Precision measurements of τ lepton decays at Belle II

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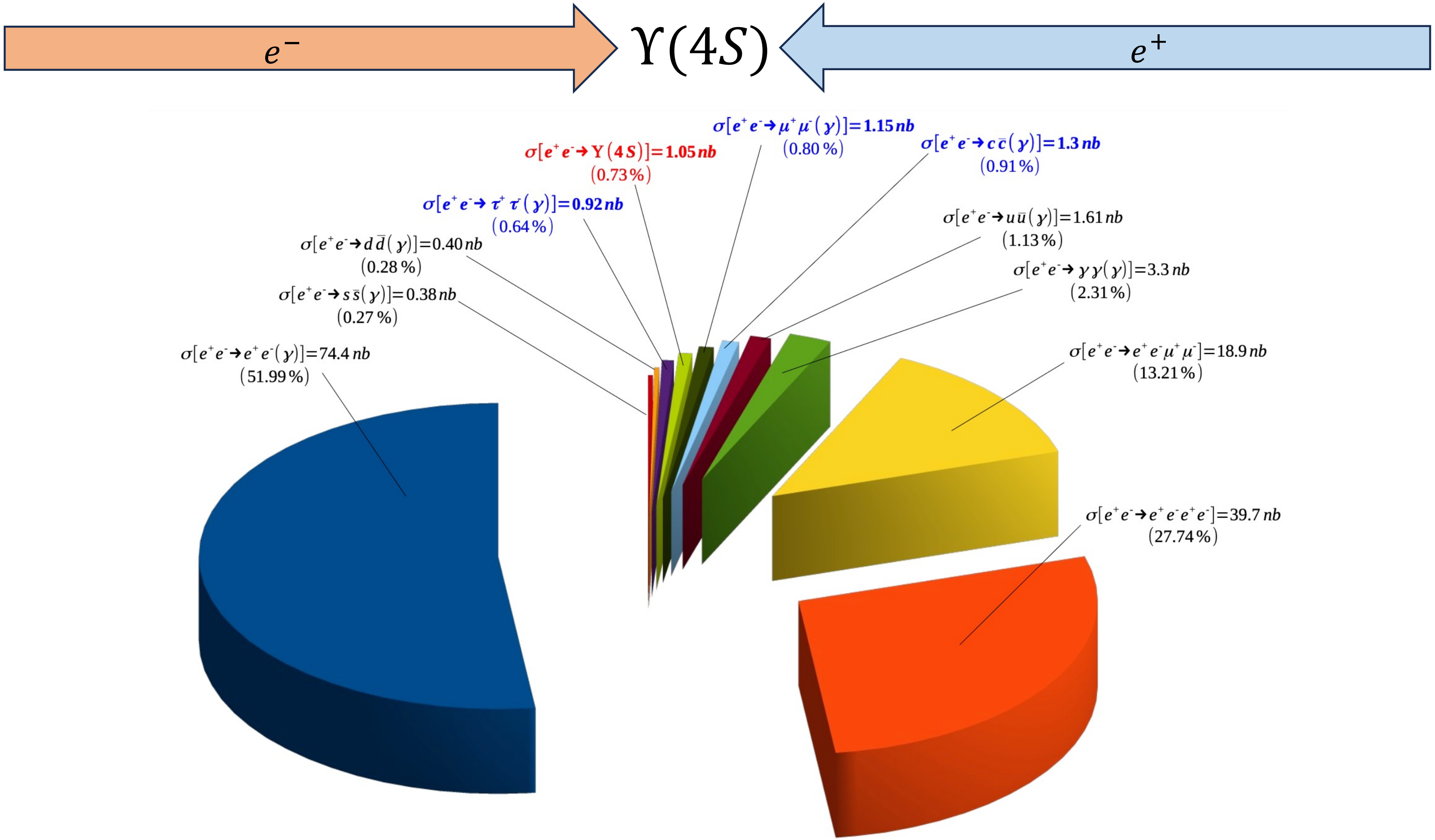
Belle II

Colliding electrons and positrons at SuperKEKB



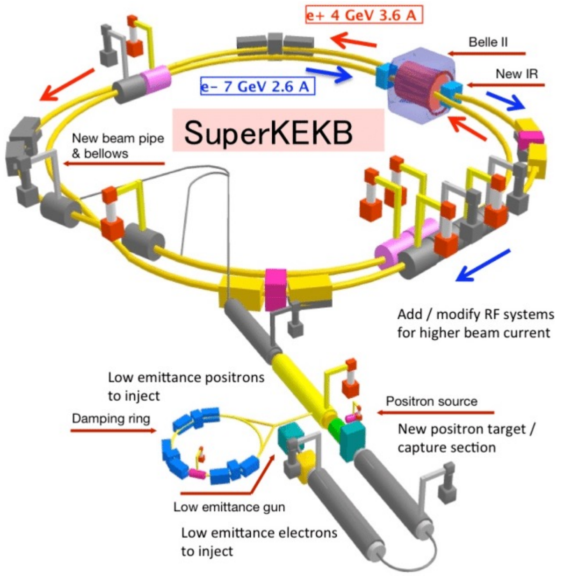
SuperKEKB is B-Factory / charm-Factory / τ-Factory

-> New dedicated low multiplicity triggers allow to exploit a very rich physics program!

(Ex. The Neural Network First-Level Hardware Track Trigger of the Belle II Experiment, 1 GeV single-γ trigger, etc.)

Colliding electrons and positrons at SuperKEKB

e^- → $\Upsilon(4S)$ ← e^+



Physics process	Cross section [nb]	Cuts
$\Upsilon(4S)$	1.05 ± 0.10	-
$u\bar{u}(\gamma)$	1.61	-
$d\bar{d}(\gamma)$	0.40	-
$s\bar{s}(\gamma)$	0.38	-
$c\bar{c}(\gamma)$	1.30	-
$e^+e^-(\gamma)$	300 ± 3 (MC stat.)	$10° < \theta^*_{e's} < 170°$, $E^*_{e's} > 0.15$ GeV
$e^+e^-(\gamma)$	74.4	e's (p >0.5GeV) in ECL
$\gamma\gamma(\gamma)$	4.99 ± 0.05 (MC stat.)	$10° < \theta^*_{\gamma's} < 170°$, $E^*_{\gamma's} > 0.15$ GeV
$\gamma\gamma(\gamma)$	3.30	γ's (p >0.5GeV) in ECL
$\mu^+\mu^-(\gamma)$	1.148	-
$\mu^+\mu^-(\gamma)$	0.831	μ's (p >0.5GeV) in CDC
$\mu^+\mu^-\gamma(\gamma)$	0.242	μ's (p >0.5GeV) in CDC, ≥ 1 γ (E_γ >0.5GeV) in ECL
$\tau^+\tau^-(\gamma)$	0.919	-
$\nu\bar{\nu}(\gamma)$	0.25×10^{-3}	-
$e^+e^-e^+e^-$	39.7 ± 0.1 (MC stat.)	$W_{\ell\ell} > 0.5$GeV
$e^+e^-\mu^+\mu^-$	18.9 ± 0.1 (MC stat.)	$W_{\ell\ell} > 0.5$GeV

https://en.wikipedia.org/wiki/Barn_(unit)

Unit	Symbol	m^2	cm^2
megabarn	Mb	10^{-22}	10^{-18}
kilobarn	kb	10^{-25}	10^{-21}
barn	b	10^{-28}	10^{-24}
millibarn	mb	10^{-31}	10^{-27}
microbarn	μb	10^{-34}	10^{-30}
nanobarn	nb	10^{-37}	10^{-33}
picobarn	pb	10^{-40}	10^{-36}
femtobarn	fb	10^{-43}	10^{-39}
attobarn	ab	10^{-46}	10^{-42}
zeptobarn	zb	10^{-49}	10^{-45}
yoctobarn	yb	10^{-52}	10^{-48}

SuperKEKB
Instantaneous luminosity
world record:
$\mathbf{4.7 \times 10^{34}\ cm^{-2}s^{-1}}$
Corresponding to
- **~49 $B\bar{B}$ events/s**
- **~43 $\tau^+\tau^-$ events/s**

~0.5 ab^{-1} collected

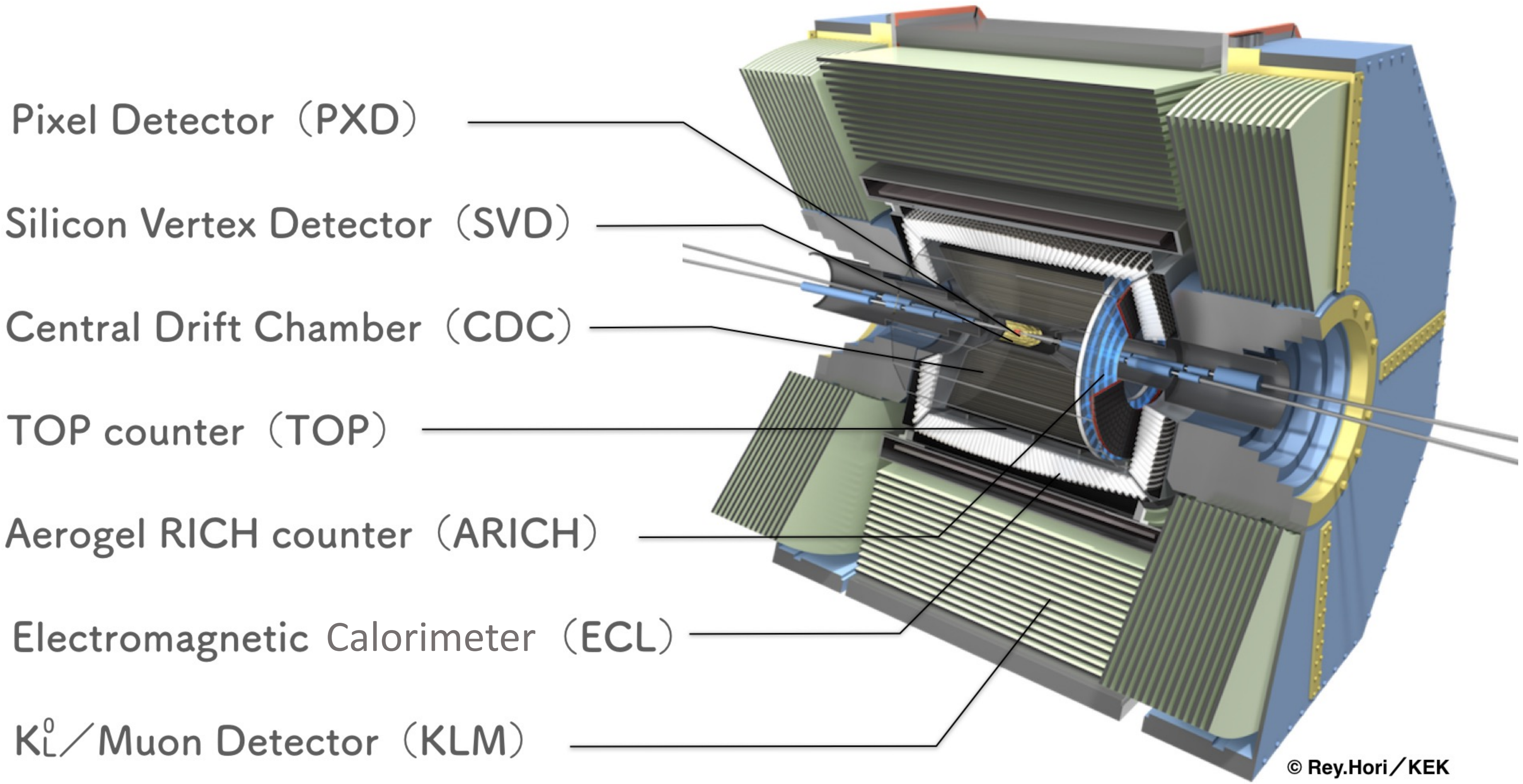
$$N = L \times \sigma$$

Cross-section of the process to be studied in the specific experiment

Number of events produced

Luminosity of an experiment

The Belle II detector



The Belle II detector

Pixel Detector（PXD）

Silicon Vertex Detector（SVD）

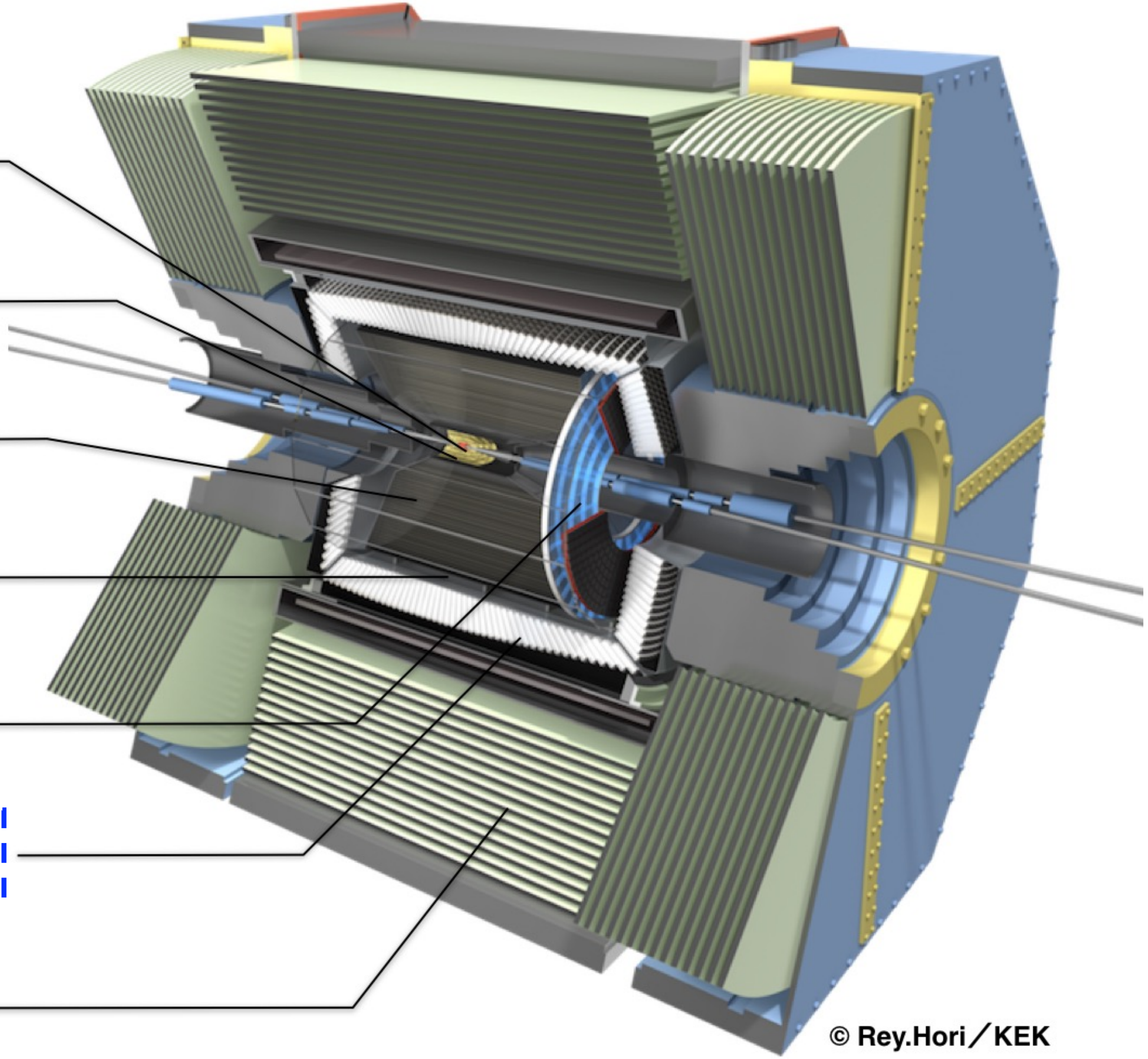
Central Drift Chamber（CDC）

TOP counter（TOP）

Aerogel RICH counter（ARICH）

Electromagnetic Calorimeter（ECL）

K_L^0／Muon Detector（KLM）

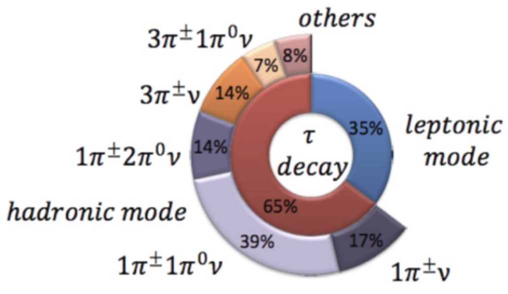


τ event topologies at Belle II

$\boldsymbol{\sigma[e^+e^- \to \tau^+\tau^-] = 0.92nb\ @\ Belle\ II}$

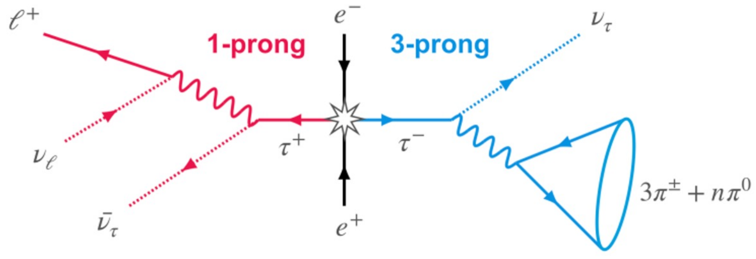
- Large production cross-section for τ pairs
- τ can be used as a probe of new physics
- τ can be used as a tool to understand detector performance (i.e. Tracking, PID, Trigger, etc.)
- τ is the only lepton sufficiently heavy to decay to hadrons

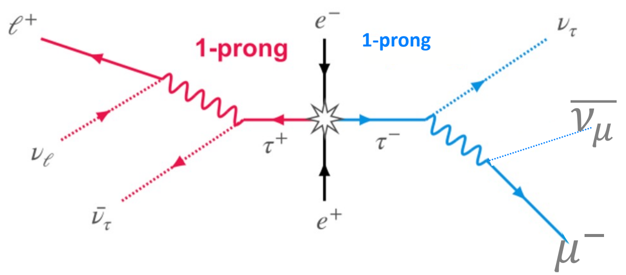
Many final states



Different reconstruction techniques

- Ex. 3x1 vs 1x1 topologies





Analyses presented at ICHEP 2024

- **τ mass (this talk)**
- **LFUV $\tau^+ \to l^+ \nu_l \nu_\tau$ (this talk)**
- LFV $\tau \to lll$ (see W. Li talk, ArXiv 2405.07386)
- LFV & LNV $\tau \to lhh$ (see W. Li talk)

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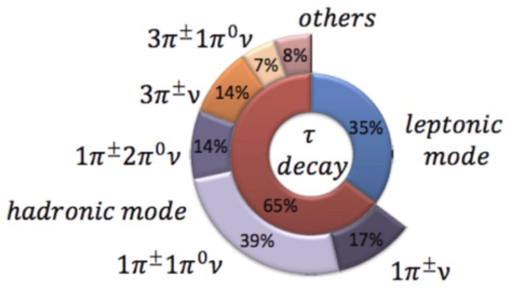

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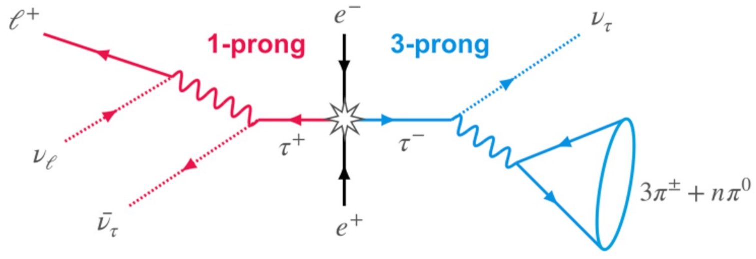

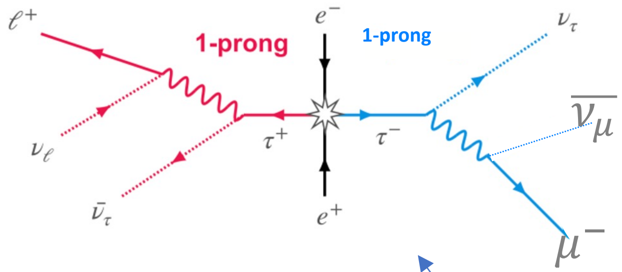

Similar logic as the $B_{TAG} - B_{SIG}$ case with B mesons

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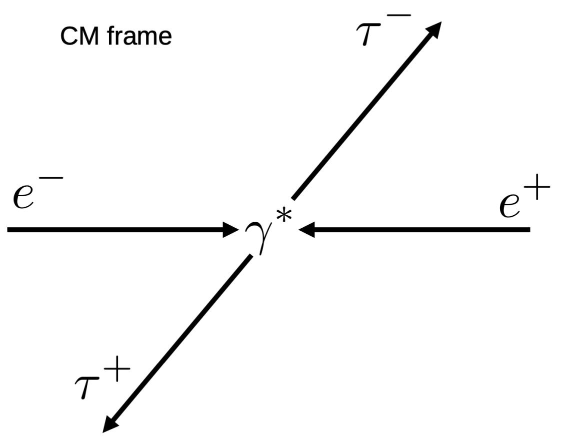
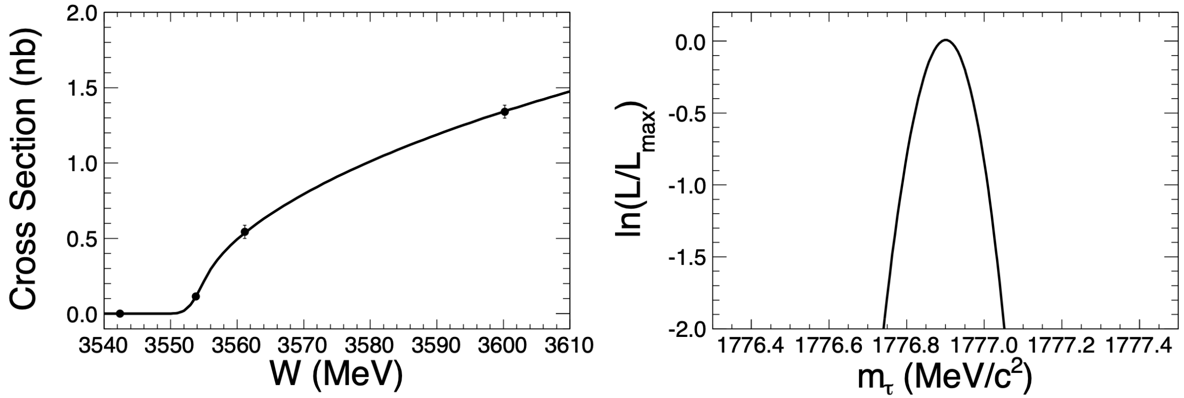
How heavy is a τ?

In e^+e^- collisions, in the CM frame, τ leptons are back-to-back.

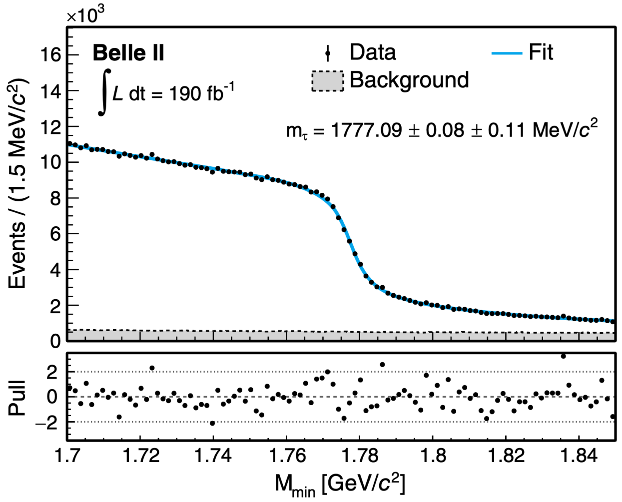
- When running at the $\tau\tau$ threshold, in a τ-charm factory (ex. BES III, [1405.1076](1405.1076)) one can infer the mass from the increase in the pair-production cross-section





- In a B-Factory the situation is different and only a pseudo-mass can be measured using the 3-prong decay $\tau^- \to \pi^-\pi^+\pi^-\upsilon_\tau$

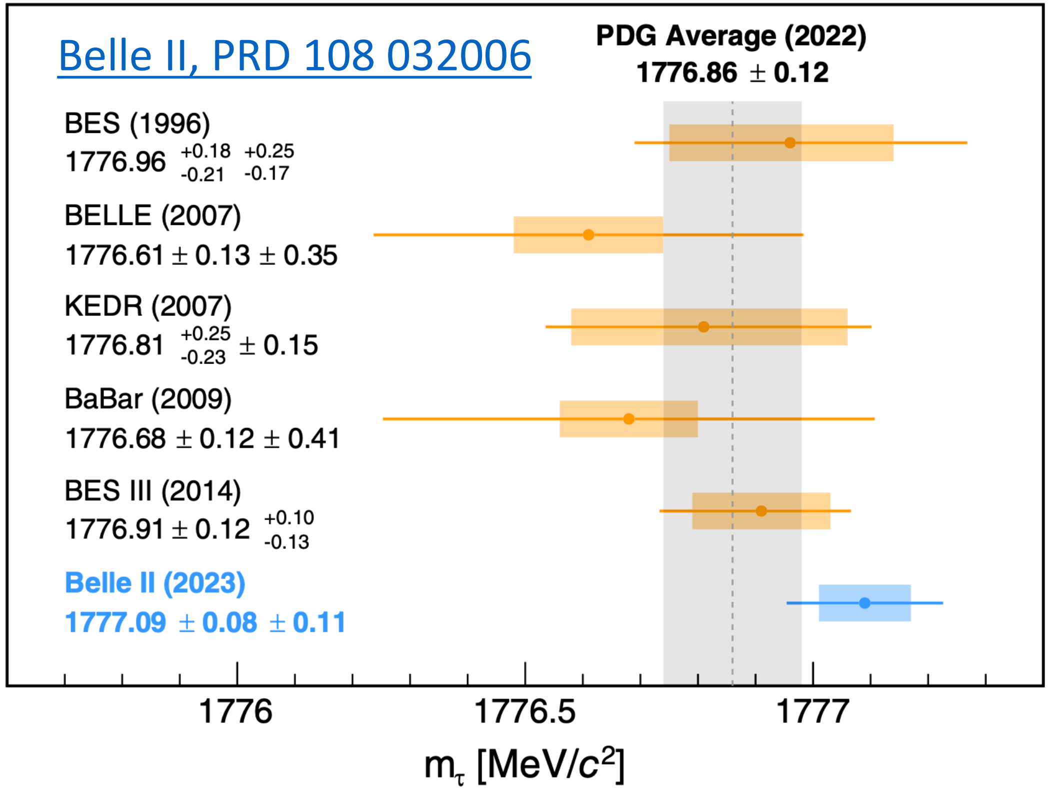
$$M_{\min} = \sqrt{M_{3\pi}^2 + 2(\sqrt{s}/2 - E_{3\pi}^*)(E_{3\pi}^* - p_{3\pi}^*)} \le m_\tau$$



"In the absence of ISR and FSR, and assuming a perfect measurement of the four-momentum of the three-pion system, the M_{min} distribution extends up to M_τ , where it has sharp edge" Belle II, PRD 108 032006

How heavy is a τ?

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



Belle II has World's most precise determination of the τ mass.

Belle II (BES III) has now accumulated x3 (x4) more luminosity since the measurement, but more control of systematics, for example beam energy precision and momentum scale needed to improve the precision.

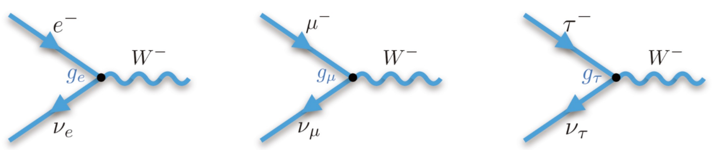
The mass of the τ is also a fundamental parameter to test lepton flavor universality

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

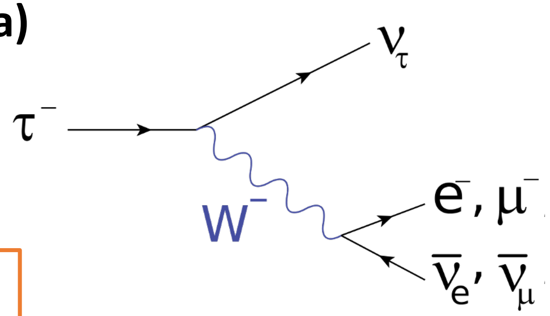
Using τ to test Lepton Flavor Universality

Lepton Flavor Universality is an intrinsic and accidental property or symmetry of the SM: **couplings of EW boson to leptons are flavor-independent and the only difference between leptons is their mass (Yukawa)**

$g_e = g_\mu = g_\tau$



In τ decays, testing LFU symmetry is in principle very simple: compare the rates of $\tau \to \mu\nu\nu$ vs $\tau \to e\nu\nu$



$$R_\mu = \frac{BF[\tau^- \to \mu^- \bar{\nu}_\mu \nu_\tau]}{BF[\tau^- \to e^- \bar{\nu}_e \nu_\tau]}$$

Slightly smaller than 1 in the SM due to the $e - \mu$ mass difference ($R_\mu^{SM} = 0.9726$)

$$\left(\frac{g_\mu}{g_e}\right)_\tau = \sqrt{\frac{BF[\tau^- \to \mu^- \bar{\nu}_\mu \nu_\tau]}{BF[\tau^- \to e^- \bar{\nu}_e \nu_\tau]} \frac{f(m_e^2/m_\tau^2)}{f(m_\mu^2/m_\tau^2)}}$$

$$f(x) = -8x + 8x^3 - x^4 - 12x^2 \log x$$

Exactly 1 in the SM

NP could enter in different ways:
- LFUV charged currents
- LFV neutral currents [ex. Soni et al., $L_\mu - L_\tau$ Z' Phys. Lett. B 2016 09 046]

Measurement by BaBar [PRL 105 051602]:

$R_\mu = 0.9796 \pm 0.0016_{stat} \pm 0.0036_{sys}$

$\left(\frac{g_\mu}{g_e}\right)_\tau = 1.0036 \pm 0.0020$

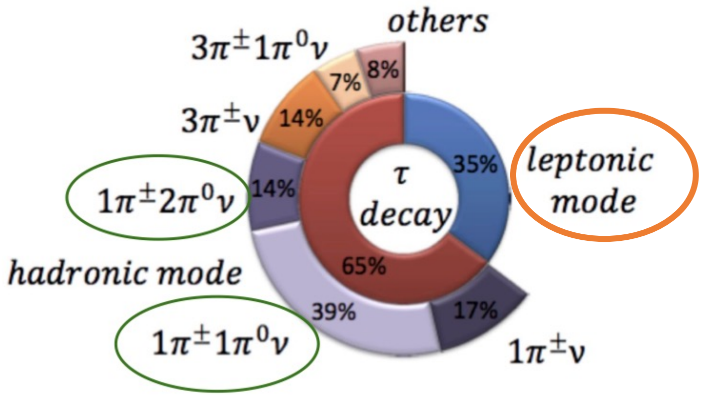
Test of LFU in leptonic τ decays at Belle II: 1x1 event topology

We use the 1x1 event topology.

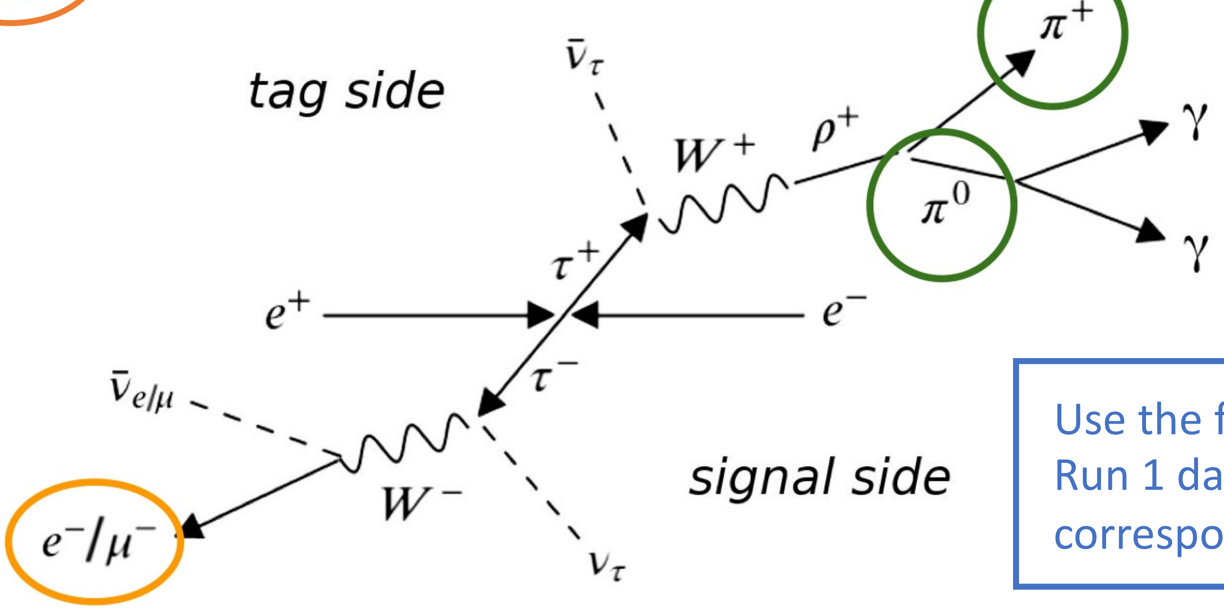
The “tag side” is a 1-prong (i.e. one charged track) τ decay containing one charged hadron ($\pi^{\pm}$) and at least a π^0 (i.e. $\boldsymbol{\tau^+ \to \pi^+\pi^0\overline{\upsilon_\tau}, \tau^+ \to \pi^+\pi^0\pi^0\overline{\upsilon_\tau}}$ and C.C.). The signal side is a fully leptonic tau decay (i.e. $\boldsymbol{\tau^- \to e^-\overline{\upsilon_e}\upsilon_\tau, \tau^- \to \mu^-\overline{\upsilon_\mu}\upsilon_\tau}$, and C.C.)

- Large BFs, low backgrounds and high trigger efficiency

Tag side pre-selection
- ✓ 1 charged track with $\frac{E_{cluster}}{p} < 0.8$
- ✓ $N(\pi^0) > 0$



Courtesy of P. Feichtinger



Signal side pre-selection
- ✓ 1 charged track identified (PID) as μ or e.

Use the full “on resonance” Run 1 data (2019-2022), corresponding to 362 fb^{-1}

Test of LFU in leptonic τ decays at Belle II: event selection

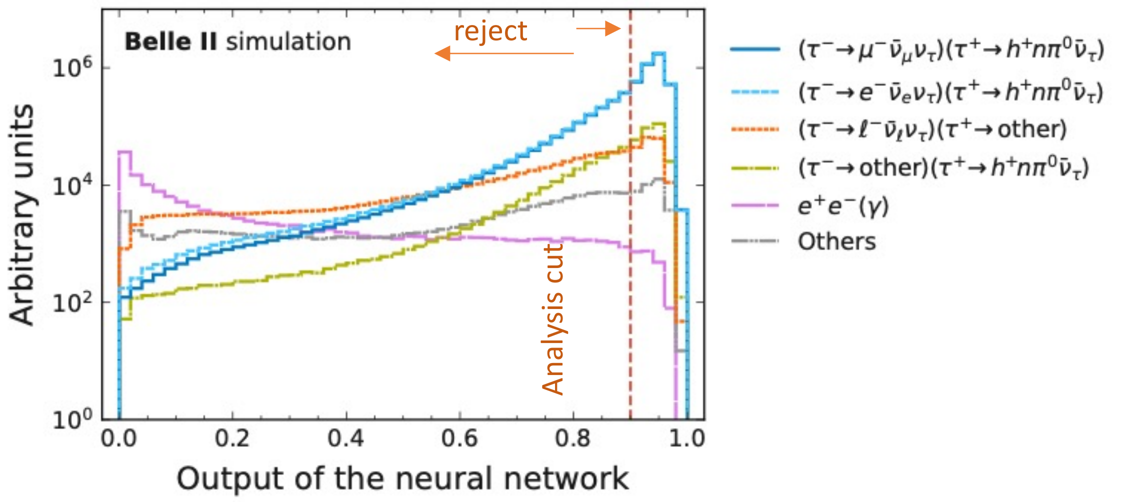
Event selection is based on rectangular cuts and a neural network. Identical selection applied to both e and μ modes

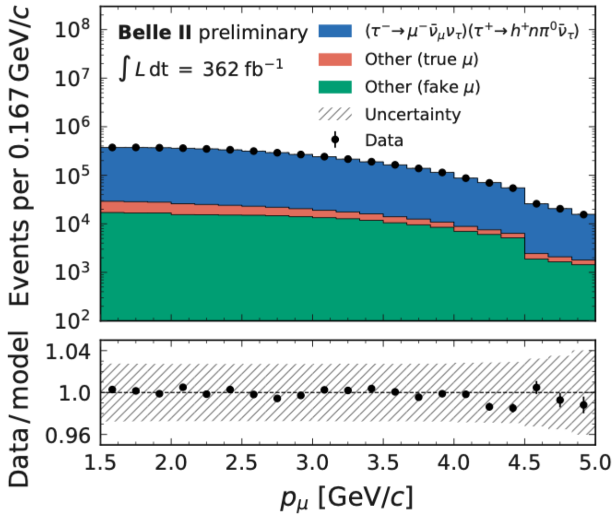
- Analysis restricted to region least sensitive to PID systematics:
    - $0.82 < \theta_{lepton} < 2.13$ (KLM barrel) and
    - $1.5\text{GeV} < p_{lepton} < 5.0$ GeV
- Final selection provides 94% purity with 9.6% signal efficiency for combined $e + \mu$ sample. Input variables:
    - Thrust value and thrust axis
    - Total visible energy in the CMS: E_{vis}
    - Missing momentum in the CMS: p_T, θ
    - Tag side kinematics in the CMS: p, θ, M

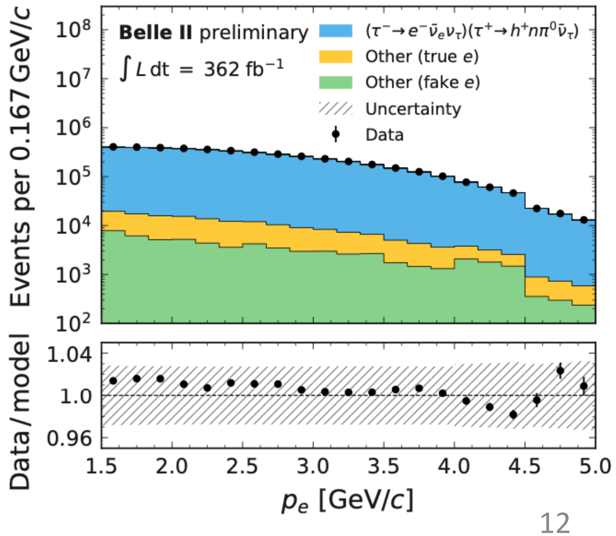
$$T = \max_{\mathbf{n}} \frac{\sum_i |\mathbf{p}_i \cdot \mathbf{n}_T|}{\sum_i |\mathbf{p}_i|}$$

Main backgrounds after the event selection

- $e^+e^- \to \tau^+\tau^-$ ($\pi^\pm$ 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%







Test of LFU in leptonic τ decays at Belle II: systematics on R_μ

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

Systematics uncertainties on R_μ dominated by Particle Identification (leading) and trigger (sub-leading)

Particle identification **(0.32%)**

- Efficiency and fake rate correction factors and uncertainties derived from multiple calibration channels
  - $J/\psi \to l^+l^-,\ e^+e^- \to e^+e^-\ l^+l^-,\ e^+e^- \to l^+l^-(\gamma)$
    Efficiency: $e(\mu) = 99.7\%\ (93.9\%)$
  - $K_S^0 \to \pi^+\pi^-, \tau^\pm \to \pi^\pm\pi^\mp\pi^\pm\upsilon_\tau$
    Fakes: $\pi \to e\ (\mu) = 0.9\%\ (3.1\%)$

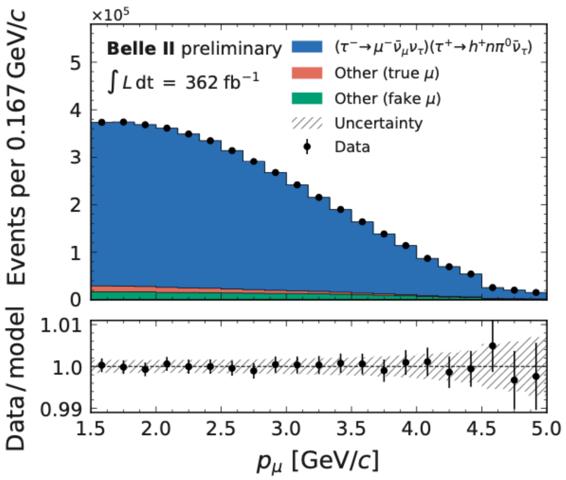
Trigger **(0.10%)**

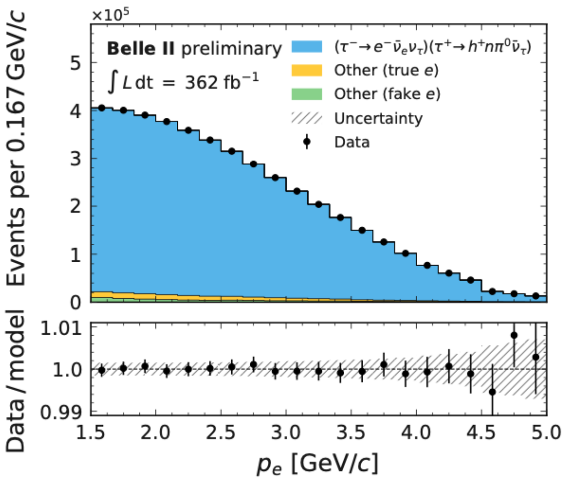
- Used triggers are based on ECL information,
  - most important: E_{ECL}>1 GeV trigger
- Correction factor for MC obtained directly from data
  ε=99.8% for $\tau^- \to e^-\overline{\upsilon_e}\upsilon_\tau$ and ε=96.6% for $\tau^- \to \mu^-\overline{\upsilon_\mu}\upsilon_\tau$

Test of LFU in leptonic τ decays at Belle II: extraction of R_μ

$\boldsymbol{R_\mu}$ extraction performed with a *binned maximum likelihood* fit

- 21 bins defined over lepton momentum from 1.5 to 5 GeV
- systematics included as (constrained) nuisance parameters

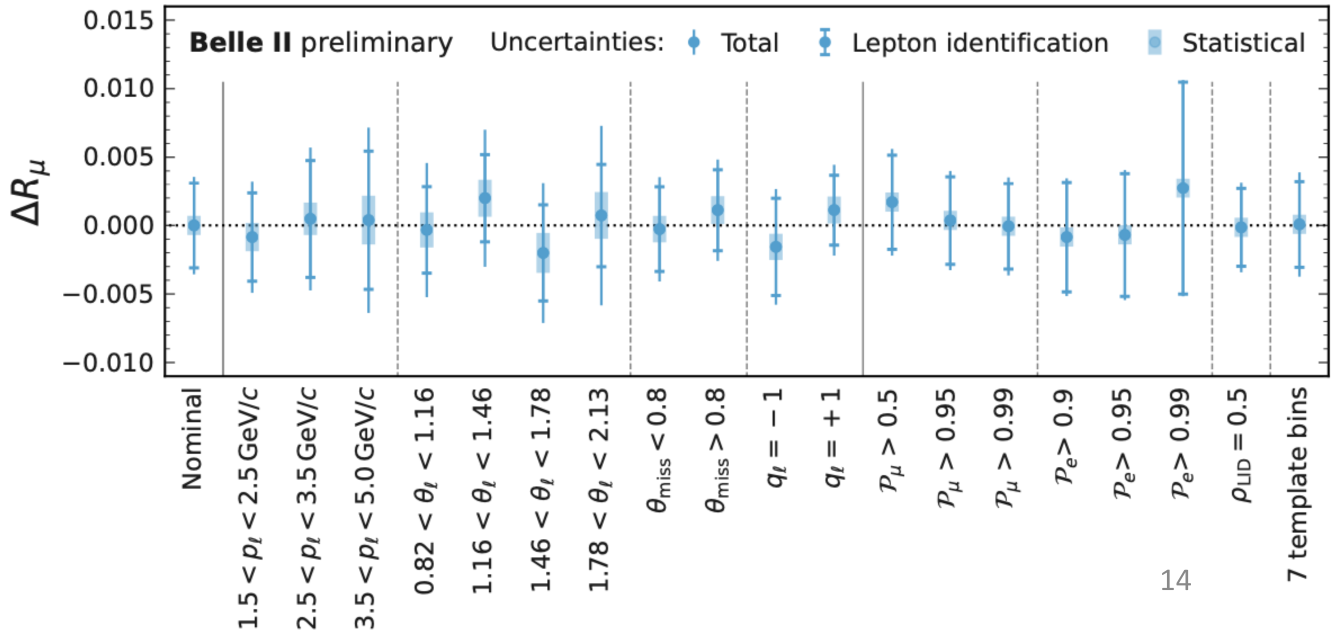




- 3 templates are used for the μ and e channels
  - signal decays
  - background with correct lepton on the signal side
  - background with misidentified particle on the signal side

Final checks

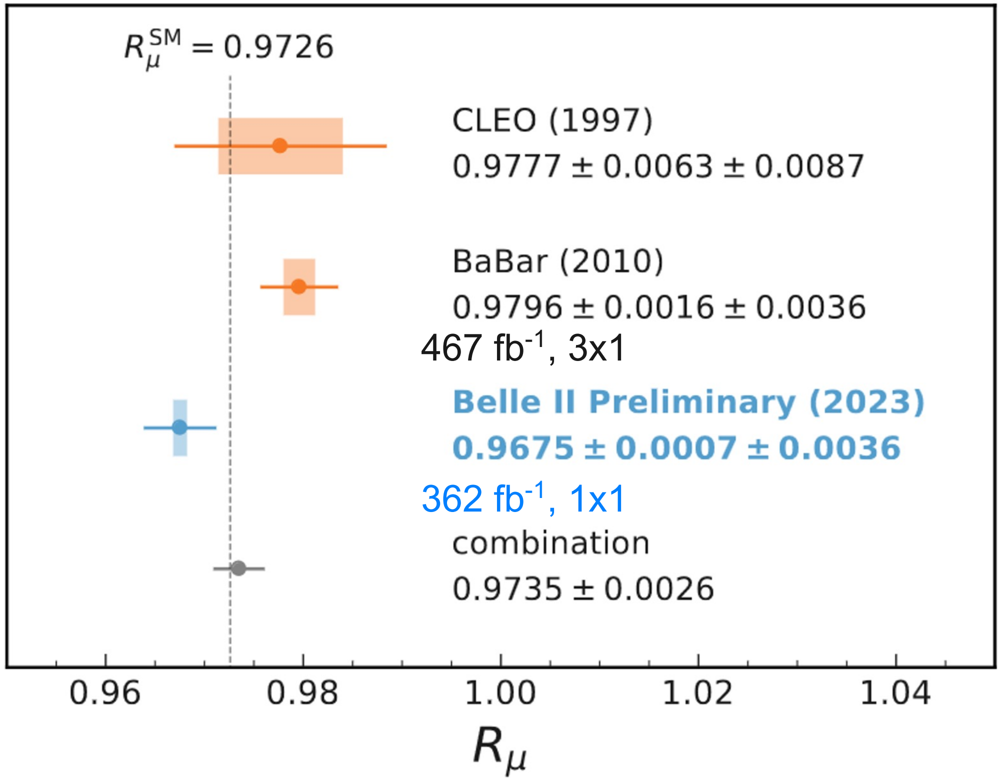
- Checked for consistency of the result before unblinding to evaluate its "stability"
  - sub-regions for different kinematic variables (momentum, polar angle, missing momentum, charge), data-taking periods as well as different requirements for PID
- Good agreement between the measured values

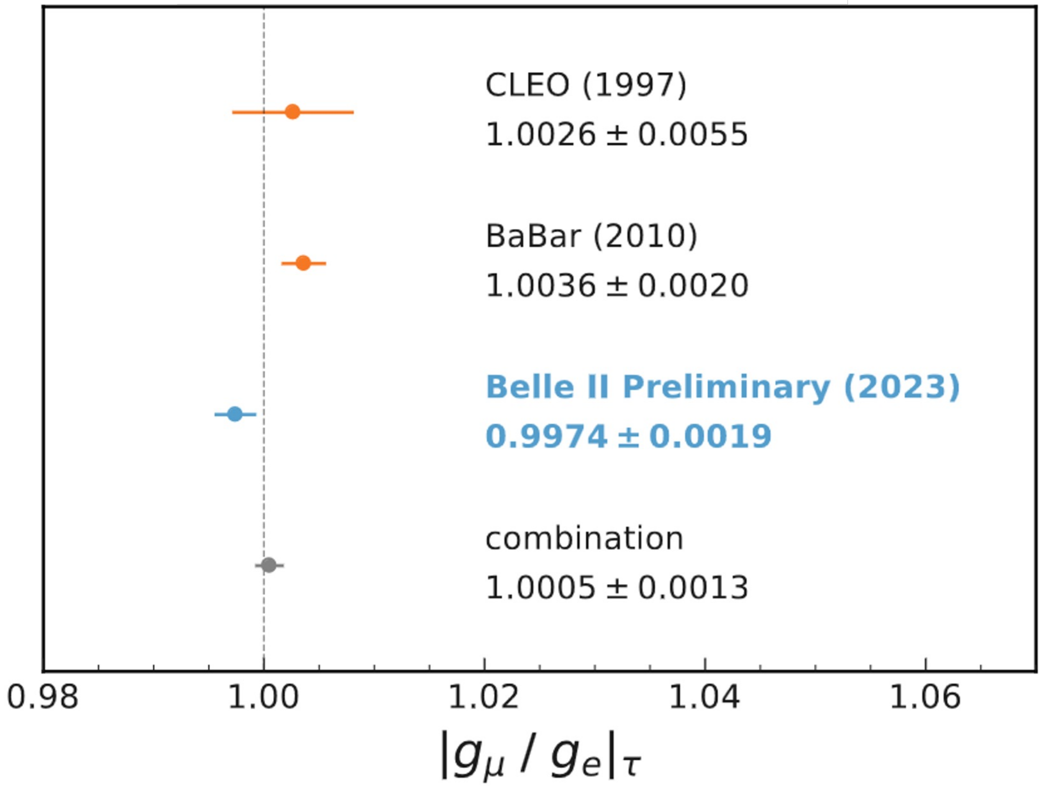


Test of LFU in leptonic τ decays at Belle II: results

$$R_\mu = \frac{BF[\tau^- \to \mu^- \bar{\nu}_\mu \nu_\tau]}{BF[\tau^- \to e^- \bar{\nu}_e \nu_\tau]}$$

$$\left(\frac{g_\mu}{g_e}\right)_\tau = \sqrt{\frac{BF[\tau^- \to \mu^- \bar{\nu}_\mu \nu_\tau]}{BF[\tau^- \to e^- \bar{\nu}_e \nu_\tau]} \frac{f(m_e^2/m_\tau^2)}{f(m_\mu^2/m_\tau^2)}}$$





World's most precise test of LFU in τ decays and most precise determination of R_μ and $|g_\mu/g_e|$

Submitted to JHEP, see ArXiv 2405.14625

Leptonic τ decays compatible with LFU at the current level of precision

Belle II

Summary

Belle II is performing the world's most precise measurements in the τ sector

- $M_\tau = 1777.09 \pm 0.08_{stat} \pm 0.11_{sys}$ MeV/c^2 , Belle II, PRD 108 032006
- $R_\mu = 0.9675 \pm 0.0007_{stat} \pm 0.0036_{sys}$ Submitted to JHEP, see ArXiv 2405.14625
- $\left(\frac{g_\mu}{g_e}\right)_\tau = 0.9974 \pm 0.0019$, Submitted to JHEP, see ArXiv 2405.14625
- Many more measurements will follow

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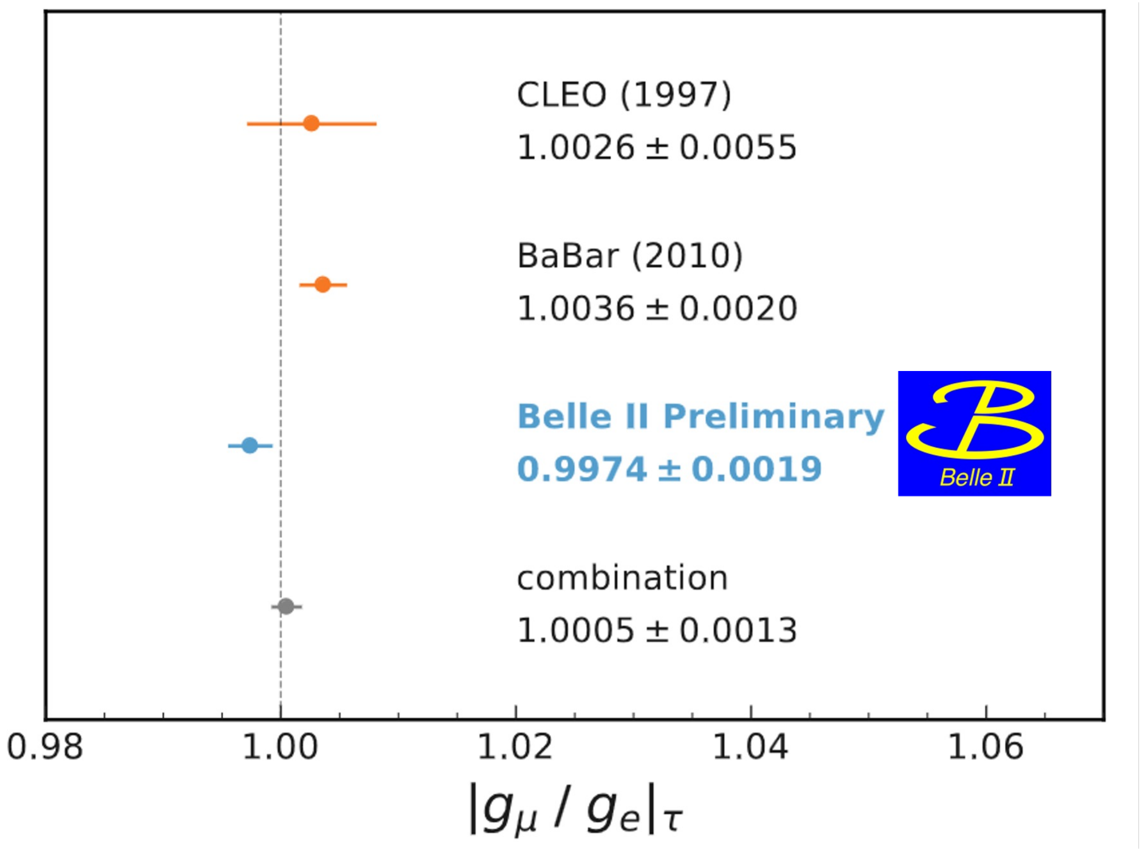
Belle II

$$\left(\frac{g_\mu}{g_e}\right)_\tau = \sqrt{\frac{BF[\tau^- \to \mu^- \bar{\nu}_\mu \nu_\tau]}{BF[\tau^- \to e^- \bar{\nu}_e \nu_\tau]} \frac{f(m_e^2/m_\tau^2)}{f(m_\mu^2/m_\tau^2)}}$$



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