τ physics prospects at Belle II

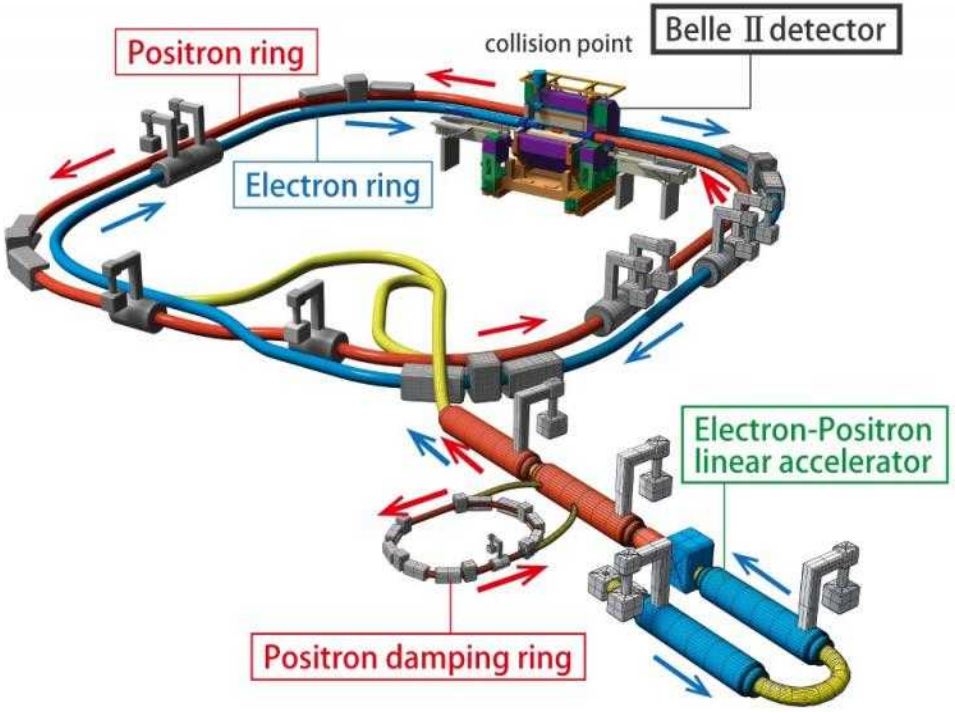
Alejandro De Yta Hernández (CINVESTAV)
on behalf of the Belle II Collaboration

EPS-HEP Conference 2021

Universität Hamburg - DESY (virtual)

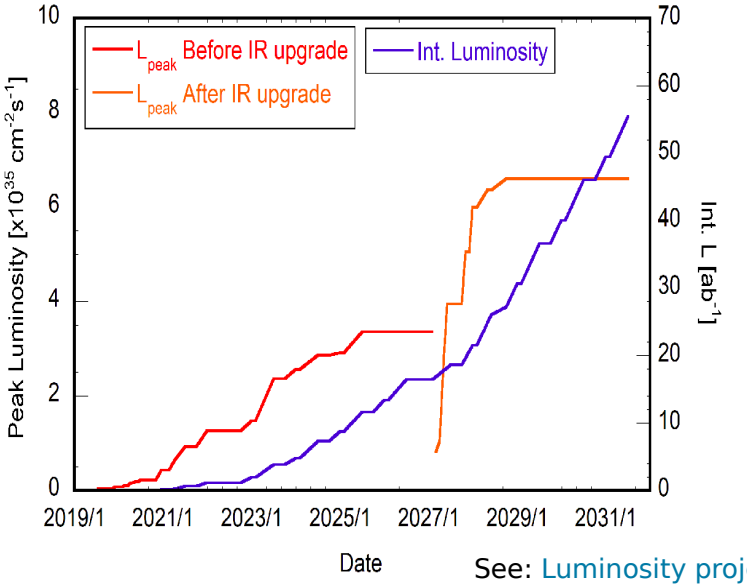
July 26-30, 2021

SuperKEKB Collider



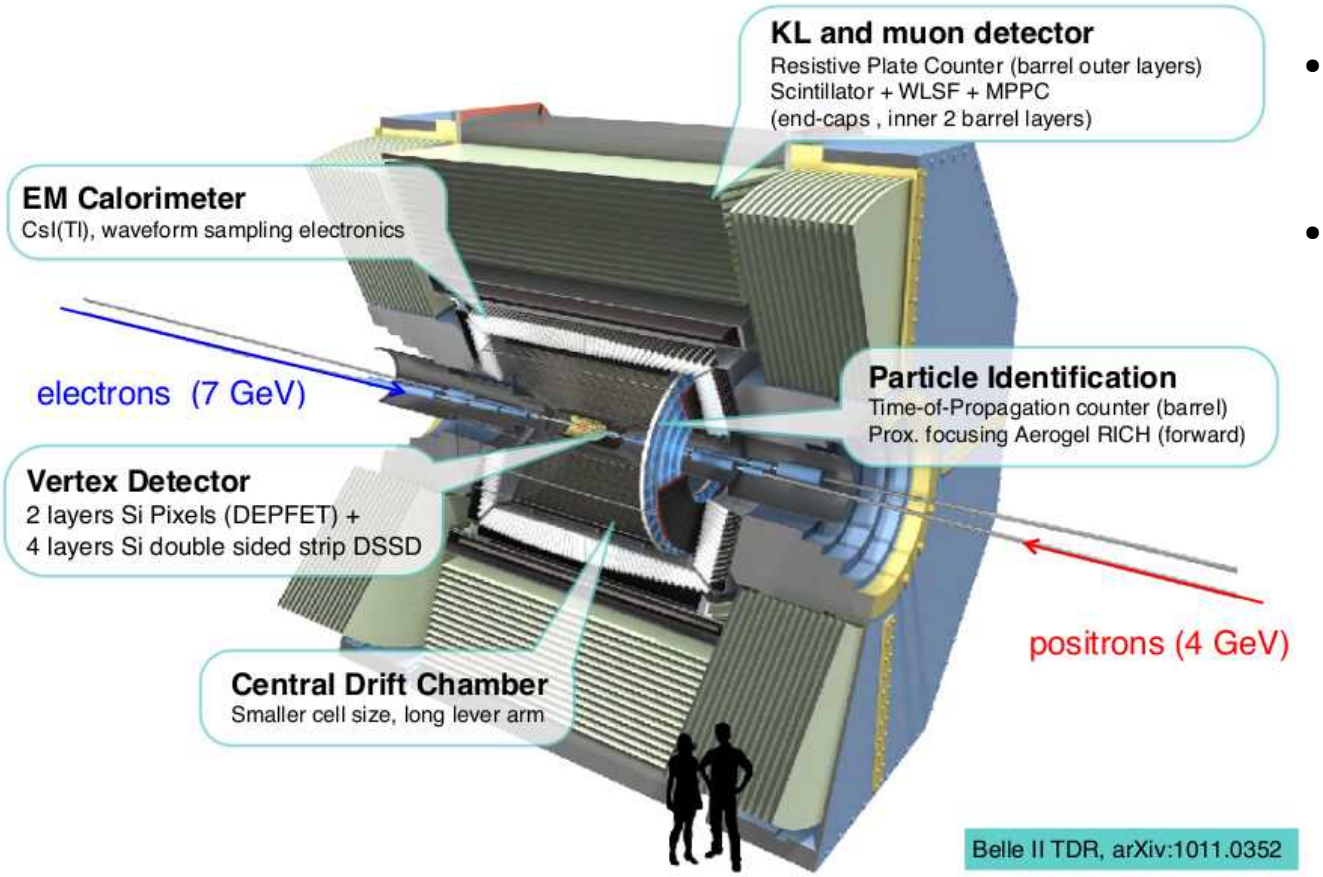
@Tsukuba, Japan

- Asymmetric collision of e^+e^-:
  - Electron (7 GeV) – Positron (4 GeV)
  - CM energy at $\Upsilon(4S)$ resonance [10.58 GeV]
  - At this energy:
    - $\sigma(e^+e^- \to \Upsilon(4S)) = 1.1$ nb (B-factory)
    - $\sigma(e^+e^- \to \tau^+\tau^-) = 0.9$ nb (τ–factory)
- Target:
  - $\mathcal{L} = 8\text{x}10^{35}\text{cm}^{-2}\text{s}^{-1}$ (40 x KEKB)
  - Integrated L = 50 ab^{-1} (50 x KEKB)
- Luminosity projection for the coming years:

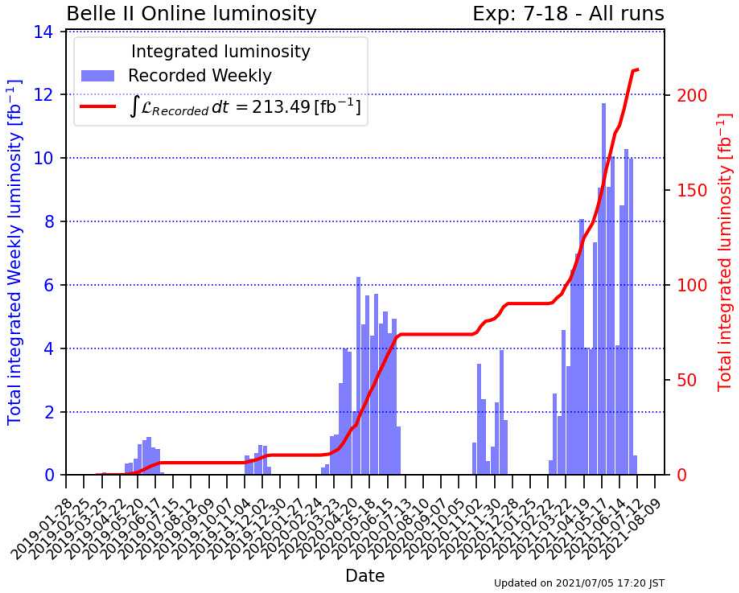


See: Luminosity projection

Belle II at SuperKEKB



- General purpose detector
- Solid angle coverage > 90%
  - High hermiticity
- So far: Integrated L ~ 200 fb^{-1}

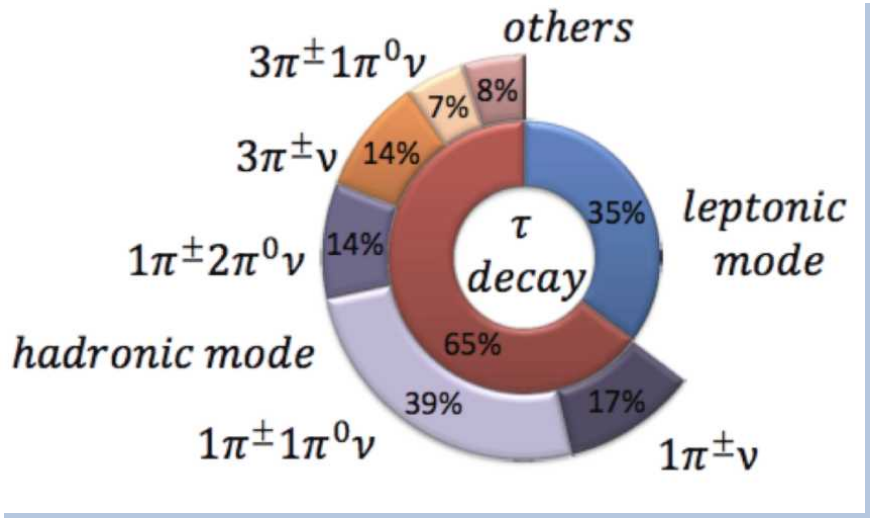


See: Luminosity projection

- Regular data-taking despite Covid-19

τ -Physics at Belle II

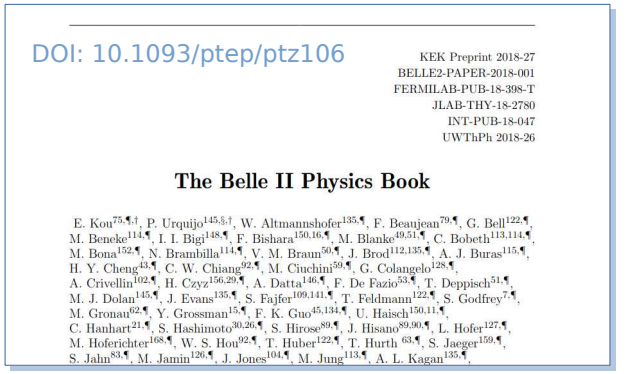
- Why τ ***physics***?
  - Large production cs:
    $\sigma(e^+e^- \to \tau^+\tau^-)$ = 0.9 nb (τ –factory)
  - The τ is the only lepton massive enough to decay into hadrons:
    - Leptonic decays: BR ~ 35%
    - Hadronic decays: BR ~ 65%



- τ **physics** program
  Rich program of precision SM measurements and new physics searches @ Belle II

Some ongoing physics analyses @ Belle II:

- Precision SM measurements / Indirect NP searches (deviations from the SM)
  - Mass
  - Lifetime
  - Lepton universality in $\tau \to l\nu\nu$ decays
  - τ EDM and MDM
  - $\tau \to eee\nu\nu$
  - CP violation $\tau \to K_S\pi\nu$
- Direct NP searches (forbidden / strongly suppressed decays)
  - $\tau \to l\,\alpha$
  - $\tau \to l\,\phi$
  - $\tau \to l\,\gamma$
  - $\tau \to \mu\mu\mu$
  - $\tau \to l\pi^0$
  - $\tau \to lhh$


DOI: 10.1093/ptep/ptz106

KEK Preprint 2018-27
BELLE2-PAPER-2018-001
FERMILAB-PUB-18-398-T
JLAB-THY-18-2780
INT-PUB-18-047
UWThPh 2018-26

The Belle II Physics Book

E. Kou[75,¶,†], P. Urquijo[145,§,†], W. Altmannshofer[135,¶], F. Beaujean[79,¶], G. Bell[122,¶], M. Beneke[114,¶], I. I. Bigi[148,¶], F. Bishara[150,16,¶], M. Blanke[49,51,¶], C. Bobeth[113,114,¶], M. Bona[152,¶], N. Brambilla[114,¶], V. M. Braun[50,¶], J. Brod[112,135,¶], A. J. Buras[115,¶], H. Y. Cheng[43,¶], C. W. Chiang[92,¶], M. Ciuchini[59,¶], G. Colangelo[128,¶], A. Crivellin[102,¶], H. Czyz[156,29,¶], A. Datta[146,¶], F. De Fazio[53,¶], T. Deppisch[51,¶], M. J. Dolan[145,¶], J. Evans[135,¶], S. Fajfer[109,141,¶], T. Feldmann[122,¶], S. Godfrey[7,¶], M. Gronau[62,¶], Y. Grossman[15,¶], F. K. Guo[45,134,¶], U. Haisch[150,11,¶], C. Hanhart[21,¶], S. Hashimoto[30,26,¶], S. Hirose[89,¶], J. Hisano[89,90,¶], L. Hofer[127,¶], M. Hoferichter[108,¶], W. S. Hou[92,¶], T. Huber[122,¶], T. Hurth[63,¶], S. Jaeger[159,¶], S. Jahn[83,¶], M. Jamin[126,¶], J. Jones[104,¶], M. Jung[113,¶], A. L. Kagan[135,¶],

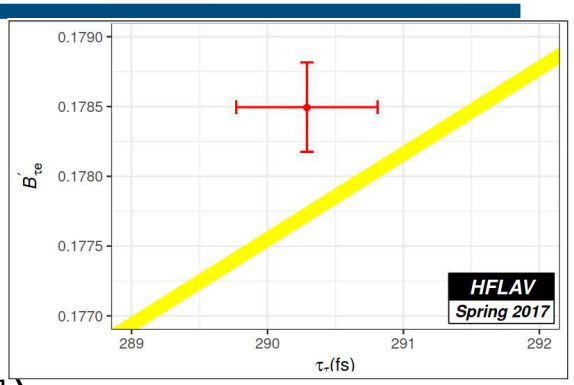
τ -Mass measurement

- τ -Mass fundamental parameter of the SM
- Leptonic decay rate proportional to m_τ^5

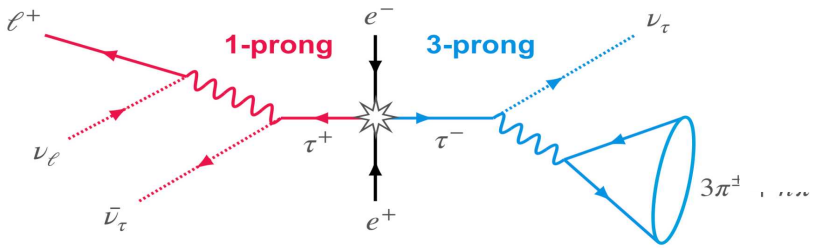
$$\Gamma(\tau \to l\,\nu\,\nu) \propto m_\tau^5$$

  - Testing lepton universality
  - Br calculations that depend on m_τ

Depend on the τ mass value and its accuracy

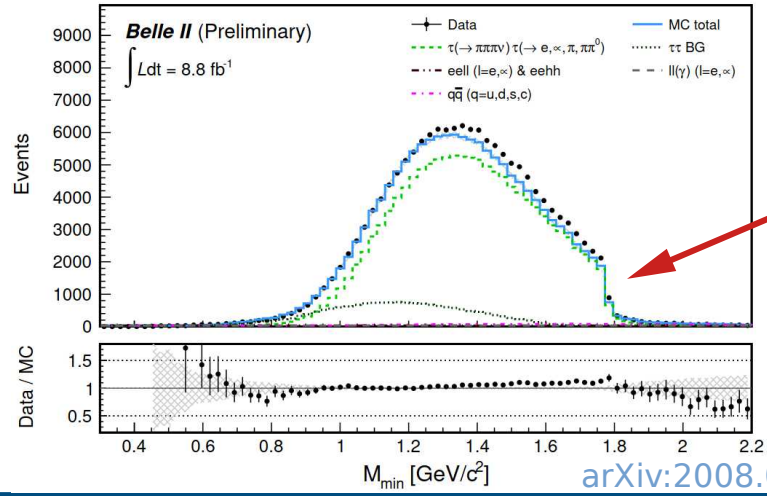


- ARGUS pseudo-mass technique & early Belle II data (8.8 fb^{-1})
- Select events with a 3x1 topology
  - Signal: $\tau \to 3\pi\nu$
  - Tag: $\tau \to$1-prong



- For the decay $\tau \to 3\pi\nu$ calculate the pseudo-mass:

$$M_{min} = \sqrt[2]{M_{3\pi}^2 + 2(E_{beam} - E_{3\pi})(E_{3\pi} - P_{3\pi})} \leqslant m_\tau$$



The mass of the τ lepton m_τ is given by the position of the endpoint of the distribution.

arXiv:2008.04665

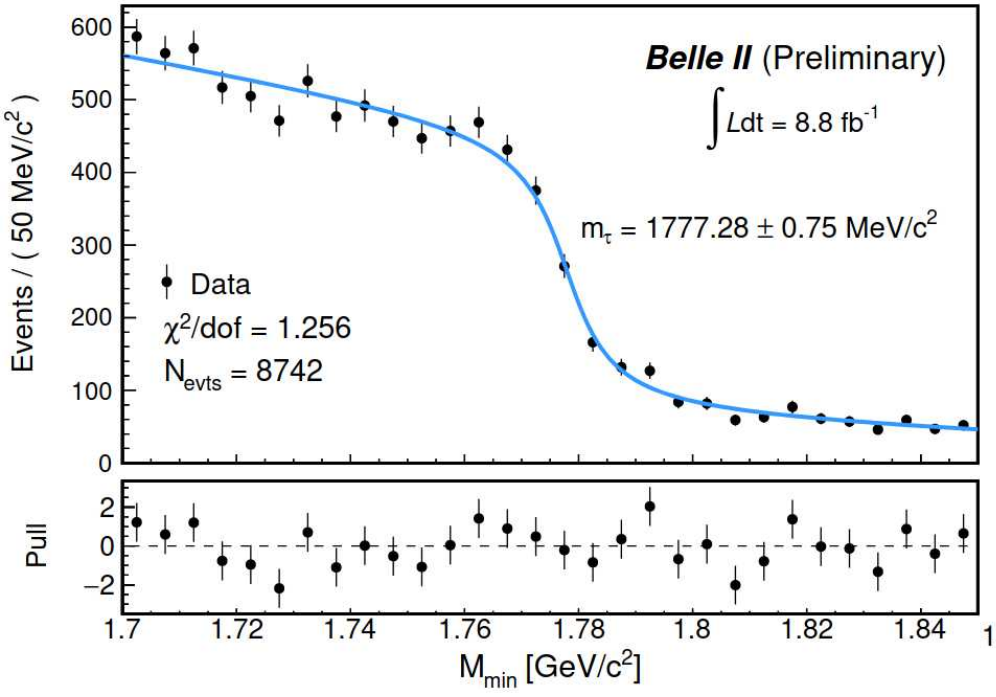
τ -Mass measurement

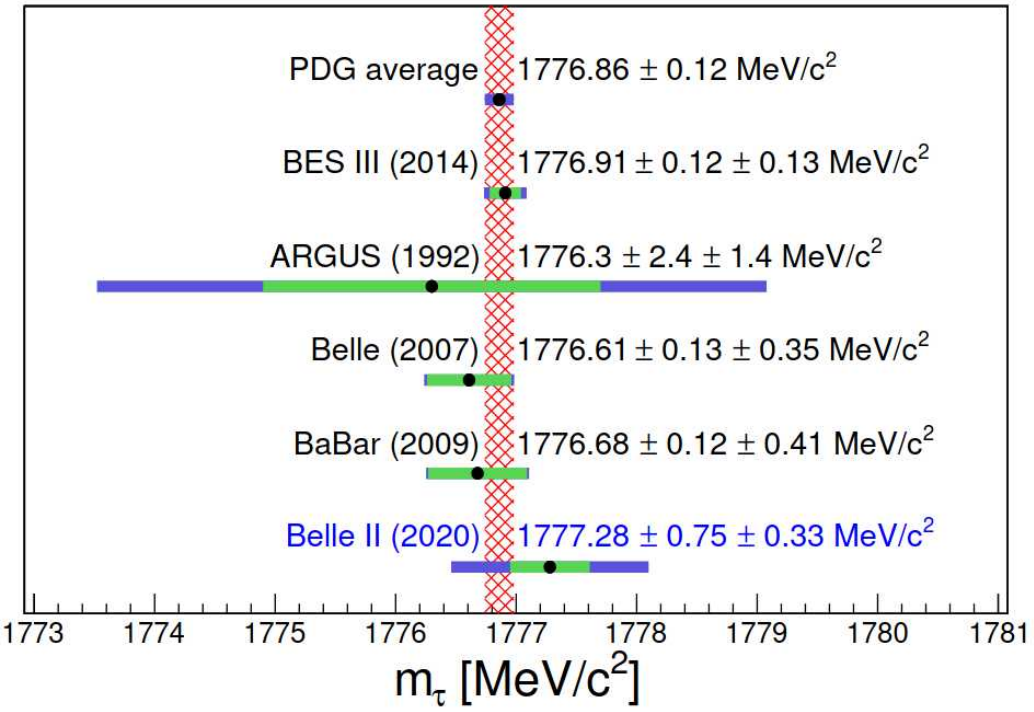
- An empirical p.d.f. is used to estimate the τ lepton mass, m_τ:

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

  - P_1 is the estimator of the τ lepton mass.

arXiv:2008.04665





$m_\tau = 1777.28 \pm 0.75_{stat} \pm 0.33_{sys}$ MeV/c^2

- Consistent with previous measurements!
- Belle II has similar systematic error as Belle

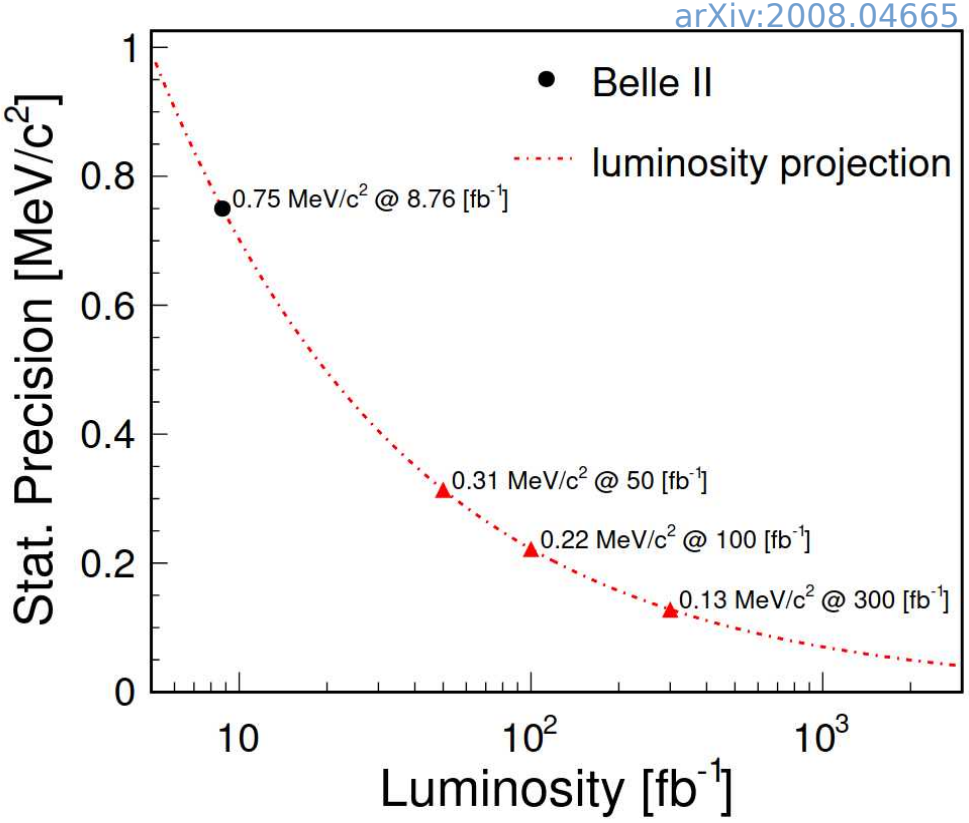
τ -Mass measurement

- Dominant systematic uncertainty due to the track momentum scale, but it is expected to be reduced

Systematic uncertainty	MeV/c^2
Momentum shift due to the 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

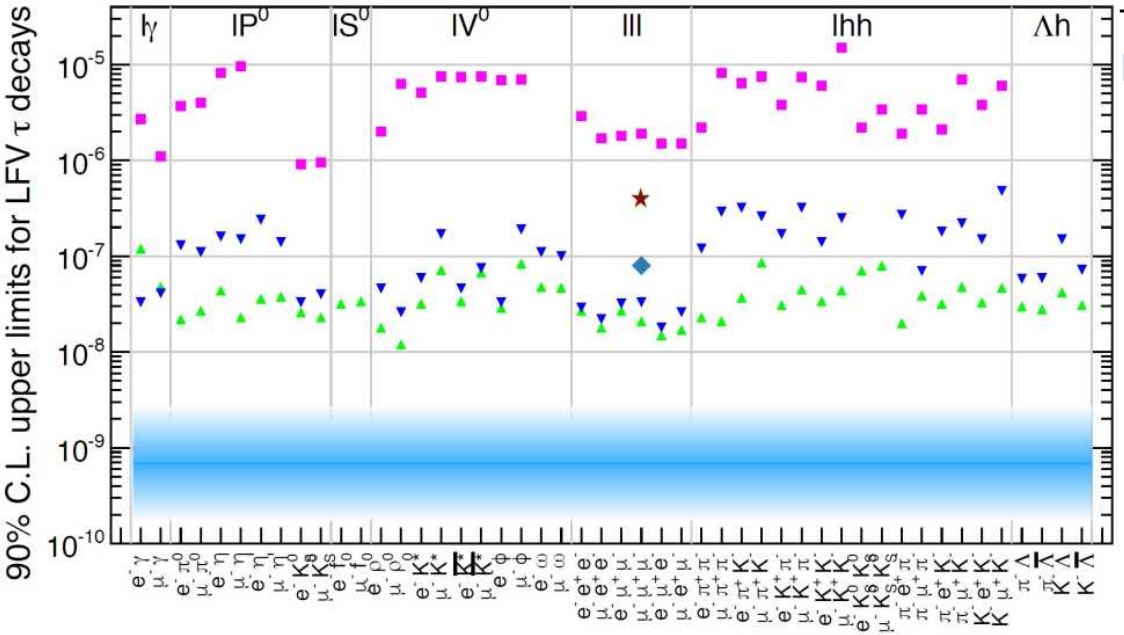
- A scenario with a total systematic uncertainty reduced is expected in the near future

arXiv:2008.04665



- With the present level of systematic uncertainties, this measurement is expected to be statistically dominated until around 50 fb^{-1} of data.
- With around 300 fb^{-1} of data, systematic uncertainties would dominate the measurement.

Prospects for τ LFV & LNV searches



The Belle II Physics Book,
DOI: 10.1093/ptep/ptz106

CLEO
BaBar
Belle
LHCb
ATLAS
Belle II

- Thanks to the large mass of the τ, we have an extensive variety of decay modes to explore

- LFV decays of the τ are strongly suppressed in the SM
  Br ~ O(10^{-54})

- Many NP models predict LFV decays of the τ at a measurable rate
  Br ~ O(10^{-10}) - O(10^{-7})

- Any observation of LFV is a clear indication of NP

- Golden channels:
  - τ→μμμ
  - τ→μγ

  } Work in progress

- Belle II is expected to push the current bounds further by more than one order of magnitude.

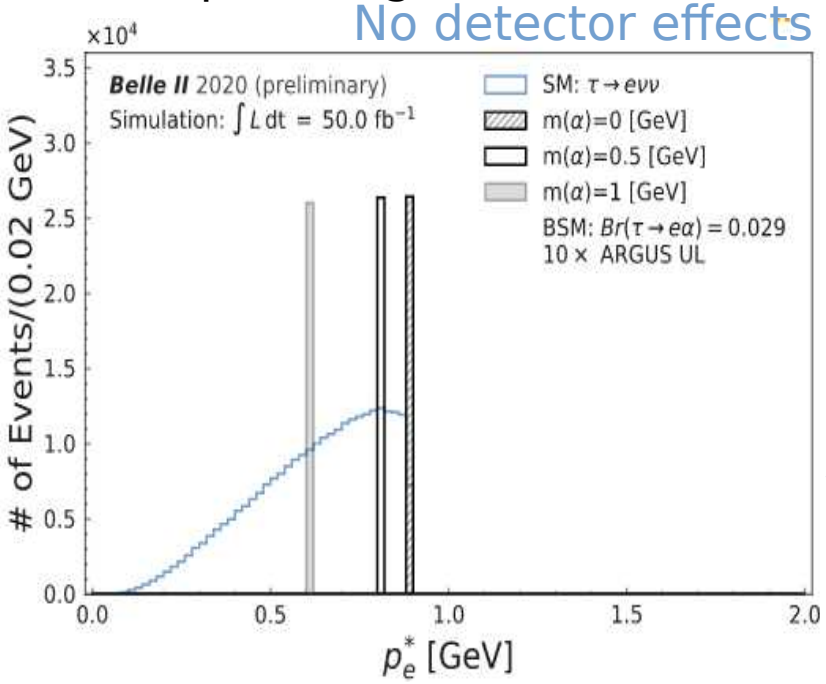
Search for $\tau \to l\alpha$

- Search for the LFV decay channels:
  $\tau \to e\alpha$ ($\tau \to \mu\alpha$ in progress)
  being α a BSM invisible particle

- This decay appers in several NP models:
  Axion-like particles, Z' gauge bosons, etc

- Idea: search for two body decay
  - The momentum of the lepton will manifest as a peak in the τ rest frame, as compared against the SM $\tau \to l\nu\nu$ (bkg).

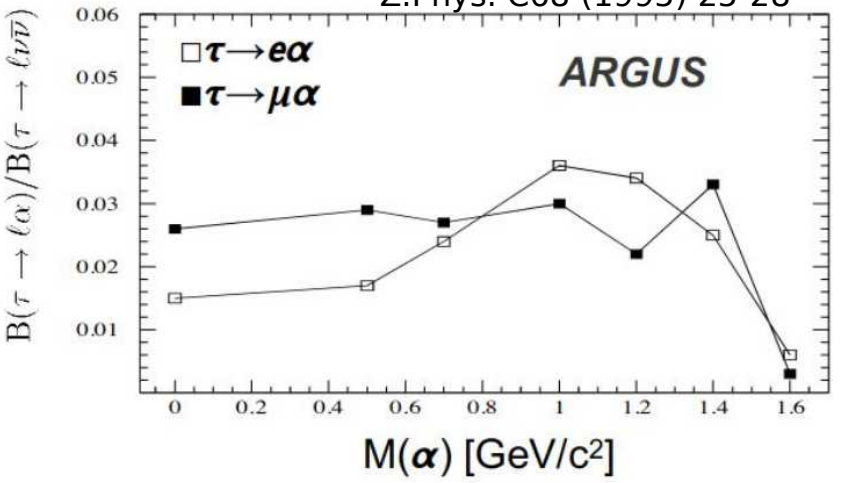
No detector effects



Signal and bkg with same final state, but different kinematics.

- Previous searches
  - Mark III (1985, 9.4 pb^{-1})
  - ARGUS (1995, 472 pb^{-1})

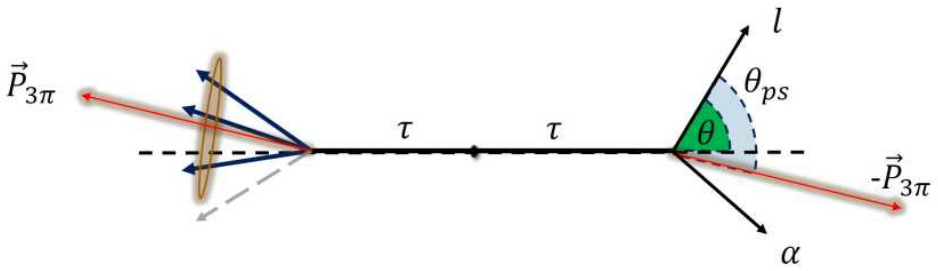
Z.Phys. C68 (1995) 25-28



Search for τ→ lα

- Select events with a 3x1 topology (4 tracks)
  - Signal: τ→1-prong
  - Tag: τ→3πν

- Challenges:
  - Disentangle the SM decay τ→lνν from the BSM signal τ→lα
    - Idea: Move to the τ rest frame
  - Cannot access the τ rest frame directly due to missing particles
    - Use ARGUS method
      - $E_\tau = \sqrt{s}/2$
      - Approximation: $\hat{p}_\tau \simeq -\hat{p}_{3\pi}$

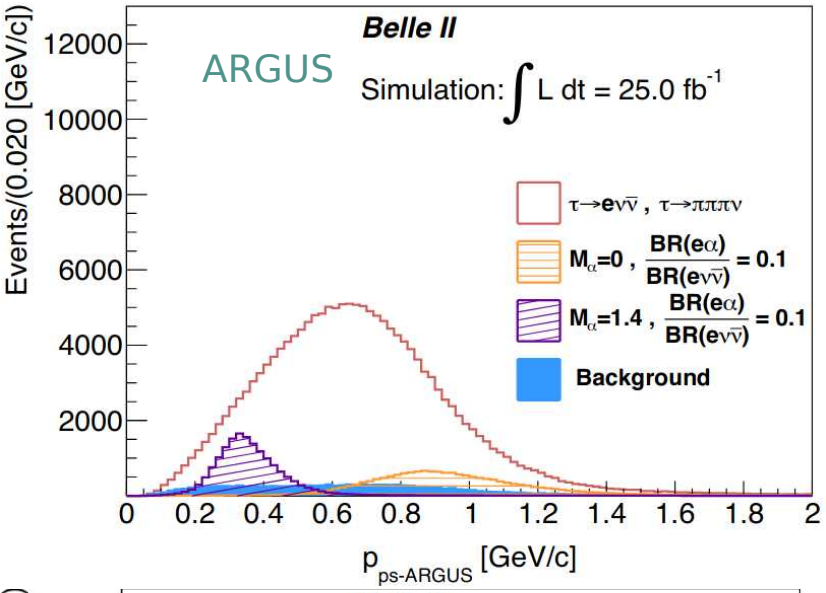


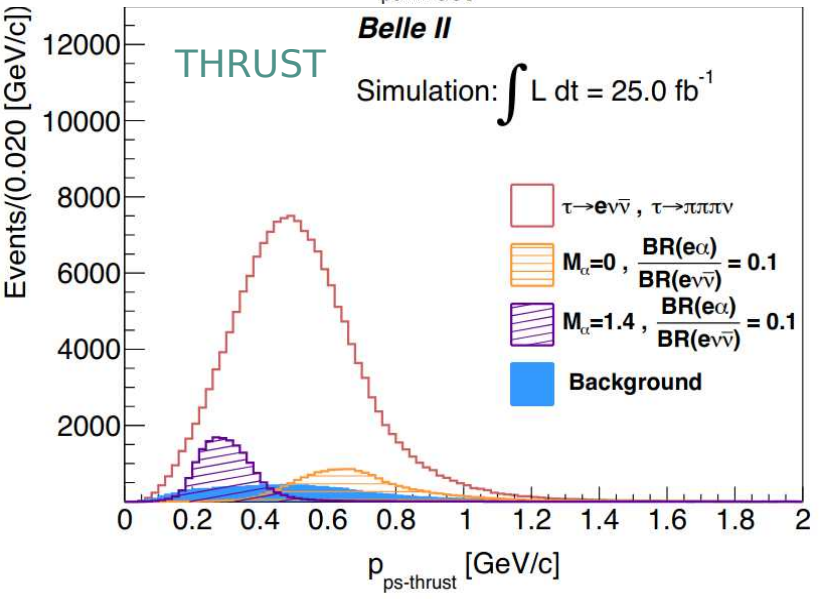
- We also tested a modification where

$$\hat{p}_\tau \simeq \hat{V}_{thrust}$$

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

BELLE2-NOTE-PL-2020-018





Search for $\tau \rightarrow l\alpha$

- Statistical treatment
  - Template based analysis
  - Fit the lepton momentum spectrum:
    - SM hypothesis
    - SM + BSM hypothesis
  - Hypothesis test

- The data can be modeled as

$$F(x) = N_{e\alpha}\, f_{e\alpha}(x) + N_{e\nu\nu} f_{e\nu\nu}(x) + N_{bkg} f_{bkg}(x)$$

$$= \frac{\varepsilon^{e\alpha}}{\varepsilon^{e\nu\nu}} N_{e\nu\nu}\, poi\, f_{e\alpha}(x) + N_{e\nu\nu} f_{e\nu\nu}(x) + N_{bkg} f_{bkg}(x)$$

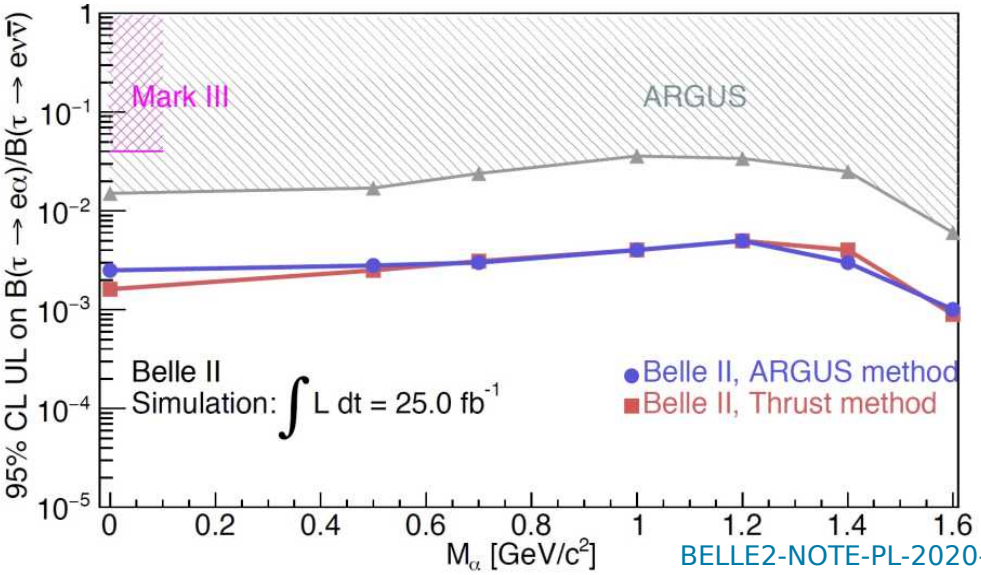
where $x=2E_e/m_\tau$ is the normalized energy in the p.r.f of the τ, and

$$poi \overset{def}{=} \frac{N_{e\alpha}}{N_{e\nu\nu}} \frac{\varepsilon^{e\nu\nu}}{\varepsilon^{e\alpha}} = \frac{Br(\tau \rightarrow e\alpha)}{Br(\tau \rightarrow e\nu\nu)}$$

- Upper limit estimation for poi (RooStats) at 95% CL for 25 fb^{-1}
- Modified frequentist approach: CLs

$$CL_s = \frac{CL_{s+b}}{CL_b}$$

- Preliminary results (no systematic effects were taken into account)



BELLE2-NOTE-PL-2020-018

- Belle II is competitive with respect to ARGUS.

- Current status
  - Include $\tau \rightarrow \mu\alpha$
  - Identification and inclusion of systematic uncertainties
  - Cross checks
    - PyHF: python package
    - BAT: Bayesian approach

Summary

- Belle II has a rich program of precision measurements and searches for NP in the τ sector
  - Large cross section of $e^+e^- \to \tau^+\tau^-$
  - High luminosity
  - Excellent detector capabilities
- Some analyses are already in good shape:
  - τ mass measurement
  - τ lifetime
  - Search for $\tau \to l\, \alpha$
  - $\tau \to \mu\mu\mu$, $\tau \to \mu\gamma$
  - And more

Stay tuned!

Backup

τ -lifetime

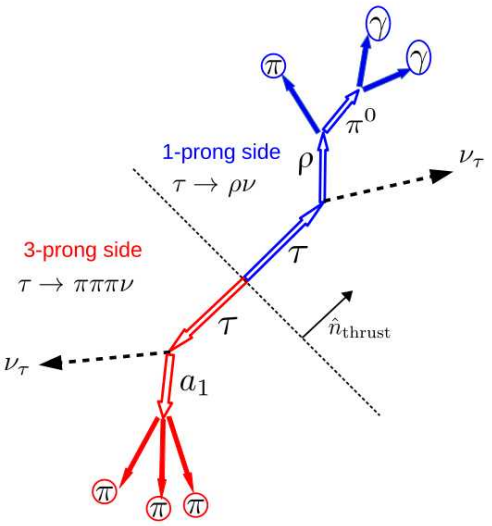
- τ lifetime fundamental parameter of the SM
  - Tests of lepton universality

- Measurement strategy
  - Proper time given by

$$t = m_\tau \frac{l_\tau}{p_\tau}$$ To be measured

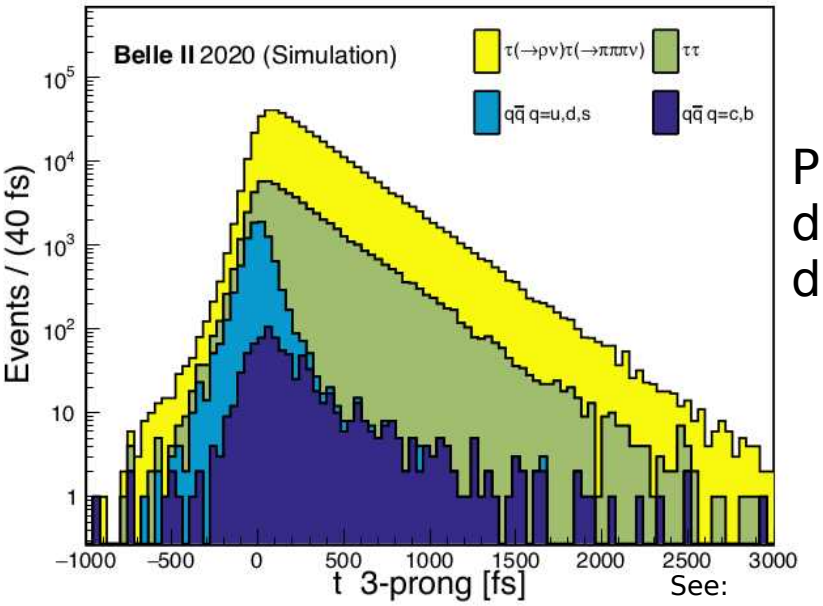
  - l_τ = decay length in lab frame
  - p_τ = momentum in lab frame
  - t = proper time

- Select events with a 3x1 topology
  - Signal: $\tau \rightarrow 3\pi\nu$
  - Tag: $\tau \rightarrow \rho\, \nu$



- Lifetime extraction
  - Fit proper decay time distribution with convolution of resolution function and exponential distribution:

$$p(t, \tau_\tau) = \frac{1}{\tau_\tau} e^{-\frac{t}{\tau_\tau}} * \Re(t)$$



Proper decay time distribution

See: BELLE2-TALK-CONF-2021-005

MC study (200 fb^{-1}):
$\tau_\tau = (287.2 \pm 0.5)$ fs
PDG:
$\tau_\tau = (290.3 \pm 0.5)$ fs

Competitive results with ~200 fb^{-1}