Measurements of radiative and electroweak penguin B decays without missing energy at Belle and Belle II

Martin Angelsmark on behalf of the Belle II Collaboration

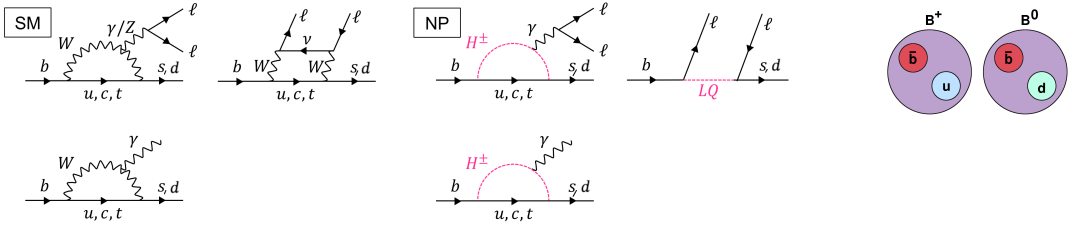
ICHEP 2024: WG3 - Quark and Lepton Flavour Physics

mangels@uni-bonn.de

July 19, 2024

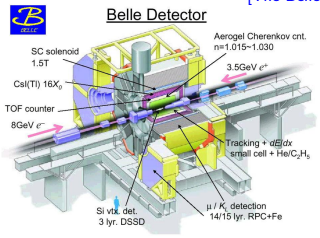
Electroweak Penguin Decays

- Sensitive to new physics contributing to Flavor Changing Neutral Current



Belle and Belle II

[The Belle detector]

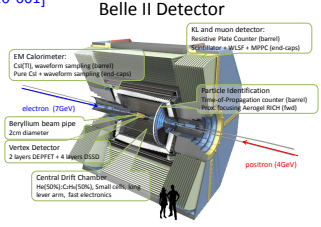


- Located at KEKB (Tsukuba, Japan)
- e^+e^- collider at $\Upsilon(4S)$ (10.58 GeV): e^+ (3.5 GeV) – e^- (8 GeV)
- 1 ab^{-1} (711 fb^{-1} $\Upsilon(4S)$ resonance) collected: 1999 – 2010
- $\Upsilon(4S) \to B\overline{B}$: Clean $B\overline{B}$ events
- Initial state well known
- $e^+e^- \to q\overline{q}$ (continuum): Largest background component

Largest instantaneous luminosity: $2.1 \cdot 10^{34}$ cm^{-2}s^{-1}

- Located at superKEKB (Tsukuba, Japan)
- e^+e^- collider at $\Upsilon(4S)$ (10.58 GeV): e^+ (4 GeV) – e^- (7 GeV)
- 424 fb^{-1} (362 fb^{-1} $\Upsilon(4S)$ resonance): Run 1: 2019 – 2022
- CsI(Tl) crystal calorimeter → better energy resolution
- $\Upsilon(4S) \to B\overline{B}$: Clean $B\overline{B}$ events
- Initial state well known
- $e^+e^- \to q\overline{q}$ (continuum): Largest background component

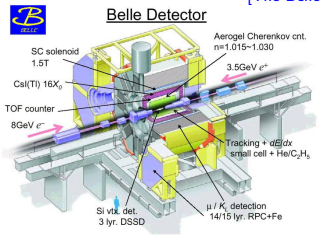
[BELLE2-REPORT-2016-001]



World record instantaneous luminosity: $4.7 \cdot 10^{34}$ cm^{-2}s^{-1}

Belle and Belle II

[The Belle detector]



- Located at KEKB (Tsukuba, Japan)
- e^+e^- collider at $\Upsilon(4S)$ (10.58 GeV): e^+ (3.5 GeV) – e^- (8 GeV)
- 1 ab^{-1} (711 fb^{-1} $\Upsilon(4S)$ resonance) collected: 1999 – 2010
- $\Upsilon(4S)$ [illegible] $B\overline{B}$ events
- e^+ [illegible]: Largest background component
- [illegible]s luminosity: $2.1 \cdot 10^{34}$ cm^{-2}s^{-1}

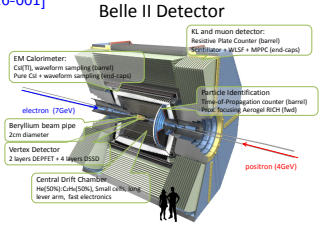
Results using combined datasets

- Located at superKEKB (Tsukuba, Jap[illegible]
- e^+e^- collider at $\Upsilon(4S)$ (10.58 GeV): [illegible]
- 424 fb^{-1} (362 fb^{-1} $\Upsilon(4S)$ reso[illegible]
- CsI(Tl) crystal calorimeter → better energy [illegible]
- $\Upsilon(4S) \to B\overline{B}$: Clean $B\overline{B}$ events
- Initial state well known
- $e^+e^- \to q\overline{q}$ (continuum): Largest background component

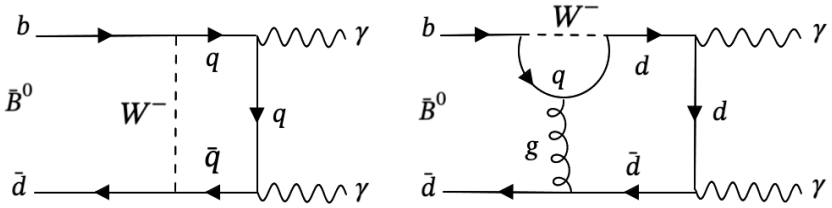
World record instantaneous luminosity: $4.7 \cdot 10^{34}$ cm^{-2}s^{-1}

[illegible]E2-REPORT-2016-001]

[illegible]GeV)



$B^0 \to \gamma\gamma$ at Belle + Belle II



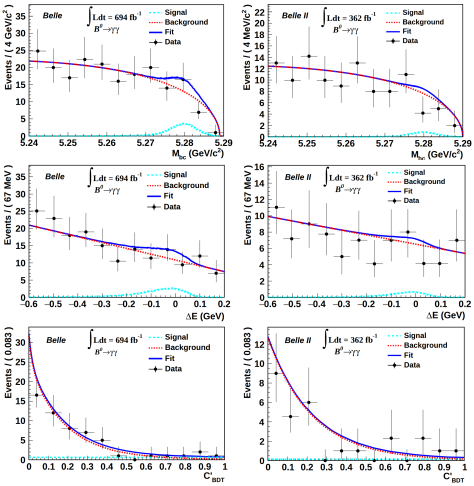
- Decay in SM through loop diagram with W^- emitted and absorbed
- Long distance penguin contribution
- Suppressed by factor $|V_{td}|/|V_{ts}| \approx 0.04$ compared to $B_s \to \gamma\gamma$
- SM prediction: $\mathcal{B}(B^0 \to \gamma\gamma) = (1.4^{+1.4}_{-0.8}) \cdot 10^{-8}$ [JHEP12(2020)169]

$B^0 \to \gamma\gamma$ at Belle + Belle II

[arXiv:2405.19734]

- Simultaneous fit of Belle (694 fb^{-1}) + Belle II (362 fb^{-1}) data
  - M_{bc} – beam constrained mass $\sqrt{(\text{Beam energy})^2 - (\text{Momentum of B}^0)^2}$
  - ΔE – energy difference $(\text{Energy of B}^0) - (\text{Beam energy})$
  - BDT trained on π^0 and η dominated events
- Signal events: $11.0^{+6.5}_{-5.5}$, 2.5σ significance
- $\mathcal{B}^{UL}(B^0 \to \gamma\gamma) < 6.4 \cdot 10^{-8}$, 90% CL
- $\mathcal{B}^{UL}_{SM}(B^0 \to \gamma\gamma) < 4.4 \cdot 10^{-8}$, 90% CL

Upper limit 5 times more restrictive than previous (BaBar) measurement [PhysRevD(2011)83]

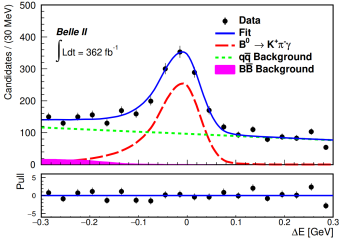


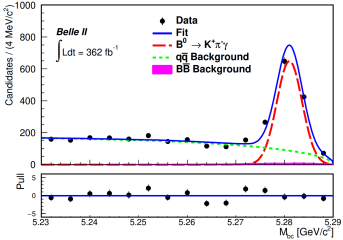
$B \to K^*\gamma$ at Belle II

Signal:

- $B^0 \to K^{*0}[\to K^+\pi^-]\gamma$
- $B^0 \to K^{*0}[\to K^0_S\pi^0]\gamma$
- $B^+ \to K^{*+}[\to K^+\pi^0]\gamma$
- $B^+ \to K^{*+}[\to K^0_S\pi^+]\gamma$

- 2D fit on Belle II (362 fb^{-1}) data
  - M_{bc}, ΔE





$B \to K^*\gamma$ at Belle II

Charge Parity Asymmetry:

$$\mathcal{A}_{CP} = \frac{\Gamma(\overline{B} \to \overline{K^*}\gamma) - \Gamma(B \to K^*\gamma)}{\Gamma(\overline{B} \to \overline{K^*}\gamma) + \Gamma(B \to K^*\gamma)}$$

Isospin Asymmetry (CP average):

$$\mathcal{A}_I = \frac{\Gamma(B^0 \to K^{*0}\gamma) - \Gamma(B^+ \to K^{*+}\gamma)}{\Gamma(B^0 \to K^{*0}\gamma) + \Gamma(B^+ \to K^{*+}\gamma)}$$

- Theoretically clean – cancellation of form factors
- Standard Model prediction: $A_I = (3 \pm 2)\%$ – $(8 \pm 2)\%$ [PhysRevD(2005)72] [PhysRevD(2002)539]
- Previous measurement (Belle): $A_I = (6.2 \pm 1.5 \pm 0.6 \pm 1.2)\%$ – 3.1σ Isospin violation [PhysRevD(2017)119]

[Paper in preparation]

- Branching fractions
  - $\mathbf{B}(B^0 \to K^{*0}\gamma) = (4.16 \pm 0.10 \pm 0.11) \cdot 10^{-5}$
  - $\mathbf{B}(B^+ \to K^{*+}\gamma) = (4.04 \pm 0.13 \pm 0.13) \cdot 10^{-5}$
- Charge Parity Asymmetry
  - $\mathcal{A}_{CP}(B^0 \to K^{*0}\gamma) = (-3.2 \pm 2.4 \pm 0.4)\%$
  - $\mathcal{A}_{CP}(B^+ \to K^{*+}\gamma) = (-1.0 \pm 3.0 \pm 0.6)\%$
  - $\Delta\mathcal{A}_I = (2.2 \pm 3.8 \pm 0.7)\%$

See Yu Nakazawa's presentation for $K_S\pi^0$ [ICHEP2024]

$B \to \rho\gamma$ at Belle + Belle II

[arXiv:2407.08984]

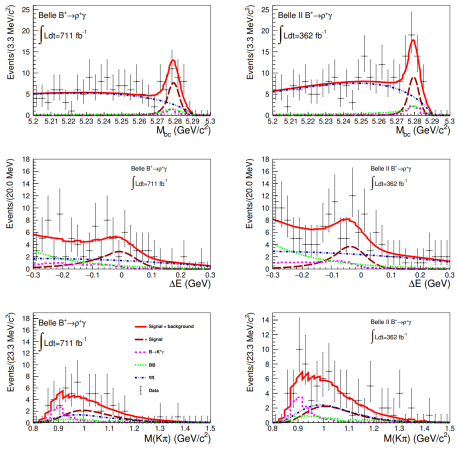
Signal:

- $B^0 \to \rho^0[\to \pi^+\pi^-]\gamma$
- $B^+ \to \rho^+[\to \pi^+\pi^0]\gamma$

Calibration:

- $B^0 \to D^-[\to K^+\pi^-\pi^-]\pi^+$
- $B^+ \to \overline{D}^0[\to K^+\pi^-]\pi^+$
- $B^0 \to K^{*0}[\to K^+\pi^-]\gamma$
- $B^+ \to K^{*+}[\to K^+\pi^0]\gamma$

- Simultaneous fit of Belle (772 fb^{-1}) + Belle II (362 fb^{-1}) data
  - M_{bc}, ΔE
  - $M(K\pi)$ – invariant mass of ρ assuming one π^+ is a K
- Background suppression using $\pi^0(\eta)$ veto and $q\overline{q}$ BDT's



$B \to \rho\gamma$ at Belle + Belle II

[arXiv:2407.08984]

Charge Parity Asymmetry:

$$\mathcal{A}_{CP} = \frac{\Gamma(\overline{B} \to \overline{\rho}\gamma) - \Gamma(B \to \rho\gamma)}{\Gamma(\overline{B} \to \overline{\rho}\gamma) + \Gamma(B \to \rho\gamma)}$$

Isospin Asymmetry (CP average):

$$\mathcal{A}_I = \frac{2\Gamma(B^{0/\overline{0}} \to \rho^0\gamma) - \Gamma(B^{+/-} \to \rho^{+/-}\gamma)}{2\Gamma(B^{0/\overline{0}} \to \rho^0\gamma) + \Gamma(B^{+/-} \to \rho^{+/-}\gamma)}$$

- Standard Model prediction: $A_I = (5.2 \pm 2.8)\%$
- World average of $A_I = (30^{+16}_{-13})\% - 2\sigma$ from Standard Model

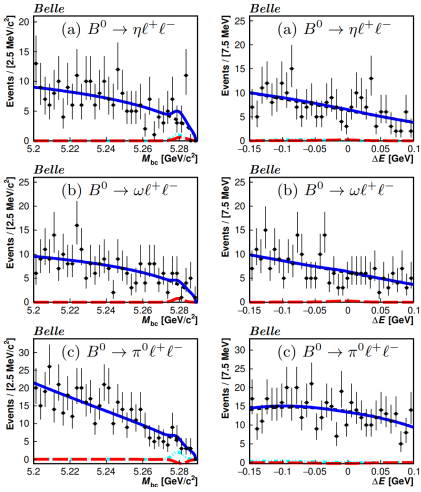
- Signal events:
  - 114 ± 12 $B^+ \to \rho^+\gamma$
  - 99 ± 12 $B^0 \to \rho^0\gamma$
- Branching fractions
  - $\mathbf{B}(B^+ \to \rho^+\gamma) = (13.1^{+2.0+1.3}_{-1.9-1.2}) \cdot 10^{-7}$
  - $\mathbf{B}(B^0 \to \rho^0\gamma) = (7.5^{+1.3+1.0}_{-1.3-0.8}) \cdot 10^{-7}$
- $\mathcal{A}_{CP} = (B^+ \to \rho^+\gamma) = (-8.2^{+15.2+1.6}_{-15.2-1.2})\%$
- $\mathcal{A}_I = (B \to \rho\gamma) = (10.9^{+11.2+7.8}_{-11.7-7.3})\%$
- Measured Asymmetries are consistent with Standard Model

$b \to d\ell^+\ell^-$ at Belle

[arXiv:2404.08133]

- $B^{+/0} \to [\eta, \omega, \pi^{+/0}, \rho^{+/0}]\ell^+\ell^-$
- Suppressed by factor $|V_{td}|/|V_{ts}| \approx 0.04$
- 2D fit on Belle (711 fb^{-1}) data
  - M_{bc}, ΔE
- Current best upper limits measured
- World first measurement: $B^0 \to \omega\ell^+\ell^-$, $B^+ \to \rho^+\ell^+\ell^-$, $B^0 \to \rho^0 e^+ e^-$

Channel	$\mathcal{B}^{UL}(10^{-8})$
$B^0 \to \eta e^+ e^-$	< 10.5
$B^0 \to \eta \mu^+ \mu^-$	< 9.4
$B^0 \to \eta \ell^+ \ell^-$	< 4.8
$B^0 \to \omega e^+ e^-$	< 30.7
$B^0 \to \omega \mu^+ \mu^-$	< 24.9
$B^0 \to \omega \ell^+ \ell^-$	< 22.0
$B^0 \to \pi^0 e^+ e^-$	< 7.9
$B^0 \to \pi^0 \mu^+ \mu^-$	< 5.9
$B^0 \to \pi^0 \ell^+ \ell^-$	< 3.8
$B^+ \to \pi^+ e^+ e^-$	< 5.4
$B^0 \to \rho^0 e^+ e^-$	45.5
$B^+ \to \rho^+ e^+ e^-$	< 46.7
$B^+ \to \rho^+ \mu^+ \mu^-$	< 38.1
$B^+ \to \rho^+ \ell^+ \ell^-$	< 18.9

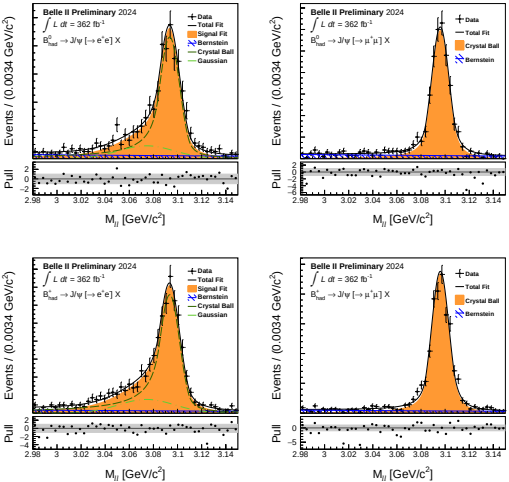


$B \to J/\psi X$ at Belle II

[Paper in preparation]

- Fully reconstruct B-meson (tag) [arXiv:1807.08680]
  - Full kinematic information of opposite B-meson (signal)
- Important for $B \to X_s \ell\ell$
- Signal extraction with unbinned likelihood fit
  - Double-sided Crystall Ball (+ Gaussian for e^+e^-)
  - Bernstein Polynomial [Comm.KharkovMath.Soc.(13)]

Channel	Yield
$B^0 \to [J/\psi \to e^+e^-]X$	930 ± 39
$B^0 \to [J/\psi \to \mu^+\mu^-]X$	766 ± 30
$B^+ \to [J/\psi \to e^+e^-]X$	1548 ± 50
$B^+ \to [J/\psi \to \mu^+\mu^-]X$	1503 ± 42



$B \to J/\psi X$ at Belle II

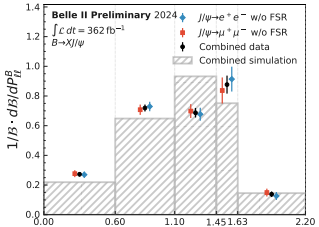
[Paper in preparation]

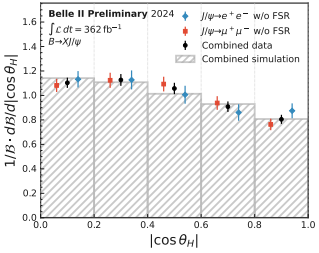
First separate branching fraction measurements (First time shown)

- $\mathcal{B}(B^0 \to J/\psi\, X) =$
  $(0.97 \pm 0.03(\text{stat}) \pm 0.06(\text{sys}))\,\%$, lepton average
- $\mathcal{B}(B^+ \to J/\psi\, X) =$
  $(1.21 \pm 0.03(\text{stat}) \pm 0.08(\text{sys}))\,\%$, lepton average

Differential distributions

- Probes Quantum Chromodynamics in the production of J/ψ





$B \to J/\psi X$ at Belle II

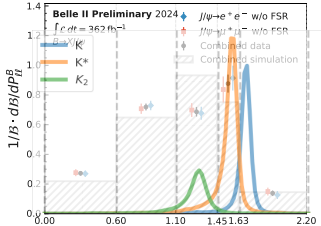
[Paper in preparation]

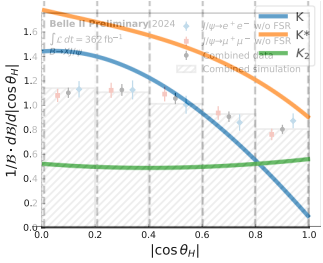
First separate branching fraction measurements (First time shown)

- $\mathcal{B}(B^0 \to J/\psi\, X) =$
  $(0.97 \pm 0.03(\text{stat}) \pm 0.06(\text{sys}))\,\%$, lepton average
- $\mathcal{B}(B^+ \to J/\psi\, X) =$
  $(1.21 \pm 0.03(\text{stat}) \pm 0.08(\text{sys}))\,\%$, lepton average

Differential distributions

- Probes Quantum Chromodynamics in the production of J/ψ





Summary

Papers covered:

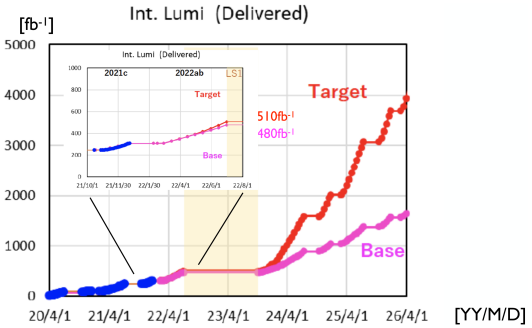
- $B^0 \to \gamma\gamma$: [arXiv:2405.19734]
- $B \to \rho\gamma$: [arXiv:2407.08984]
- $b \to d\ell^+\ell^-$: [arXiv:2404.08133]

Preliminary results:

- $B \to K^*\gamma$ at Belle II
- $B \to J/\psi X$ at Belle II

The results shown used 362 fb^{-1} (Run 1)

- More Run 1 results are coming
- Run 2 ongoing – more data to come



Thank you for listening!

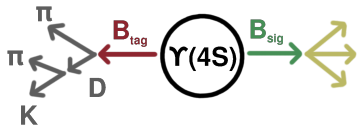
B-meson Tagging

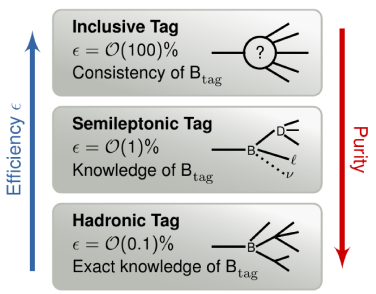
Reconstruct one of the B-meson

- Tag-side – Other B is our signal
- Used to reconstruct invisible particles in our signal

Three methods:

- Inclusive tagging
- Semileptonic tagging
- Hadronic tagging





B-meson Tagging

Reconstruct one of the B-meson

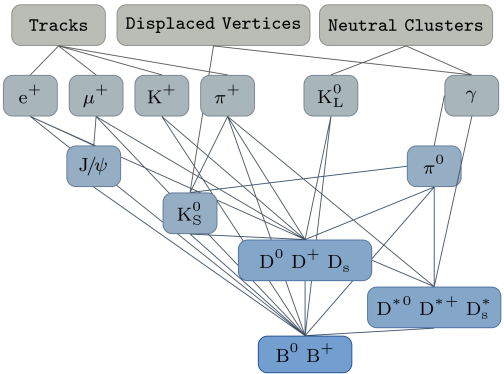
- Tag-side – Other B is our signal
- Used to reconstruct invisible particles in our signal

Three methods:

- Inclusive tagging
- Semileptonic tagging
- Hadronic tagging

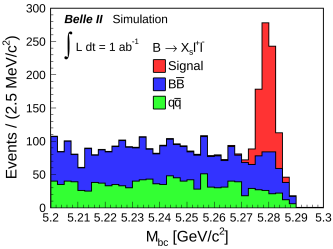
Full Event Interpreter (FEI) [arXiv:1807.08680]:

- Uses $>$ 200 BDTs
- Reconstructs 10,000 B-decay chains



$B \to X_s\ell\ell$ at Belle II

[arXiv:2012.15394], [arXiv:1709.10308]



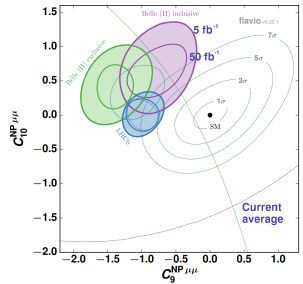
Measurement of $R(X_s) = \frac{\mathcal{B}(B \to X_s \mu^+ \mu^-)}{\mathcal{B}(B \to X_s e^+ e^-)}$ also in progress

Two methods available:

- Sum-of-exclusive modes
- Fully inclusive using tagging

Expected sensitivity:

Observables	Belle (0.71 ab^{-1})	Belle II (5 ab^{-1})	Belle II (50 ab^{-1})
R_{X_s} ($[1.0, 6.0]$ GeV$^2/c^4$)	32%	12%	4.0%
R_{X_s} ($[> 14.4]$ GeV$^2/c^4$)	28%	11%	3.4%



Angular analysis of $B \to X_s\ell\ell$ will improve constraints on Wilson coefficient C9 and C10

$B \to J/\psi K$

Control check using K resonance in $P^B_{\ell\ell} \in [1.63, 1.72]$ GeV/c:

	$\mathcal{B}(ee)$ [%]	$\mathcal{B}(\mu\mu)$ [%]	PDG [%]
B^+	0.082 ± 0.016	0.122 ± 0.019	0.102 ± 0.002
B^0	0.097 ± 0.018	0.072 ± 0.015	0.089 ± 0.002