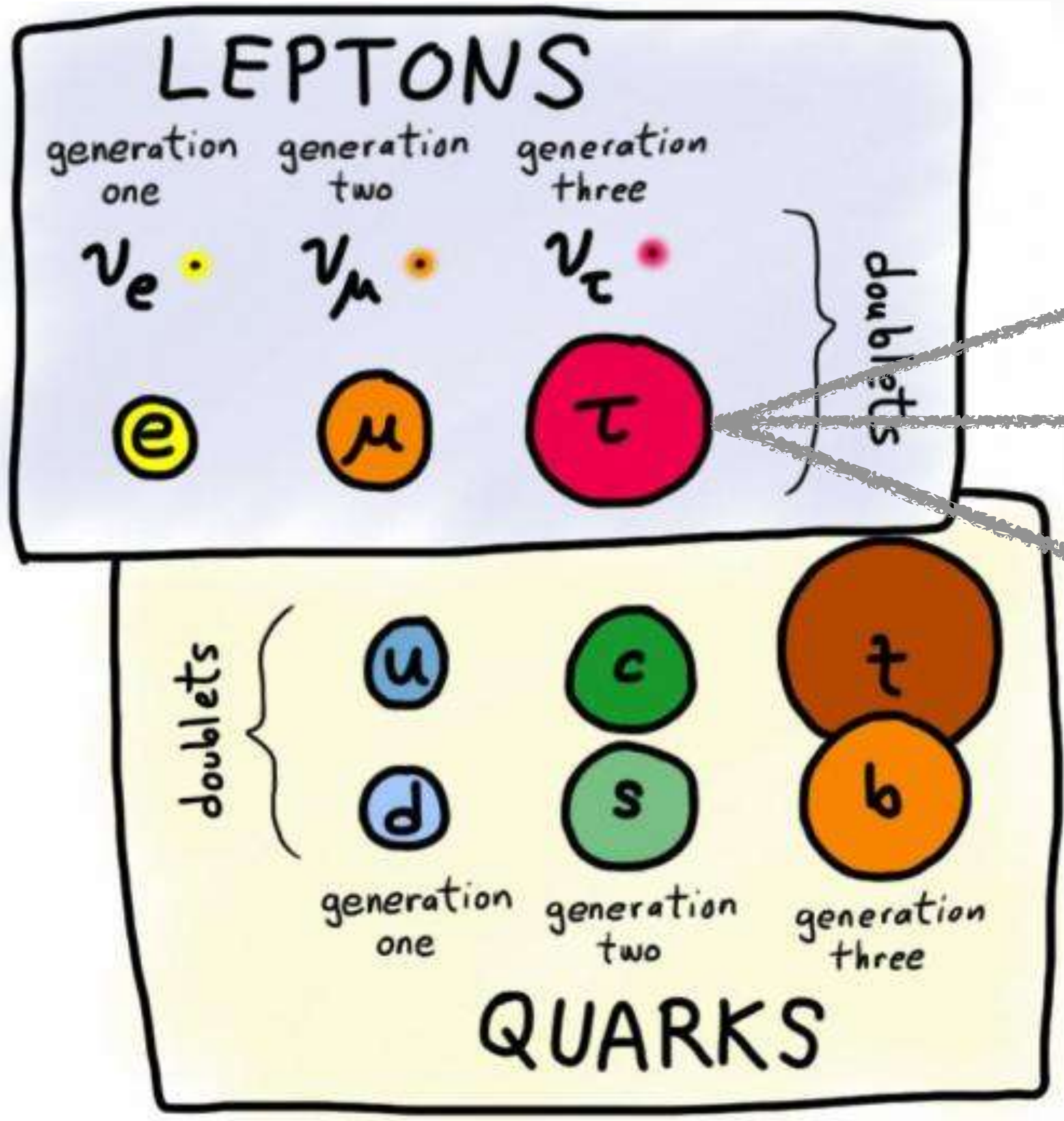
# Rare decays of τ lepton




very heavy

+

very unstable

=

VERY INTERESTING


Ami Rostomyan

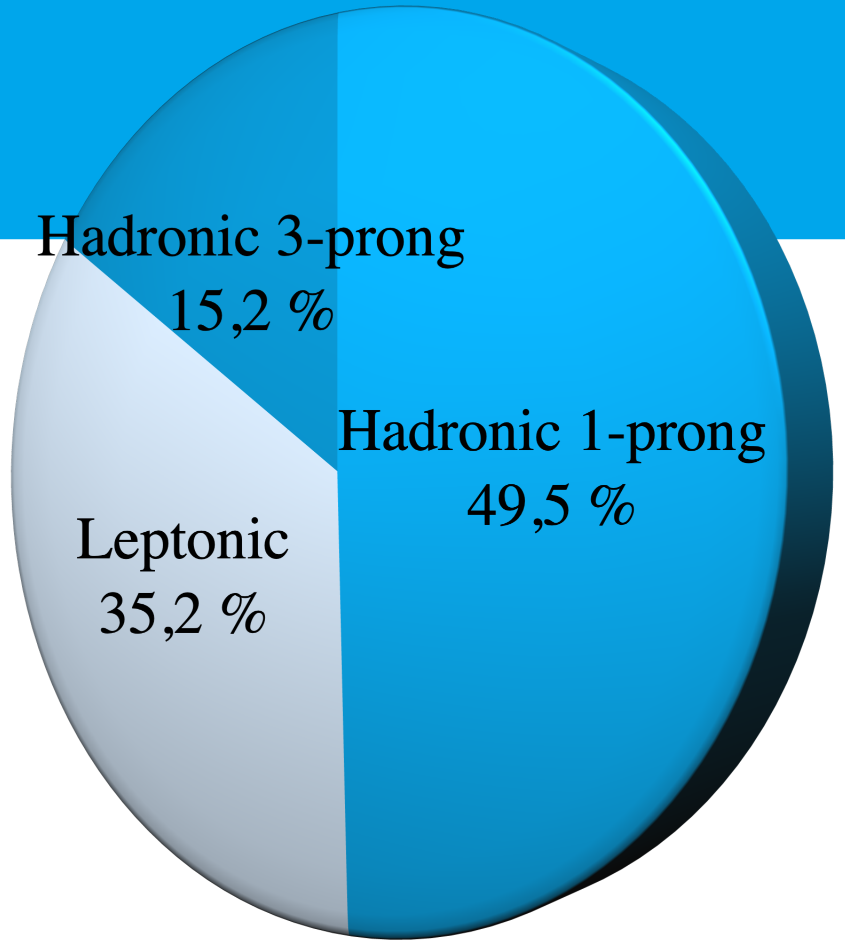


22nd Conference on Flavour Physics and CP Violation (FPCP 2024)

27th of May, 2024

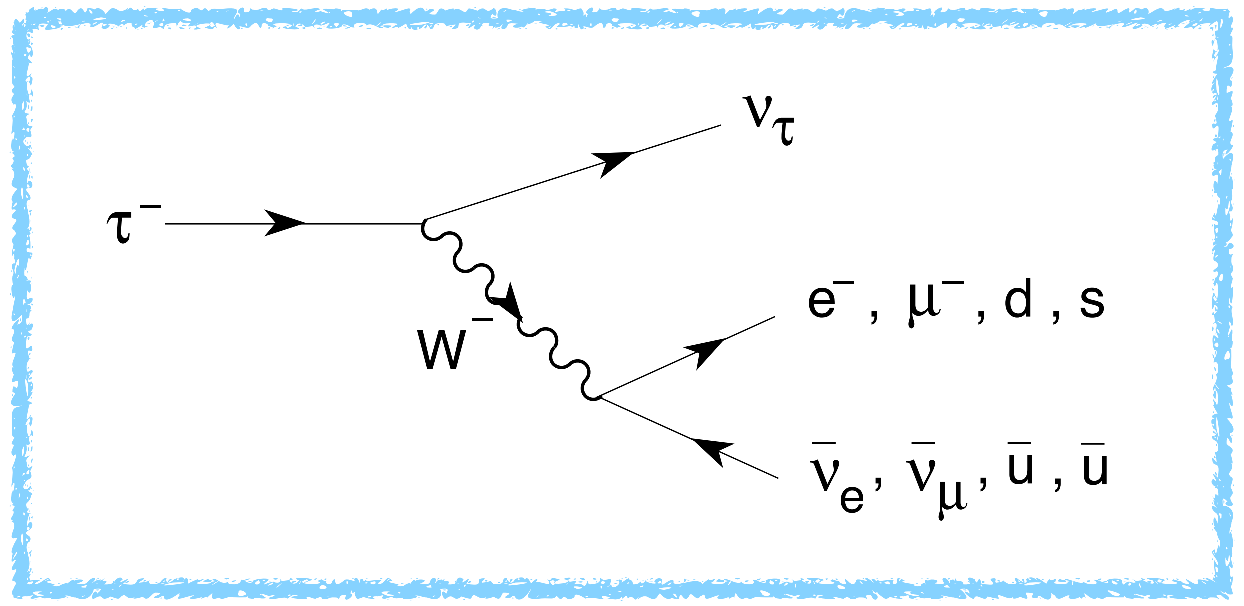

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

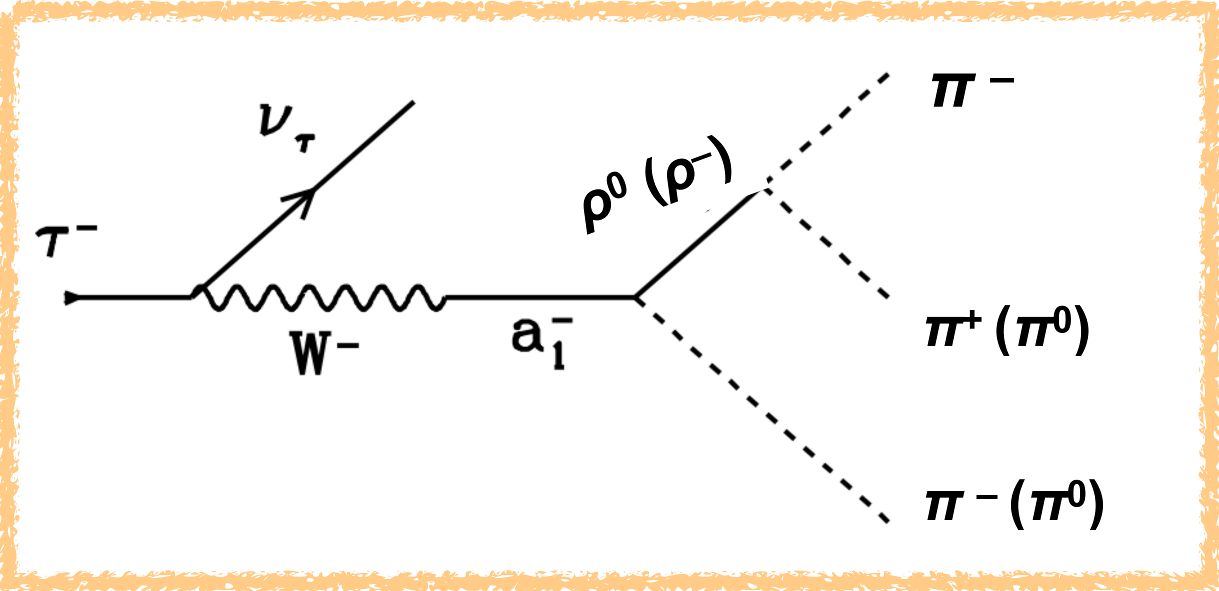
# The τ lepton




**~ 250 decay modes in PDG**

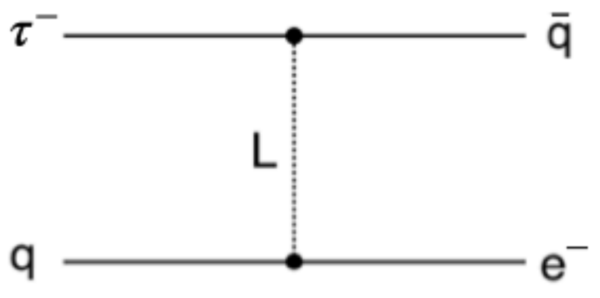
- Pure leptonic $\tau \to e\bar{\nu}\nu$ and $\tau \to \mu\nu\bar{\nu}$
- Hadronic or semi-leptonic
  - Cabibbo favoured $\tau \to \pi\nu$ and suppressed $\tau \to K\nu$



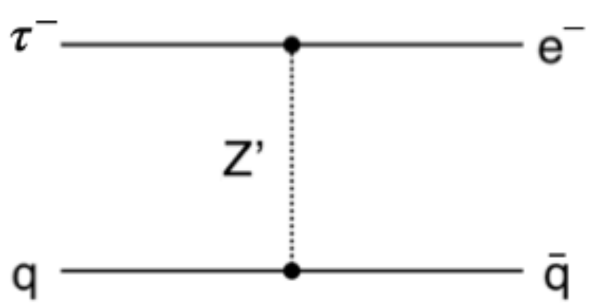




- Forbidden decays
  - Lepton flavour (LFV), lepton number (LNV), baryon number (BNV) violation

**Tree level**

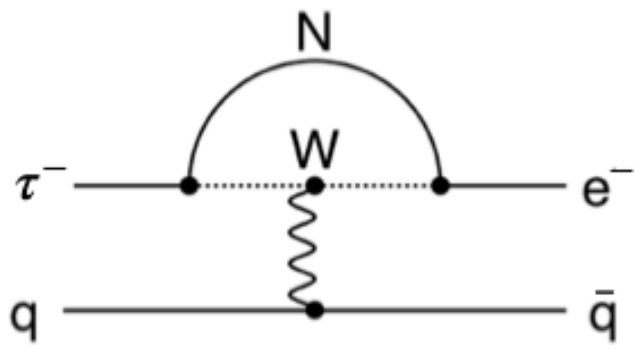



**Leptoquarks**

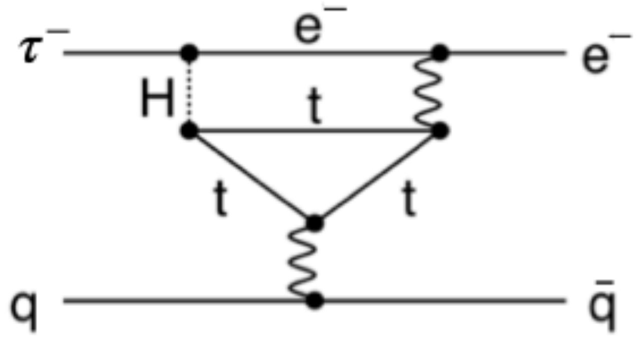



**Heavy gauge bosons**

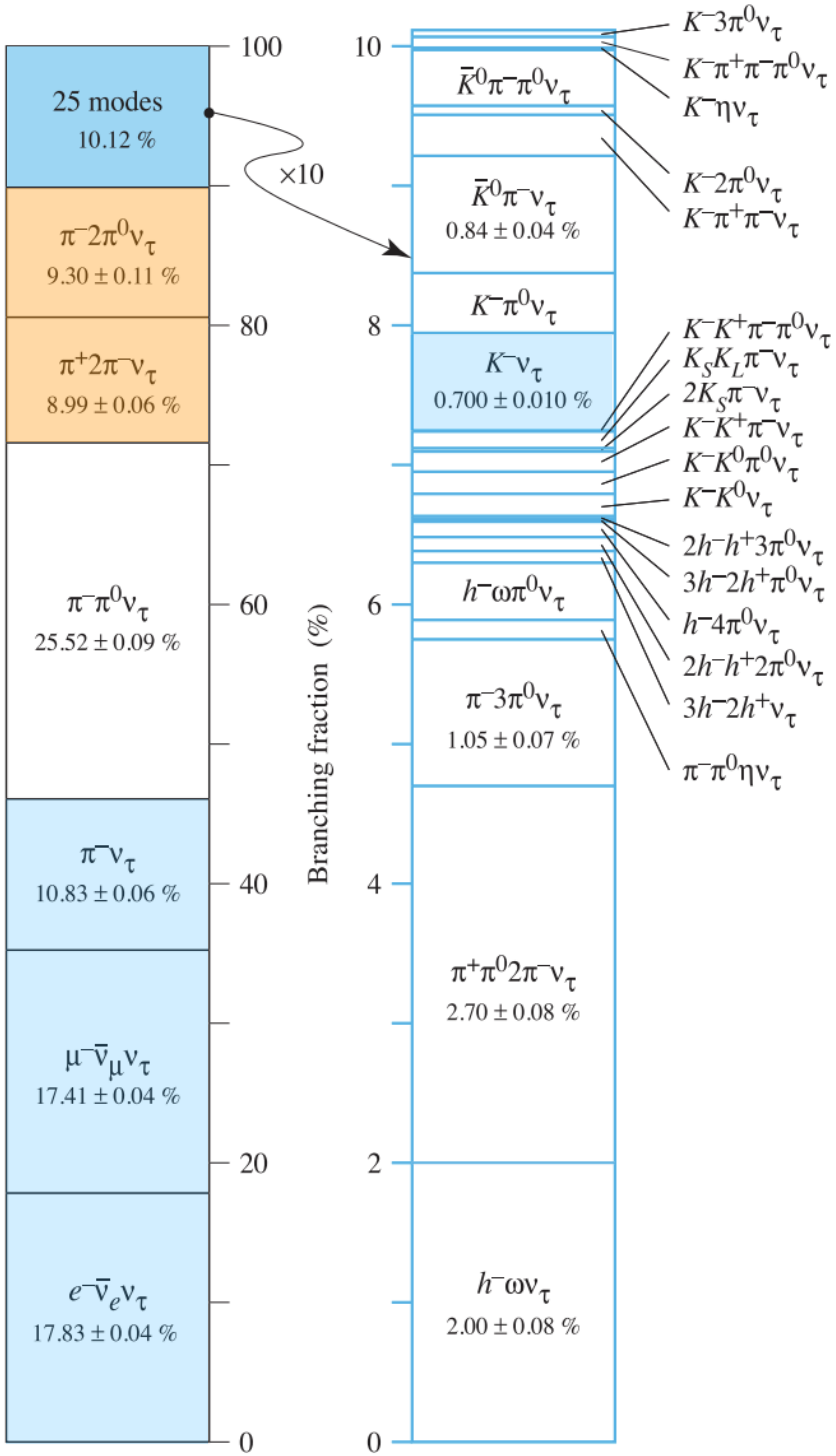
**Loop induced**




**Heavy neutrinos**




**Extended Higgs models**



# The role of $\tau$ leptons in the quest

**Laboratory to test the structure of the weak currents, the universality of the coupling to the gauge bosons and the low-energy aspects of strong interactions.**


**Wide range of observables in $\tau$ sector to confront theory!**

**Does NP couple to 3rd generation strongly?**

**Precision measurements or indirect search of BSM**

➡ *significant deviations from SM* are unambiguous signatures of NP

**Direct search of forbidden decays**

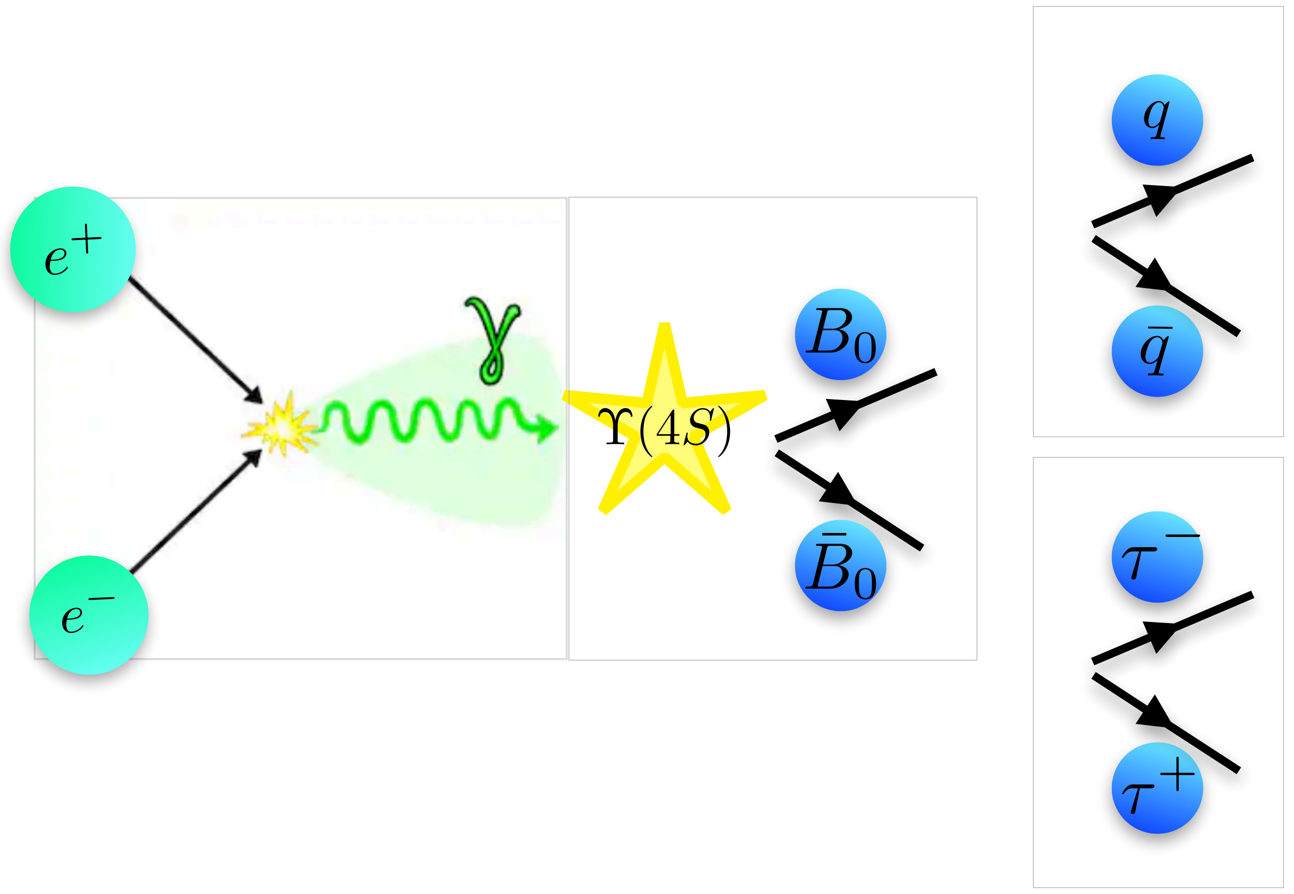
➡ *any signal* is unambiguous signature of NP

# The progress of τ physics

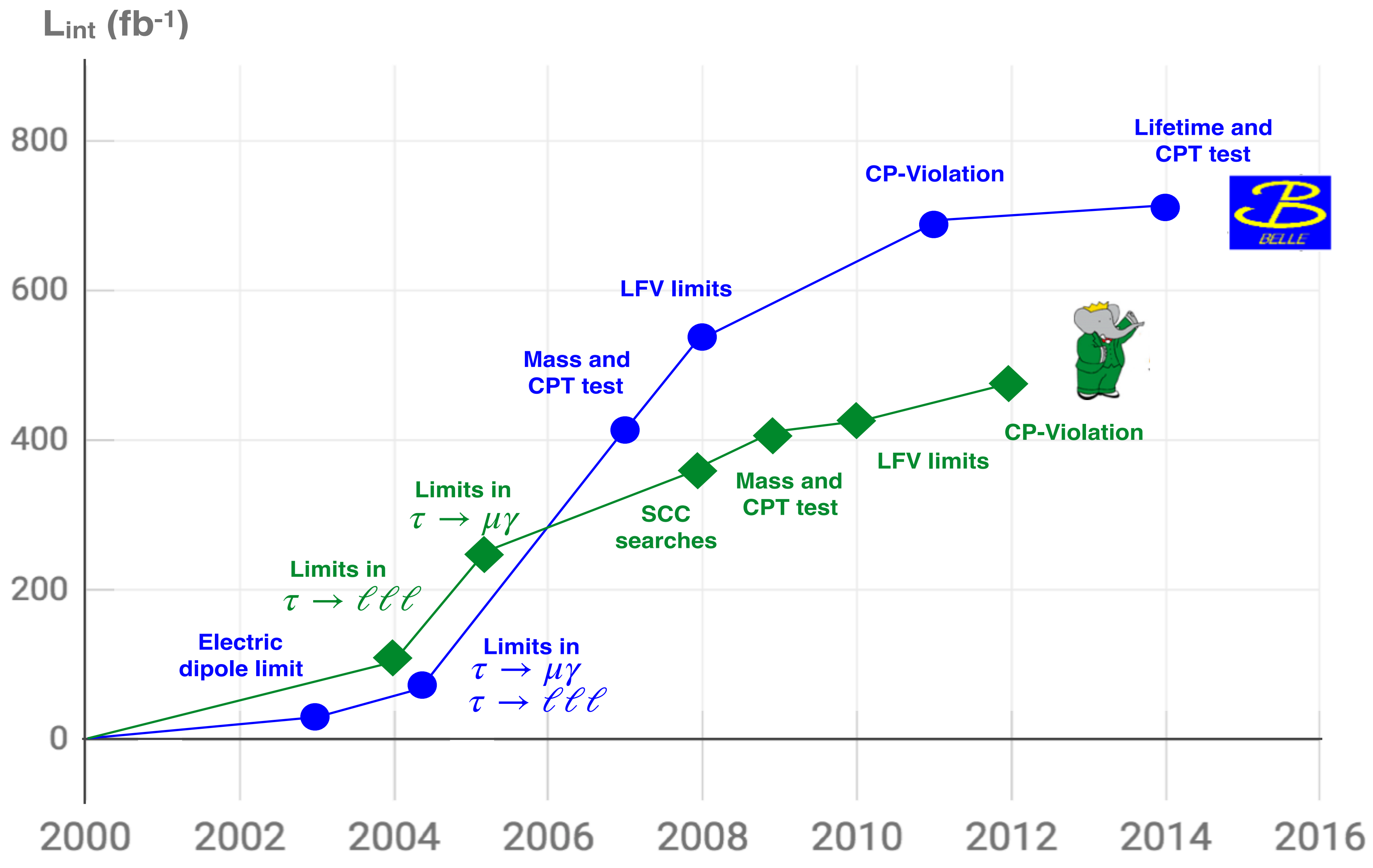
**B-factories provided a variety of very interesting results in the last two decades.**

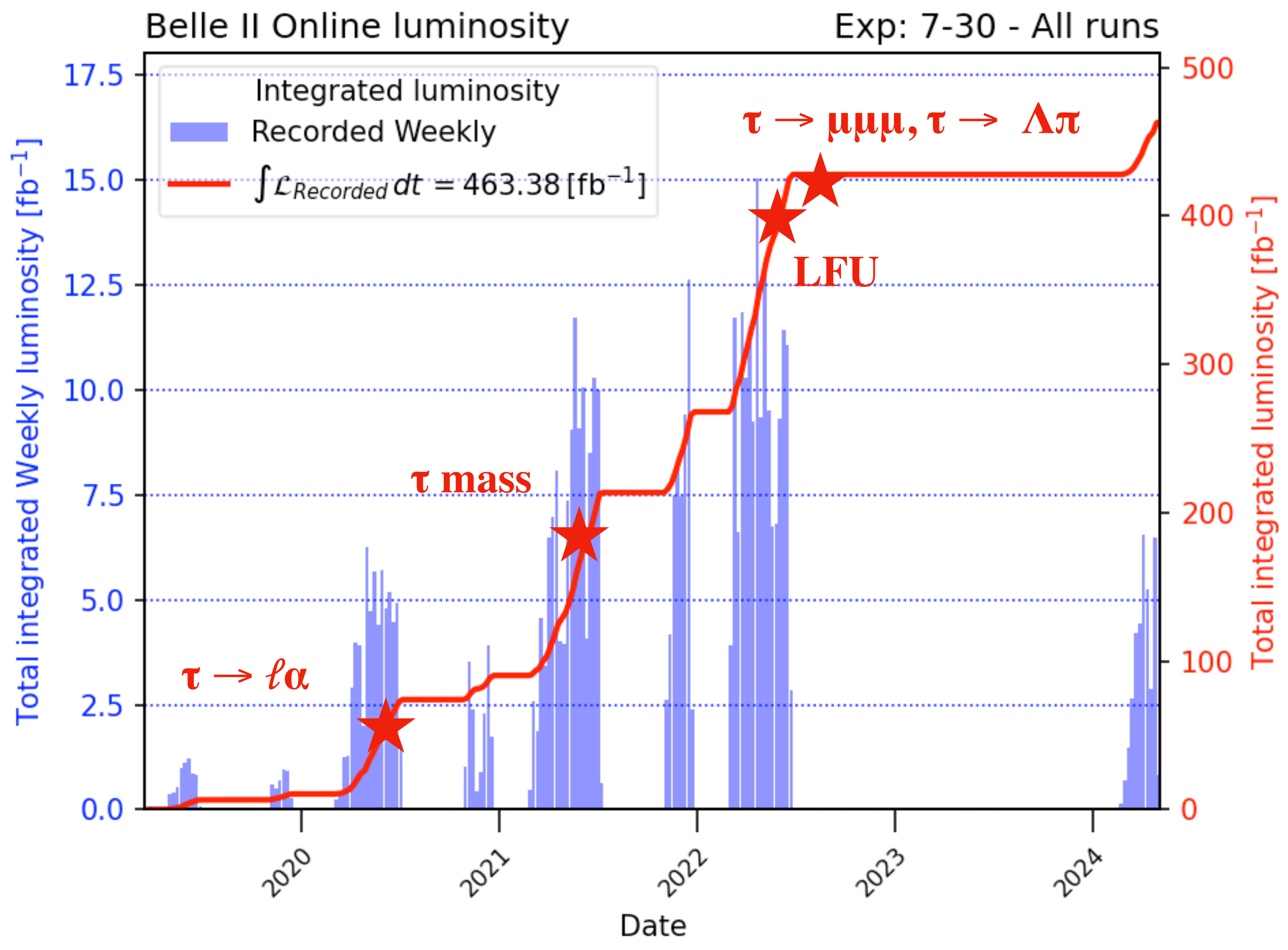
➡ The world largest number of $e^+e^- \to \tau^+\tau^-$events offer data for τ physics with high precision

**B-factories: Belle@KEKB, BaBar@PEP-II, Belle II@SuperKEKB**




$$\sigma(e^+e^- \to \Upsilon(4S)) = 1.05 \text{ [nb]}$$
$$\sigma(e^+e^- \to q\bar{q}) = 3.69 \text{ [nb]}$$
$$\sigma(e^+e^- \to \tau^+\tau^-) = 0.919 \text{ [nb]}$$




**Other players in the τ sector**

➡ BES III, ATLAS, CMS, LHCb

# Precision measurements - τ mass measurement @ Belle II

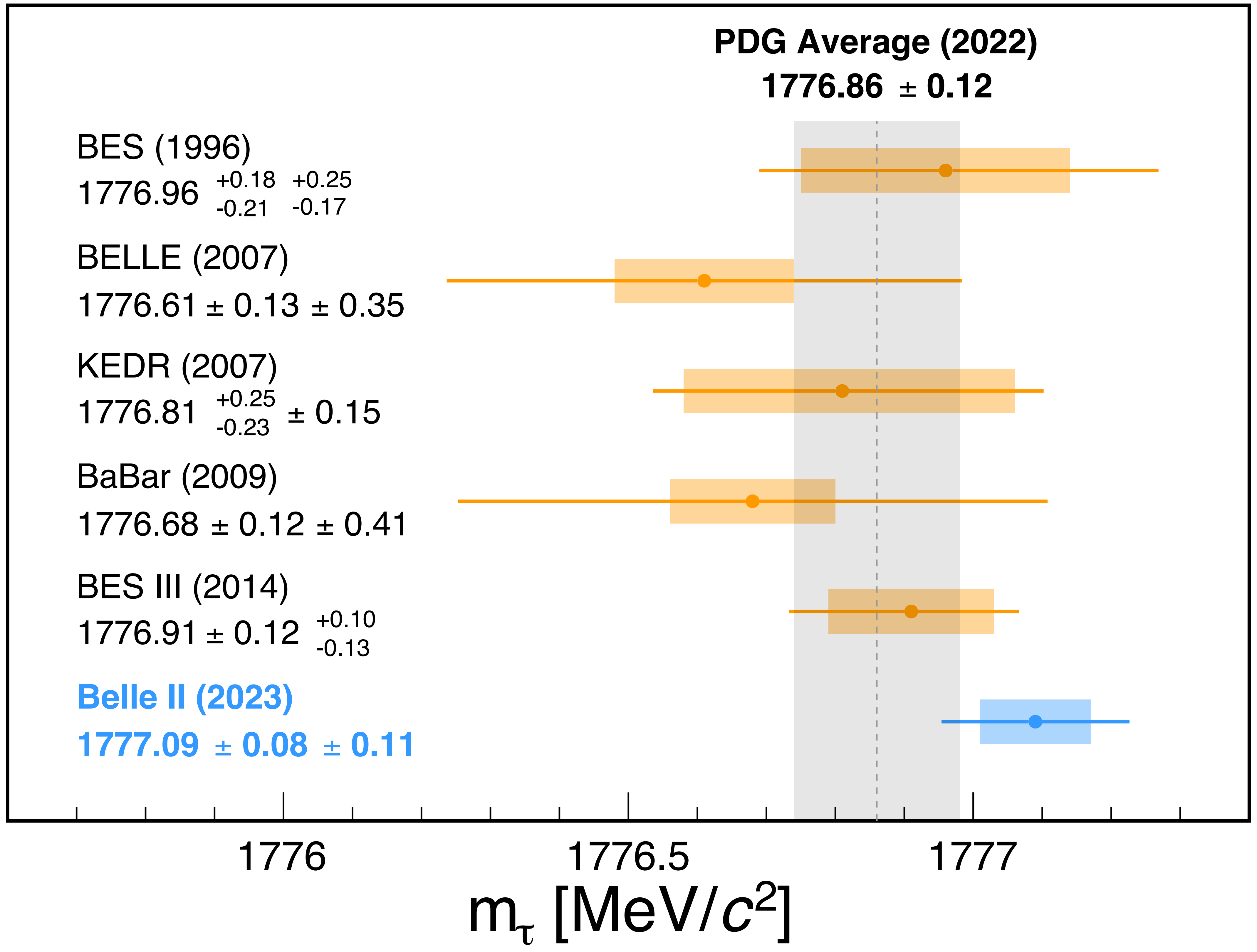
## Fundamental parameter of the standard model

- World's most precise measurement to date
- Slightly higher average value including Belle II recent measurement

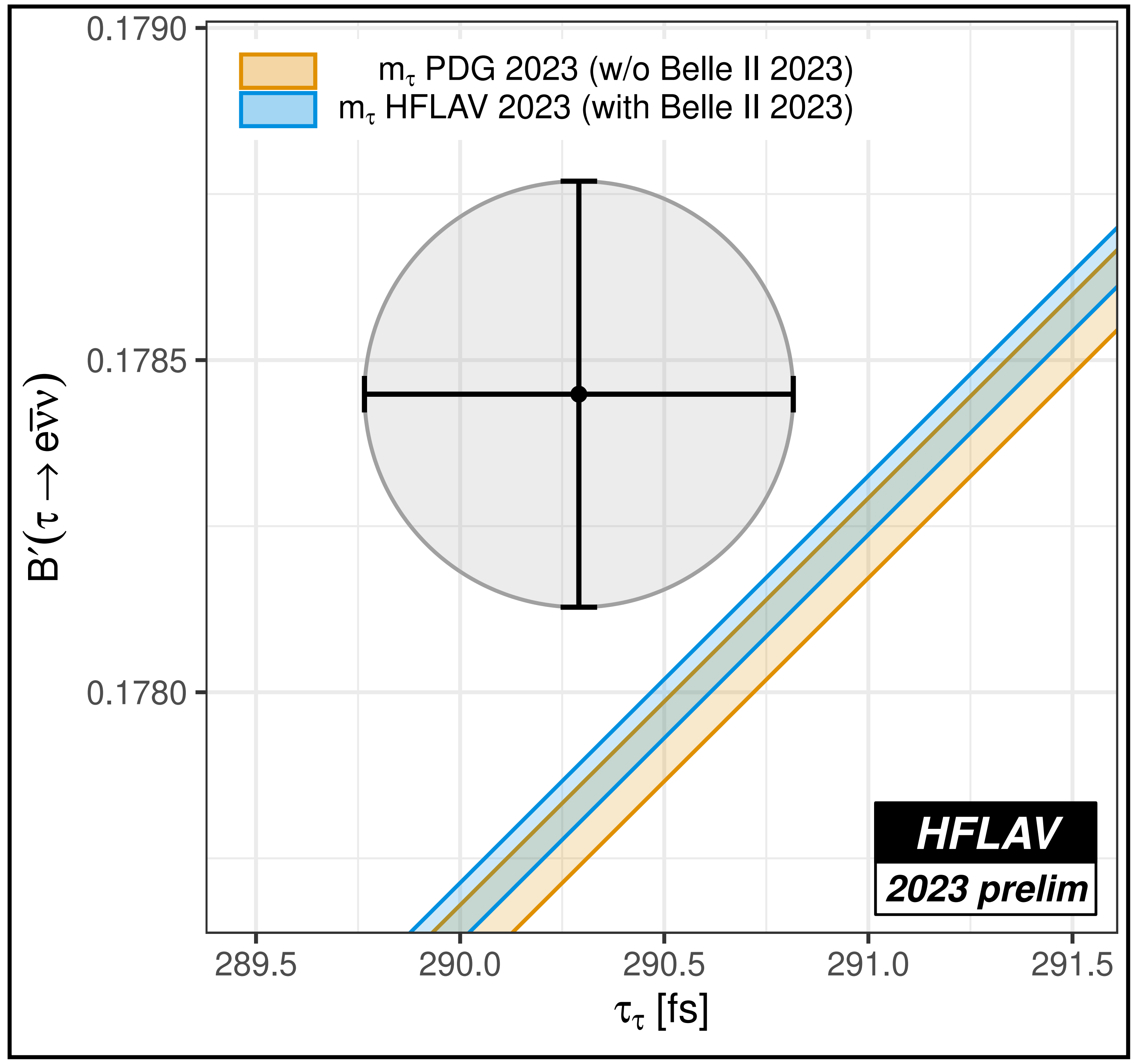
## Important input to lepton-flavour-universality tests

- The relation between $B'(\tau \to e\nu\bar{\nu})$ and the lifetime $\tau_\tau$ very sensitive to the value of the $\tau$ mass
  - slight tension decreased further

*Belle II - PRD 108 (2023) 032006*




*A. Lusiani for HFLAV TAU2023*



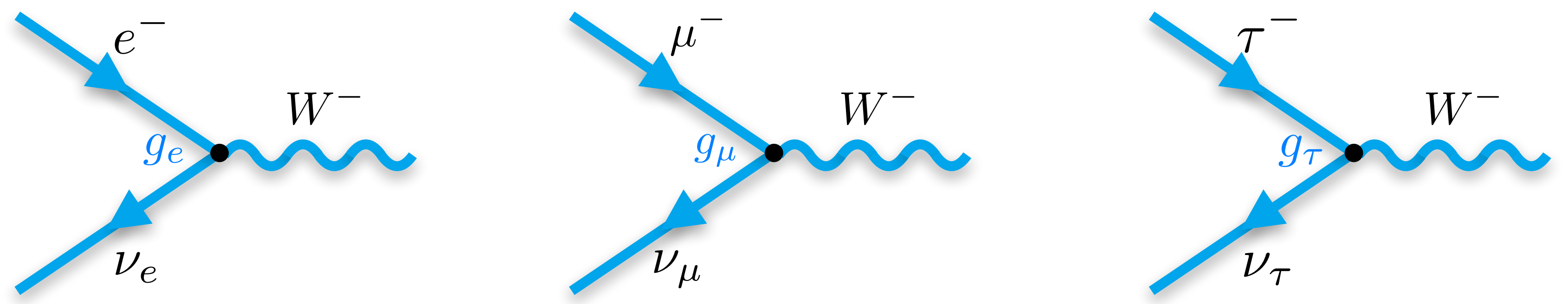

*$B'(\tau \to e\nu\bar{\nu})$ represents the average of $\mathcal{B}(\tau \to e\nu\bar{\nu})$ and the value predicted from $\mathcal{B}(\tau \to \mu\nu\bar{\nu})$ assuming lepton universality*

$$B' \propto B_{\mu e} \frac{\tau_\tau}{\tau_\mu} \frac{m_\tau^5}{m_\mu^5}$$

# Test of lepton flavour universality in τ decays @ Belle II

**The coupling of leptons to W bosons is flavour-independent in the SM**

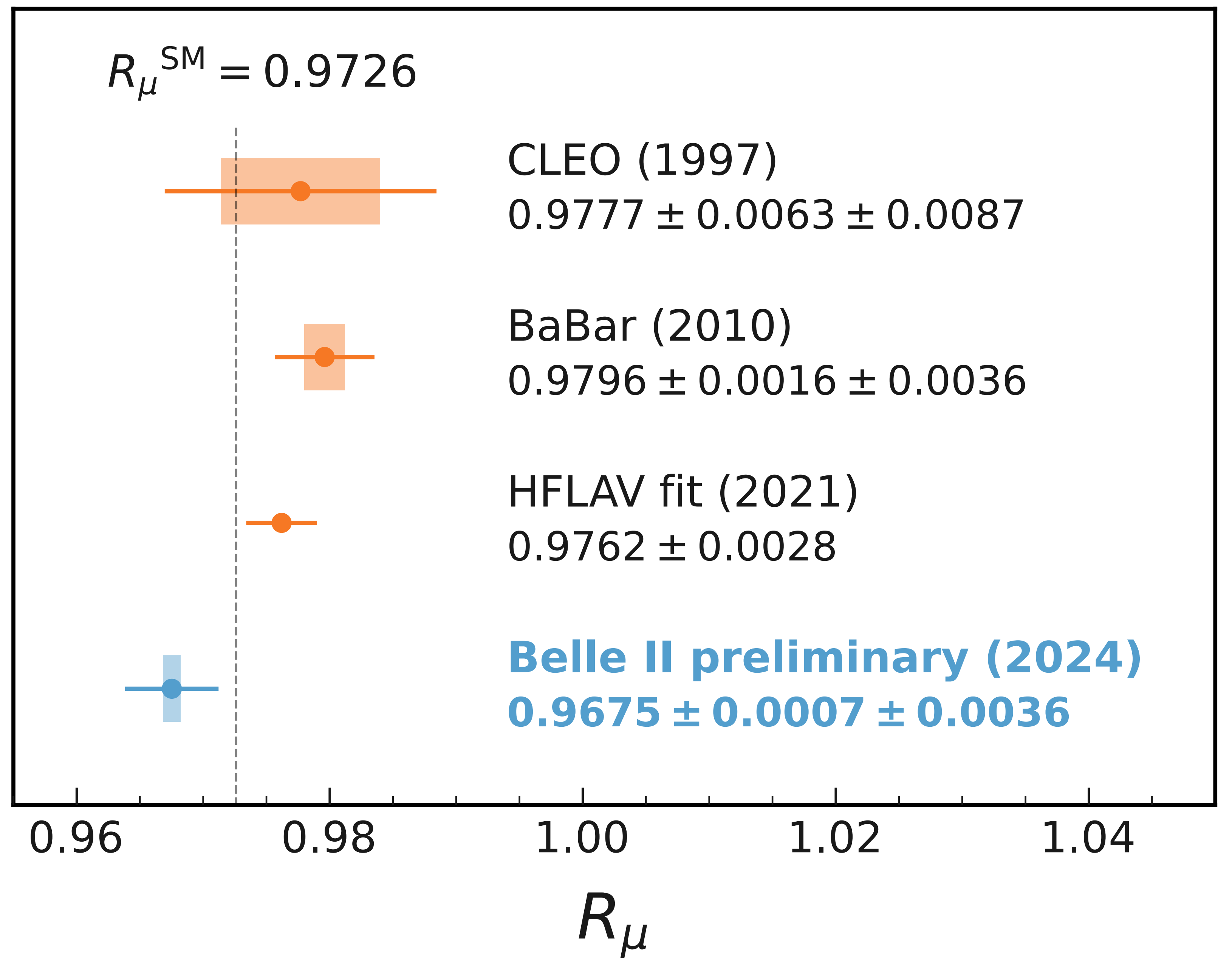
$g_e = g_\mu = g_\tau$

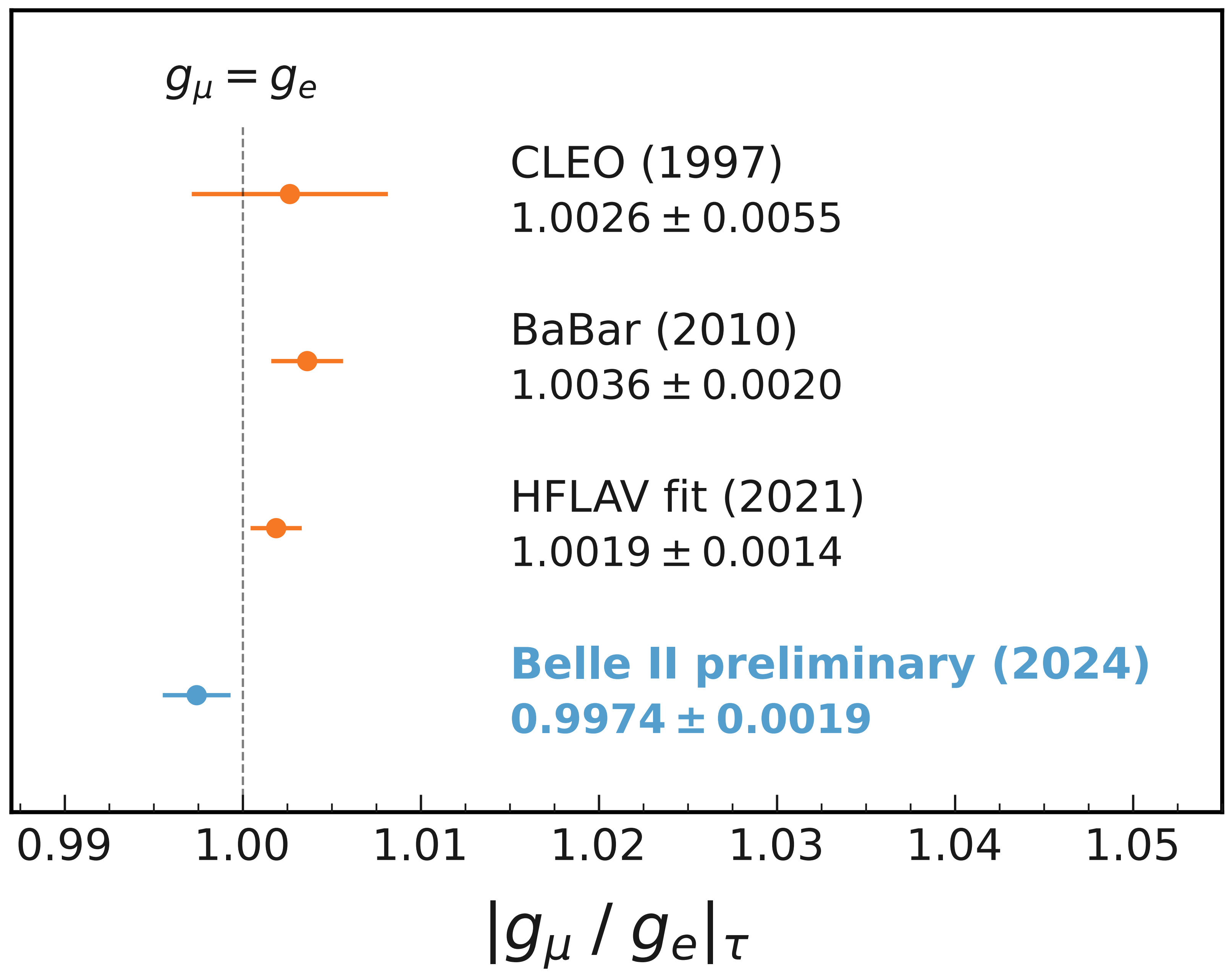



- ➡ Identical lepton interaction rates involving e, μ or τ
- ➡ Test of $\mu - e$ universality in the $\tau$ decays

$$R_\mu = \frac{B(\tau^- \to \mu^- \bar{\nu}_\mu \nu_\tau)}{B(\tau^- \to e^- \bar{\nu}_e \nu_\tau)} \stackrel{\text{SM}}{=} 0.9726$$

$$\left(\frac{g_\mu}{g_e}\right)^2_\tau \propto R_\mu \times \frac{f(m_e^2/m_\tau^2)}{f(m_\mu^2/m_\tau^2)} \stackrel{\text{SM}}{=} 1$$




- ➡ **Most precise test of $\mu - e$ universality in $\tau$ decays from a single measurement**
- ➡ Consistent with SM expectation at the level of 1.4σ

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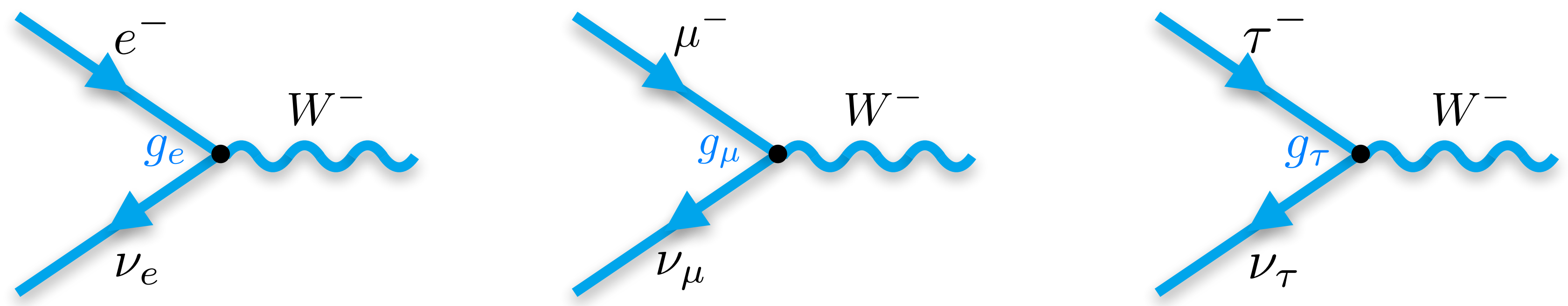


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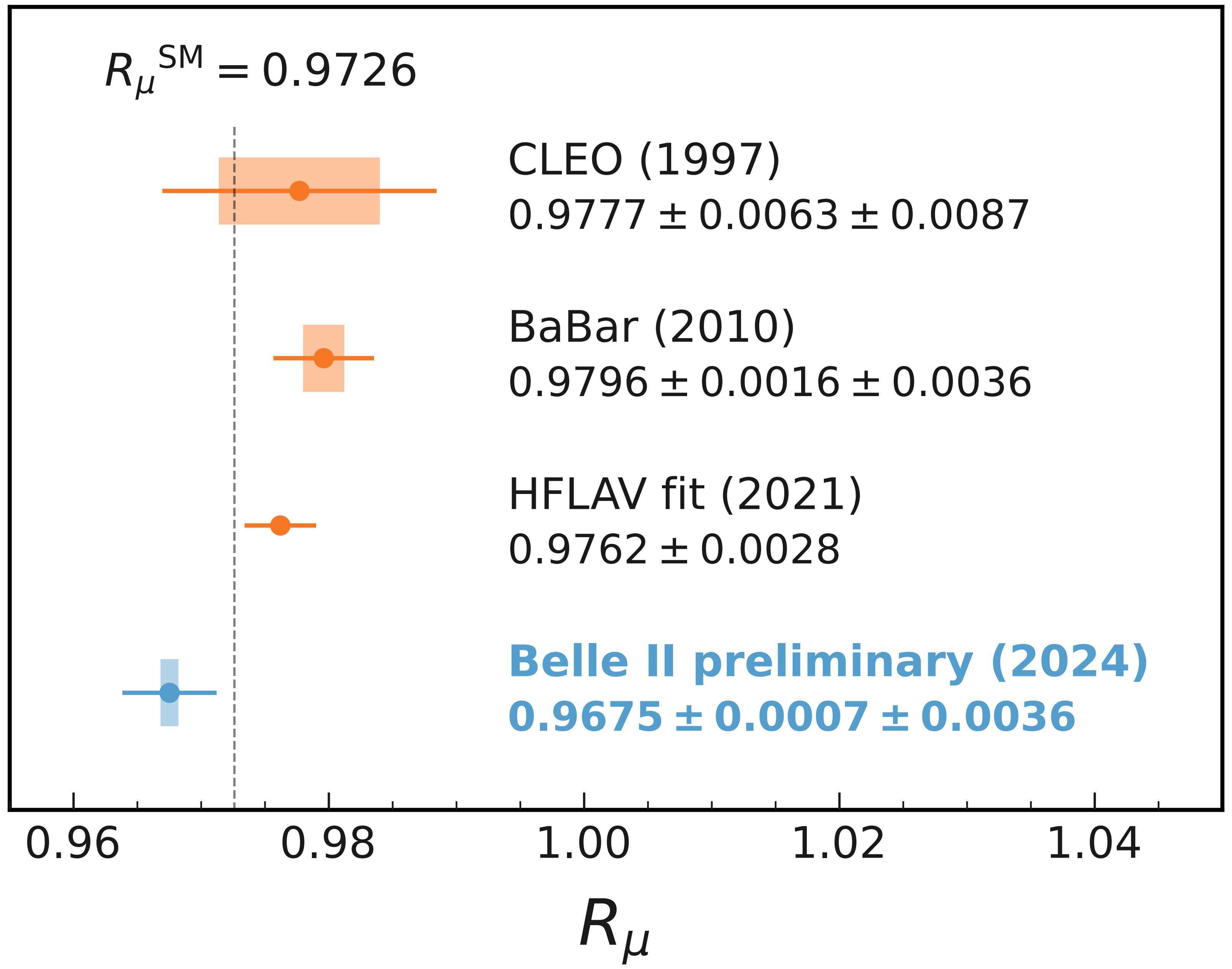


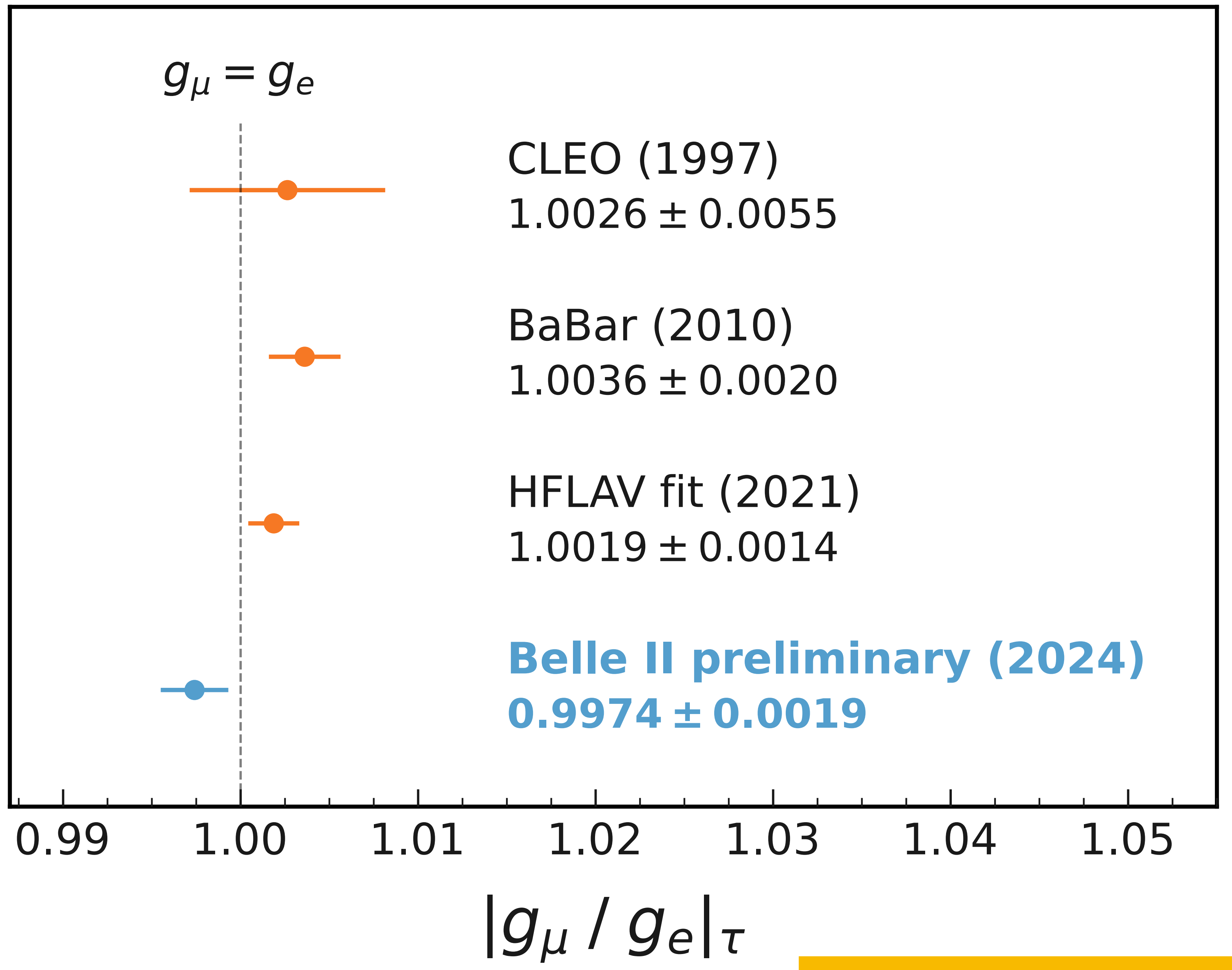


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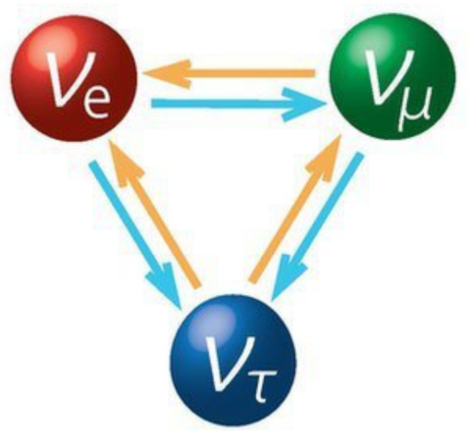
τ precision measurement from Belle II
see the talk of
Marcela Garcia Hernandez

# Lepton flavour conservation

**Conservation of the individual lepton-flavour and the total lepton numbers within the SM ($m_\nu = 0$)**

$$G_{SM}^{global} = U(1)_B \times U(1)_{L_e} \times U(1)_{L_\mu} \times U(1)_{L_\tau}$$



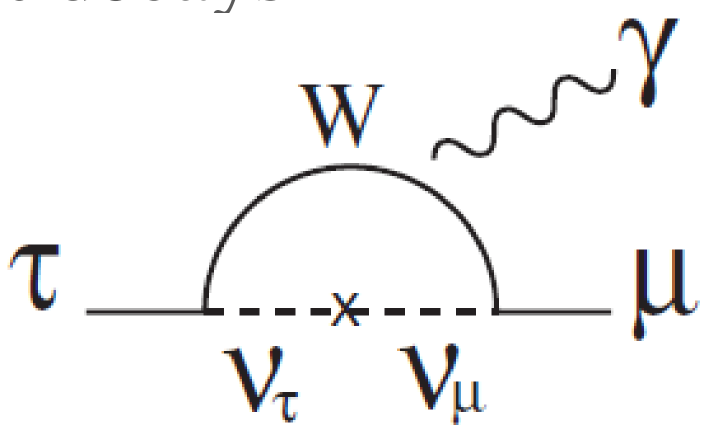

➡ The observation of neutrino oscillations as a first sign of LFV beyond the SM!

**What about the charged leptons?**

➡ The charged LFV processes can occur through oscillations in loops

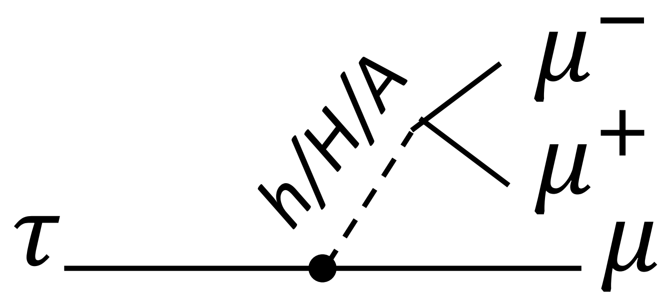
➡ Immeasurable small rates ($10^{-54}$-$10^{-49}$) for all the LFV μ and τ decays

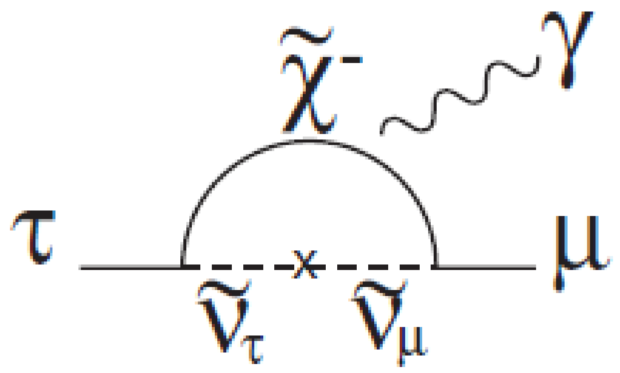
$$\mathcal{B}(\ell_1 \to \ell_2\gamma) = \frac{3\alpha}{32\pi}\left|\sum_{i=2,3} U^*_{\ell_1 i} U_{\ell_2 i} \frac{\Delta m^2_{i1}}{M_W^2}\right|^2$$




**Observation of LFV will be a clear signature of the NP!**

➡ Charged LFV enhanced in many NP models ($10^{-10}$ - $10^{-7}$)



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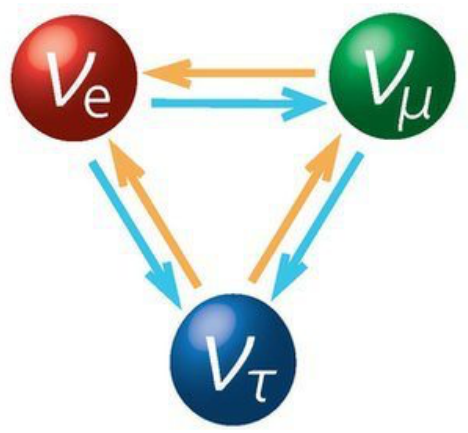


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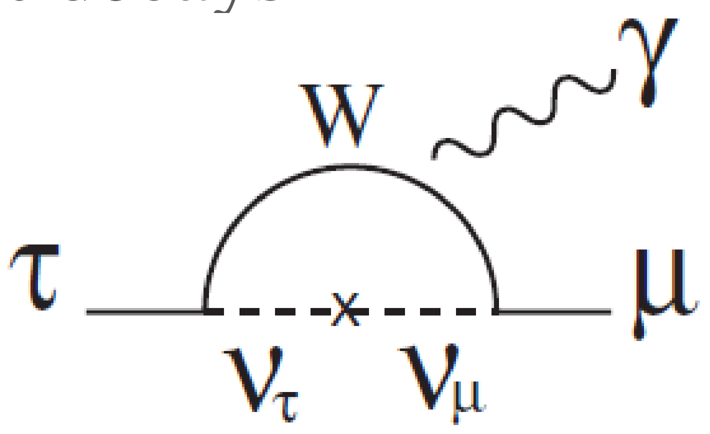


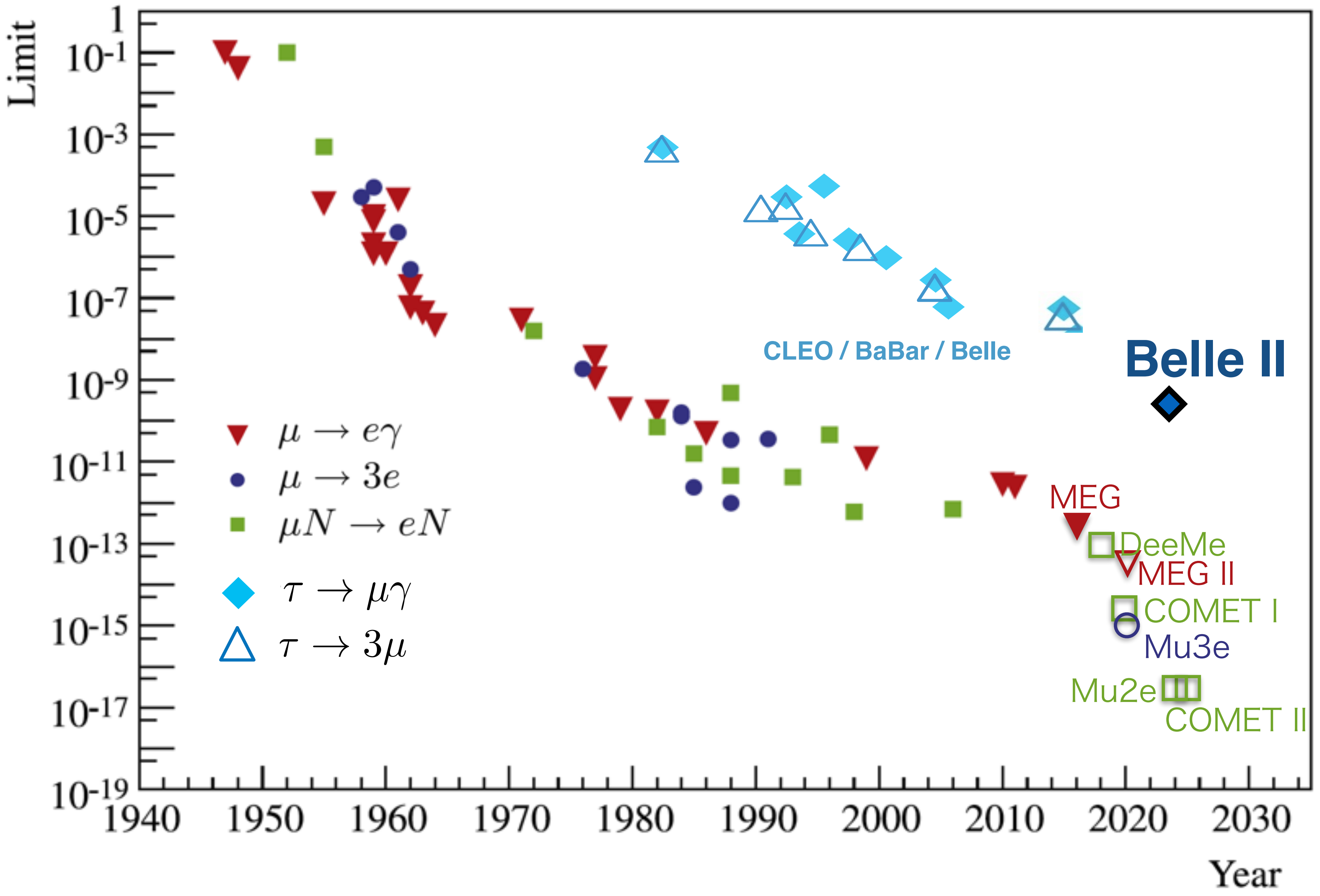


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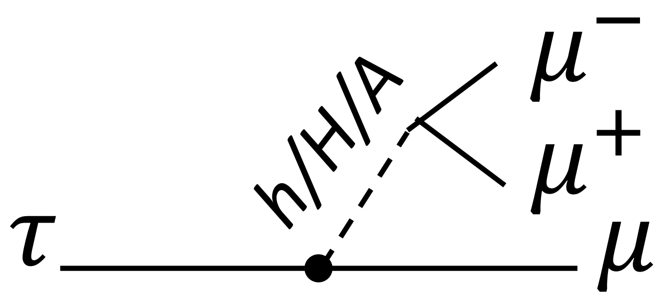
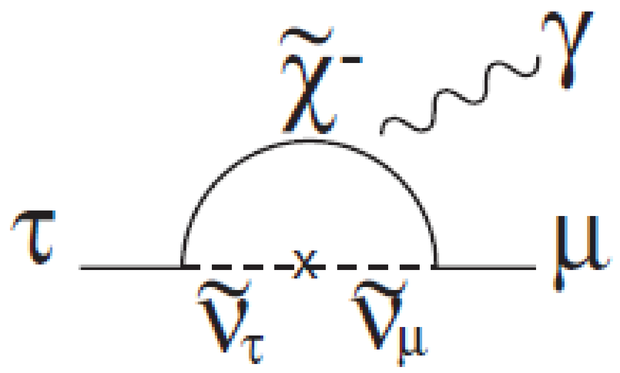
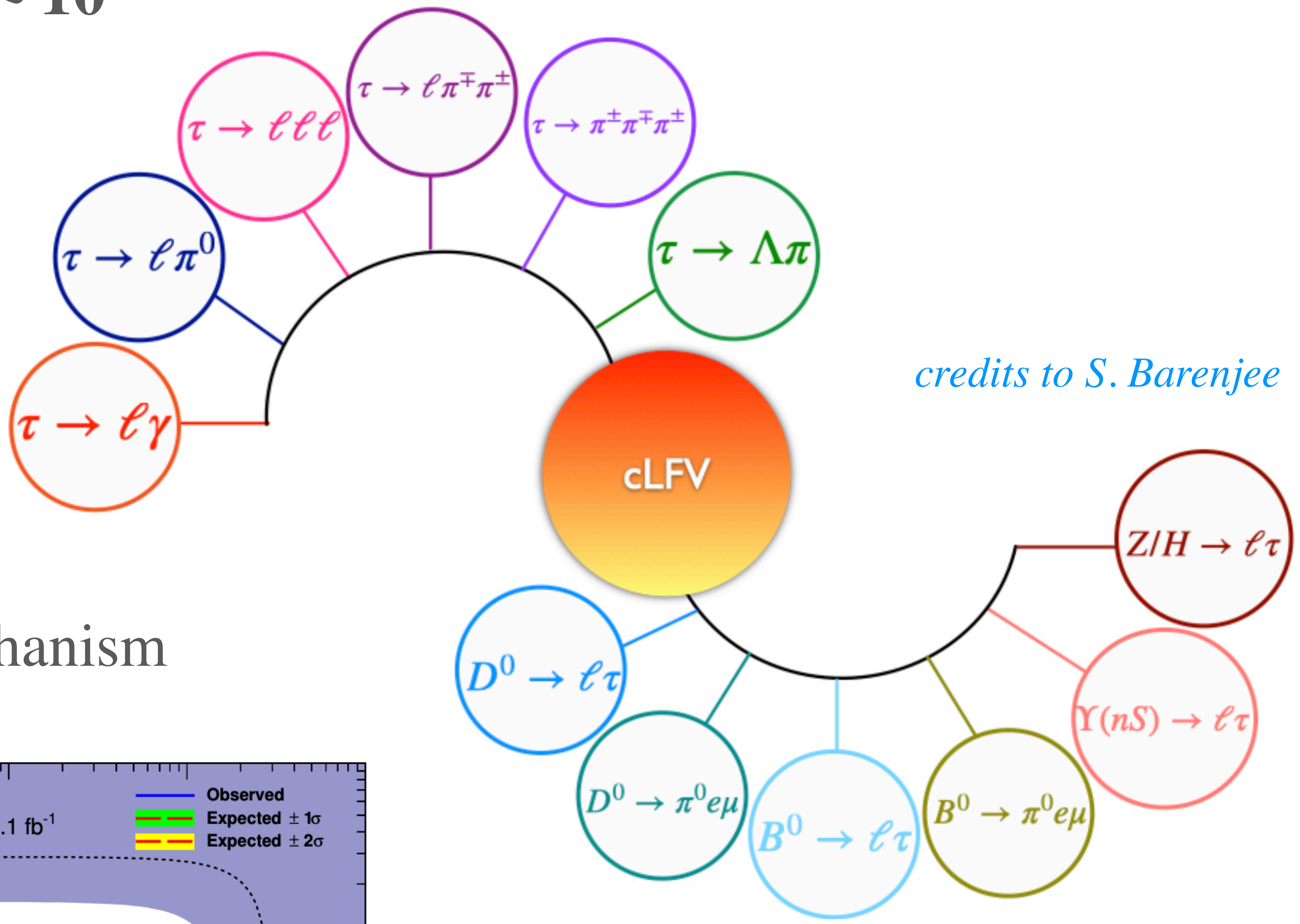


# Complementarity of τ LFV searches

**Current limit on $\mathscr{B}(\mu \to e\gamma) \sim 10^{-13}$ does not forbid $\mathscr{B}(\tau \to \ell\gamma) \sim 10^{-8}$**

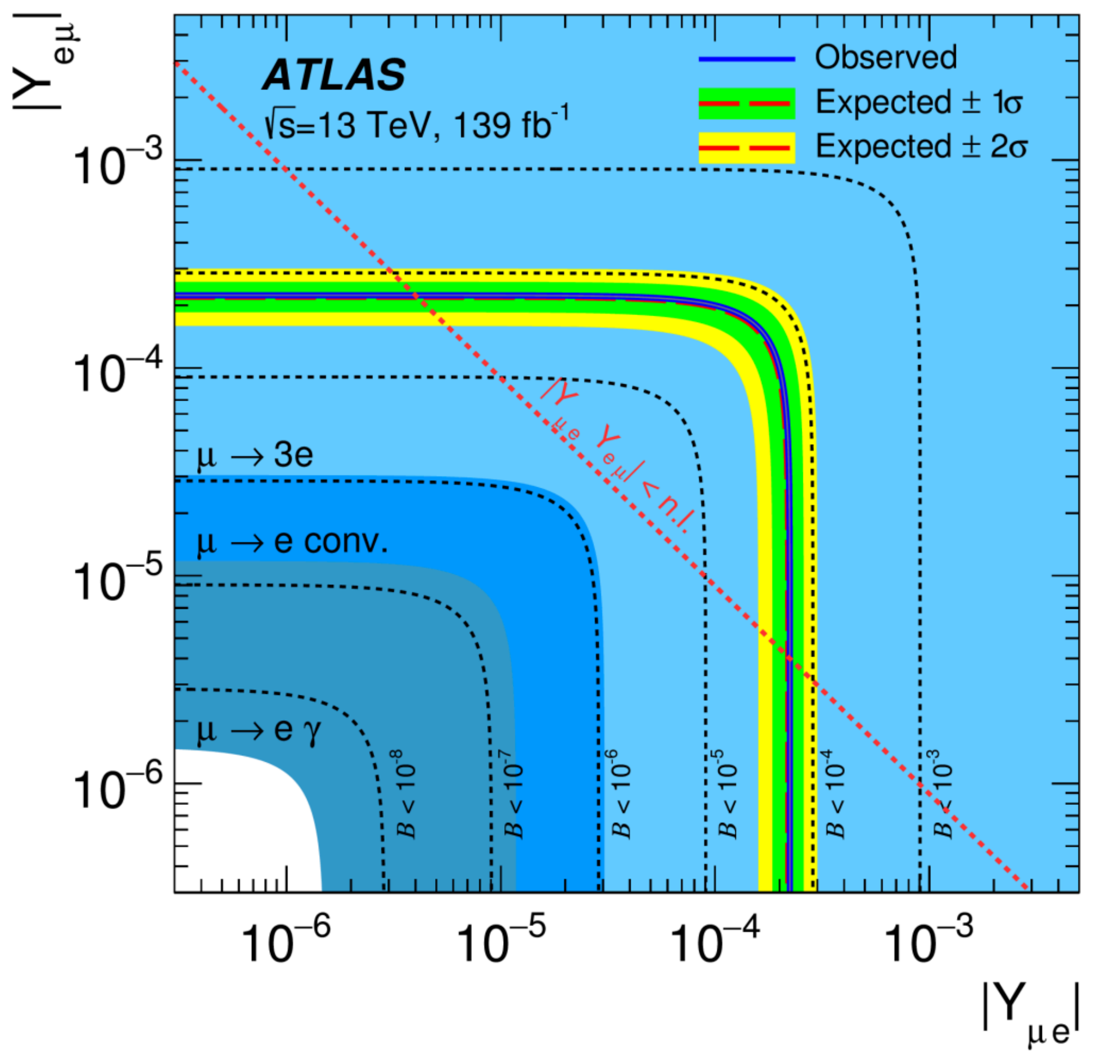
- Leptonic MFV: *Nucl.Phys. B 728 (2005) 121*
- GUT models: *Nucl.Phys. B 445 (1995) 219*

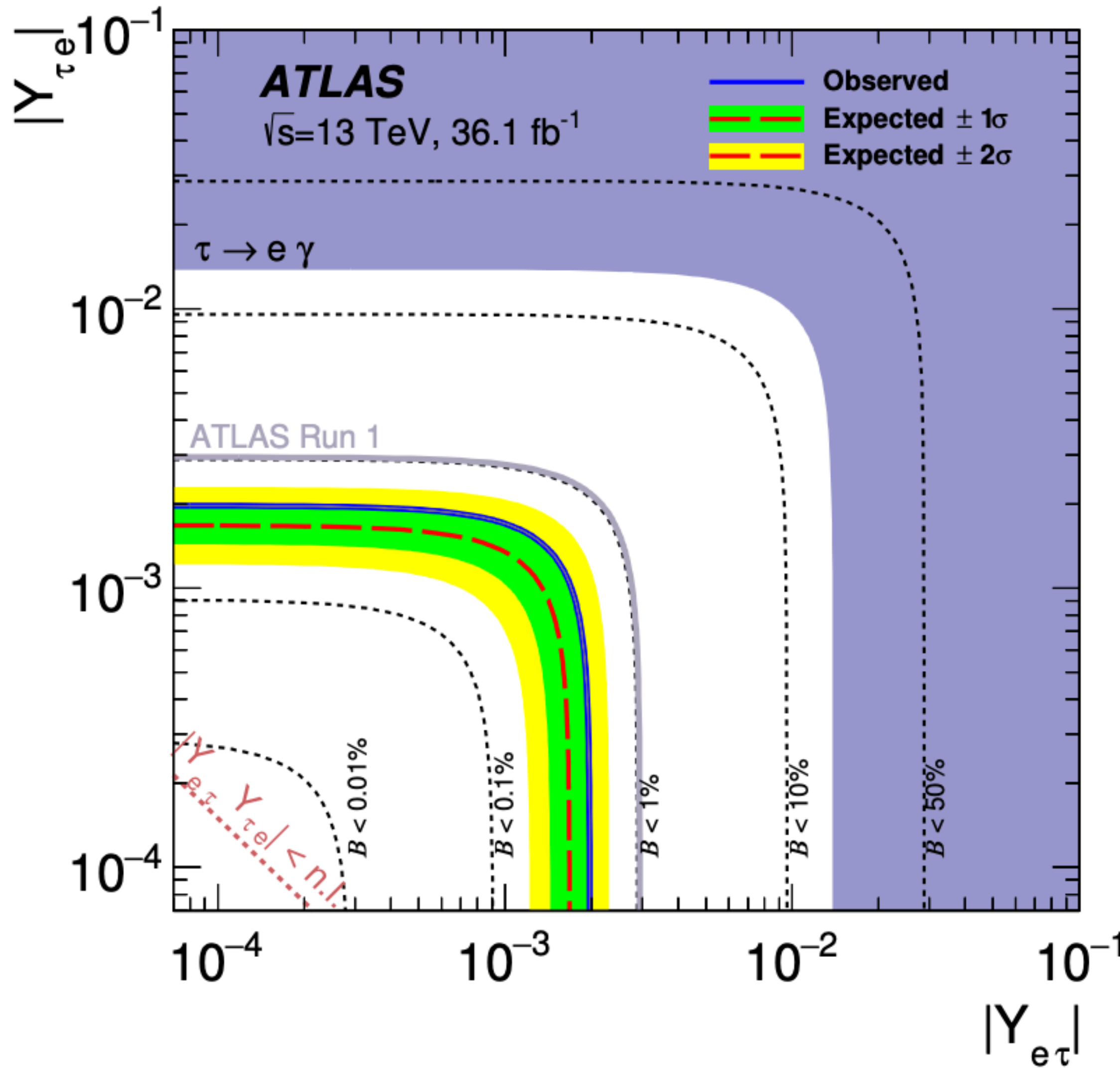


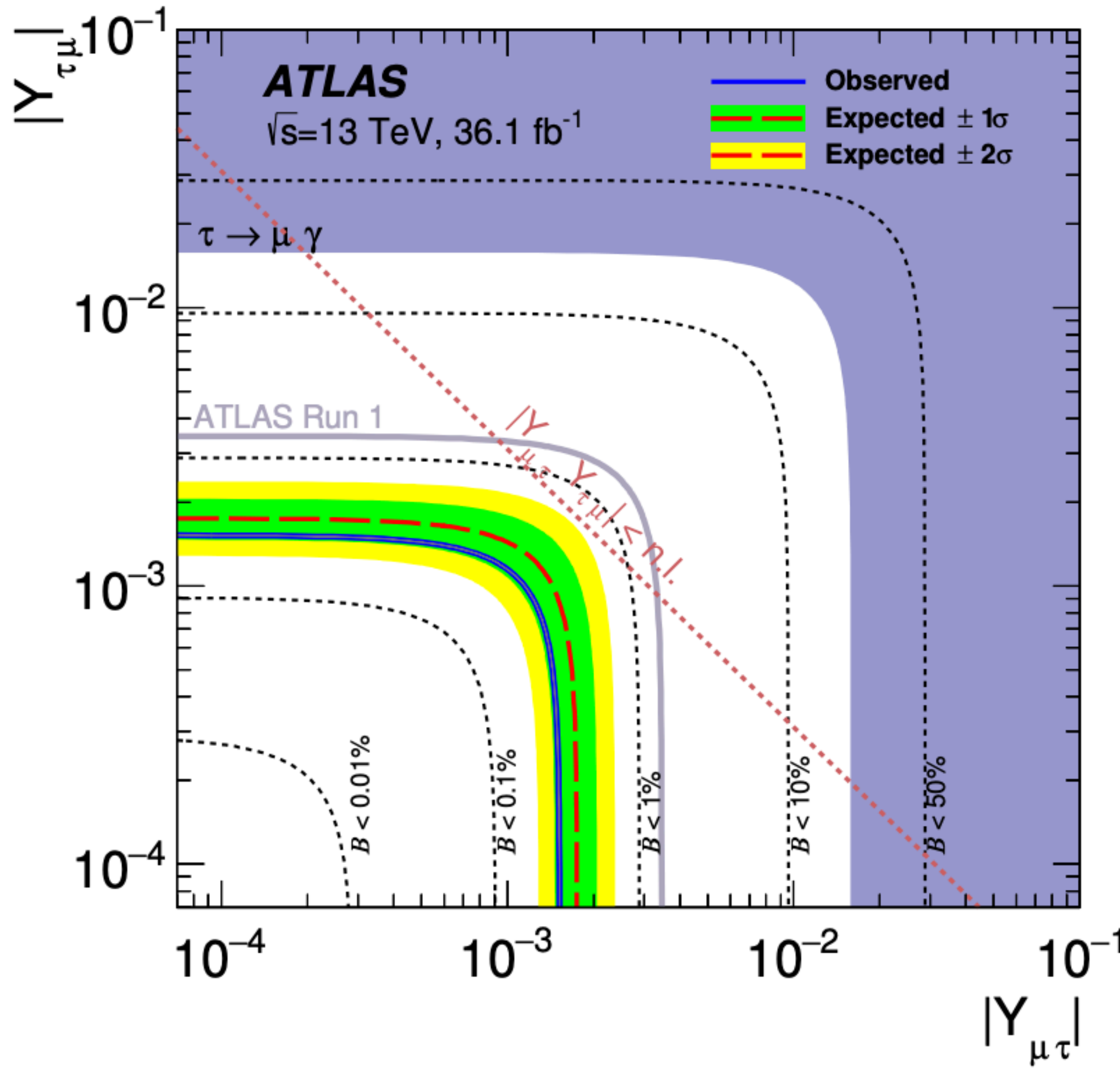

*credits to S. Barenjee*

**Indirect constraints on LFV Higgs from $\mu \to e\gamma$ and $\tau \to \ell\gamma$**

- Strongest from $\mu \to e\gamma$: $\mathscr{B}(H \to \mu e) < 1.6 \times 10^{-8}$
- Observed: BR($H \to e\mu$) < 6.1 x $10^{-5}$ (95% CL)
- Observing $H \to e\mu$ or $\tau \to \ell\gamma$ would require a non-trivial NP mechanism



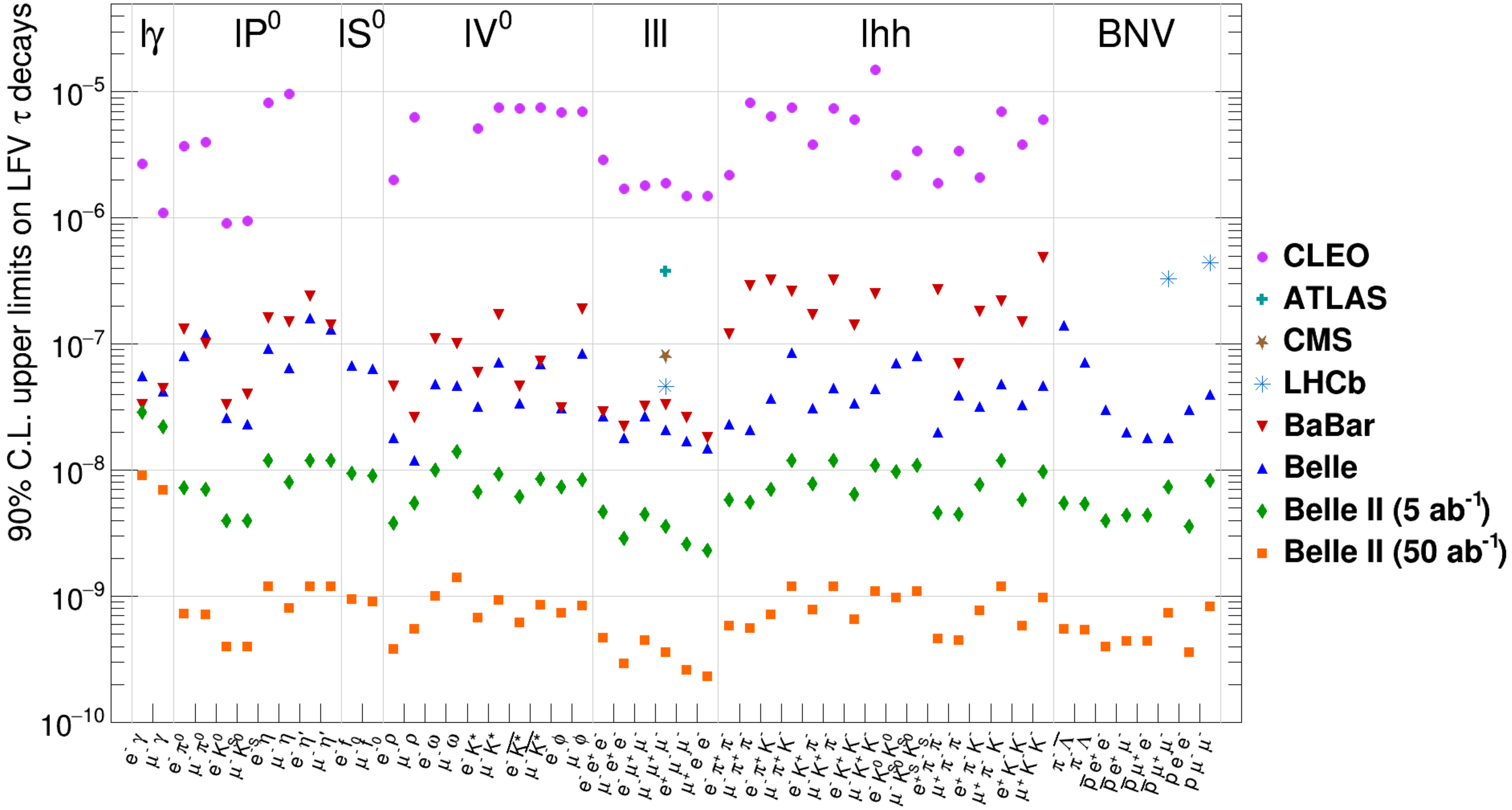




*Phys.Lett.B 800 (2020) 135069*
*Phys.Lett.B 801 (2020) 135148*

# Status and perspectives of LFV searches

*As of the Snowmass 2021: cLFV in τ sector - arXiv:2203.14919*




**Test the SM in 52 benchmark τ decays**

- ➡ radiative ($\tau \to \ell\gamma$)
- ➡ leptonic decays ($\tau \to \ell\ell\ell$)
- ➡ a large variety of LFV and LNV semi-leptonic decays
- ➡ BNV decays
- ➡ τ → μ and τ → e: test of the lepton flavour structure

- ➡ One of the factors pushing up the sensitivity of probes is the increase of the luminosity
- ➡ Equally important is the increase of the signal detection efficiency
  - ➡ high trigger efficiencies; improvements in the vertex reconstruction, charged track and neutral-meson reconstructions, particle identification, refinements in the analysis techniques…

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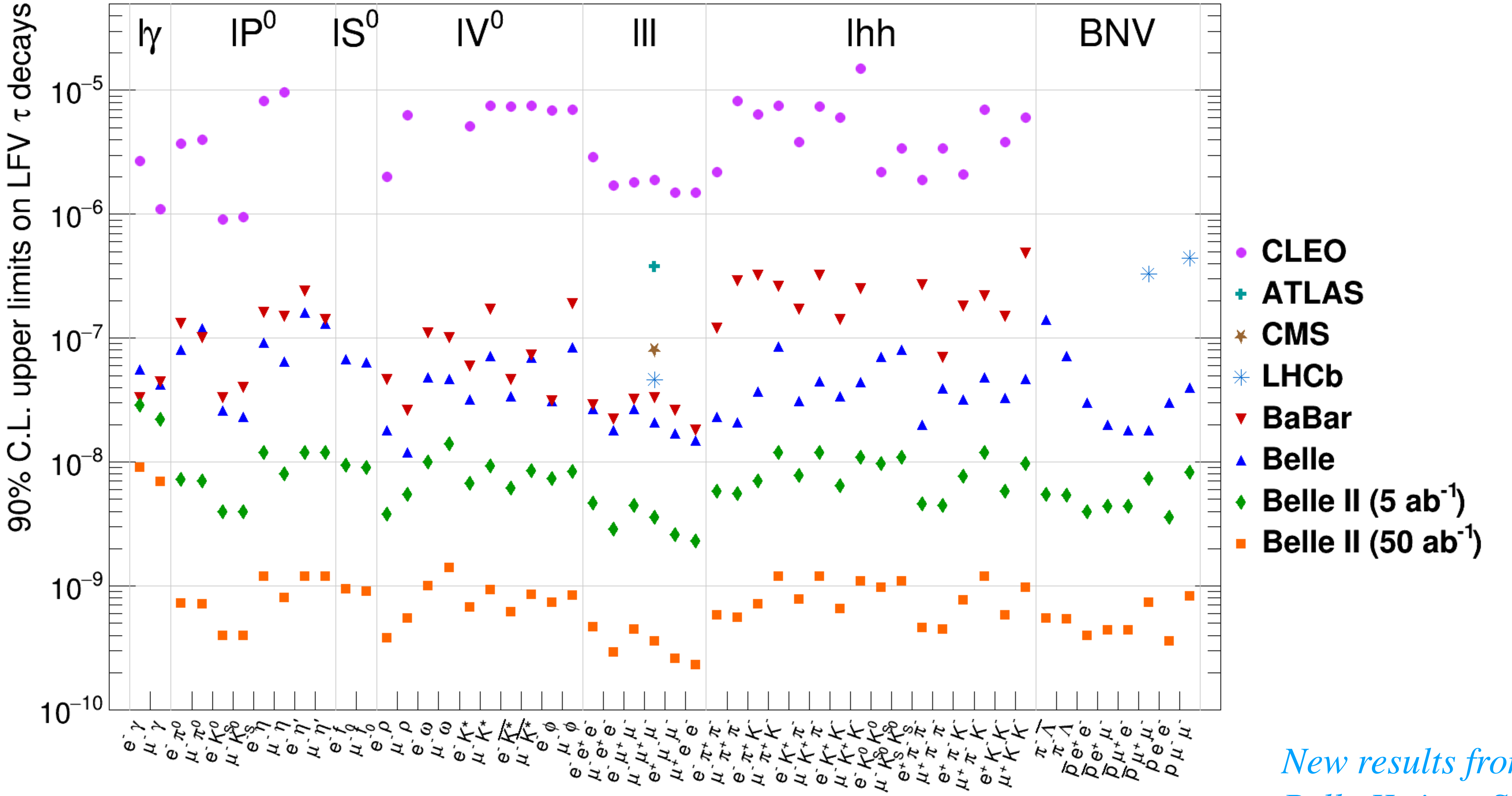


*New results from CMS, Belle and Belle II since Snowmass report*

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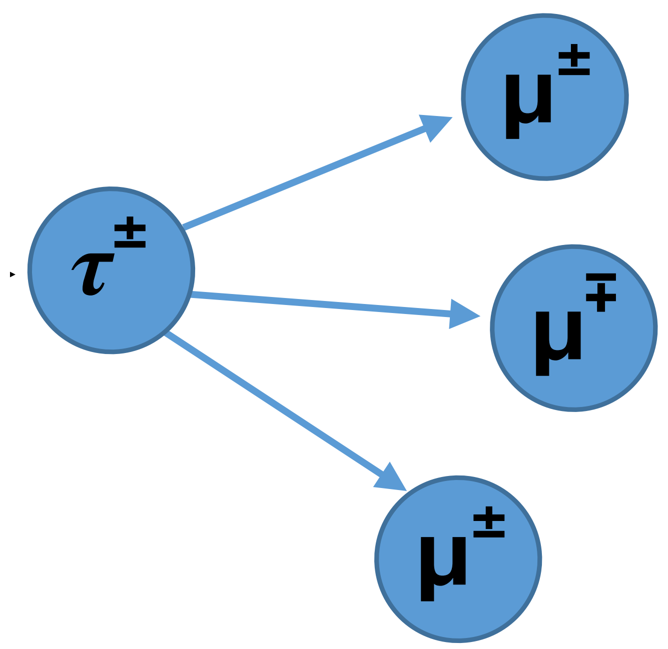
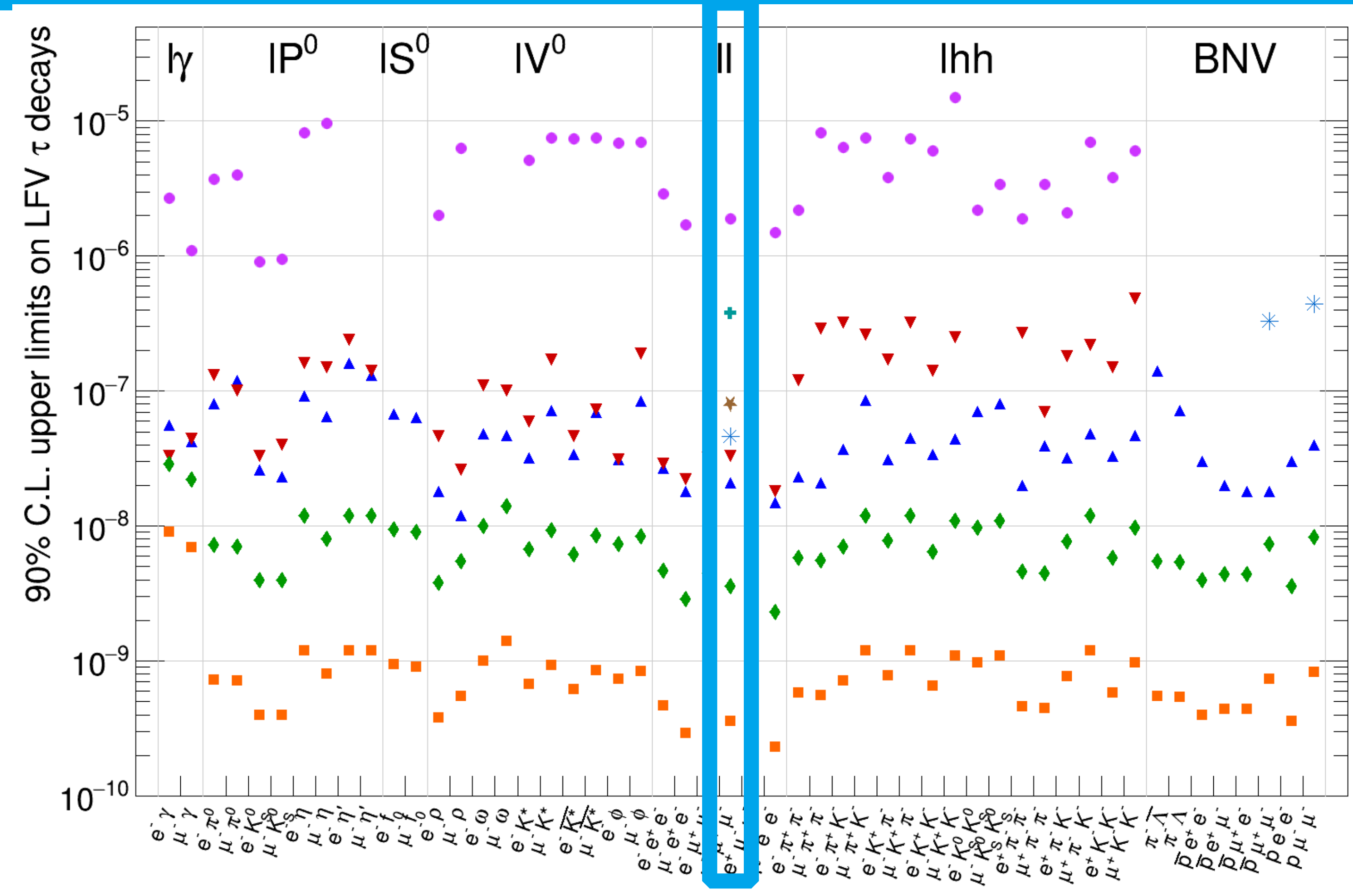
# Search for $\tau \to \mu\mu\mu$ decay @ Belle II

**Search at Belle II with 424 fb$^{-1}$**

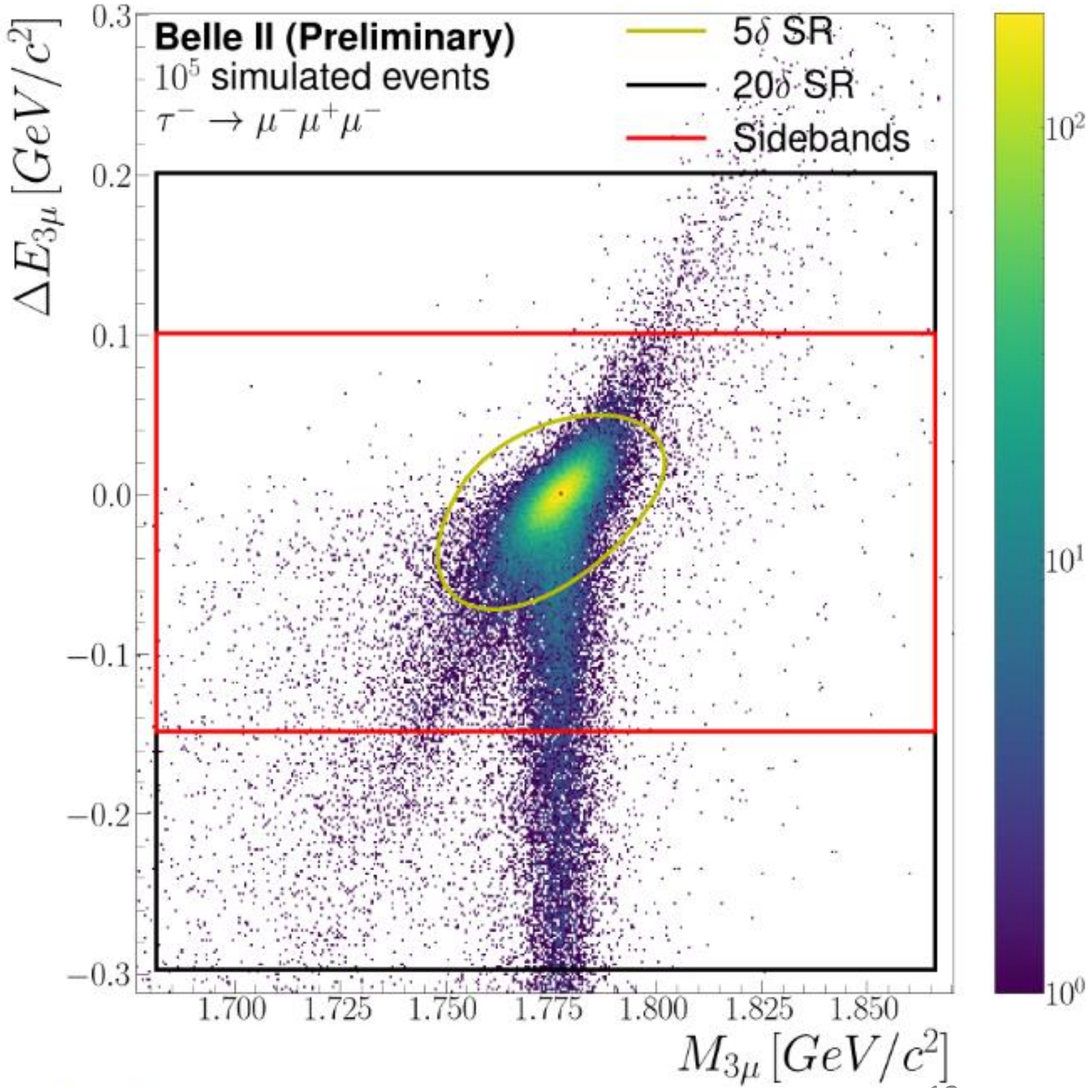
- µ identification is the most powerful discriminating variable
- Momentum dependent optimisation of the muID requirement




**Signal region definition**

(typical for all 52 LFV searches $e^+e^-$ in searches)




**Two independent variables:**

$$M_{3\mu} = \sqrt{E_{3\mu}^2 - P_{3\mu}^2}$$

$$\Delta E = E_{3\mu}^{CMS} - E_{\text{beam}}^{CMS}$$

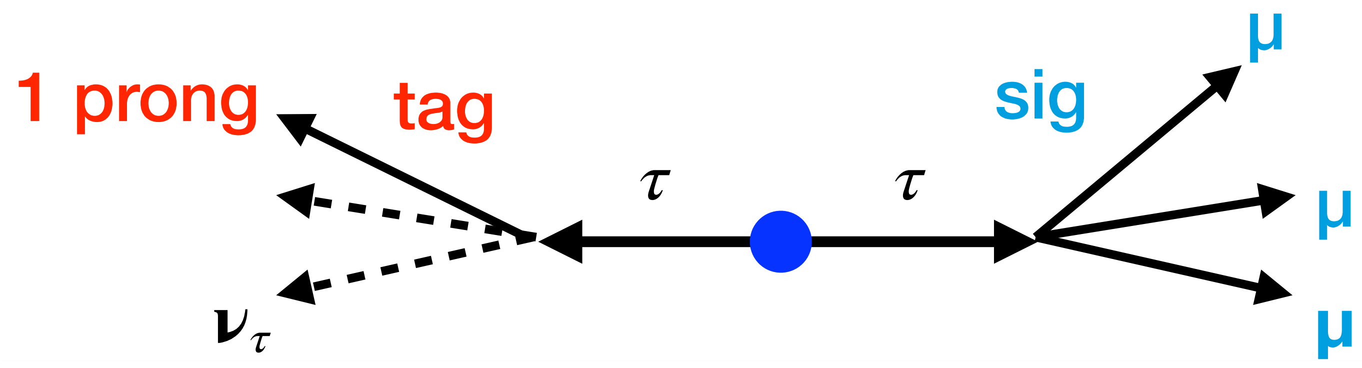
For signal:

- $\Delta E$ close to 0 and $M_{3\mu}$ close to τ mass
- Tails due to ISR and FSR

# Search for $\tau \to \mu\mu\mu$ decay @ Belle II

## 1-prong

- **Used before by Belle and BaBar:**
  - 3x1 topology
  - Cut-based selection optimised using the Punzi FOM

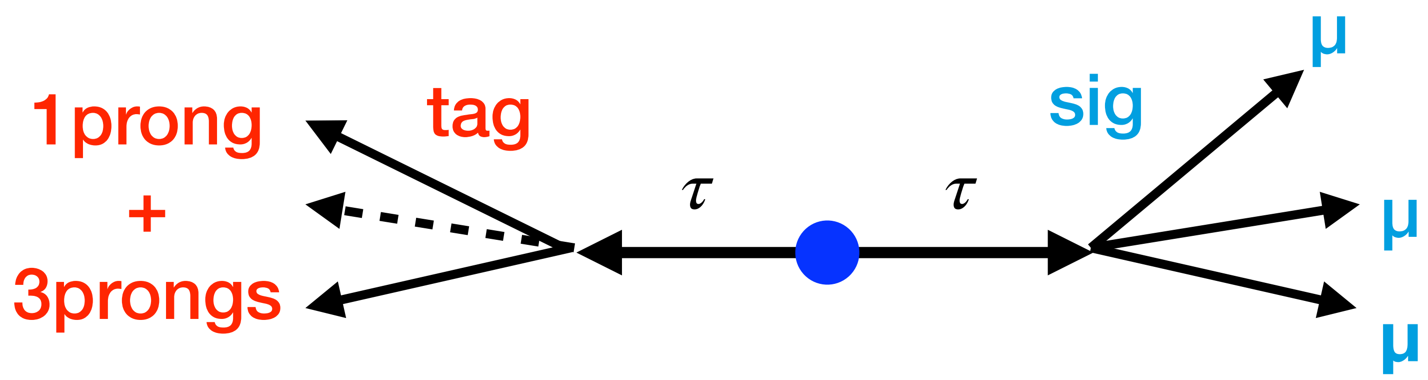



Signal efficiency: 14.9% (2 x Belle efficiency)

- Number of expected BG from simulation : 0.43
- 0 event observed inside the SR
- Observed $\mathscr{B}(\tau \to 3\mu) < 2.0 \times 10^{-8}$

## Inclusive approach

- **Main analysis approach:**
  - Inclusion of 3x1 and 3x3 topologies
  - Selection and background rejection using BDT




- Signal efficiency: 20.4% (2.7 x Belle efficiency)
- Number of expected BG using ABCD method : 0.5
- 1 event observed inside the SR
- Observed $\mathscr{B}(\tau \to 3\mu) < 1.9 \times 10^{-8}$

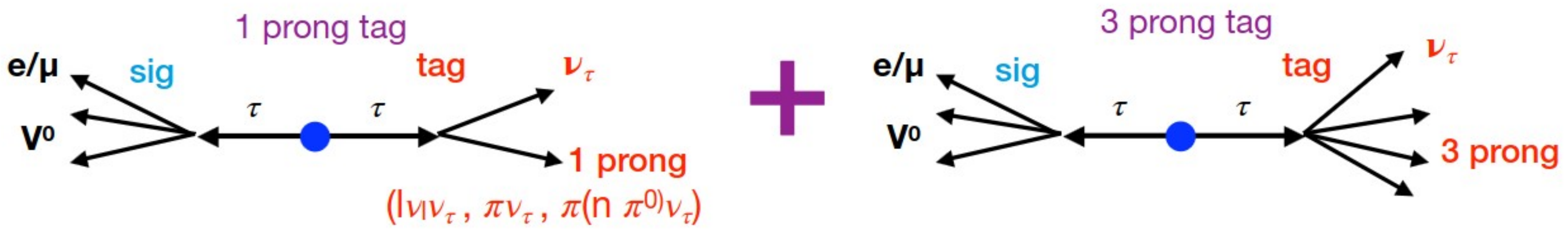
| Experiment | Upper Limit at 90% C.L. |
|---|---|
| Belle | $2.1 \times 10^{-8}$ ($\mathscr{L} = 782\ \text{fb}^{-1}$) |
| BaBar | $3.3 \times 10^{-8}$ ($\mathscr{L} = 486\ \text{fb}^{-1}$) |
| CMS | $2.9 \times 10^{-8}$ ($\mathscr{L} = 131\ \text{fb}^{-1}$) |
| LHCb | $4.6 \times 10^{-8}$ ($\mathscr{L} = 2.0\ \text{fb}^{-1}$) |
| **Belle II** | $1.9 \times 10^{-8}$ ($\mathscr{L} = 424\ \text{fb}^{-1}$) |

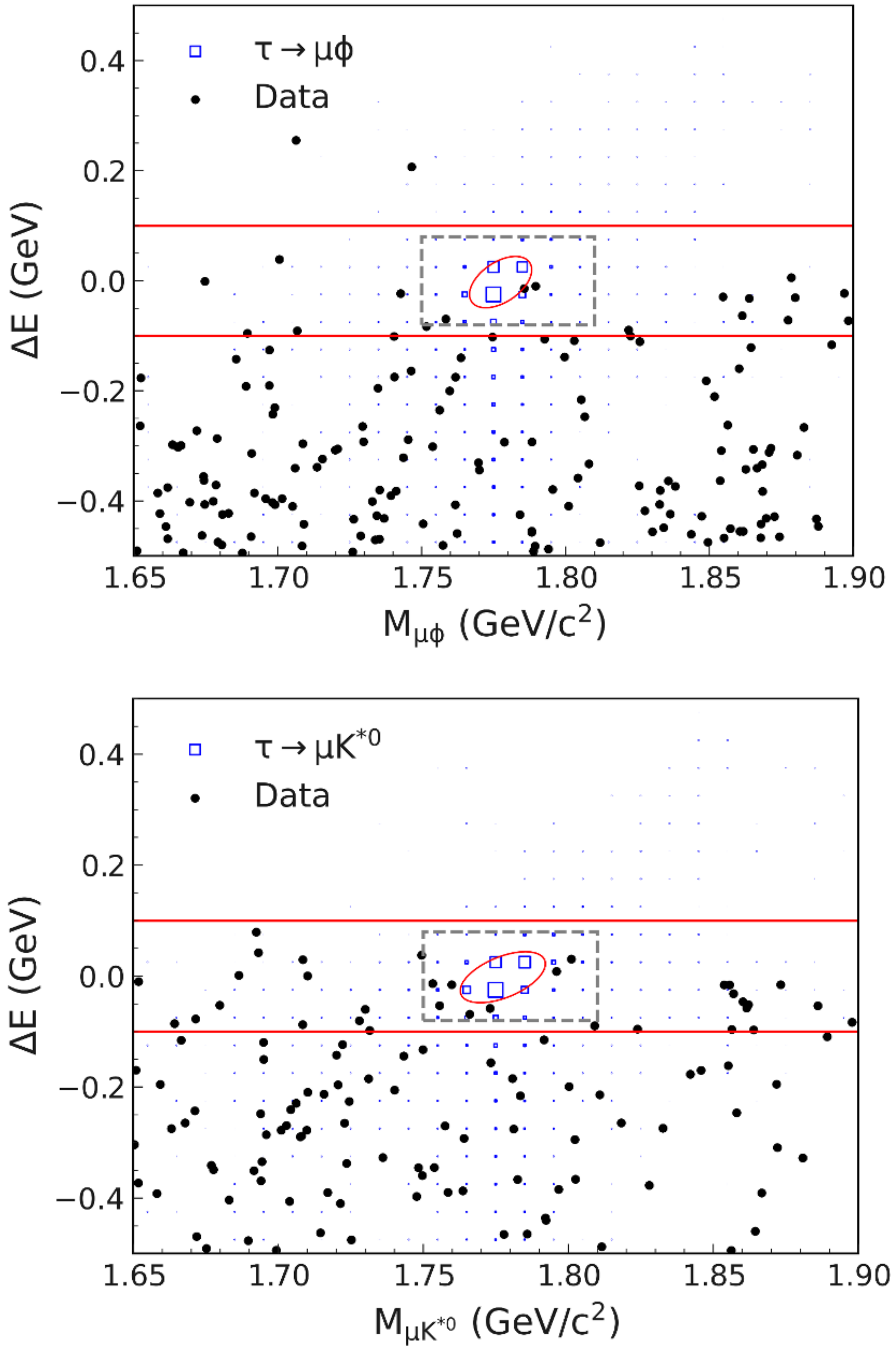
**Most stringent limit to date**

# Search for $\tau \to \ell V^0 (V^0 = \rho, \omega, \phi, K^*)$ decays @ Belle

**Previous search at Belle on 854 fb$^{-1}$ exploiting 1-prong tag**

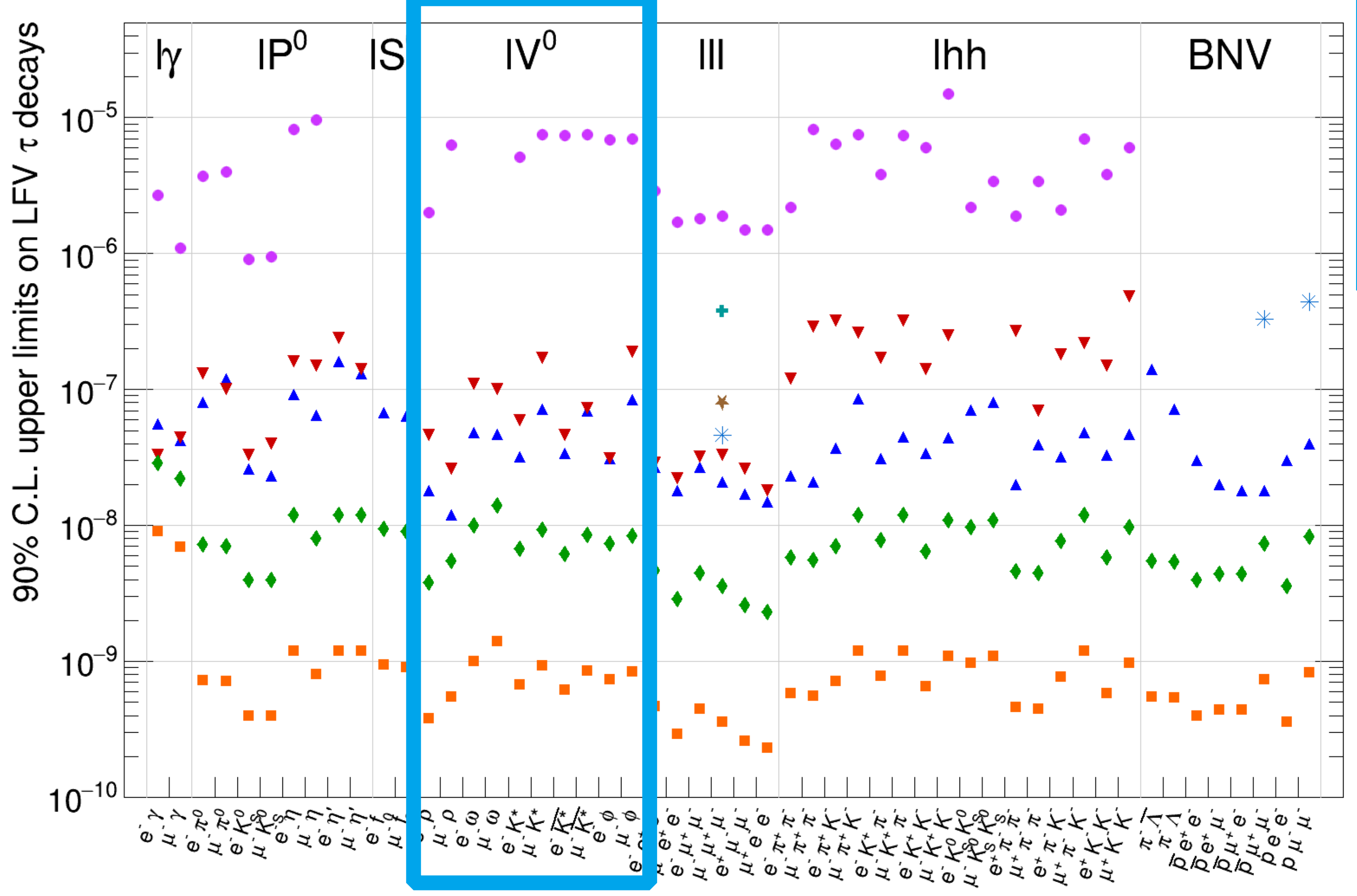
- Increase the efficiency using
  - full data set of 980 fb$^{-1}$
  - more decay modes in the tag side
  - background suppression with BDT




- Exploit topology and event/tag kinematics to the backgrounds that mimic
  - the presence of neutrinos in the tag side,
  - wrong PID in the signal side
- Further suppress $\tau \to 3\pi\nu$ and ee → qq with BDT
- Estimate expected background in SR from **sideband interpolation**

# Search for $\tau \rightarrow \ell V^0$ decay @ Belle




**No significant access in all $\ell V^0$ modes**

- 30% improvement over previous measurements
  - increased statistics (124 fb$^{-1}$)
  - higher signal efficiency (9%)

*Belle - JHEP 06 (2023) 118*

| Mode | $\varepsilon$ (%) | $N_{\mathrm{BG}}$ | $\sigma_{\mathrm{syst}}$ (%) | $N_{\mathrm{obs}}$ | $\mathcal{B}_{\mathrm{obs}}$ ($\times 10^{-8}$) |
|---|---|---|---|---|---|
| $\tau^\pm \rightarrow \mu^\pm \rho^0$ | 7.78 | 0.95±0.20(stat.) ±0.15(syst.) | 4.6 | 0 | $< 1.7$ |
| $\tau^\pm \rightarrow e^\pm \rho^0$ | 8.49 | 0.80±0.27(stat.) ±0.04(syst.) | 4.4 | 1 | $< 2.2$ |
| $\tau^\pm \rightarrow \mu^\pm \phi$ | 5.59 | 0.47±0.15(stat.) ±0.05(syst.) | 4.8 | 0 | $< 2.3$ |
| $\tau^\pm \rightarrow e^\pm \phi$ | 6.45 | 0.38±0.21(stat.) ±0.00(syst.) | 4.5 | 0 | $< 2.0$ |
| $\tau^\pm \rightarrow \mu^\pm \omega$ | 3.27 | 0.32±0.23(stat.) ±0.19(syst.) | 4.8 | 0 | $< 3.9$ |
| $\tau^\pm \rightarrow e^\pm \omega$ | 5.41 | 0.74±0.43(stat.) ±0.06(syst.) | 4.5 | 0 | $< 2.4$ |
| $\tau^\pm \rightarrow \mu^\pm K^{*0}$ | 4.52 | 0.84±0.25(stat.) ±0.31(syst.) | 4.3 | 0 | $< 2.9$ |
| $\tau^\pm \rightarrow e^\pm K^{*0}$ | 6.94 | 0.54±0.21(stat.) ±0.16(syst.) | 4.1 | 0 | $< 1.9$ |
| $\tau^\pm \rightarrow \mu^\pm \overline{K}^{*0}$ | 4.58 | 0.58±0.17(stat.) ±0.12(syst.) | 4.3 | 1 | $< 4.3$ |
| $\tau^\pm \rightarrow e^\pm \overline{K}^{*0}$ | 7.45 | 0.25±0.11(stat.) ±0.02(syst.) | 4.1 | 0 | $< 1.7$ |

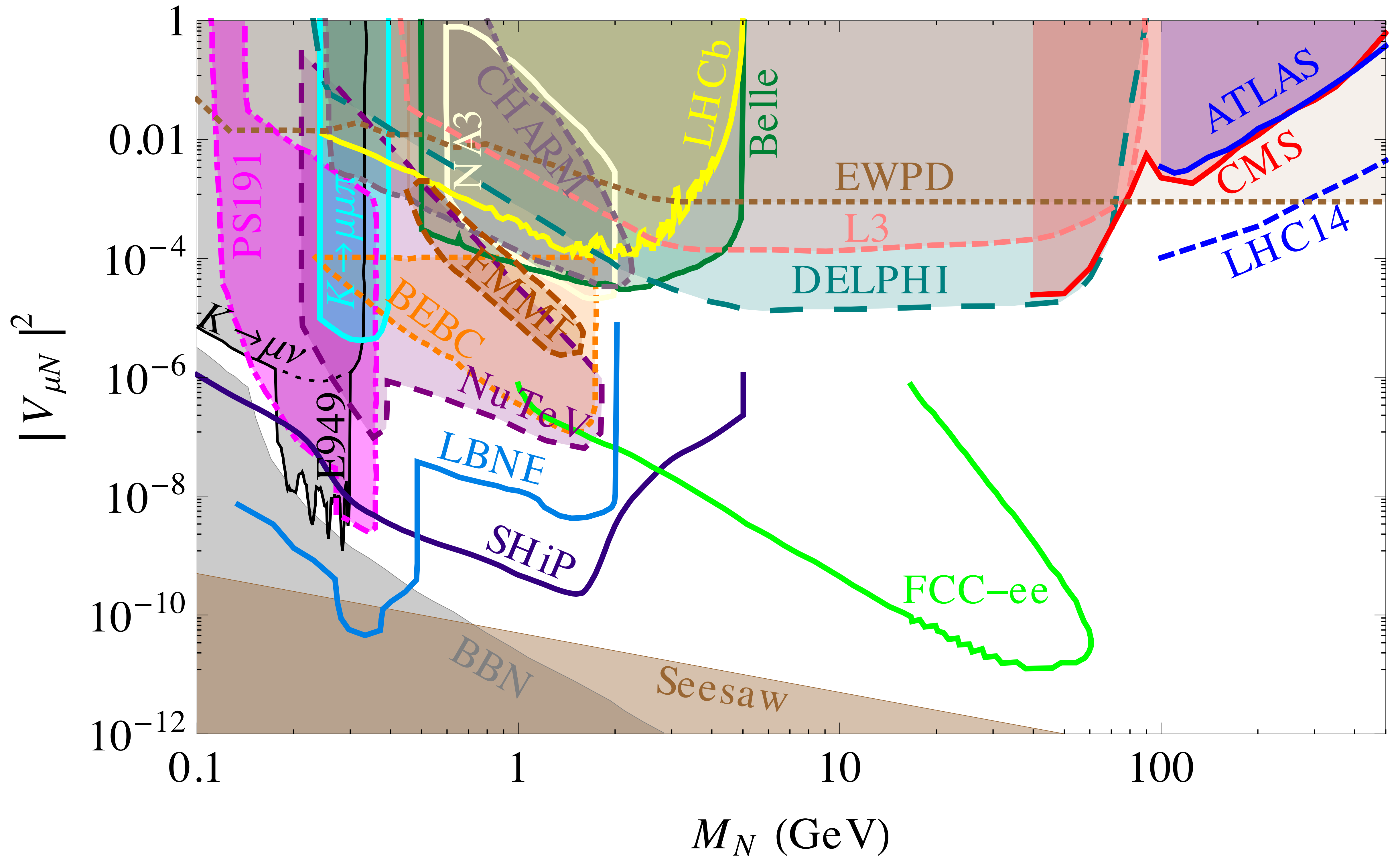
World leading results

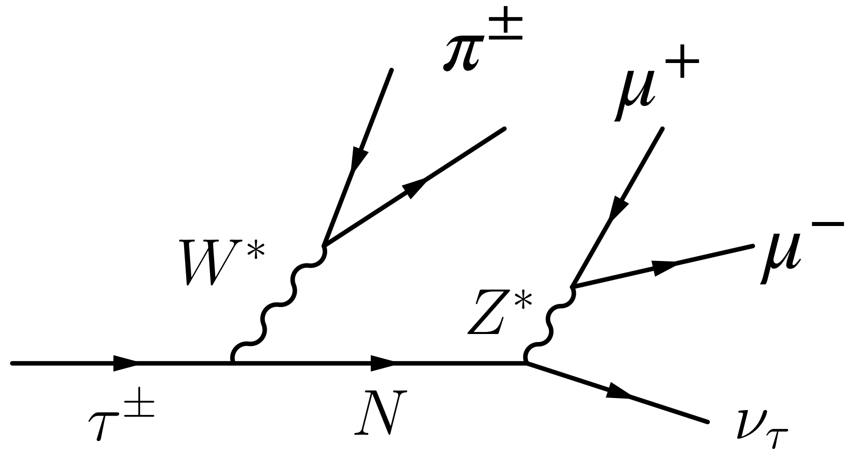
# Search for heavy neutral leptons (HNL)

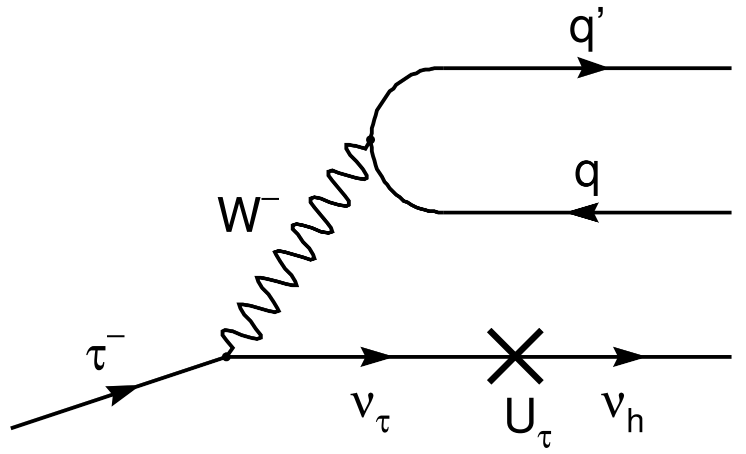
**N (or $\nu_h$) interacts with $\nu_{SM}$ through mixing: N ↔ $\nu_{SM}$**

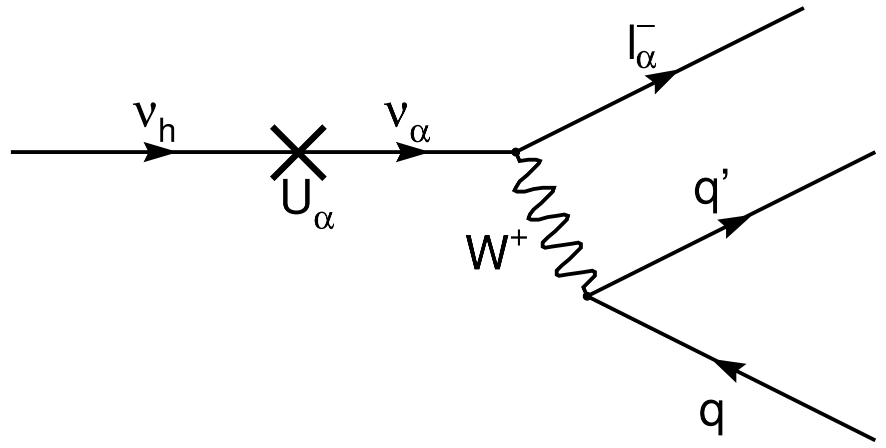
$$\nu_\ell = \sum_{i=1}^{3} U_{\ell i}\nu_i + \sum_j V_{\ell N_j} N_j .$$

- Can have Majorana mass
- Long lifetime $c\tau_N \propto |U_{\tau N}|^2 m_N^{-5}$
- In keV-scale could be a dark matter candidate
- In GeV-scale can explain the origin of the baryon asymmetry
- **Direct search of HNL in τ decays** $M_N < M_\tau$



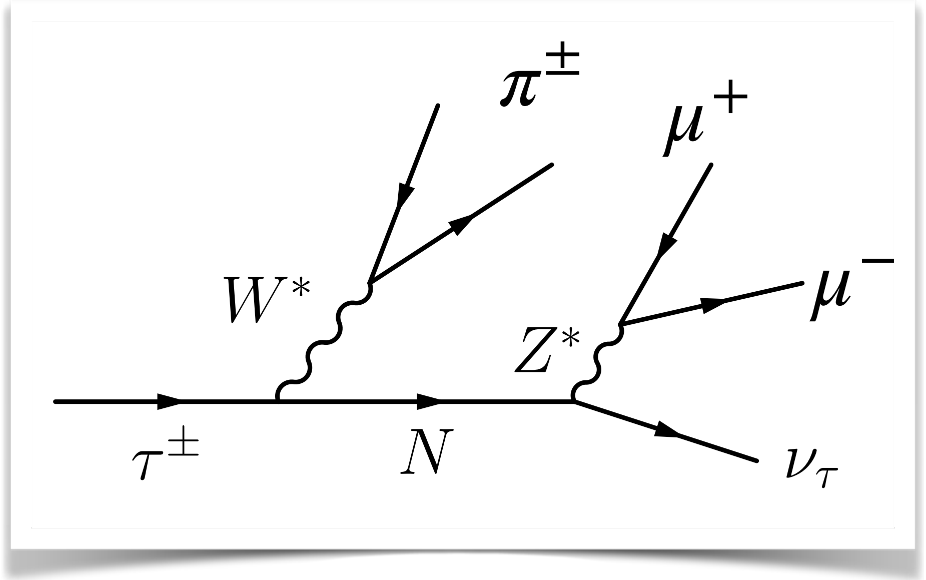




- Explored regions by different experiments
  - $M_N > M_Z$: $pp > N\ell^\pm$ @LHC
  - $M_N < M_{Z,W}$: $Z^0 \to \nu N$ @ DELPHI and $W^\pm \to \ell^\pm N$ @ LHC
  - $M_N > M_{K,D,B}$: @NA62, beam-dump, Belle
- All above experiments provide tight limits on $|V_{eN}|, |V_{\mu N}|$
- Fewer experiments have directly probed $|V_{\tau N}|$

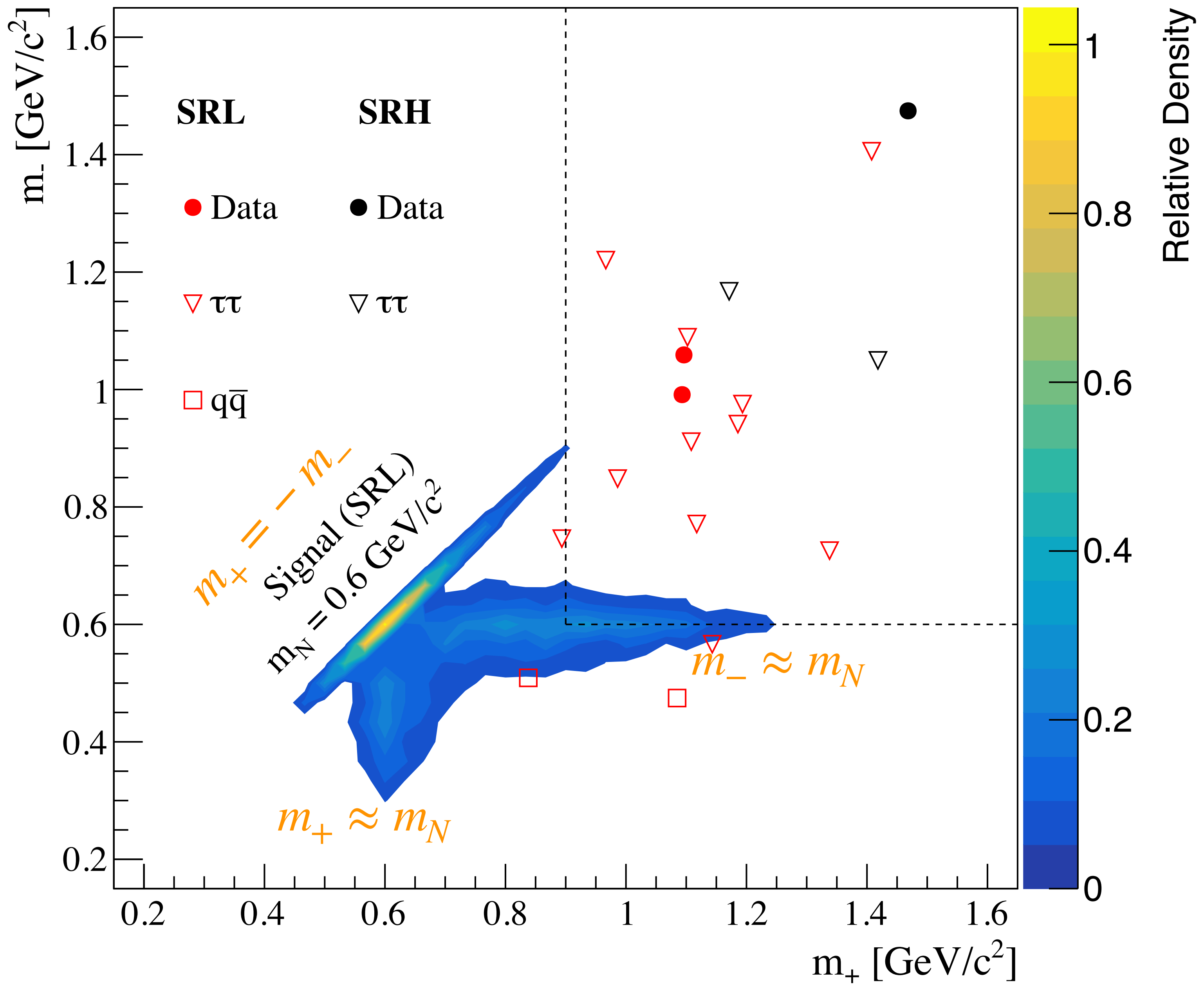
# Search for $\tau^- \to \pi^- N\ (N \to \mu^+\mu^-\nu_\tau)$ decay @ Belle

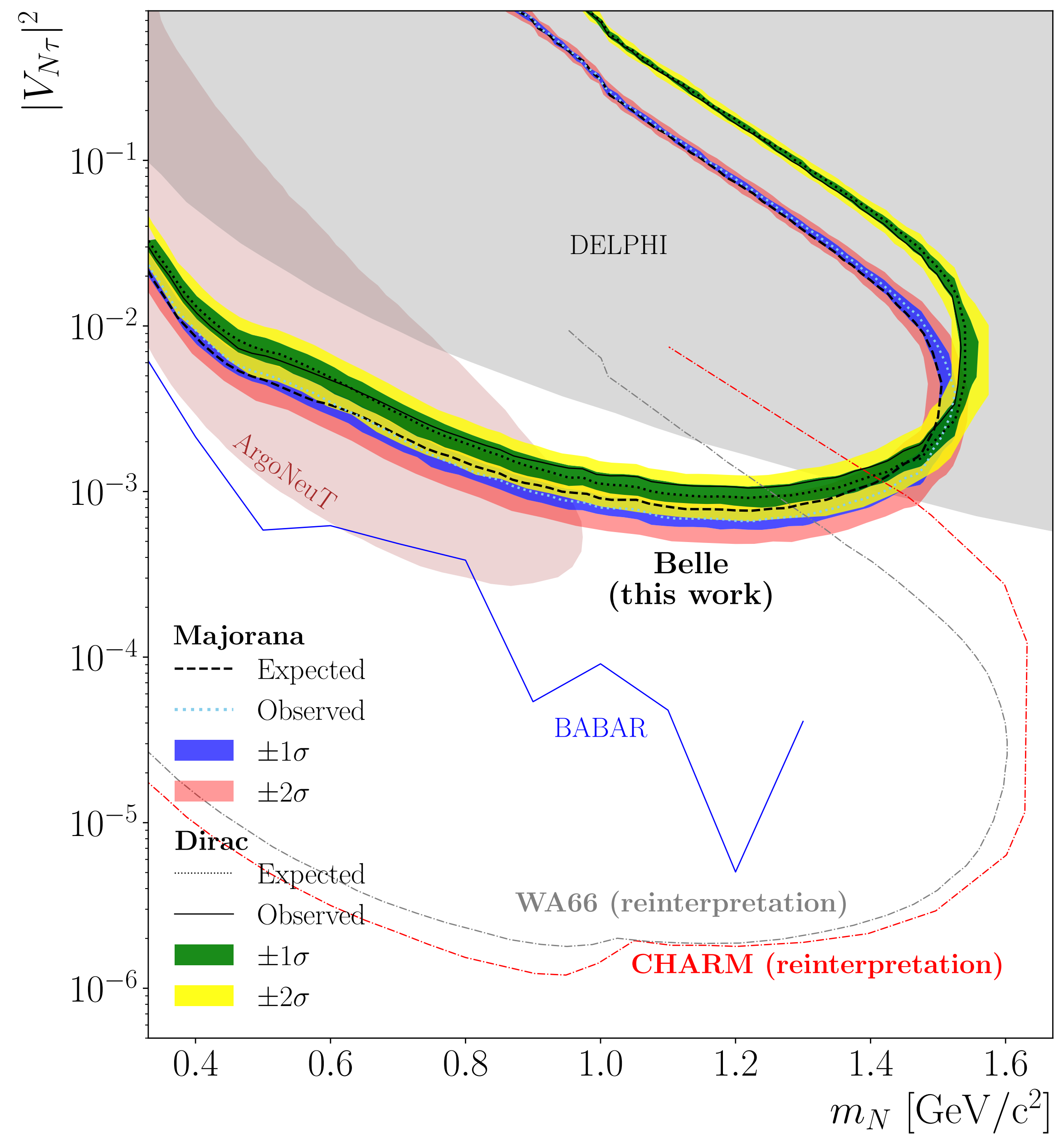
*accepted by PRD*

**Search for a heavy neutrino** $300 < M_N < 1600$ MeV **that mixes predominantly with** $\nu_\tau$



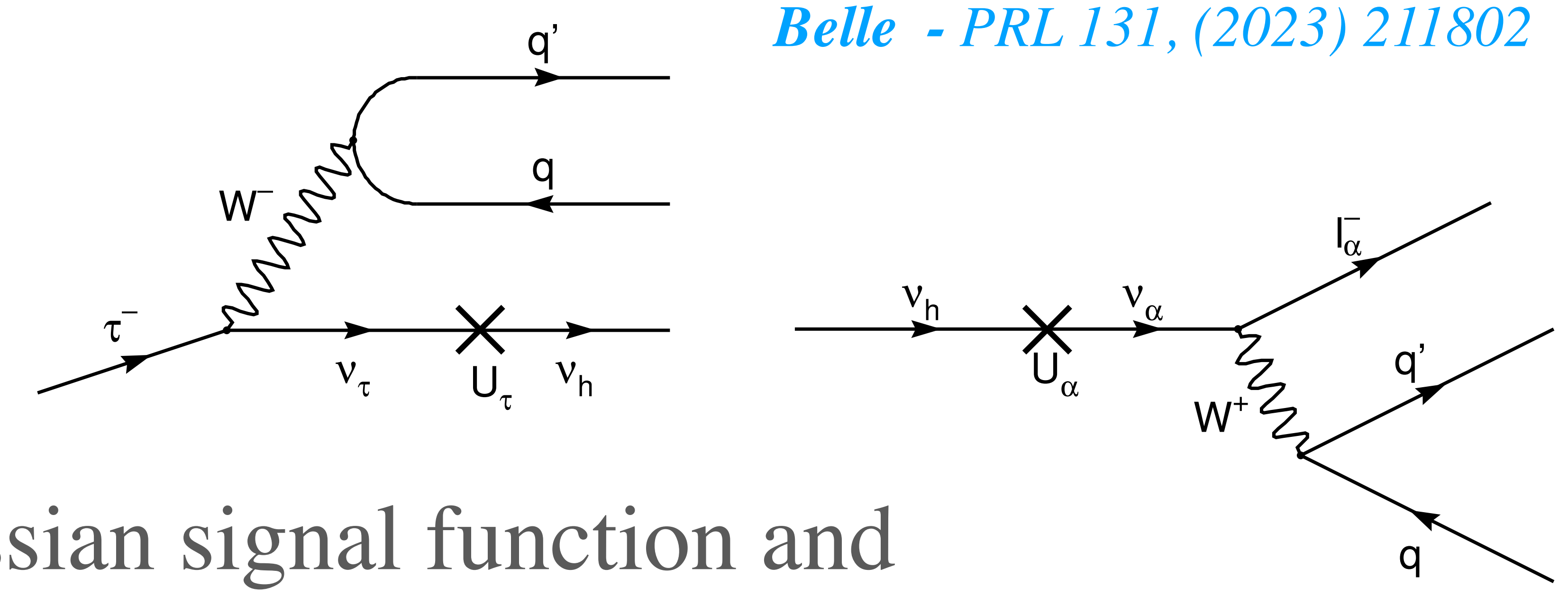

- The search uses the data set of Belle with $N_{\tau\tau} = (836 \pm 12) \times 10^6$
- Signature: prompt pion and **long-lived**, heavy neutrino $N \to \mu^+\mu^-\nu_\tau$
- Constrain of the signal decay using the full kinematics of τ decay (two-fold ambiguity)
- Rejects $K_S \to \pi^+\pi^-$ ($420 < m < 520$ MeV) → pions decay to or are misidentified as muons
- Two signal regions targeting heavy and light HNLs
- 1 and 0 observed events, in agreement with the background expectation.
- Set 95% C.L. upper limits on $|V_{N_\tau}|$ as a function of $m_N$



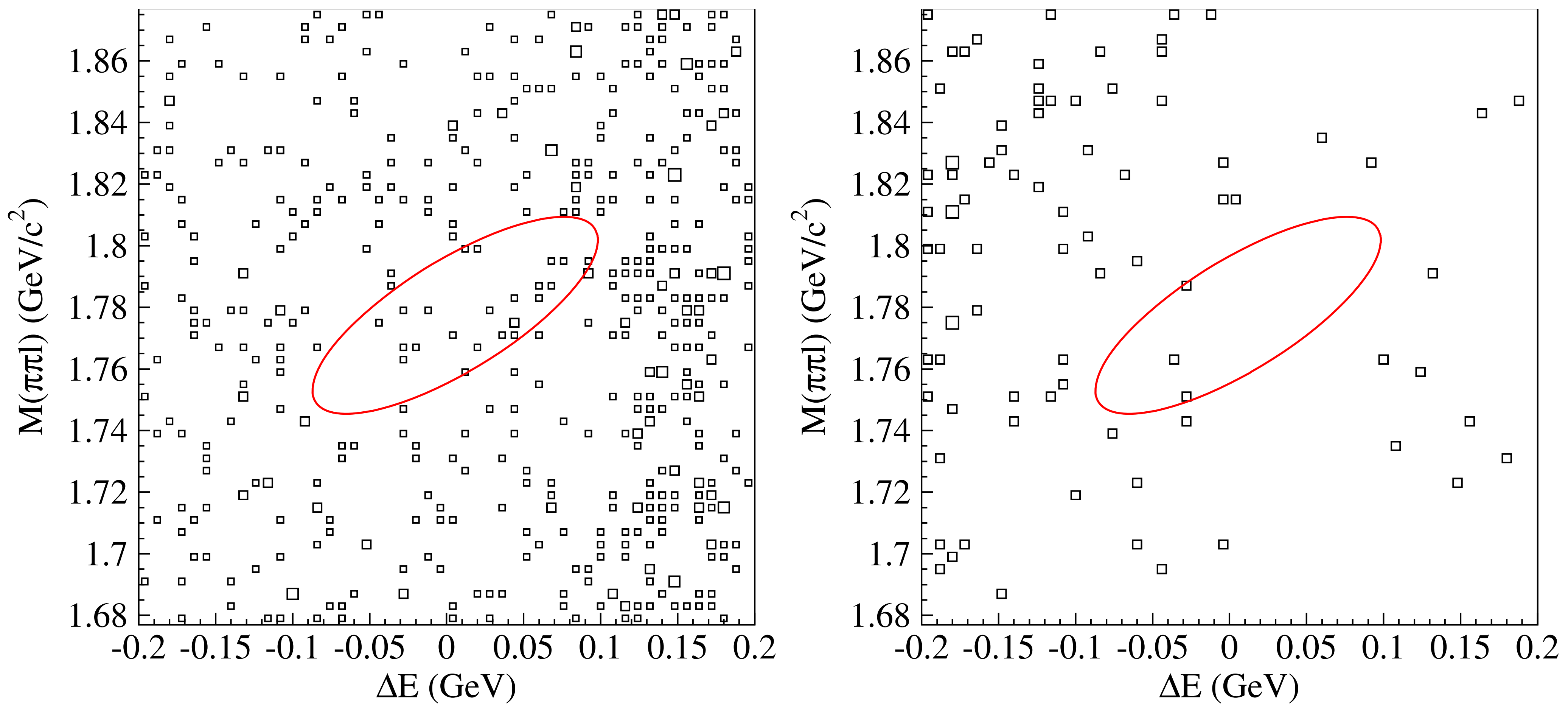
# Search for $\tau^- \rightarrow \pi^- \nu_h (\nu_h \rightarrow \pi^\pm \ell^\mp)$ decay @ Belle

***Belle* - *PRL 131, (2023) 211802***

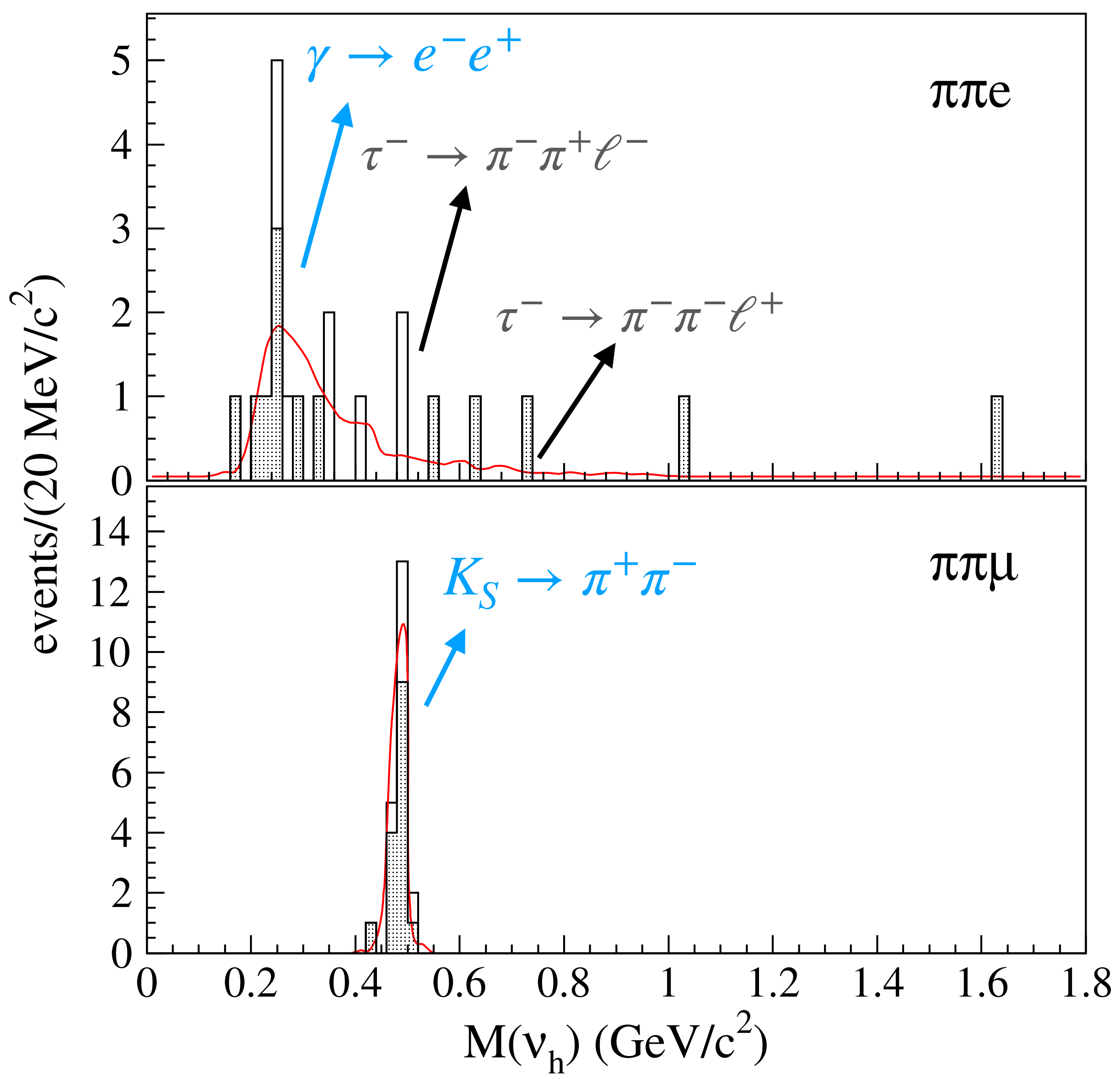


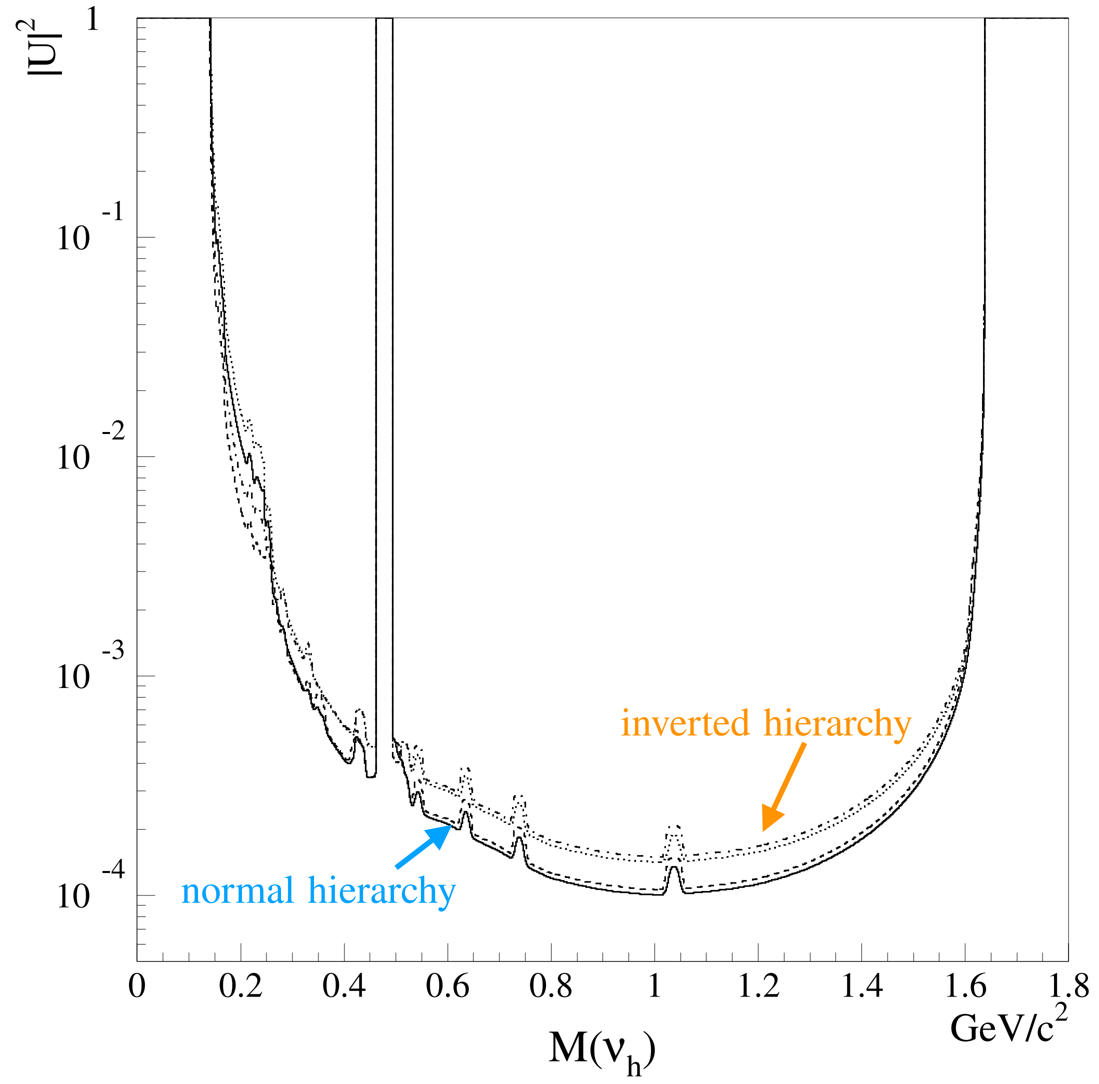

**Search for a heavy neutrino** $200 < M_{\nu_h} < 1600$ MeV

- The search uses the data set of Belle with $N_{\tau\tau} = (912 \pm 13) \times 10^6$
- Signature: prompt pion and **long-lived**, heavy neutrino $\nu_h \rightarrow \pi^\pm \ell^\mp$
- A series of binned likelihood fits to the mass distributions using the sum of a Gaussian signal function and background varying the mass hypothesis in each fit.
- No significant access
- Set 95% C.L. upper limits on $|U|^2 = |U_e|^2 + |U_\mu|^2 + |U_\tau|^2$ as a function of $M_{\nu_h}$ for the two neutrino-mass hierarchy scenarios



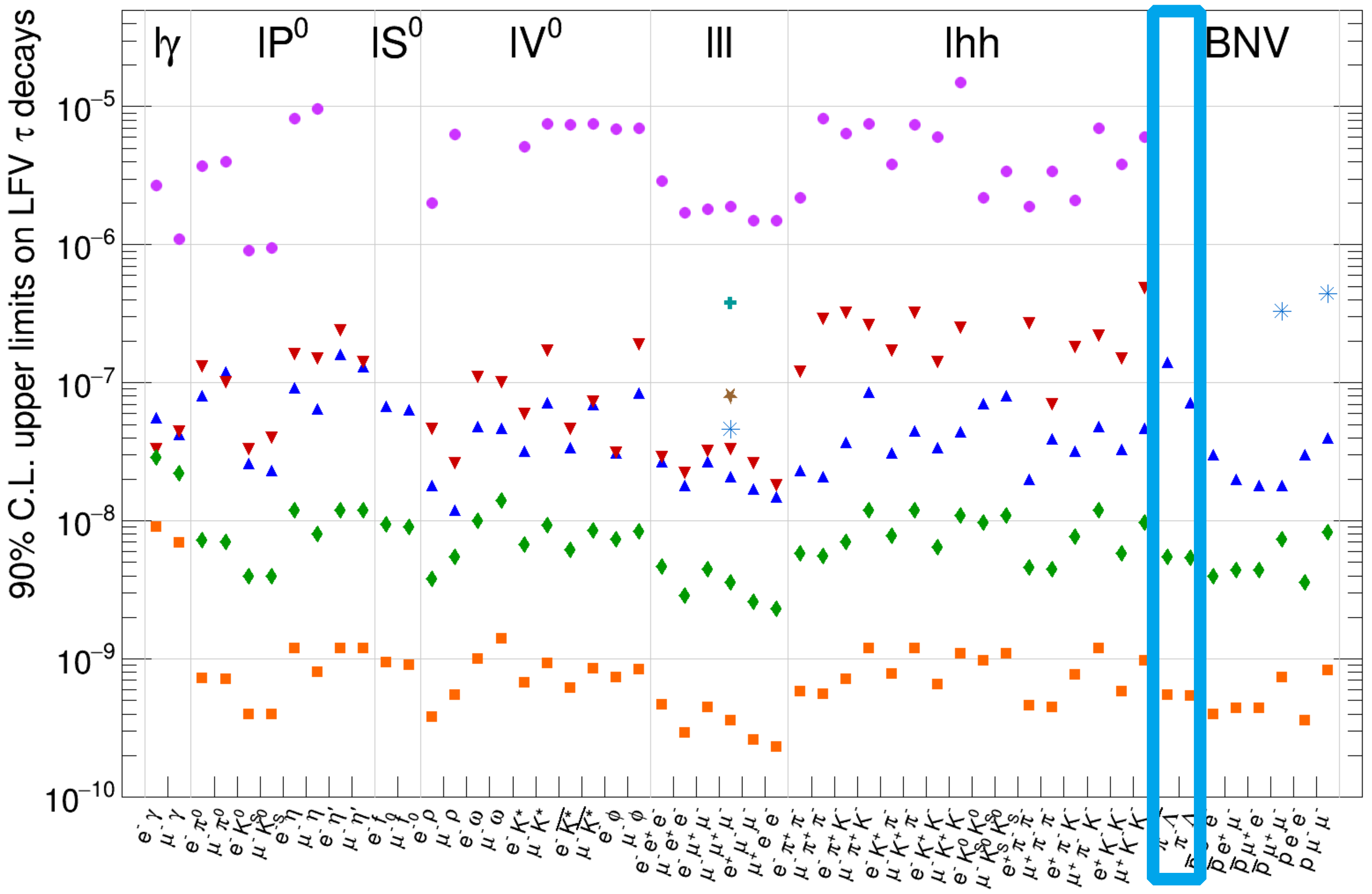

(a) (b)



# Search for $\tau \to \Lambda(\bar{\Lambda})\pi$ decay @ Belle

- BNV is one of the necessary conditions to explain the asymmetry of matter
- Beyond SM scenarios allow for BNV and LNV
  - $B - L$ conservation
  - $|\Delta(B - L)| = 2$
- Previous BNV searches:
  - $p \to e^{\pm}\pi^0$ and $p \to \mu^{\pm}\pi^0$ @ Super-Kamiokande
  - $Z^0 \to pe^-$ and $Z^0 \to p\mu^-$ @ OPAL
  - $D^0 \to \bar{p}e^+$ and $D^0 \to pe^-$ @ CLEO & Belle
  - $D^+, D_s^+, \Lambda_c \to h^{\pm}\ell^{\mp}\ell^{\pm}$ at BaBar
  - $B^0 \to \Lambda_c\ell^-, B^- \to \Lambda\ell^-, \bar{\Lambda}\ell^-$ @BaBar
  - $\tau \to \bar{p}X$ ($X = \gamma, \pi^0, \eta, 2\pi^0, \pi^0\eta$) @ CLEO
  - $\tau^- \to \Lambda\pi^-$ and $\tau^- \to \bar{\Lambda}\pi^-$ @ Belle
  - $\tau^- \to p\mu^-\mu^-$ and $\tau^- \to \bar{p}\mu^+\mu^-$ @LHCb
- Experimental limits $10^{-8} - 10^{-5}$




| | $\tau^- \to \Lambda\pi^-$ | | $\tau^- \to \bar{\Lambda}\pi^-$ | |
|---|---|---|---|---|
| | initial state | final state | initial state | final state |
| B | 0 | 1 | 0 | -1 |
| L | 1 | 0 | 1 | 0 |
| $B - L$ | -1 | 1 | -1 | -1 |
| $\lvert\Delta(B - L)\rvert$ | 2 | | 0 | |

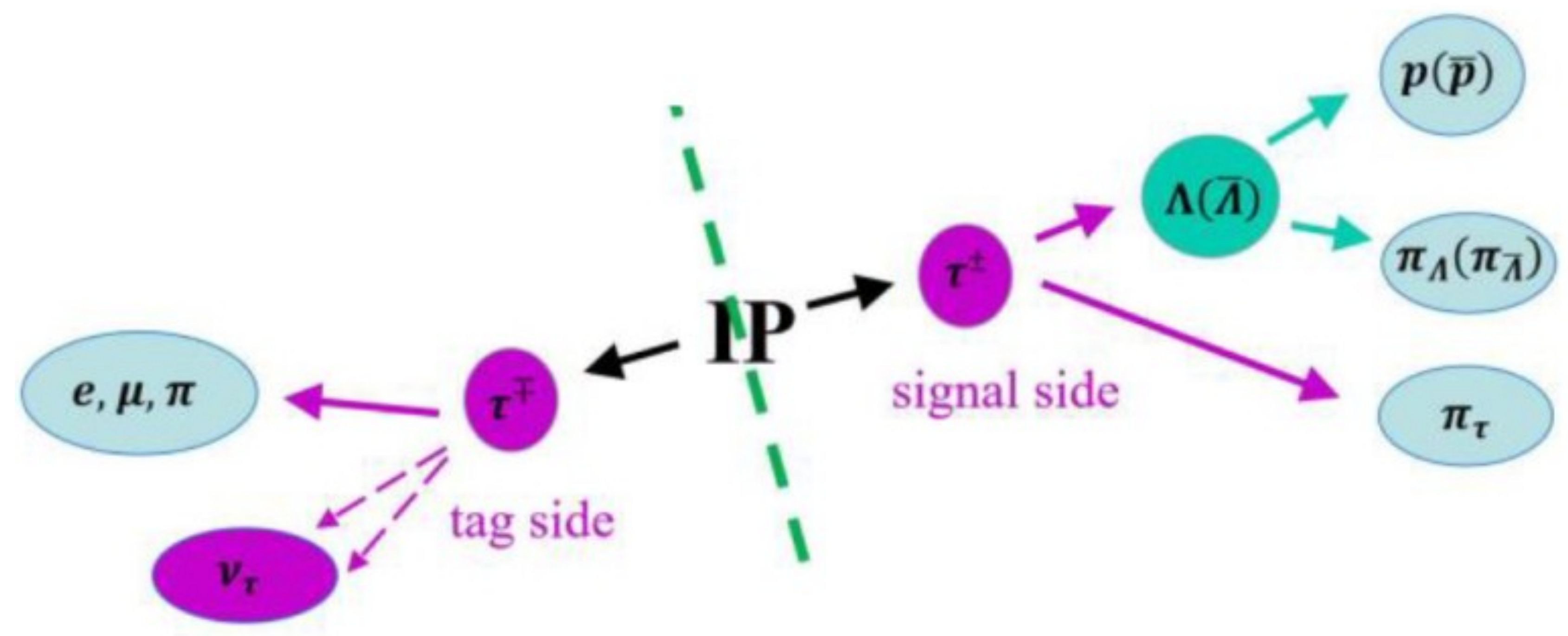
# Search for $\tau \to \Lambda(\bar{\Lambda})\pi$ decay @ Belle II

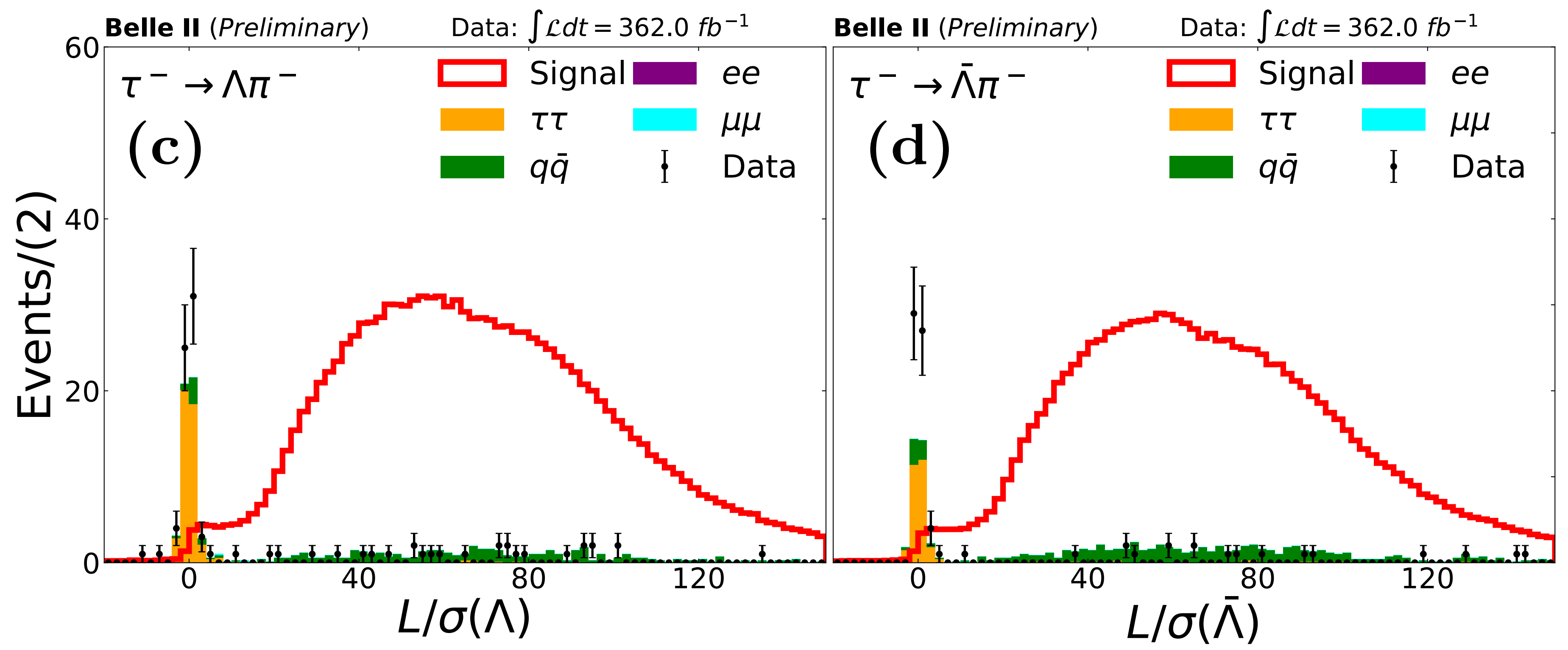
**Previous search @ Belle on 154 fb$^{-1}$**

- Set upper limits at 90% C.L. of $0.72 \times 10^{-7}$ for $\mathscr{B}(\tau^- \to \Lambda\pi^-)$ and $1.4 \times 10^{-7}$ for $\mathscr{B}(\tau^- \to \bar{\Lambda}\pi^-)$

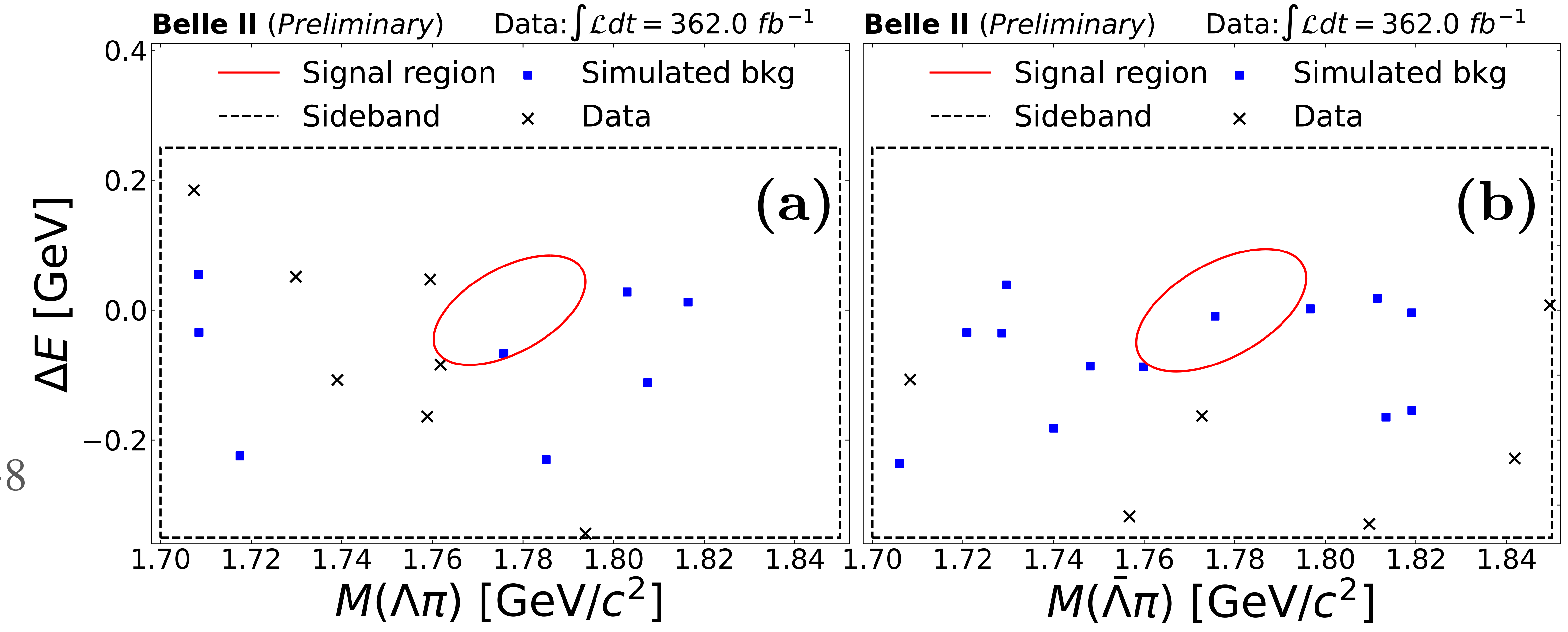
**This search @ Belle II on 362 fb$^{-1}$**

- Signal selection using loose pre-selections, followed by GBDT
  - The flight significance of $\Lambda$ and $\bar{\Lambda}$ candidates is one of the powerful variables



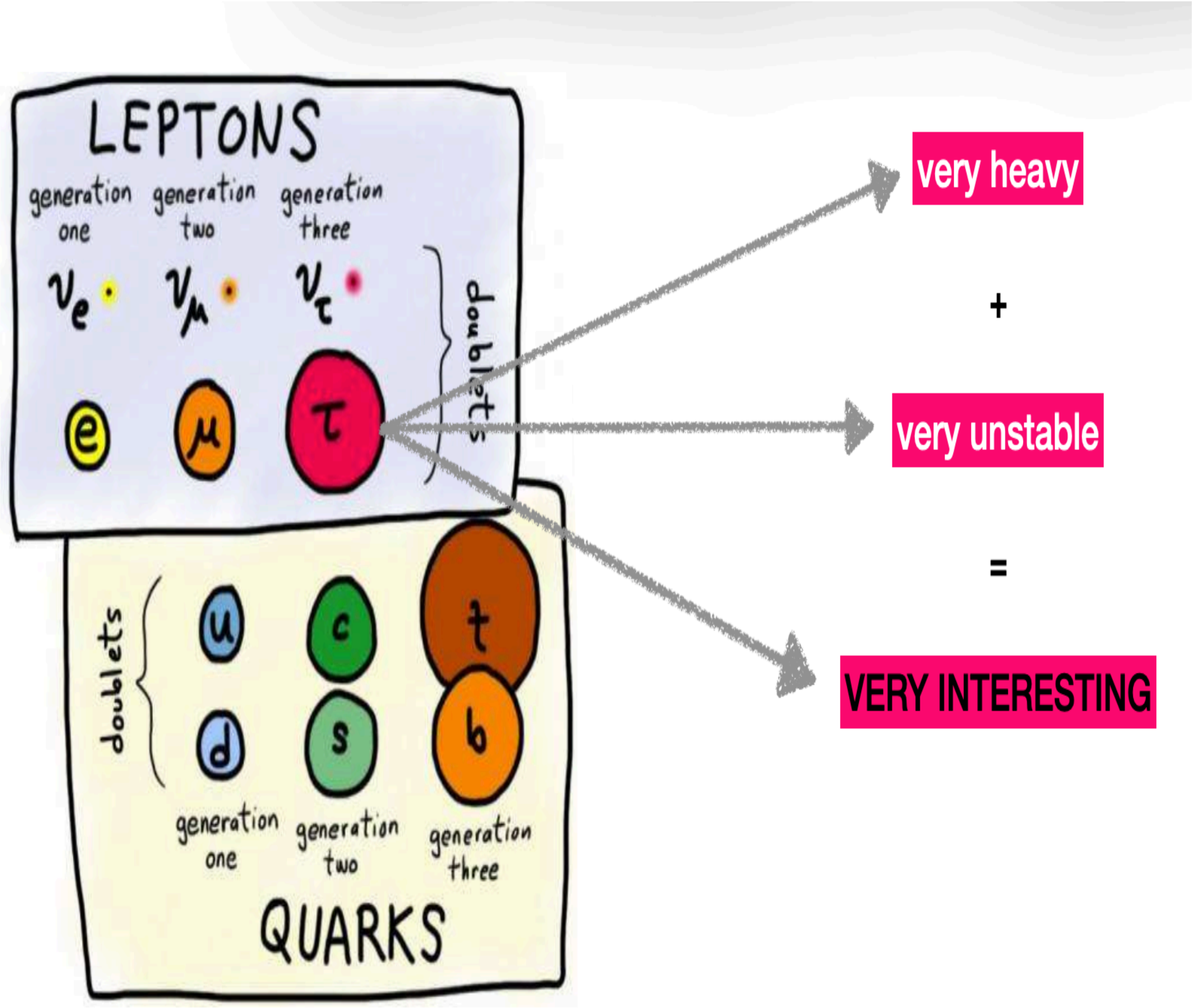

- Signal efficiencies 9.5% (9.8%) for $\tau \to \Lambda\pi^-$ ($\tau^- \to \bar{\Lambda}\pi^-$)
- Expected events 1 (0.5) for $\tau \to \Lambda\pi^-$ ($\tau^- \to \bar{\Lambda}\pi^-$)
- No observed events
- **World leading results on upper limits at 90% C.L. of** $4.7 \times 10^{-8}$ **for** $\mathscr{B}(\tau^- \to \Lambda\pi^-)$ **and** $4.3 \times 10^{-8}$ **for** $\mathscr{B}(\tau^- \to \bar{\Lambda}\pi^-)$



# Outlook

## Very exciting times ahead!

- A very interesting era in the τ LFV searches, with expectations of significant improvements in current limits, spanning from a few parts in $10^{-10}$ to $10^{-9}$.
  - On horizon @ Belle II
  - Polarised beams can further improve the sensitivity
  - Similar sensitivities will be probed at ATLAS, CMS & LHCb
  - The proposed experiments at STCF and FCC-ee will further explore LFV in the τ sector.
- This goes hand in hand with precision measurements, where the possibility of new physics emerging is also possible.
- The discovery of LFV would mark a new era in particle physics.
  - Synergies between different experiments enhance both the potential for new discoveries and the confirmation of existing ones.

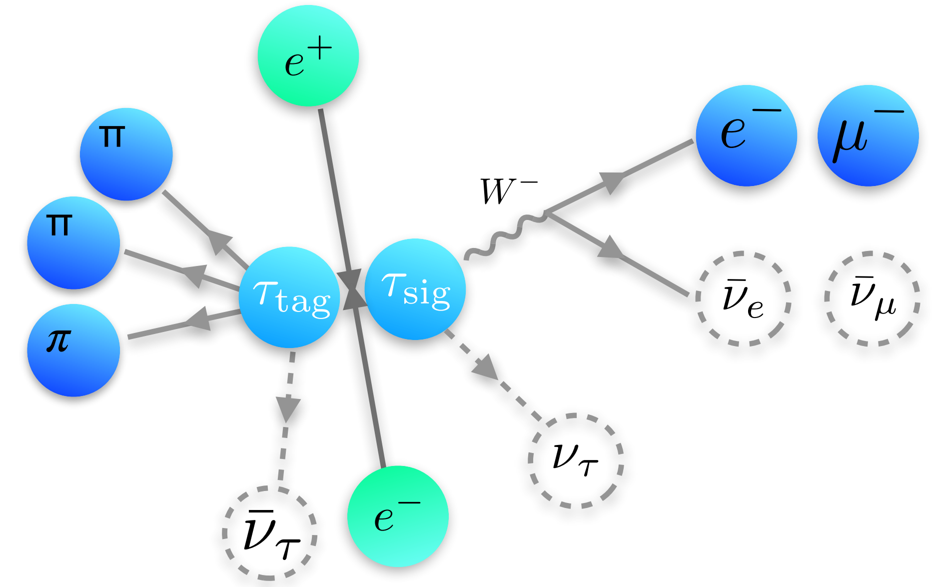


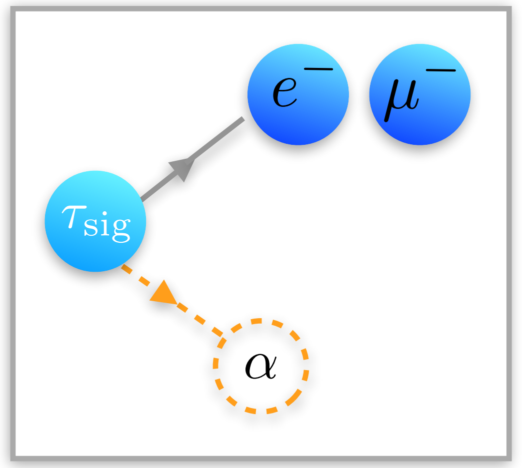
# Backup

# Search for LFV $\tau \to \ell\alpha$ ($\alpha \to$ invisible)

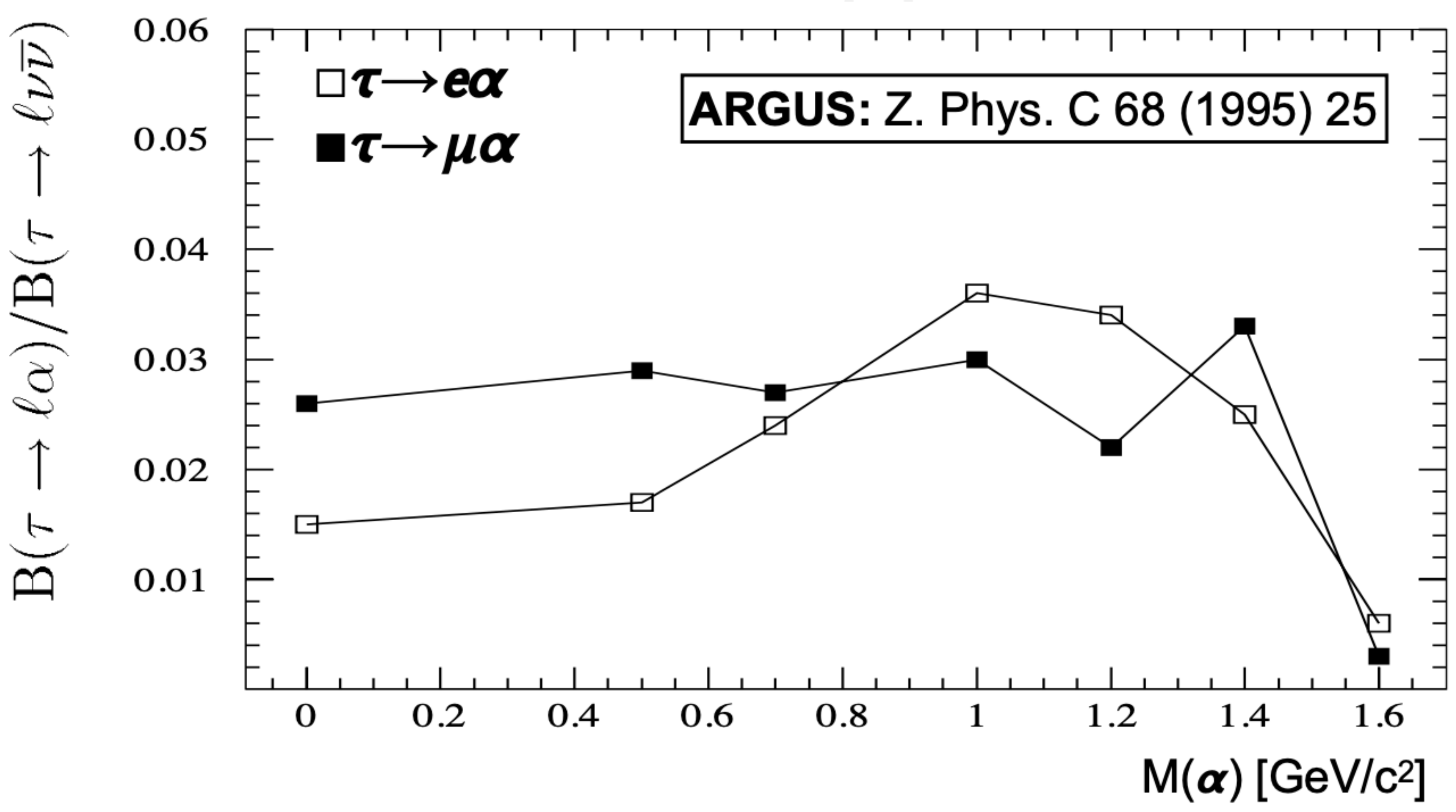
**Probe the existence of a new boson α**

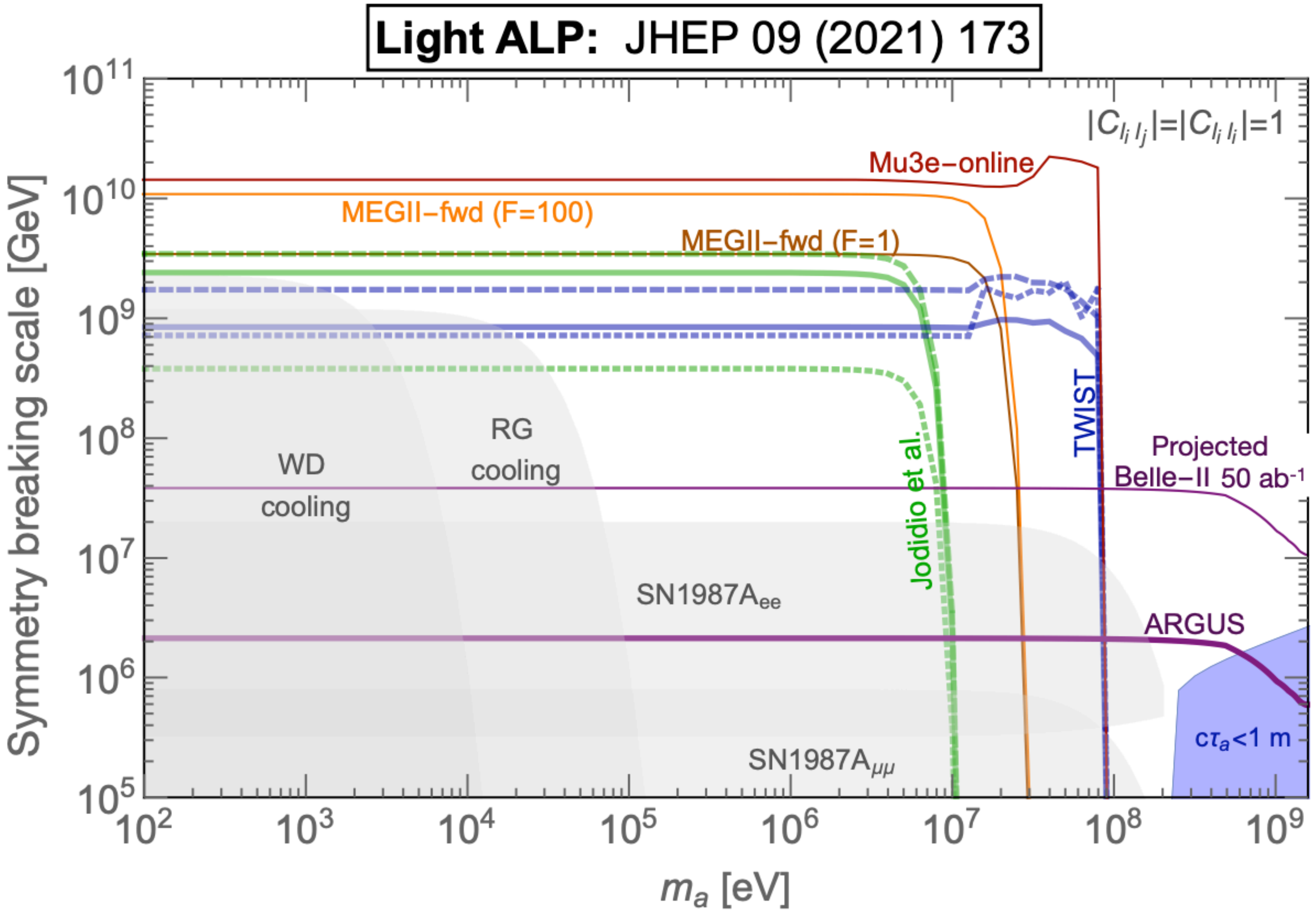
- α is an invisible particle
  - e.g, an axion-like particle




- Previous searches from Mark III (9.4 pb$^{-1}$) and ARGUS (476 pb$^{-1}$)



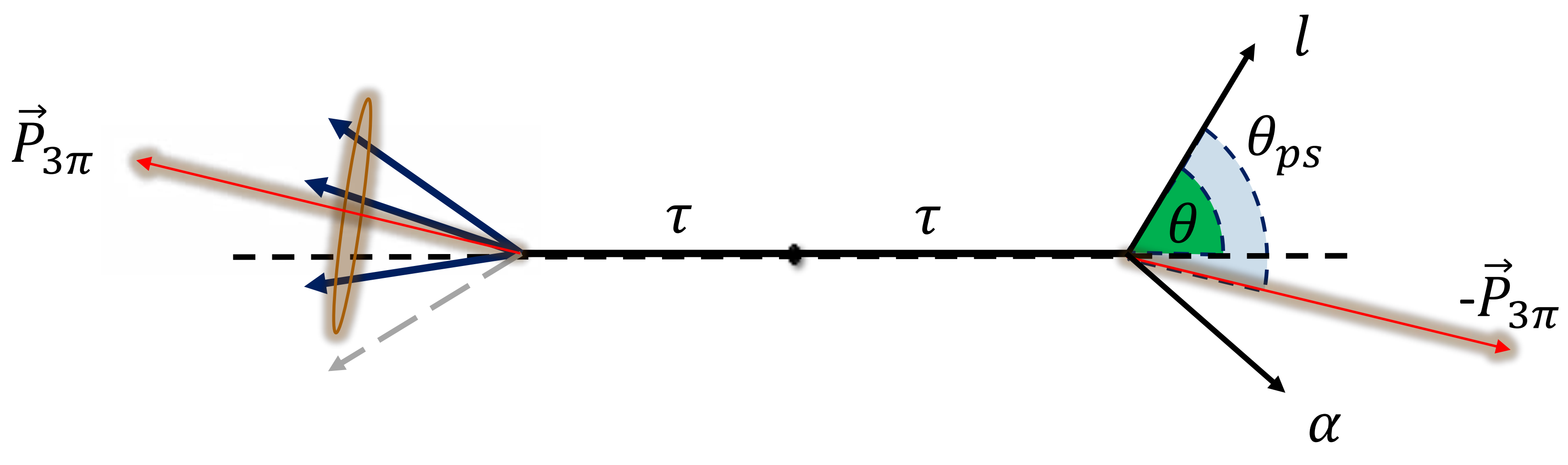

- Interesting mass range from 100 MeV-1.6 GeV
  - not covered by other searches

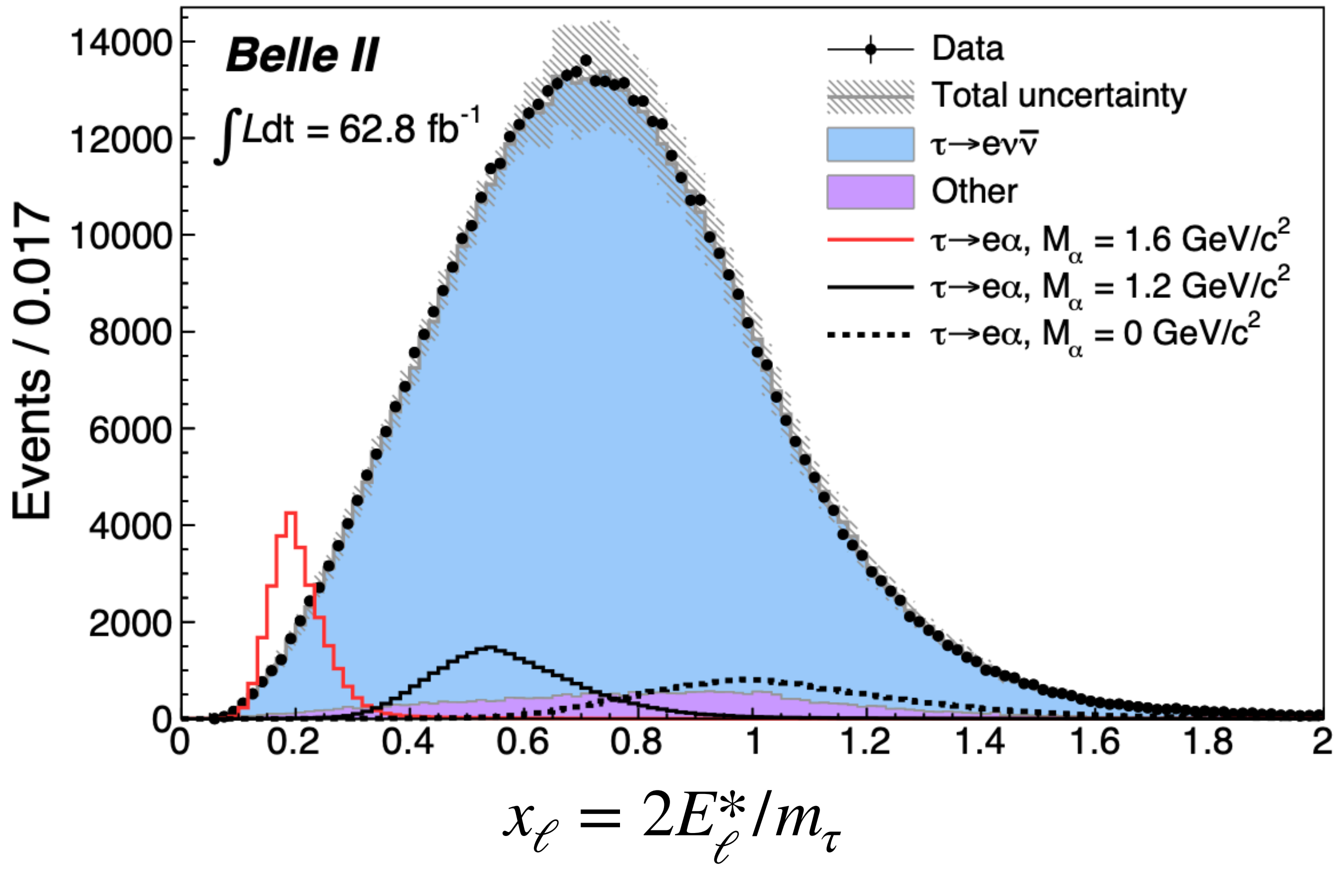
# Search for LFV $\tau \to \ell\alpha$ ($\alpha \to$ invisible)

**Search for a two body decay spectrum**

*Belle II - PRL 130, 181803 (2023)*

- Signal will manifest itself as a peak in the τ rest frame
- True τ rest frame not accessible due to the missing neutrino



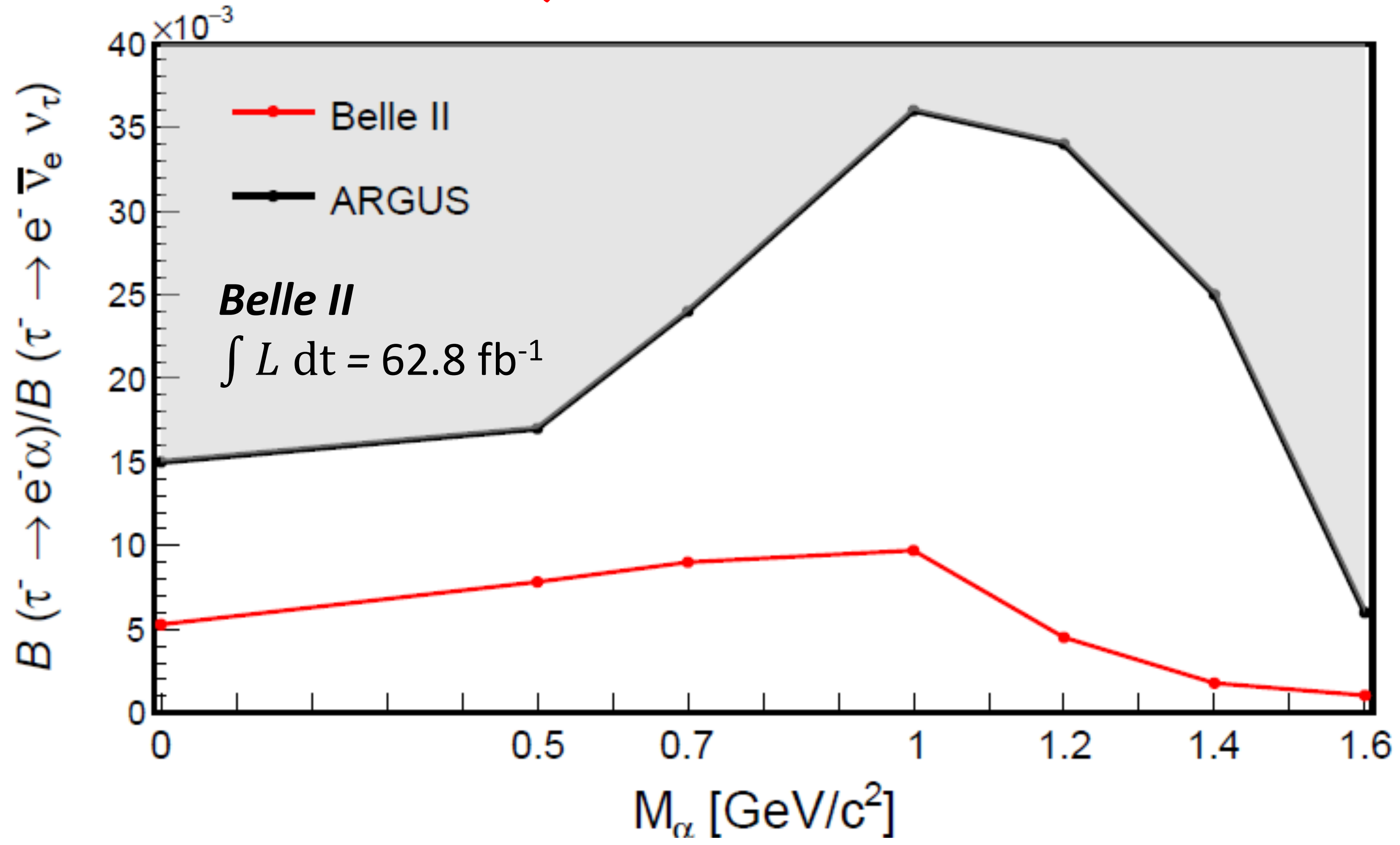




- Approximate using the tag side:

$$\hat{p}_\tau \approx -\hat{p}_{3\pi} \qquad E_\tau = \sqrt{s}/2$$

- Search for access over the irreducible background: $\tau \to l\nu\nu$
- Mass range: $M_\alpha$ from 0 to 1.6 GeV
- No access is observed
- Set 95% (90%) C.L. branching fraction limits
- **2 to 14 times more stringent than ARGUS**

**τ→αe search**




**τ→αμ search**