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New Physics Explenations of the Flavour Anomalies

Outline:

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

Flavour Anomalies

“Missing Energy” Decays

New Physics in b→sμμ

More details in Ben Grinstein's talk

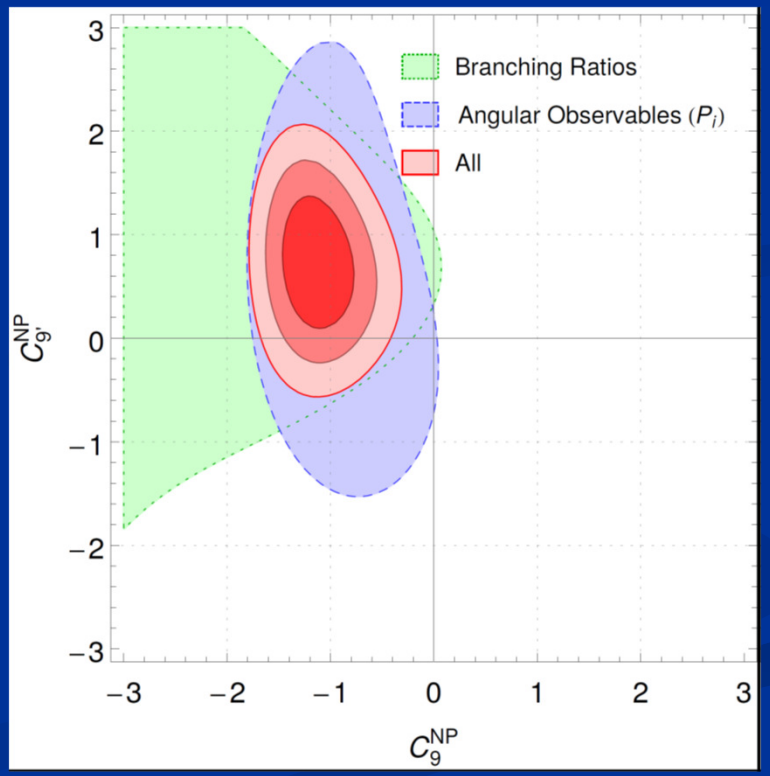
- Global analysis give a very good fit to data

  W. Altmannshofer, D. M. Straub, arXiv:1503.06199. T. Hurth, F. Mahmoudi, and S. Neshatpour, 1410.4545. Descotes-Genon et al. 1501.04239

- Symmetry based solutions give a very good fit to data:
  - C_9
  - $C_9 = -C_{10}$
  - $C_9 = -C_9'$

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

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

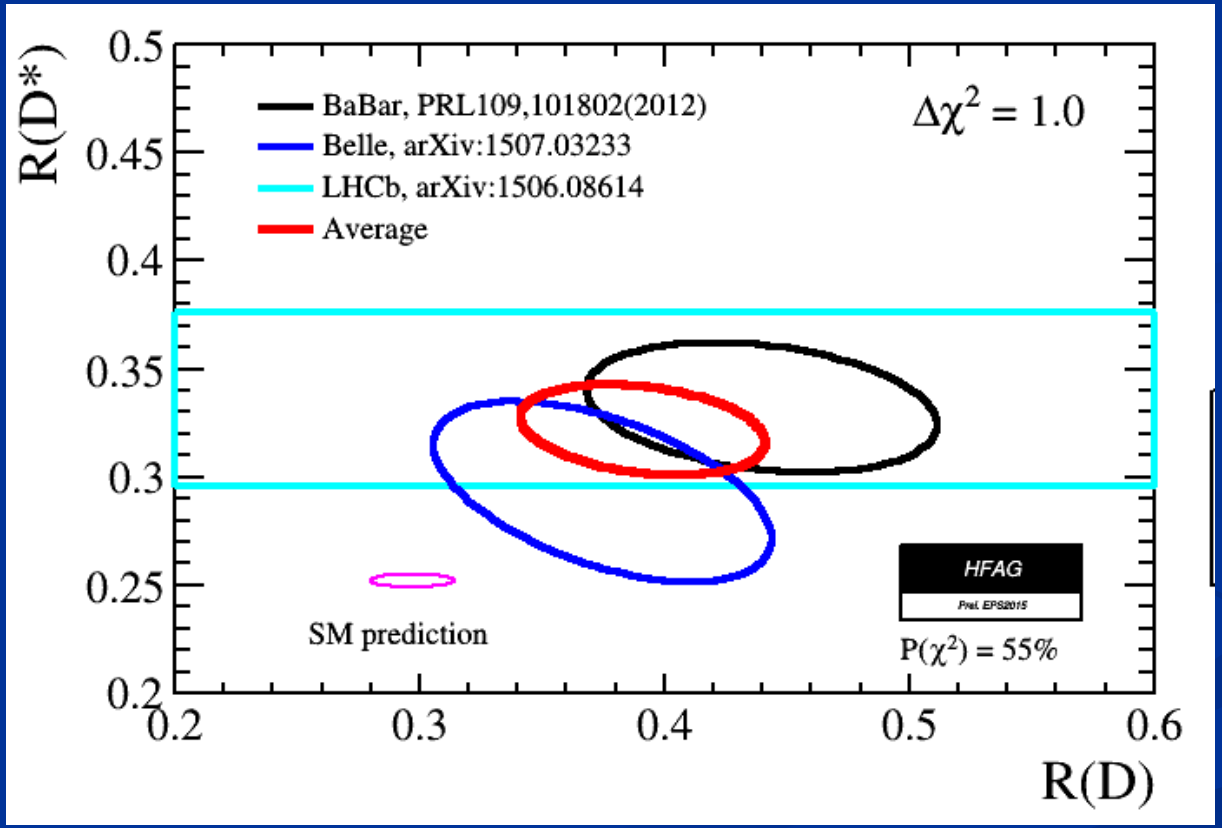


➡ Fit is 4-5 σ better than in the SM

Tauonic B decays

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

$$R\left(D^{(*)}\right) = B \to D^{(*)}\tau\nu \Big/ B \to D^{(*)}\ell\nu$$



➡ Combined ≈4 σ deviation

$h \to \tau\mu$

- 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
.....
.....

$\tau \to \mu\nu\nu$ and a_μ

- Tau decays

$$\mathrm{Br}[\tau \to \mu\nu\nu]_{\mathrm{exp}} = (17.41 \pm 0.04)\,\%$$

$$\Delta_{\tau\to\mu\nu\nu} = \frac{\mathrm{Br}[\tau \to \mu\nu\nu]_{\mathrm{exp}}}{\mathrm{Br}[\tau \to \mu\nu\nu]_{SM}} - 1 = (0.69 \pm 0.29)\,\%$$

- Anomalous magnetic moment of the muon

$$\Delta a_\mu = (236 \pm 87) \times 10^{-11}$$

$\Rightarrow$ $2-3\,\sigma$ deviations in the lepton sector

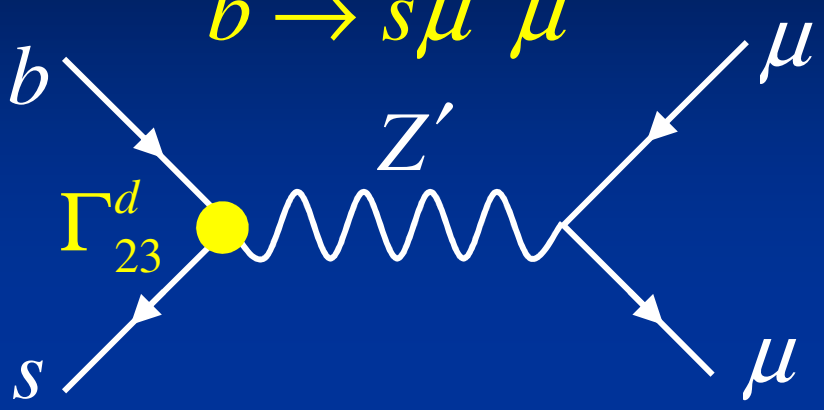
Much more in the g-2 session…

NP in ε'/ε Andrzej Buras' talk

Explanations of the Anomalies

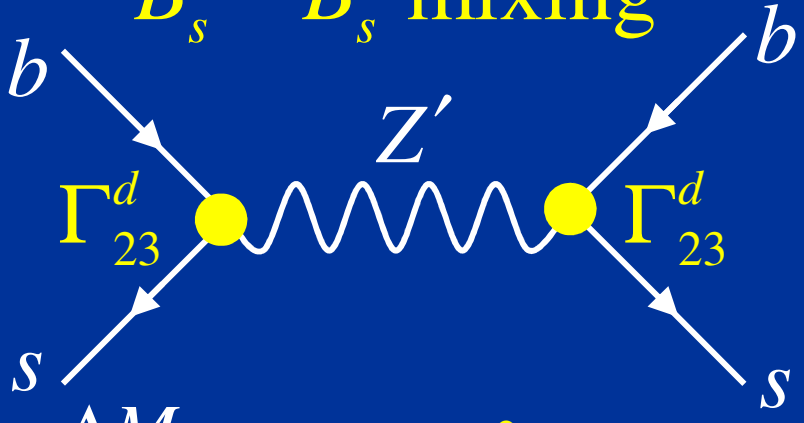
Z' explanations

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



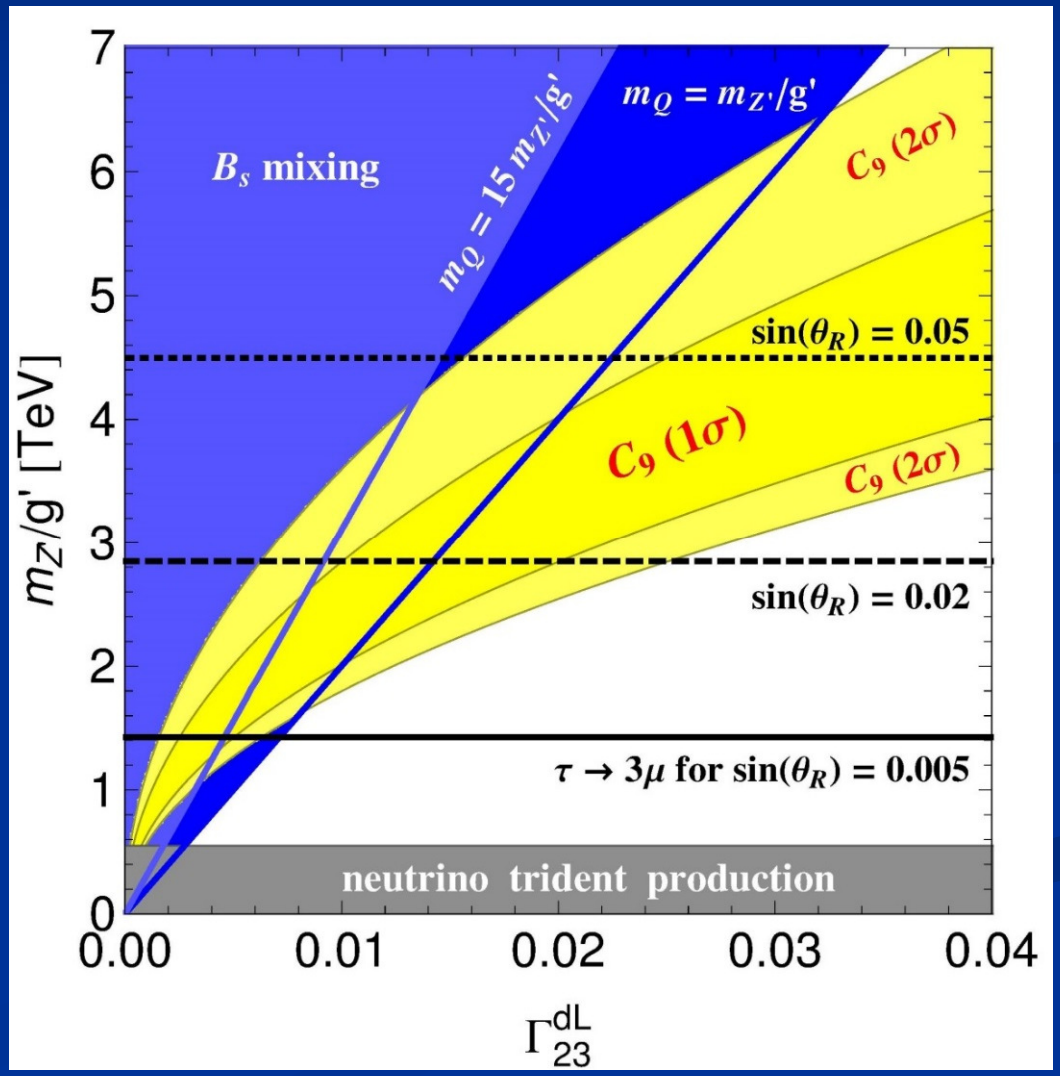
$$C_9^{\mu\mu} \propto \Gamma_{23}^{dL}\, g'^2 / m_{Z'}^2$$

$B_s - \bar{B}_s$ mixing



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

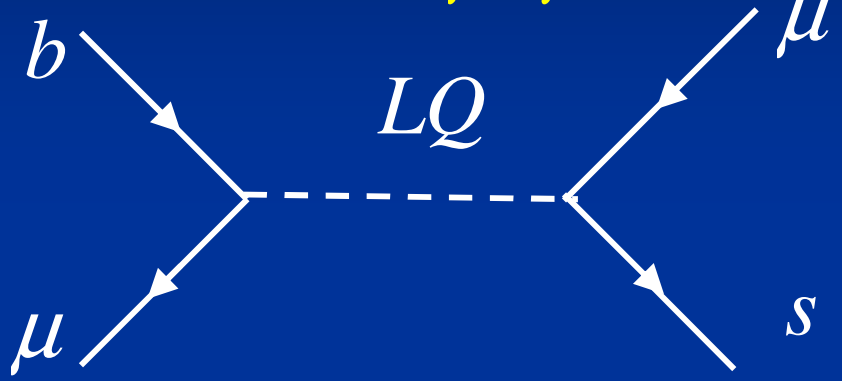
U. Haisch et al. 1308.1959
Buras et al. 1311.6729
W. Altmannshofer et al. 1403.1269
AC. et al. 1501.00993
.....

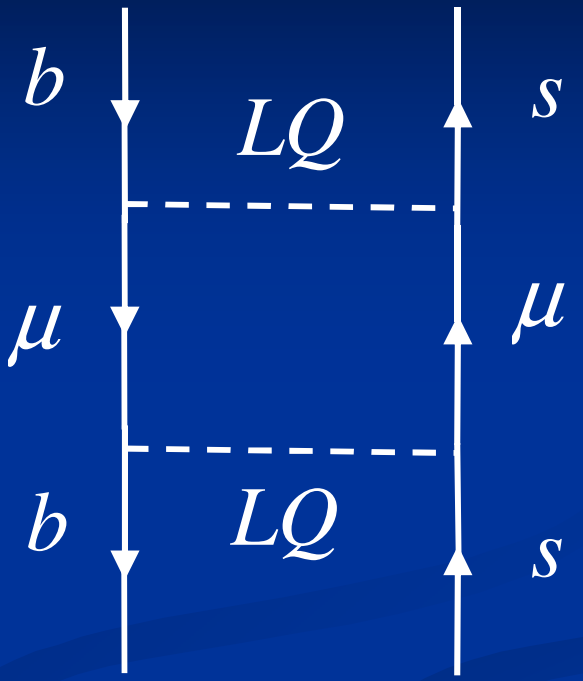


Leptoquarks

$B_s - \overline{B}_s$ mixing

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

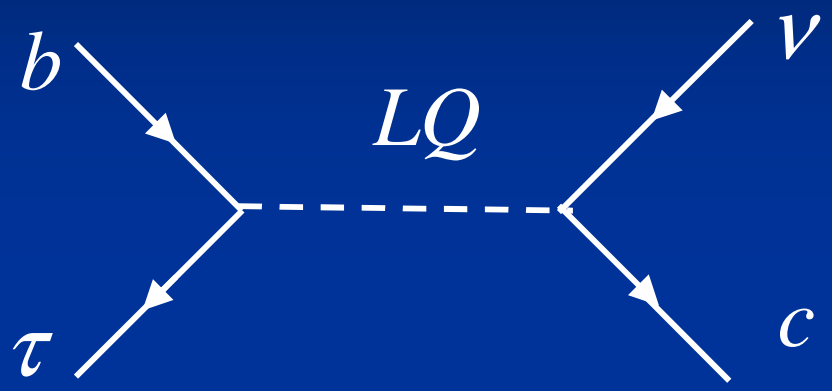




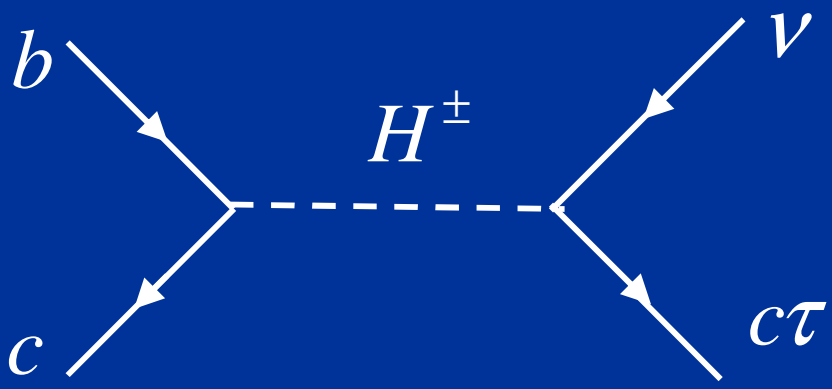
- Only weak constraints from other flavour observables (loop compared to tree)
- Possible effect in the anomalous magnetic moment of the muon
- Large production cross section at the LHC

R(D) Explanations

- Leptoquark (scalar or vector)



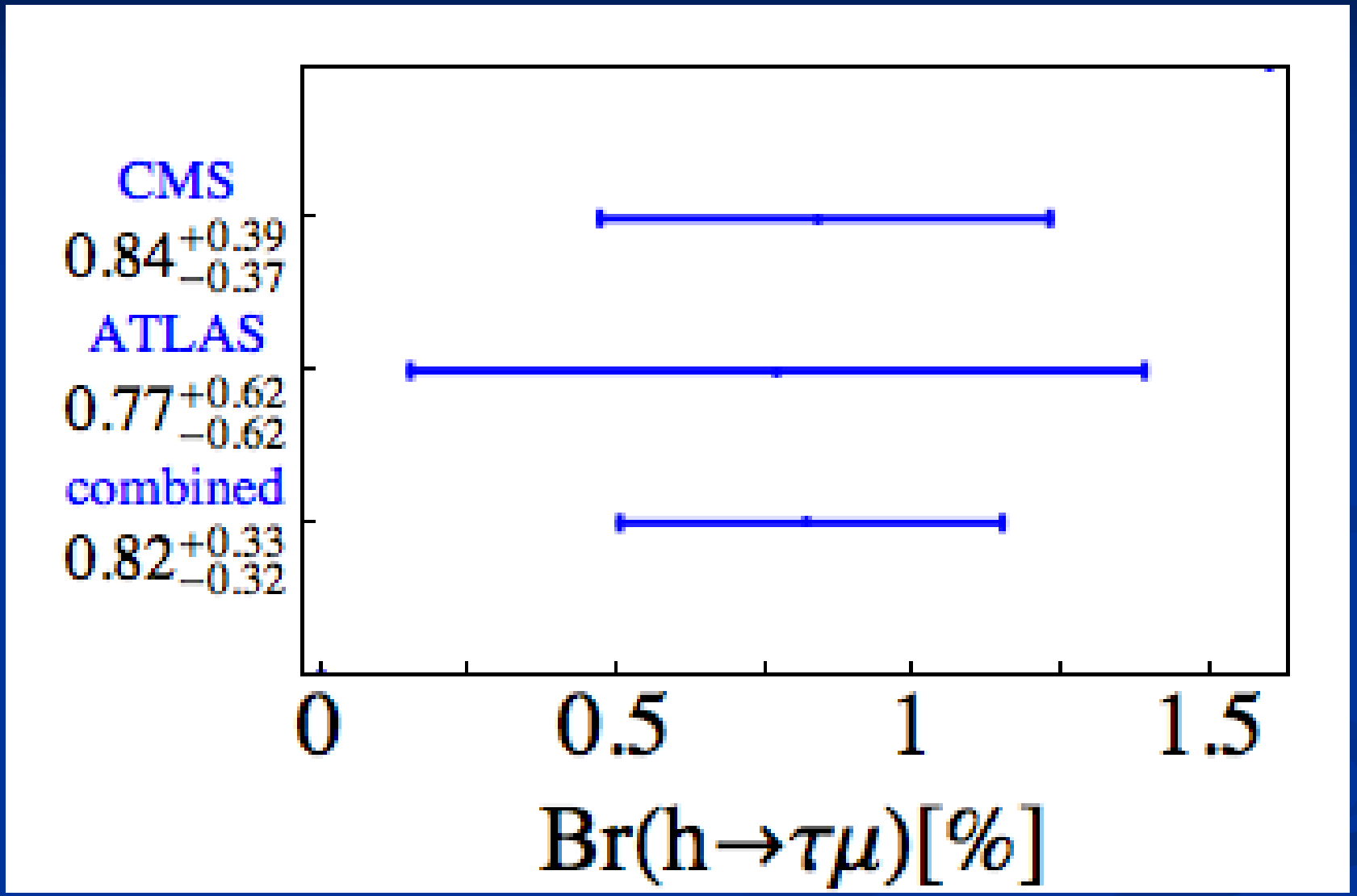
- Charged Higgs ➡ different differential distribution



- W' ???

A. Greljo, G. Isidori and D. Marzocca 1506.01705

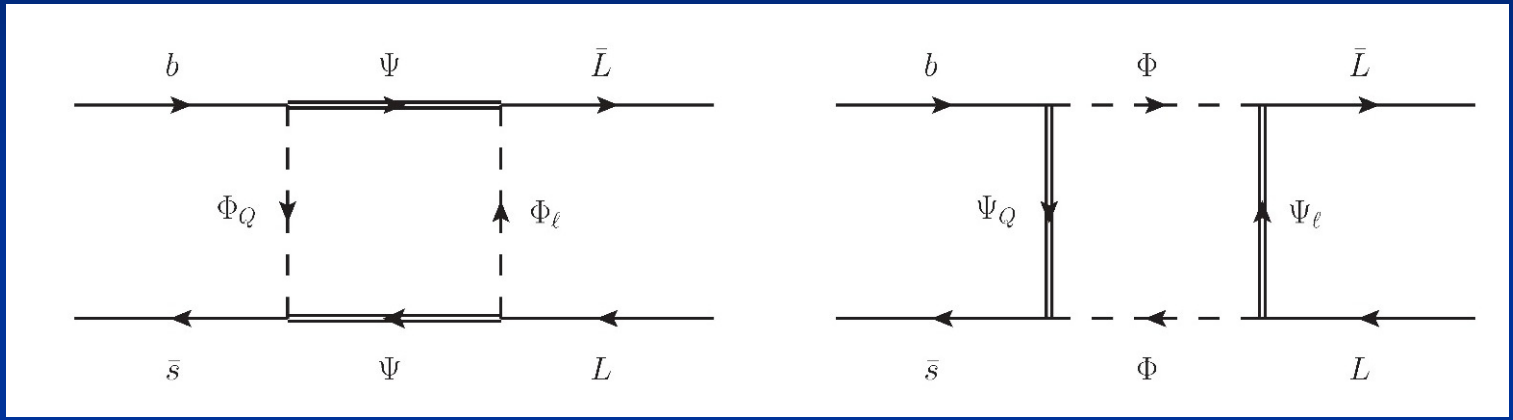
$h \to \tau\mu$



- 2.6 σ difference from zero

New Scalars and Fermions in b→sμμ

B. Gripaios, M. Nardecchia, S. Renner, arXiv:1509.05020



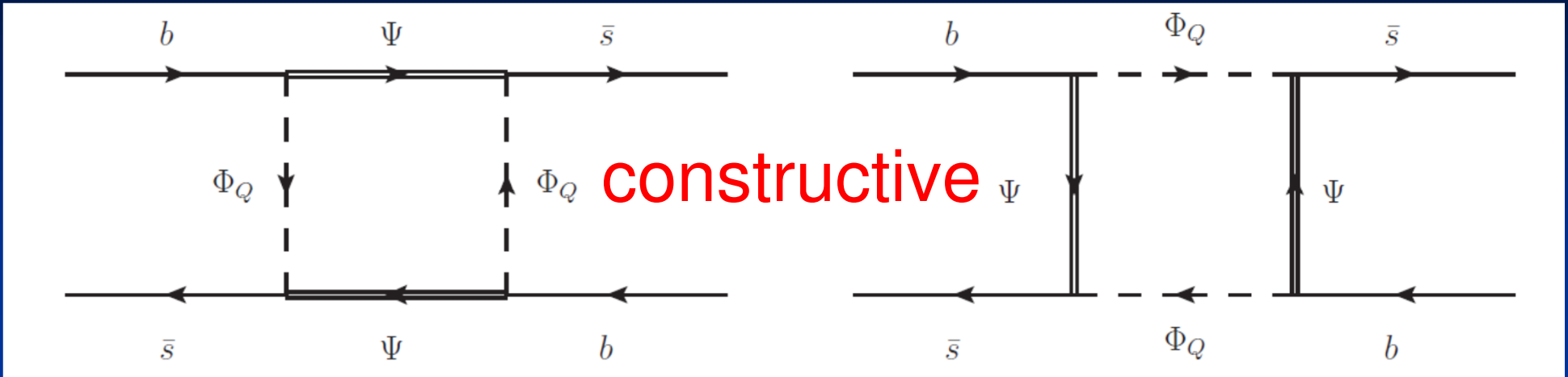
- Possible representations

$SU(2)$	Φ_Q, Ψ_Q	Φ_ℓ, Ψ_ℓ	Ψ, Φ
I	2	2	1
II	1	1	2
III	3	3	2
IV	2	2	3
V	3	1	2
VI	1	3	2

$SU(3)$	Φ_Q, Ψ_Q	Φ_ℓ, Ψ_ℓ	Ψ, Φ
A	3	1	1
B	1	$\bar{3}$	3
C	3	8	8
D	8	$\bar{3}$	3

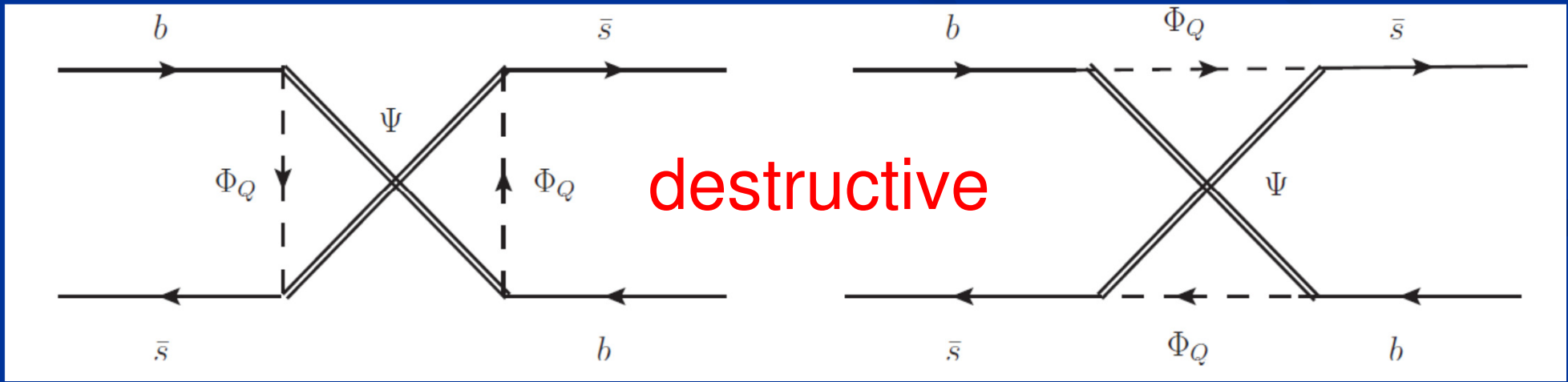
P. Arnan, L. Hofer, F.Mescia, AC, arXiv:1608.07832

Constraints from B_s mixing

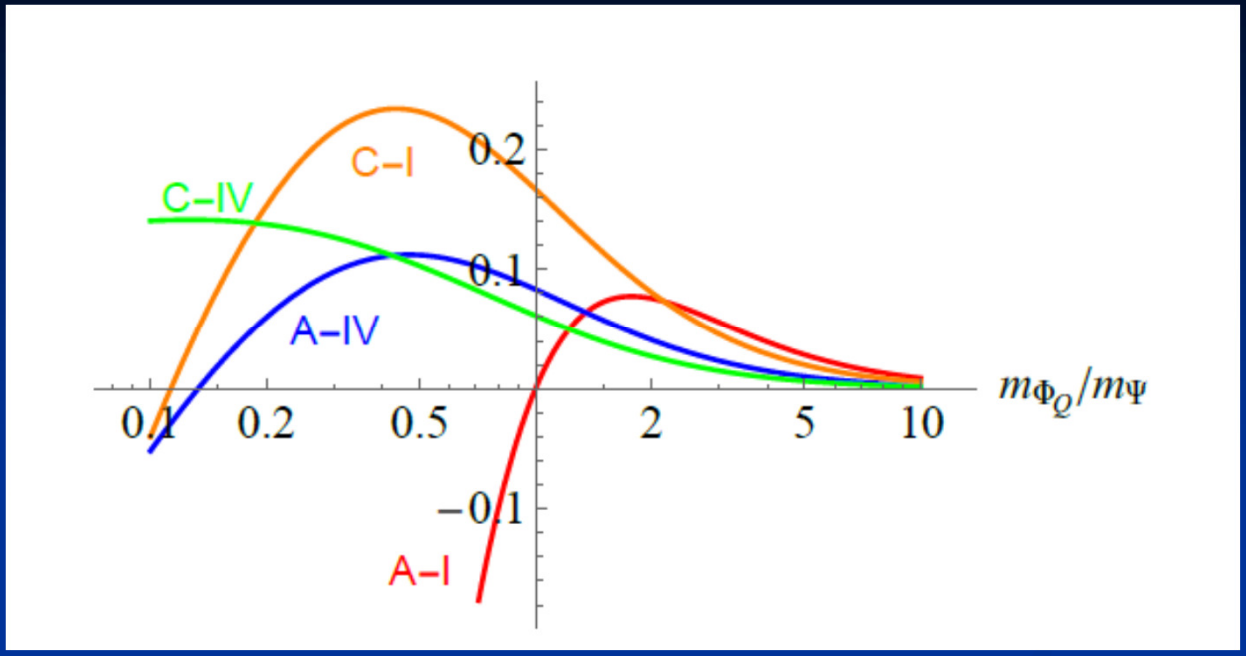


Constructive interference, but current data and lattice results prefers destructive interference MILC, 1602.03560

- Majorana representations: cancellations



Effect in B_s mixing

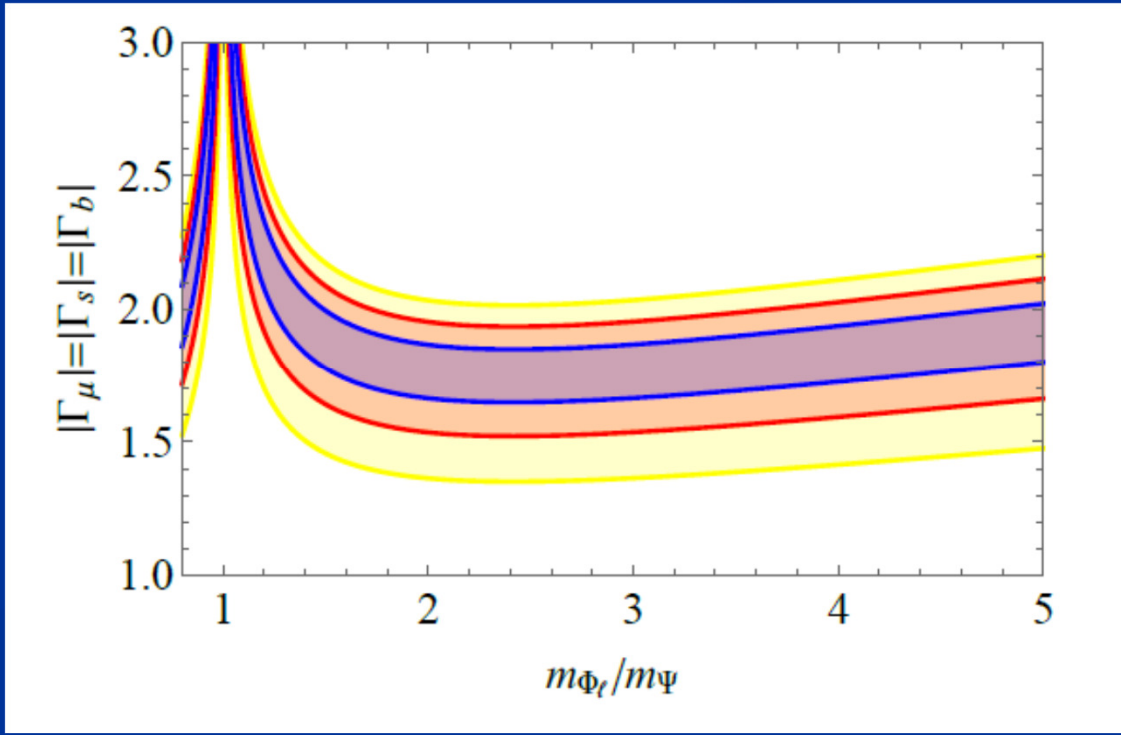


Representation I-A can explain $b\to s\mu\mu$ at

3σ

2σ

1σ



Models for Simultaneous Explanations of Anomalies

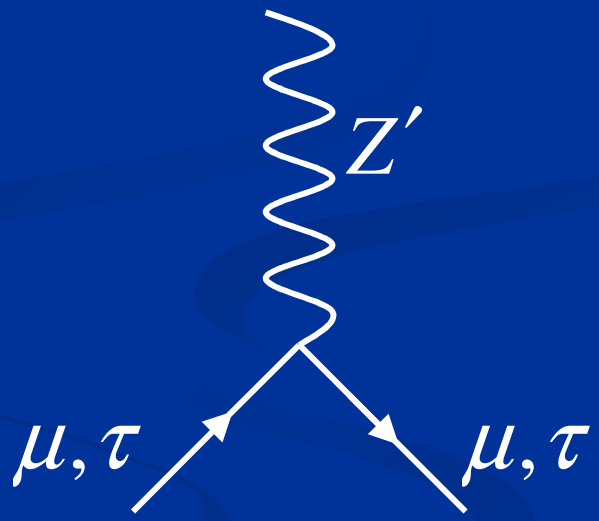
2HDM with gauged $L_\mu - L_\tau$

- Vectorial U(1) gauge group:
  Q(e) = 0, Q(μ) = 1, Q(τ) = -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

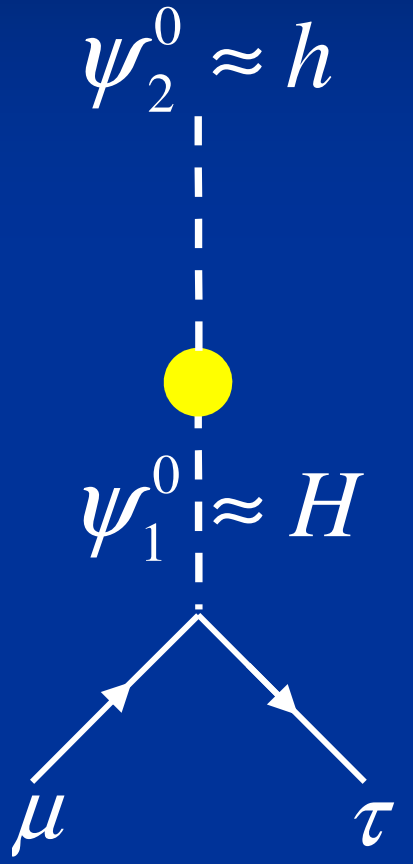
$$\mathcal{L}_Y \supset -\bar{\ell}_f Y_i^\ell \delta_{fi} \Psi_2 e_i - \xi_{\tau\mu} \bar{\ell}_3 \Psi_1 e_2$$
$$-\bar{Q}_f Y_{fi}^u \tilde{\Psi}_2 u_i - \bar{Q}_f Y_{fi}^d \Psi_2 d_i + \text{h.c.}.$$

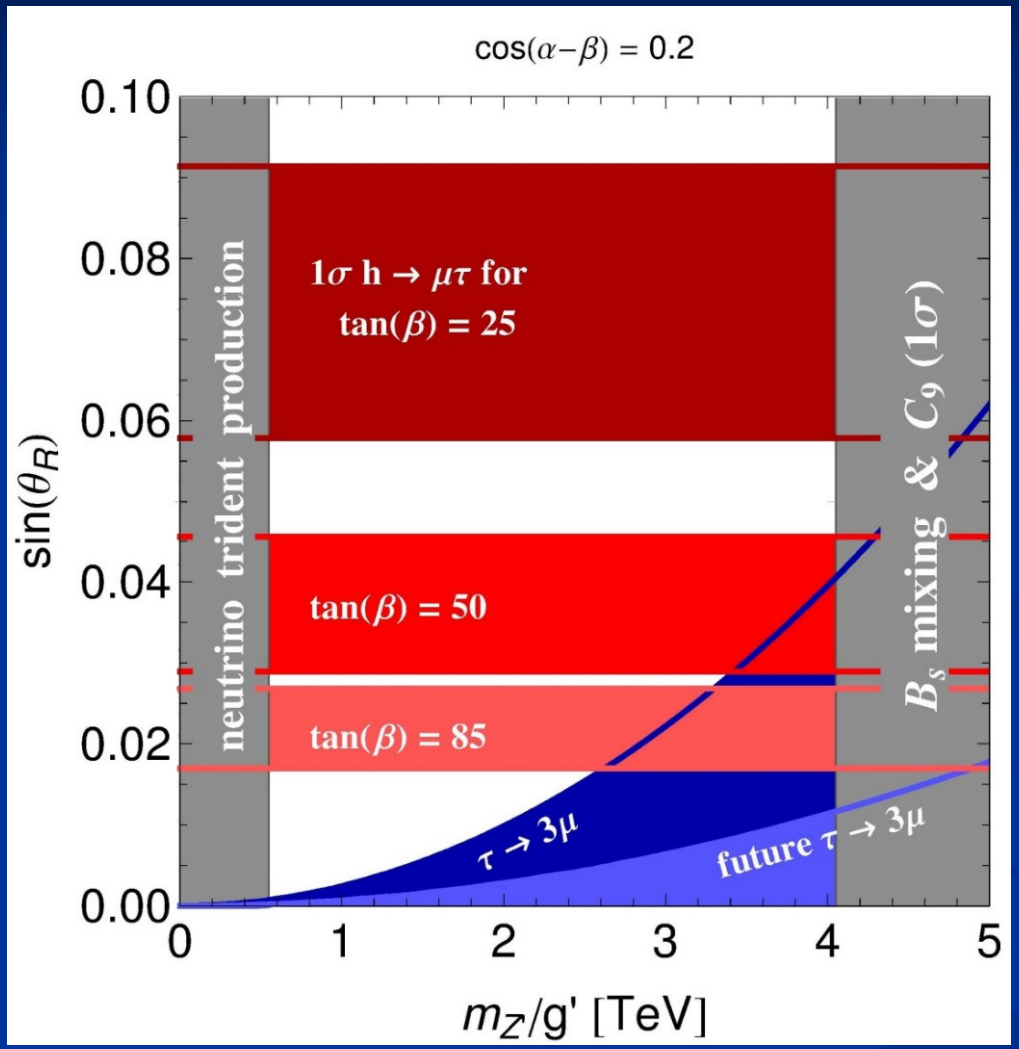


- θ_R diagonalizes the τ-μ block of the mass matrix

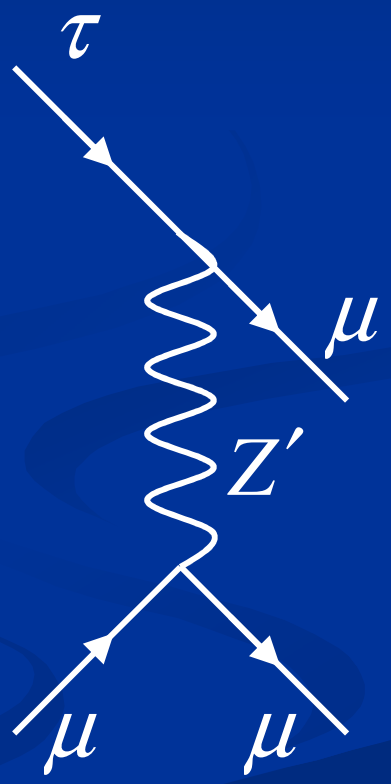
2HDM with gauged L_μ-L_τ

$h \to \mu\tau$





$\tau \to \mu\mu\mu$

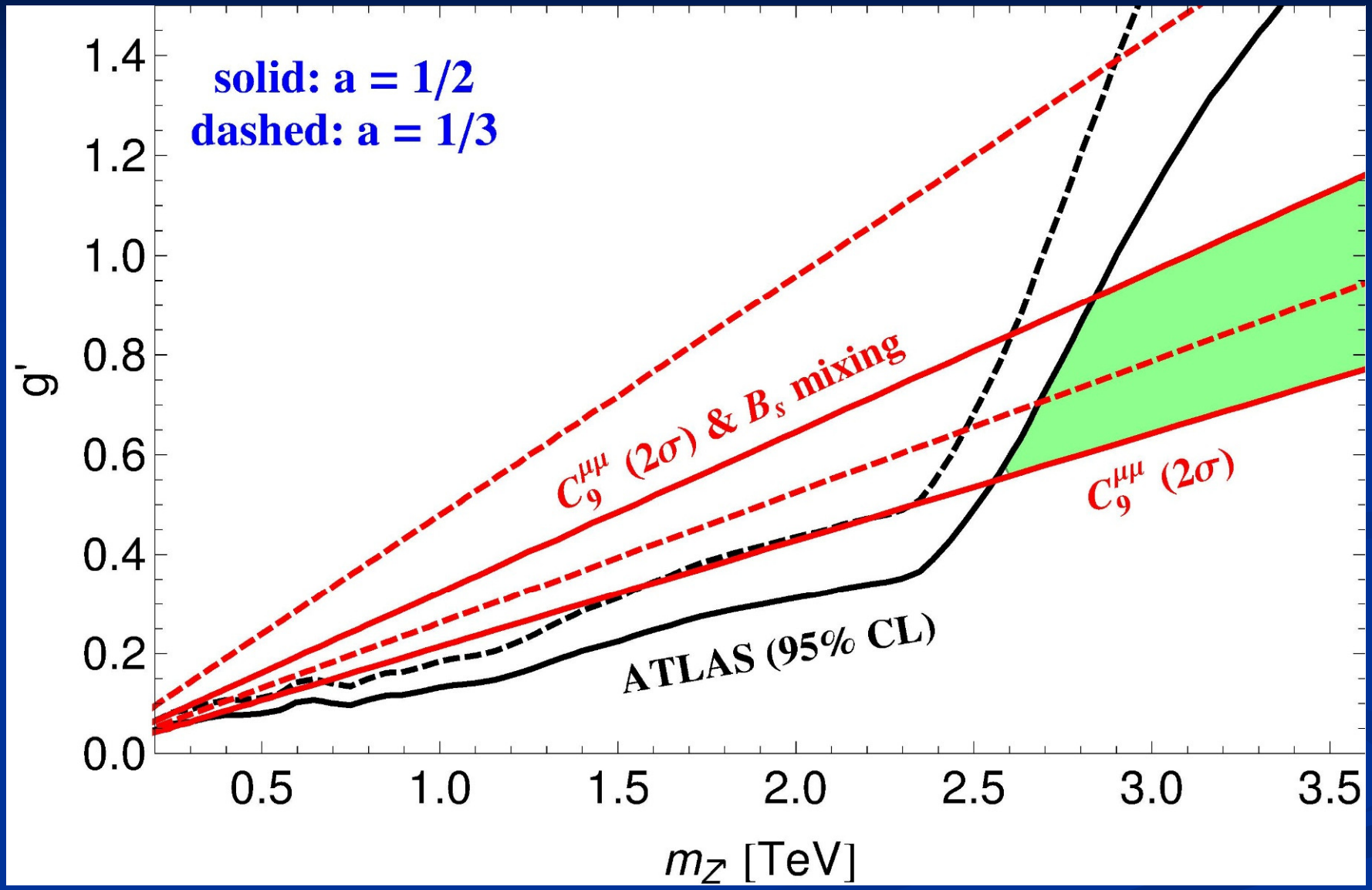


allowed by $h \to \tau\mu$

allowed by $\tau \to \mu\mu\mu$

excluded

Horizontal charges: LHC limits



ATLAS $C_9^{\mu\mu}$ & $B_s - \overline{B}_s$ a = 1/2 allowed

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

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

M. Bauer, M. Neubert arXiv:1511.01900

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

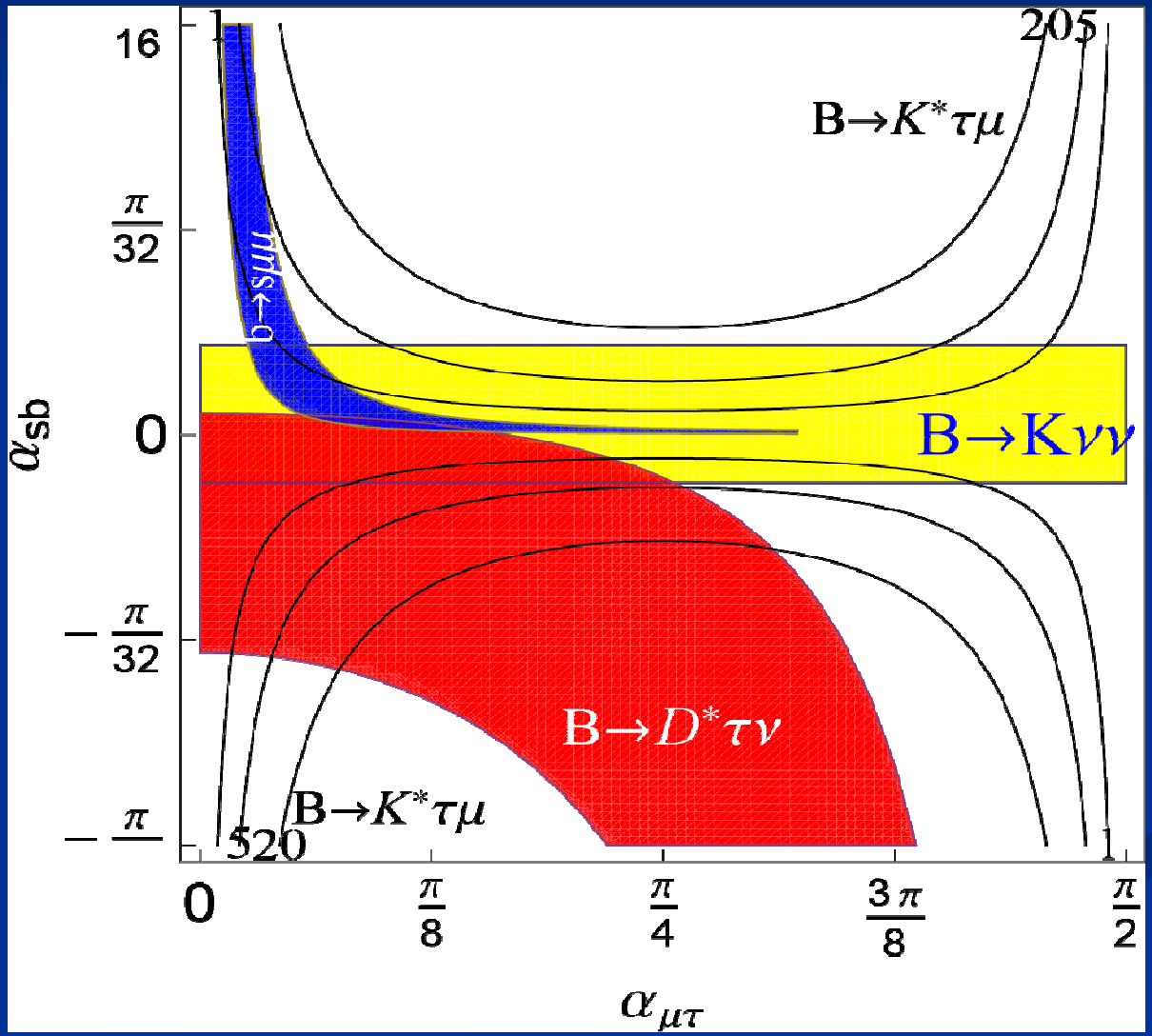
R. Alonso, B. Grinstein, J. Camalich, 1505.05164
R. Barbieri et al. 1512.01560

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



L. Calibbi, A.C. and T. Ota, PRL, arXiv:1506.02661

2HDM of type X

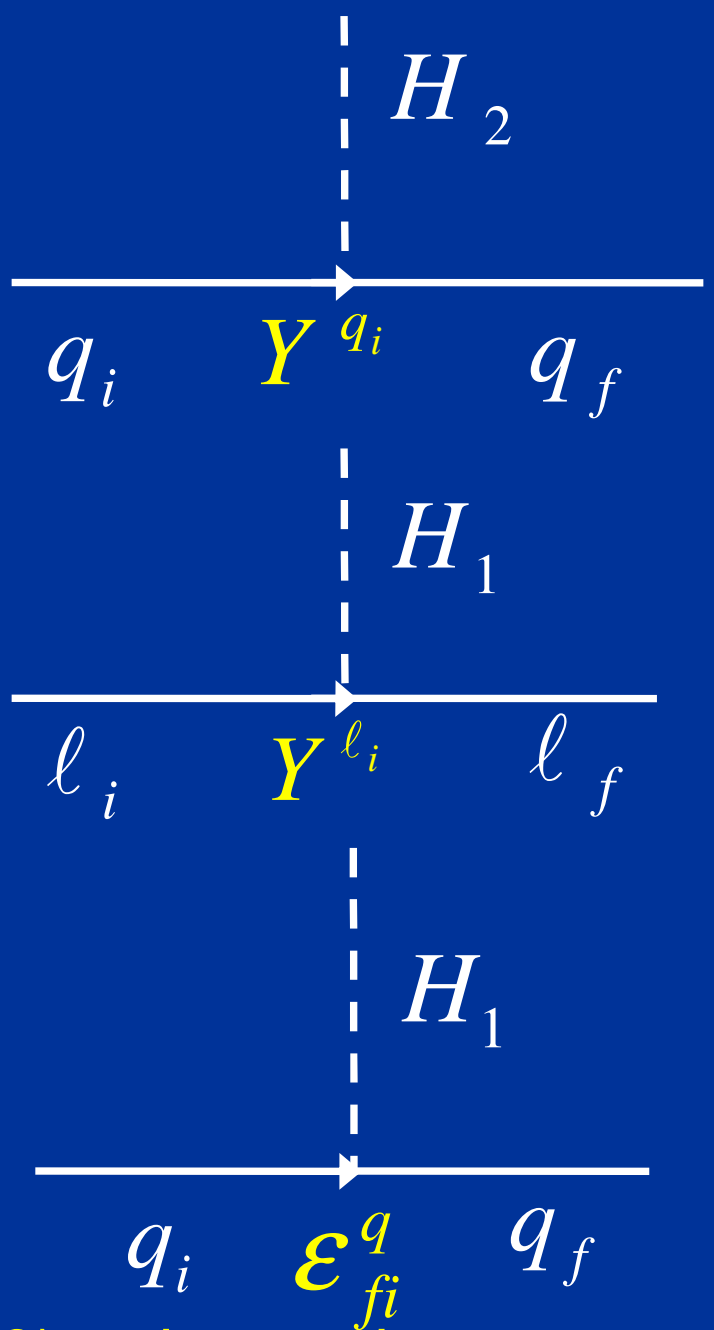
See Talk of Eung Jin Chun

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

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

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

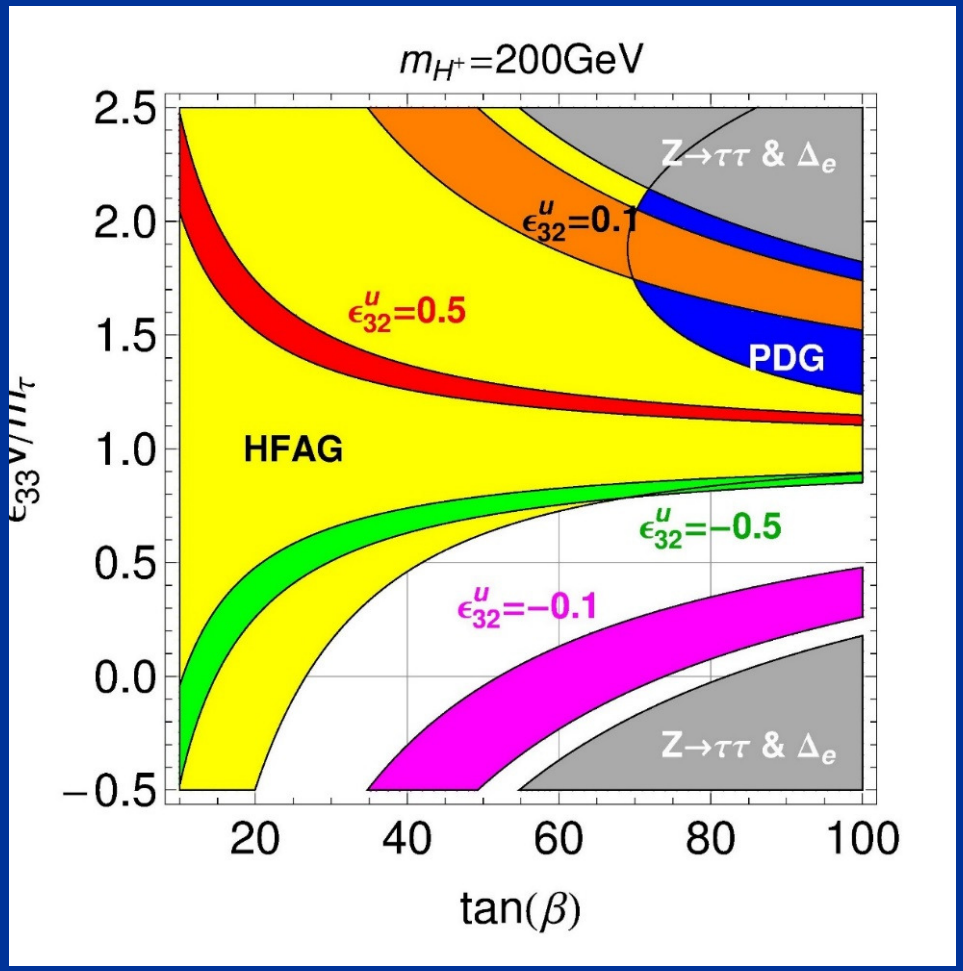
$$\varepsilon_{fi}^{u,\ell} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & \varepsilon_{32}^{u,\ell} & \varepsilon_{33}^{u,\ell} \end{pmatrix}$$

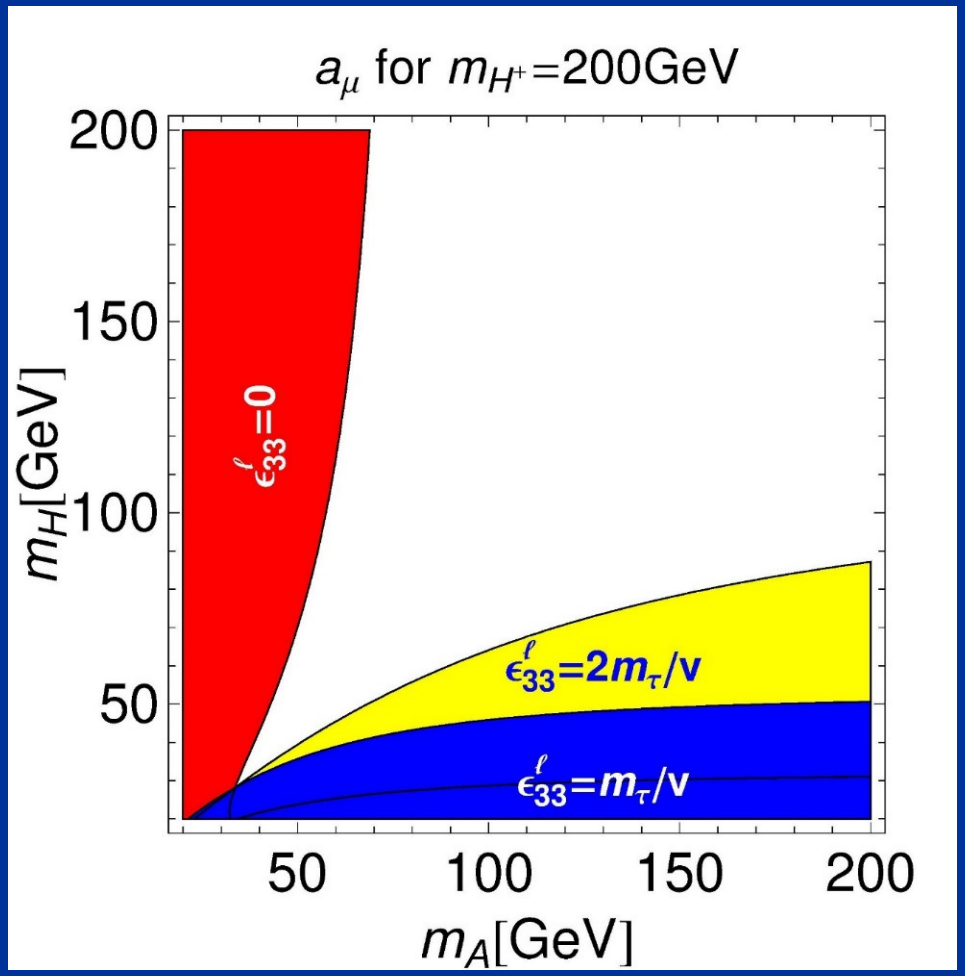


➡ Couplings to leptons are tan(β) enhanced

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

a_μ



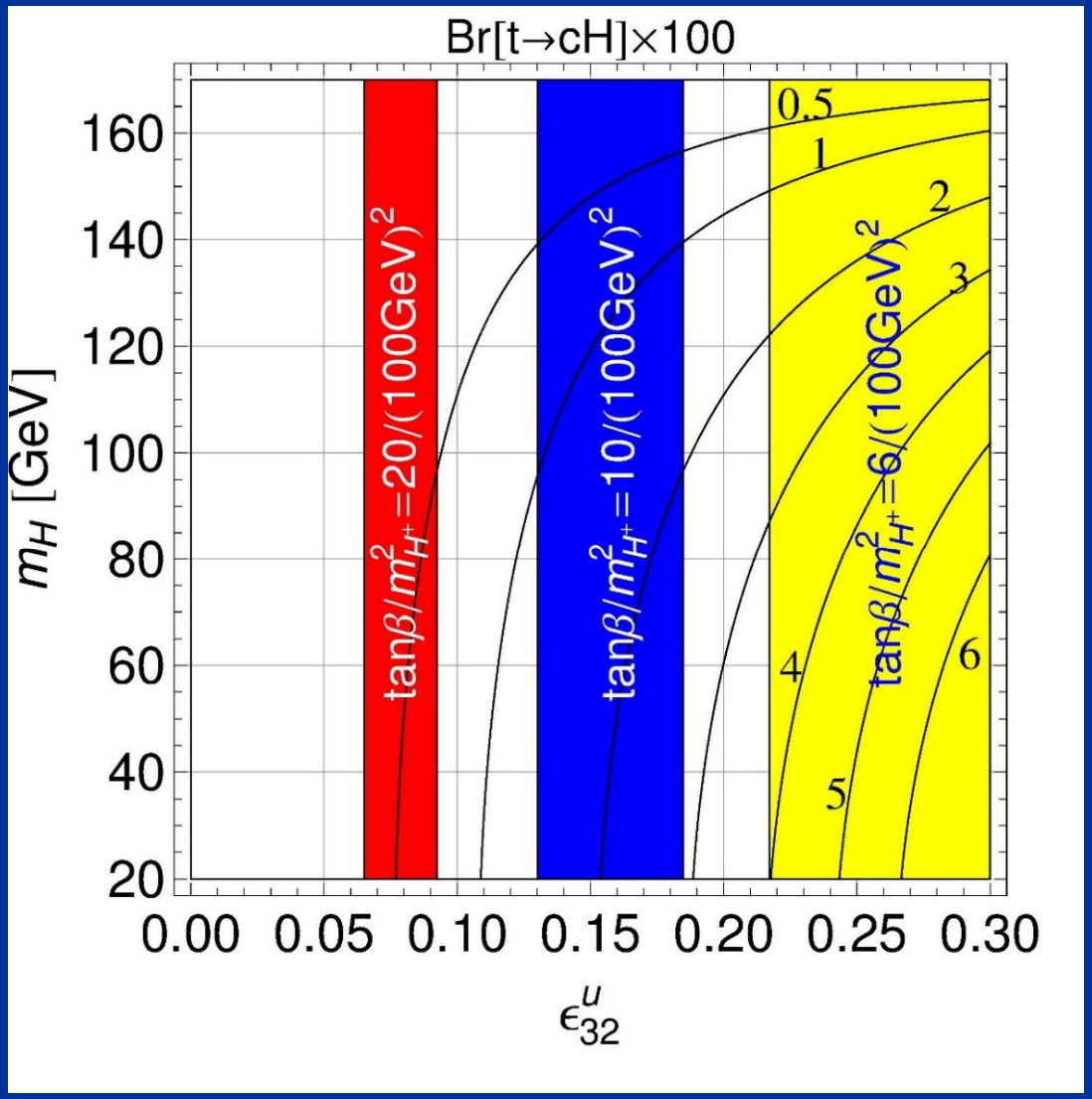


$\varepsilon_{33}^{\ell} > 0$

$m_H < m_A$

AC, Julian Heeck, Peter Stoffer. arXiv:1507.07567. PRL 2016

Prediction: $t \to Hc$



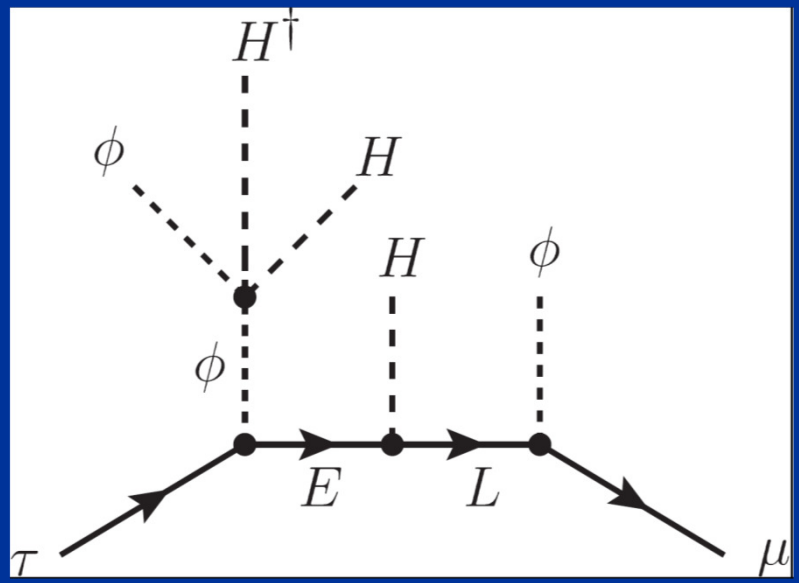
Branching ratio can even reach the percent level

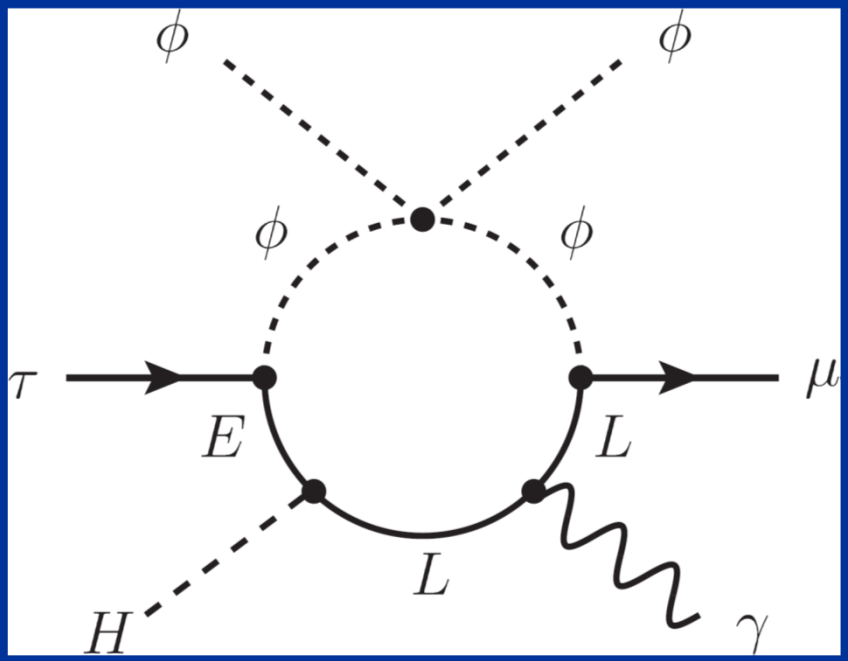
AC, Julian Heeck, Peter Stoffer. arXiv:1507.07567. PRL 2016

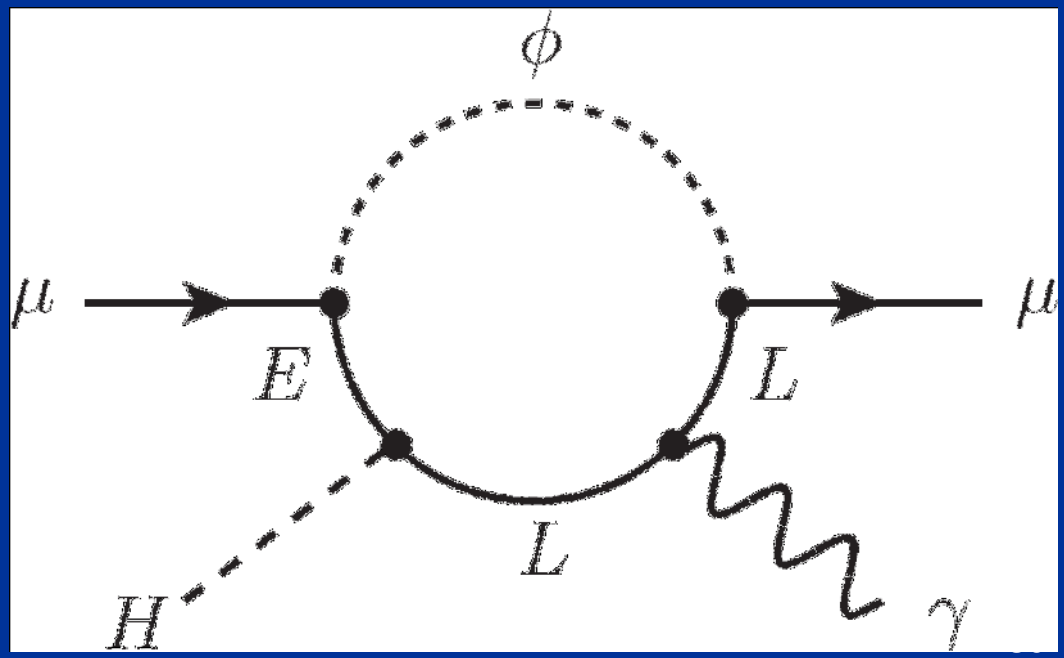
L_μ-L_τ model for a_μ and $h \to \tau\mu$

W. Altmannshofer, M. Carena, AC, 1604.08221

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



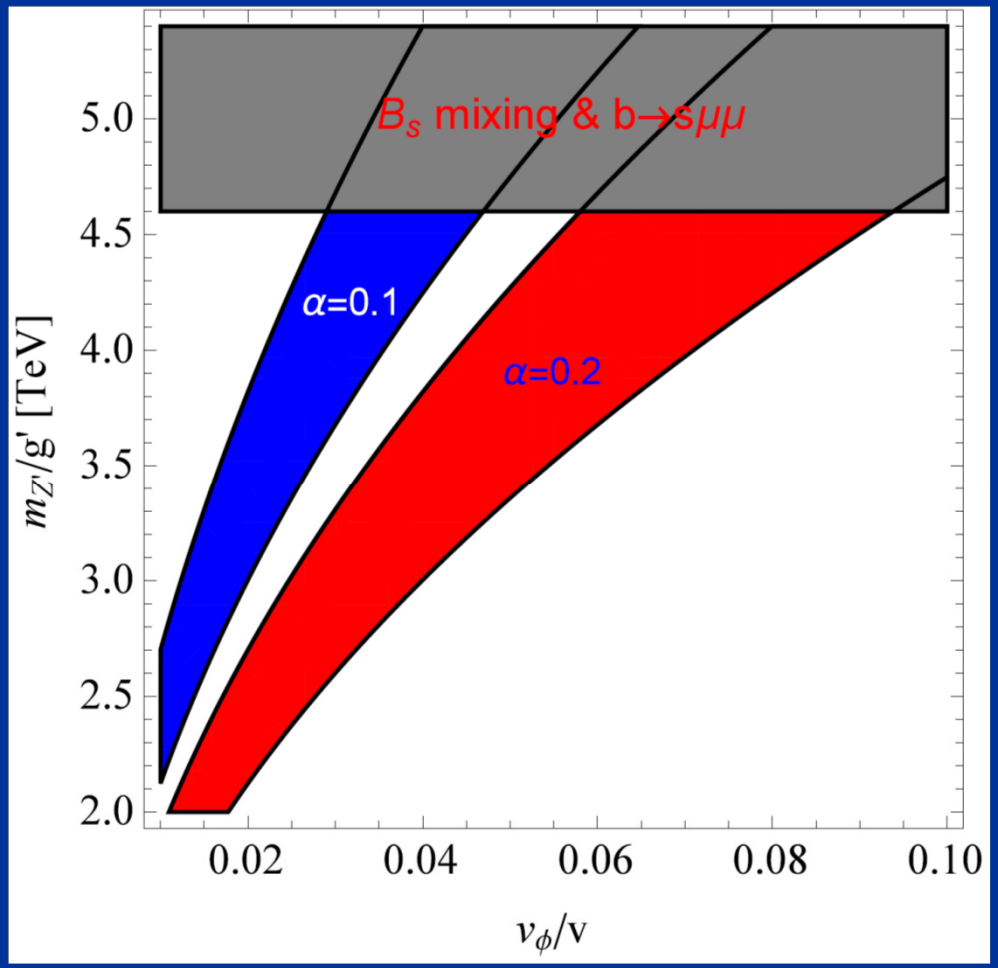




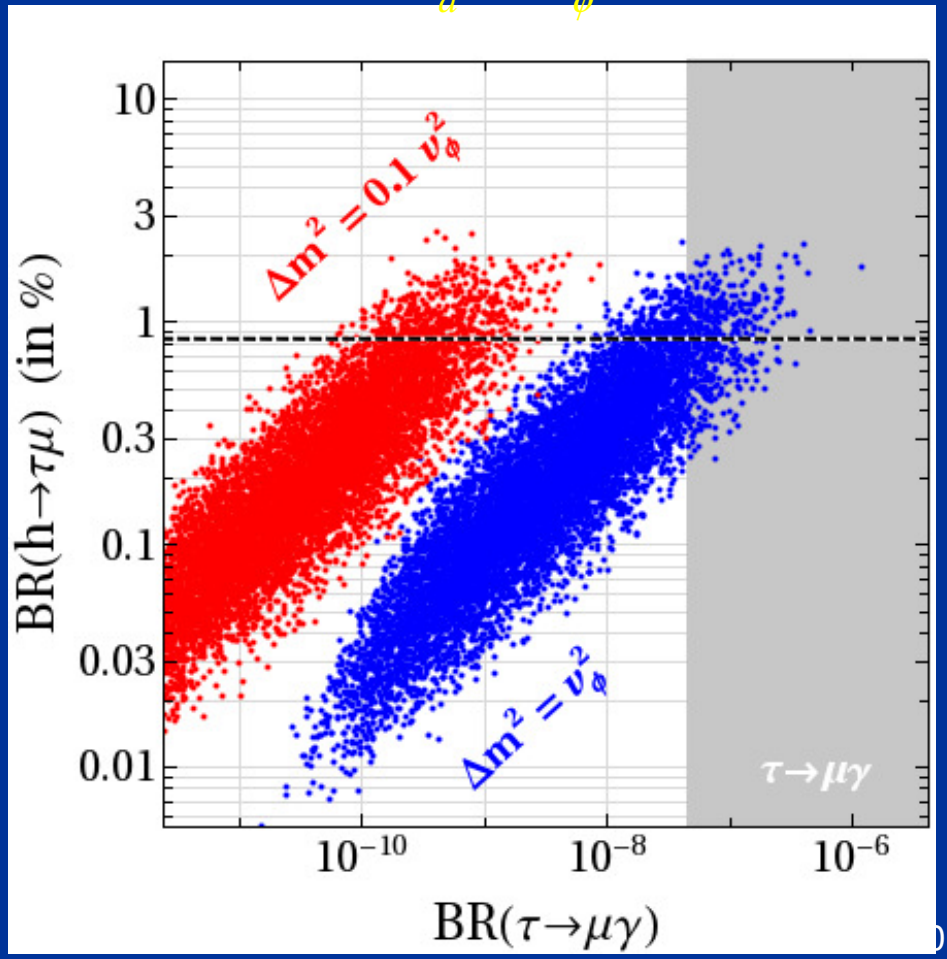
L_μ-L_τ model for a_μ and $h \to \tau\mu$

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

α : mixing among CP even Higgses



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



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

$b \to c\tau\nu$

Conclusions

Z' gauge boson

Leptoquarks

Extended Higgs sector

Conclusions

a_μ

$h \to \tau\mu$