Precision measurements of τ lepton decays at Belle II

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on behalf of the Belle II collaboration.

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

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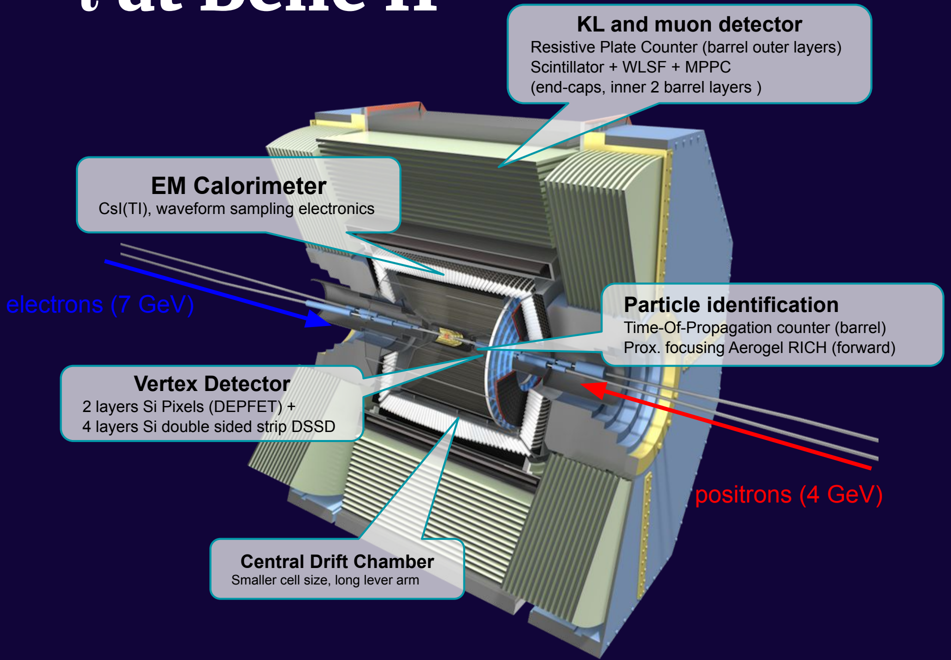
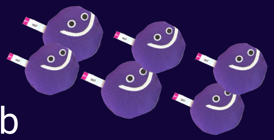
τ at Belle II



Belle II at **SuperKEKB** electron-positron asymmetric beams collider.
Center-of-mass energy of $\sqrt{s} \approx m_{\Upsilon(4S)} \approx 10.58$ GeV.
Luminosity **world record**: 4.7 x 10^{34} $\text{cm}^{-2}\ \text{s}^{-1}$.



B-factories are also **τ**-factories:

- $\sigma(e^+e^- \rightarrow \Upsilon(4s) \rightarrow B\bar{B})$ = 1.05 nb
- $\sigma\ (e^+e^- \rightarrow \tau^+\tau^-)$ = **0.919** nb

Belle II has recorded **> 470 fb^{-1}** ≈ **432 million τ pairs.**
The goal is to reach **50 ab^{-1}** ≈ **46 billion τ pairs.**

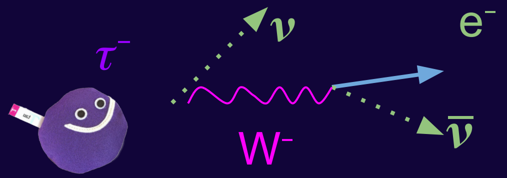
Run 1 (2019-2022): 424 fb^{-1} . } on-resonance (10.58 GeV) and off-resonance.

Run 2 (February 2024-): Currently taking data.

Features:

- Clean environment
- Well defined initial state energy
  → Well known E_{missing}.
- Efficient neutrals reconstruction
- Low multiplicity trigger menus
- Particle Identification system.
- High tracking resolution.

τ Lepton



τ decay into hadrons (> 200 channels) and leptons.

PDG 2023
M_τ = 1776.86 ± 0.12 MeV/c²
$\tau_\tau = (290.3 \pm 0.5) \times 10^{-15}$ s

τ Lepton allows us to perform **Standard Model (SM) precision measurements** and search for **new physics**.

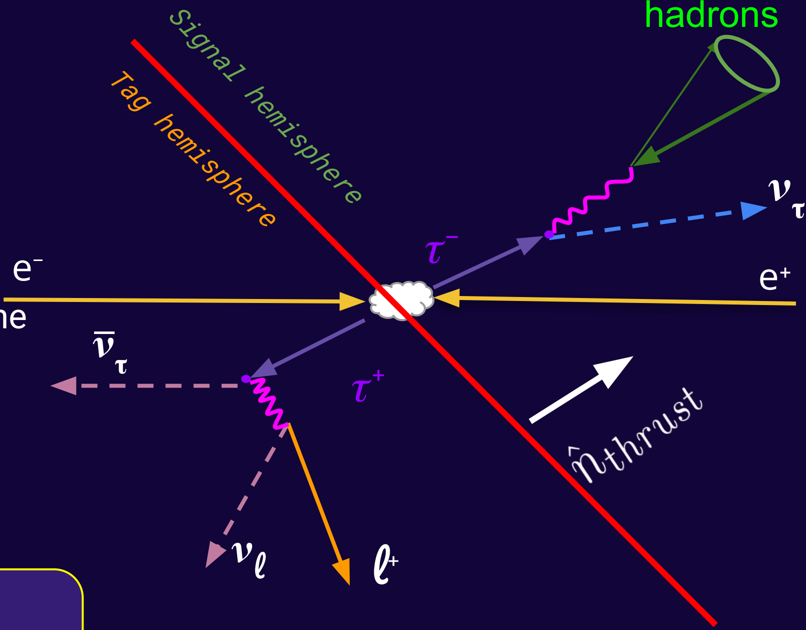
- τ events are produced back-to-back in CM frame.

$$E_\tau^{CMS} \sim \frac{\sqrt{(s)}}{2}$$

*In absence of ISR.

- Events can be classified in two hemispheres (sig, tag) using the thrust axis.

$$V_{thrust} = \frac{\sum_i \vec{p}_i^{\,CMS} \cdot \hat{n}_{thrust}}{\sum_i |\vec{p}_i^{\,CMS}|}$$



In this talk:
- Measurement of the τ-lepton mass.
- Test of Lepton Flavor Universality.

Phys. Rev. D 108, 032006

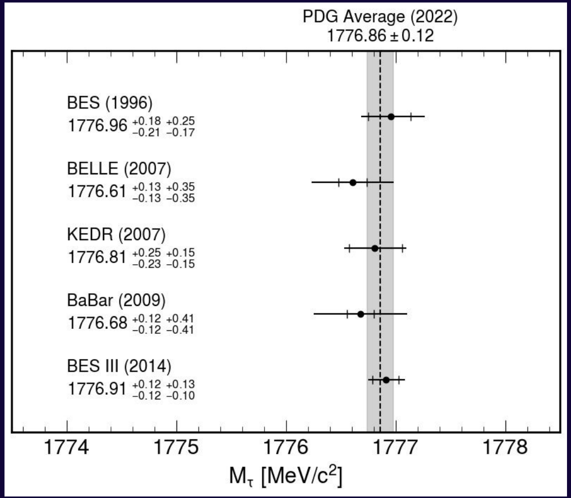
1.777 GeV/c²
-1
½ τ
tau

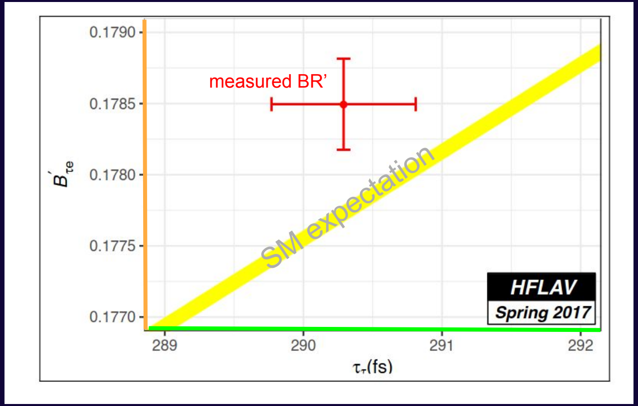
Measurement of the τ-lepton mass

- One of the fundamental parameter of the Standard Model.
    - Precision is important for predictions of τ branching fractions.
- Involved in the Test of Lepton flavor universality.
- Previous results dominated by systematic uncertainties.
- Deviation from SM prediction →evidence of New Physics.

SM predicts the relation:

$$\boxed{B_{\tau l}^{SM}} \propto B_{\mu e} \cdot \frac{\boxed{\tau_\tau}}{\tau_\mu} \cdot \frac{m_\tau^5}{m_\mu^5}$$





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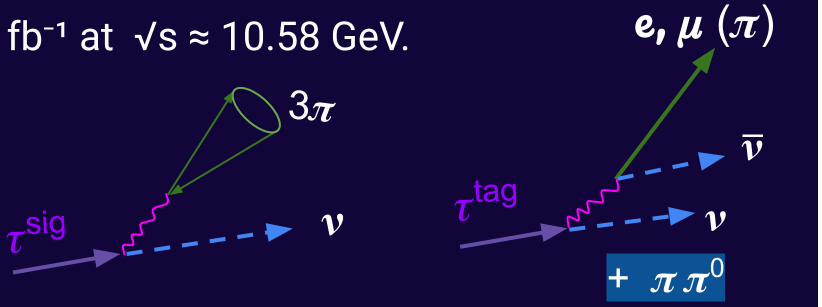
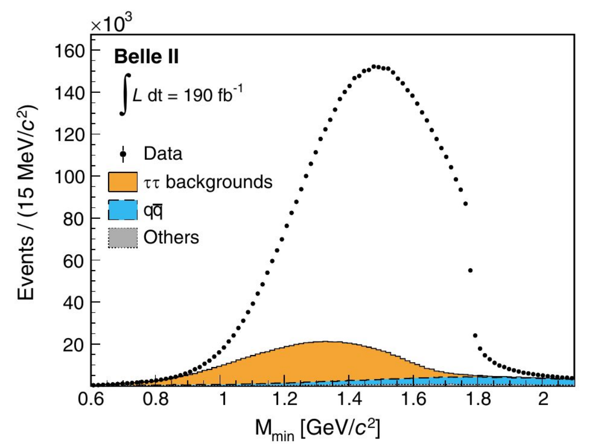
Measurement of the τ-lepton mass

Belle II dataset of 190 fb^{-1} at $\sqrt{s} \approx 10.58$ GeV.

Event Selection





- Main backgrounds $e^+e^- \to q\bar{q}$ & $e^+e^- \to \tau^+\tau^-$, with other tau decays than $\tau^\mp \to \pi^\mp \pi^+ \pi^- \nu$.
- Background suppression via FOM maximization. Purity = 90%.

Method

Then , the τ mass, assuming zero mass of the neutrino, is given by

$$m_\tau = \sqrt{M_{3\pi}^2 + 2(E_\tau^* - E_{3\pi}^*)(E_{3\pi}^* - p_{3\pi}^* \cos\alpha^*)}$$

* = CMS

The energy of the τ is half of the collision energy, and assuming α zero, we defined the pseudomass

$$M_{min} = \sqrt{M_{3\pi}^2 + 2(\sqrt{s}/2 - E_{3\pi}^*)(E_{3\pi}^* - p_{3\pi}^*)} \leq m_\tau$$

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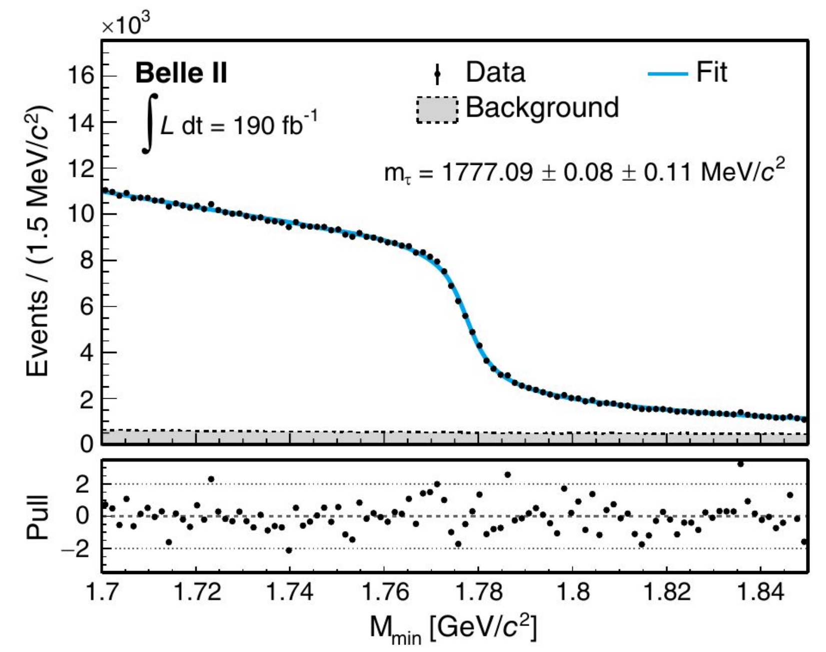
Measurement of the τ-lepton mass

The distribution of the pseudomass is fitted to a empirical edge function to estimate **τ** lepton mass.

$$F(M,\vec{P}) = -P_3 \cdot \tan^{-1}[(M-P_1)/P_2] + P_4(M-P_1) + P_5(M-P_1)^2 + 1$$

P_1 is the estimator of the mass. An unbinned maximum-likelihood fit is performed.



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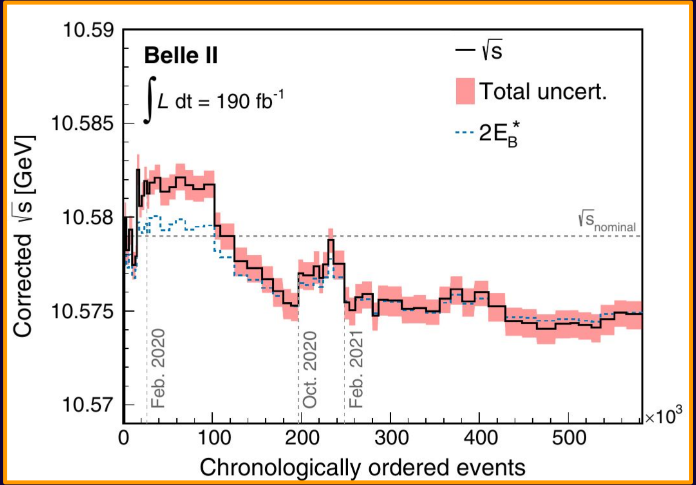
Measurement of the τ-lepton mass

Systematic Uncertainties

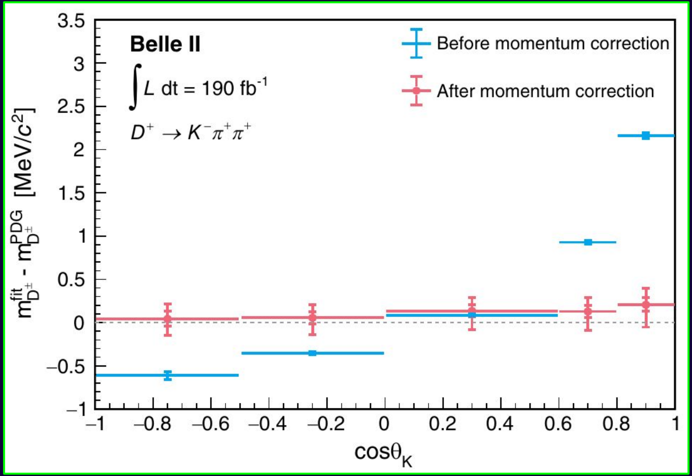
$$M_{min} = \sqrt{M_{3\pi}^2 + 2(\underline{\sqrt{s}/2} - E_{3\pi}^*)(E_{3\pi}^* \underline{- p_{3\pi}^*})} \leq m_\tau$$

Calibrated from fully reconstructed B-mesons.



~ 0.07MeV/c²
~ 70 KeV/c²

Calibrated from $D^0 \to K^- \pi^+$.



~ 0.06MeV/c²
~ 60 KeV/c²

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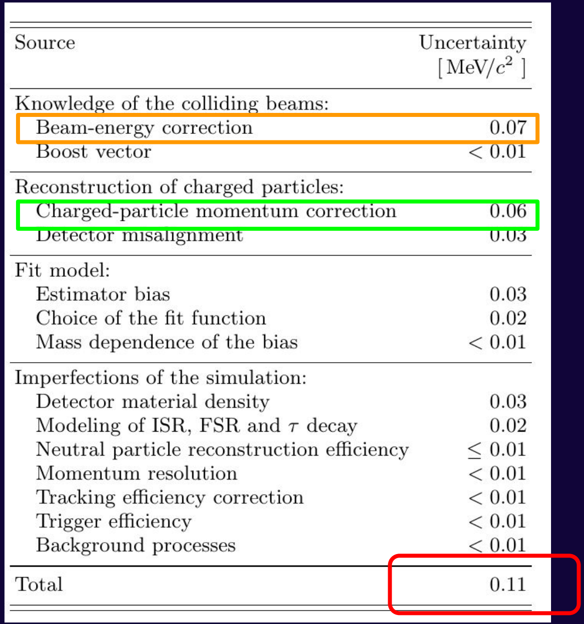
Measurement of the τ-lepton mass

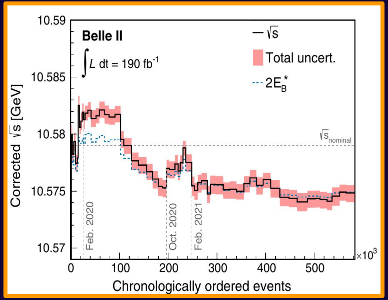
Systematic Uncertainties

$$M_{min} = \sqrt{M_{3\pi}^2 + 2(\underline{\sqrt{s}/2} - E_{3\pi}^*)(E_{3\pi}^* - \underline{p_{3\pi}^*})} \leq m_\tau$$



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

Calibrated from fully reconstructed B-mesons.



~ 0.07MeV/c²
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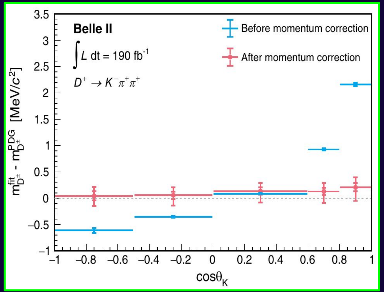

~ 0.06MeV/c²
~ 60 KeV/c²

- ❖ Additional consistency test were carried out, time and kinematic region dependence, simulation modeling.
→ Everything was found consistent.

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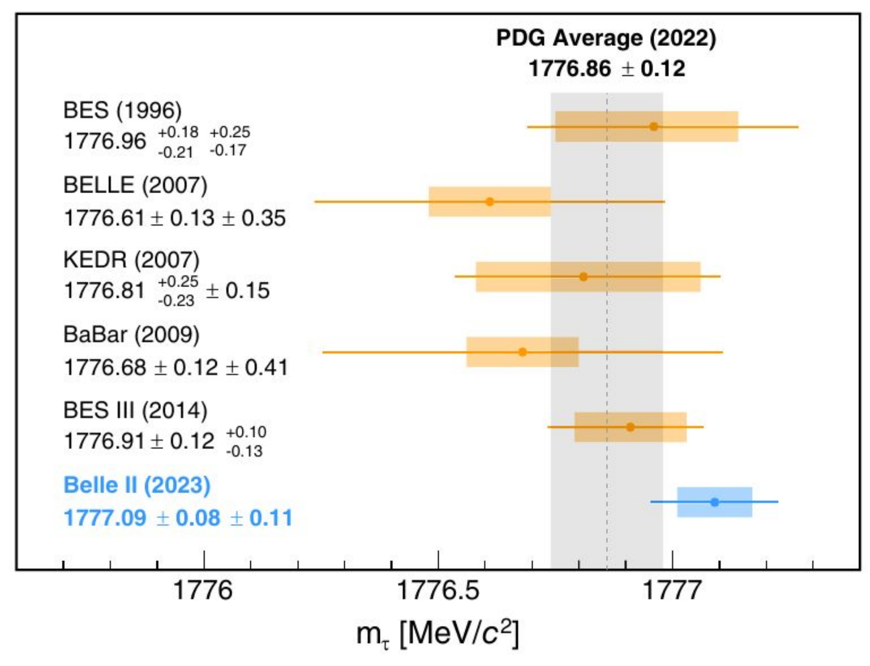
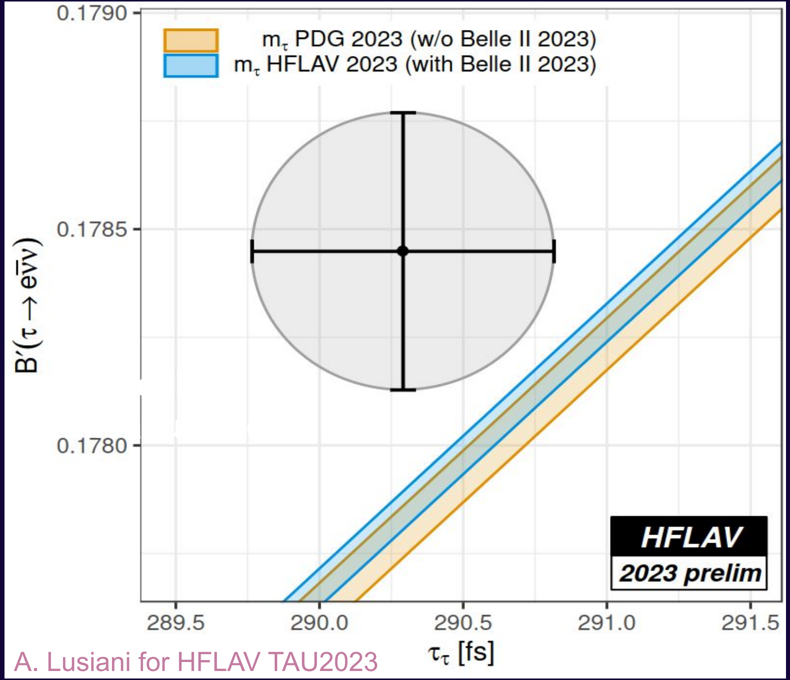
Measurement of the τ-lepton mass

The most precise to date!

Belle II

Results $$m_\tau = 1777.09 \pm 0.08 \pm 0.11\ \mathrm{MeV}/c^2$$





A. Lusiani for HFLAV TAU2023

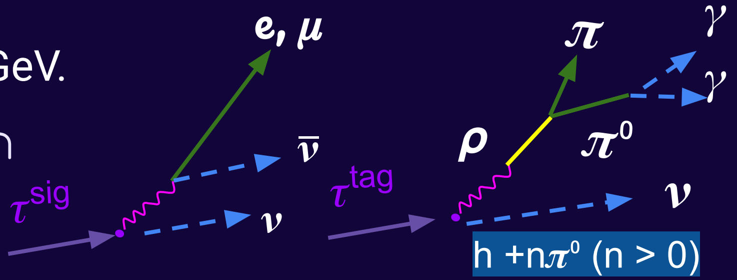
Test of Lepton Flavor Universality

with $f(x) = 1 - 8x + 8x^3 - x^4 - 12x^2 \ln x$

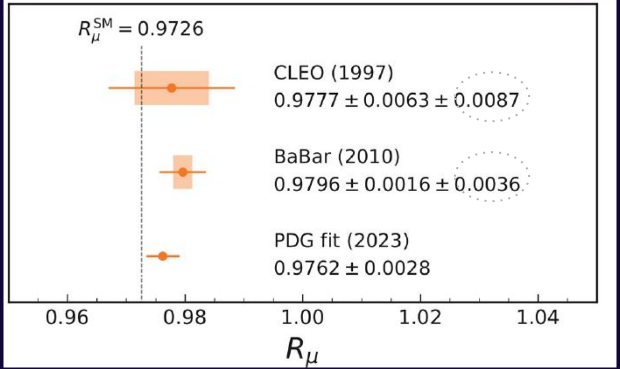
- Test for μ-e universality: $$R_\mu = \frac{\mathcal{B}(\tau^- \to \mu^- \bar{\nu}_\mu \nu_\tau)}{\mathcal{B}(\tau^- \to e^- \bar{\nu}_e \nu_\tau)} \Rightarrow \left(\frac{g_\mu}{g_e}\right)_\tau = \sqrt{R_\mu \frac{f(m_e^2/m_\tau^2)}{f(m_\mu^2/m_\tau^2)}}\ .$$
- **τ** decays are sensitive to charged and non-SM neutral currents.
- LFU violation. →evidence for New Physics.

➔ Belle II dataset of 362 fb^{-1} at $\sqrt{s} \approx 10.58$ GeV.

Event Selection



Previous measurements:



➔ $\tau_{sig} \to \pi\nu$, $\rho\nu$ X $\tau_{tag} \to \rho\nu$.

- Main backgrounds ➔ Correctly reconstructed signal but wrong tag.
  ➔ $e^+e^- \to q\bar{q}$, $e^+e^-\gamma$, $\mu^+\mu^-\gamma$.

- Background suppression of both channels via Neural Network.
- Purity 96% and 92% for electron and muon channel.

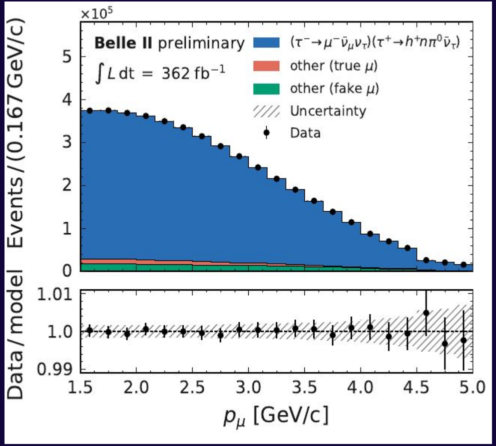
Test of Lepton Flavor Universality

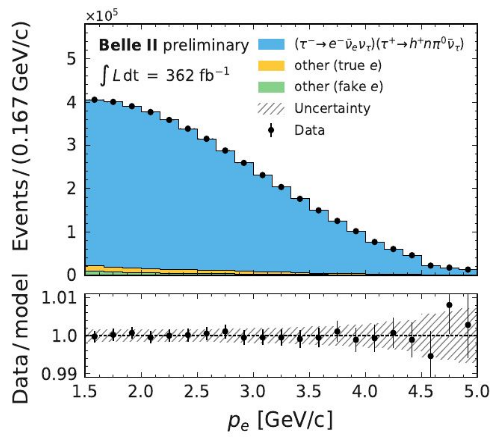
Method

The measurement is done in the lepton momentum P_l, where a binned maximum likelihood is constructed:

$$f(\vec{n}|R_\mu,\vec{\chi}) = \overbrace{\prod_{b\in\text{bins}} \mathcal{P}(\underbrace{n_b^e}_{\text{obs}}|\underbrace{\nu_b^e(\vec{\chi})}_{\text{exp from simulation}}))}^{\text{electron channel}} \times \underbrace{\prod_{b\in\text{bins}} \mathcal{P}(n_b^\mu|\nu_b^\mu(R_\mu,\vec{\chi}))}_{\text{muon channel}} \times \prod_{\chi\in\vec{\chi}} c_\chi(a_\chi|\chi)$$

The background templates are split by the signal-side particle type. →true or fake lepton.





$$\nu_b^e(\vec{\chi}) = \kappa_e \times \nu_b^{e,\text{sig}} + \nu_b^{e,\text{bkg(true)}} + \nu_b^{e,\text{bkg(fake)}}$$

$$\nu_b^\mu(R_\mu,\vec{\chi}) = R_\mu \times \kappa_{e/\mu}^{\text{gen}} \times \kappa_e \times \nu_b^{\mu,\text{sig}} + \nu_b^{\mu,\text{bkg(true)}} + \nu_b^{\mu,\text{bkg(fake)}}$$

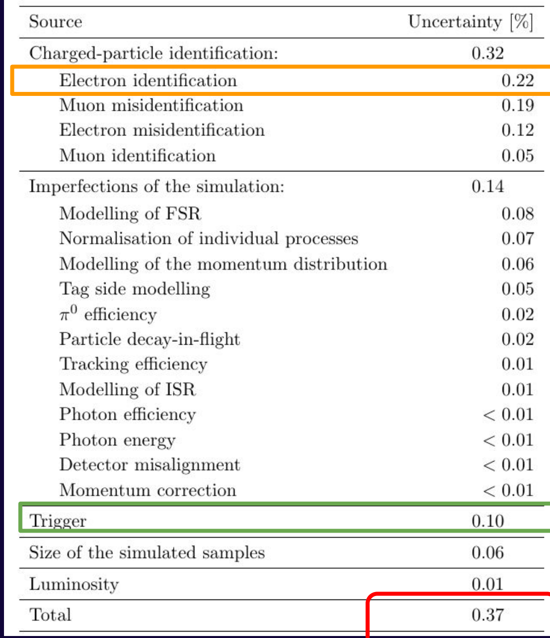
R_μ is directly extracted from the fit.

The systematics are included in the likelihood as a set of nuisance parameters.

Test of Lepton Flavor Universality

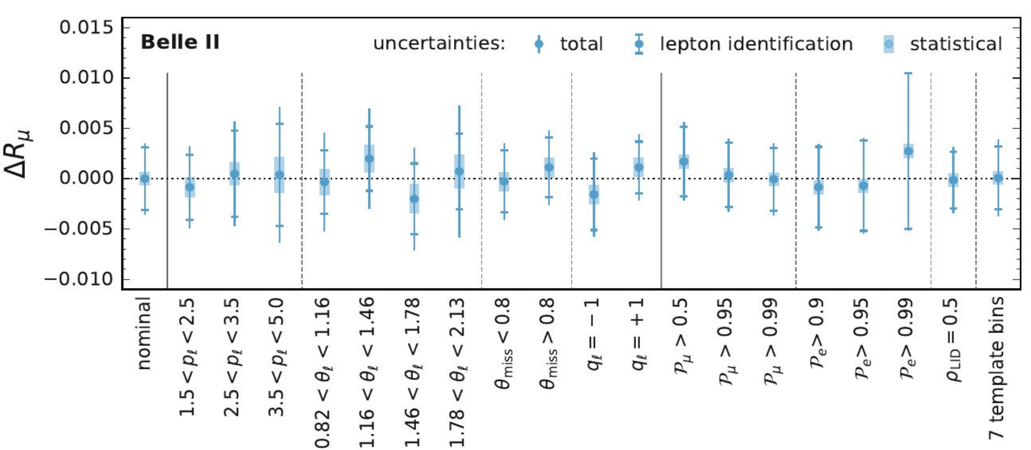
Systematic uncertainties

- Main systematics come from lepton identification and triggers.



Source	Uncertainty [%]
Charged-particle identification:	0.32
Electron identification	0.22
Muon misidentification	0.19
Electron misidentification	0.12
Muon identification	0.05
Imperfections of the simulation:	0.14
Modelling of FSR	0.08
Normalisation of individual processes	0.07
Modelling of the momentum distribution	0.06
Tag side modelling	0.05
π^0 efficiency	0.02
Particle decay-in-flight	0.02
Tracking efficiency	0.01
Modelling of ISR	0.01
Photon efficiency	< 0.01
Photon energy	< 0.01
Detector misalignment	< 0.01
Momentum correction	< 0.01
Trigger	0.10
Size of the simulated samples	0.06
Luminosity	0.01
Total	0.37

Consistency of the result



Good agreement between results.

submitted to JHEP; arXiv:2405.14625

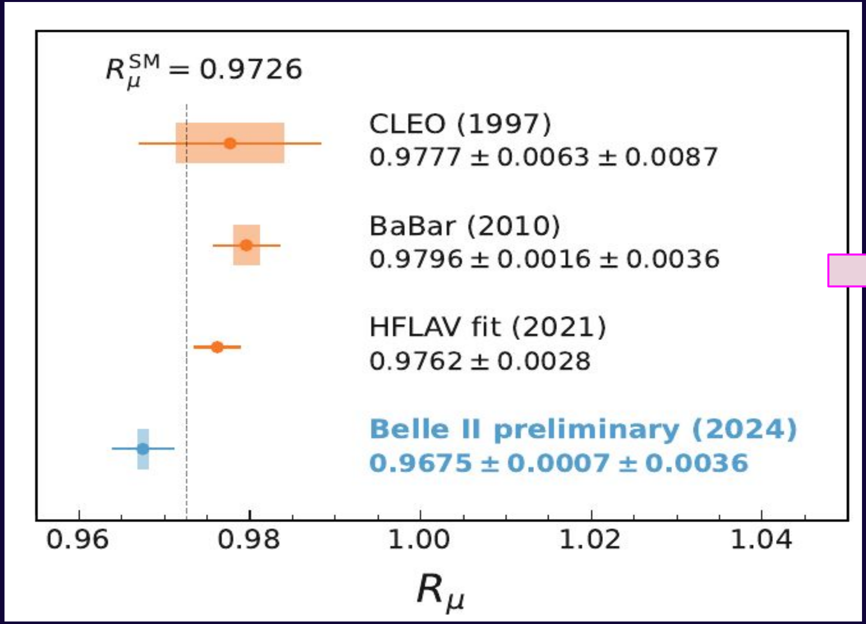
Test of Lepton Flavor Universality

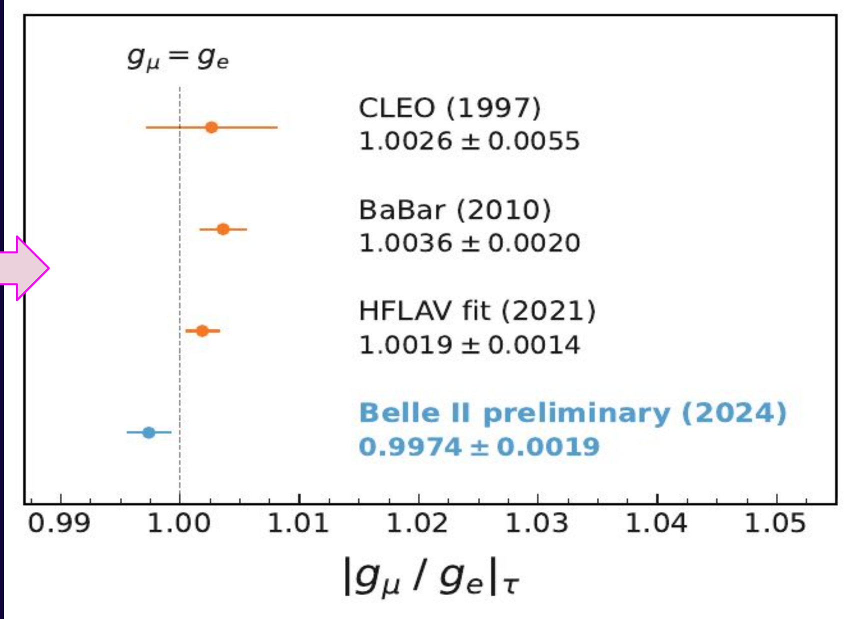
Results $$R_\mu = \frac{\mathcal{B}(\tau^- \to \mu^- \bar{\nu}_\mu \nu_\tau)}{\mathcal{B}(\tau^- \to e^- \bar{\nu}_e \nu_\tau)} = 0.9675 \pm 0.0007 \pm 0.0036$$

The most precise to date!

Belle II

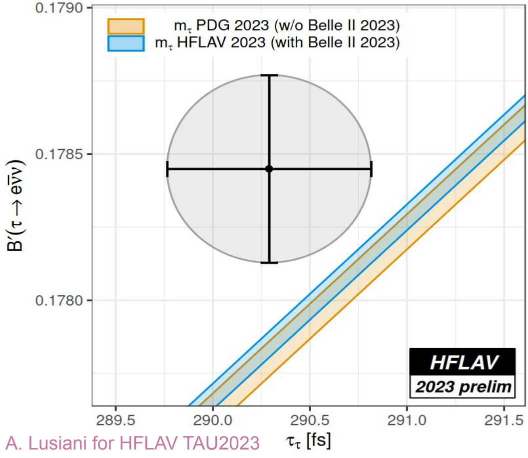
- ➢ Consistent with the SM at 1.4 **σ**.





Summary

Belle II has provided the most precise measurements in M_τ and LFU (μ-e).
These measurements bring us closer to the Standard Model's predictions.



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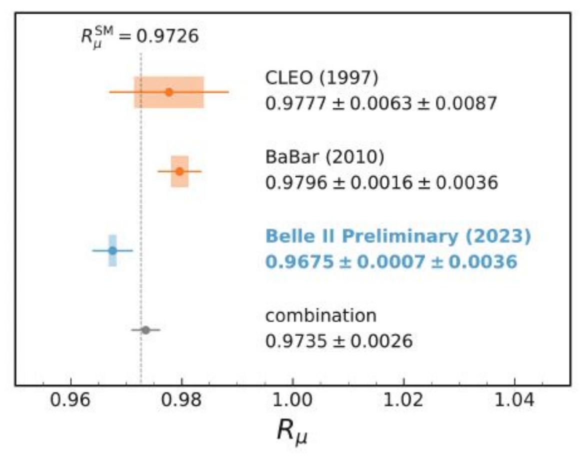
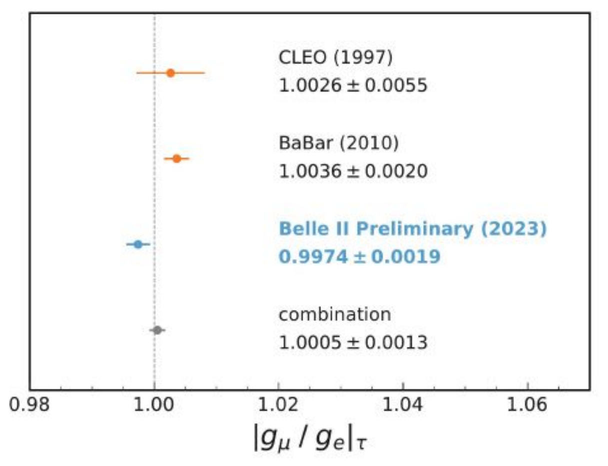




Assuming independent systematics.

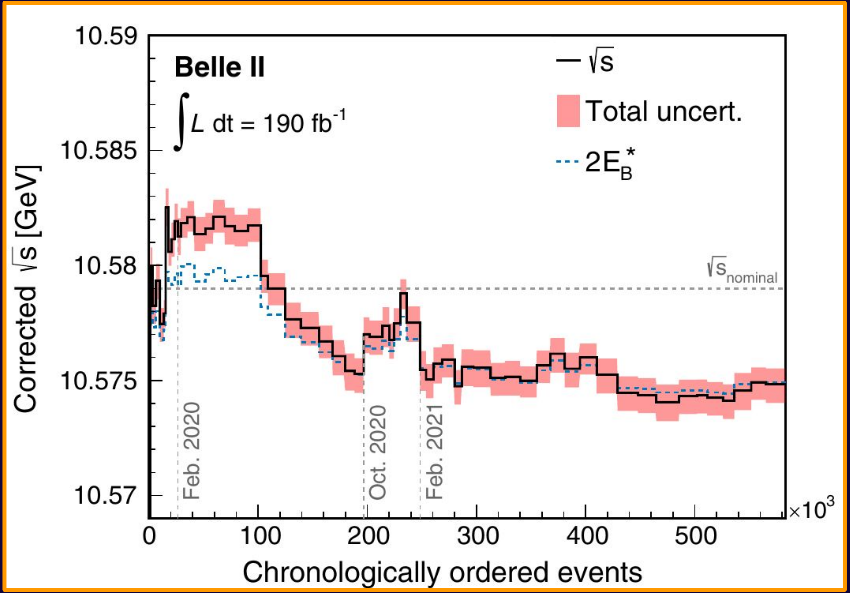
Coming soon:

- Measurement of Vus element. Using the $\tau \to K\nu$, $\tau \to \pi\nu$ decays.
- Update of the LFU measurement.
- τ Lifetime
- Search of CP violation in the $\tau \to K^0_S \pi \nu$ ($\geq 0\ \pi^0$) decay.

BACKUP

Bean-Energy correction

Beam energy was calibrated using fully reconstructed B decays.



We exploit the fact that the collision energy is just slightly above the kinematic production threshold for BB pairs.

Uncorrected energy

$$E^*_B = \sqrt{m_B^2 + (p^*_B)^2} \approx m_B + \frac{1}{2m_B}(p^*_B)^2.$$

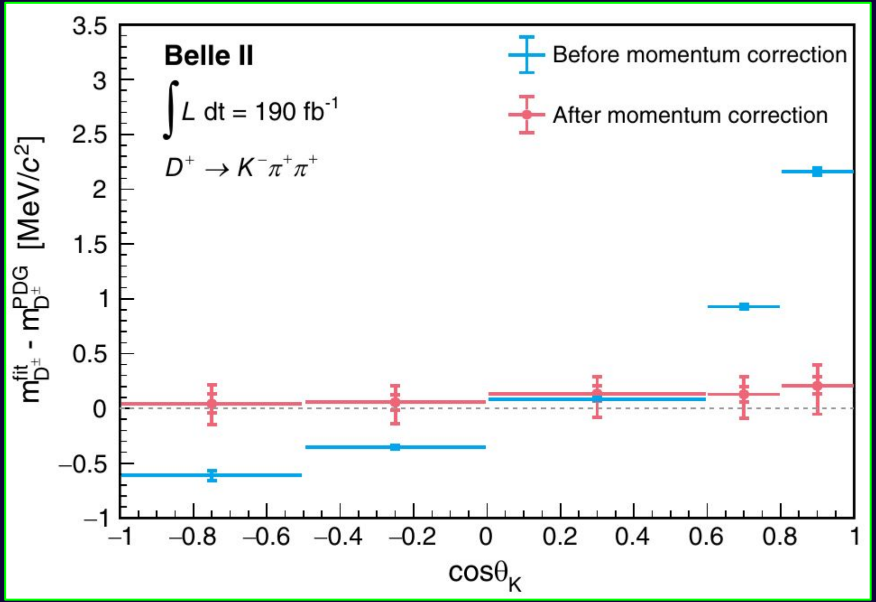
Relation considering event by event center of mass energy

$$E^*_B = \frac{1}{2}\sqrt{s'(1-x)}.$$

x is the energy carried by the ISR.

The collision energy is obtained from E^*_B after correcting for the effect of ISR and by accounting for the energy dependence of the ee →BB cross section.

Charged-Particle momentum correction

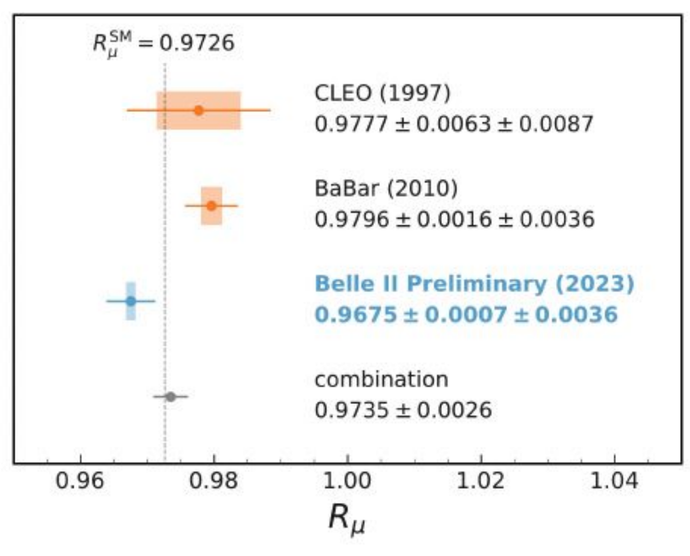


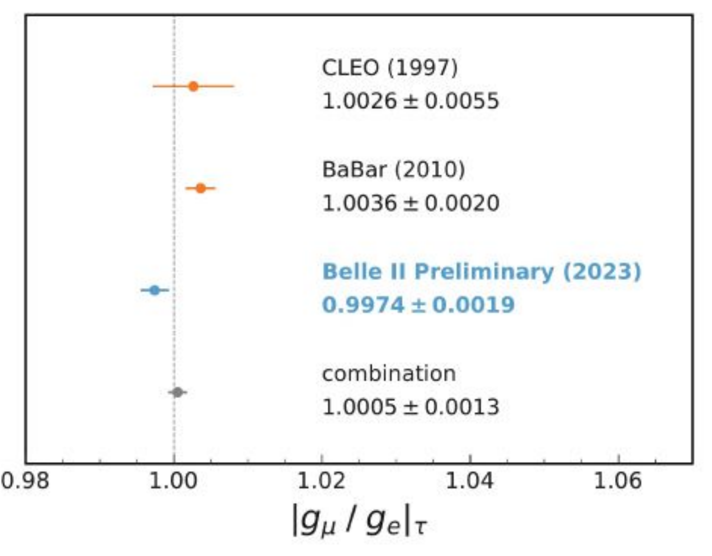
The corrections for the daughter pion momenta were obtained from the $D^0 \to K^- \pi^+$ sample with cross-checks in the

$D^+ \to K^- \pi^+\pi^+$, $D^0 \to K^- \pi^+ \pi^- \pi^+$, and $J/\psi \to \mu^+ \mu^-$ samples.

The difference between the reconstructed and nominal masses of the D+ meson before and after corrections.

Combination LFU





Assuming independent systematics.

Vus

$$|V_{us}| = R_{K/\pi}^{1/2} |V_{ud}| \frac{f_\pi}{f_K} \frac{1 - m_\pi^2/m_\tau^2}{1 - m_K^2/m_\tau^2} \left(\frac{1}{1+\delta_{LD}} \right)^{1/2},$$

$$R_{K/\pi} = \frac{\mathcal{B}(\tau^- \to K^- \nu_\tau)}{\mathcal{B}(\tau^- \to \pi^- \nu_\tau)} \equiv \frac{\mathcal{B}_K}{\mathcal{B}_\pi},$$

CP

SM prediction:

$$\boxed{A_\tau^{SM} = \frac{\Gamma(\tau^+ \to \pi^+ K_S^0 \bar{\nu}_\tau) - \Gamma(\tau^- \to \pi^- K_S^0 \nu_\tau)}{\Gamma(\tau^+ \to \pi^+ K_S^0 \bar{\nu}_\tau) + \Gamma(\tau^- \to \pi^- K_S^0 \nu_\tau)} \simeq (3.3 \pm 0.1) \times 10^{-3}}$$

BaBar

$$A_\tau = \frac{\Gamma(\tau^+ \to \pi^+ K_S^0 \bar{\nu}_\tau) - \Gamma(\tau^- \to \pi^- K_S^0 \nu_\tau)}{\Gamma(\tau^+ \to \pi^+ K_S^0 \bar{\nu}_\tau) + \Gamma(\tau^- \to \pi^- K_S^0 \nu_\tau)}$$

$$\boxed{A_\tau^{BaBar} = (-0.36 \pm 0.23 \pm 0.11)\%}$$

Belle

A^{CP} using angular observables.

$$\boxed{A^{CP}(W = \sqrt{s}) = \frac{\int \cos\beta \cos\phi (\frac{d\Gamma_{\tau^-}}{d\omega} - \frac{d\Gamma_{\tau^+}}{d\omega}) d\omega}{\frac{1}{2} \int (\frac{d\Gamma_{\tau^-}}{d\omega} + \frac{d\Gamma_{\tau^+}}{d\omega}) d\omega}}$$