Implication of Higgs/EW precision on 2HDM

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1709.06103 (J. Gu, H. Li, Z. Liu, S. Su ,WS)
1808.02037 (N. Chen, T. Han, S. Su, WS, Y. Wu)
1912.01431 (N. Chen, T. Han, S. Li, S. Su, WS, Y. Wu)
2008.05492 (T. Han, S. Li, S. Su, WS, Y. Wu)

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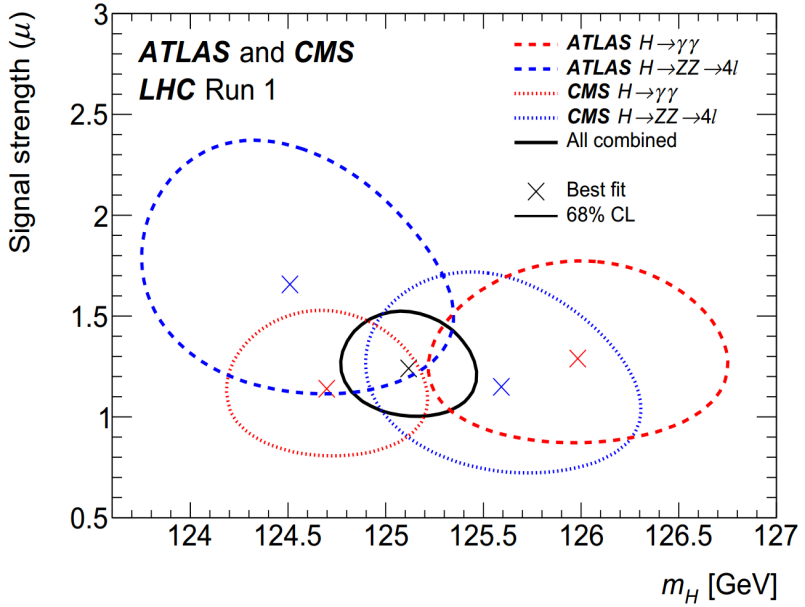
Outline

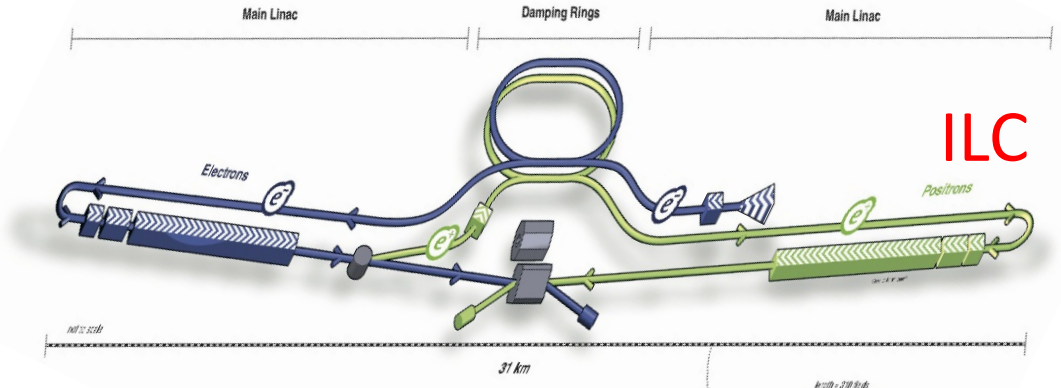
- Higgs/Z-pole Precision Measurements
- 2HDM: tree level
- 2HDM: one-loop level
- Conclusion

Higgs Precision Measurements

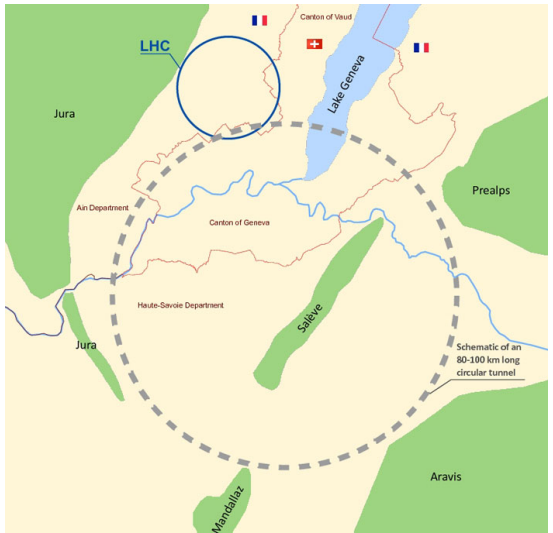
CMS-HIG-14-042
ATLAS-HIGG-2014-14



CEPC



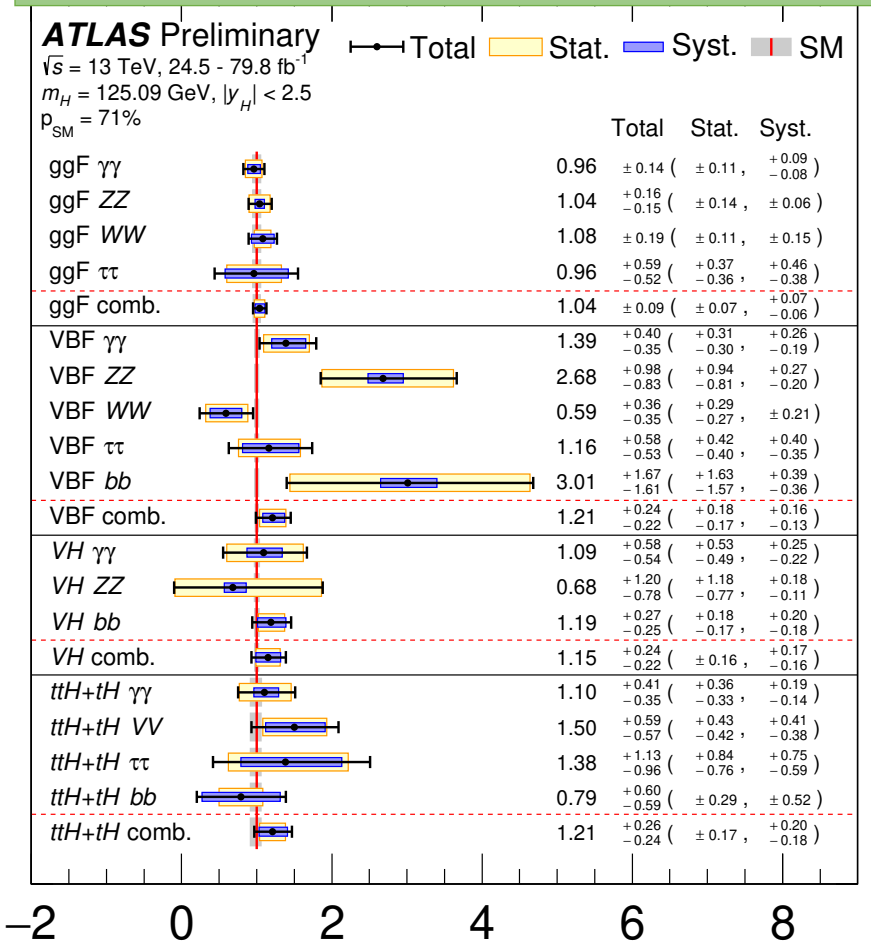
ILC



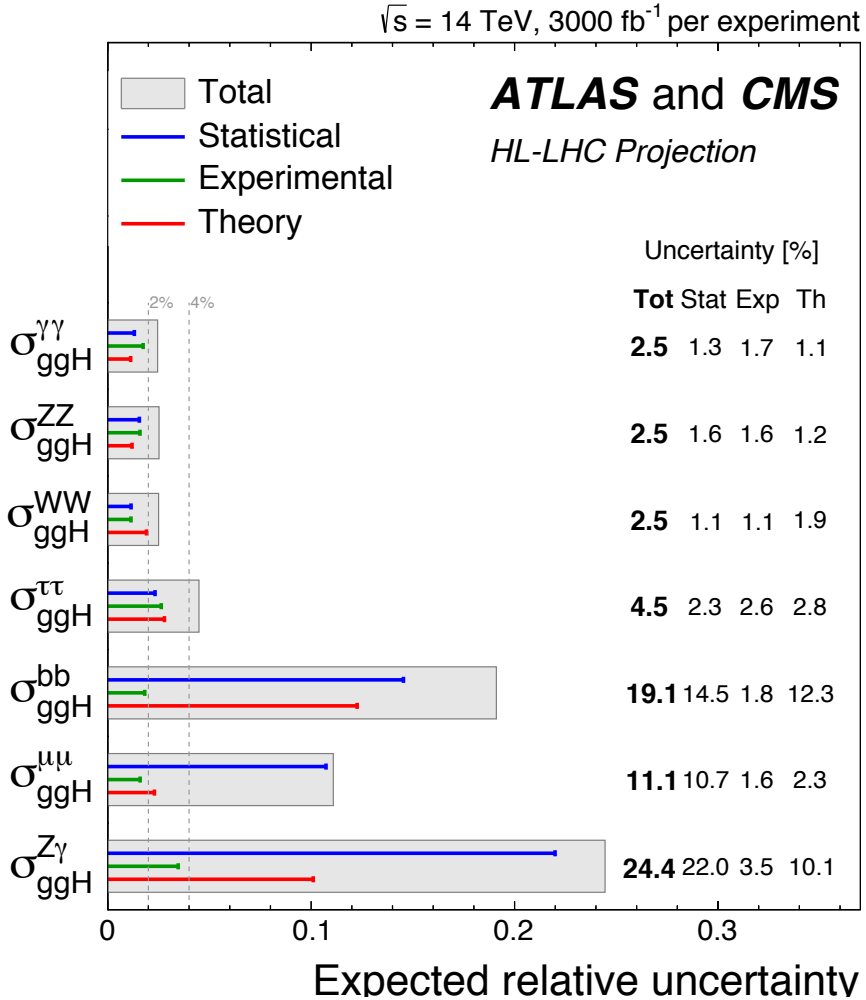
LHC
HL-LHC
FCC

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%	–	–	–	–

Precision: EW observables

CEPC-CDR , FCC-ee, ILC Operating Scenarios

Observables	FCC-ee	CEPC	ILC
δm_h [GeV]	1.0×10^{-2}	5.9×10^{-3}	1.5×10^{-2}
$\delta \alpha_{\rm had}$	3.8×10^{-5} *	4.7×10^{-5}	3.8×10^{-5} *
δm_Z [GeV]	1.0×10^{-4}	5.0×10^{-4}	2.1×10^{-3}
δm_t [GeV]	2.0×10^{-2}	6.0×10^{-1}	1.7×10^{-2}
δm_W [GeV]	7.0×10^{-4}	1.0×10^{-3}	2.5×10^{-3}
$\delta \Gamma_W$ [GeV]	1.5×10^{-3}	2.8×10^{-3}	5.0×10^{-3}
$\delta \Gamma_Z$ [GeV]	1.0×10^{-4}	5.0×10^{-4}	7.0×10^{-4}
$\delta A_b^{\rm FB}$	3.0×10^{-4}	1.0×10^{-4}	1.6×10^{-3} *
$\delta A_c^{\rm FB}$	5.9×10^{-4}	2.2×10^{-4}	3.5×10^{-3} *
$\delta A_\ell^{\rm FB}$	9.0×10^{-6}	5.0×10^{-5}	1.0×10^{-3} *
δR_b	6.0×10^{-5}	4.3×10^{-5}	1.5×10^{-4}
δR_c	1.7×10^{-4}	1.7×10^{-4}	5.2×10^{-4}
δR_ℓ	1.0×10^{-3}	2.1×10^{-3}	4.0×10^{-3}
$\delta \sigma_{\rm had}$ [nb]	4.0×10^{-3}	5.0×10^{-3}	3.7×10^{-2} *

Precision: EW observables

CEPC-CDR , FCC-ee, ILC Operating Scenarios

Oblique parameters

Observables	FCC-ee	CEPC	ILC
m_h [GeV]	1.0×10^{-2}	5.9×10^{-3}	1.5×10^{-2}
$\delta\alpha_{\rm had}$	3.8×10^{-5} *	4.7×10^{-5}	3.8×10^{-5} *

	Current				CEPC				FCC-ee				ILC			
	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	1.82	1	0.9963	−0.9745	0.370	1	0.9898	−0.8394	2.57	1	0.9947	−0.9431
T	0.09 ± 0.14	–	1	−0.87	2.56	–	1	−0.9844	0.514	–	1	−0.8636	3.59	–	1	−0.9569
U	-0.02 ± 0.11	–	–	1	1.83	–	–	1	0.416	–	–	1	2.64	–	–	1

$\delta A_c^{\rm FB}$	5.9×10^{-4}	2.2×10^{-4}	3.5×10^{-3} *
$\delta A_\ell^{\rm FB}$	9.0×10^{-6}	5.0×10^{-5}	1.0×10^{-3} *
δR_b	6.0×10^{-5}	4.3×10^{-5}	1.5×10^{-4}
δR_c	1.7×10^{-4}	1.7×10^{-4}	5.2×10^{-4}
δR_ℓ	1.0×10^{-3}	2.1×10^{-3}	4.0×10^{-3}
$\delta\sigma_{\rm had}$ [nb]	4.0×10^{-3}	5.0×10^{-3}	3.7×10^{-2} *

2HDM: Brief Introduction

- Two Higgs Doublet Model

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

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

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

	Φ_1	Φ_2
Type I	u,d,l	
Type II	u	d,l
lepton-specific	u,d	l
flipped	u,l	d

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

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

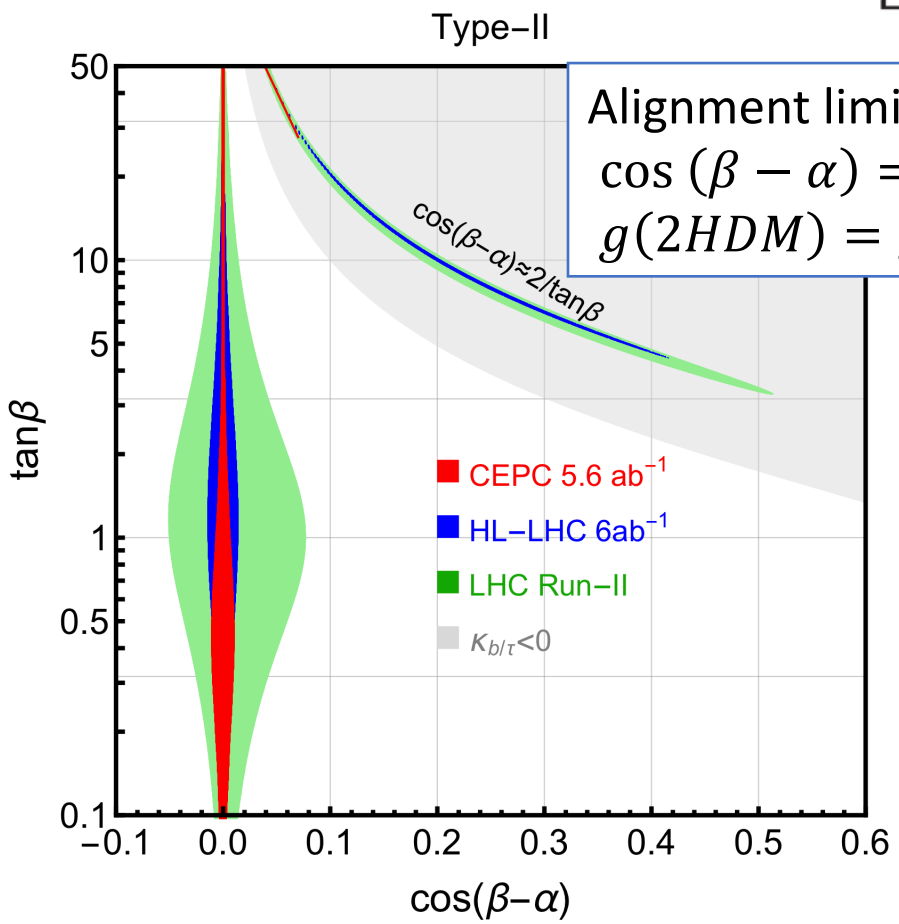
Soft Z_2 symmetry breaking: m_{12}^2

246 GeV

125. GeV

2HDM: Tree Level

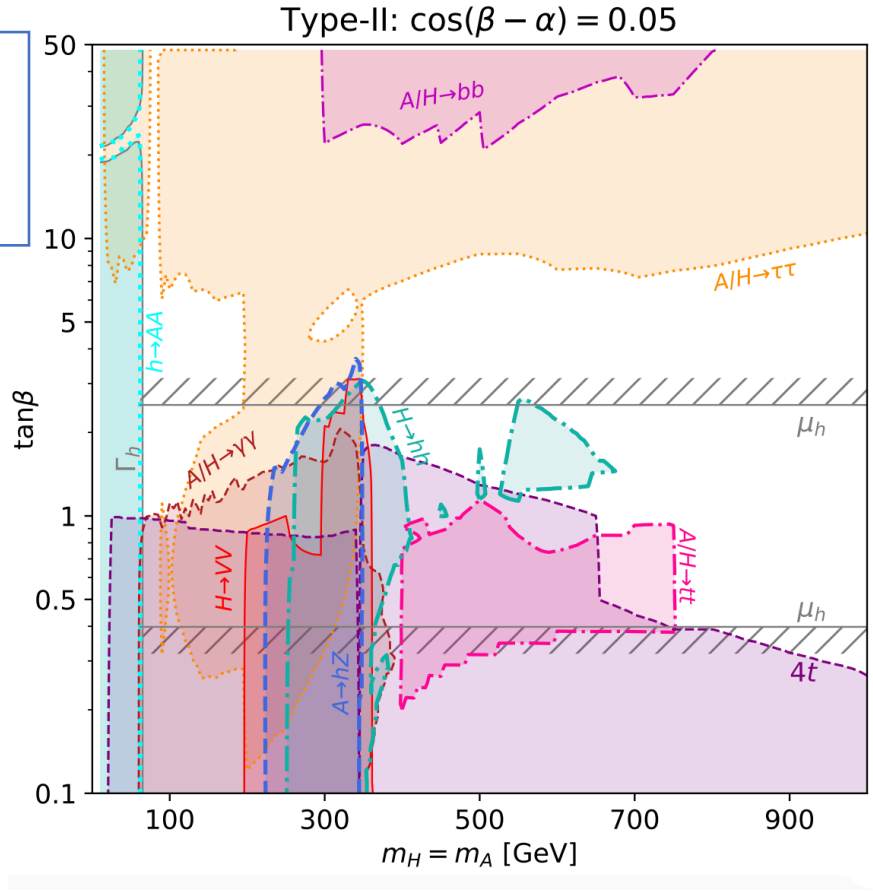
Model	κ_V	κ_u	κ_d	κ_ℓ
2HDM-I	$\sin(\beta-\alpha)$	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$
2HDM-II	$\sin(\beta-\alpha)$	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$	$-\sin\alpha/\cos\beta$
2HDM-L	$\sin(\beta-\alpha)$	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$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



Alignment limit :

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

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



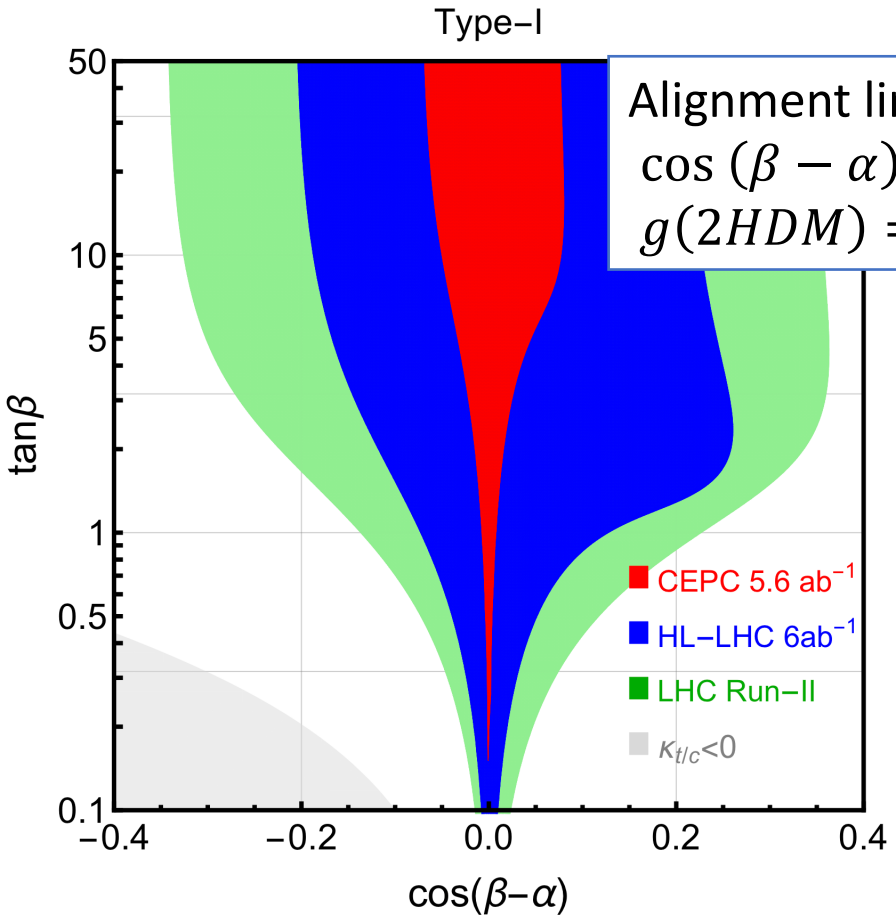
2004.04172

F. Kling, S. Su, WS

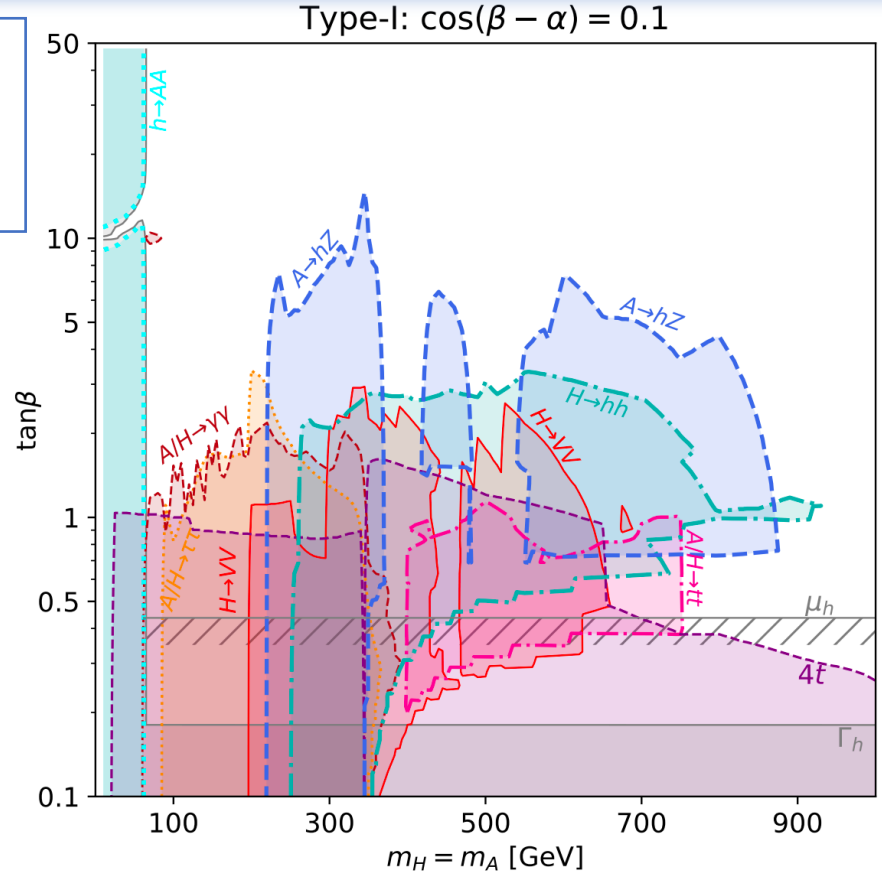
2HDM: Tree Level

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

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



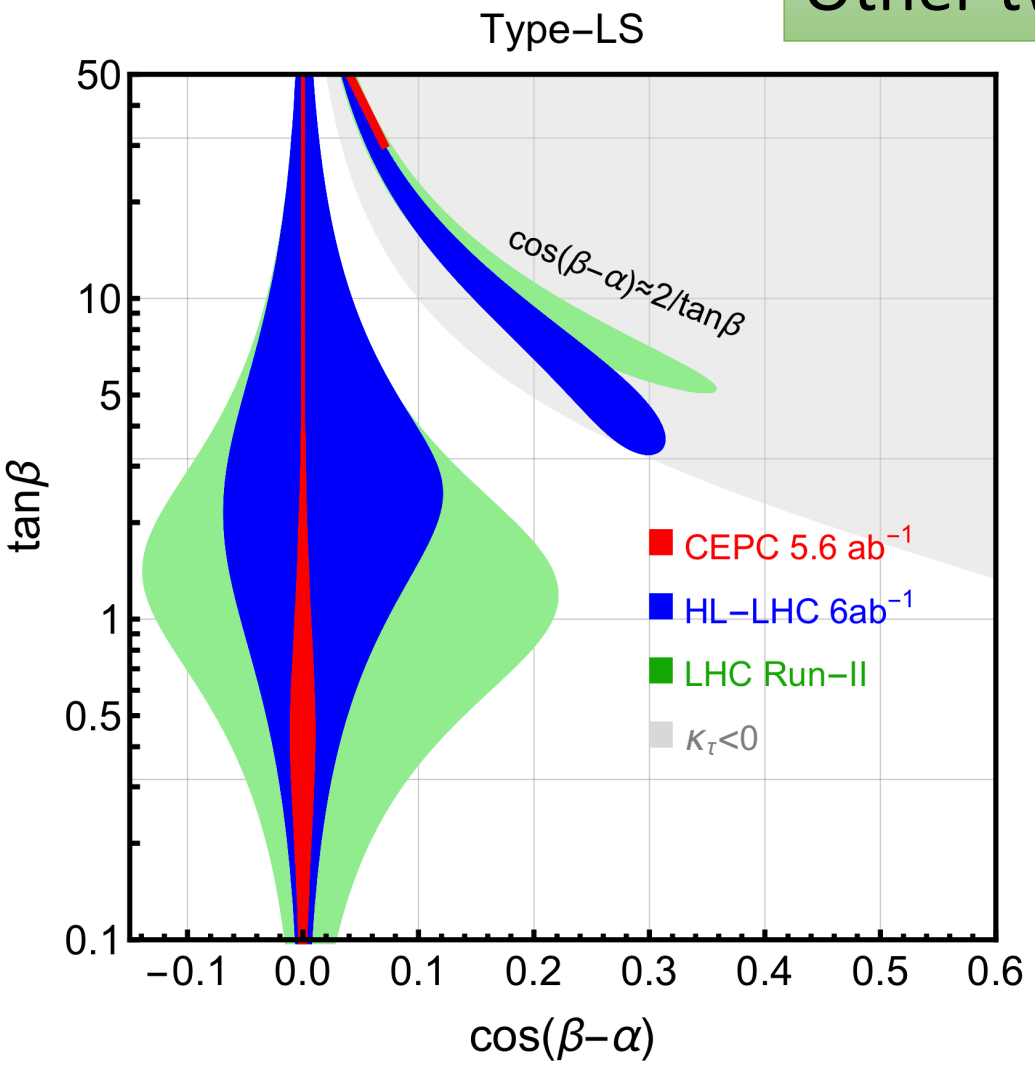
Alignment limit :
$\cos(\beta-\alpha) = 0$
$g(2HDM) = g(SM)$

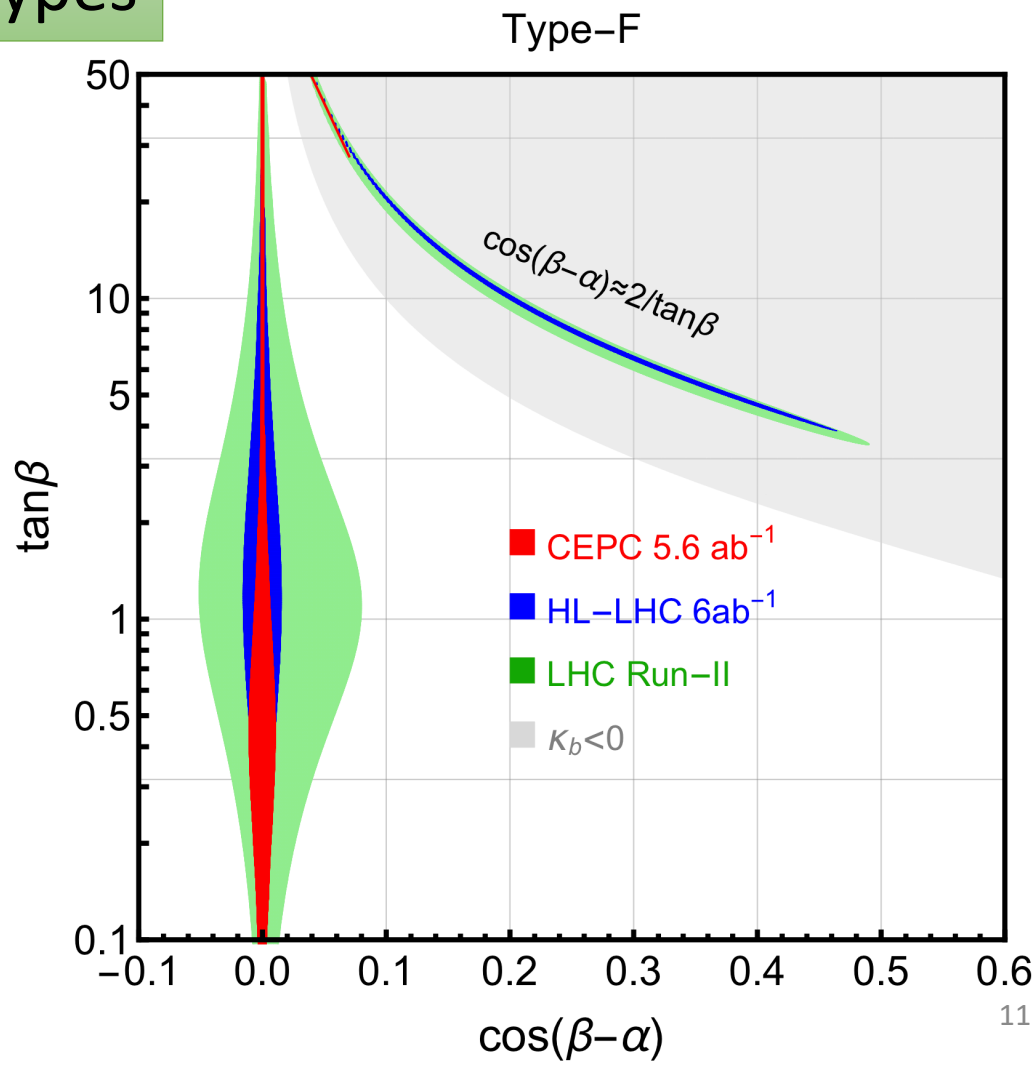


2004.04172
F. Kling, S. Su, WS

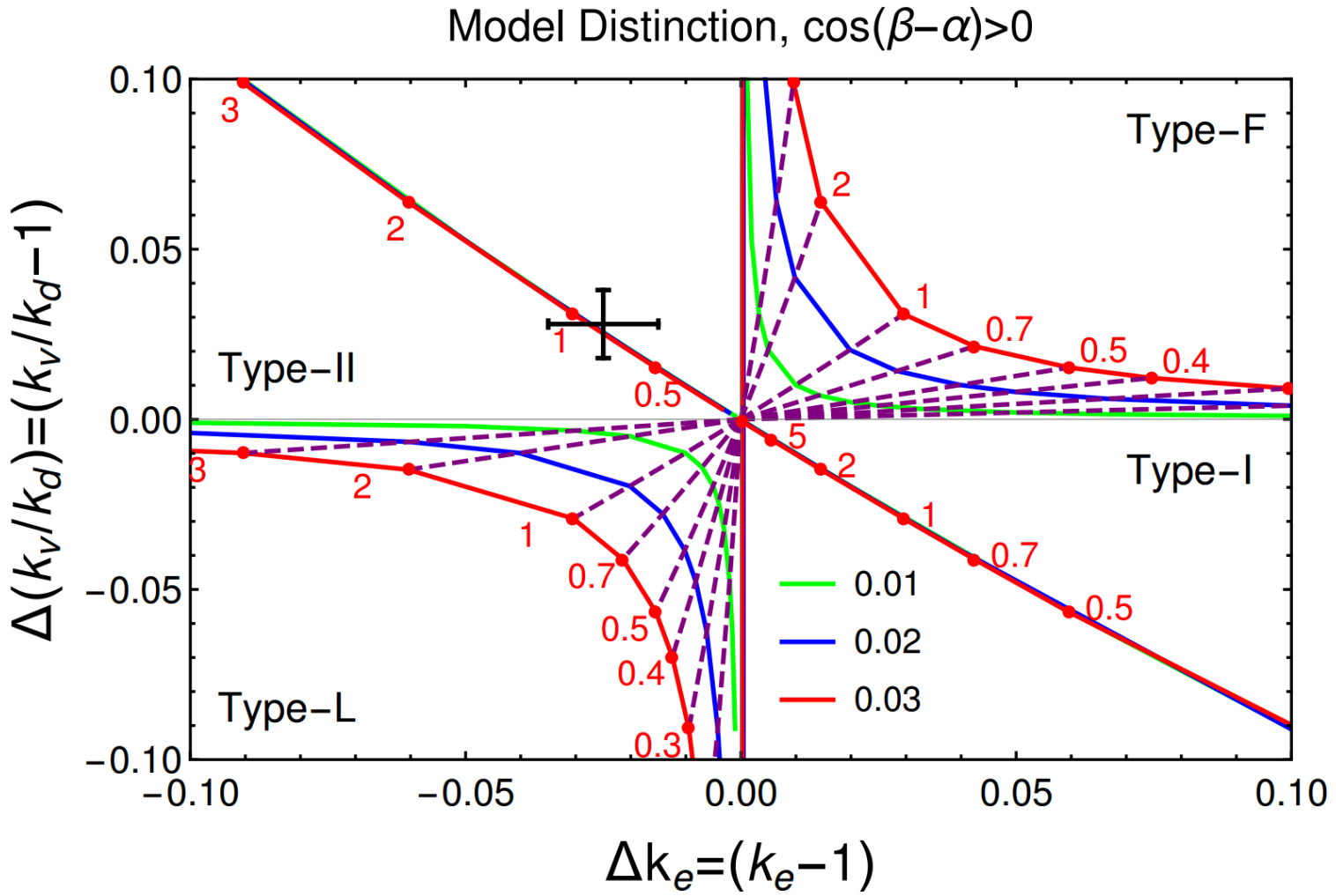
2HDM: Tree Level

Other two types





2HDM: Tree Level Model Distinction



Varying tan β

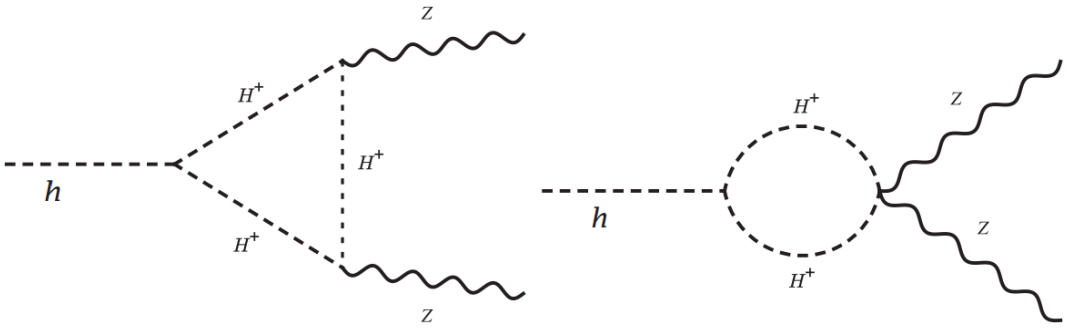
$\cos(\beta - \alpha)$

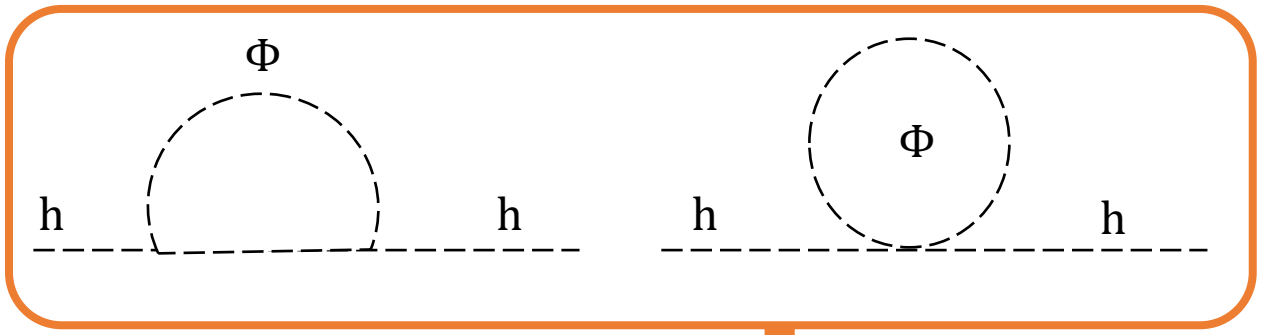
0.01

0.02

0.03

2HDM: One-Loop Level





Main contribution

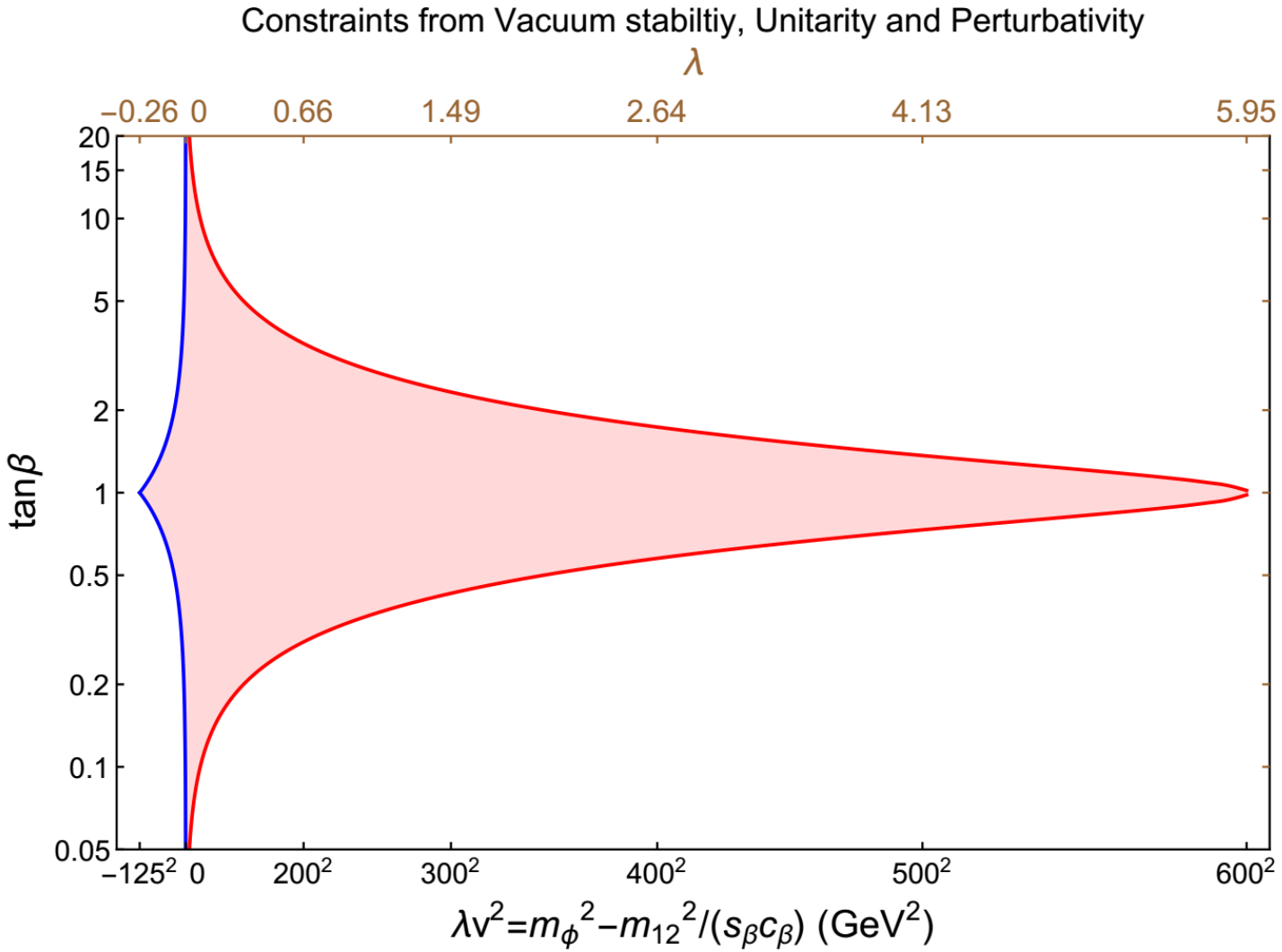
Parameter : $\cos(\beta-\alpha), \tan\beta, m_H, m_A, m_{H^\pm}, m_{12}^2$

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: *Loop + degenerate*



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

Theoretical constraints

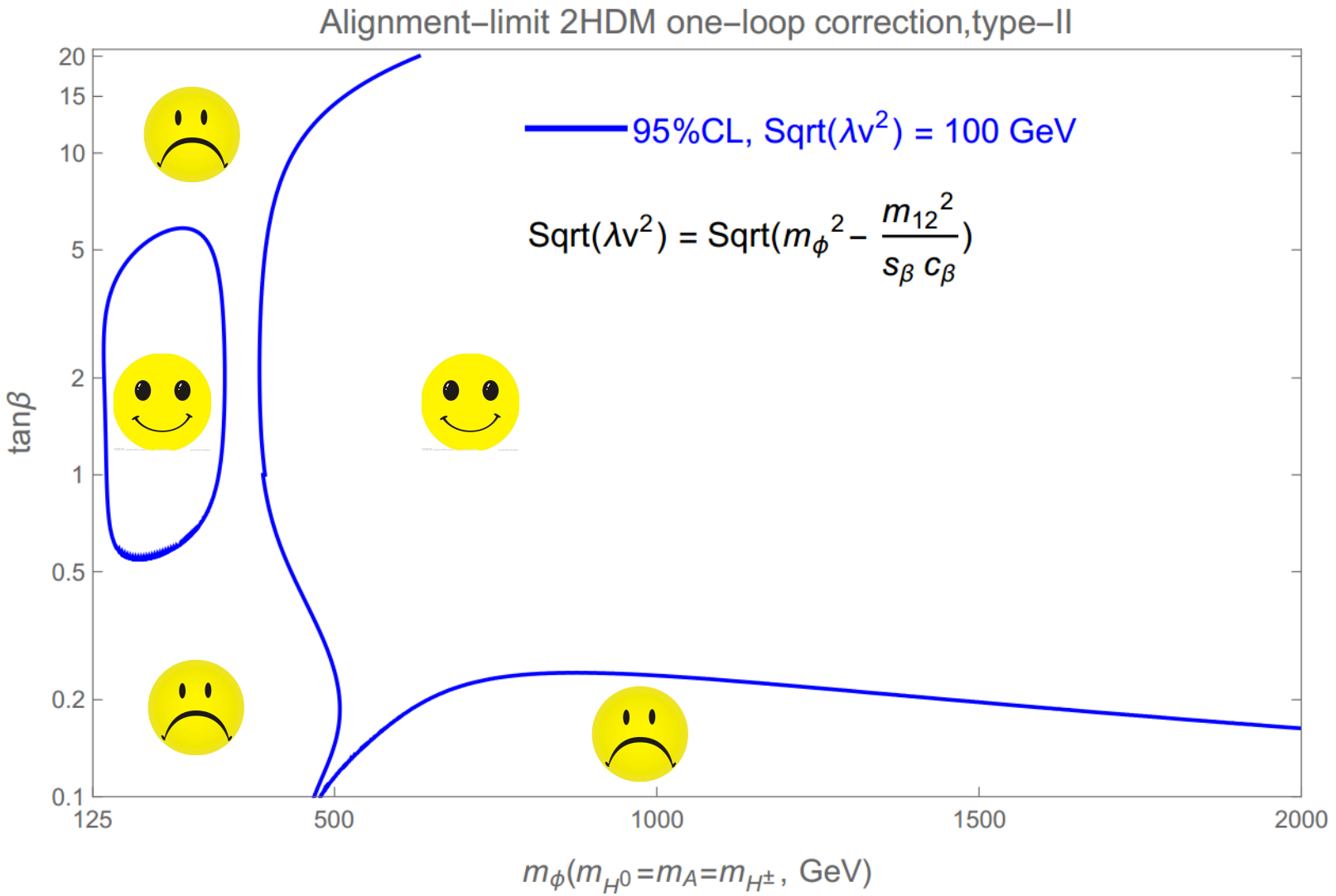
$$\lambda v^2 \equiv m_\Phi^2 - m_{12}^2/s_\beta c_\beta$$

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

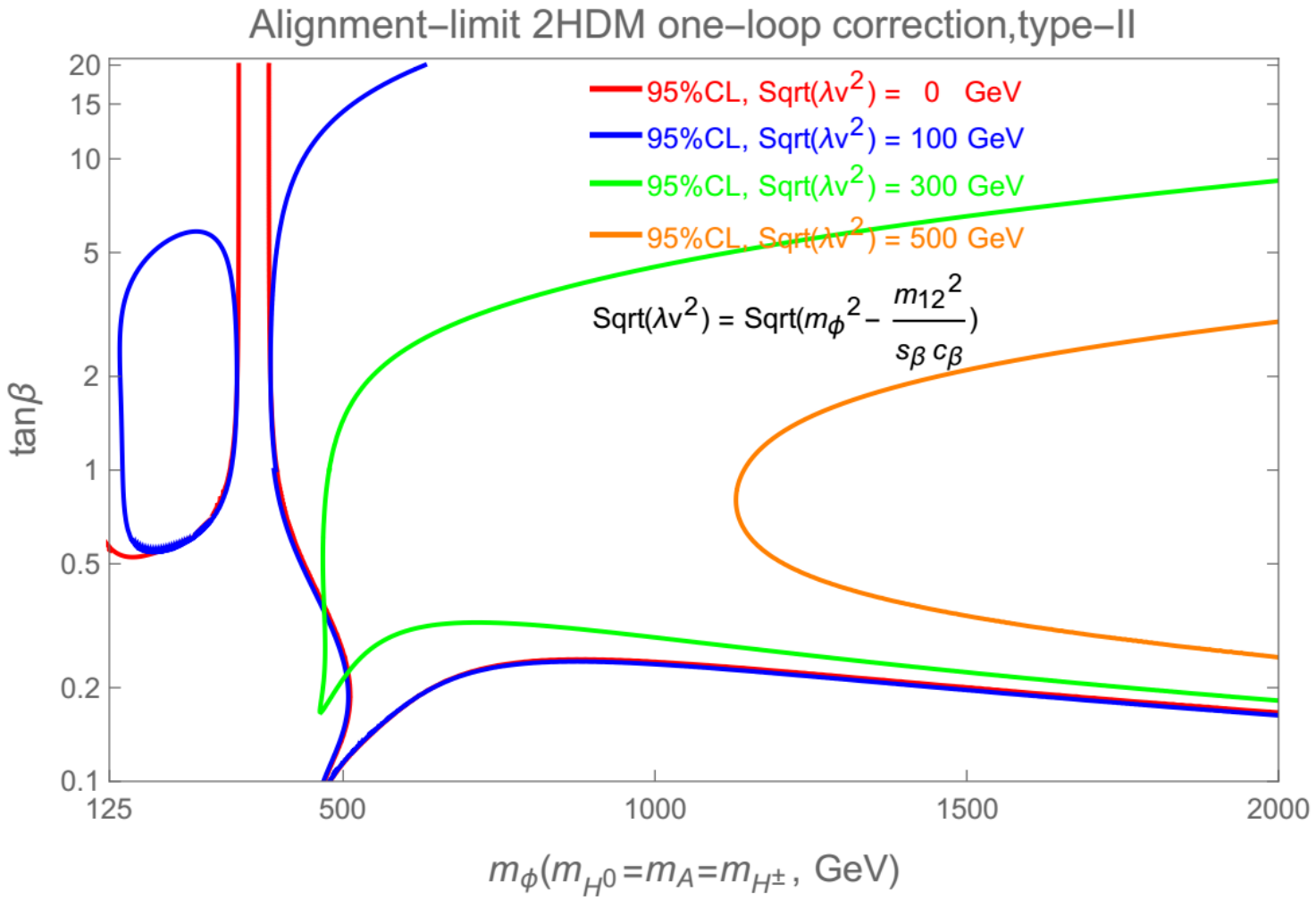
$$\lambda \in (-0.26, 5.95)$$
$$\lambda_4 = \lambda_5 = \lambda_3 - 0.258 = -\lambda$$

2HDM: *Loop + degenerate*

CEPC fit, Type-II



2HDM: *Loop + degenerate*



CEPC fit, Type-II

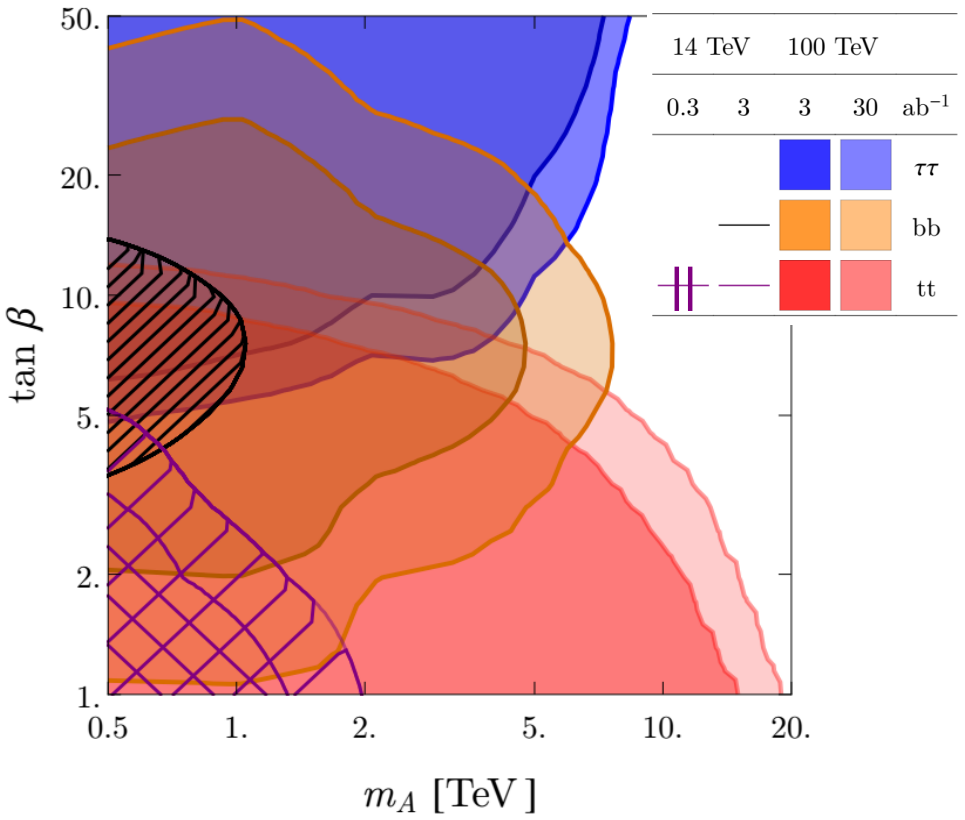
$-125^2\mathrm{GeV}^2 < \lambda v^2 < 600^2\mathrm{GeV}^2$

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

(GeV)

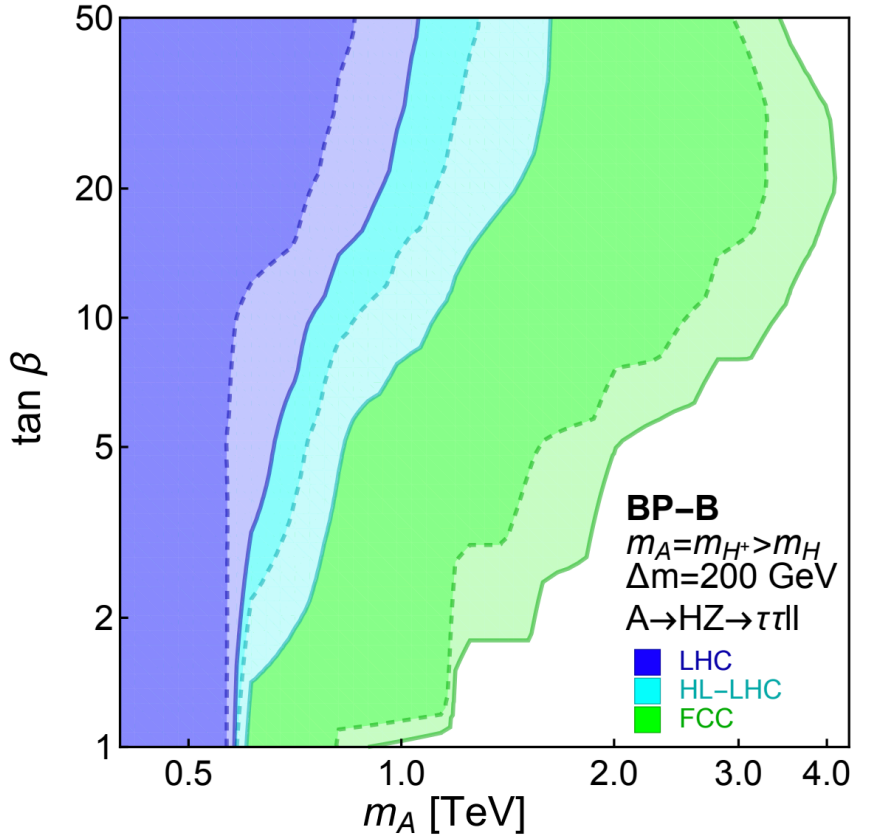
Higgs direct search at LHC

Conventional Search



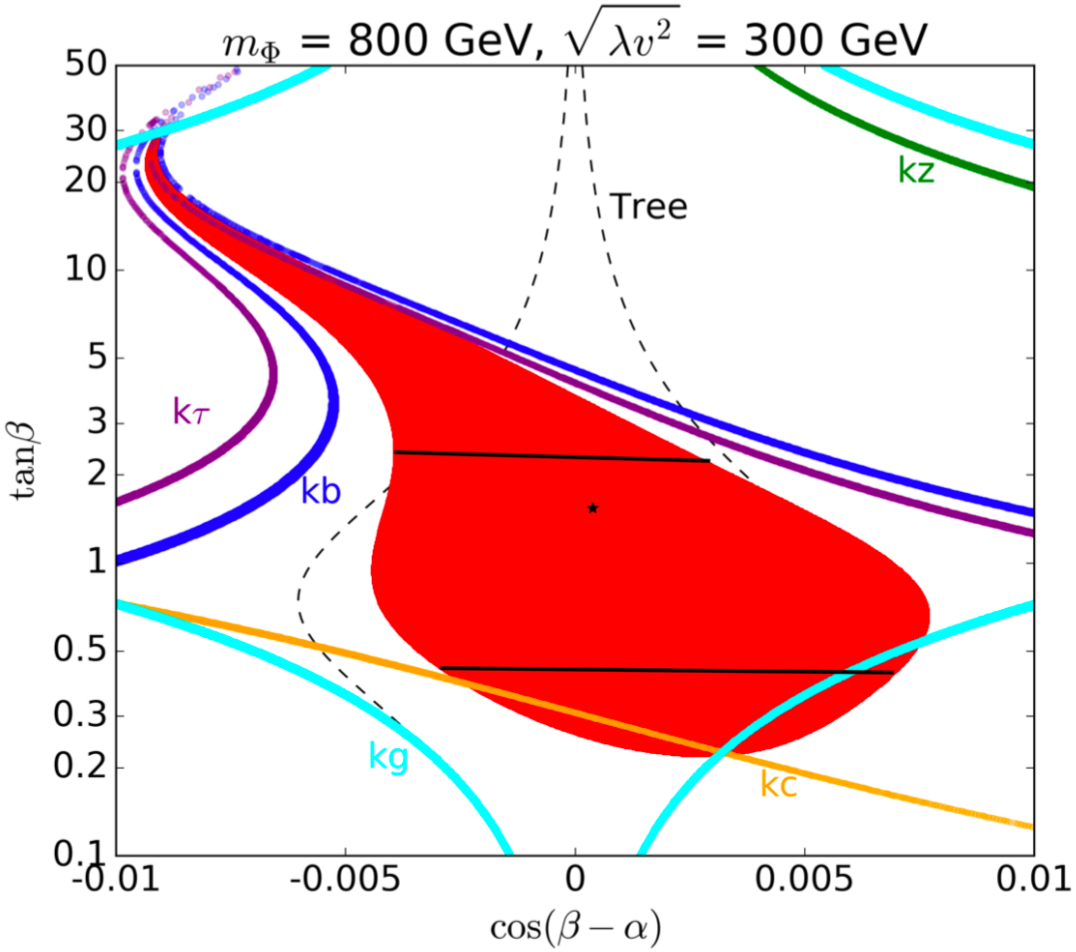
Craig et. al., 1605.08744

Exotic: A -> HZ



S. Su et. al., 1812.01633

2HDM: *Tree + Loop + degenerate*

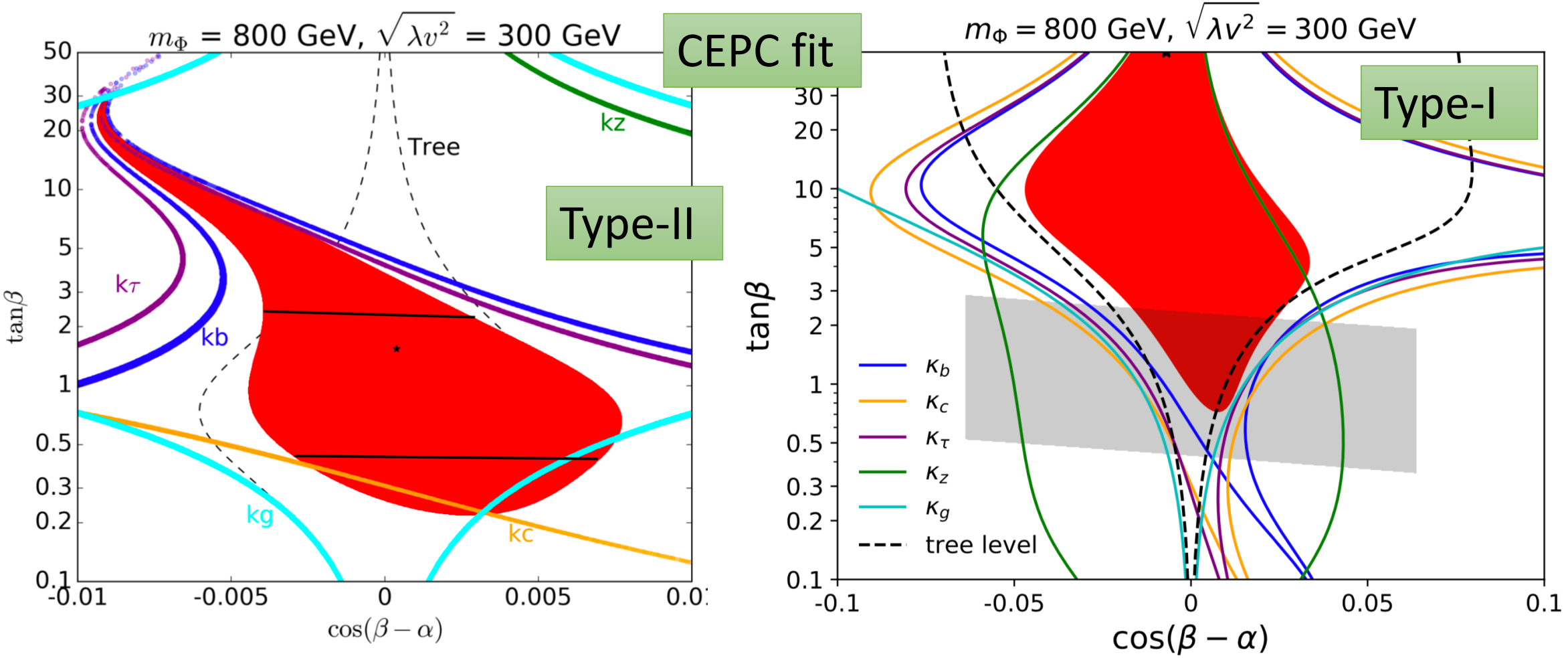


$\cos(\beta-\alpha) \neq 0,$

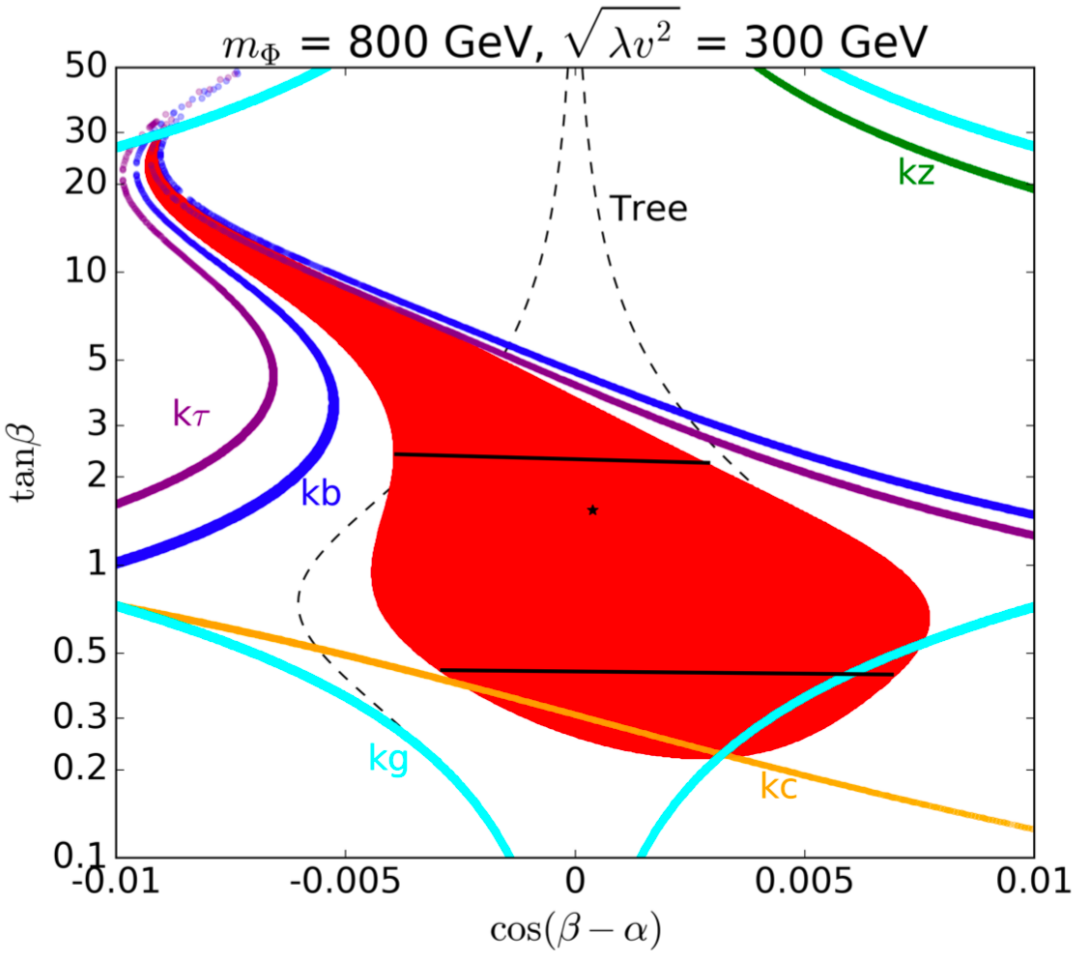
$m_\Phi \equiv m_H = m_A = m_{H^\pm}$

CEPC fit, Type-II

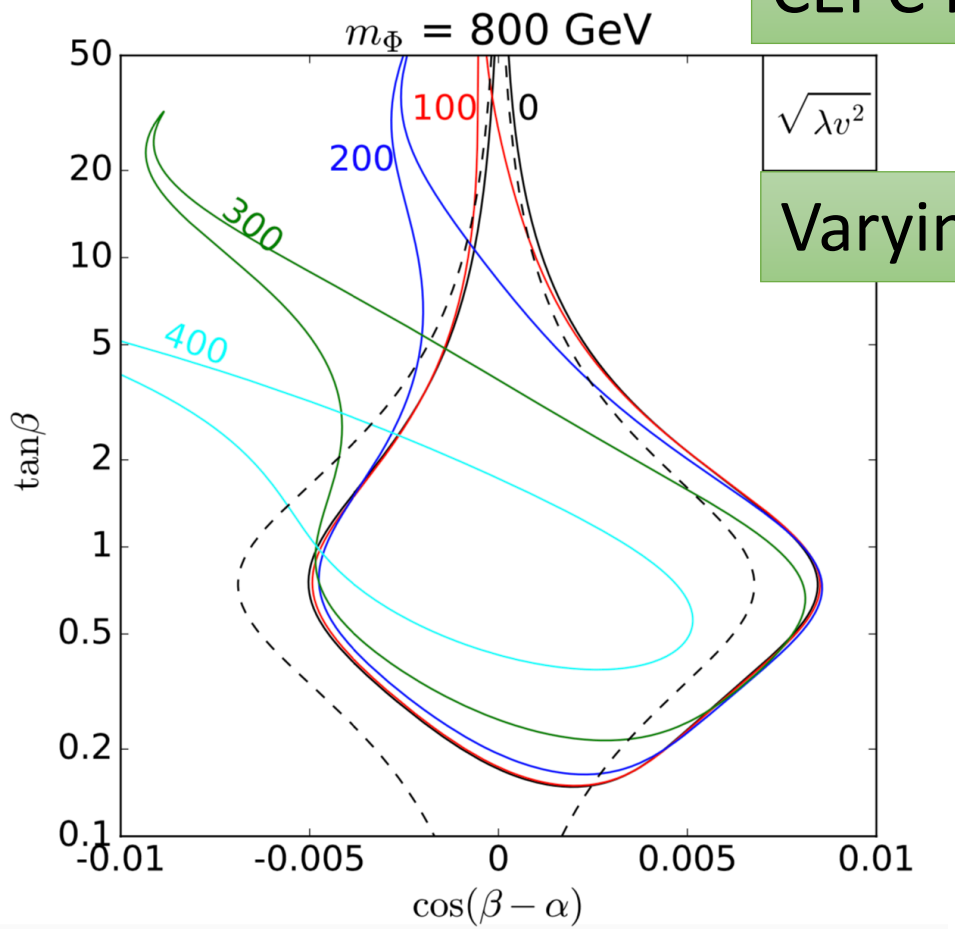
2HDM: *Tree + Loop + degenerate*



2HDM: *Tree + Loop + degenerate*

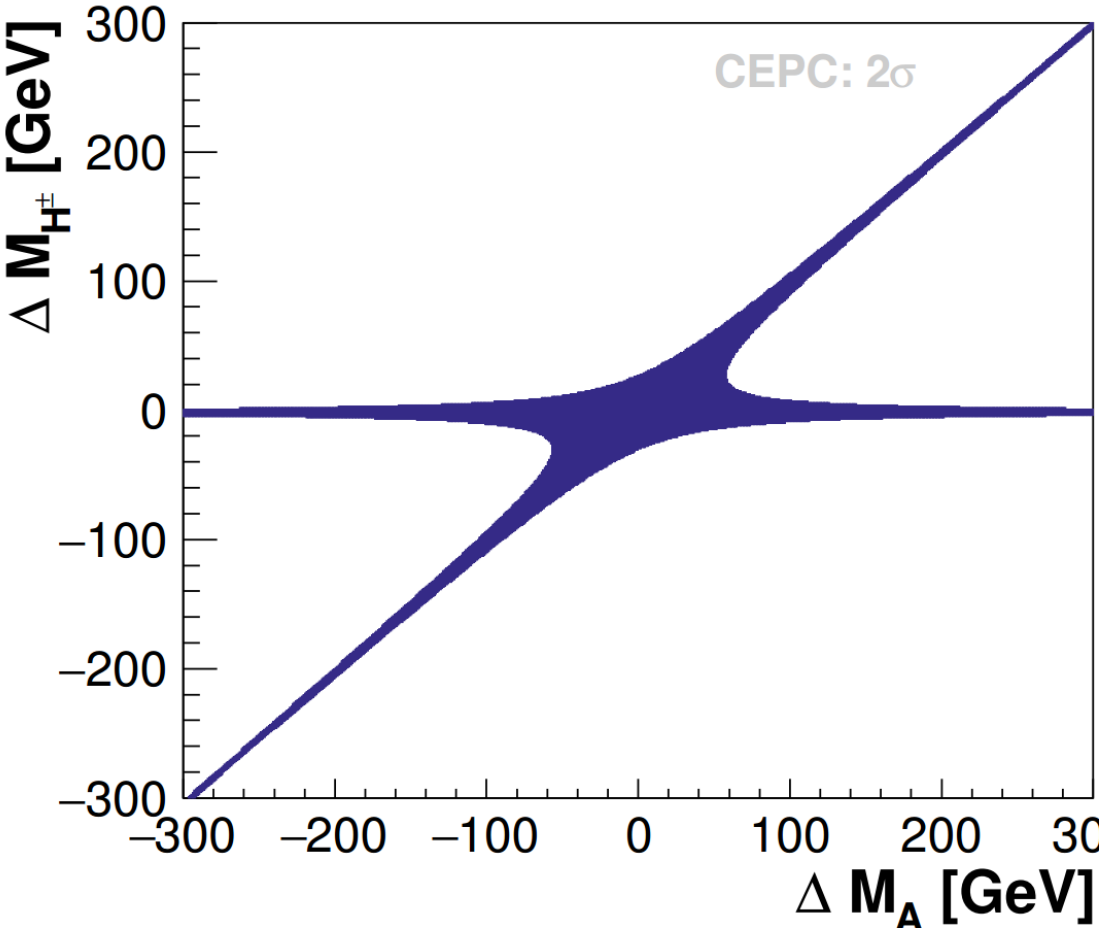


CEPC fit, Type-II



Varying $\lambda\, v$^2

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



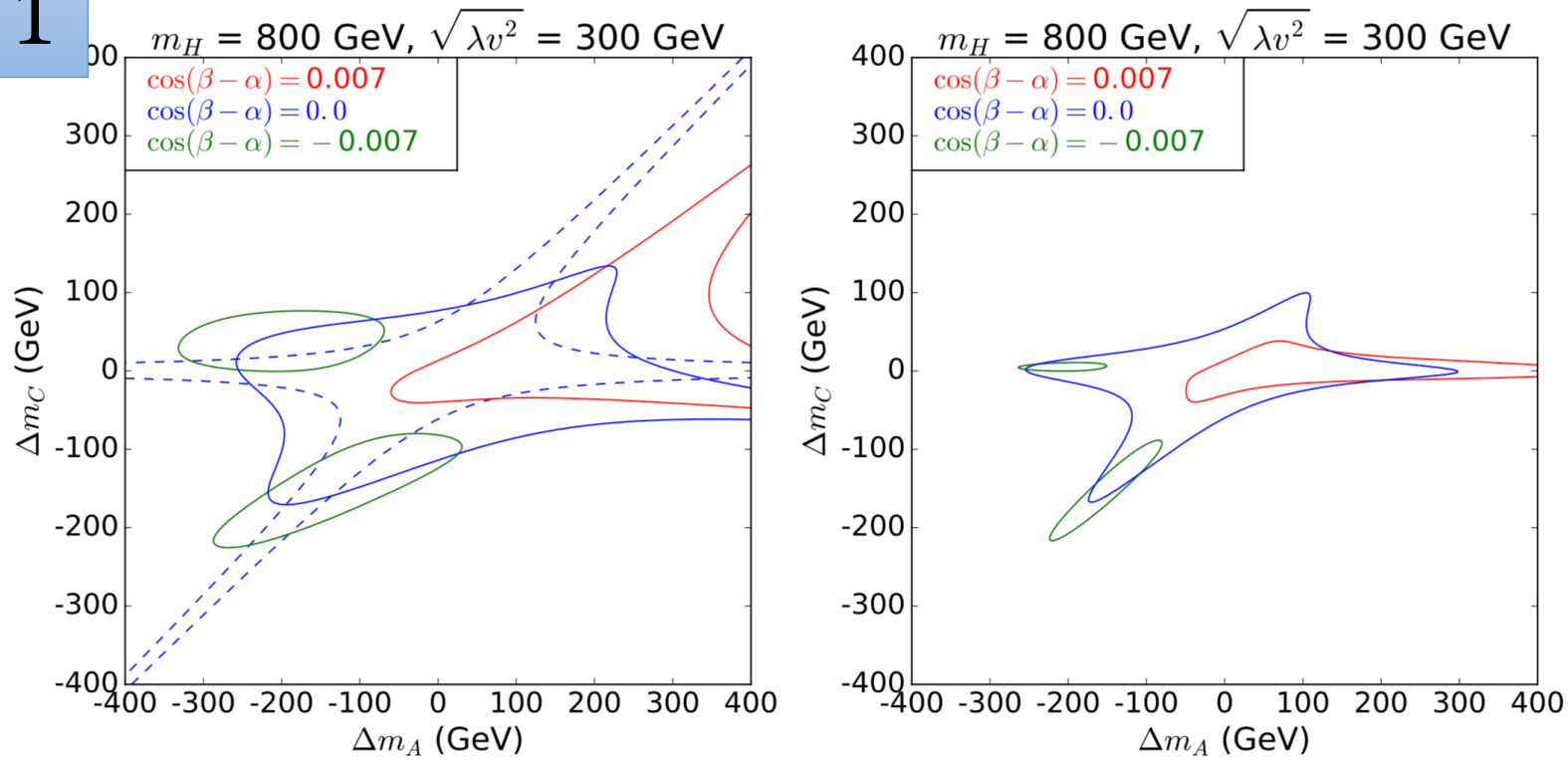
$$\Delta m_a = m_A - m_H,$$
$$\Delta m_c = m_{H^\pm} - m_H$$

Z pole

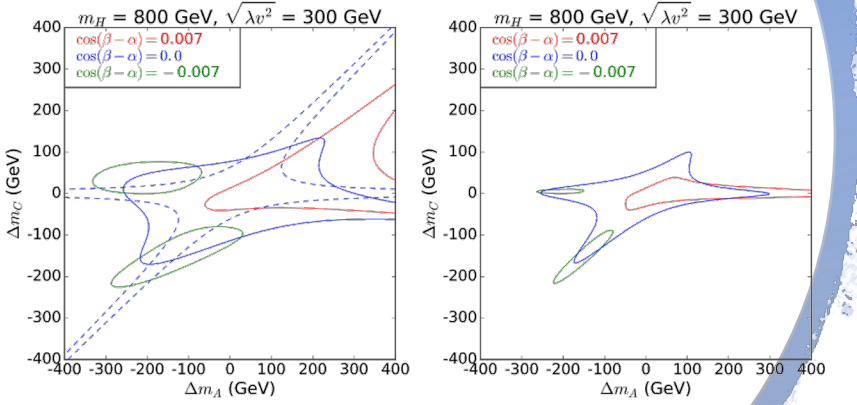
$$m_{H^\pm} = m_H$$
$$m_{H^\pm} = m_A$$

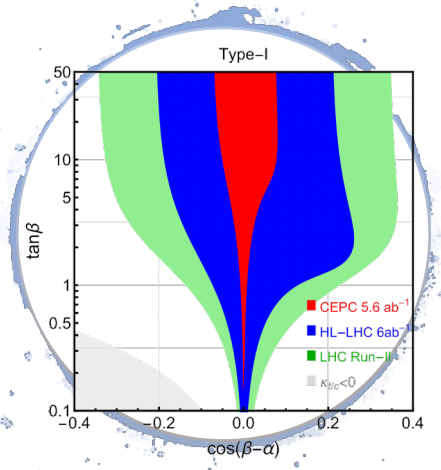
2HDM: $Tree + Loop + non - degenerate$

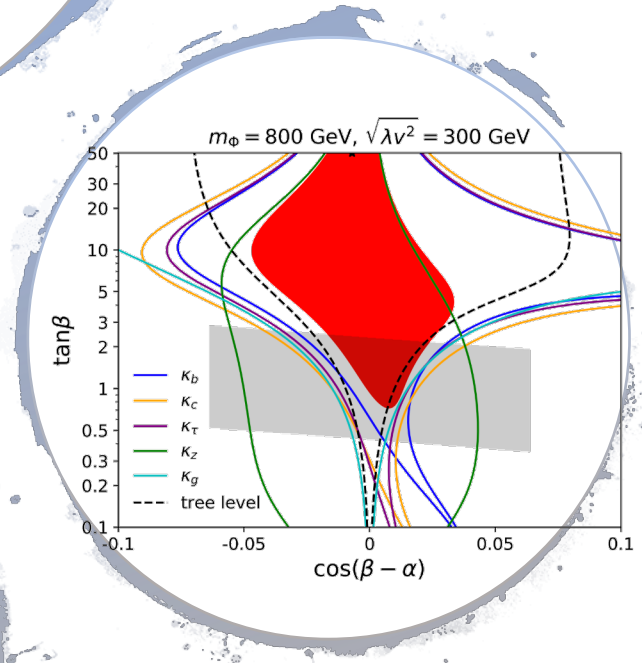
$\tan\beta = 1$

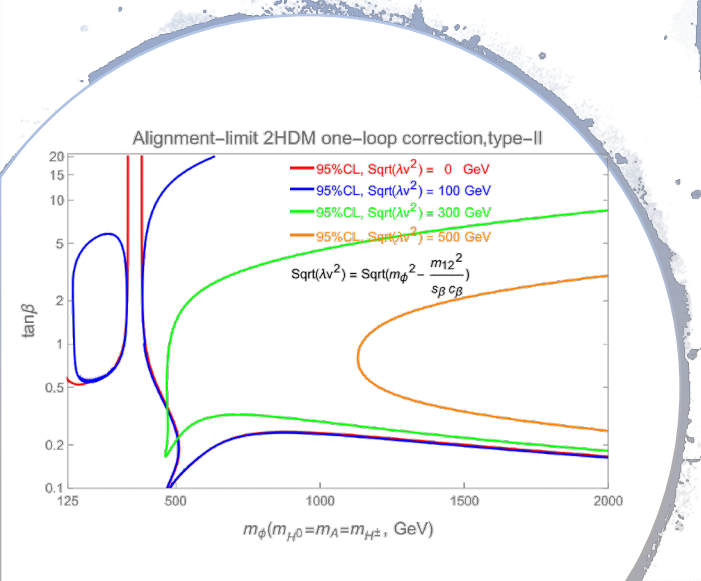


Complementary to Z pole precision









Conclusion

- Tree level studies
- Loop level studies

- Large $tan\beta$ of Type-I
- Complementary to HL-LHC
- Higgs precisions also constrain non-SM Higgs mass splitting
- (lepton collider comparison …)

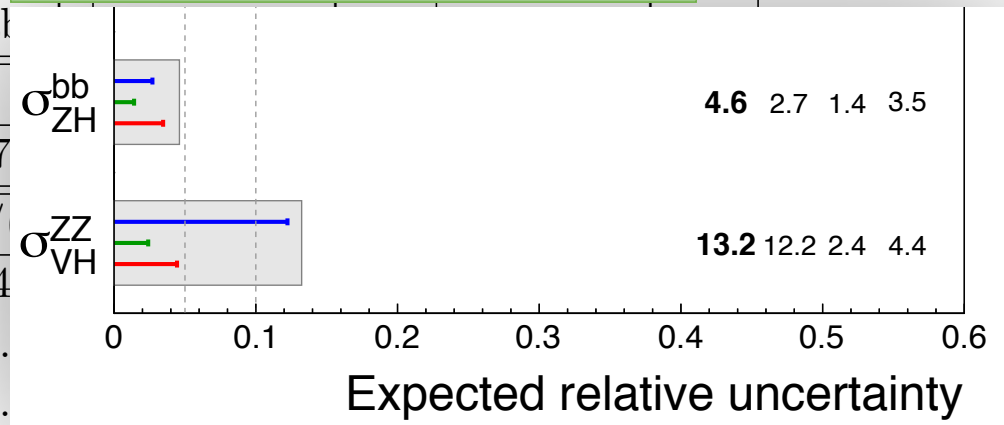
Thanks for your attention!

Precision: Higgs couplings

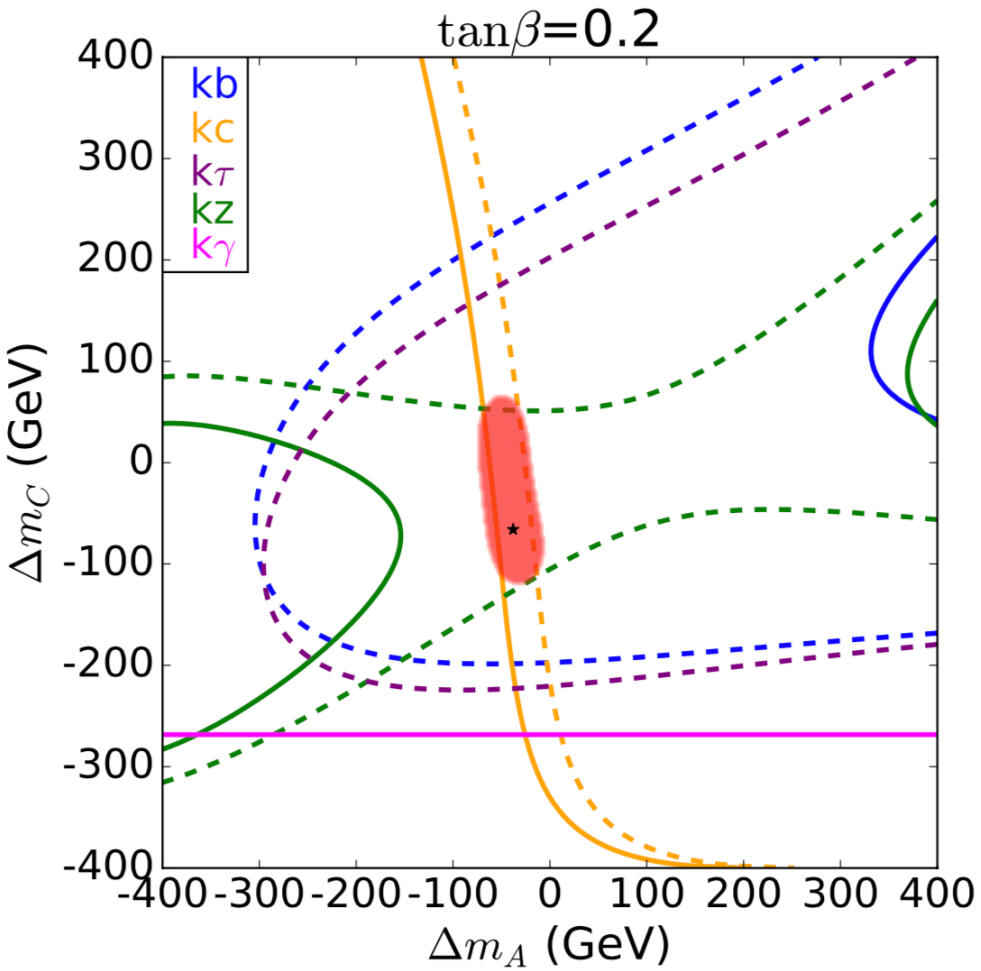
CEPC-CDR , FCC-ee, ILC Operating Scenarios

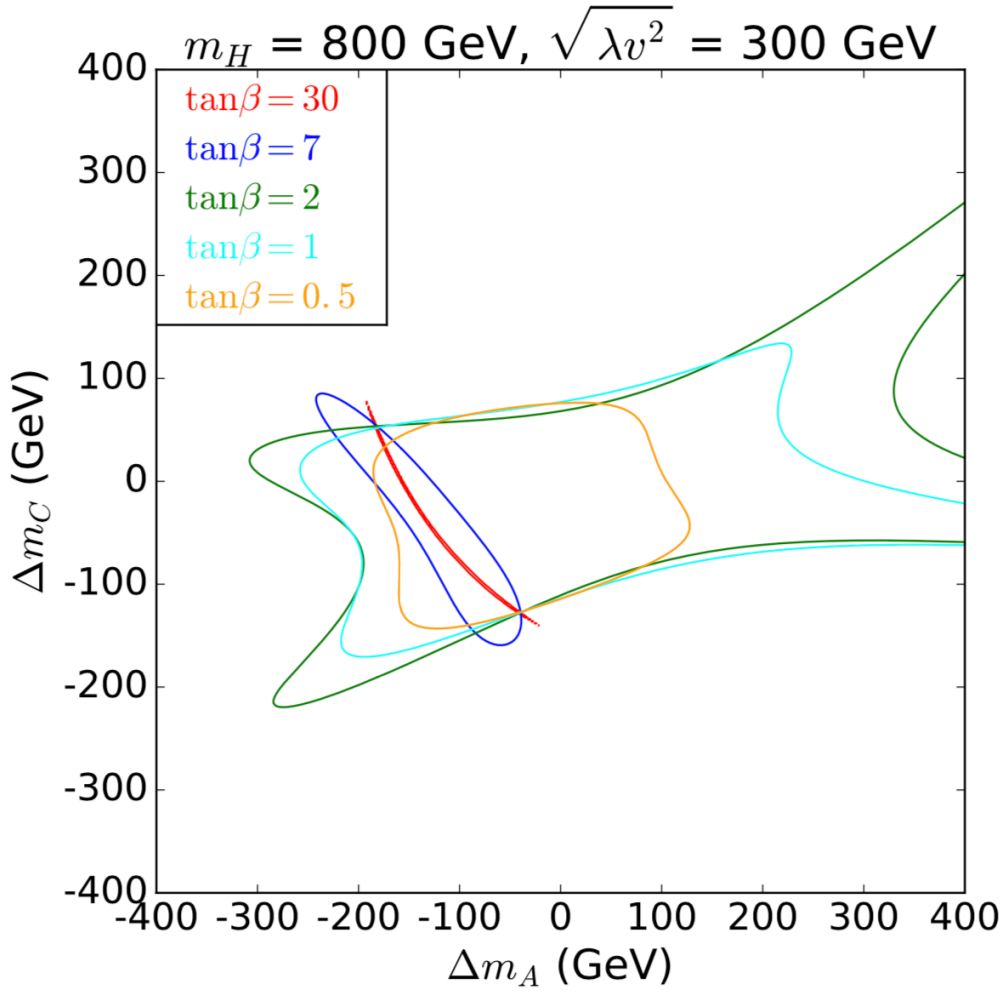
collider	CEPC	FCC-ee			ILC				
$\sqrt{s}$	240 GeV	240 GeV	365 GeV		250 G				
$\int \mathcal{L}dt$	5.6 ab^{-1}	5 ab^{-1}	1.5 ab^{-1}		2 ab				
production	Zh	Zh	Zh	$\nu\bar{\nu}h$					
$\Delta\sigma/\sigma$	0.5%	0.5%	0.9%	–	0.7				
decay					$\Delta(\sigma \cdot BR)/$				
$h \to b\bar{b}$	0.27%	0.3%	0.5%	0.9%	0.4				
$h \to c\bar{c}$	3.3%	2.2%	6.5%	10%	2.				
$h \to gg$	1.3%	1.9%	3.5%	4.5%	2.				
$h \to WW^*$	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%	–	–	–	–

HL-LHC: 1902.00134



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

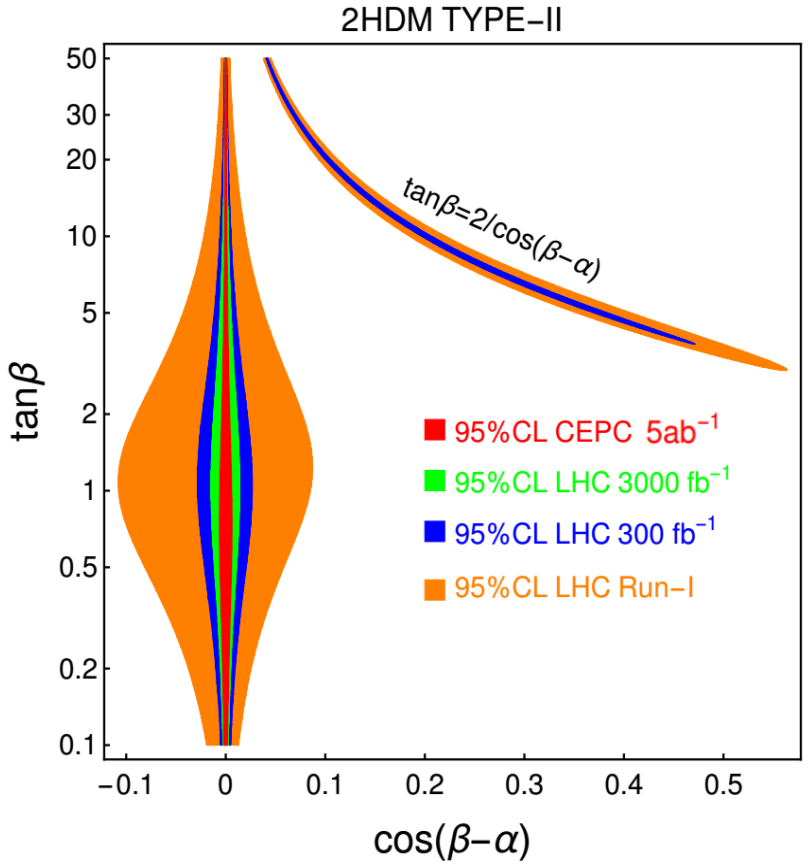


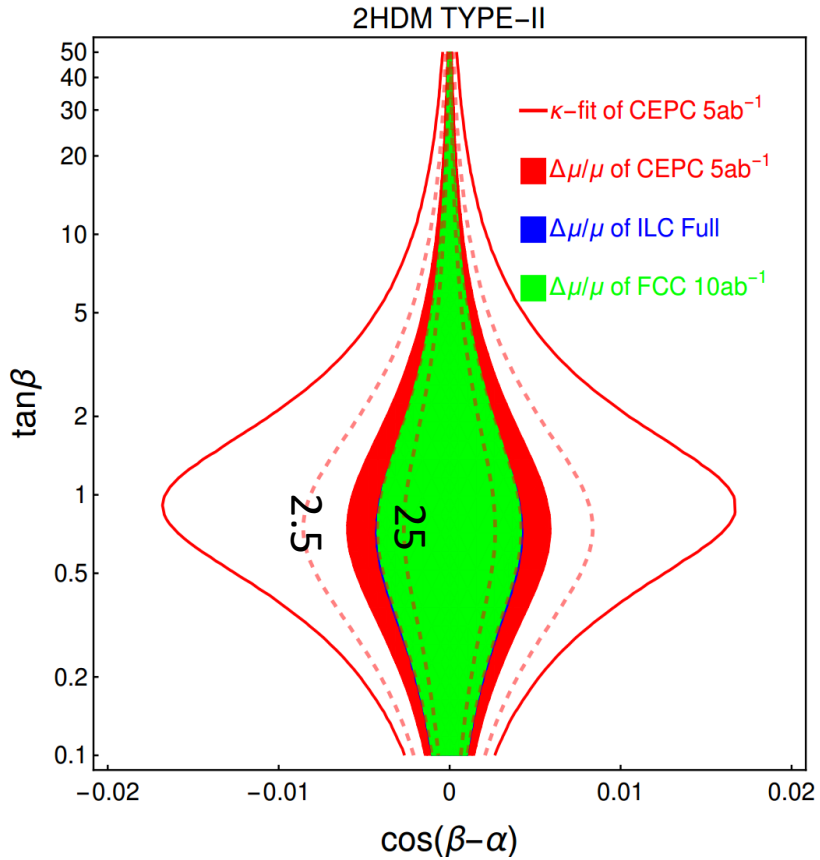


2HDM: Tree Level

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



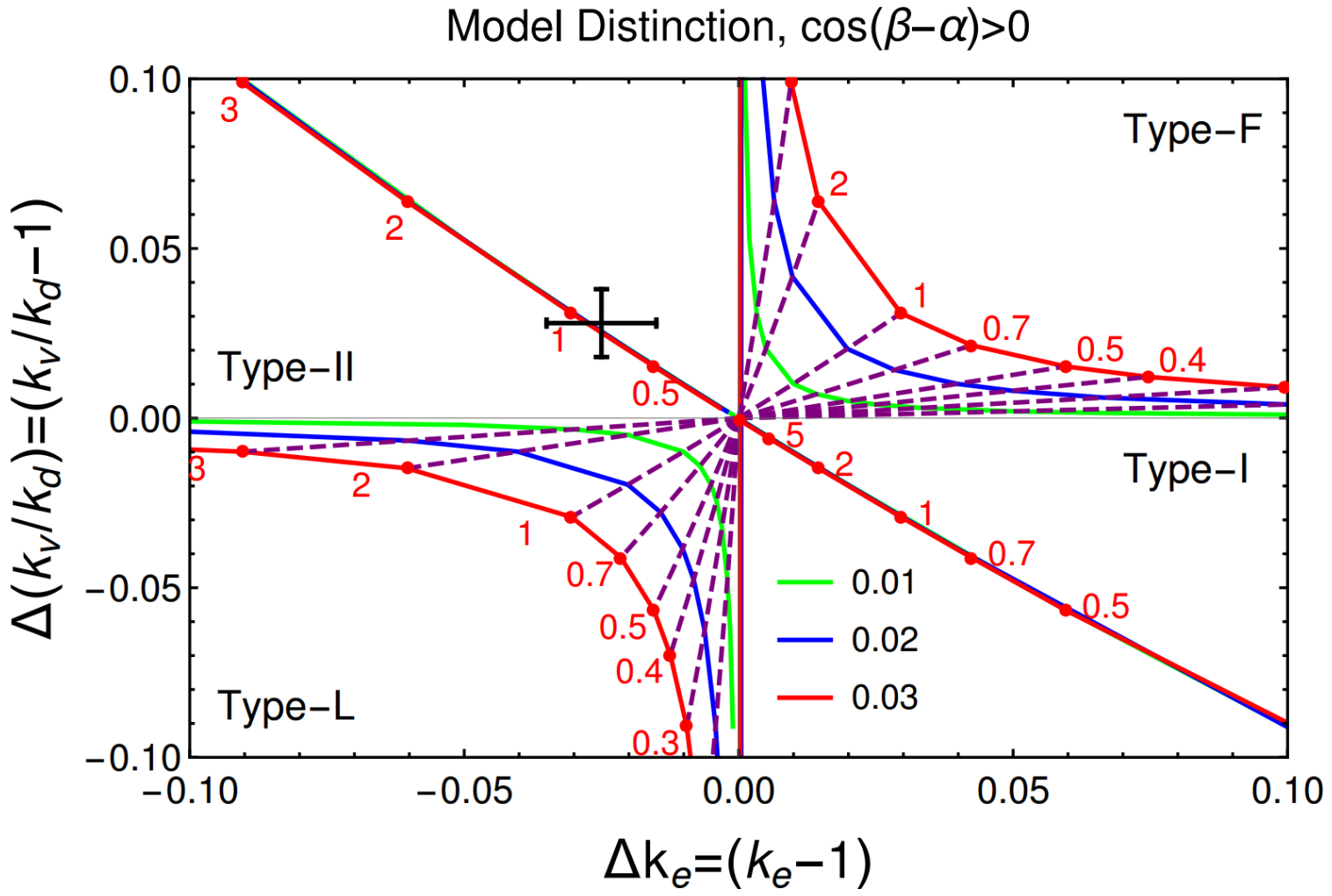


Alignment limit :

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

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

2HDM: One-Loop Level Model Distinction



Varying tan β

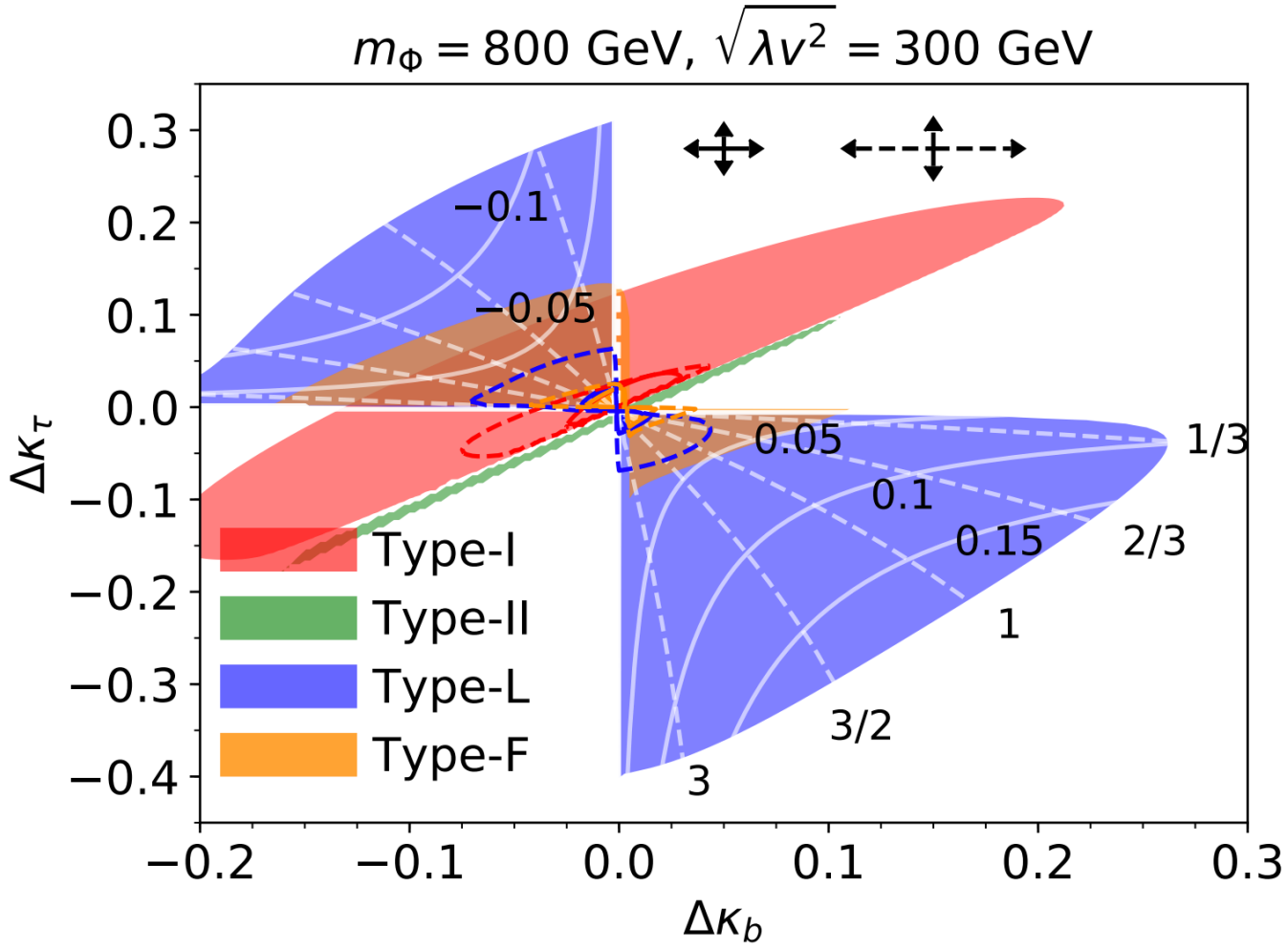
$\cos(\beta - \alpha)$

0.01

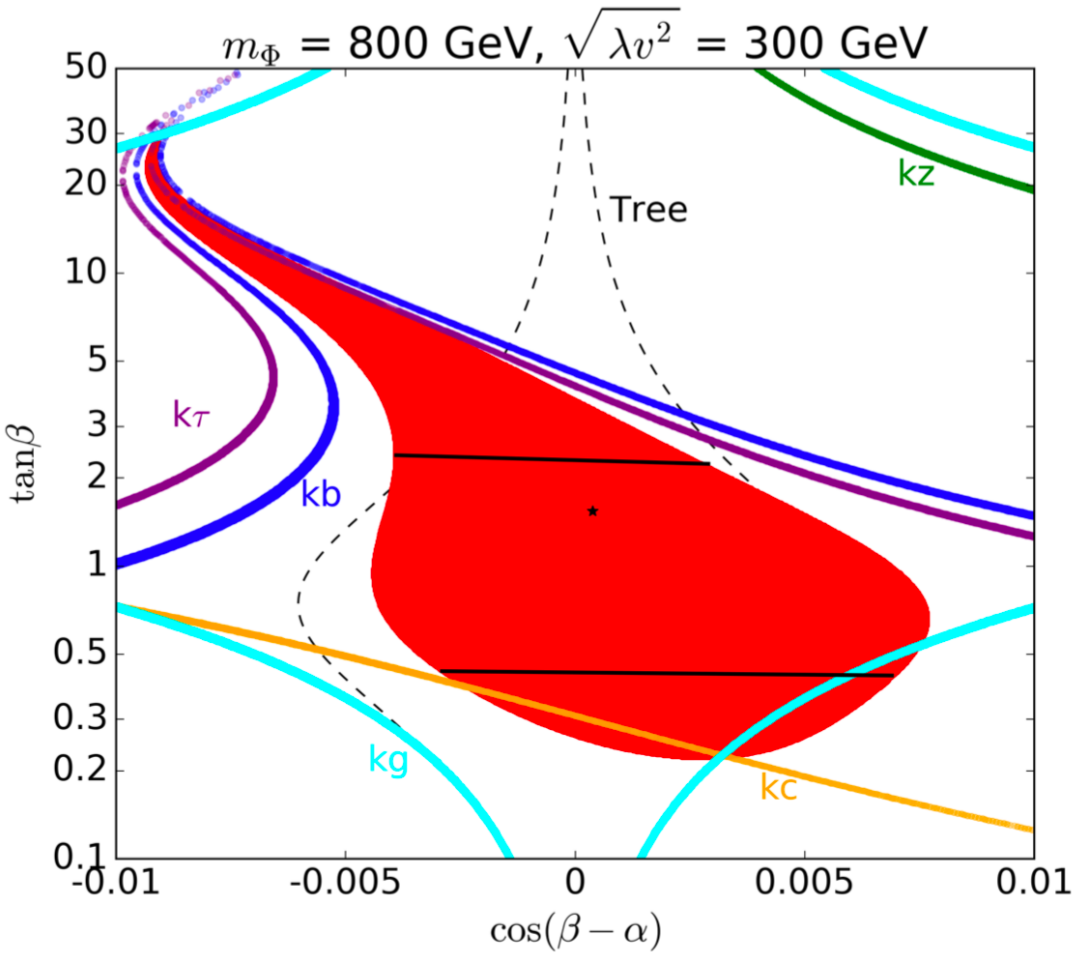
0.02

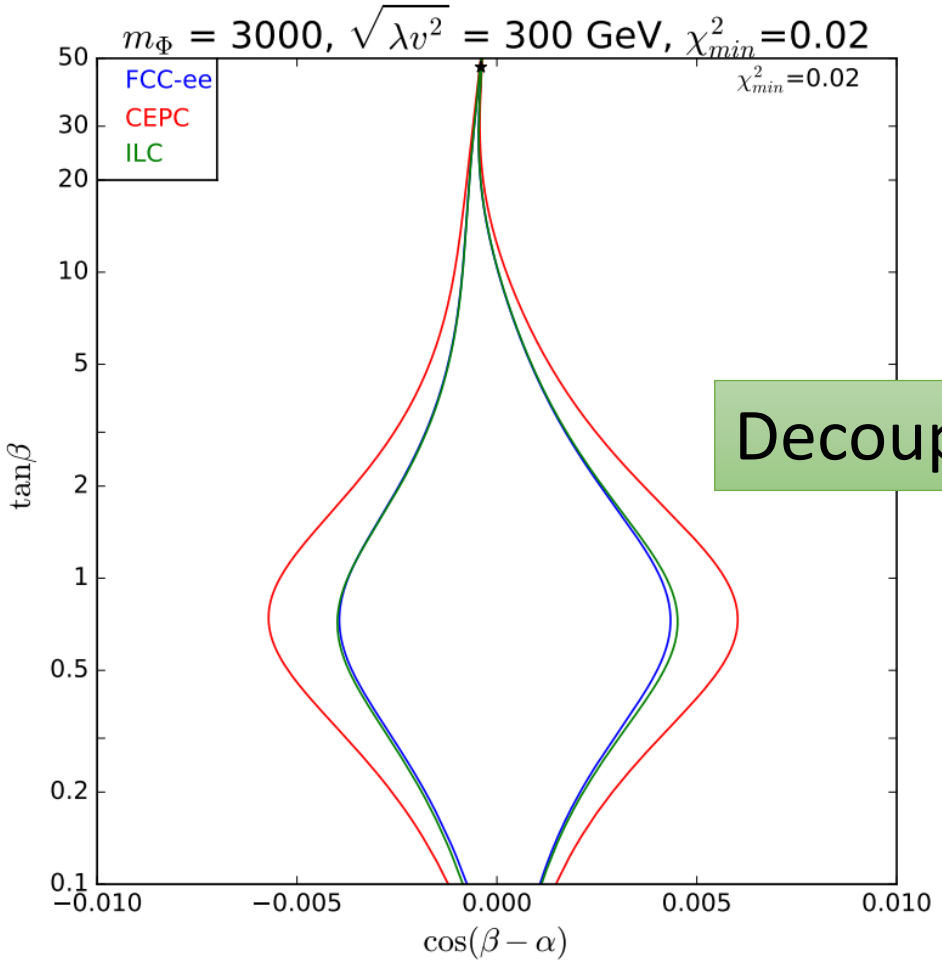
0.03

2HDM: One-Loop Level Model Distinction



2HDM: *Tree + Loop + degenerate*





Decouple

2HDM: *Tree + Loop + degenerate*