Measurements of electroweak penguin decays at Belle and Belle II

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On behalf of Belle and Belle II collaborations

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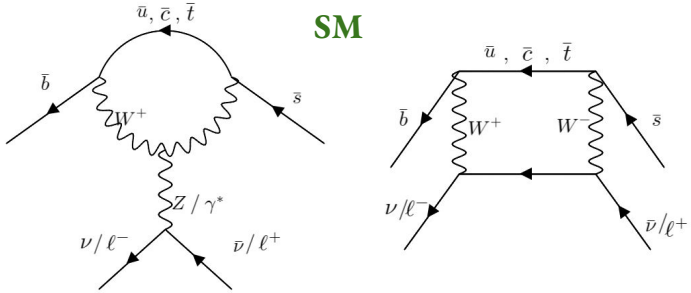
Electroweak Penguin and New Physics

- $b \to s$ as flavor changing neutral current (FCNC), occur in loop/box level in standard model (SM)

  $Br\,(b \to s) < 10^{-5}$



Electroweak Penguin and New Physics

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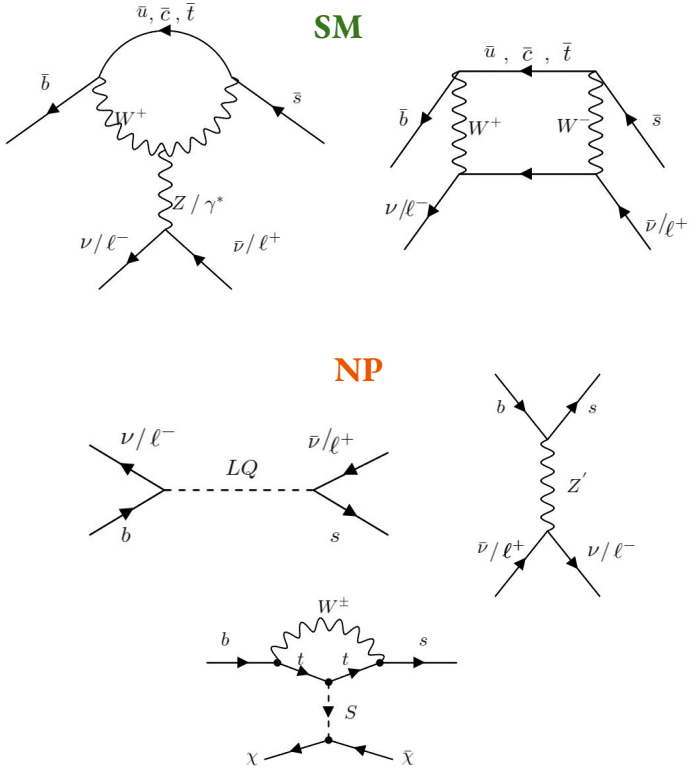
- Sensitive to new physics (NP): **new particles** such as new vector bosons, leptoquarks or dark scalar that mediate the decays



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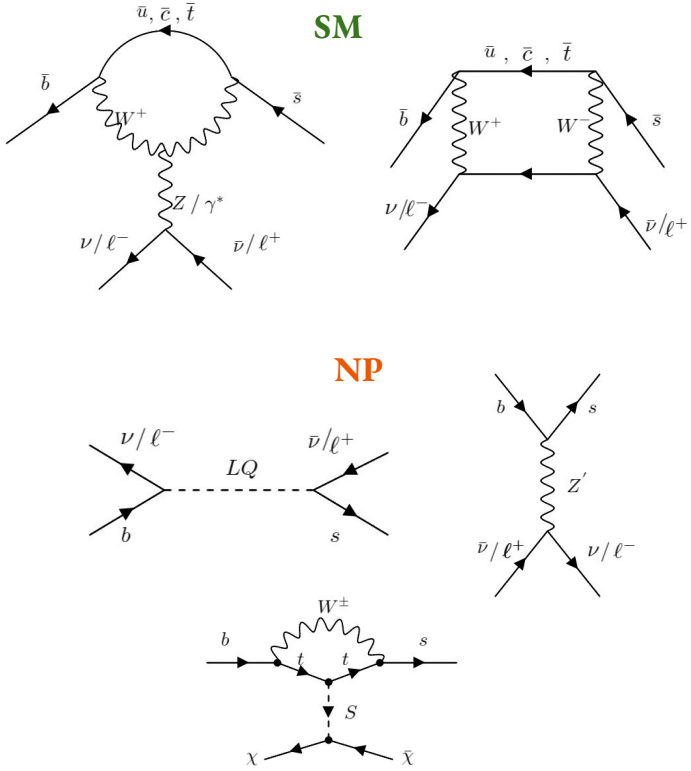
- Experimental challenges:

  > Require high identification efficiency of electron and muon of leptons final state

  > Impossible to fully reconstruct the event kinematics with missing nutritions in the final state



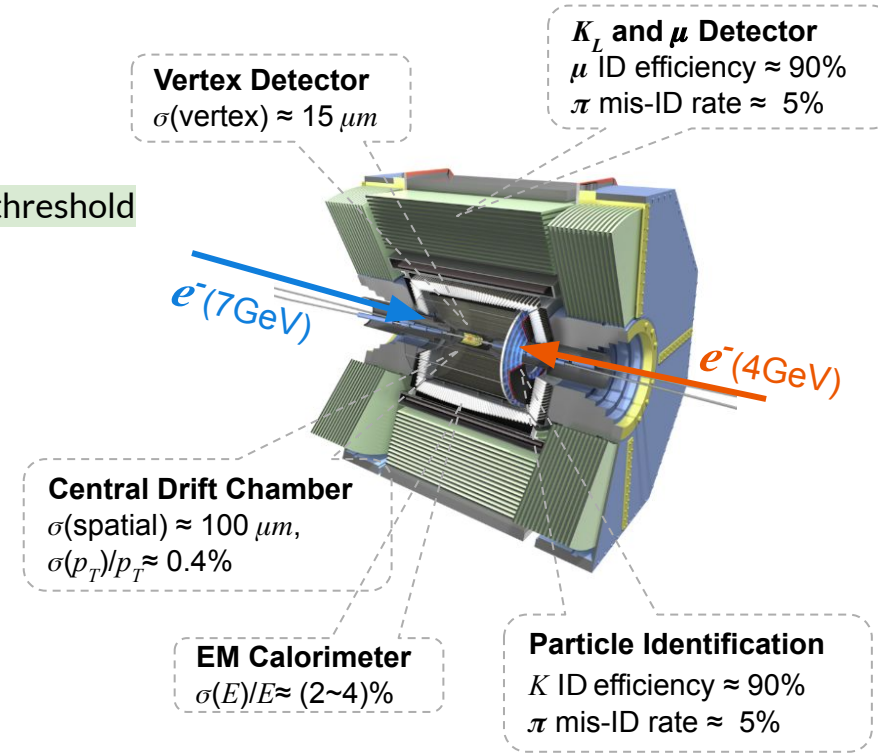
B Factory

(Super) KEKB is an electron-positron collider with asymmetric beam energies

- $\sqrt{S}$ = 10.58 GeV @ $\Upsilon(4S)$ resonance , BB production threshold
- Hermetic detector
- High luminosity

Belle (II) experiment

- Accelerating by (Super) KEKB
- Operating from 1999 to 2010 (2019-)
- Achieved the work highest peak luminosity **$2.018 \times 10^{34} cm^{-2} s^{-1}$ ($5.105 \times 10^{34} cm^{-2} s^{-1}$)**
- Collected luminosity $\mathcal{L}$ = 1 ab^{-1} (0.58 ab^{-1})
- **Belle II targeted integrated luminosity: 50 ab^{-1}**



BELLE II detector

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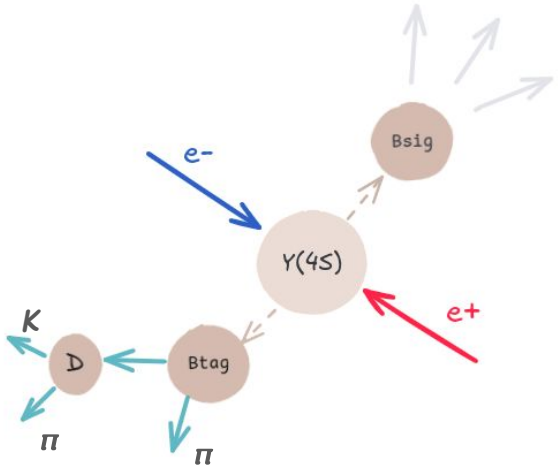
- $\sqrt{S}$ = 10.58 GeV @ $\Upsilon(4S)$ resonance , $B\bar{B}$ production threshold
  Initial energy constraint & low background
- Hermetic detector
  Full event reconstruction
- High luminosity
  Dataset used: Belle 772 M $B\bar{B}$ pairs, Belle II 387 M $B\bar{B}$ pairs

→ **Large amount of $B\bar{B}$ pairs and clear topology make Belle (II) an ideal place to search for electroweak penguin process.**



Hadronic tagging:
solely uses hadronic B decay channels;
$\epsilon = \mathcal{O}(0.1)\%$, high purity

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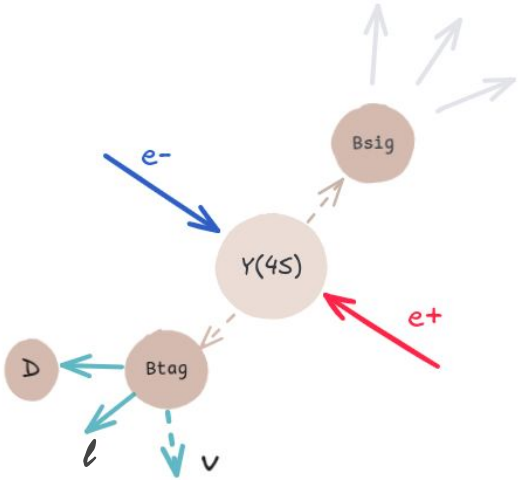

Semileptonic tagging:
solely uses semileptonic B decay channels; $\epsilon = \mathcal{O}(1)\%$, suffers from missing kinematic information

B Factory

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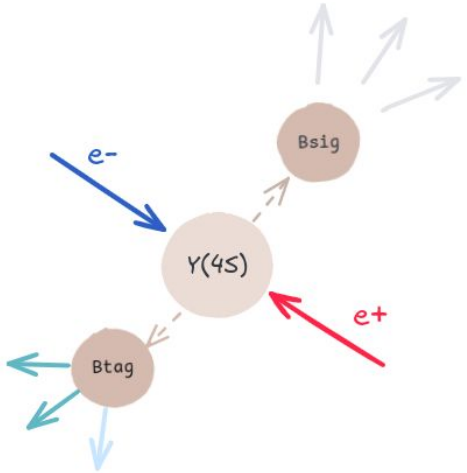
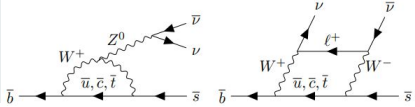


Inclusive tagging:
combines the four-momenta of all particles of ***B***
very high efficiency ; high background level

$b \to s\, \nu\, \bar{\nu}$



FCNC process, highly suppressed in SM

Relatively precise rate prediction in SM, compared with $b \to s\, \ell\ell$

New particles act as either mediators can enhance the branching fractions

Experimental challenging: **two neutrinos in the final state**

Decay	SM prediction (10^{-6})	Experimental value (10^{-6}) (90% CL)	
$B^+ \to K^+ \nu\nu$	5.22 ± 0.32	< 16 (PDG 2022)	
$B^0 \to K_S\, \nu\nu$	2.12 ± 0.15	< 13 (Belle 1702.03224)	STA
$B^+ \to K^{*+} \nu\nu$	11.27 ± 1.51	< 40 (Belle 1303.3719)	HTA
$B^0 \to K^{*0} \nu\nu$	9.47 ± 1.40	< 18 (Belle 1702.03224)	STA
$B \to X_s\, \nu\nu$	29 ± 3	< 64 (ALEPH 0010022)	

Corresponding measurements on Belle (II):

Recent results in this report:
$B^+ \to K^+ \nu\bar{\nu}$ (ITA and HTA @ Belle II)
$B \to X_s\, \nu\bar{\nu}$ (HTA @ Belle II)

On-going:
$B^+ \to K^+ \nu\bar{\nu}$ (ITA @ Belle)
$B \to K^{(*)} \nu\bar{\nu}$ (ITA @ Belle II)
$B \to K^{(*)} \nu\bar{\nu}$ (STA @ Belle II)

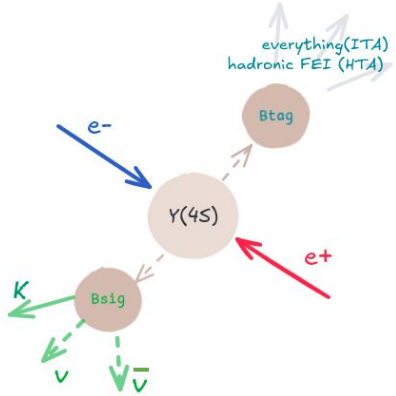
Evidence for $B^+ \to K^+ \nu \bar{\nu}$ @ Belle II

2311.14647

- Belle II 362 fb^{-1} $\Upsilon(4S)$ data
  Inclusive tagging analysis (ITA) , hadronic tagging analysis (HTA)

- Background suppression:
  Binary classifiers (BDTs) exploit the event shape, the missing energy, the kinematics of K and the features of rest of events

  ~ 40% $e^+e^- \to q\bar{q}$ (q=u, d, c, s) and $e^+e^- \to \tau^+\tau^-$ contribute in the signal region: correct the normalization and shape



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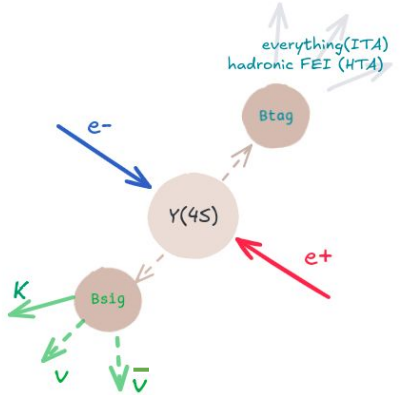

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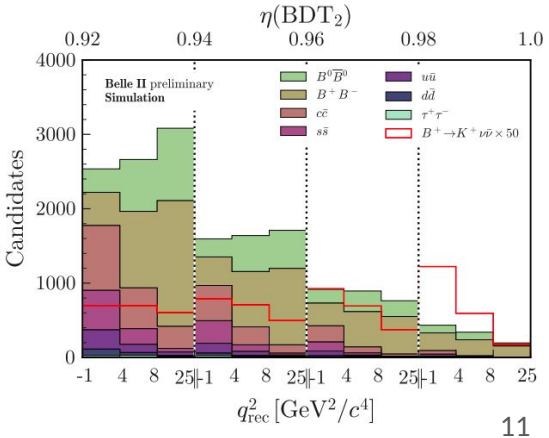
  Correct/control the major / special BB background that mimic the signal
  $B \to D(\to \bar{K}^{(*)})l\nu$, $B \to D(\to K_L)X$,
  $B^+ \to K^+K^0\bar{K}^0$, $B^+ \to K^+n\bar{n}(p\bar{p})$,
  $B^+ \to K^{*+}\nu\bar{\nu}$ and $B^+ \to \tau^+(\to K^+\bar{\nu})\nu$



- Signal region: mass square of neutrino pair q^2 and classifier output (ITA)
  classifier output (HTA)

Evidence for $B^+ \to K^+ \nu\,\bar{\nu}$ @ Belle II

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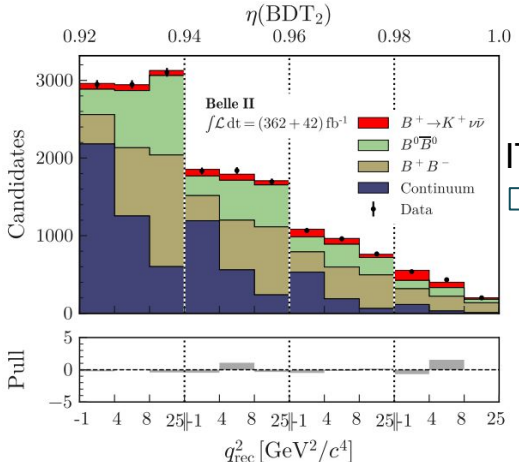
Binned maximum likelihood fit

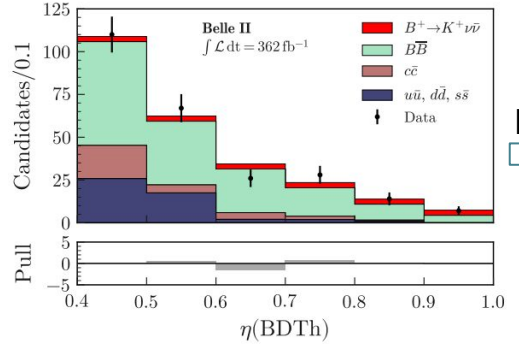


ITA

Simultaneous fit to mass square of neutrino pair q^2 and classifier output

$Br(B^+ \to K^+\nu\bar{\nu}) = (2.7 \pm 0.7) \times 10^{-5}$

~ **2.9 σ** deviation to SM prediction



HTA

Fit to classifier output

$Br(B^+ \to K^+\nu\bar{\nu}) = (1.1^{+1.2}_{-1.1}) \times 10^{-5}$

~ consistent with ITA at **1.2 σ**

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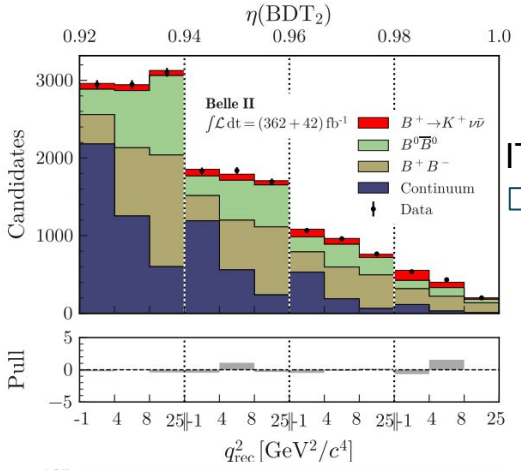

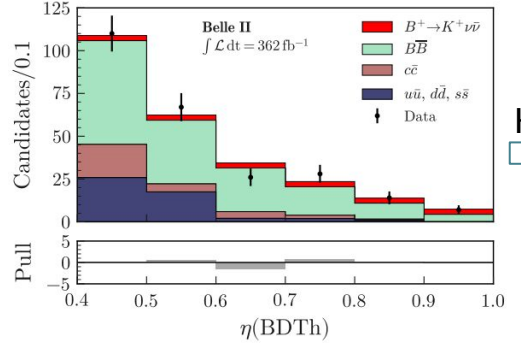

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$Br(B^+ \to K^+\nu\bar{\nu}) = (2.7 \pm 0.7) \times 10^{-5}$

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Combined result: $(2.3 \pm 0.7) \times 10^{-5}$
2.7 σ to SM expectation

HTA

Fit to classifier output

$Br(B^+ \to K^+\nu\bar{\nu}) = (1.1^{+1.2}_{-1.1}) \times 10^{-5}$

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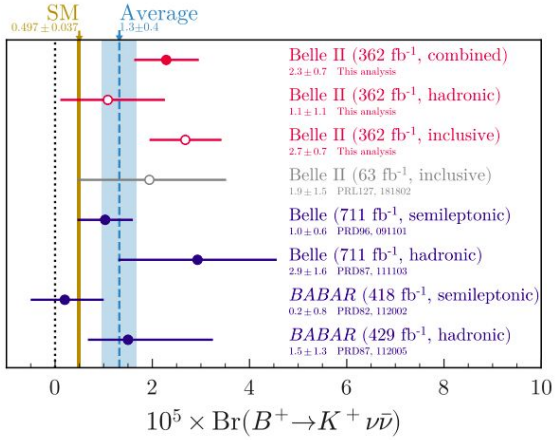


First Evidence of $B^+ \to K^+ \nu\bar{\nu}$

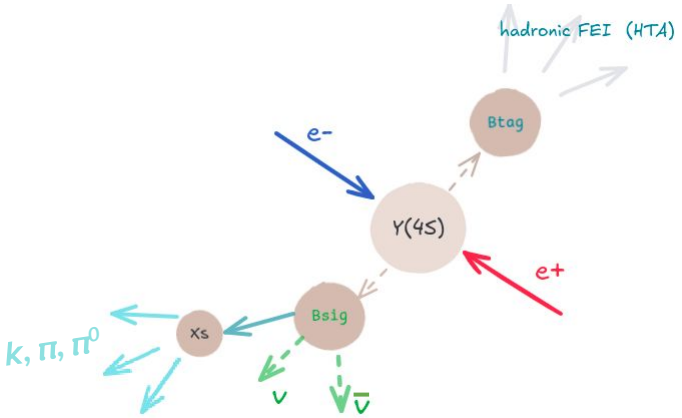
Search for $B \to Xs\ \nu\ \bar{\nu}$ @ Belle II

NEW

- Using hadronic tagging and Belle II 365 fb^{-1} $\Upsilon(4S)$ data
- 30 decay modes are reconstructed for the sum of exclusive method

	$B^0\bar{B}^0$			$B^\pm$		
K	K_S^0			$K^\pm$		
$K\pi$	$K^\pm\pi^\mp$	$K_S^0\pi^0$		$K^\pm\pi^0$	$K_S^0\pi^\pm$	
$K2\pi$	$K^\pm\pi^\mp\pi^0$	$K_S^0\pi^\pm\pi^\mp$	$K_S^0\pi^0\pi^0$	$K^\pm\pi^\mp\pi^\pm$	$K_S^0\pi^\pm\pi^0$	$K^\pm\pi^0\pi^0$
$K3\pi$	$K^\pm\pi^\mp\pi^\pm\pi^\mp$	$K_S^0\pi^\pm\pi^\mp\pi^0$	$K^\pm\pi^\mp\pi^0\pi^0$	$K^\pm\pi^\mp\pi^\pm\pi^0$	$K_S^0\pi^\pm\pi^\mp\pi^\pm$	$K_S^0\pi^\pm\pi^0\pi^0$
$K4\pi$	$K^\pm\pi^\mp\pi^\pm\pi^\mp\pi^0$	$K_S^0\pi^\pm\pi^\mp\pi^\pm\pi^\mp$	$K_S^0\pi^\pm\pi^\mp\pi^0\pi^0$	$K^\pm\pi^\mp\pi^\pm\pi^\mp\pi^\pm$	$K_S^0\pi^\pm\pi^\mp\pi^\pm\pi^0$	$K^\pm\pi^\mp\pi^\pm\pi^0\pi^0$
$3K$	$K^\pm K^\mp K_S^0$			$K^\pm K^\mp K^\pm$		
$3K\pi$	$K^\pm K^\mp K^\pm\pi^\mp$	$K^\pm K^\mp K_S^0\pi^0$		$K^\pm K^\mp K^\pm\pi^0$	$K_S^0 K^\pm K^\mp\pi^\pm$	

~ covering ~93% of entire $Xs\nu\bar{\nu}$ decay based on simulation sample, with assuming K^0 equally decays into K_S and K_L



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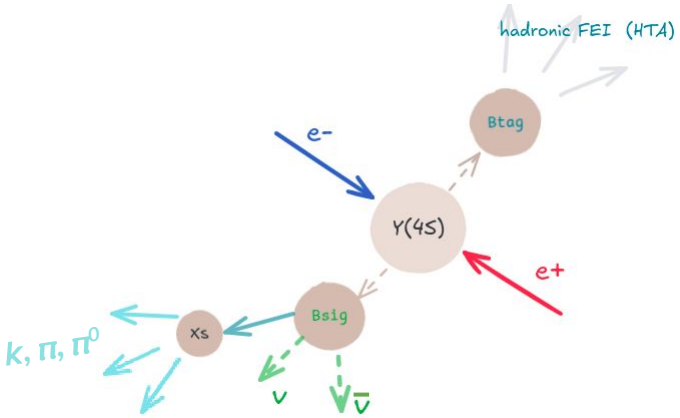
~ covering ~93% of entire $Xs\nu\bar{\nu}$ decay based on simulation sample, with assuming K^0 equally decays into K_S and K_L

- Background suppression: Binary classifiers (BDT)
- Signal region: reconstructed Xs mass and classifier output



Correct/control the major / special BB background that mimic the signal:

- ❏ Correct the fragmentation of Xs system using $B \to Xs\ \gamma$
- ❏ $B \to Xs\ n\bar{n}(p\bar{p})$, $B \to XsK^0\bar{K}^0$

Search for $B \to Xs\ \nu\ \bar{\nu}$ @ Belle II

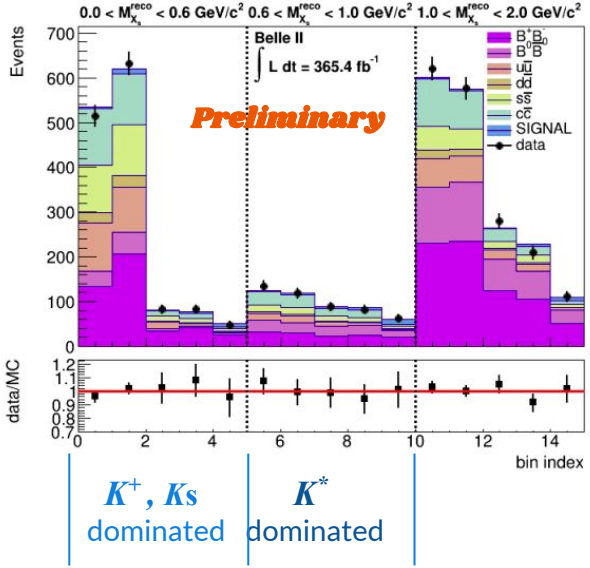
NEW

Binned maximum likelihood fit to Xs mass and classifier output

Fit results

$$BR(B \to X_s \nu\bar{\nu}) = \begin{cases} [0.5^{+0.9}_{-0.8}(\text{stat})^{+0.9}_{-0.8}(\text{syst})] \times 10^{-5} & (0.0 < M_{X_s} < 0.6\ \text{GeV}/c^2) \\ [3.8^{+2.8}_{-2.6}(\text{stat})^{+3.3}_{-2.7}(\text{syst})] \times 10^{-5} & (0.6 < M_{X_s} < 1.0\ \text{GeV}/c^2) \\ [7.3^{+9.6}_{-9.2}(\text{stat})^{+13.8}_{-11.5}(\text{syst})] \times 10^{-5} & (1.0\ \text{GeV}/c^2 < M_{X_s}) \end{cases}$$

$$BR(B \to X_s \nu\bar{\nu}) = [11.6^{+8.9}_{-8.6}(\text{stat})^{+13.5}_{-11.3}(\text{syst})] \times 10^{-5}$$



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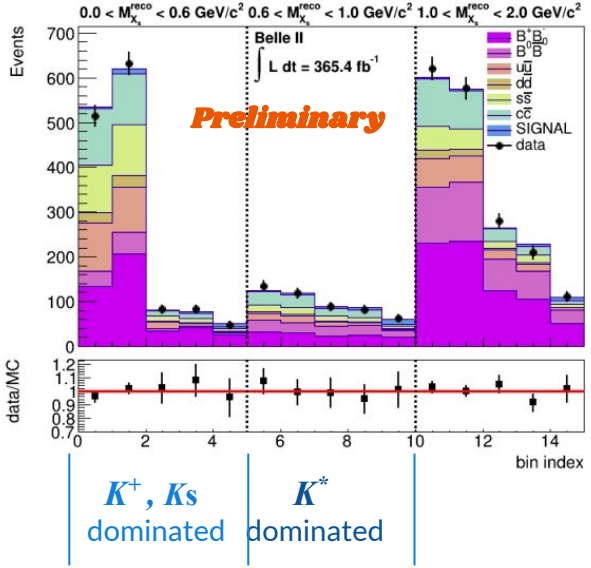
$$BR(B \to X_s \nu\bar{\nu}) = [11.6^{+8.9}_{-8.6}(\text{stat})^{+13.5}_{-11.3}(\text{syst})] \times 10^{-5}$$

90% CL

Upper limits

$$UL(B \to X_s \nu\bar{\nu}) = \begin{cases} 2.5 \times 10^{-5} & (0.0 < M_{X_s} < 0.6\ \text{GeV}/c^2) \\ 1.0 \times 10^{-4} & (0.6 < M_{X_s} < 1.0\ \text{GeV}/c^2) \\ 3.5 \times 10^{-4} & (1.0\ \text{GeV}/c^2 < M_{X_s}) \end{cases}$$

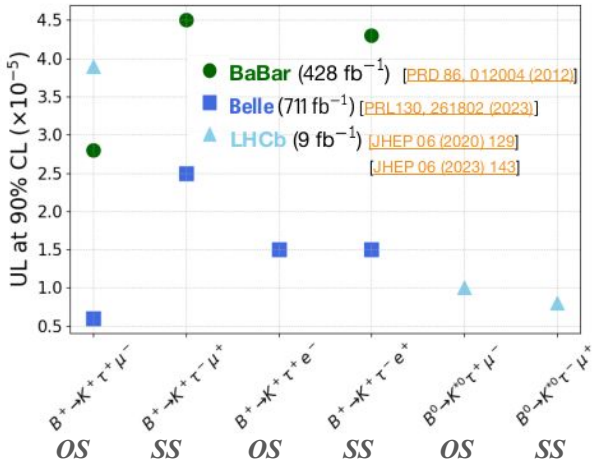
$$UL(B \to X_s \nu\bar{\nu}) = 3.6 \times 10^{-4}$$



The most stringent upper limit on inclusive $B \to Xs\ \nu\bar{\nu}$

$b \to s\,\tau\,l(l = e, \mu)$

- Lepton flavor violating process, forbidden in SM
- $B^+ \to K^+ \nu\bar{\nu}$ excess and $b \to c\tau\,\nu$ anomalies indicate the possibility of new particle coupled preferentially to second and third generation leptons
  2309.02246 1602.00881
- Third-generation b-couplings accompany with the heaviest lepton, sensitivity to new physics 1411.0565



OS: opposite sign of lepton charge and b quark flavor
SS: same sign of lepton charge and b quark flavor

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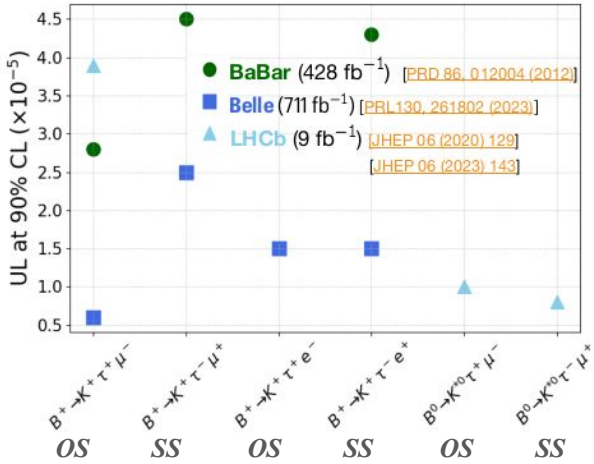
Recent results in this report:
$B^0 \to Ks\,\tau^{\pm} l^{\mp}$ @ Belle and Belle II
$B^0 \to K^{*0}\,\tau^{\pm} l^{\mp}$ @ Belle and Belle II

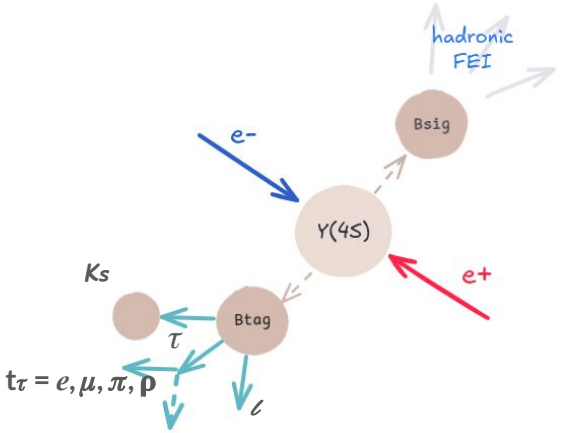


OS: opposite sign of lepton charge and b quark flavor
SS: same sign of lepton charge and b quark flavor

Search for $B^0 \to Ks\ \tau^{\pm} l^{\mp} (l = e, \mu)$ @ Belle and Belle II

2412.16470v1 (**Ks**)

- Using hadronic tagging and combined Belle 711 fb^{-1} + Belle II 365 fb^{-1} $\Upsilon(4S)$ data
- Background suppression
  - > Dominated background $B^0 \to D^{(*)} (\to Ks\ t_\tau\ X)\ l\ \nu$ and $B^0 \to D^{(*)} (\to Ks\ l\ X)\ t_\tau\ \nu$ constrained by invariant mass of $M(Ks, t_\tau)$ and $M(Ks, l)$
  - > The $e^+e^- \to q\bar{q}$ and remaining $B\bar{B}$ and backgrounds are rejected by event-shape related variables and a binary classifier

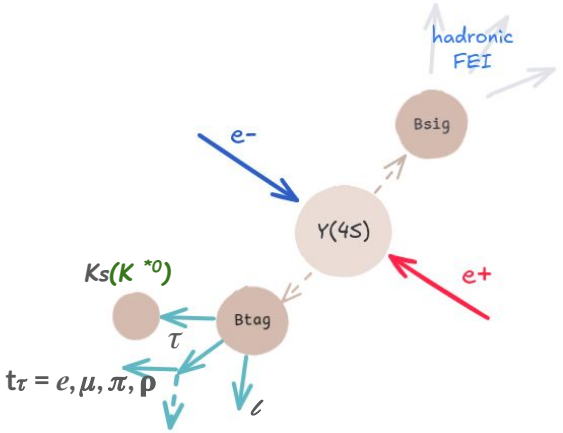


Search for $B^0 \to Ks\ (K^{*0})\tau^{\pm} l^{\mp} (l = e, \mu)$ @ Belle and Belle II

2412.16470v1 (Ks)

2505.08418v1 (K^{*0})

- Using hadronic tagging and combined Belle 711 fb^{-1} + Belle II 365 fb^{-1} $\Upsilon(4S)$ data
- Background suppression
  - > Dominated background $B^0 \to D^{(*)}\ (\to Ks/K^{*0}\ t_\tau\ X)\ l\ \nu$ and $B^0 \to D^{(*)}\ (\to Ks/K^{*0}\ l\ X)\ t_\tau\ \nu$ constrained by invariant mass of $M(Ks(K^{*0}), t_\tau)$ and $M(Ks(K^{*0}), l)$
  - > The $e^+e^- \to q\bar{q}$ and remaining $B\bar{B}$ and backgrounds are rejected by event-shape related variables and a binary classifier



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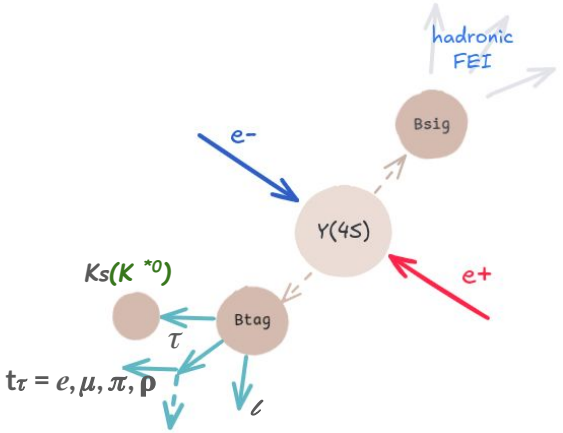
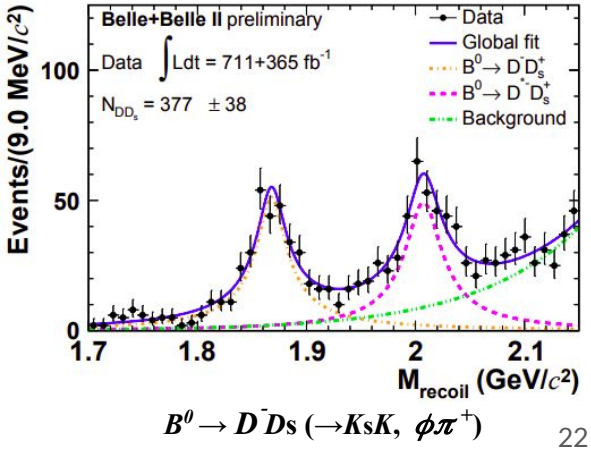
  - > The $e^+e^- \to q\bar{q}$ and remaining $B\bar{B}$ and backgrounds are rejected by event-shape related variables and a binary classifier
- Calibration and validation
  - > Using $B^0 \to D^- \pi^+$ (and $B \to Xc\ l\ \nu$)to calibrate B tagging efficiency (fitting to recoil D mass)
  - > Using $B^0 \to D^- Ds\ (\to Ks(K^{*0})K^+,\ \phi\pi^+)$ to calibrate signal shape and classifier efficiency (fitting recoiling D mass)





$B^0 \to D^- Ds\ (\to KsK,\ \phi\pi^+)$

Search for $B^0 \to Ks\ \tau^{\pm} l^{\mp} (l = e, \mu)$ @ Belle and Belle II

2412.16470v1

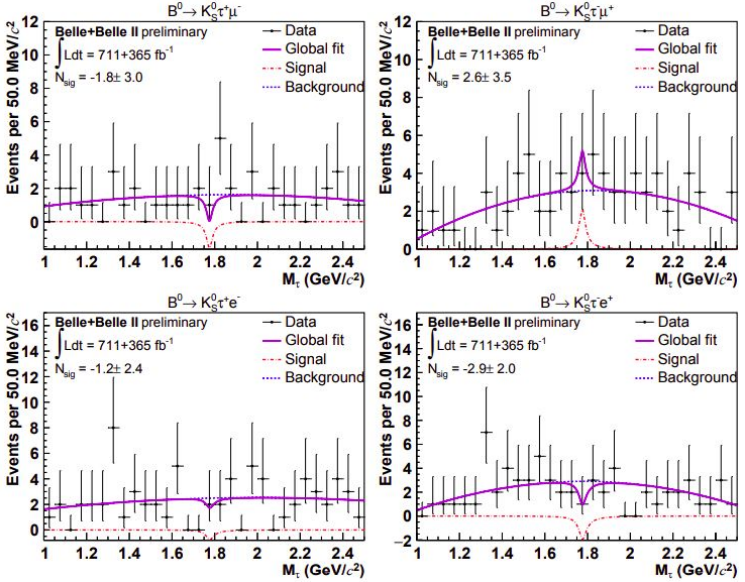
$$M^2_{\text{recoil}} = M^2_{\tau} = (p_{e^+e^-} - p_{K_S} - p_{\ell} - p_{B_{tag}})^2$$

A single unbinned-maximum-likelihood fit to recoil τ mass with combined Belle and Belle II data

Fit results

Channels	$\epsilon(10^{-4})$	N_{sig}	$\mathcal{B}(10^{-5})$ Central value	UL
$B^0 \to K^0_S \tau^+ \mu^-$	1.7	-1.8 ± 3.0	$-1.0 \pm 1.6 \pm 0.2$	1.1
$B^0 \to K^0_S \tau^- \mu^+$	2.1	2.6 ± 3.5	$1.1 \pm 1.6 \pm 0.3$	3.6
$B^0 \to K^0_S \tau^+ e^-$	2.0	-1.2 ± 2.4	$-0.5 \pm 1.1 \pm 0.1$	1.5
$B^0 \to K^0_S \tau^- e^+$	2.1	-2.9 ± 2.0	$-1.2 \pm 0.9 \pm 0.3$	0.8

90% CL



Total systematic uncertainty: 22-24%

First search for $B^0 \to Ks\ \tau^{\pm} l^{\mp}$ decays

Search for $B^0 \to K^{*0}\tau^{\pm}l^{\mp}(l = e, \mu)$ @ Belle and Belle II

2505.08418v1

A simultaneous unbinned-maximum-likelihood fit to recoil τ mass of Belle and Belle II dataset

Fit results

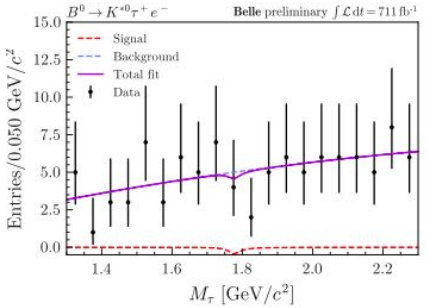
Decay	$\mathcal{B}^{\text{fit}}$ $(\times 10^{-5})$	$\mathcal{B}^{\text{UL}}_{\text{obs(exp)}}$ $(\times 10^{-5})$
OSe: $B^0 \to K^{*0}\tau^+e^-$	-0.24 ± 1.46	2.9 (2.8)
SSe: $B^0 \to K^{*0}\tau^-e^+$	1.17 ± 2.77	6.4 (4.4)
$OS\mu$: $B^0 \to K^{*0}\tau^+\mu^-$	1.07 ± 1.80	4.2 (3.0)
$SS\mu$: $B^0 \to K^{*0}\tau^-\mu^+$	0.48 ± 2.61	5.6 (5.5)

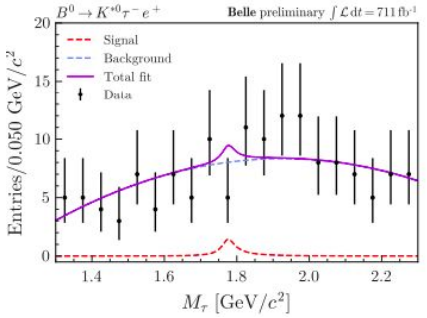
90% CL

Leading systematics:
- Classifier efficiency and 18-34%
- Background shape assumption

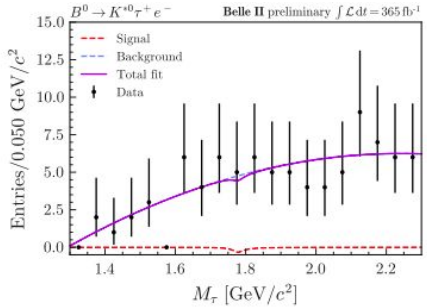
$$M^2_{\text{recoil}} = M^2_{\tau} = (p_{e^+e^-} - p_{K^{*0}} - p_{\ell} - p_{B_{tag}})^2$$

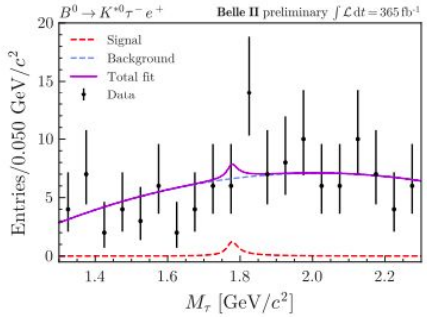
Belle





Belle II





First search for decays of $B^0 \to K^{*0}\tau^{\pm}e^{\mp}$

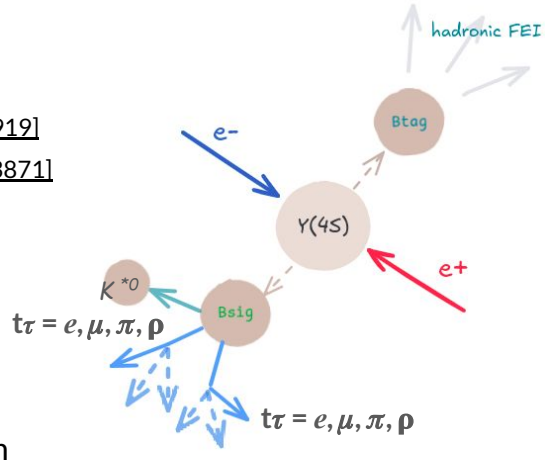
Search for $B^0 \to K^{*0}\tau^+\tau^-$ @ Belle II

2504.10042

- SM predicts $Br(B \to K^{(*)}\tau\tau) \sim 10^{-7}$ and new physics enhances it to 10^{-3} [1712.01919]
  Previous measurement $Br(B \to K^{(*)}\tau\tau) < 3.1 \times 10^{-3}$ @ 90% CL on Belle [2110.03871]
- Using hadronic tagging and Belle II 365 fb^{-1} $\Upsilon(4S)$ data
- Background suppression

  Binary classifiers exploit the event shape, the kinematics of K^* and τ, residual calorimeter energy and missing energy to distinguish the signals from background
- Calibration and validation

  Using kinematics modified $B^0 \to K^{*0} J/\psi\,(\mu^+\mu^-)$ to validate the signal efficiency
  Using same-flavor control sample to correct the rest-of-event cluster multiplicity

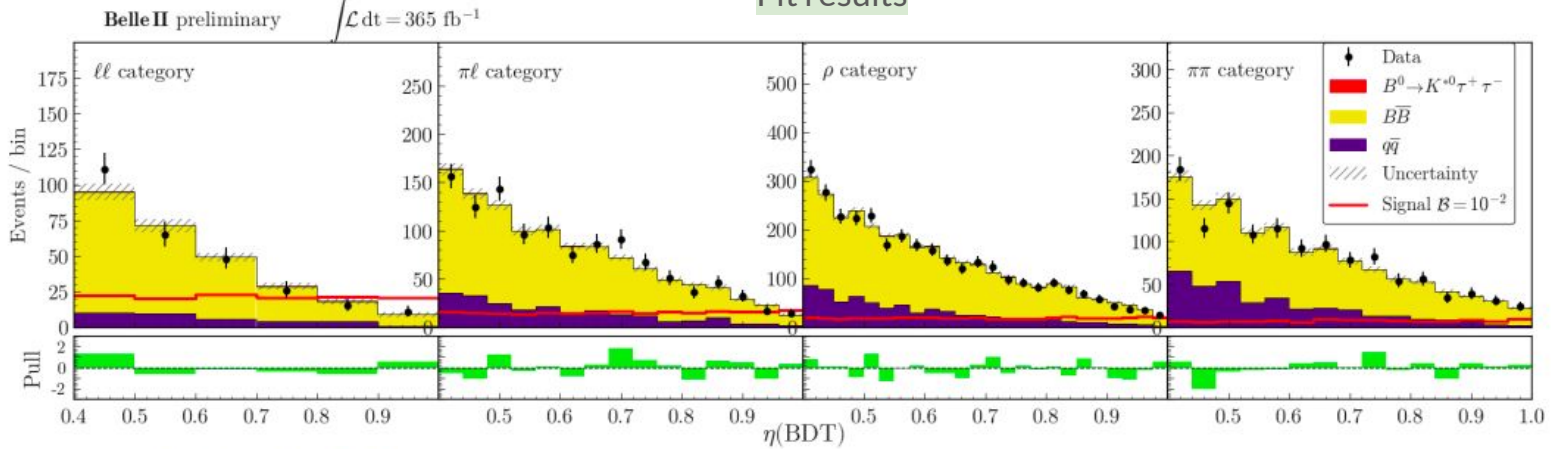


Search for $B^0 \to K^{*0}\tau^+\tau^-$ @ Belle II

2504.10042

A binned maximum likelihood fit to the classifier output, simultaneously for four signal categories

Fit results



$\ell\ell : \tau(\to \ell\nu\nu)\ \tau(\to \ell\nu\nu)$ $\quad \pi\ell : \tau(\to \ell\nu\nu)\ \tau(\to \pi\nu)$ $\quad \rho : \tau(\to \rho\nu)\ \tau(\to \pi, \rho, \ell\nu)$ $\quad \pi\pi : \tau(\to \pi\nu)\ \tau(\to \pi\nu)$

$$Br(B^0 \to K^{*0}\tau^+\tau^-) = [-0.15 \pm 0.86(stat) \pm 0.52(syst)] \times 10^{-3}$$

$$Br(B^0 \to K^{*0}\tau^+\tau^-) < 1.8 \times 10^{-3} \quad @\ 90\%\ \text{CL}$$

Most stringent limit on $B^0 \to K^{*0}\tau^+\tau^-$

Summary

- Belle and Belle II provide unique environment to measure electroweak penguin decays which are sensitive to probe new physics

- Recent results shown in this report:

✓ First evidence for $B^+ \to K^+ \nu\nu$

✓ The most stringent upper limit on inclusive $B \to Xs\,\nu\nu$ 👈 preliminary

✓ The most stringent upper limit on $B^0 \to K^{*0}\tau^+\tau^-$

✓ Search for $B^0 \to Ks\,(K^{*0})\tau^{\pm}l^{\mp}(l = e, \mu)$