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Implications of the flavour anomalies

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

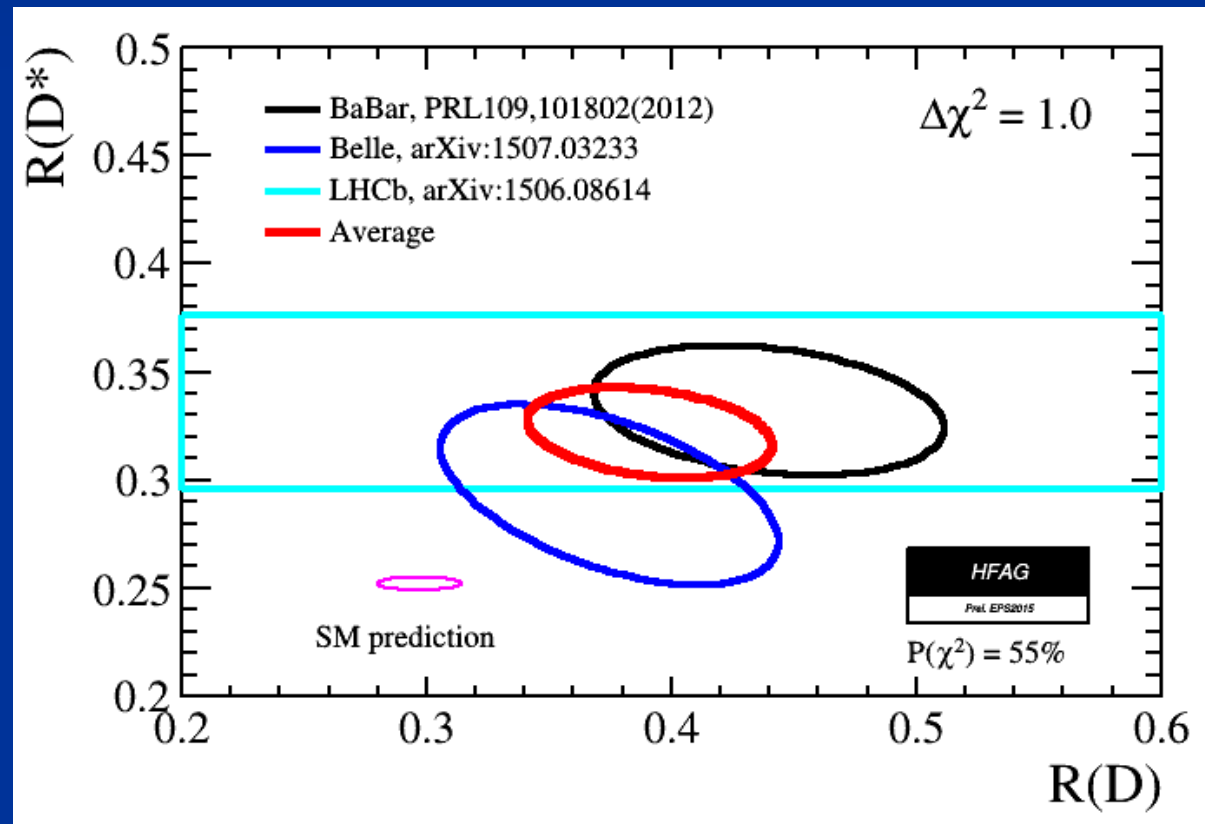
Flavour Anomalies

Tauonic B decays

See talk of Patrick

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

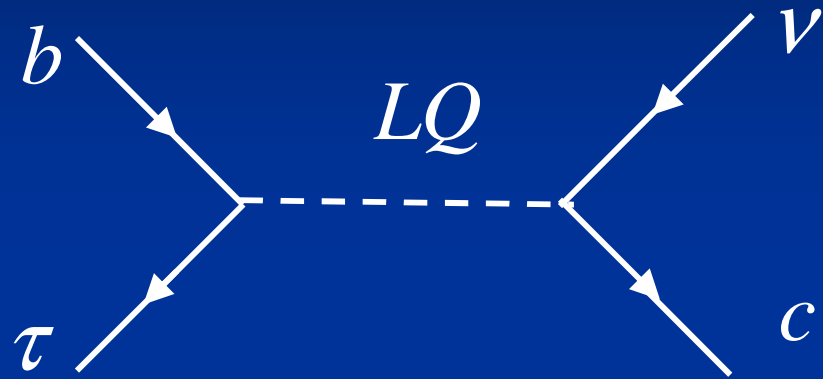
$$R(D^{(*)}) = B \rightarrow D^{(*)} \tau \nu / B \rightarrow D^{(*)} \ell \nu$$



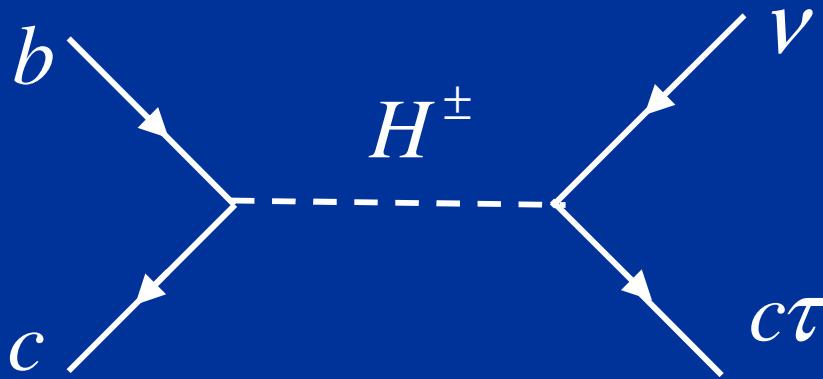
➔ Combined $\approx 4 \sigma$ deviation

R(D) Explanations

- Leptoquark (scalar or vector)



- Charged Higgs  different differential distribution



- W' ????

$b \rightarrow s \mu \mu$

See talks of Patrick and Nicola

- Global analysis give a very good fit to data
Lepton Flavour Universality Violation
- Symmetry based solutions give a very good fit to data:

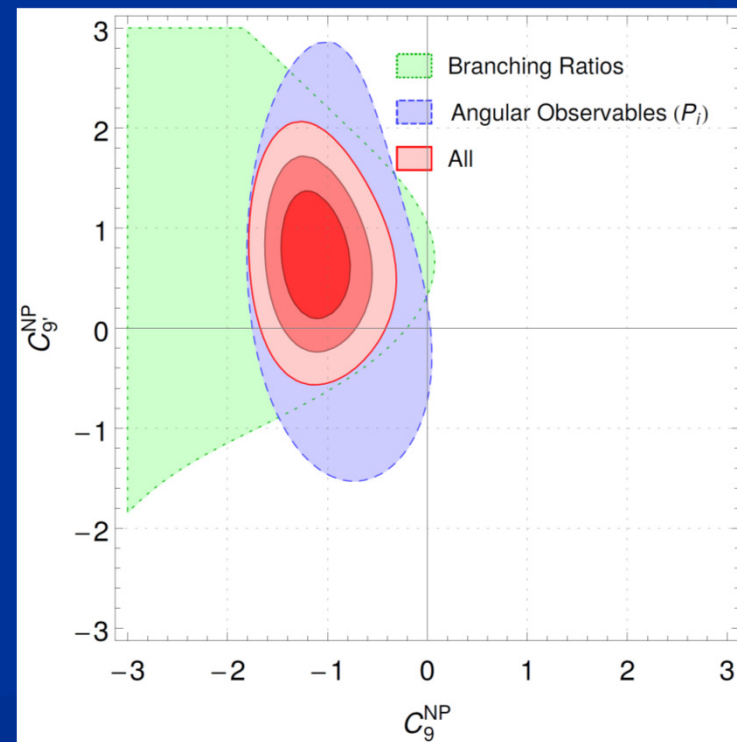
- C_9

- $C_9 = -C_{10}$

- $C_9 = -C'_9$

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

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



➔ Fit is 4-5 σ better than in the SM ^{1501.04239}

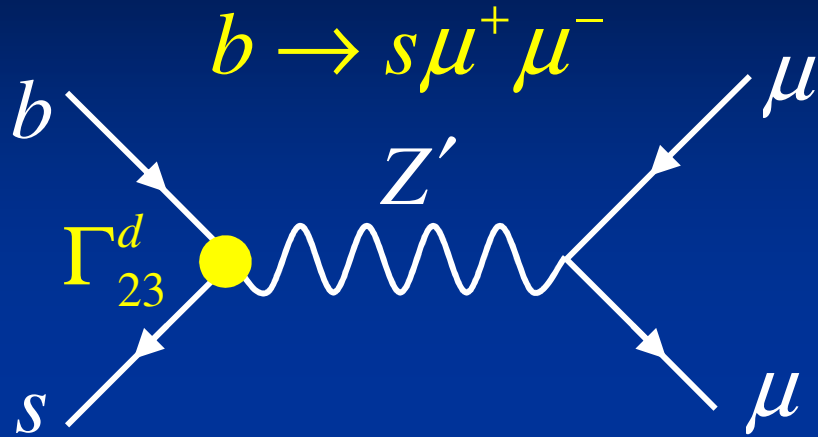
Z' explanations

U. Haisch et al. 1308.1959

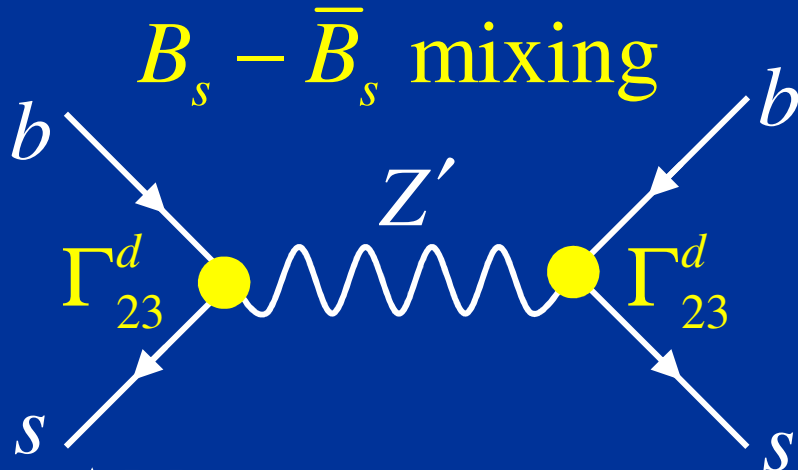
W. Altmannshofer et al. 1403.1269

A. C. et al. 1501.00993

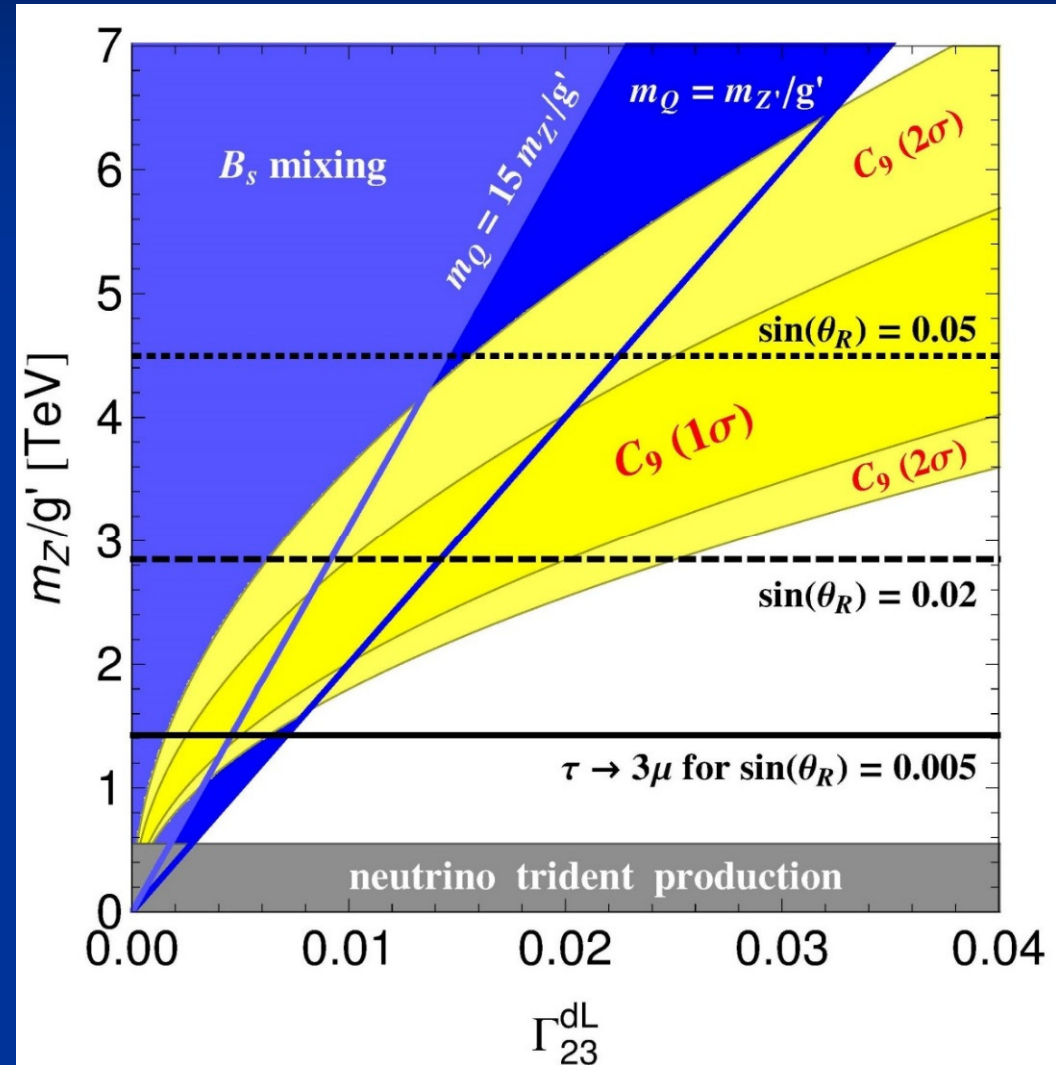
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$$C_9^{\mu\mu} \propto \Gamma_{23}^{dL} g'^2 / m_{Z'}^2$$

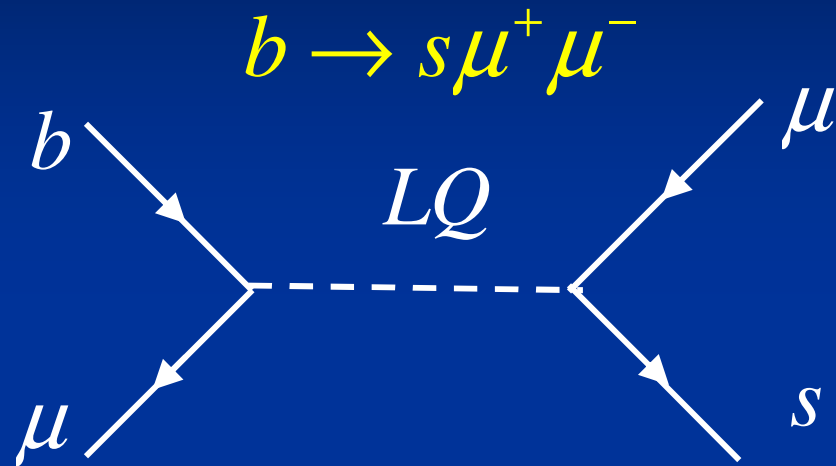


$$\frac{\Delta M_{12}}{M_{12}^{\text{SM}}} \propto \left(\Gamma_{23}^{dL} \right)^2 g'^2 / m_{Z'}^2$$

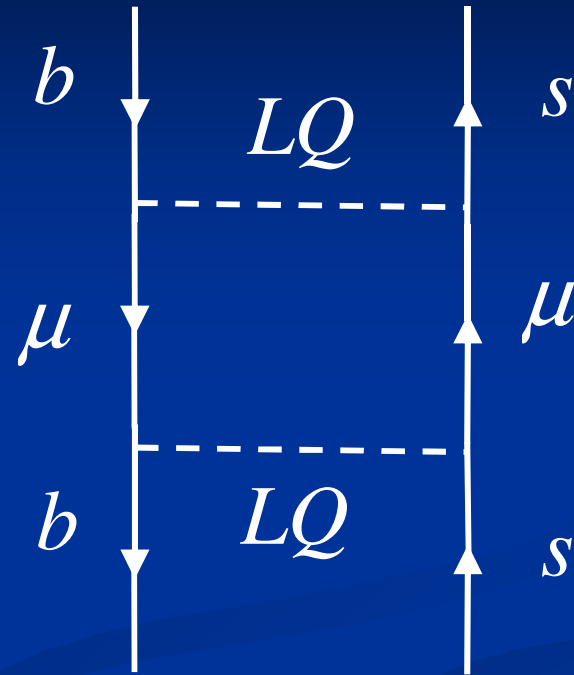


allowed regions

Leptoquarks

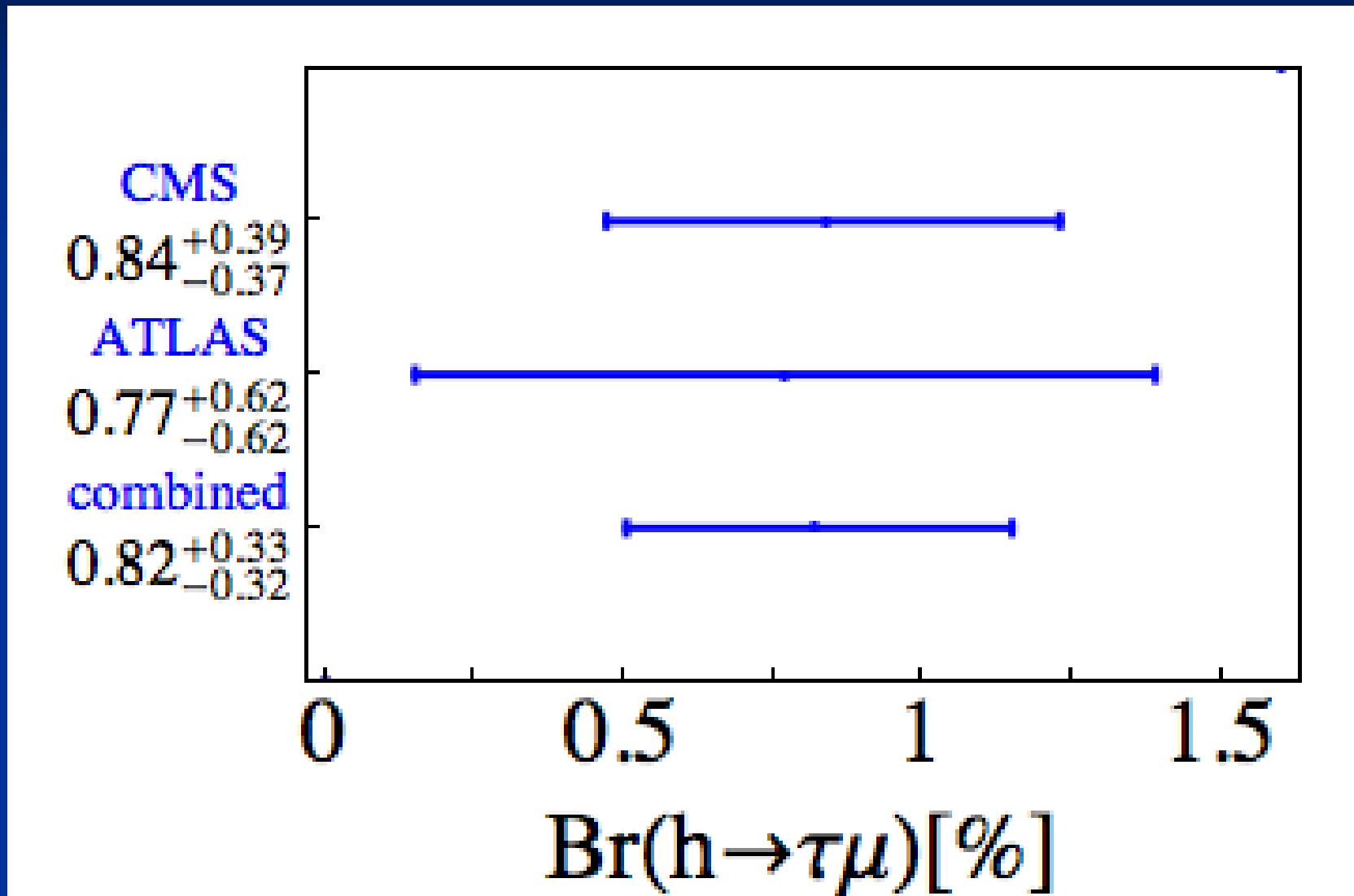


$B_s - \bar{B}_s$ mixing



- 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 (but no excess in run II) 8

$$h \rightarrow \tau\mu$$

- Can be explained in the effective field theory approach by

$$\mathcal{Q}_{e\phi}^{fi} = \ell_f \phi e_i \phi^\dagger \phi$$

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

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Models for Simultaneous Explanations of Anomalies

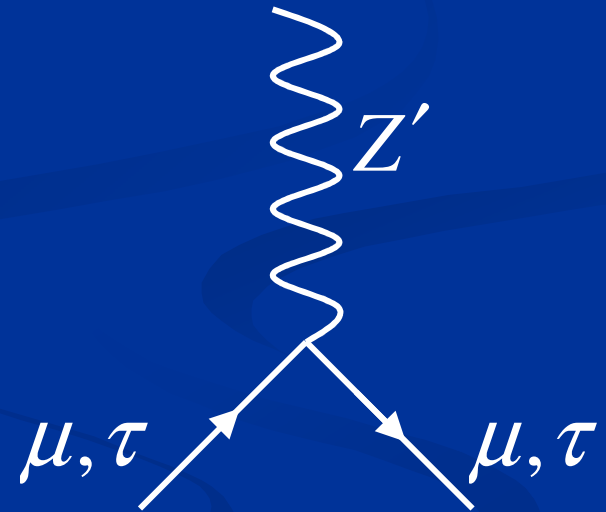
2HDM with gauged $L_\mu - L_\tau$

- 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

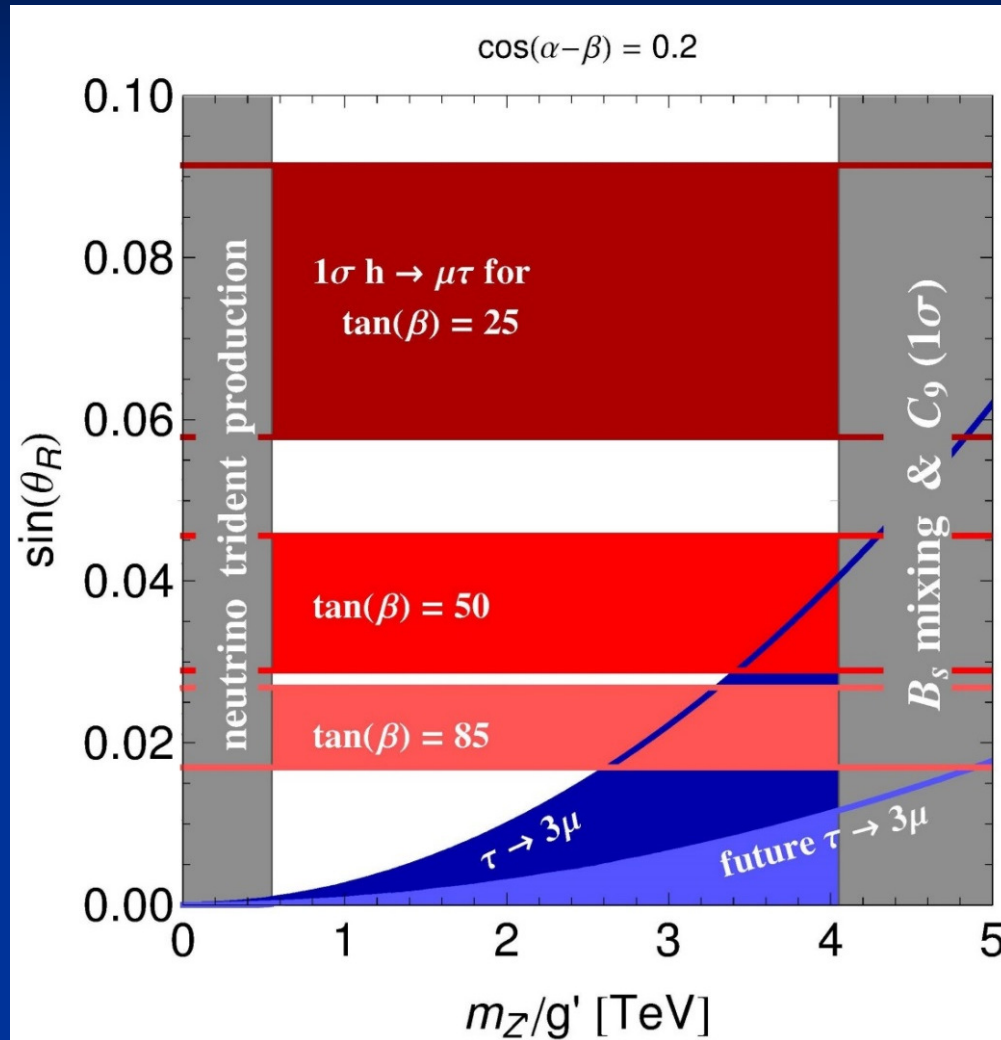
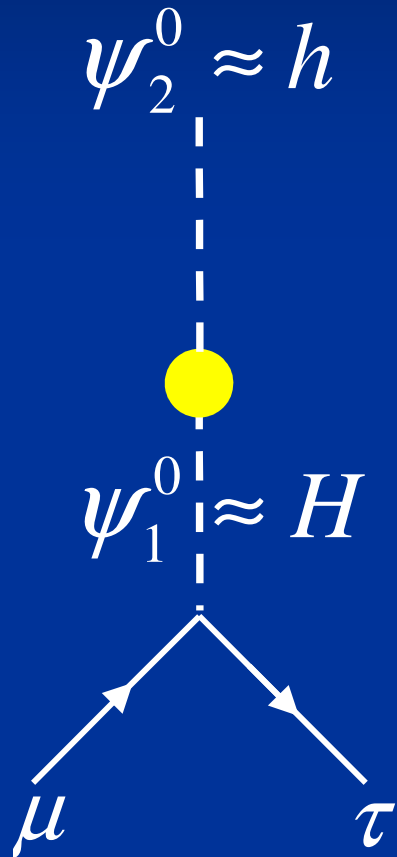
$$\begin{aligned} \mathcal{L}_Y \supset & -\bar{\ell}_f Y_i^\ell \delta_{fi} \Psi_2 e_i - \xi_{\tau\mu} \bar{\ell}_3 \Psi_1 e_2 \\ & -\bar{Q}_f Y_{fi}^u \tilde{\Psi}_2 u_i - \bar{Q}_f Y_{fi}^d \Psi_2 d_i + \text{h.c.} \end{aligned}$$



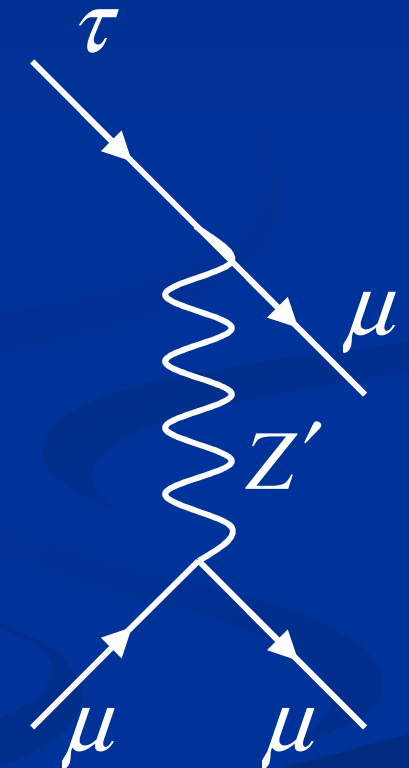
- θ_R diagonalizes the τ - μ block of the mass matrix

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.
 - SU(2) flavour

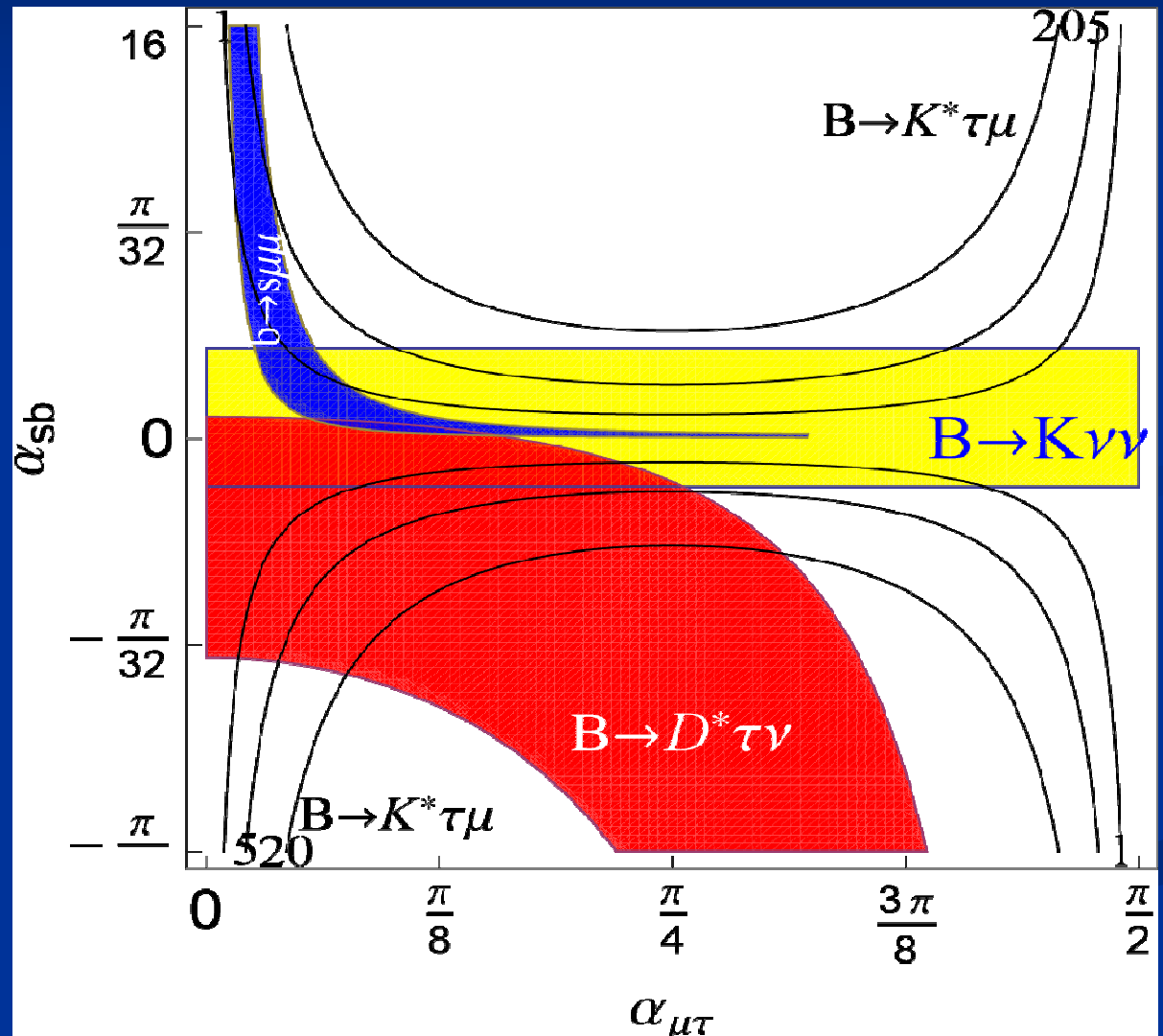
R. Barbieri, G. Isidori, A. Pattori, F. Senia. 1512.01560.

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



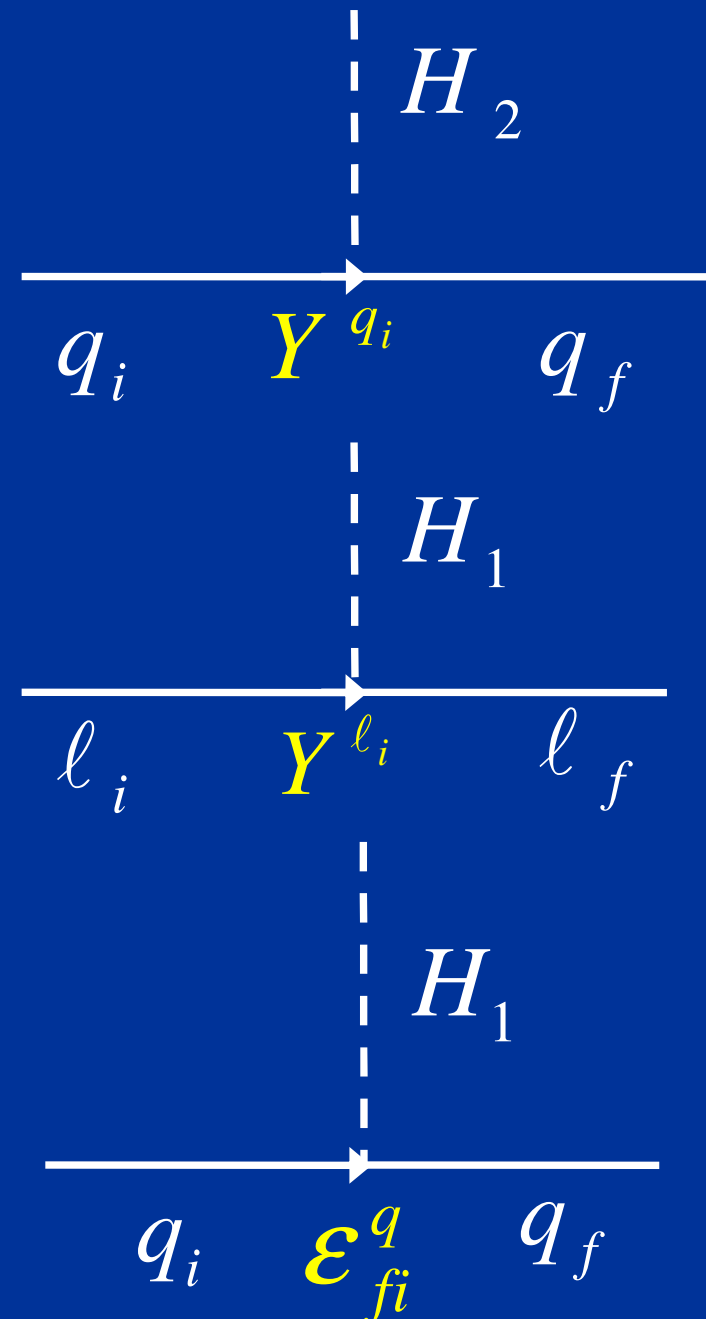
2HDM of type X

- One Higgs doublet couples only to quarks the other Higgs doublet to leptons.
- Additional free parameters:

$$\tan \beta = v_1 / v_2$$

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

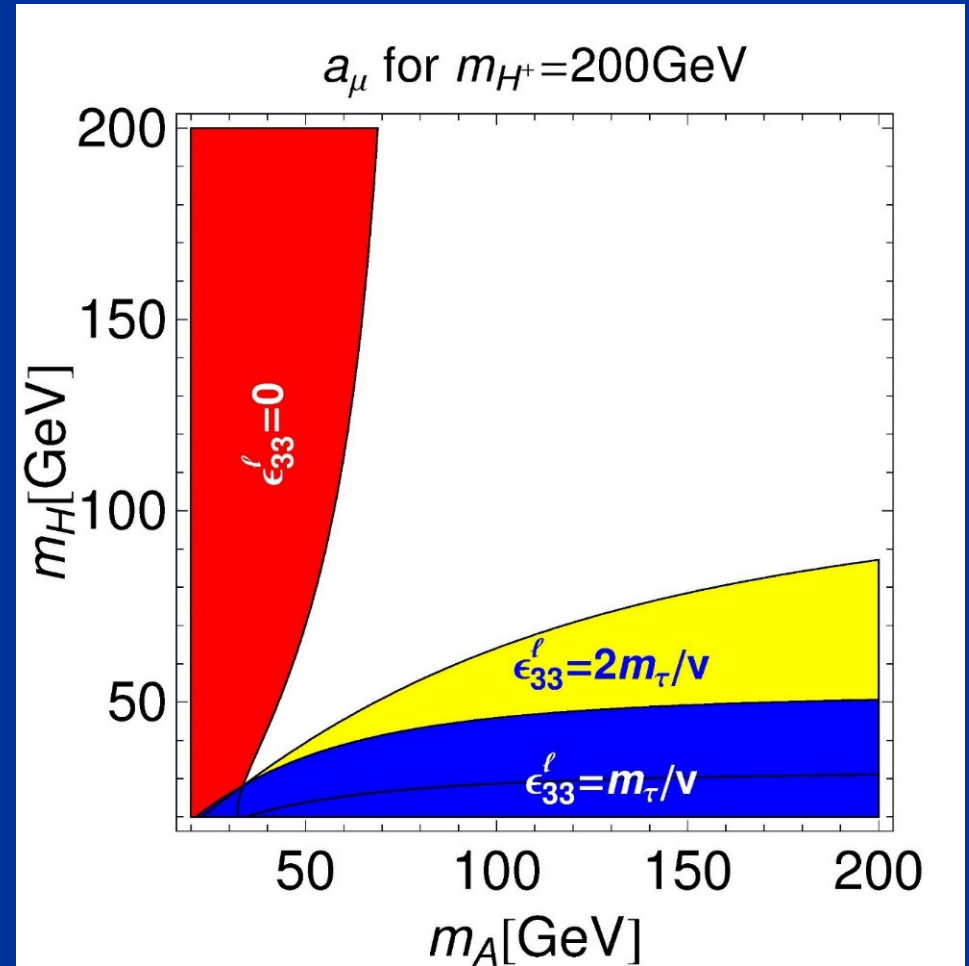
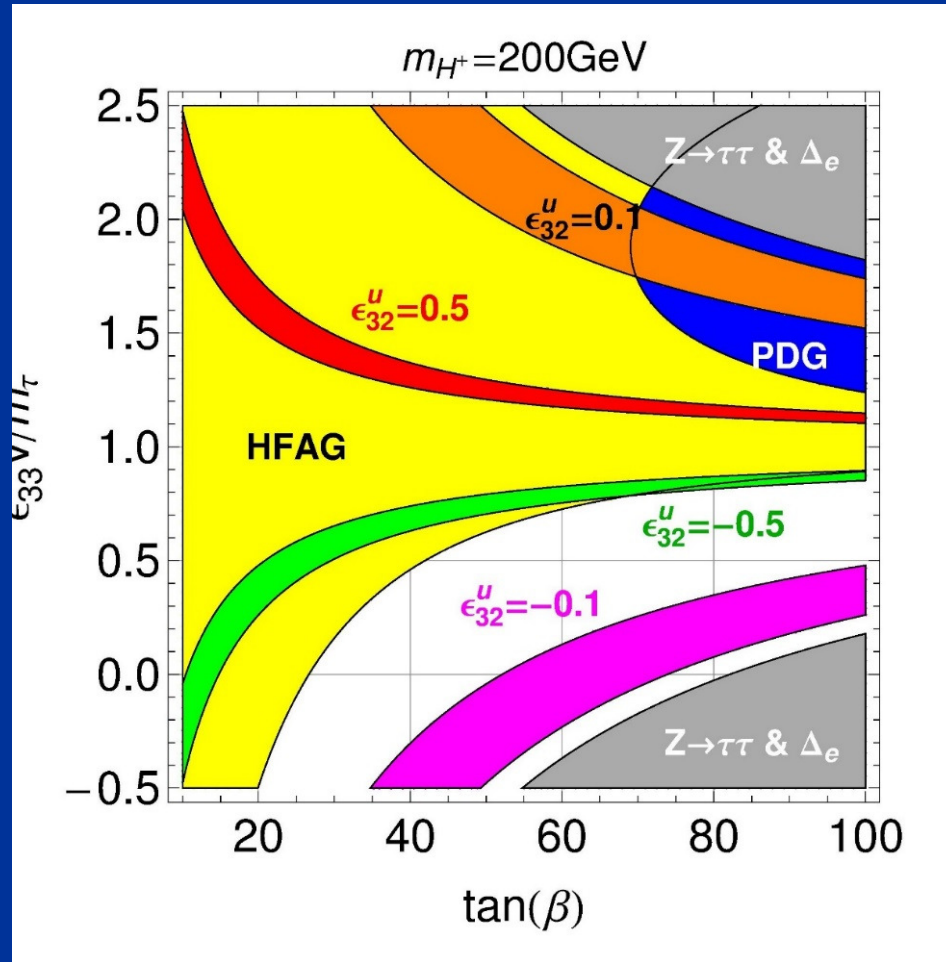
$$\mathcal{E}_{fi}^{u,l} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & \mathcal{E}_{32}^{u,l} & \mathcal{E}_{33}^{u,l} \end{pmatrix}$$



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

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

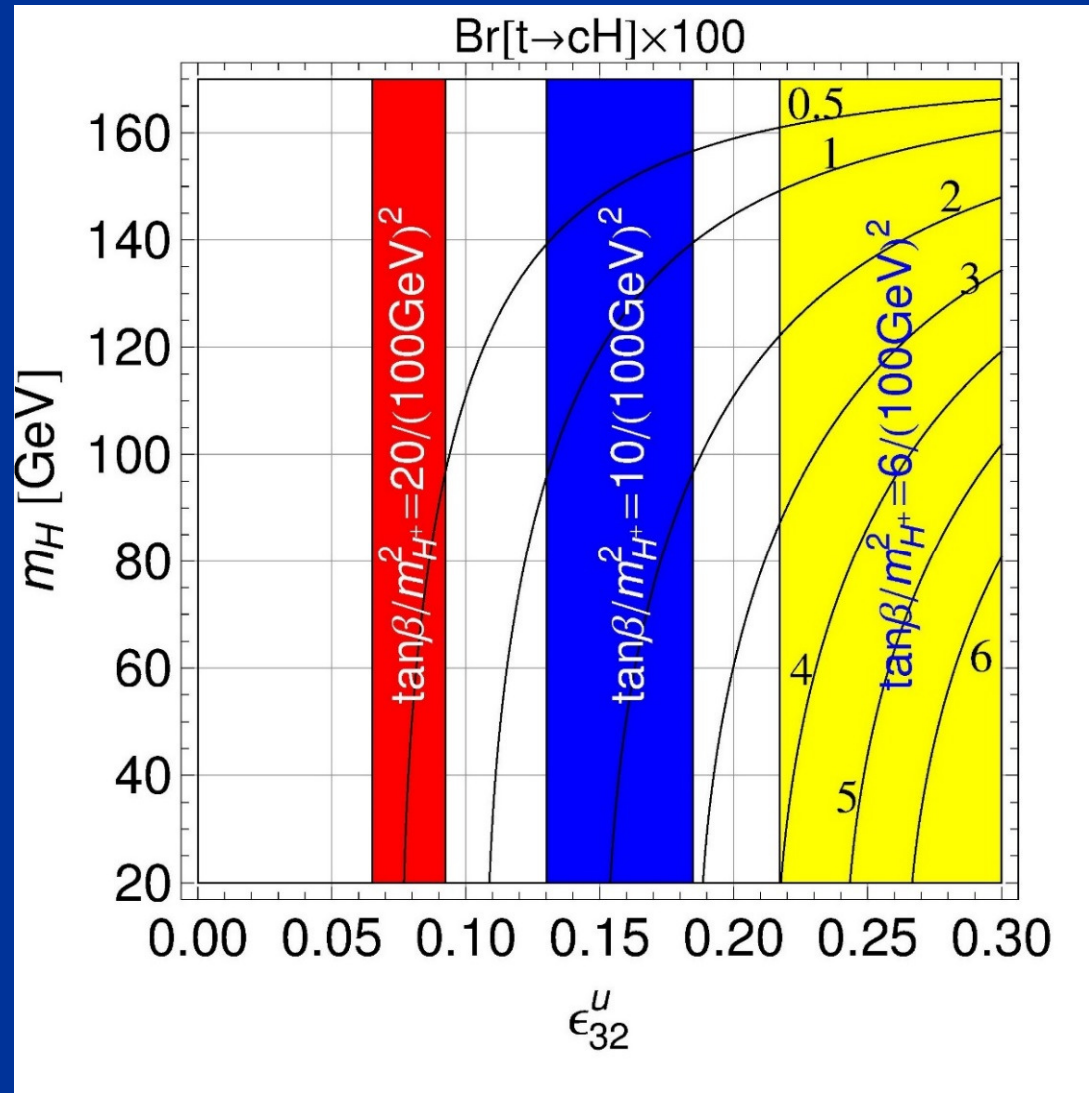
a_μ



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

$$m_H < m_A$$

Prediction: $t \rightarrow Hc$

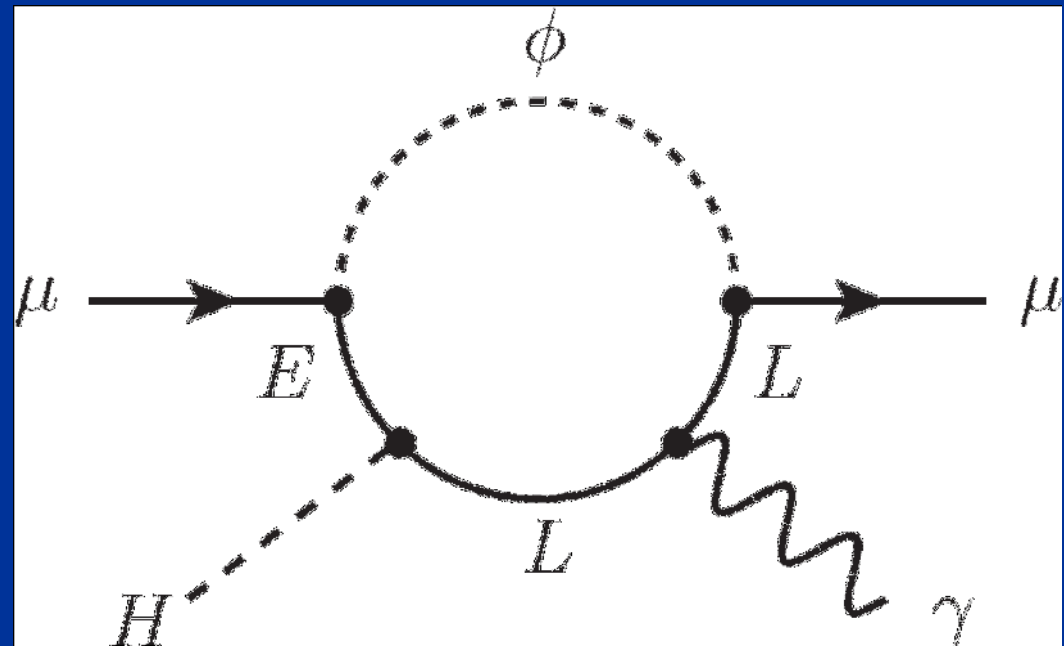
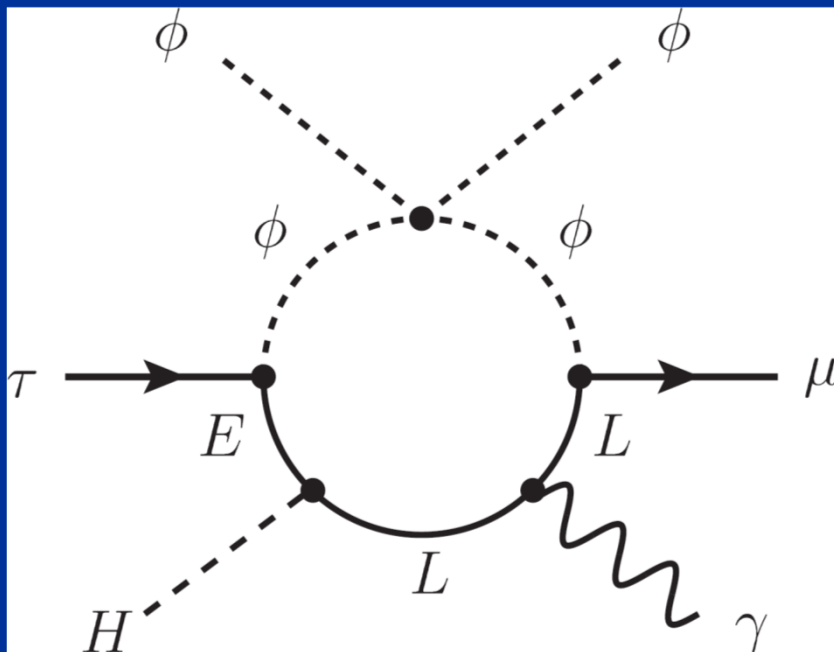
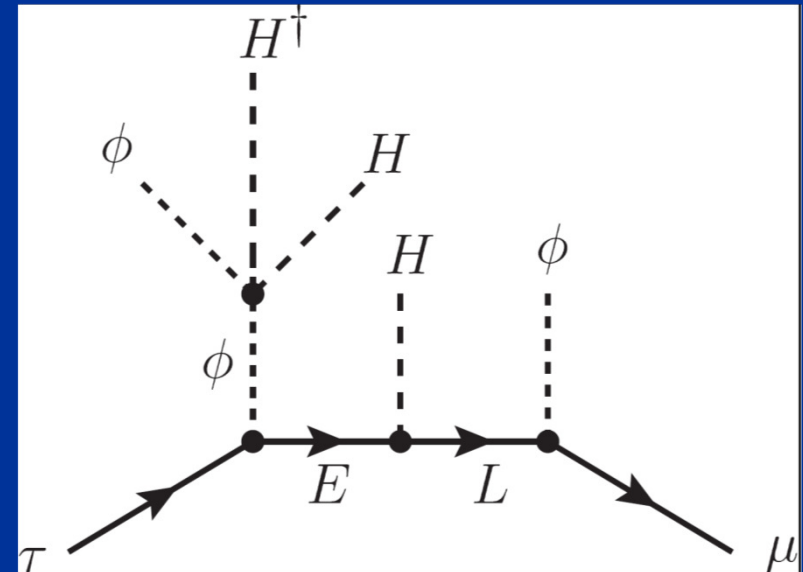


Branching ratio
can even reach
the percent level

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

W. Altmannshofer, M. Carena, AC, 1604.08221

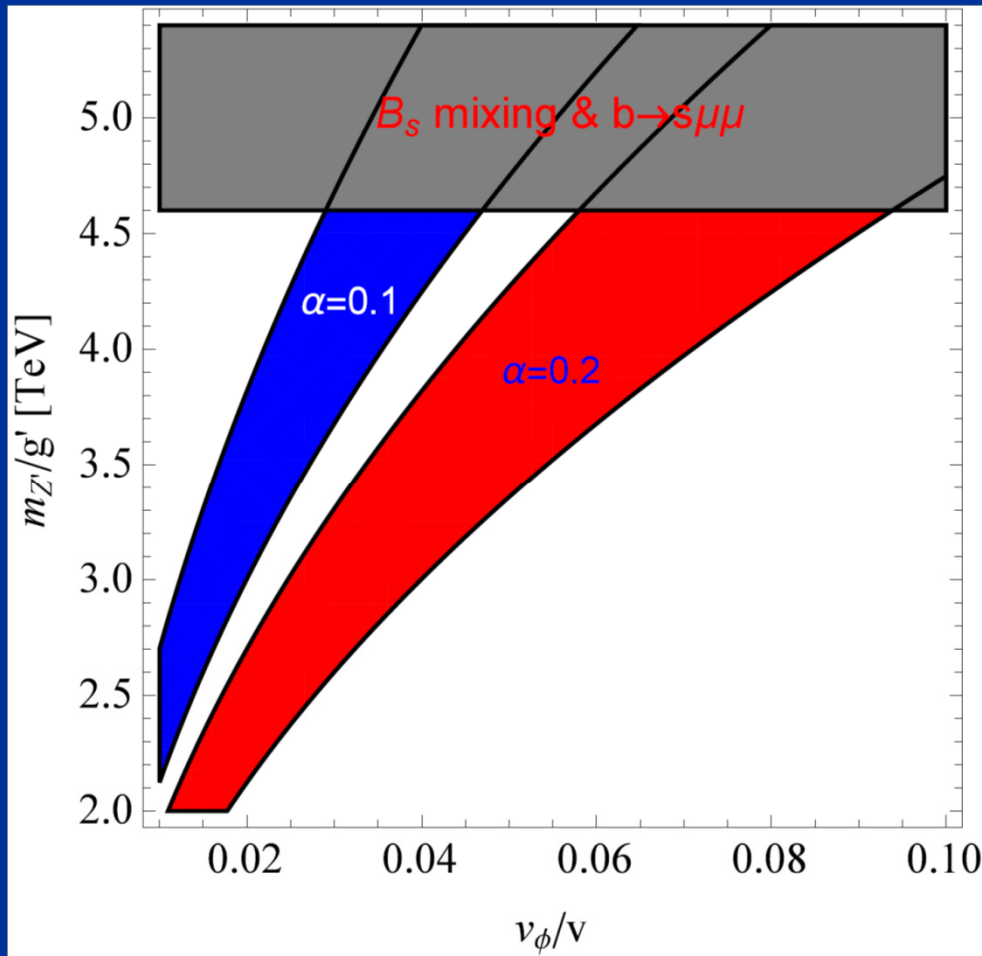
- L_μ - L_τ flavour symmetry
- Flavon mixes with the Higgs
- $\tau \rightarrow \mu\gamma$ is protected
- a_μ is not protected
- Effects in $h \rightarrow \mu\mu$



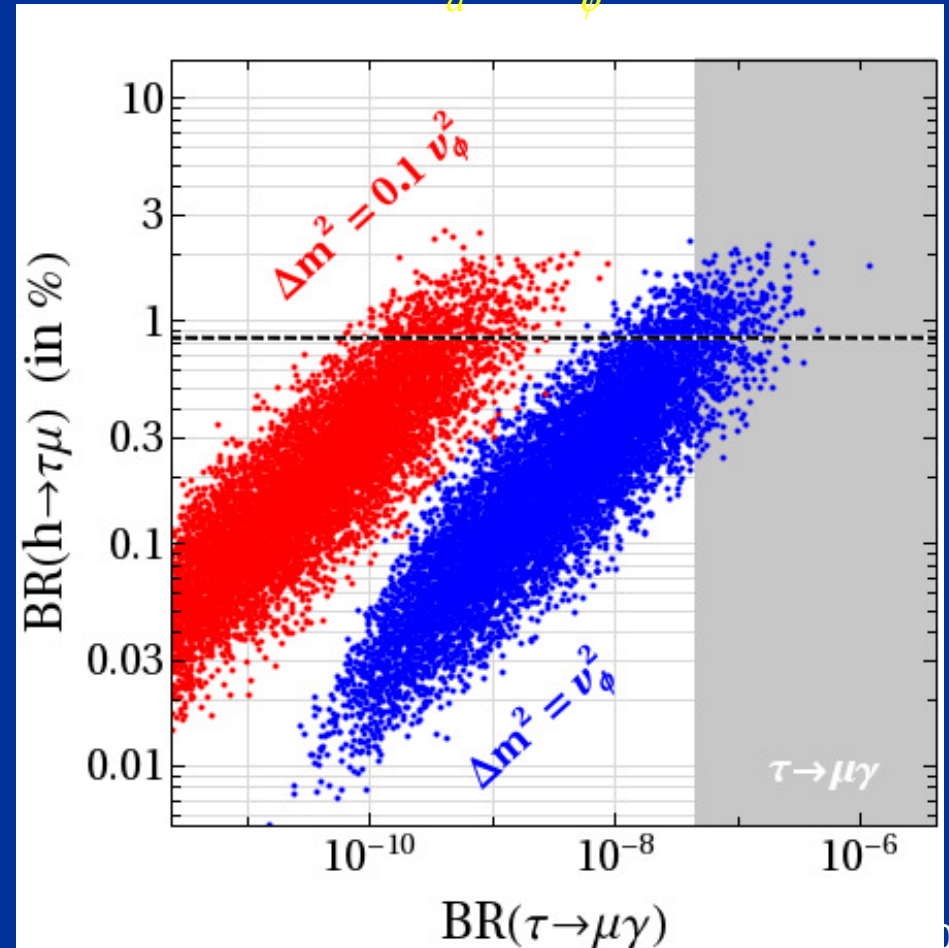
L_μ - L_τ model for a_μ and $h \rightarrow \tau\mu$

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

α : mixing among CP even Higgses

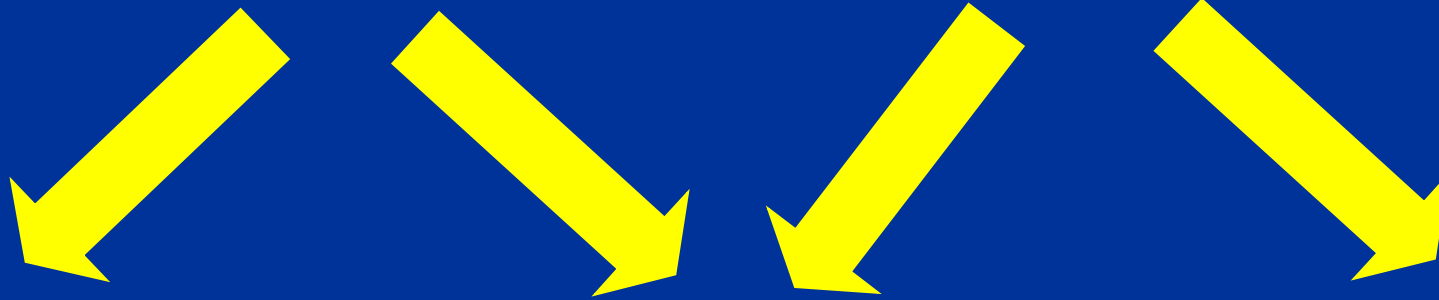


$$\Delta m^2 = m_a^2 - m_\phi^2$$



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

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



Z' gauge boson

Leptoquarks

Extended Higgs sector

$$a_\mu$$


$$h \rightarrow \tau \mu$$

Outlook (personal view)

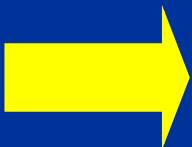
■ $b \rightarrow s\mu\mu + R(D^{(*)})$  Leptoquarks

■ $B_s \rightarrow \mu\mu$


■ $b \rightarrow s\tau\tau$

■ $a_\mu + R(D^{(*)})$  2HDM X

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

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

■ $\tau \rightarrow \mu\mu\mu$

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

■ $h \rightarrow \mu\mu$

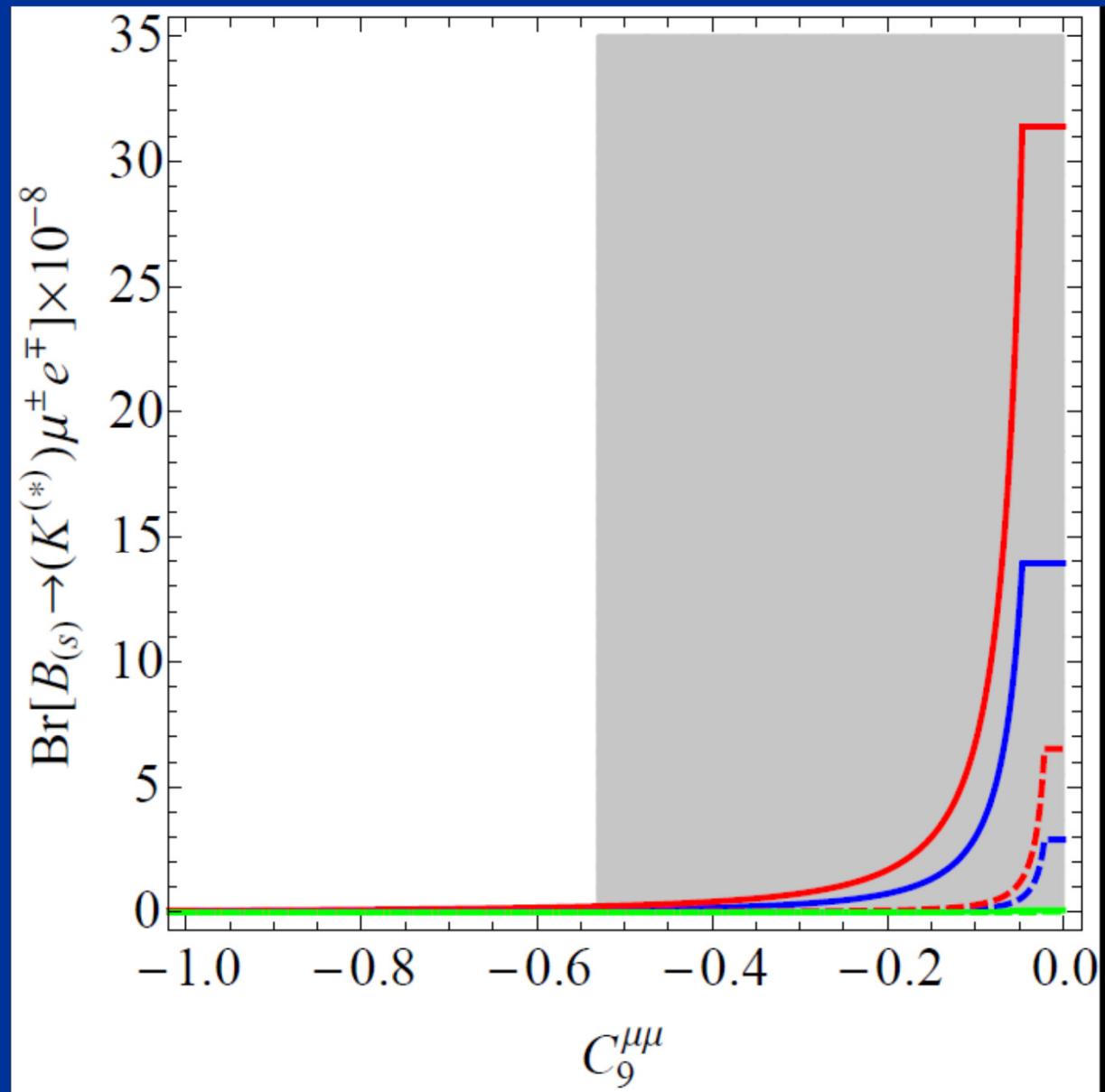
$$\mu \rightarrow e\gamma, \mu \rightarrow 3e$$

- Any observation would directly prove NP
- $\mu \rightarrow e\gamma$ currently best limit of cLFV
- $\mu \rightarrow 3e$ complementary to $\mu \rightarrow e\gamma$
 - Z' models
- Leptoquark explanations of $B \rightarrow D^{(*)}\tau\nu + b \rightarrow s\mu^+\mu^-$
 - ➔ $Br[\mu \rightarrow e\gamma] \neq 0$ (in general)
- Z' models and $h \rightarrow \tau\mu$ motivate $\tau \rightarrow 3\mu$
 - ➔ $Br[\mu \rightarrow 3e] \neq 0$

$B \rightarrow K^{(*)} e \mu$ and $B_s \rightarrow e \mu$

- Generic Z' model
- Bounds from $\mu \rightarrow e \gamma$
- $B_s \rightarrow e \mu$
- $B \rightarrow K^{*} e \mu$
- $B \rightarrow K e \mu$

Solid:
Fine-tuning 100
Dashed:
Fine-tuning 20



PEN and Muonic Lamb Shift

- $B \rightarrow D^{(*)} \tau \nu$

- Also LFUV in $\pi \rightarrow \mu \nu / \pi \rightarrow e \nu$?

-  PEN

- $\alpha_\mu + R(K) + h \rightarrow \tau \mu$

- New Physics with muon but not with electrons?

-  Connection to the proton radius problem???
 - Muonic Lamb Shift experiment