Rare B decays at Belle & Belle II

WIFAI 2025

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on behalf of the Belle II collaboration

13 November 2025

Outline

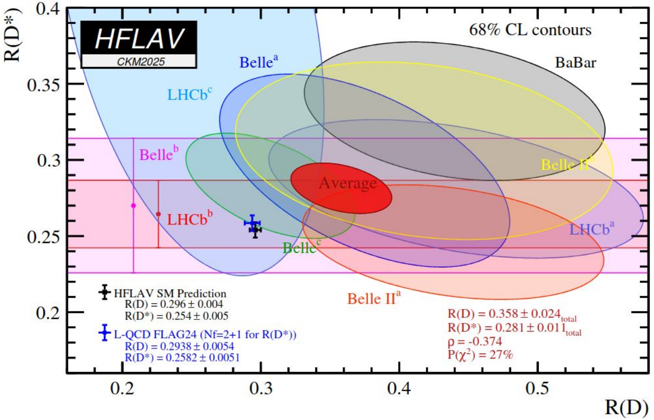
- ➢ Electroweak penguin B decays $\leftrightharpoons$ New Physics
- ➢ Belle II experiment and B-tagging technique
- ➢ Latest results in rare $b \rightarrow s\,\tau\,\tau$ decays
- ➢ Latest results in rare $b \rightarrow s\,\nu\,\bar{\nu}$ decays
- ➢ Summary and prospects

Motivation for EWP B decays

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

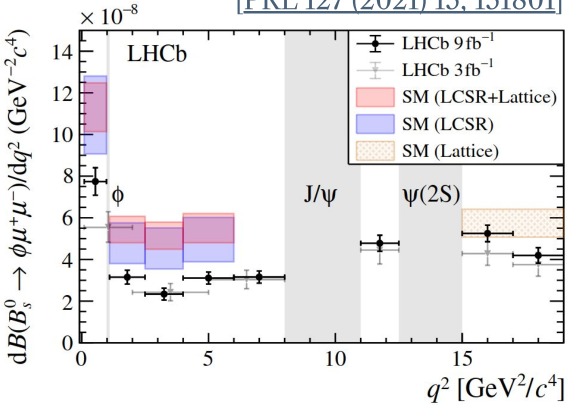
$$R^{\tau/\ell}_{D^{(*)}} = \frac{\Gamma\left(\bar{B} \to D^{(*)}\tau^-\bar{\nu}_\tau\right)}{\Gamma\left(\bar{B} \to D^{(*)}\ell^-\bar{\nu}_\ell\right)} \qquad (\ell = e, \mu)$$

[HFLAV]



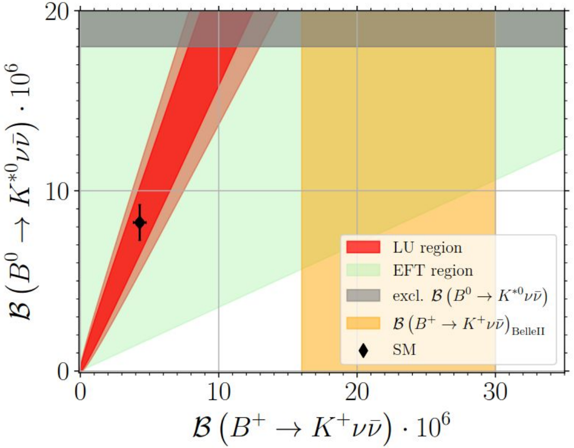
Combined deviation of 3.8σ from SM.
⇒ Larger coupling to τ

[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]

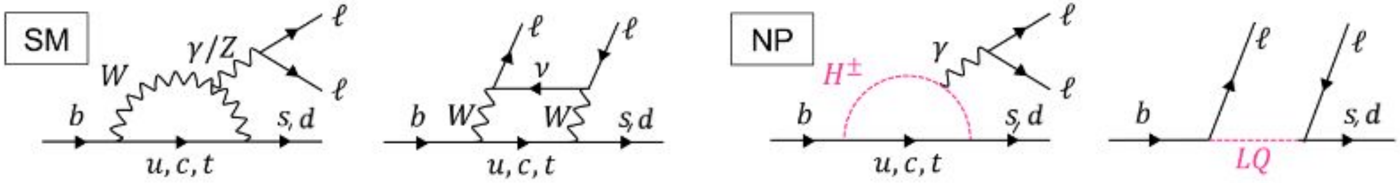
[Phys.Rev.D 109 (2024) 1, 015006]



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

Motivation for EWP B decays

- B anomalies in semileptonic decays and recently $B \to K\nu\nu$ 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

- New physics models propose larger coupling to third generation and/or larger mass $\Rightarrow \tau$

  (like leptoquarks) (Yukawa-like)
  - May cause enhancement in $B \to K \tau \tau$, violating Lepton Flavor Universality (LFU)
  - May even allow Lepton Flavor Violation (LFV) like in $B \to (K) \tau \ell$

[See more details by Arthur tomorrow]

- New physics models propose larger coupling to ν.
  - No intermediate gamma $\Rightarrow$ Theoretically cleaner

They all have ν (missing energy) in common

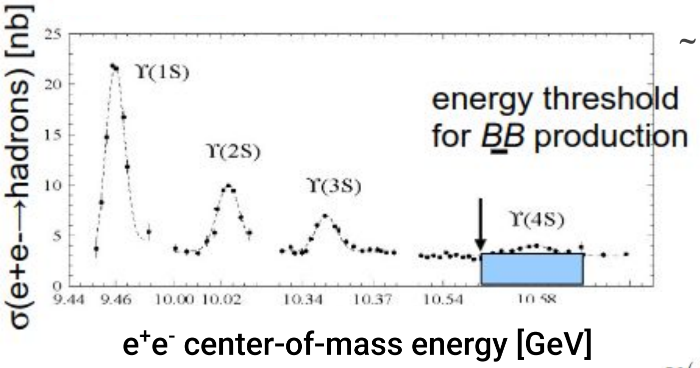
The Belle II detector

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

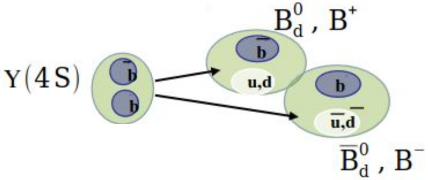
2 B's and nothing else

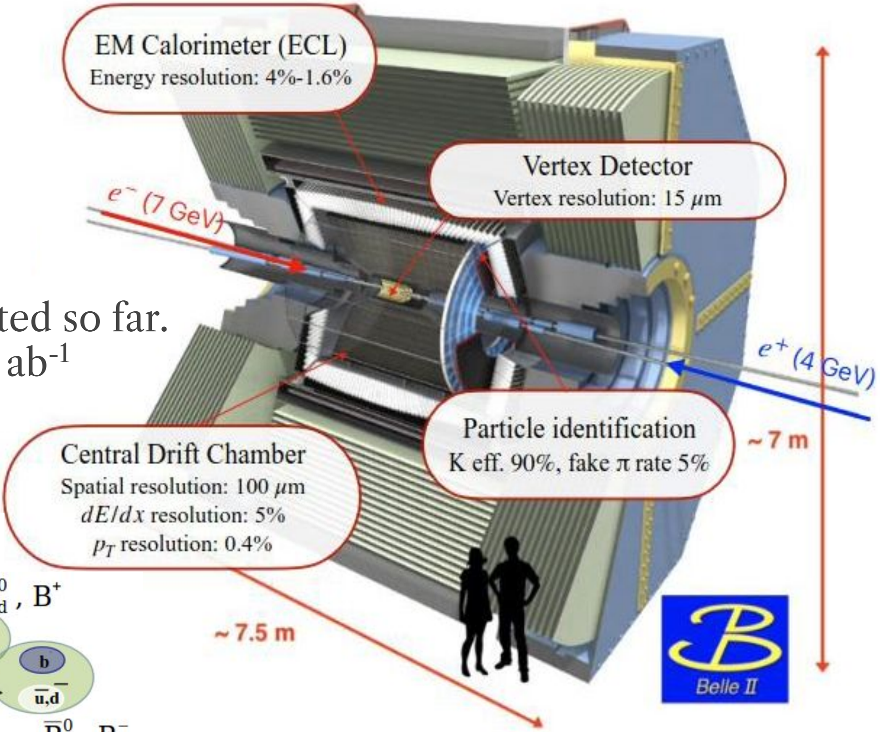
SuperKEKB: asymmetric e^-e^+ collisions at (or close to) $\Upsilon(4S)$ resonance.

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}).

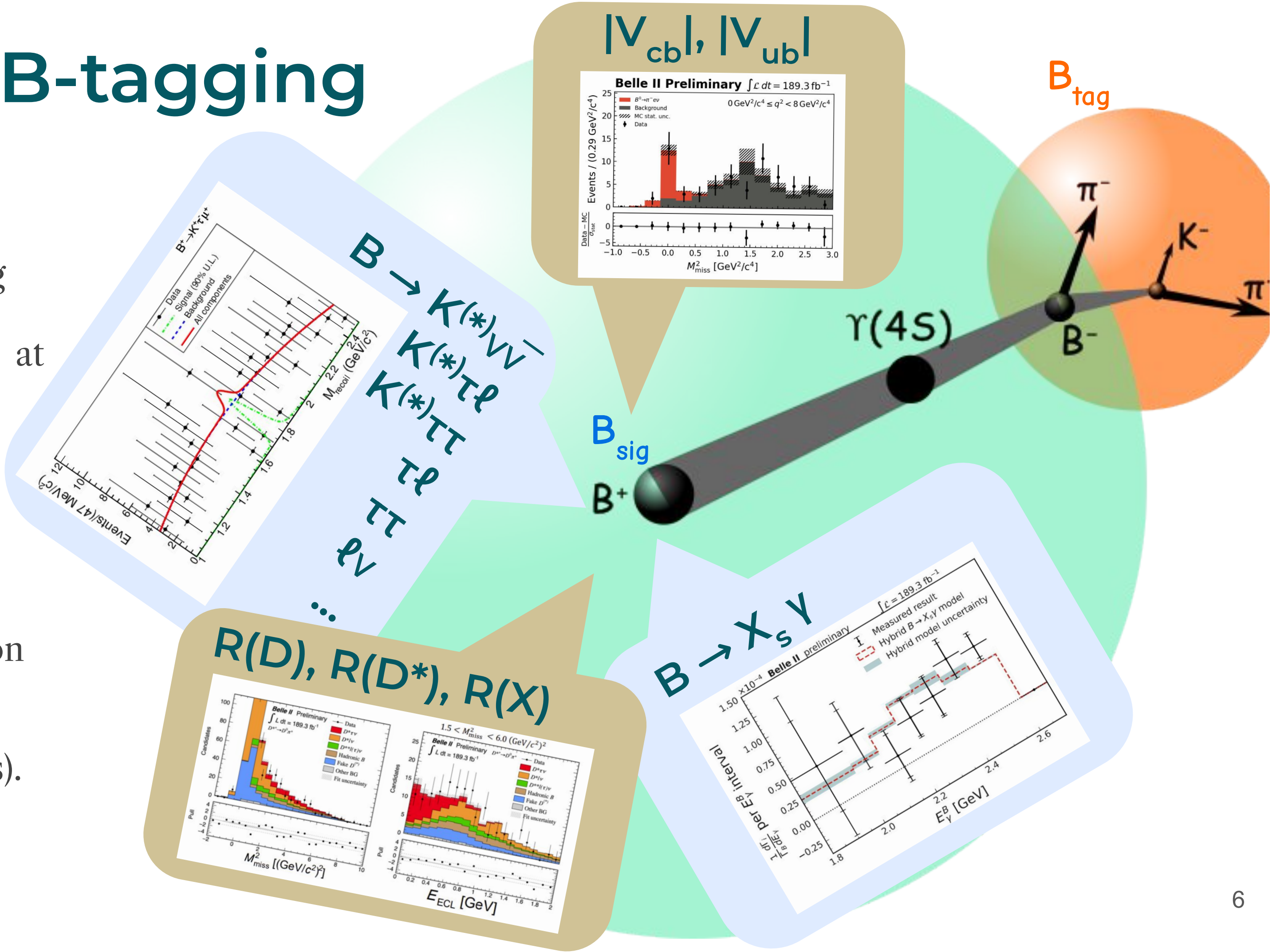
Hadronic B-tagging

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).

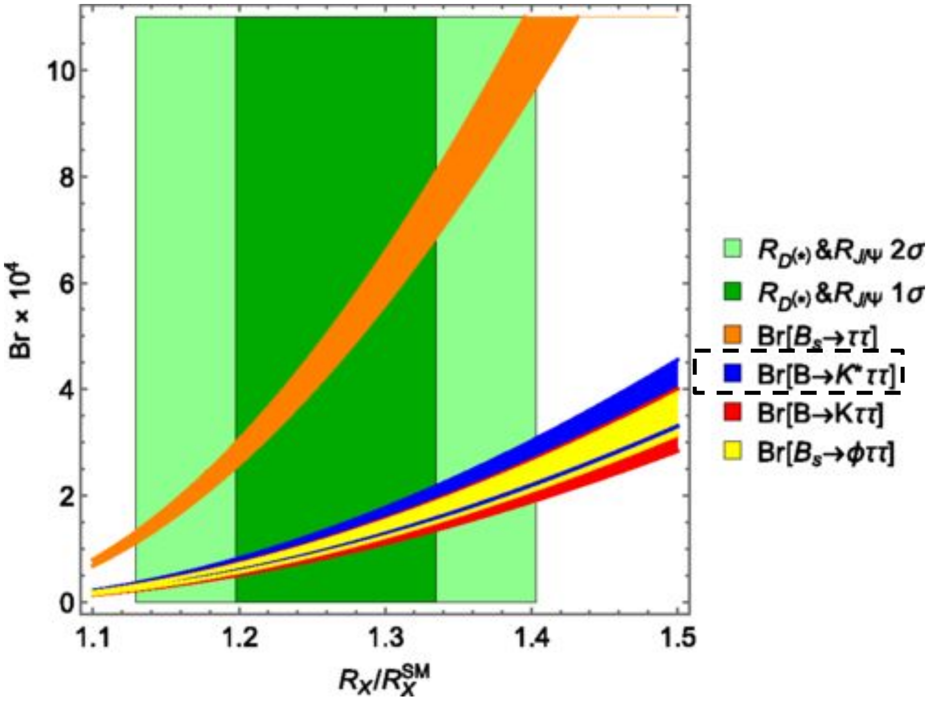


$B^0 \to K^{*0}\tau\,\tau$

[PRL 135 (2025) 15, 151801]

- ➢ Allowed in SM but highly suppressed: $O(10^{-7})$
  [Phys. Rev. Lett. **120**, 181802 (2018)]
- ➢ 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 $\times10^3$ branching fraction enhancement

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

[PRL 135 (2025) 15, 151801]

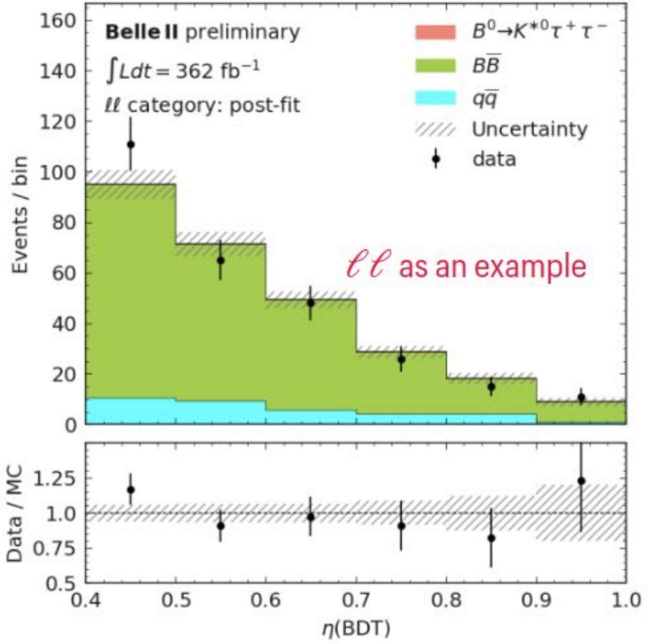
- SM prediction: $O(10^{-7})$
- Current best UL: BF < 3.1×10^{-3} @ Belle
- Two τ in the final state [Phys. Rev. D 108, L011102]
  ⇒ no signal peaking kinematic observable

- $\tau \rightarrow$ one-prong (μ, e, π, ρ) reconstruction
- Categorized into: ℓℓ, ℓπ, ππ, 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 $B^0 \rightarrow K^{*0}\,J/\psi$

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

Simultaneous fit of BDT score to 4 categories

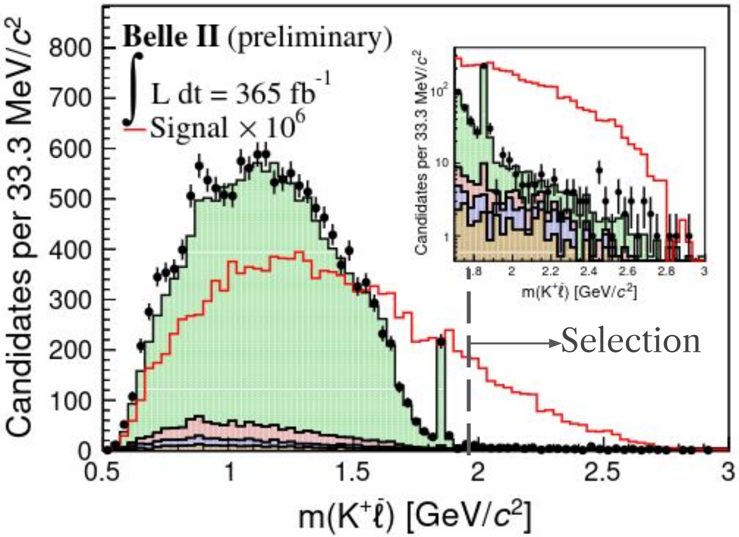


$$\mathscr{B}(B^0 \rightarrow K^{*0}\tau^+\tau^-) < 1.8 \times 10^{-3}$$

at 90% CL.

$B^+ \to K^+\tau\,\tau$

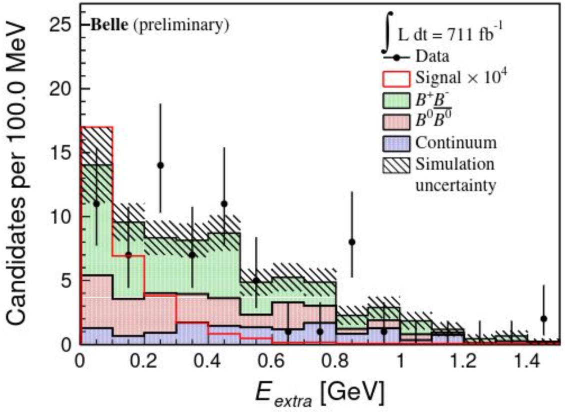
- ➢ SM prediction: $O(10^{-7})$ [PRD 107 (2023) 1, 014511]
- ➢ Current best UL: BF < 2.2×10^{-3} @ BaBar (469 fb^{-1})
  [PRL 118 (2017) 3, 031802]
- ➢ Two τ in the final state
  $\Rightarrow$ no signal peaking kinematic observable
- ➢ Combine Belle and Belle II datasets for higher statistics
- ➢ Only $\tau \to$ lepton (μ, e) reconstruction
  - ○ Primary background: $B^+ \to D\,[\to K\,\ell^+\,\nu]\,\ell^-\,\nu$
- ➢ Charm-depleted signal region in $M(K^+\ell^-) > 1.9$ GeV
- ➢ Require no extra tracks and kinematically suppress simpler background ($B \to K\,J/\psi$ and $B \to K\,\psi(2S)$).
- ➢ Require large squared missing mass, p_ℓ and small E_{extra} (residual energy in calorimeter).
- ➢ Purely cut-based, no BDT

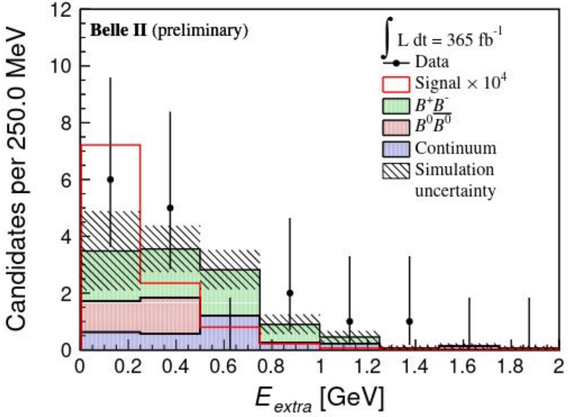


$B^+ \to K^+\tau\,\tau$

Compare counts with background-only expectation, extrapolated from sidebands in E_{extra}, q^2 and M_{bc}^{tag} sidebands.

	Belle	Belle II
$N_{\rm bkg}$	$14.05 \pm 1.60 \pm 1.85$	$3.48 \pm 0.73 \pm 0.91$
$N_{\rm obs}$	11	6
$\epsilon_{\rm sig}(\times 10^{-5})$	$1.4 \pm 0.05 \pm 0.15$	$1.26 \pm 0.04 \pm 0.17$
$\mathcal{B}(B^+ \to K^+\tau^+\tau^-)(\times 10^{-4})$	$-2.76^{+3.31}_{-2.70} \pm 2.24$	$5.05^{+5.62}_{-4.27} \pm 2.46$
Observed (expected) limit	$0.6\ (1.0) \times 10^{-3}$	$2.1\ (1.2) \times 10^{-3}$





No evidence for signal.

Combined upper limit $\mathcal{B}(B^+ \to K^+\tau\tau) < 0.87 \cdot 10^{-3}$ at 90% CL.

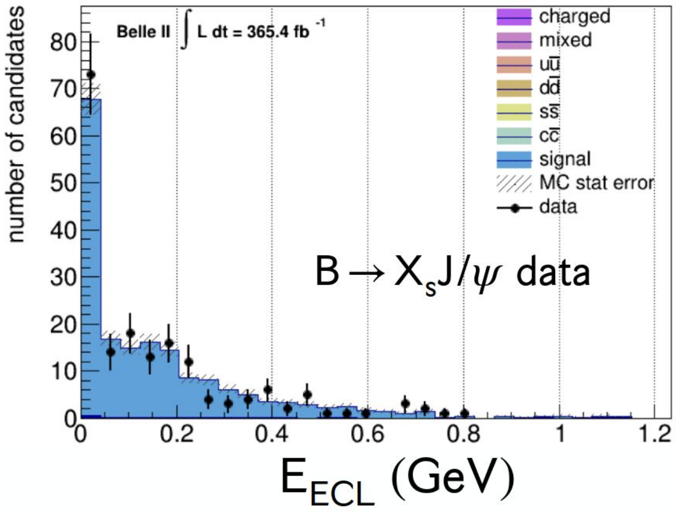
2.6 times better than previous BaBar measurement and complementary with LHCb.

$B \to X_s \nu \bar{\nu}$

- SM prediction: $(2.9 \pm 0.3) \times 10^{-5}$ [JHEP02(2015)184]
- Theoretically clean and complementary to exclusive searches
- Only measurement from ALEPH: $\mathcal{B} < 6.4 \times 10^{-4}$
- Only possible at e^+e^- machines [EPJC 19,2130227(2001)]

- Sum-of-exclusive method: Reconstructed total of 30 exclusive final states:
  - $K + i\pi$ with $0 \le i \le 4$
  - $3K + i\pi$ with $0 \le i \le 1$

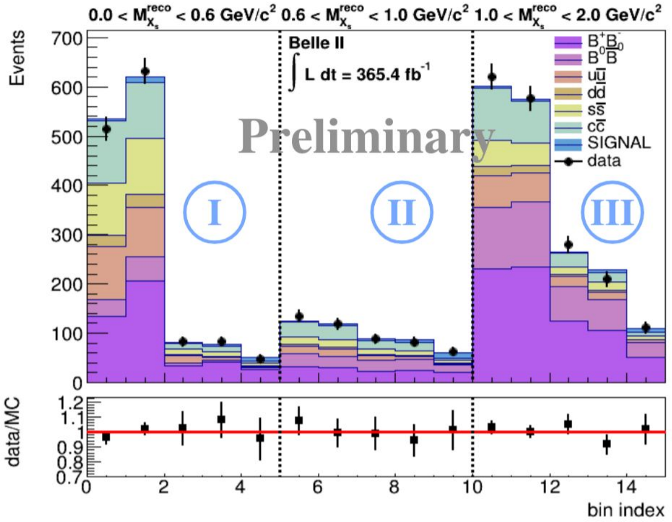
- Multivariate analysis (BDT) for background suppression $\mapsto$ output ($\mathcal{O}$)
- Calibrate simulations and obtain systematic uncertainties with
  - Off-resonance data
  - $B \to X_s J/\psi(\to \mu^+ \mu^-)$: BDT feature validation
  - $\mathcal{O}$ and M_{bc}^{tag} sidebands



$B \to X_s \nu \bar{\nu}$

2D signal region $\mathcal{O}$ x M_{Xs}^{reco} plane mapped into a 1D index in three regions enhanced in K, K*and $(K n\pi)_{\text{non-resonant}}$ modes

M_{X_s} [GeV/c^2]	ϵ	N_{sig}	$\mathcal{B}$ [10^{-5}] Central value	UL_{obs}	UL_{exp}
[0, 0.6] *	0.26%	10^{+18+18}_{-17-16}	$0.5^{+0.9+0.9}_{-0.8-0.8}$	2.5	2.4
[0.6, 1.0]	0.12%	37^{+27+31}_{-25-26}	$3.8^{+2.8+3.3}_{-2.6-2.7}$	10.1	7.3
[1.0, m_B]	0.06%	33^{+44+63}_{-42-53}	$7.3^{+9.6+13.8}_{-9.2-11.5}$	35.1	27.9



*Compatible with the hadronically-tagged Belle II $B^+ \to K^+ \nu \bar{\nu}$

No signal at $\mathcal{B}$ = [$1.2^{+0.9}_{-0.9}$(stat.)$^{+1.4}_{-1.1}$(syst.)],

yielding best upper limit 3.6 x 10^{-4} at 90% CL.

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

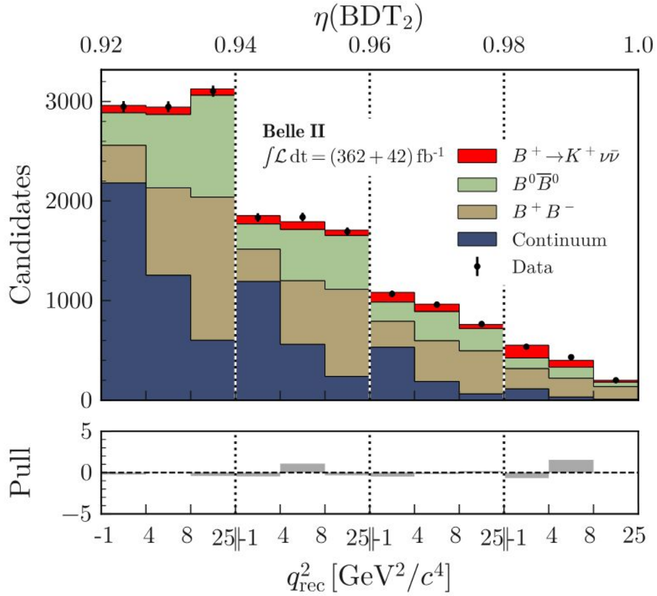
- Belle II has reported "Evidence for $B^+ \to K^+\nu\bar{\nu}$ decays"

- Combining Inclusive Tag Analysis with Hadronic Tag Analysis exceeds SM prediction by 2.7σ.

- Measured using SM signal templates.
- What BSM models does this favor?
- Reweighting must take into account experimental acceptance and efficiencies.

- Re-simulating event-by-event is expensive and non-reproducible.
- Re-weight the number density of expected events after selection for the cross section $\sigma(q^2)$.

[PRD 109.112006]



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

Belle II Preliminary

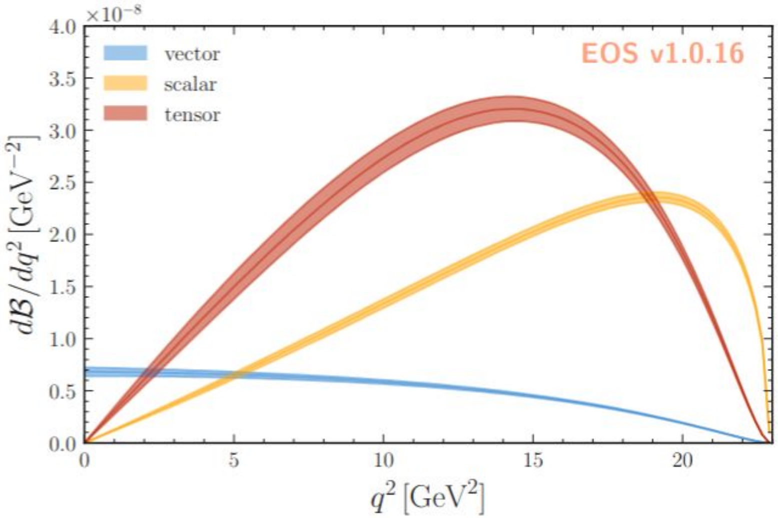
First demonstration of the feasibility using Weak Effective Theory using 6 dimensional operators.

WET = low energy EFT including NP above the electroweak scale

$$\frac{d\mathcal{B}}{dq^2} = \alpha(q^2)\,|C_{\mathrm{VL}} + C_{\mathrm{VR}}|^2 + \beta(q^2)\,|C_{\mathrm{SL}} + C_{\mathrm{SR}}|^2 + \gamma(q^2)\,|C_{\mathrm{TL}}|^2$$

SM contains only vector contribution.

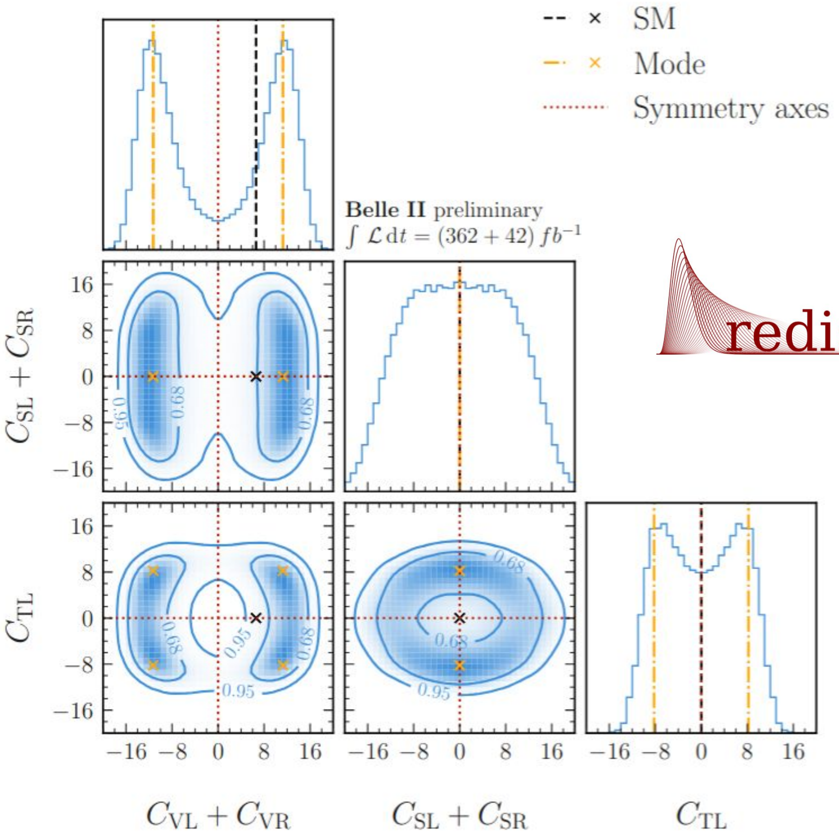
[2111.04327]

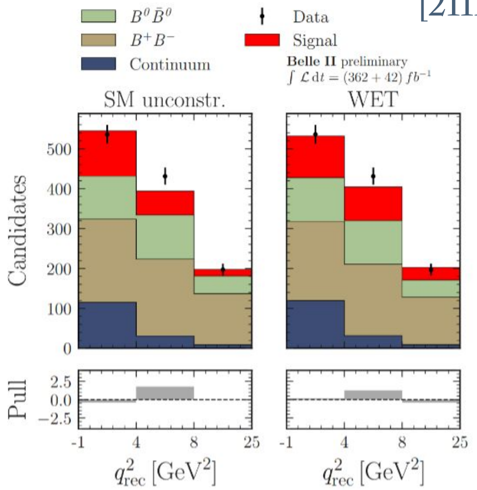


Reinterpreting $B^+ \to K^+ \nu\bar{\nu}$

Belle II Preliminary

[2111.04327]





Parameters	Mode	68% HDI	95% HDI
$\lvert C_{VL} + C_{VR}\rvert$	11.3	[7.82, 14.6]	[1.86, 16.2]
$\lvert C_{SL} + C_{SR}\rvert$	0.00	[0.00, 9.58]	[0.00, 15.4]
$\lvert C_{TL}\rvert$	8.21	[2.29, 9.62]	[0.00, 11.2]

WET is favored over SM with large $|C_{VL} + C_{VR}|$ and non-zero $|C_{TL}|$.

Highest Density credible Intervals (HDI):
The smallest possible credible interval at a given probability level.

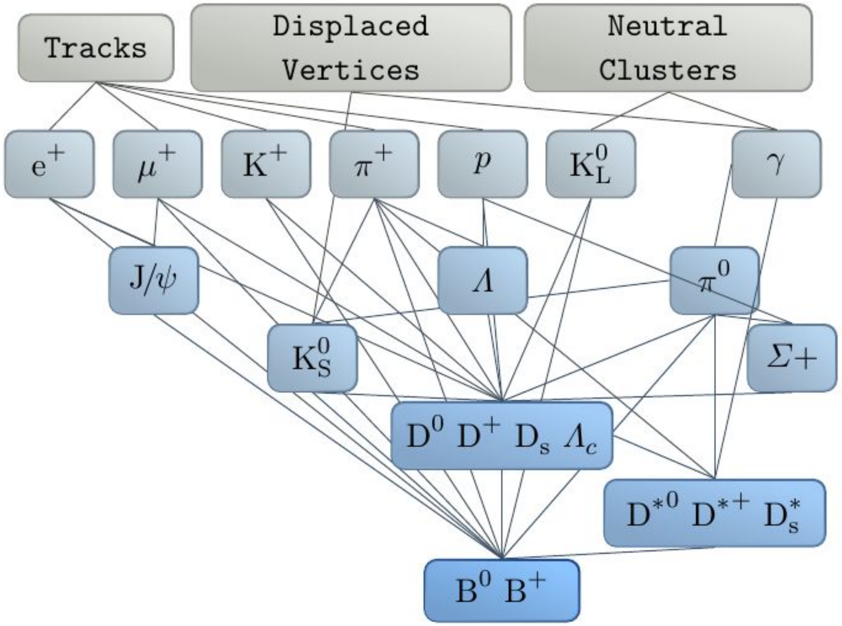
Summary

- Rare $b \to s\ell\ell$ and $b \to s\nu\bar{\nu}$ 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
- Many ongoing analyses to search rare decays and exploring techniques beyond hadronic B-tagging.

Backup

Hadronic B-tagging tool at Belle & Belle II

called Full Event Interpretation (FEI)



Designed for Belle II software,
now used with Belle data also.

For each decay, BDTs trained on MC.

B^+-tagging uses 36 decays.
But only 11 of them, essentially $B \to D^{(*)}\, m\pi^{\pm}\, n\pi^0$, gives >80% of the efficiency.

Total efficiency < 1%.

But, large data-MC discrepancy over the years

Calibration factors used as normalization to account for it
⇒ large source of systematics
⇒ And also poor performance?