“H-COUP”で物理を探る

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1. H-COUP とは？
2. なぜ H-COUP？
3. H-COUPでどのように物理を探るのか？
4. まとめと展望

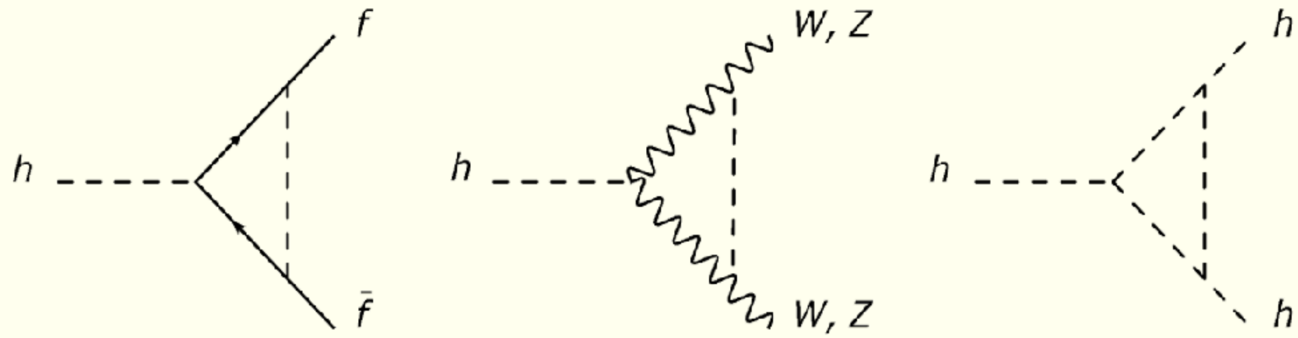
1. H-COUPとは？

http://www-het.phys.sci.osaka-u.ac.jp/~kanemu/HCOUP_HP1013/HCOUP_HP.html

www-het.phys.sci.osaka-u.ac.jp

H-COUP

Version 2 is coming very soon!



H-COUP is a calculation tool composed of a set of Fortran codes to compute the renormalized Higgs boson couplings with radiative corrections in various non-minimal Higgs models, such as the Higgs singlet model, four types of two Higgs doublet models and the inert doublet model. The impolved on-shell renormalization scheme is adopted, where the gauge depdence is eliminated.

Authors: Shinya Kanemura, Mariko Kikuchi, Kodai Sakurai and Kei Yagyu +K. Mawatari

The manual for H-COUP version 1.0 can be taken on arXiv:1710.04603 [hep-ph].

Comput.Phys.Commun.233(2018)134

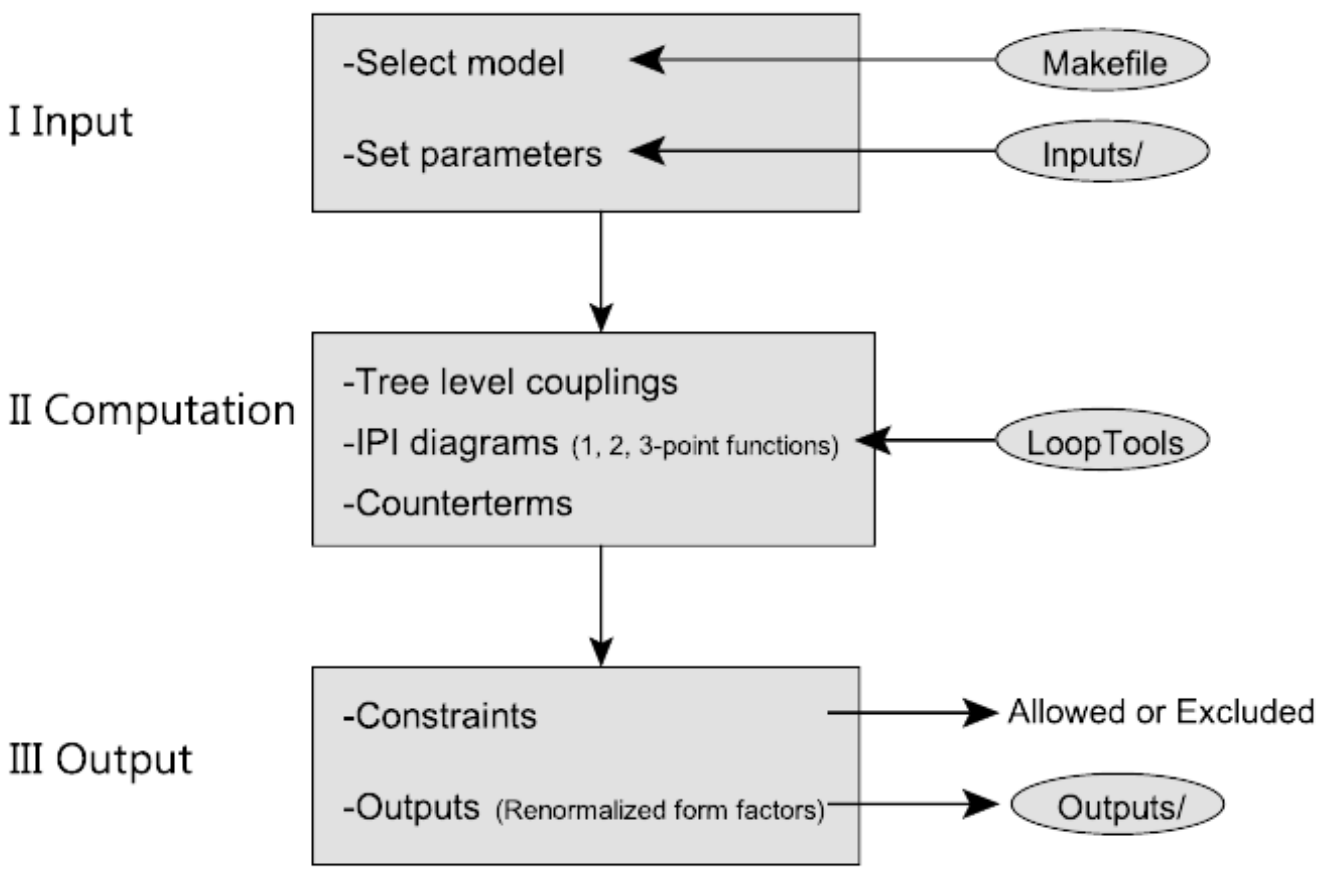
Loop effects on the Higgs decay widths in extended Higgs models [1803.01456, PLB]
Full NLO calculations of Higgs boson decay rates in models with non-minimal scalar sectors [1906.10070]

Downloads

- H-COUP version 1.0 : [HCOUP-1.0.zip] [The manual is here]

H-COUP v1 and v2: 1-min tutorial

- go to the H-COUP webpage.
- download the H-COUP file.
- (install LoopTools.)
- $ unzip H-COUP-2.0.zip
- edit Makefile to specify the PATH to LoopTools
- $ make (to compile)
- edit an input file (HSM, THDMs, IDM)
- $ ./hcoup (to run the program)



H-COUP v1: Input and Output

Input

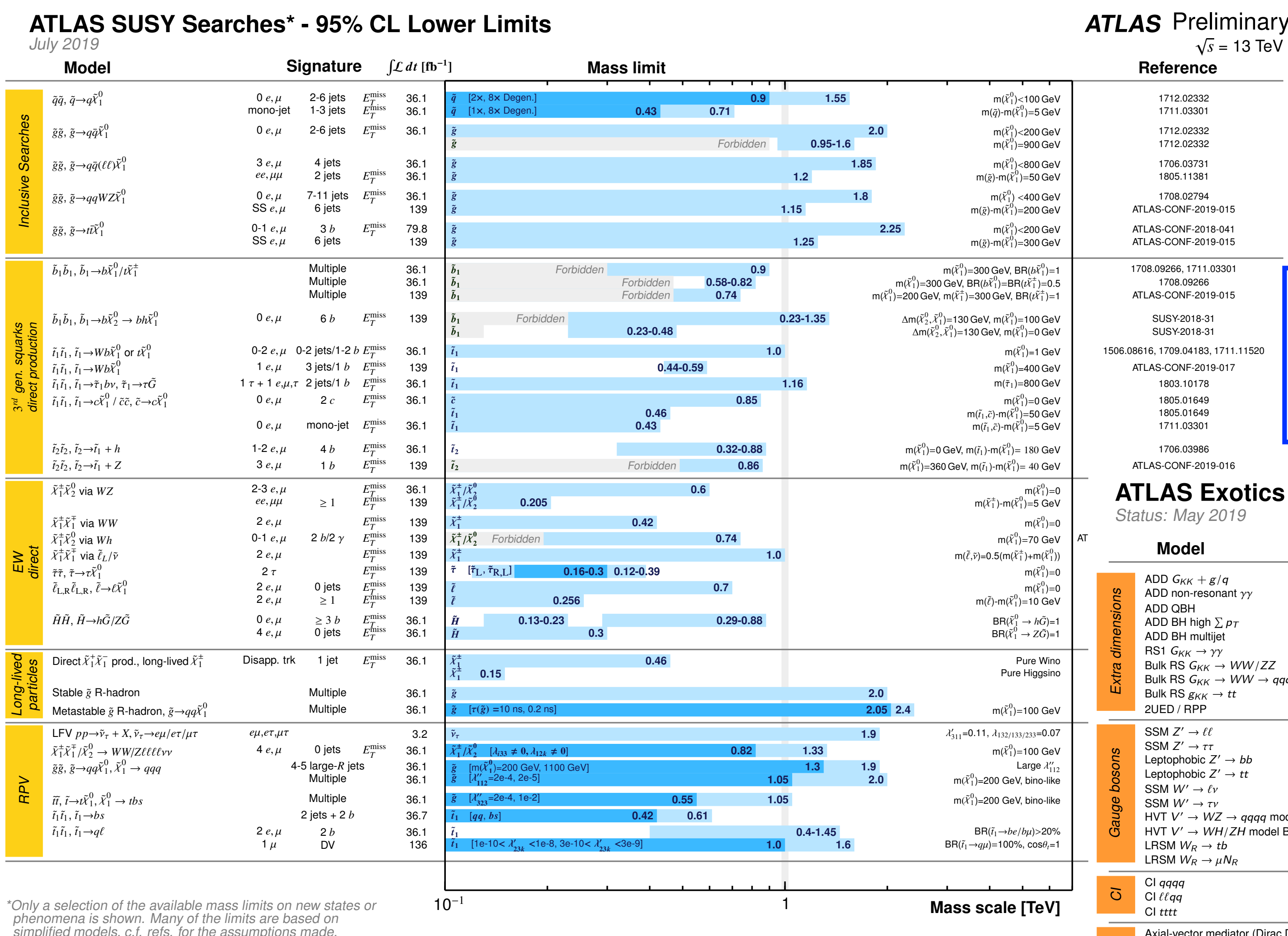
```
!===============================!
!                               !
! Input parameters for the HSM  !
!                               !
!===============================!

!==============================================================================
! Type of valuable  | Name of parameter  | Value             | Description
!==============================================================================
!------------------------------------------------------------------------------
double precision::   mbh                 = 500.d0            ! m_H in GeV
double precision::   alpha               = 0.1d0             ! alpha
double precision::   lam_ps              = 0.d0              ! lambda_{phi S}
double precision::   lam_s               = 0.d0              ! lambda_S
double precision::   mu_s                = 0.d0              ! mu_S in GeV
double precision::   cutoff              = 3.d3              ! cutoff in GeV
!==============================================================================
```

Output

```
Re[rGam_hZZ(1)]:   6.63606456E+01   Im[rGam_hZZ(1)]:  -1.55052694E+00
Re[rGam_hZZ(2)]:  -1.13818683E-01   Im[rGam_hZZ(2)]:  -9.24725320E-01
Re[rGam_hZZ(3)]:   4.43306800E-03   Im[rGam_hZZ(3)]:  -2.48999837E-06
Re[rGam_hWW(1)]:   5.31463661E+01   Im[rGam_hWW(1)]:  -1.41296896E+00
Re[rGam_hWW(2)]:  -9.76599594E-02   Im[rGam_hWW(2)]:  -9.09232189E-01
Re[rGam_hWW(3)]:   1.45357025E-03   Im[rGam_hWW(3)]:  -4.38354919E-02
Re[rGam_htt(S)]:  -7.26874884E-01   Im[rGam_htt(S)]:  -1.08793467E-03
Re[rGam_hbb(S)]:  -1.88039217E-02   Im[rGam_hbb(S)]:   7.78472272E-05
Re[rGam_hcc(S)]:  -5.13690642E-03   Im[rGam_hcc(S)]:  -3.68162893E-05
Re[rGam_hll(S)]:  -6.98376220E-03   Im[rGam_hll(S)]:  -1.90054055E-04
   Re[rGam_hhh]:  -1.84513810E+02      Im[rGam_hhh]:   1.67554069E+00
```

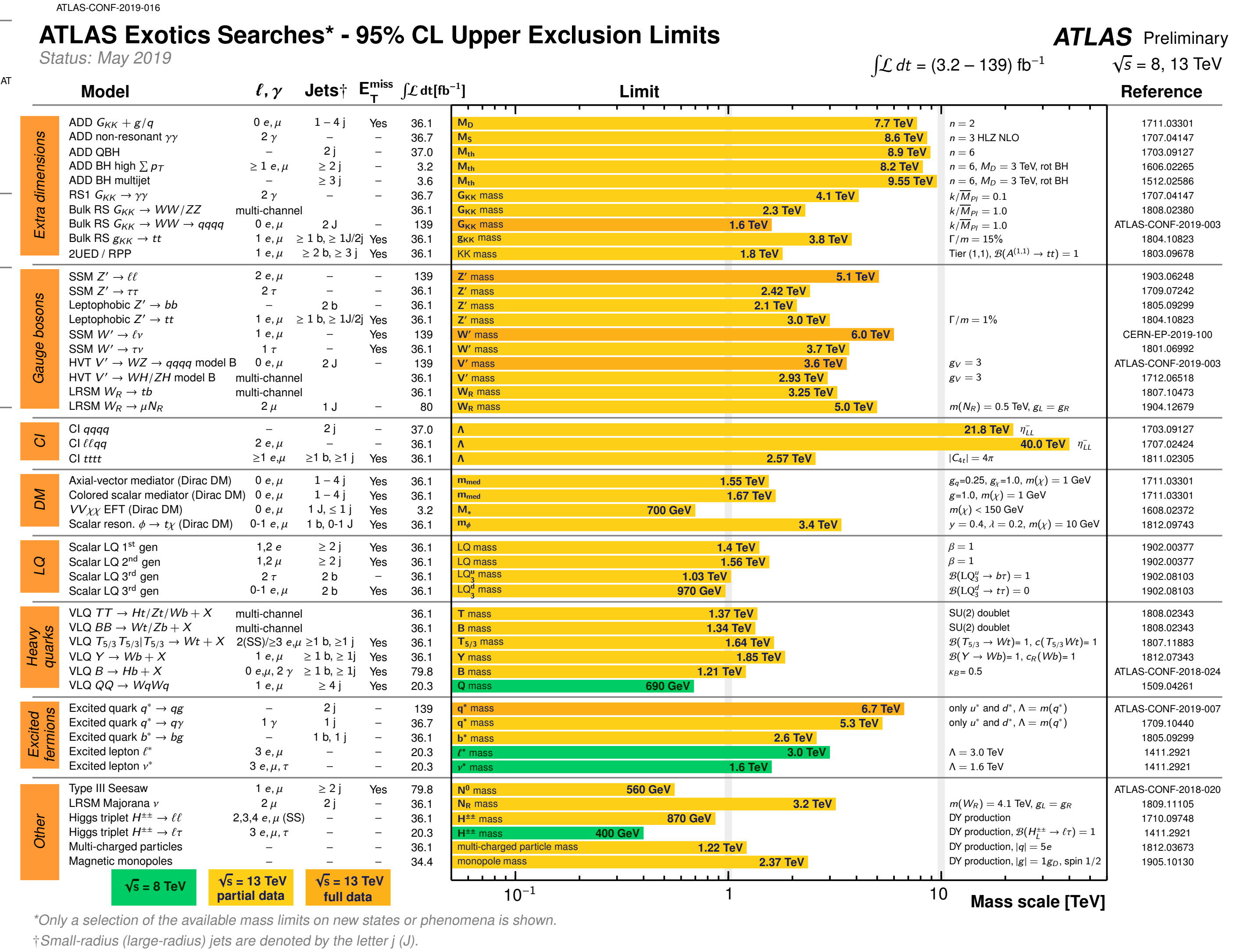
2. なぜH-COUP ?

新物理(New Physics)の兆候が未だに現れない…

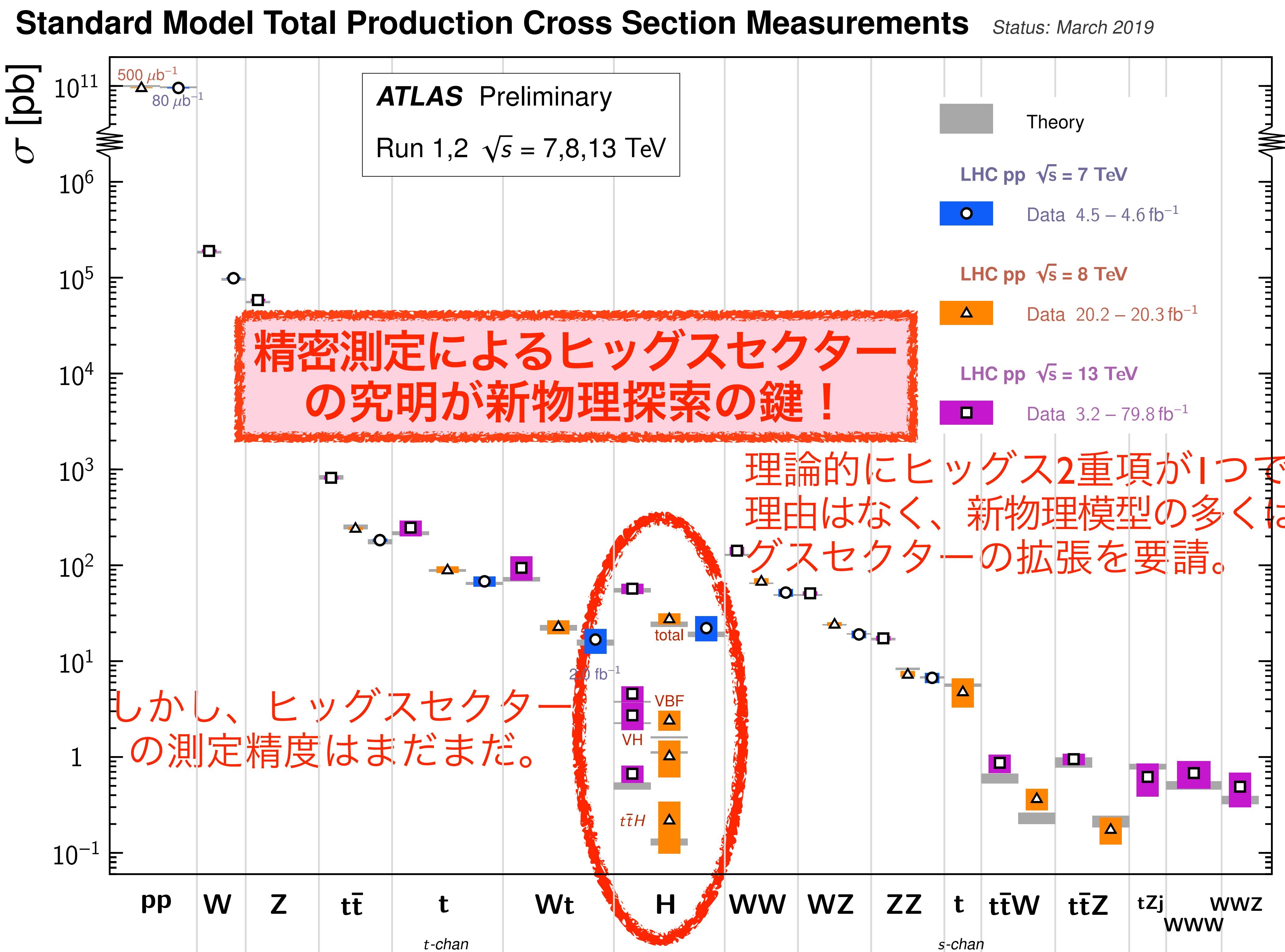


SUSY(超対称性)粒子の質量への制限

Non-SUSY粒子(e.g. 余剰次元模型のKaluza-Klein粒子)の質量への制限



LHCデータ≈標準模型(SM)の予言



精密測定によるヒッグスセクターの究明が新物理探索の鍵！

理論的にヒッグス2重項が1つである理由はなく、新物理模型の多くはヒッグスセクターの拡張を要請。

しかし、ヒッグスセクターの測定精度はまだまだ。

拡張ヒッグス模型の例

- HSM: Higgs singlet model (a real singlet scalar)

$$V(\Phi, S) = m_\Phi^2|\Phi|^2 + \lambda|\Phi|^4 + \mu_{\Phi S}|\Phi|^2 S + \lambda_{\Phi S}|\Phi|^2 S^2 + t_S S + m_S^2 S^2 + \mu_S S^3 + \lambda_S S^4$$

[free parameters] $m_H,\ M^2(\equiv 2m_S^2),\ \mu_S,\ \lambda_S,\ \alpha$

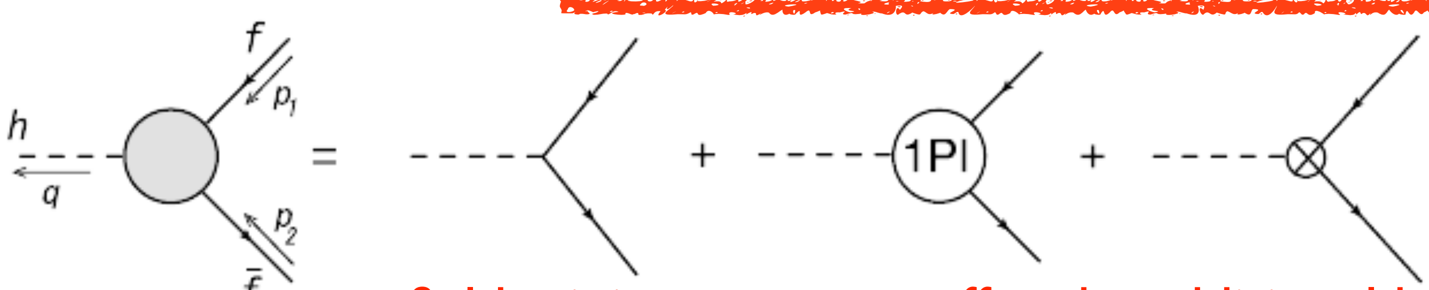
- THDM: Two Higgs doublet model (with softly broken Z_2 symmetry +CP conservation)

$$V(\Phi_1, \Phi_2) = m_1^2|\Phi_1|^2 + m_2^2|\Phi_2|^2 - m_3^2(\Phi_1^\dagger\Phi_2 + \mathrm{h.c.})$$
$$+ \frac{1}{2}\lambda_1|\Phi_1|^4 + \frac{1}{2}\lambda_2|\Phi_2|^4 + \lambda_3|\Phi_1|^2|\Phi_2|^2 + \lambda_4|\Phi_1^\dagger\Phi_2|^2 + \frac{1}{2}\lambda_5[(\Phi_1^\dagger\Phi_2)^2 + \mathrm{h.c.}]$$

[free parameters] $m_H,\ m_A,\ m_{H^\pm},\ M^2(\equiv m_3^2/s_\beta c_\beta),\ \tan\beta,\ s_{\beta-\alpha}(\geq 0),\ \mathrm{Sign}(c_{\beta-\alpha})$

- h(125)以外のスカラー粒子の存在 (H,A,H±,…)
- h(125) couplingのSM予言からのずれ

＊愛甲さんのポスター発表 (明日)



field mixing (tree)

quantum effect by additional bosons (loop)

$$g_{hff}^{\mathrm{tree}} = -\frac{m_f}{v}\kappa_f,\quad g_{hVV}^{\mathrm{tree}} = \frac{2m_V^2}{v}\kappa_V$$

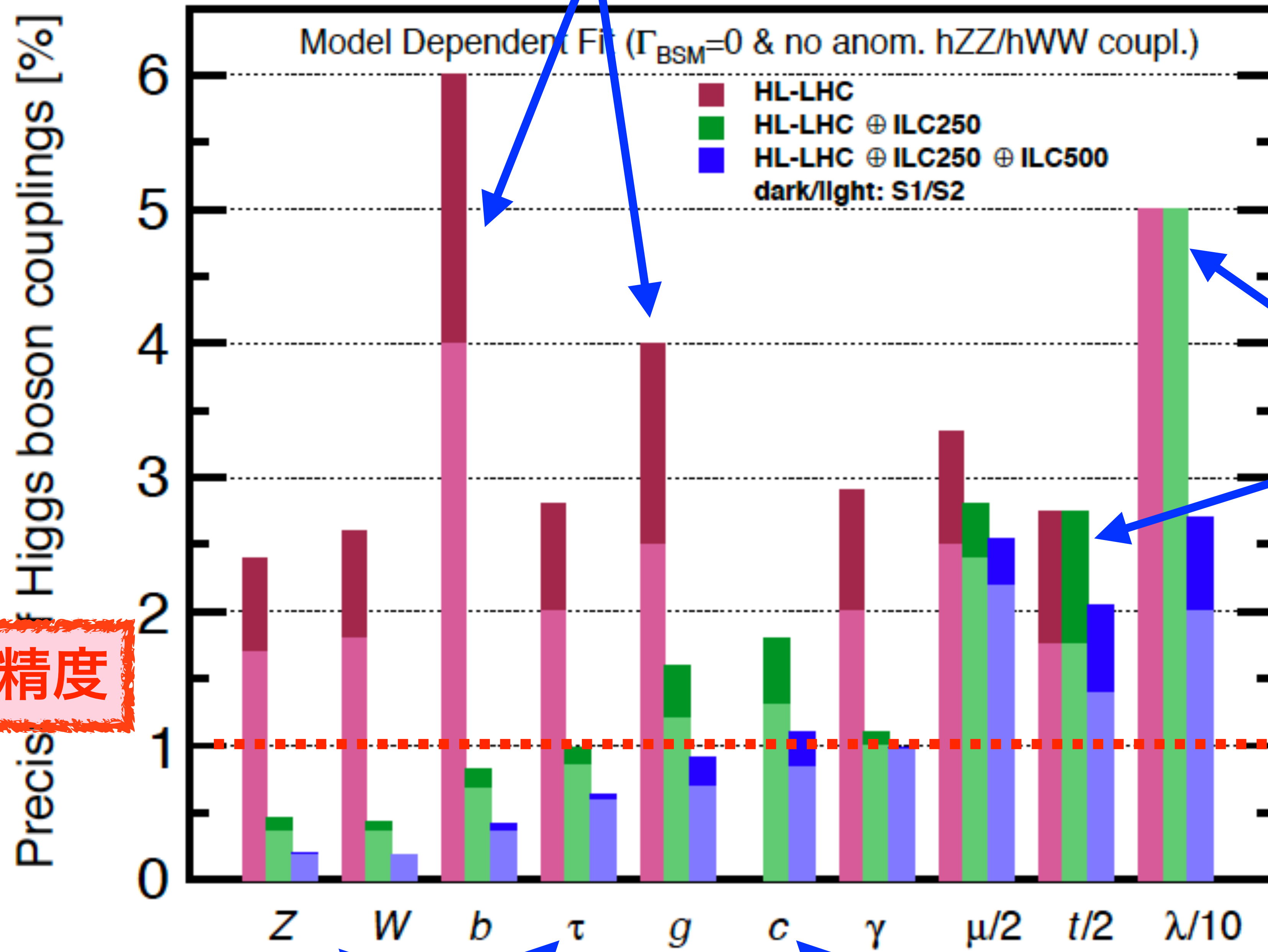
(HSM) $\kappa_f = \kappa_V = c_\alpha$

(THDM) $\kappa_f = s_{\beta-\alpha} + \zeta_f c_{\beta-\alpha},\ \kappa_V = s_{\beta-\alpha}$

ヒッグス結合の測定精度@HL-LHC+ILC

ILC can improve significantly.

European strategy: ILC [1901.09829]



180M Higgs (HL-LHC)
+ 0.6M (ILC250)

ILC500 is necessary.

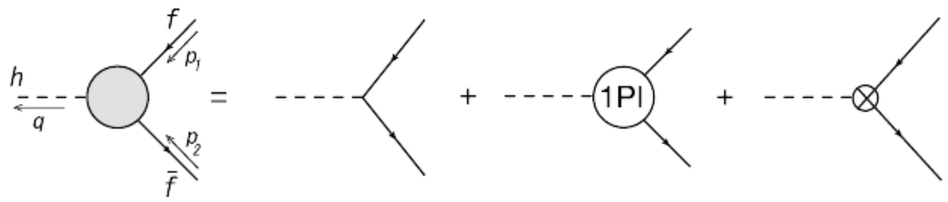
O(1%) の精度

より精密な予言が必要不可欠

➡ H-COUP !

relatively clean even at the LHC.

Only ILC can measure.



$$\Gamma^{\rm 1PI}_{hff}(p_1^2,p_2^2,q^2)=F^S_{hff}+\gamma_5F^P_{hff}+\not{p}_1F^{V1}_{hff}+\not{p}_2F^{V2}_{hff}+\not{p}_1\gamma_5F^{A1}_{hff}+\not{p}_2\gamma_5F^{A2}_{hff}+\not{p}_1\not{p}_2F^{T}_{hff}+\not{p}_1\not{p}_2\gamma_5F^{PT}_{hff}.$$

Kanemura, Kikuchi, Yagyu
[1511.06211, NPB]+[1608.01582, NPB]

Kanemura, Okada, Senaha, Yuan [hep-ph/0408364, PRD]
Kanemura, Kikuchi, Yagyu [1401.0515, PLB]+[1502.07716, NPB]

Singlet extension

$$\Gamma^{S,\rm tree}_{hf\bar{f},\rm HSM}=-\frac{m_f}{v}c_\alpha$$

$$\begin{aligned}(16\pi^2)F^{\rm 1PI}_{hff,S}[p_1^2,p_2^2,q^2]=&-4c_\alpha\frac{m_f}{v}\left\{\frac{m_Z^2}{v^2}(v_f^2-a_f^2)C^{hff,S}_{FVF}[f,Z,f]+(Q_fe)^2C^{hff,S}_{FVF}[f,Z,f]\right\}\\&+\frac{m_f^3}{v^3}c_\alpha\left\{c_\alpha^2C^{hff,S}_{FSF}[f,h,f]+s_\alpha^2C^{hff,S}_{FSF}[f,H,f]-c_\alpha C^{hff,S}_{FSF}[f,G^0,f]\right\}\\&-2c_\alpha\frac{m_fm_{f'}^2}{v^3}C^{hff,S}_{FSF}[f',G^\pm,f']-8c_\alpha\frac{m_Z^4}{v^3}m_f(v_f^2-a_f^2)C_0[Z,f,Z]\\&-2\frac{m_f^2}{v^2}\{3c_\alpha^2\lambda_{hhh}C_0[h,f,h]+s_\alpha^2\lambda_{hHH}C_0[H,f,H]+c_\alpha s_\alpha\lambda_{hhH}(C_0[h,f,H]+C_0[H,f,h])\}\\&+2\frac{m_f^2}{v^2}\left\{\lambda_{hG^0G^0}\frac{m_f}{v}C_0[G^0,f,G^0]+\lambda_{hG^+G^-}\frac{m_{f'}}{v}C_0[G^\pm,f',G^\pm]\right\}\\&-c_\alpha\frac{m_W^2m_f}{v^3}(C^{hff,S}_{SFV}[G^\pm,f',W]+C^{hff,S}_{VFS}[W,f',G^\pm])\\&-c_\alpha\frac{m_Z^2m_f}{2v^3}(C^{hff,S}_{SFV}[G^0,f,Z]+C^{hff,S}_{VFS}[Z,f,G^0]),\end{aligned}\quad\text{(D41)}$$

Z_2 charge assignment

	Φ_1	Φ_2	Q_L	L_L	u_R	d_R	e_R	ζ_u	ζ_d	ζ_e
Type-I	+	−	+	+	−	−	−	$\cot\beta$	$\cot\beta$	$\cot\beta$
Type-II	+	−	+	+	−	+	+	$\cot\beta$	$-\tan\beta$	$-\tan\beta$
Type-X (lepton-specific)	+	−	+	+	−	−	+	$\cot\beta$	$\cot\beta$	$-\tan\beta$
Type-Y (flipped)	+	−	+	+	−	+	−	$\cot\beta$	$-\tan\beta$	$\cot\beta$

THDM

$$\Gamma^{S,\rm tree}_{hf\bar{f},\rm THDM}=-\frac{m_f}{v}(s_{\beta-\alpha}+\zeta_fc_{\beta-\alpha})$$

$$\begin{aligned}\left(\frac{m_f}{v}\right)^{-1}F^S_{hff}=&-2g_Z^4v^2(v_f^2-a_f^2)s_{\beta-\alpha}C_0(Z,f,Z)\\&-4\xi_h^f\Big\{e^2Q_f^2[m_f^2C_0+p_1^2(C_{11}+C_{21})+p_2^2(C_{12}+C_{22})+p_1\cdot p_2(2C_{23}-C_0)+4C_{24}-1](f,\gamma,f)\\&+g_Z^2(v_f^2-a_f^2)[m_f^2C_0+p_1^2(C_{11}+C_{21})+p_2^2(C_{12}+C_{22})+p_1\cdot p_2(2C_{23}-C_0)+4C_{24}-1](f,Z,f)\Big\}\\&+\xi_h^f\frac{m_f^2}{v^2}\Big[(\xi_h^f)^2C^{FSF}_{hff}(f,h,f)+(\xi_H^f)^2C^{FSF}_{hff}(f,H,f)-C^{FSF}_{hff}(f,G^0,f)-\xi_f^2C^{FSF}_{hff}(f,A,f)\Big]\\&-\xi_h^{f'}\frac{2m_{f'}^2}{v^2}\Big[C^{FSF}_{hff}(f',G^\pm,f')+\xi_f\xi_{f'}C^{FSF}_{hff}(f',H^\pm,f')\Big]\\&-\frac{m_f^2}{v}\Big\{6(\xi_h^f)^2\lambda_{hhh}C_0(h,f,h)+2(\xi_H^f)^2\lambda_{HHh}C_0(H,f,H)+2\xi_h^f\xi_H^f\lambda_{Hhh}[C_0(h,f,H)+C_0(H,f,h)]\\&\qquad-2\lambda_{G^0G^0h}C_0(G^0,f,G^0)-2\xi_f^2\lambda_{AAh}C_0(A,f,A)-\xi_f\lambda_{AG^0h}[C_0(A,f,G^0)+C_0(G^0,f,A)]\Big\}\\&+\frac{2m_{f'}^2}{v}\Big\{\lambda_{G^+G^-h}C_0(G^\pm,f',G^\pm)+\xi_f\xi_{f'}\lambda_{H^+H^-h}C_0(H^\pm,f',H^\pm)\\&\qquad+\frac{1}{2}\lambda_{H^+G^-h}(\xi_f+\xi_{f'})[C_0(G^\pm,f',H^\pm)+C_0(H^\pm,f',G^\pm)]\Big\}\\&-\frac{g^2}{4}s_{\beta-\alpha}\Big[C^{VFS}_{hff}(W,f',G^\pm)+C^{SFV}_{hff}(G^\pm,f',W)\Big]\\&-\frac{g^2}{4}\xi_fc_{\beta-\alpha}\Big[C^{VFS}_{hff}(W,f',H^\pm)+C^{SFV}_{hff}(H^\pm,f',W)\Big]\\&-\frac{g_Z^2}{8}s_{\beta-\alpha}\Big[C^{VFS}_{hff}(Z,f,G^0)+C^{SFV}_{hff}(G^0,f,Z)\Big]\\&-\frac{g_Z^2}{8}\xi_fc_{\beta-\alpha}\Big[C^{VFS}_{hff}(Z,f,A)+C^{SFV}_{hff}(A,f,Z)\Big],\end{aligned}\quad\text{(C36)}$$

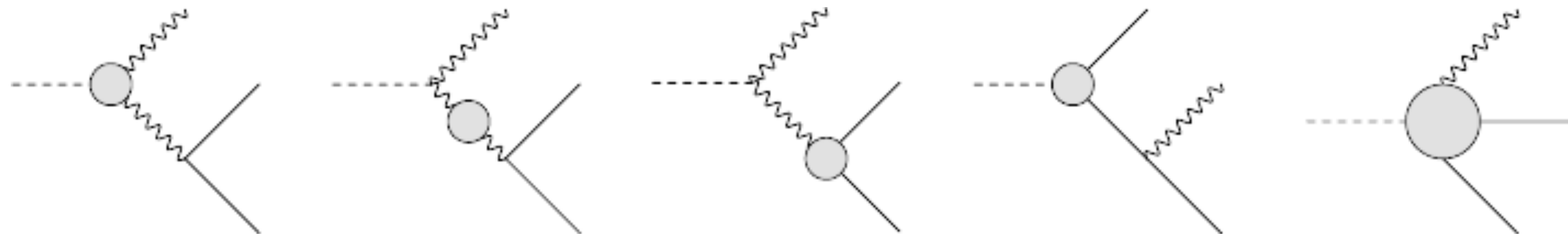
Kanemura, Kikuchi, Sakurai, Yagyu
[1605.08520, PRD]

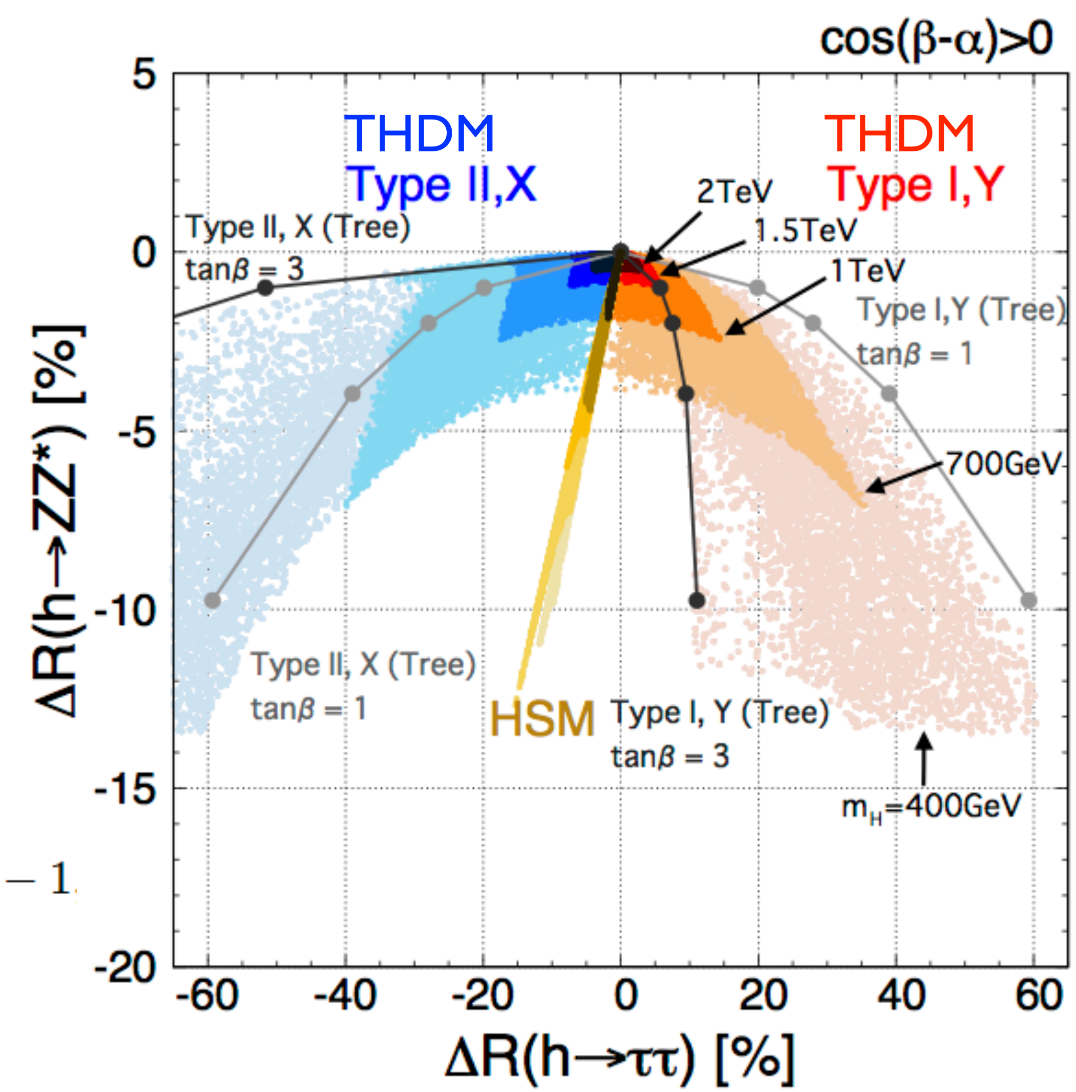
IDM

3. H-COUPでどのように物理を探るのか？

H-COUP applications: Higgs decays

Kanemura, Kikuchi, Mawatari, Sakurai, Yagyu [1803.01456 (PLB), 1906.10070]

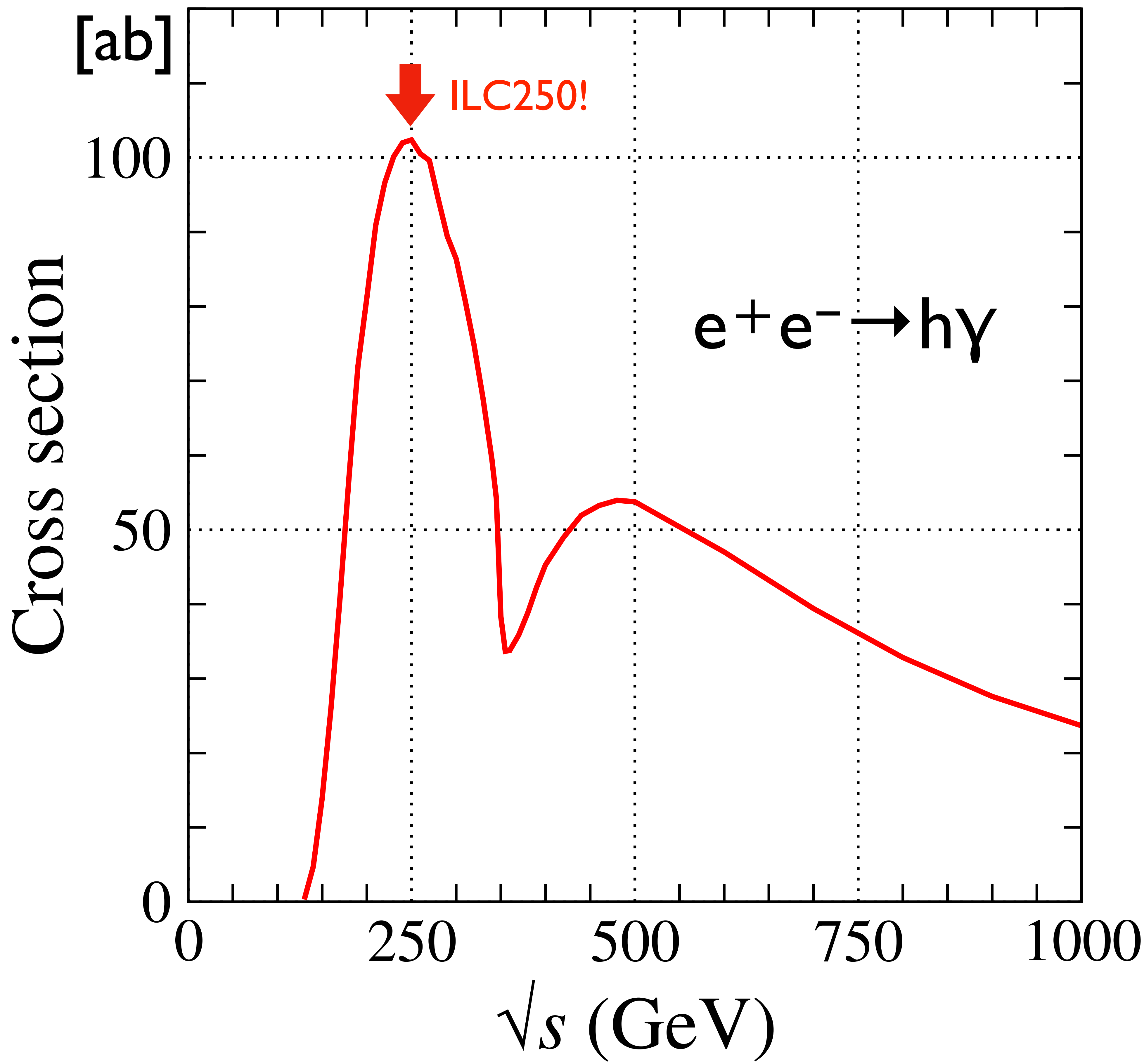




$$\Delta R(h \to XX) = \frac{\Gamma_{\rm NP}(h \to XX)}{\Gamma_{\rm SM}(h \to XX)} - 1$$

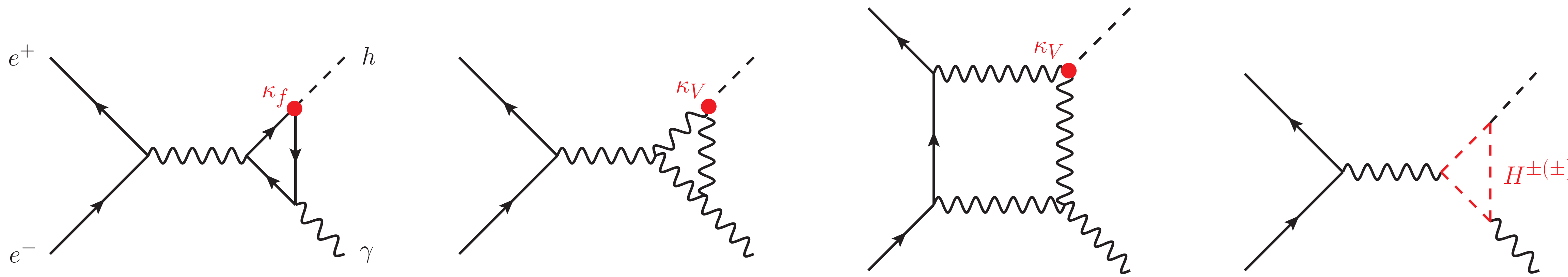
pattern of the deviations
➡ selection of NP models
magnitude of the deviations
➡ NP scales

＊桜井さんのポスター発表 (去年)

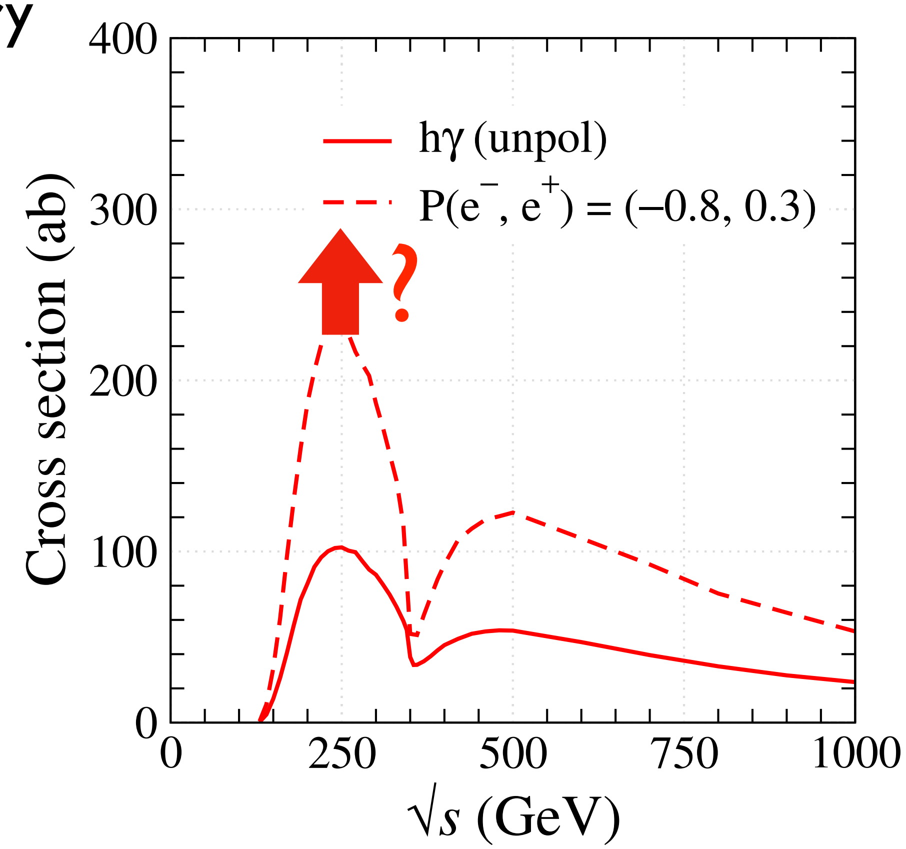

[ab]
ILC250!
100
50
0
Cross section
e⁺e⁻→hγ
0
250
500
750
1000
√s (GeV)

$$\kappa_X = \frac{g^{\rm NP}_{hXX}}{g^{\rm SM}_{hXX}}$$

H-COUP applications: Higgs productions



crossing symmetry with h→Zff



	κ_f (=t)	κ_V	H+	H++
IDM	1	1	○	×
ITM (Y=1)	1	1	○	○
THDM	$s_{\beta-\alpha}$ $-c_{\beta-\alpha}/t_\beta$	$s_{\beta-\alpha}$	○	×

Kanemura, Mawatari, Sakurai [1808.10268, PRD]

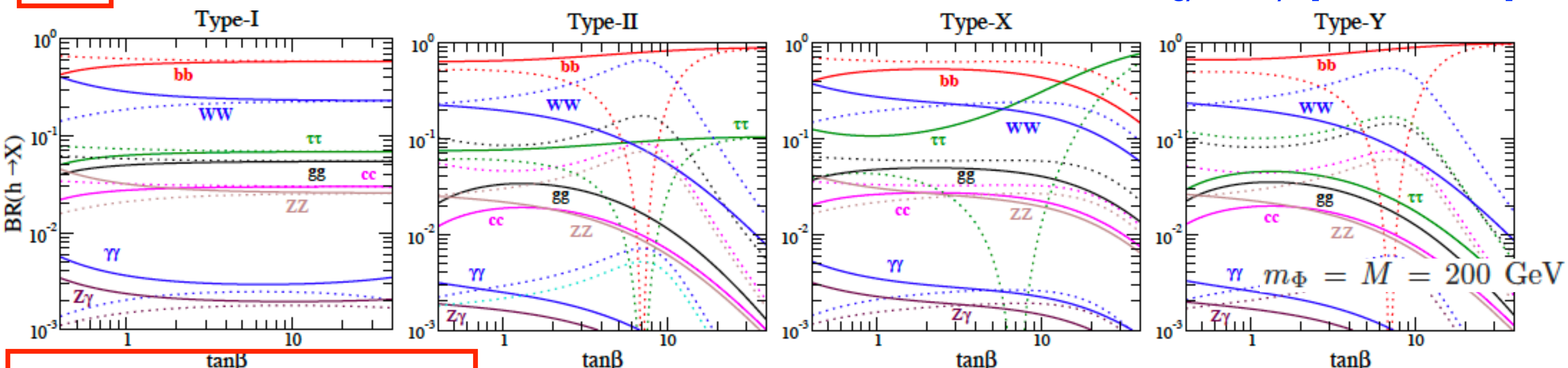
How much can new physics enhance (or reduce) the production rate?

＊馬渡の口頭発表 (去年)

H-COUP v2: Branching ratios

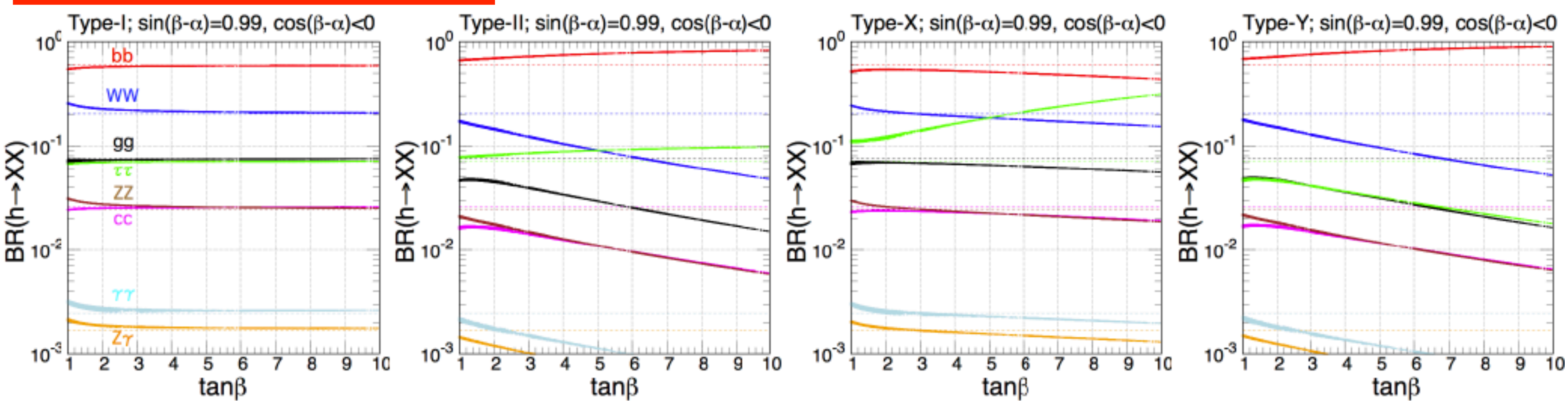
LO

Kanemura, Tsumura, Yagyu, Yokoya [1406.3294, PRD]



NLO in EW+QCD

Kanemura, Kikuchi, Mawatari, Sakurai, Yagyu [1906.10070]



Loop effects by additional Higgs bosons

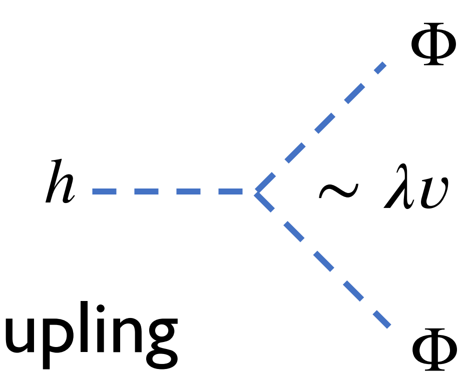
$$\Gamma(h \to Zf\bar{f}) = \Gamma_0(h \to Zf\bar{f})\left[1 + \Delta^Z_{\rm EW} + \Delta^Z_{\rm QCD}\right]$$

New physics effects of the EW corrections:

$$\overline{\Delta}^X_{\rm EW} = \Delta^X_{\rm EW}\big|_{\rm NP} - \Delta^X_{\rm EW}\big|_{\rm SM}$$

$$\simeq -\frac{1}{16\pi^2}\frac{1}{6}\sum_\varphi c_\varphi \frac{m_\varphi^2}{v^2}\left(1 - \frac{M^2}{m_\varphi^2}\right)^2$$

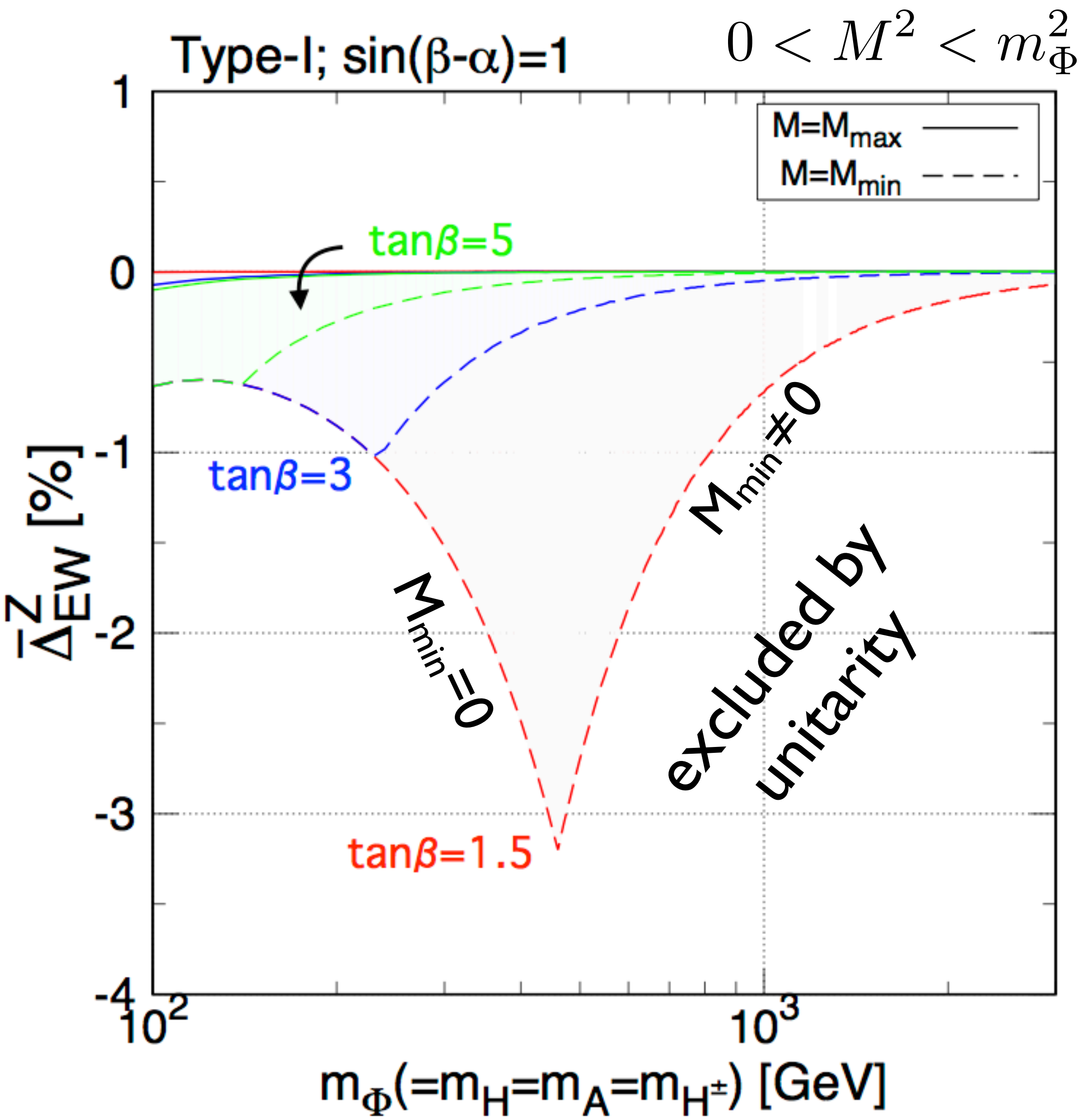
$m_\Phi^2 \sim \lambda v^2 + M^2$



$m_\Phi^2 \sim M^2$: Decoupling

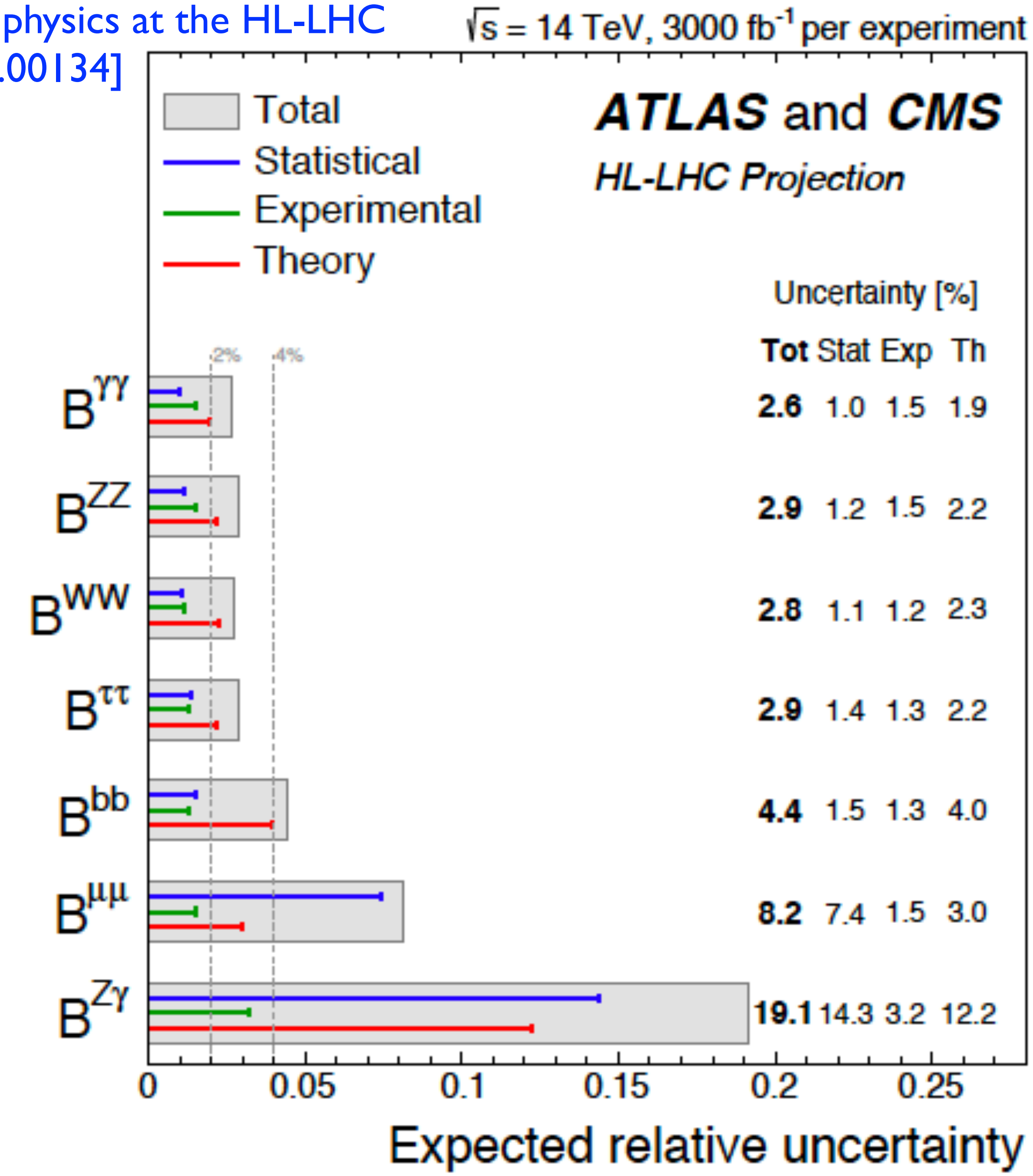
$m_\Phi^2 \sim \lambda v^2$: Non-decoupling

(Φ=H,A,H⁺)



Precision of the Higgs branching ratios at future colliders

Higgs physics at the HL-LHC [1902.00134]



ILC250 [1710.07621]

2000 fb^{-1}

1σ	2σ
13%	26%
6.7%	13.4%
1.9%	3.8%
1.4%	2.8%
0.89%	1.78%
27%	54%

(3.2% 6.4% for B^{cc})

Let's consider 3 scenarios:

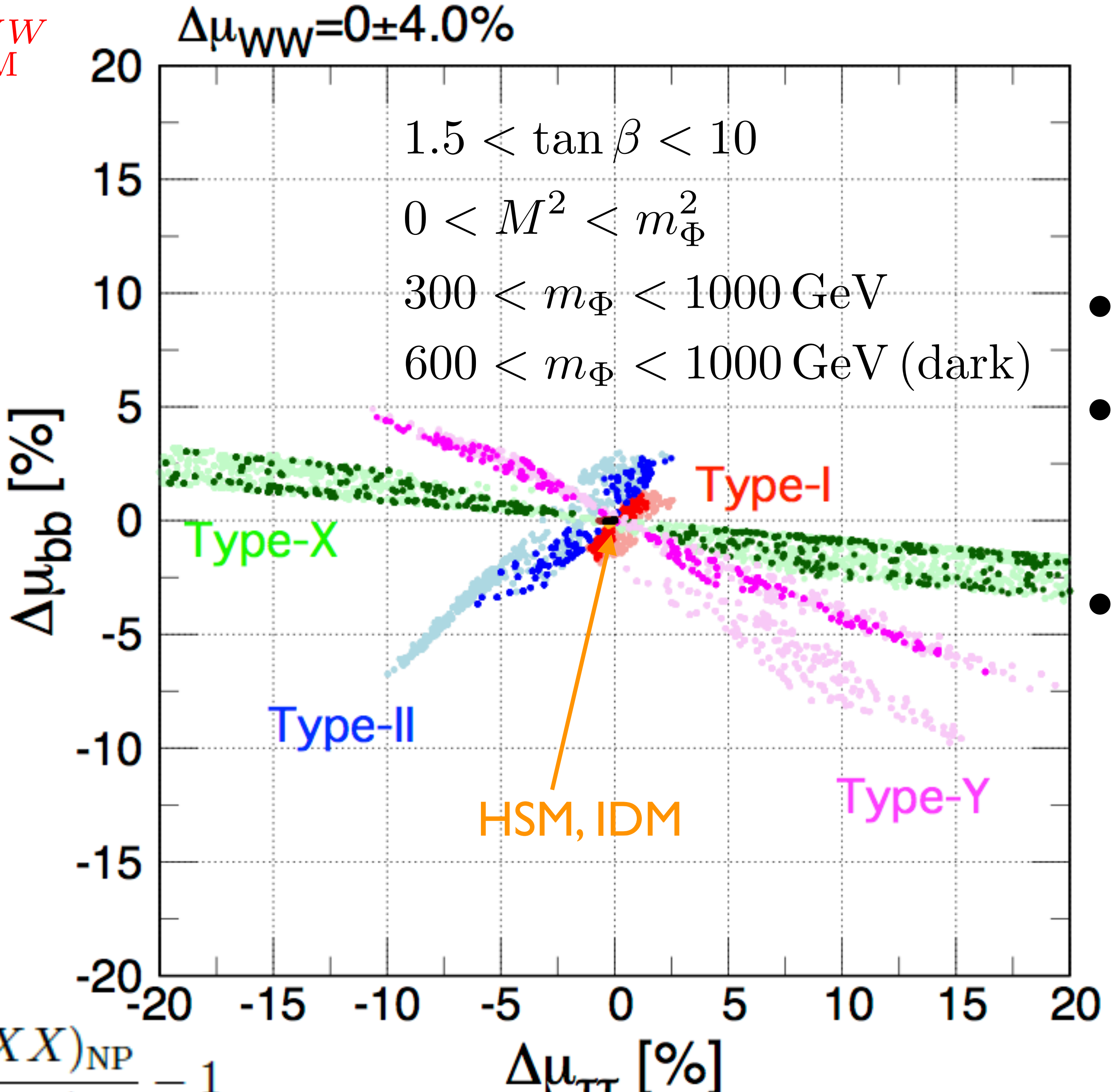
$A)\ B^{WW}_{\rm NP} \sim B^{WW}_{\rm SM}$

$B)\ B^{WW}_{\rm NP} > B^{WW}_{\rm SM}$

$C)\ B^{WW}_{\rm NP} < B^{WW}_{\rm SM}$

Correlations among the Higgs branching ratios

$A)\ B^{WW}_{\rm NP} \sim B^{WW}_{\rm SM}$

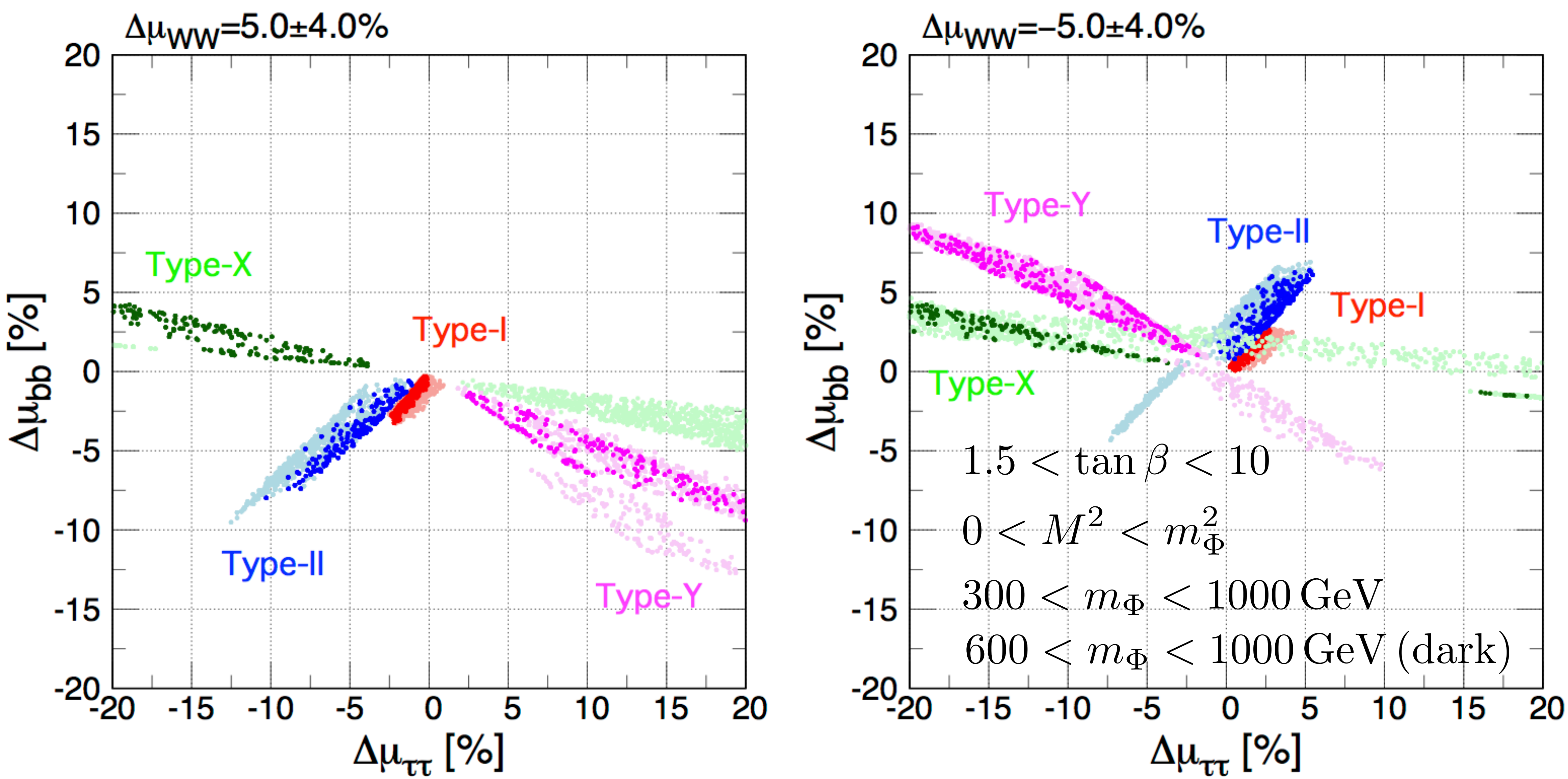


- HSM/IDM predict Δμ∼0.
- THDMs predict different correlations depending on the type of Yukawa int.
- The mass bounds from the direct searches/flavor constraints significantly reduce the allowed regions.

$$\Delta\mu_{XX} \equiv \frac{{\rm BR}(h\to XX)_{\rm NP}}{{\rm BR}(h\to XX)_{\rm SM}} - 1$$

Correlations among the Higgs branching ratios

$B)\ B^{WW}_{\rm NP} > B^{WW}_{\rm SM}$ $\qquad$ $C)\ B^{WW}_{\rm NP} < B^{WW}_{\rm SM}$



$1.5 < \tan\beta < 10$

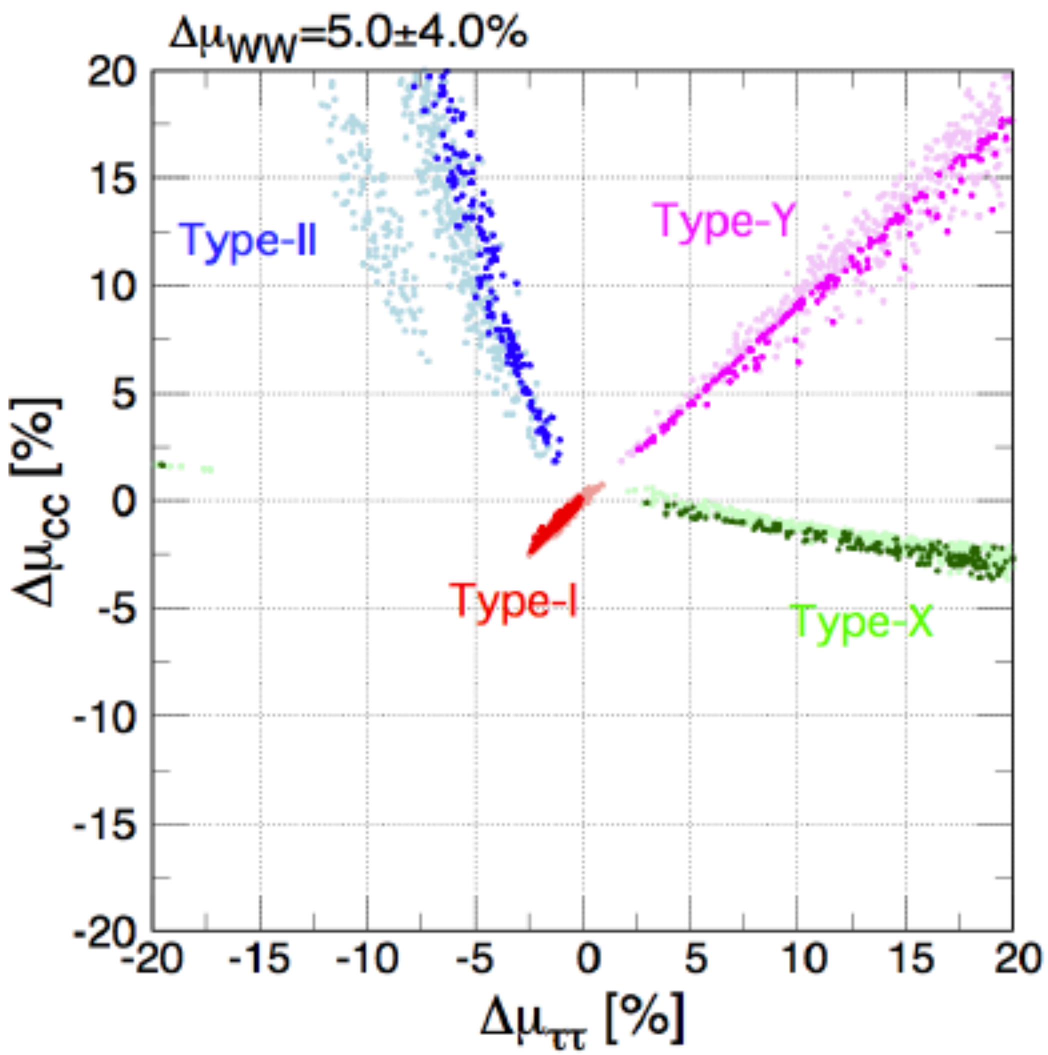
$0 < M^2 < m_\Phi^2$

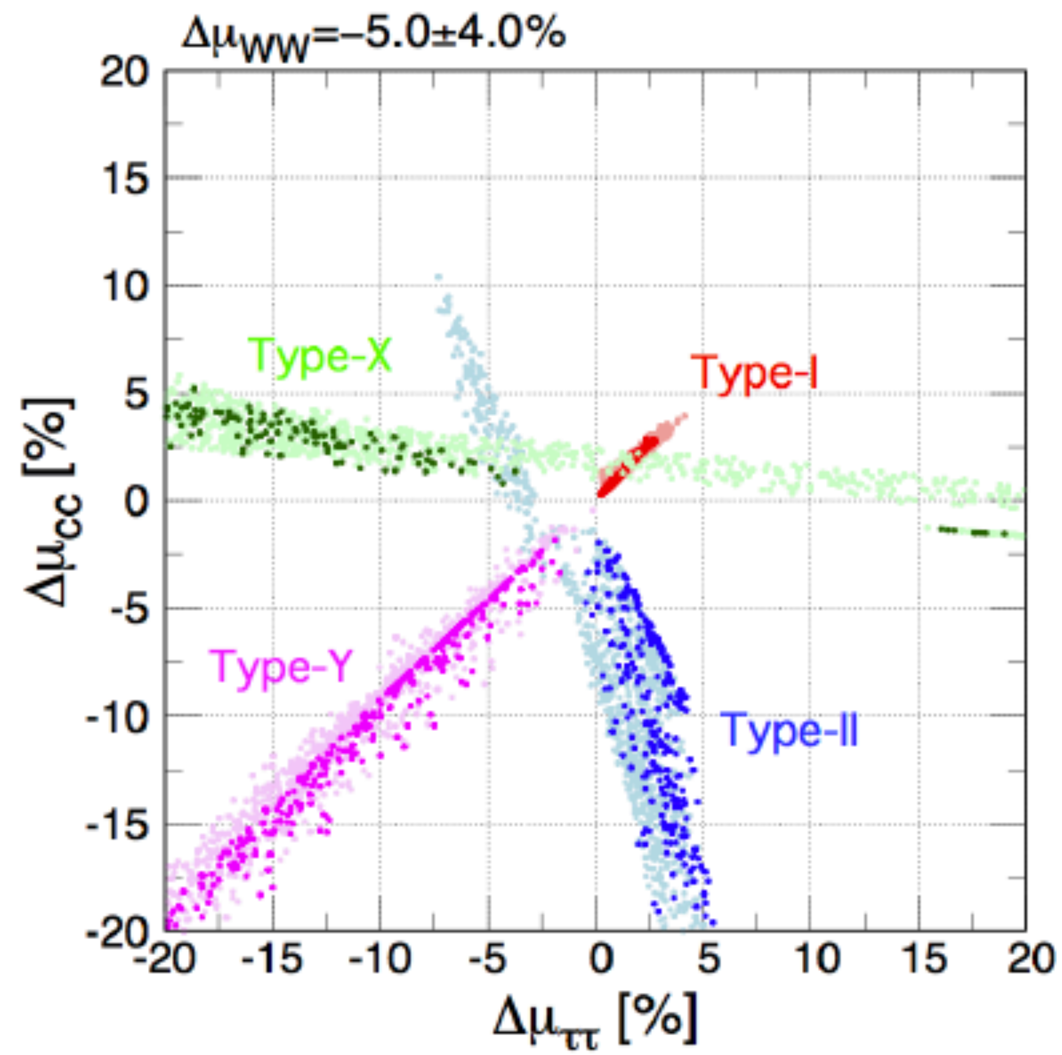
$300 < m_\Phi < 1000\,{\rm GeV}$

$600 < m_\Phi < 1000\,{\rm GeV}$ (dark)

Since the BRs are correlated among all the decay modes,
each model predicts a particular pattern of the deviations for each scenario.

BR(ττ) vs. BR(cc)

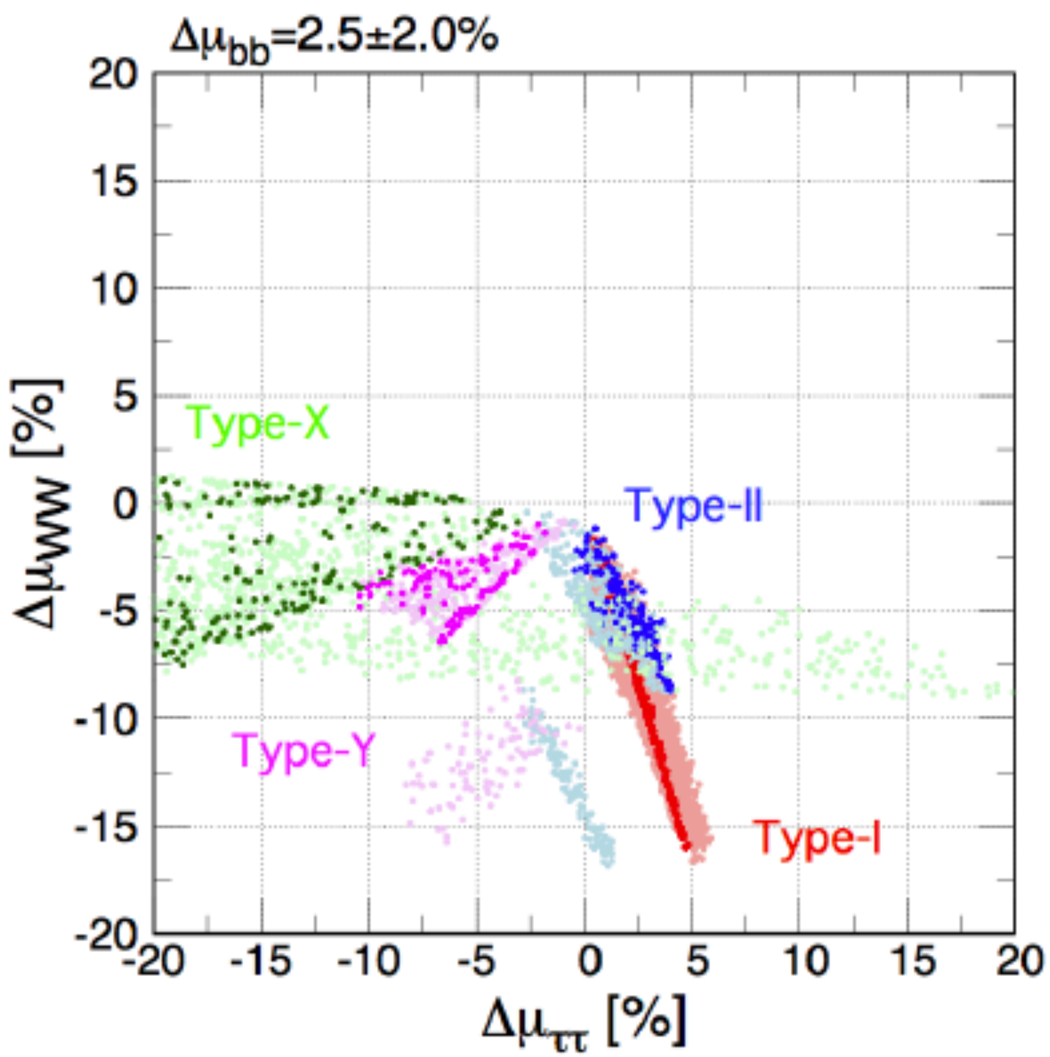


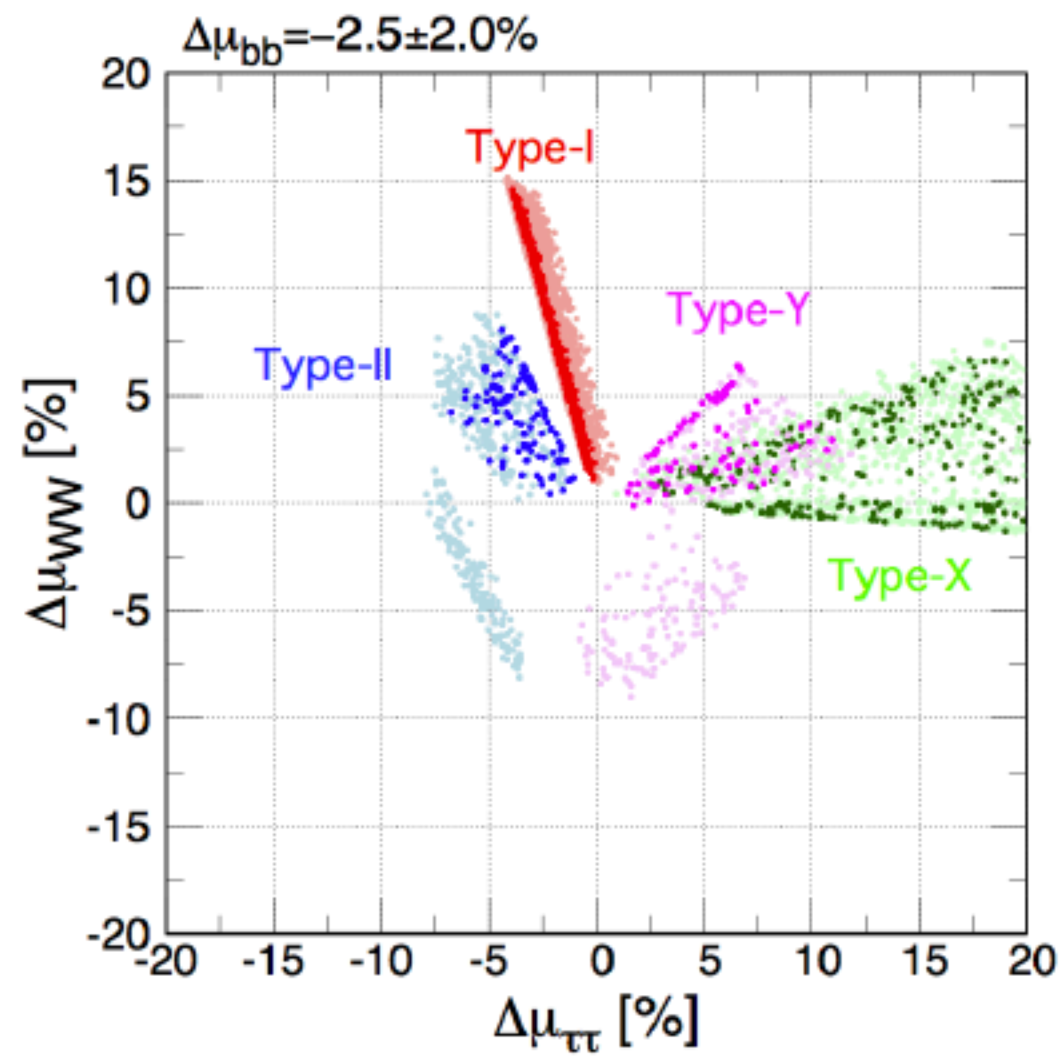


The measurement of h→cc is very important to disentangle the models.

➡ ILC is necessary!

BR(ττ) vs. BR(WW)





Synergy

- Higgs coupling precision measurements at the ILC
- direct searches for additional Higgs bosons at the LHC
- indirect searches in flavor experiments

4. まとめと展望

精密測定によるヒッグスセクターの究明が新物理探索の鍵！

- H-COUP v.1 was released in October, 2017. Kanemura, Kikuchi, Sakurai, Yagyu [1710.04603, CPC]
  - ***systematically*** calculates the renormalized 125GeV Higgs couplings at one-loop EW+QCD in various extended Higgs models (singlet extension, THDMs, inert doublet model).
- H-COUP v.2 will be released very soon. Kanemura, Kikuchi, Mawatari, Sakurai, Yagyu [1803.01456, PLB] + [1906.10070]
  - ***systematically*** calculates the 125GeV Higgs decay branching ratios at one-loop EW+QCD in various extended Higgs models (singlet extension, THDMs, inert doublet model).
- H-COUP v.3 ?
  - other models? couplings/decays for additional Higgs bosons?
  - other renormalization schemes?
  - Higgs productions? $e^+e^-\to h\gamma$; Kanemura, Mawatari, Sakurai [1808.10268, PRD]
  - …

H-COUP webpage: http://www-het.phys.sci.osaka-u.ac.jp/~kanemu/HCOUP_HP1013/HCOUP_HP.html