Learning from Higgs Physics at Future Higgs Factories

Shufang Su • U. of Arizona

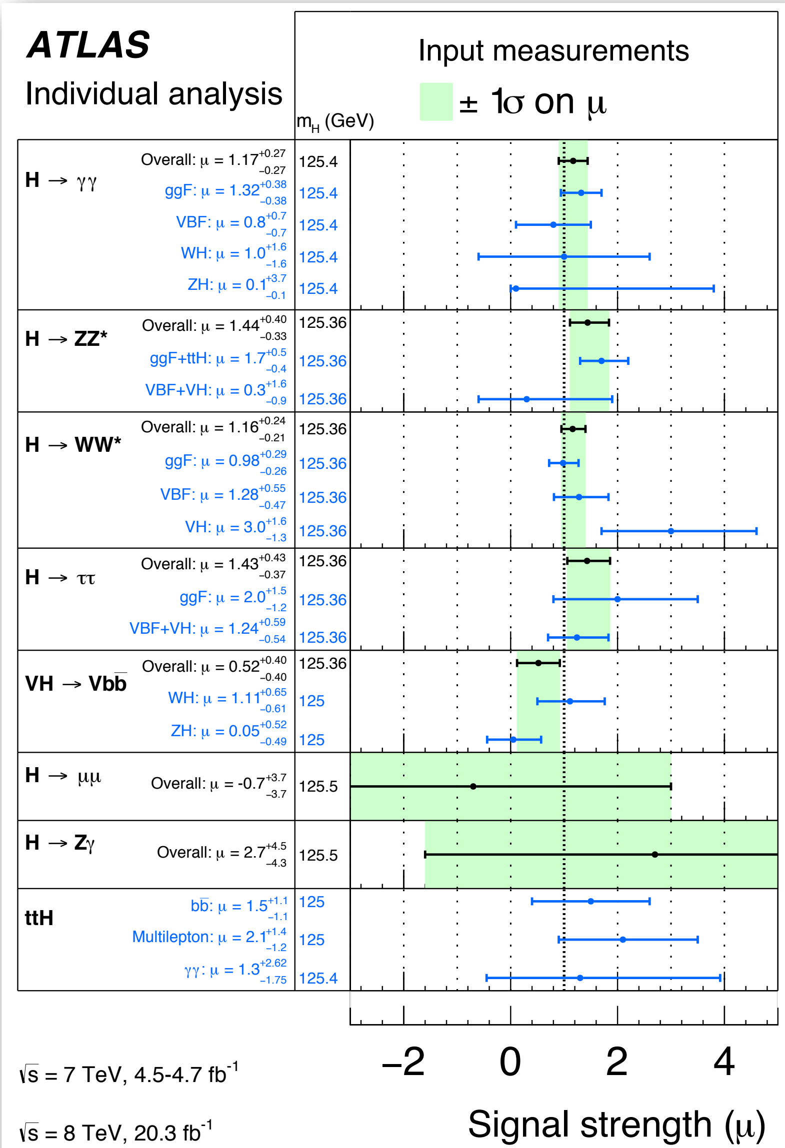
SUSY 2019
May 20, 2019

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

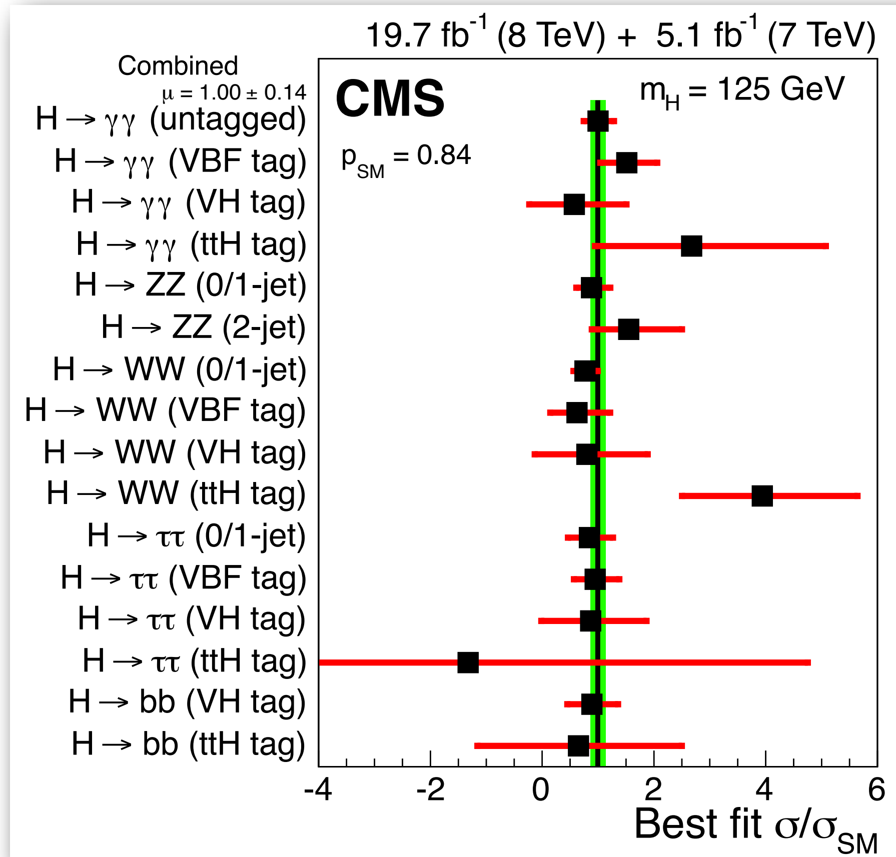
Outline

- Higgs precision measurements
- Global fit framework
- Perturbative models
  - SM with a real singlet extension (skip in this talk)
  - 2HDM (tree + loop, Higgs + Zpole)
  - MSSM (skip in this talk)
- Strong dynamics models (skip in this talk)
- Complementarity with direct search @ 100 pp
- Conclusion

Higgs Precision Measurements

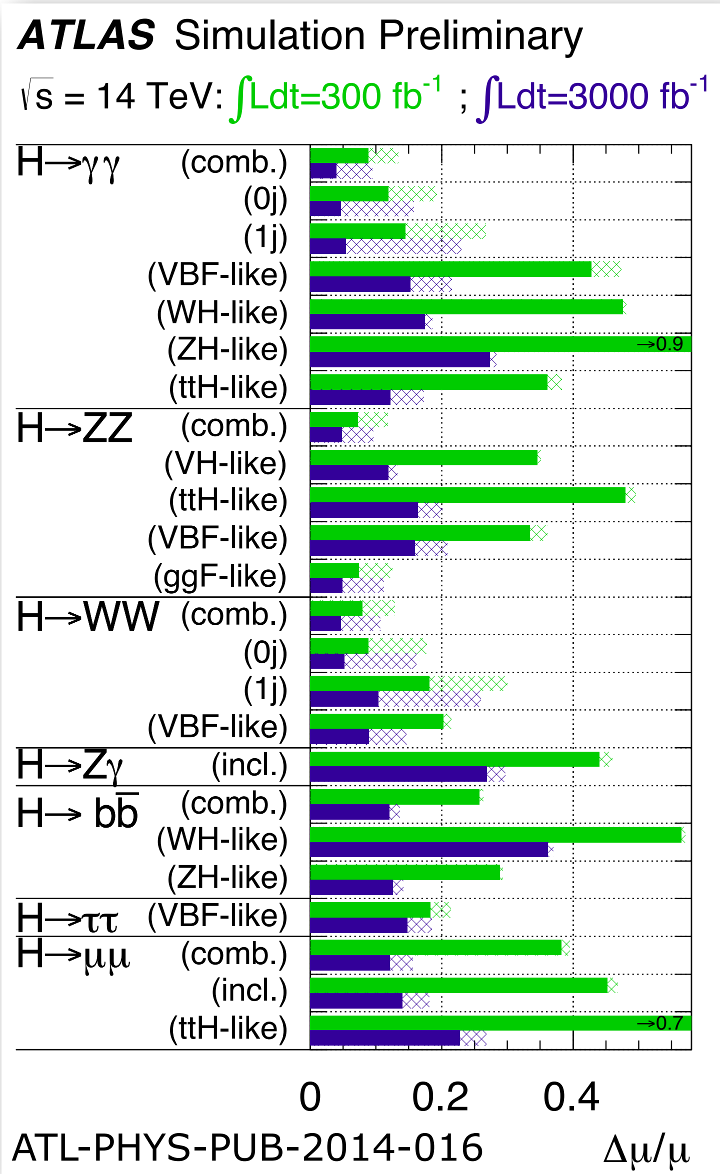


LHC: 7+8 TeV



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

Higgs Precision Measurements



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

$\Delta\mu/\mu$	300 fb^{-1}		3000 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

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

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Kappa framework and EFT Framework

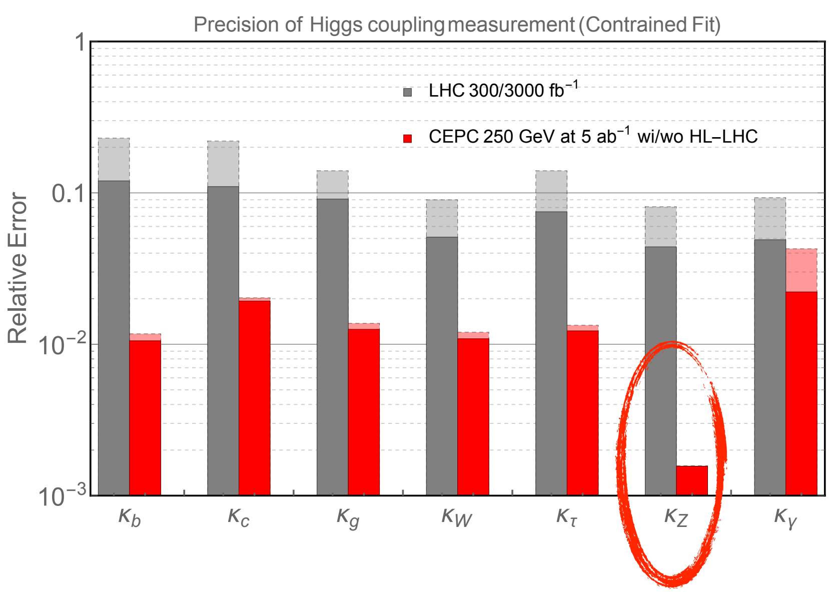
Two model-independent approaches

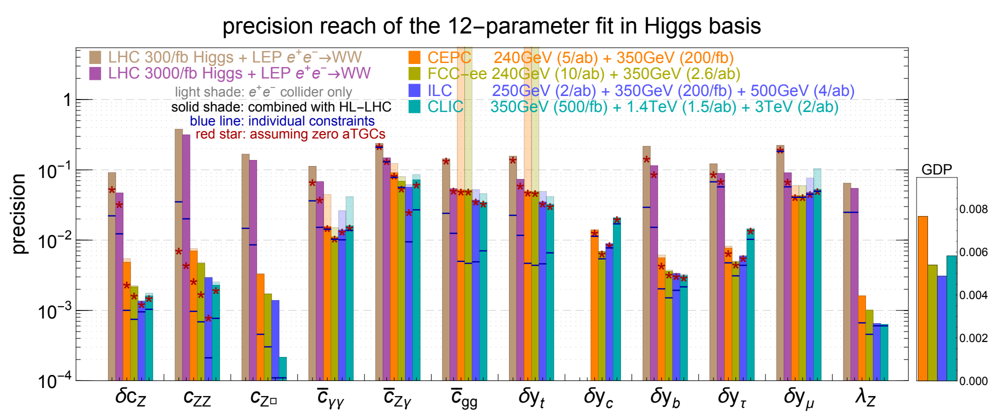
kappa framework

EFT framework

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

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





1704.02333

New Physics Implication

Experimental observables

Various K_i
(with correlation)

Coeff of EFT operators
(with correlation)

parameters in New Physics Models

Kappa Framework and EFT Framework

limitations of model-independent approaches

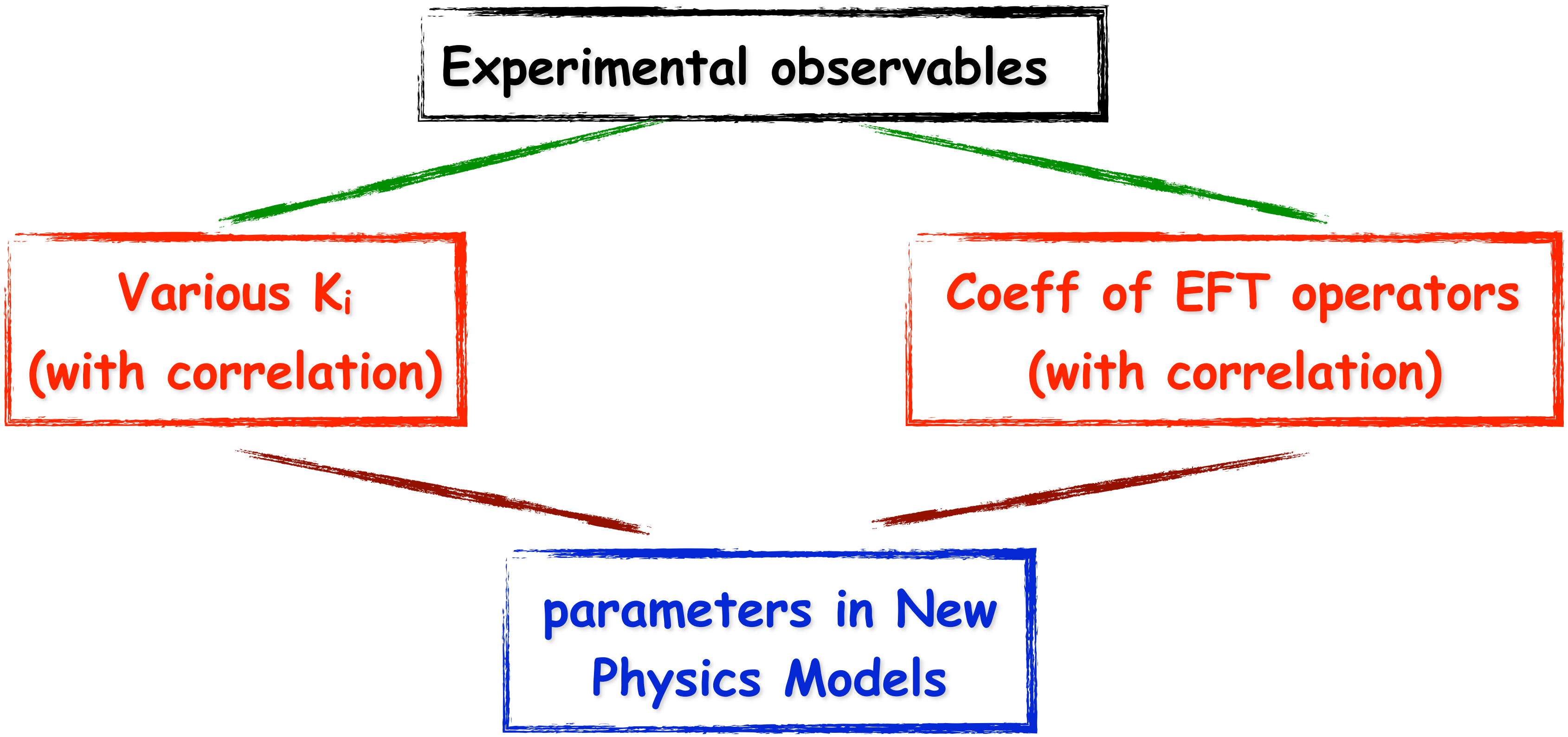
- large level of degeneracy

  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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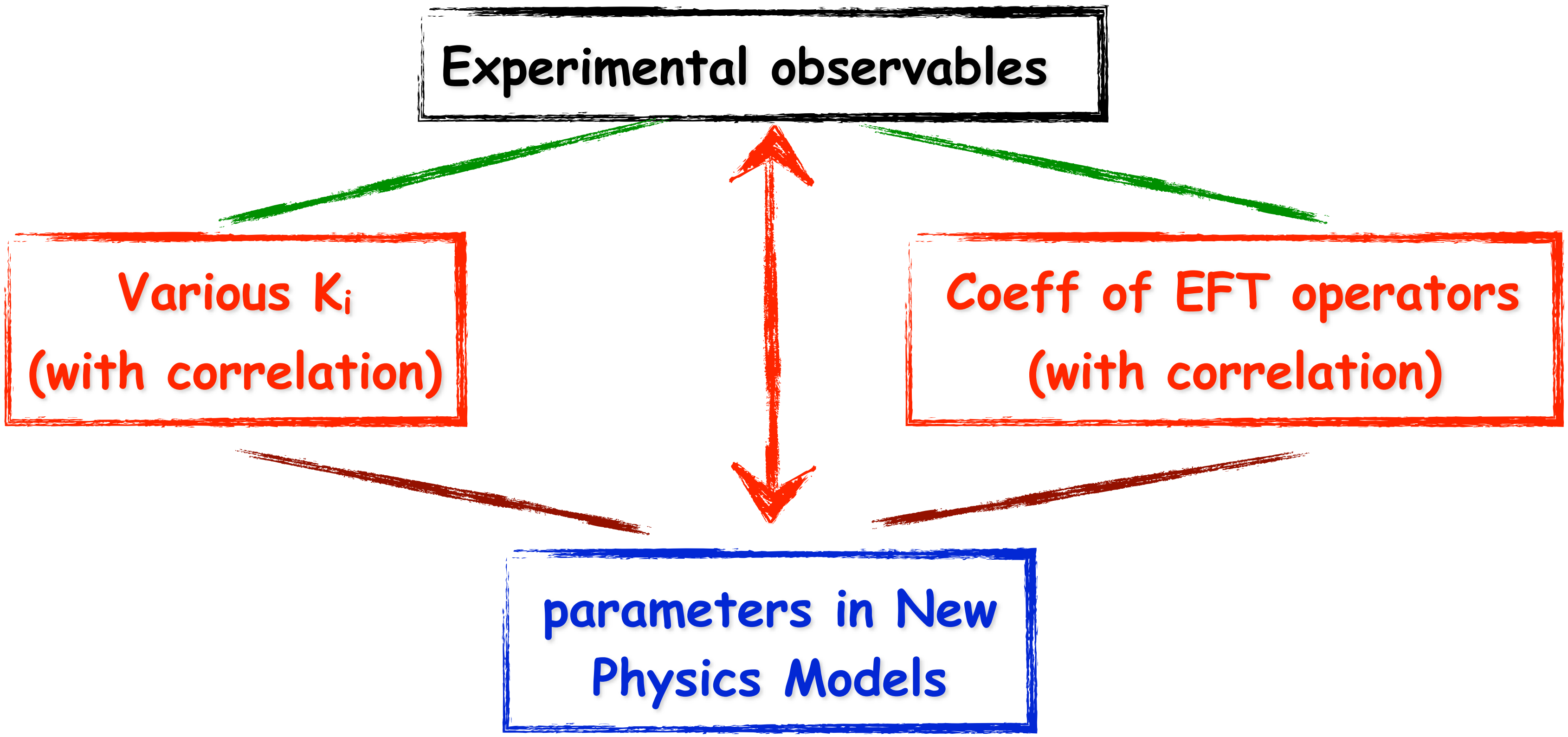

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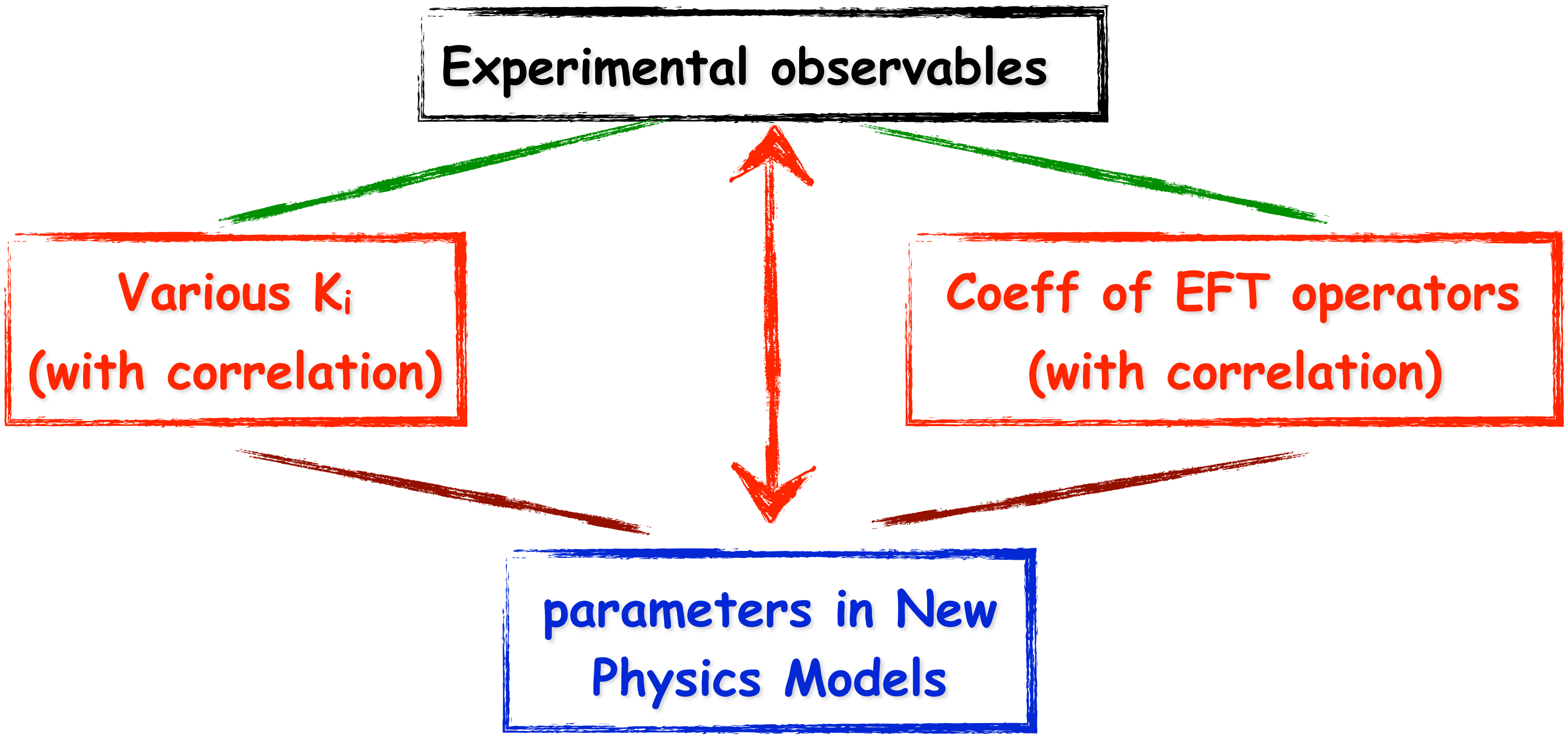

$$\chi^2 = \sum_i \frac{(\mu_i^{\rm BSM} - \mu_i^{\rm obs})^2}{\sigma_{\mu_i}^2} \qquad \mu_i^{\rm BSM} = \frac{(\sigma \times {\rm Br})_{\rm BSM}}{(\sigma \times {\rm Br})_{\rm SM}}$$

Perturbative Models

- SM with a real singlet extension (skip)
- 2HDM (Type I, II, L, F)
- MSSM (skip)

2HDM in one slide

- **Two Higgs Doublet Model (CP-conserving)**

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

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

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

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

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

soft Z2 breaking: m_{12}^2

tanβ, cos(β-α),

control tree level h^0 couplings

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2HDM-L	$\sin(\beta-\alpha)$	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$
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soft Z2 breaking: m_{12}^2

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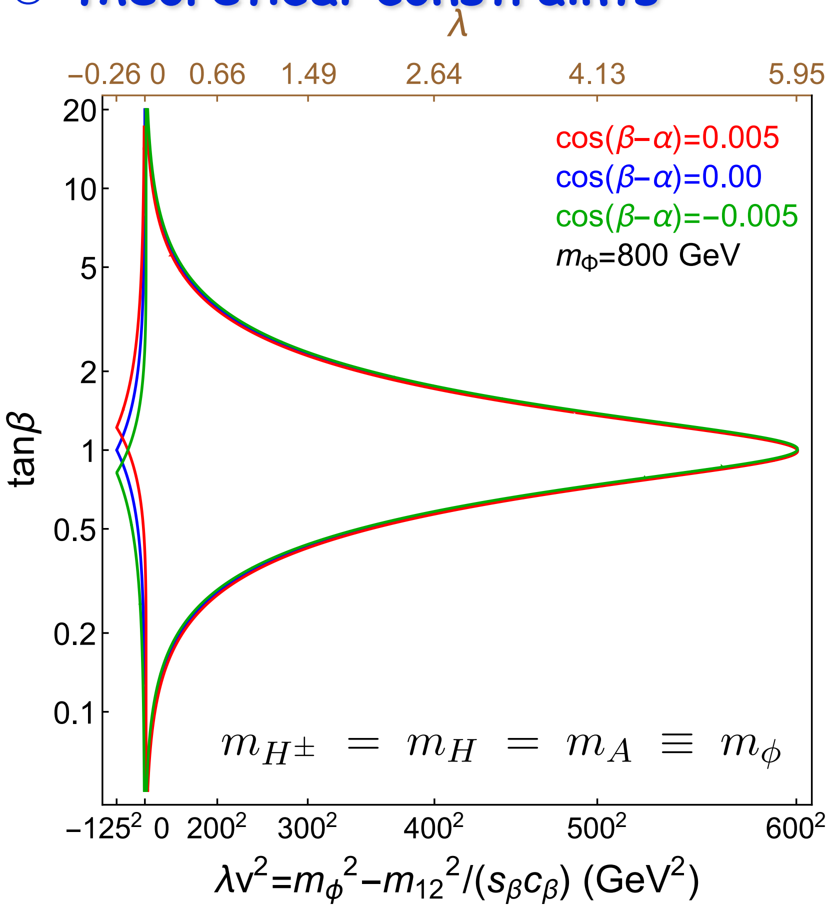
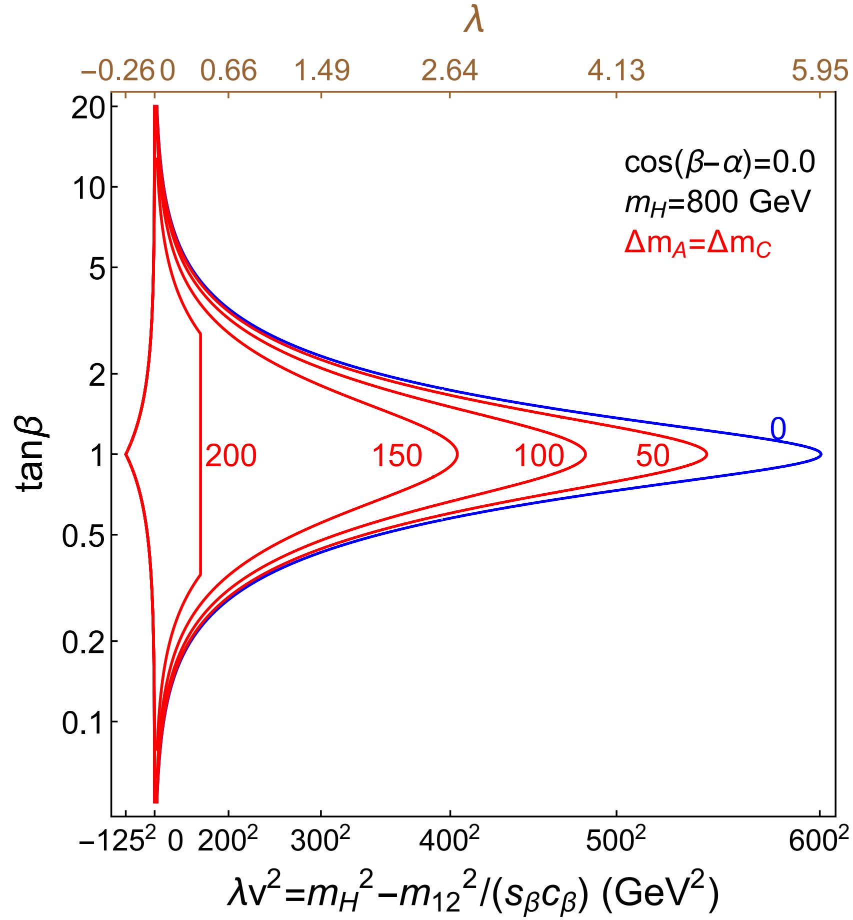
2HDM: Loop in the Alignment Limit

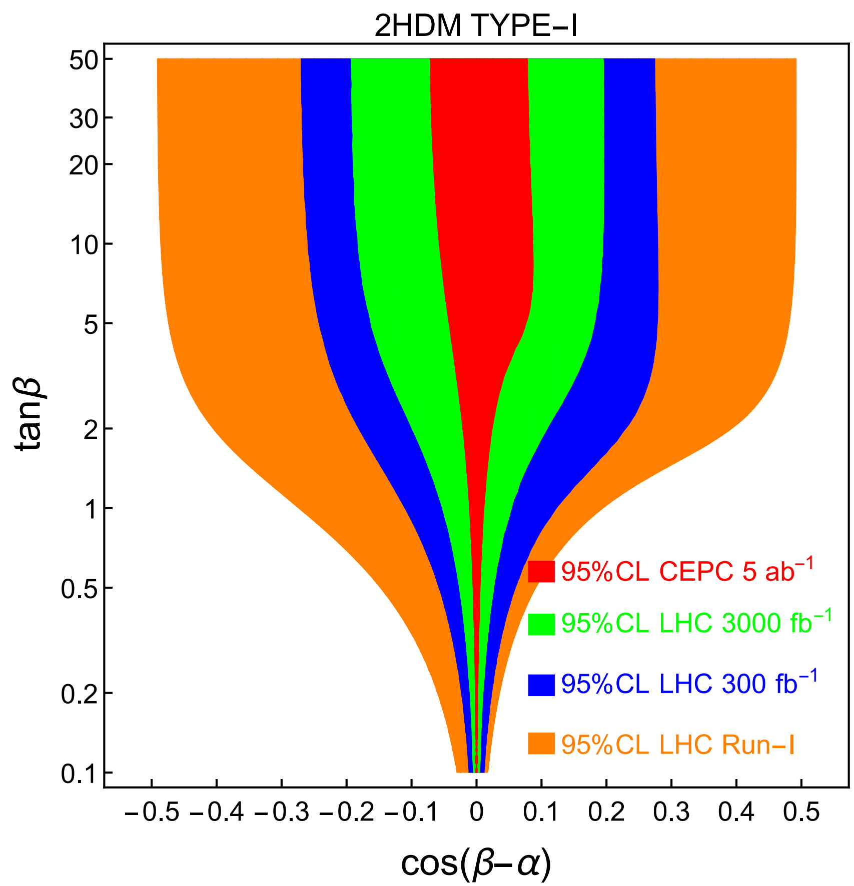
- **theoretical constraints**

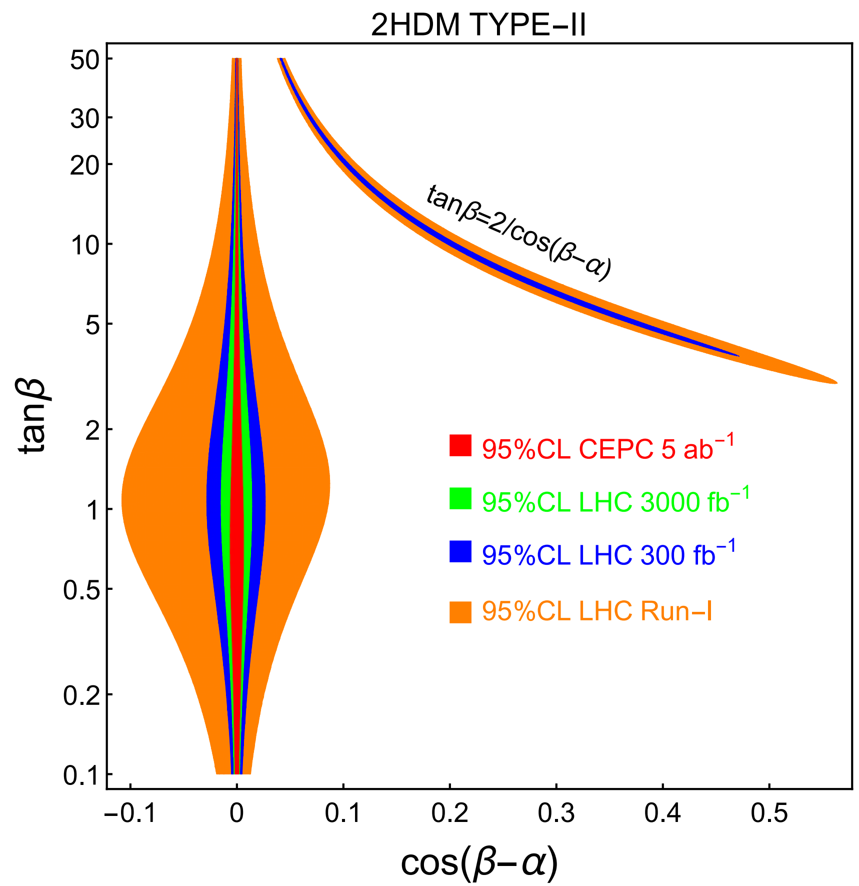




Tree-level 2HDM fit

2HDM, LHC/FCC fit





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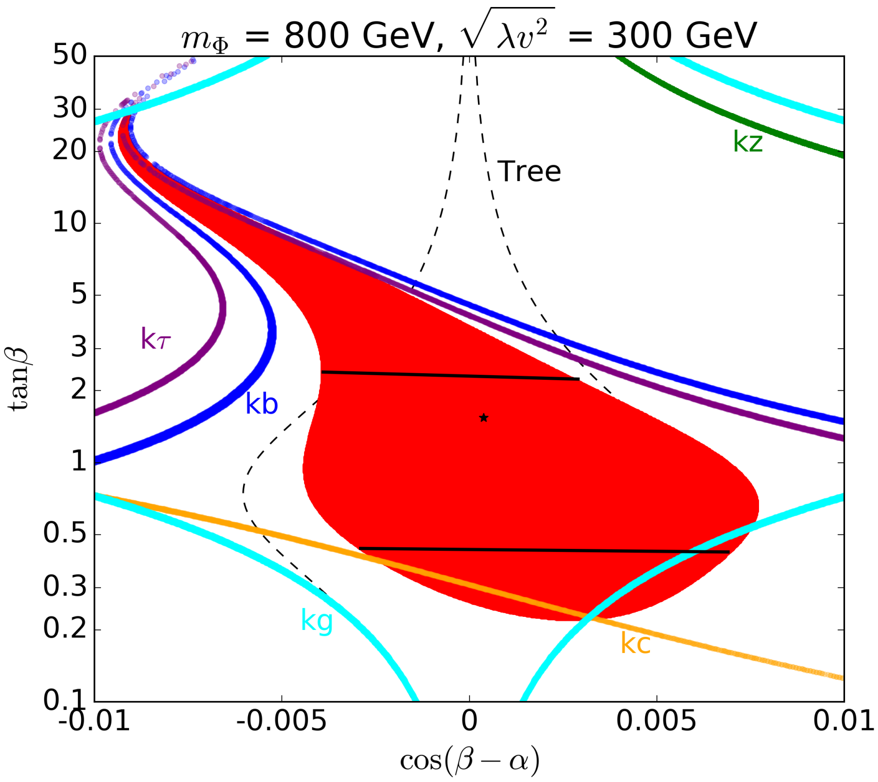
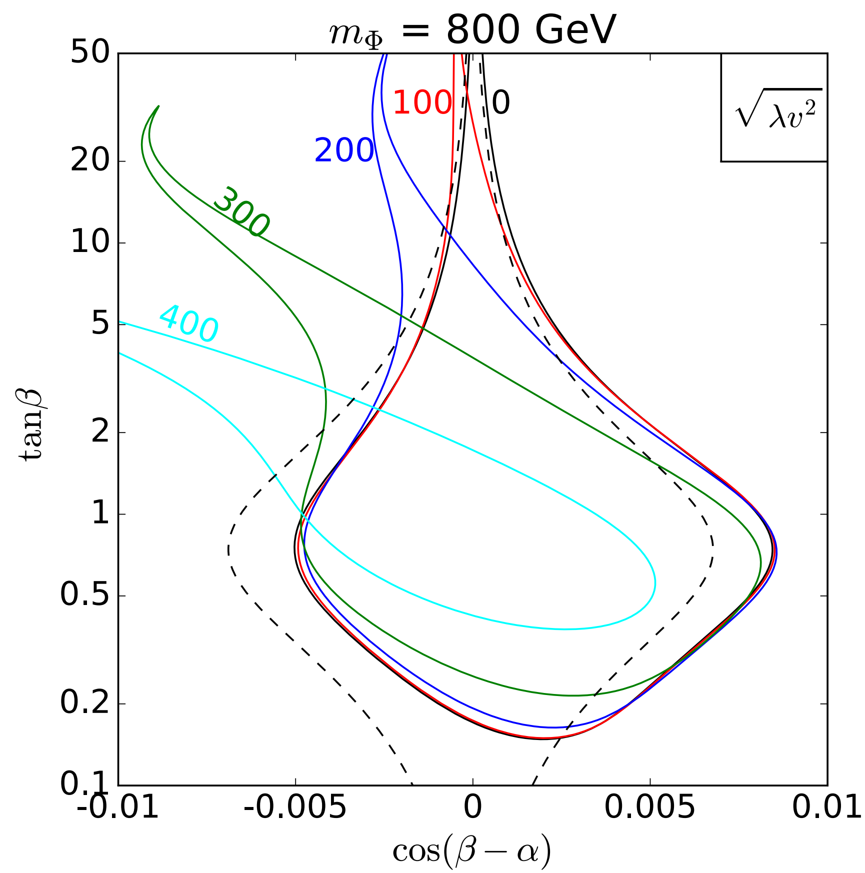
TYPE II 2HDM: Tree + Loop





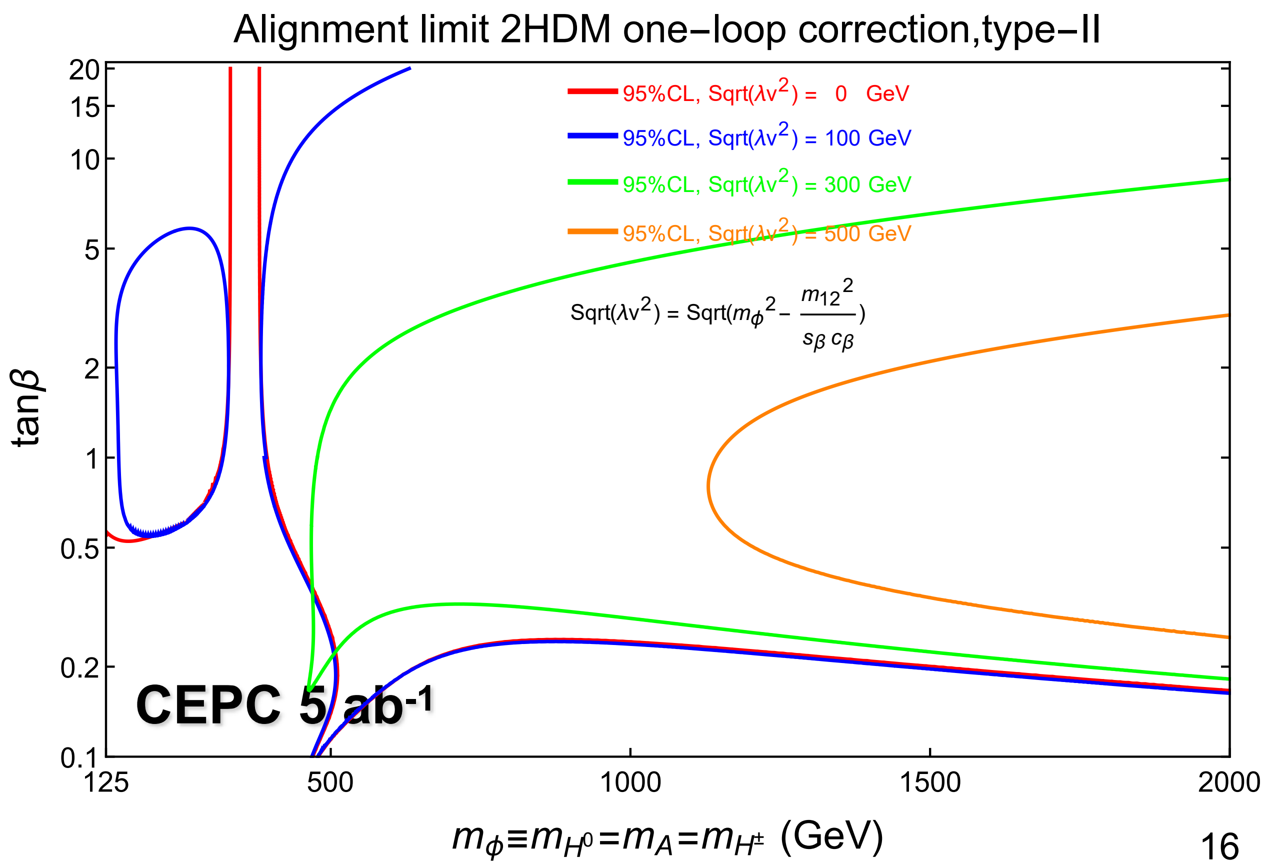
N. Chen, T. Han, SS, W. Su, Y. Wu, 1808.02037

2HDM: Loop in the Alignment Limit

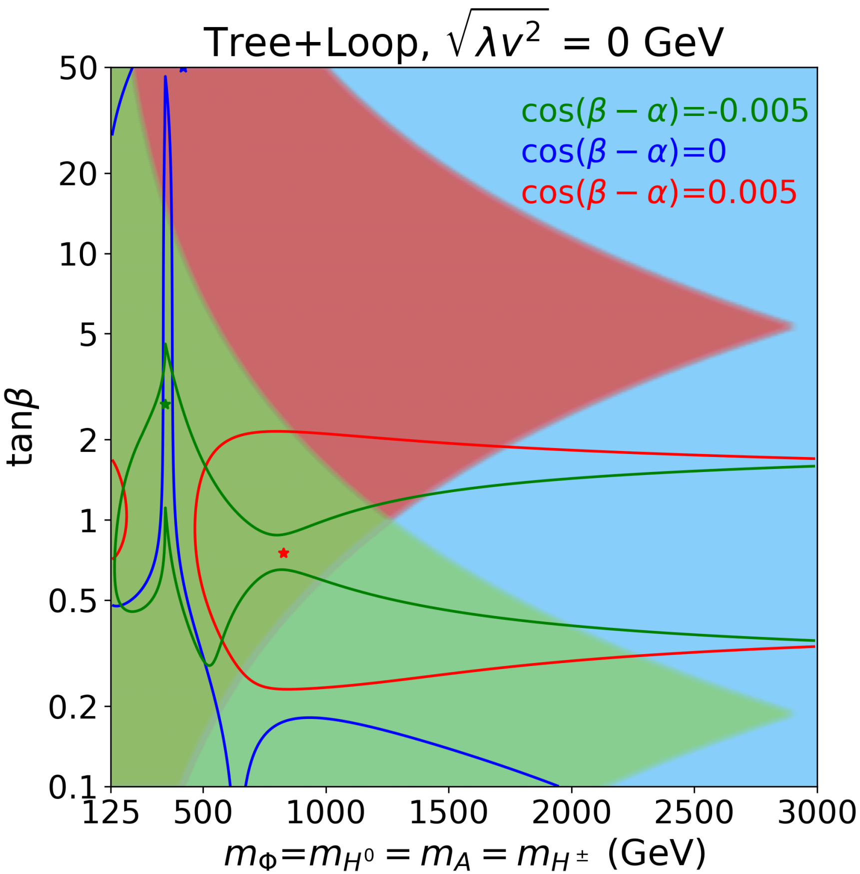
- **Type II**

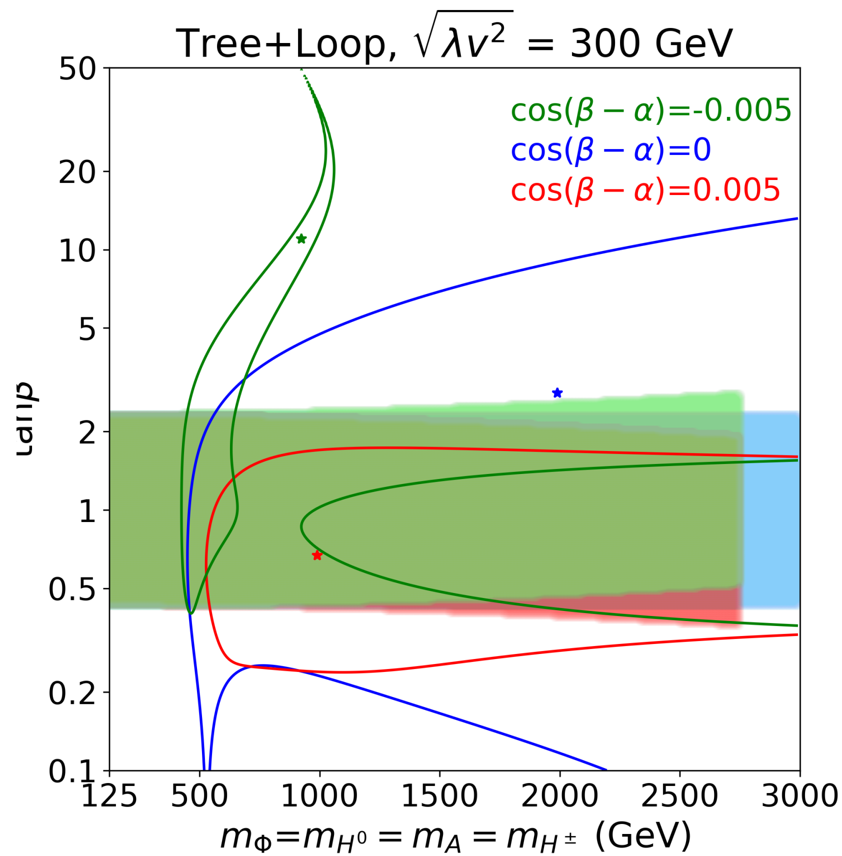
$$\kappa^{\rm 2HDM}_{\rm loop} \equiv \frac{g^{\rm 2HDM}_{\rm tree} + g^{\rm 2HDM}_{\rm loop}}{g^{\rm SM}_{\rm tree} + g^{\rm SM}_{\rm loop}}$$

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



2HDM: Tree + Loop

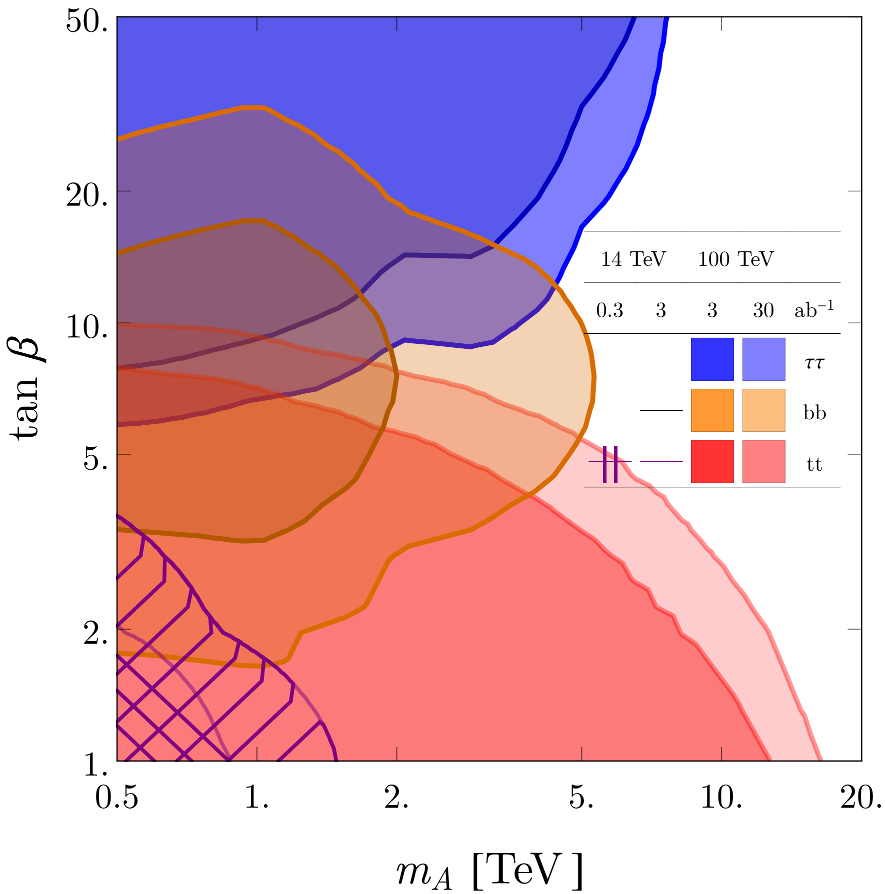




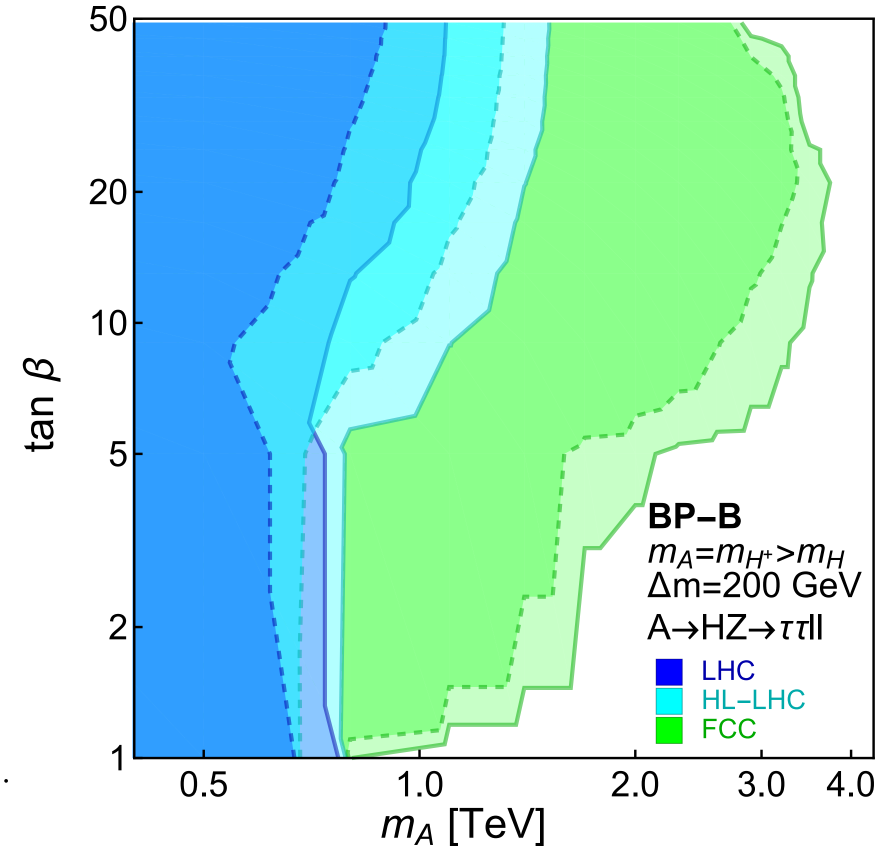
N. Chen, T. Han, SS, W. Su, Y. Wu, 1808.02037

Direct Search of Heavy Higgses @ 100 pp

Conventional search



Exotic Decay



S. Su Craig et. al., 1605.08744

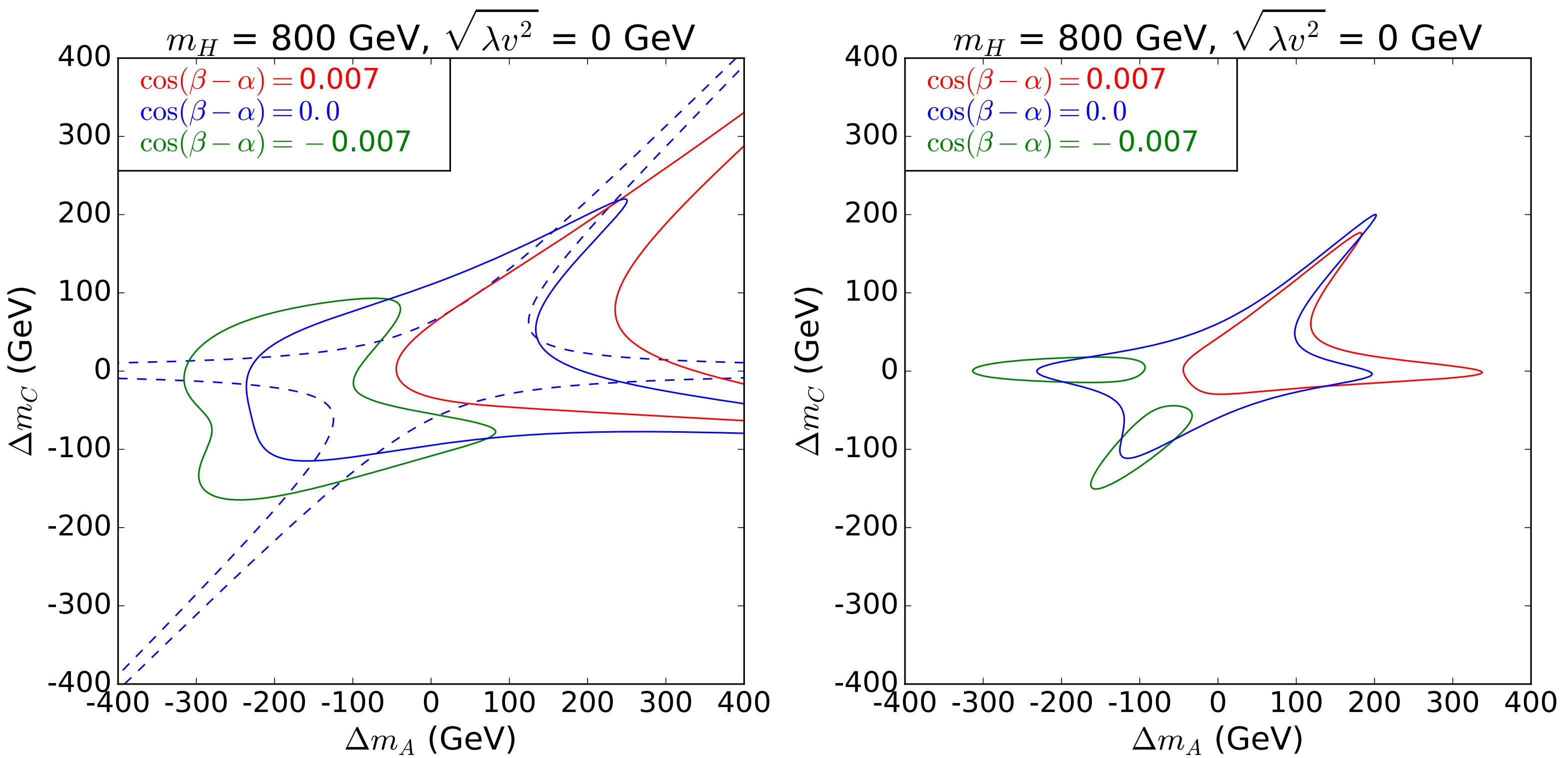
Z-pole precision

	CEPC	ILC	TLEP-W/TLEP-Z
$\alpha_s(M_Z^2)$	$\pm 1.0 \times 10^{-4}$	$\pm 1.0 \times 10^{-4}$	$\pm 1.0 \times 10^{-4}$
$\Delta\alpha_{\rm had}^{(5)}(M_Z^2)$	$\pm 4.7 \times 10^{-5}$	$\pm 4.7 \times 10^{-5}$	$\pm 4.7 \times 10^{-5}$
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	$(\pm 1_{\rm exp} \pm 0.8_{\rm th}) \times 10^{-4}$

	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	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

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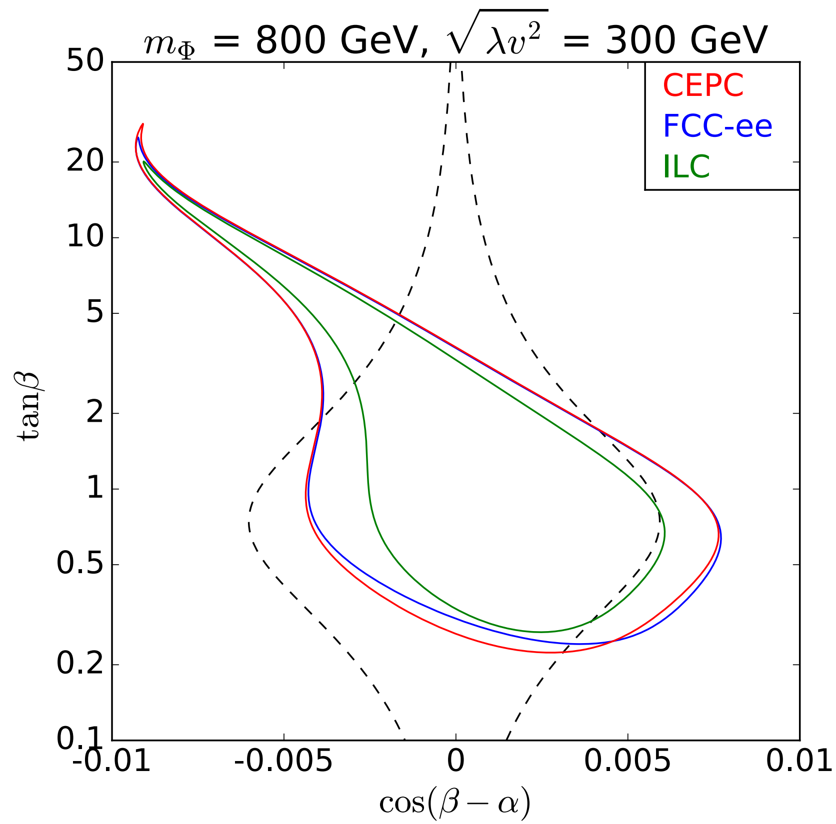
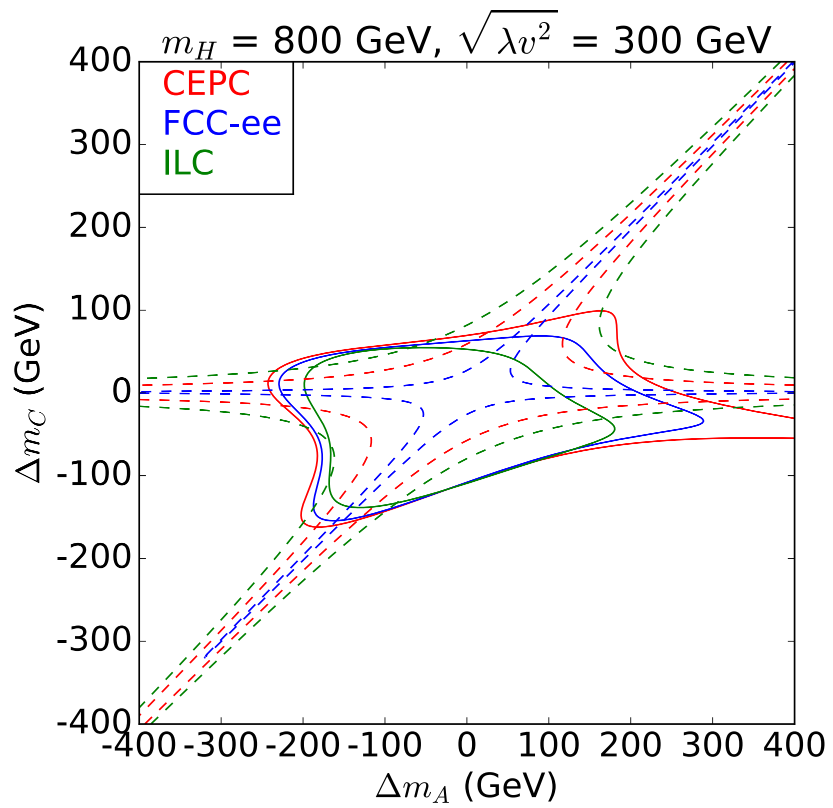
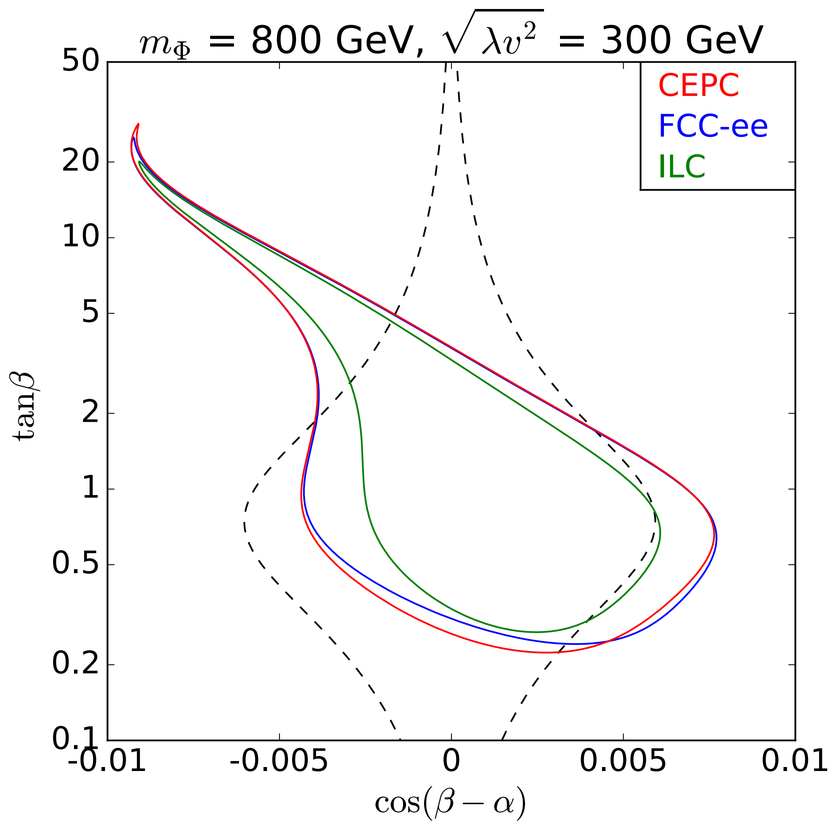
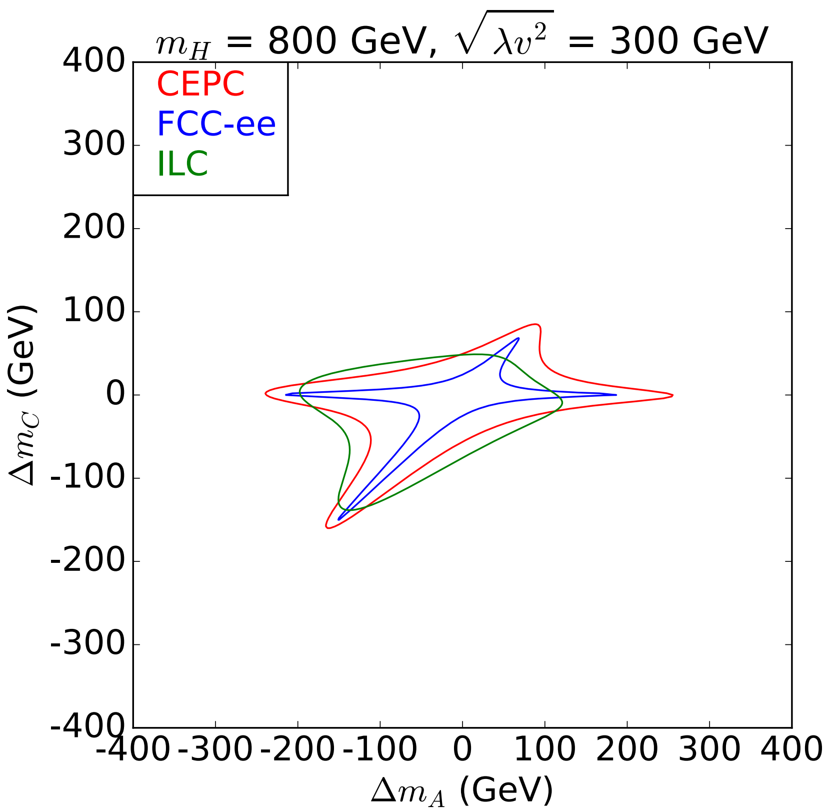
Different Higgs Factories





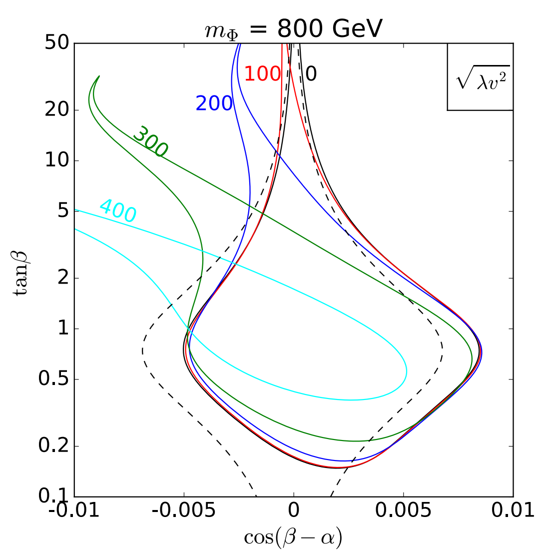
Different Higgs Factories

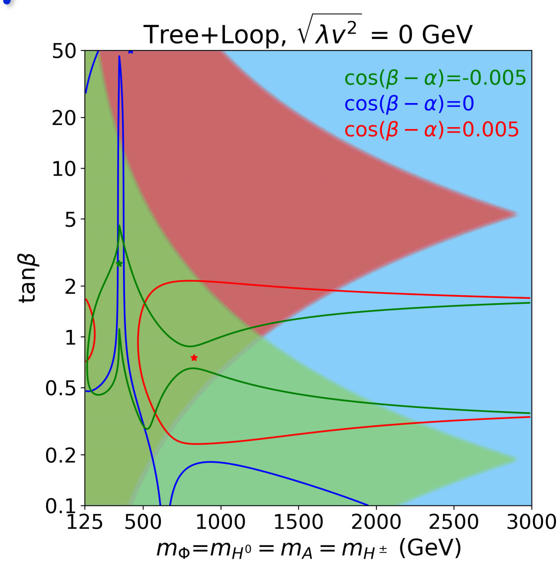


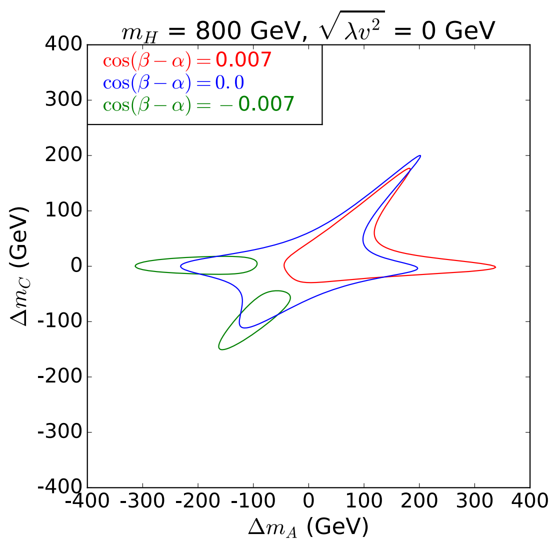


Conclusion

- 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!