Full NLO calculations of the Higgs decay branching ratios in various extended Higgs models

[arXiv:1906.10070]

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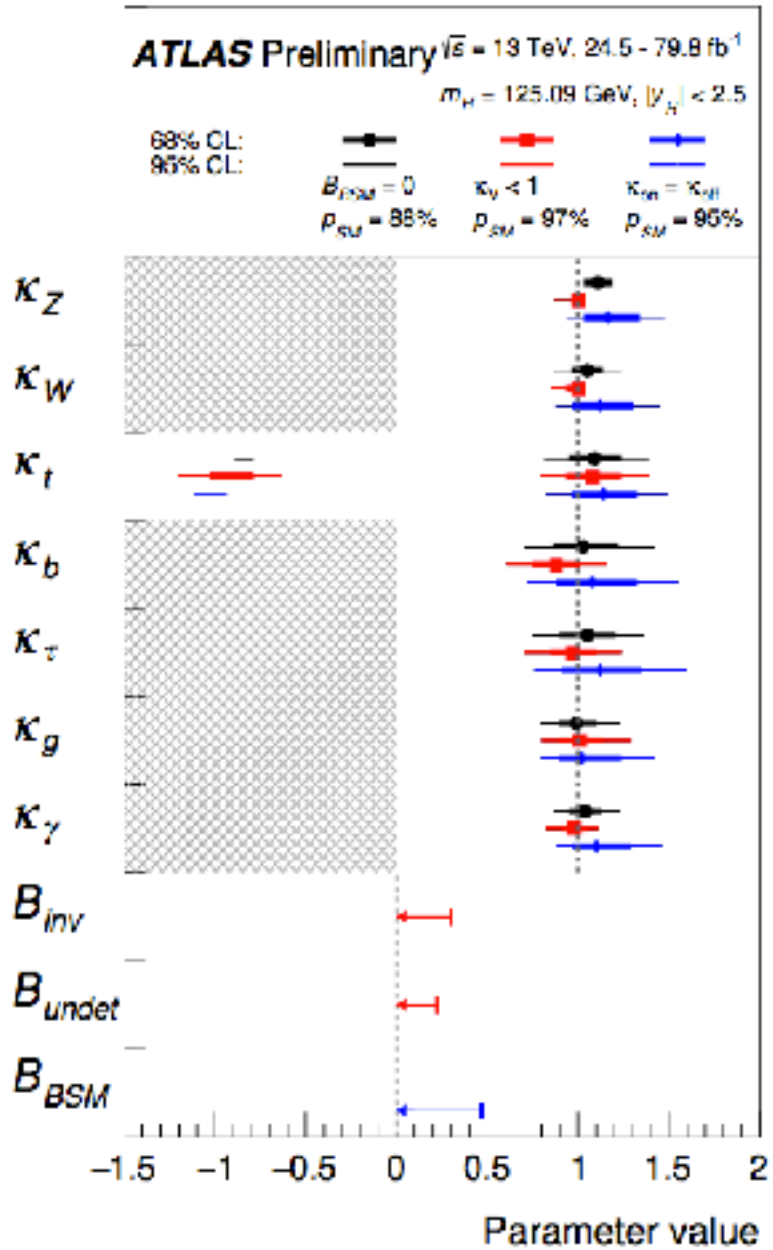
Scalars2019, Warsaw, 14.09.19

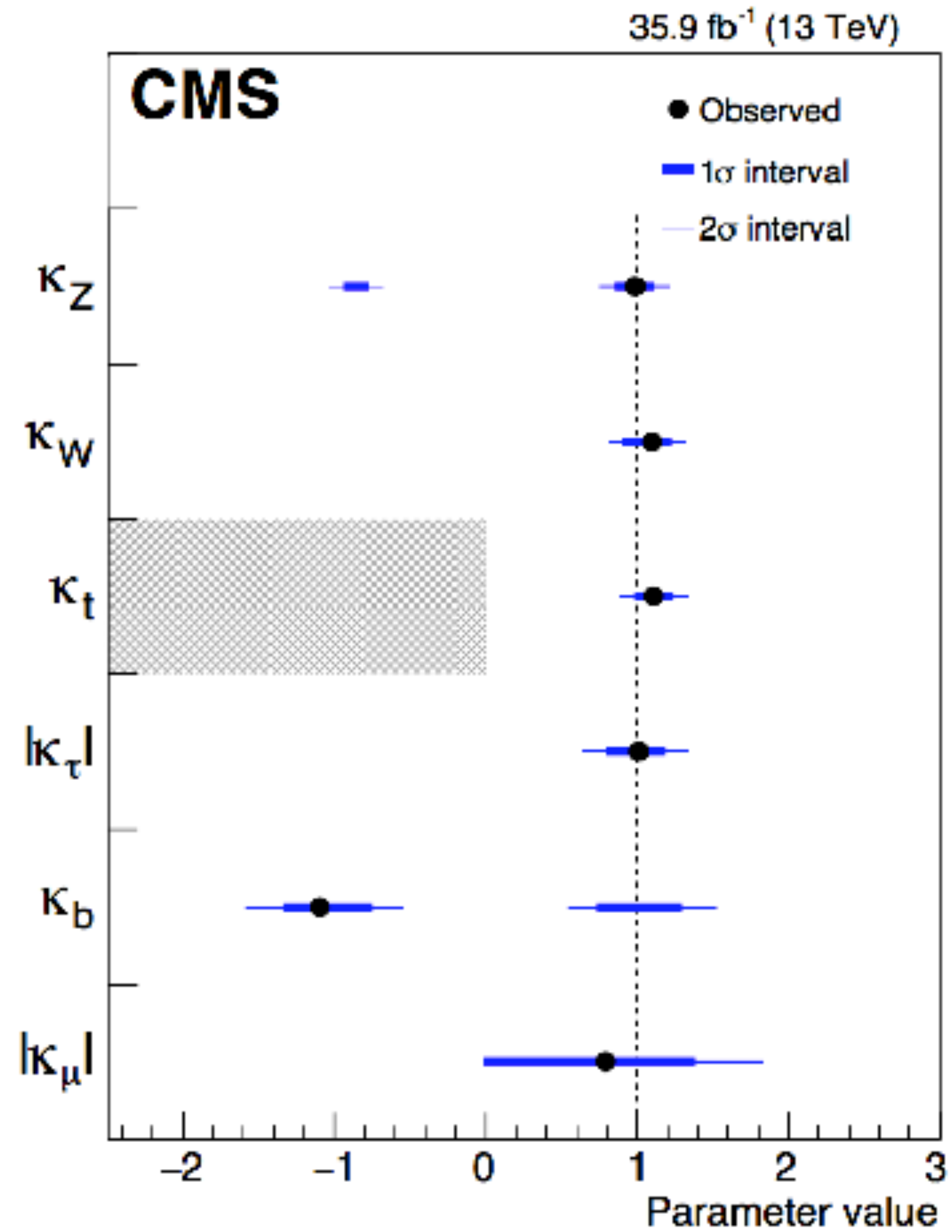
Motivation

Properties of the Higgs boson have been tested at the LHC.

[ATLAS-CONF-2019-005]



[CMS, Eur.Phys. J. C79 (2019), 421]



Current measurements are consistent with predictions of the SM within O(10)% uncertainty .

On the other hands, the structure of Higgs sector remains unknown.

- Negative mass term of the Higgs potential in the SM

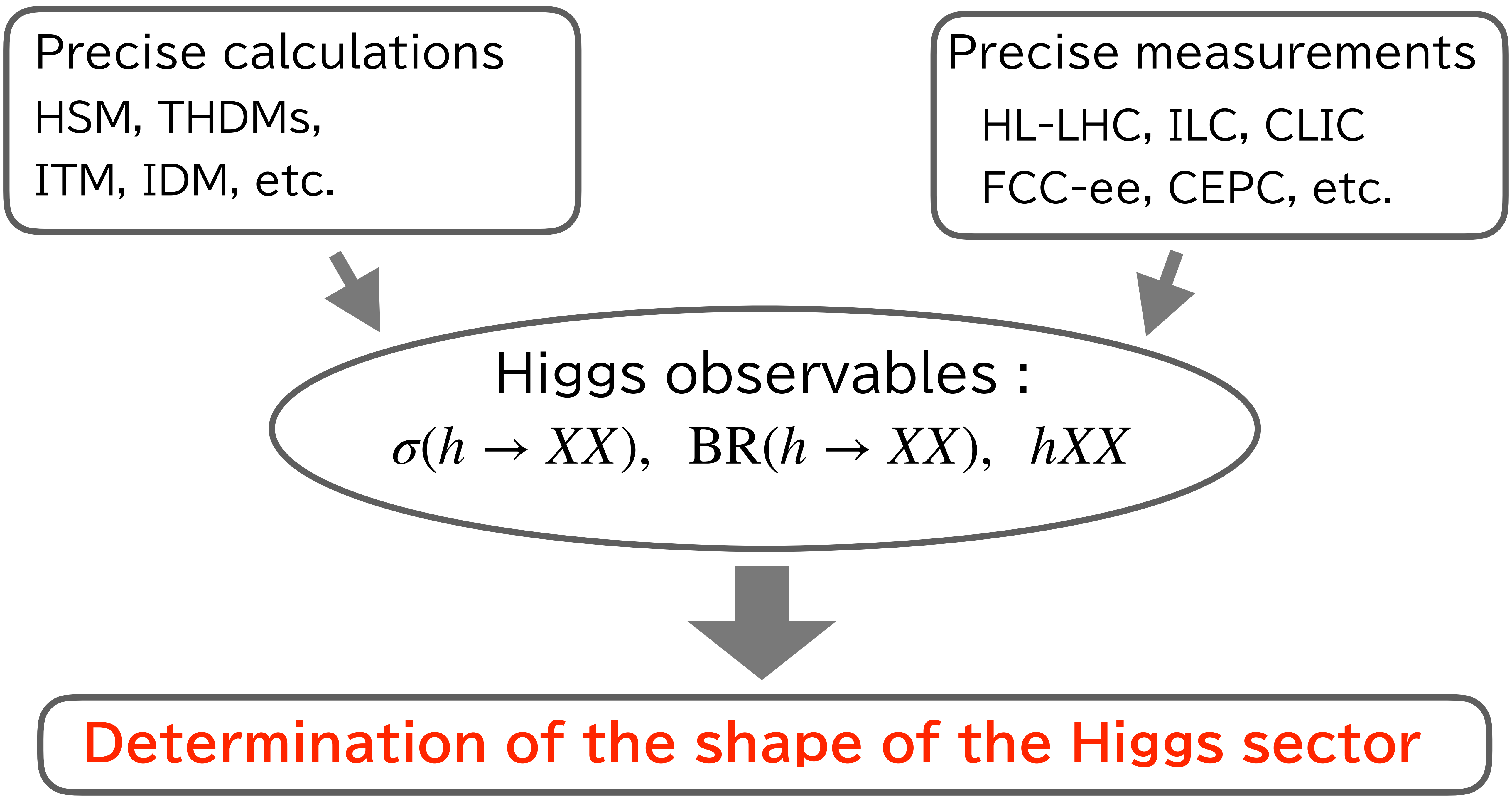
$$V = -\mu^2 |\Phi|^2 + \lambda |\Phi|^4$$

- Shape of the Higgs sector
  - Number of Higgs fields $\Phi + X + \ldots$
  - Representations of additional Higgs
  - Symmetry of the Higgs potential
- Relation with BSM phenomena
- …

→ Determination of the shape of Higgs sector is essential for exploring NP.

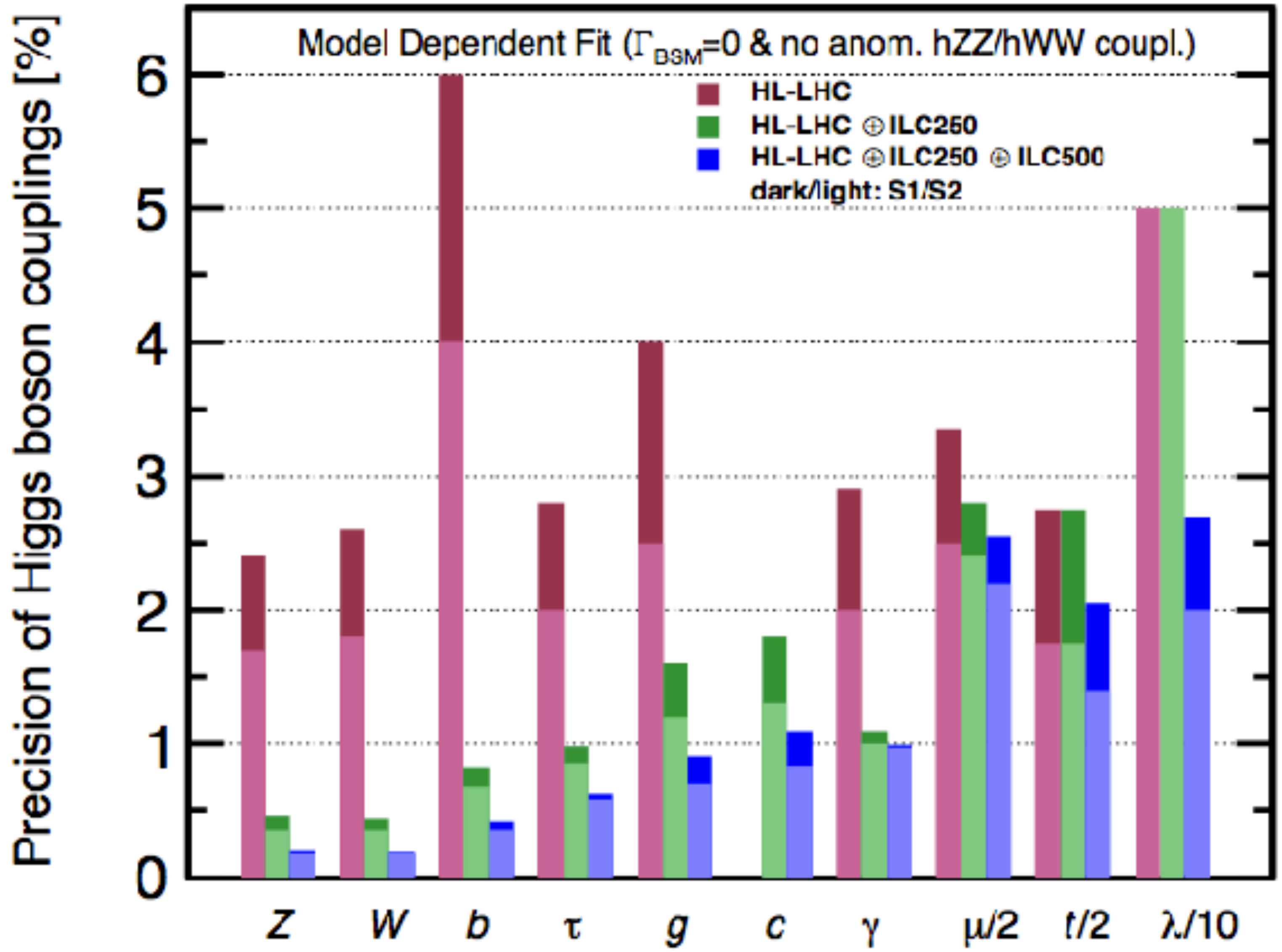
Concept

Our approaches to the determination of the shape of the Higgs sector is following:



Measurements accuracy of the Higgs couplings (prospect)

[arXiv:1901.09829]



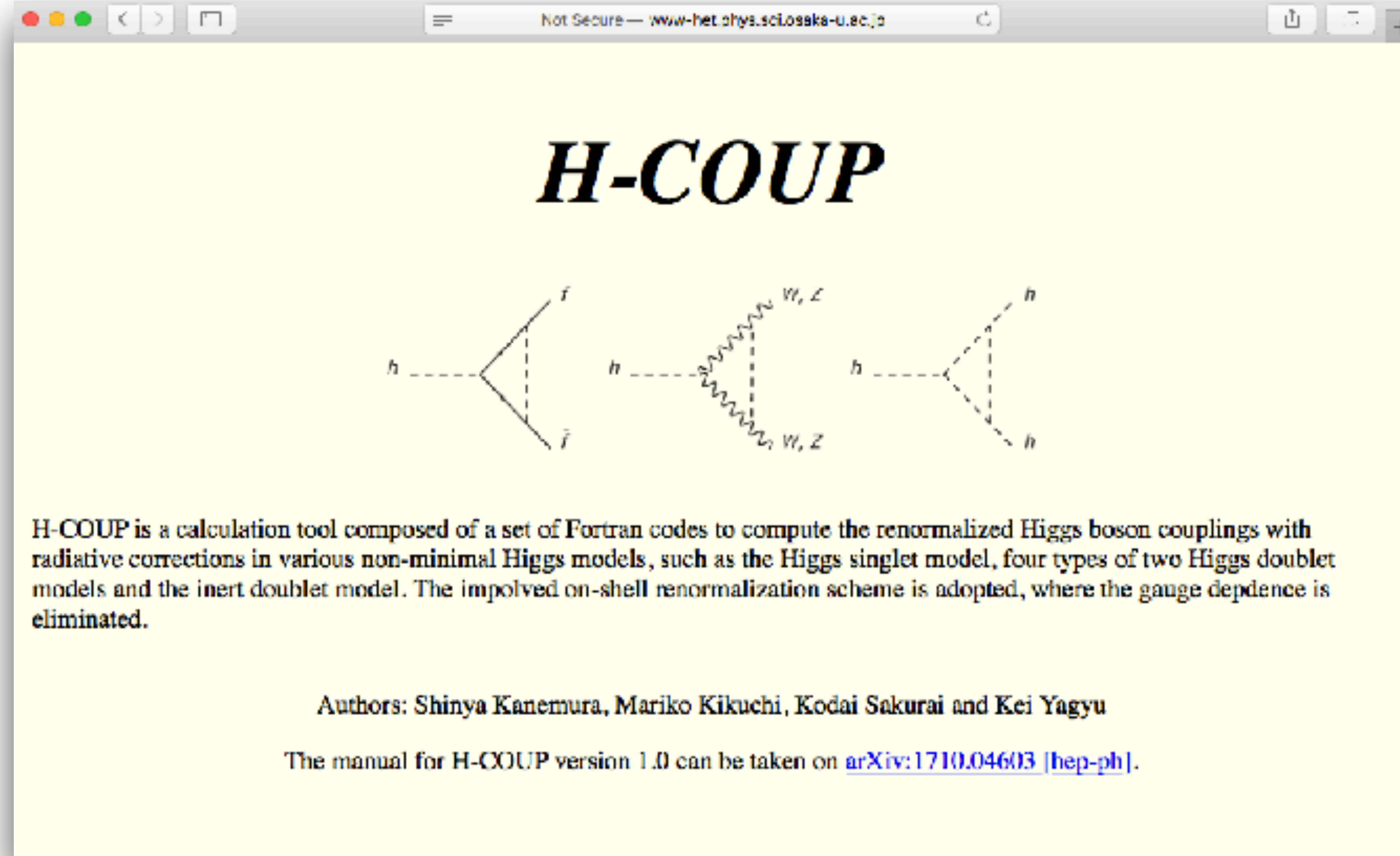
HL -LHC: $\mathcal{O}(1)\,\%$

ILC: $\mathcal{O}(1) \sim \mathcal{O}(0.1)\,\%$

Considerably improved

Challenging at LHC

- Sensitivity of most of couplings are improved by the ILC.
- In oder to compare with such precise measurements, we should evaluate theoretical predictions with radiative corrections.



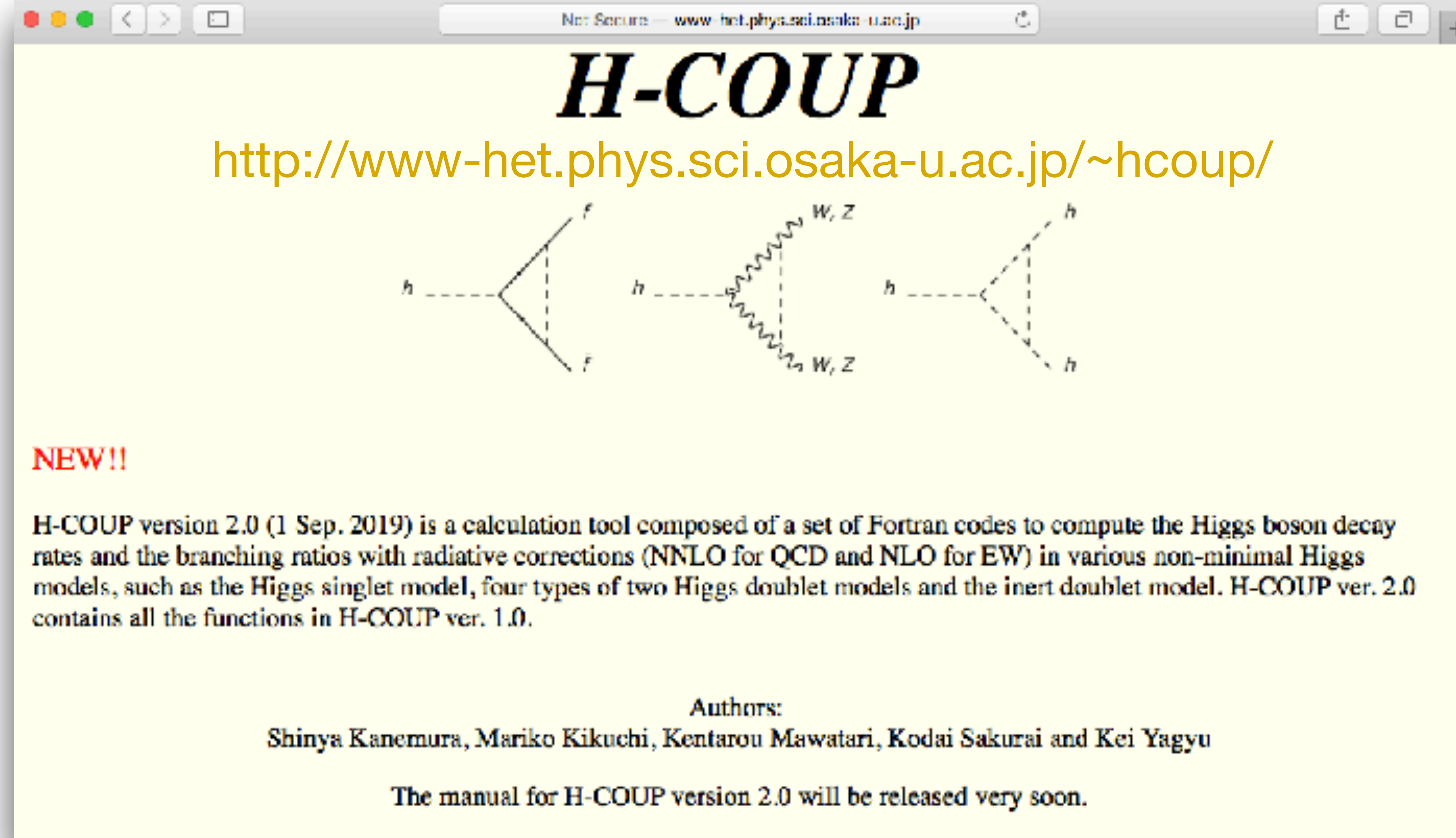
H-COUP1.0(13.10.18~)

Model:

- Singlet extension of the SM
- 4 types of 2HDMs
- Inert doublet model

Evaluation:

- Higgs vertex functions (at 1-loop)


H-COUP

http://www-het.phys.sci.osaka-u.ac.jp/~hcoup/

NEW!!

H-COUP version 2.0 (1 Sep. 2019) is a calculation tool composed of a set of Fortran codes to compute the Higgs boson decay rates and the branching ratios with radiative corrections (NNLO for QCD and NLO for EW) in various non-minimal Higgs models, such as the Higgs singlet model, four types of two Higgs doublet models and the inert doublet model. H-COUP ver. 2.0 contains all the functions in H-COUP ver. 1.0.

Authors:
Shinya Kanemura, Mariko Kikuchi, Kentarou Mawatari, Kodai Sakurai and Kei Yagyu

The manual for H-COUP version 2.0 will be released very soon.

H-COUP1.0(13.10.18~)

Model:

- Singlet extension of the SM
- 4 types of 2HDMs
- Inert doublet model

Evaluation:

- Higgs vertex functions (at 1-loop)

H-COUP2.0(03.09.19~)

Model:

Same as ver. 1.0

Evaluation:

- Higgs vertex functions (at 1-loop)
- New – Higgs branching ratios (with NLO EW and NNLO QCD)

In this talk

By using **H-COUP**, We have evaluated Higgs BRs with full 1-loop corrections in 6 different models.

The predictions can be directory compared with exp. data

Open questions:

- how is decoupling property of additional Higgs bosons for BRs?
- What is pattern of deviations from the SM for BRs for each model?

→ We show size of additional Higgs boson loop cont. for BRs.

→ We discuss if various extended Higgs models are discriminated by using precise measurements of Higgs BRs.

Set up

We treat 6 simple extended Higgs models.

- **Higgs singlet models (HSM)**

The potential has shift invariance → $< S > = 0$
$[\ S \to S + v_s'\ ]$

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

- Physical state : h, H
- Free parameters : $m_H,\ \cos\alpha,\ m_s^2,\ \mu_S,\ \lambda_S$
- Higgs couplings : $\kappa_V = \kappa_f = \cos\alpha$

$$\kappa_X = \frac{g(hXX)^{EX.}}{g(hXX)^{SM}}$$

- **Inert doublet model (IDM)** [exact Z2 symmetry] → Dark matte candidate

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

- Physical state : h,H,A,$H^\pm$
- Free parameters : $m_H, m_A, m_{H^\pm},\ \lambda_2,\ m_2$
- Higgs couplings : $\kappa_V = \kappa_f = 1$

- **Two Higgs doublet models (THDMs)**

[softly broken Z_2 symmetry]
→ 4types of Yukawa int.
(Type-I, II, X, Y)

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

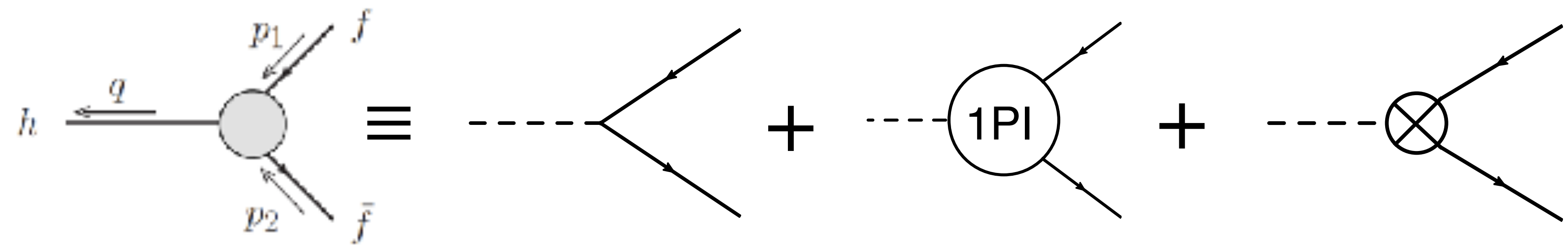
- Physical state : $h, H, A, H^\pm$
- Free parameters : $m_H, m_A, m_{H^\pm}, s_{\beta-\alpha}, t_\beta, M^2(=m_3^2/(s_\beta c_\beta))$
- Higgs couplings : $\kappa_V = \sin(\beta-\alpha),\ \kappa_f = \sin(\beta-\alpha) + \xi_f \cos(\beta-\alpha)$

	ξ_u	ξ_d	ξ_e
Type-I	$\cot\beta$	$\cot\beta$	$\cot\beta$
Type-II	$\cot\beta$	$-\tan\beta$	$-\tan\beta$
Type-X	$\cot\beta$	$\cot\beta$	$-\tan\beta$
Type-Y	$\cot\beta$	$-\tan\beta$	$\cot\beta$

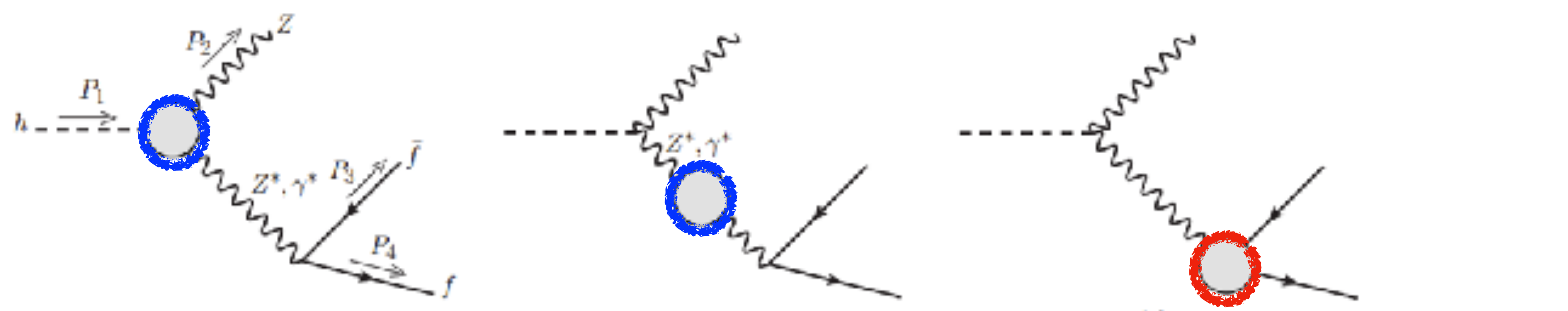
One-loop calculation of Higgs decay rates

By using **H-COUP**, we calculated Higgs decay rates at the 1-loop.
in the on-shell scheme.

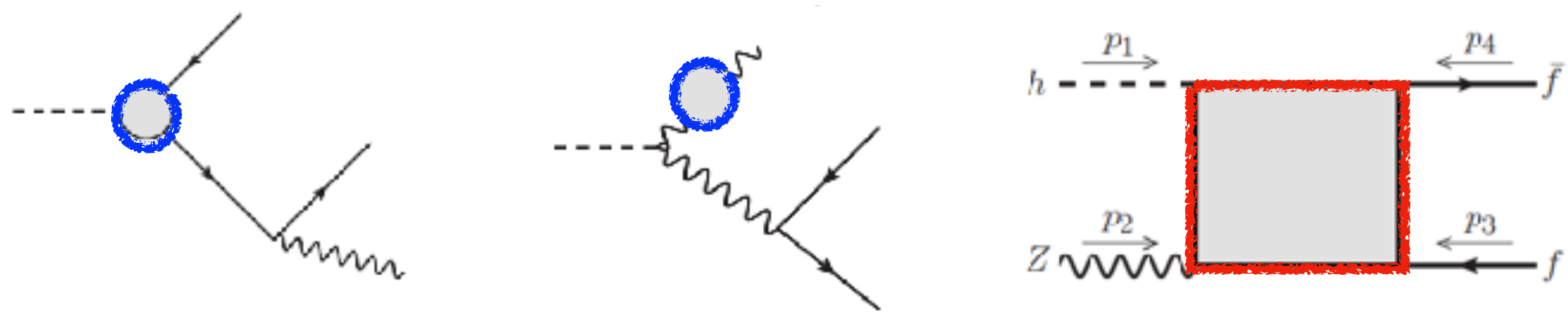
$h \to ff$:



$h \to VV^*$:



hVV vertex correction | Self-energy correction | *Vff* vertex correction



hff vertex correction | Wave function | Box diagram correction

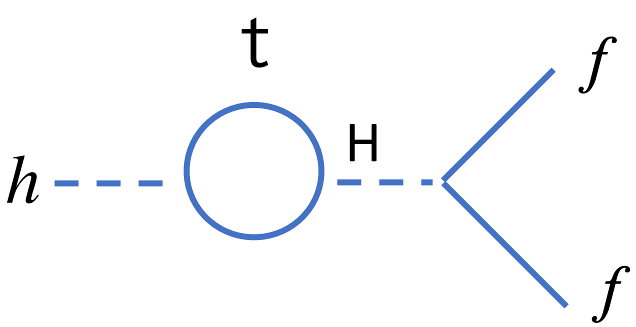
Higgs vertices and self -energy are computed by H-COUP ver.1.0.

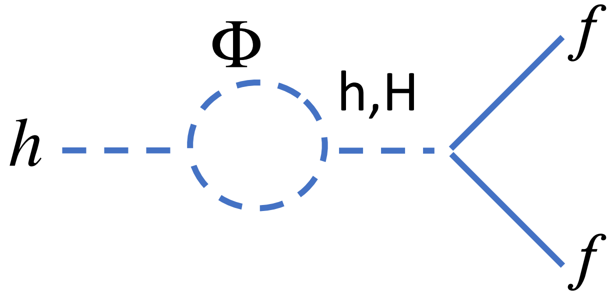
New ingredients of ver. 2.0

Higgs branching ratios at the 1-loop

We examined magnitude of additional Higgs boson loop contributions for Higgs branching ratios in 2HDMs

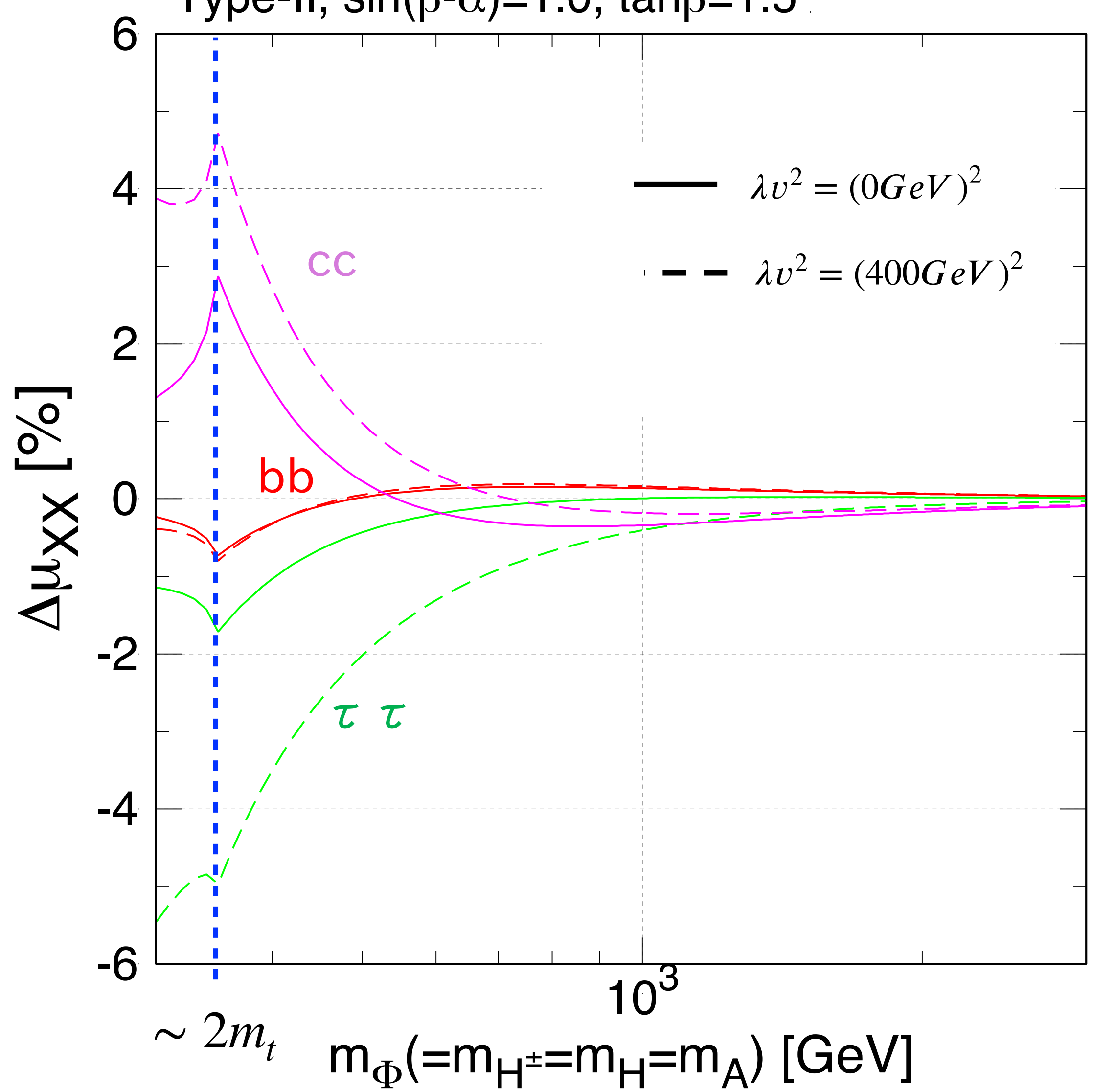
Typical graph :





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

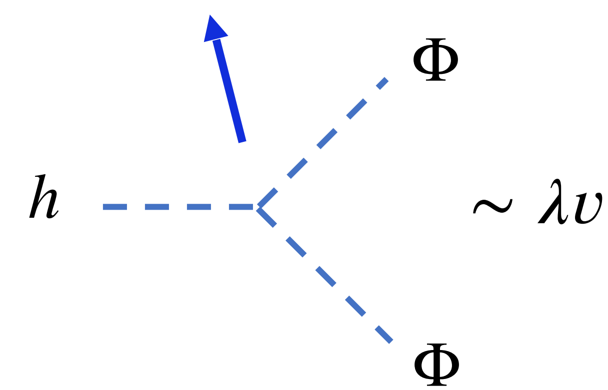
[Kanemura, Kikuchi, Mawatari ,KS, Yagyu]



Deviations from SM :

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

$$\lambda v^2 \equiv m_\Phi^2 - M^2$$



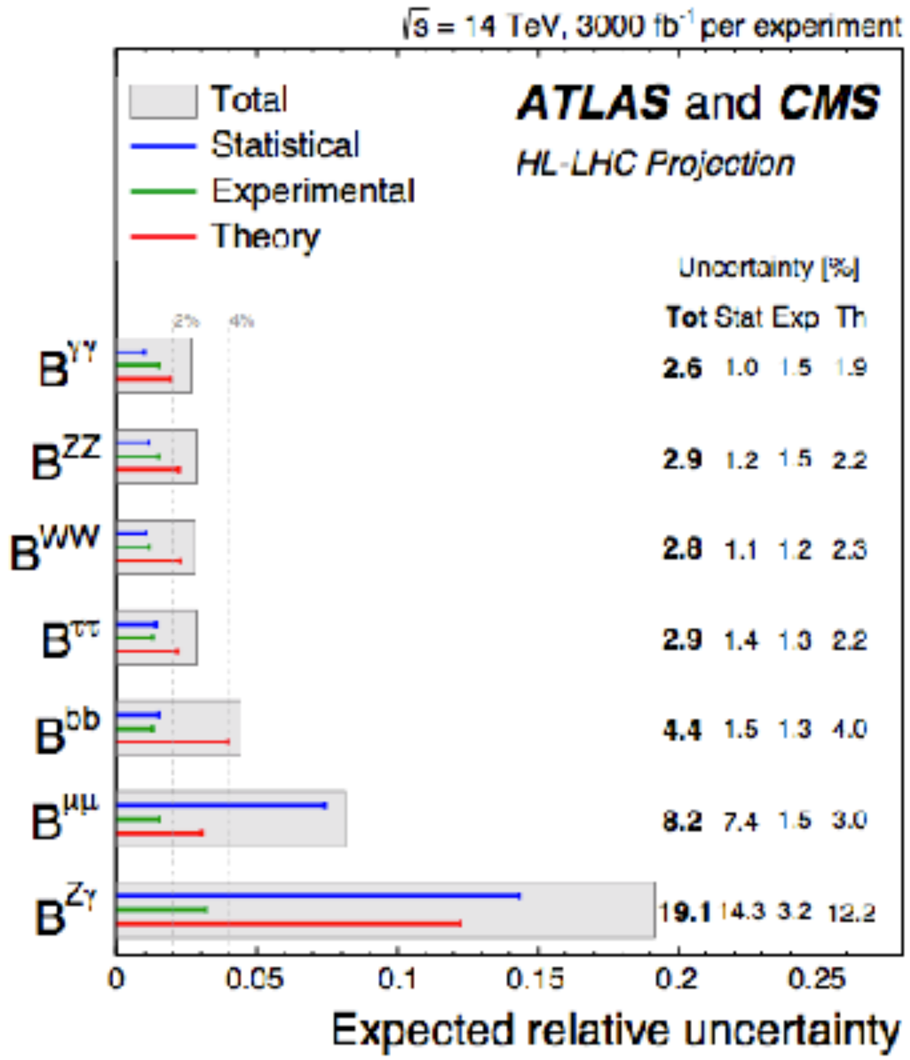
$m_\Phi \gg v$: Additional Higgs loop contributions decouple.

$m_\Phi \sim v$: Non-decoupling effect can be appeared at few %.

Discrimination of the models

We discuss whether 6 different models are discriminated by precise measurements of Higgs branching ratios.

HL-LHC [1902.00134]



ILC [1710.07621]

	1σ	2σ
$B^{\gamma\gamma}$	13%	26%
B^{ZZ}	6.7%	13.4%
B^{WW}	1.9%	3.8%
$B^{\tau\tau}$	1.4%	2.8%
B^{bb}	0.89%	1.78%
$B^{\mu\mu}$	27%	54%

We consider situations that B^{WW} are measured with few % accuracy at the ILC.

→We studied three cases:

①: $\Delta\mu_{WW} = 0 \pm 4\,\%$ ②: $\Delta\mu_{WW} = 5 \pm 4\,\%$ ③: $\Delta\mu_{WW} = -5 \pm 4\,\%$

Case ① : $\Delta\mu_{WW} = 0 \pm 4\,\%$

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

- Plot of color :
  Predictions of each model

- Brightness of color :
  Value of m_Φ

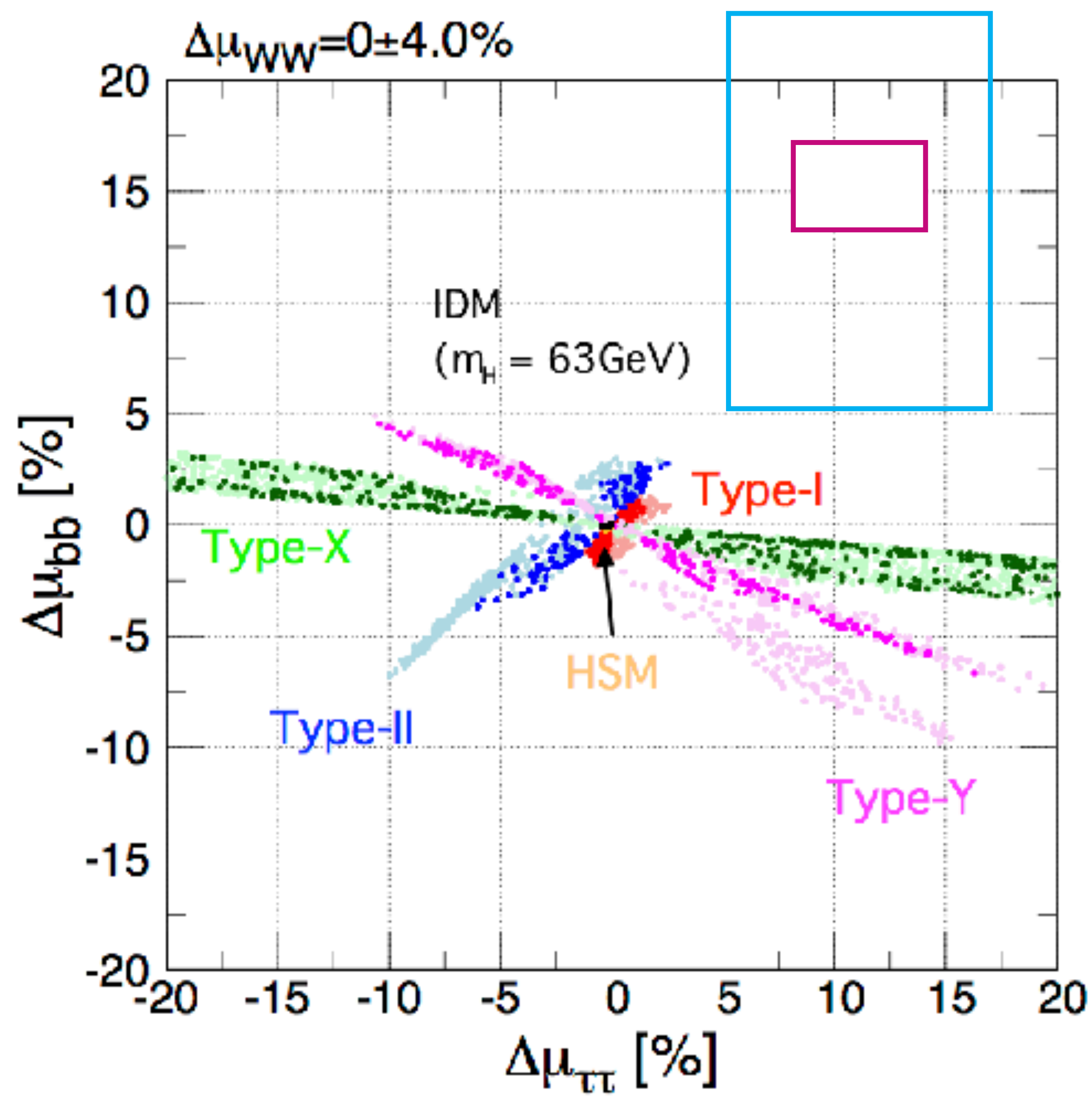
  - Lighter colors: $m_\Phi < 600\mathrm{GeV}$
  - Darker colors: $m_\Phi > 600\mathrm{GeV}$

Lower bound from $b \to s\gamma$
(for Type-II,Y)

HL-LHC(2σ):
[ATLAS, CMS,1902.00134]

ILC(2σ):
[T. Barlow et al. 1710.07621]

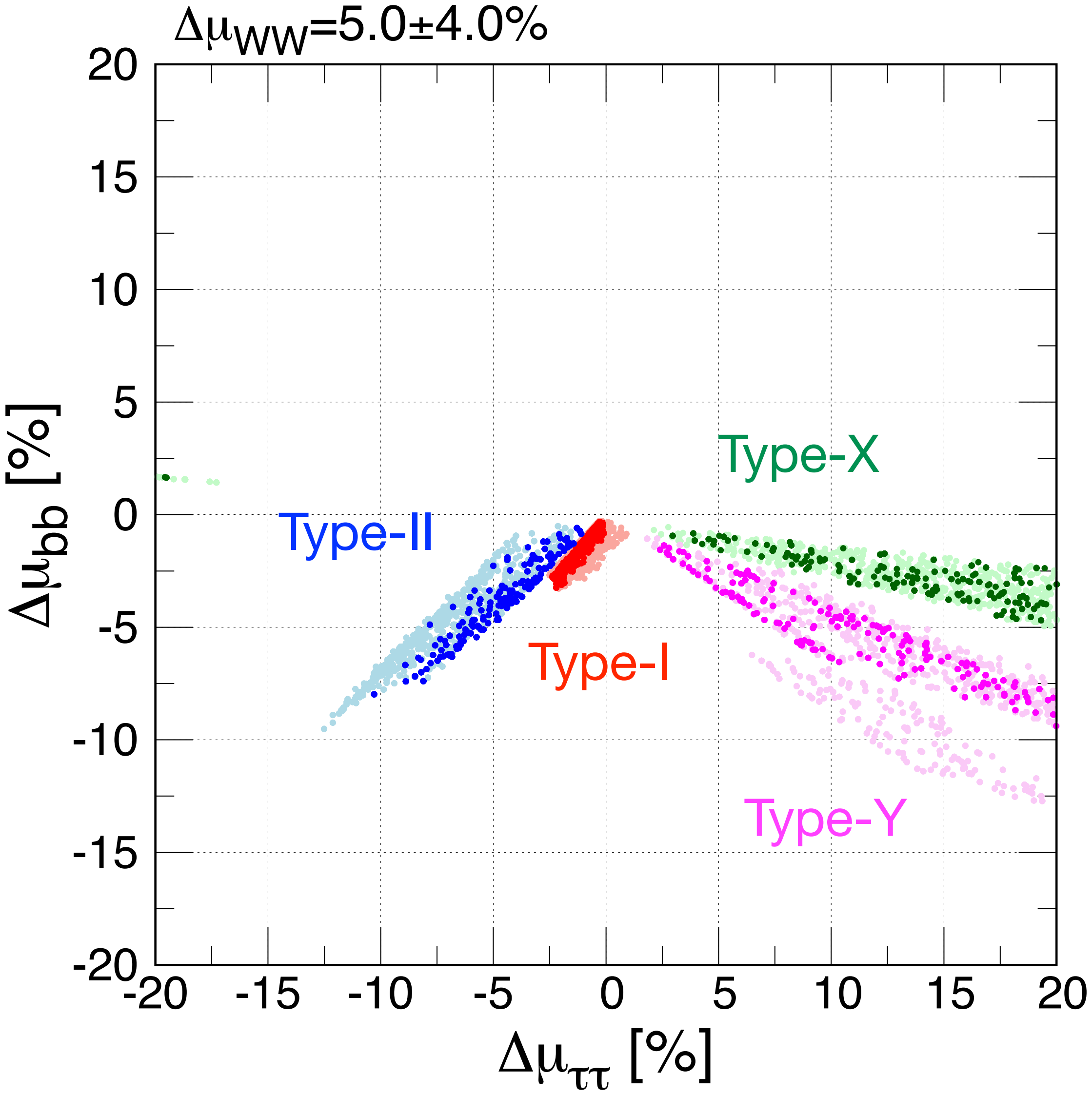
[Kanemura, Kikuchi, Mawatari ,KS, Yagyu]



If $|\Delta\mu_{\tau\tau}| \gtrsim 5\,\%$, 4 types of THDMs can be separated.

Case ② : $\Delta\mu_{WW} = 5 \pm 4\,\%$

[Kanemura, Kikuchi, Mawatari ,KS, Yagyu]

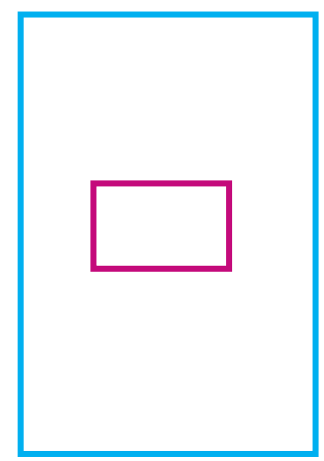


HL-LHC(2 σ):

[ATLAS, CMS,1902.00134]

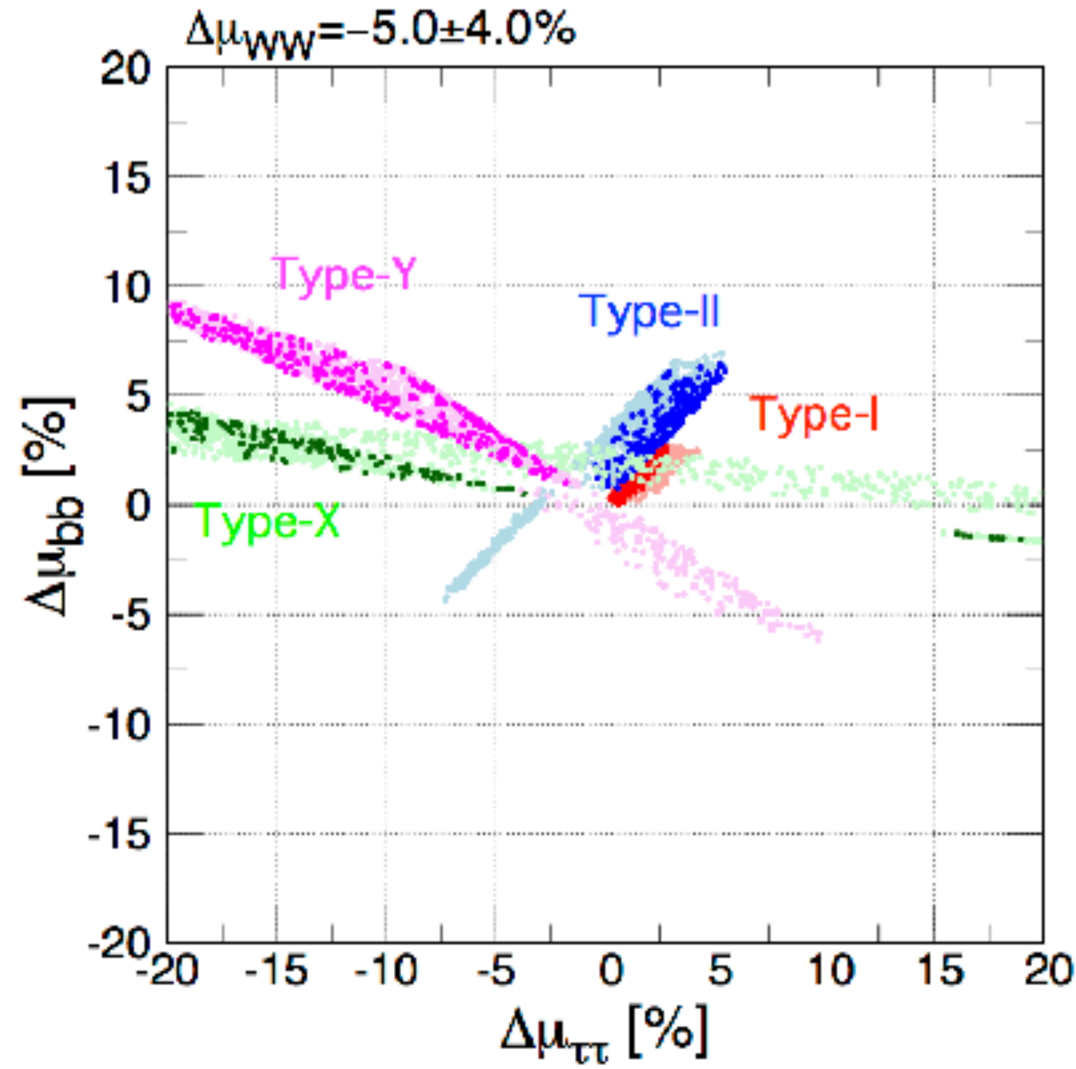
ILC(2 σ):

[T. Barlow et al. 1710.07621]



Case ③ : $\Delta\mu_{WW} = -5 \pm 4\,\%$

[Kanemura, Kikuchi, Mawatari ,KS, Yagyu]



- In both case, HSM and IDM are already excluded.
- In case② all models predictions are completely separated.
- In case③, if m_Φ>600 GeV, we can distinguish all models

Summary

- We published **`H-COUP2.0`**.

- **`H-COUP2.0`** can evaluate Higgs branching ratios at NLO EW and NNLO QCD in various extended Higgs modlels.

- We investigated the deviations from the SM in the 3 cases:

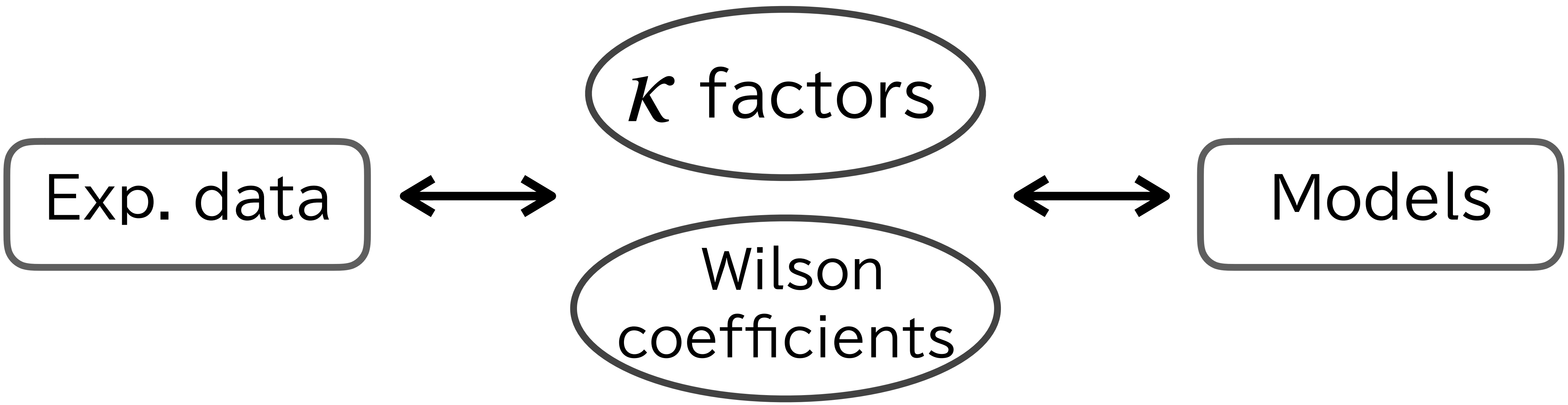
	Constraint for $\Delta\mu_{WW}$	Discriminations of models
①	$\Delta\mu_{WW} = 0 \pm 4\,\%$	Possible (if $\lvert\Delta\mu_{\tau\tau}\rvert \gtrsim 5\,\%$)
②	$\Delta\mu_{WW} = 5 \pm 4\,\%$	Possible
③	$\Delta\mu_{WW} = -5 \pm 4\,\%$	Possible (if m_Φ>600 GeV)

→In any case, there are situations all models can be discriminated.

Buck up slide

Comparison with exp. data

- κ-framework, EFT framework



- Higgs branching ratios

Deviations

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

$$\Delta\mu_{XX} \simeq \overline{\Delta}^{X}_{\mathrm{EW}} - \sum_{f} \mathrm{BR}^{0}(h \to f f)\overline{\Delta}^{f}_{\mathrm{EW}} - \sum_{V} \mathrm{BR}^{0}(h \to V V^{*})\overline{\Delta}^{V}_{\mathrm{EW}}$$

Two Higgs doublet model(THDM)

- Higgs potential

$$\Phi_i = \begin{pmatrix} w_i^+ \\ \frac{1}{\sqrt{2}}(v_i + h_i + iz_i) \end{pmatrix} \quad \text{with} \quad i = 1, 2$$

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

- Mass eigenstates

$$\begin{pmatrix} h_1 \\ h_2 \end{pmatrix} = R(\alpha)\begin{pmatrix} H \\ h \end{pmatrix}, \quad \begin{pmatrix} z_1 \\ z_2 \end{pmatrix} = R(\beta)\begin{pmatrix} z \\ A \end{pmatrix}, \quad \begin{pmatrix} w_1^+ \\ w_2^+ \end{pmatrix} = R(\beta)\begin{pmatrix} w^+ \\ H^+ \end{pmatrix}$$

Physical state :h, H, A, $H^{\pm}$

- Physical parameters

$$\mathrm{v}, \mathrm{m_h}, \mathrm{m_H}, \mathrm{m_A}, \mathrm{m_{H^\pm}}, \alpha, \beta, M^2$$

Higgs singlet model(HSM)

- Higgs potential

$$\Phi = \begin{pmatrix} G^+ \\ \frac{1}{\sqrt{2}}(v + \phi + iG^0) \end{pmatrix}, \quad S = v_S + s$$

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

- Mass eigenstates

$$\begin{pmatrix} s \\ \phi \end{pmatrix} = R(\alpha) \begin{pmatrix} H \\ h \end{pmatrix} \quad \text{with} \quad R(\alpha) = \begin{pmatrix} c_\alpha & -s_\alpha \\ s_\alpha & c_\alpha \end{pmatrix}$$

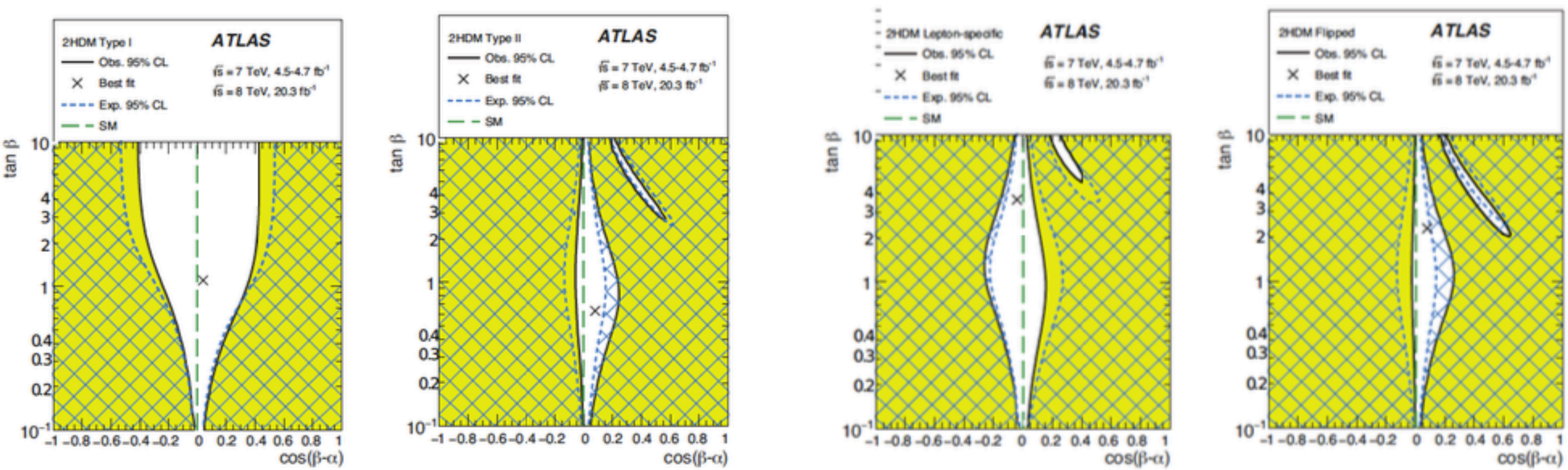
Physical state :*h, H*

- Physical parameters

$$\mathrm{v}, \mathrm{m_h}, \mathrm{m_H}, , \alpha, m_S^2, \lambda_S, \mu_{\Phi S}$$

constraint for THDMs (Higgs signal strength)

[ATLAS, JHEP1511(2015)206]



(a) Type I (b) Type II (c) Lepton-specific (d) Flipped

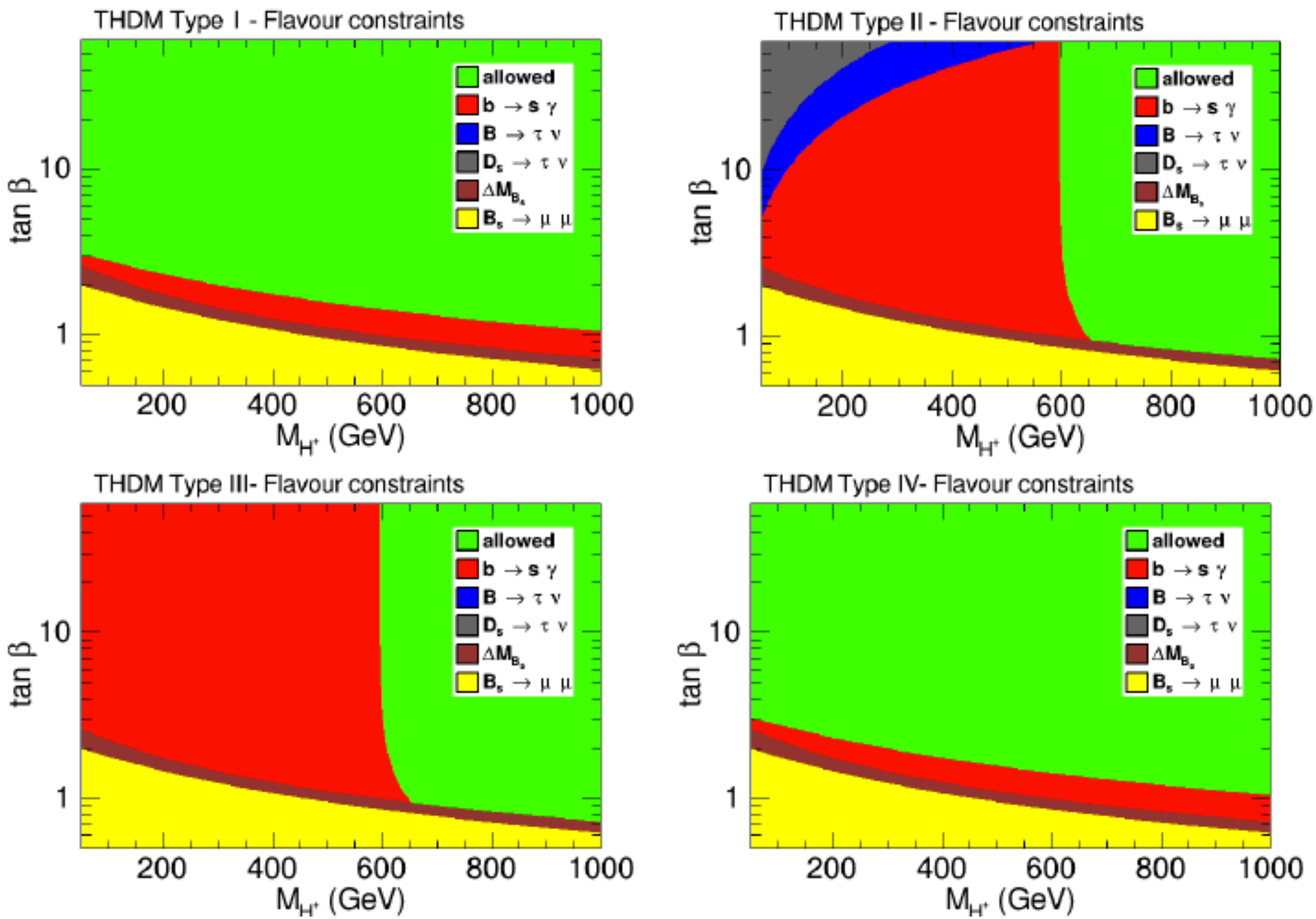
$c_{\beta-\alpha} = 0.1 \rightarrow s_{\beta-\alpha} = 0.99$

$c_{\beta-\alpha} = 0.2 \rightarrow s_{\beta-\alpha} = 0.98$

$c_{\beta-\alpha} = 0.3 \rightarrow s_{\beta-\alpha} = 0.95$

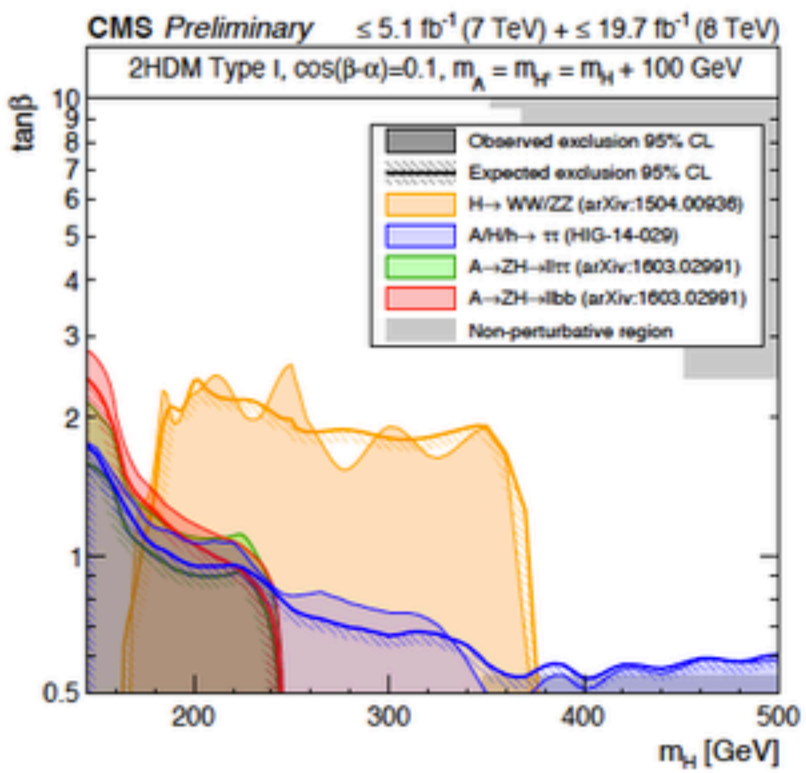
Constraint from flavor experiments

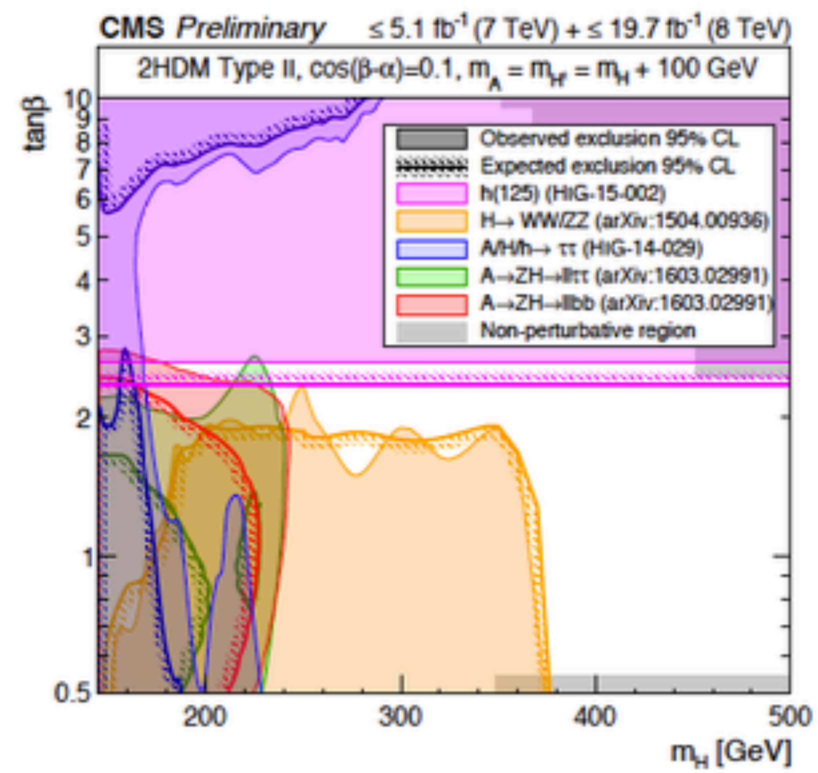
A. Arbey, F. Mahmoudi,O. Stal T. Stefaniak arXiv:1706.07414v1



Status of direct search of extra Higgs

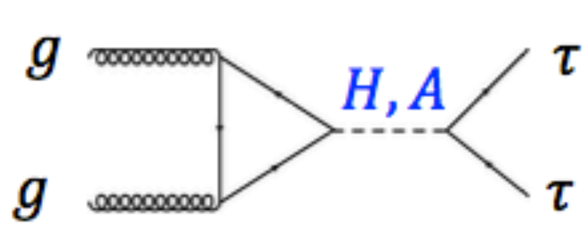
- constraint for THDMs (LHC Run I, Summary plots by CMS) [CMS PAS HIG-16-007]

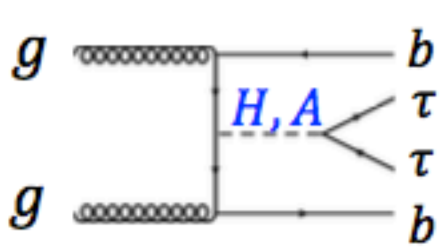


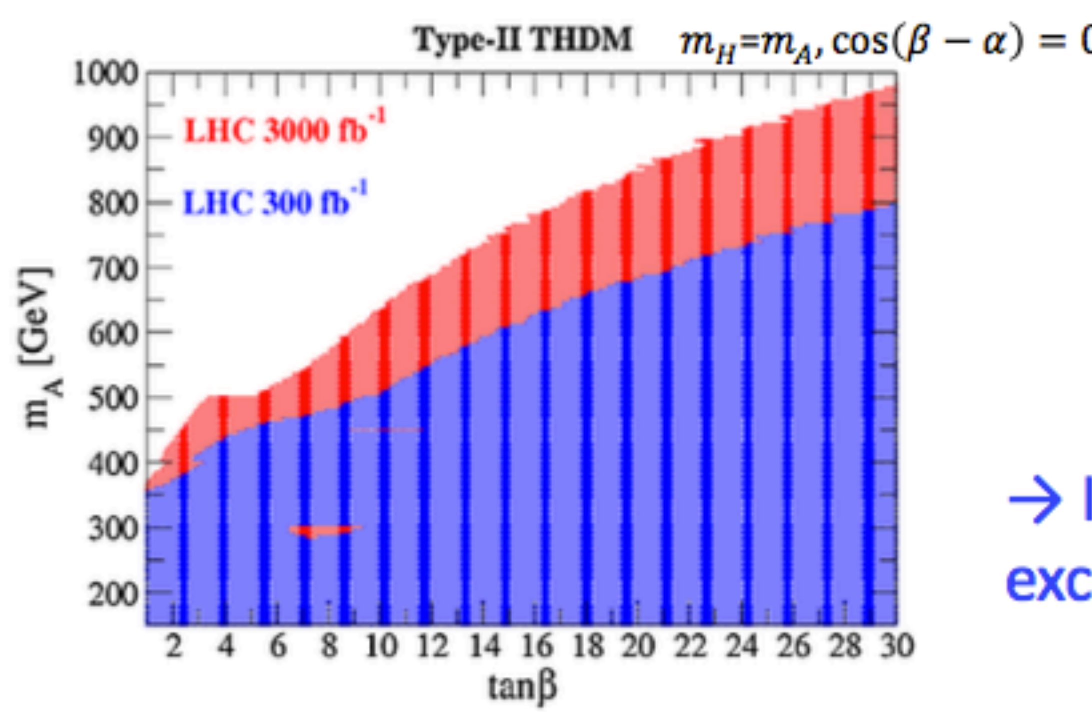


→ Basically, for Type II $tan\beta < 2$, $m_H < 380$ GeV are excluded.

- Future prospect of excluded regions [Kanemura, Tsumura, Yagyu, Yokoya, PRD90(2014)075001]







→ In the future exp. excluded regions are spread.

Definition of form factors for *hVV* and hff

$$\hat{\Gamma}^{\mu\nu}_{hVV} = \hat{\Gamma}^{1}_{hVV} g^{\mu\nu} + \hat{\Gamma}^{2}_{hVV} \frac{p_1^{\mu} p_2^{\nu}}{m_V^2} + i \hat{\Gamma}^{3}_{hVV} \epsilon^{\mu\nu\rho\sigma} \frac{p_{1\rho} p_{2\sigma}}{m_V^2} ,$$

$$\hat{\Gamma}_{hff} = \hat{\Gamma}^{S}_{hff} + \gamma_5 \hat{\Gamma}^{P}_{hff} + \not{p}_1 \hat{\Gamma}^{V1}_{hff} + \not{p}_2 \hat{\Gamma}^{V2}_{hff}$$
$$+ \not{p}_1 \gamma_5 \hat{\Gamma}^{A1}_{hff} + \not{p}_2 \gamma_5 \hat{\Gamma}^{A2}_{hff} + \not{p}_1 \not{p}_2 \hat{\Gamma}^{T}_{hff} + \not{p}_1 \not{p}_2 \gamma_5 \hat{\Gamma}^{PT}_{hff},$$

hVV: 7 form factors

hff: 3 form factors

Constraint of direct search (HSM)

[T. Robens, T. Stefaniak, Eur. Phys. J. C (2016) 76,268]

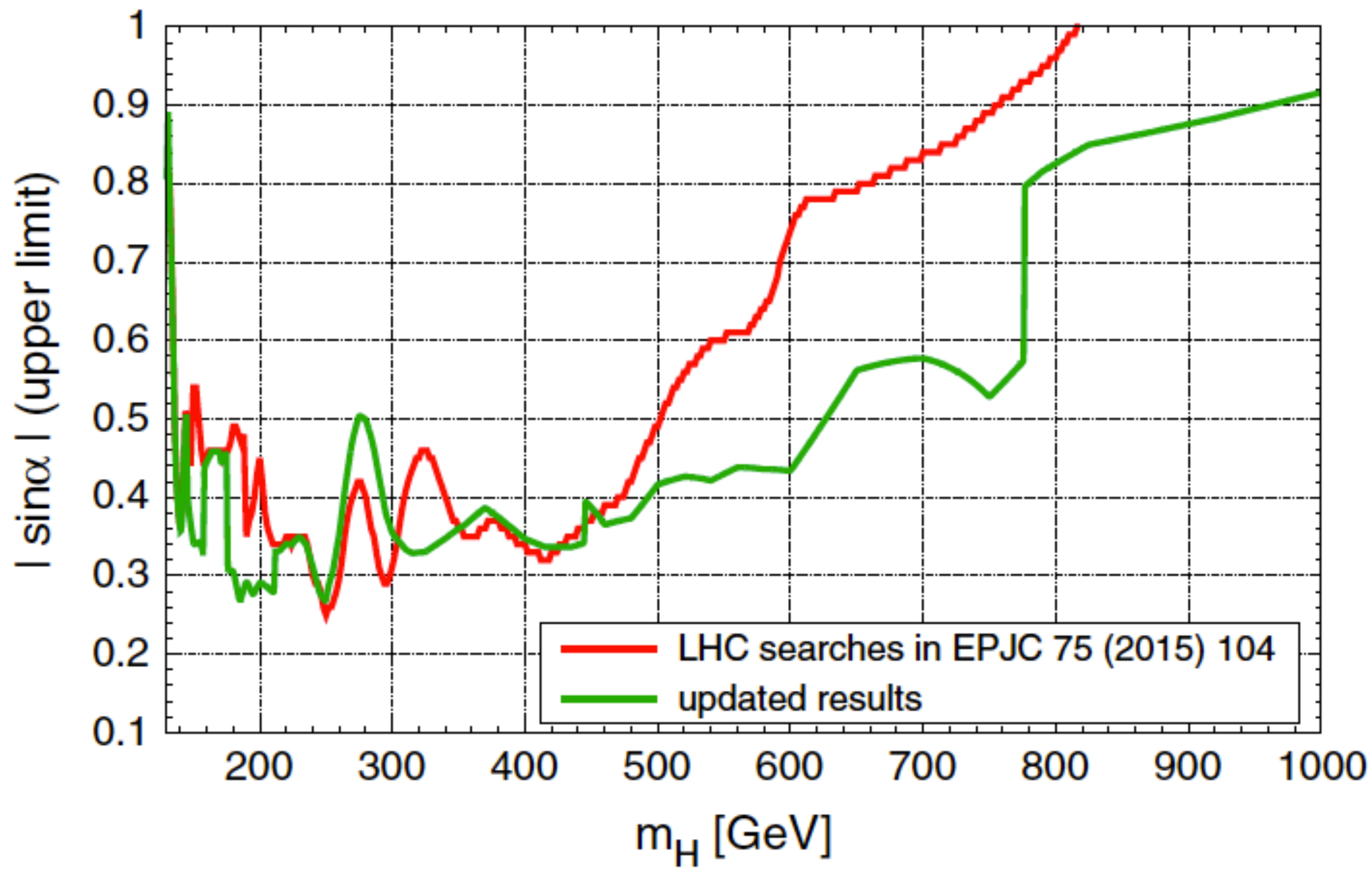
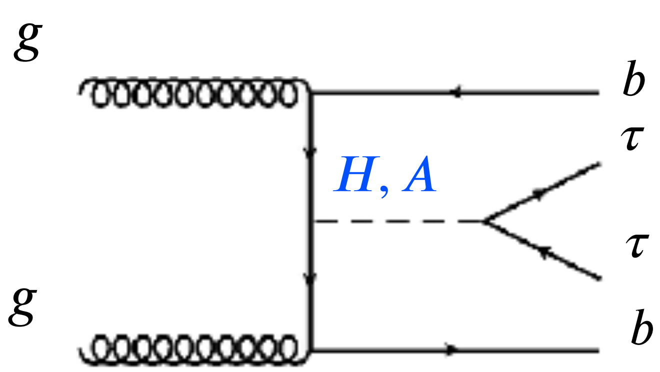


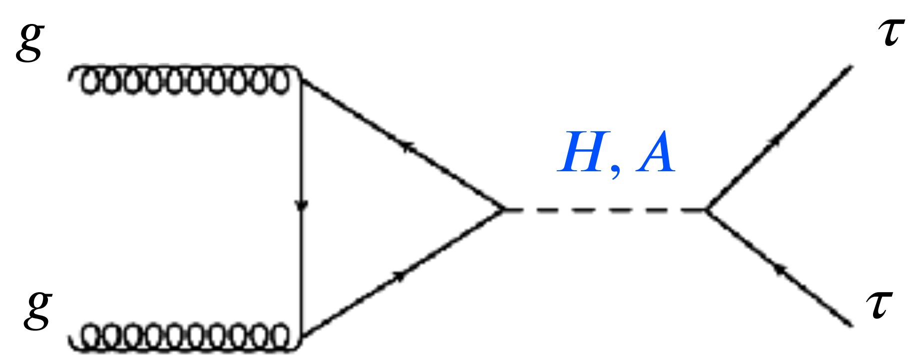
Table 1 List of LHC Higgs search channels that are applied by HiggsBounds in the high-mass region, yielding the upper limit on $|\sin\alpha|$ shown in Figs. 1 and 2

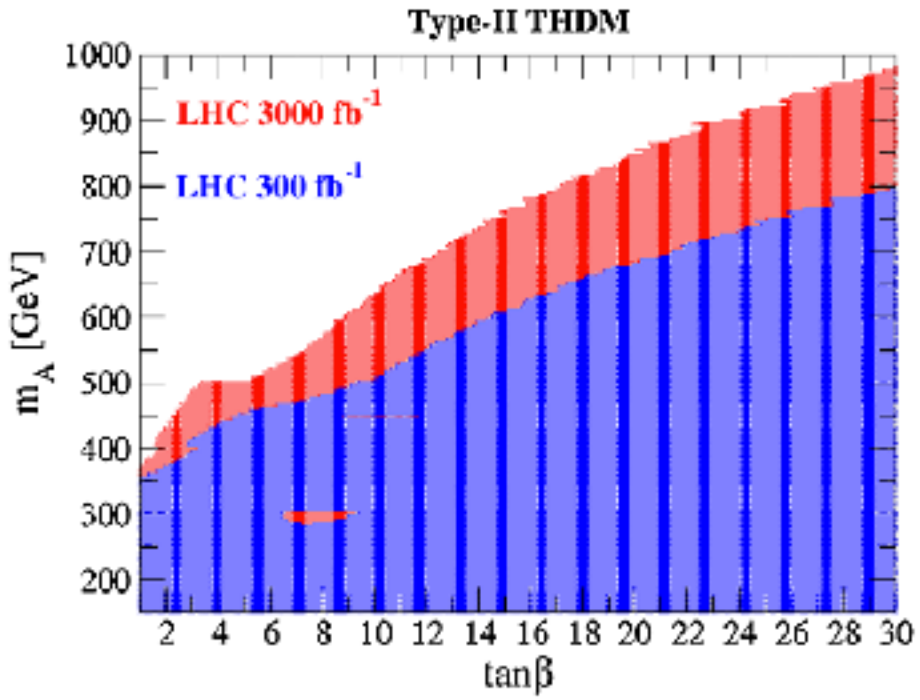
Range of m_H [GeV]	Search channel	Reference
130–145	H→ZZ→4l	[94] (CMS)
145–158	H→VV (V=W,Z)	[66] (CMS)
158–163	SM comb.	[95] (CMS)
163–170	H→WW	[96] (CMS)
170–176	SM comb.	[95] (CMS)
176–211	H→VV (V=W,Z)	[66] (CMS)
211–225	H→ZZ→4l	[94] (CMS)
225–445	H→VV (V=W,Z)	[66] (CMS)
445–776	H→ZZ	[70] (ATLAS)
776–1000	H→VV (V=W,Z)	[66] (CMS)

Status of direct search of extra Higgs (Future)

- Future prospect of excluded regions [Kanemura, Tsumura, Yagyu, Yokoya, PRD90(2014)075001]







→ In the future exp.
excluded regions are spread.

Status of the ILC

MEXT : Ministry of Education, Culture, Sports, Science and Technology
SCJ: The Science Council of Japan

[https://www.kek.jp/en/newsroom/2019/03/13/2100/]

MEXT's view in regard to the ILC project Executive Summary

March 7, 2019
Research Promotion Bureau, MEXT

○ Following the opinion of the SCJ, MEXT has not yet reached declaration for hosting the ILC in Japan at this moment. The ILC project requires further discussion in formal academic decision-making processes such as the SCJ Master Plan, where it has to be clarified whether the ILC project can gain understanding and support from the domestic academic community.

○ MEXT will pay close attention to the progress of the discussions at the European Strategy for Particle Physics Update.

○ The ILC project has certain scientific significance in particle physics particularly in the precision measurements of the Higgs boson, and also has possibility in the technological advancement and in its effect on the local community, although the SCJ pointed out some concerns with the ILC project. Therefore, considering the above points, MEXT will continue to discuss the ILC project with other governments while having an interest in the ILC project.

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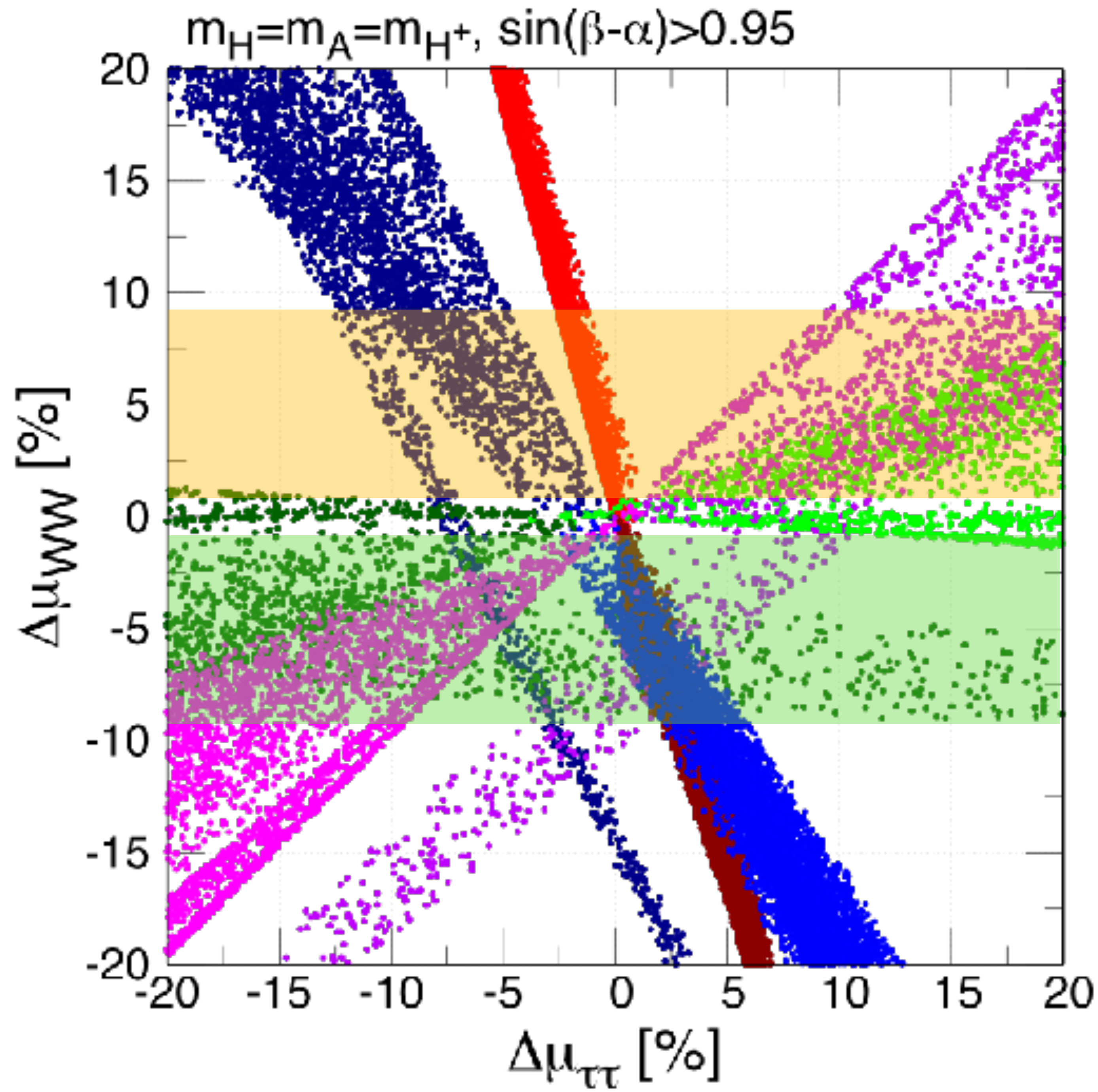
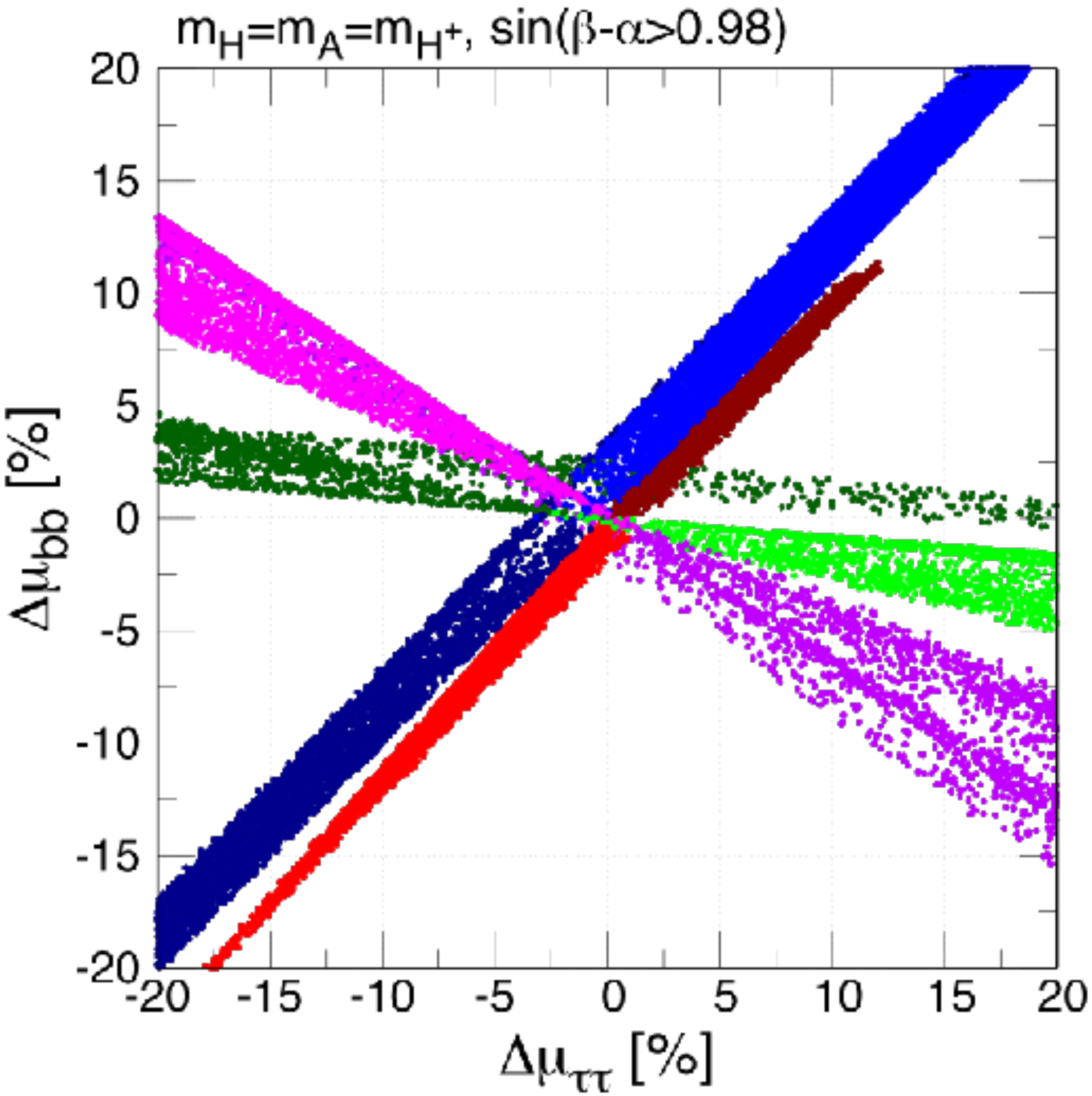


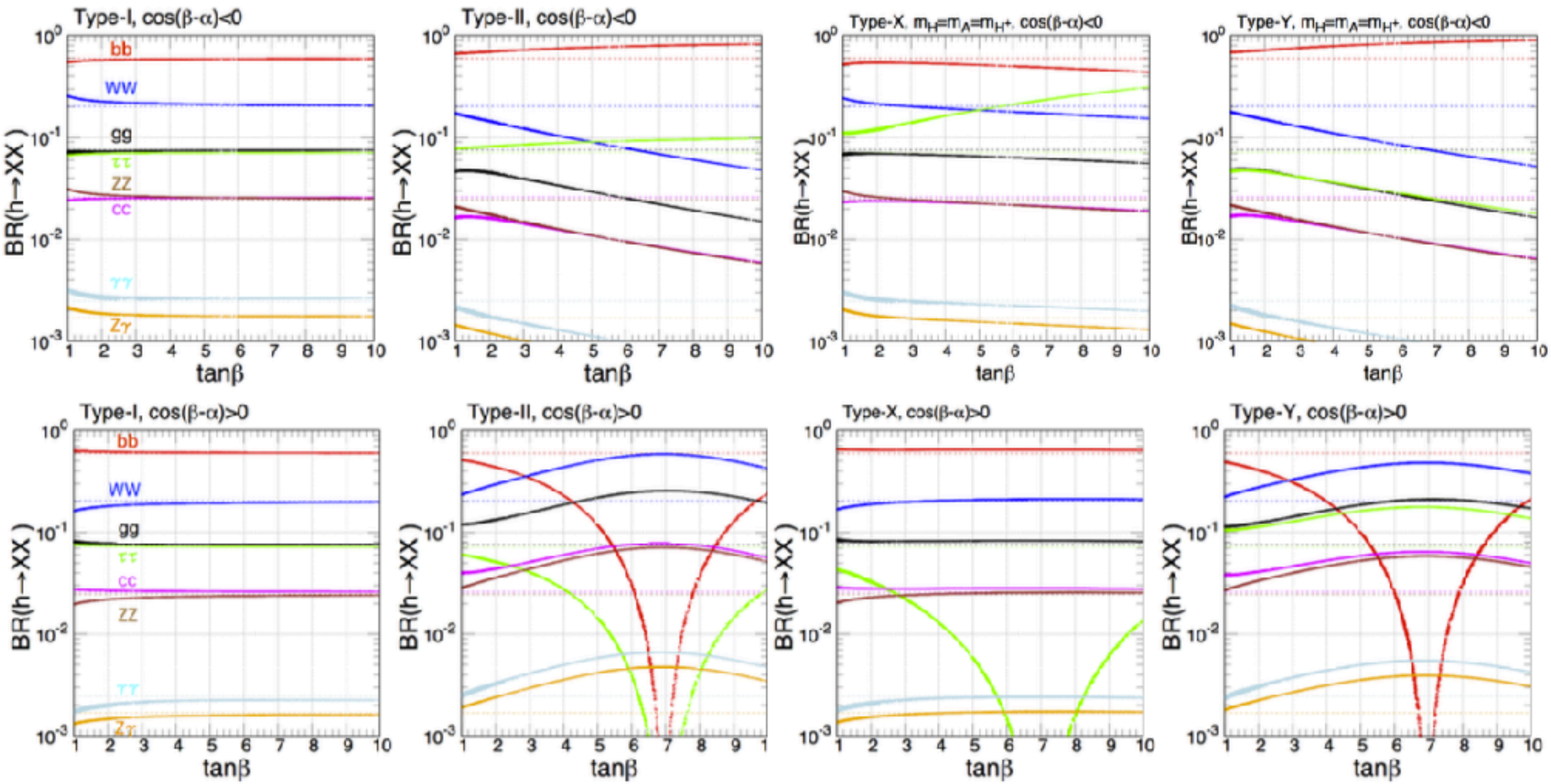
mH=mA=mH+, sin(β-α)>0.95
20
15
10
5
0
-5
-10
-15
-20
-20
-15
-10
-5
0
5
10
15
20
ΔμWW [%]
Δμττ [%]

-

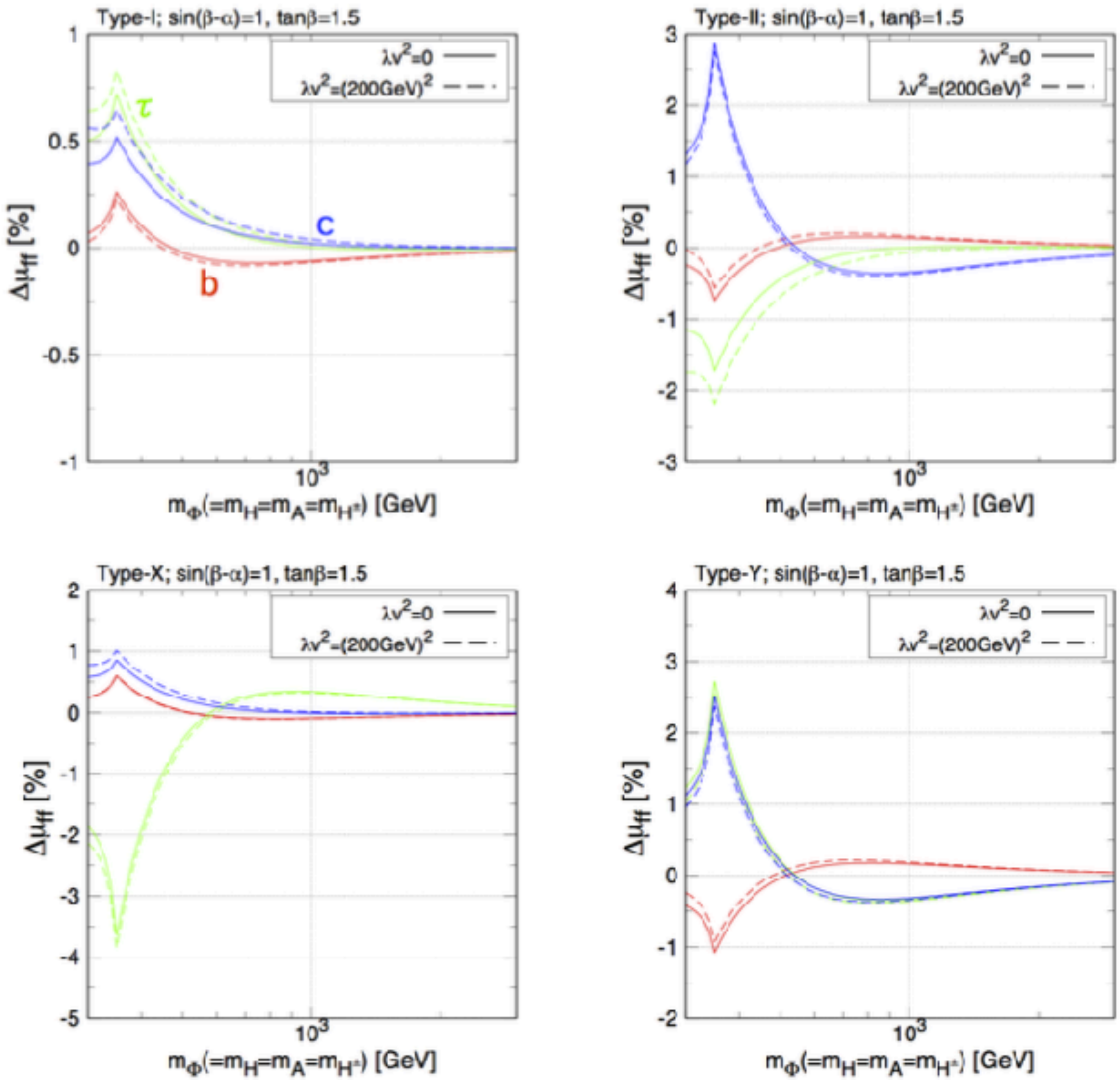


m_H=m_A=m_H+, sin(β-α>0.98)
20
15
10
5
0
-5
-10
-15
-20
Δμ_bb [%]
-20
-15
-10
-5
0
5
10
15
20
Δμ_ττ [%]

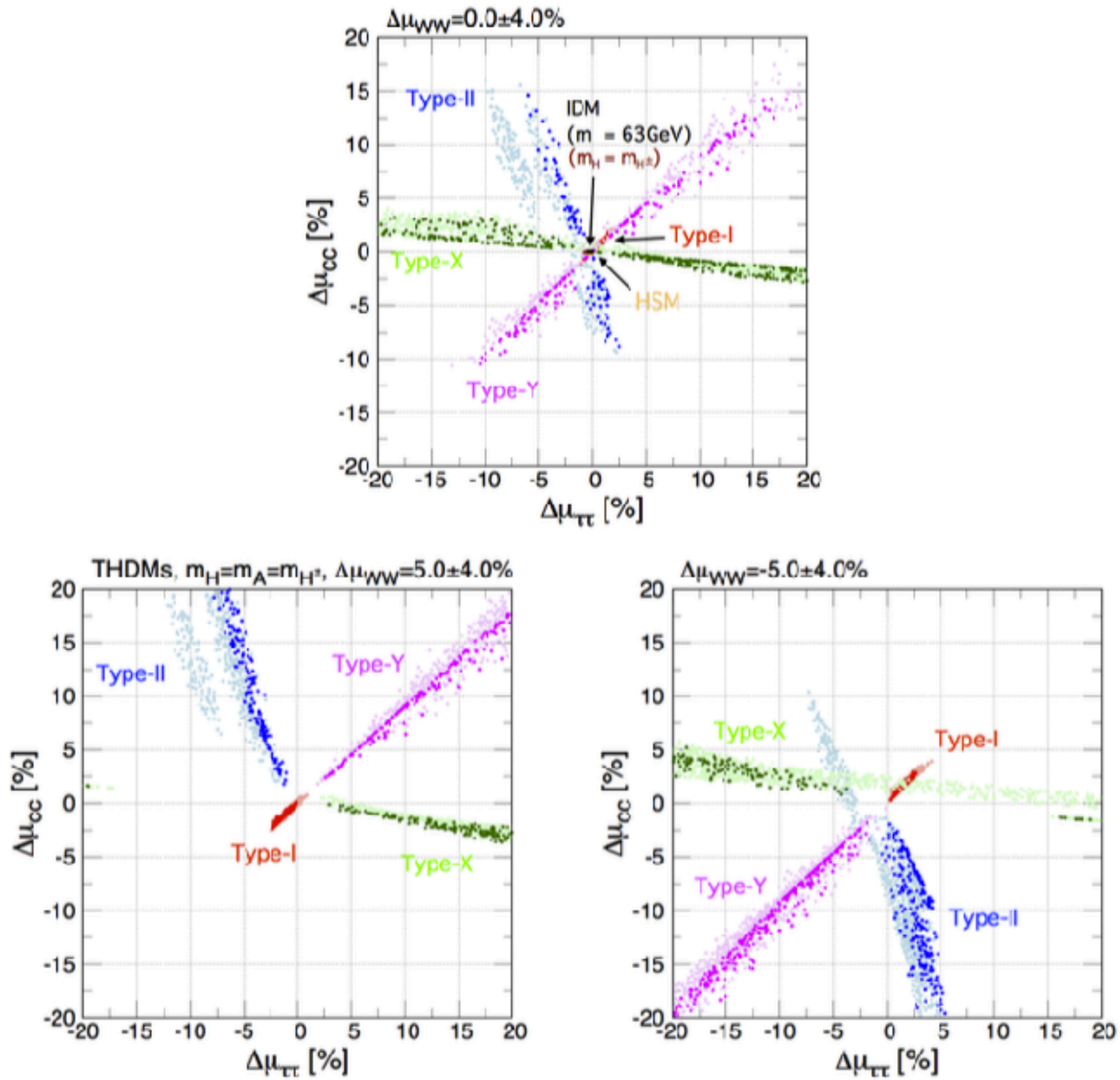
Branching ratios (THDMs)



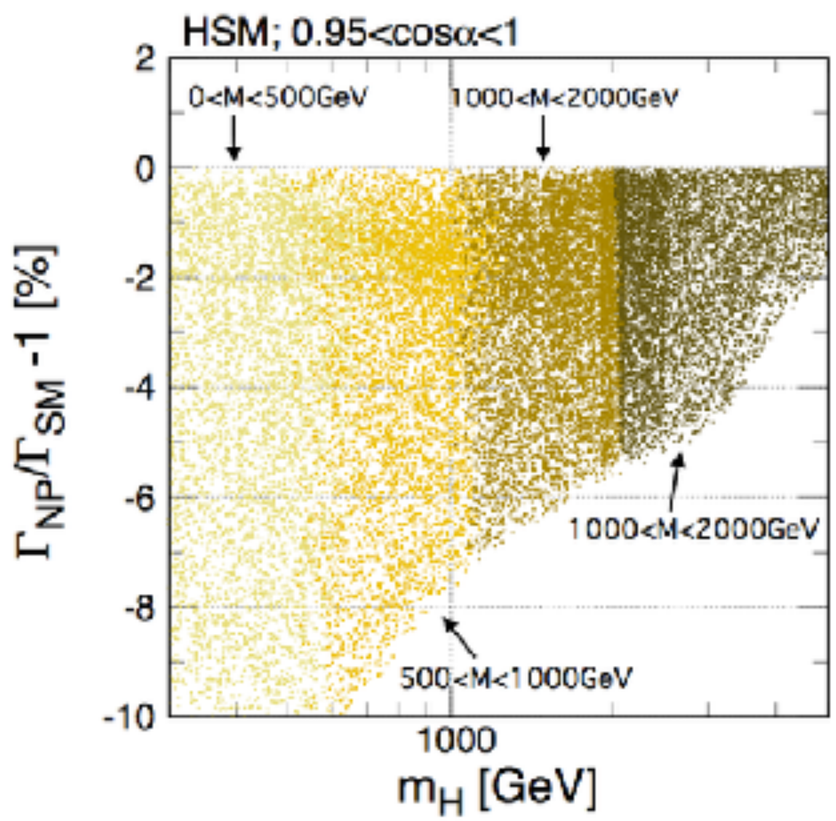
$\Delta\ \mu_{ff}$ vs m_{Φ}

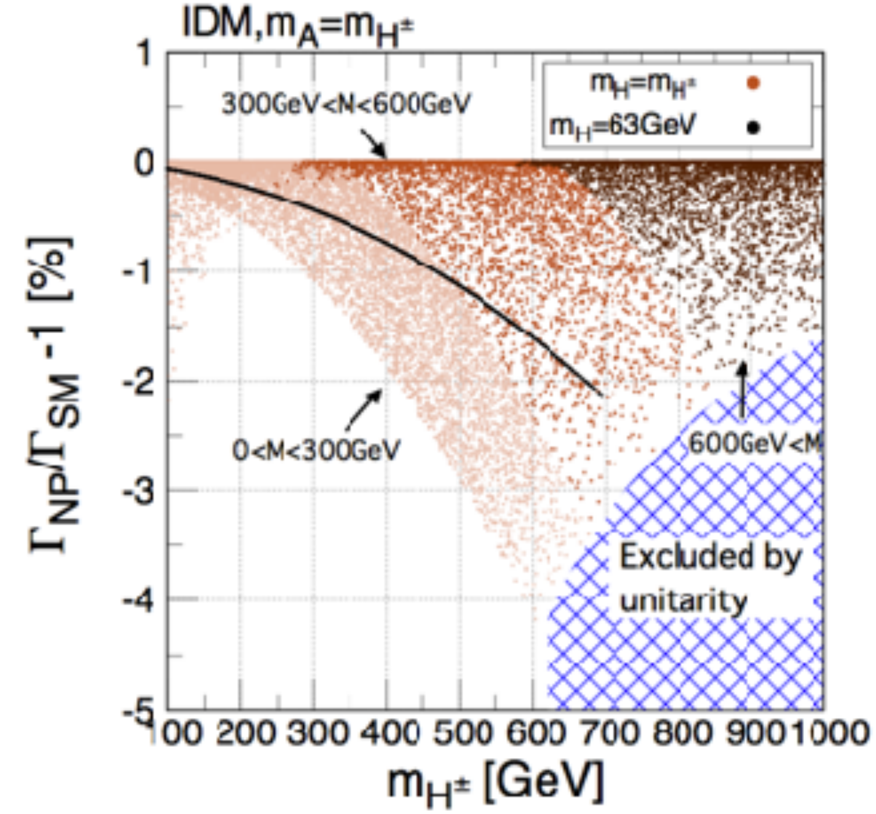


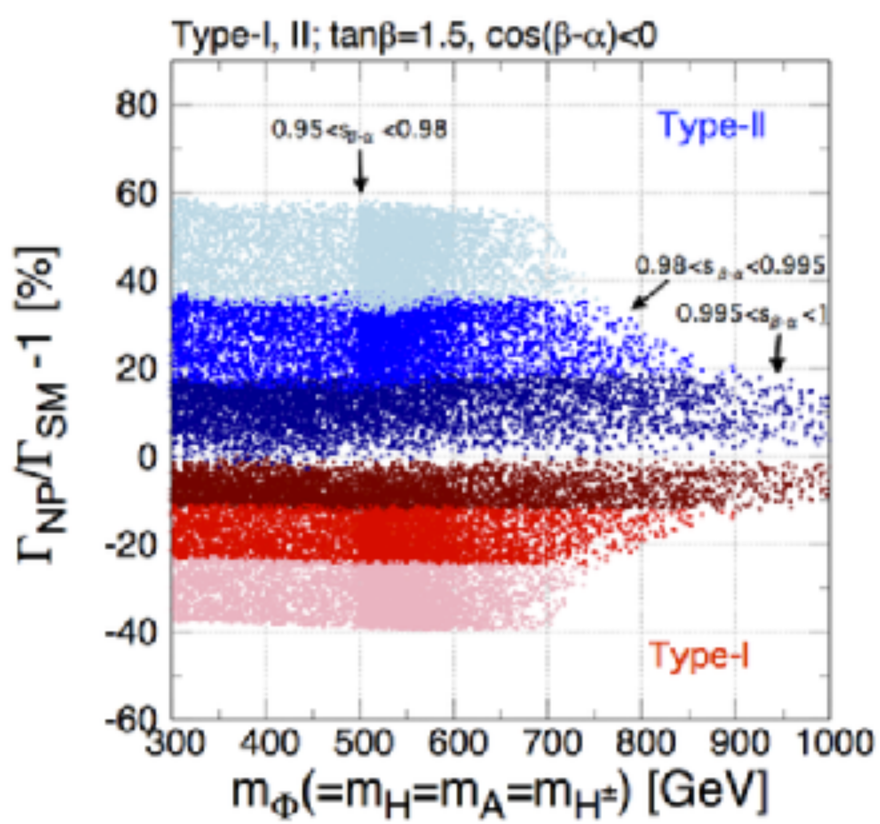
Other correlations

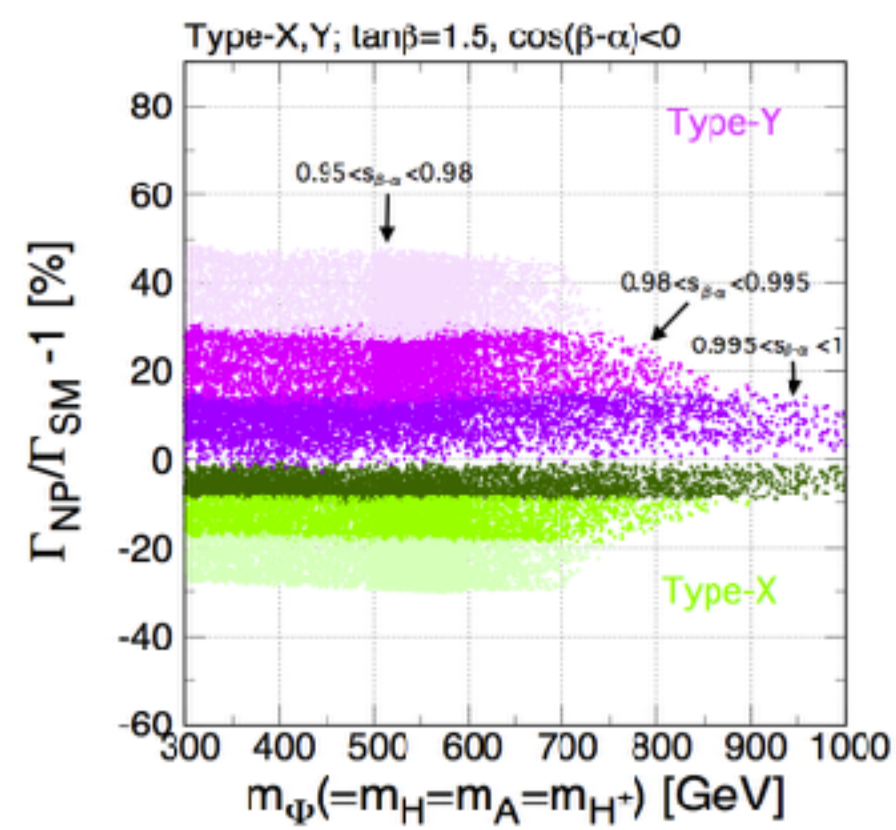


Total decay rate

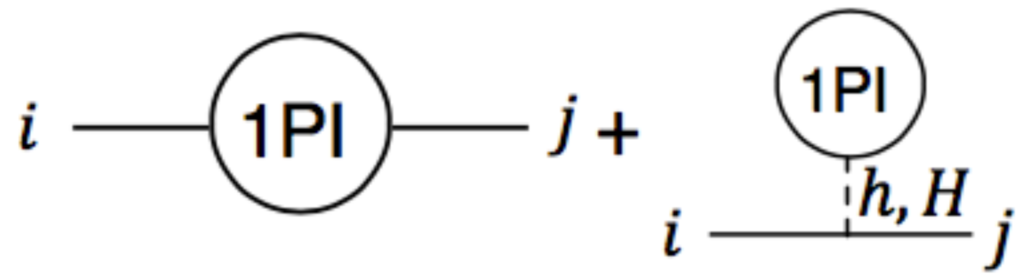








Gauge dependence on the counter terms

$\Pi_{ij}(q^2) \equiv$ 

Nielsen identity : [N. K. Nielsen, NPB101 (1975) 173, Y. Yamada, PRD64(2001)036008]

$$\partial_\xi \Pi_{ij}(q^2) = \left(q^2 - m_i^2\right)\Lambda_i(q^2) + \left(q^2 - m_j^2\right)\Lambda_j(q^2)$$

$\Lambda_i(q^2), \Lambda_j(q^2)$: sum of loop function

ex.2) $\delta\beta$ (the counter term of the mixing angle β)

$$\delta\beta = -\frac{1}{2m_A^2}\left[\Pi_{AG^0}\left(m_{\mathrm{A}}^2\right) + \Pi_{AG^0}(0)\right]$$

Appling to the Nielsen identity

$$\partial_\xi(\delta\beta) = -\frac{1}{2m_A^2}\left[\left(m_{\mathrm{A}}^2 - 0\right)\Lambda_G(0) + \left(0 - m_A^2\right)\Lambda_A(0)\right]$$

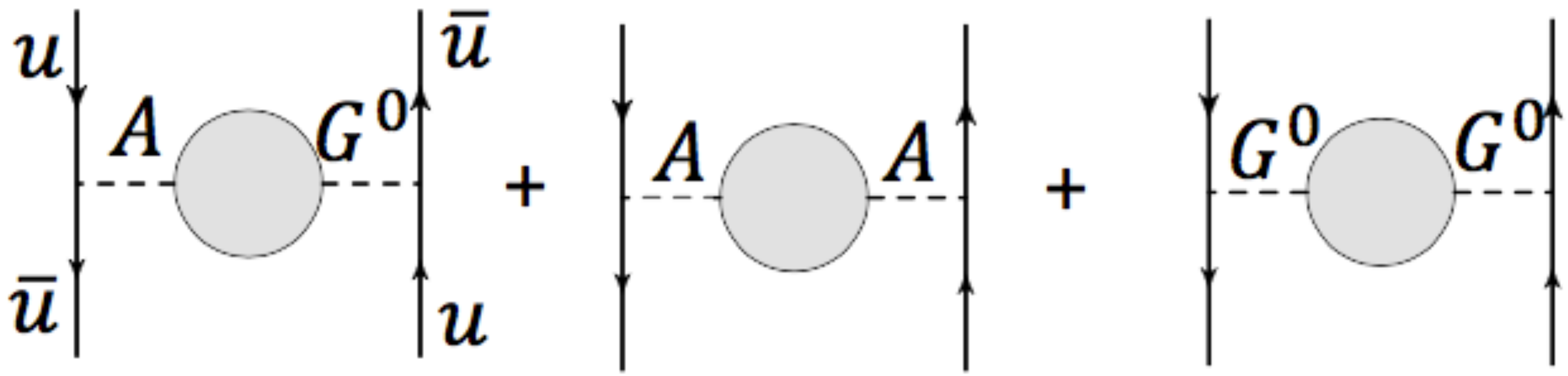
➡ $\partial_\xi(\delta\beta) \neq 0$

With the same argument, we can also find $\partial_\xi(\delta\alpha) \neq 0$

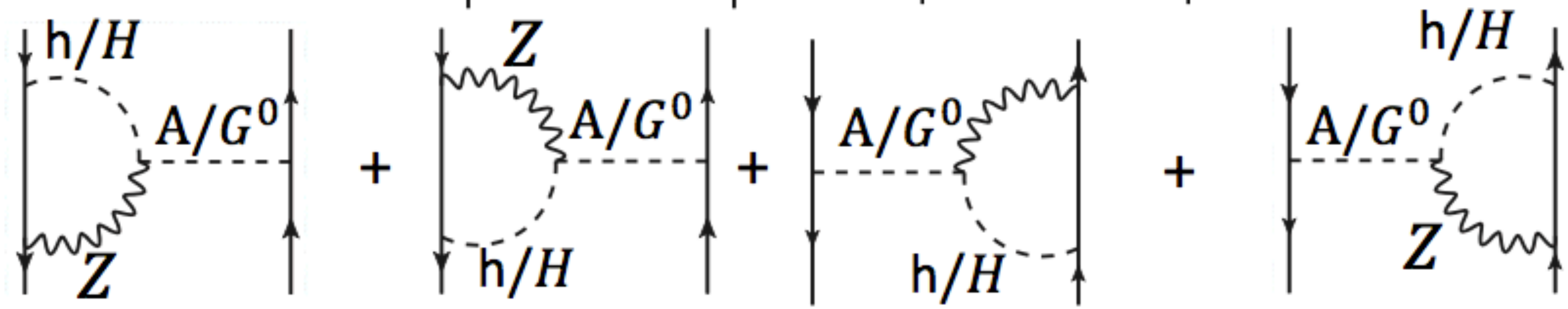
Pinch technique

I demonstrate that ξ_Z dependence for $\Pi_{AG}(q^2)$ are removed.

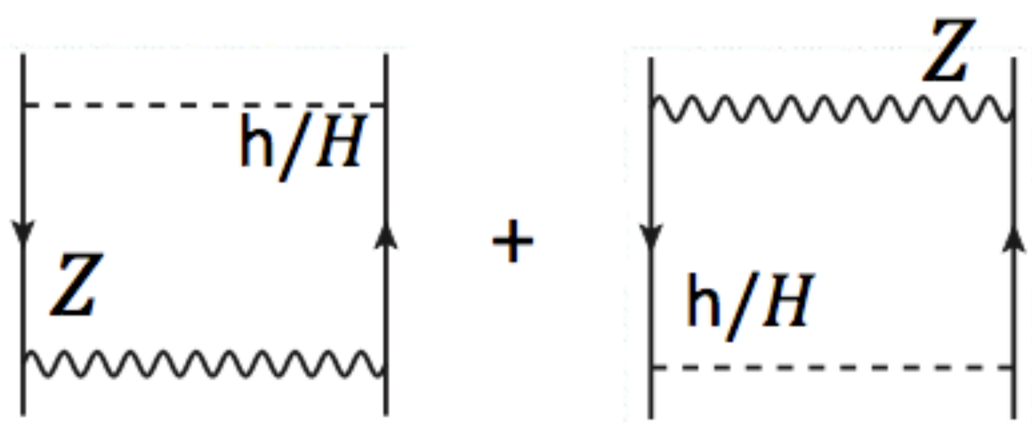
$\mathcal{M}_{self} =$



$\mathcal{M}_{vert}^{pinch} \ni$

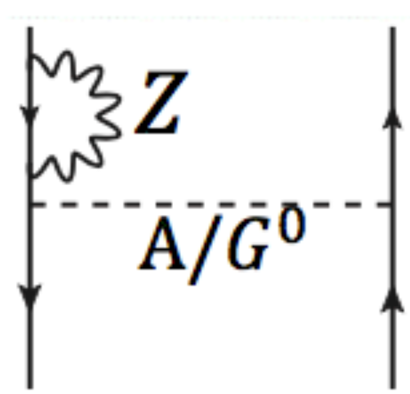


$\mathcal{M}_{box}^{pinch} \ni$



+ ...

$\mathcal{M}_{wave}^{pinch} \ni$

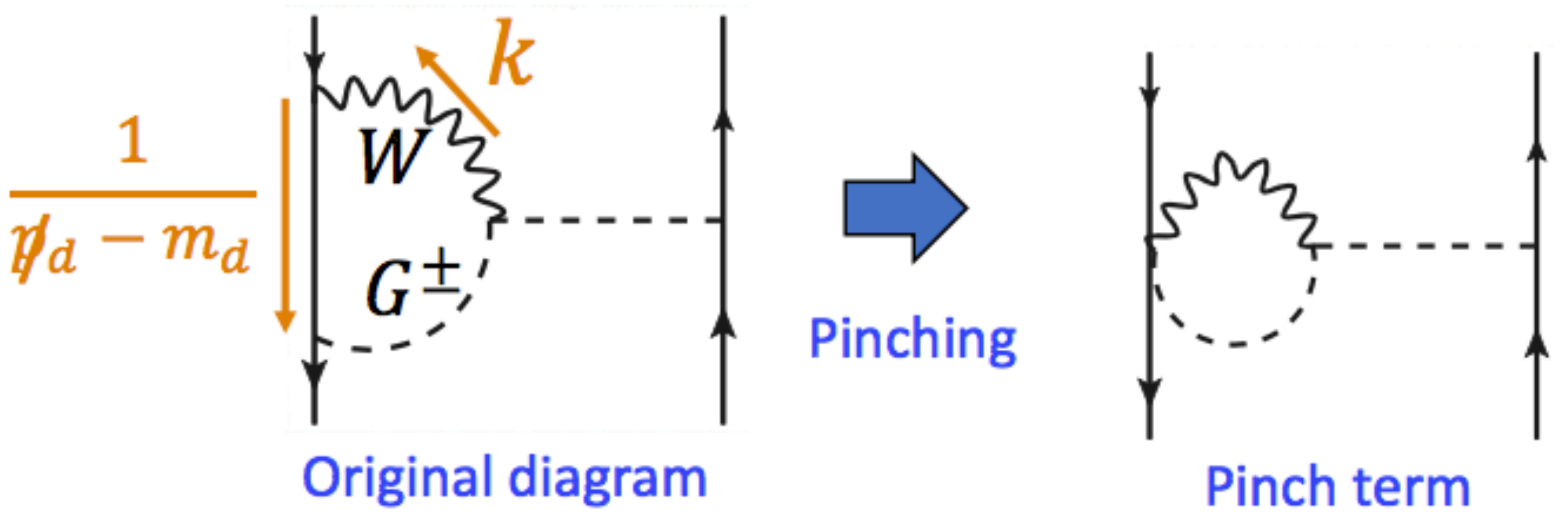


Pinch technique

Toy process : $u\bar{u} \to u\bar{u}$

$\mathcal{M}^{PT}_{vert}, \mathcal{M}^{PT}_{box}, \mathcal{M}^{PT}_{wave}$: Pinch term

$\mathcal{M}_{sel}$



$\mathcal{M}^{PT}_{ver}$

Wff coupling

$$\gamma^{\mu} k_{\mu} = (\not{p}_d - m_d) - (\not{p}_d - \not{k} - m_d)$$

$\mathcal{M}^{PT}_{bo}$

Derivative coupling or W boson propagator

$\mathcal{M}^{PT}_{wa}$

$^{T}_{ave}$) =0

We obtained the gauge invariant Π_{hH} , adding the pinch terms