Tau physics at Belle and Belle II

European Research Council
Established by the European Commission

BELLE

Belle II

Klemens Lautenbach

Epiphany 2024, Krakow, 08.01.2024

Outline

- **Belle / Belle II Experiments**

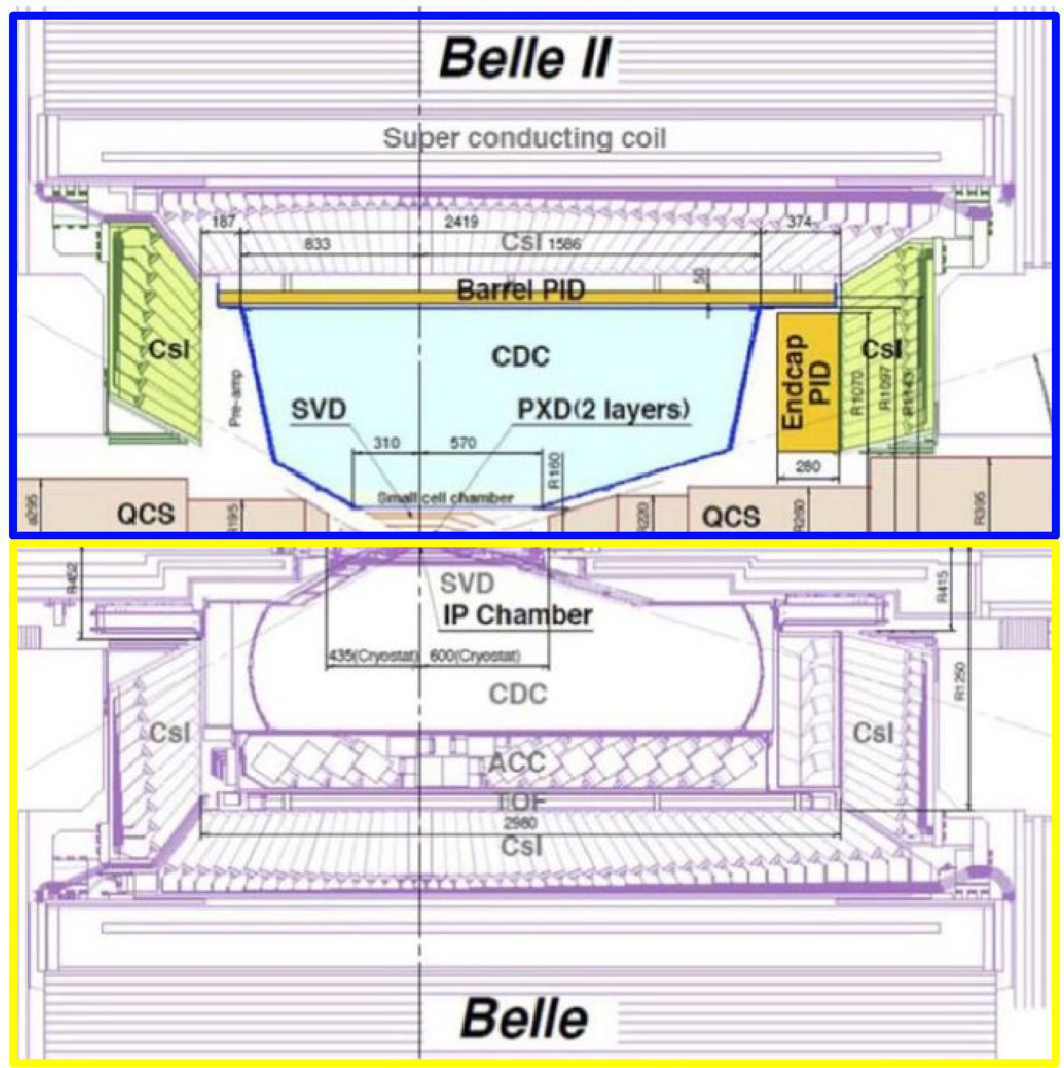
- **Tau physics**
  - Program and Motivation
  - Why at Belle / Belle II ?
  - How to reconstruct tau at Belle / Belle II

- **Standard Model measurements**
- **Lepton Flavor Universality (LFU)**
- **Lepton Flavor Violation (LFV)**

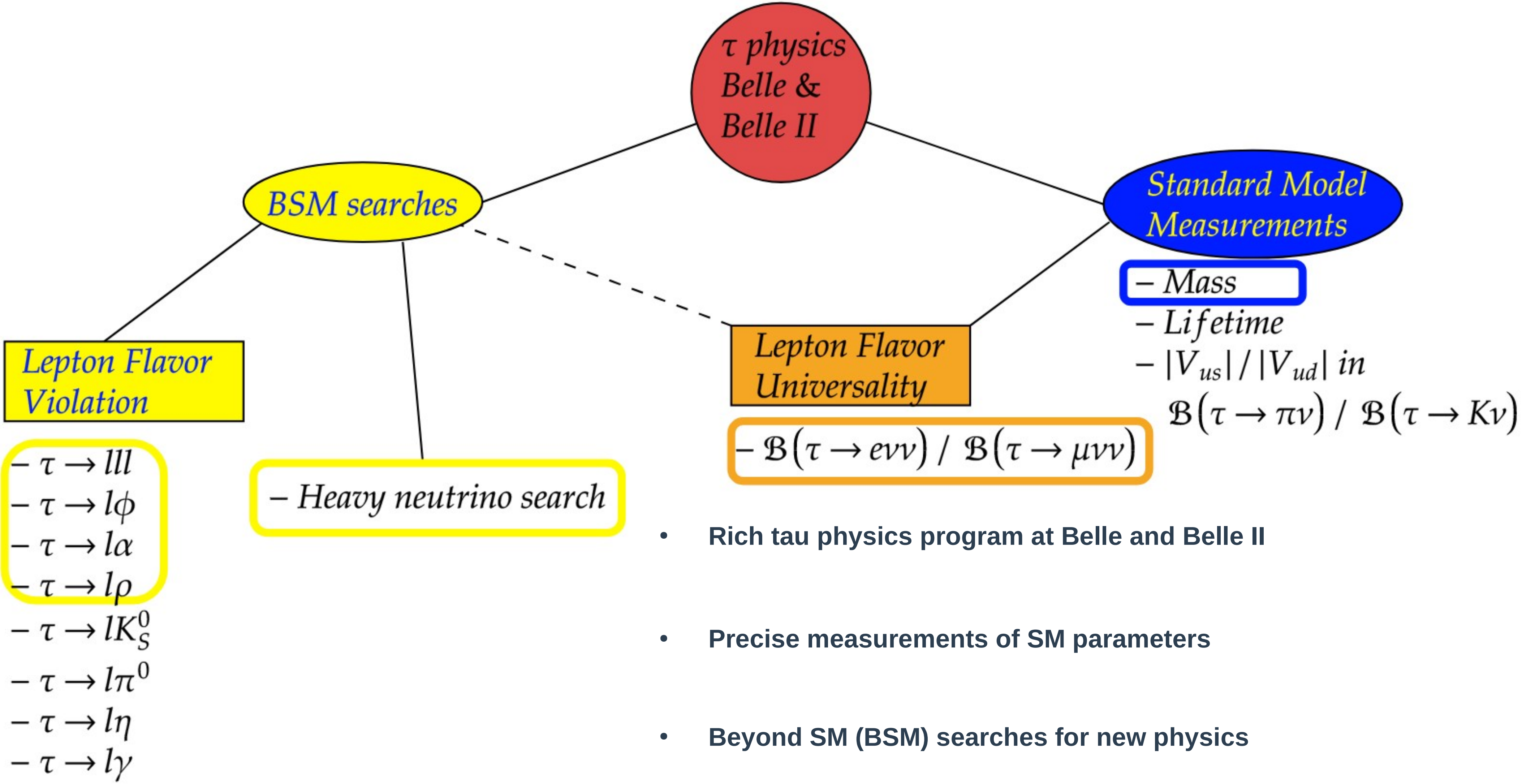
- **Summary and Outlook**

Belle and Belle II

- **General purpose detector with almost 4π coverage**
- **Located at (Super)KEKB**
  → asymmetric e^+e^- collider in Tsukuba Japan
- **Belle**
  - 1999 – 2010
  - 8 GeV electron and 3.5 GeV positron beams
  - 980/fb collected
- **Belle II (successor of Belle)**
  - 2018 - ??
  - 7 GeV electron and 4 GeV positron beams
    - Smaller boost → new vertex detector using 2 layers of pixels and 4 layers of strips
  - 424/fb up to now → goal : 50/ab
- **Detection**
  - Good momentum resolution & particle ID
  - Good efficiency for neutral particles
  - Missing energy reconstruction
  - Specific low-multiplicity event triggers at Belle II



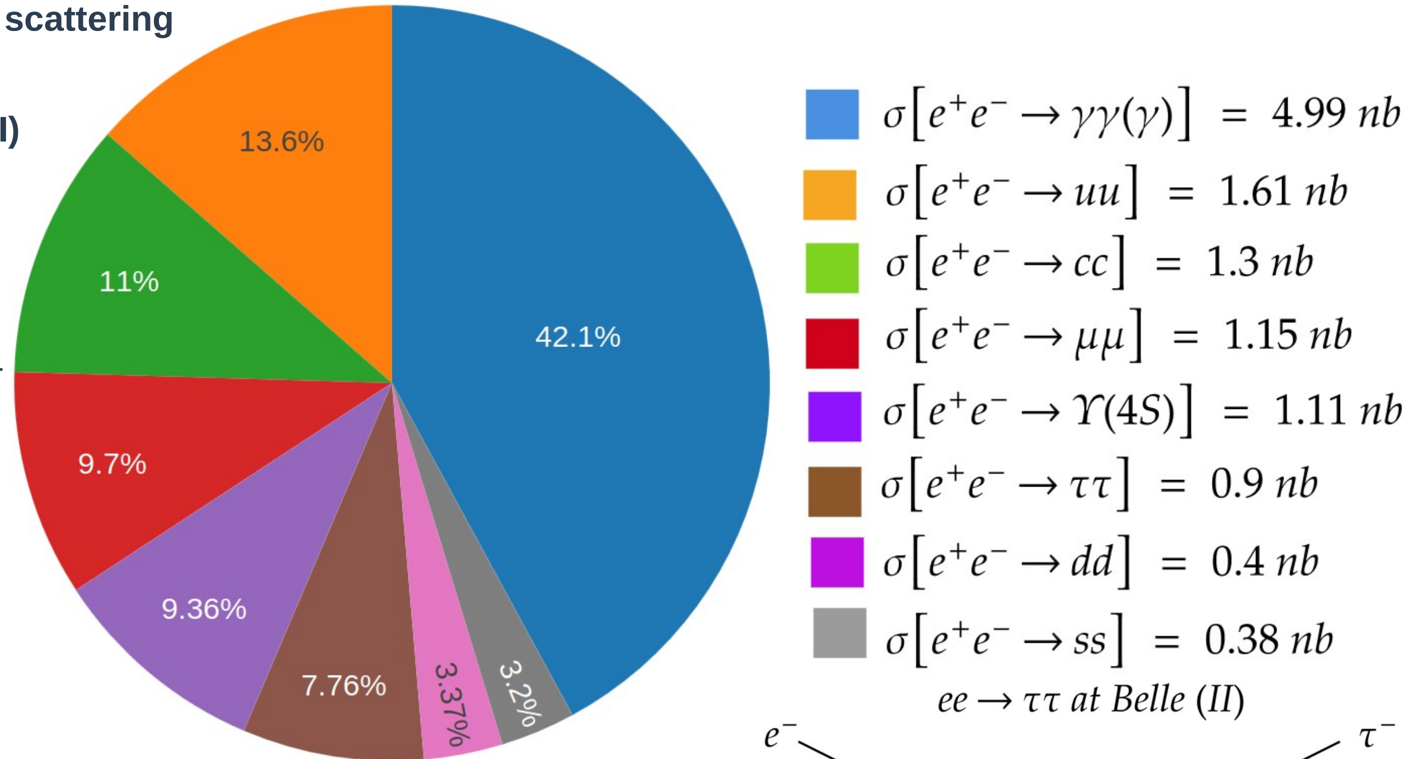
Tau physics : Program and Motivation

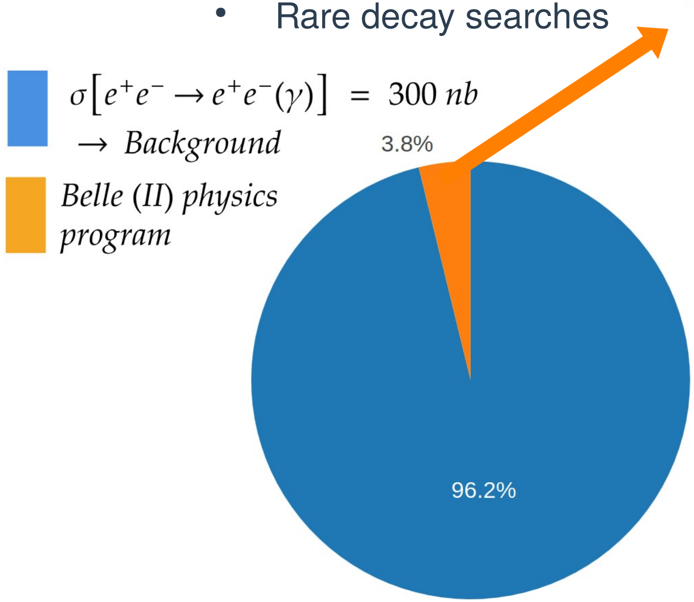


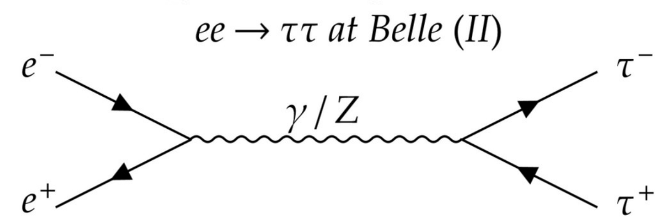
- **Rich tau physics program at Belle and Belle II**
- **Precise measurements of SM parameters**
- **Beyond SM (BSM) searches for new physics**

Tau physics : Why at Belle (II) ?

- **96.2 % of ee collisions do Bhabha scattering → Background**
- **Remaining 3.8 % compose Belle (II) physics program**
  - 9.7 % Υ(4S) → BB
  - 7.76 % taupair production → <u>45 billion taupairs @ Belle II</u>
    - High precision studies
    - Rare decay searches







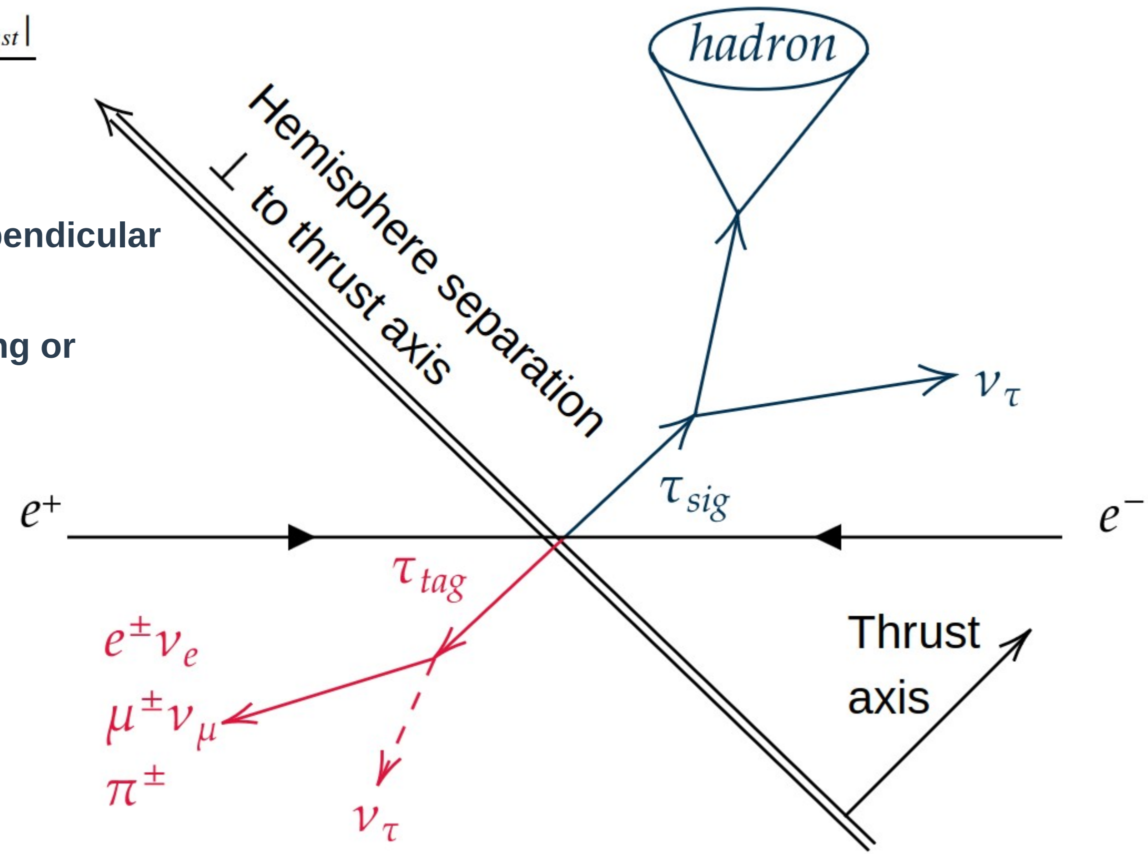
- **Clean physics environment, known initial state**
- **Missing energy reconstruction**
- **Dedicated low multiplicity triggers (not present in Belle)**

Tau physics : How to reconstruct τ at Belle (II)

- **SM τ decays are not fully reconstructable due to missing neutrino**
- **Identify τ+τ- events using thrust axis**
  - Maximizes projection of all particle momenta in event

Find $\vec{n}_{thrust}$ which maximizes $\frac{\sum_i |\vec{p}_i^{\,CM} \cdot \vec{n}_{thrust}|}{\sum_i |\vec{p}_i^{\,CM}|}$

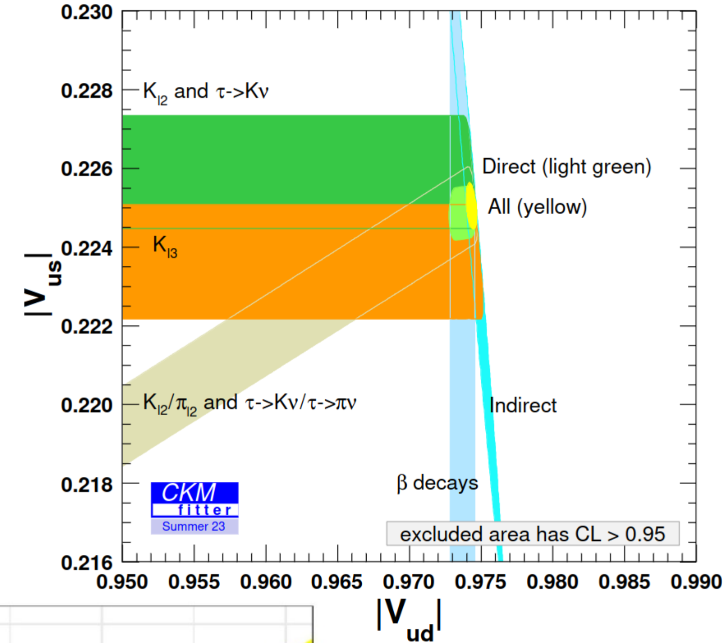
- **Define two hemispheres divided by the plane perpendicular to the thrust axis**
- **Reconstruct tag-side tau in standard model 1-prong or 3-prong decay**
  - Exclusive → use only 1-prong OR 3-prong events
    - High purity, less efficieny
  - Inclusive → do not reconstruct tag-side tau in a specific mode
    - Higher signal efficiency
    - Higher background levels



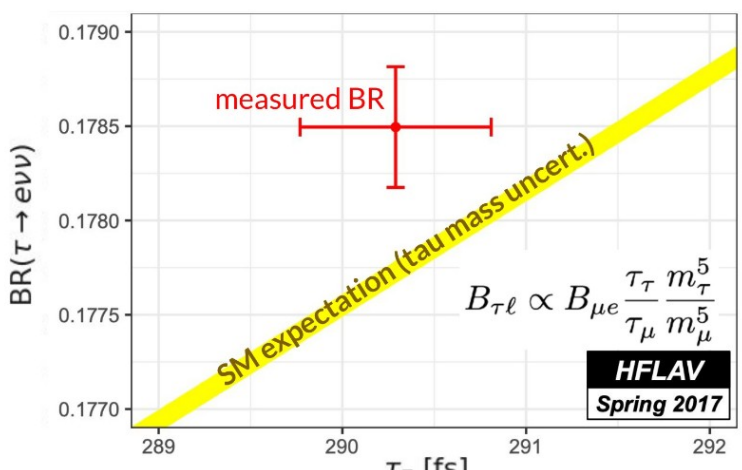
SM Measurements : Motivation

- **Precision measurement of tau quantities can have significant impact**
  - First row unitarity of CKM-Matrix (Cabbibo-angle-anomaly)
  - B(τ→Kν) / B(τ→πν) ~ $|V_{us}|$ / $|V_{ud}|^2$
  - Mass of tau is the one with worst precision among leptons

$$m_e = (0.51099895000 \pm 0.00000000015)\ \text{MeV}$$
$$m_\mu = (105.6583755 \pm 0.0000023)\ \text{MeV}$$
$$m_\tau = (1776.86 \pm 0.12)\ \text{MeV}$$



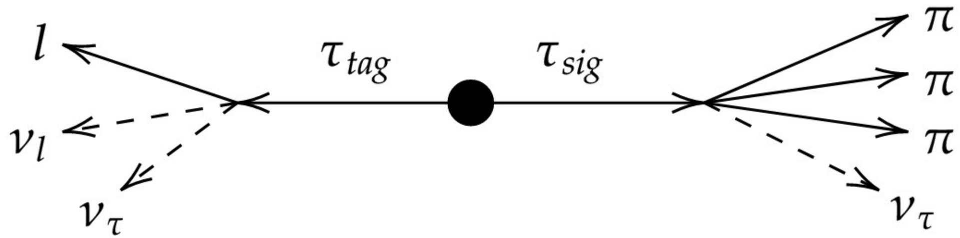
- **Lepton Flavor Universality**
  - All leptons are expected to have same coupling strength to W-Boson in SM
    - Different observations would suggest NP contributions
  - Mass and lifetime of τ are important inputs to those calculations



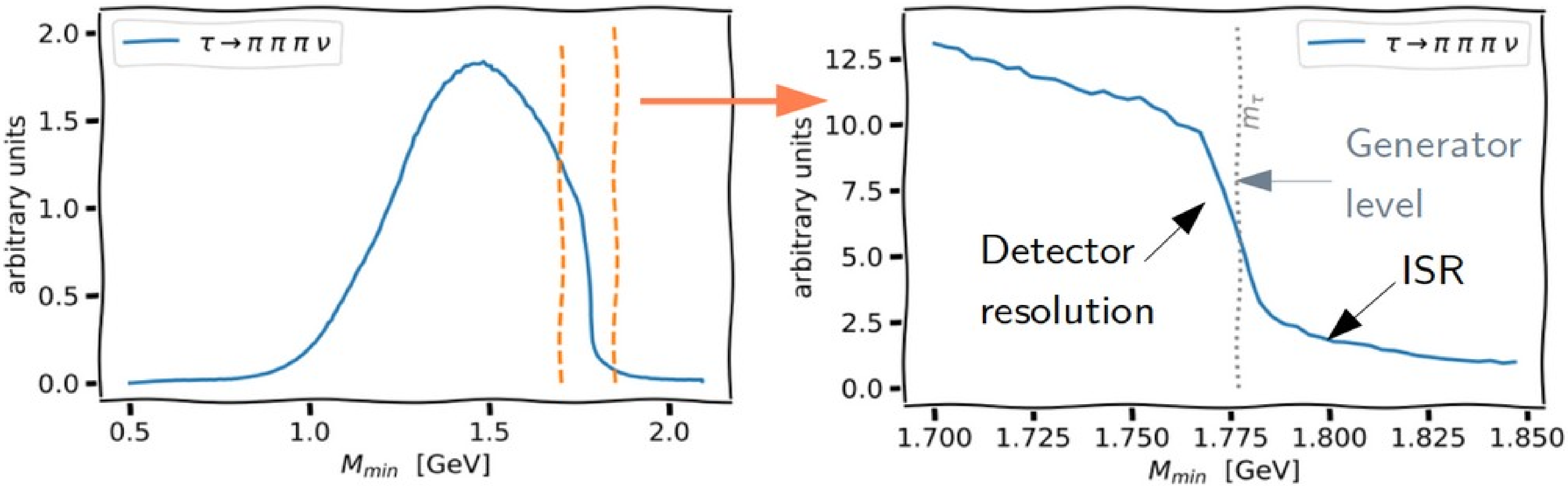
SM Measurements : τ Mass – I

PhysRev D. 108.032006 (2013)

- **The τ mass is a fundamental parameter of the SM**
- **A precise measurement is an important input to LFU tests**
- **Belle II uses the Pseudomass method**
  - Fit kinematic edge of M_{min} distribution in $\tau \to 3\pi\nu$ decays with empirical function
  - Smeared edge due to ISR/FSR and detector resolution

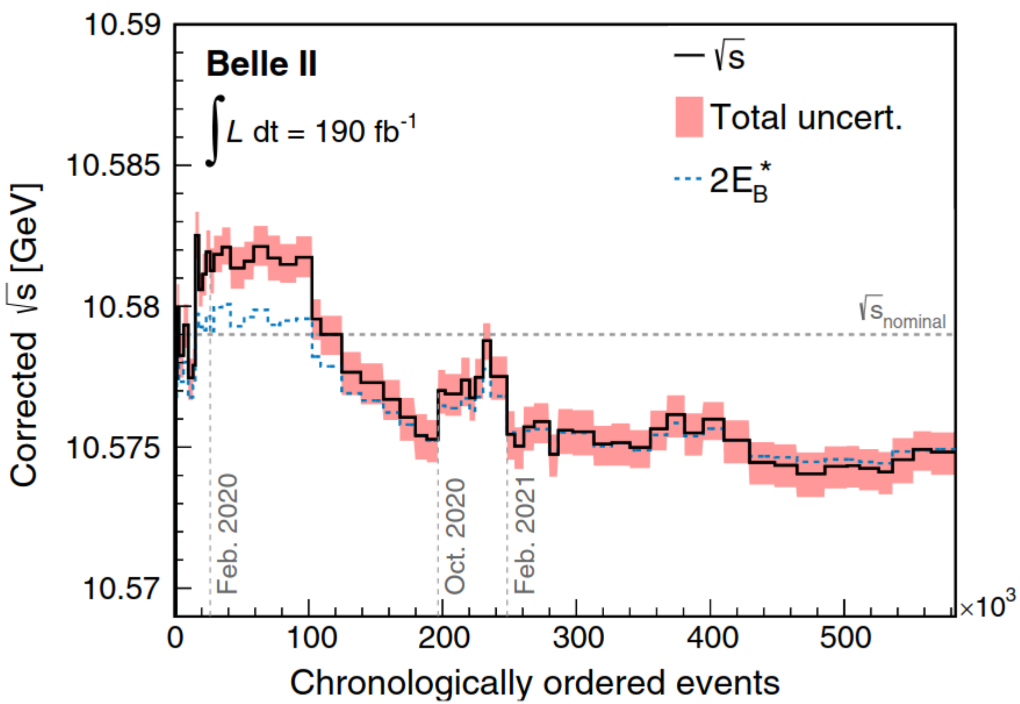


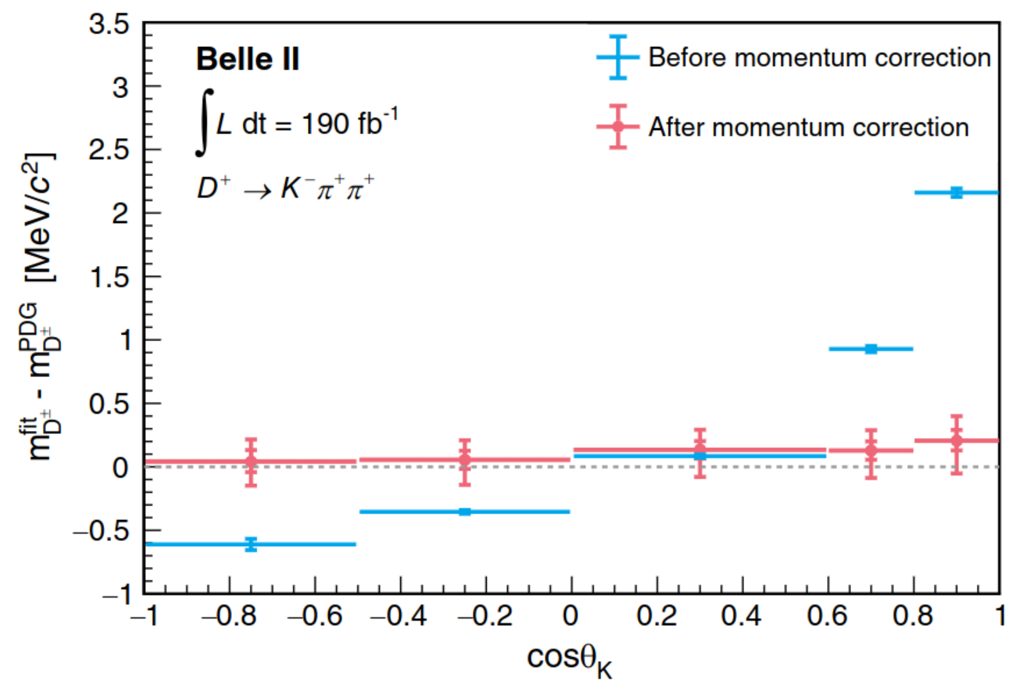
$$M_{\min} = \sqrt{m_{3\pi}^2 + 2(\sqrt{s}/2 - E_{3\pi})(E_{3\pi} - |\vec{p}_{3\pi}|)} \leq m_\tau$$



SM Measurements : τ Mass – II

- **Beam energy calibration and momentum correction are crucial for this measurement**
  - E_{beam} corrected by hadronic B-Meson decays
  - Momentum correction is done with scale factors for π using $D^{*+} \rightarrow D^0(\rightarrow K^-\pi^+)\pi^+$
    - Originates from imperfect B-field, mismodeling in simulation → bias in mass extraction





PhysRev D. 108.032006 (2013)

SM Measurements : τ Mass – III

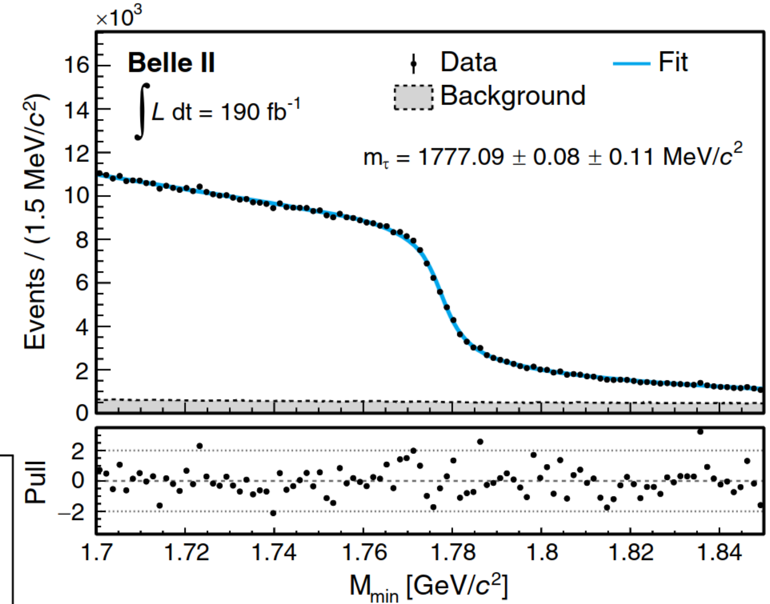
- **Perform unbinned maximum likelihood fit to the kinematic edge of the mass distribtion**

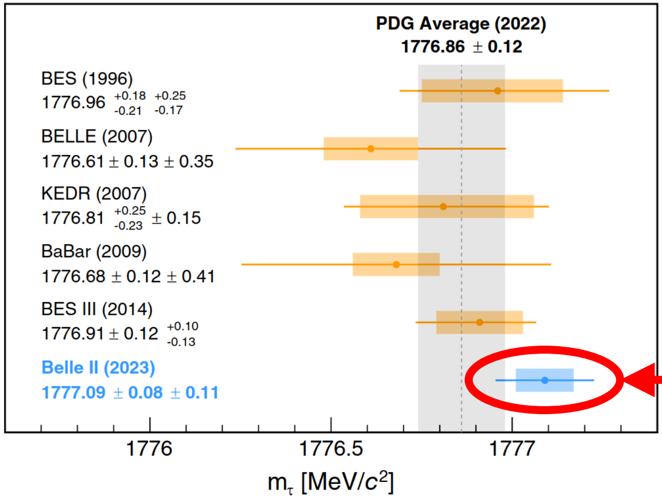
$$M_\tau = 1777.09 \pm 0.08 \pm 0.11 \text{ MeV/c}^2$$

Source	Uncertainty (MeV/c^2)
Knowledge of the colliding beams:	
Beam-energy correction	0.07
Boost vector	< 0.01
Reconstruction of charged particles:	
Charged-particle momentum correction	0.06
Detector misalignment	0.03
Fit model:	
Estimator bias	0.03
Choice of the fit function	0.02
Mass dependence of the bias	< 0.01
Imperfections of the simulation:	
Detector material density	0.03
Modeling of ISR, FSR and τ decay	0.02
Neutral particle reconstruction efficiency	≤ 0.01
Momentum resolution	< 0.01
Tracking efficiency correction	< 0.01
Trigger efficiency	< 0.01
Background processes	< 0.01
Total	0.11

$$\int \mathcal{L}dt = 190 \text{ fb}^{-1}$$

$$\sim 175 \text{ Million } ee \rightarrow \tau\tau$$





Worlds most precise measurement

PhysRev D. 108.032006 (2013)

SM Measurements : LFU – I (NEW)

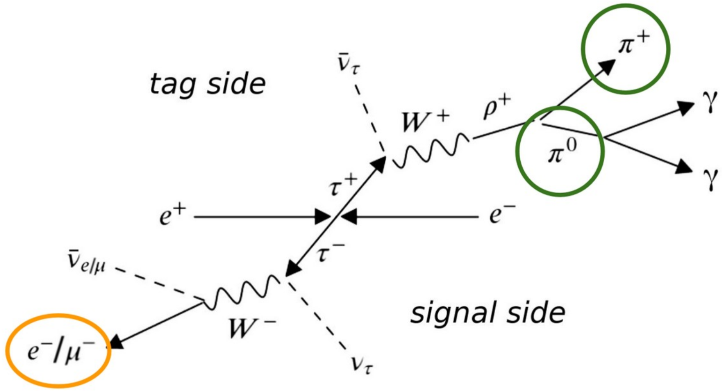
- **SM picture of leptons**
  - 3 families with different masses and different, separately conserved lepton numbers
  - Coupling to W boson is flavor-independent (?) → $g_e = g_\mu = g_\tau$
    → lepton universality
- **Test LFU (e-μ) in tau decays with g_e , g_μ being proportional to the leptonic branching fractions**

$$\left(\frac{g_\mu}{g_e}\right)_\tau^2 \sim \frac{\mathcal{B}(\tau \to \mu\nu\nu)}{\mathcal{B}(\tau \to e\nu\nu)}$$

$$\int \mathcal{L}dt = 362\ \mathbf{fb}^{-1}$$

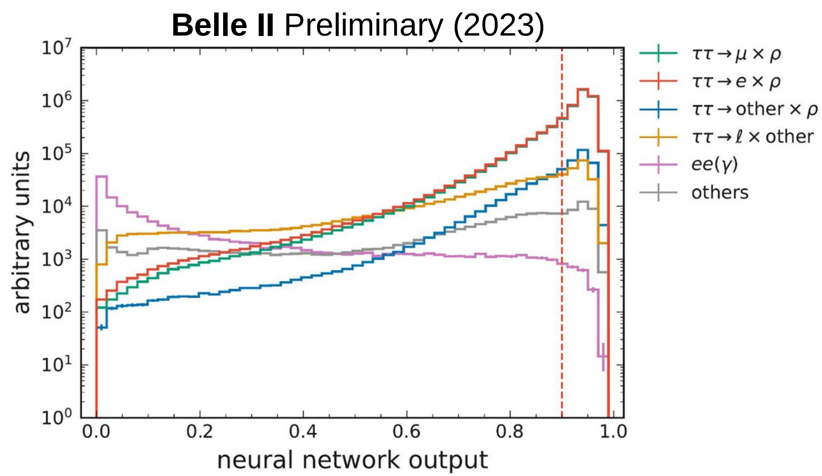
$$\sim 334\ \textbf{Million}\ ee \to \tau\tau$$

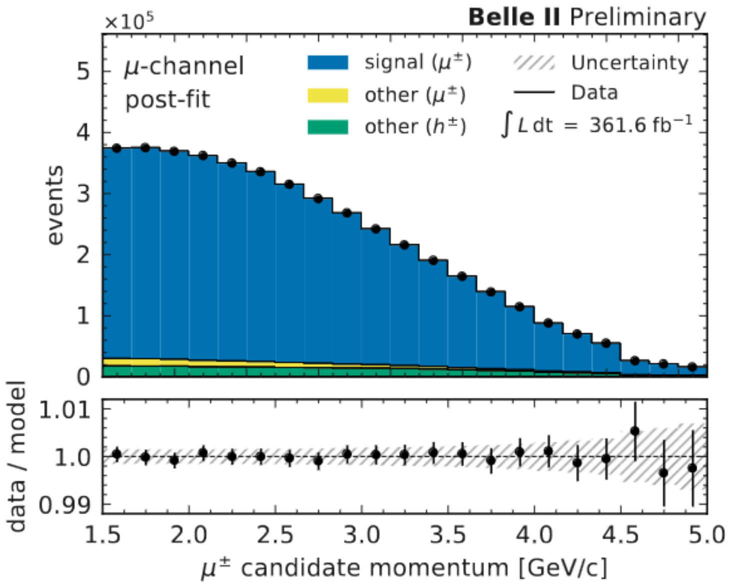
- **LFU is sensitive to new physics if it violates lepton flavor and/or lepton universality in weak charged-currents**
- **Belle II analysis uses 1-prong decays with one charged hadron and at least one neutral pion on the tag-side**
  - Large BF ~ 35% on tag-side, low backgrounds, high trigger efficier
- **Signal side:**
  - One particle track with lepton ID requirement
- **Tag side:**
  - One track with $E_{cluster} / p < 0.8$
  - At least one neutral pion on tag side



SM Measurements : LFU – II (NEW)

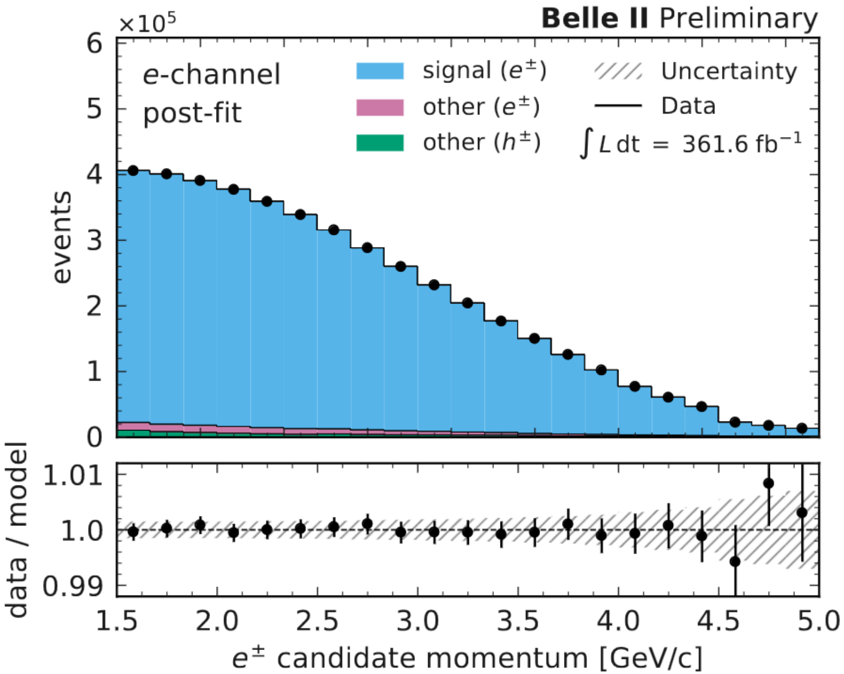
- **Event selection is performed with rectangular cuts + neural network**
- **94 % purity with 9.6 % signal efficiency for the combined sample**
- **Main backgrounds:**
  - ee → ττ (π faking e/μ) ~ 3.3 %
  - ee → ττ (wrong tag) ~ 2.3 %
  - ee → eeττ ~ 0.2%
- **Extraction of R_μ**
  - Binned maximum likelihood template fit with pyhf in lepton momentum [1.5, 5] GeV
    - Simultaneous for e/μ channel for better constraints
  - Systematics included with nuisance parameters modifying the templates
  - 3 templates for electron and muon channel
    - Signal decays
    - Background with correct signal side lepton
    - Background with misidentified particle on signal side

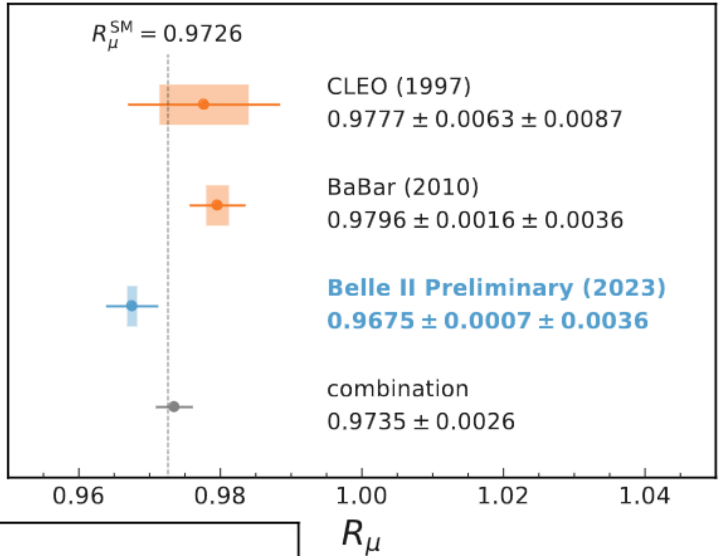


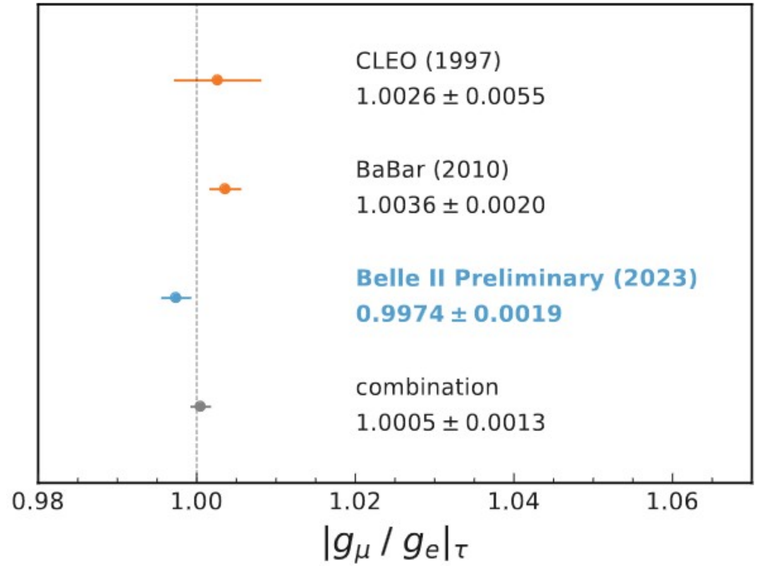


SM Measurements : LFU – III (NEW)

- **Leading systematics**
  - **Particle identification 0.32%**
  - **Trigger 0.10%**
- **Measured R= 0.9675 +/- 0.0007 +/- 0.0036**
  - Most precise e-mu universality from tau decays in single measurement







BSM : Heavy neutrino search – I

- **Neutrino mass is not zero, which needs a mechanism to generate it**
  - Including heavy, right-handed neutrinos is an approach to introduce neutrino mass

$$\int \mathcal{L} dt = 980\ \mathbf{fb}^{-1}$$

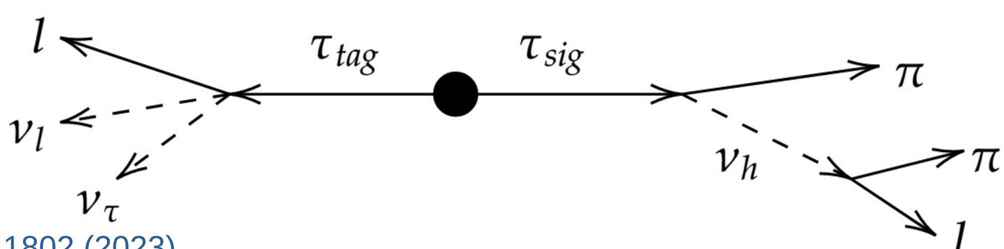
$$\sim 905\ \textbf{Million}\ ee \rightarrow \tau\tau$$

- $\tau^{\pm} \rightarrow \pi^{\pm}\nu_h$ **with** $\nu_h \rightarrow \pi^{\pm} l^{\mp}$
  - ν_h long-lived Majorana neutrino, l = e/μ

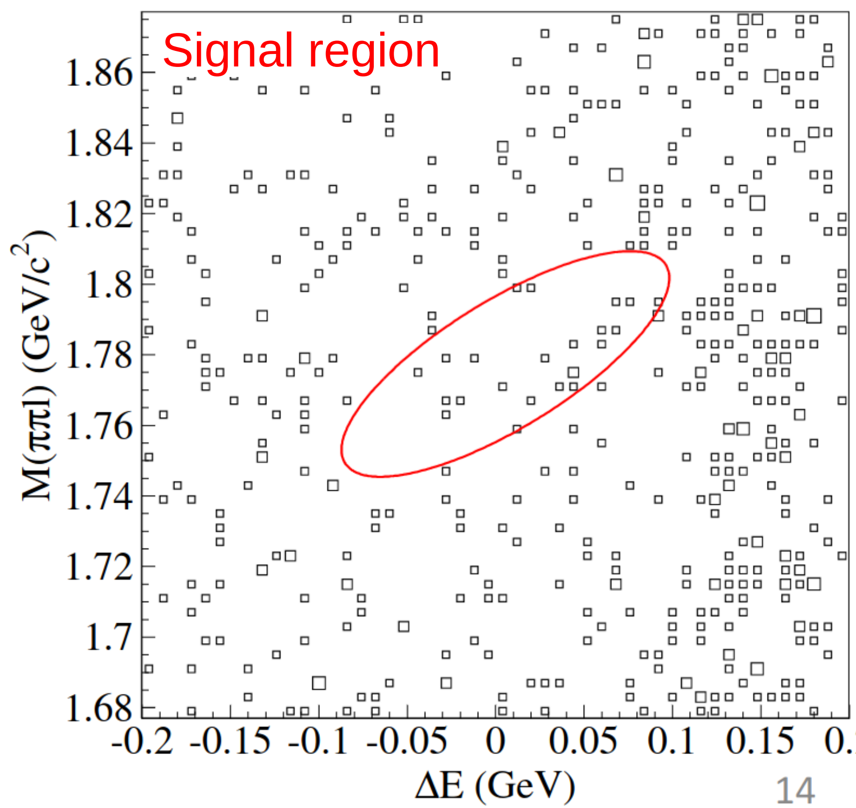
- **Signal-side : require two pions and a lepton with common vertex**
- **Tag-side : 1 or 3-prong tau decay**
- **Backgrounds originate from ee→qq, ττ, ll, eell**
  - Suppress them with M and ΔE cuts

$$\Delta E = (E_{\pi\pi l}^{CM} - \sqrt{s}/2)$$

  - Search for signal-like narrow peak



Data in M-ΔE plane



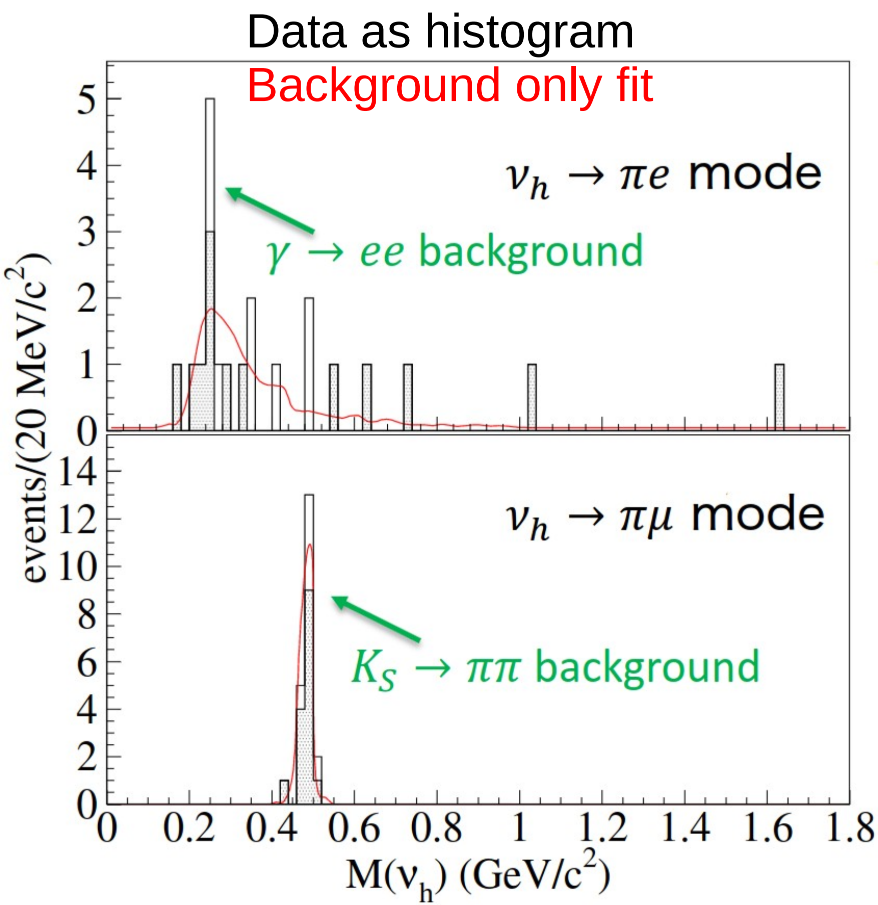
PRL 131.211802 (2023)

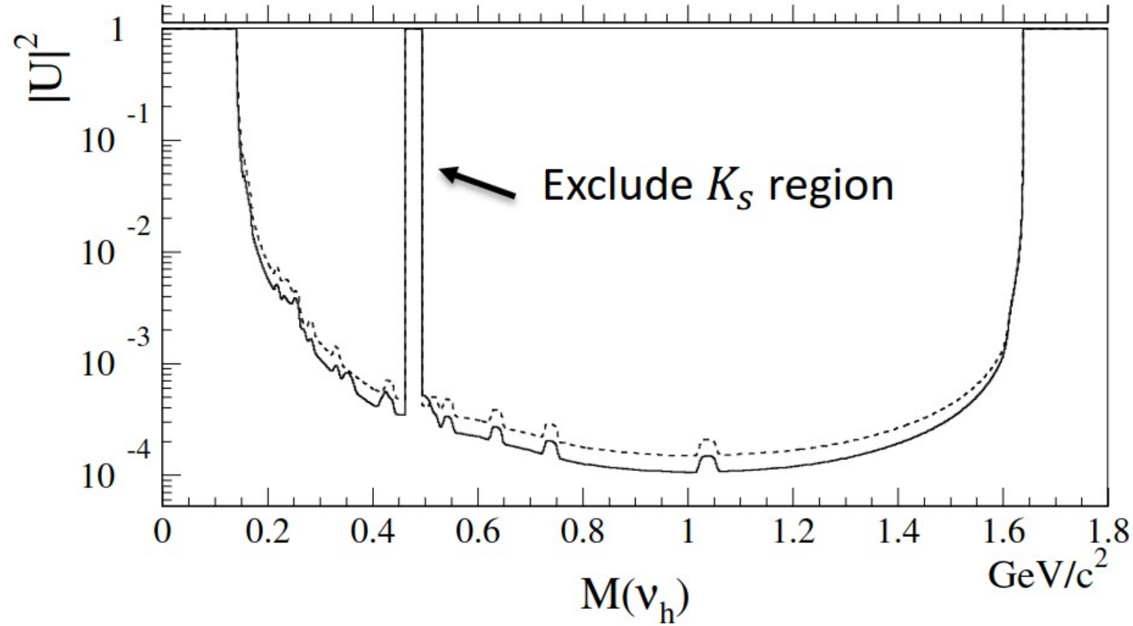
BSM : Heavy neutrino search – II

- **No narrow signal peak found in $M(\nu_h \to \pi l)$ distribution**
  - Set upper limit at 95% confidence level

$\int \mathcal{L}dt = 980\ \mathrm{fb}^{-1}$

~ 905 **Million** $ee \to \tau\tau$





UL on the heavy neutrino mixing set in the mass range

$0.2 < M(\nu_h) < 1.6\ \mathrm{GeV/c^2}$

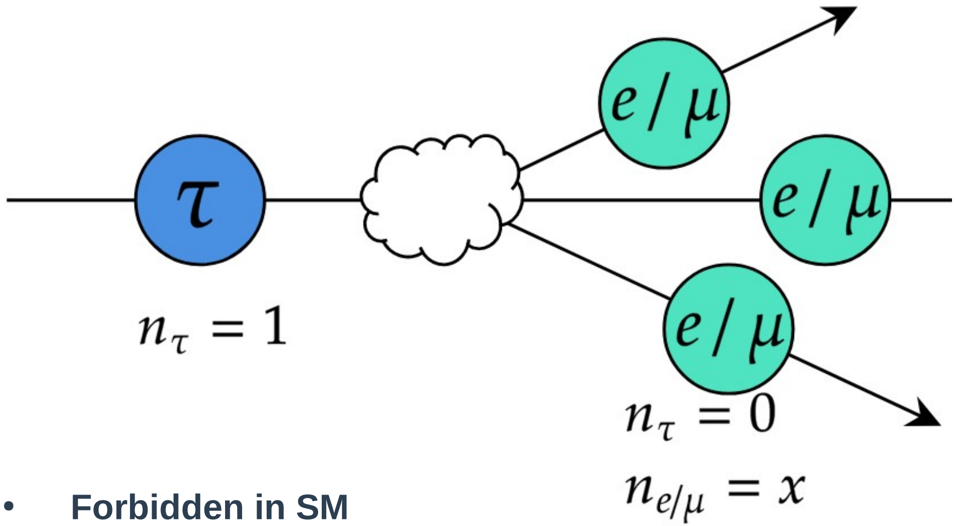
1.4×10^{-4} (1.5×10^{-4}) in Dirac-like limit for normal (inverted) hierarchy

1.0×10^{-4} (1.1×10^{-4}) in Majorana-like limit for normal (inverted) hierarchy

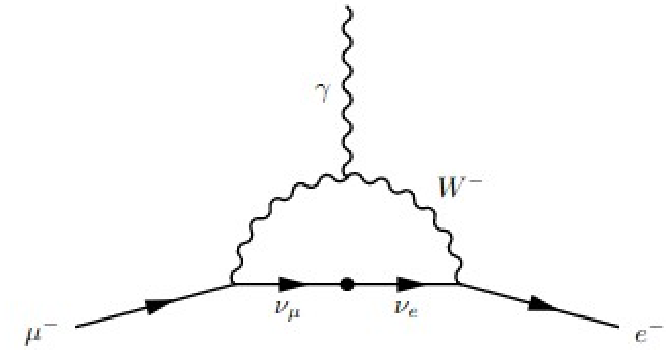
PRL 131.211802 (2023)

LFV – Motivation

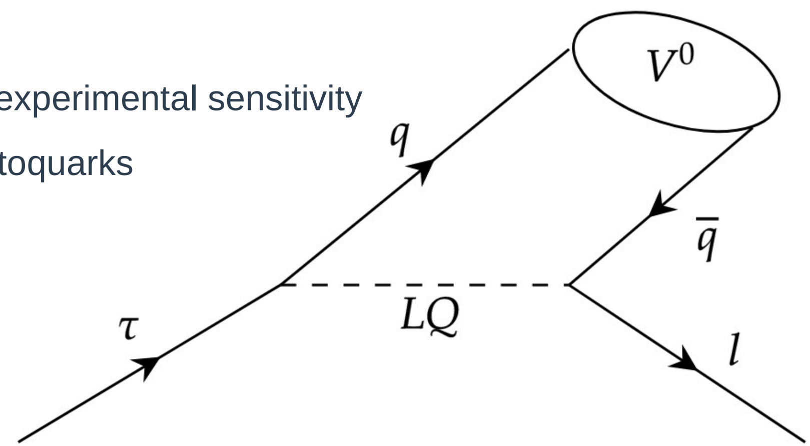
- **Lepton Flavor Violation (LFV)**



Example: LFV decay $\mu^- \rightarrow e^-\gamma$ via neutrino oscillations:

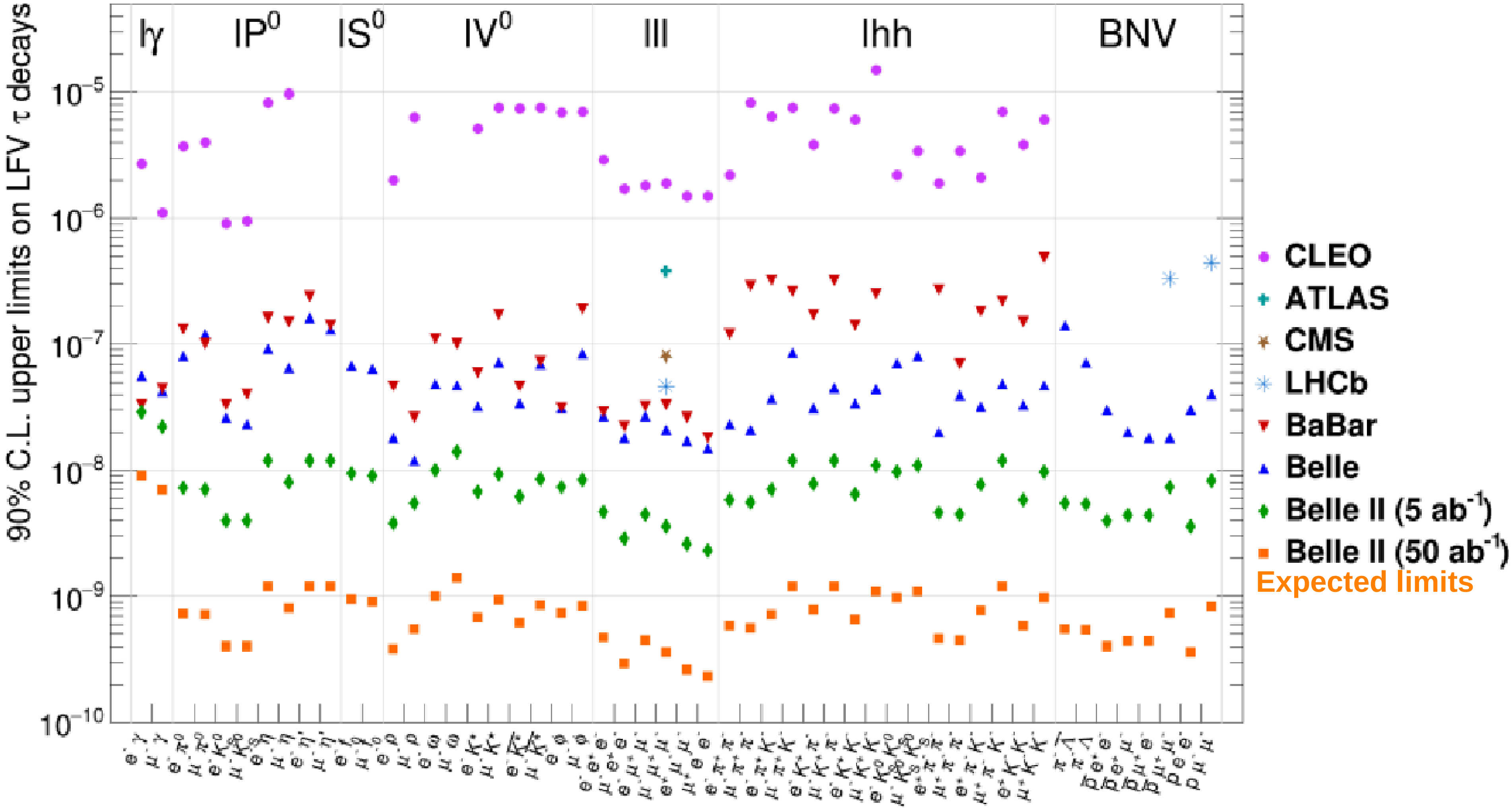


- **Forbidden in SM**
  - Only possible due to neutrino oscillation BR ~O(10^{-50}) → beyond any experimental sensitivity
  - Extensions to the SM (New Physics) predict such decays e.g. via Leptoquarks
    - Can couple to quarks and leptons and so feature LFV decays
  - Observation would be new physics



$\tau \rightarrow l\, V^0$ *via leptoquark interaction*

LFV – Past searches and projections



→ ***Belle II is expected to set new upper limits on a wide range of channels***

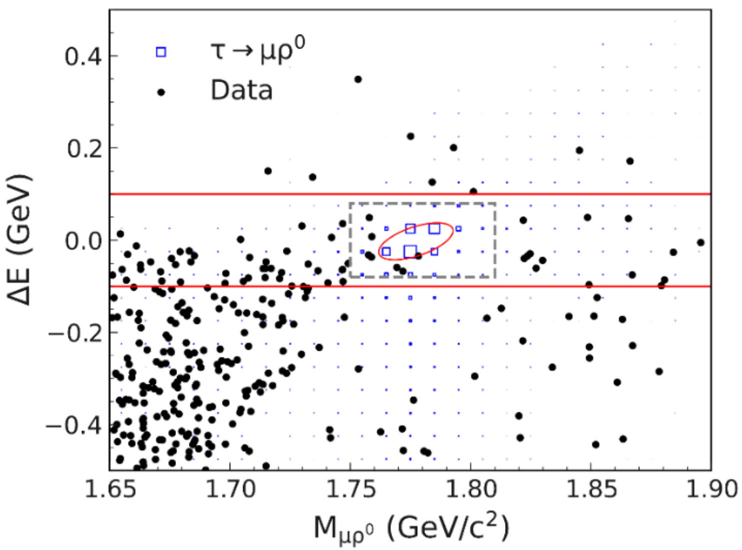
LFV : τ → l V⁰ – l

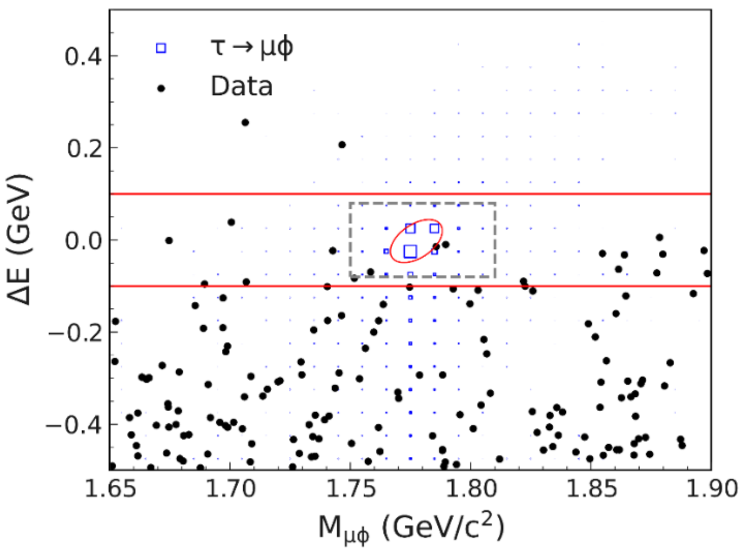
- **Signal side:**
  - Reconstruct lepton and $V^0 \in$ [ρ, ϕ, ω, K*]
- **Tag side:**
  - Reconstruct 1 or 3-prong tau
- **Backgrounds:**
  - τ → 3πν and ee → qq
  - Suppression with BDT

Source	σ_{syst} (%)
Integrated luminosity	1.4
$ee \to \tau\tau(\gamma)$ cross section [48]	0.3
$\mathcal{B}(\phi \to K^+K^-)$ and $\mathcal{B}(\omega \to \pi^+\pi^-\pi^0)$	1.2 and 0.7
Trigger efficiency	0.2–0.9
Tracking efficiency	$0.35 \times N_{\text{track}}$
Electron identification efficiency	$1.7 \times N_{\text{electron}}$
Muon identification efficiency	$1.8 \times N_{\text{muon}}$
$K^\pm$ and $\pi^\pm$ identification efficiency	1.6 (ρ^0), 1.8 (ϕ) and 1.1 (K^{*0} and $\overline{K}^{*0}$)
π^0 efficiency	$2.2 \times N_{\pi^0}$
Electron veto for hadrons	0.4–1.2
MC statistics	0.3–0.5
Track energy resolution	0.3–1.3
Photon energy resolution	0.0–0.4

$\int \mathcal{L}dt = 980\ \mathbf{fb}^{-1}$

~ 905 **Million** $ee \to \tau\tau$





JHEP06(2023)118

LFV : τ → l V^0 – II

- **No significant excess observed → set ULs at 90% CL**

World leading results

Mode	ε (%)	N_{BG}	σ_{syst} (%)	N_{obs}	$\mathcal{B}_{obs}$ ($\times 10^{-8}$)
$\tau^\pm \to \mu^\pm \rho^0$	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 *

$$B(\tau \to eV^0) < (1.7 - 2.4)\times 10^{-8}$$

$$B(\tau \to \mu V^0) < (1.7 - 4.3)\times 10^{-8}$$

Improvement ~30% compared to previous results!

JHEP06(2023)118

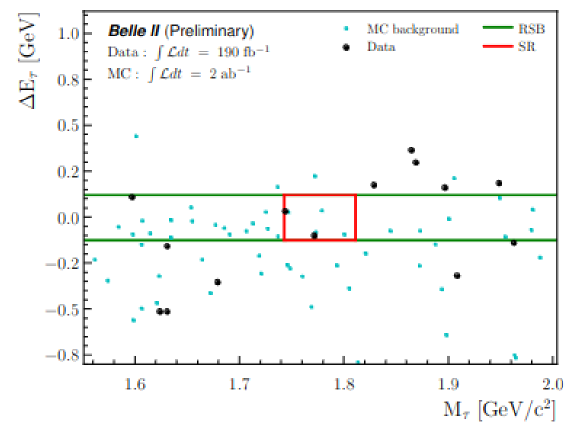
LFV : τ → l ϕ

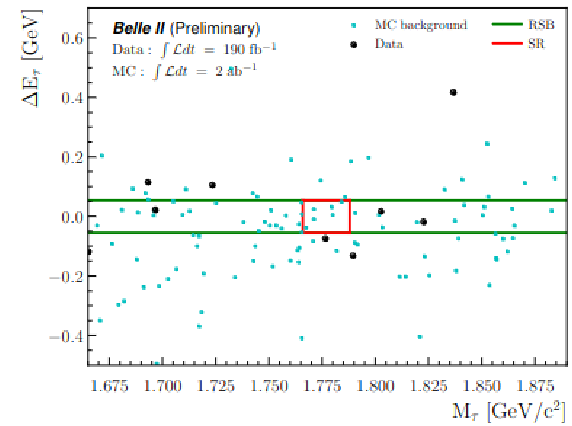
- **Untagged inclusive reconstruction: do not reconstruct the tag side into a specific decay**
  - Higher Signal efficiency (~32% improvement), more background, use of rest of event variables

$$\int \mathcal{L}dt = 190\ \mathbf{fb}^{-1}$$

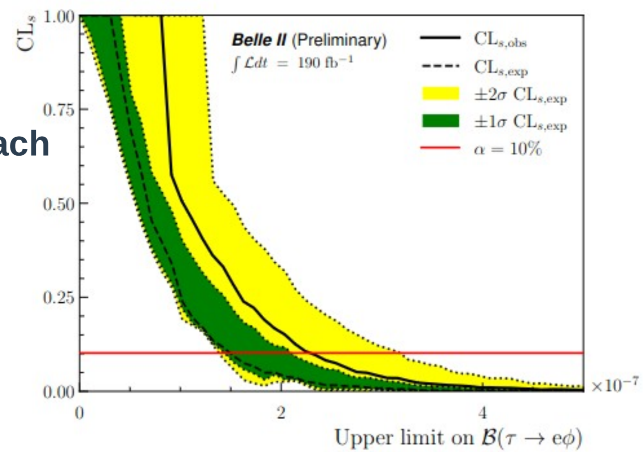
$$\sim 75\ \textbf{Million}\ ee \rightarrow \tau\tau$$

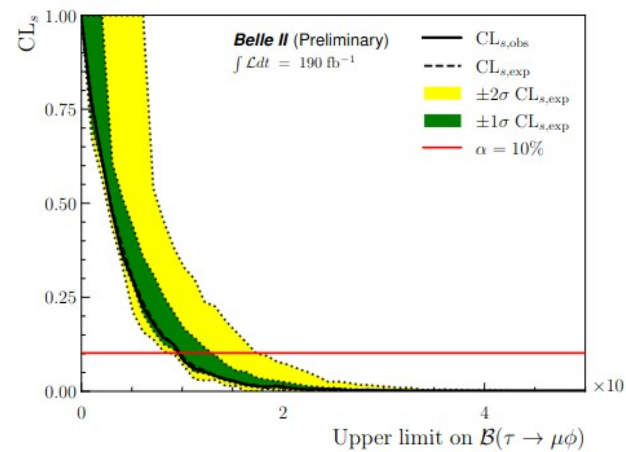
- **Backgrounds reduced with pre selections and a BDT trained against qqbar events**
- **Oberved UL @ 90% CL**
  - Electron channel : $1.0\text{x}10^{-7}$
  - Muon channel : $6.6\text{x}10^{-8}$
- **No improvement to Belle/BaBar → Small data set**
- **First, successfull untagged strategy approach for tau physics**





Experiment	$\mathcal{B}^{90}_{\text{UL}}(e\phi)\ (\times 10^{-8})$ exp. / obs.	$\mathcal{B}^{90}_{\text{UL}}(\mu\phi)\ (\times 10^{-8})$ exp / obs.
BaBar	5.0 / 3.1	8.2 / 19
Belle	4.3 / 3.1	4.9 / 8.4





https://arxiv.org/abs/2305.04759

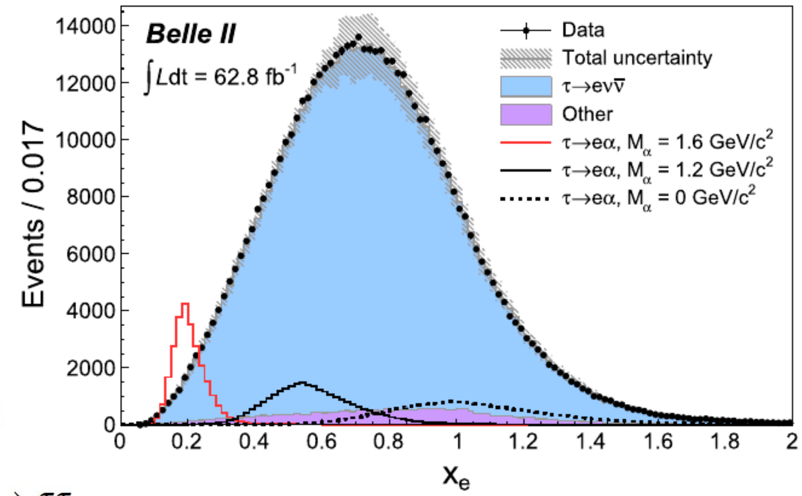
Babar : 451/fb
Belle : 854/fb

LFV : τ → lα – l

- α is an invisible spin-0 boson
  - Predicted by many models trying to incorporate neutrino-oscillation, muon magnetic moment anomaly or indirect evidence of dark matter in SM
- **This direct search probes BSM theories with high sensitivity**
- **Previous limits from ARGUS: 10^{-2} to 10^{-3} 0.5/fb of data**
  - Result from 1995

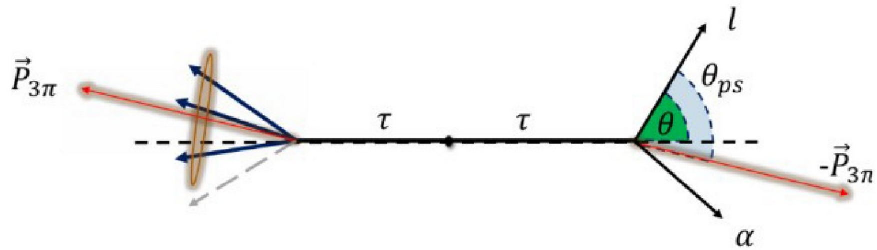
$$\int \mathcal{L}dt = 62.8\ \mathbf{fb}^{-1}$$

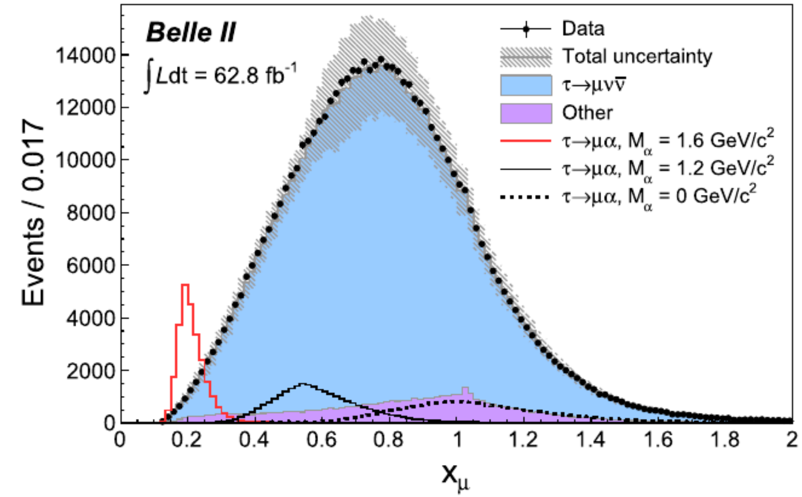
$$\sim 57.7\ \mathbf{Million}\ ee \rightarrow \tau\tau$$



- **Tau momentum cannot be determined from the decay particles directly**
  - Approximate the energy in CMS as half of the beam energy and its direction opposite to the 3 hadrons on the tag-side pseudo rest frame
  - Search for an excess above the τ → lνν nomalized lepton energy spectrum with E_l^* the energy of the charged lepton in pseudo rest frame

$$x_\ell \equiv \frac{E_\ell^*}{m_\tau c^2/2}$$





PRL 130 181803 (2023)

LFV : τ → lα – II

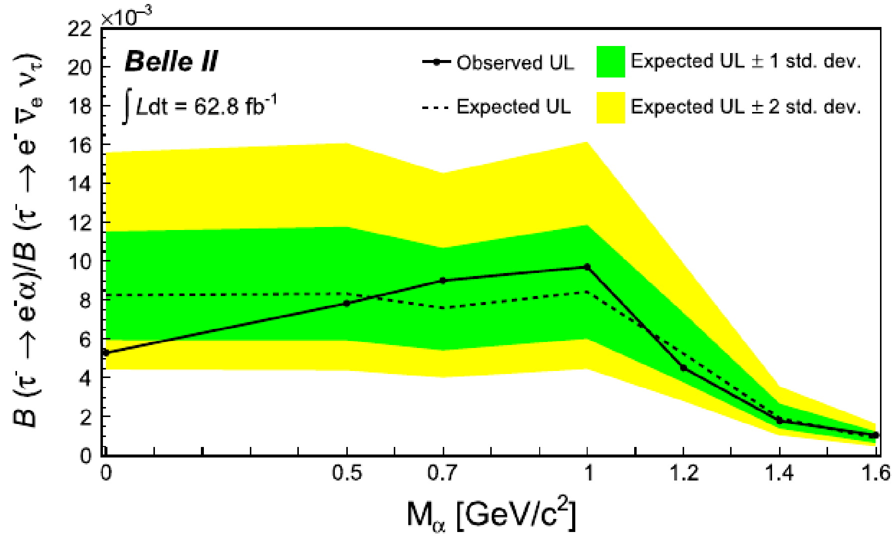
- **Simulation derived templates fit for different α mass hypotheses**
- **Measure** $\mathcal{B}_{\ell\alpha}/\mathcal{B}_{\ell\bar{\nu}\nu} \equiv \mathcal{B}(\tau^- \to \ell^-\alpha)/\mathcal{B}(\tau^- \to \ell^-\bar{\nu}_\ell\nu_\tau)$ **with τ → lνν as normalization channel**
  - Some systematics cancel → higher precision
- **2 to 14 times more stringent than ARGUS**
  - Still only early data set in use

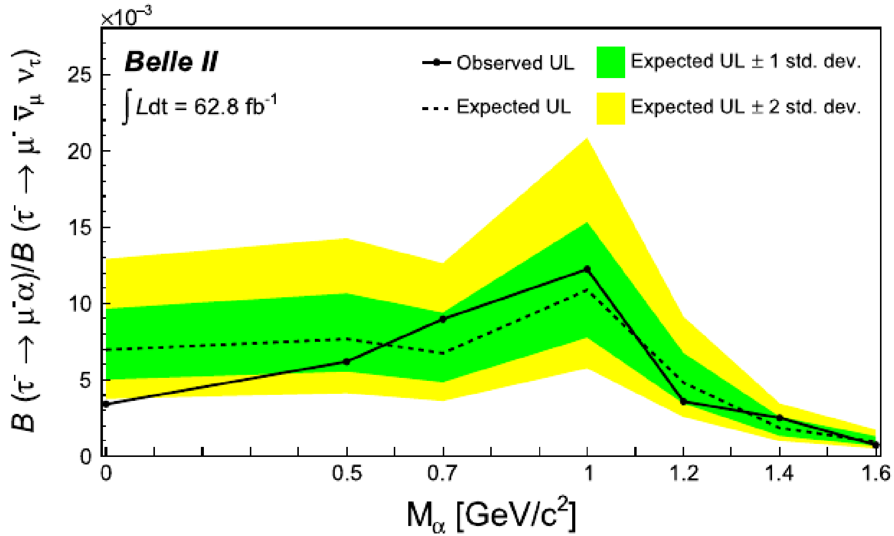
$\int \mathcal{L}dt = 62.8$ **fb**$^{-1}$

~ 57.7 **Million** $ee \to \tau\tau$

M_α [GeV/c^2]	$\mathcal{B}_{e\alpha}/\mathcal{B}_{e\bar{\nu}\nu}$ ($\times 10^{-3}$)	UL at 95% C.L. ($\times 10^{-3}$)	UL at 90% C.L. ($\times 10^{-3}$)
0.0	-8.1 ± 3.9	5.3(0.94)	4.3(0.76)
0.5	-0.9 ± 4.3	7.8(1.40)	6.5(1.15)
0.7	1.7 ± 4.0	9.0(1.61)	7.6(1.36)
1.0	1.7 ± 4.2	9.7(1.73)	8.2(1.47)
1.2	-1.1 ± 2.6	4.5(0.80)	3.7(0.66)
1.4	-0.3 ± 1.0	1.8(0.32)	1.5(0.26)
1.6	0.2 ± 0.5	1.1(0.19)	0.9(0.16)

M_α [GeV/c^2]	$\mathcal{B}_{\mu\alpha}/\mathcal{B}_{\mu\bar{\nu}\nu}$ ($\times 10^{-3}$)	UL at 95% C.L. ($\times 10^{-3}$)	UL at 90% C.L. ($\times 10^{-3}$)
0.0	-9.4 ± 3.7	3.4(0.59)	2.7(0.47)
0.5	-3.2 ± 3.9	6.2(1.07)	5.1(0.88)
0.7	2.7 ± 3.4	9.0(1.56)	7.8(1.35)
1.0	1.7 ± 5.4	12.2(2.13)	10.3(1.80)
1.2	-0.2 ± 2.4	3.6(0.62)	2.9(0.51)
1.4	0.9 ± 0.9	2.5(0.44)	2.2(0.38)
1.6	-0.3 ± 0.5	0.7(0.13)	0.6(0.10)

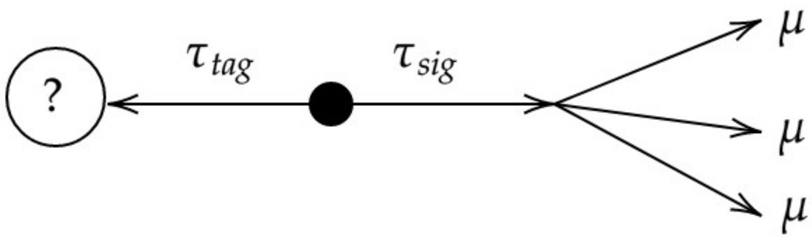




PRL 130 181803 (2023)

LFV : τ → μ μ μ – I (NEW)

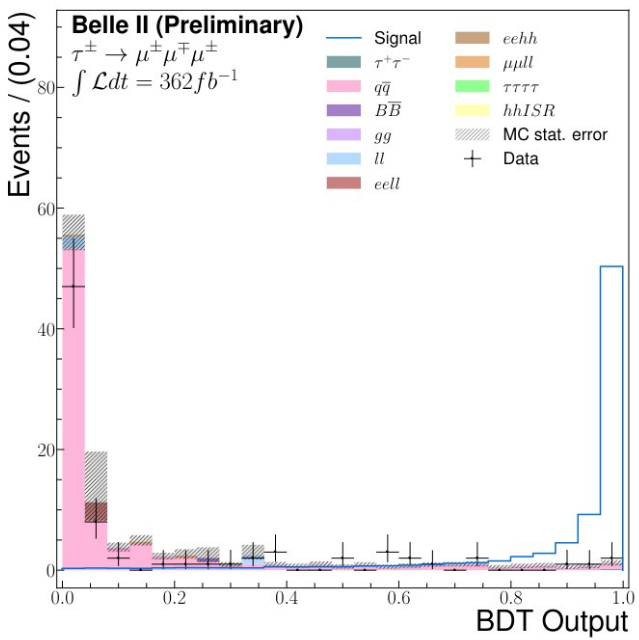
- **Best privious upper limit from Belle 2.1x10^{-8} @90% CL with 782/fb**
- **Inclusive → ~30% gain in signal efficiency, larger backgrounds**
  - Selection and background rejection based on BDT

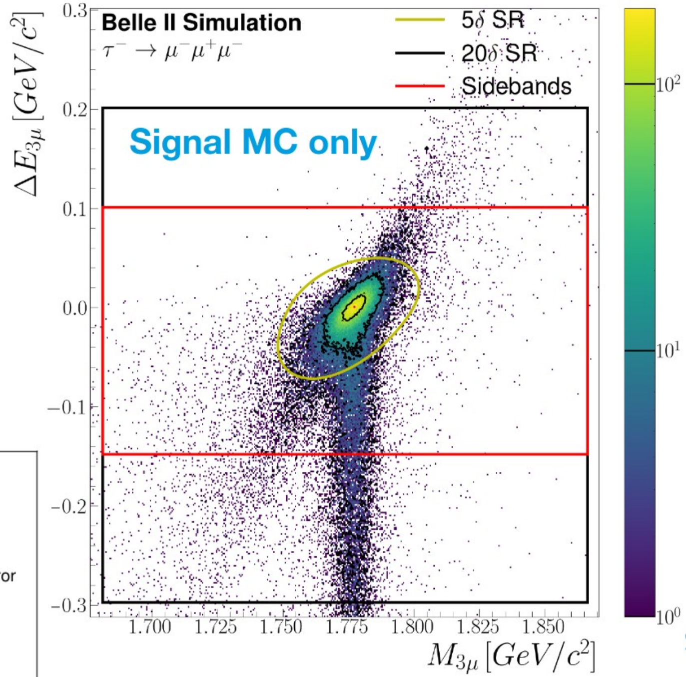


- **Fully reconstructed tau signal**
- **No peaking background from SM processes**

$$\int \mathcal{L}dt = 424\ \text{fb}^{-1}$$

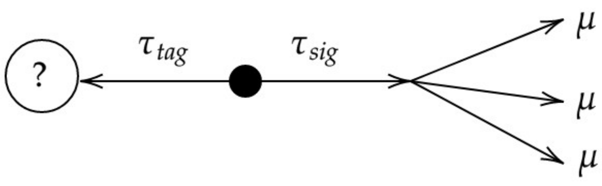
$$\sim 391\ \text{Million}\ ee \to \tau\tau$$





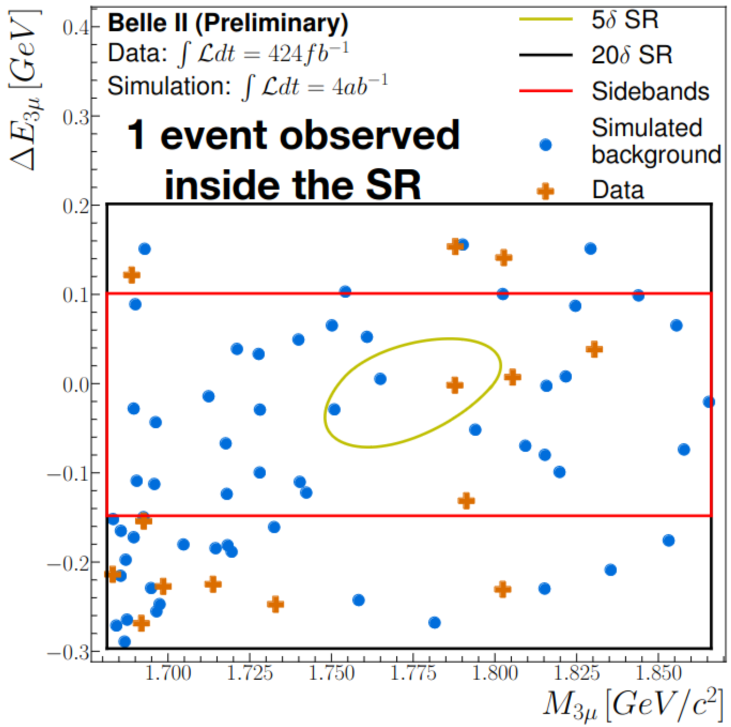
LFV : $\tau \to \mu\,\mu\,\mu$ – II (NEW)

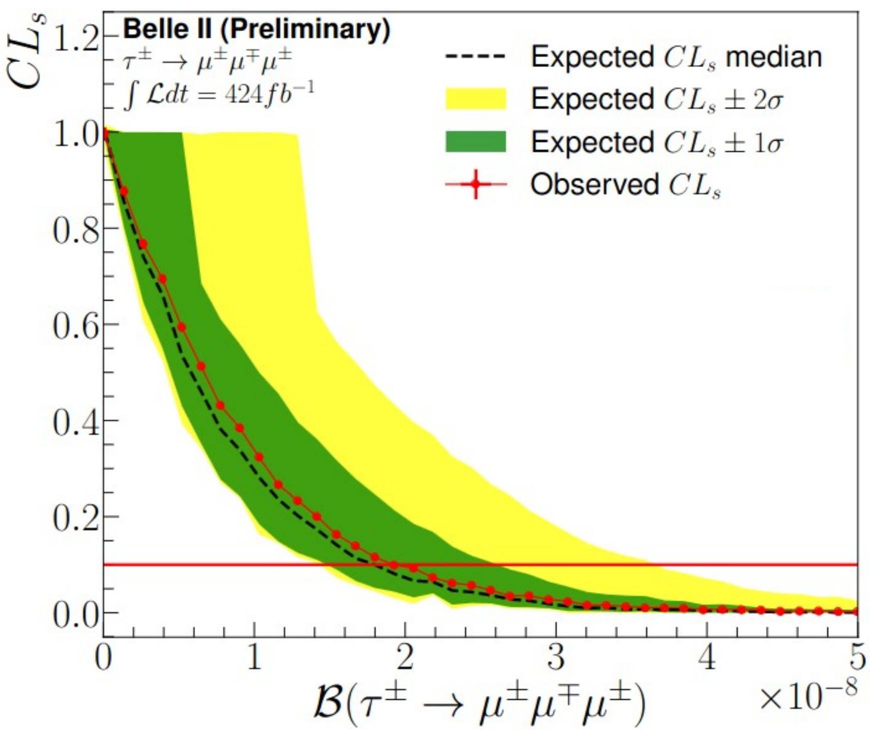
- **XGBoost BDT with 32 variables**
  - Inputs from signal tau, event tag-side and event shape/kinematic variables
  - ε = 20.42 % ~ 3 times larger than Belle
  - Expected background events : $0.5^{+1.4}_{-0.5}$
- **No significant excess → calculate UL @90% CL with 424/fb using CLs method**



Recent CMS result

UL @ 90%CL : 2.9×10^{-8}





UL @ 90% CL: 1.9×10^{-8} → most stringent!

Summary

- **B factories are a good environment for tau physics!**

- **Belle and Belle II will contribute to the understanding of tau lepton properties**
  - Searches for BSM physics
  - LFU
  - Presicion measurements of SM parameters

- **Analysis with combined Belle & Belle II data sets are ongoing**

- **A lot more to come with more data**
  - Now 424/fb, next run starting in the coming weeks

- **Topics not covered:**
  - Michel Parameters : PRL 131.021801 (2023)
  - Tau lifetime → ongoing study
  - LFV → ongoing studies