MEASUREMENTS OF ELECTROWEAK PENGUIN AND RADIATIVE B DECAYS AT BELLE AND BELLE II

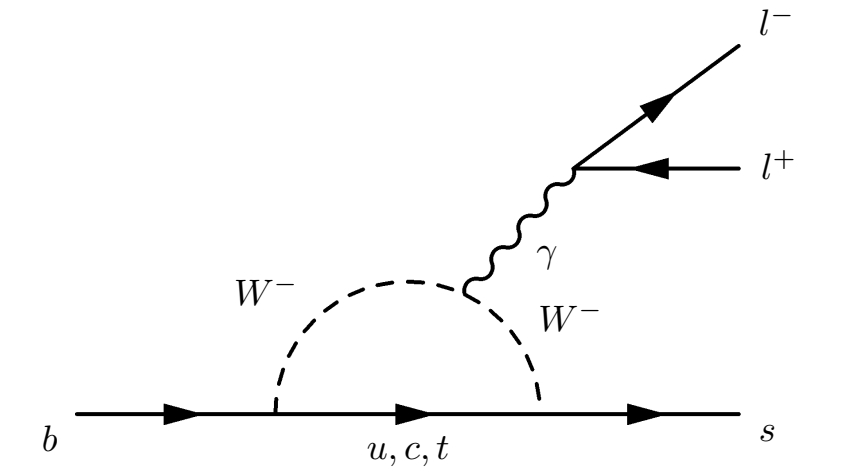
Noah Brenny (Iowa State University)
On behalf of Belle and Belle II collaborations

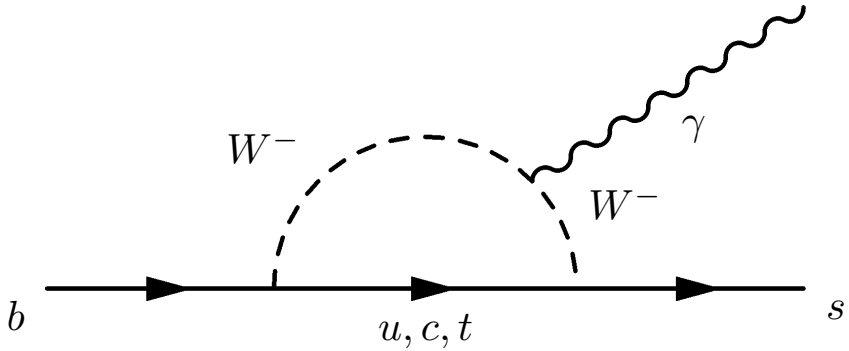
IOWA STATE UNIVERSITY

Lake Louise Winter Institute 2025
March 5th, 2025

Introduction

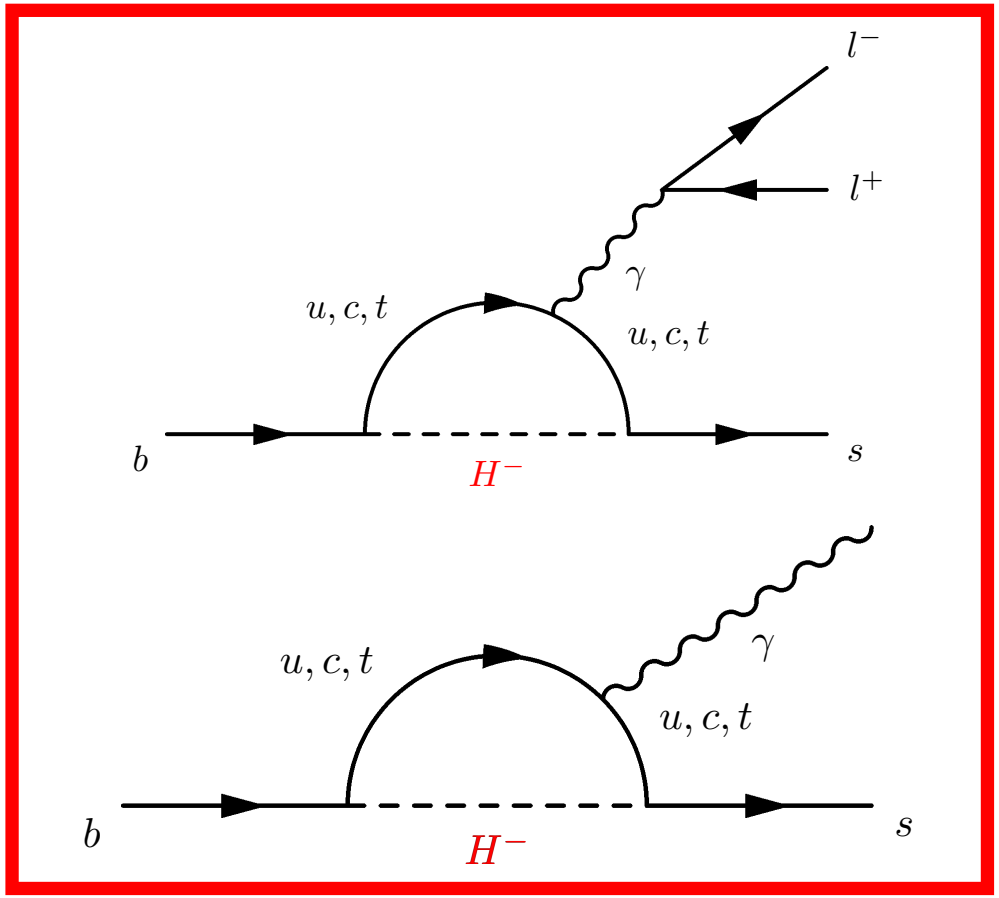
- FCNC processes $b \to s(d)$ are forbidden in SM at tree level
- Low branching fractions due to CKM and GIM suppression

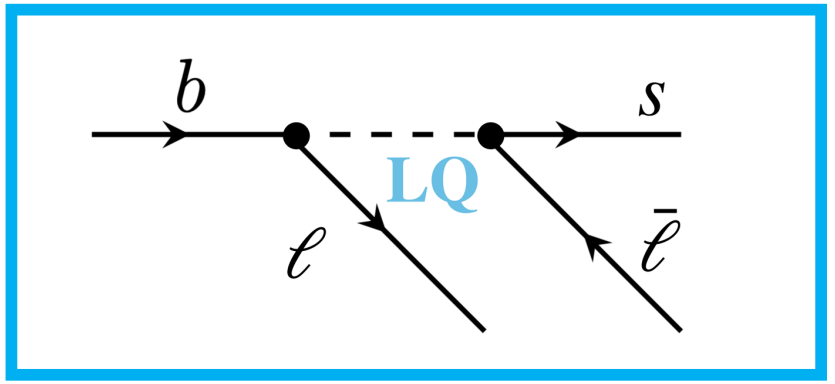




Introduction

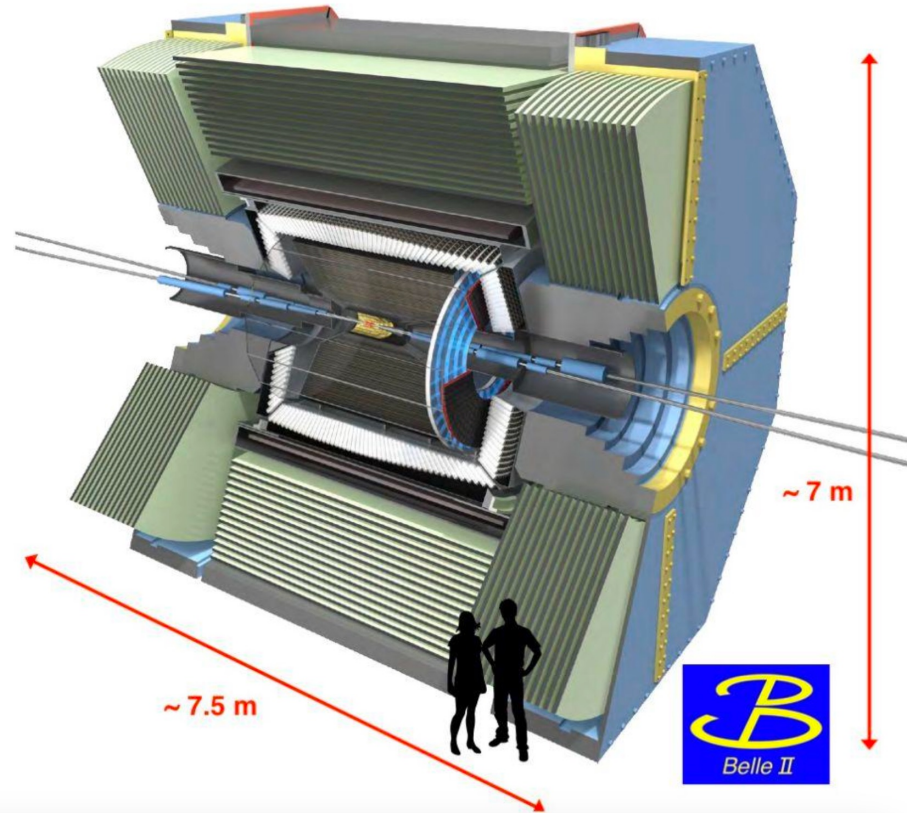
- FCNC processes $b \to s(d)$ are forbidden in SM at tree level
- Low branching fractions due to CKM and GIM suppression
- Look for enhancements in FCNC due to NP contributions
  - Weaker GIM cancellations due to new particles in loop corrections
  - New interactions at tree level
  - Channels with 3rd generation are particularly interesting due to connections to anomalies in semi-tauonic decays ($R(D^{(*)})$)





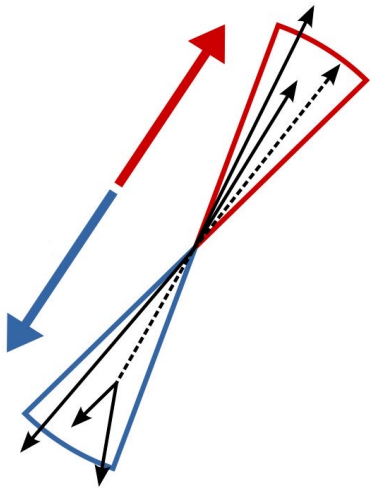
Belle and Belle II environment

- Threshold $B\bar{B}$ production at $\Upsilon(4S)$ resonance
  - Relatively clean environment
- Near 4π detector coverage
  - Full event reconstruction
- Well-equipped to measure decays with missing energy, neutrals in the final state, inclusive measurements

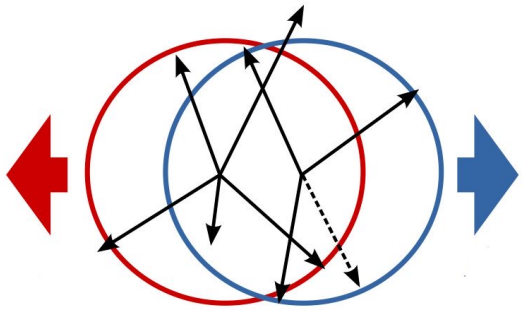


B-factory experimental techniques

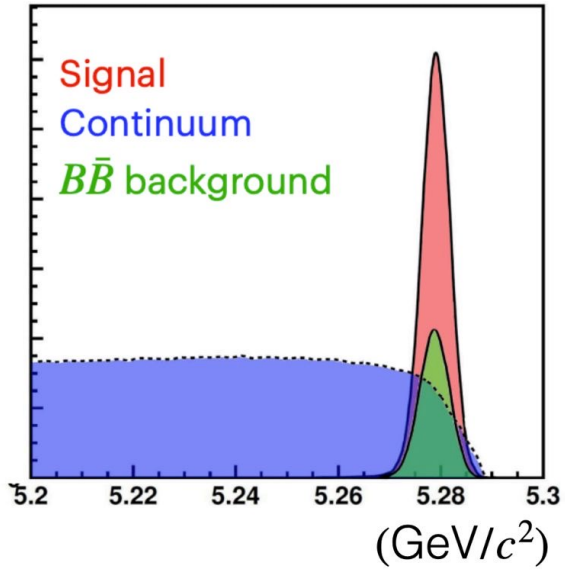
- Kinematics constrained from knowledge of initial state
- Suppress $e^+e^- \to q\bar{q}$ events ($q = u, d, s, c$) with event shape variables



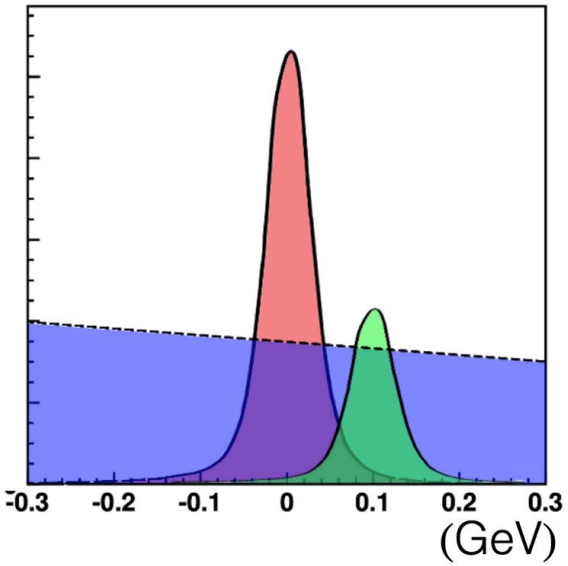
$e^+e^- \to q\bar{q}$ "continuum"



$e^+e^- \to \Upsilon(4S) \to B\bar{B}$



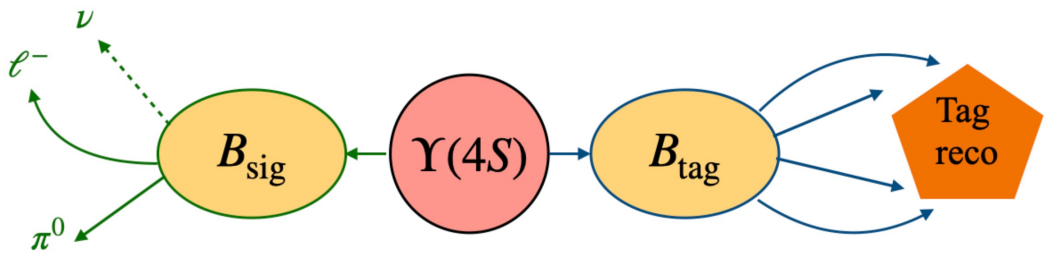
$M_{\mathrm{bc}} = \sqrt{s/4 - p_B^{*2}}$

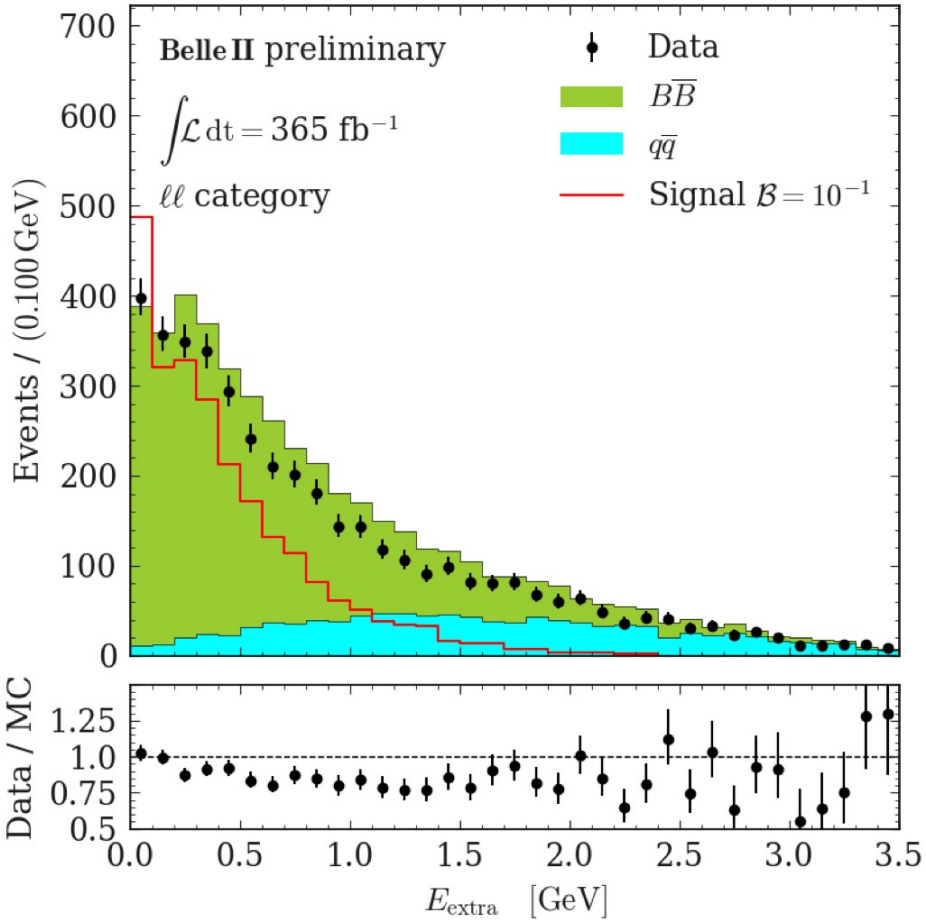


$\Delta E = E_B^* - \sqrt{s}/2$

B-factory experimental techniques

- B-meson tagging using hadronic or semileptonic B-meson decays
- Full Event Interpretation algorithm [Comput. Software Big Sci. 2, 9 (2018)]
- A useful variable is the residual energy in the calorimeter after fully reconstructing the event, E_{extra}





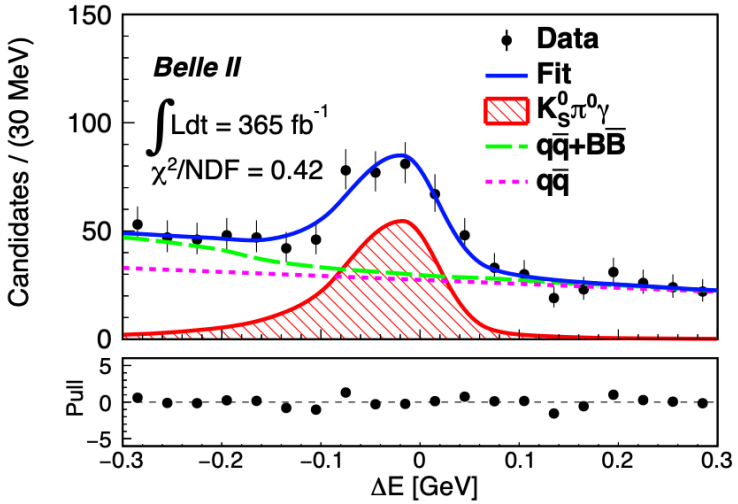
All results are new since LLWI 2024 and are from the datasets:

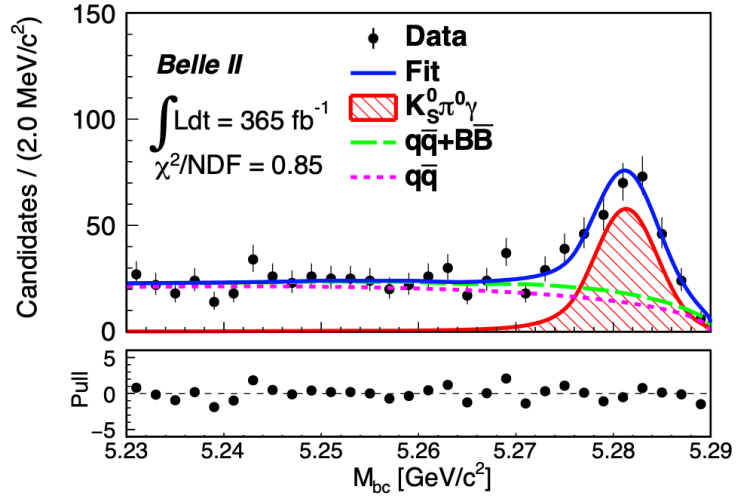
	Luminosity @ $\Upsilon(4S)$ [fb^{-1}]
Belle	711
Belle II	365

Measurement of $B \to K^*\gamma$ with Belle II

- $K^{*0} \to K^+\pi^-$, $K^{*0} \to K_S^0\pi^0$, $K^{*+} \to K^+\pi^0$, $K^{*+} \to K_S^0\pi^+$ modes
- Dominant background from continuum with $\pi^0/\eta \to \gamma\gamma$ faking hard photon
- Dedicated MVAs to suppress π^0/η and continuum backgrounds
- 2D unbinned fit in M_{bc} and ΔE
- Precision measurement with ~4000 signals

arXiv:2411.10127





Measurement of $B \to K^*\gamma$ with Belle II

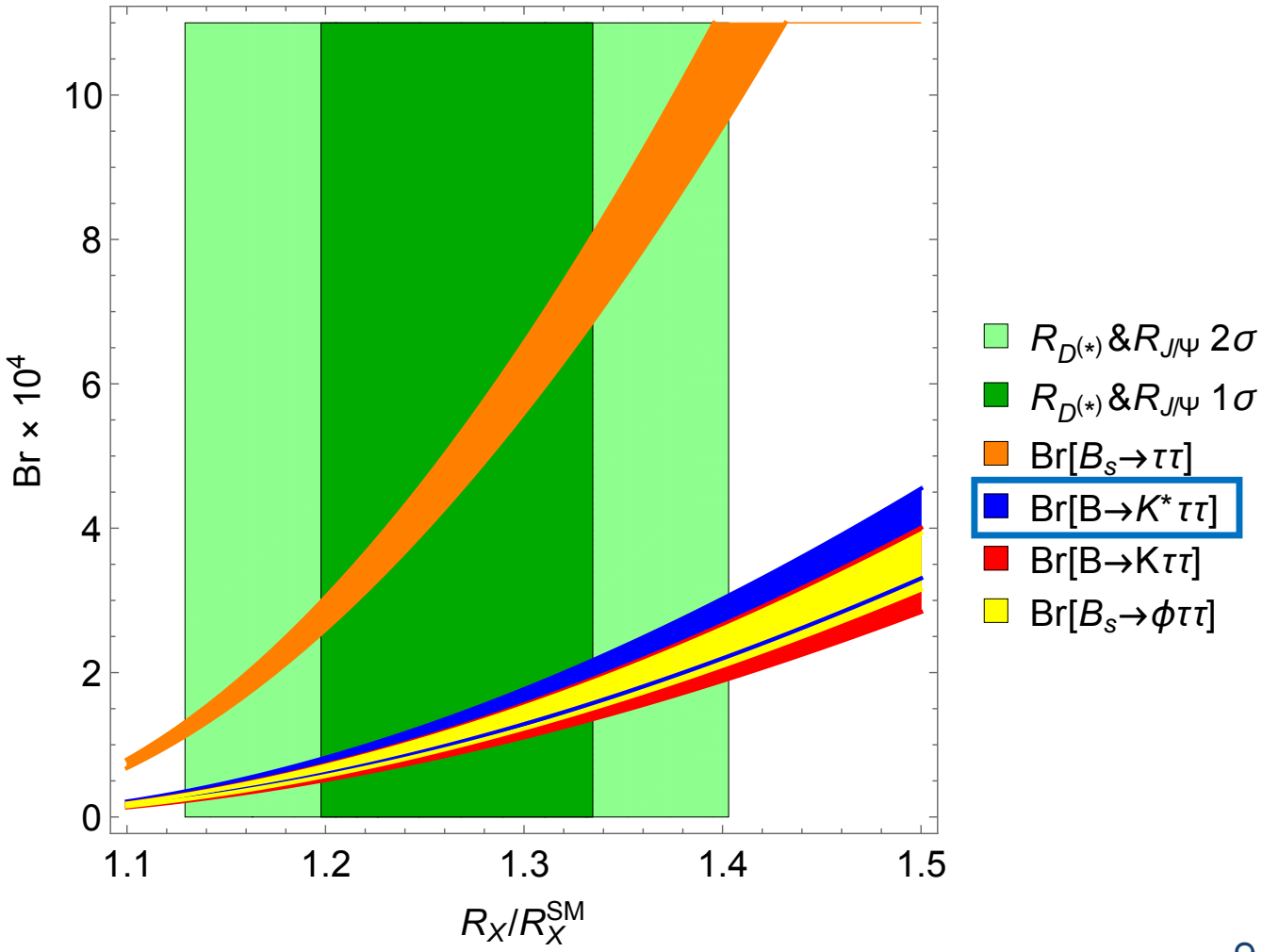
- Comparable statistical and systematic uncertainties for the branching fractions
- Dominant systematic from π^0 reconstruction efficiency (3.9%)
- CP and isospin asymmetries: statistical uncertainty dominates
- Isospin asymmetry consistent with SM expectation and previous Belle [PRL 89 231801 (2002)] and BaBar [PRD 70 091105 (2004)] measurements

Channel	$\mathcal{B}$ (10^{-5})	$\mathcal{A}_{CP}$ (%)
$B^0 \to K^{*0}[K^+\pi^-]\gamma$	$4.14 \pm 0.10 \pm 0.11$	$-3.3 \pm 2.3 \pm 0.4$
$B^0 \to K^{*0}[K^0_S\pi^0]\gamma$	$4.07 \pm 0.33 \pm 0.23$	$-$
$B^0 \to K^{*0}\gamma$	$4.14 \pm 0.10 \pm 0.10$	$-3.3 \pm 2.3 \pm 0.4$
$B^+ \to K^{*+}[K^+\pi^0]\gamma$	$3.97 \pm 0.17 \pm 0.20$	$+1.7 \pm 4.0 \pm 0.9$
$B^+ \to K^{*+}[K^0_S\pi^+]\gamma$	$4.06 \pm 0.18 \pm 0.13$	$-3.5 \pm 4.3 \pm 0.7$
$B^+ \to K^{*+}\gamma$	$4.02 \pm 0.13 \pm 0.13$	$-0.7 \pm 2.9 \pm 0.6$
	Δ_{0+} (%)	$\Delta\mathcal{A}_{CP}$ (%)
$B \to K^*\gamma$	$+5.0 \pm 2.0 \pm 1.0 \pm 1.1$	$+2.6 \pm 3.8 \pm 0.7$

Search for $B^0 \to K^{*0}\tau\tau$ with Belle II

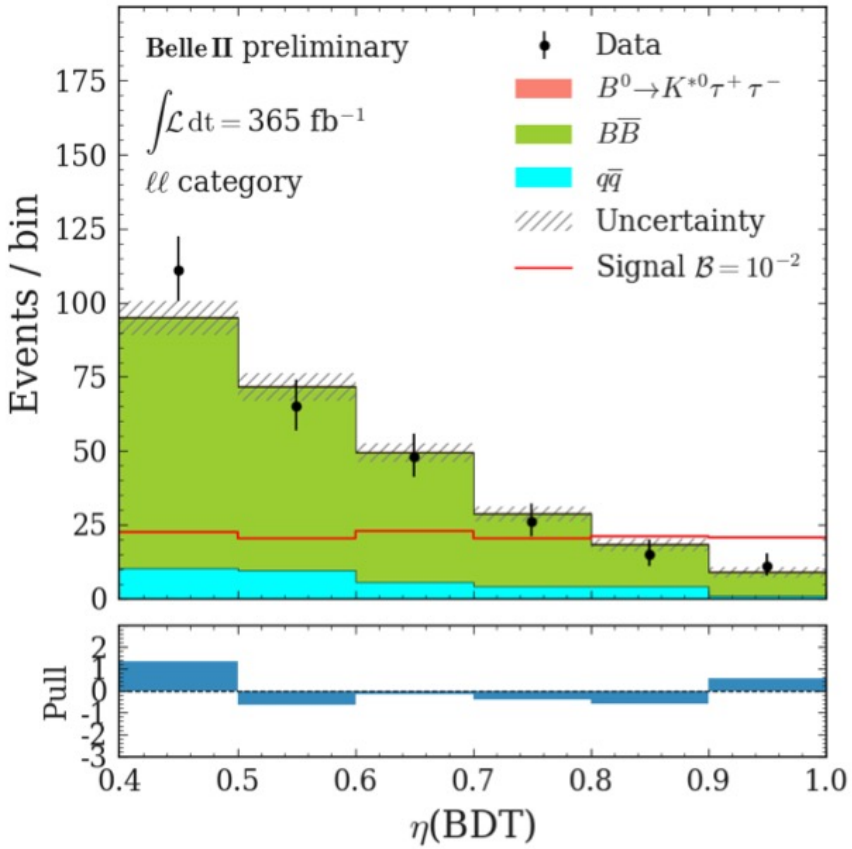
- Branching fraction in SM of 1×10^{-7}
- NP models describing $R(D^{(*)})$ predict $\times10^4$ branching fraction enhancement
- Experimentally very challenging
  - Low efficiency
  - Large missing energy
  - Low K^{*0} momentum
  - No signal peaking kinematic observable due to 2+ ν final state
- Most recent limit from Belle (711 fb^{-1}) BR < 3.1×10^{-3} @ 90% CL [PRD 108 011102 (2023)]

[PRL 120, 181802 (2018)]



Search for $B^0 \to K^{*0}\tau\tau$ with Belle II

- Hadronic tag companion B
- $\tau\tau$ reconstructed in $ll, l\pi, \pi\pi, \rho X$ categories
- BDT trained using missing energy, residual energy in calorimeter, $M(K^{*0}, \tau$ track), dilepton mass, etc.
- Fit BDT score simultaneously across categories

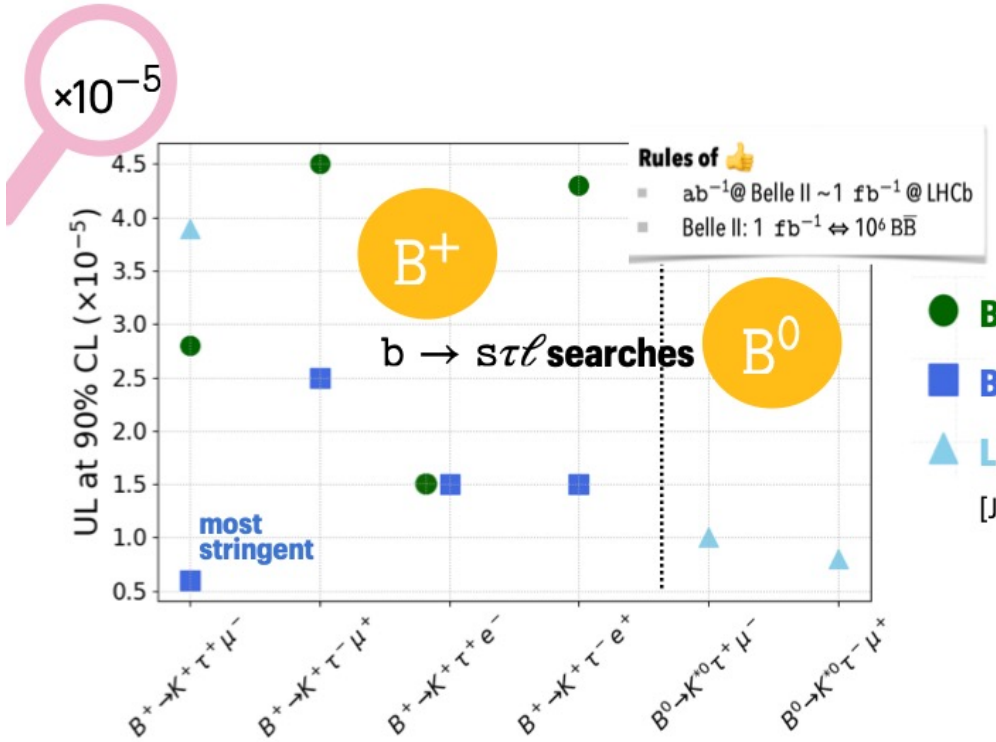


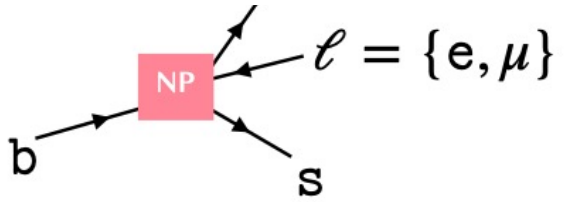
$\text{BF}(B^0 \to K^{*0}\tau\tau) < 1.8\times10^{-3}$ at 90% CL

Better tagging + more categories + BDT →
Twice better limit than Belle with half the statistics
Most stringent limit on $b \to s\tau\tau$ transition

Search for $B^0 \to K_S^0 \tau^{\pm} l^{\mp}$ with Belle + Belle II

- $R(D^{(*)})$ anomalies and $B(B^+ \to K^+ \nu\bar{\nu})$ excess can be explained by a new heavy particle coupling differently to 3rd generation leptons
- BSM extensions predict $b \to s\tau l$ branching fractions near current experimental limits ~ 10^{-5} [1,2]





- **BaBar** (428 fb^{-1}) $B^+ \to K^+\tau^{\pm}\ell^{\mp}$ [PRD86, 012004, 2012]
- **Belle** (711 fb^{-1}) $B^+ \to K^+\tau^{\pm}\ell^{\mp}$ [PRL130, 261802, 2023]
- **LHCb** (9 fb^{-1}) $B^+ \to K^+\tau^+\mu^-$, $B^0 \to K^{*0}\tau^{\pm}\mu^{\mp}$ [JHEP06,129,2020] [JHEP06,143,2023]

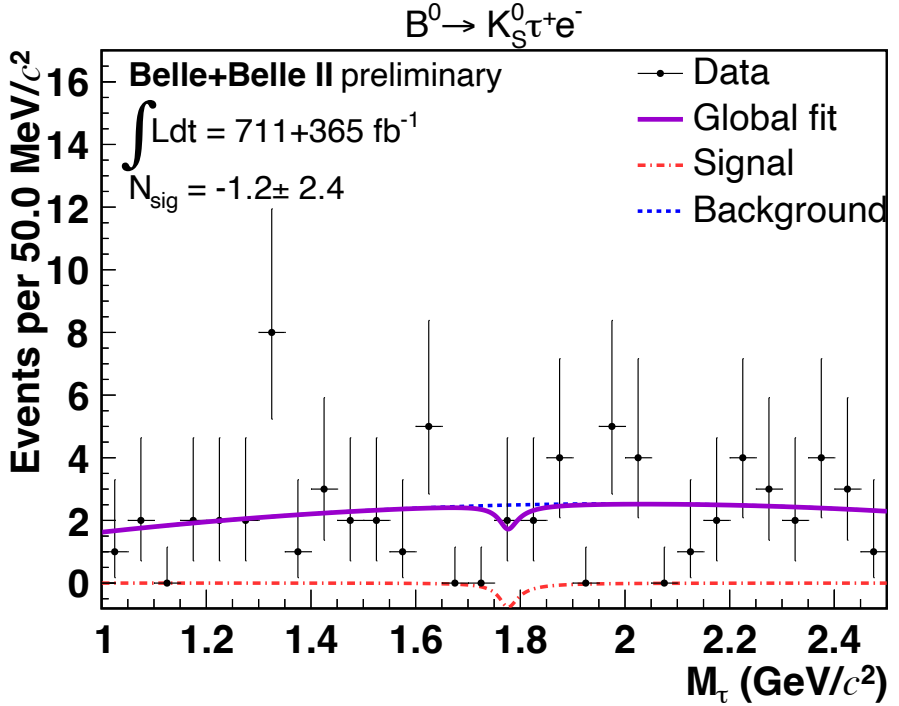
No search yet in $B^0 \to K_S^0\tau^{\pm}\ell^{\mp}$

[1] Eur. Phys. J. C 76, 134 (2016)
[2] PRL 114 091801 (2015)

Search for $B^0 \to K_S^0 \tau^{\pm} l^{\mp}$ with Belle + Belle II

- Challenges:
  - Missing energy
  - Large backgrounds
- Hadronic tag companion B_{tag}
- Four channels: $l \in \{e^+, e^-, \mu^+, \mu^-\}$
- Reconstruct one-prong τ decays into μ, e, π, ρ: >70% of τ decays
- One τ in final state → $M^2_{\text{recoil}} = m^2_\tau = \left(p_{e^+e^-} - p_{K_S^0} - p_l - p_{B_{\text{tag}}}\right)^2$
- Dedicated veto for semileptonic decays and BDT for other backgrounds

Comparable to best existing limits
First search for $B^0 \to K_S^0 \tau^{\pm} l^{\mp}$ decays



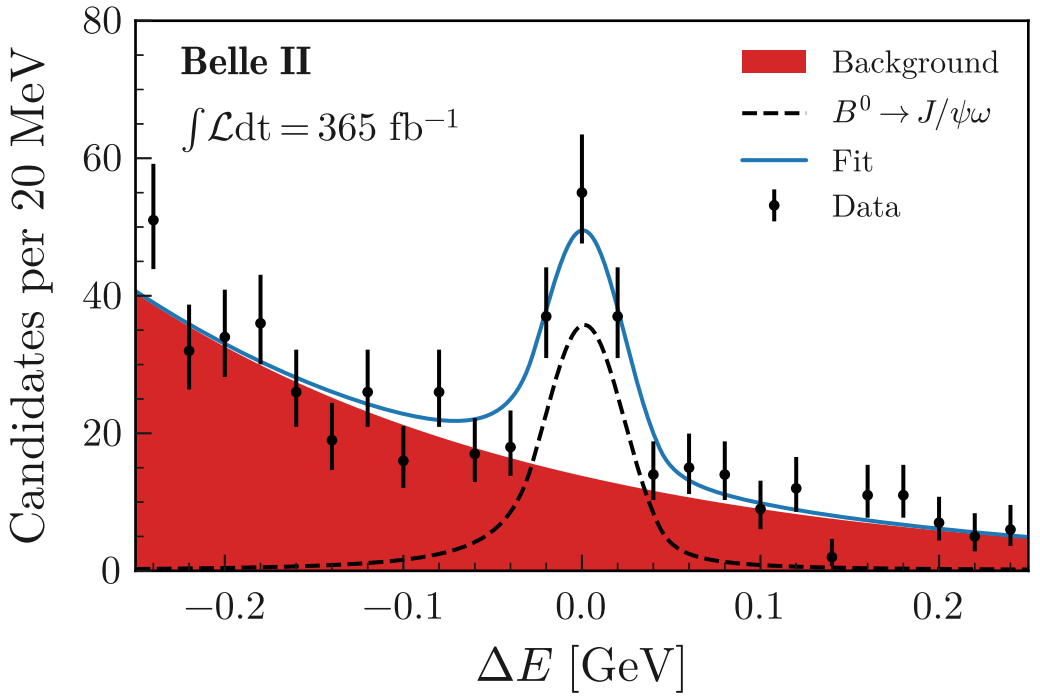
Channels	$\epsilon(10^{-4})$	N_{sig}	$\mathcal{B}(10^{-5})$ Central value	UL
$B^0 \to K_S^0 \tau^+ \mu^-$	1.7	-1.8 ± 3.0	$-1.0 \pm 1.6 \pm 0.2$	1.1
$B^0 \to K_S^0 \tau^- \mu^+$	2.1	2.6 ± 3.5	$1.1 \pm 1.6 \pm 0.3$	3.6
$B^0 \to K_S^0 \tau^+ e^-$	2.0	-1.2 ± 2.4	$-0.5 \pm 1.1 \pm 0.1$	1.5
$B^0 \to K_S^0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

arXiv:2412.16470

Measurement of $B^0 \to J/\psi\omega$ with Belle II

- Color-suppressed tree diagrams with $b \to c\bar{c}d$ transitions
- Time-dependent CPV mode to measure C and S, control mode for $b \to dll$ decays at B-factories
- Reconstruct $\omega \to \pi^+\pi^-\pi^0$ decay mode: 89% of ω decays
- BDT to reject dominant $B^0 \to J/\psi X$ backgrounds

PRD 111 032012 (2025)



First observation (6.5σ) and consistent with world average

$$\mathrm{BF}(B^0 \to J/\psi\omega) = (2.16 \pm 0.30 \pm 0.14) \times 10^{-5}$$

Summary

- Belle and Belle II provide unique opportunities for studies of $b \to s$ transitions, including channels with third generation couplings
- $B \to K^* \gamma$ branching fraction and A_{CP} precision measurements
- First search for $B^0 \to K_S^0 \tau^{\pm} l^{\mp}$ with sensitivity similar to adjacent LFV channels
- Best limits for $B^0 \to K^{*0} \tau\tau$
- First observation of $B^0 \to J/\psi\omega$
- More results to come!

Backup

Search for $B^0 \to K^{*0}\tau\tau$ with Belle II

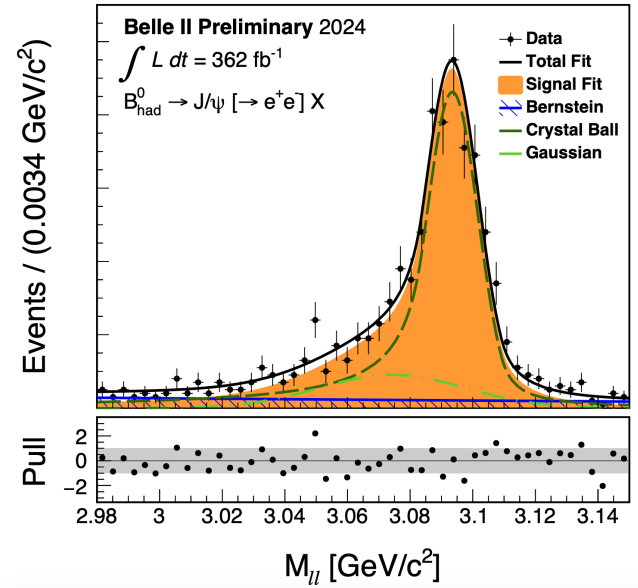
Source	Impact on $\mathcal{B} \times 10^{-3}$
$B \to D^{**}\ell/\tau\nu$ branching fractions	0.29
Simulated sample size	0.27
$q\bar{q}$ normalization	0.18
ROE cluster multiplicity	0.17
π and K ID	0.14
B decay branching fraction	0.11
Combinatorial $B\overline{B}$ normalization	0.09
Signal and peaking $B^0\overline{B}^0$ normalization	0.07
Lepton ID	0.04
π^0 efficiency	0.03
f_{00}	0.01
$N_{\Upsilon(4S)}$	0.01
$D \to K_L$ decays	0.01
Signal form factors	0.01
Luminosity	< 0.01
Total systematics	0.52
Statistics	0.86

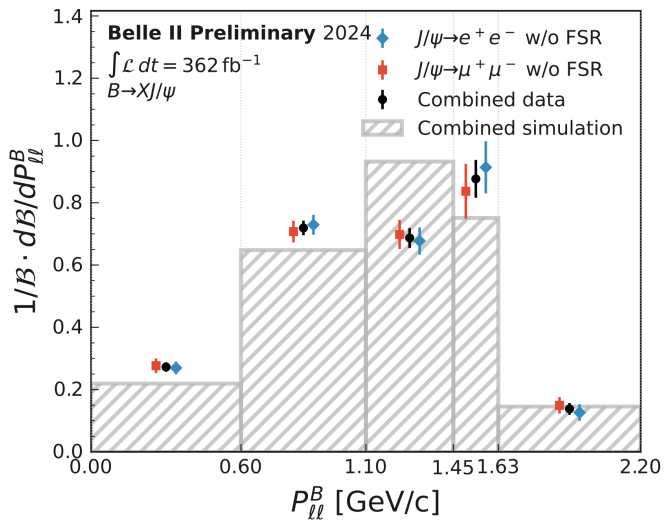
Systematic uncertainties

Measurement of inclusive $B \to J/\psi X$ with Belle II

- Useful for (semi) inclusive $B \to Xll$ and $B \to X\nu\nu$ measurements
- Differential measurement of the J/ψ momentum and polarization
- Hadronic tag companion B
- Fit yields with $M(l^+l^-)$
- First separate branching fraction measurement of B^0 and B^+

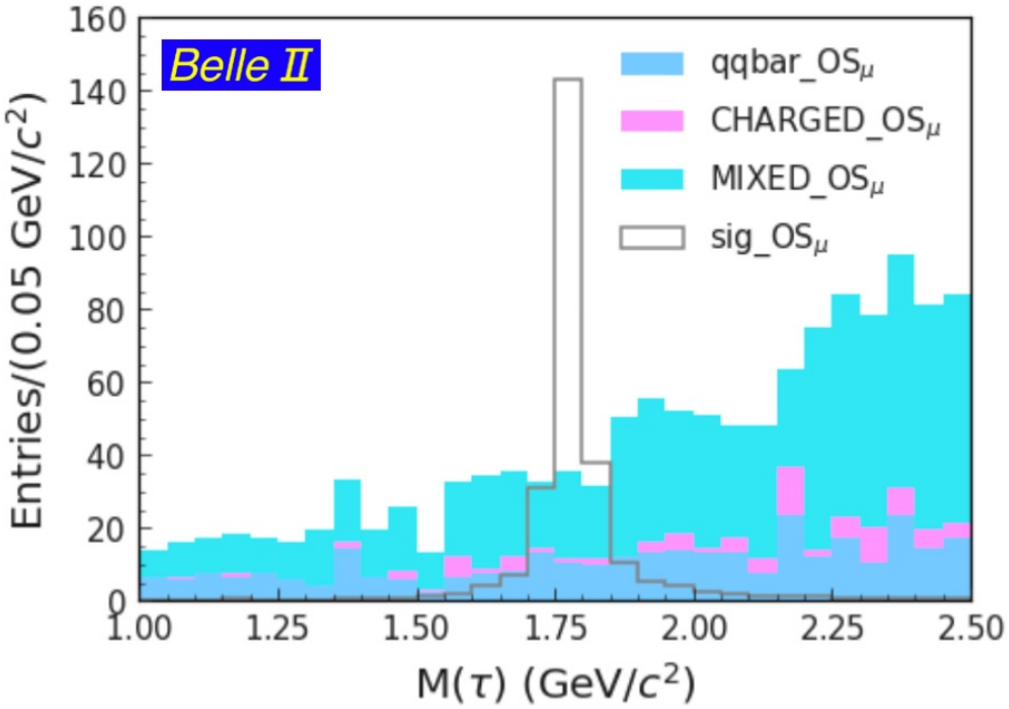
$$\mathrm{BF}(B^0 \to J/\psi X) = (0.95 \pm 0.03 \pm 0.04)$$
$$\mathrm{BF}(B^+ \to J/\psi X) = (1.19 \pm 0.03 \pm 0.05)$$





Search for $B^0 \to K_S^0 \tau^{\pm} l^{\mp}$ with Belle + Belle II

- One τ in final state → $M^2_{\text{recoil}} = m_\tau^2 = \left(p_{e^+e^-} - p_{K_S^0} - p_l - p_{B_{\text{tag}}}\right)^2$



Search for $B^0 \to K_S^0 \tau^{\pm} l^{\mp}$ with Belle + Belle II