Breaking of Standard Model symmetries with the tau lepton

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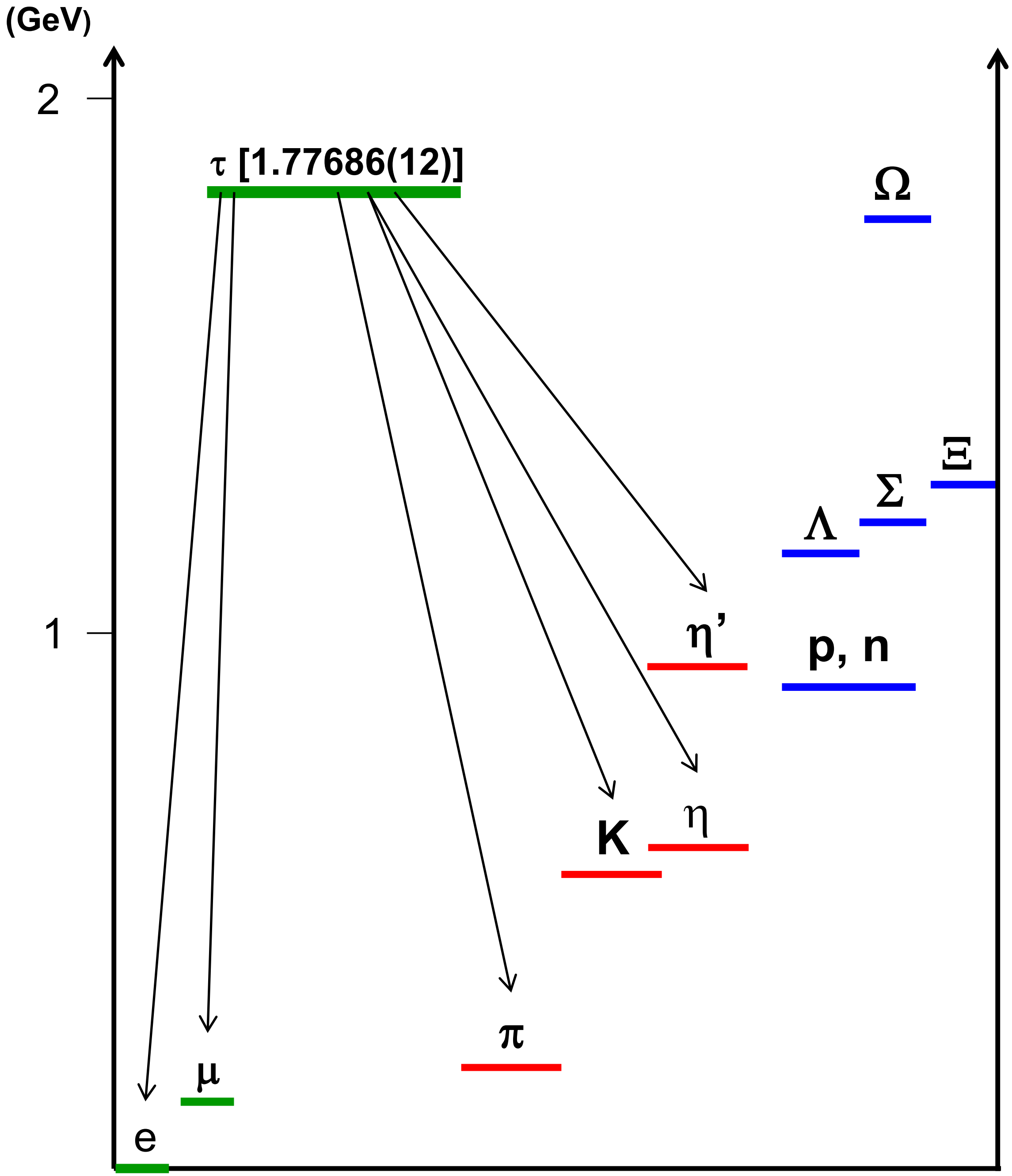
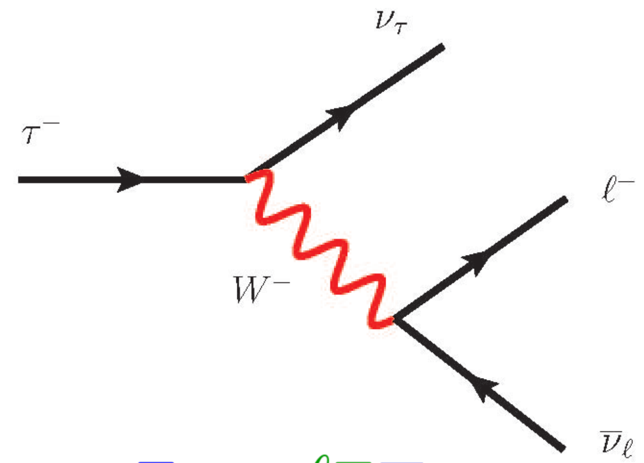
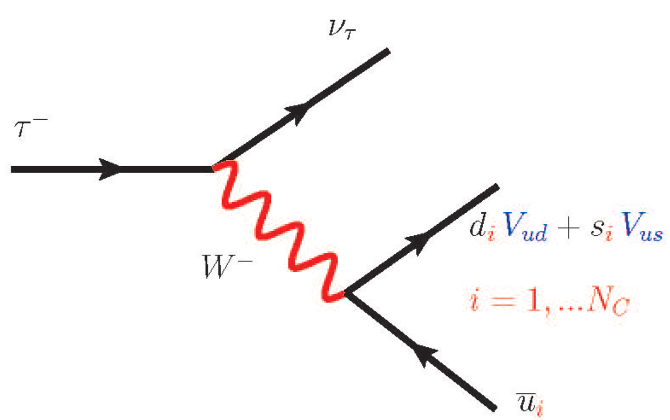
TAU 2021

Decay spectrum



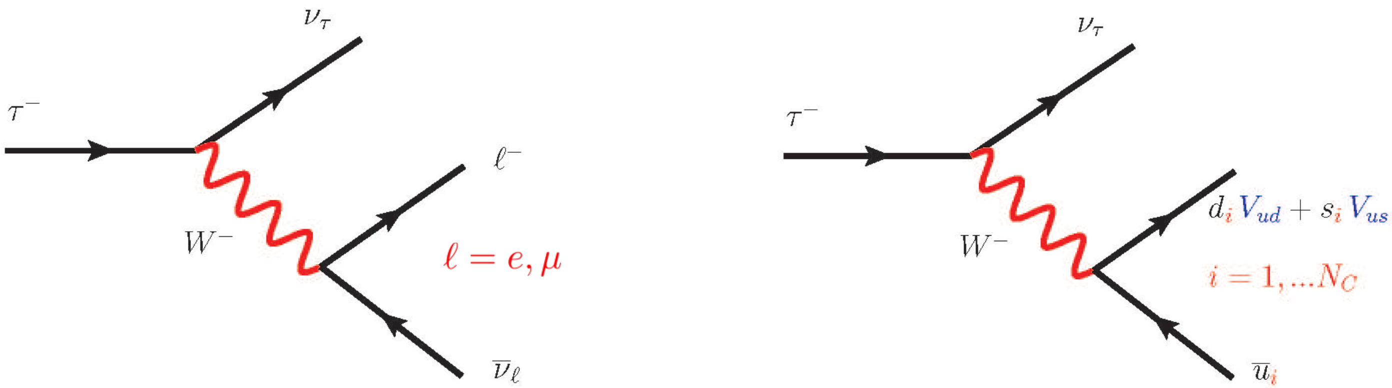


$$\tau^- \to \ell^- \overline{\nu}_\ell \nu_\tau$$



$$\tau^- \to (P, PP, \dots)^- \nu_\tau$$

P ≡ Pseudoscalar meson



Process	Estimate	Experiment
$B_e \equiv \mathrm{Br}(\tau \to e\overline{\nu}\nu)$ $B_\mu \equiv \mathrm{Br}(\tau \to \mu\overline{\nu}\nu)$	$\dfrac{1}{2 + N_C \left(\lvert V_{ud}\rvert^2 + \lvert V_{us}\rvert^2\right)}$ $\simeq 20\,\%$	$(17.82 \pm 0.04)\%$ $(17.39 \pm 0.04)\%$
$\mathrm{Br}(\tau \to \text{non-strange hadrons})$	$\dfrac{N_C \lvert V_{ud}\rvert^2}{2 + N_C \left(\lvert V_{ud}\rvert^2 + \lvert V_{us}\rvert^2\right)}$ $\simeq 58\,\%$	$(62 \pm 4)\%$
$\mathrm{Br}(\tau \to \text{strange hadrons})$	$\dfrac{N_C \lvert V_{us}\rvert^2}{2 + N_C \left(\lvert V_{ud}\rvert^2 + \lvert V_{us}\rvert^2\right)}$ $\simeq 2\,\%$	$(2.6 \pm 0.7)\%$

Outline

- Lepton universality
- Charged lepton flavour violation
- Lepton or baryon numbers violation
- Outlook

Lepton Universality

The largest group of global unitary field transformations commuting with the **SM** electroweak gauge group, consisting of three families.

[Chivukula, 1987]

Standard Model	Group
Yukawa couplings = 0	$U(3)_Q \times U(3)_u \times U(3)_d \times U(3)_\ell \times U(3)_e$
	One family breaks universality $\left[U(2) \times U(1)\right]^5$
Yukawa couplings ≠ 0	$U(1)_L \times U(1)_B \times U(1)_Y$

$$W \longrightarrow \ell\, \nu_\ell$$

$$\ell_1/\ell_2 \equiv \frac{\Gamma(W \to \ell_1 \nu_{\ell_1})}{\Gamma(W \to \ell_2 \nu_{\ell_2})} = 1 \text{ (SM)}$$

	[PDG, 2020]
μ/e	0.996 ± 0.008
τ/e	1.043 ± 0.024
τ/μ	1.070 ± 0.026

[Han, 2006] [Filipuzzi, 2012]

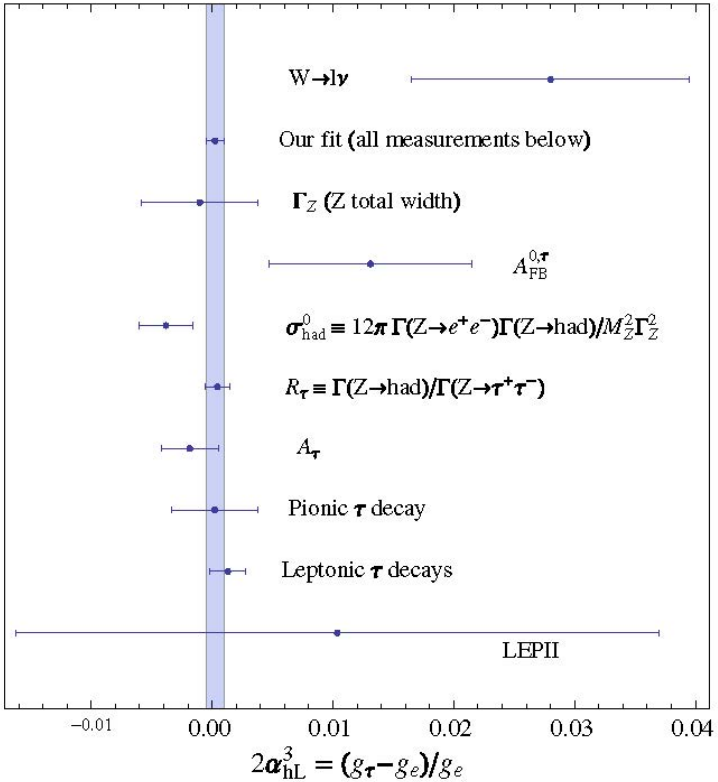
D = 6 operators with symmetry

$$\left[U(2)_{\mu\, e} \times U(1)_\tau \right]^5$$

⇓

Violation of lepton universality not due to

$$\Lambda \gg \Lambda_{EW}$$



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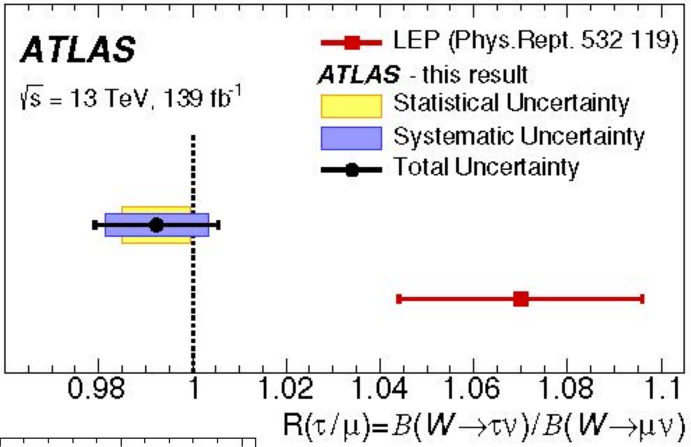
	[PDG, 2020]	[ATLAS, 2021]
μ/e	0.996 ± 0.008	
τ/e	1.043 ± 0.024	
τ/μ	1.070 ± 0.026	0.992 ± 0.013



[Han, 2006] [Filipuzzi, 2012]

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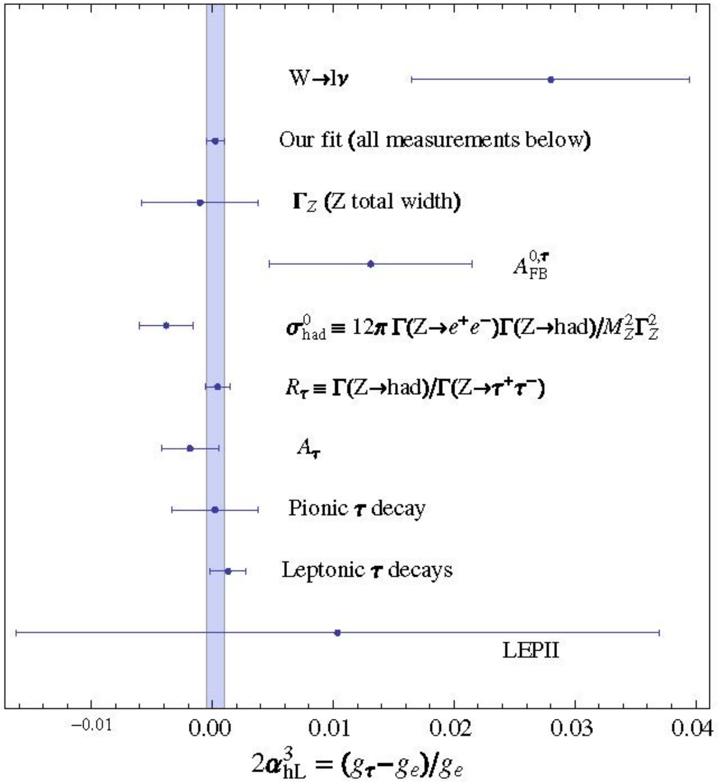
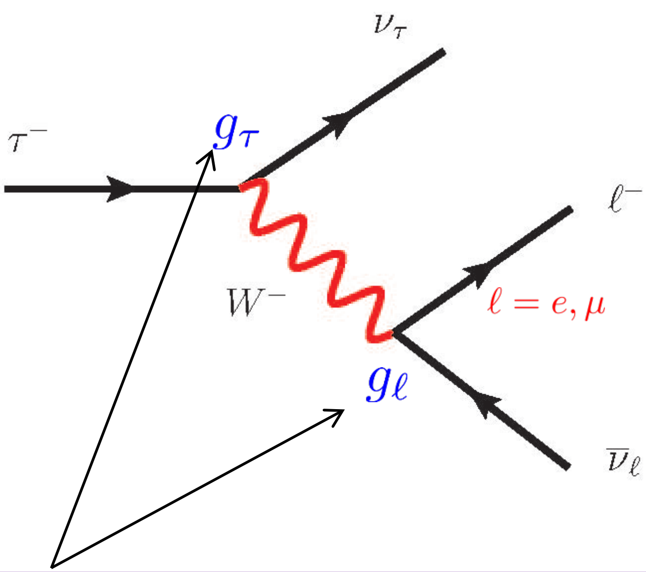


Charged current universality



$$\Gamma\left(\tau \to \ell\,\overline{\nu}_\ell\,\nu_\tau\right) = \frac{G_F^2 M_\tau^5}{192\,\pi^3}\, f\left(M_\ell^2/M_\tau^2\right) r_{\mathrm{EW}}$$

$$f(x) = 1 - 8\,x + 8\,x^3 - x^4 - 12\,x^2 \ln x$$

$$f\left(\frac{M_e{}^2}{M_\tau^2}\right) = 0.999999, \qquad f\left(\frac{M_\mu{}^2}{M_\tau^2}\right) = 0.972559$$

$$r_{\mathrm{EW}} = \left(1 + \frac{3}{5}\frac{M_\tau^2}{M_W^2}\right)\left[1 + \frac{\alpha(M_\tau)}{2\pi}\left(\frac{25}{4} - \pi^2\right)\right] = 0.9960$$

Charged current universality $\quad g_\tau = g_\mu = g_e$

$\mathrm{Br}\left(\mu^- \to e^- \overline{\nu}_e \nu_\mu\right) \simeq 100\,\%$

	$\lvert g_\tau/g_e \rvert$
$\Gamma_{\tau\to\mu}/\Gamma_{\mu\to e}$	1.0028(15)
$\Gamma_{W\to\tau}/\Gamma_{W\to e}$	1.022(12)

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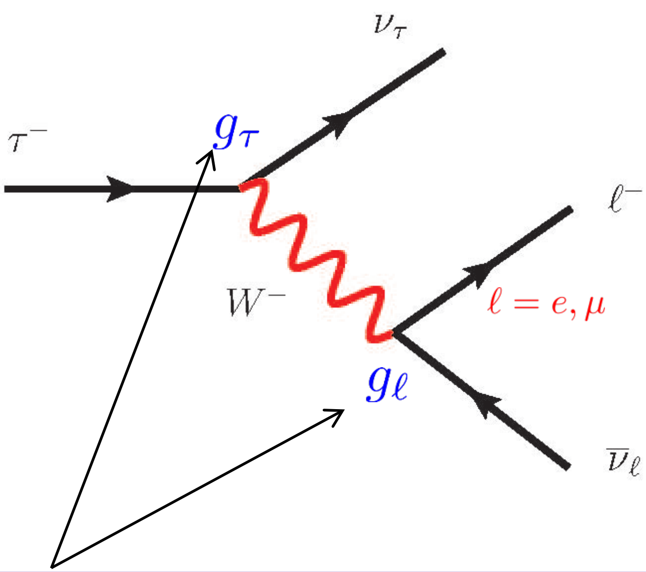
$\Gamma_{W\to\tau}/\Gamma_{W\to\mu}$	1.004(16)

	$\lvert g_\mu/g_e \rvert$
$\Gamma_{\tau\to\mu}/\Gamma_{\tau\to e}$	1.0017(16)
$\Gamma_{W\to\mu}/\Gamma_{W\to e}$	0.998(4)

[Pich, 2020]

Charged current universality



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[Pich, 2020]

Charged lepton flavour violation

$$\left.\begin{array}{c}\text{SM}\\ m_\nu = 0\end{array}\right\} \left[U(1)_{\mathrm{B}} \otimes U(1)_e \otimes U(1)_\mu \otimes U(1)_\tau \supset U(1)_{e+\mu+\tau}\right]_{\mathrm{global}}$$

Charged lepton flavour violation

SM
$m_\nu = 0$ $\Big\} \; \left[U(1)_B \otimes U(1)_e \otimes U(1)_\mu \otimes U(1)_\tau \supset U(1)_{e+\mu+\tau} \right]_{\text{global}}$

LFV is large in the neutrino sector :

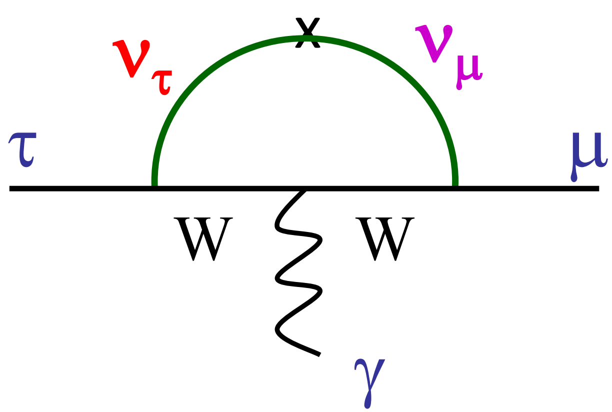
Oscillations

$\theta_{12} \approx 30^0, \quad \theta_{23} \approx 45^0, \quad \theta_{13} \approx 0^0$

Solar neutrinos

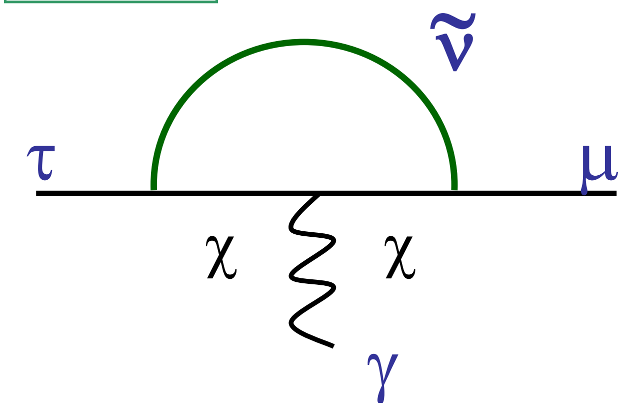
$\nu_e \;\; \Rightarrow \;\; \frac{1}{3}\left(\nu_e + \nu_\mu + \nu_\tau\right)$

SM + ν_R $|_{\text{Dirac}}$



$$\frac{B(\tau \to \mu\,\gamma)}{B(\tau \to \mu \bar{\nu}_\mu \nu_\tau)} = \frac{3\alpha}{128\pi}\left(\frac{\Delta m^2_{23}}{m^2_W}\right)^2 \sin^2 2\theta_{mix} \approx O\left(10^{-53}\right)$$

BSM



some SUSY models can bring up to

$$\frac{B(\tau \to \mu\,\gamma)}{B(\tau \to \mu \bar{\nu}_\mu \nu_\tau)} \approx O\left(10^{-6} - 10^{-7}\right)$$

ATLAS

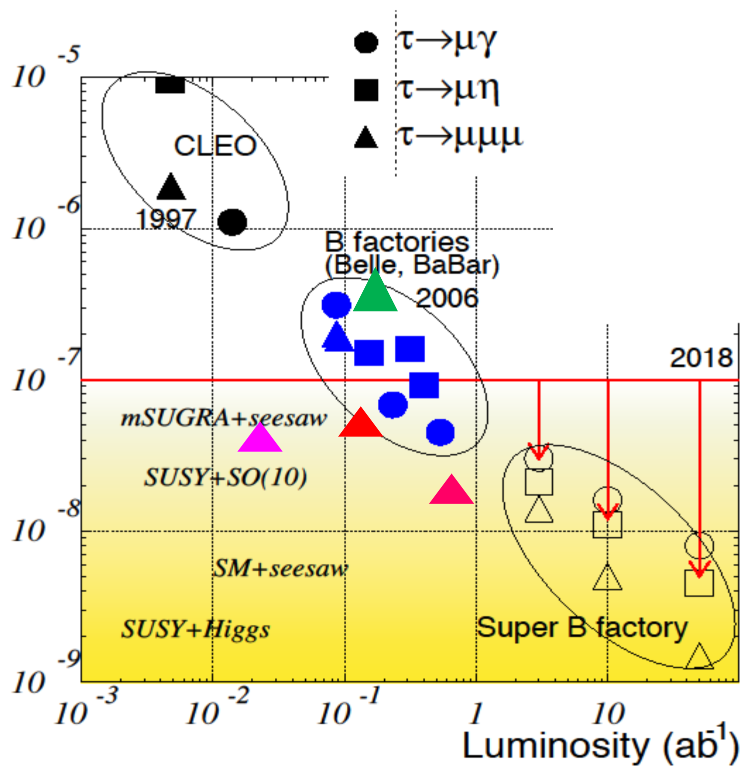
2016

LHCb

2015

CMS

2021



Theoretical predictions of the branching ratio for $\tau \to \mu\gamma$ and $\tau \to \mu\mu\mu$.

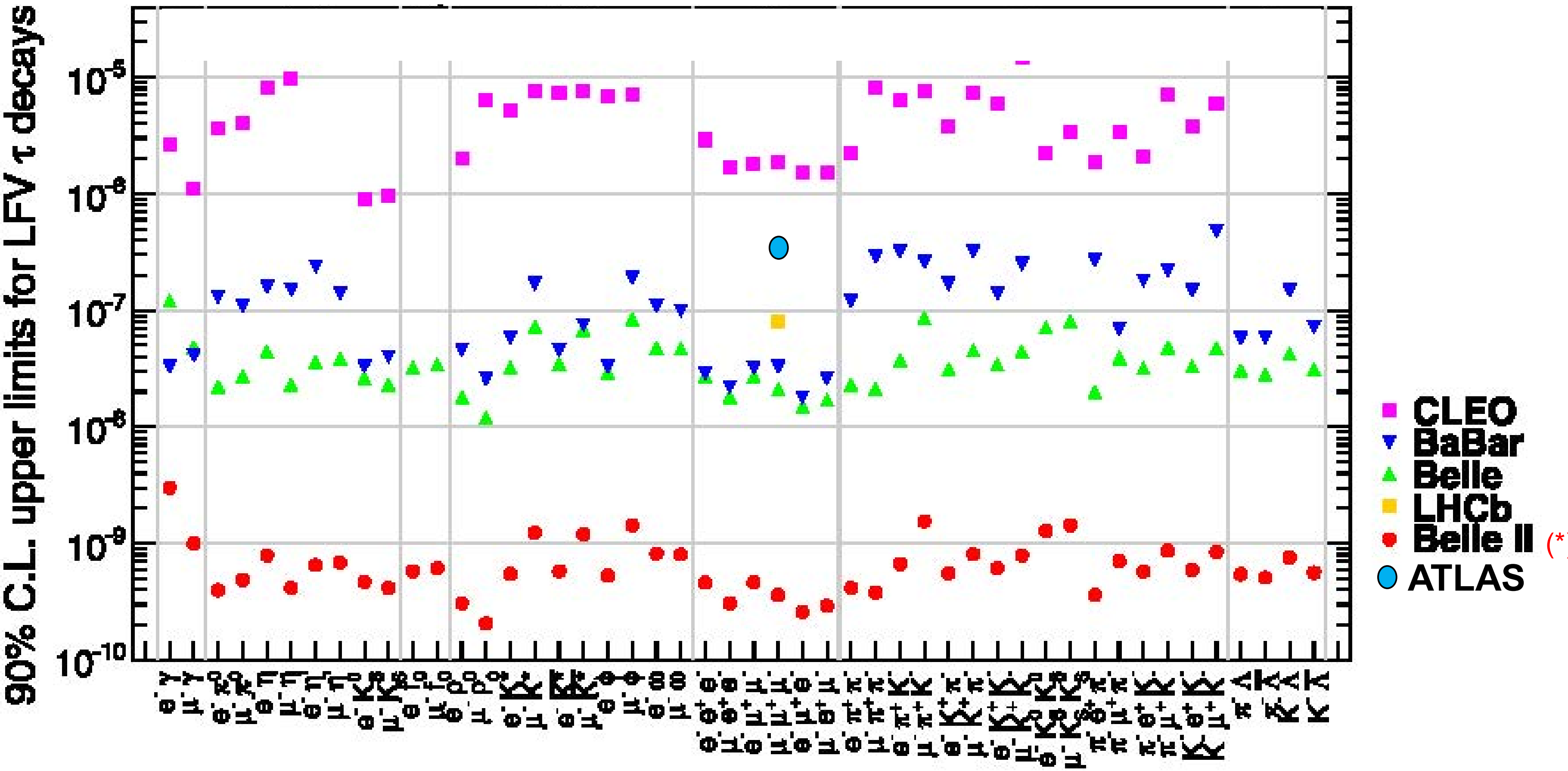
Model	$\tau \to \mu\gamma$	$\tau \to \mu\mu\mu$
SM + ν mixing	10^{-40}	10^{-14}
SM + heavy ν_R	10^{-9}	10^{-10}
Non-universal Z'	10^{-9}	10^{-8}
SUSY SO(10)	10^{-8}	10^{-10}
mSUGRA + seesaw	10^{-7}	10^{-9}
SUSY Higgs	10^{-10}	10^{-7}

[Inami, 2008]

Belle

2010

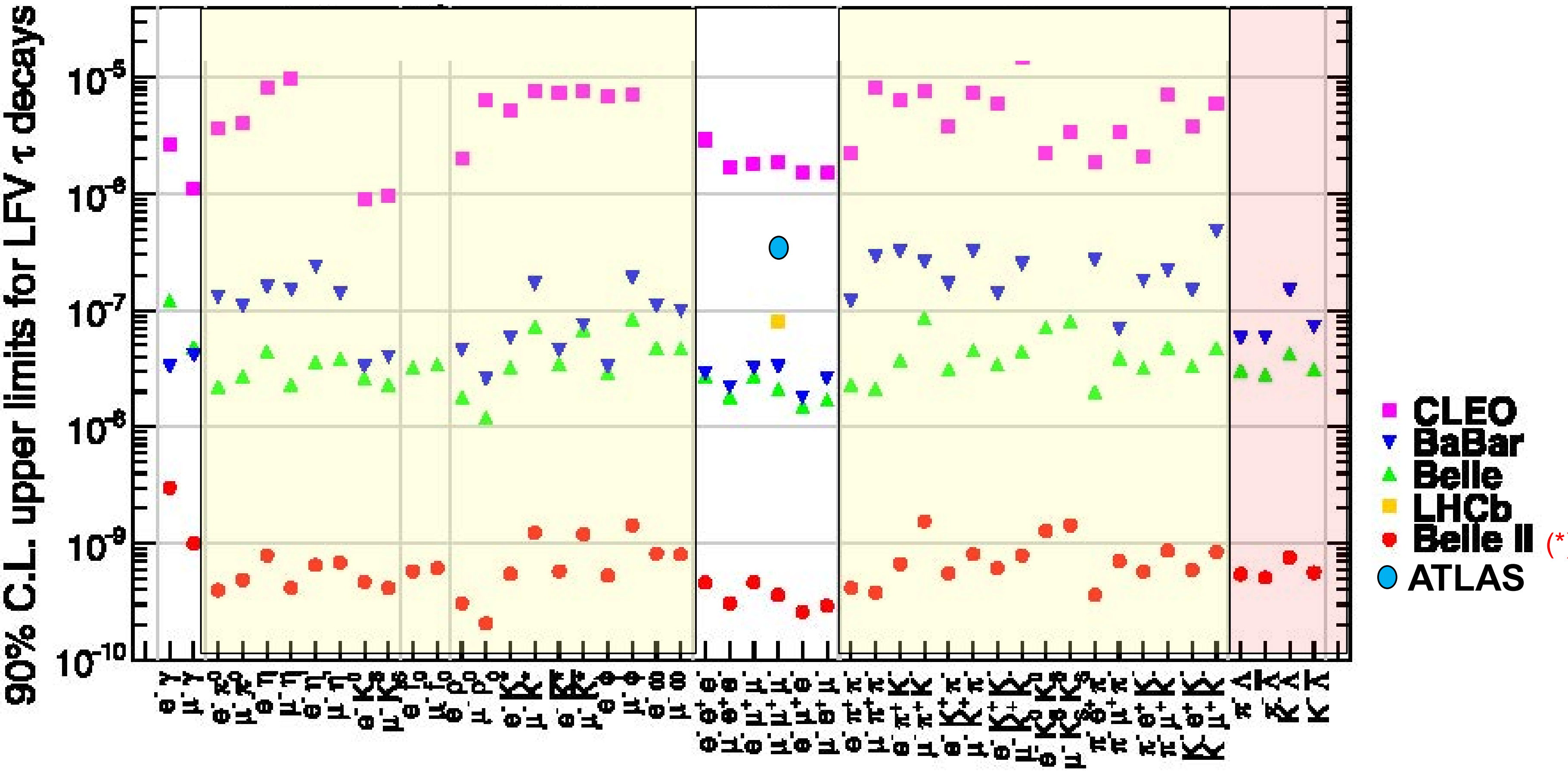
Y. Kwon, SUSY08



[Belle-II, 2019]

(*) Integrated luminosity of 50 ab^{-1}

$\tau \to (P,V)\ell$ $\tau \to PP\ell$



$\tau \to BP$

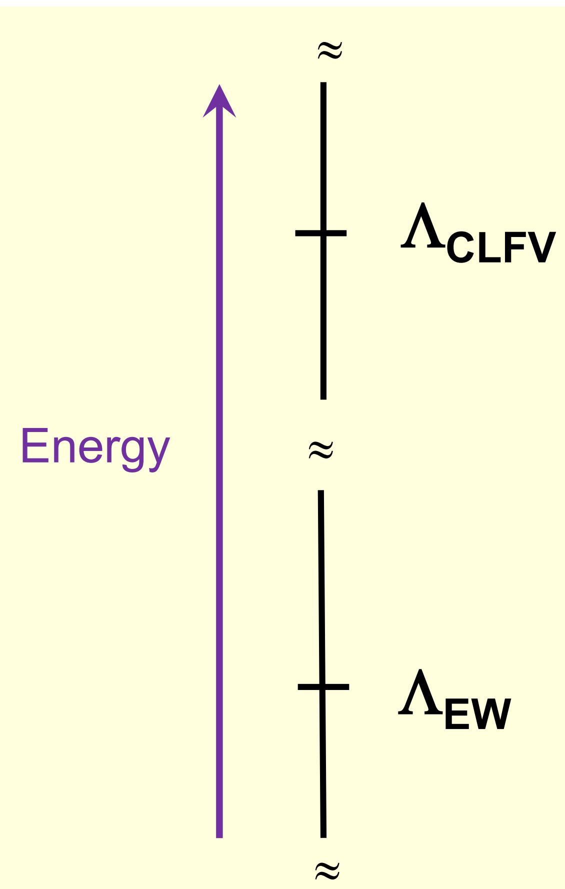
[Belle-II, 2019]

(*) Integrated luminosity of 50 ab^{-1}

Dynamics of CLFV

- ✓ The mass scale of New Physics
- ✓ Symmetries and flavour structure of New Physics

} SMEFT [Buchmüller, 1986]



$$\mathcal{L}_{\rm UV} = \mathcal{L}(\text{your model})$$

New symmetries?
New flavour structure?
New degrees of freedom?

$$M_{\rm H} \gg M_{\rm SM}$$

$$E \ll \Lambda_{\rm CLFV} \quad \Downarrow$$

$$\mathcal{L}_{\rm SMEFT} = \mathcal{L}_{\rm SM} + \sum_{D>4} \left(\frac{1}{\Lambda^{D-4}} \sum_i C_i^{(D)} \, \mathcal{O}_i^{(D)} \right)$$

Model-independent analysis with SMEFT

[Celis1, 2014] [Celis2, 2014] [Gninenko, 2018] [Husek, 2021]

$$\mathcal{L}_{\rm SMEFT} = \mathcal{L}_{\rm SM} + \sum_{D>4} \left(\frac{1}{\Lambda_{\rm CLFV}^{D-4}} \sum_i C_i^{(D)} \mathcal{O}_i^{(D)} \right)$$

CLFV scale

Hadron decays

$$\tau \to \ell P : \qquad P = \pi^0, K^0, \eta, \eta'$$

$$\tau \to \ell P_1 P_2 : \qquad P_1 P_2 = \pi^+\pi^-, K^0\bar{K}^0, K^+K^-, \pi^+K^-.K^+\pi^-$$

$$\tau \to \ell V : \qquad V = \rho^0(770), \omega(782), \phi(1020), K^{*0}(892), \bar{K}^{*0}(892)$$

$\ell - \tau$ conversion in nuclei (NA64 ?) $\qquad \ell = e, \mu$

$$\ell N(A,Z) \to \tau X : \qquad N(A,Z) = \mathrm{Fe}(56,26), \mathrm{Pb}(208,82)$$

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CLFV scale

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$$\Lambda_{\text{CLFV}} > \text{few-tens TeVs}$$

(see Kevin Monsálvez-Pozo's talk)

Lepton and baryon numbers violation

$$\partial_\mu \mathcal{J}_{\rm B}{}^\mu = \partial_\mu \mathcal{J}_{\rm L}{}^\mu = n_g \frac{g^2}{32\pi^2} \varepsilon^{\mu\nu\alpha\beta} W^a_{\mu\nu} W^a_{\alpha\beta} \simeq \mathcal{O}(\hbar)$$

$U(1)_{\rm B - L}$ non-anomalous → Gauge theory (extension of the SM)

Lepton and baryon numbers violation

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$U(1)_{\mathrm{B - L}}$ non-anomalous $\longrightarrow$ Gauge theory (extension of the SM)

SMEFT

New scale Λ_{LB}

$$\mathcal{L}_{\mathrm{SMEFT}} = \mathcal{L}_{\mathrm{SM}} + \sum_{D>4} \left(\frac{1}{\Lambda_{\mathrm{LB}}^{D-4}} \sum_i C_i^{(D)} \mathcal{O}_i^{(D)} \right)$$

$D = 5 \longrightarrow \Delta L = 2\,, \Delta B = 0$

$D = 6 \longrightarrow \Delta L = \Delta B$

[Buchmüller, 1986]
[Grzadkowski, 2010]

$D = 7 \longrightarrow \Delta L \neq 0$ or $\Delta B \neq 0$

[deGouvêa, 2008]

Lepton and baryon numbers violation

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SMEFT

New scale $\Lambda_{\rm LB}$

$$\mathcal{L}_{\rm SMEFT} = \mathcal{L}_{\rm SM} + \sum_{D>4} \left(\frac{1}{\Lambda_{\rm LB}^{D-4}} \sum_i C_i^{(D)} \mathcal{O}_i^{(D)} \right)$$

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$D = 7 \longrightarrow \Delta L \neq 0$ or $\Delta B \neq 0$ [deGouvêa, 2008]

$$D = \text{even} \longrightarrow |\Delta B - \Delta L| = 0, 4, 8, 12, \ldots$$

$$D = \text{odd} \longrightarrow |\Delta B - \Delta L| = 2, 6, 10, 14, \ldots$$

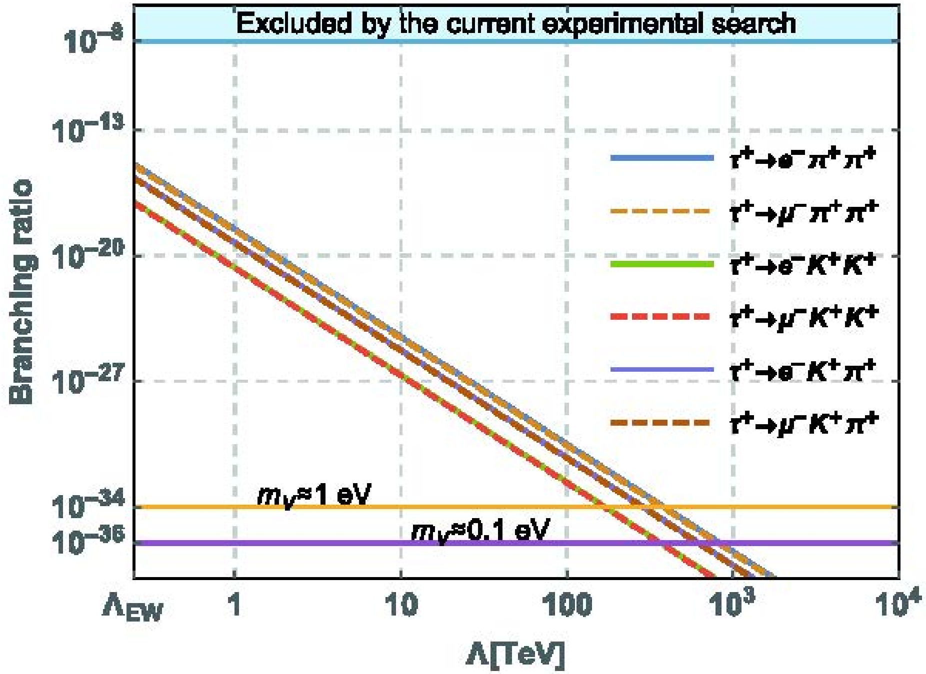
[Kobach, 2016]

[Liao, 2021]

$$\tau^+ \to \ell^- P_i^+ P_j^+ \qquad \ell = e, \mu$$

$$\Delta L = 2 \longrightarrow D = 5, 7$$

$$C_i = 1, \ \forall\, i$$



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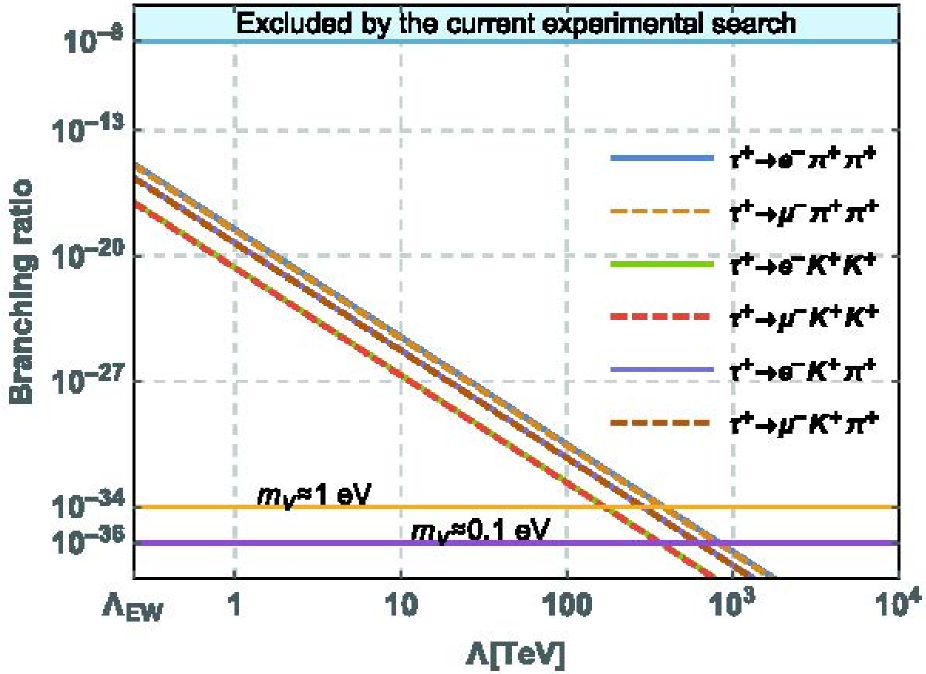

$$\Delta B = \Delta L = \pm 1$$

BR x 10^8	[Belle, 2020]	[LHCb, 2013]
$Br(\tau^- \to \bar{p}\mu^+\mu^-)$	< 1.8	< 23
$Br(\tau^- \to p\mu^-\mu^-)$	< 4.0	< 44
$Br(\tau^- \to \bar{p}e^+e^-)$	< 3.0	
$Br(\tau^- \to pe^-e^-)$	< 3.0	
$Br(\tau^- \to \bar{p}e^+\mu^-)$	< 2.0	
$Br(\tau^- \to \bar{p}e^-\mu^+)$	< 1.8	90% CL

Outlook

Accidental symmetries of the SM seem to stay on the razor's edge:

- If we look for violation of **Universality** in the lepton families we will have to pay close attention to the processes that involve the **tau lepton** in comparison with those involving the lighter leptons.
- We already have seen neutral lepton flavour violation: **neutrinos mix**. There seems to be no reason why **charged lepton flavour violation** should not happen in Nature: the quest on the experimental side is a major task and **Belle II** will play a major role. On the theory side I bet for an interplay between **models** and **SMEFT**.
- **Charged Lepton Flavour Violation** could easily become a window to see **extensions of the Standard Model**. For tau involved processes the time is now.

References (alphabetical order)

[ATLAS, 2021] G. Aad et al (ATLAS Collaboration) Nature Phys. 17 (2021) 7, 813-818.
[Belle-II, 2019] E. Kou (ed.) et al. (Belle-II Collaboration), PTEP 2019 (2019) 12, 123C01.
[Belle, 2020]] D. Sahoo et al. (Belle Collaboration) Phys. Rev. D102 (2020) 111101 (R).
[Buchmüller, 1986] W. Buchmüller, D. Wyler, Nucl. Phys. B268 (1986) 621.
[Celis 1, 2014] A. Celis et al., Phys. Rev. D89 (2014) 013008.
[Celis 2, 2014] A. Celis et al., Phys. Rev. D89 (2014) 095014.
[Chivukula, 1987] B. S. Chivukula, H. Georgi, Phys. Lett. B188 (1987) 99-104.
[deGouvêa, 2008] A. de Gouvêa et al., Phys. Rev. D77 (2008) 013008.
[Filipuzzi, 2012] A. Filipuzzi, J. Portolés, M. González-Alonso, Phys. Rev. D85 (2012) 116010.
[Gninenko, 2018] S. Gninenko et al., Phys. Rev. D98 (2018) 015007.
[Grzadkowski, 2010] B. Grzadkowski et al., JHEP 10 (2010) 085.
[Han, 2006] Z. Han, Phys. Rev. D73 (2006) 015005.
[Husek, 2021] T. Husek et al., JHEP 01 (2021) 059.
[Inami, 2008] K. Inami, Nuclear Physics B (Proc. Suppl.) 181–182 (2008) 295–299.
[Kobach, 2016] A. Kobach, Phys. Lett. B758 (2016) 455-457.
[LHCb, 2013] R. Aaij et al. (LHCb Collaboration), Phys. Lett. B724 (2013) 36-45.
[Liao, 2021] Yi Liao et al., Chinese Phys. C45 (2021) 073102.
[PDG, 2020] P. A. Zyla et al,(Particle Data Group) Prog. Theor. Exp. Phys. 2020, 083C01 (2020).
[Pich, 2020] A. Pich, arXiv 2012.07099 [hep-ph].