

PAUL SCHERRER INSTITUT



FNSNF

FONDS NATIONAL SUISSE
SCHWEIZERISCHER NATIONALFONDS
FONDO NAZIONALE SVIZZERO
SWISS NATIONAL SCIENCE FOUNDATION

B-flavour anomalies:

NP interpretations

Andreas Crivellin

Outline:

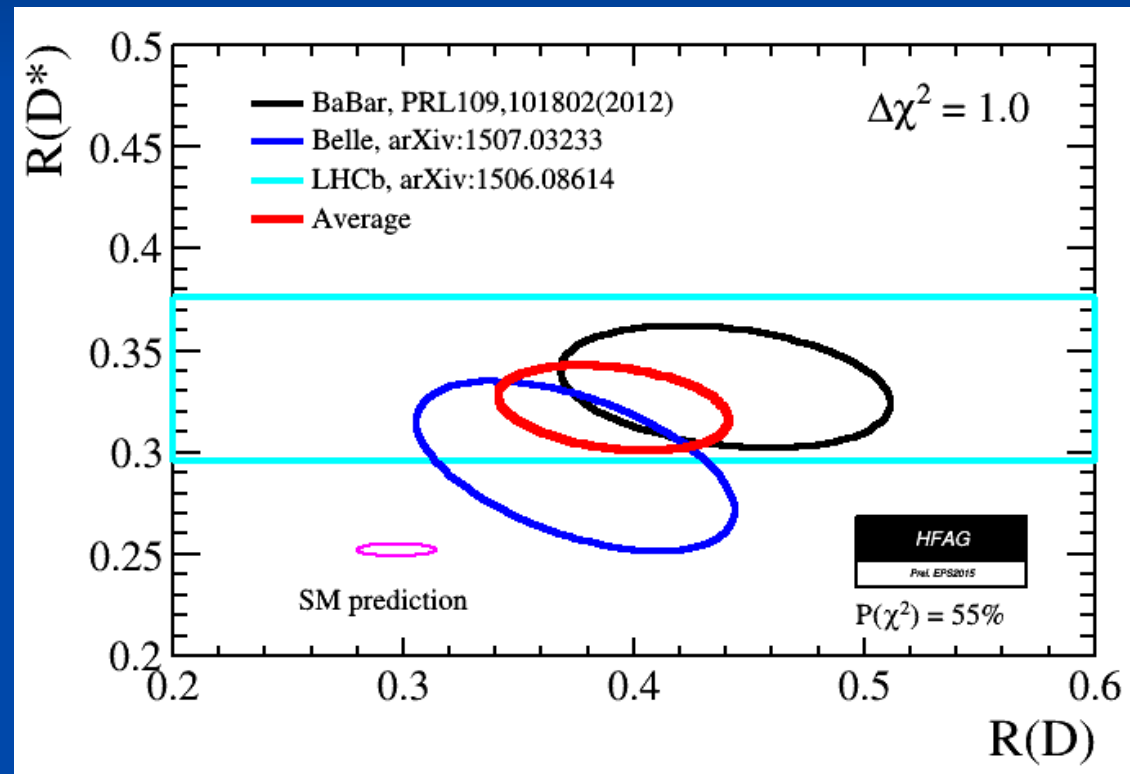
- Introduction: Flavour anomalies
 - $B \rightarrow D^{(*)} \tau \nu$
 - $b \rightarrow s \mu^+ \mu^-$
 - $h \rightarrow \tau \mu$
 - a_μ
- Possible New Physics Explanations
 - Z'
 - Extended Higgs sector
 - Leptoquarks
- Simultaneous Explanations of Anomalies and predictions
- Outlook and Conclusions

Flavour Anomalies

Tauonic B decays

- Tree-level decays in the SM via W-boson

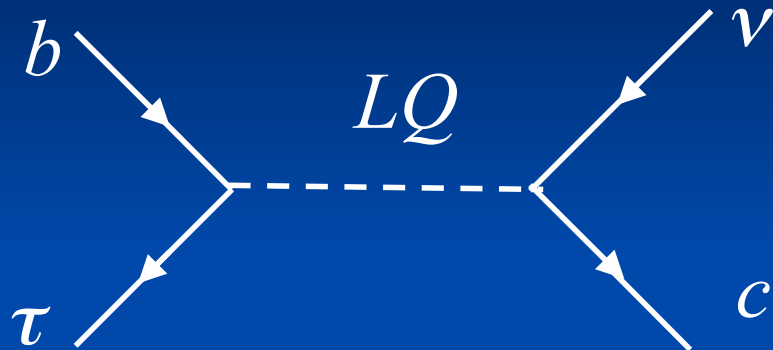
$$R(D^{(*)}) = B \rightarrow D^{(*)} \tau \nu / B \rightarrow D^{(*)} \ell \nu$$



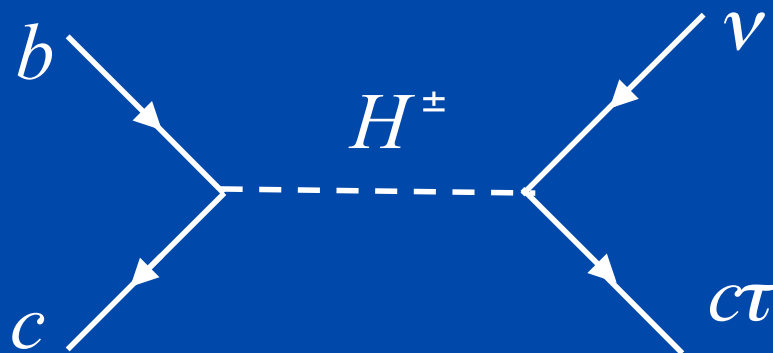
➔ Combined $\approx 4 \sigma$ deviation

R(D) Explanations

- Leptoquark (scalar or vector)



- Charged Higgs  different differential distribution



- W' ????

$b \rightarrow s \mu \mu$

- Global analysis give a very good fit to data
See talks of Sebastian and Quim
- Lepton Flavour Universality Violation
- Symmetry based solutions give a very good fit to data:

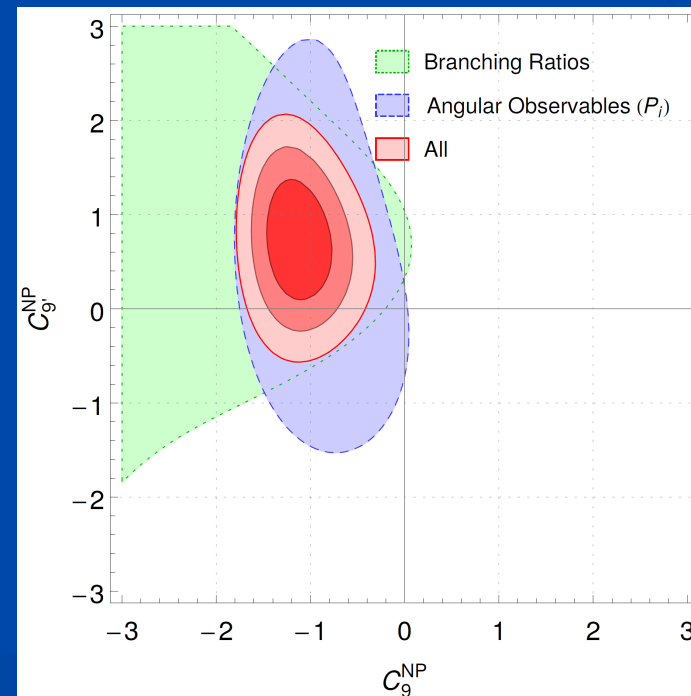
- C_9

- $C_9 = -C_{10}$

- $C_9 = -C'_9$

$$O_9 = \bar{s} \gamma^\mu P_L b \bar{\ell} \gamma_\mu \ell$$

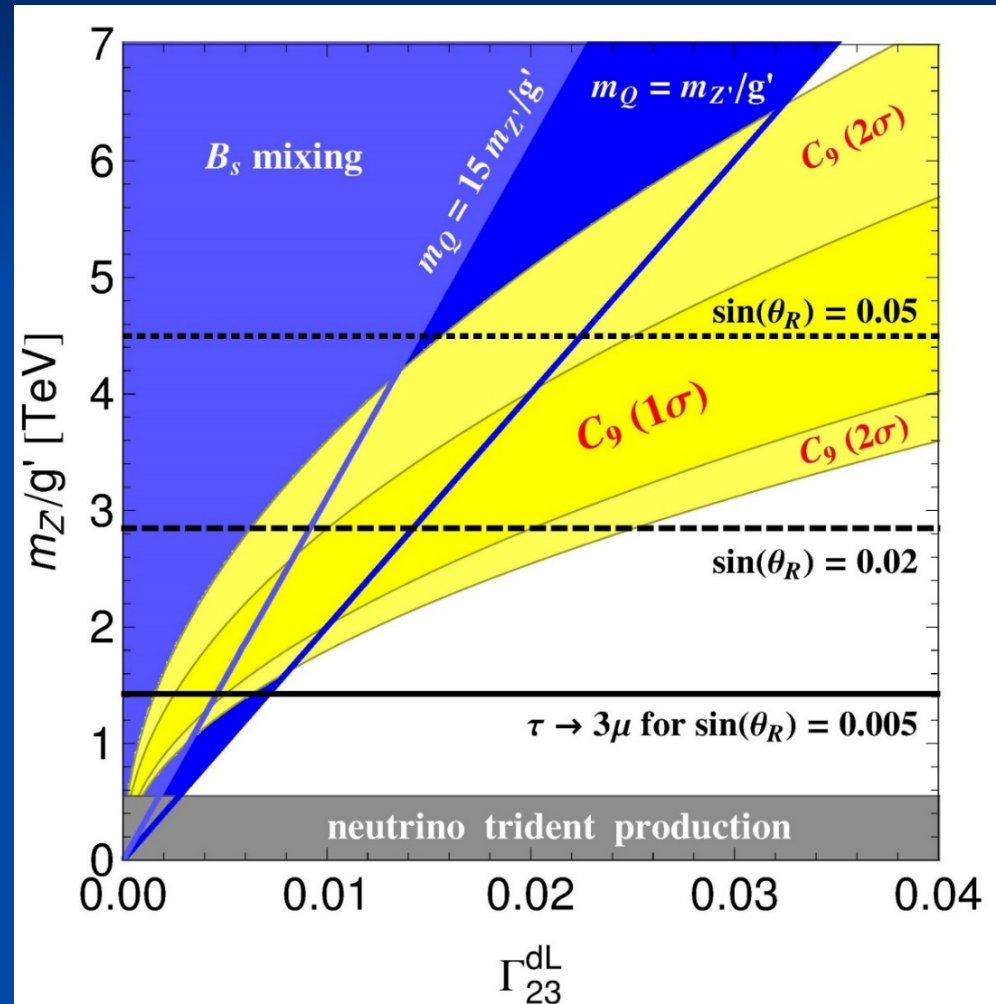
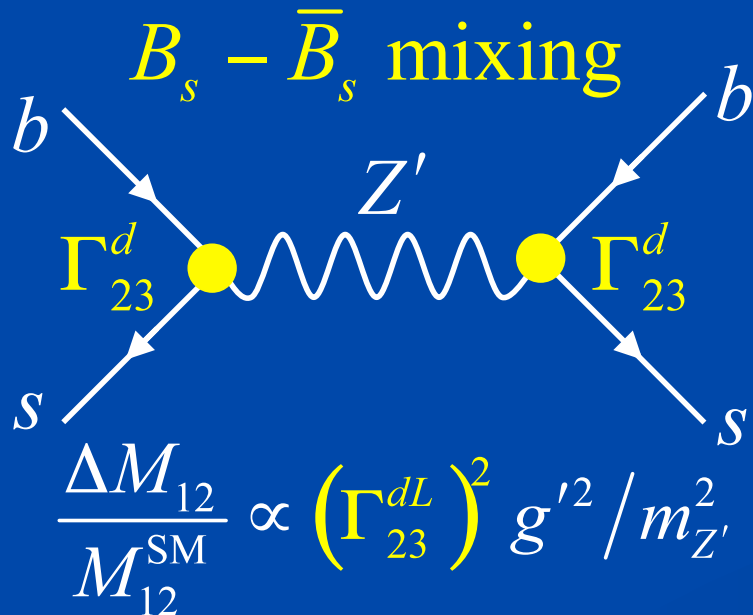
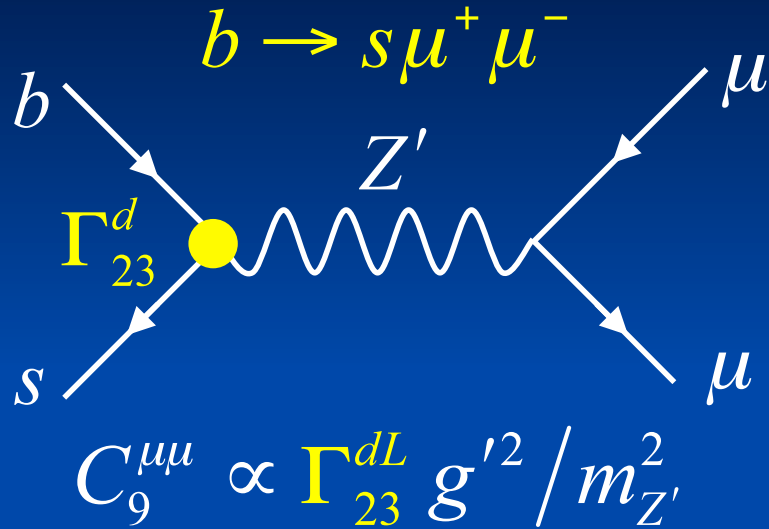
$$O_{10} = \bar{s} \gamma^\mu P_L b \bar{\ell} \gamma_\mu \gamma^5 \ell$$



➔ Fit is 4-5 σ better than in the SM [1501.04239](#)

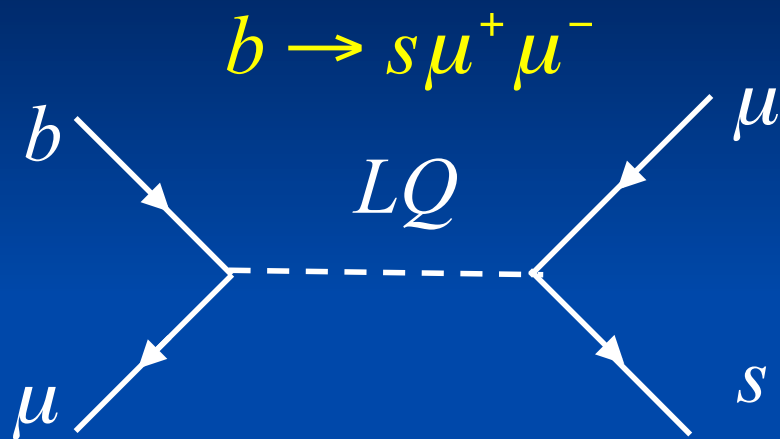
Z' explanations

U. Haisch et al. 1308.1959
 W. Altmannshofer et al. 1403.1269
 A. C. et al. 1501.00993

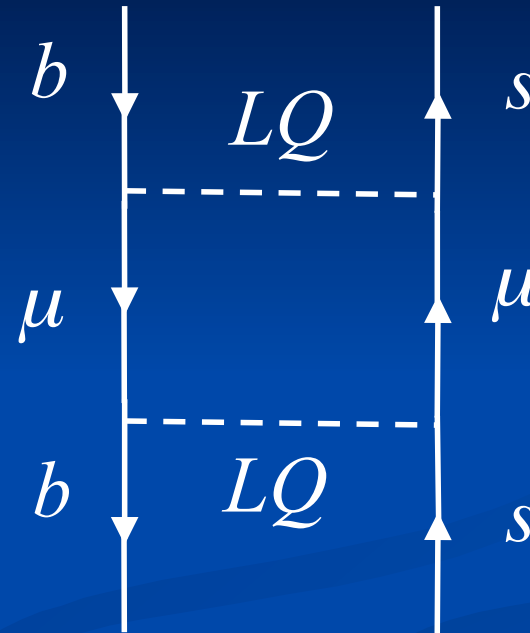


allowed regions

Leptoquarks

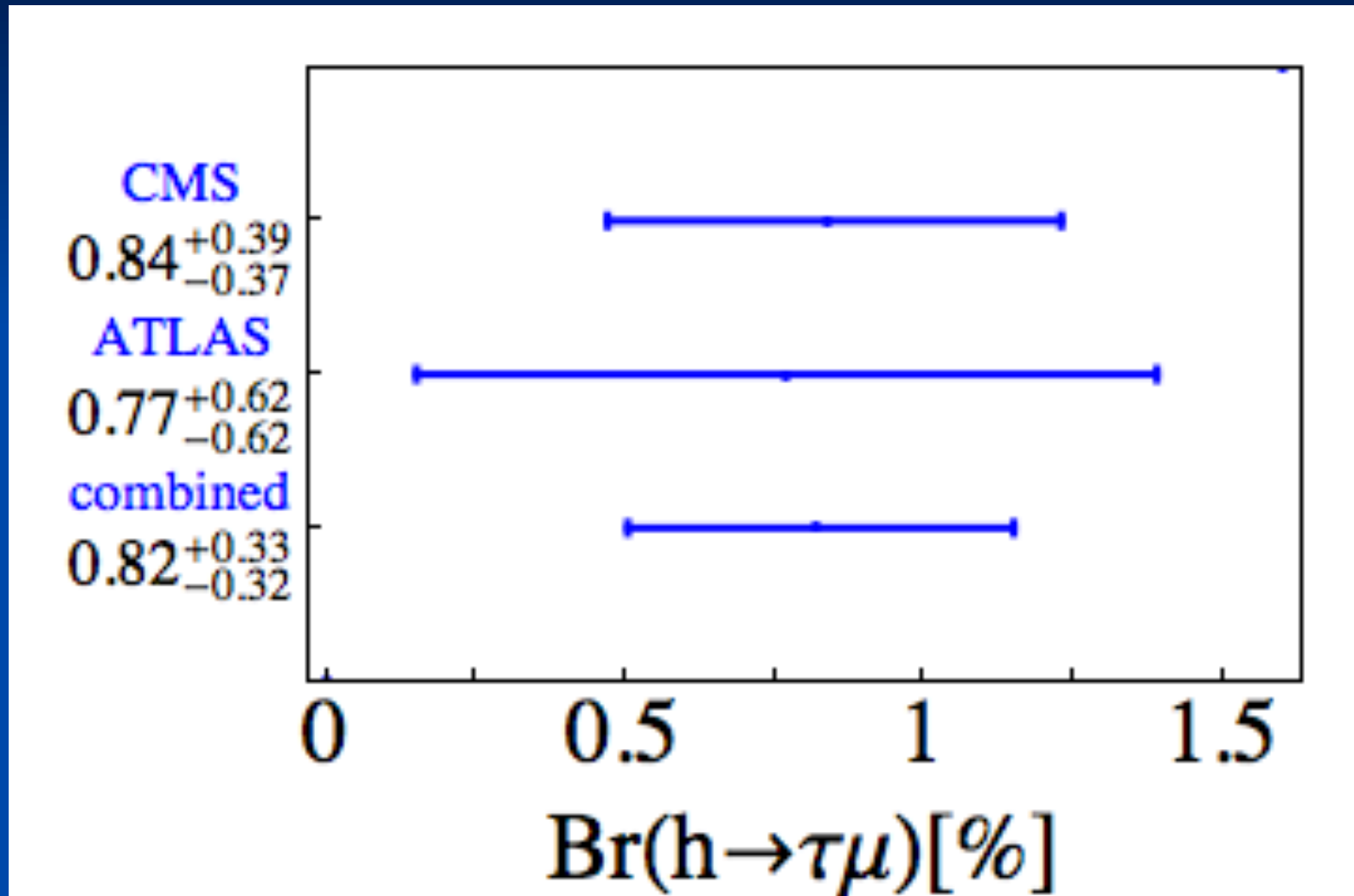


$B_s - \bar{B}_s$ mixing



- Only weak constraints from other flavour observables (loop compared to tree)
- Possible effect in the anomalous magnetic moment of the muon
- Large production cross section at the LHC

$h \rightarrow \tau\mu$



- 2.6 σ difference from zero

$h \rightarrow \tau\mu$

- Can be explained in the effective field theory approach by

$$Q_{e\phi}^{fi} = \ell_f \phi e_i \phi^\dagger \phi$$

R. Harnik, J. Kopp, and J. Zupan, 1209.1397.

G. Blankenburg, J. Ellis, and G. Isidori, 1202.5704.

S. Davidson and P. Verdier, 1211.1248.

- No dominant contribution from vector-like fermions

A. Falkowski, D. M. Straub, and A. Vicente, 1312.5329

Extended Higgs sector

J. Heeck et al. 1412.3671

A. Greljo et al. arXiv:1502.07784

A. C. et al. arXiv:1501.00993

.....

.....

Models for Simultaneous Explanations of Anomalies

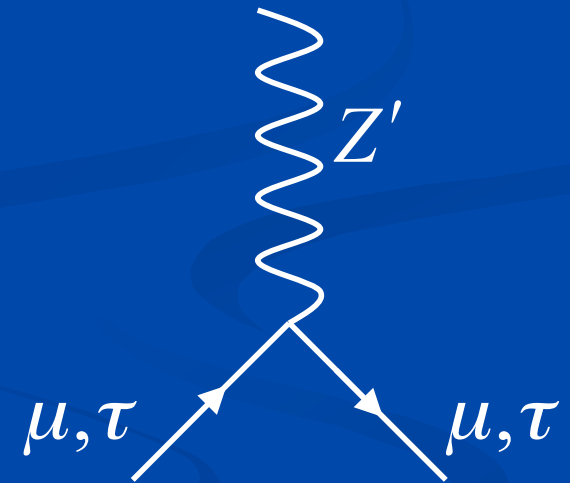
2HDM with gauged $L_\mu - L_\tau$

- Vectorial U(1) gauge group:
 $Q(e) = 0, Q(\mu) = 1, Q(\tau) = -1$
- b-s couplings generated with vector-like quarks
- Two Higgs doublets

$$Q_{L_\mu - L_\tau}(\Psi_2) = 0 \quad Q_{L_\mu - L_\tau}(\Psi_1) = 2$$

- Yukawa couplings

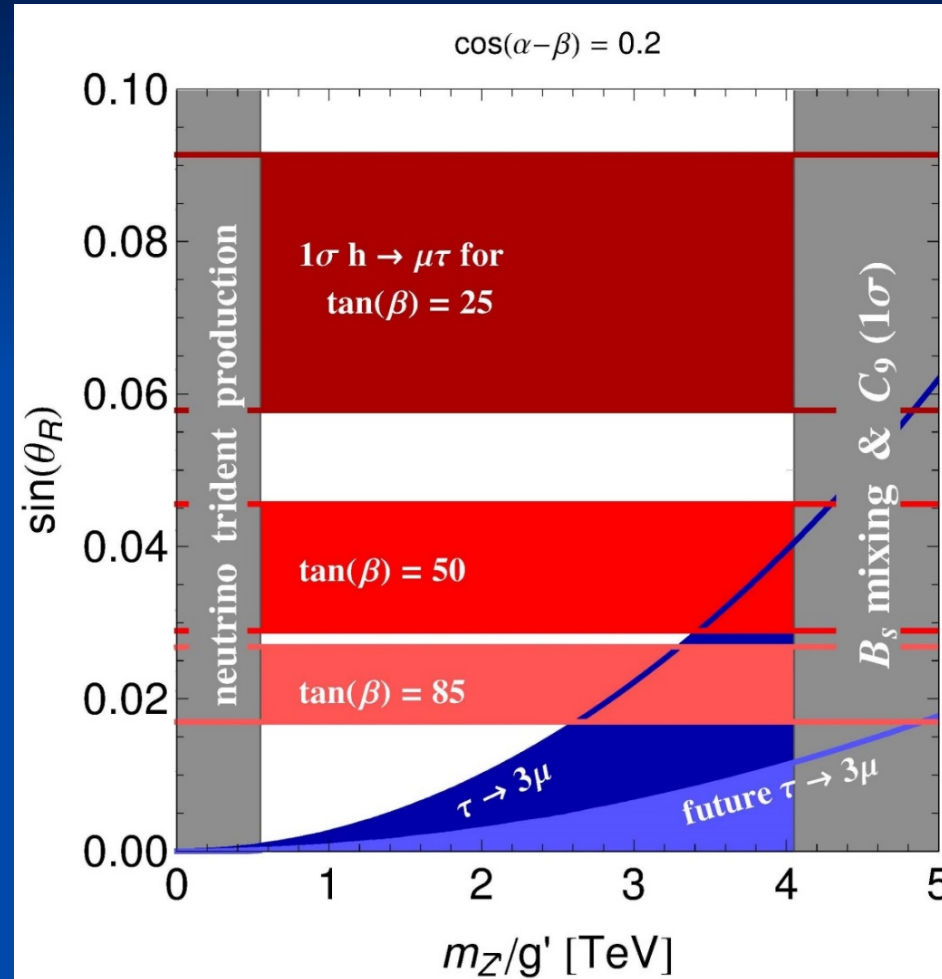
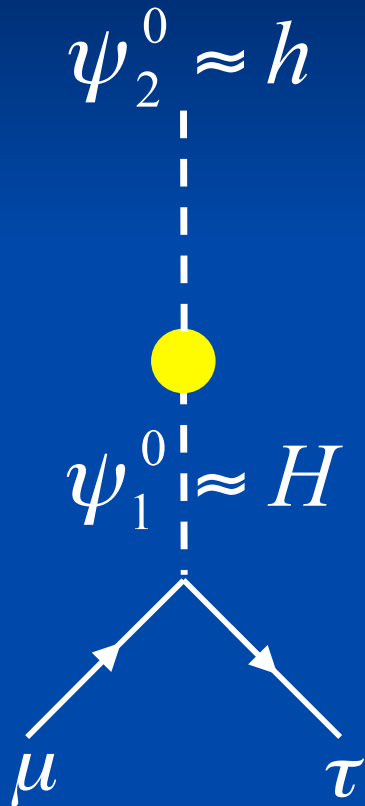
$$\begin{aligned} \mathbf{L}_Y \supset & -\bar{\ell}_f Y_i^\ell \delta_{fi} \Psi_2 e_i - \xi_{\tau\mu} \bar{\ell}_3 \Psi_1 e_2 \\ & - \bar{Q}_f Y_{fi}^u \tilde{\Psi}_2 u_i - \bar{Q}_f Y_{fi}^d \Psi_2 d_i + \text{h.c.} \end{aligned}$$



- θ_R diagonalizes the τ - μ block of the mass matrix

2HDM with gauged $L_\mu-L_\tau$

$h \rightarrow \mu\tau$



$\tau \rightarrow \mu\mu\mu$



■ allowed by $h \rightarrow \tau\mu$

■ allowed by $\tau \rightarrow \mu\mu\mu$

■ excluded

Leptoquark Explanations of $b \rightarrow s\mu\mu$ and $B \rightarrow D^{(*)}\tau\nu$

- Tree-level contribution to $b \rightarrow c\tau\nu$ but loop effect in $b \rightarrow s\mu^+\mu^-$
 - can explain a_μ
 - Anarchic flavor structure

M. Bauer, M. Neubert arXiv:1511.01900

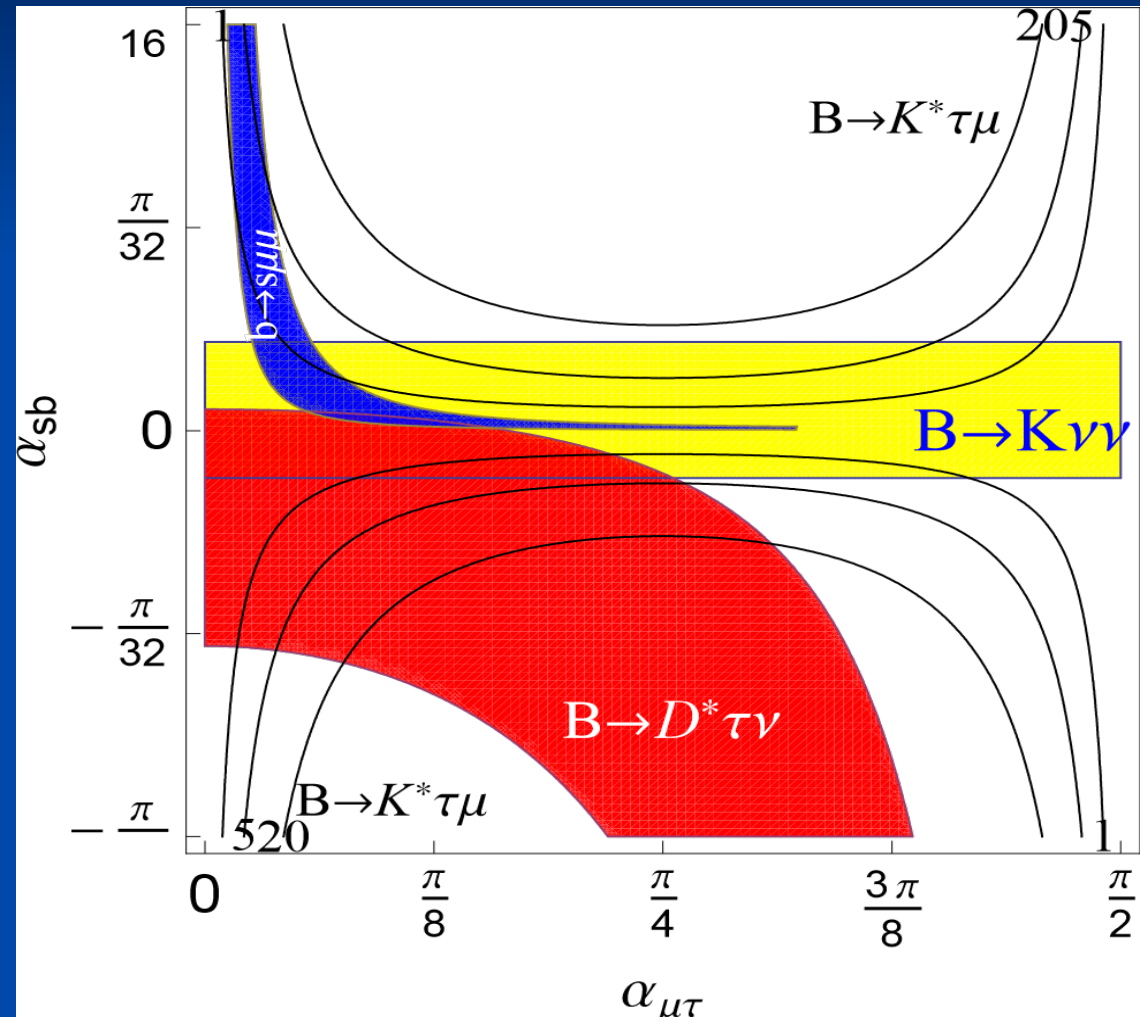
- Tree-level contribution to $b \rightarrow s\mu^+\mu^-$ and $b \rightarrow c\tau\nu$
 - Hierarchical flavor structure, large third generations couplings, small first and second ones.

Tree-level Leptoquark Explanation

Third generation couplings

$$\begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

α Misalignment between interaction and mass basis

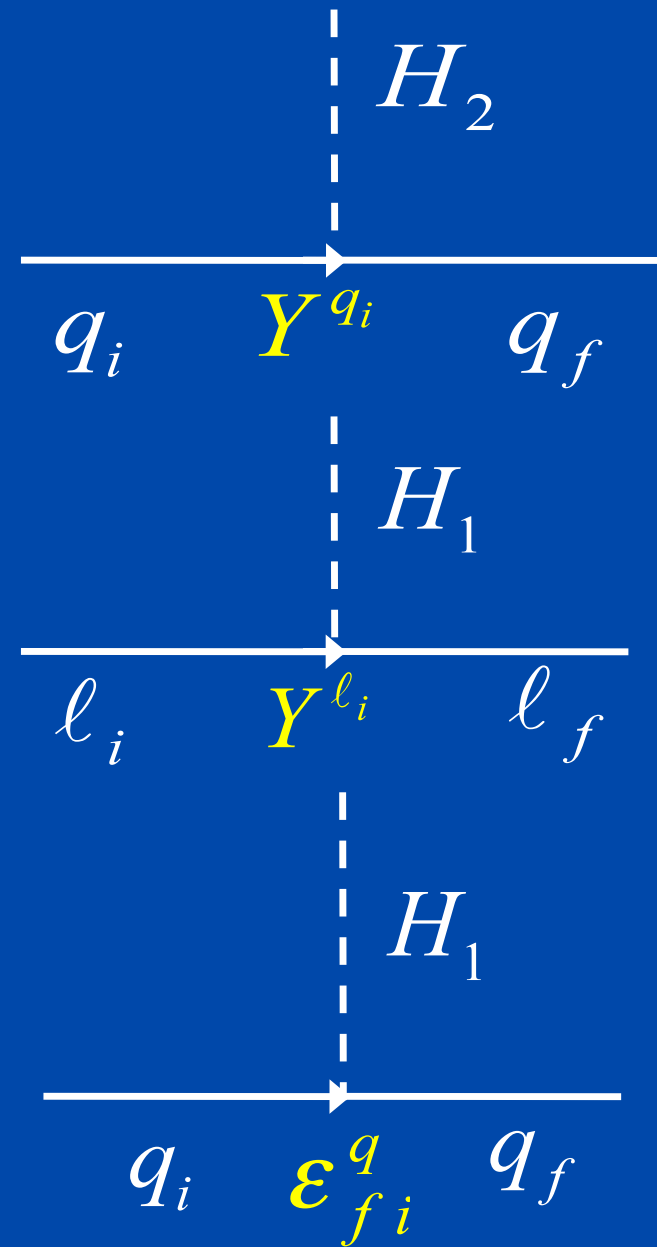


2HDM of type X

- One Higgs doublet couples only to quarks the other Higgs doublet to leptons.
- Additional free parameters:
 $\tan \beta = v_1 / v_2$

$$m_H, m_{A^0}, m_{H^\pm}, m_{H^0}$$

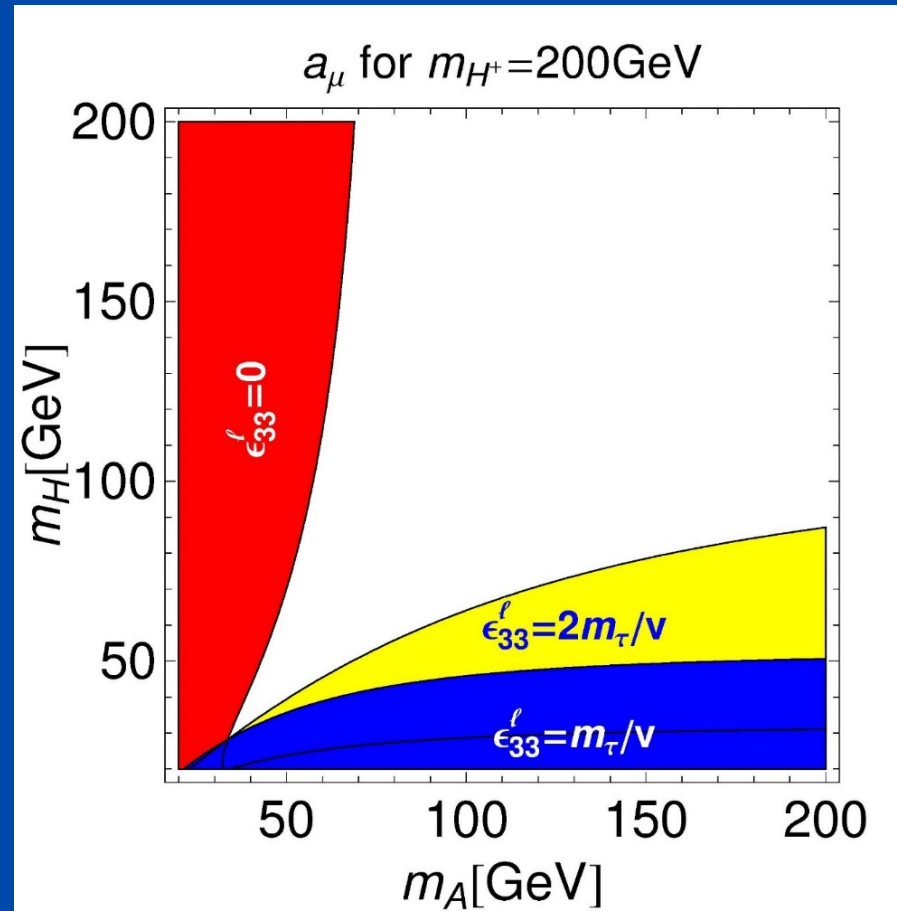
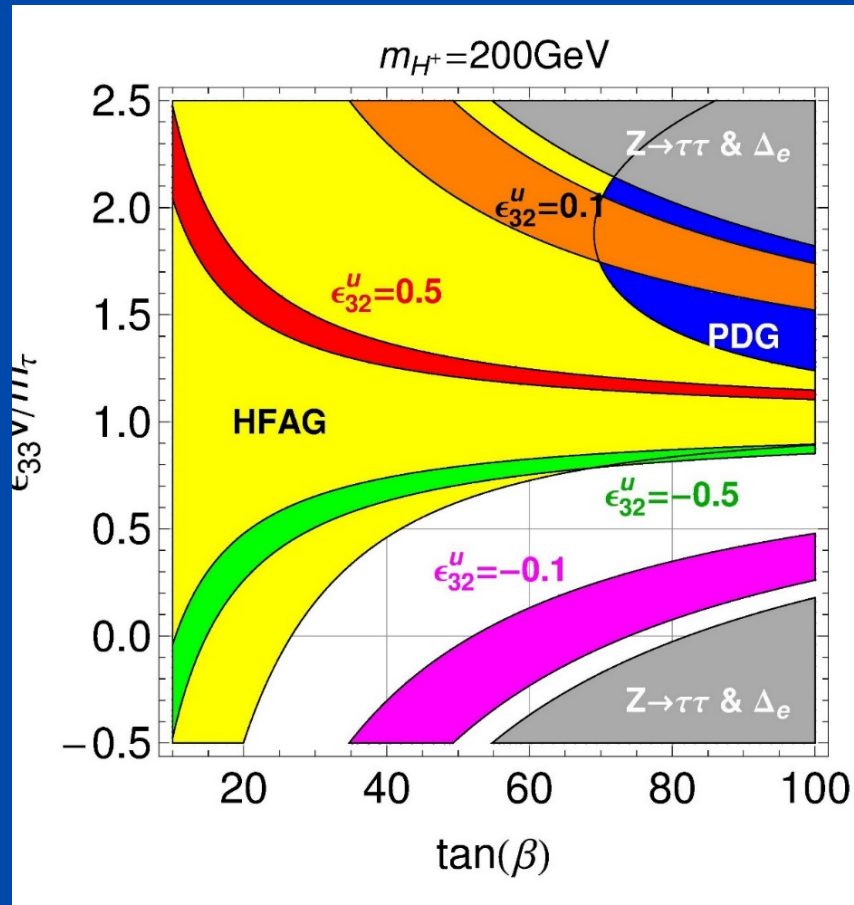
$$\epsilon_{fi}^{u,l} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & \epsilon_{32}^{u,l} & \epsilon_{33}^{u,l} \end{pmatrix}$$



→ Couplings to leptons are $\tan(\beta)$ enhanced

$$\tau \rightarrow \mu \nu \nu + R(D)$$

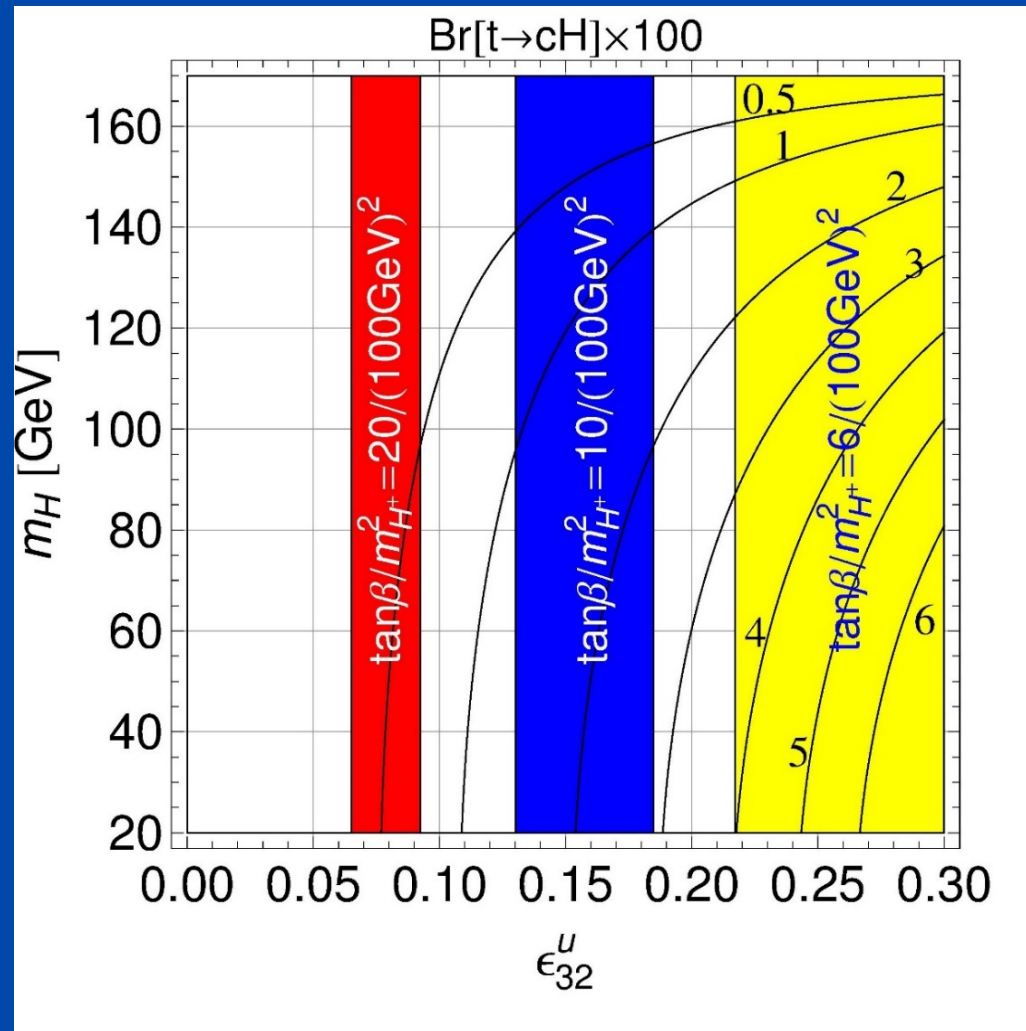
$$a_\mu$$



$$\epsilon_{33}^l > 0$$

$$m_H < m_A$$

Prediction: $t \rightarrow Hc$

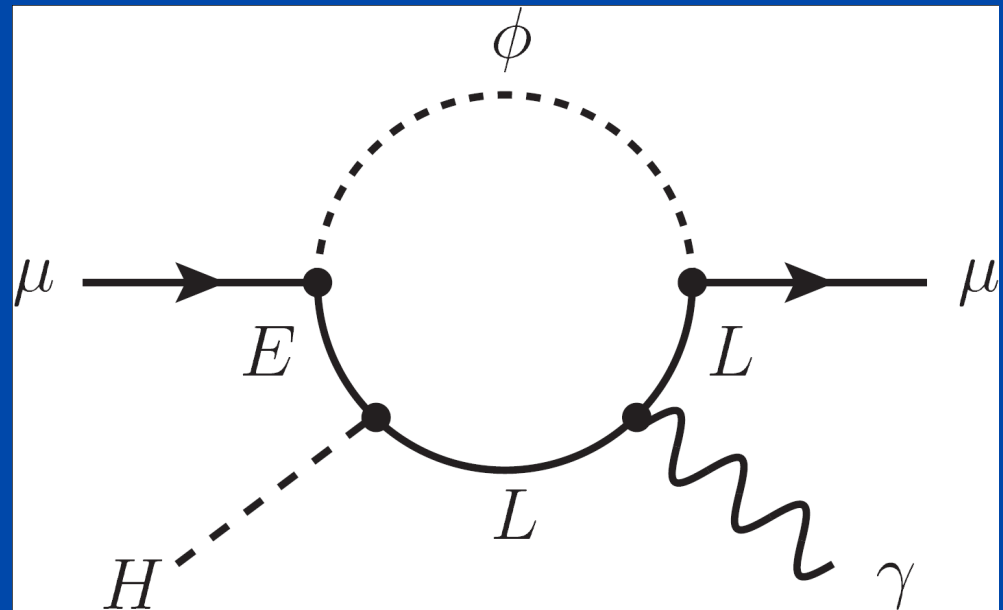
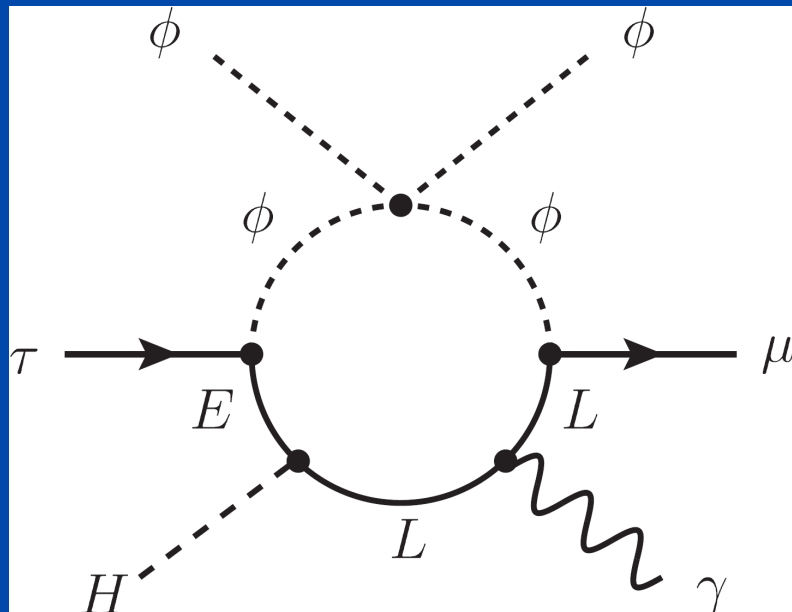
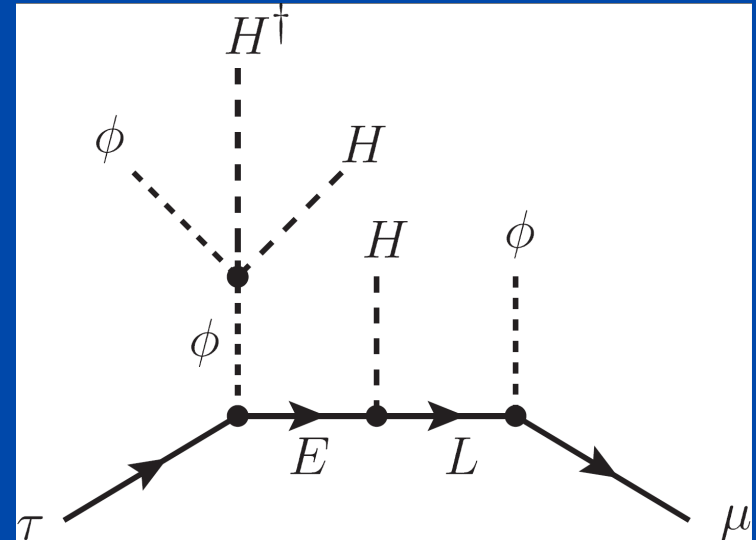


Branching ratio
can even reach
the percent level

L_μ - L_τ model for a_μ and $h \rightarrow \tau\mu$

W. Altmannshofer, M. Carena, AC, 1604.08221

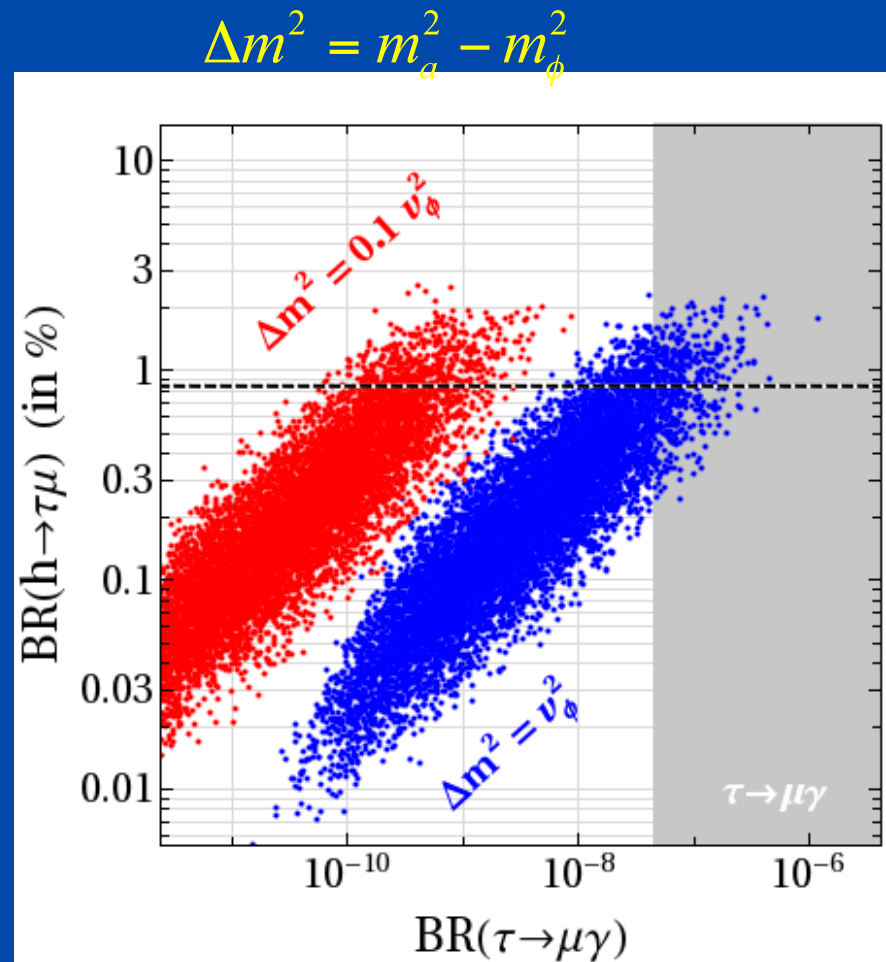
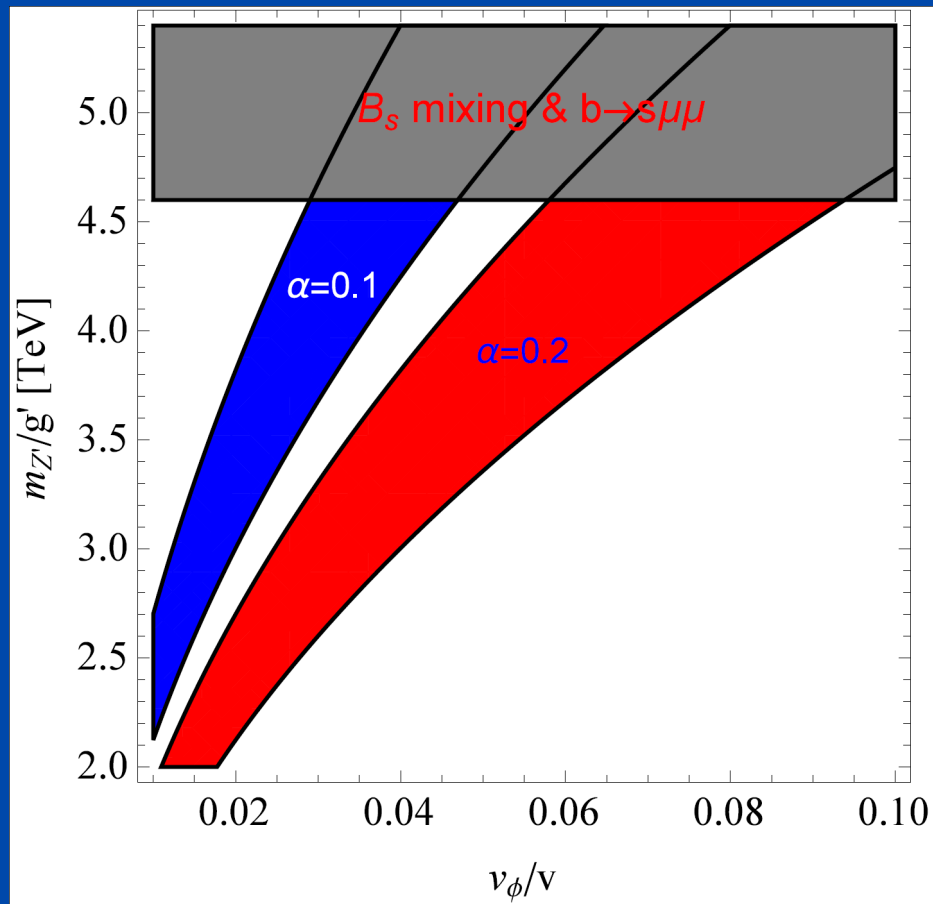
- L_μ - L_τ flavour symmetry
- Flavon mixes with the Higgs
- $\tau \rightarrow \mu\gamma$ is protected
- a_μ is not protected
- Effects in $h \rightarrow \mu\mu$



L_μ - L_τ model for a_μ and $h \rightarrow \tau\mu$

- Can also explain $b \rightarrow s\mu\mu$ without violating $\tau \rightarrow 3\mu$ bound

α : mixing among CP even Higgses



$$\Delta m^2 = m_a^2 - m_\phi^2$$

$$b \rightarrow s \mu^+ \mu^-$$

$$b \rightarrow c \tau \nu$$

Conclusions

Z' gauge
boson

Leptoquarks

Extended
Higgs sector

Conclusions

$$a_\mu$$

$$h \rightarrow \tau \mu$$

Outlook (personal view)

■ $b \rightarrow s\mu\mu + R(D^{(*)}) \longrightarrow$ Leptoquarks

■ $B_s \rightarrow \mu\mu$

■ $b \rightarrow s\tau\tau$

■ $a_\mu + R(D^{(*)}) \longrightarrow$ 2HDM X

■ $t \rightarrow Hc, \tau \rightarrow \mu\nu\nu$

■ $b \rightarrow s\mu\mu + h \rightarrow \tau\mu \longrightarrow$ Z'

■ $\tau \rightarrow \mu\mu\mu$

■ $h \rightarrow \tau\mu + a_\mu \longrightarrow$ Flavon model

■ $h \rightarrow \mu\mu$