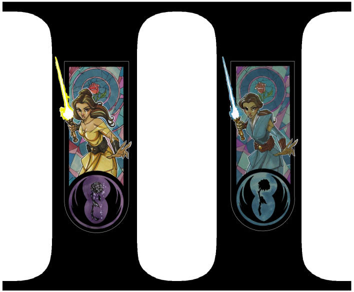
Towards the Particle Collider Luminosity Frontier: The latest from the Belle II Experiment

Ewan Hill (4hill@uvic.ca)
on behalf of
Belle II Canada

University of British Columbia

June 9 2021



Belle II à la Carmilla webseries

Jedi Disney Princesses by Tom Hodges

The SuperKEKB accelerator is pushing the collider luminosity frontier for Belle II to study the matter/antimatter asymmetry

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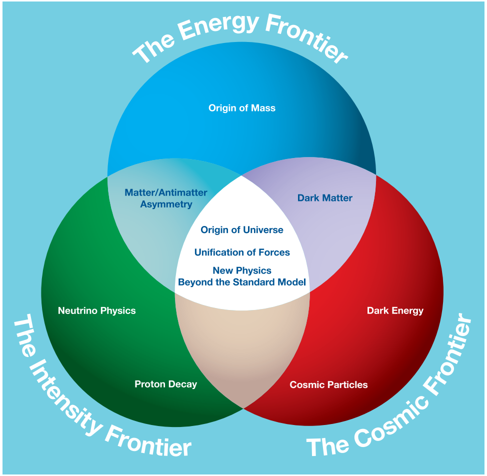
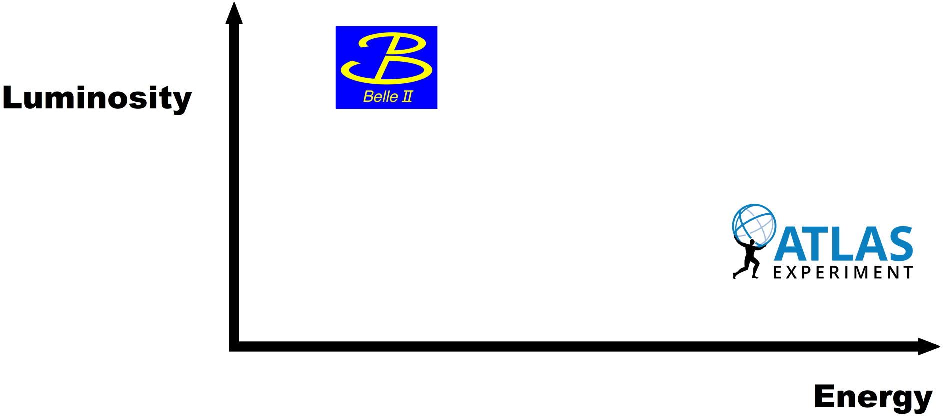


https://www.fnal.gov/directorate/plan_for_discovery/pdfs/ch2_01.pdf

Higher luminosities → higher precision measurements at Belle II. LHC+ATLAS prioritize energy. All parts of the bigger picture.



$$\text{Integrated Luminosity} = \int \frac{1}{\sigma} \frac{\mathrm{d}N_{\text{events}}}{\mathrm{d}t} \mathrm{d}t$$

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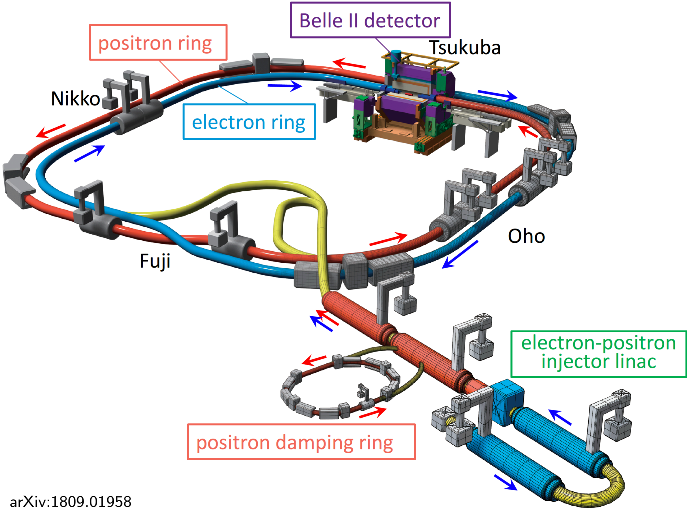
The SuperKEKB particle collider accelerates beams of electrons and positrons, stores them in a ring, and collides them.



arXiv:1809.01958

- e^- beam: 7 GeV
- e^+ beam: 4 GeV
- Centre of mass energy: $\sqrt{s} = 10.58$ GeV
- Beam energies increased in the linear accelerator
- ~ 3 bunches per ring are topped up at ~ 50 Hz for continuous collisions.

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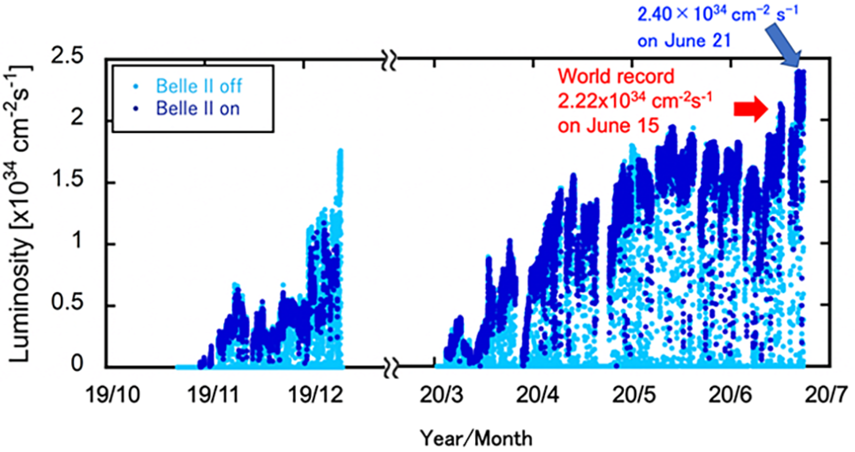
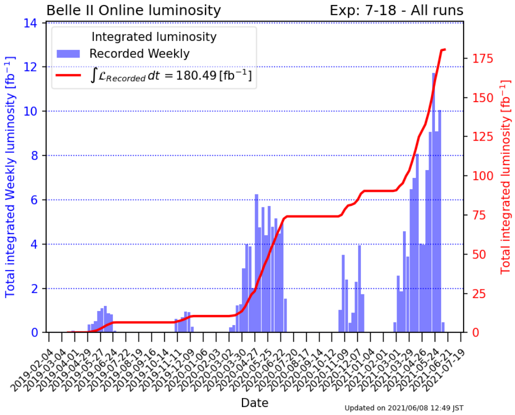
SuperKEKB set a world record for instantaneous luminosity in June 2020 while on our way to target nominal specifications

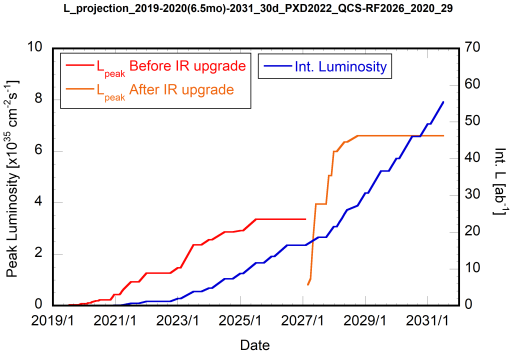


Continuously improving... Unofficially on May 17th: $L^{\text{peak}}_{\text{inst.}} = 2.957 \times 10^{34}\ \text{cm}^{-2} s^{-1}$

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

Recorded $> 180\text{fb}^{-1}$ of data but the target $= 50\text{ab}^{-1}$. Early days for experiment but enough data for initial or new studies.





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

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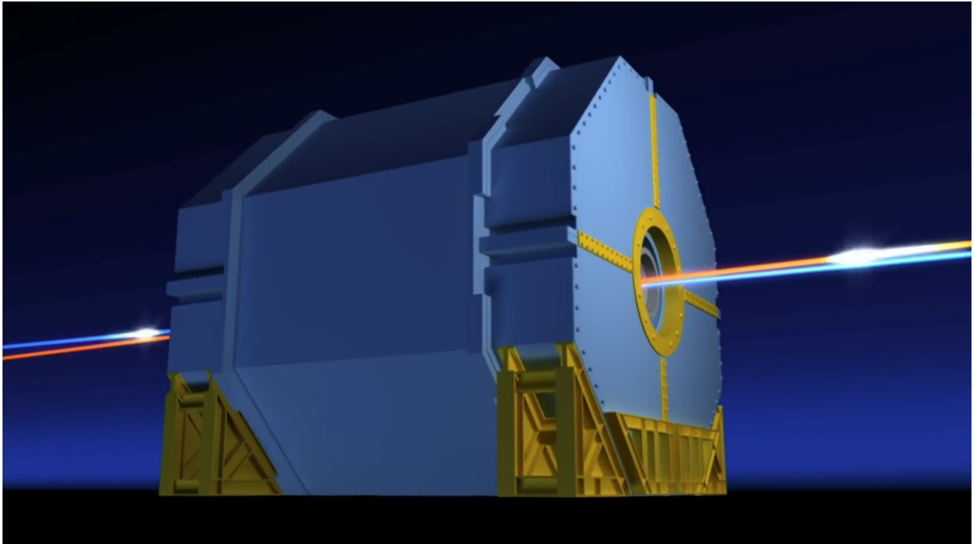
Belle II is the only detector along the collider ring



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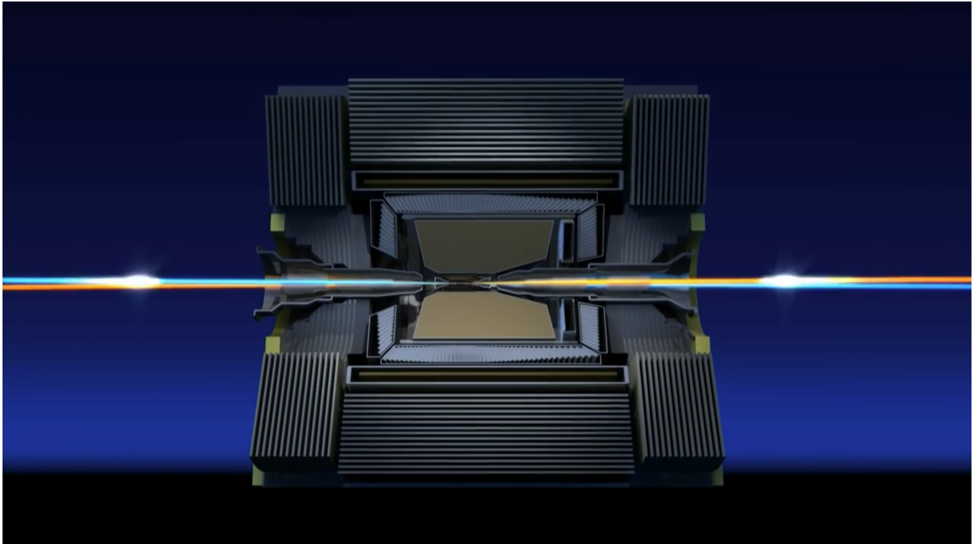
The accelerator collides the beams at the centre of the Belle II detector, nominally every $4\ \mathrm{ns}$



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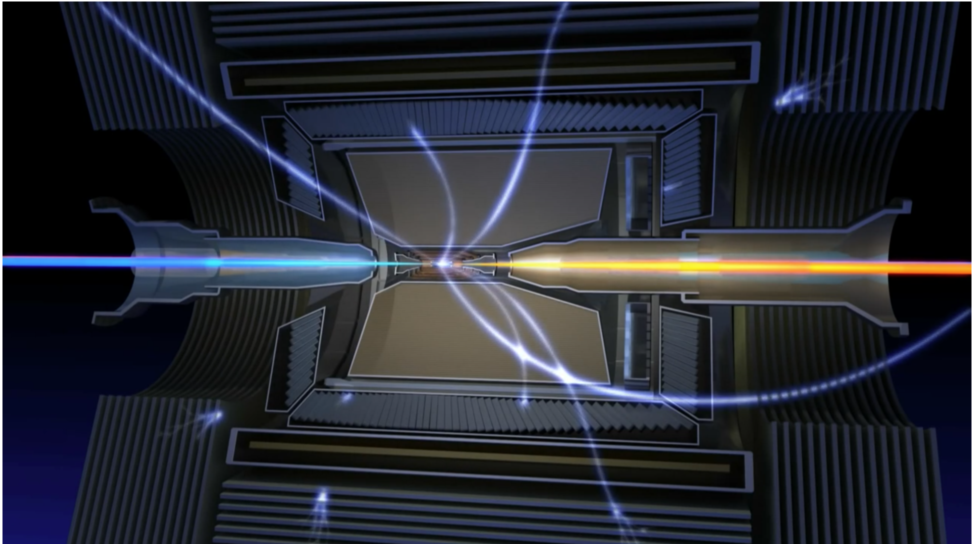
The final state particles are measured by Belle II.



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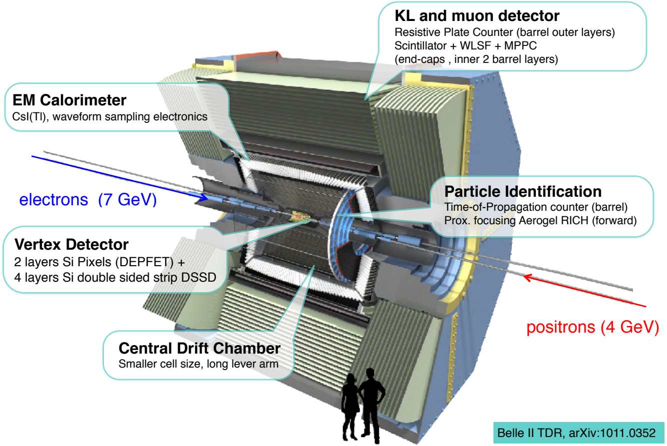
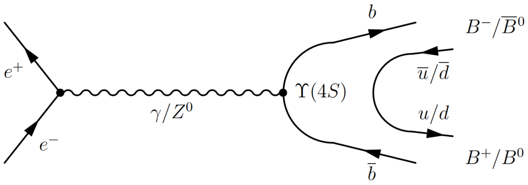
Various sub-detectors measure the trajectories of charged particles, the energies of particles, and perform particle identification



- Asymmetric particle beam energies + detector
- Cylindrical layout of layers of detectors
- Solenoid (1.5 T) bends trajectories of charged particles in ϕ (in plane orthogonal to beam axis)
- The K Long and Muon detector is a tracking detector with alternating layers of iron and detectors: make K_L^0 shower for more hits.
- Particle identification detectors to distinguish $K^\pm$ from $\pi^\pm$ etc.

SuperKEKB will produce a relatively large number of B^0 and $B^{\pm}$ mesons

- The collider centre of mass energy $= 10.58$ GeV $\sim m\left[\Upsilon(4S)\right]$ $\rightarrow$ large cross-section for producing $\Upsilon(4S)$.
- $\Upsilon(4S) \rightarrow B\bar{B}$
  - $\Upsilon(4S) \rightarrow B^0\bar{B}^0$: 47% of decays
  - $\Upsilon(4S) \rightarrow B^+B^-$: 49% of decays
- SuperKEKB is 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

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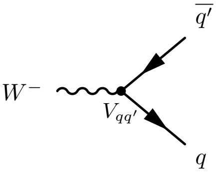
Goals are to study matter/anti-matter asymmetry, perform precision measurements, and search for new physics

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 and rare B decays)
- Direct searches for physics beyond the standard model (e.g. Axion-like particles, Dark matter)
- Matter/antimatter asymmetry: Investigation of CP violation and the weak force largely by looking at B decays (e.g. through decay time dependent studies of the $B^0 - \bar{B}^0$ system)



CKM matrix $V = \begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix}$, where some $V_{qq'}$ contain a CP violating complex phase, δ.

MEASUREMENT OF THE TAU MASS

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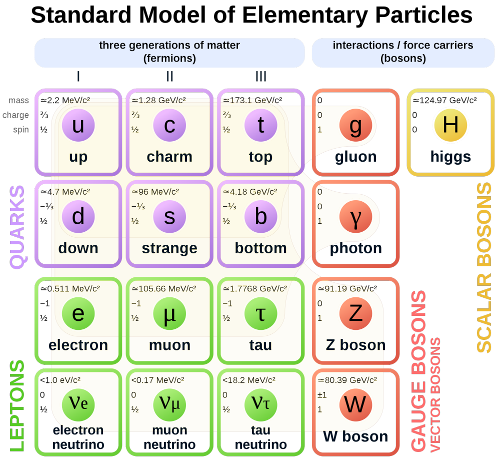
The tau mass is a SM quantity that needs measuring and will help test the SM.



- m_τ is a SM quantity that needs measuring.
- Deviations from certain relations involving the lepton masses in the SM could (indirectly) signal the presence of physics beyond our current understanding. e.g.
  - $\mathcal{B}\left(\tau \to e \text{ or } \mu\right) \propto {m_\tau}^5$

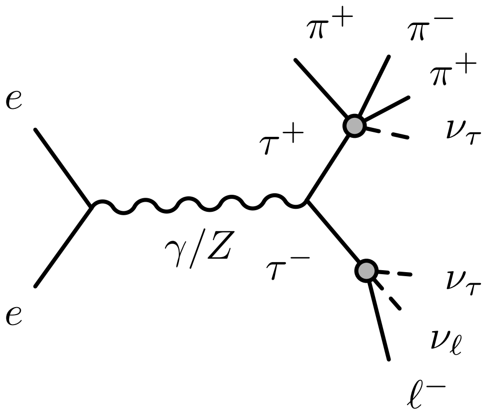
    SM branching ratio of $\tau \to e$ or μ is highly sensitive to the tau mass.

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

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

Require four track final state:

- two tau decays = 1-prong decay + 3-prong decay
- Selected 3-prong tau decays:
  - $\tau^+ \to \bar{\nu_\tau}\pi^+\pi^-\pi^+$
- A variety of 1-prong tau decays are selected
- Only one $\pi^0 \to \gamma\gamma$ allowed in final state (on the 1-prong side).



Assume charge conjugates throughout

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

Measure the mass of the τ that underwent the 3-prong decay.

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

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

... Assume $\cos\alpha = 1$, $m_\nu = 0$ ...

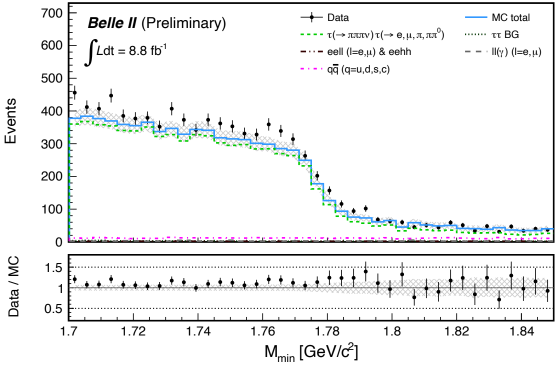
$$M_{\text{min}} \equiv \sqrt{{m_{3\pi}}^2 + 2\left(E_{\text{beam}}^{\text{COM}} - E_{3\pi}\right)\left(E_{3\pi} - |\mathbf{p_{3\pi}}|\right)} \leq m_\tau$$

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

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

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

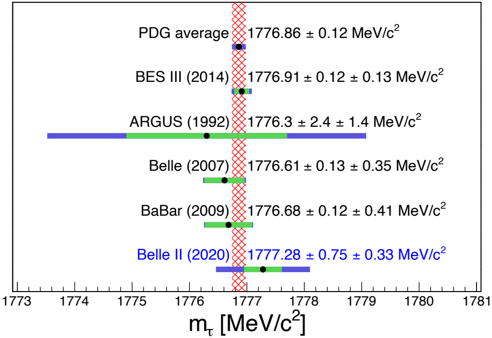
Correct end-point position by $0.72\ \mathrm{MeV}/c^2$ to get tau mass measurement.



- 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.

BELLE2-CONF-PH-2020-010 https://arxiv.org/abs/2008.04665

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



- 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.

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

BELLE2-CONF-PH-2020-010 https://arxiv.org/abs/2008.04665

MEASUREMENT OF THE BRANCHING FRACTIONS OF $B \to \eta' K$ DECAYS

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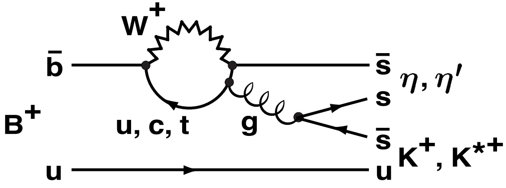
$B \to \eta' K$ branching ratios sensitive to new physics and a good channel for CP violation measurements



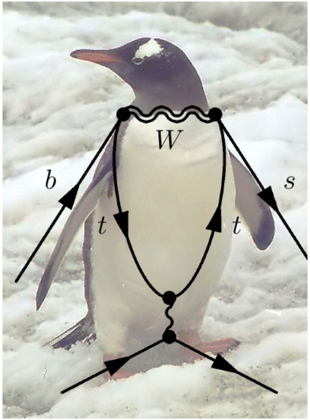
$B \to \eta' K$ decays are:

- rare charless hadornic B decays
- sensitive to new physics via the hadronic loop
- good for precise measurements of CP violation parameters because of relatively large branching fractions $(\mathcal{O}[10^{-5}])$

BELLE2-CONF-PH-2021-007 https://arxiv.org/abs/2104.06224

https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.85.520

Penguin diagrams ! :D



https://en.wikipedia.org/wiki/Penguin_diagram

Measure branching ratio for four different decay chains

Look at four specific decays chains:

- $B^+ \to \eta' K^+$
- $B^0 \to \eta' K_s^0, \quad K_s^0 \to \pi^+\pi^-$
- with two selected η' decays:
  - $\eta' \to \eta\pi^+\pi^-, \quad \eta \to \gamma\gamma$
  - $\eta' \to \rho\gamma, \quad \rho \to \pi^+\pi^-$

B^+ final state: K^+, charged pions, and photons

B^0 final state: charged pions and photons

Assume charge conjugates throughout

BELLE2-CONF-PH-2021-007 https://arxiv.org/abs/2104.06224

Maximum likelihood fit performed on several variables like mass and energy

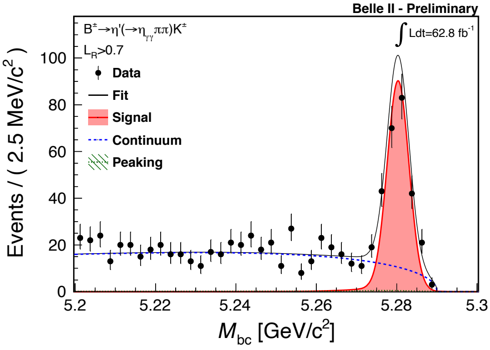
Use multidimensional maximum likelihood fit to data to determine number of signal events. Inputs:

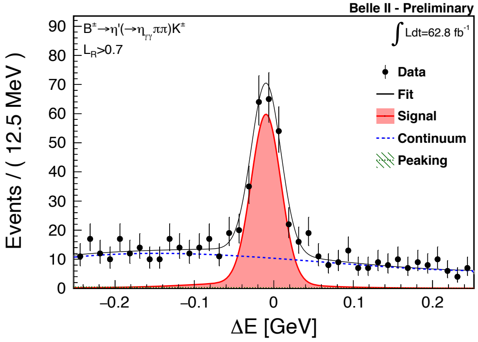
- $\Delta E = E_B^{\text{COM}} - E_{\text{beam}}^{\text{COM}}$
  - Difference in the energies of the beam and the B.
  - $\Delta E \sim 0$ for true B since all particle-antiparticle decays leave each with half the centre of mass energy.
- $M_{bc} = \sqrt{E_{\text{beam}}^{\text{COM}} - \mathbf{p}_{\mathbf{B}}^{\text{COM}}}$
  - Measurement of the reconstructed B mass.
  - $M_{bc} = m_B$ for true B
- Output classifier from a Boosted Decision Tree trained to remove the $ee \to q\bar{q}$ background $(q = u, d, s, c)$.

BELLE2-CONF-PH-2021-007 https://arxiv.org/abs/2104.06224

Mass and energy plots look reasonable

For likelihood ratio, $\mathcal{L} > 0.7$ and the decay chain:
$B^+ \to \eta' K^+, \quad \eta' \to \eta\pi^+\pi^-, \quad \eta \to \gamma\gamma$





PDG world average: $m_{B+} = 5279.25 \pm 0.26\ \mathrm{MeV}/c^2$

BELLE2-CONF-PH-2021-007 https://arxiv.org/abs/2104.06224

Measured branching ratio consistent with world averages to within the uncertainties

TABLE 1. Summary of results for the four decay channels, corresponding to an integrated luminosity of $\mathcal{L} = 62.8\,\text{fb}^{-1}$. Measured signal yields (N_{sig}), statistical significances ($sig.$), efficiencies (ε), total efficiencies including the secondary branching ratios ($\varepsilon\mathcal{B}$), and the measured $\mathcal{B}$ are reported. The uncertainties are statistical, the second uncertainty in the last column ($\mathcal{B}$) is the systematic uncertainty.

Mode	N_{sig}	$sig.$	$\varepsilon(\%)$	$\varepsilon\mathcal{B}(\%)$	$\mathcal{B}\ (10^{-6})$
$B^\pm \to \eta'(\to \eta(\to \gamma\gamma)\pi^+\pi^-)K^\pm$	$263\ ^{+18}_{-19}$	25.7	31.7 ± 0.03	5.45	$63.9\ ^{+4.6}_{-4.4} \pm 4.0$
$B^\pm \to \eta'(\rho(\to \pi^+\pi^-)\gamma)K^\pm$	$335\ ^{+26}_{-25}$	22.2	24.2 ± 0.04	7.05	$62.9\ ^{+4.8}_{-4.8} \pm 5.5$
$B^0 \to \eta'(\to \eta(\to \gamma\gamma)\pi^+\pi^-)K^0_S$	$80.0\ ^{+11.2}_{-10.4}$	13.8	31.0 ± 0.03	1.80	$61.6\ ^{+8.6}_{-8.0} \pm 3.9$
$B^0 \to \eta'(\rho(\to \pi^+\pi^-)\gamma)K^0_S$	$99.7\ ^{+14.2}_{-12.7}$	14.2	23.6 ± 0.04	2.35	$58.5\ ^{+7.9}_{-7.4} \pm 4.4$

Each of the four channels has a different largest systematic uncertainty.

PDG world averages:

$$\mathcal{B}\left(B^+ \to \eta' K^+\right) = (70.4 \pm 2.5) \times 10^{-6}$$

$$\mathcal{B}\left(B^0 \to \eta' K^0\right) = (66 \pm 4) \times 10^{-6}$$

BELLE2-CONF-PH-2021-007 https://arxiv.org/abs/2104.06224

SEARCH FOR AXION-LIKE PARTICLES

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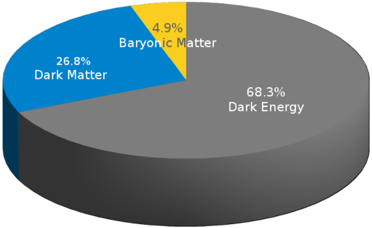
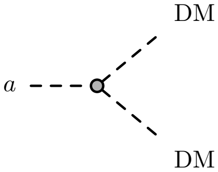
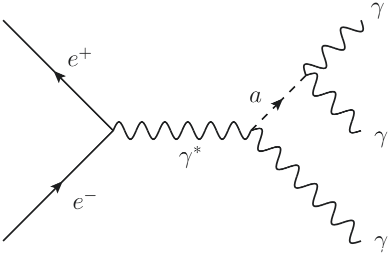
Belle II sensitive to axion-like particles as portals to dark matter.

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 $m_a \sim \mathcal{O}(1\ \mathrm{GeV})$
- has mass and couplings that are independent







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

- $445 \pm 3\text{pb}^{-1}$ of data taken in 2018
- Search for bump on large $ee \to \gamma\gamma\gamma$ background
- Require that the photon $t/\Delta t$ are all consistent with each other
- No tracks from the interation 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.

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

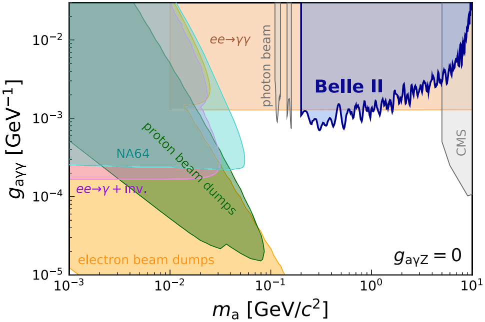


FIG. 5. Upper limit (95% C.L.) on the ALP-photon coupling from this analysis and previous constraints from electron beam-dump experiments and $e^+e^- \to \gamma +$ invisible [6,9], proton beam-dump experiments [8], $e^+e^- \to \gamma\gamma$ [11], a photon-beam experiment [12], and heavy-ion collisions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

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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 50ab^{-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: Start applications for next postdoc position :D

For all the latest Belle II results see:
https://docs.belle2.org/
https://arxiv.org/archive/hep-ex

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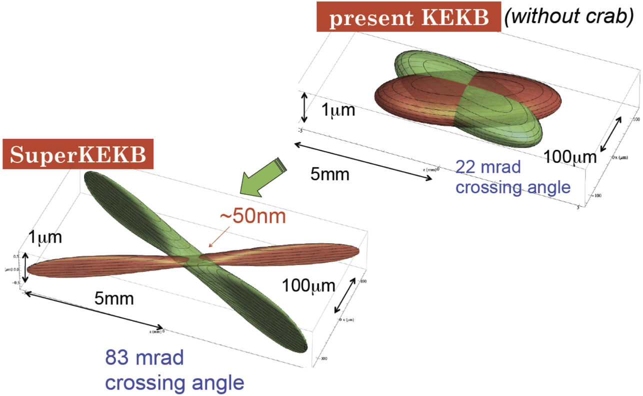
AVENGERS: BELLE II - POST-CREDITS SCENE.... i.e. BACKUP SLIDES

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)

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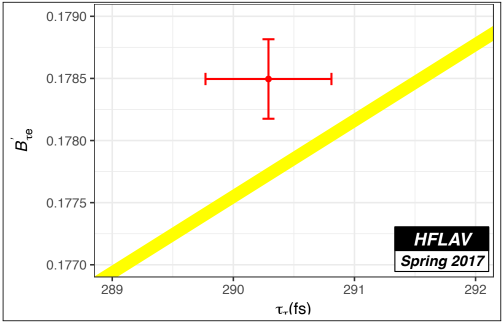
Test of lepton universality

I'm not entirely clear on this...

$$B_{\tau\ell}^{\mathrm{SM}} = B_{\mu e} \frac{\tau_\tau}{\tau_\mu} \frac{m_\tau}{m_\mu} \frac{f_{\tau\ell} r_W^\tau r_\gamma^\tau}{f_{\mu e} r_W^\mu r_\gamma^\mu}$$
...
$$B_{\tau e}^{\mathrm{SM}} \propto m_\tau^5 \tau_\tau$$



https://arxiv.org/abs/1804.08436

Skip most the definitions...

- 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 $B_{\tau e}^{\mathrm{SM}}$ 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 $B_{\tau e}^{\mathrm{SM}}$, 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.

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:
  - $\tau^- \to \nu_\tau h^-, \quad h^- \equiv \pi^-$ or K^-
  - $\tau^- \to \nu_\tau \pi^- \pi^0$
  - $\tau^- \to \nu_\tau \ell^- \nu_\ell, \quad \ell^- \equiv e^-$ or μ^-
  - $\tau^- \to \nu_\tau \left(\leq 1\pi^0\right)$ (1 charged particle)
- 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

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

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

Some of the event selections:

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

After selections:

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

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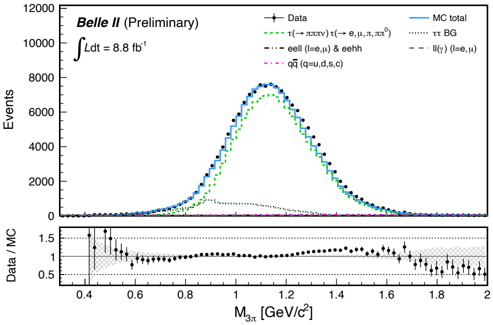
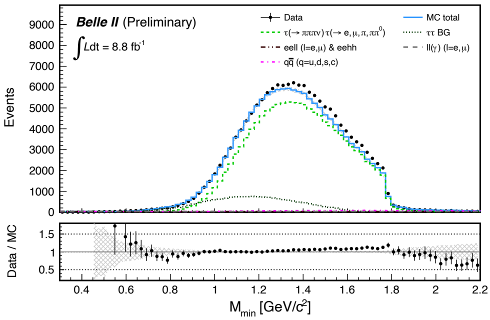
Backgrounds small and flat in the end-point region





- 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

BELLE2-CONF-PH-2020-010. https://arxiv.org/abs/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	$\leq$ 0.01
Initial parameters	$\leq$ 0.01
Background processes	$\leq$ 0.01
Tracking efficiency	$\leq$ 0.01

BELLE2-CONF-PH-2020-010 https://arxiv.org/abs/2008.04665

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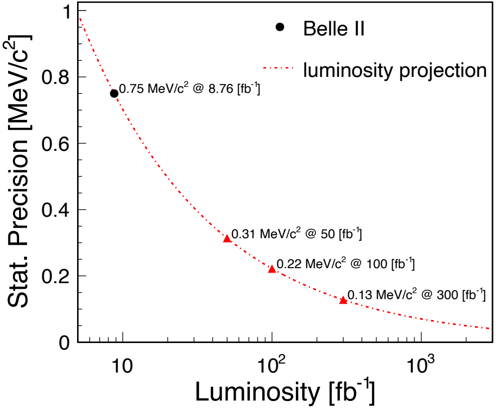
Future of the Belle II tau mass measurement



- 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 $\sim 300\mathrm{fb}^{-1}$ of data for the measurement to become systematically dominated.

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

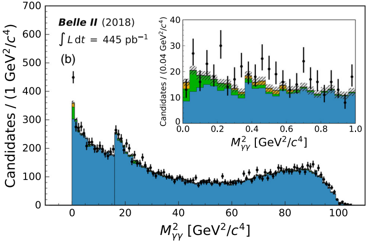
BELLE2-CONF-PH-2020-010 https://arxiv.org/abs/2008.04665

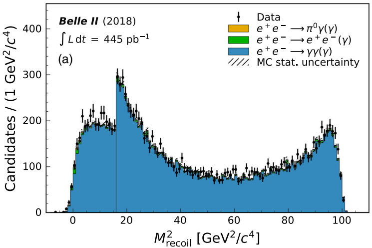
Each of the four decay channels of the B has a different largest systematic uncertainty

TABLE 2. Summary of systematics uncertainties (in %) by category and channel.

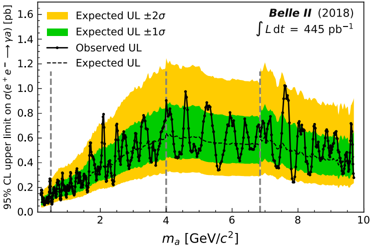
Channel	$B^{\pm} \to \eta' K^{\pm}$	$B^{0} \to \eta' K_S^{0}$	$B^{\pm} \to \eta' K^{\pm}$	$B^{0} \to \eta' K_S^{0}$
Source	$\eta' \to \eta\pi^+\pi^-$		$\eta' \to \rho\gamma$	
Tracking efficiency	2.1	2.8	2.1	2.8
Photon efficiency	0.5	0.5	0.5	0.5
K_S^0 efficiency	-	4.5	-	4.5
$\pi^{\pm}$ PID	-	-	2.4	2.4
$K^{\pm}$ PID	2.5	-	2.5	-
Cont. supp. modelling	5.0	1.0	5.5	2.3
SxF fraction	2.6	1.8	5.9	3.2
N($B\overline{B}$)	1.4			
Total	6.6	5.9	9.1	7.2

BELLE2-CONF-PH-2021-007 https://arxiv.org/abs/2104.06224





- 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)