Implication of Higgs Factory Precision Measurements on New Physics Models

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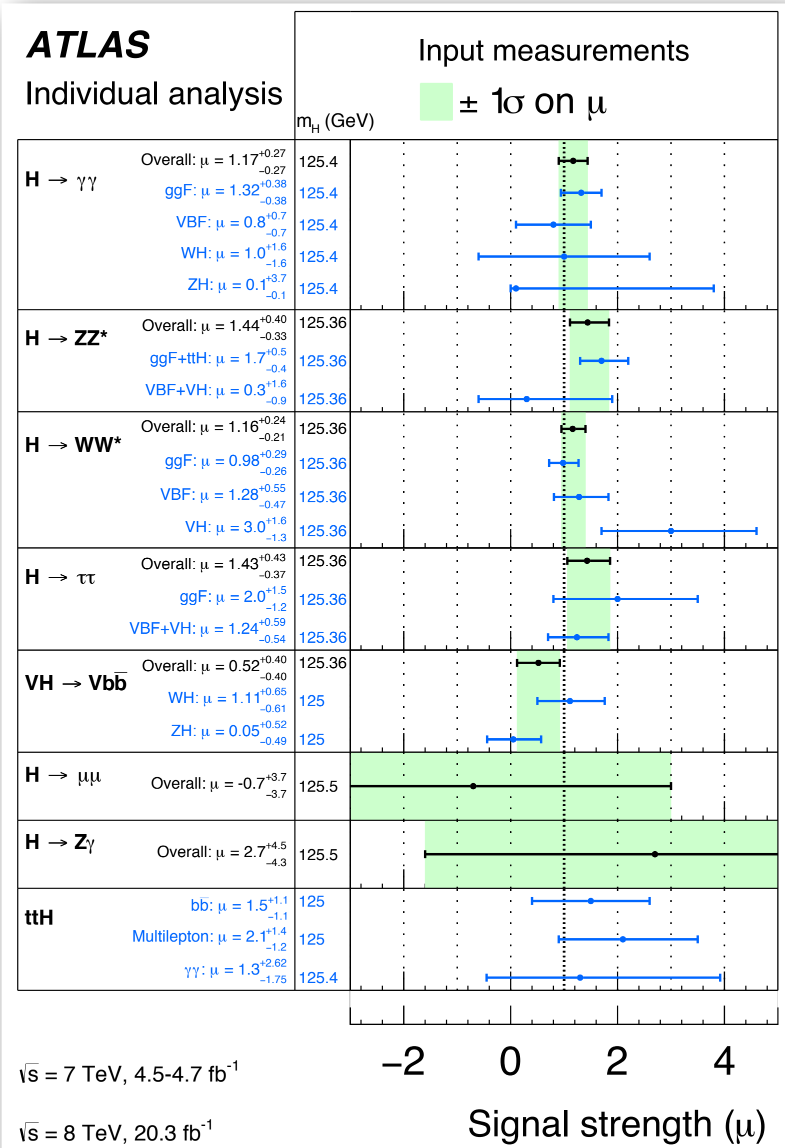
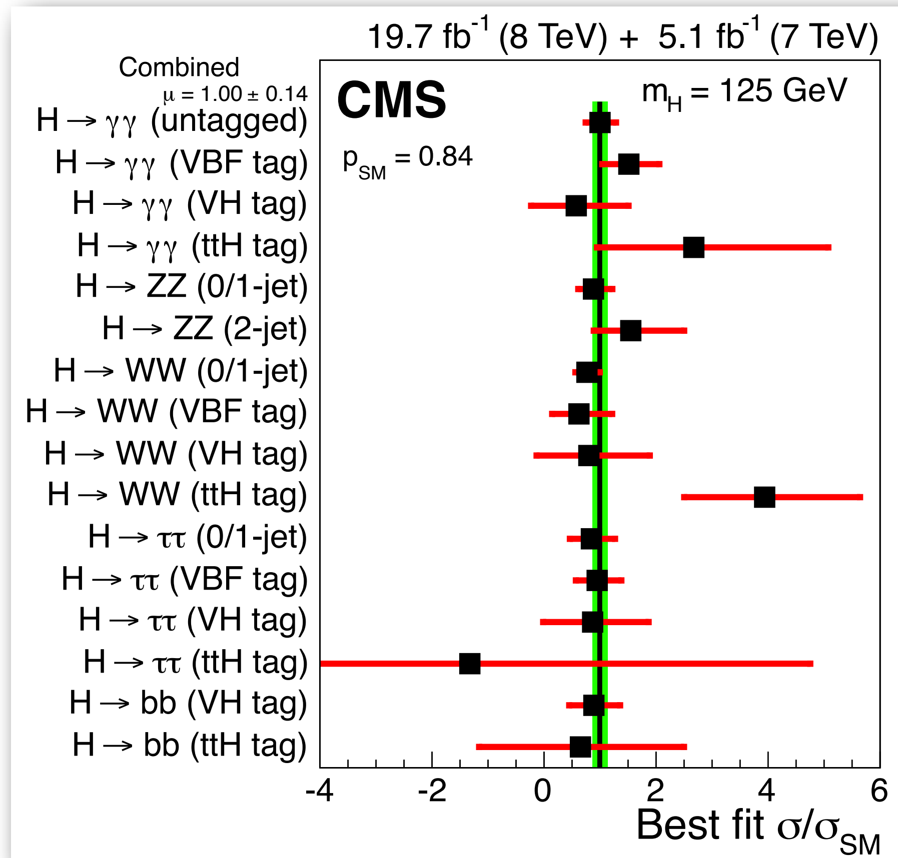
Outline

- Higgs precision measurements
- Global fit framework
- Perturbative models
  - SM with a real singlet extension
  - 2HDM
- Strong dynamics
  - Minimal composite Higgs Model (MCHM)
  - General EFT patterns of strongly interacting models
- Conclusion

Higgs Precision Measurements

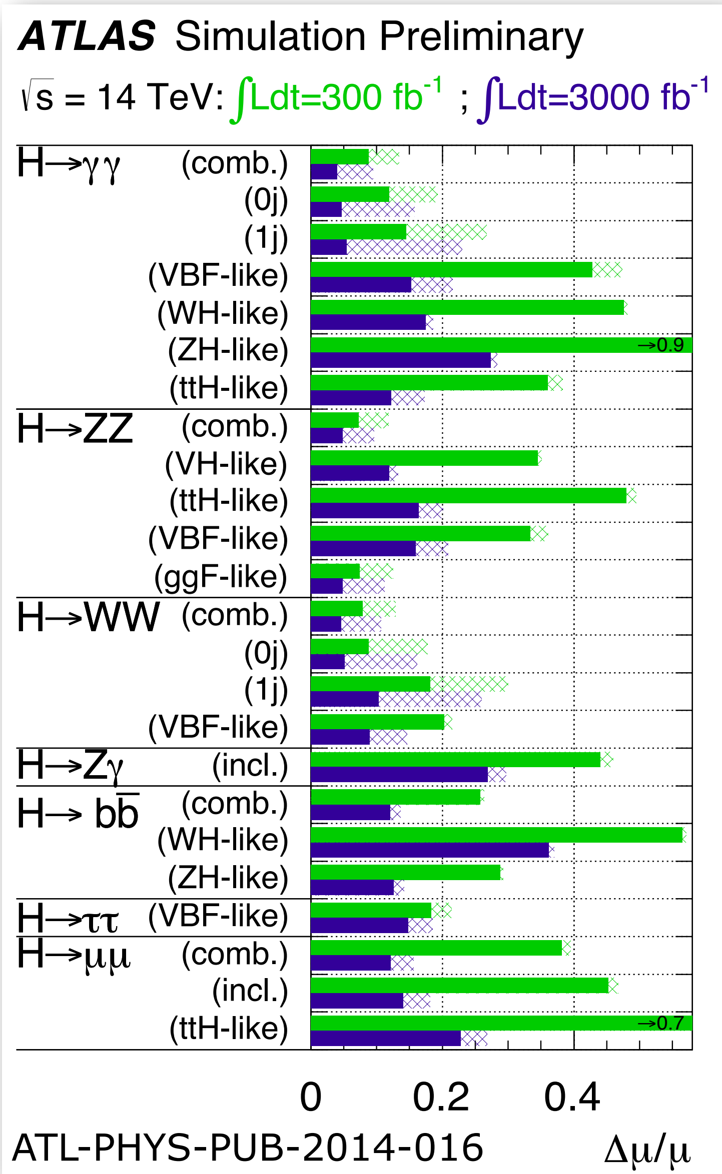


LHC: 7+8 TeV



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					
$\sqrt{s}$ $\int \mathcal{L}dt$	240 GeV 5 ab^{-1}	240 GeV 10 ab^{-1}	250 GeV 2 ab^{-1}	350 GeV 200 fb^{-1}		500 GeV 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%	0.4%	0.71%	2.1%	-	1.06	-	-
decay	$\Delta(\sigma \cdot BR)/(\sigma \cdot BR)$							
$h \to b\bar{b}$	0.28%	0.2%	0.42%	1.67%	1.67%	0.64%	0.25%	9.9%
$h \to c\bar{c}$	2.2%	1.2%	2.9%	12.7%	16.7%	4.5%	2.2%	-
$h \to gg$	1.6%	1.4%	2.5%	9.4%	11.0%	3.9%	1.5%	-
$h \to WW^*$	1.5%	0.9%	1.1%	8.7%	6.4%	3.3%	0.85%	-
$h \to \tau^+\tau^-$	1.2%	0.7%	2.3%	4.5%	24.4%	1.9%	3.2%	-
$h \to ZZ^*$	4.3%	3.1%	6.7%	28.3%	21.8%	8.8%	2.9%	-
$h \to \gamma\gamma$	9.0%	3.0%	12.0%	43.7%	50.1%	12.0%	6.7%	-
$h \to \mu^+\mu^-$	17%	13%	25.5%	97.6%	179.8%	31.1%	25.5%	-
$(\nu\bar{\nu})h \to b\bar{b}$	2.8%	2.2%	3.7%	-	-	-	-	-

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

Kappa framework and EFT Framework

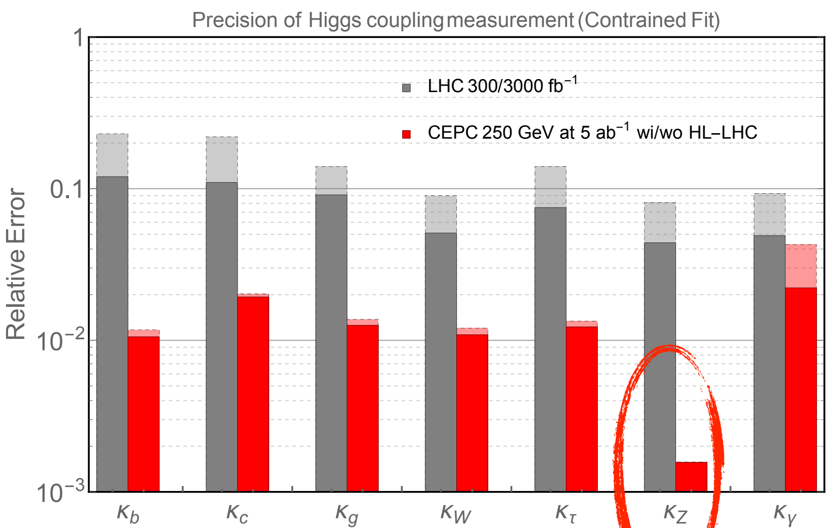
Two model-independent approaches

kappa framework

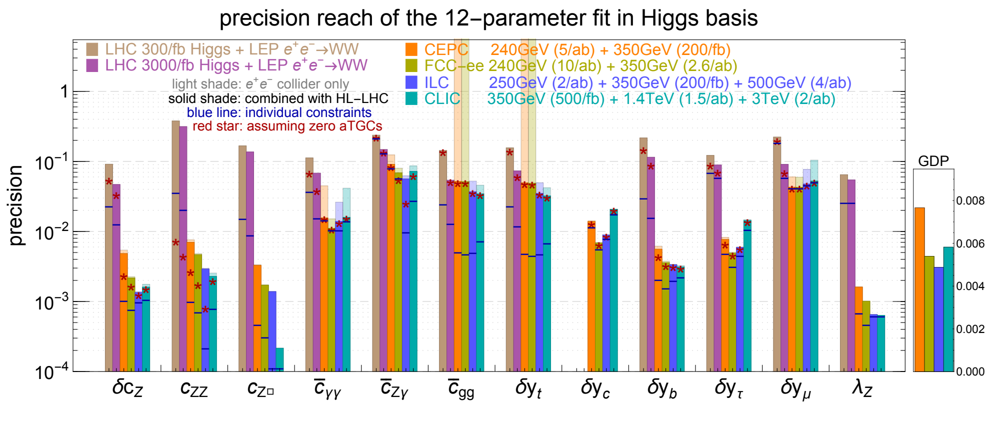
$$\kappa_f = \frac{g(hff)}{g(hff;\mathrm{SM})}, \ \kappa_V = \frac{g(hVV)}{g(hff;\mathrm{SM})}$$

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-preCDR



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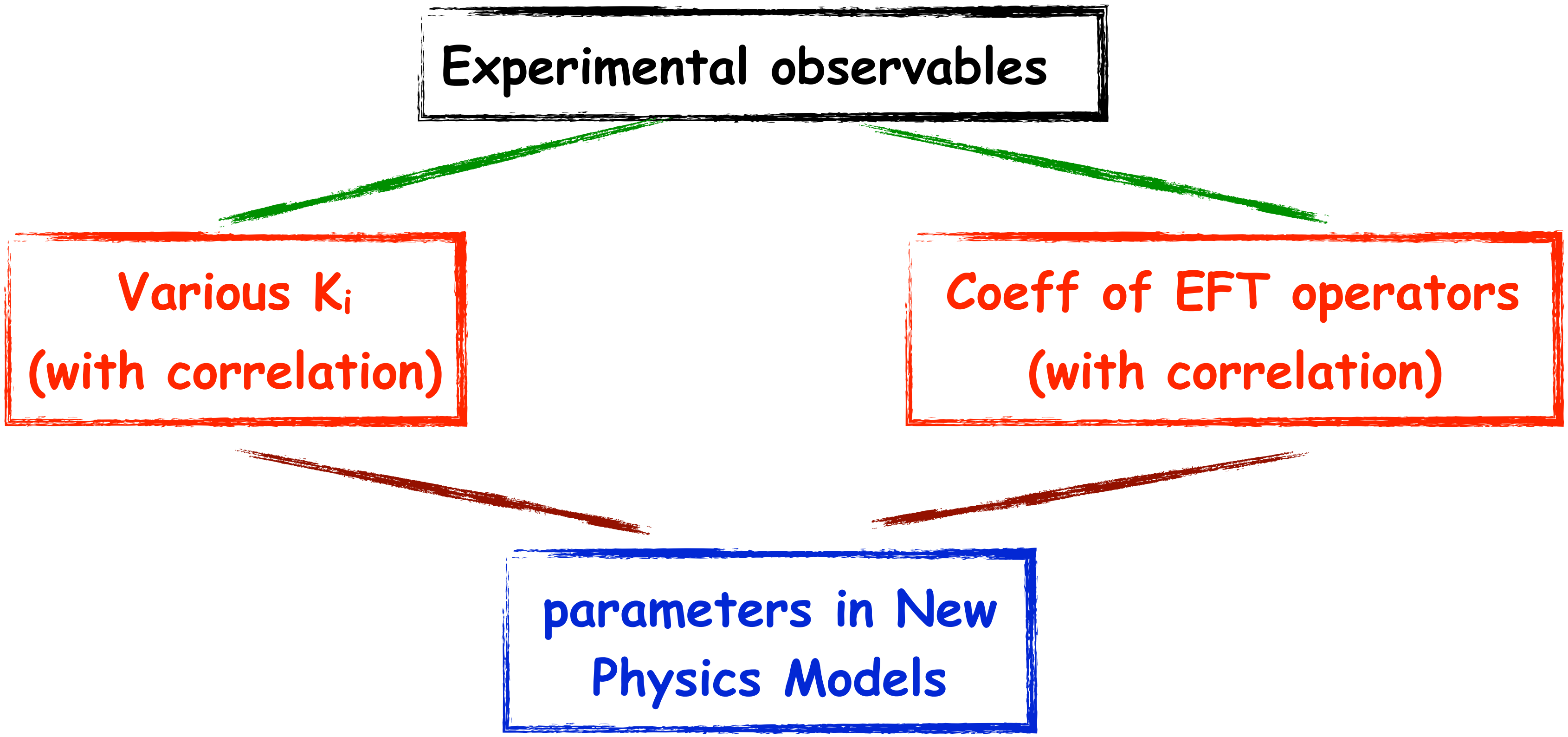
New Physics Implication



Kappa Framework and EFT Framework

<u>limitations of model-independent approaches</u>

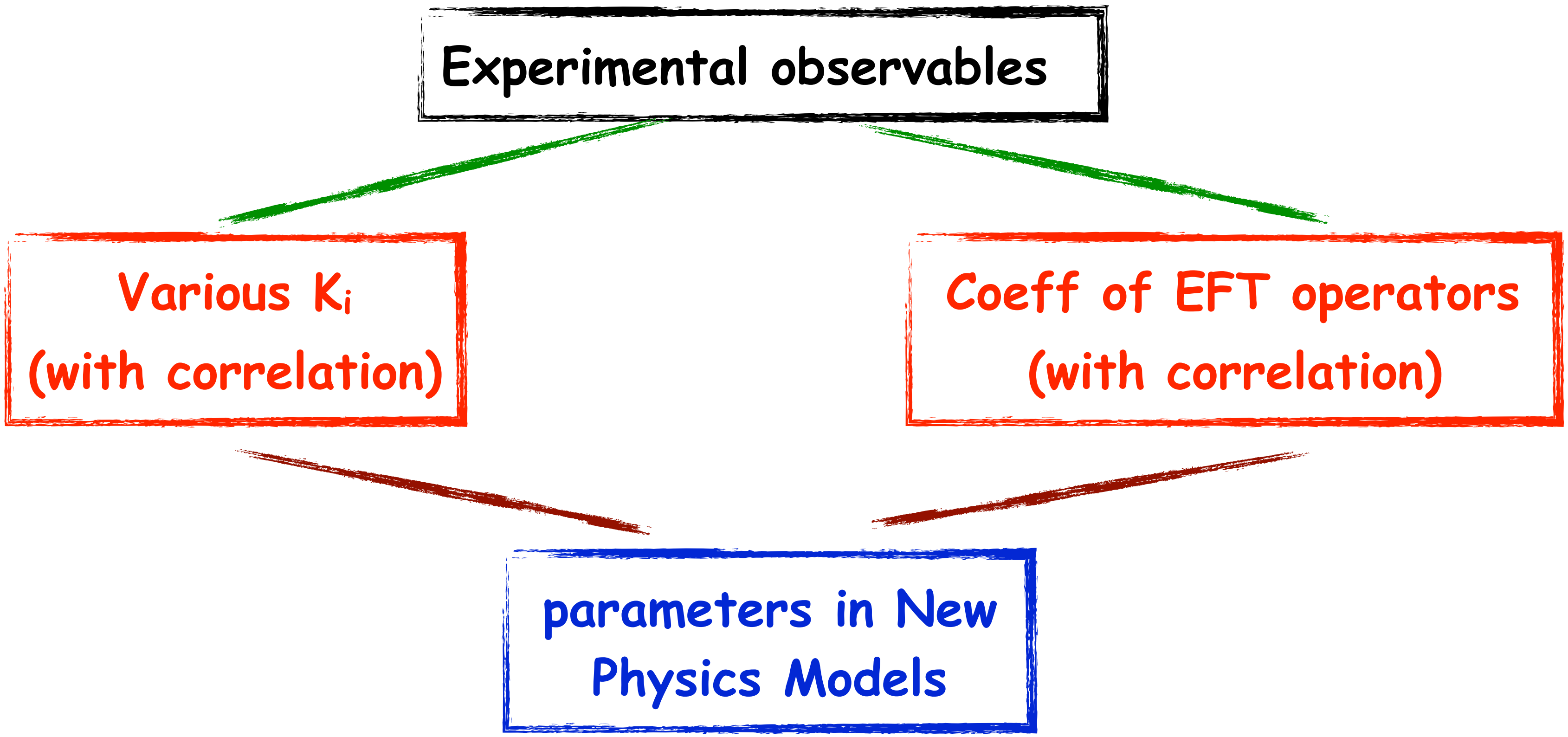
- large level of degeneracy

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

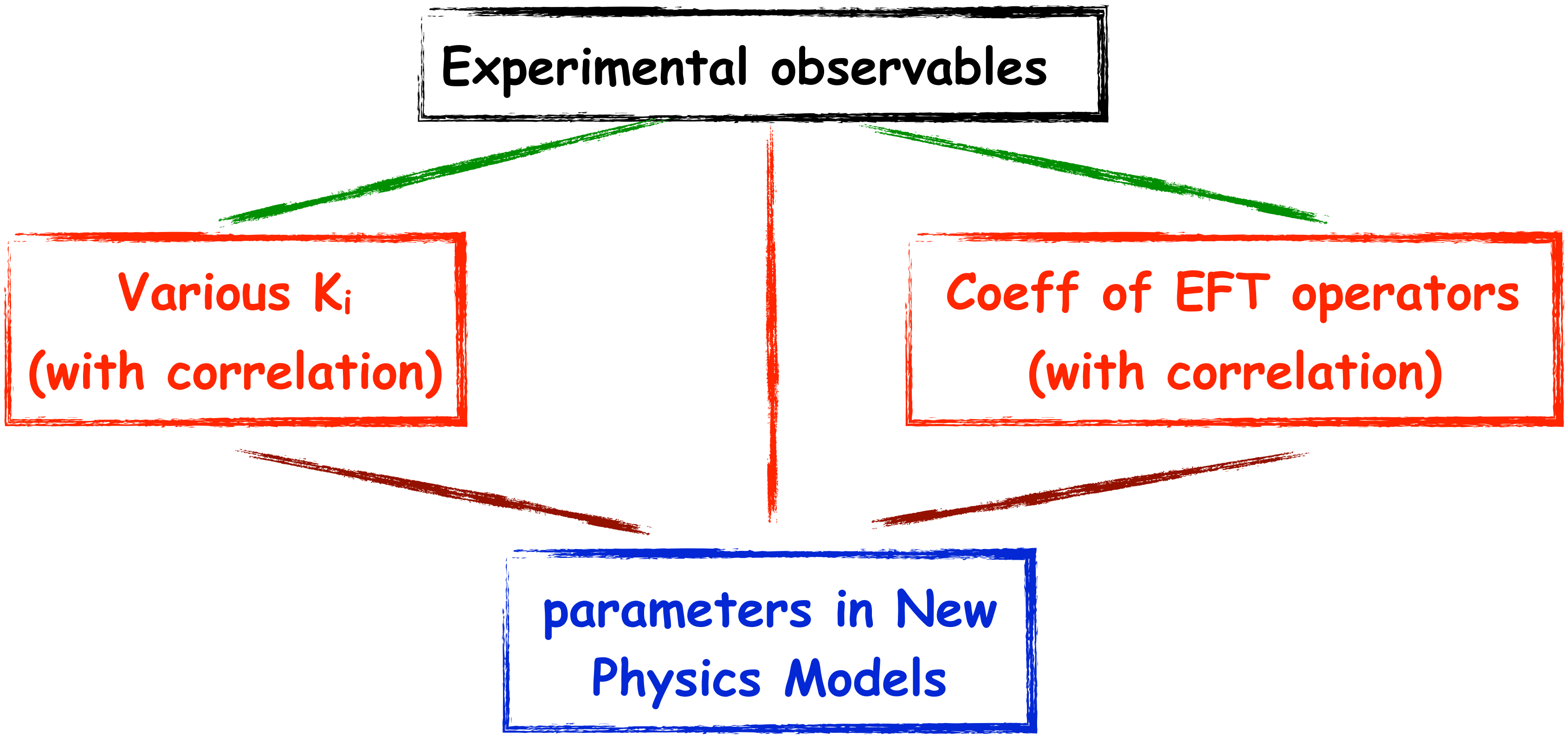
  over conservative estimation when not include correlation
- assumptions and simplifications

  may not be valid for a particular model

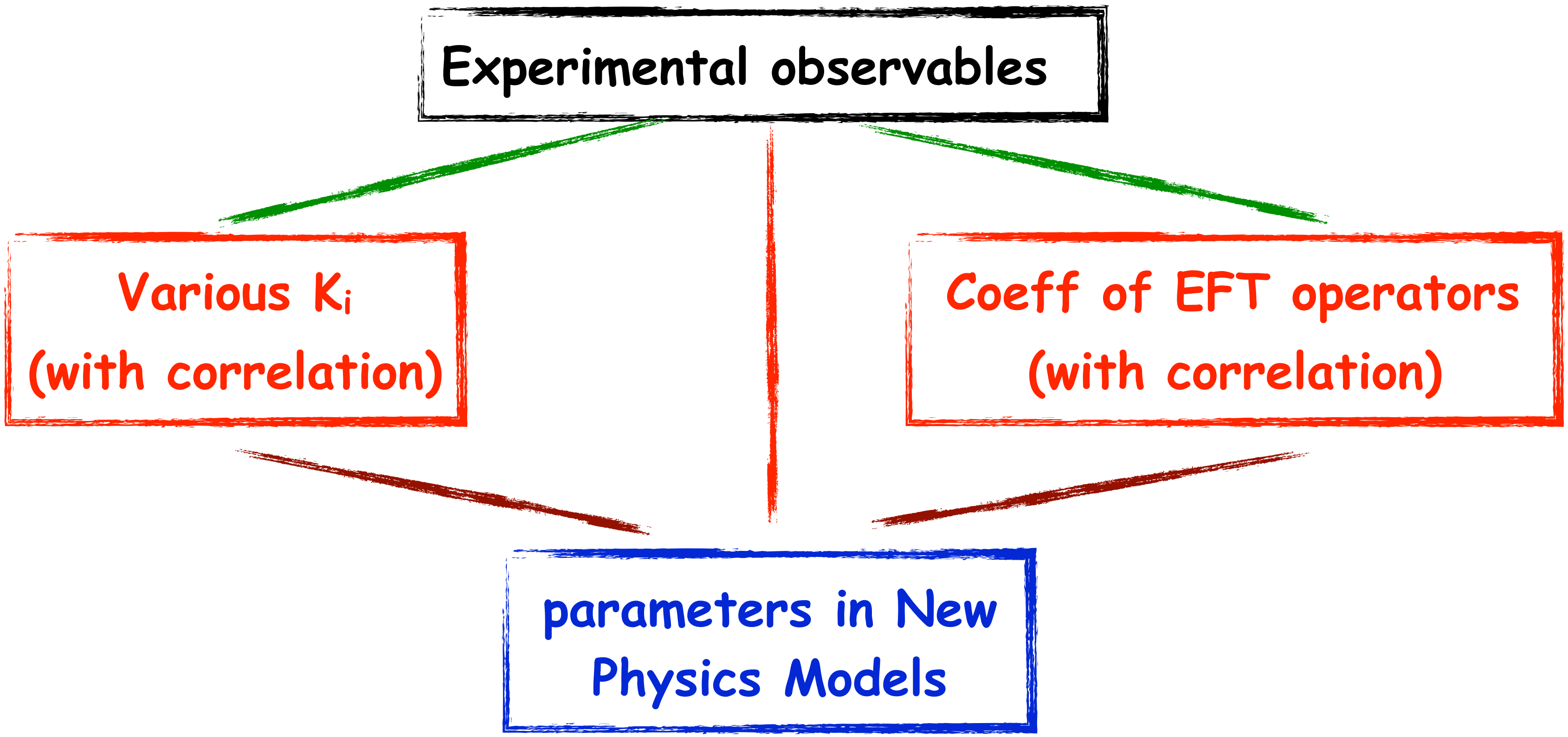
New Physics Implication



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**
- **2HDM (Type I, II, L, F)**

SM + Real Scalar Singlet

- **SM + real scalar singlet**

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{1}{2}(\partial_\mu S)^2 - \frac{1}{2}m_S^2 S^2 - \Lambda_{SH} S(H^\dagger H) - \frac{1}{2}\lambda_{SH} S^2(H^\dagger H) - \frac{1}{3!}\Lambda_S S^3 - \frac{1}{4!}\lambda_S S^4$$

- **after EWSB, 2 physical Higgse: CP-even Higgses: h_{SM}, singlet S**

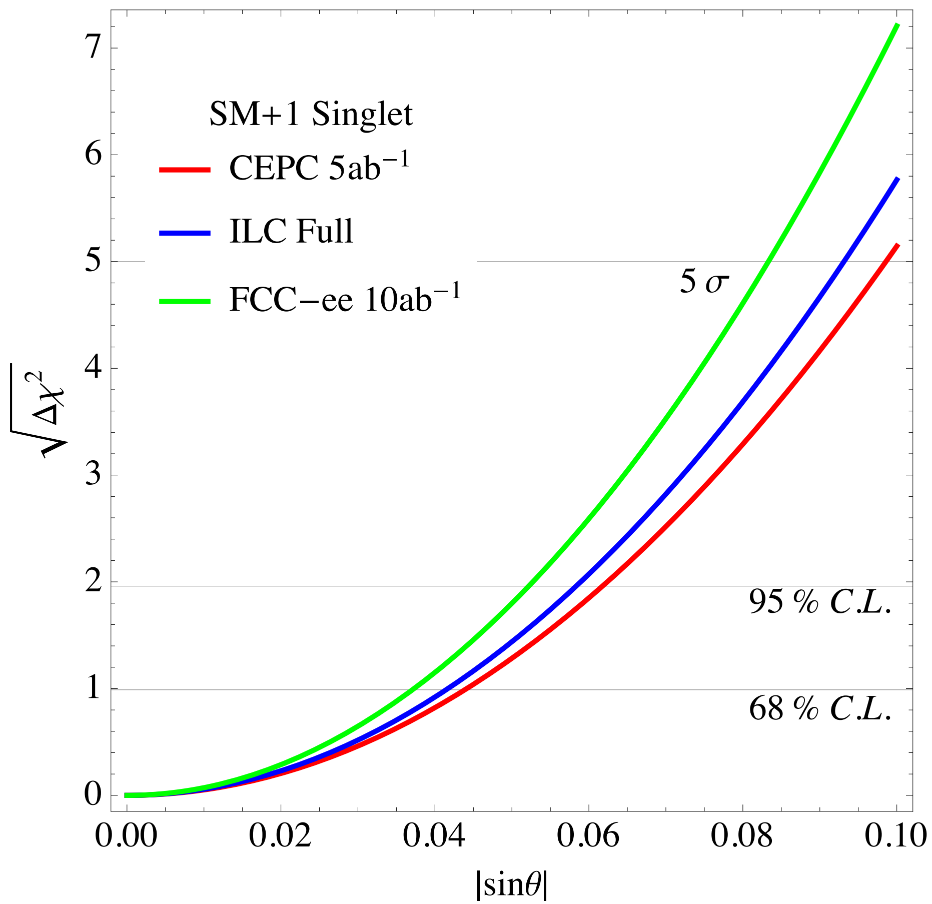
- **Z_2 breaking: mixing between h_{SM} and S**

$$h_{125} = \cos\theta\ h_{\rm SM} + \sin\theta\ S$$

$$\kappa_i = g_i^{\rm SM+singlet}/g_i^{SM} = \cos\theta$$

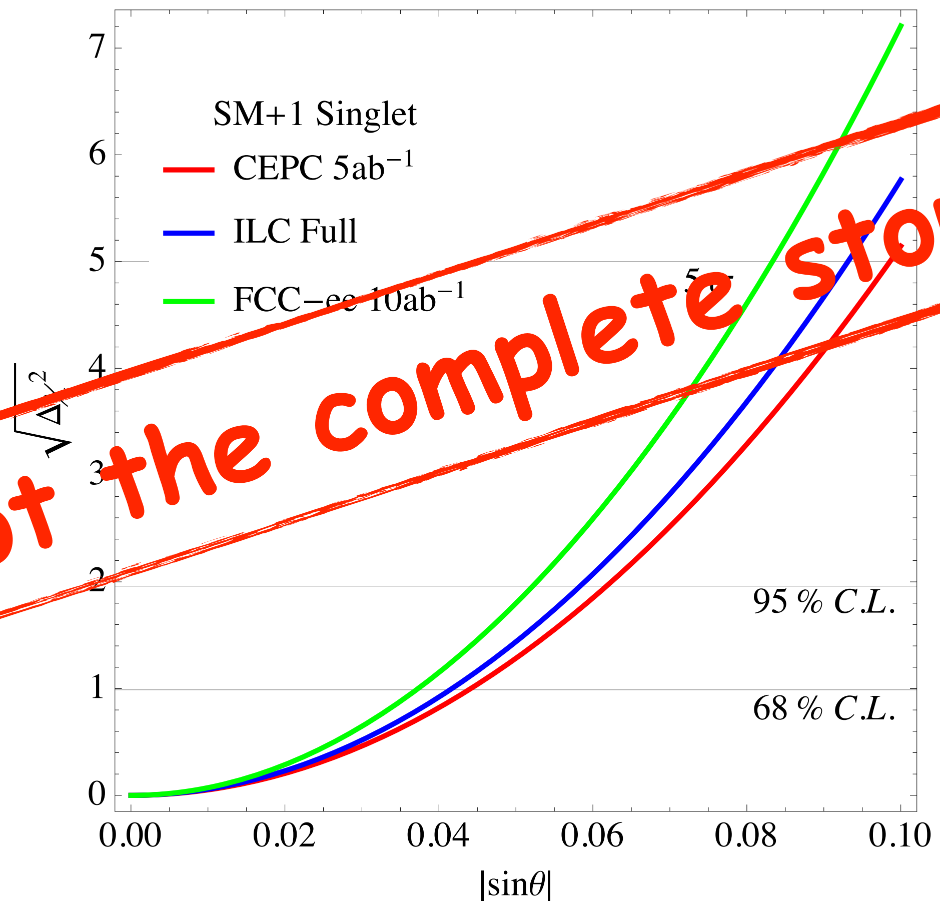
SM + Real Scalar Singlet

- fit to sin θ



SM + Real Scalar Singlet

- fit to sin θ



Not the complete story!

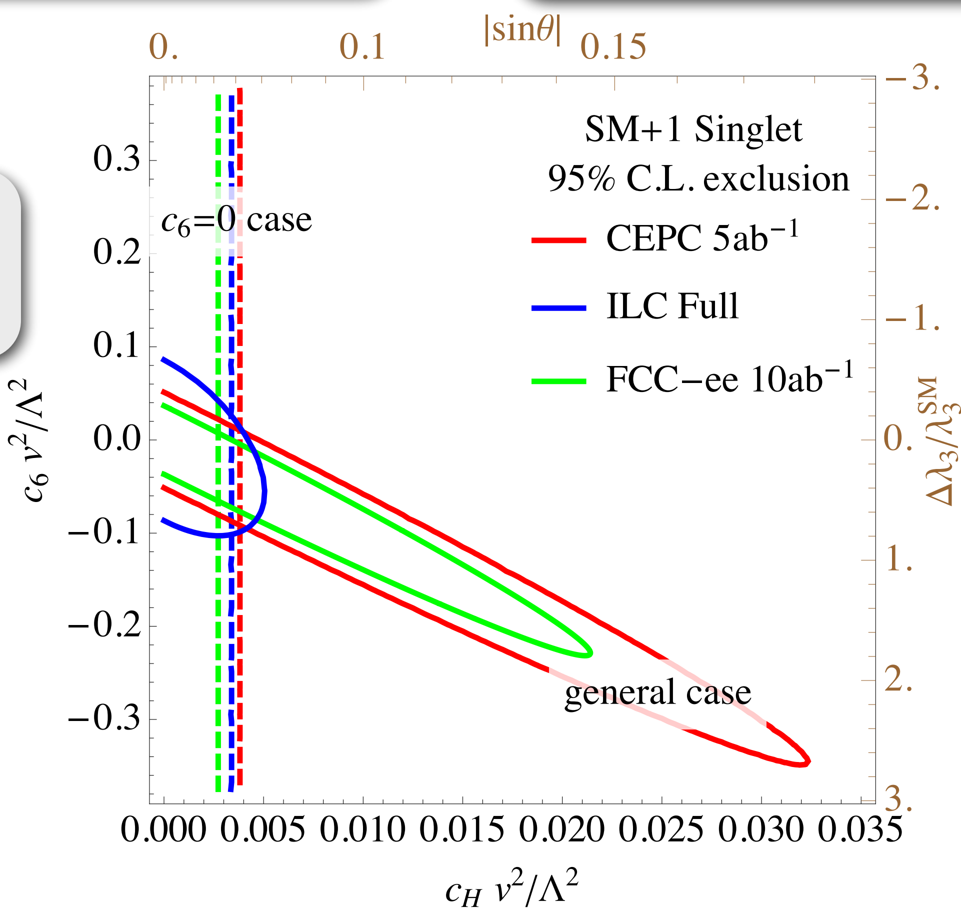
SM + Real Scalar Singlet

- fit to c_6 and c_H

$$\Delta\mathcal{L} = \frac{c_H}{\Lambda^2}\mathcal{O}_H + \frac{c_6}{\Lambda^2}\mathcal{O}_6$$

$$\mathcal{O}_H \equiv \frac{1}{2}(\partial_\mu |H^\dagger H|)^2 \qquad \mathcal{O}_6 \equiv |H^\dagger H|^3$$

$$1 - \cos\theta \simeq \theta^2/2 \simeq 1/2 \times c_H v^2/\Lambda^2$$



Perturbative Models

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

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

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

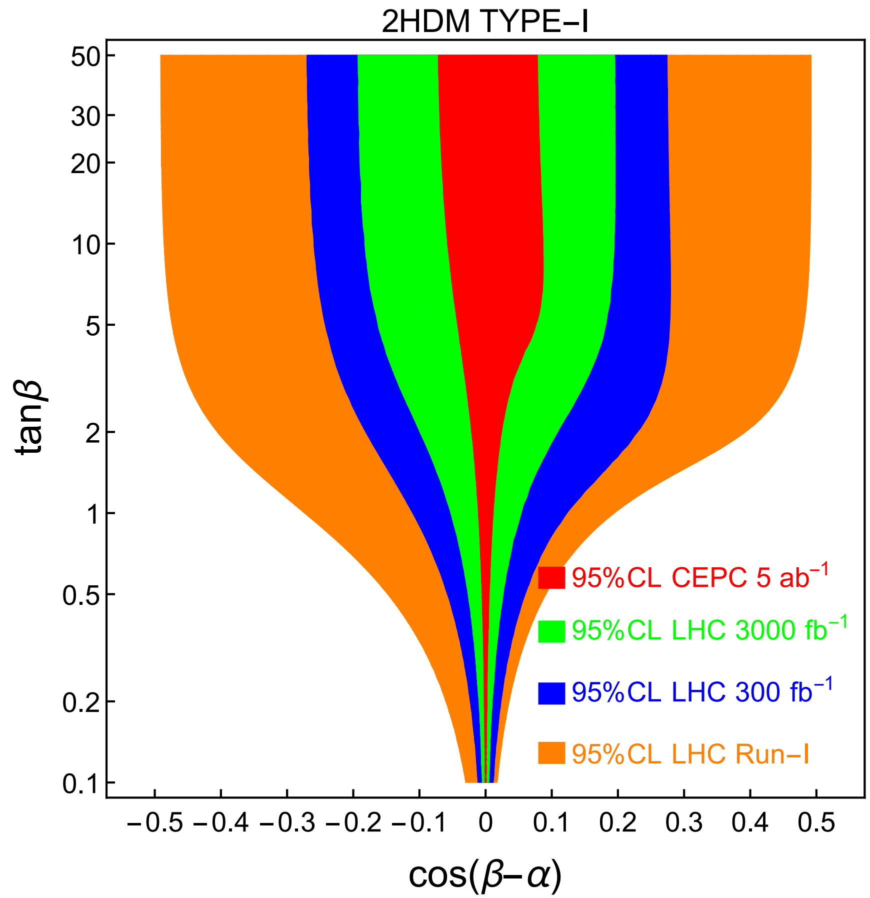
soft Z2 breaking: m_{12}^2

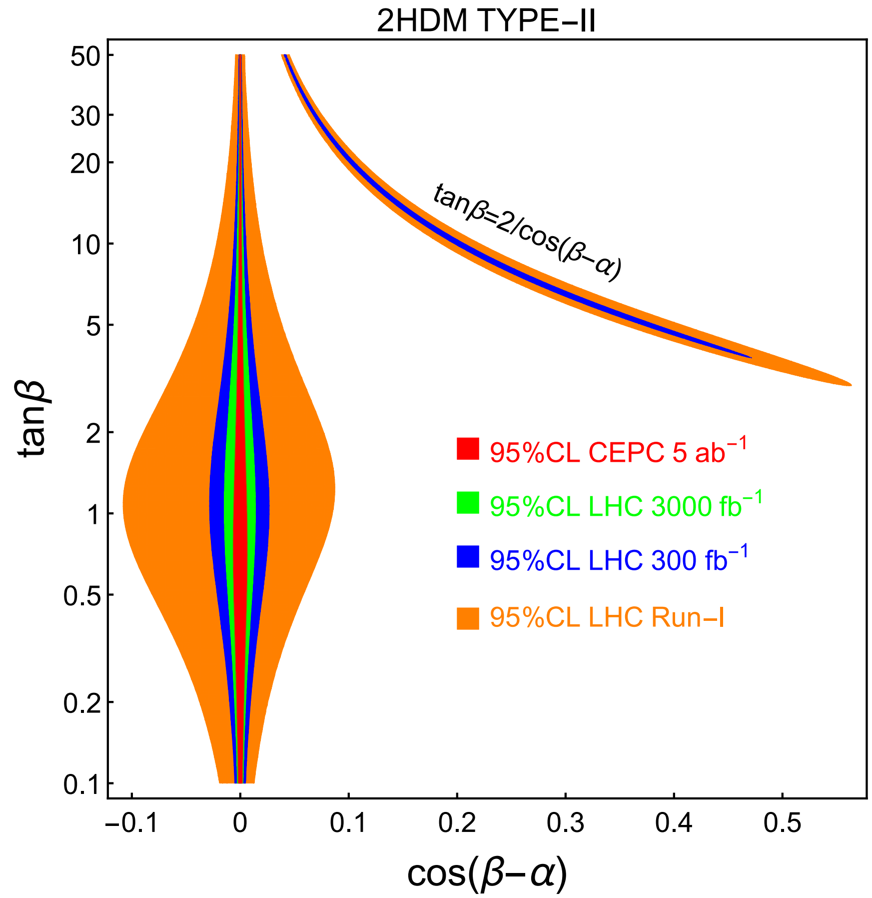
tanβ, cos(β-α),

control tree level h^0 couplings

Tree-level 2HDM fit

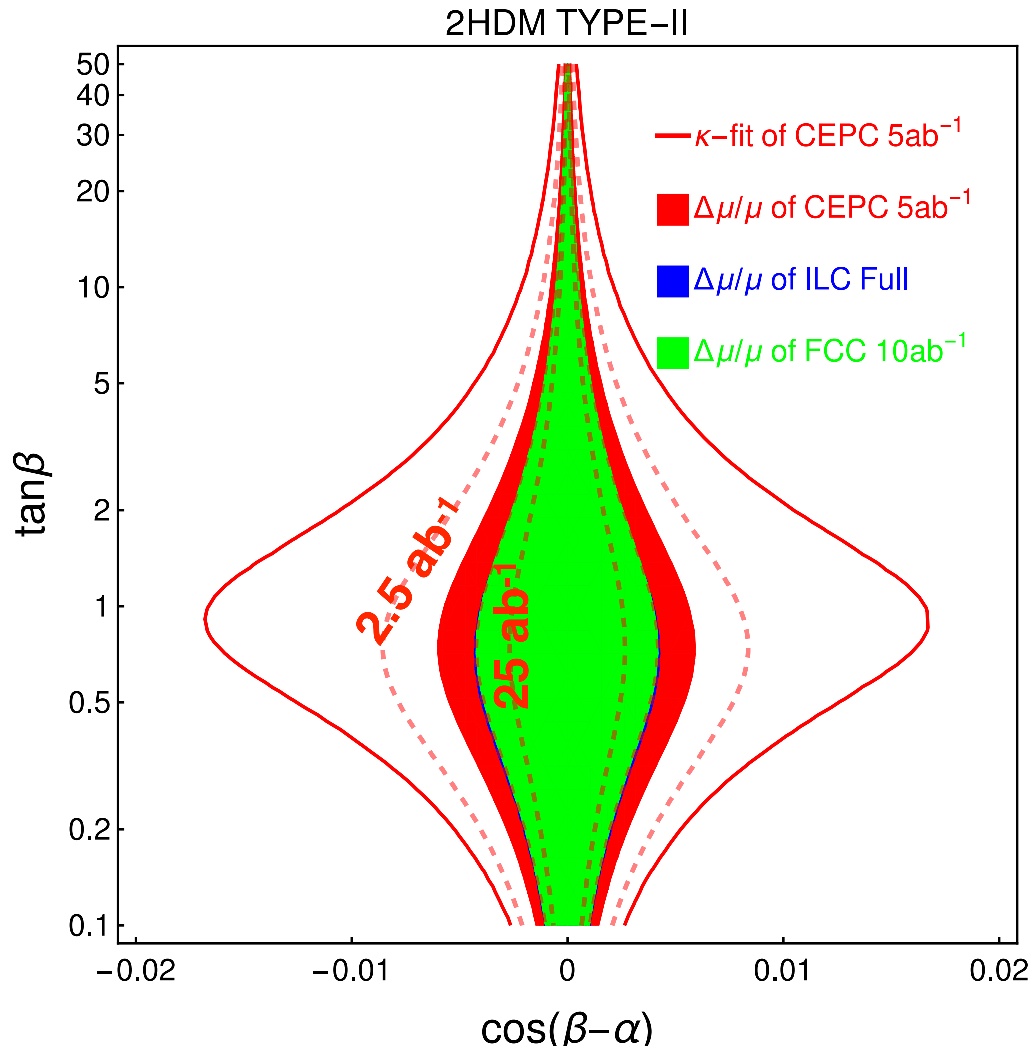
2HDM, LHC/CEPC fit





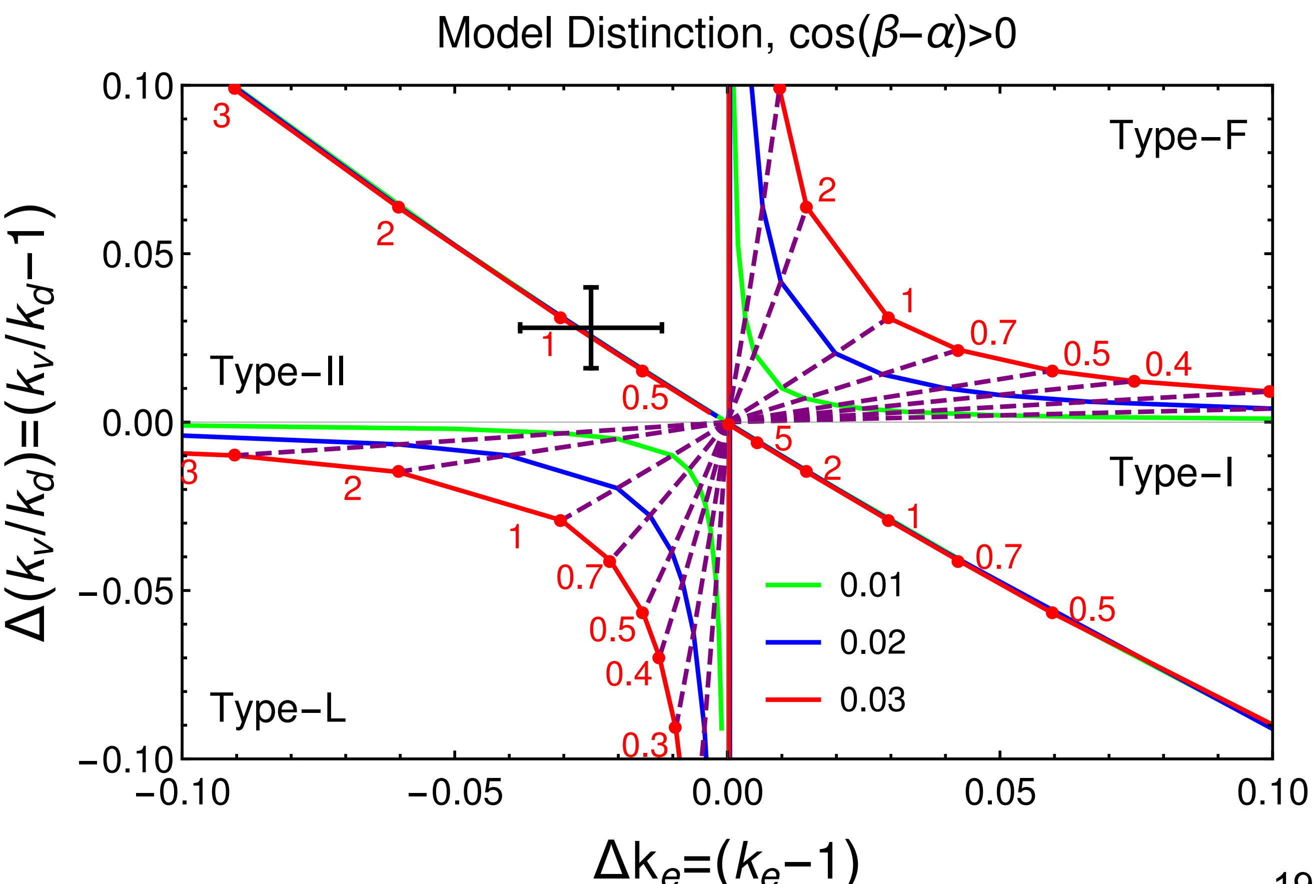
Tree-level 2HDM fit

- **κ-fit vs Δμ/μ fit,**
- **CEPC/FCC/ILC,**
- **luminosity dependence**



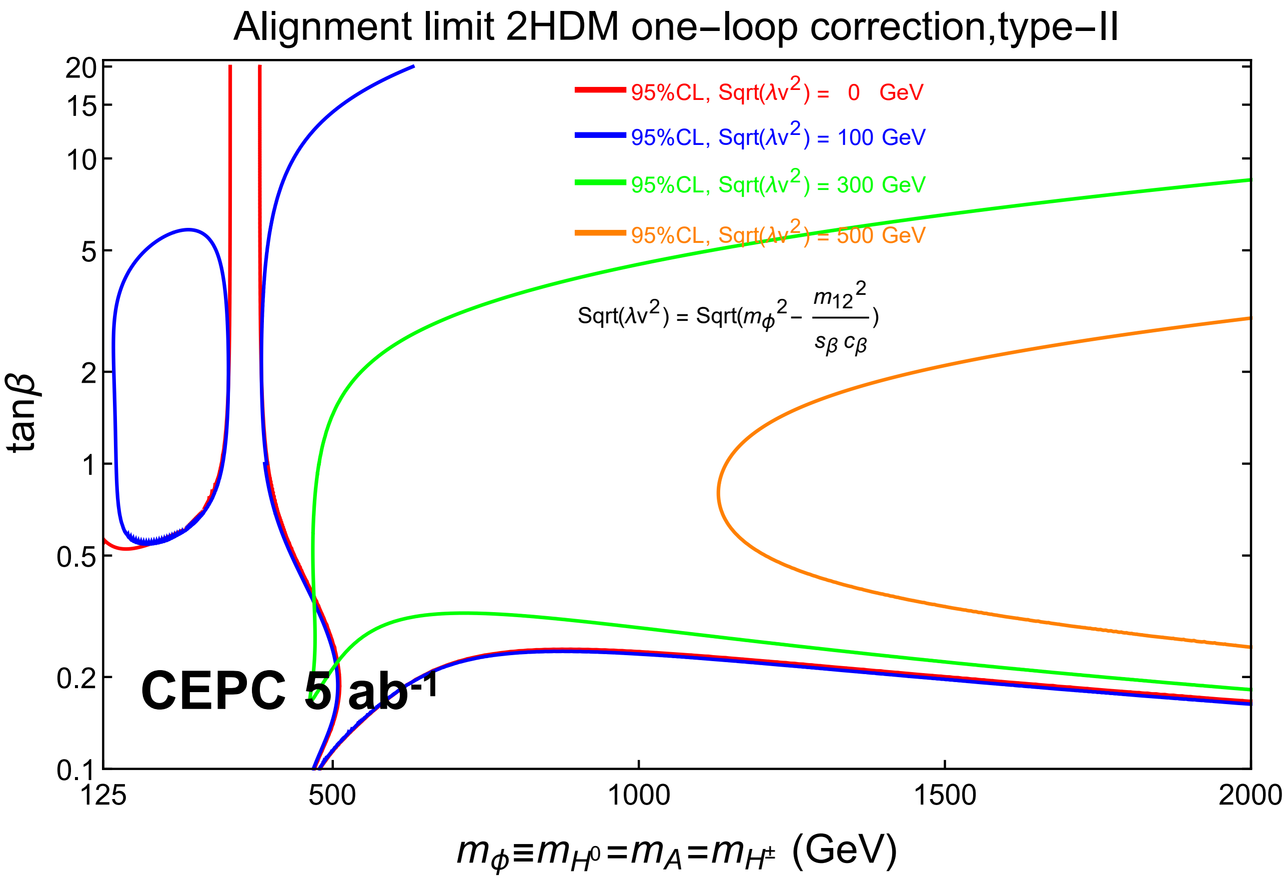
2HDM Model Distinction

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**



Strong Dynamics

- Minimum composite Higgs Model (MCHM)
- General EFT patterns of strong interacting models with a light Higgs

Composite Higgs in one slide

- Higgs is the PNGB of the spontaneous breaking of G⇒H
- EWSB is induced by vacuum misalignment, parametrized by $\xi = v^2/f^2$
- mass of SM fermion generated by mixing with composite states
- light top partners can be searched at the LHC
- minimal composite Higgs Model (MCHM): SO(5)/SO(4)
  - hVV

$$\kappa_V \equiv \frac{g_{hVV}^{\mathrm{CH}}}{g_{hVV}^{\mathrm{SM}}} = \sqrt{1-\xi}$$

  - hff: depends on the fermion representation

$$F_1 \equiv \frac{1-2\xi}{\sqrt{1-\xi}}, \qquad F_2 \equiv \sqrt{1-\xi}$$

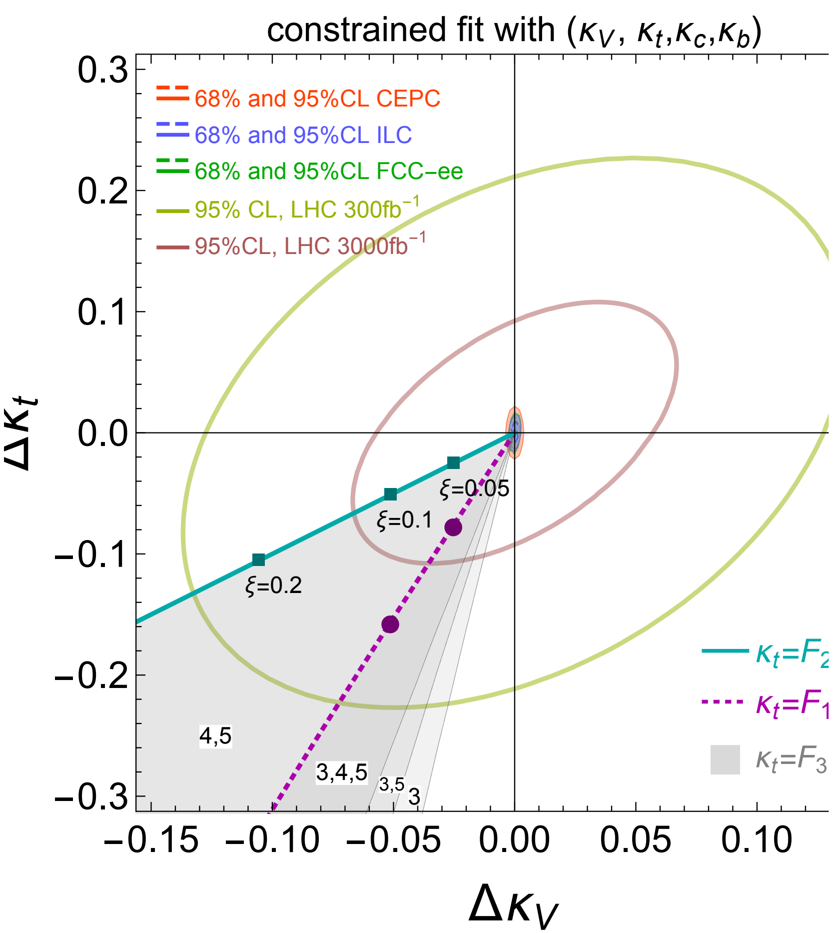
MCHM

- **Fermion representation**

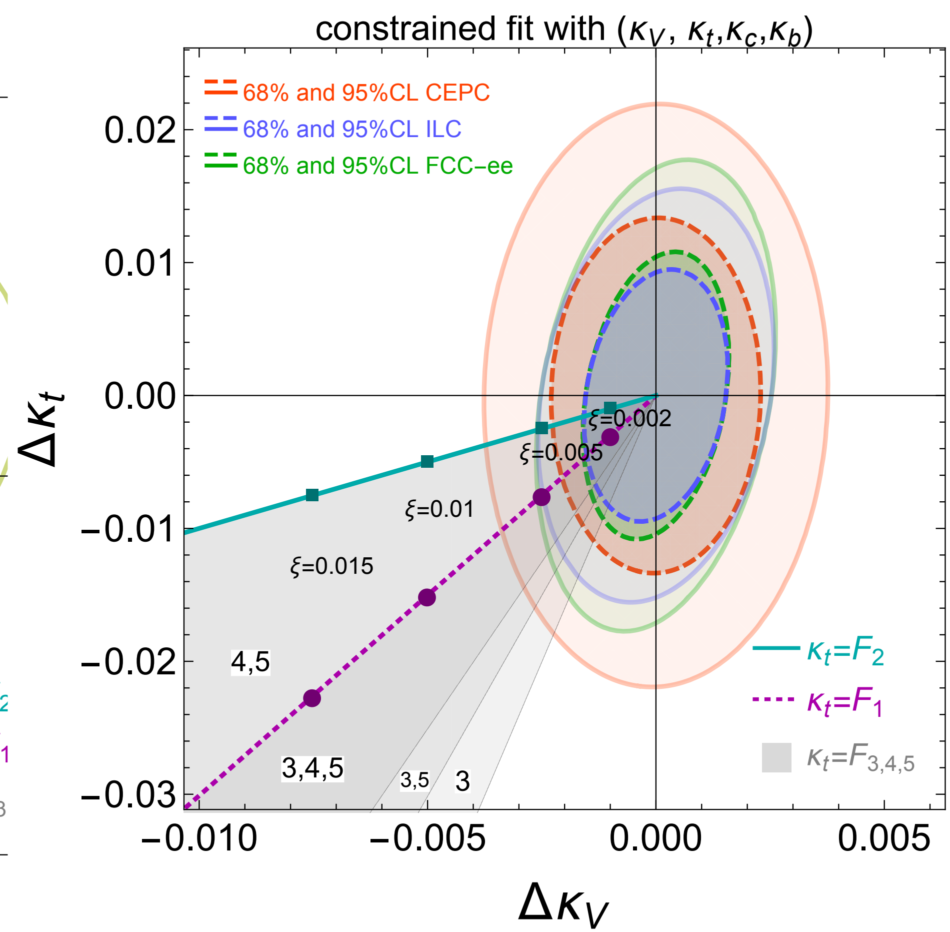
MCHM: $\xi = v^2/f^2 < 10^{-3}$, $f > 4$ TeV

MCHM Reps.	5, 10 14-1-10 14-10-10 10-14-10	10-5-10	5-5-10	5-10-10 5-1-10	14-14-10	14-5-10	5-14-10
$\kappa_t,\ \kappa_g$	F_1	F_2	F_1	F_2	F_3	F_4	F_5
κ_b	F_1	F_1	F_2	F_2	F_1	F_1	F_1
CEPC							
$\xi \times 10^3$	2.56	2.36	4.19	3.87	2.78 – 2.56	2.71 – 2.36	2.36 – 2.04
f [TeV]	4.86	5.06	3.80	3.95	4.67 – 4.86	4.72 – 5.07	5.07 – 5.45
ILC							
$\xi \times 10^3$	2.19	2.02	3.44	3.20	2.31 – 2.19	2.06 – 2.01	1.87 – 1.72
f [TeV]	5.26	5.48	4.19	4.35	5.12 – 5.26	5.42 – 5.48	5.69 – 5.93
FCC-ee							
$\xi \times 10^3$	1.80	1.66	3.06	2.74	1.85 – 1.80	1.70 – 1.66	1.66 – 1.41
f [TeV]	5.79	6.04	4.45	4.70	5.72 – 5.80	5.97 – 6.05	6.05 – 6.56

MCHM



constrained fit with (κ_V, κ_t,κ_c,κ_b)
68% and 95%CL CEPC
68% and 95%CL ILC
68% and 95%CL FCC−ee
95% CL, LHC 300fb^{-1}
95%CL, LHC 3000fb^{-1}
ξ=0.05
ξ=0.1
ξ=0.2
4,5
3,4,5
3,5
3
κ_t=F_2
κ_t=F_1
κ_t=F_3
$\Delta\kappa_t$
$\Delta\kappa_V$



constrained fit with (κ_V, κ_t,κ_c,κ_b)
68% and 95%CL CEPC
68% and 95%CL ILC
68% and 95%CL FCC−ee
ξ=0.002
ξ=0.005
ξ=0.01
ξ=0.015
4,5
3,4,5
3,5
3
κ_t=F_2
κ_t=F_1
κ_t=$F_{3,4,5}$
$\Delta\kappa_t$
$\Delta\kappa_V$

Strong Dynamics in EFT Language

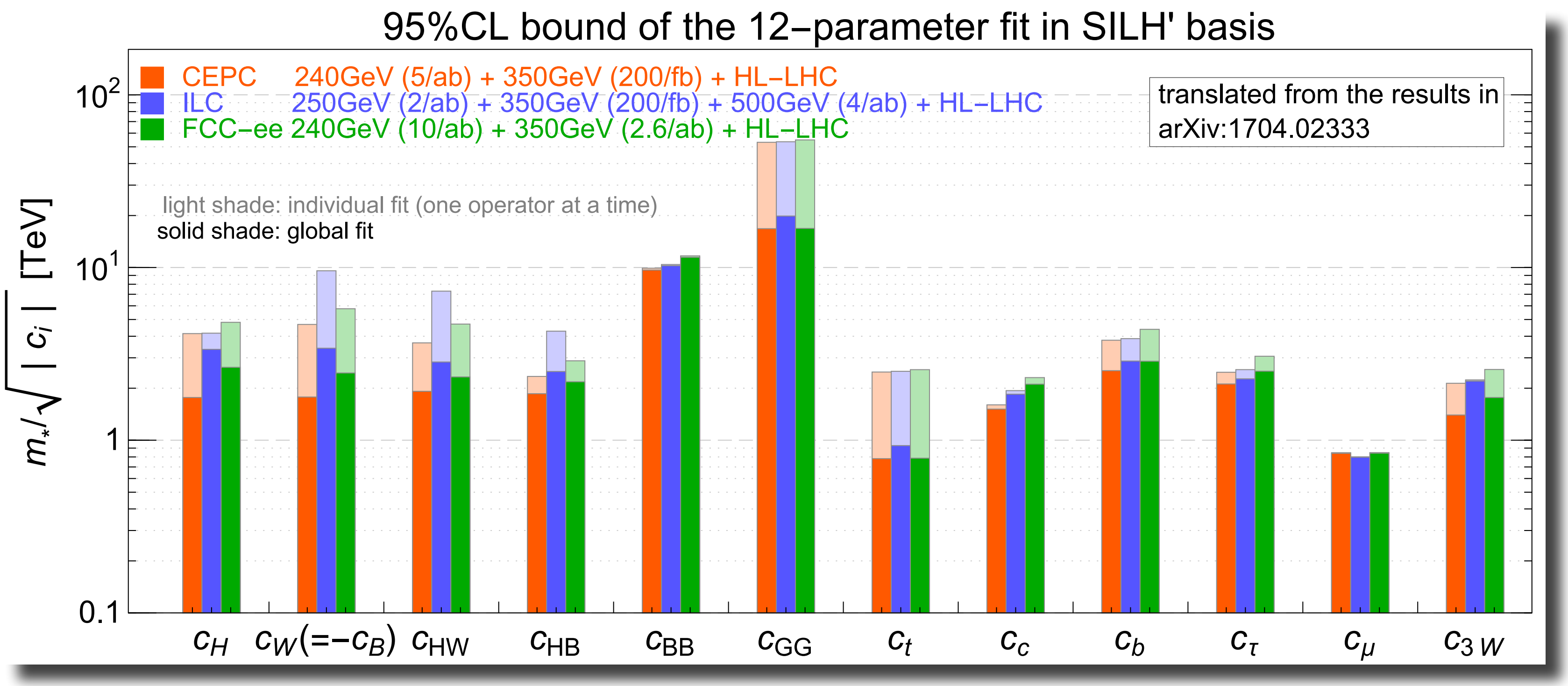
- **EFT operators**

$$\mathcal{L}_6 = \frac{1}{m_*^2}\sum_i c_i \mathcal{O}_i$$

$\mathcal{O}_H = \frac{1}{2}(\partial_\mu \lvert H^2 \rvert)^2$	$\mathcal{O}_{GG} = g_s^2 \lvert H\rvert^2 G^A_{\mu\nu} G^{A,\mu\nu}$
$\mathcal{O}_W = \frac{ig}{2}(H^\dagger \sigma^a \overleftrightarrow{D}^\mu H) D^\nu W^a_{\mu\nu}$	$\mathcal{O}_{Y_u} = Y_u \lvert H\rvert^2 \bar{Q}_L \tilde{H} u_R$
$\mathcal{O}_B = \frac{ig'}{2}(H^\dagger \overleftrightarrow{D}^\mu H)\partial^\nu B_{\mu\nu}$	$\mathcal{O}_{Y_d} = Y_d \lvert H\rvert^2 \bar{Q}_L H d_R$
$\mathcal{O}_{HW} = ig(D^\mu H)^\dagger \sigma^a (D^\nu H) W^a_{\mu\nu}$	$\mathcal{O}_{Y_e} = Y_e \lvert H\rvert^2 \bar{L}_L H e_R$
$\mathcal{O}_{HB} = ig'(D^\mu H)^\dagger (D^\nu H) B_{\mu\nu}$	$\mathcal{O}_{3W} = \frac{1}{3!} g \epsilon_{abc} W^{a\,\nu}_\mu W^b_{\nu\rho} W^{c\,\rho\mu}$
$\mathcal{O}_{BB} = g'^2 \lvert H\rvert^2 B_{\mu\nu} B^{\mu\nu}$	

	$\mathcal{O}_H$	$\mathcal{O}_W$	$\mathcal{O}_B$	$\mathcal{O}_{HW}$	$\mathcal{O}_{HB}$	$\mathcal{O}_{BB}$	$\mathcal{O}_{GG}$	$\mathcal{O}_{y_u}$	$\mathcal{O}_{y_d}$	$\mathcal{O}_{y_e}$	$\mathcal{O}_{3W}$
ALH	g_*^2	1	1	1	1	1	1	g_*^2	g_*^2	g_*^2	$\frac{g^2}{g_*^2}$
GSILH	g_*^2	1	1	1	1	$\frac{y_t^2}{16\pi^2}$	$\frac{y_t^2}{16\pi^2}$	g_*^2	g_*^2	g_*^2	$\frac{g^2}{g_*^2}$
SILH	g_*^2	1	1	$\frac{g_*^2}{16\pi^2}$	$\frac{g_*^2}{16\pi^2}$	$\frac{y_t^2}{16\pi^2}$	$\frac{y_t^2}{16\pi^2}$	g_*^2	g_*^2	g_*^2	$\frac{g^2}{16\pi^2}$

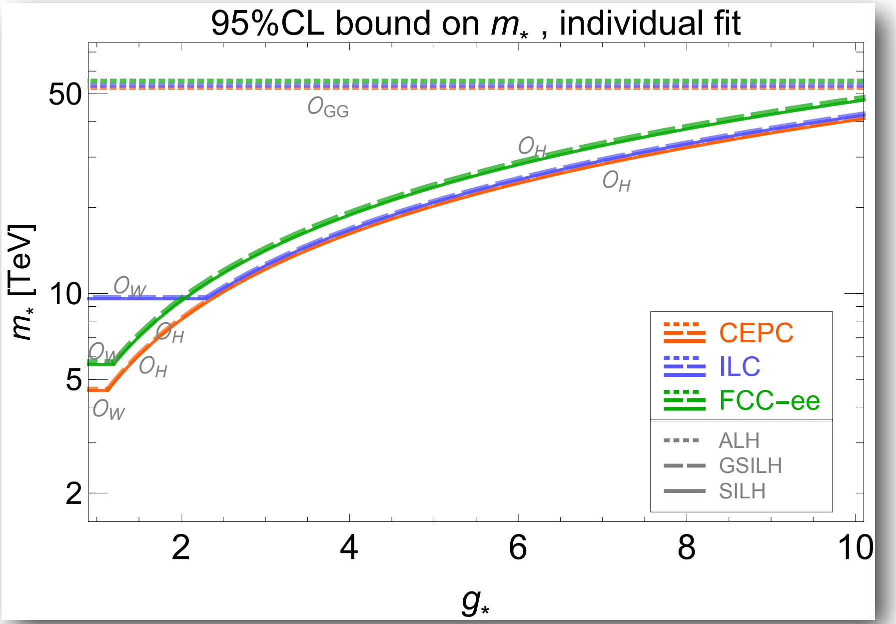
Strong Dynamics in EFT Language

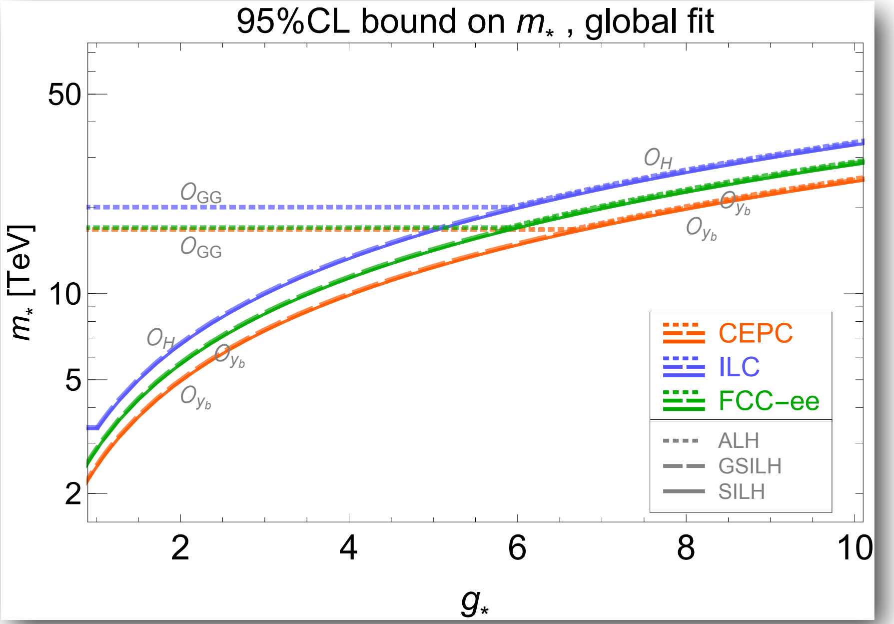


Strong Dynamics in EFT Language

individual fit

global fit

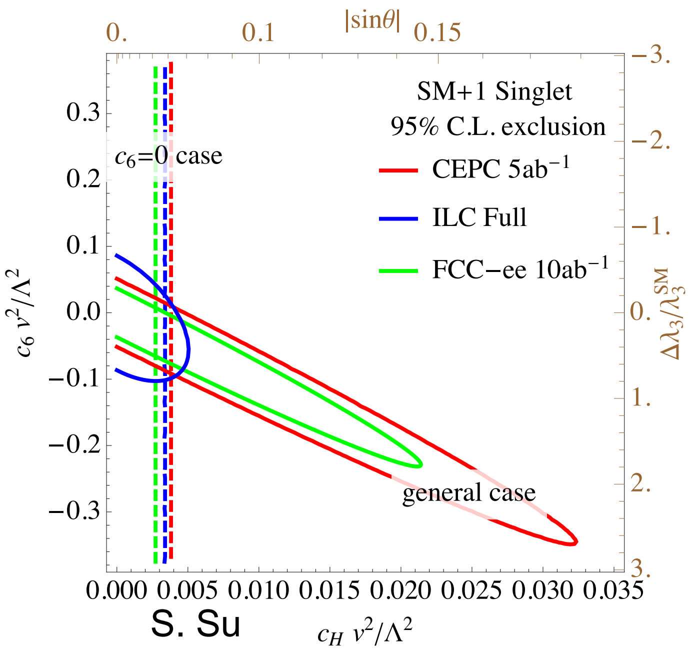




Conclusion

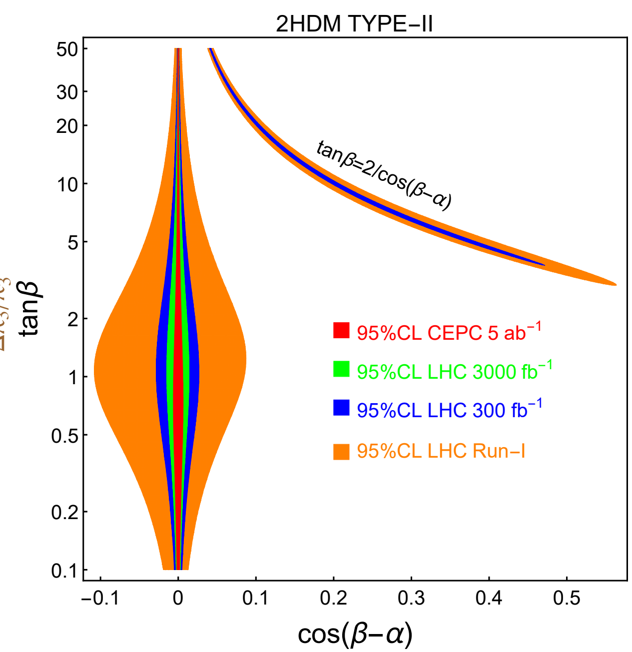
- future Higgs factories measure Higgs properties to a high precision
- Kappa-scheme/EFT scheme/model specific fit
- perturbative model

SM+singlet

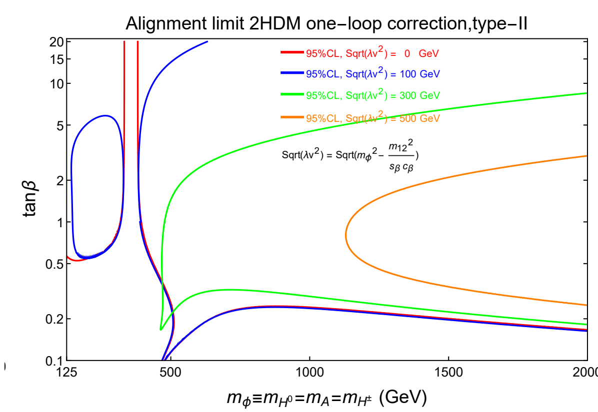


S. Su

2HDM tree



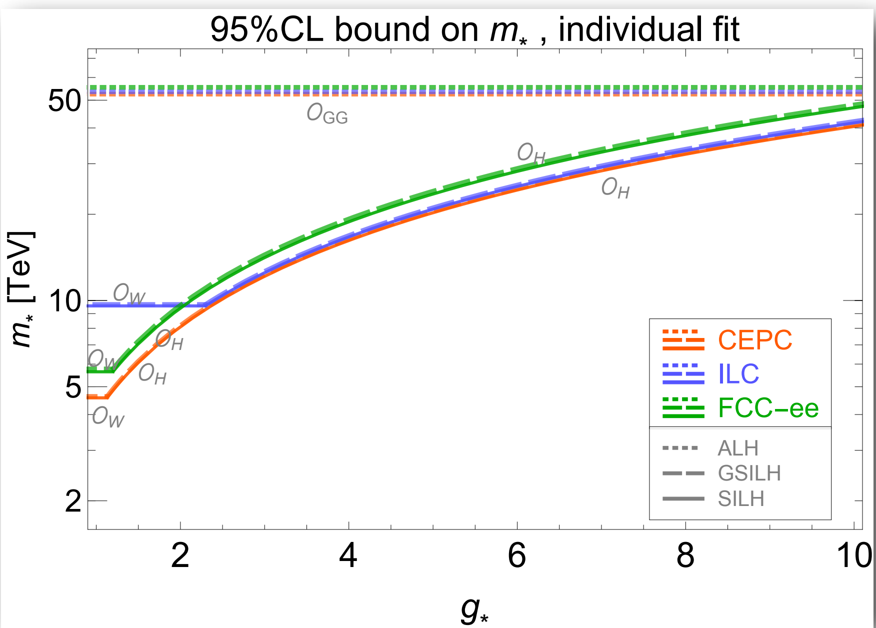
2HDM loop @ alignment

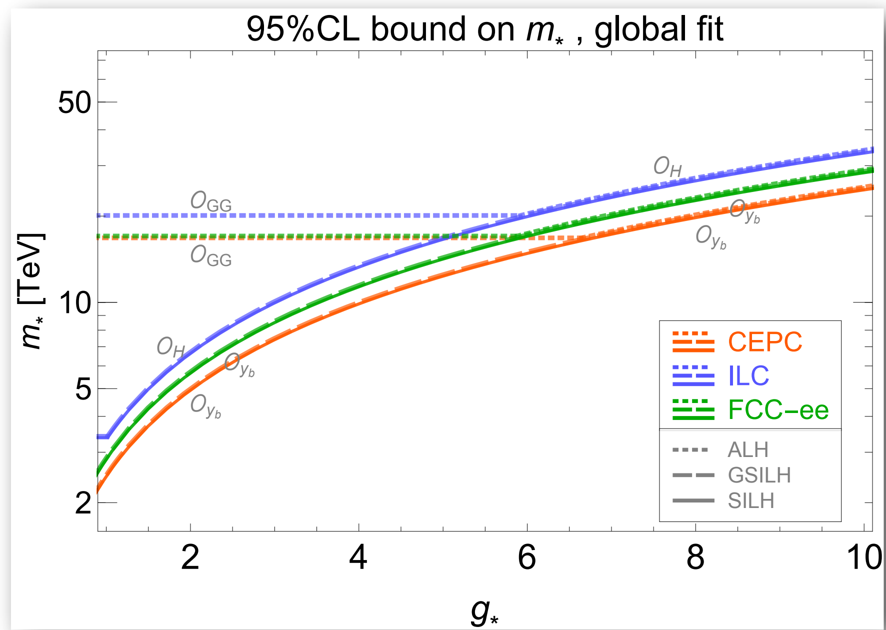


Conclusion

- **strong dynamics models**
  - **MCHM:** $\xi = v^2/f^2 < 10^{-3}$, f > 4 TeV
  - **ALH/GSILH/SILH**

individual fit | **global fit**





Conclusion

LHC

Lepton Collider

100 TeV pp

An exciting journey ahead of us!