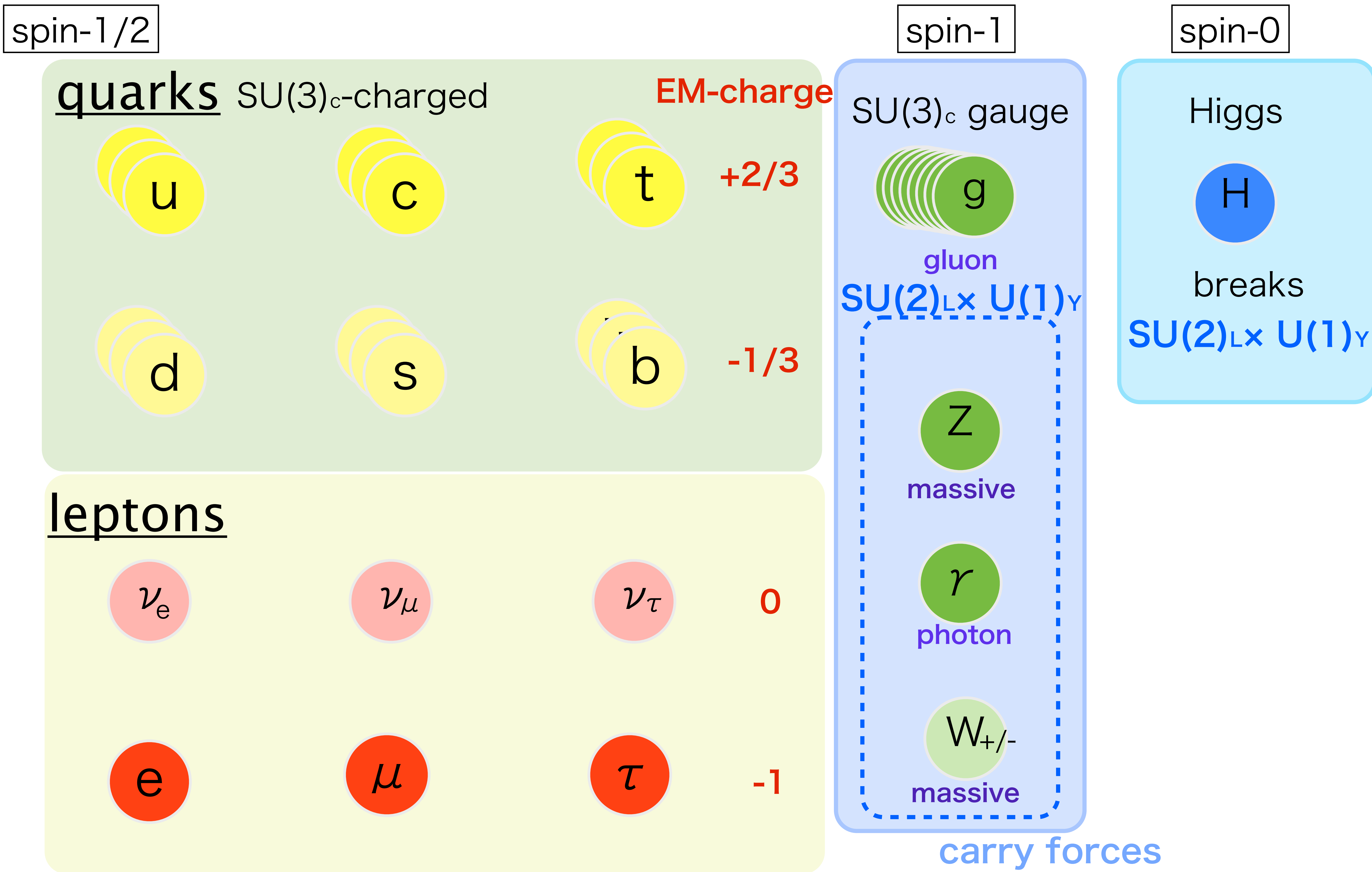
# Introduction and Current Status of 2HDMs

**Yuji Omura (KMI, Nagoya Univ.)**

# Background and Motivation

# Standard Model $(SU(3)_c \times SU(2)_L \times U(1)_Y)$ is very successful in particle physics



# Why do we study BSM?

*We expect that there are something behind*

*EW scale*

*flavor structure*

*strong CP problem*

*baryon asymmetry*

*gauge symmetry*

*dark matter*

# Possible BSMs

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*EW scale* ➡ SUSY etc.

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| *EW scale* | ➡ | SUSY etc. |
| *flavor structure* | ➡ | flavor symmetry |
| *strong CP problem* | ➡ | $U(1)_{PQ}$, LR symmetry |
| *baryon asymmetry* | | |
| *gauge symmetry* | | |
| *dark matter* | | |

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| *dark matter* | ➡ | extra stable particles |

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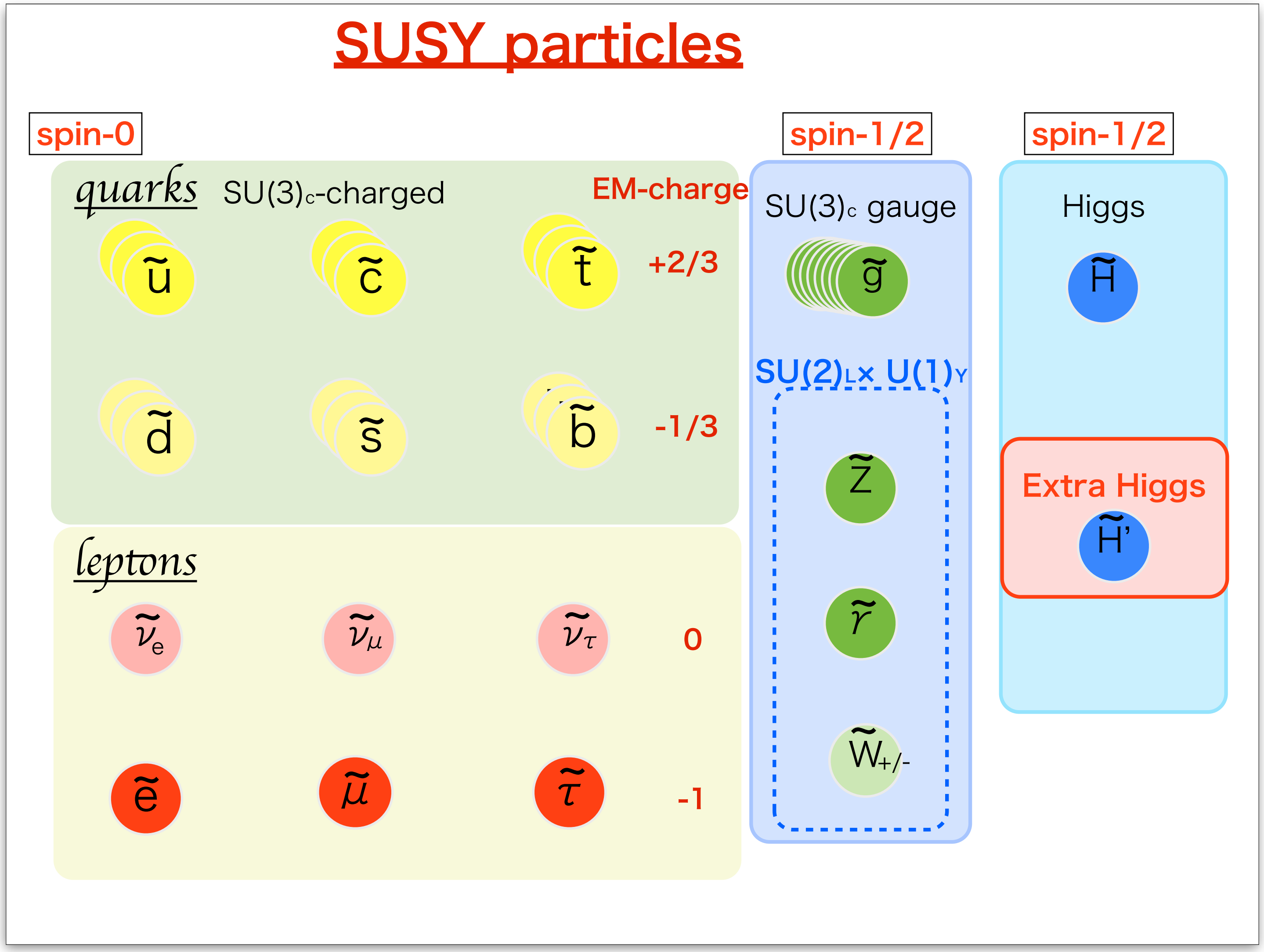
SUSY *predicts so many new scalars:*



*There are many interesting candidates for BSMs,*

*and we are looking for the evidences of new physics*

flavor symmetry *predicts extra scalars*

quark Yukawa in SM: $\overline{Q_L^i} H_1 y_d^i d_R^i + \overline{Q_L^i} (V^\dagger)^{ij} \widetilde{H}_1 y_u^j u_R^j$

In flavor symmetric model,

$$y_d^{ij}(\Phi)\,\overline{Q_L^i} H_1 d_R^j + y_u^{ij}(\Phi)\,\overline{Q_L^i} \widetilde{H}_1 u_R^j$$

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In flavor symmetric model,

or $\overline{Q_L^i} H_1 y_d^i d_R^i + y_u^i \overline{Q_L^i} \widetilde{H}_{ij} u_R^j$

*There are many interesting candidates for BSMs,*

*and we are looking for the evidences of new physics*

## $U(1)_{PQ}$ and LR symmetry   *predict extra Higgs*

$U(1)_{PQ}$ :   $H_1 \to e^{iq_1\theta} H_1,\ H_2 \to e^{iq_2\theta} H_2$

$$\overline{Q_L^i} H_2 y_d^i d_R^i + \overline{Q_L^i} (V^\dagger)^{ij} \widetilde{H}_1 y_u^j u_R^j$$

[Zhitnitsky SJNP 31 (1980); Dine, Fischler, Srednicki PLB 104 (1981)]

LR symmetry: $Q_L^i \leftrightarrow Q_R^i$

[Babu, Mohapatra, PRD41, 1286 (1990)]

$$Y_{ij} \overline{\hat{Q}_L^i} \Phi \hat{Q}_R^j$$

where $\Phi = (\widetilde{H}_u,\ H_d)$  $\hat{Q}_R^j = (\hat{u}_R^j,\ \hat{d}_R^j)^T$

*There are many interesting candidates for BSMs,*

*and we are looking for the evidences of new physics*

GUT *also predict extra Higgs*

$$Y_{10}^{ij}\mathbf{16}_i\mathbf{16}_j\mathbf{10}+Y_{126}^{ij}\mathbf{16}_i\mathbf{16}_j\overline{\mathbf{126}}+Y_{120}^{ij}\mathbf{16}_i\mathbf{16}_j\mathbf{120}.$$

[Georgi, Nanopoulos, NPB159, 16 (1979); Georgi, Jarlskog, Phys.Lett.86B, 297 (1979); et.al]

*There are many interesting candidates for BSMs,*

*and we are looking for the evidences of new physics*

*baryon asymmetry may also require extra Higgs*

*See, for instance, Dorsch, Huber, No, 1305.6610; Haarr, Kvellestad, Petersen, 1611.05757; Fuyoto, Hou, Senaha, 1705.05034,*

There are many *dark matter* models with *extra Higgs doublets.*

***Inert doublet model***

$$H_1 = \begin{pmatrix} G^+ \\ \frac{v+h+iG}{\sqrt{2}} \end{pmatrix}, \quad H_2 = \begin{pmatrix} H^+ \\ \frac{H+iA}{\sqrt{2}} \end{pmatrix}$$

Lighter one is DM

***Extra Higgs doublet*** *may be a promising candidate that will be discovered near future.*

*There are actually so many works on the physics of the extra Higgs doublets.*

*From phenomenological point of view, the extension is "very easy", but quite attractive and interesting:*

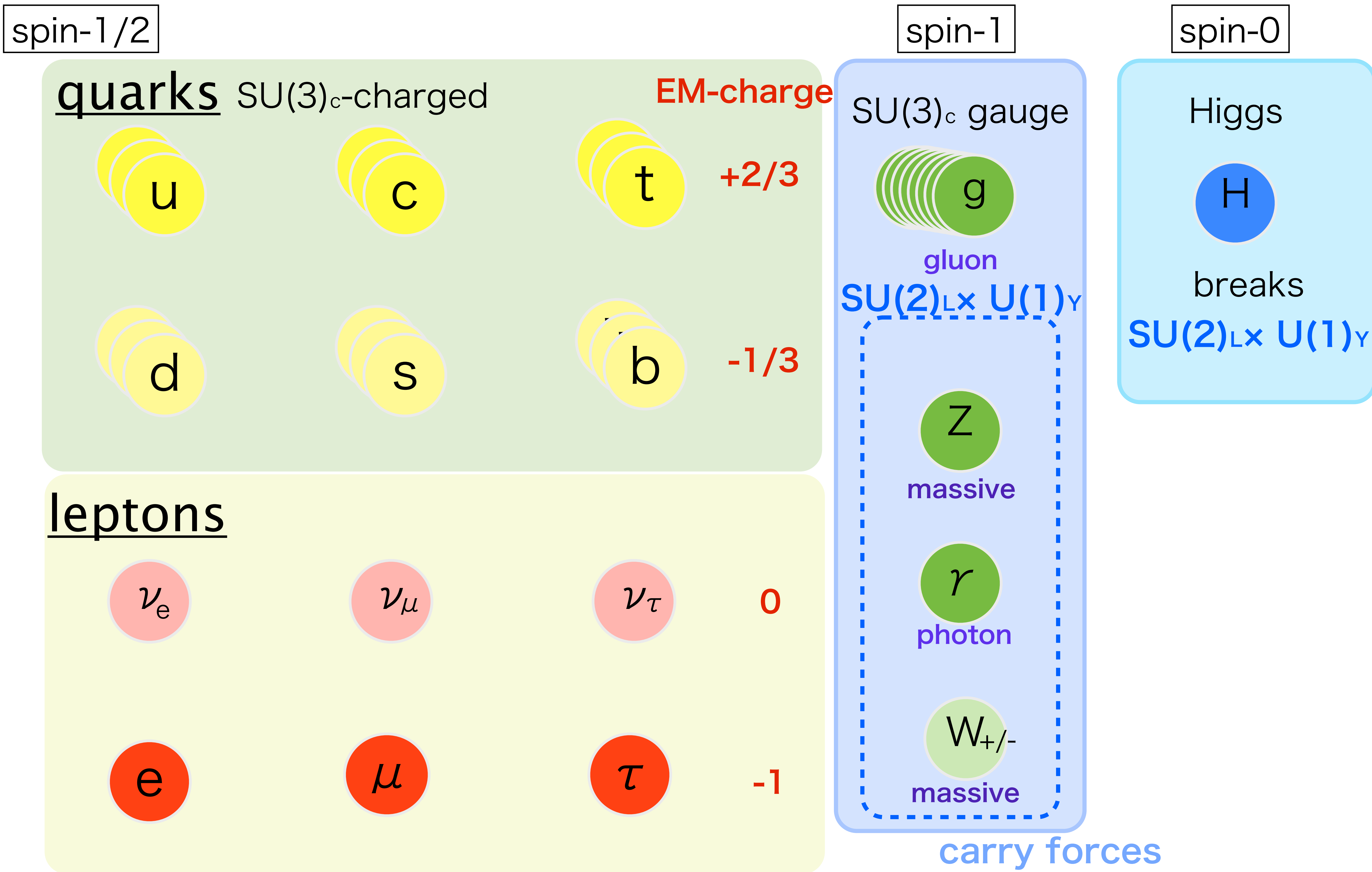
- *simple but have rich phenomenology: Higgs physics, flavor physics, etc.*
- *do not break the gauge anomaly-free conditions,*
- *do not break the SM prediction so much: ($\rho$ para. =1 @tree)*
- *may explain the discrepancies in flavor physics.*

# Contents

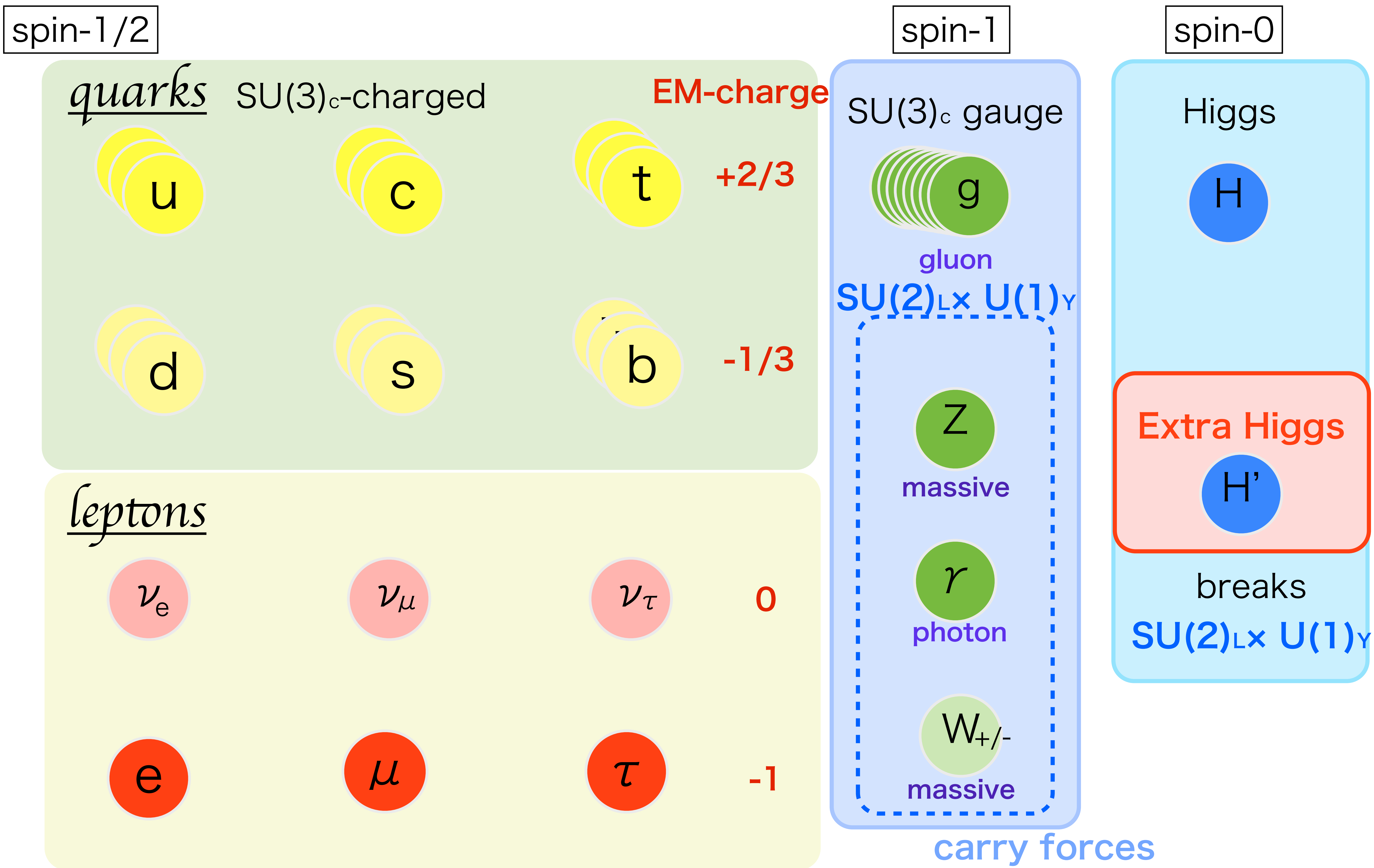
- Setup of 2HDM
- Hunting for the scalars
- About the discrepancies in 2HDMs
- What can we expect from the underlying theory?
- Summary

# Setup of 2HDM

# Let me start from the SM.



# Add just one extra Higgs doublet.



*Both Higgs doublets generally obtain non-vanishing VEVs.*

$$\langle H_1 \rangle = \begin{pmatrix} 0 \\ \frac{1}{\sqrt{2}} v_1 \end{pmatrix}, \; \langle H_2 \rangle = \begin{pmatrix} 0 \\ \frac{1}{\sqrt{2}} v_2 \end{pmatrix}$$

*Both VEVs contribute to Z and W masses.*

$$M_Z^2 = \frac{1}{4} g_Z^2 (v_1^2 + v_2^2)$$

$$M_W^2 = \frac{1}{4} g^2 (v_1^2 + v_2^2)$$

# *The 2 doublets predict extra scalars:*

$$H_1 = \begin{pmatrix} H_1^+ \\ \frac{v_1 + h_1 + iA_1}{\sqrt{2}} \end{pmatrix}, \quad H_2 = \begin{pmatrix} H_2^+ \\ \frac{v_2 + h_2 + iA_2}{\sqrt{2}} \end{pmatrix}$$

*Mass eigenstates*

Goldstones

charged Higgs

$$\hat{H}_1 = \begin{pmatrix} G^+ \\ \frac{v + \phi_1 + iG}{\sqrt{2}} \end{pmatrix}, \quad \hat{H}_2 = \begin{pmatrix} H^+ \\ \frac{\phi_2 + iA}{\sqrt{2}} \end{pmatrix}$$

pseudo-scalar

$v = \sqrt{v_1^2 + v_2^2}$

2 CP-even scalars

Mass base of CP-even is different from H+ and A.

heavy Higgs

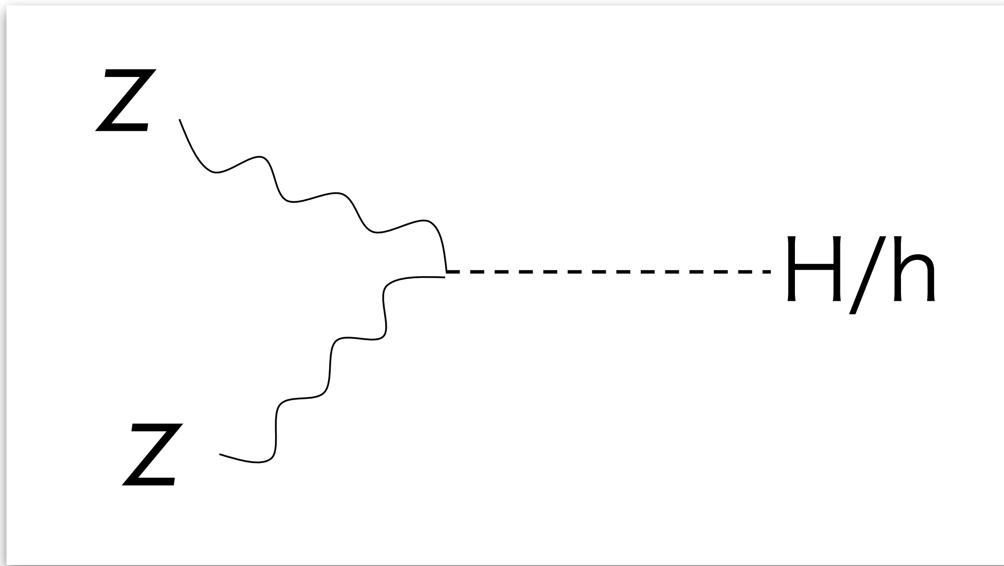
$$\begin{pmatrix} \phi_1 \\ \phi_2 \end{pmatrix} = \begin{pmatrix} \cos\theta_{\beta\alpha} & \sin\theta_{\beta\alpha} \\ -\sin\theta_{\beta\alpha} & \cos\theta_{\beta\alpha} \end{pmatrix} \begin{pmatrix} H \\ h \end{pmatrix}$$

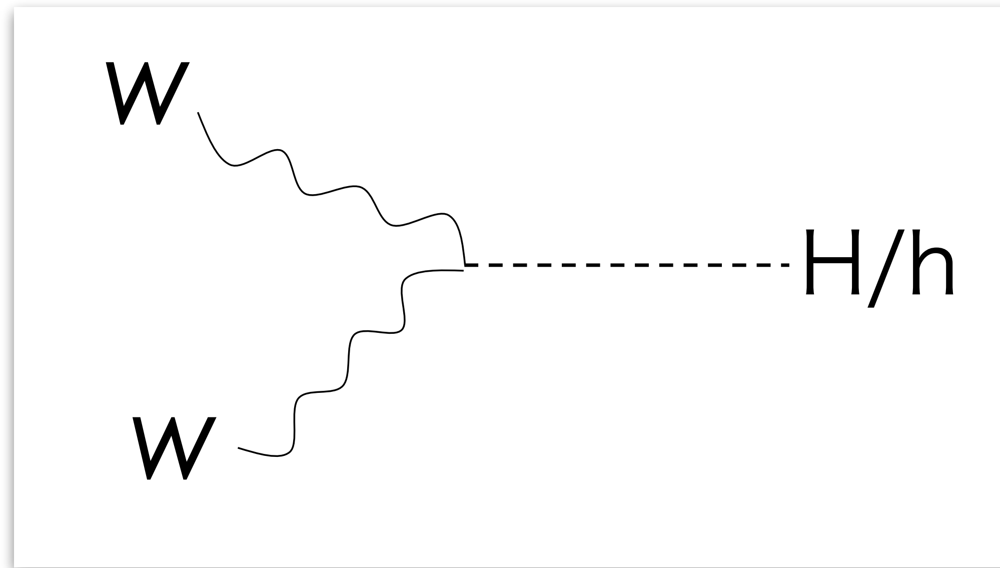
$\sin\theta_{\beta\alpha} \to 1$ (SM limit)

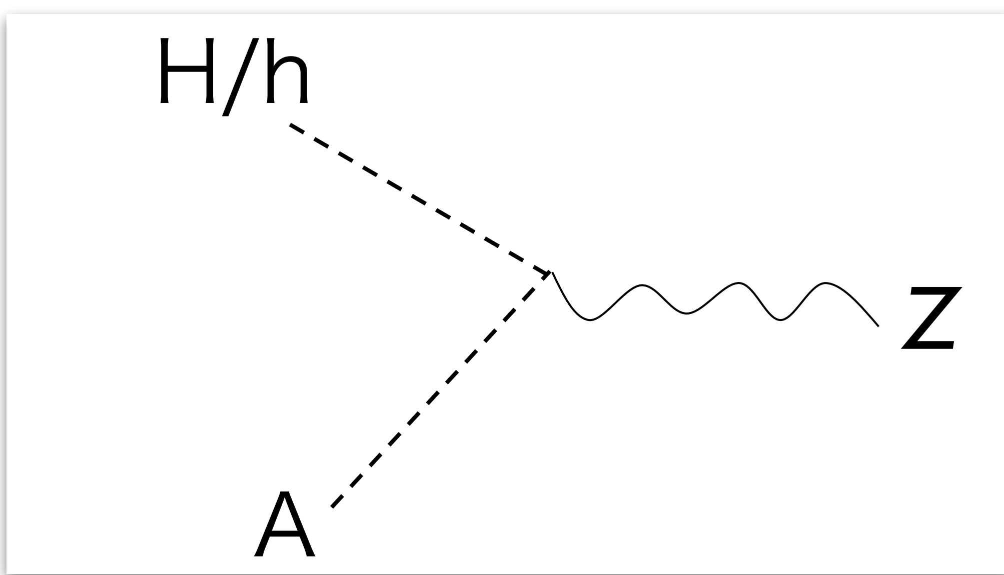
125-GeV Higgs

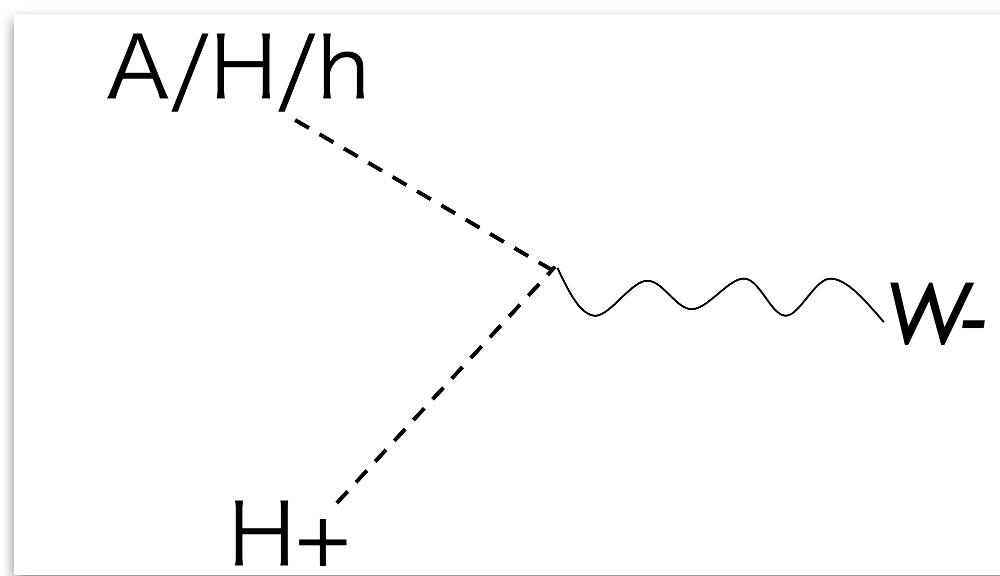
# How the scalars interact with the SM?

**EW gauge interaction @tree**



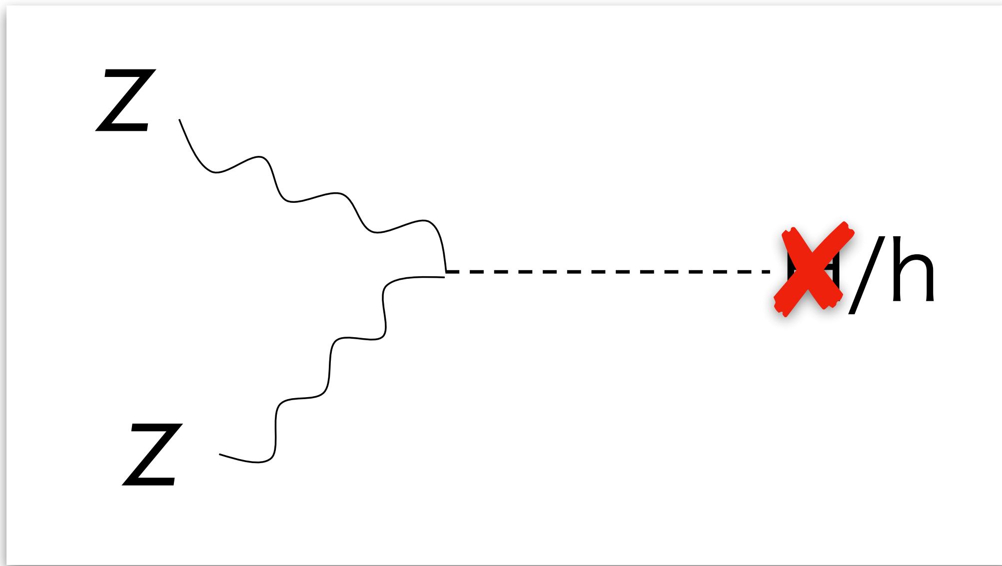



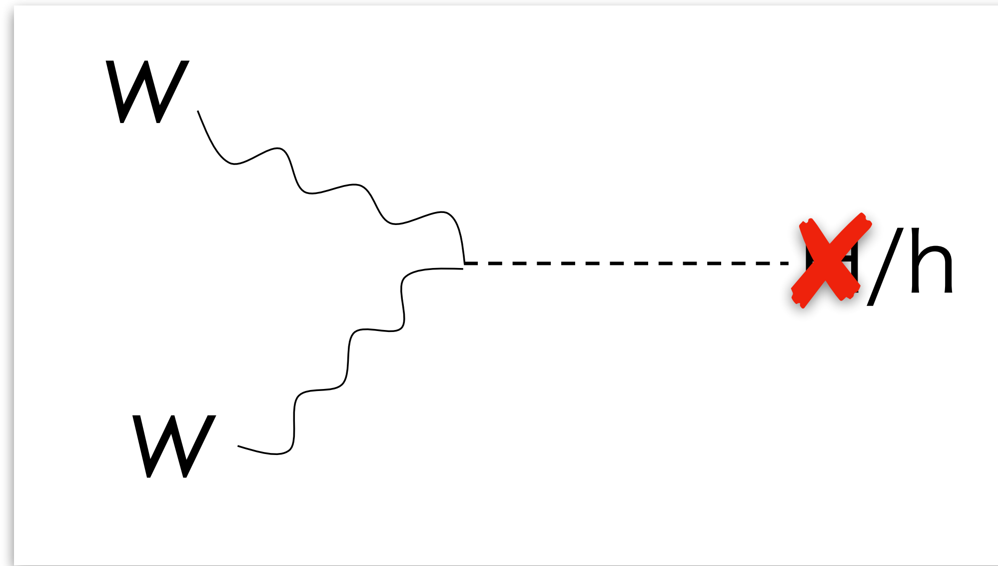



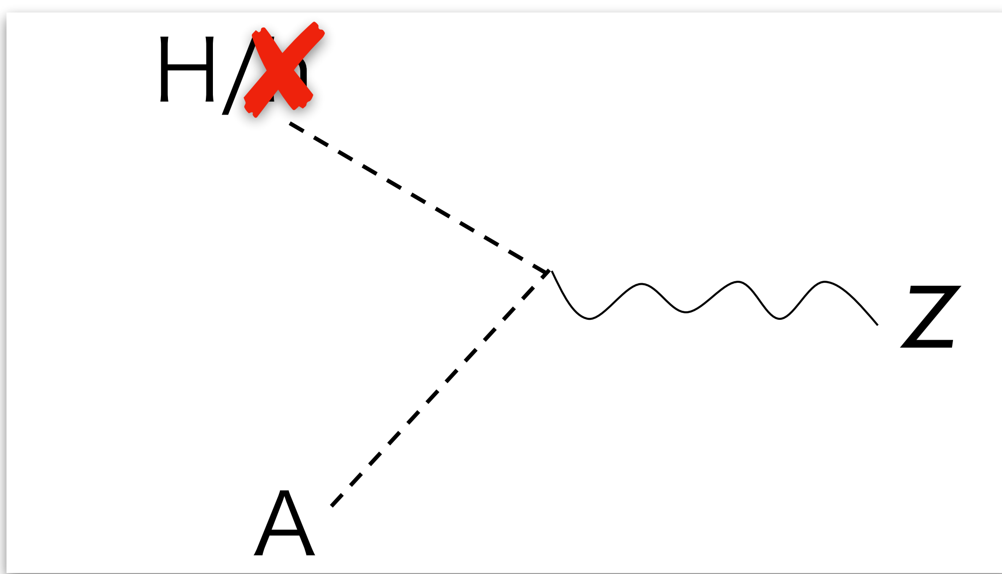
# How the scalars interact with the SM?

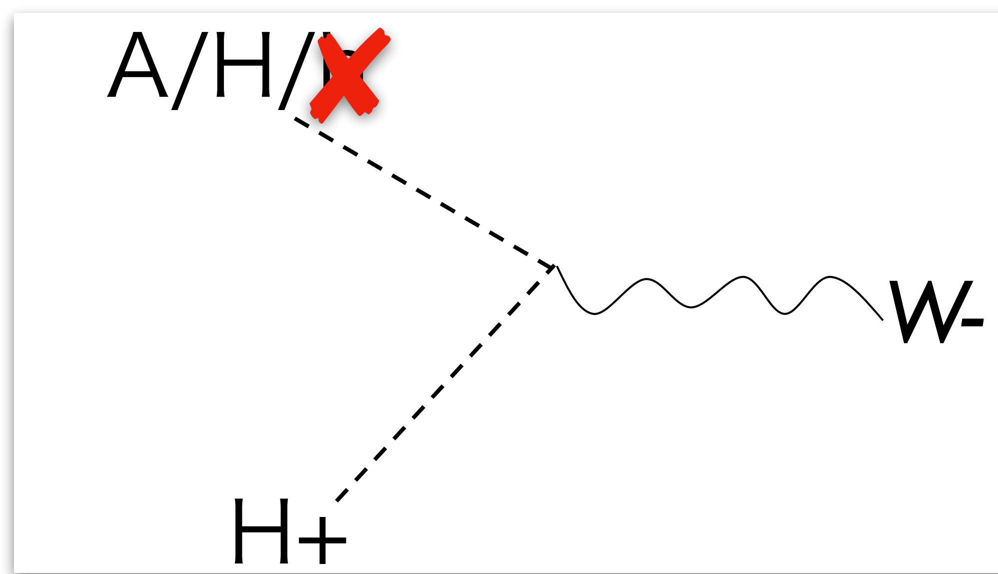
## EW gauge interaction @tree



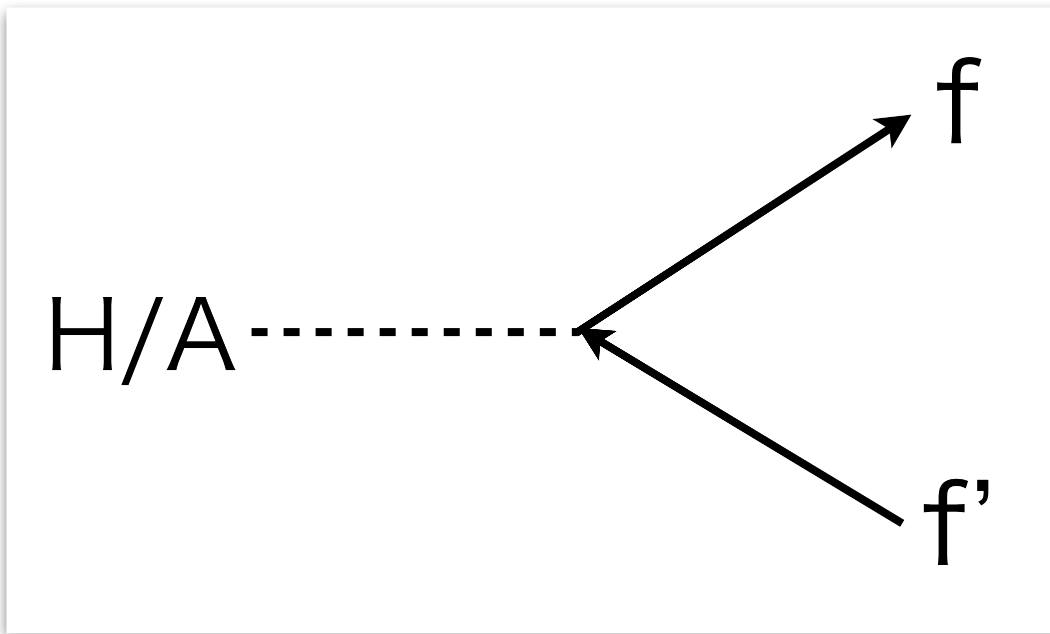

**In the SM limit**

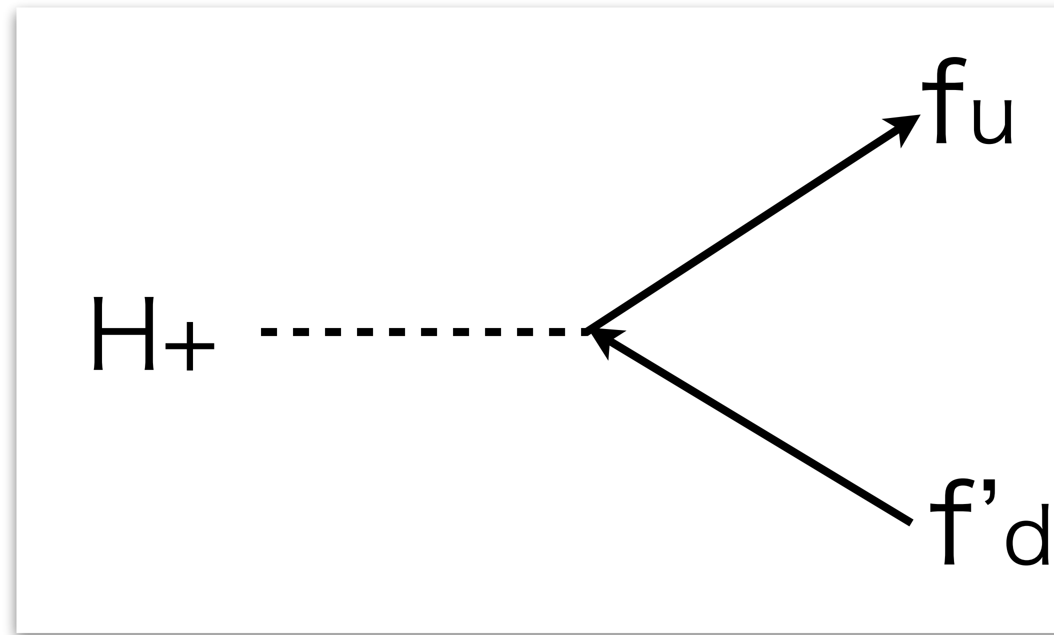


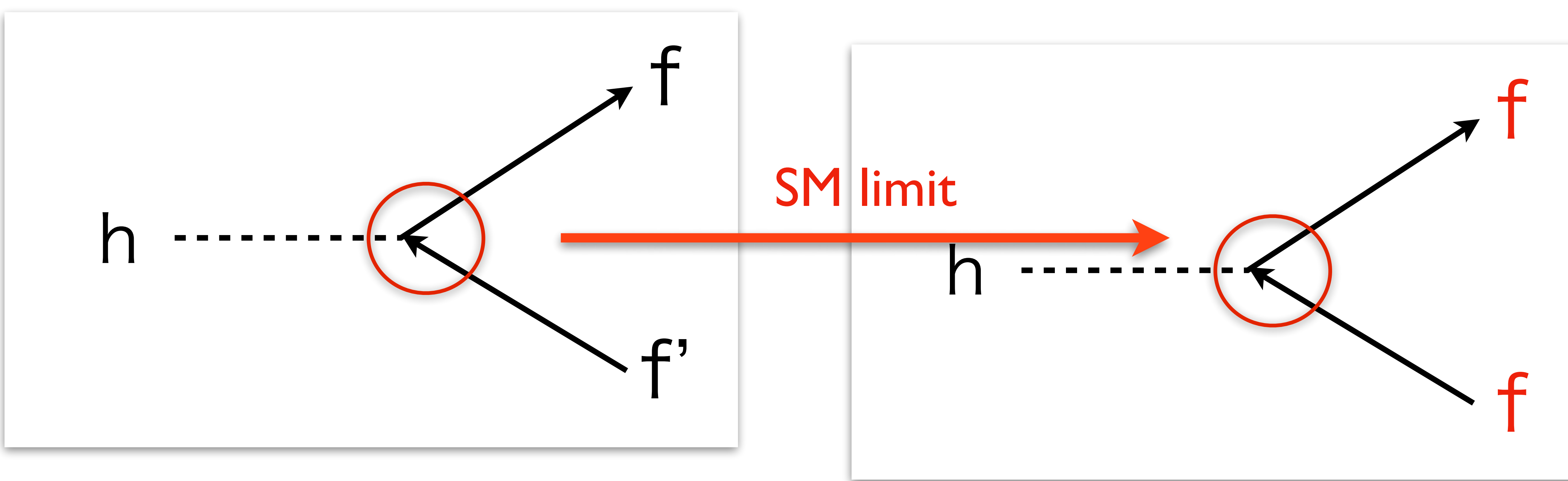



# How the scalars interact with the SM?

## Yukawa interaction



# How heavy are they?

*There is a source to shift the extra scalar masses:*

$$V \supset M^2 H_1^\dagger H_2$$

*They can be heavy as much as we want, in principle.*

*The mass difference is at most EW scale:*

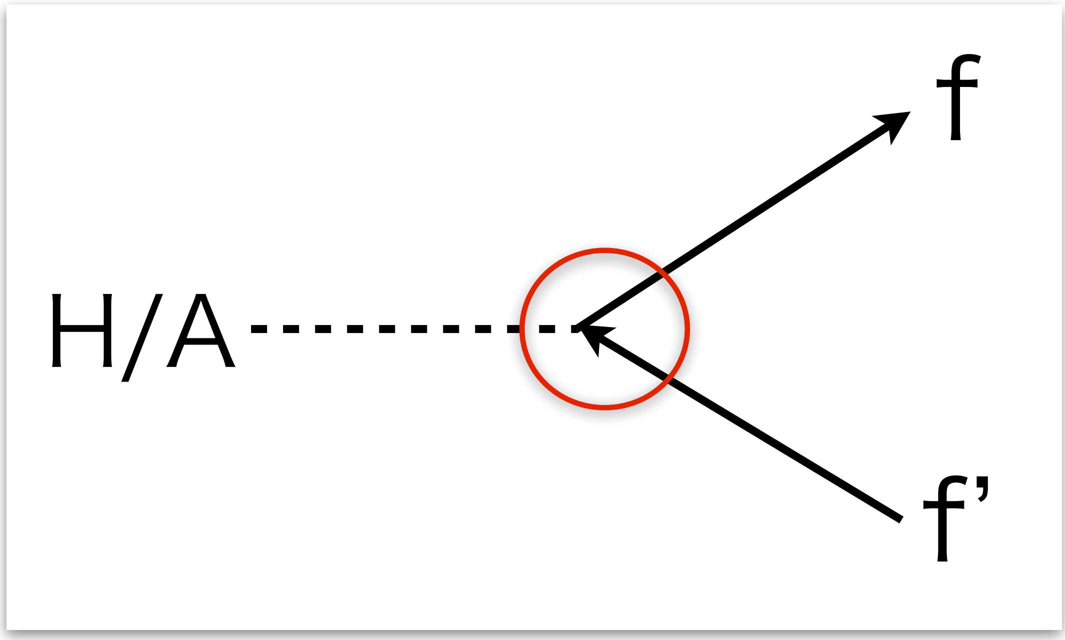
$$m_H^2 \simeq m_A^2 + \mathcal{O}(v^2)$$

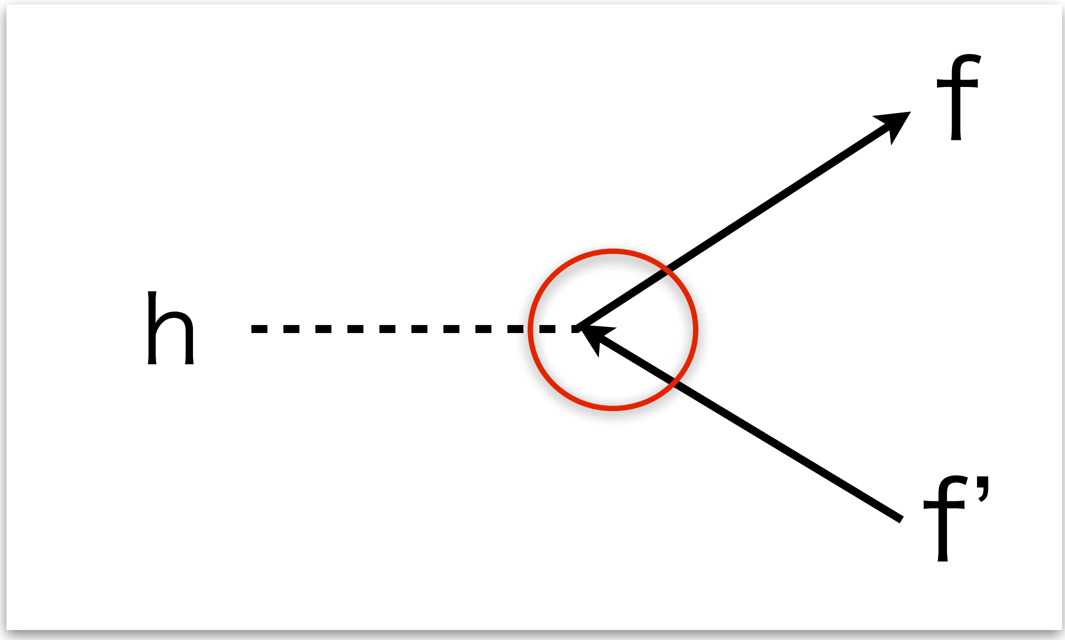
$$m_{H_\pm}^2 \simeq m_A^2 + \mathcal{O}(v^2)$$

# Hunt for the scalars

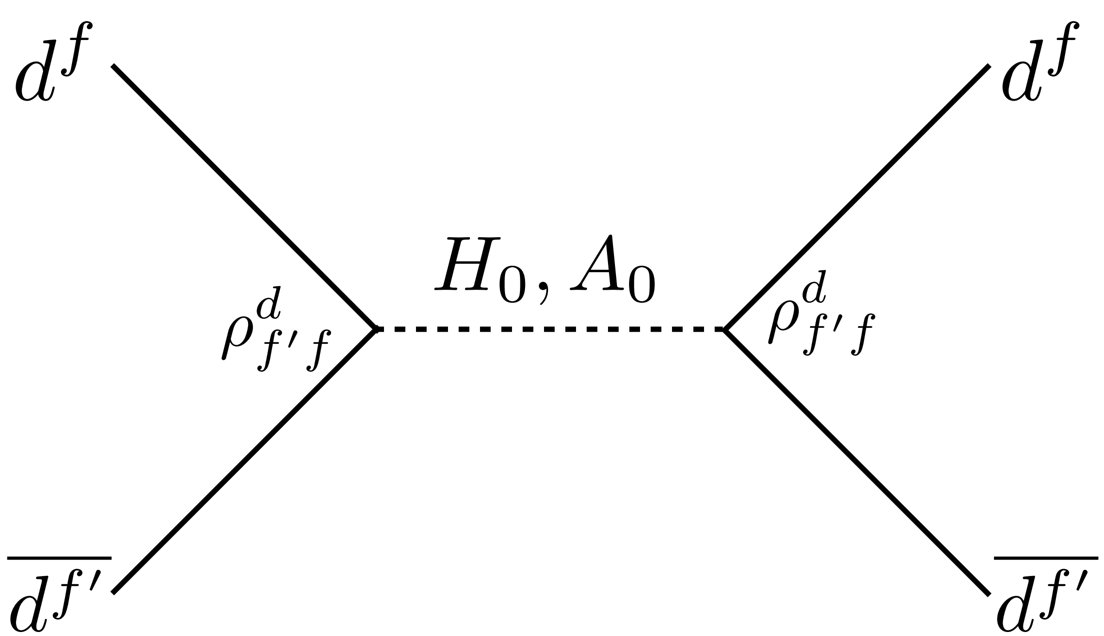
Strong constrain comes from flavor physics

In general, there are new flavor violating couplings



# Strong constrain comes from flavor physics




<u>*Constraints from ΔF=2 processes*</u>

$$\mathcal{H}_{eff} = C_4(\overline{q_L}q'_R)(\overline{q_R}q'_L)$$

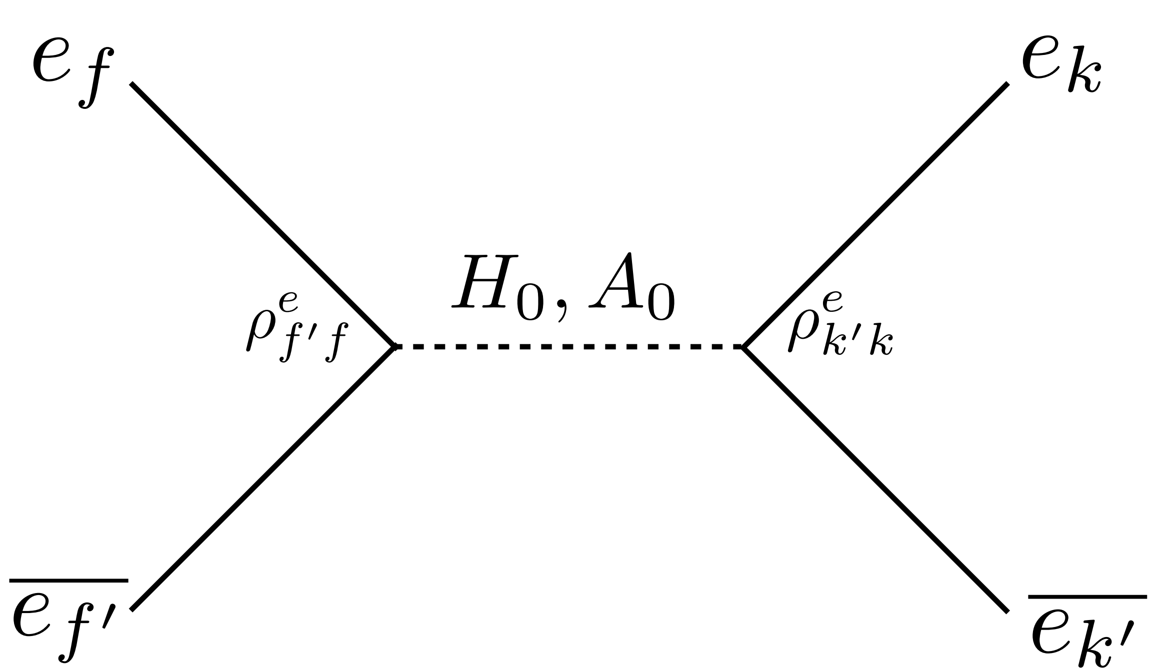
$$K-\overline{K} : m_H/\sqrt{\rho^d_{sd}\rho^{d*}_{ds}} \gtrsim \mathcal{O}(10^5)\ \mathrm{TeV}$$

$$B_d-\overline{B_d} : m_H/\sqrt{\rho^d_{bd}\rho^{d*}_{db}} \gtrsim \mathcal{O}(10^3)\ \mathrm{TeV}$$

$$B_s-\overline{B_s} : m_H/\sqrt{\rho^d_{bs}\rho^{d*}_{sb}} \gtrsim \mathcal{O}(10^2)\ \mathrm{TeV}$$

$$D-\overline{D} : m_H/\sqrt{\rho^u_{cu}\rho^{u*}_{uc}} \gtrsim \mathcal{O}(10^3)\ \mathrm{TeV}$$

# Strong constrain comes from flavor physics




***LFV constraints***

$$\mathcal{H}_{eff} = C_4(\overline{l'_L} l_R)(\overline{l^1_R} l^2_L)$$

From $\mu \to 3e$

$$m_H/(\sqrt{\rho^e_{e\mu}\rho^e_{ee}}) \gtrsim 150\,\mathrm{TeV}$$

From $\tau \to l' l\, l$ $(l',\, l = \mu,\, e)$

$$m_H/(\sqrt{\rho^e_{\tau l'}\rho^e_{ll}}) \gtrsim 10\,\mathrm{TeV}$$

If we assign the symmetry to distinguish the two doublets, we can evade the strong bounds.

U(1)$_{PQ}$ : $H_1 \to e^{iq_1\theta} H_1,\ H_2 \to e^{iq_2\theta} H_2$

Z$_2$ : $H_1 \to +H_1,\ H_2 \to -H_2$

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no new flavor violating coupling

$$\overline{Q_L^i} H_2 y_d^i d_R^i + \overline{Q_L^i} (V^\dagger)^{ij} \widetilde{H}_1 y_u^j u_R^j$$

but this symmetry causes a problem:

$$V \supset \cancel{M}^2 H_1^\dagger H_2$$

scalar masses become EW-scale!

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U(1)PQ : $H_1 \to e^{iq_1\theta} H_1,\ H_2 \to e^{iq_2\theta} H_2$

Z2 : $H_1 \to +H_1,\ H_2 \to -H_2$

➡ no new flavor violating coupling

$$\overline{Q^i_L} H_2 y^i_d d^i_R + \overline{Q^i_L} (V^\dagger)^{ij} \widetilde{H}_1 y^j_u u^j_R$$

people often say that

“Z2 is broken in only mass para.,” and allow

$V \supset M^2 H_1^\dagger H_2$ to shift the scalar masses

Then, the Yukawa couplings are controlled by the symmetry.

There are several choices for the charge assignment:

**Type-I 2HDM:** $Y^u_{ff'}\overline{Q^f_L}\widetilde{H_1}u^{f'}_R + Y^d_{ff'}\overline{Q^f_L}H_1 d^{f'}_R + Y^e_{ff'}\overline{l^f_L}H_1 e^{f'}_R$

**Type-II 2HDM:** $Y^u_{ff'}\overline{Q^f_L}\widetilde{H_1}u^{f'}_R + Y^d_{ff'}\overline{Q^f_L}H_2 d^{f'}_R + Y^e_{ff'}\overline{l^f_L}H_2 e^{f'}_R$

*(inspired by MSSM)*

**Type-X 2HDM:** $Y^u_{ff'}\overline{Q^f_L}\widetilde{H_1}u^{f'}_R + Y^d_{ff'}\overline{Q^f_L}H_1 d^{f'}_R + Y^e_{ff'}\overline{l^f_L}H_2 e^{f'}_R$

**Type-Y 2HDM:** $Y^u_{ff'}\overline{Q^f_L}\widetilde{H_1}u^{f'}_R + Y^d_{ff'}\overline{Q^f_L}H_2 d^{f'}_R + Y^e_{ff'}\overline{l^f_L}H_1 e^{f'}_R$

**(flipped)**

Then, the Yukawa couplings are controlled by the symmetry.

There are several choices for the charge assignment:

**Let me focus on type-II**

Type-I 2HDM: $Y^u_{ff'}\overline{Q^f_L}\widetilde{H_1}u^{f'}_R + Y^d_{ff'}\overline{Q^f_L}H_1 d^{f'}_R + Y^e_{ff'}\overline{l^f_L}H_1 e^{f'}_R$

Type-II 2HDM: $Y^u_{ff'}\overline{Q^f_L}\widetilde{H_1}u^{f'}_R + Y^d_{ff'}\overline{Q^f_L}H_2 d^{f'}_R + Y^e_{ff'}\overline{l^f_L}H_2 e^{f'}_R$

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(flipped)

*Even if there is no new flavor violating couplings,*
*the CKM predicts enough large deviations in flavor physics:*

**Experiment:** $(E_\gamma > 1.6\text{GeV})$

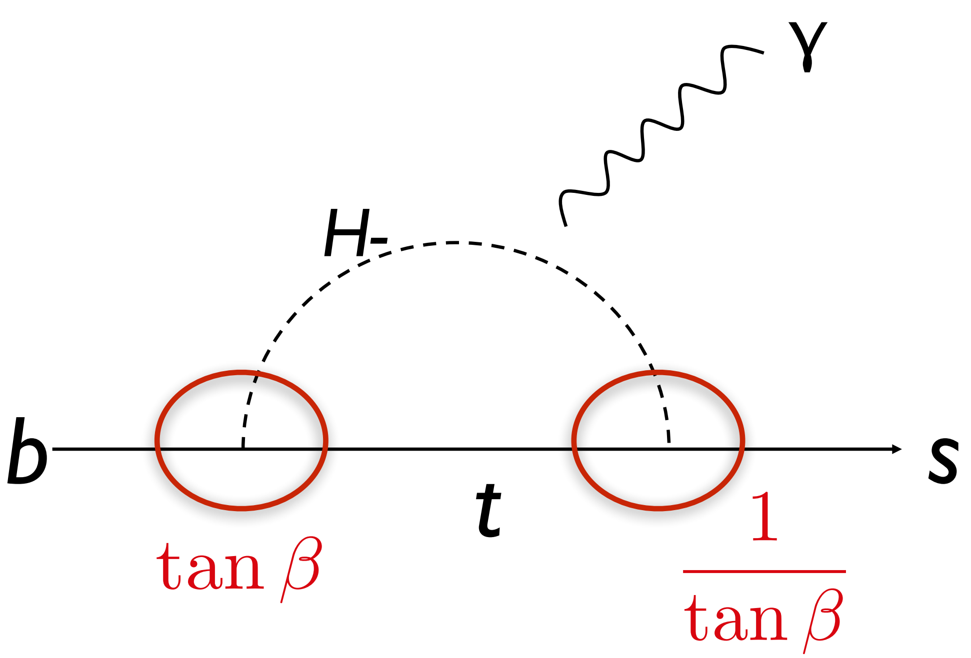
$$Br(b \to s\gamma)_{\text{exp}} = (3.32 \pm 0.16) \times 10^{-4}$$

(Y.Amhis, arXiv:1612.07233)

**SM prediction (NNLO):** $(E_\gamma > 1.6\text{GeV})$

$$Br(b \to s\gamma)_{\text{SM}} = (3.36 \pm 0.23) \times 10^{-4}$$

(Misiak, et.al., arXiv:1208.2788;1503.01789;1702.04571)



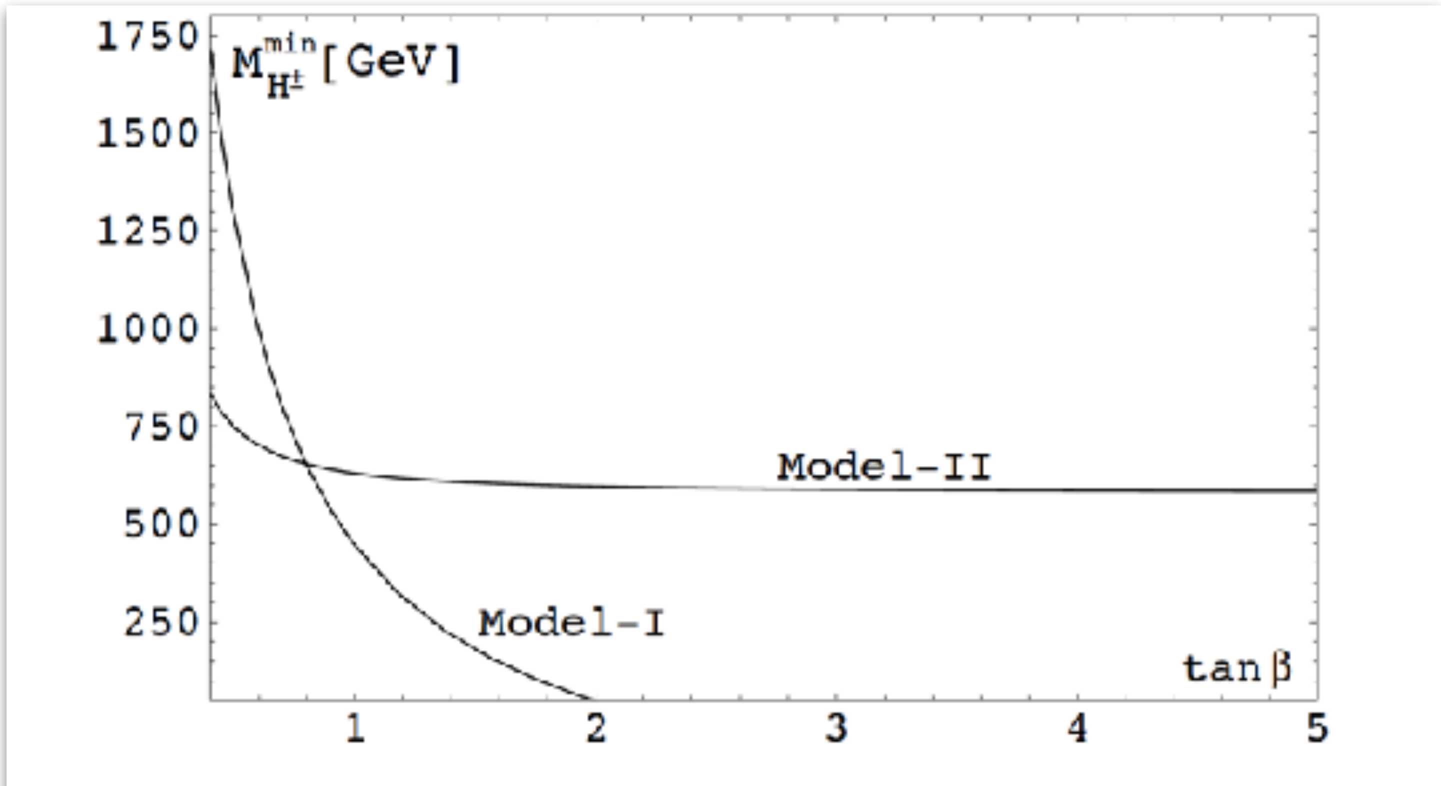




Figure 4: 95% C.L. lower bounds on $M_{H^\pm}$ as functions of $\tan\beta$.

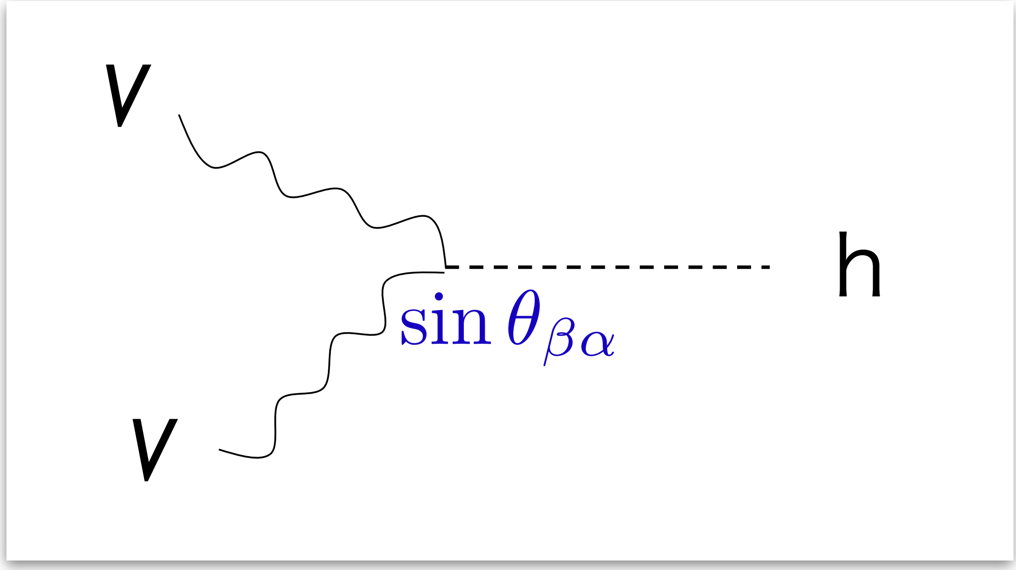
$$Q_7 = \frac{e}{16\pi^2} m_b (s_L \sigma^{\mu\nu} b_R) F_{\mu\nu}$$

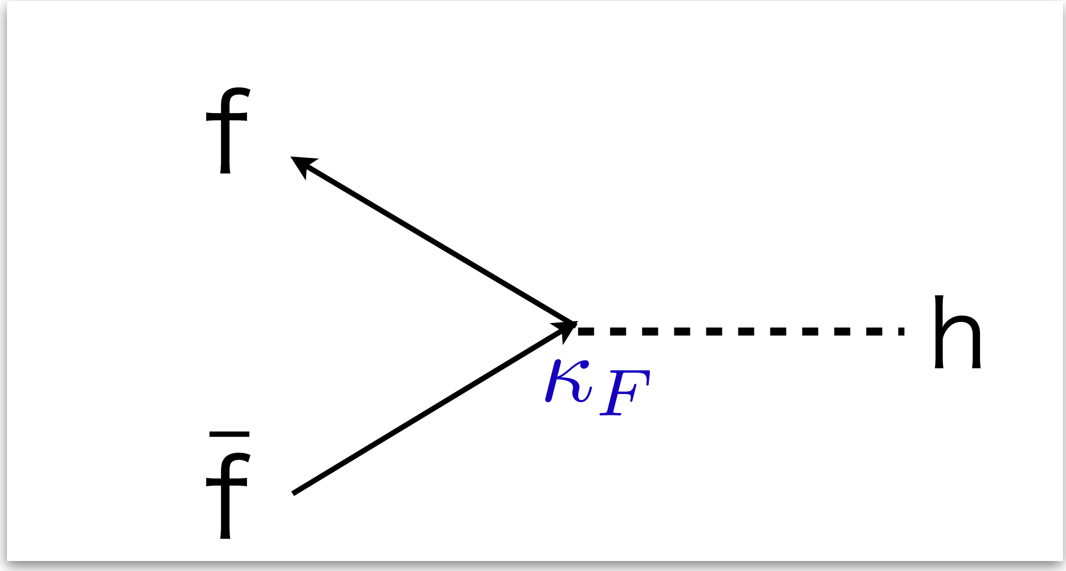
$$m_{H_\pm} \gtrsim 580GeV$$

(Belle,arXiv:1608.02344;Misiak, et.al., arXiv:1702.04571)

## We could see the scalars directly/indirectly at the LHC

*The SM prediction about the 125 GeV Higgs is deviated.*



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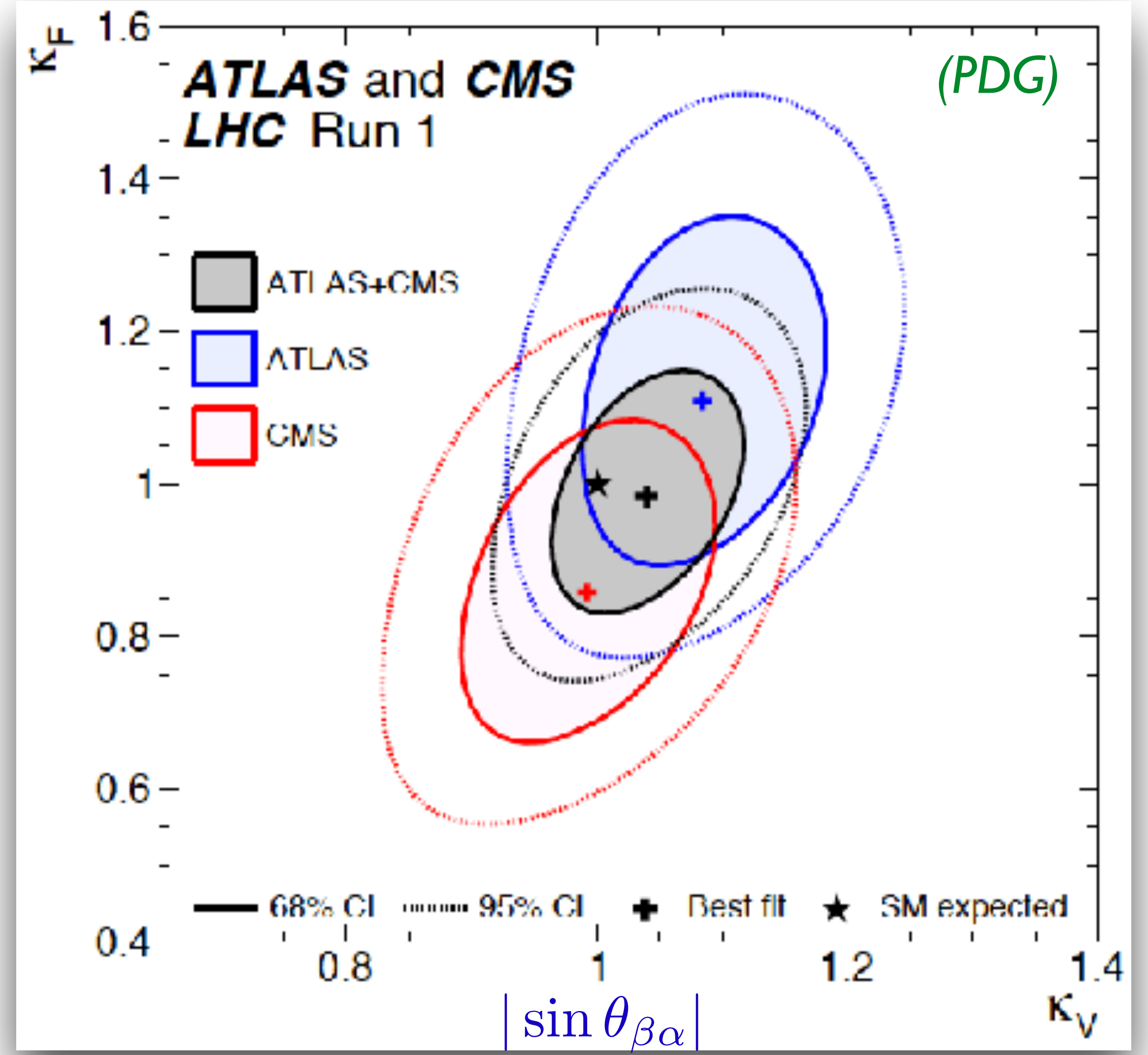
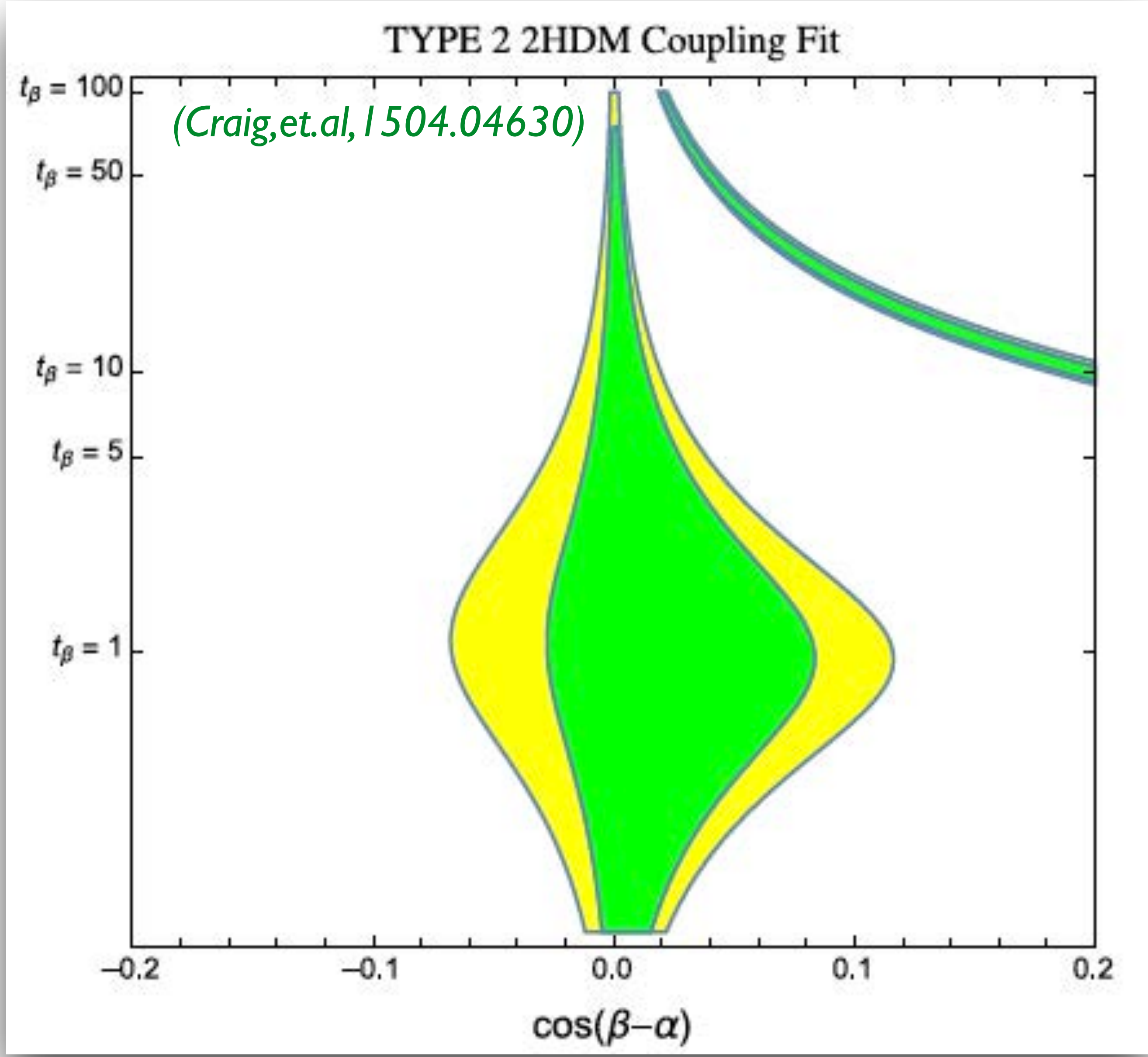
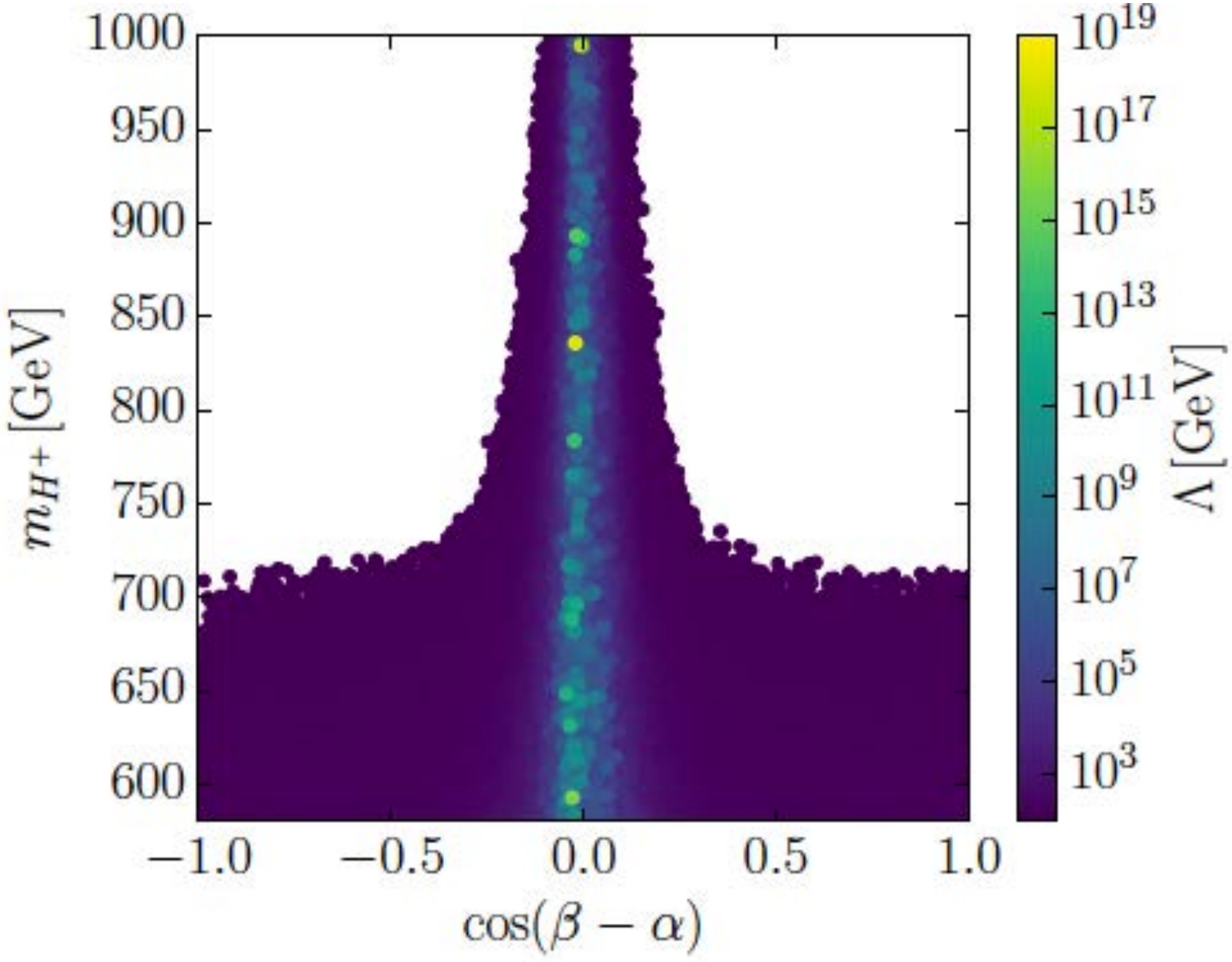



*Less than 10 % deviation is only allowed.*

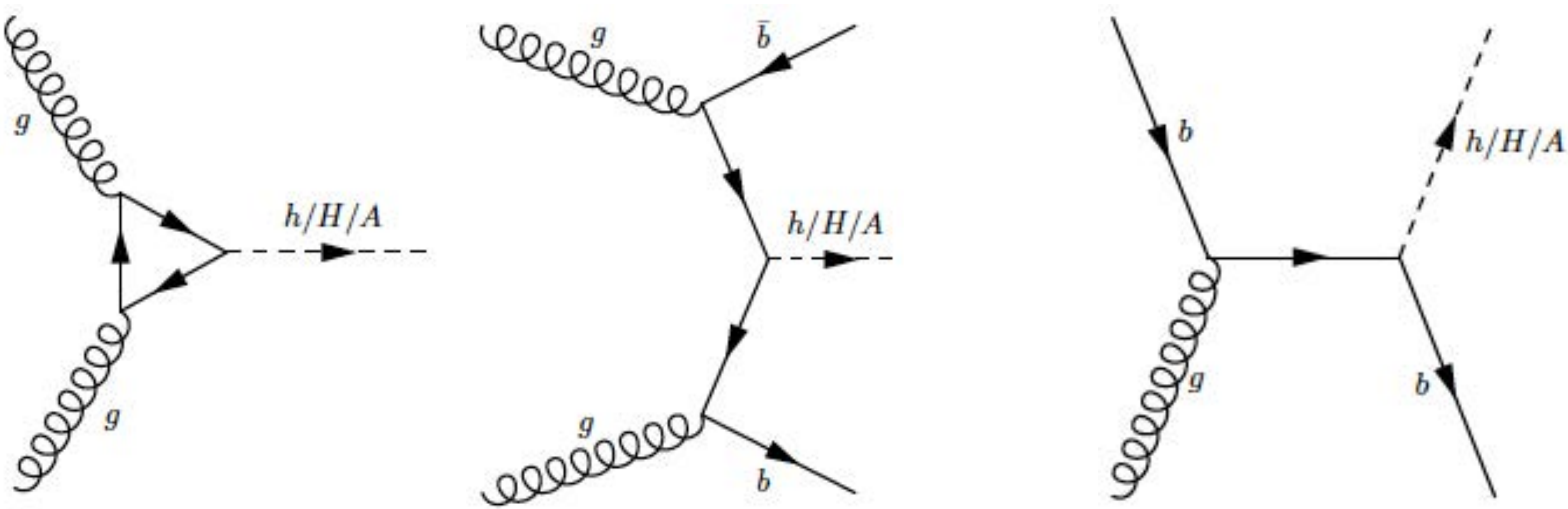
# The Landau pole appears, if the Higgs signal is deviated from the SM one.

*(Philipp Basler , Pedro M. Ferreira, Margarete Muhlleitner, Rui Santos,1710.10410)*



# We could see the scalars directly at the LHC

*Then, the heavy scalars are produced at the LHC:*

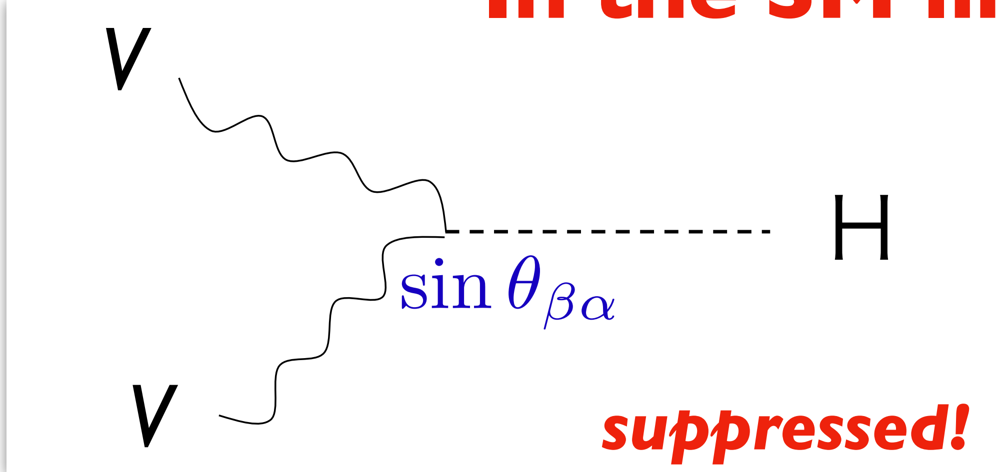


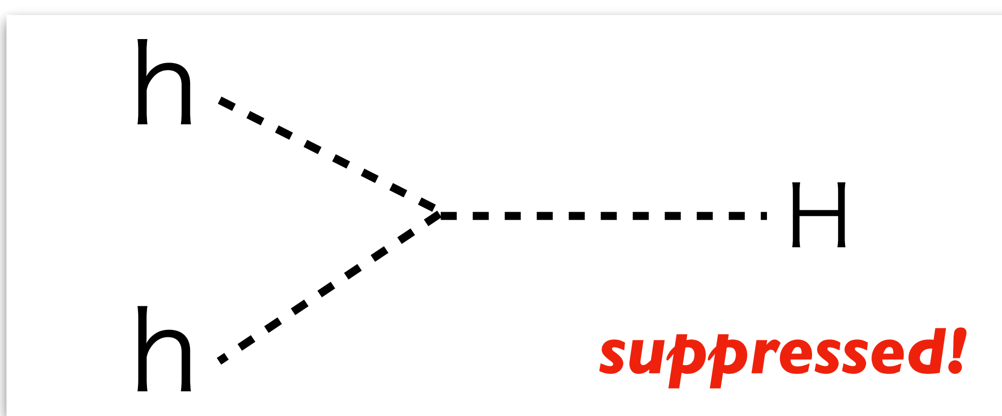

*The scalars decays to heavy fermions and di-bosons*

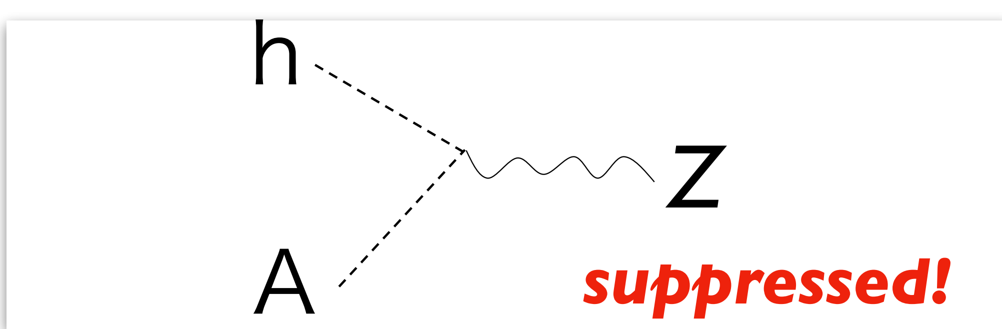
# We could see the scalars directly at the LHC

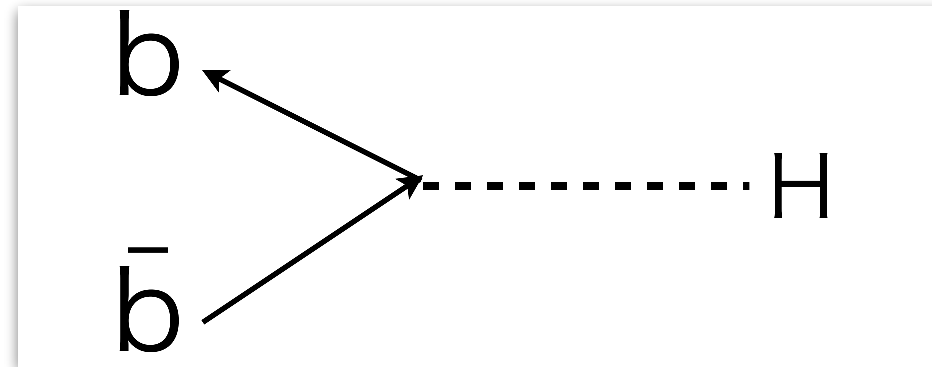
*The scalars decays to heavy fermions and di-bosons*

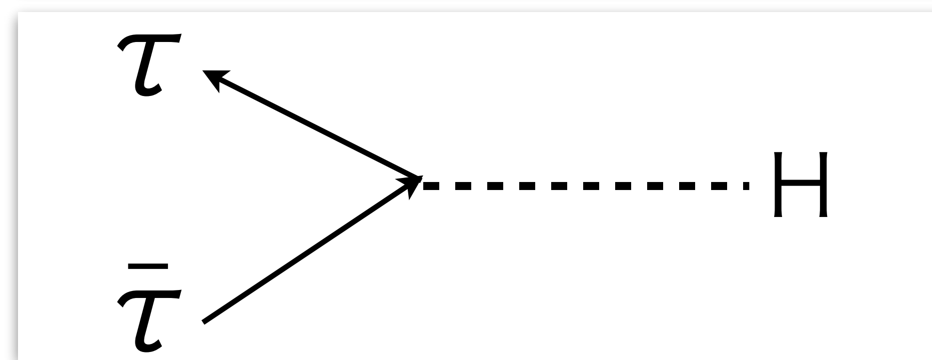
**In the SM limit,**

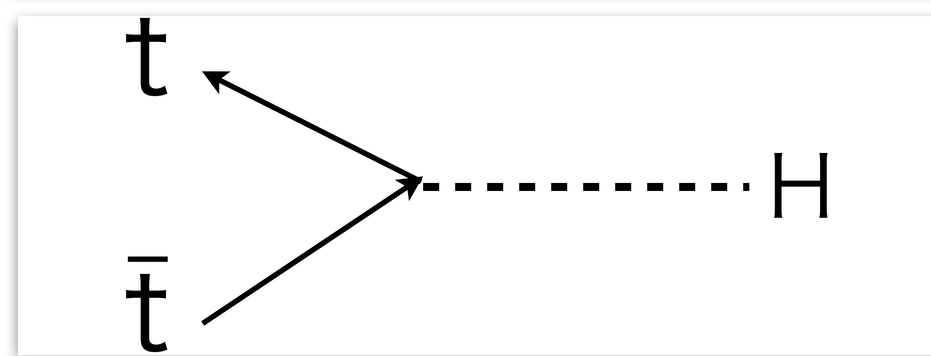


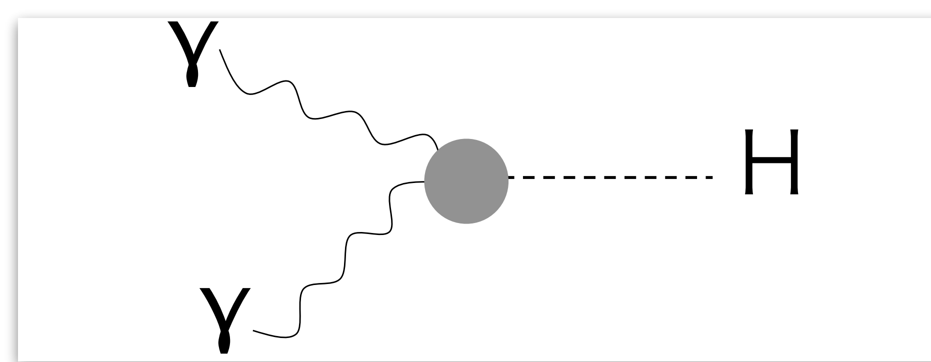



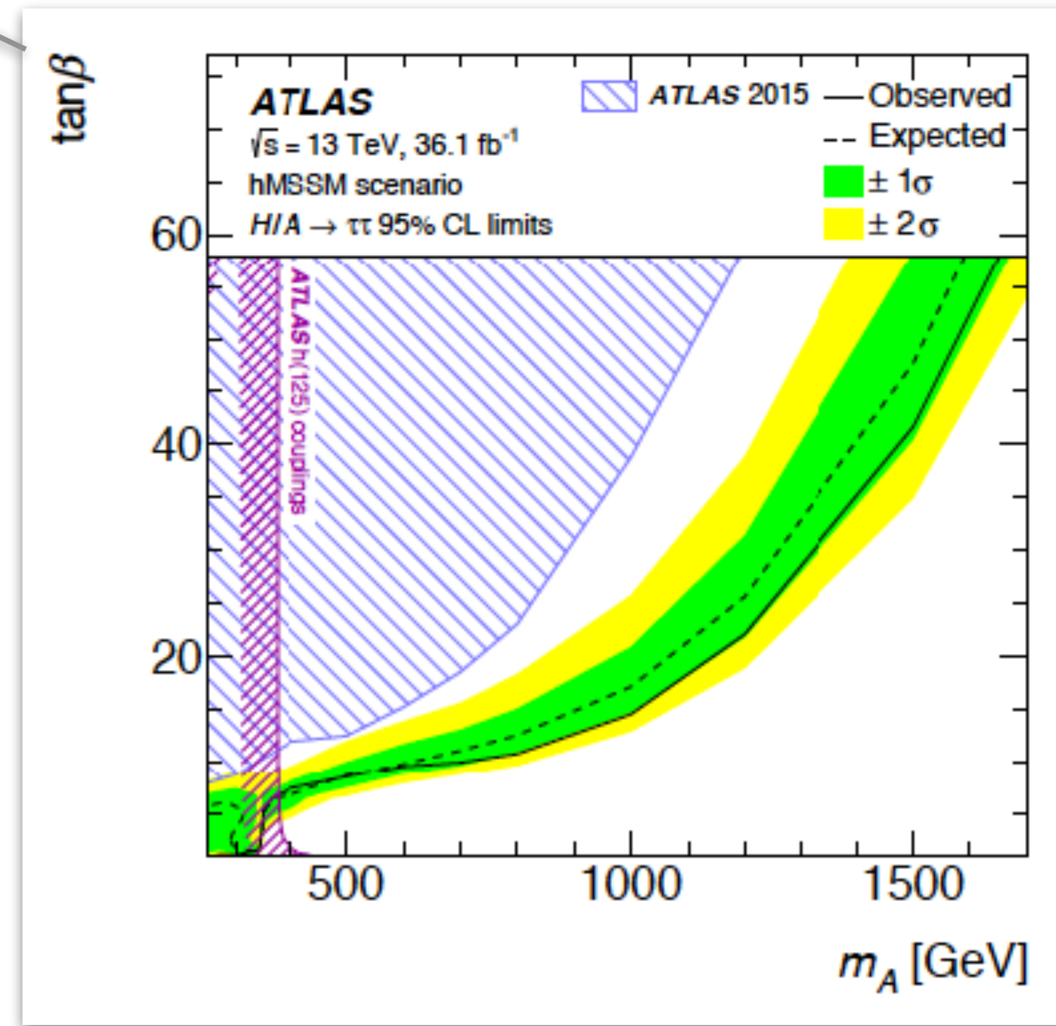



# Actually, many modes have been already studied.

| Label | | Channel | Experiment | | Mass range [GeV] | $\mathcal{L}$ [fb$^{-1}$] |
|---|---|---|---|---|---|---|
| $C_{13}^{bb}$ | | $pp \to H/A \to bb$ | CMS | [75] | [0.55;1.2] | 2.69 |
| $A_{13}^{\tau\tau}$ | | $gg \to H/A \to \tau\tau$ | ATLAS | [76] | [0.2;2.25] | 36.1 |
| $C_{13}^{\tau\tau}$ | | | CMS | [77] | [0.09;3.2] | 12.9 |
| $A_{13b}^{\tau\tau}$ | | $bb \to H/A \to \tau\tau$ | ATLAS | [76] | [0.2;2.25] | 36.1 |
| $C_{13b}^{\tau\tau}$ | | | CMS | [77] | [0.09;3.2] | 12.9 |
| $A_{13}^{\gamma\gamma}$ | | $pp \to H/A \to \gamma\gamma$ | ATLAS | [78] | [0.2;2.7] | 36.7 |
| $C_{13}^{\gamma\gamma}$ | | $gg \to H/A \to \gamma\gamma$ | CMS | [79] | [0.5;4] | 35.9 |
| $A_{13}^{Z\gamma}$ | | $gg \to H/A \to Z\gamma[\to (\ell\ell)\gamma]$ | ATLAS | [45] | [0.25;2.4] | 36.1 |
| $C_{13}^{Z\gamma}$ | | $gg \to H/A \to Z\gamma$ | CMS | [80] | [0.35;4] | 35.9 |
| $A_{13}^{2\ell 2L}$ | | $gg \to H \to ZZ[\to (\ell\ell)(\ell\ell,\nu\nu)]$ | ATLAS | [81] | [0.2;1.2] | 36.1 |
| $A_{13V}^{2\ell 2L}$ | | $VV \to H \to ZZ[\to (\ell\ell)(\ell\ell,\nu\nu)]$ | ATLAS | [81] | [0.2;1.2] | 36.1 |
| $C_{13}^{2\ell 2\nu}$ | | $pp \to H \to ZZ[\to (\ell\ell)(\nu\nu)]$ | CMS | [82] | [0.6;2.5] | 35.9 |
| $C_{13g}^{2\ell 2\nu}$ | | $gg \to H \to ZZ[\to (\ell\ell)(\nu\nu)]$ | CMS | [83] | [0.2;0.6] | 2.3 |
| $C_{13V}^{2\ell 2\nu}$ | | $VV \to H \to ZZ[\to (\ell\ell)(\nu\nu)]$ | CMS | [83] | [0.2;0.6] | 2.3 |
| $C_{13V}^{4\ell}$ | | $(VV+VH) \to H \to ZZ \to (\ell\ell)(\ell\ell)$ | CMS | [84] | [0.13;2.53] | 12.9 |
| $C_{13}^{2\ell 2q}$ | | $pp \to H \to ZZ[\to (\ell\ell)(qq)]$ | CMS | [85] | [0.5;2] | 12.9 |
| $A_{13}^{2L2q}$ | | $gg \to H \to ZZ[\to (\ell\ell,\nu\nu)(qq)]$ | ATLAS | [86] | [0.3;3] | 36.1 |
| $A_{13V}^{2L2q}$ | | $VV \to H \to ZZ[\to (\ell\ell,\nu\nu)(qq)]$ | ATLAS | [86] | [0.3;3] | 36.1 |
| $A_{13}^{2(\ell\nu)}$ | | $gg \to H \to WW[\to (e\nu)(\mu\nu)]$ | ATLAS | [87] | [0.25;4] | 36.1 |
| $A_{13V}^{2(\ell\nu)}$ | | $VV \to H \to WW[\to (e\nu)(\mu\nu)]$ | ATLAS | [87] | [0.25;3] | 36.1 |
| $C_{13}^{2(\ell\nu)}$ | | $(gg+VV) \to H \to WW \to (\ell\nu)(\ell\nu)$ | CMS | [88] | [0.2;1] | 2.3 |
| $A_{13}^{\ell\nu 2q}$ | | $gg \to H \to WW[\to (\ell\nu)(qq)]$ | ATLAS | [89] | [0.3;3] | 36.1 |
| $A_{13V}^{\ell\nu 2q}$ | | $VV \to H \to WW[\to (\ell\nu)(qq)]$ | ATLAS | [89] | [0.3;3] | 36.1 |
| $A_{13}^{4q}$ | | $pp \to H \to VV[\to (qq)(qq)]$ | ATLAS | [90] | [1.2;3] | 36.7 |
| $A_{13}^{4b}$ | | $pp \to H \to hh \to (bb)(bb)$ | ATLAS | [91] | [0.3;3] | 13.3 |
| $C_{13}^{4b}$ | | | CMS | [92] | [0.26;1.2] | 35.9 |
| $C_{13g}^{4b}$ | | $gg \to H \to hh \to (bb)(bb)$ | CMS | [93] | [1.2;3] | 35.9 |
| $A_{13}^{2\gamma 2b}$ | | $pp \to H \to hh[\to (\gamma\gamma)(bb)]$ | ATLAS | [94] | [0.275;0.4] | 3.2 |
| $C_{13}^{2\gamma 2b}$ | | $pp \to H \to hh \to (\gamma\gamma)(bb)$ | CMS | [95] | [0.25;0.9] | 35.9 |
| $C_{13}^{2b2\tau}$ | | $pp \to H \to hh \to (bb)(\tau\tau)$ | CMS | [96] | [0.25;0.9] | 35.9 |
| $C_{13}^{2b2V}$ | | $pp \to H \to hh \to (bb)(VV \to \ell\nu\ell\nu)$ | CMS | [97] | [0.26;0.9] | 36 |
| $A_{13}^{2\gamma 2W}$ | | $gg \to H \to hh[\to (\gamma\gamma)(WW)]$ | ATLAS | [98] | [0.25;0.5] | 13.3 |
| $A_{13}^{bbZ}$ | | $gg \to A \to hZ \to (bb)Z$ | ATLAS | [99] | [0.2;2] | 36.1 |
| $A_{13b}^{bbZ}$ | | $b\bar{b} \to A \to hZ \to (bb)Z$ | ATLAS | [99] | [0.2;2] | 36.1 |

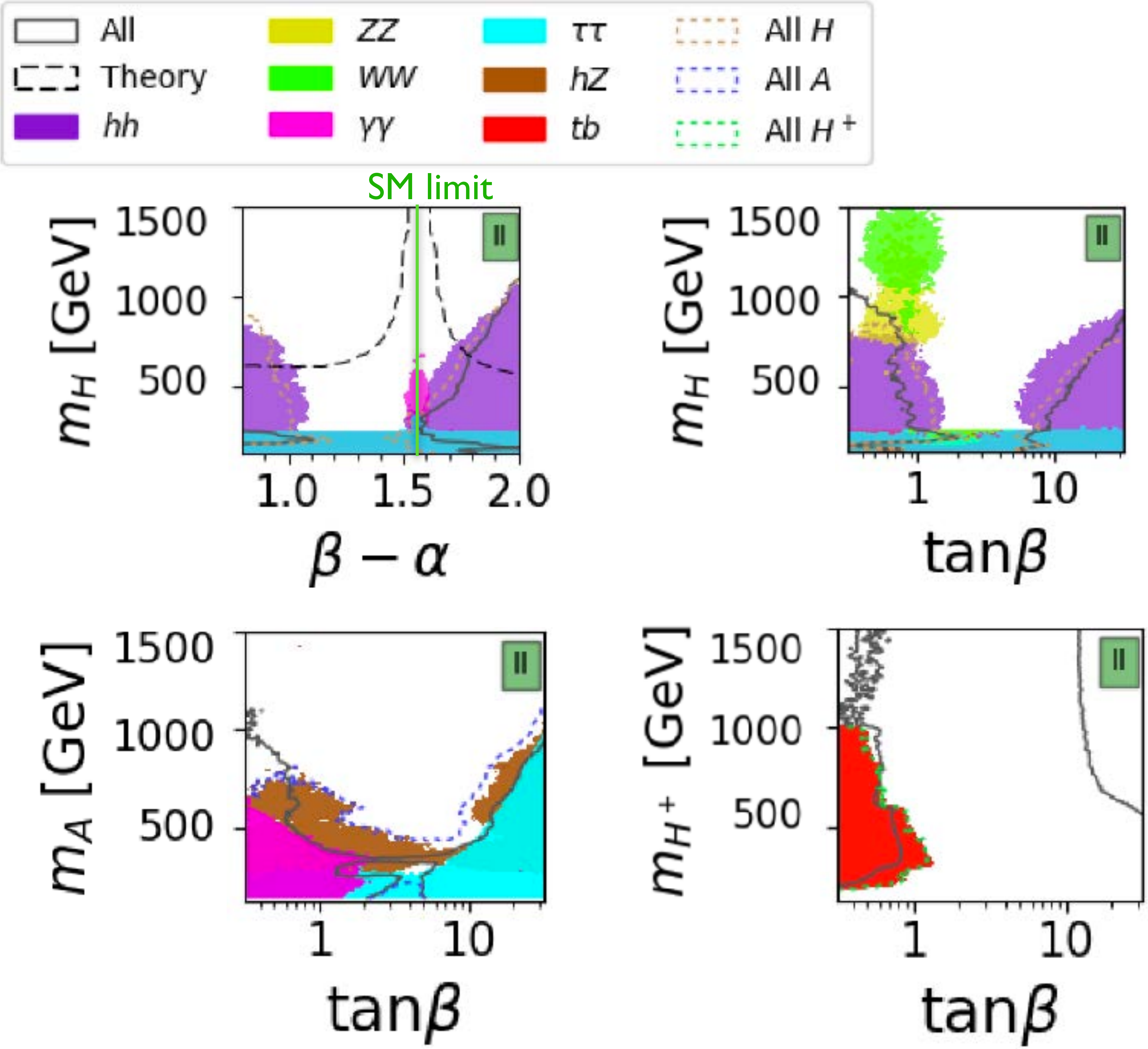
| Channel | Experiment | | Mass range [TeV] | $\mathcal{L}$ [fb$^{-1}$] |
|---|---|---|---|---|
| $pp \to H^{\pm} \to \tau^{\pm}\nu$ | ATLAS | [100] | [0.2;2] | 14.7 |
| | CMS | [101] | [0.18;3] | 12.9 |
| $pp \to H^{+} \to t\bar{b}$ | ATLAS | [102] | [0.3;1] | 13.2 |
| | ATLAS | [103] | [0.2;0.3]∪[1;2] | 13.2 |

(Chowdhury,Eberhardt,1711.02095)



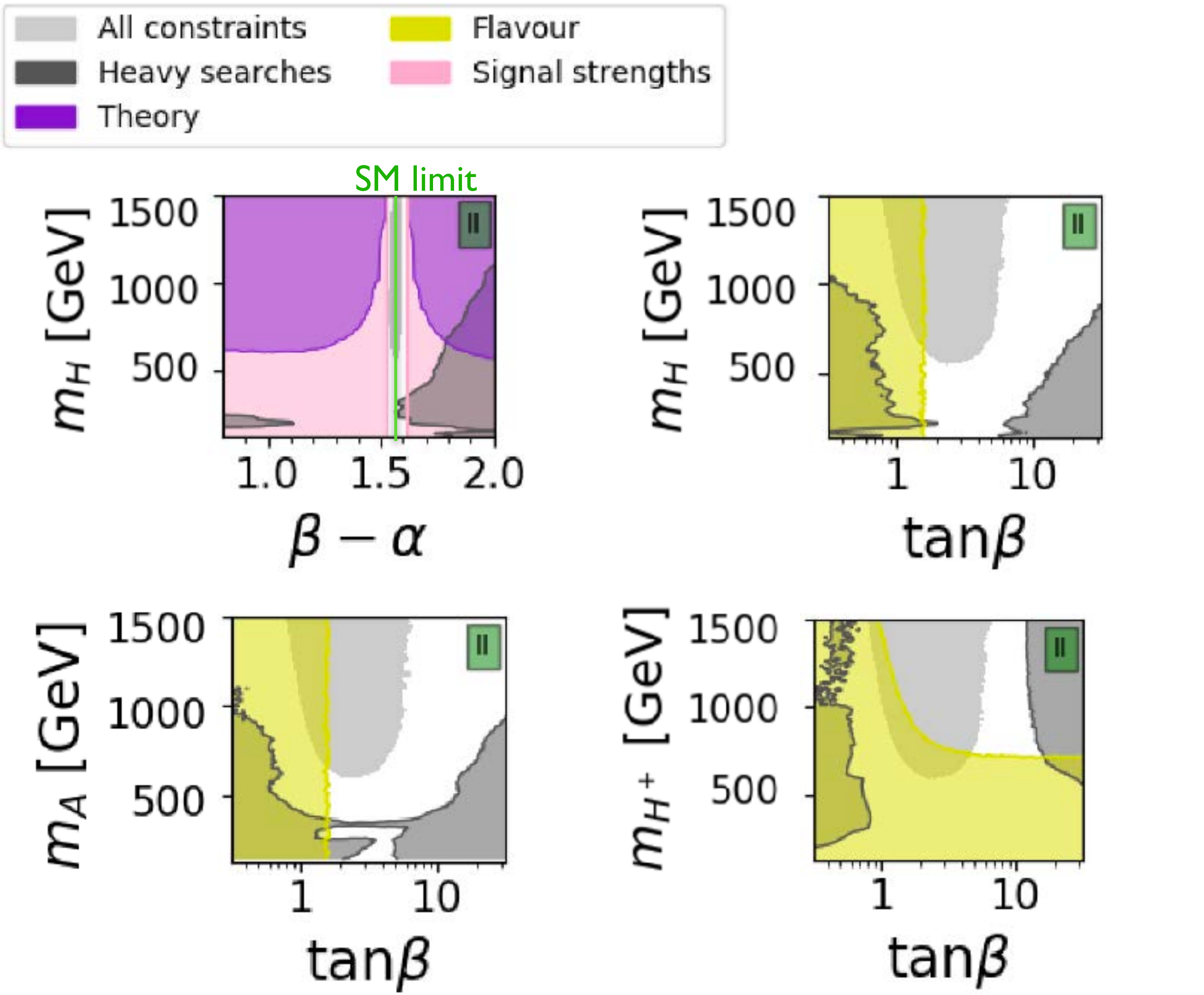
# Summary plots

*(Chowdhury,Eberhardt,1711.02095)*



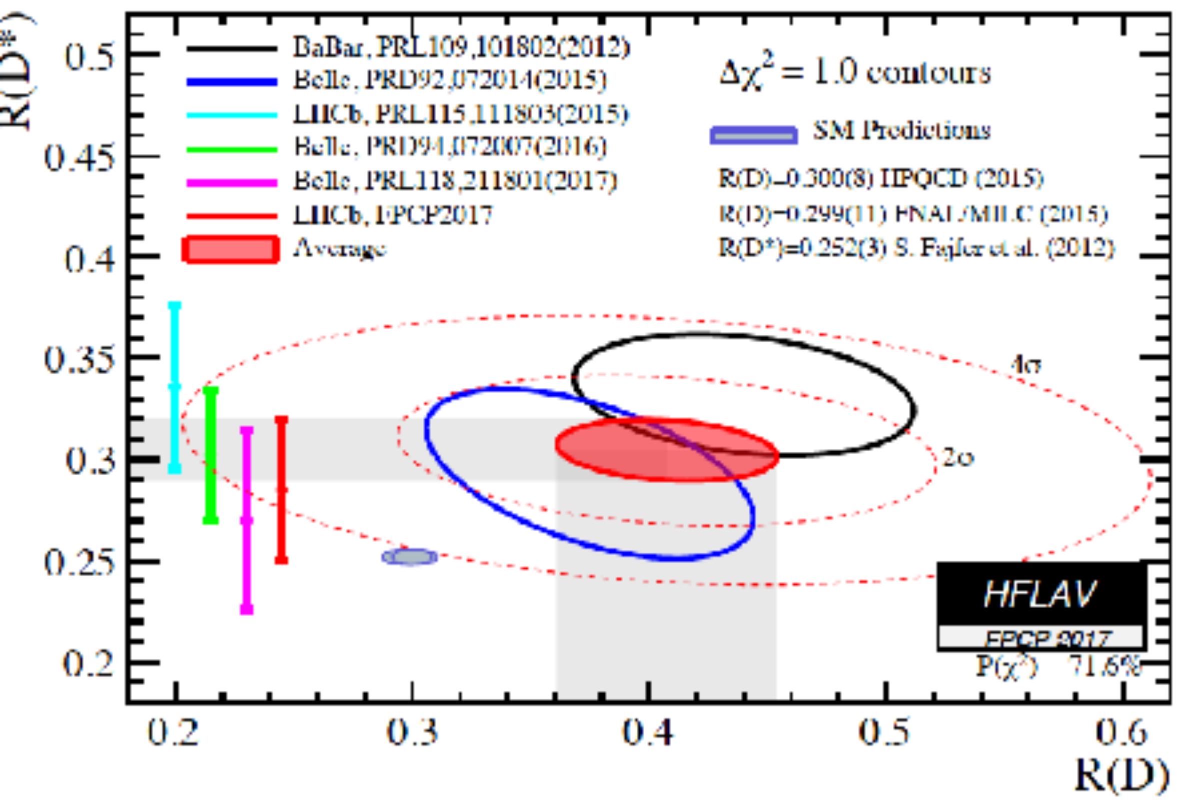
# Compare with others

*(Chowdhury,Eberhardt,1711.02095)*



# Impact of the 2HDM on the excesses in the flavor physics

# The excess in Lepton Flavor Universality (LFU) in B→D(*)lν

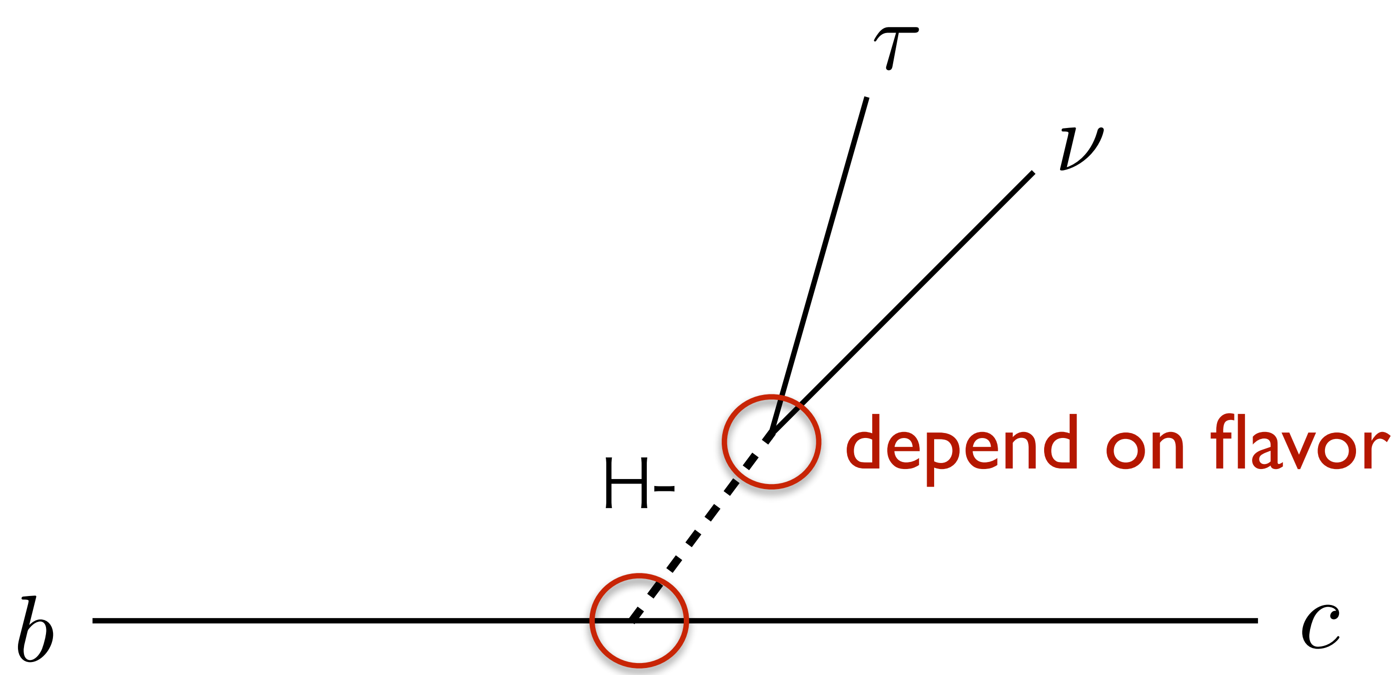



*lepton universality of B→D(*)τν*

$$R(D^{(*)}) \equiv \frac{\Gamma(B \to D^{(*)}\tau\nu)}{\Gamma(B \to D^{(*)}\ell\nu)}$$

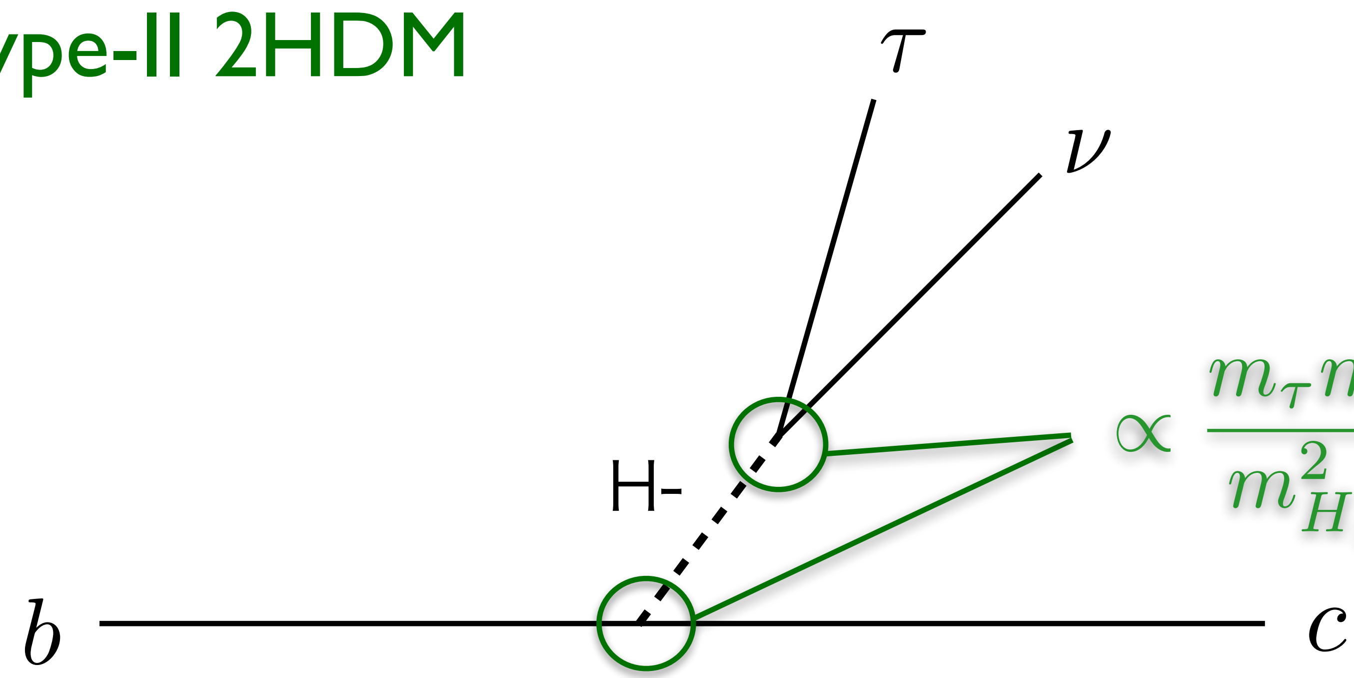
where $\ell = e, \mu$

Charged Higgs is a very good candidate!



# The type-II 2HDM is strongly constrained.

## In type-II 2HDM

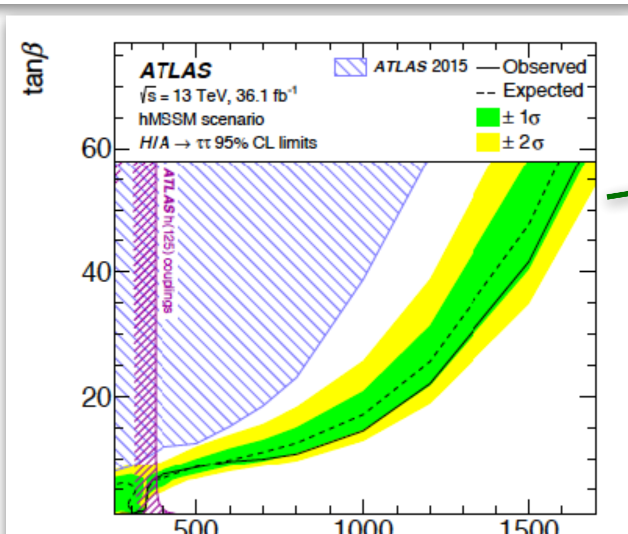



$$\propto \frac{m_\tau m_b}{m_{H_\pm}^2} \tan^2\beta$$

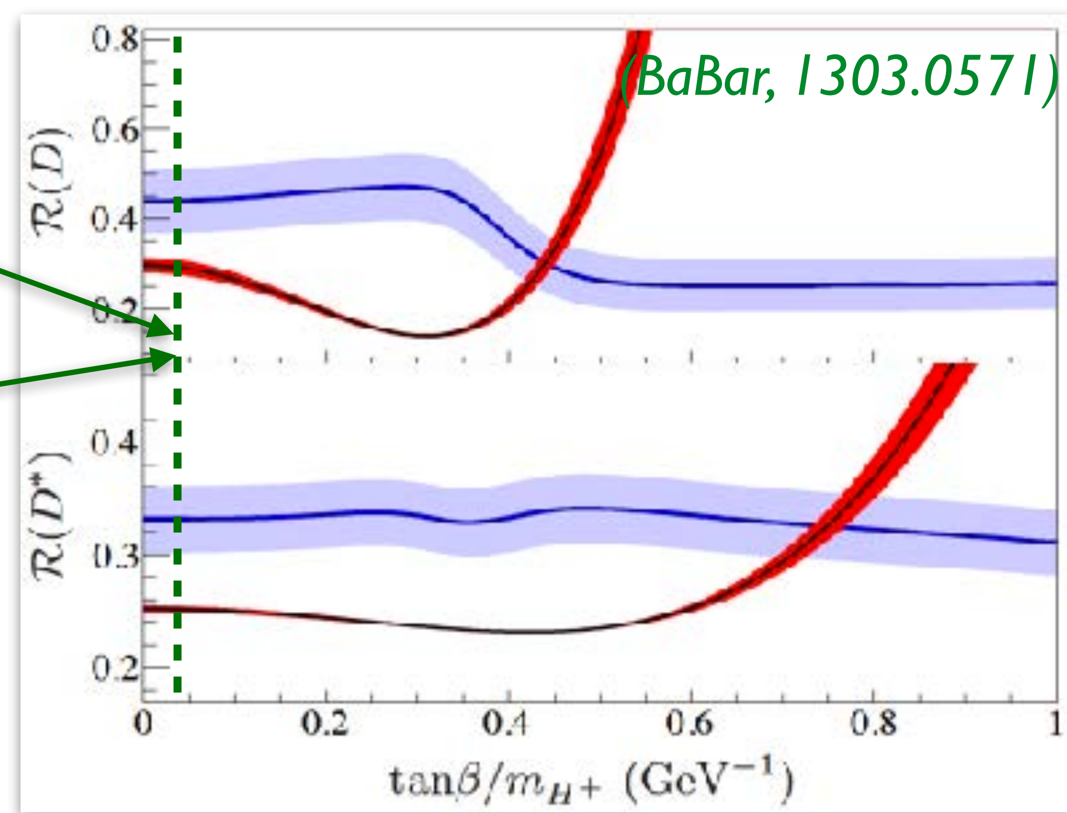
*bound is from b →s γ:*

$$m_{H_\pm} > 580\,\mathrm{GeV}$$

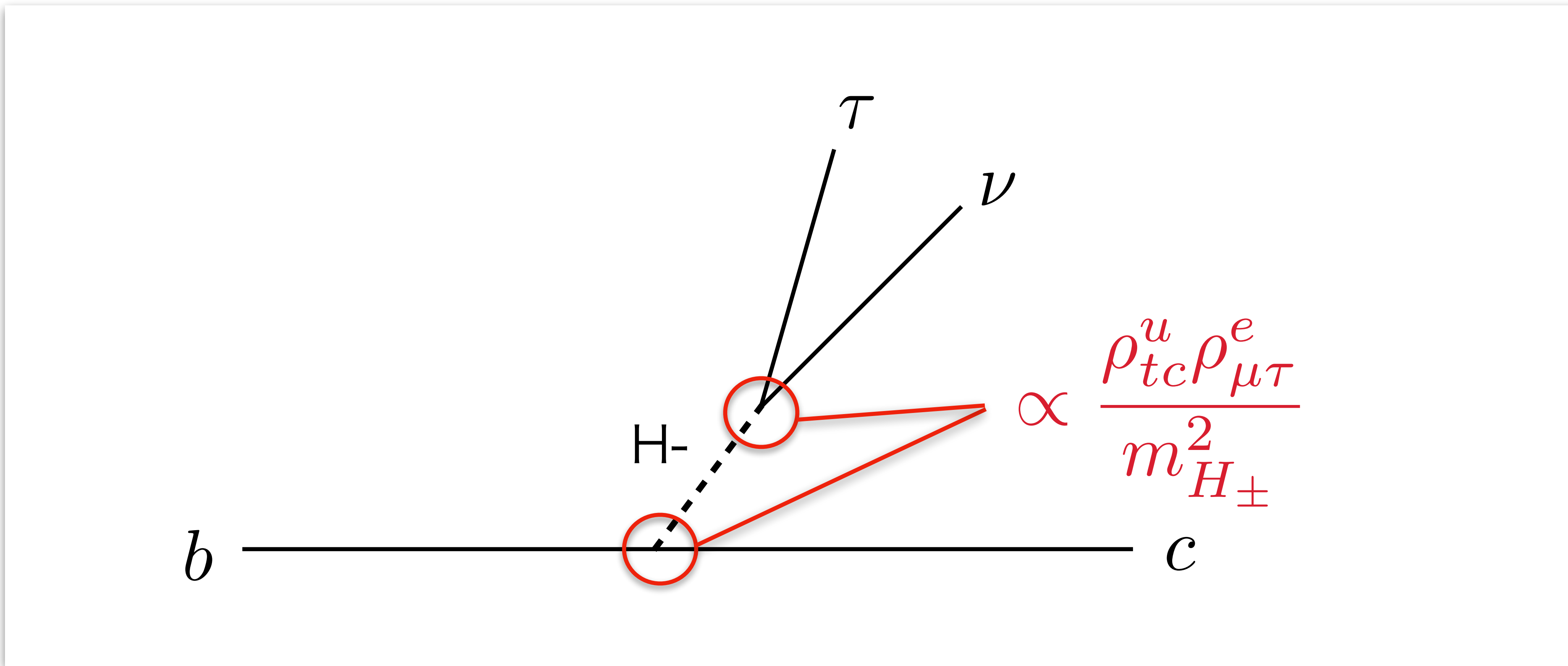
Misiak, Steinhauser, 1702.04571




1709.07242



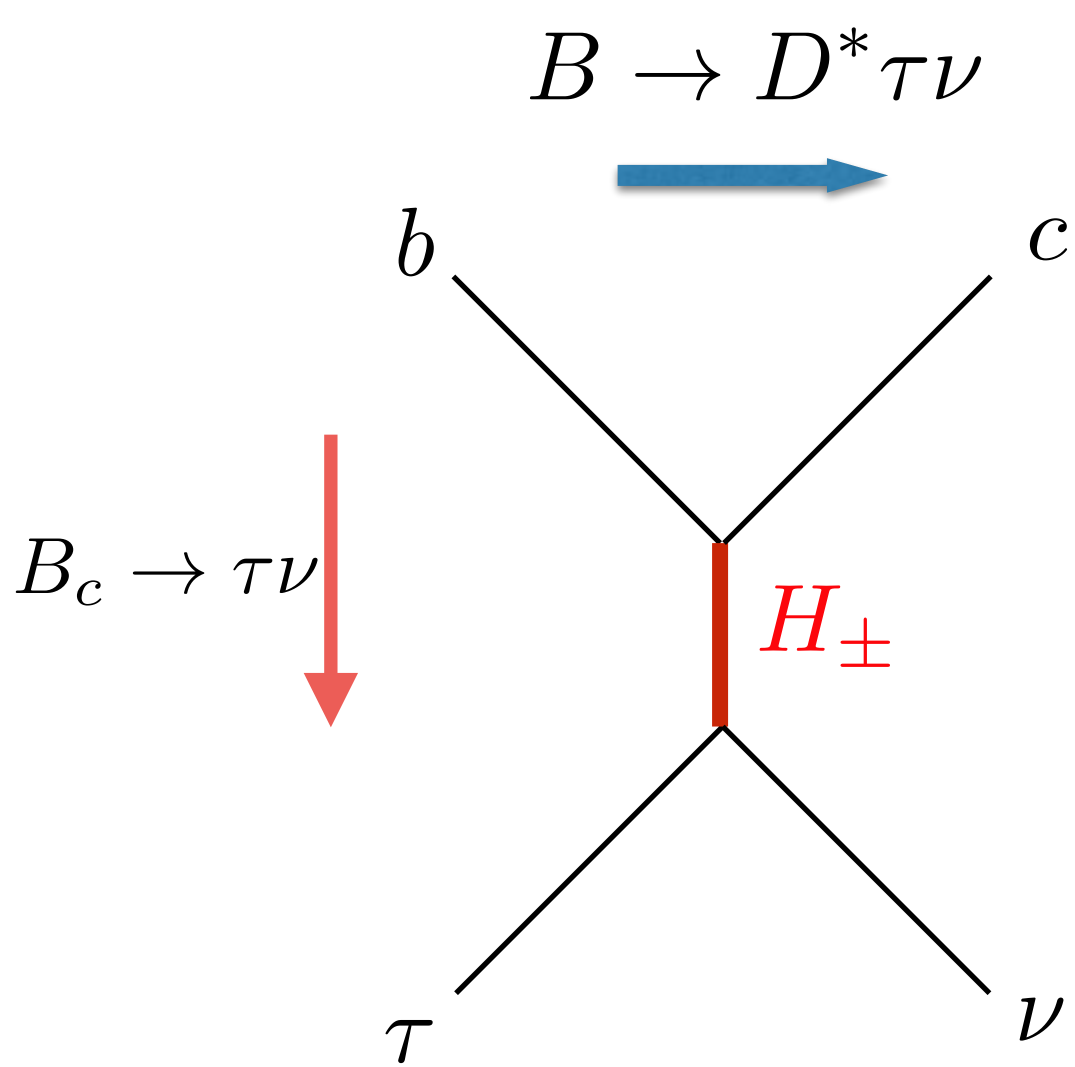
We have to think about the 2HDM with tree-level FCNCs,

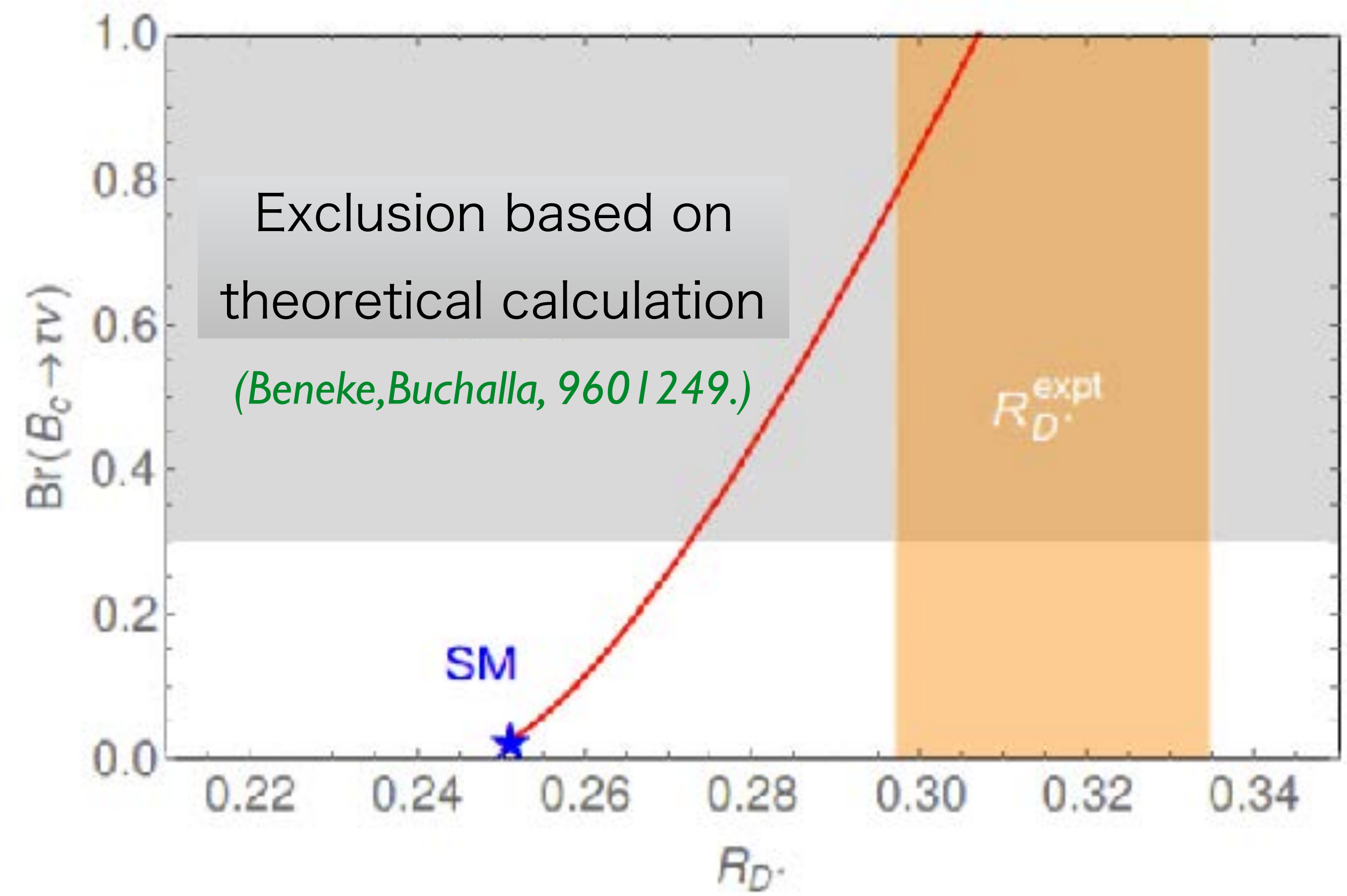



although we have to tune many para. to avoid the flavor constraints.

# Bc decay limits the R(D*) in 2HDM.

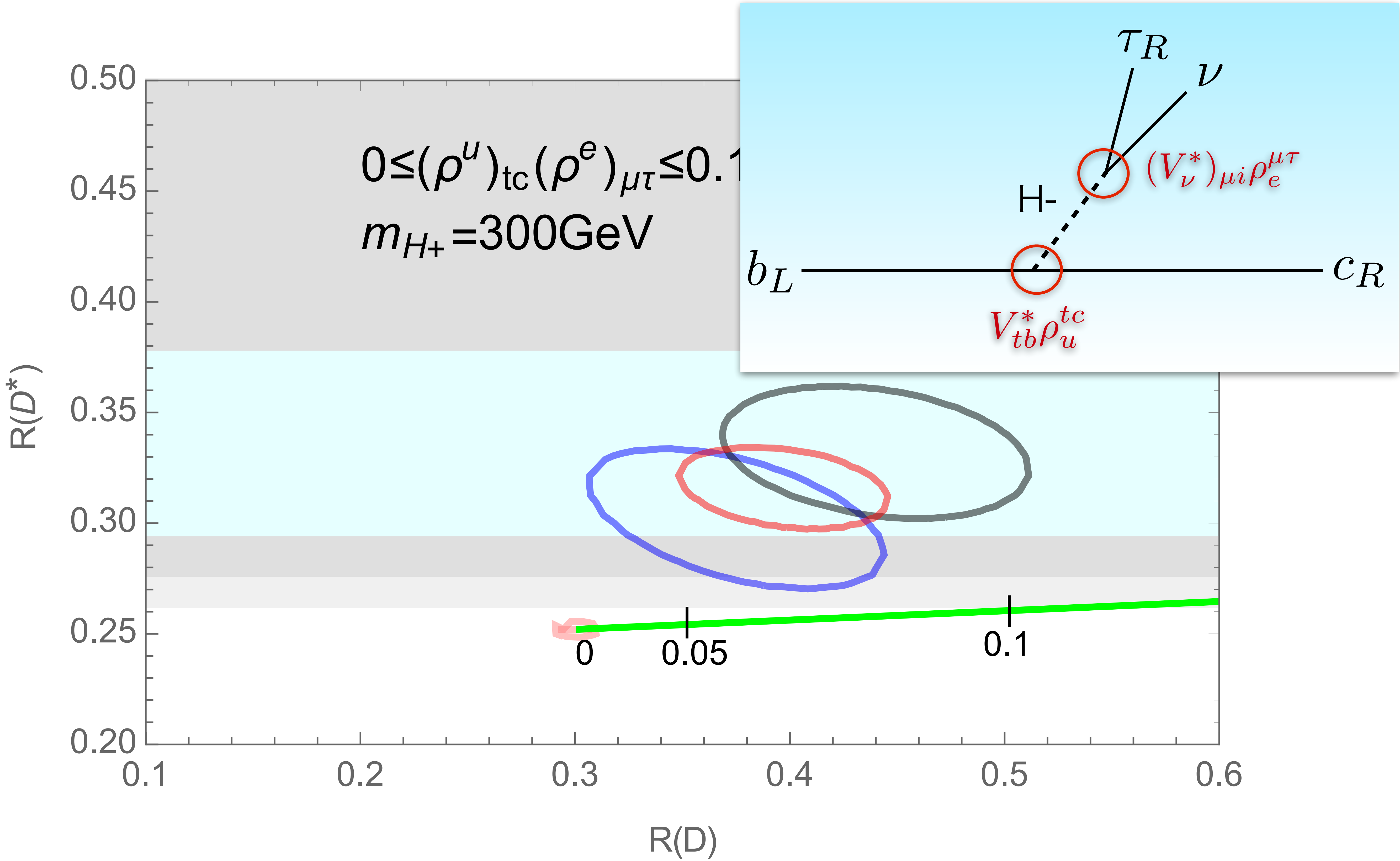
(Alonso,Grinstein,et al., 1611.06676;Akeroyd,Chen,1708.04072)



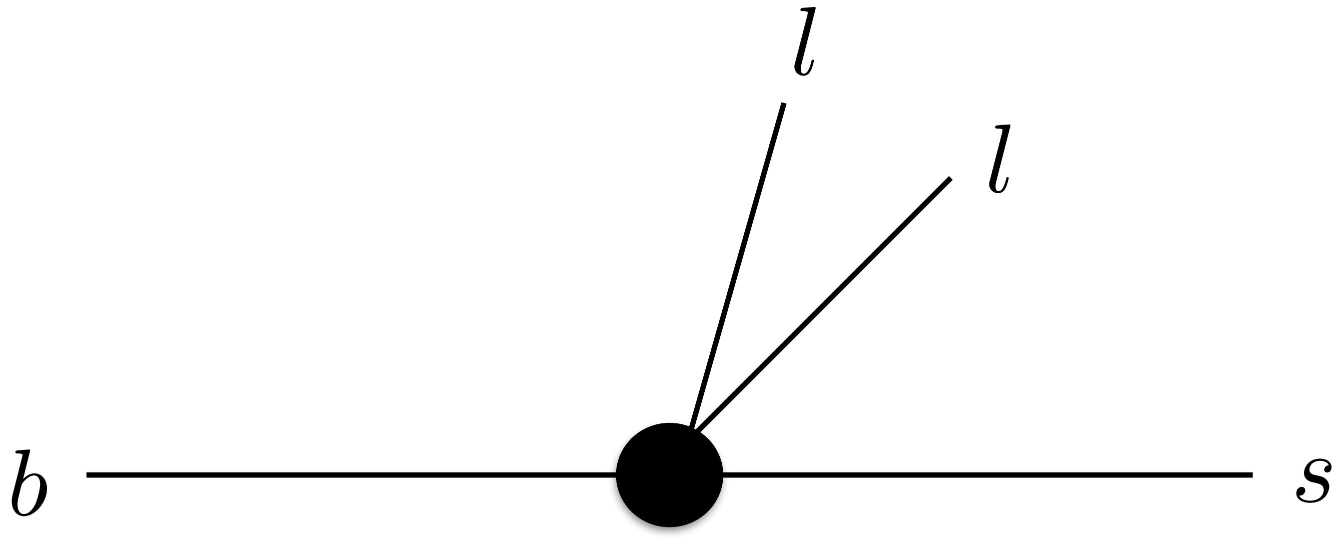

$$Br(B_c \to \tau\nu) = \left|1 + \delta_{LQ} + \frac{m_{B_c}^2}{m_\tau(m_b + m_c)}\delta_{H_\pm}\right|^2 Br(B_c \to \tau\nu)_{SM}$$

# R(D) and R(D*) in a 2HDM

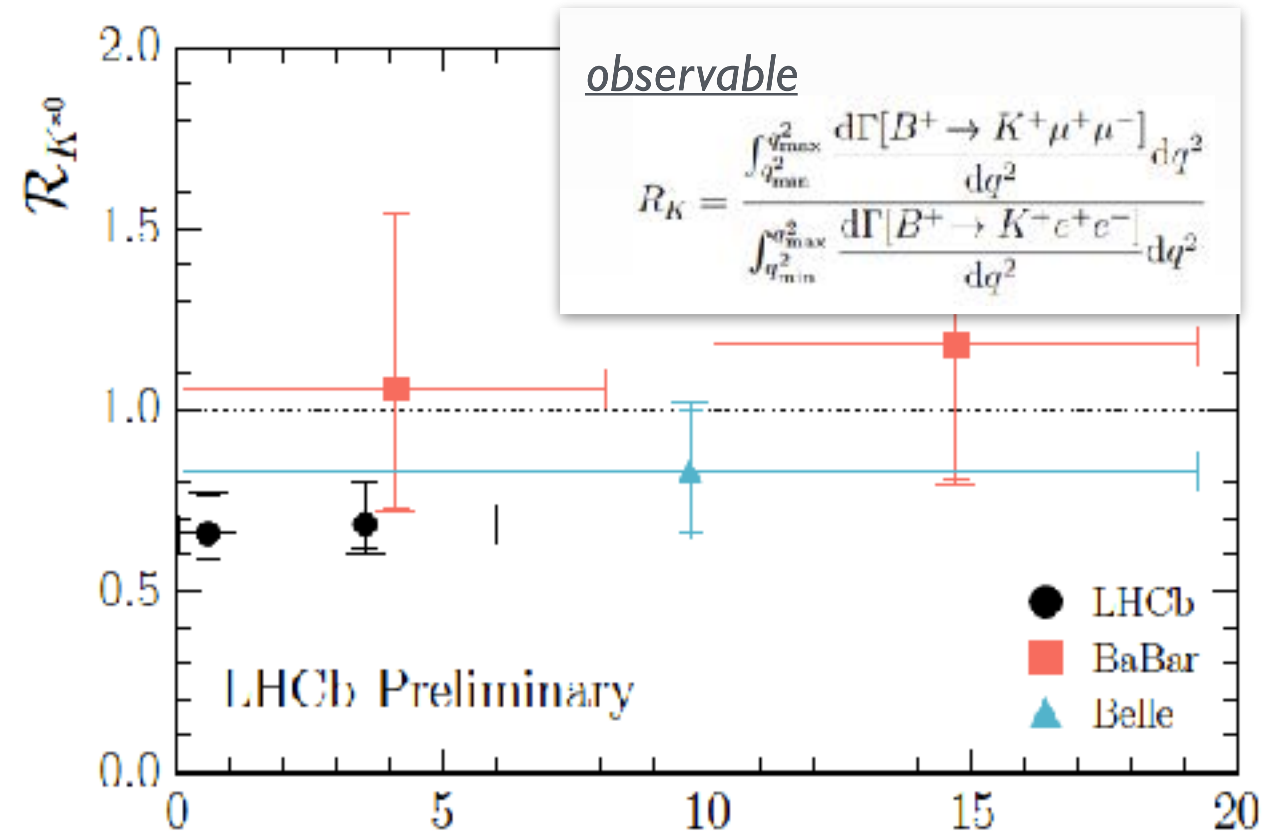



(Iguro, YO, 1802.01732)

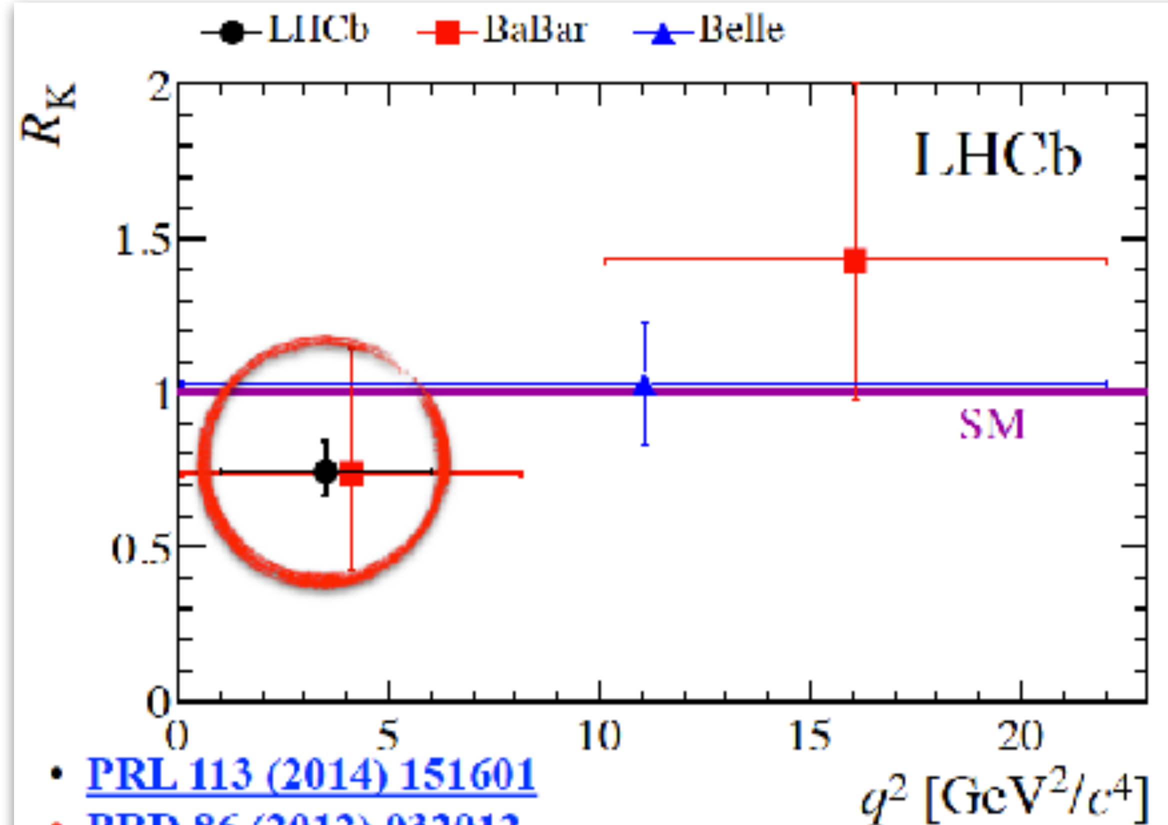
# There are several excesses in B→K(*)ll



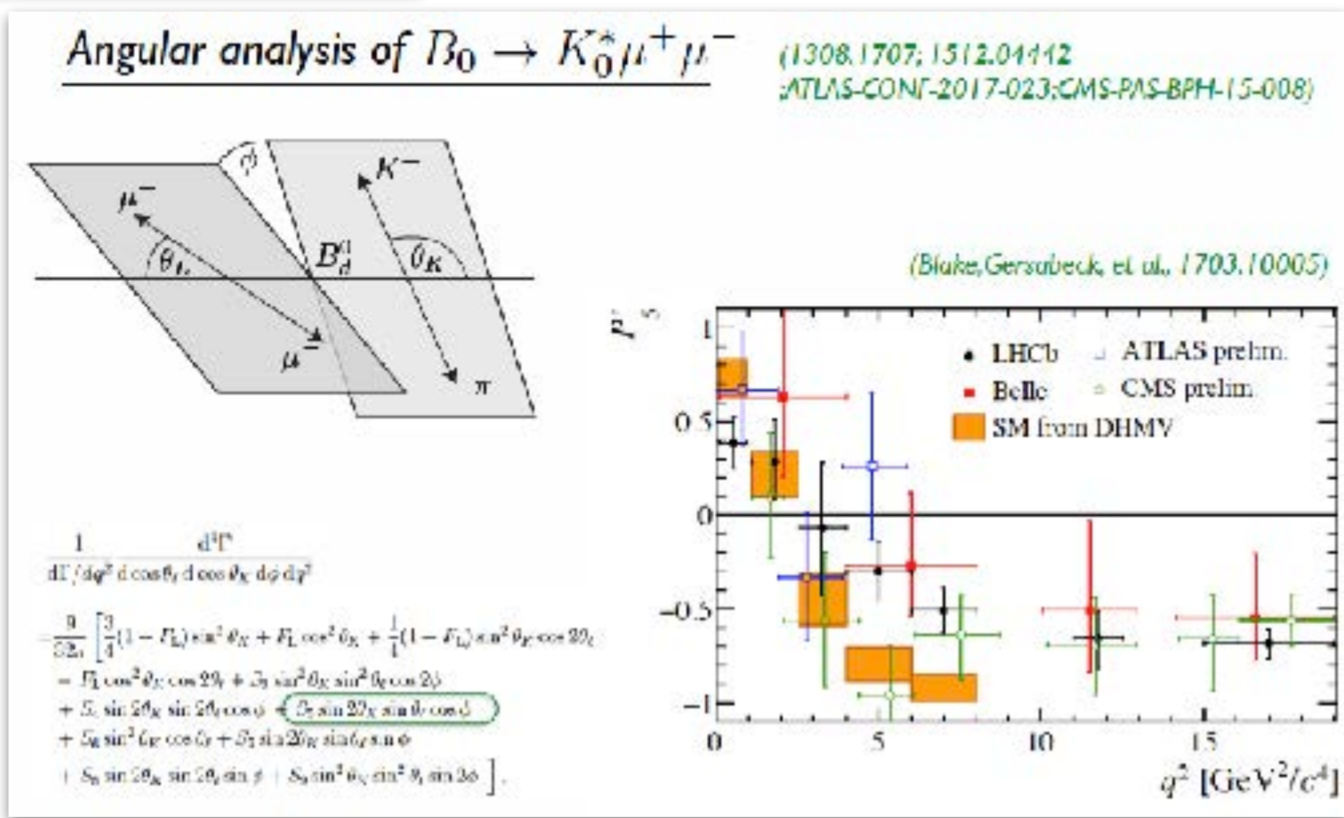
# There are several excesses in B→K(*)ll




- PRD 86 (2012) 032012
- PRL 103 (2009) 171801

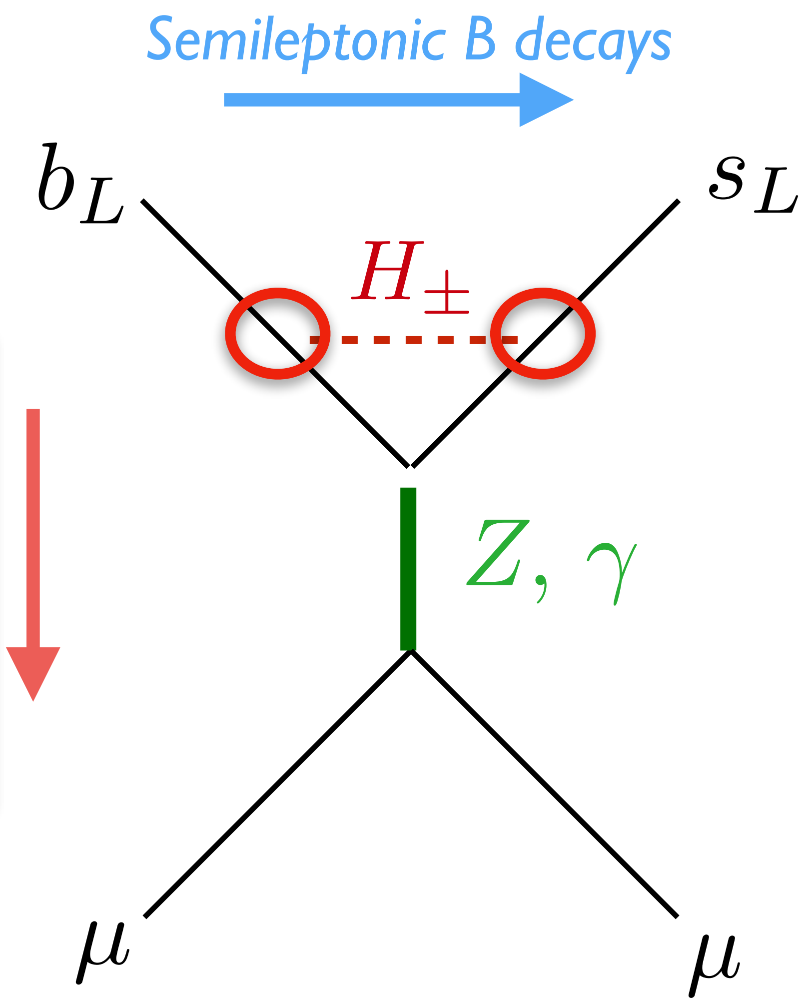



- PRL 113 (2014) 151601
- PRD 86 (2012) 032012
- PRL 103 (2009) 171801



# In 2HDM

## One-loop contribution




$B_s \to \mu\mu$

$$BR(B_s \to \mu^+\mu^-)^{\rm exp} = (2.8^{+0.7}_{-0.6}) \times 10^{-9}$$

$$BR(B_s \to \mu^+\mu^-)^{\rm SM} = (3.65 \pm 0.23) \times 10^{-9}$$

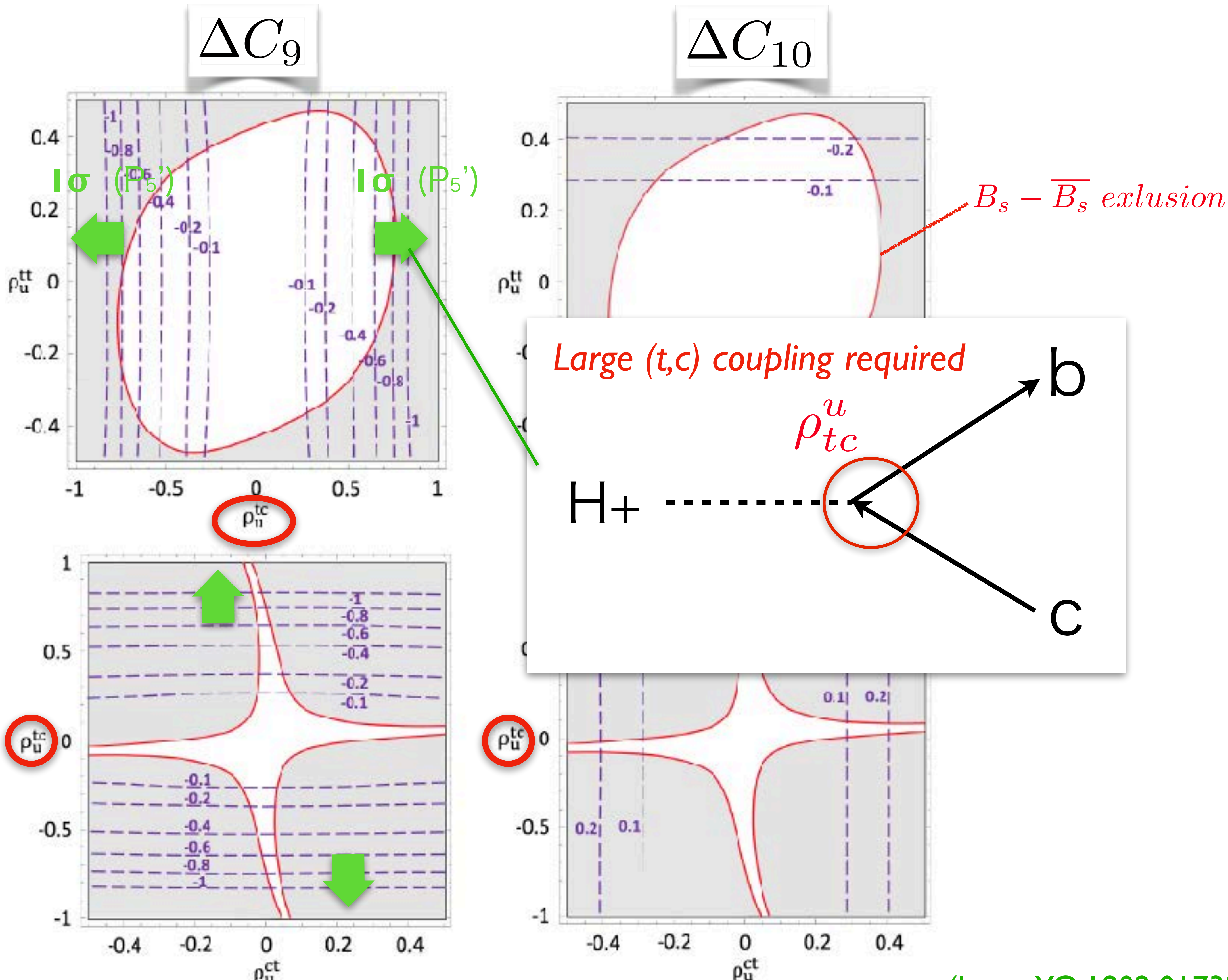
*Generated ope. are C9 and C10 :*

$$\mathcal{H}_{\rm eff} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \frac{e^2}{16\pi^2} \{C_9 (\overline{s_L}\gamma_\mu b_L)(\overline{\mu}\gamma^\mu \mu) + C_{10}(\overline{s_L}\gamma_\mu b_L)(\overline{\mu}\gamma^\mu\gamma_5\mu) + h.c.\}$$

*C10 contributes to Bs →μμ:*

$$\frac{BR(B_s \to \mu\mu)}{BR(B_s \to \mu\mu)_{SM}} = |1 - 0.24\, C_{10}^\mu|^2$$

# Results in 2HDM with only ρu @ $m_{H_\pm} = 200\,\mathrm{GeV}$




(Iguro, YO, 1802.01732)

What can we expect from the underlying theories?

In MSSM, for instance,

EW scale relates to SUSY breaking para.:

CP-odd scalar mass

$$m_A^2 = \frac{1}{\cos 2\beta}(m_{H_d}^2 - m_{H_u}^2) + M_Z^2$$

SUSY breaking para.

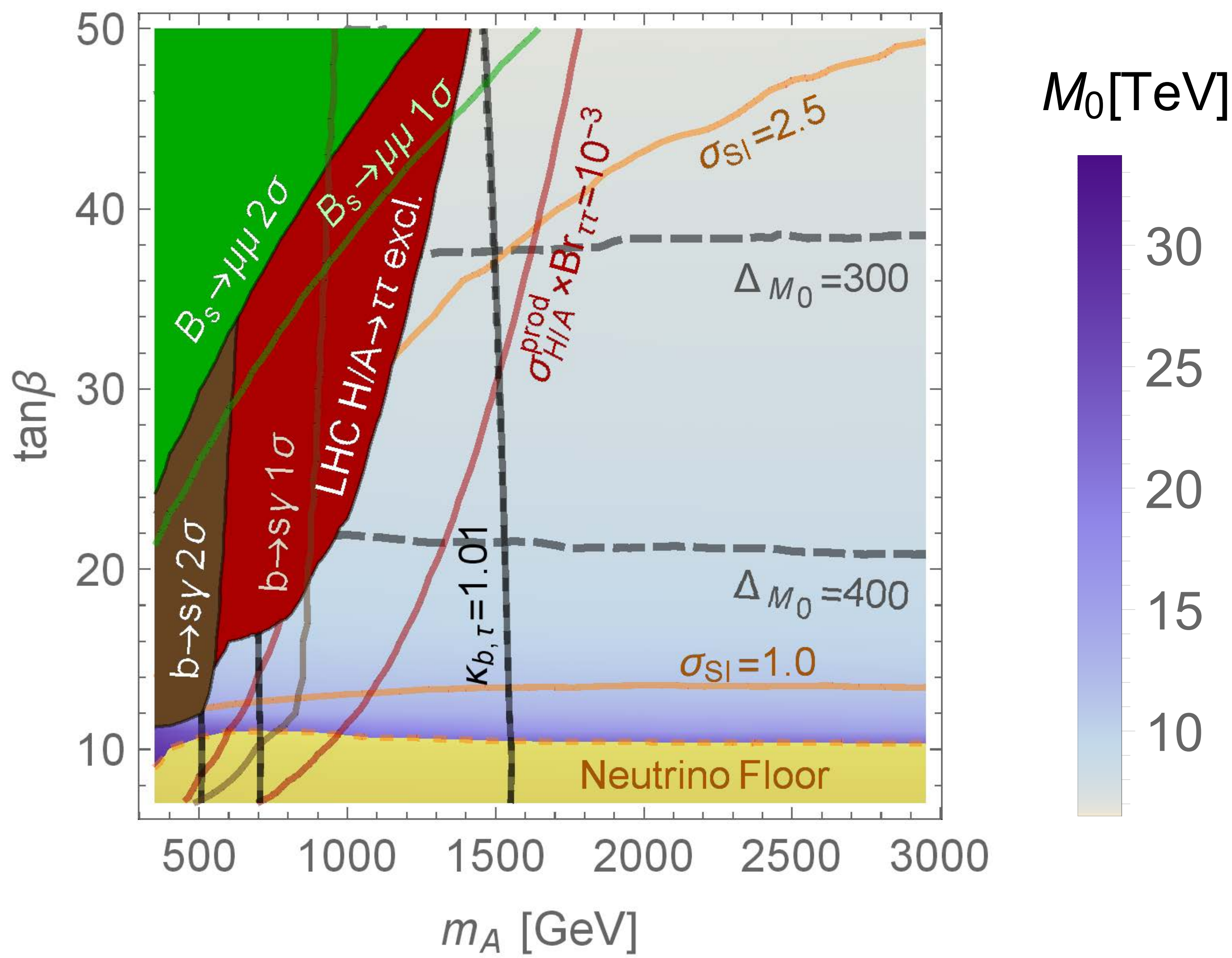
(Higgsino)

$$\mu^2 = \frac{m_{H_u}^2 \tan^2\beta - m_{H_d}^2}{1 - \tan^2\beta} - \frac{1}{2}M_Z^2$$

*SUSY scale. have to be much higher than we expected,*
*so that the extra Higgs mass is expected to be also high.*

# One scenario to predict <u>Type-II 2HDM</u> is *mirage mediation (moduli-anomaly mixture)*

Type-II 2HDM with Higgsino DM




*(Kawamura, YO, arXiv:1710.03412)*

# BSMs that unify the SM Yukawa also lead 2HDM at the low energy

(Iguro,Muramatsu,YO,Shigekami, arXiv:1804.07478)

## Left-Right symmetric model

$$Y_{ij}\overline{\hat{Q}^i_L}\,\Phi\,\hat{Q}^j_R$$

where $\Phi = (\widetilde{H}_u,\, H_d)$ $\hat{Q}^j_R = (\hat{u}^j_R,\, \hat{d}^j_R)^T$ defined.

*For the realistic Yukawa,*

$$Y^1_{ij}\overline{\hat{Q}^i_L}\,\Phi\,\hat{Q}^j_R + Y^2_{ij}\overline{\hat{Q}^i_L}\,\widetilde{\Phi}\,\hat{Q}^j_R$$

in non-SUSY;

$$Y^1_{ij}\overline{\hat{Q}^i_L}\,\Phi_1\,\hat{Q}^j_R + Y^2_{ij}\overline{\hat{Q}^i_L}\,\Phi_2\,\hat{Q}^j_R$$

in SUSY.

# After the LR symmetry breaking,

# 2HDM (4HDM) with large FCNCs appears.

*(Iguro,Muramatsu,YO,Shigekami, arXiv:1804.07478)*

in non-SUSY,

$$\rho^u_{ij}\overline{\hat{Q}^i_L}\,\widetilde{H}\,\hat{u}^j_R + \rho^d_{ij}\overline{\hat{Q}^i_L}\,H\,\hat{d}^j_R$$

in SUSY,

$$\sum_{A=1}^{3}\left(\rho^u_{A\,ij}\overline{\hat{Q}^i_L}\,\widetilde{H}_A\,\hat{u}^j_R + \rho^d_{A\,ij}\overline{\hat{Q}^i_L}\,H_A\,\hat{d}^j_R\right)$$

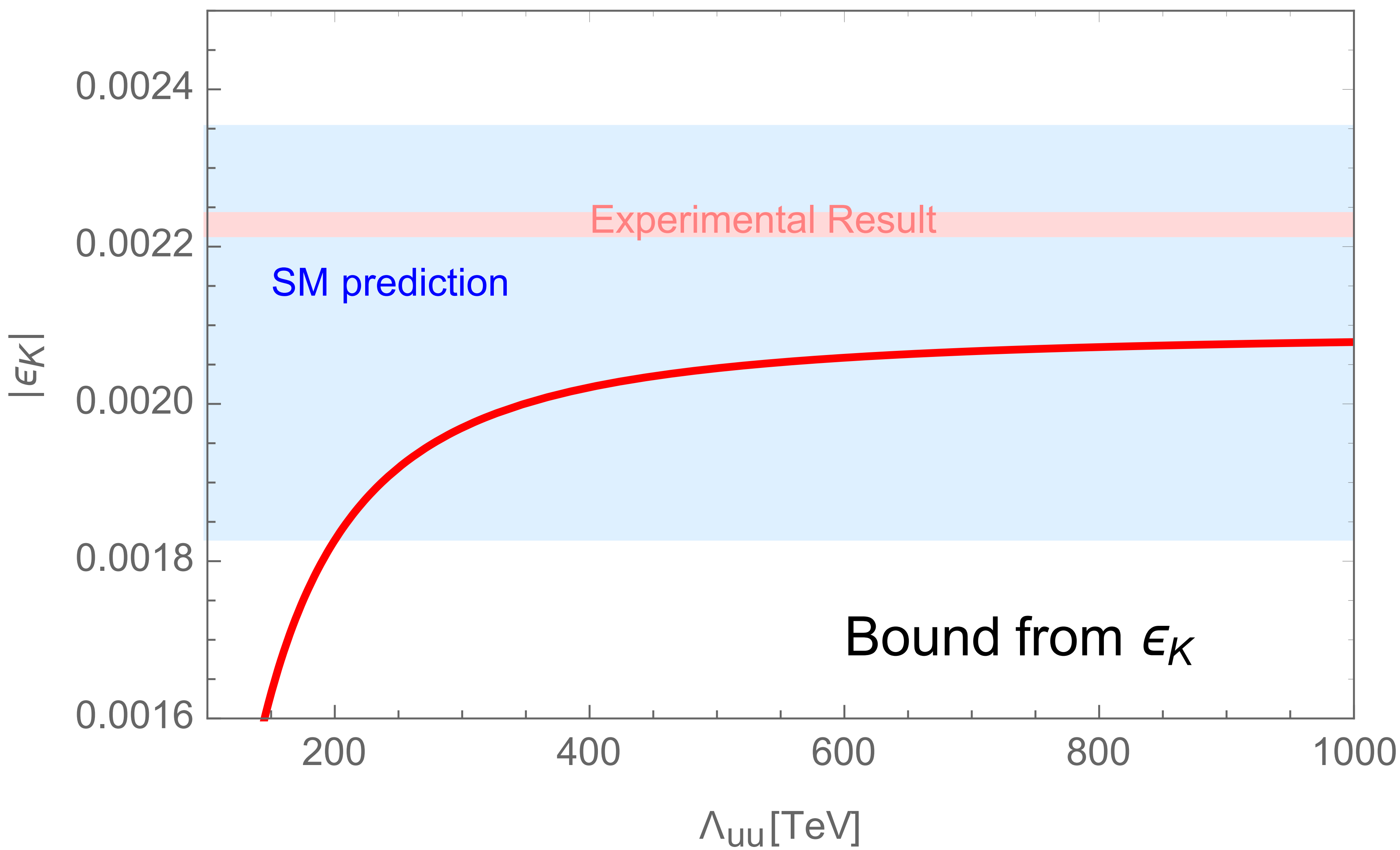
Relation between the FCNC and the measured values

$$\begin{pmatrix}\rho^u_{A\,ij}\\ \rho^d_{A\,ij}\end{pmatrix} = \begin{pmatrix}U^A_{11} & U^A_{12}\\ U^A_{21} & U^A_{22}\end{pmatrix}\begin{pmatrix}V^\dagger_{ik}\frac{\sqrt{2}m^u_k}{v}V_{kj}\\ \frac{\sqrt{2}m^d_i}{v}\delta_{ij}\end{pmatrix}$$

Very “predictable,”

so that the flavor constraint is very severe.

*(Iguro,Muramatsu,YO,Shigekami, arXiv:1804.07478)*




Extra Higgs scales are naively O(100) TeV.

# Summary and Discussion

## *Why do we need the scalar?*

*Additional symmetry often requires extra Higgs to realize the realistic Yukawa.*

*SUSY, GUT,*
*flavor symmetry, $U(1)_{PQ}$, etc.*

## *Where is the scalar?*

*In "MSSM-like" 2HDM,*

*$b \to s\gamma$ constrains strongly: $m_{H^+} > 580$ GeV.*

*125 GeV Higgs couplings need to be SM-like.*

*In the bottom-up approach, the scalars may be O(100) TeV.*

*$H \to hh$ search, for instance, constrains a lot.*
*→Integrated research would be important.*

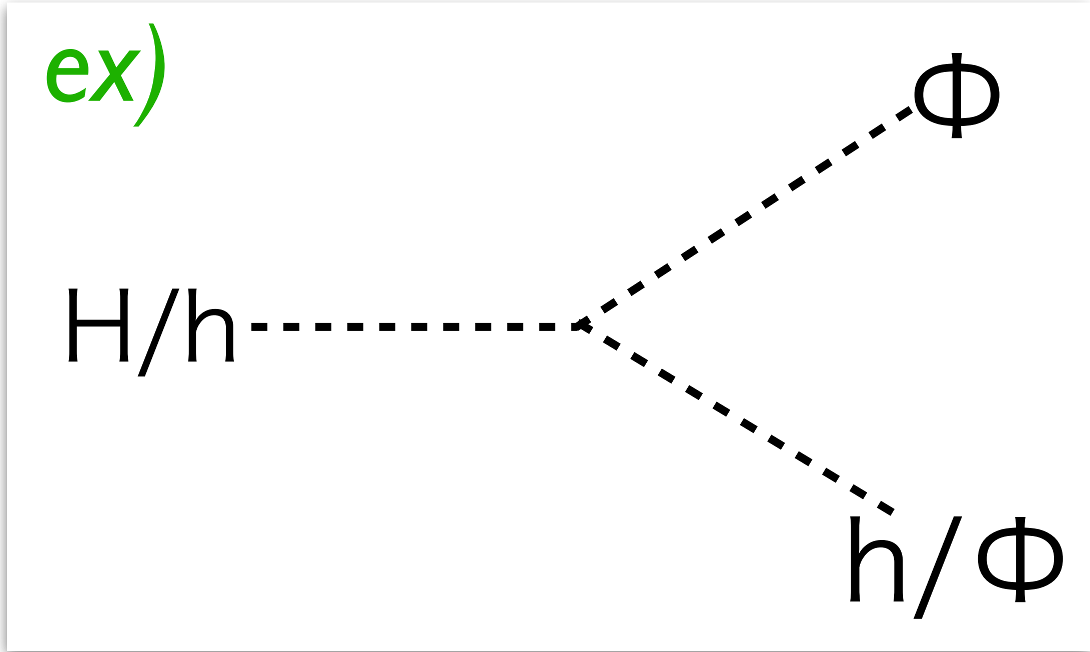
*In other-type 2HDMs,*

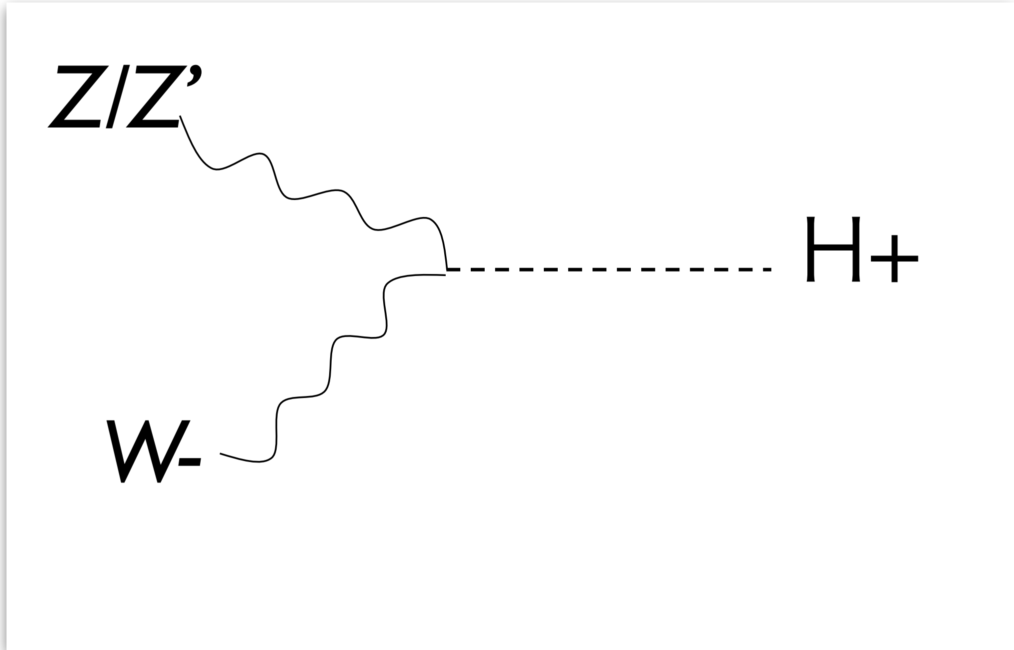
*scalars can be light depending on the Yukawa couplings.*

# *What is interesting and what can we do?*

- *We can discuss the scenario where the predictions are deviated from the SM, in the other-type 2HDMs.*
- *Is there something new behind the excesses? How can we test?*
  *Large (t,c), (τ, μ) couplings in 2HDM.*
- *2HDM may be too minimal*

  → *2HDM+(scalar, Higgsino, or Z', etc.) is more realistic?*




END

# Backup

# In the Type-I 2HDM