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Rare or forbidden B → τ decays at Belle & Belle II

Moriond EWP Flavor session

Vidya Sagar Vobbilisetti
on behalf of the Belle II collaboration

24 March 2025

Belle II

Outline

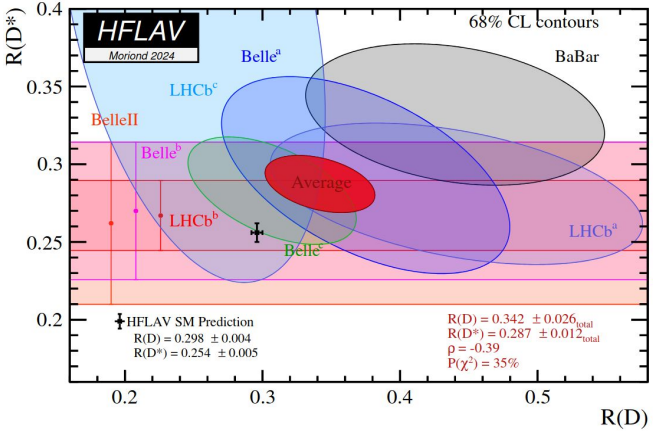
- Electroweak penguin B → τ decays ⇋ New Physics
- Belle II experiment and B-tagging technique
- Latest results in forbidden B → K τ ℓ and rare B → K τ τ decays
- Summary and prospects

Motivation for EWP B → τ decays

- B anomalies in semileptonic decays and recently B → Kνν point towards possible new physics which can be present in the loops:

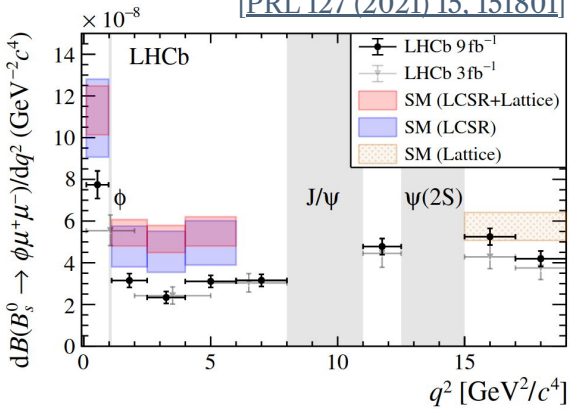
$$R^{\tau/\ell}_{D^{(*)}} = \frac{\Gamma\left(\bar{B} \to D^{(*)}\tau^-\bar{\nu}_\tau\right)}{\Gamma\left(\bar{B} \to D^{(*)}\ell^-\bar{\nu}_\ell\right)} \qquad (\ell = e, \mu)$$

[HFLAV]



Combined deviation of 3.3σ from SM.
⇒ Larger coupling to τ

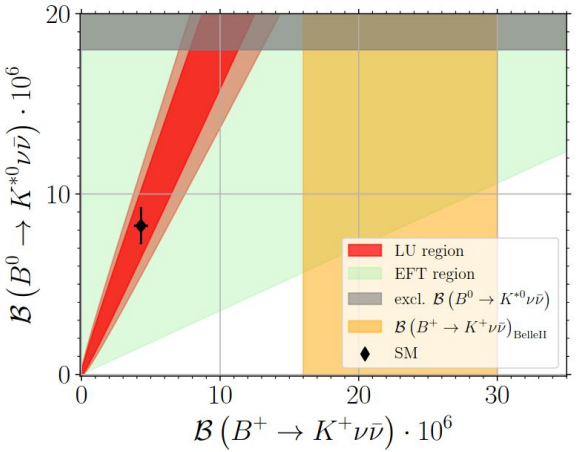
[PRL 127 (2021) 15, 151801]



Amplitude analysis of
$B^0 \to K^{*0}\mu^+\mu^-$
shows a 2.1σ deviation in
$\mathscr{C}_9$ Wilson coefficient.

[JHEP 09 (2024) 026]

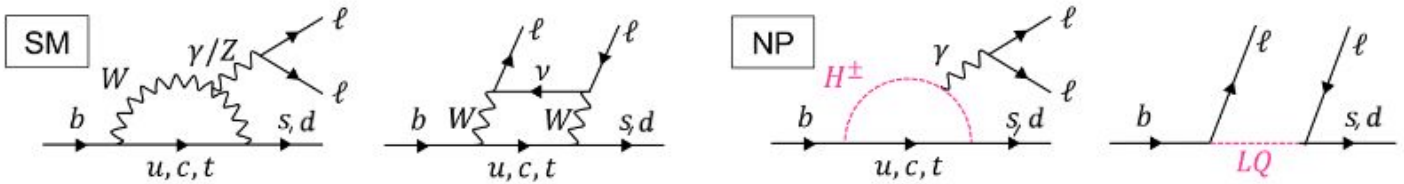
[Phys.Rev.D 109 (2024) 1, 015006]



Excess in $B^+ \to K^+\nu\nu$ from SM
⇒ LFU violation

Motivation for EWP B → τ decays

- B anomalies in semileptonic decays and recently B → Kνν point towards possible new physics which can be present in the loops:



- Flavour Changing Neutral Current prohibited @ tree level in the standard model (SM):
  - Ideal probes of Standard Model and unique portals to New Physics

- Many new physics models propose larger coupling to third generation and/or larger mass ⇒ τ!
  (like leptoquarks) (Yukawa-like)
  - May cause enhancement in B → K τ τ, violating Lepton Flavor Universality (LFU)
    [PRL 120 (2018) 18, 181802, Phys.Lett.B 848 (2024) 138411, Phys.Rev.D 109 (2024) 1, 015006]
  - May even allow Lepton Flavor Violation (LFV) like in B → (K) τ ℓ
    [Phys. Lett. B 848 (2024) 138411]

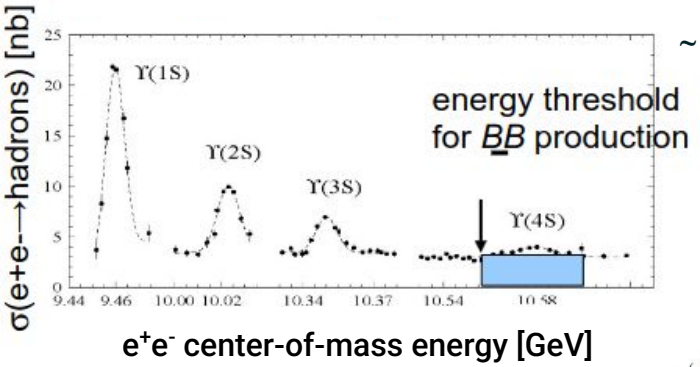
The Belle II detector

2 B's and nothing else

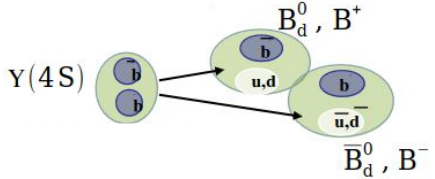
More details by previous Belle II speakers
[talk by Tommy Martinov]

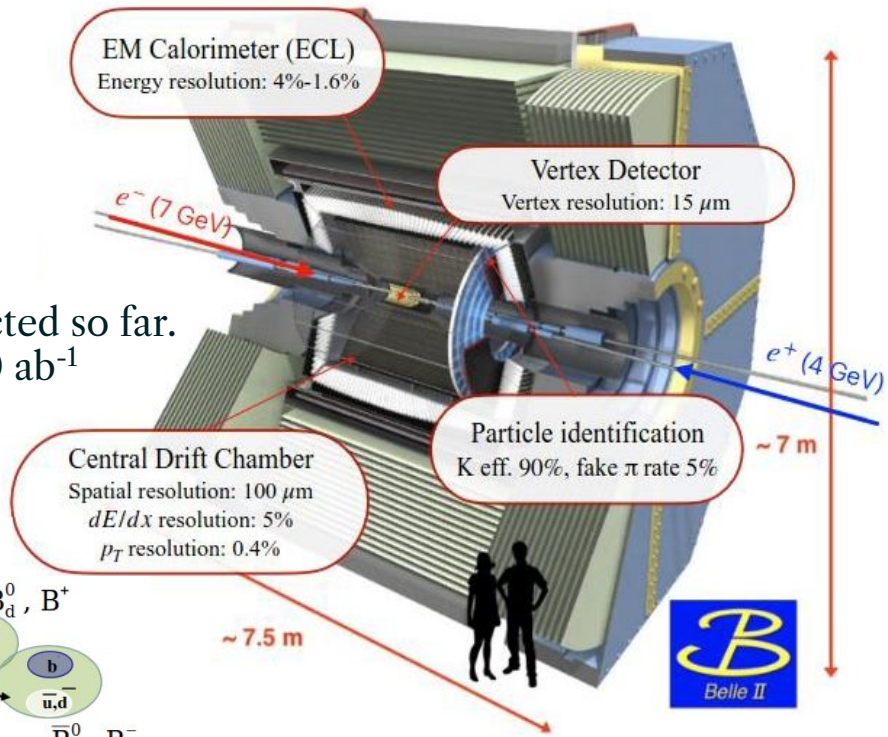
SuperKEKB: asymmetric e^-e^+ collisions at (or close to) $\Upsilon(4S)$ resonance.

Belle II: B-factory (~1.1×10^9 $B\bar{B}$ pairs per ab^{-1})



~600 fb^{-1} collected so far.
Target: 50 ab^{-1}





Near 4π detector coverage
2 B's and nothing else from Υ(4S)
⇒ B-tagging and flavour tagging

All results today are based on 365 fb^{-1} collected at Belle II
Can be combined with Belle (711 fb^{-1}).

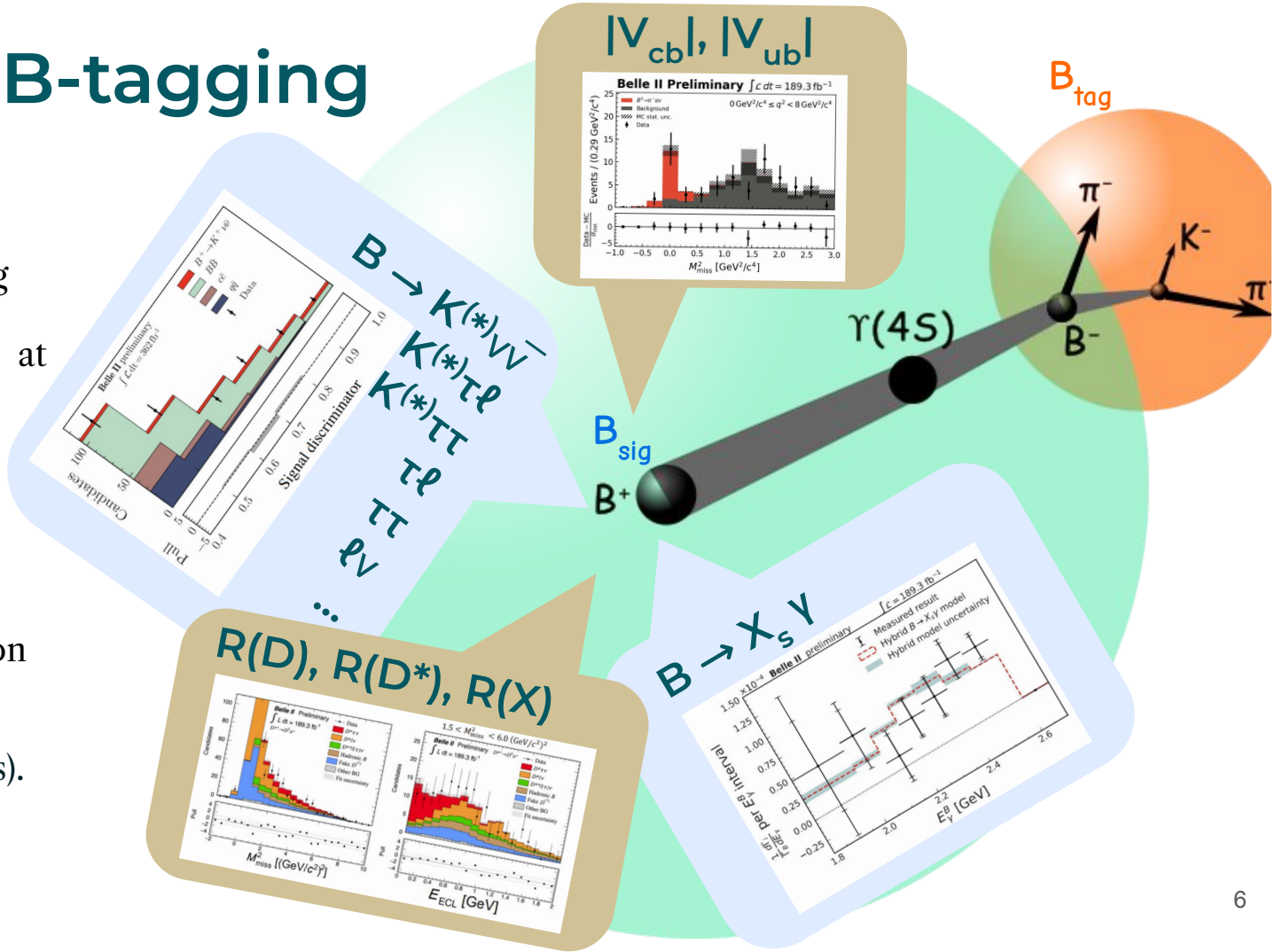
Hadronic B-tagging

A common tool

It allows reconstructing missing energy decays (neutrino or inclusive) at Belle II.

Filters $B\bar{B}$ events with high purity.

Can provide the direction of the signal B-meson and residual energy (unique to e^-e^+ machines).



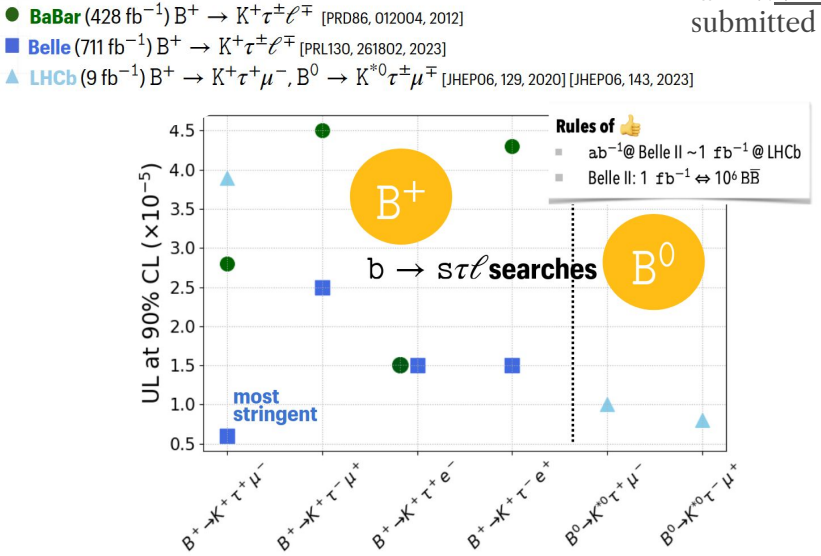
$B^0 \to K_S^0 \tau \ell$

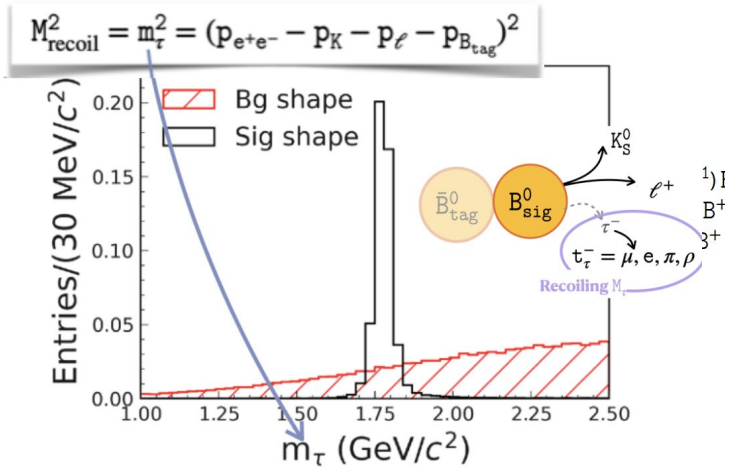
arXiv:2412.16470
submitted to PRL

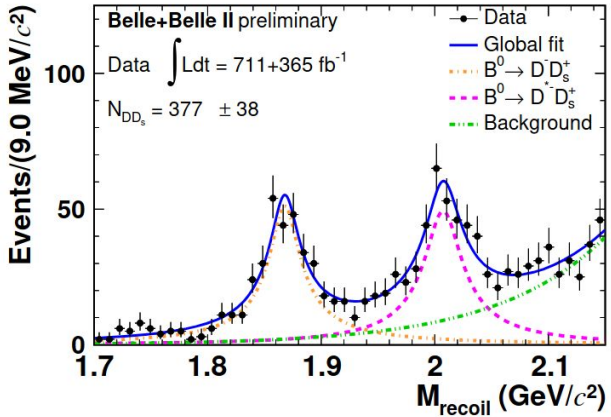
- LFV transition: Forbidden in Standard Model
- New Physics models predict up to 10^{-6}

[Phys. Lett. B 848 (2024) 138411]

- Only one missing particle (τ) ⇒ Recoil mass
- B^0 hadronic tag has lower efficiency than B^+
- K_S^0 has purity > 98%
- Search using combined Belle + Belle II data





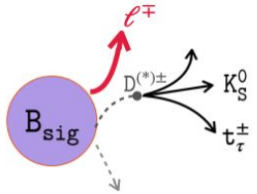


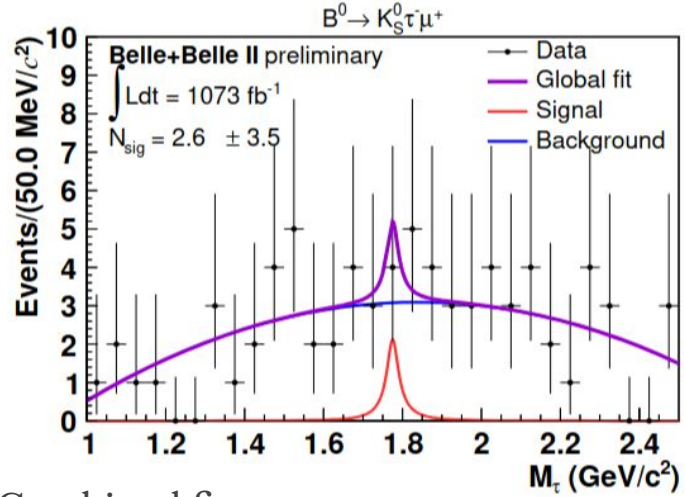
$B^0 \to D_s^+ D^{(*)-}$ control sample for BDT efficiency and PDF signal shape validation

$B^0 \to K_s^0 \tau \ell$

arXiv:2412.16470
submitted to PRL

- $\tau \to$ one-prong (μ, e, π, ρ) reconstruction: >70% of τ decays
- Reject dominant background: semi-leptonic B decay with a dedicated veto
- BDT for remaining background suppression





Combined fit

+3 more combinations

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

at 90% CL.

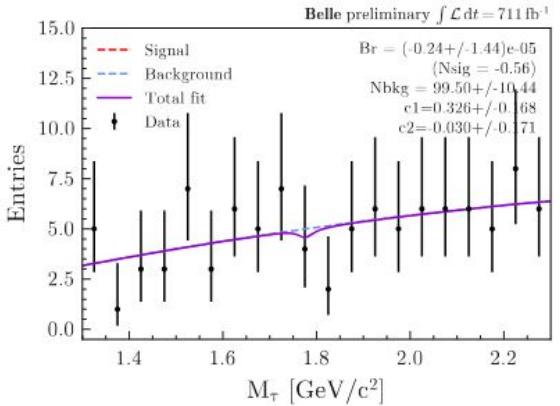
Comparable to other limits among b → s τ l transitions
World's first!

$B^0 \to K^{*0} \tau \ell$

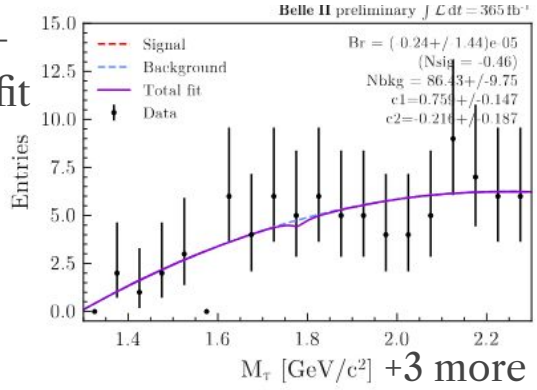
New for Moriond

Belle II Preliminary

- LHCb measured $B^0 \to K^{*0} \tau \mu$, but no results for $B^0 \to K^{*0} \tau e$
- Search using combined Belle + Belle II data
- $\tau \to$ one-prong (μ, e, π, ρ) reconstruction
- Vertex information of K^*_0 is helpful
- BDTs (4 modes × Belle II/Belle) for background suppression with input variables : invariant masses, ℓ/τ-prong/Rest of the event energies, eventshape variables, vertex fit variables
- Validation using tau mass sideband
- $B^0 \to D_s^+ D^{(*)-}$ control sample for validation



$B^0 \to K^{*0} \tau^+ e^-$
Simultaneous fit



+3 more combinations

ULs at 90% CL:

$$\mathcal{B}(B^0 \to K^{*0}\tau^+ e^-) < 2.7 \times 10^{-5}$$
$$\mathcal{B}(B^0 \to K^{*0}\tau^- e^+) < 5.6 \times 10^{-5}$$
$$\mathcal{B}(B^0 \to K^{*0}\tau^+ \mu^-) < 3.9 \times 10^{-5}$$
$$\mathcal{B}(B^0 \to K^{*0}\tau^- \mu^+) < 5.1 \times 10^{-5}$$

Comparable to other limits among $b \to s \tau l$ transitions
First results for $B^0 \to K^{*0} \tau e$

See more details in the dedicated talk
[talk by Clotilde Lemettais]

$B^0 \to K^{*0}\tau\,\tau$

Belle II Preliminary
Paper in preparation

- Allowed in SM but highly suppressed: $O(10^{-7})$
- Excess in $B \to K\nu\nu$, combined with $R_{K^{(*)}}$ constraints, suggests LFU violation in τ

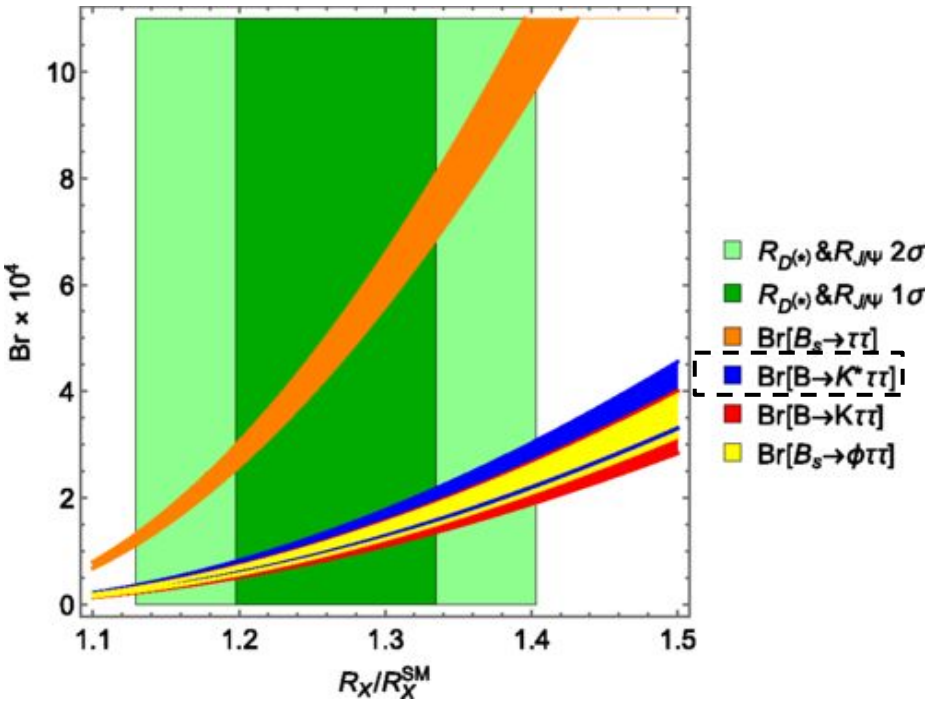
  [Phys.Lett.B 848 (2024) 138411]
  [Phys.Rev.D 109 (2024) 1, 015006]

- Challenge: Two τ in the final state
  $\Rightarrow$ no signal peaking kinematic observable
  - low efficiency
  - low K^{*0} momentum

- Current best UL: BF < 3.1×10^{-3} @ Belle using older hadronic B tagging
  Signal as no residual energy in calorimeter.

  [Phys. Rev. D 108, L011102]

[PRL 120 (2018) 18, 181802]



NP models describing $R(D^{(*)})$ predict $\times 10^3$ branching fraction enhancement

$B^0 \to K^{*0}\tau\,\tau$

- SM prediction: $O(10^{-7})$
- Current best UL: BF < 3.1×10^{-3} @ Belle
- Two τ in the final state [Phys. Rev. D 108, L011102]
  $\Rightarrow$ no signal peaking kinematic observable

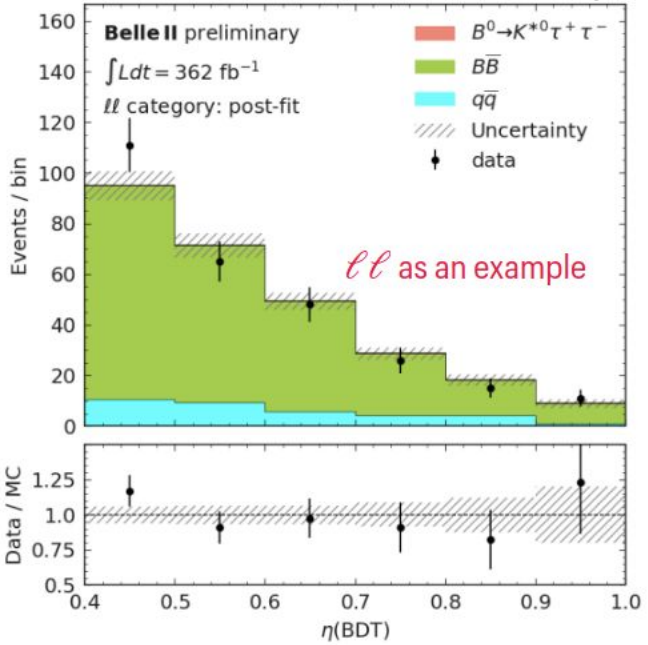
- $\tau \to$ one-prong (μ, e, π, ρ) reconstruction
- Categorized into: $\ell\ell$, $\ell\pi$, $\pi\pi$, ρX (X = ℓ, π, ρ)
- BDT based on: missing energy, residual energy in calorimeter, q^2, $m(K^*t_2)$

- Additional calibrations are performed in same-flavor, off-resonance samples.
- Validation using embedded sample with $B^0 \to K^{*0}\,J/\psi$

Twice better limit with only half sample wrt Belle!
Better tagging + more categories + BDT classifier...

Most stringent limit among b → s τ τ transition

Simultaneous fit of BDT score to 4 categories



$$\mathcal{B}(B^0 \to K^{*0}\tau^+\tau^-) < 1.8 \times 10^{-3}$$

at 90% CL.

The landscape now...

	K^+	K_S^0	K^{*0}	K^{*+}	Experimental sensitivity
$B \to K \tau e$	Belle BaBar	Belle + Belle II	Belle + Belle II	-	$O(10^{-5})$
$B \to K \tau \mu$	Belle LHCb ($B^+ \to K^+ \tau^+ \mu^-$) BaBar	Belle + Belle II	Belle + Belle II LHCb	-	$O(10^{-5})$
$B \to K \tau \tau$	BaBar	-	Belle II Belle LHCb (from unbinned fit of $B^0 \to K^{*0}\mu\mu$) [JHEP09(2024)026]	-	$O(10^{-3})$

Results shown today are either world's best limits or first searches.

Summary

- $B \to \tau$ decays are powerful probes for physics beyond SM.
- Belle II is accumulating high-quality data and leveraging the potential of combining it with Belle data
  - suitable environment to study missing energy modes.
  - healthy complementarity with LHCb
- Results shown today are either world's best or first time searches.
  - Also see $B \to \tau \nu$ branching fraction measurement [talk by Giovanni Gaudino]
- Many ongoing analyses to search for other combinations and exploring techniques beyond hadronic B-tagging.