Precision measurements of τ lepton decays at Belle II

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on behalf of the Belle II collaboration.

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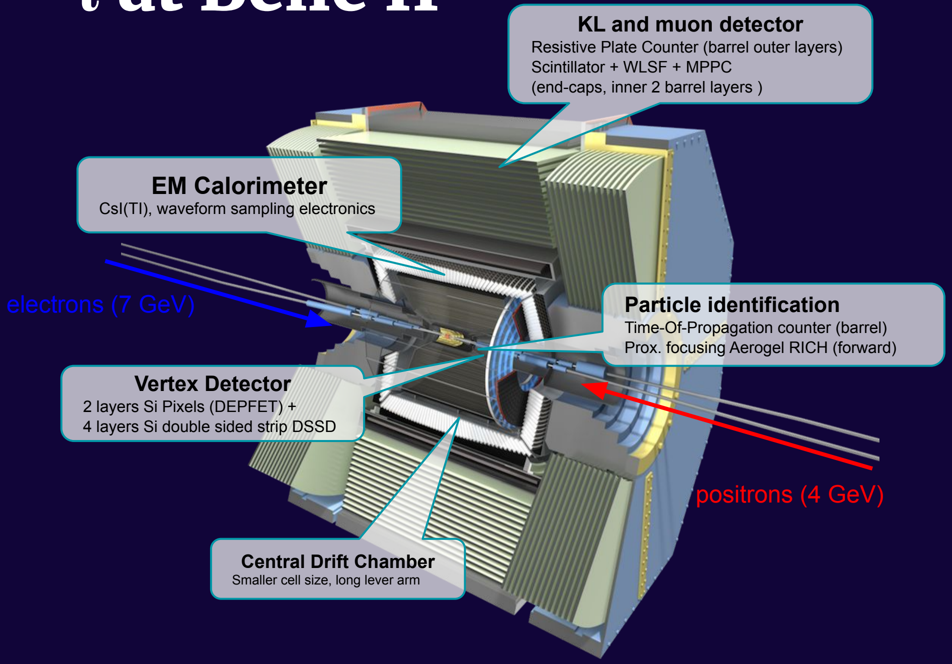
Belle II

KEK

素粒子原子核研究所
Institute of Particle and Nuclear Studies

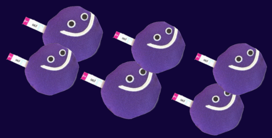
τ at Belle II



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**: 4.7×10^{34} cm^{-2} s^{-1} .



B-factories are also **τ**-factories:

- $\sigma(e^+e^- \to \Upsilon(4s) \to BB) = 1.05$ nb
- $\sigma(e^+e^- \to \tau^+\tau^-) = \mathbf{0.919}$ nb

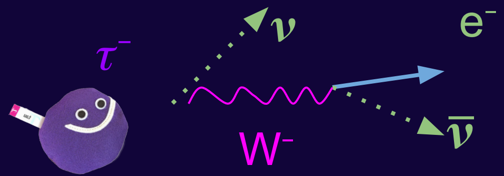
Belle II has recorded **424 fb^{-1}** ≈ **390 million τ pairs.**
The goal is to reach **50 ab^{-1}** ≈ **46 billion τ pairs.**

Run 1 (2019-2022): 362 fb^{-1} on Υ(4S) resonance.
Run 2 (February 2024-): Currently taking data.

Features:

- Clean environment
- Well defined initial state energy → Well known E_{miss}
- Efficient neutrals reconstruction
- Low multiplicity triggers menu
- PID

τ Lepton



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

PDG 2023
M_τ = 1776.86 ± 0.12 MeV/c²
τ_τ = (290.3 ± 0.5) × 10^{-15} s

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

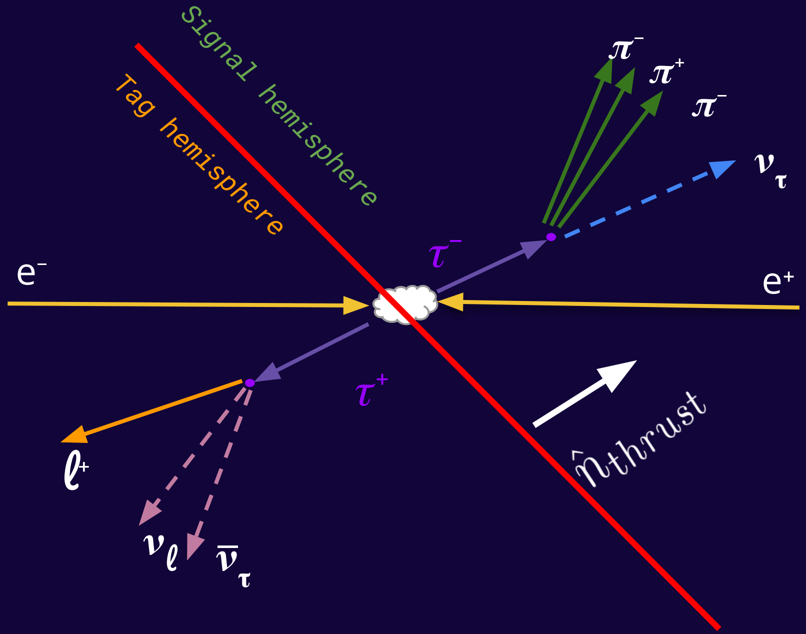
- τ events are produced back-to-back in CM frame.

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

*In absence of ISR.

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

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



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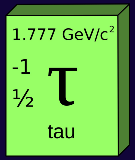
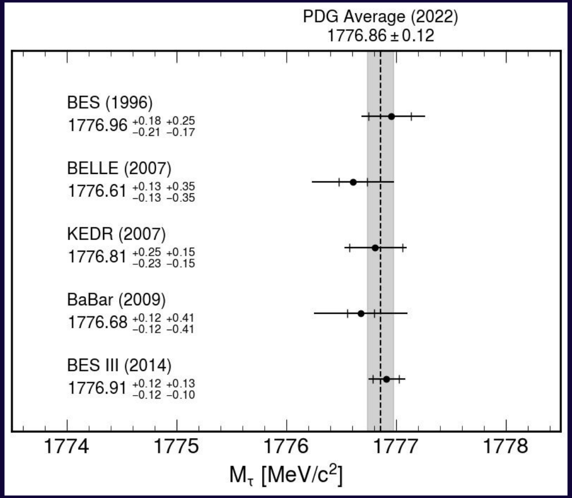


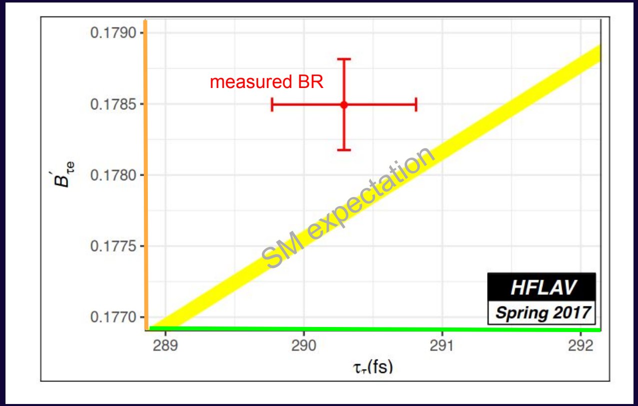
Measurement of the τ-lepton mass

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

SM predicts the relation:

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



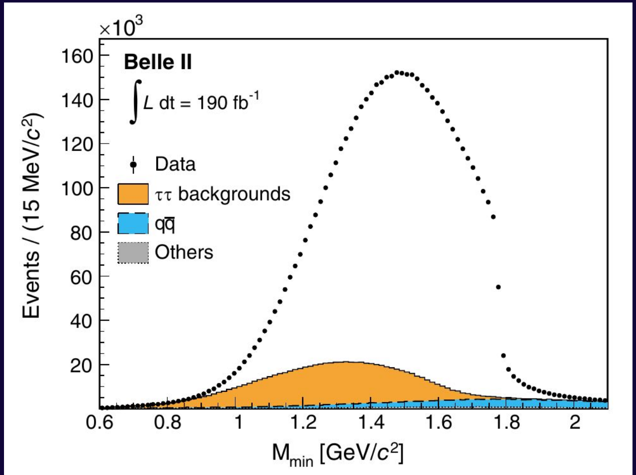


Measurement of the τ-lepton mass

Belle II dataset Υ(4s) on-resonance: 190 fb^{-1} .

Event Selection

- 3 x 1 prong topology → 4 good quality charged tracks.
- Signal $\boldsymbol{\tau}^{\mp} \rightarrow \boldsymbol{\pi}^{\mp} \boldsymbol{\pi}^{+} \boldsymbol{\pi}^{-} \boldsymbol{\nu}$, Tag $e\bar{\nu}\nu$, $\mu\bar{\nu}\nu$, $\boldsymbol{\pi}^{\mp}\boldsymbol{\nu}$ & $\boldsymbol{\pi}^{\mp}\boldsymbol{\pi}^{0}$.
- Main backgrounds $e^+e^- \rightarrow \bar{q}q$, $e^+e^- \rightarrow \boldsymbol{\tau}^+\boldsymbol{\tau}^-$, with other tau decays than $\boldsymbol{\tau}^{\mp} \rightarrow \boldsymbol{\pi}^{\mp} \boldsymbol{\pi}^{+} \boldsymbol{\pi}^{-} \boldsymbol{\nu}$.
- Background suppression via FOM maximization. Purity = 90%.



Method

Then , the $\boldsymbol{\tau}$ mass, assuming zero mass of the neutrino, is giving by

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

The energy of the $\boldsymbol{\tau}$ is half of the beam energy, and assuming $\boldsymbol{\alpha}$ zero, we defined the pseudomass

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

Measurement of the τ-lepton mass

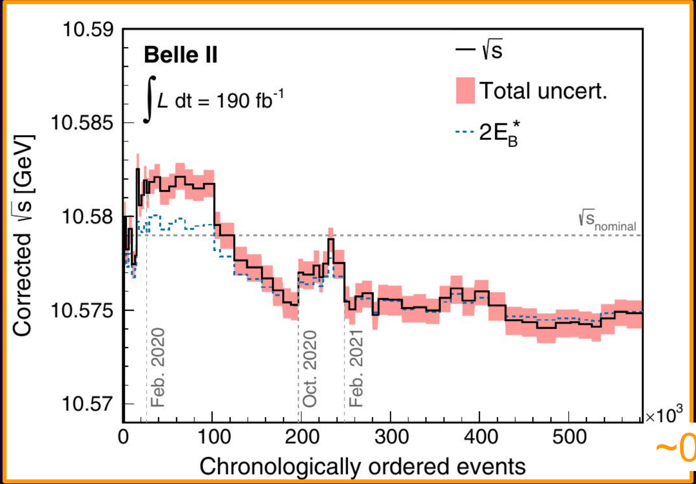
The distribution of the pseudomass is fitted to a empirical edge function to estimate **τ** lepton mass.

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

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

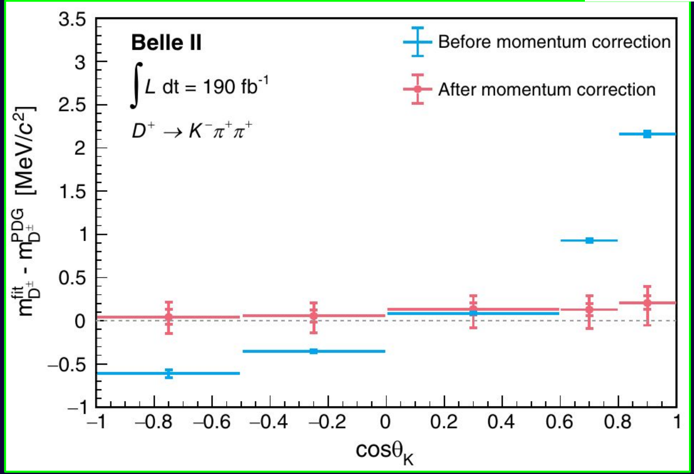
Systematics Uncertainties

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



~0.07MeV/c²

~0.06MeV/c²



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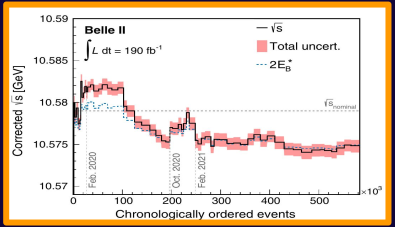

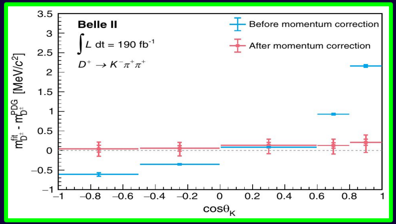

Source	Uncertainty [MeV/c^2]
Knowledge of the colliding beams:	
Beam-energy correction	0.07
Boost vector	< 0.01
Reconstruction of charged particles:	
Charged-particle momentum correction	0.06
Detector misalignment	0.03
Fit model:	
Estimator bias	0.03
Choice of the fit function	0.02
Mass dependence of 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

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

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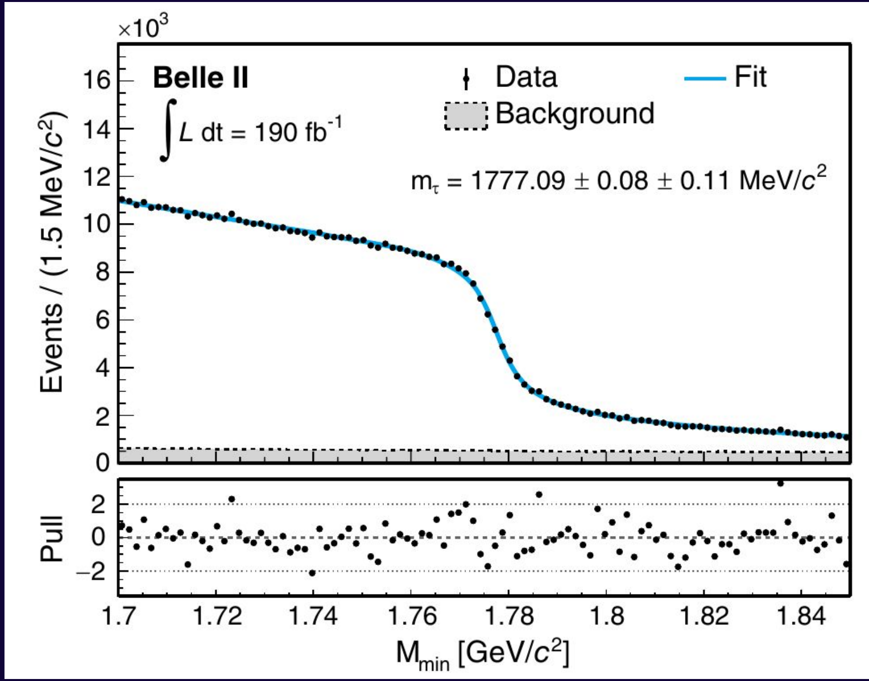
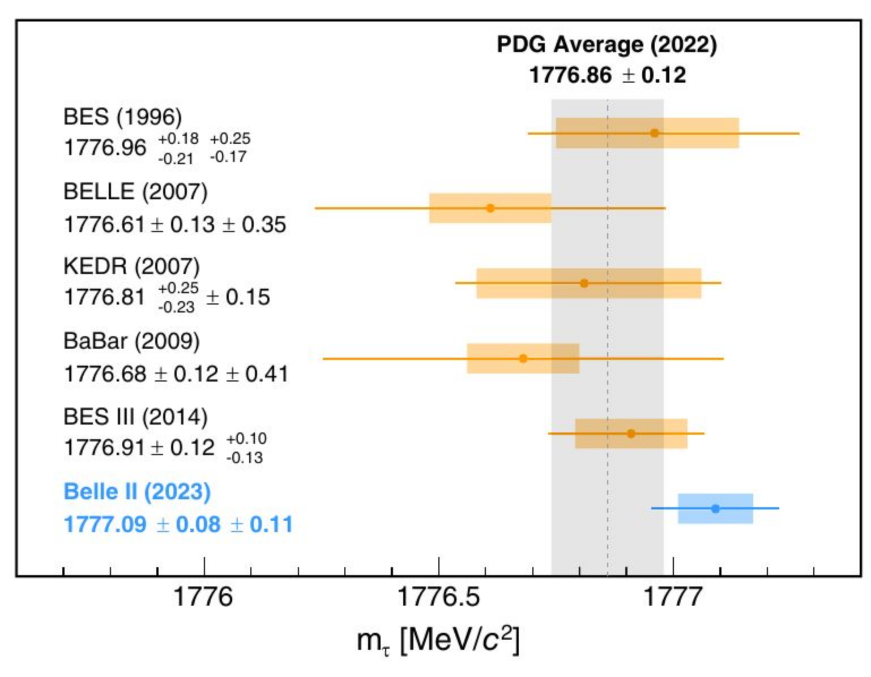
Measurement of the τ-lepton mass

The most precise to date!

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



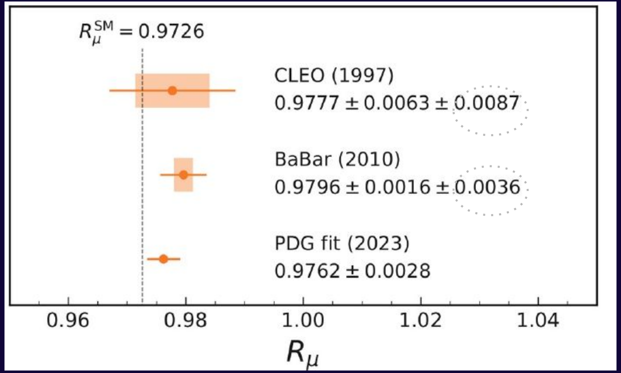


Test of Lepton Flavor Universality

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

- Test for μ-e universality: $R_\mu = \frac{\mathcal{B}(\tau^- \to \mu^- \bar{\nu}_\mu \bar{\nu}_\tau)}{\mathcal{B}(\tau^- \to e^- \bar{\nu}_e \bar{\nu}_\tau)}$ then $\left(\frac{g_\mu}{g_e}\right)_\tau = \sqrt{R_\mu \frac{f(m_e^2/m_\tau^2)}{f(m_\mu^2/m_\tau^2)}}$
- $\boldsymbol{\tau}$ decays are sensitive to non-SM neutral currents.
- LFU violation. →Lead to NP.
- Belle II dataset Υ(4s) on-resonance: 362 fb^{-1} .

Previous measurements



Event Selection

- 1 x 1 prong topology. 2 good quality tracks.
- Signal $\boldsymbol{\tau}^\mp \to e^\mp \bar{\boldsymbol{\nu}}\, \boldsymbol{\nu}$, $\mu^\mp \bar{\boldsymbol{\nu}}\, \boldsymbol{\nu}$. Tag $\boldsymbol{\tau}^\mp \to h^\mp (n\pi^0)\boldsymbol{\nu}$. *n > 0*
- Main backgrounds $\boldsymbol{\tau}_{sig} \to \pi\boldsymbol{\nu}$, $\rho\boldsymbol{\nu}$ X $\boldsymbol{\tau}_{tag} \to \rho\boldsymbol{\nu}$. Well identified signal but wrong tag. And $e^+e^- \to \bar{q}q$, $e^+e^-\gamma$, $\mu^+\mu^-\gamma$.
- Background suppression via Neural Network.
- Purity 96% and 92% for electron and muon channel.

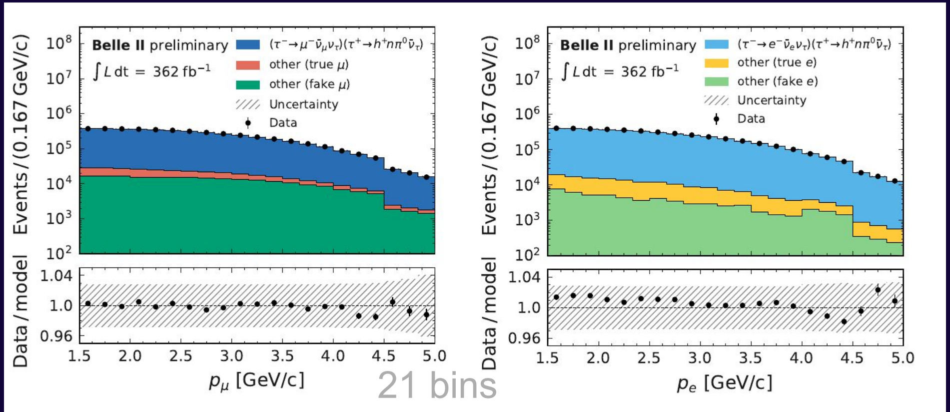
Test of Lepton Flavor Universality

Method

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

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

The background templates are splitted 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.

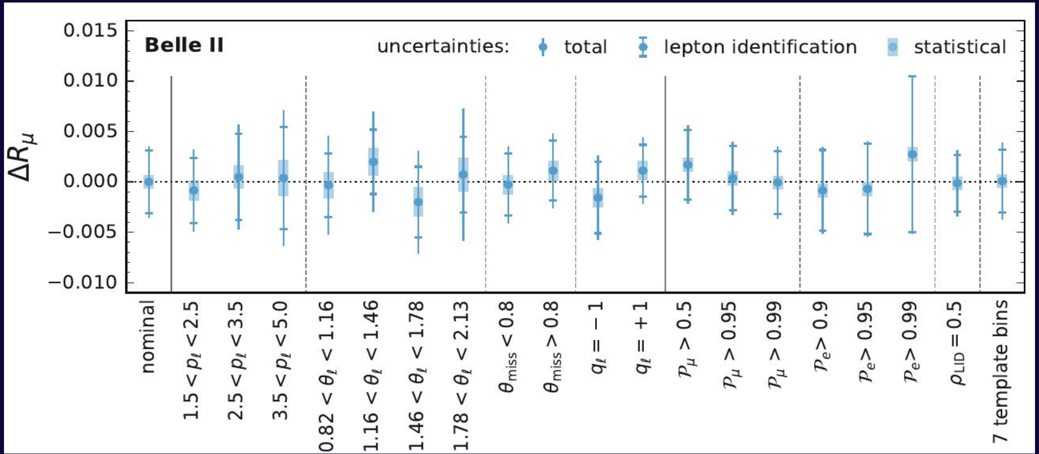
Test of Lepton Flavor Universality

Systematics uncertainties

- Main systematics comes from lepton identification and triggers (ECL based).

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



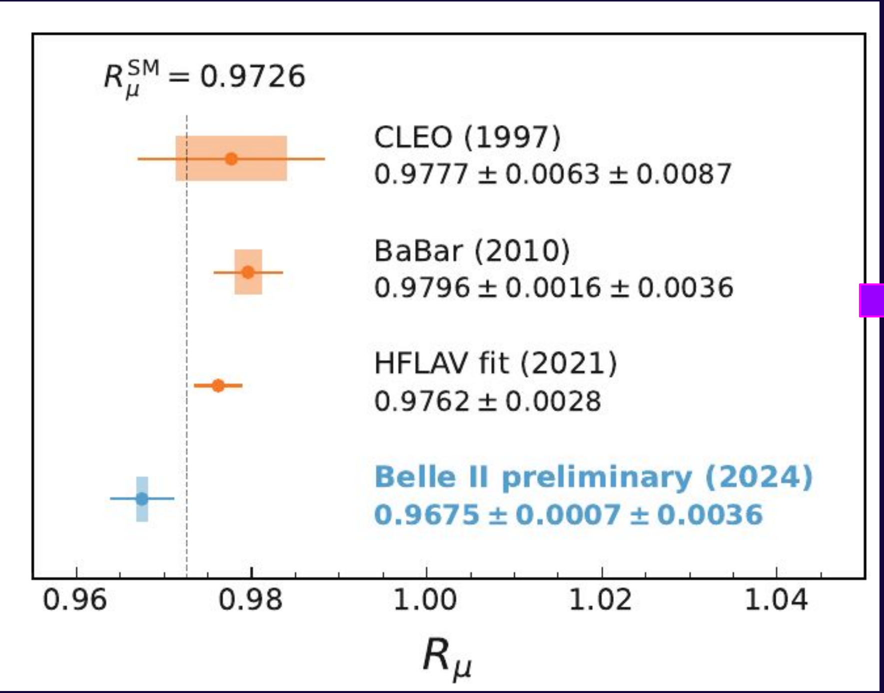
Good agreement between results.

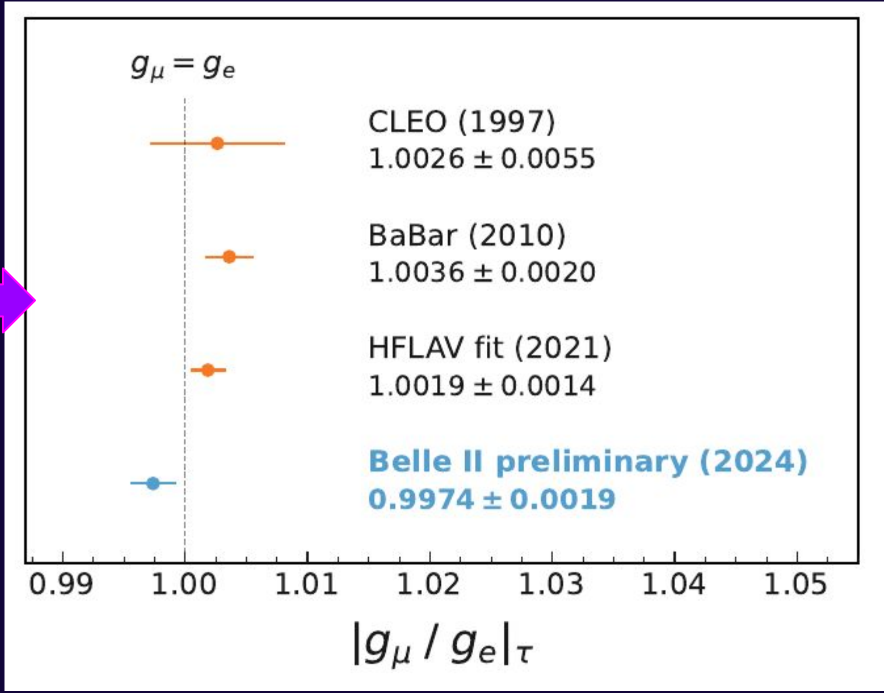
Test of Lepton Flavor Universality

The most precise to date!

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

➢ Consistent with the SM 1.4 **σ**.





Prospects

LFU

- A updated measurement with more statistics is in progress with combined results of the 1x1 and 3x1 topology. Note: Only the 3x1 was used in the previous Babar (2010) result.

Vus

- Important to update the measurements of the CKM matrix elements, any deviation from unitarity could lead to NP. Vus is determined through the ratio: $R_{K/\pi} = \frac{\mathcal{B}(\tau^- \to K^- \nu_\tau)}{\mathcal{B}(\tau^- \to \pi^- \bar{\nu}_\tau)} \equiv \frac{\mathcal{B}_K}{\mathcal{B}_\pi}$
- The analysis is being done with a 3x1 topology and the Belle II dataset of 362 fb^{-1} .

Lifetime

- A updated measurement with more statistics (19 times more events) is ongoing with a 3x1 topology. Note: Previous Belle measurement uses 3x3 topology.

CP

- Search in the $\tau^- \to K^0_s \pi^- \nu$ ($\geq 0\ \pi^0$) decay, Babar 2.8 deviation from SM, Belle did not see any apparently asymmetry.

More results in τ physics are coming, with larger statistics and new methods to reduce systematics uncertainties!

BACKUP

Event Selection τ mass

$$FOM = \frac{S}{\sqrt{S + 100 \times B}}$$

Selection on the p_T of 3 tracks:

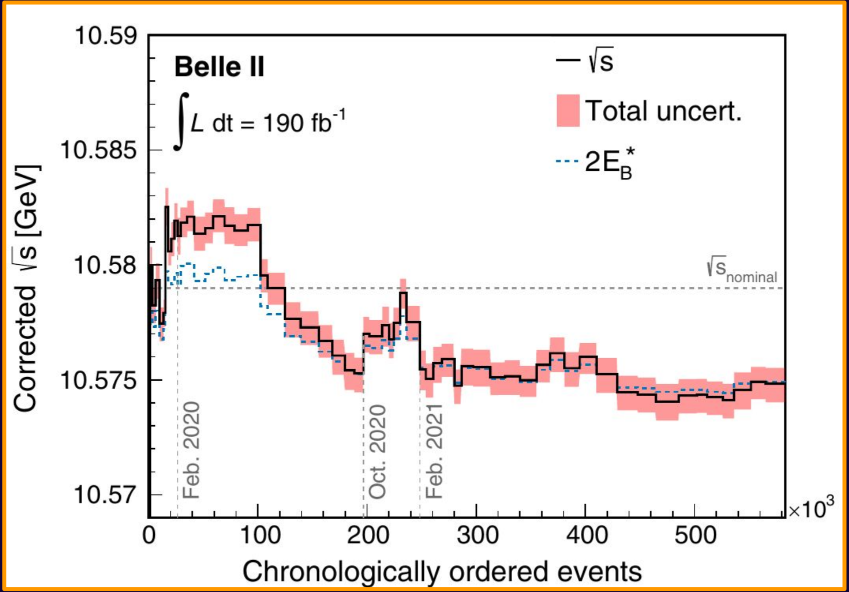
- pT (leading track) > 0.6 GeV/c
- pT (subleading track) > 0.2 GeV/c
- pT (trailing track) > 0.1 GeV/c

Additional selection on:

- Thrust
- Visible energy in CMS
- Missing momentum in the CMS.
- The polar angle of missing momentum in the CMS frame.
- The square of the missing mass in the event

Bean-Energy correction

Beam energy was calibrated using BB-pair and its hadronic decays.



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

Uncorrected energy

$$E_B^* = \sqrt{m_B^2 + (p_B^*)^2} \approx m_B + \frac{1}{2m_B}(p_B^*)^2.$$

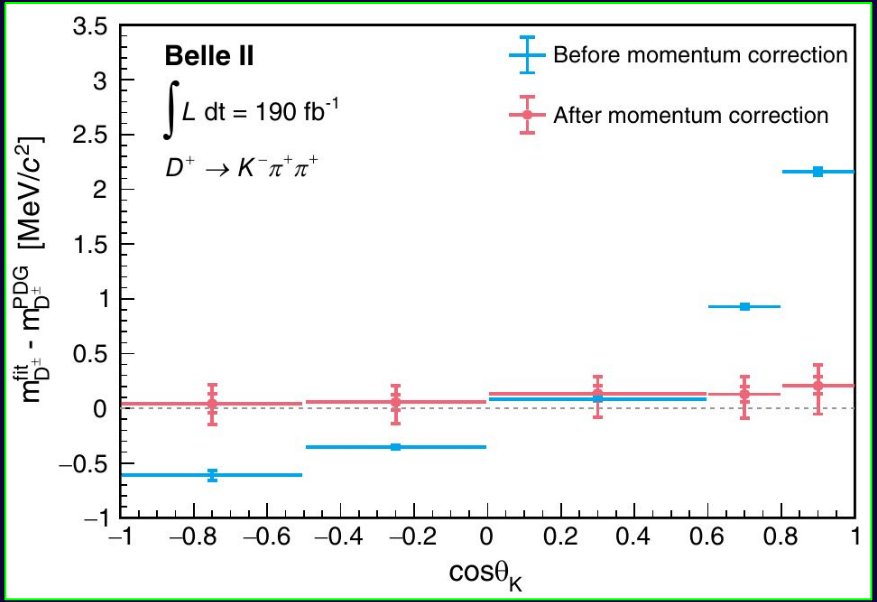
Relation considering event by event center of mass energy

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

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. Mapping corrected-observed, used to obtain corrected values.

Charged-Particle momentum correction

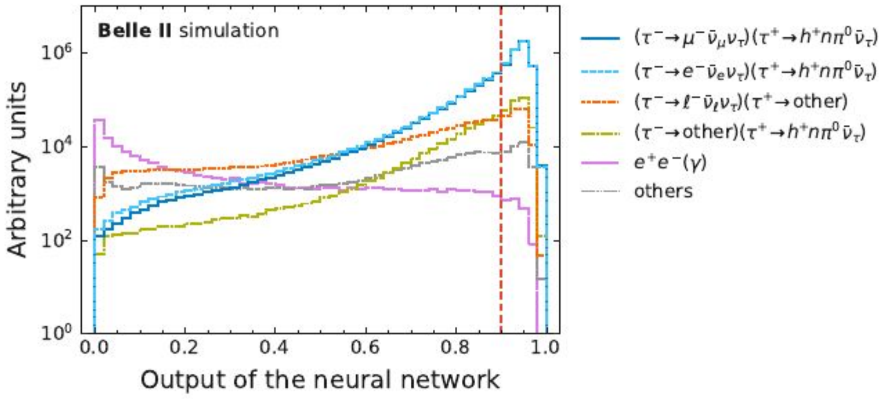


The corrections for the daughter pion momenta were obtained from the $D^0 \to K^- \pi^+$ sample with cross-checks in the $D^+ \to K^- \pi^+\pi^+$, $D^0 \to K \pi^+ \pi^- \pi$, and $J/\psi \to \mu^+ \mu^-$ samples.
The difference between the reconstructed and nominal masses of the D+ meson before and after corrections.

Event Selection LFU

The exact cuts of the preselection are:

- $2.1 \leq E_{\text{visible}}^{\text{CM}} < 9.2$
- $0.23 \leq \theta_{\text{missing}}^{\text{CM}} < 2.97$
- $0.85 \leq \text{thrust} < 0.996$
- $0.62 \leq p_{\tau(\text{tag})}^{\text{CM}}$
- $-0.91 \leq \cos\left(\theta_{\tau(\text{tag})}^{\text{CM}}\right) < 0.91$
- $0.32 \leq m_{\tau(\text{tag})}$
- $0.02 \leq \text{angle}\left(\pi, \gamma\left(\pi^0\right)\right)_{\min}$



The seven features used in training are:

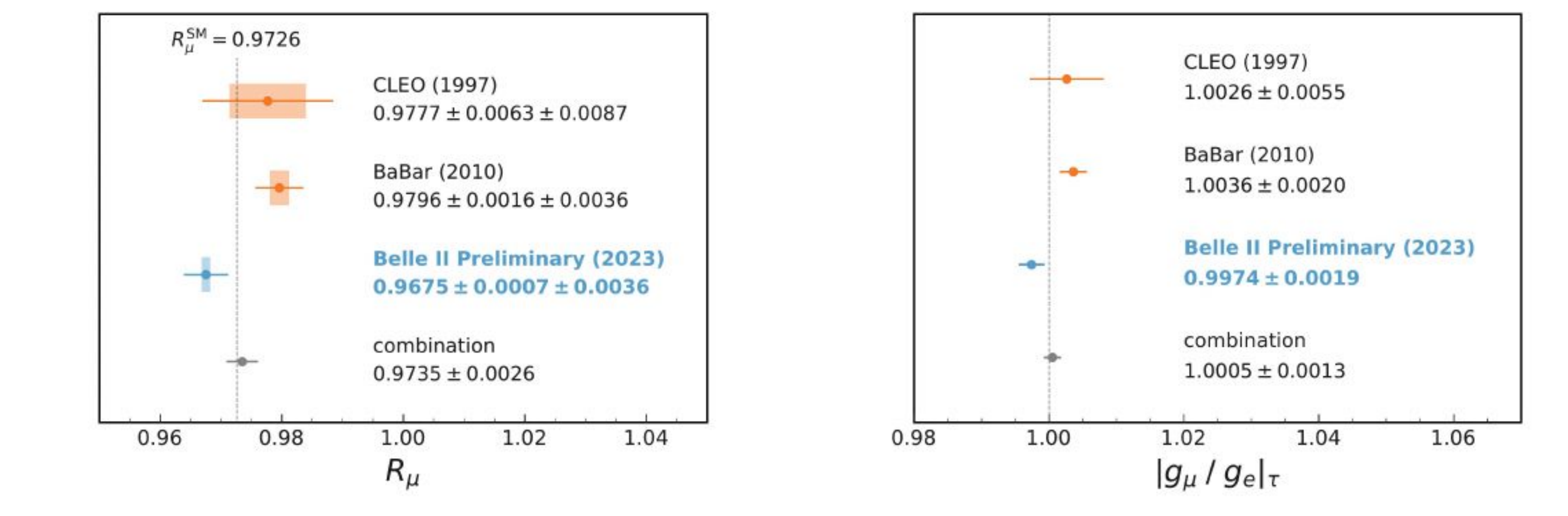
- m_τ (tag) : also used in preselection.
- cos θτ CM (tag) : also used in preselection.
- thrust: also used in preselection.
- thrust-axis (cos θ): cosine of the polar angle of the thrust axis.

- Evisible CM : also used in preselection.
- p^{CM} τ (tag) : also used in preselection.
- p^{CM} t, missing : transverse component of missing momentum direction.

Main backgrounds

- $e^+e^- \to \tau^+\tau^-$ ($\pi^\pm$ faking $\mu^\pm/e^\pm$): ~3.3%
- $e^+e^- \to \tau^+\tau^-$ (wrong tag): ~2.3%
- $e^+e^- \to e^+e^-\tau^+\tau^-$: 0.2%

Combination LFU



Assuming independent systematics.

Vus

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

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

- Background reduction using a BDT approach.
- Method: Unbinned likelihood fit.
- Measurement using the signal hadron momentum in the lab frame.
- Systematics are being included as nuisance parameters in the model.

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

CP

Babar Result 2.8 **σ** from SM.

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

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

Belle: Using angular observables:

A^{CP} using angular observables.

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

Belle 2:

- New method to extract K^0-$\overline{K}^0$ CP.
- Background suppression with two steps BDT (Event, Ks information).
- Similar efficiencies and purity than previous results.