Latest results on dark sector and tau physics at Belle II
$\sim$ Lomonosov Conference $\sim$

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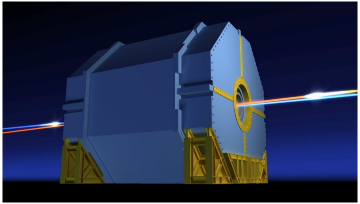
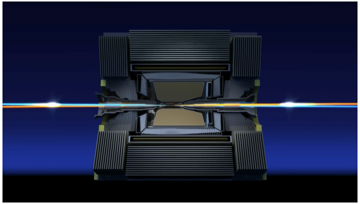
on behalf of the
Belle II Collaboration

University of British Columbia

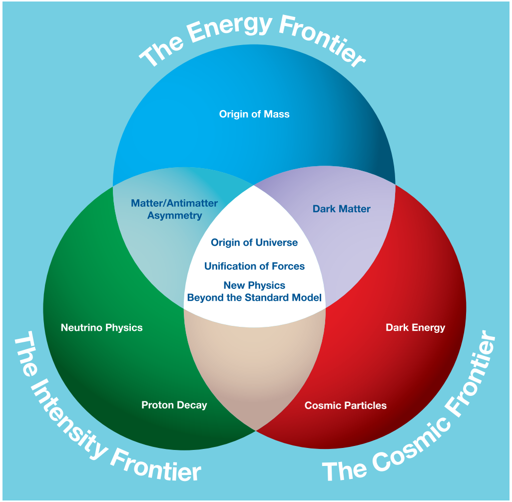
August 24 2021





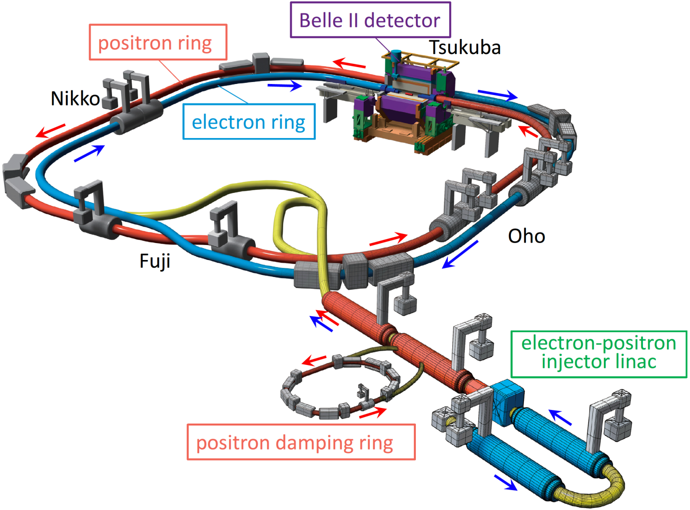
The SuperKEKB accelerator is pushing the collider luminosity frontier for Belle II to study lots of different kinds of physics

B-physics, matter-antimatter asymmetry, precision measurements, direct searches for new physics, …



Fermilab image

The SuperKEKB particle collider accelerates beams of electrons and positrons, stores them in a ring, and collides them.

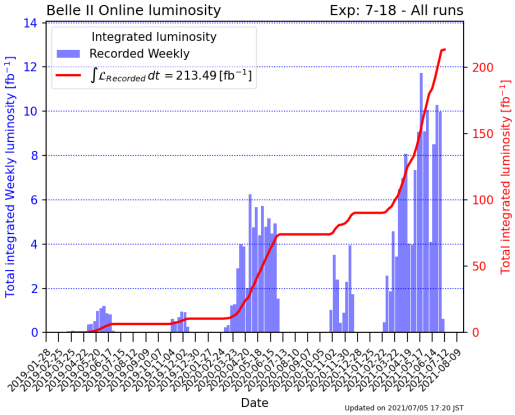


arXiv:1809.01958

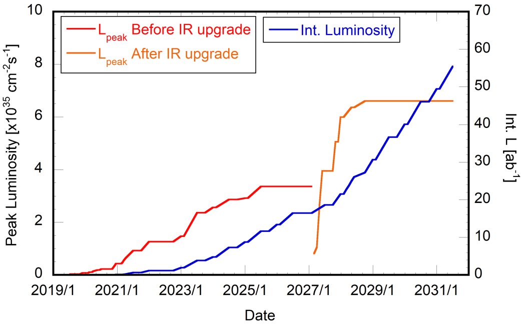
- e^- beam: 7 GeV
- e^+ beam: 4 GeV
- Centre of mass energy: $\sqrt{s} = 10.58$ GeV
- Continuous collision of beams in storage rings
- World record instantaneous luminosities June 21 2021:

$$L^{\text{peak}}_{\text{inst.}} = 3.12 \times 10^{34}\ \text{cm}^{-2}\ \text{s}^{-1} = 31.2\ \text{nb}^{-1}\ \text{s}^{-1}$$

Recorded 213 fb^{-1} of data but the target = 50 ab^{-1}. Early days for experiment but enough data for initial or new studies.

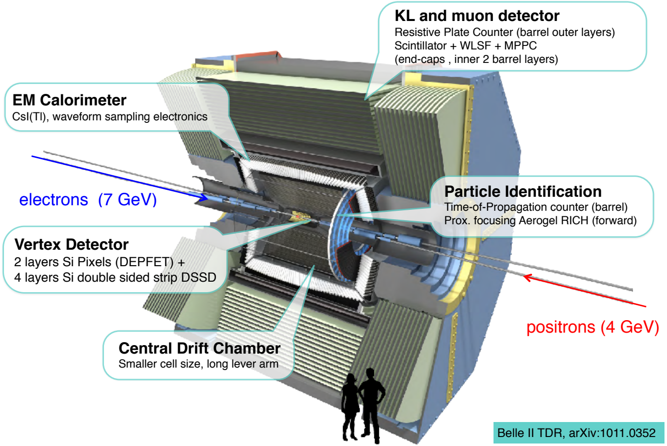


Luminosity projection:



https://confluence.desy.de/display/BI/Belle+II+Luminosity

Various sub-detectors measure the trajectories of charged particles, the energies of particles, and perform particle identification



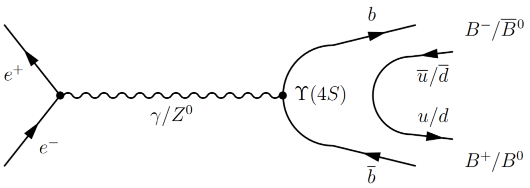
Belle II TDR, arXiv:1011.0352

Belle II detector:

- Asymmetric particle beam energies + detector
- Cylindrical layout of layers of detectors
- Solenoid (1.5 T) bends trajectories of charged particles in ϕ
- Particle identification detectors to distinguish $K^{\pm}$ from $\pi^{\pm}$ etc.

SuperKEKB will produce a large number of B^0 and $B^\pm$ mesons to study B-physics

- The collider centre of mass energy $= 10.58\ \text{GeV} \sim m\left[\Upsilon(4S)\right]$
  $\rightarrow$ large cross-section for producing $\Upsilon(4S)$
  - $\Upsilon(4S) \rightarrow B\bar{B}$: $> 96\%$ of decays
- SuperKEKB designed to be a "B factory" .... b-quarks !!!



$\Upsilon(4S) = b\bar{b}$ meson
$B \equiv B^\pm, B^0, \bar{B}^0$
$B^+ = u\bar{b}$ meson
$B^0 = d\bar{b}$ meson

Main goal to study B-physics but ...

Other major goals include performing precision measurements, and searches for new physics

Other major Belle II physics goals:

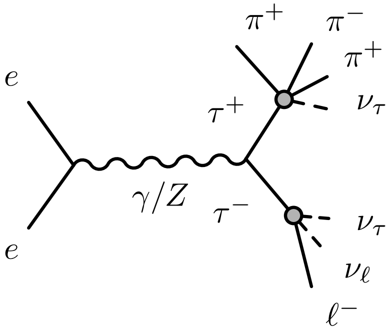
- Search for new physics through precision measurements that are sensitive to the presence of heavy virtual particles (e.g. through studies of the τ-lepton)
  - $\sigma\left[e^+e^- \rightarrow \Upsilon(4S)\right] = 1.05$ nb
  - $\sigma\left[e^+e^- \rightarrow \tau^+\tau^-\right] = 0.92$ nb
    - SuperKEKB makes lots of τ's too !
- Direct searches for physics beyond the standard model (e.g. Axion-like particles, Z', dark photon)

TAU MASS MEASUREMENT

The tau mass is a SM quantity that needs measuring and will help test the SM.

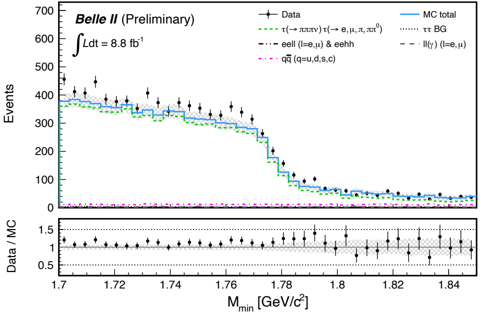
- m_τ is a SM quantity that needs measuring.
- Deviations of relations involving the lepton masses in the SM could signal new physics: e.g. test lepton universality
  - $\mathcal{B}(\tau \to e \text{ or } \mu) \propto m_\tau^5 \tau_\tau$

    SM branching ratio of $\tau \to e$ or μ is highly sensitive to the tau mass.
- Measure m_τ in: $e^+e^- \to \tau^+\tau^-$ events in 4-track final states
- Only one $\pi^0 \to \gamma\gamma$ allowed in final state (on the 1-prong side)



Measure m_τ in just the 3-prong decays by determining the endpoint of the distribution of $M_{\text{min}} \leq m_\tau$

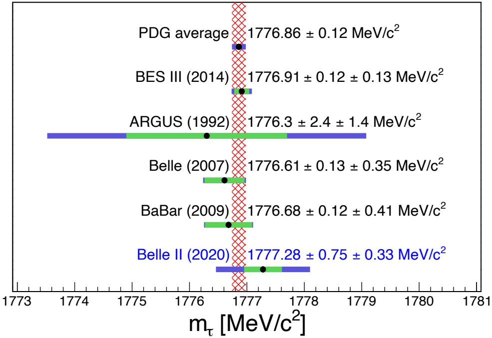
- Measure m_τ (3-prong decay)
- Pseudomass, M_{min}, method developed by the ARGUS Collaboration
- Fit M_{min} distribution to determine end-point
- Correct for endpoint bias, $0.72 \pm 0.12 \ \ \text{MeV}/c^2$ (from MC), to get m_τ



$$M_{\text{min}} \equiv \sqrt{m_{3\pi}{}^2 + 2\left(E_{\text{beam}}^{\text{COM}} - E_{3\pi}\right)\left(E_{3\pi} - |\mathbf{p_{3\pi}}|\right)} \leq m_\tau$$

ARGUS Collaboration, Phys. Lett. B 292, 221 (1992)
arXiv:2008.04665

First Belle II tau mass measurement: $m_\tau = 1777.28 \pm 0.75\,(\text{stat.}) \pm 0.33\,(\text{syst.})\ \ \text{MeV}/c^2$



Colour legend:
Systematic uncertainty and Total uncertainty

- Largest systematic uncertainty: momentum shift due to B field map $= 0.29\ \text{MeV}/c^2$
- Second largest systematic: estimator bias for conversion from end-point to mass $= 0.12\ \text{MeV}/c^2$
- Each remaining systematic $< 0.1\ \text{MeV}/c^2$
- Comparatively small overall $\sigma_{\text{syst.}}$; BES III better having done an energy scan.

$$m_\tau = 1777.28 \pm 0.75\,(\text{stat.}) \pm 0.33\,(\text{syst.})\ \ \text{MeV}/c^2$$

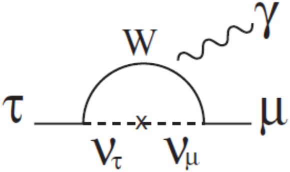
Improving systematics (B-field re-mapped): will be systematics dominated after $\sim 300\ \text{fb}^{-1}$

arXiv:2008.04665

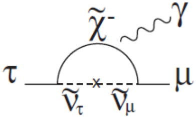
LEPTON-FLAVOUR VIOLATING TAU DECAYS

Belle II will push the exclusion limits of many lepton flavour violating τ-decays.

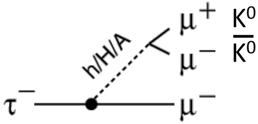
Add neutrino oscillations to SM:
Branching ratio $\sim \mathcal{O}\left(10^{-54}\right)$



New physics:
Branching ratio $\sim \mathcal{O}\left(10^{-10}\right) - \mathcal{O}\left(10^{-7}\right)$



SUSY



Higgs-mediation LFV

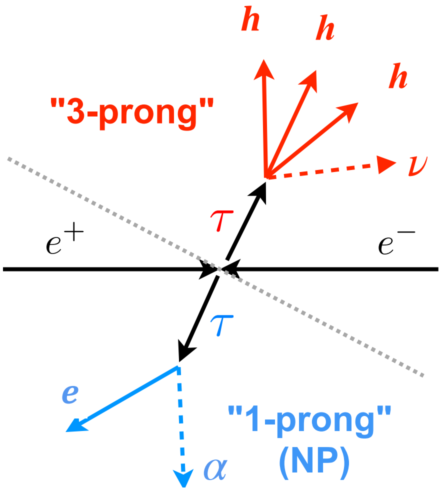
- Search for lepton flavour violating τ decay
  - Test lepton flavour conservation in SM
- Dozens of possible lepton flavour violating τ decay channels to be studied...
- Projection: extend the exclusion limits by 1-2 orders of magnitude with $50\ \text{ab}^{-1}$: see backup slides

The Belle II physics book

Belle II starting search for $\tau \to e\alpha$, where α is invisible

Example lepton flavour violating τ decay that connects to dark matter studies:

- Search for $\tau \to e\alpha$, where α is invisible
- General search but α possibly a DM candidate in some models [1, 2, 3]
- Previous searches:
  - Mark III (1985, 9.4 pb^{-1})
  - ARGUS (1995, 476 pb^{-1})
- Since two-body decay, search for resonance in $e^{\pm}$ momentum measured in approximation of τ rest frame
- Require other τ to have 3-prong decay for better approximation of τ rest frame
- Current data set should give order of magnitude improvement in exclusion



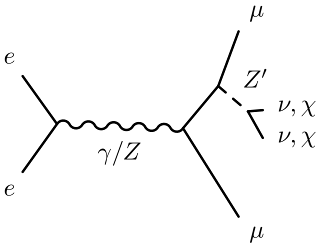
BELLE2-NOTE-PL-2020-018

SEARCH FOR THE Z'

Search for invisibly decaying Z' in $\mu^+\mu^-$ events.

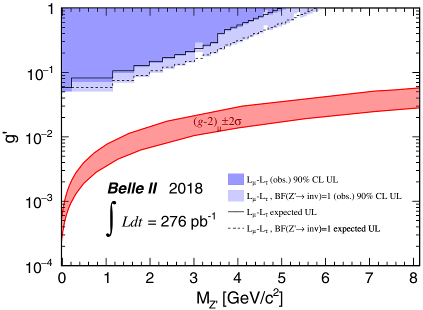
$L_\mu - L_\tau$ model:

- Z' does not interact with 1st generation leptons
- includes dark matter candidate
- potentially addresses $(g-2)_\mu$ anomaly



Phys. Rev. D, 89, 113004. June 2014

Search for resonance in mass of system recoiling again muon pair:



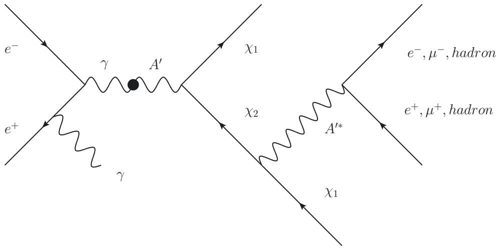
- Simulations: can probe $(g-2)_\mu$ band with ~ 50 fb^{-1}

Belle II, Phys. Rev. Lett. 124, 141801. April 2020, BELLE2-NOTE-PL-2020-012

SEARCH FOR DARK PHOTONS

Dark photon model could produce events with missing energy or displaced vertices

Inelastic DM model



- χ_1 = DM candidate
- Will have competitive results with the existing data set.

If χ_2 decays outside of detector:

- Single photon search
- Only directly detect initial state radiation: γ
- Single photon trigger with 0.5 GeV threshold
- Large background from $e^+e^- \to \gamma\gamma(\gamma)$
- Some cosmic muons background

If χ_2 decay in the detector:

- search for displaced vertex

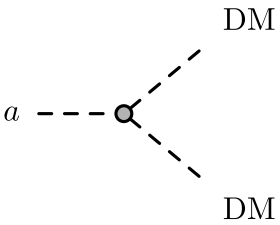
Journal of High Energy Physics, Article number: 39 (2020)

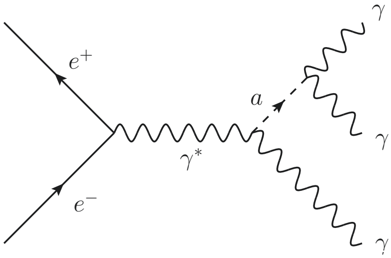
SEARCH FOR AXION-LIKE PARTICLES

Belle II sensitive to axion-like particles as portals to dark matter.

An Axion-like particle, a

- couples to bosons. Here focus on $a \to \gamma\gamma$
- could be a "portal" or "mediator" to connect SM to Dark Matter candidates if $m_a \sim \mathcal{O}\left(1\ \mathrm{GeV}/c^2\right)$





After selecting clean events with self-consistent photons, no excess observed and exclusions set

- 445 ± 3 pb^{-1} of data taken in 2018
- Search for bump on large $e^+e^- \to \gamma\gamma\gamma$ background
- Require that the photon $t/\Delta t$ are all consistent with each other
- No tracks from the interaction point
- $0.88\sqrt{s} \leq m_{\gamma\gamma\gamma} \leq 1.03\sqrt{s}$
- No significant excesses observed
- Even with a small data set, results exclude previously unexplored parts of phase space.

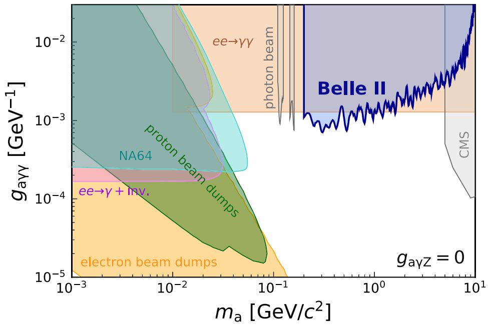


FIG. 5. Upper limit (95% C.L.) on the ALP-photon coupling from this analysis and previous constraints from electron beam-dump experiments and $e^+e^- \to \gamma +$ invisible [6,9], proton beam-dump experiments [8], $e^+e^- \to \gamma\gamma$ [11], a photon-beam experiment [12], and heavy-ion collisions [13].

Belle II, Physics Review Letters 125, 161806 (2020)

OUTRO

Early Belle II results show signs of promise for the future

Summary:

- Some early results already probing the unexplored
- Other early measurements show promise for the future
- The collider has set a new world record for instantaneous luminosity
- There is still a lot of work to be done to reach target of 50 ab^{-1}

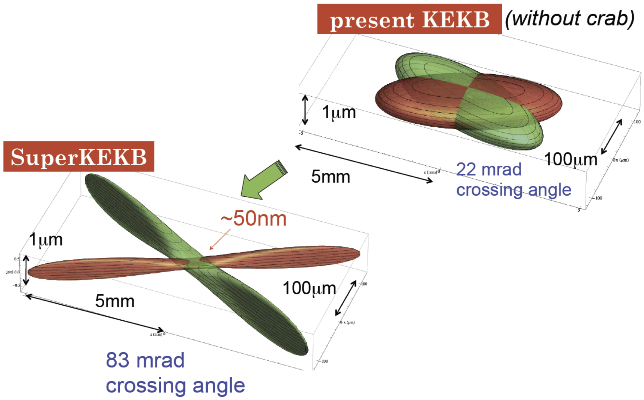
To get to the future:

- Remove "draft" pixel detector and insert full one
- Upgrades to accelerator (shorter term)
- Upgrades to detector (longer term)
- Polarized beams?
- Me: job applications :D

For all the latest Belle II results see:
https://confluence.desy.de/display/BI/Journal+Publications
https://docs.belle2.org/
https://arxiv.org/archive/hep-ex

AVENGERS: BELLE II - POST-CREDITS SCENE.... i.e. BACKUP SLIDES

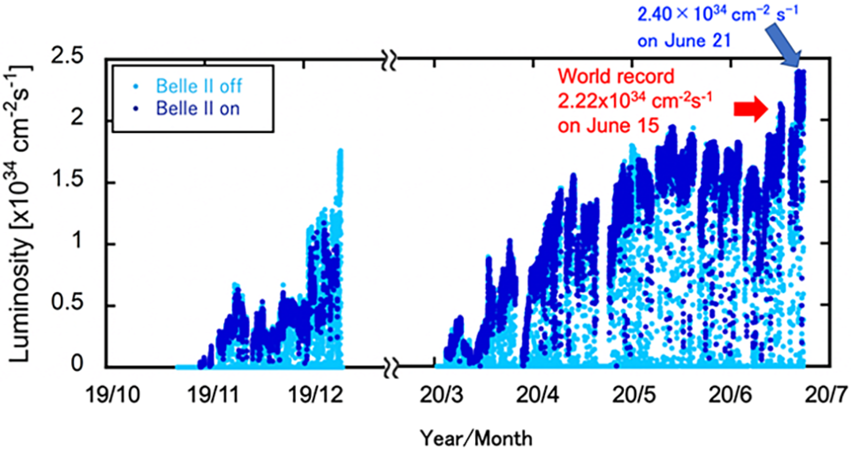
The higher luminosities are largely achieved by squeezing the beams to be even smaller at the collision point



Instantaneous luminosity of SuperKEKB $\times 30$ that of KEKB (old collider):

- $\times 1.5$: more particles per beam (increased current, number of bunches, etc.)
- $\times 20$: squeezing the beams ("nano-beam" collision scheme)

SuperKEKB set a world record for instantaneous luminosity in June 2020 while on our way to target nominal specifications



https://www.kek.jp/en/newsroom/2020/06/26/1400/

https://www.bnl.gov/newsroom/news.php?a=117285

Look at di-tau events with one 1-prong tau decay and one tau decay to 3 charged pions

Measure tau mass in di-tau events: $e^+e^- \to \tau^+\tau^-$

Require four track final state: Require one 1-prong decay and one 3-prong decay of the two taus:

- Selected 1-prong tau decays:
  - $\tau^- \to (1 \text{ or } 2\ \nu)\left(\leq 1\ \pi^0\right)(1 \text{ charged particle})$
    - $\tau^- \to \nu_\tau h^-, \quad h^- \equiv \pi^-$ or K^-
    - $\tau^- \to \nu_\tau \pi^- \pi^0$
    - $\tau^- \to \nu_\tau \ell^- \bar{\nu}_\ell, \quad \ell^- \equiv e^-$ or μ^-
- Selected 3-prong tau decays:
  - $\tau^+ \to \bar{\nu}_\tau \pi^+ \pi^- \pi^+$
- Results in at most one π^0 in the final state.

Assume charge conjugates throughout

A simple selection to pick out clean events and good charged pions is used

$8.8\ \mathrm{fb}^{-1}$ of data taken in 2019

Some of the event selections:

- $E_{\mathrm{ECL}}/p_{\mathrm{lab}} < 0.8$ for charged pions
  - Enhances the selection of $\tau^+ \to \bar{\nu}_\tau \pi^+\pi^-\pi^+$
- For $\pi^0 \to \gamma\gamma$:
  - Require $E_{\mathrm{ECL}}(\gamma) > 100\ \mathrm{MeV}$
  - Require $0.115 < m_{\gamma\gamma} < 0.152\ \mathrm{GeV}/c^2$
- Reject events with a photon of $E > 200\ \mathrm{MeV}$ that is not the daughter of a π^0
  - Reduces background contamination from $e^+e^- \to q\bar{q}$ processes.

After selections:

- Efficiency of reconstructing signal events $= 16.6\%$
- Purity of sample $= 84.5\%$ (over non-zoomed M_{min} window).

Measure m_τ in just the 3-prong decays by determining the endpoint of the distribution of $M_{\text{min}} \leq m_\tau$

Measure m_τ (3-prong decay)

Pseudomass, M_{min}, method developed by the ARGUS Collaboration.

Take $p_\tau = p_{3\pi} + p_{\nu_\tau}$

... Assume $\cos\alpha\,(p_{3\pi}, p_{\nu_\tau}) = 1$, $m_\nu = 0$ ...

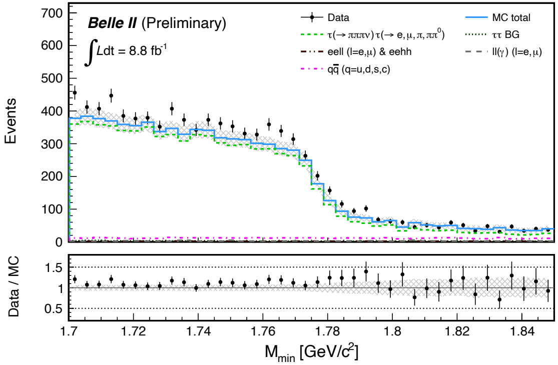
$$M_{\text{min}} \equiv \sqrt{{m_{3\pi}}^2 + 2\left(E^{\text{COM}}_{\text{beam}} - E_{3\pi}\right)\left(E_{3\pi} - |\mathbf{p_{3\pi}}|\right)} \leq m_\tau$$

- Fit the M_{min} distribution for the end-point $\rightarrow m_\tau$.
- Apply corrections to compensate for the neutrino assumptions etc.

Apply somewhat simple event selection to $8.8\ \text{fb}^{-1}$ of data taken in 2019....

ARGUS Collaboration, Phys. Lett. B 292, 221 (1992)

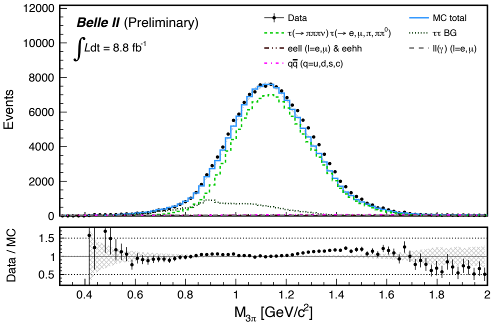
Correct end-point position by $0.72\ \mathrm{MeV}/c^2$ to get tau mass measurement.

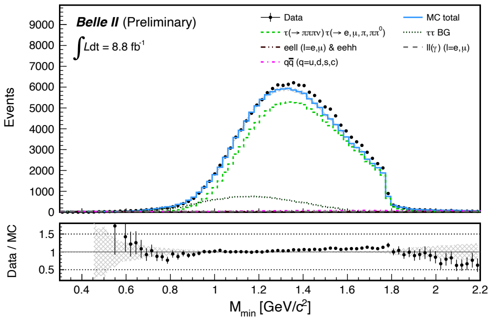


- Fit $M_{\text{min}}^{\text{MC}}$ distribution to determine end-point.
- Difference between measured MC end-point and $m_\tau^{\text{MC truth}}$ is $0.72 \pm 0.12\ \mathrm{MeV}/c^2$.
- Use this measured bias in MC to convert measured end-point in data to m_τ measurement.

arXiv:2008.04665

Backgrounds small and flat in the end-point region





- Dominant background in these plots is from other 3-prong tau decays but does not contaminate the end-point region where fit is performed.
- Small and flat background in the fit region

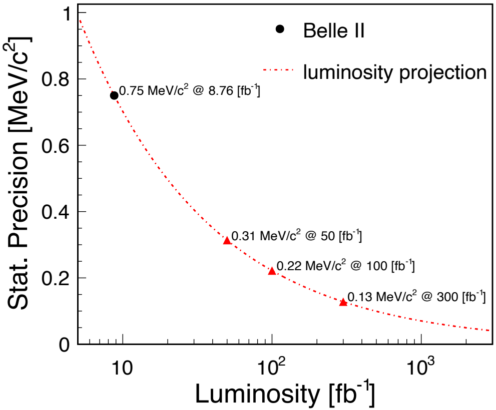
arXiv:2008.04665

Tau mass measurement systematics

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

arXiv:2008.04665

Future of the Belle II tau mass measurement



- Magnetic field has been remapped
- After improvements in the momentum scale factor systematic uncertainty, expect a future total systematic uncertainty of $\sim 0.15\ \mathrm{MeV}/c^2$.
- After that, need ~ 300 fb^{-1} of data for the measurement to become systematically dominated.

$$m_\tau = 1777.28 \pm 0.75\,(\text{stat.}) \pm 0.33\,(\text{syst.})\ \ \mathrm{MeV}/c^2$$

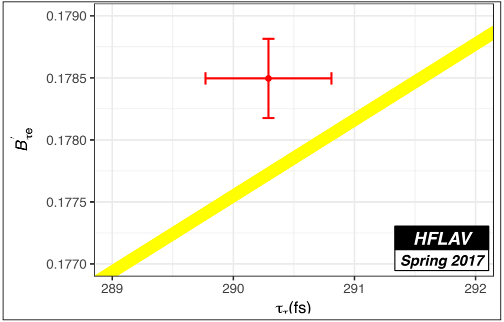
arXiv:2008.04665

Test of lepton universality

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

...

$B^{\text{SM}}_{\tau e} \propto m_\tau^5 \tau_\tau$



arXiv:1804.08436

- Uncertainties on m_μ are much smaller than uncertainties on m_τ
- τ_τ is the lifetime of the τ
- $B_{\tau\ell}$ is the branching ratio of τ decaying to $\ell\nu\nu$
- We can measure $B_{\tau e}$, m_τ, and τ_τ
- The $B^{\text{SM}}_{\tau e}$ equation is what the Standard Model says on how $B_{\tau e}$ varies with τ_τ after inputting m_τ.
- The red point is $\left(\tau_\tau^{\text{data measurement}}, B_{\tau e}^{\text{data measurement}}\right) = ((290.3 \pm 0.5)\ \text{fs}, (17.85 \pm 0.04)\ \%)$.
- The yellow line is $B^{\text{SM}}_{\tau e}$, based on the measured value of m_τ with a width corresponding to the τ lifetime uncertainty, which is dominated by the τ mass uncertainty.

(projected) exclusion limits for lepton flavour violating τ decays

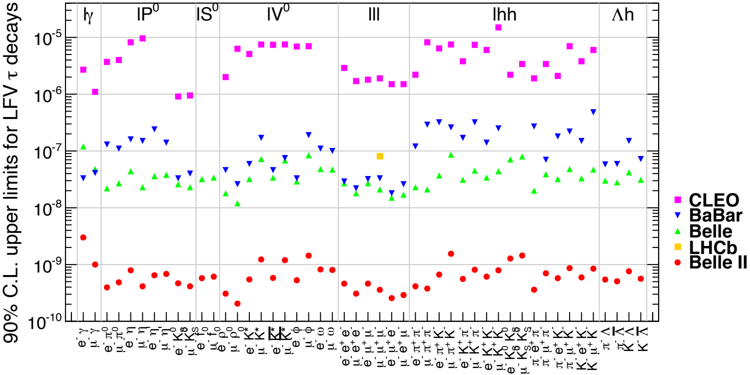
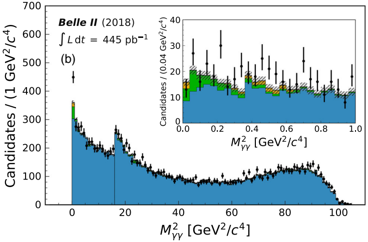
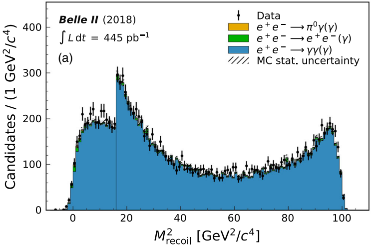


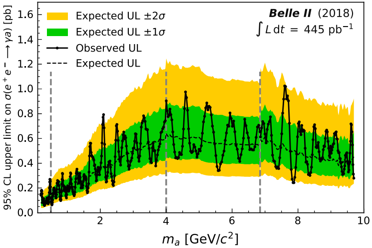
Fig. 177: Current 90% C.L. upper limits for the branching fraction of τ LFV decays obtained in the CLEO, BaBar, and Belle experiments. Purple boxes, blue inverted triangles, green triangles and yellow boxes show CLEO, BaBar, Belle and LHCb results, respectively, while red circles express the Belle II future prospects, where they are extrapolated from Belle results assuming the integrated luminosity of 50 ab^{-1}.

The Belle II physics book





- Photon energy cuts:
  - $m_a > 4$ GeV: $E_\gamma > 0.65$ GeV
  - $m_a \leq 4$ GeV : $E_\gamma > 1$ GeV
  - Helps avoid shaping effects on the background mass distribution
- Look at $m_{\gamma\gamma}$, and similar quantity calculated from recoil photon energy



Belle II, Physics Review Letters 125, 161806 (2020)