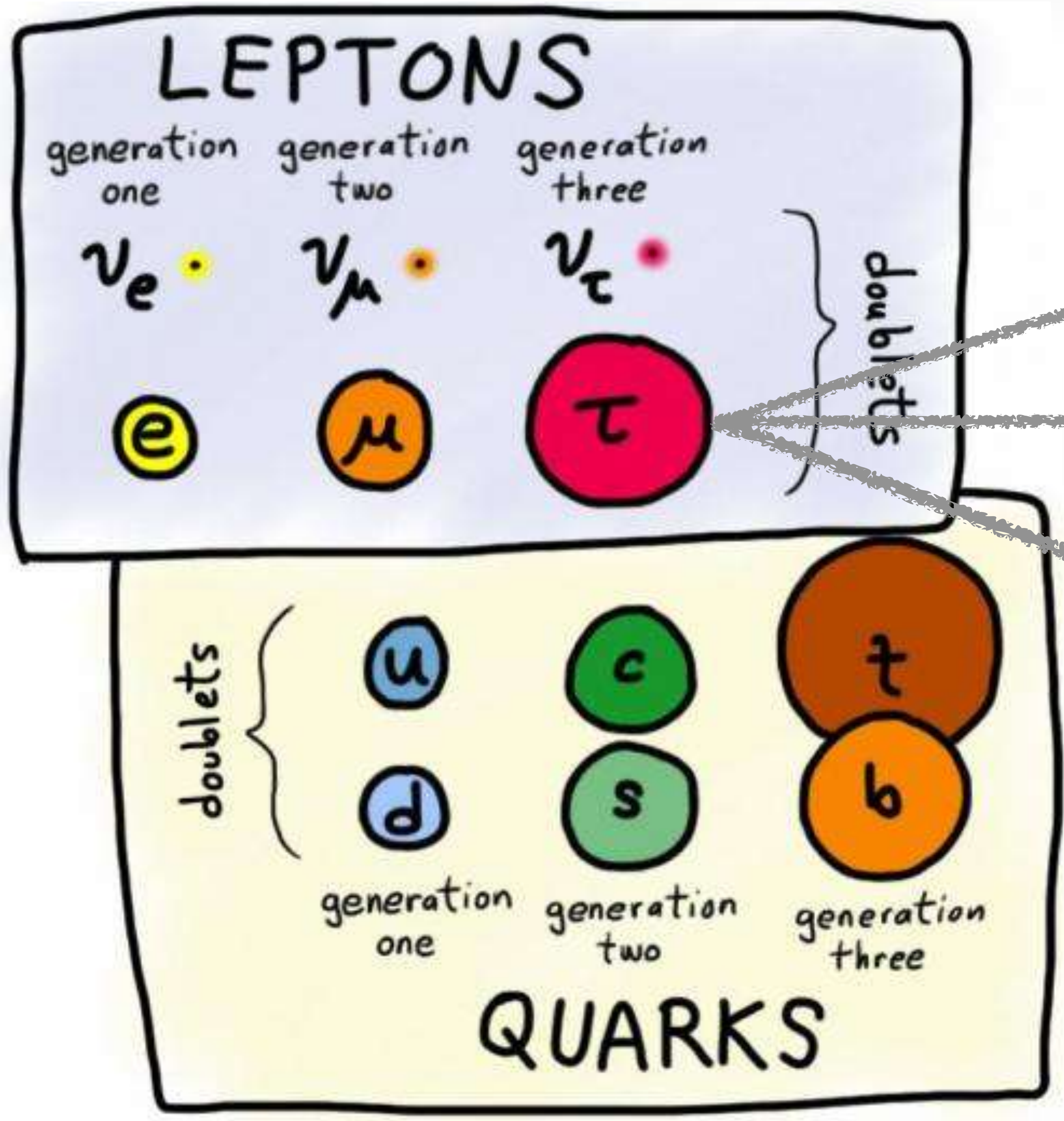
Rare decays of τ lepton



very heavy

+

very unstable

=

VERY INTERESTING

Ami Rostomyan

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

27th of May, 2024

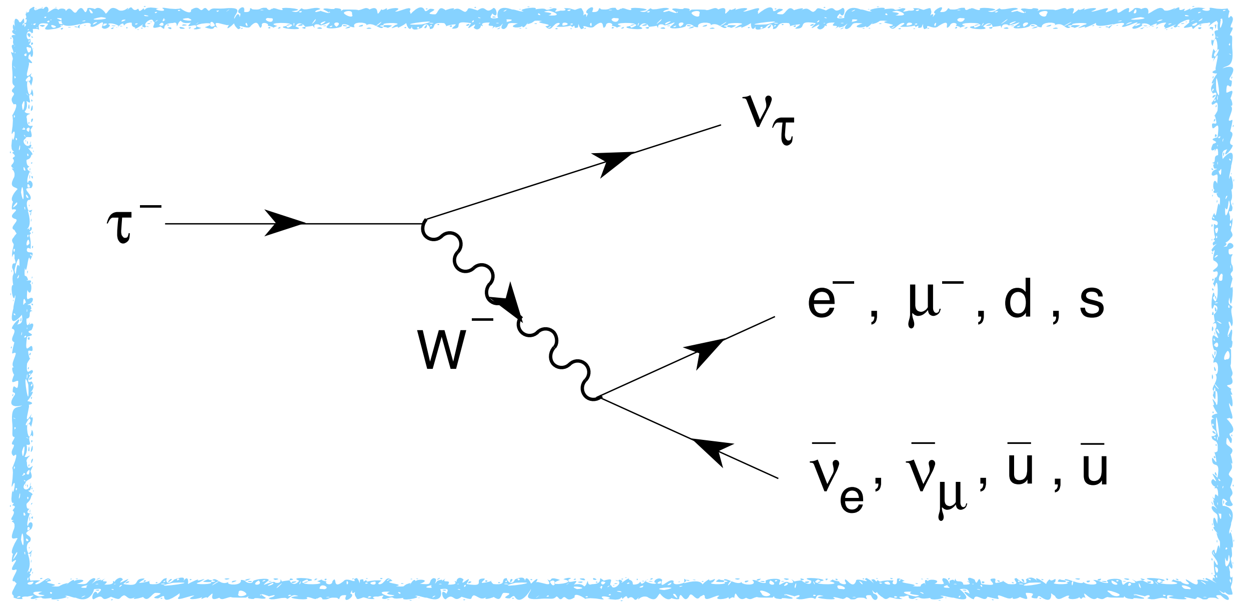
HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

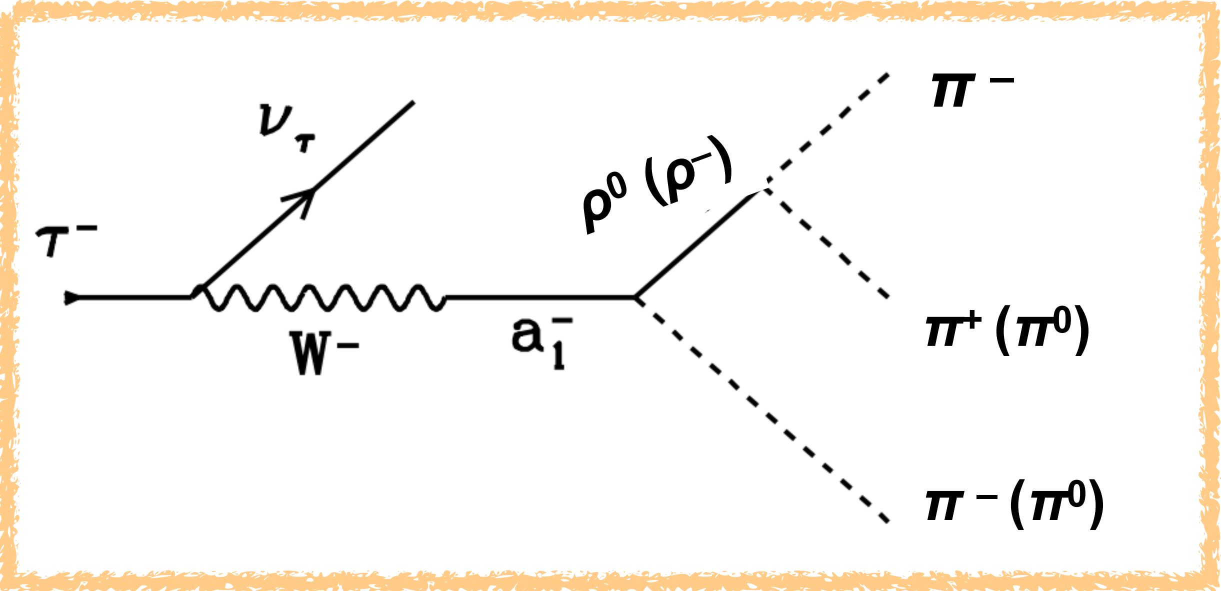
DESY.

The τ lepton

~ 250 decay modes in PDG

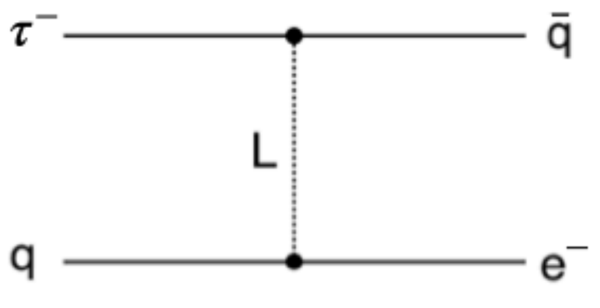
- Pure leptonic $\tau \to e\bar{\nu}\nu$ and $\tau \to \mu\nu\bar{\nu}$
- Hadronic or semi-leptonic
  - Cabibbo favoured $\tau \to \pi\nu$ and suppressed $\tau \to K\nu$



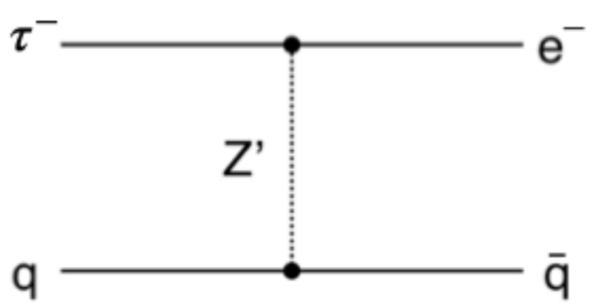


- Forbidden decays
  - Lepton flavour (LFV), lepton number (LNV), baryon number (BNV) violation

Tree level

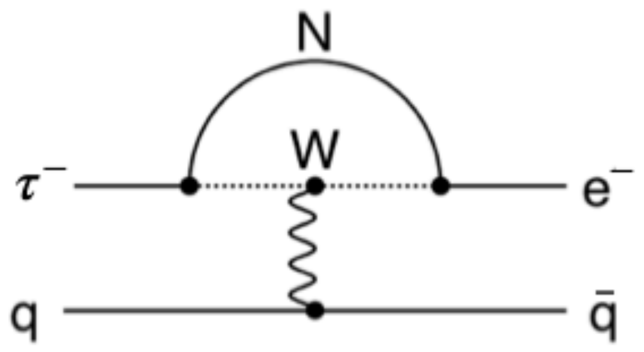


Leptoquarks

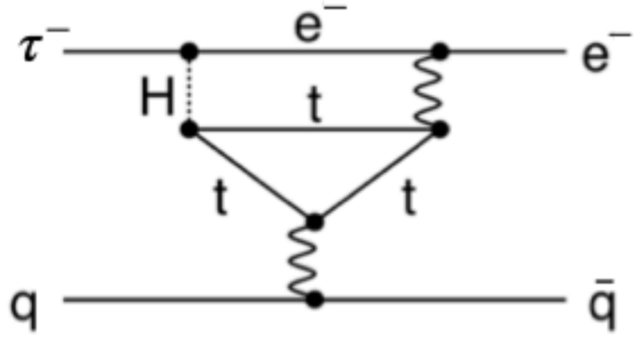


Heavy gauge bosons

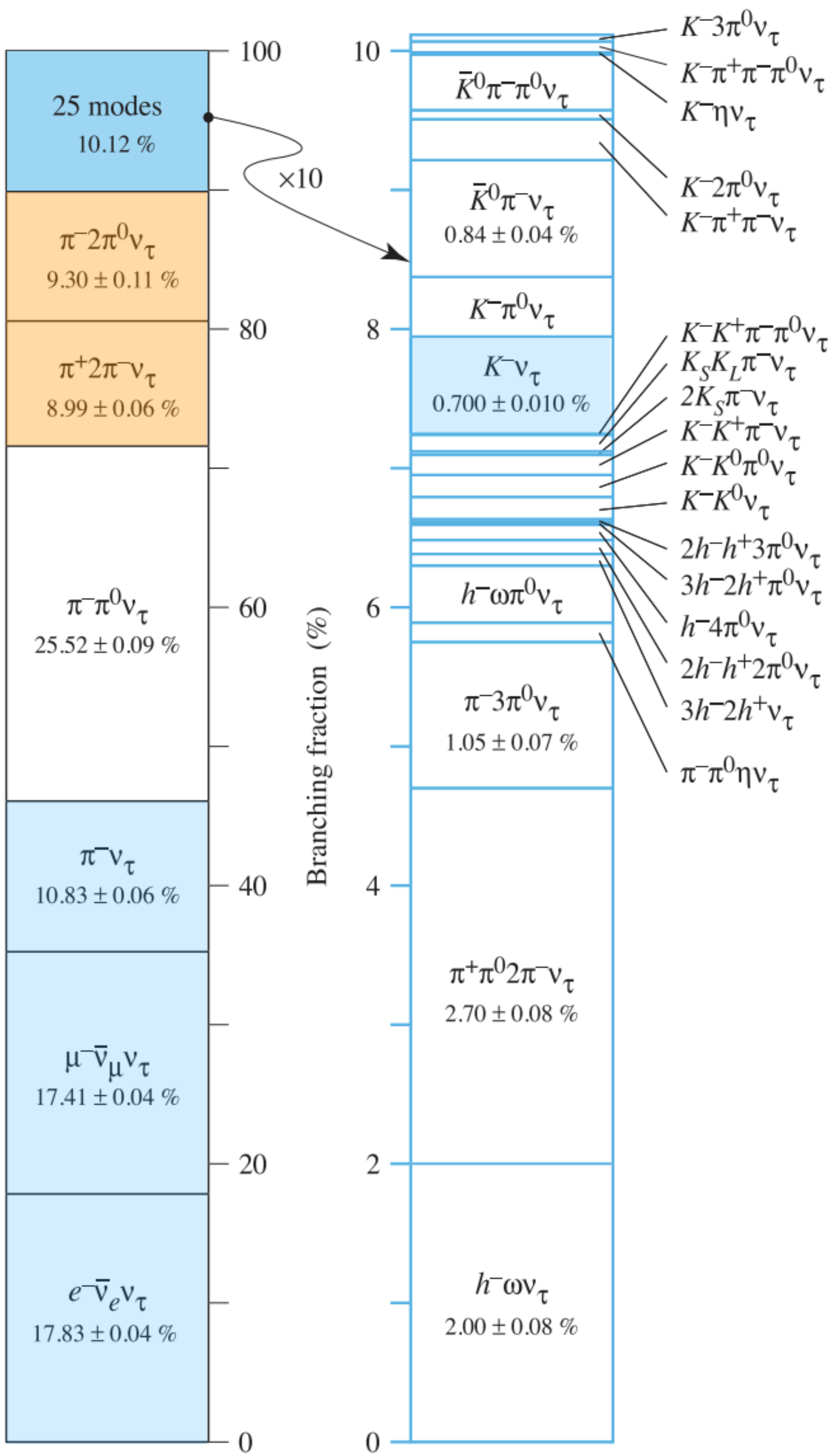
Loop induced



Heavy neutrinos



Extended Higgs models



The role of τ 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 τ 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

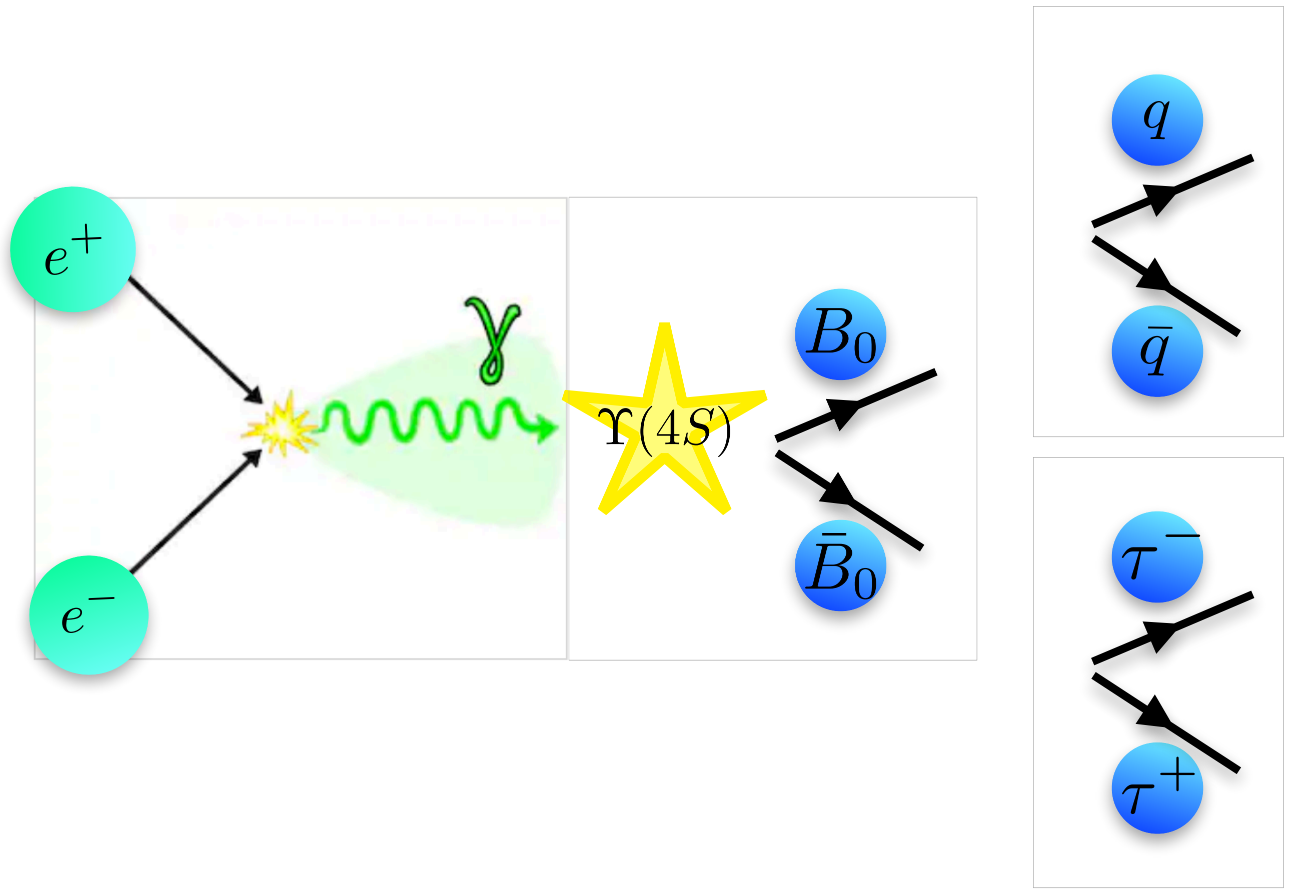
➡ *any signal* is unambiguous signature of NP

The progress of τ physics

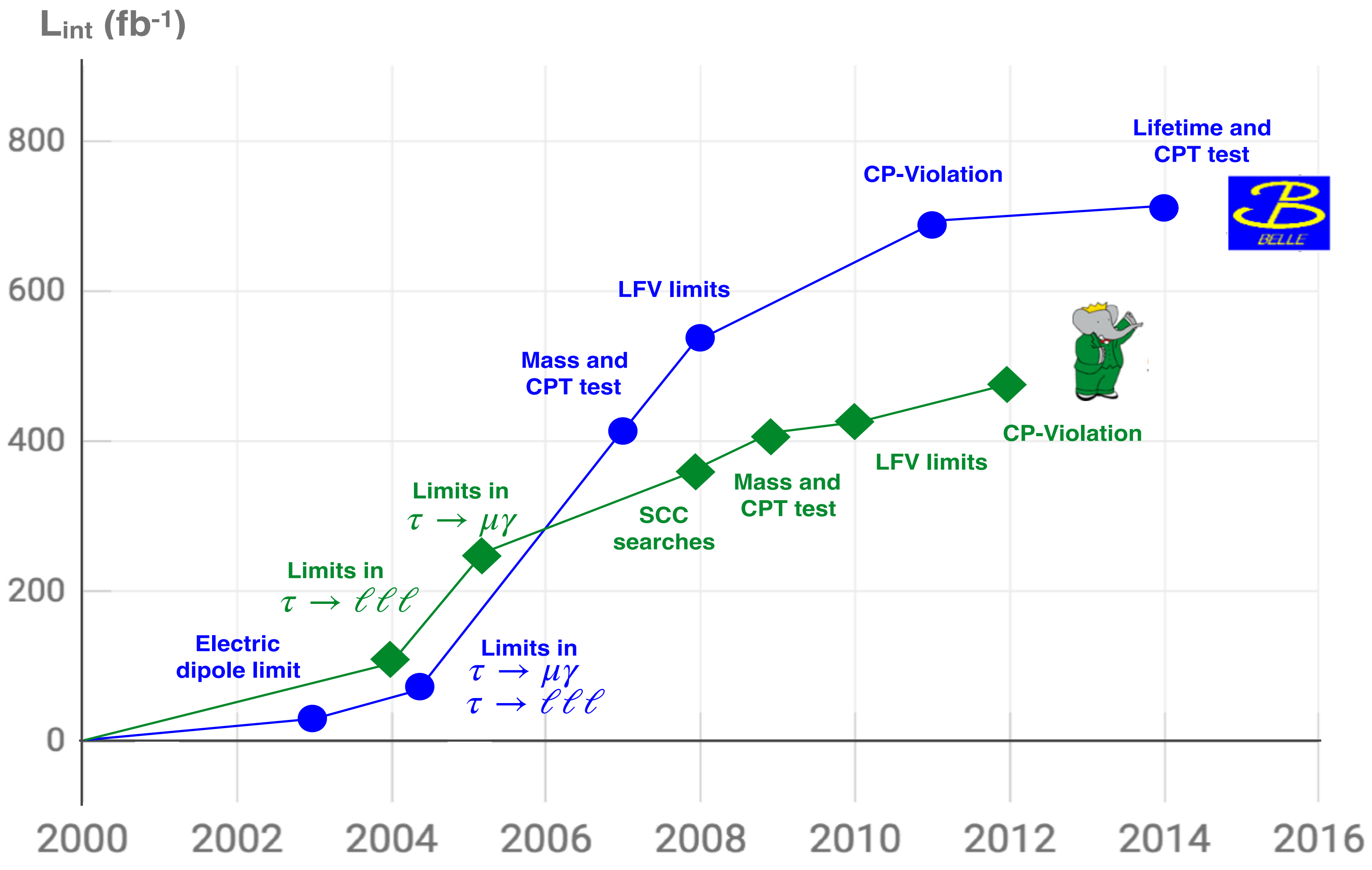
B-factories provided a variety of very interesting results in the last two decades.

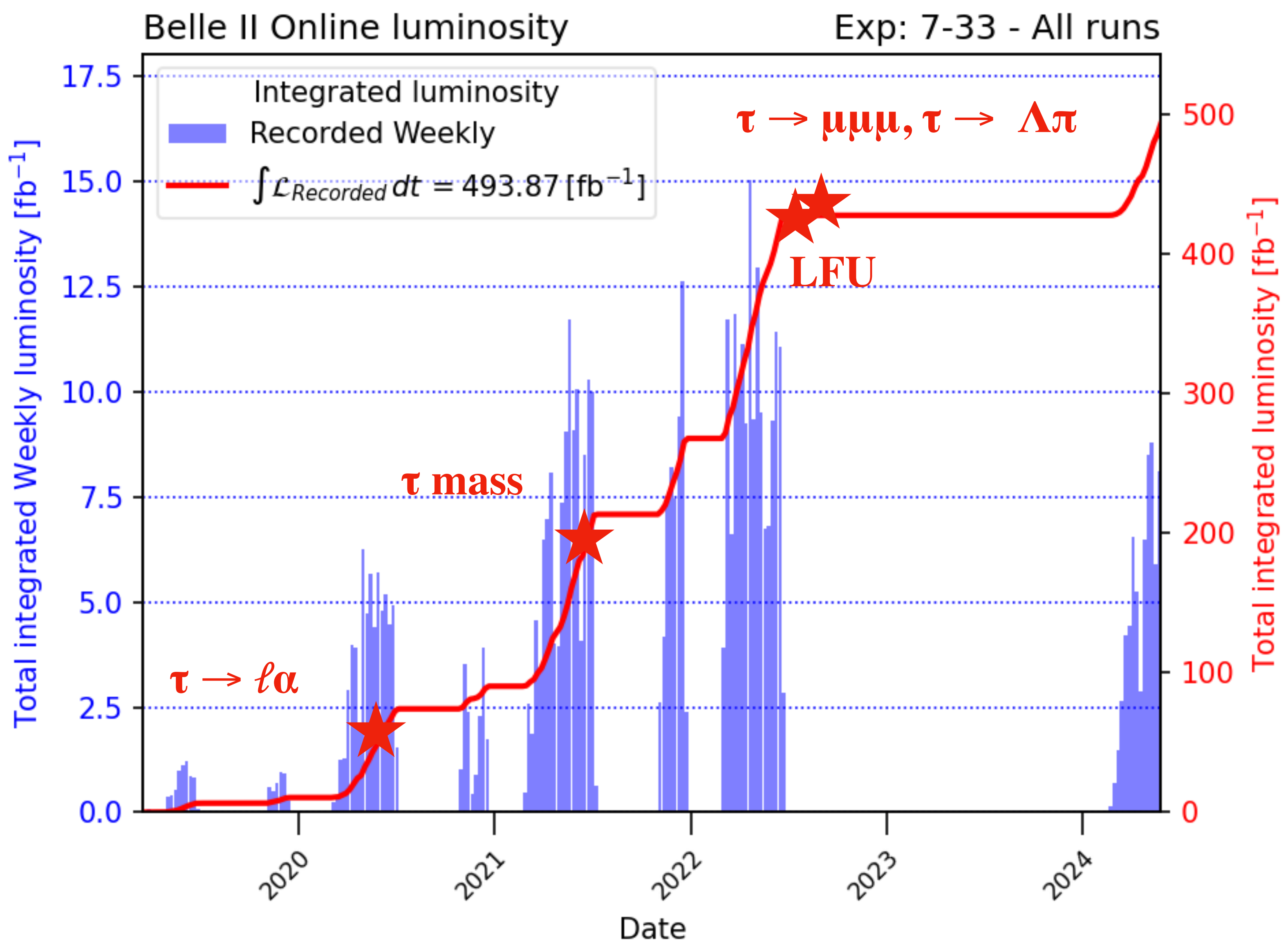
➡ The world largest number of $e^+e^- \to \tau^+\tau^-$events offer data for τ physics with high precision

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



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





Other players in the τ sector

➡ BES III, ATLAS, CMS, LHCb

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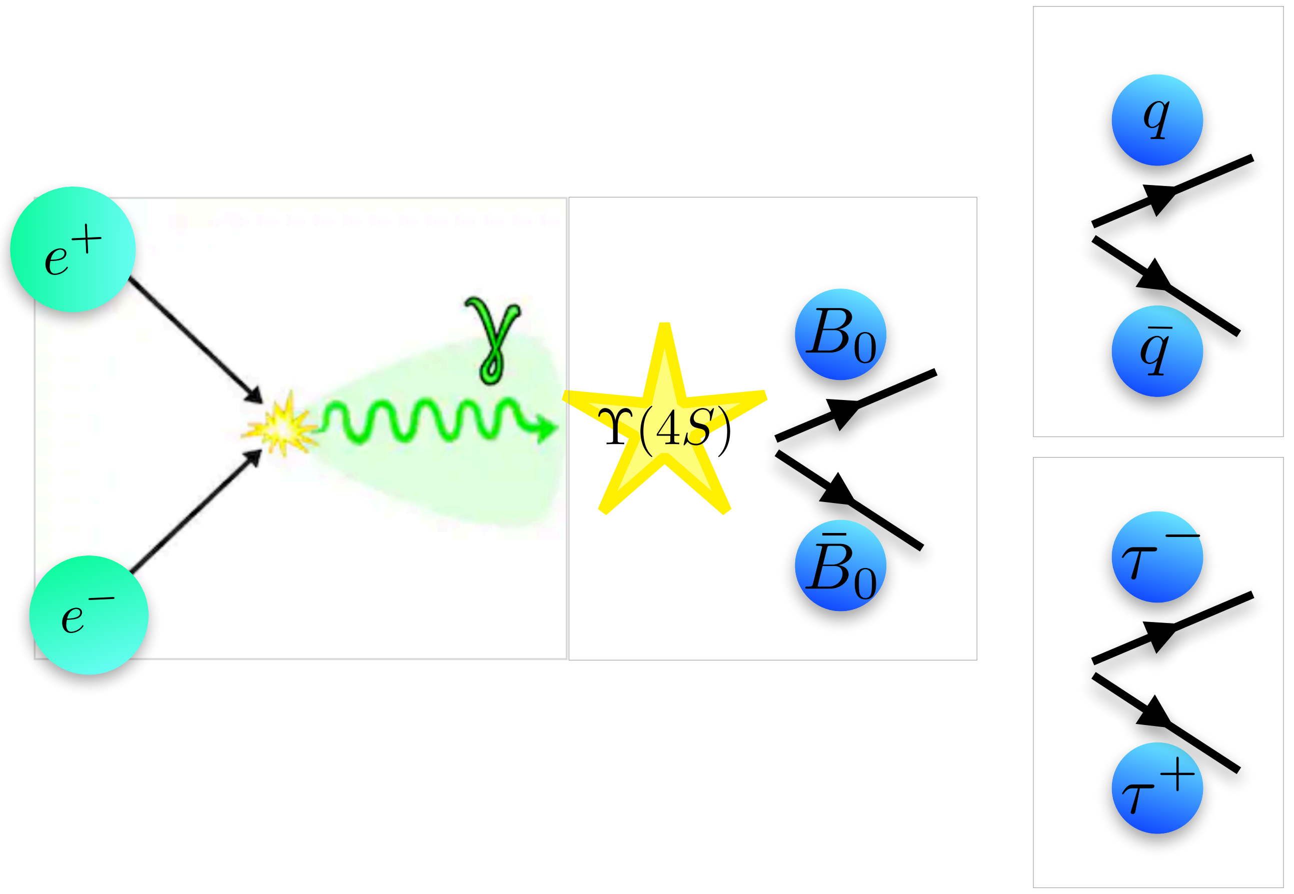

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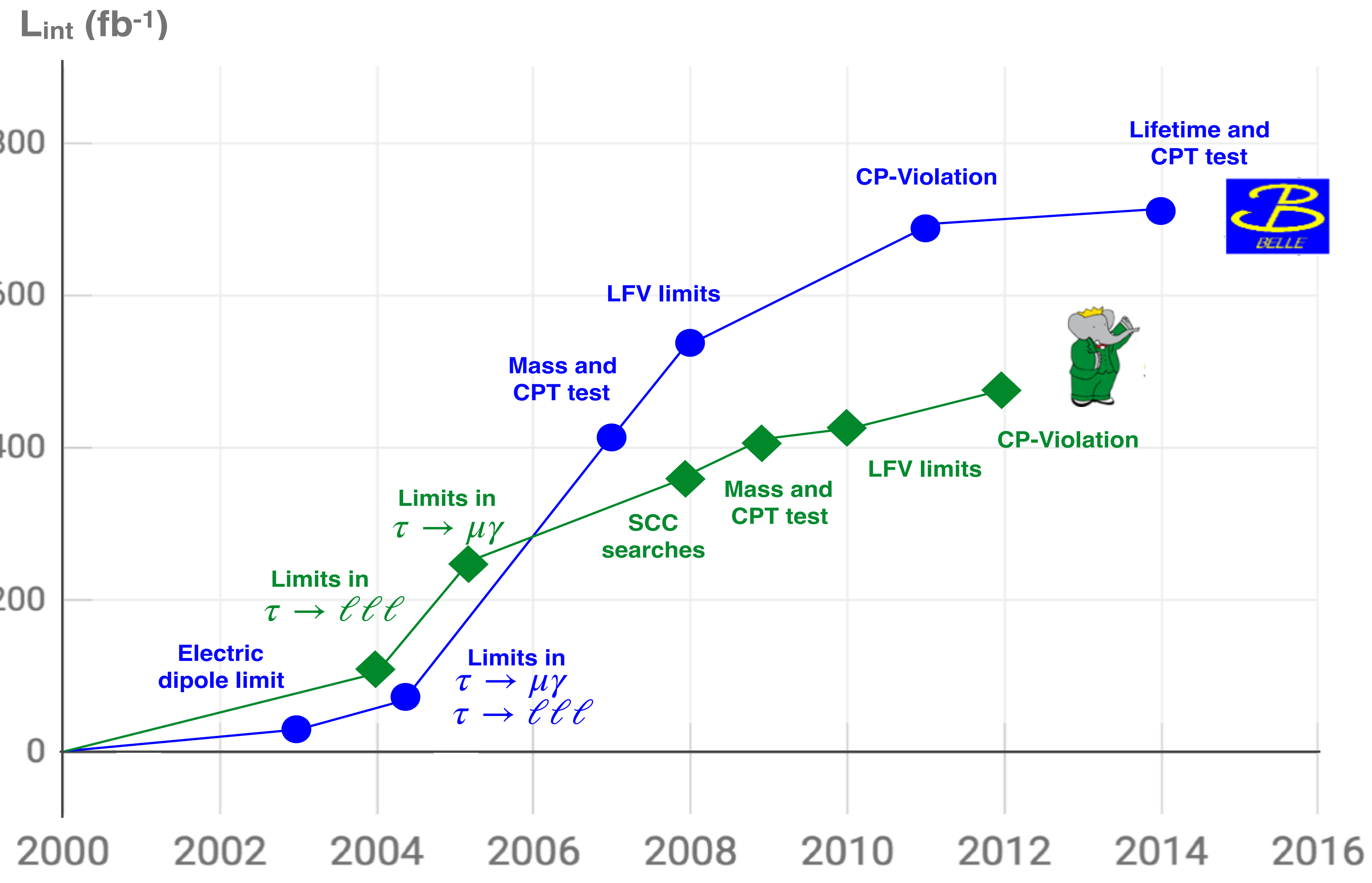

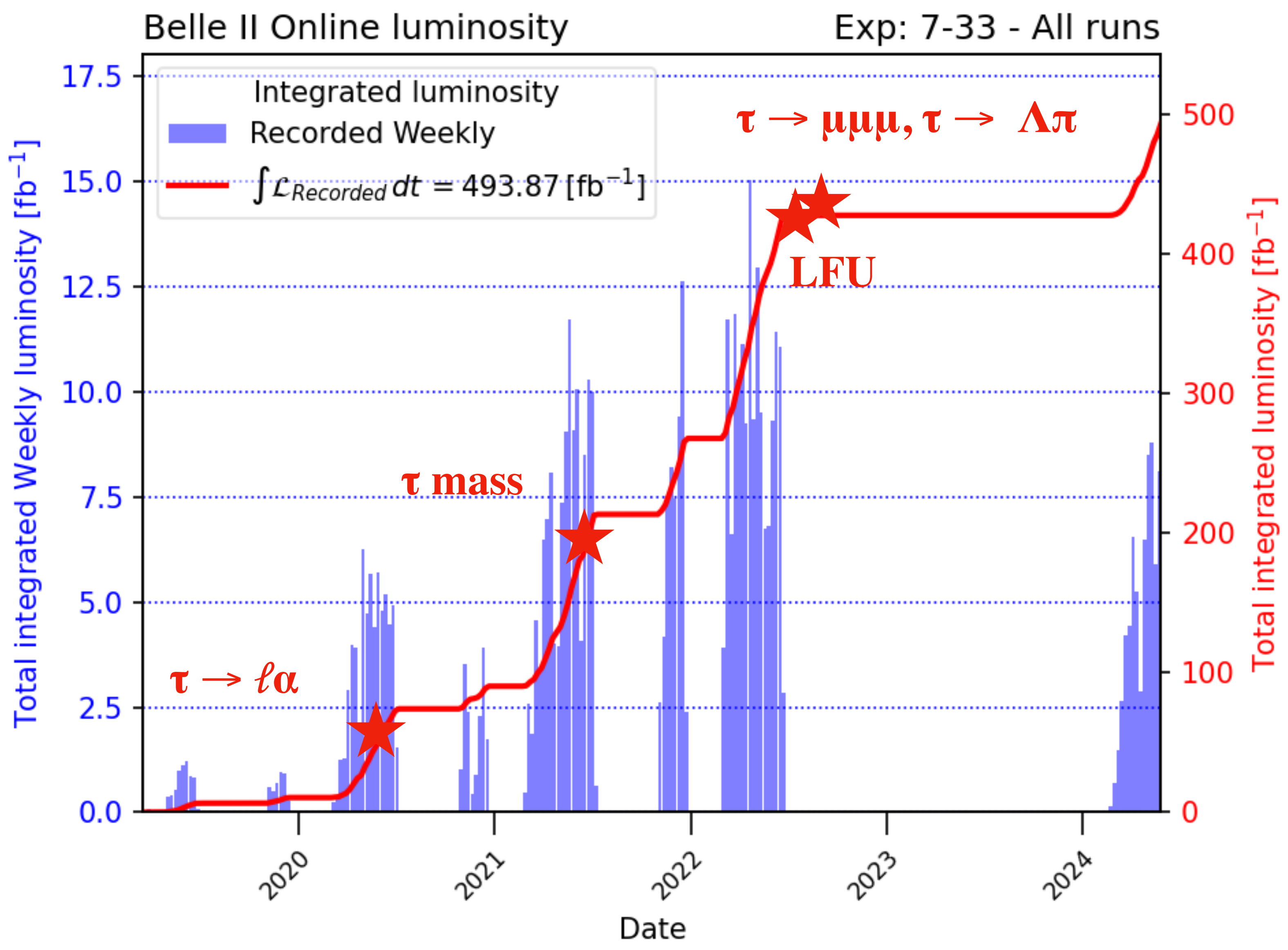

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Reach physics program from Belle II (see the parallel sessions)

Precision measurements - τ mass measurement @ Belle II

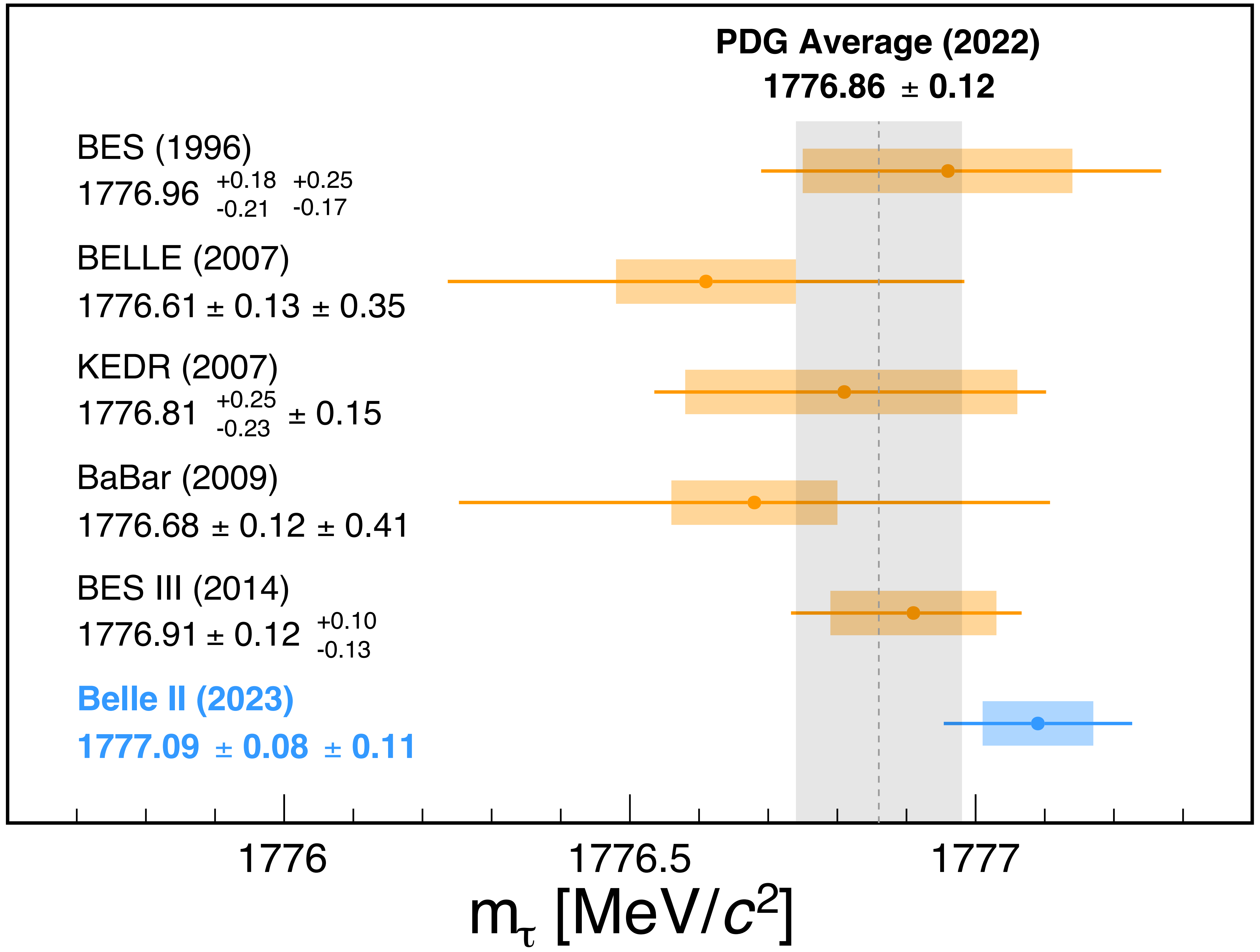
Fundamental parameter of the standard model

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

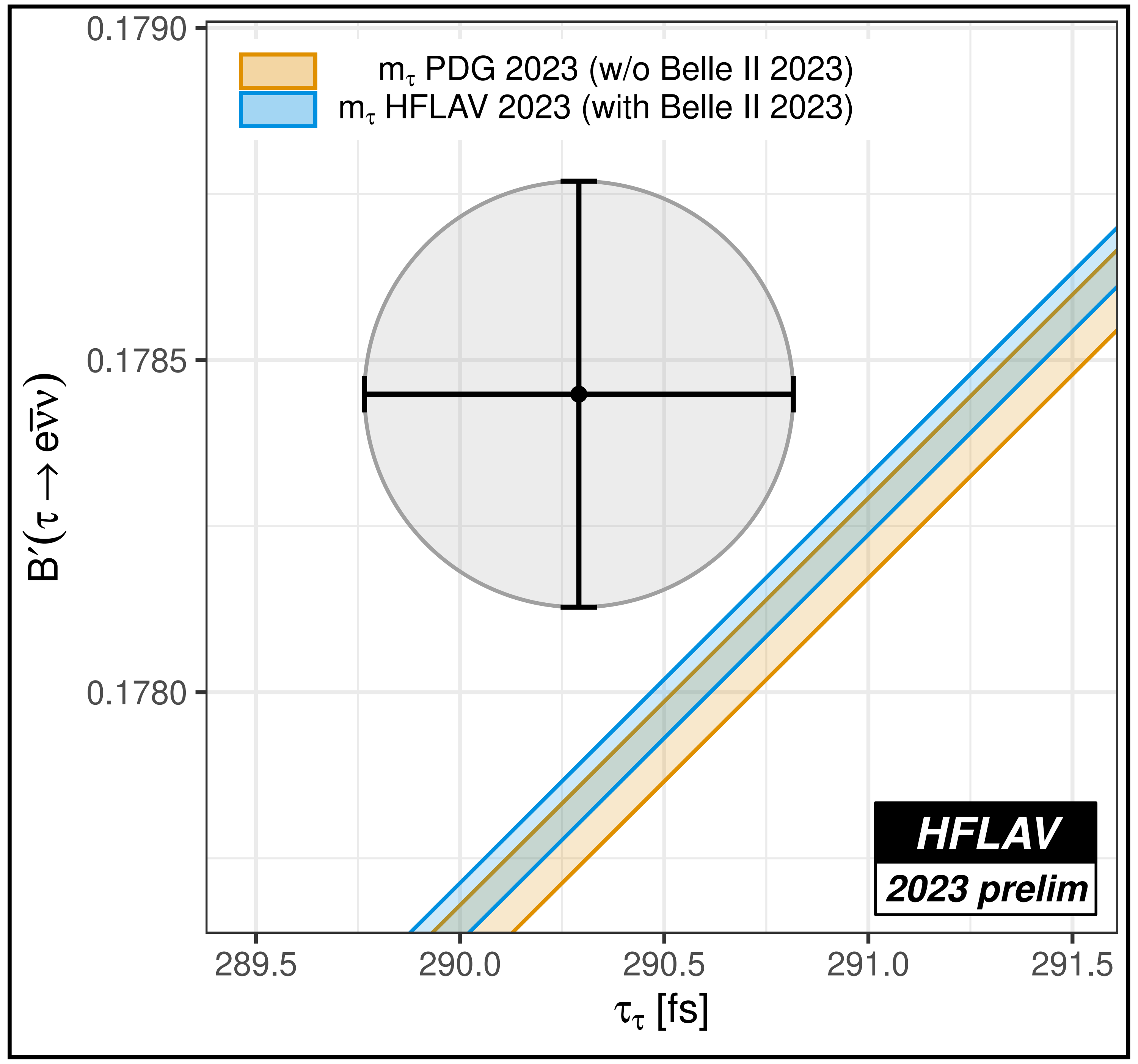
Important input to lepton-flavour-universality tests

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

Belle II - PRD 108 (2023) 032006



A. Lusiani for HFLAV TAU2023



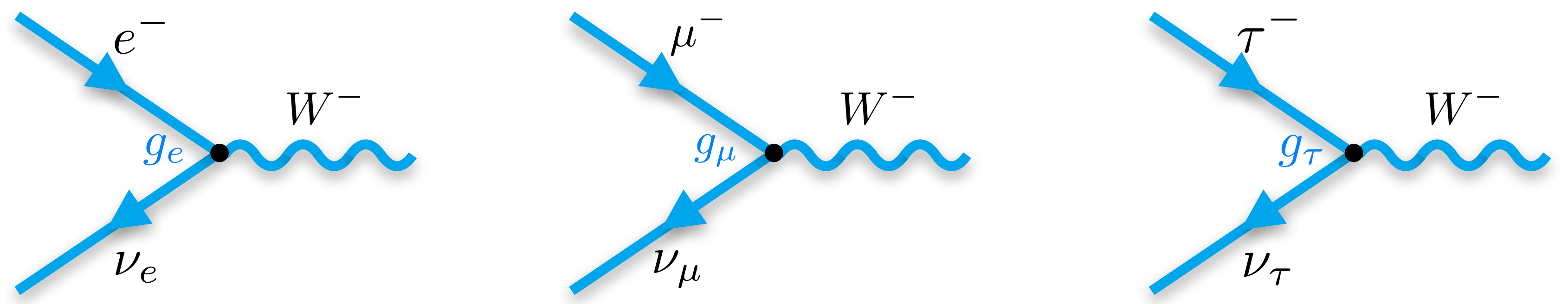
$B'(\tau \to e\nu\bar{\nu})$ represents the average of $\mathcal{B}(\tau \to e\nu\bar{\nu})$ and the value predicted from $\mathcal{B}(\tau \to \mu\nu\bar{\nu})$ assuming lepton universality

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

Test of lepton flavour universality in τ decays @ Belle II

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

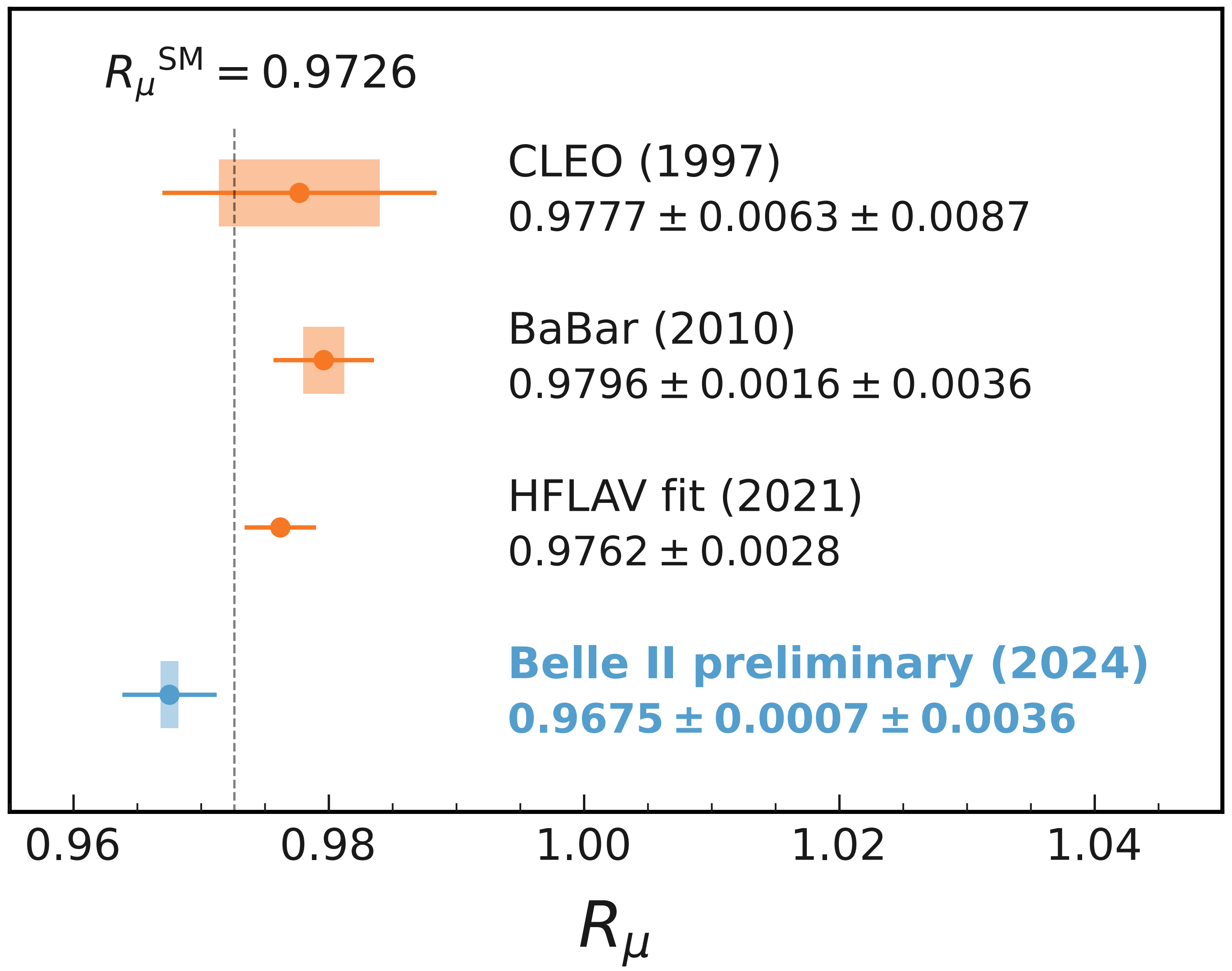
$g_e = g_\mu = g_\tau$

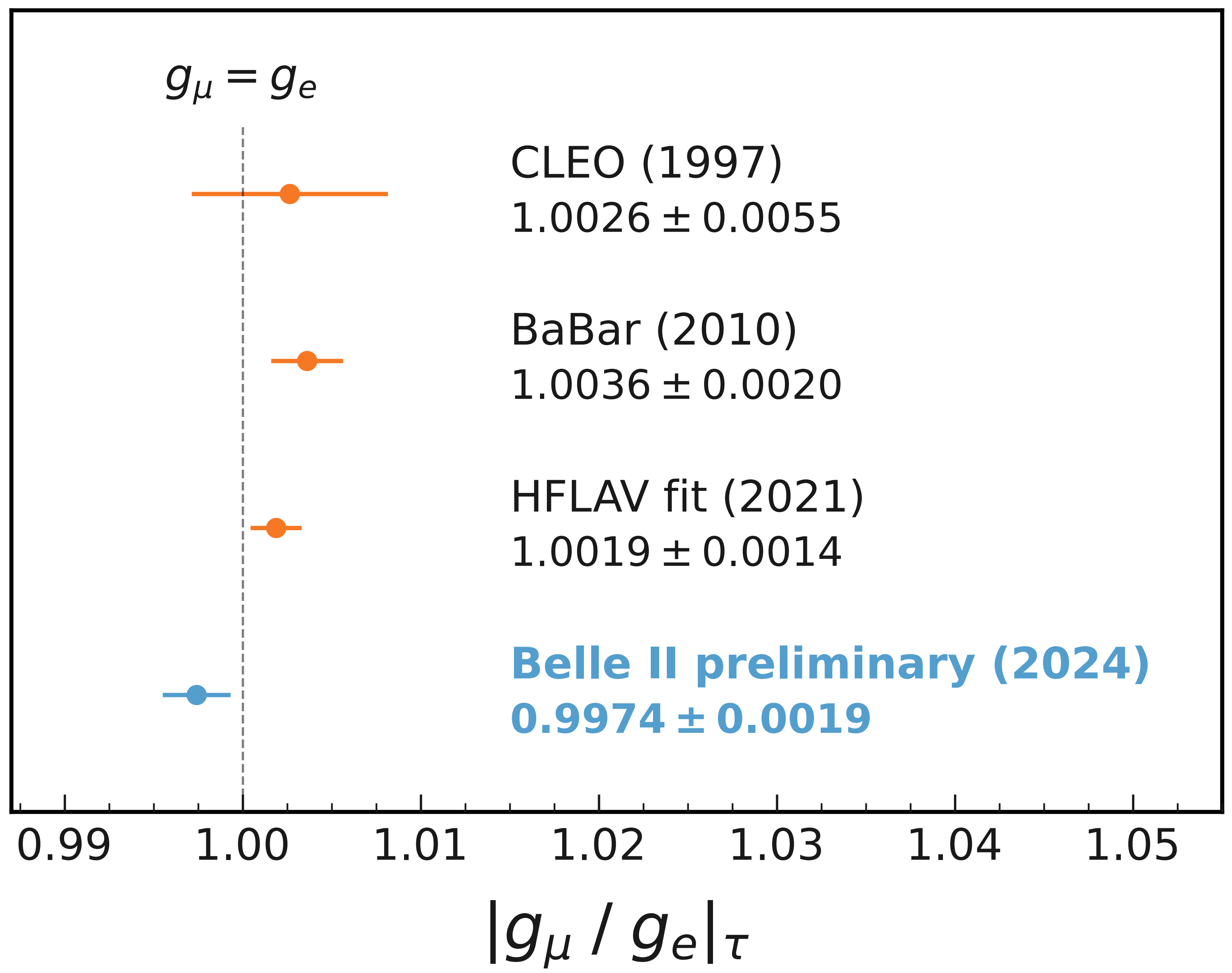


- Identical lepton interaction rates involving e, μ or τ
- Test of $\mu - e$ universality in the τ decays

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

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





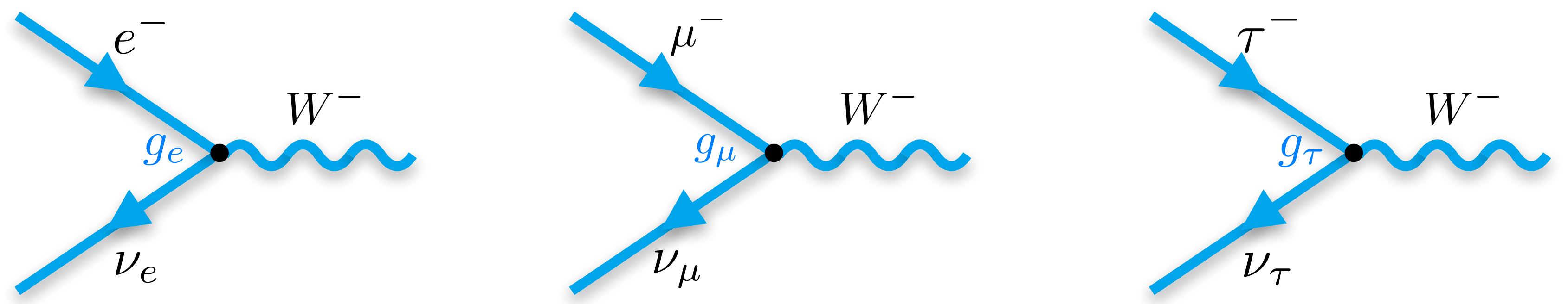
Belle II - arXiv:2405.14625

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

Test of lepton flavour universality in τ decays @ Belle II

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

$g_e = g_\mu = g_\tau$



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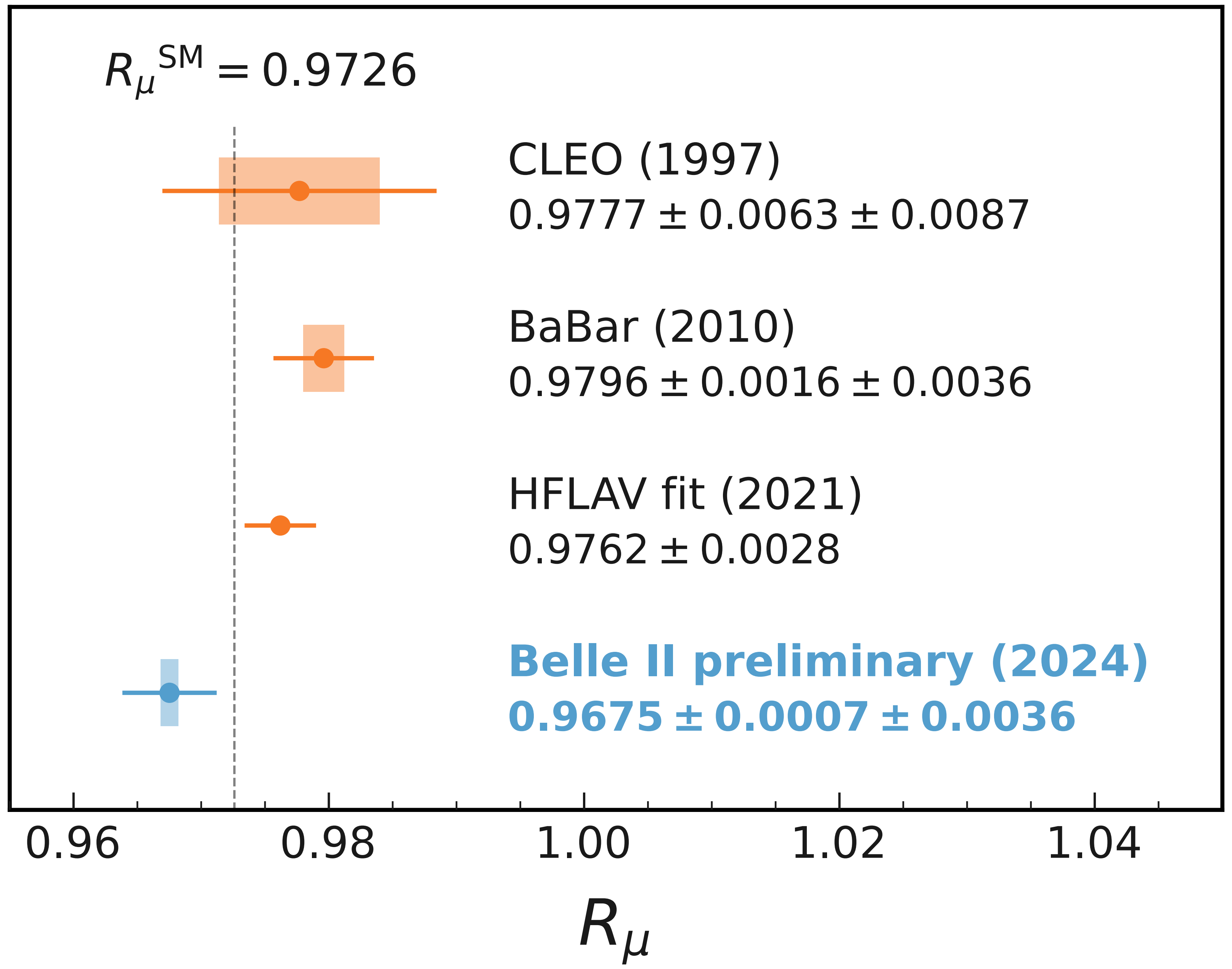
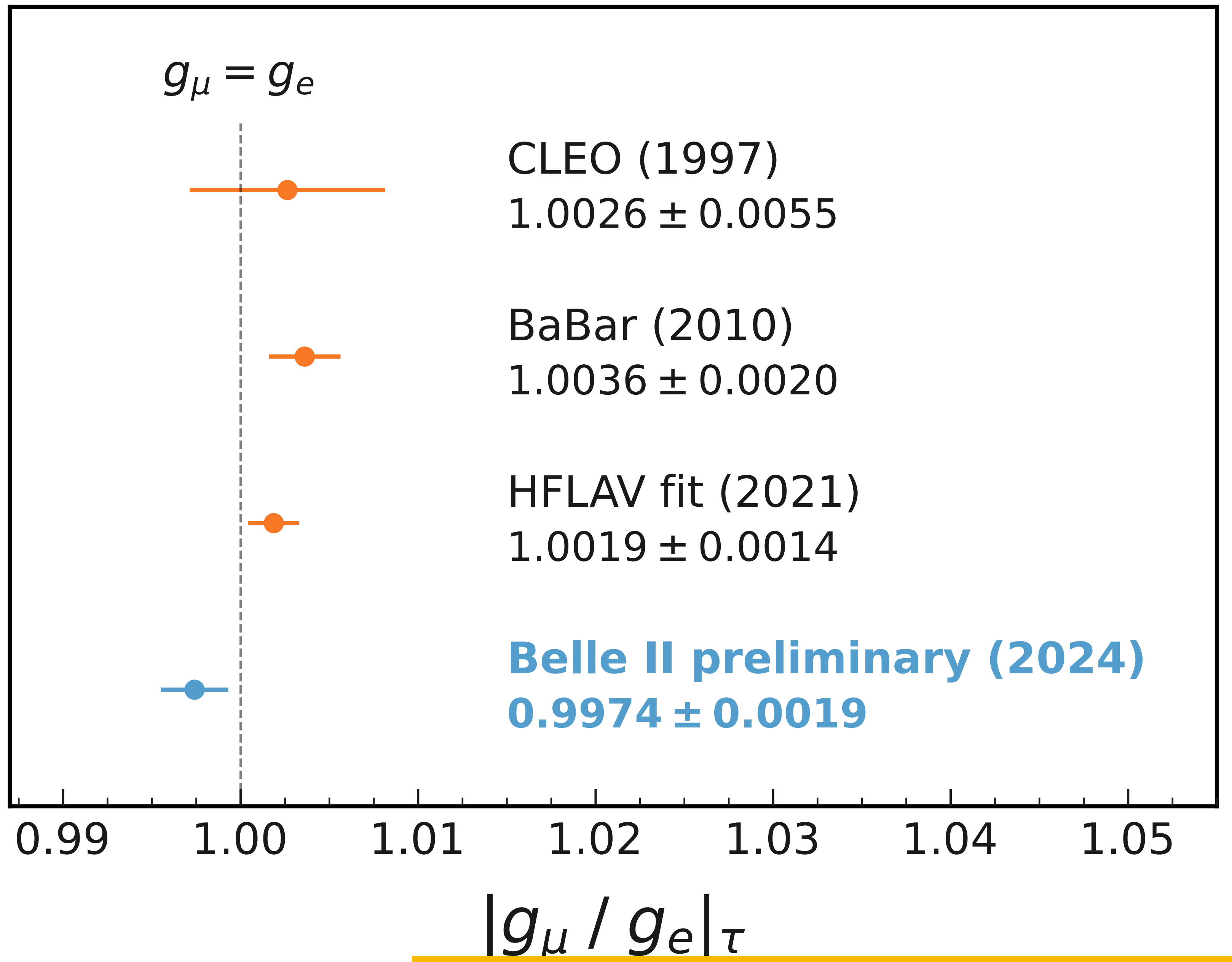




Belle II - arXiv:2405.14625

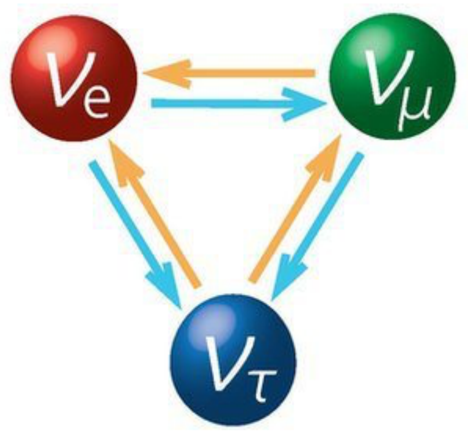
- **Most precise test of $\mu - e$ universality in τ decays from a sin**
- Consistent with SM expectation at the level of 1.4σ

Precision τ measurements from Belle II
see the talk of Marcela Garcia Hernandez
(Today at 14:45, Parallel-2)

Lepton flavour conservation

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

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



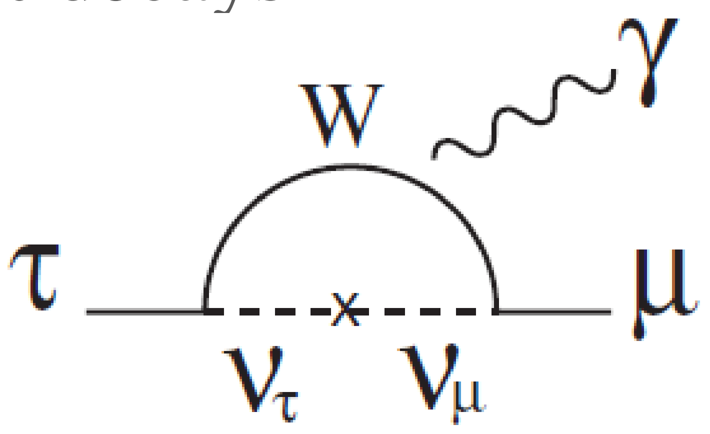
➡ The observation of neutrino oscillations as a first sign of LFV beyond the SM!

What about the charged leptons?

➡ The charged LFV processes can occur through oscillations in loops

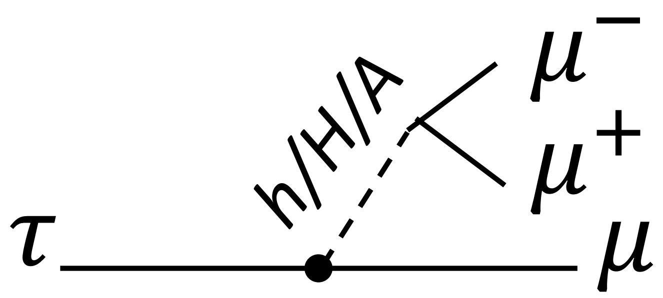
➡ Immeasurable small rates (10^{-54}-10^{-49}) for all the LFV μ and τ decays

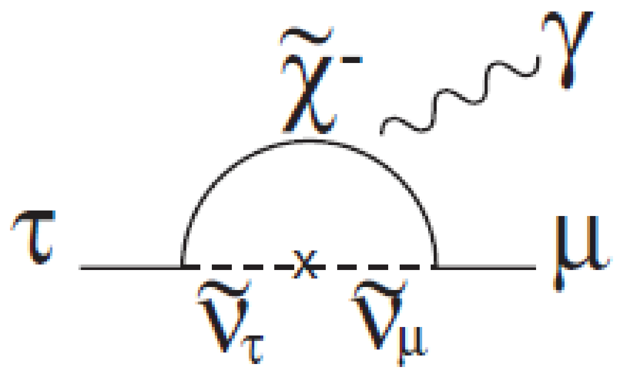
$$\mathcal{B}(\ell_1 \to \ell_2 \gamma) = \frac{3\alpha}{32\pi} \left| \sum_{i=2,3} U^*_{\ell_1 i} U_{\ell_2 i} \frac{\Delta m^2_{i1}}{M_W^2} \right|^2$$



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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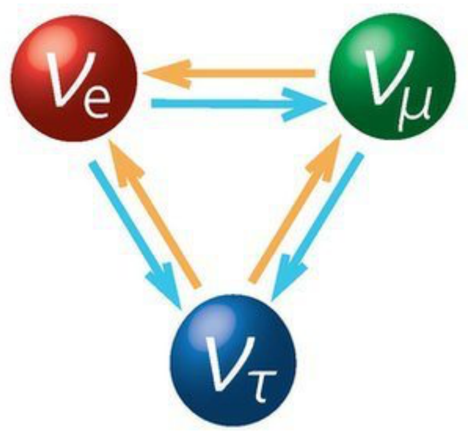

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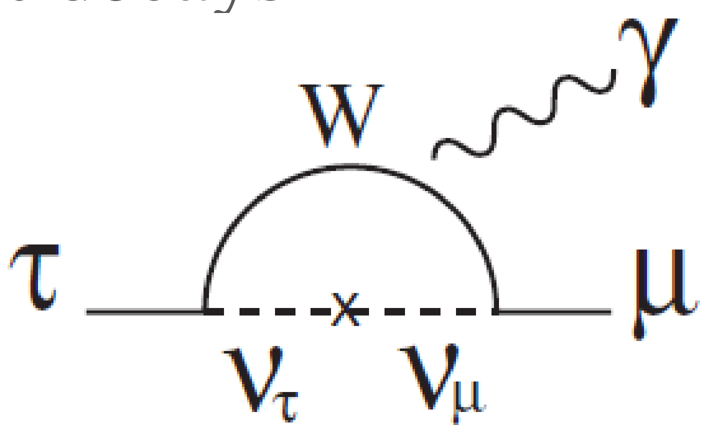

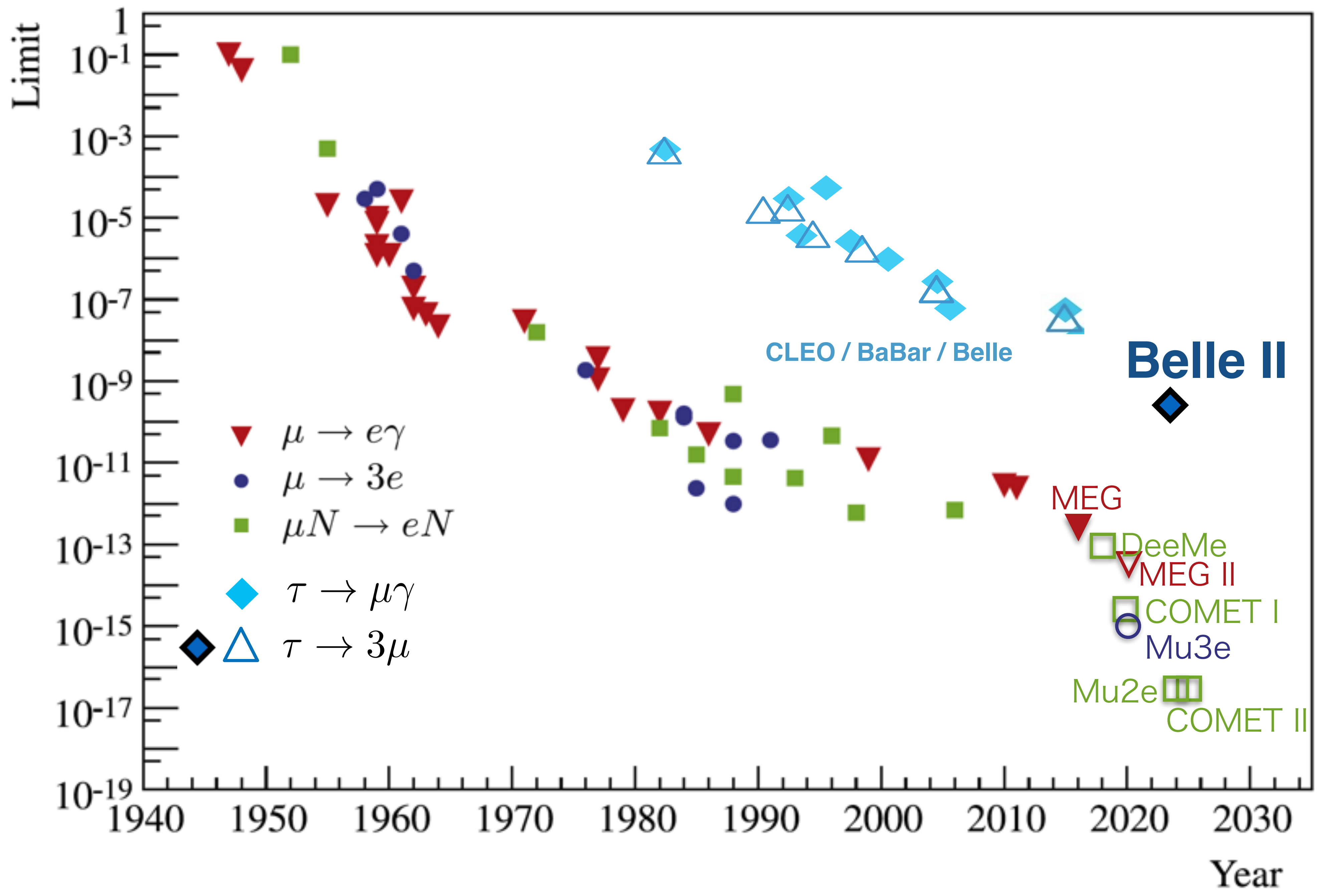

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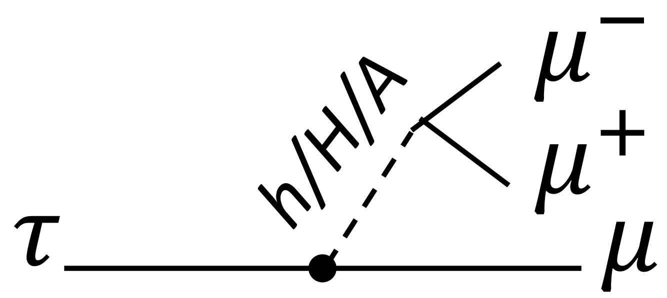
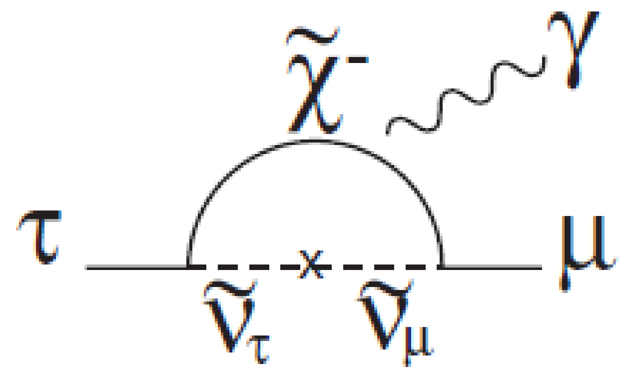
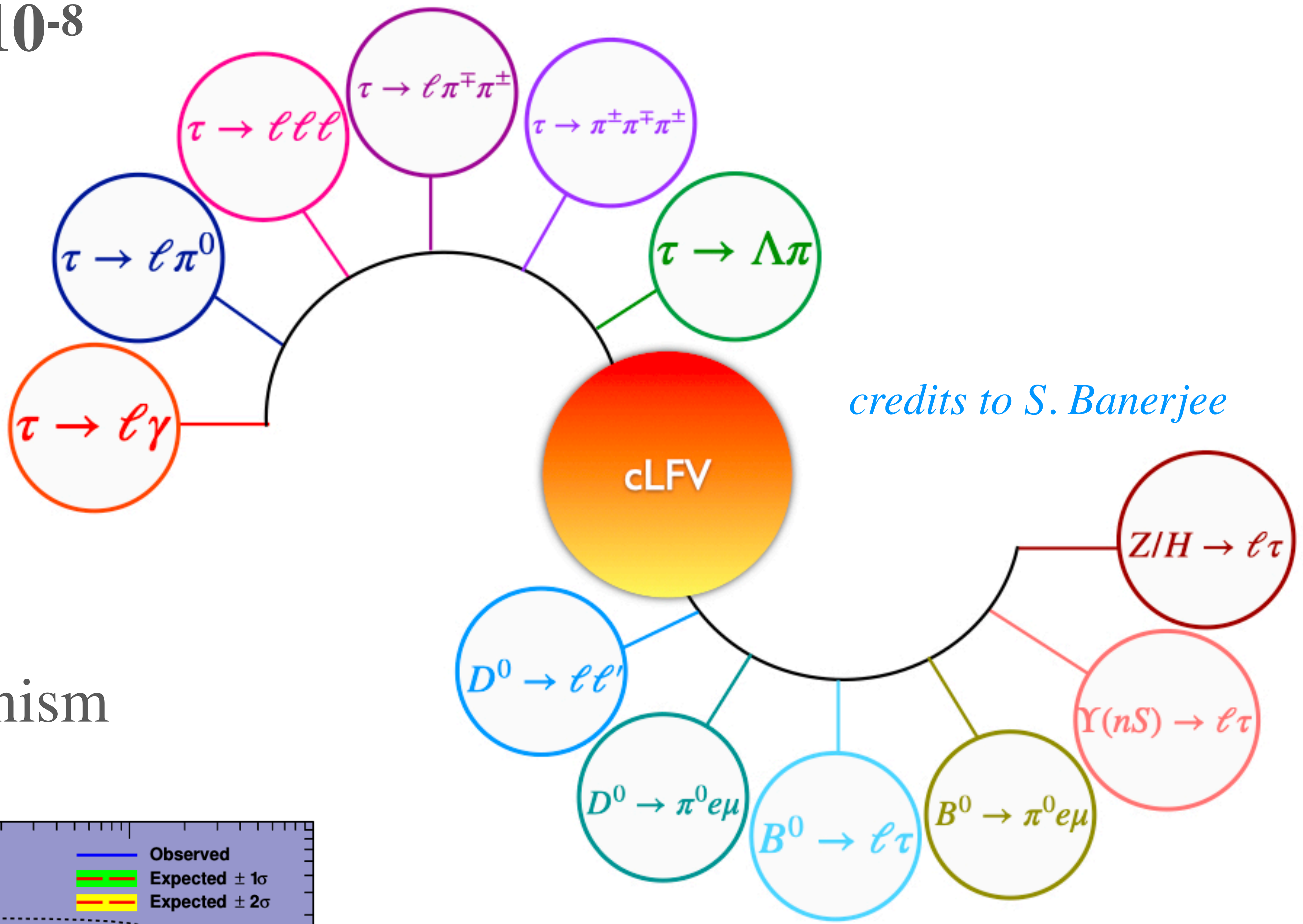




Complementarity of τ LFV searches

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

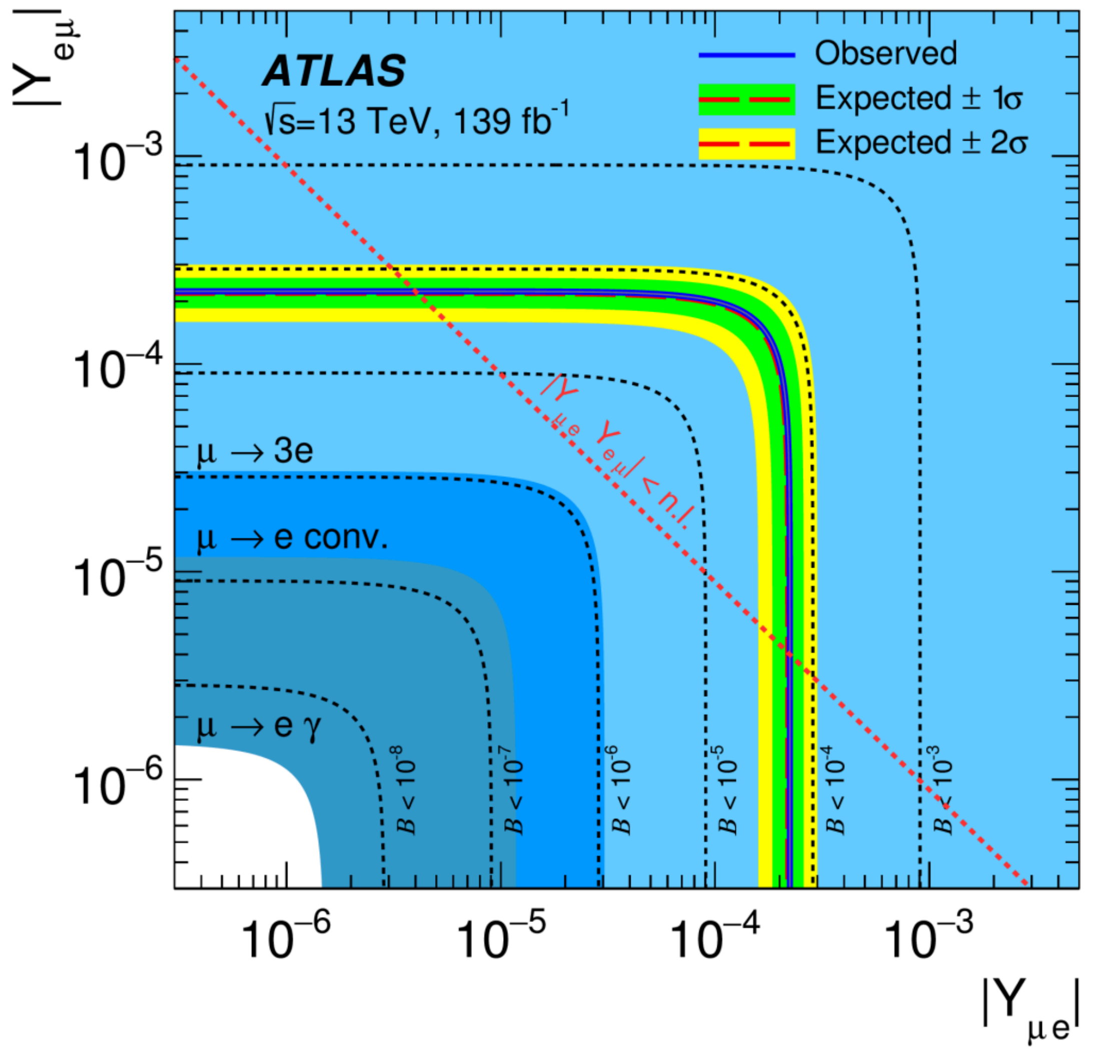
- Leptonic MFV: *Nucl.Phys. B 728 (2005) 121*
- GUT models: *Nucl.Phys. B 445 (1995) 219*

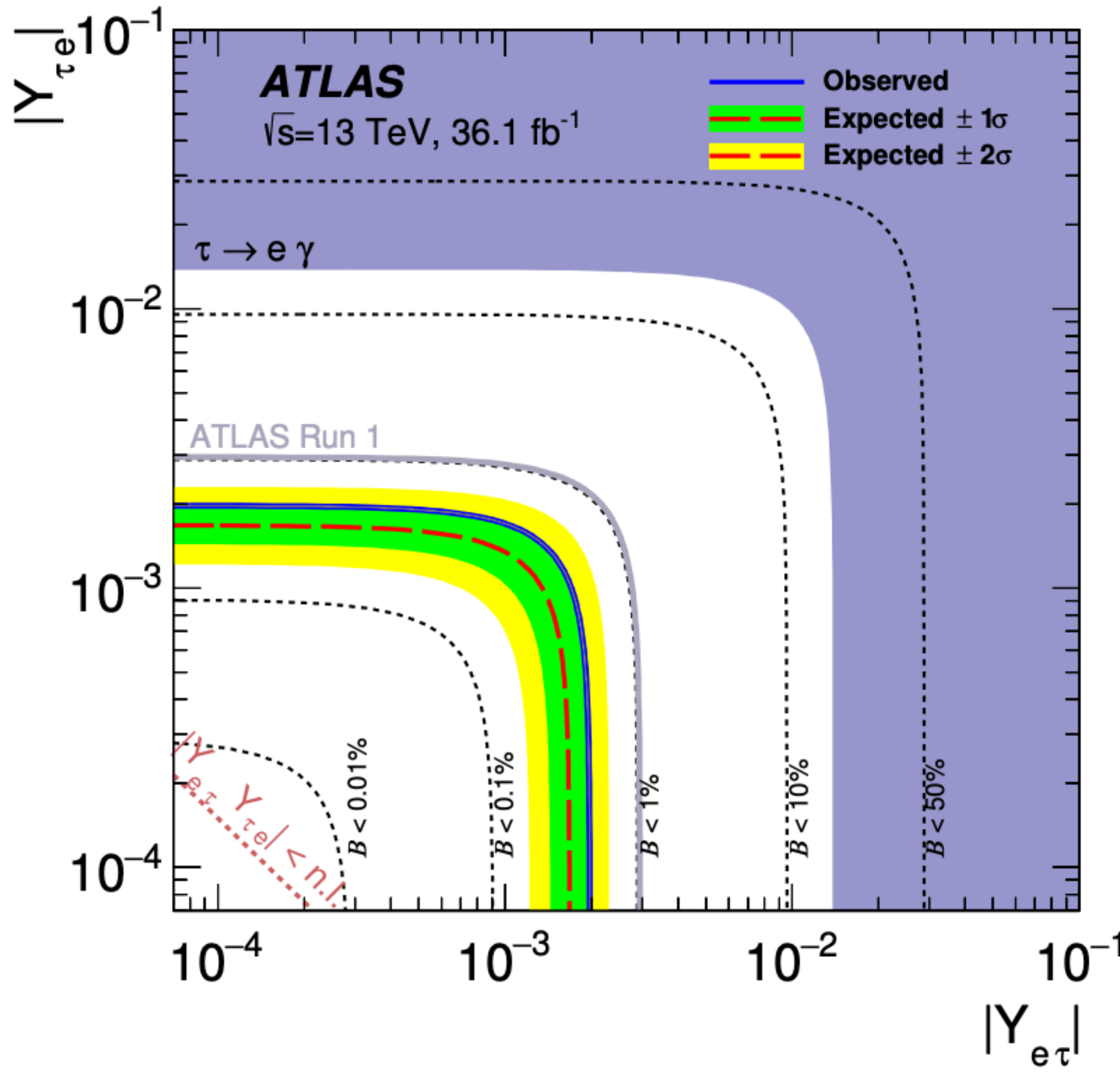


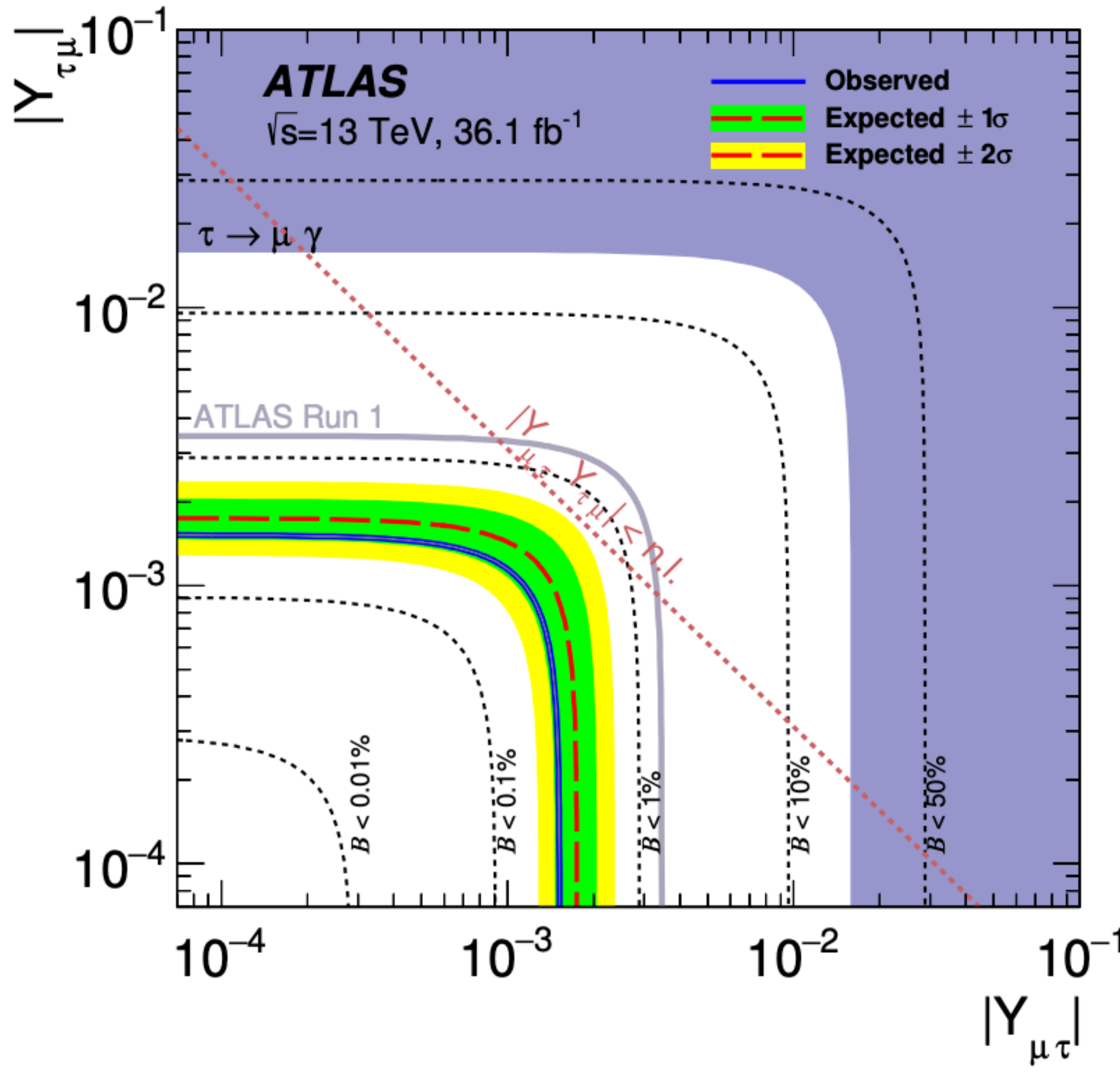
credits to S. Banerjee

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



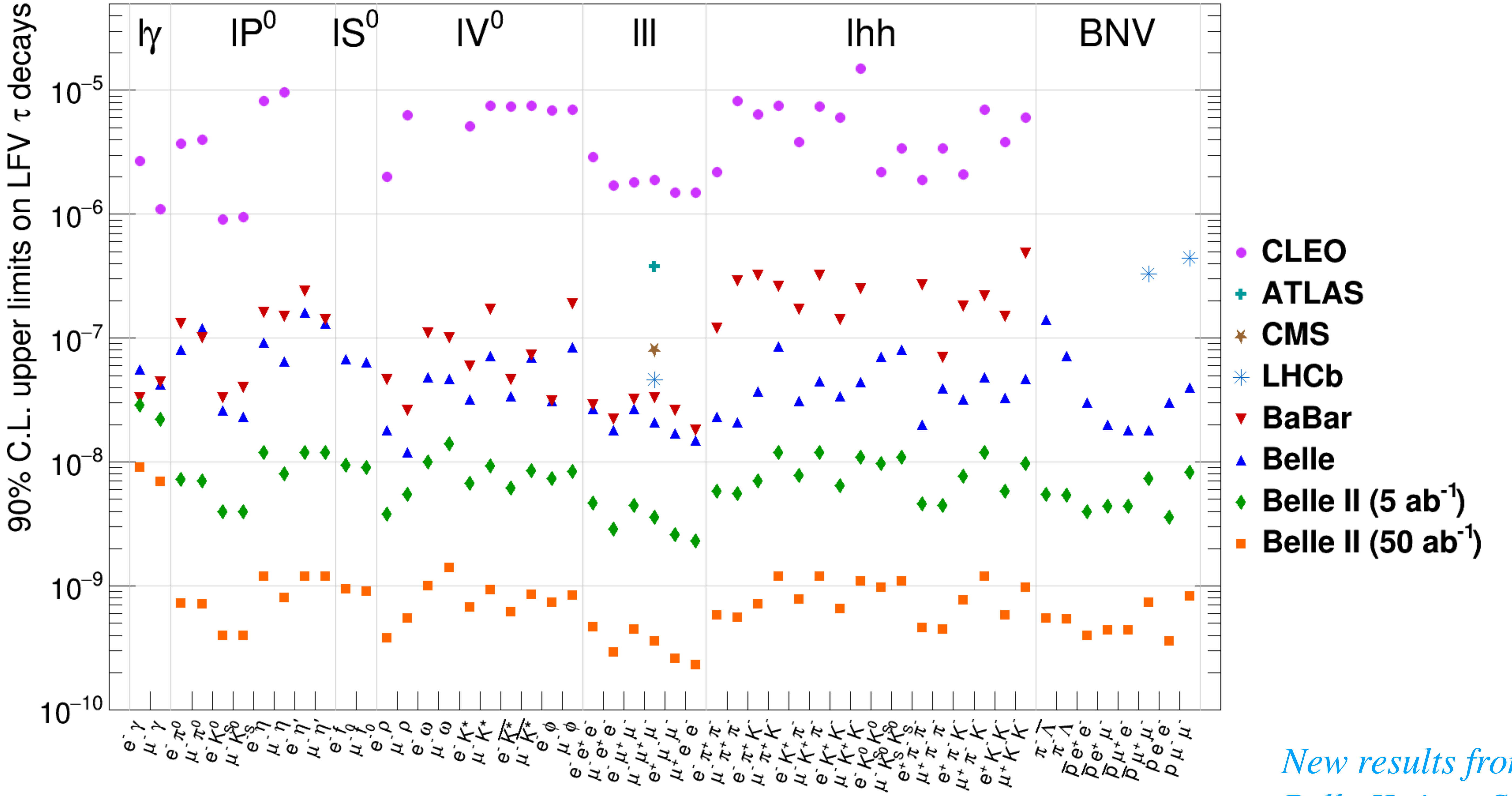




Phys.Lett.B 800 (2020) 135069
Phys.Lett.B 801 (2020) 135148

Status and perspectives of LFV searches

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



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

Test the SM in 52 benchmark τ decays

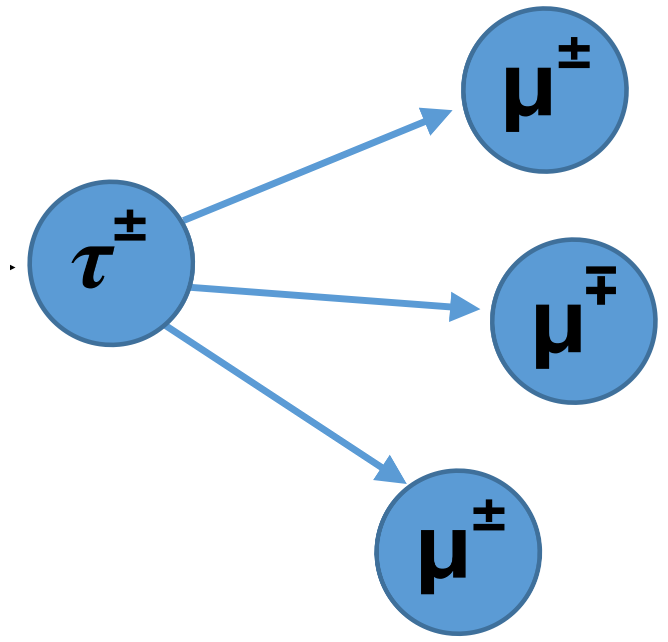
- ➡ radiative ($\tau \to \ell\gamma$)
- ➡ leptonic decays ($\tau \to \ell\ell\ell$)
- ➡ a large variety of LFV and LNV semi-leptonic decays
- ➡ BNV decays
- ➡ τ → μ and τ → e: test of the lepton flavour structure

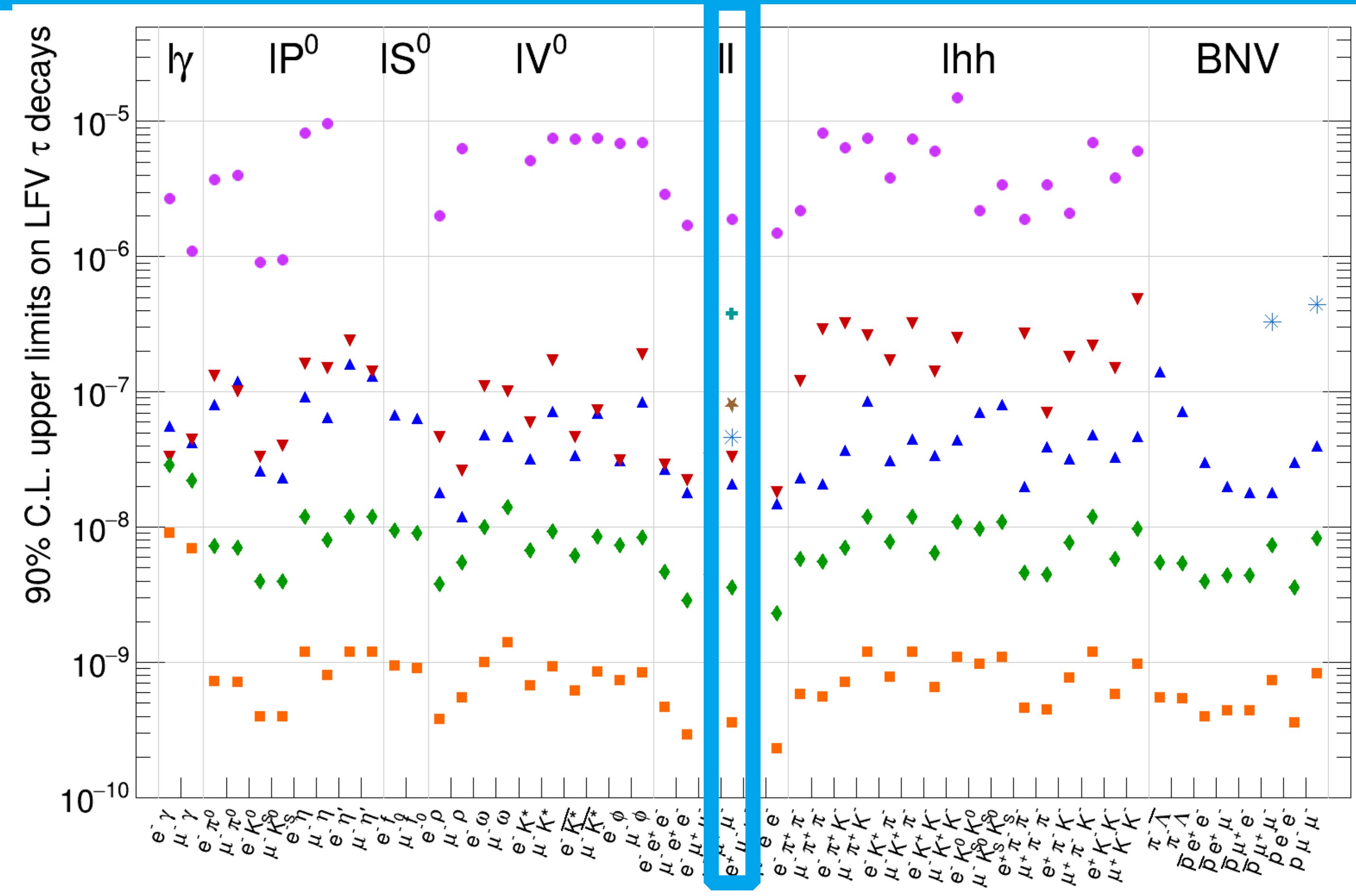
- ➡ One of the factors pushing up the sensitivity of probes is the increase of the luminosity
- ➡ Equally important is the increase of the signal detection efficiency and background suppression
  - ➡ high trigger efficiencies; improvements in the vertex reconstruction, charged track and neutral-meson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

Search for $\tau \rightarrow \mu\mu\mu$ decay @ Belle II

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

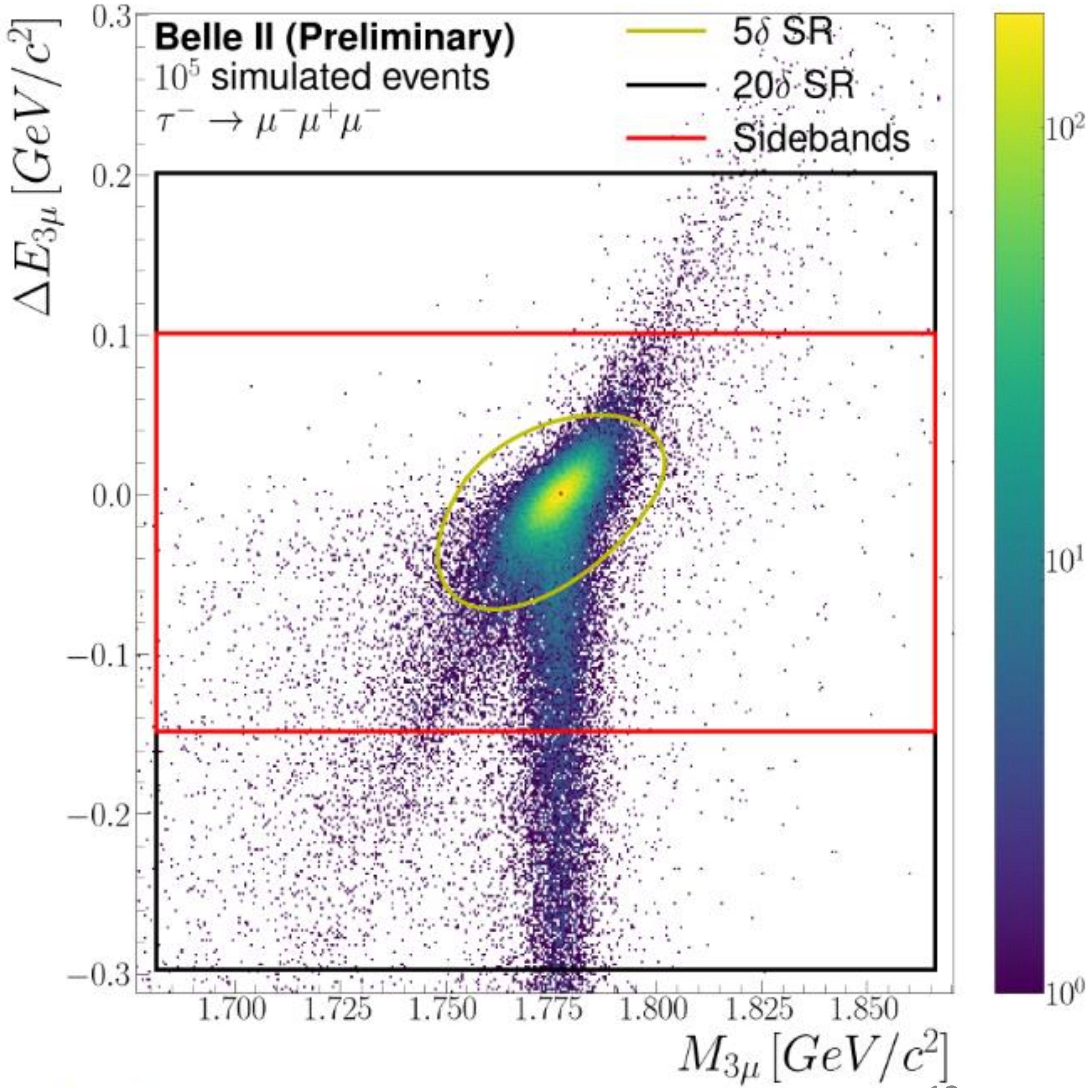
- μ identification is the most powerful discriminating variable
- Momentum dependent optimisation of the muID requirement





Signal region definition

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



Two independent variables:

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

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

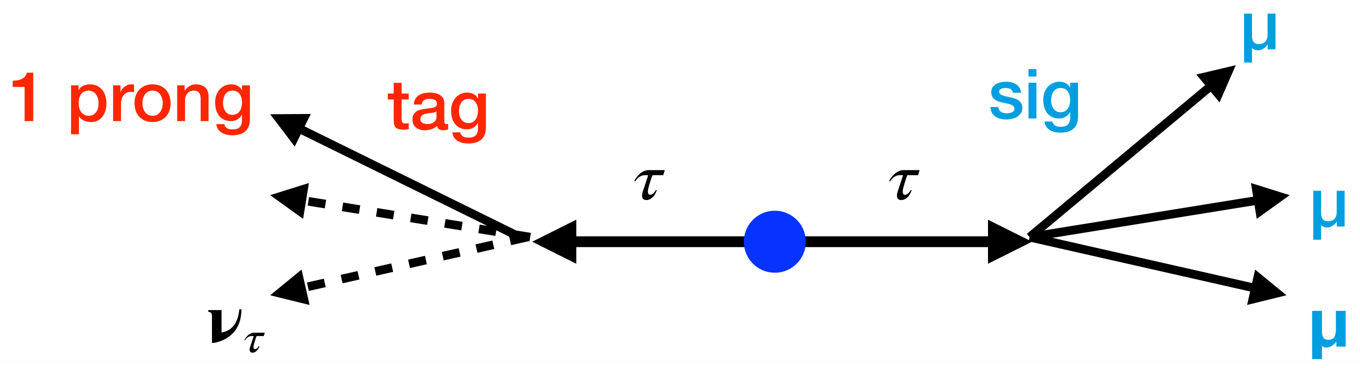
For signal:

- ΔE close to 0 and $M_{3\mu}$ close to τ mass
- Tails due to initial and final state radiation

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

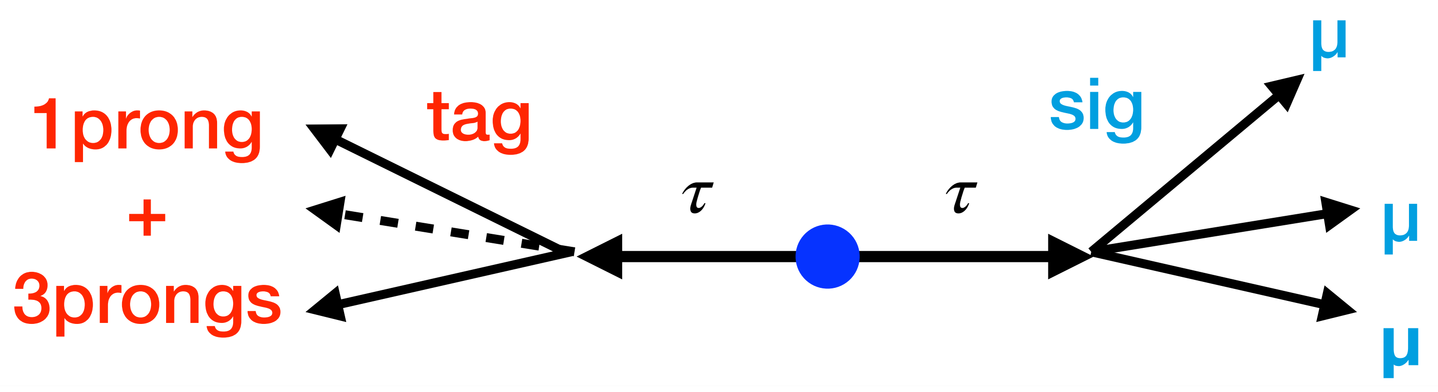


Signal efficiency: 14.9% (2 x Belle efficiency)

- 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.
ATLAS	3.8×10^{-7} ($\mathscr{L} = 20.3$ fb^{-1})
LHCb	4.6×10^{-8} ($\mathscr{L} = 3.0$ fb^{-1})
CMS	2.9×10^{-8} ($\mathscr{L} = 131$ fb^{-1})

CMS - PLB 853 (2024) 138633

Experiment	Upper Limit at 90% C.L.
Belle	2.1×10^{-8} ($\mathscr{L} = 782$ fb^{-1})
BaBar	3.3×10^{-8} ($\mathscr{L} = 486$ fb^{-1})
Belle II	1.9×10^{-8} ($\mathscr{L} = 424$ fb^{-1})

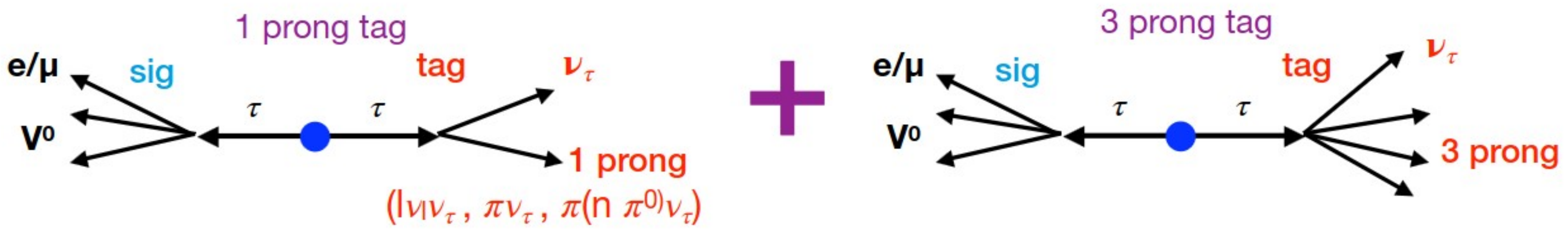
Belle II - arXiv:2405.07386

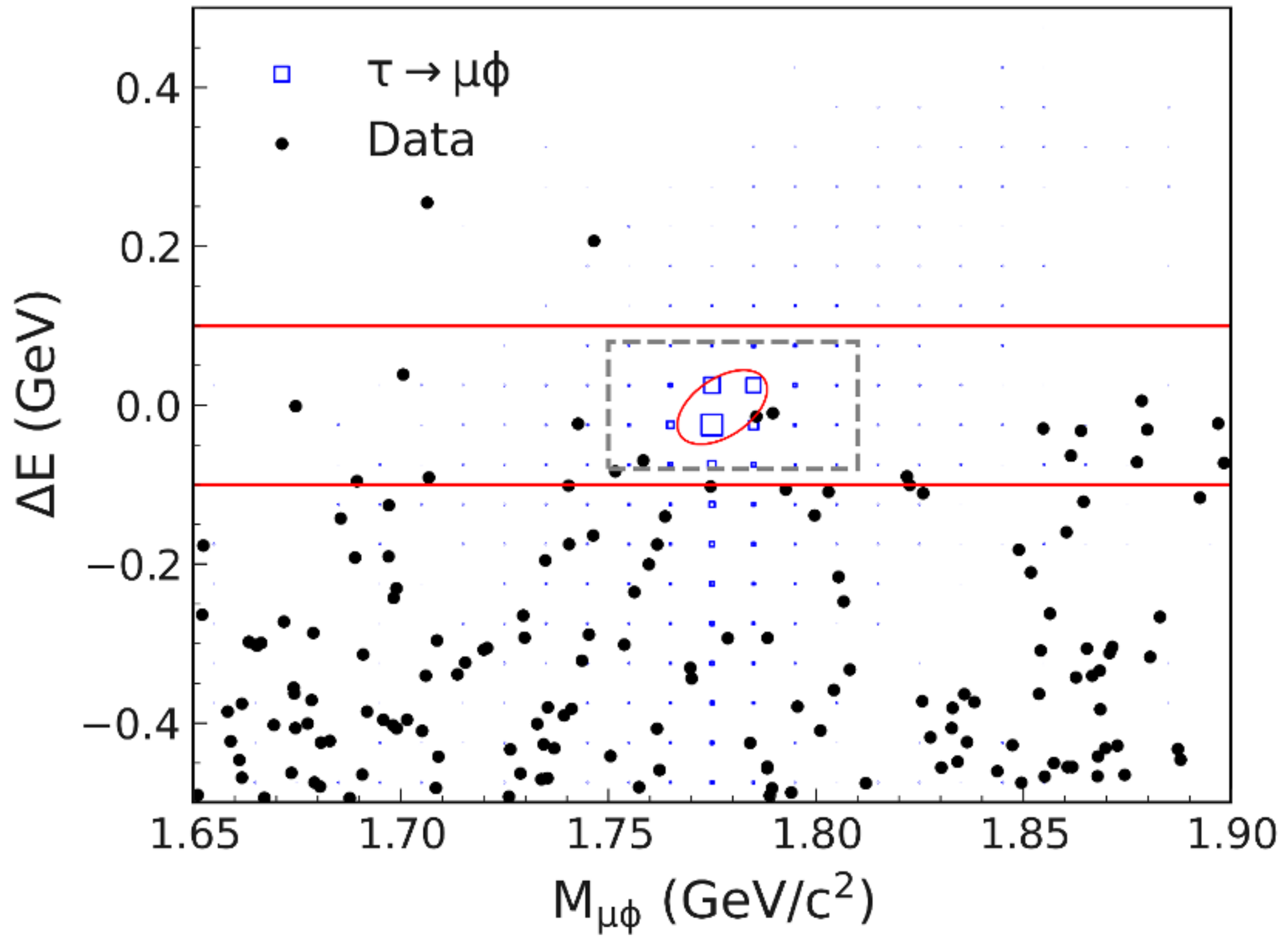
Most stringent limit to date

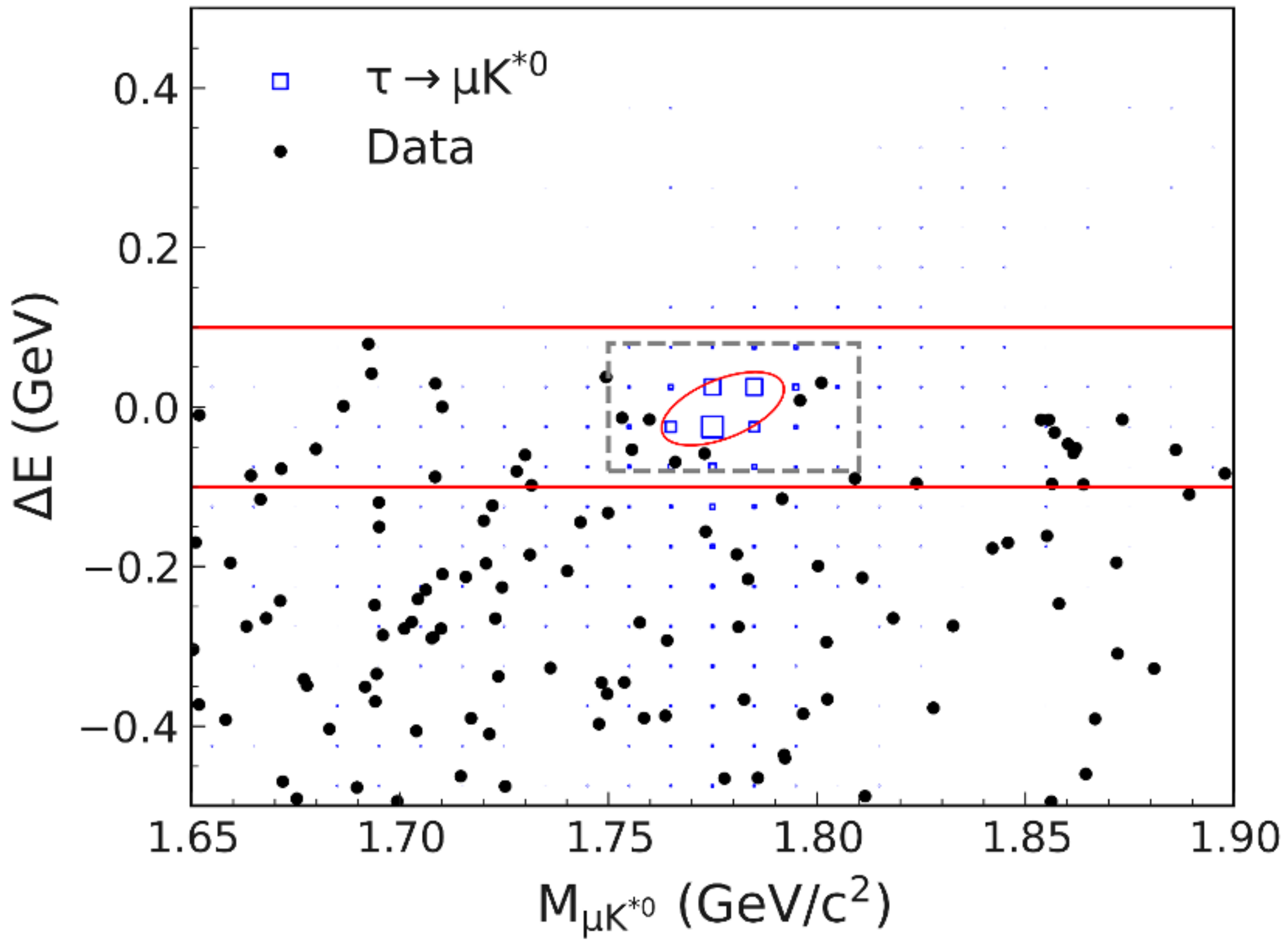
Search for $\tau \to \ell V^0 (V^0 = \rho, \omega, \phi, K^*)$ decays @ Belle

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

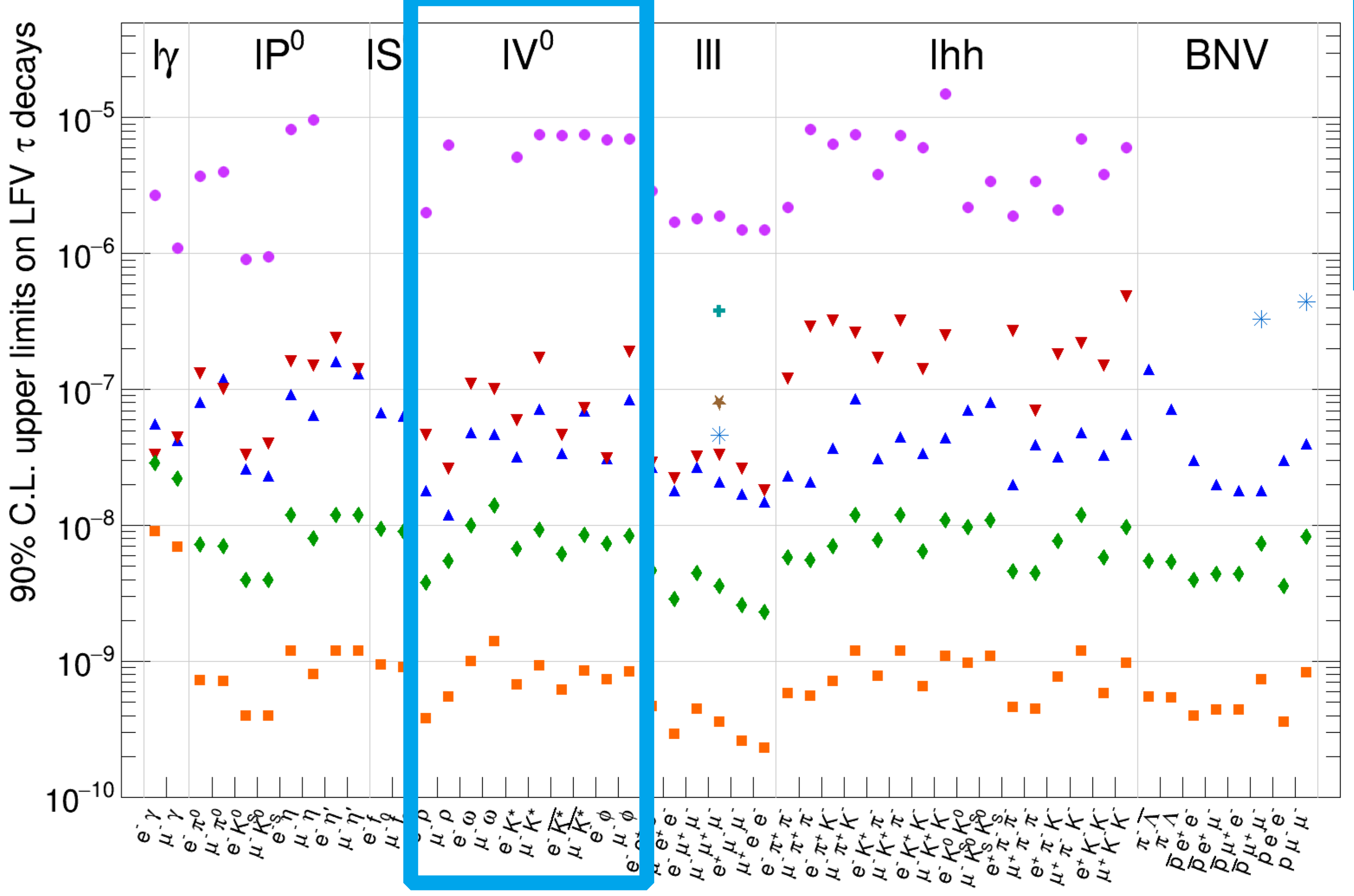






- Exploit topology and event/tag kinematics to the backgrounds that mimic
  - the presence of neutrinos in the tag side,
  - wrong PID in the signal side
- Further suppress $\tau \to 3\pi\nu$ and ee → qq with BDT
- Estimate expected background in SR from **sideband interpolation**

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



No significant access in all ℓV^0 modes

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

Belle - JHEP 06 (2023) 118

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

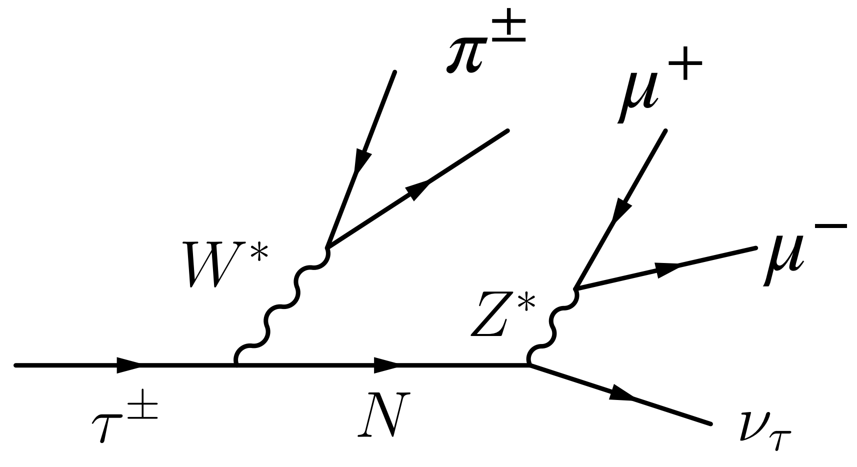
World leading results

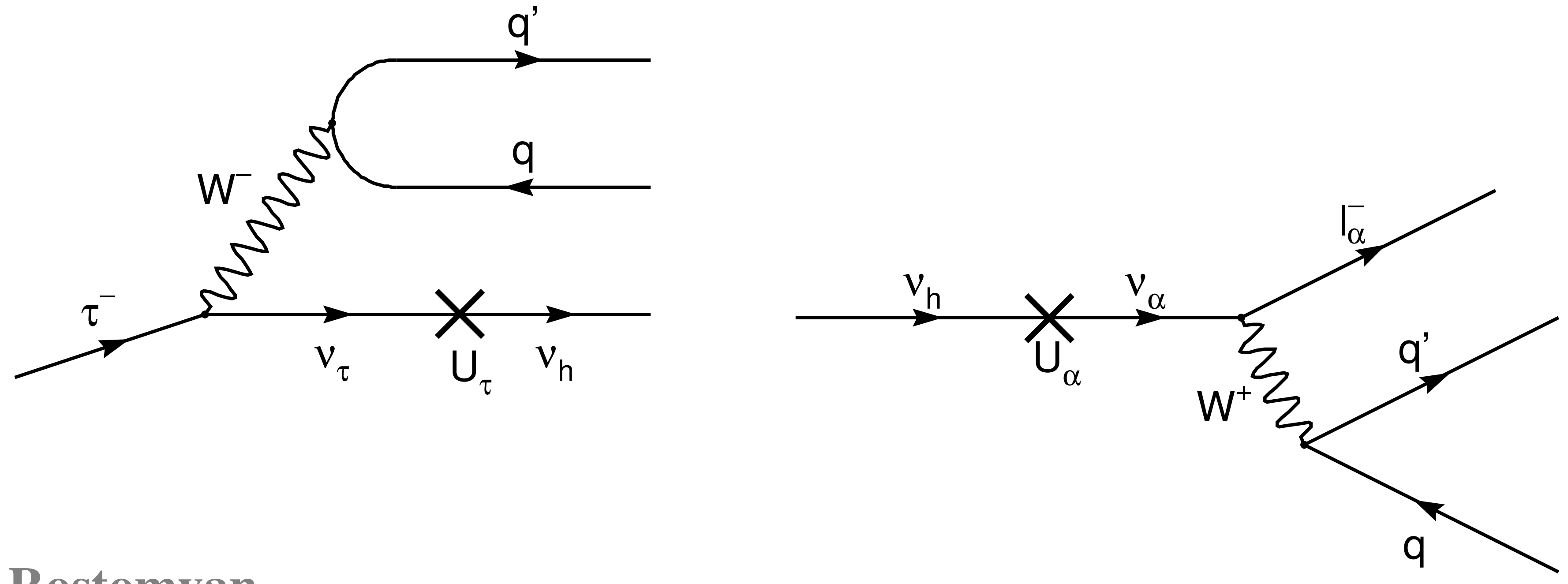
Search for heavy neutral leptons (HNL)

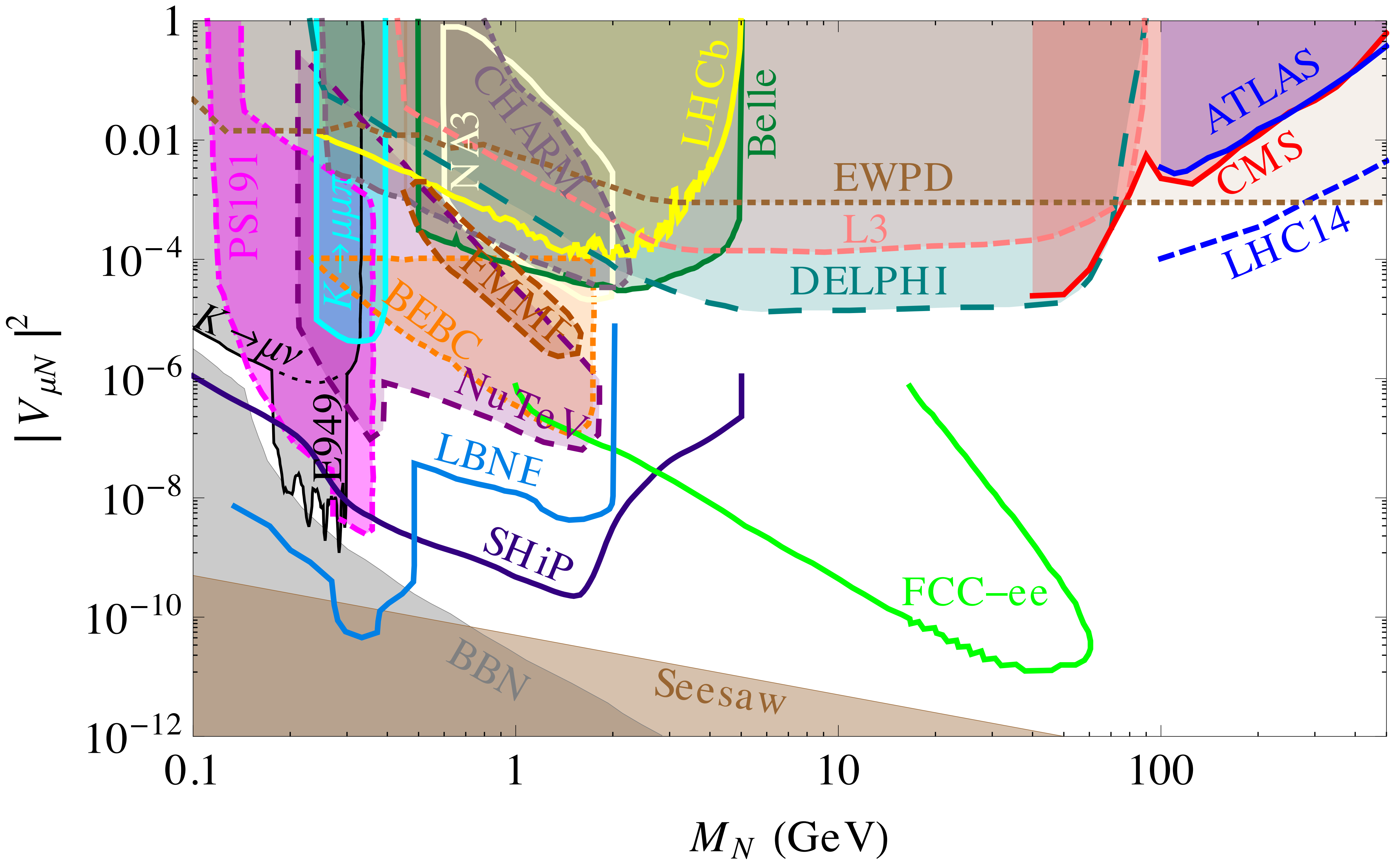
N (or ν_h) interacts with ν_{SM} through mixing: N ↔ ν_{SM}

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

- 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 $M_N < M_\tau$**







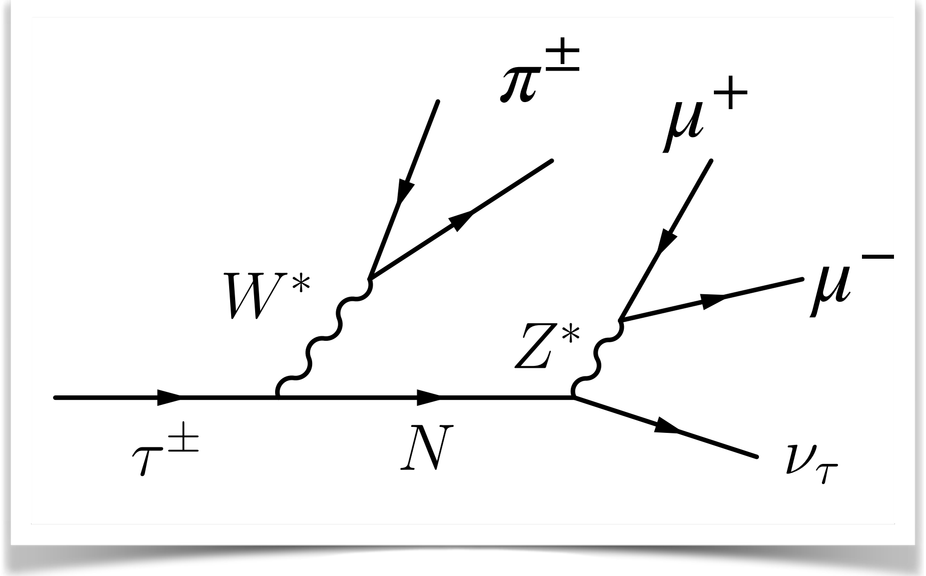
- Explored regions by different experiments
  - $M_N > M_Z$: $pp > N\ell^\pm$ @LHC
  - $M_N < M_{Z,W}$: $Z^0 \to \nu N$ @ DELPHI and $W^\pm \to \ell^\pm N$ @ LHC
  - $M_N > M_{K,D,B}$: @NA62, beam-dump, Belle
- All above experiments provide tight limits on $|V_{eN}|, |V_{\mu N}|$
- Fewer experiments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

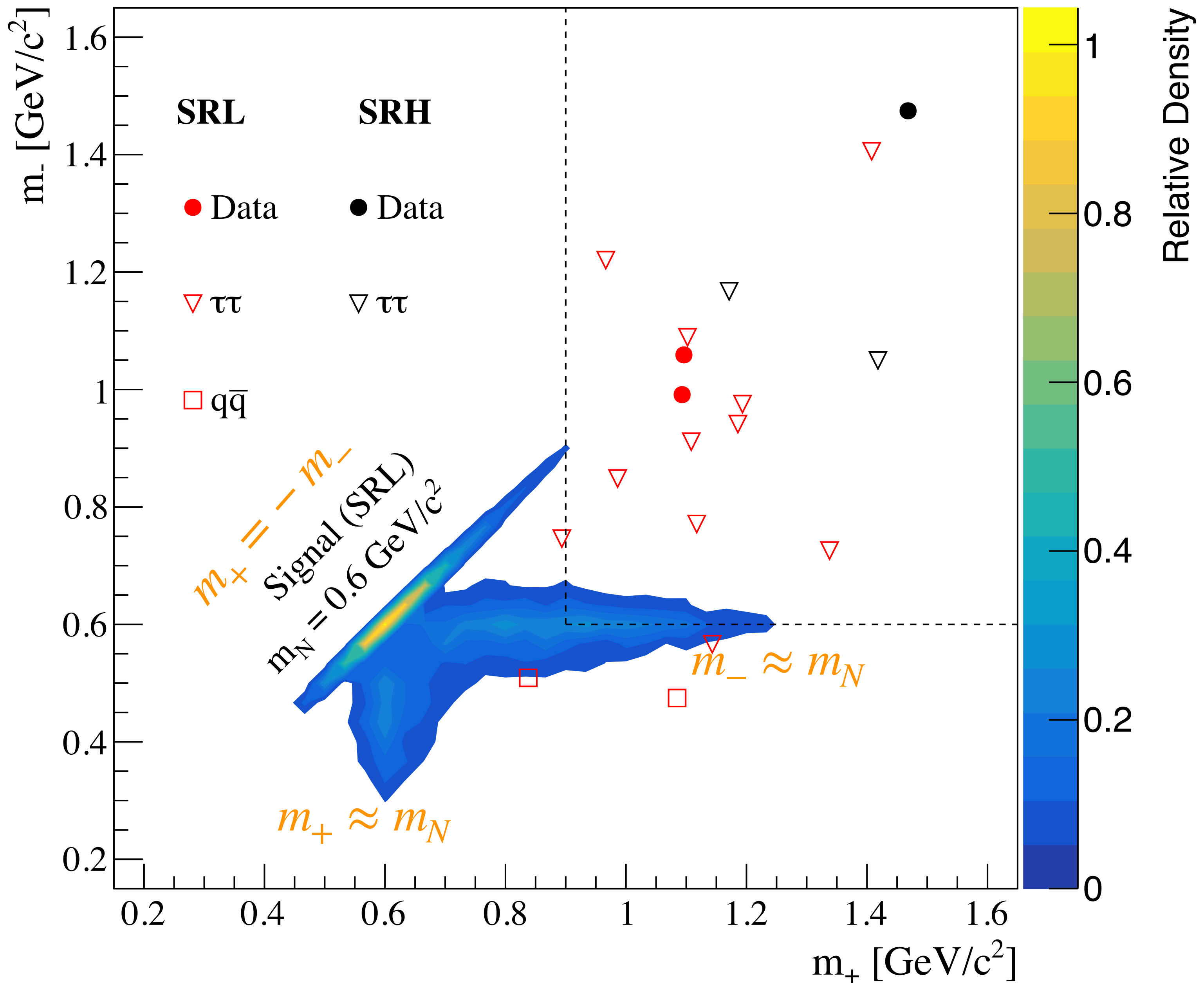
Search for $\tau^- \to \pi^- N$ ($N \to \mu^+\mu^-\nu_\tau$) decay @ Belle

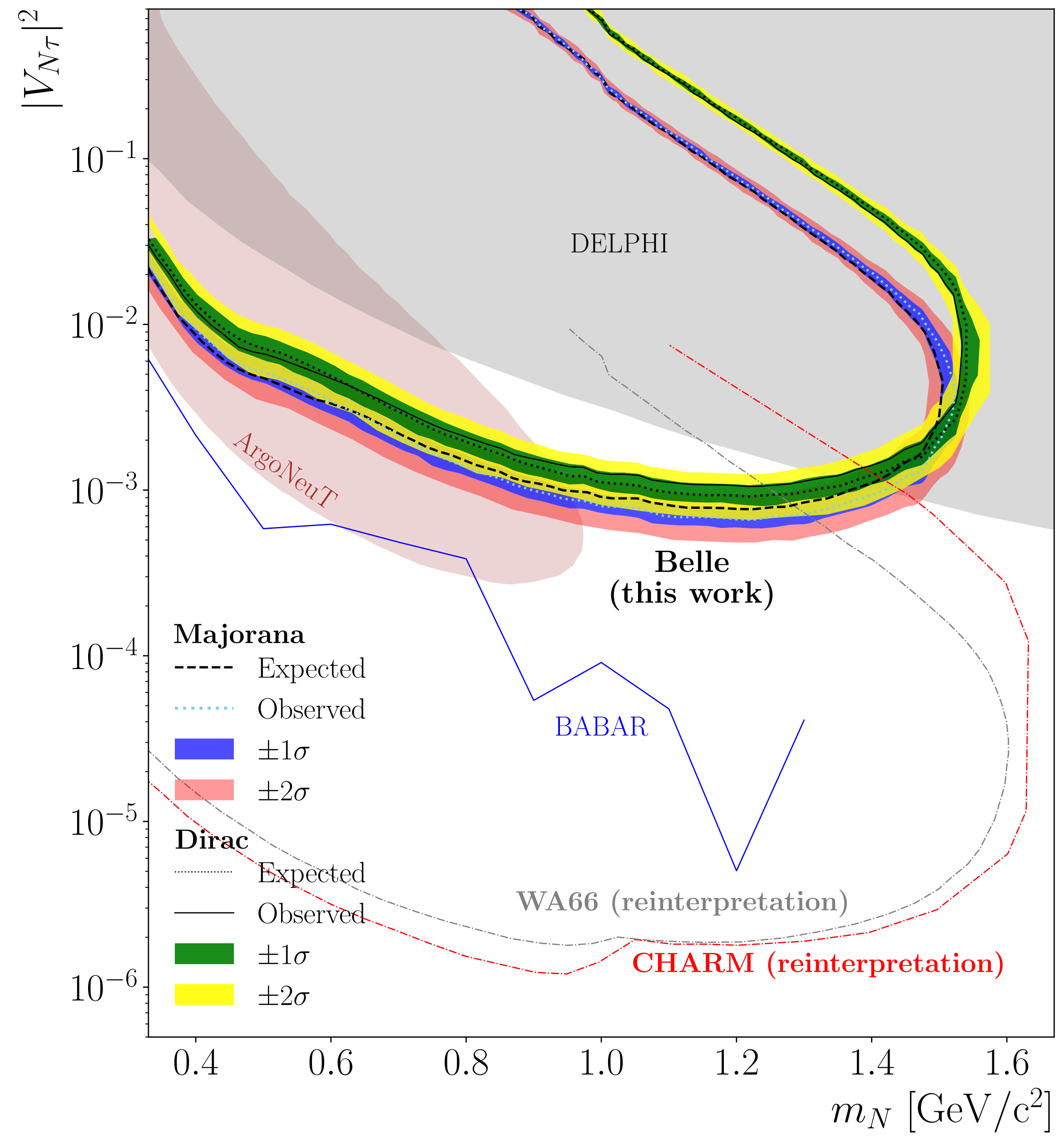
Search for a heavy neutrino $300 < M_N < 1600$ MeV **that mixes predominantly with** ν_τ

accepted by PRD

- 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)
- Reject $K_S \to \pi^+\pi^-$ ($420 < m < 520$ MeV) → pions decay to or are misidentified as muons
- Two signal regions targeting light ($M_N < 420$ MeV) and heavy ($M_N > 520$ MeV) 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

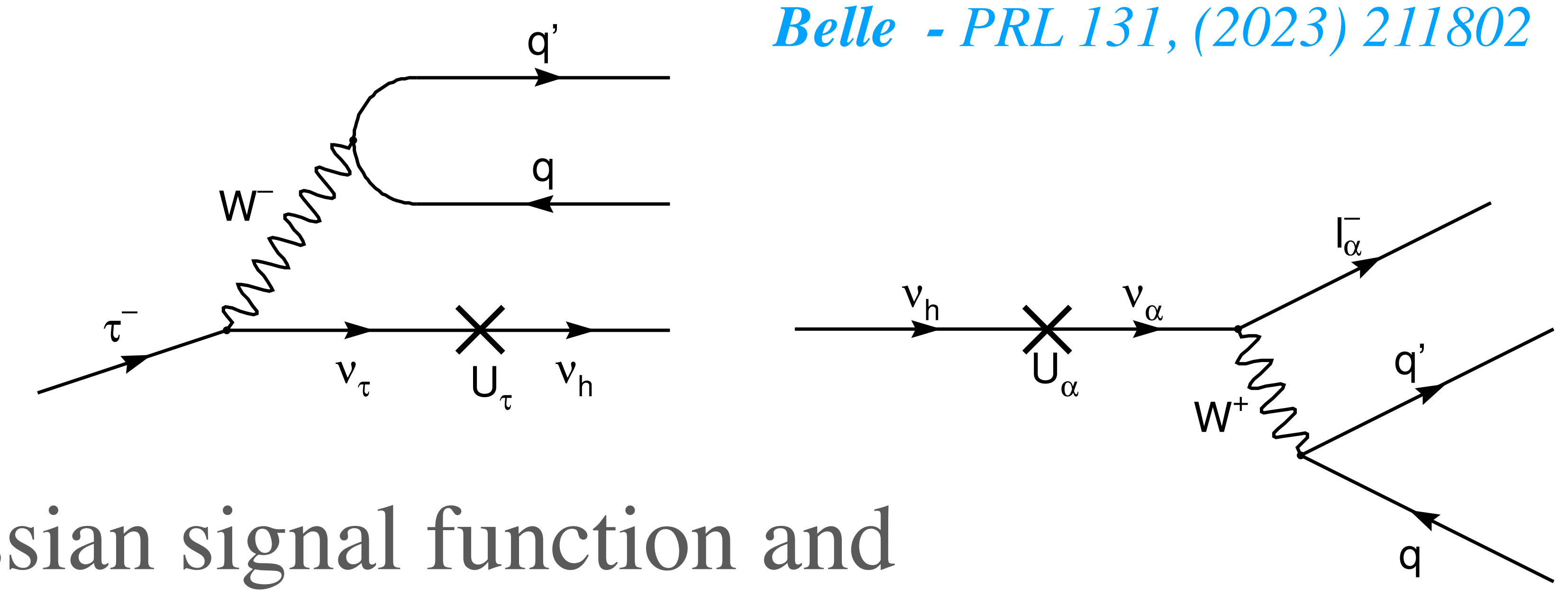






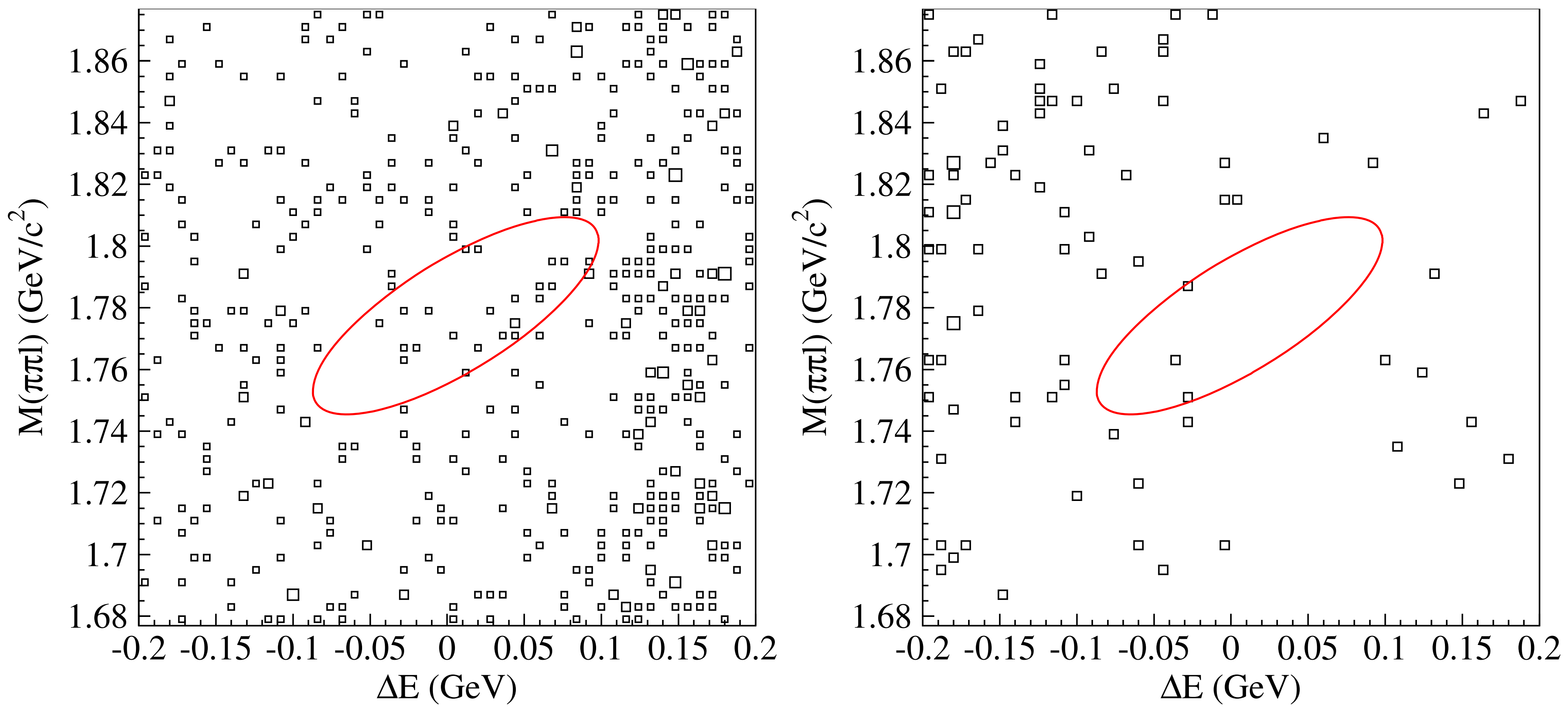
Search for $\tau^- \to \pi^-\nu_h(\nu_h \to \pi^\pm\ell^\mp)$ decay @ Belle

Belle - PRL 131, (2023) 211802

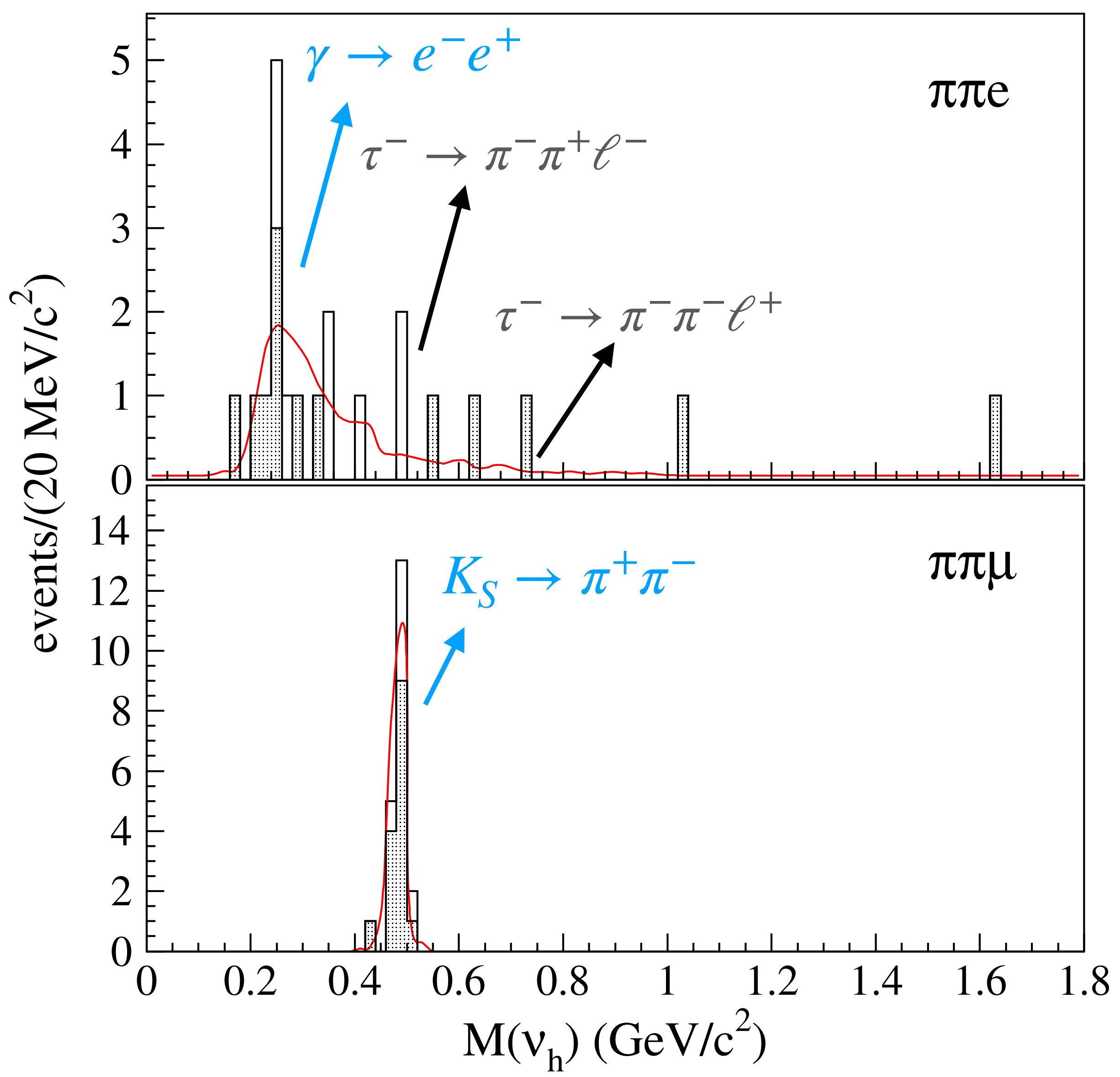


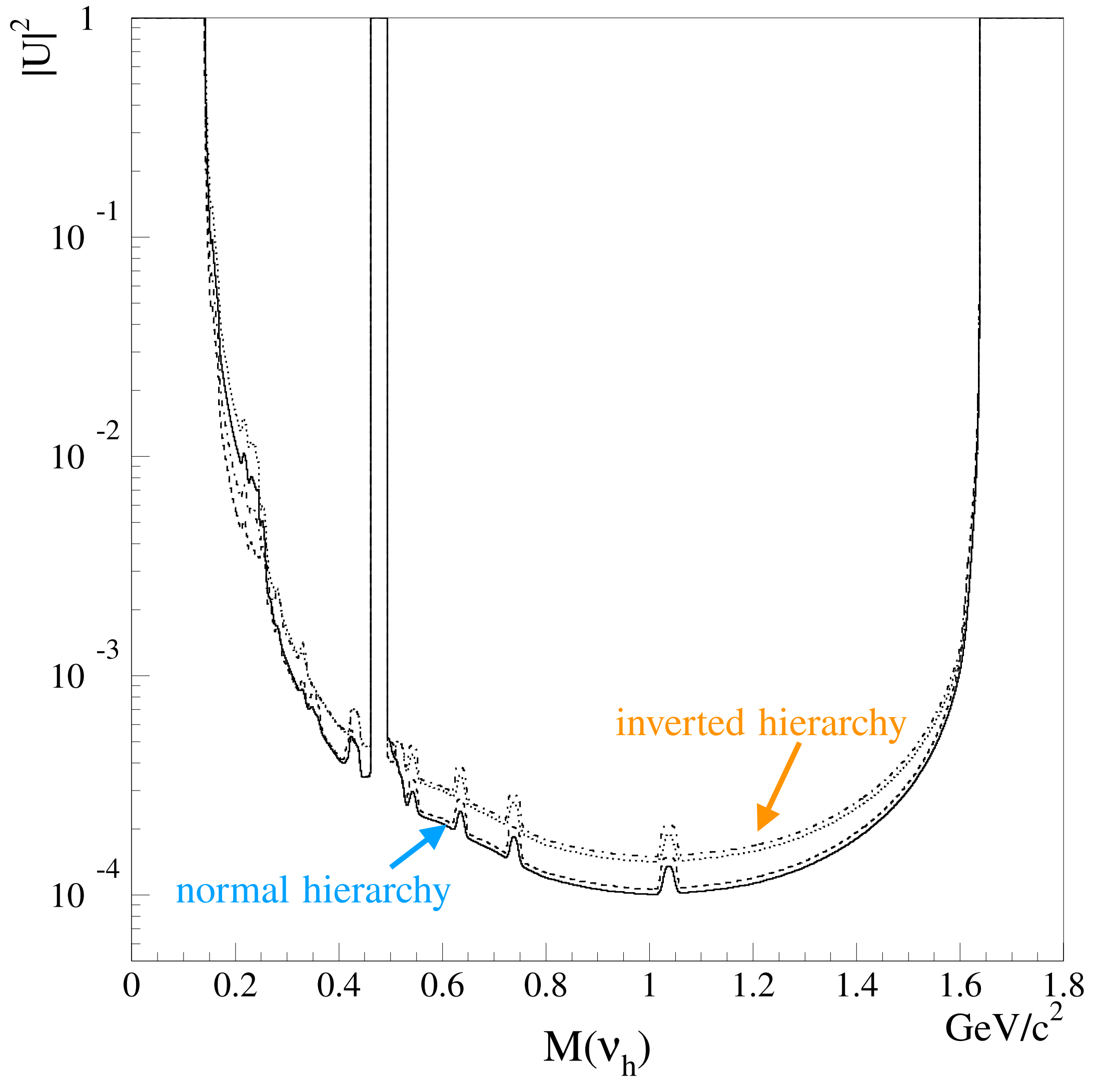
Search for a heavy neutrino $200 < M_{\nu_h} < 1600$ MeV

- 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 $\nu_h \to \pi^\pm\ell^\mp$
- 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_{ν_h} for the two neutrino-mass hierarchy scenarios



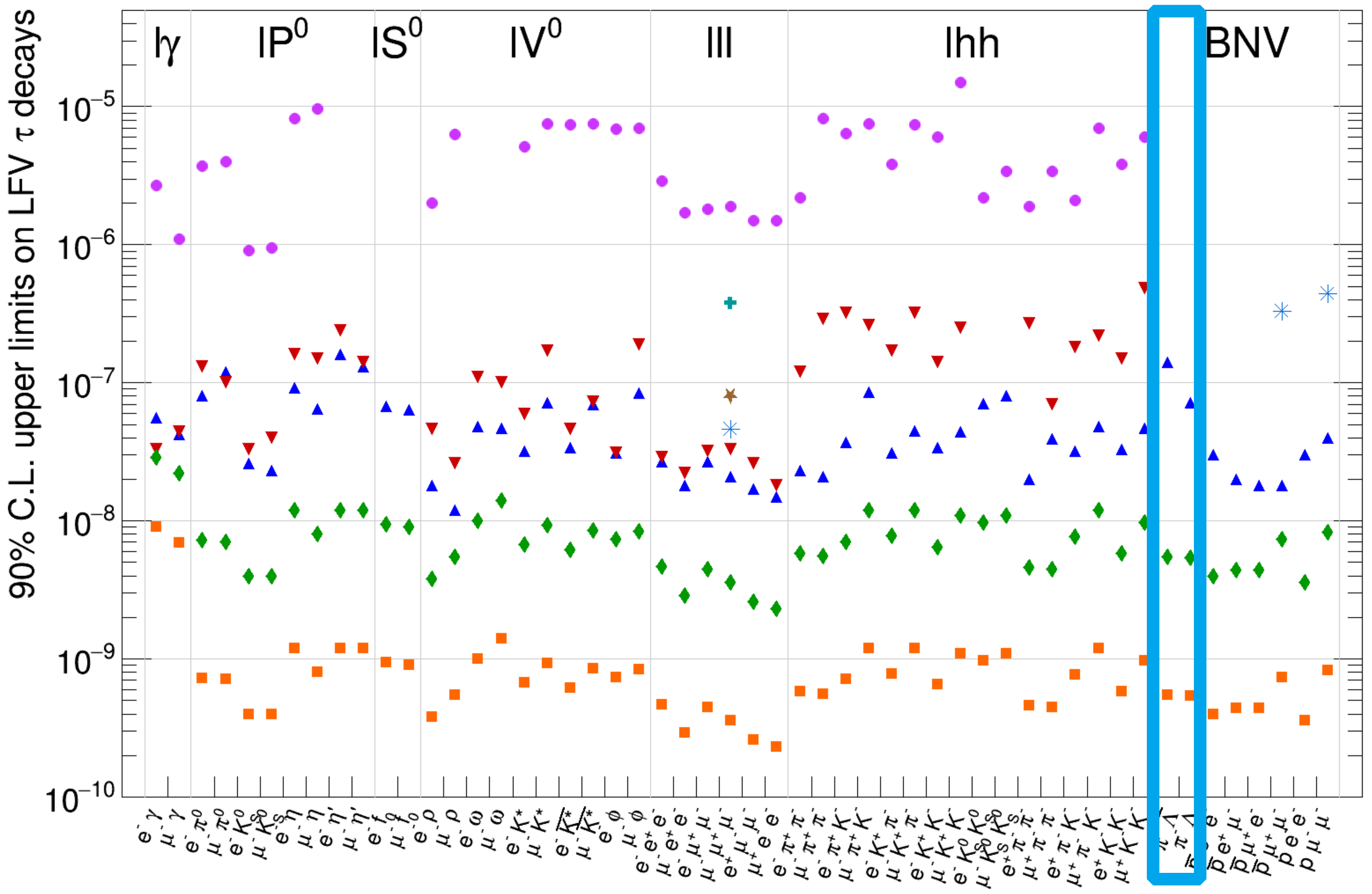
(a) (b)





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	

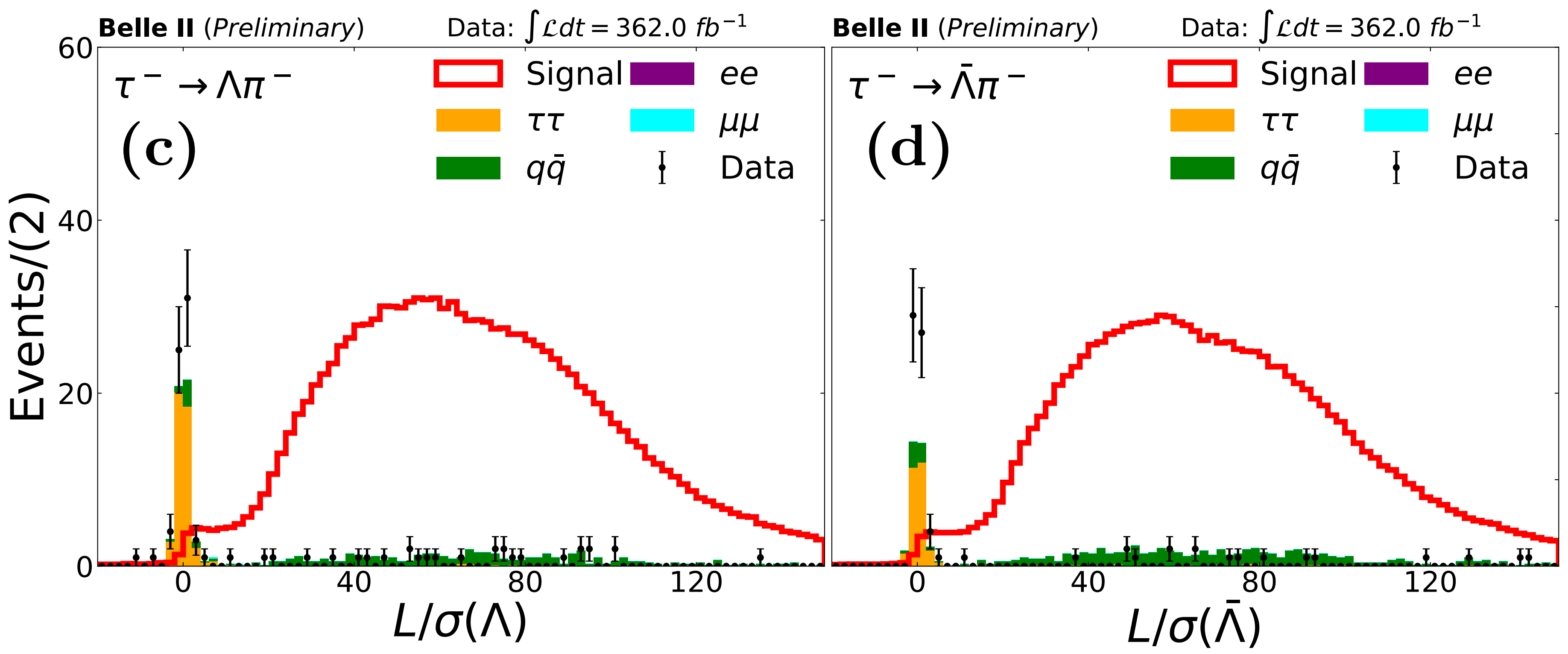
Search for $\tau \to \Lambda(\bar{\Lambda})\pi$ decay @ Belle II

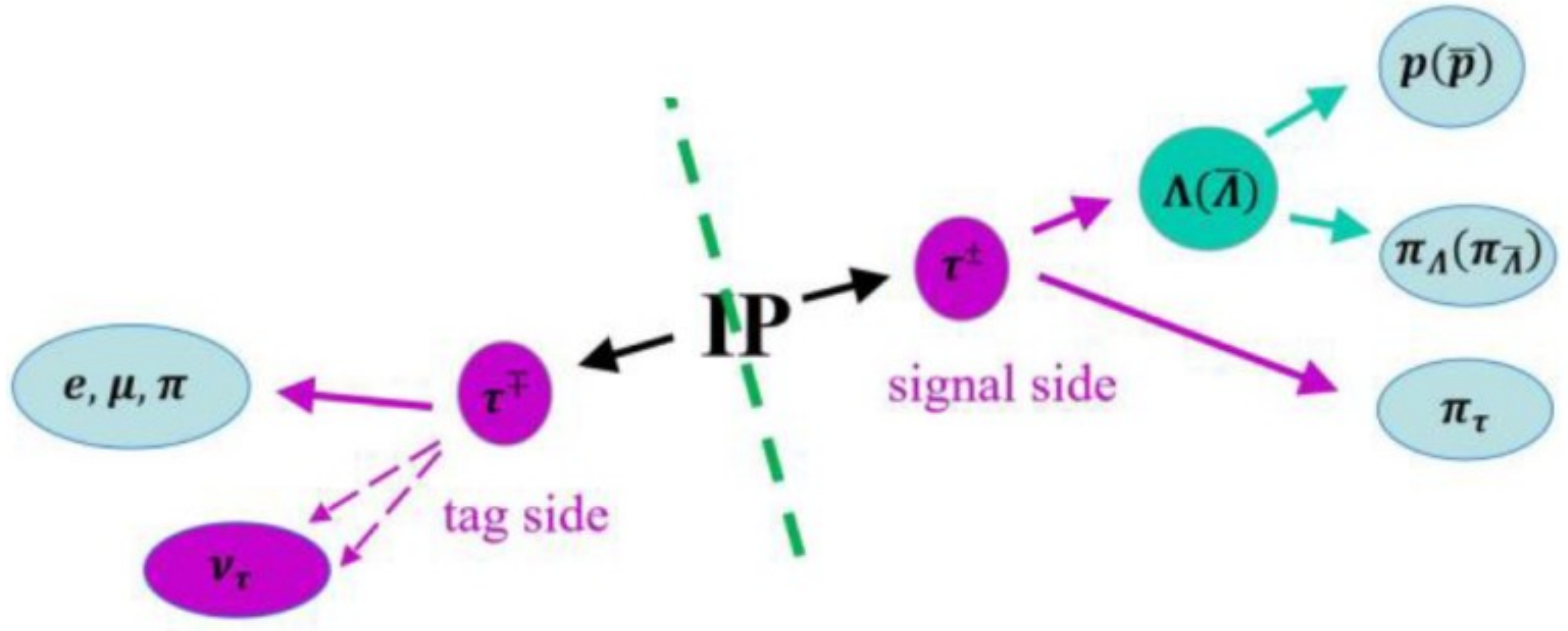
Previous search @ Belle on 154 fb^{-1}

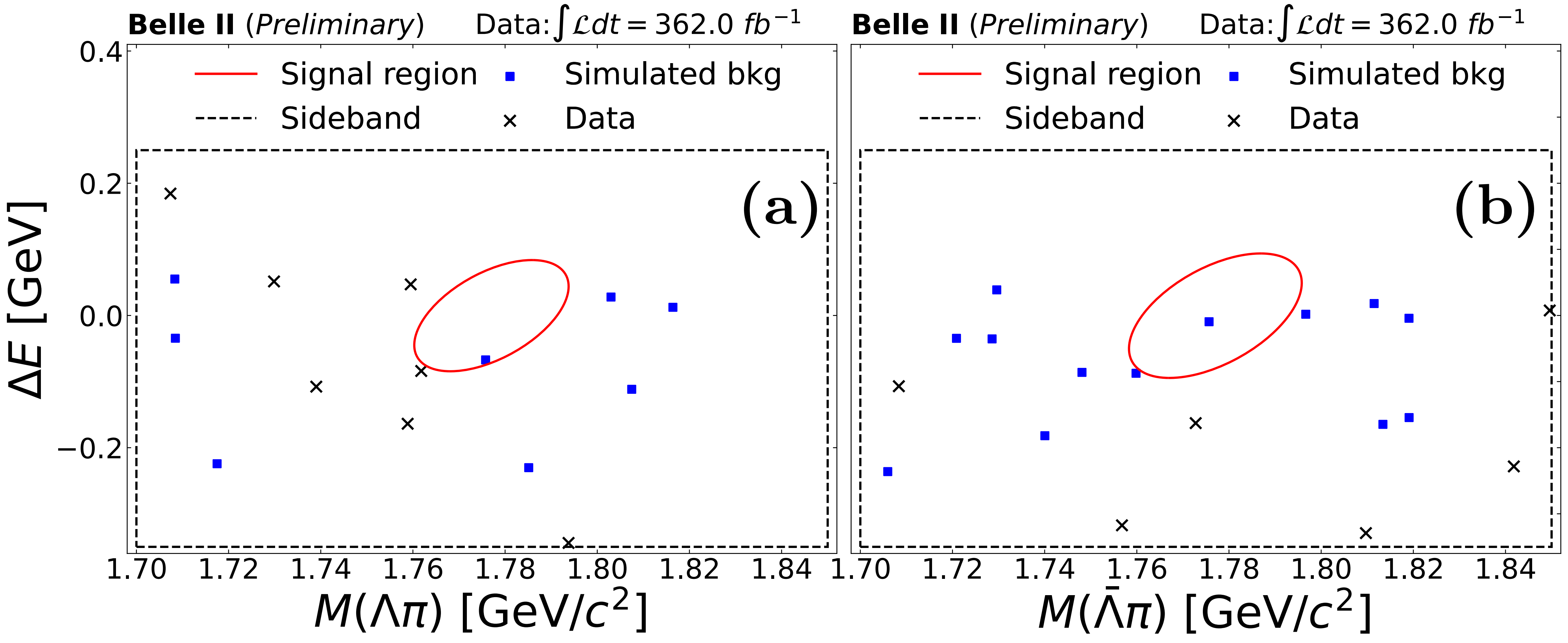
- Set upper limits at 90% C.L. of 0.72×10^{-7} for $\mathscr{B}(\tau^- \to \Lambda\pi^-)$ and 1.4×10^{-7} for $\mathscr{B}(\tau^- \to \bar{\Lambda}\pi^-)$

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

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





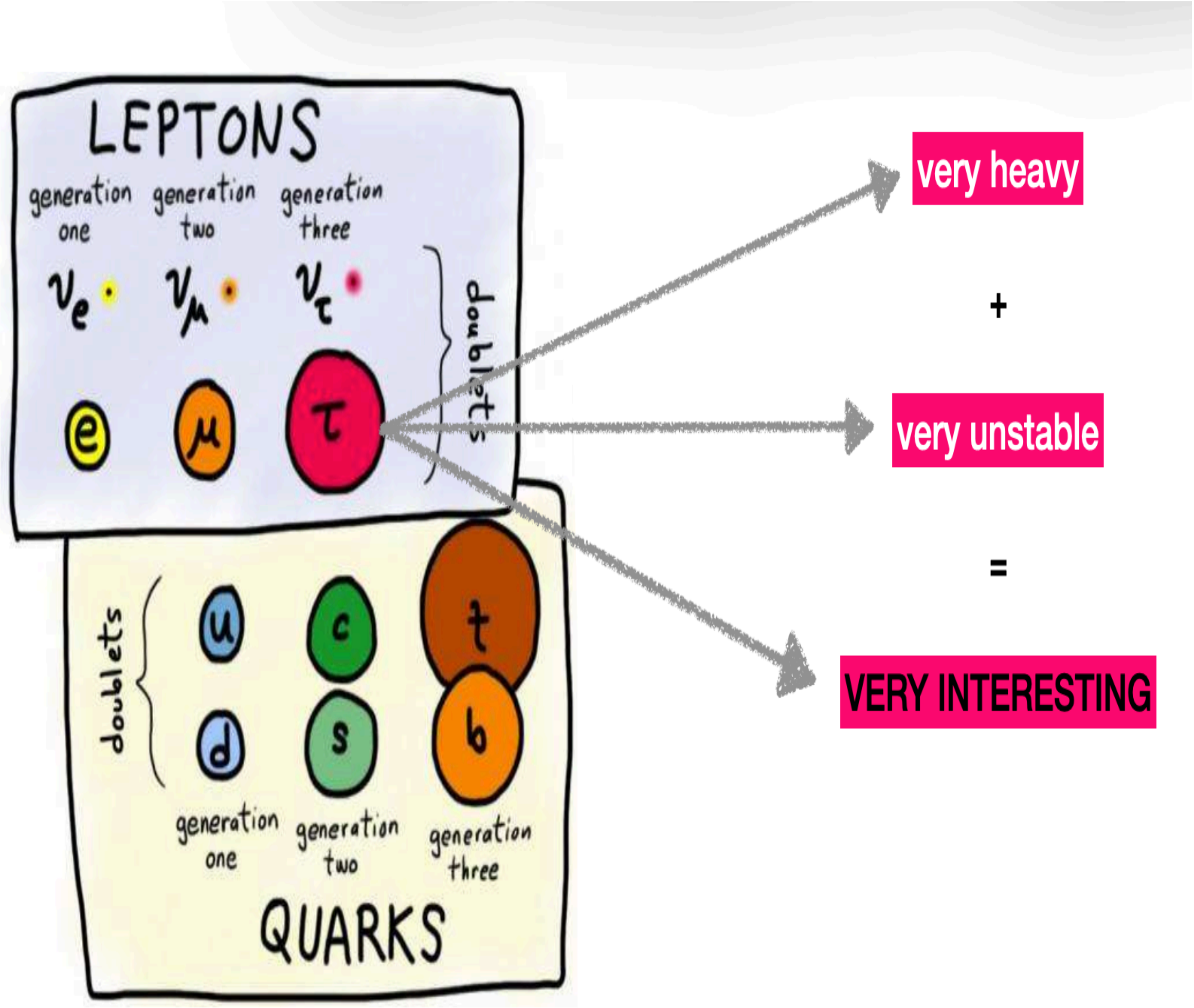


- Signal efficiencies 9.5% (9.8%) for $\tau \to \Lambda\pi^-$ ($\tau^- \to \bar{\Lambda}\pi^-$)
- Expected events 1 (0.5) for $\tau \to \Lambda\pi^-$ ($\tau^- \to \bar{\Lambda}\pi^-$)
- No observed events
- **World leading results on upper limits at 90% C.L. of** 4.7×10^{-8} **for** $\mathscr{B}(\tau^-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

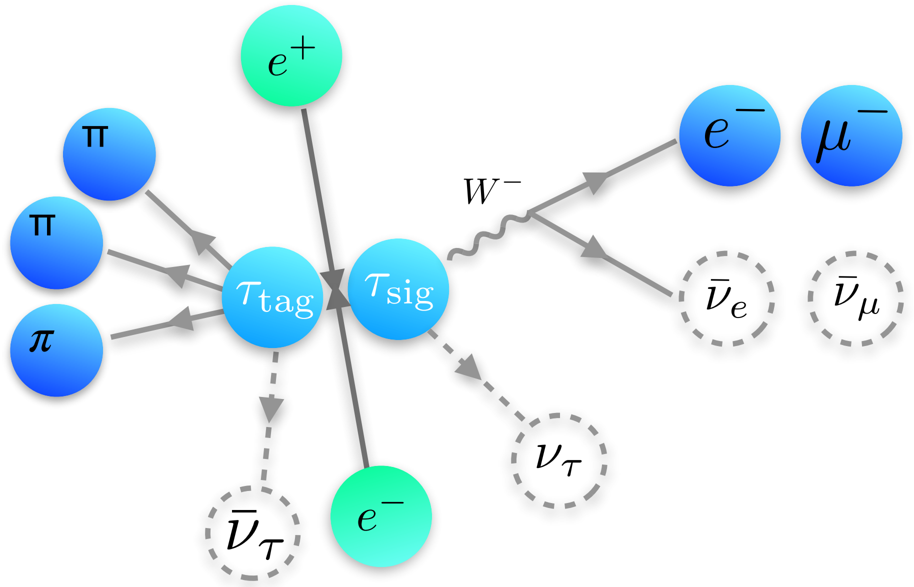


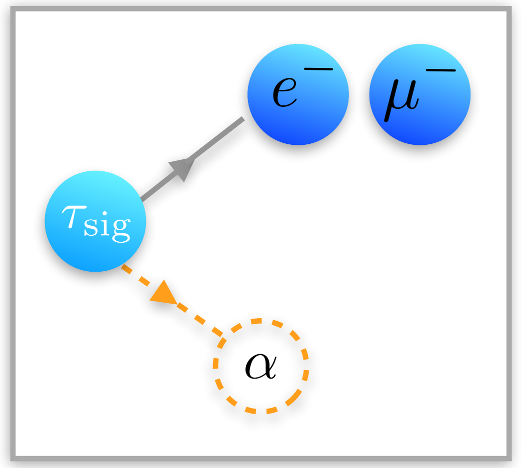
Backup

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

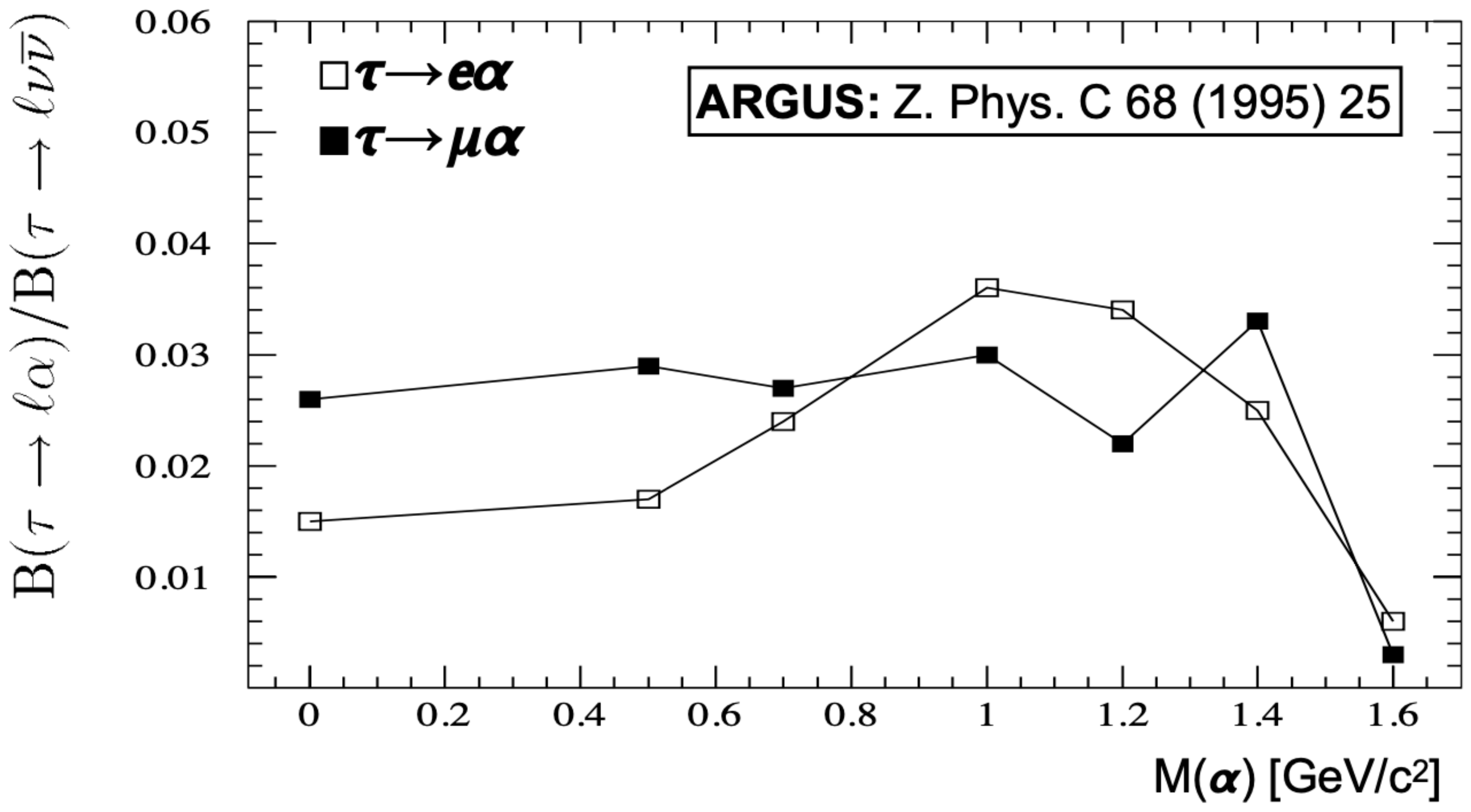
Probe the existence of a new boson α

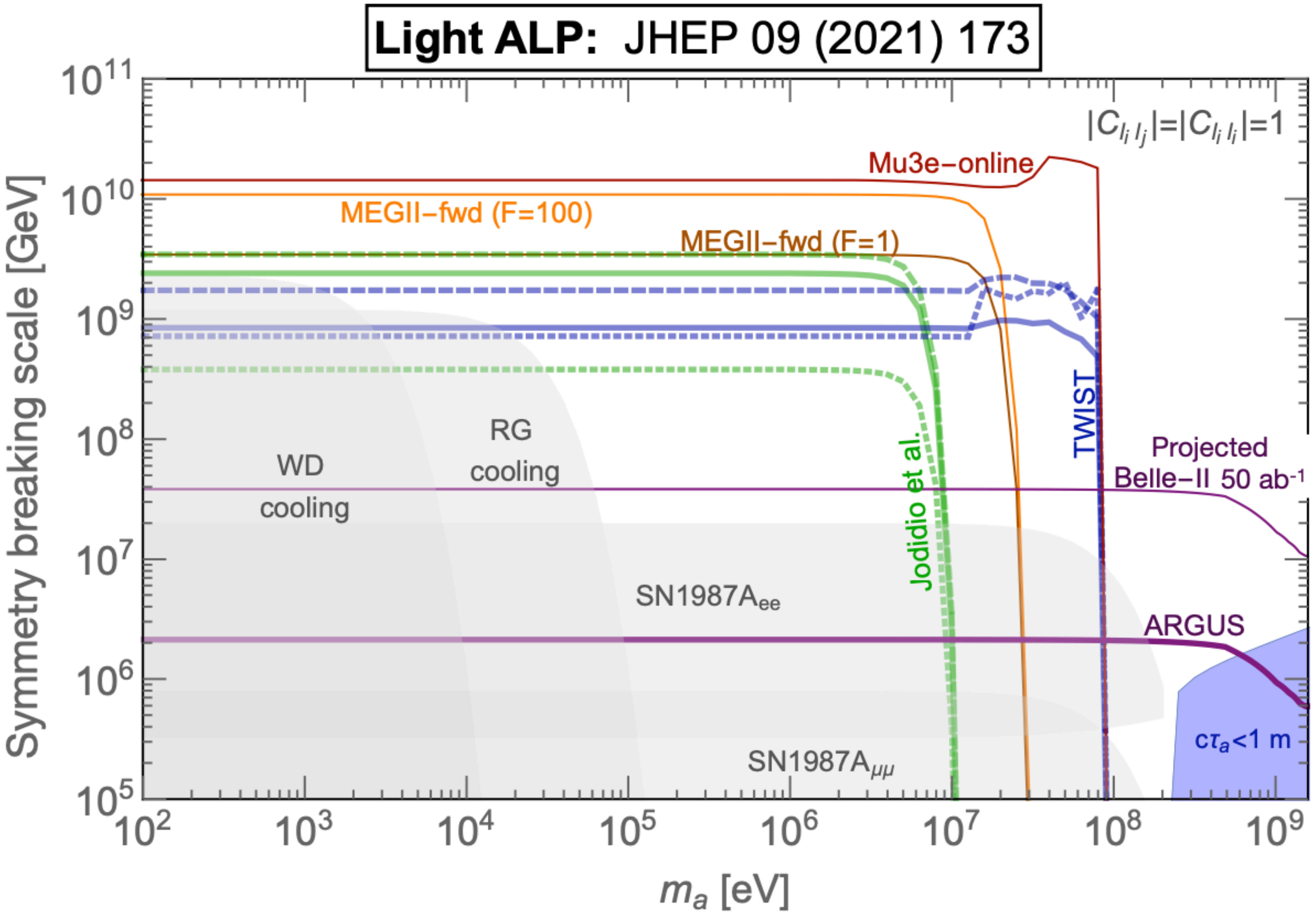
- α is an invisible particle
  - e.g, an axion-like particle





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





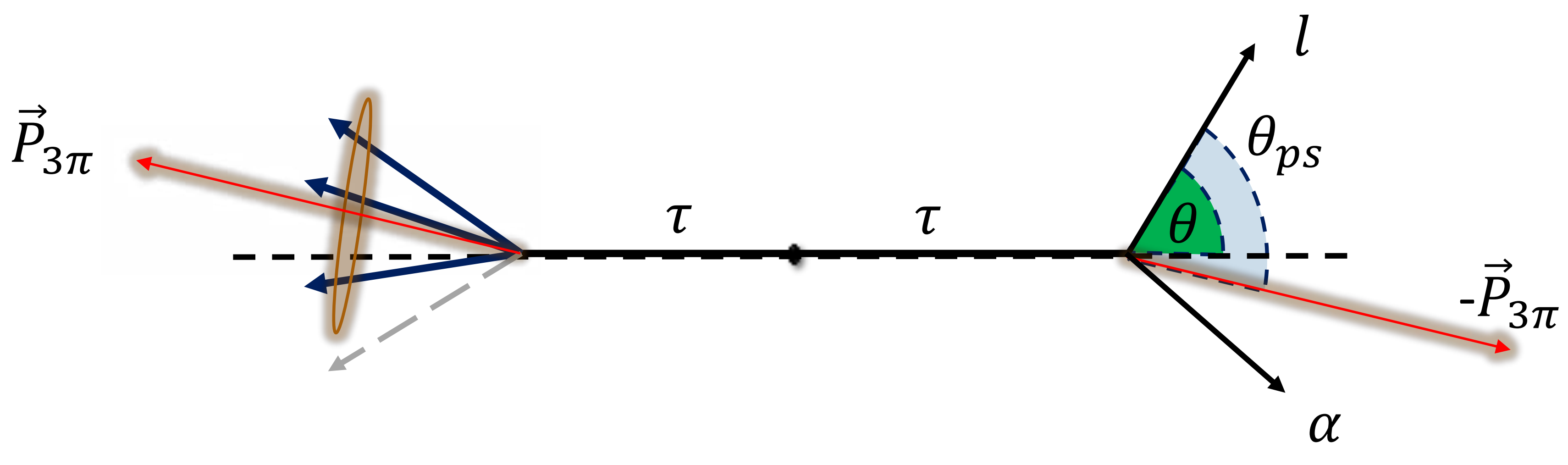
- Interesting mass range from 100 MeV-1.6 GeV
  - not covered by other searches

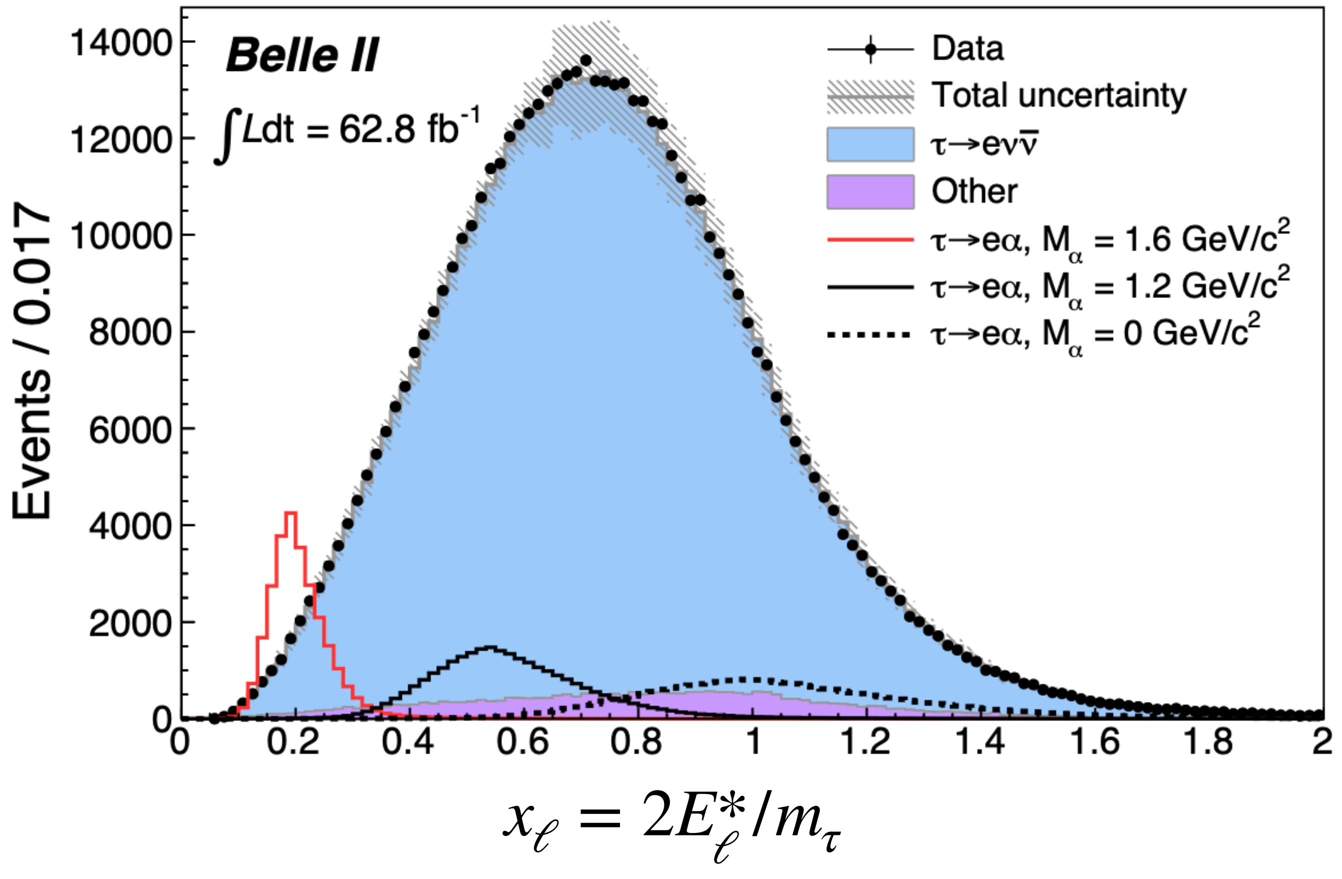
Search for LFV $\tau \to \ell\alpha$ ($\alpha \to$ invisible)

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



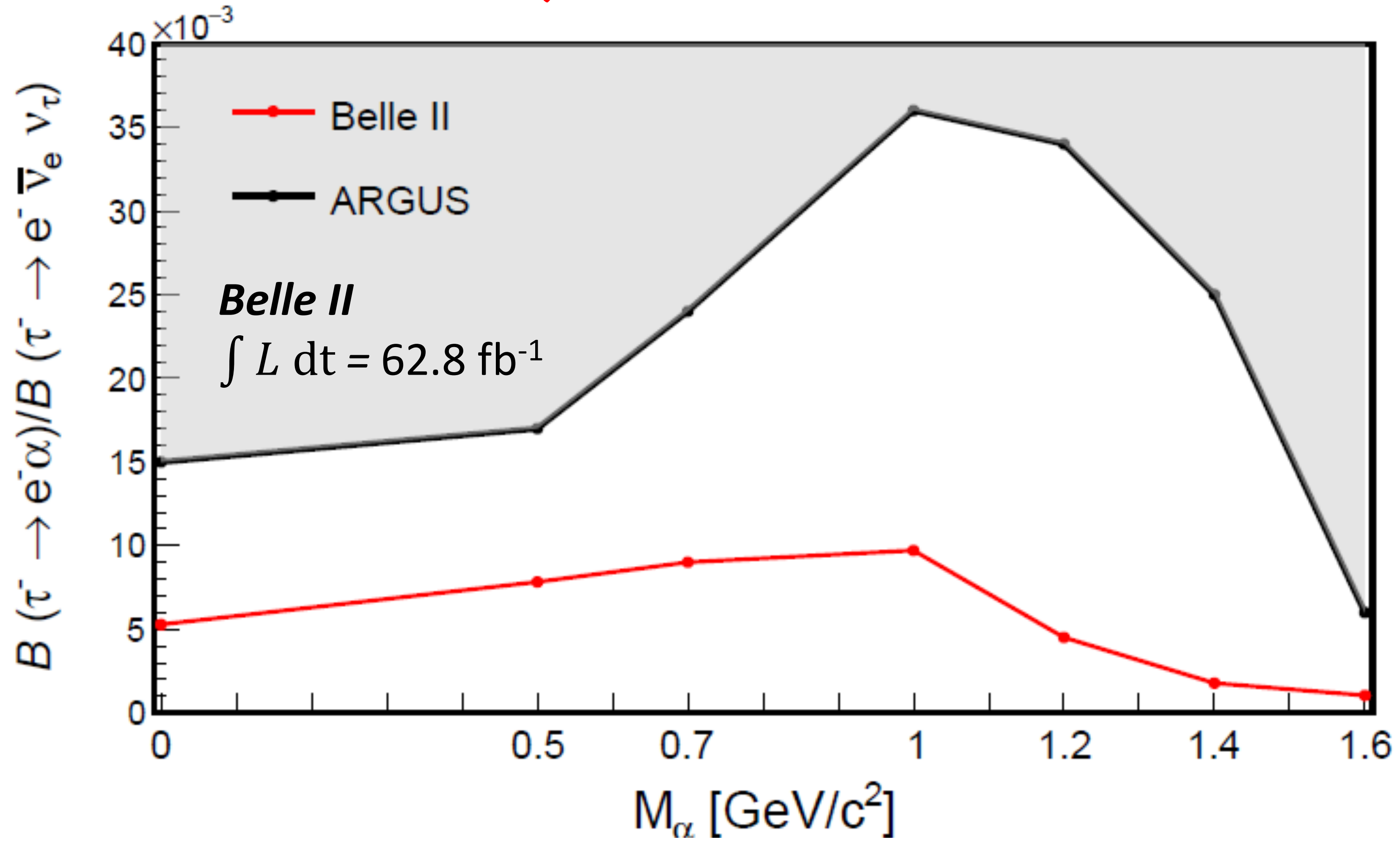


- Approximate using the tag side:

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

- Search for access over the irreducible background: $\tau \to l\nu\nu$
- Mass range: M_α 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