Extended Higgs Sector at Future Higgs Factories

Shufang Su • U. of Arizona

CEPC Workshop

IHEP

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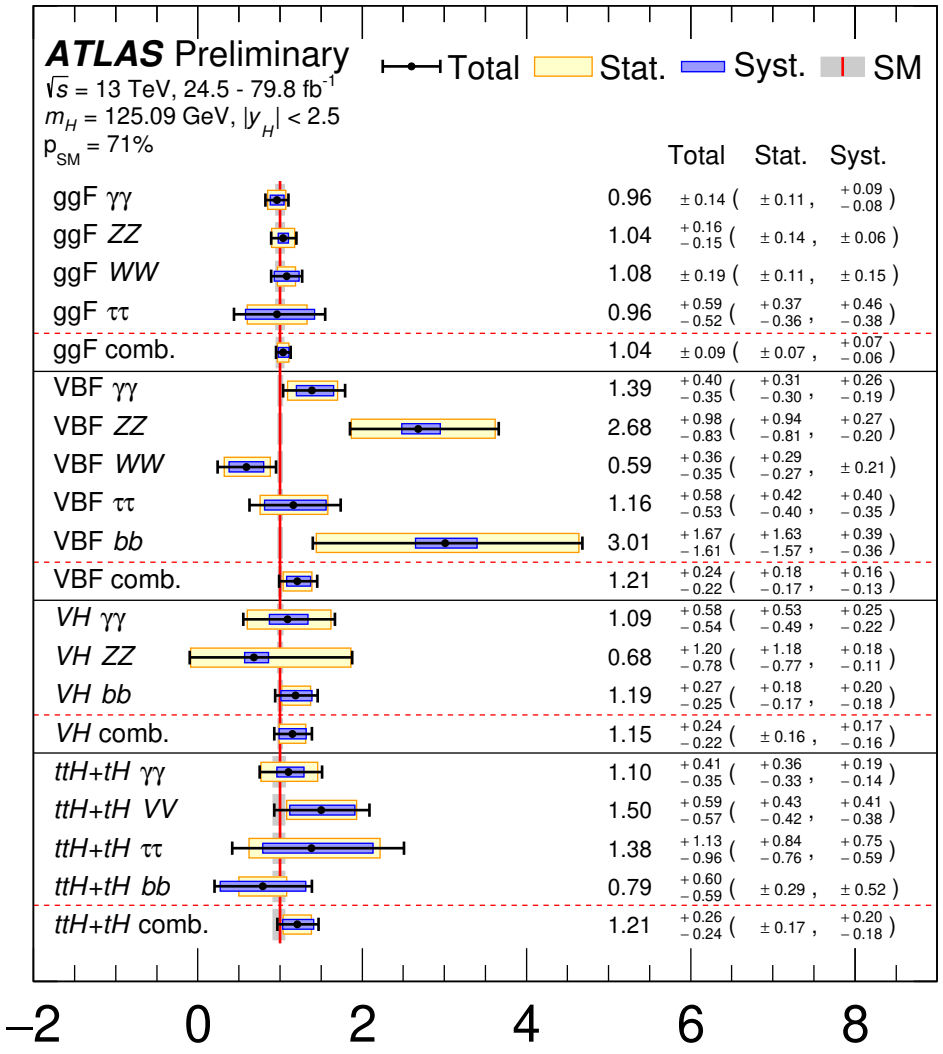
J. Gu, H. Li, Z. Liu, W. Su, 1709.06103
N. Chen, T. Han, SS, W. Su, Y. Wu, 1808.02037
N. Chen, S. Li, T. Han, SS, W. Su, Y. Wu, work in progress

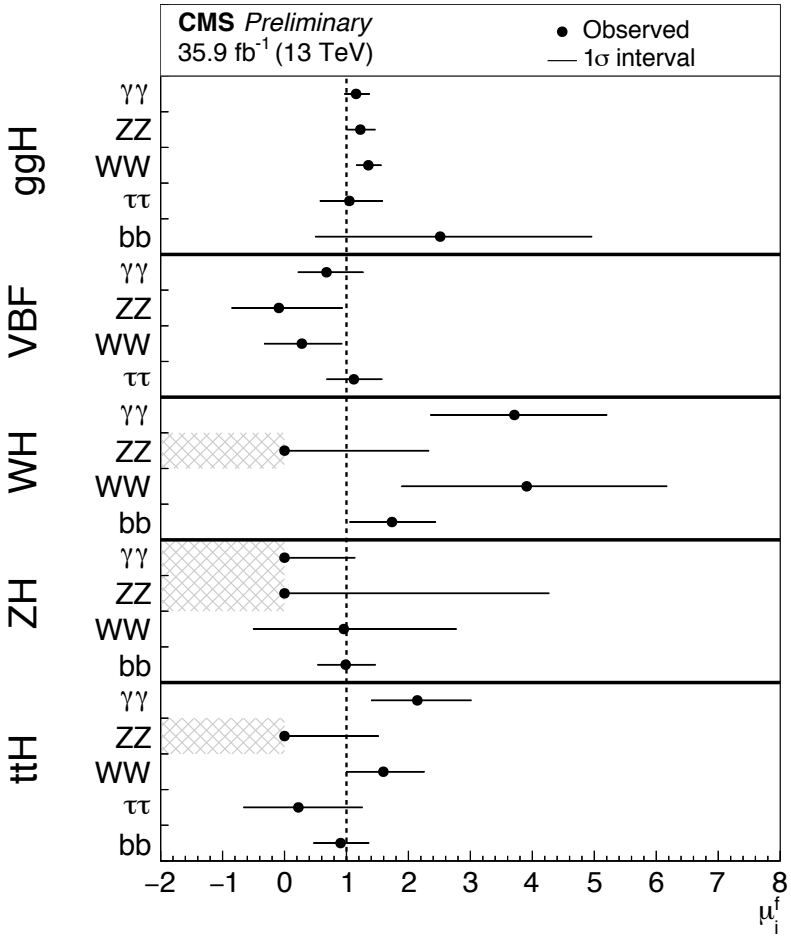
Outline

- Higgs precision measurements
- Global fit framework
- Extended Higgs Sector: 2HDM
  - Tree vs Loop
  - Degenerate vs. Non-degenerate
  - Higgs vs. Z-pole
- Complementarity with direct search @ 100 pp
- Conclusion

Higgs Precision Measurements

LHC: 13 TeV

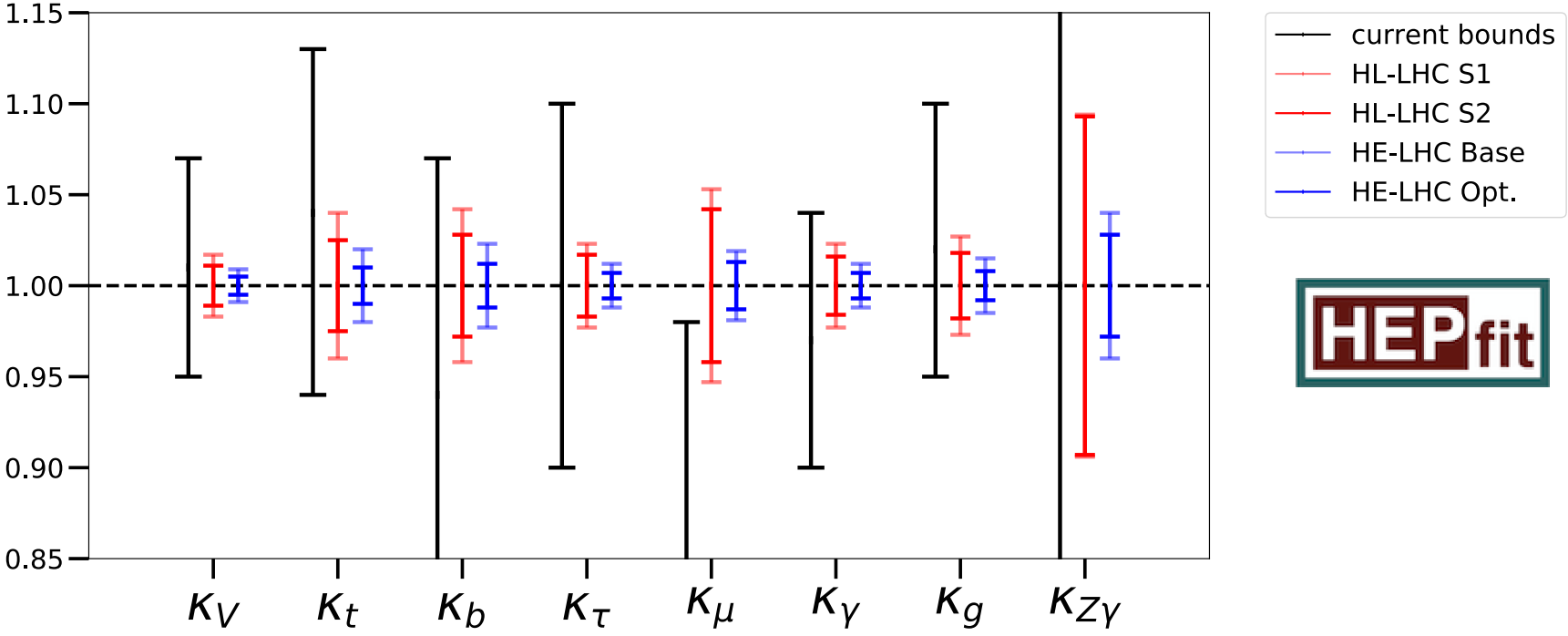




ATLAS-CONF-2019-005
CMS-PAS-HIG-17-031

Higgs Precision Measurements

LHC: 14 TeV, 300 fb^{-1}, 3000 fb^{-1}



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Higgs Precision Measurements

CEPC / FCC / ILC

collider	CEPC	FCC-ee	ILC					
$\sqrt{s}$	240 GeV	240 GeV	250 GeV	350 GeV		500 GeV		
$\int \mathcal{L}dt$	5 ab^{-1}	5 ab^{-1}	2 ab^{-1}	200 fb^{-1}		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%	0.57%	0.71%	2.1%	-	1.06	-	-
decay	$\Delta(\sigma \cdot BR)/(\sigma \cdot BR)$							
$h \to b\bar{b}$	0.28%	0.28%	0.42%	1.67%	1.67%	0.64%	0.25%	9.9%
$h \to c\bar{c}$	2.2%	1.7%	2.9%	12.7%	16.7%	4.5%	2.2%	-
$h \to gg$	1.6%	1.98%	2.5%	9.4%	11.0%	3.9%	1.5%	-
$h \to WW^*$	1.5%	1.27%	1.1%	8.7%	6.4%	3.3%	0.85%	-
$h \to \tau^+\tau^-$	1.2%	0.99%	2.3%	4.5%	24.4%	1.9%	3.2%	-
$h \to ZZ^*$	4.3%	4.4%	6.7%	28.3%	21.8%	8.8%	2.9%	-
$h \to \gamma\gamma$	9.0%	4.2%	12.0%	43.7%	50.1%	12.0%	6.7%	-
$h \to \mu^+\mu^-$	17%	18.4%	25.5%	97.6%	179.8%	31.1%	25.5%	-
$(\nu\bar{\nu})h \to b\bar{b}$	2.8%	3.1%	3.7%	-	-	-	-	-

S. Su CEPC-CDR, FCC Physics Opportunities, ILC 1903.01629.

Higgs Precision Measurements

CEPC / FCC / ILC

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$(\nu\bar{\nu})h \to b\bar{b}$	2.8%	3.1%	3.7%	-	-	-	-	-

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Kappa framework and EFT Framework

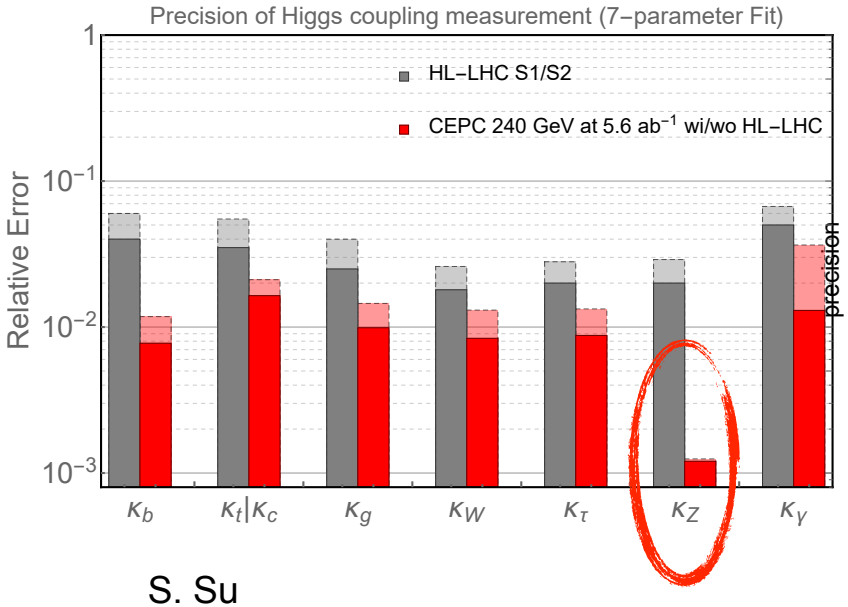
Two model-independent approaches

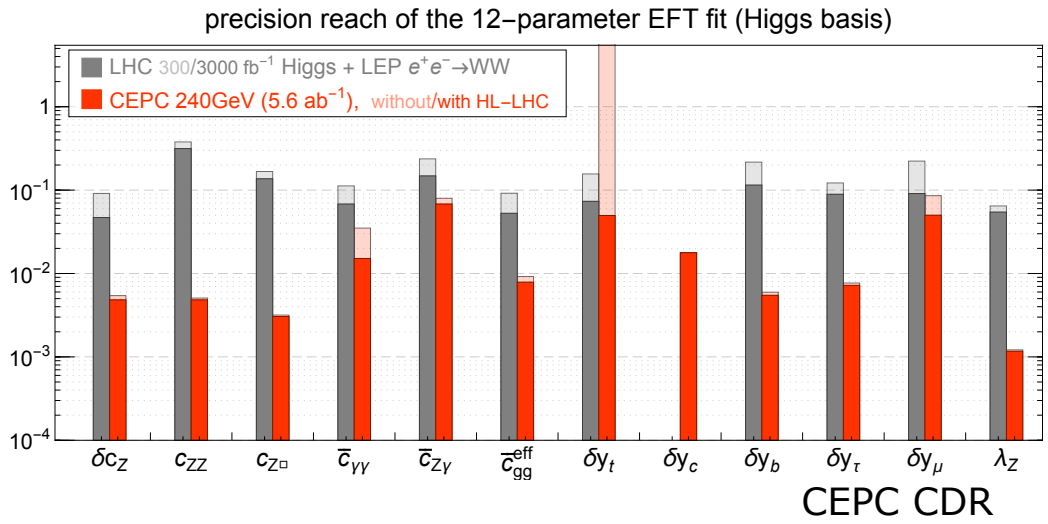
kappa framework

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

EFT framework

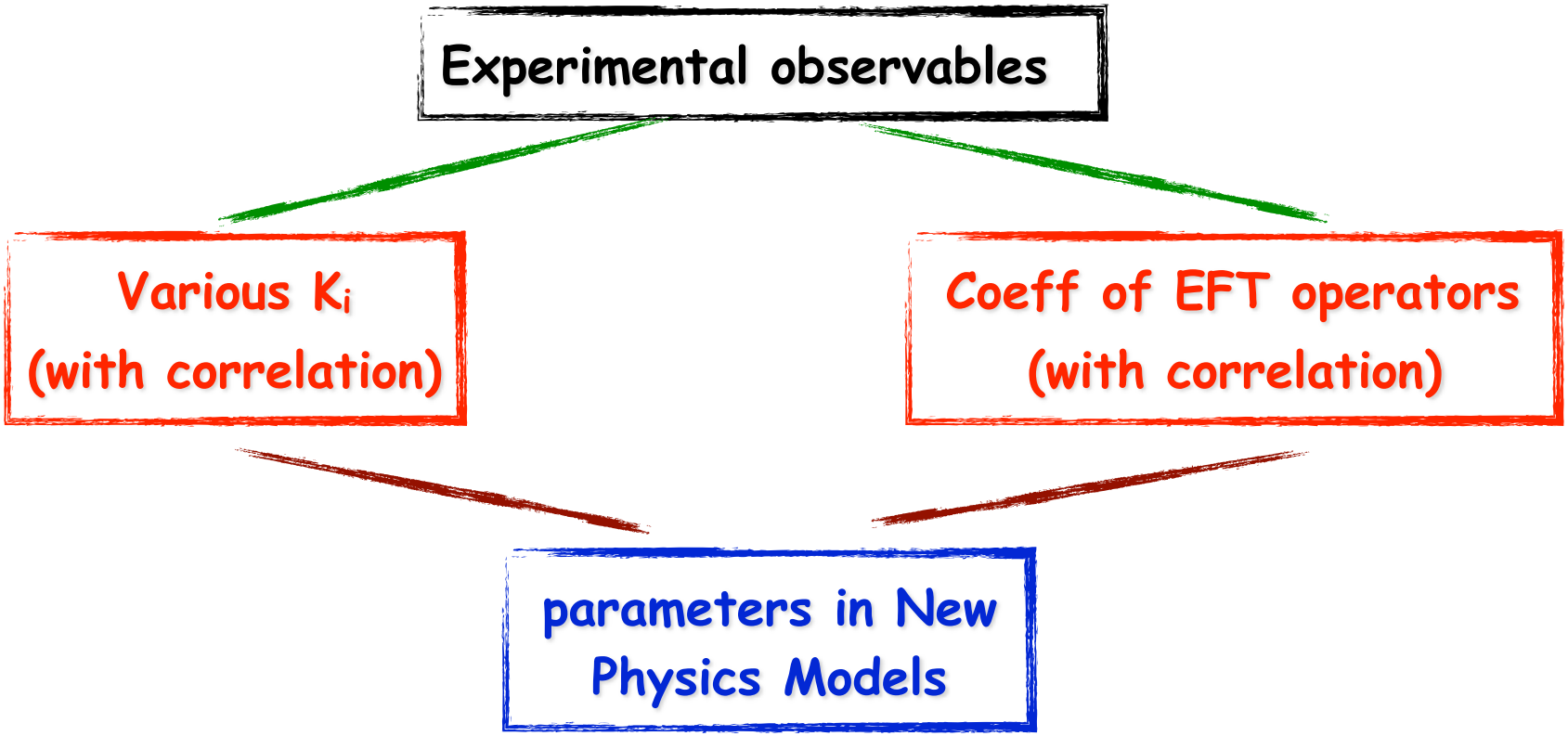
$$\delta c_Z\,,\quad c_{ZZ}\,,\quad c_{Z\Box}\,,\quad c_{\gamma\gamma}\,,\quad c_{Z\gamma}\,,\quad c_{gg}\,,\quad \delta y_u\,,\quad \delta y_d\,,\quad \delta y_e\,,\quad \lambda_Z$$





CEPC CDR

New Physics Implication



Kappa Framework and EFT Framework

limitations of model-independent approaches

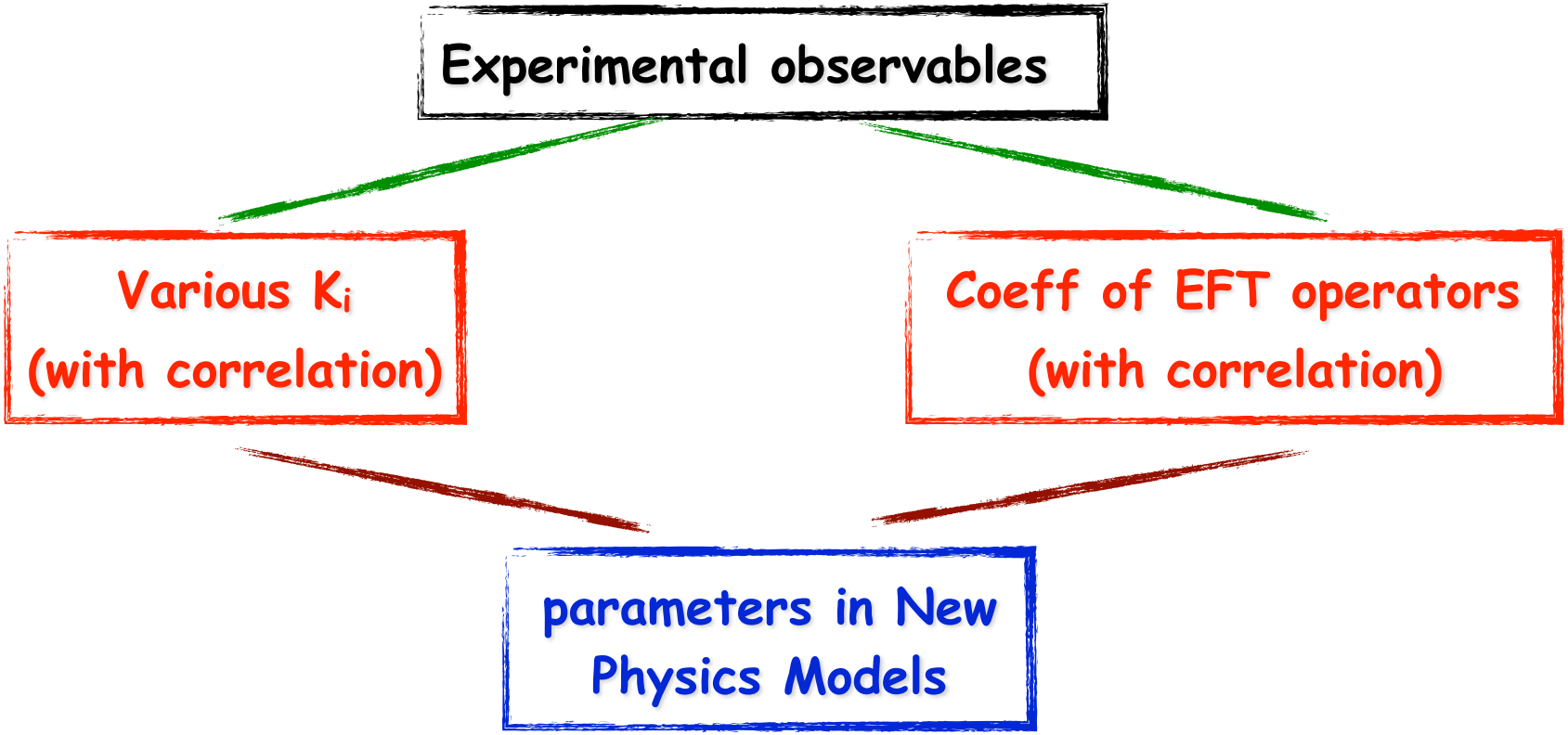
- large level of degeneracy

  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



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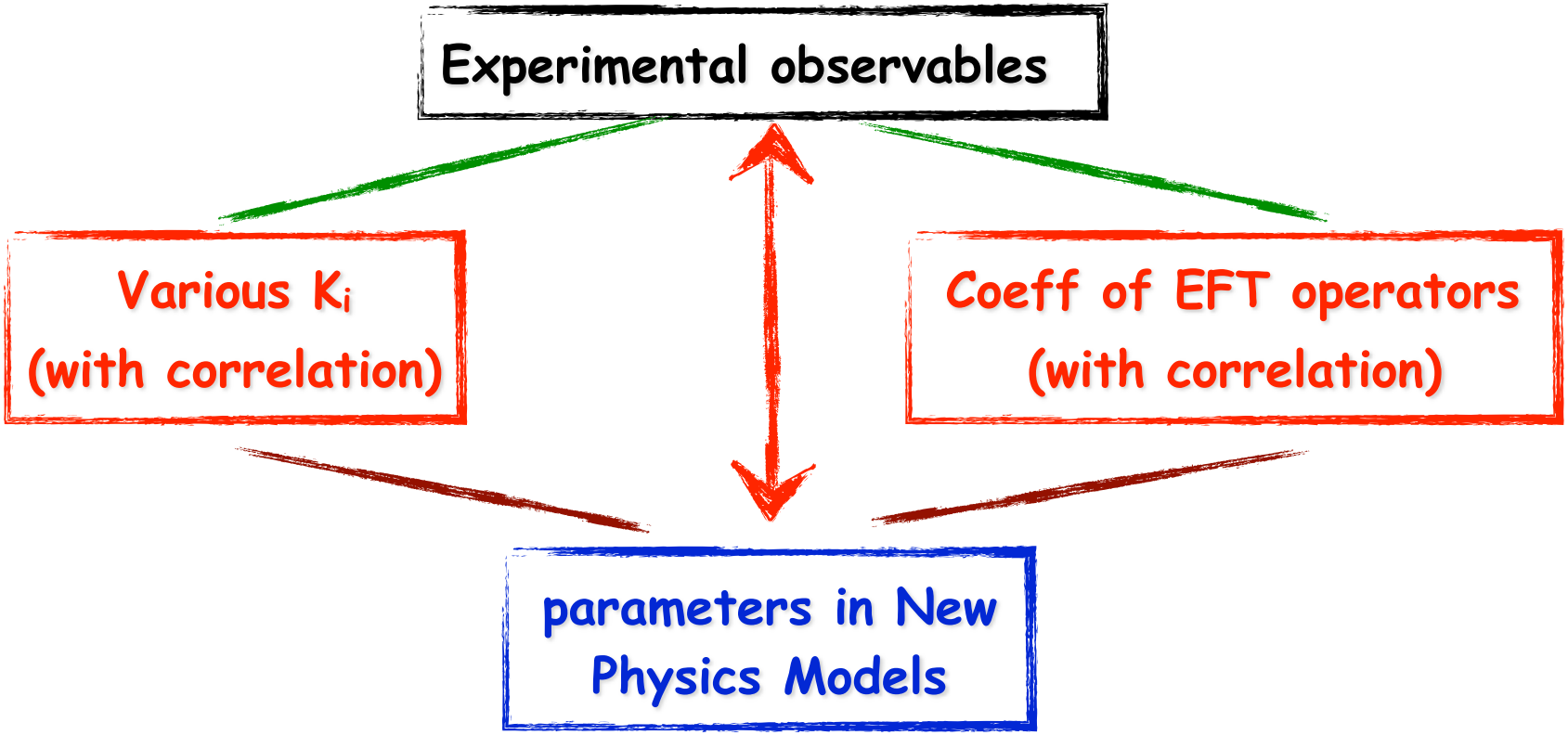

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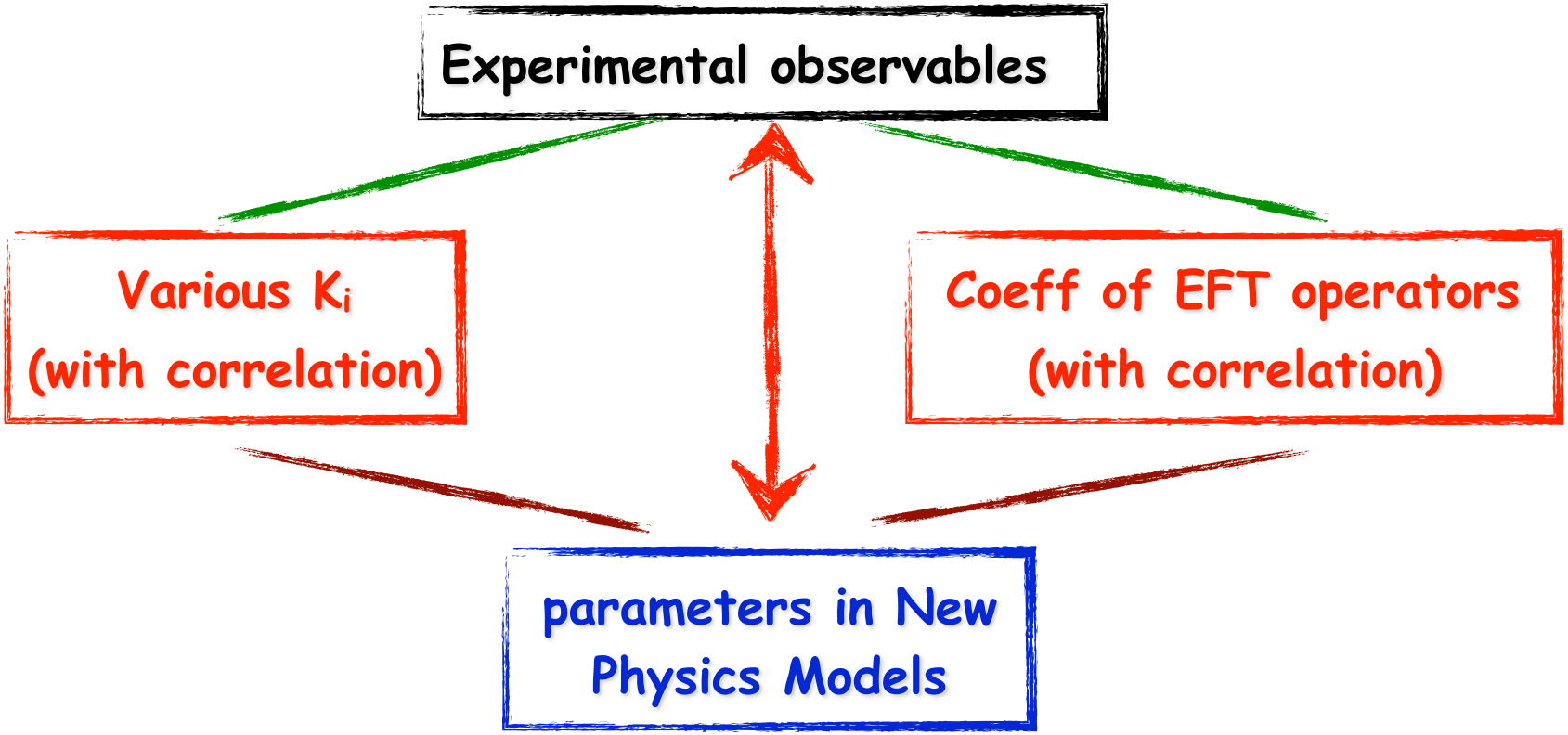

$$\chi^2 = \sum_i \frac{(\mu_i^{\rm BSM} - \mu_i^{\rm obs})^2}{\sigma_{\mu_i}^2} \qquad \mu_i^{\rm BSM} = \frac{(\sigma \times {\rm Br})_{\rm BSM}}{(\sigma \times {\rm Br})_{\rm SM}}$$

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: $H^\pm$

- **h^0/H^0 VV coupling**

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

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)

246 GeV 125 GeV

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

soft Z2 breaking: m_{12}^2

tanβ, cos(β-α),
control tree level h^0 couplings

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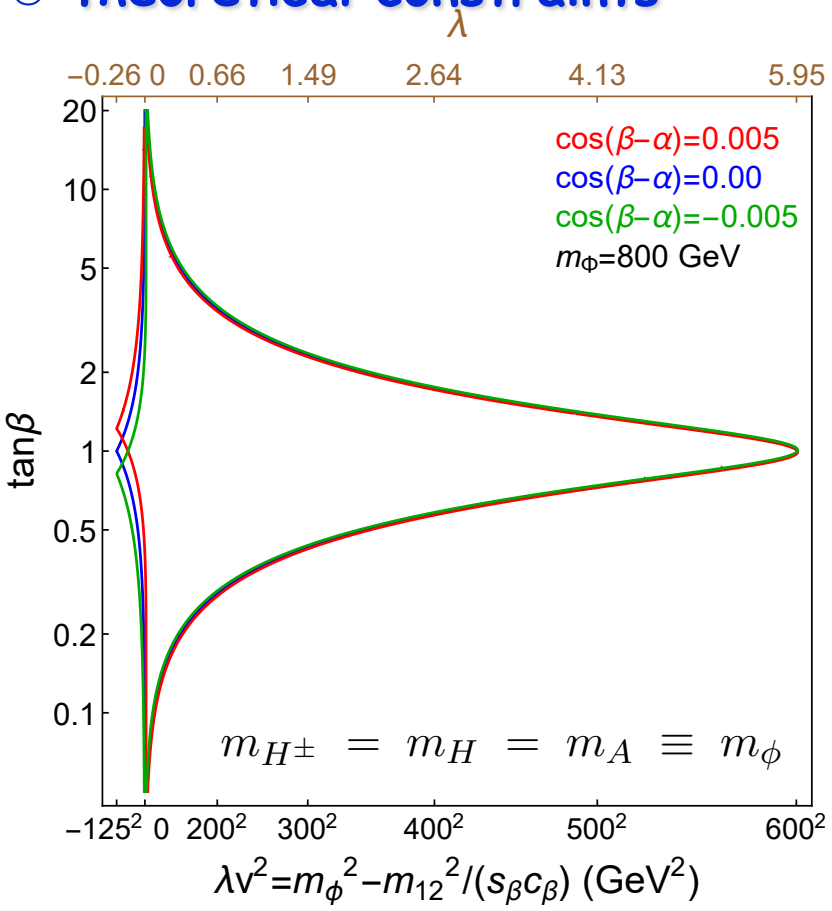
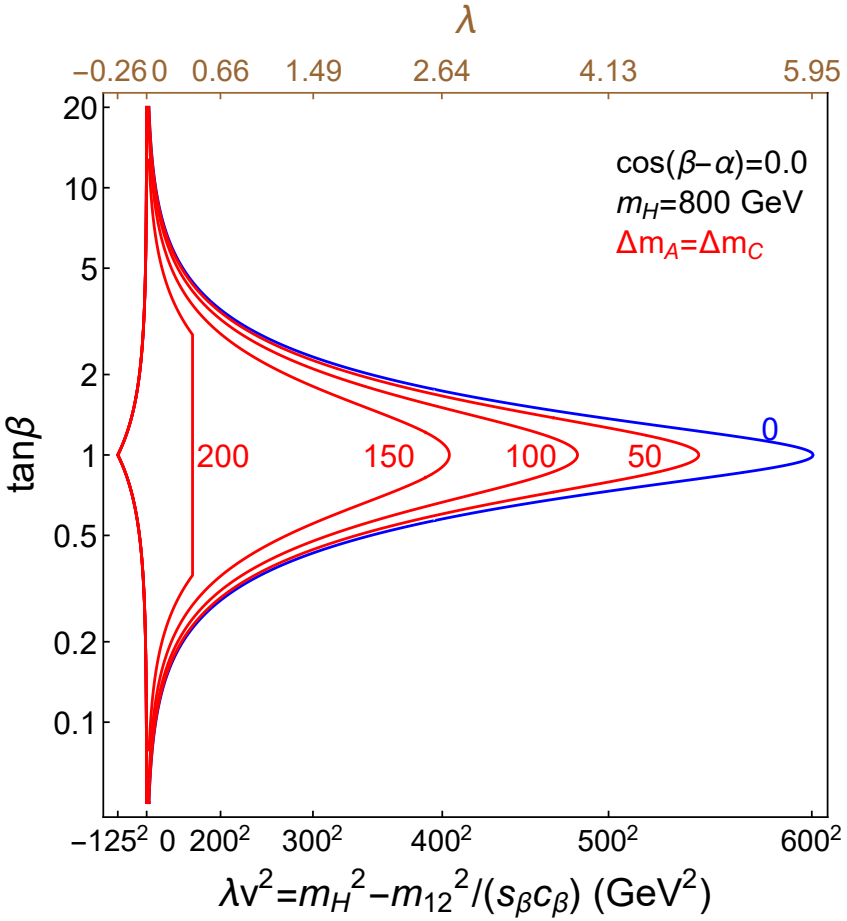
control tree level h^0 couplings

2HDM: Loop in the Alignment Limit

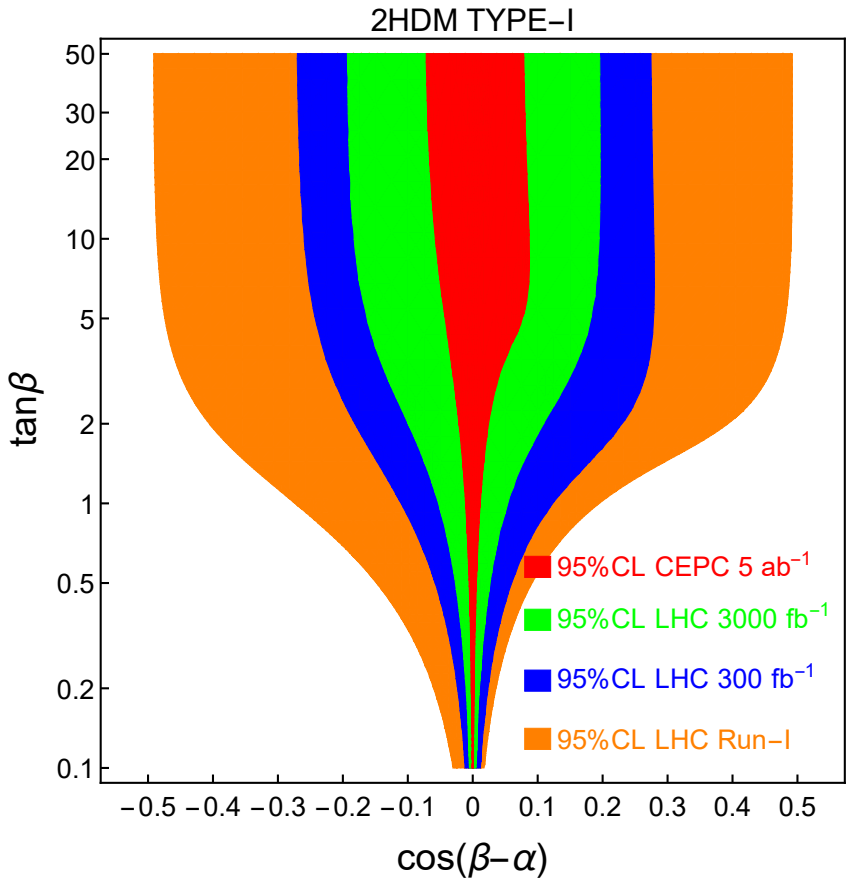
- **theoretical constraints**

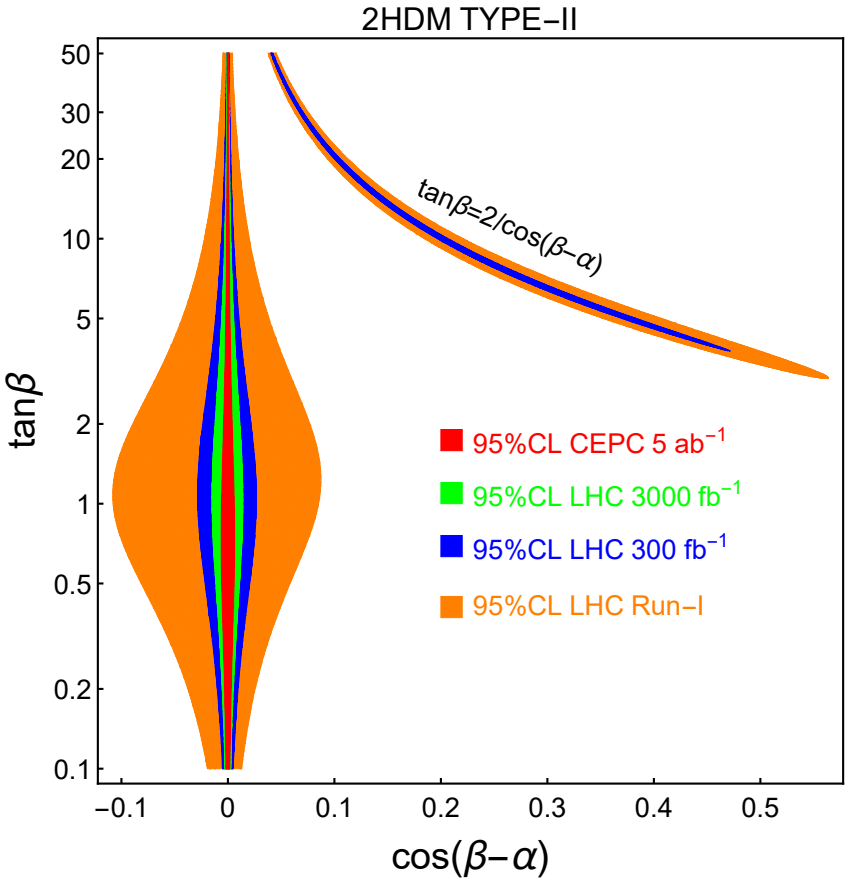




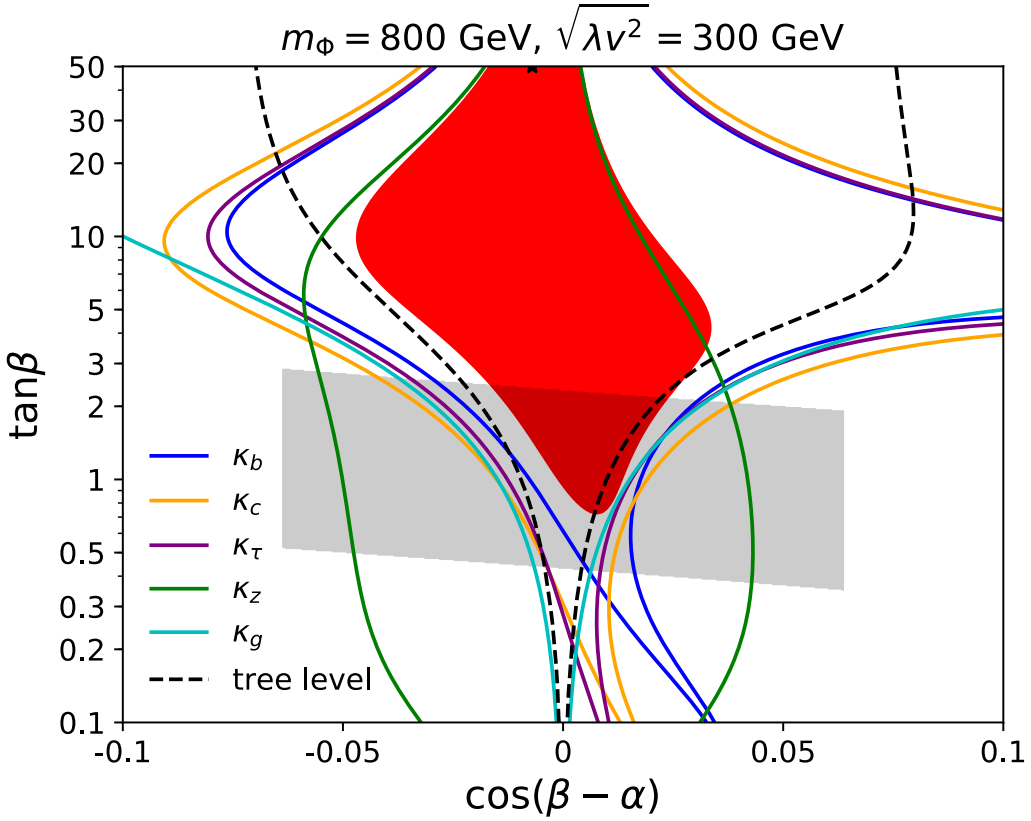
Tree-level 2HDM fit

2HDM, LHC/CEPC fit

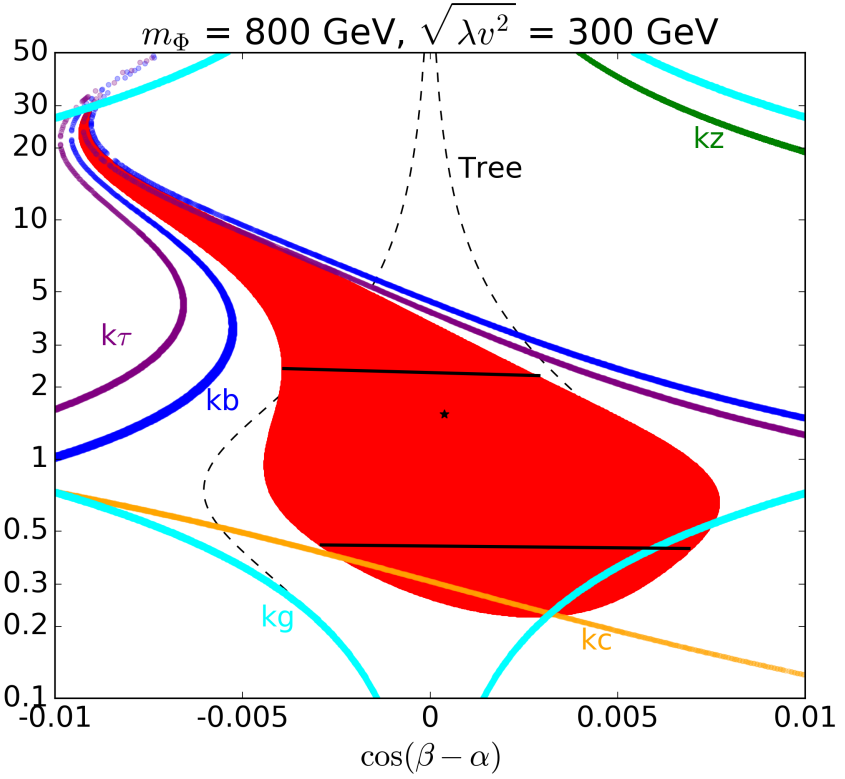




2HDM: Tree + Loop

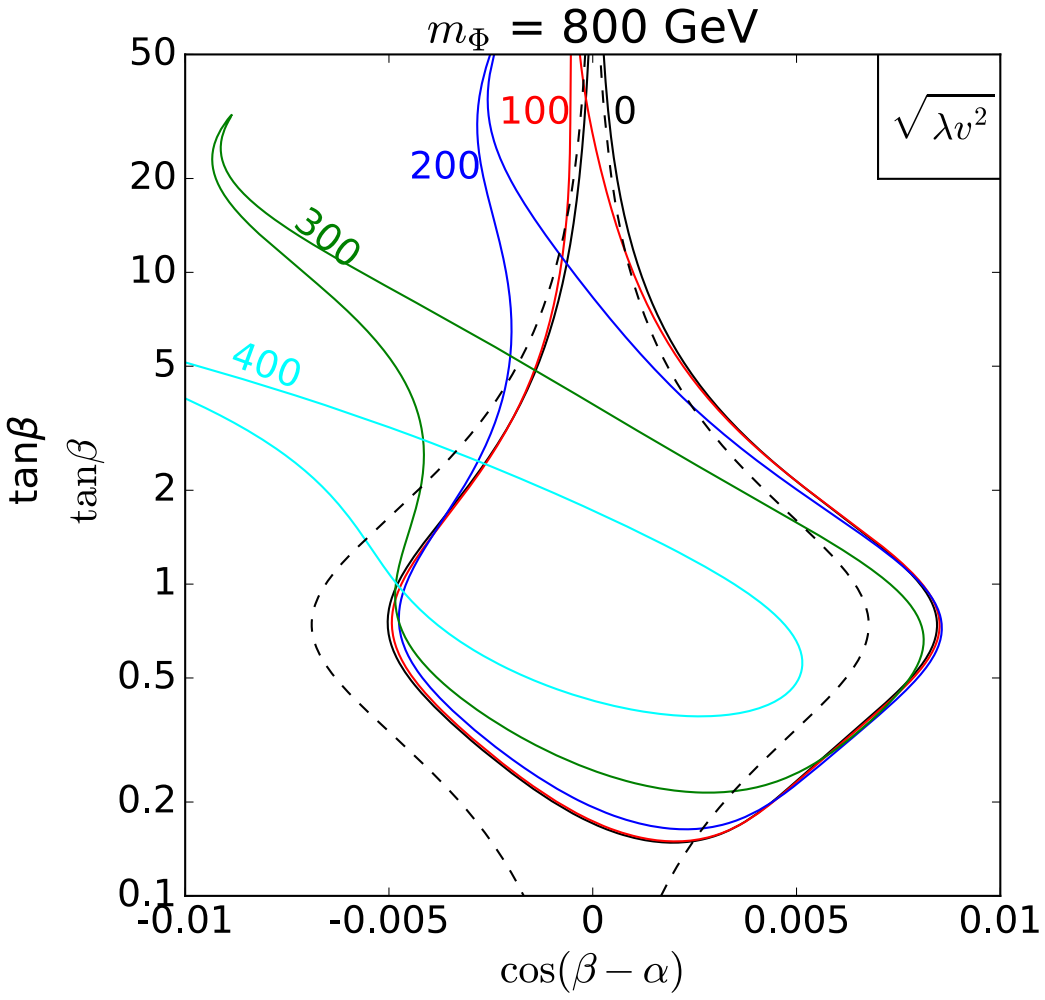


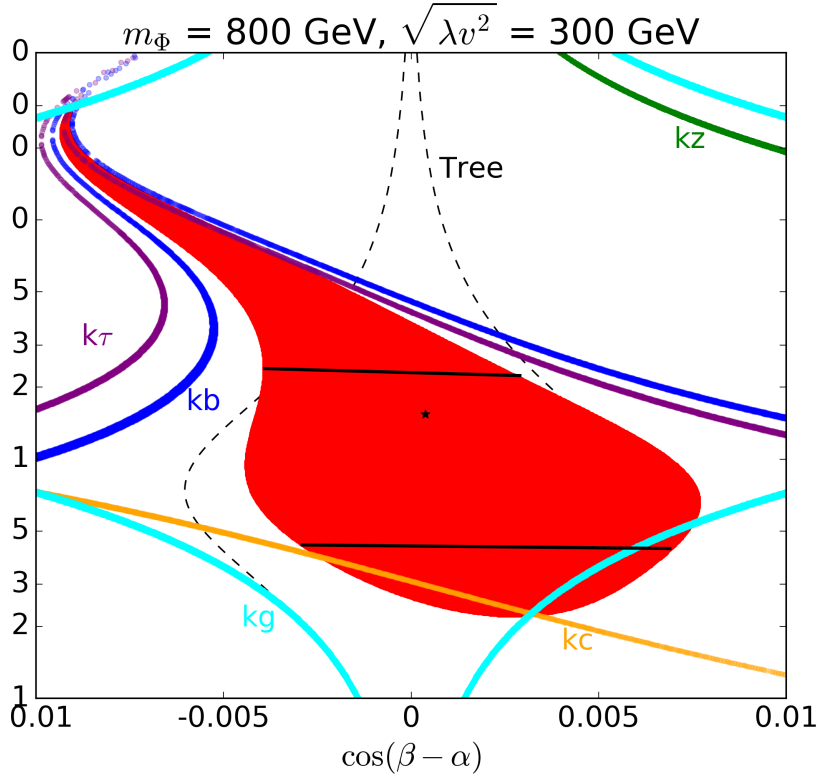
N. Chen, S. Li, T. Han, SS, W. Su, Y. Wu, work in progress



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

2HDM: Tree + Loop

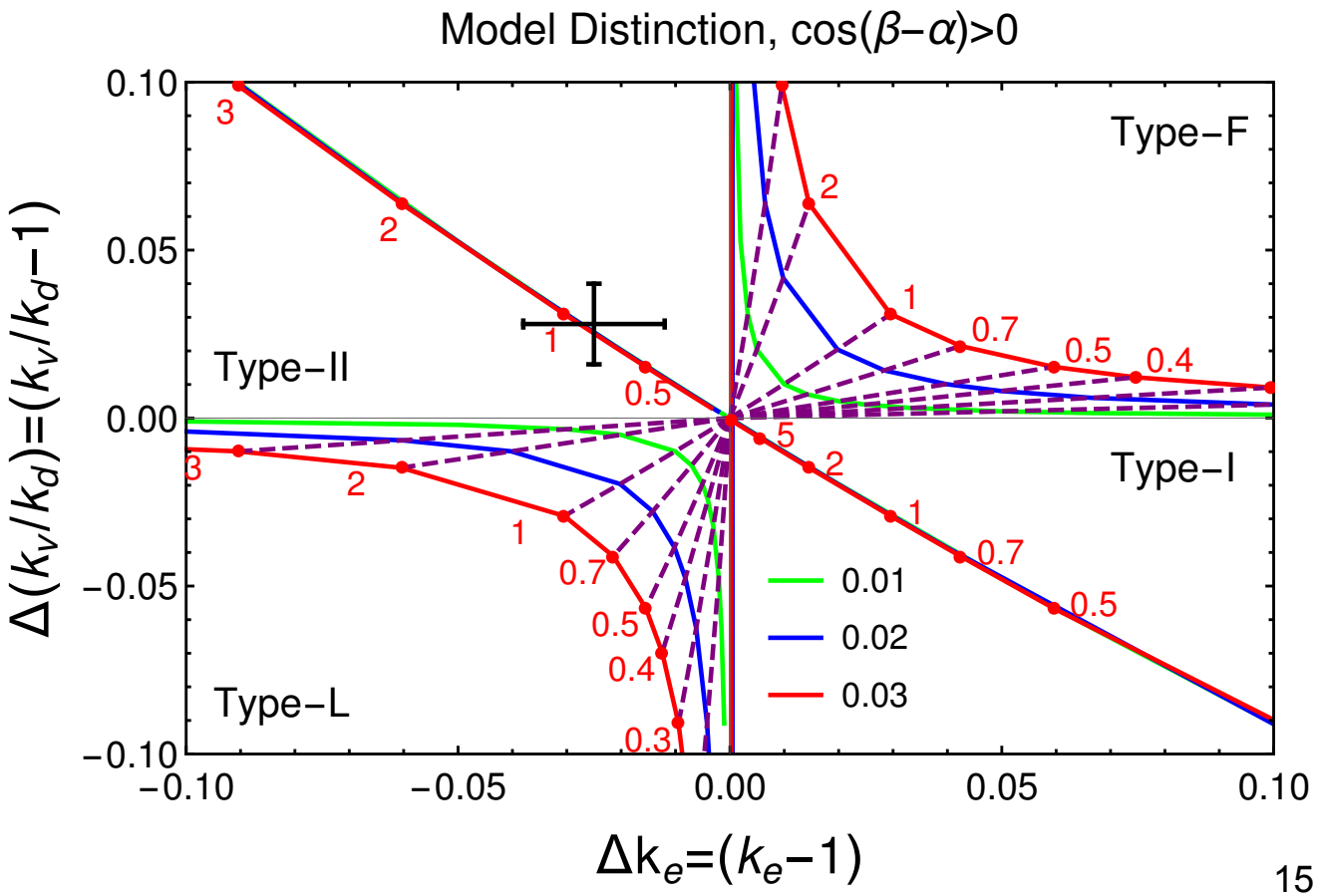




N. Chen, T. Han, SS, W. Su, Y. Wu, 1808.02037

2HDM Model Distinction

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

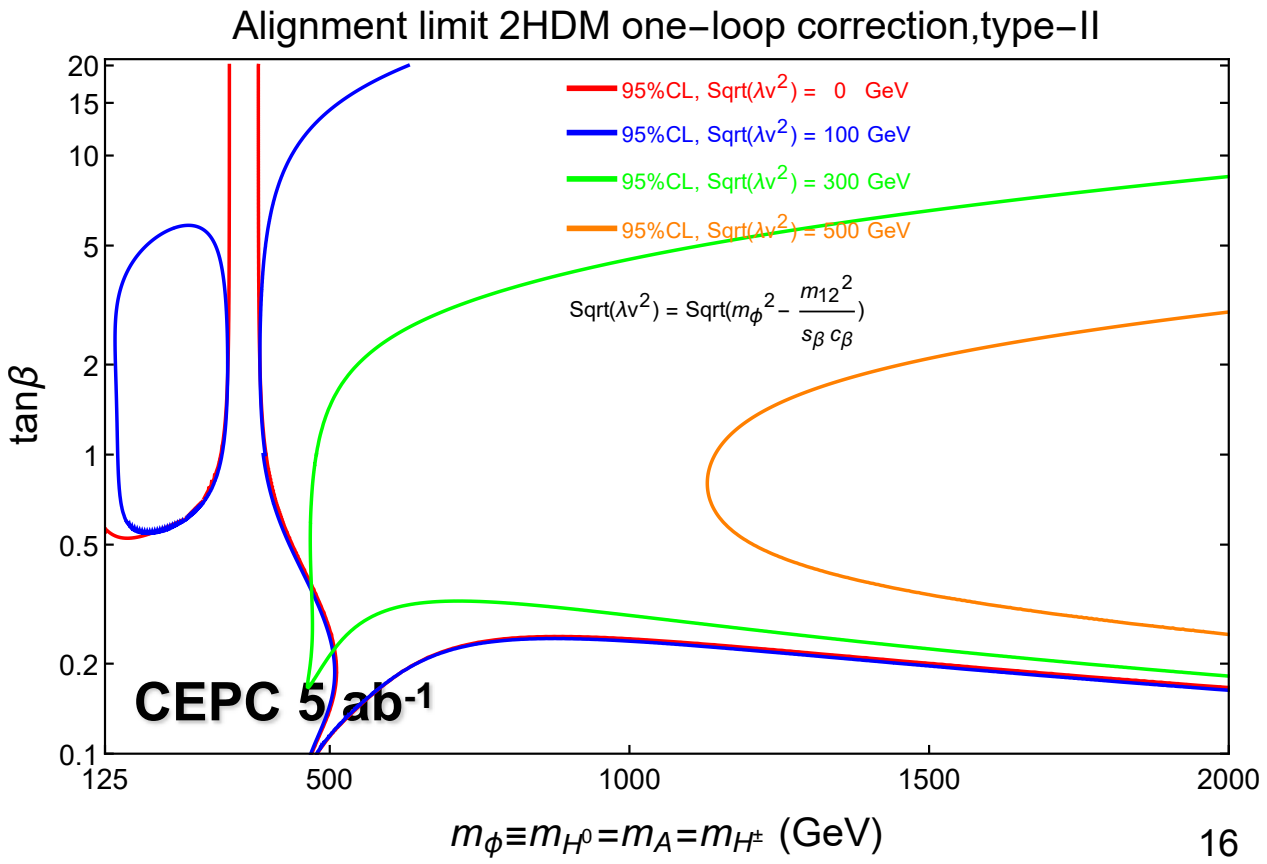


2HDM: Loop in the Alignment Limit

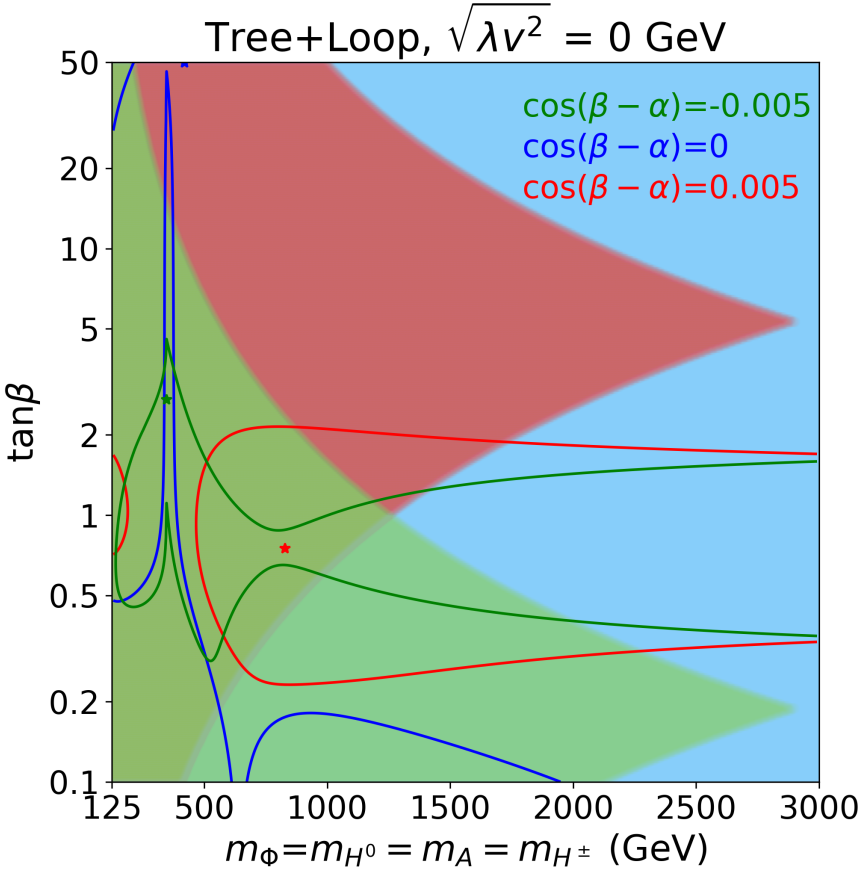
- **Type II**

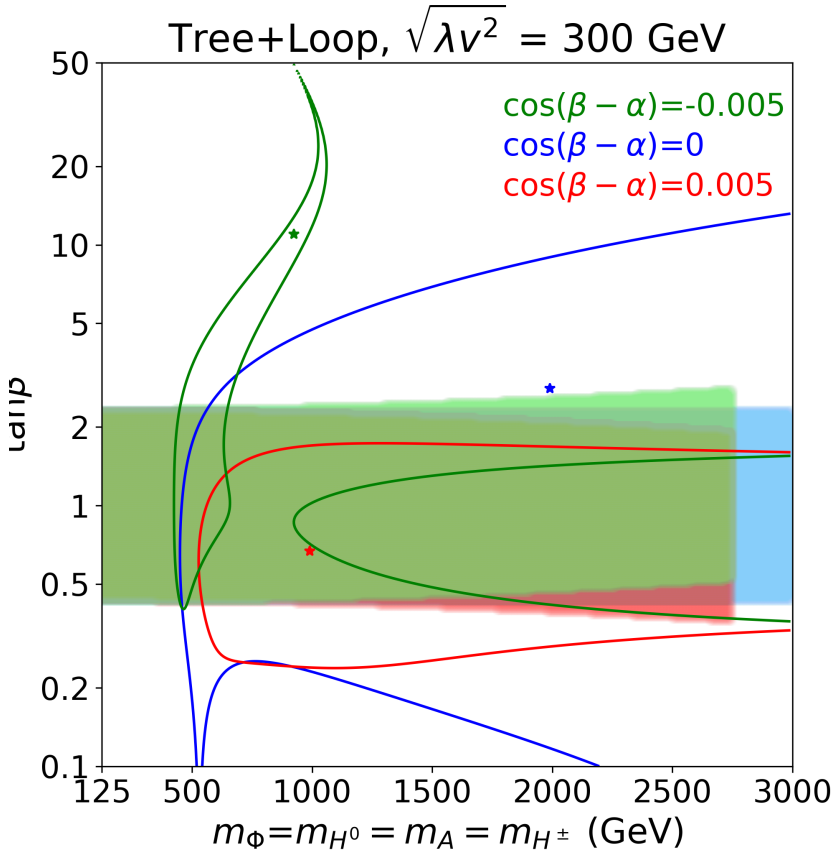
$$\kappa_{\rm loop}^{\rm 2HDM} \equiv \frac{g_{\rm tree}^{\rm 2HDM} + g_{\rm loop}^{\rm 2HDM}}{g_{\rm tree}^{\rm SM} + g_{\rm loop}^{\rm SM}}$$

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



2HDM: Tree + Loop

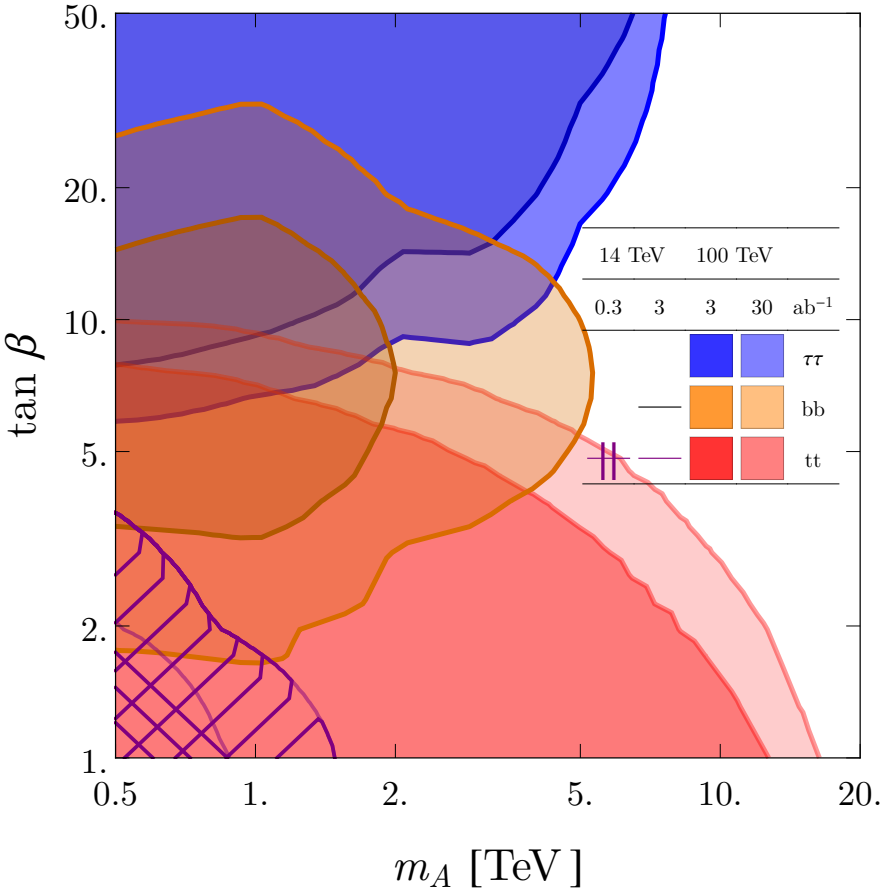




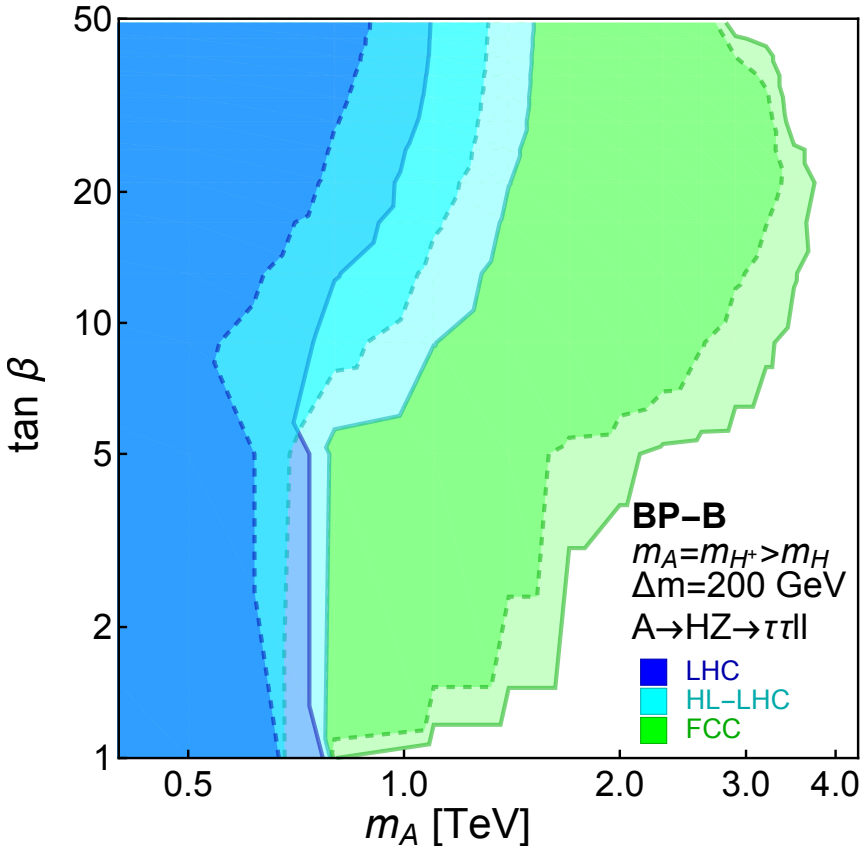
N. Chen, T. Han, SS, W. Su, Y. Wu, 1808.02037

Direct Search of Heavy Higgses @ 100 pp

Conventional search



Exotic Decay



S. Su Craig et. al., 1605.08744

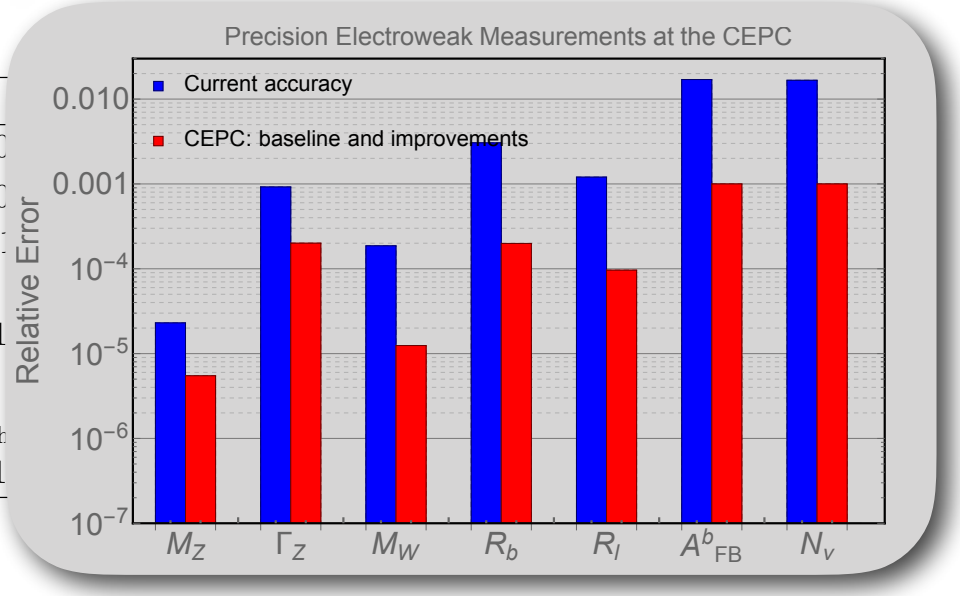
Z-pole precision

	CEPC	ILC	TLEP-W/TLEP-Z
$\alpha_s(M_Z^2)$	$\pm 1.0 \times 10^{-4}$	$\pm 1.0 \times 10^{-4}$	$\pm 1.0 \times 10^{-4}$
$\Delta\alpha^{(5)}_{\rm had}(M_Z^2)$	$\pm 4.7 \times 10^{-5}$	$\pm 4.7 \times 10^{-5}$	$\pm 4.7 \times 10^{-5}$
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]	$(\pm 3_{\rm exp} \pm 1_{\rm th}) \times 10^{-3}$	$(\pm 5_{\rm exp} \pm 1_{\rm th}) \times 10^{-3}$	$(\pm 8_{\rm exp} \pm 1_{\rm th}) \times 10^{-3}$
$\sin^2\theta^\ell_{\rm eff}$	$(\pm 4.6_{\rm exp} \pm 1.5_{\rm th}) \times 10^{-5}$	$(\pm 1.3_{\rm exp} \pm 1.5_{\rm th}) \times 10^{-5}$	$(\pm 0.3_{\rm exp} \pm 1.5_{\rm th}) \times 10^{-5}$
Γ_Z [GeV]	$(\pm 5_{\rm exp} \pm 0.8_{\rm th}) \times 10^{-4}$	± 0.001	$(\pm 1_{\rm exp} \pm 0.8_{\rm th}) \times 10^{-4}$

	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	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

Z-pole precision

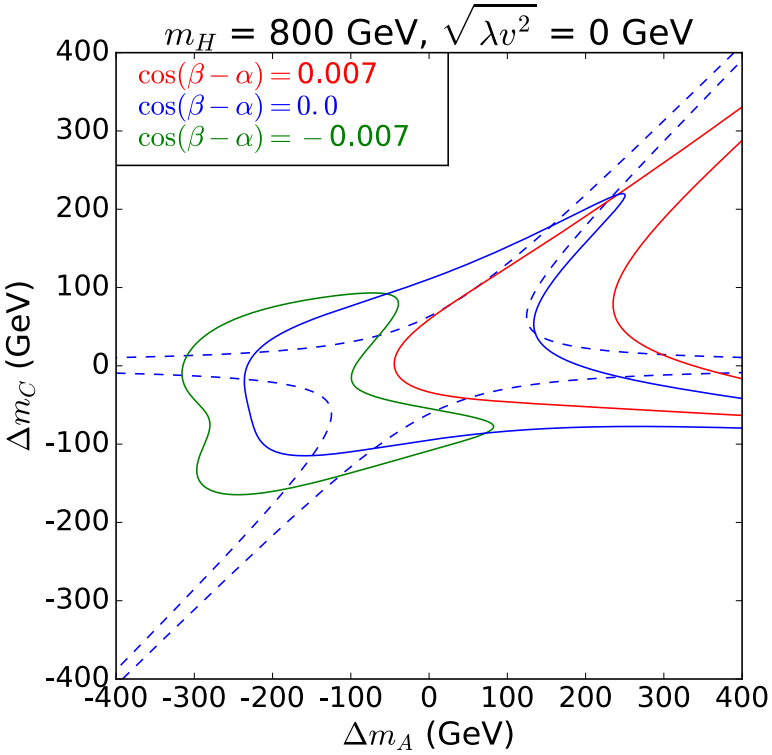
	CEPC	ILC
$\alpha_s(M_Z^2)$	$\pm 1.0 \times 10^{-4}$	$\pm 1.0 \times 10$
$\Delta\alpha^{(5)}_{\rm had}(M_Z^2)$	$\pm 4.7 \times 10^{-5}$	$\pm 4.7 \times 10$
m_Z [GeV]	± 0.0005	± 0.002
m_t [GeV] (pole)	$\pm 0.6_{\rm exp} \pm 0.25_{\rm th}$	$\pm 0.03_{\rm exp} \pm$
m_h [GeV]	$< \pm 0.1$	$< \pm 0.1$
m_W [GeV]	$(\pm 3_{\rm exp} \pm 1_{\rm th}) \times 10^{-3}$	$(\pm 5_{\rm exp} \pm 1_{\rm th})$
$\sin^2\theta^\ell_{\rm eff}$	$(\pm 4.6_{\rm exp} \pm 1.5_{\rm th}) \times 10^{-5}$	$(\pm 1.3_{\rm exp} \pm 1.5_{\rm th}$
Γ_Z [GeV]	$(\pm 5_{\rm exp} \pm 0.8_{\rm th}) \times 10^{-4}$	± 0.001

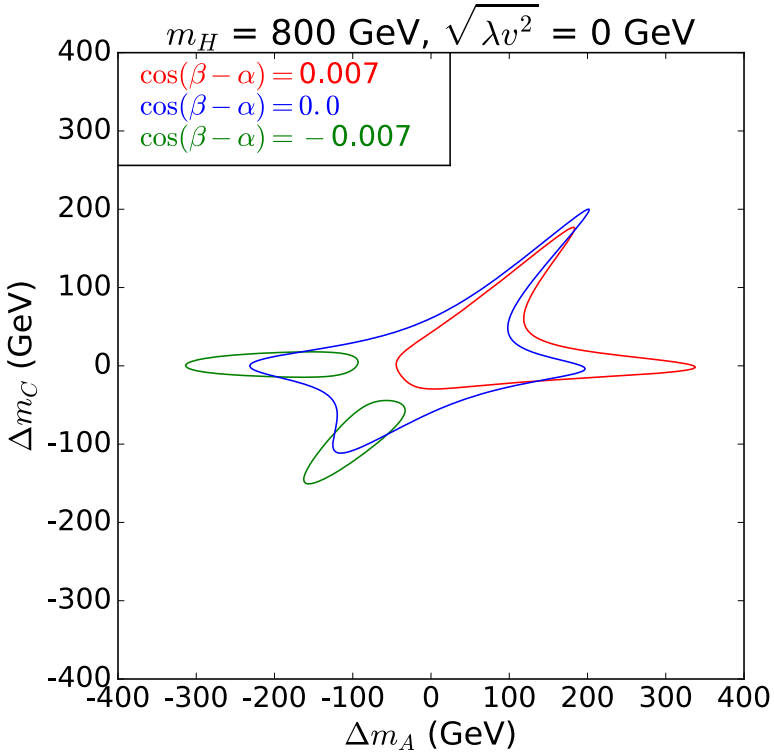


	Current				CEPC				FCC-ee				ILC			
	σ	correlation			σ	correlation			σ	correlation			σ	correlation		
		S	T	U	(10^{-2})	S	T	U	(10^{-2})	S	T	U	(10^{-2})	S	T	U
S	0.04 ± 0.11	1	0.92	-0.68	2.46	1	0.862	-0.373	0.67	1	0.812	0.001	3.53	1	0.988	-0.879
T	0.09 ± 0.14	-	1	-0.87	2.55	-	1	-0.735	0.53	-	1	-0.097	4.89	-	1	-0.909
U	-0.02 ± 0.11	-	-	1	2.08	-	-	1	2.40	-	-	1	3.76	-	-	1

2HDM: non-degenerate

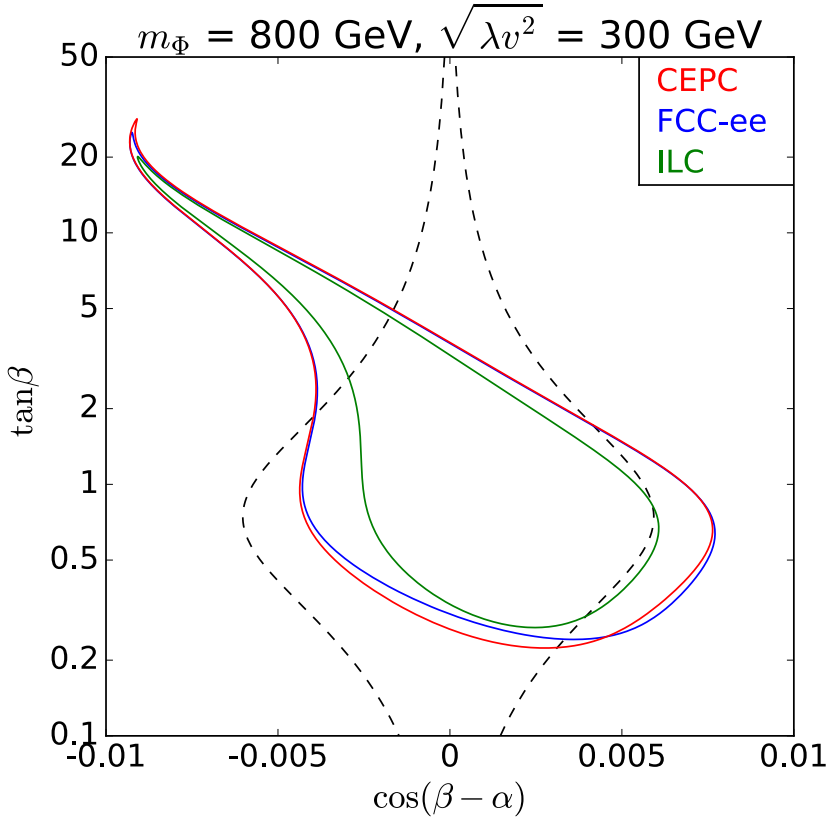
$$\Delta m_a = m_A - m_H,\ \Delta m_c = m_{H^\pm} - m_H$$

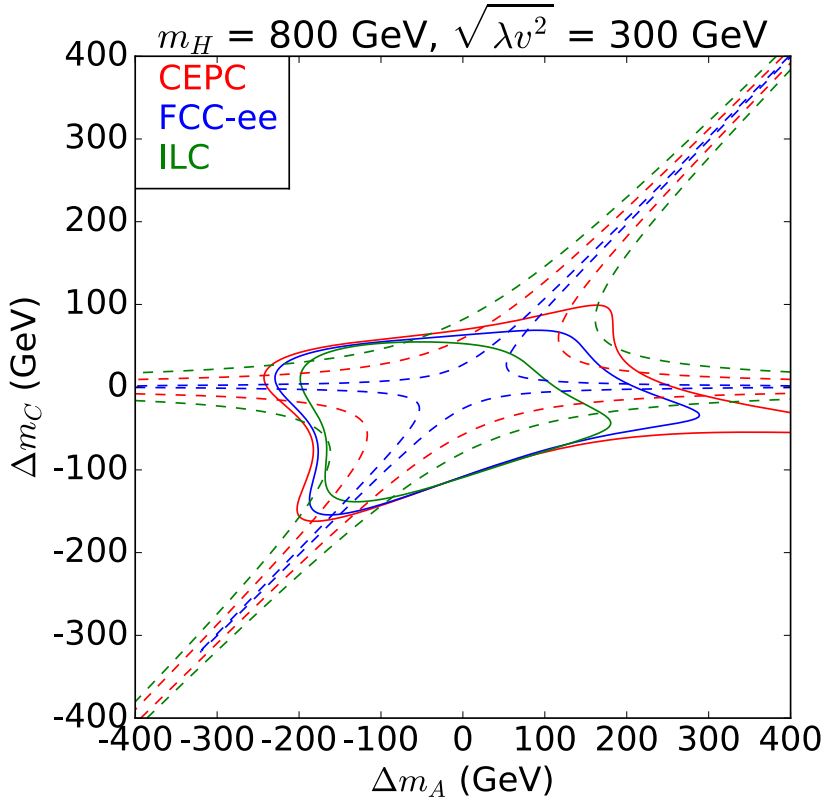




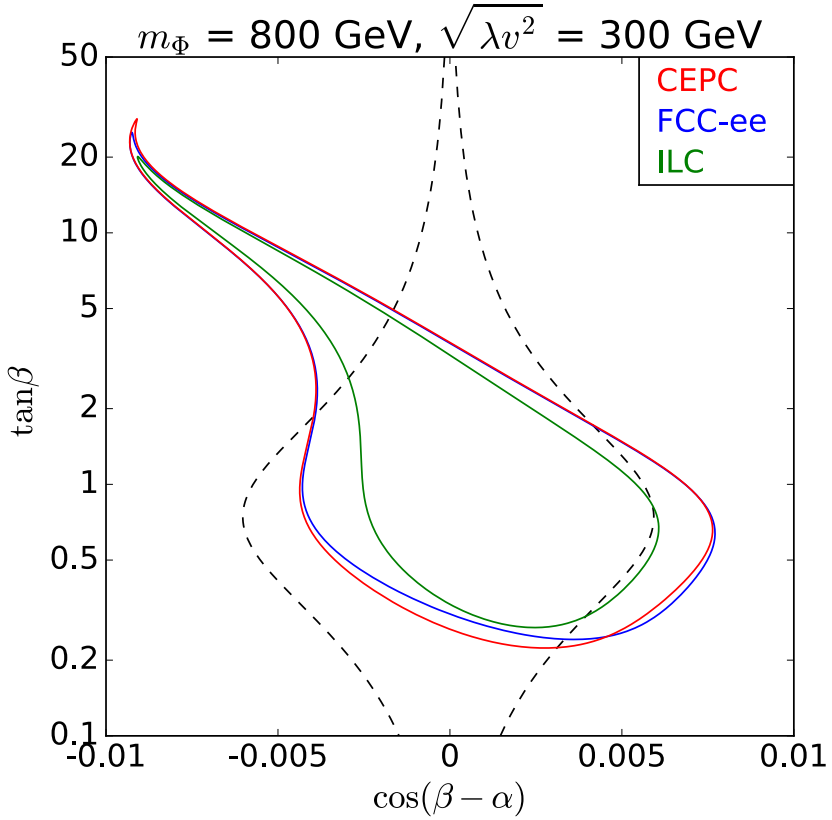
Complementary to Zpole precision

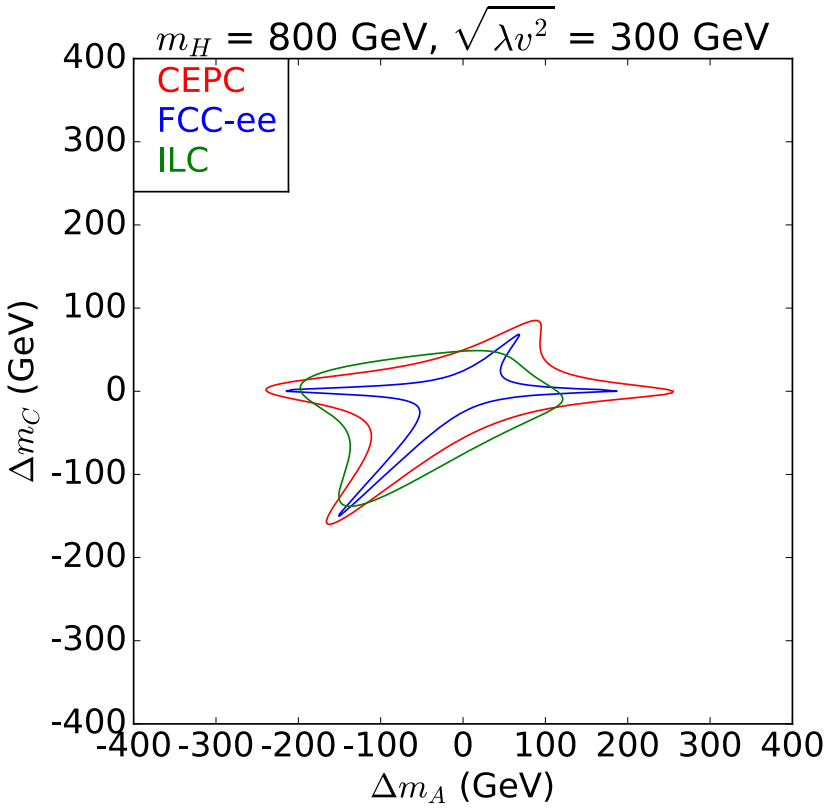
Different Higgs Factories





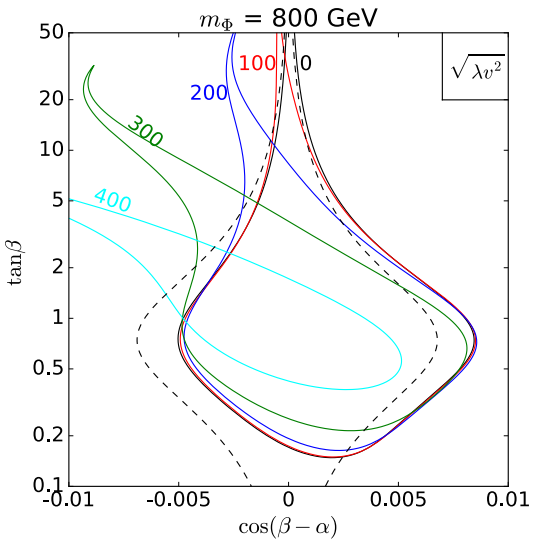
Different Higgs Factories

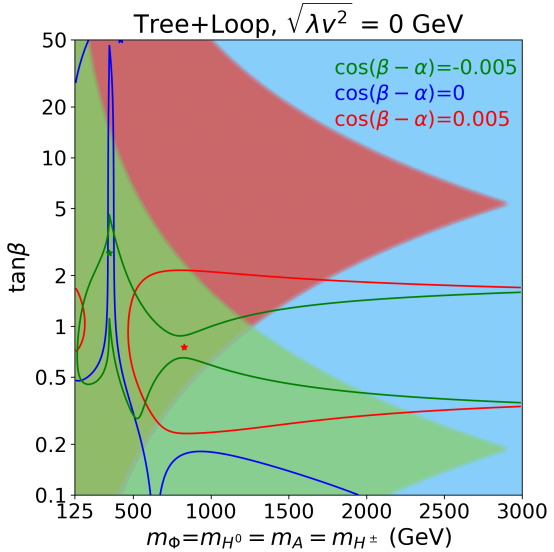


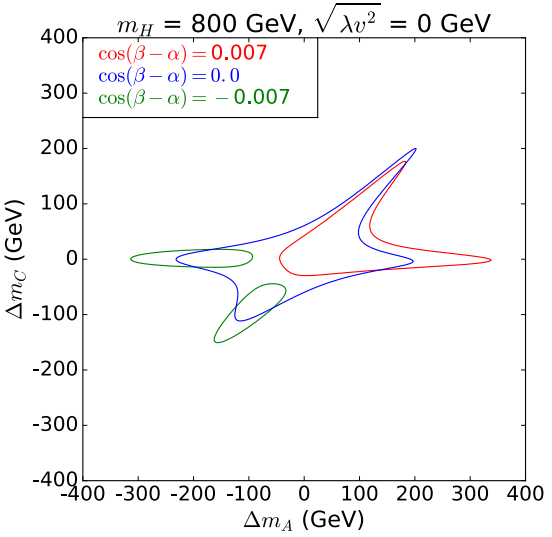


Conclusion

- 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







2HDM tree + loop

Conclusion

LHC

Lepton Collider

100 TeV pp

An exciting journey ahead of us!