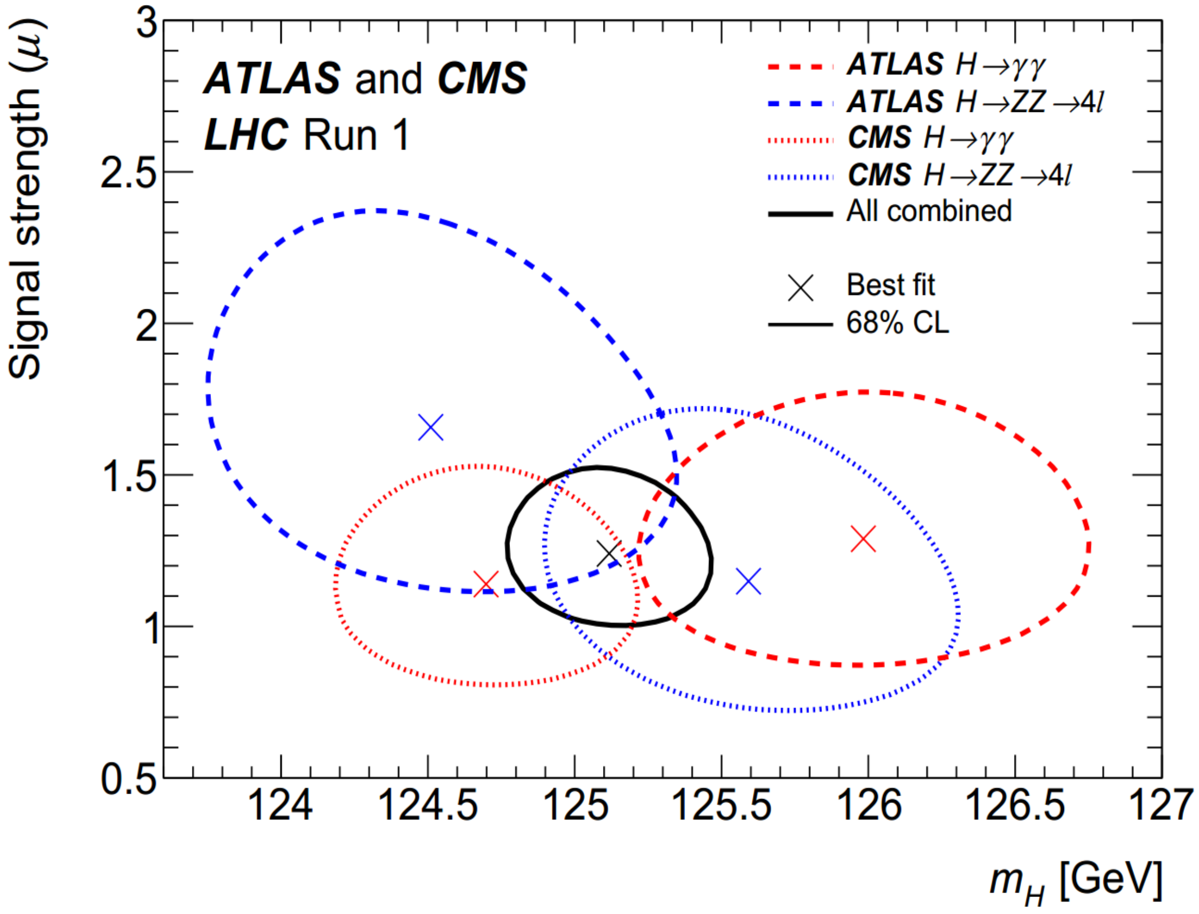
Higgs, Z pole

Higgs Mass

Higgs Couplings

STU, Rb…

Higgs discovery

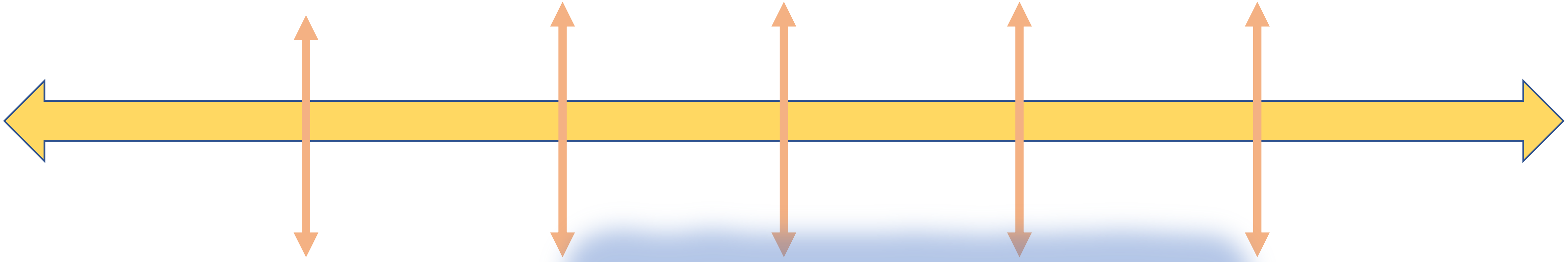


CMS-HIG-14-042
ATLAS-HIGG-2014-14

LHC Run-I:

$$m_h = 125.09 \pm 0.24 \text{ GeV}$$

Scenarios

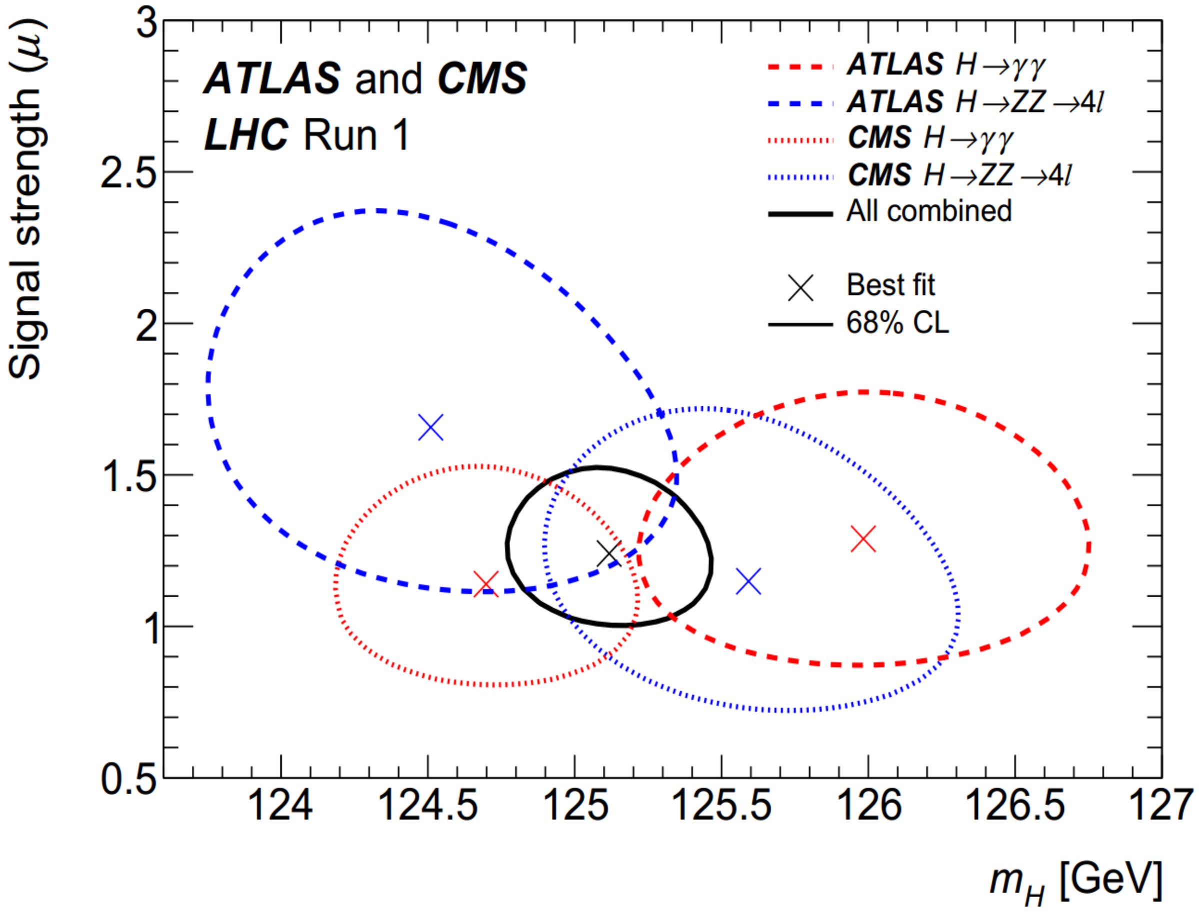


Mass hierarchy

LHC era

- $m_{h_S} < 0.1$ GeV
- 0.1 GeV$< m_{h_S} < 10$ GeV
- 10 GeV $< m_{h_S} < 62.5$ GeV
- 62.5 GeV $< m_{h_S} < 1$ TeV
- 1 TeV $< m_{h_S} < 10$TeV
- 10 TeV $< m_{h_S}$

LHC era： Higgs discovery

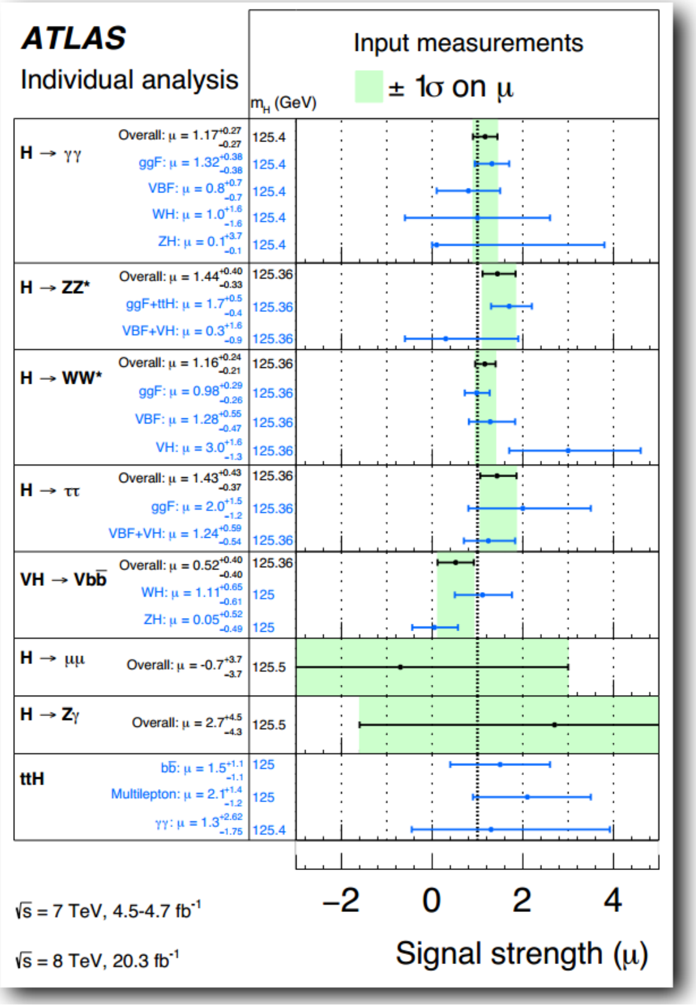


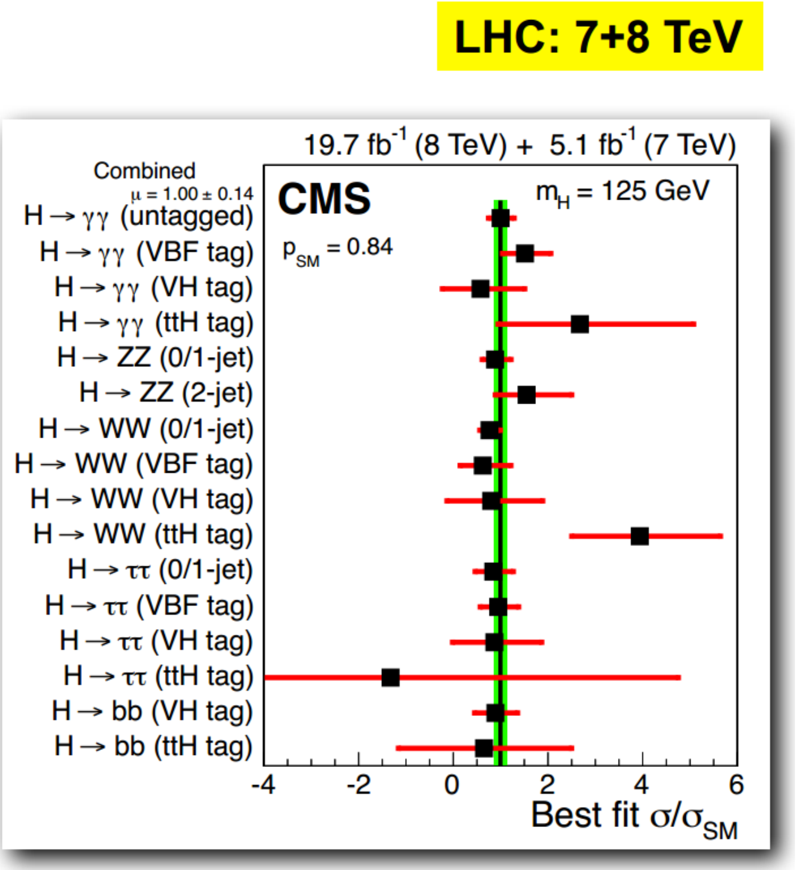
CMS-HIG-14-042
ATLAS-HIGG-2014-14

LHC Run-I:

$$m_h = 125.09 \pm 0.24 \text{ GeV}$$

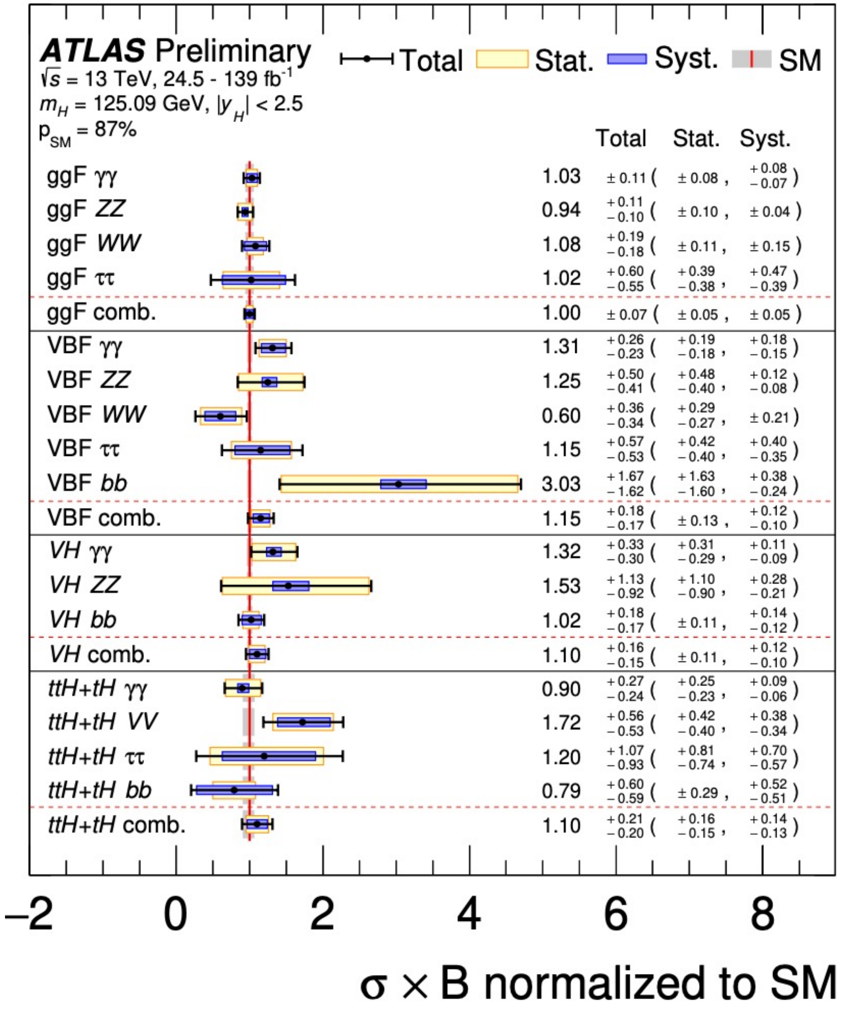
Higgs property at LHC Run-I



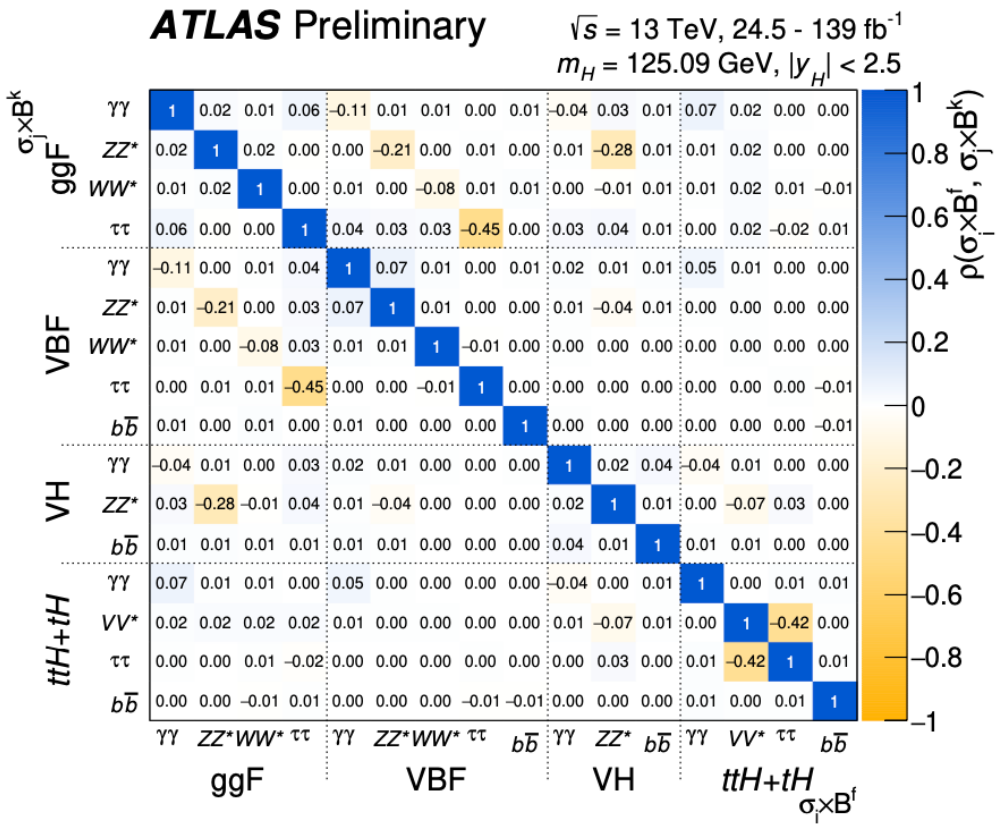


CERN-PH-EP-2015-125
CERN-PH-EP-2013-037

Higgs property at LHC Run-II

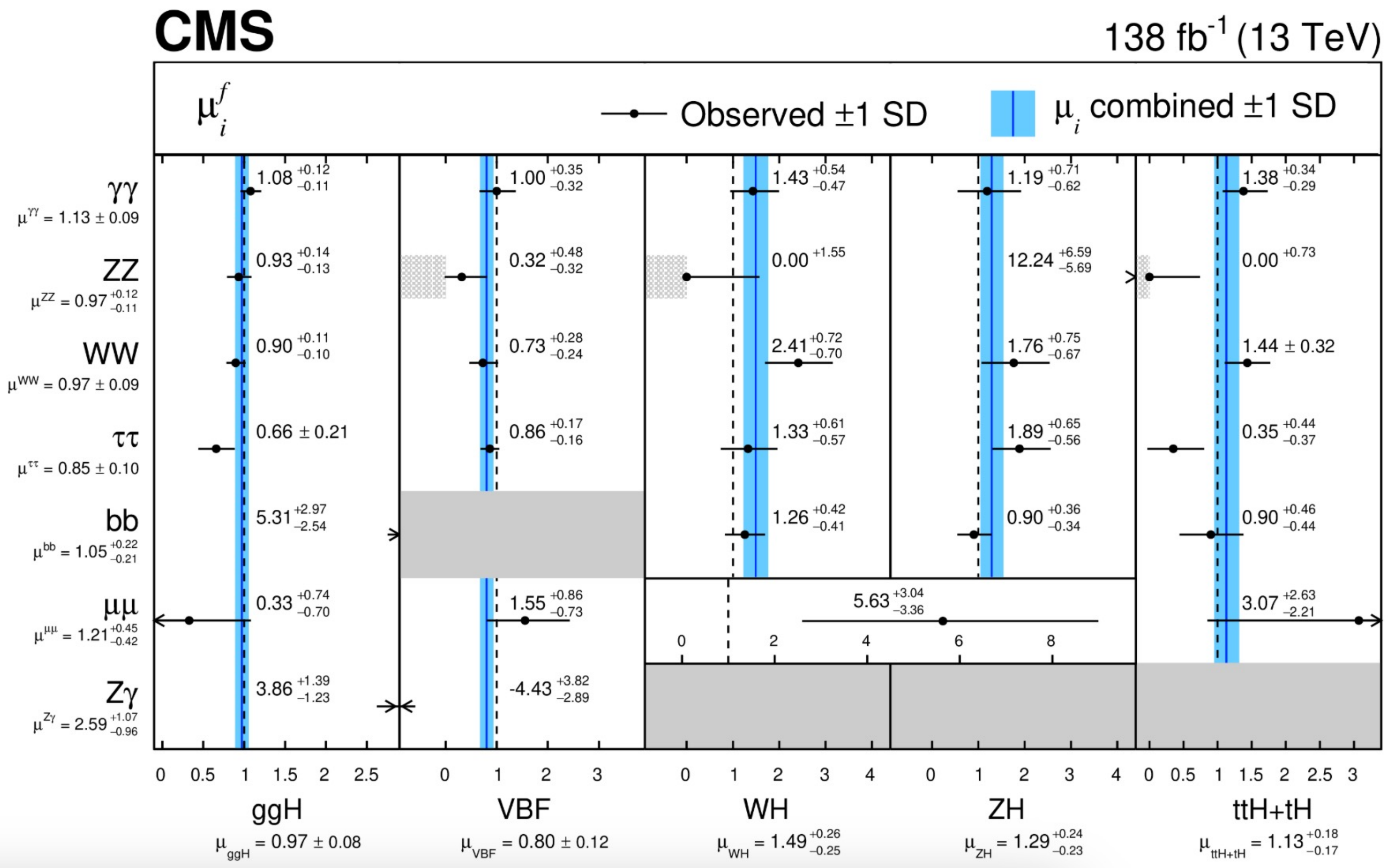


ATLAS-CONF-2020-027



		ggF				VBF					VH			ttH+tH			
		γγ	ZZ*	WW*	ττ	γγ	ZZ*	WW*	ττ	$b\bar{b}$	γγ	ZZ*	$b\bar{b}$	γγ	VV*	ττ	$b\bar{b}$
ggF	γγ	1	0.02	0.01	0.06	–0.11	0.01	0.01	0.00	0.01	–0.04	0.03	0.01	0.07	0.02	0.00	0.00
	ZZ*	0.02	1	0.02	0.00	0.00	–0.21	0.00	0.01	0.00	0.01	–0.28	0.01	0.01	0.02	0.00	0.00
	WW*	0.01	0.02	1	0.00	0.01	0.00	–0.08	0.01	0.01	0.00	–0.01	0.01	0.01	0.02	0.01	–0.01
	ττ	0.06	0.00	0.00	1	0.04	0.03	0.03	–0.45	0.00	0.03	0.04	0.01	0.00	0.02	–0.02	0.01
VBF	γγ	–0.11	0.00	0.01	0.04	1	0.07	0.01	0.00	0.01	0.02	0.01	0.01	0.05	0.01	0.00	0.00
	ZZ*	0.01	–0.21	0.00	0.03	0.07	1	0.01	0.00	0.00	0.01	–0.04	0.01	0.00	0.00	0.00	0.00
	WW*	0.01	0.00	–0.08	0.03	0.01	0.01	1	–0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	ττ	0.00	0.01	0.01	–0.45	0.00	0.00	–0.01	1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	–0.01
	$b\bar{b}$	0.01	0.00	0.01	0.00	0.01	0.00	0.00	0.00	1	0.00	0.00	0.00	0.00	0.00	0.00	–0.01
VH	γγ	–0.04	0.01	0.00	0.03	0.02	0.01	0.00	0.00	0.00	1	0.02	0.04	–0.04	0.01	0.00	0.00
	ZZ*	0.03	–0.28	–0.01	0.04	0.01	–0.04	0.00	0.00	0.00	0.02	1	0.01	0.00	–0.07	0.03	0.00
	$b\bar{b}$	0.01	0.01	0.01	0.01	0.01	0.01	0.00	0.00	0.00	0.04	0.01	1	0.01	0.01	0.00	0.00
ttH+tH	γγ	0.07	0.01	0.01	0.00	0.05	0.00	0.00	0.00	0.00	–0.04	0.00	0.01	1	0.00	0.01	0.01
	VV*	0.02	0.02	0.02	0.02	0.01	0.00	0.00	0.00	0.00	0.01	–0.07	0.01	0.00	1	–0.42	0.00
	ττ	0.00	0.00	0.01	–0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.03	0.00	0.01	–0.42	1	0.01
	$b\bar{b}$	0.00	0.00	–0.01	0.01	0.00	0.00	0.00	–0.01	–0.01	0.00	0.00	0.00	0.01	0.00	0.01	1

Higgs property at LHC Run-II



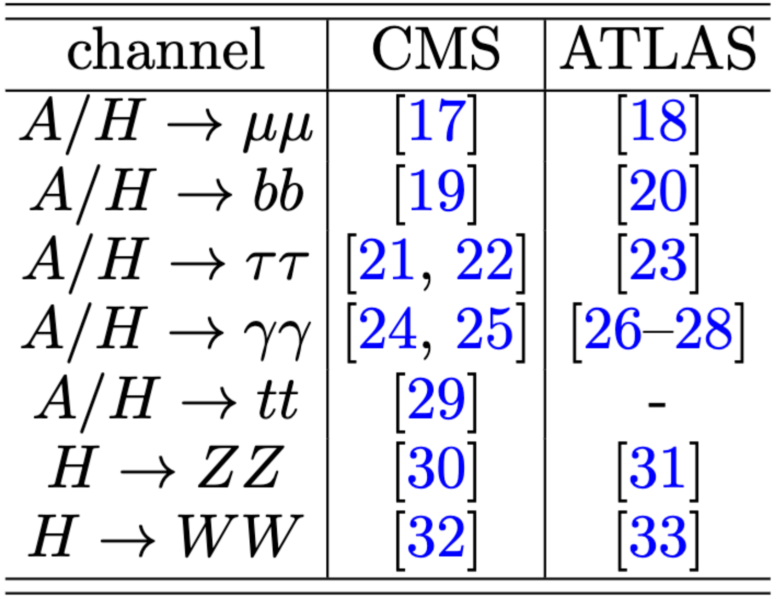
CMS_137_HIG-19-005-pas

Nature 607 (2022) 52-59

Nature 607 (2022) 60-68

LHC era： 62.5 GeV - 1 TeV

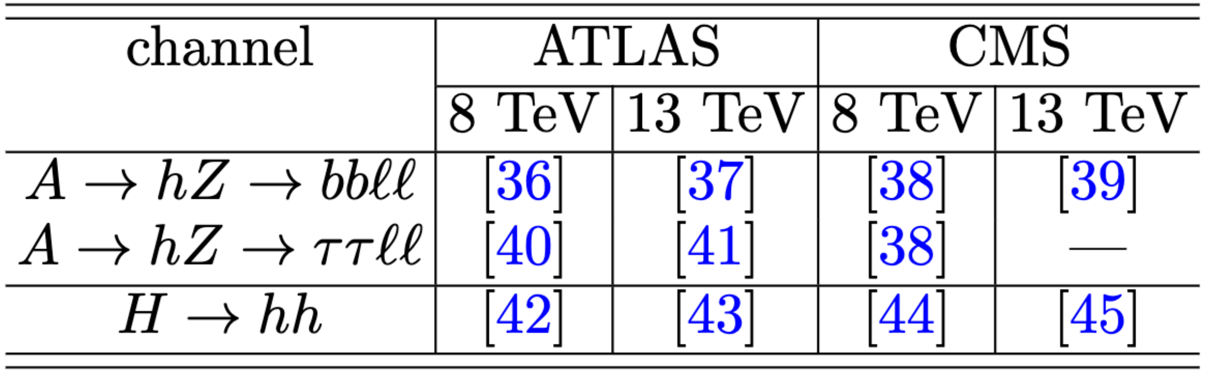
- Conventional channels:



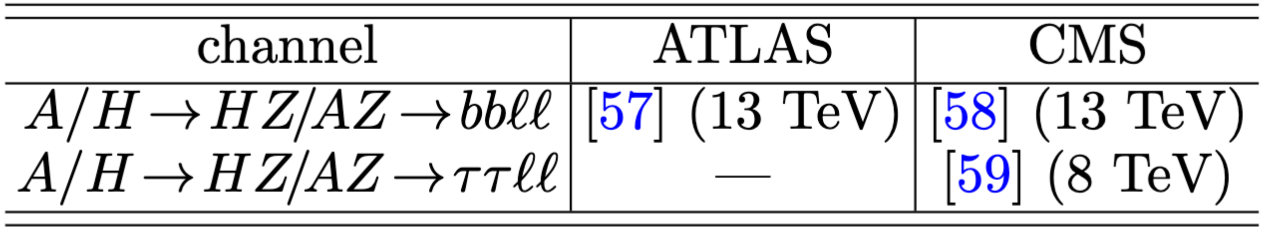
channel	CMS	ATLAS
$A/H \to \mu\mu$	[17]	[18]
$A/H \to bb$	[19]	[20]
$A/H \to \tau\tau$	[21, 22]	[23]
$A/H \to \gamma\gamma$	[24, 25]	[26–28]
$A/H \to tt$	[29]	-
$H \to ZZ$	[30]	[31]
$H \to WW$	[32]	[33]

2212.06186 (F. Kling, S. Li, S. Su, H.Song, WS)

Exotic Decays



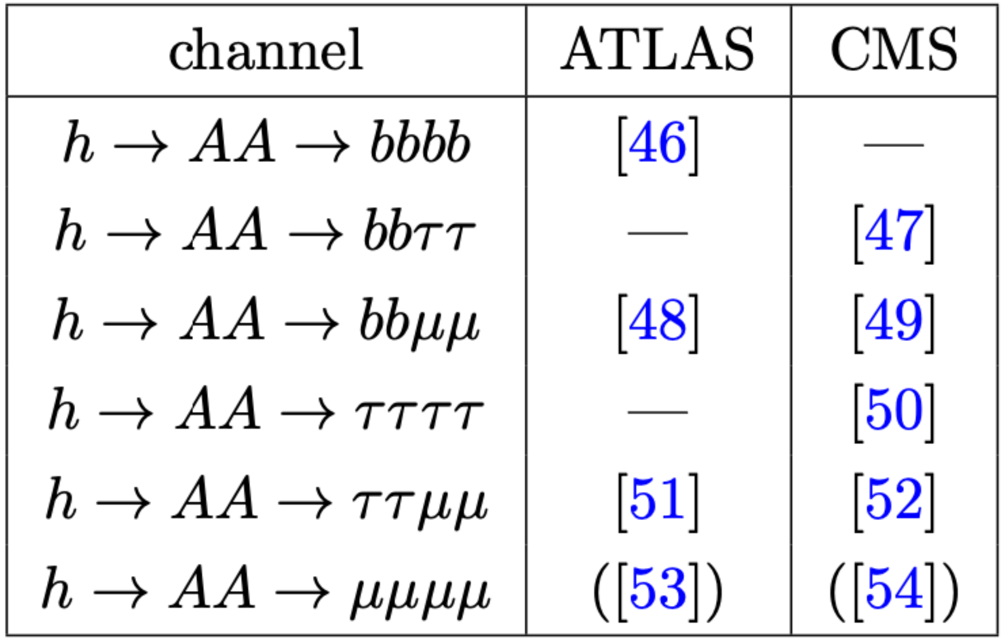
channel	ATLAS		CMS	
	8 TeV	13 TeV	8 TeV	13 TeV
$A \to hZ \to bb\ell\ell$	[36]	[37]	[38]	[39]
$A \to hZ \to \tau\tau\ell\ell$	[40]	[41]	[38]	—
$H \to hh$	[42]	[43]	[44]	[45]



channel	ATLAS	CMS
$A/H \to HZ/AZ \to bb\ell\ell$	[57] (13 TeV)	[58] (13 TeV)
$A/H \to HZ/AZ \to \tau\tau\ell\ell$	—	[59] (8 TeV)

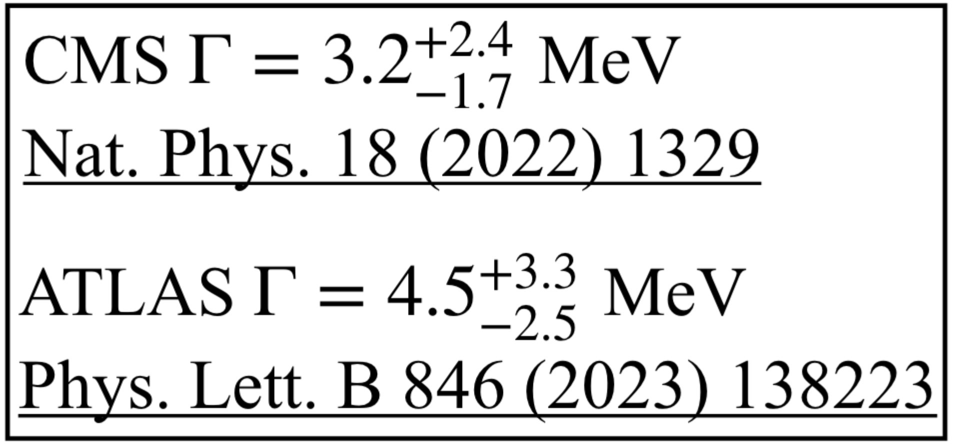
LHC era： 10 GeV ~ 62.5 GeV

- Exotic Decays



channel	ATLAS	CMS
$h \to AA \to bbbb$	[46]	—
$h \to AA \to bb\tau\tau$	—	[47]
$h \to AA \to bb\mu\mu$	[48]	[49]
$h \to AA \to \tau\tau\tau\tau$	—	[50]
$h \to AA \to \tau\tau\mu\mu$	[51]	[52]
$h \to AA \to \mu\mu\mu\mu$	([53])	([54])

· SM Higgs decay width



CMS $\Gamma = 3.2^{+2.4}_{-1.7}$ MeV

Nat. Phys. 18 (2022) 1329

ATLAS $\Gamma = 4.5^{+3.3}_{-2.5}$ MeV

Phys. Lett. B 846 (2023) 138223

LHC era： 10 GeV ~ 62.5 GeV

- Precision Higgs Measurements： Global fit

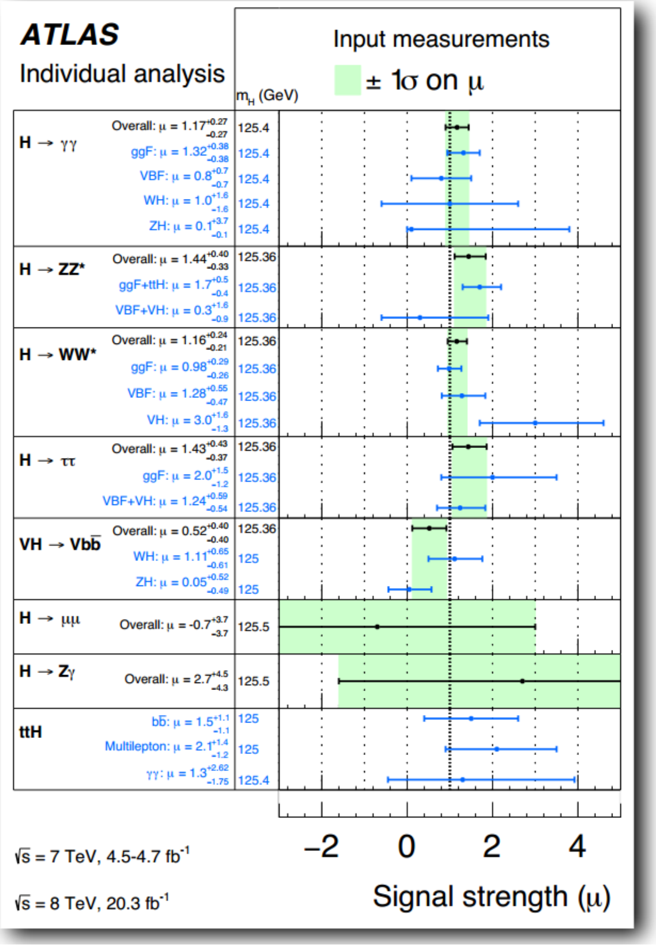
- SM Higgs invisible decays： Eur. Phys. J. C 83 (2023) 933

  Phys. Lett. B 842 (2023) 137963_

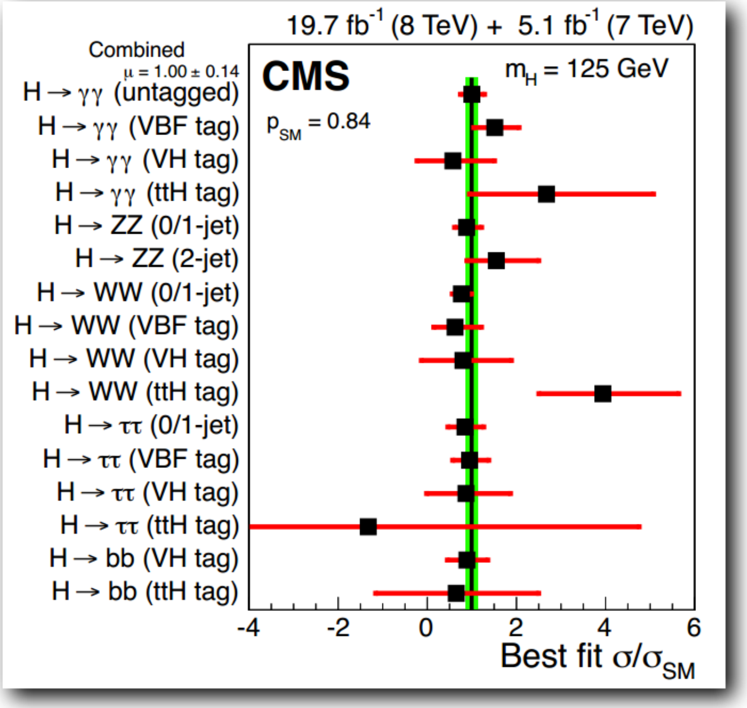
- 95% CL limit for H→ inv

ATLAS: 10.7% (7.7% exp.) CMS: 15% (8% exp.)

Higgs property



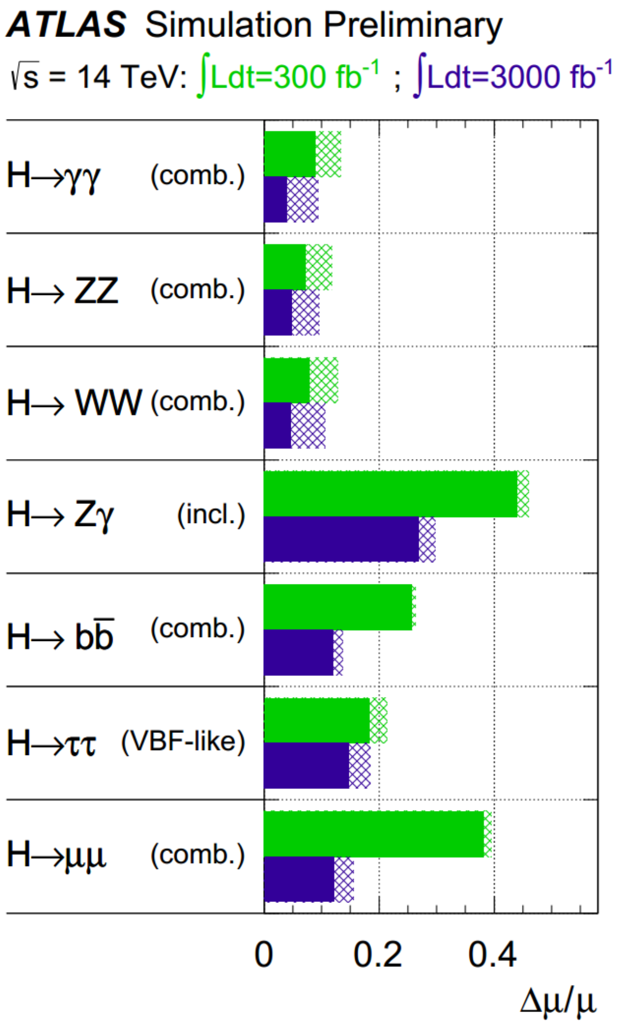
LHC: 7+8 TeV



CERN-PH-EP-2015-125 3
CERN-PH-EP-2013-037

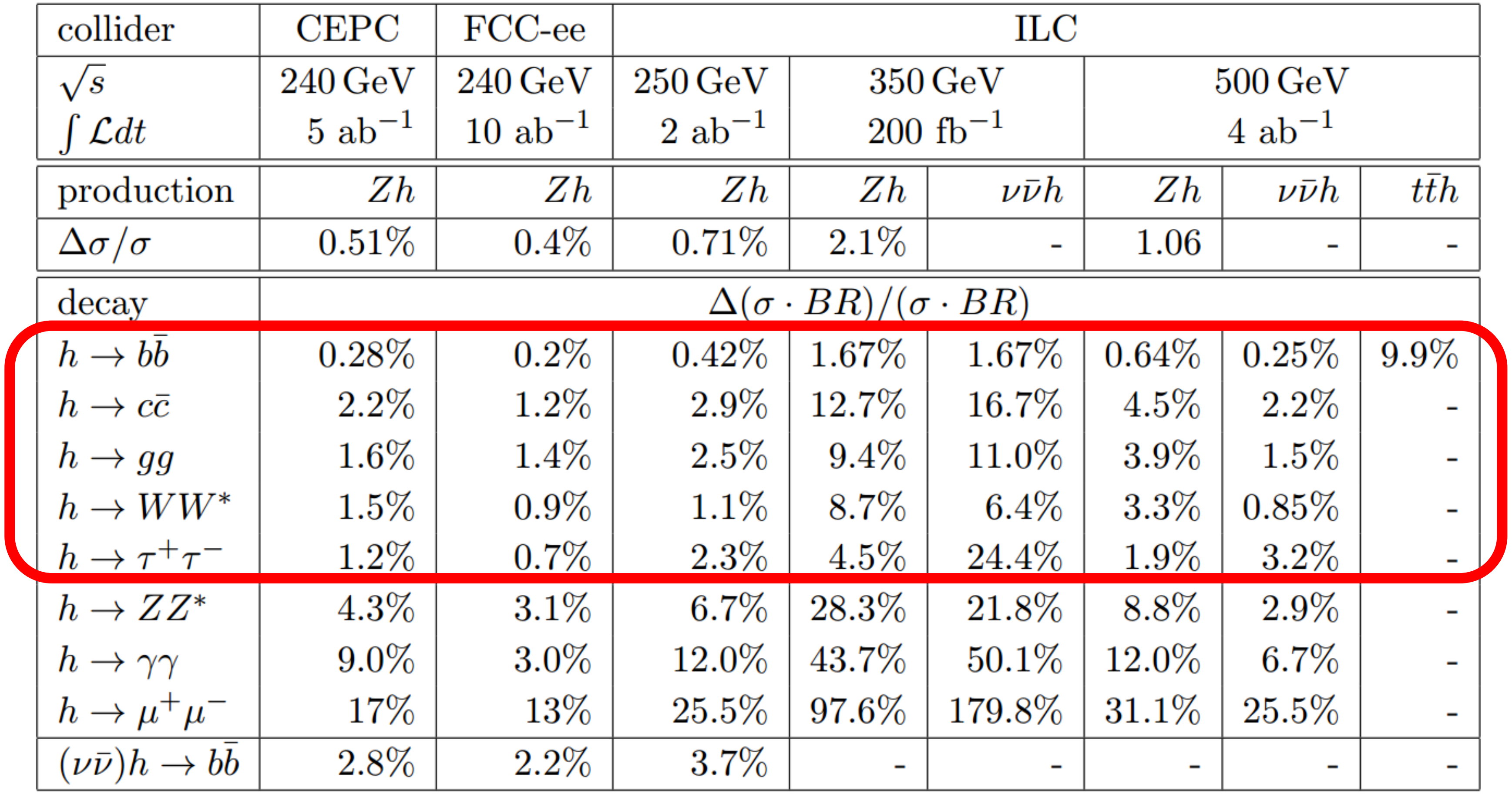
Higgs property

ATL-PHYS-PUB-2014-016

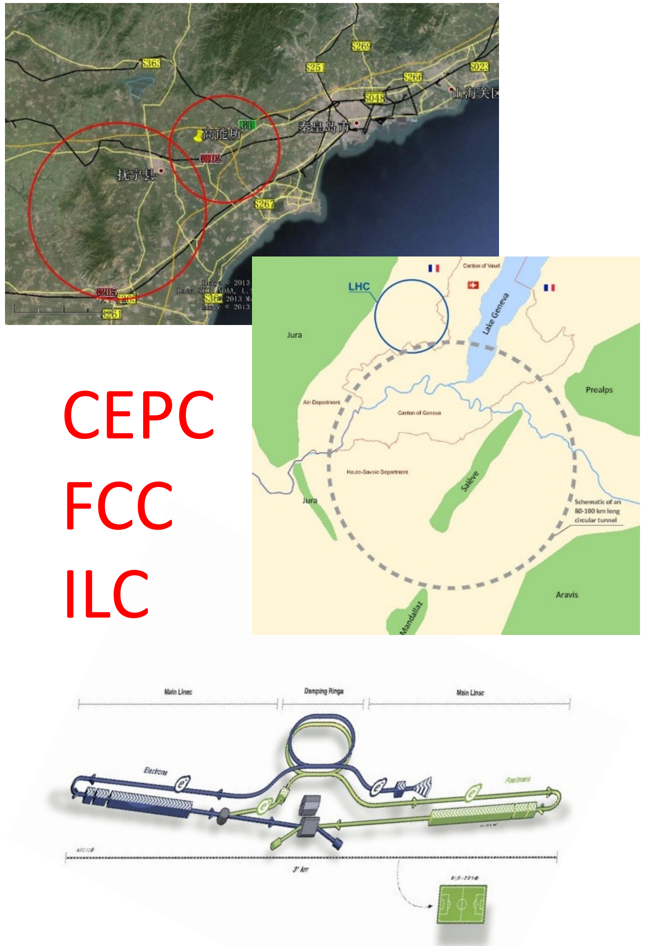


$\Delta\mu/\mu$	$300\ \text{fb}^{-1}$		$3000\ \text{fb}^{-1}$	
	All unc.	No theory unc.	All unc.	No theory unc.
$H \to \gamma\gamma$ (comb.)	0.13	0.09	0.09	0.04
(0j)	0.19	0.12	0.16	0.05
(1j)	0.27	0.14	0.23	0.05
(VBF-like)	0.47	0.43	0.22	0.15
(WH-like)	0.48	0.48	0.19	0.17
(ZH-like)	0.85	0.85	0.28	0.27
(ttH-like)	0.38	0.36	0.17	0.12
$H \to ZZ$ (comb.)	0.11	0.07	0.09	0.04
(VH-like)	0.35	0.34	0.13	0.12
(ttH-like)	0.49	0.48	0.20	0.16
(VBF-like)	0.36	0.33	0.21	0.16
(ggF-like)	0.12	0.07	0.11	0.04
$H \to WW$ (comb.)	0.13	0.08	0.11	0.05
(0j)	0.18	0.09	0.16	0.05
(1j)	0.30	0.18	0.26	0.10
(VBF-like)	0.21	0.20	0.15	0.09
$H \to Z\gamma$ (incl.)	0.46	0.44	0.30	0.27
$H \to b\bar{b}$ (comb.)	0.26	0.26	0.14	0.12
(WH-like)	0.57	0.56	0.37	0.36
(ZH-like)	0.29	0.29	0.14	0.13
$H \to \tau\tau$ (VBF-like)	0.21	0.18	0.19	0.15
$H \to \mu\mu$ (comb.)	0.39	0.38	0.16	0.12
(incl.)	0.47	0.45	0.18	0.14
(ttH-like)	0.74	0.72	0.27	0.23

Higgs precision measurements



collider	CEPC	FCC-ee	ILC					
$\sqrt{s}$ $\int \mathcal{L}dt$	240 GeV 5 ab^{-1}	240 GeV 10 ab^{-1}	250 GeV 2 ab^{-1}	350 GeV 200 fb^{-1}		500 GeV 4 ab^{-1}		
production	Zh	Zh	Zh	Zh	$\nu\bar{\nu}h$	Zh	$\nu\bar{\nu}h$	$t\bar{t}h$
$\Delta\sigma/\sigma$	0.51%	0.4%	0.71%	2.1%	-	1.06	-	-
decay	$\Delta(\sigma \cdot BR)/(\sigma \cdot BR)$							
$h \to b\bar{b}$	0.28%	0.2%	0.42%	1.67%	1.67%	0.64%	0.25%	9.9%
$h \to c\bar{c}$	2.2%	1.2%	2.9%	12.7%	16.7%	4.5%	2.2%	-
$h \to gg$	1.6%	1.4%	2.5%	9.4%	11.0%	3.9%	1.5%	-
$h \to WW^*$	1.5%	0.9%	1.1%	8.7%	6.4%	3.3%	0.85%	-
$h \to \tau^+\tau^-$	1.2%	0.7%	2.3%	4.5%	24.4%	1.9%	3.2%	-
$h \to ZZ^*$	4.3%	3.1%	6.7%	28.3%	21.8%	8.8%	2.9%	-
$h \to \gamma\gamma$	9.0%	3.0%	12.0%	43.7%	50.1%	12.0%	6.7%	-
$h \to \mu^+\mu^-$	17%	13%	25.5%	97.6%	179.8%	31.1%	25.5%	-
$(\nu\bar{\nu})h \to b\bar{b}$	2.8%	2.2%	3.7%	-	-	-	-	-



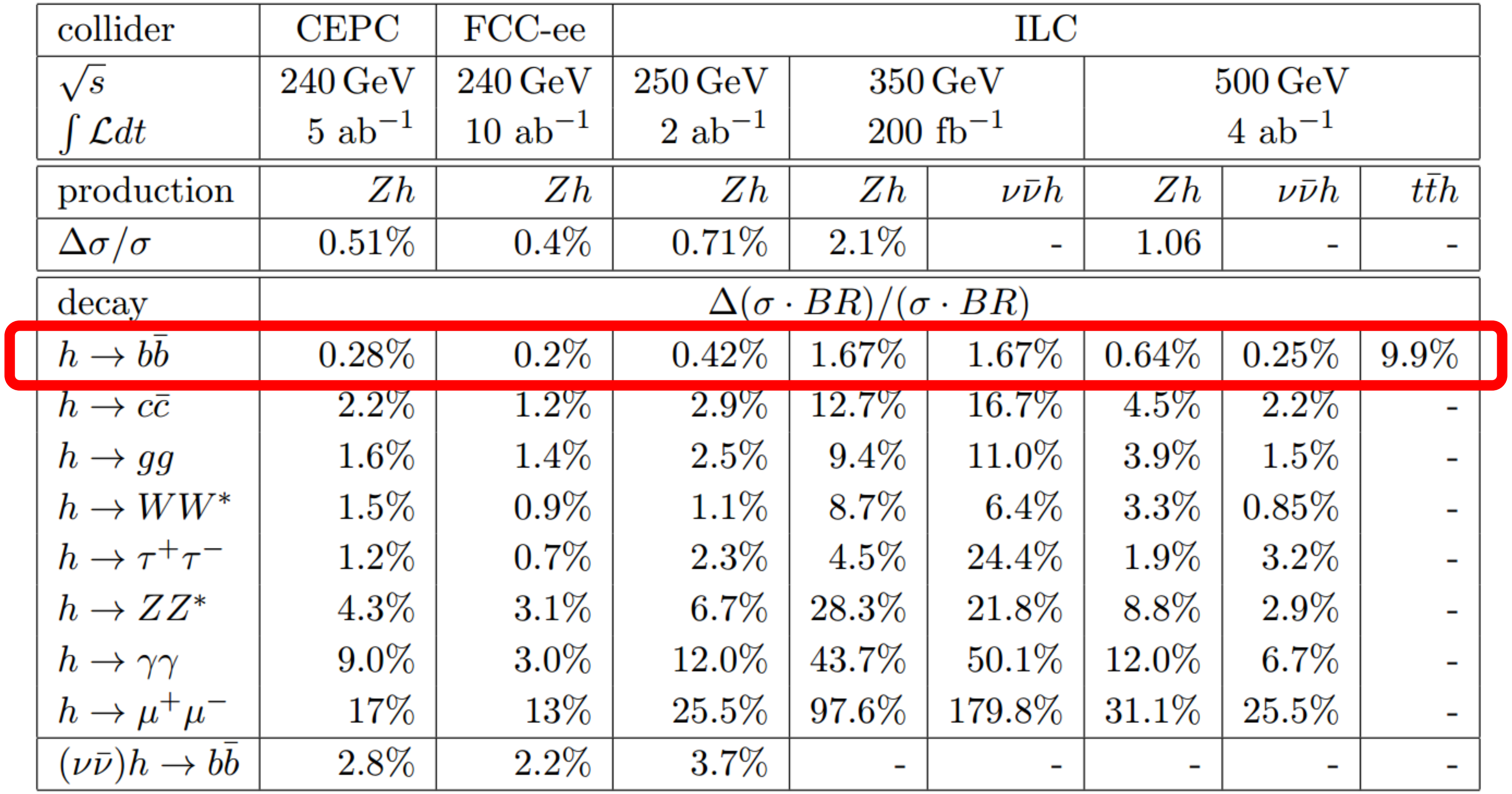
CEPC

FCC

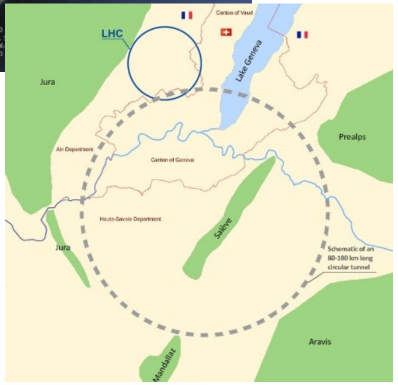
ILC

CEPC-preCDR , TLEP Design Study Working Group, ILC Operating Scenarios

Higgs precision measurements



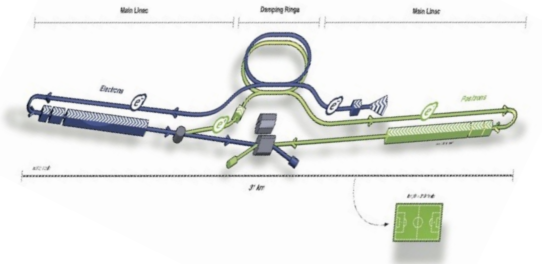
collider	CEPC	FCC-ee	ILC					
$\sqrt{s}$ $\int \mathcal{L}dt$	240 GeV 5 ab^{-1}	240 GeV 10 ab^{-1}	250 GeV 2 ab^{-1}	350 GeV 200 fb^{-1}		500 GeV 4 ab^{-1}		
production	Zh	Zh	Zh	Zh	$\nu\bar{\nu}h$	Zh	$\nu\bar{\nu}h$	$t\bar{t}h$
$\Delta\sigma/\sigma$	0.51%	0.4%	0.71%	2.1%	-	1.06	-	-
decay	$\Delta(\sigma \cdot BR)/(\sigma \cdot BR)$							
$h \to b\bar{b}$	0.28%	0.2%	0.42%	1.67%	1.67%	0.64%	0.25%	9.9%
$h \to c\bar{c}$	2.2%	1.2%	2.9%	12.7%	16.7%	4.5%	2.2%	-
$h \to gg$	1.6%	1.4%	2.5%	9.4%	11.0%	3.9%	1.5%	-
$h \to WW^*$	1.5%	0.9%	1.1%	8.7%	6.4%	3.3%	0.85%	-
$h \to \tau^+\tau^-$	1.2%	0.7%	2.3%	4.5%	24.4%	1.9%	3.2%	-
$h \to ZZ^*$	4.3%	3.1%	6.7%	28.3%	21.8%	8.8%	2.9%	-
$h \to \gamma\gamma$	9.0%	3.0%	12.0%	43.7%	50.1%	12.0%	6.7%	-
$h \to \mu^+\mu^-$	17%	13%	25.5%	97.6%	179.8%	31.1%	25.5%	-
$(\nu\bar{\nu})h \to b\bar{b}$	2.8%	2.2%	3.7%	-	-	-	-	-



CEPC

FCC

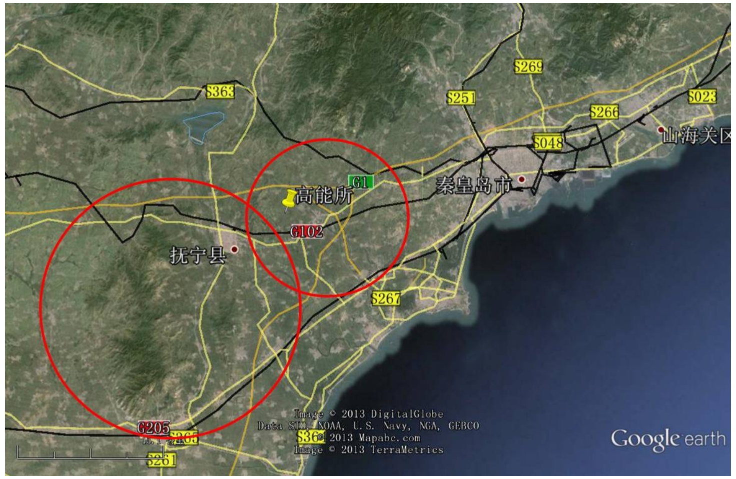
ILC



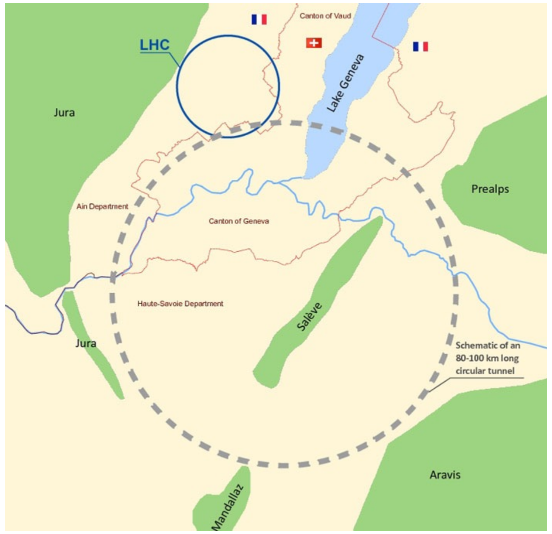
CEPC-preCDR , TLEP Design Study Working Group, ILC Operating Scenarios

Higgs precision measurements

Collider	$\Delta\mu$ (hbb)
LHC Run-I	50% (wh)
LHC 14 TeV $300 fb^{-1}$	26%
LHC 14 TeV $3000 fb^{-1}$	12%
CEPC 240 GeV $5ab^{-1}$ (zh)	0.28%
FCC-ee 240 GeV $10ab^{-1}$ (zh)	0.2%
ILC 240 GeV $2ab^{-1}$ (zh)	0.42%
ILC 350 GeV $0.2ab^{-1}$ (zh)	1.6%
ILC 500 GeV $4ab^{-1}$ (vvh)	0.24%



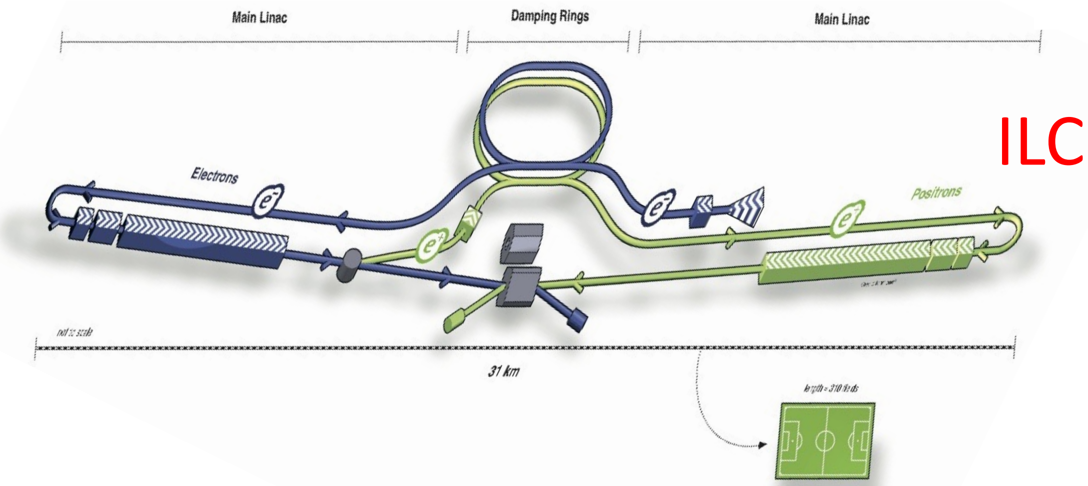
CEPC



LHC

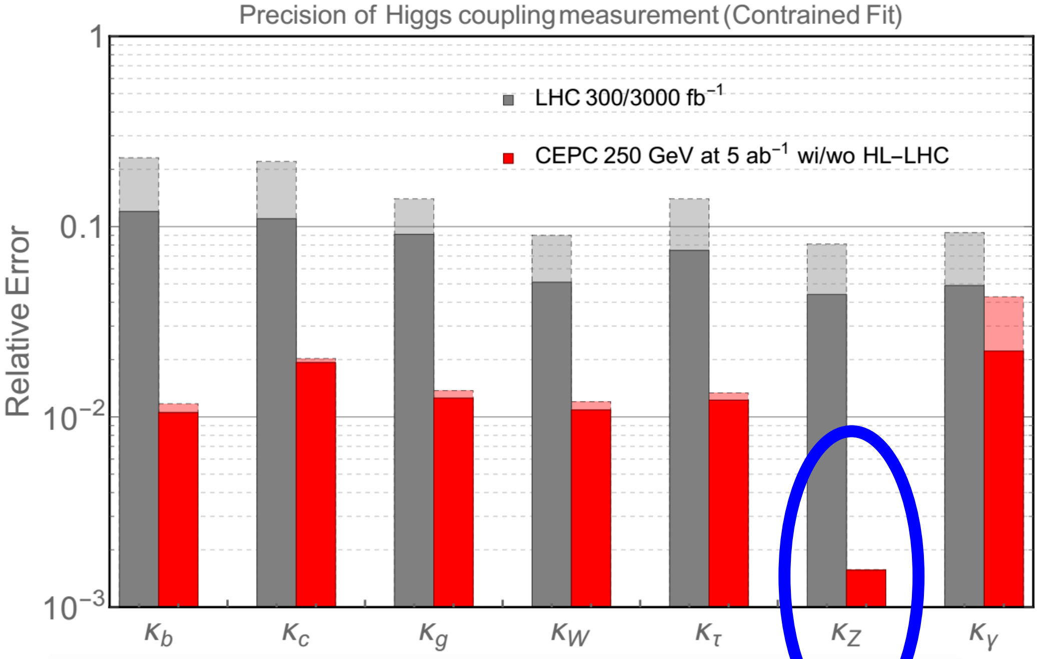
HL-LHC

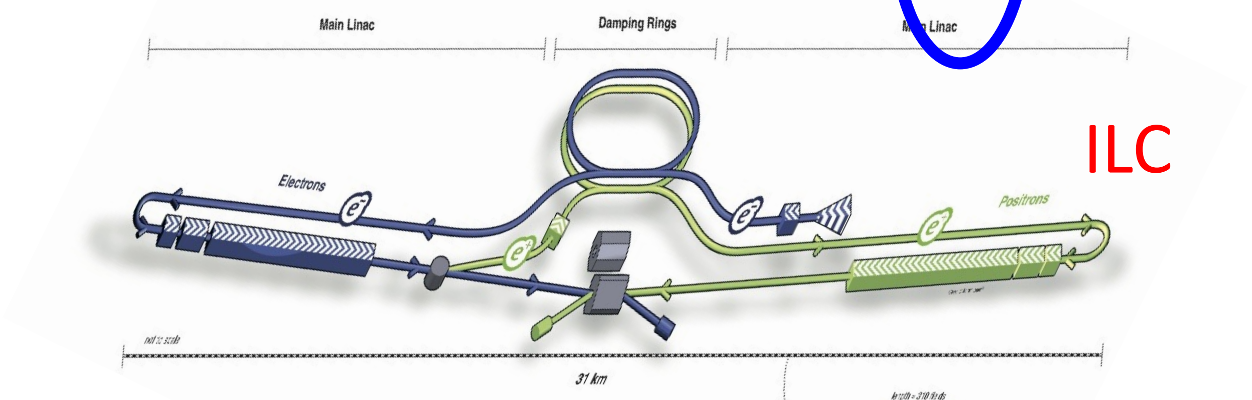
FCC



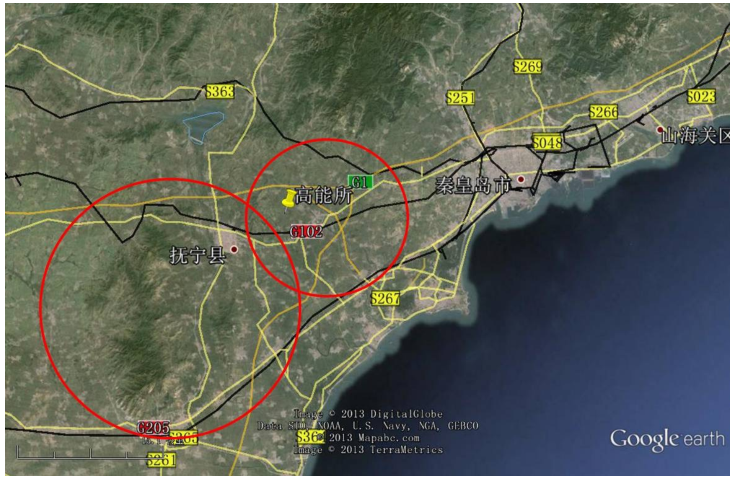
ILC

Higgs precision measurements

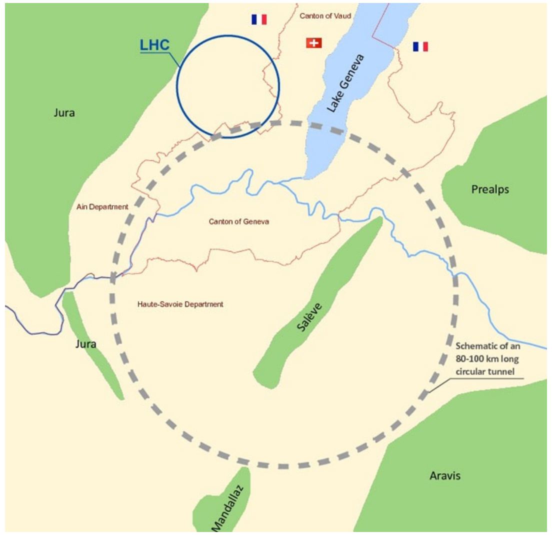




ILC



CEPC

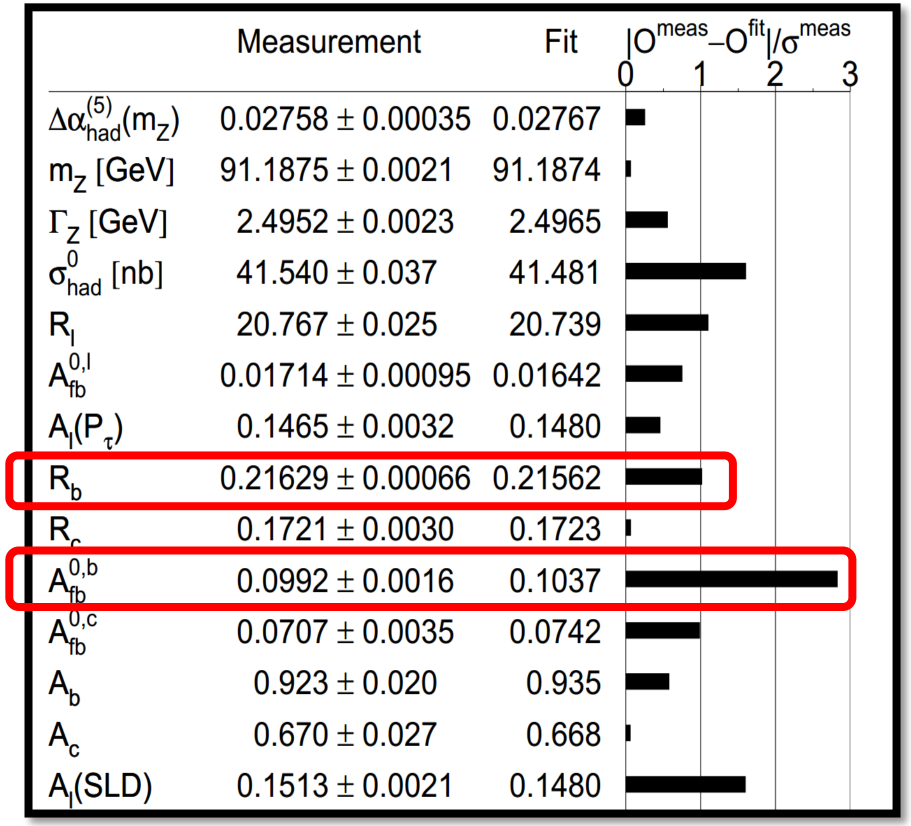


LHC

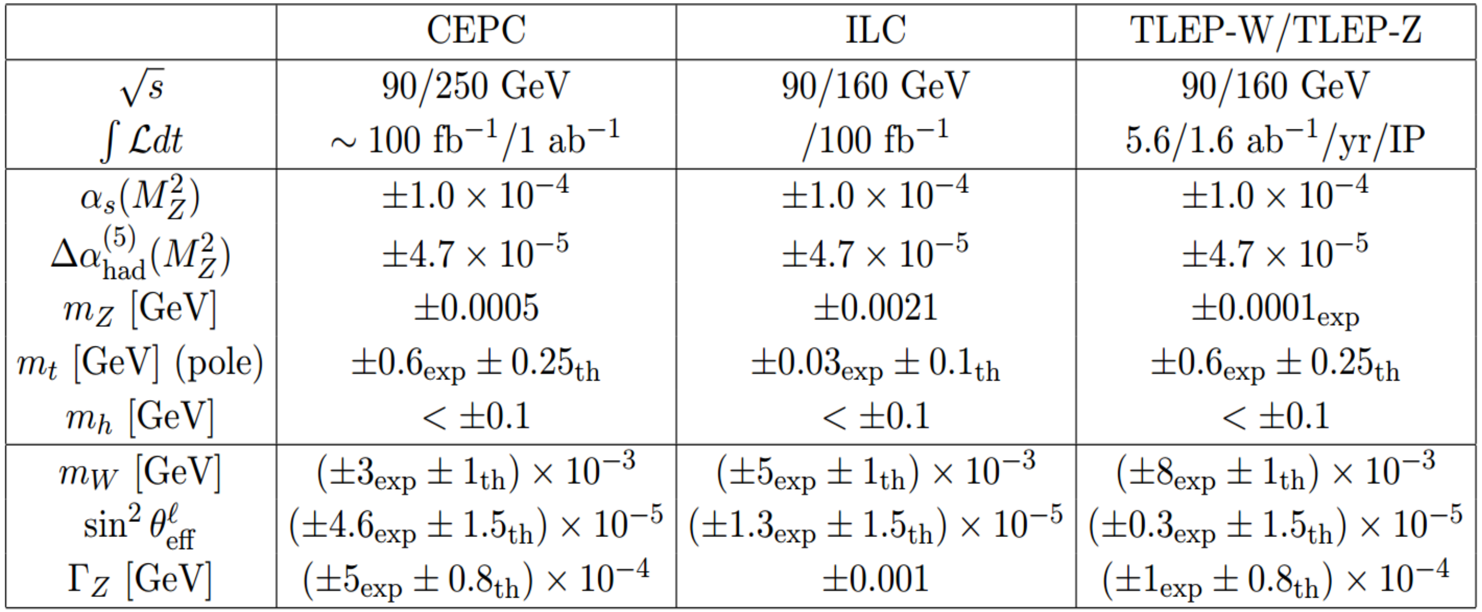
HL-LHC

FCC

Z-pole precision measurements



	Measurement	Fit
$\Delta\alpha_{had}^{(5)}(m_Z)$	0.02758 ± 0.00035	0.02767
m_Z [GeV]	91.1875 ± 0.0021	91.1874
Γ_Z [GeV]	2.4952 ± 0.0023	2.4965
σ_{had}^0 [nb]	41.540 ± 0.037	41.481
R_l	20.767 ± 0.025	20.739
$A_{fb}^{0,l}$	0.01714 ± 0.00095	0.01642
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1480
R_b	0.21629 ± 0.00066	0.21562
R_c	0.1721 ± 0.0030	0.1723
$A_{fb}^{0,b}$	0.0992 ± 0.0016	0.1037
$A_{fb}^{0,c}$	0.0707 ± 0.0035	0.0742
A_b	0.923 ± 0.020	0.935
A_c	0.670 ± 0.027	0.668
A_l(SLD)	0.1513 ± 0.0021	0.1480

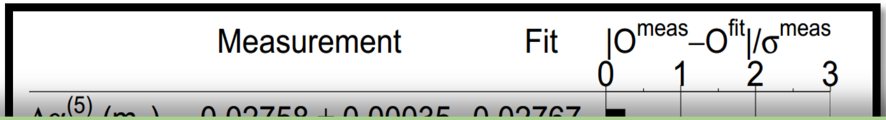


	CEPC	ILC	TLEP-W/TLEP-Z
$\sqrt{s}$	90/250 GeV	90/160 GeV	90/160 GeV
$\int \mathcal{L}dt$	~ 100 fb^{-1}/1 ab^{-1}	/100 fb^{-1}	5.6/1.6 ab^{-1}/yr/IP
$\alpha_s(M_Z^2)$	$\pm 1.0 \times 10^{-4}$	$\pm 1.0 \times 10^{-4}$	$\pm 1.0 \times 10^{-4}$
$\Delta\alpha_{\rm had}^{(5)}(M_Z^2)$	$\pm 4.7 \times 10^{-5}$	$\pm 4.7 \times 10^{-5}$	$\pm 4.7 \times 10^{-5}$
m_Z [GeV]	± 0.0005	± 0.0021	$\pm 0.0001_{\rm exp}$
m_t [GeV] (pole)	$\pm 0.6_{\rm exp} \pm 0.25_{\rm th}$	$\pm 0.03_{\rm exp} \pm 0.1_{\rm th}$	$\pm 0.6_{\rm exp} \pm 0.25_{\rm th}$
m_h [GeV]	$< \pm 0.1$	$< \pm 0.1$	$< \pm 0.1$
m_W [GeV]	$(\pm 3_{\rm exp} \pm 1_{\rm th}) \times 10^{-3}$	$(\pm 5_{\rm exp} \pm 1_{\rm th}) \times 10^{-3}$	$(\pm 8_{\rm exp} \pm 1_{\rm th}) \times 10^{-3}$
$\sin^2\theta_{\rm eff}^{\ell}$	$(\pm 4.6_{\rm exp} \pm 1.5_{\rm th}) \times 10^{-5}$	$(\pm 1.3_{\rm exp} \pm 1.5_{\rm th}) \times 10^{-5}$	$(\pm 0.3_{\rm exp} \pm 1.5_{\rm th}) \times 10^{-5}$
Γ_Z [GeV]	$(\pm 5_{\rm exp} \pm 0.8_{\rm th}) \times 10^{-4}$	± 0.001	$(\pm 1_{\rm exp} \pm 0.8_{\rm th}) \times 10^{-4}$

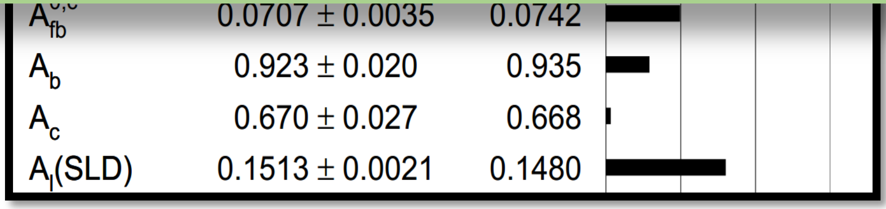
LEP

CEPC-preCDR , TLEP Design Study , ILC Operating Scenarios

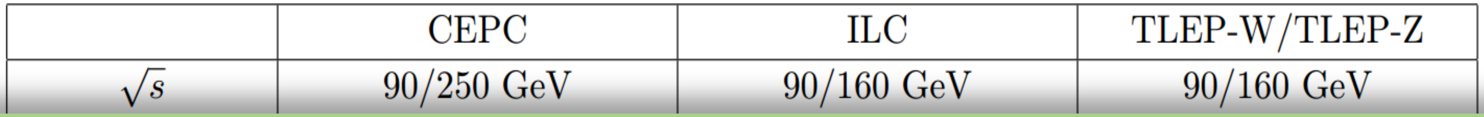
Z-pole precision measurements



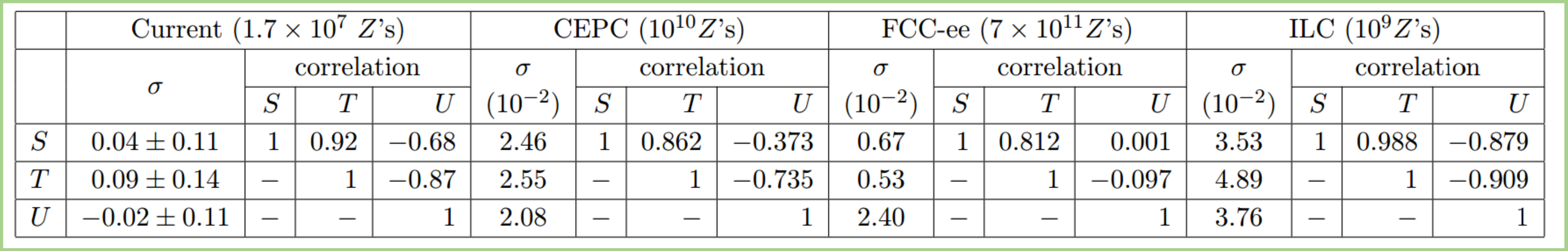
	Measurement	Fit
$\Delta\alpha_{had}^{(5)}(m_Z)$	0.02758 ± 0.00035	0.02767



	Measurement	Fit
$A_{fb}^{0,c}$	0.0707 ± 0.0035	0.0742
A_b	0.923 ± 0.020	0.935
A_c	0.670 ± 0.027	0.668
A_l(SLD)	0.1513 ± 0.0021	0.1480



	CEPC	ILC	TLEP-W/TLEP-Z
$\sqrt{s}$	90/250 GeV	90/160 GeV	90/160 GeV

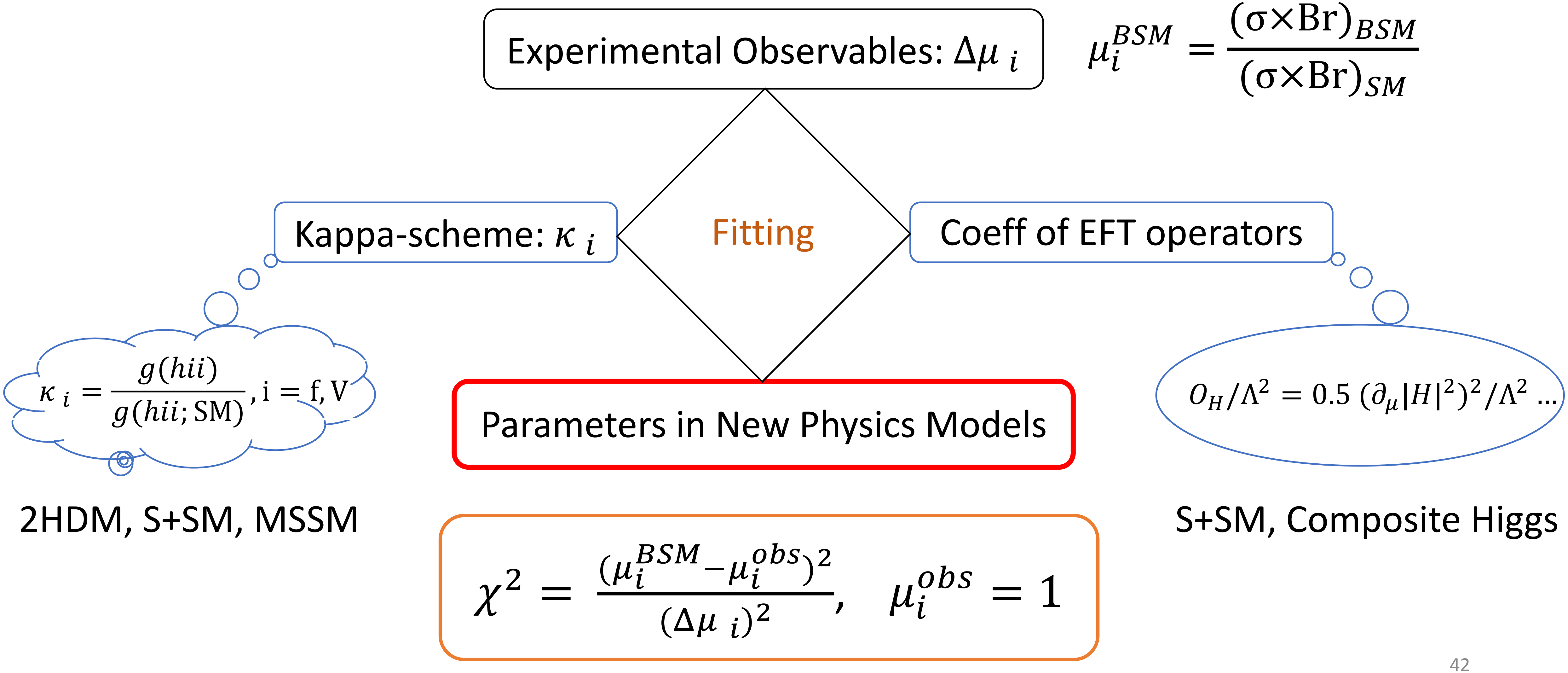


	Current (1.7×10^7 Z's)				CEPC ($10^{10}Z$'s)				FCC-ee ($7 \times 10^{11}Z$'s)				ILC (10^9Z's)			
	σ	correlation			σ	correlation			σ	correlation			σ	correlation		
		S	T	U	(10^{-2})	S	T	U	(10^{-2})	S	T	U	(10^{-2})	S	T	U
S	0.04 ± 0.11	1	0.92	−0.68	2.46	1	0.862	−0.373	0.67	1	0.812	0.001	3.53	1	0.988	−0.879
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

LEP

CEPC-preCDR , TLEP Design Study , ILC Operating Scenarios

Study strategies



Experimental Observables: $\Delta\mu_{\ i}$

$$\mu_i^{BSM} = \frac{(\sigma\times\text{Br})_{BSM}}{(\sigma\times\text{Br})_{SM}}$$

Fitting

Kappa-scheme: $\kappa_{\ i}$

$$\kappa_{\ i} = \frac{g(hii)}{g(hii;\text{SM})}, \text{i} = \text{f}, \text{V}$$

2HDM, S+SM, MSSM

Coeff of EFT operators

$$O_H/\Lambda^2 = 0.5\ (\partial_\mu|H|^2)^2/\Lambda^2\ ...$$

S+SM, Composite Higgs

Parameters in New Physics Models

$$\chi^2 = \frac{(\mu_i^{BSM} - \mu_i^{obs})^2}{(\Delta\mu_{\ i})^2}, \quad \mu_i^{obs} = 1$$

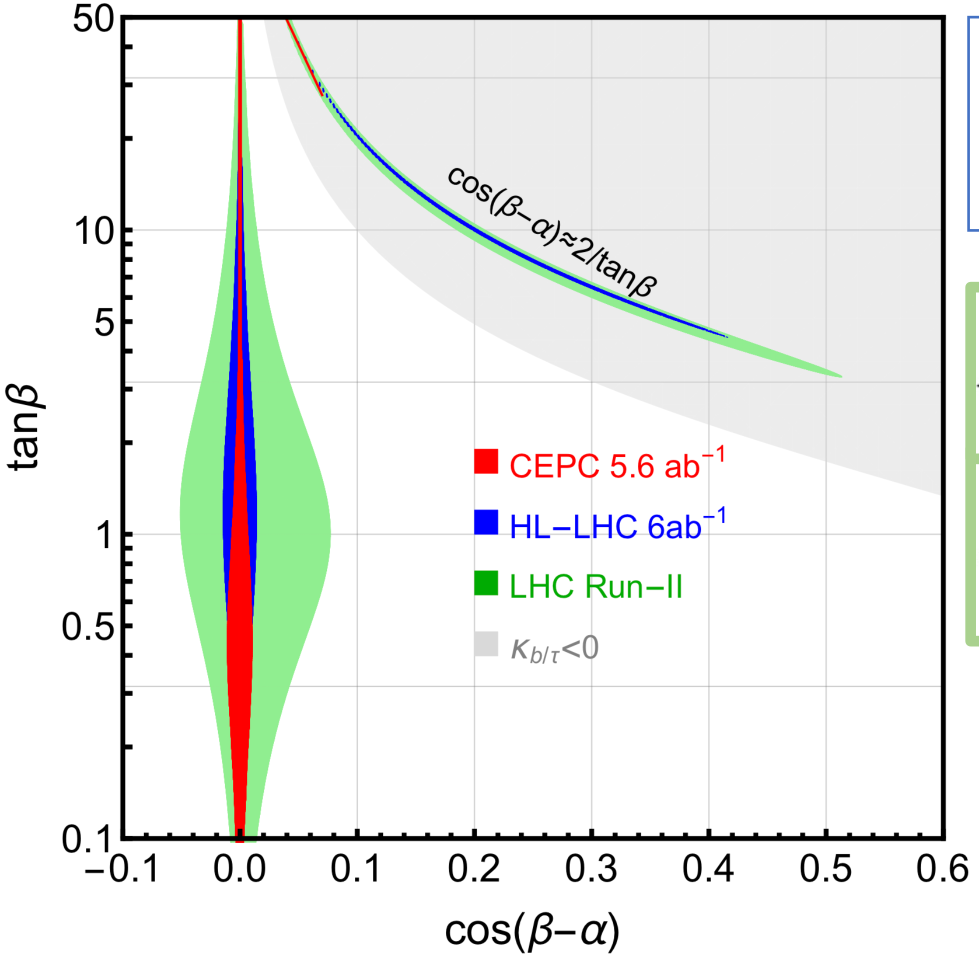
Results

- **Study Results:** Tree **& one-loop Level**
- Flavor physics
- 2HDM & Electroweak Phase Transition

2HDM: Tree Level

Model	κ_V	κ_u	κ_d	κ_ℓ
2HDM-I	$\sin(\beta-\alpha)$	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$
2HDM-II	$\sin(\beta-\alpha)$	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$	$-\sin\alpha/\cos\beta$
2HDM-L	$\sin(\beta-\alpha)$	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$
2HDM-F	$\sin(\beta-\alpha)$	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$	$\cos\alpha/\sin\beta$

2HDM Type-II



Alignment limit :

$\cos(\beta-\alpha)=0$

$g(2HDM)=g(SM)$

1910.06269

WS

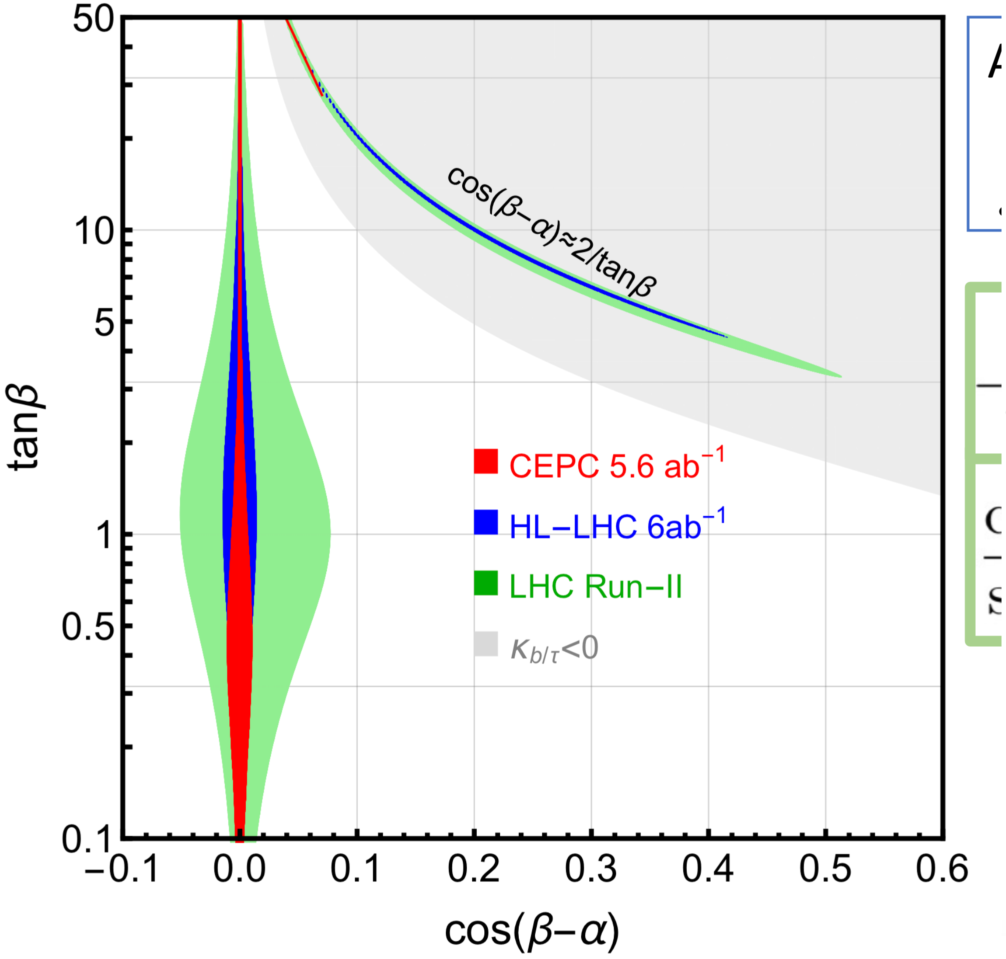
$$-\frac{\sin\beta}{\cos\alpha}-1=-\frac{1}{2}\cos^2(\beta-\alpha)-\cos(\beta-\alpha)\times\tan\beta$$

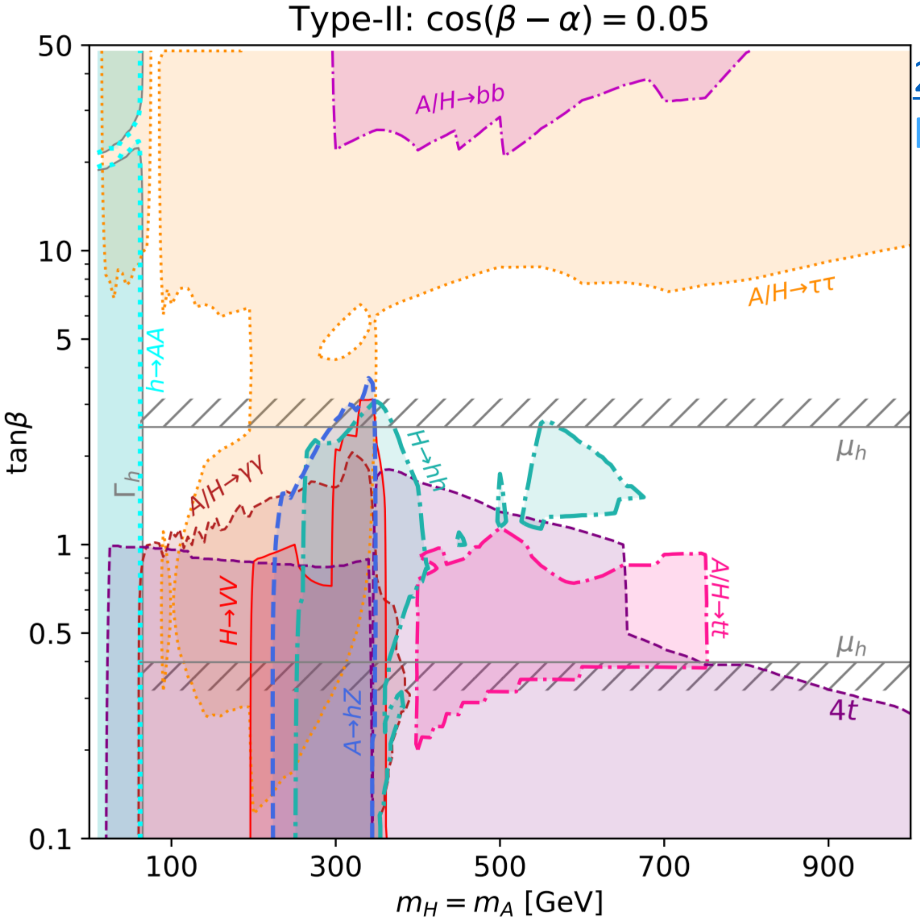
$$\frac{\cos\alpha}{\sin\beta}-1=-\frac{1}{2}\cos^2(\beta-\alpha)+\frac{\cos(\beta-\alpha)}{\tan\beta}$$

2HDM: Tree Level

Model	κ_V	κ_u	κ_d	κ_ℓ
2HDM-I	$\sin(\beta-\alpha)$	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$
2HDM-II	$\sin(\beta-\alpha)$	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$	$-\sin\alpha/\cos\beta$
2HDM-L	$\sin(\beta-\alpha)$	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$
2HDM-F	$\sin(\beta-\alpha)$	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$	$\cos\alpha/\sin\beta$

2HDM Type-II





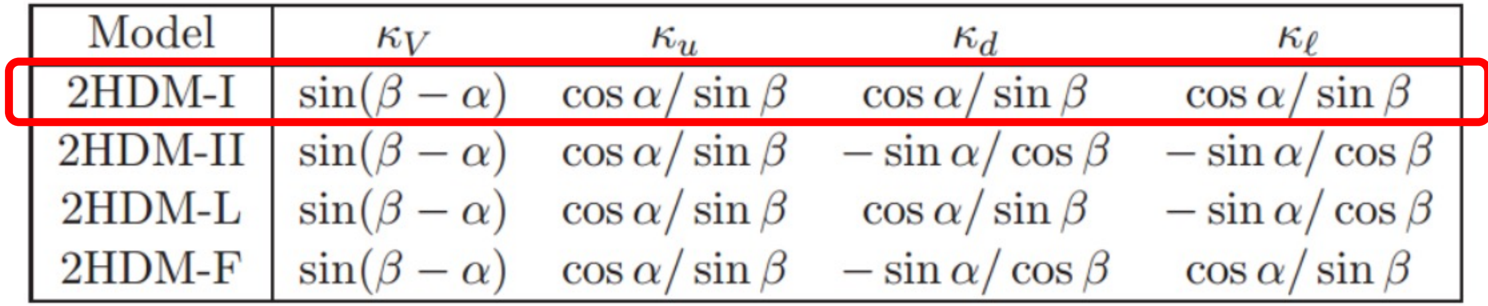
2004.04172

F. Kling, S. Su, WS

$\alpha) \times \tan\beta$

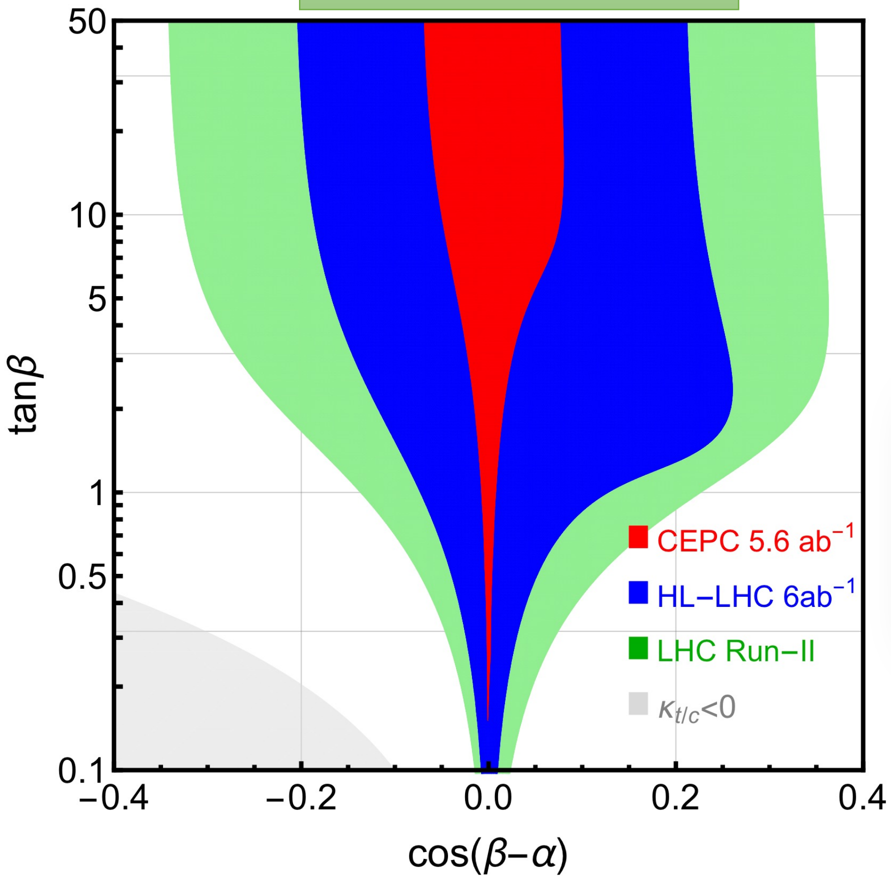
$\alpha)$

2HDM: Tree Level



Model	κ_V	κ_u	κ_d	κ_ℓ
2HDM-I	$\sin(\beta-\alpha)$	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$
2HDM-II	$\sin(\beta-\alpha)$	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$	$-\sin\alpha/\cos\beta$
2HDM-L	$\sin(\beta-\alpha)$	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$
2HDM-F	$\sin(\beta-\alpha)$	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$	$\cos\alpha/\sin\beta$

2HDM Type-I



Alignment limit :

$$\cos(\beta-\alpha)=0$$

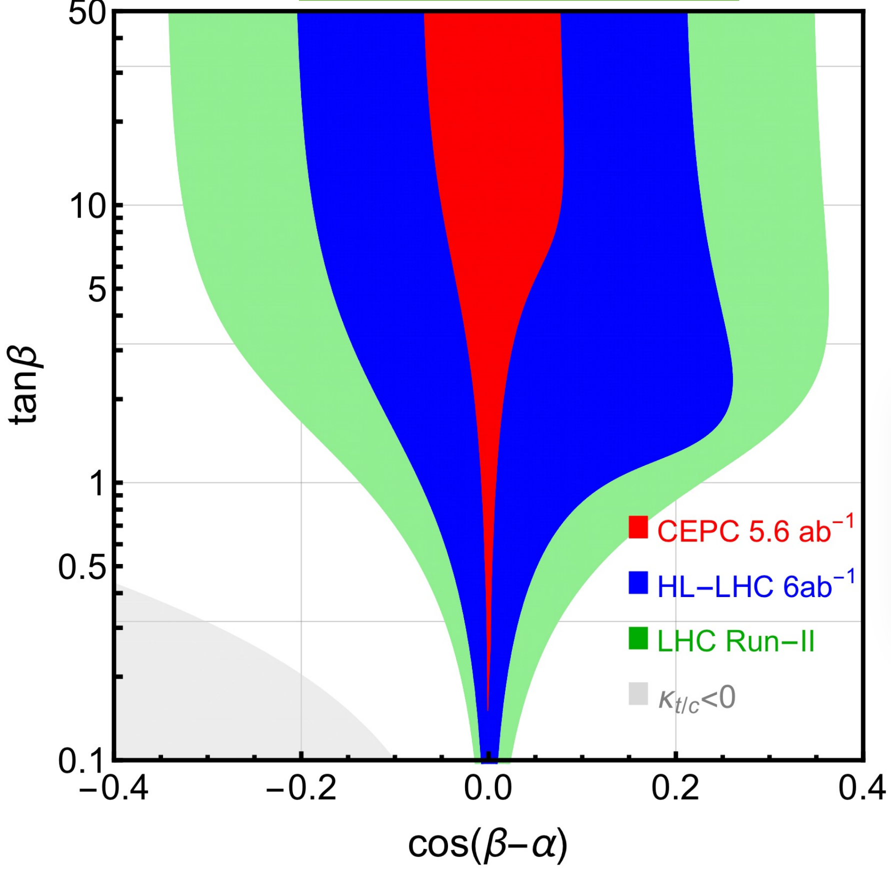
$$g(2HDM)=g(SM)$$

$$\Delta\kappa_{u,d,e}=\frac{\cos\alpha}{\sin\beta}-1=-\frac{1}{2}\cos^2(\beta-\alpha)+\frac{\cos(\beta-\alpha)}{\tan\beta}$$

2HDM: Tree Level

Model	κ_V	κ_u	κ_d	κ_ℓ
2HDM-I	$\sin(\beta-\alpha)$	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$
2HDM-II	$\sin(\beta-\alpha)$	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$	$-\sin\alpha/\cos\beta$
2HDM-L	$\sin(\beta-\alpha)$	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$
2HDM-F	$\sin(\beta-\alpha)$	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$	$\cos\alpha/\sin\beta$

2HDM Type-I



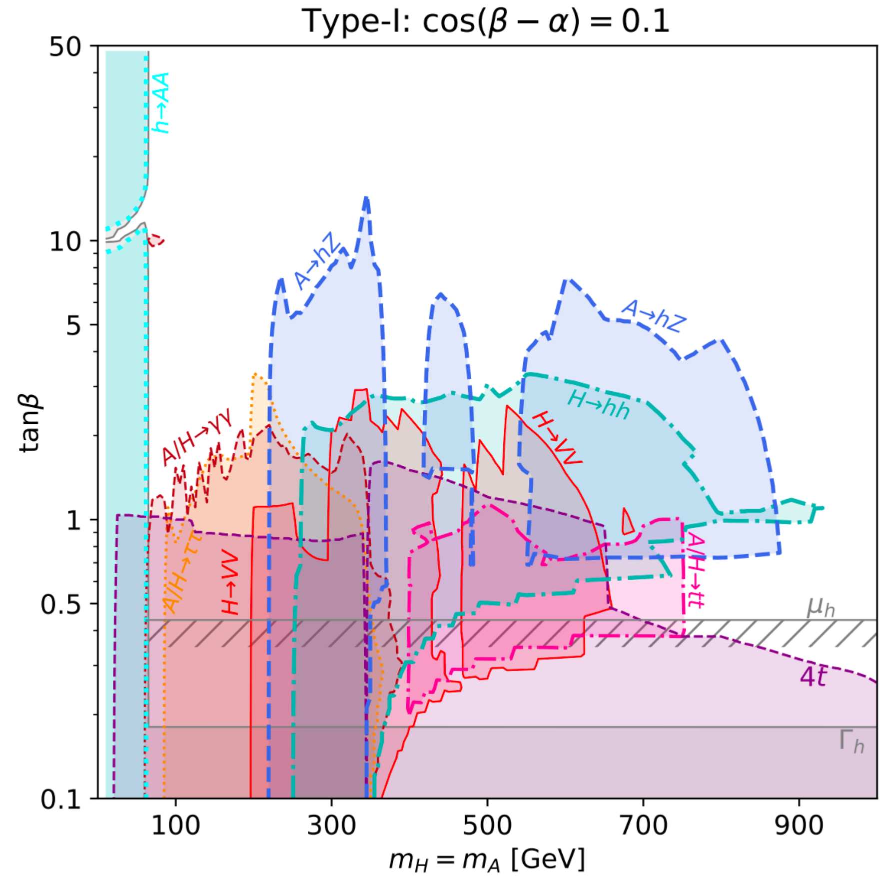
Alignme

cos (β

$g(2HD$

$\Delta\kappa_u,$

$$\frac{\cos(\beta-\alpha)}{\tan\beta}$$



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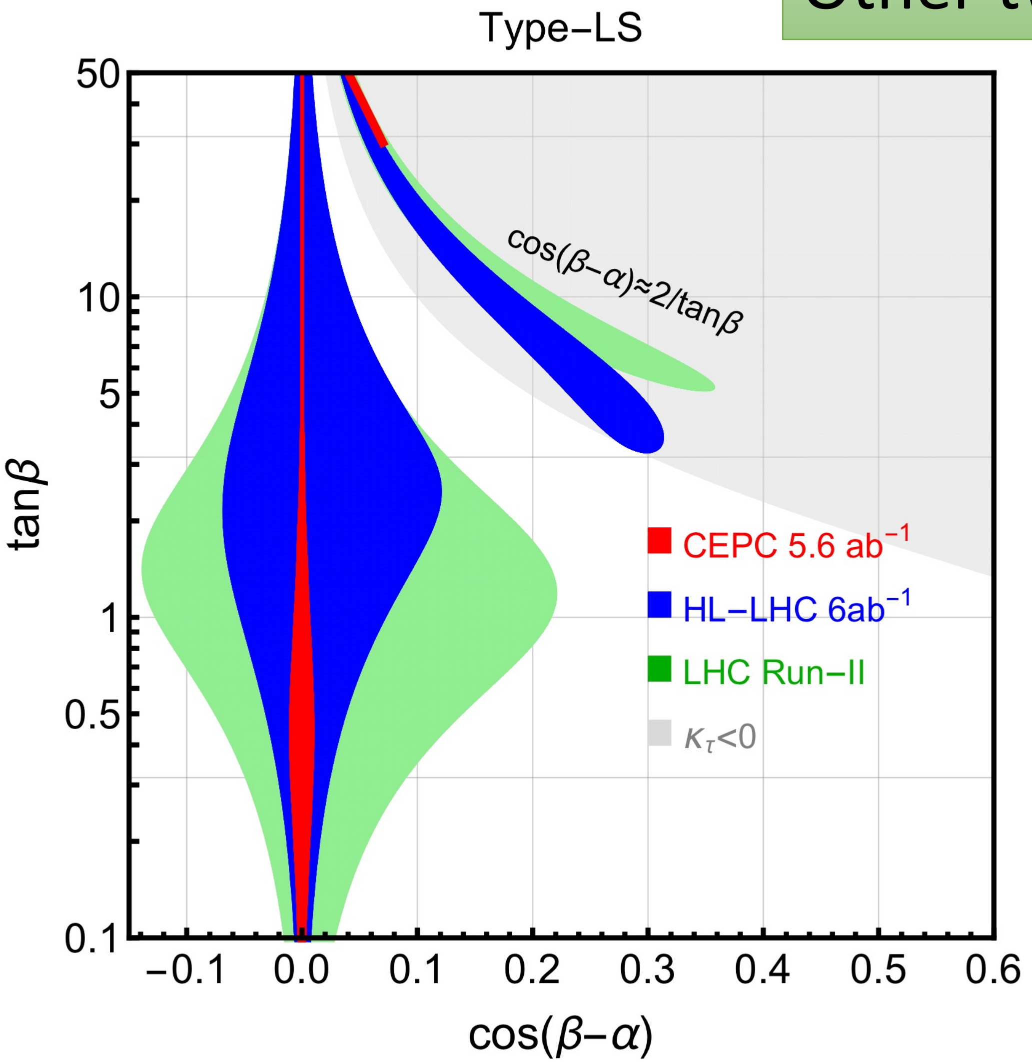
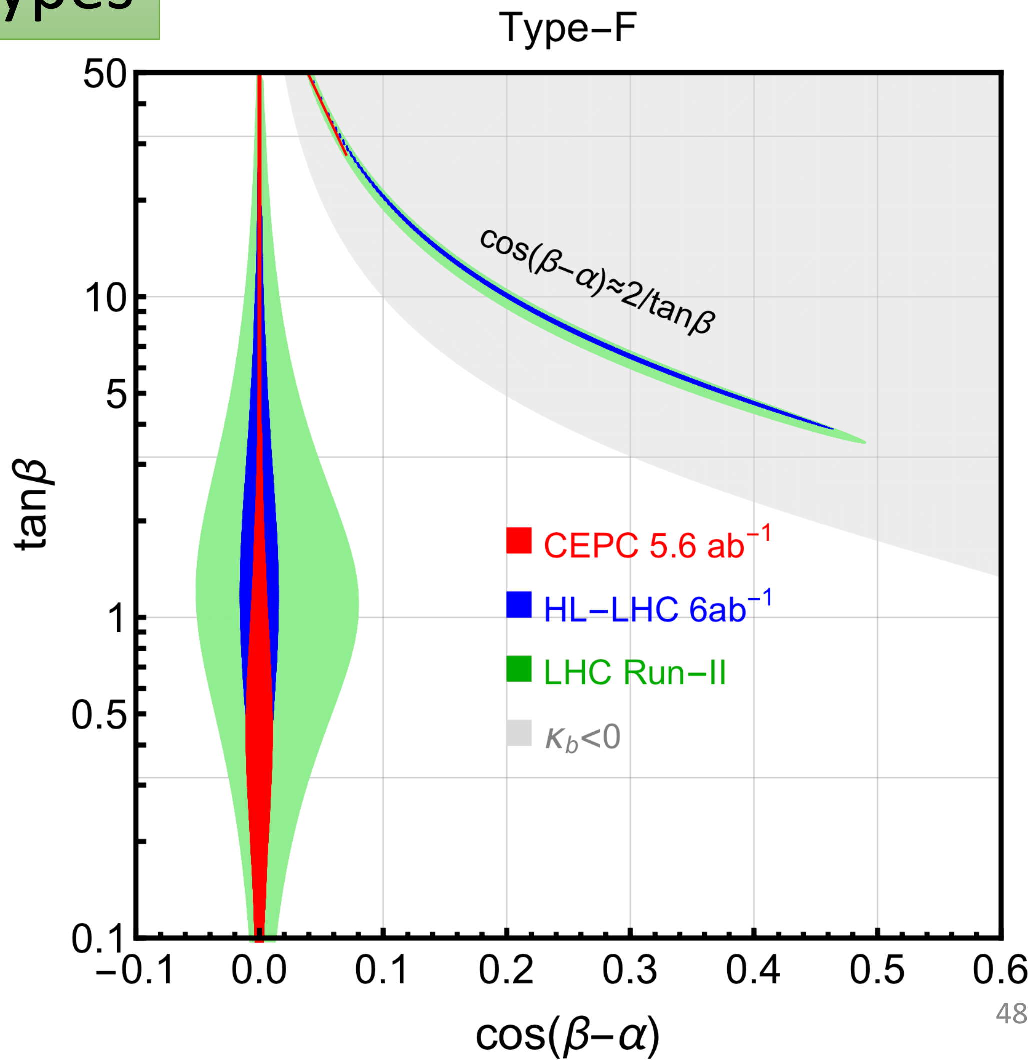
F. Kling, S. Su, WS

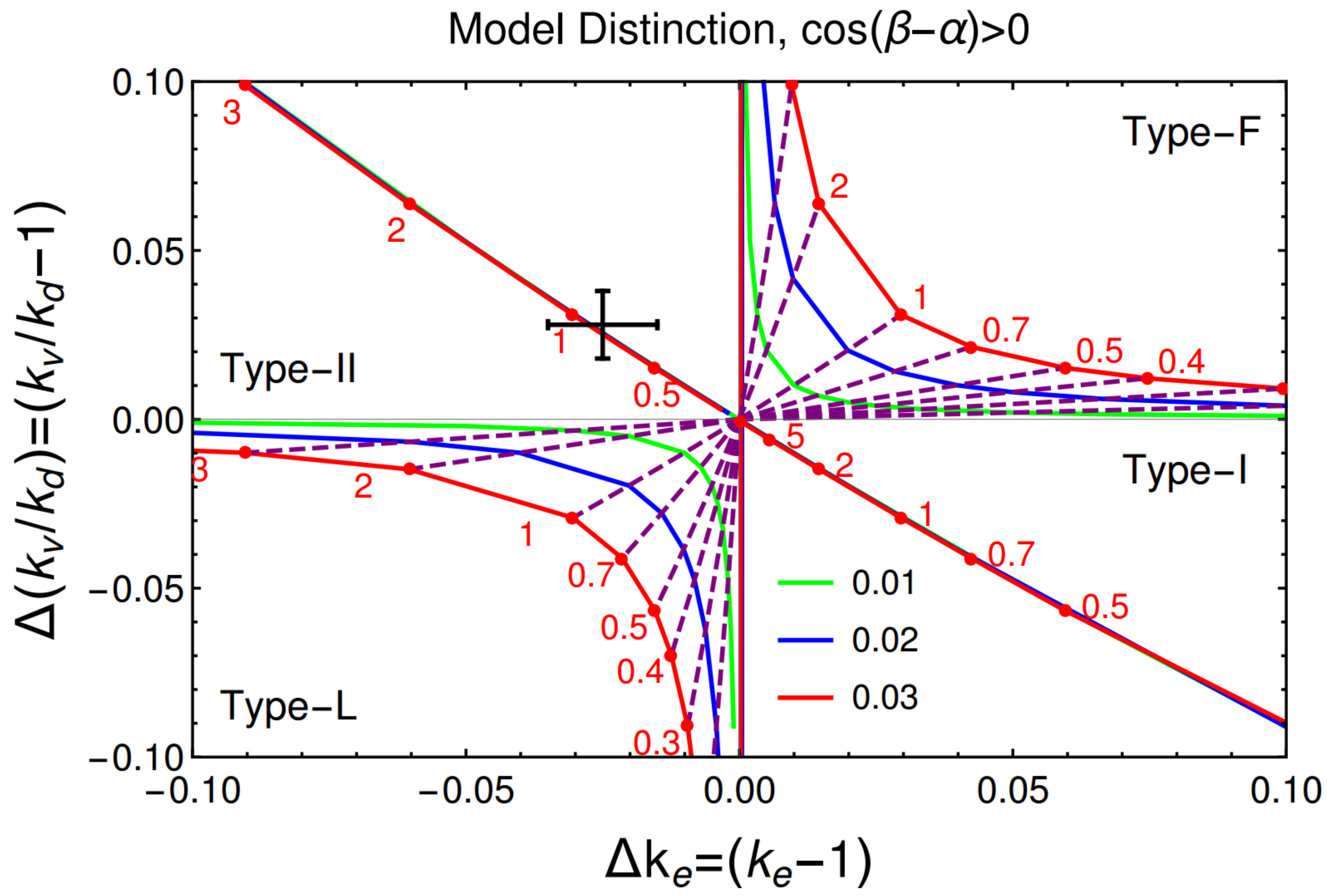
2HDM: Tree Level

Other two types





2HDM: Tree Level Model Distinction

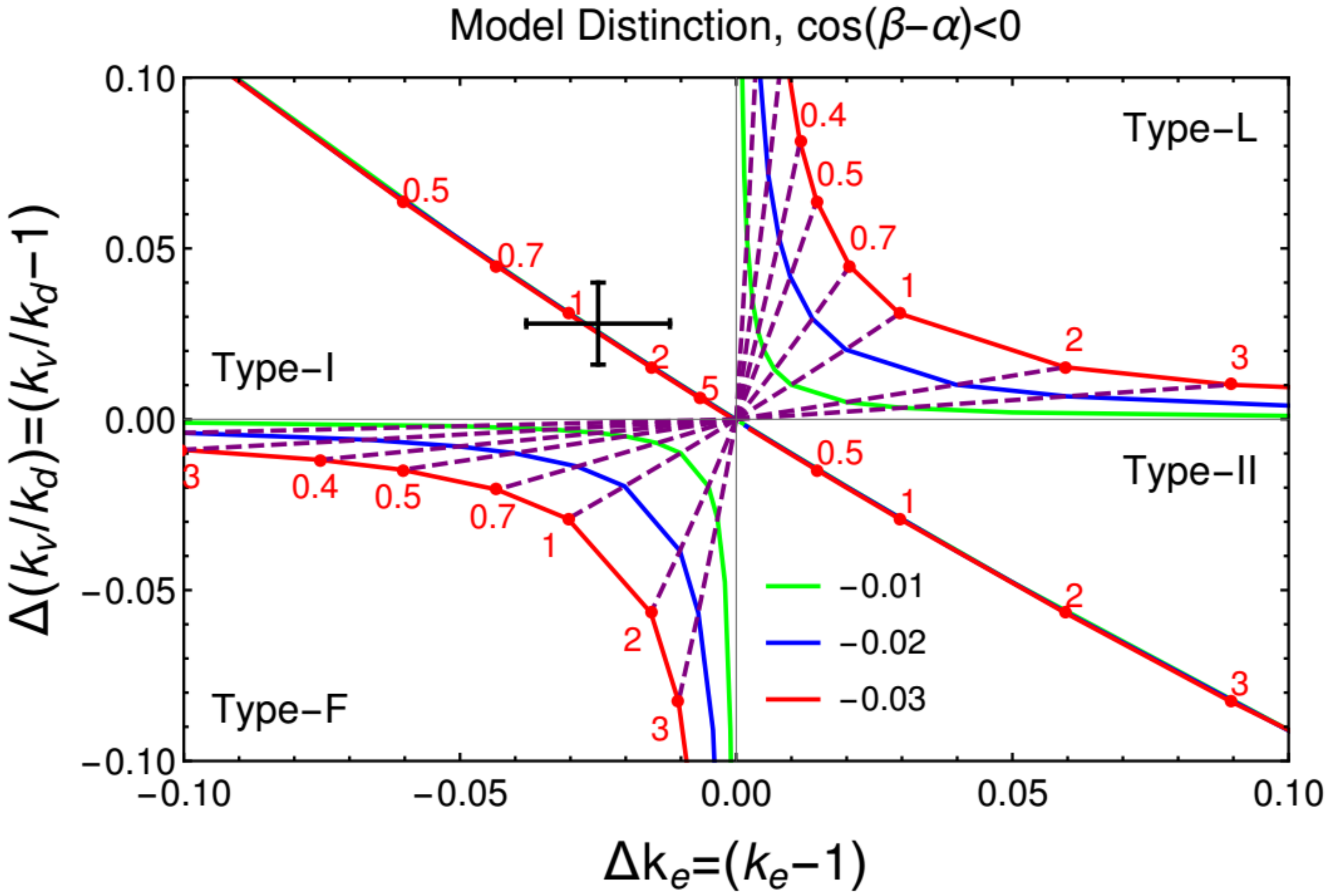


Varying $\tan\beta$

$\cos(\beta-\alpha)$

- 🟩 0.01
- 🟦 0.02
- 🟥 0.03

2HDM: Tree Level Model Distinction



Varying tan β

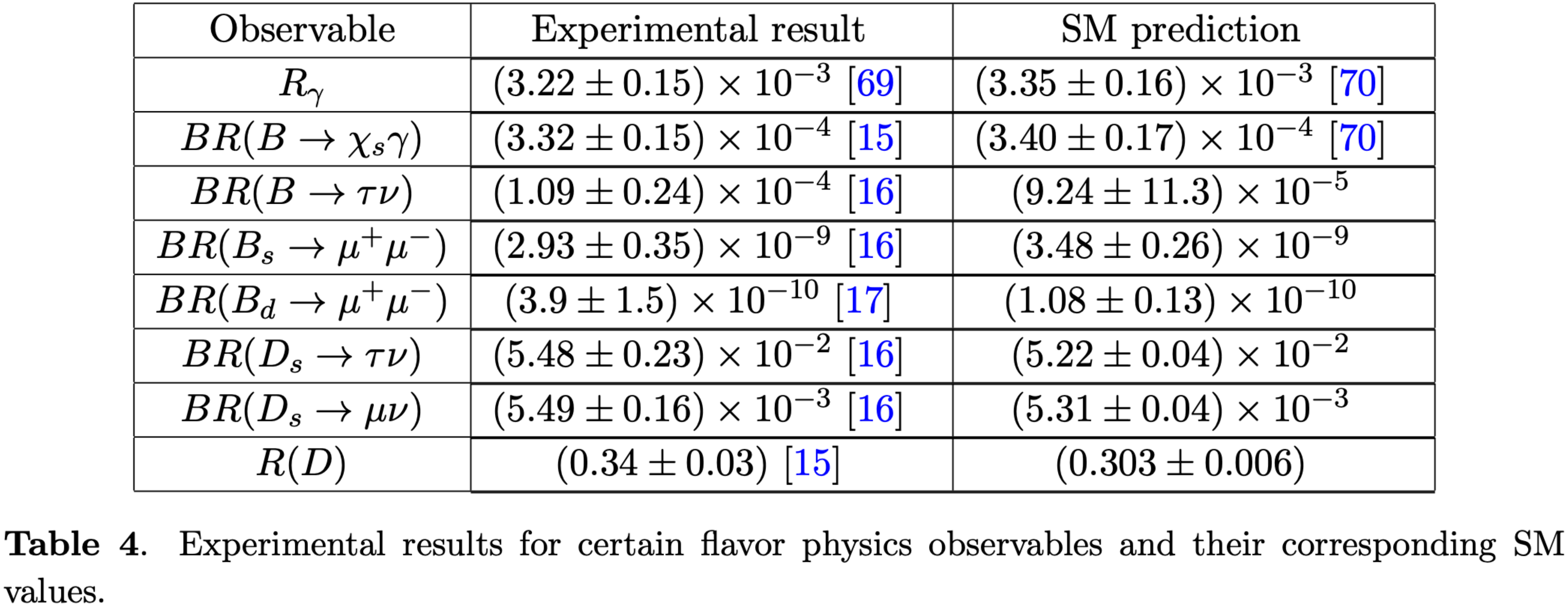
$\cos(\beta-\alpha)$

- 🟩 0.01
- 🟦 0.02
- 🟥 0.03

Type-I ↔ Type-II

Type-L ↔ Type-F

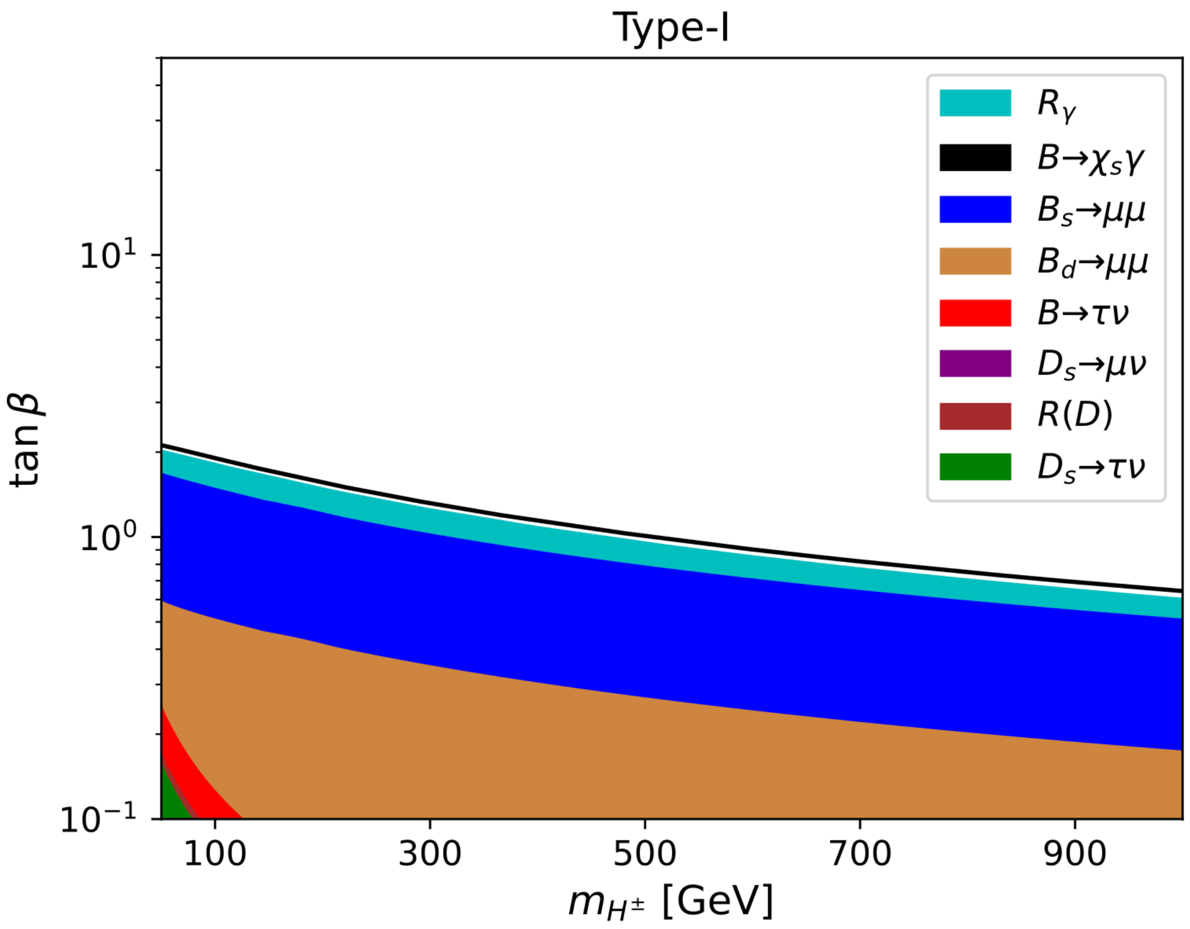
Flavour searches

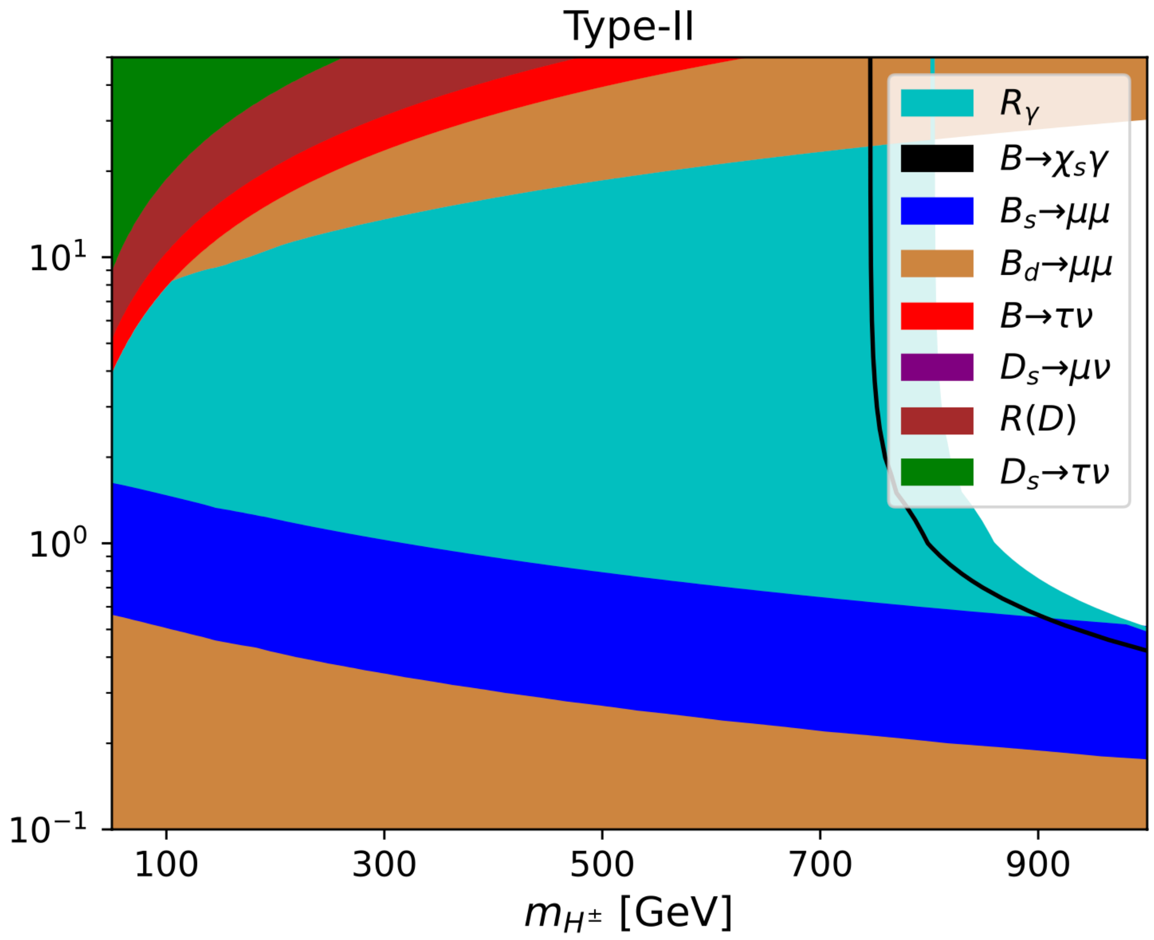


Observable	Experimental result	SM prediction
R_γ	$(3.22 \pm 0.15) \times 10^{-3}$ [69]	$(3.35 \pm 0.16) \times 10^{-3}$ [70]
$BR(B \to \chi_s \gamma)$	$(3.32 \pm 0.15) \times 10^{-4}$ [15]	$(3.40 \pm 0.17) \times 10^{-4}$ [70]
$BR(B \to \tau\nu)$	$(1.09 \pm 0.24) \times 10^{-4}$ [16]	$(9.24 \pm 11.3) \times 10^{-5}$
$BR(B_s \to \mu^+\mu^-)$	$(2.93 \pm 0.35) \times 10^{-9}$ [16]	$(3.48 \pm 0.26) \times 10^{-9}$
$BR(B_d \to \mu^+\mu^-)$	$(3.9 \pm 1.5) \times 10^{-10}$ [17]	$(1.08 \pm 0.13) \times 10^{-10}$
$BR(D_s \to \tau\nu)$	$(5.48 \pm 0.23) \times 10^{-2}$ [16]	$(5.22 \pm 0.04) \times 10^{-2}$
$BR(D_s \to \mu\nu)$	$(5.49 \pm 0.16) \times 10^{-3}$ [16]	$(5.31 \pm 0.04) \times 10^{-3}$
$R(D)$	(0.34 ± 0.03) [15]	(0.303 ± 0.006)

Table 4. Experimental results for certain flavor physics observables and their corresponding SM values.

Flavour searches

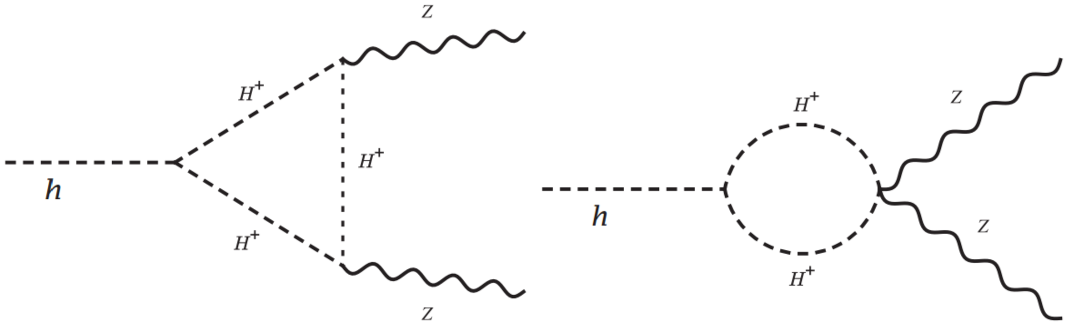


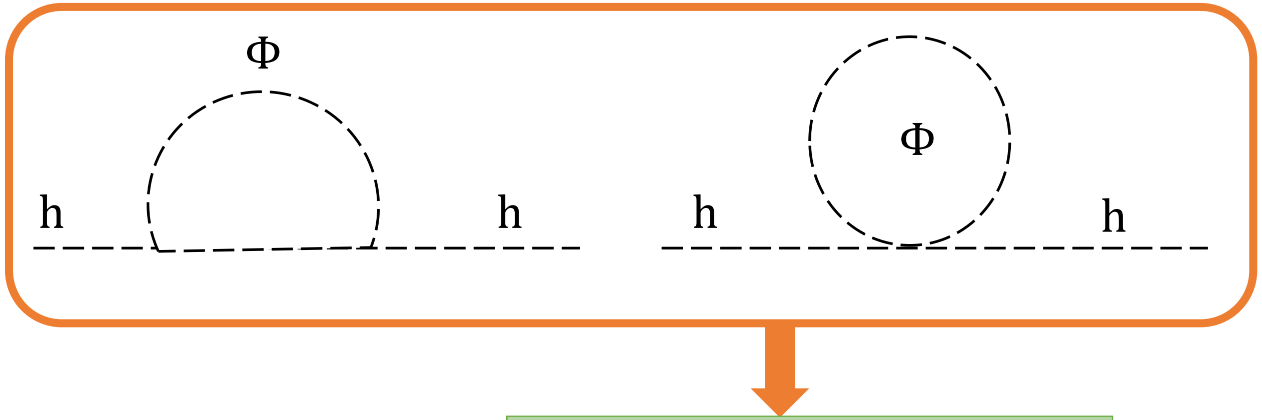


Results

- **Study Results:** Tree **<u>& one-loop Level</u>**

2HDM: One-Loop Level





Main contribution

Parameter : $\boldsymbol{\cos(\beta-\alpha), \tan\beta, m_H, m_A, m_{H^\pm}, m_{12}^2}$

① Loop + degenerate: $\cos(\beta-\alpha)=0,\ m_\Phi \equiv m_H = m_A = m_{H^\pm}$

② Tree + Loop + degenerate: $\cos(\beta-\alpha)\neq 0,\ m_\Phi \equiv m_H = m_A = m_{H^\pm}$

③ Tree + Loop + non-degenerate: $\Delta m_a = m_A - m_H,\ \Delta m_c = m_{H^\pm} - m_H$

2HDM: theoretical consideration

- Vacuum Stability

$$\lambda_1 > 0, \quad \lambda_2 > 0, \quad \lambda_3 > -\sqrt{\lambda_1 \lambda_2},$$
$$\lambda_3 + \lambda_4 - |\lambda_5| > -\sqrt{\lambda_1 \lambda_2}.$$

$$\begin{aligned}\lambda_1 v^2 = {} & (m_H^2 \tan^2\beta + m_h^2)\sin^2(\beta-\alpha) + (m_H^2 + m_h^2 \tan^2\beta)\cos^2(\beta-\alpha) \\ & + 2(m_H^2 - m_h^2)\sin(\beta-\alpha)\cos(\beta-\alpha)\tan\beta - M^2\tan^2\beta,\end{aligned}$$

$$\begin{aligned}\lambda_2 v^2 = {} & (m_H^2 \cot^2\beta + m_h^2)\sin^2(\beta-\alpha) + (m_H^2 + m_h^2 \cot^2\beta)\cos^2(\beta-\alpha) \\ & - 2(m_H^2 - m_h^2)\sin(\beta-\alpha)\cos(\beta-\alpha)\tan\beta - M^2\cot^2\beta, \\ \lambda_3 v^2 = {} & (m_H^2 - m_h^2)[\cos^2(\beta-\alpha) - \sin^2(\beta-\alpha) + (\tan\beta - \cot\beta)\sin(\beta-\alpha)\cos(\beta-\alpha)] \\ & + 2m_{H^\pm}^2 - M^2, \\ \lambda_4 v^2 = {} & M^2 + m_A^2 - 2m_{H^\pm}^2, \\ \lambda_5 v^2 = {} & M^2 - m_A^2.\end{aligned}$$

2HDM: theoretical consideration

- Vacuum Stability

$$\lambda_1 > 0, \quad \lambda_2 > 0, \quad \lambda_3 > -\sqrt{\lambda_1\lambda_2},$$

$$\lambda_3 + \lambda_4 - |\lambda_5| > -\sqrt{\lambda_1\lambda_2}.$$

- Unitary $|\lambda_i| \leq 4\pi$

- Perturbativity $|\Lambda_i \leq 16\pi|$

$$\Lambda_{1,2} = \lambda_3 \pm \lambda_4,$$

$$\Lambda_{3,4} = \lambda_3 \pm \lambda_5,$$

$$\Lambda_{5,6} = \lambda_3 + 2\lambda_4 \pm 3\lambda_5,$$

$$\Lambda_{7,8} = \frac{1}{2}\left[(\lambda_1 + \lambda_2) \pm \sqrt{(\lambda_1 - \lambda_2)^2 + 4\lambda_4^2}\right],$$

$$\Lambda_{9,10} = \frac{1}{2}\left[(\lambda_1 + \lambda_2) \pm \sqrt{(\lambda_1 - \lambda_2)^2 + 4|\lambda_5|^2}\right],$$

$$\Lambda_{11,12} = \frac{1}{2}\left[3(\lambda_1 + \lambda_2) \pm \sqrt{9(\lambda_1 - \lambda_2)^2 + 4(2\lambda_3 + \lambda_4)^2}\right]$$

2HDM: theoretical consideration

- Vacuum Stability

$$\lambda_1 > 0, \quad \lambda_2 > 0, \quad \lambda_3 > -\sqrt{\lambda_1\lambda_2},$$

$$\lambda_3 + \lambda_4 - |\lambda_5| > -\sqrt{\lambda_1\lambda_2}.$$

- Unitary $|\lambda_i| \leq 4\pi$

- Perturbativity $|\Lambda_i \leq 16\pi|$

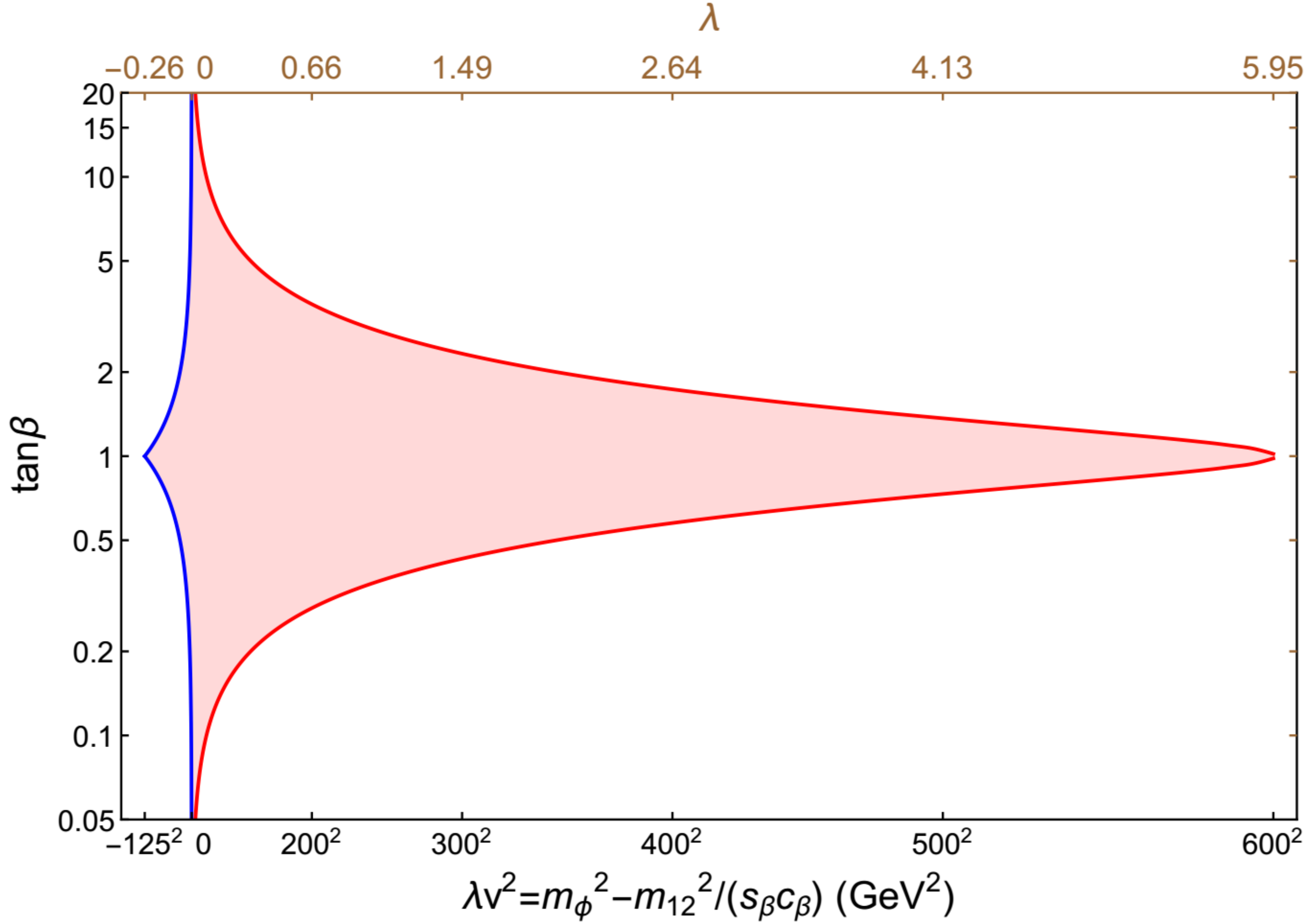
$\cos(\beta - \alpha) = 0,$
$m_\Phi \equiv m_H = m_A = m_{H^\pm}$

$$\begin{aligned} v^2\lambda_1 &= m_h^2 + t_\beta^2\lambda v^2 , \\ v^2\lambda_2 &= m_h^2 + \lambda v^2/t_\beta^2 , \\ v^2\lambda_3 &= m_h^2 + \lambda v^2 , \\ v^2\lambda_4 &= -\lambda v^2 , \\ v^2\lambda_5 &= -\lambda v^2 . \end{aligned}$$

2 Free parameters

2HDM: theoretical consideration

Constraints from Vacuum stabiltiy, Unitarity and Perturbativity



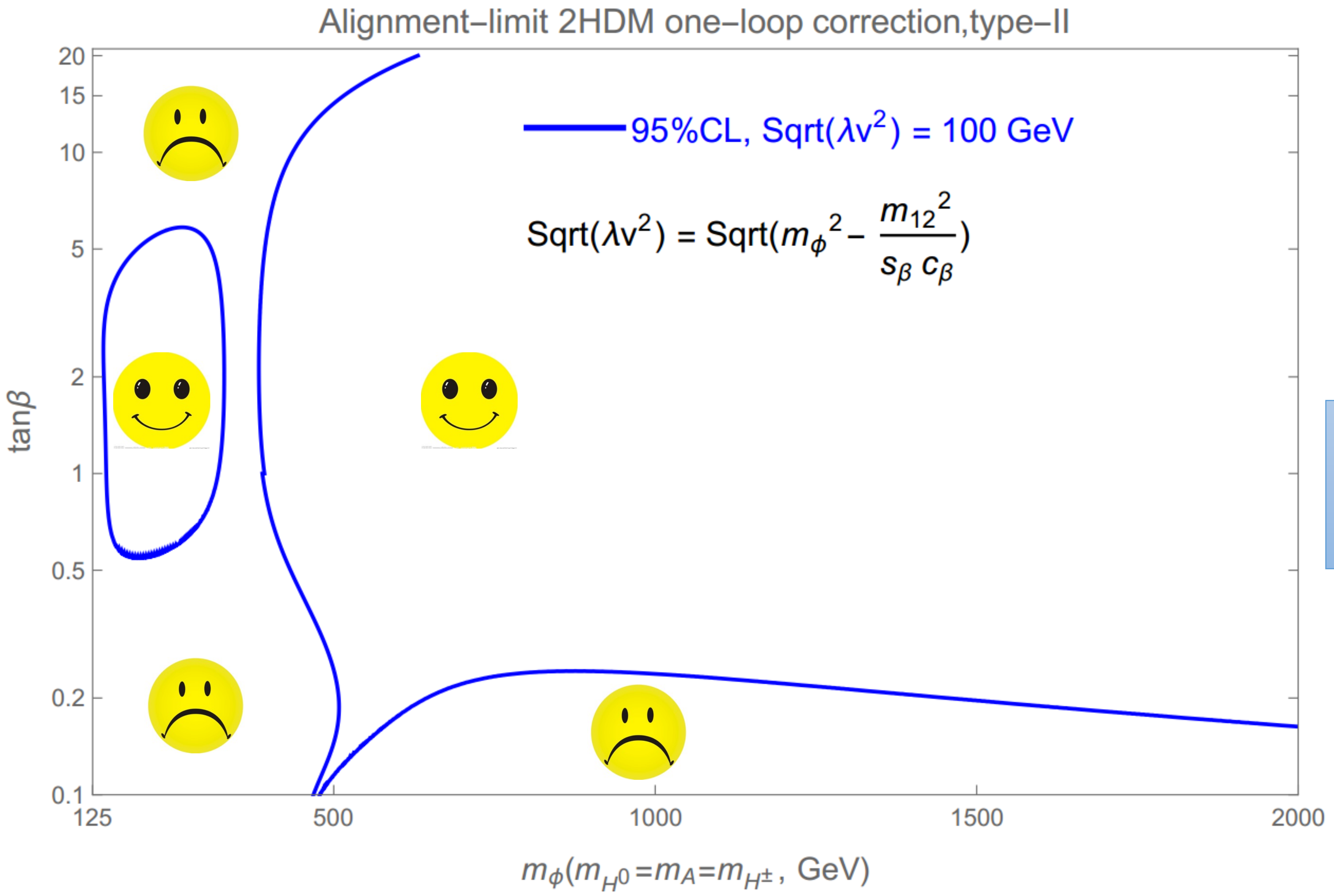
$$\cos(\beta - \alpha) = 0,$$
$$m_\Phi \equiv m_H = m_A = m_{H^\pm}$$

Theoretical constraints

$$-125^2\mathrm{GeV}^2 < \lambda v^2 < 600^2\mathrm{GeV}^2$$

$$\lambda \in (-0.26, 5.95)$$
$$\lambda_4 = \lambda_5 = \lambda_3 - 0.258 = -\lambda$$

2HDM: $Loop + degenerate$

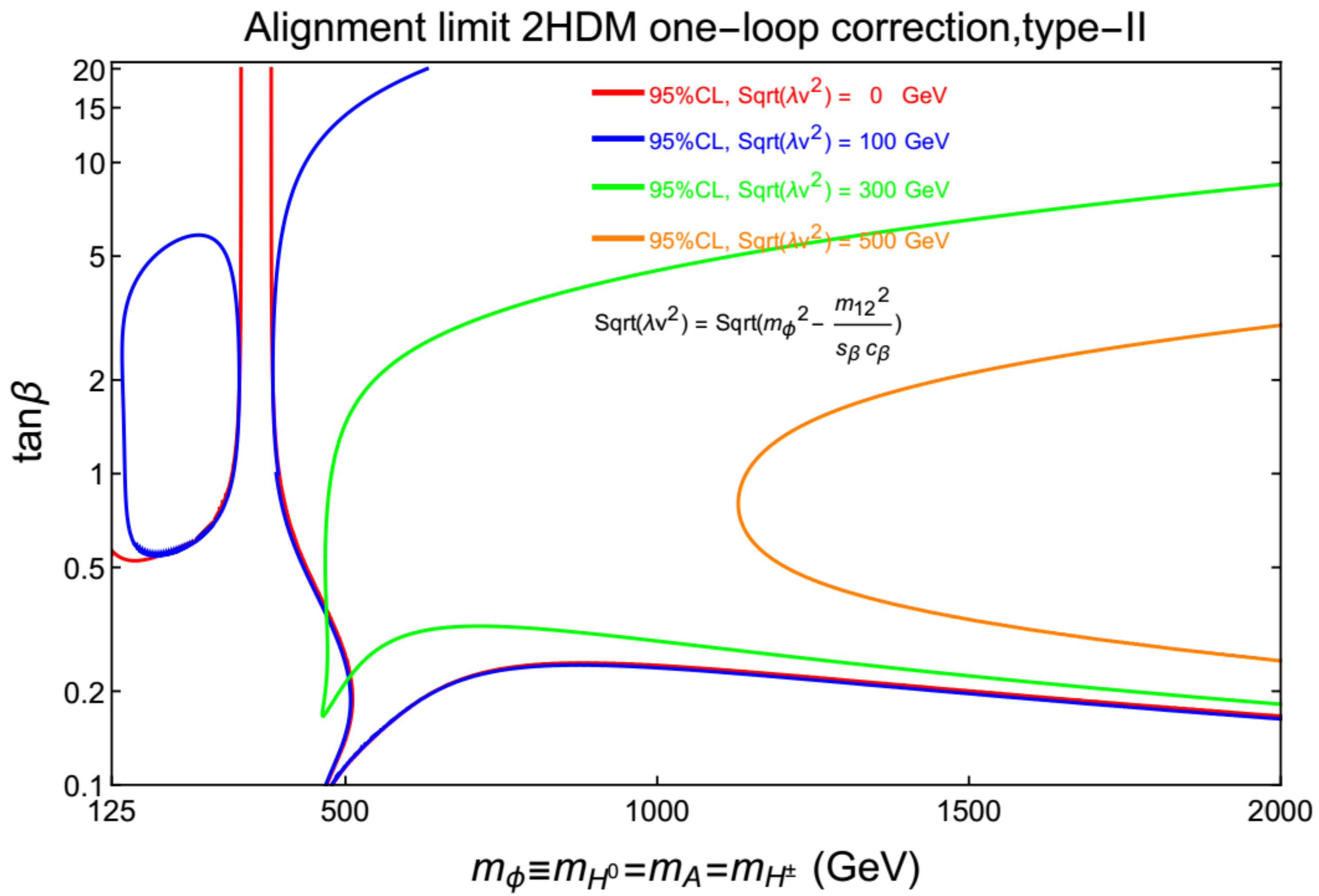


CEPC fit,
Type-II

$\cos(\beta - \alpha) = 0,$

$m_\Phi \equiv m_H = m_A = m_{H^\pm}$

2HDM: *Loop + degenerate*



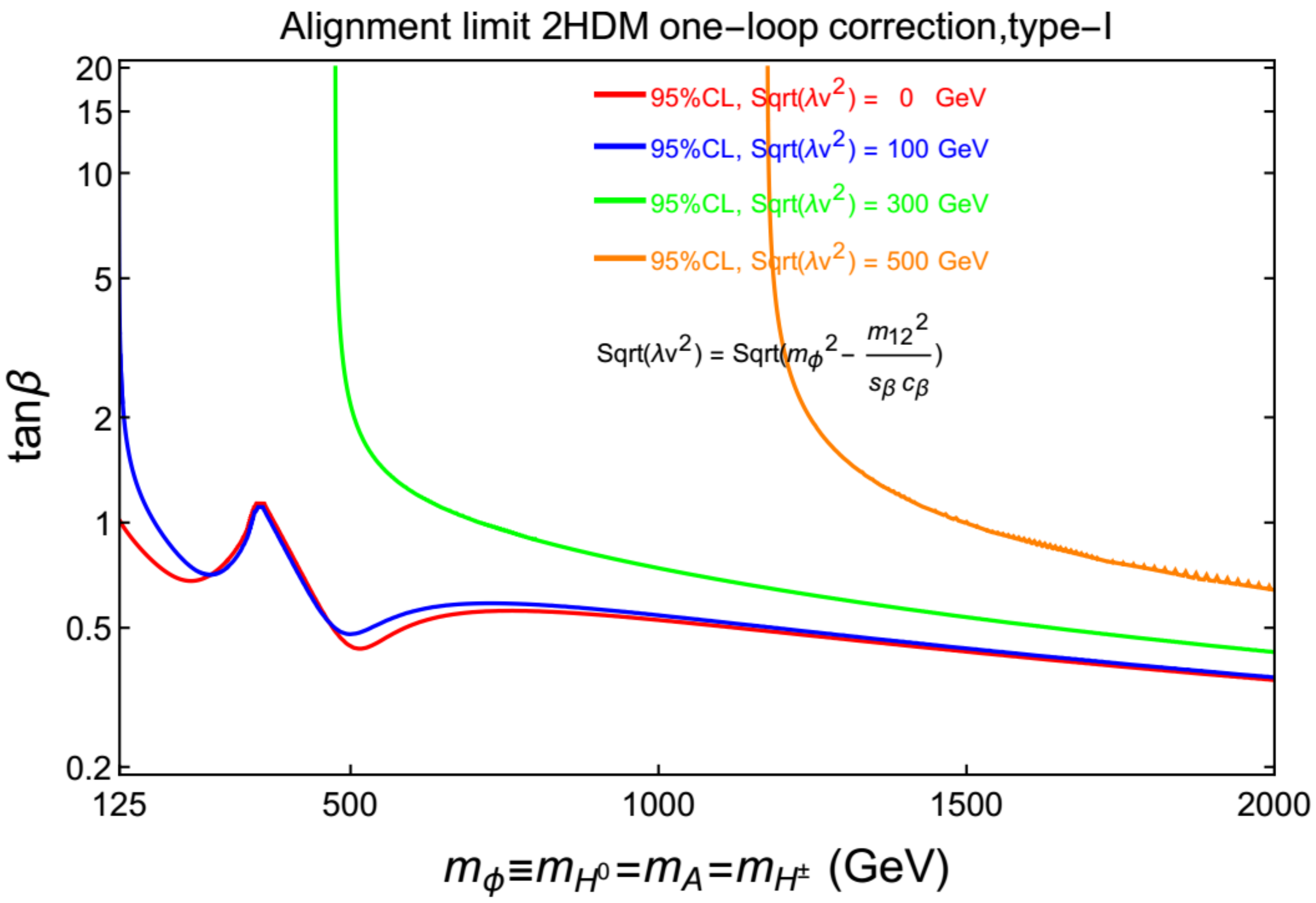
CEPC fit, Type-II

$$-125^2\mathrm{GeV}^2 < \lambda \mathrm{v}^2 < 600^2\mathrm{GeV}^2$$

Sqrt(λv^2)	$\boldsymbol{m_{\Phi}} >$
100	400
300	500
500	1100

(GeV)

2HDM: $Loop + degenerate$



CEPC fit, Type-I

$$-125^2\mathrm{GeV}^2 < \lambda \mathrm{v}^2 < 600^2\mathrm{GeV}^2$$

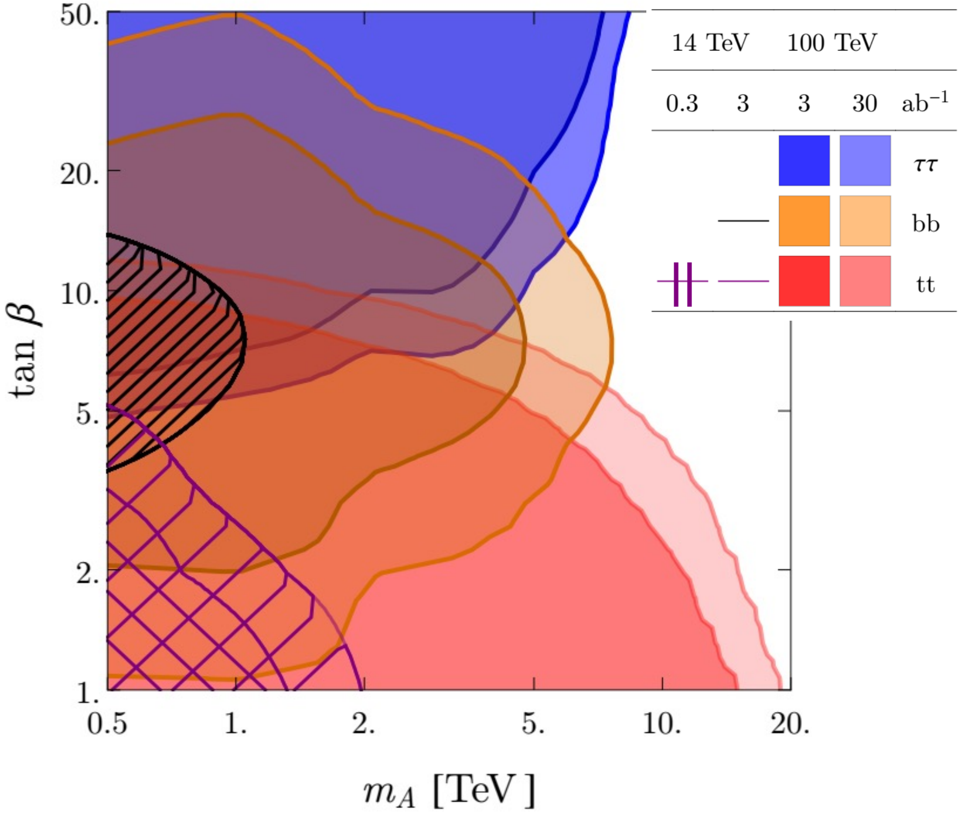
$\mathrm{Sqrt}(\lambda \mathrm{v}^2)$	$m_\Phi >$
100	--
300	500
500	1100

(GeV)

Higgs direct search at LHC

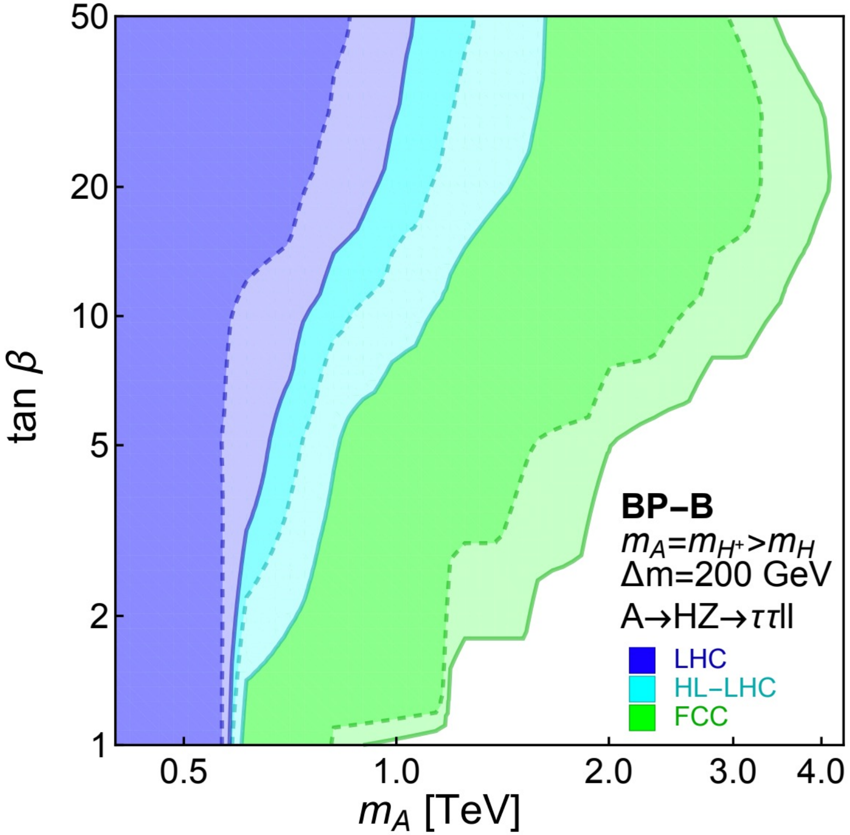
Type-II

Conventional Search



Craig et. al., 1605.08744

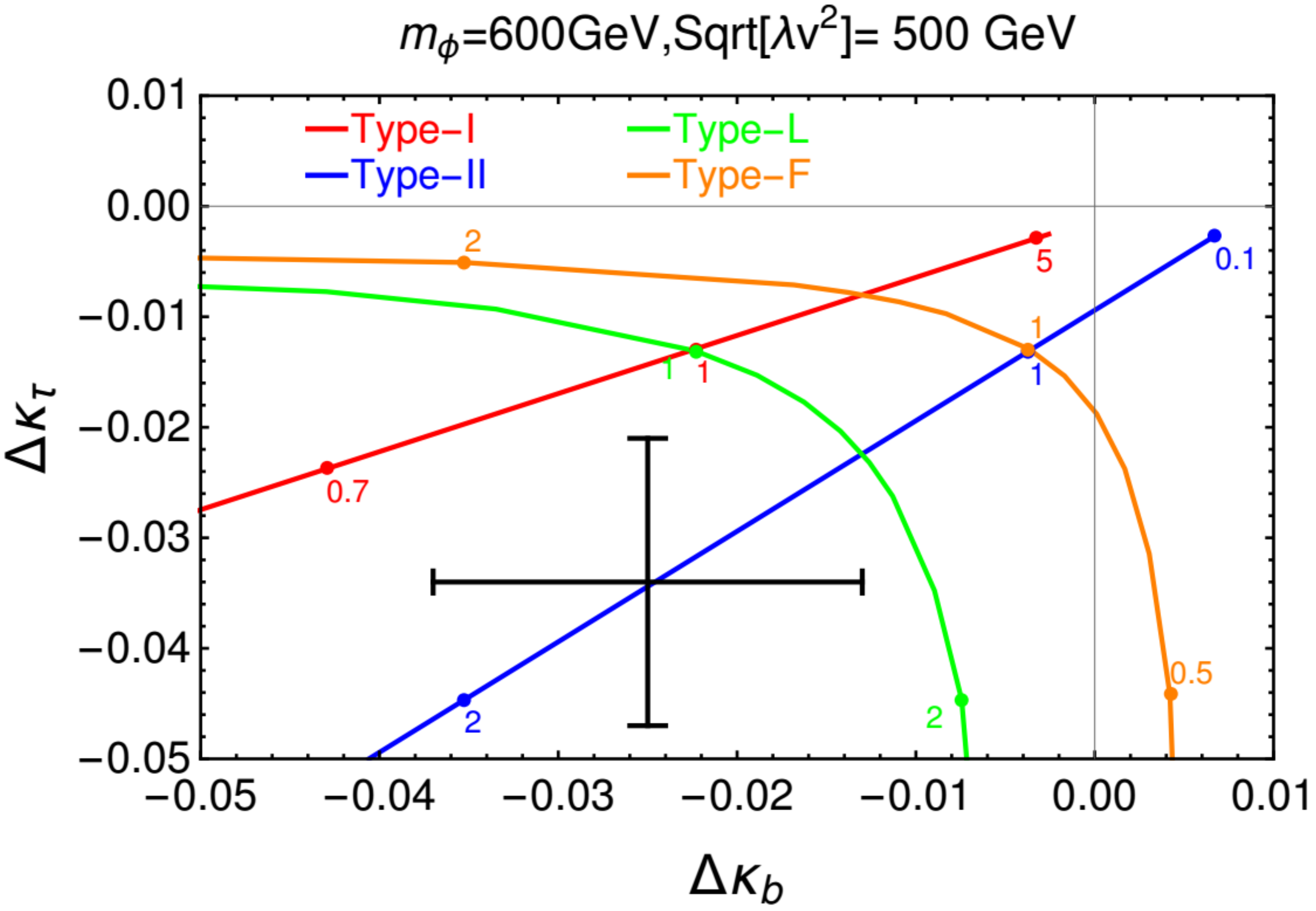
Exotic: A -> HZ



S. Su et. al., 1812.01633

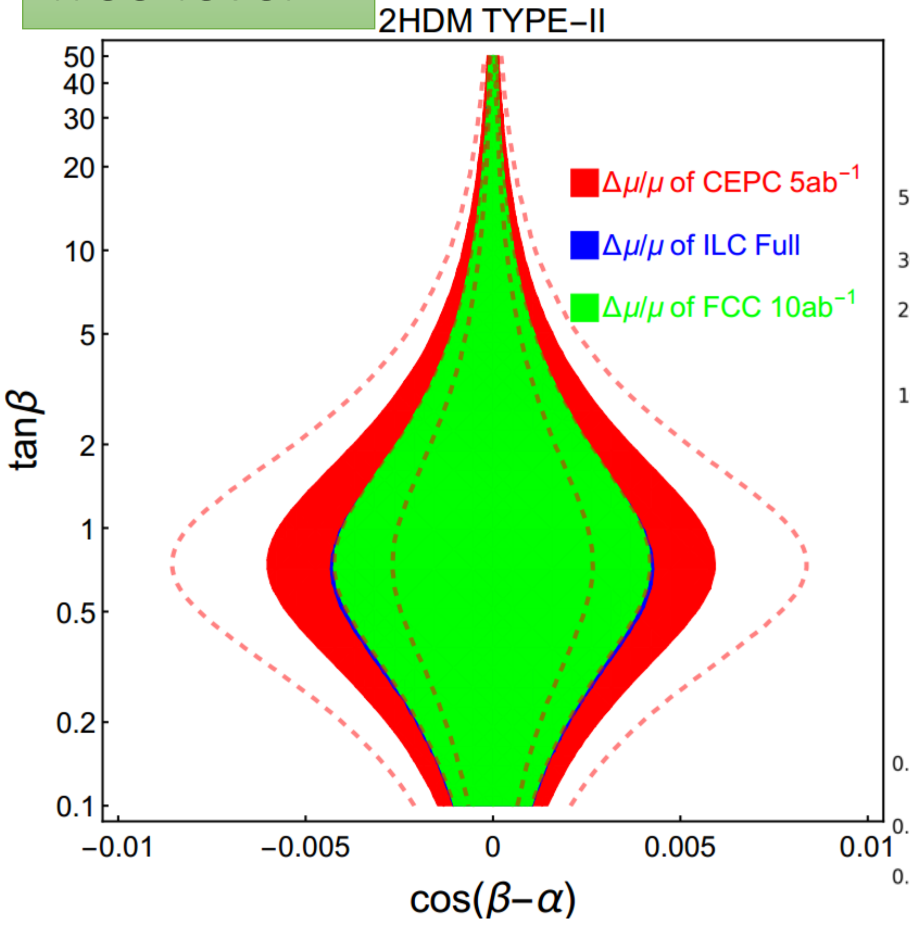
2HDM: $Loop\ +\ degenerate$

Varying tan β

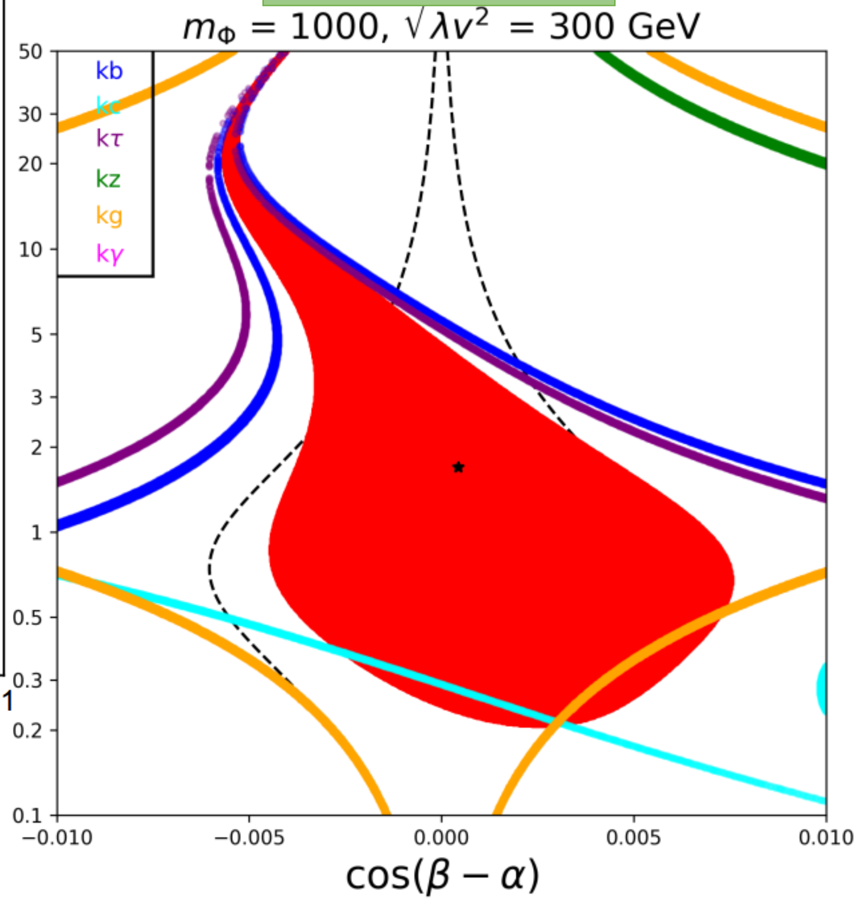


2HDM: $Tree + Loop\ +\ degenerate$

Tree-level



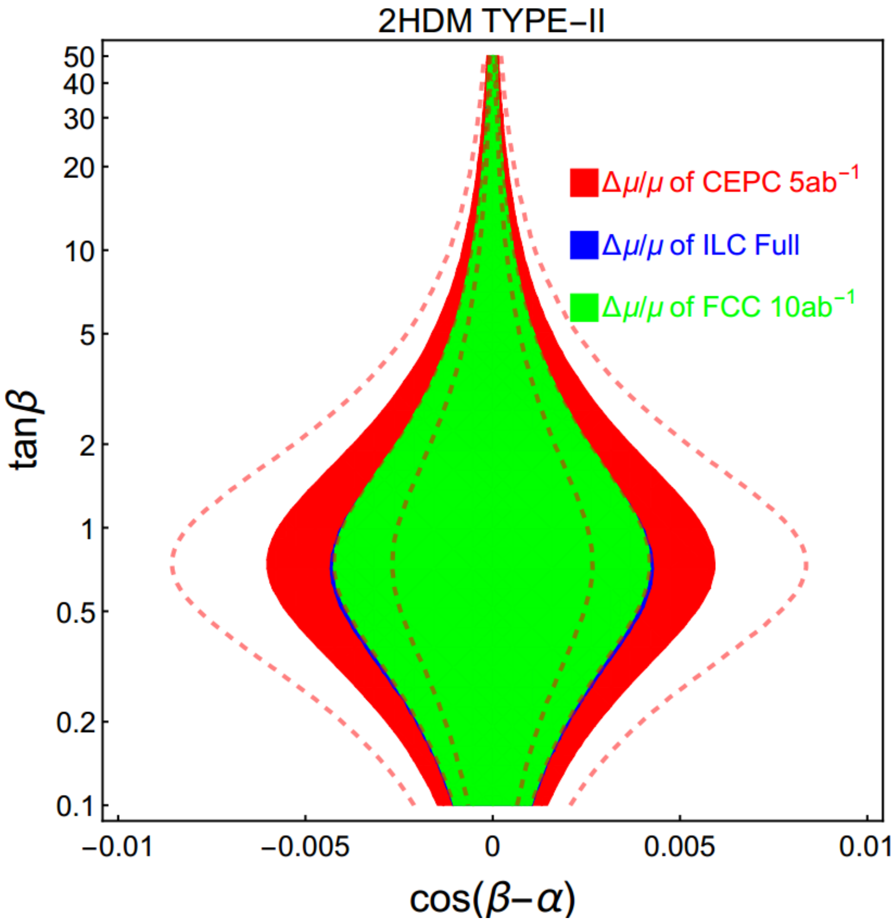
Loop-level



$\cos(\beta-\alpha)\neq 0,$

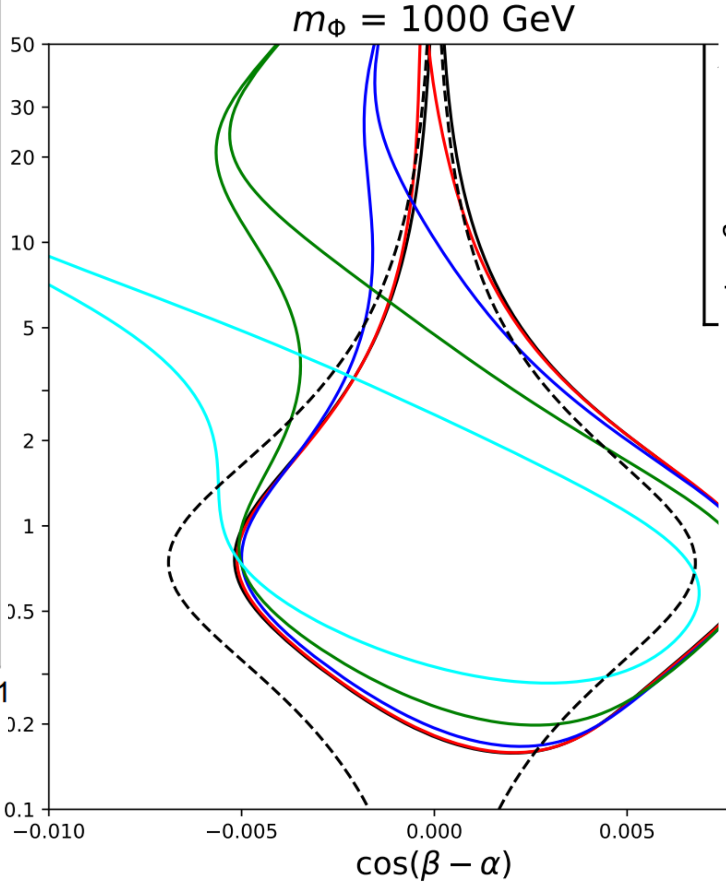
$m_\Phi \equiv m_H = m_A = m_{H^\pm}$

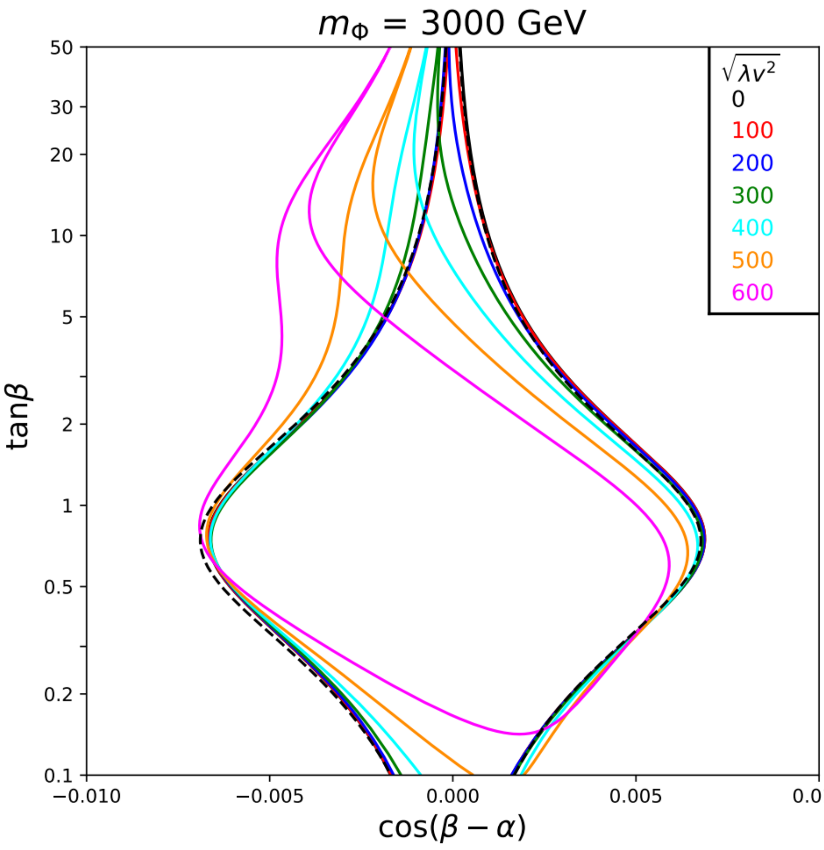
2HDM: $\mathit{Tree + Loop\ +\ degenerate}$



Tree-level

Loop-level

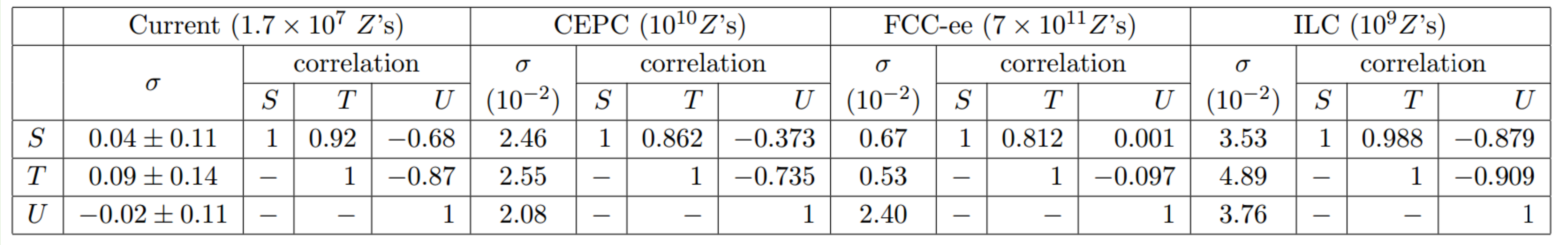




Loop-level decouple

2HDM: $Tree + Loop \ + non - degenerate$

Z Pole Precision

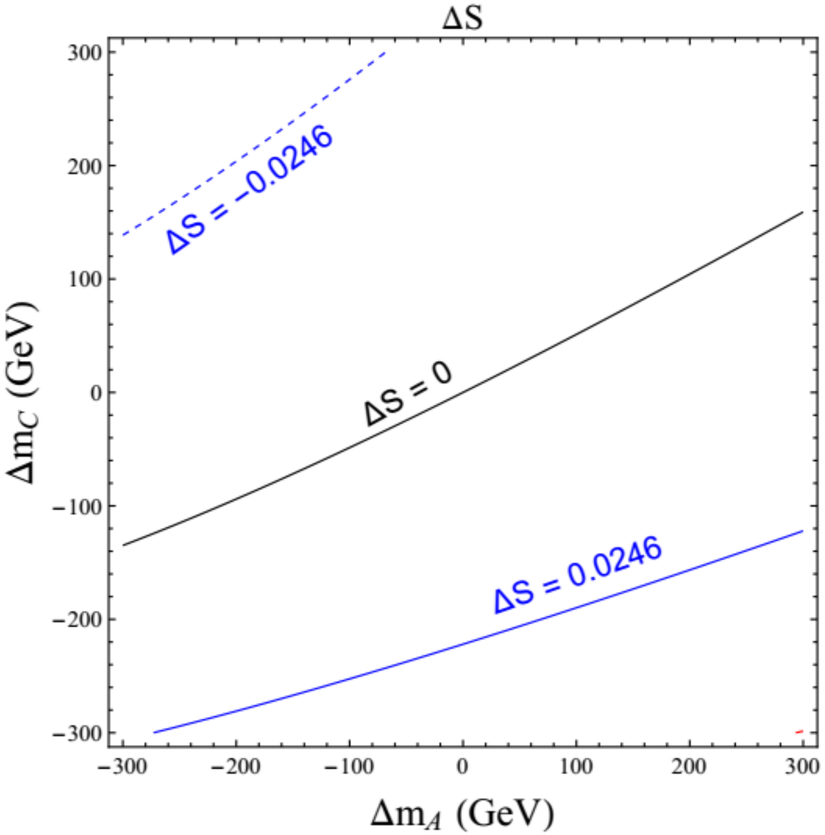


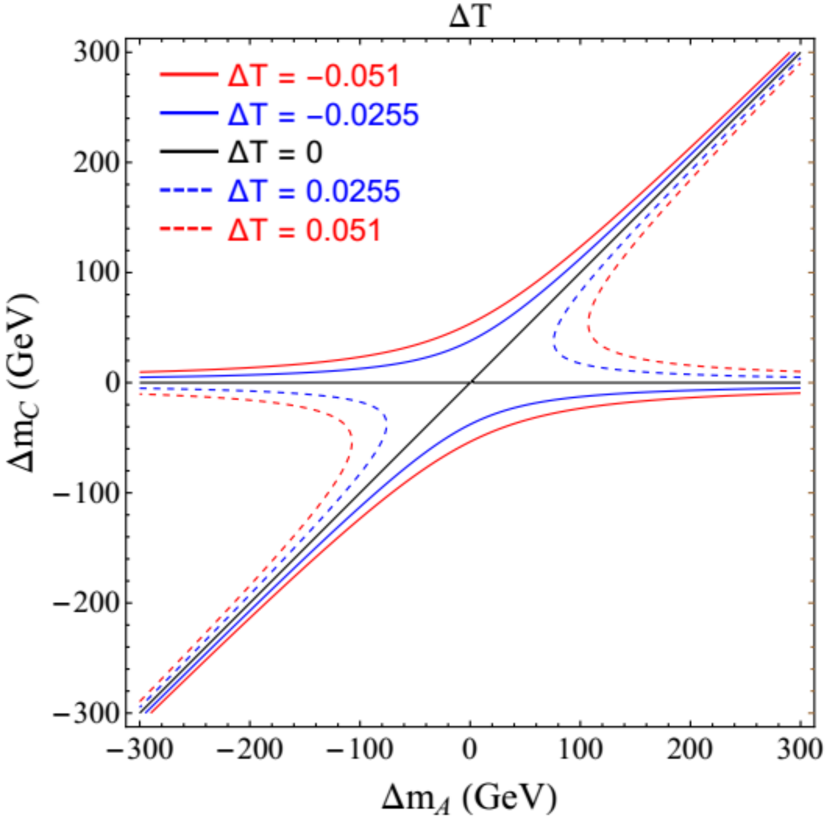
	Current (1.7×10^7 Z's)				CEPC ($10^{10} Z$'s)				FCC-ee ($7 \times 10^{11} Z$'s)				ILC ($10^9 Z$'s)			
	σ	correlation			σ	correlation			σ	correlation			σ	correlation		
		S	T	U	(10^{-2})	S	T	U	(10^{-2})	S	T	U	(10^{-2})	S	T	U
S	0.04 ± 0.11	1	0.92	-0.68	2.46	1	0.862	-0.373	0.67	1	0.812	0.001	3.53	1	0.988	-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

2HDM: $Tree + Loop\ + non - degenerate$

Z Pole Precision

	Current	$(10^9 Z$'s)	
	σ	correlation	
		T	U
S	0.04 ± 0.11	0.988	-0.879
T	0.09 ± 0.14	1	-0.909
U	-0.02 ± 0.1	–	1



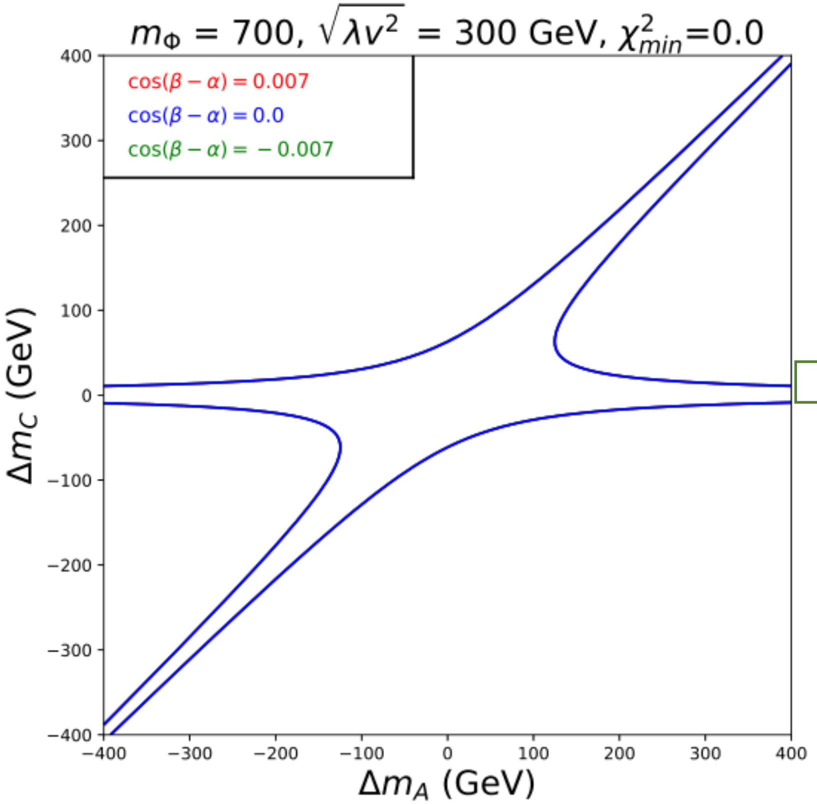


2HDM: $Tree + Loop \ + non - degenerate$

CEPC fit

$$\Delta m_A = m_A - m_H,$$
$$\Delta m_C = m_{H^\pm} - m_H,$$
$$m_H = 700 \text{ GeV}$$

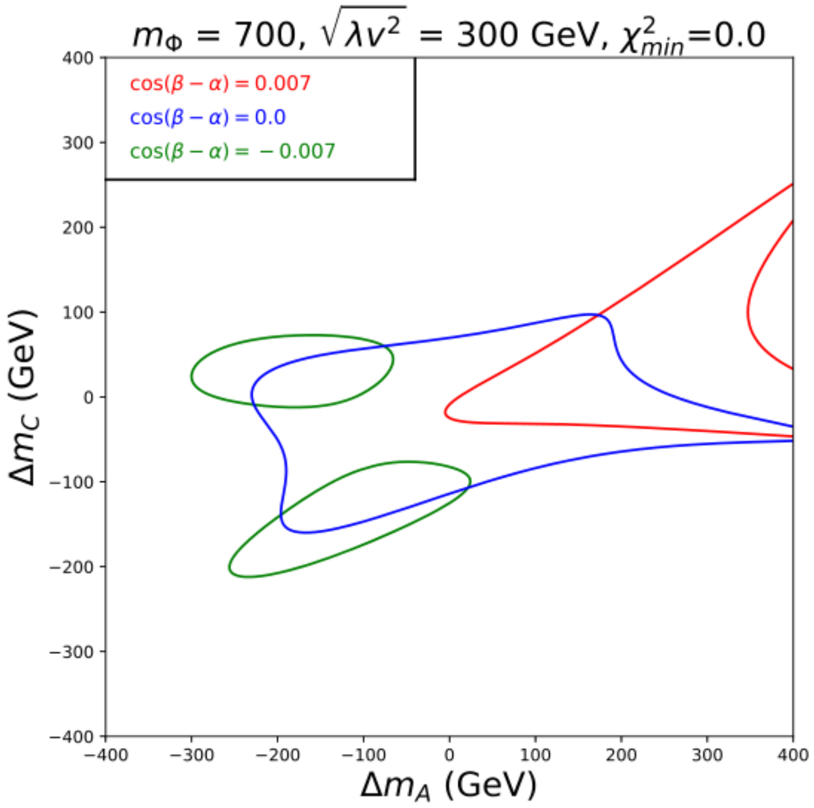
Z Pole Precision



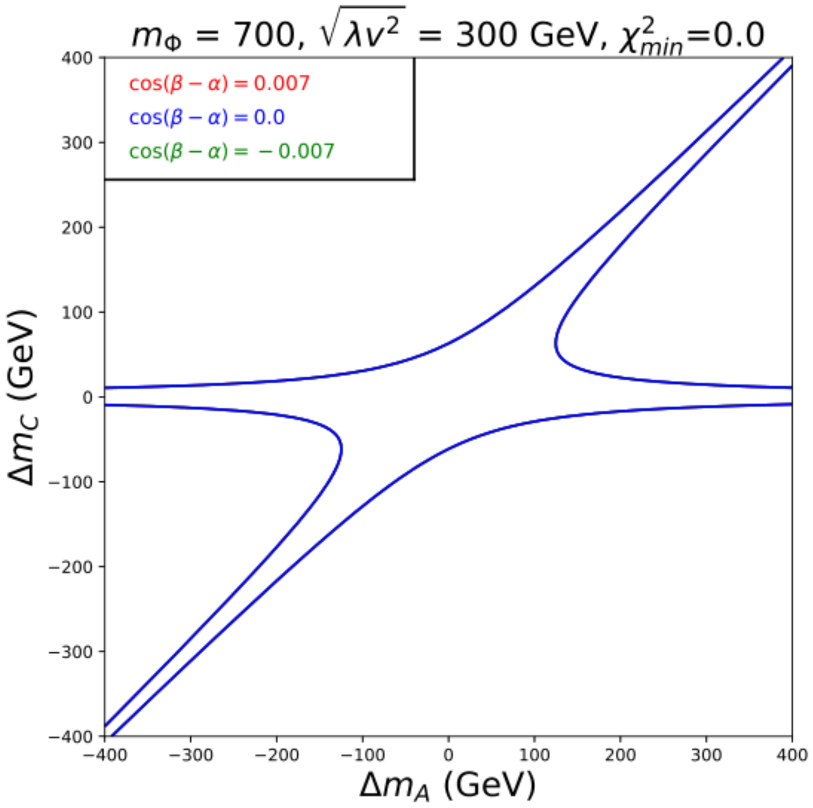
$$m_{H^\pm} = m_H$$
$$m_{H^\pm} = m_A$$

2HDM: $Tree + Loop\ \ + non - degenerate$

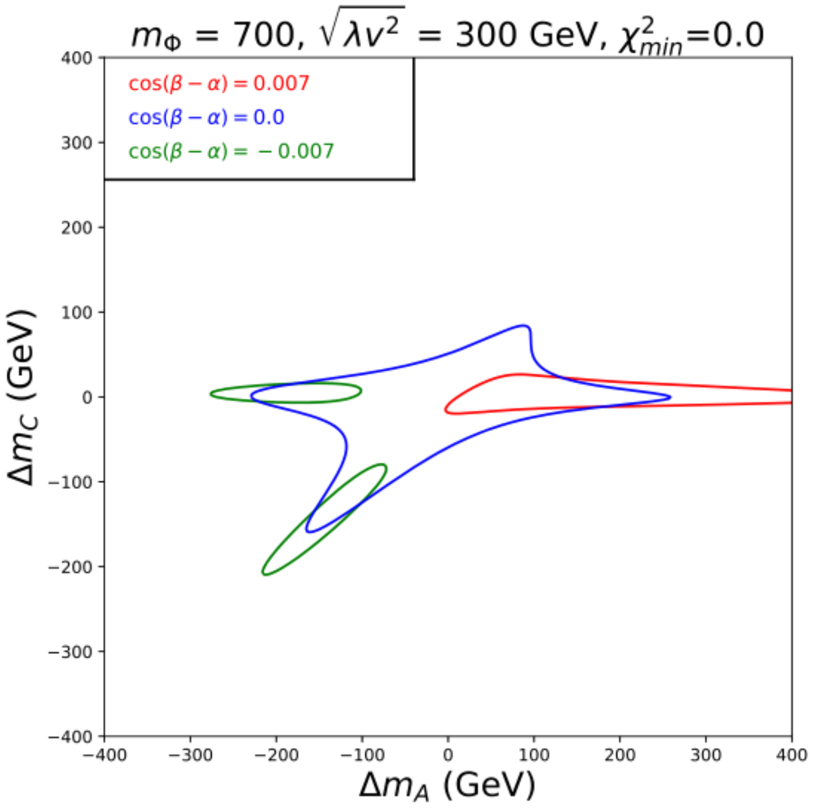
Higgs Precision



Z Pole Precision



Combined

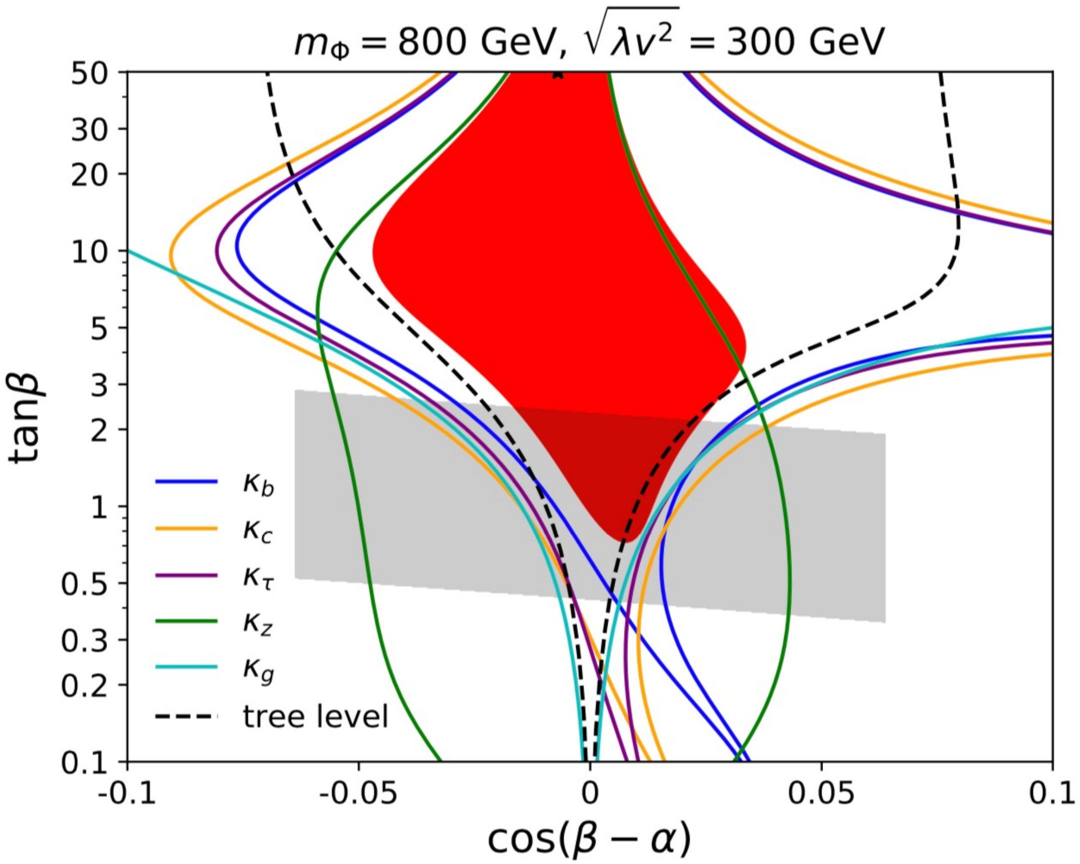


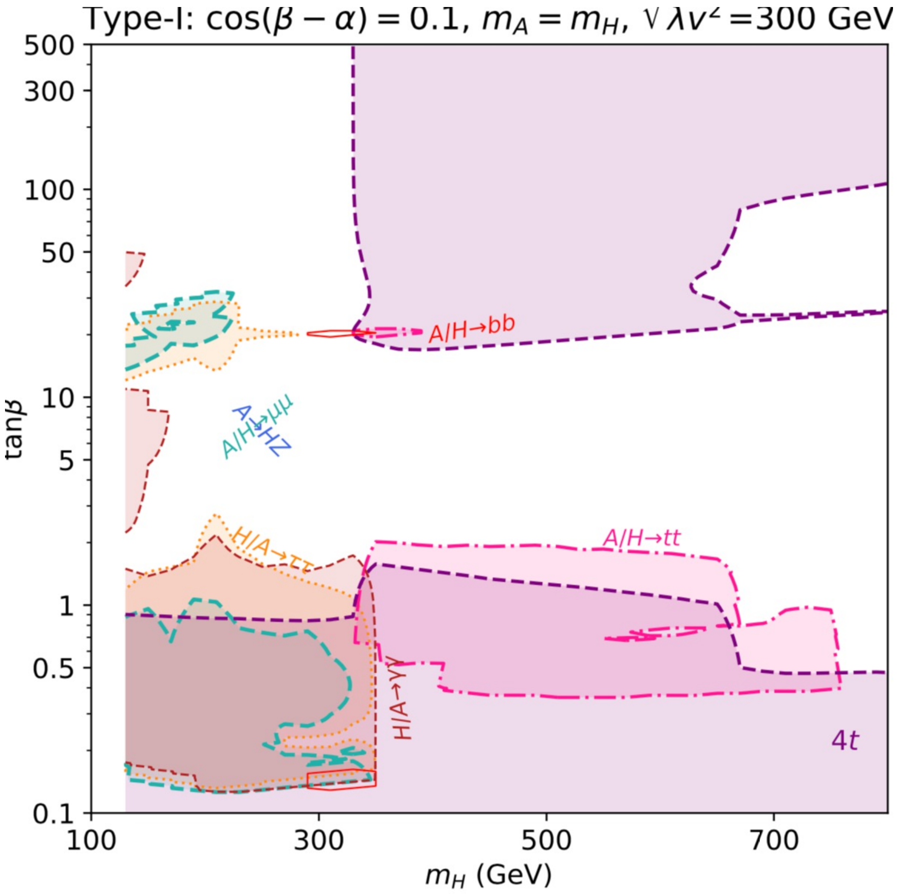
$m_H = 700\ \mathrm{GeV}$

Complementary to each other

2HDM: Type-I

Constraints at Large tanβ





1912.01431 N. Chen, T. Han,
S. Su, Y. Wu

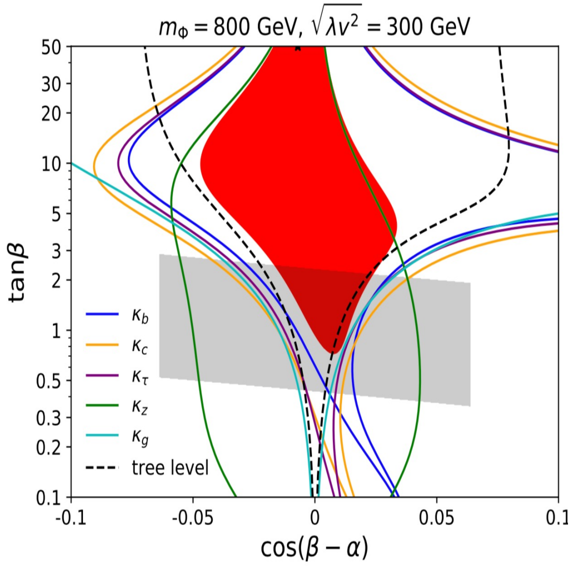
Part Summary : Higgs precision

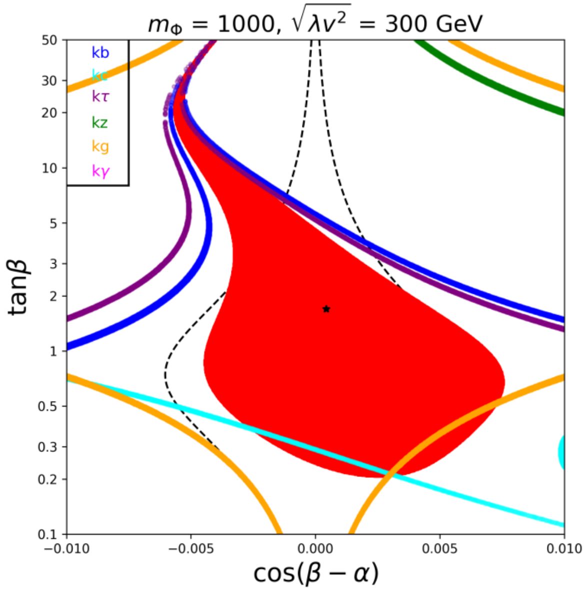
2HDM

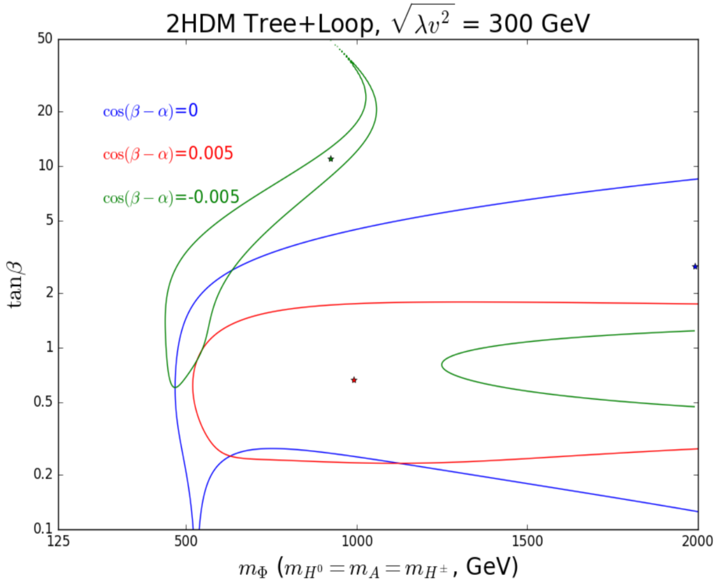
- Tree vs Loop
- Alignment vs Non-alignment
- Degenerate vs Non-gedenerate

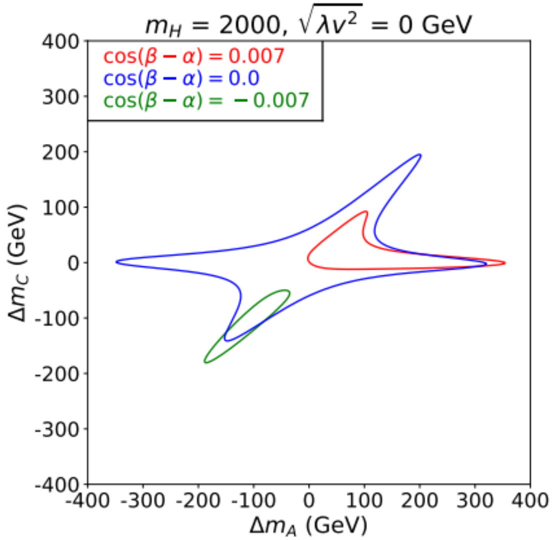
Complementary to

- Z pole precision
- LHC direct search







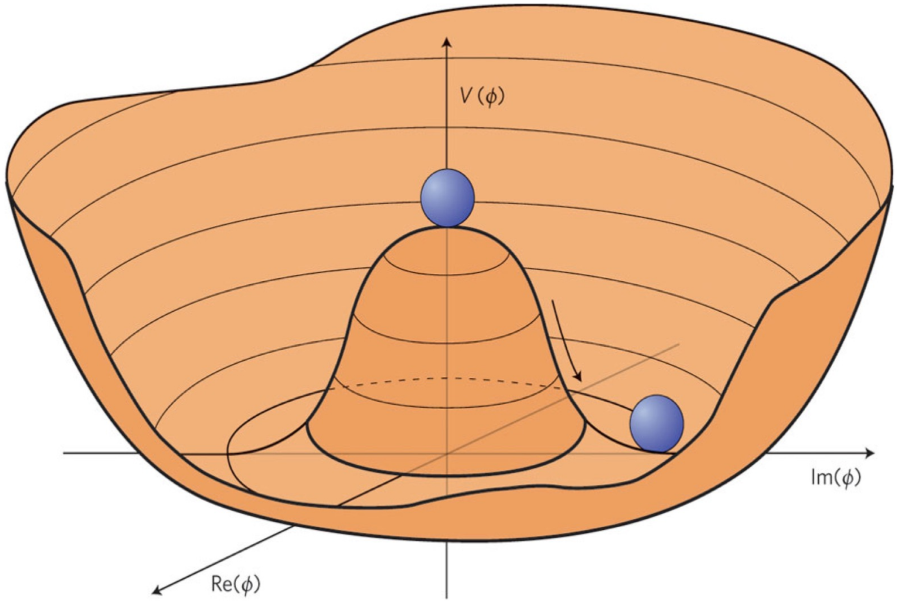


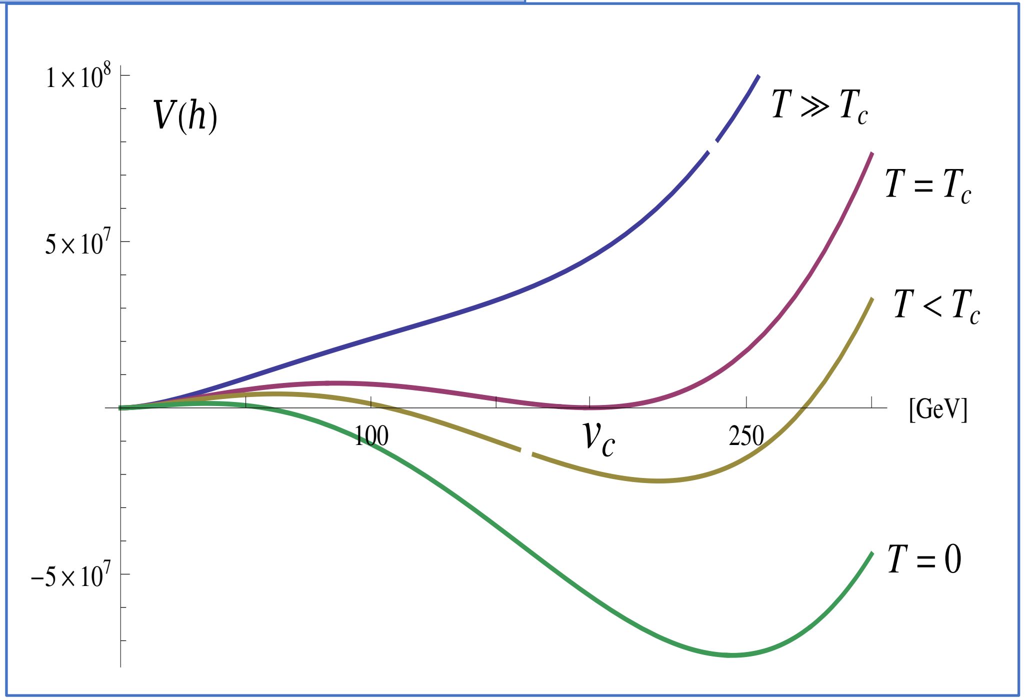
Results

- Higgs and Z-pole Precision Measurements
- Study Results: Tree & one-loop Level
- **2HDM & Electroweak Phase Transition**

Electroweak Phase Transition

baryon asymmetry of the Universe (BAU)





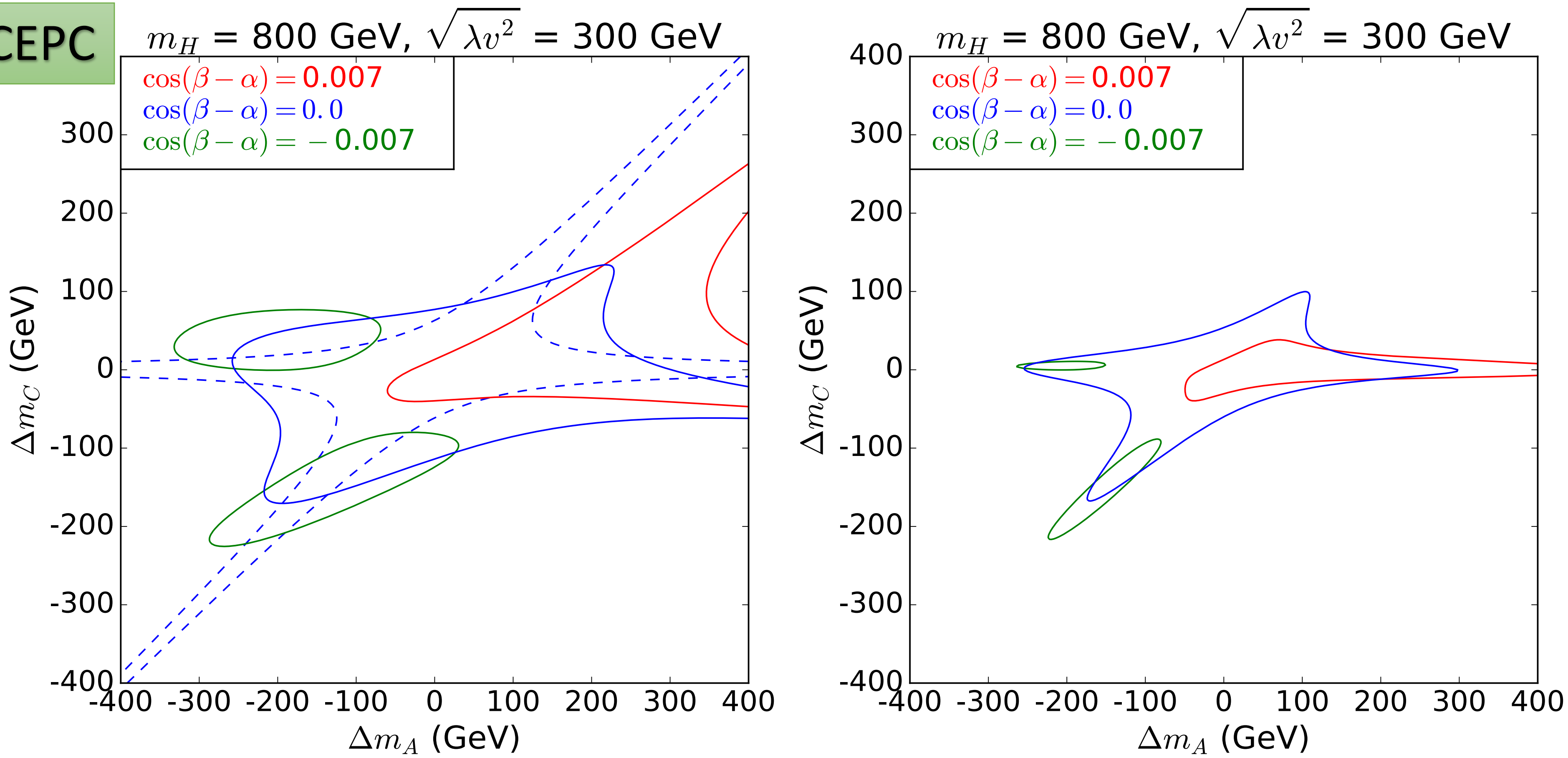
SM: Cross-over around T=100 GeV

BSM: bubble formation → asymmetry

2HDM: precision

1808.02037 N. Chen, T. Han, S. Su, WS, Y. Wu

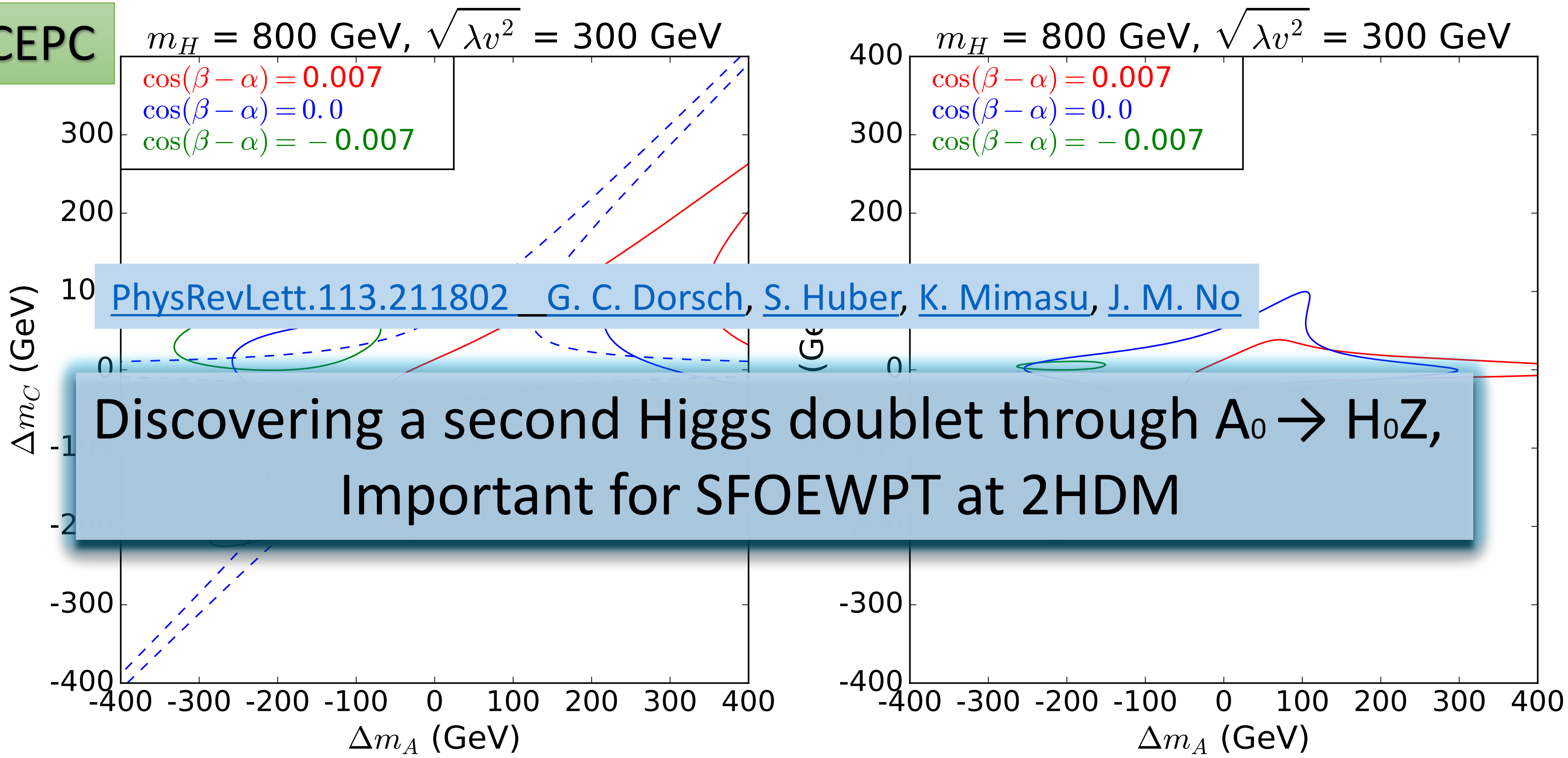
Type-II, CEPC



2HDM: precision

1808.02037 N. Chen, T. Han, S. Su, WS, Y. Wu

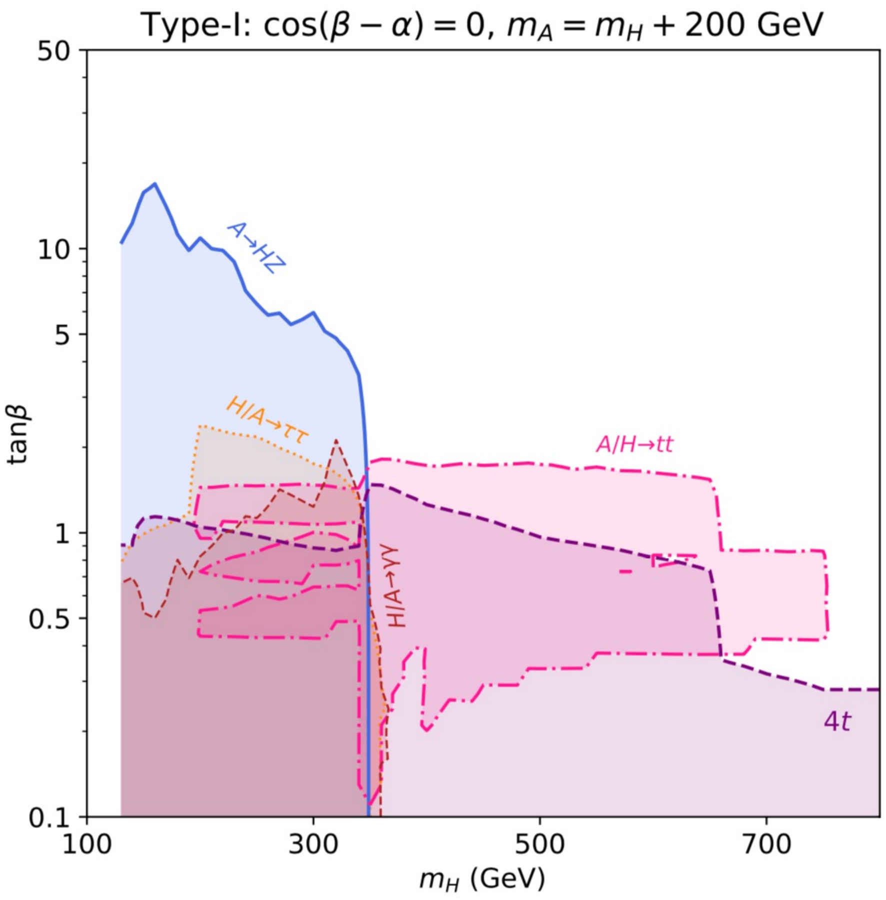
Type-II, CEPC

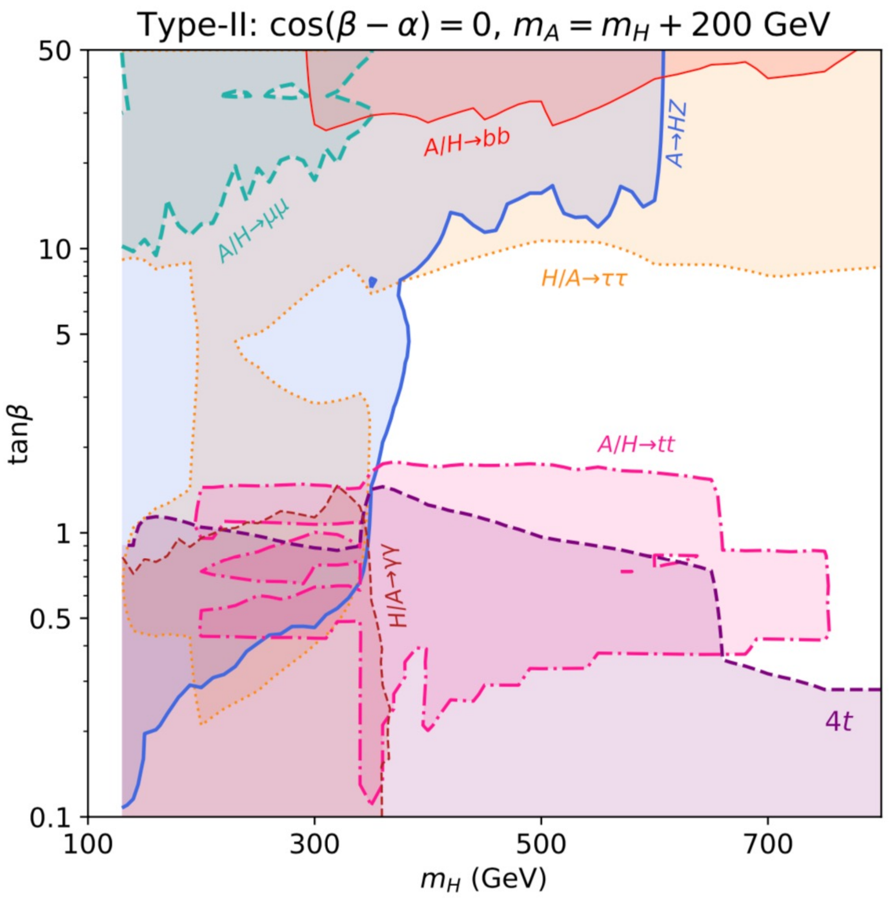


PhysRevLett.113.211802 G. C. Dorsch, S. Huber, K. Mimasu, J. M. No

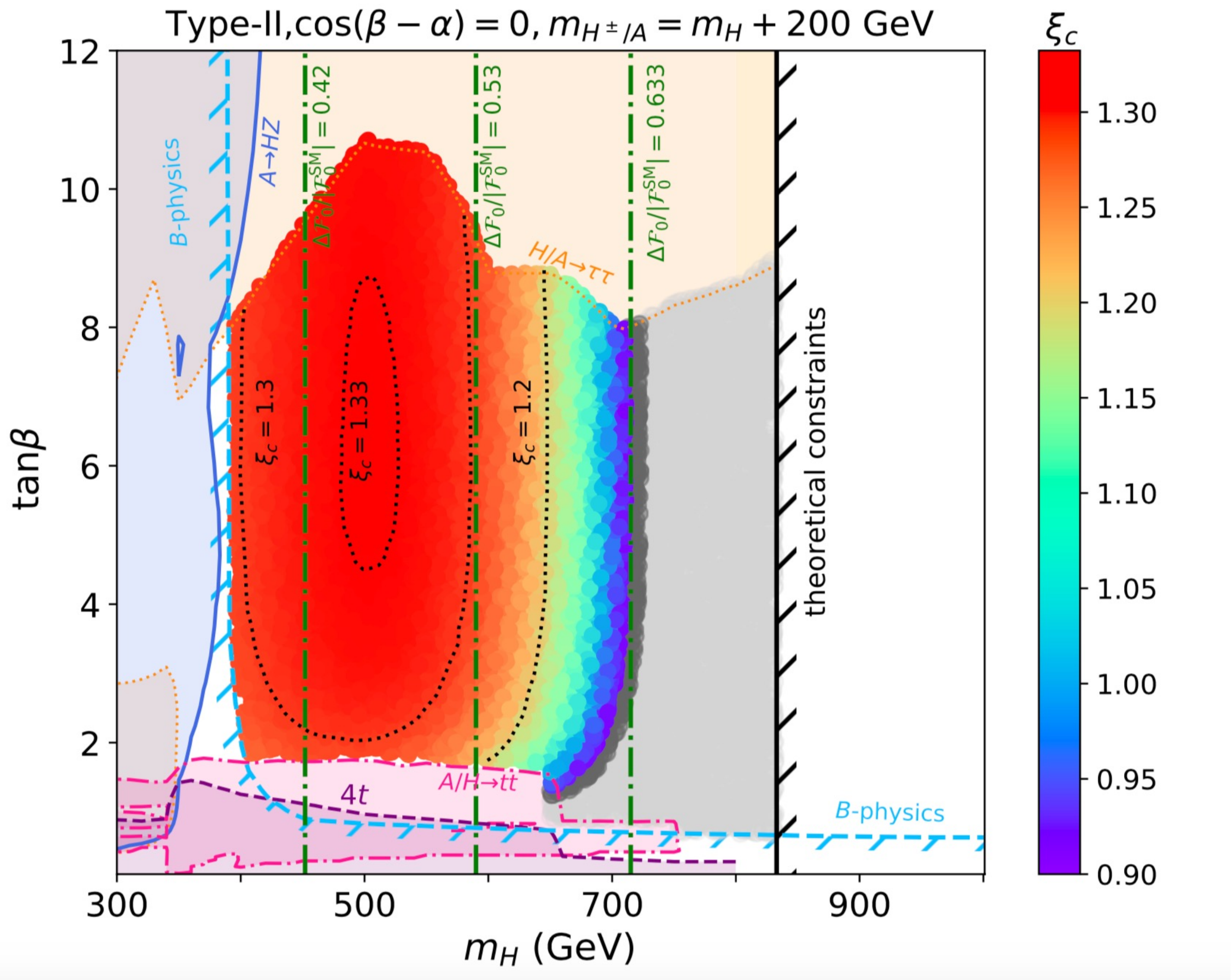
Discovering a second Higgs doublet through $A_0 \to H_0 Z$, Important for SFOEWPT at 2HDM

2HDM: LHC direct search





Results: Case-1



Type-II
fixed mass splitting 200 GeV

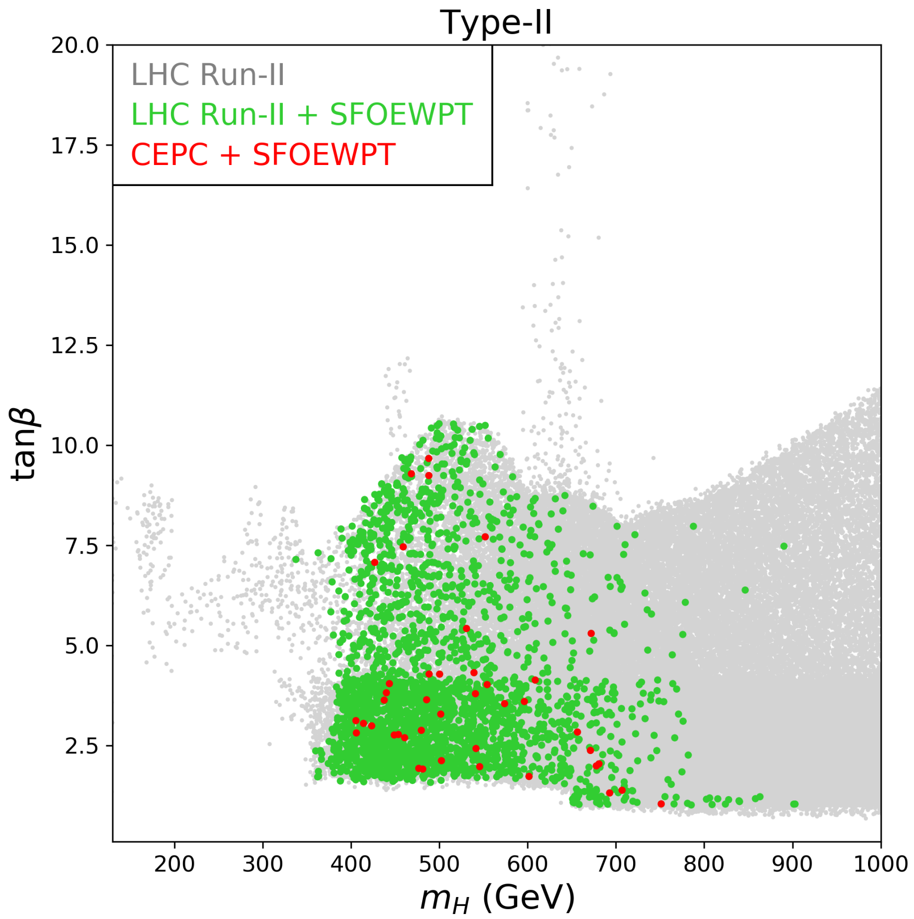
$m_H < 710$ GeV
$tan\beta \; \epsilon \; (1.8{,}10)$

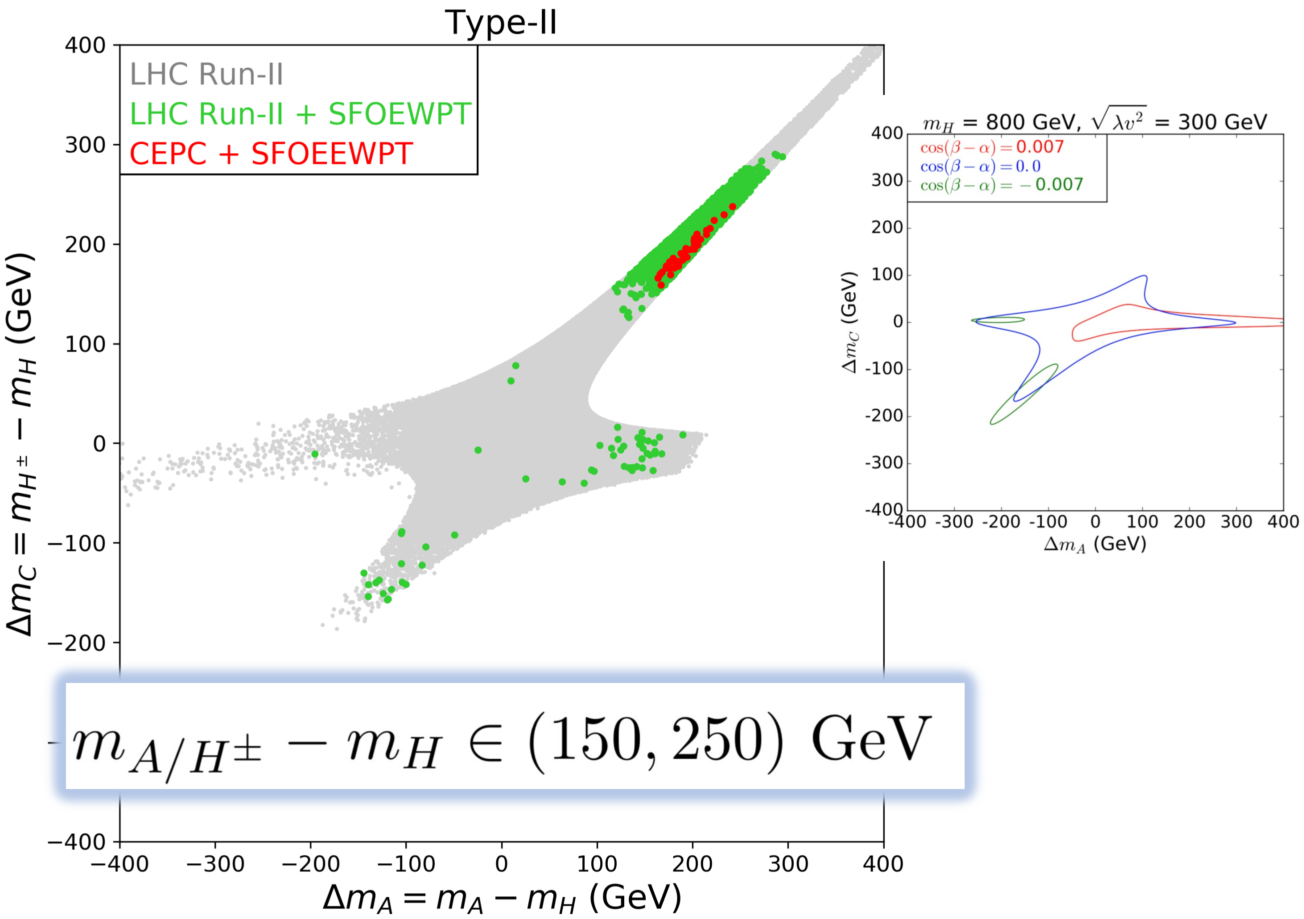
Vacuum uplifting:

arXiv:1705.09186
G. C. Dorsch, S. Huber, K. Mimasu, J. M. No

$$\Delta\mathcal{F}_0 = \frac{1}{64\pi^2}\left[\left(m_h^2-2M^2\right)^2\left(\frac{3}{2}+\frac{1}{2}\log\left[\frac{4m_Am_Hm_{H\pm}^2}{\left(m_h^2-2M^2\right)^2}\right]\right)\right.$$
$$\left.+\frac{1}{2}\left(m_A^4+m_H^4+2m_{H\pm}^4\right)+\left(m_h^2-2M^2\right)\left(m_A^2+m_H^2+2m_{H\pm}^2\right)\right]$$

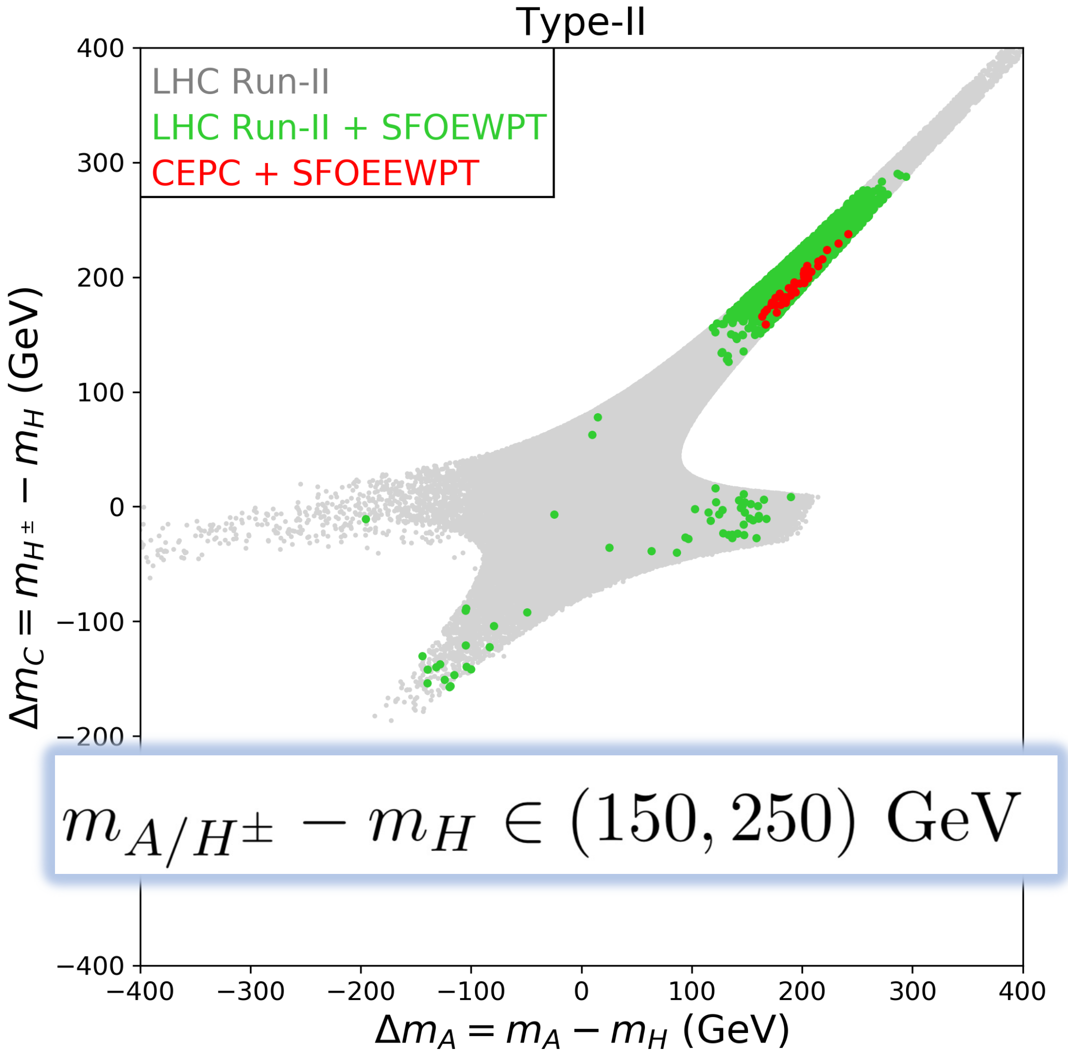
Results: Type-II



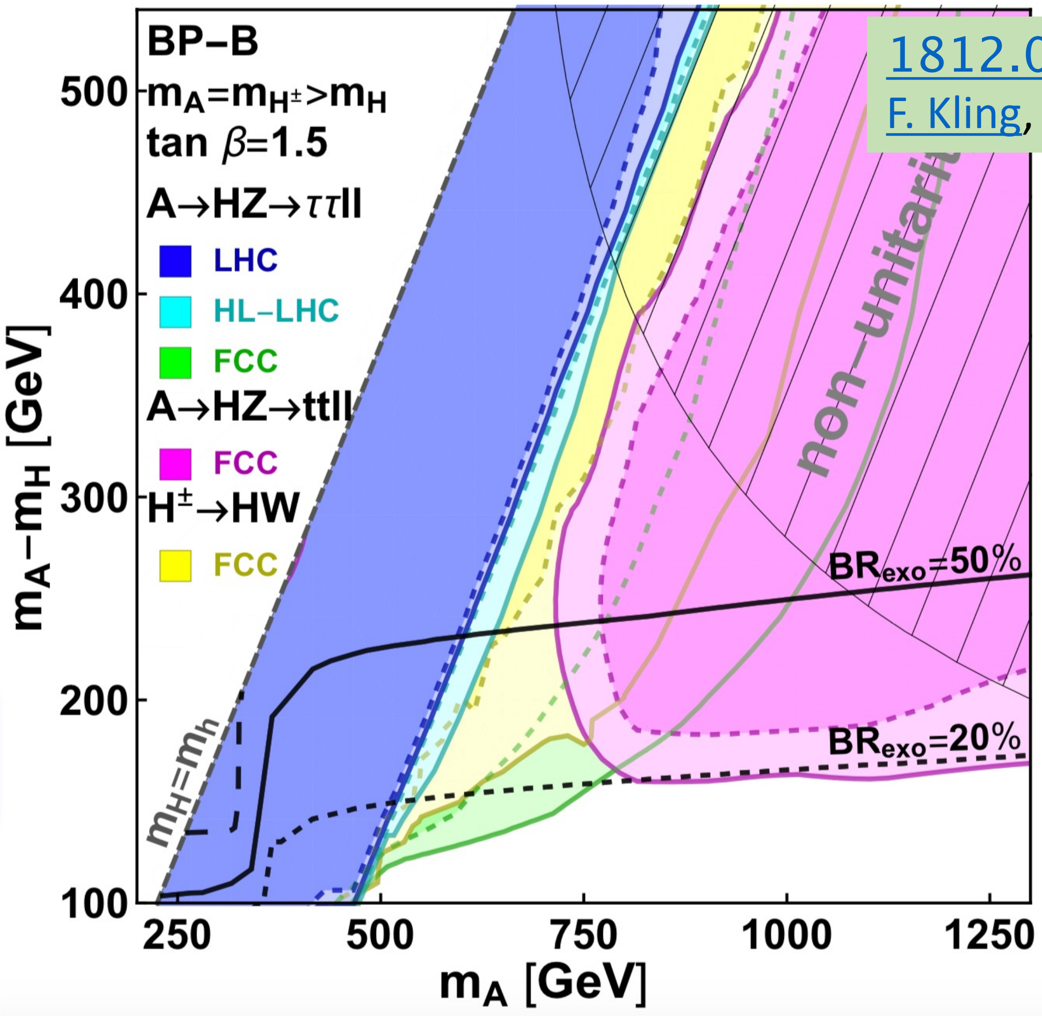


$$m_{A/H^\pm} - m_H \in (150, 250)\ \text{GeV}$$

Future

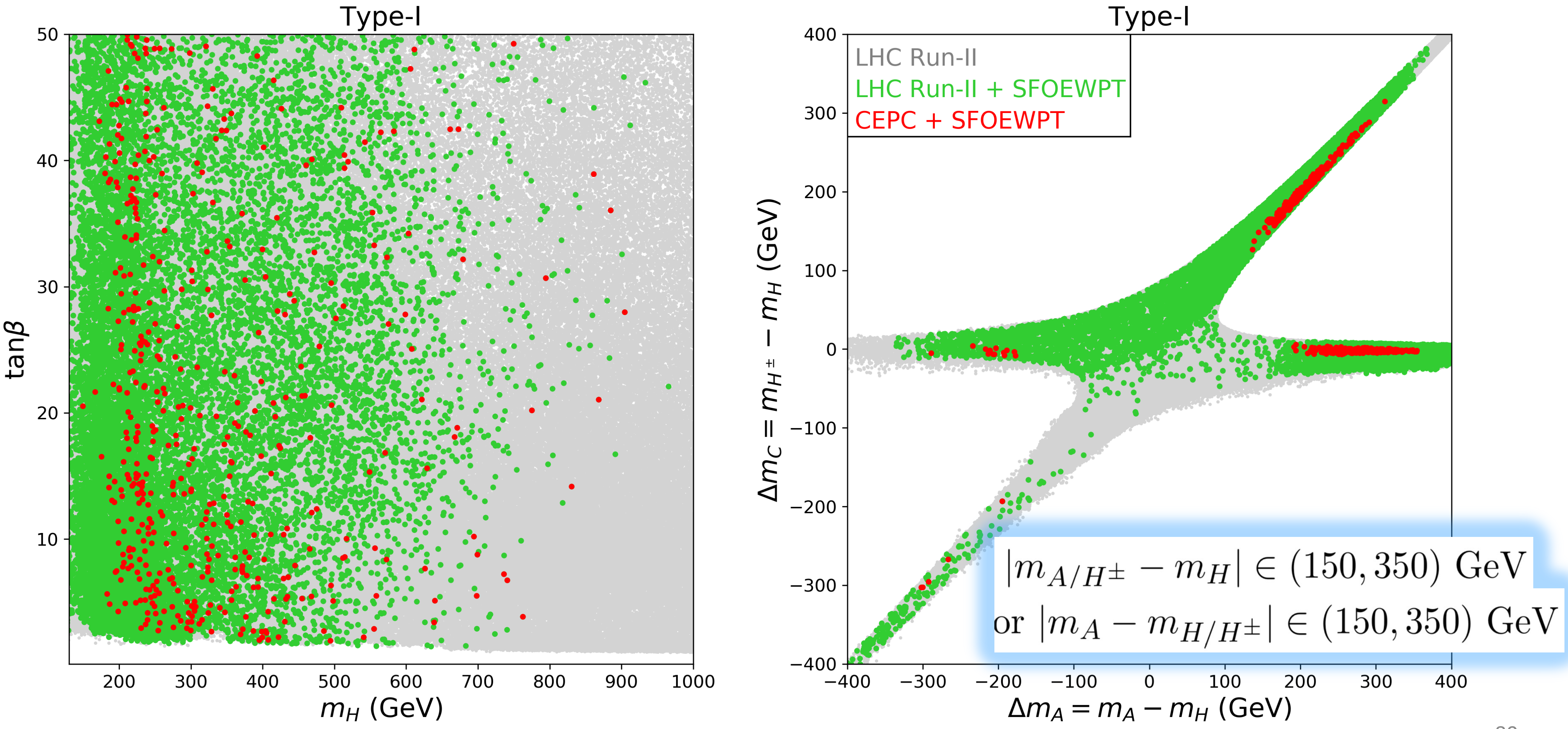


$$m_{A/H^\pm} - m_H \in (150, 250)\ \text{GeV}$$



1812.01633
F. Kling, H. Li, etc

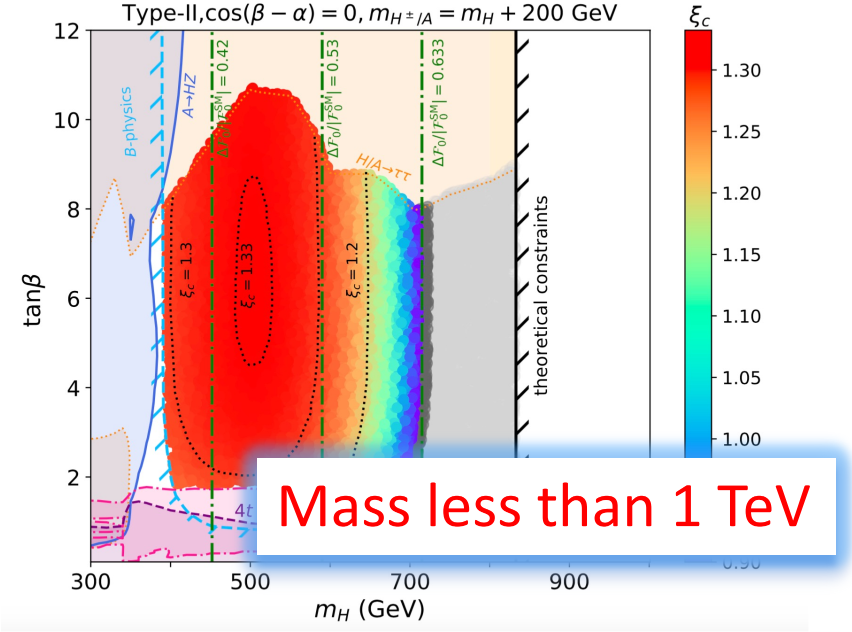
Results: Type-I



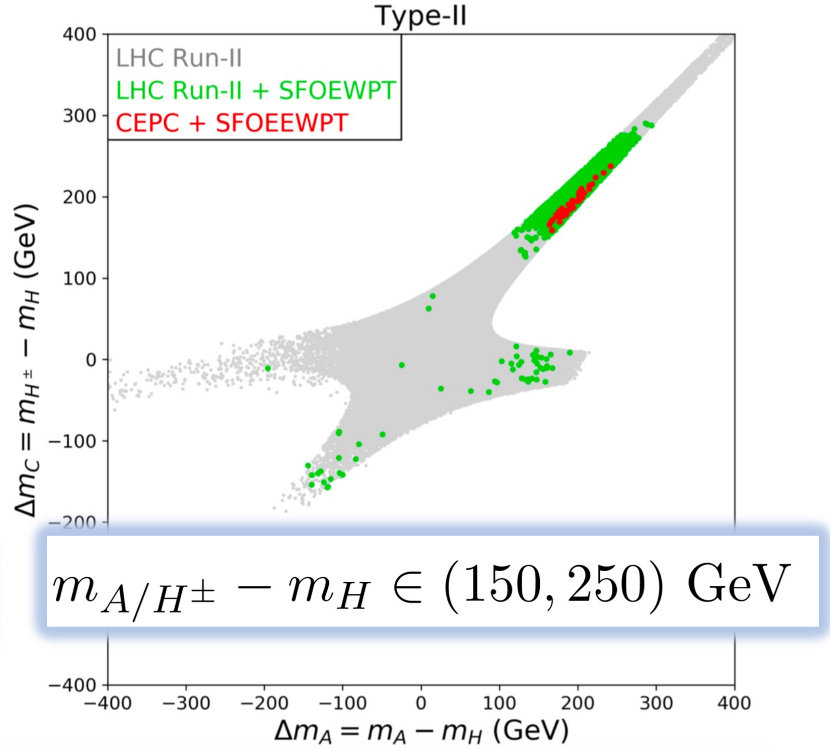
$|m_{A/H^\pm} - m_H| \in (150, 350)$ GeV

or $|m_A - m_{H/H^\pm}| \in (150, 350)$ GeV

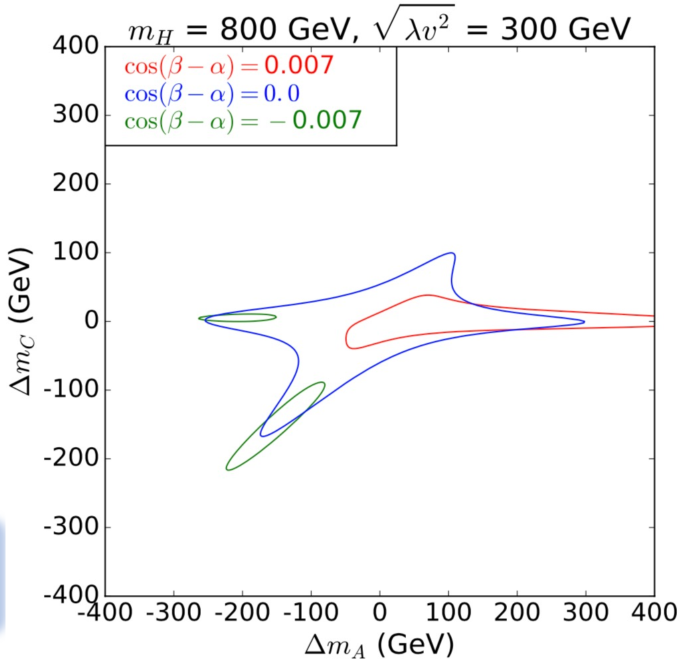
Part Summary



Mass less than 1 TeV



$$m_{A/H^\pm} - m_H \in (150, 250)\ \text{GeV}$$



IDM

- The inert 2HDM

In this model, one imposes a symmetry $H_2 \to -H_2$ in the Higgs basis. As a result, The Higgs sector is CP-conserving. In the CP-conserving neutral Higgs-fermion Lagrangian, this model corresponds to $\sin(\beta - \alpha) = 1$, $\cos(\beta - \alpha) = 0$ and $\rho^U = \rho^D = 0$. The CP-even h^0 is identical to the SM Higgs boson, and H^0, A^0 and $H^\pm$ appear only quadratically in interactions and so the lightest among these states is absolutely stable.

Fermiophobic 2HDM

This is a model that purports to invent a Higgs scalar that couples only to gauge bosons and is decoupled from fermions. This can be realized in a Type-I 2HDM where $\cos\alpha = 0$. In this case, h^0 has no tree-level couplings to fermions. However, the h^0 couplings to W^+W^- and ZZ are suppressed by a factor of $\cos\beta$.

$$
\begin{aligned}
-\mathcal{L}_Y^{\text{int}} = \sum_{f=u,d,e} \frac{m_f}{v} \left(\xi_h^f \overline{f} f h + \xi_H^f \overline{f} f H - 2i I_f \xi_f \overline{f} \gamma_5 f A \right) \\
+ \frac{\sqrt{2}}{v} \left[V_{ud} \bar{u} \left(m_d \xi_d P_R - m_u \xi_u P_L \right) d H^+ + m_e \xi_e \bar{\nu} P_R e H^+ + \text{h.c.} \right],
\end{aligned}
$$

The Higgs sector of the MSSM

The Higgs sector of the MSSM is a 2HDM, whose Yukawa couplings and Higgs potential are constrained by SUSY. Instead of employing to hypercharge-one scalar doublets $\Phi_{1,2}$, it is more convenient to introduce a $Y=-1$ doublet $H_d \equiv i\sigma_2\Phi_1^*$ and a $Y=+1$ doublet $H_u \equiv \Phi_2$:

$$H_d = \begin{pmatrix} H_d^1 \\ H_d^2 \end{pmatrix} = \begin{pmatrix} \Phi_1^{0\,*} \\ -\Phi_1^- \end{pmatrix}, \qquad H_u = \begin{pmatrix} H_u^1 \\ H_u^2 \end{pmatrix} = \begin{pmatrix} \Phi_2^+ \\ \Phi_2^0 \end{pmatrix}.$$

The origin of the notation originates from the Higgs Yukawa Lagrangian:

$$\mathcal{L}_{\text{Yukawa}} = -h_u^{ij}(\bar{u}_R^i u_L^j H_u^2 - \bar{u}_R^i d_L^j H_u^1) - h_d^{ij}(\bar{d}_R^i d_L^j H_d^1 - \bar{d}_R^i u_L^j H_d^2) + \text{h.c.}\,.$$

Note that the neutral Higgs field H_u^2 couples exclusively to up-type quarks and the neutral Higgs field H_d^1 couples exclusively to down-type quarks. This is a Type-II 2HDM.