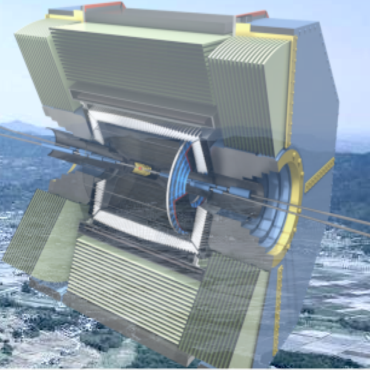


Belle II

Zuzana Gruberová (Charles University in Prague)

University of Birmingham Particle Physics Seminar, May 18, 2022

Outline

» **Introduction**
- Physics motivation
- B-factories

» **Experiment**
- SuperKEKB
- Belle II

» **Status and Prospects**
- Luminosity and data taking
- Selected physics results

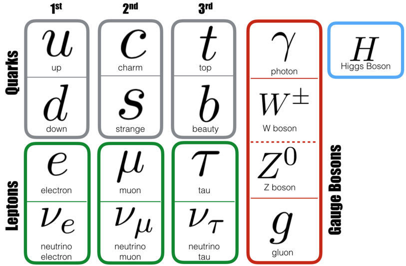
» **Summary**

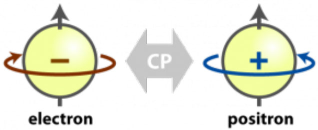
Physics motivation

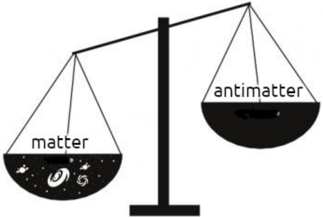
Exploring our universe

- **Big questions**
  - origin of particles generations and the role of flavour
  - CP violation and matter-antimatter asymmetry

  → not addressed by the Standard Model
  → we need New Physics







Physics motivation

Exploring our universe

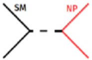
» **Big questions**

- origin of particles generations and the role of flavor
- CP violation and matter-antimatter asymmetry

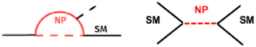
  → not addressed by the Standard Model
  → we need New Physics

» **Where to look for NP at colliders?**

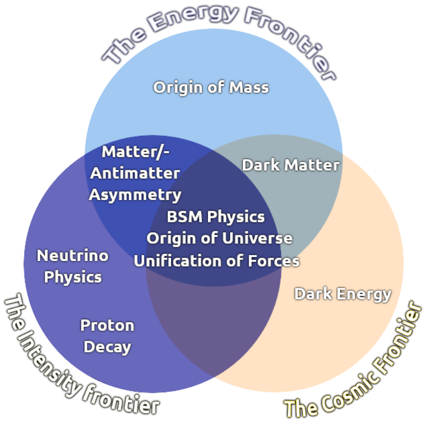
- direct searches at the Energy Frontier → direct production of new particles, limited by the collision energy



- indirect searches at the Intensity Frontier → new virtual particles, even if no new particles are found, the NP effects can still appear in high precision measurements as deviation from SM predictions



» Belle II is a leading Flavour Physics experiment at the Intensity Frontier



B-factories

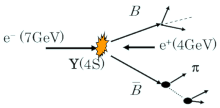
First generation B-factories

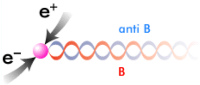
» **Asymmetric beam energies**

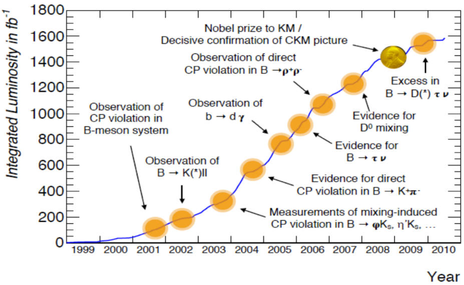
- boosted collision products

» **Collision energy at $\Upsilon(4S)$ resonance 10.6 GeV**

- $\sigma(e^+e^- \to B\bar{B}) = 1.05$ nb
  $\to$ 50% decays: coherent production of $B^0\bar{B}^0$
- full reconstruction of one of the B's, taging the flavor of the other B







» **Assets of B-factories**

- well-defined kinematics of initial state
- high vertex resolution and excellent calorimetry
- sophisticated particle ID

» **Belle@KEKB and BaBar@PEP-II**

- past B-factory experiments
- high luminosities:
  711 fb^{-1} @Belle, 424 fb^{-1} @BaBar

» **Wide physics program**

$\to$ success culminated in 2008 Nobel prize in Physics

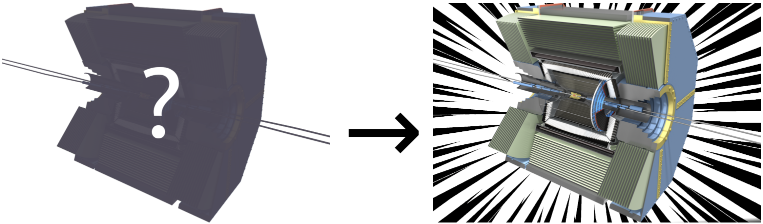
$\to$ rich legacy left for next generation experiments

B-factories

Motivation for another e^+e^- flavour factory

- probing the Standard Model? $\rightarrow$ high precision measurements of CKM matrix element
- looking for new CP violating phases? $\rightarrow$ study CP violation in B and D decays
- imprint of new physics in FCNC transitions? $\rightarrow$ examine radiative and electroweak penguin decays
- charged Higgs boson? $\rightarrow$ study tree-level decay $B \rightarrow \tau\nu$ or $B \rightarrow D^*\tau\nu$
- new physics in τ sector $\rightarrow$ search for lepton flavor violating τ decays
- dark matter? $\rightarrow$ search for hidden dark sector, invisible decays

$\rightarrow$ Belle II @ SuperKEKB will address these and other questions with almost two orders of magnitude larger dataset than Belle+BABAR



SuperKEKB

@ KEK, Tsukuba, Japan

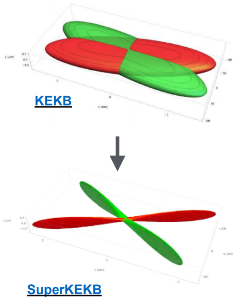
» **major upgrade of KEKB, first collision in 2018**

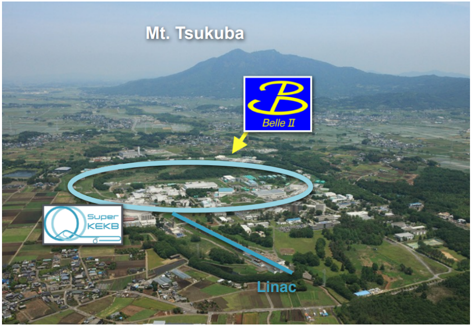
- 3 km long circular e^+e^- collider + linac
- asymetric beam energies of 7.0 GeV (e^-) and 4.0 GeV (e^+)
- nano-beam focusing, small interaction point, increased currents

» **Design luminosity of** $6 \times 10^{\mathbf{35}} \mathrm{cm}^{-2}\mathrm{s}^{-1}$

→ higher background

→ higher trigger rates

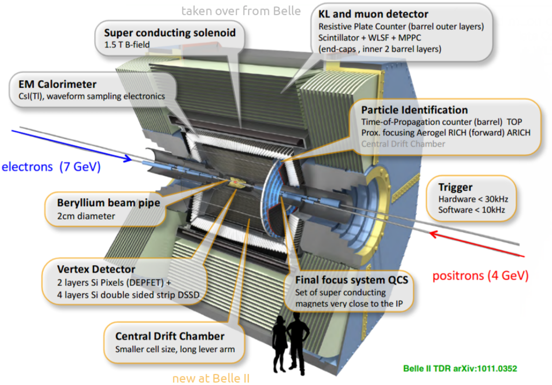




B-factory of the next generation

» **Belle II**

- successor of the Belle experiment
- upgraded trigger system
  → allows for the selection of signals that were not possible to trigger at Belle
- excellent tracking efficiency and improved vertex resolution
  → enables for new measurement approaches



Belle II

Luminosity status and plans

» **Despite the global pandemic, SuperKEKB managed to set new peak luminosity records in the past year**

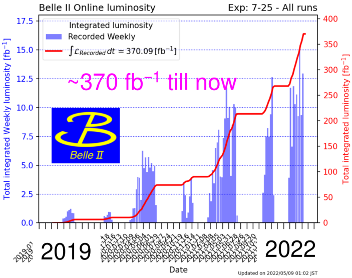
https://cerncourier.com/a/superkekb-raises-the-bar/

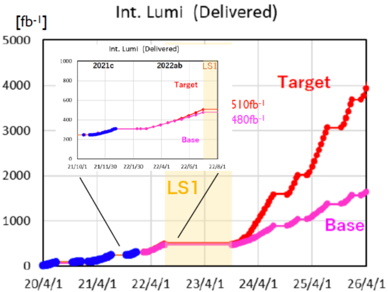
→ luminosity above the B-factories and LHC, with a product of beam currents 3.5 times lower than KEKB

→ new record $3.93 \times 10^{34} \mathrm{cm}^{-2}\mathrm{s}^{-1}$ reached just days ago!

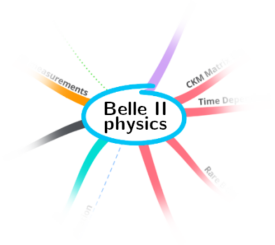
» **Operation plans**

- long shutdown (LS1) starts from summer 2022 for 15 months to replace the vertex detector (VXD)
- additional improvements are being discussed
- long shutdown for machine improvements could happen on the time frame of 2026-2027





Only a small fraction of recent Belle II results will be presented!



...and the selection of the presented analyses is also sligthly biased

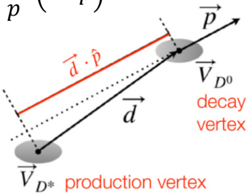
D^0, D^+ and Λ_c^+ lifetime measurements

» **Motivation**

- test of non-perturbative QCD
- large number of charm mesons are produced at B-factories
- no D^0, D^+ lifetime measurement from Belle/BaBar/LHCb
- no Λ_c^+ measurement from Belle/BaBar

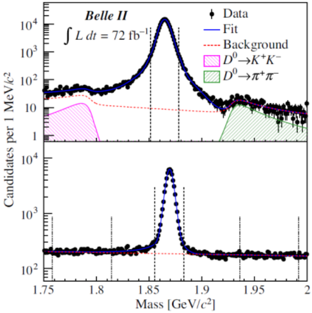
→ Belle II has better vertex resolution compared to Belle and BaBar thanks to new vertex detectors located at a closer position to the IP

$$t = \frac{m_D}{p}\left(\vec{d} \cdot \hat{\vec{p}}\right)$$



Decay vertex displaced by $\sim 200/500\ \mu m$ for D^0/D^+

72 fb^{-1}



$D^0 \to K^-\pi^+$

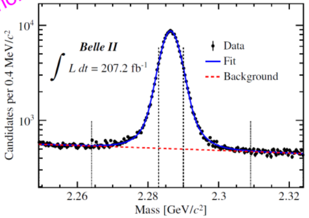
$D^+ \to K^-\pi^+\pi^+$

D from D* are selected ($D^* \to D$ + slow pion)

Preliminary (Moriond)

$\Lambda_c^+ \to pK^-\pi^+$

207 fb^{-1}



D^0, D^+ and Λ_c^+ lifetime measurements

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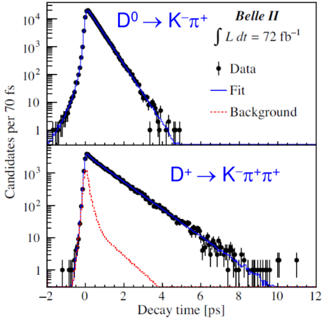
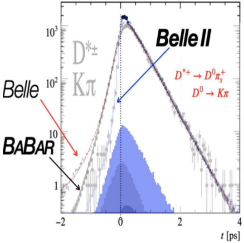


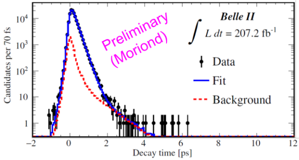
[PRL 127, 211801]

» **Strategy**

- 2D fit of decay time and its uncertainty
- all PDF parameters extracted directly from the data without simulation input



$\Lambda_c^+ \to pK^-\pi^+$ [paper in preparation]



PRL 127, 211801

D^0, D^+ and Λ_c^+ lifetime measurements

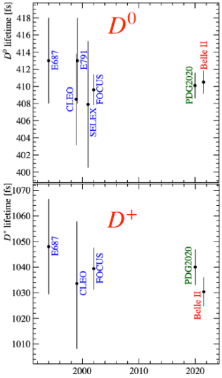
» **Results**

- consistent with and the world average
- still statistically limited, dominant syst. uncertainties come from detector alignment and modelling of background (for D^+)

→ first and most precise measurement in last 20 years

→ demonstration of Belle II vertexing capabilities compared to its predecessors

	Belle II	World average
$\tau(D^0)$ =	$(410.5 \pm 1.1 \pm 0.8)$ fs	(410.1 ± 1.5) fs
$\tau(D^+)$ =	$(1030.4 \pm 4.7 \pm 3.1)$ fs	(1040 ± 7) fs
$\tau(\Lambda_c^+)$ =	$(204.1 \pm 0.8 \pm 0.7 - 1.4)$ fs	(202.4 ± 3.1) fs

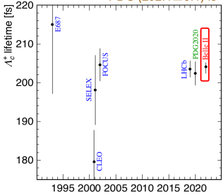


Source	$D^0 \to K^-\pi^+$ $\tau(D^0)$ [fs]	$D^+ \to K^-\pi^+\pi^+$ $\tau(D^+)$ [fs]
Resolution model	0.16	0.39
Backgrounds	0.24	2.52
Detector alignment	0.72	1.70
Momentum scale	0.19	0.48
Total	0.80	3.10

$\Lambda_c^+ \to pK^-\pi^+$

Source	Uncertainty [fs]
Resolution model	0.46
Backgrounds	0.20
Detector alignment	0.46
Momentum scale	0.09
Ξ_c contamination	1.39
Total	$0.69_{-1.39}$

systematic uncertainties



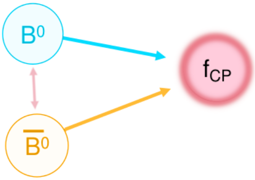
B^0 lifetime and mixing frequency

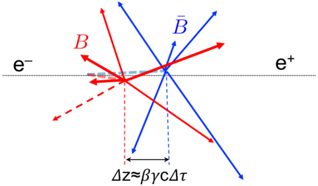
» **Goal**

- one of the main targets of Belle II – mixing-induced CP asymmetry
- B^0 and $\bar{B}^0$ decay to a common CP eigenstate f_{CP}
- CP violation appears as a decay time difference

$$A_{CP}(\Delta t) = \frac{\Gamma(\overline{B}^0(\Delta t) \to f_{CP}) - \Gamma(B^0(\Delta t) \to f_{CP})}{\Gamma(\overline{B}^0(\Delta t) \to f_{CP}) + \Gamma(B^0(\Delta t) \to f_{CP})}$$
$$= S \sin(\Delta m \Delta t) + A \cos(\Delta m \Delta t)$$
$$S = -\xi \sin(2\phi_1) \text{ for } B \to J/\psi K_S \qquad (\phi_1 = \beta)$$

S – mixing induced CPV, A – direct CPV





$\beta\gamma \approx$ **0.27**

$\to$ **mean vertex separation** $\Delta z \approx$ **130**μm

» **Current analysis**

- measuring decays to final state $D^{(*)-}K^+/\pi^+$ (instead of f_{CP})
  $\to$ fully reconstructed hadronic decay vertex

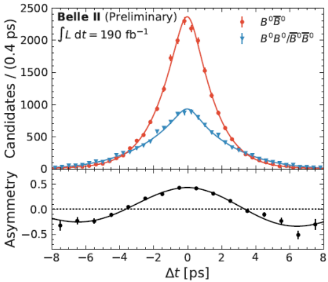
$\to$ measurement of mixing frequency (Δm) and lifetime

B^0 lifetime and mixing frequency

- **Results**

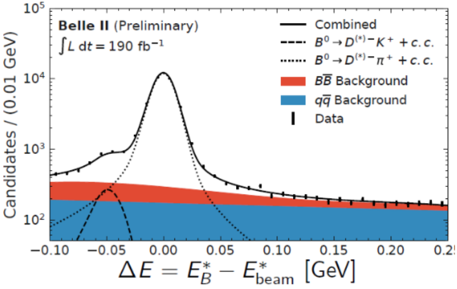
$$\tau_{B^0} = 1.499 \pm 0.013\,(\text{stat.}) \pm 0.008\,(\text{syst.})\ \text{ps},$$
$$\Delta m_d = 0.516 \pm 0.008\,(\text{stat.}) \pm 0.005\,(\text{syst.})\ \text{ps}^{-1}$$

  - similar uncertainty as Belle and BaBar
- **Next steps**
  - include semileptonic mode $D^*\ell\nu$
  - measure $\sin(2\phi_1)$ ($= \sin(2\beta)$)



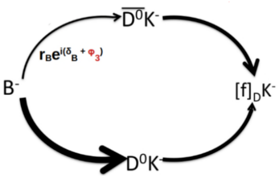
190 fb^{-1}

Preliminary (Moriond)

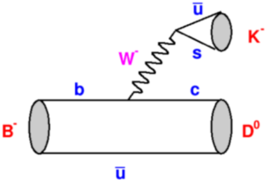


Measurement of ϕ_3

- **ϕ_3 (γ) is a weak phase between $b \to u$ and $b \to c$ transition**
  - proceeding only through tree-level $B^- \to D^0 K^-$ decays
  - SM benchmark, no theory uncertainties
  - the phase can be accesed through the interference between two possible paths to the common final state
  - interference depends on B and D physics



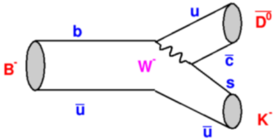
$$\frac{\mathcal{A}^{\text{suppr.}}(B^- \to \overline{D}{}^0 K^-)}{\mathcal{A}^{\text{favor.}}(B^- \to D^0 K^-)} = r_B e^{i(\delta_B + \phi_3)}$$



color favored

$$B^- \to D^0 K^- \approx V_{cb} V^*_{us}$$

$$\mathbf{A_1}$$



color suppressed

$$B^- \to \bar{D}^0 K^- \approx V_{ub} V^*_{cs}$$

$$\mathbf{A_1 r_B e^{i(\delta_B + \phi_3)}}$$

Measurement of ϕ_3

» **ϕ_3 (γ) is a weak phase between $b \to u$ and $b \to c$ transition**

- proceeding only through tree-level $B^- \to D^0 K^-$ decays
- SM benchmark, no theory uncertainties
- the phase can be accesed through the interference between two possible paths to the common final state
- interference depends on B and D physics

» **Analytical approach**

- experimentally challenging due to small branching fractions

→ Binned Dalitz plot analysis using $B^- \to D^0 h^-$ with $D^0 \to K_S^0 h^+ h^-$ (GGSZ method [PRD 68. 054018 (2003)])

→ this method is model-independent

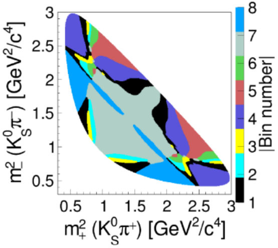
yields in each bin

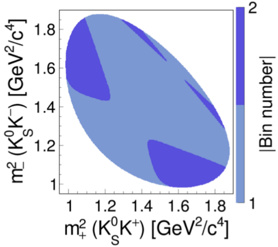
$$N_i^{\pm} = h_B^{\pm}\left[F_i + r_B{}^2\overline{F}_i + 2\sqrt{F_i\overline{F}_i}(c_i x_{\pm} + s_i y_{\pm})\right]$$

$(x_{\pm}, y_{\pm}) = r_B\left(\cos(\gamma + \delta_B),\ \sin(\gamma + \delta_B)\right)$

c_i, s_i: D^0-$\overline{D}^0$ strong phase differences (inputs from BES III/CLEO)

F_i: fraction of D decays to i-th bin

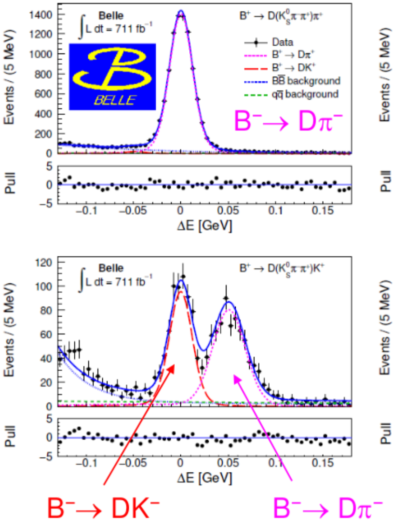




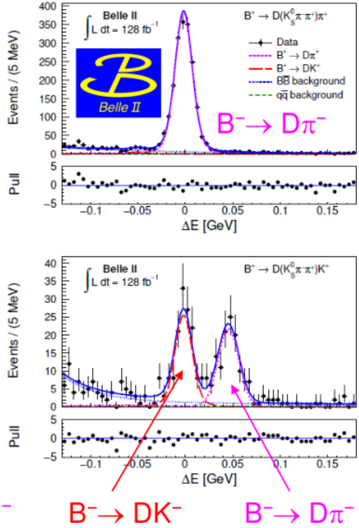
Measurement of ϕ_3

» combined Belle (711 fb^{-1}) and Belle II (128 fb^{-1}) analysis [JHEP 02 (2022) 063]

Belle



Belle II



Belle:
$K_S{}^0\pi\pi$: 1467 ± 53
$K_S{}^0KK$: 194 ± 17

Belle II :
$K_S{}^0\pi\pi$: 280 ± 21
$K_S{}^0KK$: 34 ± 7

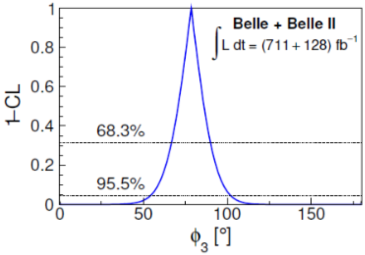
Measurement of ϕ_3

» **Results**

$$\delta_B[^\circ] = 124.8 \pm 12.9\ (\text{stat})\ \pm 0.5\ (\text{syst})\ \pm 1.7\ (\text{ext})$$

$$r_B^{DK} = 0.129 \pm 0.024\ (\text{stat})\ \pm 0.001\ (\text{syst})\ \pm 0.002\ (\text{ext})$$

$$\gamma[^\circ] = 78.4 \pm 11.4\ (\text{stat})\ \pm 0.5\ (\text{syst})\ \pm 1.0\ (\text{ext})$$



» **Many improvements with respect to the previous result from Belle**

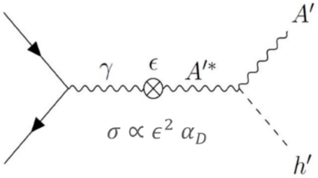
- use of $D(K_S^0 K^- K^+)$ channel
- improved suppression of continuum background
  $\rightarrow$ improvevent equivalent to doubling the statistics
- reduction of systematics thanks to latest inputs on strong phase from BESIII
- fractions F_i obtained directly from simultaneous fit to data (LHCb strategy)
- expected reduction of statistical uncertainty to $< 3^\circ$ with 10 ab^{-1} and using more D final states (but still will be statistically dominated)

Dark Higgsstrahlung

» **Next-to-minimal dark photon model**

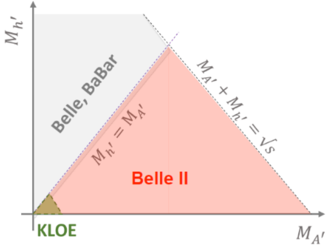
- dark photon (A') couples to the SM photon via kinetic mixing parameter ϵ
- A' mass can be generated via spontaneous symmetry breaking mechanism

  $\rightarrow$ a dark Higgs boson (h') is added to the theory [PRD 79, 115008 (2009)]
- h' does not mix with the SM Higgs
- both particles A' and h' can be produced via dark Higgsstrahlung process



» **Mass hierarchy scenarios**

- $m_{h'} > m_{A'}$: $h' \rightarrow A'A' \rightarrow 4\ell$, 4had, 2ℓ + 2had $\Rightarrow$ 6 charged tracks
  Investigated by BaBar (2012) and Belle (2015).
- $m_{h'} < m_{A'}$: h' is long-lived and thus invisible $\Rightarrow$ 2 charged tracks
  Partially constrained by KLOE (2015).



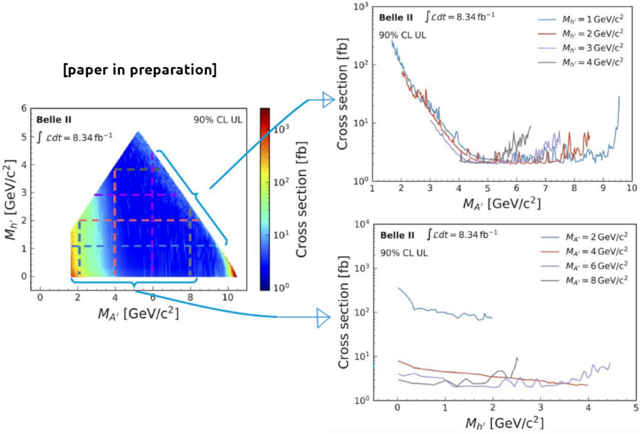
$\rightarrow$ exploring unconstrained territories at Belle II

Dark Higgsstrahlung

- » **New result from Belle II using 8.34 fb^{-1}**
  - upper limits are set on σ and $\epsilon^2 \alpha_D$
  - covered region of masses $1.65 < M_{A'} < 10.51$ GeV and $M_{h'} < M_{A'}$

→ 90% CL UL on σ ranges from 1.7 to 5 fb

- » **Sensitivity**
  - $4 < M_{A'} < 9.7$ GeV the most sensitive region
  - $M_{A'} < 4$ GeV low sesitivity due to trigger efficiency
  - $M_{A'} > 9$ GeV large dimuon background



→ unique results in previously unexplored regions

The τ mass measurement

» **Lepton masses are fundamental parameters of the SM**

$$m_e = (0.5109989461 \pm 0.0000000031)\ \text{MeV}$$
$$m_\mu = (105.6583745 \pm 0.0000024)\ \text{MeV}$$
$$m_\tau = (1776.86 \pm 0.12)\ \text{MeV}$$

→ the m_τ precision impacts LFU tests!

» **Pseudomass measurement at Belle II**

- method developed by ARGUS collaboration
- measured in $\tau \to 3\pi\nu$ decay channel
- τ mass can be calculated as $(h \leftrightarrow 3\pi)$

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

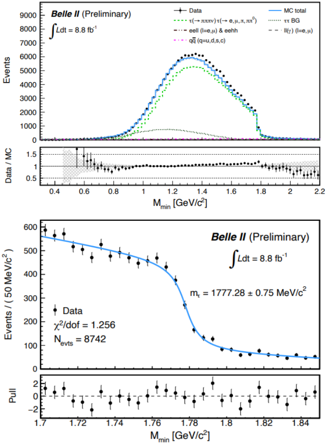
- since the direction of the neutrino is unknown, $\cos(\vec{p_h}, \vec{p_\nu}) = 1$ is taken and M_{min} is defined as

$$M_{min}^2 = 2E_h(E_\tau - E_h) + m_h^2 - 2|\vec{p_h}|(E_\tau - E_h) < m_\tau^2$$

- the M_{min} distribution is then fitted to an empirical edge function, and the position of the cutoff indicates the value of the τ mass

» **Challenges of the measurement**

- find the most accurate empirical fitting function
- properly evaluate the estimator bias



Belle II measurement from 2020

arXiv:2008.04665

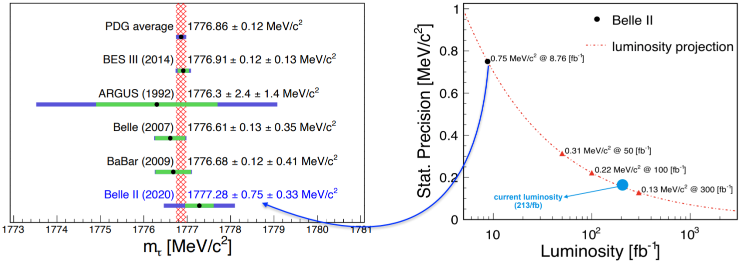
The τ mass measurement

» **The goal is to achieve best precision among pseudomass measurements**

- best measurement from pseudomass technique by Belle
- world-leading result by BES III using a different method (measurement in the production threshold)

» **Belle II measurement from 2020**

- statistically dominated and in agreement with the world average
  → we will match the statistical precision of Belle/BaBar with 300 fb^{-1}
- systematic uncertainty at the level of Belle
  → we expect significant reduction in the main systematic uncertainties and further improvements of reconstruction efficiency



Tau mass poster (TAU2021)

The τ lifetime measurement

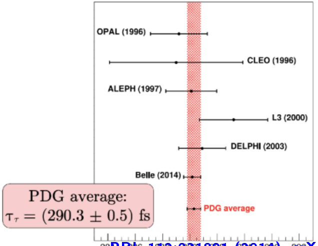
» **Important SM parameter**

- its precision affects LFU measurements, $\alpha_s(m_\tau)$, etc.

» **World-leading measurement by Belle**

- uses a 3×3 topology, with both tau leptons decaying to $3\pi\nu$

$$\tau_\tau = 290.17 \pm 0.53(\text{stat}) \pm 0.33(\text{syst})\ \text{fs}$$

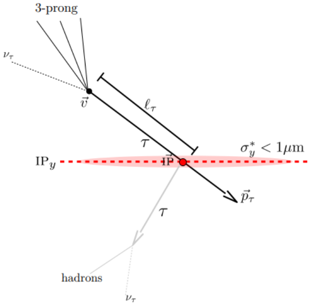


PRL 112:031801 (2014), arXiv:1310.8503

» **Belle II approach**

1. reconstruct vertex for 3-prong τ
   - only one 3-prong τ $\rightarrow$ higher statistics
2. estimate the τ momentum
   - hadronic decays in both sides
3. find the production vertex
   - intersection of τ momentum with the plane IPy

$\rightarrow$ possible due to the tiny beamspot size at the IP at Belle II



» **Greatest challenge of this method**

- the τ momentum estimation and reconstruction of the production vertex

The τ lifetime measurement

- **Belle II MC measurement**

  $$\tau_\tau = 287.2 \pm 0.5(\text{stat})\ \text{fs}$$

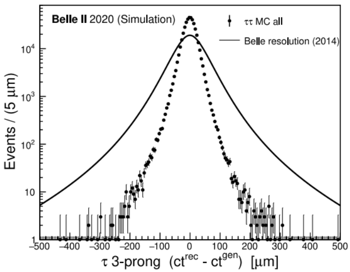
→ competitive statistical precision was reached already with 200 fb^{-1} (compared to 711 fb^{-1} used at Belle)

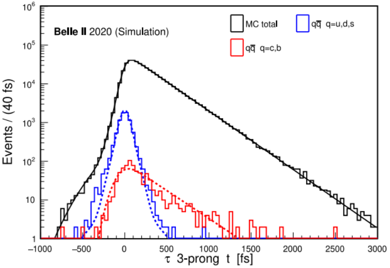
→ the resolution at Belle II is nearly 2× narrower than at Belle

- **The measured lifetime presents $\simeq$ 3 fs bias** (generated value: 290.57 fs)
  - ISR/FSR losses → underestimation of the proper time
  - an intrinsic bias in the measurement

- **Further studies to estimate systematics**
  - test dependence on the resolution function in the fit
  - beam-spot position
  - ISR/FSR simulation
  - vertex detector alignment (dominant systematic uncertainty at Belle)

Tau lifetime poster (TAU2021)





Lepton flavour universality in τ decays

» **Three lepton generations:** e, μ, τ

- different masses
- different and separately conserved lepton numbers
- the coupling of leptons to W bosons is flavour-independent, $g_e = g_\mu = g_\tau$

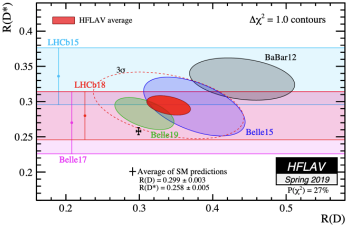
→ This is the SM picture of leptons, however various experimental results presented in the past years suggest LFU violation!

» **Anomalies in quark sector**

- $R(D) - R(D^*)$ plane (3.1σ),
- $R(K)$ (3.1σ), also P_5' in $B \to K^* \mu^+ \mu^-$ (3.4σ)
- and more..!

» **Significant tensions in lepton sector**

- anomalous magnetic moment of μ (4.5σ) and e (2.5σ)



» **LFU tests with τ decays**

- $e - \mu$ universality

$$\left(\frac{g_\mu}{g_e}\right)^2_\tau \propto \frac{BR(\tau^- \to \mu^- \bar{\nu}_\mu \nu_\tau)}{BR(\tau^- \to e^- \bar{\nu}_e \nu_\tau)}$$

- $\tau - \mu$ universality

$$\left(\frac{g_\tau}{g_\mu}\right)^2_h \propto \frac{BR(\tau \to h \nu_\tau)}{BR(h \to \mu \nu_\tau)}$$

» **Most precise measurements (BaBar)**

$$\left(\frac{g_\mu}{g_e}\right)_\tau = 1.0036 \pm 0.0020$$

→ in agreement with the SM

$$\left(\frac{g_\tau}{g_\mu}\right)_h = 0.9850 \pm 0.0054$$

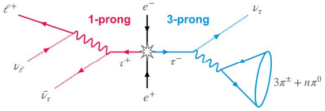
→ 2.8 σ below the SM prediction

PRL 105:051602 (2010)

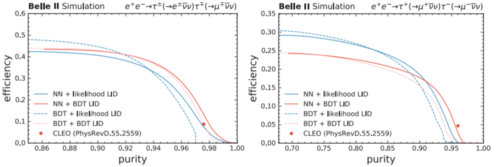
Lepton flavour universality in τ decays

» **Use 3×1-prong and 1×1-prong τ-pair events**

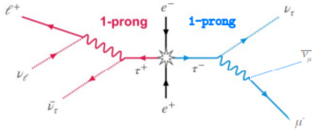
BELLE2-NOTE-PL-2021-009



- $4\times$ higher efficiency with better purity compared to BaBar for 3×1



Belle II and CLEO performance for 1×1



- 1×1 not used at BaBar but possible at Belle II thanks to the trigger performance
- better performance for $e-\mu$ and very close for $\mu-\mu$ compared to CLEO

» **Main challenges of the analysis**

- select signal with the highest possible purity
  → testing different lepton ID approaches (BDT-, likelihood-based)
  → employing MVA techniques (NN, BDT)
- reduce the LID systematic uncertainty
  → main systematics source at BaBar

$B \to$ charm, weak phases, forbidden decays, dark sector...

» $B \to X_c \ell \nu$ [paper in preparation]

- new measurement of the inclusive $B \to X_c \ell \nu$ with tagged method at Belle II
- novel idea: reduction of HQE parameters ($13 \to 8$) by reparametrization $\to$ [arXiv:1812.00747]

» ϕ_2 [arXiv:2107.02373]

- unique capability of Belle II to study all the $B \to \pi\pi, \rho\rho$ decays to determine phase ϕ_2 (α)
- 20% precision improvement with respect to Belle at the same luminosity

» $B^+ \to K^+ \nu \bar{\nu}$ [arXiv:2104.12624]

- probing of a FCNC decay
- novel inclusive tagging technique at Belle II $\to$ signal efficiency 4.3% (compared to at best 0.2% efficiency of the previous measurements by Belle and BaBar)

» Dark sector studies

- $e^+e^- \to \mu^+\mu^- Z', Z' \to$ invisible (0.28 fb^{-1}) $\to$ [PRL124 (2020), 141801]
- Axion-like Particle (ALP) search in $e^+e^- \to a(\to \gamma\gamma)\gamma$ (0.44 fb^{-1}) $\to$ [PRL125 (2020), 161806]

» $A_{CP}(B^0 \to K^0_S \pi^0), B^+ \to \rho^+\rho^-$ angular analysis

» electroweak penguin B decays $B \to K^* \ell^+ \ell^-$

» hadron spectroscopy (Belle II took energy scan data above $\Upsilon(4S)$ in 2021)

...and more analyses published and in progress!

Summary

» **Belle II is a B-factory of the next generation**

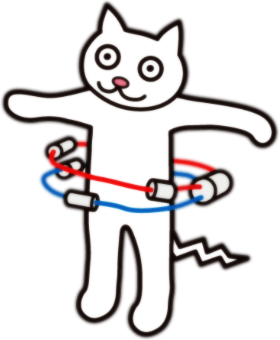
- setting peak luminosity records thanks to nano-beam scheme
- opening new possibilities for measurements thanks to upgraded trigger, vertex resolution and tracking efficiency

→ since its first collision in 2018, Belle II has collected almost 400 fb^{-1} of data

» **Belle II contributes to wide range of physics topics**

- D^0, D^+ and Λ_c^+ lifetime measurements
- B^0 lifetime and mixing frequency
- measurement of ϕ_3
- dark Higgsstrahlung
- the τ mass measurement
- the τ lifetime measurement
- lepton flavour universality in τ decays
- ...and various other topics

Stay tuned for more exciting results!



Thank you for your attention