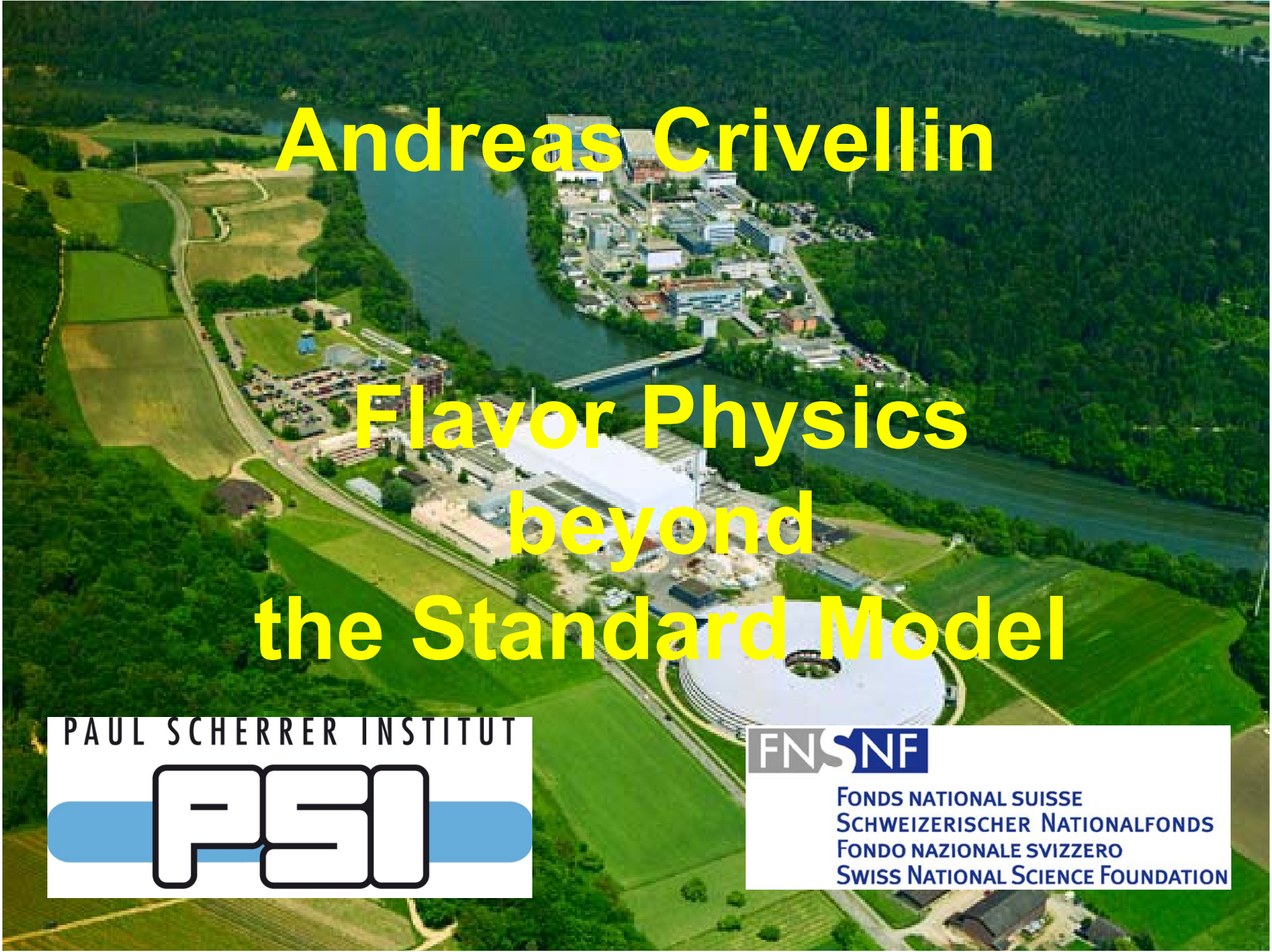

Andreas Crivellin

Flavor Physics beyond the Standard Model

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SWISS NATIONAL SCIENCE FOUNDATION

Outline:

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

New Physics Models

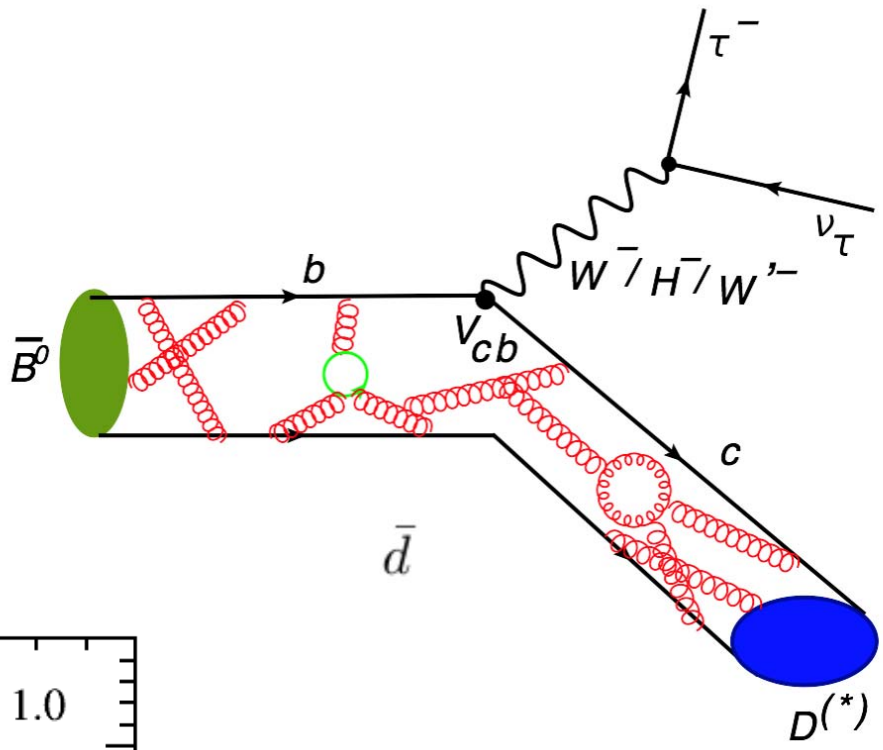
- MSSM?
  - No SUSY Particles
  - No Direct Detection Signals
- Extra Dimension?
  - No Kaluza Klein Excitations
  - No 750 GeV excess
- What do we do now?
- Look at the experimental data and see what it suggests!

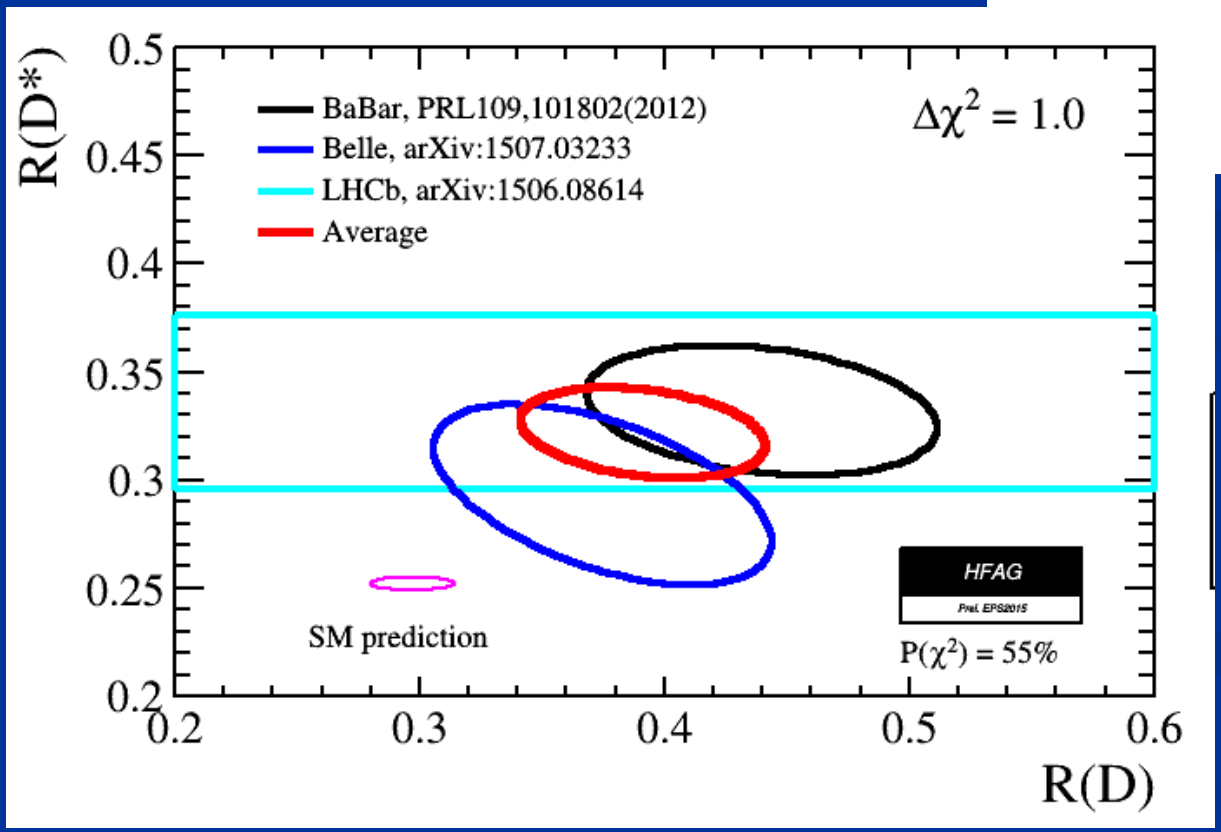
Flavour Anomalies

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

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

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

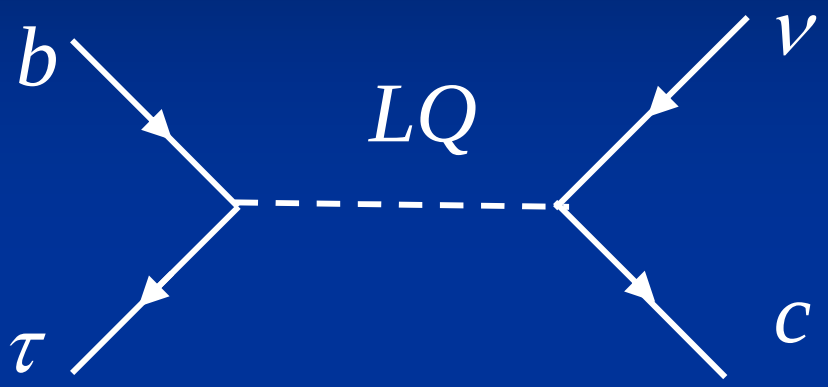




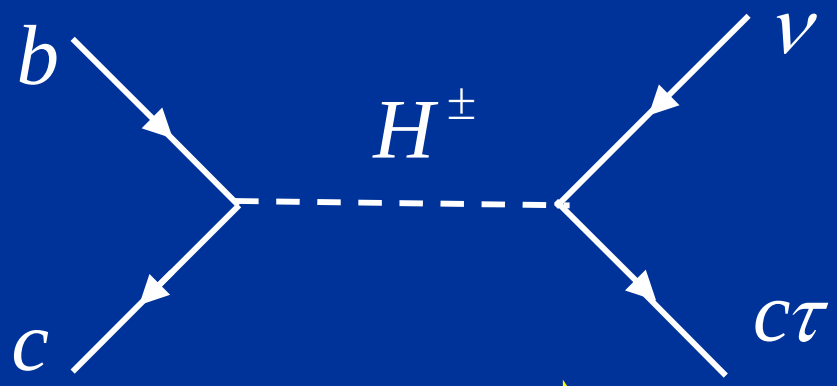
➡ Combined 4σ deviation

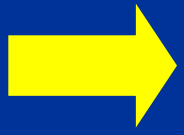
R(D) Explanations

- Leptoquark (scalar or vector)



- Charged Higgs





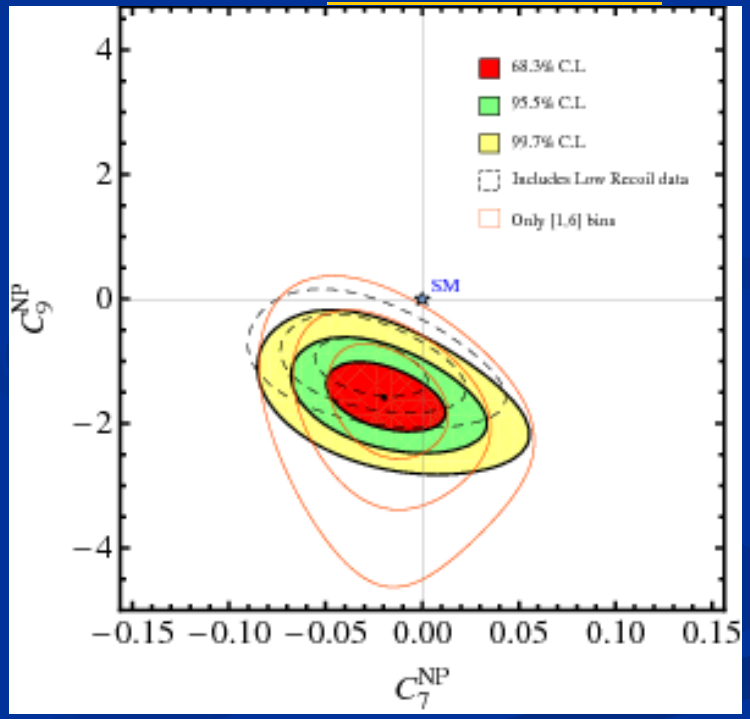
different differential distribution

- W' ???

$B \to K^* \mu\mu$

- 2-3 σ deviation from the SM mostly in P5'
- Can be explained by $O_9 = \bar{s}\gamma^\mu P_L b \bar{\ell}\gamma_\mu \ell$
  Descotes-Genon et al. 1307.5683, Altmannshofer and DS 1308.1501, Beaujean et al. 1310.2478
- New physics explanation is not easy (MSSM, 2HDM).
- Most natural explanation: Z'
  Gauld et al. 1310.1082,
  Buras et al. 1311.6729, …
- Subleading hadronic effects might be larger than expected…

arXiv:1307.5683



- Further supported by $B_s \to \phi\mu\mu$
  R. Horgan, Z. Liu, S. Meinel, and M. Wingate (2015), 1501.00367.

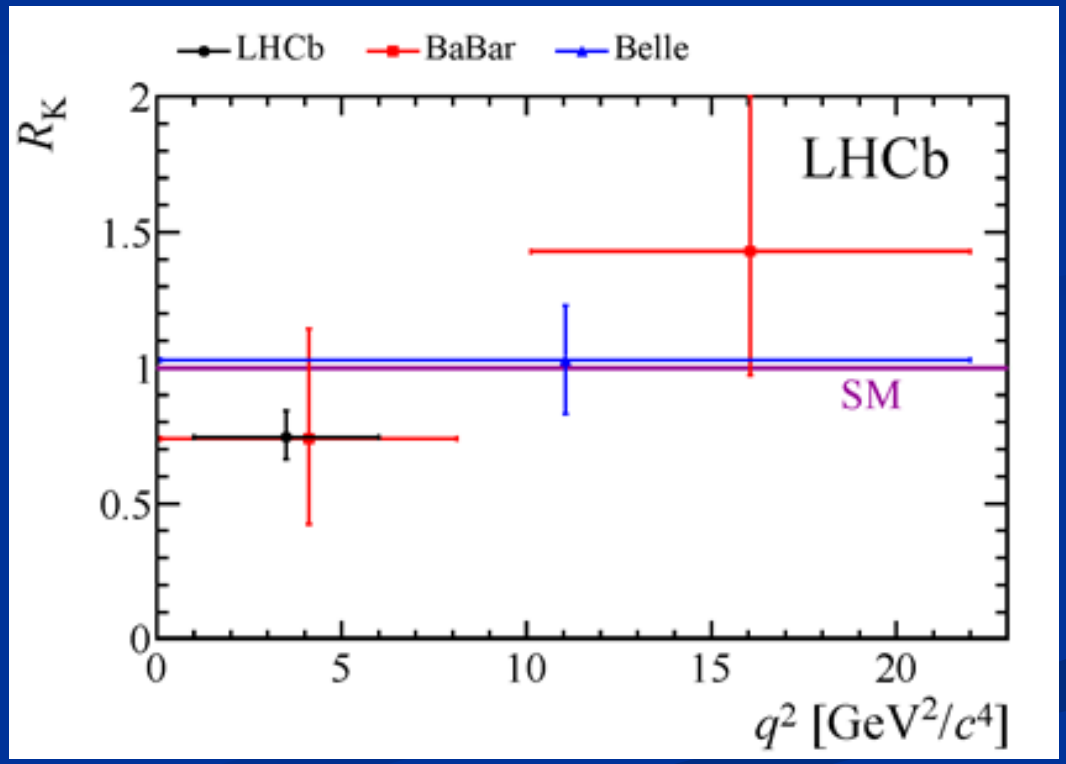
R(K) = B→Kμμ/B→Kee

- Lepton flavour universality violation
- 2.6 σ deviation from the theoretically rather clean SM expectation

$$R_K^{\mathrm{SM}} = 1.0003 \pm 0.0001$$

$$R_K^{\mathrm{exp}} = 0.745^{+0.090}_{-0.074} \pm 0.036$$

- Explanation:
  - Leptoquarks
  - Extra dimensions
  - flavour non-universal Z'



LHCb 1406.6482

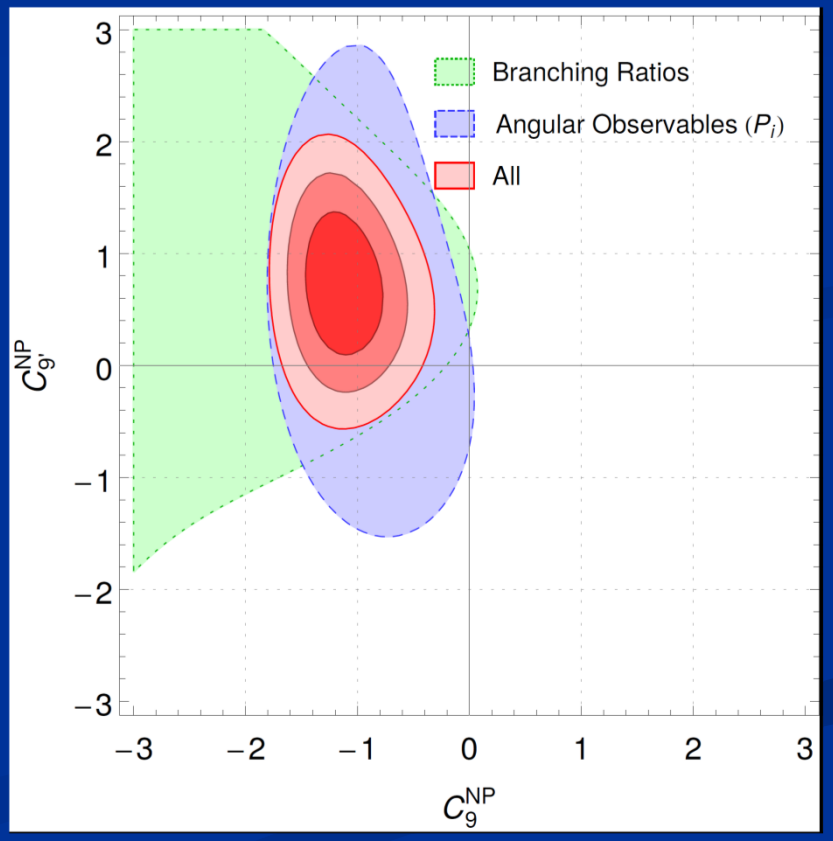
➡ Also LFV in B decays?

b→sμμ

- 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

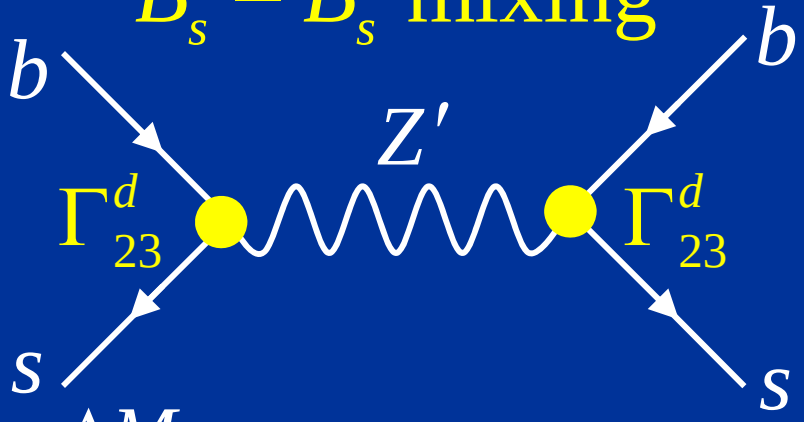
Z' explanations

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

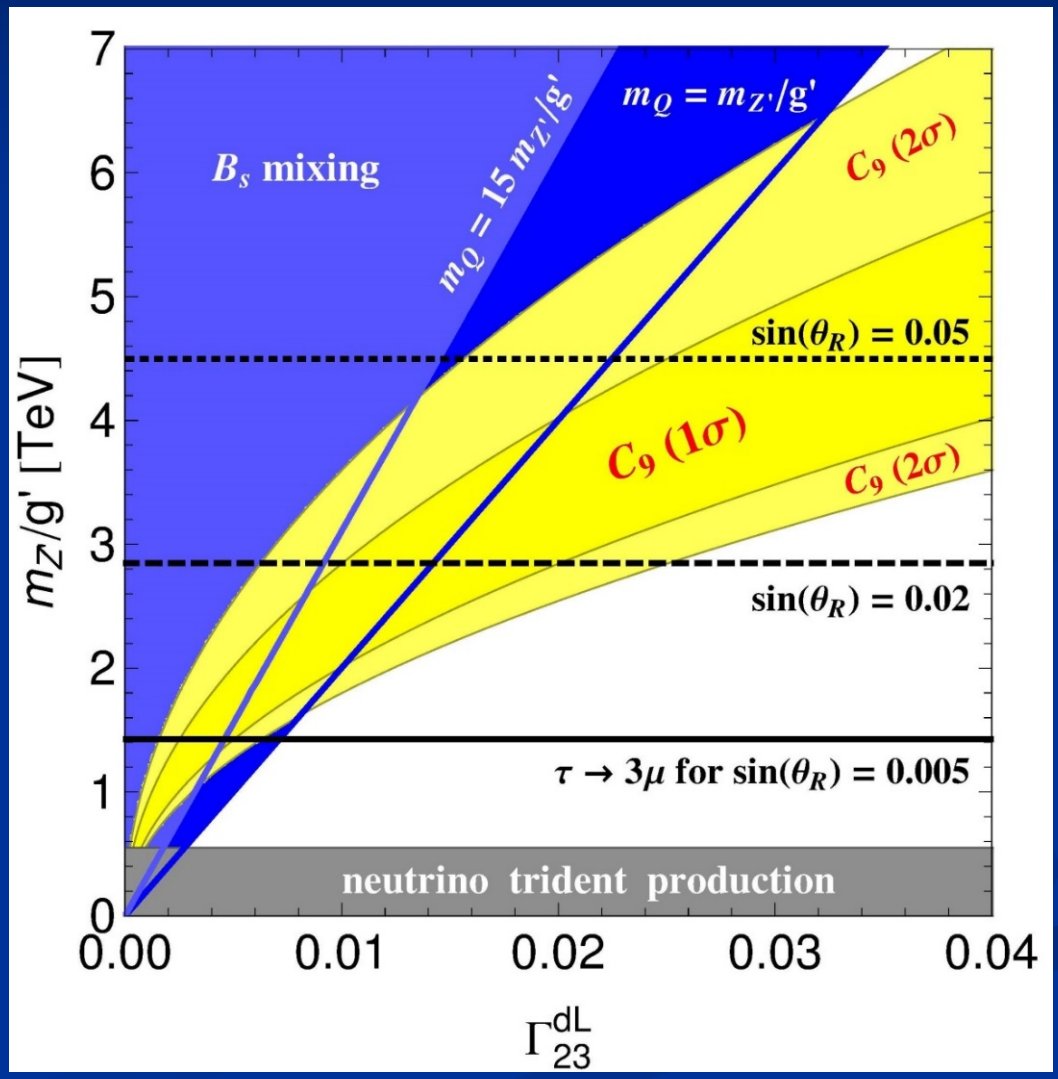
$b \to s\mu^+\mu^-$

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

$B_s - \bar{B}_s$ mixing



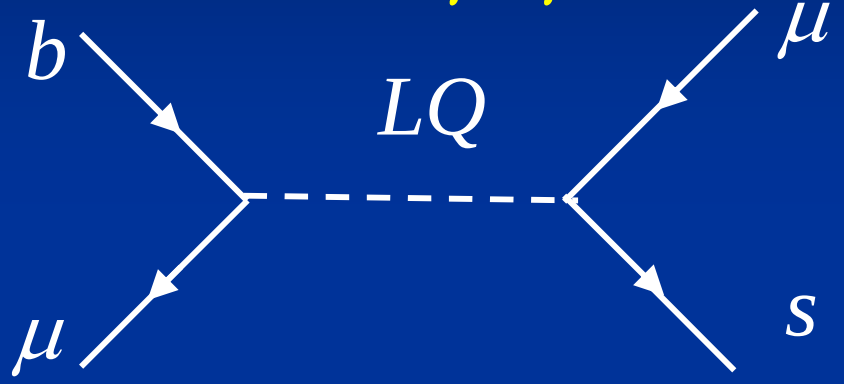
$$\frac{\Delta M_{12}}{M_{12}^{\rm SM}} \propto \left(\Gamma_{23}^{dL}\right)^2 g'^2 / m_{Z'}^2$$



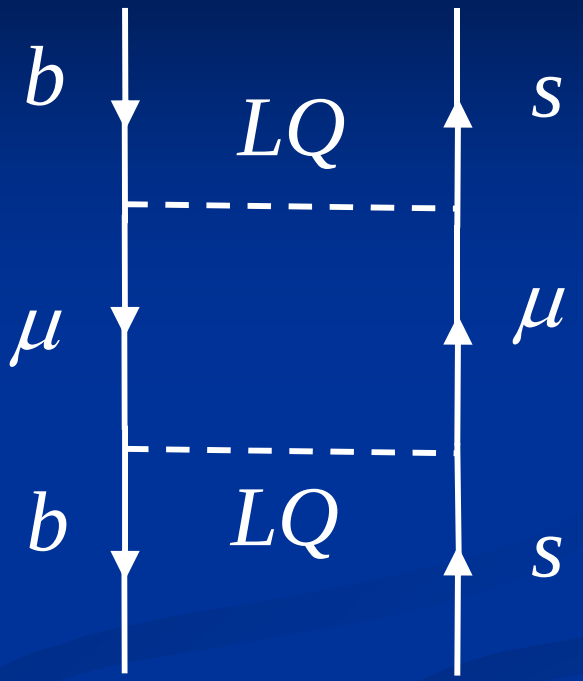
allowed regions

Leptoquarks

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

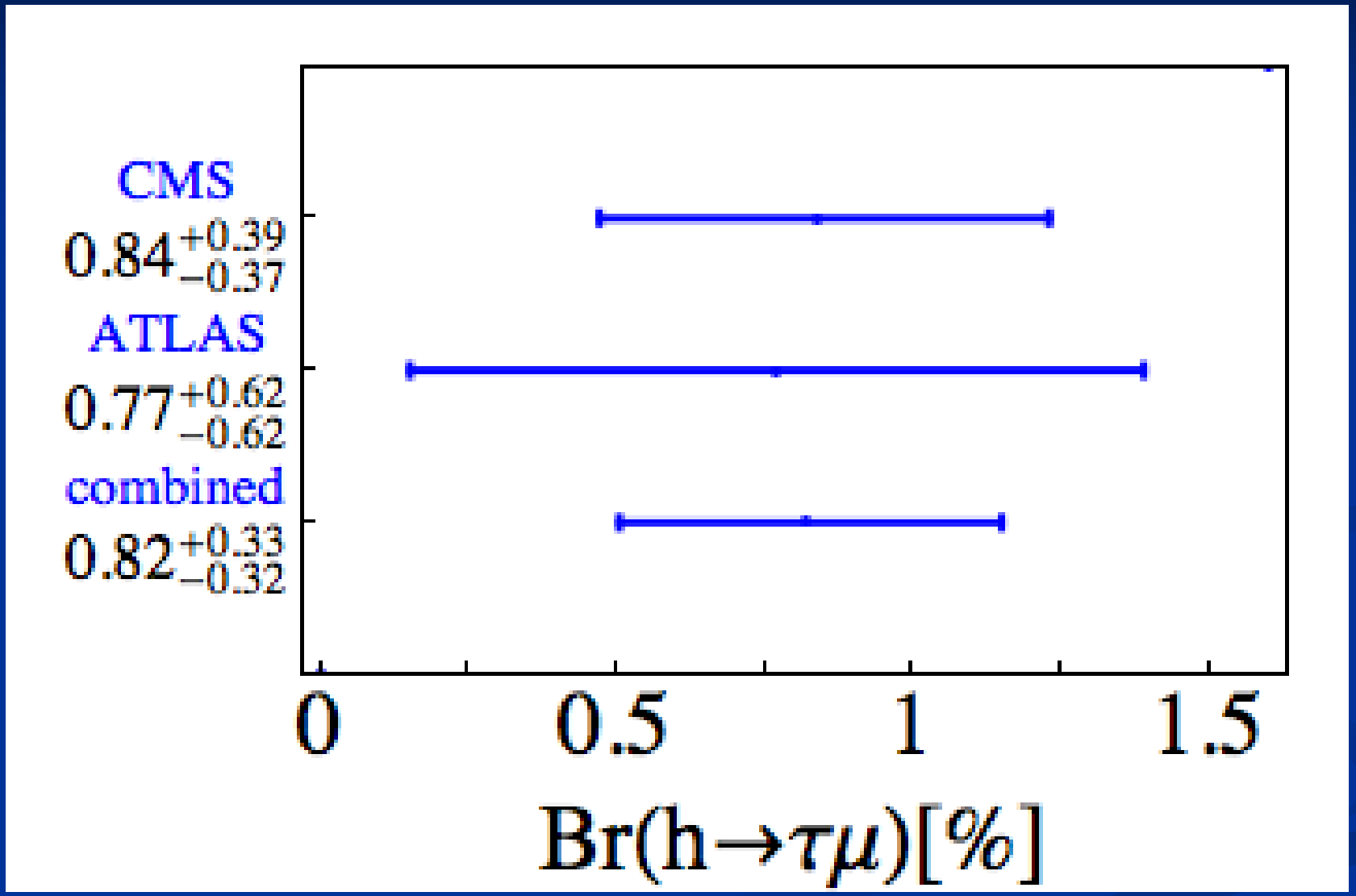


$B_s - \bar{B}_s$ mixing



- 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

$h \to \tau\mu$



- 2.6 σ difference from zero

$h \to \tau\mu$

- 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
.....
.....

Models for Simultaneous Explanations of Anomalies

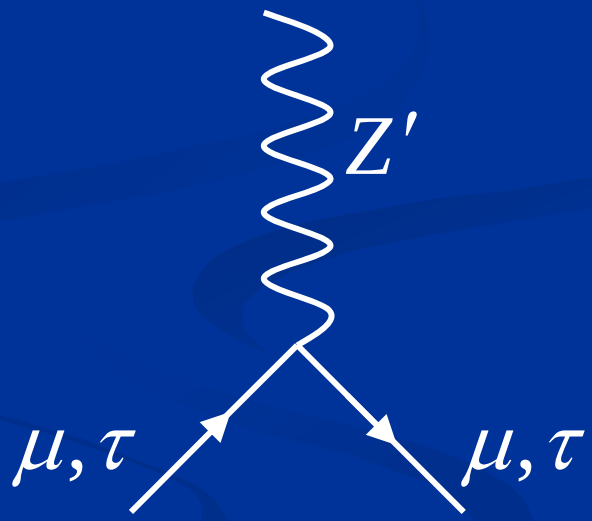
2HDM with gauged $L_\mu - L_\tau$

- 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

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

- Yukawa couplings

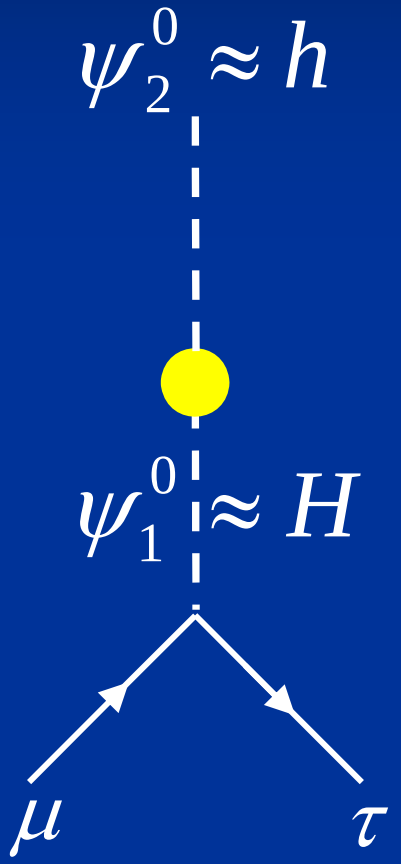
$$\mathcal{L}_Y \supset -\bar{\ell}_f Y_i^{\ell} \delta_{fi} \Psi_2 e_i - \xi_{\tau\mu} \bar{\ell}_3 \Psi_1 e_2$$
$$-\bar{Q}_f Y_{fi}^{u} \tilde{\Psi}_2 u_i - \bar{Q}_f Y_{fi}^{d} \Psi_2 d_i + \text{h.c.}.$$

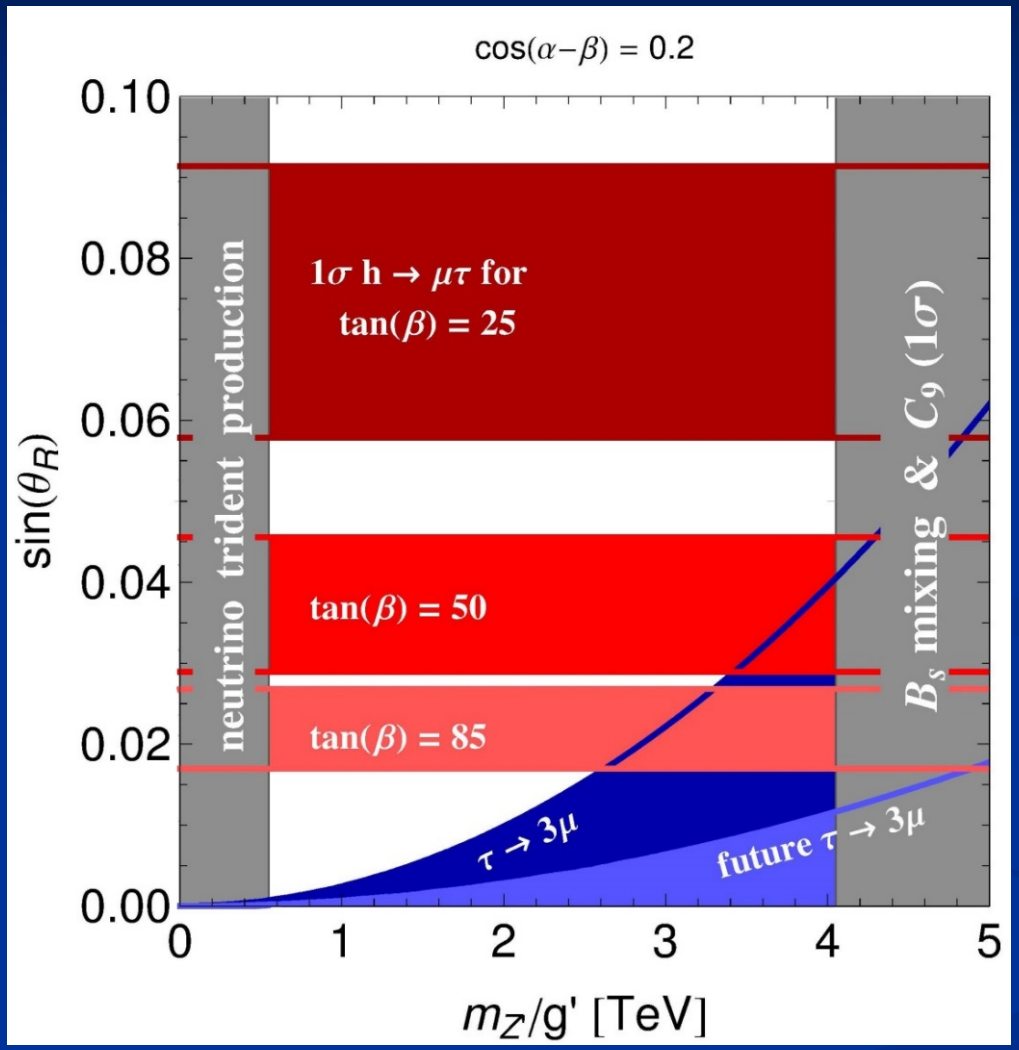


- θ_R diagonalizes the τ-μ block of the mass matrix

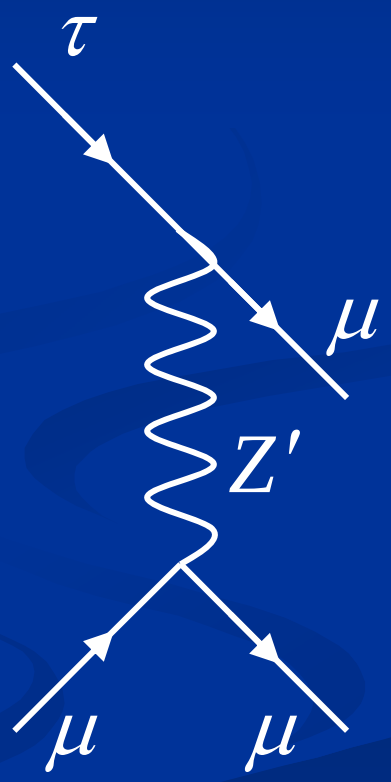
2HDM with gauged L_μ-L_τ

$h \to \mu\tau$





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



allowed by $h \to \tau\mu$

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

excluded

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

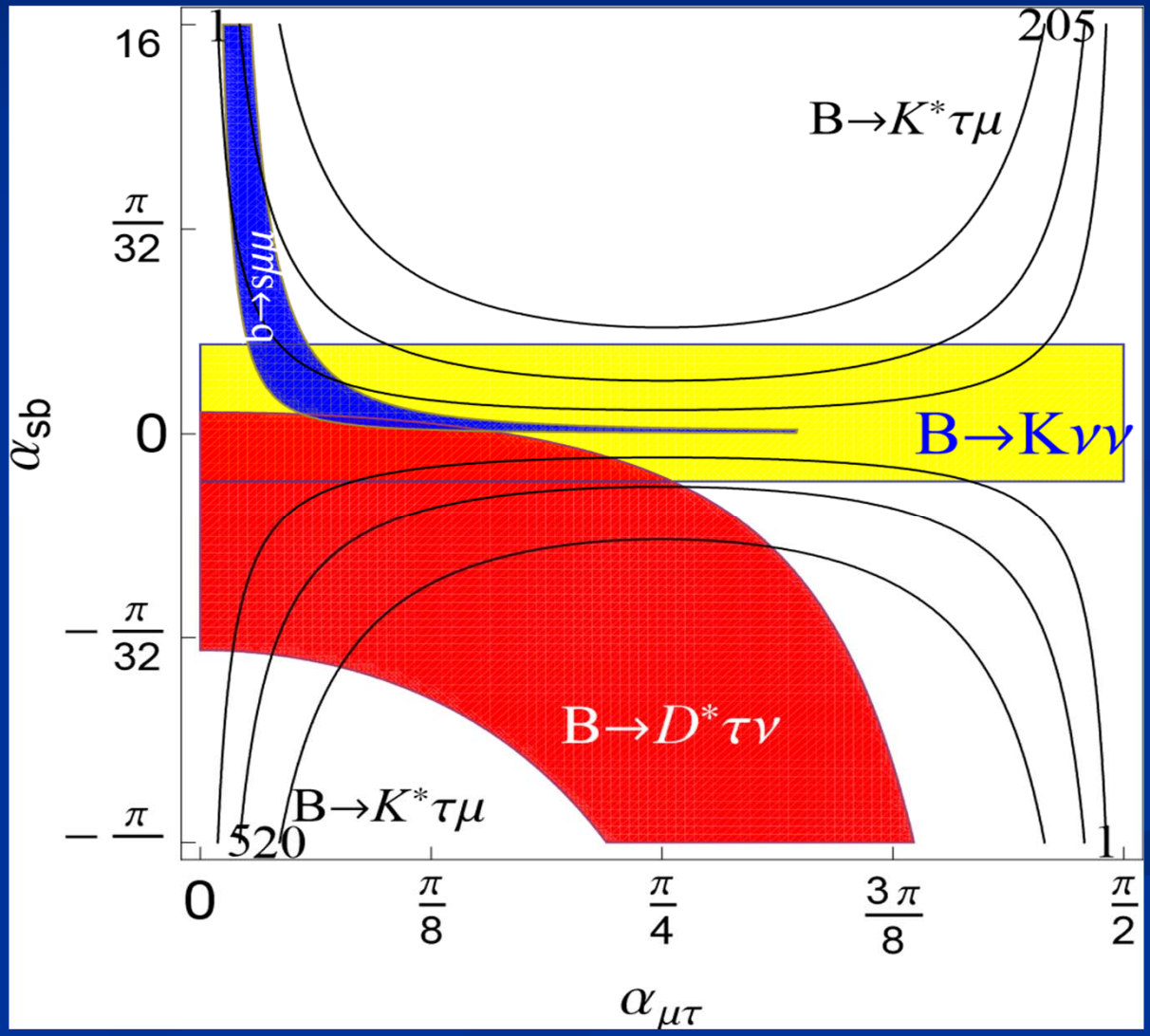
- Tree-level contribution to $b \to s\mu^+\mu^-$ and $b \to c\tau\nu$
  - Hierarchical flavor structure, large third generations couplings, small first and second ones.

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

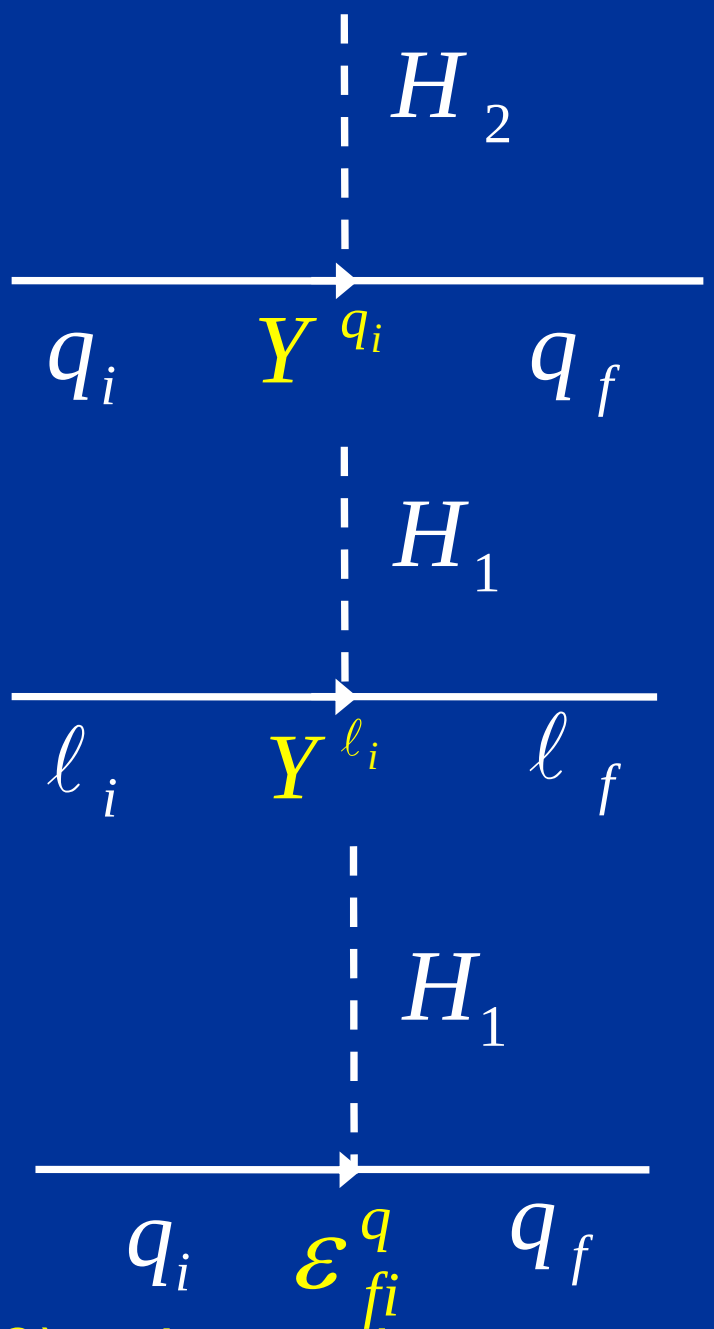
2HDM of type X

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

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

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

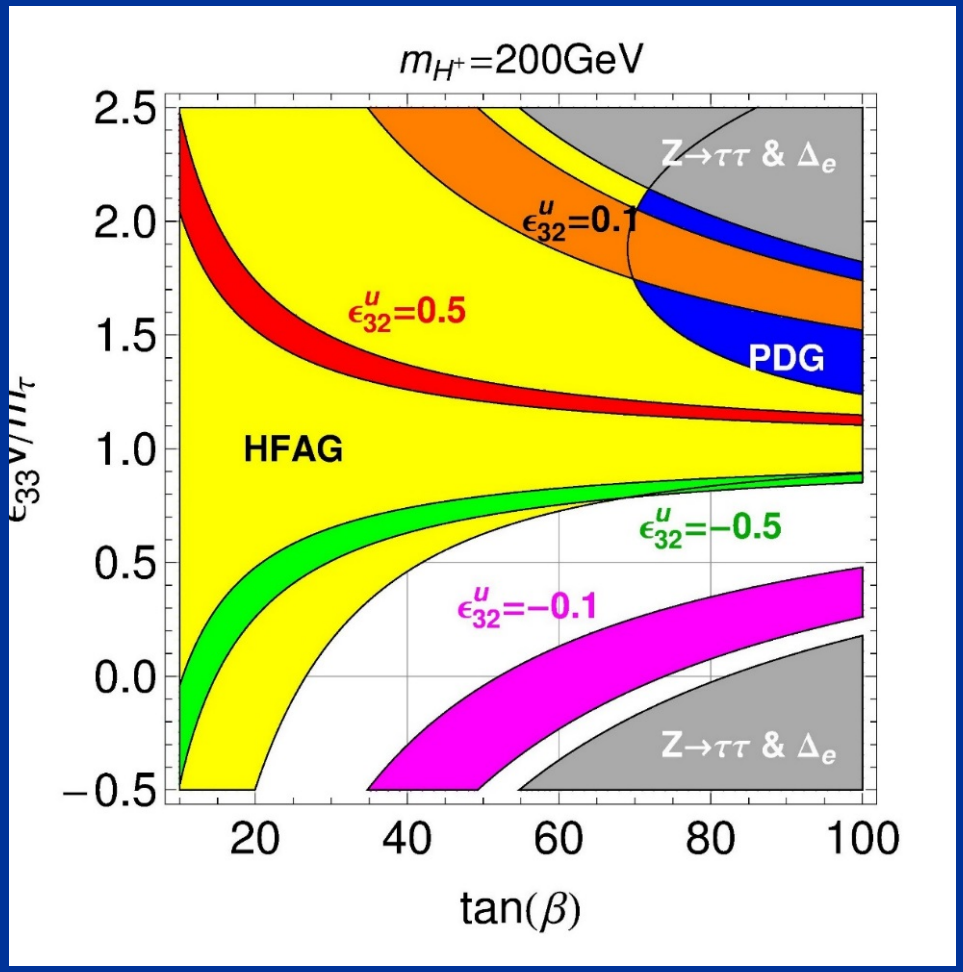
$$\varepsilon_{fi}^{u,\ell} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & \varepsilon_{32}^{u,\ell} & \varepsilon_{33}^{u,\ell} \end{pmatrix}$$

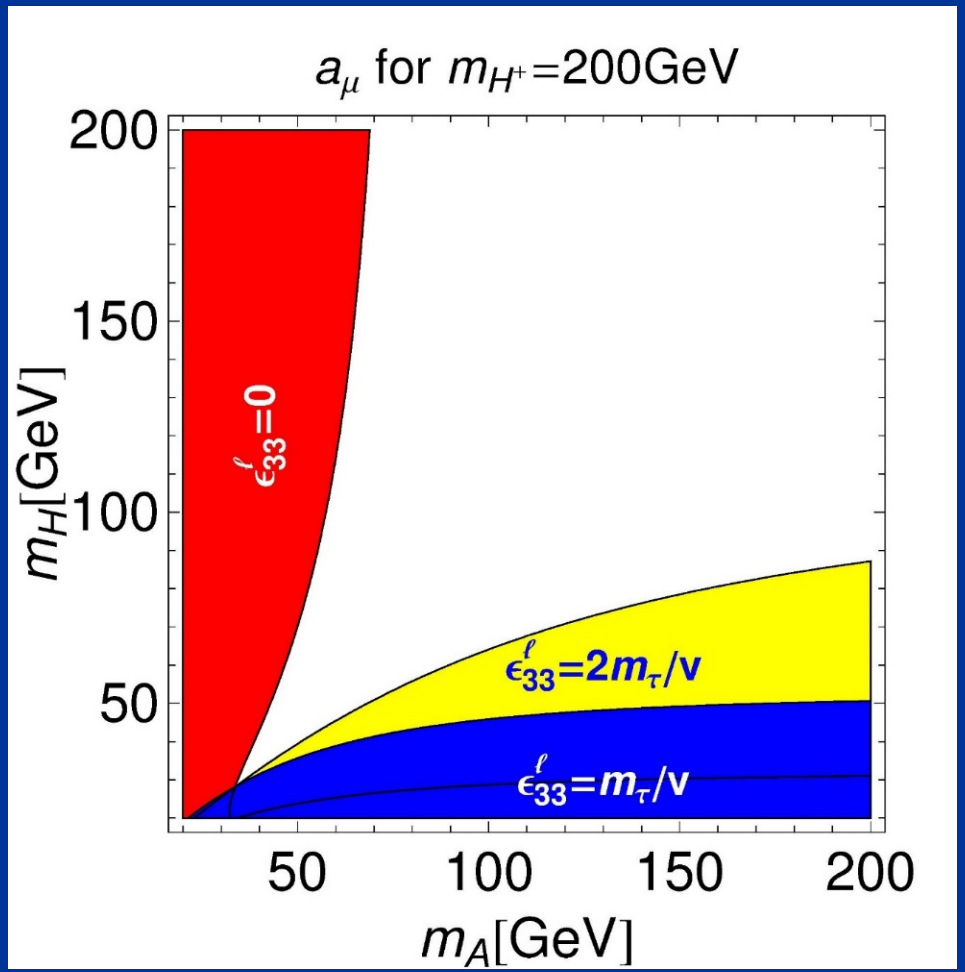


➡ Couplings to leptons are tan(β) enhanced

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

a_μ



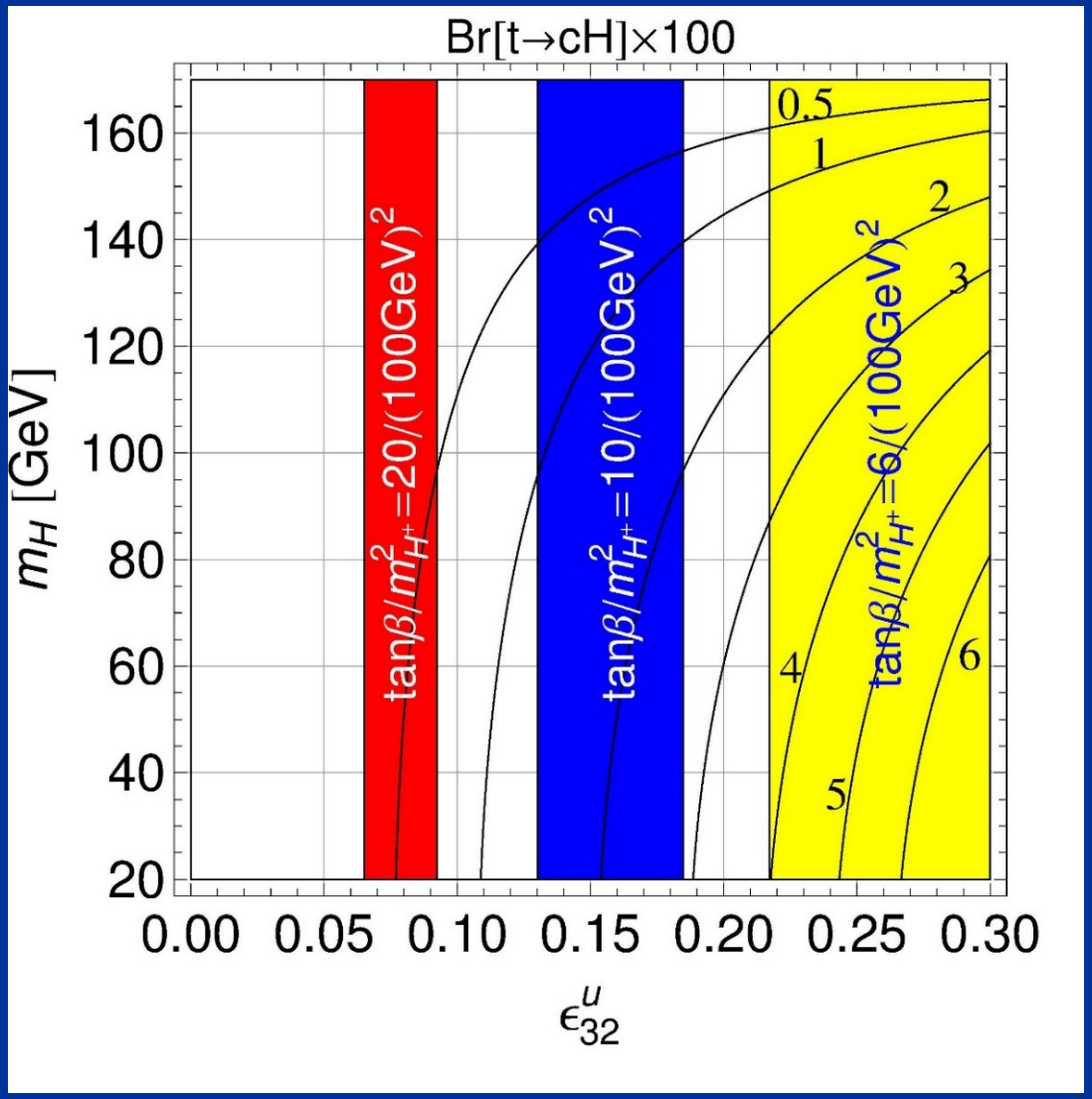


$\varepsilon_{33}^{\ell} > 0$

$m_H < m_A$

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

Prediction: $t \to Hc$

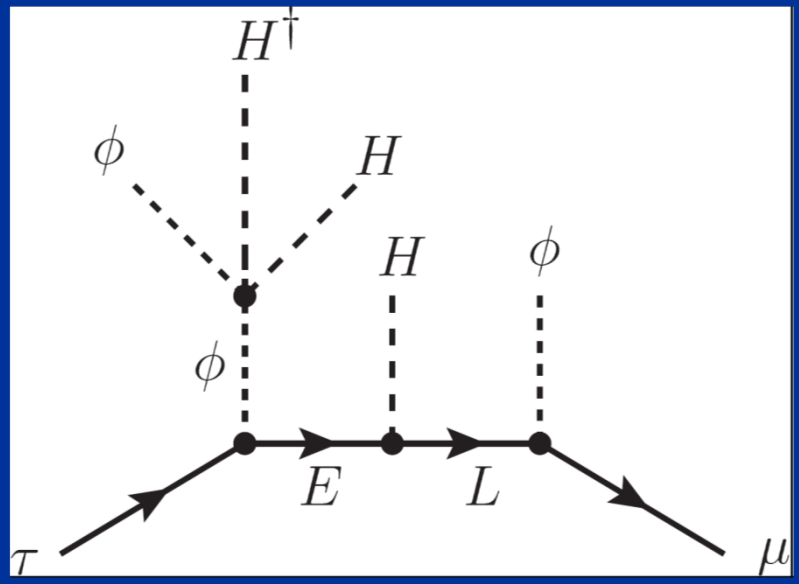


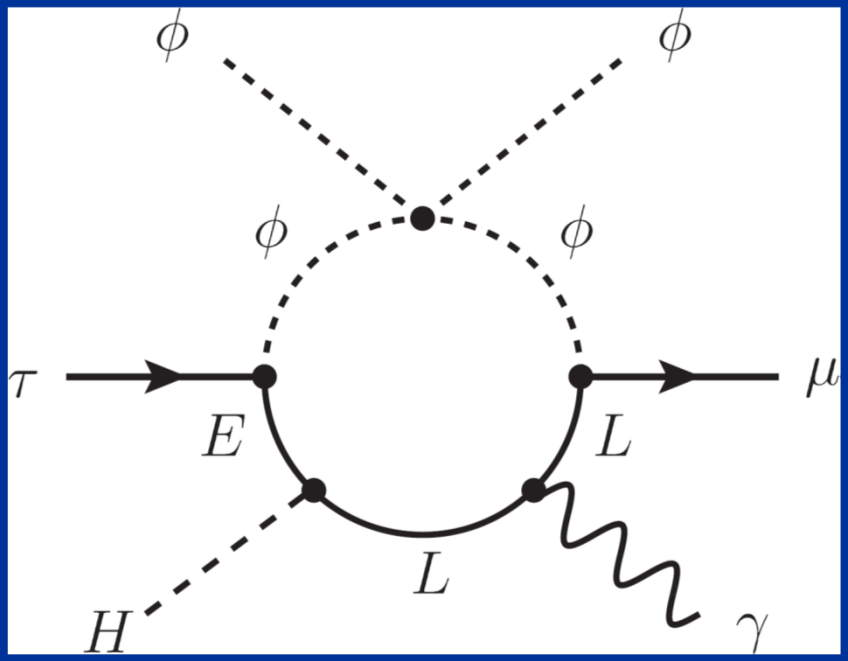
Branching ratio can even reach the percent level

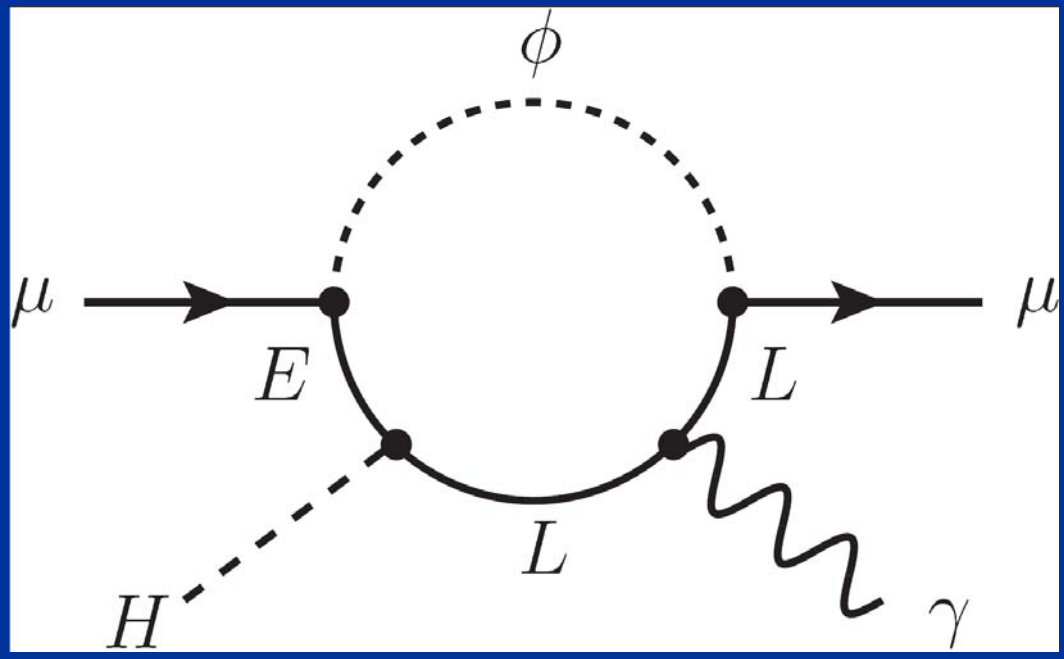
AC, Julian Heeck, Peter Stoffer. arXiv:1507.07567. PRL 2016

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

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



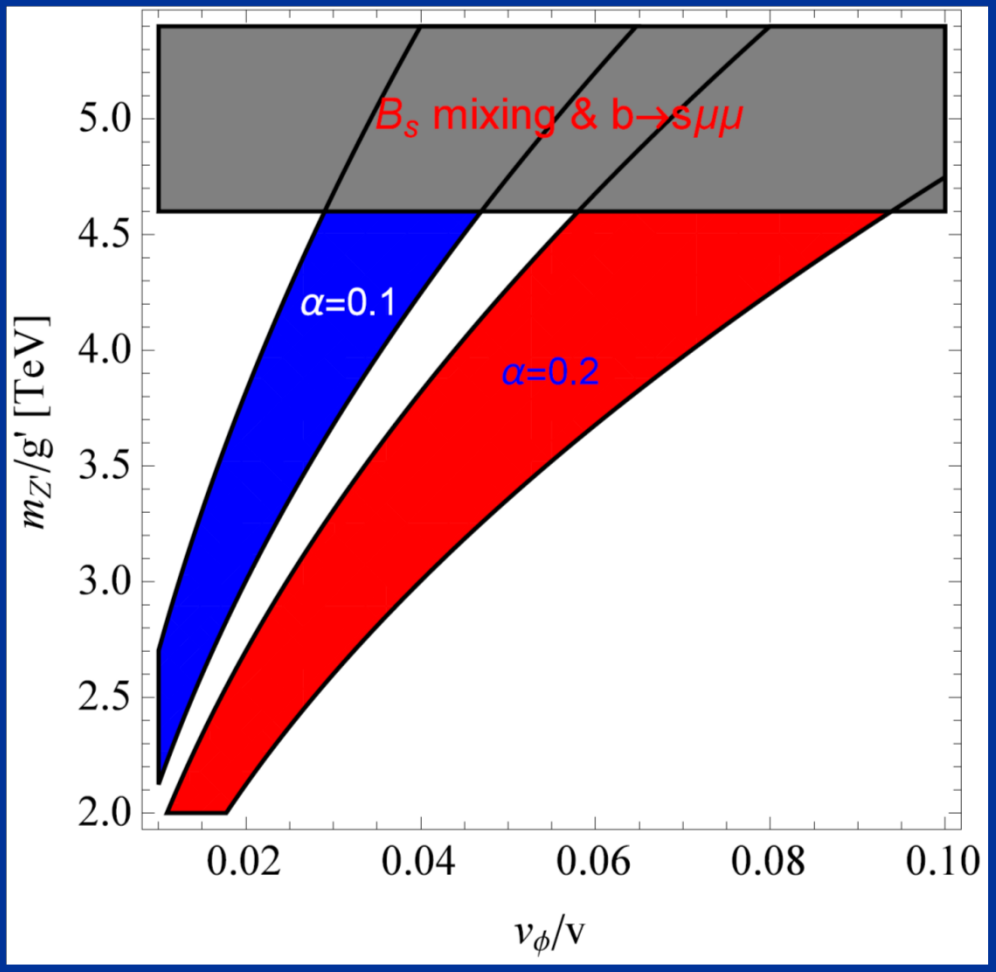




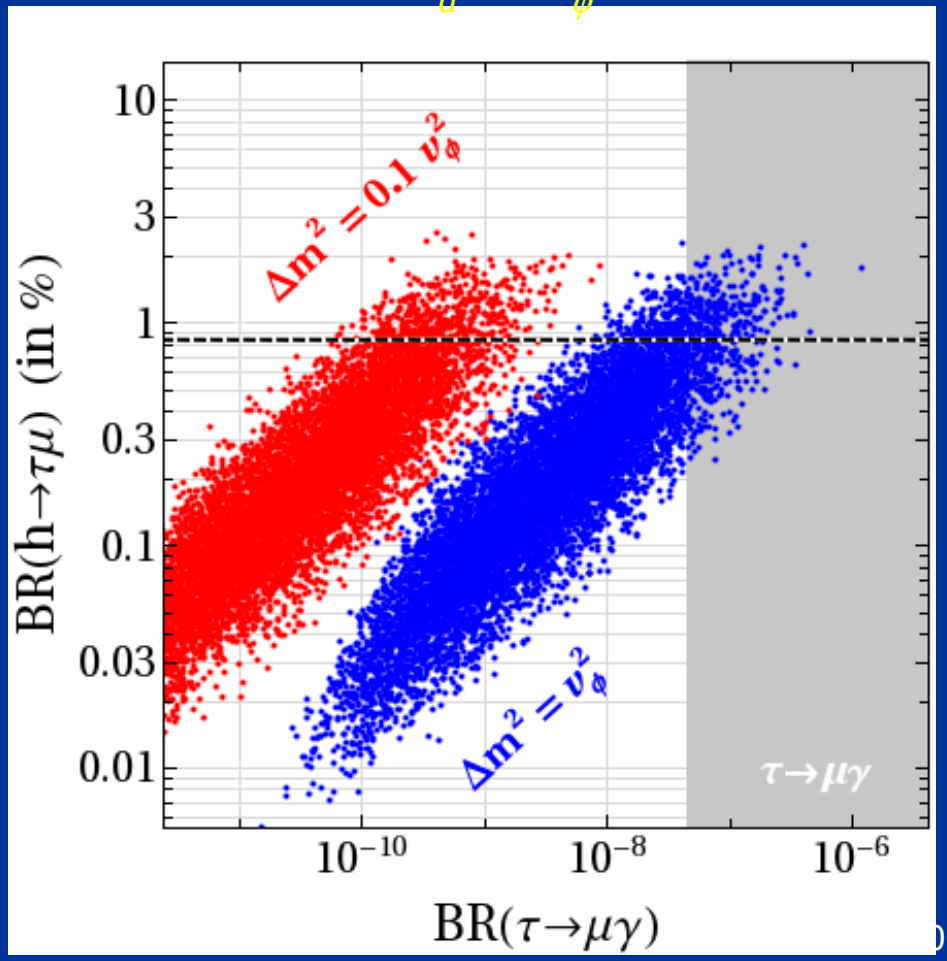
L_μ-L_τ model for a_μ and $h \to \tau\mu$

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

α : mixing among CP even Higgses



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



Outlook (personal view)

- $b \to s\mu\mu + R\left(D^{(*)}\right)$ ⇒ Leptoquarks
  - $B_s \to \mu\mu$
  - $b \to s\tau\tau$
- $a_\mu + R\left(D^{(*)}\right)$ ⇒ 2HDM X
  - $t \to Hc, \quad \tau \to \mu\nu\nu$
- $b \to s\mu\mu + h \to \tau\mu$ ⇒ Z'
  - $\tau \to \mu\mu\mu$
- $h \to \tau\mu + a_\mu$ ⇒ Flavon model
  - $h \to \mu\mu$

$\mu \to e\gamma$, $\mu \to 3e$

- Any observation would directly prove NP
- $\mu \to e\gamma$ currently best limit of cLFV
- $\mu \to 3e$ complementary to $\mu \to e\gamma$
  - Z' models
- Leptoquark explanations of $B \to D^{(*)}\tau\nu + b \to s\mu^+\mu^-$

  $\Rightarrow Br[\mu \to e\gamma] \neq 0$ (in general)
- Z' models and $h \to \tau\mu$ motivate $\tau \to 3\mu$

  $\Rightarrow Br[\mu \to 3e] \neq 0$

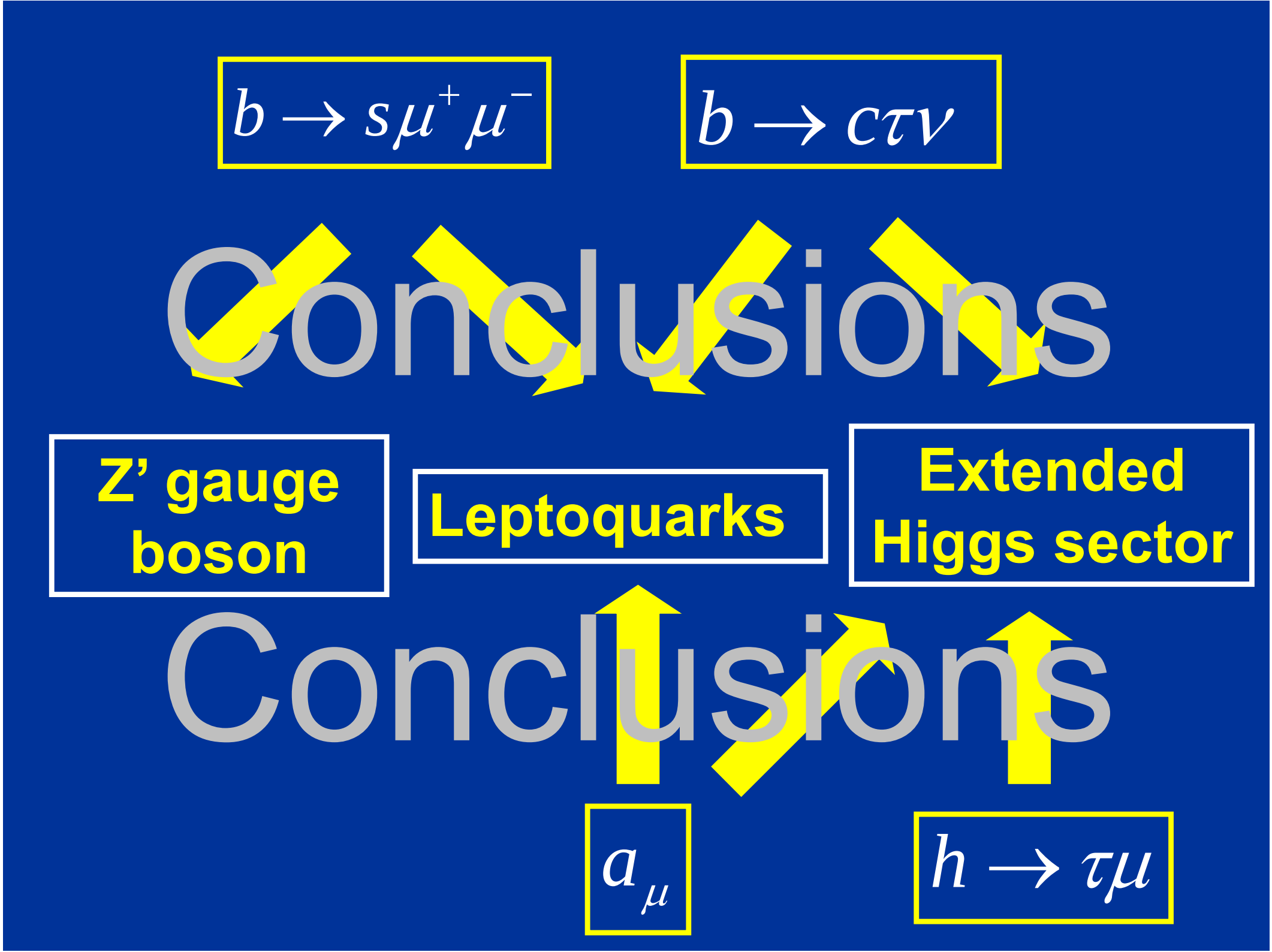
PEN and Muonic Lamb Shift

- $B \to D^{(*)}\tau\nu$
  - Also LFUV in $\pi \to \mu\nu / \pi \to e\nu$?

  ➡ PEN
- $\alpha_\mu + R(K) + h \to \tau\mu$
  - New Physics with muon but not with electrons?

  ➡ Connection to the proton radius problem???

  ➡ Muonic Lamb Shift experiment


$b \to s\mu^+\mu^-$
$b \to c\tau\nu$
Conclusions
Z' gauge boson
Leptoquarks
Extended Higgs sector
Conclusions
a_μ
$h \to \tau\mu$