Highlights from Belle II results published during 2023

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On behalf of AANL-Belle II group

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Belle II

A. ALIKHANYAN National Laboratory
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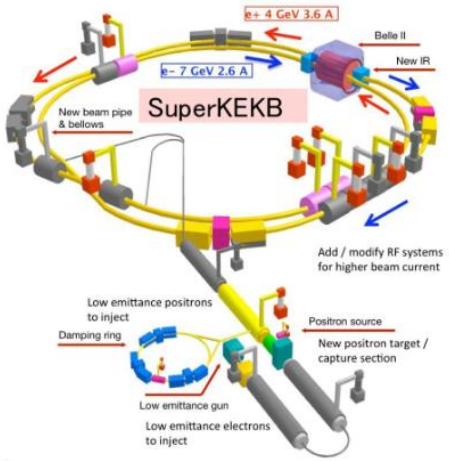
Belle II and SuperKEKB

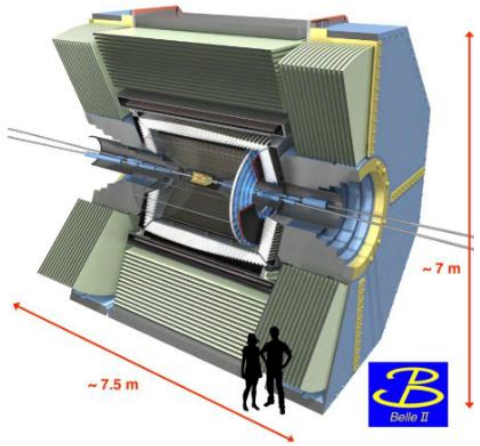
Collected at Y(4S): 362 fb^{-1}, about 0.4 x 10^9 BB

in total: 424 fb^{-1} aimed to reach 30-50 ab^{-1} in 10-15 years

SuperKEKB:

- e^+e^- collider with energies 4 GeV and 7 GeV operating around *Y(4S)* resonance.
- Achieved world-record peak luminosity of **4.7 x 10^{34} cm^{-2} s^{-1}**





Belle II:

- Nearly 4π detector
- Tracking, PID, and photon reconstruction capabilities
- Similar performance for **electrons** and **muons**

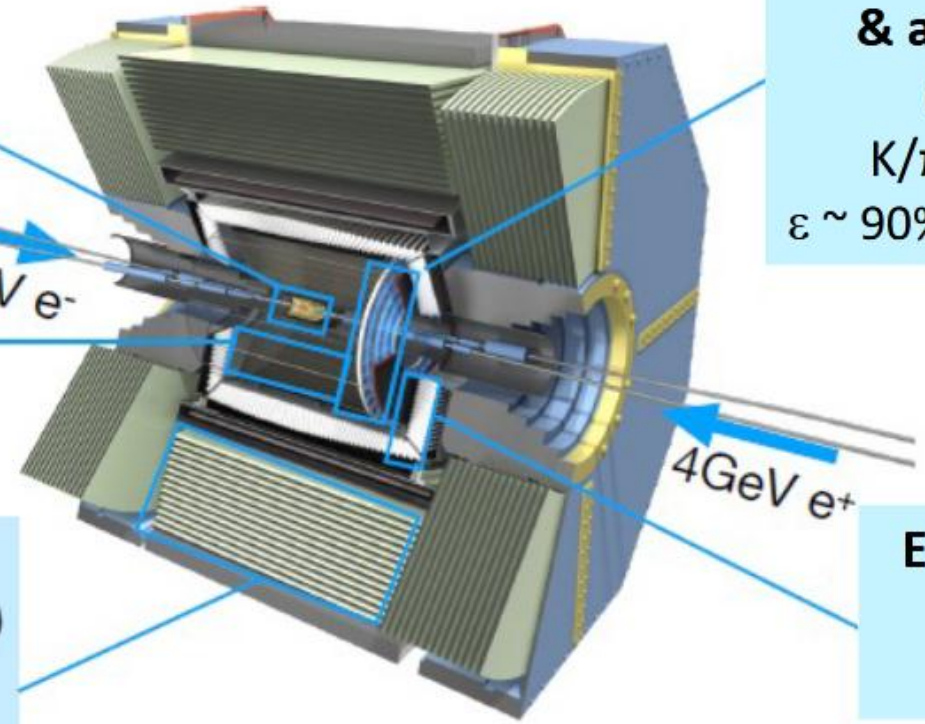
Well-suited to measure decays with missing energy, π^0 in the final state, inclusive measurements.

Belle II detector

Vertex detector
Tracking
$\sigma_{z0} \sim 15\ \mu m$
(2x better than Belle)

Drift chamber
Tracking
$\sigma_{r\phi} \sim 100\ \mu m$
$\sigma_{dE/dx} \sim 5\%$

K_L and Muon detector
$\Delta\phi = \Delta\theta \sim$ 10-20 *mrad (for K_L)*
μ/π separation:
ε~90% @ 1.5% fake



Time of propagation & aerogel RICH detectors
K/π separation
ε ~ 90% @ 5% fake rate

EM Calorimeter
σE/E~ 2% @
E =1 GeV

Measurement of lepton mass squared moments in $\mathbf{B \to X_c l^+ \bar{\nu}_l}$ Decays with the Belle II Experiment. PRD 107, 072002 (2023)

- The simultaneous analysis of these moments can determine the non-perturbative matrix elements as their contributions vary with the q^2 threshold; moments with a lower q^2 threshold retain more information about the inclusive $B \to X_c l^+ \bar{\nu}_l$ process.
- The current world average $|V_{cb}|$ determined from exclusive and inclusive approaches is:

$$|V_{cb}^{incl.}| = (42.19 \pm 0.78) \times 10^{-3}$$

$$|V_{cb}^{excl.}| = (39.25 \pm 0.56) \times 10^{-3}$$

Measurement of lepton mass squared moments in $\mathbf{B \to X_c l^+ \bar{\nu}_l}$ Decays with the Belle II Experiment. PRD 107, 072002 (2023)

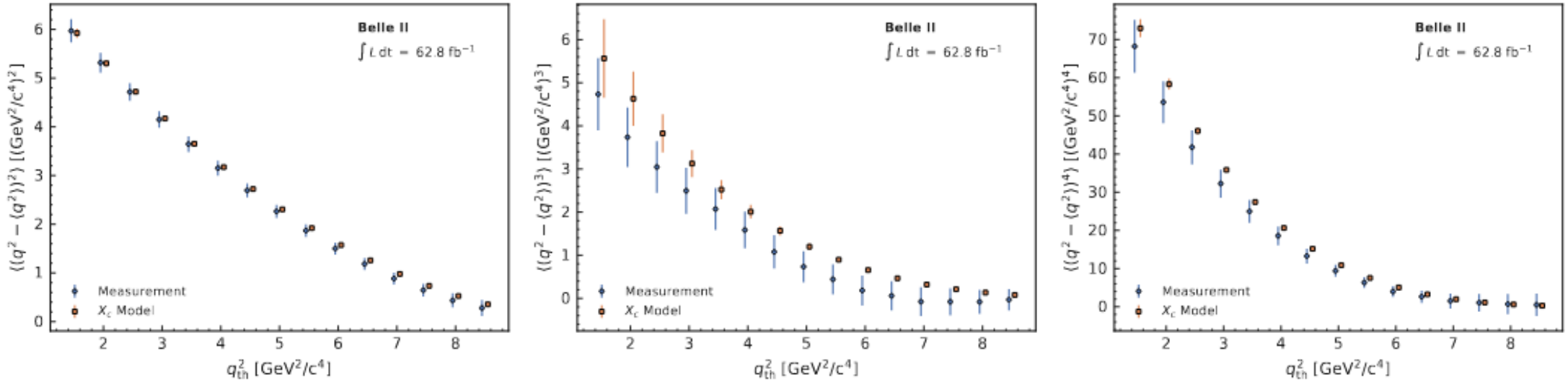
- The values for the central q^2 moments are calculated by expanding the binomial relation:

$$\langle (q^2 - \langle q^2 \rangle)^n \rangle = \sum_{j=0}^{n} \binom{n}{j} (-1)^{n-j} \langle q^{2j} \rangle \langle q^2 \rangle^{n-j}$$

and applying the following non-linear transformation:

$$\begin{pmatrix} \langle q^2 \rangle \\ \langle q^4 \rangle \\ \langle q^6 \rangle \\ \langle q^8 \rangle \end{pmatrix} \to \begin{pmatrix} \langle q^2 \rangle \\ \langle (q^2 - \langle q^2 \rangle)^2 \rangle \\ \langle (q^2 - \langle q^2 \rangle)^3 \rangle \\ \langle (q^2 - \langle q^2 \rangle)^4 \rangle \end{pmatrix}$$

Measurement of lepton mass squared moments in $B \to X_c l^+ \bar{\nu}_l$ Decays with the Belle II Experiment. PRD 107, 072002 (2023)



Central q^2 moments as functions of q^2 threshold with full uncertainties. The simulated moments (orange) are shown for comparison.

Recently, a first value of |Vcb| was determined using this measurement: Ref. [F. Bernlochner et al., JHEP 10, 068 (2022)] finds:

$|Vcb| = (41.70 \pm 0.69) \times 10^{-3}$,

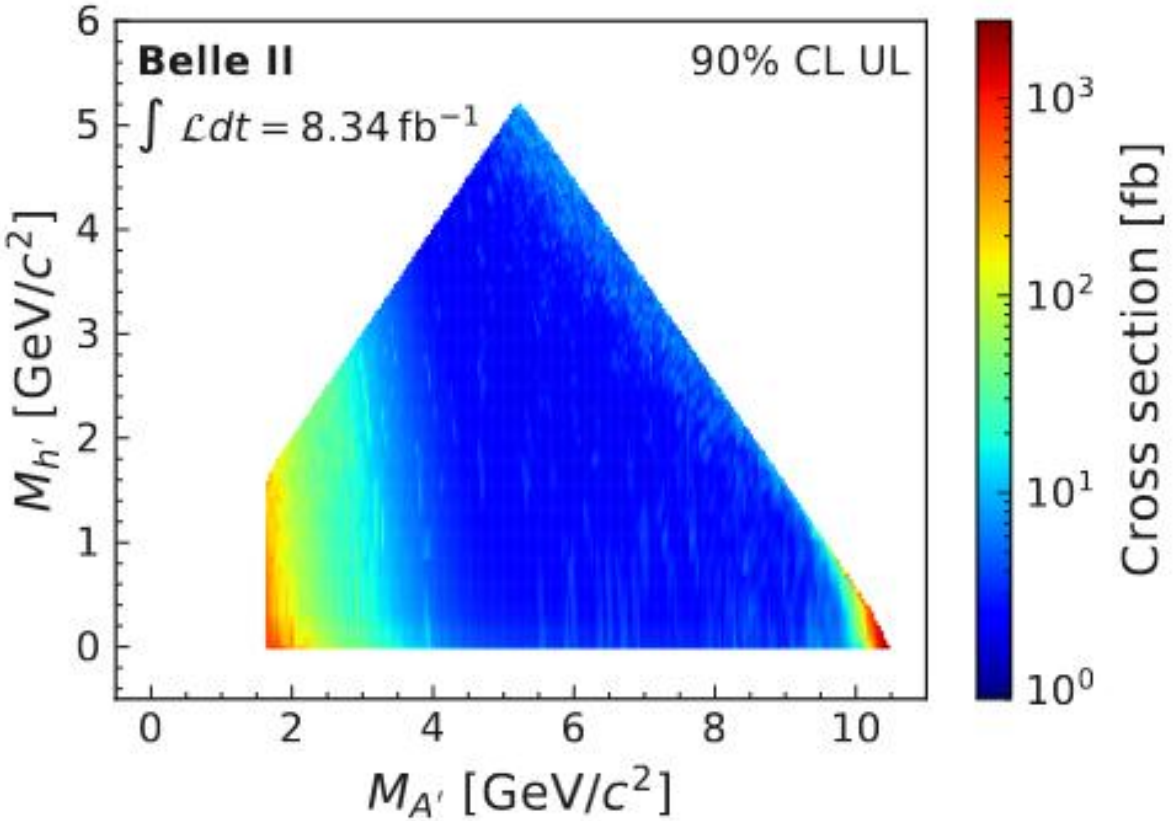
which is **in good agreement with other inclusive determinations**.

Search for a dark photon and an invisible dark Higgs boson in $\mu^+\mu^-$ and missing energy final states with the Belle II experiment. PRL **130, 071804** (2023)

The search for the simultaneous production of A' and h' in the dark Higgsstrahlung process $e^+e^- \to A'h'$ with $A' \to \mu^+\mu^-$ – and h' invisible in electron-positron collisions at a center-of-mass energy of 10.58 GeV in data collected by the Belle II experiment in 2019 is performed. With an integrated luminosity of 8.34 fb^{-1} no evidence for signal is observed. The exclusion limits at 90% Bayesian credibility in the range 1.7–5.0 fb on the cross section and in the range 1.7 $\times 10^{-8}$–200 $\times 10^{-8}$ on the effective coupling $\varepsilon^2 \times \alpha_D$, for A' mass 4.0 $GeV/c^2 < M_{A'} < 9.7\ GeV/c^2$ and h' mass $M_{h'} < M_{A'}$ has been estimated. **Belle II limits are the first in this mass range.**

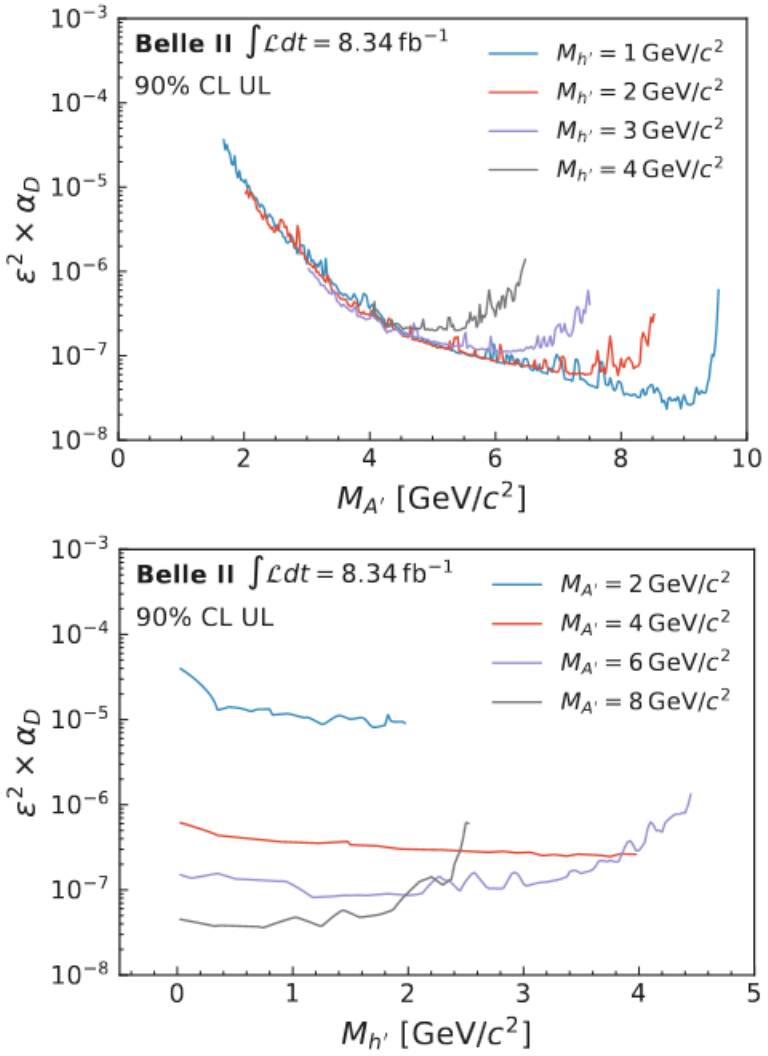
Search for a dark photon and an invisible dark Higgs boson in $\mu^+\mu^-$ and missing energy final states with the Belle II experiment. PRL 130, 071804 (2023)

Observed 90% CL upper limit on the cross section of e+e− → A′ h′ with A′ → μ+μ− and h′ invisible as a function of the A′ and h′ masses. Values are computed at search window centers and then interpolated to points of the search plane.

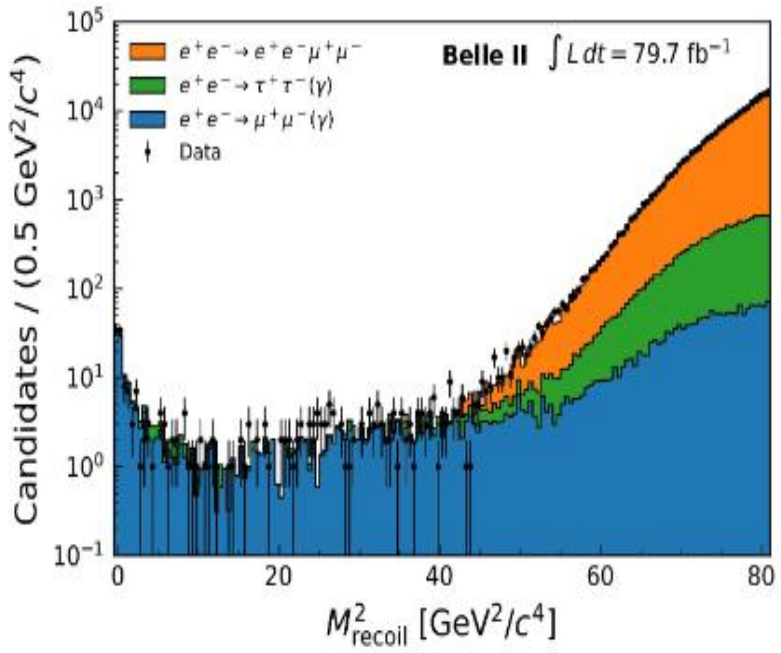


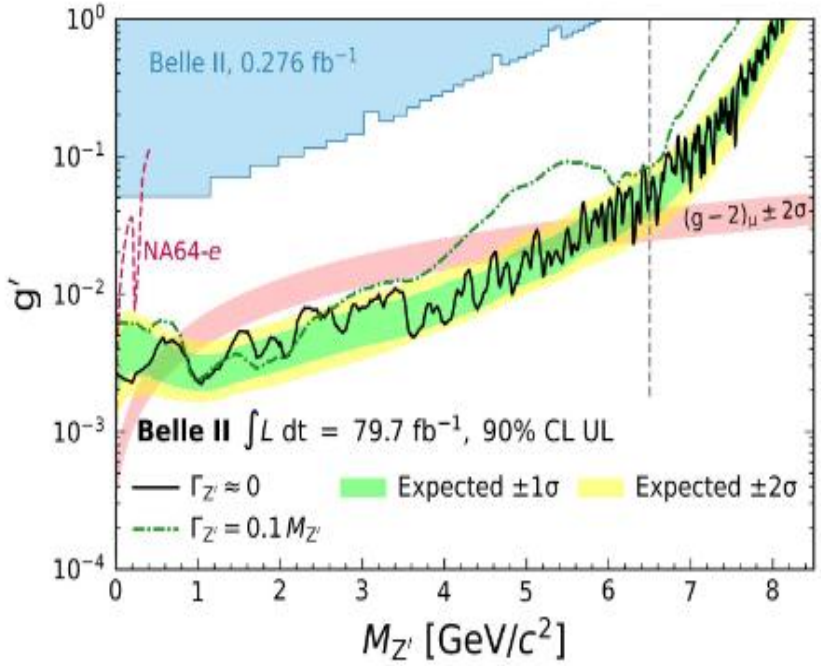
Search for a dark photon and an invisible dark Higgs boson in $\mu^+\mu^-$ and missing energy final states with the Belle II experiment. PRL 130, 071804 (2023)

Observed 90% CL upper limits on $\varepsilon^2 \times \alpha_D$ (top) as functions of $M_{A'}$ for four values of $M_{h'}$ and (bottom) as functions of $M_{h'}$ for four values of $M_{A'}$ .With α_D = 1, our constraints would improve on previous searches across almost the full mass range. For α_D = 0.1, this conclusion would still hold in a substantial part of the mass range. These results can be interpreted in a wider class of models, for example those with a long-lived invisible h' that mixes with the SM Higgs boson.



Search for an invisible Z′ in a final state with two muons and missing energy at Belle II PRL 130, 231801 (2023)





The $L_\mu - L_\tau$ extension of the SM predicts the existence of a lepton-flavor-universality-violating Z′ boson that couples only to the heavier lepton families: μ, τ , ν_μ and ν_τ with coupling constant ***g′*** *. Z′ was searched through its invisible decay in the process $e^+e^- \to \mu^+\mu^- Z'$. Could explain current* ***g − 2 muon tension*** *and mediate interactions between SM and dark matter.* **No excess over the expected standard-model background was found.**

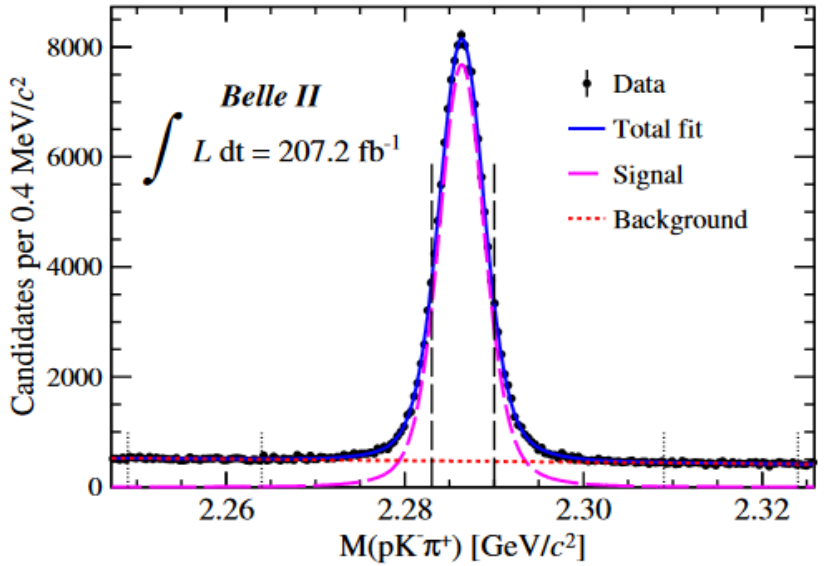
Search for an invisible Z′ in a final state with two muons and missing energy at Belle II PRL 130, 231801 (2023)

Squared recoil mass spectrum (**on left**) of the μ+μ− sample, compared with the stacked contributions from the various simulated background samples normalized to the integrated luminosity. Observed 90% CL upper limits (**on right**) on the coupling g′ for the fully invisible $L_\mu - L_\tau$ model as functions of the Z′ mass for the cases of negligible $\Gamma_{Z'}$ and for $\Gamma_{Z'} = 0.1\, M_{Z'}$.

Upper limits was set on the coupling g′ ranging from 3×10^{-3} at low Z′ masses to 1 for a mass of 8 $\mathbf{GeV/c^2}$.

Measurement of the Λ_c^+ lifetime. PRL 130, 071802 (2023)

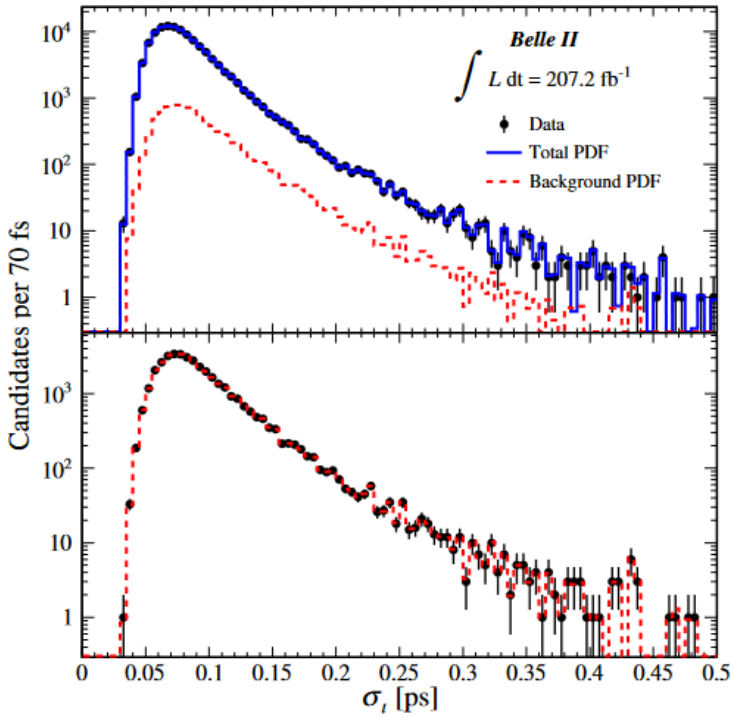
Λ_c^+ lifetime is extracted using $\Lambda_c^+ \to pK^-\pi^+$ decays in events reconstructed from data collected by the Belle II experiment at the SuperKEKB asymmetric-energy electron-positron collider. The total integrated luminosity of the data sample collected at center-of-mass energies at or near the Y (4S) resonance, is $207.2 fb^{-1}$. The result, $\tau(\Lambda_c^+)$ = 203.20 ± 0.89 (stat) ± 0.77 (syst) fs, is **the most precise measurement to date** and is consistent with previous determinations.



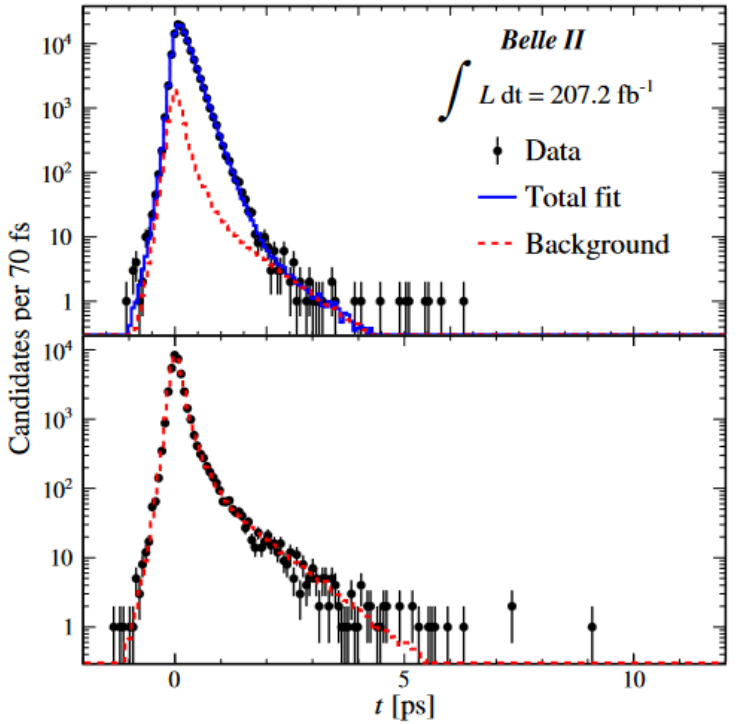
Mass distribution of $\Lambda_c^+ \to pK^-\pi^+$ candidates with fit projections overlaid. The vertical dashed lines enclose the signal region and the short, vertical dotted lines enclose the sidebands.

The Λ_c^+ lifetime is measured with an unbinned maximum-likelihood fit to the (t, σ_t) distribution for events in the signal region. The signal probability density function (PDF) is the product of an exponential function in t convolved with a Gaussian resolution function, which depends on t, and a PDF for σ_t. The latter is a histogram template formed from signal candidates subtracted by the distribution of sideband candidates after scaling according to the size of the signal and background regions. To account for a possible bias in the decay-time determination, the mean of the resolution function is determined by the fit.

Measurement of the Λ_c^+ lifetime.[PRL 130, 071802](#) (2023)



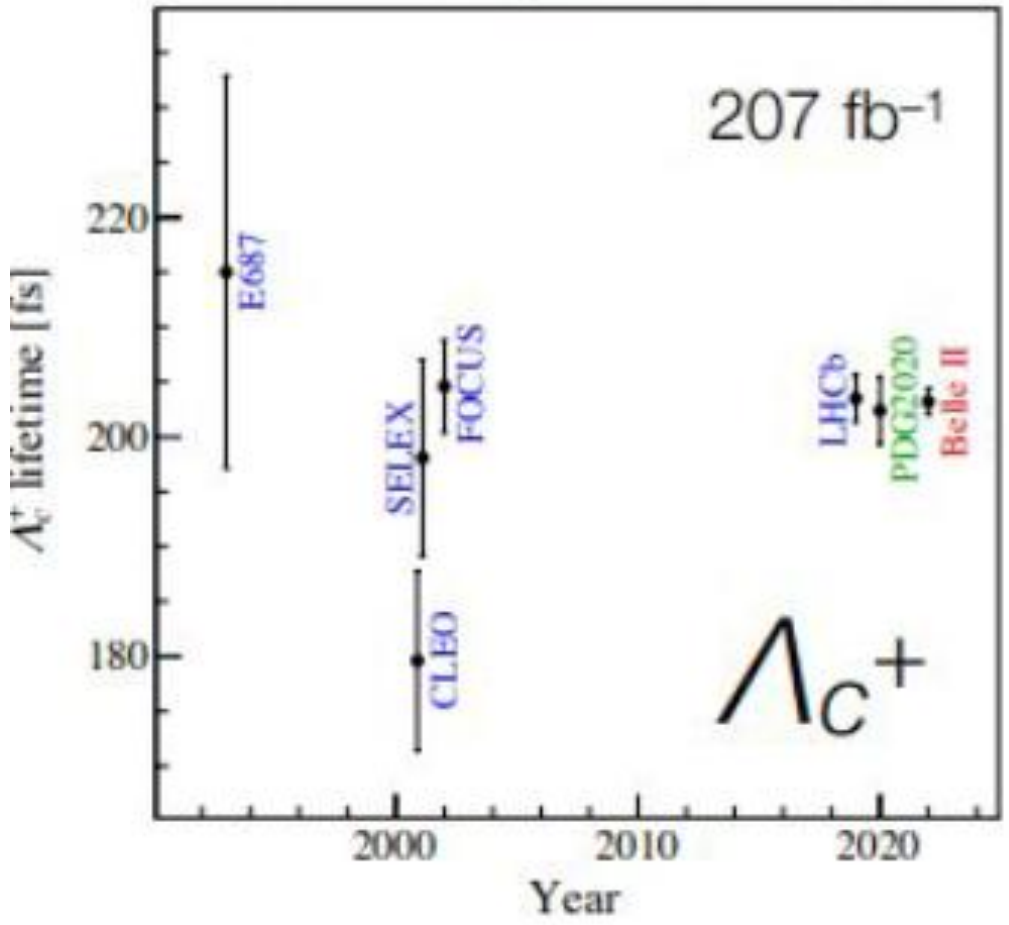
Decay-time uncertainty distribution of $\Lambda_c^+ \to pK^-\pi^+$ events in the signal region (top) and sidebands (bottom).



Decay-time distribution of $\Lambda_c^+ \to pK^-\pi^+$ events in the signal region (top) and sidebands (bottom) with fit projections overlaid.

Measurement of the Λ_c^+ lifetime.PRL 130, 071802 (2023)

The measured Λ_c^+ lifetime is extracted to be **203.20 ± 0.89 (stat) ± 0.77 (syst)** $\boldsymbol{fs}$ using data with an integrated luminosity of 207.2 fb^{-1} collected by the Belle II experiment. This is consistent with the recent, relative measurement by LHCb and other previous results, though the mild tension between the measurement by CLEO and all other measurements remains. The absolute measurement presented here **is the most precise Λ_c^+ lifetime measurement to date**

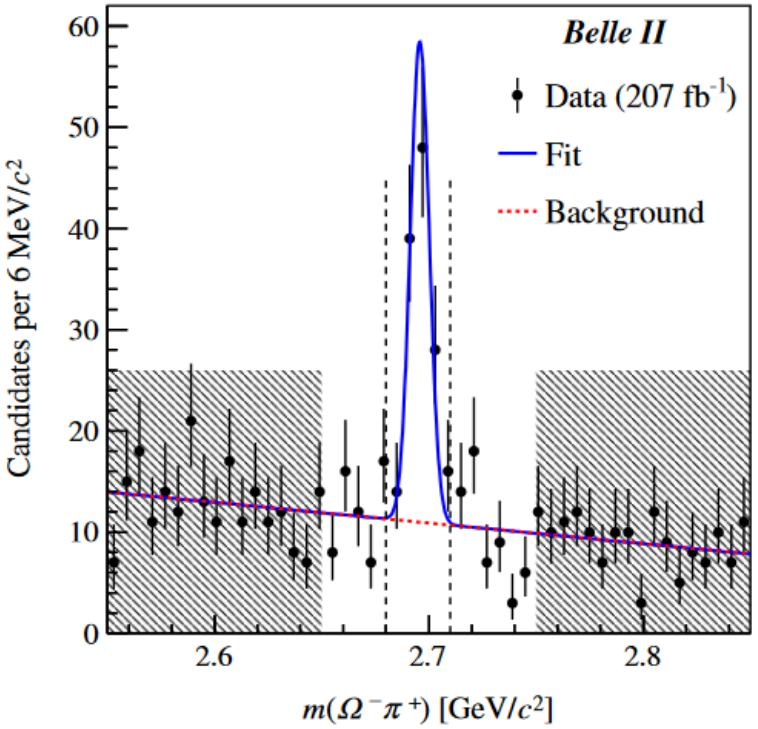


Measurement of the Ω_c^0 lifetime at Belle II

PRD 107, L031103 (2023)

Ω_c^0 lifetime is extracted using $\Omega_c^0 \to \Omega^-\pi^+$ decays reconstructed in $e^+e^- \to c\bar{c}$ data collected by the Belle II experiment and corresponding to 207 fb^{-1} of integrated luminosity. The result, $\tau(\Omega_c^0)$ = 243 ± 48 (stat) ± 11 (syst) fs, agrees with recent measurements indicating that the Ω_c^0 is not the shortest-lived weakly decaying charmed baryon.

The lifetime is determined similarly to Λ_c^+ using a maximum-likelihood fit to the unbinned (t, σ_t) distribution of the candidates populating the signal region.



Mass distribution for $\Omega_c^0 \to \Omega^-\pi^+$ candidates with fit projections overlaid. The vertical dashed lines enclose the signal region; the shaded area indicates the sideband.

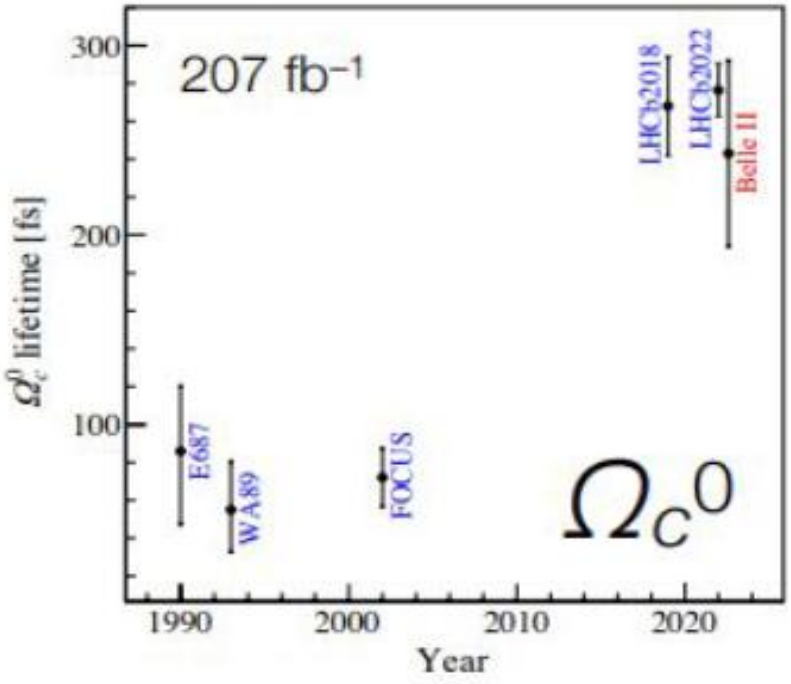
Measurement of the Ω_c^0 lifetime at Belle II

PRD 107, L031103 (2023)

The Ω_c^0 lifetime finally is defined as: $\boldsymbol{\tau(\Omega_c^0) = 243 \pm 48(stat) \pm 11(syst) fs}$

This result **is consistent** with the LHCb average of **274.5 ± 12.4 $\boldsymbol{fs}$**, and inconsistent at 3.4 standard deviations with the pre-LHCb world average of **69 ± 12 $\boldsymbol{fs}$**. Confirmed new **lifetime hierarchy** observed by LHCb:

$$\tau(\Xi_c^0) < \tau(\Lambda_c^+) < \tau(\Omega_c^0) < \tau(\Xi_c^+)$$



Measurement of the branching fraction and CP asymmetry of $B^0 \to \pi^0\pi^0$ decays using 198×10^6 $B\bar{B}$ pairs in Belle II data

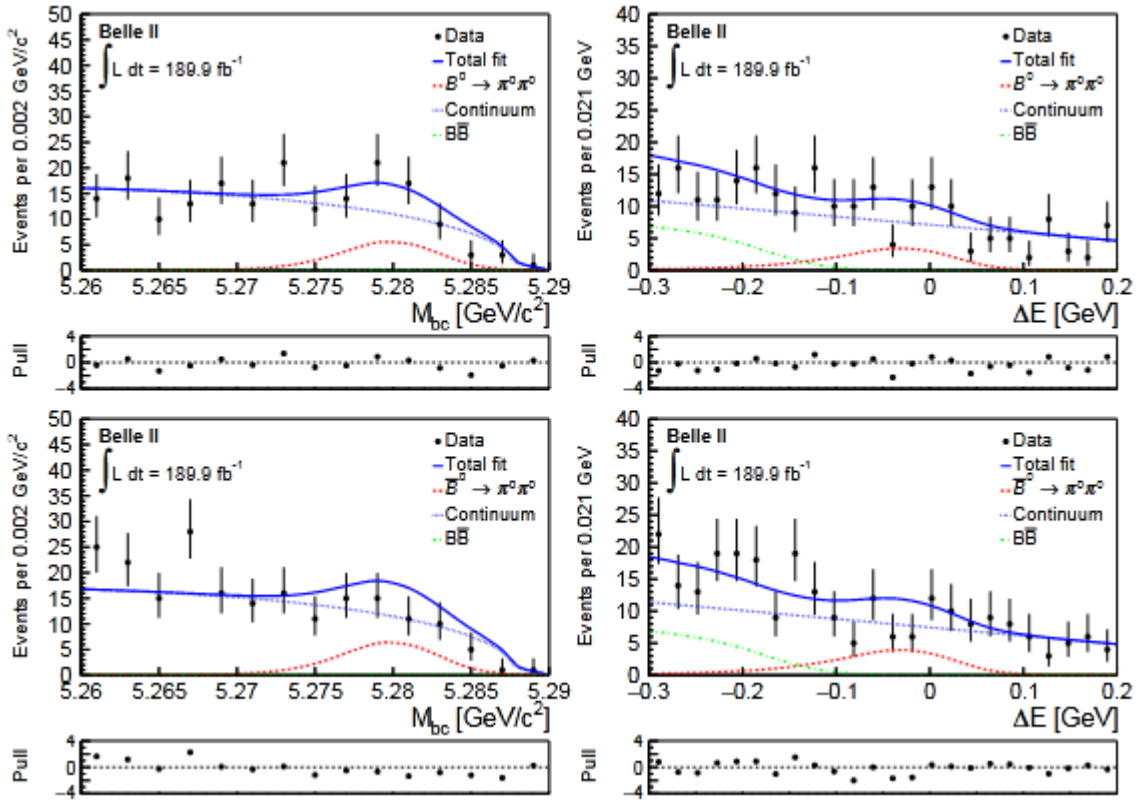
PRD 107, 112009 (2023)

- The branching fraction and CP asymmetry in $B^0 \to \pi^0\pi^0$ decays is measured with integrated luminosity of 189 fb^{-1}.
- $Br(B^0 \to \pi^0\pi^0) = \frac{N_S(1+\frac{f^{\pm}}{f^{00}})}{2\varepsilon N_{B\bar{B}} Br(\pi^0 \to \gamma\gamma)^2}$
- $A_{CP} = \frac{\Gamma(\bar{B}^0 \to \pi^0\pi^0) - \Gamma(B^0 \to \pi^0\pi^0)}{\Gamma(\bar{B}^0 \to \pi^0\pi^0) + \Gamma(B^0 \to \pi^0\pi^0)}$

Measurement of the branching fraction and CP asymmetry of $B^0 \to \pi^0\pi^0$ decays using 198×10^6 $B\bar{B}$ pairs in Belle II data PRD 107, 112009 (2023)

- Measuring $B^0 \to \pi^0\pi^0$ decay properties is challenging, as the decay is both CKM-suppressed and color-suppressed.
- As the final state consists of photons with no tracks, it is difficult to reconstruct. In addition, the large number of neutral pions produced in $e^+e^- \to q\bar{q}$ continuum events can be combined to mimic the $B^0 \to \pi^0\pi^0$ signal.
- Conventional and machine-learning based approaches, validated on data, are employed to achieve optimized selections. The signal yield and A_{CP} are determined by performing a maximum likelihood fit to the data.

Measurement of the branching fraction and CP asymmetry of $B^0 \to \pi^0\pi^0$ decays using 198×10^6 $B\bar{B}$ pairs in Belle II data PRD 107, 112009 (2023)



Measurement of the branching fraction and CP asymmetry of $B^0 \to \pi^0\pi^0$ decays using 198×10^6 $B\bar{B}$ pairs in Belle II data PRD 107, 112009 (2023)

- $M_{bc} = \sqrt{E_{beam}^2 - |\vec{p}_b|^2}$, $\Delta E = E_B - E_{beam}$
- $5.275 < M_{bc} < 5.285\ GeV/c^2$ $-0.1 < \Delta E < 0.05\ GeV$
- The whole analysis chain was tuned with the control data sample for $B^0 \to \bar{D}^0(\to K^+\pi^-\pi^0)\pi^0$ decay
- The branching fraction and direct *CP* asymmetry are measured to be:
- $Br(B^0 \to \pi^0\pi^0) = (1.38 \pm 0.27 \pm 0.22) * 10^{-6}$
- $A_{CP} = 0.14 \pm 0.46 \pm 0.07$
- **Agree** with previous measurements

Measurement of the B^0 lifetime and flavor-oscillation frequency using hadronic decays reconstructed in 2019-2021 Belle II data PRD 107, L091102 (2023)

- B^0lifetime τ_{B^0} and flavor-oscillation frequency Δ_{m_d} using $B^0 \rightarrow D^{(*)-}\pi^+$ decays with the data sample corresponding to 190 fb^{-1}integrated luminosity are extracted at Belle II
- Knowledge of τ_{B^0} and Δ_{m_d} allows us to test both the QCD theory of strong interactions at low energy and the Cabibbo-Kobayashi-Maskawa (CKM) theory of weak interactions
- PDF of *B* being initially in certain flavor state and decaying after time

Δt in the same (q_f=+1) or in opposite state (q_f=-1) is:

- $P(\Delta t, q_f \mid \tau_{B^0}, \Delta_{m_d}) = \frac{e^{-|\Delta t|/\tau_{B^0}}}{4\tau_{B^0}} [1 + q_f \cos(\Delta_{m_d} \Delta t)]$

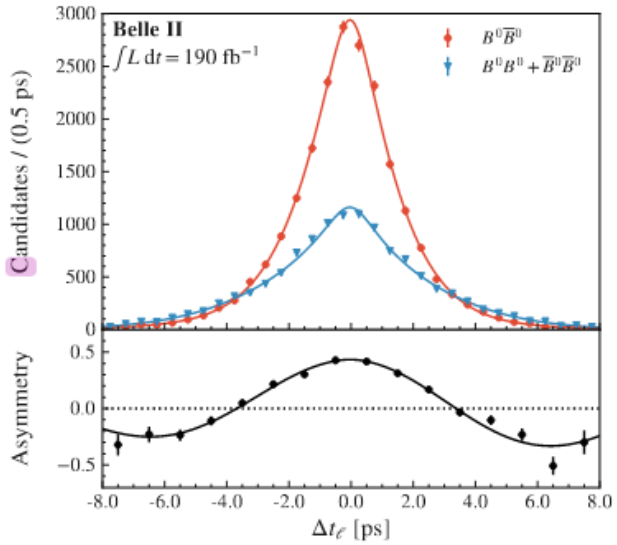
Measurement of the B^0 lifetime and flavor-oscillation frequency using hadronic decays reconstructed in 2019-2021 Belle II data PRD 107, L091102 (2023)

- In each event, the "signal-side" B (B_{sig}) via $B^0 \to D^{(*)-}\pi^+$ decays is fully reconstructed , identifying its flavor via the pion charge, as the contribution from $\bar{B}^0 D^{(*)-}\pi^+$ decays is of the order of 10^{-4}

- $\boldsymbol{B_{sig}}$ selection was done with $\boldsymbol{M_{bc} = \sqrt{E^2_{beam} - |\vec{p}_b|^2}}$ and $\boldsymbol{\Delta E = E_B - E_{beam}}$ values to be: $\boldsymbol{M_{bc} > 5.27 GeV}$

$\boldsymbol{and\ -0.1 < \Delta E < 0.25 GeV}$

Measurement of the B^0 lifetime and flavor-oscillation frequency using hadronic decays reconstructed in 2019-2021 Belle II data PRD 107, L091102 (2023)



- The final result extracted with $190 fb^{-1}$ integrated luminosity:
- τ_{B^0}=$(1.499 \pm 0.013 \pm 0.008) ps$ and Δ_{m_d}=$(0.516 \pm 0.008 \pm 0.005) ps^{-1}$
- **Agree with previous measured by Belle and Babar** with very similar systematic uncertainties

More papers published by Belle II in 2023

- **Measurement of the τ -lepton mass with the Belle II experiment, PRD 108, 032006 (2023):** 175 million $e^+e^- \to \tau^+\tau^-$ events corresponding to an integrated luminosity of 190 fb^{-1} were used to determine with τ pseudomass distribution in the decay $\tau^- \to \pi^-\pi^+\pi^-\nu_\tau$ the m_τ to be **1777.09 ± 0.08 ± 0.11** $\boldsymbol{MeV/c^2}$ **.** This result is **the most precise to date**.
- **Novel method for the identification of the production flavor of neutral charmed mesons, PRD 107, 112010 (2023): a new algorithm for the identification of the production flavor** of neutral D mesons in the Belle II experiment is developed. Exploiting the correlation between the flavor of a reconstructed neutral signal D meson and the electric charges of particles reconstructed in the rest of the $e^+e^- \to c\bar{c}$ event provides effective tagging efficiency in data on the level of (47.91 ± 0.07(stat) ± 0.51(syst))% Effective tagging efficiency calibrated in data with flavor-specific decays, roughly doubling the size of tagged D0 sample

More papers published by Belle II in 2023

- **A test of light-lepton universality in the rates of inclusive semileptonic B-meson decays at Belle II, PRL 131, 051804 (2023):** the **first measurement** of the ratio for inclusive semileptonic B-meson decays, R(Xe/μ) = B(B → X e ν)/B(B → X μ ν), a precision test of e/μ universality, using data corresponding to 189 fb^{-1}. In events where the partner B meson is fully reconstructed, using fits to the lepton momentum spectra above 1.3 GeV/c to obtain **R(Xe/μ) = 1.007 ± 0.009 (stat) ± 0.019 (syst),** which is the most precise lepton-universality test and **agrees with the SM expectations**
- **Observation of $e^+e^- \to \omega\chi_{bJ}(1P)$ and search for $X_b \to \omega$Y(1S) at √s near 10.75 GeV, PRL 130, 091902 (2023):** $e^+e^- \to \omega\chi_{bJ}(1P)$ (J= 0,1,2) process was studied at $\sqrt{s}$ = 10.701, 10.745 and 10.805 GeV with integrated luminosity 1.6, 9.8 and 4.7 fb^{-1} respectively. **First observation of $\omega\chi_{bJ}(1P)$ at $\sqrt{s}$ = 10.745 GeV**. Combining Belle and Belle II results at $\sqrt{s}$ = 10.867 $GeV \to \sigma_{Born}(E)$ for $\omega\chi_{b1,b2}(1P)$ final states is consistent with with the shape of the Y(10753) state. **No significant signal is observed for masses between 10.45 and 10.65** GeV/c^2

Coming soon (EPS + Moriond)

- **Measurement of the D_s lifetime — world leading**, arXiv: 2306.00365
- **ϒ(nS) dipion transitions**— unique, paper in preparation
- **Search for $e^+e^- \to \omega\eta_b$ at 10.75 GeV** — unique, paper in preparation
- **CPV in $B^0 \to \eta K_s$** — unique, paper in preparation
- **CPV in $B^0 \to K_s\pi^0\gamma$** — unique and world leading paper in preparation
- **GNN and $\sin(2\varphi_1)$** — paper in preparation
- **R(D*) — high profile** — paper in preparation
- **R(X) — high profile**, unique — paper in preparation
- **Evidence for ~3.6σ deviation from SM in $B^+ \to K^+\nu\nu$ — high profile**, unique — paper in preparation
- ***BF*, *CP*/isospin asymmetries in $B \to \rho\gamma$** — unique, Belle +Belle II — paper in preparation
- **Search for $Z' \to \mu\mu$** — paper in preparation
- **Energy-dependence of $B^{(*)}\bar{B}^{(*)}$ cross sections** — unique — paper in preparation
- **Measurement of CKM angle γ using GLW** — Belle + Belle II, arXiv: 2308.05048
- **Test of light-lepton universality in $B^0 \to D^{*-}l^+\nu$ decays** — unique — arXiv: 2308.02023
- **Measurement of CKM angle γ using GLS — Belle + Belle II**, arXiv: 2306.02940

Coming soon (EPS + Moriond)

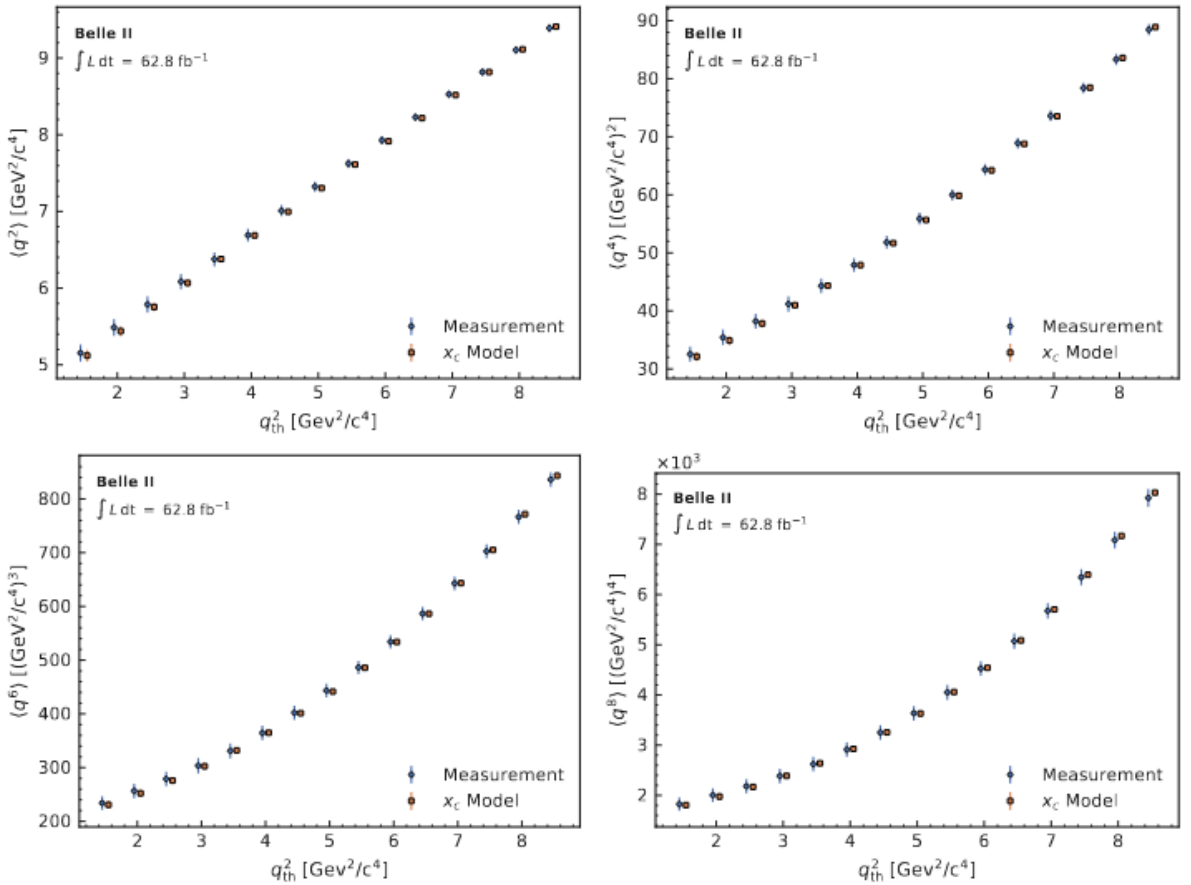
- **Search for long-lived spin-0 mediator in $b \to s$ transitions— world leading**, arXiv: 2306.02830
- **BF, CP asymmetry and isospin sum rule in $B^0 \to h^+h^-$ decays— world leading** — paper in preparation
- **A_{CP} in $B^0 \to K_s^0 K_s^0 K_s^0$ decay** — paper in preparation
- **|Vcb| using untagged $B \to D^* l\nu$ decays — competitive** — paper in preparation
- **CPV in $B^0 \to K_s^0 \pi^0$ decays — competitive**, arXiv: 2305.07555. **Accepted**
- **CPV in $B^0 \to \varphi K_s^0$** — arXiv: 2307.02802
- **Search for $\tau^- \to e^-(\mu^-)\varphi$ decays** — arXiv: 2305.04759 (conf note)
- **Observation of $B \to D^{(*)} K^- K_s^0$ decays**— world leading (conf note)

Conclusions

- Since summer 2022 data taking, SuperKEKB and Belle II are in LS1, until fall 2023. Several **improvements for accelerator complex**, to reduce background and improve luminosity, and detector upgrades, such as **installation of the complete two-layer vertex pixel detector**.
- Belle II has about 360 fb-1 on disk (Sept. 2023)
- scan data and new PXD is in
- 23 papers submitted on the arXiv (and another 17 very close)
- 25 new results in 2023
- As to the latest estimation done by **D. Tonelli** -> **Belle II switched from "Hey, we just started" to "Let's put Belle II on the map" to the current phase of "Belle II does world class stuff".**

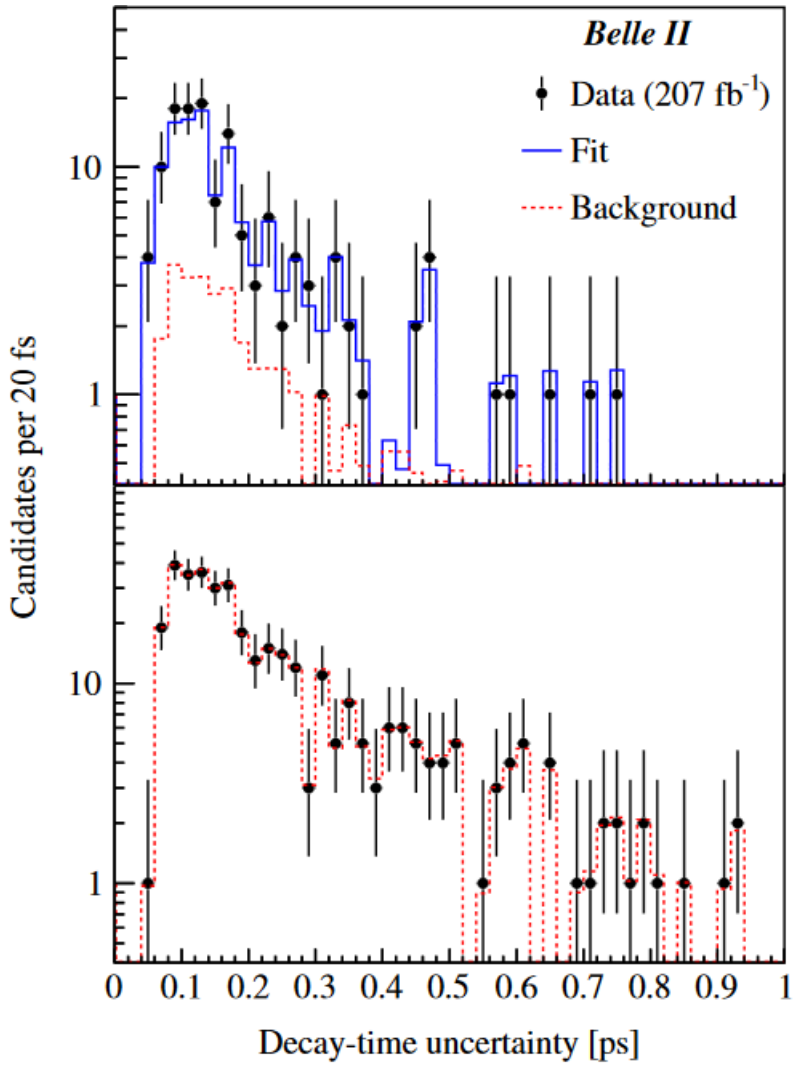
Thank you

Backup



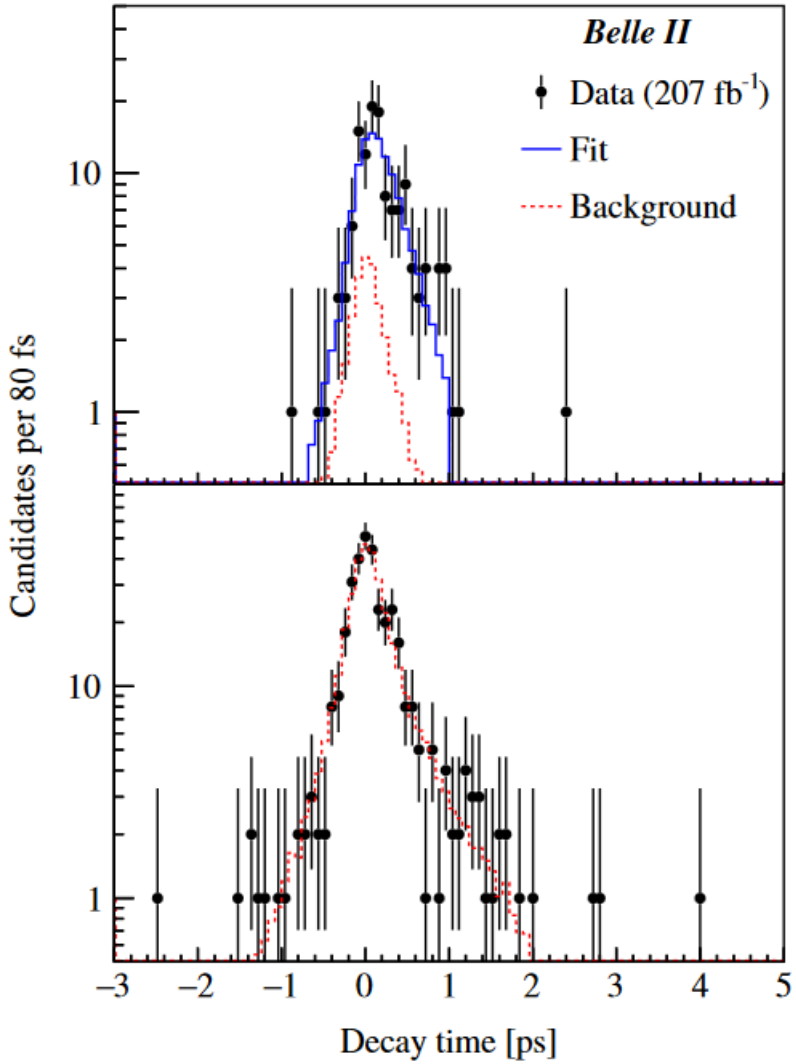
q^2Moments (blue) as functions of q^2threshold with full uncertainties. The simulated moments (orange) are show for comparison.

Backup



Decay-time-uncertainty distributions for $\Omega_c^0 \to \Omega^-\pi^+$ candidates populating (top) the signal region and (bottom) the sideband with fit projections overlaid.

Backup



Decay-time distributions for $\Omega_c^0 \to \Omega^-\pi^+$ candidates populating (top) the signal region and (bottom) the sideband with fit projections overlaid.

where ε is the mixing strength between the Standard Model and the dark photon and α_D is the coupling of the dark photon to the dark Higgs boson.
Masses of Λ_c^+ andΩ_c^0 are 2286 MeV and 2697MeV
Superconducting solenoid, which provides a 1.5 tesla magnetic field, which bends the trajectories of the final state charged particles to measure their charge and momentum