Tau Lepton Physics at Belle II

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Physics Department, Nuclear & Particle Physics SW

Early Career and Research Associates Retreat
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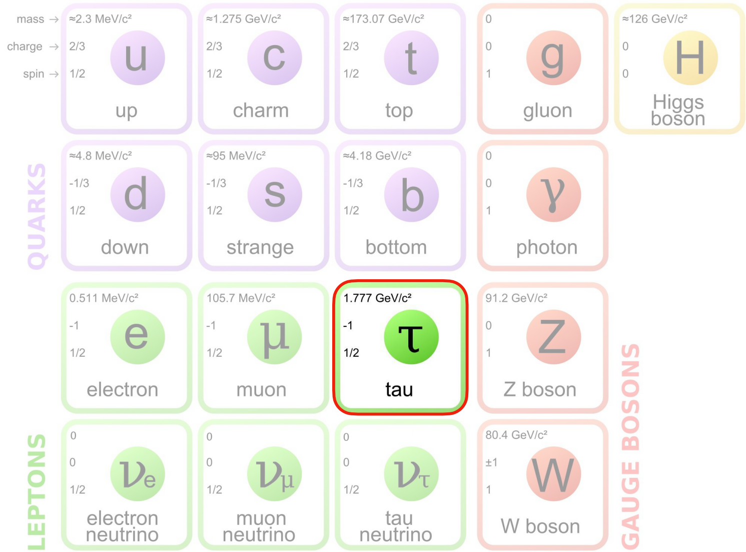
What makes τ leptons interesting?

- The τ is the charged lepton of the third generation



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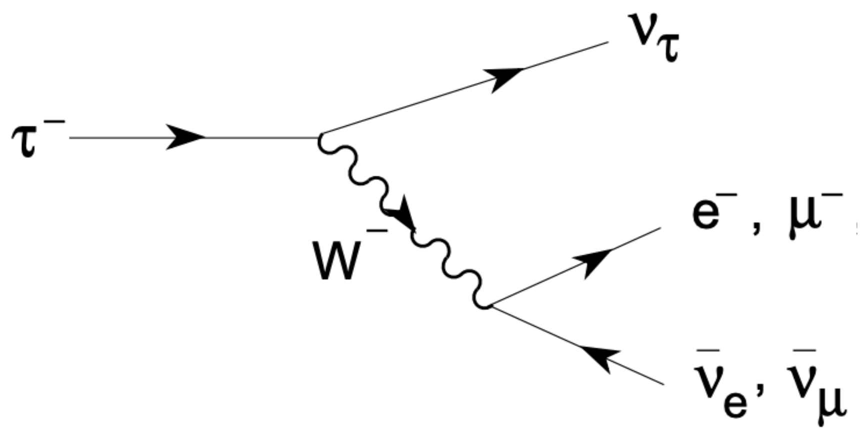
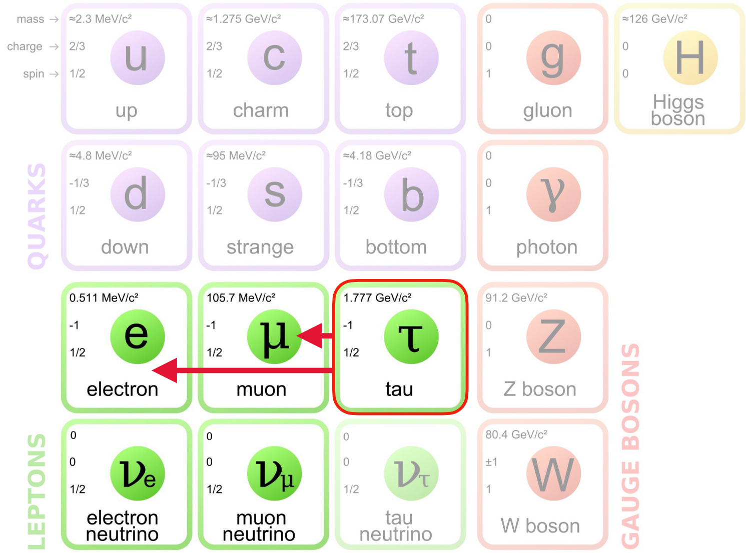
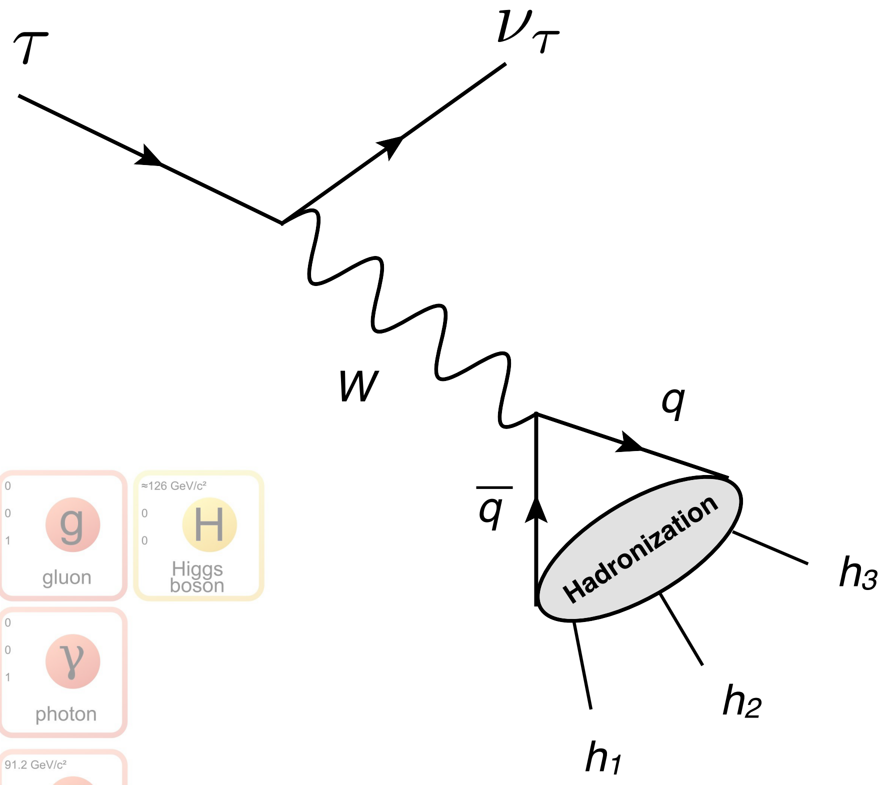
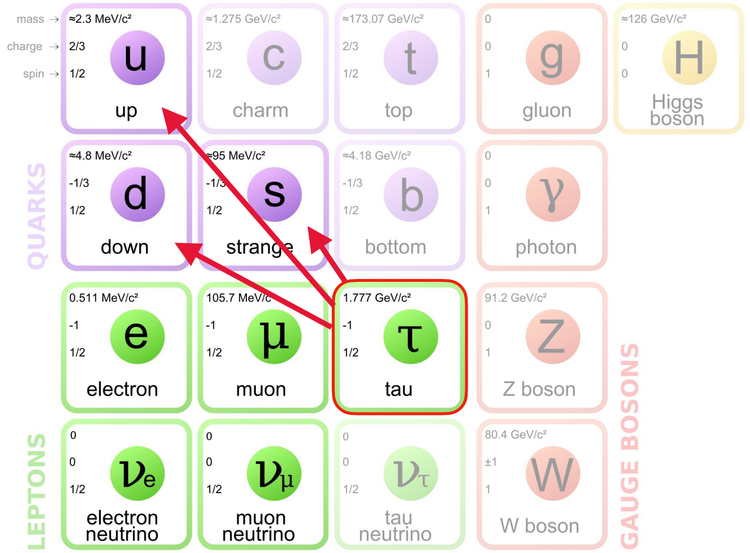




What makes τ leptons interesting?

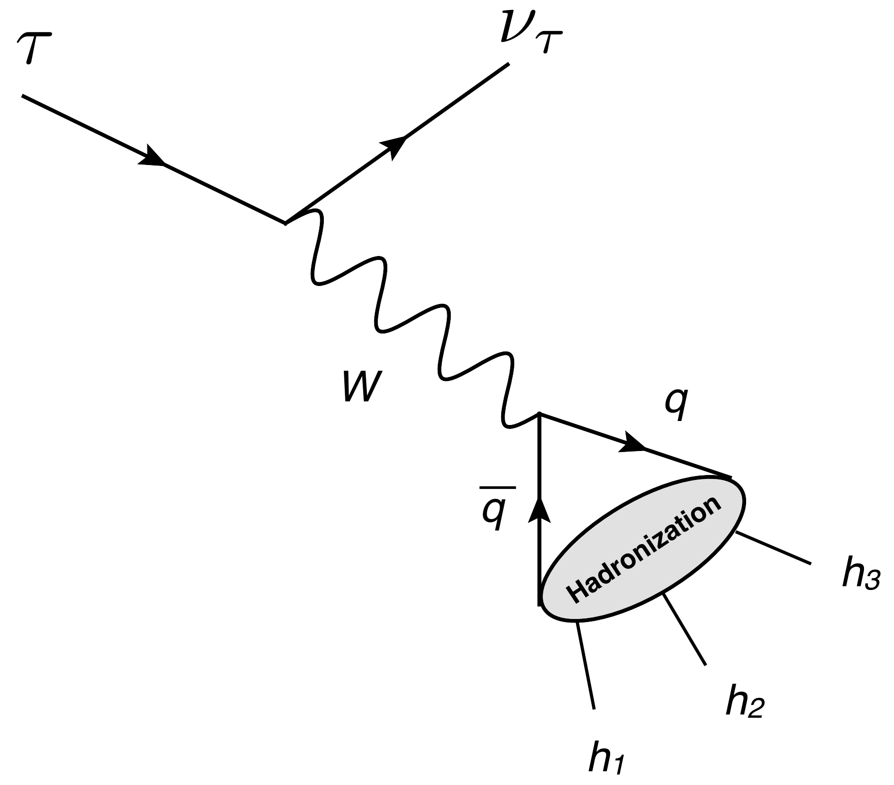
- The τ is the charged lepton of the third generation
- It is the only lepton massive enough to decay into hadrons





What makes τ leptons interesting?

- The τ is the charged lepton of the third generation
- It is the only lepton massive enough to decay into hadrons
- Allow a clean study of
  - Standard Model parameters m_{τ}, $|V_{us}|$, etc.
  - CP violation
  - Contributions to $(g-2)_{\mu}$
  - New physics searches, like lepton flavor violation
  - …



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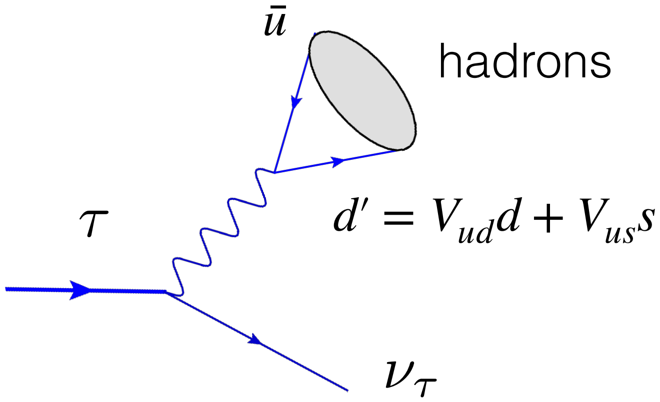
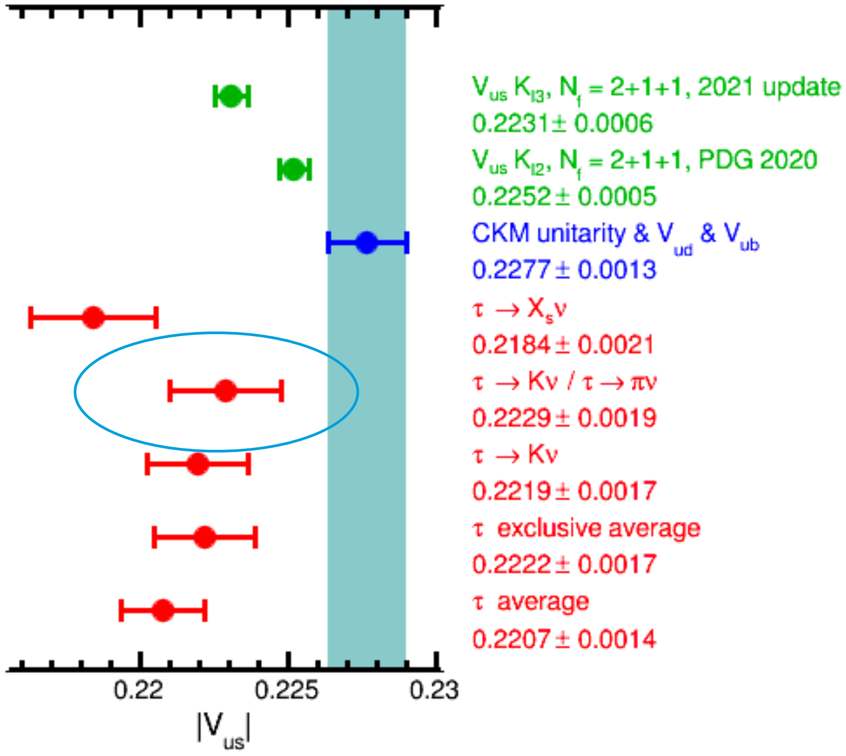
$$\frac{B(\tau \to K^-\nu_\tau)}{B(\tau \to \pi^-\nu_\tau)} = \frac{f_K^2|V_{us}|^2}{f_\pi^2|V_{ud}|^2}\frac{(1-m_K^2/m_\tau^2)^2}{(1-m_\pi^2/m_\tau^2)^2}R_{\tau K/\tau\pi}$$





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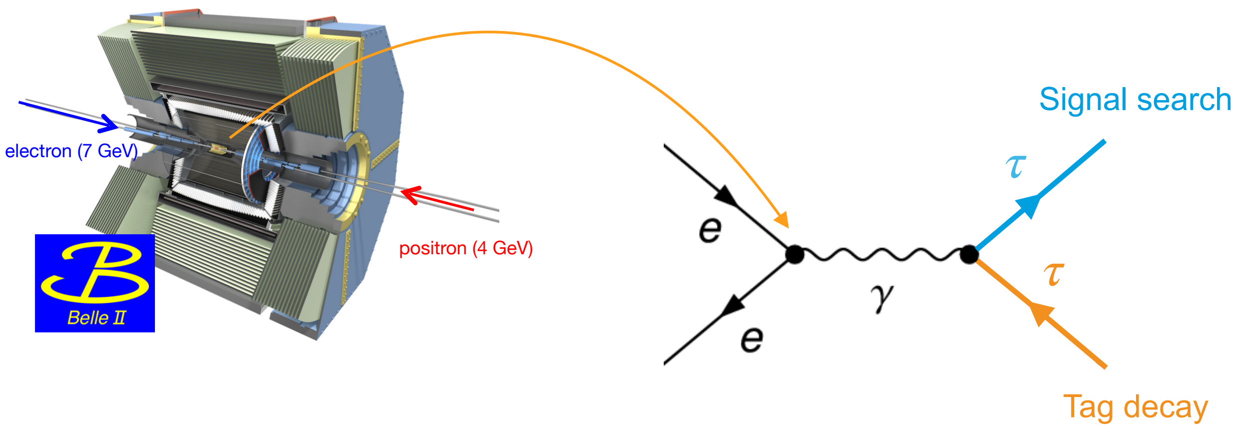
Belle II is a B (and τ) Factory



- At Y(4S):

  $\sigma(e^+e^- \rightarrow BB)$ = 1.05 nb

  $\sigma(e^+e^- \rightarrow \tau^+\tau^-)$ = **0.92 nb**

- Suitable environment for the study of tau lepton decays
  - Well-defined initial state
  - Good tracking and vertex resolution
  - Reliable particle identification

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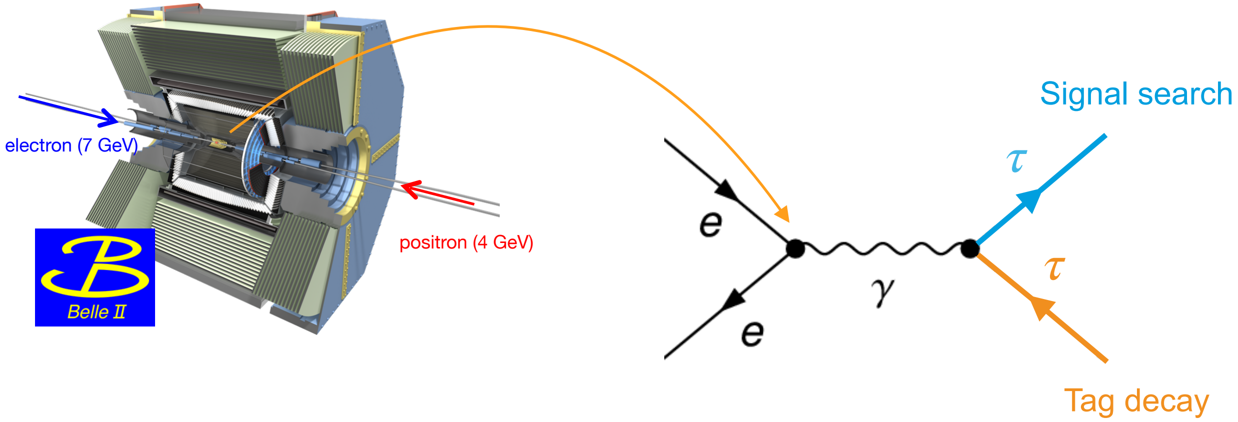
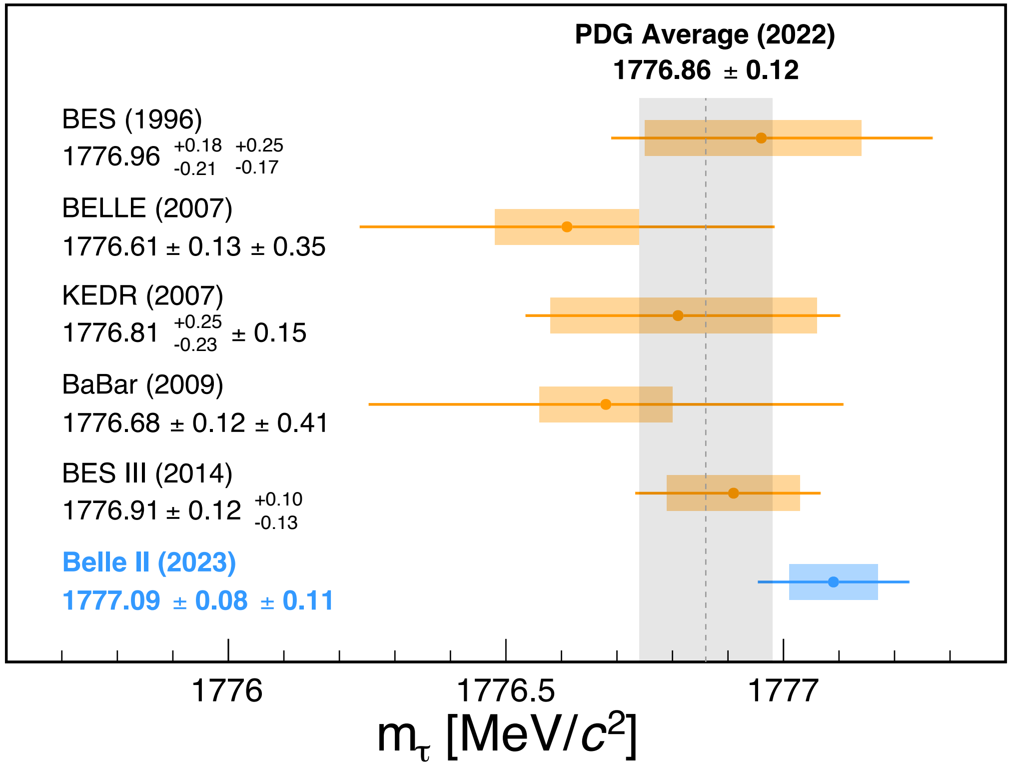


Most precise tau mass measurement to date:



Phys. Rev. D 108, 032006

- At Y(4S):
  - σ(e+e- --> BB) = 1.05 nb
  - σ(e+e- --> τ +τ-) = **0.92 nb**
- Suitable environment for the study of tau lepton decays
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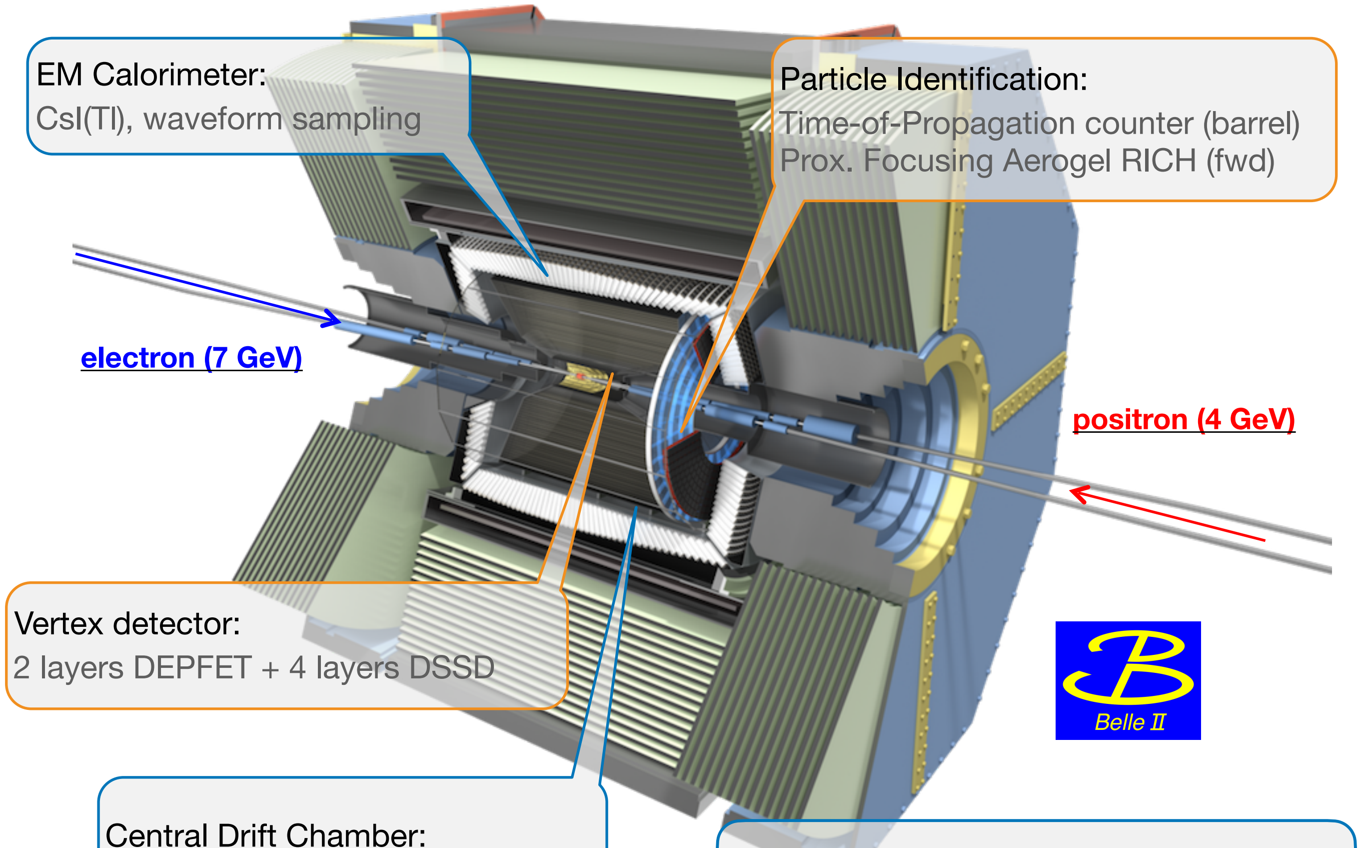
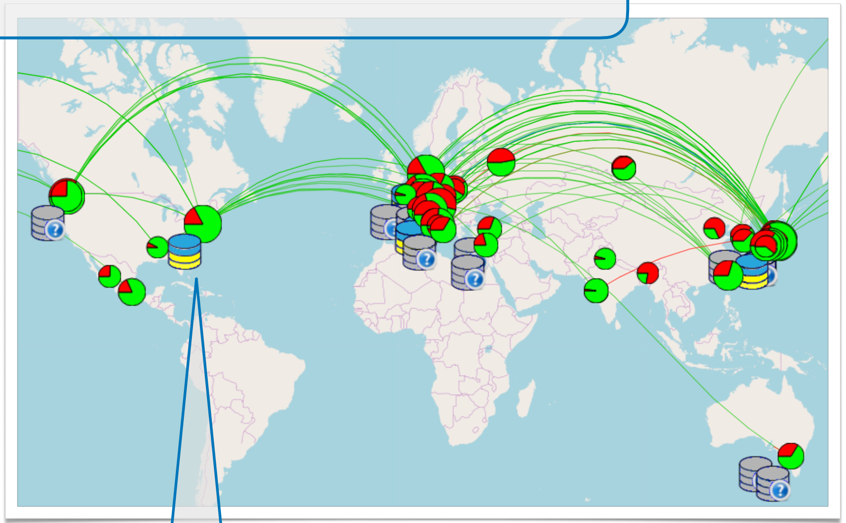
Belle II in a Nutshell



arXiv:1011.0352 [physics.ins-det]

Offline computing:
Distributed over the world via grid



EPJ Web Conf., 245 (2020) 11007

Major contributions from BNL
- Largest raw data center outside host lab (KEK)
- Prompt processing center
- Conditions database
- Key positions in management
  - Computing coordinator
  - Physics performance coordinator
  - ConditionsDB managers

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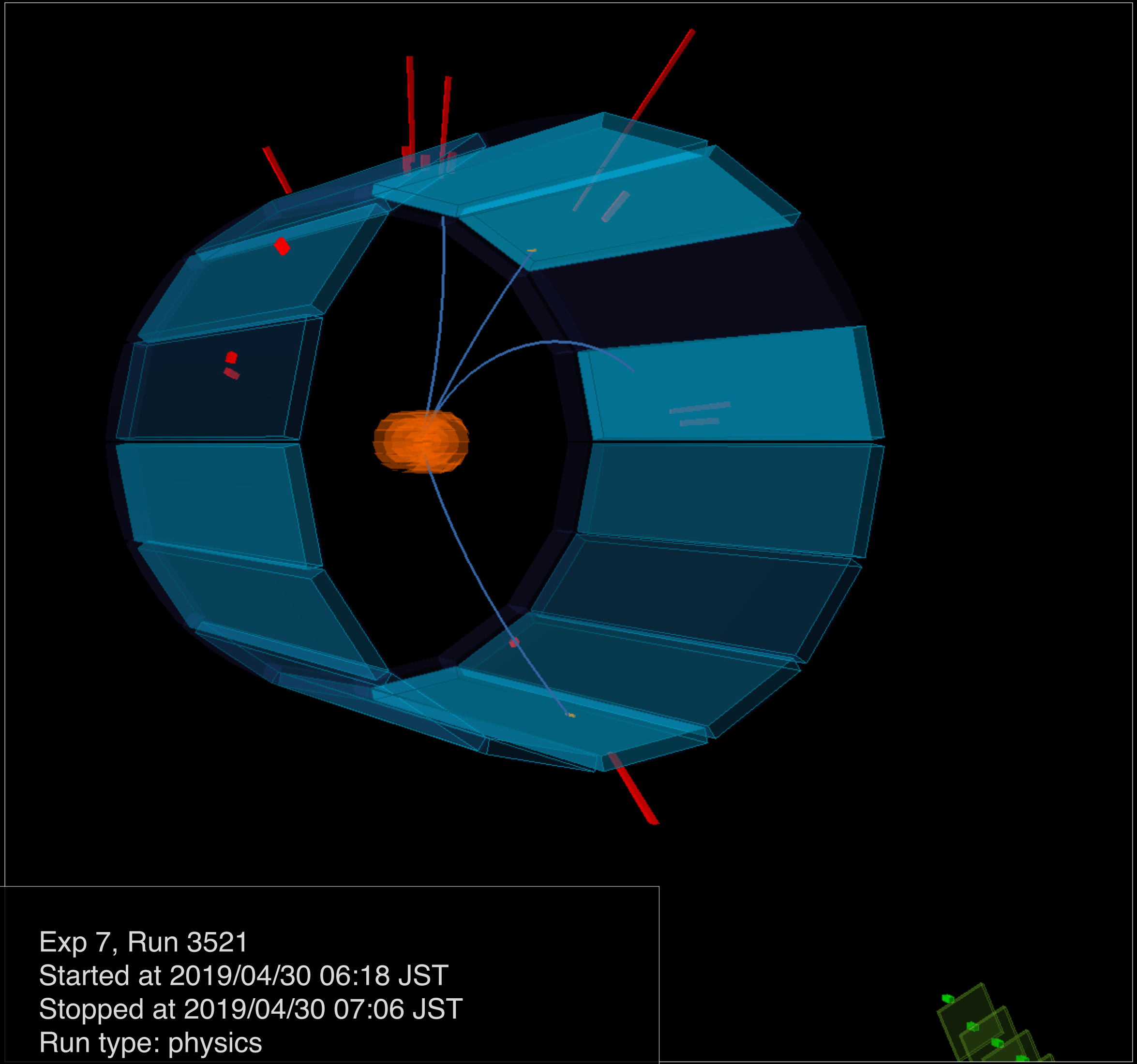
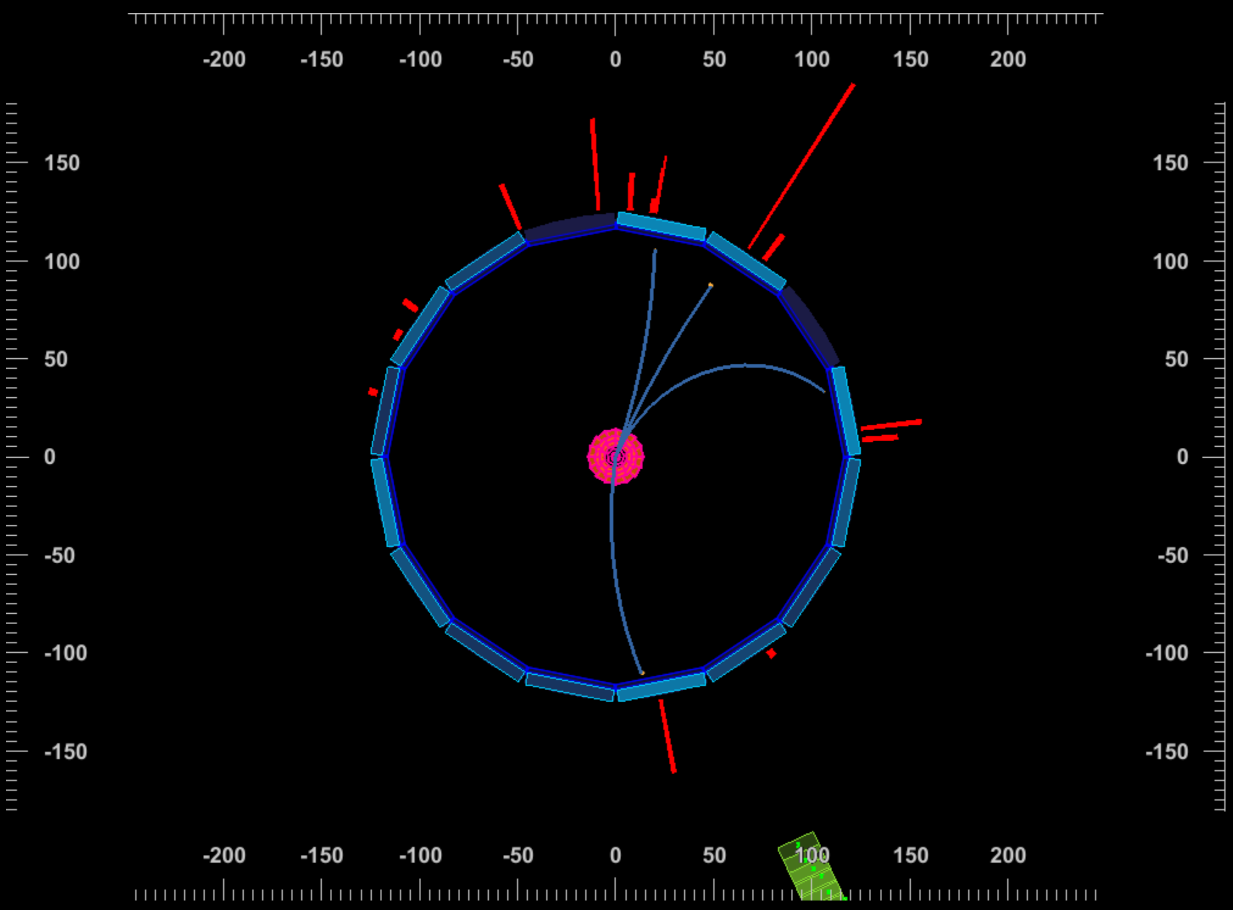


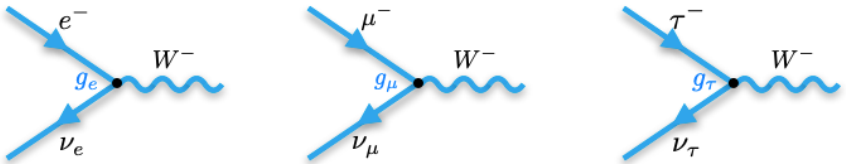


Exp 7, Run 3521
Started at 2019/04/30 06:18 JST
Stopped at 2019/04/30 07:06 JST
Run type: physics

Lepton Flavor Universality Test

- The coupling of leptons to W bosons is flavor-independent in the SM
- τ decays enable a test of μ – e universality

$g_e = g_\mu = g_\tau$?



$$\left(\frac{g_\mu}{g_e}\right)^2_\tau \propto R_\mu \times \frac{f(m_e^2/m_\tau^2)}{f(m_\mu^2/m_\tau^2)} \overset{\text{SM}}{=} 1 \qquad R_\mu = \frac{B(\tau^- \to \mu^- \bar{\nu}_\mu \nu_\tau)}{B(\tau^- \to e^- \bar{\nu}_e \nu_\tau)} \overset{\text{SM}}{=} 0.9726$$

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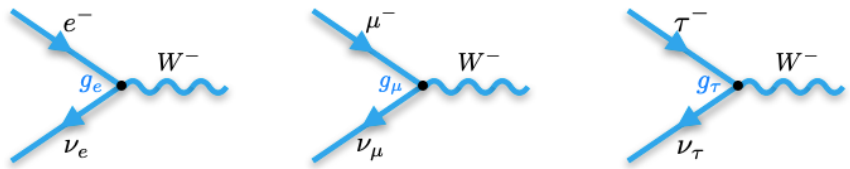

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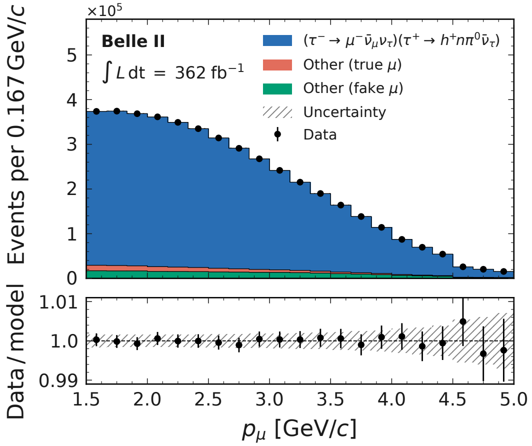
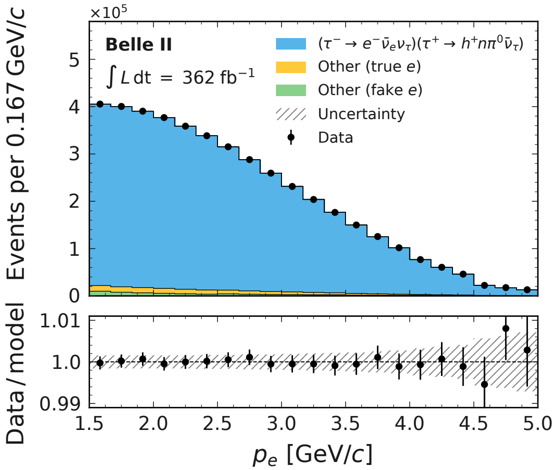
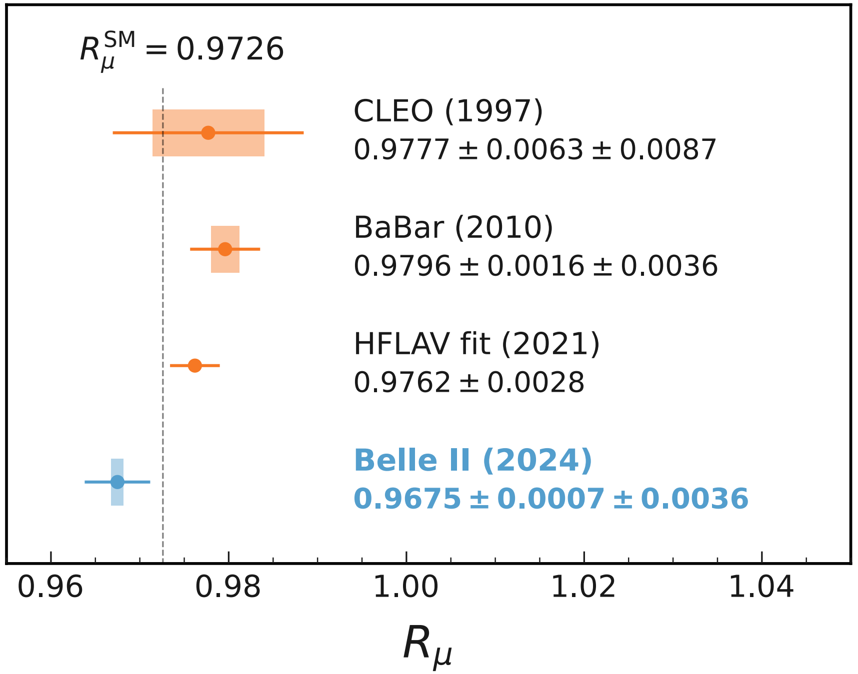
- Most precise test of universality in τ decays from a single measurement
- Consistent with the SM at 1.4σ







J. High Energ. Phys. 2024, 205 (2024)

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Summary

- Quick overview of tau lepton physics at Belle II
  - Focus on activities with our direct involvement
- With an early data set, Belle II is delivering the world-best measurements for several observables
  - Most precise **tau mass measurement** to date
  - Most precise **test of universality i**n τ decays from a single measurement
- Since its discovery, the tau lepton has been studied at every e^+e^- collider into operation
  - In Belle II we are very motivated, and ready to reach new limits in the precision
- **Stay tuned!** More results are coming

Backup

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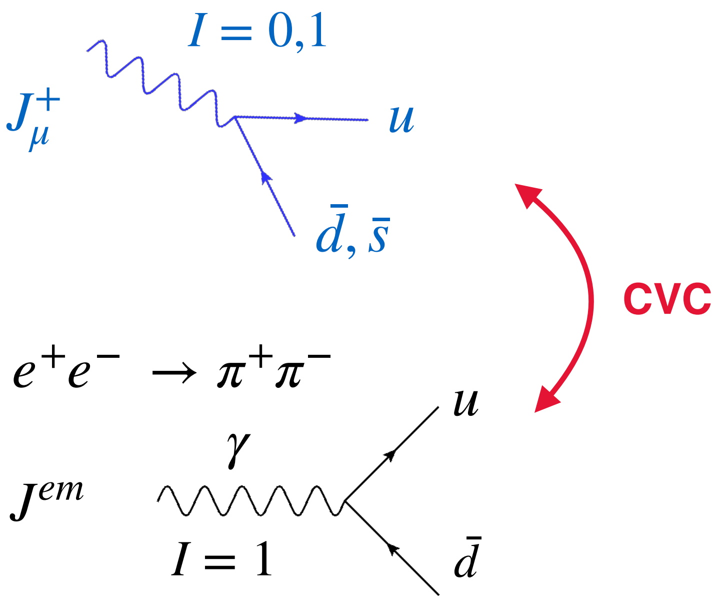
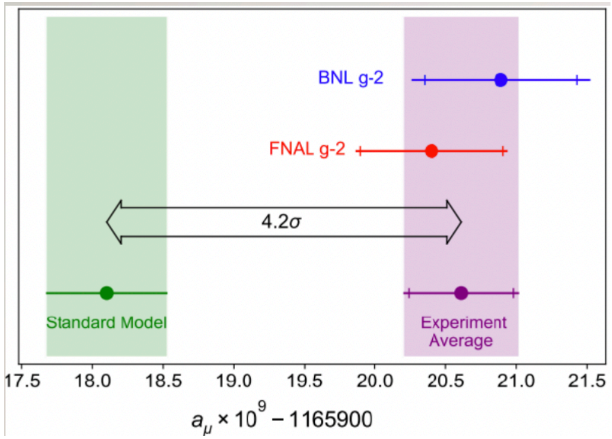
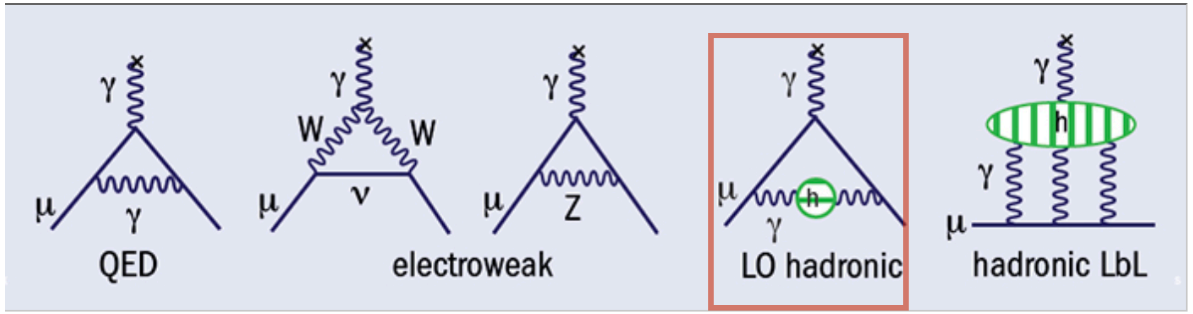
$\tau^- \to \pi^- \pi^0 \nu$







T. Aoyama et. al, Phys. Rept. 887 (2020) 1-166

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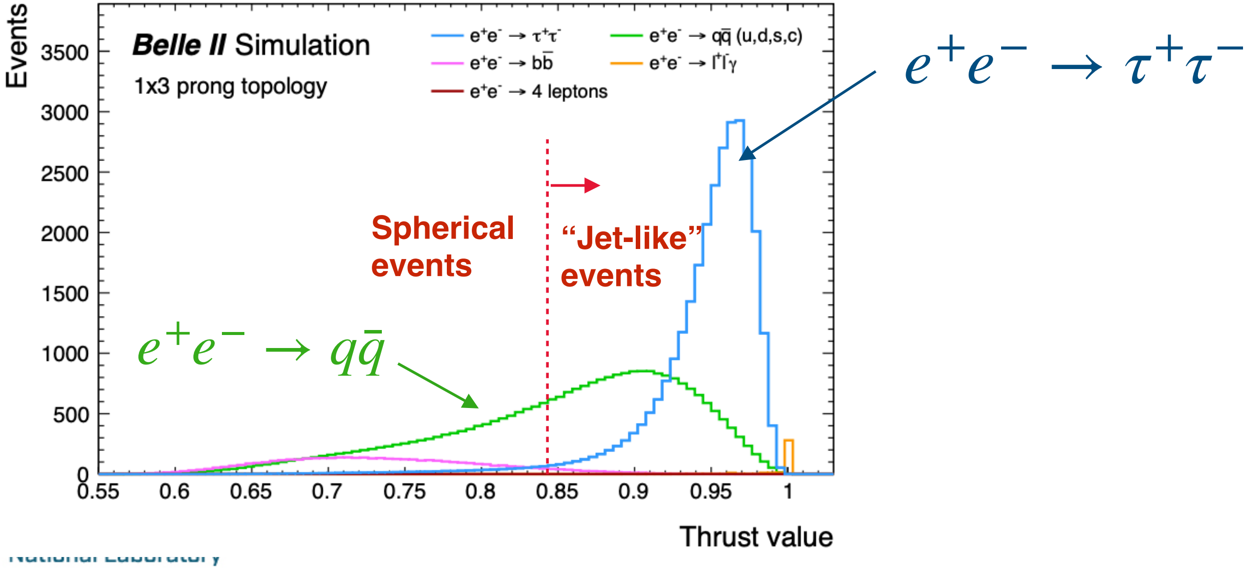
How do we reconstruct taus at Belle II?

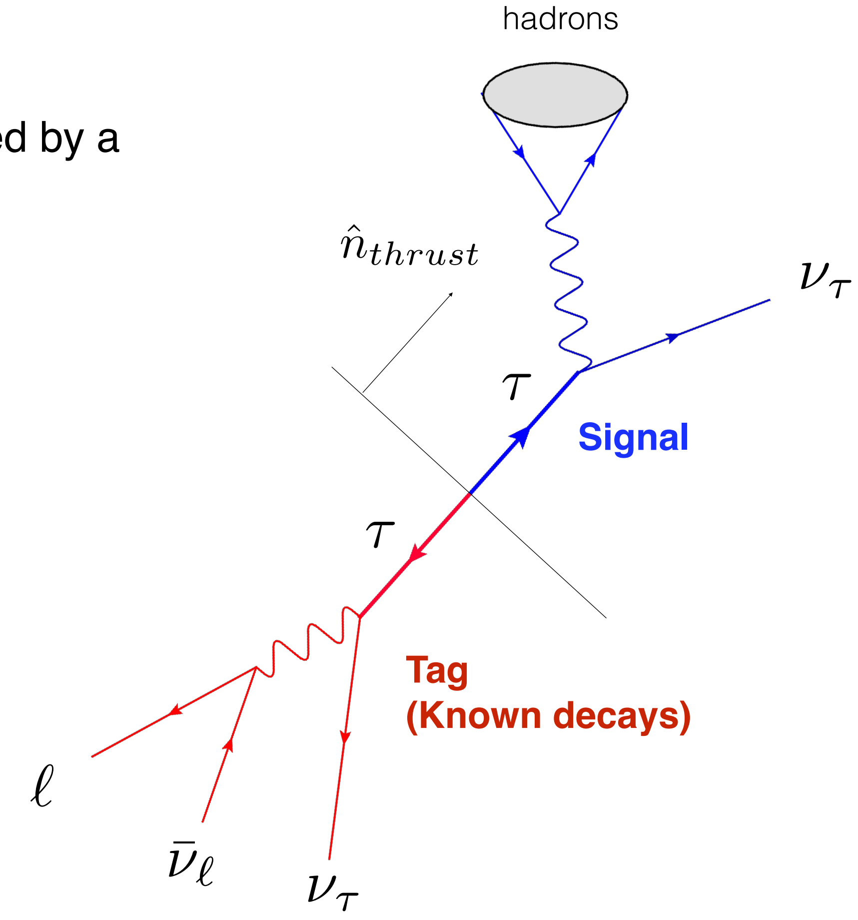
- A τ event is never reconstructed completely (we lose neutrinos), then we use features of the event to identify τ-pair candidates.

- Event is divided in two sides (signal and tag) using a plane defined by a **thrust axis**, build with all the final state particles:

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

- Thrust axis: $\hat{n}_{thrust}$ such that V_{thrust} is maximum.





Tau Lepton Mass Measurement

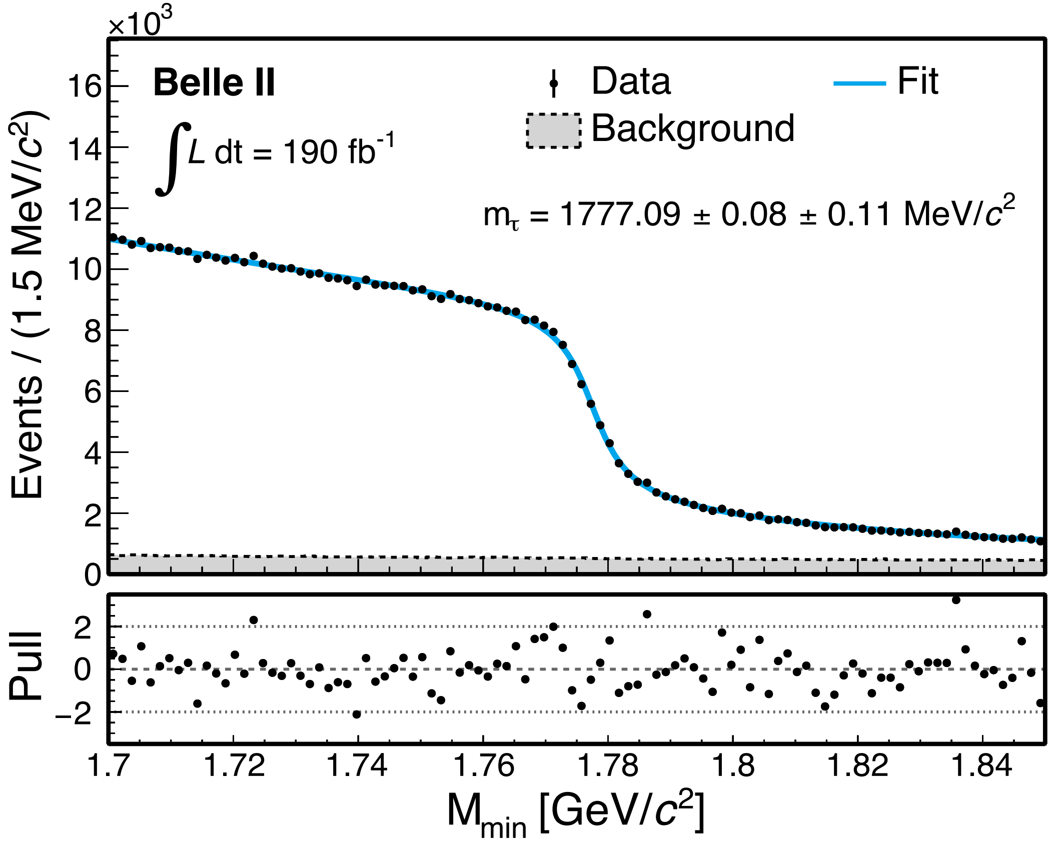
- Measured in the decay mode $\tau \to 3\pi\nu$, using a pseudomass technique

- The tau mass can be calculated as

$$m_\tau^2 = (p_h + p_\nu)^2$$
$$= 2E_h(E_\tau - E_h) + m_h^2 - 2|\vec{p}_h|(E_\tau - E_h)\ \cos(\vec{p}_h, \vec{p}_\nu)$$

- As the direction of the neutrino is not known, the approximation $\cos(\vec{p}_\nu, \vec{p}_h) = 1$ is taken, resulting in
  - $M_{\text{min}}^2 = 2E_h(E_\tau - E_h) + m_h^2 - 2|\vec{p}_h|(E_\tau - E_h) \ < m_\tau^2$

- Then, the distribution of the pseudomass is fitted to an empirical edge function, and the position of the cutoff indicates the value of the mass



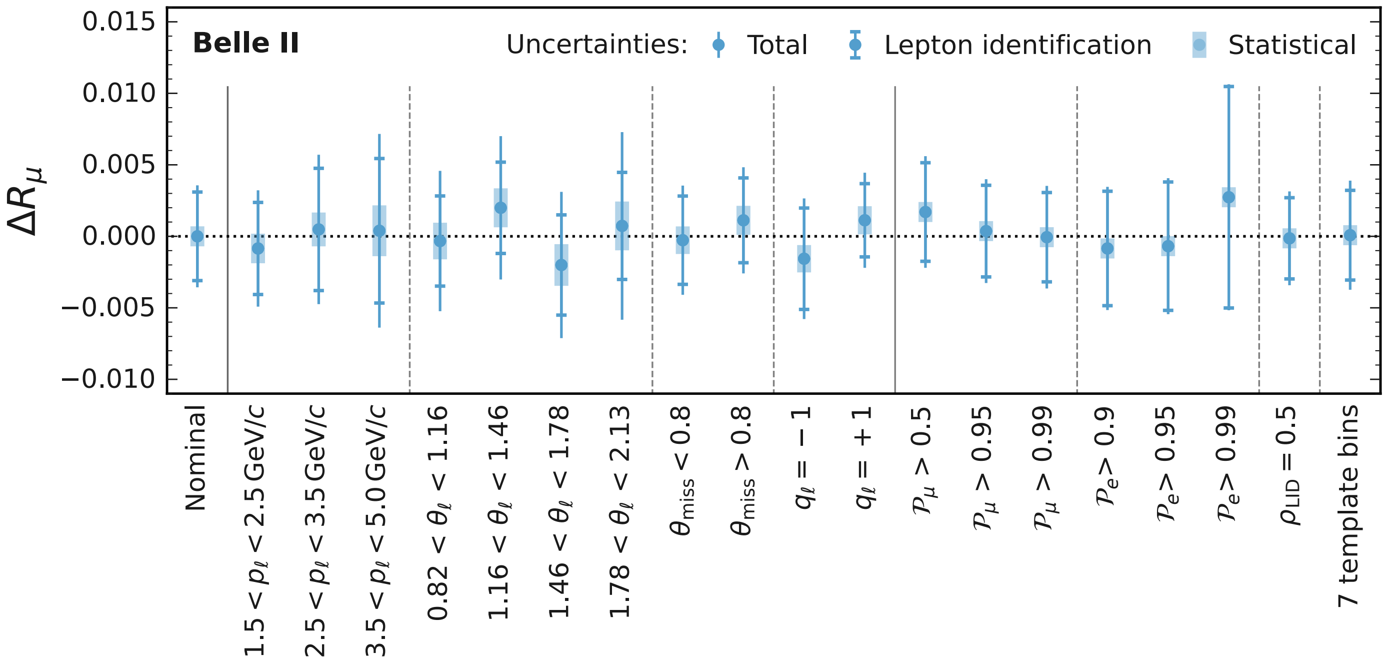
Tests of LFU

Table 2. Experimental determinations of the ratios $|g_\ell/g_{\ell'}|$.[1, 11, 14, 15]

	$\Gamma_{\tau\to e}/\Gamma_{\mu\to e}$	$\Gamma_{\tau\to\pi}/\Gamma_{\pi\to\mu}$	$\Gamma_{\tau\to K}/\Gamma_{K\to\mu}$	$\Gamma_{W\to\tau}/\Gamma_{W\to\mu}$
$\|g_\tau/g_\mu\|$	1.0009 (14)	0.9964 (38)	0.986 (8)	1.001 (10)
	$\Gamma_{\tau\to\mu}/\Gamma_{\tau\to e}$	$\Gamma_{\pi\to\mu}/\Gamma_{\pi\to e}$	$\Gamma_{K\to\mu}/\Gamma_{K\to e}$	$\Gamma_{K\to\pi\mu}/\Gamma_{K\to\pi e}$
$\|g_\mu/g_e\|$	1.0002 (11)	1.0010 (9)	0.9978 (18)	1.0010 (25)
	$\Gamma_{W\to\mu}/\Gamma_{W\to e}$		$\Gamma_{\tau\to\mu}/\Gamma_{\mu\to e}$	$\Gamma_{W\to\tau}/\Gamma_{W\to e}$
$\|g_\mu/g_e\|$	1.001 (3)	$\|g_\tau/g_e\|$	1.0027 (14)	1.007 (10)

A. Pich, https://arxiv.org/pdf/2405.19955

Tests of LFU at Belle II



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

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