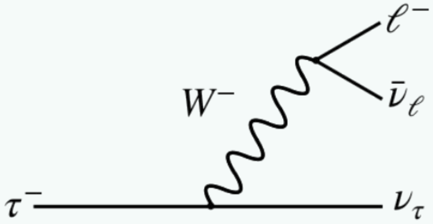
Institut "Jožef Stefan" Ljubljana, Slovenija

European Research Council
Established by the European Commission

Test of light-lepton universality in τ decays at Belle II

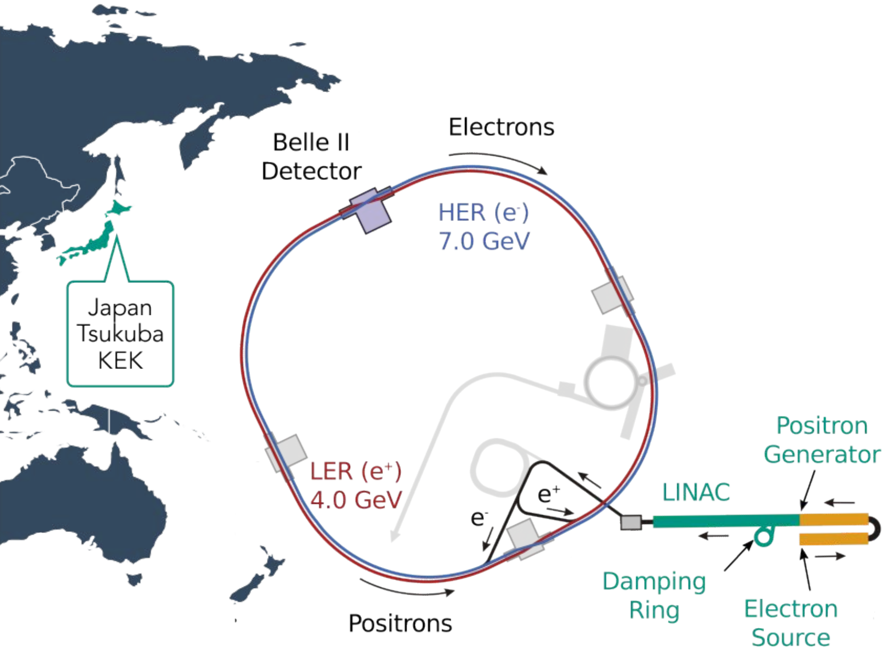


Paul Feichtinger, on behalf of the Belle II Collaboration

Discrete 2024, Ljubljana

4th December 2024

SuperKEKB and Belle II

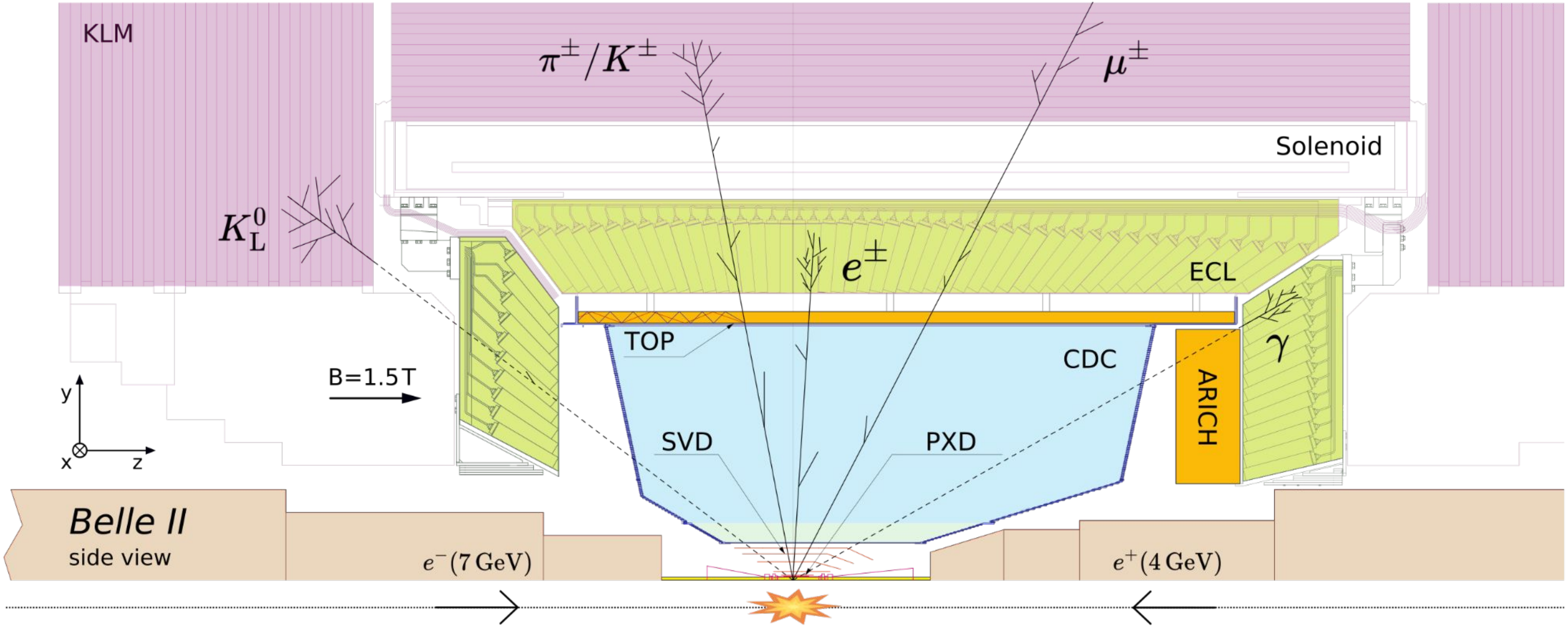


SuperKEKB

- nominal operation at a centre-of-mass energy of 10.58 GeV

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

- well suited to study tau leptons
  - clean collision environment
  - good missing energy reconstruction
    - clean and well understood initial state
    - hermetic detector (> 90% large solid angle coverage)
  - good track reconstruction, particle identification
- collected ~550 fb^{-1} up to now (5×10^8 $\tau^+\tau^-$ pairs)
- 365 fb^{-1} used for the following measurement
  - taken between 2019 and 2022



» [arXiv:1011.0352 (Technical Design Report)](https://arxiv.org/abs/1011.0352)

- **SVD, PXD:** vertex detectors
- **CDC:** central drift chamber
- **TOP/ARICH:** particle identification detectors (π/K separation)
- **ECL:** electromagnetic calorimeter
- **KLM:** K_L and μ detector

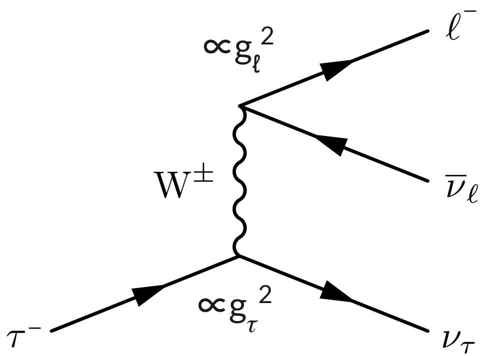
Lepton universality with taus

- theoretically very clean prediction of decay rate of leptons
- ratio of weak coupling constants for test of μ-e universality ($g_\mu = g_e$ in SM)

$$\left(\frac{g_\mu}{g_e}\right)_\tau = \sqrt{\frac{\mathcal{B}(\tau^- \to \nu_\tau \mu^- \overline{\nu}_\mu(\gamma))}{\mathcal{B}(\tau^- \to \nu_\tau e^- \overline{\nu}_e(\gamma))} \frac{f(m_e^2/m_\tau^2)}{f(m_\mu^2/m_\tau^2)}} \qquad f(x) = 1 - 8x + 8x^3 - x^4 - 12x^2 \ln x$$

- can be obtained from ratio of leptonic τ branching fractions

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



Lepton universality with taus

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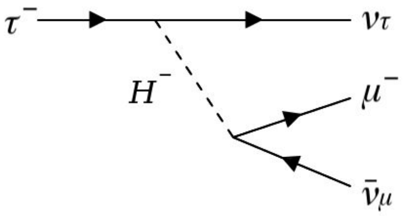
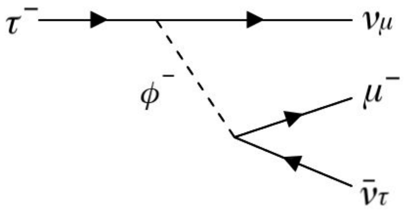
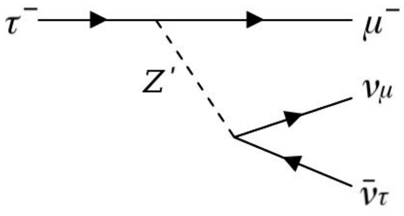
- ratio is sensitive to new physics if it has different couplings to electrons and muons



Charged Higgs
(aligned two-Higgs-doublet)
can explain $R(D^{(*)})$ anomaly
» JHEP 2010.11, 3 (2010)

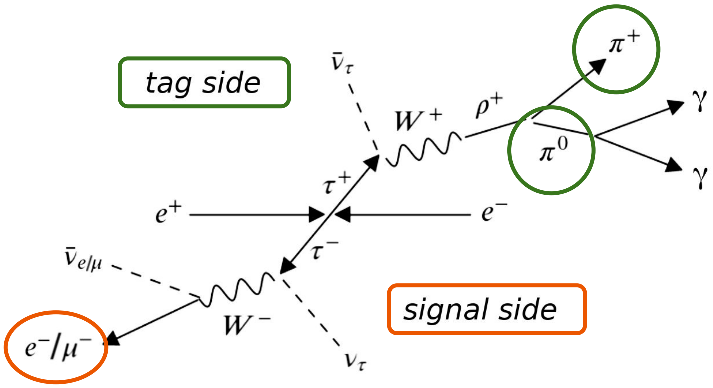


Singly charged $SU(2)_L$ scalar singlet
(lepton flavour violating)
can explain Cabibbo angle anomaly
» Phys. Rev. D 103, 073002 (2021)

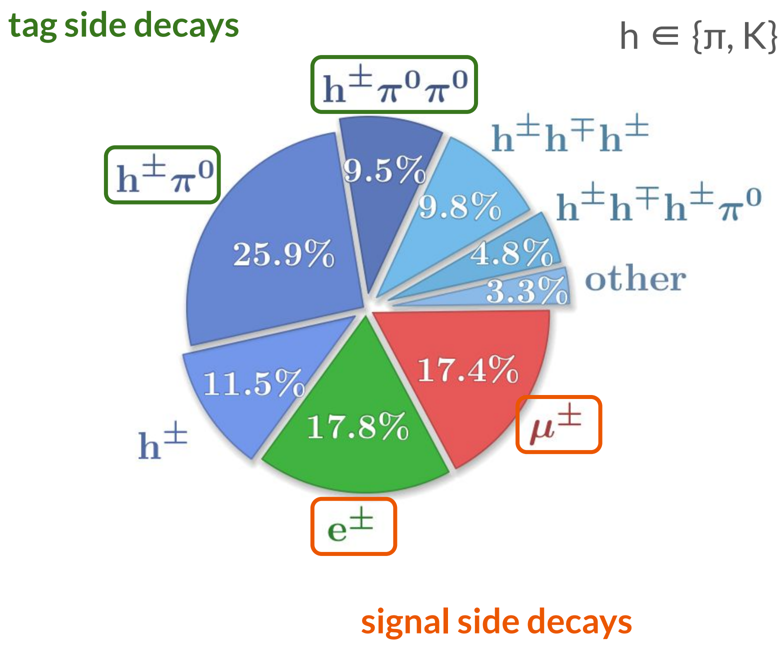


$SU(2)_L$ neutral vector boson (Z′)
(lepton flavour violating)
can explain $(g-2)_\mu$ anomaly
» Phys. Lett. B 762, 389-398 (2016)

Event topology

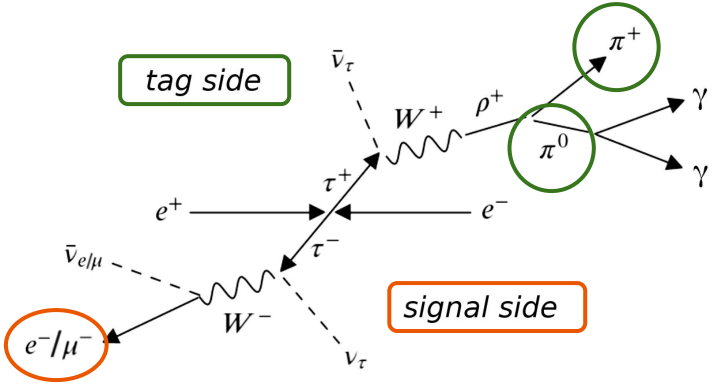


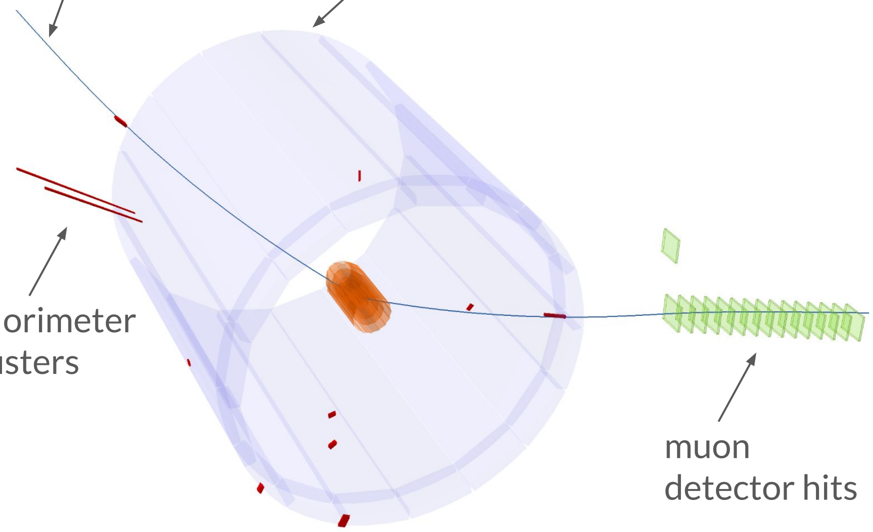
Tau decay channels (omitting neutrinos)



- tau pairs in $e^+e^- \rightarrow \tau^+\tau^-$ events produced back-to-back
- possible to separate event into two opposite hemispheres
- chosen tag side τ decays have high branching ratios, trigger efficiency, low backgrounds

Event topology





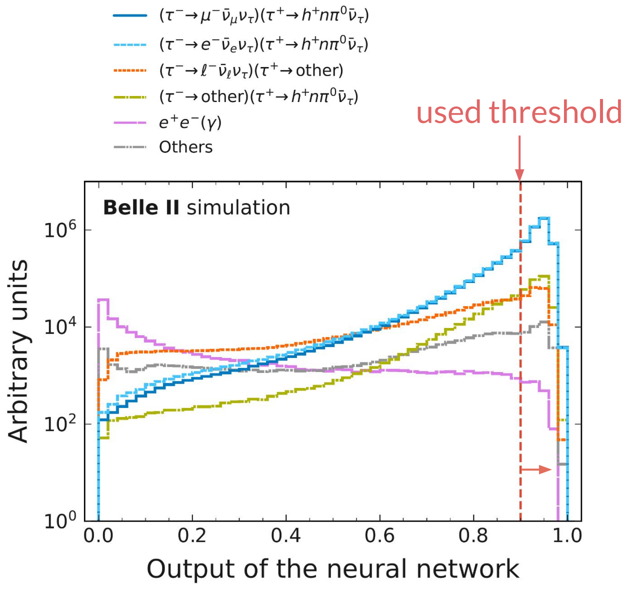
One out of 4.4 million muon signal candidates in data

Event selection

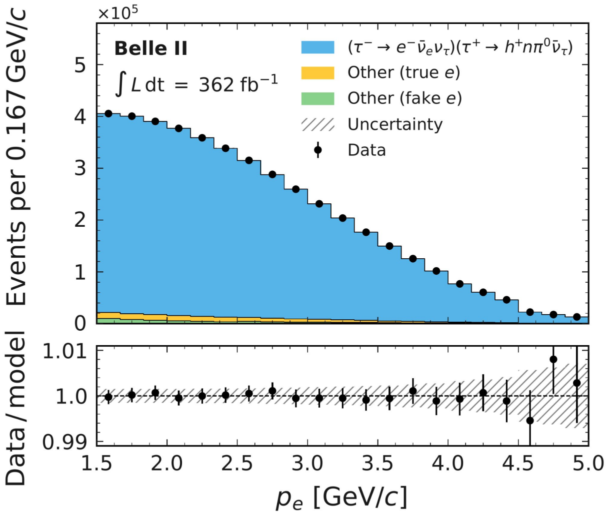
1. preselection with rectangular cuts using 6 variables related to event kinematics
2. restrict lepton kinematics due to particle identification uncertainties
   - ➢ $0.82 < \theta_{lepton} < 2.13$ (barrel of muon detector, θ_{lepton} = polar angle)
   - ➢ $1.5\ \text{GeV} < p_{lepton} < 5.0\ \text{GeV}$
3. background suppression with artificial neural network

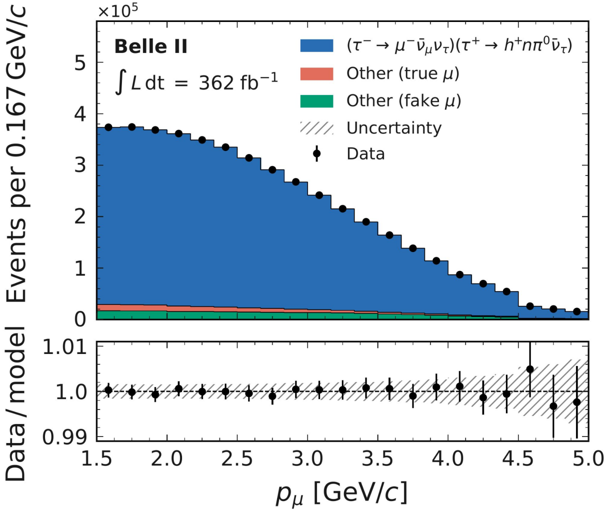
   - ○ total visible energy
   - ○ missing momentum: p_T
   - ○ thrust value
   - ○ thrust axis θ
   - ○ tag side: p, θ, M

   inputs to the neural network



- ~9.6% signal efficiency for combined sample





R_μ extraction

- binned maximum likelihood fit using the momentum spectra of lepton candidates
- simultaneous fit of e and μ channels, each with three templates based on simulated samples

	e-channel	μ-channel
$e^+e^- \to \tau^+\tau^-$ (signal)	96%	92%
$e^+e^- \to \tau^+\tau^-$ (true $\ell^\pm$, wrong tag decay)	2.3 %	2.3 %
$e^+e^- \to \tau^+\tau^-$ (misidentified $\pi^\pm$ as $\ell^\pm$)	1.3 %	5.2 %

- systematics are included with (constrained) nuisance parameters that modify the templates

$$f(\vec{x} \mid R_\mu, \vec{\theta}) = \prod_{b \in \text{bins}} \text{Pois}\Big(x_b \mid \nu_b(R_\mu, \vec{\theta})\Big) \quad \prod_{\theta \in \vec{\theta}} \mathcal{N}(x_\theta \mid \theta)$$

Systematics

Particle identification (0.32%)

- correction factors and uncertainties derived from calibration channels
  - eff.: $J/\psi \to \ell^+\ell^-$, $e^+e^- \to e^+e^-\ell^+\ell^-$ and $e^+e^- \to \ell^+\ell^-(\gamma)$
    - e/μ eff.: 99.7% / 93.9%
  - fakes: $K_S^0 \to \pi^+\pi^-$ and $\tau^\pm \to \pi^\pm\pi^\mp\pi^\pm\nu_\tau$
    - $\pi \to e/\mu$: 0.9% / 3.1%

Trigger (0.10%)

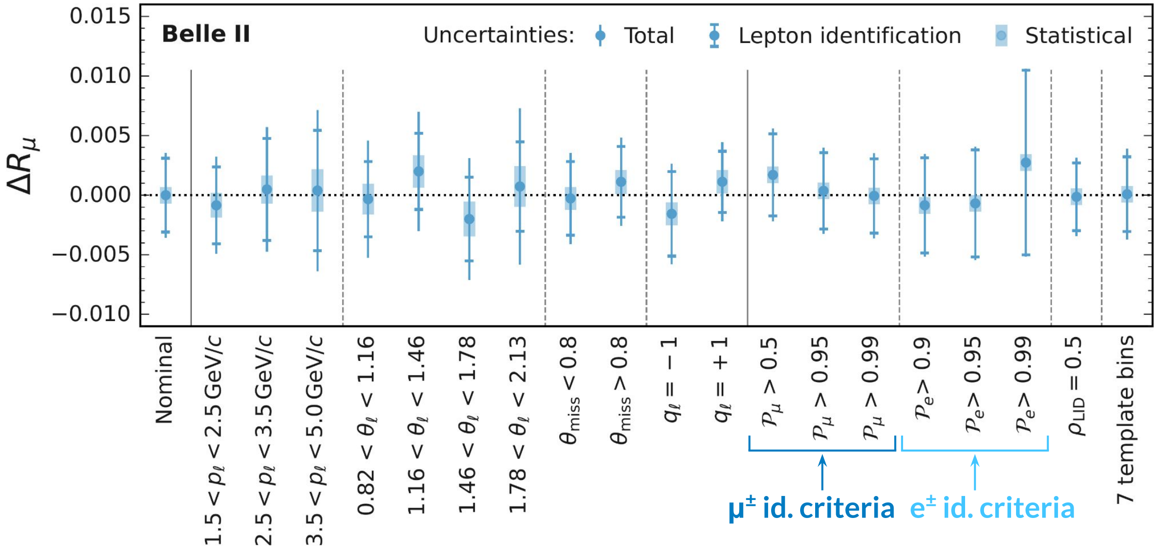
- used triggers are based on EM calorimeter information, targeting low multiplicity events
  - most important: E_{ECL}>1 GeV trigger
- trigger efficiency measured in data, corrected in MC
  - ε=99.8% for $\tau^-\to e^-\bar{\nu}_e\nu_\tau$ and ε=96.6% for $\tau^-\to\mu^-\bar{\nu}_\mu\nu_\tau$

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

fractional systematic uncertainties on R_μ

Stability of the result

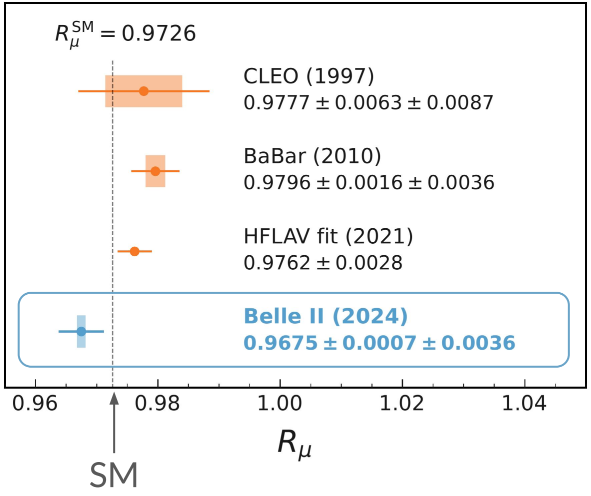
- checked for consistency of the result before unblinding
  - sub-regions for different kinematic variables (e.g. momentum, polar angle, charge)
  - different requirements for particle identification, assumptions about the correlation
- good agreement between the measured values

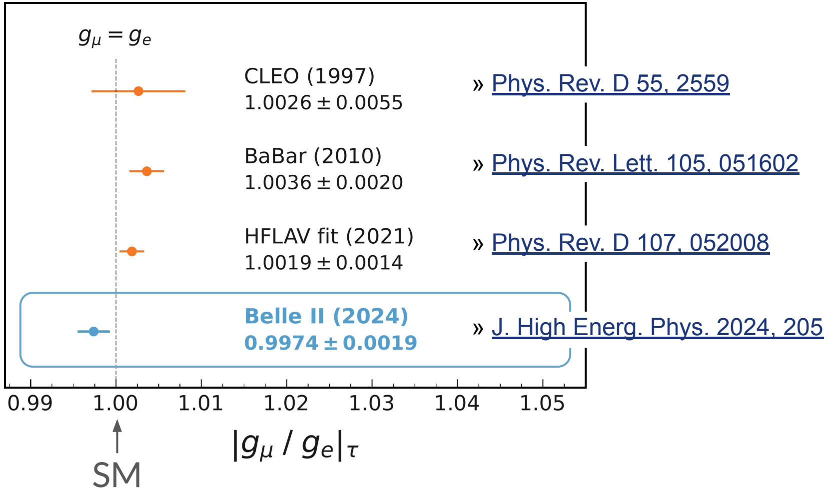


Result

$$R_\mu = \frac{\mathcal{B}(\tau^- \to \nu_\tau \mu^- \overline{\nu}_\mu(\gamma))}{\mathcal{B}(\tau^- \to \nu_\tau e^- \overline{\nu}_e(\gamma))}$$

$$\left(\frac{g_\mu}{g_e}\right)_\tau = \sqrt{R_\mu \frac{f(m_e^2/m_\tau^2)}{f(m_\mu^2/m_\tau^2)}}$$

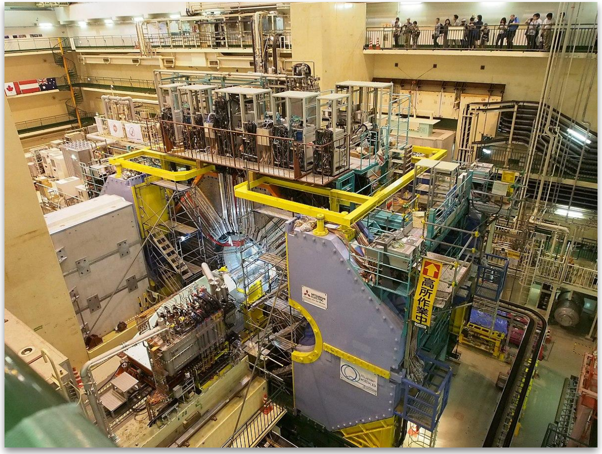




- most precise test of μ-e universality in τ decays from a single measurement
  - consistent with SM, with similar size of systematics as BaBar measurement (with 467 fb^{-1})
- updated value from global HFLAV fit presented at ICHEP 2024, which includes this measurement
  - $(g_\mu/g_e)_\tau$ = 1.0002 ± 0.0011

Summary

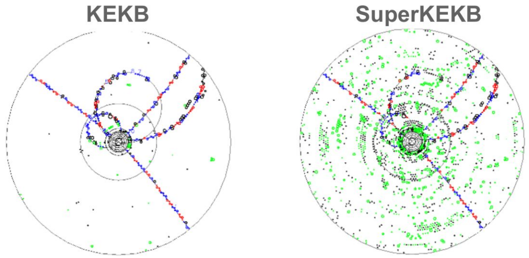
- test of μ-e universality with τ decays indicates no new physics at current precision
  - required good understanding of systematic uncertainties, in particular associated with particle identification
- Belle II can also test τ-e and τ-μ universality in the future, with precise measurements of
  - τ mass (Phys. Rev. D 108, 032006)
  - τ lifetime
  - absolute leptonic τ BFs



backup slides ⤵

KEKB → SuperKEKB accelerator

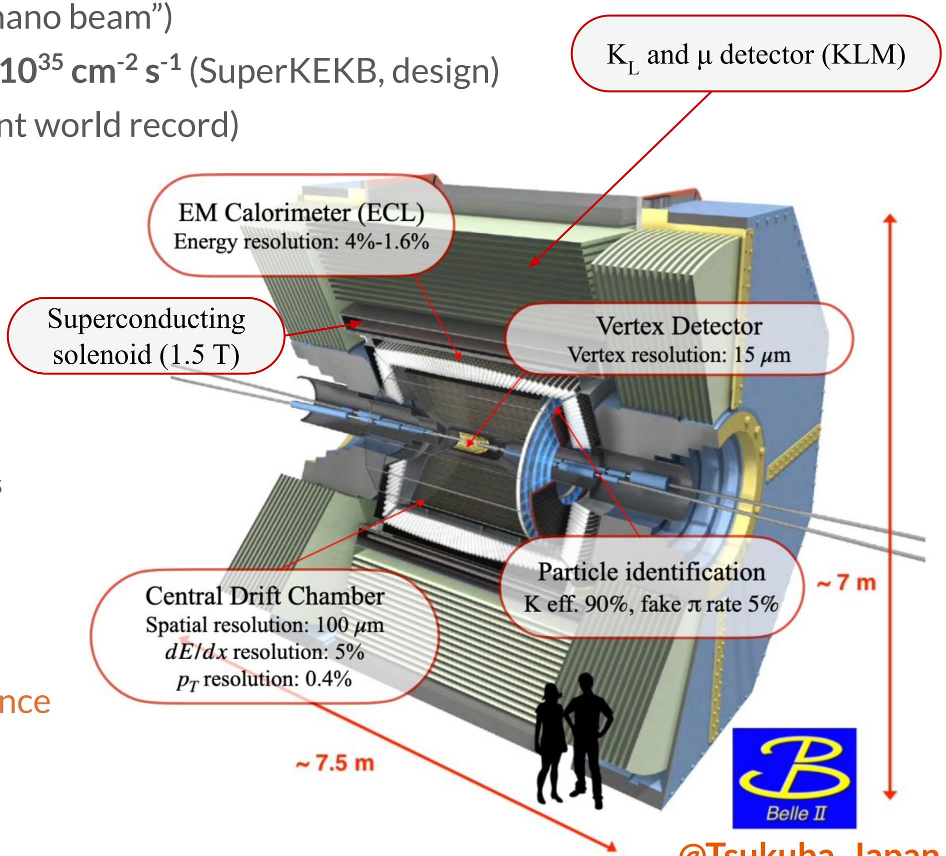
- 2x beam currents, 50 nm vertical beam spot size (“nano beam”)
- peak luminosity 2.1×10^{34} (KEKB, achieved) → **6.0×10^{35} cm^{-2} s^{-1}** (SuperKEKB, design)
- so far SuperKEKB achieved 4.7×10^{34} cm^{-2}s^{-1} (current world record)



challenge: increased beam backgrounds and trigger rates

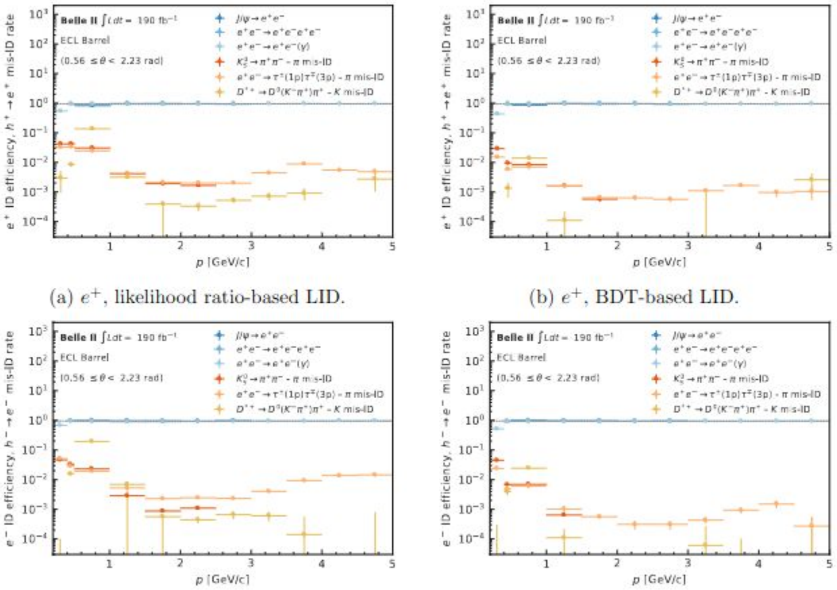
Belle → Belle II detector

- new 2-layer Pixel Detector with first layer at 1.4cm
- 4-layer Silicon Vertex Detector with larger acceptance
- Central Drift Chamber with larger outer radius
- improved particle ID (K/π separation)
- improved trigger, and faster electronics in general



@Tsukuba, Japan

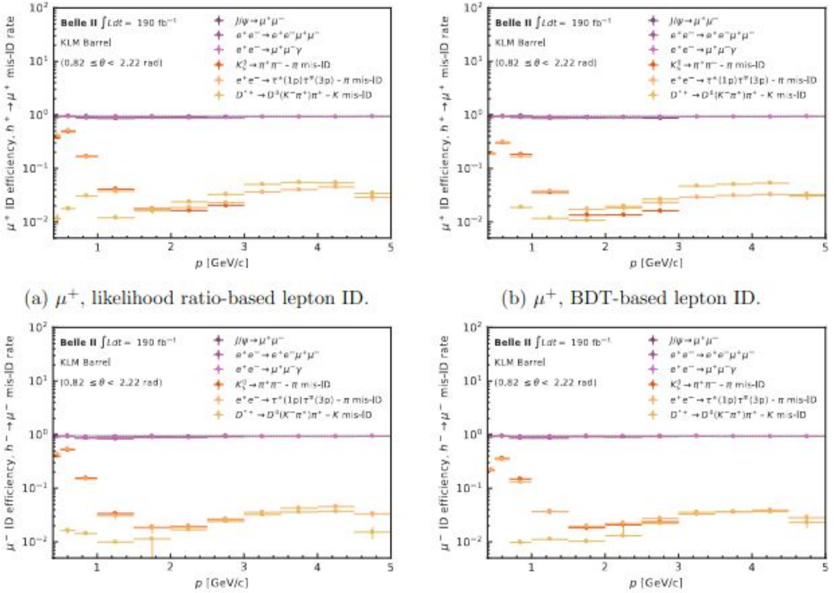
» arXiv:1011.0352 (Technical Design Report)



(a) e^+, likelihood ratio-based LID. (b) e^+, BDT-based LID.

(c) e^-, likelihood ratio-based LID. (d) e^-, BDT-based LID.

FIG. 26: Electron identification performance in data: efficiencies and pion, kaon mis-identification probabilities from the various channels are shown as a function of p_{lab} in the ECL barrel region. Results for the likelihood ratio-based lepton ID are on the left, and for the BDT-based lepton ID are on the right. The top row shows the results for positively charged tracks, and the bottom row for negatively charged tracks. The selection criteria for the lepton ID variables are tuned in MC to achieve 95% electron identification efficiency, uniform across the bins shown.



(a) μ^+, likelihood ratio-based lepton ID. (b) μ^+, BDT-based lepton ID.

(c) μ^-, likelihood ratio-based lepton ID. (d) μ^-, BDT-based lepton ID.

FIG. 27: Muon identification performance in data: efficiencies and pion, kaon mis-identification probabilities from the various channels are shown as a function of p_{lab} in the ECL barrel region. Results for the likelihood ratio-based lepton ID are on the left, and for the BDT-based lepton ID are on the right. The top row shows the results for positively charged tracks, and the bottom row for negatively charged tracks. The selection criteria for the lepton ID variables are tuned in MC to achieve 95% muon identification efficiency, uniform across the bins shown.

BELLE2-NOTE-PH-2022-035

Previous measurements

- BaBar (3x1) 2010, 467 fb^{-1}:

  $R_\mu = 0.9796 \pm 0.0016(stat) \pm 0.0036(sys)$

  → 0.4% precision

	μ	π	K
N^D	731102	369091	25123
Purity	97.3%	78.7%	76.6%
Total Efficiency	0.485%	0.324%	0.330%
Particle ID Efficiency	74.5%	74.6%	84.6%
Systematic uncertainties:			
Particle ID	0.32	0.51	0.94
Detector response	0.08	0.64	0.54
Backgrounds	0.08	0.44	0.85
Trigger	0.10	0.10	0.10
$\pi^-\pi^-\pi^+$ modelling	0.01	0.07	0.27
Radiation	0.04	0.10	0.04
$\mathcal{B}(\tau^- \to \pi^-\pi^-\pi^+\nu_\tau)$	0.05	0.15	0.40
$\mathcal{L}\sigma_{e^+e^-\to\tau^+\tau^-}$	0.02	0.39	0.20
Total [%]	0.36	1.0	1.5

- CLEO (1x1) 1997, 3.6 fb^{-1}:

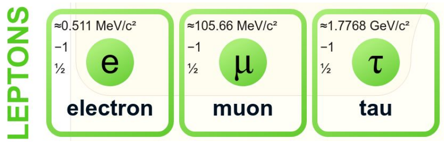
  $R_\mu = 0.9777 \pm 0.0063(stat) \pm 0.0087(sys)$

  → 1.1% precision

TABLE XI. Relative errors (%) by source.

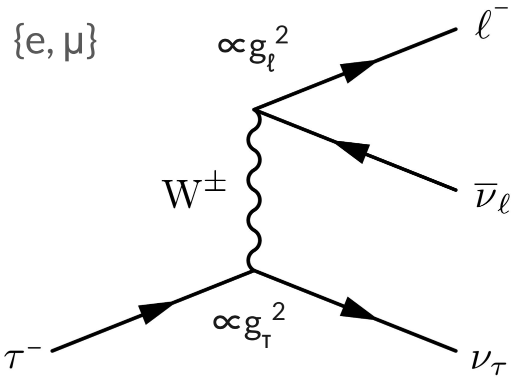
Source	$\mathcal{B}_e$	$\mathcal{B}_\mu$	$\mathcal{B}_h$	$\mathcal{B}_\mu/\mathcal{B}_e$	$\mathcal{B}_h/\mathcal{B}_e$
Statistics (n)	0.36	0.47	0.46	0.65	0.63
Normalization ($N_{\tau\tau}$)	0.71	0.71	0.71		
Acceptance ($\mathcal{A}$)	0.48	0.54	0.54	0.56	0.56
Trigger ($\mathcal{T}$)	0.28	0.40	0.37	0.51	0.48
Background (f)	0.19	0.23	0.39	0.32	0.43
Particle Id ($\mathcal{P}$)	0.16	0.32	0.31	0.36	0.34
Quadrature sum	1.00	1.15	1.18	1.10	1.12

Lepton universality



- in the SM, the coupling of leptons to the gauge bosons is flavour-independent
  - the only difference in charged lepton generations is their mass
- can be tested by using the theoretically very clean prediction of decay rate of leptons
  - if charged current lepton universality holds: $\mathbf{g_e = g_\mu = g_\tau}$

$\ell \in \{e, \mu\}$



$$\frac{\mathcal{B}(\tau \to \ell \nu_\ell \nu_\tau)}{\tau_\tau} = \frac{g_\tau^2 g_\ell^2 m_\tau^5}{6144\pi^3 M_W^4} f(m_\ell^2/m_\tau^2) R_\gamma^\tau R_W^{\tau\ell}$$

» Tsai, Phys. Rev. D 4, 2821 (1971)

Lepton universality with taus

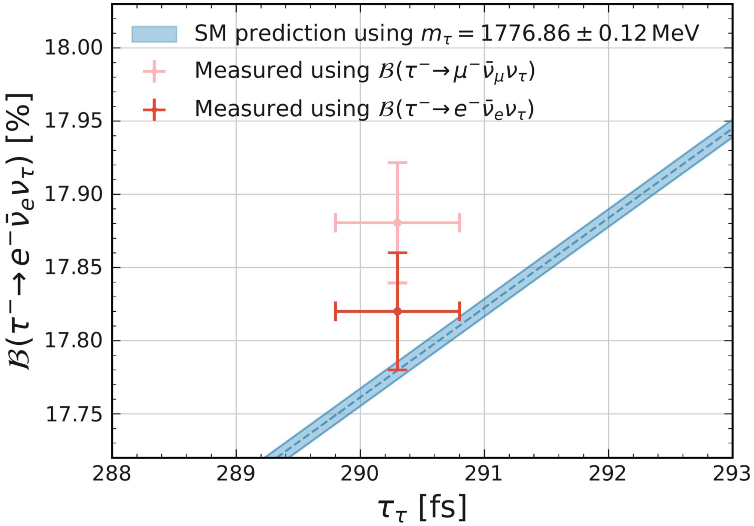
- world averages of coupling ratios » [HFLAV, Phys.Rev.D 107 (2023), 052008]
  - ➢ any deviation from unity would indicate new physics

$$\left(\frac{g_\tau}{g_\mu}\right)_\tau = 1.0009 \pm 0.0014 \quad \left(\propto \sqrt{\frac{\mathcal{B}_{\tau e}}{\mathcal{B}_{\mu e}} \frac{\tau_\mu m_\mu^5}{\tau_\tau m_\tau^5}}\right)$$

$$\left(\frac{g_\tau}{g_e}\right)_\tau = 1.0027 \pm 0.0014 \quad \left(\propto \sqrt{\frac{\mathcal{B}_{\tau \mu}}{\mathcal{B}_{\mu e}} \frac{\tau_\mu m_\mu^5}{\tau_\tau m_\tau^5}}\right)$$

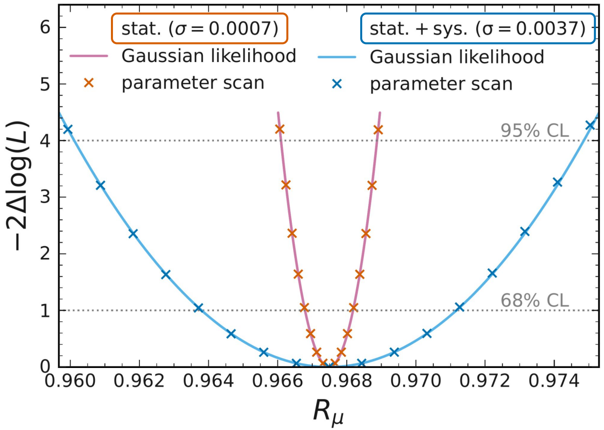
$$\left(\frac{g_\mu}{g_e}\right)_\tau = 1.0019 \pm 0.0014 \quad \left(\propto \sqrt{\frac{\mathcal{B}_{\tau \mu}}{\mathcal{B}_{\tau e}}}\right)$$

ratio of leptonic τ branching fractions, experimentally very clean and no additional inputs needed

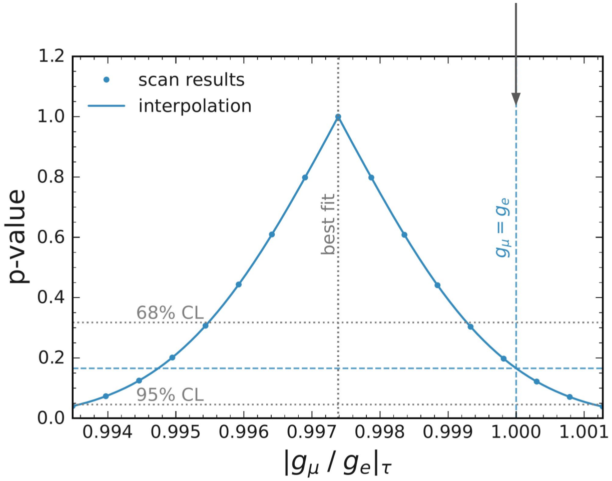


Belle II result

- fit result $\mathbf{R_\mu}$ **= 0.9675 ± 0.0007 (stat) ± 0.0036 (sys)**
- translates to $(\mathbf{g_\mu/g_e})_\tau$ **= 0.9974 ± 0.0019**
- consistent with Standard Model expectation at the level of ~1.37 sigma (p-value 0.17)

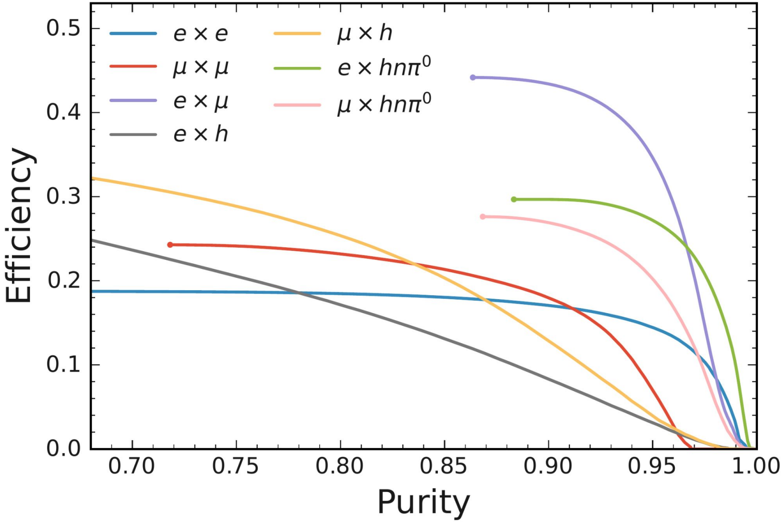


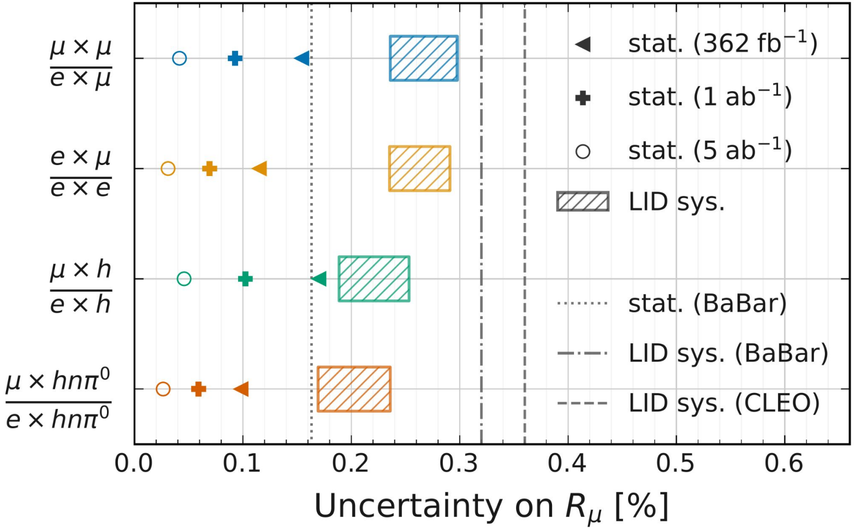
$$R_\mu = \frac{\mathcal{B}\left(\tau^- \to \nu_\tau \mu^- \overline{\nu}_\mu(\gamma)\right)}{\mathcal{B}\left(\tau^- \to \nu_\tau e^- \overline{\nu}_e(\gamma)\right)}$$



$$\left(\frac{g_\mu}{g_e}\right)_\tau = \sqrt{R_\mu \frac{f(m_e^2/m_\tau^2)}{f(m_\mu^2/m_\tau^2)}}$$

Decay channels





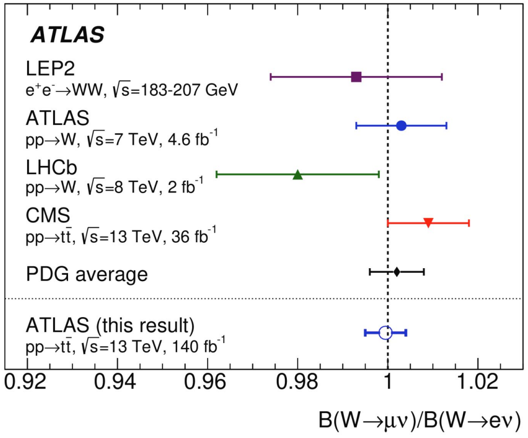
Other LFU tests

$$\left|\frac{g_e}{g_\mu}\right|_\pi = 0.9996 \pm 0.0012. \qquad \text{(PIENU)}$$

» Phys. Rev. Lett. 115, 071801

	CMS	LEP	ATLAS	LHCb	CDF	D0
$R_{\mu/e}$	1.009 ± 0.009	0.993 ± 0.019	1.003 ± 0.010	0.980 ± 0.012	0.991 ± 0.012	0.886 ± 0.121
$R_{\tau/e}$	0.994 ± 0.021	1.063 ± 0.027	—	—	—	—
$R_{\tau/\mu}$	0.985 ± 0.020	1.070 ± 0.026	0.992 ± 0.013	—	—	—
$R_{\tau/\ell}$	1.002 ± 0.019	1.066 ± 0.025	—	—	—	—

» CMS Phys. Rev. D 105, 072008



$$R_W^{\mu/e} = \mathcal{B}(W^\pm \to \mu^\pm \nu_\mu)/\mathcal{B}(W^\pm \to e^\pm \nu_e)$$

$$R_W^{\mu/e} = 0.9995 \pm 0.0022\,(stat.) \pm 0.0036\,(sys.) \pm 0.0014\,(ext.),$$

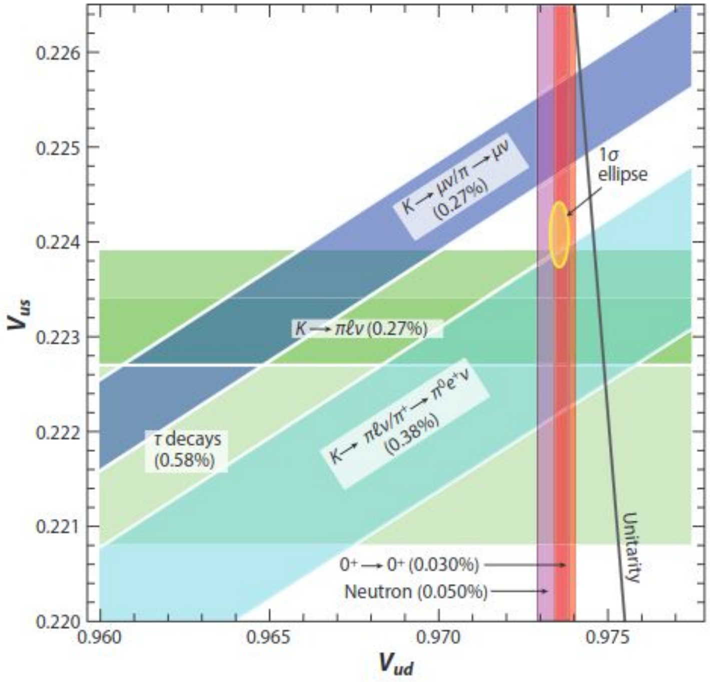
0.45% uncertainty → 0.225% on g_μ/g_e

$$R_{WZ}^{\mu/e} = \frac{R_W^{\mu/e}}{\sqrt{R_Z^{\mu\mu/ee}}}$$

$$R_W^{\mu/e}(\text{ATLAS}) = R_{WZ}^{\mu/e}(\text{ATLAS}) \cdot \sqrt{R_Z^{\mu\mu/ee}(\text{LEP+SLD})}$$

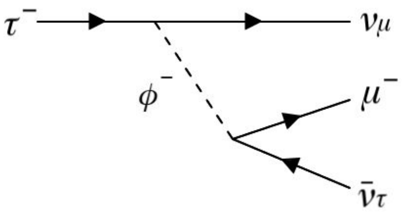
» ATLAS arXiv:2403.02133

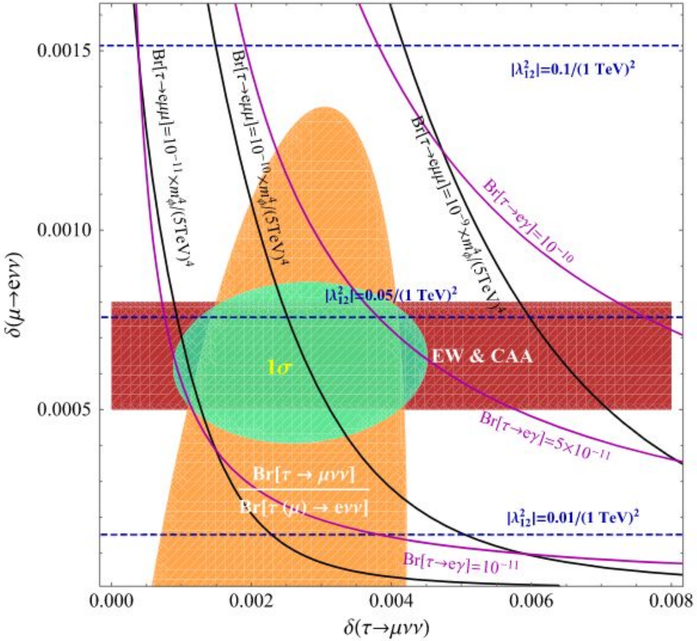
Cabibbo Angle Anomaly



$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 0.9985 \pm 0.0005$$

» Annual Review of Nuclear and Particle Science Volume 72, 2022

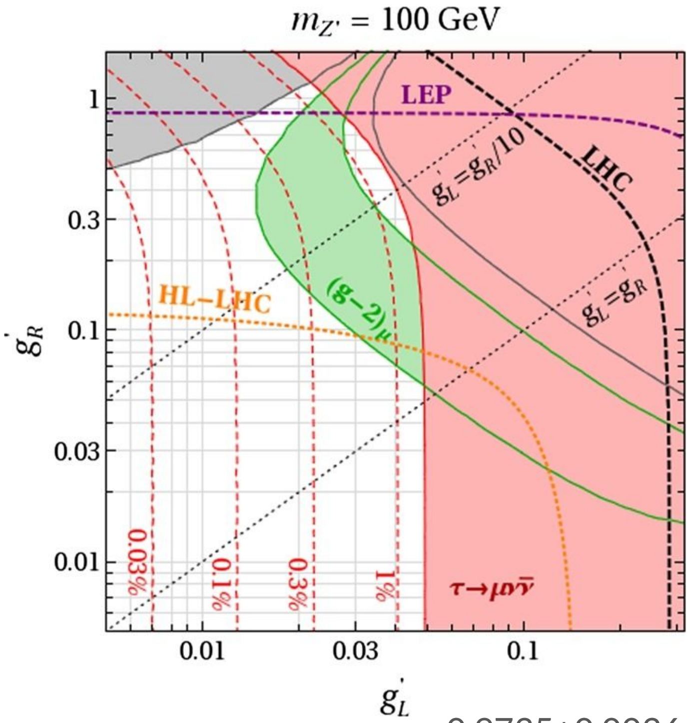


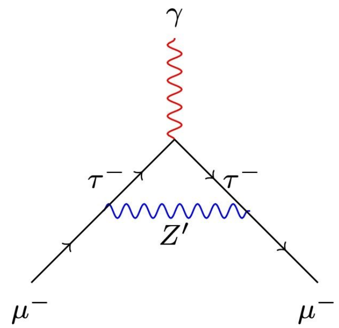


» Phys. Rev. D 103, 073002 (2021)

Lepton flavour violating Z'

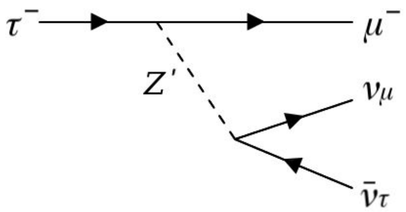
» Phys. Lett. B 762, 389-398 (2016)

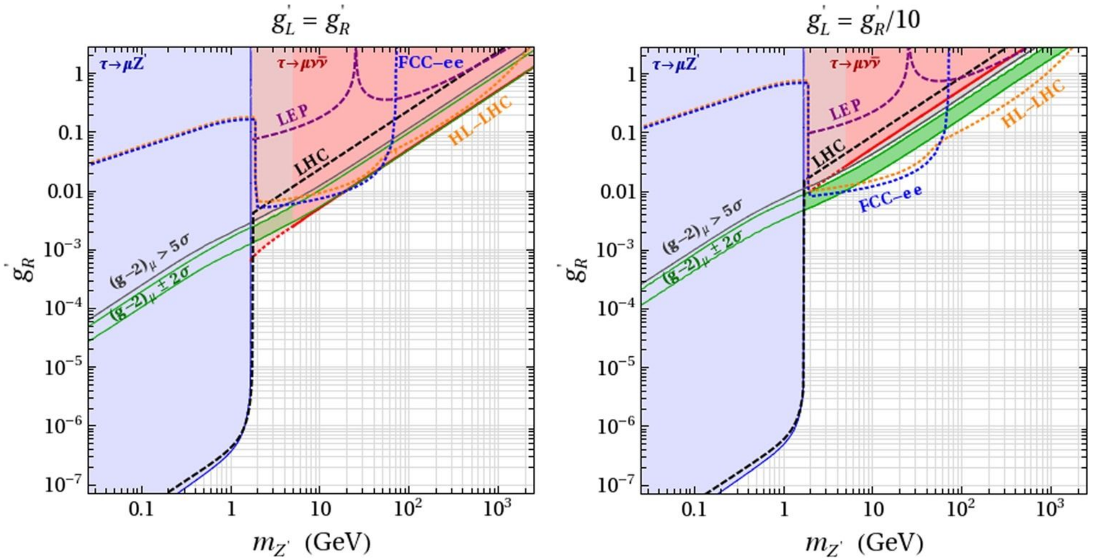




$$\mathcal{L}_{Z'} = g'_L\left(\bar{\mu}\gamma^\alpha P_L\tau + \bar{\nu}_\mu\gamma^\alpha P_L\nu_\tau\right)Z'_\alpha + g'_R\left(\bar{\mu}\gamma^\alpha P_R\tau\right)Z'_\alpha + \text{H.c.}$$

$$P_{L,R} = (1 \mp \gamma^5)/2$$





0.9735±0.0026 / 0.9726 = 1.0009±0.0027