Precision Higgs/EW Physics
and
Other Higgses

Shufang Su • U. of Arizona

Pheno 2019

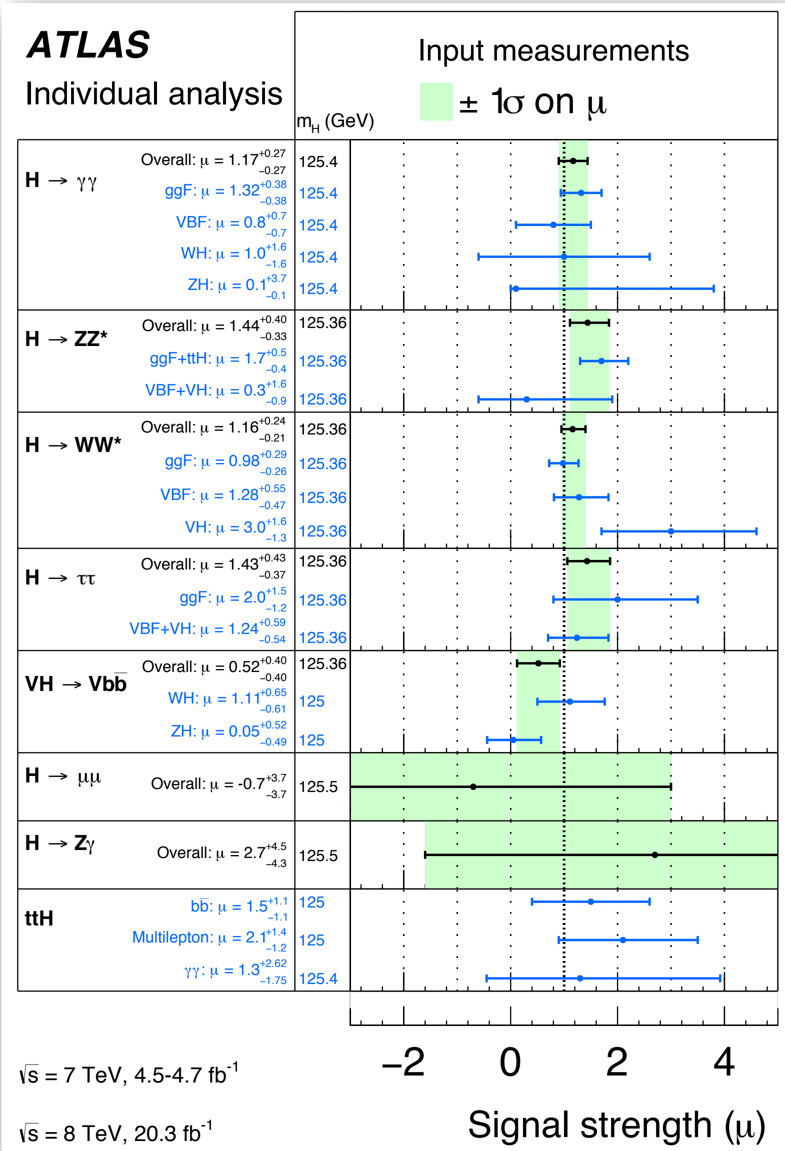
May 7, 2019

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

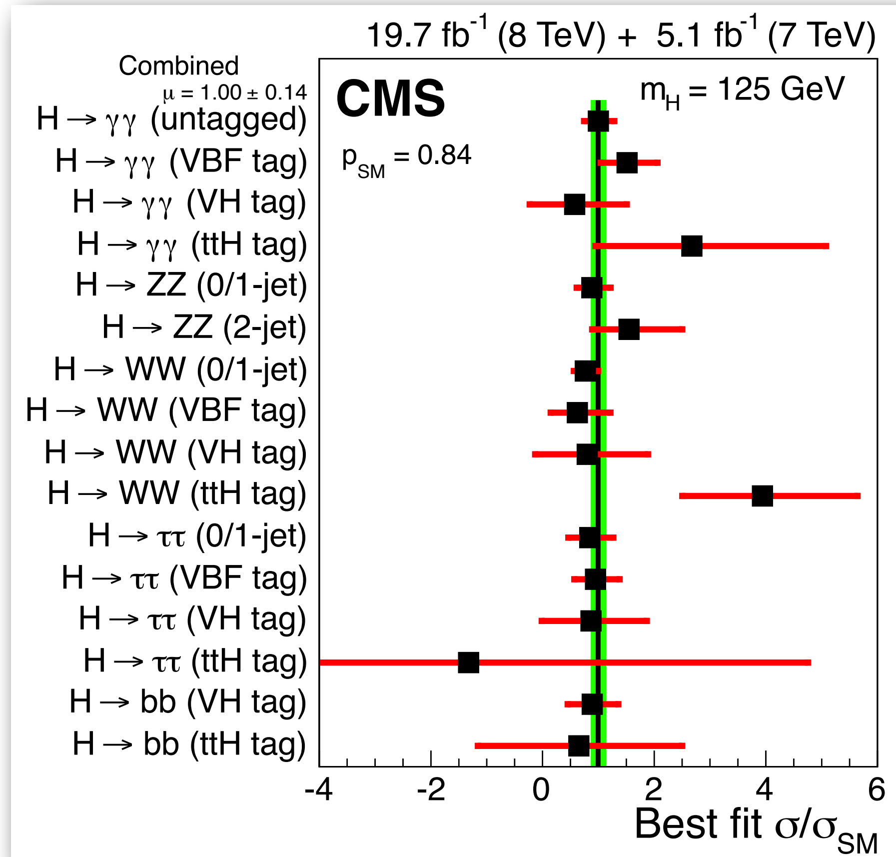
Outline

- 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

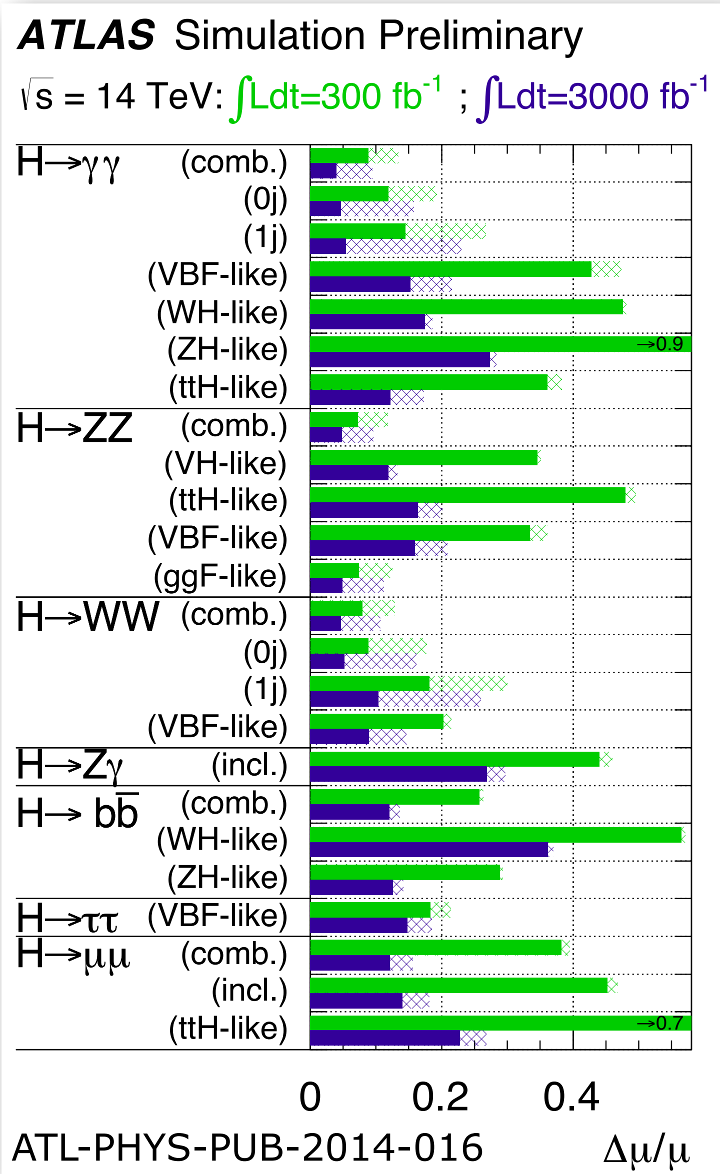


LHC: 7+8 TeV



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					
$\sqrt{s}$ $\int \mathcal{L}dt$	240 GeV 5 ab^{-1}	240 GeV 5 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%	0.57%	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.

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	$\Delta(\sigma \cdot BR)/(\sigma \cdot BR)$							
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Kappa framework and EFT Framework

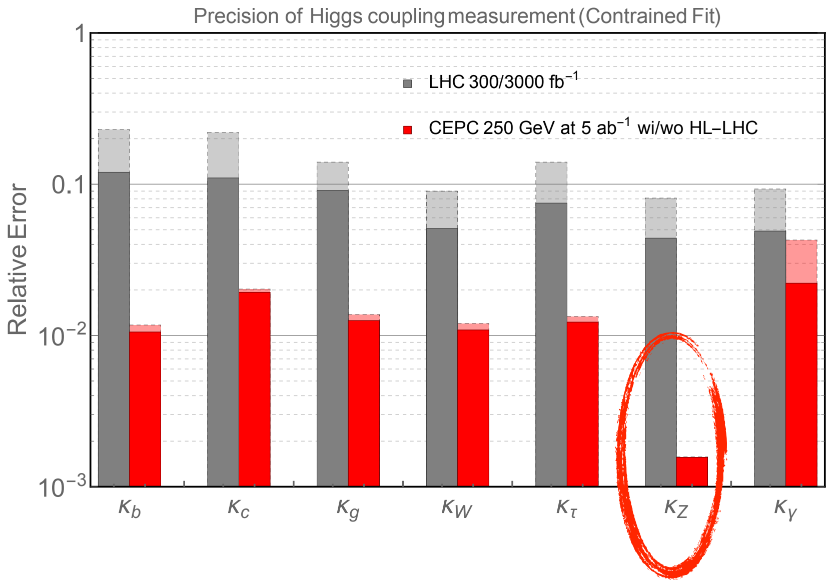
Two model-independent approaches

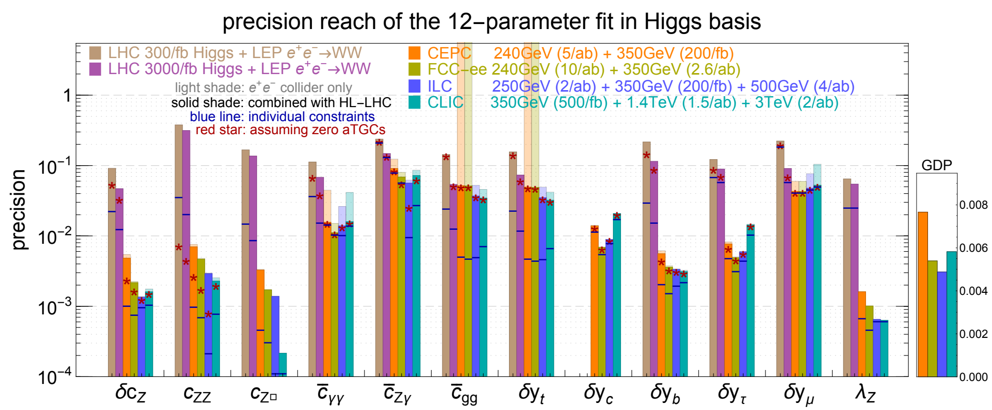
kappa framework

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

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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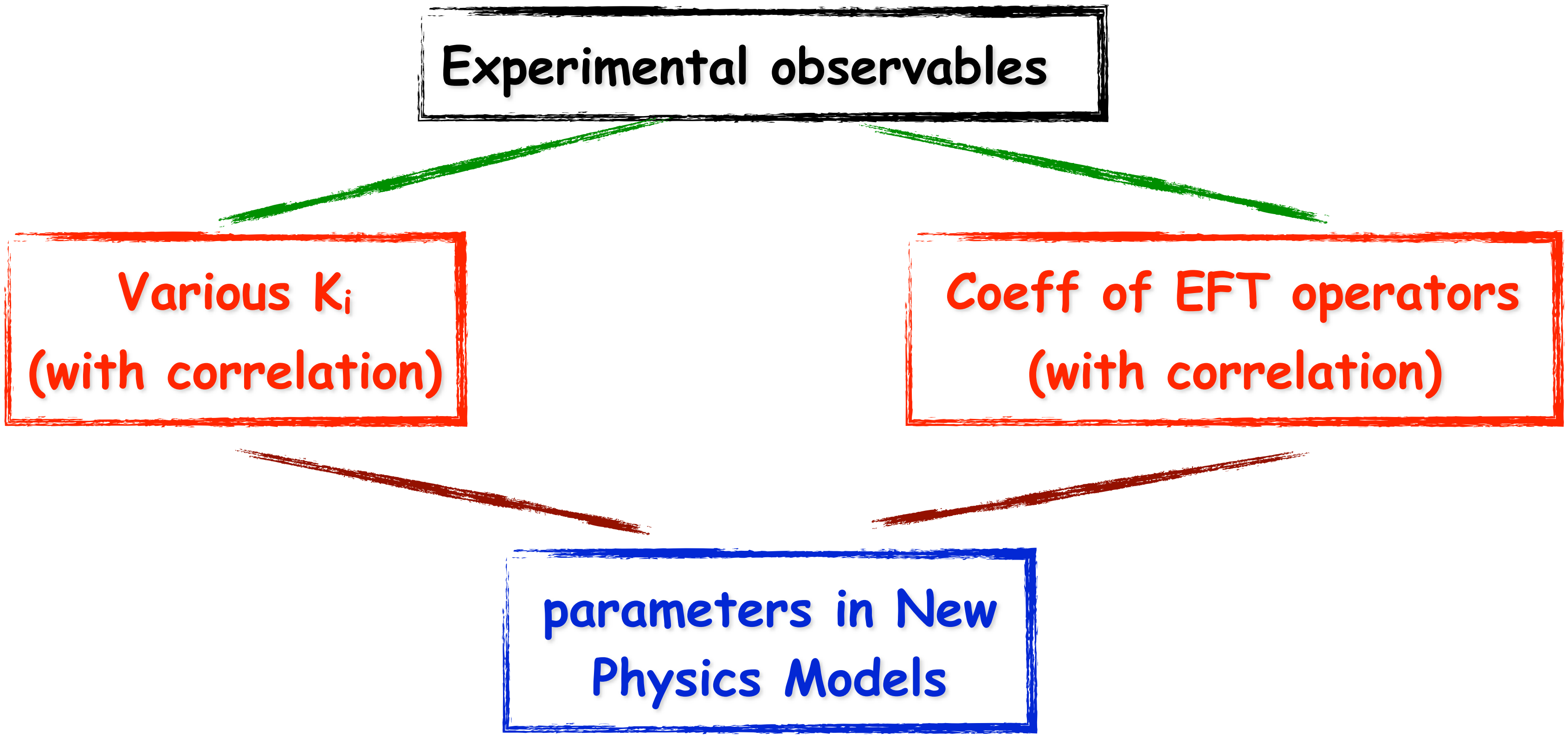
New Physics Implication



Kappa Framework and EFT Framework

limitations of model-independent approaches

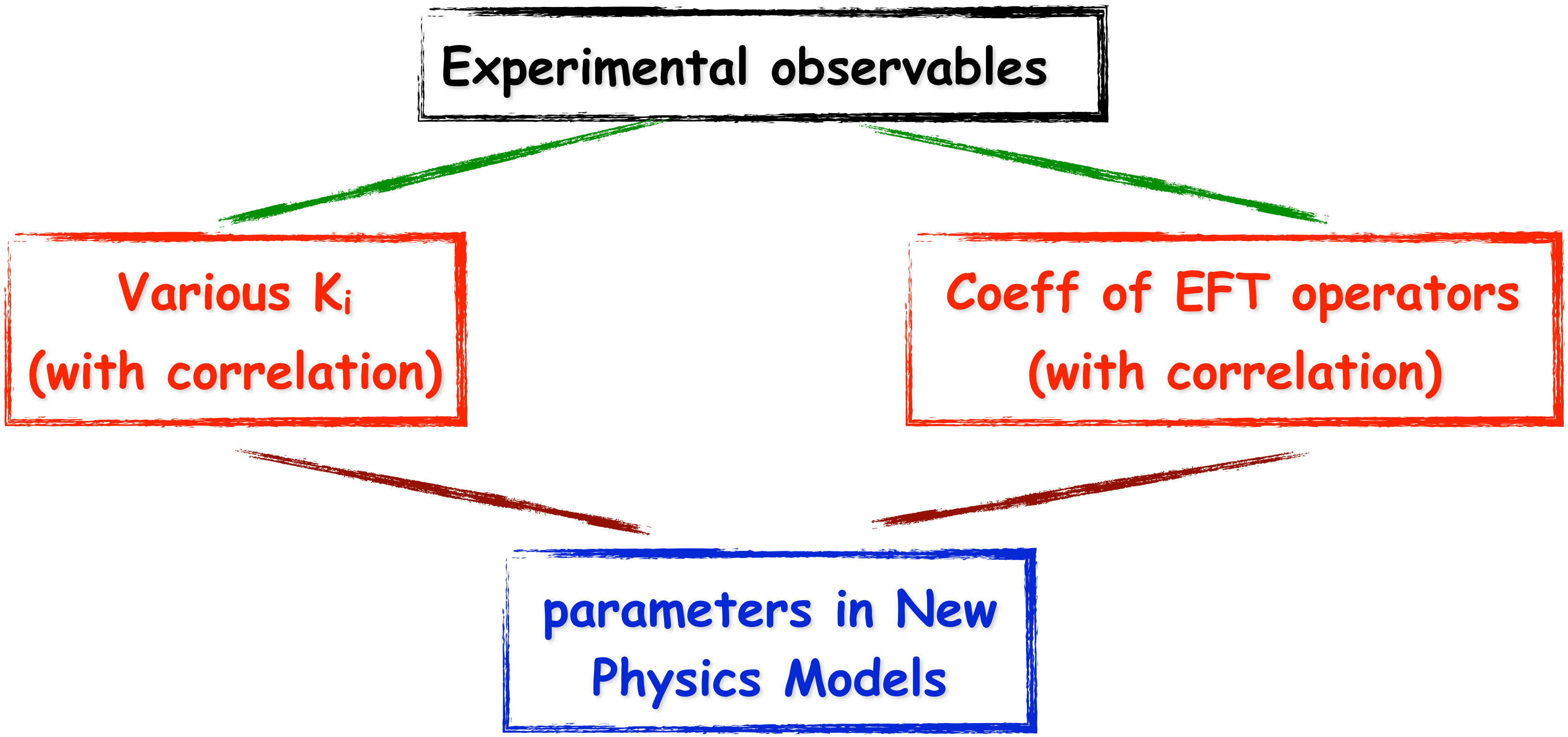
- large level of degeneracy

  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



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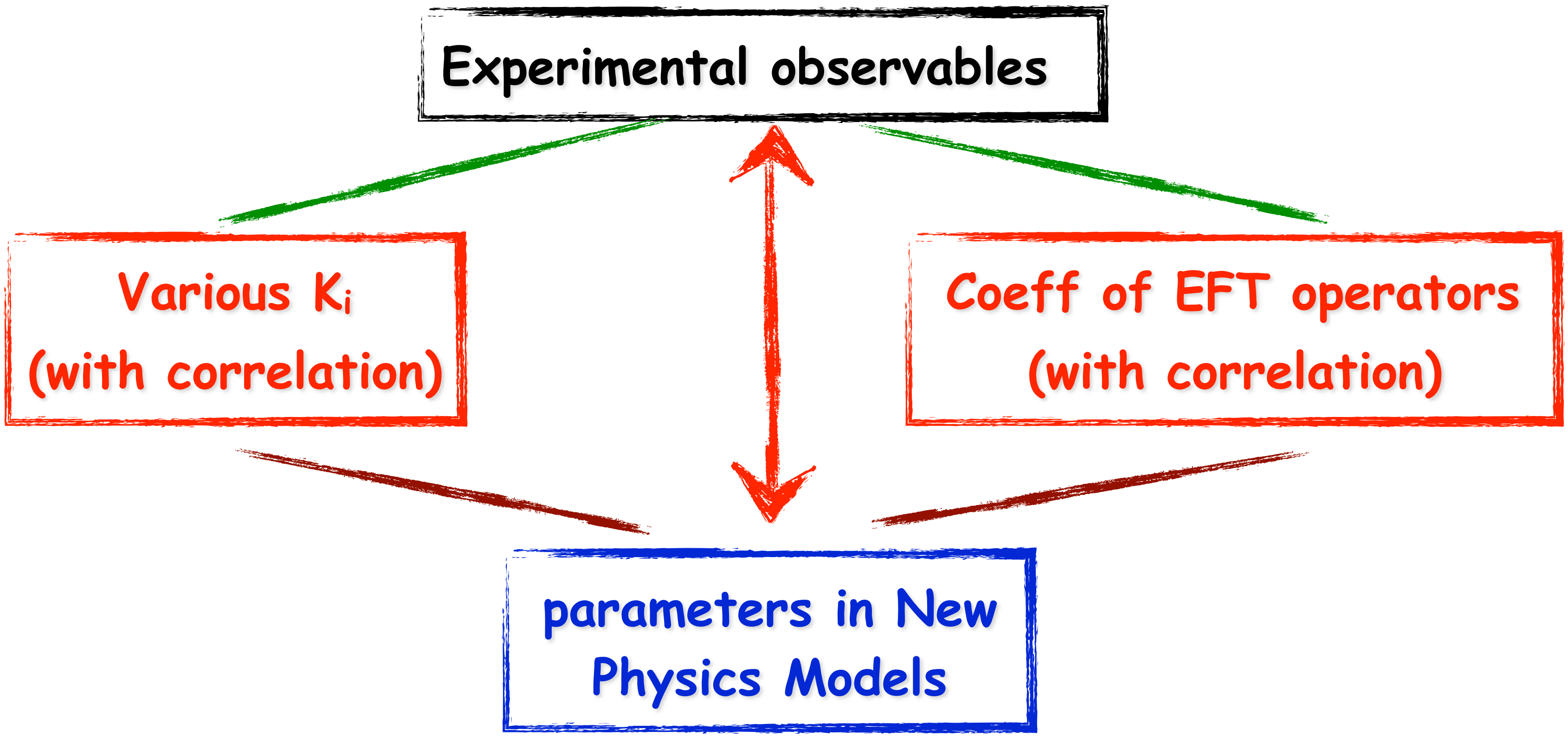

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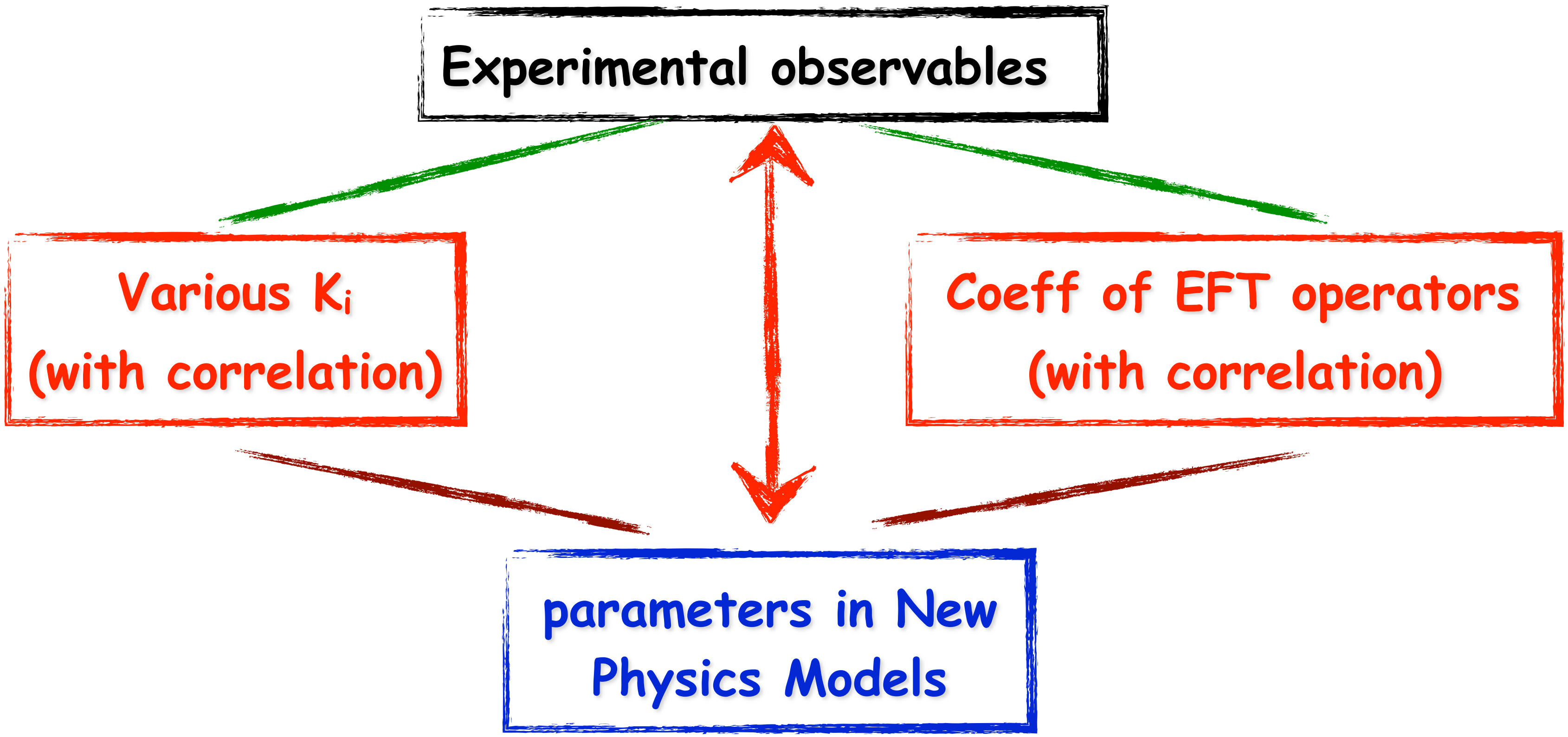

$$\chi^2 = \sum_i \frac{(\mu_i^{\rm BSM} - \mu_i^{\rm obs})^2}{\sigma_{\mu_i}^2} \qquad \mu_i^{\rm BSM} = \frac{(\sigma\times{\rm Br})_{\rm BSM}}{(\sigma\times{\rm Br})_{\rm SM}}$$

Perturbative Models

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

Perturbative Models

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Shuailong Li's talk

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

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

soft Z2 breaking: m_{12}^2

tanβ, cos(β-α),

control tree level h^0 couplings

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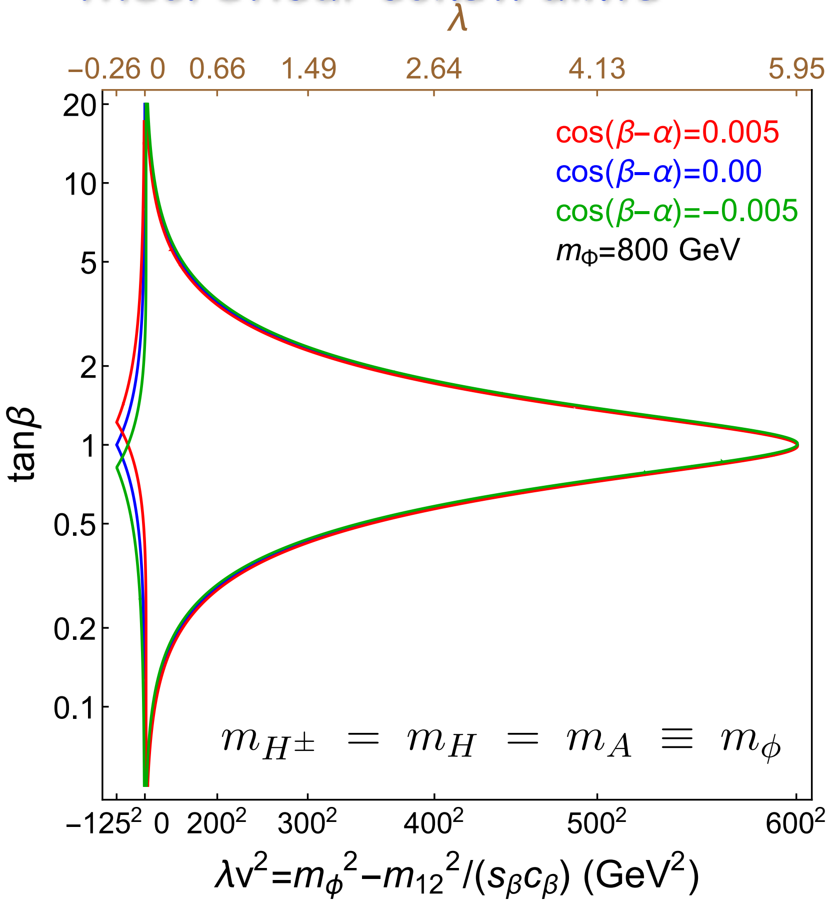
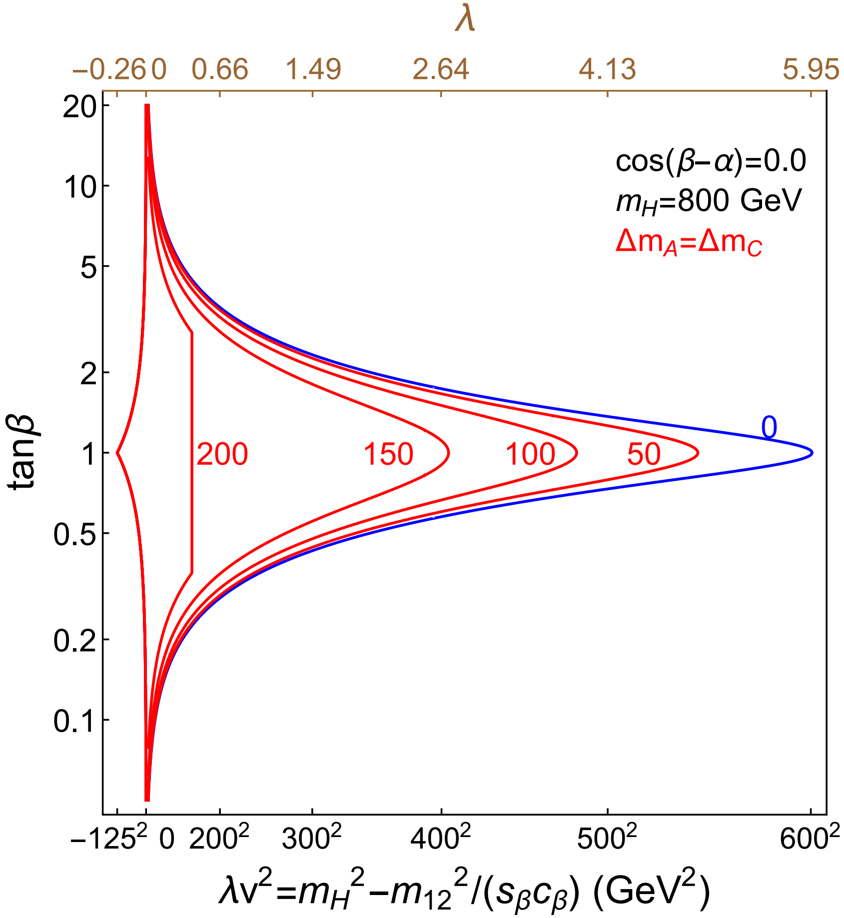
S. Su

2HDM: Loop in the Alignment Limit

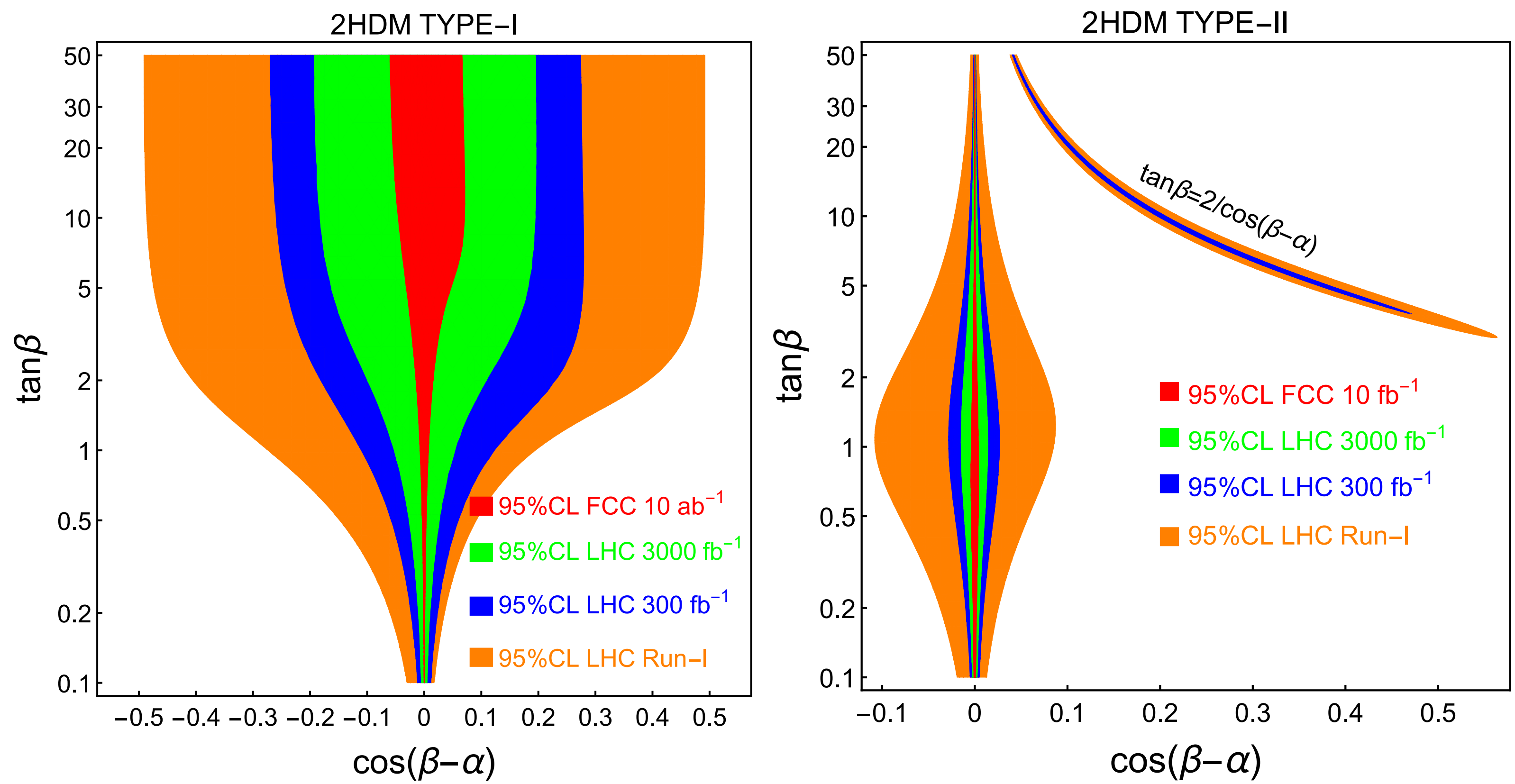
- **theoretical constraints**



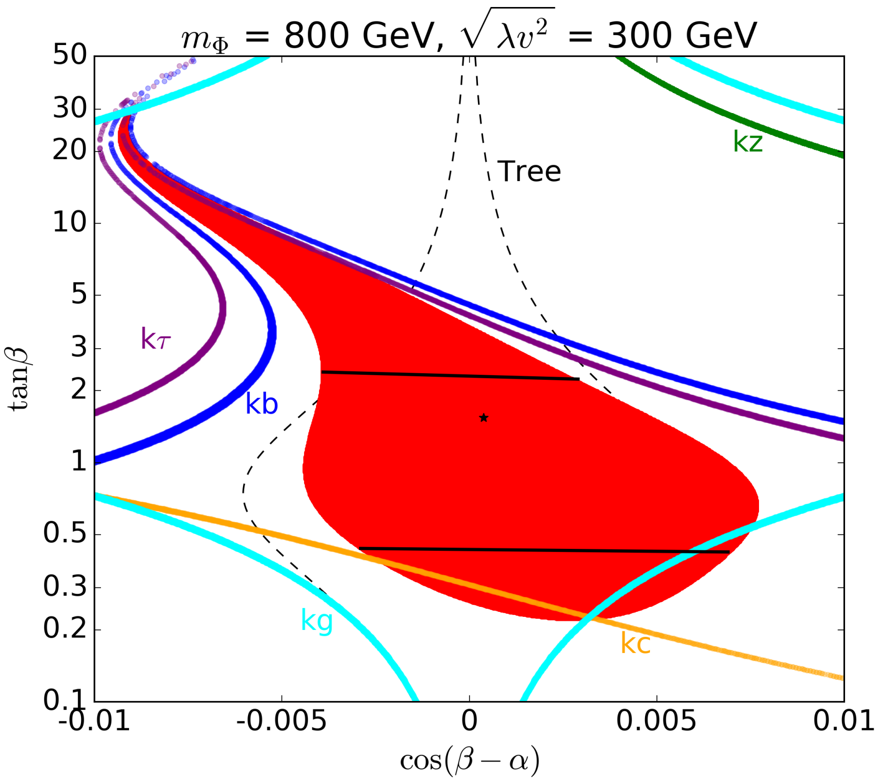


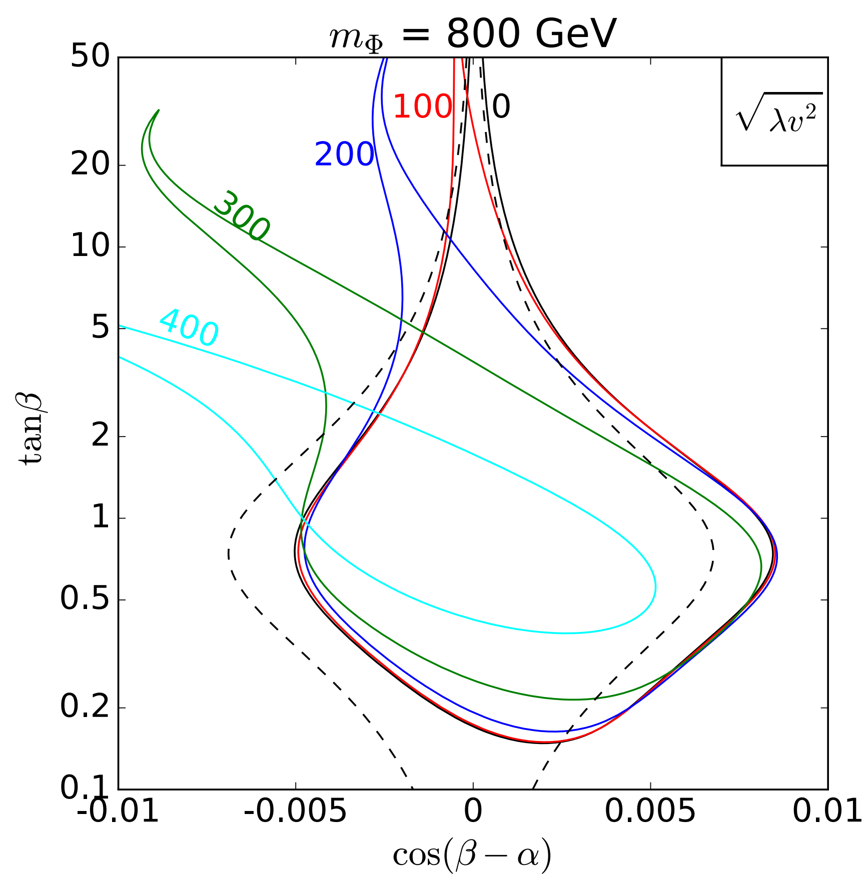
Tree-level 2HDM fit

2HDM, LHC/FCC fit



TYPE II 2HDM: Tree + Loop





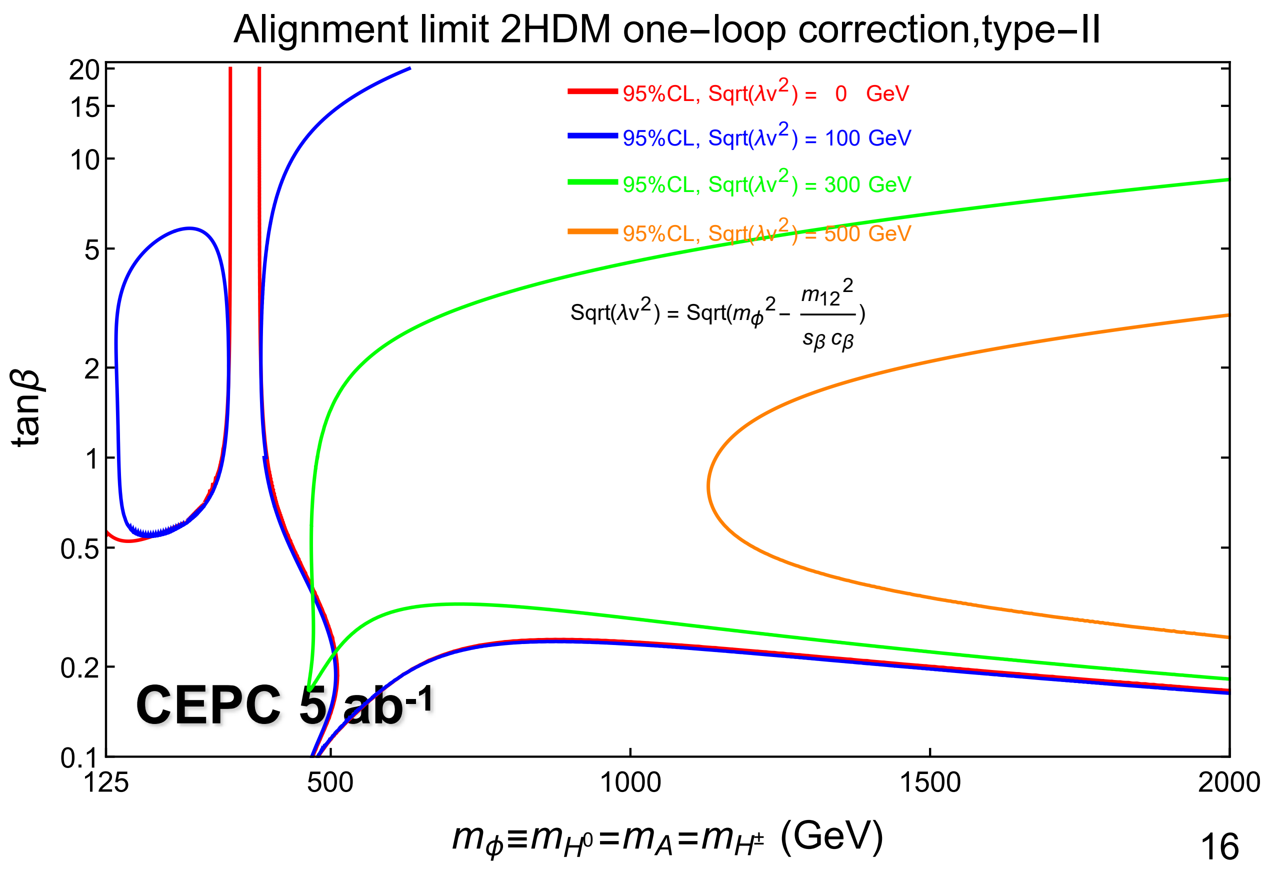
N. Chen, T. Han, SS, W. Su, Y. Wu, 1808.02037

2HDM: Loop in the Alignment Limit

- **Type II**

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

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



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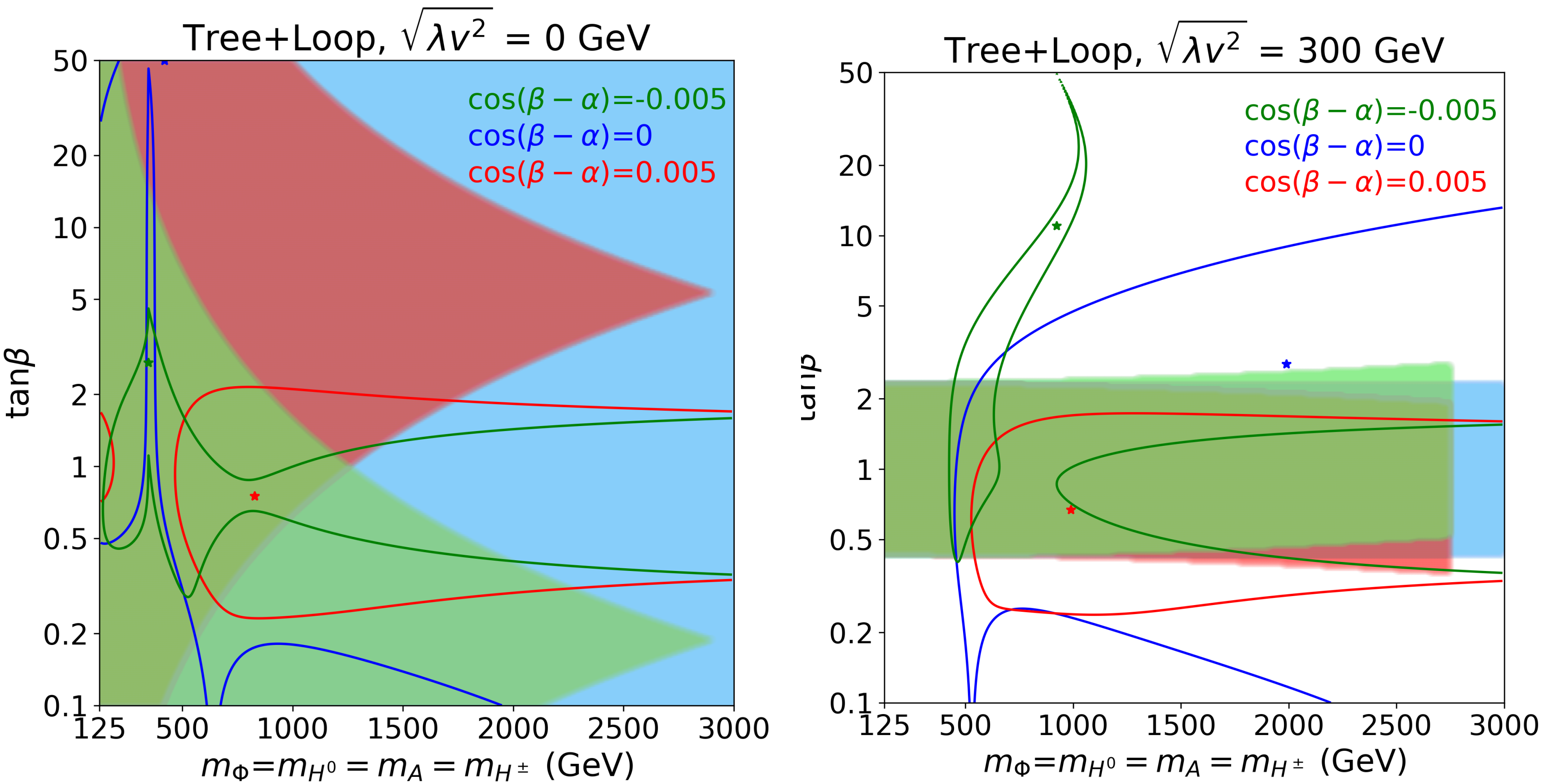
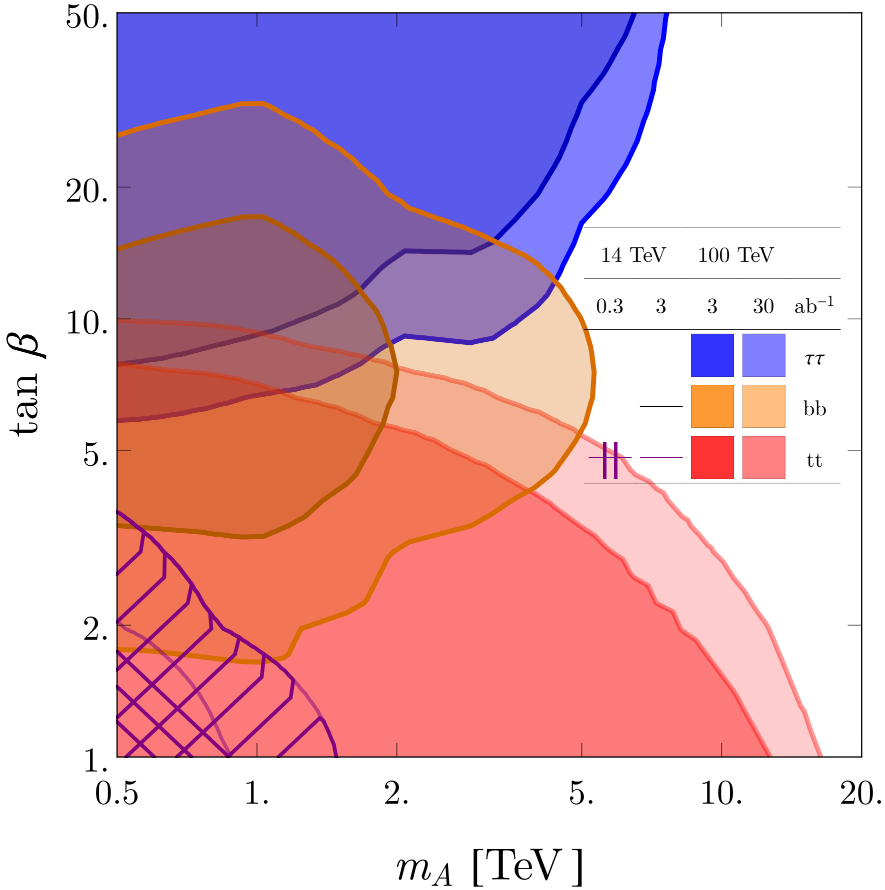
2HDM: Tree + Loop



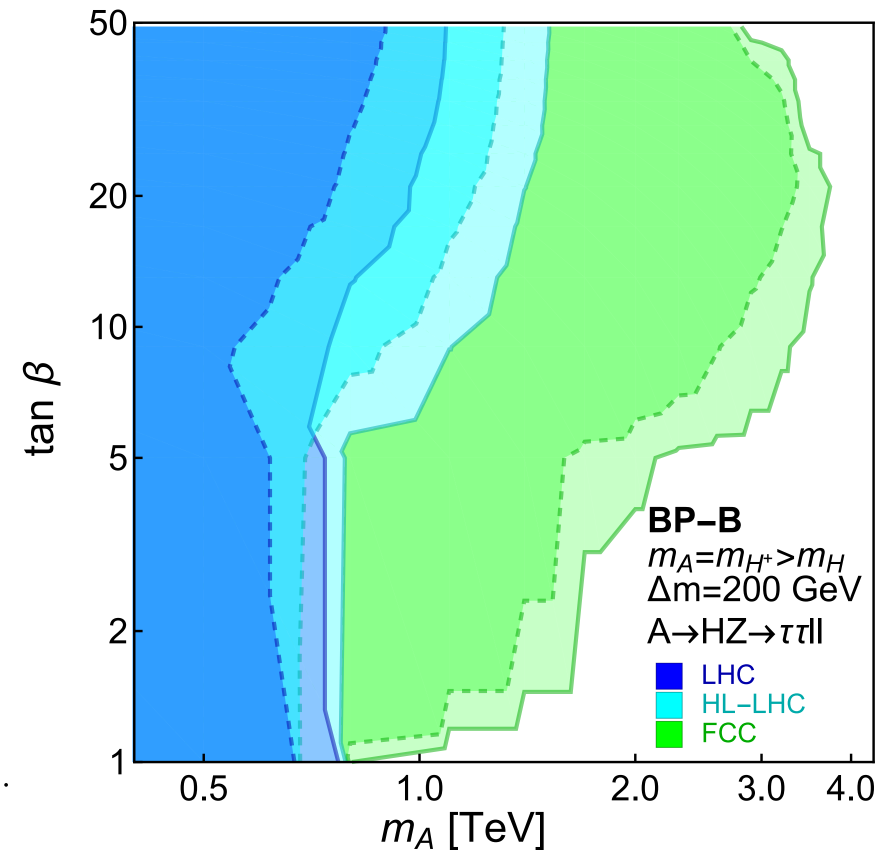
N. Chen, T. Han, SS, W. Su, Y. Wu, 1808.02037

Direct Search of Heavy Higgses @ 100 pp

Conventional search



Exotic Decay



Craig et. al., 1605.08744

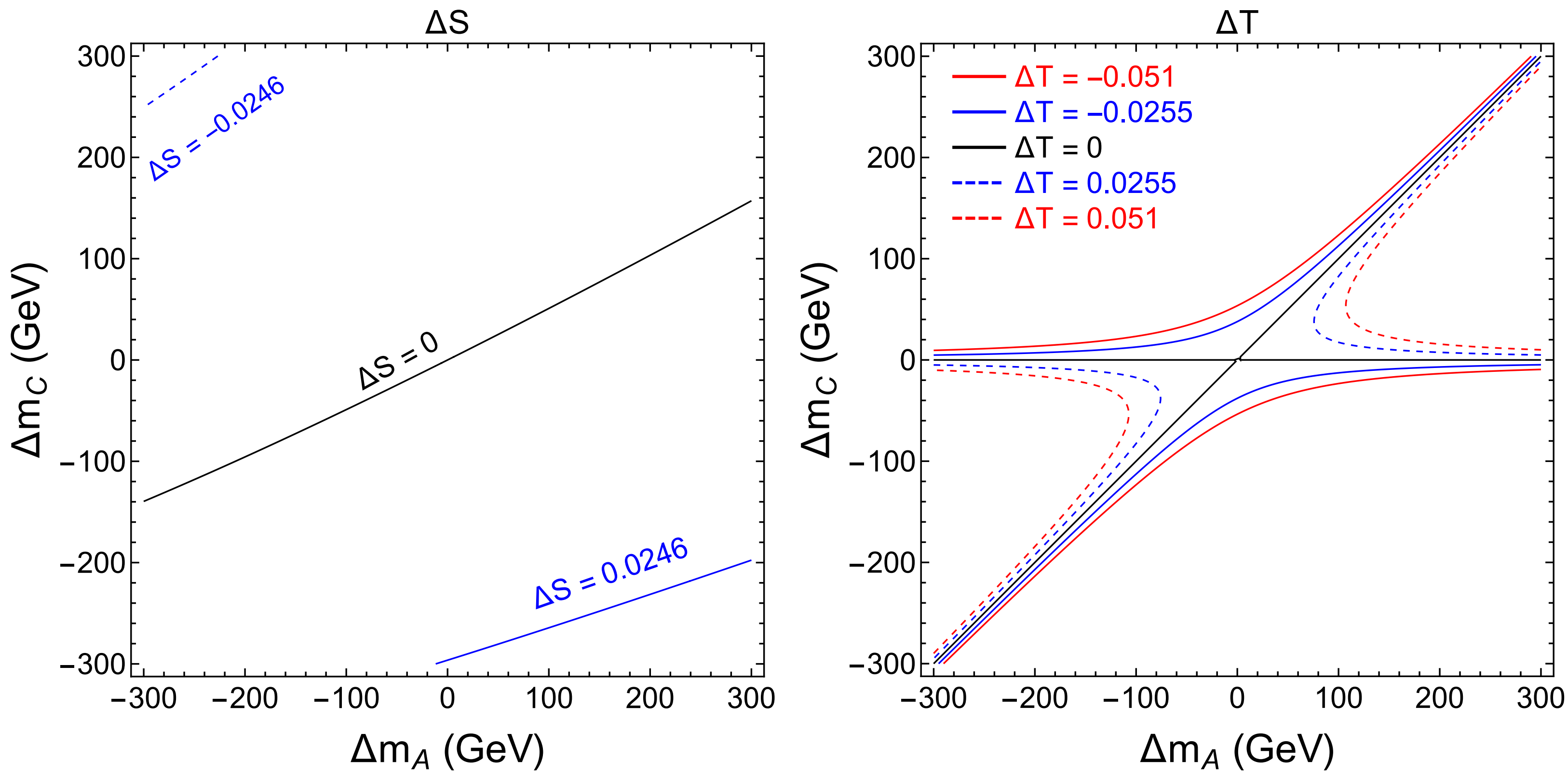
Z-pole precision

	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	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

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



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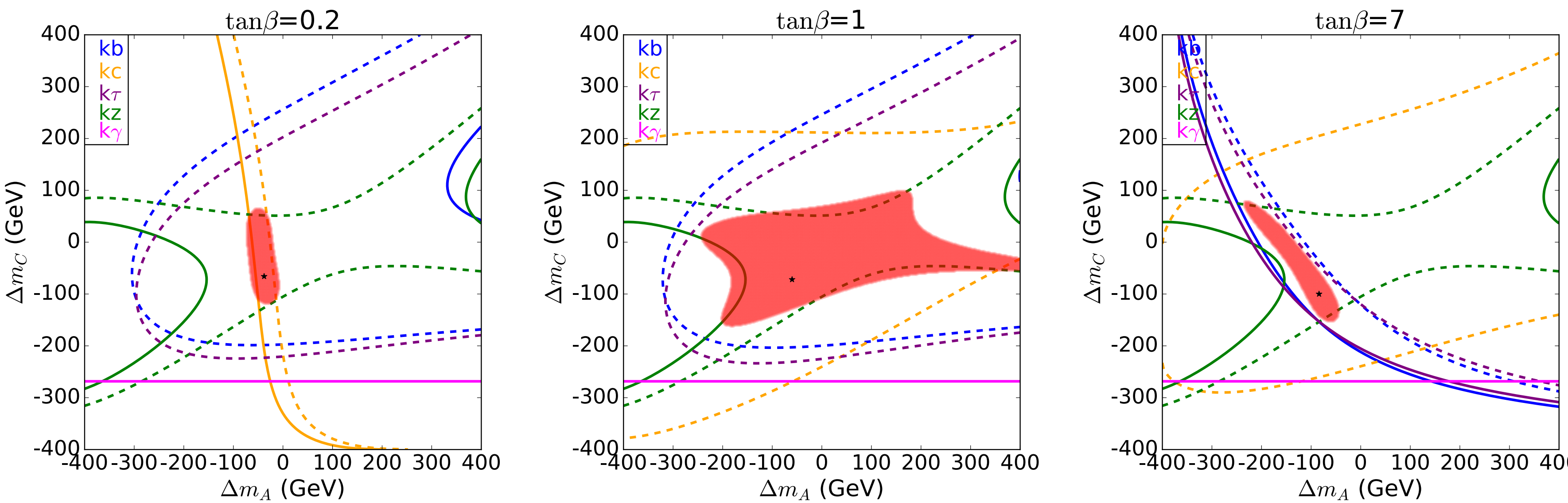

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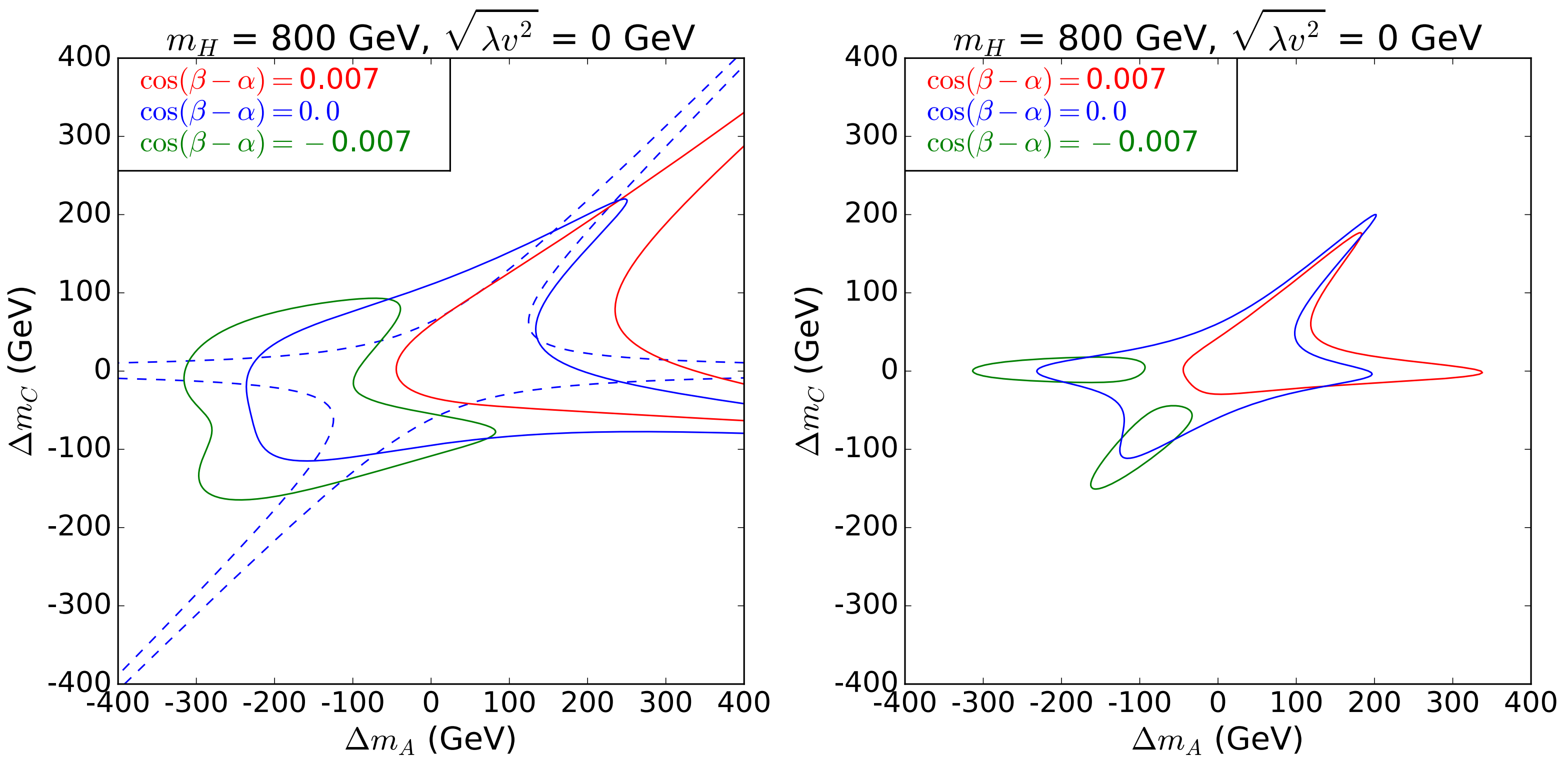
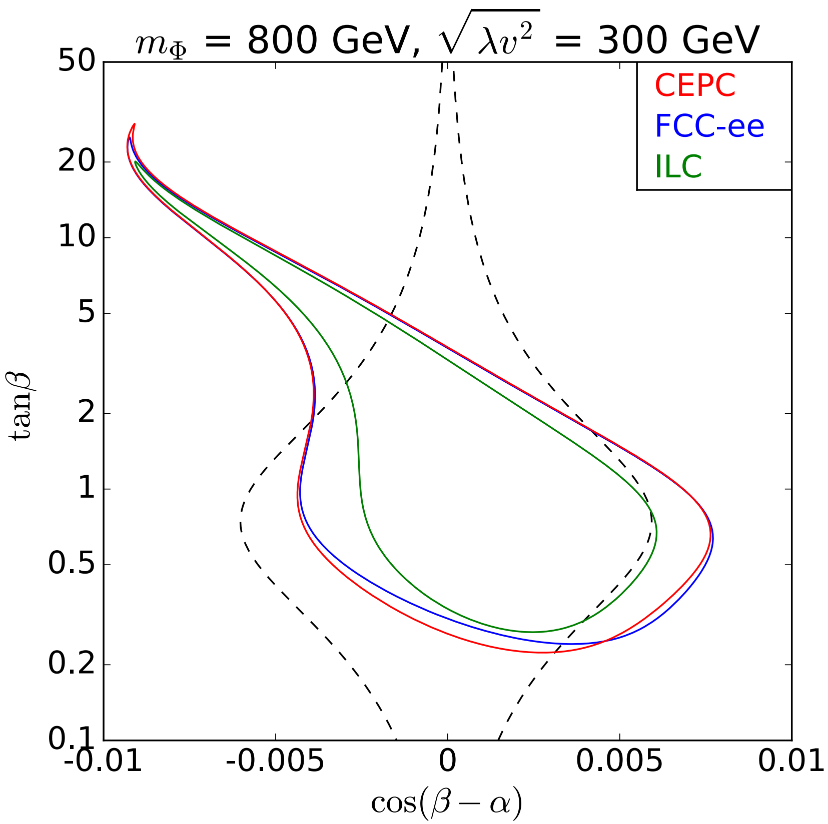
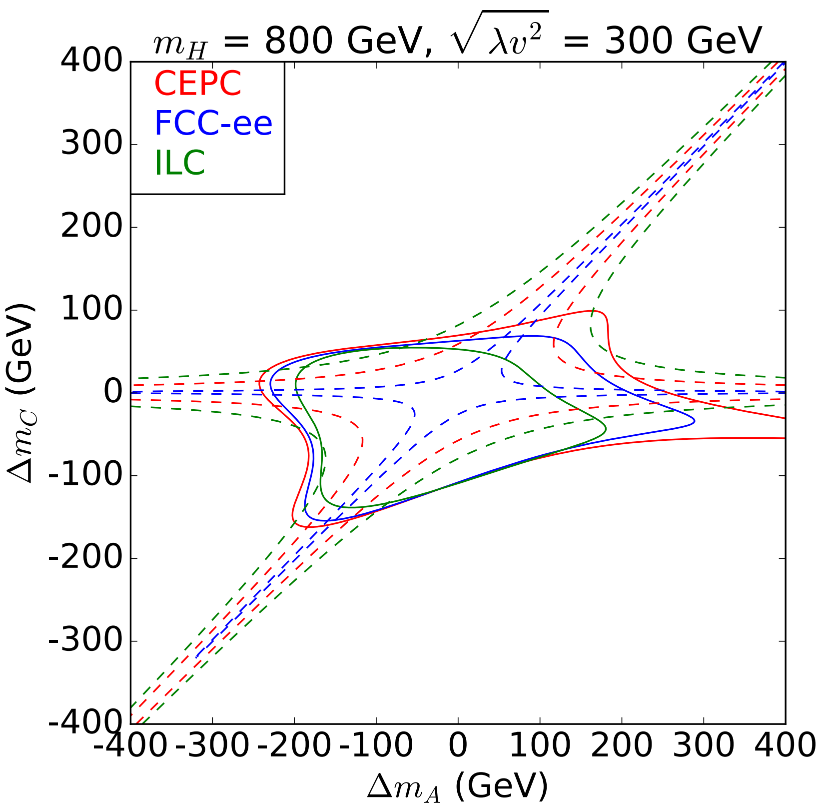


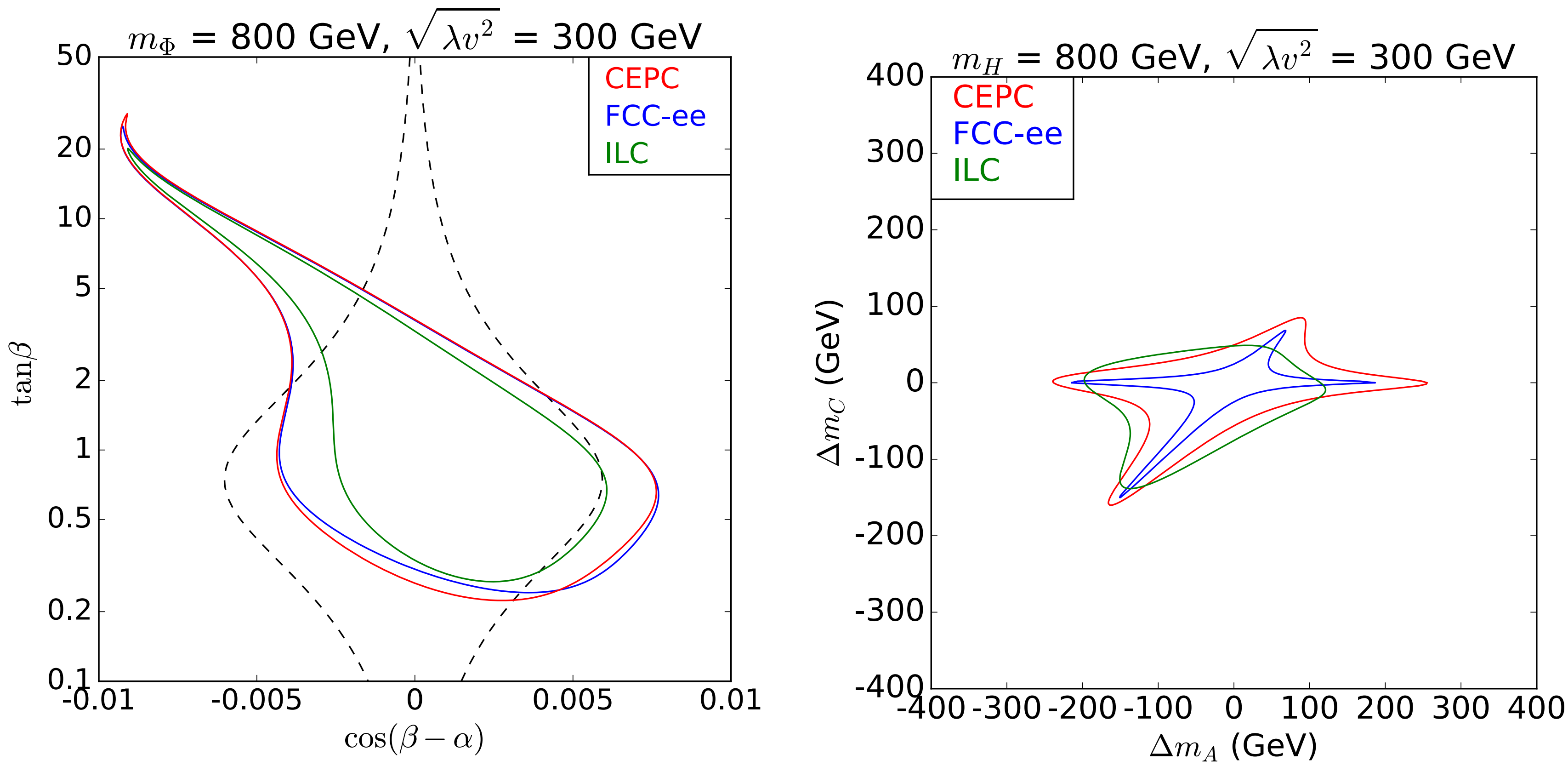
Complementary to Zpole precision

Different Higgs Factories



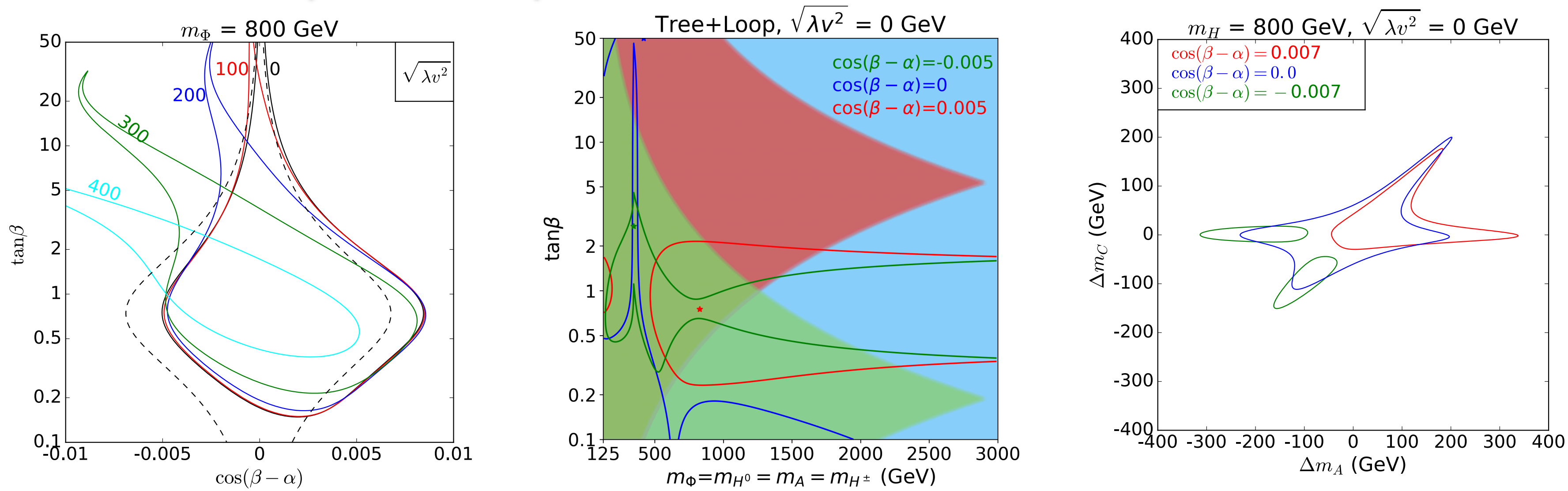


Different Higgs Factories



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



S. Su

2HDM tree + loop

Conclusion

LHC

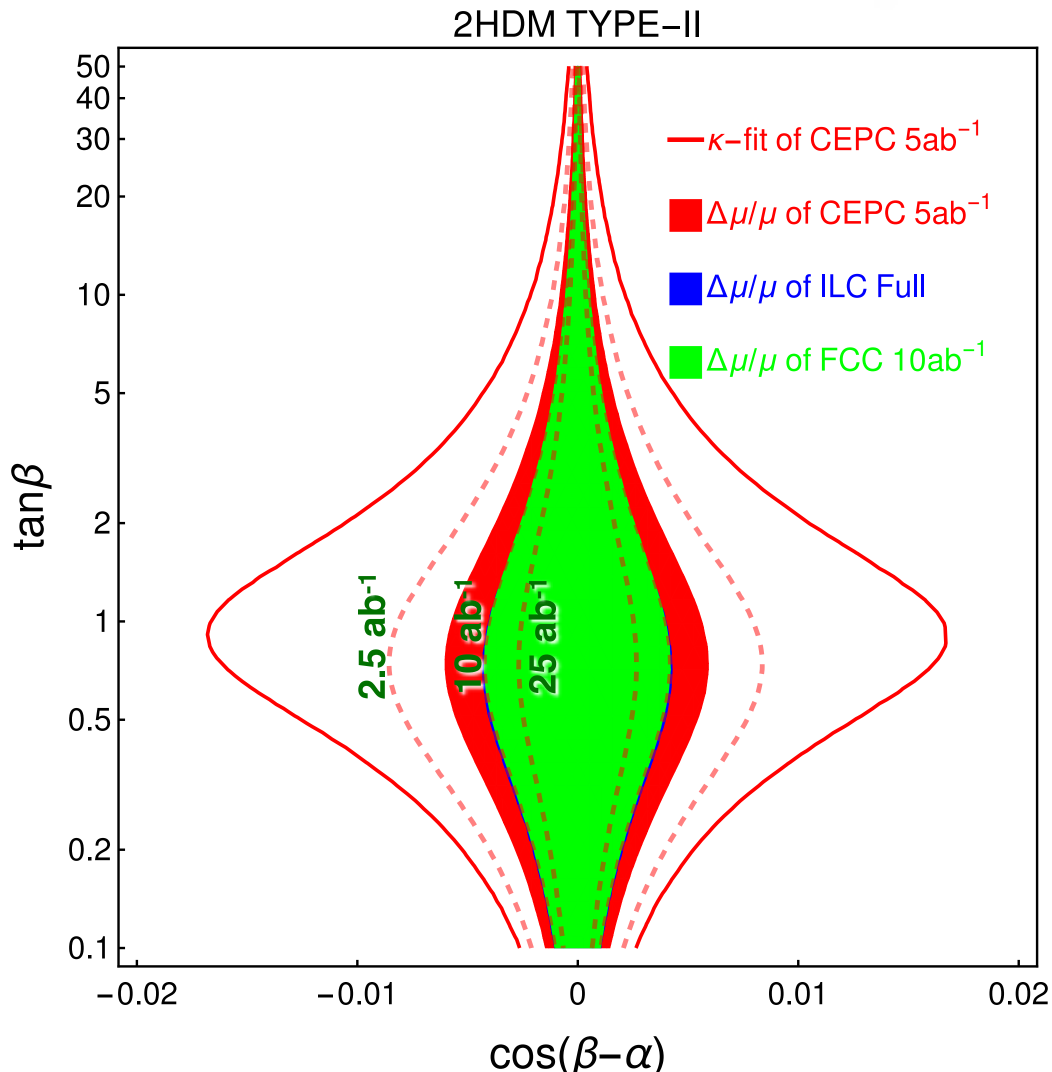
Lepton Collider

100 TeV pp

An exciting journey ahead of us!

Backup Slides

Tree-level 2HDM fit



κ-fit vs Δμ/μ fit

CEPC/FCC/ILC luminosity

Perturbative Models

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

MSSM

- Higgs mass

$$M_h^2 = m_h^{2,\mathrm{tree}} + \frac{3}{2}\frac{G_F\sqrt{2}}{\pi^2}\overline{m}_t^4\left\{-\ln\left(\frac{\overline{m}_t^2}{M_S^2}\right) + \frac{X_t^2}{M_S^2}\left(1 - \frac{1}{12}\frac{X_t^2}{M_S^2}\right)\right\}$$

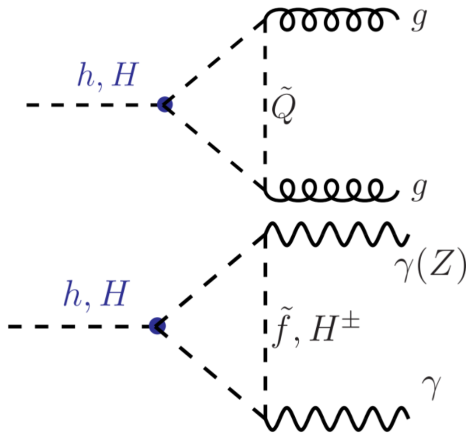
~ 3 GeV uncertainties (higher loops, m_t,…)

- gauge and Yukawa couplings

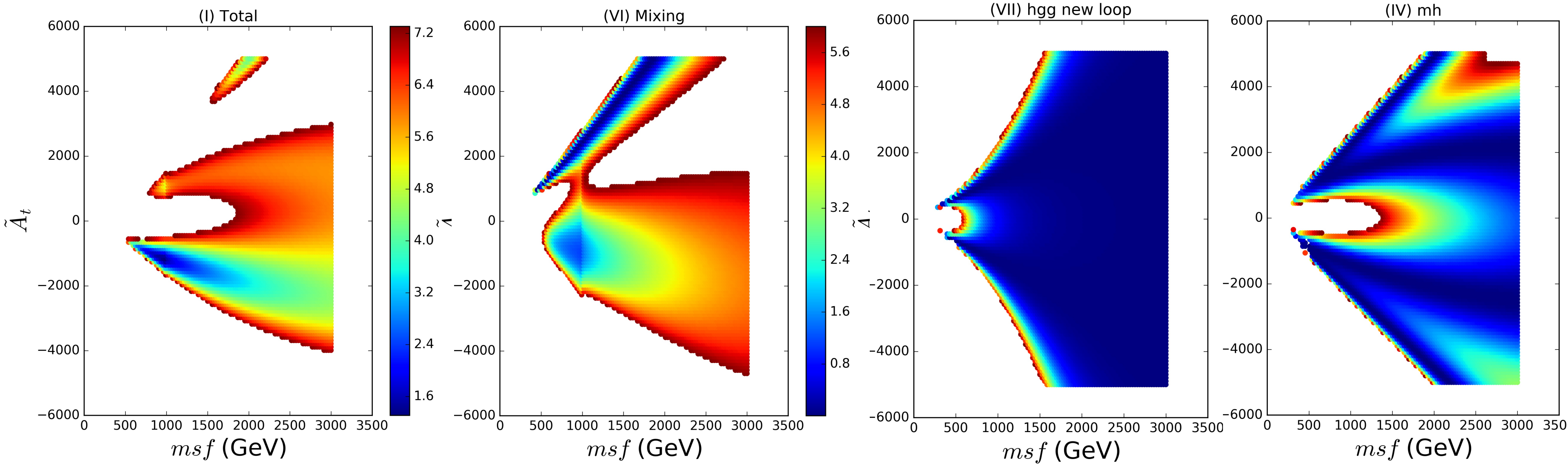
$$\begin{pmatrix} H \\ h \end{pmatrix} = \begin{pmatrix} \cos\alpha_{eff} & \sin\alpha_{eff} \\ -\sin\alpha_{eff} & \cos\alpha_{eff} \end{pmatrix} \begin{pmatrix} H^d \\ H^u \end{pmatrix}$$

MSSM parameters:
m_A, $\tan\beta$, M_S, X_t,
μ=500 GeV, other irrelevant

- hgg and hγγ



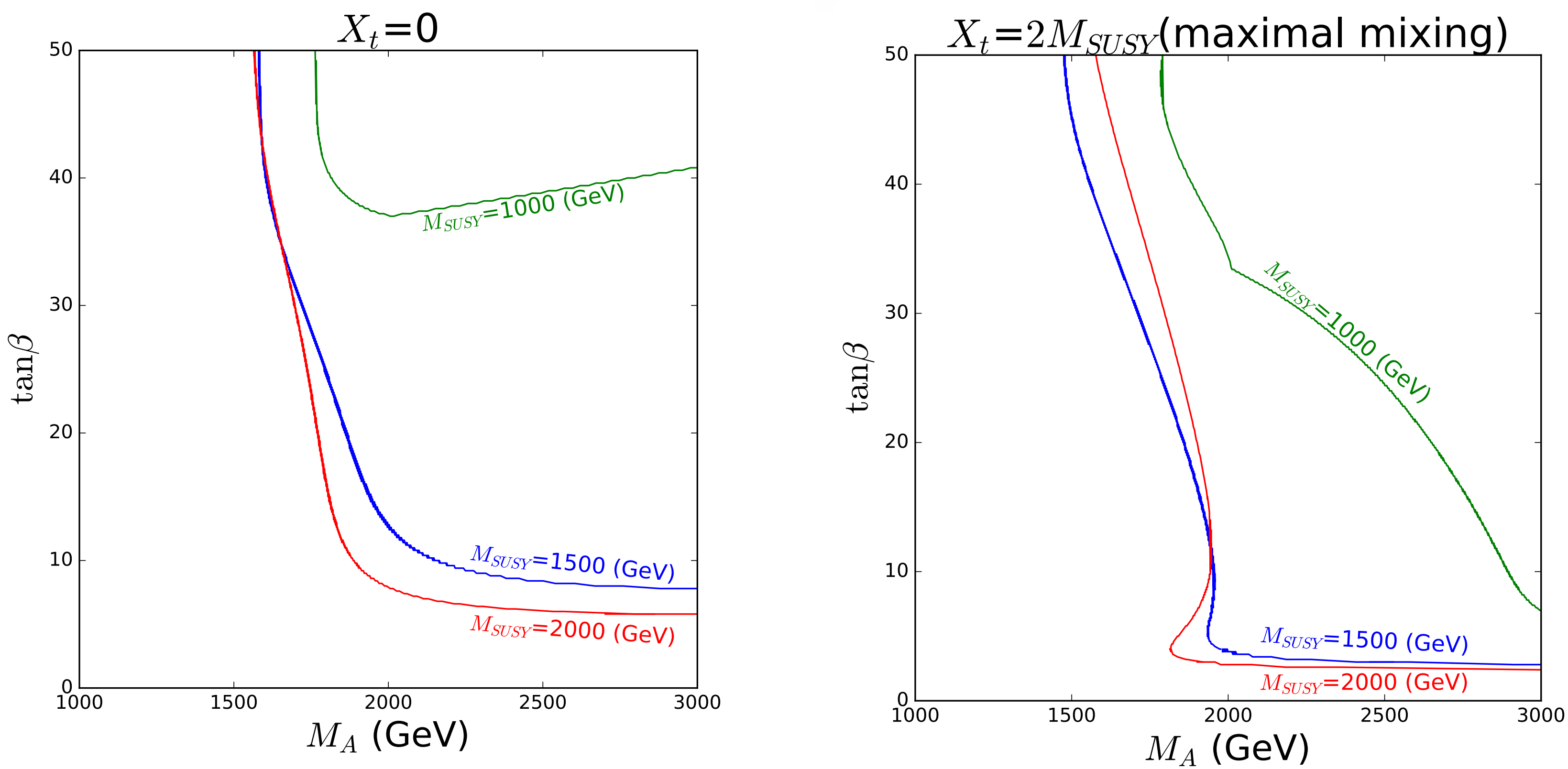
m_A vs. X_t



tanβ=30, μ=500 GeV, m_A=2000 GeV

H. Li, SS, W. Su, J. Yang, work in progress

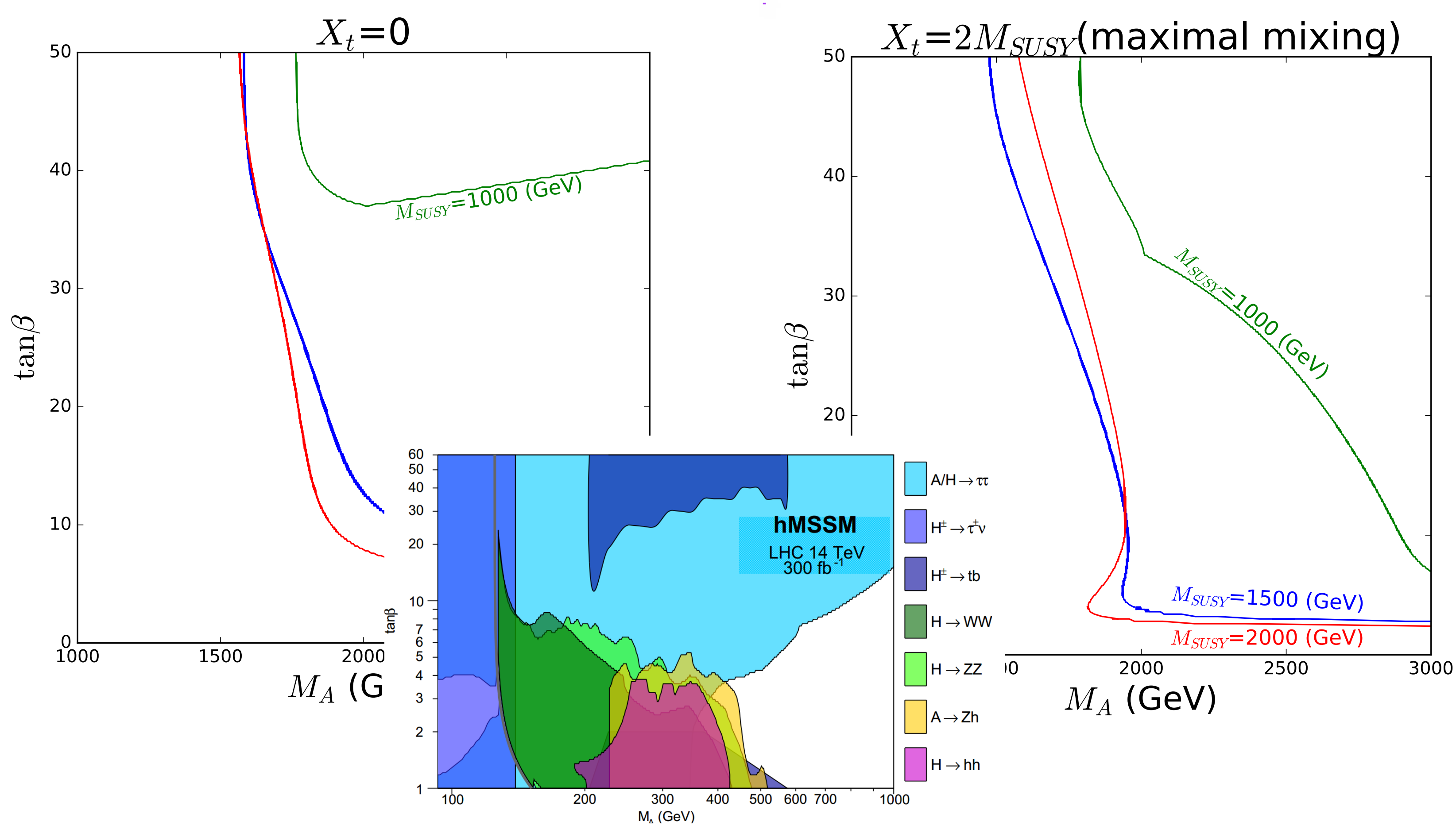
m_A vs. tanβ



S. Su

H. Li, SS, W. Su, J. Yang, work in progress

m_A vs. $\tan\beta$



Complementary to LHC direct search

S. Su

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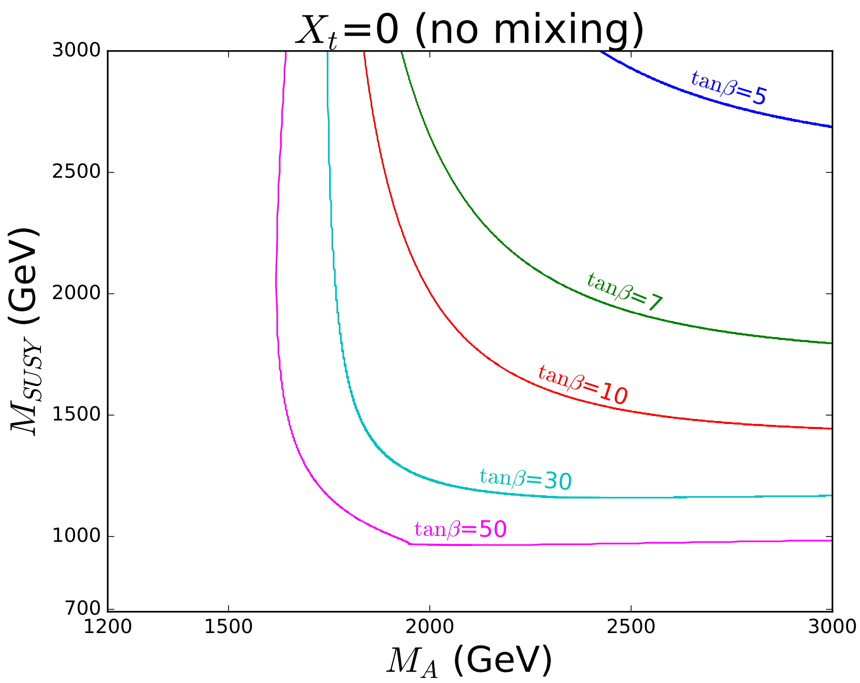
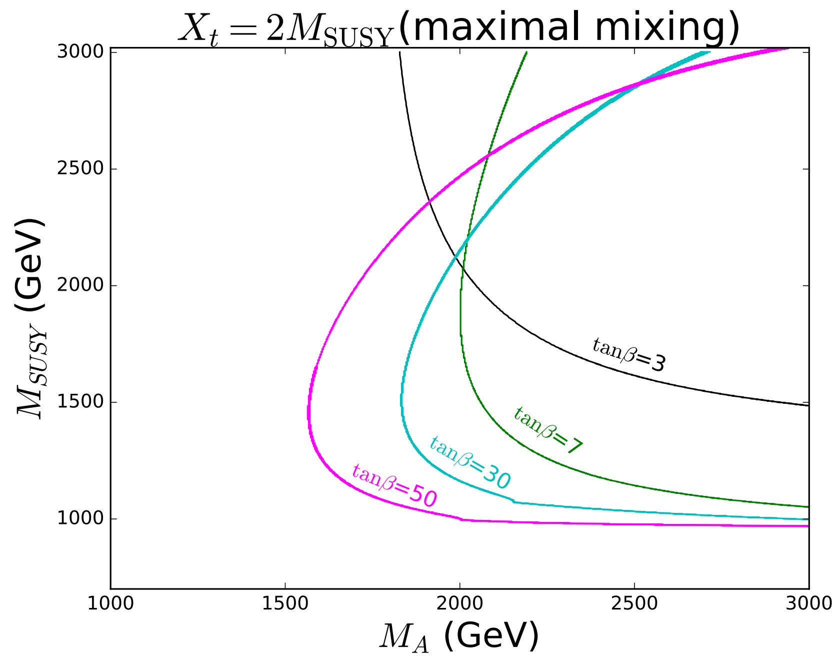
m_A vs. M_S





H. Li, SS, W. Su, J. Yang, work in progress

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

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

  - hff: depends on the fermion representation

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

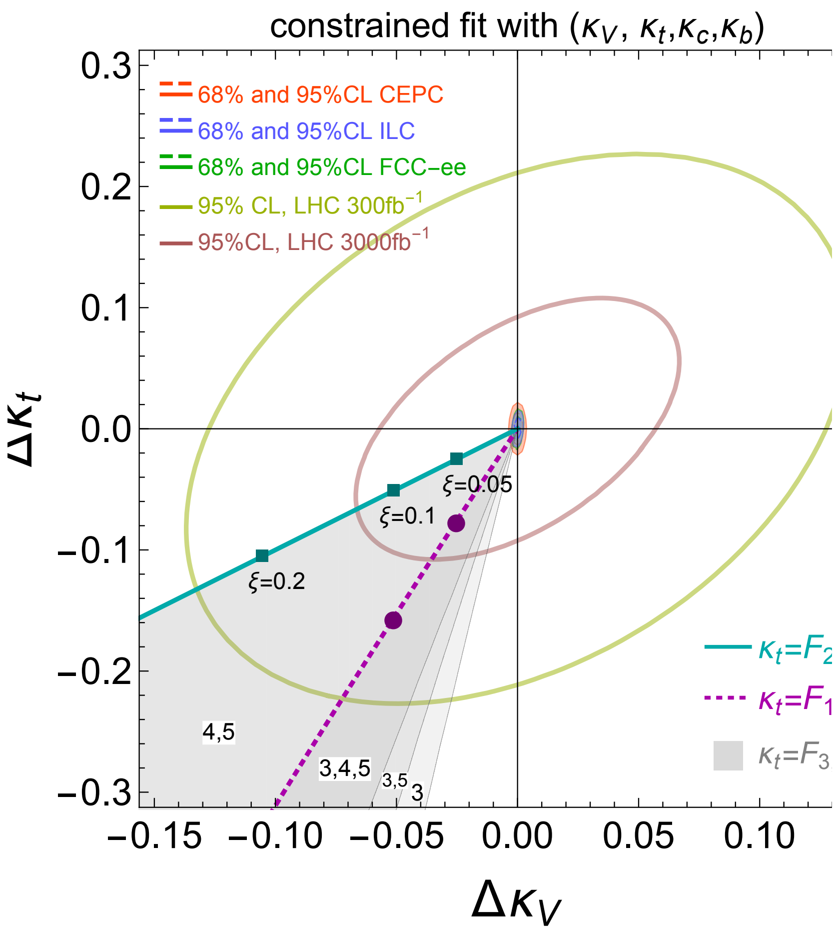
MCHM

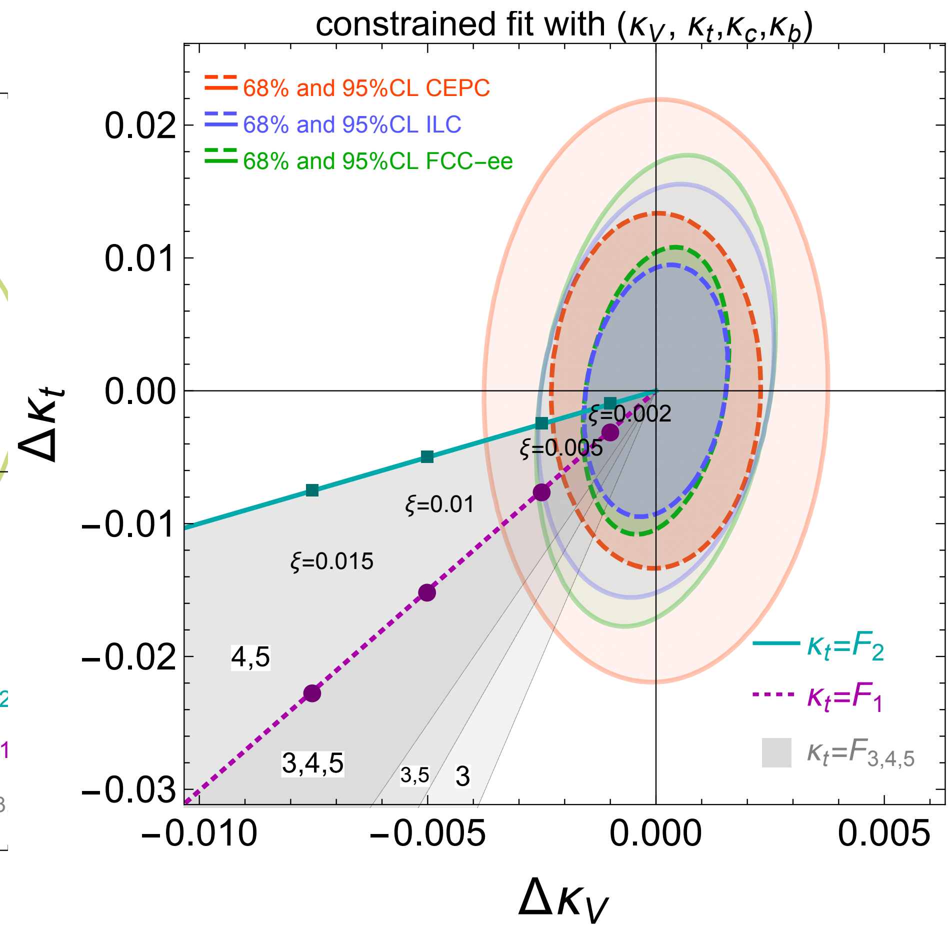
- **Fermion representation**

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
κ_t, κ_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

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

Strong Dynamics in EFT Language

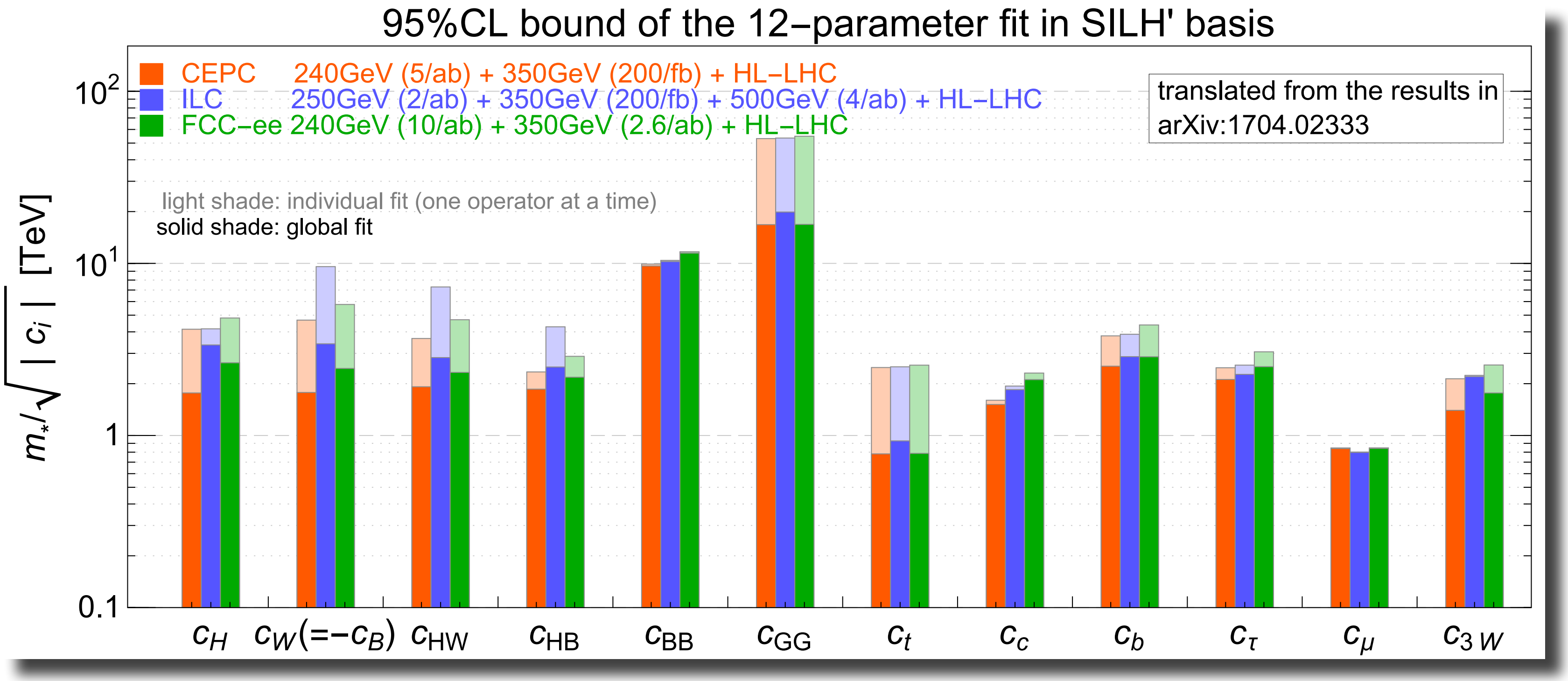
- **EFT operators**

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

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

	$\mathcal{O}_H$	$\mathcal{O}_W$	$\mathcal{O}_B$	$\mathcal{O}_{HW}$	$\mathcal{O}_{HB}$	$\mathcal{O}_{BB}$	$\mathcal{O}_{GG}$	$\mathcal{O}_{y_u}$	$\mathcal{O}_{y_d}$	$\mathcal{O}_{y_e}$	$\mathcal{O}_{3W}$
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	$\frac{g^2}{16\pi^2}$

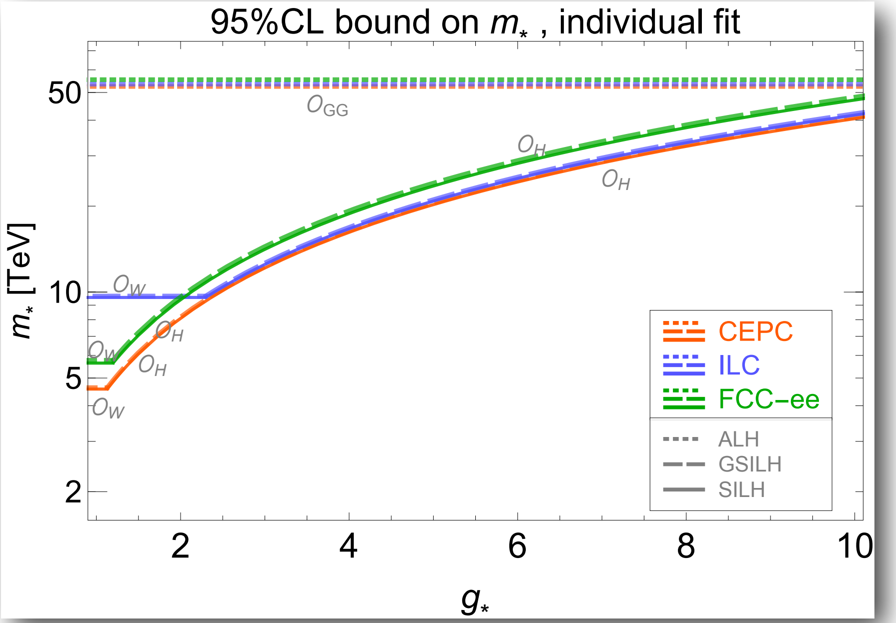
Strong Dynamics in EFT Language

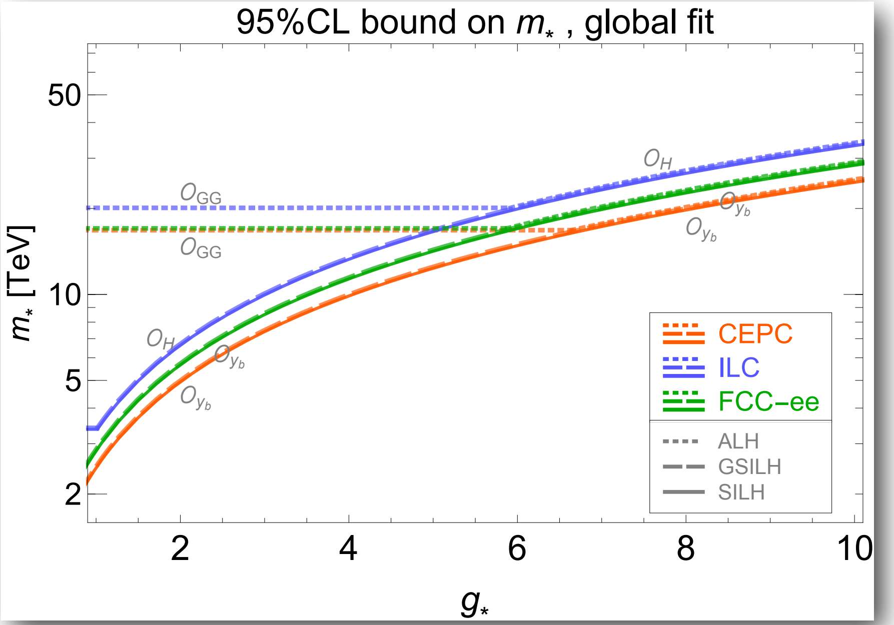


Strong Dynamics in EFT Language

individual fit

global fit

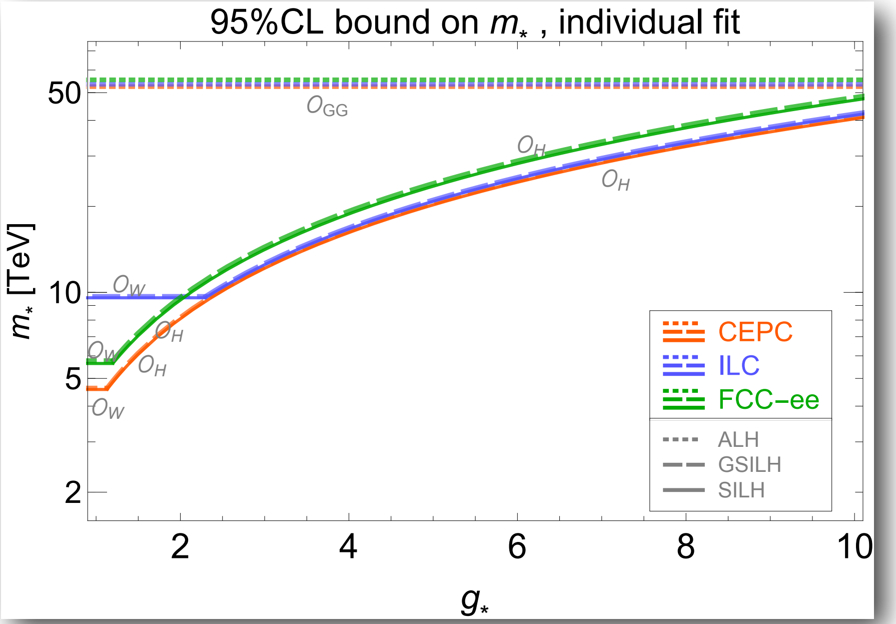




Conclusion

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

individual fit



global fit