Recent Results from Belle and Belle II

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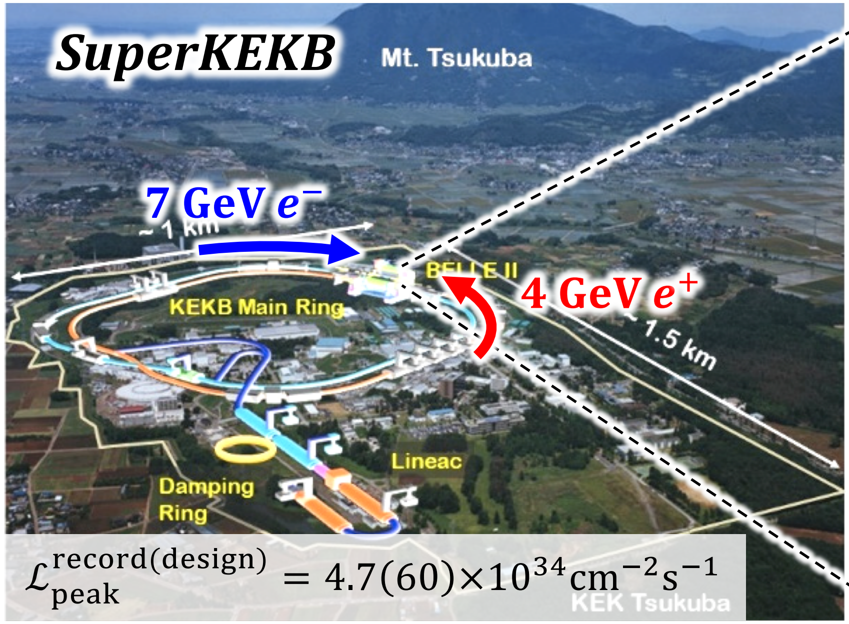
B-Factory Experiment in Japan

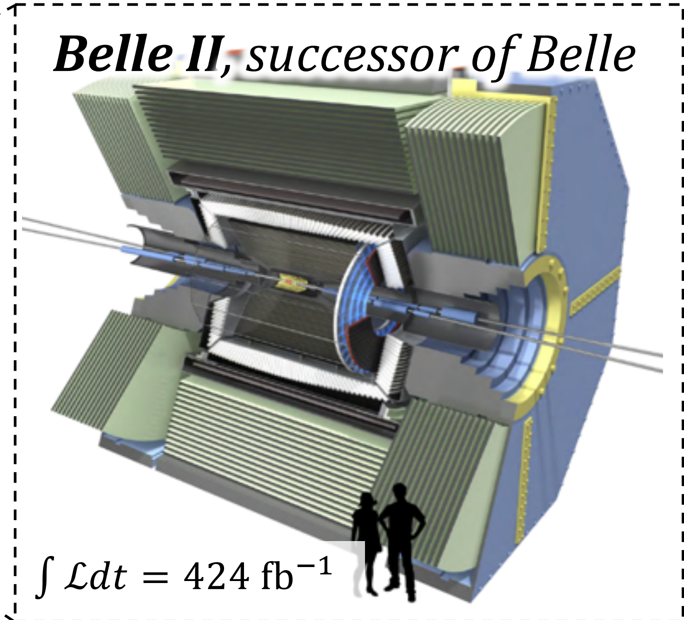
- What made the matter-antimatter asymmetry in the Universe?
- What is dark matter?
- What gave masses to the neutrinos?
- What makes the Higgs boson so light? …

New physics beyond the SM?

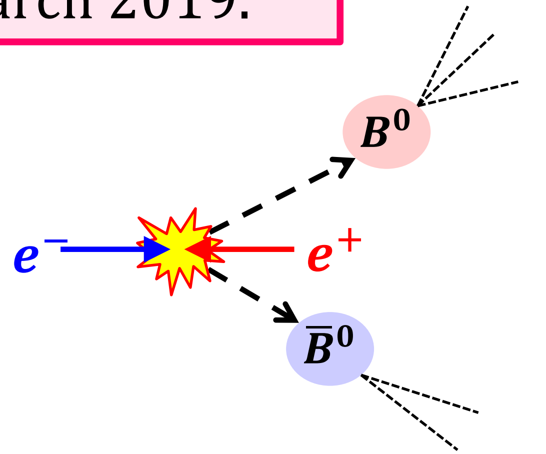
In the quest for a physics beyond the Standard Model, we started an e^+-e^- collider experiment **Belle II** in Japan in March 2019.



$\mathcal{L}_{\text{peak}}^{\text{record(design)}} = 4.7(60)\times 10^{34}\,\text{cm}^{-2}\text{s}^{-1}$



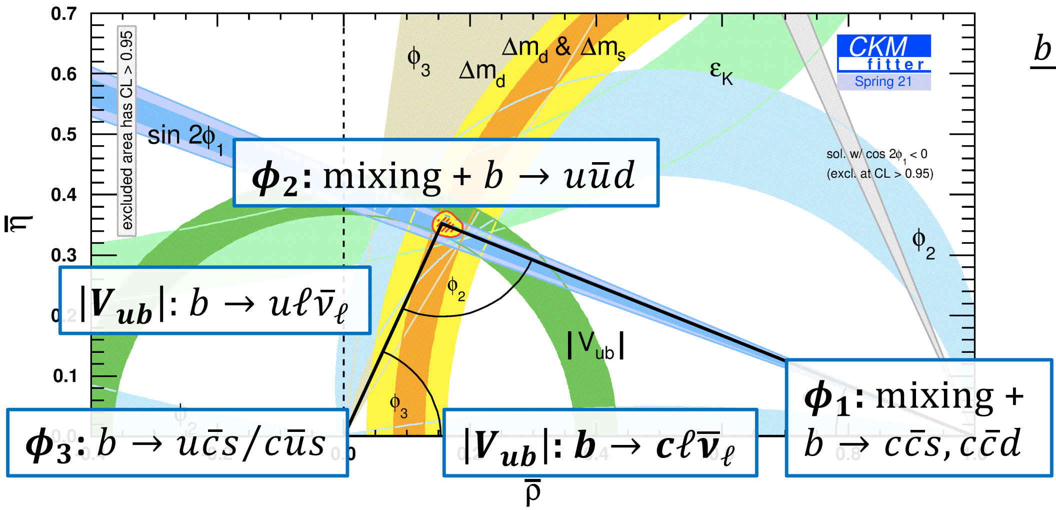
$\int \mathcal{L}dt = 424\ \text{fb}^{-1}$



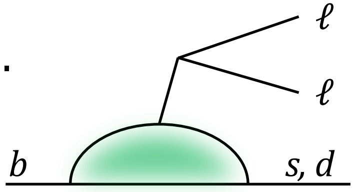
$$\begin{aligned} e^+e^- &\longrightarrow b\bar{b}\ (B^0\bar{B}^0, B^+B^-) \\ &\longrightarrow \tau^+\tau^- \\ &\longrightarrow c\bar{c}\ \ldots \end{aligned}$$

New Physics Search Programs at Belle/Belle II

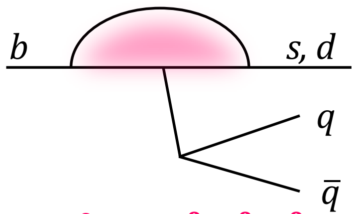
- Tests of the quark-mixing matrix unitarity
  - Precise measurements of the unitarity triangle parameters: $\phi_1, \phi_2, \phi_3, |V_{cb}|, |V_{ub}|$.



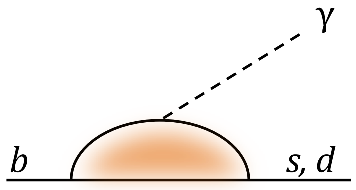
- Searches for the NP in the $b \to s, d$ loops



$B \to K^{(*)}\ell^+\ell^-$,
$B \to K\nu\bar{\nu}$, ...



$B^0 \to K_S^0 K_S^0 K_S^0$,
$B^0 \to \phi K_S^0$, ...



$B^0 \to K^*\gamma$,
$B^0 \to \rho^0\gamma$, ...

- Measurements of charm properties
- Spectroscopy of quarkonia
- Studies on exotic hadron properties, ...

- Tests of the lepton flavor universality
- Searches for LFV'ing τ decays
- Searches for dark sector particles

26 new results in 2022 only, and several of them are already world leading. Highlights of the new and recent results are presented for today.

New for summer 2022

Belle II 190 fb^{-1}

ϕ_1 Measurement

Time-dependent decay rate (time-dependent *CP* violation)

$$\Gamma(\Delta t, q; B_{CP} \to f_{CP}) \propto \exp\left(-\frac{|\Delta t|}{\tau_{B^0}}\right)[\mathcal{A}\cos(\Delta m_d \Delta t) + q\mathcal{S}\sin(\Delta m_d \Delta t)]$$

- Δt … signed difference of the two B decay times
- q … flavor of the B: $B^0(q{=}-1)$ or $\bar{B}^0(q{=}+1)$

τ_{B^0}: B^0 lifetime

Δm_d: B^0-$\bar{B}^0$ mixing

$\mathcal{A}$: direct CPV

$\mathcal{S}$: mixing-induced CPV

$\mathcal{S} = \sin 2\phi_1$ in the SM for $b \to c\bar{c}s$

Analysis procedure validation

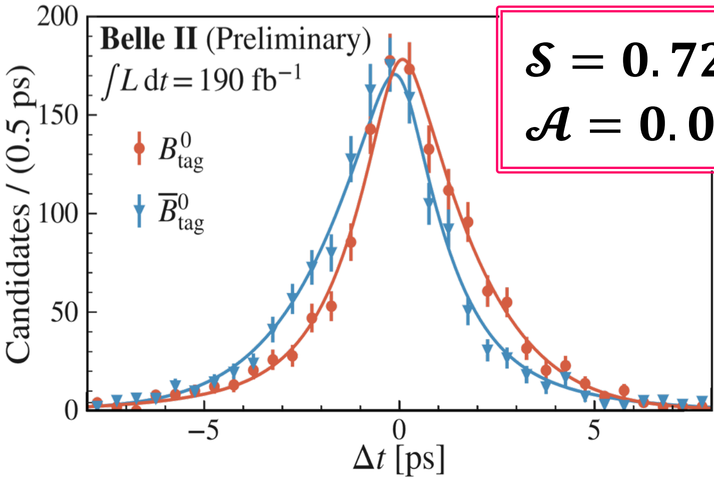
- Apply the analysis procedure to $B \to D^{(*)}h$.
- Extract τ_{B^0} and Δm_d from the $(\Delta t, q)$ distribution.

$\boldsymbol{\tau_{B^0} = 1.499 \pm 0.013 \pm 0.008}$

$\boldsymbol{\Delta m_d = 0.516 \pm 0.008 \pm 0.005}$ **(ps^{-1})**

… consistent with the WA

$\mathcal{S}$ and $\mathcal{A}$ in $B^0 \to J/\psi K_S^0$ $(b \to c\bar{c}s)$



$\boldsymbol{\mathcal{S} = 0.720 \pm 0.062 \pm 0.016}$

$\boldsymbol{\mathcal{A} = 0.094 \pm 0.044^{+0.042}_{-0.017}}$

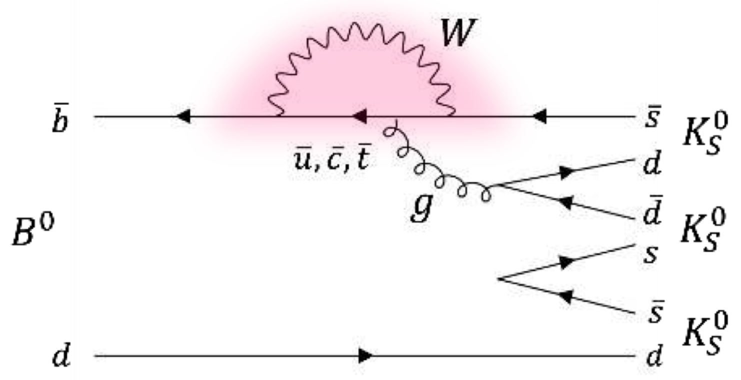
$\sigma_{\rm syst}^{\rm Belle\ II} < \sigma_{\rm syst}^{\rm Belle}$ for Belle 140 fb^{-1} $(c\bar{c})K^0$ analysis, thanks to improved vertex resolution.

$\phi_1^{sq\bar{q}}$ Measurement

New for summer 2022

Belle II 189 fb^{-1}

- $\mathcal{S}$ for $b \to sq\bar{q}$ is approximately the same as $\sin 2\phi_1$ since no CP-violating phase exists in the least-order $b \to sq\bar{q}$ diagram.
- $\mathcal{S}$ may change from the SM-predicted value due to a possible NP effect that may appear in the $b \to sq\bar{q}$ loop.



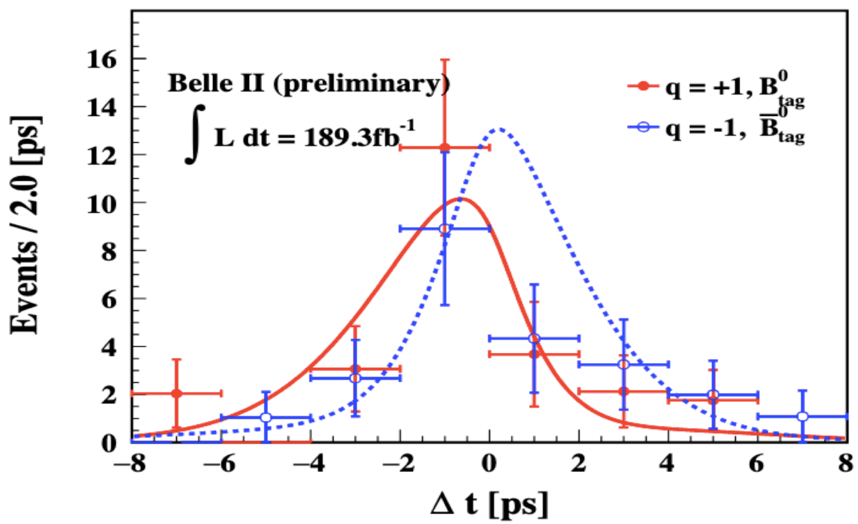
Measurement of $\mathcal{S}$ and $\mathcal{A}$ for $B^0 \to K_S^0 K_S^0 K_S^0$

- The SM predicts that $\mathcal{S}$ for $B^0 \to K_S^0 K_S^0 K_S^0$ (mediated by $b \to sd\bar{d}$) is $\mathcal{S}_{K_S^0 K_S^0 K_S^0} = -\sin 2\phi_1 + 0.024^{+0.007}_{-0.018}$.

H. Cheng, C. Chua, and A. Soni, Phys. Rev. D **72**, 094003 (2005)

- Events with poorly reconstructed Δt are not just rejected but used for the $\mathcal{A}$ determination.

$$\mathcal{S}_{CP} = -1.86 \pm 0.83 \pm 0.09$$
$$\mathcal{A}_{CP} = -0.22 \pm 0.29 \pm 0.04$$



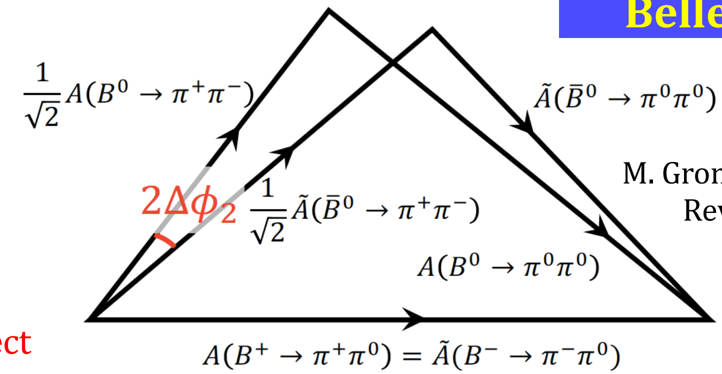
$\mathcal{A}_{\pi\pi}$ Measurement

New for summer 2022

Belle II 189 fb^{-1}

- $\mathcal{A}_{\pi\pi}$ ($B \to \pi\pi$ mediated by $b \to u\bar{u}d$ tree) is an essential input to determine ϕ_2.
  - $S_{\pi\pi} = -\eta_{CP}\sqrt{1-\mathcal{A}^2_{\pi\pi}}\sin(2\phi_2 + 2\Delta\phi_2)$.

    $b \to d u \bar{u}$ loop effect



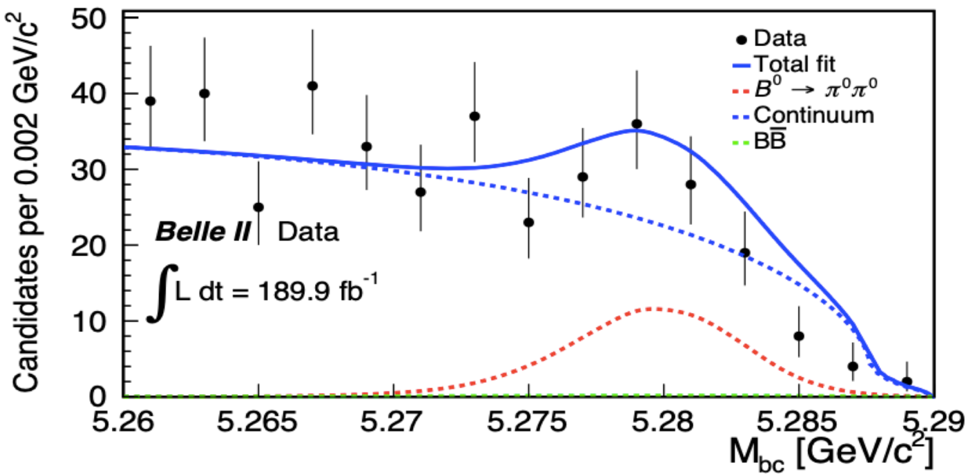
M. Gronau and D. London, Phys Rev. Lett. **65**, 3381 (1990).

$\mathcal{A}_{\pi^0\pi^0}$ and $\mathcal{B}r(B^0 \to \pi^0\pi^0)$ measurement

- All neutrals suitable for Belle II.
- Reconstruct γ with a FastBDT

  → $\varepsilon_{\text{Belle II}}$ = **35.5%** > $\varepsilon_{\text{Belle}}$ = 22%.
- Signal extraction by a 3D fit to ΔE, M_{bc}, and FastBDT output distributions.
  - $\Delta E \equiv E^{\text{CMS}}_{B-\text{cand}} - \sqrt{s}/2,$

    $M_{bc} \equiv \sqrt{\frac{s}{4} - \left(p^{\text{CMS}}_{B-\text{cand}}\right)^2}$



$$\mathcal{A}_{\pi^0\pi^0} = +0.14 \pm 0.46 \pm 0.07$$
$$\mathcal{B}r(B^0 \to \pi^0\pi^0) = (1.27 \pm 0.25 \pm 0.17)\times 10^{-6}$$

Similar σ^{stat} to Belle already with only ¼ of the Belle data size

ϕ_3 Measurement

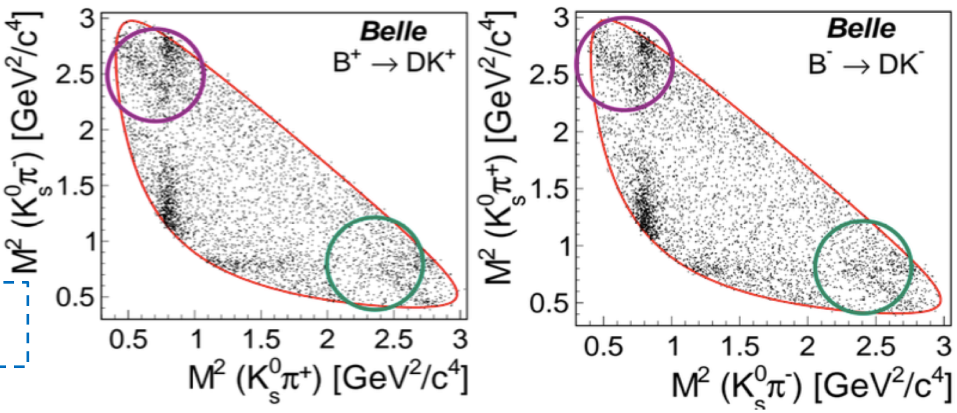
Belle 711 fb^{-1}
Belle II 128 fb^{-1}

Belle and Belle II, JHEP **02**, 063 (2022)

ϕ_3 measurement with $B^+ \to D(K_S^0 h^+ h^-)K^+$

- ϕ_3 with r_B^{DK} and δ_B^{DK} manifests itself in the difference of the Dalitz distributions $(m_-^2, m_+^2) \equiv (m_{K_S^0 h^-}^2, m_{K_S^0 h^+}^2)$ between B^+ and B^-.

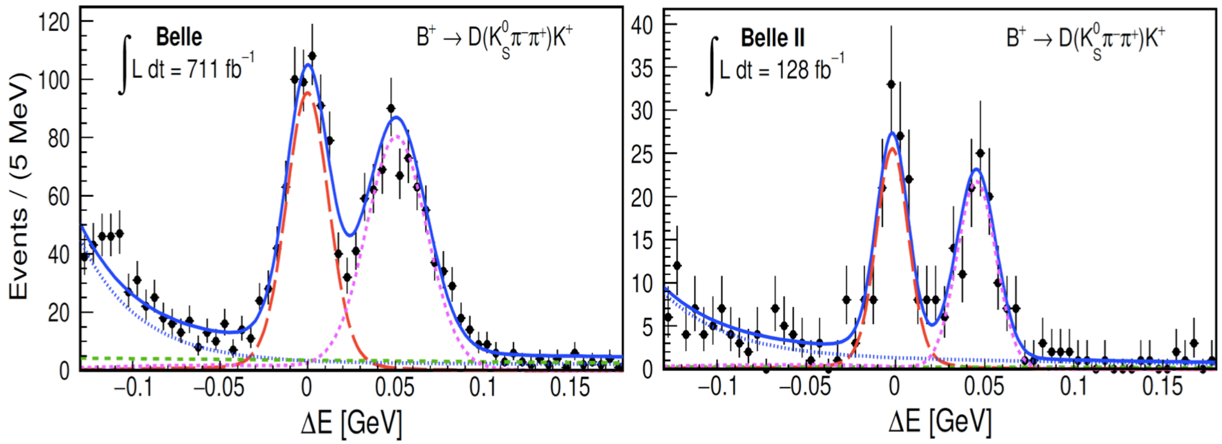
$$A_{B^+}(m_-^2, m_+^2) \propto A_{\bar{D}}(m_-^2, m_+^2) + r_B^{DK} e^{i(\delta_B^{DK} - \phi_3)} A_D(m_-^2, m_+^2)$$



Belle + Belle II combined analysis

- Improvements to the last Belle analysis [Belle, Phys. Rev. D **85**, 112014 (2012)]:
  - NN-based MVA for K_S^0 reconstruction.
  - Additional statistics from $D \to K_S^0 K^+ K^-$ on top of $D \to K_S^0 \pi^+ \pi^-$.
  - Improved BG rejection method.

Yield increase by 40% for Belle and additional 17% statistics from Belle II.



$$\boldsymbol{\phi_3 = (78.4 \pm 11.4 \pm 0.5 \pm 1.0)^\circ}$$

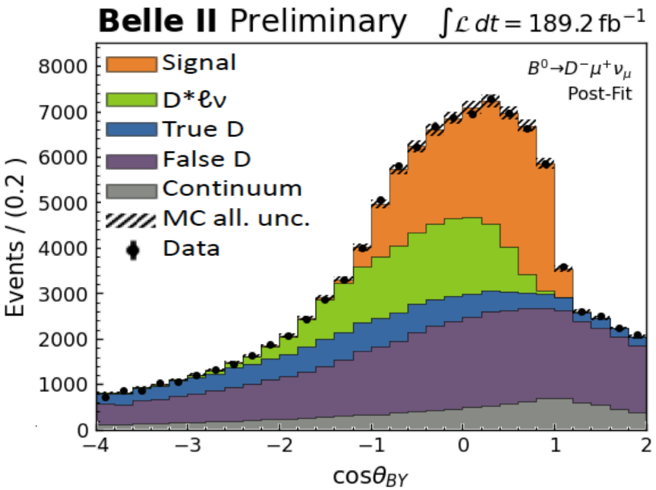
The third error arises from the uncertainty in the input from BESIII.

$|V_{cb}|$ Measurement

New for summer 2022
Belle II 189 fb^{-1}

Event reconstruction

- $B^0 \to D^-(K^+\pi^-\pi^-)\ell^+\nu_\ell$,
  $B^+ \to \overline{D}^0(K^+\pi^-)\ell^+\nu_\ell$.
- $e^+e^- \to q\bar{q}$ and combinatorial BG rejection by event shape and energy cuts.

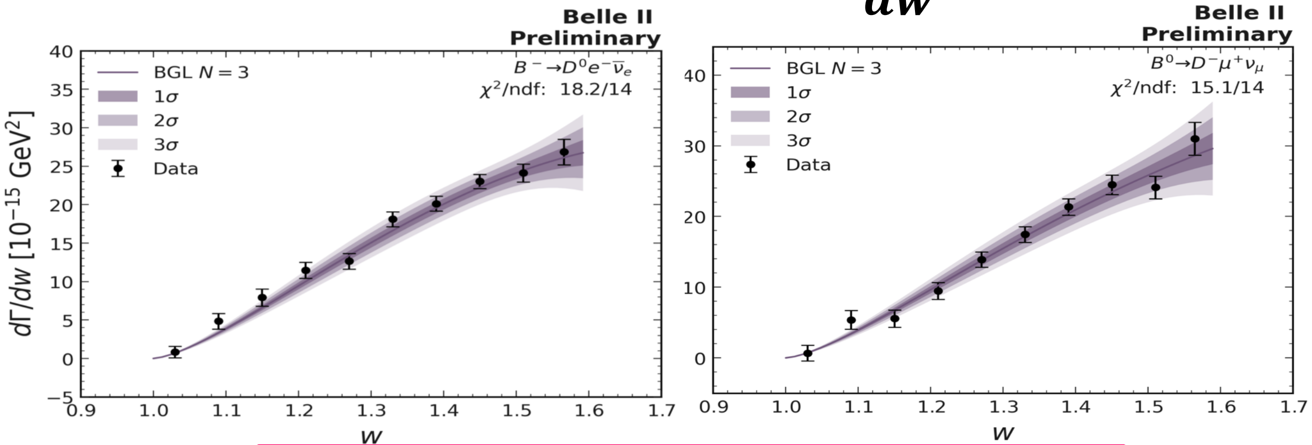


Signal extraction with the cosine angle distribution between the B and $(D\ell)$ systems.

D recoil momentum q^2 calculation

- Obtain q^2 by inferring the $\vec{p}_B$ with the *diamond-frame* approach.
- Transfer the $q \to w \equiv (m_B^2 + m_D^2 - q^2)/2m_B m_D$.
- Split the w distributions into 10 bins.

$|V_{cb}|$ **exclusive extraction:** $\dfrac{d\Gamma(w)}{dw} \propto \eta_{EW}|V_{cb}|^2$



$$\eta_{EW}|V_{cb}| = (38.53 \pm 1.15)\times 10^{-3}$$

… consistent with the exclusive WA

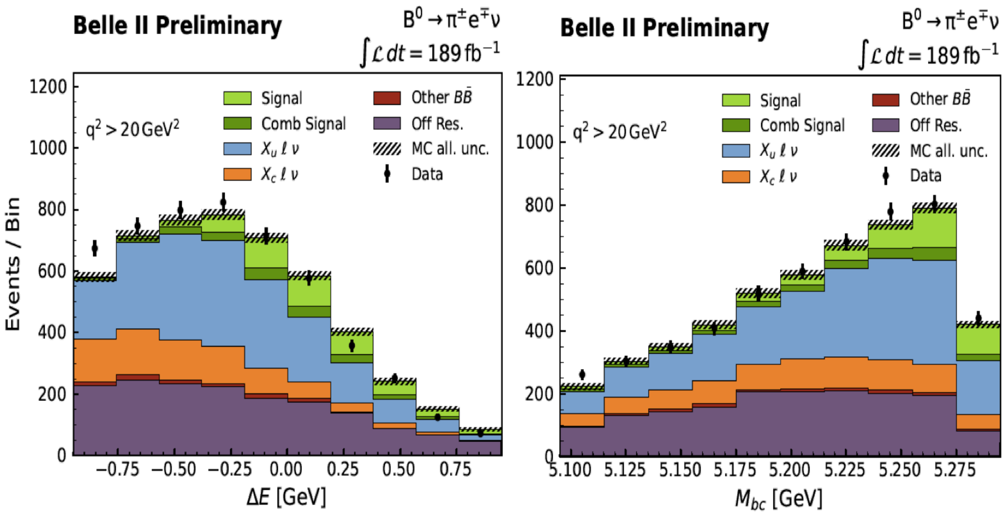
$|V_{ub}|$ Measurement

New for summer 2022

Belle II 189 fb^{-1}

Event reconstruction

- $B^0 \to \pi^- \ell^+ \nu_\ell$.
- $e^+e^- \to q\bar{q}$ and combinatorial BG rejection with a BDT.

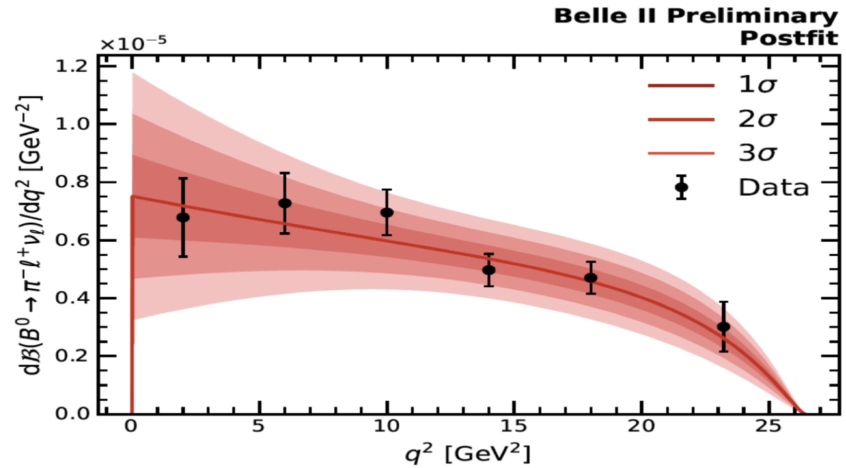


Signal extraction with the 2D distribution of the ΔE and M_{bc}.

Recoil momentum q^2 calculation

- Obtain q^2 by inferring the $\vec{p}_B$ with a modified *diamond-frame* approach.
- Split the q^2 distribution into 6 bins.

$|V_{ub}|$ exclusive extraction: $\frac{d\Gamma(q^2)}{dq^2} \propto |V_{ub}|^2$



$$|V_{ub}|_{\pi^-\ell^+\nu_\ell} = (3.54 \pm 0.12 \pm 0.15 \pm 0.16) \times 10^{-3}$$

... consistent with the WAs

Test of the LFU $(b \to c\ell\nu_\ell)$

New for summer 2022

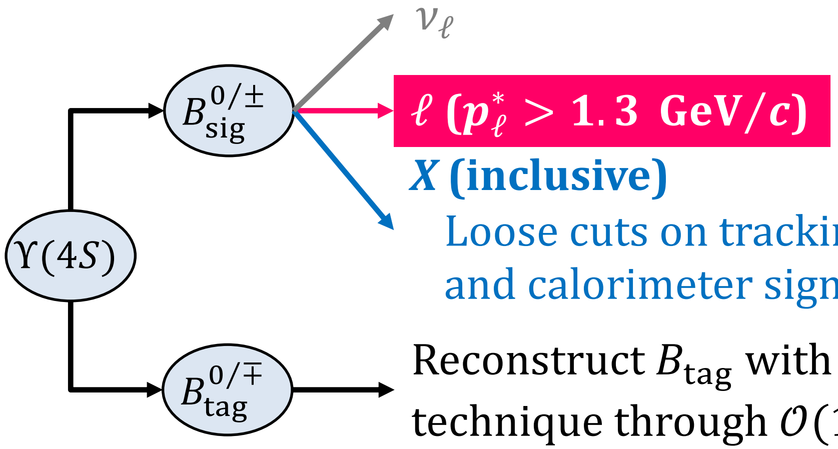
Belle II 189 fb^{-1}

$$\boldsymbol{R(X_{e/\mu}) \equiv \mathcal{B}r(B \to X e \nu_\mu)/\mathcal{B}r(B \to X \mu \nu_e)}$$

- The $R(X_{e/\mu})$ measurement complements the LFU tests made using $R(D), R(D^*)$.
  - SM prediction: $R(X_{e/\mu}) = 1 + \mathcal{O}(10^{-3})$.

C. Bobeth et al., Eur. Phys. J. C **81**, 984 (2021)

Event reconstruction



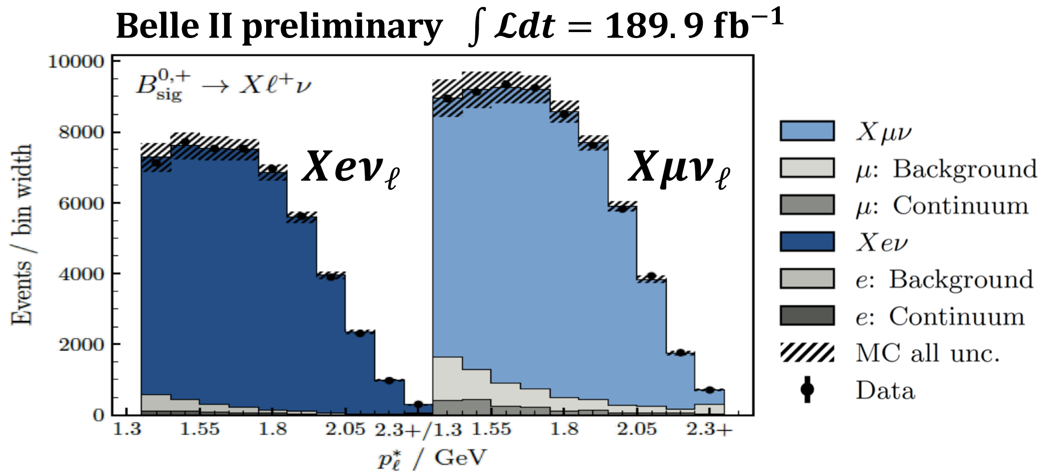
Loose cuts on tracking detector and calorimeter signals.

Reconstruct $B_{\rm tag}$ with multivariate technique through $\mathcal{O}(10^3)$ modes.

- EID utilizes calorimeter shower shapes; MuID utilizes all PID detector information.

Signal extraction with p_ℓ^*

- Prepare p_ℓ^* distribution template for each of $(X\ell\nu_\ell, q\bar{q}$, other BG$) \times (\ell{=}e, \ell{=}\mu)$.
- Obtain the $X\ell\nu_\ell$ yields by a simultaneous binned likelihood fit of the e and μ templates to individual p_ℓ^* distributions.



$$\boldsymbol{R(X_{e/\mu}) = 1.0333 \pm 0.010 \pm 0.020}$$

First inclusive test of (e/μ) LFU in $B \to X\ell\nu_\ell$.

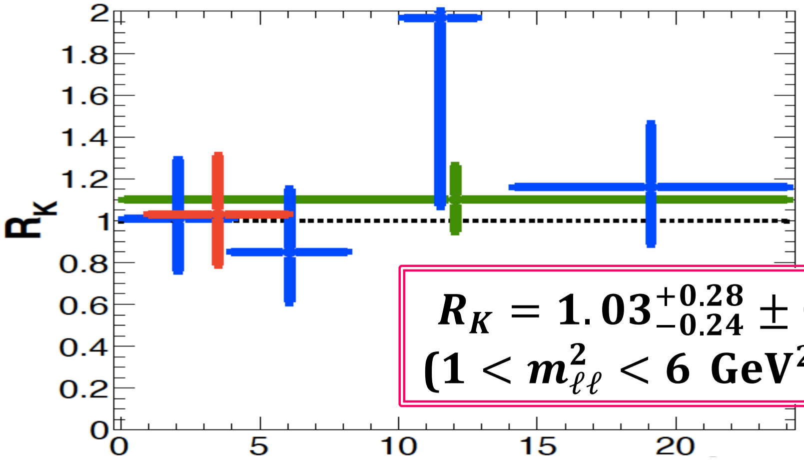
Test of the LFU $(b \to s\ell\ell)$

Belle 711 fb^{-1}

711 fb^{-1}; JHEP 03, 105 (2021)

$R_K \equiv \mathcal{B}r(Ke^+e^-)/\mathcal{B}r(K\mu^+\mu^-)$ update

- $B^0 \to K_S^0(\pi^+\pi^-)\ell^+\ell^-$, $B^+ \to K^+\ell^+\ell^-$
- Signal extraction with 3D ΔE-M_{bc}-NN.



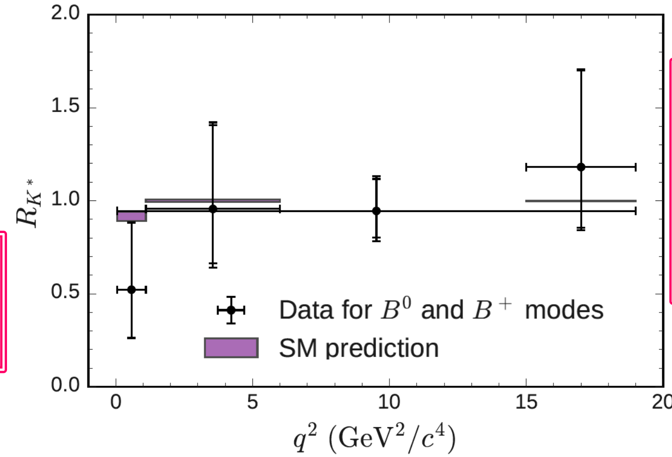
$$R_K = 1.03^{+0.28}_{-0.24} \pm 0.01$$
$$(1 < m^2_{\ell\ell} < 6\ \mathrm{GeV}^2/c^4)$$

Belle 711 fb^{-1}

711 fb^{-1}; PRL **126**, 161801 (2021)

$R_{K^*} \equiv \mathcal{B}r(K^*e^+e^-)/\mathcal{B}r(K^*\mu^+\mu^-)$ update

- $B^0 \to K^{*0}(K^+\pi^-, K_S^0\pi^0)\ \ell^+\ell^-$,
  $B^+ \to K^{*+}(K^+\pi^0, K_S^0\pi^+)\ell^+\ell^-$
- Signal extraction with M_{bc}.



$$R_{K^*} = 0.96^{+0.45}_{-0.29} \pm 0.11$$
$$R_{K^{*0}} = 1.06^{+0.63}_{-0.38} \pm 0.14$$
$$R_{K^*-\mathrm{all}} = 0.72^{+0.99}_{-0.44} \pm 0.15$$

... consistent with the SM

The first result for $R_{K^{*+}}$

Belle II 189 fb^{-1}

arXiv:2206.05946

- Belle II measured the $\mathcal{B}r$ for $B \to K^*\ell^+\ell^-$ as the preparation for the R_{K^*} measurements.

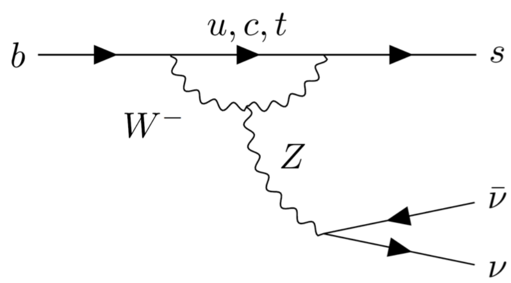
$$\mathcal{B}r(B \to K^*\mu^+\mu^-) = \left(1.19 \pm 0.31^{+0.08}_{-0.07}\right)\times 10^{-6}$$
$$\mathcal{B}r(B \to K^*e^+e^-) = (1.42 \pm 0.48 \pm 0.09)\times 10^{-6}$$

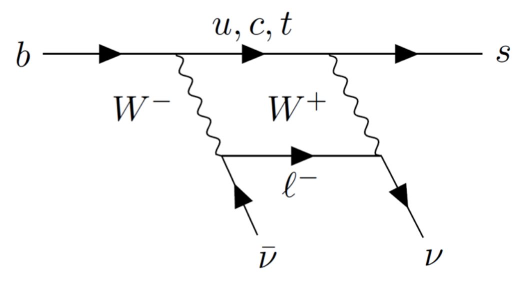
$\mathcal{B}r(B^+ \to K^+ \nu\bar{\nu})$ Measurement

Belle II $(63+9)\ \mathrm{fb}^{-1}$

Phys. Rev. Lett. **127**, 181802 (2021)

- The SM predicts of $\mathcal{B}r(B^+ \to K^+ \nu\bar{\nu})$ $= (4.6 \pm 0.5)\times 10^{-6}$.
  T. Blake *et al.*, Prog. Part. Nucl. Phys. **92**, 50 (2017)
- No evidence of signal is observed so far, but the NP could potentially enhance the $\mathcal{B}r$.





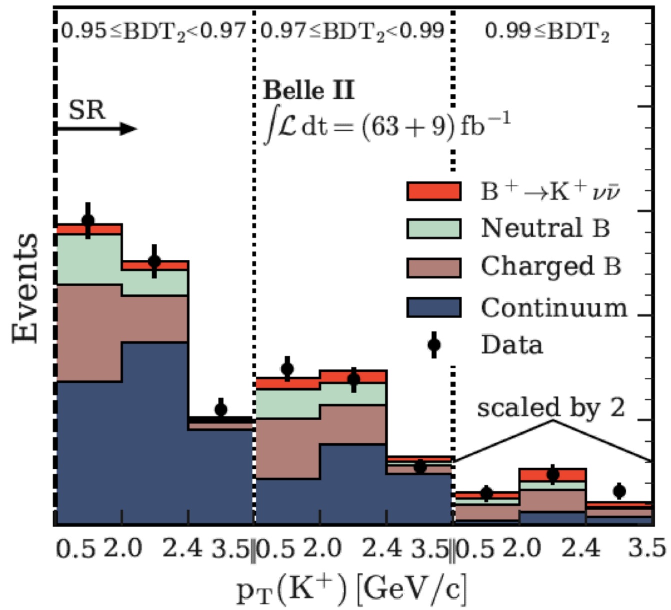
$B^+ \to K^+ \nu\bar{\nu}$ reconstruction

- The signal K^+ candidates are required to have **the largest p_T in the event**, and good PID.
- ×2 FastBDTs are developed for signal event extraction:
  - BDT_1 for the event selection (BDT_1>0.9).
  - BDT_2 for background suppression (see →)

$$\mathcal{B}r(B^+ \to K^+ \nu\bar{\nu}) = \left(1.9^{+1.3}_{-1.3}{}^{+0.8}_{-0.7}\right)\times 10^{-5}$$

4.1×10^{-5} @ 90% CL

... no signal excess above the expected BG



Charmed-Baryon Lifetime Measurement

New for summer 2022
Belle II 207 fb^{-1}

arXiv:2208.08573, to appear in PRD(L)

Debate on the charmed-baryon lifetimes

- The hierarchy of the charmed-baryon lifetimes, recently measured by LHCb, is different from old measurements. It suggests a revision of the higher order correction of the HQE.

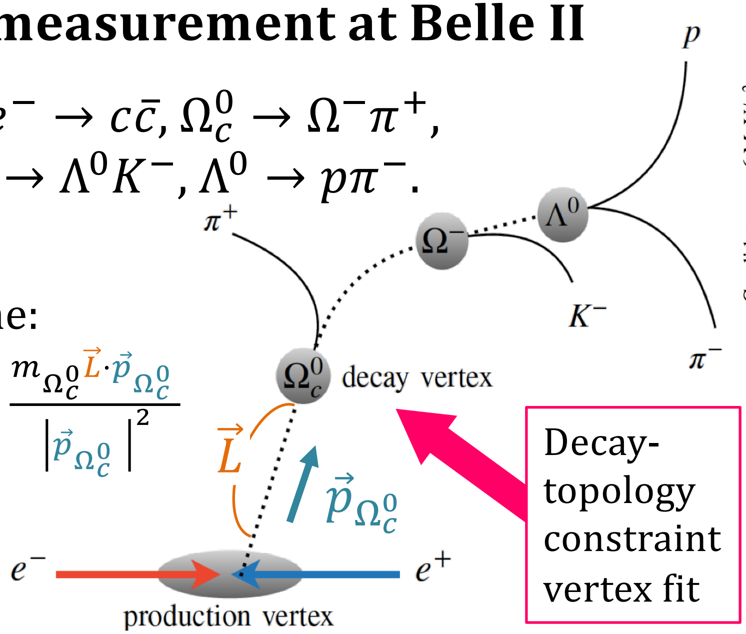
Pre-LHCb		From LHCb results
$\tau_{\Omega_c^0} < \tau_{\Xi_c^0} < \tau_{\Lambda_c^+} < \tau_{\Xi_c^+}$	$\neq$	$\tau_{\Xi_c^0} < \tau_{\Lambda_c^+} < \tau_{\Omega_c^0} < \tau_{\Xi_c^+}$

$\tau_{\Omega_c^0}$ measurement at Belle II

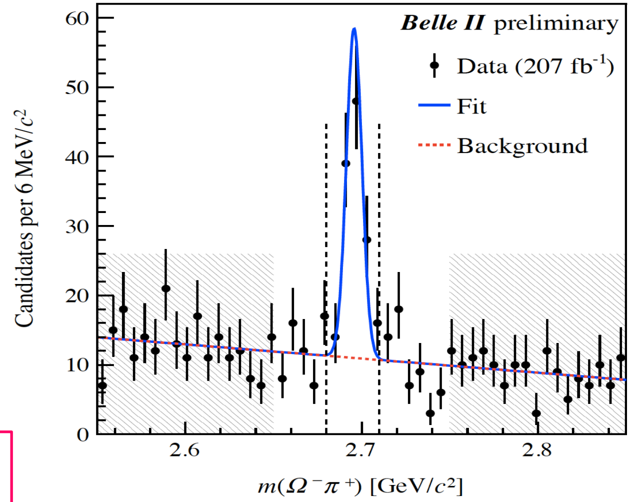
- $e^+e^- \to c\bar{c}, \Omega_c^0 \to \Omega^-\pi^+$, $\Omega^- \to \Lambda^0 K^-, \Lambda^0 \to p\pi^-$.

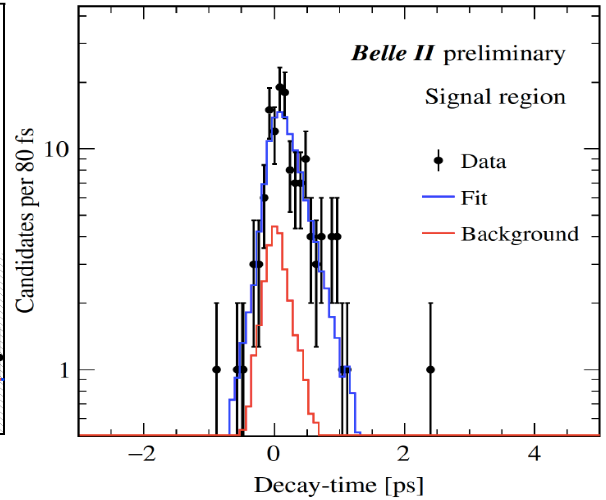
Decay time:

$$t = \frac{m_{\Omega_c^0} \vec{L} \cdot \vec{p}_{\Omega_c^0}}{\left|\vec{p}_{\Omega_c^0}\right|^2}$$



Decay-topology constraint vertex fit





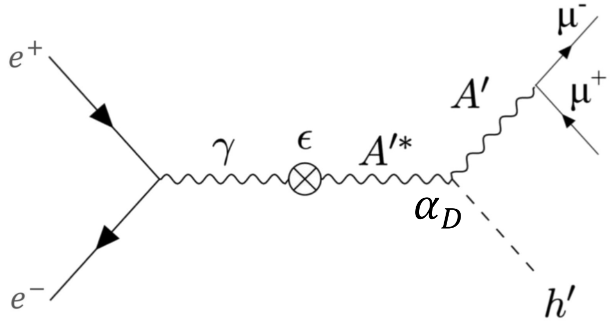
$$\tau_{\Omega_c^0} = (243 \pm 48 \pm 11)\ \text{fs}$$

... Belle II confirms the LHCb results

Dark-Sector Particle Search (A', h')

Belle II $8.34\ \mathrm{fb}^{-1}$

arXiv:2207.00509



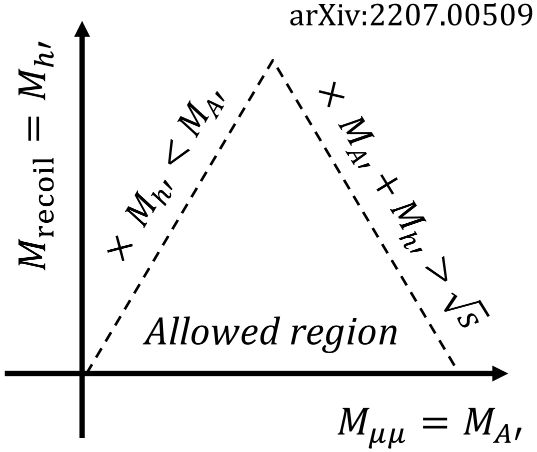
- Dark photon A'
  - Couples to the SM particles via kinetic mixing parameter ϵ.
- Dark Higgs h'
  - Couples to A' with α_D
  - Does not mix with the SM Higgs.

Mass hierarchy scenarios

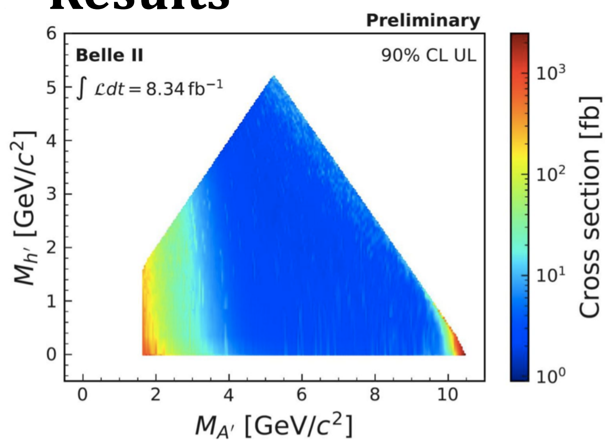
- $M_{h'} > M_{A'}$: $h' \to A'A'$ is possible
  $\Rightarrow$ event signature is 6 charged tracks.
- $M_{h'} < M_{A'}$: h' is long-lived (invisible)
  ↑ this work.

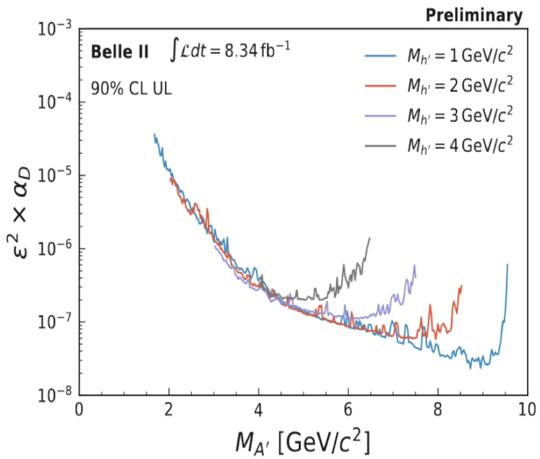
Event signature

- 2 oppositely charged muons + missing energy.
- Scan the event in 9k connected scan windows in the allowed region.



Results





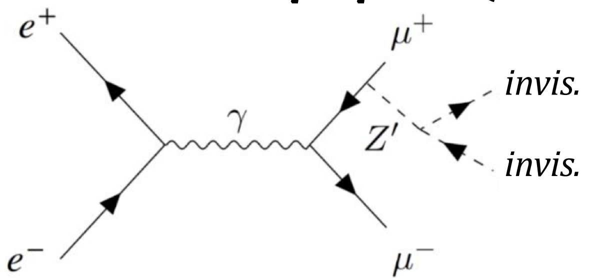
World leading limits on $\epsilon^2 \times \alpha_D$ for $1.65 < M_{A'} < 10.51\ \mathrm{GeV}/c^2$

Dark-Sector Particle Search (Z', S, ALP)

New for summer 2022

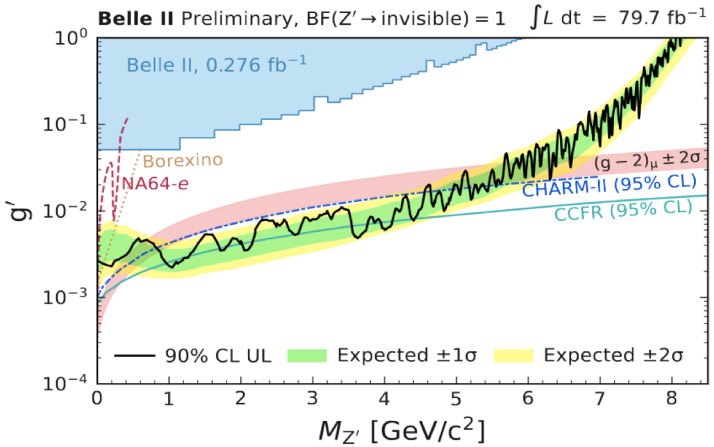
Belle II $79.7\ \text{fb}^{-1}$

$e^+e^- \to \mu^+\mu^- Z'(\to \text{invisible})$



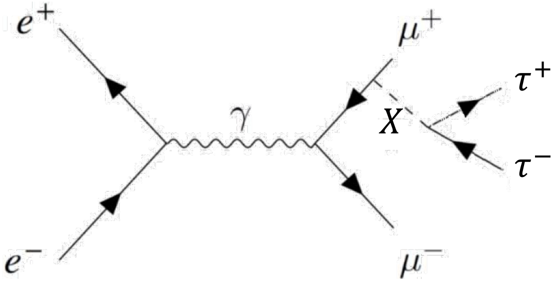
Z' … new gauge boson that couples only to τ, μ

- Use 2 oppositely charged tracks.
- Search for an $M_{\text{recoil}}^{\mu\mu}$ peak.



First exclsion of Z' from a candidate explaining the $(g-2)_\mu$ anomaly for $0.8 < M_{Z'} < 5\ \text{GeV}/c^2$.

$e^+e^- \to \mu^+\mu^- X(\tau^+\tau^-);\ X = S, ALP$



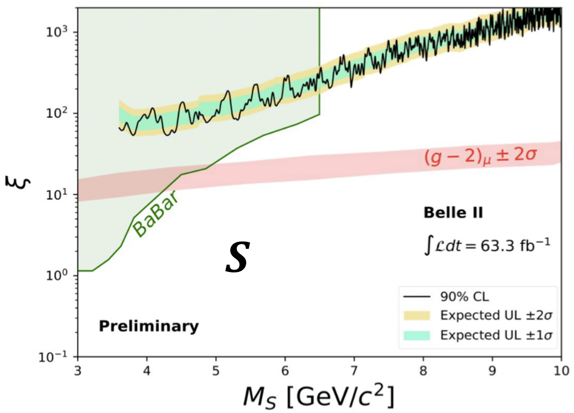
S … new scalar particle that makes only Yukawa coupling to leptons

ALP … axion-like particle

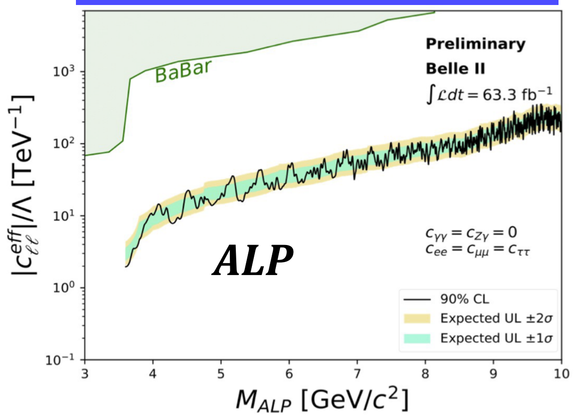
- Use 4 tracks: $2\mu + 2(e, \mu, \pi)$ (from τ).
- Fit for a signal in $M_{\text{recoil}}^{\mu\mu}$.

New for summer 2022

Belle II $63.3\ \text{fb}^{-1}$



First constraint on S for $M_S > 6.5\ \text{GeV}/c^2$



First direct constraint on $ALP \to \tau\tau$

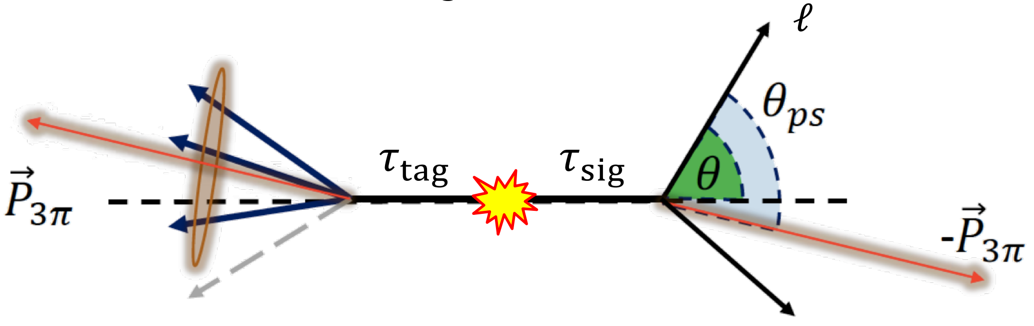
New for summer 2022

Belle II $62.8\ \mathrm{fb}^{-1}$

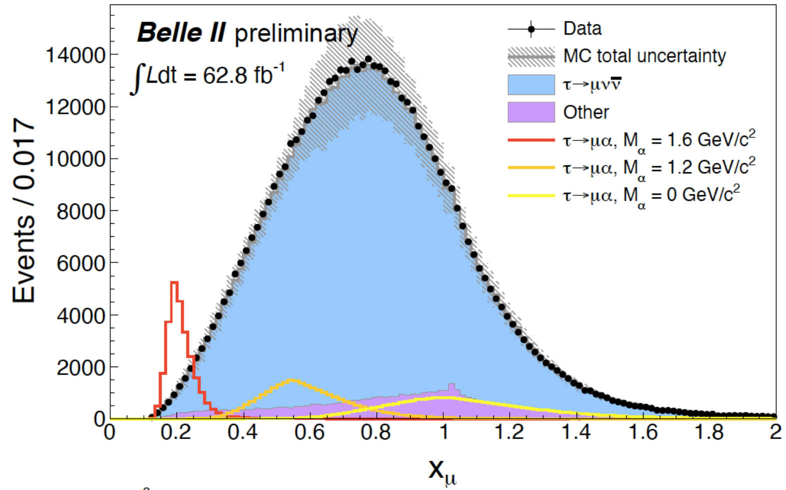
Search for $\tau^+ \to \ell^+\alpha$ (α = invisible boson)

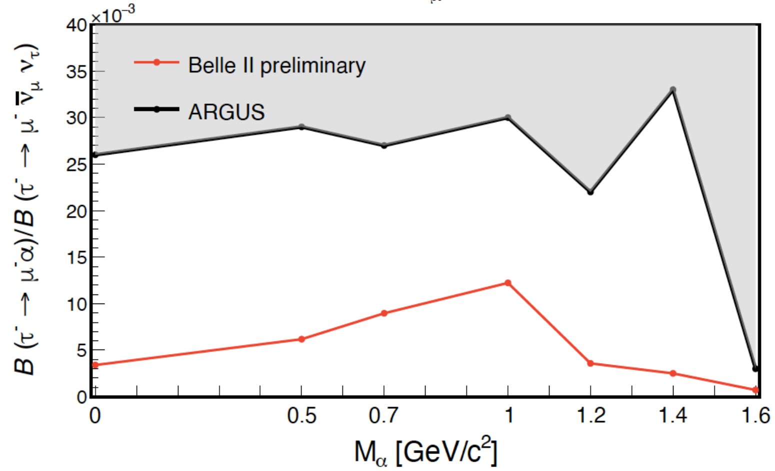
$\tau^+ \to \ell^+\alpha$ search reconstruction

- Search for $\tau \to \ell\alpha$ in events with 1 + 3 charged tracks ($\tau_{\text{sig}} \to \ell\alpha + \tau_{\text{tag}} \to 3\pi\nu$) and zero γ or π^0.
- The event signature is a peak in the $x_\ell \equiv E_\ell/2m_\tau$ distribution in the τ_{sig} rest frame.
  - A pseudo rest-frame for τ_{sig} is reconstructed from the $\vec{p}_{3\pi}$ of the τ_{tag} decay.



$$(E_{\text{pseudo}}, \hat{p}_{\text{pseudo}}) = \left(\frac{E_{\text{beam}}}{2}, \frac{\sum_{3\pi}\vec{p}}{|\sum_{3\pi}\vec{p}|}\right)$$

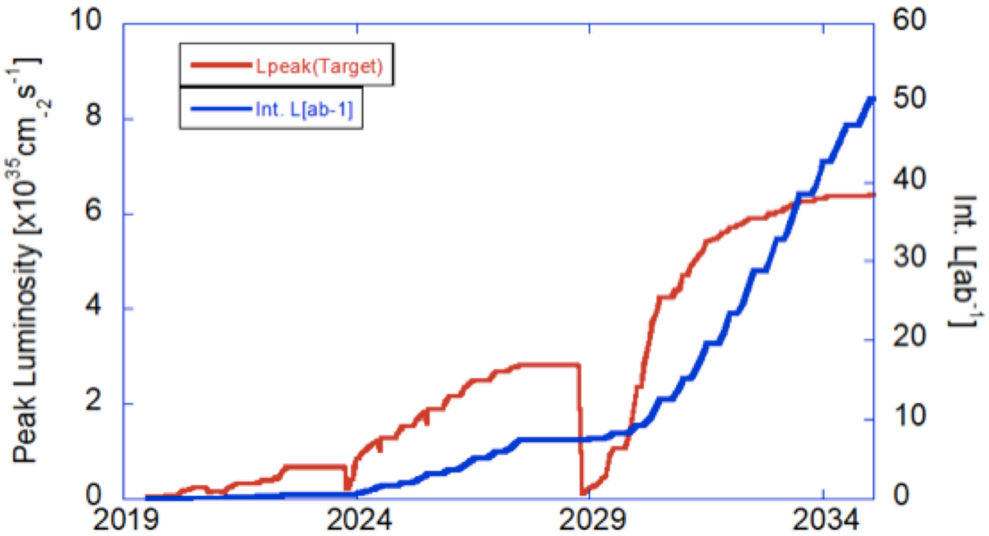




Most stringent UL constraint on the $\mathcal{Br}$ ratio to date

Belle II Operational Prospects

- Belle II has collected 424 fb^{-1} data.
- The Belle II operation is suspended since Jun. 2022 for upgrade work on the Belle II apparatus.
  - Installation of new pixel detector modules.
  - Replacement of MCP-PMT for the time-of-propagation counters before their quantum efficiency gets deteriorated.
  - Full replacement of the DAQ platform with faster PCIe-based cards (PCIe40).
- The Belle II operation is planned to resume in autumn 2023.
- In the next decade, Belle II will collect the data that amounts to $\sim$ 50 ab^{-1}.
  - With the aim of the SuperKEKB luminosity at $\mathcal{L} = 6{\times}10^{35}\ \text{cm}^{-2}\text{s}^{-1}$.



Summary

Plentiful physics results have been produced by the Belle and Belle II data analyses. Several of them are already world leading. Highlights of the new and recent results have been presented today, which include:

- Precise measurements of the CKM matrix elements,
- Tests of the LFU and search for a LFV'ing τ decay,
- Measurement of a charmed-baryon lifetime, and
- Searches for dark-sector particles.