1st Workshop of the WG1-SRCH group

New physics hints with 2HDM under the Higgs Precision Measurements

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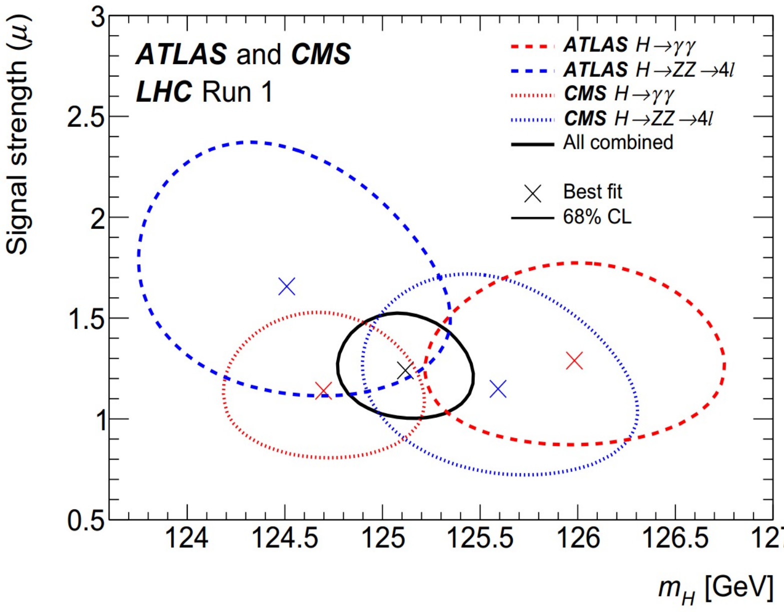
2008.05492 (T. Han, S. Li, S. Su, WS, Y. Wu)
1808.02037 (N. Chen, T. Han, S. Su, WS, Y. Wu)
1912.01431 (N. Chen, T. Han, S. Li, S. Su, WS, Y. Wu)

KOREA INSTITUTE FOR ADVANCED STUDY

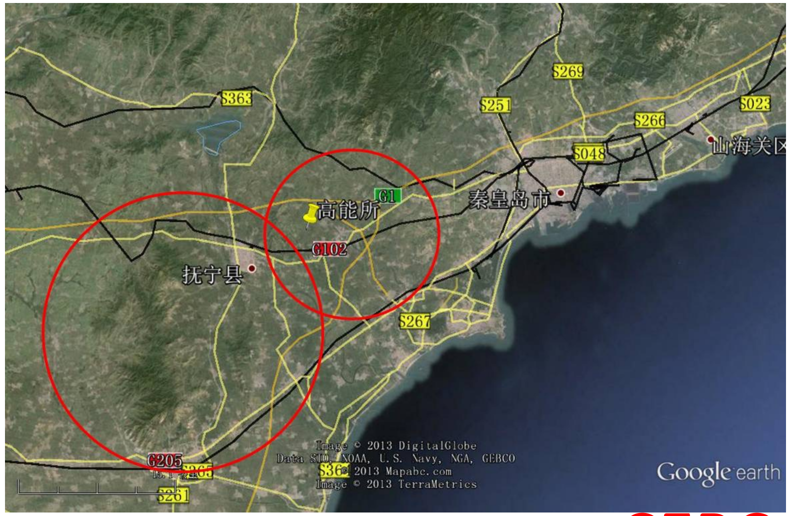
Outline

- Higgs Precision Measurements and 2HDM
- Study Results: exclusion ability
- Study Results: discovery potential
- Study Results: discrimination ability
- Study Results: Compatibility test
- Summary

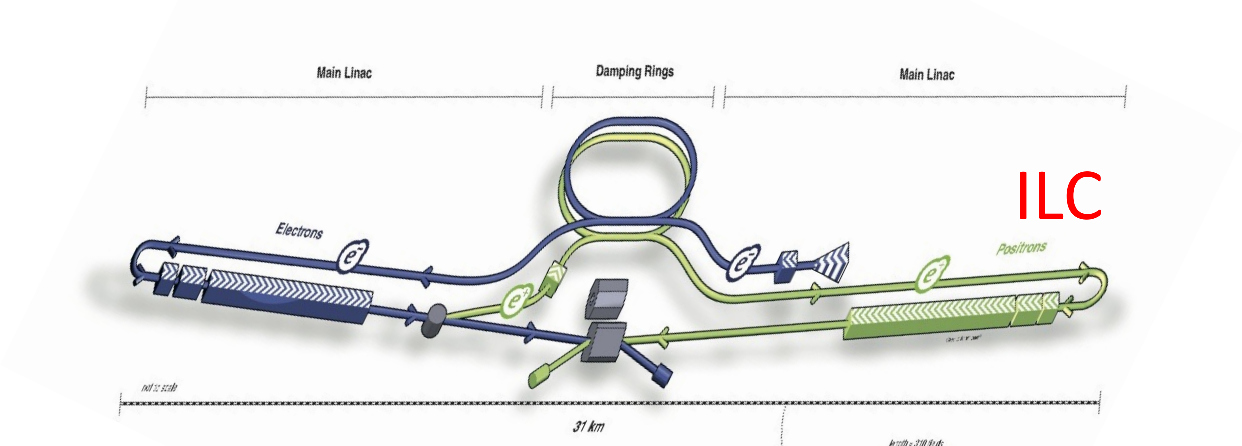
Higgs Precision Measurements



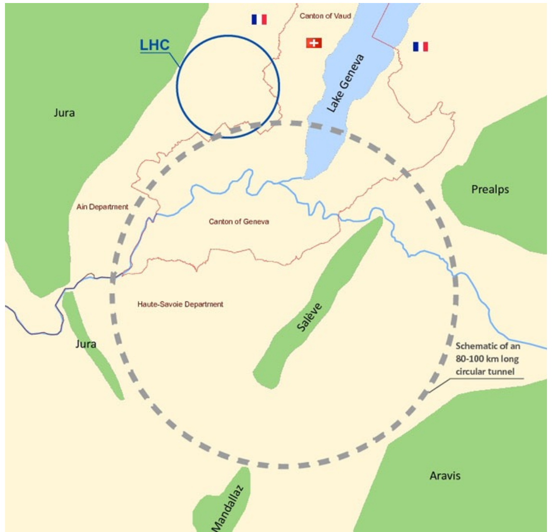
CMS-HIG-14-042
ATLAS-HIGG-2014-14



CEPC



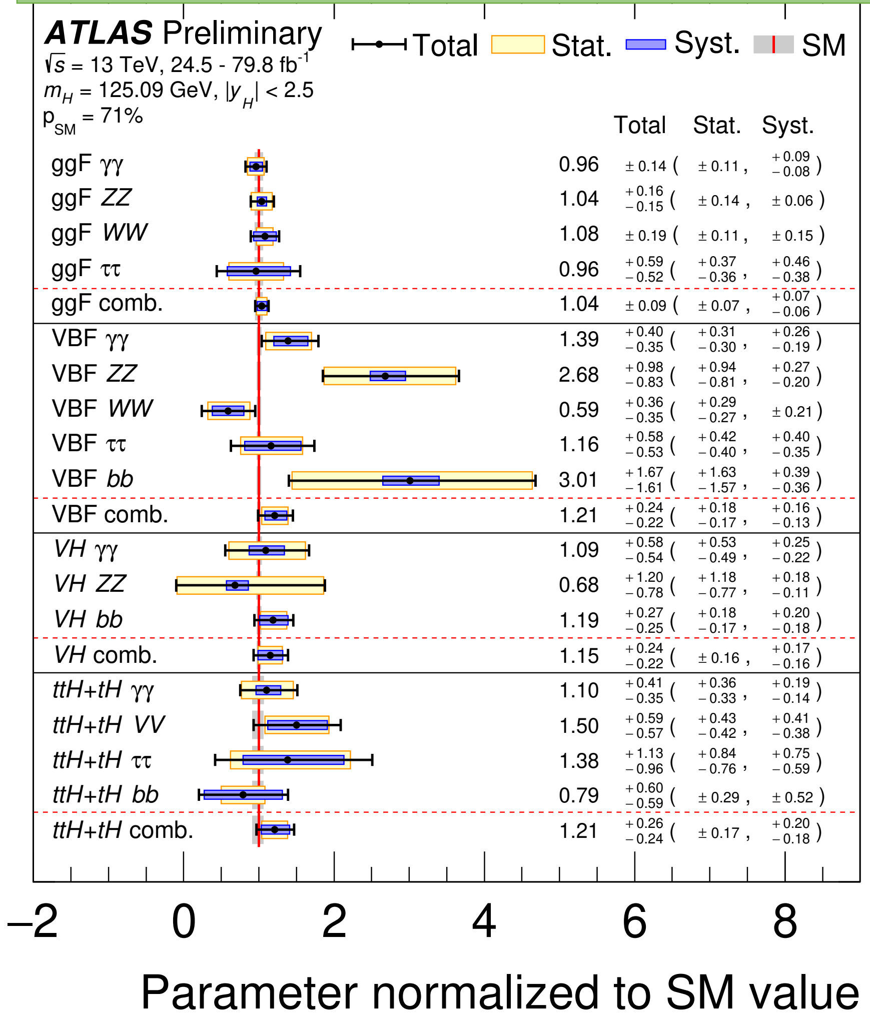
ILC



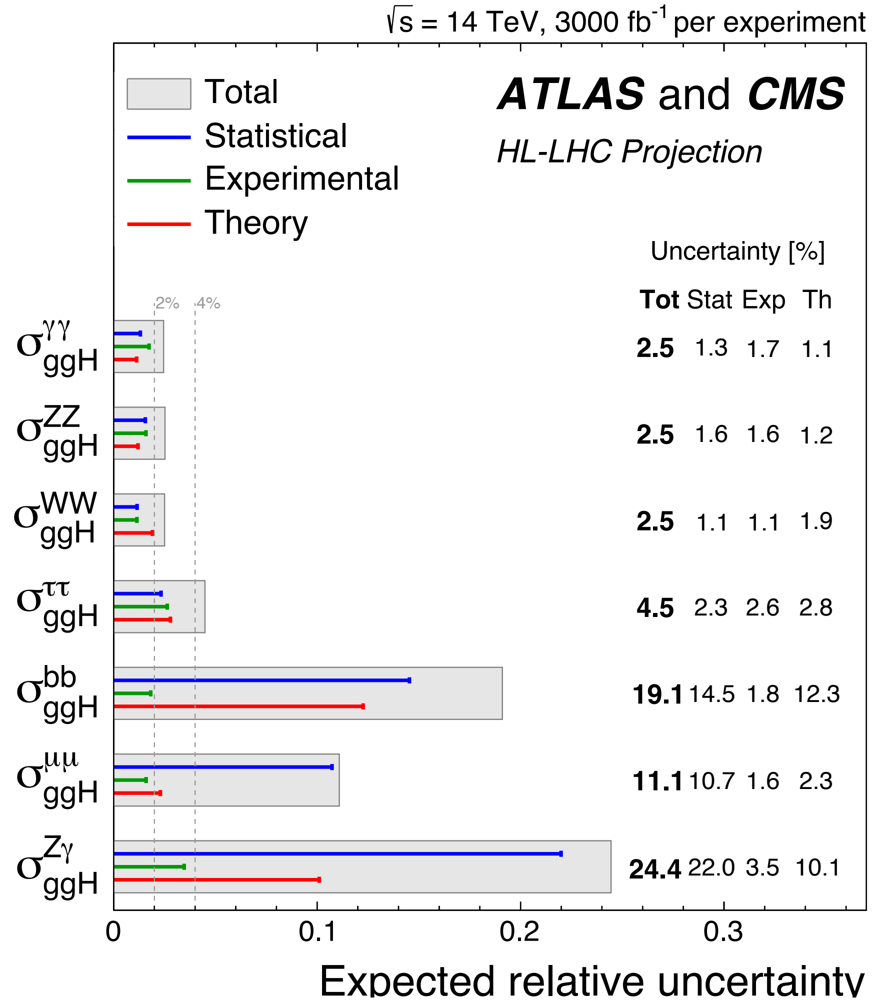
LHC
HL-LHC
FCC

Precision: Higgs couplings

LHC Run-II: ATLAS-CONF-2019-005



HL-LHC: 1902.00134



Precision: Higgs couplings

CEPC-CDR , FCC-ee, ILC Operating Scenarios

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	$\Delta(\sigma \cdot BR)/(\sigma \cdot BR)$								
$h \to b\bar{b}$	0.27%	0.3%	0.5%	0.9%	0.46%	1.7%	2.0%	0.63%	0.23%
$h \to c\bar{c}$	3.3%	2.2%	6.5%	10%	2.9%	12.3%	21.2%	4.5%	2.2%
$h \to gg$	1.3%	1.9%	3.5%	4.5%	2.5%	9.4%	8.6%	3.8%	1.5%
$h \to WW^*$	1.0%	1.2%	2.6%	3.0%	1.6%	6.3%	6.4%	1.9%	0.85%
$h \to \tau^+\tau^-$	0.8%	0.9%	1.8%	8.0%	1.1%	4.5%	17.9%	1.5%	2.5%
$h \to ZZ^*$	5.1%	4.4%	12%	10%	6.4%	28.0%	22.4%	8.8%	3.0%
$h \to \gamma\gamma$	6.8%	9.0%	18%	22%	12.0%	43.6%	50.3%	12.0%	6.8%
$h \to \mu^+\mu^-$	17%	19%	40%	–	25.5%	97.3%	178.9%	30.0%	25.0%
$(\nu\bar{\nu})h \to b\bar{b}$	2.8%	3.1%	–	–	3.7%	–	–	–	–

2HDM: Brief Introduction

- Two Higgs Doublet Model

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

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

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

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

2HDM: Brief Introduction

- Two Higgs Doublet Model

Soft breaking of Z2

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

Hard breaking of Z2

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

$$v_u^2 + v_d^2 = v^2 = (246\text{GeV})^2$$
$$\tan\beta = v_u/v_d$$

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

2HDM: Brief Introduction

	Φ_1	Φ_2
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	$\sin(\beta-\alpha)$	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$	$\cos\alpha/\sin\beta$

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

$m_{11}^2, m_{22}^2, \lambda_1, \lambda_2, \lambda_3, \lambda_4, \lambda_5$ → $v, \tan\beta, \alpha, m_h, m_H, m_A, m_{H^\pm}$

v → 246 GeV; m_h → 125. GeV

Soft Z_2 symmetry breaking: m_{12}^2

Exclusion ability : Study strategies

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

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

Fitting

Maximal likelihood: $\Delta\chi^2$

$d.o.f. = free\ parameter$

Absolute χ^2

$d.o.f. = num\ of\ observables\ ...$

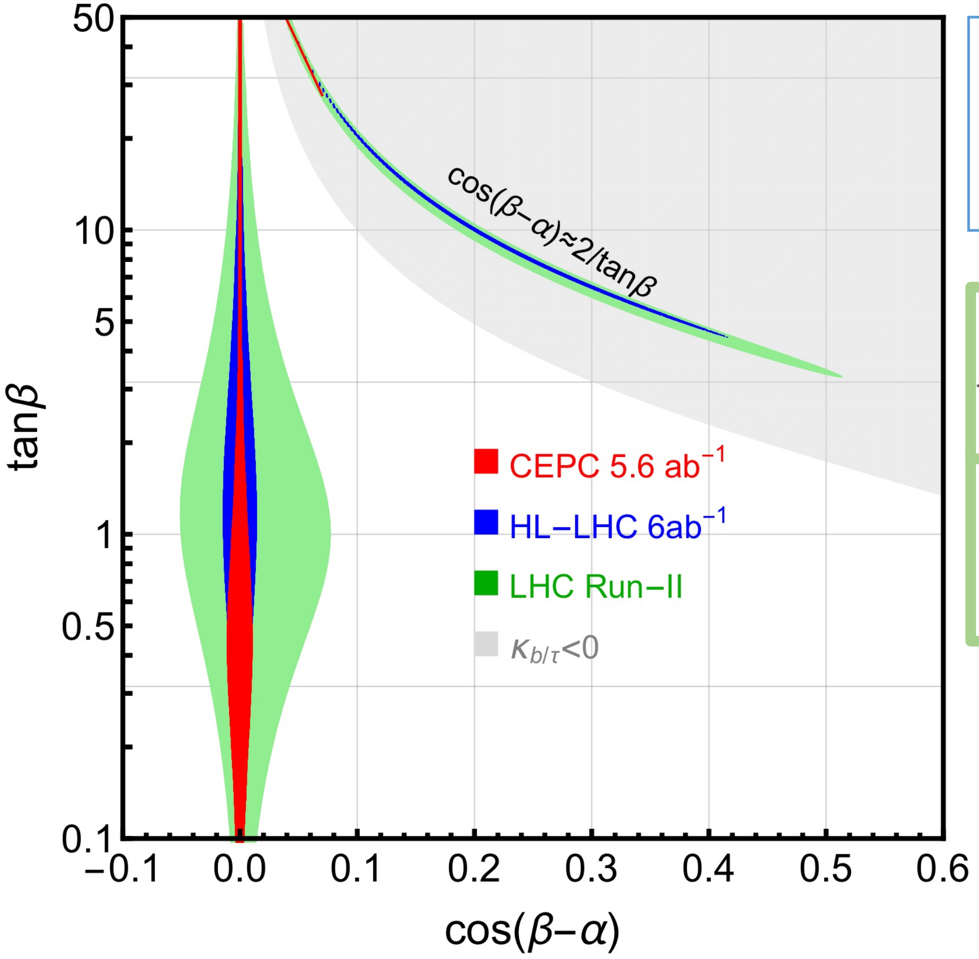
Parameters in New Physics Models

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

Exclusion: 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

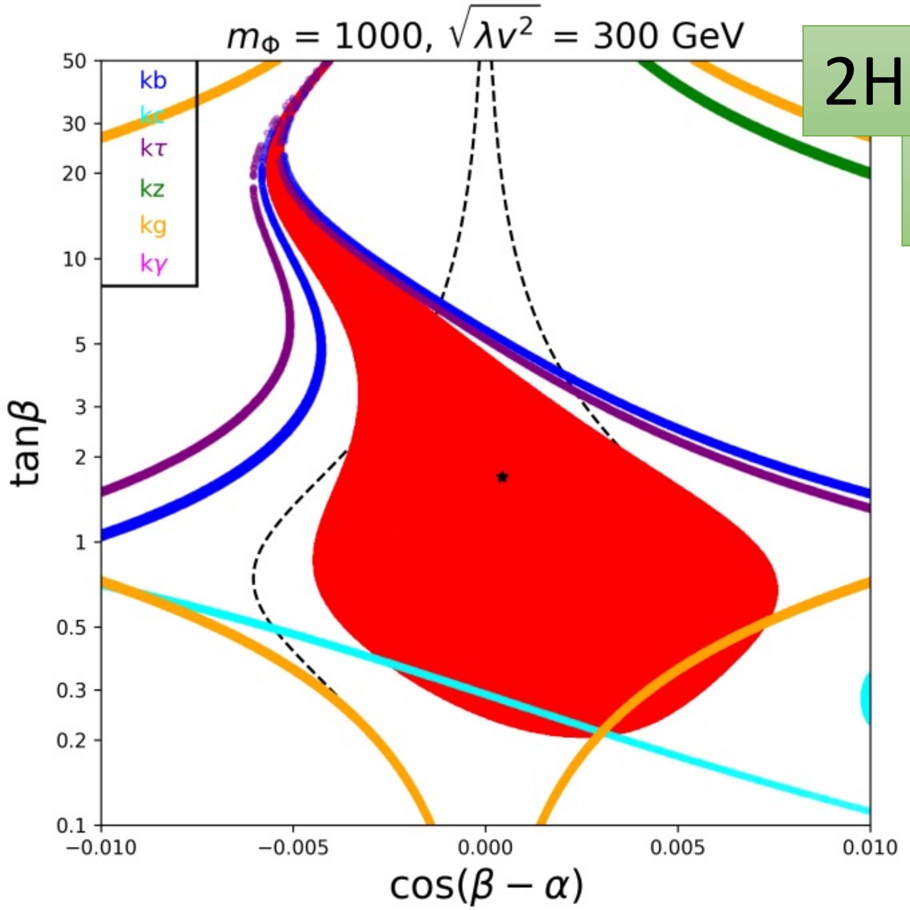
$$-\frac{\sin\beta}{\cos\alpha} - 1 = -\frac{1}{2}\cos^2(\beta-\alpha) - \cos(\beta-\alpha)\times\tan\beta$$

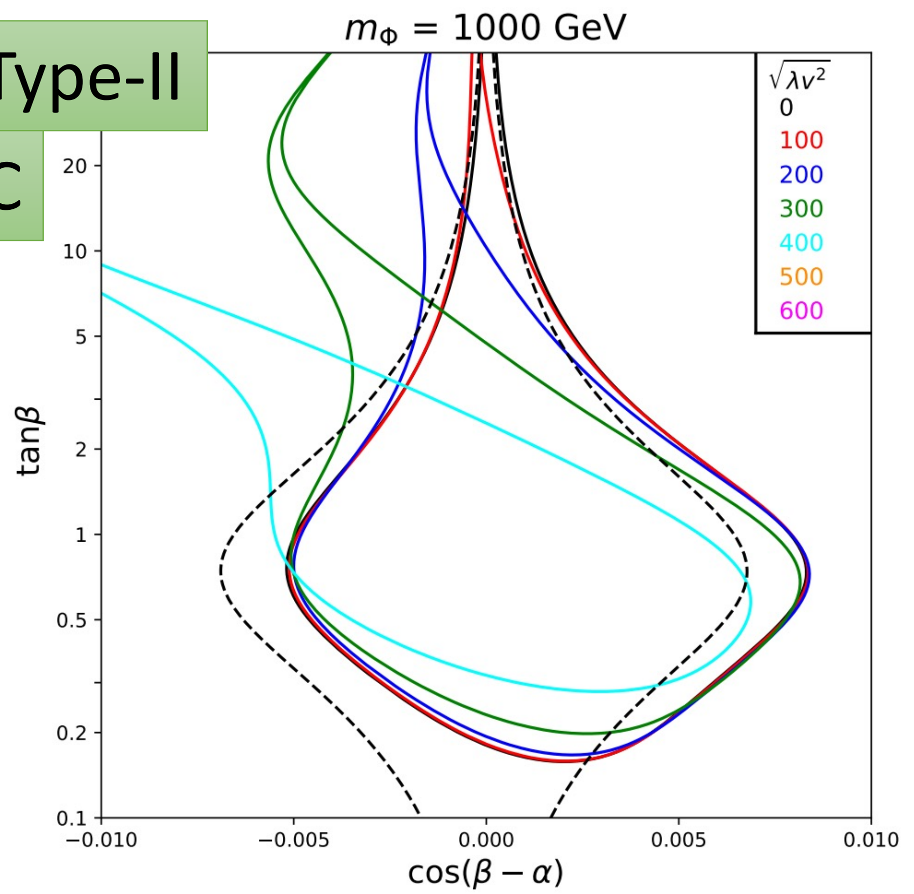
$$\frac{\cos\alpha}{\sin\beta} - 1 = -\frac{1}{2}\cos^2(\beta-\alpha) + \frac{\cos(\beta-\alpha)}{\tan\beta}$$

Exclusion : Loop Level

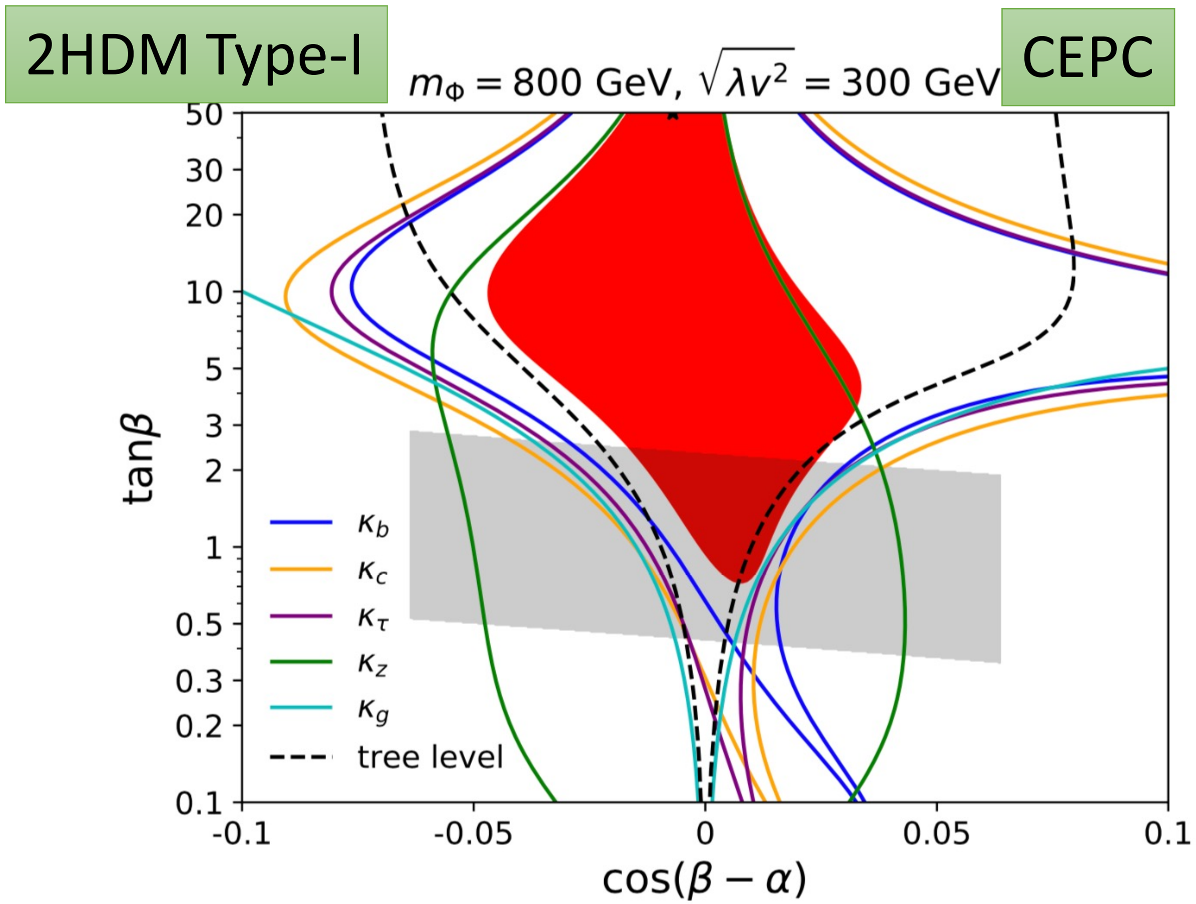
2HDM Type-II

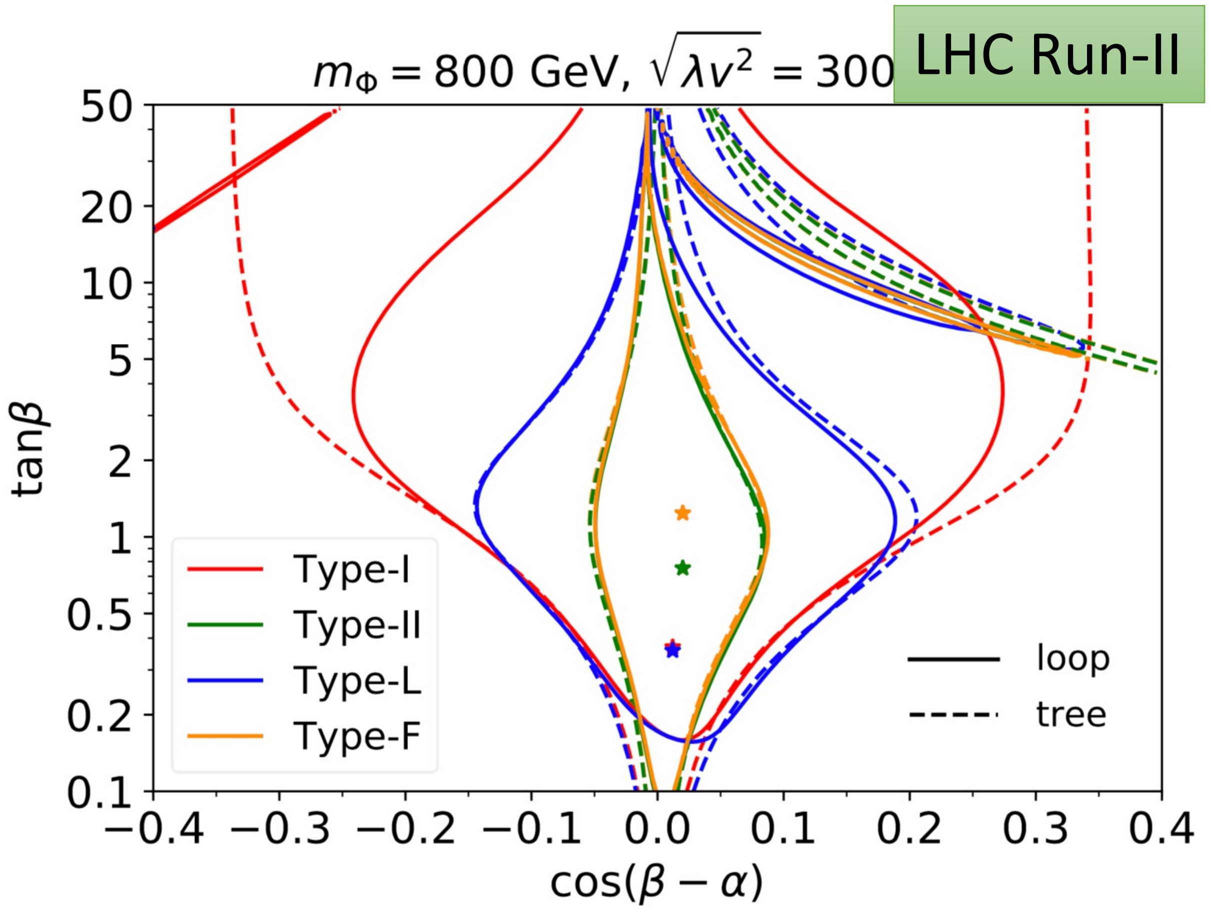
CEPC





Exclusion : Loop Level





Study Results: discovery potential

- method

$$\chi^2 = \sum_i \frac{(\mu_i^{\text{hyp}} - \mu_i^{\text{obs}})^2}{\sigma_{\mu_i}^2}$$

null hypothesis H0 : SM

To claim the discovery of BSM at
5σ significance : p=5.7*10^(-7)

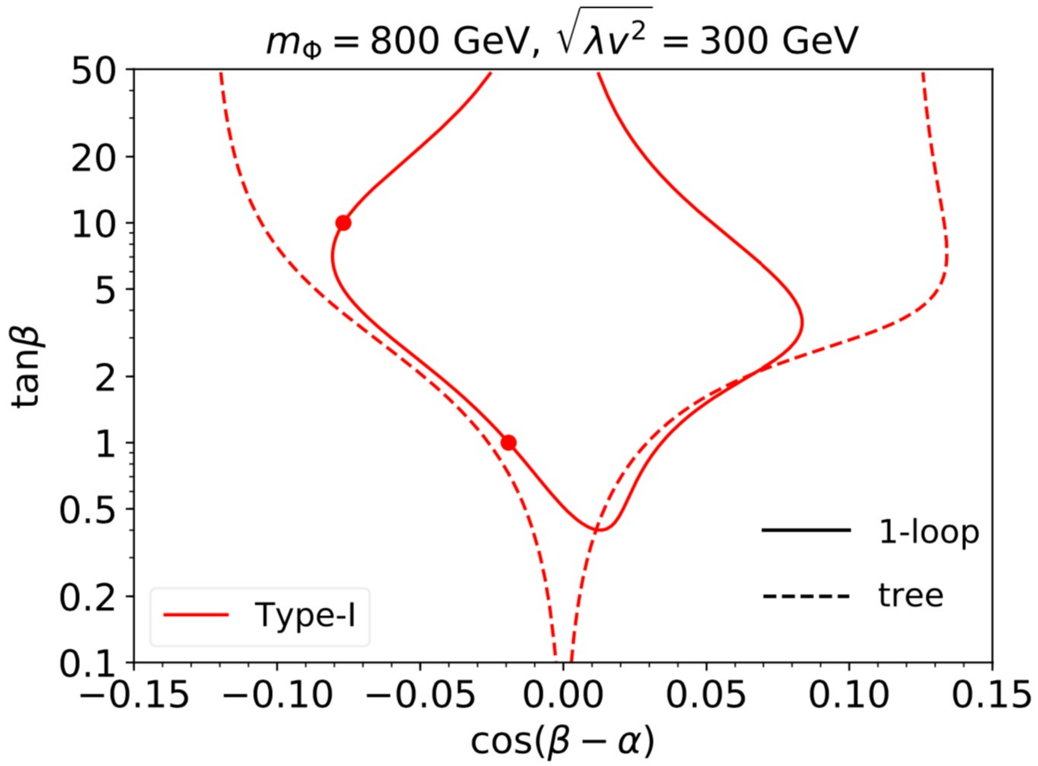
$$\chi^{\text{SM}} > 48.2$$

$$\mu^{\text{hyp}} = \mu^{\text{SM}} = 1$$

degrees of freedom : signal strength modifiers (SSM),
or μ parameter : 10 for CEPC

Study Results: discovery potential

Choose one point of BSM as the observed, to see if SM is rejected.

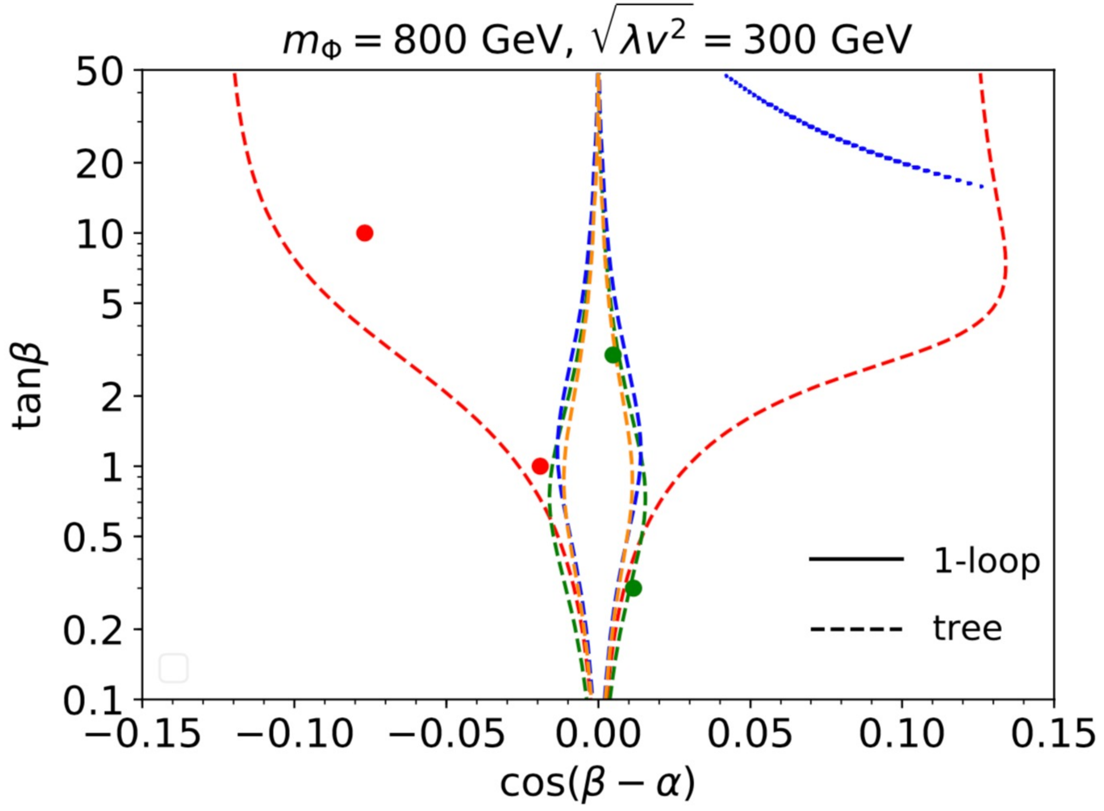


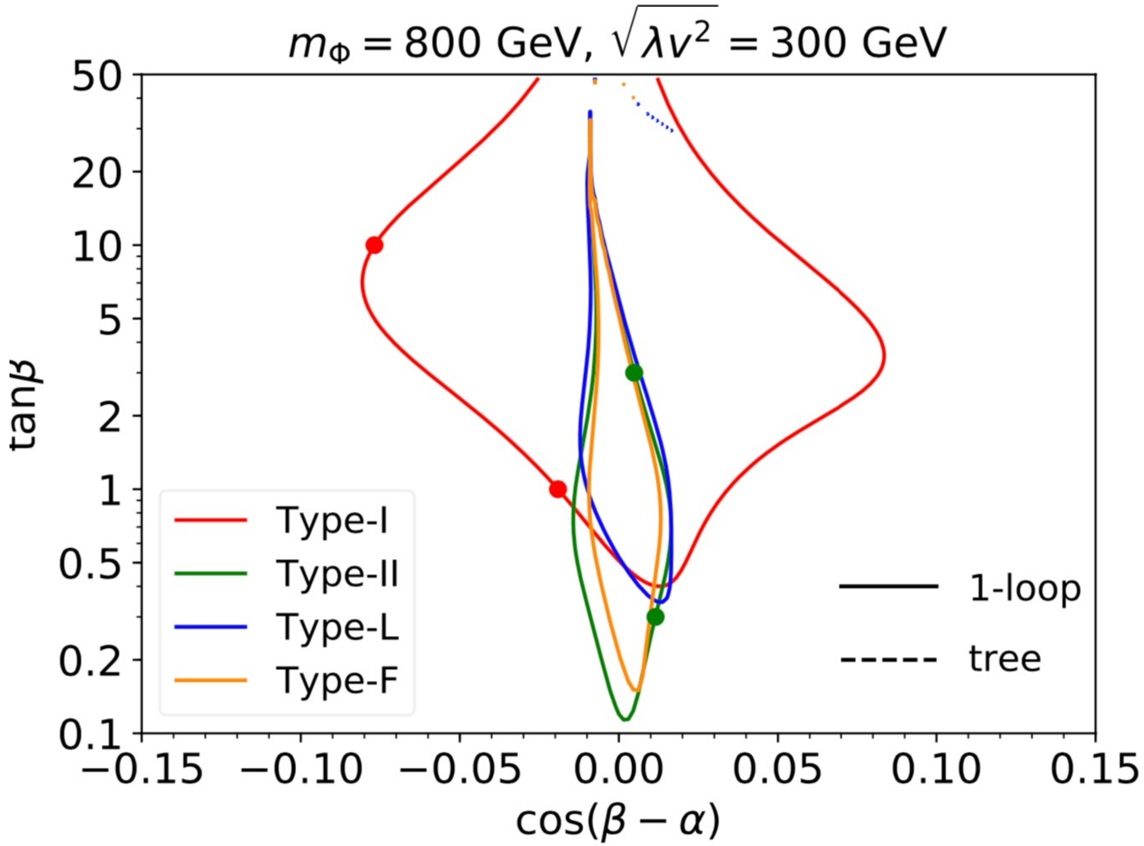
If the future observable is same to Type-I,
The center region can not claim a discovery
The two sides region can claim

$$\cos(\beta - \alpha) \lesssim -0.1$$

$$\cos(\beta - \alpha) \gtrsim 0.08$$

Study Results: discovery potential





Type-II, L, F: $|\cos(\beta - \alpha)| \gtrsim 0.02$ for $\tan\beta \sim 1$

Study Results: discrimination ability

- method

performing the χ^2 statistic

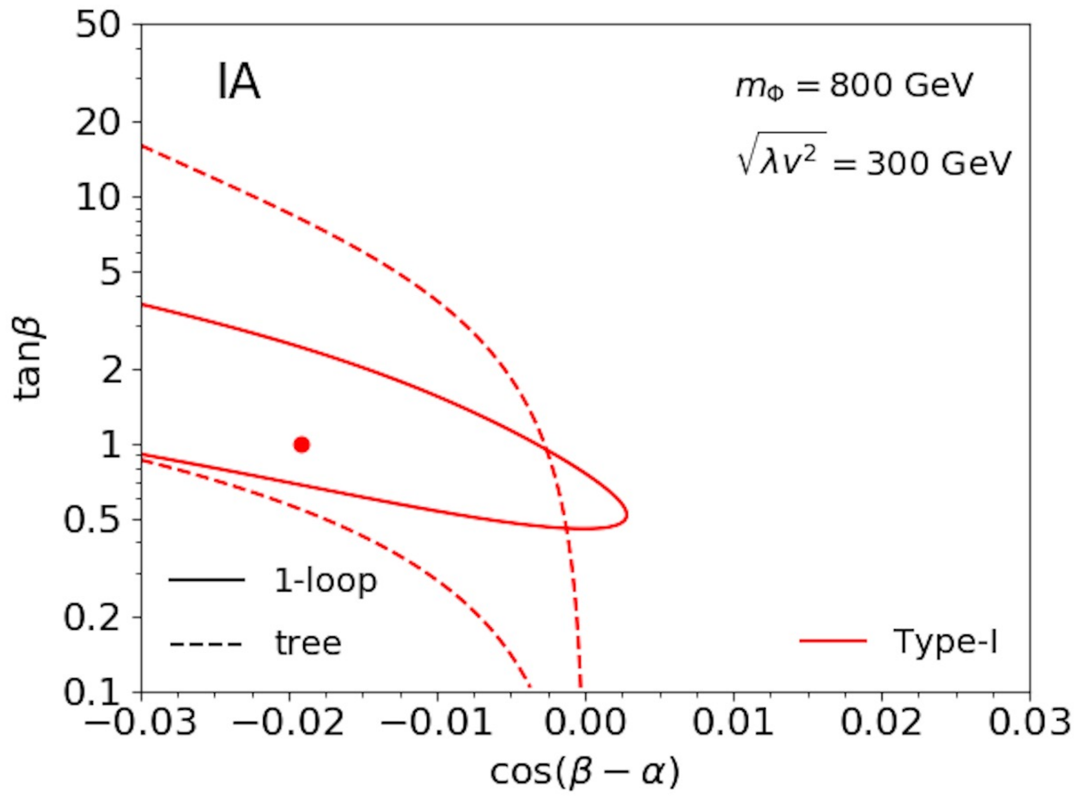
d.o.f. = # SSMs (μ)   hypothesized model (Null model): One physical point

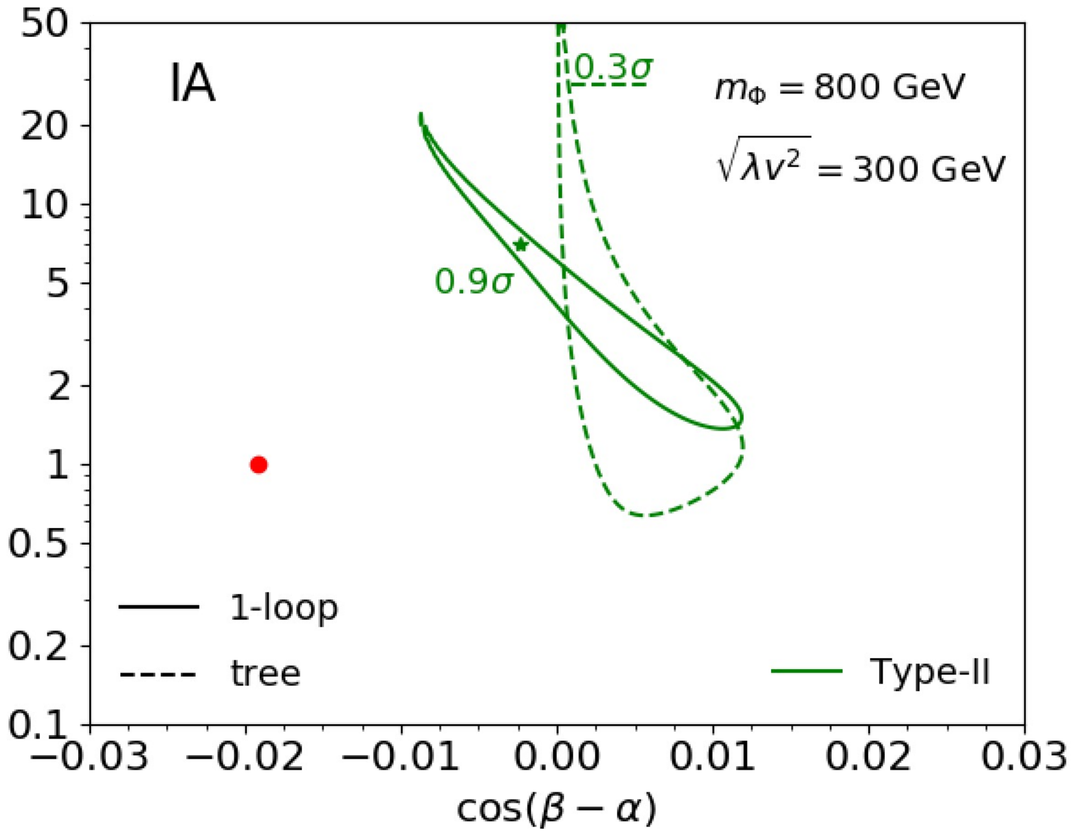
d.o.f.	1	2	3	4	5	6	7	8	9	10
$\chi^2(p=0.05)$	3.84	5.99	7.81	9.49	11.1	12.6	14.1	15.5	16.9	18.3

BMs:

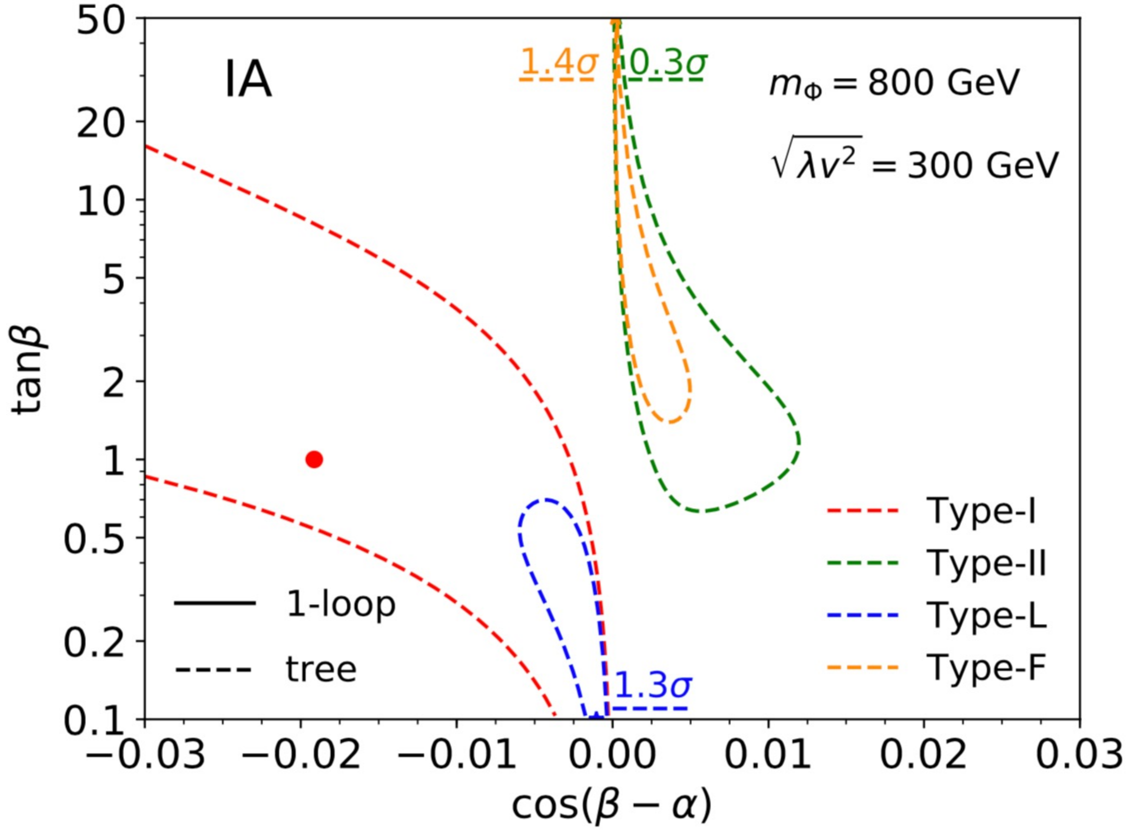
$(\cos(\beta-\alpha), \tan\beta)$	Small $\tan\beta$	Large $\tan\beta$
Type-I	**IA:** $(-0.019, 1.0)$	**IB:** $(-0.077, 10)$
Type-II	**IIA:** $(0.012, 0.3)$	**IIB:** $(0.005, 3.0)$

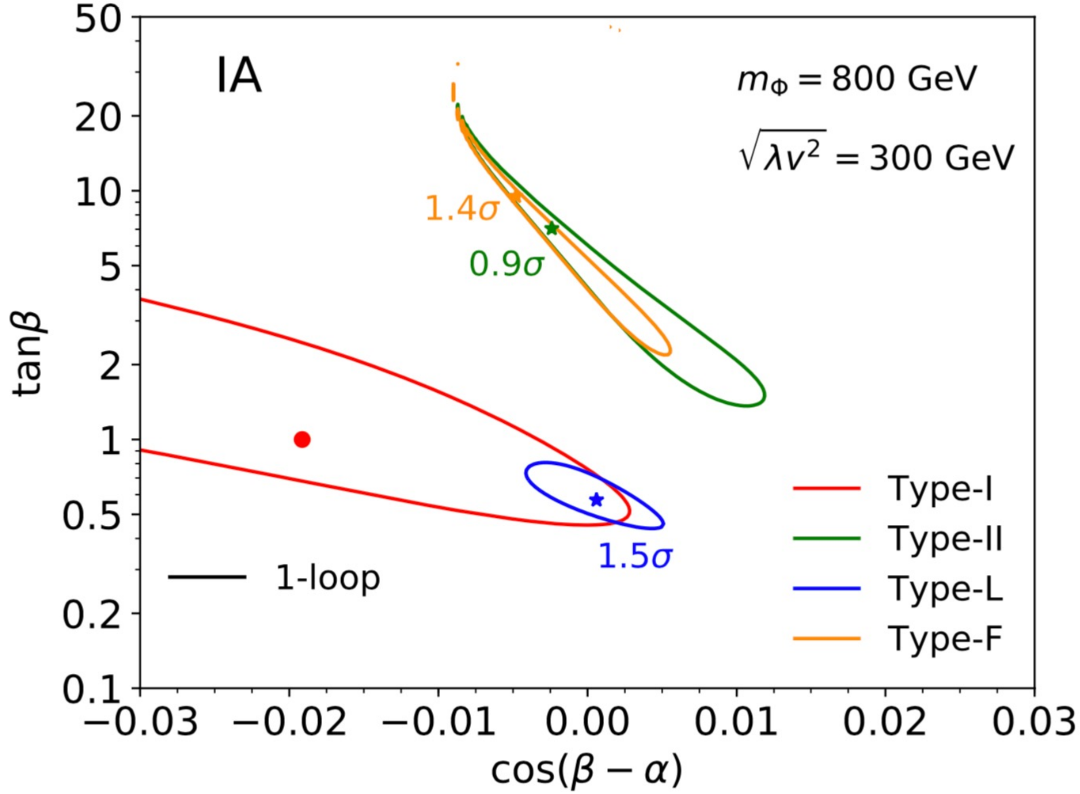
Study Results: discrimination ability





Study Results: discrimination ability





Study Results: compatibility test

- compatibility test method

Test Type-I with Type-II:

observable : one point of type-II (accepted model),

test type-I by performing the χ^2 statistic

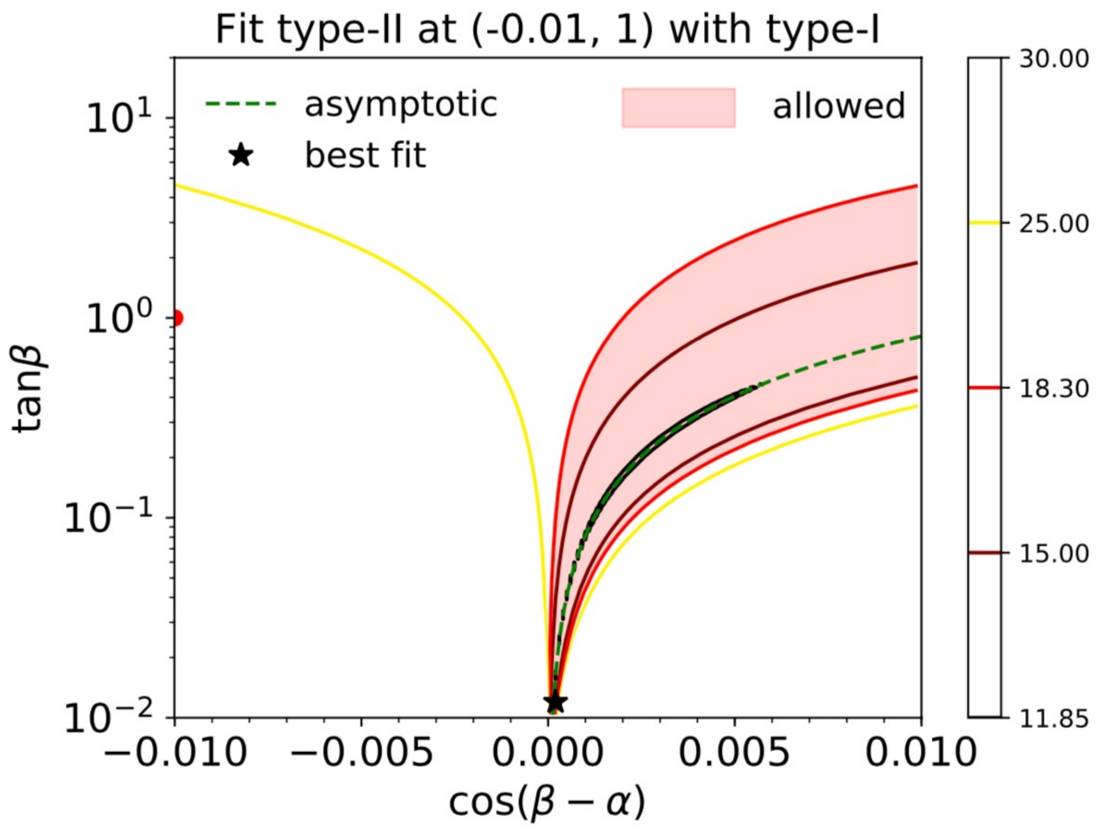
d.o.f. = # SSMs (μ)

hypothesized model (Null model): Type-II, instead of SM

d.o.f.	1	2	3	4	5	6	7	8	9	10
$\chi^2(p=0.05)$	3.84	5.99	7.81	9.49	11.1	12.6	14.1	15.5	16.9	18.3

Study Results: compatibility test

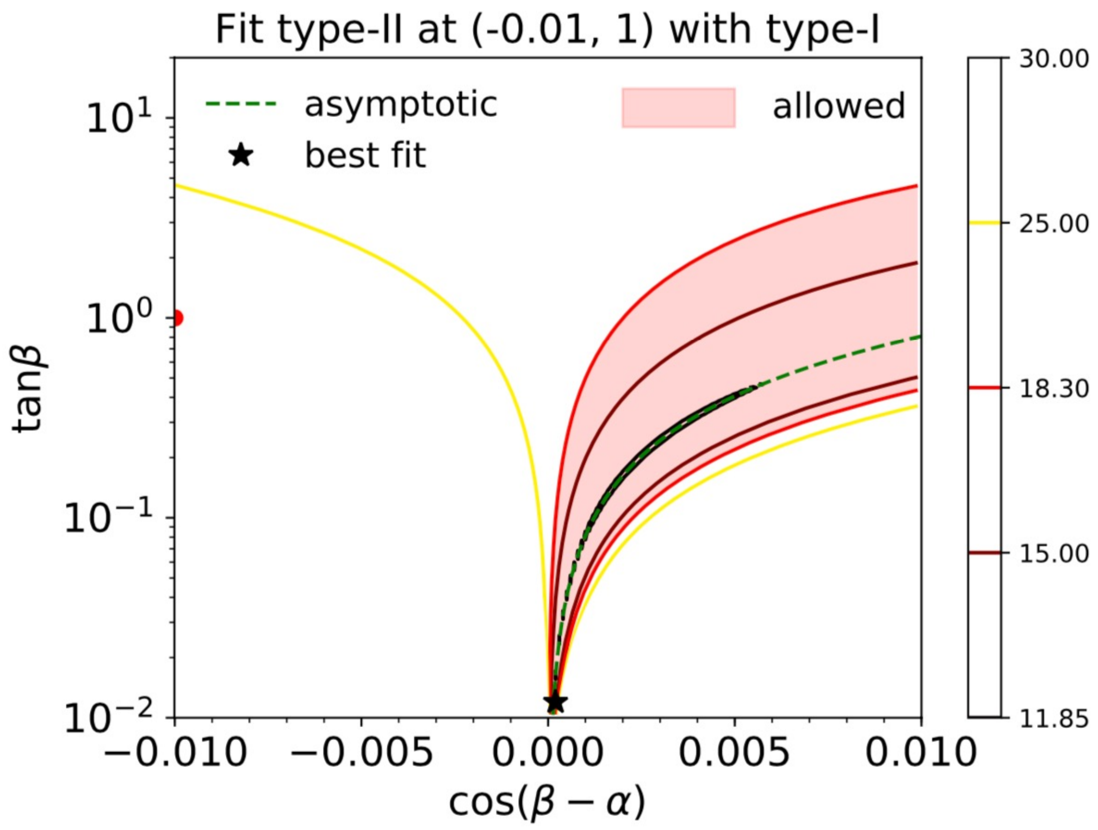
- Type-II $(\cos(\beta - \alpha), \tan\beta) = (-0.01, 1)$

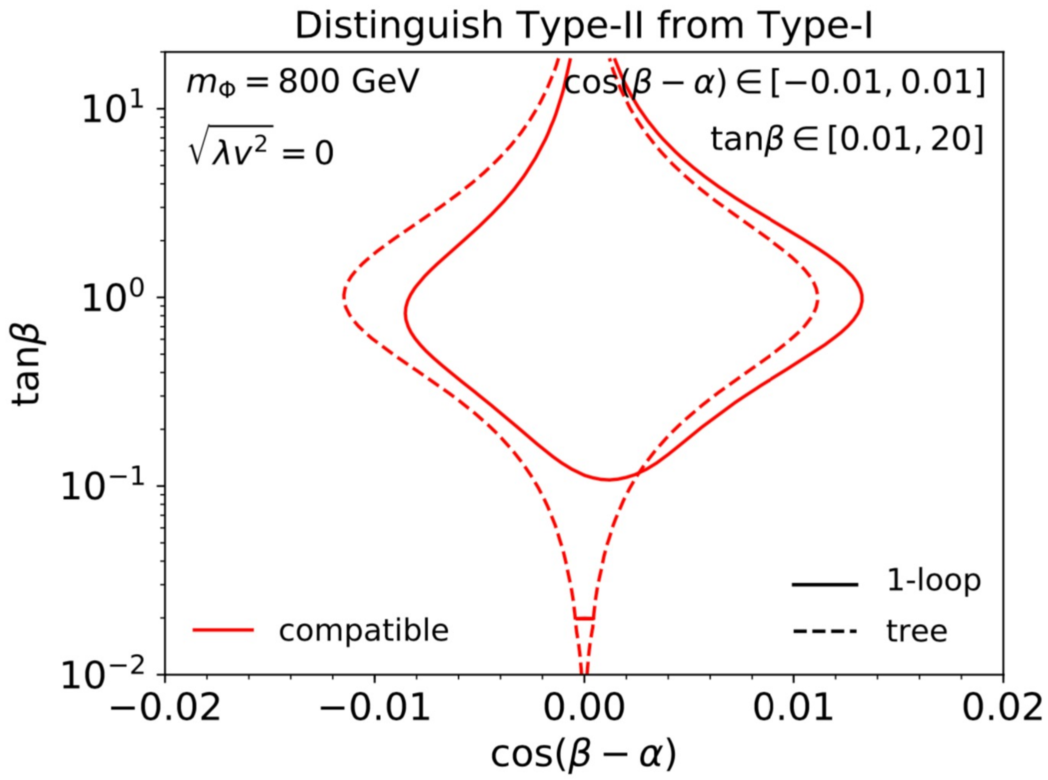


If there is points of Type-I is allowed, then BM of Type-II is compatible under CEPC precision

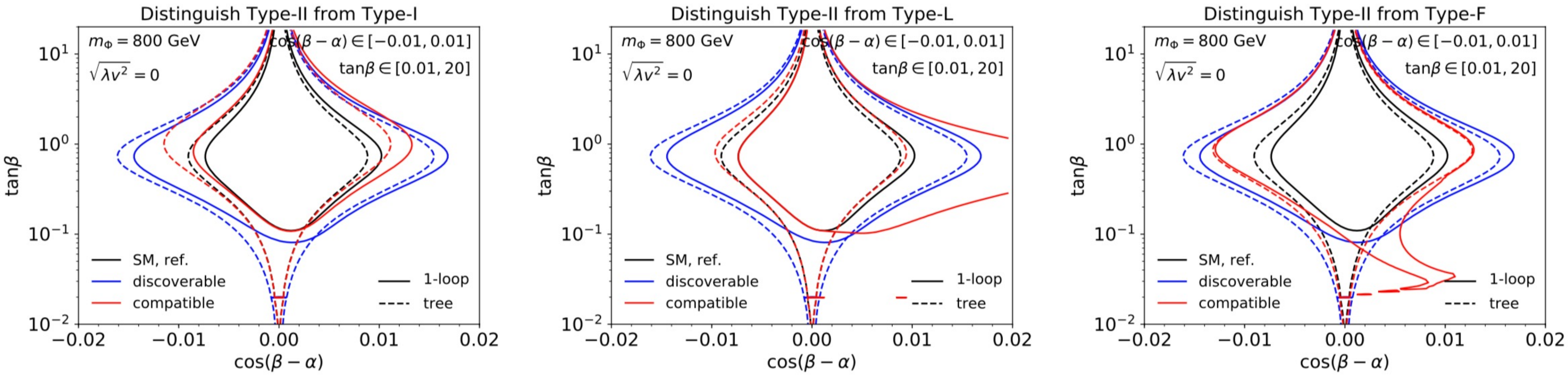
Study Results: compatibility test

- Type-II $(\cos(\beta-\alpha), \tan\beta) = (-0.01, 1)$





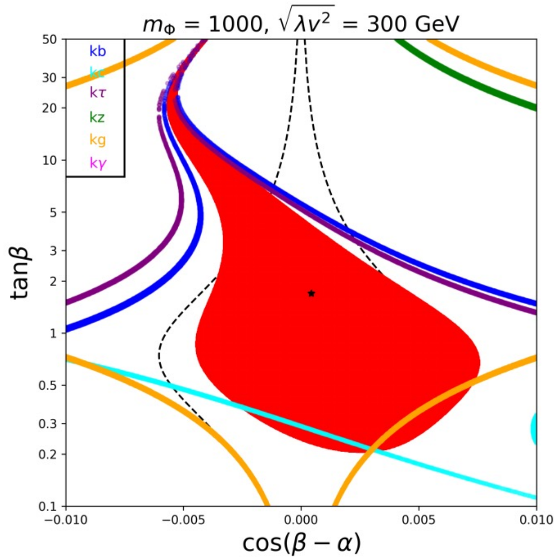
Study Results: compatibility test

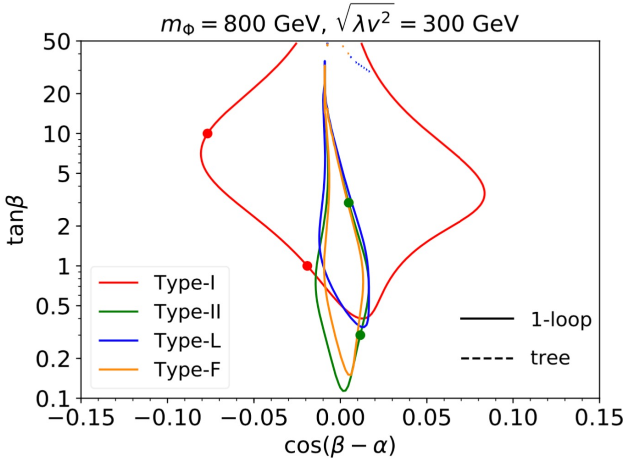


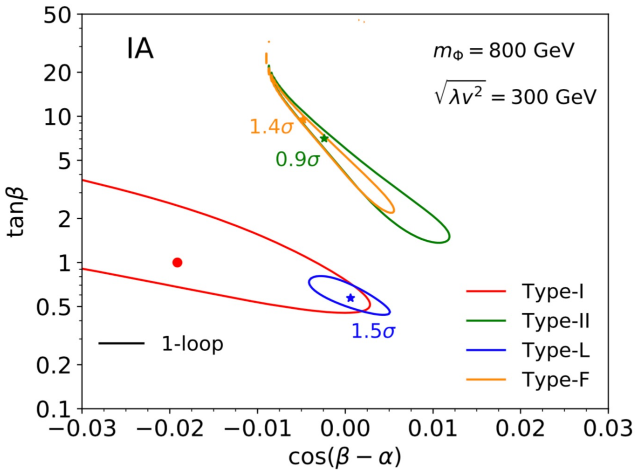
We can do the similar research between any two models

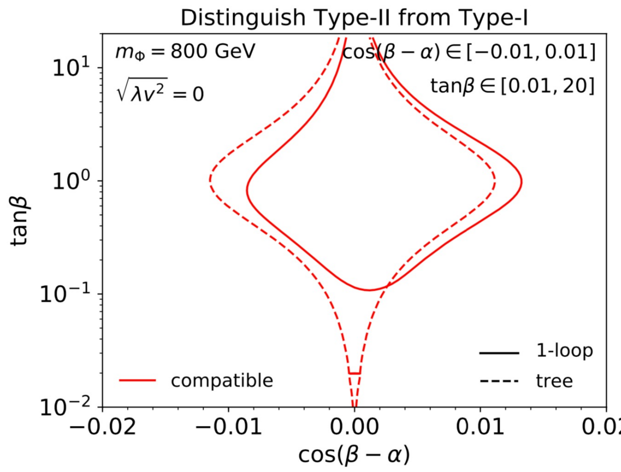
Summary: Higgs precision measurements

- Exclusion :Maximal likelihood vs. absolute χ^2 study
- Discovery potential: test null model SM
- Discrimination ability: a deviation observed
- Compatibility test: different BSMs





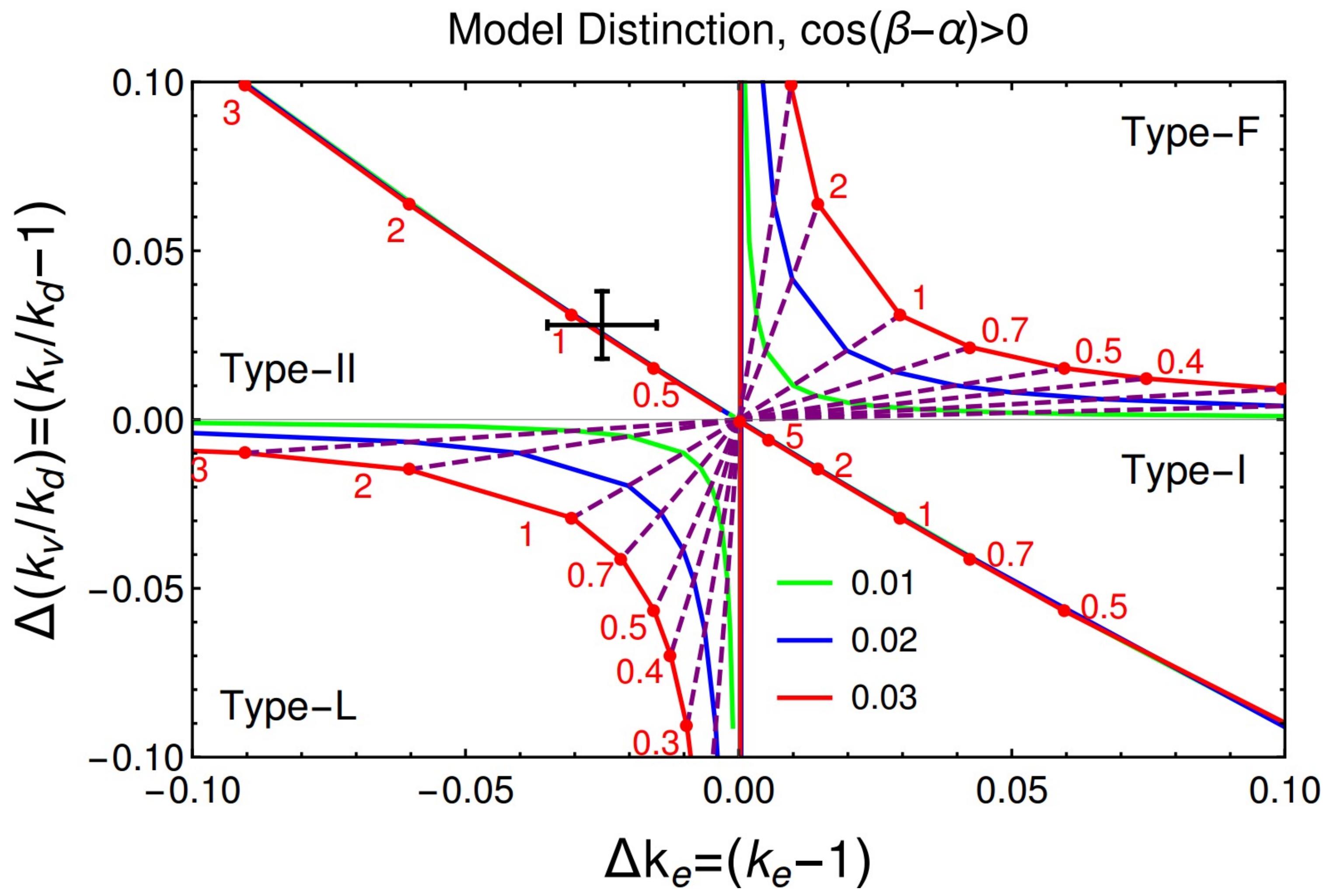




Thanks !

Backup

2HDM: Tree Level Model Distinction

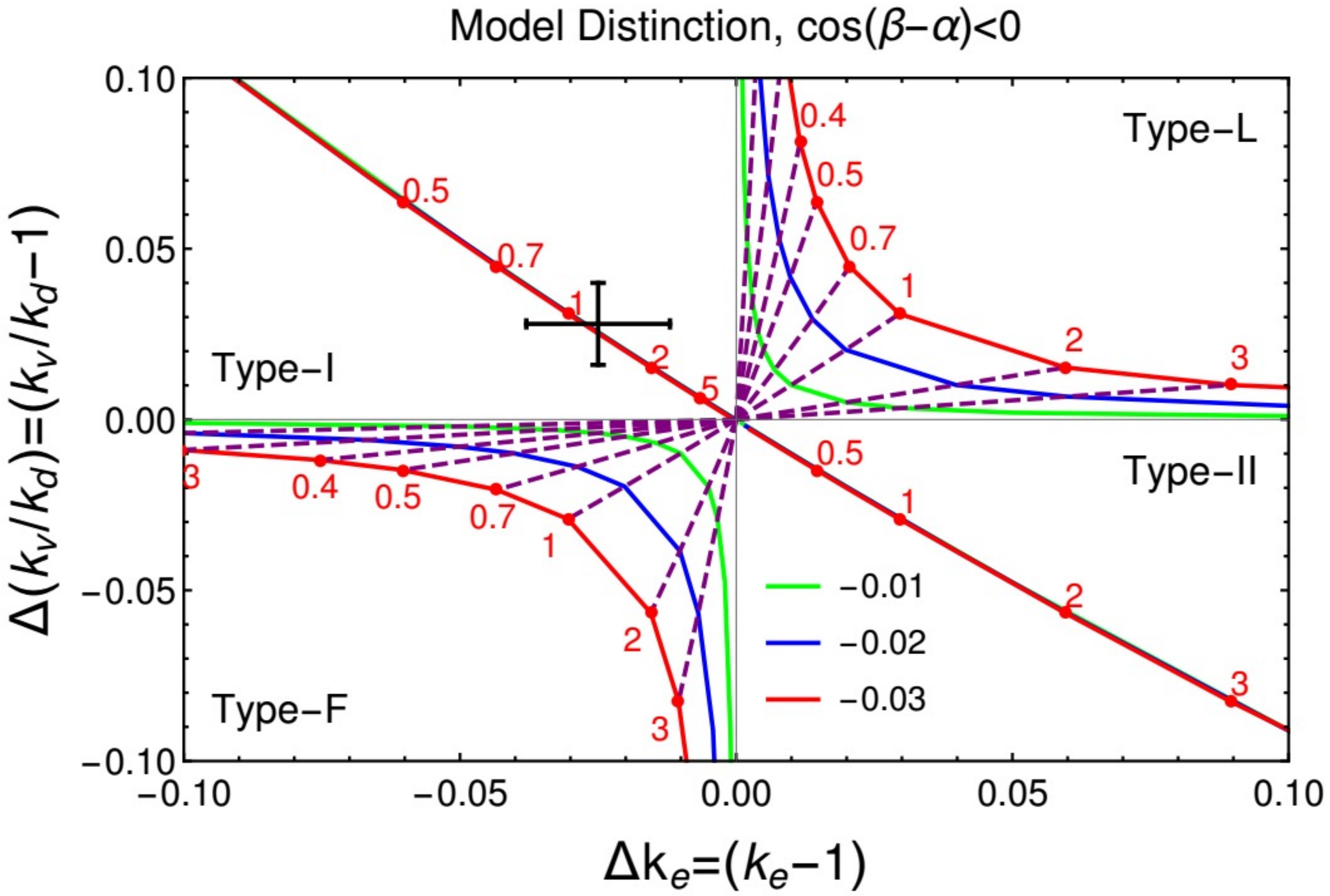


Varying $\tan\beta$

$\cos(\beta-\alpha)$

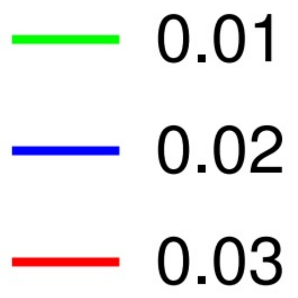
- 0.01
- 0.02
- 0.03

2HDM: Tree Level Model Distinction



Varying $\tan\beta$

$\cos(\beta - \alpha)$



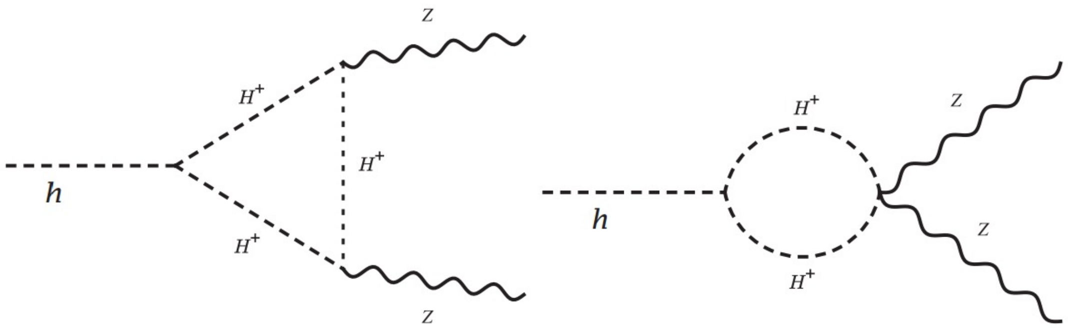
Type-I ↔ Type-II

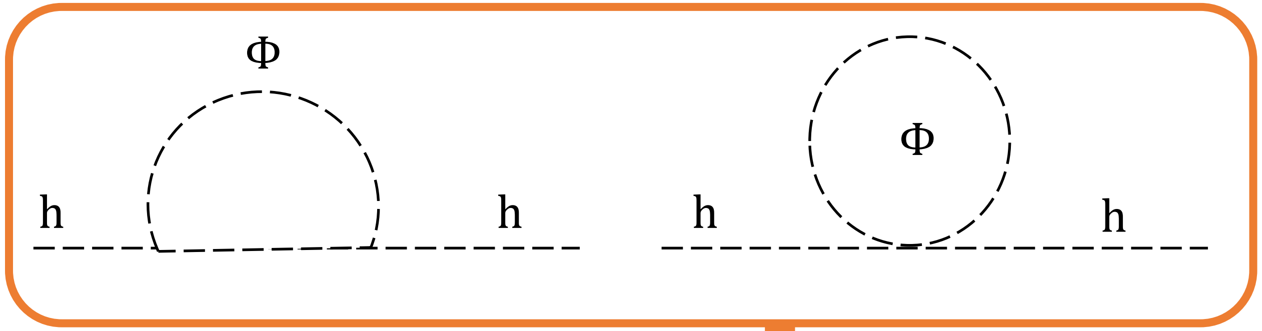
Type-L ↔ Type-F

Outline

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

2HDM: One-Loop Level





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

Main contribution

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

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

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

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

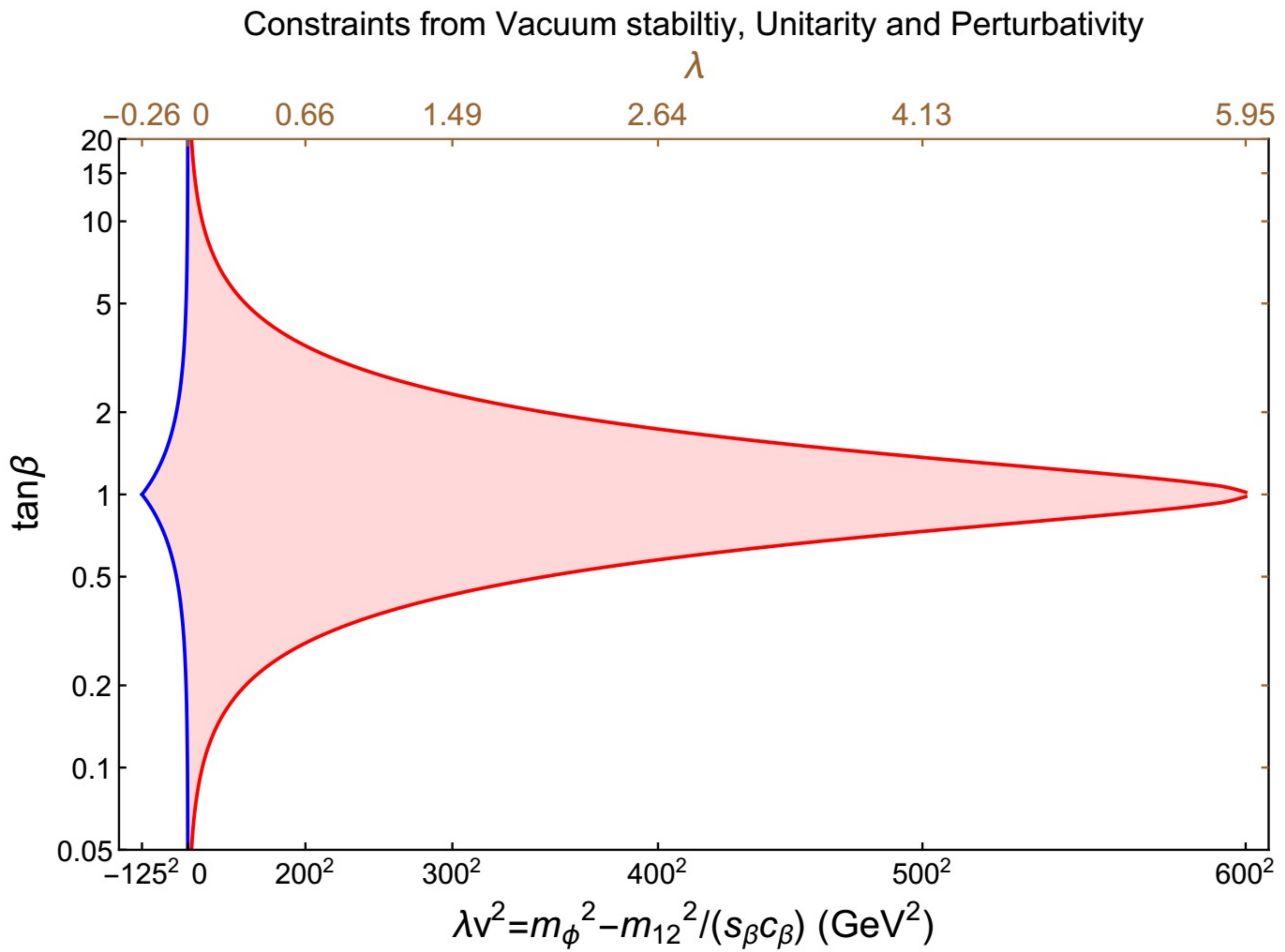
- Perturbativity $|\Lambda_i \leq 16\pi|$

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

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

2 Free parameters

2HDM: theoretical consideration



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

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

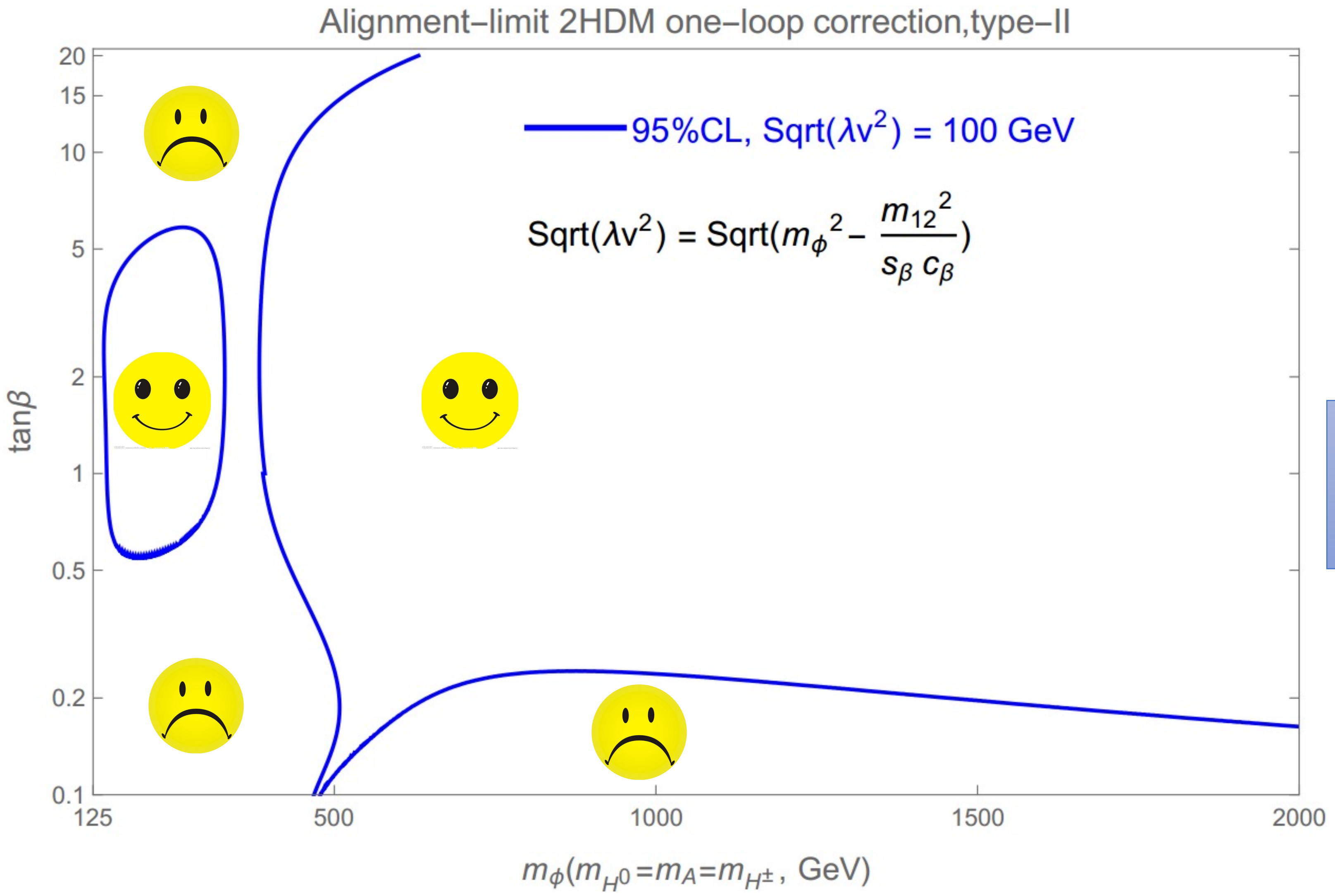
Theoretical constraints

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

$\lambda \in (-0.26, 5.95)$

$\lambda_4 = \lambda_5 = \lambda_3 - 0.258 = -\lambda$

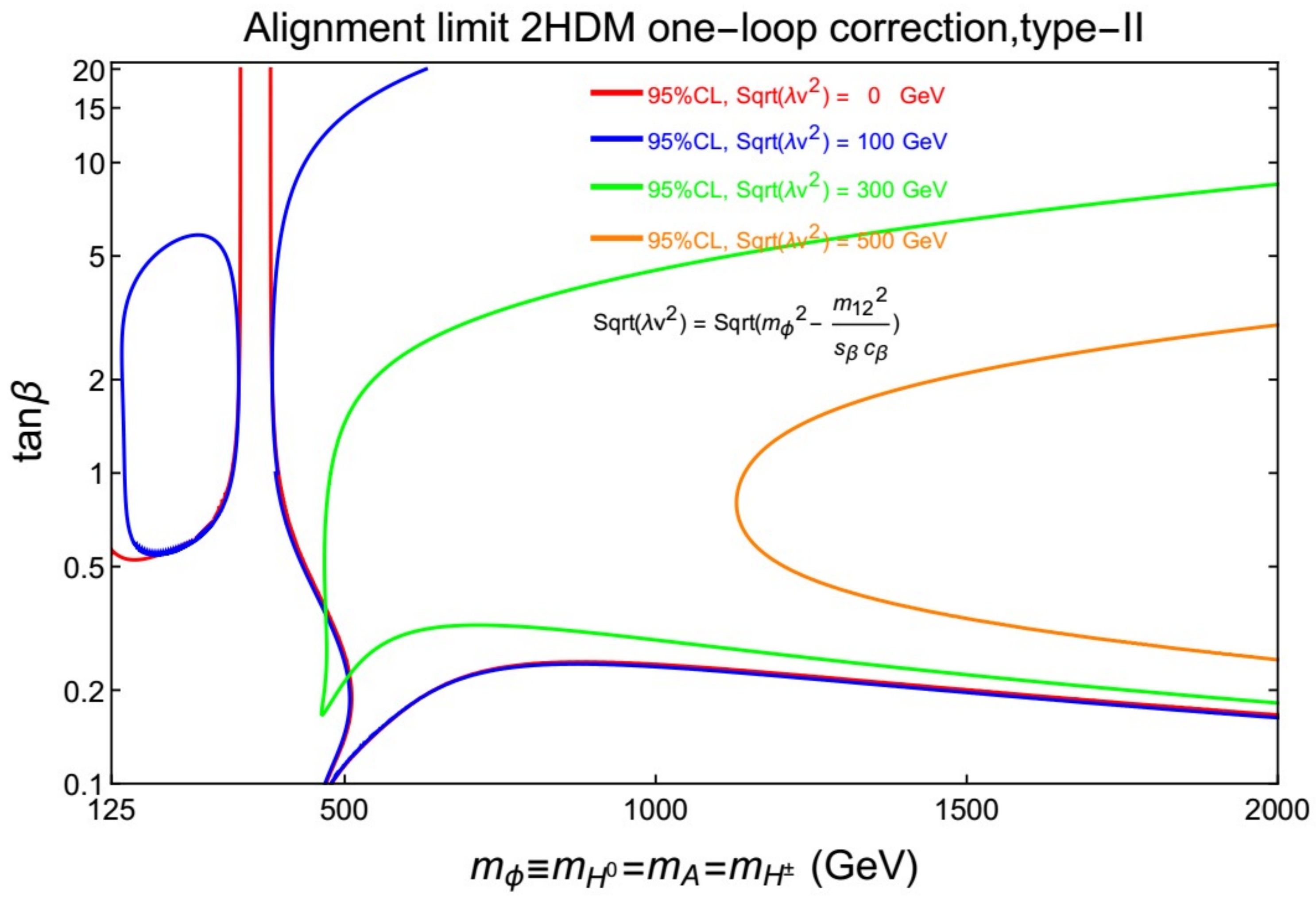
2HDM: *Loop + degenerate*



CEPC fit, Type-II

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

2HDM: $Loop + degenerate$



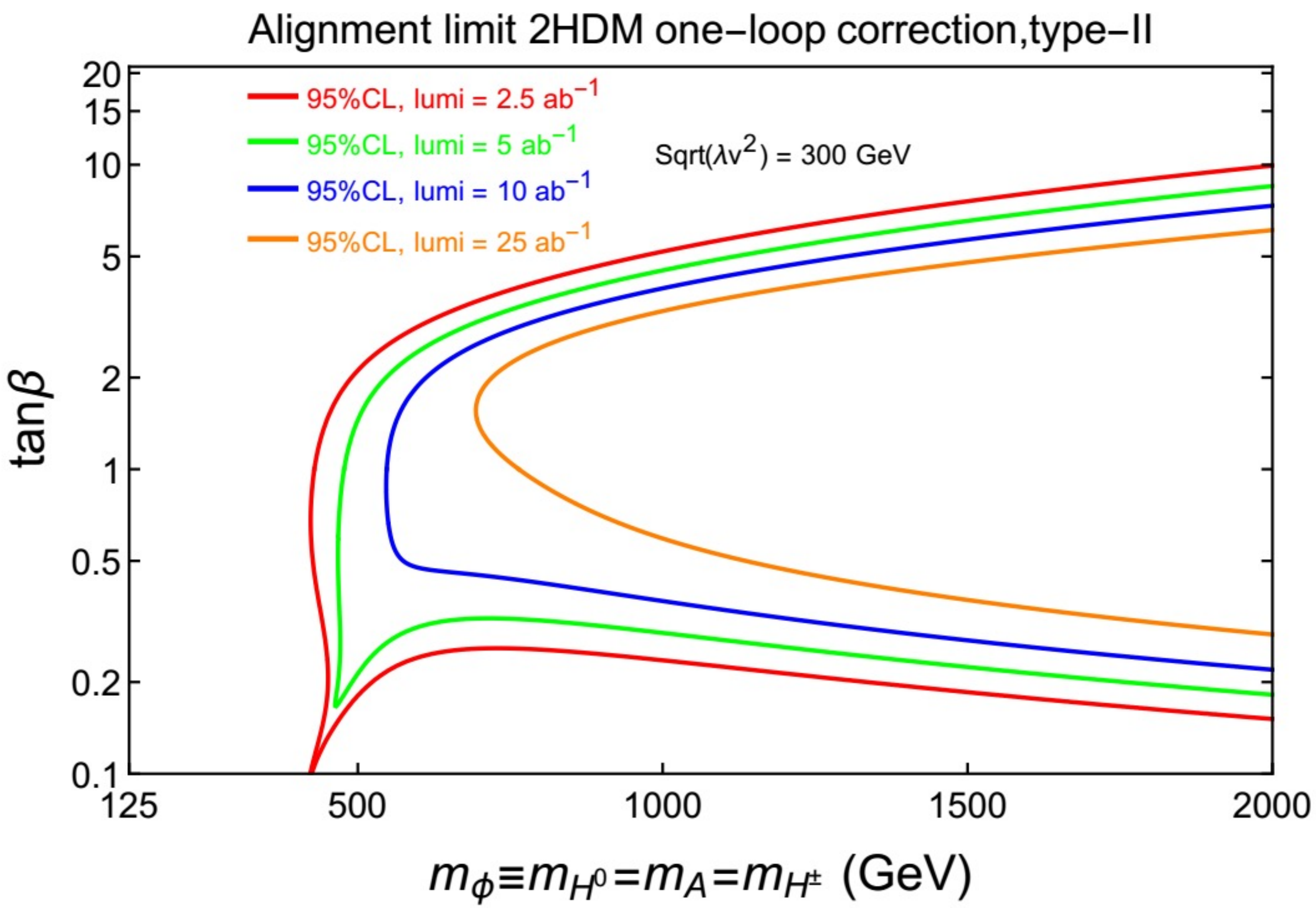
CEPC fit, Type-II

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

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

(GeV)

2HDM: $Loop + degenerate$



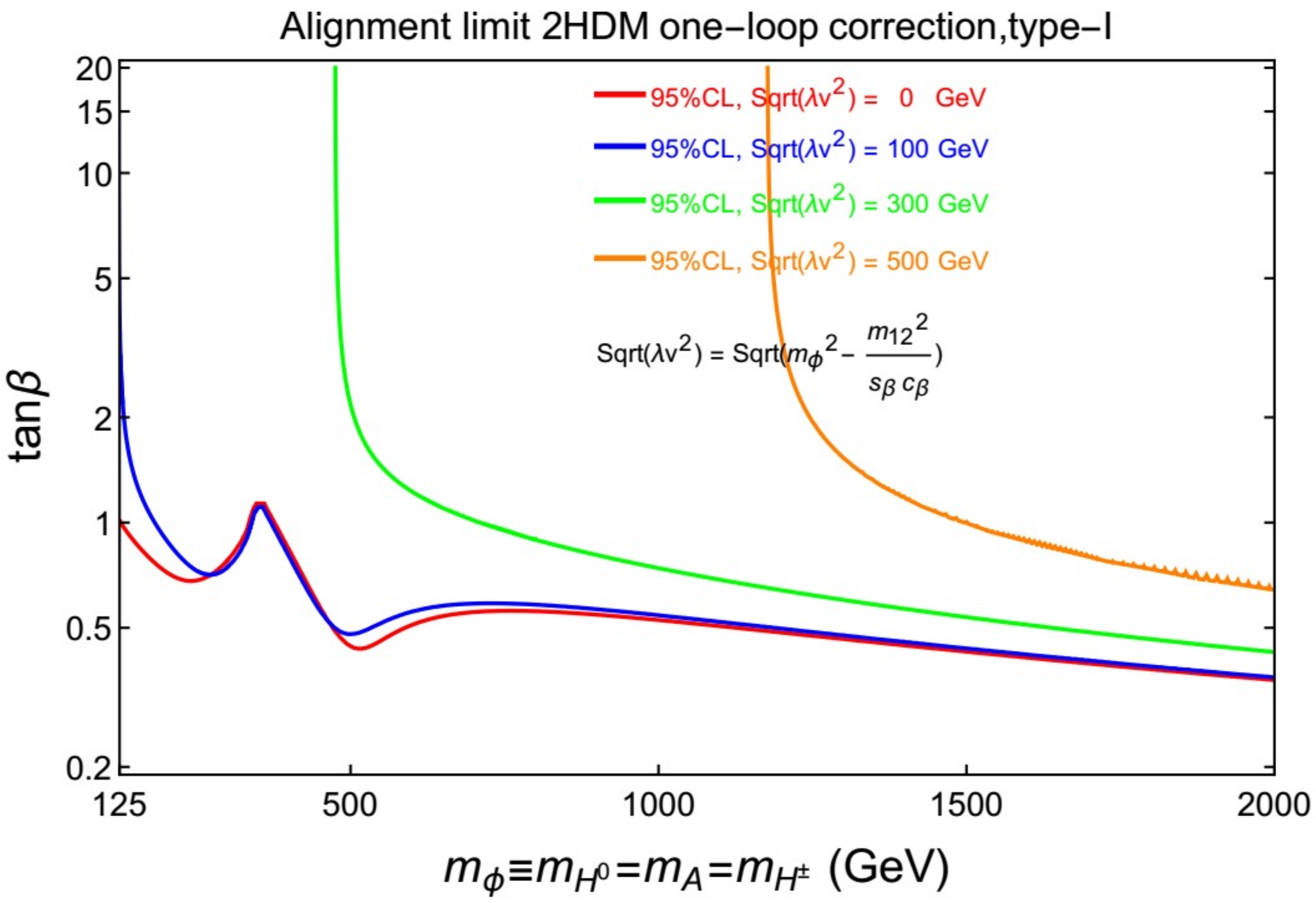
CEPC fit, Type-II

$\lambda v^2 = 300^2 \text{GeV}^2$

Lumi = 25 ab^{-1}

$\boldsymbol{m_\Phi} >$ 700 GeV

2HDM: $Loop + degenerate$



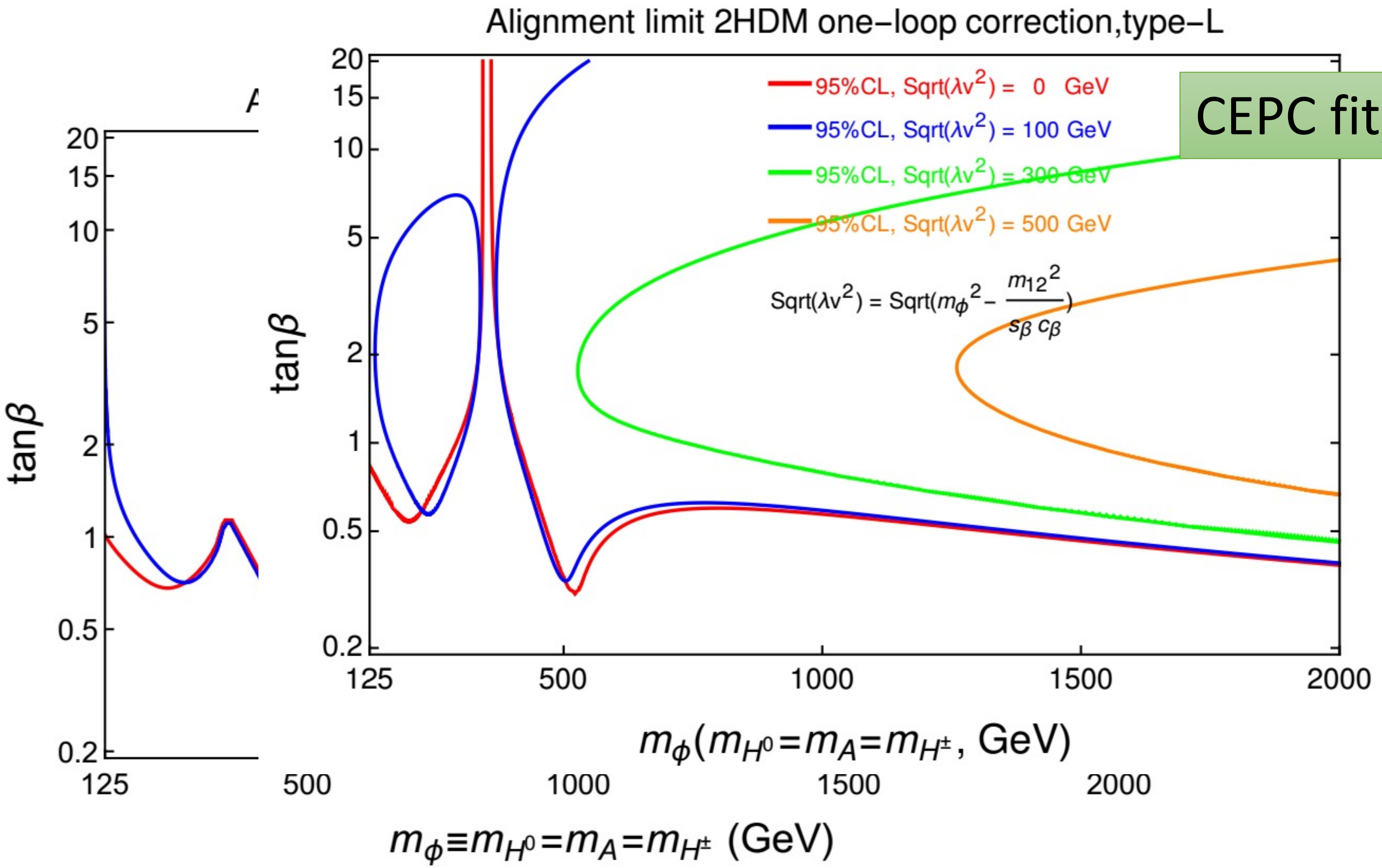
CEPC fit, Type-I

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

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

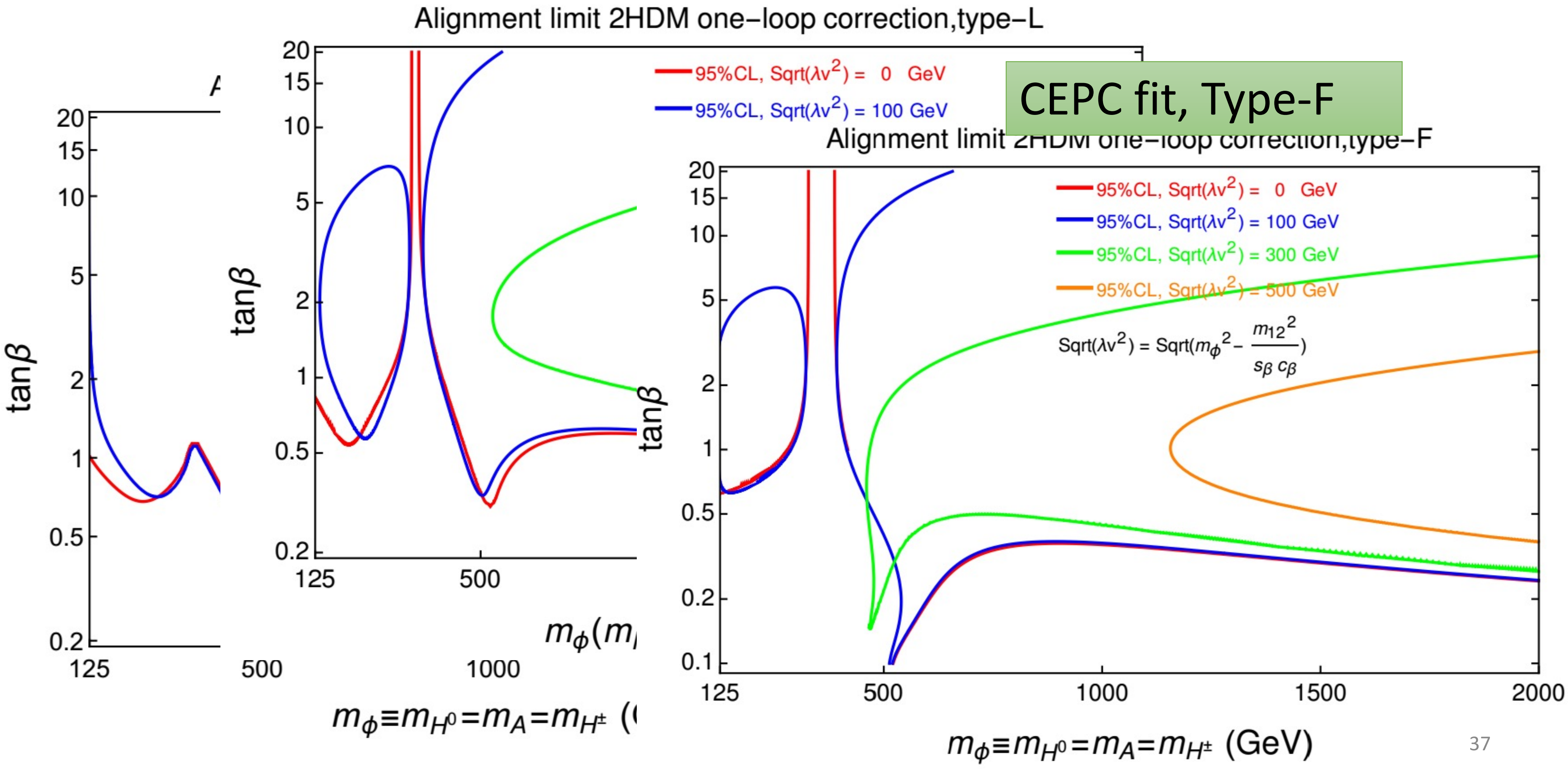
(GeV)

2HDM: $Loop\ +\ degenerate$



CEPC fit, Type-L

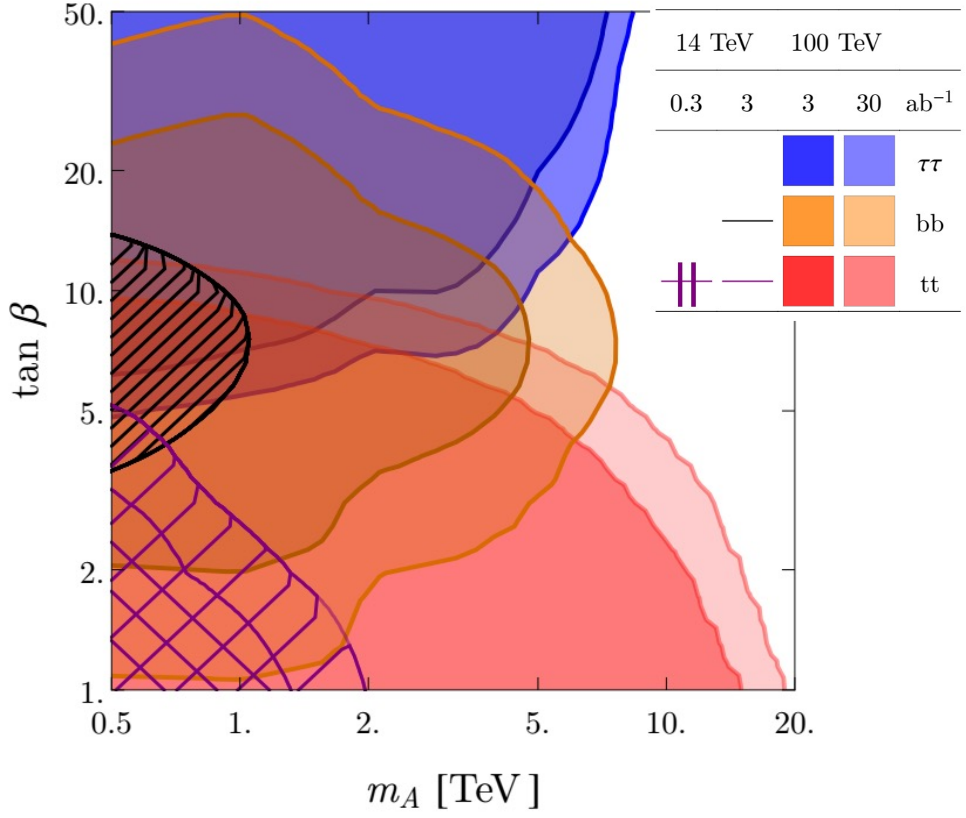
2HDM: *Loop + degenerate*



Higgs direct search at LHC

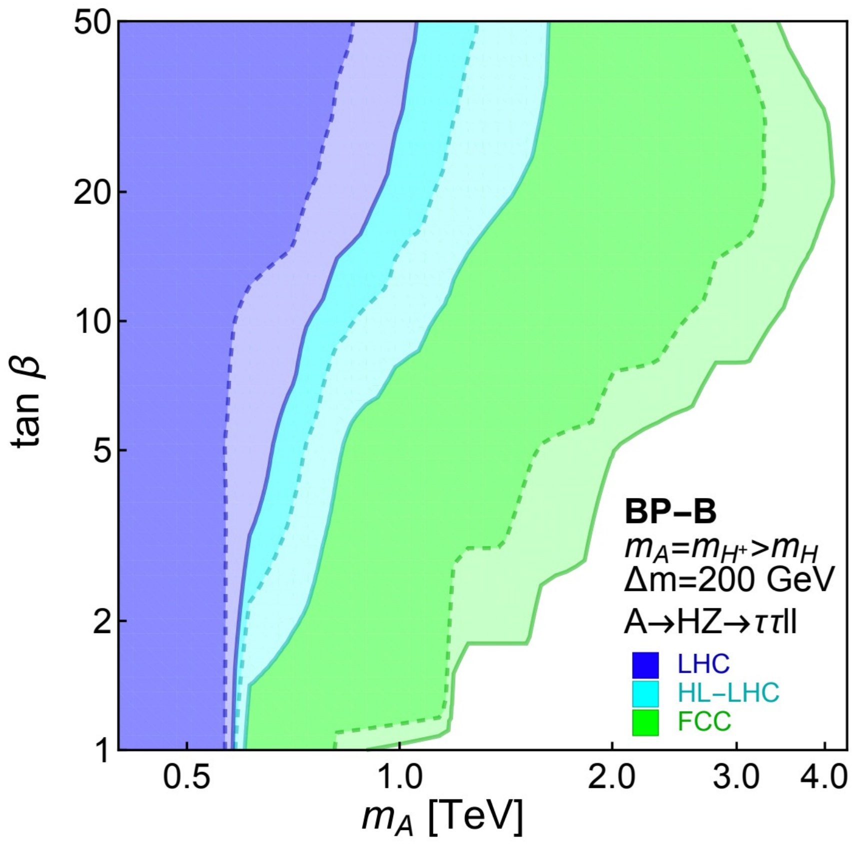
Type-II

Conventional Search



Craig et. al., 1605.08744

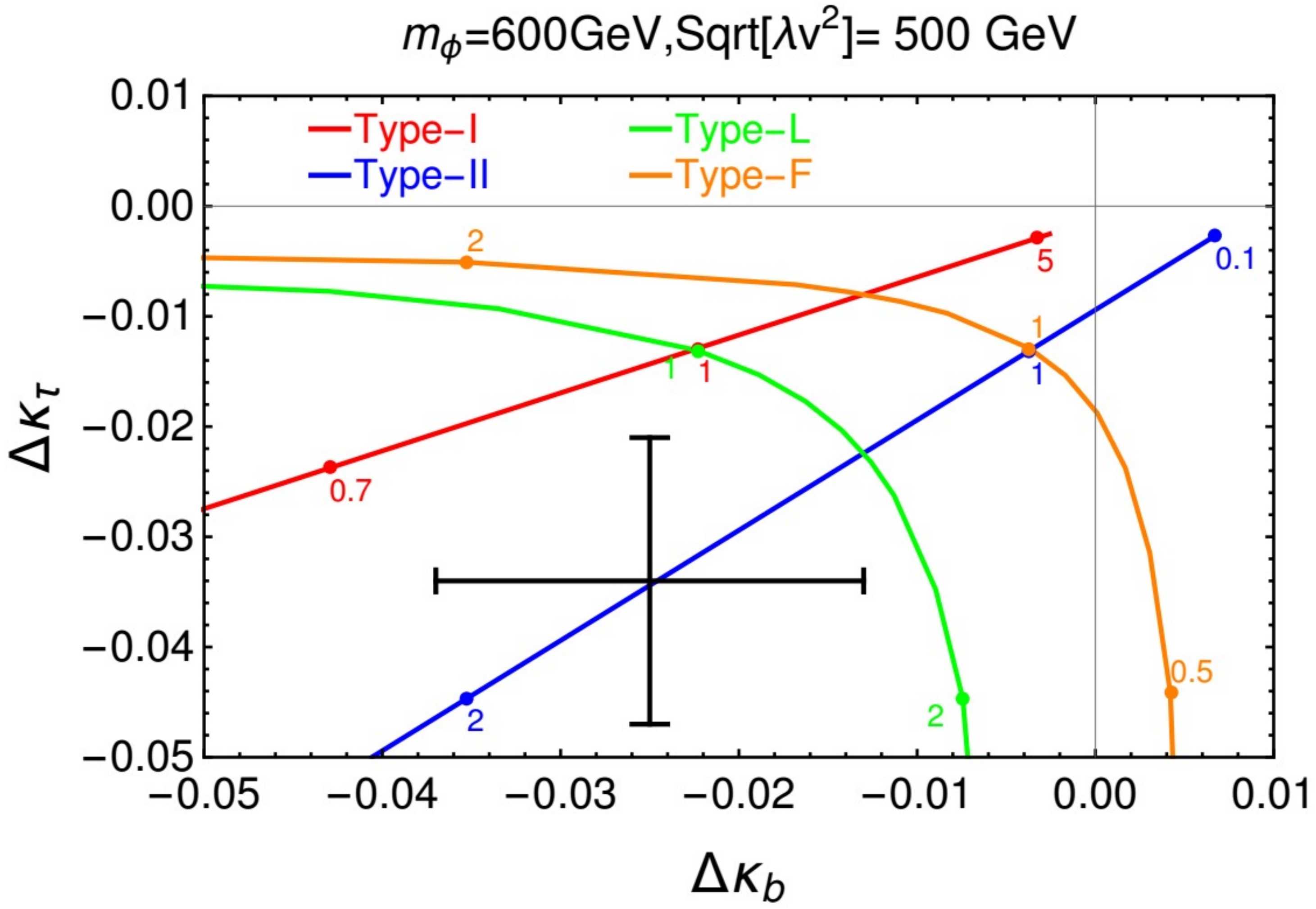
Exotic: A -> HZ



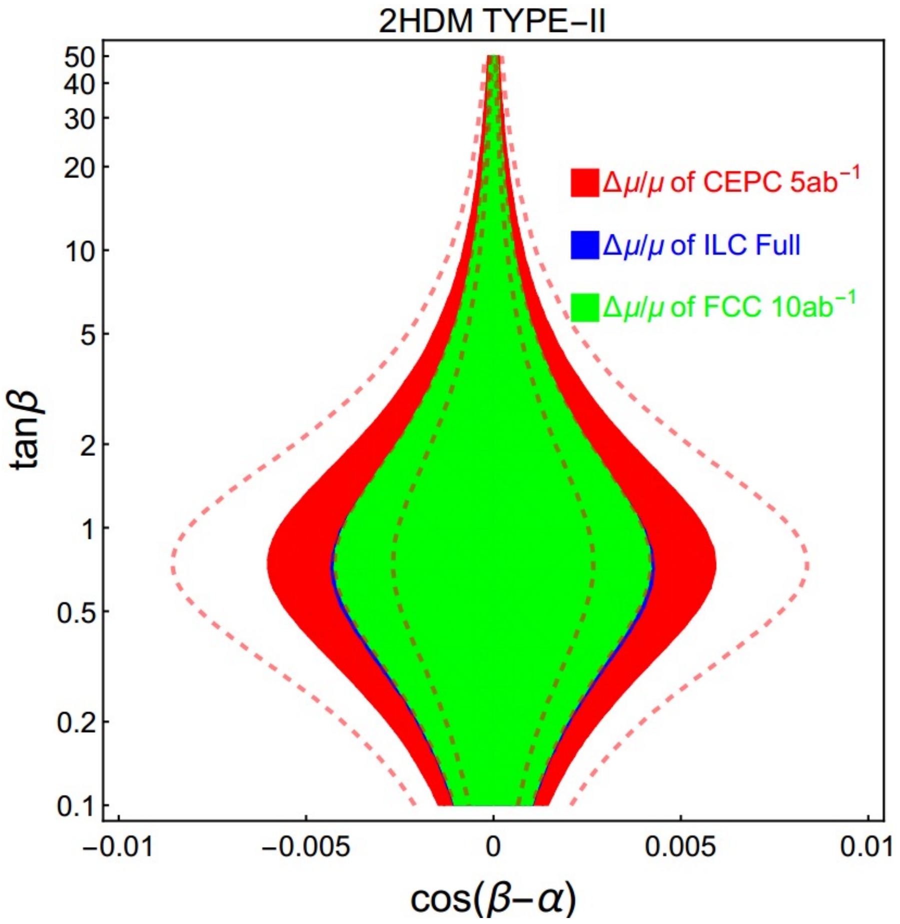
S. Su et. al., 1812.01633

2HDM: $Loop\ +\ degenerate$

Varying $\tan\beta$



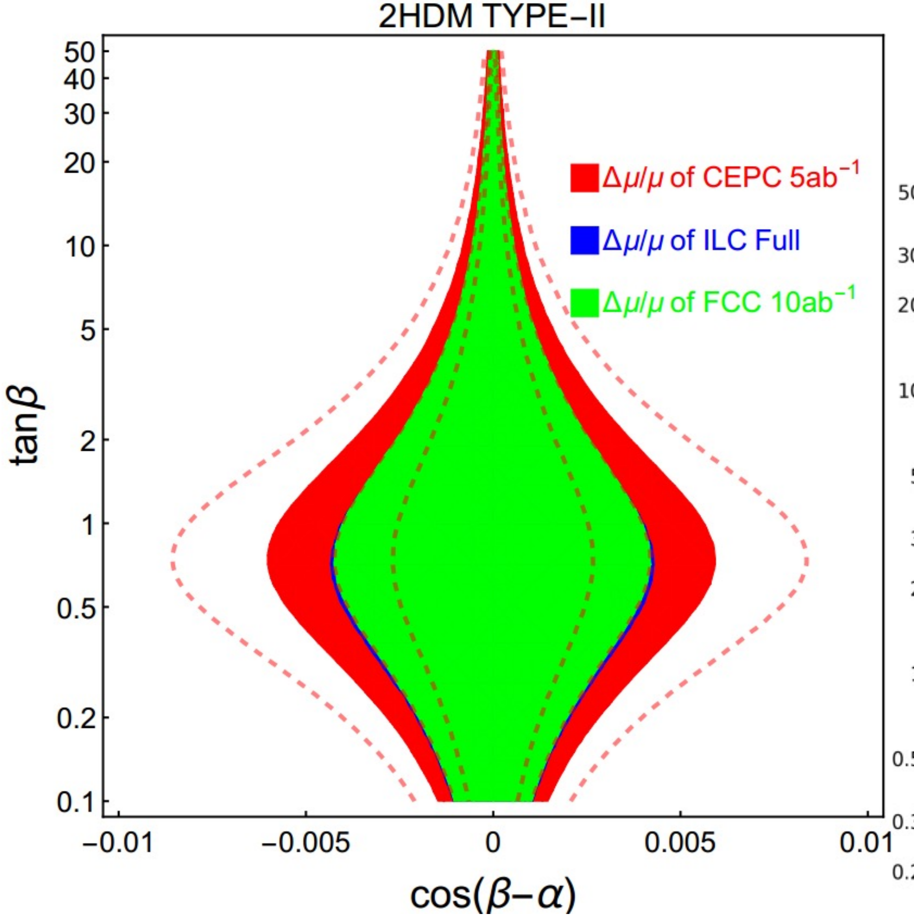
2HDM: $Tree + Loop\ +\ degenerate$



Tree-level

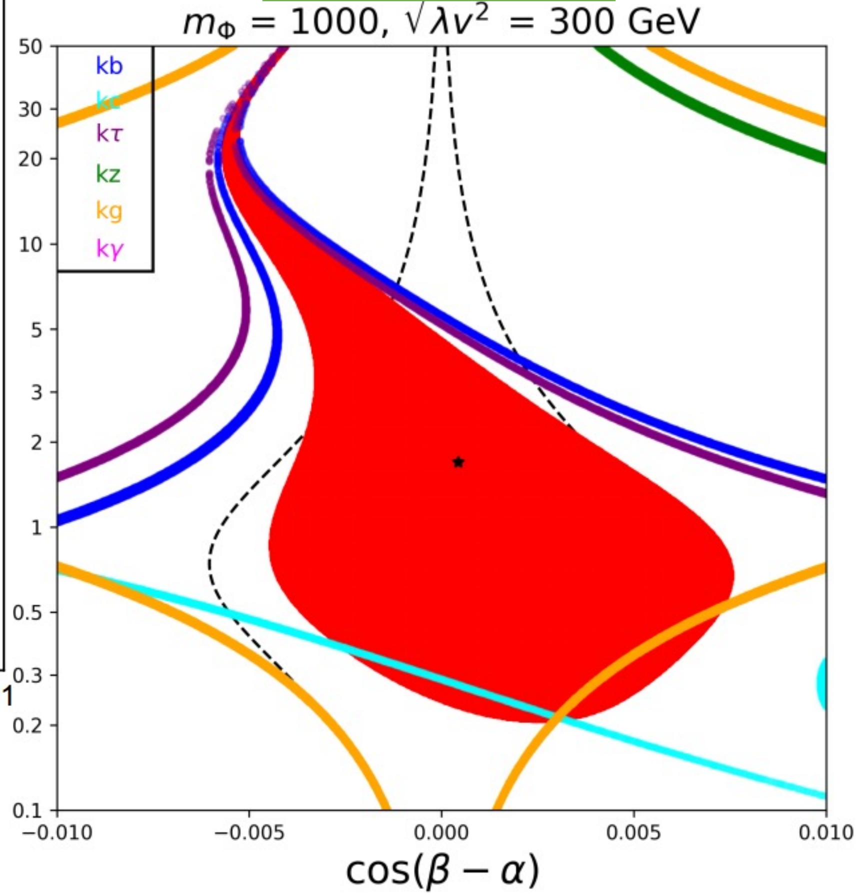
$$\cos(\beta - \alpha) \neq 0,$$
$$m_\Phi \equiv m_H = m_A = m_{H^\pm}$$

2HDM: $Tree + Loop + degenerate$

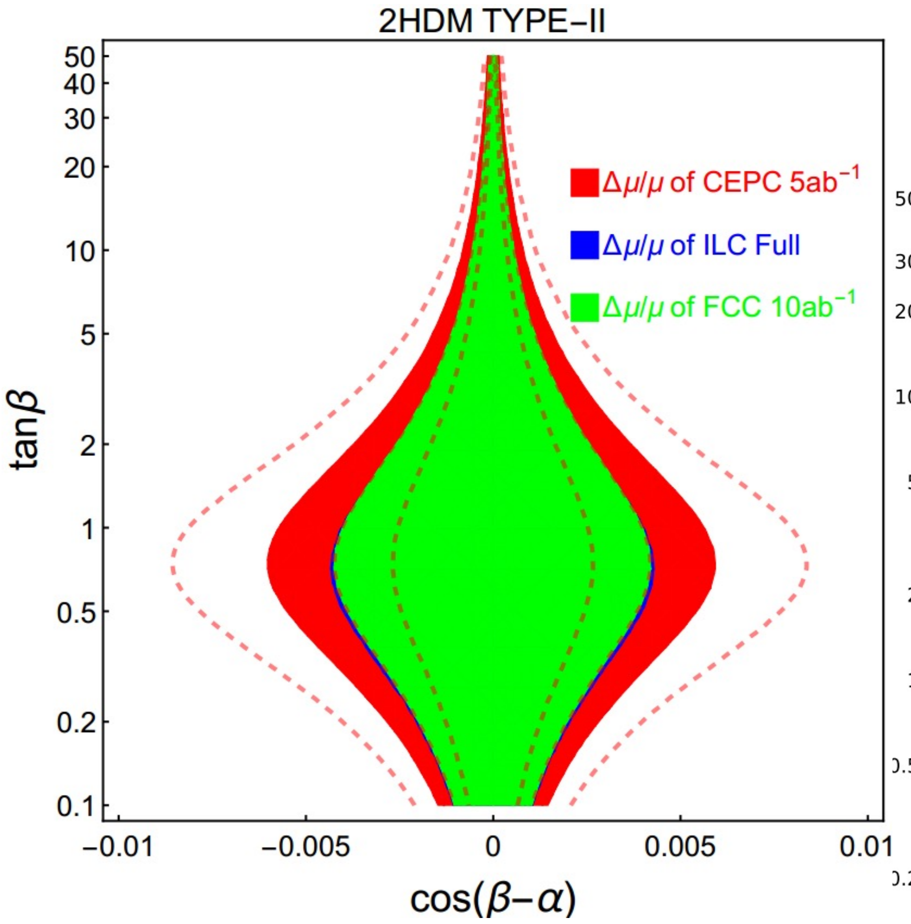


Tree-level

Loop-level

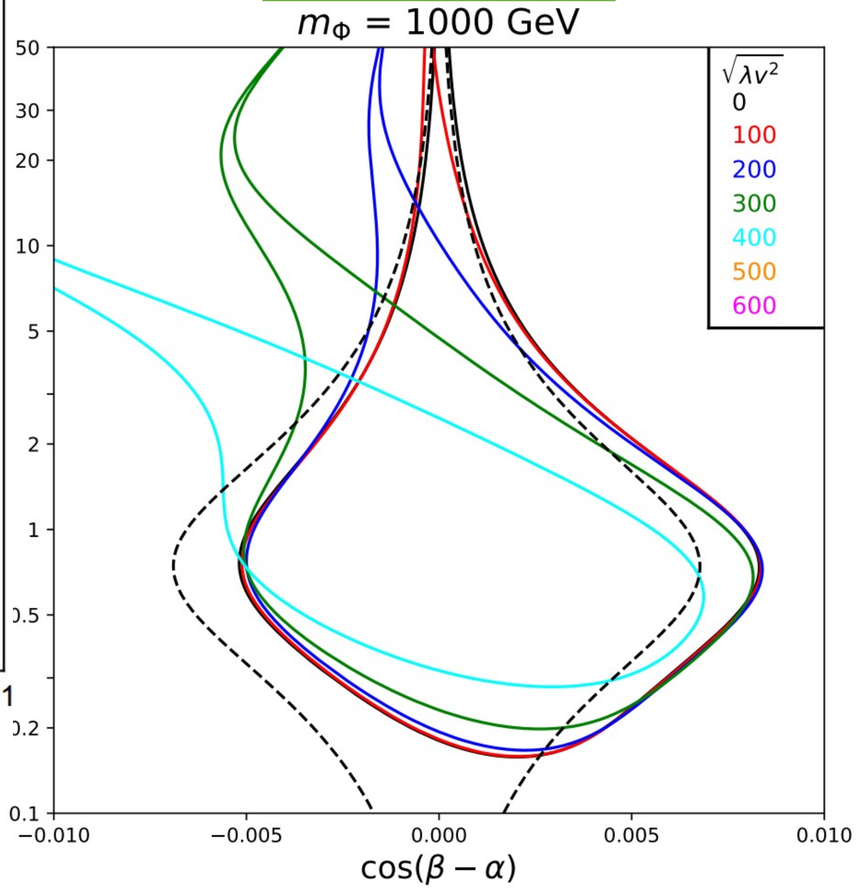


2HDM: $Tree + Loop\ +\ degenerate$

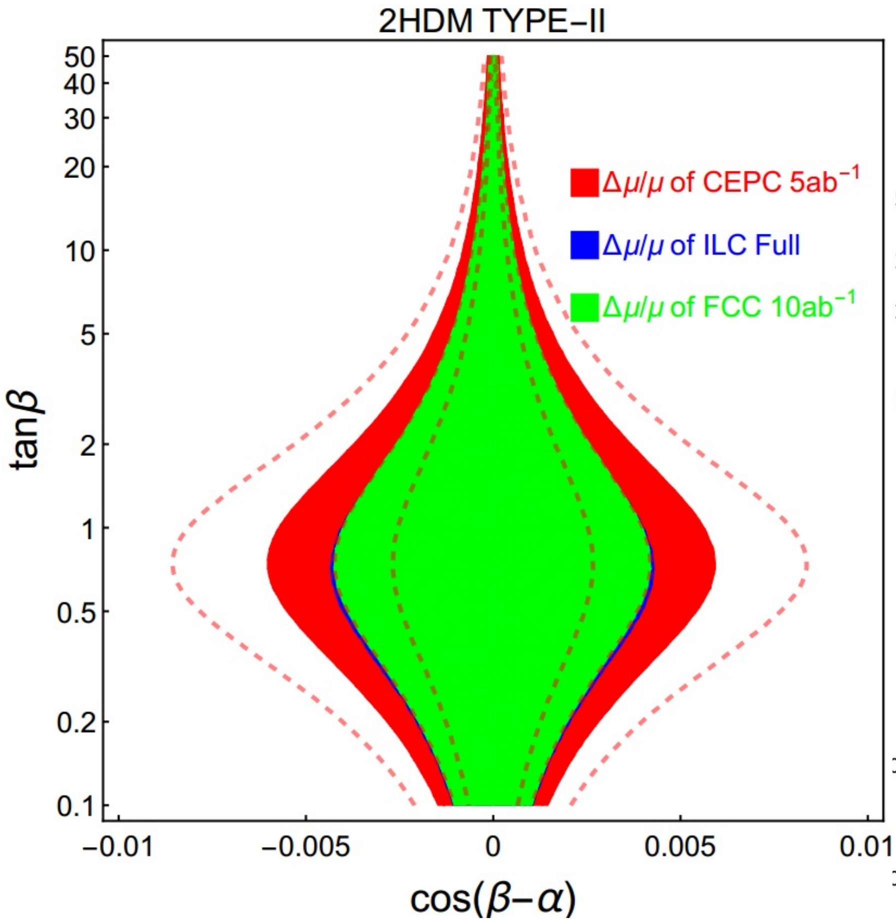


Tree-level

Loop-level

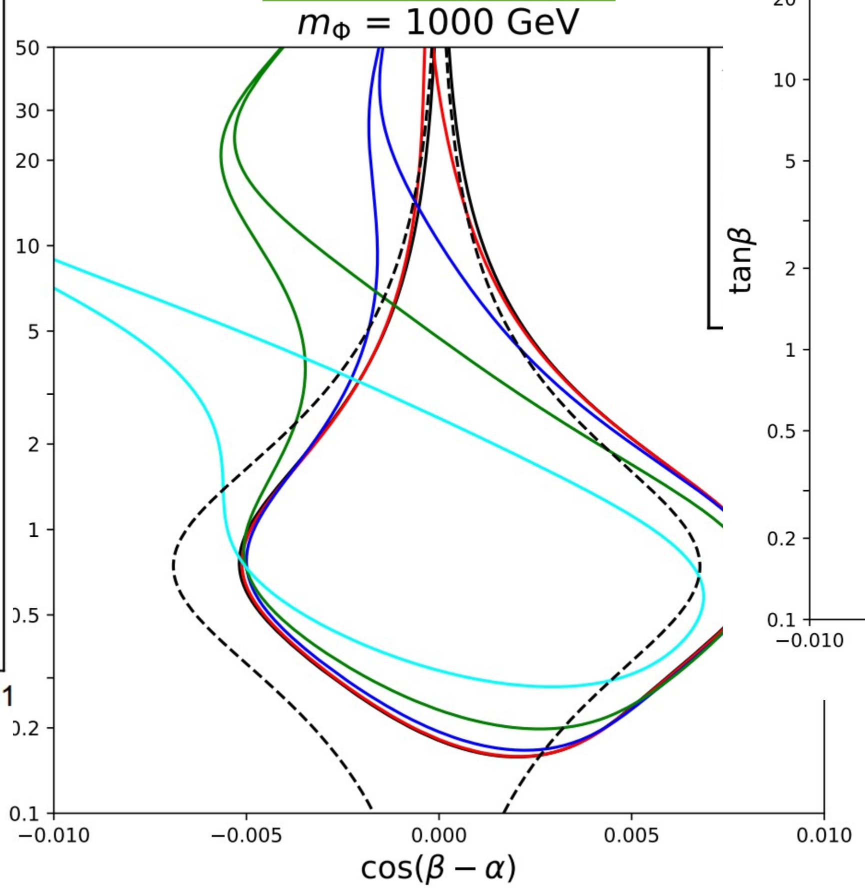


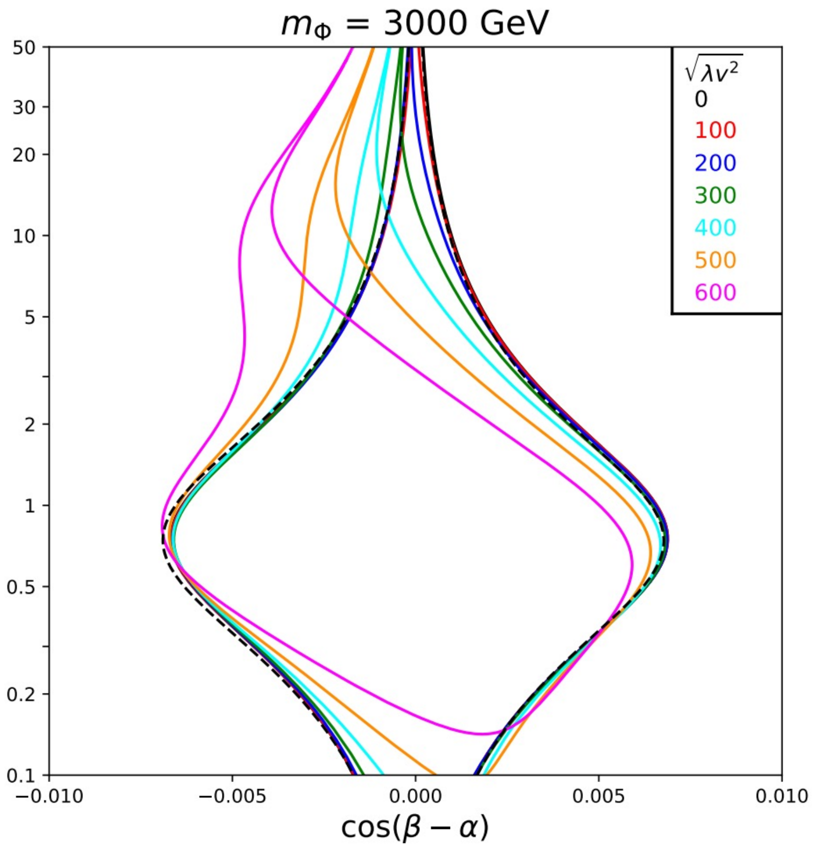
2HDM: $\color{red}{Tree + Loop + degenerate}$



Tree-level

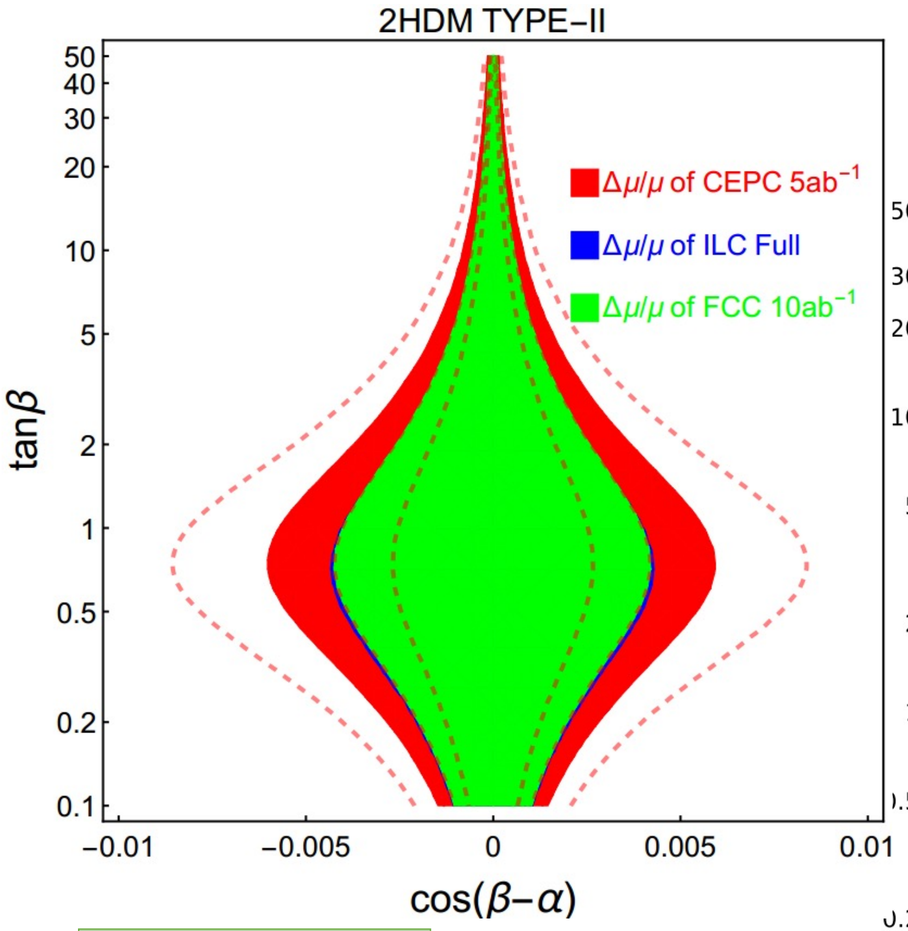
Loop-level





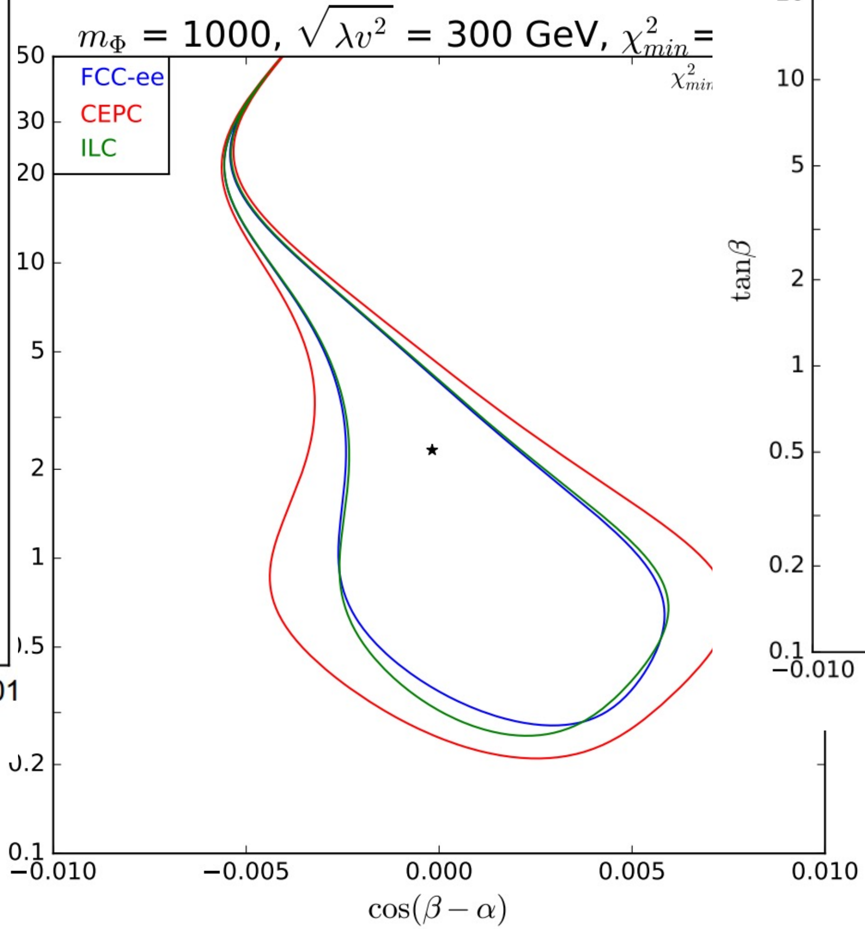
Loop-level decouple

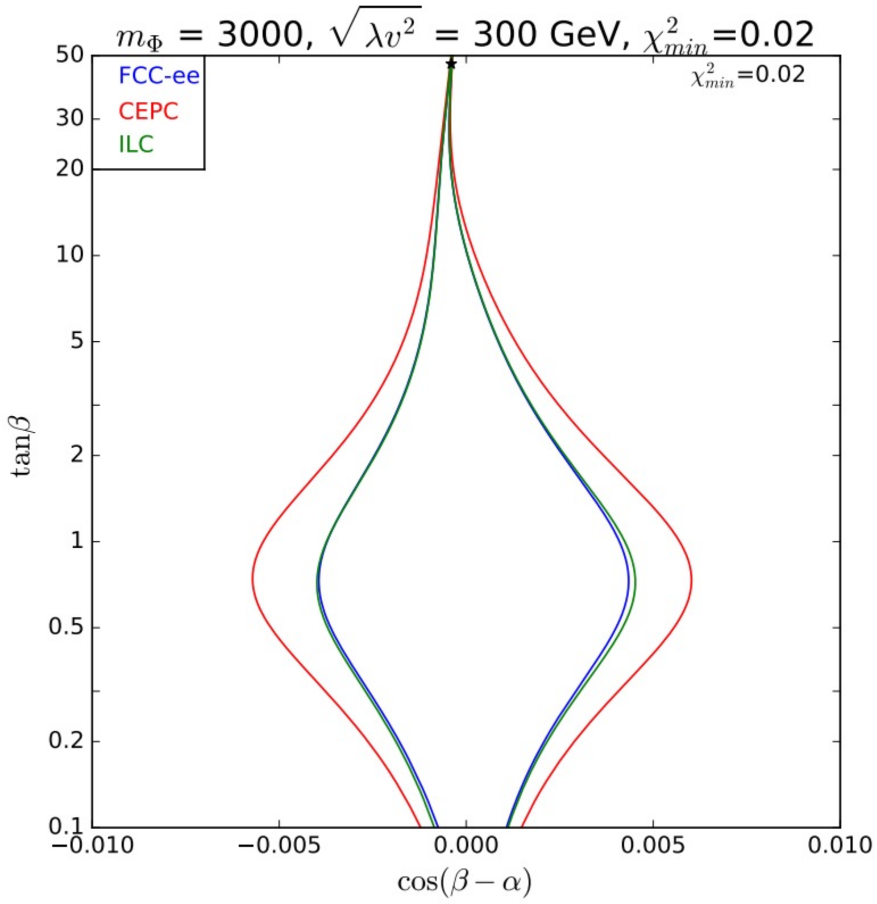
2HDM: $Tree + Loop\ +\ degenerate$



Tree-level

Loop-level





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

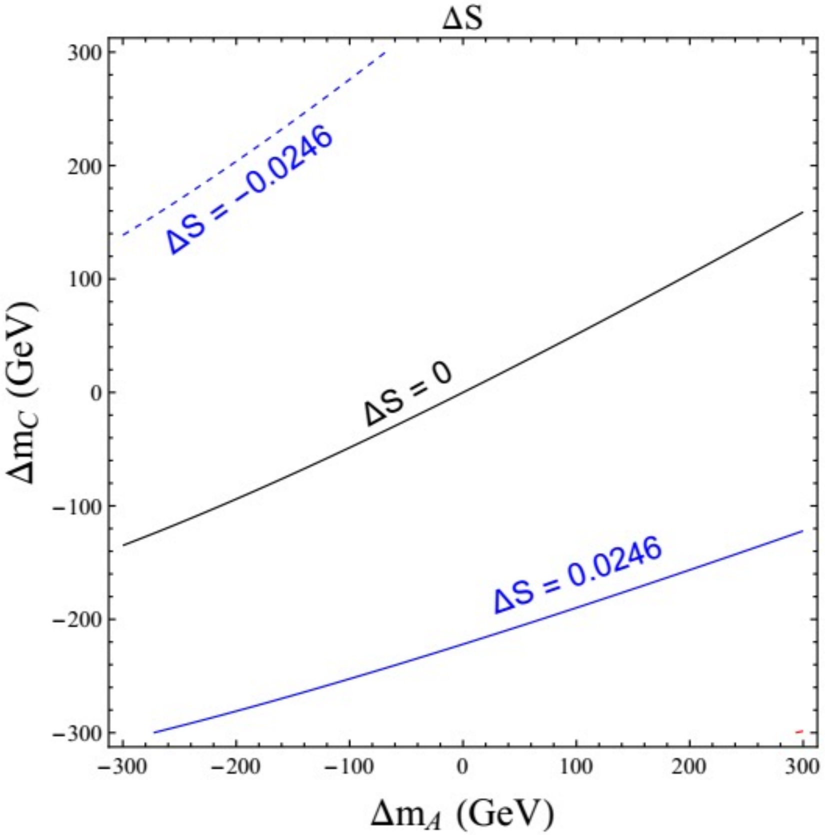
Z Pole Precision

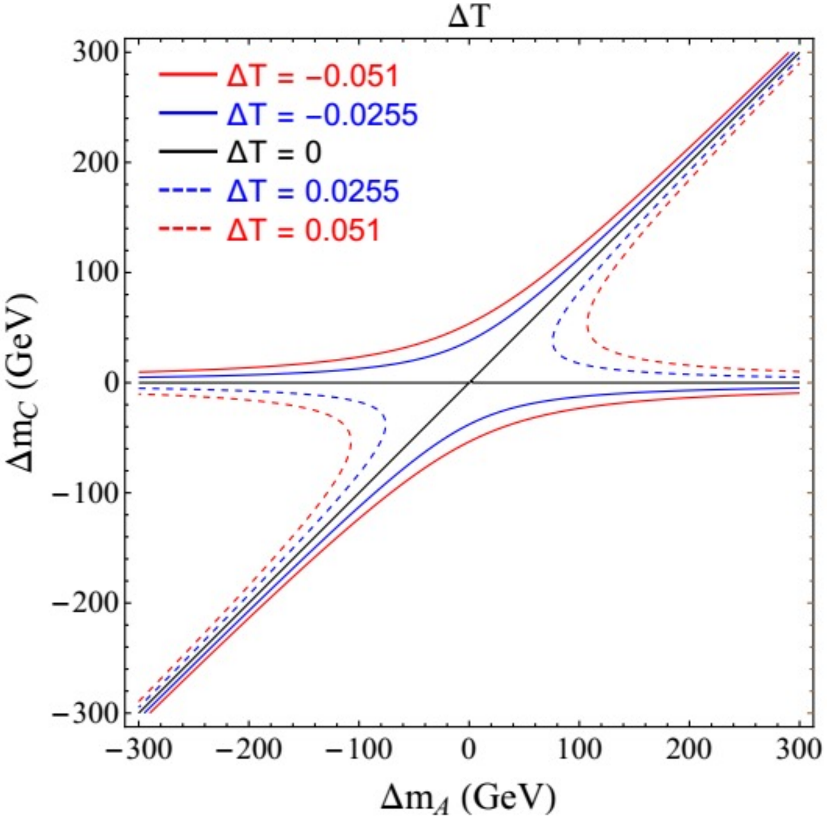
	Current (1.7×10^7 Z's)				CEPC ($10^{10} Z$'s)				FCC-ee ($7 \times 10^{11} Z$'s)				ILC ($10^9 Z$'s)			
	σ	correlation			σ	correlation			σ	correlation			σ	correlation		
		S	T	U	(10^{-2})	S	T	U	(10^{-2})	S	T	U	(10^{-2})	S	T	U
S	0.04 ± 0.11	1	0.92	-0.68	2.46	1	0.862	-0.373	0.67	1	0.812	0.001	3.53	1	0.988	-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
	σ
S	0.04 ± 0.11
T	0.09 ± 0.14
U	-0.02 ± 0.1





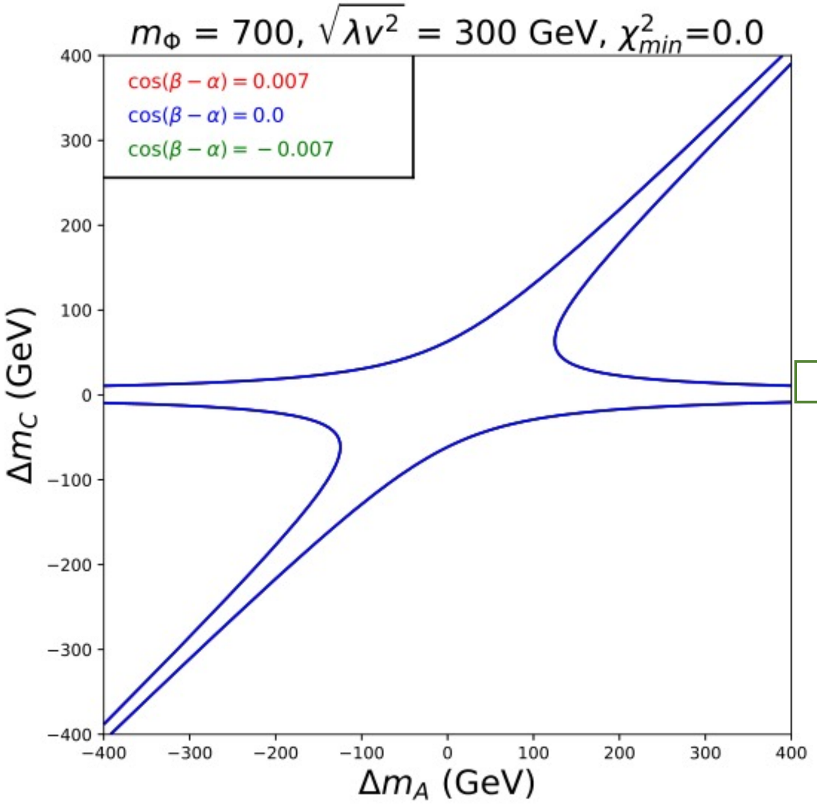
$(10^9 Z$'s)	
correlation	
T	U
0.988	−0.879
1	−0.909
–	1

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

Z Pole Precision

CEPC fit

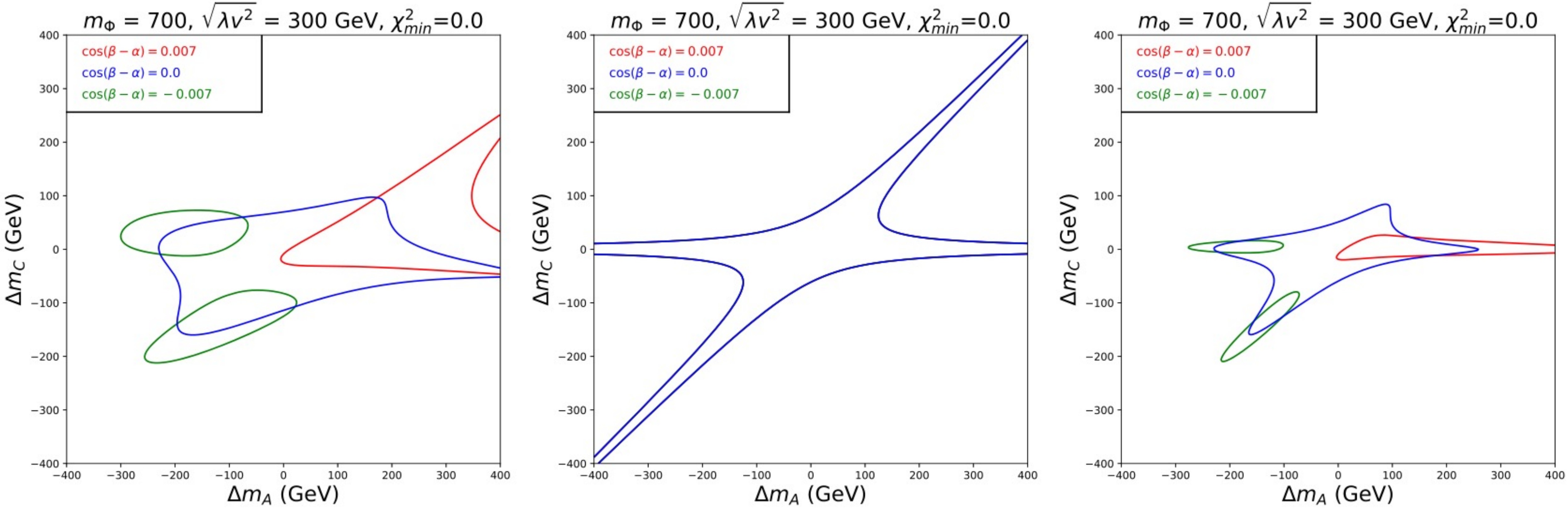
$$\Delta m_A = m_A - m_H,$$
$$\Delta m_C = m_{H^\pm} - m_H,$$
$$m_H = 700 \text{ GeV}$$



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

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

Higgs Precision | **Z Pole Precision** | **Combined**

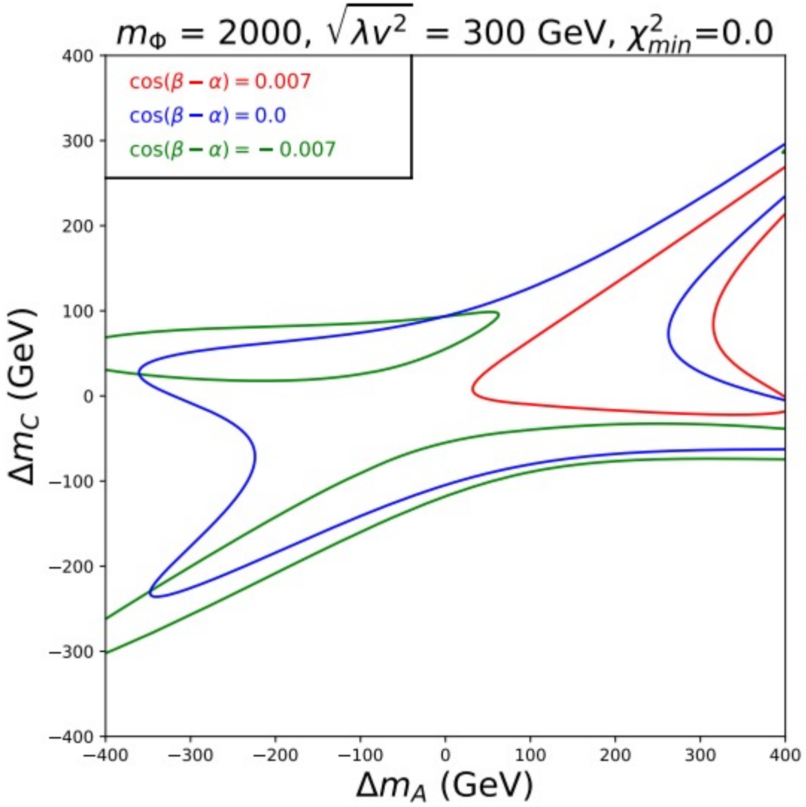


$m_H = 700$ GeV

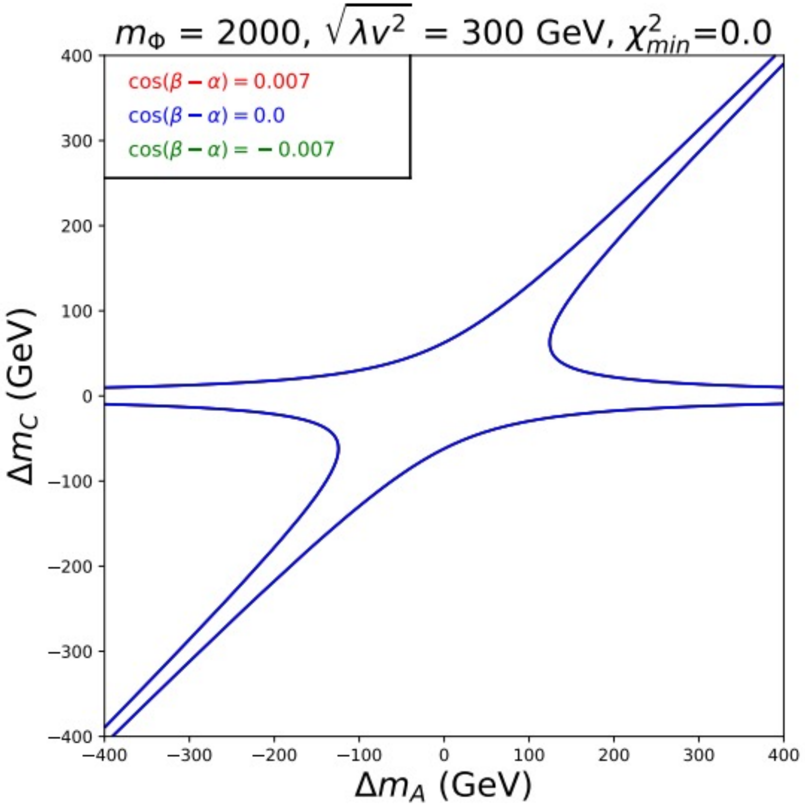
Complementary to each other

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

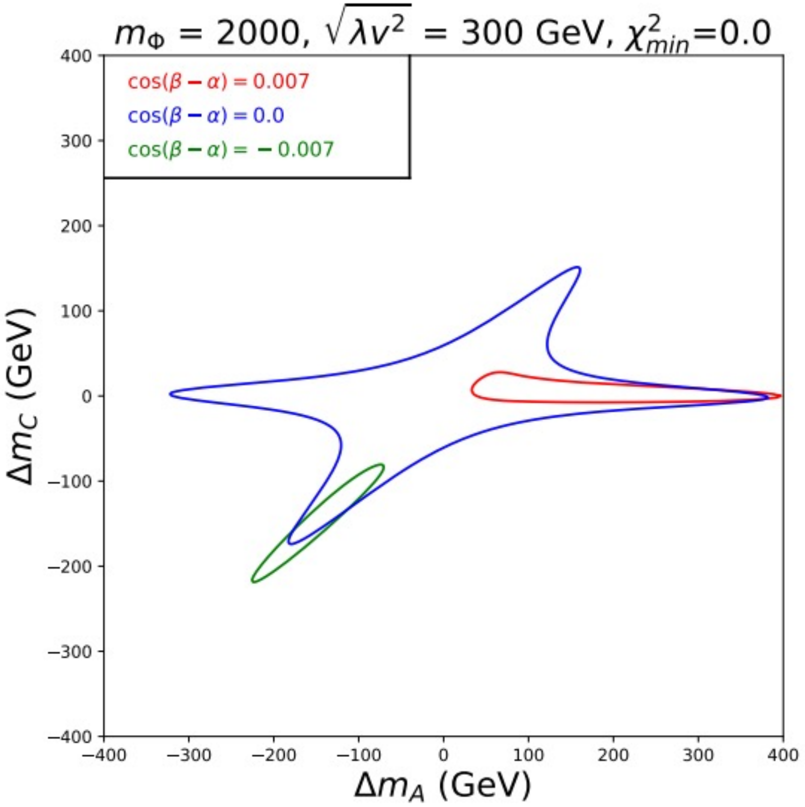
Higgs Precision



Z Pole Precision



Combined

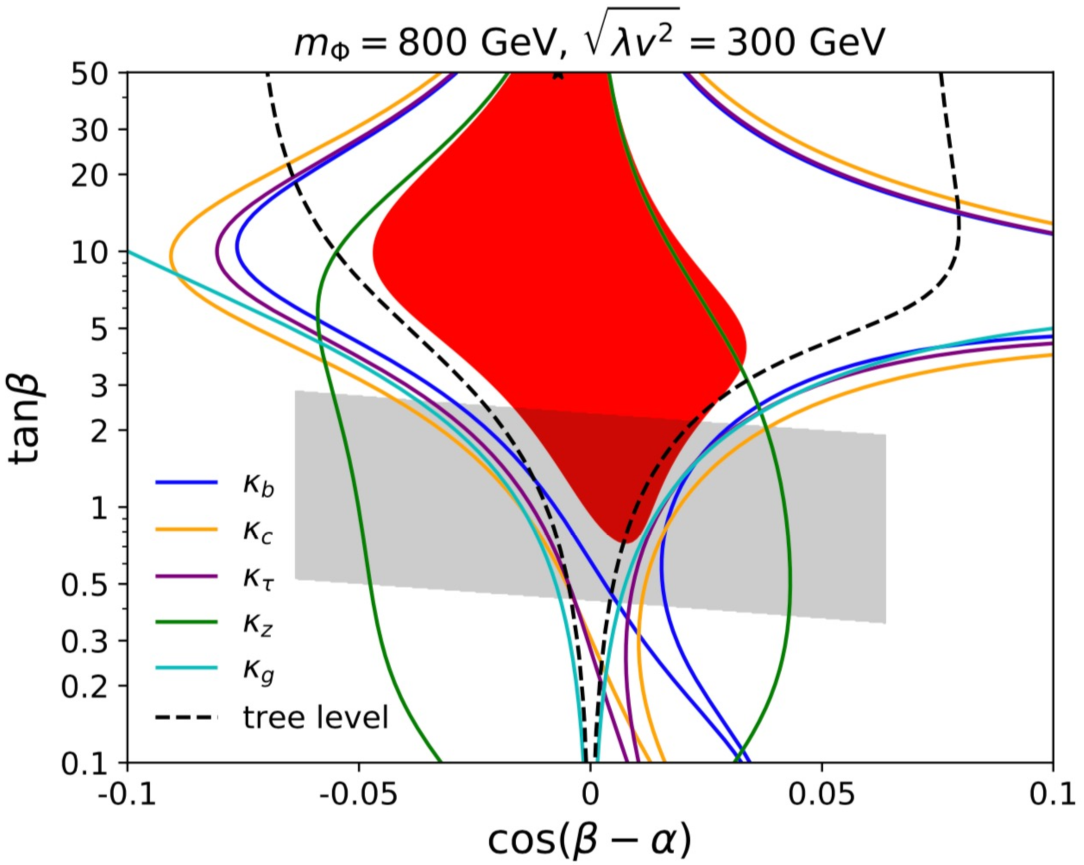


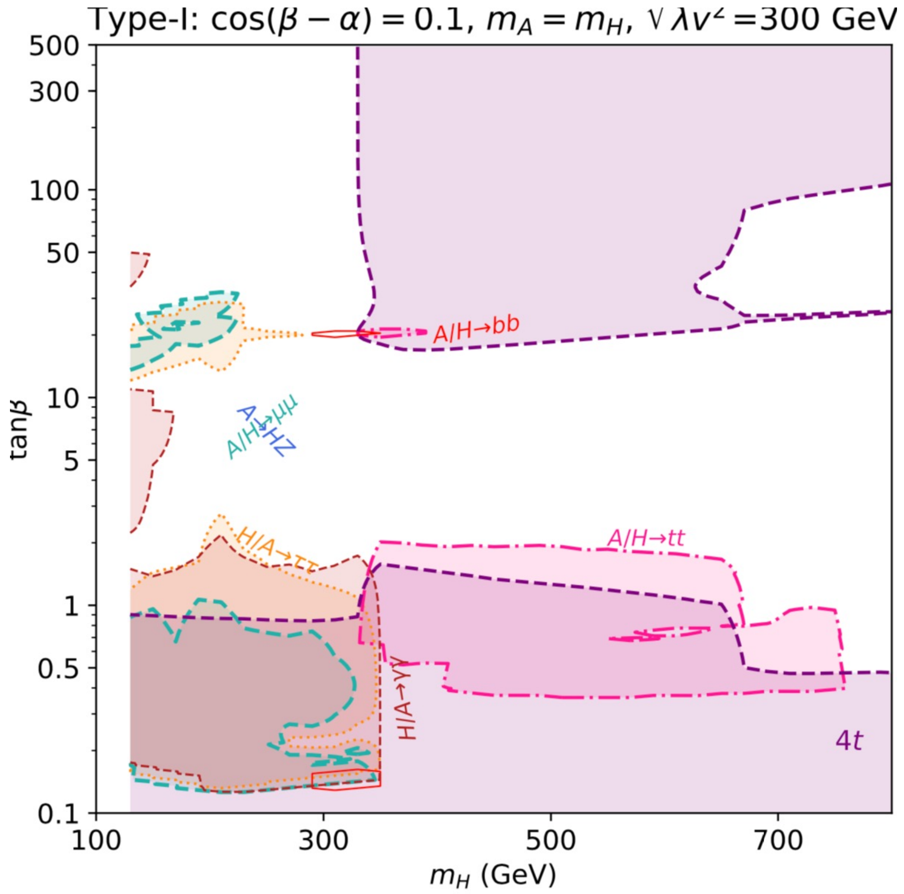
$m_H = 2000$ GeV

Complementary to each other

2HDM: Type-I

Constraints at Large tanβ





[1912.01431](https://arxiv.org/abs/1912.01431) N. Chen, T. Han, S. Su, Y. Wu

Summary 1: Higgs precision

2HDM

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

Complementary to

- Z pole precision
- LHC direct search