Combined upper limits on lepton-flavor-violating tau branching fractions

On behalf of the Heavy Flavor Averaging Group (HFLAV)

Swagato Banerjee

UNIVERSITY OF LOUISVILLE

Lepton Flavor Violation (LFV)

Global symmetry of the Standard Model can be written as:

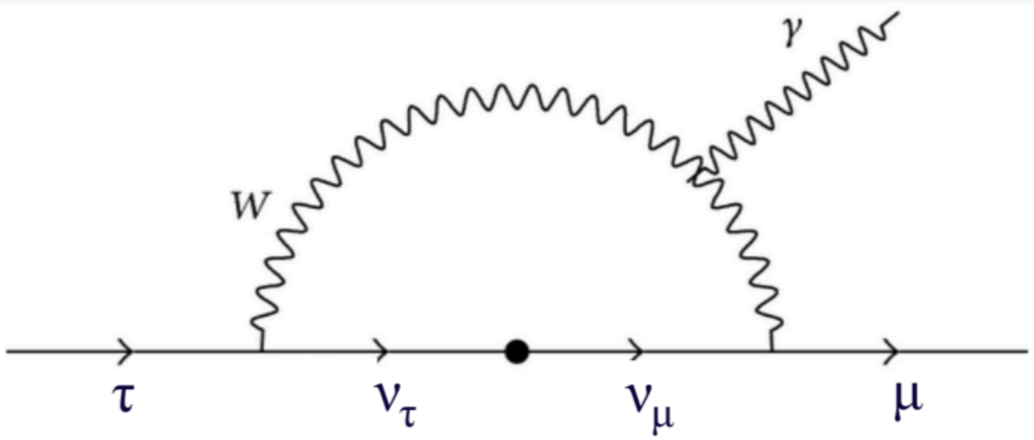
$$U(1)_B \times U(1)_{L_e} \times U(1)_{L_\mu} \times U(1)_{L_\tau} = U(1)_{B+L} \times U(1)_{B-L} \times \mathbf{U(1)_{L_\mu - L_\tau}} \times \mathbf{U(1)_{L_\mu + L_\tau - 2L_e}}$$

where $L \equiv L_e + L_\mu + L_\tau$ is the total lepton number.

LFV conserves L and B but violates $U(1)_{L_\mu - L_\tau} \times U(1)_{L_\mu + L_\tau - 2L_e}$

$\Rightarrow$ generic classification of all LFV processes J. Heeck: Phys. Rev. D 95, 015022 (2017)

LFV via ν mixing is very small $\Rightarrow$ LFV is unambiguous signature of new physics (NP)

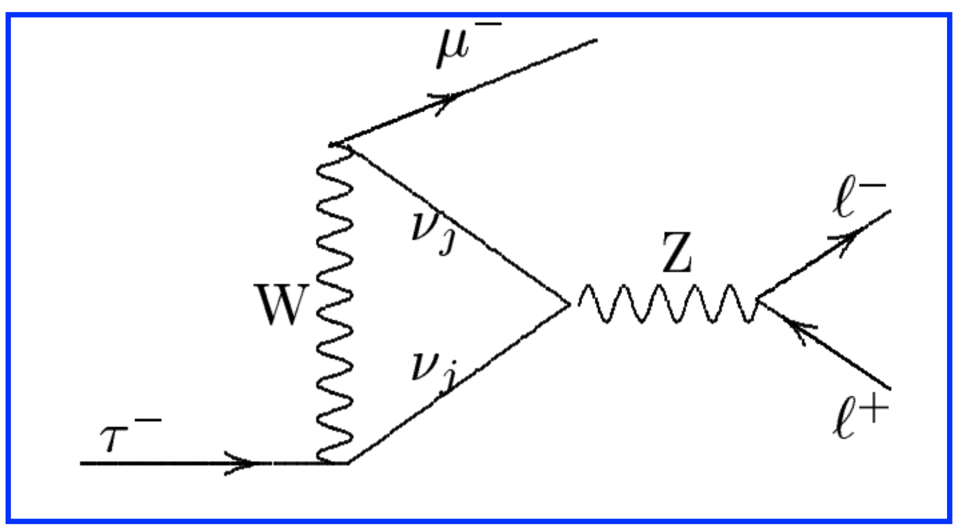


$\mathcal{B}(\tau^\pm \to \mu^\pm \gamma)$ Lee & Shrock: Phys.Rev.D 16 (1977) 1444

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

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)



P. Blackstone, M. Fael, E. Passemar : Eur.Phys.J.C 80 (2020) 6, 506

G. Hernández-Tomé, G. López Castro, P. Roig:
Eur.Phys.J.C 79 (2019) 1, 84, Eur.Phys.J.C 80 (2020) 5, 438 (erratum)

$$\mathcal{B}(\tau^\pm \to \mu^\pm \ell^+ \ell^-) \leq [10^{-56}, 10^{-53}]$$

LFV in τ vs μ sector

LFV in tau sector is complementary to muon sector in NP parameter space:
current limit on $\mathcal{B}(\mu \to e\gamma) \sim 10^{-13}$ does not forbid $\mathcal{B}(\tau \to \ell\gamma) \sim 10^{-8}$

Leptonic MFV:	$BR(\mu \to e\gamma)$ / $BR(\tau \to \mu\gamma) \sim s_{13}^2 \sim 10^{-2}$
GUT models:	$BR(\mu \to e\gamma)$ / $BR(\tau \to \mu\gamma) \sim |V_{us}|^6 \sim 10^{-4}$

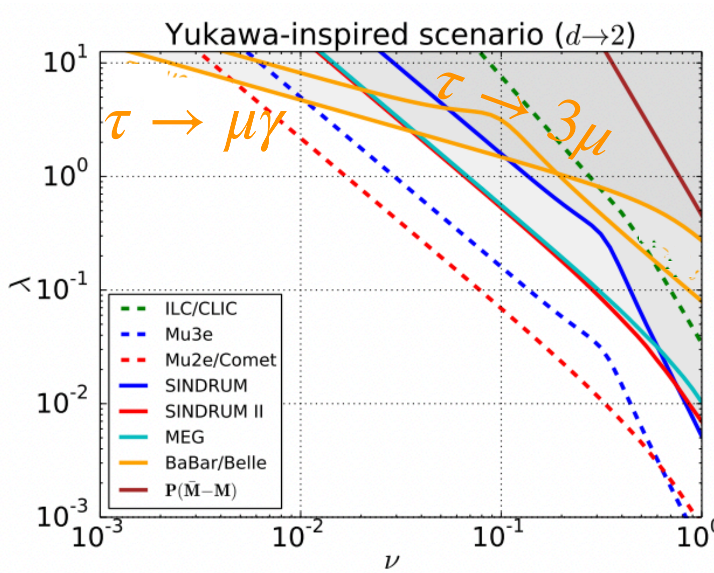
Courtesy: V. Cirigliano's talk at Snowmass 2021

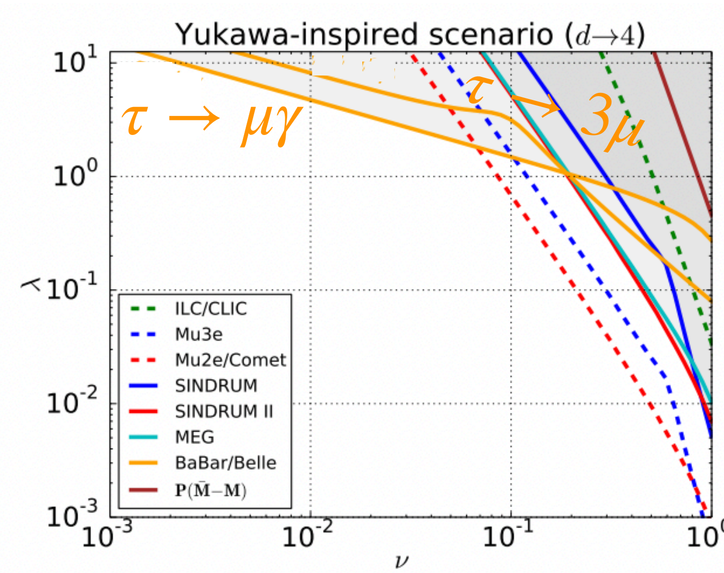
Vincenzo Cirigliano, Benjamin Grinstein, Gino Isidori, Mark B. Wise: hep-ph/0507001 [hep-ph], hep-ph/0608123 [hep-ph]
R. Barbieri, L. Hall, A. Strumia: hep-ph/9501334 [hep-ph]

- Mass dependent couplings enhance tau LFV w.r.t. lighter leptons

$$\lambda_{ab} \sim (y^l_a y^l_b)^{-1}$$

$$\lambda_{ab} = \lambda \begin{pmatrix} \pm 1 & \nu^2 & \nu^3 \\ \nu^2 & \nu^4 & \nu^5 \\ \nu^3 & \nu^5 & \nu^6 \end{pmatrix}$$



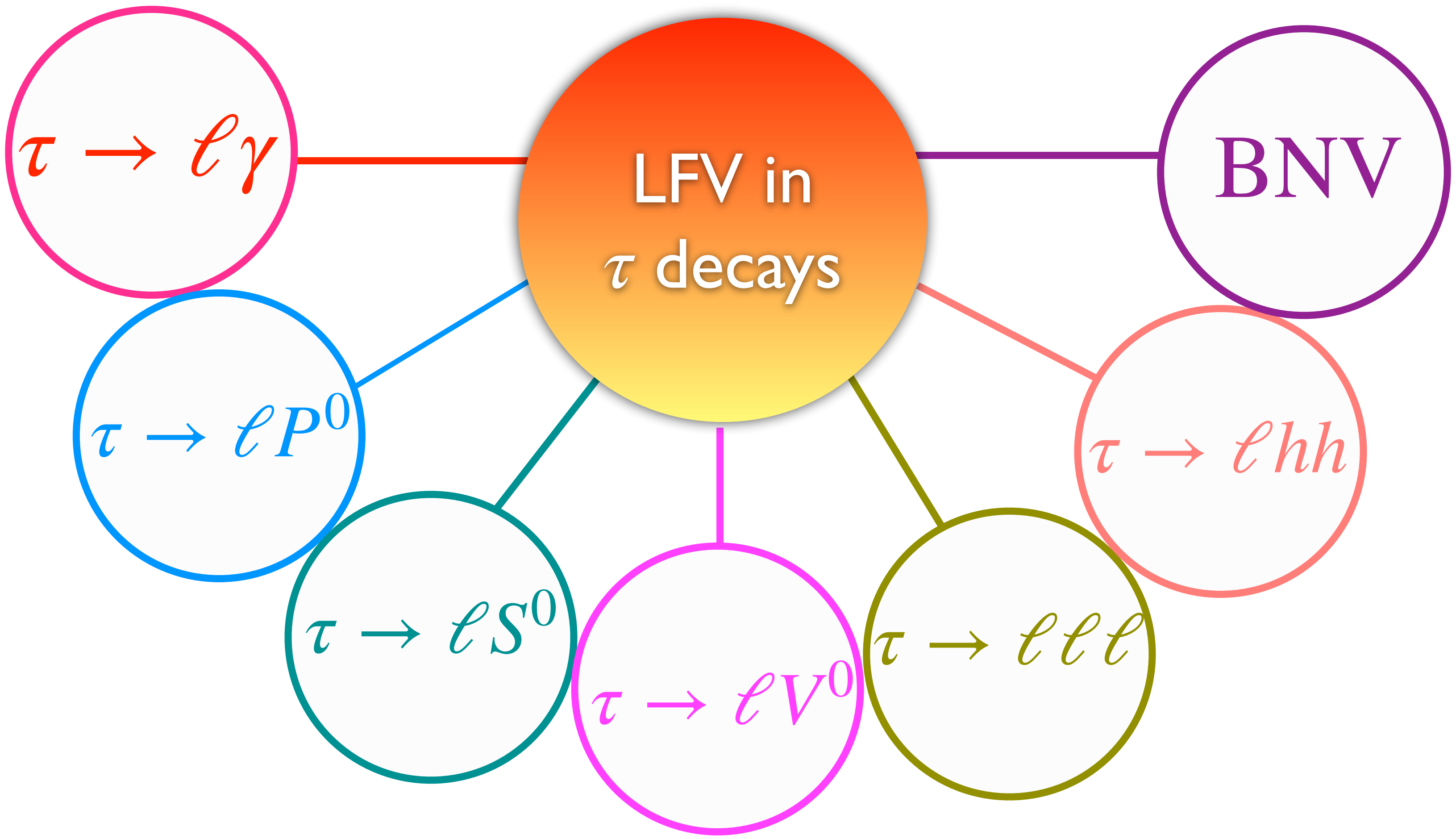


Low- and high-energy phenomenology of a doubly charged scalar

A. Crivellin et. al. Phys. Rev. D 99, 035004 (2019) arXiv:1807.10224 [hep-ph]

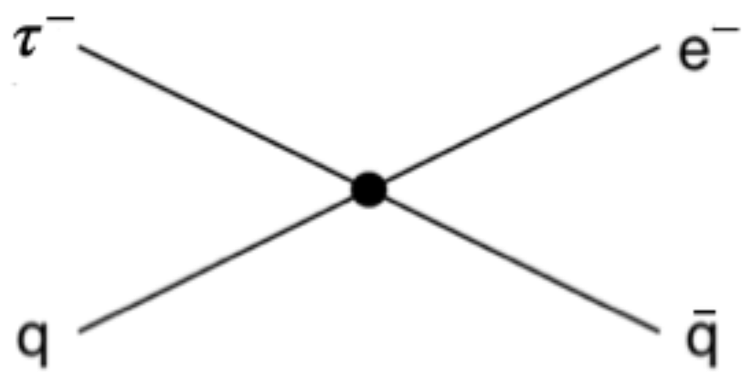
More than 50 τ LFV decays studied at e^+e^- and proton colliders

- **Lepton flavor violation (charge conjugate modes implied)**
  - **$\tau \to e/\mu\, \gamma$ (CLEO, BaBar, Belle)**
  - **$\tau \to e/\mu$ (Pseudoscalar (P^0), Scalar (S^0), Vector (V^0) mesons) (CLEO, BaBar, Belle)**
  - **$\tau \to e\, e\, e$, $e\, \mu\, \mu$, $\mu\, e\, e$ (CLEO, BaBar, Belle (II)), $\mu\, \mu\, \mu$ (also ATLAS, CMS, LHCb)**
  - **$\tau \to e/\mu\, h\, h$ (non-resonant states with $h=\pi/K$) (CLEO, BaBar, Belle)**
- **Lepton number violation**
  - **$\tau^- \to e^+/\mu^+\, h^-\, h^-$ (non-resonant final states with $h=\pi/K$) (CLEO, BaBar, Belle)**
- **Baryon number violation**
  - **$\tau^- \to \Lambda\, \pi^-$, $\bar{\Lambda}\, \pi^-$ (Belle (II), $\bar{p}\, \mu^+\, \mu^-$, $p\, \mu^-\, \mu^-$ (Belle, LHCb)**

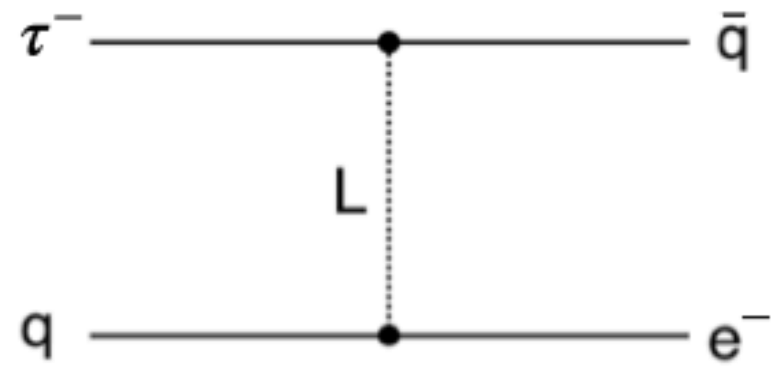


New Physics illustrations for LFV in τ decays

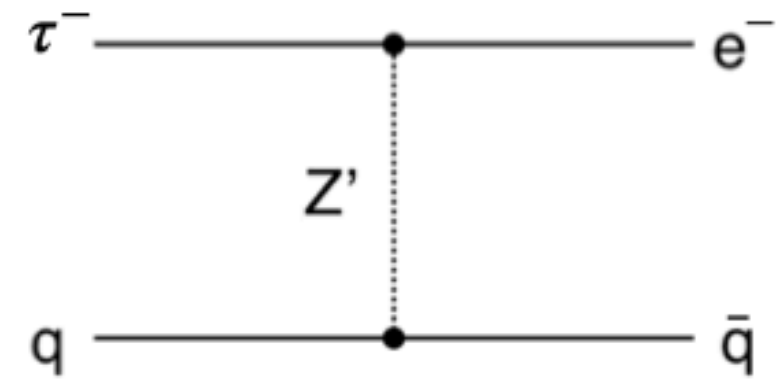
Tree level:



Compositeness

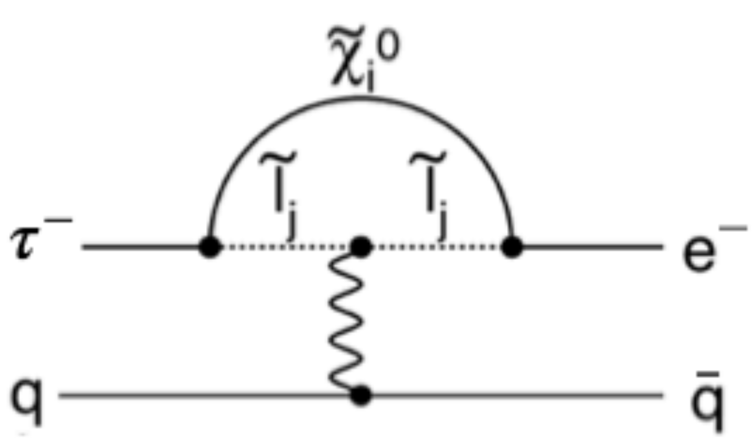


Leptoquarks

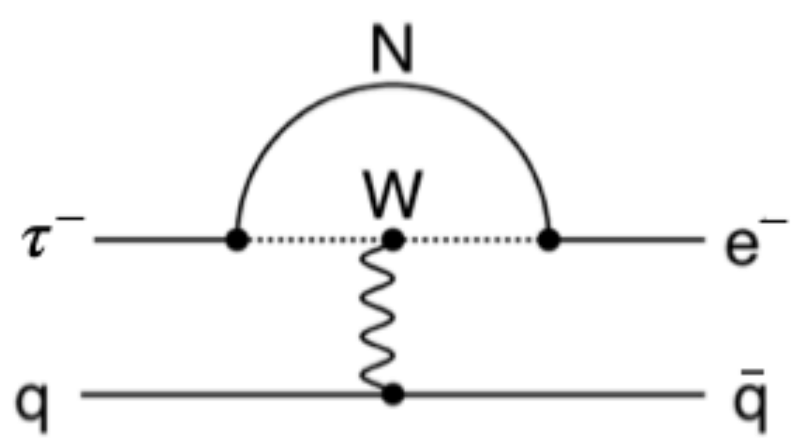


Heavy gauge bosons

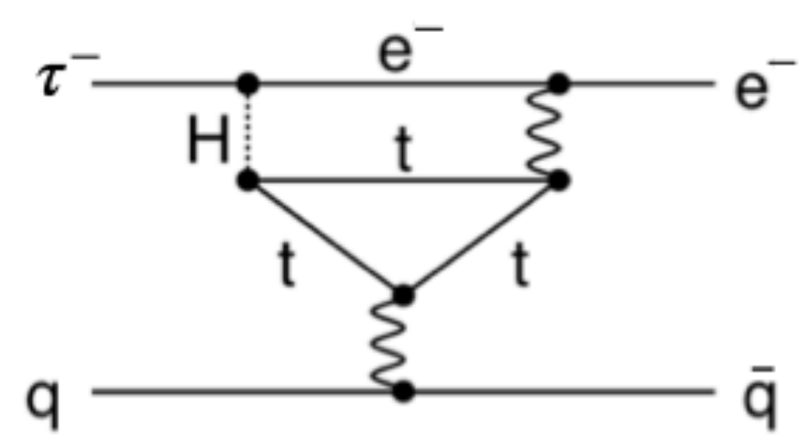
Loop induced:



Supersymmetry



Heavy neutrinos



Extended Higgs models

Expected rates from NP are slightly less than current experimental bounds.

Estimates of experimental sensitivity in LFV searches

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

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

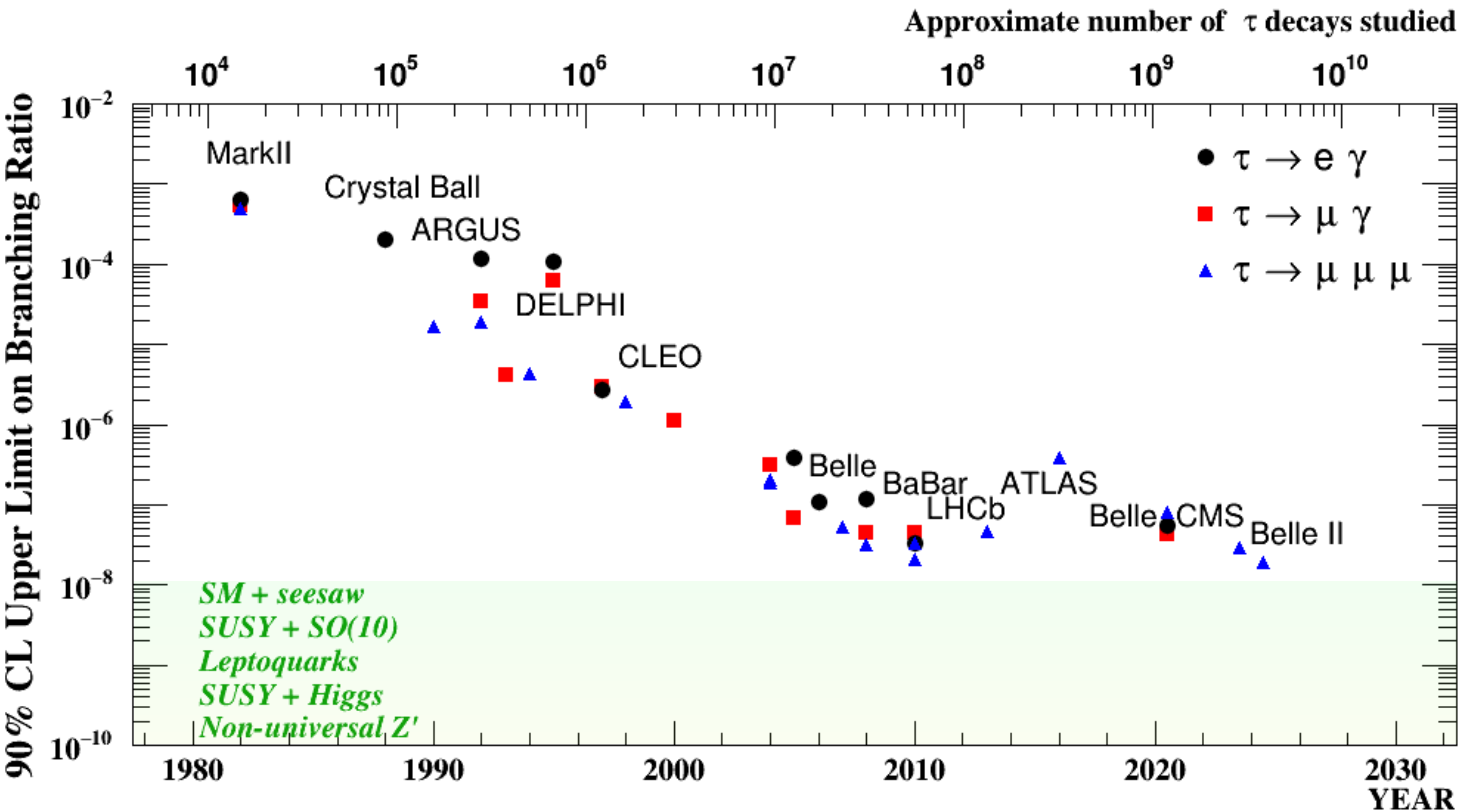
ε = **Trigger . Reco . Topology . PID . Cuts . Signal–Box**

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

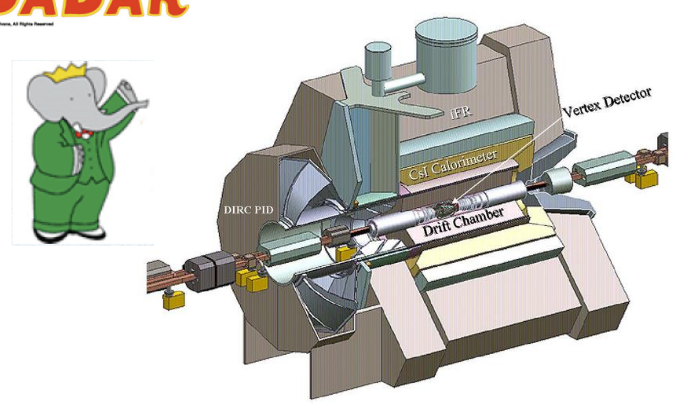
[in a typical e^+e^- collider]

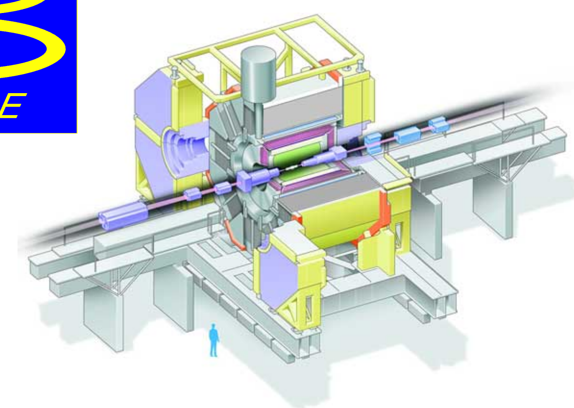
	$\sqrt{s}$	Luminosity	$N_\tau = 2L\sigma_{\tau\tau}$
CLEO	10.58 GeV	14 fb^{-1}	2×10^7
BaBar	10.58 GeV	432 fb^{-1}	9×10^8
Belle	10.58 GeV	1 ab^{-1}	2×10^9
Belle II	10.58 GeV	50 ab^{-1}	9×10^{10}
LHC	7-14 TeV	3 ab^{-1}	10^{15} [efficiency much lower]

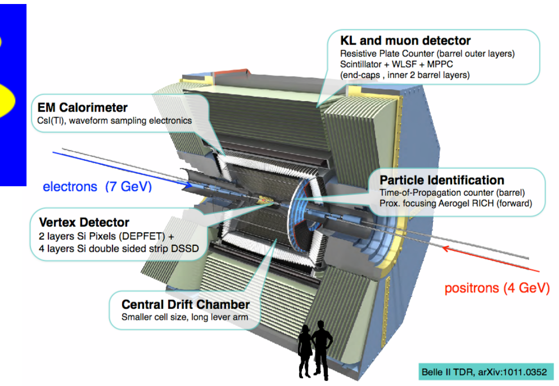
Current status of LFV τ decays

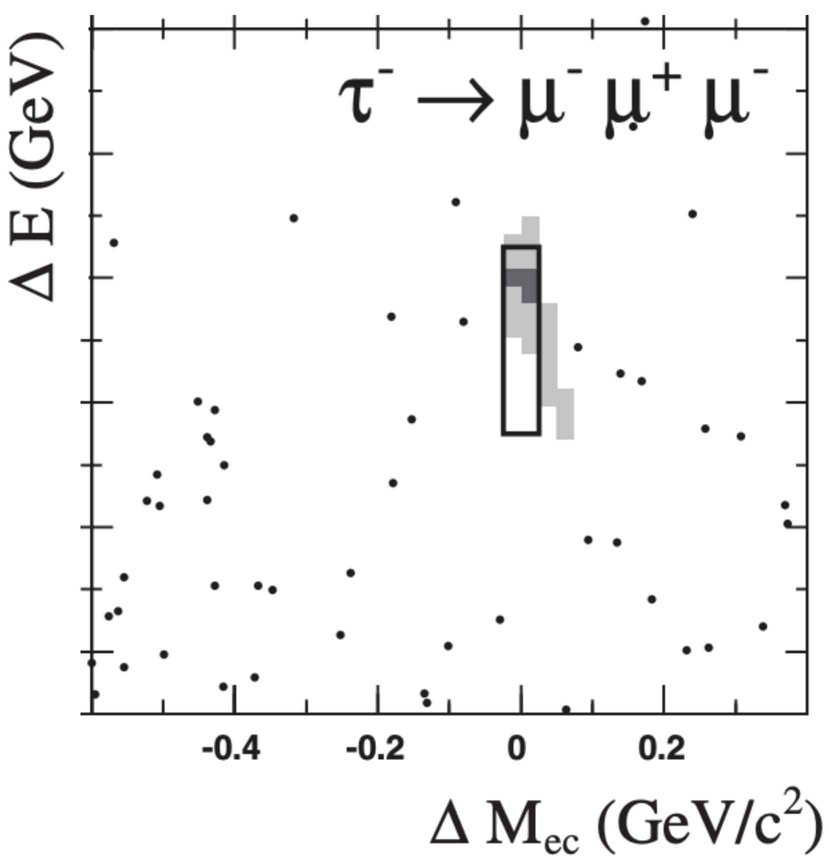


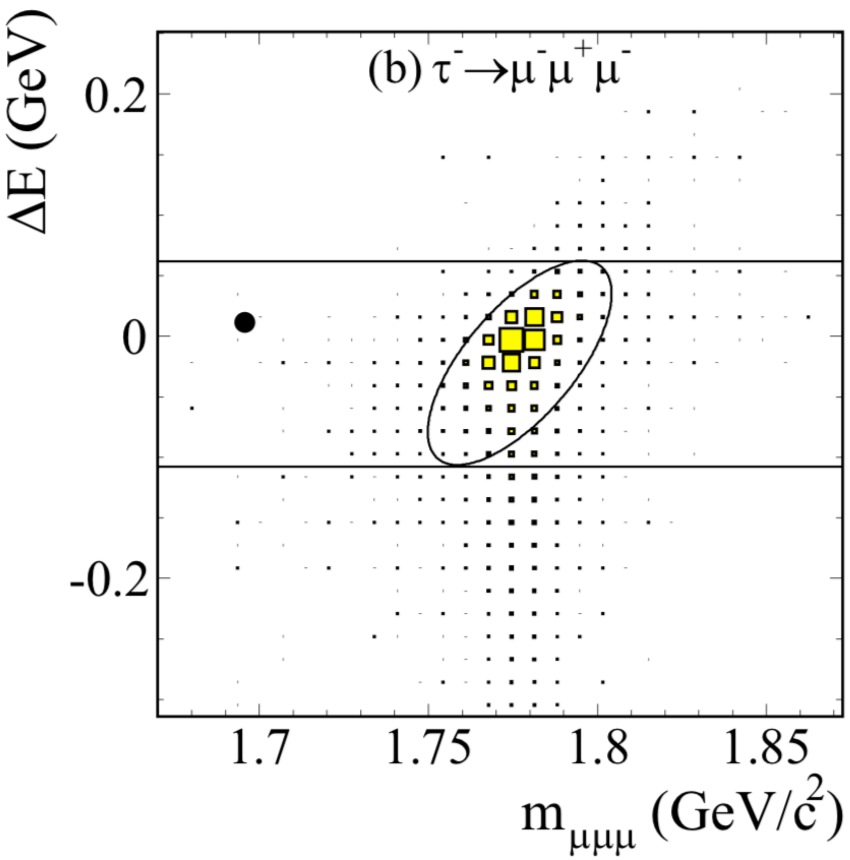
$\tau \to \mu\mu\mu$ at e^+e^- colliders

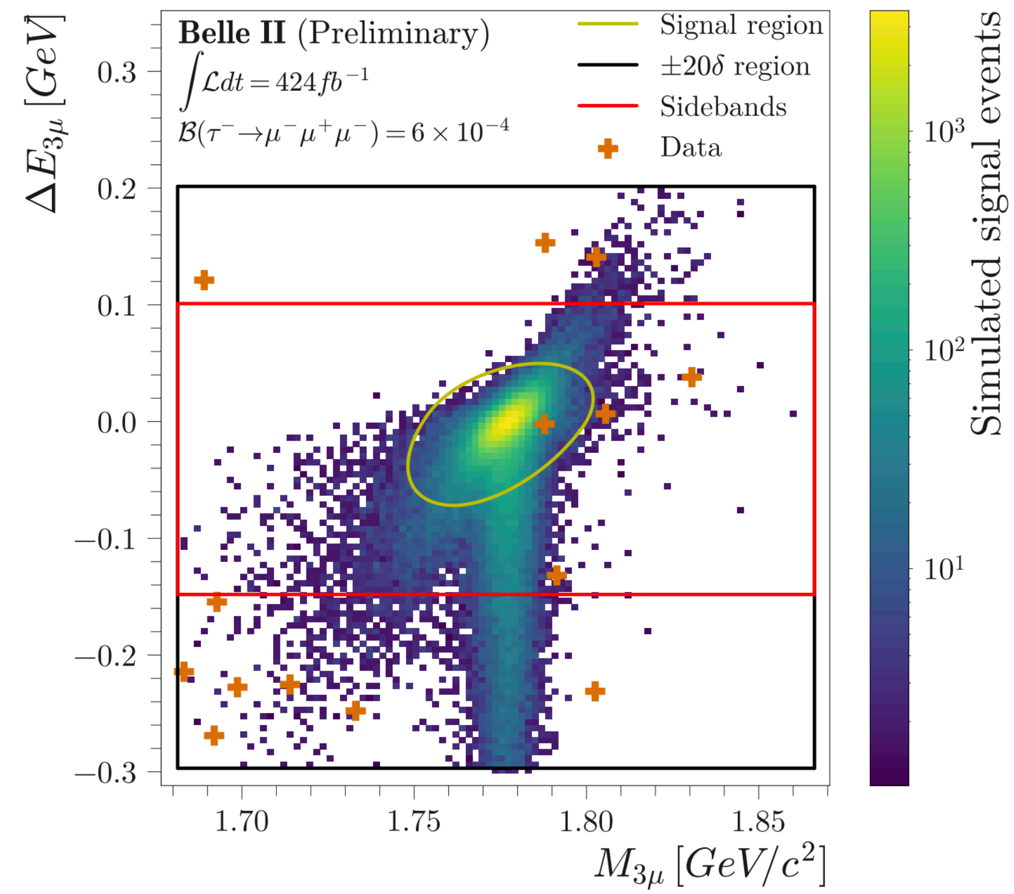












$\mathcal{B}(\tau \to \mu\mu\mu) < 3.3 \times 10^{-8}$ at 90% C.L. with 468 fb^{-1}

Phys.Rev.D 81 (2010) 111101

$\mathcal{B}(\tau \to \mu\mu\mu) < 2.1 \times 10^{-8}$ at 90% C.L. with 782 fb^{-1}

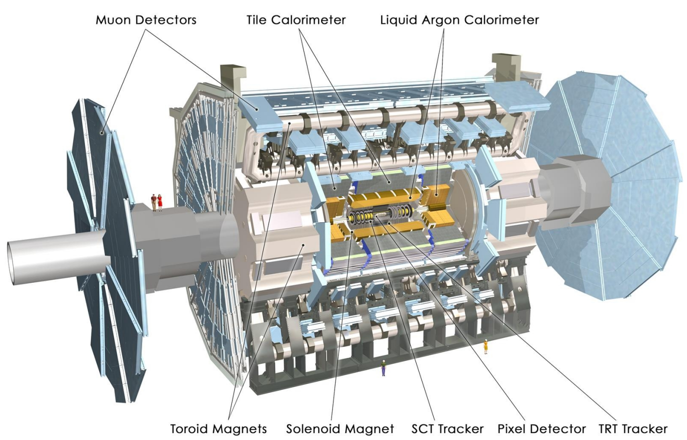
Phys. Lett. B687 (2010) 139

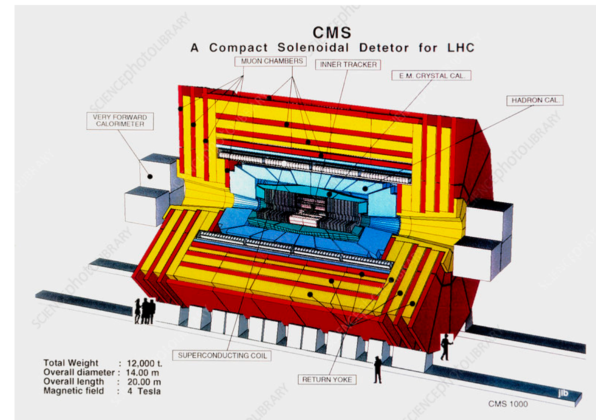
$\mathcal{B}(\tau \to \mu\mu\mu) < 1.9 \times 10^{-8}$ at 90% C.L. with 424 fb^{-1}

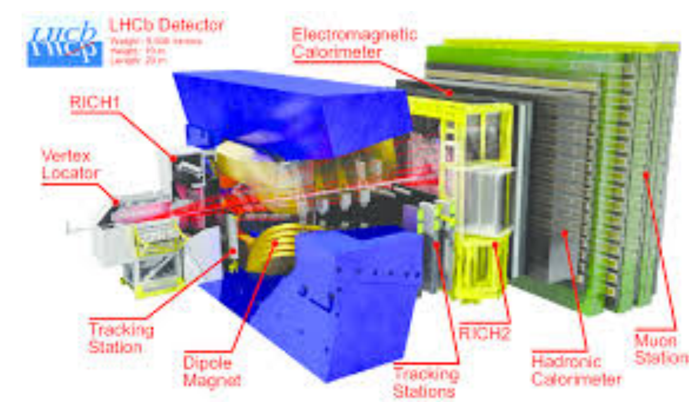
2405.07386 [hep-ex]

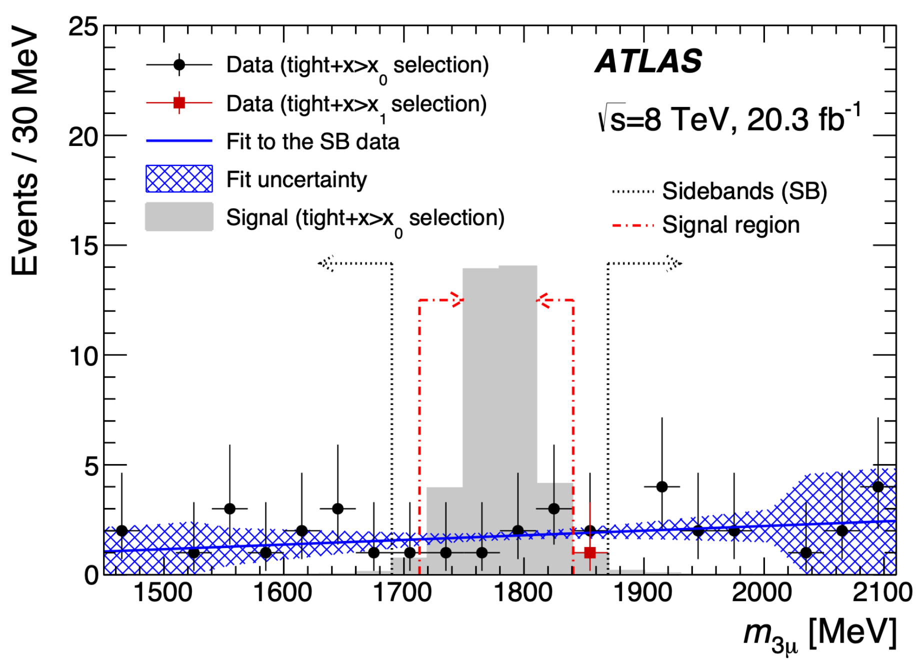
$\tau \to \mu\mu\mu$ at proton colliders

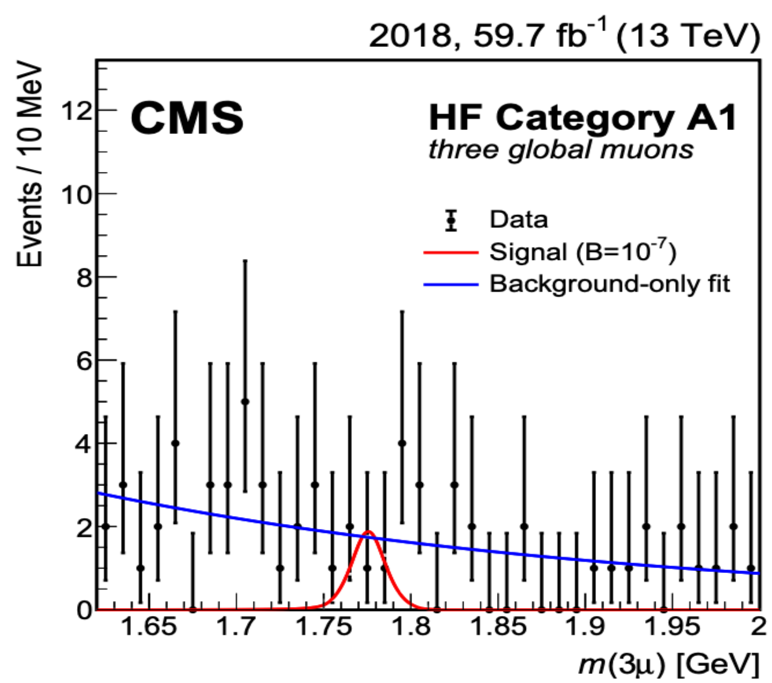
ATLAS	CMS	LHCb

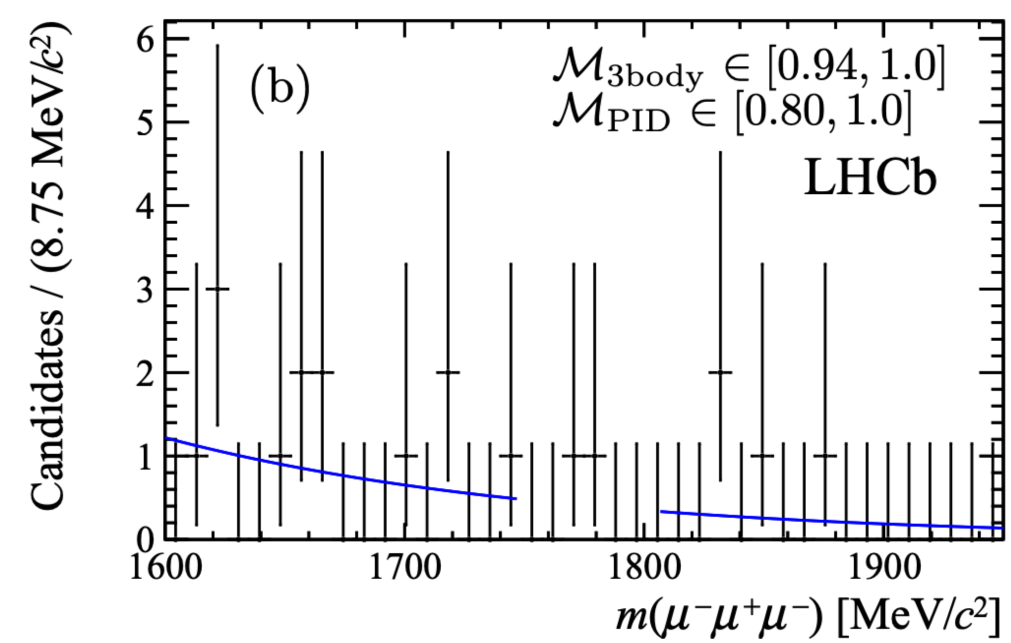












$\mathscr{B}(\tau \to \mu\mu\mu) < 3.8 \times 10^{-7}$ at 90% C.L. with 20 fb^{-1}

$\mathscr{B}(\tau \to \mu\mu\mu) < 2.1 \times 10^{-8}$ at 90% C.L. with 131 fb^{-1}

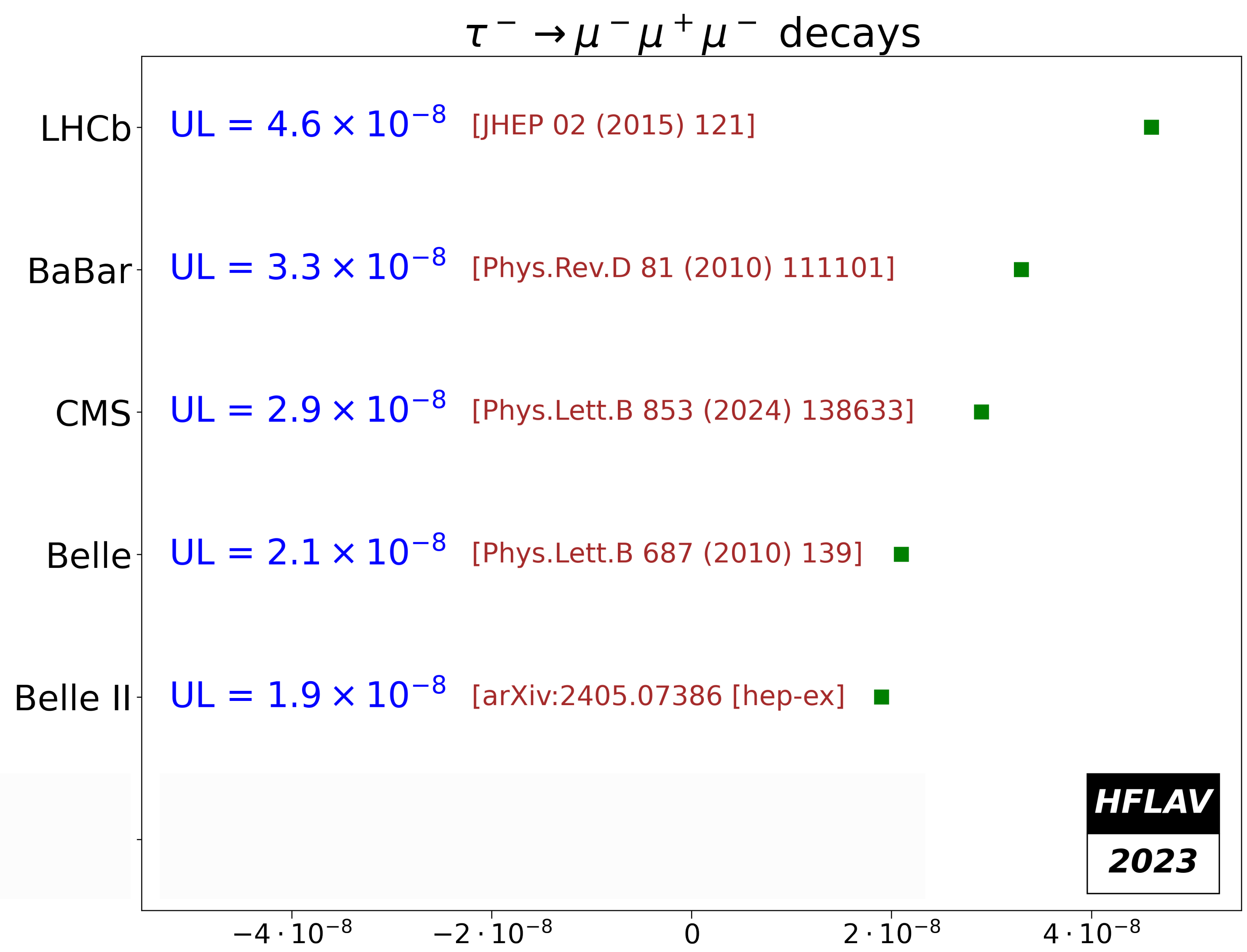
$\mathscr{B}(\tau \to \mu\mu\mu) < 3.6 \times 10^{-8}$ at 90% C.L. with 3 fb^{-1}

Eur.Phys.J.C 76 (2016) 5, 232

Phys. Lett. B 853 (2024) 138633

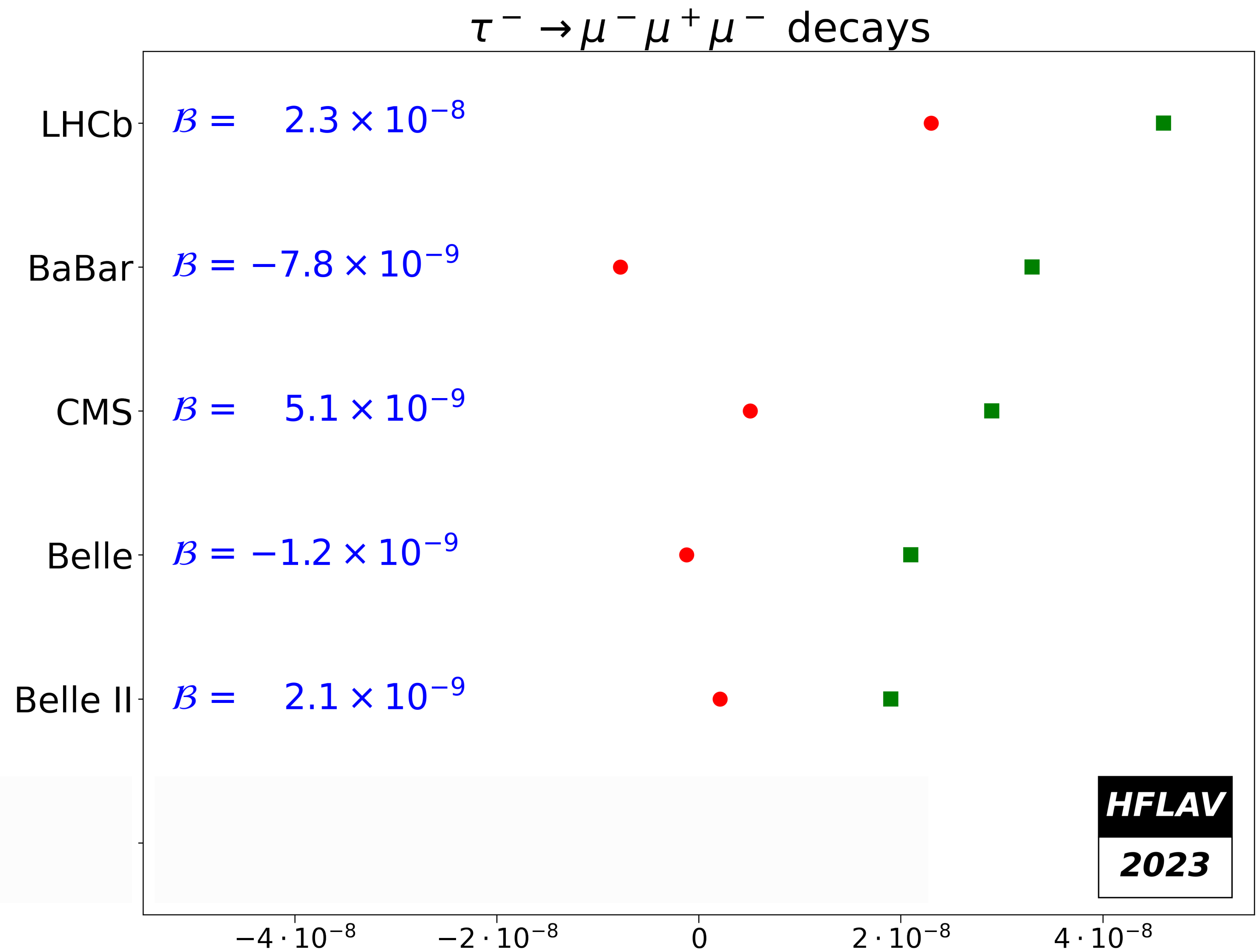
JHEP 02 (2015) 121

Upper limits at 90% confidence level (CL)



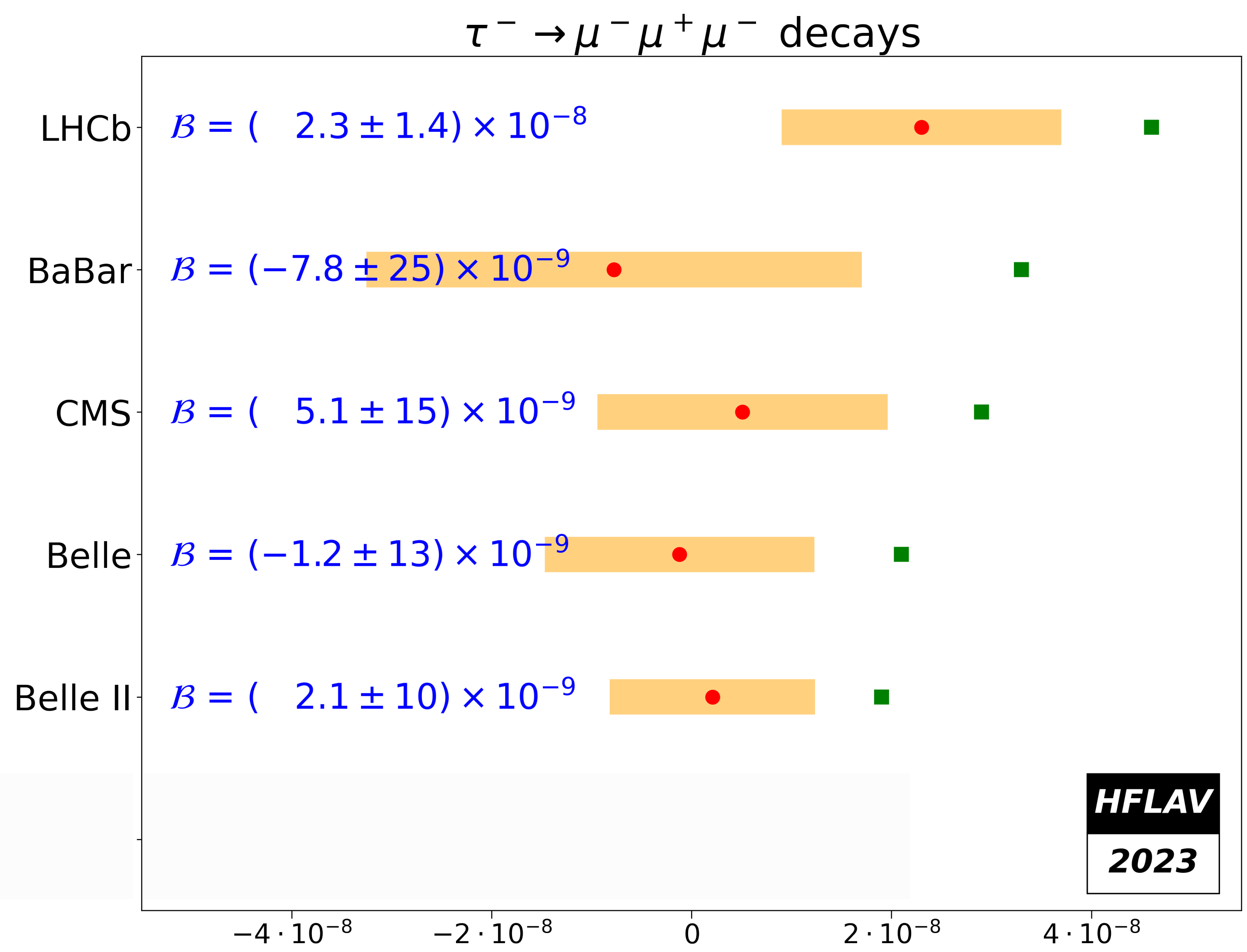
Since there is negligible gain in combining limits of very different strength, the combinations do not include the limits that are more than 10 times larger than the strictest limit in the respective channel. This excludes limits from CLEO and ATLAS.

Central value of branching fractions



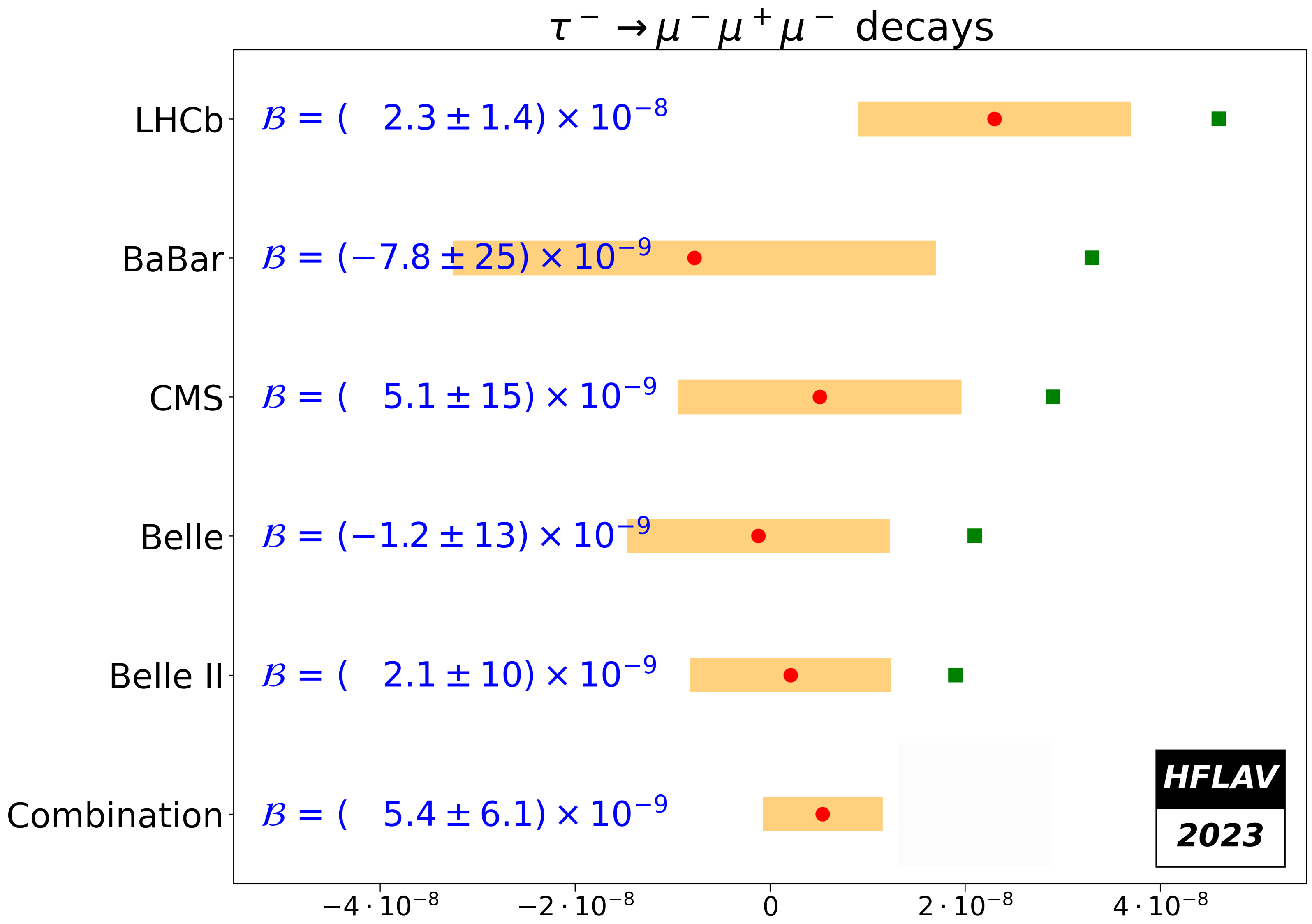
Many publication do not have reported values for central value of branching fraction ($\mathscr{B}$). CMS and LHCb contacts provided central values. In other cases, we calculate the central value using the formula: $\mathscr{B}_i = (N^i_{\rm obs} - N^i_{\rm bkg})/(N^i_\tau \varepsilon^i)$, where $N^i_{\rm obs}$ is the number of observed events, $N^i_{\rm bkg}$ is the number of expected background events, N^i_τ is the number of τ decays in the data sample, and ε^i is the signal reconstruction efficiency in the signal region.

Gaussian approximation



All the quoted upper limits (UL) include both statistical as well as systematic uncertainties.
The total uncertainty (σ_i) for each measurement is obtained using the relation:
$\mathrm{UL}_i = \mathscr{B}_i + 1.645\sigma_i$ assuming a Gaussian quantile for the 2-sided upper limit at 90% CL.

Combination methodology

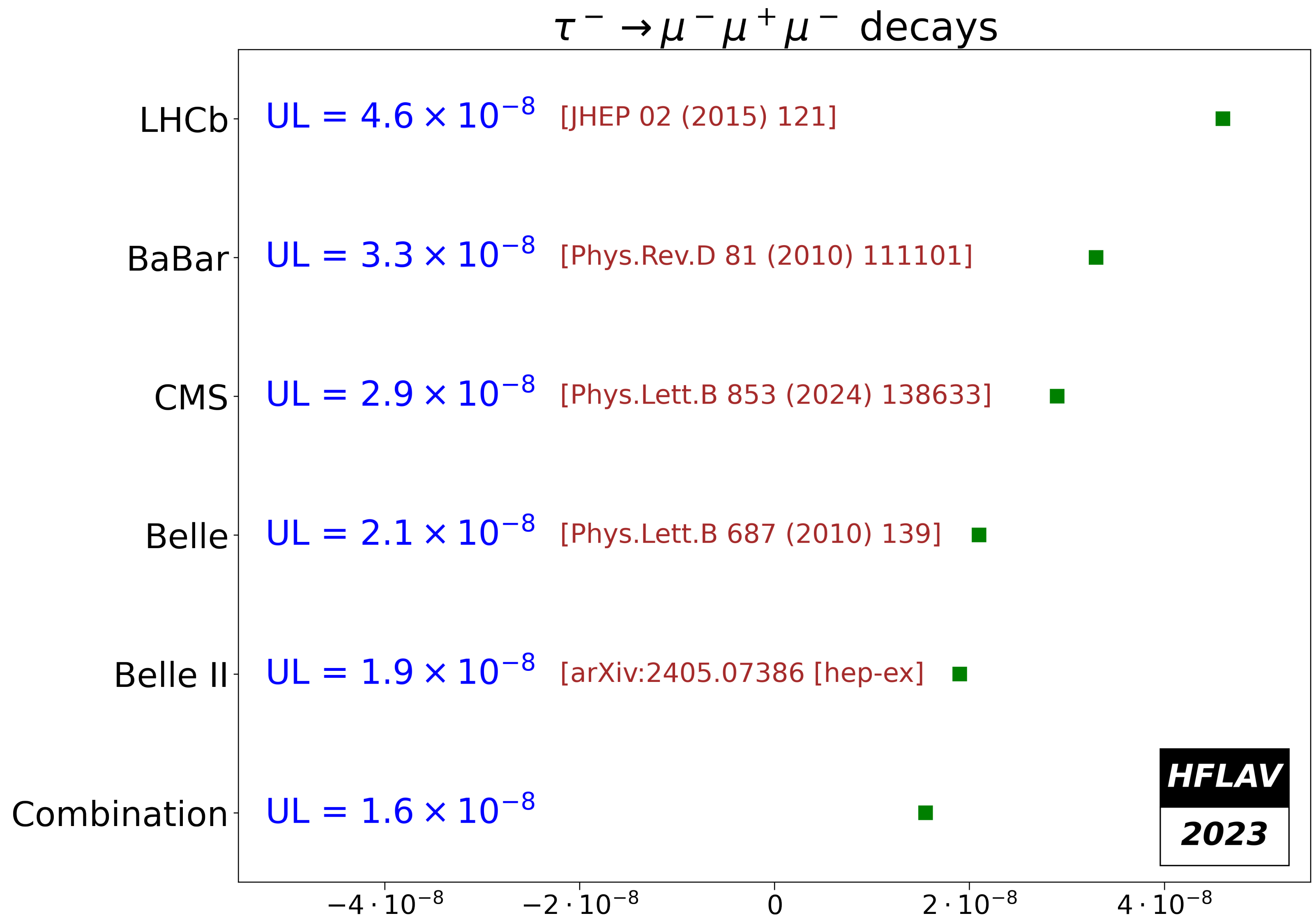


Average value of branching fraction ($\overline{\mathscr{B}} \pm \overline{\sigma}$) is obtained using:

$$\overline{\mathscr{B}} = \frac{\sum_i \omega_i \mathscr{B}_i}{\sum_i \omega_i}, \quad \overline{\omega} = \sqrt{\frac{1}{\sum_i \omega_i}}, \text{ where } \omega_i = \frac{1}{\sigma_i^2}.$$

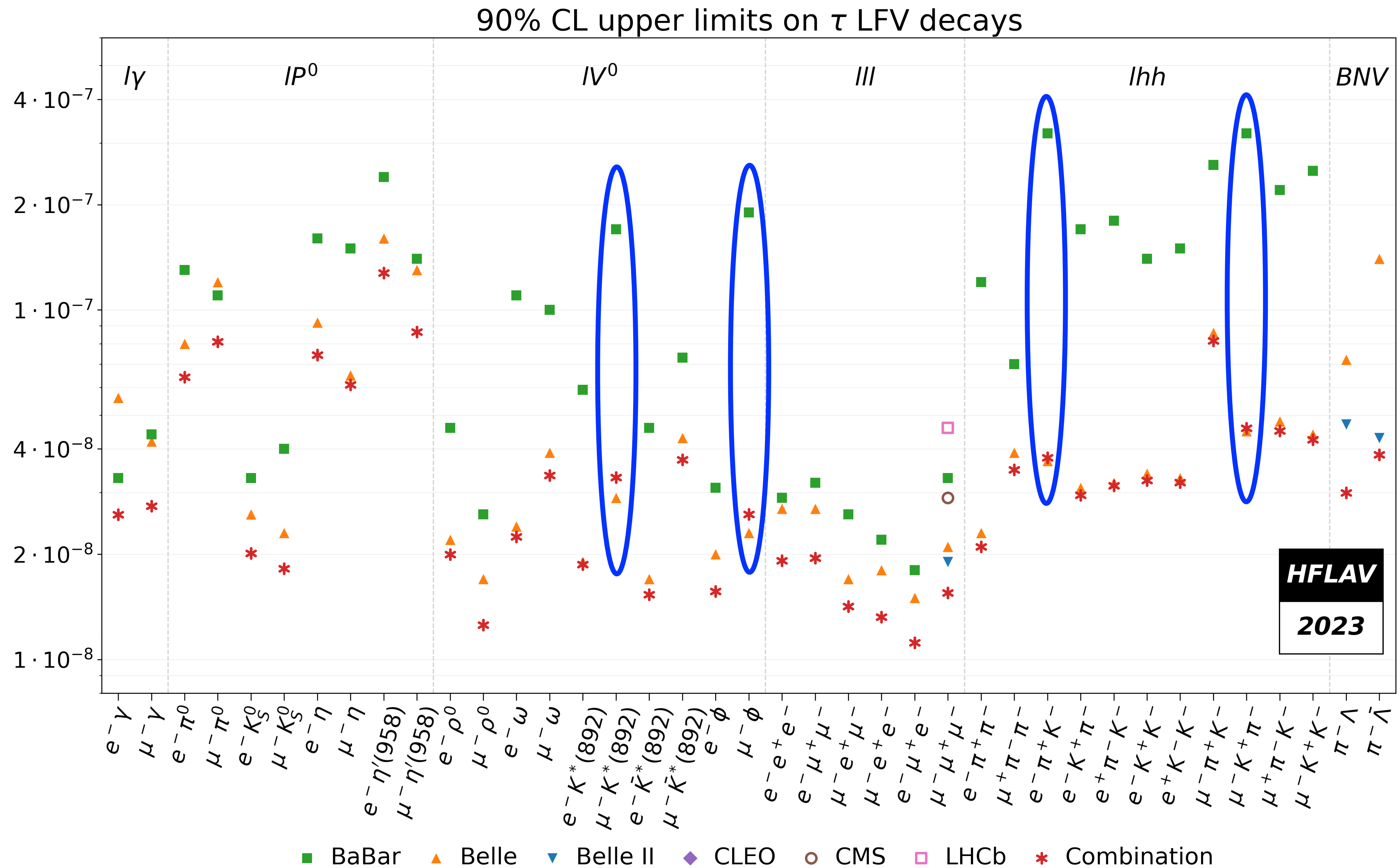
The correlated uncertainty on τ−pair production cross-section of 0.36% plays a numerically insignificant role in results of this uncorrelated averaging.

Combination methodology



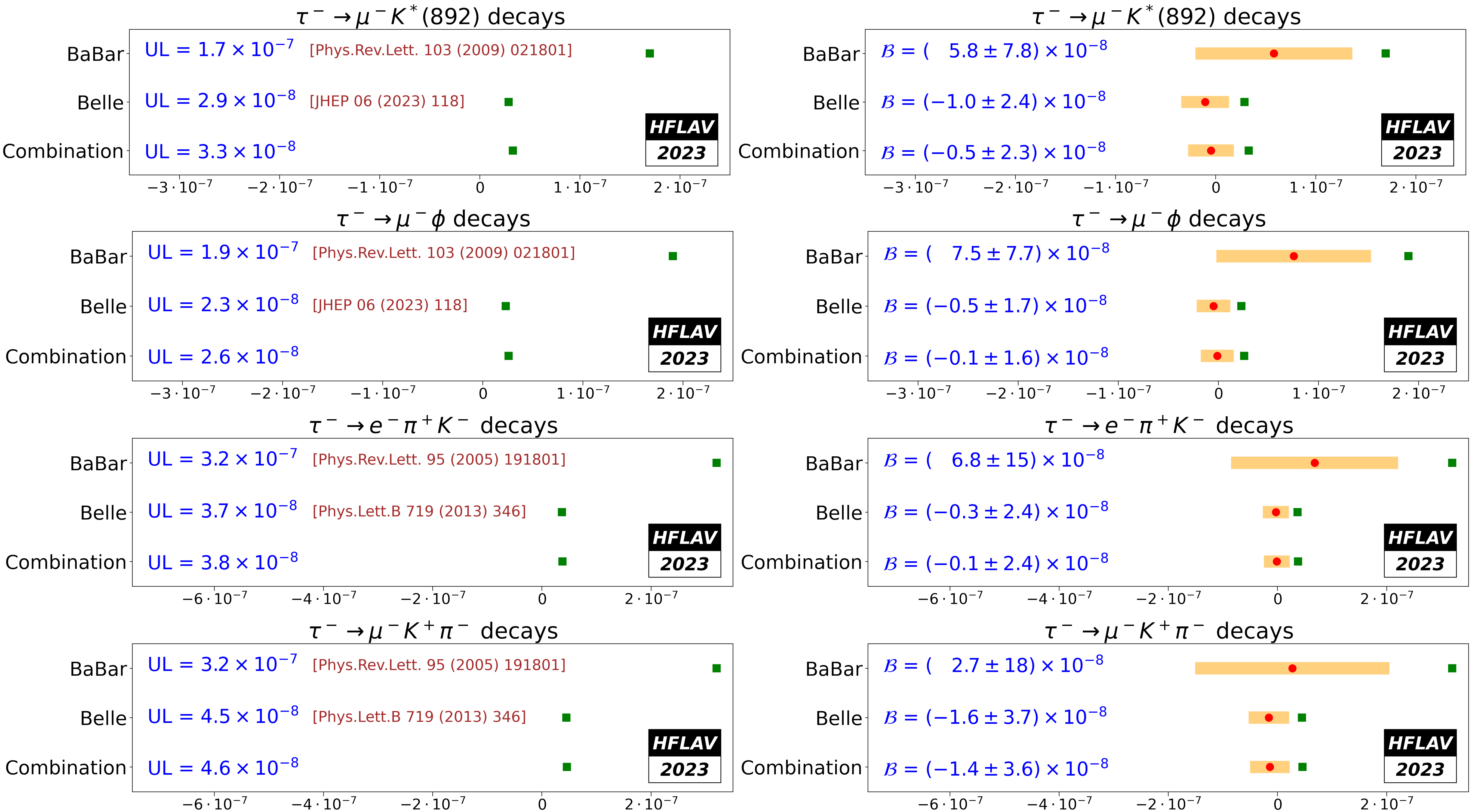
The combined upper limit ($\overline{\text{UL}}$) is obtained from the averaged branching fraction ($\overline{\mathscr{B}} \pm \overline{\sigma}$) using the formula: $\overline{\text{UL}} = \overline{\mathscr{B}} + 1.645\overline{\sigma}$, again using the Gaussian approximation.

Combined upper limits for 39 τ LFV decays



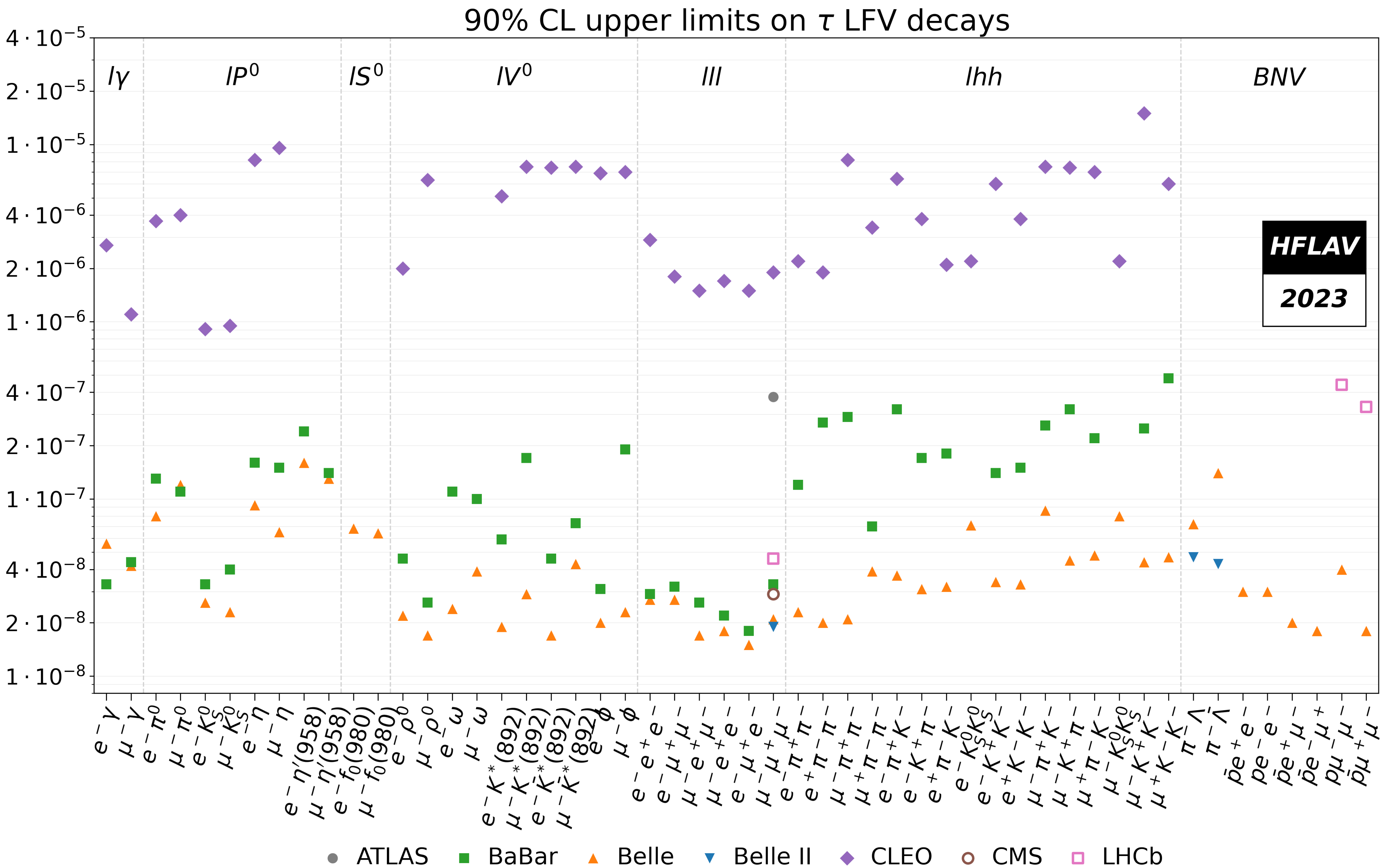
Combined upper limits are obtained for 39 decays having more than 1 measurement in the set of upper limits less than 10 times strictest limit in that channel out of 52 τ LFV decays studied. 4 out of 39 combined limits are more than the strictest limit in the set.

Combined upper limits for the 4 τ LFV decays



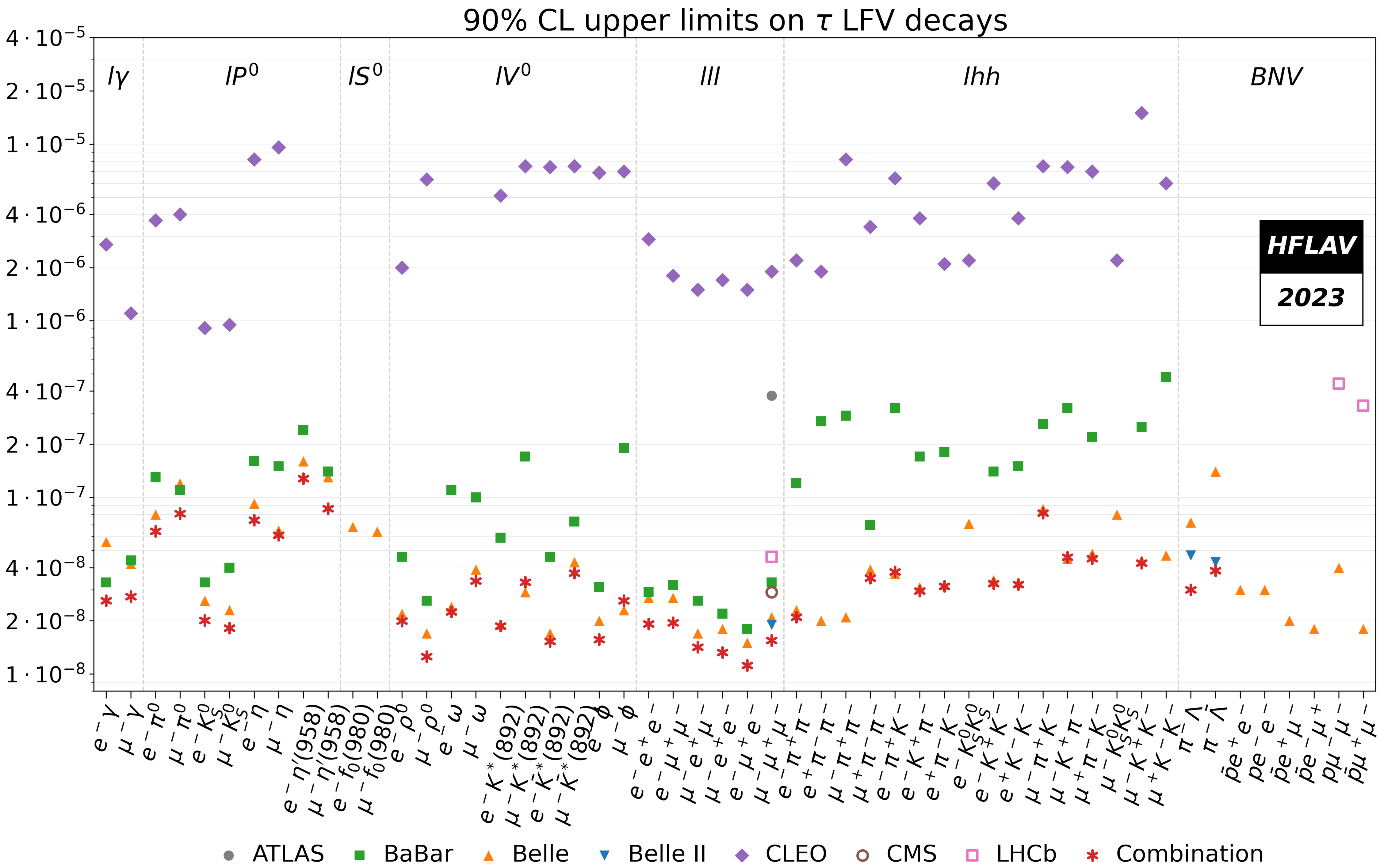
For these 4 modes, BaBar and Belle saw upward and downward fluctuations, respectively.
Combined results have better precision, even though limits are higher than Belle by ~10%.

Summary & Outlook



Inputs to combination are 52 τ decay modes from different experiments.

Summary & Outlook



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. Then we can stop at combining central values and do not have to calculate upper limits.