

Higgs Measurements @ CEPC and Its Implication on 2HDM



Shufang Su • U. of Arizona

CEPC Workshop

Yangzhou

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J. Gu, H. Li, Z. Liu, W. Su, 1709.06103

N. Chen, T. Han, SS, W. Su, Y. Wu, 1808.02037

N. Chen, T. Han, S. Li, SS, W. Su, Y. Wu, 1912.01431

T. Han, S. Li, SS, W. Su, Y. Wu, 2008.05492

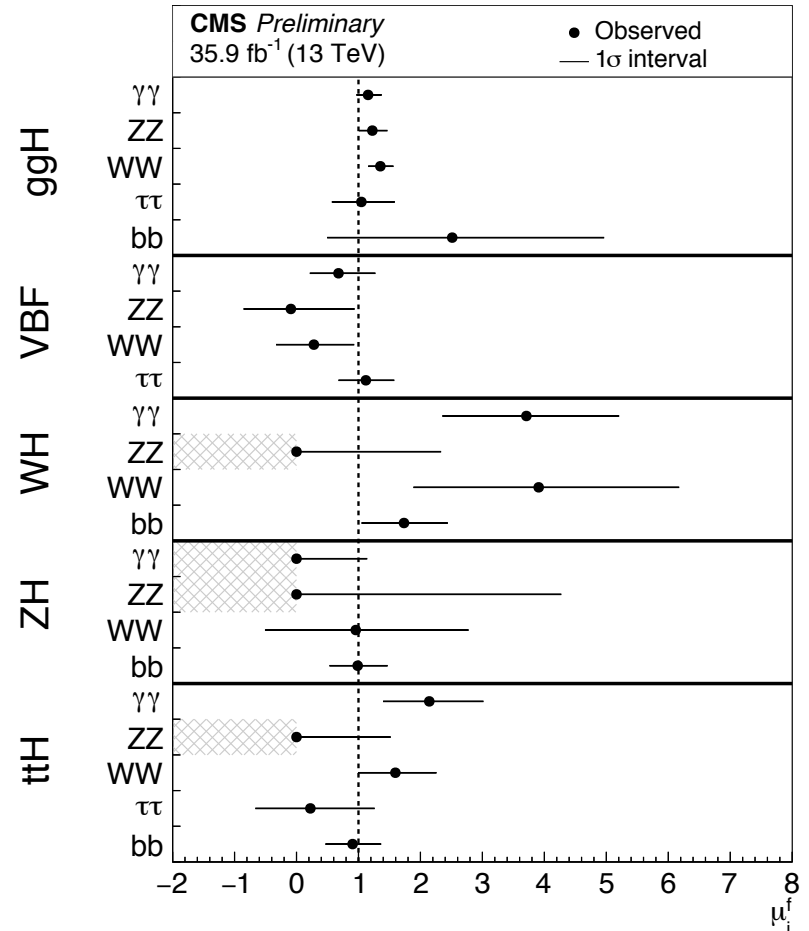
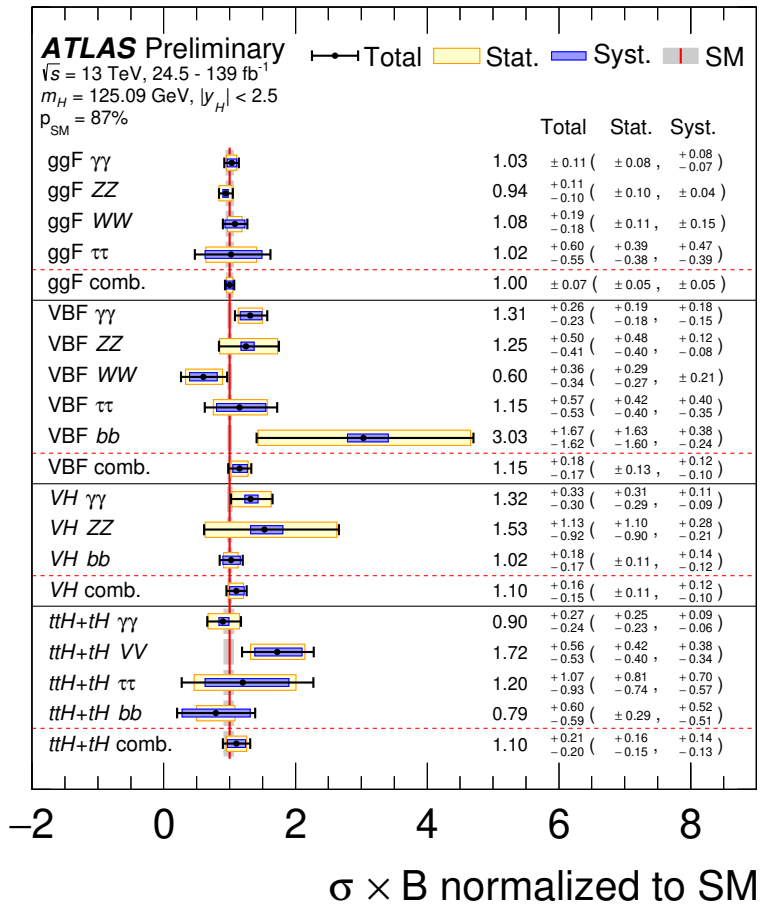
S. Su

Outline

- Higgs precision measurements
- Global fit framework
- Extended Higgs Sector: 2HDM
 - Tree vs Loop
 - Degenerate vs. Non-degenerate
 - Higgs vs. Z-pole
- Distinguish different types of 2HDMs **new**
- Conclusion

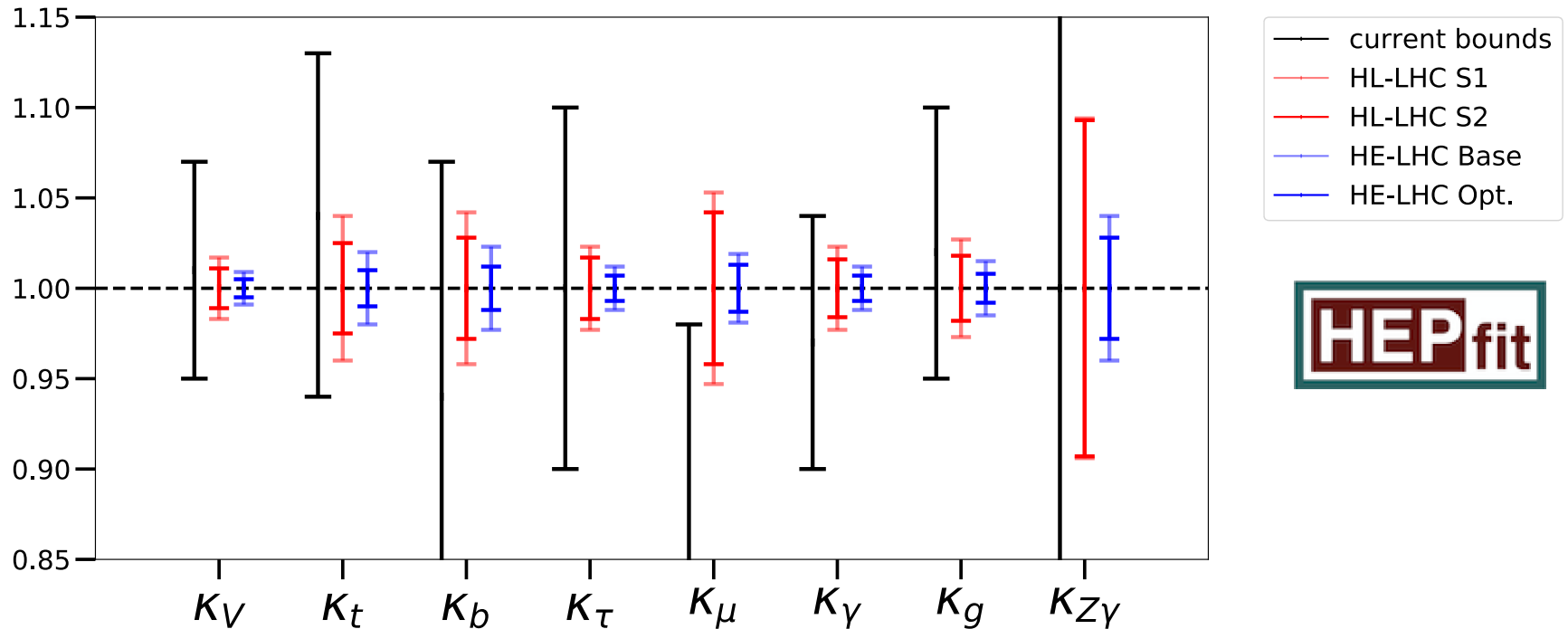
Higgs Precision Measurements

LHC: 13 TeV



Higgs Precision Measurements

LHC: 14 TeV, 300 fb⁻¹, 3000 fb⁻¹



Higgs Precision Measurements

CEPC / FCC / ILC

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

Higgs Precision Measurements

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Kappa framework and EFT Framework

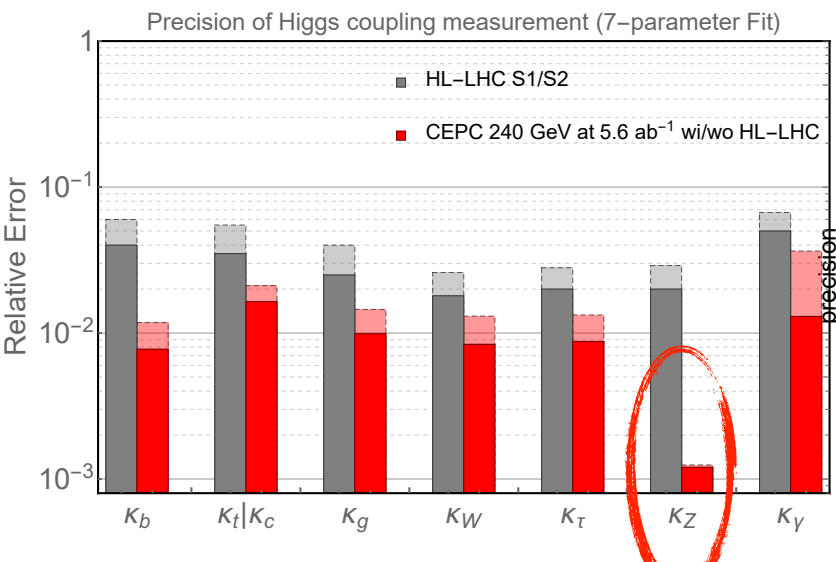
Two model-independent approaches

kappa framework

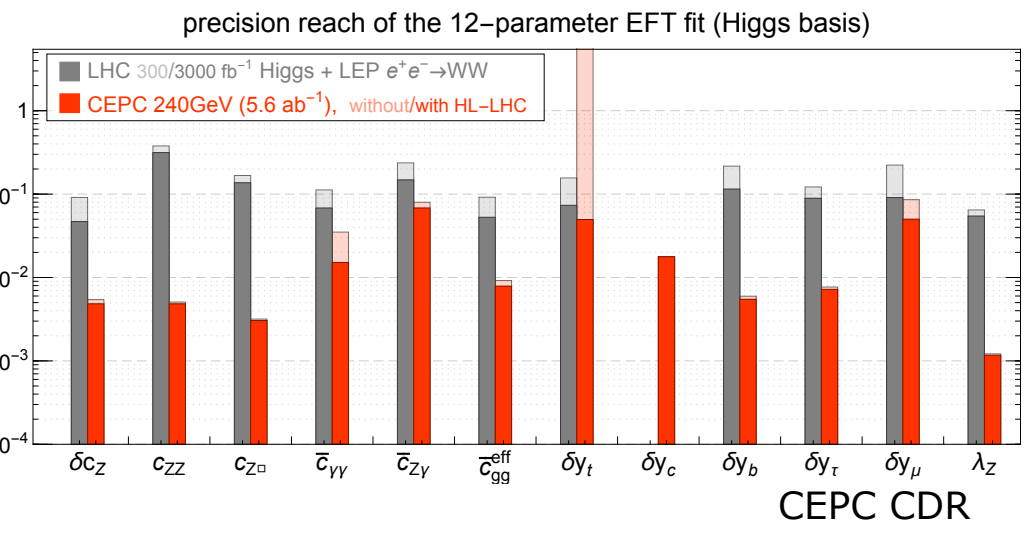
$$\kappa_f = \frac{g(hff)}{g(hff; SM)}, \quad \kappa_V = \frac{g(hVV)}{g(hVV; SM)}$$

EFT framework

$$\delta c_Z, c_{ZZ}, c_{Z\Box}, c_{\gamma\gamma}, c_{Z\gamma}, c_{gg}, \delta y_u, \delta y_d, \delta y_e, \lambda_Z$$

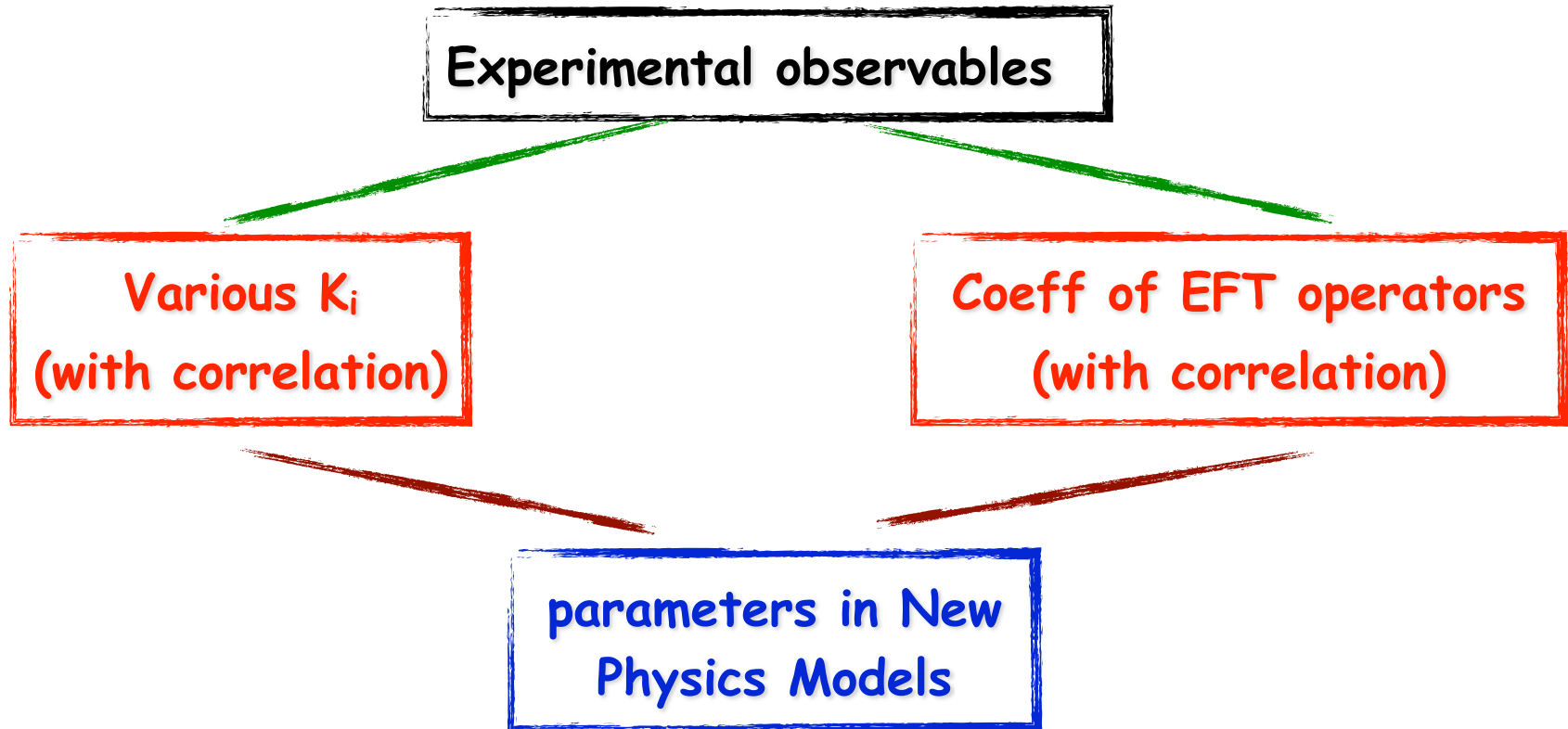


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New Physics Implication

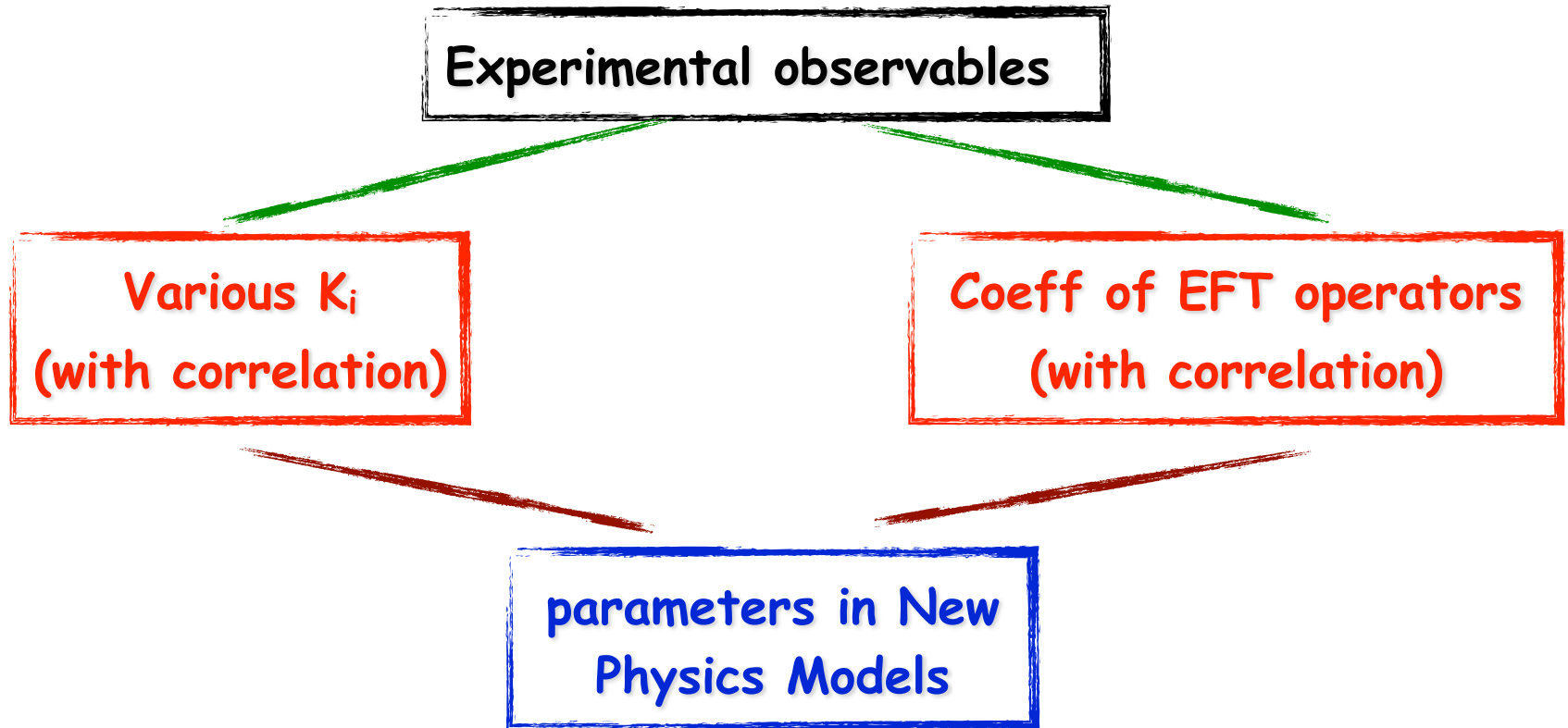


Kappa Framework and EFT Framework

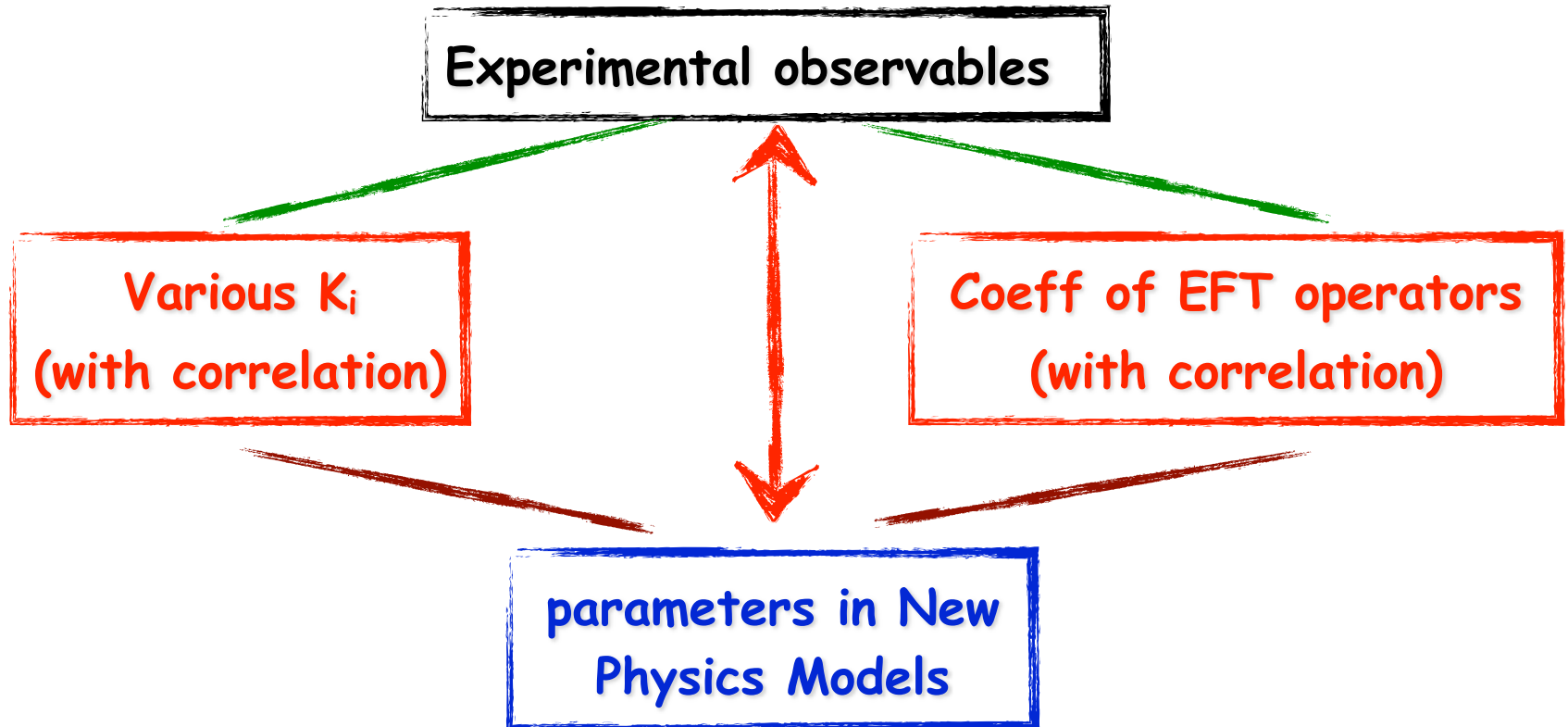
limitations of model-independent approaches

- large level of degeneracy
 - parameter space for specific model much smaller
- correlation matrix often not provided
 - over conservative estimation when not include correlation
- assumptions and simplifications
 - may not be valid for a particular model

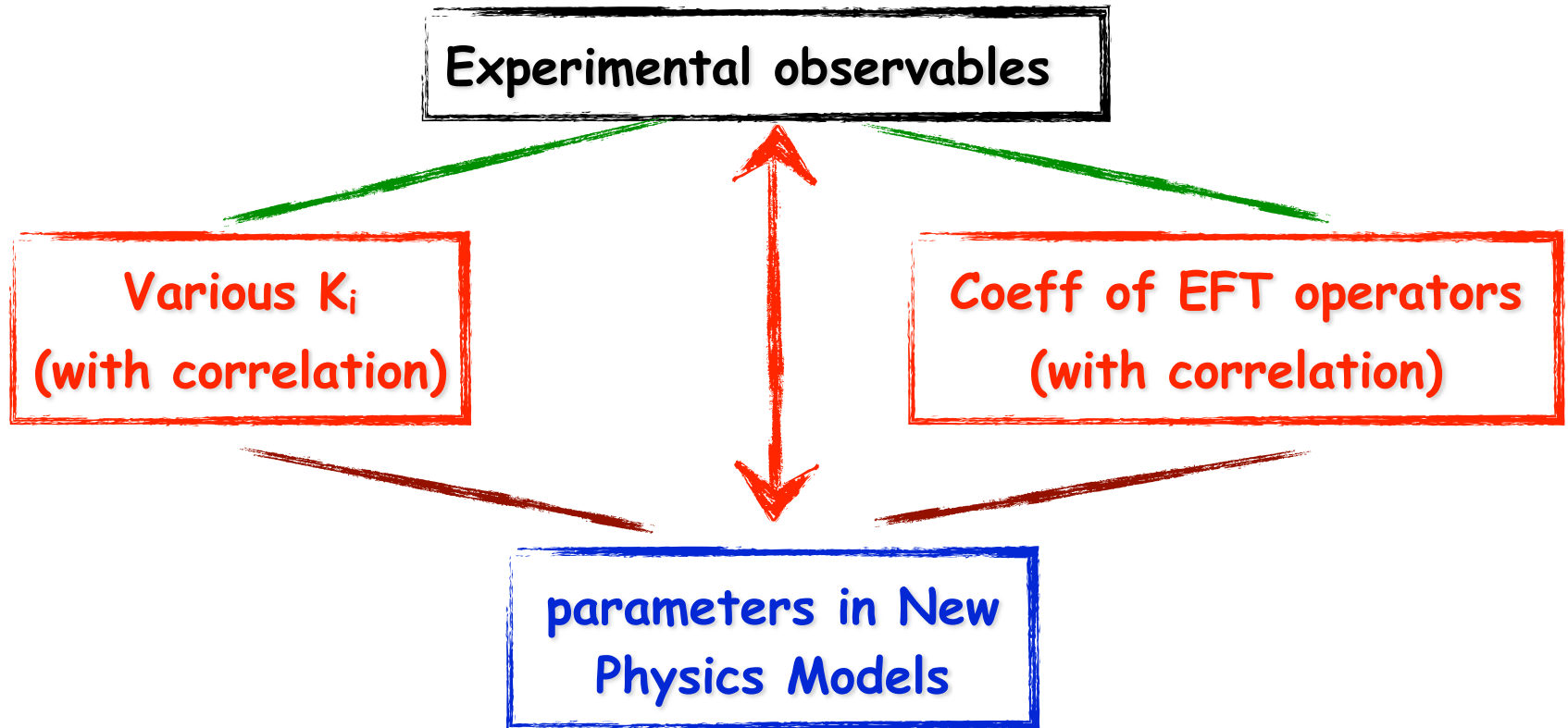
New Physics Implication



New Physics Implication



New Physics Implication



$$\chi^2 = \sum_i \frac{(\mu_i^{\text{BSM}} - \mu_i^{\text{obs}})^2}{\sigma_{\mu_i}^2} \quad \mu_i^{\text{BSM}} = \frac{(\sigma \times \text{Br})_{\text{BSM}}}{(\sigma \times \text{Br})_{\text{SM}}}$$

2HDM in one slide

Two Higgs Doublet Model (CP-conserving)

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

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

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

after EWSB, 5 physical Higgses

CP-even Higgses: h^0, H^0 , CP-odd Higgs: A^0 , Charged Higgses: H^\pm

h⁰/H⁰ VV coupling

$$g_{H^0 VV} = \frac{m_V^2}{v} \cos(\beta - \alpha), \quad g_{h^0 VV} = \frac{m_V^2}{v} \sin(\beta - \alpha).$$

alignment limit: $\cos(\beta - \alpha) = 0$, h^0 is the SM Higgs with SM couplings.

2HDM parameters

	ϕ_1	ϕ_2
Type I	u,d,l	
Type II	u	d,l
lepton-specific	u,d	l
flipped	u,l	d

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)

$$m_{11}^2, m_{22}^2, \lambda_1, \lambda_2, \lambda_3, \lambda_4, \lambda_5$$

soft Z_2 breaking: m_{12}^2



246 GeV

125 GeV

$$v, \tan \beta, \alpha, m_h, m_H, m_A, m_{H^\pm}$$

$\tan \beta, \cos(\beta - \alpha)$,

control tree level h^0 couplings

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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)

$m_{11}^2, m_{22}^2, \lambda_1, \lambda_2, \lambda_3, \lambda_4, \lambda_5$

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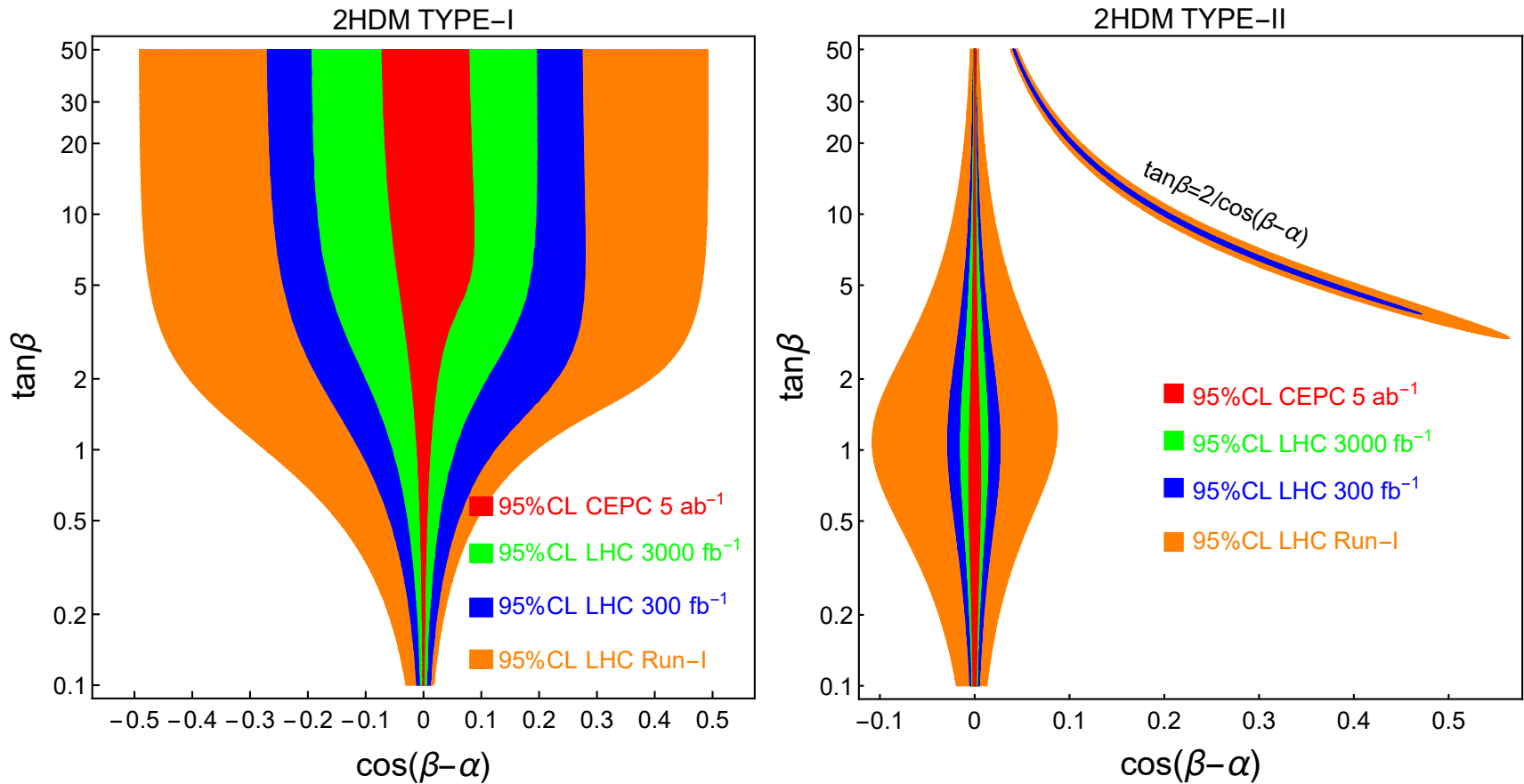
$v, \tan \beta, \alpha, m_h, m_H, m_A, m_{H^\pm}$

$\tan \beta, \cos(\beta - \alpha),$

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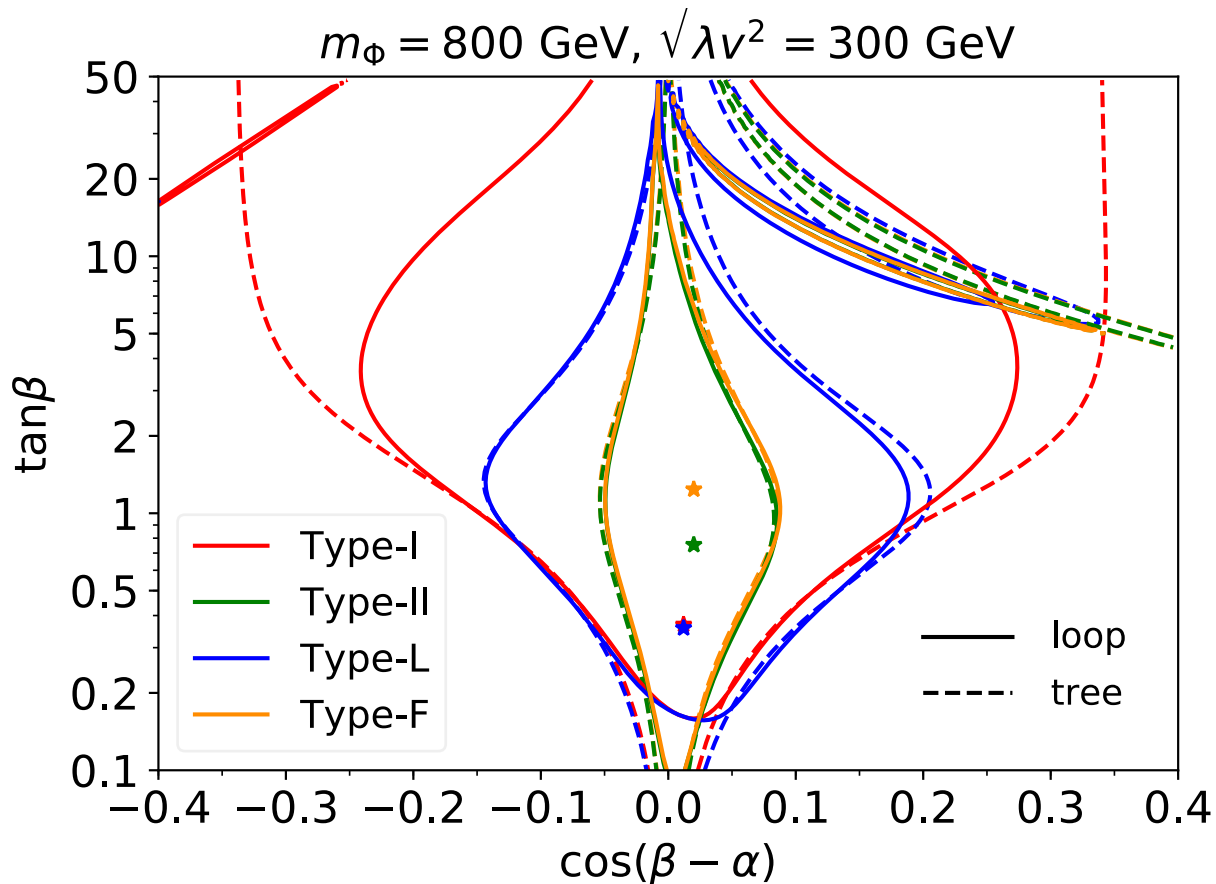
Tree-level 2HDM fit

2HDM, LHC/CEPC fit



Tree-level 2HDM fit

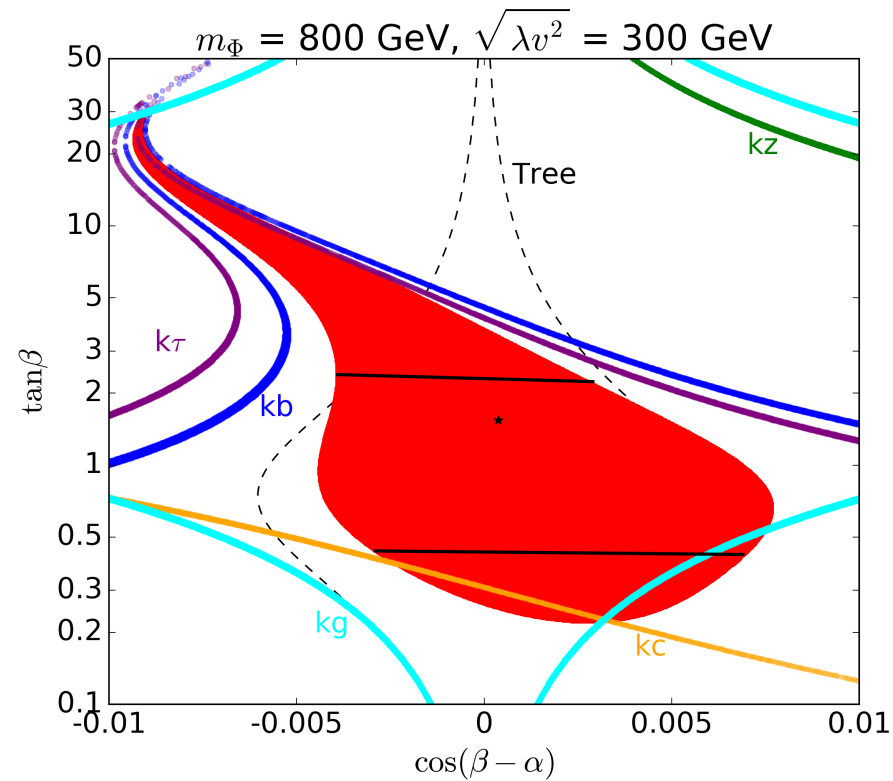
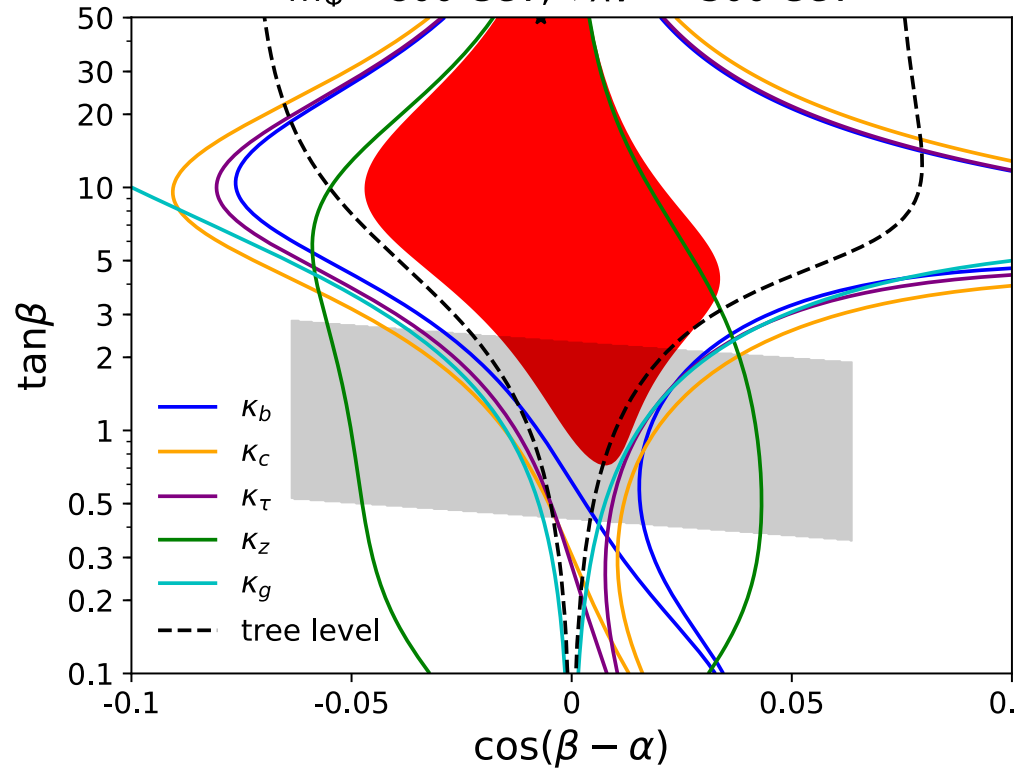
2HDM, LHC fit



2HDM: Tree + Loop

2HDM, CEPC fit

$m_\phi = 800 \text{ GeV}, \sqrt{\lambda v^2} = 300 \text{ GeV}$

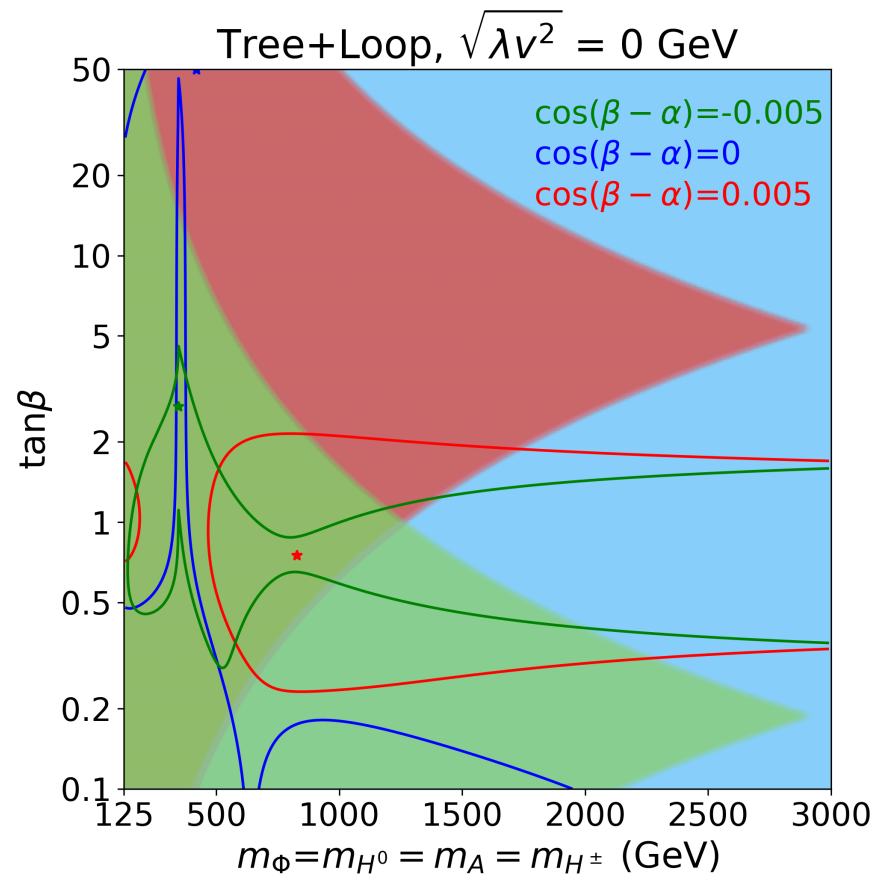
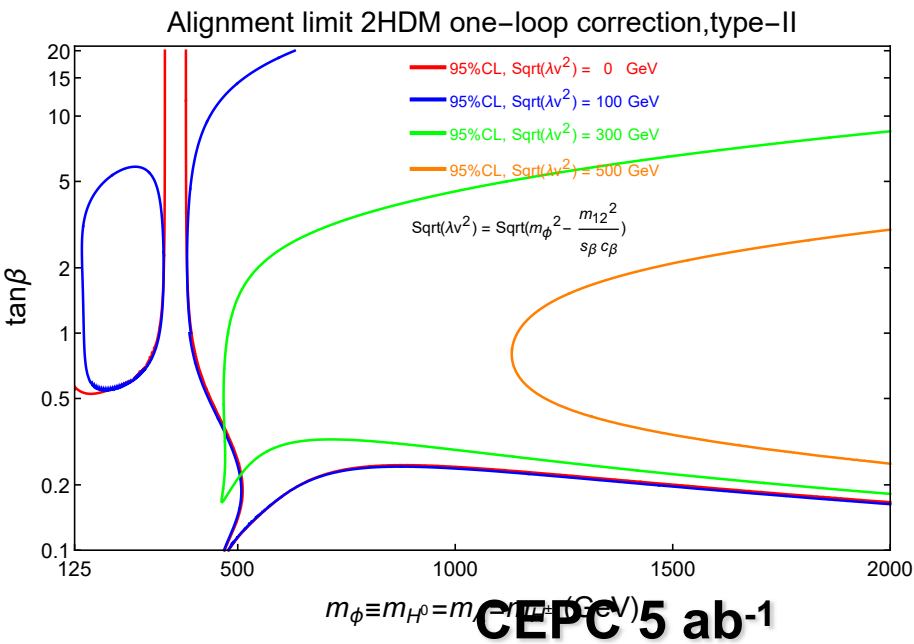


2HDM: Loop in the Alignment Limit

● Type II

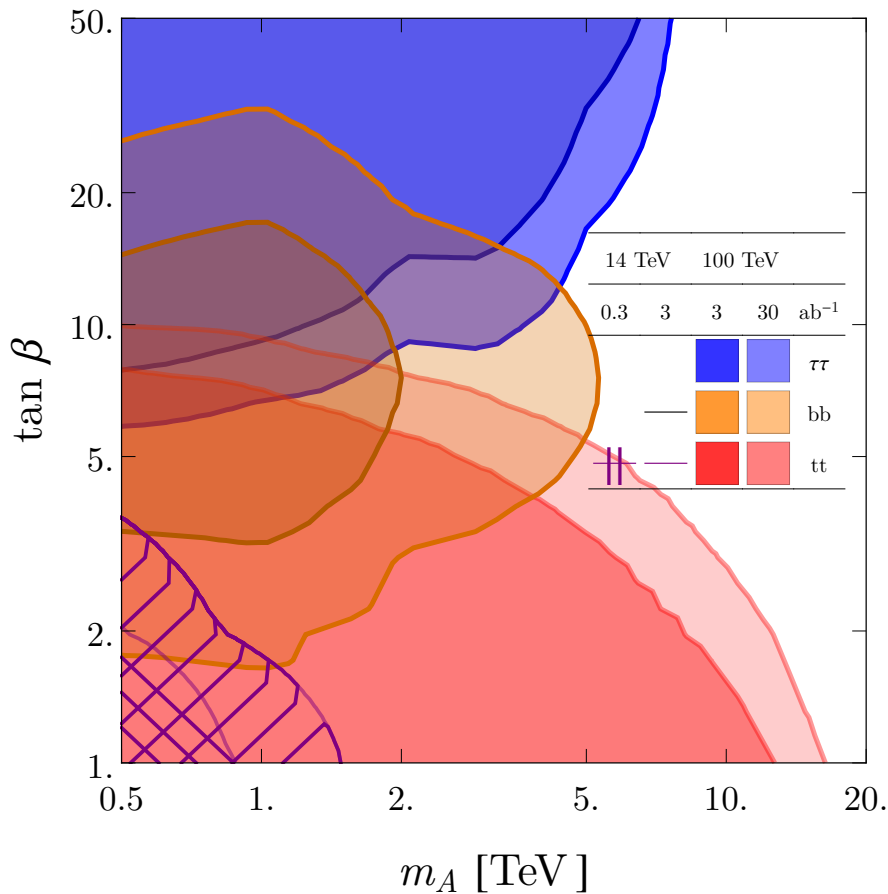
$$\kappa_{\text{loop}}^{\text{2HDM}} \equiv \frac{g_{\text{tree}}^{\text{2HDM}} + g_{\text{loop}}^{\text{2HDM}}}{g_{\text{tree}}^{\text{SM}} + g_{\text{loop}}^{\text{SM}}}$$

$$\kappa_{1\text{-loop}}^{\text{2HDM}}|_{\text{alignment}} = 1 + \Delta\kappa_{1\text{-loop}}^{\text{2HDM}}$$

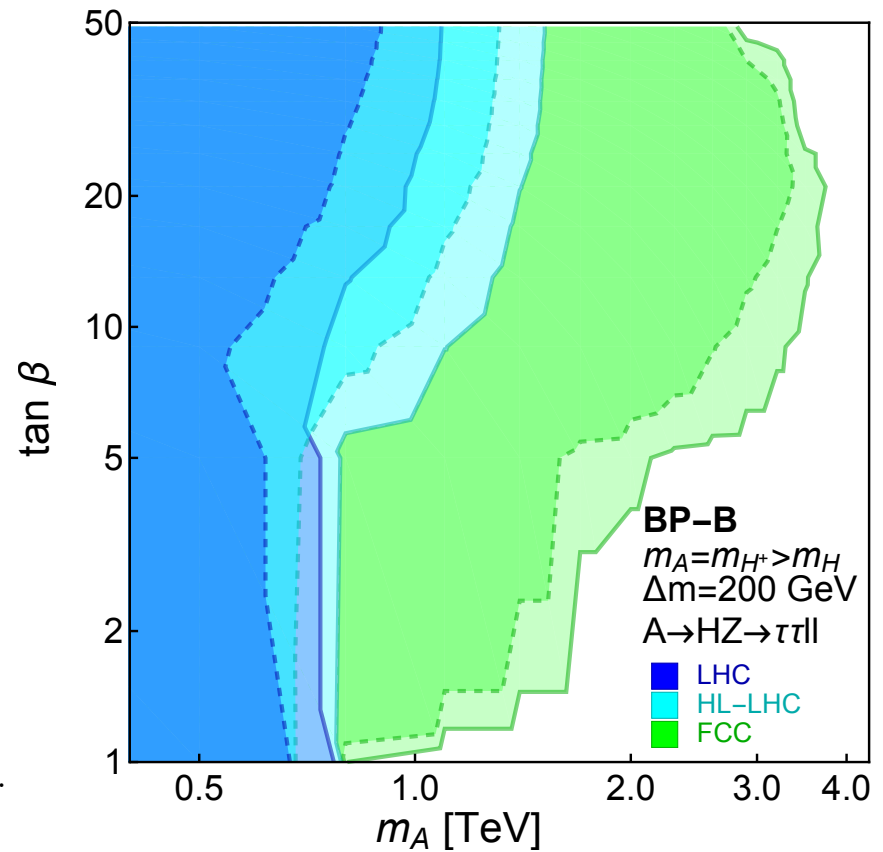


Direct Search of Heavy Higgses @ 100 pp

Conventional search

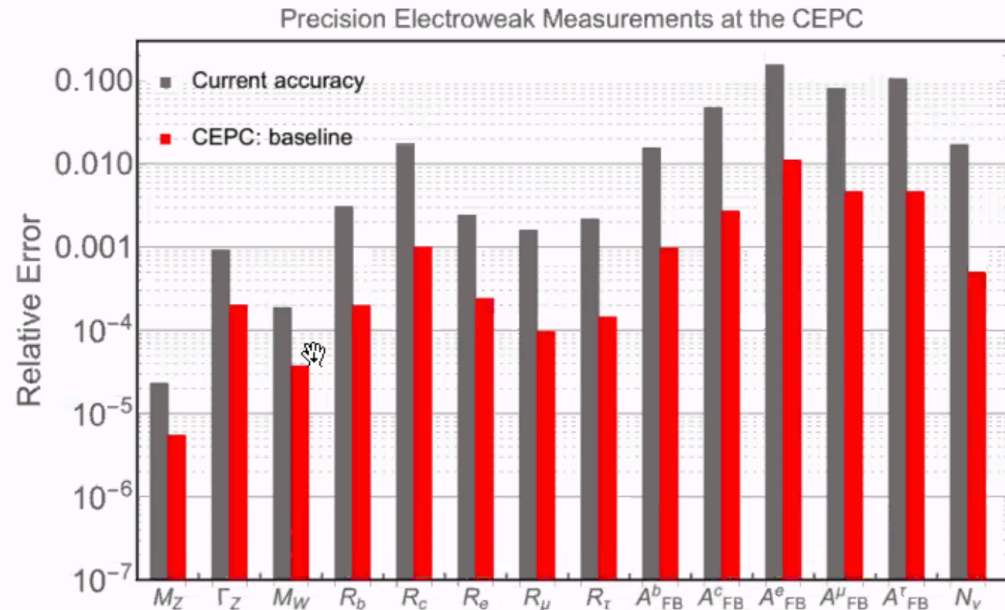


Exotic Decay



Z-pole precision

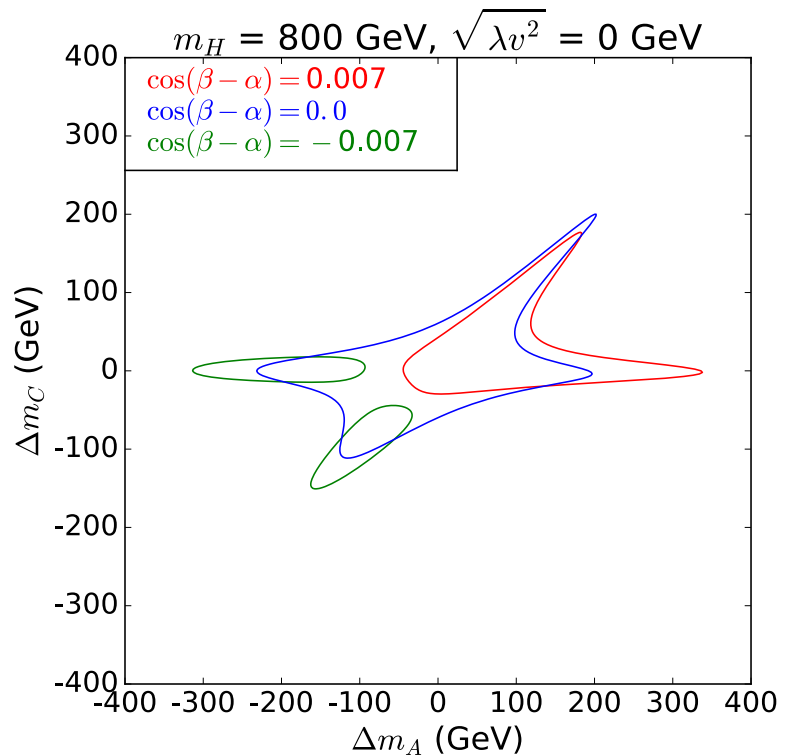
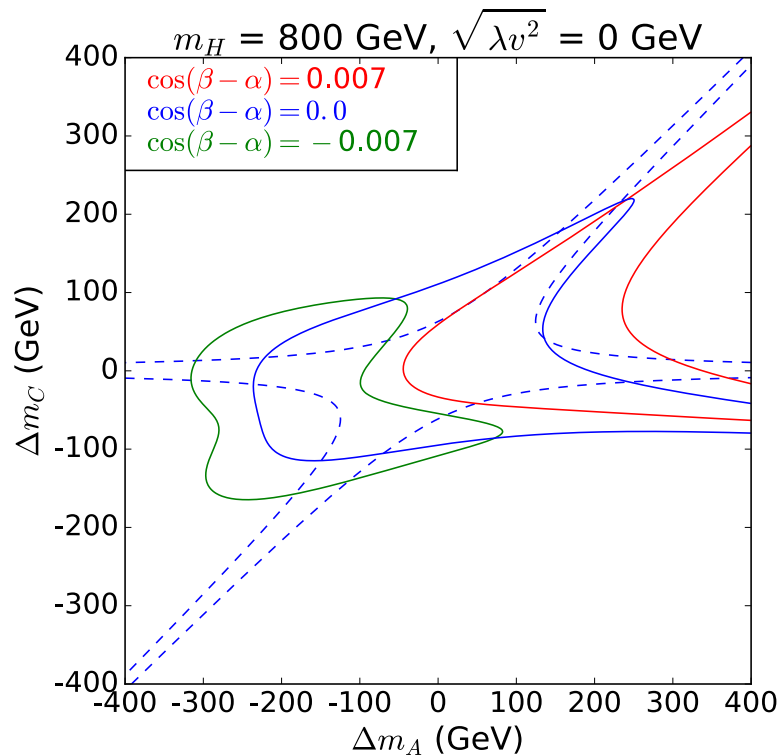
Observables	FCC-ee	CEPC	ILC
δm_h [GeV]	1.0×10^{-2}	5.9×10^{-3}	1.5×10^{-2}
$\delta \alpha_{\text{had}}$	$3.8 \times 10^{-5} *$	4.7×10^{-5}	$3.8 \times 10^{-5} *$
δm_Z [GeV]	1.0×10^{-4}	5.0×10^{-4}	2.1×10^{-3}
δm_t [GeV]	2.0×10^{-2}	6.0×10^{-1}	1.7×10^{-2}
δm_W [GeV]	7.0×10^{-4}	1.0×10^{-3}	2.5×10^{-3}
$\delta \Gamma_W$ [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}
δA_b^{FB}	3.0×10^{-4}	1.0×10^{-4}	$1.6 \times 10^{-3} *$
δA_c^{FB}	5.9×10^{-4}	2.2×10^{-4}	$3.5 \times 10^{-3} *$
$\delta A_\ell^{\text{FB}}$	9.0×10^{-6}	5.0×10^{-5}	$1.0 \times 10^{-3} *$
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}
$\delta \sigma_{\text{had}}$ [nb]	4.0×10^{-3}	5.0×10^{-3}	$3.7 \times 10^{-2} *$



	Current				CEPC				FCC-ee				ILC			
	σ	correlation			σ (10^{-2})	correlation			σ (10^{-2})	correlation			σ (10^{-2})	correlation		
		S	T	U		S	T	U		S	T	U		S	T	U
S	0.04 ± 0.11	1	0.92	-0.68	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

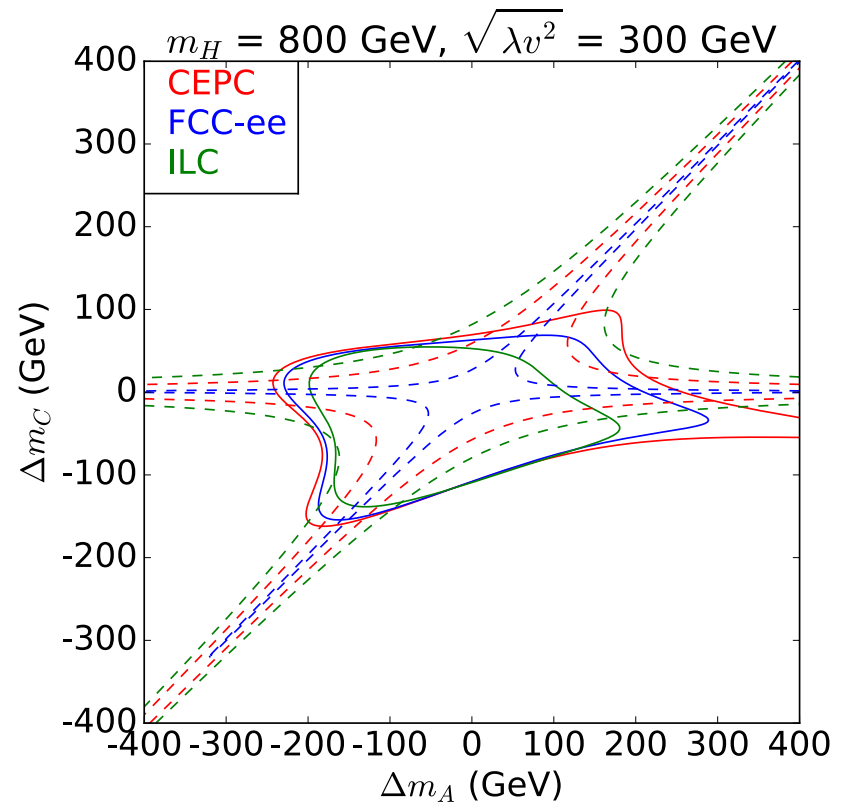
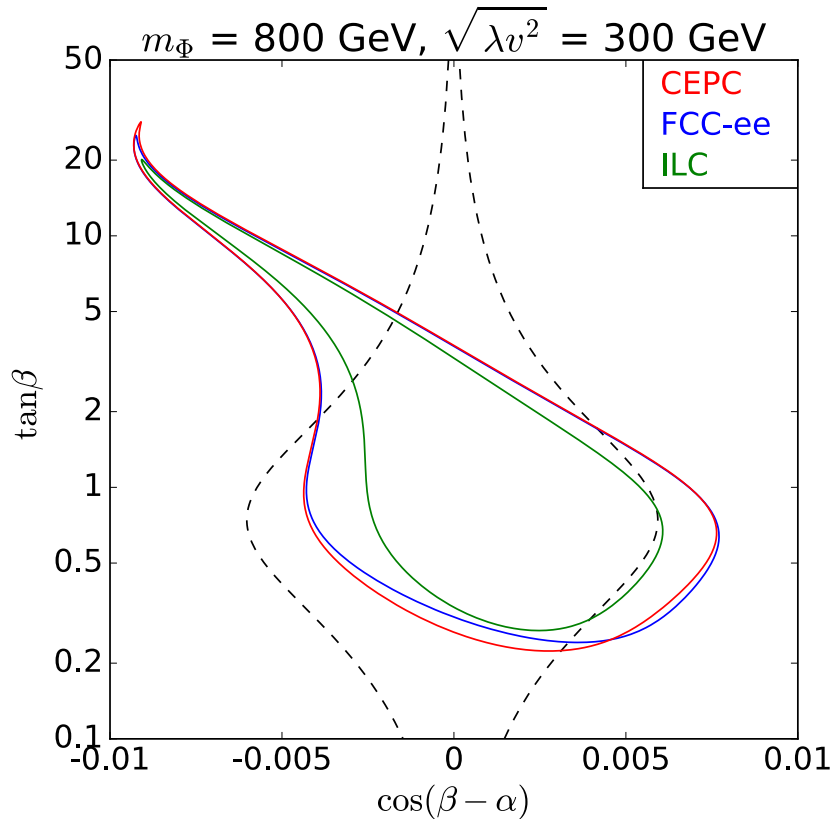
Type-II 2HDM: non-degenerate

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

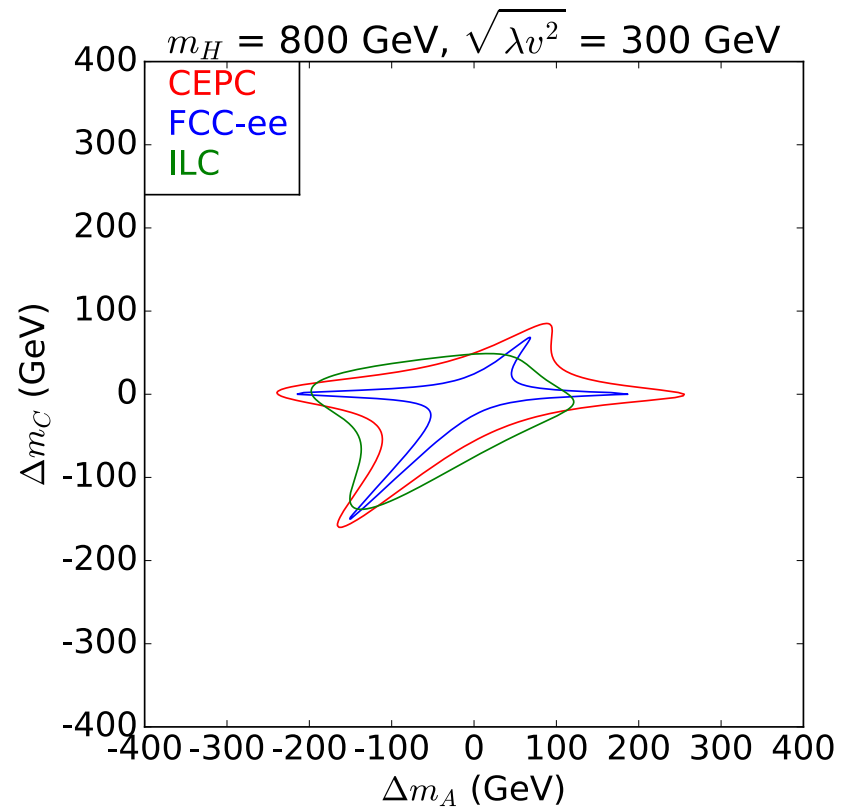
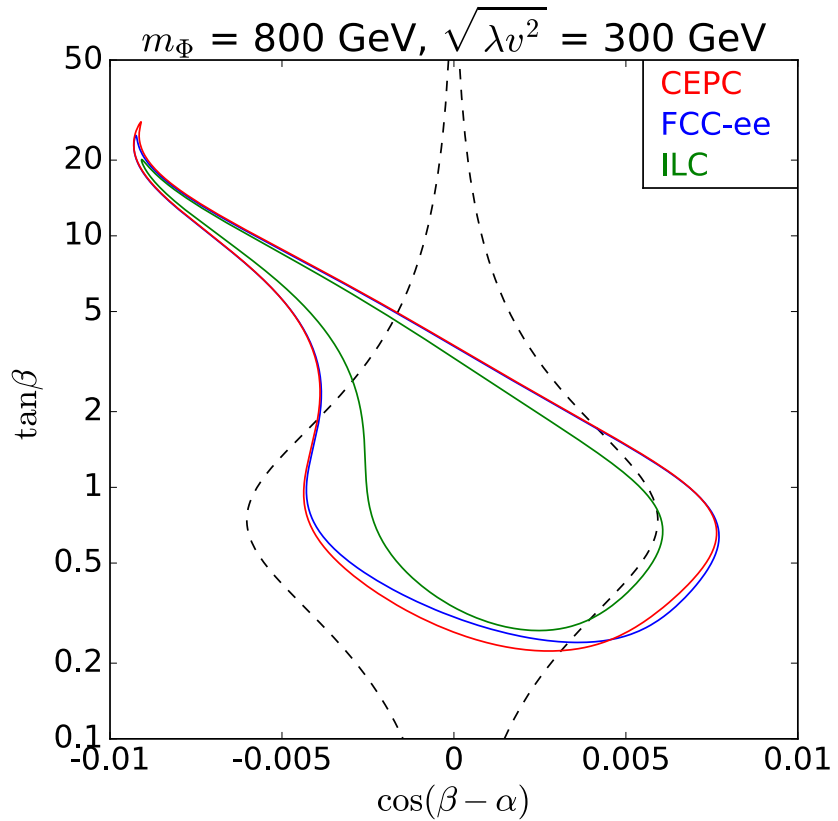


Complementary to Zpole precision

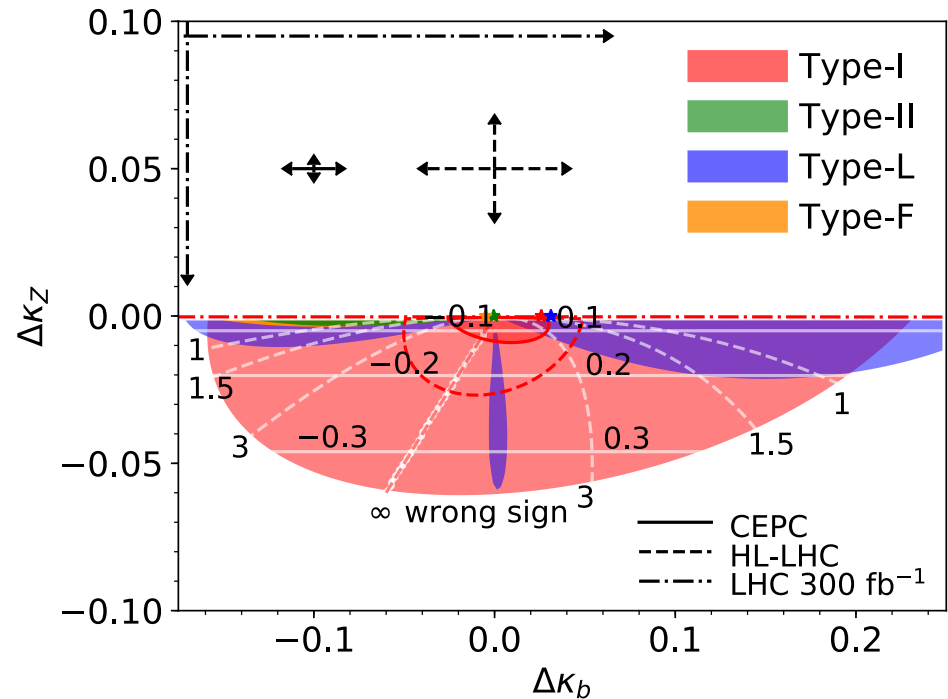
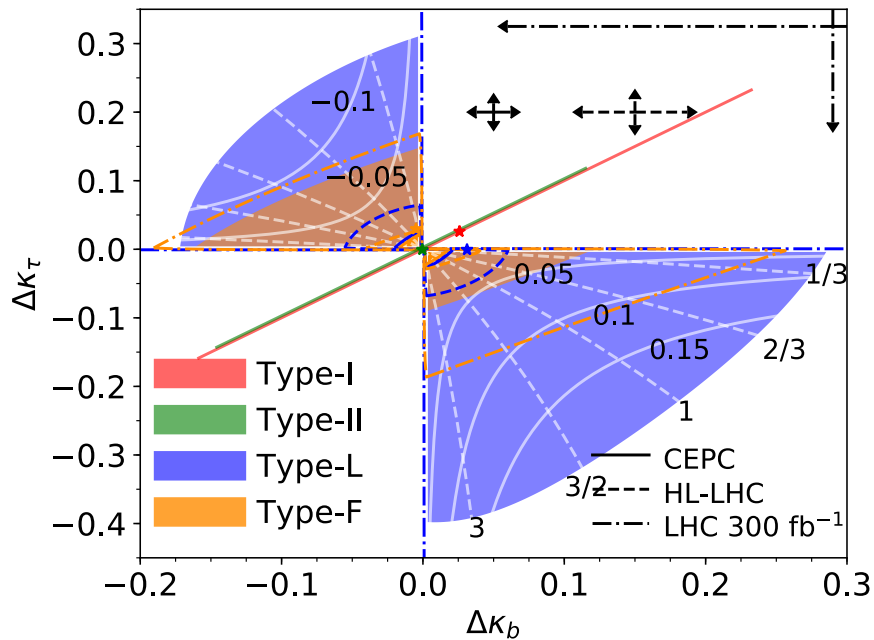
Different Higgs Factories



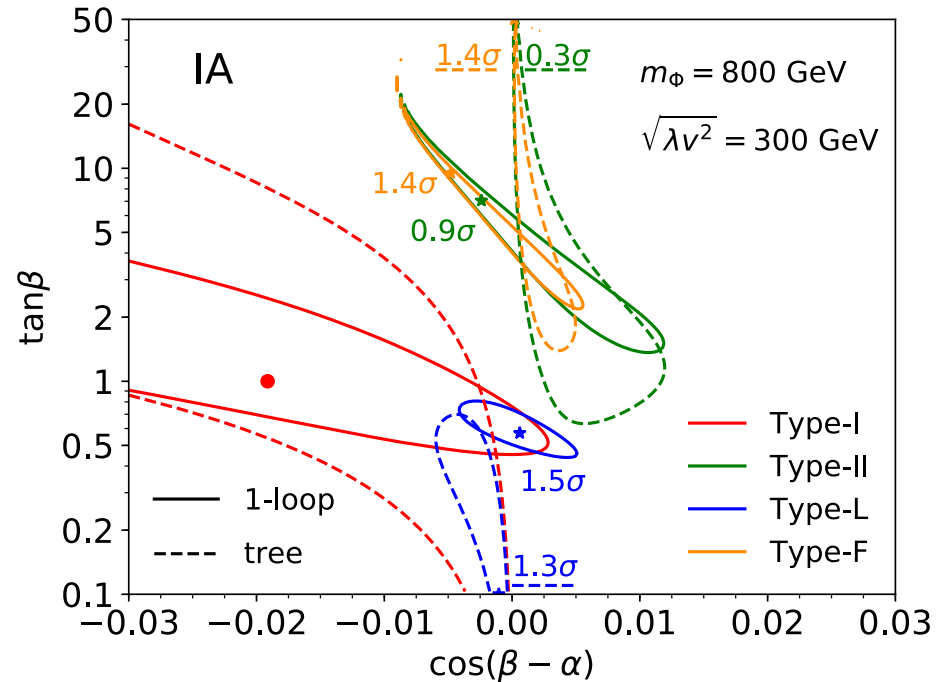
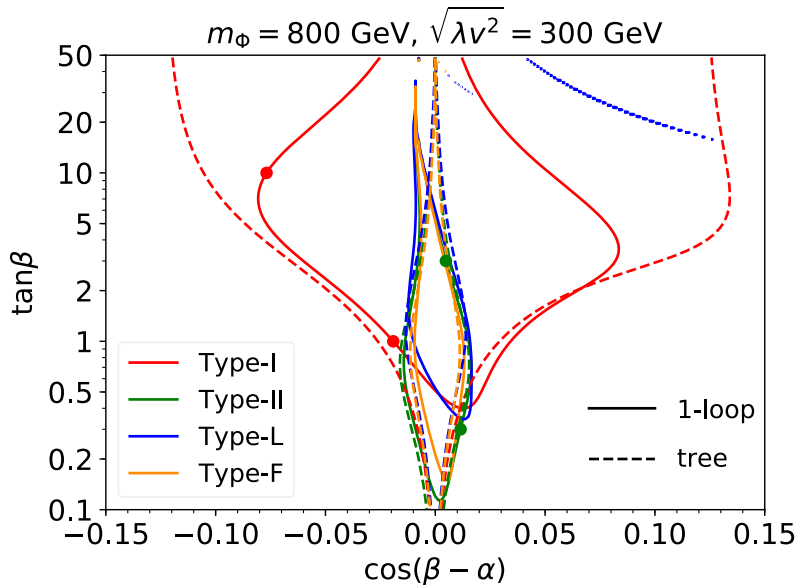
Different Higgs Factories



Distinguish different types of 2HDMs



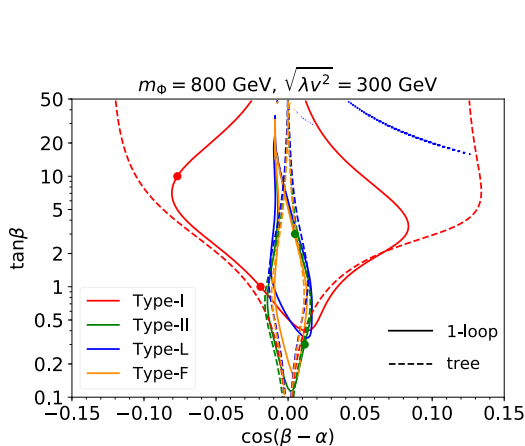
Distinguish different types of 2HDMs



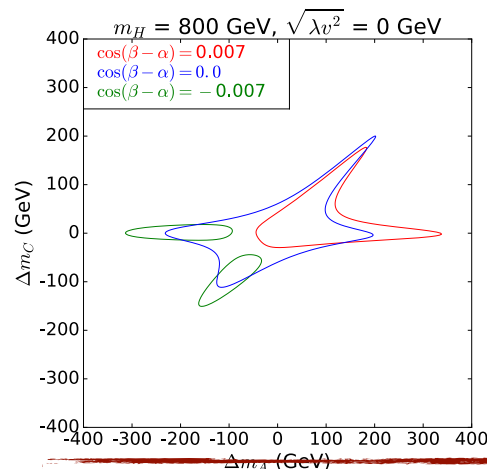
$(\cos(\beta - \alpha), \tan\beta)$	Small $\tan\beta$	Large $\tan\beta$
Type-I	IA: $(-0.019, 1.0)$	IB: $(-0.077, 10)$
Type-II	IIA: $(0.012, 0.3)$	IIB: $(0.005, 3.0)$

Conclusion

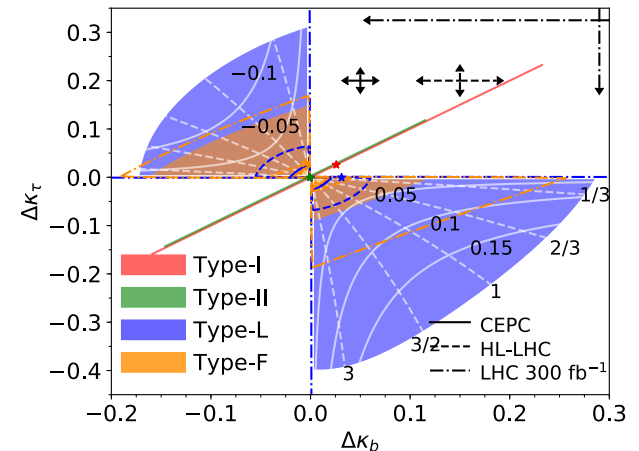
- Higgs factory reach impressive precision
- Kappa-scheme/EFT scheme/model specific fit
- indirect constraints on new physics models
- complementary to Zpole precision program
- complementary to direct search @ 100 TeV pp
- distinguish different types of 2HDMs



2HDM tree + loop



non-degenerate



Conclusion



LHC



Lepton Collider

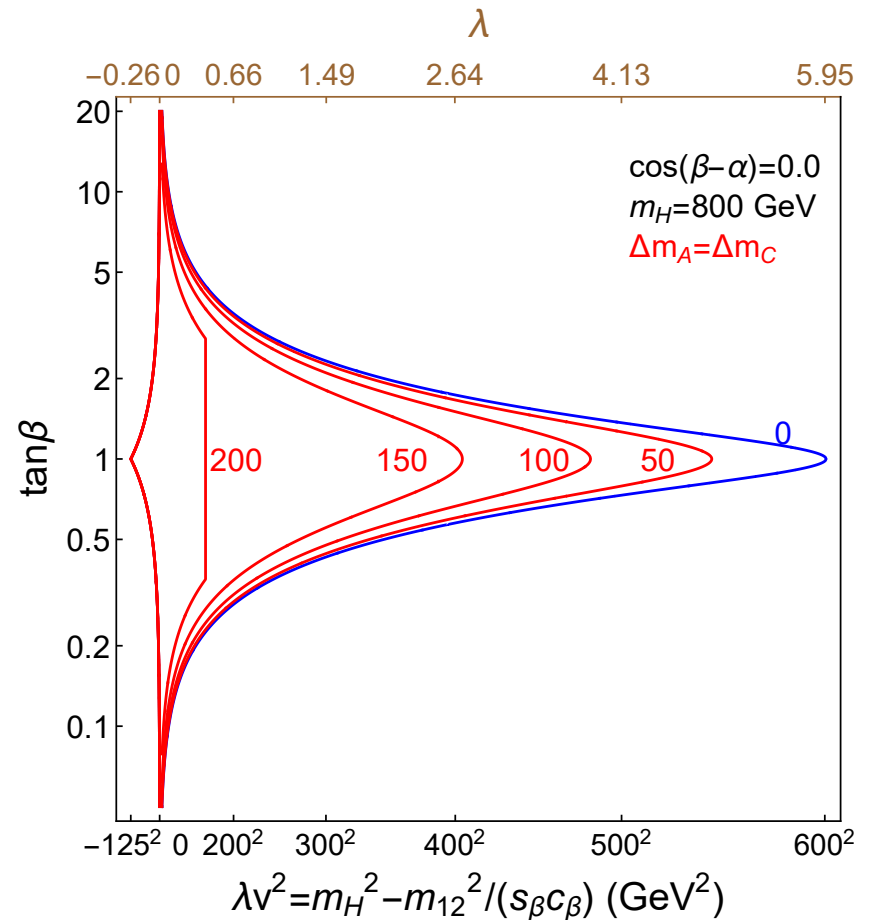
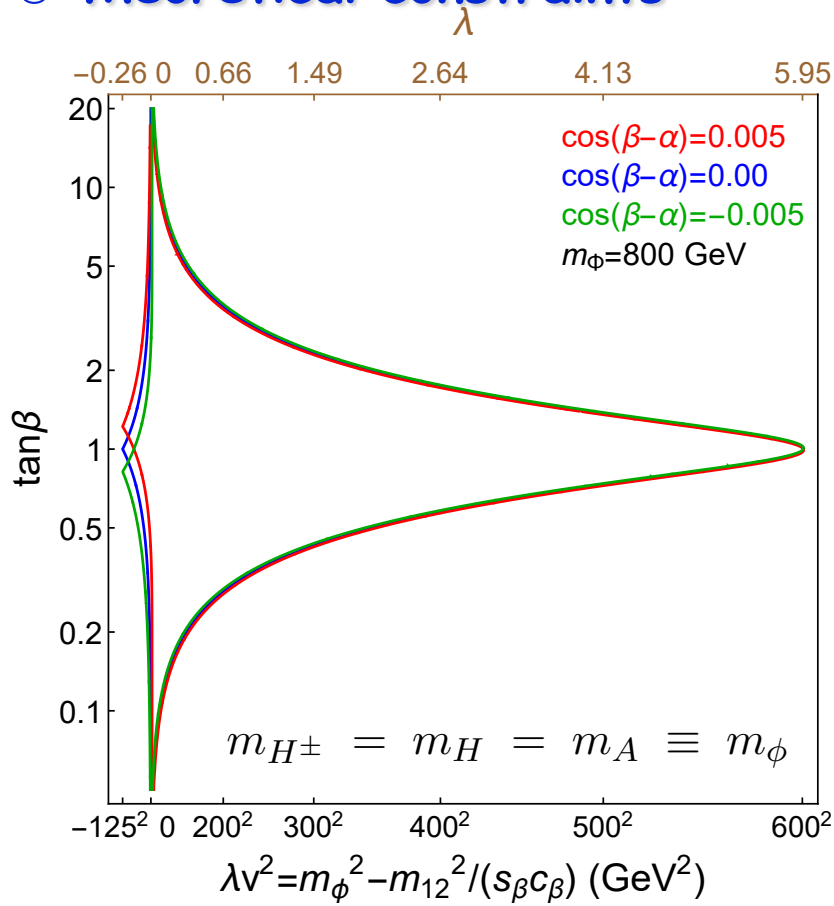


100 TeV pp

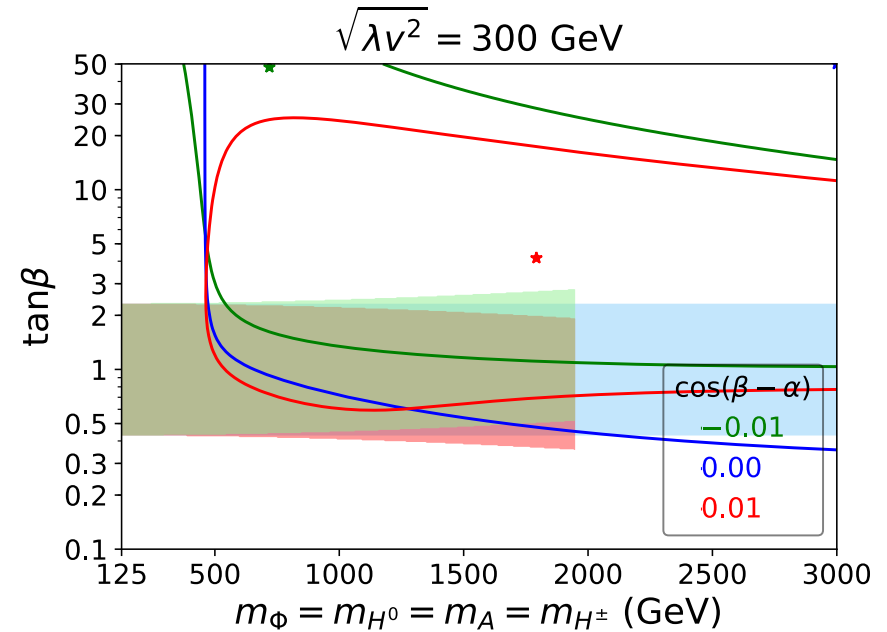
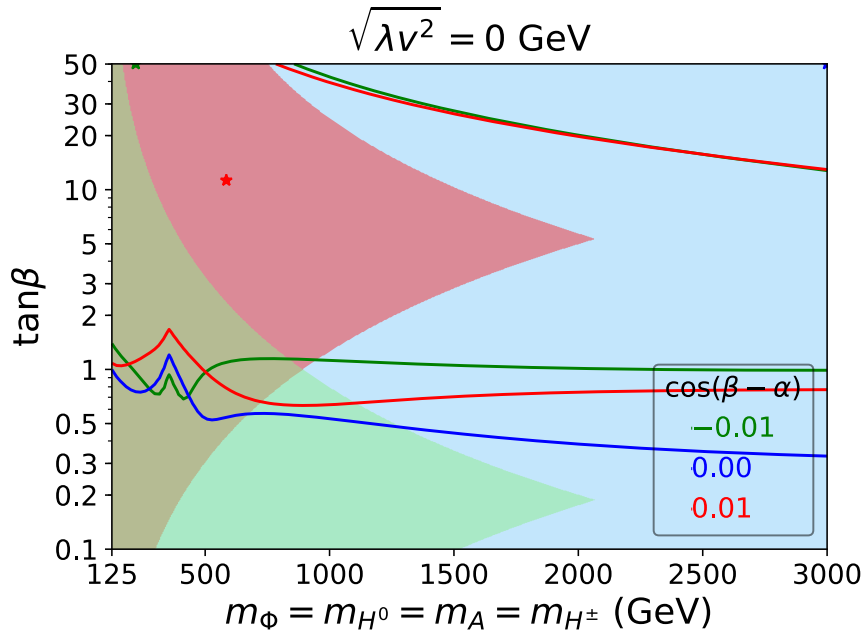
An exciting journey ahead of us!

2HDM: Loop in the Alignment Limit

theoretical constraints

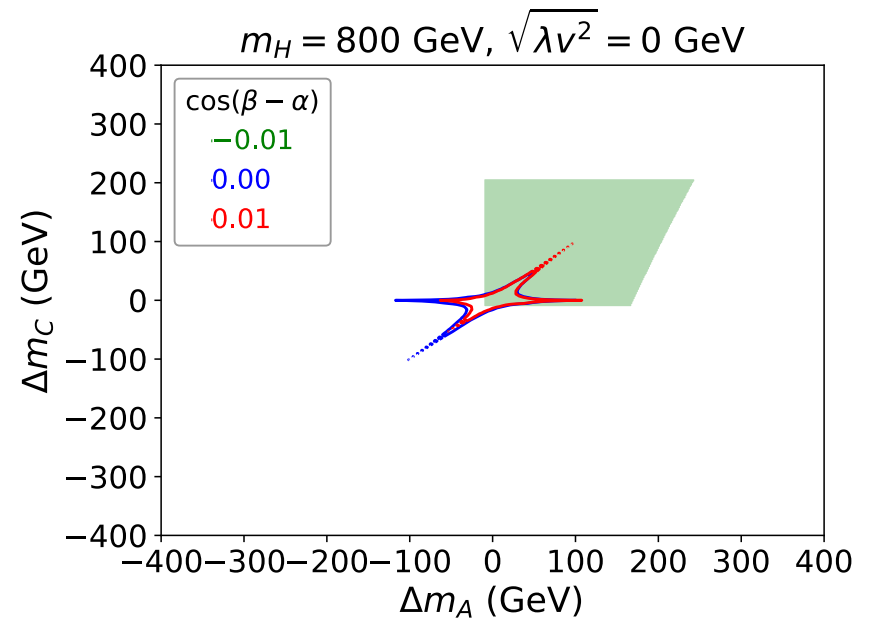
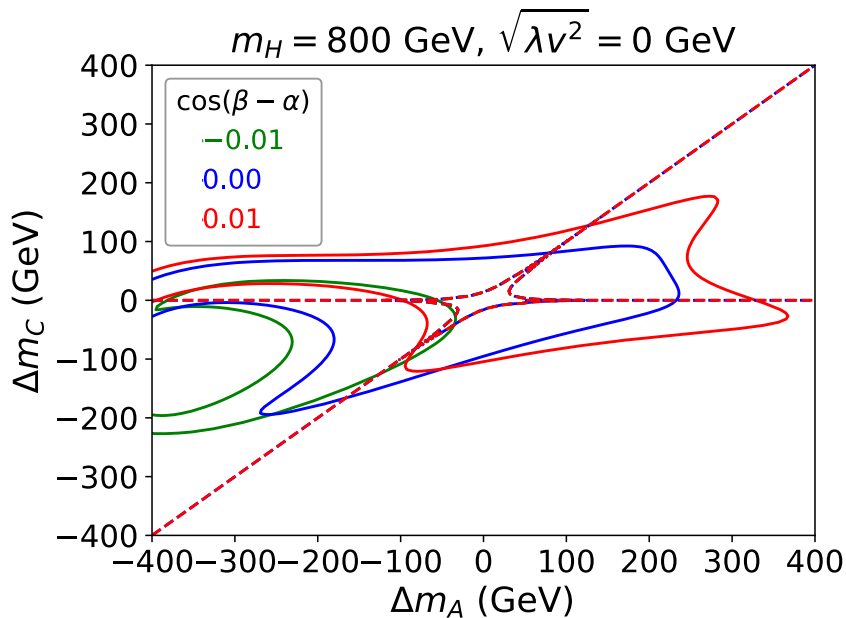


Type-I 2HDM: Tree + Loop



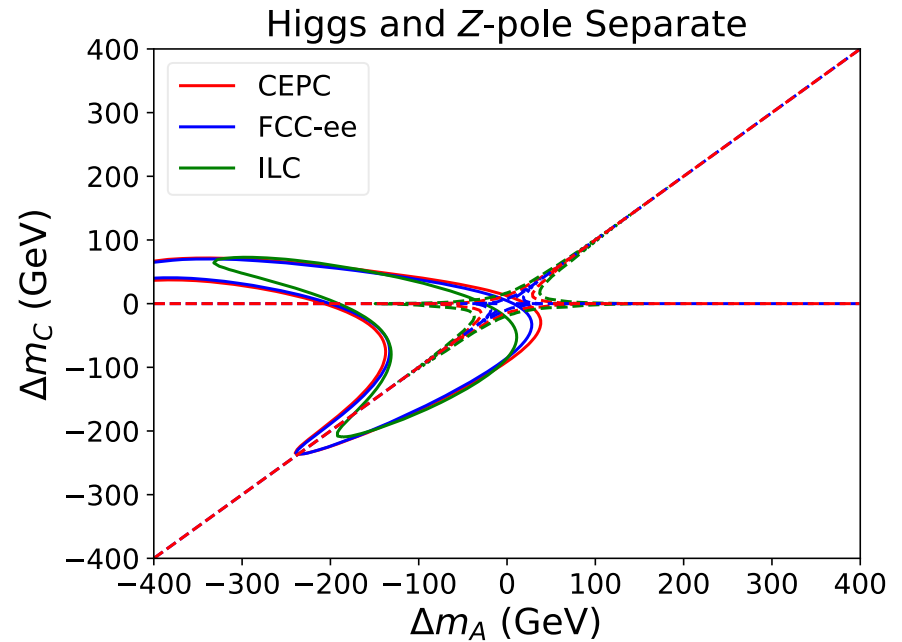
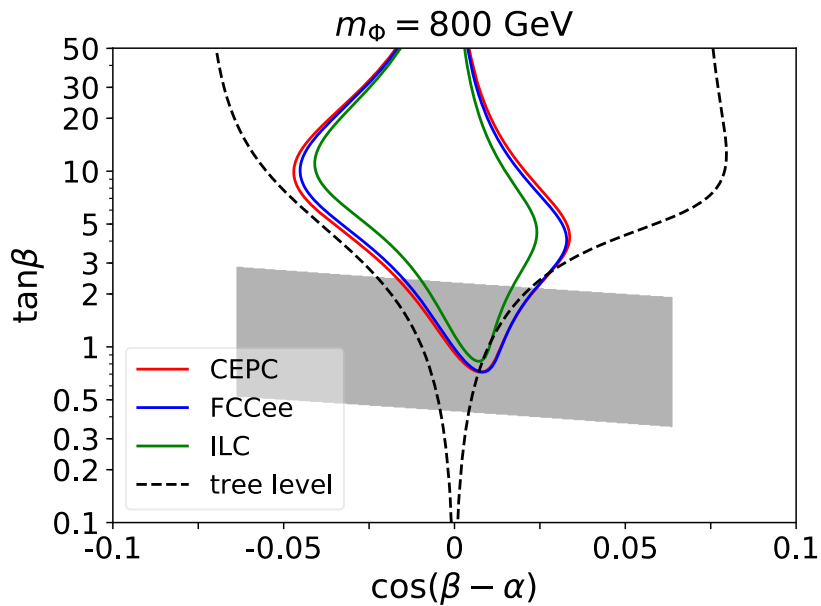
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Complementary to Zpole precision

Different Higgs Factories



Different Higgs Factories

