Recent results from the Belle II experiment

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Belle II experiment

> 1100 active members
124 institutes
27 countries

KEK
Tsukuba, Japan

$\sqrt{s} = 10.58 \text{ GeV}$
$(\Upsilon(4S) \text{ resonance})$

- $\int L \, dt = 424 \text{ fb}^{-1}$
- $362 \text{ fb}^{-1} \text{ on } \Upsilon(4S)$

- Max instantaneous luminosity
  $L = 4.7 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ (world record)

- LS1 starts from summer 2022 to fully install the PXD detector
- Operation will be resumed around the end of 2023.

- 362/fb at $\Upsilon(4S)^*$
- 42/fb off-resonance, 60 MeV below $\Upsilon(4S)$
- 19/fb energy scan between 10.6 to 10.8 GeV for exotic hadron studies
The instrument

It looks like the “old” Belle, but it is effectively a brand new detector

Only structure, magnet and calorimeter crystals are re-used

**Vertex detector (VXD)**
- Inner 2 layers: pixel detector (PXD)
- Outer 4 layers: strip sensor (SVD)
- Vertex resolution: 15 µm

**Central Drift Chamber (CDC)**
- Track efficiency ~ 99%
- $dE/dx$ resolution: 5%
- $p_T$ resolution: 0.4 %

**ElectroMagnetic Calorimeter (ECL)**
- Barrel: CsI(Tl) + waveform sampling
- Endcap: waveform sampling
- Energy resolution: 1.6 - 4%

**Particle Identification**
- Barrel: Time-Of-Propagation counters (TOP)
- Forward: Aerogel RICH (ARICH)

**$K_{L/\mu}$ detector (KLM)**
- Outer barrel: Resistive Plate Counter (RPC)
- Endcap/inner barrel: Scintillator
A diversified physics program

Belle II Data

New Hadrons, QCD measurements
- New hadron states Zb's, bbar gluon
- Upsilon(5S, 6S) runs
- New Charmonium-like states
- New bottomonium-like states
- New baryons
- e+e- --> HS R, pi+ pi- cross-sections (e-2)

Spin Fragmentation Functions (CSB)

New hadrons, QCD measurements
- Dark Photon
- Axion-Like Particles (ALPs)
- Invisible Z's
- Dark Higgs
- Heavy tau neutrinos
- LLPs (Long-Lived Particles)
- Magnetic Monopoles
- Gazelle (LD search)

Belle II Data

Dark Sector
- tau mass, lifetime
- Tau Spectral Functions
- Lepton Flavor Violation (LFV)
- Tau Electric Dipole Moment (EDM) 
- sin^2 theta_w
- A_FB (tau, mu, e+ b, c)
-improved tau LFV

Elctroweak physics with e-polarization

Electroweak physics with e-polarization
- B->c decays
- B->pi, pi pi pi CPV, isospin sum rules
- B->Xgamma, radiative penguins
- B->K(*) nu nubar
- B->VV, right-handed currents, triple products
- electroweak penguins: b->s l+l-, lepton universality, NP
- gamma determinations
- New charmed resonances

Charm Physics
- D-Char mixing and c+ c-
- Charm Lifetimes
- Branching Fractions, Dalitz analyses
- B->l+nu, Lepton flavor violation
- Exclusive charm decays
- Inclusive Measurements
- vtd/vts from penguins
- Exclusive measurements
- B->Xu tau nu, lepton universality

CKM Matrix Elements (Vcb, Vub)

Time Dependent Measurements
- alpha, beta, gamma
- Direct T violation
- New physics phases in b->s, B->phi Ks

Rare B decays
- hadronic B decays, B->K pi, pl pi Direct CPV, isospin sum rules

[Snowmass white paper]
(Some) \(B\)-factory basics

Low-background production of 30 (now)—600 (design) \(B\bar{B}\) per second.

Threshold \(B\) production from point-like colliding particles, \(e^+e^- \rightarrow Y(4S) \rightarrow B\bar{B}\). Kinematic well constrained.

The asymmetric collision gives the boost to measure the displacement.
Full Event Interpretation

- **Full Event Interpretation algorithm** ([Comput Softw Big Sci 3, 6 (2019)]) to reconstruct $B_{\text{tag}}$
  - Reconstruct $B$ candidate with all combination of daughters
  - Calculate signal probability with multivariate classifiers

- **Hadronic FEI**
  - Over 200 BDTs to reconstruct $\mathcal{O}(10000)$ distinct decay chains
  - $\epsilon_{B^+} \approx 0.5\%$, $\epsilon_{B^0} \approx 0.3\%$ at $\sim 15\%$ purity
    - $\sim 50\%$ increase over Belle tag

\[ M_{bc} = \sqrt{\frac{E_{beam}^2}{4} - (p_{B_{\text{tag}}}^{cm})^2} > 5.27 \text{ GeV}/c^2 \]
SEMILEPTONIC $B$-MESON DECAYS

- **The universality of the lepton coupling**, $g_\ell (\ell = e, \mu, \tau)$, to the electroweak gauge bosons can be probed
  - Lepton universality (LU) is challenged by several current measurements. Deviations would be a clear sign of BSM physics
- SL $B$ decays are studied to **determine the CKM elements** $|V_{cb}|$ and $|V_{ub}|$
  - $|V_{xb}|$ are limiting the global constraining power of UT fits
  - Important inputs in predictions of the SM rates for ultrarare decays such as $B_s \to \mu \nu$ and $K \to \pi \nu \nu$

$q^2 = (p_\ell + p_\nu)^2$
Anomalies in $b\to c$ decays

Standard Model assumes **lepton flavor universality** (LFU): $g_e = g_\mu = g_\tau$

- Observed $\sim 3\sigma$ tension in $R(D^{(*)})$ could hint possible new physics scenarios


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$\mathcal{R}(D^{(*)}) = \frac{B(B \to D^{(*)}\tau\nu)}{B(B \to D^{(*)}\ell\nu)}$

![Graph showing $R(D^{(*)})$ values with contours and data points from various experiments: Belle18, Belle15, BBar12, LHCb22, LHCb17, HFLAV, etc.]

$B$-mesons are produced in pairs with opposite flavors

- Tag a $B$-meson ($B_{\text{tag}}$) in fully hadronic decays
  - $\ell(0.1\%)$ efficiency of correctly reconstructed $B_{\text{tag}}$
- The other $B$-meson has well-defined energy and momentum

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$\varepsilon_{\text{tag}} = \alpha(0.1\%)$
$R(X_{e/\mu})$

$$R(X_{e/\mu}) = \frac{\text{Br}(B \rightarrow Xe\nu)}{\text{Br}(B \rightarrow X\mu\nu)}$$

$p_{B_{\text{sig}}} = p_{CM} - p_{B_{\text{tag}}}$

- Tag a $B$-meson ($B_{\text{tag}}$) in **fully hadronic** decays
- Lepton momentum in $B_{\text{sig}}$ rest-frame: $p_{\ell}^B > 1.3 \text{ GeV}/c$
  - reduce fakes and secondaries
  - suppress $B \rightarrow X\tau\nu$
  - if more leptons, keep the one with highest lepton-ID probability
- Rest of the event assigned to fully-inclusive $X$

$\varepsilon_{\text{tag}} = \mathcal{O}(0.1\%)$

$$\varepsilon(Xe\nu) = 53\%$$
$$\varepsilon(X\mu\nu) = 66\%$$

Signal modelling
$R(X_{e/\mu})$

**Extract signal yields** $N^{\text{meas}}$ by fit in 10 bins of $p^B_\ell$ (simultaneously for $e$ and $\mu$-channel)

- Maximize binned likelihood, systematics included as nuisance parameters
- 3 model templates (for $e, \mu$ separately):
  - $X\ell\nu$ signal
  - continuum background
  - other backgrounds (fakes and secondaries)

Obtain $N^{\text{meas}}$ by fit on signal-region data and evaluate $R(X)$, reweighting for signal efficiency:

$$R(X_{e/\mu}) = \frac{N^{\text{meas}}_e}{N^{\text{meas}}_\mu} \cdot \frac{\varepsilon_\mu}{\varepsilon_e}$$

Signal **efficiency** $\varepsilon$ for each channel is:

$$\varepsilon_\ell = \frac{N^{\text{sel}}_\ell}{N^{\text{gen}}_\ell}$$

- $N^{\text{sel}}_\ell \rightarrow$ signal yield extracted by fit on MC
- $N^{\text{gen}}_\ell \rightarrow$ total generated signal events

$$\varepsilon_e = (1.62 \pm 0.03) \times 10^{-3}$$

$$\varepsilon_\mu = (2.04 \pm 0.05) \times 10^{-3}$$

$R(X_{e/\mu}) = 1.033 \pm 0.010\,\text{(stat)} \pm 0.019\,\text{(syst)}$

$R(X_{e/\mu})_{\text{SM}} = 1.006 \pm 0.001$

IJHEP11(2022)007
$B^0 \rightarrow D^* \ell \nu$ angular asymmetries

- Fully reconstruct a $B$-meson ($B_{\text{tag}}$) in hadronic decay
- Reconstruct signal-side $D^* \ell \nu$ exclusively
  - select one lepton with $p_{\ell} > 1.0$ GeV/c
  - look for clean and abundant $D^0$ decay modes
  - combine with a charged slow pion: $D^* \rightarrow D^0 \pi_S$

Study semileptonic $B$ decays to $D^*$ vector

- 4 parameters to fully describe $B \rightarrow D^* \ell \nu$ decay:
  - $q^2 = (p_B - p_{D^*})^2$
  - Three angle $\theta_\ell$, $\theta_V$, $\chi$

We measure angular distributions asymmetries as function of $q^2$

World’s first experimental measurement of complete set of angular asymmetries
Define a set of 5 asymmetries for angular observables $x$.

1. Light lepton universality tested by comparing **five angular asymmetries** of $e$ and $\mu$, $\Delta A_x = A_x^e - A_x^\mu$ using $B^0 \rightarrow D^* \ell^+ \nu$ decays.

2. The simultaneous determination of all asymmetries in **different $w$ ranges** is performed.

   - $w_{low} = 1.0$, $w_{incl} = 1.275$, $w_{high} = 1.5$
   - Highly sensitive to lepton universality violation.
   - Less sensitive or insensitive to NP. Control tests of the analysis method.

   \[
   A_x(w) = \left( \frac{d\Gamma}{dw} \right)^{-1} \left[ \int_0^1 - \int_{-1}^0 \right] dx \frac{d^2\Gamma}{dw dx}
   \]

   \[
   w : \text{Recoil parameter} \quad w = \frac{m_B^2 + m_{D^*}^2 - q^2 c^2}{2 m_B m_{D^*}}
   \]

   - $A_{FB}(w)$: $dx = d(\cos \theta_\ell)$
   - $S_3(w)$ : $dx = d(\cos 2\chi)$
   - $S_5(w)$ : $dx = d(\cos \chi \cos \theta_\nu)$
   - $S_7(w)$ : $dx = d(\sin \chi \cos \theta_\nu)$
   - $S_9(w)$ : $dx = d(\sin 2\chi)$

Asymmetries $A$ are **experimentally clean** (most systematics cancel).

$\Delta A$ difference is **theoretically well-known** (form factors uncertainty cancel).

- $\sim 4\sigma$ deviation in $\Delta A_{FB}$ was claimed by theoretical reinterpretation of Belle data [Eur. Phys. J. C 81, 984 (2021), Phys. Rev. D 103, 079901 (2021)]
B^0 \rightarrow D^* \ell \nu$ angular asymmetries

- The signal yields are extracted through a binned maximum-likelihood fit to $M^2_{\text{miss}}$ distributions

**Observed overall agreement with Standard Model**

<table>
<thead>
<tr>
<th>$\chi^2$/ndof</th>
<th>$w_{\text{incl.}}$</th>
<th>$w_{\text{low}} + w_{\text{high}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta A_{FB}, \Delta S_3, \Delta S_5$</td>
<td>2.1 / 3 ($p=0.56$)</td>
<td>10.2 / 6 ($p=0.12$)</td>
</tr>
<tr>
<td>$\Delta S_7, \Delta S_9$</td>
<td>0.6 / 2 ($p=0.32$)</td>
<td>1.1 / 4 ($p=0.89$)</td>
</tr>
</tbody>
</table>

**Uncertainties statistically dominated**

- $w_{\text{high}}$
- $w_{\text{low}}$
- $w_{\text{incl.}}$
- SM
- Belle (2023) [2301.07529]
- Belle II (2023) [arXiv:2301.04716]
- Bobeth, et al.
35 new hadrons at Belle
Observation of a Narrow Charmoniumlike State in Exclusive $B^\pm \to K^\pm \pi^+ \pi^- J/\psi$ Decays

S.-K. Choi et al. (Belle Collaboration)
Phys. Rev. Lett. 91, 262001 – Published 23 December 2003

ABSTRACT

We report the observation of a narrow charmoniumlike state produced in the exclusive decay process $B^\pm \to K^\pm \pi^+ \pi^- J/\psi$. This state, which decays into $\pi^+ \pi^- J/\psi$, has a mass of $3872.0 \pm 0.6$ (stat) $\pm 0.5$ (syst) MeV, a value that is very near the $M_{D^*} + M_{D^*}$ mass threshold. The results are based on an analysis of 152M $B\bar{B}$ events collected at the $\Upsilon'(4S)$ resonance in the Belle detector at the KEKB collider. The signal has a statistical significance of $\approx 10\sigma$.

FIG. 2 (color online). Signal-band projections of (a) $M_{bc}$, (b) $M_{\pi^+ \pi^- J/\psi}$, and (c) $\Delta E$ for the $X(3872) \to \pi^+ \pi^- J/\psi$ signal region with the results of the unbinned fit superimposed.
The Nature of X(3872): Prospects with Belle II

- Many decay modes have been observed: $J/\psi \rho$, $J/\psi \omega$, $J/\psi \gamma$, $\psi(2S) \gamma$, $D D^*$, $D D \pi^0$. etc.
- Branching fractions and decay widths not known
  - Essential dynamic information!
- Belle II can contribute to a deeper understanding of this state!

Belle II measurement

Known variables

- $\text{Br}(B^+ \rightarrow X(3872)K^+) \times \text{Br}(X(3872) \rightarrow f)$
- $\sigma(X(3872)) \times \text{Br}(X(3872) \rightarrow f)$

Newly determined variables

- $B(B^\pm \rightarrow X(3872)K^\pm) = (2.1 \pm 0.6 \pm 0.3) \times 10^{-4}$

LHC, Tevatron...

$\psi(3770)$, $X(3915)$, $X(3872)$
Toward $X(3872)$ Total and Partial Widths Measurements with Belle II

Mass resolution for $D\bar{D}\pi^0$ is $\sim 680$ keV: ~3 times better than $J/\psi\pi^+\pi^-$
Previously unmeasured due to low statistics

With the full data sample of Belle II (50 ab$^{-1}$), total width with values up to
[90% C.L.] $\sim 180$ keV
[3$\sigma$ significance] $\sim 280$ keV
[5$\sigma$ significant] $\sim 570$ keV can be measured.

Current upper limit (90% C.L.)

Belle II simulation

90 % C.L.
3$\sigma$ significance
5$\sigma$ significance

Width [MeV]
Integrated luminosity [ab$^{-1}$]
Bottomonium(-like) prospects at Belle II

Run at Υ(6S) and Υ(5S) and high energy scan:
- Search for new missing bottomonia $\eta_b(3S), h_b(3P), \Upsilon(D)$, exotic states $Y_b, Z_b$, etc
- Improve precision of already known processes and states, e.g., $Z_b$
- Measure the effect of the coupled channel contribution
- Study $B^{(*)}\overline{B}^{(**)}$ and $B_s^{(*)}B_s^{(**)}$ threshold regions (challenging for Super-KEKB)

Run at Υ(3S) and Υ(2S):
- Search for missing $\pi\pi/\eta$ transitions in inclusive decays to constrain further models
- Search for new physics: LFV, LFU, light Higgs, ...

Observation of $e^+e^- \rightarrow \omega \chi_{bJ}$ at $\sqrt{s}$ near 10.75 GeV

- Belle: several $\sim 1\text{fb}^{-1}$ scan points below $\Upsilon(5S)$
- New structure observed in $\pi^+\pi^-\Upsilon(nS)$ transitions

<table>
<thead>
<tr>
<th>$\Upsilon(10860)$</th>
<th>$\Upsilon(11020)$</th>
<th>New structure</th>
</tr>
</thead>
<tbody>
<tr>
<td>M (MeV/c$^2$)</td>
<td>$10853 \pm 1.5^{+2.2}_{-0.9}$</td>
<td>$10752.7 \pm 5.9^{+0.7}_{-1.1}$</td>
</tr>
<tr>
<td>$\Gamma$ (MeV)</td>
<td>$36.0^{+4.5}_{-3.9} +0.5$</td>
<td>$35.5^{+17.6}_{-11.3} +3.9$</td>
</tr>
</tbody>
</table>

- Theoretical interpretations

Conventional D- or 5-D mixed bottomonium:
PRD 105, 074007 (2022), PRD 104, 034036 (2021)
EPJC 80, 59 (2020), PRD 101,397 014020 (2020)
PRD 102, 014036399 (2020), EPJP 137, 357 (2022)
PRD 105, 114041 (2022), PLB 803, 135340 (2020)

A tetraquark:
PLB 802, 135217 (2020)
PRD 103, 074007 (2021)
arXiv:2205.11475

- Interpretations as an admixture of the conventional 4S and 3D states predict comparable branching fractions of $10^{-3}$ for $\Upsilon(10753) \rightarrow \pi^+\pi^-\Upsilon(nS)$ and $\Upsilon(10753) \rightarrow \omega \chi_{bJ}$ [PRD 104, 034036 (2021), PRD 105, 074007 (2022)].
Observation of $e^+e^- \to \omega \chi_{bJ}$

PRL 130, 091902 (2023)

Two dimensional unbinned maximum likelihood fits to the $M(\gamma\Upsilon(1S))$ and $M(\pi^+\pi^-\pi^0)$ distributions.

The total $\chi_{bJ}$ signal significances are 11.1σ and 4.5σ at $\sqrt{s} = 10.745$ and 10.805 GeV.

Note that the $\sigma_{\text{Born}}(e^+e^- \to \omega \chi_{b1}/\omega \chi_{b2})$ is only $(0.76 \pm 0.16)/(0.29 \pm 0.14)$ pb at $\sqrt{s} = 10.867$ GeV [PRL 113, 142001(2014)].
### Observation of $\Upsilon(10753) \to \omega \chi_{bJ}$

**PRL 130, 091902 (2023)**

The $e^+e^- \to \omega \chi_{bJ} \ (J = 1, 2)$ cross sections peak at $\Upsilon(10753)$.

**Fit cross section with function:**

$$
\sigma_{e^+e^-\to\omega \chi_{bJ}}(\sqrt{s}) = \sqrt{PS_2(\sqrt{s})} + \text{BW}(\sqrt{s})e^{i\phi}|^2, \text{BW}(\sqrt{s})
$$

$$
= \frac{\sqrt{12\pi \Gamma_{ee} B_B \Gamma}}{s - M^2 + i\Gamma} \sqrt{PS_2(\sqrt{s})} \sqrt{PS_2(M)}
$$

M and $\Gamma$ of $\Upsilon(10753)$ are fixed according to Ref. [JHEP 10, 220(2019)].

### Table

<table>
<thead>
<tr>
<th>$\Gamma_{ee} B(f)$</th>
<th>Solution I (constructive interference)</th>
<th>Solution II (destructive interference)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Gamma_{ee} B(\Upsilon(10753) \to \omega \chi_{b1})$</td>
<td>$(0.63\pm0.39\pm0.20)\ eV$</td>
<td>$(2.01\pm0.38\pm0.76)\ eV$</td>
</tr>
<tr>
<td>$\Gamma_{ee} B(\Upsilon(10753) \to \omega \chi_{b2})$</td>
<td>$(0.53\pm0.46\pm0.15)\ eV$</td>
<td>$(1.32\pm0.44\pm0.55)\ eV$</td>
</tr>
</tbody>
</table>

1. $\sigma(e^+e^- \to \omega \chi_{b1})/\sigma(e^+e^- \to \omega \chi_{b2})=1.3\pm0.6$ at 10.745 GeV, contradicts the expectation for a pure D-wave bottomonium state of 15 [PLB 738, 172 (2014)]
2. There is also a 1.8σ difference with the prediction for a S-D-mixed state of 0.2 [PRD 104, 034036 (2021)]
There’s more to it

Journal-paper results approved in past 12 months

- Energy-dependence of $B(\bar{B})/B(\bar{B})$ bar cross section — unique
- Observation of $ee \rightarrow \omega x b$ at 10.75 GeV — unique, PRL. 130, 091902 (2023)
- Test of light-lepton universality in $B \rightarrow D^{*\pm} \ell^{\pm} \nu$ decays — unique
- Test of light lepton universality in inclusive $B \rightarrow [Xc] \ell \nu$ decays — unique, arXiv: 2301.08266
- Measurement of CKM angle $\gamma$ using GLW — Belle + Belle II sample
- Measurement of CKM angle $\gamma$ using GLS — Belle + Belle II sample
- Search for long-lived spin-0 mediator in $b \rightarrow s$ transitions — world leading
- Measurement of of the $\tau$ mass — world leading
- BF and ACP in $B^0 \rightarrow h^+ h^0$ decays and isospin sum rule — world leading
- BF and ACP of $B^0 \rightarrow \pi^0 \pi^0$ decays — competitive, arXiv: 2303.08354
- ACP in $B^0 \rightarrow K^0_S K^0_S K^0_S$
- $|V_{cb}|$ using untagged $B \rightarrow D^{*\pm} \ell^{\pm} \nu$ decays — competitive
- CPV in $B^0 \rightarrow K^0_S \pi^0$ decays — competitive, arXiv: 2305.07555
- CPV in $B^0 \rightarrow \phi K^0_S$
- $B^0$ lifetime and oscillations in $B^0 \rightarrow D^{(*)0} h$ decays, PRD 107, L091102 (2023)
- Search for a dark-sector $\tau \tau$ resonance in $ee \rightarrow ee \tau \tau$ decays — world leading
- Search for a dark-sector $Z'$ to invisible — world leading, arXiv: 2212.03066
- Search for $\tau \rightarrow \ell \alpha$ — world leading, PRL 130, 181803 (2023)
- Search for a dark $\gamma$ and invisible dark-Higgs in $\mu \mu +$MET — world leading, PRL 130, 071804 (2023)
- Measurement of the Omega_c lifetime — PRD 107, L031103 (2023)

(Plus a bunch of conference-note results)
Summary & prospects

- SuperKEKB/Belle II is the luminosity frontier project to search for physics beyond SM with ultimate sensitivity.

- The project has achieved so far, by Summer 2022;
  - $L_{\text{peak}} = 4.7 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ (the world highest luminosity)
  - $L_{\text{int}} = 428 \text{ fb}^{-1}$ (similar to BaBar, about 1/2 of Belle)

- Many physics results are coming.
  - Benefited by improved detector performance and analysis technique!
  - Some of them are already world-leading!

- Currently, we are in the long shutdown I (LS1). Many components are to be improved.
  - We plan to resume in the coming winter, and will try to achieve higher luminosity.

- LS2 is planned for the major upgrade of the IR region and detector subsystems to further boost the luminosity frontier!
感谢您的批评指正

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