Search for new phenomena beyond the Standard Model at Belle II

Junewoo PARK (UTokyo)

on behalf of the Belle II collaboration

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Belle and Belle II Experiments

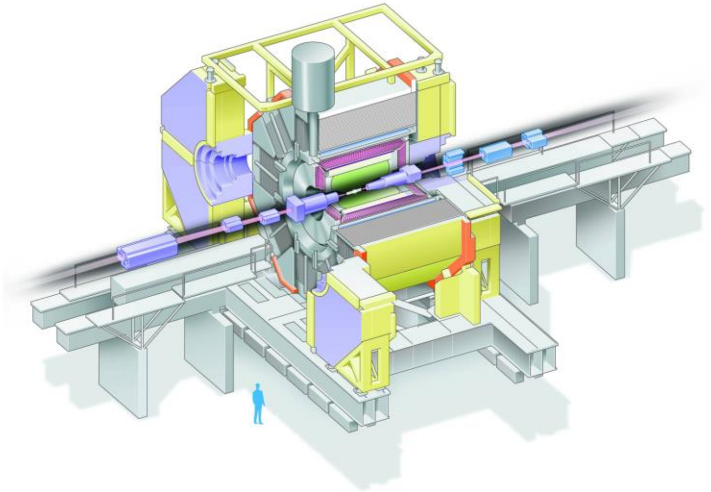
- Asymmetric energy collisions of electrons and positrons
- Its energy corresponds to $\sqrt{s} = 10.58\ \mathrm{GeV}$, which is the resonance energy of $\Upsilon(4S)$
  - $\Upsilon(4S)$ mainly decays into B meson pairs

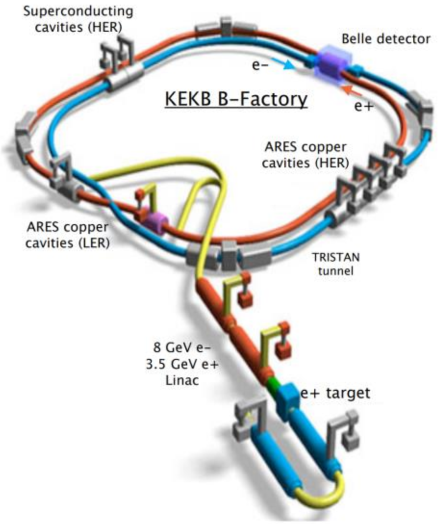
Belle experiment

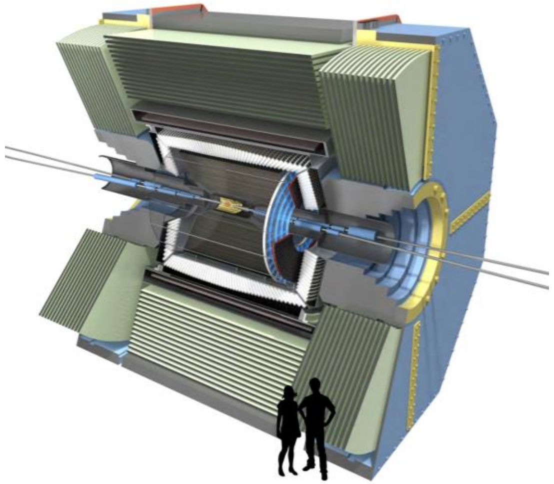
- 1999 - 2010
- $\mathcal{L}_{int} = 1\ ab^{-1}$
- $e^{+}(3.5\ \mathrm{GeV})\ e^{-}(8\ \mathrm{GeV})$ accelerated by KEKB

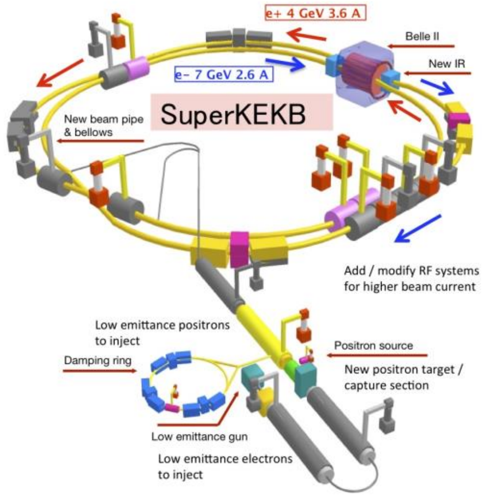
Belle II experiment

- 2019 - current
- $\mathcal{L}_{int} = 0.55\ ab^{-1}$ by December 2024
- $e^{+}(4\ \mathrm{GeV})\ e^{-}(7\ \mathrm{GeV})$ accelerated by SuperKEKB



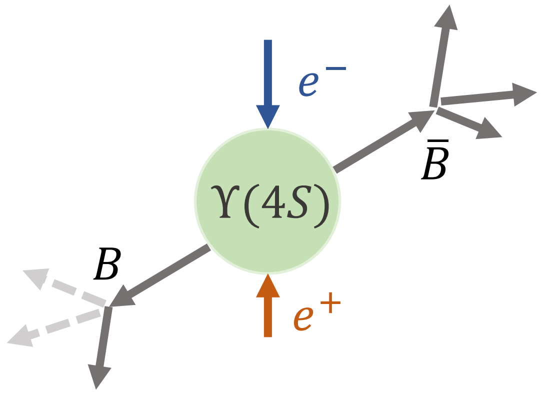






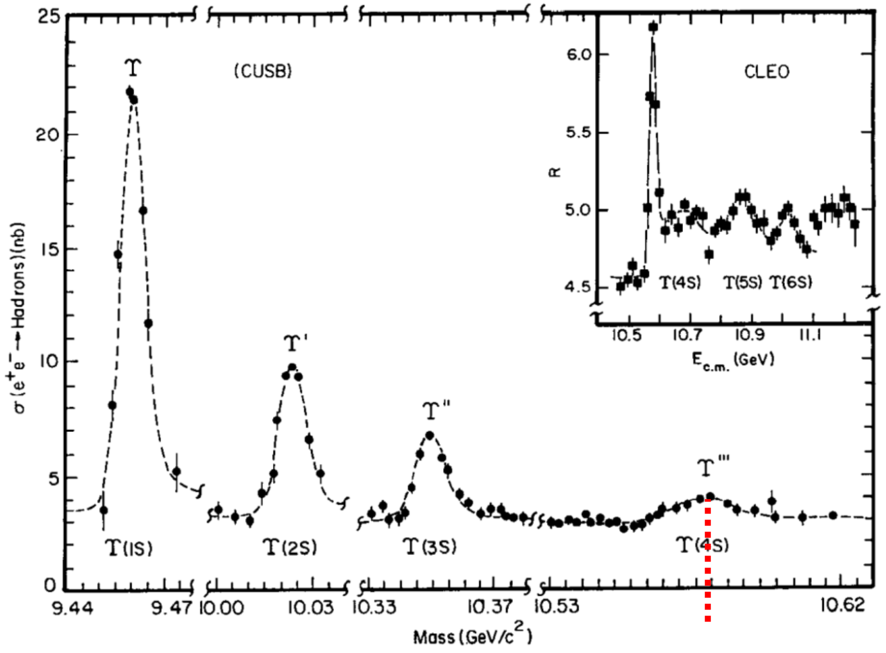
Belle and Belle II Experiments

- Entire information of initial states is known in Belle II experiment.
  → Belle II has an advantage on the decay modes with invisible particles, like neutrinos



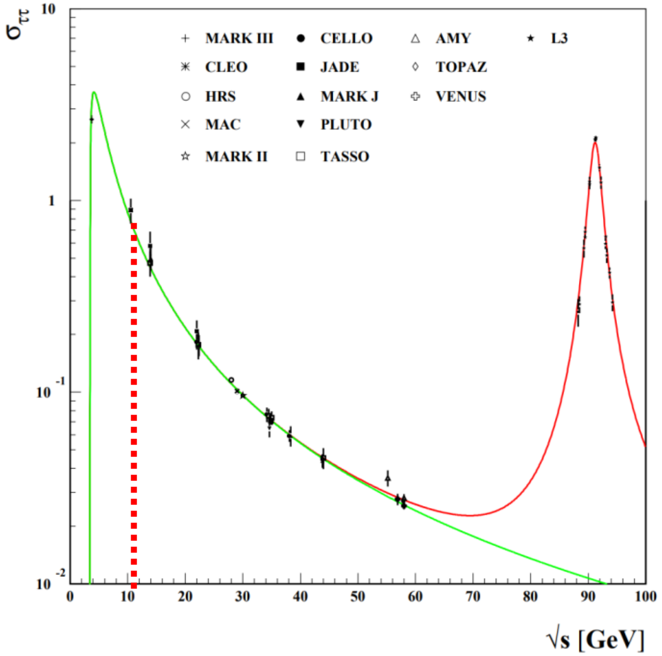
- Belle II experiment is not only B factory, but also tau factory.

[Ann Rev Nucl Part Sci 43:333–378]



$\sigma(e^+e^- \to \Upsilon(4S)) \sim 1.1$ nb @ 10.58 GeV

[*Phys.Rept.* 274 (1996) 287-376]



$\sigma(e^+e^- \to \tau^+\tau^-) \sim 0.9$ nb @ 10.58 GeV

- We can also enjoy tau physics!

Overview

Electroweak penguin $B^+ \to K^+ \nu\bar{\nu}$ [Phys. Rev. D 109, 112006 (2024)]

Lepton flavor violation $\tau^- \to \mu^+\mu^-\mu^-$ [JHEP09(2024)062]

Lepton flavor universality $R(D^*)$ [Phys. Rev. D 110, 072020 (2024)]

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

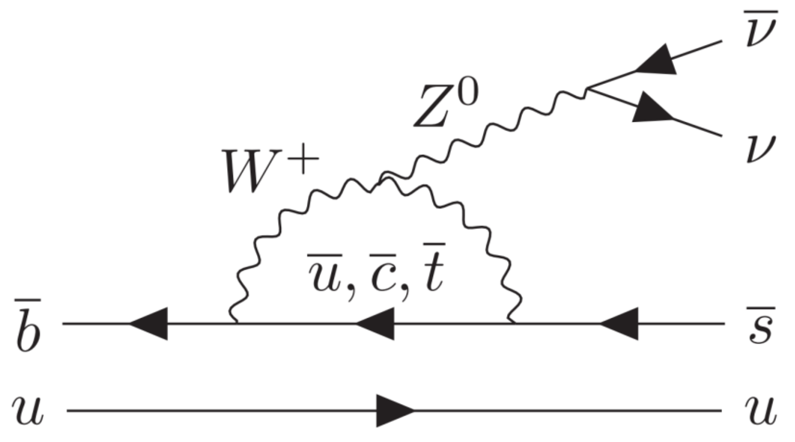
[Phys. Rev. D 109, 112006 (2024)]

[Phys. Rev. D 109, 112006 (2024)]

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

- $B^+ \to K^+ \nu\bar{\nu}$ decay
  - Flavour-changing neutral currents process
  - $\mathrm{BR} = (5.6 \pm 0.4) \times 10^{-6}$ at SM [Phys. Rev. D 107, 119903 (2023)]

- This decay can give a clue for non-SM particles
  - Leptoquark [Phys. Rev. D 98, 055003]
  - Axion [Phys. Rev. D 102, 015023]
  - Dark sector mediator [Phys. Rev. D 101, 095006]

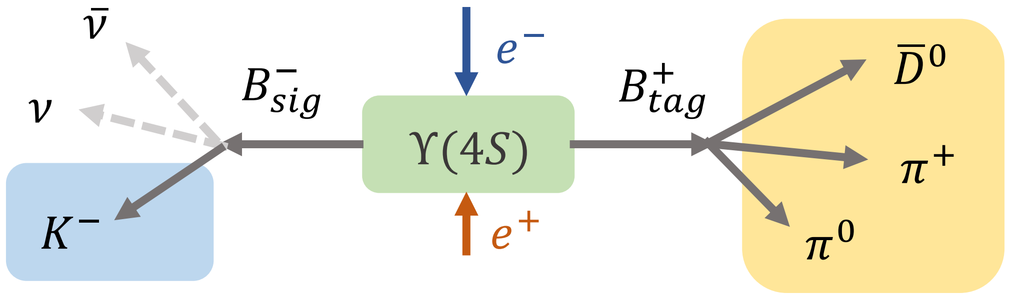


experiment	Upper limit (90% CL)	$\mathcal{L}_{int}$	Tagging method	reference
BABAR	3.7×10^{-5}	$429\ fb^{-1}$	hadronic	Phys. Rev. D 87, 112005 (2013)
BABAR	1.3×10^{-5}	$418\ fb^{-1}$	semileptonic	Phys. Rev. D 82, 112002 (2010)
Belle	5.5×10^{-5}	$711\ fb^{-1}$	hadronic	Phys. Rev. D 87, 111103 (2013)
Belle	1.9×10^{-5}	$711\ fb^{-1}$	semileptonic	Phys. Rev. D 96, 091101 (2018)
Belle II	4.1×10^{-5}	$63\ fb^{-1}$	inclusive	Phys. Rev. Lett. 127, 181802 (2021)

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

- $362\ fb^{-1}$ on-resonance data is used for this analysis
- Two tagging methods are done
  - hadronic tagging analysis (HTA)
  - inclusive tagging analysis (ITA)

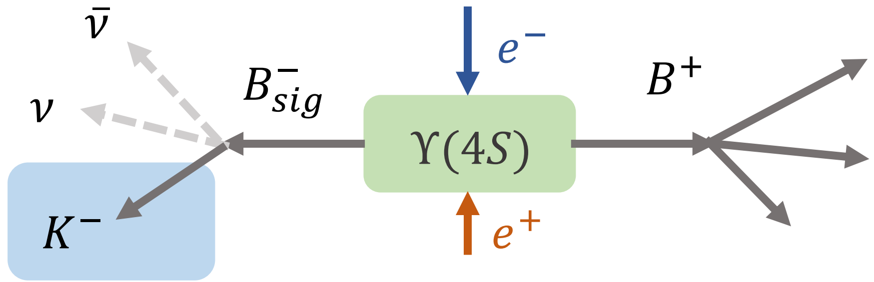
- In HTA, one of B meson is reconstructed by hadronic decay modes



- Exact kinematics of B_{tag} is known
- high purity
- low efficiency

- In ITA, the second B meson is not explicitly reconstructed

* ROE: rest of event



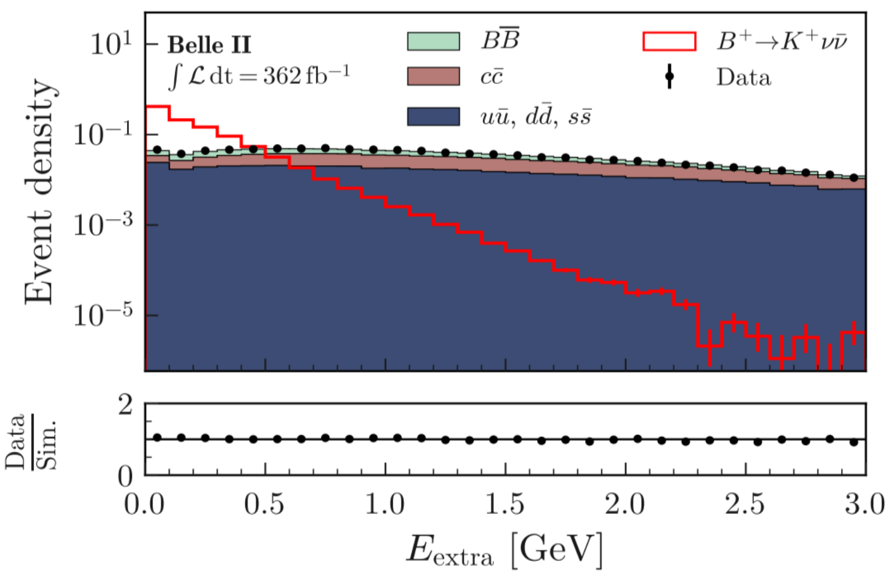
- Information of remaining particles (ROE) is used
- low purity
- high efficiency

[Phys. Rev. D 109, 112006 (2024)]

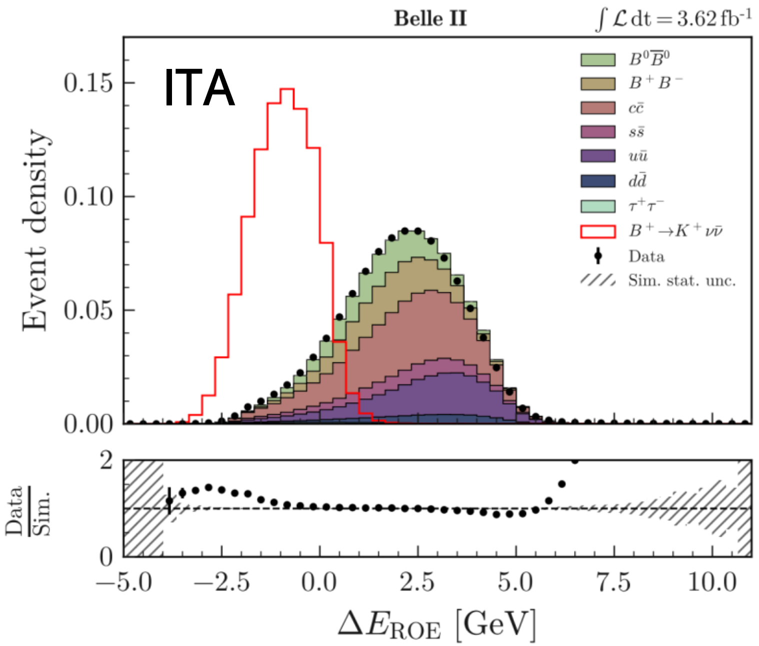
$B^+ \to K^+ \nu \bar{\nu}$

- For the background suppression, boosted decision tree (BDT) is used as the multivariate analysis technique
  - For HTA, total 12 variables are used
    - most powerful variable:
      → sum of remaining energy in the electromagnetic calorimeter (E_{extra})
  - For ITA, total 12 and 35 variables are used for two consecutive BDTs
    - most powerful variables:
      → Energy of ROE in c.m. frame $- \frac{\sqrt{s}}{2}$ (ΔE_{ROE})
      → event shape variable ($\cos((\text{thrust}_K), \text{thrust}_{\text{ROE}})$)

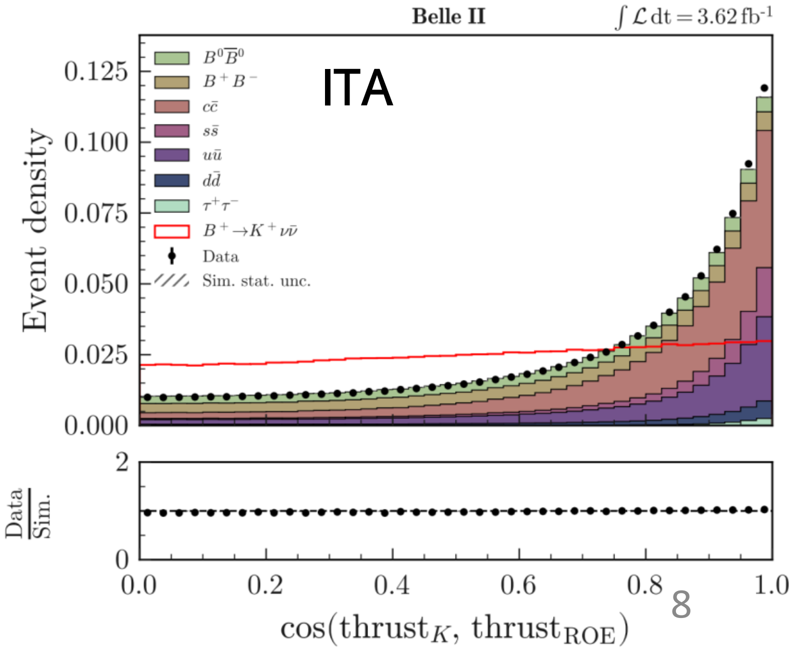
HTA



ITA



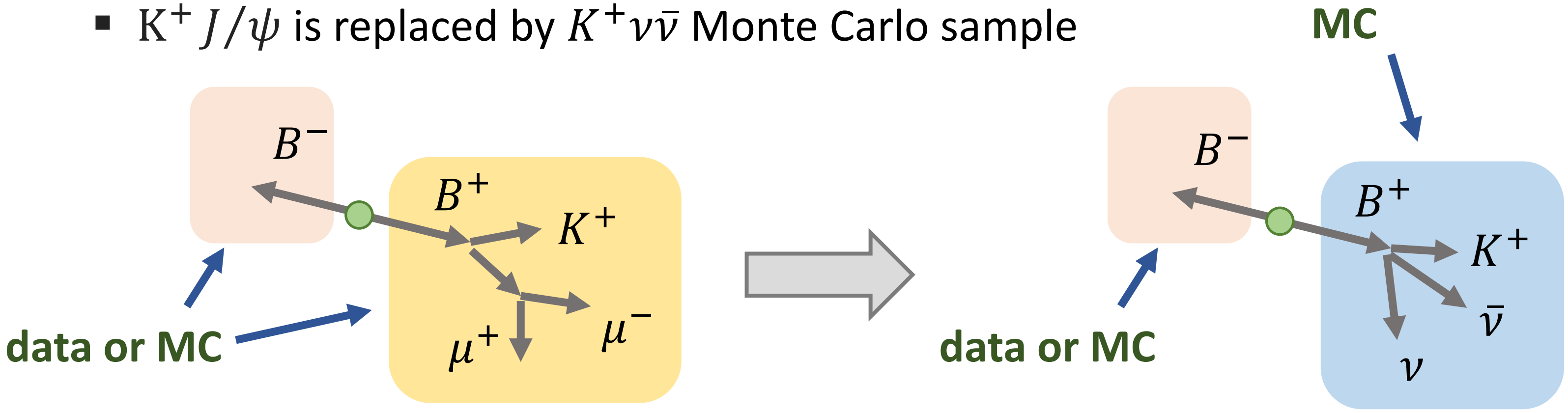
ITA

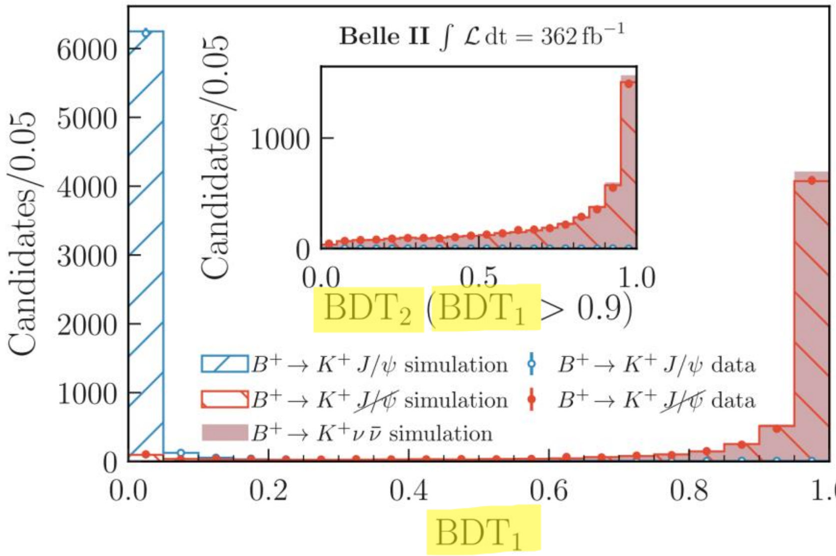


[Phys. Rev. D 109, 112006 (2024)]

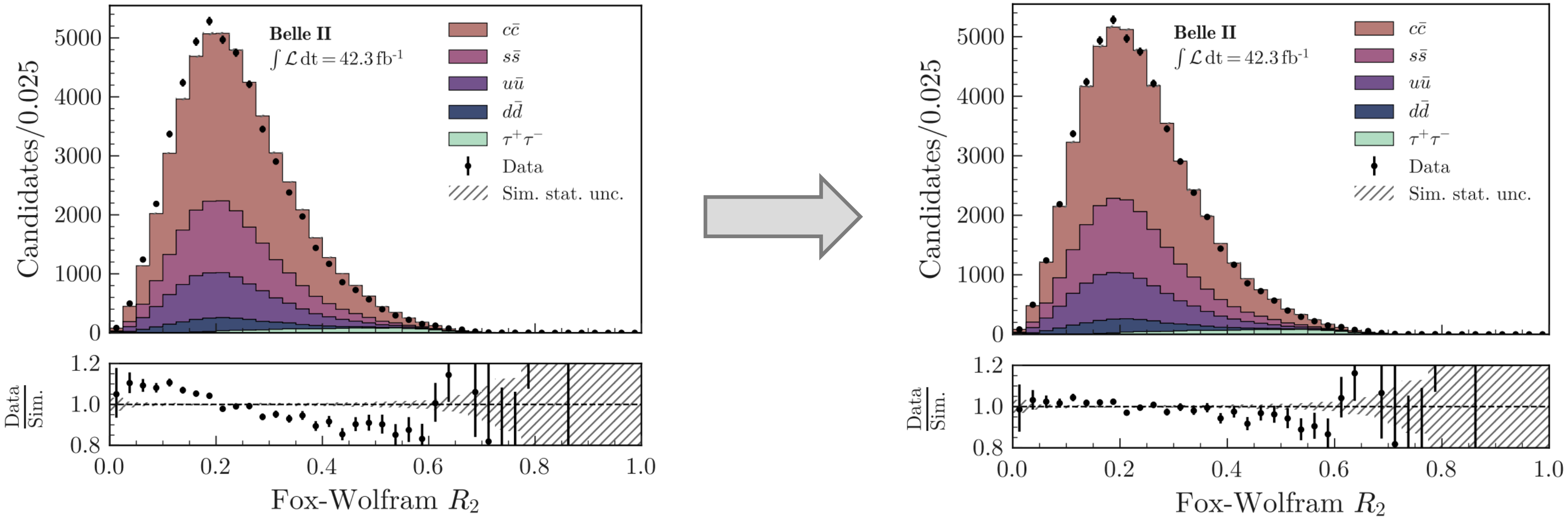
$B^+ \to K^+ \nu\bar{\nu}$

- $B^+ \to K^+ J/\psi\,(\to \mu^+\mu^-)$ is used for the signal efficiency validation
  - $K^+ J/\psi$ is replaced by $K^+\nu\bar{\nu}$ Monte Carlo sample





- The lower beam energy sample is used to correct the $e^+e^- \to q\bar{q}\ (q = u, d, s, c)$ background

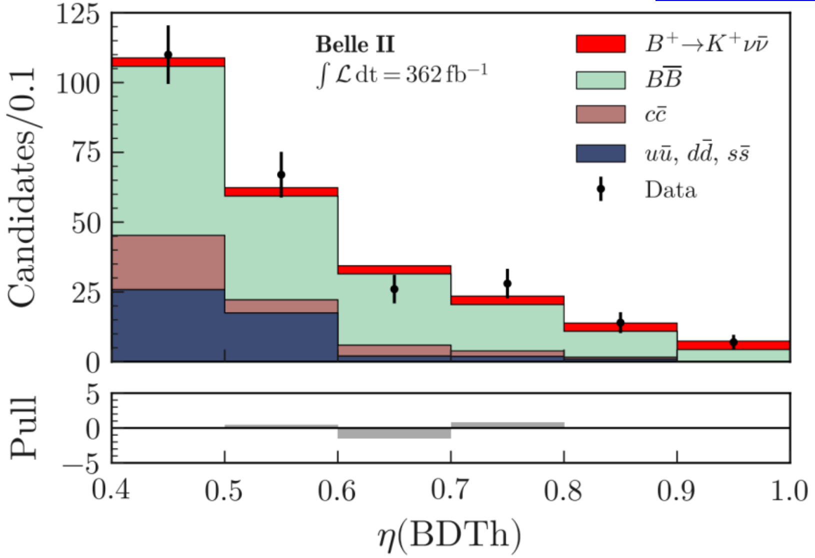


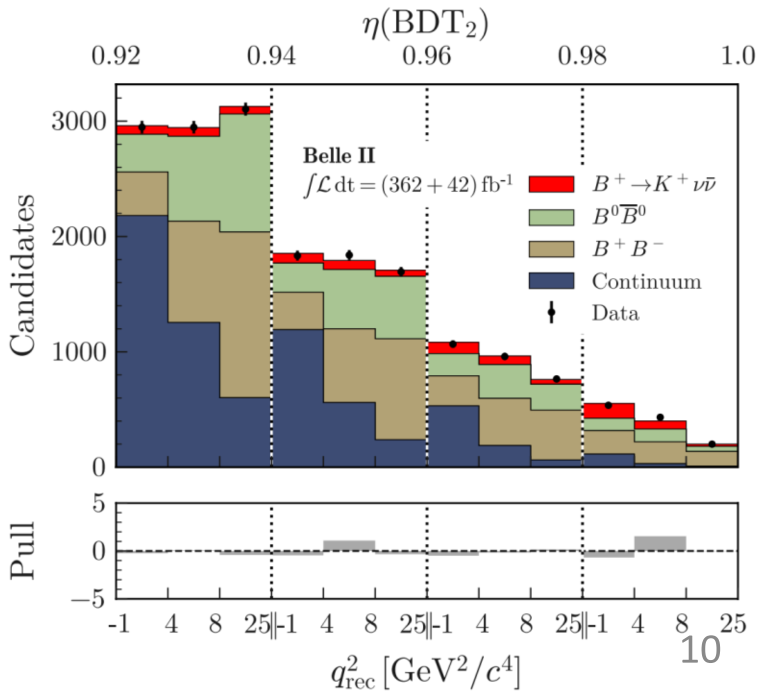
- Different BDT is trained to distinguish between data and MC
- Output of this BDT is used as a correction factor

[Phys. Rev. D 109, 112006 (2024)]

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

- Binned maximum likelihood fit is done to extract the signal yield
- Signal regions
  - For HTA, signal yield extraction is done on $\boldsymbol{\eta(\mathrm{BDT}_h)}$ space
    - $\eta(\mathrm{BDT_h})$: variables related to the efficiency as a function of BDT cut
  - For ITA, signal yield extraction is done on $\boldsymbol{\eta(\mathrm{BDT}_2)} \times \boldsymbol{q^2_{\mathrm{rec}}}$ space
    - $\eta(\mathrm{BDT}_2)$: variables related to the efficiency as a function of BDT cut
    - q^2_{rec}: invariant mass square of the neutrino pair

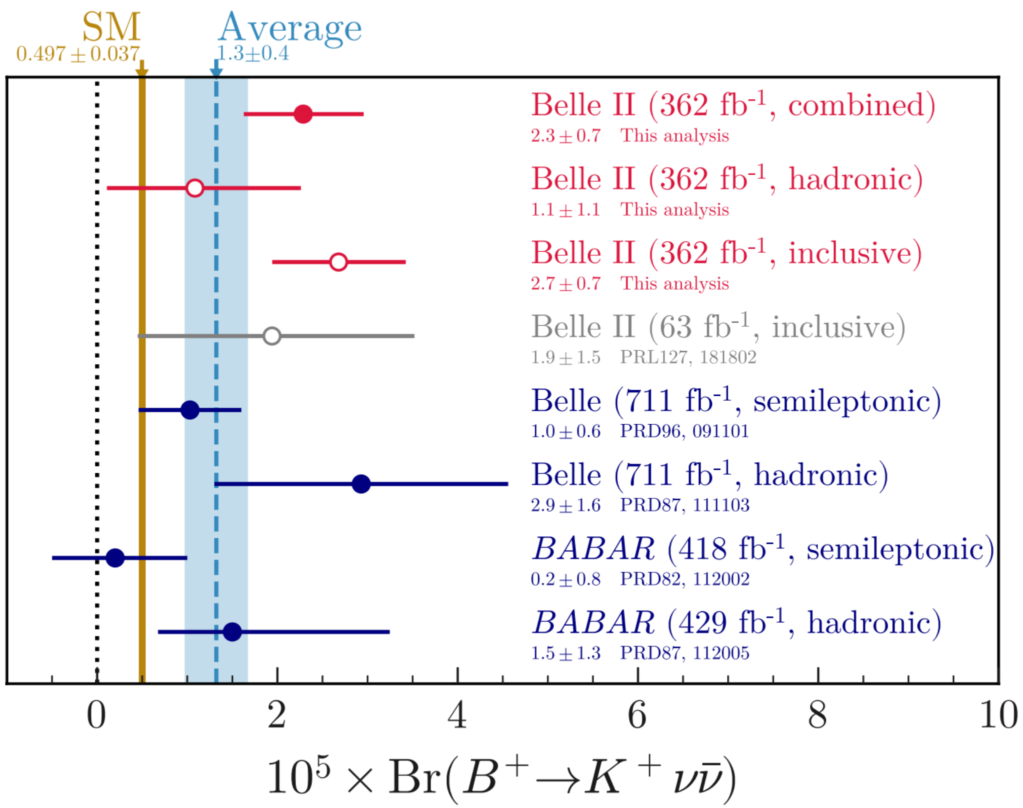




$q^2_{\mathrm{rec}} = s/(4c^4) + M_K^2 - \sqrt{s}E_K^*/c^4$ with assuming the signal B to be at rest in c.m. frame

[Phys. Rev. D 109, 112006 (2024)]

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



- Hadronic tag:

$$BR(B^+ \to K^+ \nu\bar{\nu}) = \left[1.1^{+0.9}_{-0.8}(\text{stat})^{+0.8}_{-0.5}(\text{syst})\right] \times 10^{-5}$$

- Inclusive tag:

$$BR(B^+ \to K^+ \nu\bar{\nu}) = [2.7 \pm 0.5(\text{stat}) \pm 0.5(\text{syst})] \times 10^{-5}$$

- Combined result:

$$BR(B^+ \to K^+ \nu\bar{\nu}) = \left[2.3 \pm 0.5(\text{stat})^{+0.5}_{-0.4}(\text{syst})\right] \times 10^{-5}$$

→ first evidence for the $B^+ \to K^+ \nu\bar{\nu}$ decay (3.5σ)

- Compatibility with SM: 2.7σ

$$\tau^{-} \rightarrow \mu^{+}\mu^{-}\mu^{-}$$

[JHEP09(2024)062]

$\tau^- \to \mu^+\mu^-\mu^-$

[JHEP09(2024)062]

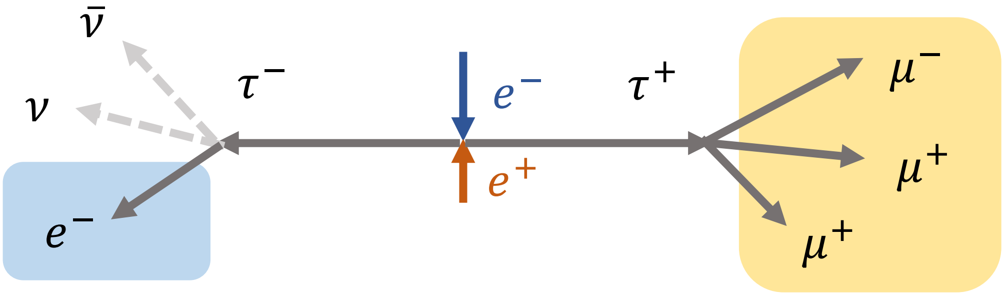
Belle II

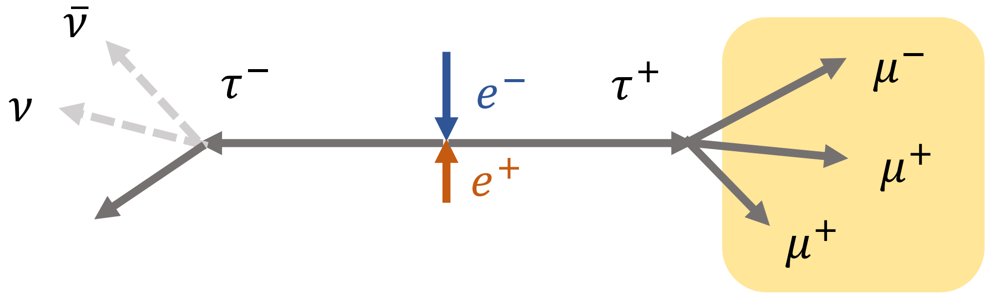
- Belle II experiment is not only B factory but also tau factory
- $\tau^- \to \mu^+\mu^-\mu^-$ decay
  - Hard to occur in SM ($\mathrm{BR} \sim \mathcal{O}(10^{-50})$) [Eur. Phys. J. C 79 (2019) 84]
- This decay can be enhanced by new physics
  - Inverse Seesaw mechanism [J. Phys. Conf. Ser. 888 (2017) 012029]
- $424\ fb^{-1}$ data is used for the analysis

experiment	Upper limit (90% CL)	$\mathcal{L}_{int}$	Tagging method	reference
CLEO	1.9×10^{-6}	$4.79\ fb^{-1}$	one-prong	Phys. Rev. D 57 (1998) 5903
BABAR	3.3×10^{-8}	$468\ fb^{-1}$	one-prong	Phys. Rev. D 81 (2010) 111101
LHCb	4.6×10^{-8}	$3\ fb^{-1}$	-	JHEP 02 (2015) 121
ATLAS	3.8×10^{-7}	$20.3\ fb^{-1}$	-	Eur. Phys. J. C 76 (2016) 232
CMS	8.0×10^{-8}	$33.2\ fb^{-1}$	-	JHEP 01 (2021) 163

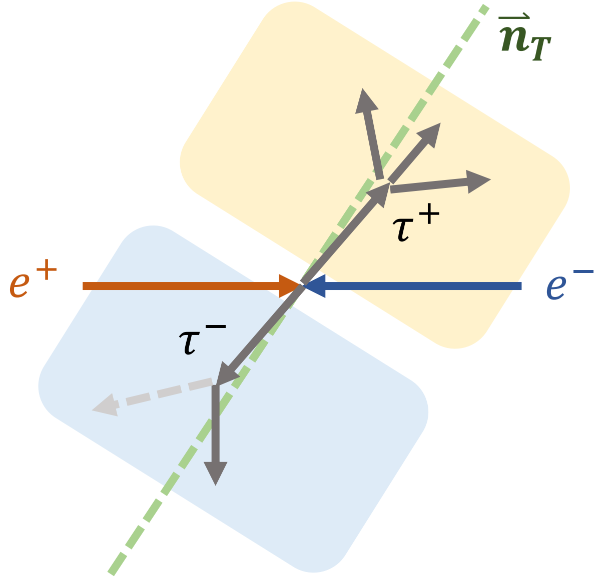
$\tau^- \to \mu^+ \mu^- \mu^-$

- Two analysis methods are done in this analysis
  - one-prong tagging analysis (for the validation)
  - inclusive tagging analysis



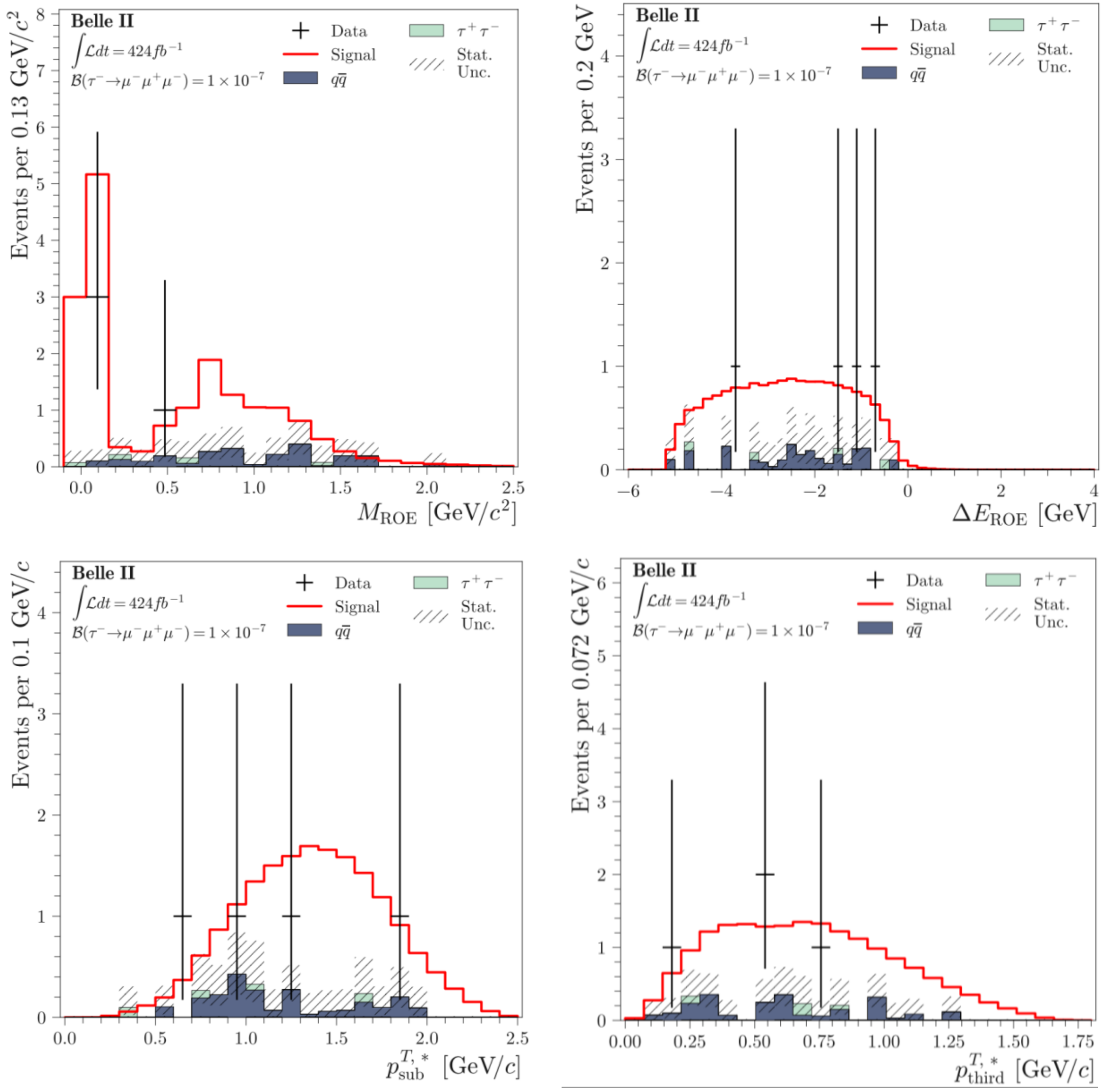


- The space is divided into two hemispheres
  - determine a vector $\vec{n}_T$ that the sum of inner products with visible particles' momentum is maximized
  - Then, we can define two hemispheres by the plane perpendicular to $\vec{n}_T$
  - All three μ are required to be included in the same hemisphere



$\tau^- \to \mu^+\mu^-\mu^-$

- BDT is used to suppress backgrounds
  - total 32 variables are used
  - the most discriminating variables:
    - mass of ROE (M_{ROE})
    - Energy of ROE in c.m. frame $- \frac{\sqrt{s}}{2}$ (ΔE_{ROE})
    - transverse momentum of the second highest momentum muon ($p^{T,*}_{\text{sub}}$)
    - transverse momentum of the lowest momentum muon ($p^{T,*}_{\text{thrid}}$)
  - cross-validation (k-folding) algorithm † is used to reduce the impacts from the statistical fluctuation

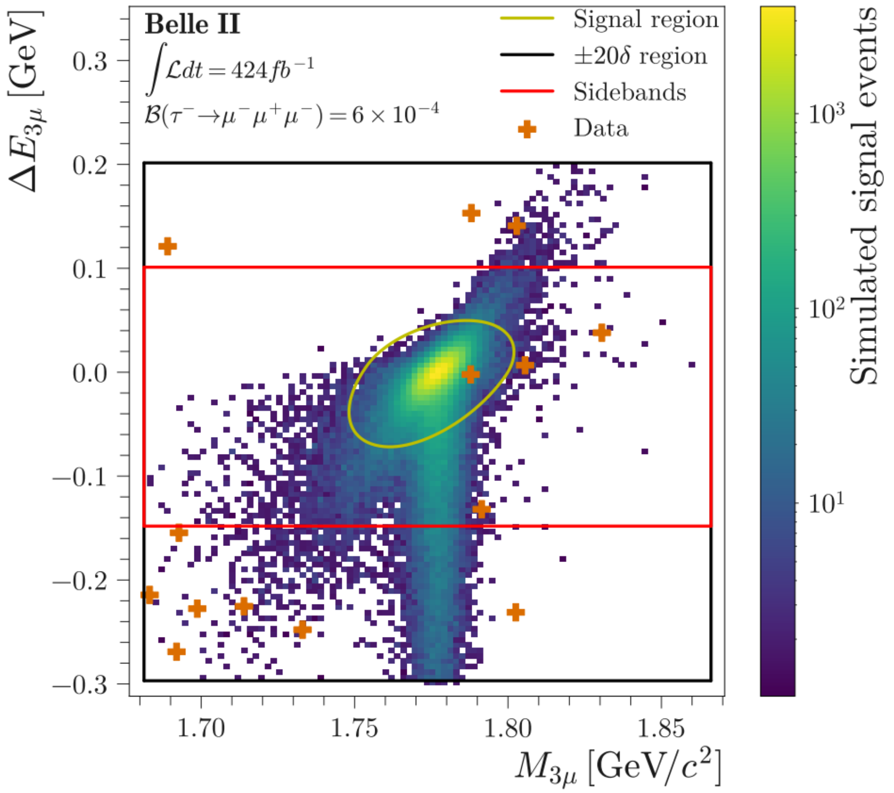


† Association for Computing Machinery, (1999), p. 203

[JHEP09(2024)062]

$\tau^- \rightarrow \mu^+\mu^-\mu^-$

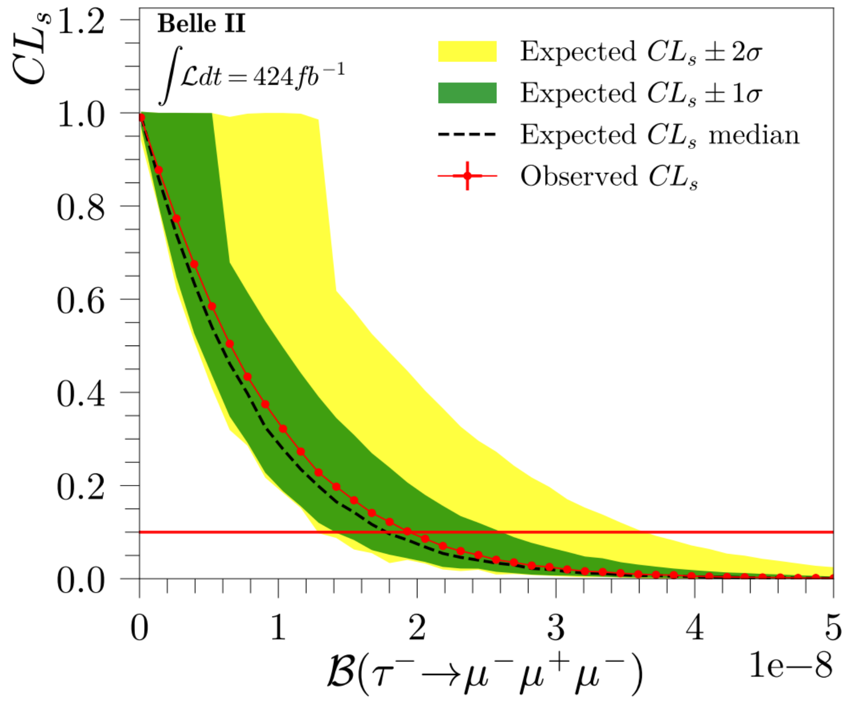
- Counting method is used in $(M_{3\mu}, \Delta E_{3\mu})$ plane
  - $M_{3\mu}$: invariant mass of three muons
  - $\Delta E_{3\mu}$: (Energy of three muons - a half of beam energy) in c.m. frame
- The signal region and sideband region are defined
  - Signal region (yellow line):
    - elliptical region is obtained from the MC sample
    - $\pm 5\ \delta$ region, where δ is expected resolution
  - Sideband region (region between red and yellow lines)
    - $\pm 20\ \delta_M, \pm 10\ \delta_{\Delta E}$ wide rectangular region
- The number of expected background is obtained from the 2D plane (BDT output) X (distance from signal peak)



$\tau^- \to \mu^+\mu^-\mu^-$

- Result
  - $N_{\text{exp}} = 0.7^{+0.6}_{-0.5}$: the expected number of background events
  - $N_{obs} = 1$: the number of observed events
  - $BR(\tau^- \to \mu^+\mu^-\mu^-) = \left(2.1^{+5.1}_{-2.4} \pm 0.4\right) \times 10^{-9}$
    - $BR(\tau^- \to \mu^+\mu^-\mu^-) = \frac{N_{obs}-N_{exp}}{\mathcal{L}\times 2\sigma_{\tau\tau}\times\epsilon_{3\tau}}$
  - Upper limit of branching ratio = 1.9×10^{-8} at 90% confidence level

→ World's best limit



$R(D^*)$

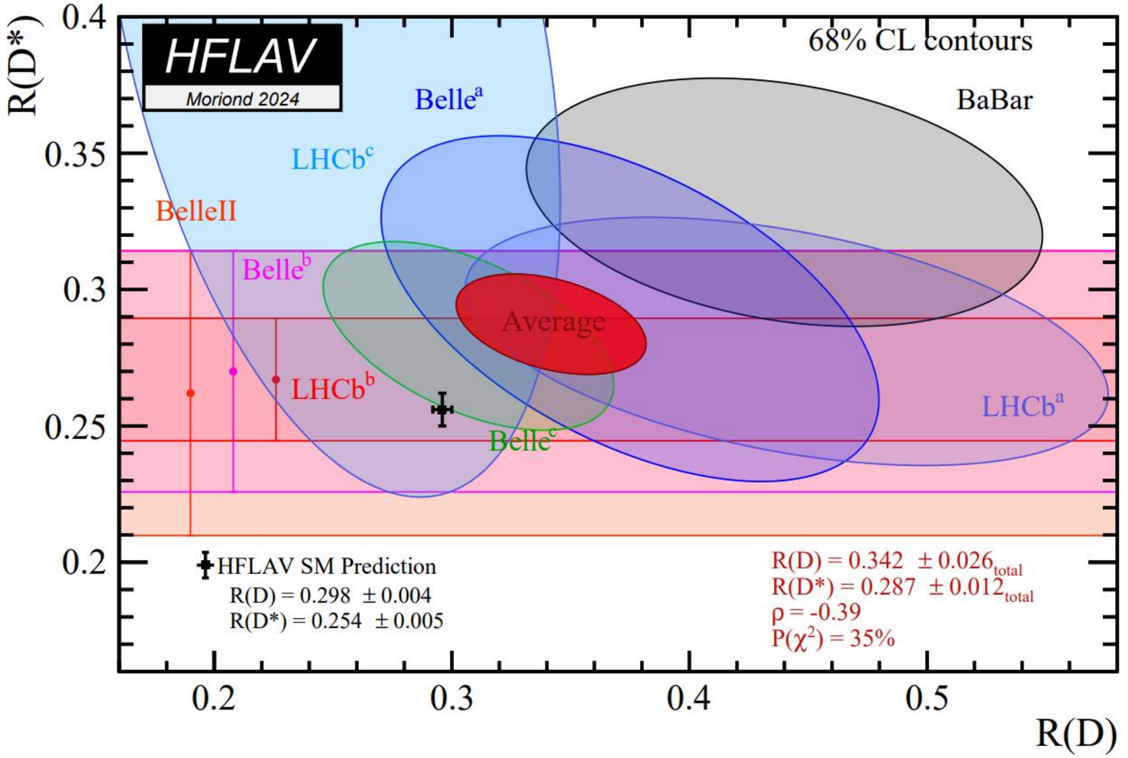
[Phys. Rev. D 110, 072020 (2024)]

[Phys. Rev. D 110, 072020 (2024)]

$R(D^*)$

- Measuring $R(D^{(*)})$ is the direct test for the lepton flavour universality (LFU)
  - $R(D^{(*)}) = \frac{BR(\bar{B}\to D^{(*)}\tau\bar{\nu}_\tau)}{BR(\bar{B}\to D^{(*)}\ell\bar{\nu}_\ell)}$
  - In SM, [Phys. Rev. D 107, 052008]
    - $R(D) = 0.298 \pm 0.004$
    - $R(D^*) = 0.254 \pm 0.005$
  - Several systematic uncertainties are canceled for $R(D^{(*)})$, like quark mixing element $|V_{cb}|$
  - $R(D^{(*)})$ can be changed by new physics
    - Leptoquark [Phys. Rev. D 104, 055017]
    - W' boson [JHEP12(2016)059]

[Moriond 2024]

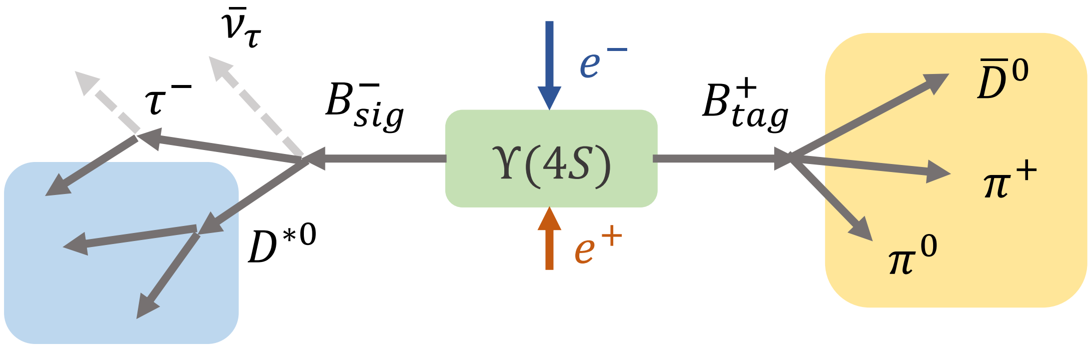


- Currently, it shows some tension from SM prediction: $\sim 3.17\sigma$

[Phys. Rev. D 110, 072020 (2024)]

$R(D^*)$

- $189\ fb^{-1}$ on-resonance data is used for this analysis
- Hadronic tagging method is used



- The following decay modes are reconstructed for the signal side

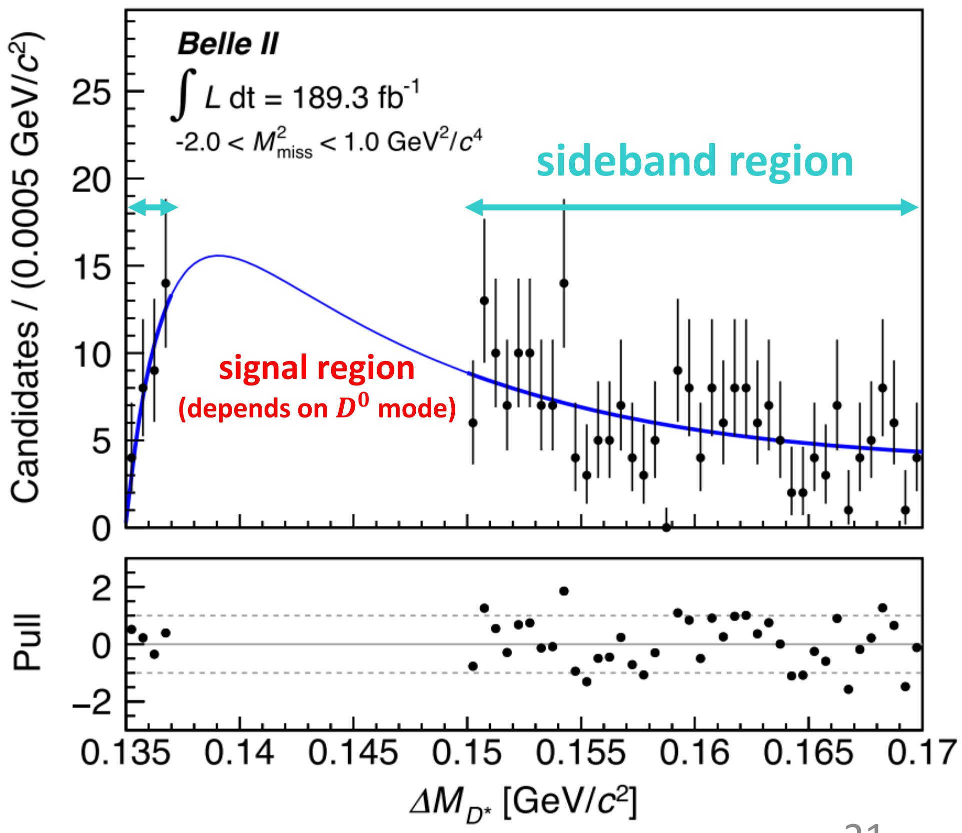
particle	Decay modes	remark
τ	$e^-\bar{\nu}_e\nu_\tau$ $\quad$ $\mu^-\bar{\nu}_\mu\nu_\tau$	Leptonic mode
D^{*+}	$D^0\pi^+$ $\quad$ $D^+\pi^0$	
D^{*0}	$D^0\pi^0$	
D^+	$K^-\pi^+\pi^+$ $\quad$ $K^0_S\pi^+$ $\quad$ $K^-K^+\pi^+$	
D^0	$K^-\pi^+\pi^0$ $\quad$ $K^-\pi^+\pi^-\pi^+$ $\quad$ $K^0_S\pi^+\pi^-\pi^0$ $\quad$ $K^-\pi^+$ $K^0_S\pi^+\pi^-$ $\quad$ $K^0_S\pi^0$ $\quad$ K^-K^+ $\quad$ $\pi^-\pi^+$	

[Phys. Rev. D 110, 072020 (2024)]

$R(D^*)$

- Dominant background comes from the misreconstructed D^* candidates:
  - (Correctly reconstructed D) + (low-momentum pion not from D^*)
  - misreconstructed D with low-momentum pion
- This fake D^* yield is calibrated from the sideband for each D^* mode
  - The **sideband region** is defined in ΔM_{D^*} region, where $\Delta M_{D^*} = M_{D^*} - M_D$
  - The fit is done on the sideband, to obtain the data-simulation ratio of fake D^* yield

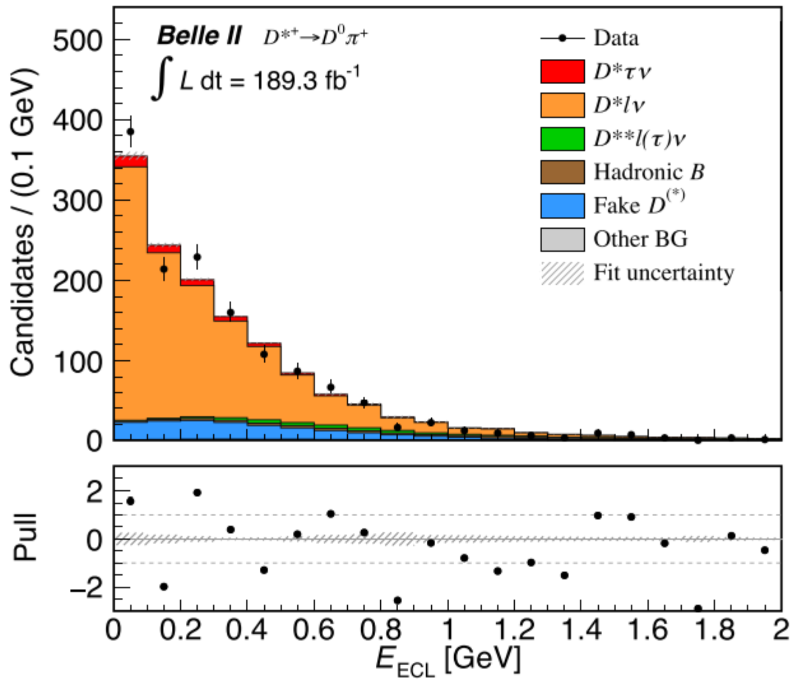
$D^{*0} \to D^0\pi^0$



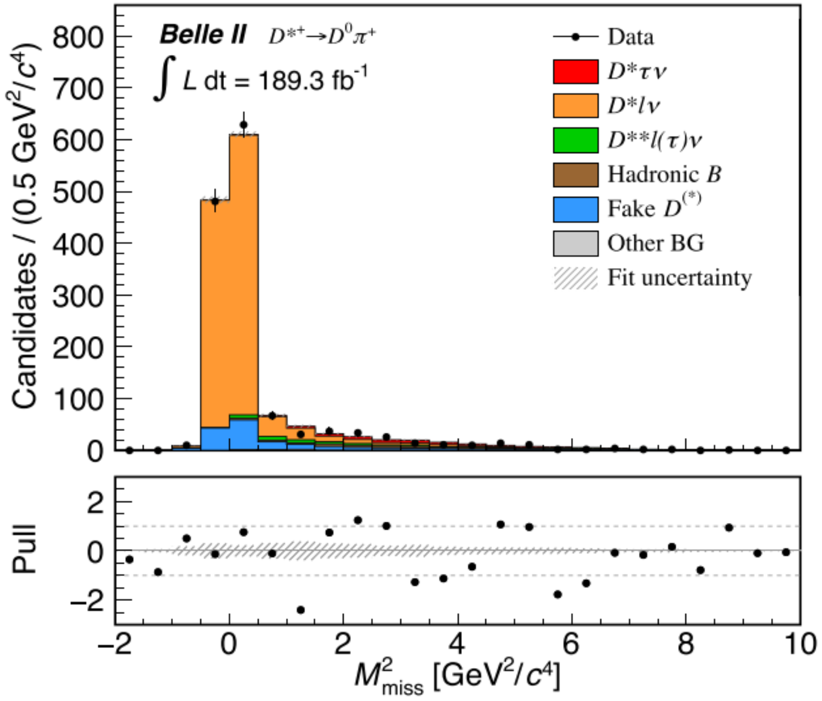
$R(D^*)$

- To extract the signal yield, extended binned maximum likelihood fit is done
- Signal region
  - $E_{\mathrm{ECL}} \times \mathrm{M}^2_{\mathrm{miss}}$ $*\ E_{\mathrm{ECL}} = E_{\mathrm{extra}}$
- The probability density functions are constructed for each D^* modes

$D^{*+} \to D^0\pi^+$



$D^{*+} \to D^0\pi^+$



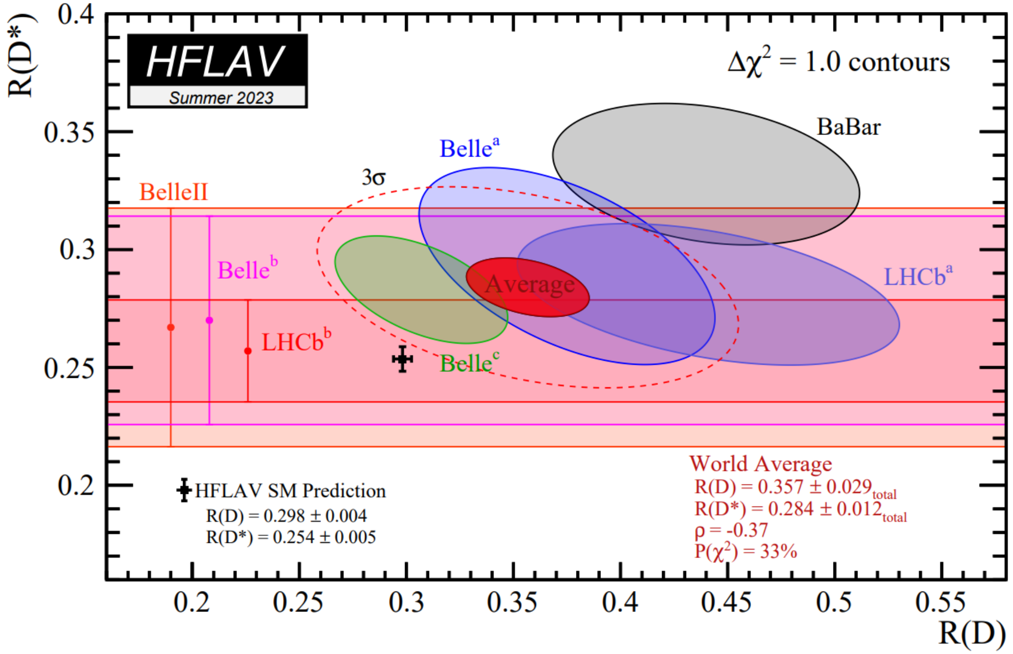
$R(D^*)$

- Result
  - $R(D^*) = 0.262^{+0.041}_{-0.039}(\mathrm{stat})^{+0.035}_{-0.032}(\mathrm{syst})$

→ Statistical uncertainty ($^{+15.7\%}_{-14.7\%}$) is comparable to Belle result (13.0%), even though this analysis uses much smaller data size (189 fb^{-1} vs 711 fb^{-1}) 🎉

  - Consistent with SM prediction

[HFLAV]



Summary

- Belle II experiment has advantages in B and tau physics
  - Target energy is appropriate for B and tau production
  - decays with invisible particles can be analyzed
- Broad range of analysis have been successfully done in Belle II experiment
  - EWP: $B^+ \to K^+ \nu\bar{\nu}$

    → first evidence for the $B^+ \to K^+ \nu\bar{\nu}$ decay (3.5σ)
  - LFV: $\tau^- \to \mu^+\mu^-\mu^-$

    → World's best result
  - LFU: $R(D^*)$

    → comparable statistical uncertainty, with much smaller data size, compared to Belle experiment

more exciting results will come!

Backup

[Phys. Rev. D 109, 112006 (2024)]

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

BDT_1

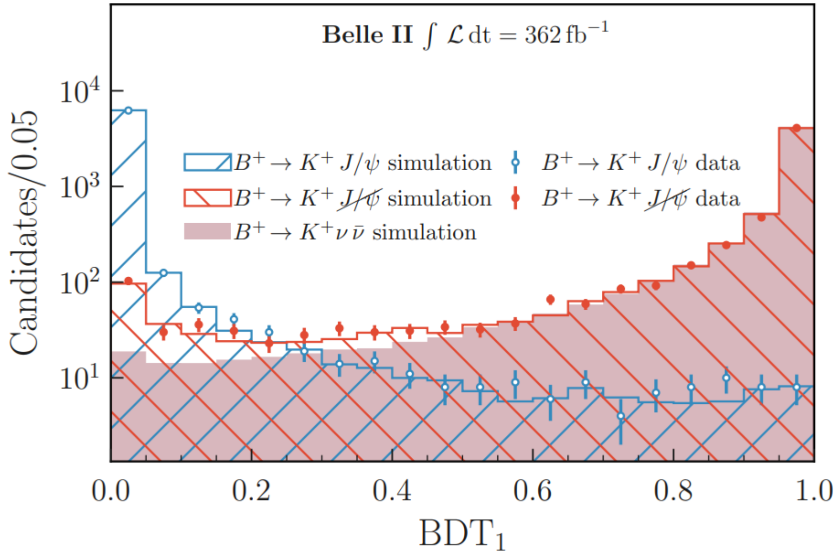
$BDT_1 > 0.9$

BDT_2

12 input variables are used

- discriminating variables:

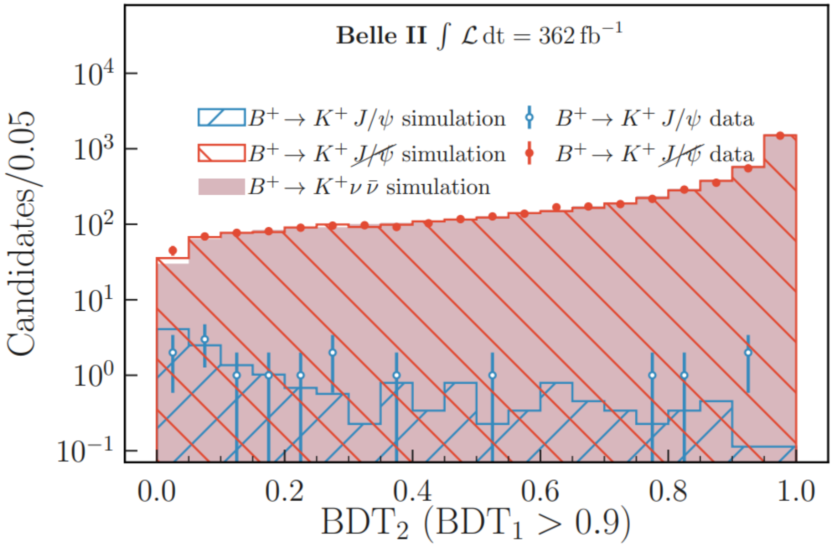
Energy of ROE in c.m. frame $- \frac{\sqrt{s}}{2}$



35 input variables are used

- discriminating variables:

$\cos((\text{thrust}_K), \text{thrust}_{\text{ROE}})$



[Phys. Rev. D 109, 112006 (2024)]

Belle II

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

TABLE I. Sources of systematic uncertainty in the ITA, corresponding correction factors (if any), their treatment in the fit, their size, and their impact on the uncertainty of the signal strength μ. The uncertainty type can be "Global", corresponding to a global normalization factor common to all SR bins, or "Shape", corresponding to a bin-dependent uncertainty. Each source is described by one or more nuisance parameters (see the text for more details). The impact on the signal strength uncertainty σ_μ is estimated by excluding the source from the minimization and subtracting in quadrature the resulting uncertainty from the uncertainty of the nominal fit.

Source	Correction	Uncertainty type, parameters	Uncertainty size	Impact on σ_μ
Normalization of $B\bar{B}$ background		Global, 2	50%	0.90
Normalization of continuum background		Global, 5	50%	0.10
Leading B-decay branching fractions		Shape, 6	$O(1\%)$	0.22
Branching fraction for $B^+ \to K^+ K^0_L K^0_L$	q^2 dependent $O(100\%)$	Shape, 1	20%	0.49
p-wave component for $B^+ \to K^+ K^0_S K^0_L$	q^2 dependent $O(100\%)$	Shape, 1	30%	0.02
Branching fraction for $B \to D^{**}$		Shape, 1	50%	0.42
Branching fraction for $B^+ \to K^+ n\bar{n}$	q^2 dependent $O(100\%)$	Shape, 1	100%	0.20
Branching fraction for $D \to K^0_L X$	+30%	Shape, 1	10%	0.14
Continuum-background modeling, BDT$_c$	Multivariate $O(10\%)$	Shape, 1	100% of correction	0.01
Integrated luminosity		Global, 1	1%	<0.01
Number of $B\bar{B}$		Global, 1	1.5%	0.02
Off-resonance sample normalization		Global, 1	5%	0.05
Track-finding efficiency		Shape, 1	0.3%	0.20
Signal-kaon PID	p, θ dependent $O(10–100\%)$	Shape, 7	$O(1\%)$	0.07
Photon energy		Shape, 1	0.5%	0.08
Hadronic energy	−10%	Shape, 1	10%	0.37
K^0_L efficiency in ECL	−17%	Shape, 1	8.5%	0.22
Signal SM form-factors	q^2 dependent $O(1\%)$	Shape, 3	$O(1\%)$	0.02
Global signal efficiency		Global, 1	3%	0.03
Simulated-sample size		Shape, 156	$O(1\%)$	0.52

data/MC for off-resonance sample

potential difference between $B^+ \to K^+ K^0_L K^0_L$ and $B^+ \to K^+ K^0_S K^0_S$

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

[Phys. Rev. D 109, 112006 (2024)]

Belle II

TABLE II. Sources of systematic uncertainty in the HTA (see caption of Table I for details).

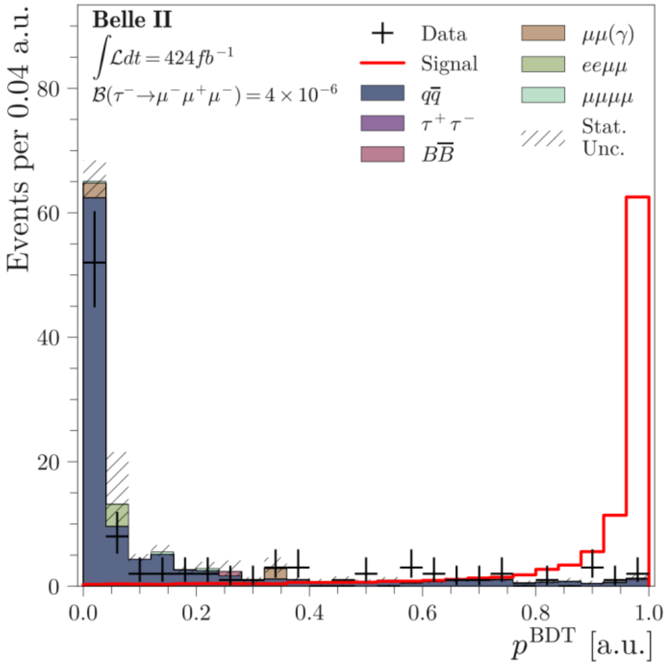
Source	Correction	Uncertainty type, parameters	Uncertainty size	Impact on σ_μ
Normalization of $B\bar{B}$ background		Global, 1	30%	0.91
Normalization of continuum background		Global, 2	50%	0.58
Leading B-decay branching fractions		Shape, 3	$O(1\%)$	0.10
Branching fraction for $B^+ \to K^+ K_L^0 K_L^0$	q^2 dependent $O(100\%)$	Shape, 1	20%	0.20
Branching fraction for $B \to D^{**}$		Shape, 1	50%	<0.01
Branching fraction for $B^+ \to K^+ n\bar{n}$	q^2 dependent $O(100\%)$	Shape, 1	100%	0.05
Branching fraction for $D \to K_L^0 X$	+30%	Shape, 1	10%	0.03
Continuum-background modeling, $\mathrm{BDT_c}$	Multivariate $O(10\%)$	Shape, 1	100% of correction	0.29
Number of $B\bar{B}$		Global, 1	1.5%	0.07
Track finding efficiency		Global, 1	0.3%	0.01
Signal-kaon PID	p, θ dependent $O(10–100\%)$	Shape, 3	$O(1\%)$	<0.01
Extra-photon multiplicity	$n_{\gamma\mathrm{extra}}$ dependent $O(20\%)$	Shape, 1	$O(20\%)$	0.61
K_L^0 efficiency		Shape, 1	17%	0.31
Signal SM form-factors	q^2 dependent $O(1\%)$	Shape, 3	$O(1\%)$	0.06
Signal efficiency		Shape, 6	16%	0.42
Simulated-sample size		Shape, 18	$O(1\%)$	0.60

data/MC for pion enriched sample

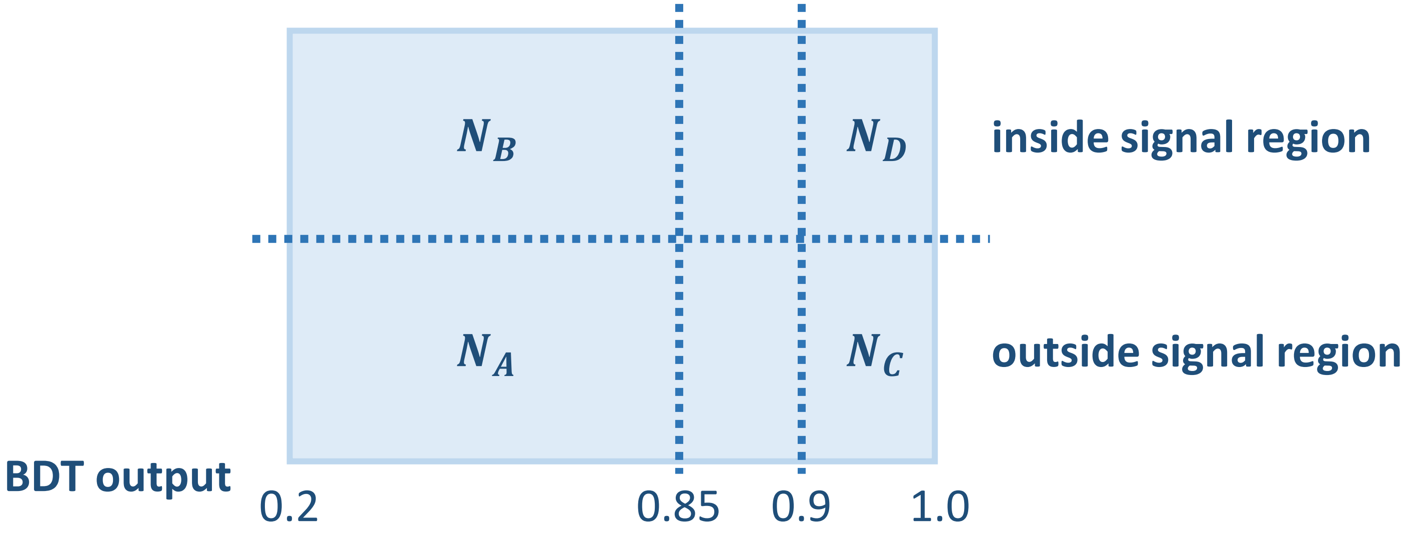
data/MC for off-resonance sample

$\tau^- \to \mu^+\mu^-\mu^-$

- The validation is done on the sideband region
  - Agreement on (BDT output) is checked
  - After the BDT selection,
    - The expected number of event in sideband = $2.0^{+0.7}_{-0.5}$
    - The observed number of event in sideband = 3



- The number of expected background is obtained from (BDT output) and distance from signal peak
  - expected $N_D = N_C \times \frac{N_B}{N_A}$



$\tau^- \to \mu^+\mu^-\mu^-$

[JHEP09(2024)062]

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Quantity	Source	Uncertainty (%) Low	High
$\varepsilon_{3\mu}$	PID	2.1	2.4
	Tracking	1.0	1.0
	Trigger	0.9	0.9
	BDT	1.5	1.5
	Signal region	3.9	2.9
N_{exp}	Momentum Scale	16	16
$\mathcal{L}$		0.6	0.6
$\sigma_{\tau\tau}$		0.3	0.3

← BDT: use $\tau^- \to \pi^-\pi^+\pi^-\nu_\tau$ sample

← Signal region: change the signal region definition $\pm\delta$

← Momentum Scale: change the scale factor of momentum, obtained from $D^0 \to K^-\pi^+$

[Phys. Rev. D 110, 072020 (2024)]

$R(D^*)$

experiment	$\mathrm{R}(D)$	$\mathrm{R}(D^*)$	$\mathcal{L}_{int}$	Tagging method	reference
Belle	0.307	0.283	$711\ fb^{-1}$	semileptonic	Phys. Rev. Lett. 124, 161803 (2020)
LHCb	0.441	0.281	$3\ fb^{-1}$	-	Phys. Rev. Lett. 131, 111802 (2023)
LHCb	-	0.267	$2\ fb^{-1}$	-	Phys. Rev. D 108, 012018 (2023)
Belle II	-	0.262	$189\ fb^{-1}$	hadronic	Phys. Rev. D 110, 072020 (2024)
LHCb	0.249	0.402	$2\ fb^{-1}$	-	arXiv:2406.03387 (2024)

[Phys. Rev. D 110, 072020 (2024)]

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$R(D^*)$

TABLE VIII. Summary of systematic uncertainties on $R(D^*)$.

Source	Uncertainty
PDF shapes	$^{+9.1\%}_{-8.3\%}$
Simulation sample size	$^{+7.5\%}_{-7.5\%}$
$\bar{B} \to D^{**}\ell^-\bar{\nu}_\ell$ branching fractions	$^{+4.8\%}_{-3.5\%}$
Fixed backgrounds	$^{+2.7\%}_{-2.3\%}$
Hadronic B decay branching fractions	$^{+2.1\%}_{-2.1\%}$
Reconstruction efficiency	$^{+2.0\%}_{-2.0\%}$
Kernel density estimation	$^{+2.0\%}_{-0.8\%}$
Form factors	$^{+0.5\%}_{-0.1\%}$
Peaking background in ΔM_{D^*}	$^{+0.4\%}_{-0.4\%}$
$\tau^- \to \ell^-\nu_\tau\bar{\nu}_\ell$ branching fractions	$^{+0.2\%}_{-0.2\%}$
$R(D^*)$ fit method	$^{+0.1\%}_{-0.1\%}$
Total systematic uncertainty	$^{+13.5\%}_{-12.3\%}$

← change the energy shift for E_{ECL}
change the smearing factor for M_{miss}