Tau physics

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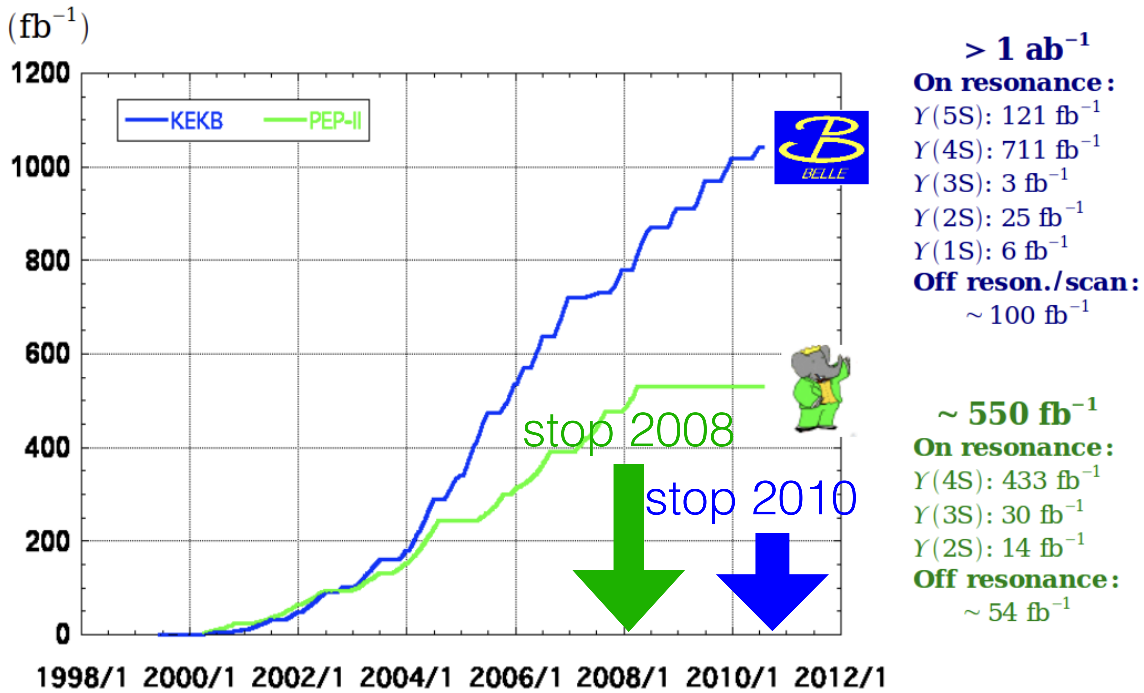
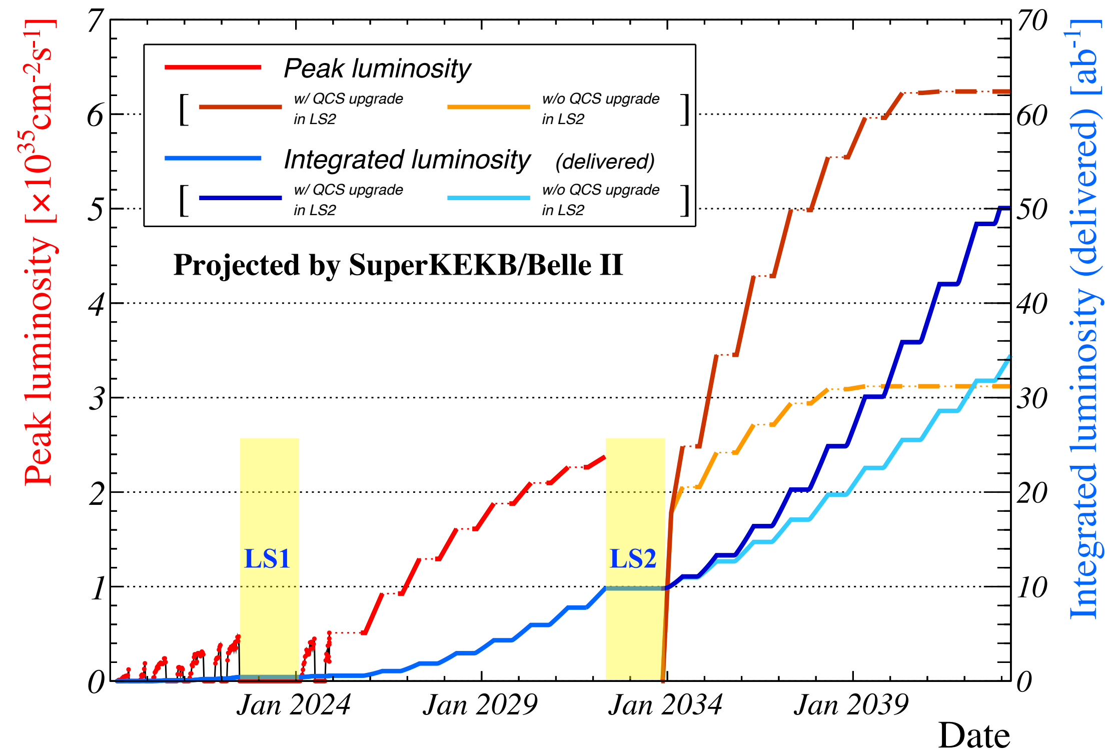
2025 Belle II Summer Workshop

B factories are also τ factories

Integrated luminosity of B factories



Projected luminosity at SuperKEKB/Belle II



500 million τ-pairs produced at BABAR with $\simeq 0.5\ ab^{-1}$ of data

1 billion τ-pairs produced at Belle with $\simeq 1\ ab^{-1}$ of data

50 billion τ-pairs expected at Belle II with $\simeq 50\ ab^{-1}$ of data

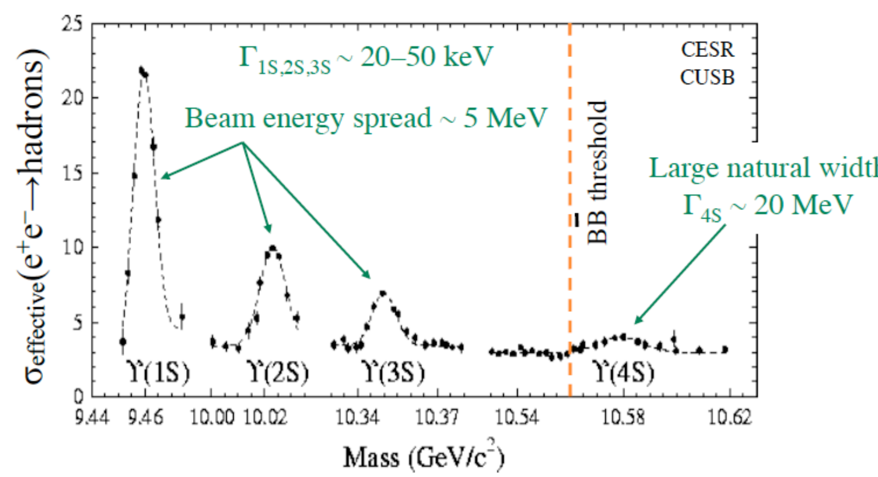
At $\Upsilon(4S)$: $e^+e^- \to Z^*/\gamma \to \tau^+\tau^-$.

Also $e^+e^- \to \Upsilon(nS) \to \tau^+\tau^-$ for n = 1, 2, 3

$B(\Upsilon(1,2,3S) \to \tau^+\tau^-) \sim 2\%$, < 0.002% at $\Upsilon(4S)$

- $\sigma(e^+e^- \to \tau^+\tau^-) = (0.919 \pm 0.003)$ nb

SwB, B. Pietrzyk, J.Roney, Z.Was Phys.Rev.D 77 (2008) 054012



Physics results from tau leptons

- **Cabibbo angle anomaly $|V_{us}|$ (BaBar, Belle (II))**
  - **Precision improved by additional measurements of**
    - **m_τ, τ_τ (BaBar, Belle (II), STCF, FCC-ee)** NEW *PRD 108 (2023) 3, 032006*
    - **$|g_\mu/g_e|, |g_\tau/g_e|, |g_\tau/g_\mu|$ (BaBar, Belle (II))** NEW *JHEP 08 (2024) 205*
- **Lepton flavor violation (charge conjugate modes implied)**
  - **$\tau \to \ell\gamma$ (BaBar, Belle (II), STCF, FCC-ee)**
  - **$\tau \to \ell$(scalar/pseudoscalar/vector mesons) (BaBar, Belle (II))** NEW!
  - **$\tau \to \ell\ell\ell$ (BaBar, Belle II, ATLAS, CMS, LHCb, STCF, FCC-ee)** NEW!
  - **$\tau \to \ell$ h h (non-resonant states with h=π/K) (BaBar, Belle (II), STCF)**
  - **$\tau \to \ell$ invisible (α) (Belle (II))** New *PRL 130 (2023) 18, 181803* *2503.22195 [hep-ex]*
  - **e → τ transitions (EIC)**

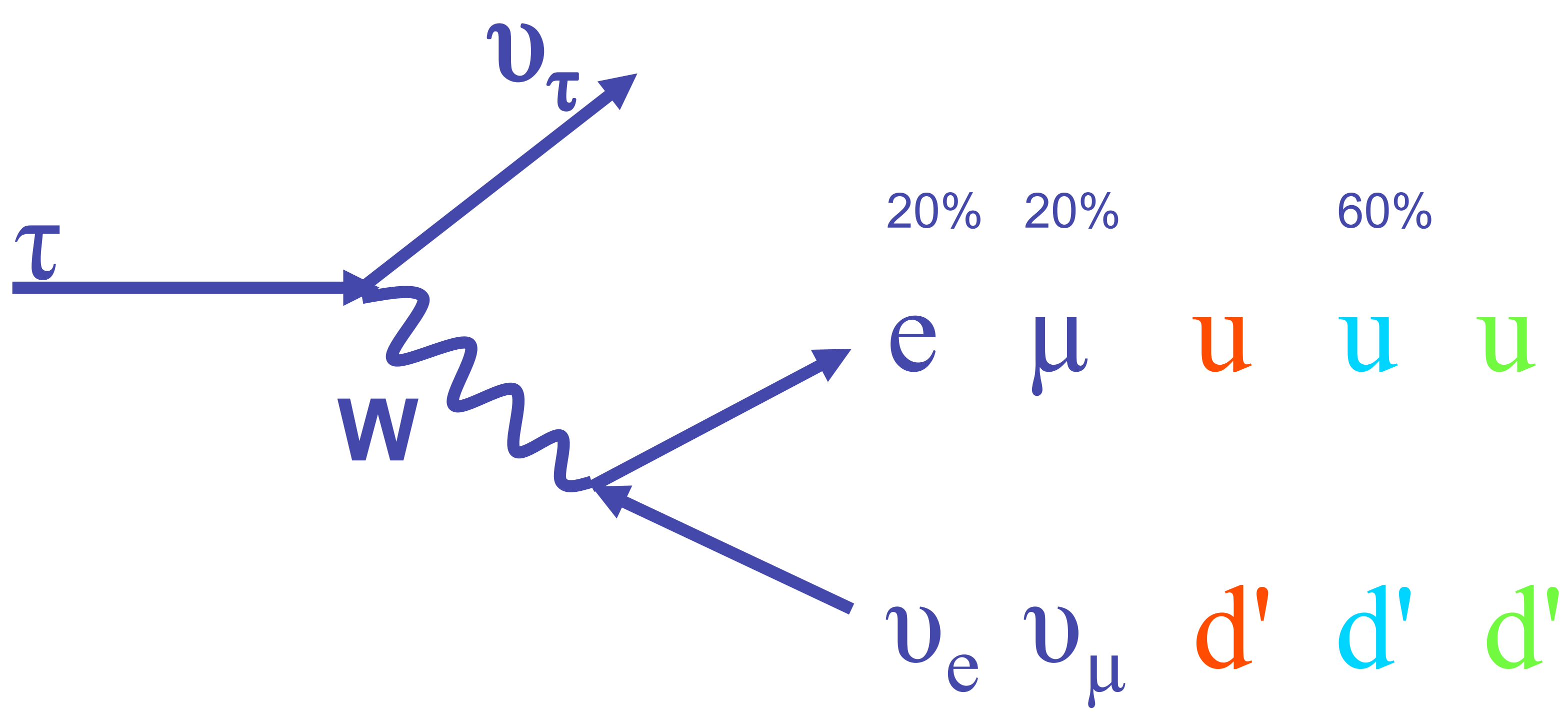
$\tau \to \ell K^0_S$ *2504.15745 [hep-ex]*

$\tau \to \mu\mu\mu$ *JHEP 09 (2024) 062*

- **Lepton number violation**
  - **$\tau^- \to e^+ h^- h^-$ (non-resonant final states with h=π/K) (BaBar, Belle (II))**
  - **$\tau^- \to \mu^+ h^- h^-$ (non-resonant final states with h=π/K) (BaBar, Belle (II))**
- **Baryon number violation**
  - **$\tau^- \to \Lambda\, \pi^-, \bar{\Lambda}\, \pi^-$ (Belle II)** NEW *PRD 110 (2024) 11, 112003*
  - **$\tau^- \to \bar{p}\, \mu^+ \mu^-, p\, \mu^- \mu^-$ (Belle)**

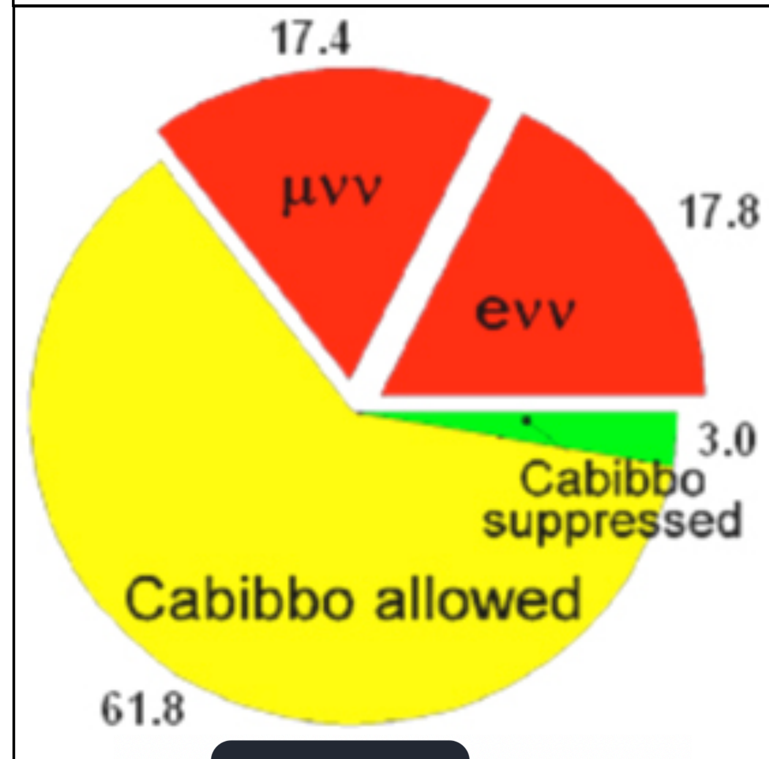
τ decays

Naive prediction:



$$|d'\rangle = V_{ud}|d\rangle + V_{us}|s\rangle$$

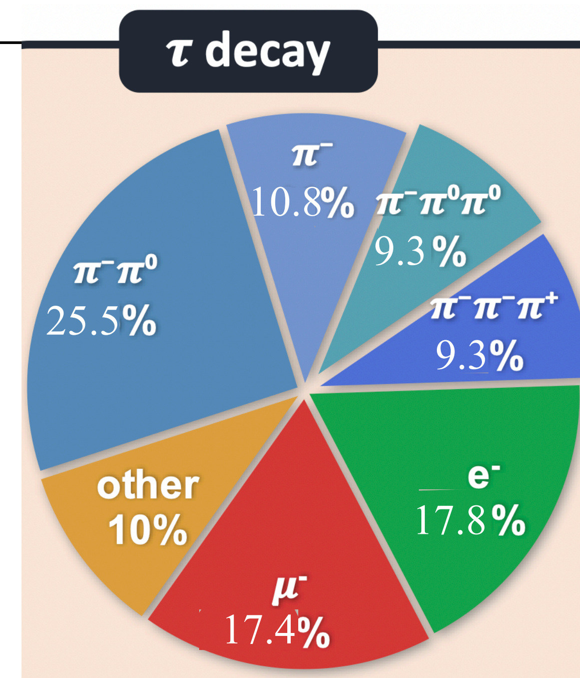
Including QED & QCD corrections:



τ^- DECAY MODES	Fraction (Γ_i/Γ)	Scale factor/ Confidence level	p (MeV/c)
Modes with one charged particle			
particle$^- \geq 0$ neutrals $\geq 0K^0\nu_\tau$ ("1-prong")	(85.24 ± 0.06) %		–
particle$^- \geq 0$ neutrals $\geq 0K^0_L\nu_\tau$	(84.58 ± 0.06) %		–
$\mu^-\overline{\nu}_\mu\nu_\tau$	[g] (17.39 ± 0.04) %		885
$\mu^-\overline{\nu}_\mu\nu_\tau\gamma$	[e] $(3.67 \pm 0.08) \times 10^{-3}$		885
$e^-\overline{\nu}_e\nu_\tau$	[g] (17.82 ± 0.04) %		888
$e^-\overline{\nu}_e\nu_\tau\gamma$	[e] (1.83 ± 0.05) %		888
$h^- \geq 0K^0_L\,\nu_\tau$	(12.03 ± 0.05) %		883
$h^-\nu_\tau$	(11.51 ± 0.05) %		883
$\pi^-\nu_\tau$	[g] (10.82 ± 0.05) %		883
$K^-\nu_\tau$	[g] $(6.96 \pm 0.10) \times 10^{-3}$		820

The Review of Particle Physics (2021)

P.A. Zyla *et al.* (Particle Data Group), Prog. Theor. Exp. Phys. 2020, 083C01 (2020) and 2021 update.



τ branching fractions are relatively well measured

- Most of the branching fractions are highly correlated.
- Sources of correlation between the same experiment:
  - Track reconstruction ~ 1% for 1-vs-1 topology
  - Secondary vertex reconstruction ~ 1.5% for K_S
  - Calorimeter bump reconstruction ~ 2-4% for π^0
  - Kaon/Pion identification ~ 2-4 %
  - Luminosity uncertainty ~ 1%

Sources of correlation between different experiments:
  - Tau-pair cross-section uncertainty ~ 0.36%
  - Uncertainty on Branching Fractions of backgrounds

➡ Simultaneous averaging of all branching fractions

Heavy Flavor Averaging Group (HFLAV)

- Minimize total χ^2 of 172 measurements with uncertainties:
  - 39 from ALEPH
  - 35 from CLEO
  - 24 from BaBar
  - 19 from OPAL
  - 15 from Belle
  - 1 from Belle II
  - 14 from DELPHI
  - 11 from L3
  - 6 from CLEO3
  - 3 from TPC
  - 2 from ARGUS
  - 2 from HRS
  - 1 from CELLO

- correlations between measurements
- common external parameters such as tau-pair cross-section and background normalization
- avoid inflating uncertainties using PDG-style scale factors
- instead, quote confidence level

HFLAV 2023 fit [e-Print: 2411.18639 [hep-ex]]

- 137 fit parameters (1 nuisance parameter)
- $\chi^2/\mathrm{d.o.f.} = 138/125, P(\chi^2) = 20.2\,\%$
- Unitarity residual $1 - \mathscr{B}_{\mathrm{all}} = 0.0007 \pm 0.0011$

The route to |Vus| from inclusive strange τ decays

HFLAV 2023 fit [e-Print: 2411.18639 [hep-ex]]

Branching fraction	HFLAV 2023 fit (%)
$\mathcal{B}(\tau^- \to K^-\nu_\tau)$	0.6959 ± 0.0096
$\mathcal{B}(\tau^- \to K^-\pi^0\nu_\tau)$	0.4321 ± 0.0148
$\mathcal{B}(\tau^- \to K^-2\pi^0\nu_\tau$ (ex.K^0))	0.0634 ± 0.0219
$\mathcal{B}(\tau^- \to K^-3\pi^0\nu_\tau$ (ex.K^0,η))	0.0465 ± 0.0213
$\mathcal{B}(\tau^- \to \pi^-\overline{K}^0\nu_\tau)$	0.8375 ± 0.0139
$\mathcal{B}(\tau^- \to \pi^-\overline{K}^0\pi^0\nu_\tau)$	0.3810 ± 0.0129
$\mathcal{B}(\tau^- \to \pi^-\overline{K}^02\pi^0\nu_\tau$ (ex.K^0))	0.0234 ± 0.0231
$\mathcal{B}(\tau^- \to \overline{K}^0h^-h^-h^+\nu_\tau)$	0.0222 ± 0.0202
$\mathcal{B}(\tau^- \to K^-\eta\nu_\tau)$	0.0155 ± 0.0008
$\mathcal{B}(\tau^- \to K^-\pi^0\eta\nu_\tau)$	0.0048 ± 0.0012
$\mathcal{B}(\tau^- \to \pi^-\overline{K}^0\eta\nu_\tau)$	0.0094 ± 0.0015
$\mathcal{B}(\tau^- \to K^-\omega\nu_\tau)$	0.0410 ± 0.0092
$\mathcal{B}(\tau^- \to K^-\phi(K^+K^-)\nu_\tau)$	0.0022 ± 0.0008
$\mathcal{B}(\tau^- \to K^-\phi(K^0_SK^0_L)\nu_\tau)$	0.0015 ± 0.0006
$\mathcal{B}(\tau^- \to K^-\pi^-\pi^+\nu_\tau$ (ex.K^0,ω))	0.2924 ± 0.0068
$\mathcal{B}(\tau^- \to K^-\pi^-\pi^+\pi^0\nu_\tau$ (ex.K^0,ω,η))	0.0388 ± 0.0142
$\mathcal{B}(\tau^- \to K^-2\pi^-2\pi^+\nu_\tau$ (ex.K^0))	0.0001 ± 0.0001
$\mathcal{B}(\tau^- \to K^-2\pi^-2\pi^+\pi^0\nu_\tau$ (ex.K^0))	0.0001 ± 0.0001
$\mathcal{B}(\tau^- \to X_s^-\nu_\tau)$	2.9078 ± 0.0478

$$|V_{us}|_{\tau s} = \sqrt{R_s \Big/ \left[\frac{R_{VA}}{|V_{ud}|^2} - \delta R_{\text{theory}}\right]}$$

$\mathcal{B}_s = (2.908 \pm 0.048)\%$

$\mathcal{B}_{all} = (99.93 \pm 0.11)\%$ instead of 100%

to account for correlations

& unobserved hadronic modes

$\mathcal{B}_{hadrons} = \mathcal{B}_{all} - \mathcal{B}_e - \mathcal{B}_\mu$

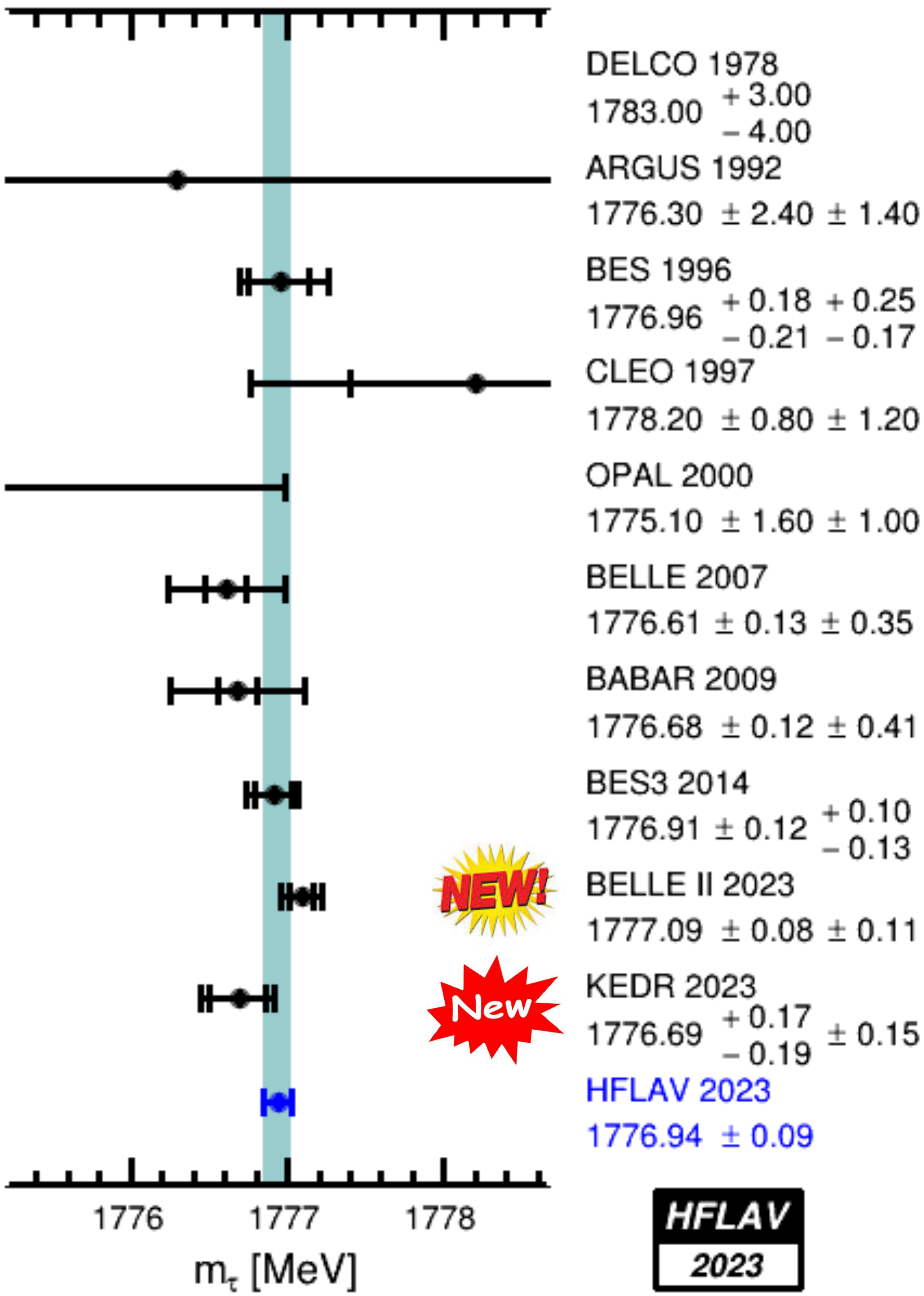
$\mathcal{B}_{VA} = \mathcal{B}_{hadrons} - \mathcal{B}_s = (61.82 \pm 0.10)\%$

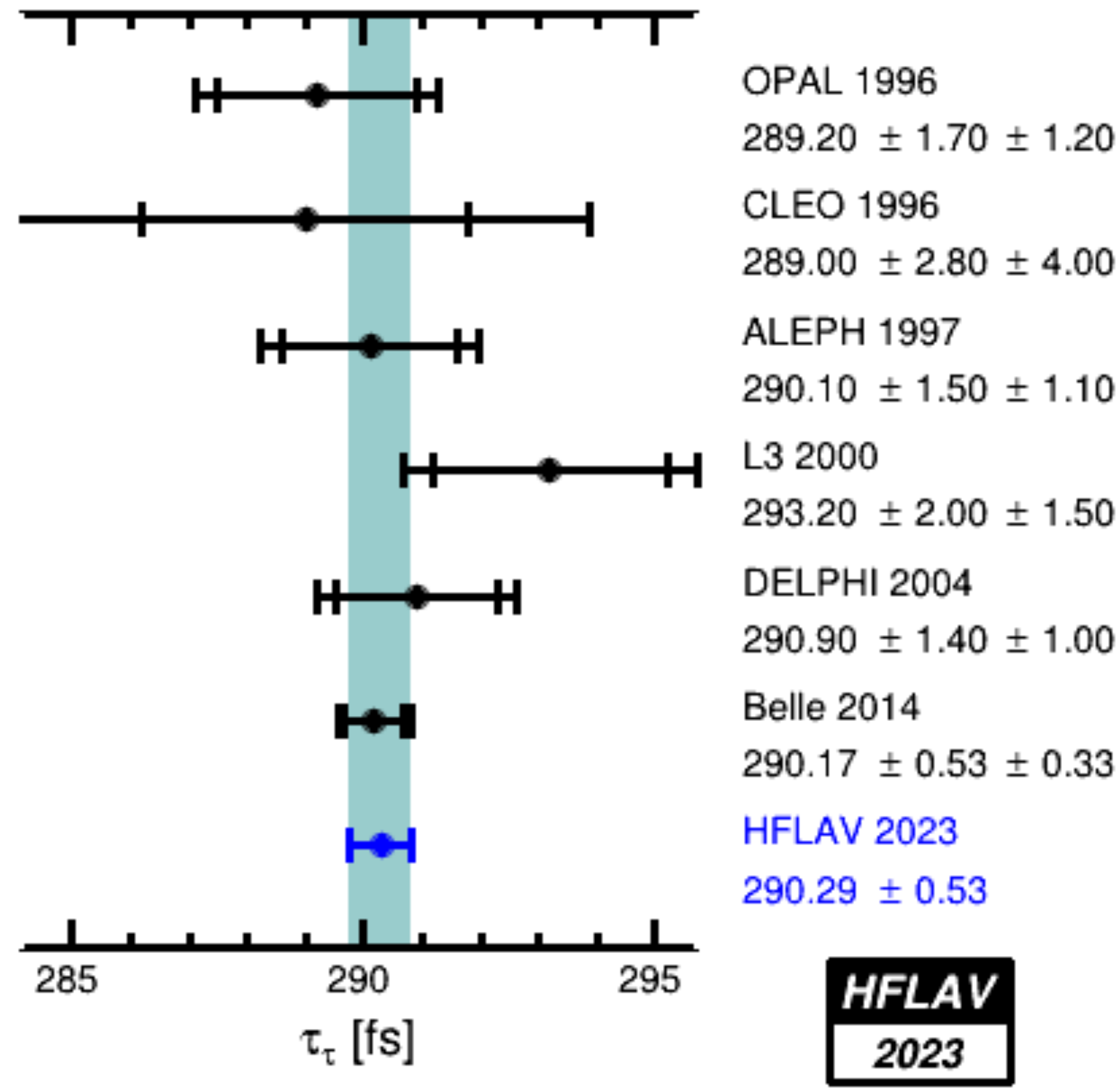
To get R, we normalize by

$\mathcal{B}_e = (17.84 \pm 0.04)\%$

- Improve $\mathcal{B}_e$ using
  - lepton universality
  - mass (m_τ)
  - lifetime (τ_τ)

Tau mass and lifetime





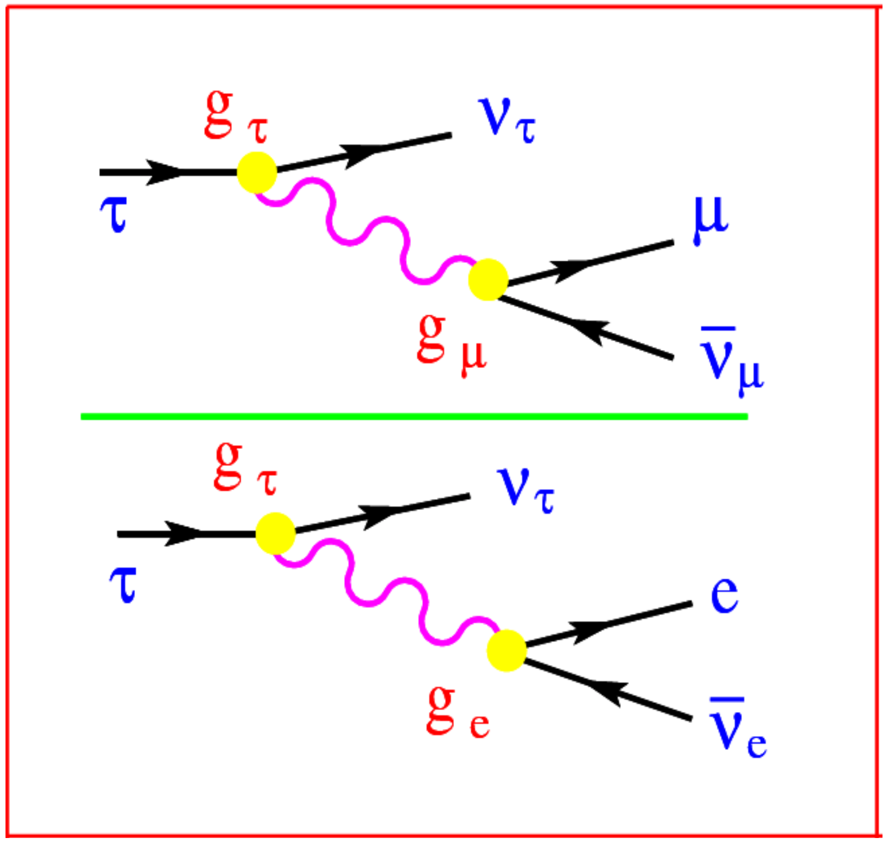
	τ mass [MeV]
PDG 2023	1776.86 ± 0.12
PDG 2024	1776.93 ± 0.09
HFLAV 2023	1776.94 ± 0.09

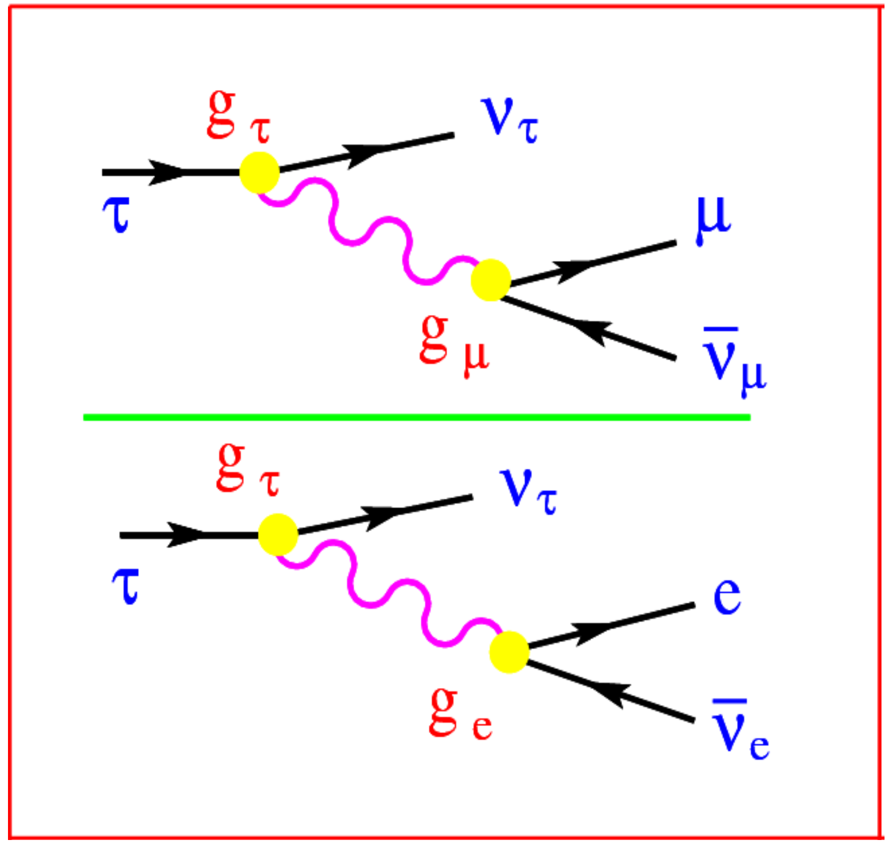
Lepton universality from leptonic decays

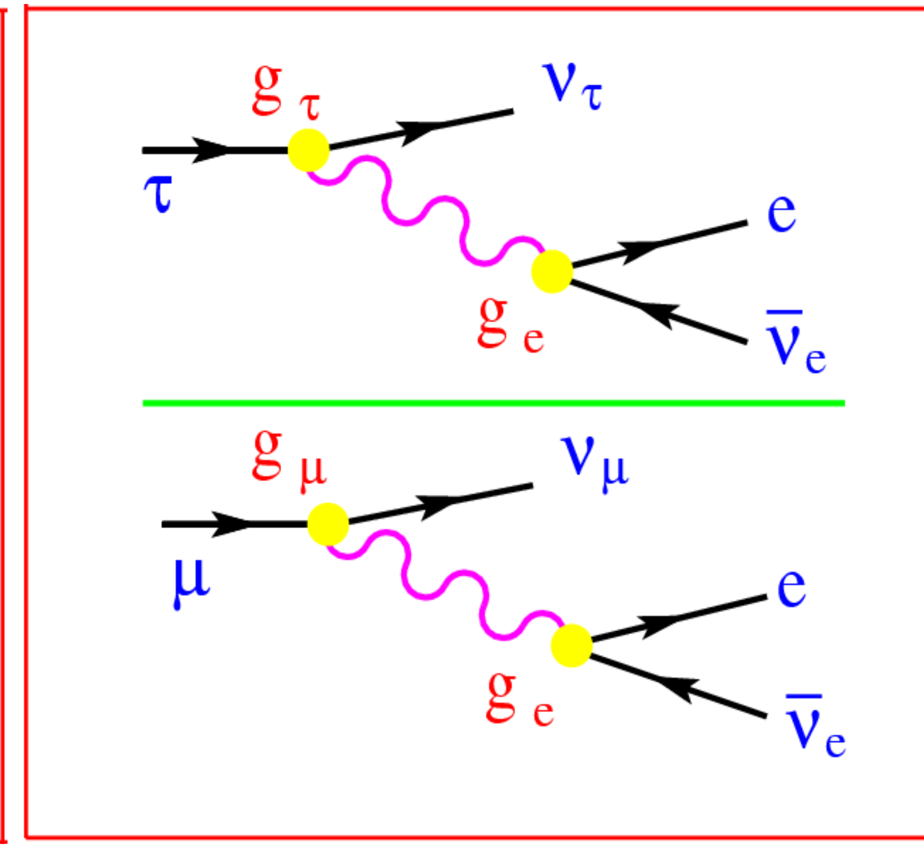
$$\left(\frac{g_\mu}{g_e}\right)^2 = \frac{\mathcal{B}(\tau^- \to \mu^- \bar{\nu}_\mu \nu_\tau)}{\mathcal{B}(\tau^- \to e^- \bar{\nu}_e \nu_\tau)} \frac{f(m_e^2/m_\tau^2)}{f(m_\mu^2/m_\tau^2)}$$

$$\left(\frac{g_\tau}{g_e}\right)^2 = \frac{\tau_\mu}{\tau_\tau}\mathcal{B}(\tau^- \to \mu^- \bar{\nu}_\mu \nu_\tau)\left(\frac{m_\mu}{m_\tau}\right)^5 \frac{f(m_e^2/m_\mu^2) r_{EW}^\mu}{f(m_\mu^2/m_\tau^2) r_{EW}^\tau}$$

$$\left(\frac{g_\tau}{g_\mu}\right)^2 = \frac{\tau_\mu}{\tau_\tau}\mathcal{B}(\tau^- \to e^- \bar{\nu}_e \nu_\tau)\left(\frac{m_\mu}{m_\tau}\right)^5 \frac{f(m_e^2/m_\mu^2) r_{EW}^\mu}{f(m_e^2/m_\tau^2) r_{EW}^\tau}$$





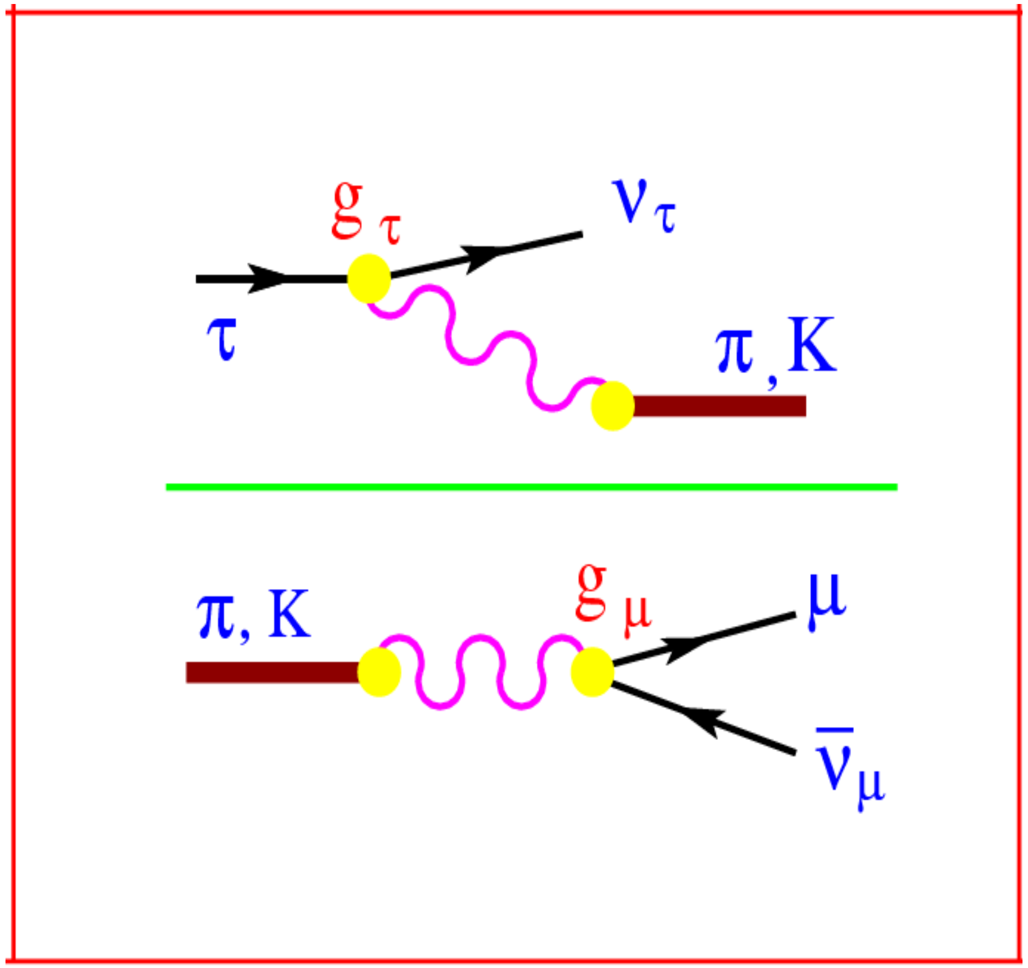


$\left(\frac{g_\mu}{g_e}\right) = 1.0002 \pm 0.0011$ improved by Belle II JHEP 08 (2024) 205 measurement of $\mathcal{B}_{\tau\mu}/\mathcal{B}_{\tau e}$ [Adachi et al., 2024], was 1.0019 ± 0.0014

Precision $\sim$ [0.20, 0.23] % before B-Factories; $\sim$ [0.14, 0.15] % end of 2024

- Improved due to Belle measurement of τ lifetime [PRL 112 (2014) 031801)
- Lepton universality tests limited by precision of $\mathcal{B}_{\tau\mu/\tau e}$, not any more by τ_τ

Lepton universality from hadronic decays



$$\left(\frac{g_\tau}{g_\mu}\right)^2 = \frac{2m_h m_\mu^2 \tau_h}{(1+\delta_{\tau/h}) m_\tau^3 \tau_\tau} \frac{\mathscr{B}(\tau^- \to h^- \nu_\tau)}{\mathscr{B}(h^- \to \mu^- \bar{\nu}_\mu)} \left(\frac{1 - m_\mu^2/m_h^2}{1 - m_h^2/m_\tau^2}\right)^2$$

Normalized with muons rather than helicity-suppressed electronic channel.

Measure:

$m_\tau, \tau_\tau, \mathscr{B}(\tau^- \to h^- \nu_\tau)$ $[h^- = \pi^-/K^-]$

Radiative corrections: $\delta_\pi = (0.18 \pm 0.57)\,\%$, $\delta_K = (0.97 \pm 0.58)\,\%$

M. A. Arroyo-Ureña et al., Phys. Rev. D 104 (2021) L091502

$$\left(\frac{g_\tau}{g_\mu}\right)_\pi = 0.9959 \pm 0.0038 \qquad \left(\frac{g_\tau}{g_\mu}\right)_K = 0.9855 \pm 0.0075$$

$$\left(\frac{g_\tau}{g_\mu}\right)_\tau = 1.0016 \pm 0.0014$$ (from leptonic modes & m_τ)

$$\left(\frac{g_\tau}{g_\mu}\right)_{\tau+\pi+K} = 1.0010 \pm 0.0014$$

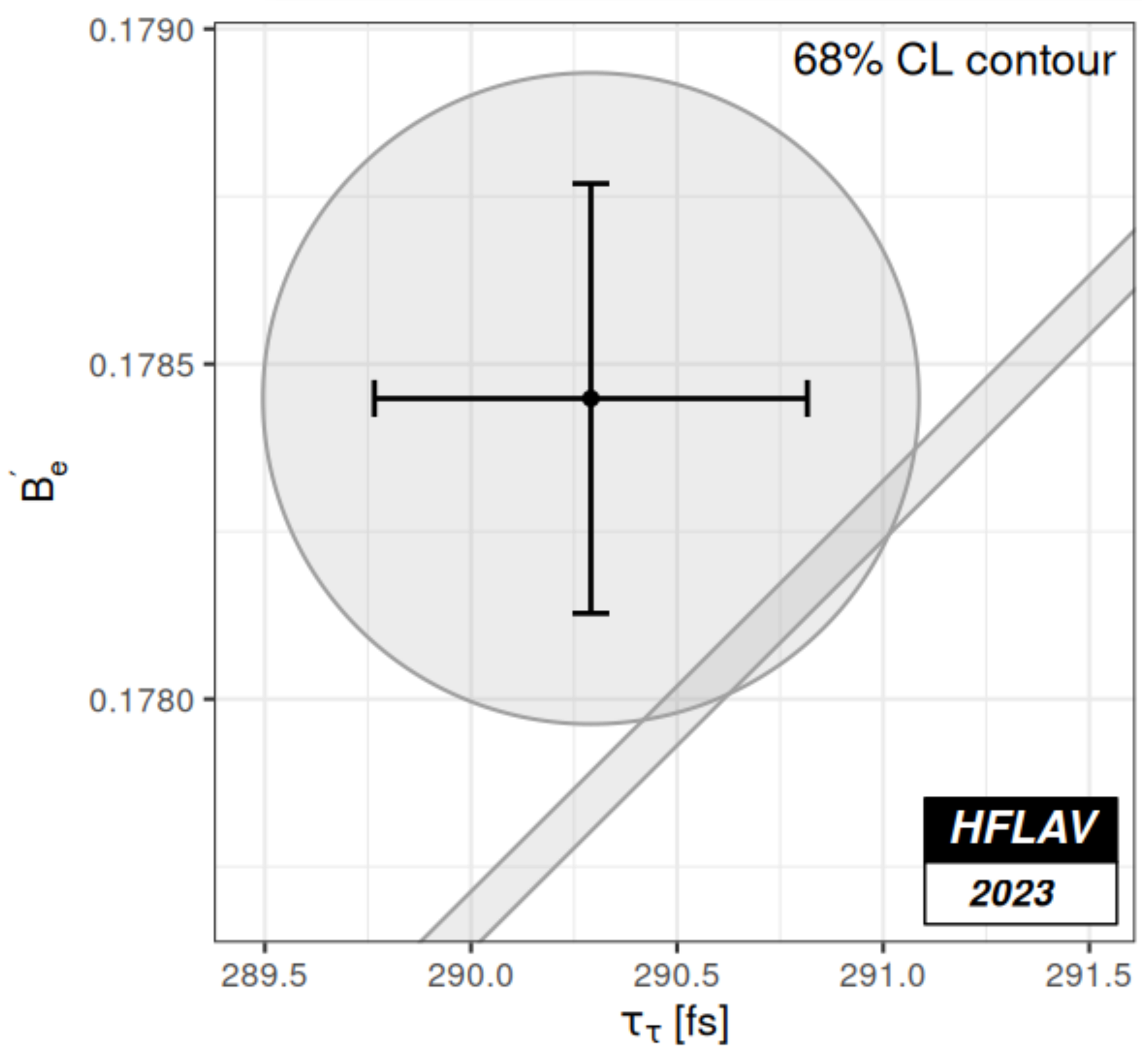
HFLAV 2023

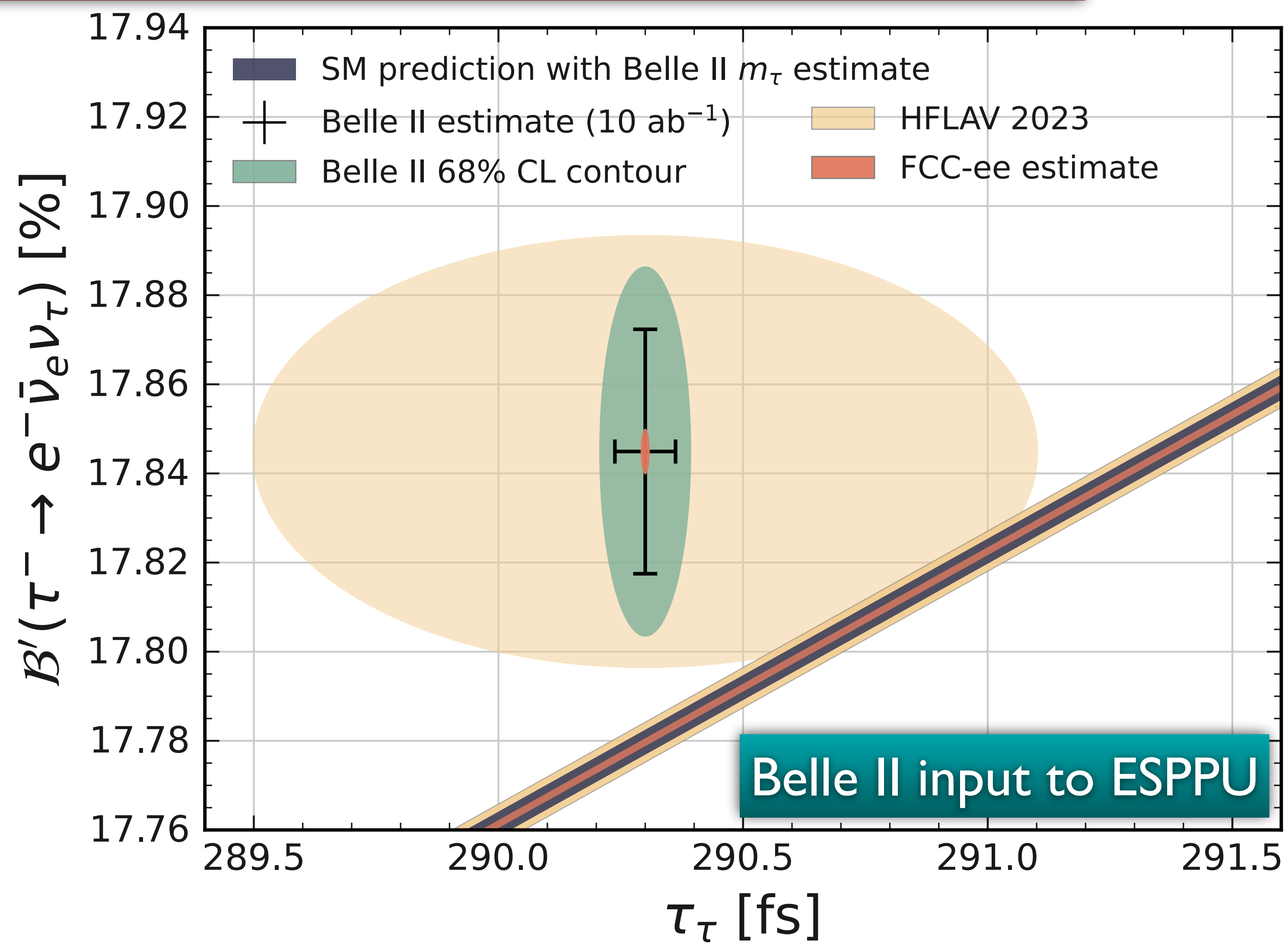
$\left(\frac{g_\tau}{g_e}\right)_\tau$	67			
$\left(\frac{g_\mu}{g_e}\right)_\tau$	-41	40		
$\left(\frac{g_\tau}{g_\mu}\right)_\pi$	18	19	1	
$\left(\frac{g_\tau}{g_\mu}\right)_K$	12	12	-1	7
	$\left(\frac{g_\tau}{g_\mu}\right)_\tau$	$\left(\frac{g_\tau}{g_e}\right)_\tau$	$\left(\frac{g_\mu}{g_e}\right)_\tau$	$\left(\frac{g_\tau}{g_\mu}\right)_\pi$

Lepton Universality Sensitivity

$\mathscr{B}'_e$
- $\mathscr{B}_e$ from standalone measurements
- $\mathscr{B}_e$ from $\mathscr{B}_\mu$ measurements assuming $|g_\mu/g_e| = 1$

Comparison of $\mathscr{B}'_e$ with $\mathscr{B}_e$ from m_τ & τ_τ assuming $|g_\tau/g_\mu| = 1$





Statistical errors $\propto 1/\sqrt{\mathscr{L}}$; assume factor of 2 improvement in systematic: momentum scale, beam energy, lepton identification, statistics of calibration

Lepton universality improved $|V_{us}|$ from inclusive τ decays

- $\mathcal{B}_e$ from standalone measurements
- $\mathcal{B}_e$ from $\mathcal{B}_\mu$ measurements assuming $|g_\mu/g_e| = 1$
- $\mathcal{B}_e$ from m_τ & τ_τ measurements assuming $|g_\tau/g_\mu| = 1$

Correlated average : $\boxed{\mathcal{B}_e^{\rm uni} = (17.815 \pm 0.023)\%}$

$\Rightarrow$ improvement by almost a factor of 2 from the value of $B_e = (17.84 \pm 0.04)\%$

We use $\mathcal{B}_e^{\rm uni}$ to obtain the ratios

$$R_{\rm had} = \frac{\Gamma(\tau \to {\rm hadrons})}{\Gamma(\tau \to e\overline{\nu}_e\nu_\tau)} = \frac{\mathcal{B}_{\rm had}}{\mathcal{B}_e^{\rm uni}} = 3.634 \pm 0.008\,, \quad R_s = 0.1632 \pm 0.0027, \quad R_{\rm ud} = 3.470 \pm 0.008.$$

$$|V_{us}|_{\tau s} = \sqrt{R_s / \left[\frac{R_{\rm VA}}{|V_{ud}|^2} - \delta R_{\rm theory}\right]}$$

$\boxed{\Rightarrow |V_{us}| = (0.2184 \pm 0.0021)}$

[relative error = 0.96%]

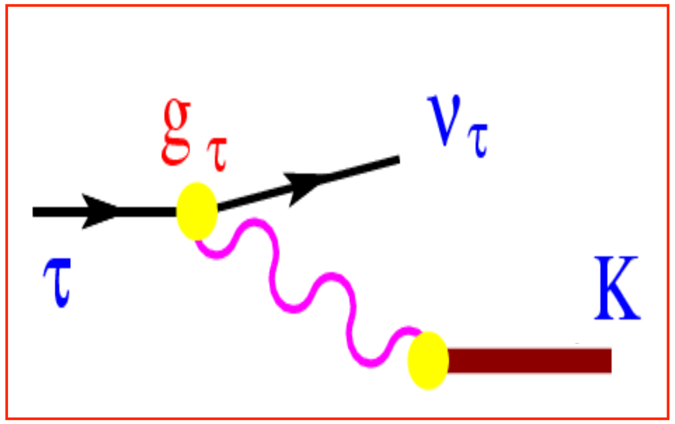
The measured $|V_{us}|$ values & errors are numerically almost identical using

- measured $B_{had} = B_{non\text{-}strange} + B_s$ from non-unity-constrained τ BR fit, OR
- $B_{had} = 1 - (1 + f_\mu/f_e)\, B_e^{univ}$ from unity constrained τ BR fit

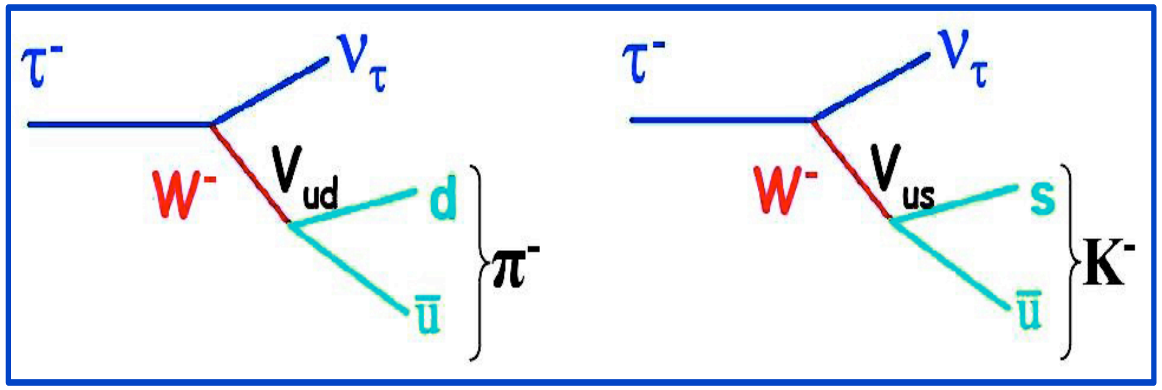
Dominant contribution to error on $|V_{us}|$ comes from error on the measured $R_{strange}$.

$\delta R_{theory} = 0.239 \pm 0.032$ [Gamiz 2007] contributes to 0.47% of the error on $|V_{us}|$.

$|V_{us}|$ from exclusive τ decays



$$\mathcal{B}(\tau^- \to K^-\nu_\tau) = \frac{G_F^2}{16\pi\hbar} f_{K\pm}^2 |V_{us}|^2 \tau_\tau m_\tau^3 \left(1 - \frac{m_K^2}{m_\tau^2}\right)^2 S_{\rm EW}^{\tau h}(1+\delta_{\tau K})$$



$$\frac{\mathcal{B}(\tau^- \to K^-\nu_\tau)}{\mathcal{B}(\tau^- \to \pi^-\nu_\tau)} = \frac{f_{K\pm}^2 |V_{us}|^2}{f_{\pi\pm}^2 |V_{ud}|^2} \frac{(m_\tau^2 - m_K^2)^2}{(m_\tau^2 - m_\pi^2)^2} (1+\delta_{\tau K/\tau\pi})$$

- Independent of convergence of OPE/FESR, as many QCD corrections cancel.
- EW corrections S_{EW} =1.01910 ± 0.00030 [Erler 2004, Pich 2014, Davier 2023]
- $\delta_{\tau K/\tau\pi}$ known [Decker & Finkmeier 1995, Marciano 2004, Arroyo-Ureña 2021]
- All non-perturbative QCD effects encapsulated as ratio of meson decay constants:

f_K/f_π = 1.1934 ± 0.0019, f_K = 155.7 ± 0.3 MeV [FLAG 2021 Lattice Averages]

Summary of $|V_{us}|$ results

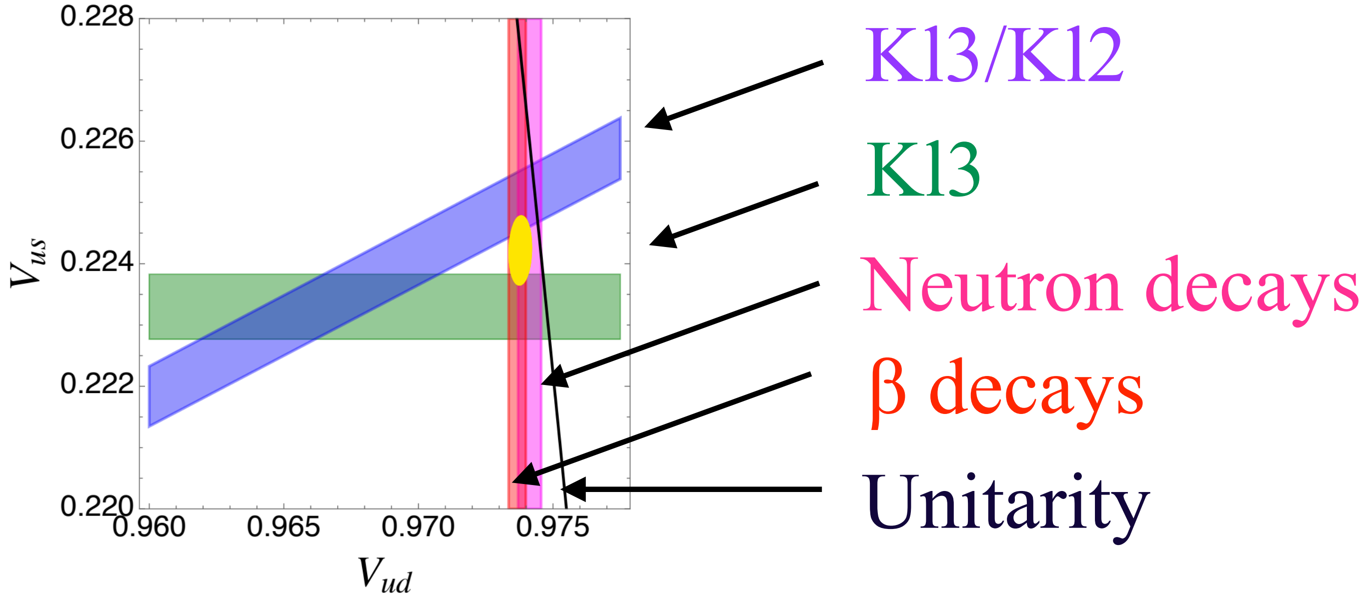
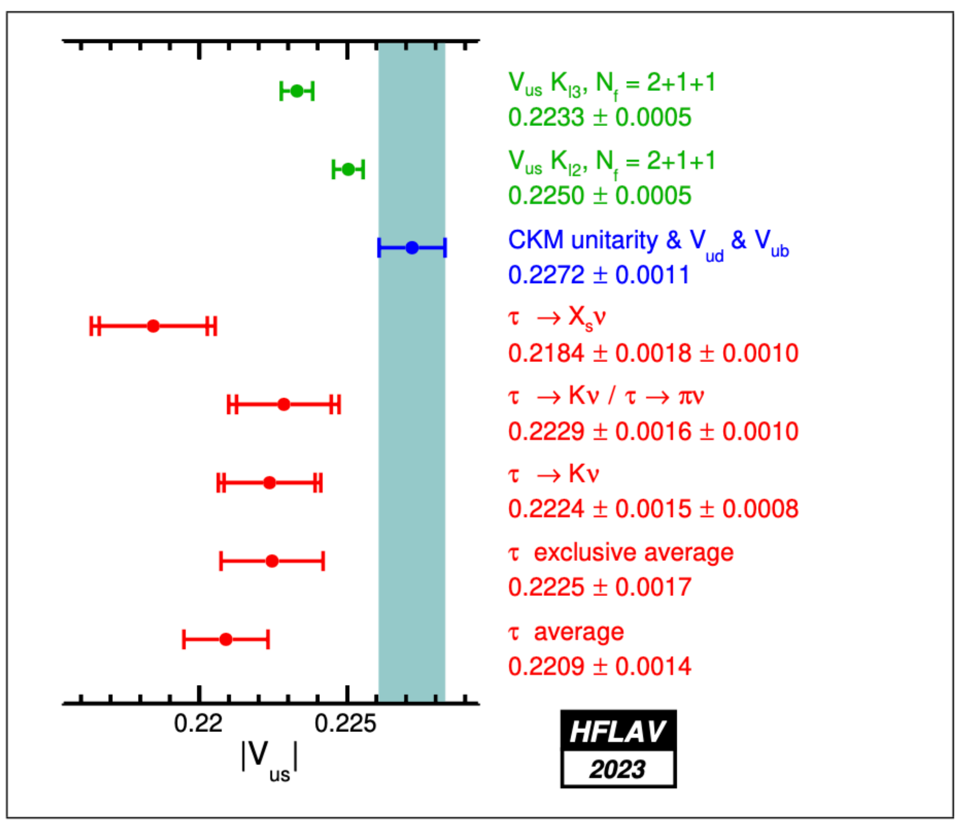


Figure 1: Constraints in the V_{ud}–V_{us} plane. The partially overlapping vertical bands correspond to $V_{ud}^{0^+\to 0^+}$ (leftmost, red) and $V_{ud}^{\text{n, best}}$ (rightmost, violet). The horizontal band (green) corresponds to $V_{us}^{K_{\ell 3}}$. The diagonal band (blue) corresponds to $(V_{us}/V_{ud})_{K_{\ell 2}/\pi_{\ell 2}}$. The unitarity circle is denoted by the black solid line. The 68% C.L. ellipse from a fit to all four constraints is depicted in yellow ($V_{ud} = 0.97378(26)$, $V_{us} = 0.22422(36)$, $\chi^2/\text{dof} = 6.4/2$, p-value 4.1%), it deviates from the unitarity line by 2.8σ. Note that the significance tends to increase in case τ decays are included.

68% C.L. ellipse shown in yellow from combination of all four constraints deviates from the unitarity prediction by -2.8 σ

V. Cirigliano, A. Crivellin, M. Hoferichter, M. Moulson,
Phys.Lett.B 838 (2023) 137748 e-Print: 2208.11707 [hep-ph]



HFLAV 2023 fit [e-Print: 2411.18639 [hep-ex]]

$$|V_{us}|_{\text{uni}} = 0.2272 \pm 0.0011 \quad 0.0\sigma \quad [\sqrt{1-|V_{ud}|^2-|V_{ub}|^2} \quad \text{(CKM unitarity)}]$$

$$|V_{us}|_{K\ell 3} = 0.2233 \pm 0.0005 \quad -3.2\sigma \quad [\mathcal{B}_{K\ell 3} \quad [106]] \; ,$$

$$|V_{us}|_{K\ell 2} = 0.2250 \pm 0.0005 \quad -1.7\sigma \quad [\mathcal{B}_{K\ell 2} \quad [106]] \; ,$$

$$|V_{us}|_{\tau s} = 0.2184 \pm 0.0021 \quad -3.6\sigma \quad [\mathcal{B}(\tau^- \to X_s^- \nu_\tau)] \; ,$$

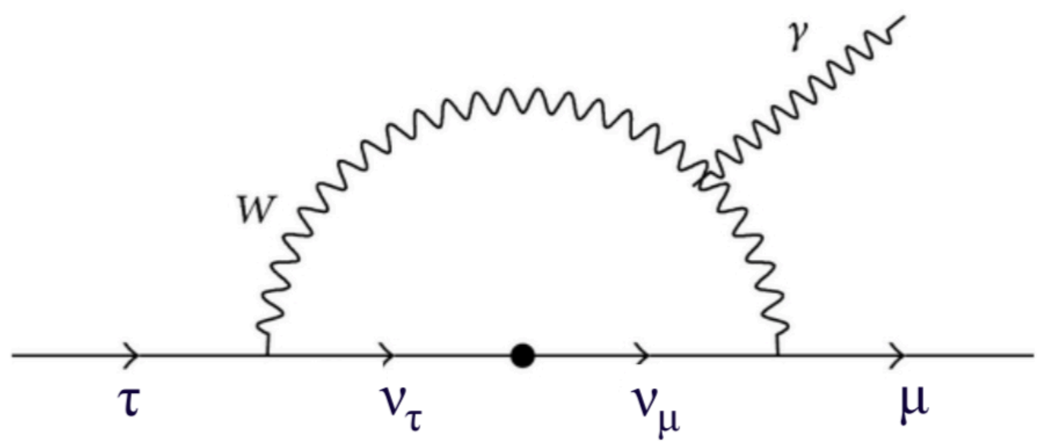
$$|V_{us}|_{\tau K/\pi} = 0.2229 \pm 0.0019 \quad -2.0\sigma \quad [\mathcal{B}(\tau^- \to K^- \nu_\tau)/\mathcal{B}(\tau^- \to \pi^- \nu_\tau)] \; ,$$

$$|V_{us}|_{\tau K} = 0.2224 \pm 0.0017 \quad -2.3\sigma \quad [\mathcal{B}(\tau^- \to K^- \nu_\tau)] \; .$$

$$|V_{us}|_{\tau \text{ excl}} = 0.2225 \pm 0.0017 \quad -2.3\sigma \quad [\text{average of } \tau \text{ exclusive measurements}]$$

$$|V_{us}|_{\tau} = 0.2209 \pm 0.0014 \quad -3.4\sigma \quad [\text{average of 3 } |V_{us}| \; \tau \text{ measurements}]$$

In SM, finite neutrino mass allows LFV via following diagram:



$\mathcal{B}(\tau^{\pm} \to \mu^{\pm}\gamma)$

Lee & Shrock: Phys.Rev.D 16 (1977) 1444

$= \frac{3\alpha}{128\pi}\left(\frac{\Delta m^2_{23}}{M^2_W}\right)^2 \sin^2 2\theta_{\rm mix}\mathcal{B}(\tau \to \mu\bar{\nu}_\mu\nu_\tau)$

With $\Delta \sim 10^{-3}\,\mathrm{eV}^2$, $M_W \sim \mathcal{O}(10^{11})\,\mathrm{eV}$

$\approx \mathcal{O}(10^{-54})$ ($\theta_{\rm mix}$: max)

many orders below experimental sensitivity!

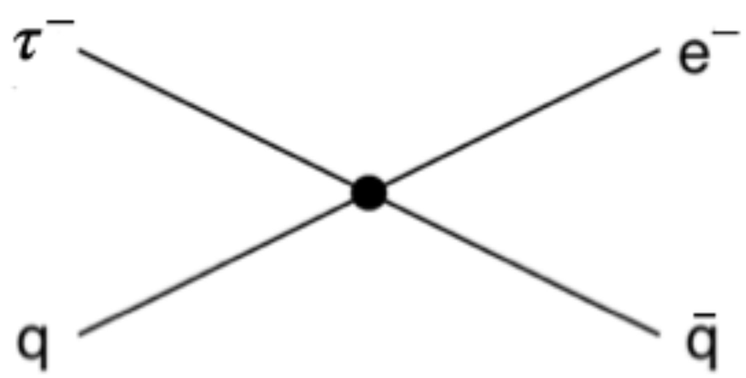
Any observation of LFV ⇒ unambiguous signature of new physics

⇒ Several models prediction LFV in tau sector at 10^{-8} - 10^{-10} level

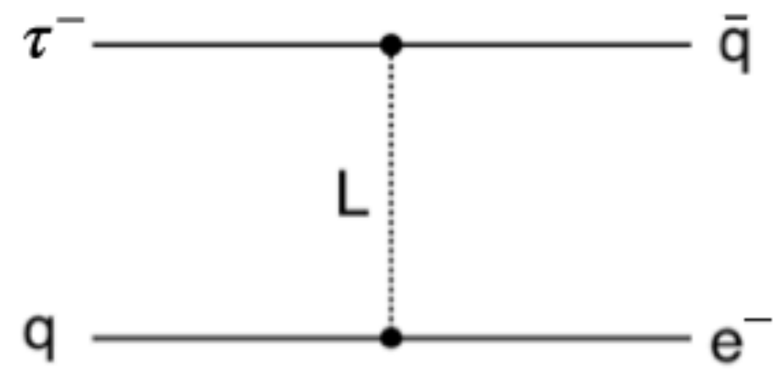
which is just below current experimental sensitivity

New Physics illustrations for LFV in τ decays

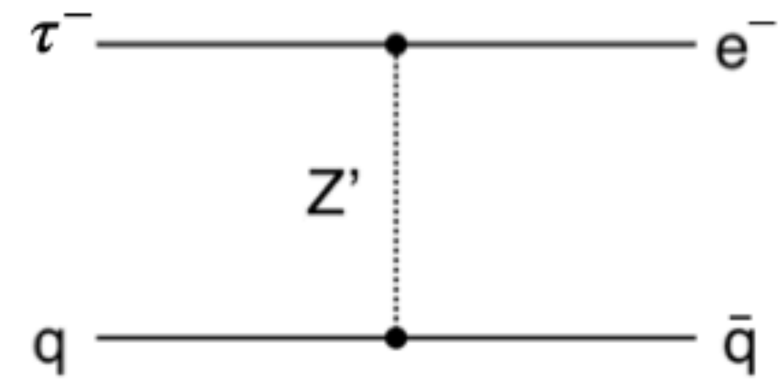
Tree level:



Compositeness

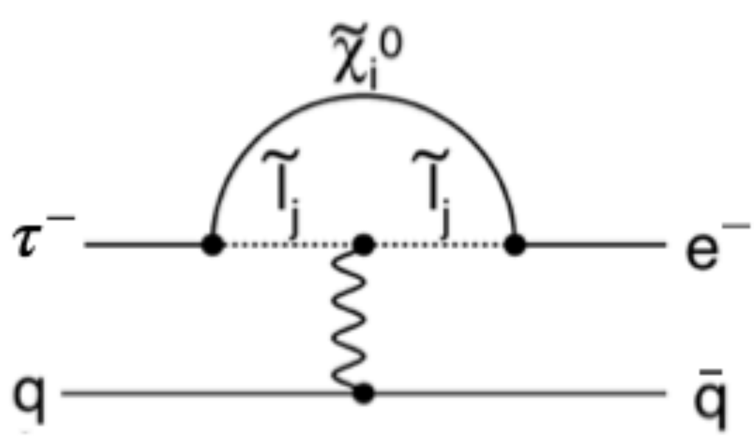


Leptoquarks

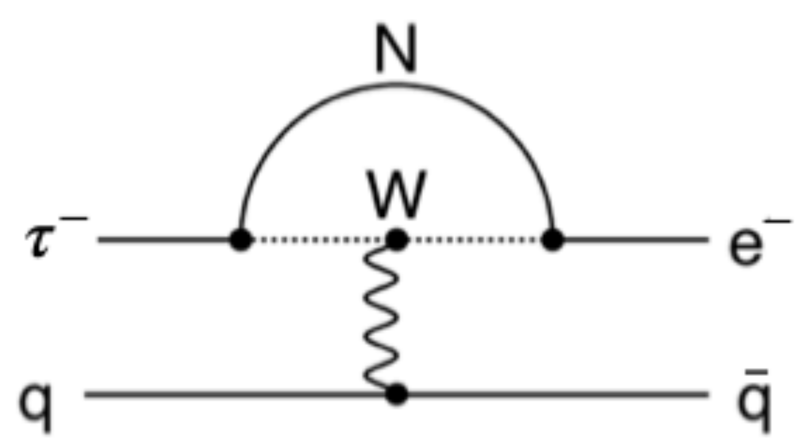


Heavy gauge bosons

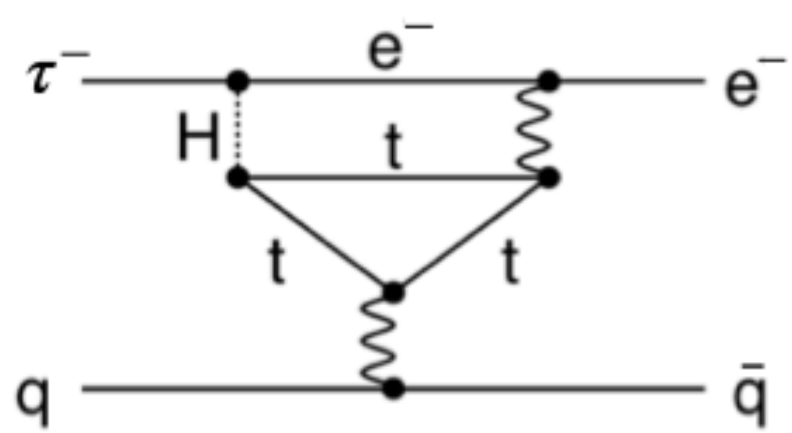
Loop induced:



Supersymmetry



Heavy neutrinos



Extended Higgs models

- **Expected rates from New Physics are slightly less than current experimental bounds.**

Salient features of LFV in τ decays from e^+e^- colliders

$e^+e^- \to \tau^+\tau^-$

- Known initial conditions (beam energy constraint)
- Clean environment (fewer backgrounds)

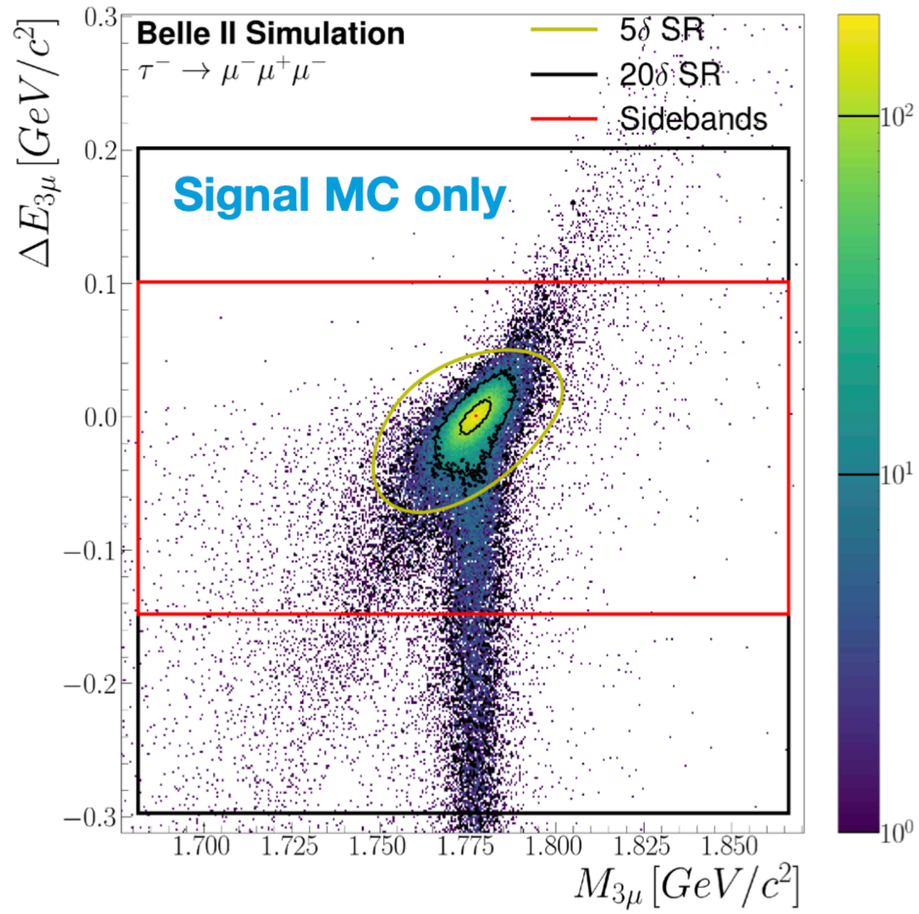
Two independent variables:

$$M_\tau = \sqrt{E^2_{\mu\mu\mu} - P^2_{\mu\mu\mu}}$$

$$\Delta E = E^{CMS}_{\mu\mu\mu} - E^{CMS}_{\text{beam}}$$

➡ ΔE close to 0 for signal

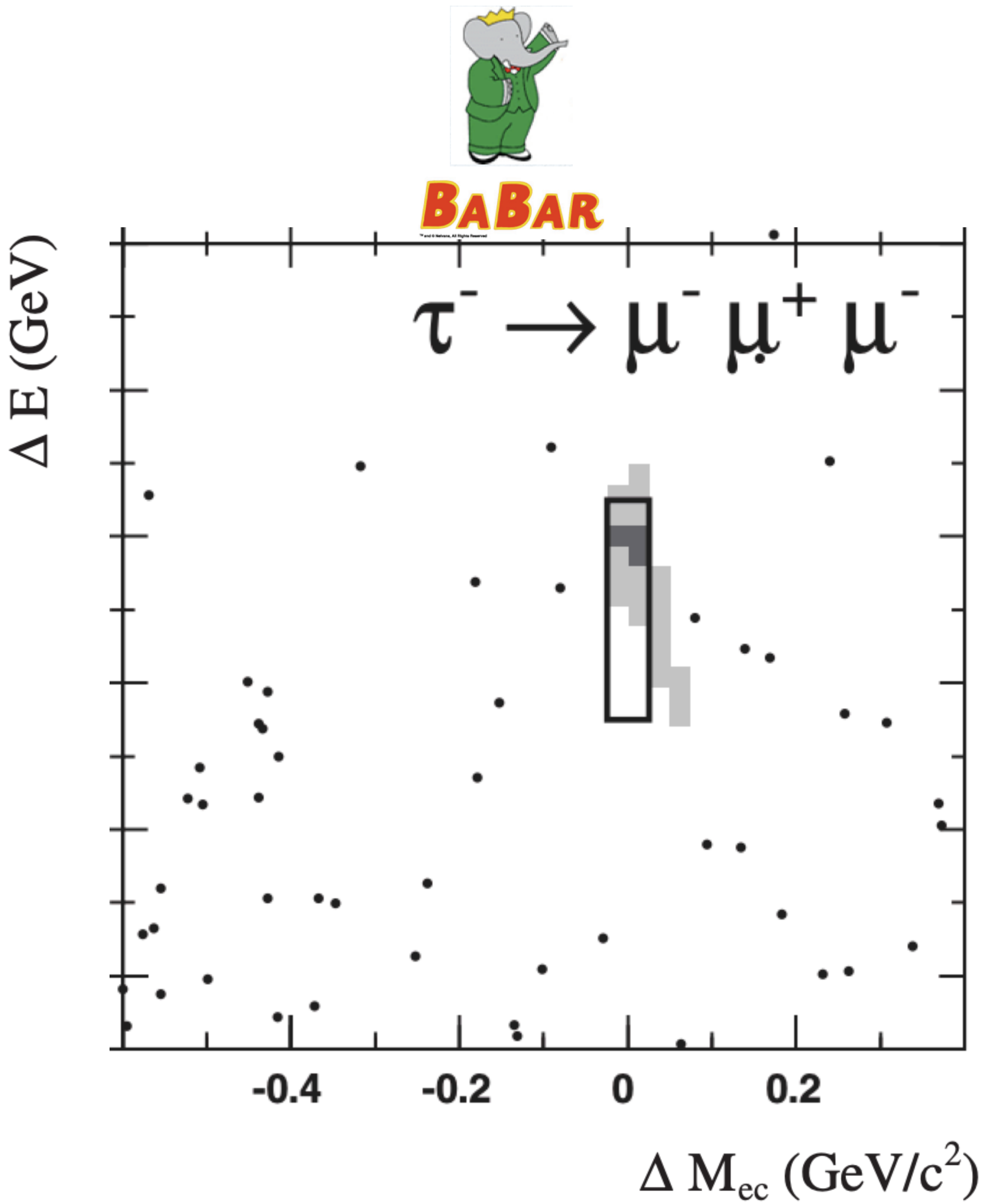
➡ Mass of tau daughters close to τ mass

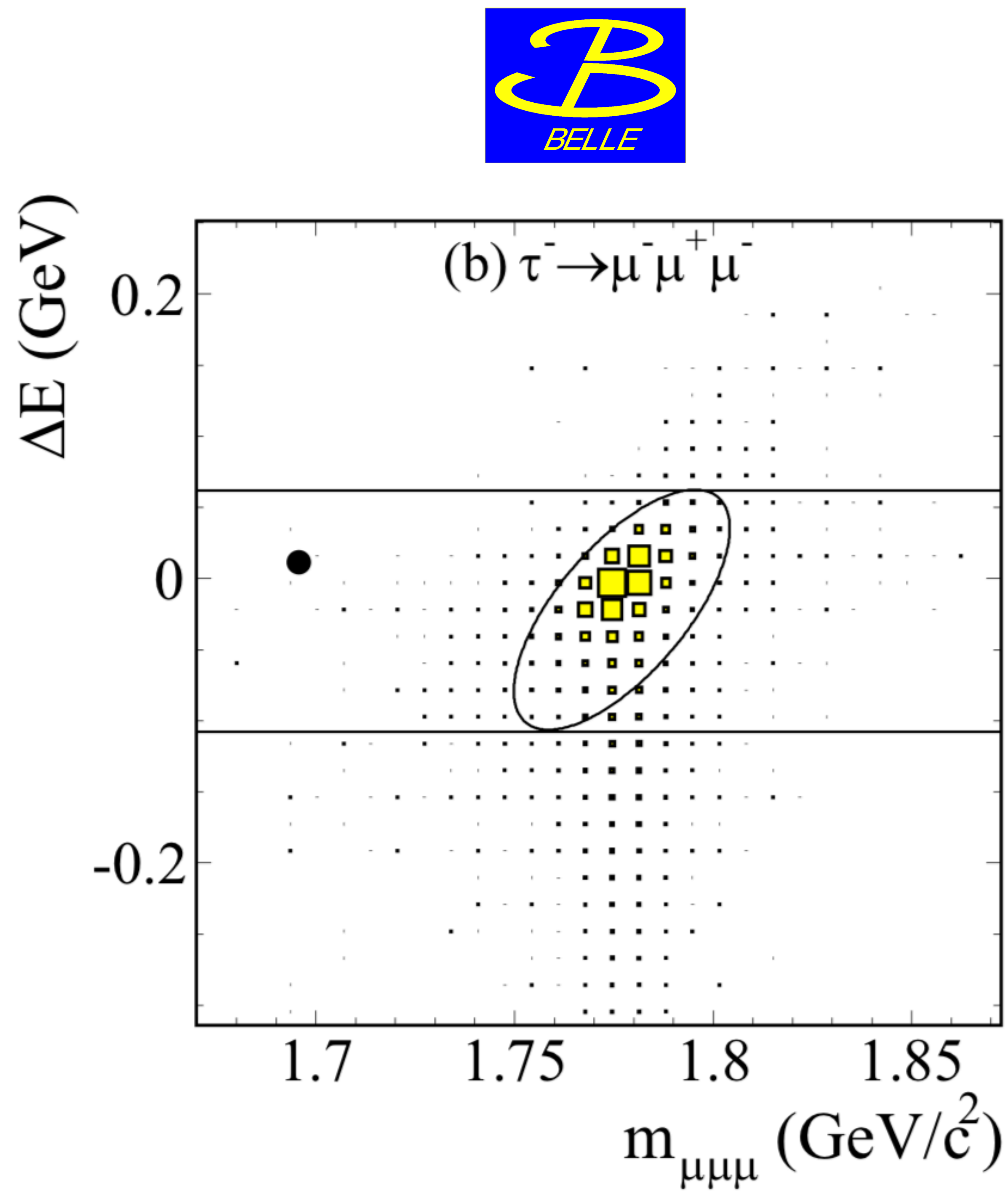


Higher signal efficiency is foreseen at Belle II than at Belle or BaBar

- **improved vertex tracking / calorimetry / muon detectors**
- **momentum dependent particle identification optimizations**
- **inclusive tagging optimized using BDT for signal extraction**

$\tau \to \mu\mu\mu$ at B-Factories





$\mathscr{B}(\tau \to \mu\mu\mu) < 3.3 \times 10^{-8}$ **with 468 fb^{-1}**

Phys.Rev.D 81 (2010) 111101

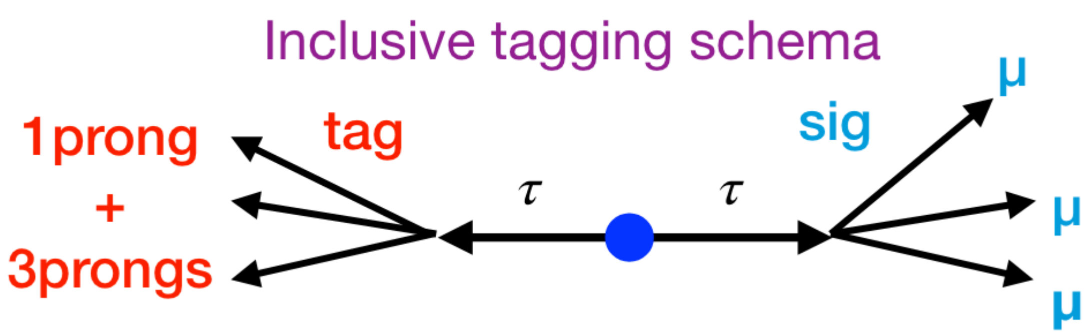
$\mathscr{B}(\tau \to \mu\mu\mu) < 2.1 \times 10^{-8}$ **with 782 fb^{-1}**

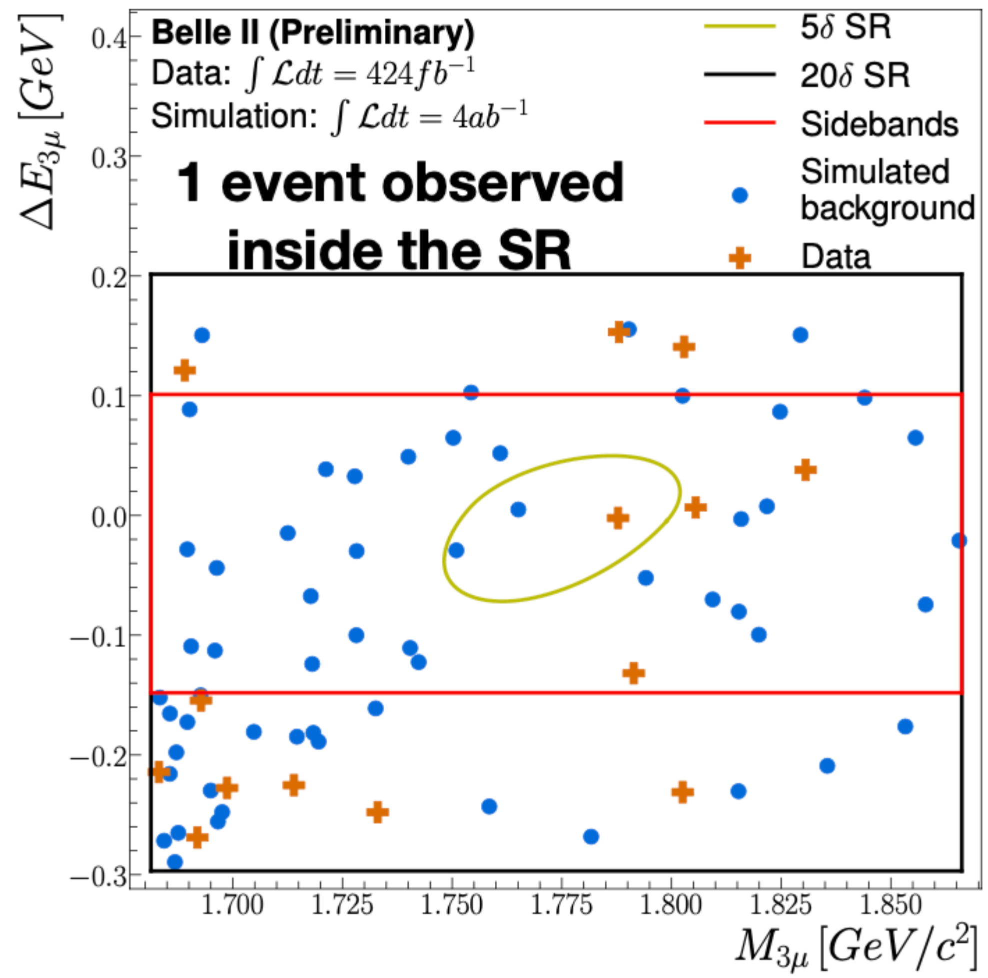
Phys. Lett. B687 (2010) 139

$\tau \to \mu\mu\mu$ at B-Factories

Observed (expected) limits: $\mathscr{B}(\tau \to \mu\mu\mu) < 1.9(1.8) \times 10^{-8}$ with 424 fb^{-1}

ε_{sig}= **20.42** ± 0.06% ~3x larger than Belle & Expected BKG: $0.7^{+0.6}_{-0.5}$ events





Dominant syst. from lepton ID efficiency
Negligible impact on the limit

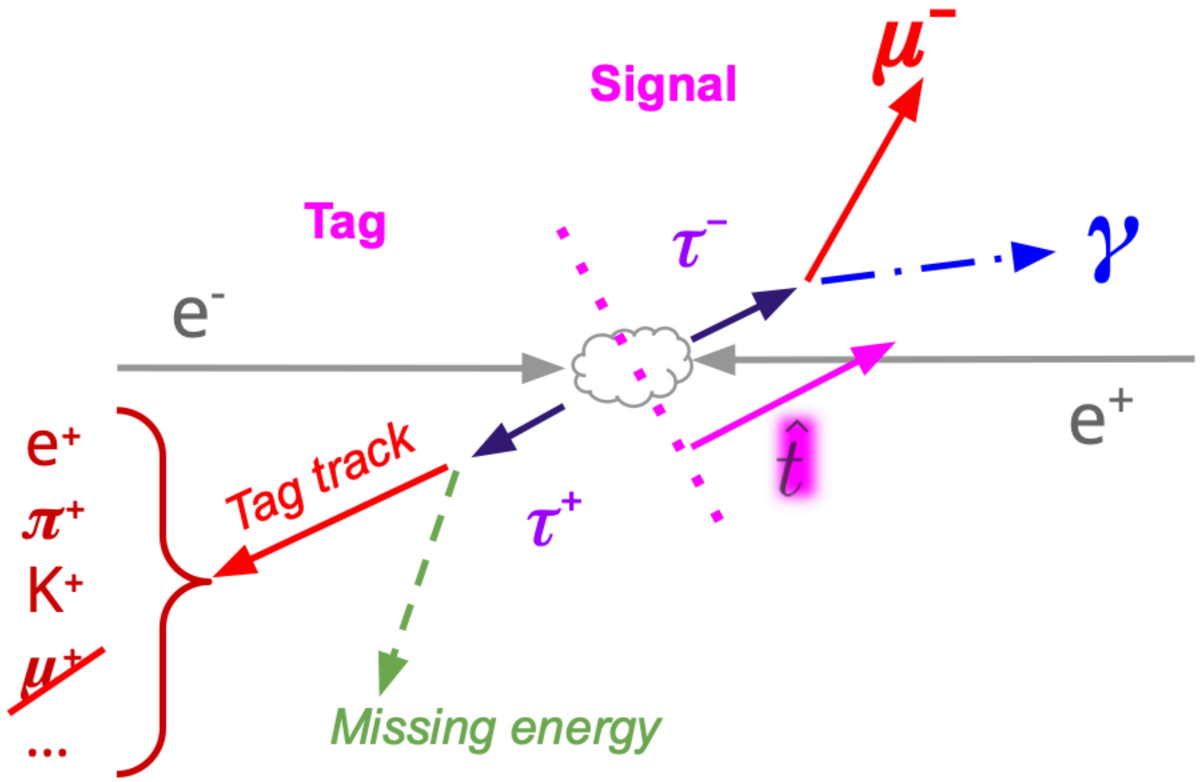
J. High Energ. Phys. 2024, 62 (2024).

2405.07386 [hep-ex]

CMS: $\mathscr{B}(\tau \to \mu\mu\mu) < 2.9 \times 10^{-8}$ at 90% C.L. with 131 fb^{-1} Phys.Rev.D 81 (2010) 111101 arXiv:2312.02371 [hep-ex]

LHCb: $\mathscr{B}(\tau \to \mu\mu\mu) < 4.6 \times 10^{-8}$ at 90% C.L. with 3 fb^{-1} JHEP 02 (2015) 121 arXiv:1409.8548 [hep-ex]

Ongoing search for $\tau \to \mu\gamma$ at Belle II



Analysis details

BELLE2-NOTE-PH-2025-02

- Signal and background on-resonance samples MCri & MCrd.
    - $\tau^{\pm} \to \mu^{\pm} + \gamma$ (4 M + 4 M)
    - $\tau^{+}\tau^{-}$ (8 ab^{-1} + 1.4 ab^{-1}), $\mu^{+}\mu^{-}(\gamma)$ (1 ab^{-1} + 1.4 ab^{-1}), + others.
- Data: On & off-resonance data ~ 427 fb^{-1}
- Moriond 2024 corrections.

Ongoing search for $\tau \to \mu\gamma$ at Belle II

- <u>Strategy</u>:
  - Reconstruct 1x1 prong topology.
  - Improved selection using BDT (11 variables). **Better performance with less data then Belle!**
  - Signal extraction via unbinned ML fit in 2D.
  - Sideband data included in fit to estimate final background, and relative fractions of ττ, μμγ.

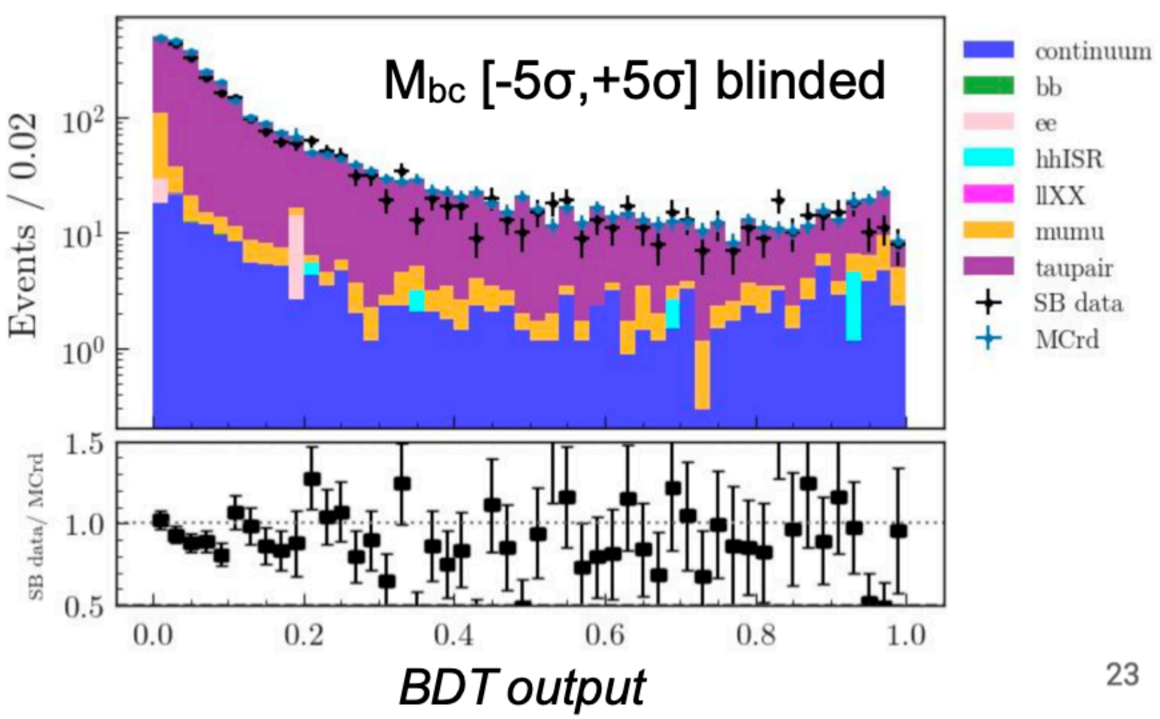
- In RC review and finalizing systematic implementation into the limit

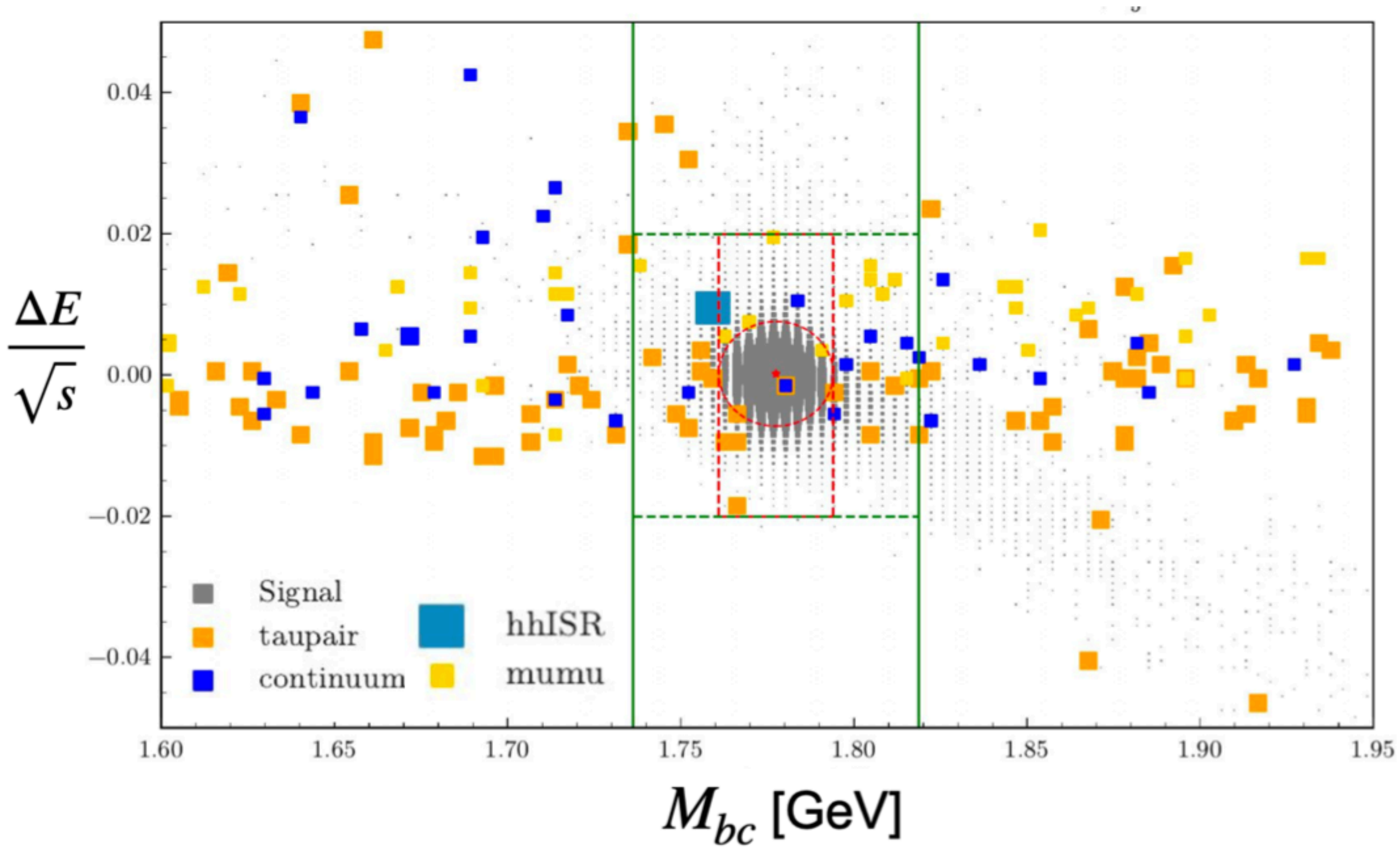
Expected UL

$BR(\tau \to \mu\gamma) < 2.6 \times 10^{-8}$

BELLE2-NOTE-PH-2025-002

Would be world-leading!





Estimates of experimental sensitivity in LFV searches

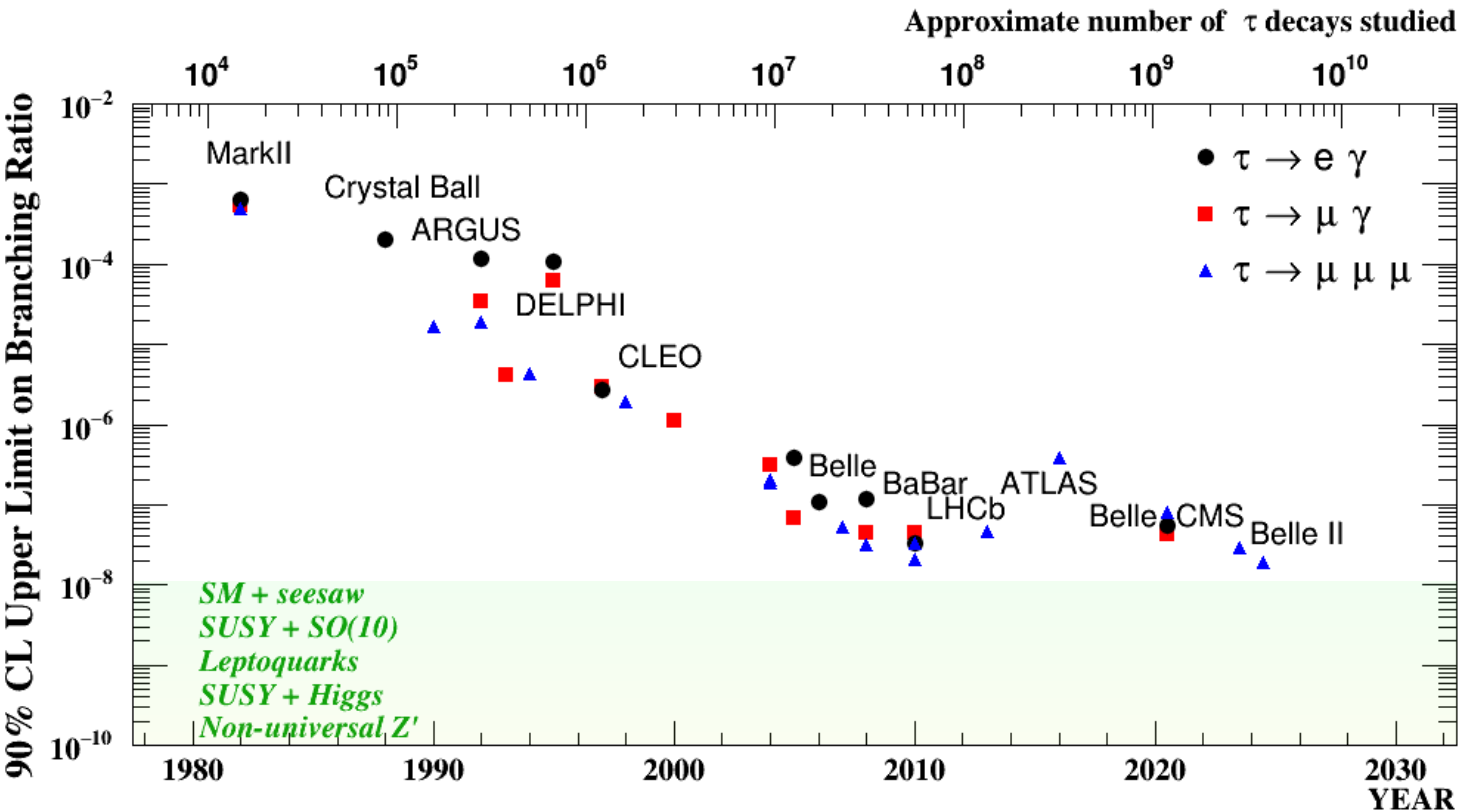
$$B^{90}_{\rm UL} = N^{90}_{\rm UL}/(N_\tau \times \varepsilon)$$

- ε: *high statistics signal MC simulated for different Data-taking periods*

$\varepsilon =$	Trigger .	Reco .	Topology .	PID .	Cuts .	Signal–Box
	90%	70%	70%	50%	50%	50%
Cumulative:						
	90%	63%	44%	22%	11%	~5%

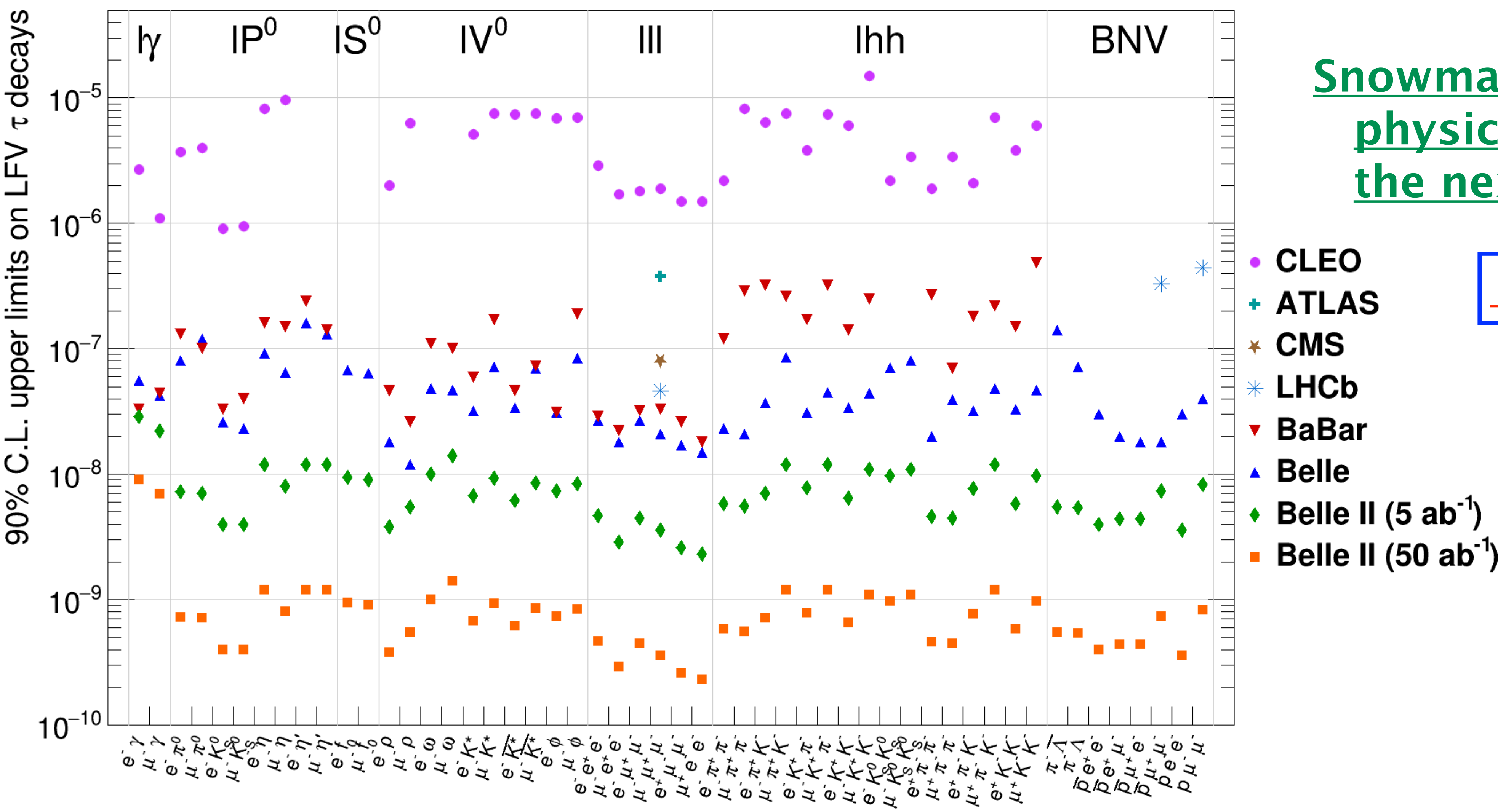
	$\sqrt{s}$	Luminosity (L)	$N_\tau = 2L\sigma$
BaBar	10.58 GeV	0.5 ab^{-1}	1 $\times 10^{9}$
Belle	10.58 GeV	1 ab^{-1}	1.8 $\times 10^{9}$
Belle II	10.58 GeV	50 ab^{-1}	9.2 $\times 10^{10}$
HL-LHC	14 TeV	3 ab^{-1}	10^{15}
STCF	2-7 GeV	1 ab^{-1}	7.0 $\times 10^{9}$
FCC-ee	91.2 GeV	150 ab^{-1}	3.4 $\times 10^{11}$

Current status of LFV τ decays



Projected limits at Belle II using expected limits

	Background limited search $\tau \to \ell\gamma$	*Background free search* ($N_{bkg} < 1$) (all other LFV τ decays shown below)
$N^{90}_{\rm UL}$	$\sqrt{\mathcal{L}}$	2.44 [Feldman – Cousins for $N_{obs} = 0$]
$B^{90}_{\rm UL}$	$\propto 1/\sqrt{\mathcal{L}}$	$\propto 1/\mathcal{L}$



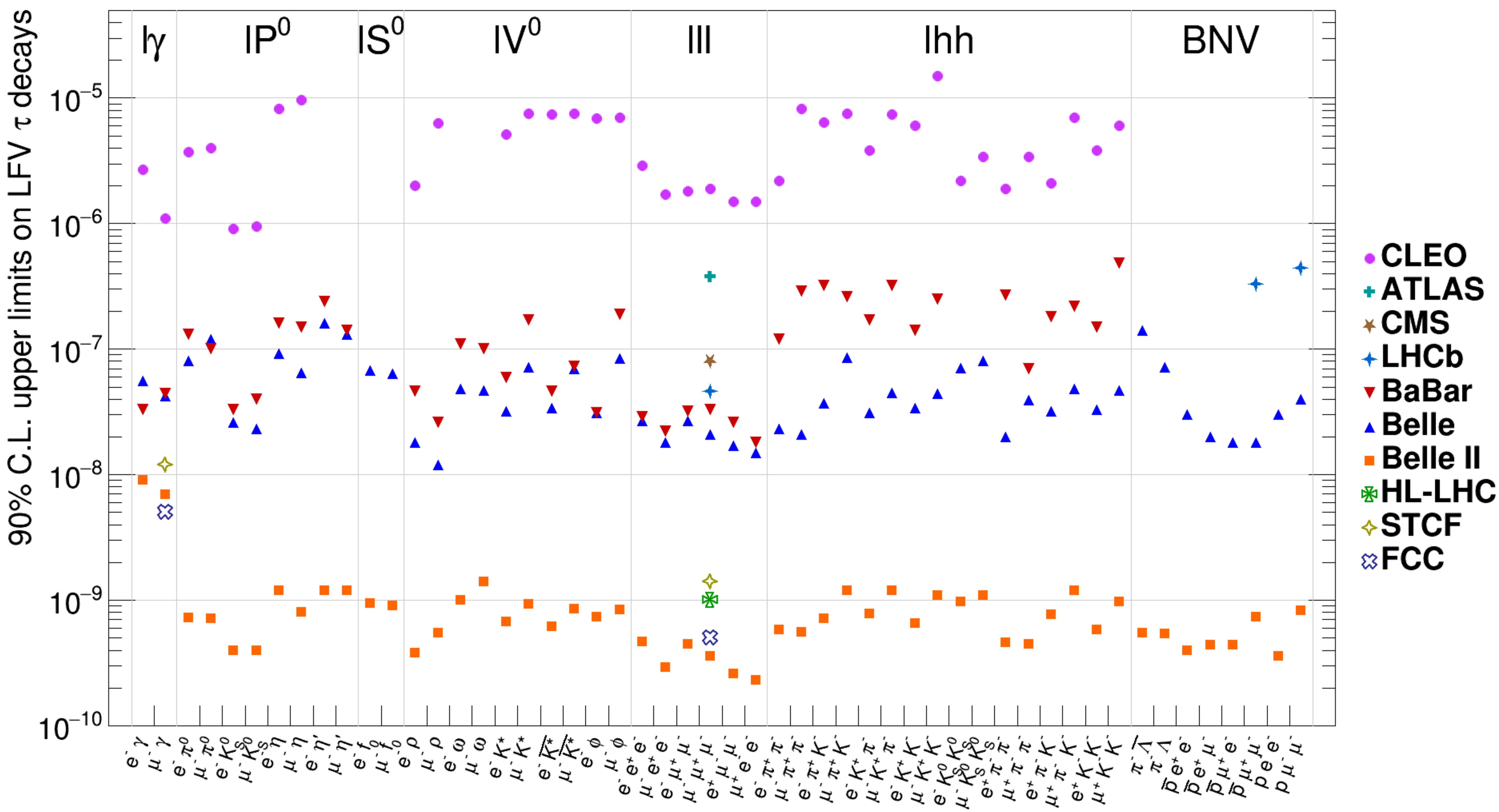
Snowmass White Paper: Belle II physics reach and plans for the next decade and beyond

2207.06306 [hep-ex]

Projections

Belle II to probe LFV in several channels ≃ $\mathcal{O}(10^{-10})$ to $\mathcal{O}(10^{-9})$ with 50 ab^{-1}

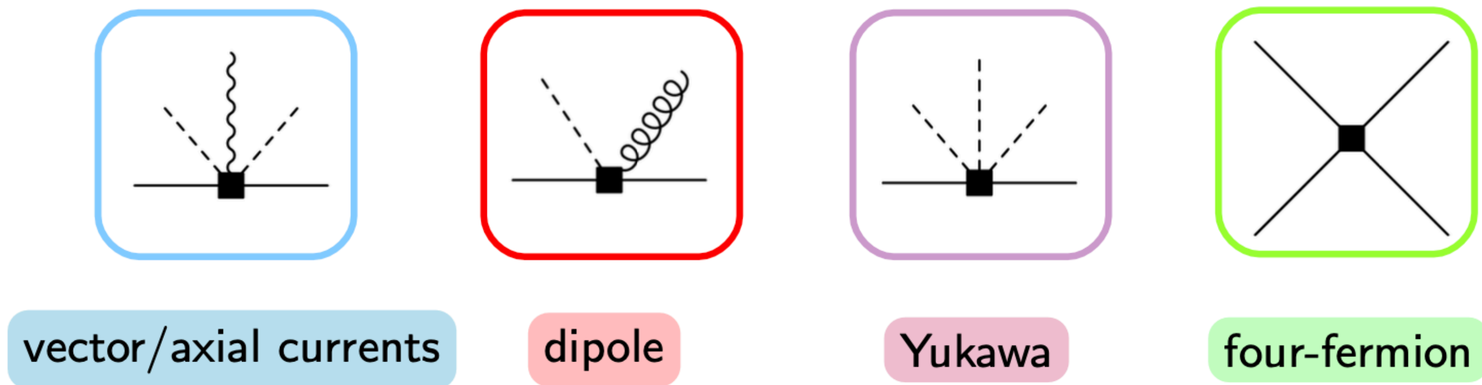
Summary of experimental prospects of τ decays



Snowmass 2021: cLFV in τ sector [e-Print: 2203.14919 [hep-ph]]

Global analysis of all LFV data

SMEFT for CLFV



τ and B CLFV decays

Constrain $\tau \to e$ transitions at EIC

Decay mode	V $q^{(0)}$	V $q^{(1)}$	V s	V c	V b	A $q^{(0)}$	A $q^{(1)}$	A s	A c	A b	S $q^{(0)}$	S $q^{(1)}$	S s	S c	S b	P $q^{(0)}$	P $q^{(1)}$	P s	P c	P b	T u	T c
$\tau \to e\gamma$																					(✓)	(✓)
$\tau \to e\ell^+\ell^-$				(✓)	(✓)				×	×												
$\tau \to e\pi^0$							✓		×	×							✓					
$\tau \to e\eta, \eta'$						✓		✓	×	×						✓		✓	(✓)	(✓)		
$\tau \to e\pi^+\pi^-$		✓		(✓)	(✓)				×	×	✓		✓	(✓)	(✓)						✓	
$\tau \to eK^+K^-$	✓	✓	✓	(✓)	(✓)				×	×	✓		✓	(✓)	(✓)						✓	

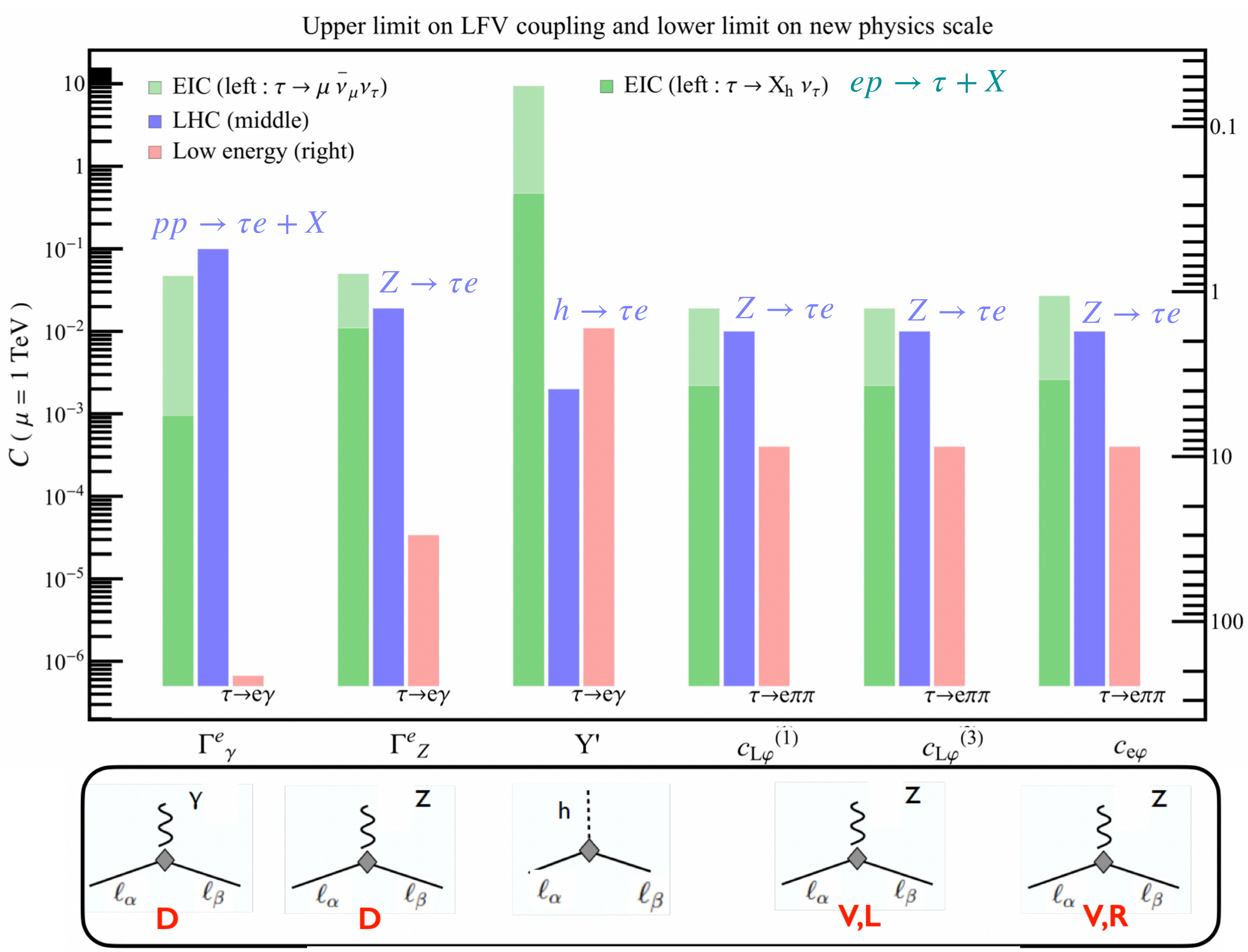
Decay mode	V ds	V db	V sb	V cu	A ds	A db	A sb	A cu	S ds	S db	S sb	S cu	P ds	P db	P sb	P cu	T cu
$\tau \to eK_S^0$					✓								✓				
$\tau^- \to e^- K\pi$	✓								✓								
$B^0 \to e\tau$						✓								✓			
$B^+ \to \pi^+ e\tau$		✓								✓							
$B^+ \to K^+ e\tau$			✓								✓						

✓ = tree (✓) = loop

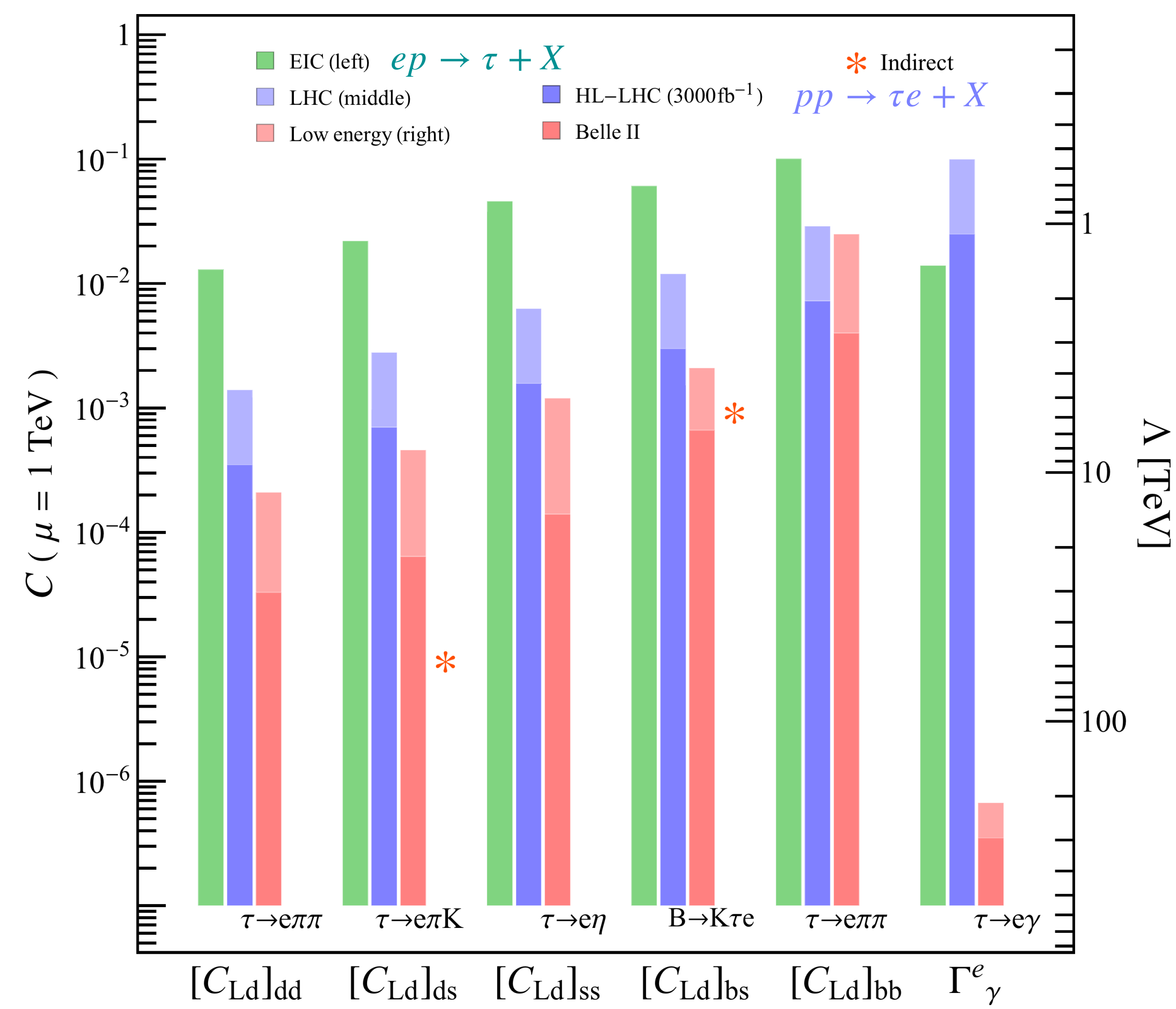
V.Cirigliano, K.Fuyuto, C.Lee, E.Mereghetti, B.Yan, JHEP03, 256 (2021) arXiv:2102.06176 [hep-ph]

Global fit: $\tau \to e$ decays and transitions with τ in the final state

Model-independent probes of new physics at scale (Λ)
encoded as Wilson coefficients (C_n) via EFT approach.
For certain operators, Higgs decay and LFV Drell-Yan compete,
which are assumed to scale by factor of 4 at HL-LHC.
For many other operators, bounds dominated by τ and B-decays.



e-Print: 2102.06176 [hep-ph]

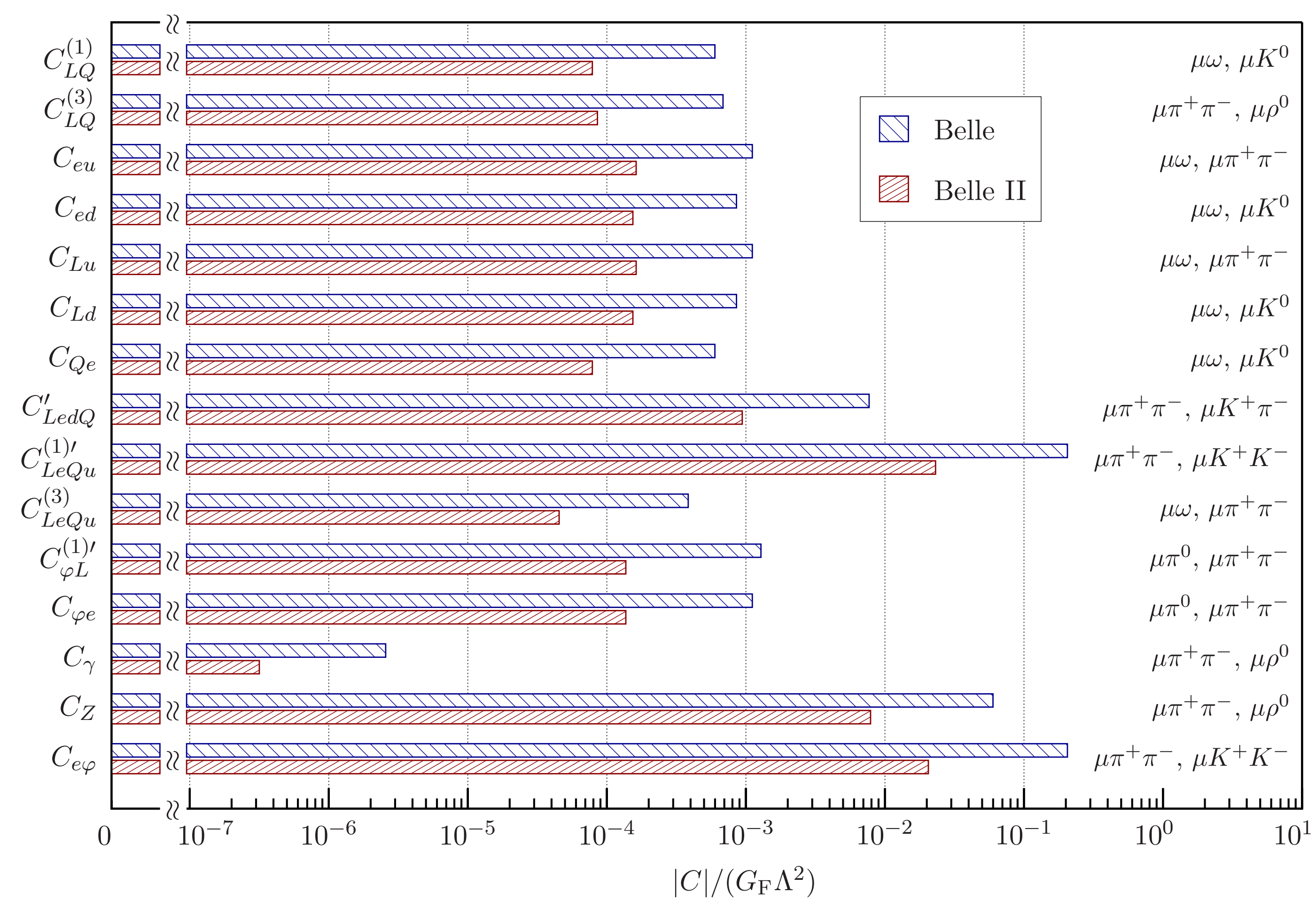


e-Print: 2203.14919 [hep-ph]

Global fit: $\tau \to \mu$ decays and transitions with τ in the final state

Model-independent probes of new physics at scale (Λ)
encoded as Wilson coefficients (C_n) via EFT approach.
For certain operators, Higgs decay and LFV Drell-Yan compete,
which are assumed to scale by factor of 4 at HL-LHC.
For many other operators, bounds dominated by τ and B-decays.

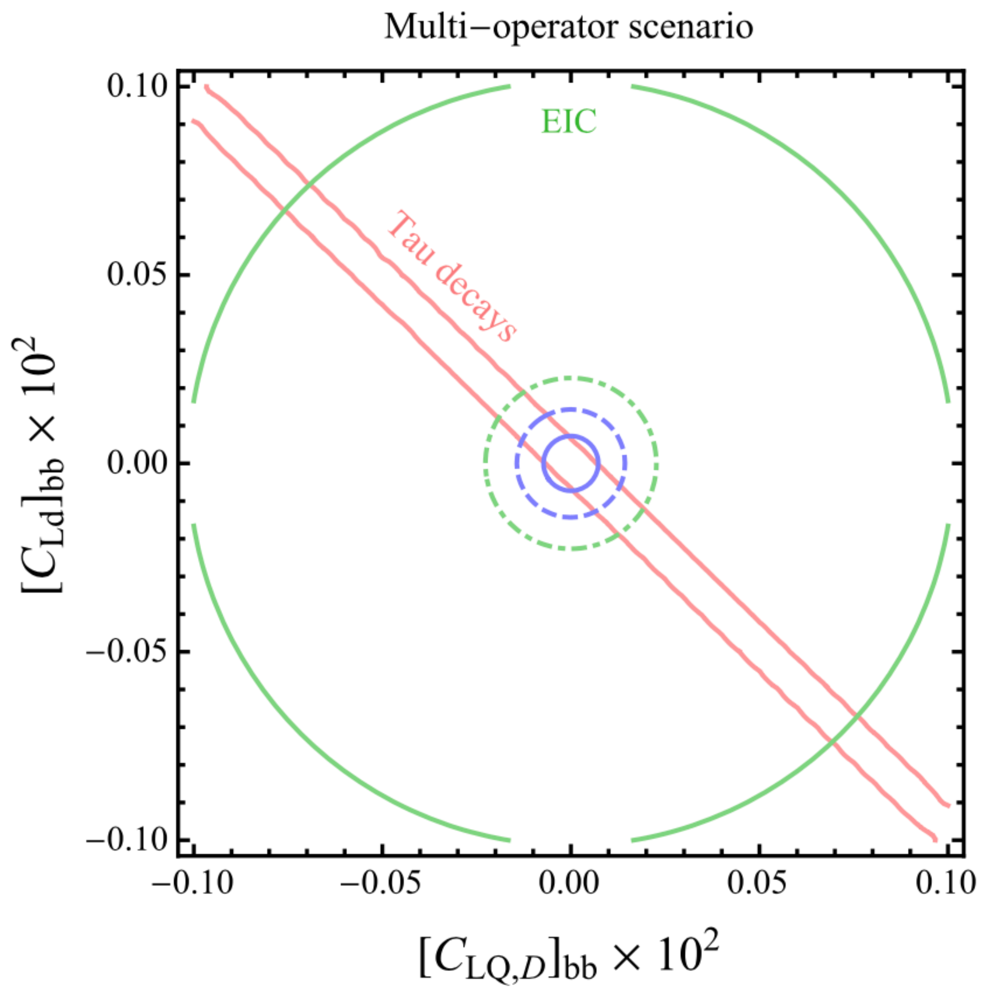
WC	Operator	WC	Operator
$C_{LQ}^{(1)}$	$(\bar{L}_p\gamma_\mu L_r)(\bar{Q}_s\gamma^\mu Q_t)$	$C_{e\varphi}$	$(\varphi^\dagger\varphi)(\bar{L}_p e_r\varphi)$
$C_{LQ}^{(3)}$	$(\bar{L}_p\gamma_\mu\sigma^I L_r)(\bar{Q}_s\gamma^\mu\sigma^I Q_t)$	$C_{\varphi e}$	$\left(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi\right)(e_p\gamma^\mu e_r)$
C_{eu}	$(\bar{e}_p\gamma_\mu e_r)(\bar{u}_s\gamma^\mu u_t)$	$C_{\varphi L}^{(1)}$	$\left(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi\right)(\bar{L}_p\gamma^\mu L_r)$
C_{ed}	$(\bar{e}_p\gamma_\mu e_r)(\bar{d}_s\gamma^\mu d_t)$	$C_{\varphi L}^{(3)}$	$\left(\varphi^\dagger i\overleftrightarrow{D}_{I\mu}\varphi\right)(\bar{L}_p\sigma_I\gamma^\mu L_r)$
C_{Lu}	$(\bar{L}_p\gamma_\mu L_r)(\bar{u}_s\gamma^\mu u_t)$	C_{eW}	$(\bar{L}_p\sigma^{\mu\nu}e_r)\,\sigma_I\varphi W_{\mu\nu}^I$
C_{Ld}	$(\bar{L}_p\gamma_\mu L_r)(\bar{d}_s\gamma^\mu d_t)$	C_{eB}	$(\bar{L}_p\sigma^{\mu\nu}e_r)\,\varphi B_{\mu\nu}$
C_{Qe}	$(\bar{Q}_p\gamma_\mu Q_r)(\bar{e}_s\gamma^\mu e_t)$		
C_{LedQ}	$(\bar{L}_p^j e_r)(\bar{d}_s Q_t^j)$		
$C_{LeQu}^{(1)}$	$(\bar{L}_p^j e_r)\,\varepsilon_{jk}\,(\bar{Q}_s^k u_t)$		
$C_{LeQu}^{(3)}$	$(\bar{L}_p^j\sigma_{\mu\nu}e_r)\,\varepsilon_{jk}\,(\bar{Q}_s^k\sigma^{\mu\nu}u_t)$		



T. Husek, K. Monsalvez-Pozo, J. Portoles '20

e-Print: 2203.14919 [hep-ph]

Towards a global fit



$$C_{LQ\,D} = \mathrm{diag}([C_{LQ\,D}]_{dd}, [C_{LQ\,D}]_{ss}, [C_{LQ\,D}]_{bb})$$

$$C_{Ld} = \mathrm{diag}([C_{Ld}]_{dd}, [C_{Ld}]_{ss}, [C_{Ld}]_{bb})$$

- turn on all V/A couplings to L leptons & d-type quarks
- contributions to hadronic τ decays cancel for $[C_{Ld}]_{bb} \sim -[C_{LQ\,D}]_{bb}$
- $\tau \to e\ell^+\ell^-$ weaker than current LHC and project EIC
- need collider or η_b decays

Courtesy: Emanuele Mereghetti, Kaori Fuyuto [Tau2023]

Summary & Outlook

- **The mystery of $|V_{us}|$ deepens from kaon and tau sector**
  - **Lattice calculations providing intriguing insights to calculate δR_{theory}:**
    Reduce theory error down to 0.0007, but long distance isospin breaking corrections pending
    ETC collaboration, Phys.Rev.Lett. 132 (2024) 26, 261901, e-Print: 2403.05404 [hep-lat]

	Observed Limits			Projected Limits		
	Experiment	Luminosity	UL (obs)	Experiment	Luminosity	UL (exp)
$\tau^- \to \mu^-\mu^+\mu^-$	Belle II [Tau2023]	424 fb^{-1}	1.9×10^{-8}	Belle II [2207.06307]	50 ab^{-1}	3.6×10^{-10}
	Belle [Phys.Lett.B 687 (2010) 139]	782 fb^{-1}	2.1×10^{-8}			
	BaBar [Phys.Rev.D 81 (2010) 111101]	468 fb^{-1}	3.3×10^{-8}			
	LHCb [JHEP 02 (2015) 121]	3 fb^{-1}	4.6×10^{-8}	LHCb [1808.08865]	300 fb^{-1}	$\mathcal{O}(10^{-9})$
	CMS [Phys. Lett. B 853 (2024) 138633]	131 fb^{-1}	2.9×10^{-8}	CMS [CMS-TDR-016]	3 ab^{-1}	3.7×10^{-9}
	ATLAS [Eur.Phys.J.C 76 (2016) 5, 232]	20 fb^{-1}	3.8×10^{-7}	ATLAS [ATL-PHYS-PUB-2018-032]	3 ab^{-1}	1.0×10^{-9}
				STCF [Eur.Phys.J.C 83 (2023) 10, 908]	1 ab^{-1}	1.4×10^{-9}
				FCC-ee [1811.09408]	150 ab^{-1}	$\mathcal{O}(10^{-10})$

- **Observation of LFV in the charged lepton sector would completely change our understanding of physics and herald a new period of discoveries in particle physics. Synergies between different experiments compliment discovery potential/confirmation.**

- **Now is a very interesting era in the searches for LFV in decays of the τ lepton, as the current limits will improve by an order of magnitude down to a few parts in 10^{-10} to 10^{-9} at the Belle II and other experiments.**

- **Similar sensitivities will be probed at ATLAS, CMS & LHCb with high luminosity upgrade.**

- **Proposed experiments at STCF, EIC & FCC-ee will continue searches for LFV in tau sector.**