

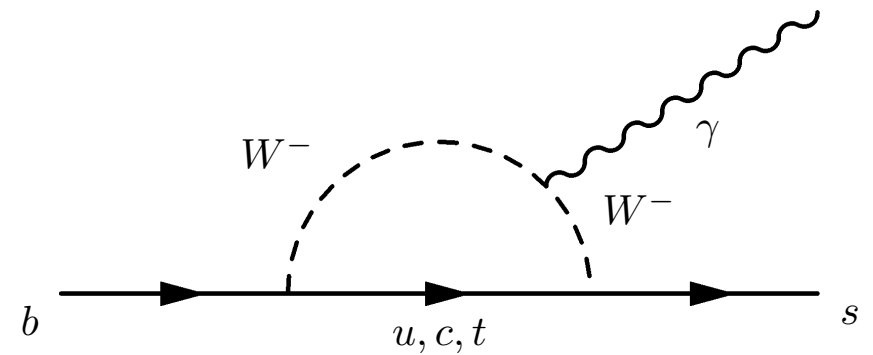
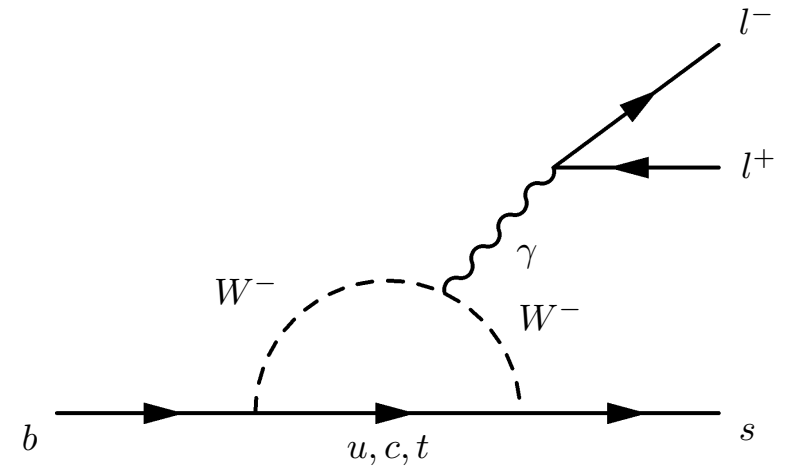


# MEASUREMENTS OF ELECTROWEAK PENGUIN AND RADIATIVE $B$ DECAYS AT BELLE AND BELLE II

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

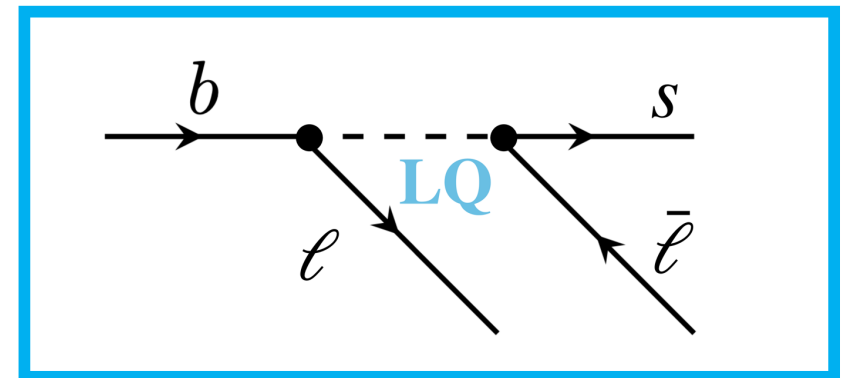
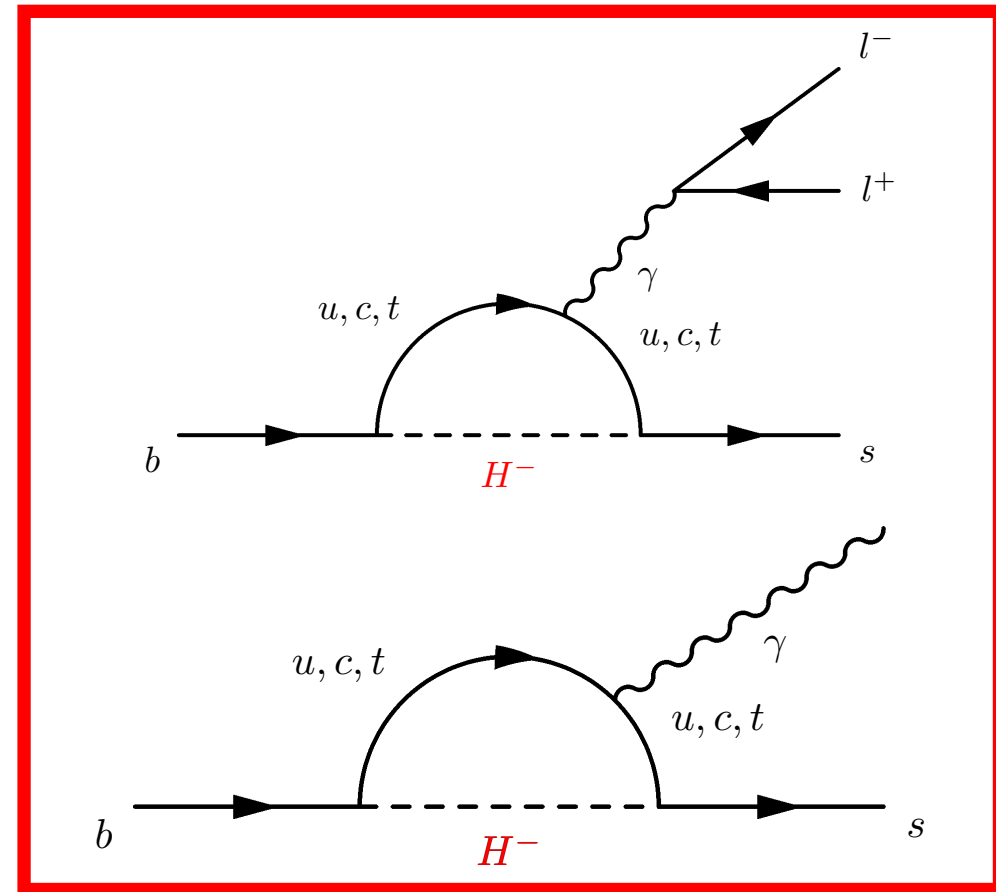
# Introduction

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



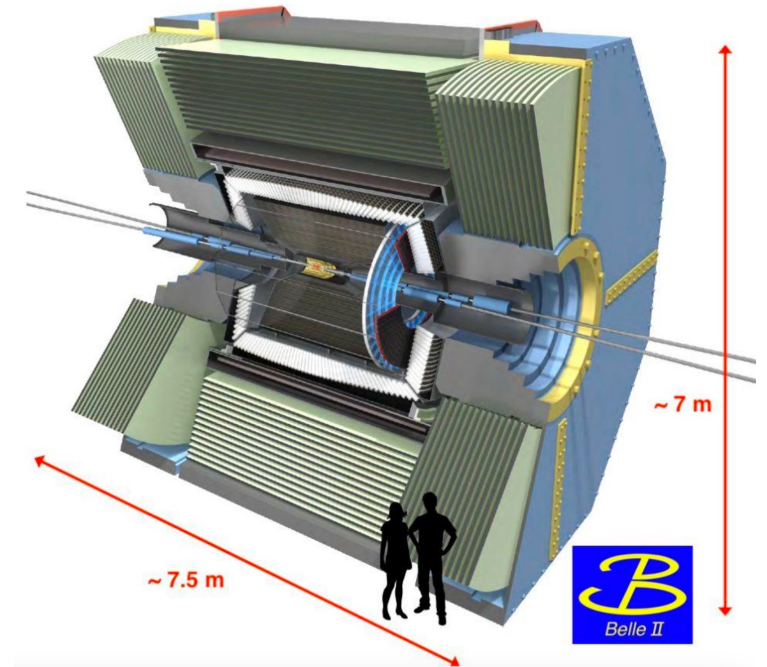
# Introduction

- FCNC processes  $b \rightarrow s(d)$  are forbidden in SM at tree level
- Low BF's 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 3<sup>rd</sup> generation are particularly interesting due to connections to anomalies in semi-taunic decays ( $R(D^{(*)})$ )



# Belle and Belle II environment

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

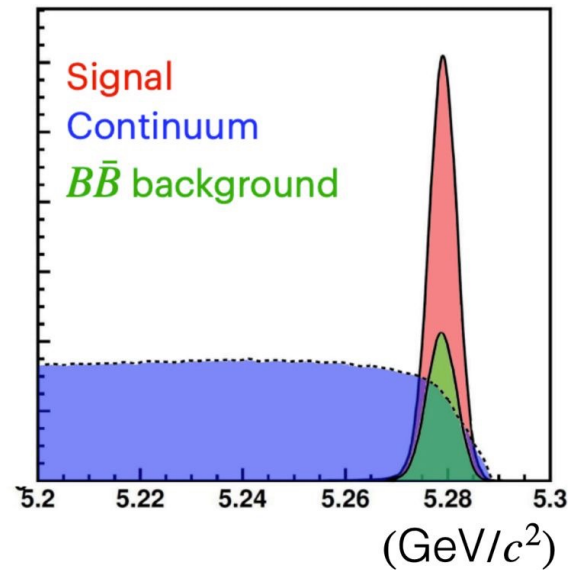
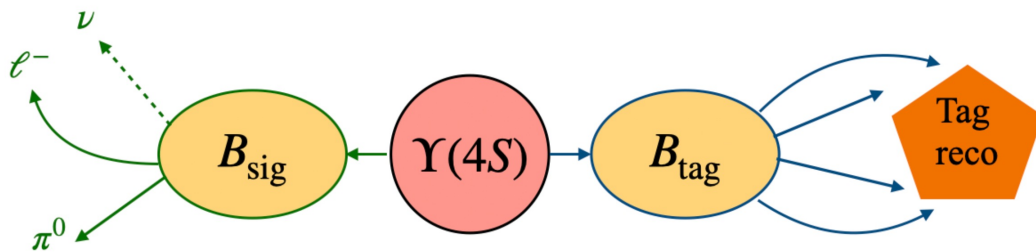


Today's results are from the datasets:

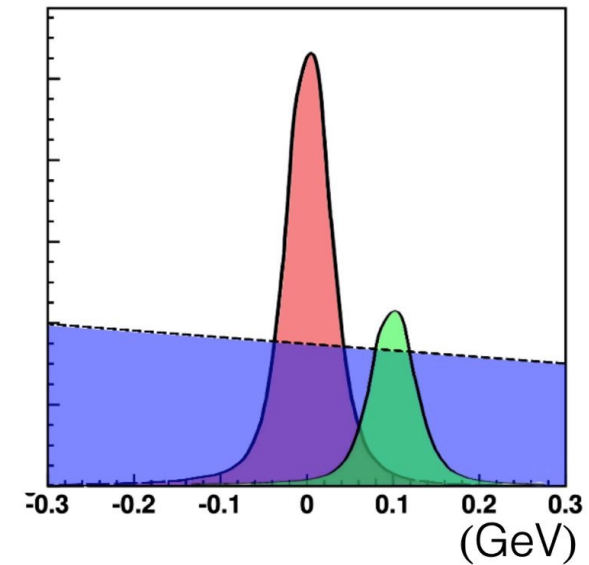
|          | Luminosity [ $\text{fb}^{-1}$ ] |
|----------|---------------------------------|
| Belle    | 711                             |
| Belle II | 365                             |

# B-factory experimental techniques

- Kinematics constrained from knowledge of initial state
- B-meson tagging using hadronic or semileptonic B-meson decays



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



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

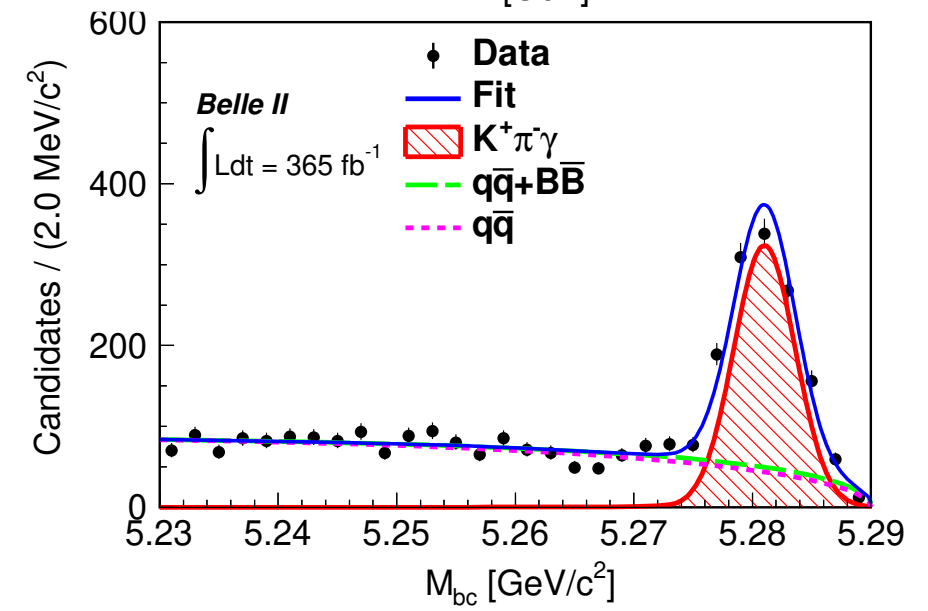
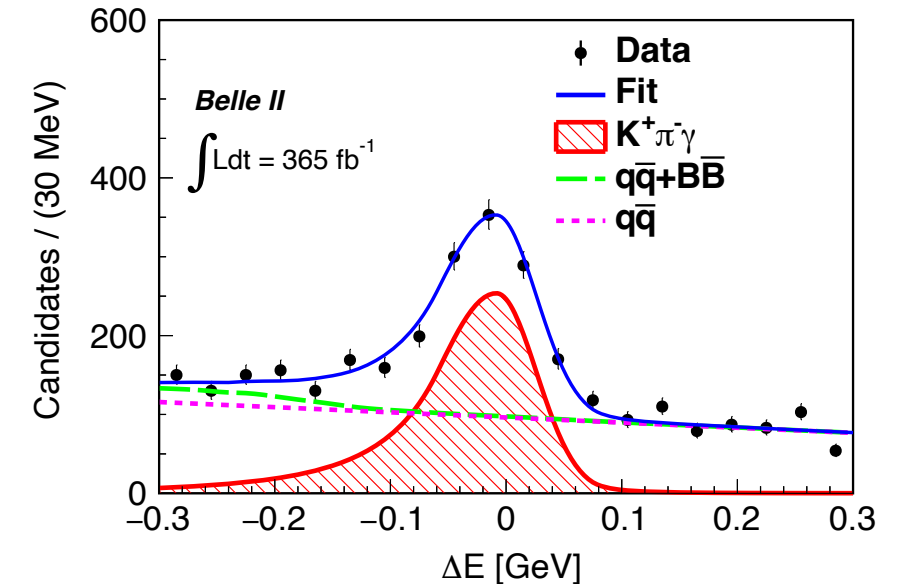
All results new since LLWI 2024

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



[arXiv:2411.10127](https://arxiv.org/abs/2411.10127)

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



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

- Comparable statistical and systematic uncertainties for the BFs
- Dominant systematic from  $\pi^0$  reconstruction efficiency (3.9%)
- $CP$  and isospin asymmetries: statistical uncertainty dominates
- Isospin asymmetry consistent with SM expectation and previous Belle and BaBar measurements

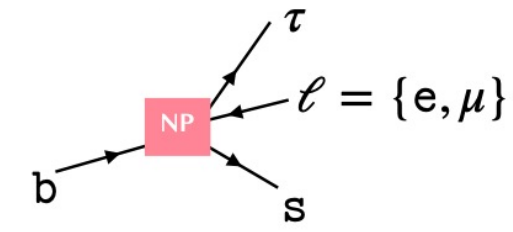
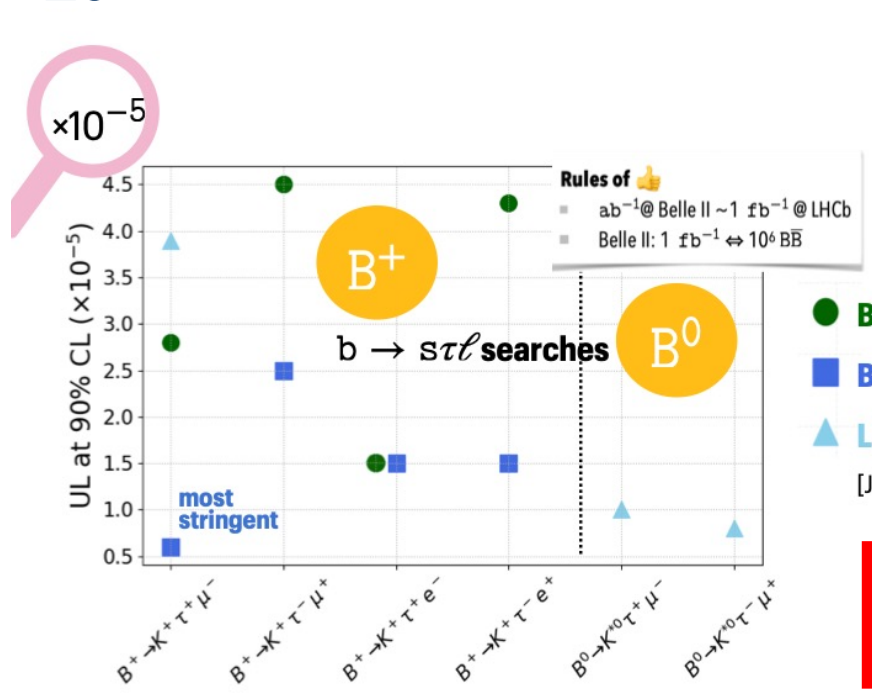
| Channel                                    | $\mathcal{B}$ ( $10^{-5}$ )    | $\mathcal{A}_{CP}$ (%)       |
|--|--------------------------------|------------------------------|
| $B^0 \rightarrow K^{*0}[K^+\pi^-]\gamma$   | $4.14 \pm 0.10 \pm 0.11$       | $-3.3 \pm 2.3 \pm 0.4$       |
| $B^0 \rightarrow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

# Search for $B^0 \rightarrow K_S^0 \tau^\pm l^\mp$ with Belle + Belle II



II

- $b \rightarrow c\tau l$  anomalies and  $B(B^+ \rightarrow K^+ \nu \bar{\nu})$  excess can be explained by a new heavy particle coupling differently to 3<sup>rd</sup> generation leptons
- BSM extensions predict  $b \rightarrow s\tau l$  BFs near current experimental limits  $\sim 10^{-5}$



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

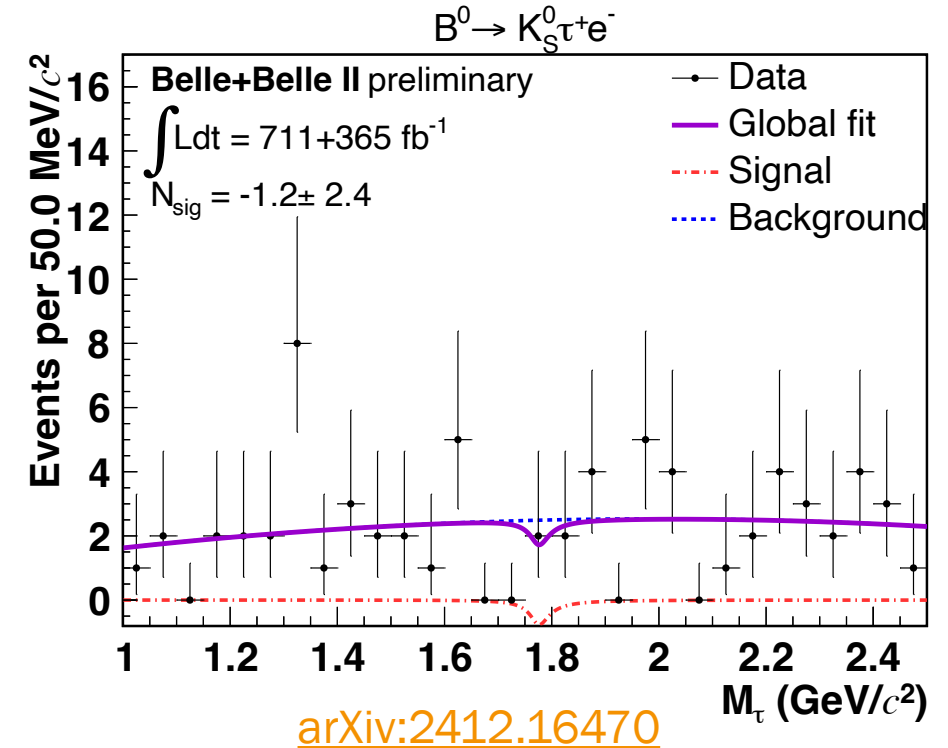
No search yet in  $B^0 \rightarrow K_S^0 \tau^\pm \ell^\mp$



# Search for $B^0 \rightarrow K_S^0 \tau^\pm l^\mp$ with Belle + Belle II



- Challenges:
  - Forbidden decay
  - Large backgrounds
- Hadronic tag companion  $B_{\text{tag}}$
- Four channels:  $l \in \{e^+, e^-, \mu^+, \mu^-\}$
- Reconstruct one-prong  $\tau$  decays into  $\mu, e, \text{ or } \pi$ : >70% of  $\tau$  decays
- One  $\tau$  in final state  $\rightarrow M_{\text{recoil}}^2 = m_\tau^2 = (p_{e^+e^-} - p_{K_S^0} - p_l - p_{B_{\text{tag}}})^2$
- Dedicated veto for semileptonic decays and BDT for other backgrounds



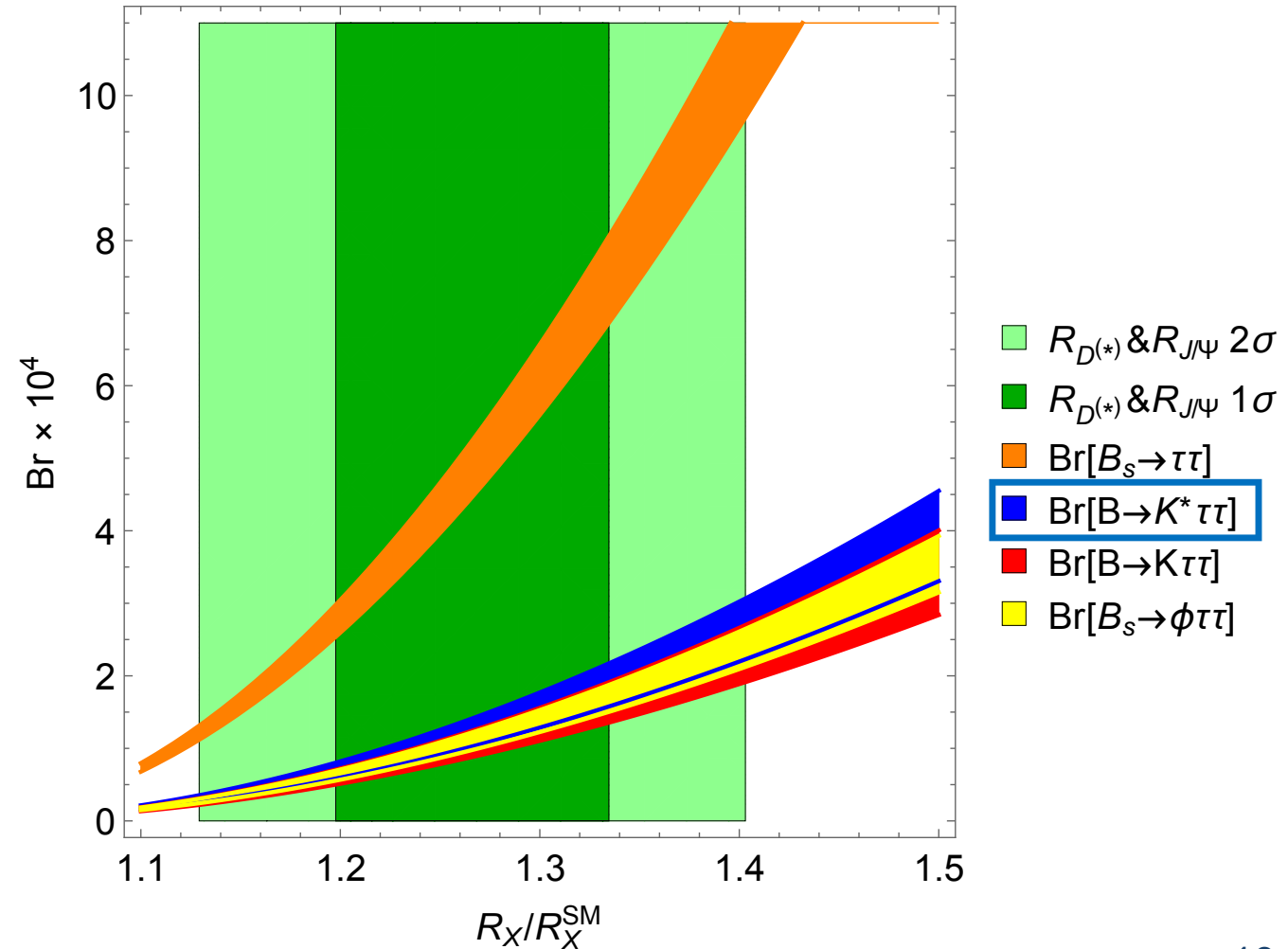
| Channels                             | $\epsilon(10^{-4})$ | $N_{\text{sig}}$ | $\mathcal{B}(10^{-5})$ |     |
|--------------------------------------|---------------------|------------------|------------------------|-----|
|                                      |                     |            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

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

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

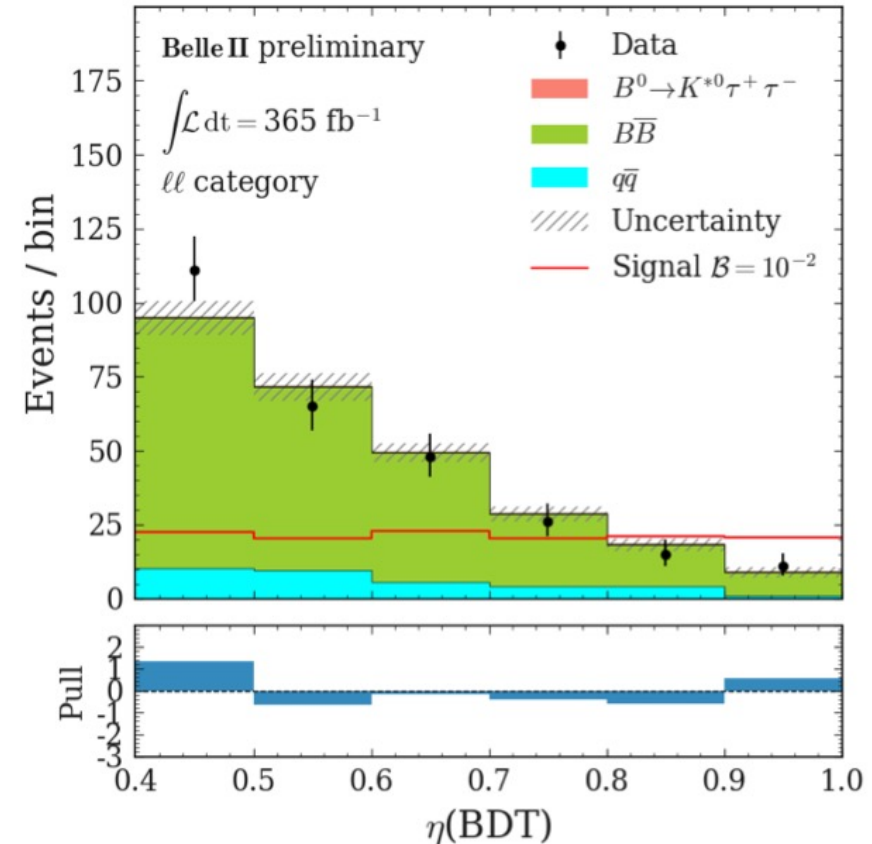
[PRL 120, 181802 (2018)]

- BF in SM of  $1 \times 10^{-7}$
- NP models describing  $b \rightarrow c \tau l$  predict  $\times 10^4$  BF enhancement
- Experimentally very challenging
  - *Low efficiency*
  - *Large missing energy*
  - *Low  $K^{*0}$  momentum*
  - *No signal peaking kinematic observable due to  $2 + \nu$  final state*
- Most recent limit from Belle ( $711 \text{ fb}^{-1}$ )  
 $\text{BR} < 3.1 \times 10^{-3}$  @ 90% CL [PRD 108 011102 (2023)]



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

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



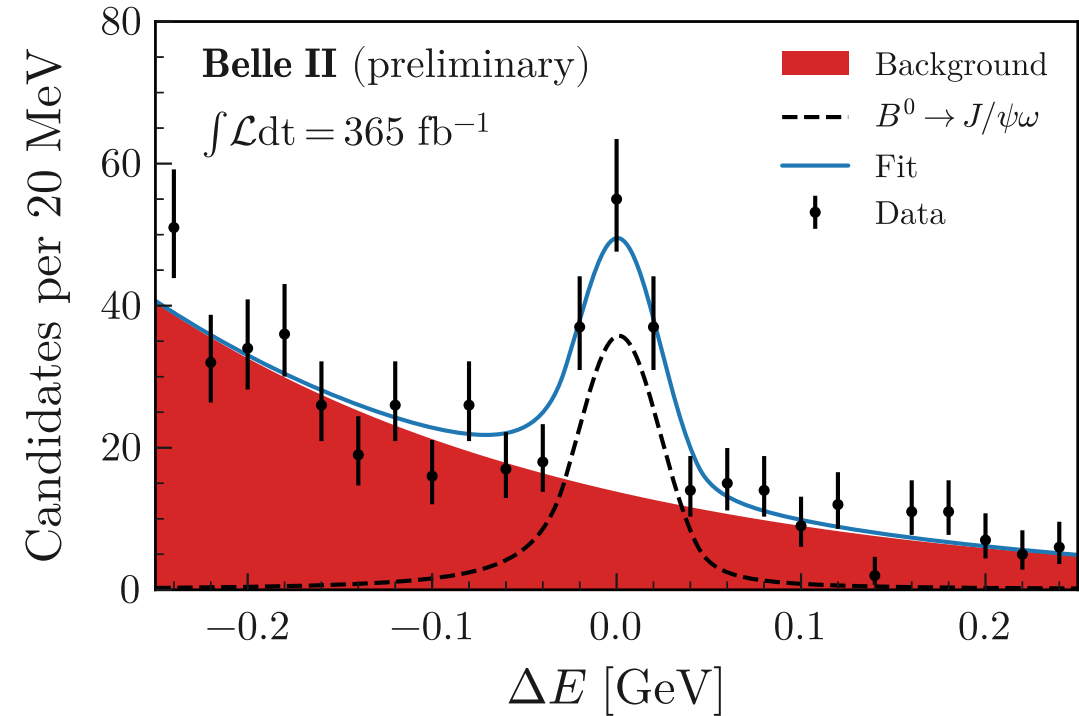
$$\text{BF}(B^0 \rightarrow K^{*0} \tau \tau) < 1.8 \times 10^{-3} \text{ at 90\% CL}$$

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

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

- Color-suppressed tree diagrams with  $b \rightarrow c\bar{c}d$  transitions
- TDCPV mode, control mode for  $b \rightarrow dll$  decays at  $B$ -factories
- BDT to reject dominant  $B^0 \rightarrow J/\psi X$  backgrounds
- First observation ( $6.5\sigma$ ) and consistent with WA

[arXiv:2412.12339](https://arxiv.org/abs/2412.12339)



$$\text{BF}(B^0 \rightarrow J/\psi\omega) = 2.16 \pm 0.30 \pm 0.14$$

# Summary

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

# Backup

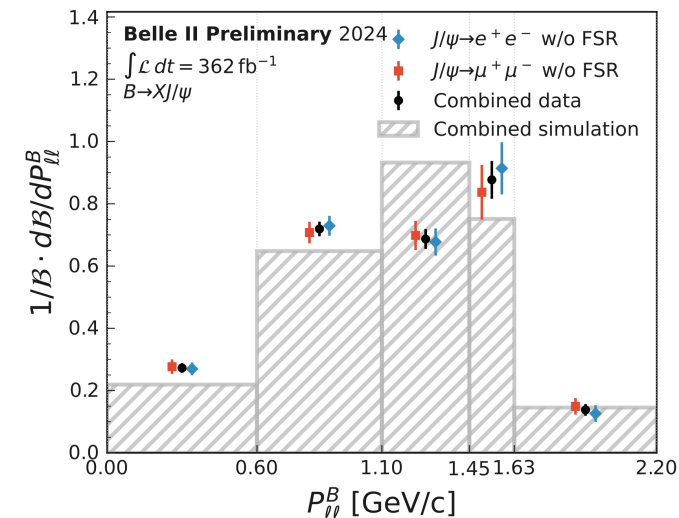
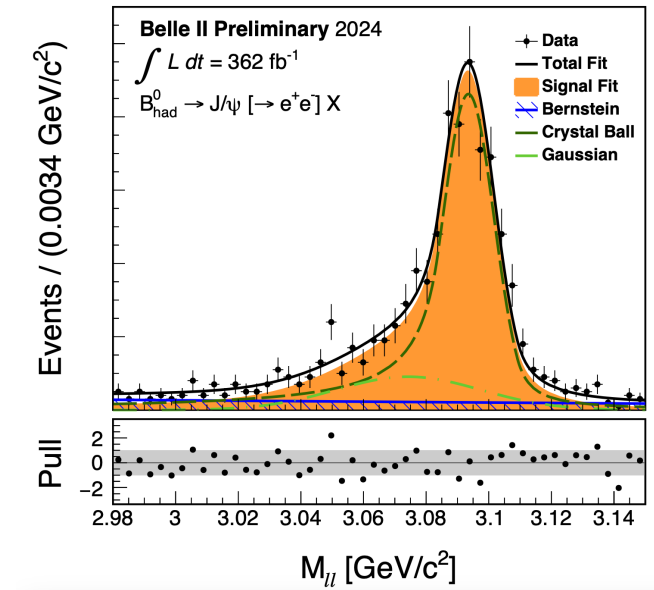
# Measurement of inclusive $B \rightarrow J/\psi X$ with Belle II



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

$$\text{BF}(B^0 \rightarrow J/\psi X) = (0.95 \pm 0.03 \pm 0.04)$$

$$\text{BF}(B^+ \rightarrow J/\psi X) = (1.19 \pm 0.03 \pm 0.05)$$



# Search for $B^0 \rightarrow K_S^0 \tau^\pm l^\mp$ with Belle + Belle II

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

