Tau lepton mass measurement at Belle II.

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SuperKEKB and the Belle II experiment.

- SuperKEKB is an energy asymmetric e^+e^- collider in Tsukuba, Japan.
- It is operating at a center-of-mass energy near the $\Upsilon(4S)$ resonance ($10.58\,\mathrm{GeV/c^2}$)
- planning to have an integrated luminosity of $50\,\mathrm{ab}^{-1}$ (50 times larger than that of its predecessor, KEK)

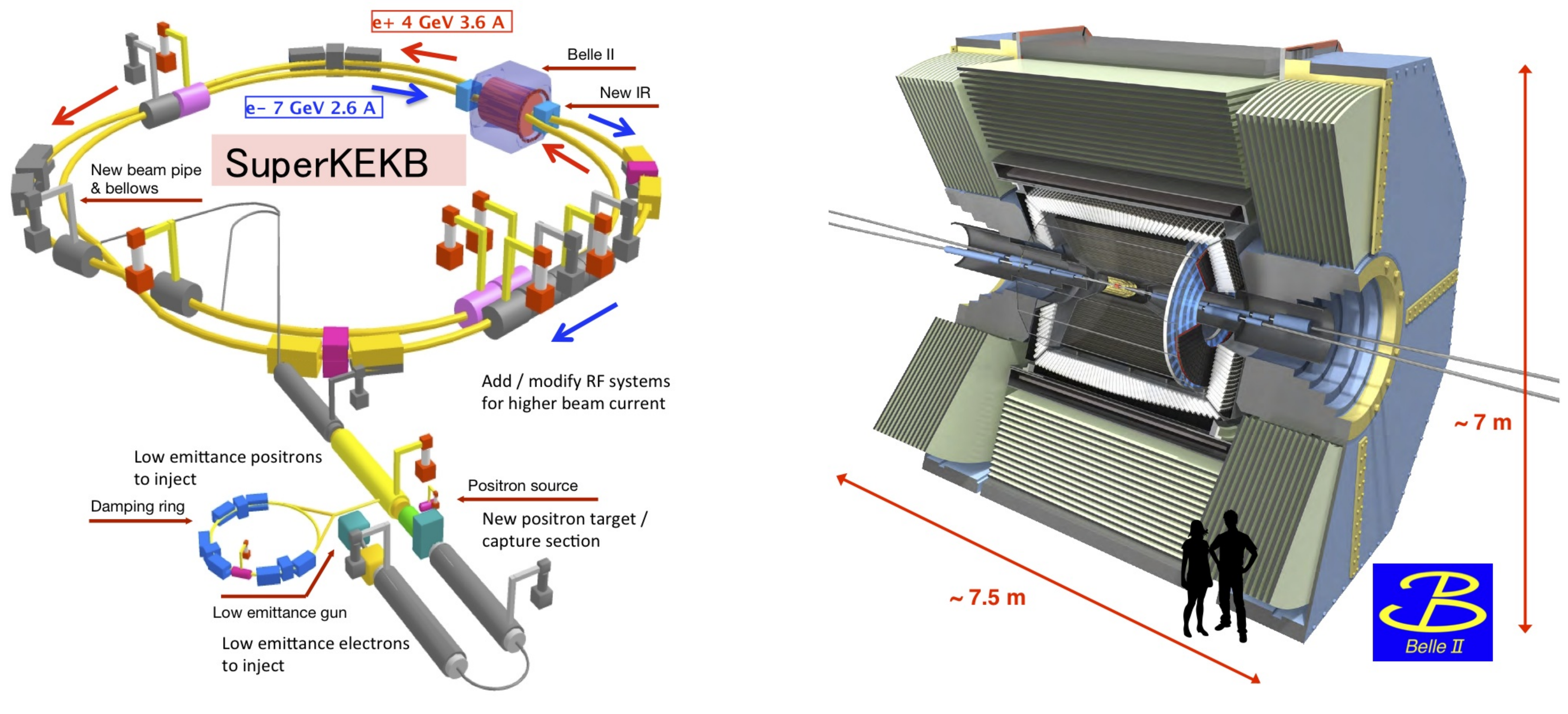

Figure 1: *Schematic diagrams of the SuperKEKB (left) and Belle II experiment (right).*

- Belle II is an upgraded version of Belle detector to deal with higher luminosities
- 2 brand new layers of pixel detectors and 4 layers of double-sided silicon strip detectors
- new drift chamber and upgraded electronic readouts for electromagnetic calorimeter
- Cherenkov detectors for particle identification

Tau leptons at Belle II.

The data collected during the lifetime of the Belle II experiment is expected to contain around 45 billion tau pair events!

- The large pair production cross section of tau leptons near the $\Upsilon(4S)$ energies, and the clean initial states of e^+e^- collisions provides an ideal environment for studying the properties the tau lepton.
- The τ lepton mass is a fundamental parameter of the Standard Model (SM) and a precise measurement of the τ mass is a crucial ingredient for lepton universality tests in SM.
- Mass of the tau cannot be measured directly due to the presence of neutrinos in its decay.
- The dependence of the pair production cross-section on the beam energy is used in experiments such as BESIII to measure the mass.
- At Belle II the *pseudomass technique* (developed by ARGUS experiment) is used

The pseudomass technique.

- In this method the tau events are used in which one tau decays to 3 charged pions and the other tau decays into e, μ, $\pi^\pm$, or $\pi^\pm\pi^0$.
- The Energy ($E_{3\pi}$), momentum ($P_{3\pi}$) and invariant mass ($M_{3\pi}$) of the 3 pion system, in addition to the he beam energy (E_{beam}) in the center of mass frame are used to define the pseudomass ($M_{\min}$) which has a kinematic edge at the true tau mass, m_τ:

$$M_{\min} = \sqrt{M_{3\pi}^2 + 2(E_{\mathrm{beam}} - E_{3\pi})(E_{3\pi} - P_{3\pi})} \leq m_\tau. \quad (1)$$

The edge point behavior of $M_{\min}$ can be seen in the figure below:

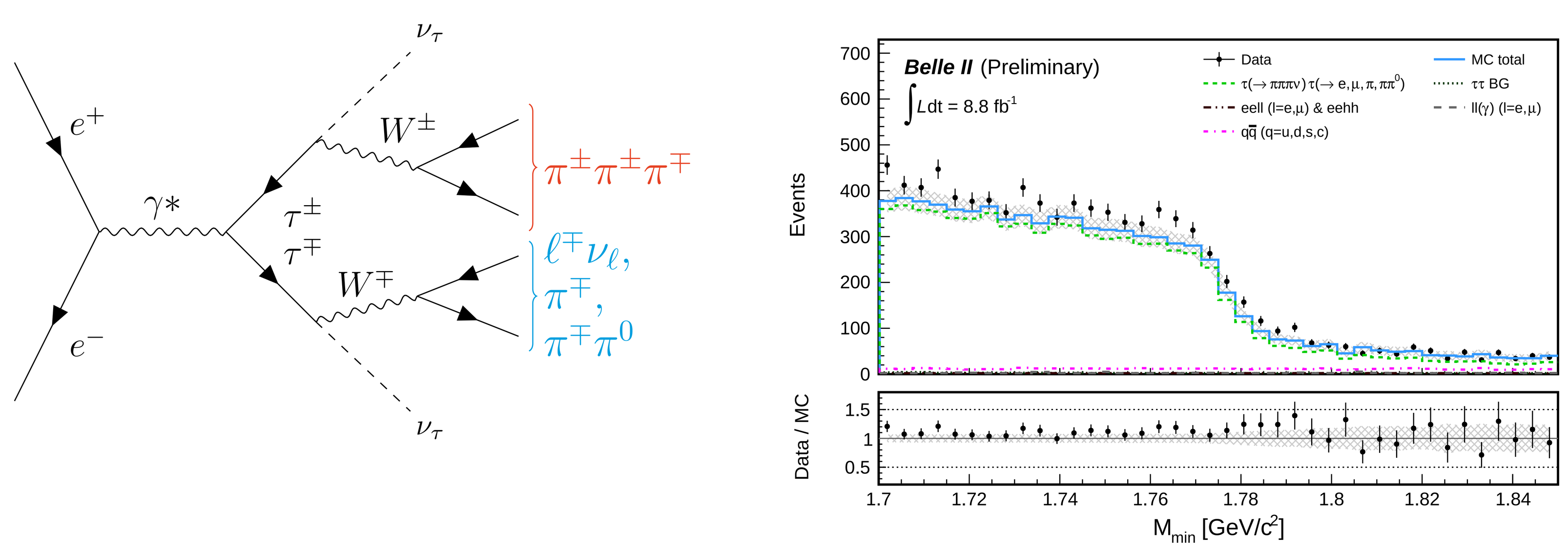

Figure 2: *Left: diagram of $e^+e^- \to \tau^+\tau^-$ process with subsequent 3-prong ($\tau^+ \to \pi^+\pi^-\pi^+\bar{\nu}_\tau$) and 1-prong ($\tau^- \to \ell^-\bar{\nu}_\ell\nu_\tau$, $\tau^- \to h^-\nu_\tau$ or $\tau^- \to \pi^-\pi^0\nu_\tau$) decay. Right: distribution of the pseudomass in data and simulated samples in the range $1.70 < M_{\min} < 1.85\,\mathrm{GeV/c^2}$.*

Fit procedure.

- The following empirical edge function (Eq. 2) is used to extract the τ mass from the $M_{\min}$ distribution:

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

where the P_1 parameter is a *biased* estimator of m_τ.

- Using simulated samples with various generated tau mass (m_τ^{gen}) values, the bias in the fit is determined to be $0.72 \pm 0.12\,\mathrm{MeV/c^2}$ as shown in Figure 3.
- The fit procedure is then performed on 2019 data collected at Belle II and the tau mass is obtained after correcting for the fit bias.

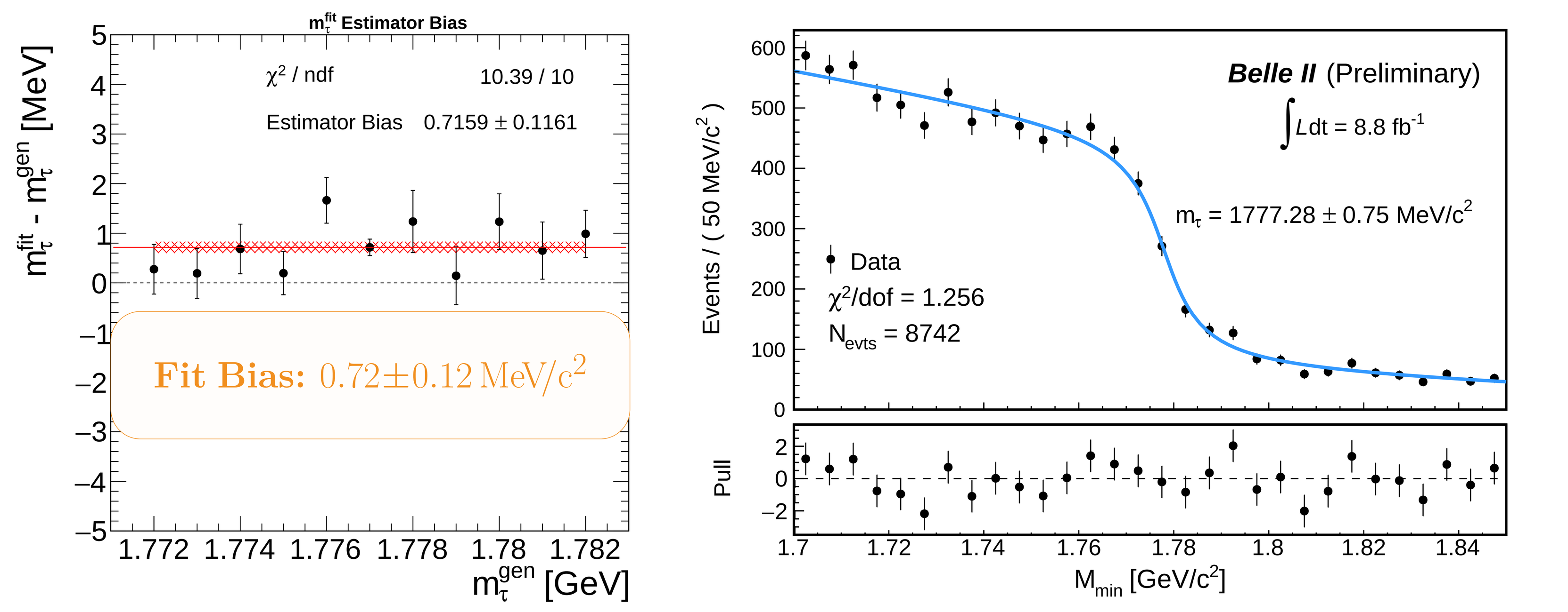

Figure 3: *Left: fit bias estimation using samples with various generated tau masses.Right: Result of the fit in data and the obtained value for τ mass after the bias correction.*

Systematical uncertainties.

- The leading systematic is due the momentum scale factor used to compensate for the imperfections of the magnetic-field map which was implemented during the data processing.
- The subleading effect is due to the limited size of the simulated samples used for determining the fit bias
- The choice of the fit window and function used to extract the mass also have a non-negligible impact.

Systematic uncertainty	$\mathrm{MeV/c^2}$
Momentum shift (B-field map)	0.29
Estimator bias	0.12
Choice of p.d.f.	0.08
Fit window	0.04
Beam energy shifts	0.03
Mass dependence of bias	0.02
Trigger efficiency	≤ 0.01
Initial parameters	≤ 0.01
Background processes	≤ 0.01
Tracking efficiency	≤ 0.01

Assuming the various effects are uncorrelated, the total systematical uncertainty is 0.33 $\mathrm{MeV/c^2}$

Results.

- Using 2019 data collected at Belle II corresponding to $8.8\,\mathrm{fb}^{-1}$, the mass of the tau lepton is measured as $1777.28 \pm 0.75(\mathrm{stat}) \pm 0.33(\mathrm{syst})\,\mathrm{MeV/c^2}$
- The systematical uncertainty are already compatible with that of Belle.
- With the data collected in 2020 the statistical uncertainty is expected to be around $0.16\,\mathrm{MeV/c^2}$.
- With the improved B-field map in place, and more precise corrections for the momentum shifts of tracks, the systematic uncertainties are expected to be reduced.

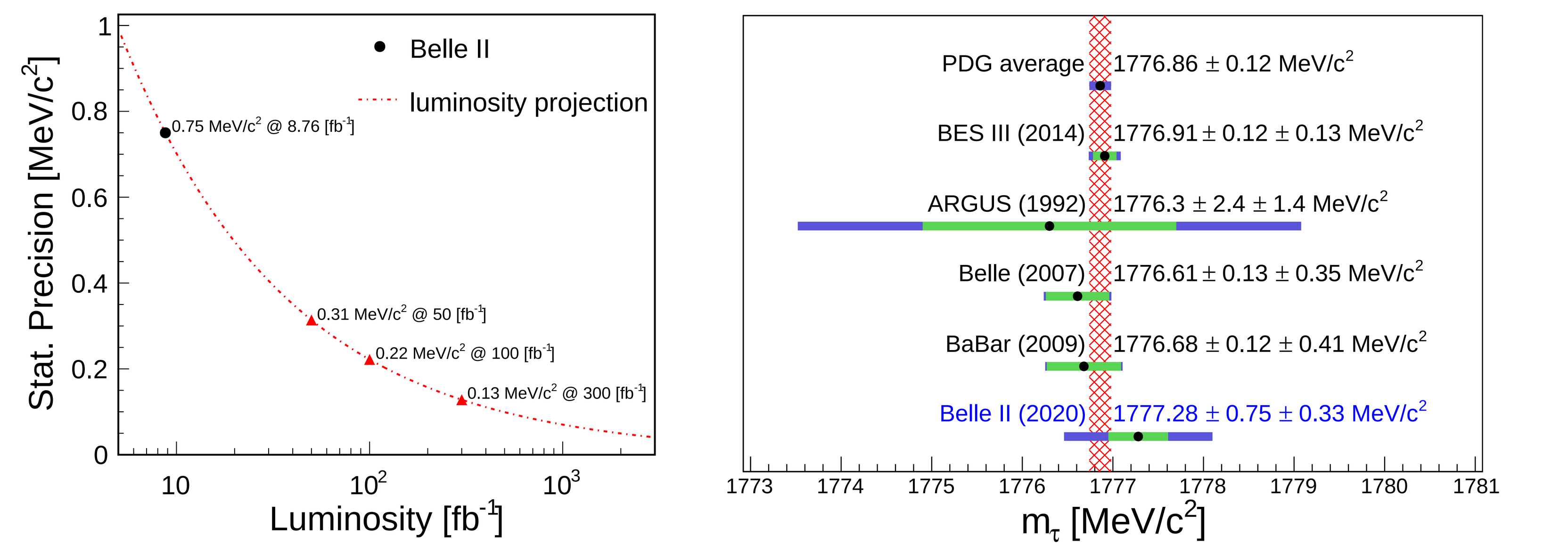

Figure 4: *Left: projections for the statistical uncertainties of the tau mass measurement. Right: world measurements of the tau mass.*

References.

[1] The Belle II Collaboration. τ lepton mass measurement at Belle II. Aug 2020. BELLE2-CONF-PH-2020-010, arXiv:2008.04665 [hep-ex], https://arxiv.org/abs/2008.04665.