Universality Tests in τ Decays at FCC-ee

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Context

- From LHC, it would seem that there is a mass gap between the electroweak scale $v \sim 100$ GeV and the scale of new physics: $\Lambda \gtrsim 1$ TeV $\rightarrow$ precision frontier
- We would like to have TeV-scale NP (hierarchy problem)
- But many flavour experiments (K-$\bar{K}$ mixing, ...) set stronger bounds: $\Lambda > 10^5$ TeV!
- This tells us that the flavour structure of NP must be very non-generic
- TeV-scale NP is still possible if it's coupled mainly to the third generation
- Interesting also in view of the Yukawa coupling structure

$\Rightarrow$ τ leptons are a very interesting indirect probe of NP, complementary to e.g. B and top physics

LFU tests

In the SM:

$$\mathcal{L}_{\text{SM}} = \mathcal{L}_{\text{gauge}} + \mathcal{L}_{\text{Higgs+Yukawa}}$$

- LFU: e, μ, τ are all the same $(\gamma, W, Z) \to$ expect $\Gamma_e = \Gamma_\mu = \Gamma_\tau$
- LFUV: $m_e \neq m_\mu \neq m_\tau$
  $y_\tau \sim 10^{-2} \Rightarrow$ very small breaking, only in interactions with H

Beyond the SM:

- New Physics may distinguish between different lepton species

hints of LFUV in ~~$b \to s\ell\ell$~~ and $b \to c\ell\nu$

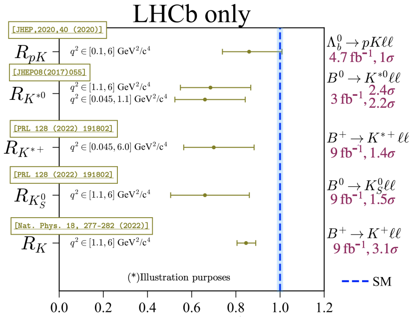
B-Anomalies: update

Neutral currents

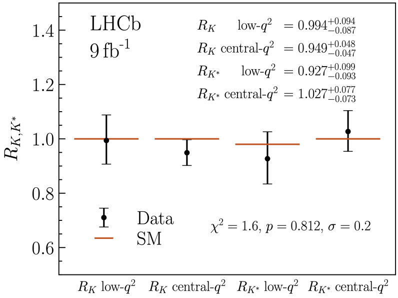
(see talk by B. Allanach)

$$R_{X_s} = \frac{\mathcal{B}(B \to X_s \mu^+ \mu^-)}{\mathcal{B}(B \to X_s e^+ e^-)}$$

Before 20/12/22:



After 20/12/22:



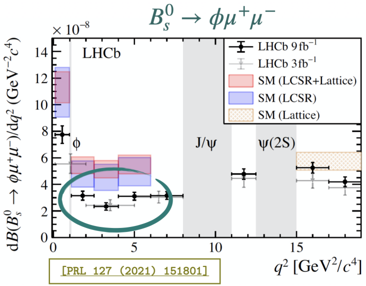
$4.3\sigma \to 0.2\sigma$!!

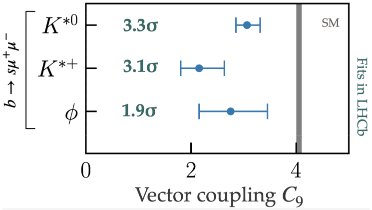
cf. R. Quagliani, CERN seminar 20/12/22

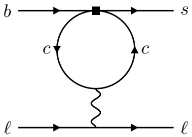
B-Anomalies: update

Neutral currents

(see talk by B. Allanach)







- Angular analyses in $b \to s\mu\mu$ transitions still show an interesting deviation from the SM
- However, theory prediction less under control (charm loops)
- Could be due to lepton flavour universal NP in the vector operator C_9

$$\mathcal{O}_9 = (\bar{b}\gamma^\mu P_L s)(\bar{\ell}\gamma_\mu \ell)$$

cf. R. Quagliani, CERN seminar 20/12/22

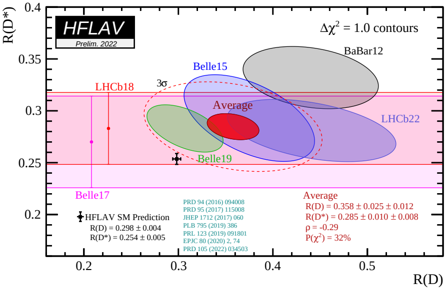
B-Anomalies: update

Charged currents

$$R_{X_c} = \frac{\mathcal{B}(B \to X_c \tau \nu)}{\mathcal{B}(B \to X_c \ell \nu)} \qquad \ell = e, \mu$$

LHCb update October '22:

- $\tau/\mu, e$ universality
- Expect first measurement by Belle-II in spring

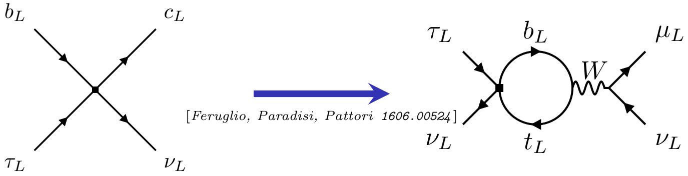


B-Anomalies and τ decays

- Consider the LH contact interaction

$$\mathcal{L} \supset \frac{1}{\Lambda^2}[C^{(3)}_{\ell q}]_{\alpha\beta ij}(\bar{\ell}_\alpha \gamma_\mu \sigma^I \ell_\beta)(\bar{q}_i \gamma^\mu \sigma^I q_j)$$

- $\delta R_{D^{(*)}} \sim V_{cb}[\mathcal{C}^{(3)}_{\ell q}]_{\tau\tau 33} + V_{cs}[\mathcal{C}^{(3)}_{\ell q}]_{\tau\tau 23}$
  $\rightarrow$ modify only couplings to τs
  $\rightarrow$ down-aligned basis (avoid B_s mixing constraints)



Deviations in $b \rightarrow c\tau\nu$ imply a modification of $\tau \rightarrow \ell\nu\bar{\nu}$ decays
(modification of W coupling to τ)

Taus at FCC-ee

- $N \sim 10^{12}$ Z-boson pairs $\Rightarrow 1.7 \times 10^{11}$ $Z \to \tau^+\tau^-$ decays
- Better τ reconstruction due to large boost
- Clean environment

[*Dam 1811.09408*]

Observable	Present value ± error	FCC-ee stat.	FCC-ee syst.
m_τ (MeV)	1776.86 ± 0.12	0.004	0.1
$\mathcal{B}(\tau \to e\bar{\nu}\nu)$ (%)	17.82 ± 0.05	0.0001	0.003
$\mathcal{B}(\tau \to \mu\bar{\nu}\nu)$ (%)	17.39 ± 0.05	0.0001	0.003
τ_τ (fs)	290.3 ± 0.5	0.001	0.04

Universality tests in τ decays: current status

Leptonic LFU ratios:

[*Pich* 1310.7922]

	$\Gamma_{\tau\to\mu}/\Gamma_{\tau\to e}$
$|g_\mu/g_e|$	1.0018(14)

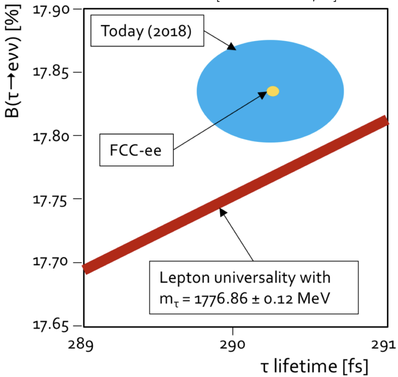
	$\Gamma_{\tau\to e}/\Gamma_{\mu\to e}$
$|g_\tau/g_\mu|$	1.0011(15)

	$\Gamma_{\tau\to\mu}/\Gamma_{\mu\to e}$
$|g_\tau/g_e|$	1.0030(15)

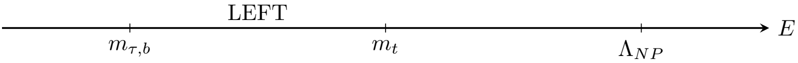
- FCC-ee expected to go below 10^{-4}!
- QED corrections known to $\mathcal{O}(\alpha^2) \lesssim 10^{-5}$

see talk by G. Isidori at
FCC Flavour Physics Workshop,
CERN 13.09.22

[*Dam* 1811.09408]



EFT for τ decays

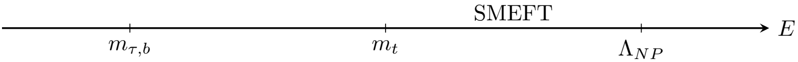


LEFT

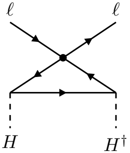
- H, $W^{\pm}$, Z, t integrated out
- $\mathrm{SU}(3)_{QCD} \times \mathrm{U}(1)_{QED}$ invariant

$$\mathcal{L}_{\text{LEFT}} = -\frac{2}{v^2}\left[L_{\nu e}^{V,LL}\right]^{\alpha\beta\gamma\delta}\left(\bar{\nu}_L^{\alpha}\gamma_\mu \nu_L^{\beta}\right)\left(\bar{e}_L^{\gamma}\gamma^{\mu} e_L^{\delta}\right) \qquad \left[L_{\nu e}^{V,LL}\right]_{SM}^{\alpha\beta\beta\alpha} = 1$$

$$R_{\beta\alpha} \equiv \frac{\Gamma(\ell_\beta \to \ell_\alpha \nu\bar{\nu})}{\Gamma_{\text{SM}}(\ell_\beta \to \ell_\alpha \nu\bar{\nu})} \equiv 1 + \delta R_{\beta\alpha}$$
$$\approx 1 + 2\,\mathrm{Re}[L_{\nu e}^{V,LL}]^{\text{NP}}_{\alpha\beta\beta\alpha}$$



SMEFT

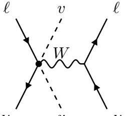


- Full SM field content
- $\mathrm{SU}(3)_{QCD} \times \mathrm{SU}(2)_L \times \mathrm{U}(1)_Y$ invariant

$$\mathcal{L}_{\text{SMEFT}} = -\frac{2}{v^2}\left[C_{\ell q}^{(3)}\right]^{\alpha\beta ij}\left(\bar{\ell}^\alpha\gamma_\mu\sigma^I\ell^\beta\right)\left(\bar{q}^i\gamma^\mu\sigma^I q^j\right)$$

Leading-Log result:

$$\left[L_{\nu e}^{V,LL}\right]_{NP,LL}^{\alpha\beta\beta\alpha} = -2\sum_{\gamma=\alpha,\beta}\left[C_{H\ell}^{(3)}\right]_{\gamma\gamma}(m_t) = -\frac{y_t^2 N_c}{8\pi^2}\log\frac{\Lambda_{NP}^2}{m_t^2}\sum_{\gamma=\alpha,\beta}\left[C_{\ell q}^{(3)}\right]^{\gamma\gamma 33}$$



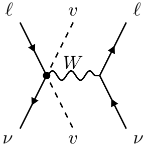
$$O_{H\ell}^{(3)} = (\bar{\ell}\gamma^\mu\sigma^I\ell)(H^\dagger i\overleftrightarrow{D}_\mu^I H)$$

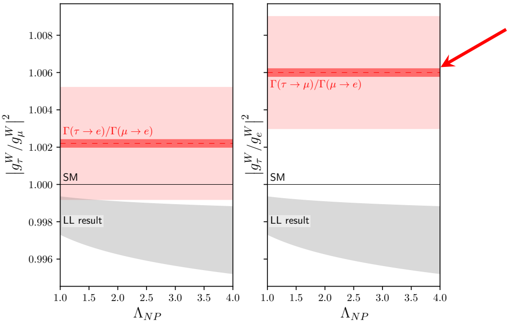
Leading Log result

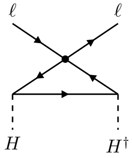
$$\left[O_{H\ell}^{(3)}\right]^{\alpha\beta} = (\bar{\ell}^{\alpha}\gamma_{\mu}\sigma^{I}\ell^{\beta})\left(H^{\dagger}i\overleftrightarrow{D^{\mu}}\sigma^{I}H\right)$$

$$|g_{\tau}/g_{\mu}|^2 \simeq 1 - 4\sum_{\gamma=\alpha,\beta}\left[C_{H\ell}^{(3)}\right]_{\gamma\gamma}(m_t) = 1 - \frac{y_t^2 N_c}{4\pi^2}\log\frac{\Lambda_{\rm NP}^2}{m_t^2}\sum_{\gamma=\alpha,\beta}[C_{\ell q}^{(3)}]_{\gamma\gamma 33}$$

[*LA, Isidori, Selimović* 2109.03833]







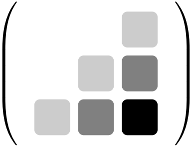
- Expect decrease of g_{τ}
- FCC-ee will be able to clarify the situation

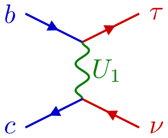
Example: the U_1 leptoquark, $U_1 \sim (\mathbf{3}, 1, 2/3)$

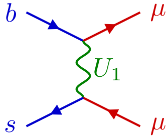
- Generates both $bc\tau\nu$ and $bs\ell\ell$ interactions
- LH couplings:

$$\mathcal{L} = \frac{g_U}{\sqrt{2}} U_1^\mu \beta_L^{i\alpha} (\bar{q}_L^i \gamma_\mu \ell_L^\alpha) + \text{ h.c.}$$

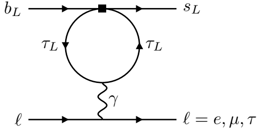
$$\beta_L = \begin{pmatrix} \beta_L^{de} & \beta_L^{d\mu} & \beta_L^{d\tau} \\ \beta_L^{se} & \beta_L^{s\mu} & \beta_L^{s\tau} \\ \beta_L^{be} & \beta_L^{b\mu} & \beta_L^{b\tau} \end{pmatrix} \sim$$







- Needs to be coupled mainly to third generation
- $bs\mu\mu \sim \beta_L^{b\mu}\beta_L^{s\mu}$
  $\rightarrow$ rescaling couplings by a factor ~ 2 restores compatibility with LFU tests
- Large $bs\tau\tau$ coupling gives universal contribution to C_9



Quark-Lepton unification: 4321 model(s)

$\mathrm{SU}(4)_3 \times \mathrm{SU}(3)_{1+2} \times \mathrm{SU}(2)_L \times \mathrm{U}(1)_X$

[1512.01560, 1708.08450, 1709.00692, 1712.01638, 1712.06844, ...]

Non universal gauge interactions
→ NP coupled mainly to 3rd generation

New gauge fields: U_1, G', Z'

$U_1 \sim (\mathbf{3}, \mathbf{1}, 2/3)$

SM fermions:

Field	$SU(4)$	$SU(3)'$	$SU(2)_L$	$U(1)_X$
ψ_L	$\mathbf{4}$	$\mathbf{1}$	$\mathbf{2}$	0
ψ_R^+	$\mathbf{4}$	$\mathbf{1}$	$\mathbf{1}$	1/2
ψ_R^-	$\mathbf{4}$	$\mathbf{1}$	$\mathbf{1}$	−1/2
$q_L'^i$	$\mathbf{1}$	$\mathbf{3}$	$\mathbf{2}$	1/6
u_R^i	$\mathbf{1}$	$\mathbf{3}$	$\mathbf{1}$	2/3
d_R^i	$\mathbf{1}$	$\mathbf{3}$	$\mathbf{1}$	−1/3
$\ell_L'^i$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{2}$	−1/2
e_R^i	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	−1

$H \sim (\mathbf{1}, \mathbf{1}, \mathbf{2}, 1/2)$

Additional fermions (vector-like)
→ mixing with light generations

Field	$SU(4)$	$SU(3)'$	$SU(2)_L$	$U(1)_X$
χ_L	$\mathbf{4}$	$\mathbf{1}$	$\mathbf{2}$	0
Q_R	$\mathbf{1}$	$\mathbf{3}$	$\mathbf{2}$	1/6
L_R	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{2}$	−1/2

$$\mathcal{L} \supset M_q \bar{Q}_R q_L^2 + M_\ell \bar{L}_R \ell_L^2$$

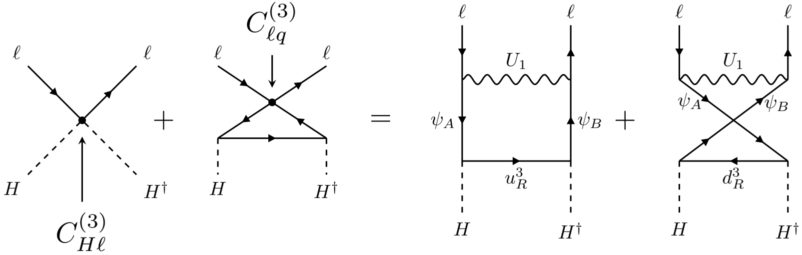
1-loop computations in the UV-complete theory

$$\left[O_{H\ell}^{(3)}\right]^{\alpha\beta} = \left(\bar{\ell}^{\alpha}\gamma_{\mu}\sigma^{I}\ell^{\beta}\right)\left(H^{\dagger}i\overleftrightarrow{D^{\mu}}\sigma^{I}H\right)$$

$$\left[O_{\ell q}^{(3)}\right]^{\alpha\beta ij} = \left(\bar{\ell}^{\alpha}\gamma_{\mu}\sigma^{I}\ell^{\beta}\right)\left(\bar{q}^{i}\gamma^{\mu}\sigma^{I}q^{j}\right)$$

[*LA, Isidori, Selimović* 2109.03833]

$$\psi_{A,B} = q_L^3, Q_L$$



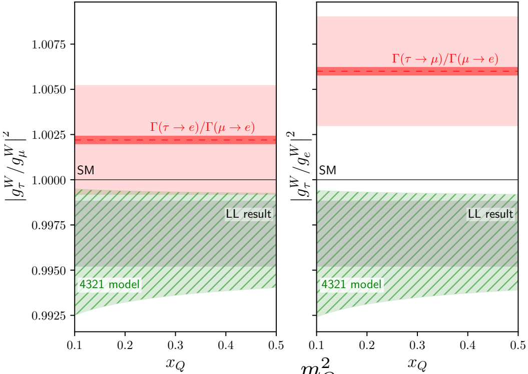
$$[C_{H\ell}^{(3)}]_{\tau\tau}(\mu) = -\frac{1}{16\pi^2}\frac{N_c C_U}{2}\Big[|\beta_L^{b\tau}|^2|y_t|^2\left(1+\log\frac{\mu^2}{m_U^2}\right)$$
$$+ c_Q 2\mathrm{Re}(\beta_L^{b\tau^*}\beta_L^{Q\tau}Y_+^* y_t)B_0(x_Q)$$
$$+ c_Q^2|\beta_L^{Q\tau}|^2(|Y_+|^2+|Y_-|^2)F(x_Q, x_Q^R)\Big]$$

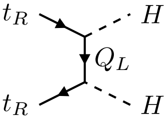
$$C_U = \frac{g_U v^2}{4m_U^2}$$

Full model results for τ LFU ratios

- Including finite pieces and the effect of the vector-like states can change the leading-log result
- The tension can only be slightly decreased
- Vector-like quarks also enter in other obervables: m_W, $Z \to t_R \bar{t}_R$

[LA, Isidori, Selimović 2109.03833]

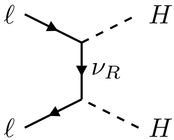




$$x_Q = \frac{m_Q^2}{m_U^2}$$

Adding neutrino masses

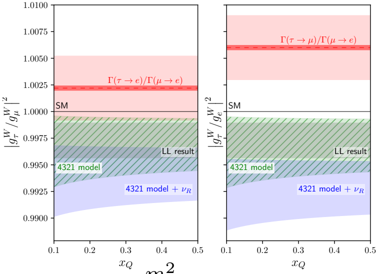
- Quark-lepton unification predicts $m_t \sim m_{\nu_\tau}$
- Inverse see-saw mechanism:

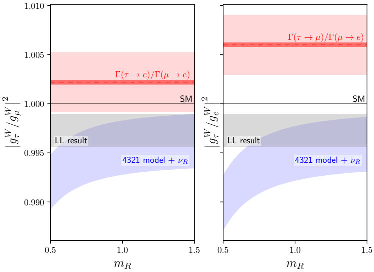


$Z \to \nu\bar{\nu}$

$$\mathcal{L} = -\lambda_R \bar{S}_R^c \Omega_1^T \psi_R^+ + \frac{1}{2}\mu \bar{S}_R^c S_R$$

$$m_R \sim \lambda_R \langle \Omega_1 \rangle \pm \mu \qquad m_{\nu_\tau} \sim \frac{y_t v}{m_R}\mu$$





$$x_Q = \frac{m_Q^2}{m_U^2}$$

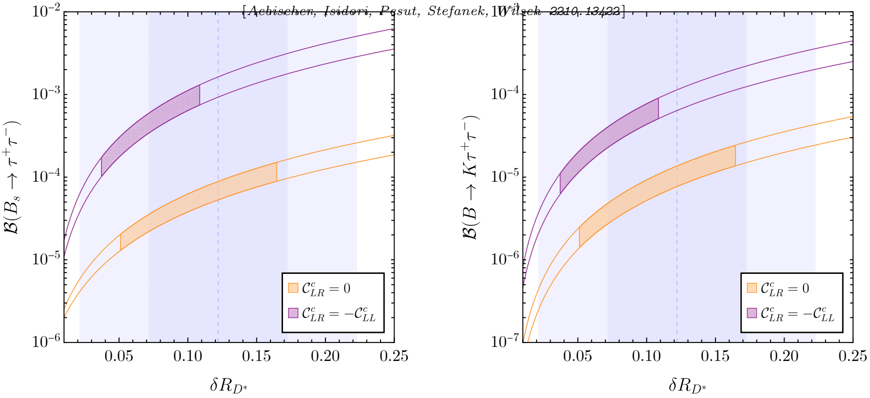
[LA, Isidori, Lizana, Selimović, Stefanek WIP]

$B_s \to \tau\tau$ and $B \to K\tau\tau$

- Decay rates strongly enhanced in the U_1 model
- Expect ~ 1000 reconstructed $\bar{B}^0 \to K^{*0}\tau\tau$ events at FCC-ee

[*Kamenik, Monteil, Semkiv, Vale Silva 1705.11106*]

[*Aebischer, Isidori, Pesut, Stefanek, Wilsch 2210.13422*]



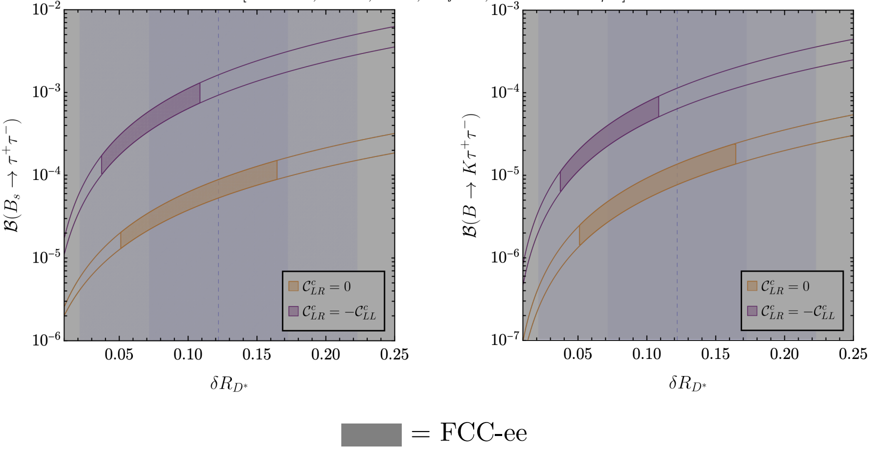
$$\mathcal{O}^c_{LL} = (\bar{c}_L\gamma_\mu b_L)(\bar{\tau}_L\gamma^\mu\nu_L) \qquad \mathcal{O}^c_{LR} = (\bar{c}_L b_R)(\bar{\tau}_R\nu_L)$$

$B_s \to \tau\tau$ and $B \to K\tau\tau$

- Decay rates strongly enhanced in the U_1 model
- Expect $\sim$ 1000 reconstructed $\bar{B}^0 \to K^{*0}\tau\tau$ events at FCC-ee

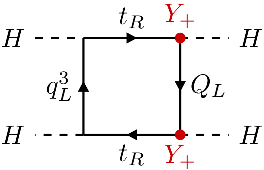
[*Kamenik, Monteil, Semkiv, Vale Silva* 1705.11106]

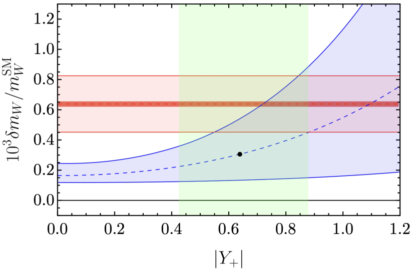
[*Aebischer, Isidori, Pesut, Stefanek, Wilsch* 2210.13422]



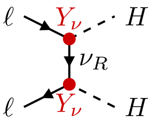
EWPO: m_W and $Z \to \nu\nu$

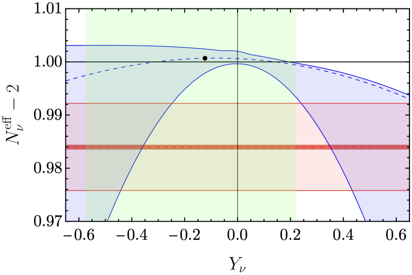
m_W





$Z \to \nu\nu$





[*LA, Isidori, Lizana, Selimović, Stefanek WIP*]

Summary and Outlook

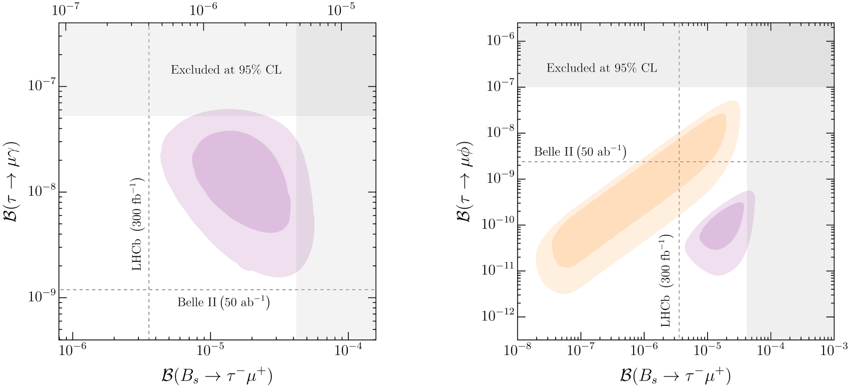
- τ leptons, being third generation fermions, are particularly interesting to look at with precision experiments
- FCC-ee is an ideal machine to do so
- LFU tests are a very clean probe of NP
- If deviations from the SM come from TeV-scale NP, not only τs will be affected
  $\rightarrow$ define models and study correlations between observables at different energy scales

Thank you!

Backup

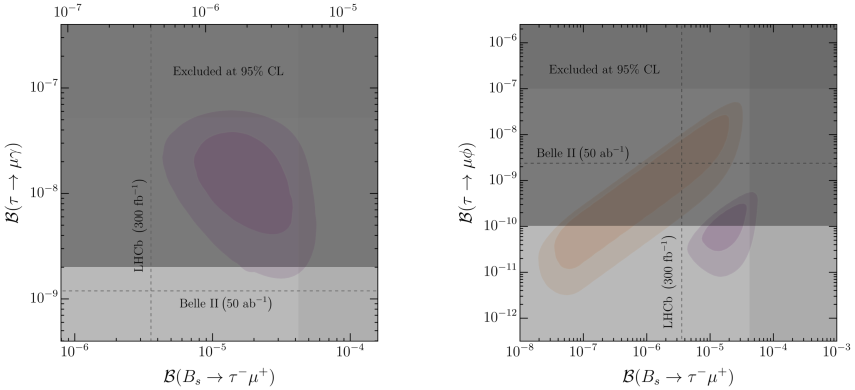
$\tau \to \mu\phi$ and $\tau \to \mu\gamma$, $B_s \to \tau\mu$

[*Cornella, Faroughy, Fuentes-Martín, Isidori, Neubert* 2103.16558]



$\tau \to \mu\phi$ and $\tau \to \mu\gamma$, $B_s \to \tau\mu$

[*Cornella, Faroughy, Fuentes-Martín, Isidori, Neubert* 2103.16558]



τ LFV decays

[Dam 1811.09408]

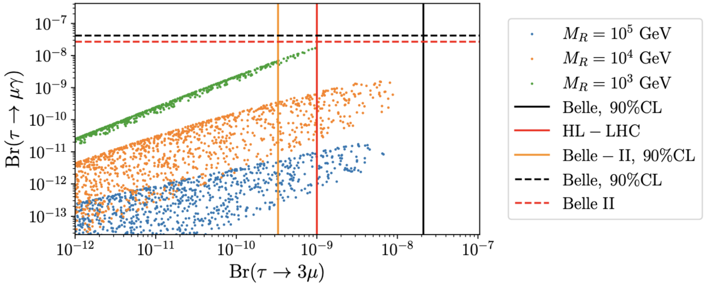
Decay	Present bound	FCC-ee sensitivity
$\tau \to \mu\gamma$	4.4×10^{-8}	2×10^{-9}
$\tau \to 3\mu$	2.1×10^{-8}	10^{-10}

Example: Type-I symmetry protected seesaw

$$\mathcal{L} = -\frac{1}{2}(\bar{\nu}_L \bar{N}_R^c) M_\nu (\nu_L^c N_R)^T \qquad M_\nu = \begin{pmatrix} 0_{3\times 3} & \frac{v}{\sqrt{2}} Y^\nu \\ \frac{v}{\sqrt{2}} Y^\nu & M_R \end{pmatrix}$$

$$m_{\nu_L} = -\frac{v^2}{2} Y^\nu M_R^{-1} Y^{\nu\, T} \equiv 0 \qquad m_{N_R} = M_R + \mathcal{O}(\frac{v^2}{M_R^2})$$

[Crivellin, Kirk, Manzari 2208.00020]



τ LFV decays

[Dam 1811.09408]

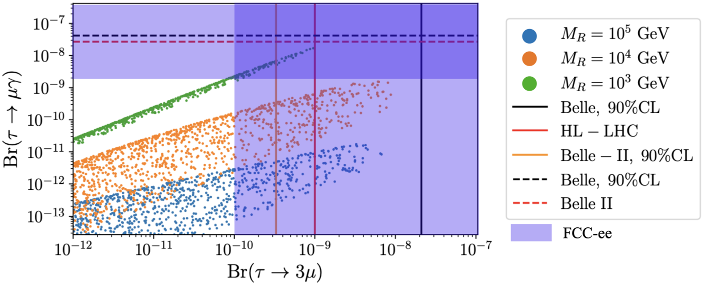
Decay	Present bound	FCC-ee sensitivity
$\tau \to \mu\gamma$	4.4×10^{-8}	2×10^{-9}
$\tau \to 3\mu$	2.1×10^{-8}	10^{-10}

Example: Type-I symmetry protected seesaw

$$\mathcal{L} = -\frac{1}{2}(\bar{\nu}_L \bar{N}_R^c) M_\nu (\nu_L^c N_R)^T \qquad M_\nu = \begin{pmatrix} 0_{3\times 3} & \frac{v}{\sqrt{2}} Y^\nu \\ \frac{v}{\sqrt{2}} Y^\nu & M_R \end{pmatrix}$$

$$m_{\nu_L} = -\frac{v^2}{2} Y^\nu M_R^{-1} Y^{\nu\, T} \equiv 0 \qquad m_{N_R} = M_R + \mathcal{O}(\frac{v^2}{M_R^2})$$

[Crivellin, Kirk, Manzari 2208.00020]



Z LFV decays

[Dam 1811.09408]

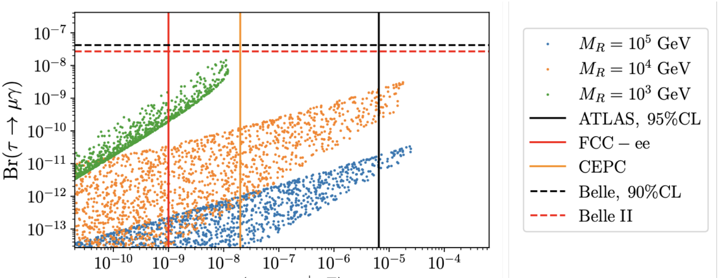
Decay	Present bound	FCC-ee sensitivity
$Z \to \mu e$	0.75×10^{-6}	$10^{-10} - 10^{-8}$
$Z \to \tau\mu$	12×10^{-6}	10^{-9}
$Z \to \tau e$	9.8×10^{-6}	10^{-9}

Example: Type-I symmetry protected seesaw

$$\mathcal{L} = -\frac{1}{2}(\bar{\nu}_L \bar{N}_R^c) M_\nu (\nu_L^c N_R)^T \qquad M_\nu = \begin{pmatrix} 0_{3\times 3} & \frac{v}{\sqrt{2}Y^\nu} \\ \frac{v}{\sqrt{2}Y^\nu} & M_R \end{pmatrix}$$

$$m_{\nu_L} = -\frac{v^2}{2} Y^\nu M_R^{-1} Y^{\nu\,T} \equiv 0 \qquad m_{N_R} = M_R + \mathcal{O}\left(\frac{v^2}{M_R^2}\right)$$

[Crivellin, Kirk, Manzari 2208.00020]



Z LFV decays

[Dam 1811.09408]

Decay	Present bound	FCC-ee sensitivity
$Z \to \mu e$	0.75×10^{-6}	$10^{-10} - 10^{-8}$
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Example: Type-I symmetry protected seesaw

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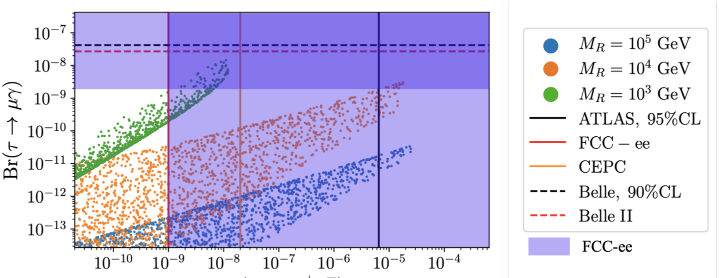
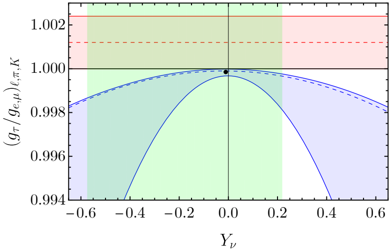
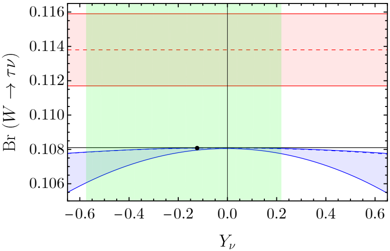
[Crivellin, Kirk, Manzari 2208.00020]



Tau related observables





Some EW pole observables