Rare & BSM decays at Belle II, and prospects

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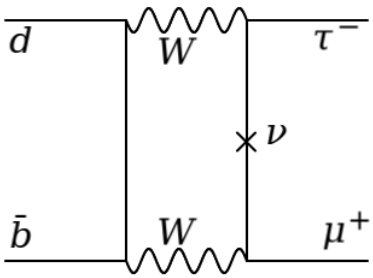
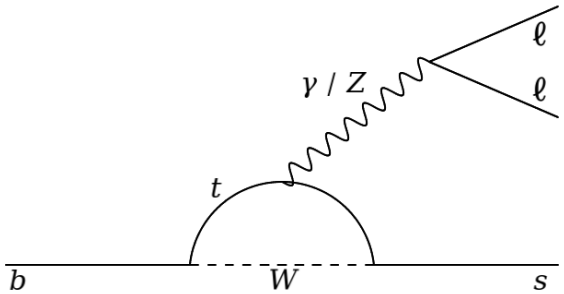
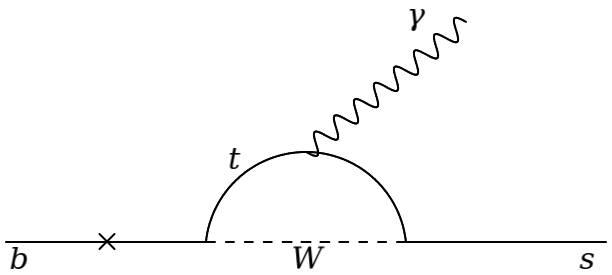
Search for New Physics in (super) rare decays

- **Probes for New Physics** at much higher scales than direct searches:
  - FCNC (high energy contributions) treated as point-like, encoded in Wilson coefficients $H_{eff}^{b\to s} = \frac{G_F}{\sqrt{2}} \sum_i V_{ib}V_{is}^* C_i(\lambda) Q_i(\lambda)$
  - Long-distance physics (low energy contributions) described by effective operators

- New Physics can modify Wilson coefficients or add new ones, thus **affecting branching ratios, angular observables, ...**







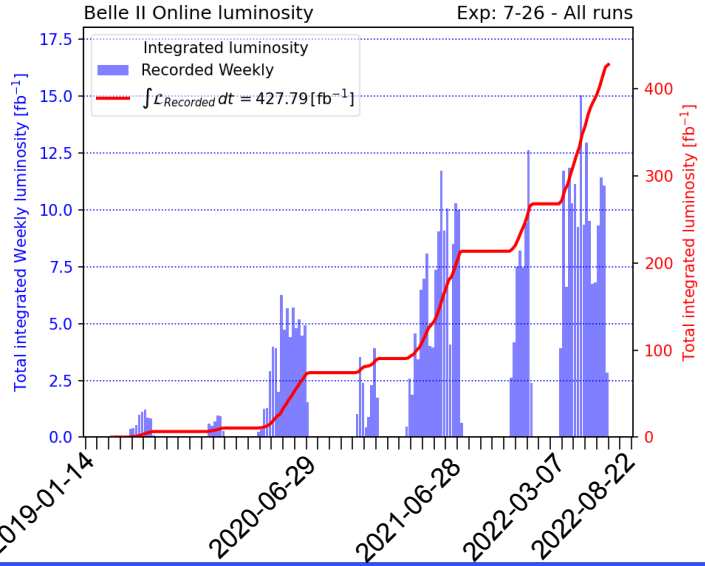
LFV ~ 10^{-50} : super rare **b → s l l ~ 10^{-7} – 10^{-5} : definitely rare** **b → s γ ~ 10^{-4} : kind of rare**

Standard Model branching ratio →

Belle II at SuperKEKB [KEK Report 2010-1]

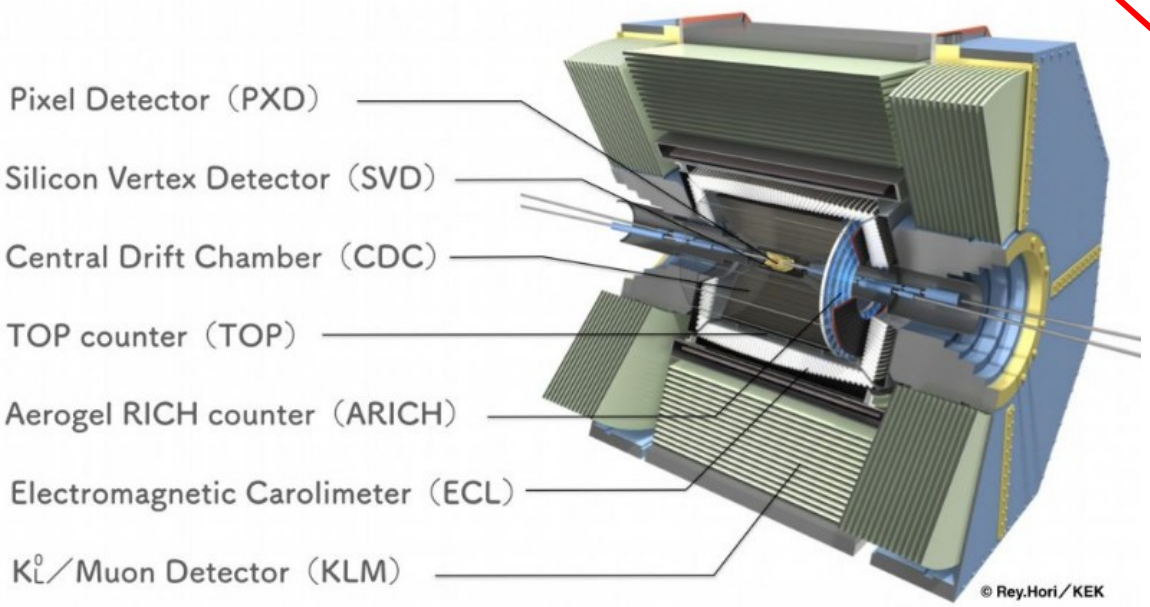
- **Multi-purpose detector @ SuperKEKB** accelerator
- Focus on *B*, charm and τ physics
- Asymmetric e^+ e^- collisions at center-of-mass energy of 10.58 GeV
  - $\sigma(e^+e^- \to \Upsilon(4S)) \sim 1$ nb
  - $\mathcal{B}(\Upsilon(4S) \to B\bar{B}) \sim 100\%$

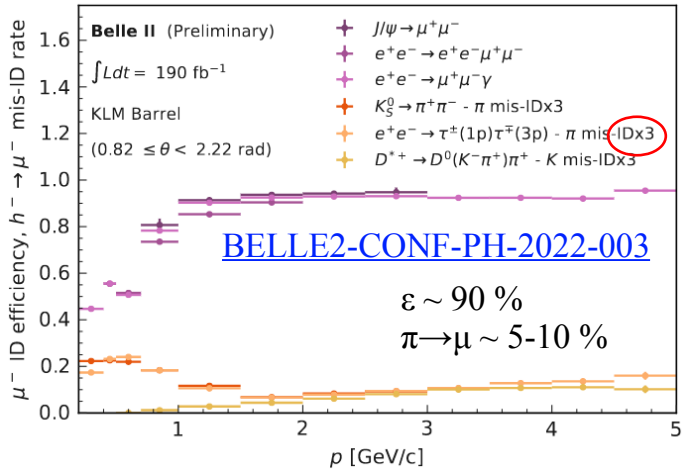
- **Collected ~ 428 fb^{-1}** (362 fb^{-1} at *Y*(4*S*) mass + 66 fb^{-1} off-resonance)
  - Target integrated luminosity: 50 ab^{-1}
- Instantaneous luminosity world record: **4.7 x 10^{34} cm^{-2} s^{-1}** (June 2022)
  - Target instantaneous luminosity: 6 x 10^{35} cm^{-2} s^{-1}

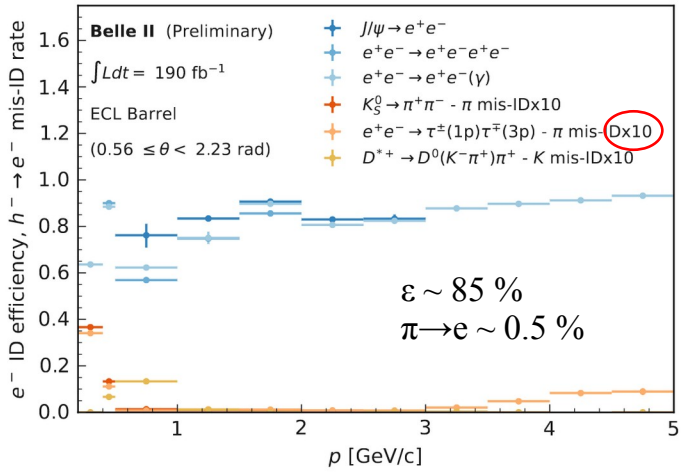


Performances of Belle II [KEK Report 2010-1]

- While good with charged, suited also for measurements with **neutrals, missing energy and inclusive decays**
- High photon detection efficiency, π^0 mass resolution ~ 5 MeV
- Good and similar electrons and muons identification efficiency
- K efficiency ~ 90 % at ~ 5 % $\pi \rightarrow$ K

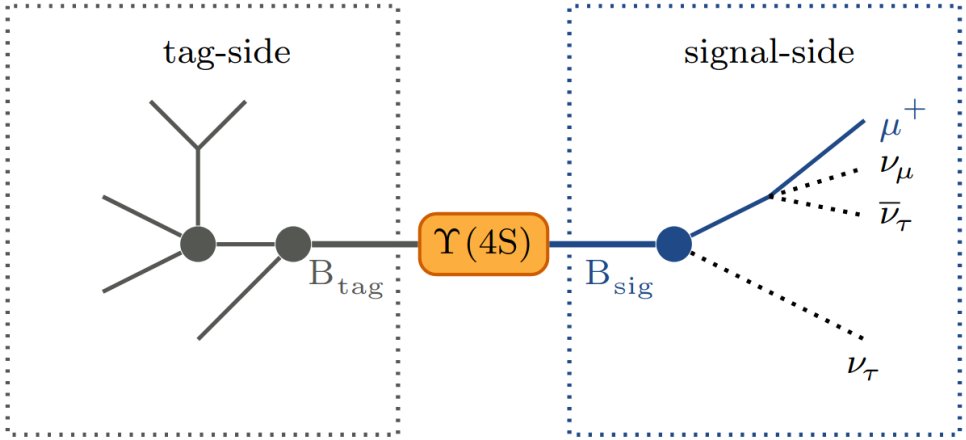


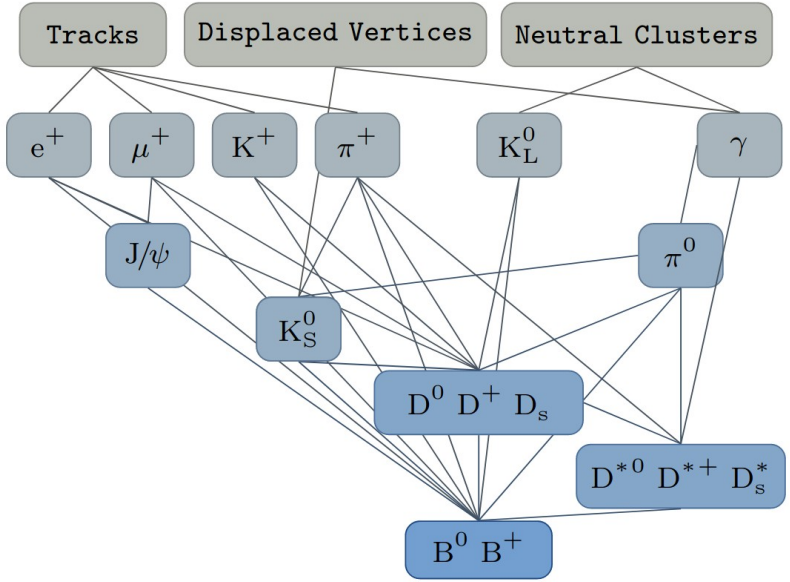




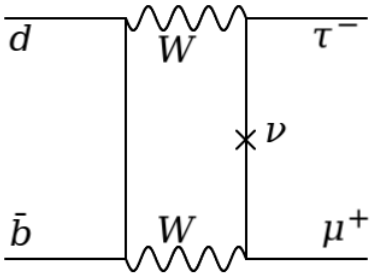
B-tagging [Comput Softw Big Sci 3, 6 (2019)]

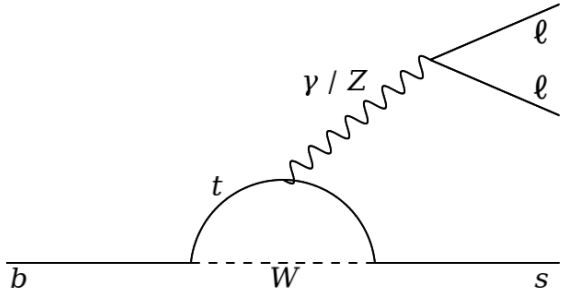
- ~ 4π coverage + knowledge of initial 4-momentum → Reconstruction of missing energy
- **Full Event Interpretation (FEI)**
  - Hierarchical approach based on BDTs
  - B reconstructed in **~10000 decay modes**
  - Overall efficiency of ~ 1-2 % at ~ 5-10 % purity

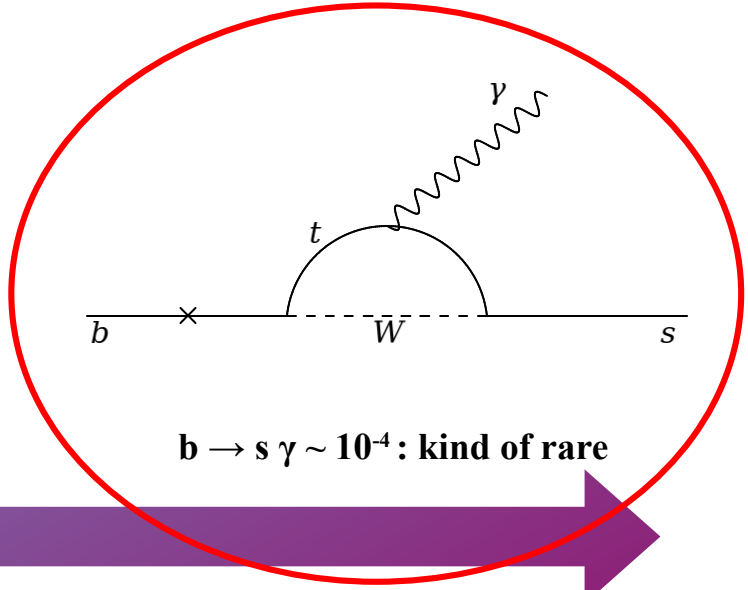




Radiative decays







LFV ~ 10^{-50} : super rare

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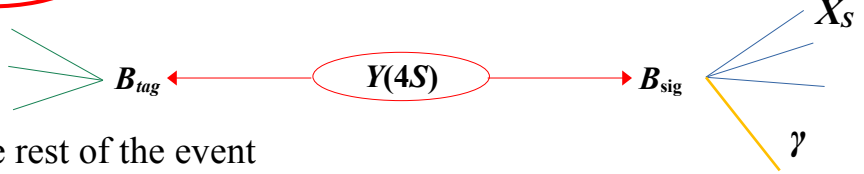
Standard Model branching ratio →

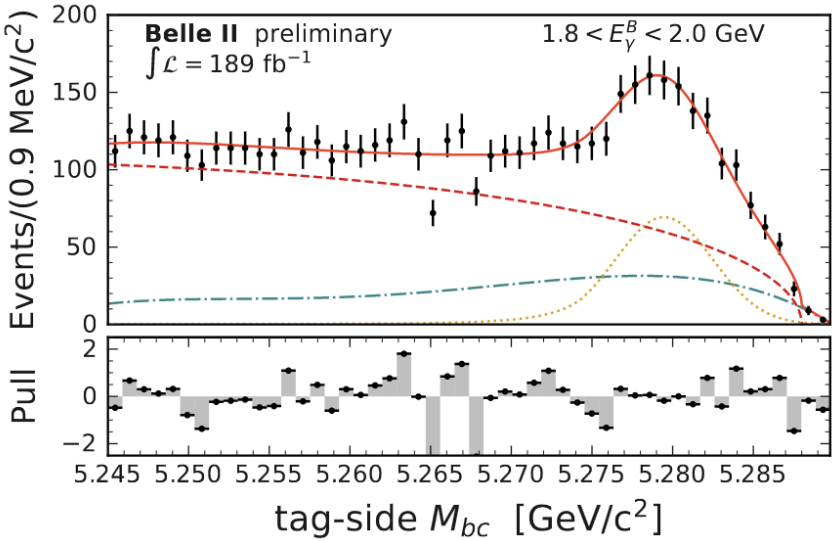
Fully inclusive $B \to X_s \gamma$ BELLE2-CONF-PH-2022-018 **189 fb^{-1}**



- **Inclusive $B \to X_s\,\gamma$ branching ratio in bins of photon energy** (E_γ^B)
- **Hadronic tag B candidate combined with highest energy photon** from the rest of the event

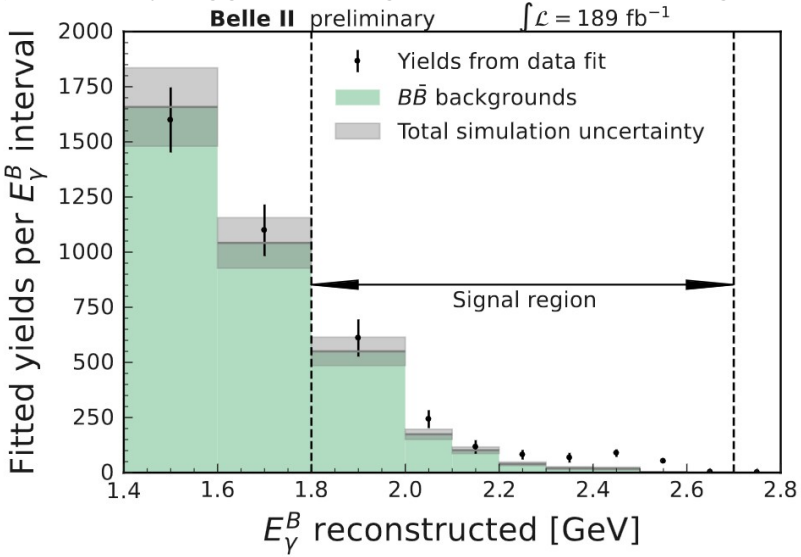
1) π^0, $\eta \to \gamma\gamma$ and $e^+e^- \to qq$ background suppressed with MVA techniques

2) **Simultaneous fit of tag-side M_{bc}** in bins of E_γ^B



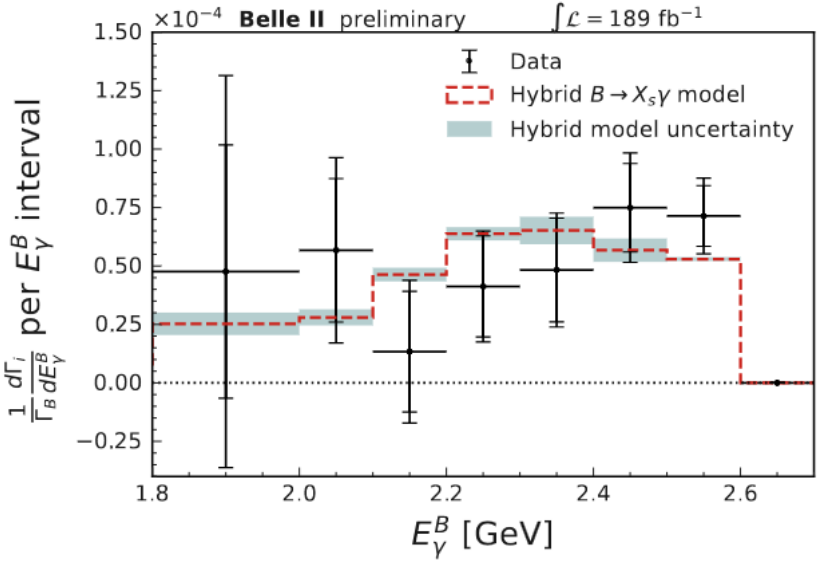
$$M_{bc} = \sqrt{(\sqrt{s}/2)^2 - p^{*}_{\mathrm{B_{tag}}}{}^2}$$

3) Correctly tagged non-signal B subtracted using simulation



Fully inclusive $B \to X_s \gamma$ BELLE2-CONF-PH-2022-018

- Dominating systematic uncertainties from limited size of simulation and fit model propagated to final result



$$\mathcal{B}(B \to X_s\gamma) = (3.54 \pm 0.78(\text{stat.}) \pm 0.83(\text{syst.})) \cdot 10^{-4} \text{ for } E_\gamma^B > 1.8 \text{ GeV}$$

- World average = $(3.49 \pm 0.19) \cdot 10^{-4}$ Prog. Theor. Exp. Phys. 2022, 083C01
- Theory = $(3.40 \pm 0.17) \cdot 10^{-4}$ JHEP06 (2020) 175

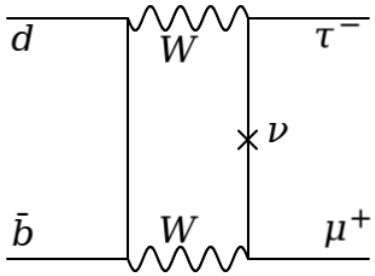
Prospects arXiv:2207.06307

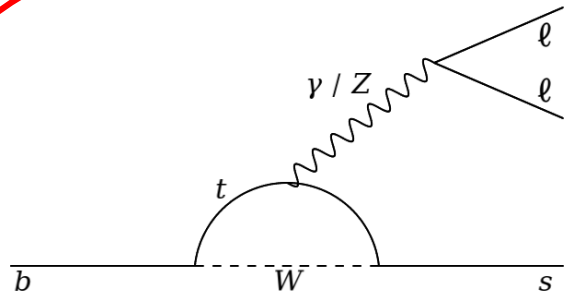
Improved $\pi^0/\eta \to \gamma\gamma$ veto modeling (ongoing)

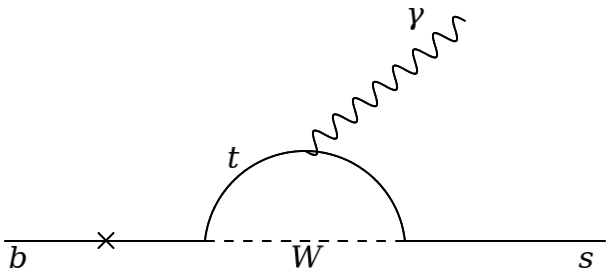
Lower E_γ^B threshold	Statistical uncertainty				Baseline (improved)
	1 ab^{-1}	5 ab^{-1}	10 ab^{-1}	50 ab^{-1}	syst. uncertainty
1.4 GeV	10.7%	6.4%	4.7%	2.2%	10.3% (5.2%)
1.6 GeV	9.9%	6.1%	4.5%	2.1%	8.5% (4.2%)
1.8 GeV	9.3%	5.7%	4.2%	2.0%	6.5% (3.2%)
2.0 GeV	8.3%	5.1%	3.8%	1.7%	3.7% (1.8%)

Lower threshold → More challenging analysis due to BB background

$b \to s\, l^+ l^-$ decays







LFV ~ 10^{-50} : super rare

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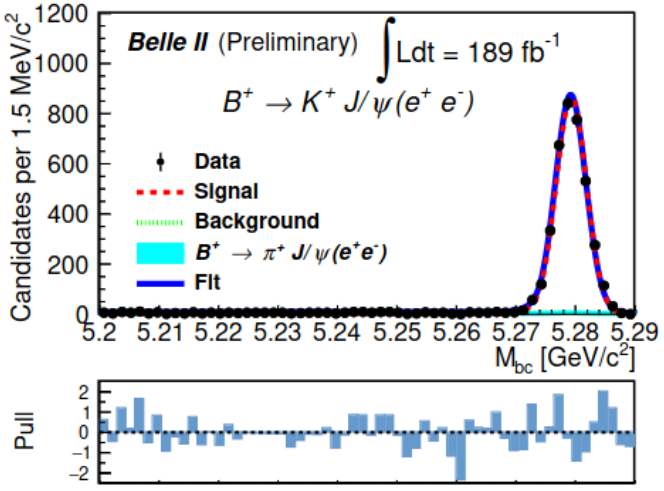
Standard Model branching ratio →

$B \to J/\psi\,(l^+l^-)\,K$ measurement arXiv:2207.11275 **189 fb^{-1}**

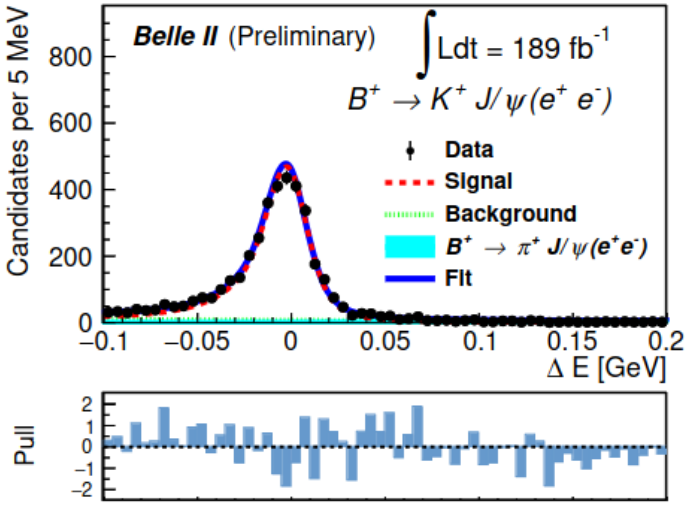
- Measurement of $B \to J/\psi\,(l^+l^-)\,K$ **branching fraction and** $R(J/\psi)$
  - Four channels: $B^+ \to J/\psi\,(l^+l^-)\,K^+$ and $B^0 \to J/\psi\,(l^+l^-)\,K^0_S$; $l = e, \mu$
- **Favored b → c transition**, control channel for $R(K)$

$$R(J/\psi) = \frac{\mathcal{B}(B \to J/\psi(\mu^+\mu^-)K)}{\mathcal{B}(B \to J/\psi(e^+e^-)K)} \overset{\text{SM}}{=} 1$$

Fit to M_{bc} and ΔE: signal + background and $B^+ \to J/\psi\,\pi^+$ component for misidentified π



$$M_{bc} = \sqrt{(\sqrt{s}/2)^2 - {p^*_{\mathrm{B_{tag}}}}^2}$$



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

$B \to J/\psi\,(l^+l^-)\,K$ measurement arXiv:2207.11275

- Main systematic uncertainty coming from $Y(4S)$ branching fraction to charged and neutral B pairs (2.6 %)
- Additional systematic uncertainty for K^0_S modes due to data-MC differences in K^0_S reconstruction efficiency (3 %)

$$\mathcal{B}\left(B^+ \to J/\psi(e^+e^-)K^+\right) = (6.00 \pm 0.10 \pm 0.19) \times 10^{-5}$$
$$\mathcal{B}\left(B^+ \to J/\psi(\mu^+\mu^-)K^+\right) = (6.06 \pm 0.09 \pm 0.19) \times 10^{-5}$$
$$\mathcal{B}\left(B^0 \to J/\psi(e^+e^-)K^0_S\right) = (2.67 \pm 0.08 \pm 0.12) \times 10^{-5}$$
$$\mathcal{B}\left(B^0 \to J/\psi(\mu^+\mu^-)K^0_S\right) = (2.78 \pm 0.08 \pm 0.12) \times 10^{-5}$$

Similar efficiencies for electron and muon modes

- World averages:

$$\mathcal{B}(B^+ \to J/\psi K^+)_{\rm WA} = (10.20 \pm 0.19) \cdot 10^{-4}$$
$$\mathcal{B}(B^0 \to J/\psi K^0)_{\rm WA} = (8.91 \pm 0.21) \cdot 10^{-4}$$
$$\mathcal{B}(J/\psi \to e^+e^-)_{\rm WA} = (5.971 \pm 0.032)\%$$
$$\mathcal{B}(J/\psi \to \mu^+\mu^-)_{\rm WA} = (5.961 \pm 0.033)\%$$

Prog. Theor. Exp. Phys. 2022, 083C01

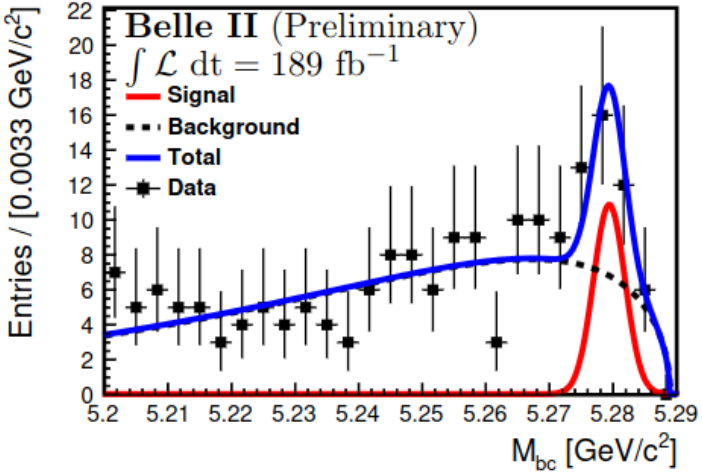
$$R_{K^+}\,(J/\psi) = 1.009 \pm 0.022 \pm 0.008$$
$$R_{K^0}\,(J/\psi) = 1.042 \pm 0.042 \pm 0.008$$

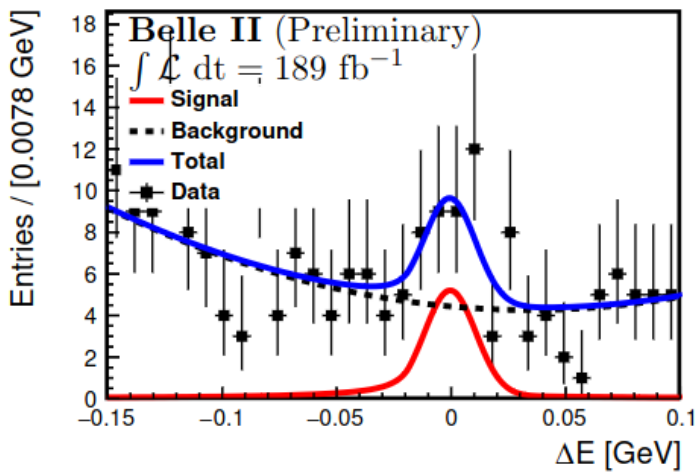
Branching fraction of $B \to K^* l^+l^-$ BELLE2-CONF-PH-2022-009 **189 fb^{-1}**

- Measurement of $\boldsymbol{B \to K^* l^+l^-}$ **branching fraction** ($l = e, \mu$)
  - $B^+ \to K^{*+}(892)\, l^+l^-$ with $K^{*+} \to K^0_S\, \pi^+, K^+\, \pi^0$
  - $B^0 \to K^{*0}(892)\, l^+l^-$ with $K^{*0} \to K^+\, \pi^-$

- Veto di-lepton mass ranges corresponding to γ, J/ψ and $\psi(2S)$, remaining background suppressed with BDT
- **Fit to M_{bc} and ΔE**, $B \to K^* J/\psi$ (l^+l^-) used as control channel to fix signal PDF parameters

$\boldsymbol{B \to K^* \mu^+\mu^-}$





Branching fraction of $B \to K^* l^+ l^-$ BELLE2-CONF-PH-2022-009

- Main systematic uncertainties from total number of *BB* (2.9 %) and data-MC differences in π^0 reconstruction efficiency (3.4 %)

$$\mathcal{B}(B \to K^* \mu^+ \mu^-) = (1.19 \pm 0.31^{+0.08}_{-0.07}) \cdot 10^{-6}$$
$$\mathcal{B}(B \to K^* e^+ e^-) = (1.42 \pm 0.48 \pm 0.09) \cdot 10^{-6}$$

- World averages:

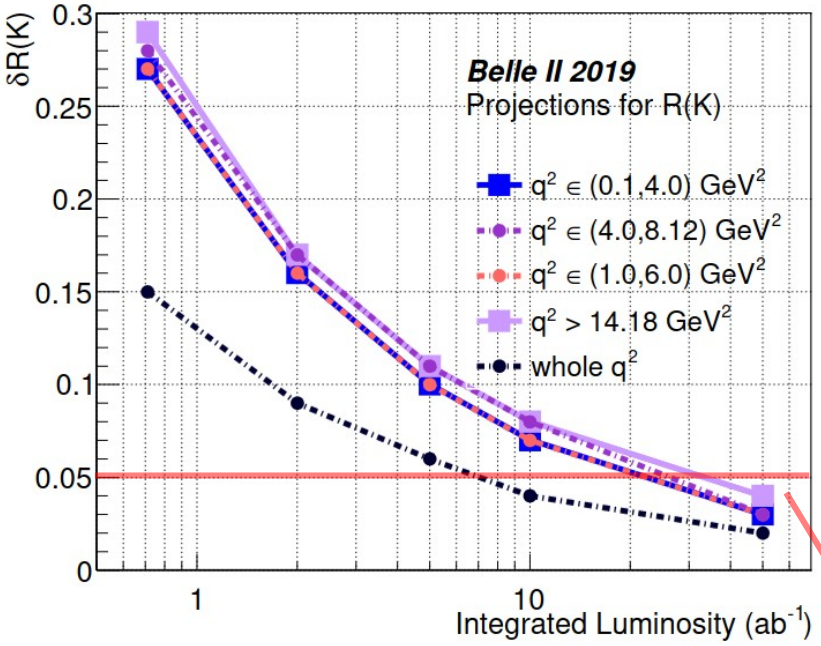
$$\mathcal{B}(B \to K^* \mu^+ \mu^-)_{\text{WA}} = (1.06 \pm 0.09) \cdot 10^{-6}$$
$$\mathcal{B}(B \to K^* e^+ e^-)_{\text{WA}} = (1.19 \pm 0.20) \cdot 10^{-6}$$

Prog. Theor. Exp. Phys. 2022, 083C01

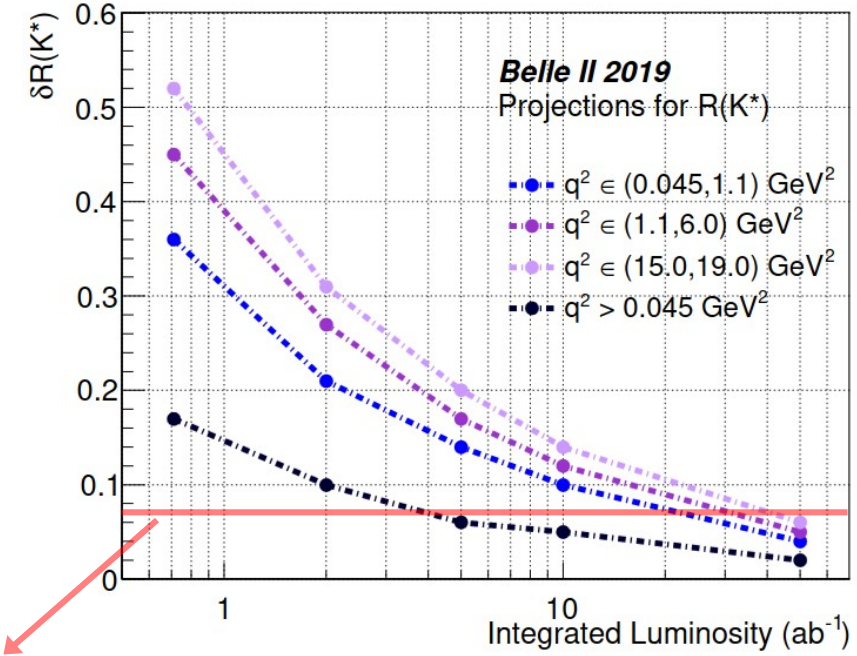
- Similar performances between electrons and muons
- Precision limited by sample size
  - First result towards determination of $R(K^*)$

LFU tests: prospects at Belle II

$$R(K) = \frac{\mathcal{B}(B^+ \to K^+ \mu^+ \mu^-)}{\mathcal{B}(B^+ \to K^+ e^+ e^-)}$$



$$R(K^*) = \frac{\mathcal{B}(B^0 \to K^{*0} \mu^+ \mu^-)}{\mathcal{B}(B^0 \to K^{*0} e^+ e^-)}$$



Current LHCb precision for q^2 in [1.1, 6.0] GeV (9 fb^{-1})

- Expected **~2 - 3 % precision with 50 ab^{-1}**

$b \to s\,\tau^+\tau^-$ searches and prospects

- b → s $\tau^+\tau^-$ expected SM branching ratios ~ 10^{-7}
- Related to R(D$^{(*)}$): $C_{9(10)}^{\tau\tau} \sim C_{9(10)}^{\mathrm{SM}} - (+)\frac{2\pi}{\alpha}\frac{V_{cb}}{V_{tb}V_{ts}^*}\left(\sqrt{\frac{R_{D^{(*)}}}{R_{D^{(*)}}^{\mathrm{SM}}}} - 1\right)$

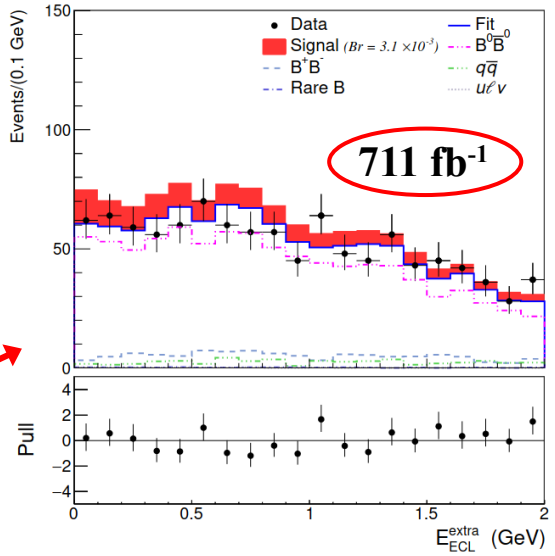
PRL 120.181802 (2018)

Limits at 90% CL

$\mathcal{B}(B_s^0 \to \tau^+\tau^-) < 5.2 \cdot 10^{-3}$ PRL 118.251802 (2017)

$\mathcal{B}(B^+ \to K^+\tau^+\tau^-) < 2.3 \cdot 10^{-3}$ PRL 118.031802 (2017)

$\mathcal{B}(B^0 \to K^{*0}\tau^+\tau^-) < 3.1 \cdot 10^{-3}$ arXiv: 2110.03871



Prospects at Belle II
arXiv:2207.06307

$\mathcal{B}(B^0 \to K^{*0}\tau\tau)$ (had tag)		
ab^{-1}	"Baseline" scenario	"Improved" scenario
1	$< 3.2 \times 10^{-3}$	$< 1.2 \times 10^{-3}$
5	$< 2.0 \times 10^{-3}$	$< 6.8 \times 10^{-4}$
10	$< 1.8 \times 10^{-3}$	$< 6.5 \times 10^{-4}$
50	$< 1.6 \times 10^{-3}$	$< 5.3 \times 10^{-4}$

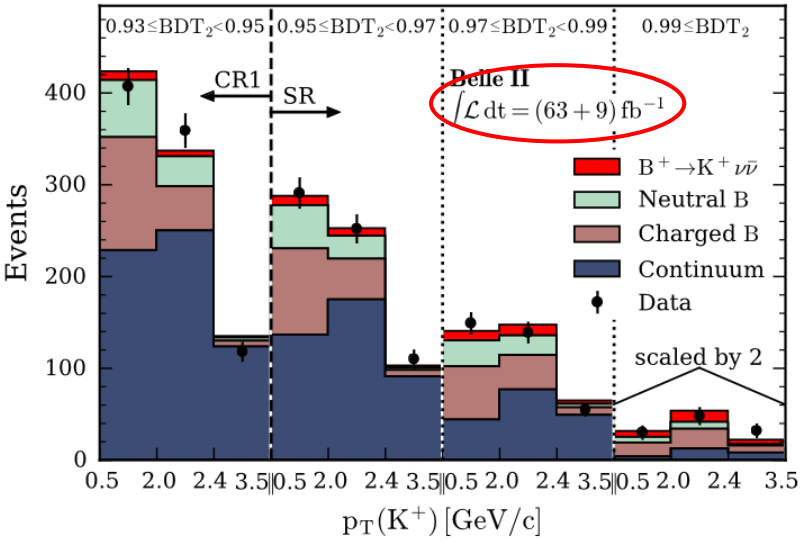
Baseline: τ→ *l* ν
Improved: includes τ→ π ν

$B \to K^{(*)}\, \nu\, \nu$ searches and prospects

- $b \to s\, \nu\, \nu$ transition:
  - **Suppressed in the SM (~ 10^{-5})**, any deviation would be a clear sign of new physics
  - **Theoretically clean**, no radiative effects from photons
- **Golden channel for Belle II**: high luminosity, clean environment and reconstruction of tag-side essential

- ***$B^+ \to K^+\, \nu\, \nu$* search performed at Belle II** PRL 127.181802 (2021)
  - Inclusive reconstruction of tag-side
  - Fit in bins of BDT and $p_T(K^+)$
  - Leading systematic uncertainty from uncertainty on background yield

$$\mathcal{B}(B^+ \to K^+ \nu\nu) > 4.1 \cdot 10^{-5} \text{ at } 90\% \text{ CL}$$

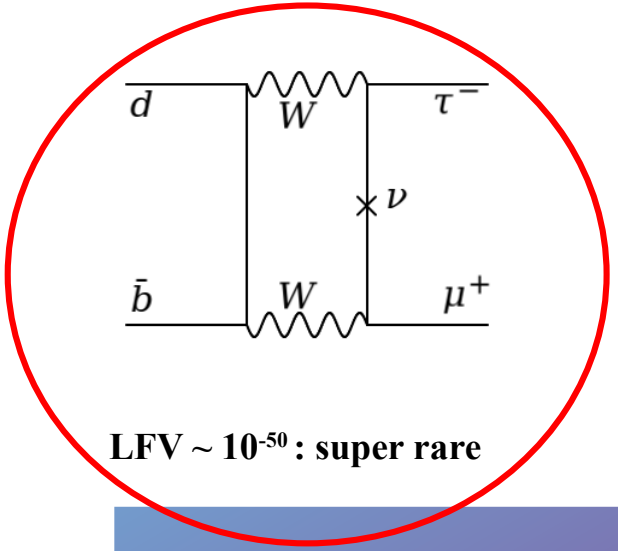


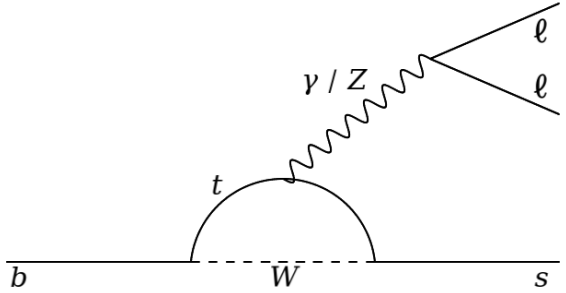
$$\delta\left(\frac{\mathcal{B}(B \to K\nu\nu)}{\mathcal{B}_{\rm SM}(B \to K\nu\nu)}\right)$$

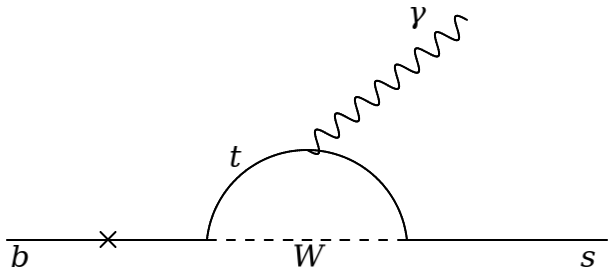
Decay	1 ab^{-1}	5 ab^{-1}	10 ab^{-1}	50 ab^{-1}
$B^+ \to K^+\nu\bar{\nu}$	0.55 (0.37)	0.28 (0.19)	0.21 (0.14)	0.11 (0.08)
$B^0 \to K^0_S\nu\bar{\nu}$	2.06 (1.37)	1.31 (0.87)	1.05 (0.70)	0.59 (0.40)
$B^+ \to K^{*+}\nu\bar{\nu}$	2.04 (1.45)	1.06 (0.75)	0.83 (0.59)	0.53 (0.38)
$B^0 \to K^{*0}\nu\bar{\nu}$	1.08 (0.72)	0.60 (0.40)	0.49 (0.33)	0.34 (0.23)

- **Update ongoing** with 362 fb^{-1}
- Expected O(10%) precision with 50 ab^{-1} arXiv:2207.06307

Lepton flavor violating decays







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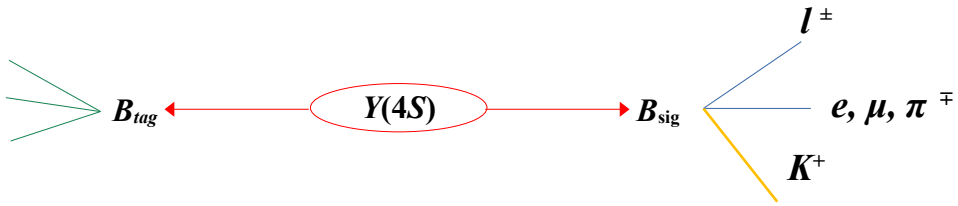
***b* → *s γ* ~ 10^{-4} : kind of rare**

Standard Model branching ratio →

$B^+ \to K^+ \tau\, l$ search at Belle arXiv: 2212.04128 (accepted by PRL)

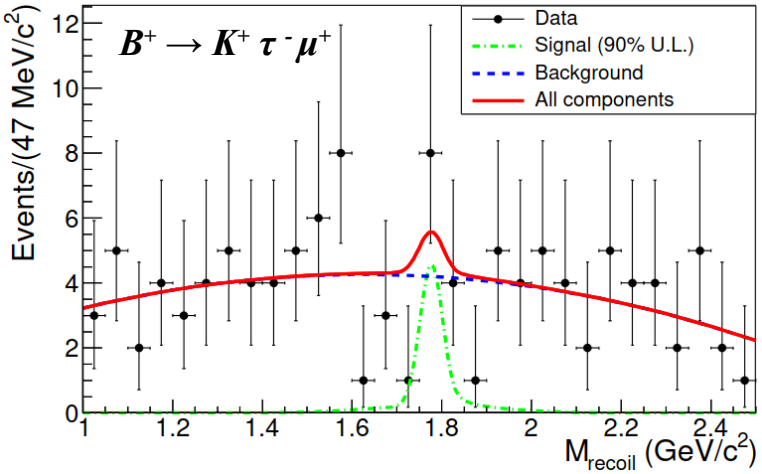
- Two charge configurations (l = e, μ): $B^+ \to K^+ \tau^- l^+$, $B^+ \to K^+ \tau^+ l^-$

1) Hadronic B_{tag} reconstruction



2) Three charged tracks not related to B_{tag}

3) *BB* and *qq* background suppression with BDTs



- Fit to the *recoil mass*: $M_{\text{recoil}} = \sqrt{m_B^2 + m_{Kl}^2 - 2 \cdot (\frac{\sqrt{s}}{2} E^*_{Kl} + |\vec{p}^{\,*}_{B_{\text{tag}}}||\vec{p}^{\,*}_{Kl}| \cos\theta)}$

Mode	ε (%)	ε^{NP} (%)	N_{sig}	$\mathcal{B}^{\text{UL}}$ (10^{-5})
$B^+ \to K^+\tau^+\mu^-$	0.064	0.058	-2.1 ± 2.9	0.59 (0.65)
$B^+ \to K^+\tau^+e^-$	0.084	0.074	1.5 ± 5.5	1.51 (1.71)
$B^+ \to K^+\tau^-\mu^+$	0.046	0.038	2.3 ± 4.1	2.45 (2.97)
$B^+ \to K^+\tau^-e^+$	0.079	0.058	-1.1 ± 7.4	1.53 (2.08)

World's best limits!

- More on this mode(s) by Belle + Belle II in the near future

Conclusions

- **Belle II is at the forefront in the search for rare and BSM decays**
  - Expected exciting interplay with LHCb in the coming years
- Many analyses ongoing with 362 fb^{-1}, data-taking will restart end of 2023
- Rich physics program (e.g. see Giulio's talk), **much more to come, stay tuned!**