Learning from Higgs Physics at Future Higgs Factories

Shufang Su • U. of Arizona

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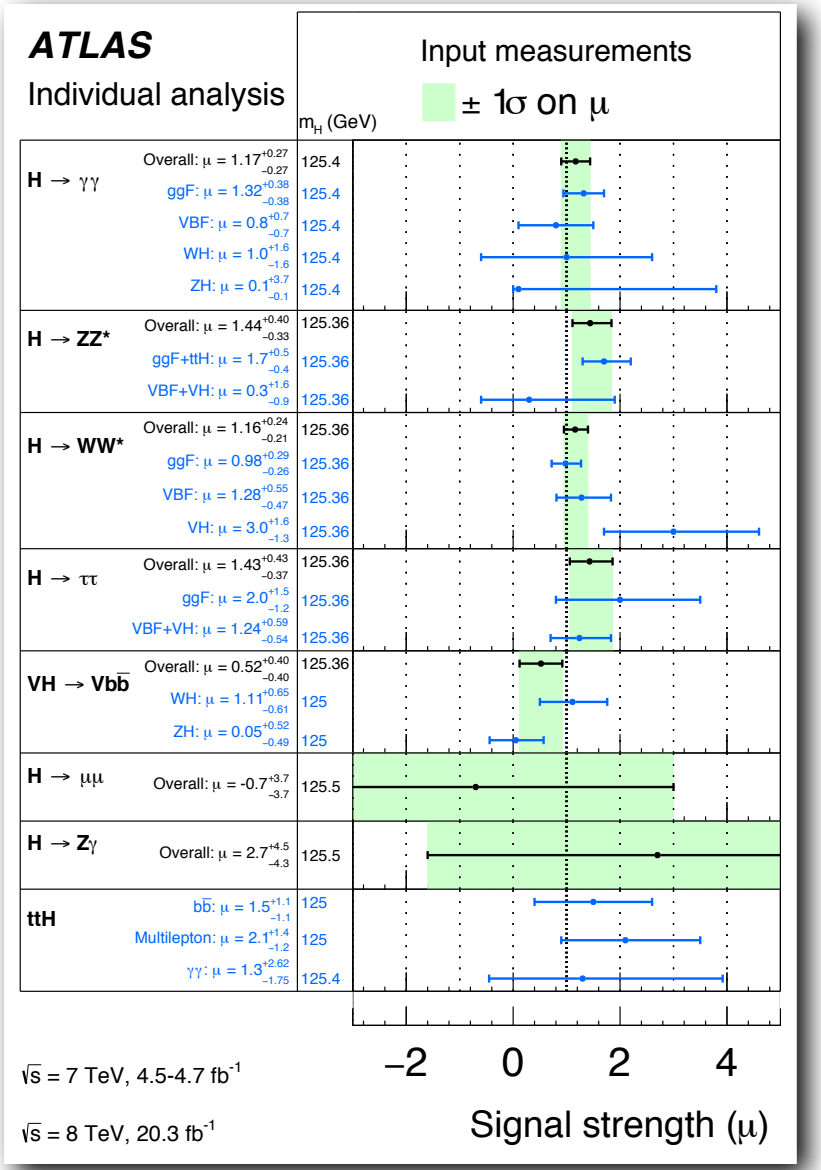
J. Gu, H. Li, Z. Liu, W. Su, 1709.06103
N. Chen, T. Han, SS, W. Su, Y. Wu, work in progress
H. Li, SS, W. Su, work in progress

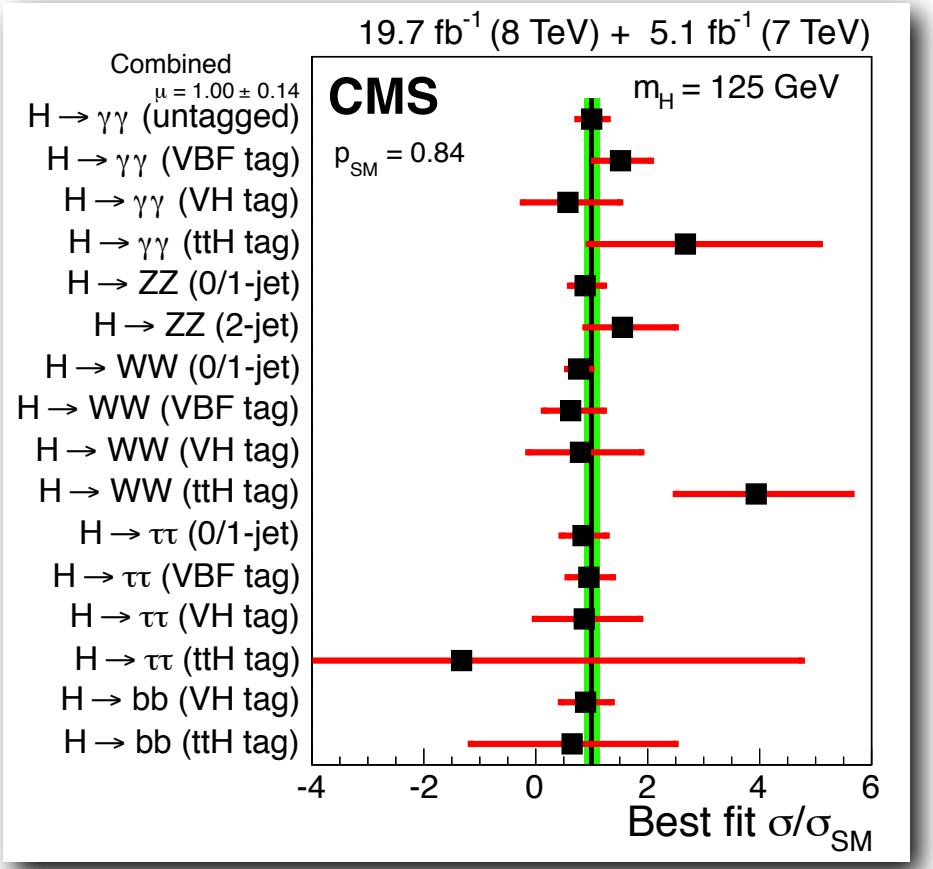
Outline

- 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

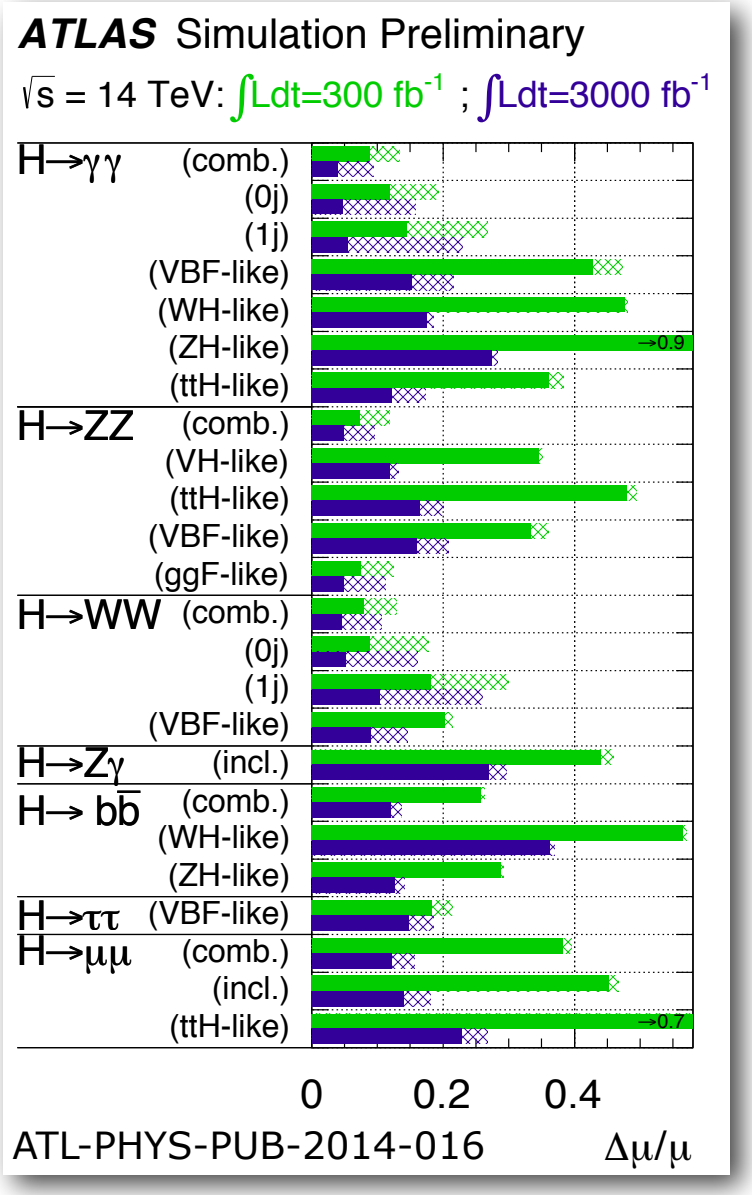


LHC: 7+8 TeV



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
($t\bar{t}H$-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
($t\bar{t}H$-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
($t\bar{t}H$-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

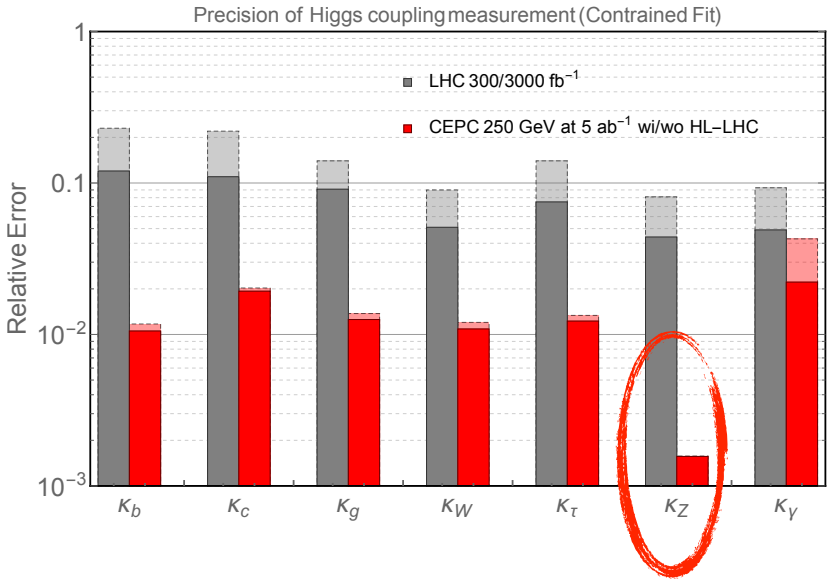
Two model-independent approaches

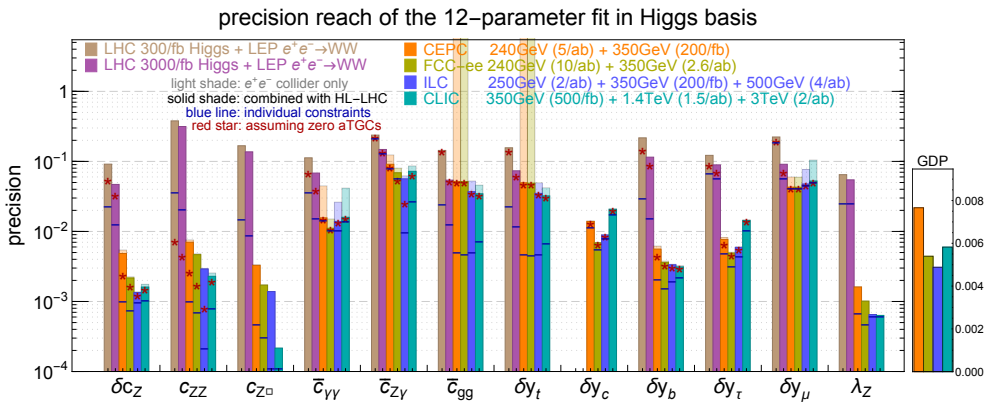
kappa framework

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

EFT framework

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





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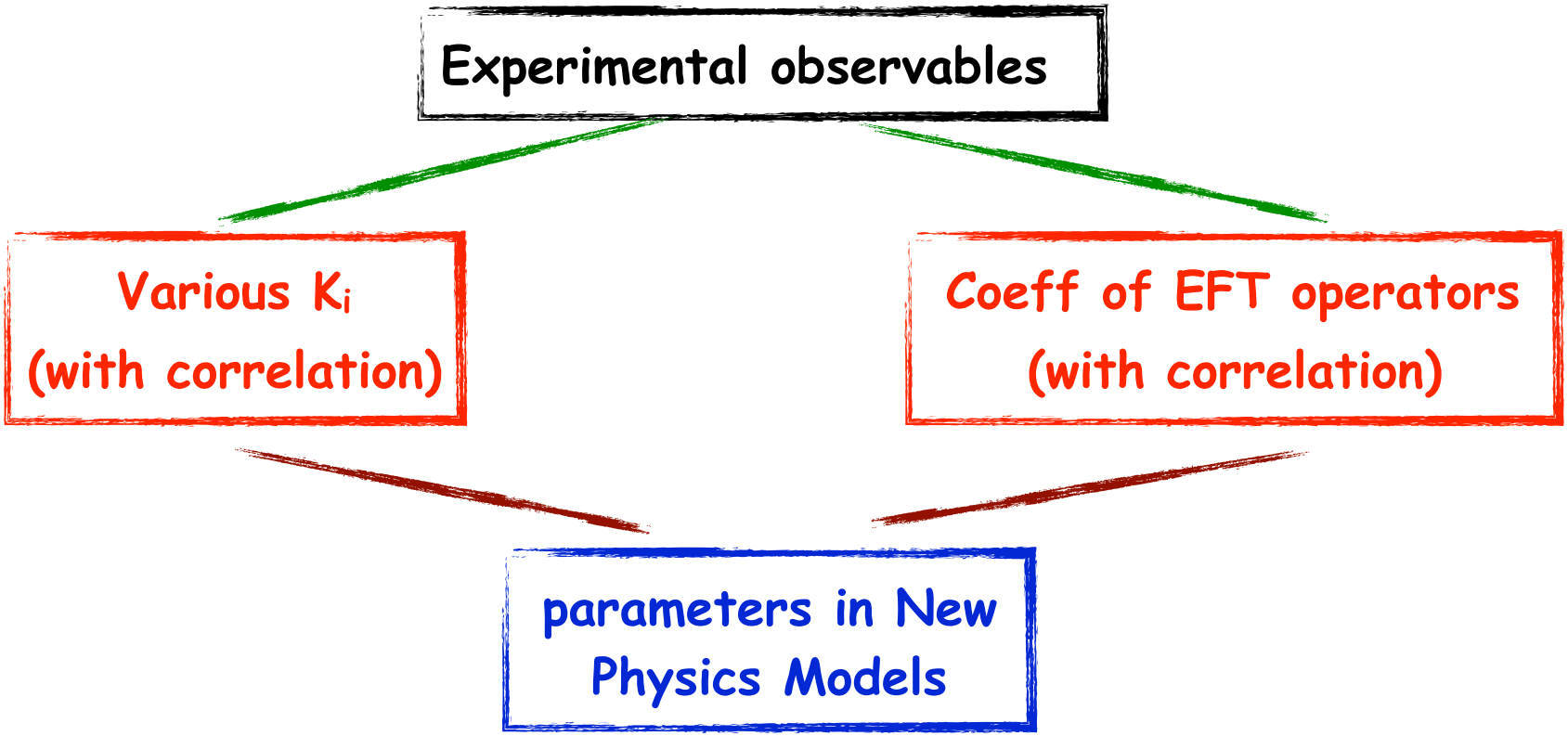
New Physics Implication



Kappa Framework and EFT Framework

limitations of model-independent approaches

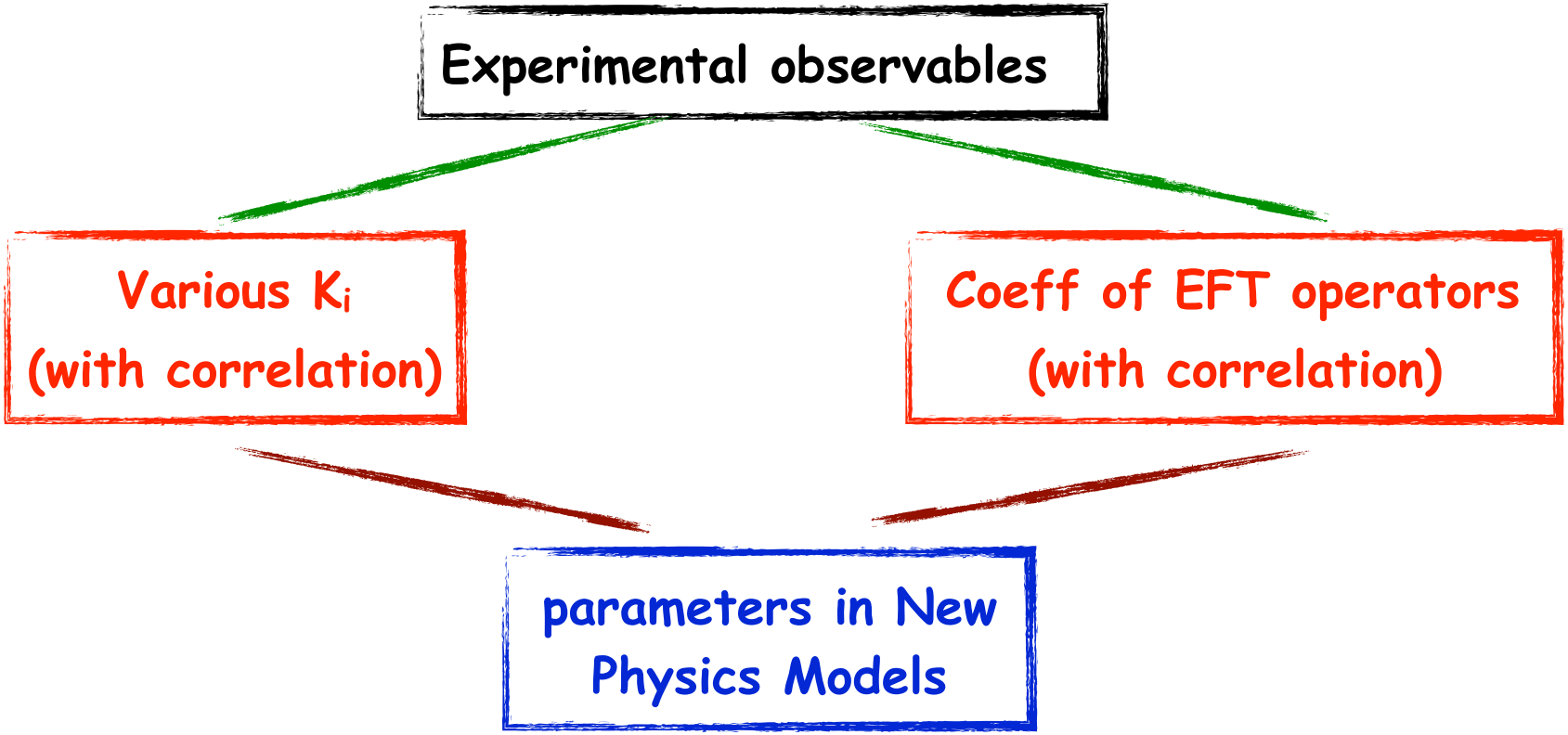
- large level of degeneracy

  parameter space for specific model much smaller
- correlation matrix often not provided

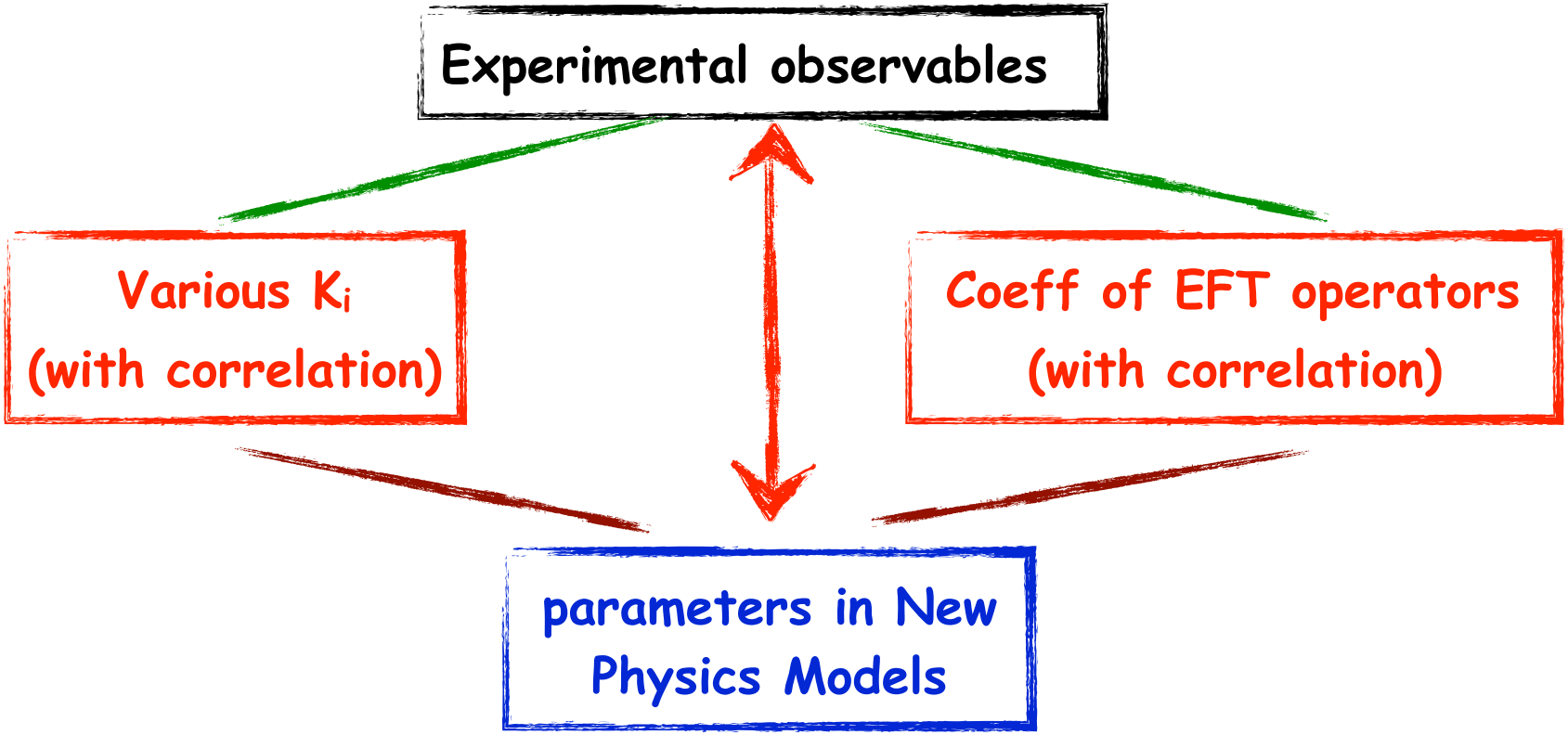
  over conservative estimation when not include correlation
- assumptions and simplifications

  may not be valid for a particular model

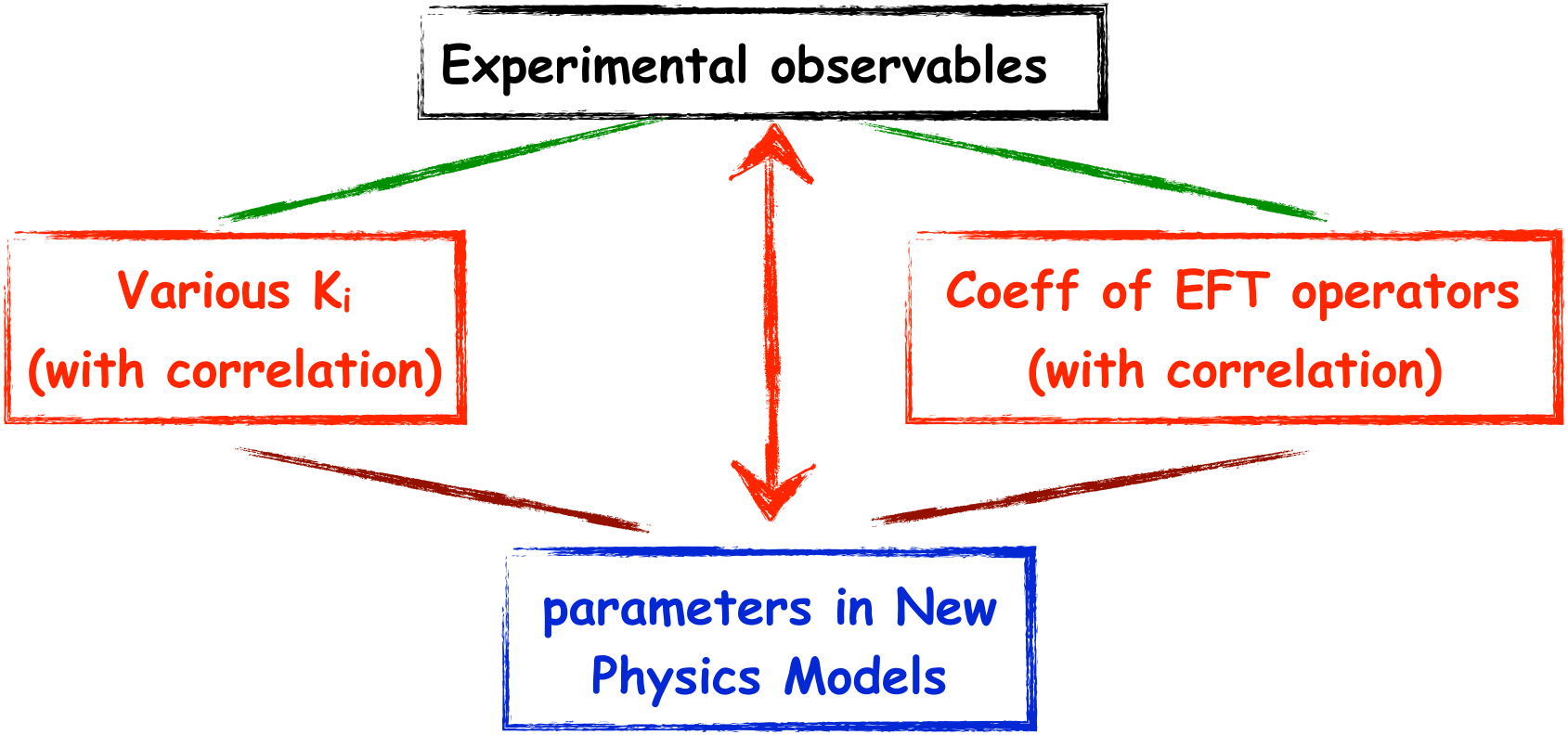
New Physics Implication



New Physics Implication



New Physics Implication



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

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)**

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

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

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

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

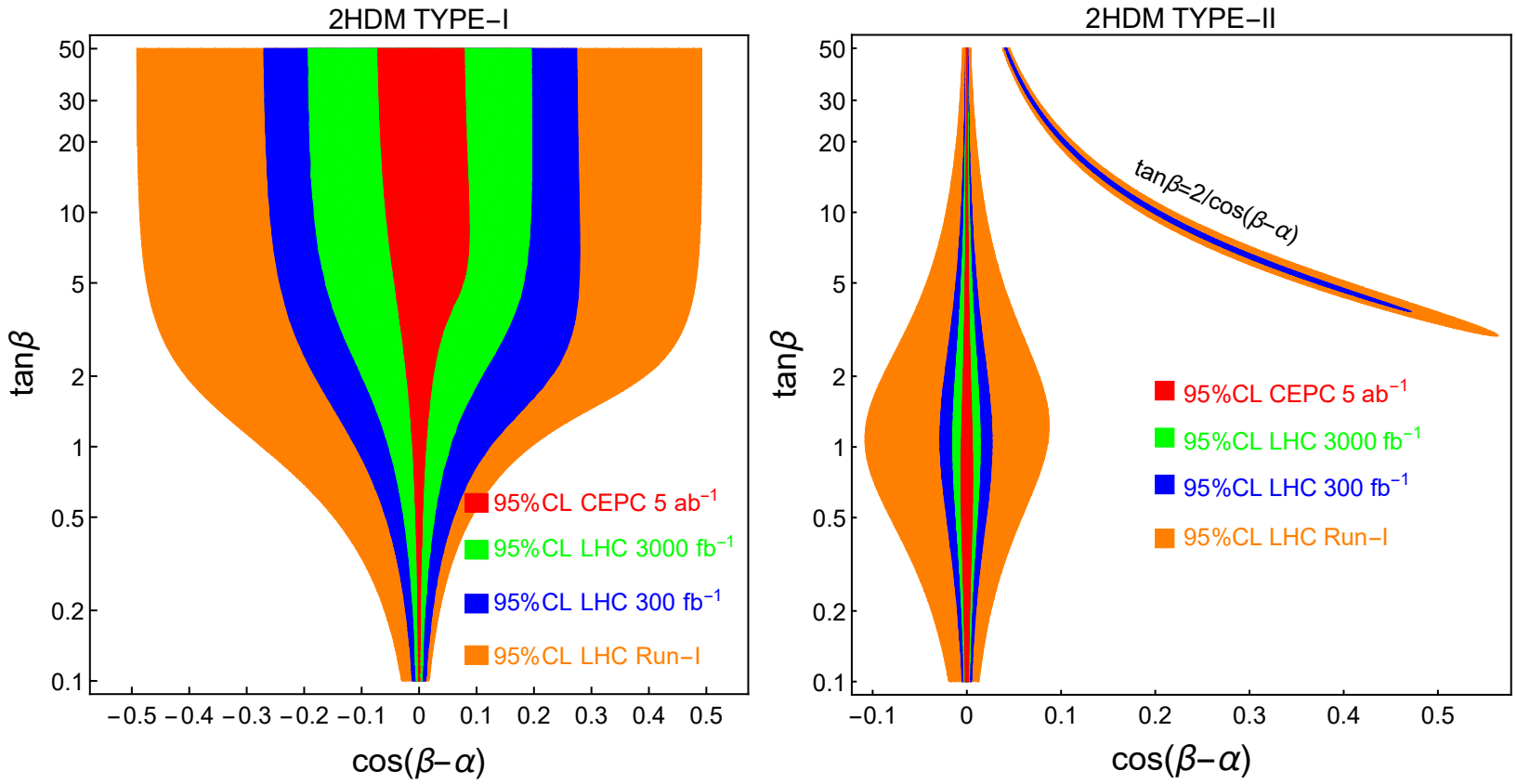
$$m_{11}^2,\ m_{22}^2,\ \lambda_1,\ \lambda_2,\ \lambda_3,\ \lambda_4,\ \lambda_5 \rightarrow v, \tan\beta, \alpha, m_h, m_H, m_A, m_{H^\pm}$$

soft Z2 breaking: m_{12}^2

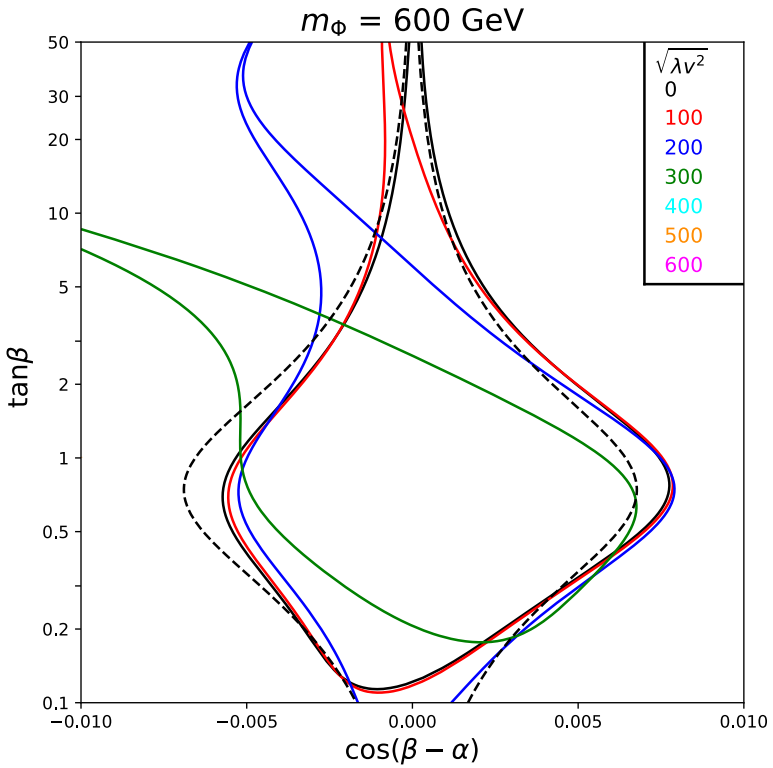
tanβ, cos(β-α),
control tree level h^0 couplings

Tree-level 2HDM fit

2HDM, LHC/FCC fit



2HDM: Tree + Loop



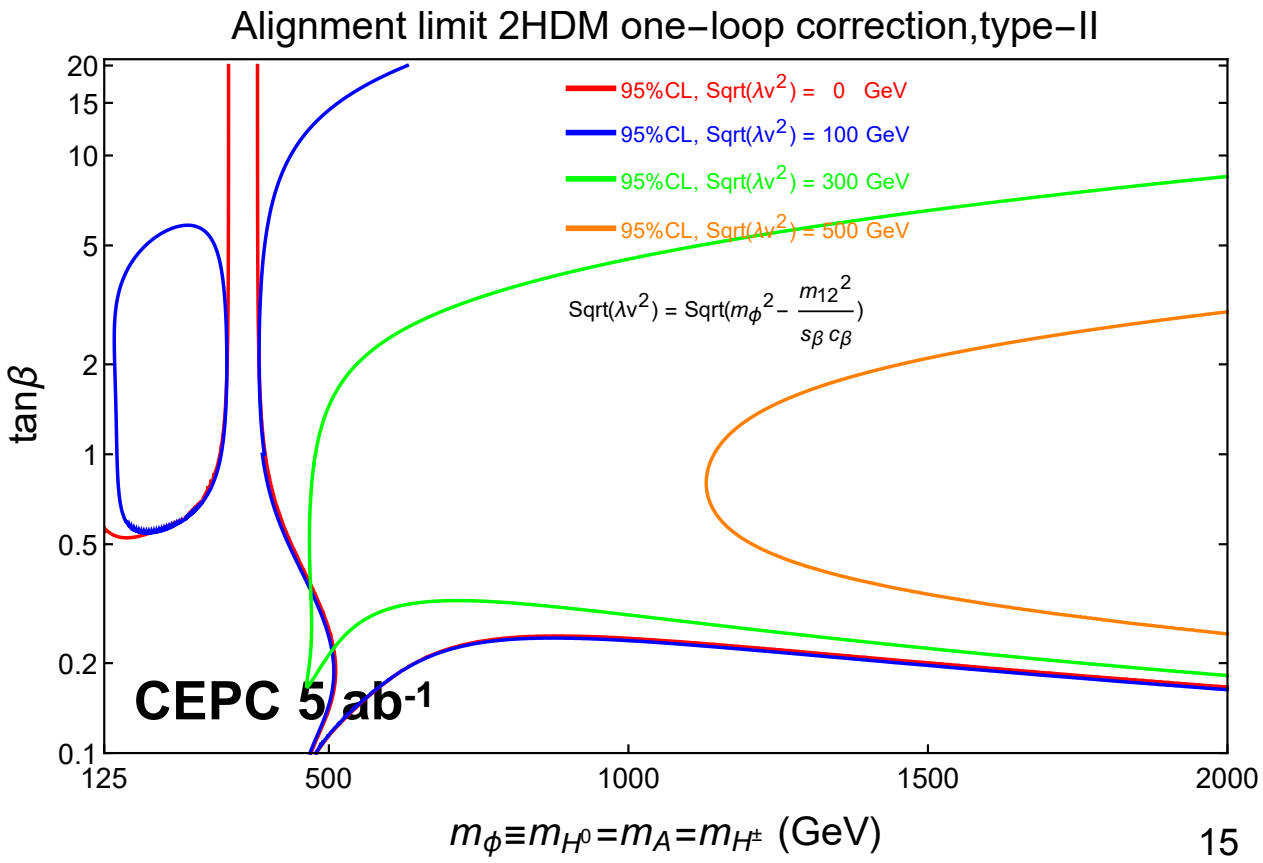
N. Chen, T. Han, SS, W. Su, Y. Wu, work in progress

2HDM: Loop in the Alignment Limit

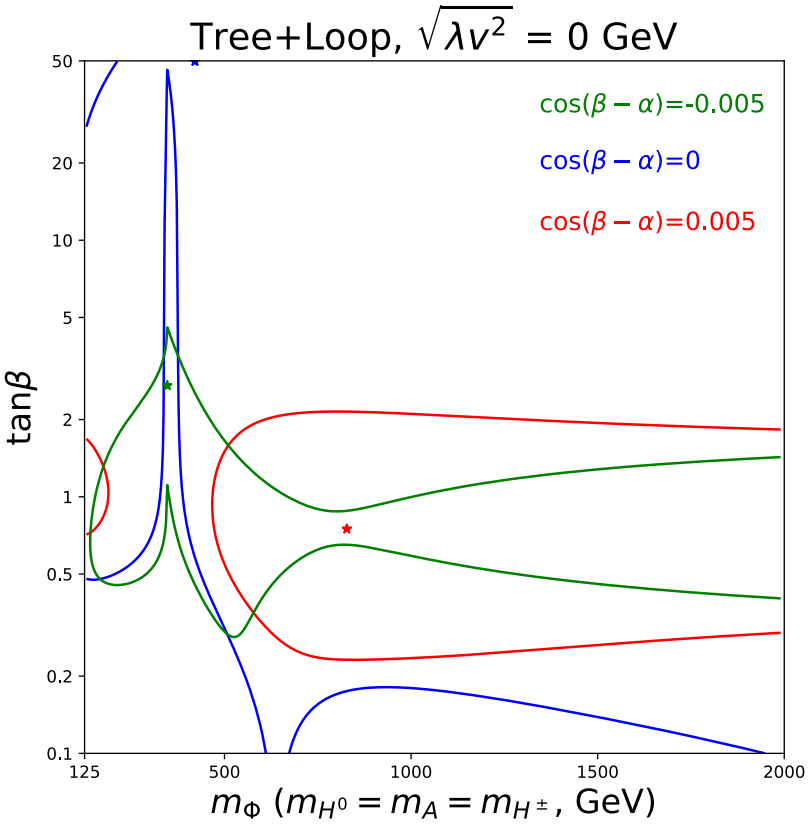
- **Type II**

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

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



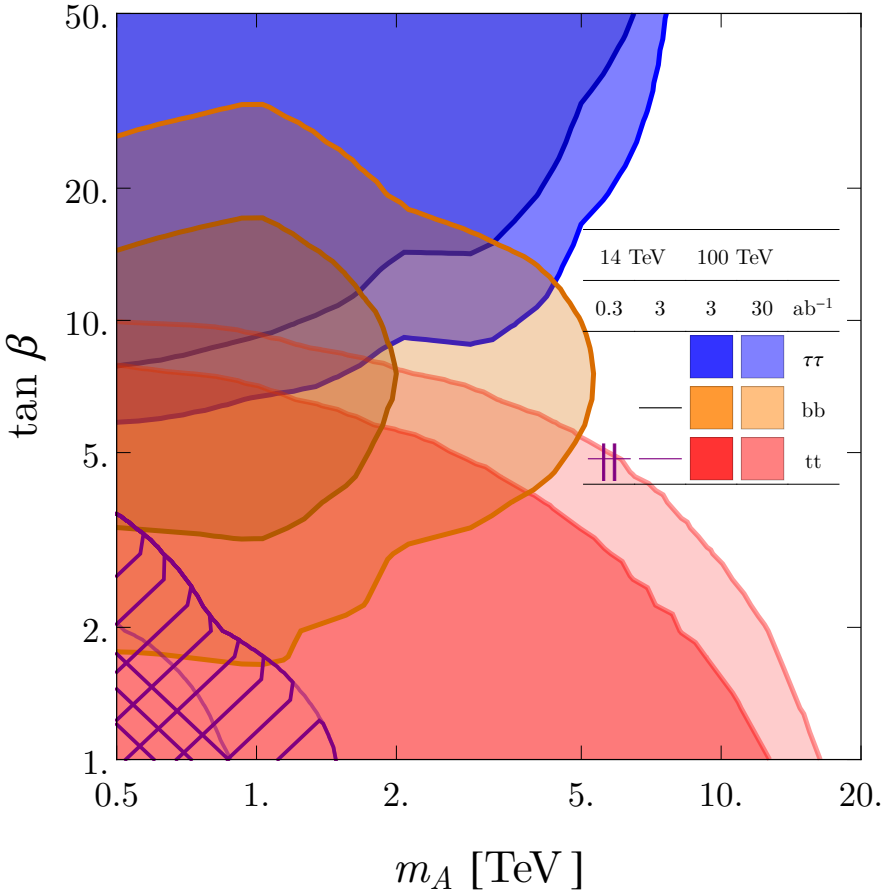
2HDM: Tree + Loop



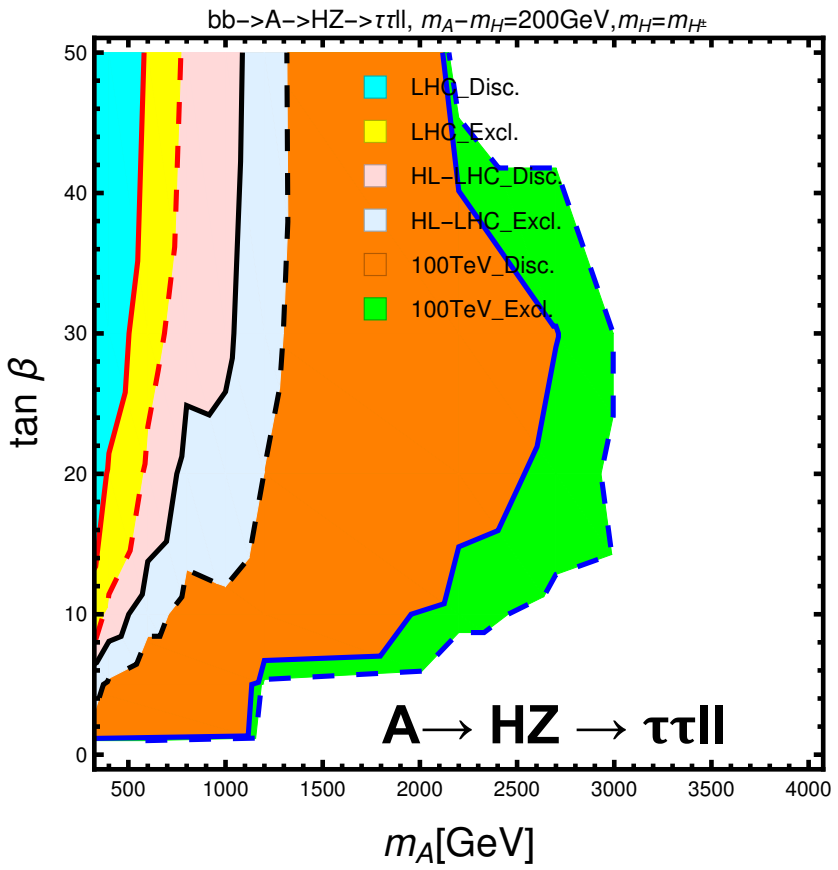
N. Chen, T. Han, SS, W. Su, Y. Wu, work in progress

Direct Search of Heavy Higgses @ 100 pp

Conventional search



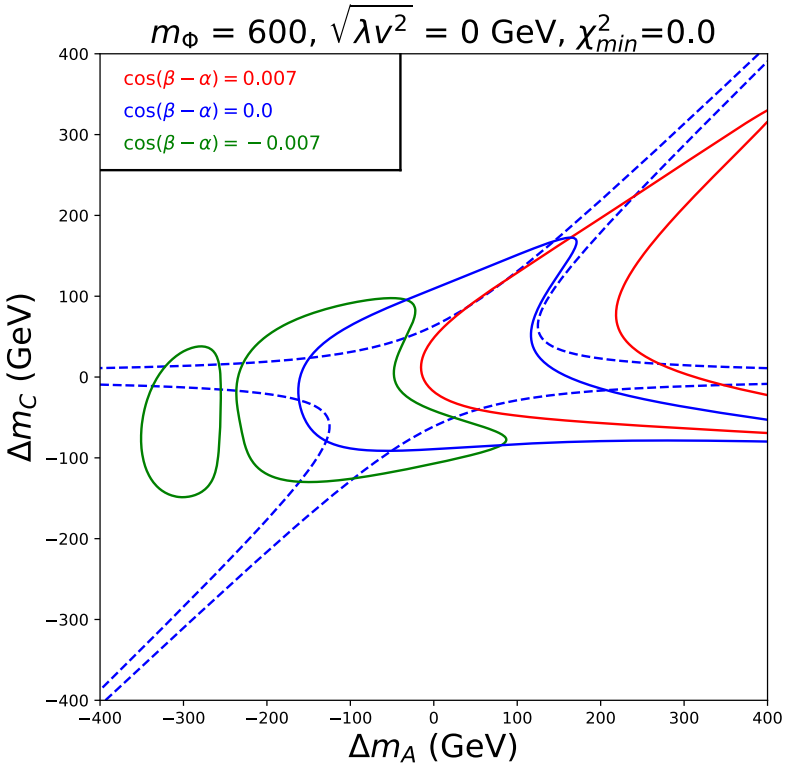
Exotic Decay

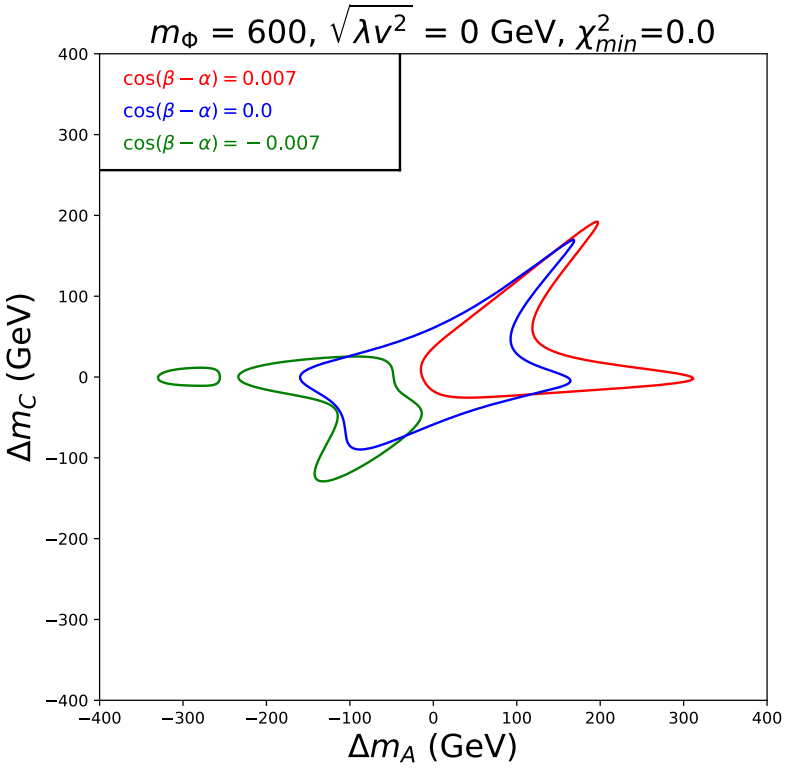


Craig et. al., 1605.08744

2HDM: non-degenerate

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

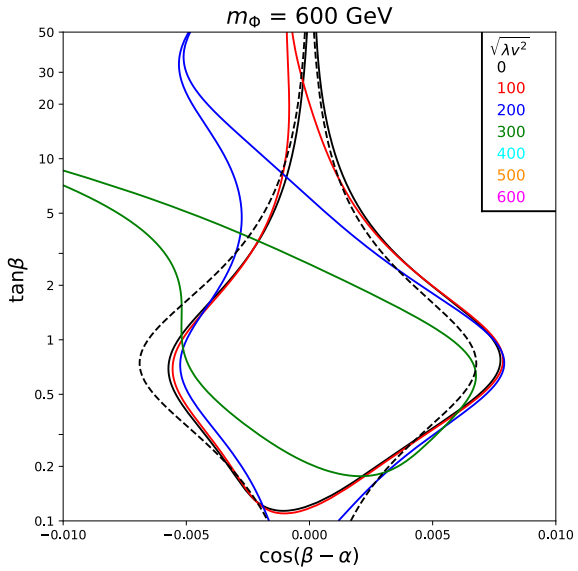


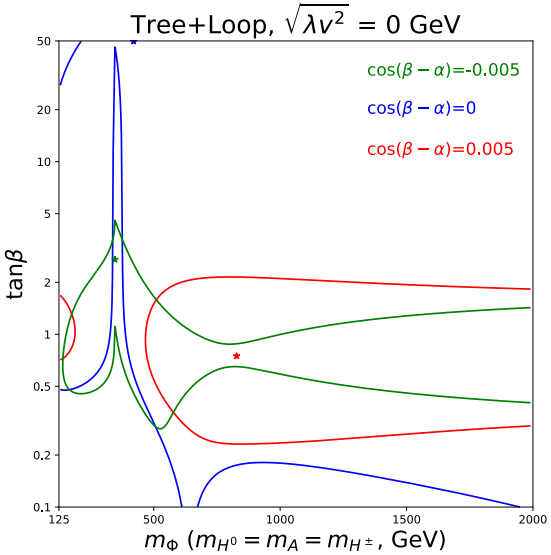


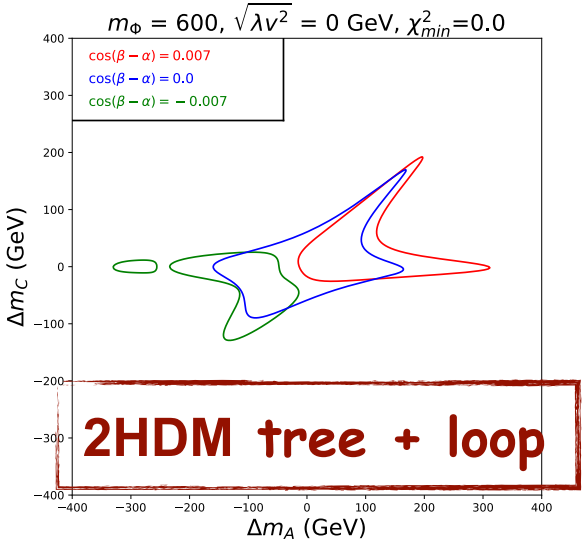
Complementary to Zpole precision

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







Conclusion

LHC

Lepton Collider

100 TeV pp

An exciting journey ahead of us!