Multi-Boson Interaction, 25 Aug 2022, Shanghai

BSM searches with Higgs precision measurements

苏伟

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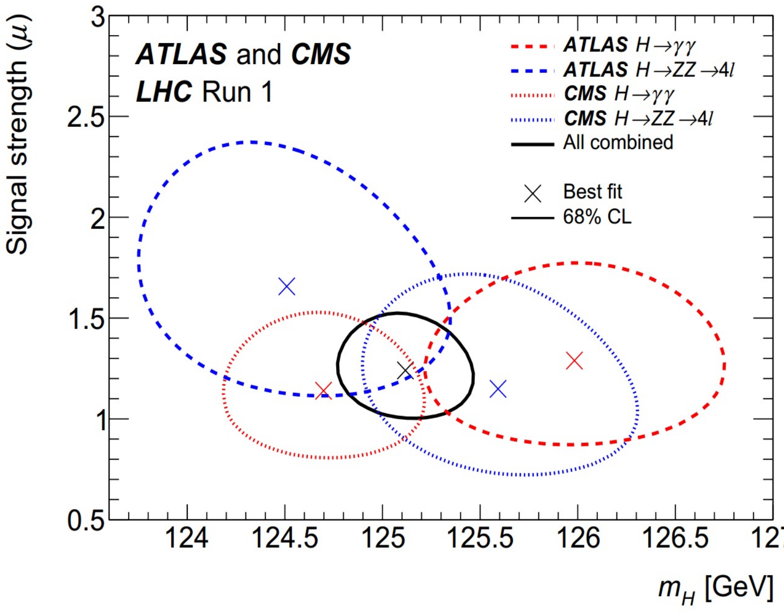
2008.05492 (T. Han, S. Li, S. Su, WS, Y. Wu)

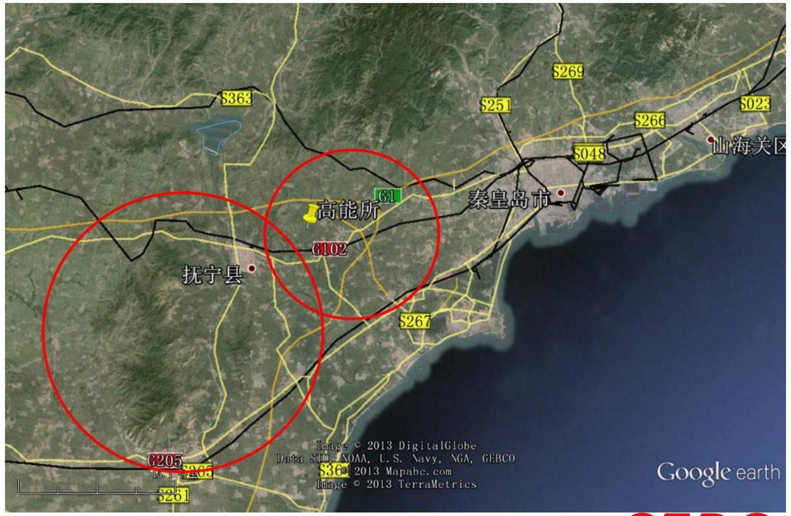
Outline

- Higgs Precision Measurements
- Study Strategy : exclusion, discovery, …
- 2HDM Introduction
- Study Results

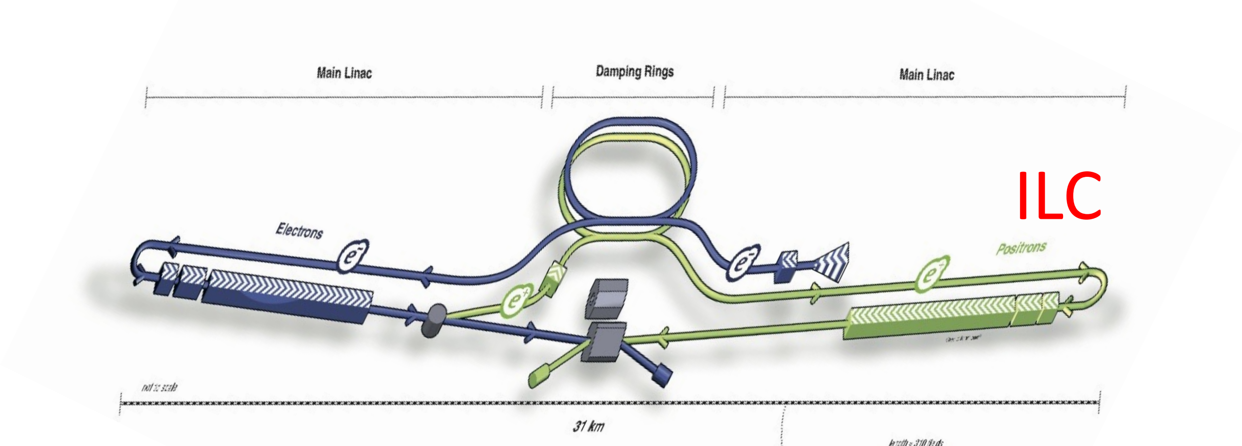
Higgs Precision Measurements



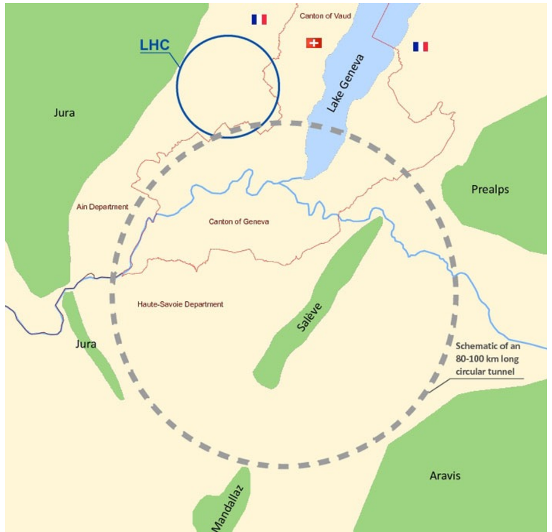
CMS-HIG-14-042
ATLAS-HIGG-2014-14



CEPC



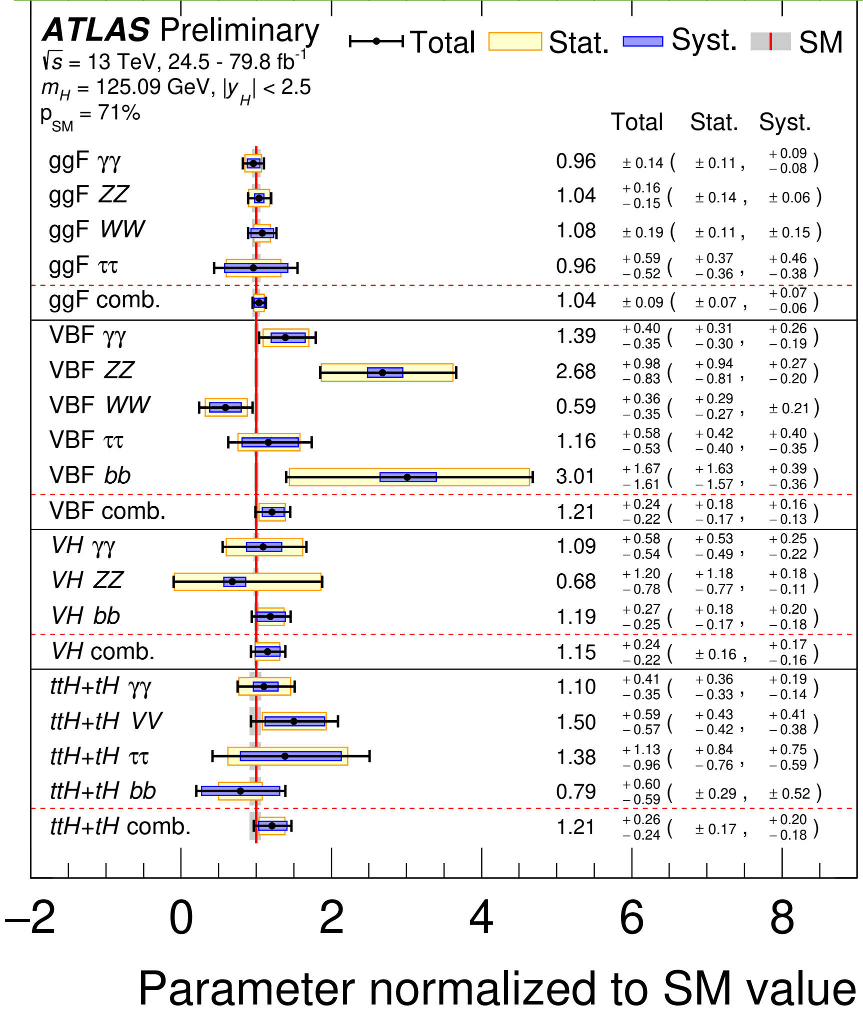
ILC



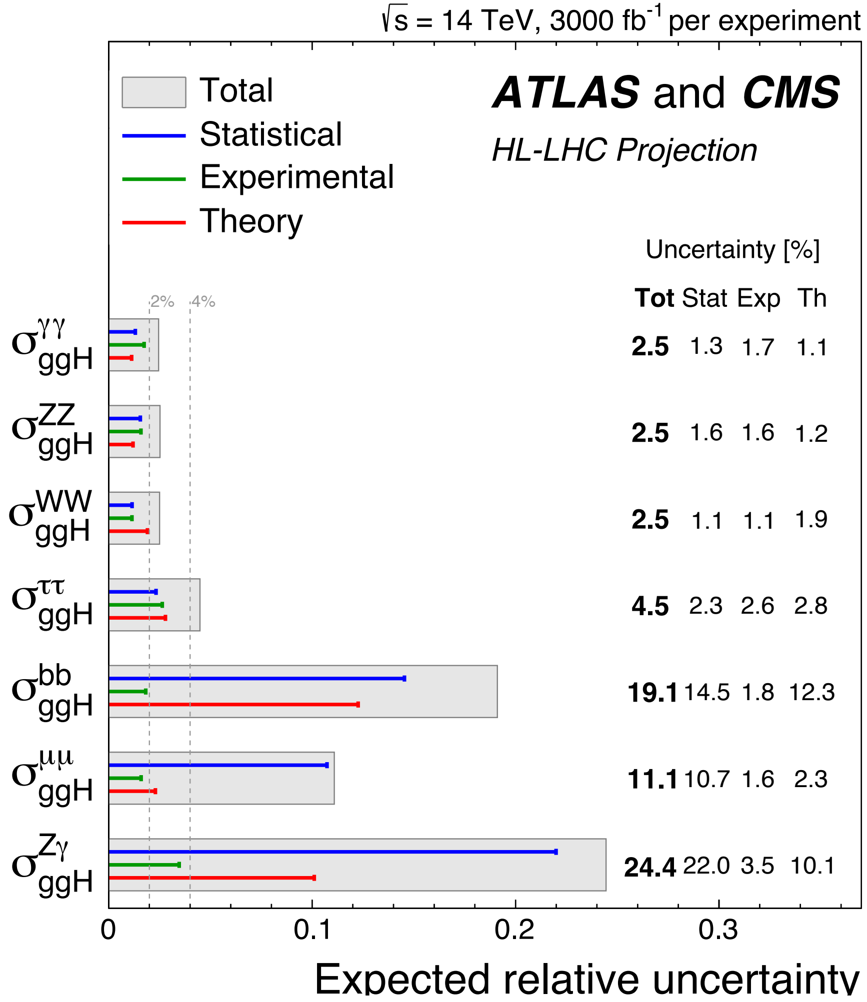
LHC
HL-LHC
FCC

Precision: Higgs couplings

LHC Run-II: ATLAS-CONF-2019-005



HL-LHC: 1902.00134



Precision: Higgs couplings

CEPC-CDR , FCC-ee, ILC Operating Scenarios

collider	CEPC	FCC-ee			ILC				
$\sqrt{s}$ $\int \mathcal{L}dt$	240 GeV 5.6 ab^{-1}	240 GeV 5 ab^{-1}	365 GeV 1.5 ab^{-1}		250 GeV 2 ab^{-1}	350 GeV 200 fb^{-1}		500 GeV 4 ab^{-1}	
production	Zh	Zh	Zh	$\nu\bar{\nu}h$	Zh	Zh	$\nu\bar{\nu}h$	Zh	$\nu\bar{\nu}h$
$\Delta\sigma/\sigma$	0.5%	0.5%	0.9%	–	0.71%	2.0%	–	1.05	–
decay	$\Delta(\sigma \cdot BR)/(\sigma \cdot BR)$								
$h \to b\bar{b}$	0.27%	0.3%	0.5%	0.9%	0.46%	1.7%	2.0%	0.63%	0.23%
$h \to c\bar{c}$	3.3%	2.2%	6.5%	10%	2.9%	12.3%	21.2%	4.5%	2.2%
$h \to gg$	1.3%	1.9%	3.5%	4.5%	2.5%	9.4%	8.6%	3.8%	1.5%
$h \to WW^*$	1.0%	1.2%	2.6%	3.0%	1.6%	6.3%	6.4%	1.9%	0.85%
$h \to \tau^+\tau^-$	0.8%	0.9%	1.8%	8.0%	1.1%	4.5%	17.9%	1.5%	2.5%
$h \to ZZ^*$	5.1%	4.4%	12%	10%	6.4%	28.0%	22.4%	8.8%	3.0%
$h \to \gamma\gamma$	6.8%	9.0%	18%	22%	12.0%	43.6%	50.3%	12.0%	6.8%
$h \to \mu^+\mu^-$	17%	19%	40%	–	25.5%	97.3%	178.9%	30.0%	25.0%
$(\nu\bar{\nu})h \to b\bar{b}$	2.8%	3.1%	–	–	3.7%	–	–	–	–

Study strategies

Experimental Observables: $\Delta\mu_i$

$$\mu_i^{BSM} = \frac{(\sigma\times\mathrm{Br})_{BSM}}{(\sigma\times\mathrm{Br})_{SM}}$$

Fitting

Maximal likelihood: $\Delta\chi^2$

$d.o.f. = model\ \ parameter$

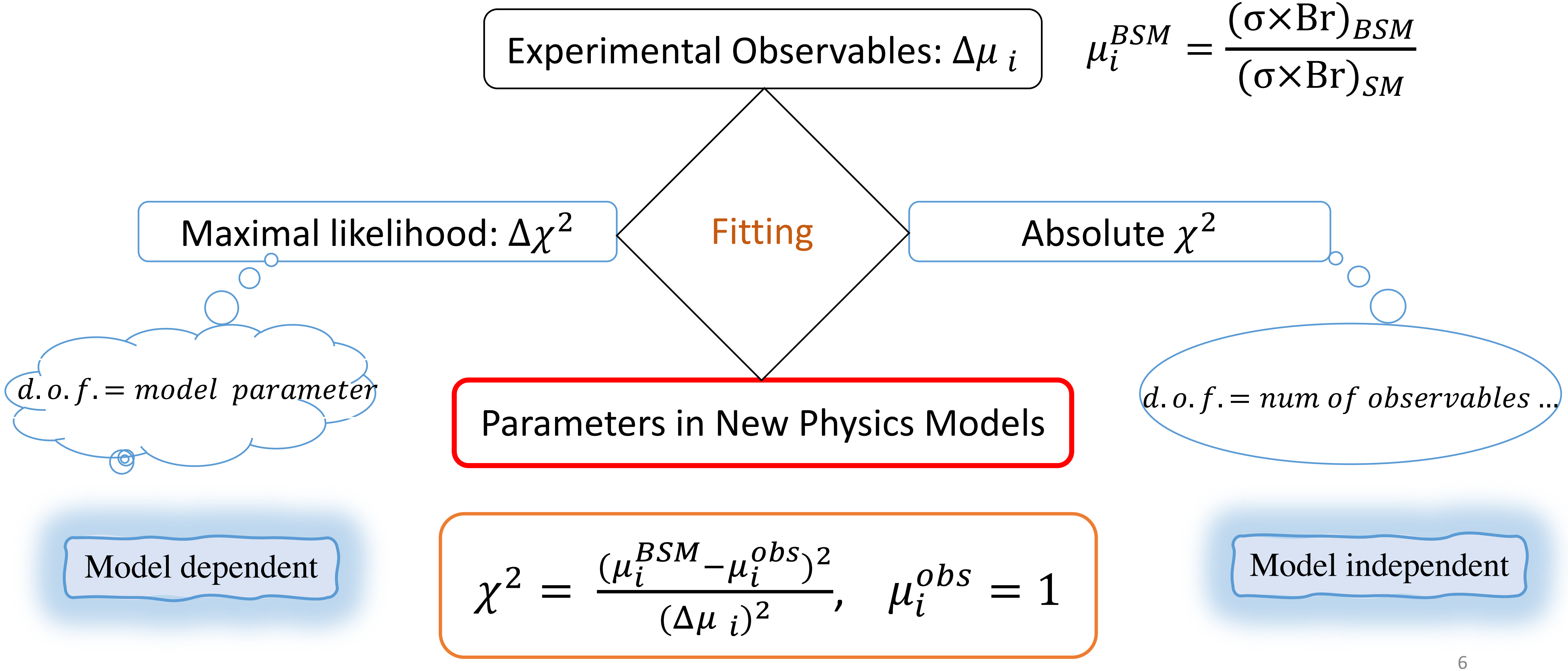
Absolute χ^2

$d.o.f. = num\ of\ observables\ ...$

Parameters in New Physics Models

$$\chi^2 = \frac{(\mu_i^{BSM} - \mu_i^{obs})^2}{(\Delta\mu_i)^2}, \quad \mu_i^{obs} = 1$$

Study strategies



Study strategies

Experimental Observables: $\Delta\mu_{\ i}$

$$\mu_i^{BSM} = \frac{(\sigma\times \mathrm{Br})_{BSM}}{(\sigma\times \mathrm{Br})_{SM}}$$

Maximal likelihood: $\Delta\chi^2$

Fitting

$d.o.f. = model\ \ parameter$

Ph

Model dependent

$$\chi^2 = \frac{(\mu_i^{BSM} - \mu_i^{obs})^2}{(\Delta\mu_{\ i})^2},$$

Model dependent :

Popularly used for various exclusion recast

Study strategies

Experimental Observables: $\Delta\mu_i$

$$\mu_i^{BSM} = \frac{(\sigma\times Br)_{BSM}}{(\sigma\times Br)_{SM}}$$

Fitting

Absolute χ^2

$d.o.f. = num\ of\ observables\ ...$

Model independent

- Exclusion
- Claim discovery ?
- Model discrimination ?
- Compatibility test ?

$-\mu_i^{obs})^2$ / $(\Delta\mu_i)^2$, $\mu_i^{obs} = 1$

Model independent

2HDM: Brief Introduction

- Two Higgs Doublet Model

$$
\begin{aligned}
V(\Phi_1,\Phi_2) = \; & m_{11}^2\Phi_1^\dagger\Phi_1 + m_{22}^2\Phi_2^\dagger\Phi_2 - m_{12}^2(\Phi_1^\dagger\Phi_2 + h.c.) + \frac{\lambda_1}{2}(\Phi_1^\dagger\Phi_1)^2 + \frac{\lambda_2}{2}(\Phi_2^\dagger\Phi_2)^2 \\
& + \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) + \frac{1}{2}\left[\lambda_5(\Phi_1^\dagger\Phi_2)^2 + h.c.\right] \\
& + \frac{1}{2}(\Phi_1^\dagger\Phi_2 + h.c.)(\lambda_6\Phi_1^\dagger\Phi_1 + \lambda_7\Phi_1^\dagger\Phi_1)
\end{aligned}
$$

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

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

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

2HDM: Brief Introduction

- Two Higgs Doublet Model

$$V(\Phi_1,\Phi_2) = m_{11}^2\Phi_1^\dagger\Phi_1 + m_{22}^2\Phi_2^\dagger\Phi_2 - m_{12}^2(\Phi_1^\dagger\Phi_2 + h.c.) + \frac{\lambda_1}{2}(\Phi_1^\dagger\Phi_1)^2 + \frac{\lambda_2}{2}(\Phi_2^\dagger\Phi_2)^2$$
$$+\lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) + \frac{1}{2}\left[\lambda_5(\Phi_1^\dagger\Phi_2)^2 + h.c.\right]$$
$$+\frac{1}{2}(\Phi_1^\dagger\Phi_2 + h.c.)(\lambda_6\Phi_1^\dagger\Phi_1 + \lambda_7\Phi_1^\dagger\Phi_1)$$

Soft breaking of Z2

Hard breaking of Z2

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

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

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

2HDM: Brief Introduction

	Φ_1	Φ_2
Type I	u,d,l	
Type II	u	d,l
lepton-specific	u,d	l
flipped	u,l	d

$$\kappa_i = g_{hii}^{BSM} / g_{hii}^{SM}$$

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)

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

Soft Z_2 symmetry breaking: m_{12}^2

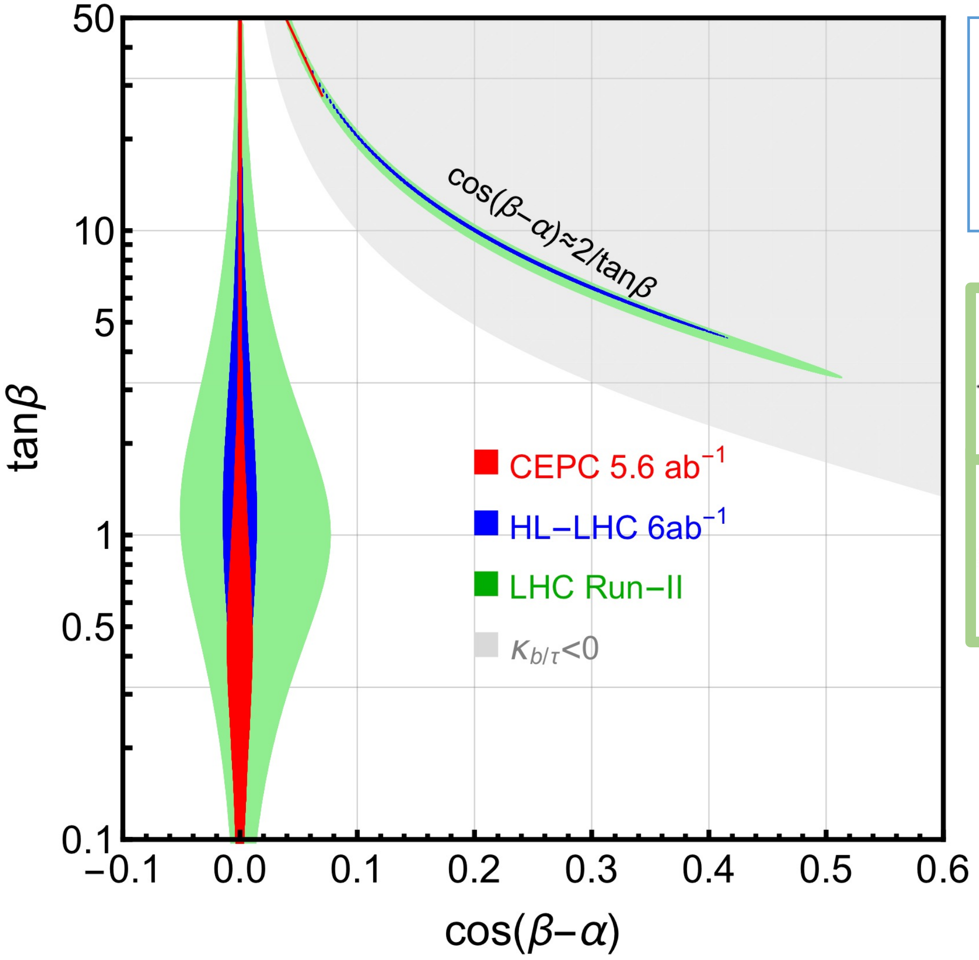
v: 246 GeV

m_h: 125. GeV

Exclusion: Tree Level

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 Type-II



Alignment limit :

$\cos(\beta-\alpha)=0$

$g(2HDM)=g(SM)$

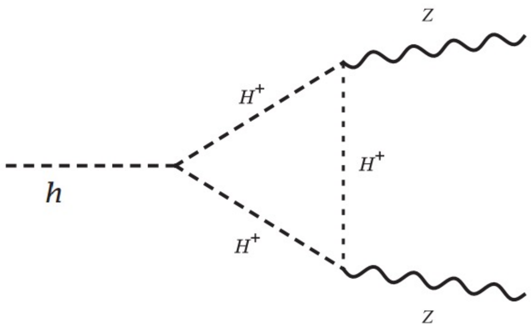
1910.06269

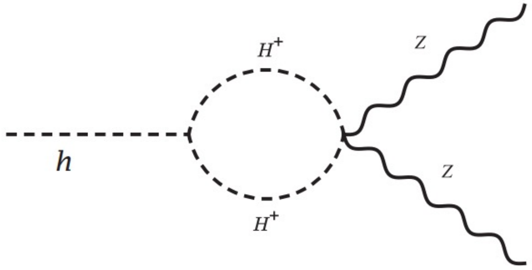
WS

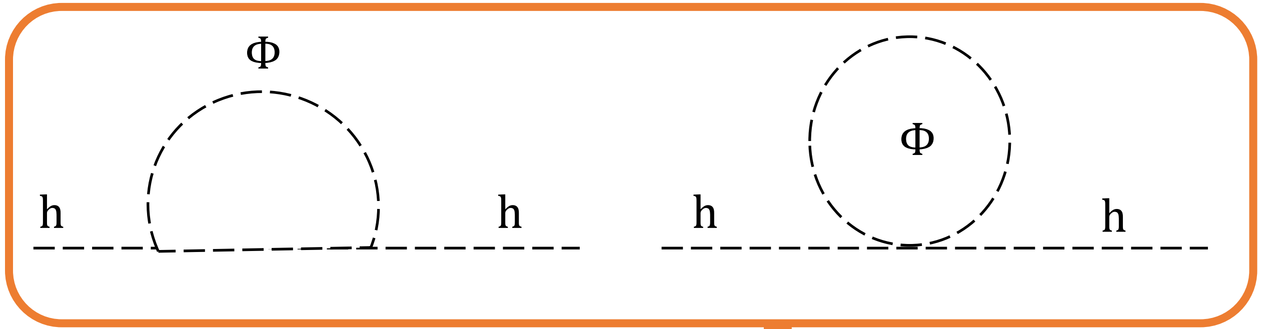
$$-\frac{\sin\beta}{\cos\alpha}-1=-\frac{1}{2}\cos^2(\beta-\alpha)-\cos(\beta-\alpha)\times\tan\beta$$

$$\frac{\cos\alpha}{\sin\beta}-1=-\frac{1}{2}\cos^2(\beta-\alpha)+\frac{\cos(\beta-\alpha)}{\tan\beta}$$

2HDM: One-Loop Level



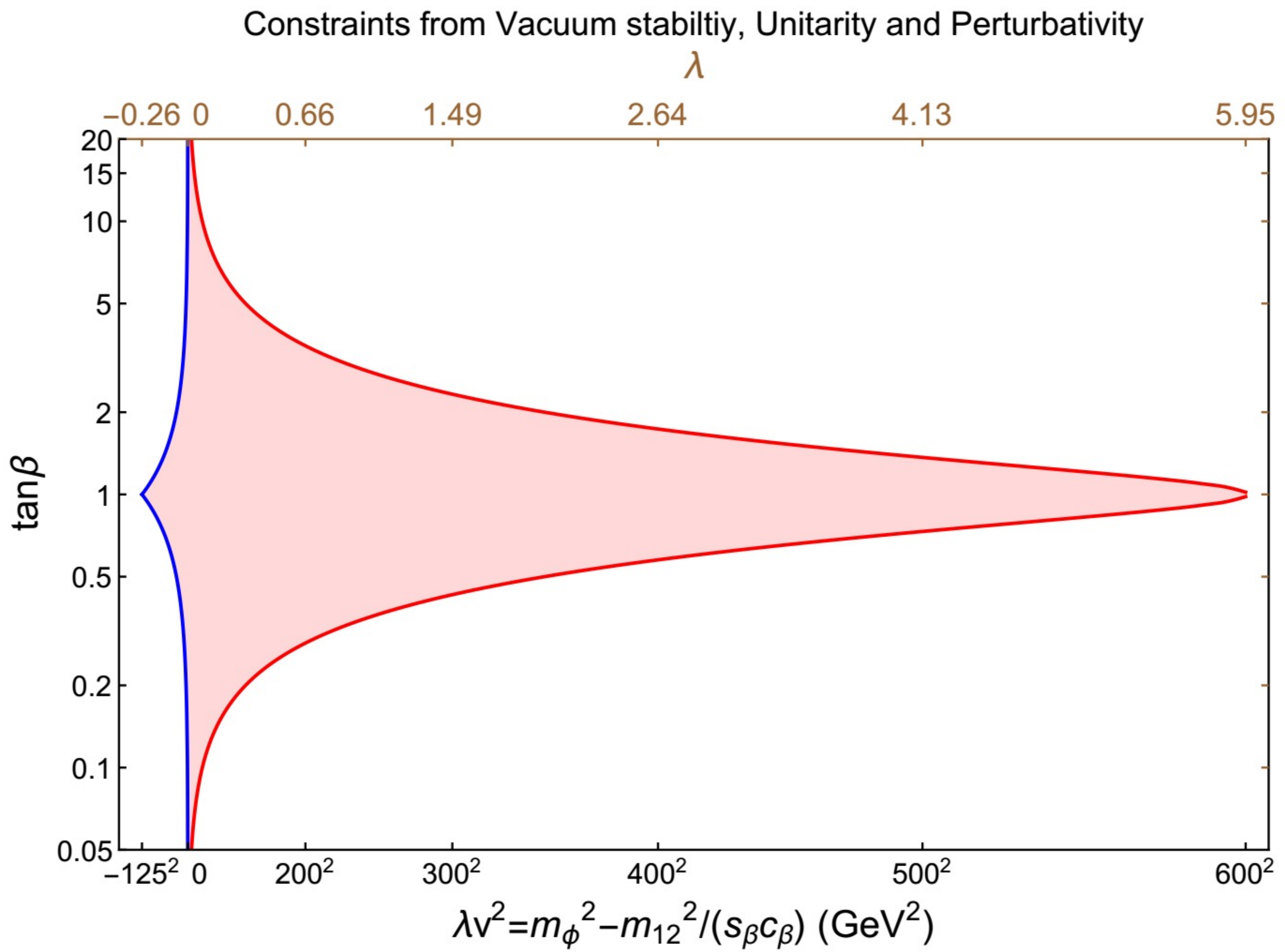




Main contribution → Various Triple Higgs couplings

Parameter : $\mathbf{\cos\,(\beta-\alpha),\tan\beta,\ m_H, m_A, m_{H^\pm}, m_{12}^2}$

2HDM: *Loop + degenerate*



$\cos(\beta - \alpha) = 0,$
$m_\Phi \equiv m_H = m_A = m_{H^\pm}$

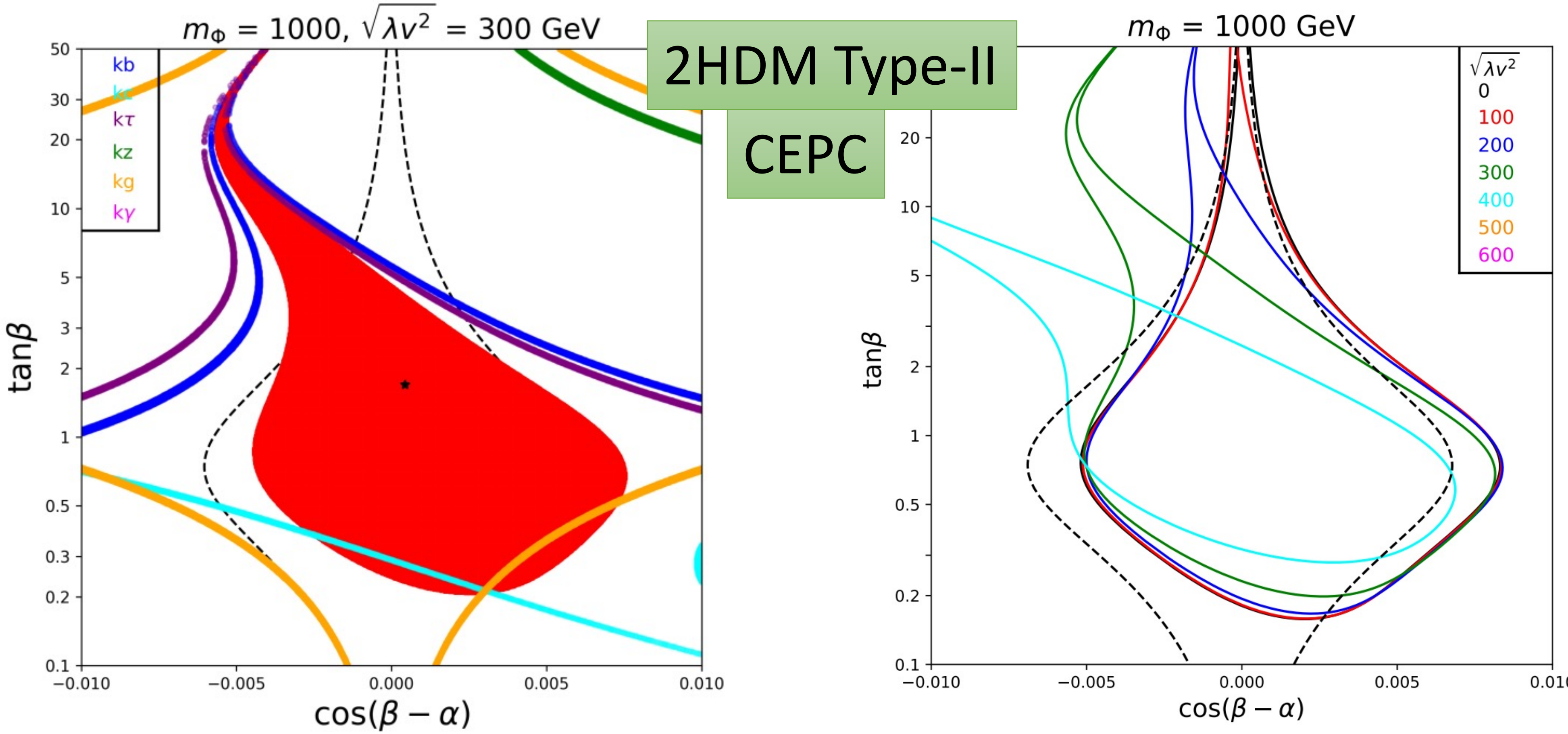
Theoretical constraints

$\lambda v^2 \equiv m_\Phi^2 - m_{12}^2/s_\beta c_\beta$

$-125^2\mathrm{GeV}^2 < \lambda v^2 < 600^2\mathrm{GeV}^2$

$\lambda \in (-0.26, 5.95)$
$\lambda_4 = \lambda_5 = \lambda_3 - 0.258 = -\lambda$

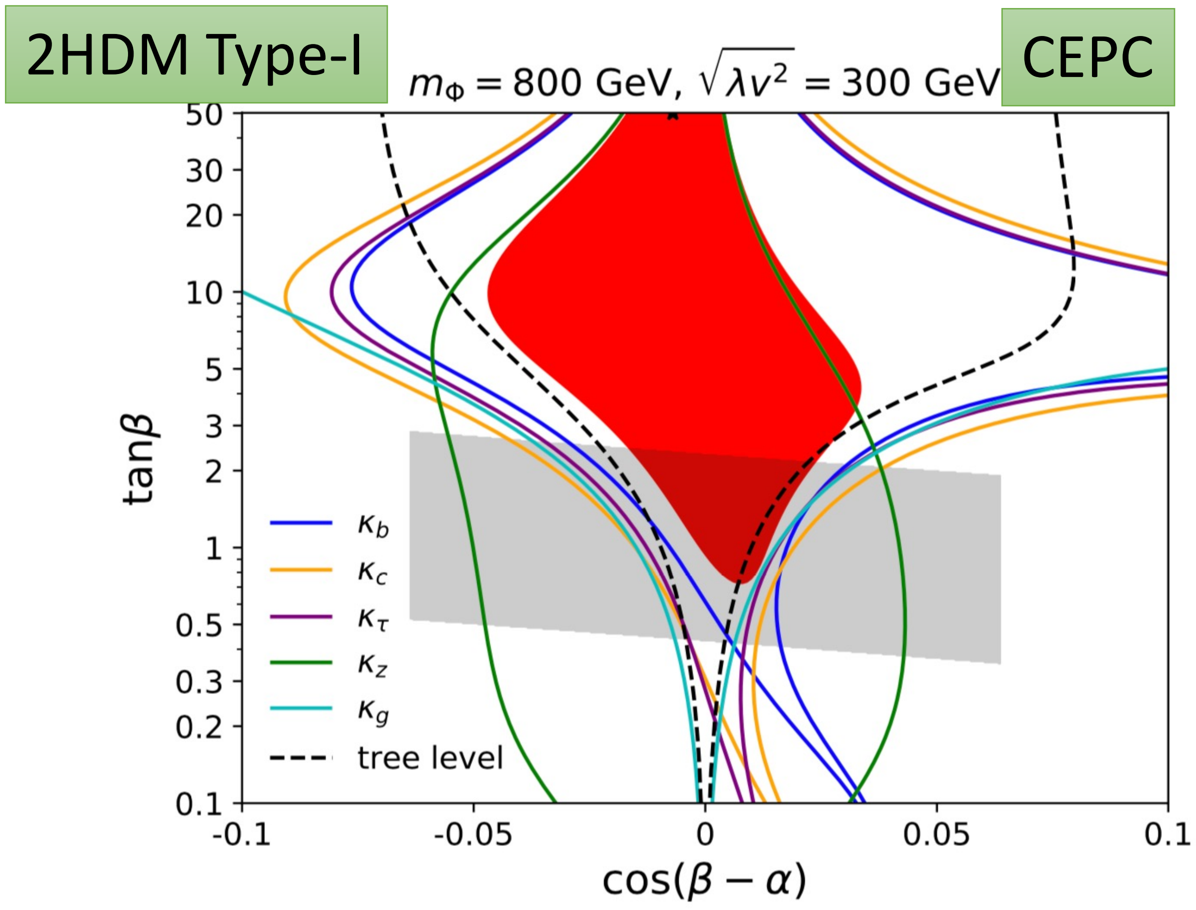
Exclusion : Loop Level

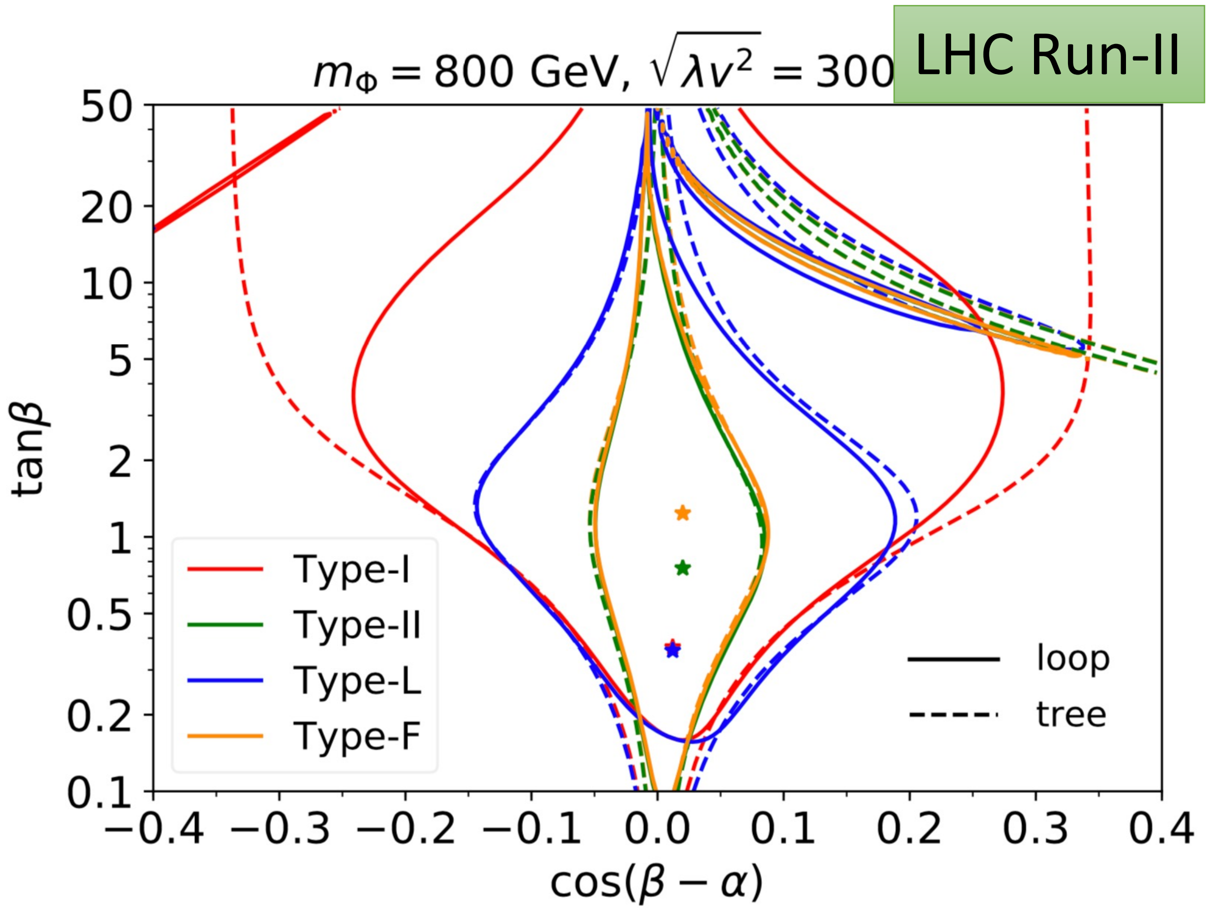


2HDM Type-II

CEPC

Exclusion : Loop Level





Study Results: discovery potential

- method

$$\chi^2 = \sum_i \frac{(\mu_i^{\text{hyp}} - \mu_i^{\text{obs}})^2}{\sigma_{\mu_i}^2}$$

null hypothesis H0 : SM

To claim the discovery of BSM at
5σ significance : p=5.7*10^(-7)

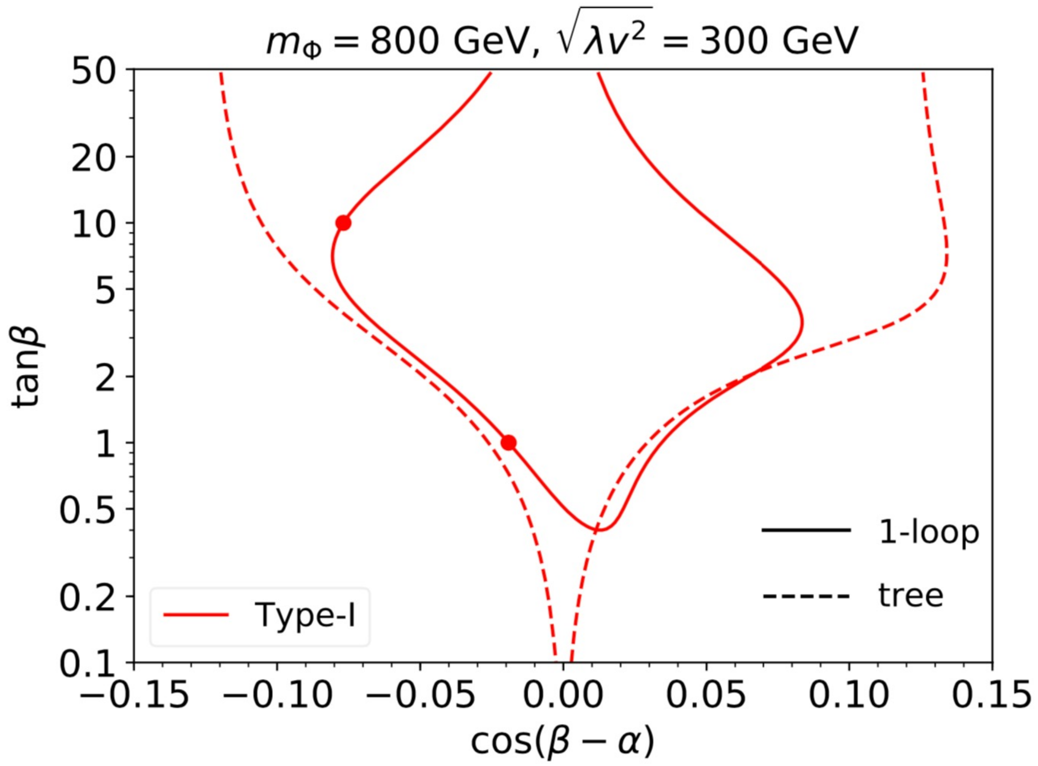
$$\chi^{\text{SM}} > 48.2$$

$$\mu^{\text{hyp}} = \mu^{\text{SM}} = 1$$

degrees of freedom : signal strength modifiers (SSM),
or μ parameter : 10 for CEPC

Study Results: discovery potential

Choose one point of BSM as the observed, to see if SM is rejected.

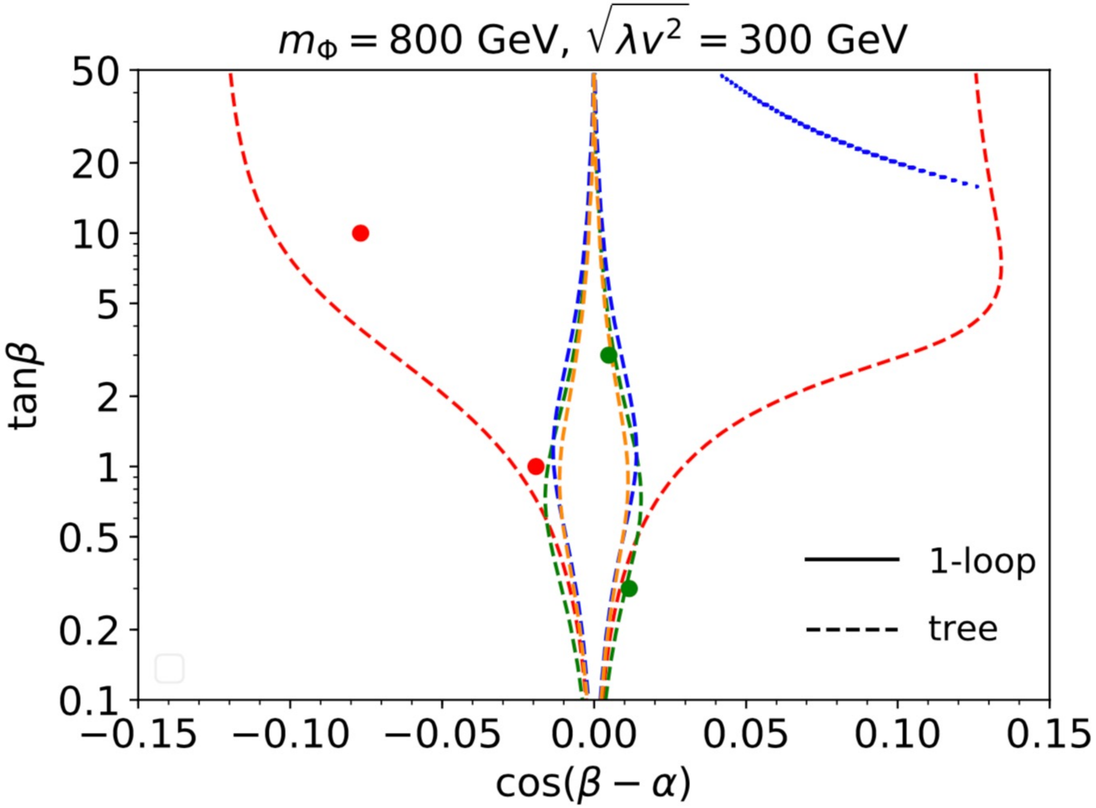


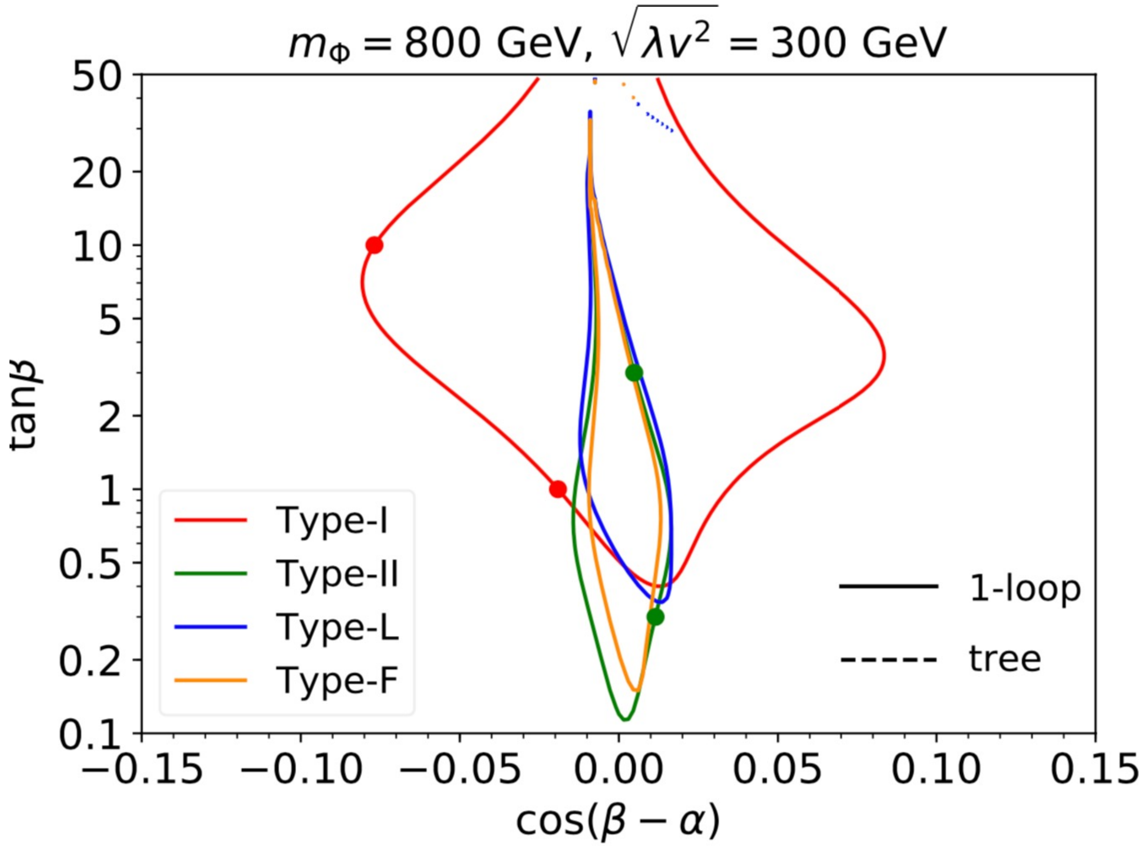
If the future observable is same to Type-I,
The center region can not claim a discovery
The two sides region can claim

$$\cos(\beta-\alpha) \lesssim -0.1$$

$$\cos(\beta-\alpha) \gtrsim 0.08$$

Study Results: discovery potential





Type-II, L, F: $|\cos(\beta-\alpha)| \gtrsim 0.02 \text{ for } \tan\beta \sim 1$

Study Results: discrimination ability

- method

performing the χ^2 statistic

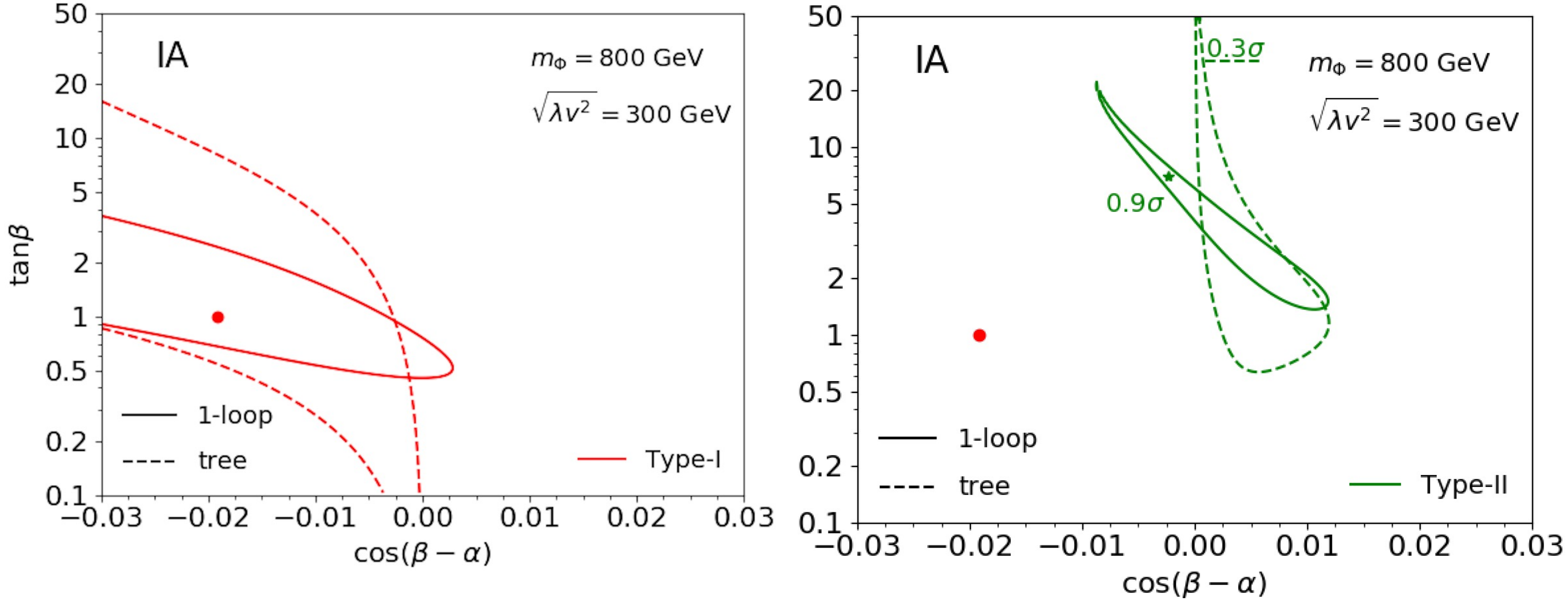
d.o.f. = # SSMs (μ) hypothesized model (Null model): One physical point

d.o.f.	1	2	3	4	5	6	7	8	9	10
$\chi^2(p = 0.05)$	3.84	5.99	7.81	9.49	11.1	12.6	14.1	15.5	16.9	18.3

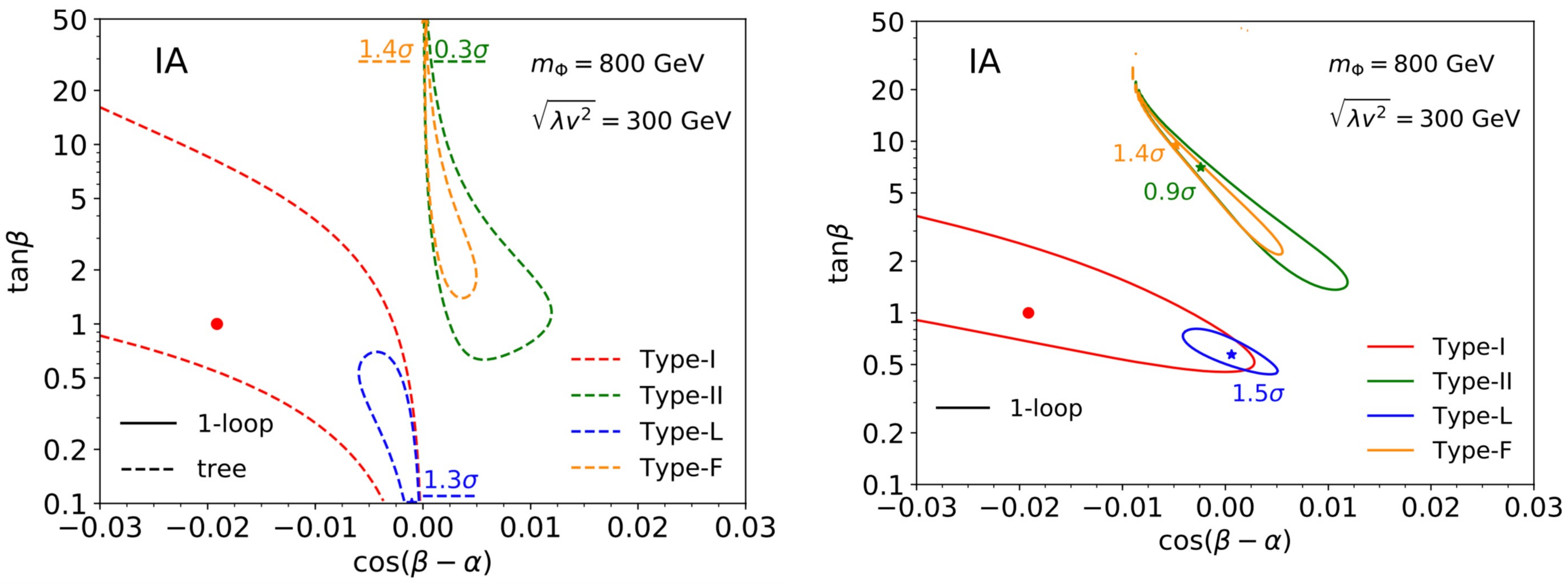
BMs:

$(\cos(\beta - \alpha), \tan\beta)$	Small $\tan\beta$	Large $\tan\beta$
Type-I	**IA:** $(-0.019, 1.0)$	**IB:** $(-0.077, 10)$
Type-II	**IIA:** $(0.012, 0.3)$	**IIB:** $(0.005, 3.0)$

Study Results: discrimination ability



Study Results: discrimination ability



Study Results: compatibility test

- compatibility test method

Test Type-I with Type-II:

observable : one point of type-II (accepted model),

test type-I by performing the χ^2 statistic

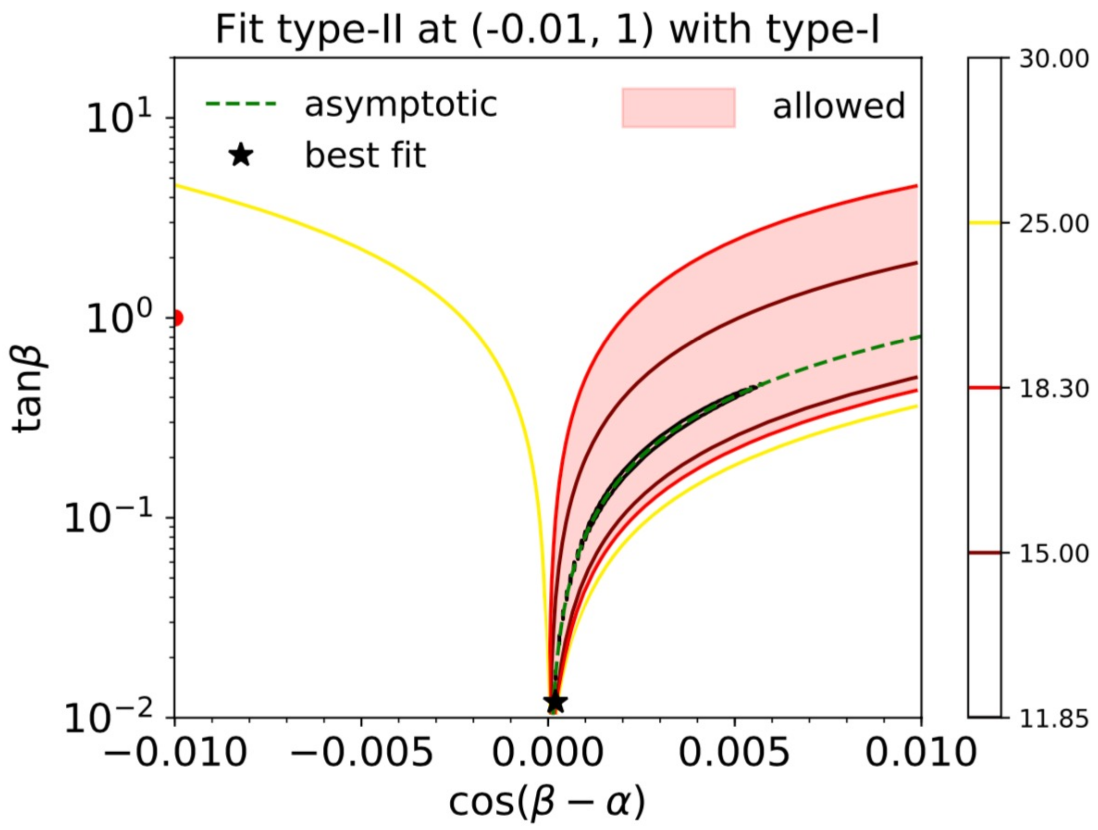
d.o.f. = # SSMs (μ)

hypothesized model (Null model): Type-II, instead of SM

d.o.f.	1	2	3	4	5	6	7	8	9	10
$\chi^2(p=0.05)$	3.84	5.99	7.81	9.49	11.1	12.6	14.1	15.5	16.9	18.3

Study Results: compatibility test

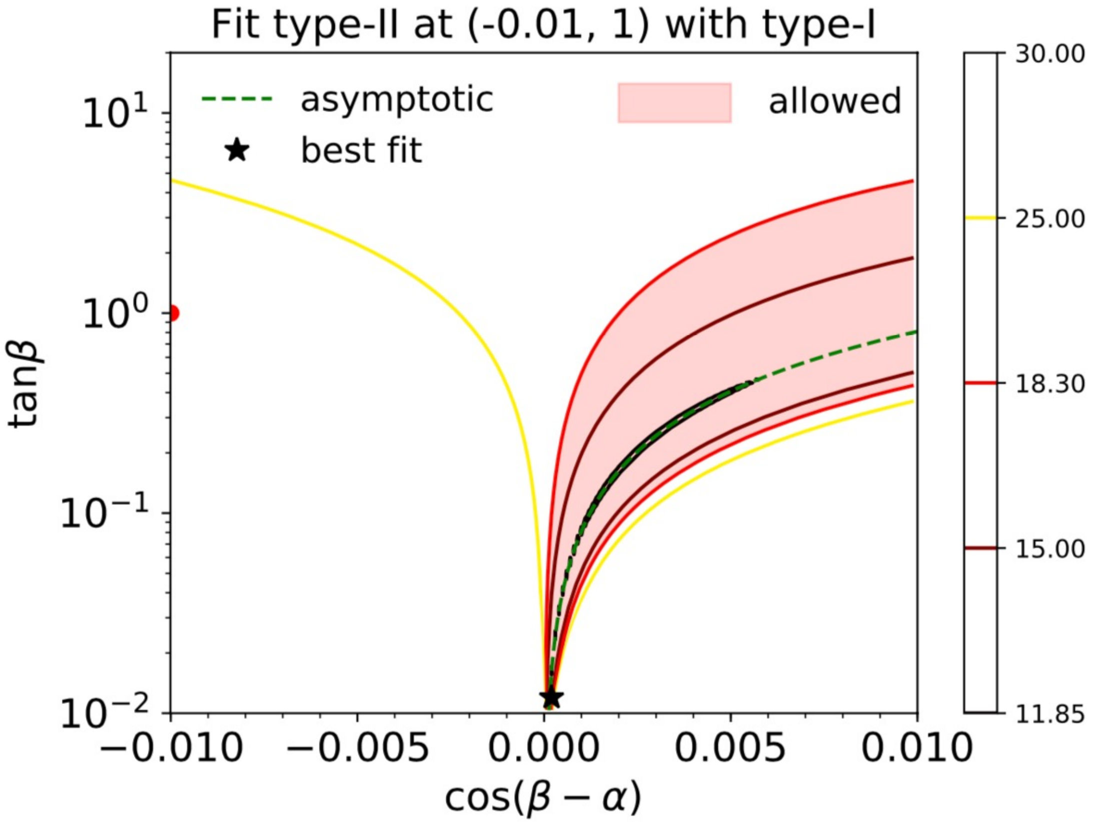
- Type-II $(\cos(\beta-\alpha), \tan\beta) = (-0.01, 1)$

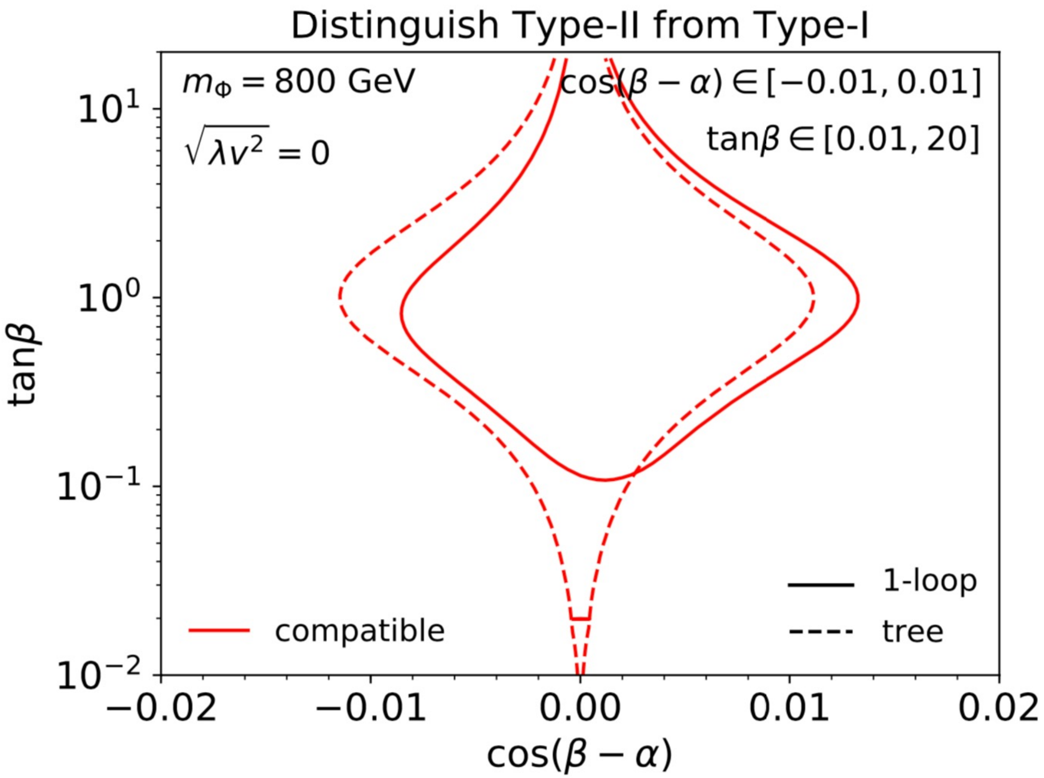


If there is points of Type-I is allowed, then BM of Type-II is compatible under CEPC precision

Study Results: compatibility test

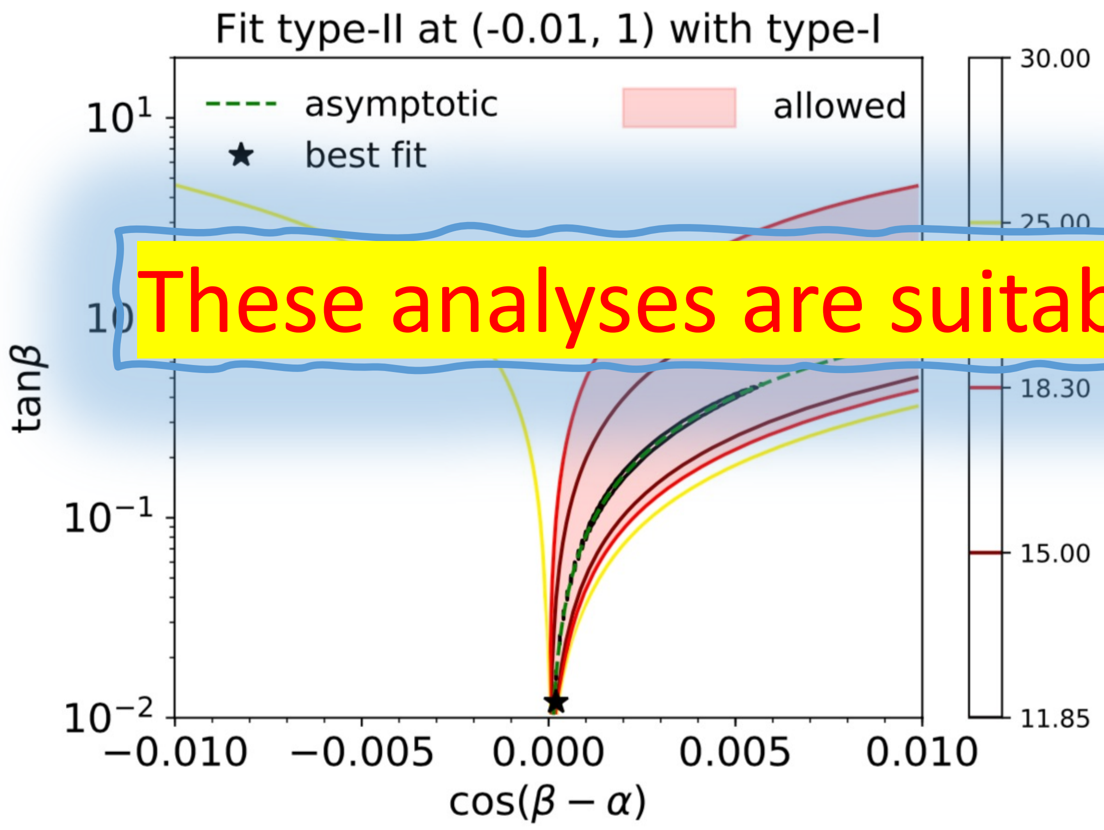
- Type-II $(\cos(\beta-\alpha), \tan\beta) = (-0.01, 1)$

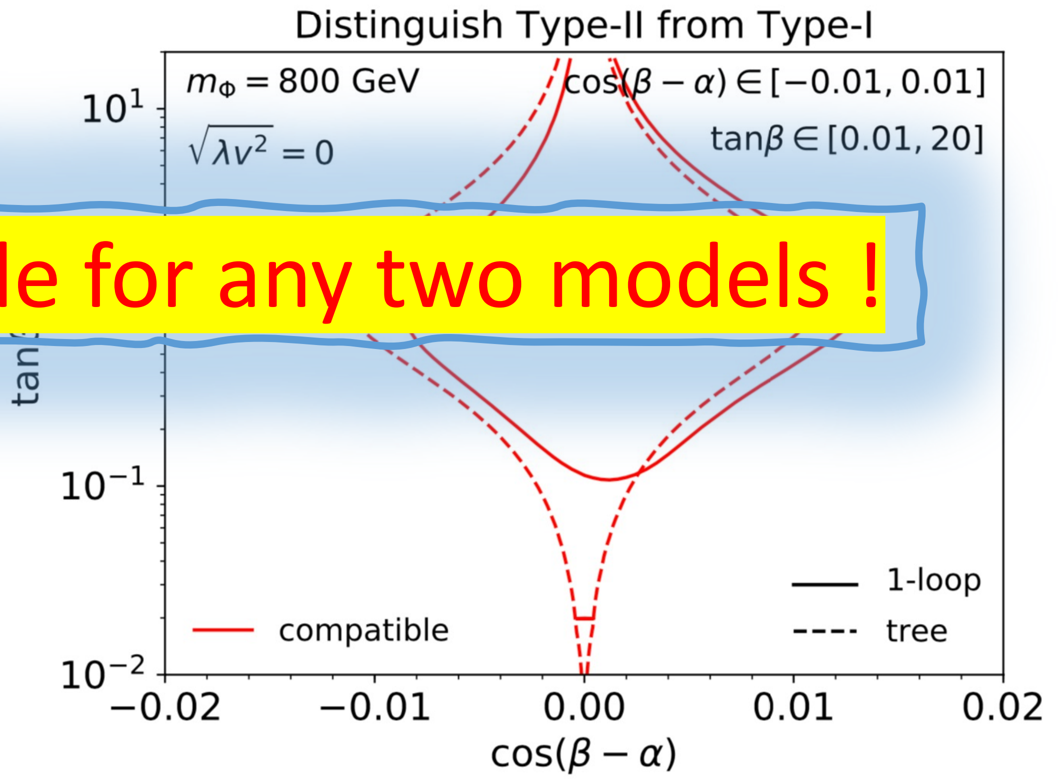




Study Results: compatibility test

- Type-II $(\cos(\beta-\alpha), \tan\beta) = (-0.01, 1)$

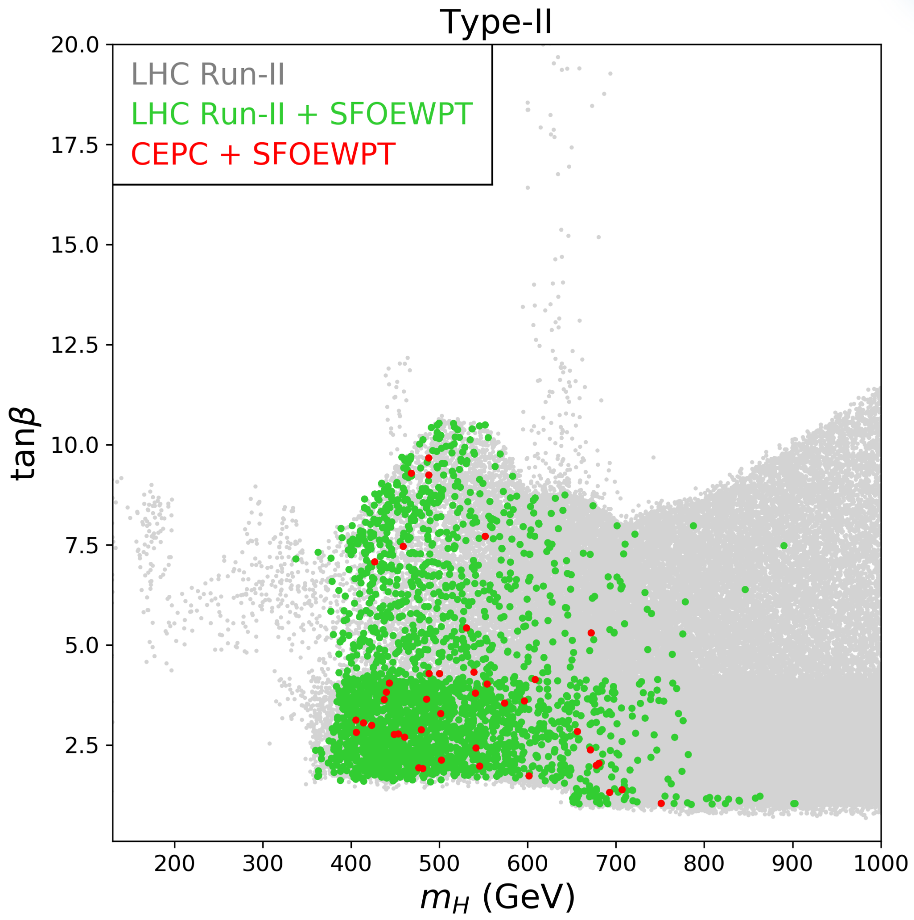


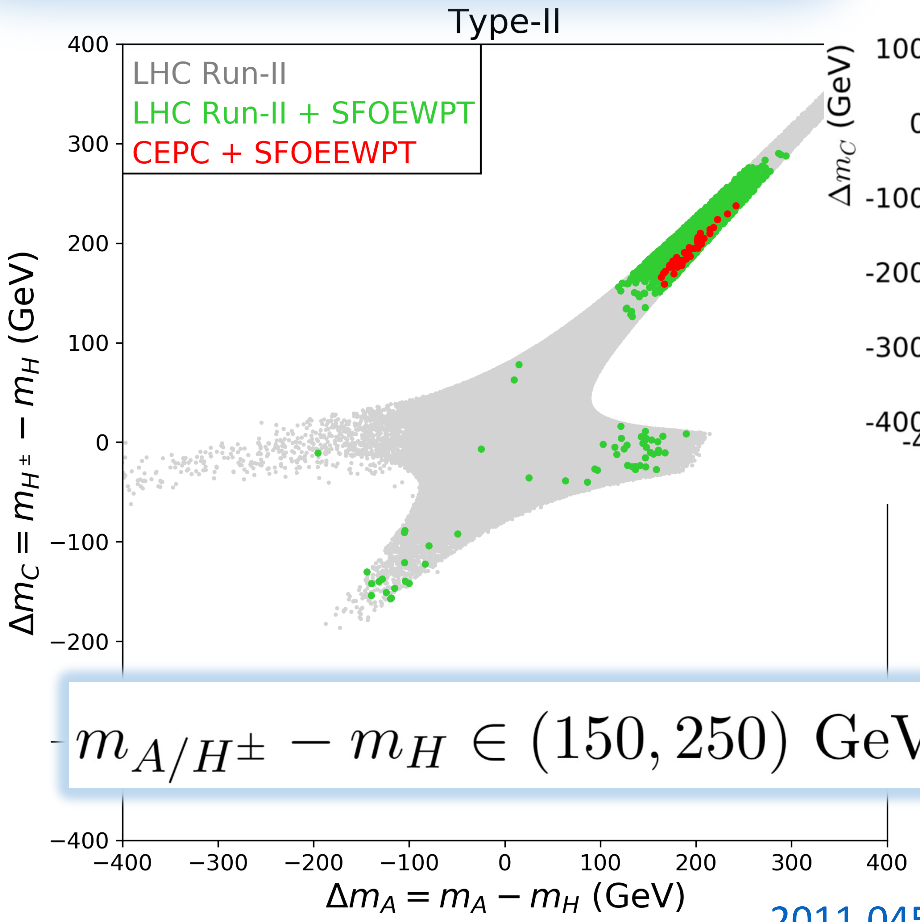


These analyses are suitable for any two models !

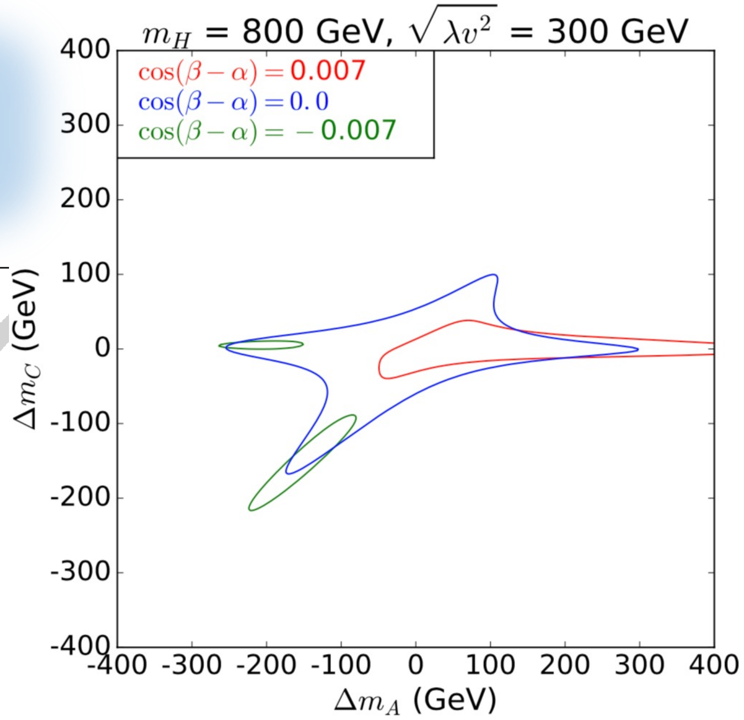
EWPT: Type-II

Electroweak phase transition



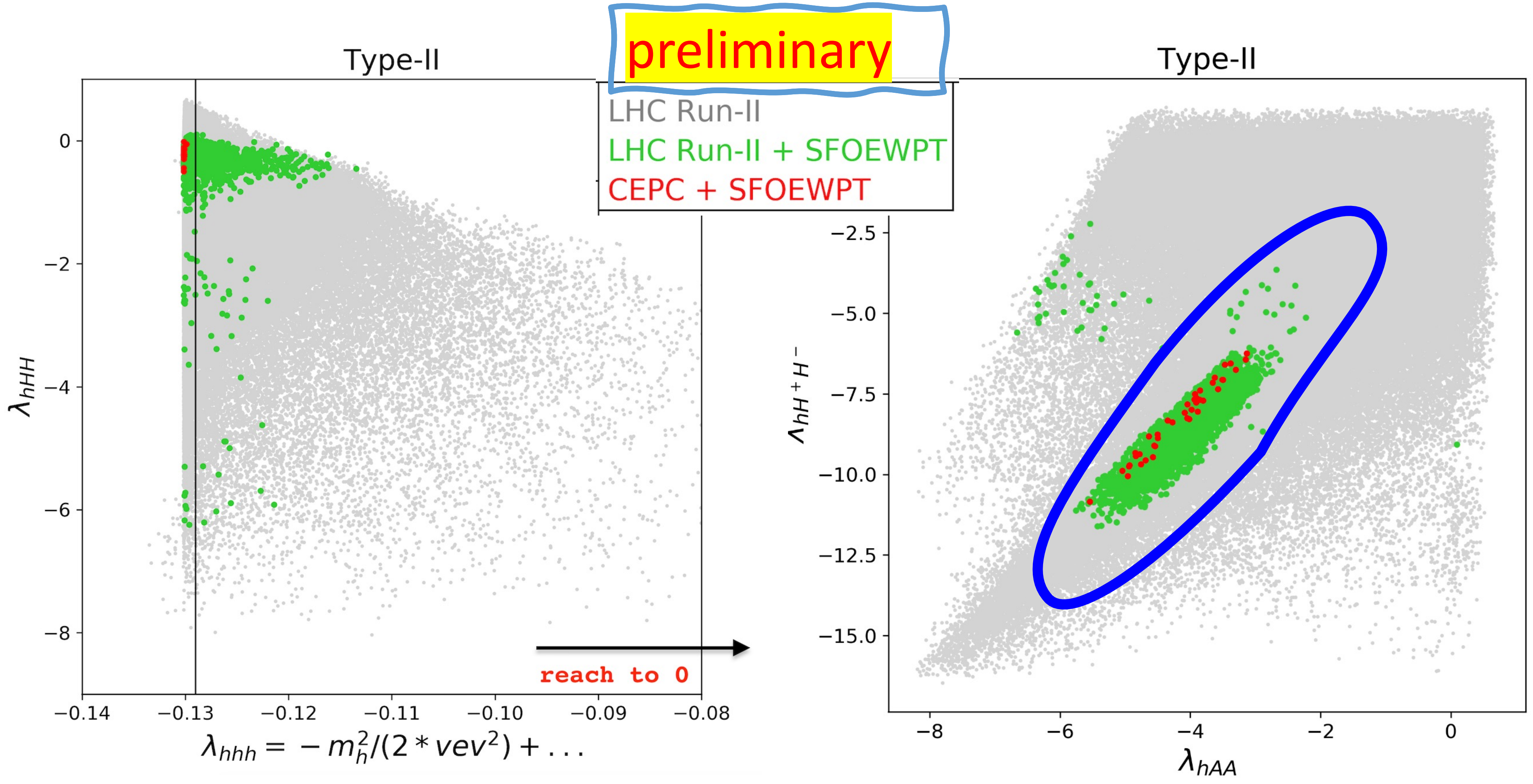


$$m_{A/H^\pm} - m_H \in (150, 250)\ \text{GeV}$$



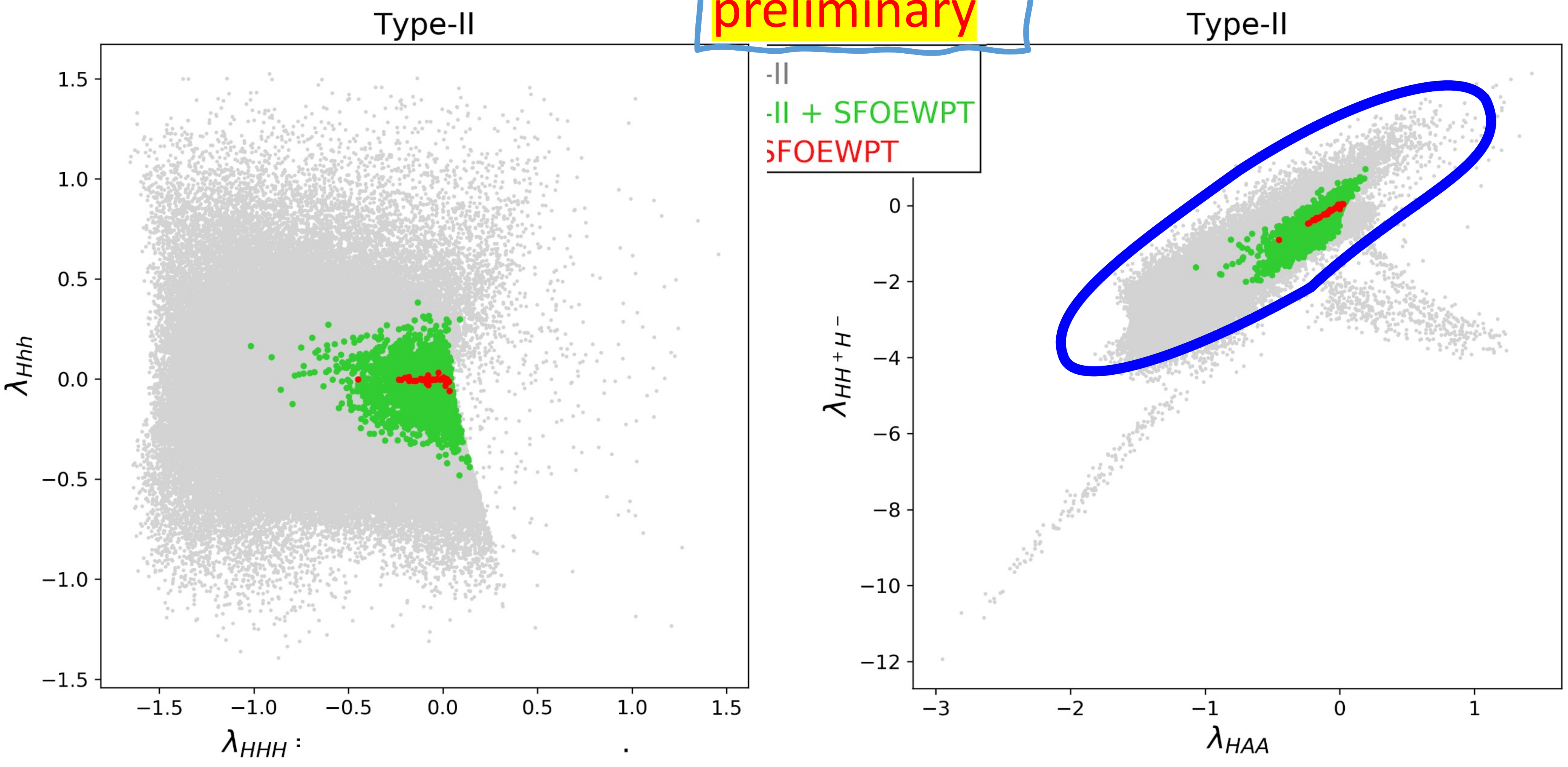
2011.04540 (WS, A G. Williams, M. Zhang)

EWPT: Triple Higgs Couplings



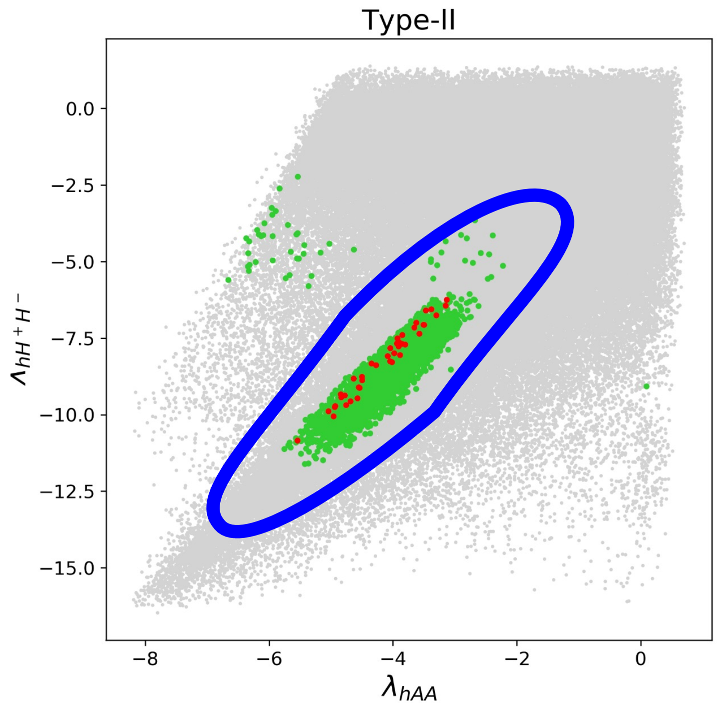
EWPT: Triple Higgs Couplings

preliminary



Summary: Higgs precision measurements

- Exclusion :Maximal likelihood vs. absolute χ^2 study
- Discovery potential: test null model SM
- Discrimination ability: a deviation observed
- Compatibility test: different BSMs



➢ These analyses are suitable for any two models !
➢ Connected to multi-Higgs couplings ...

Thanks !

Backup

Higgs+ Z

- What are various g_phphphi?

2HDM: Brief Introduction

- Two Higgs Doublet Model

$$
\begin{aligned}
V(\Phi_1,\Phi_2) = \; & m_{11}^2\Phi_1^\dagger\Phi_1 + m_{22}^2\Phi_2^\dagger\Phi_2 - m_{12}^2(\Phi_1^\dagger\Phi_2 + h.c.) + \frac{\lambda_1}{2}(\Phi_1^\dagger\Phi_1)^2 + \frac{\lambda_2}{2}(\Phi_2^\dagger\Phi_2)^2 \\
& +\lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) + \frac{1}{2}\left[\lambda_5(\Phi_1^\dagger\Phi_2)^2 + h.c.\right] \\
& +\frac{1}{2}(\Phi_1^\dagger\Phi_2 + h.c.)(\lambda_6\Phi_1^\dagger\Phi_1 + \lambda_7\Phi_1^\dagger\Phi_1)
\end{aligned}
$$

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

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

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

2HDM: Brief Introduction

	Φ_1	Φ_2
Type I	u,d,l	
Type II	u	d,l
lepton-specific	u,d	l
flipped	u,l	d

$$\kappa_i = g_{hii}^{BSM} / g_{hii}^{SM}$$

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)

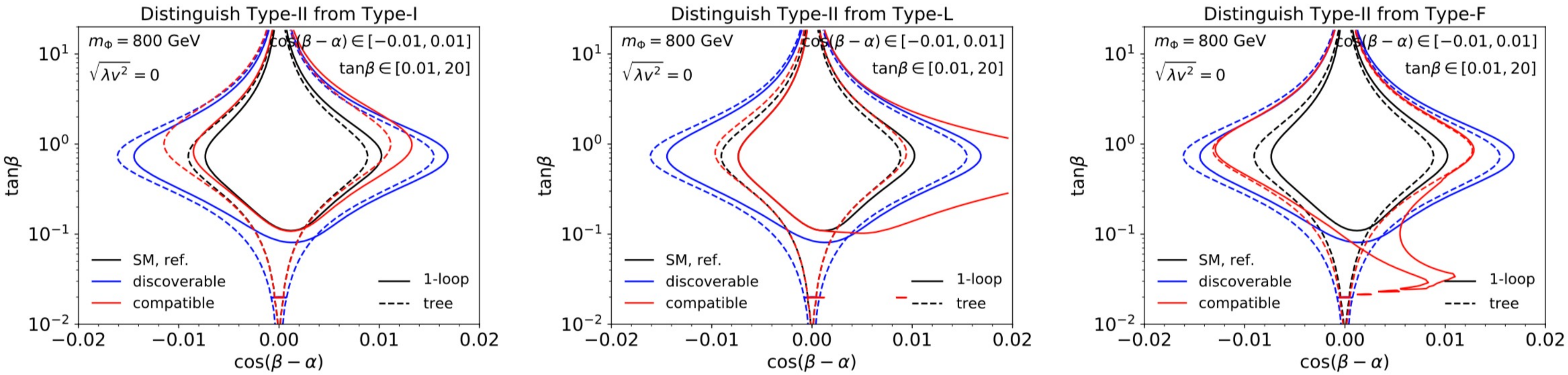
$m_{11}^2, m_{22}^2, \lambda_1, \lambda_2, \lambda_3, \lambda_4, \lambda_5$ → $v, \tan\beta, \alpha, m_h, m_H, m_A, m_{H^\pm}$

Soft Z_2 symmetry breaking: m_{12}^2

v: 246 GeV

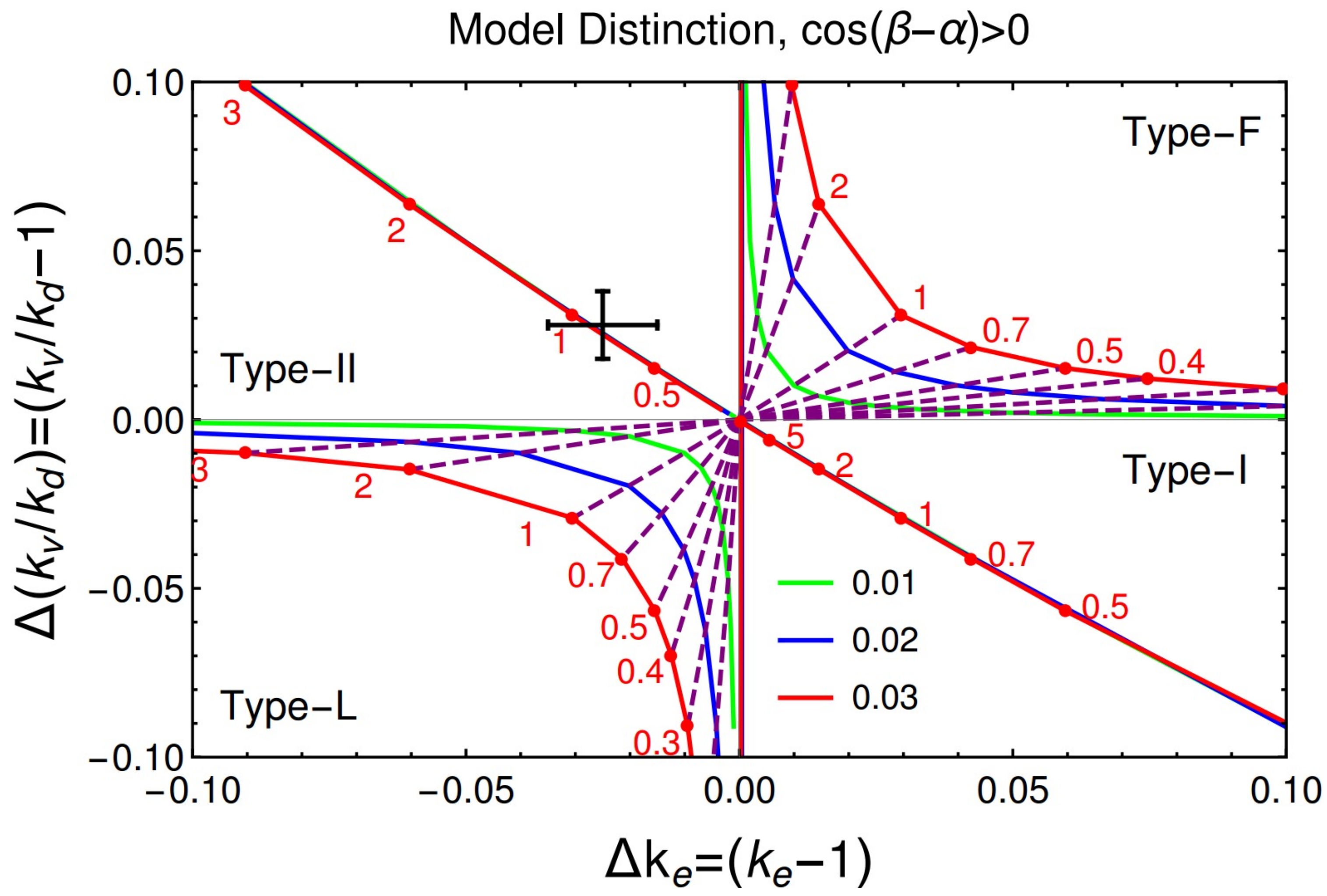
m_h: 125. GeV

Study Results: compatibility test



We can do the similar research between any two models

2HDM: Tree Level Model Distinction

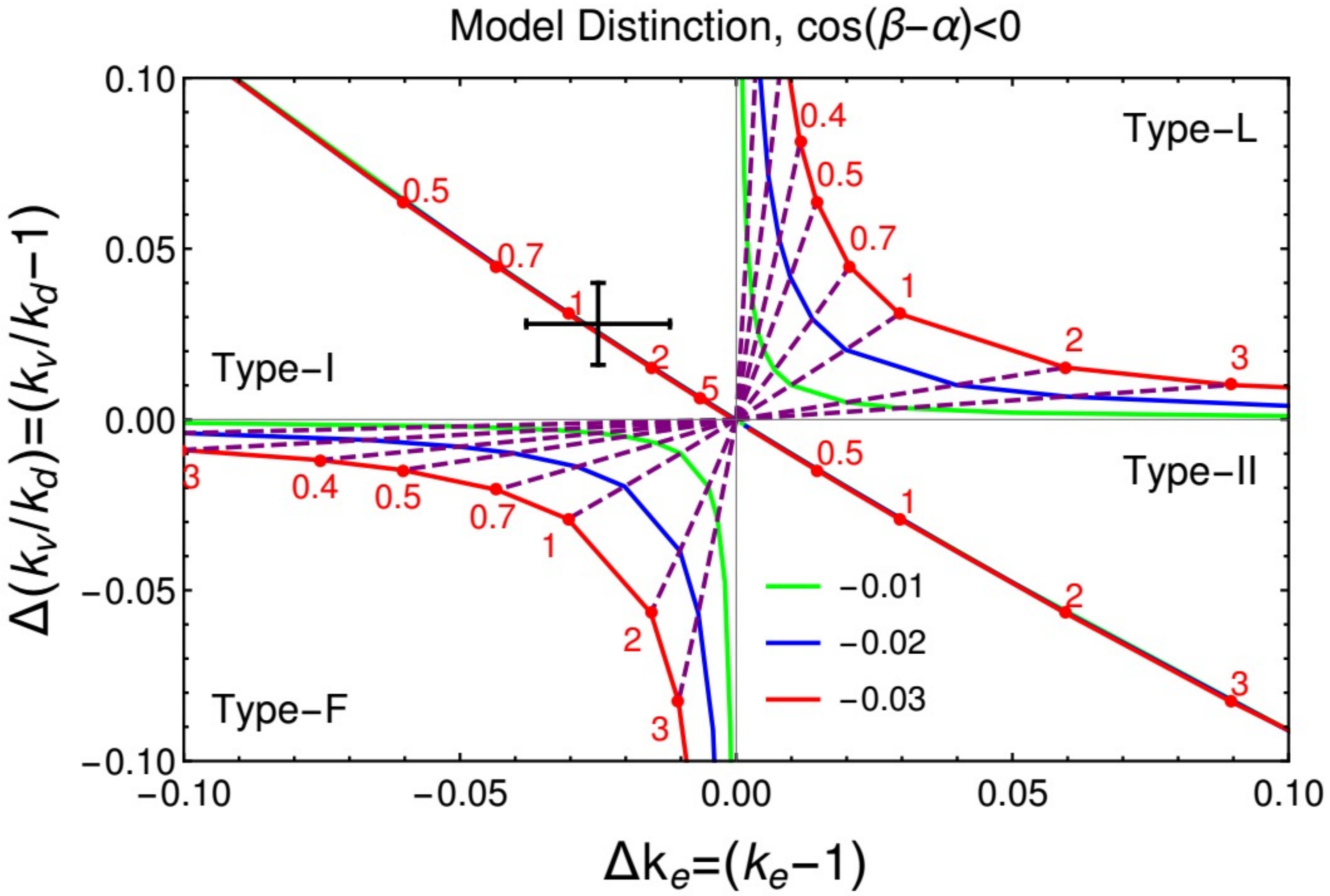


Varying $\tan\beta$

$\cos(\beta-\alpha)$

- 0.01
- 0.02
- 0.03

2HDM: Tree Level Model Distinction



Varying $\tan\beta$

$\cos(\beta - \alpha)$

- 0.01
- 0.02
- 0.03

Type-I ↔ Type-II

Type-L ↔ Type-F

Outline

- Higgs and Z-pole Precision Measurements
- Study strategies
- **Study Results:** Tree **& one-loop Level**
- 2HDM & Electroweak Phase Transition
- Summary