Search for $B \to K l^+ l^-$ at Belle II

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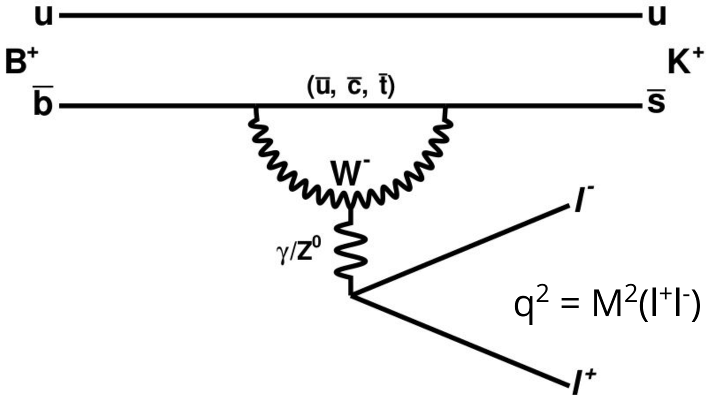
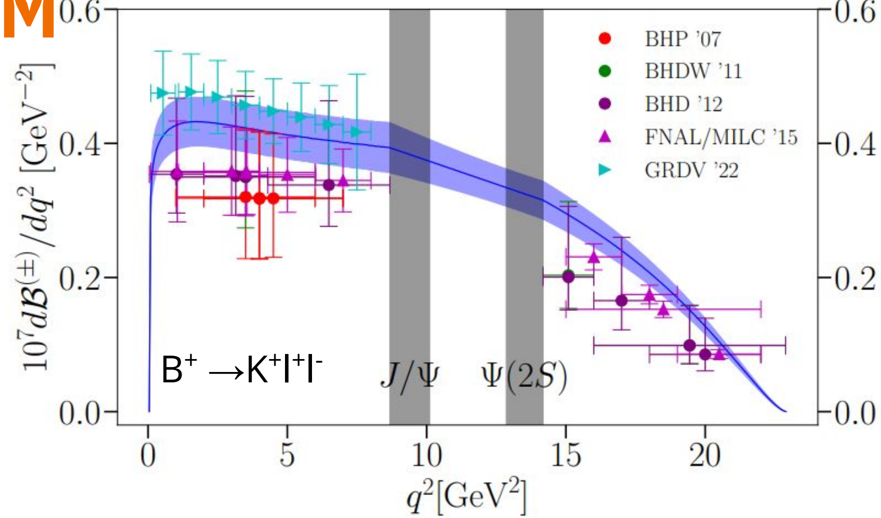
10 Feb 2023

$B \to K^{(*)} l^+l^-$ transitions in SM



$q^2 = M^2(l^+l^-)$

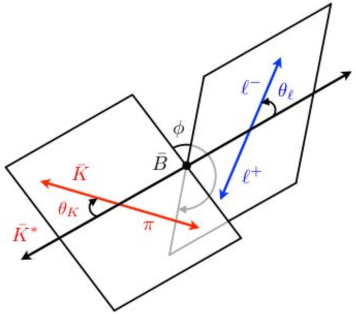
From arXiv:2207.13371



- b→s FCNC transitions are forbidden in SM at the tree level; occur via box and penguin diagrams.
- Resonant tree-level charmonium production (e.g. B→KJ/Ψ) can be isolated by the invariant mass of the lepton pair.
- O(10%) accurate predictions for the q^2 range outside resonances.

Angular distributions in $B^* \longrightarrow K^* l^+ l^-$

$$\frac{1}{\mathrm{d}\Gamma/\mathrm{d}q^2}\frac{\mathrm{d}^4\Gamma}{\mathrm{d}\cos\theta_\ell\ \mathrm{d}\cos\theta_K\ \mathrm{d}\phi\ \mathrm{d}q^2} = \frac{9}{32\pi}\Big[\frac{3}{4}(1-F_L)\sin^2\theta_K + F_L\cos^2\theta_K + \frac{1}{4}(1-F_L)\sin^2\theta_K\cos 2\theta_\ell$$
$$- F_L\cos^2\theta_K\cos 2\theta_\ell + S_3\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi + S_4\sin 2\theta_K\sin 2\theta_\ell\cos\phi$$
$$+ S_5\sin 2\theta_K\sin\theta_\ell\cos\phi + S_6\sin^2\theta_K\cos\theta_\ell + S_7\sin 2\theta_K\sin\theta_\ell\sin\phi$$
$$+ S_8\sin 2\theta_K\sin 2\theta_\ell\sin\phi + S_9\sin^2\theta_K\sin^2\theta_\ell\sin 2\phi\Big],$$



Redefinition of parameters: $P'_{i=4,5,6,8} = \dfrac{S_{j=4,5,7,8}}{\sqrt{F_L(1-F_L)}}$

Folding of variables:

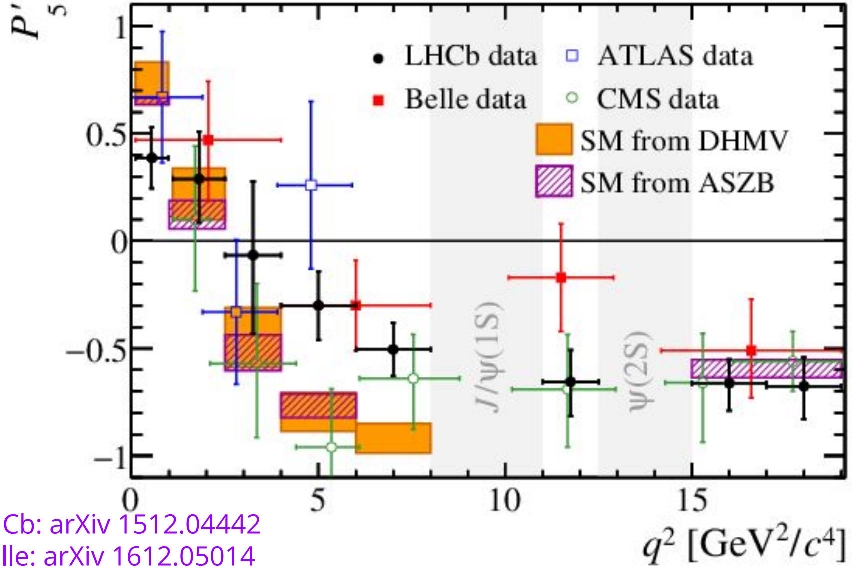
$$P'_4, S_4 : \begin{cases} \phi \to -\phi & \text{for } \phi < 0 \\ \phi \to \pi - \phi & \text{for } \theta_\ell > \pi/2 \\ \theta_\ell \to \pi - \theta_\ell & \text{for } \theta_\ell > \pi/2, \end{cases} \qquad P'_5, S_5 : \begin{cases} \phi \to -\phi & \text{for } \phi < 0 \\ \theta_\ell \to \pi - \theta_\ell & \text{for } \theta_\ell > \pi/2. \end{cases}$$

For small q^2, P'_5 is connected to semi-leptonic operators Q_9 and Q_{10}.

$$P'_5 \simeq \frac{\mathrm{Re}\left(C^*_{10}C_{9,\perp} + C^*_{9,\parallel}C_{10}\right)}{\sqrt{\left(|C_{9,\perp}|^2 + |C_{10}|^2\right)\left(|C_{9,\parallel}|^2 + |C_{10}|^2\right)}},$$

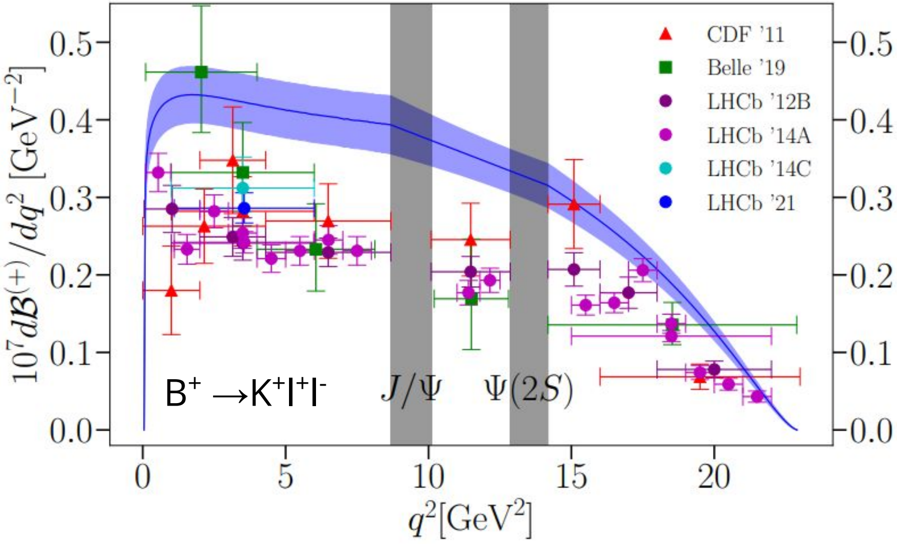
Tensions with the SM

From arXiv:2207.13371



LHCb: arXiv 1512.04442
Belle: arXiv 1612.05014
ATLAS: arXiv 1805.04000
CMS: arXiv 1710.02846

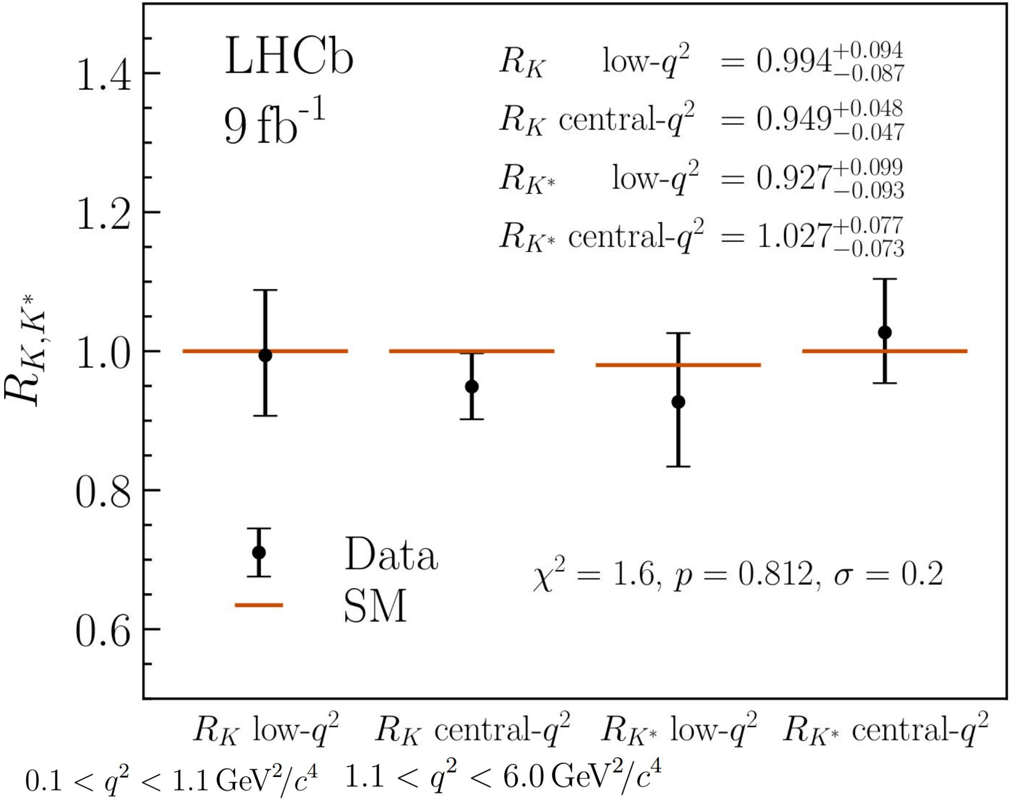
HPQCD 22



Several tensions are observed between experimental data and theoretical predictions such as partial branching fraction and angular coefficient P'_5 for $B \to K^* l^+ l^-$. Some of the tensions are experiment-dependent.

arXiv:2212.09153

Lepton universality in B →$K^{(*)}l^+l^-$: LHCb



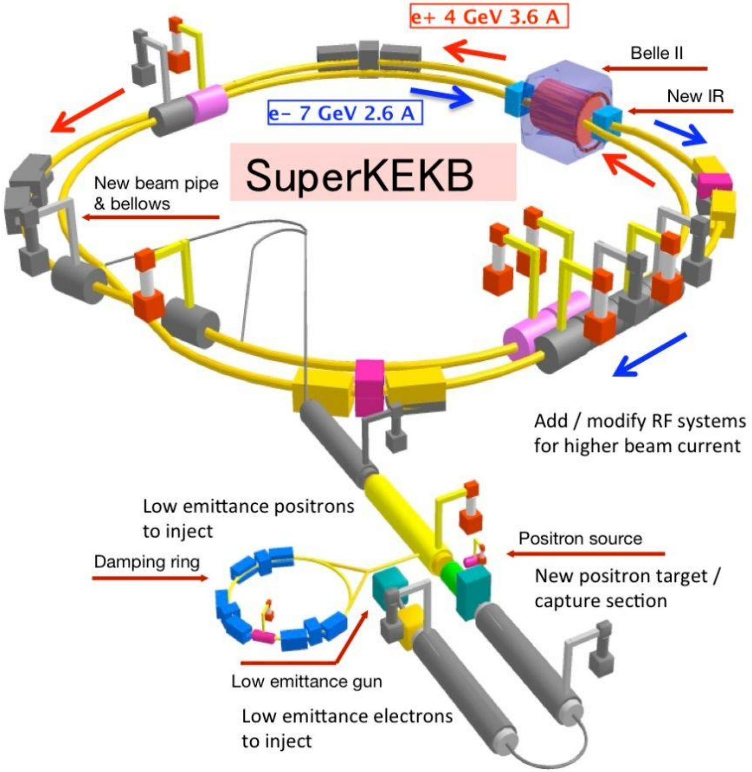
$$R_K = \frac{B(B^\pm \to K^\pm \mu^+ \mu^-)}{B(B^\pm \to K^\pm e^+ e^-)}$$

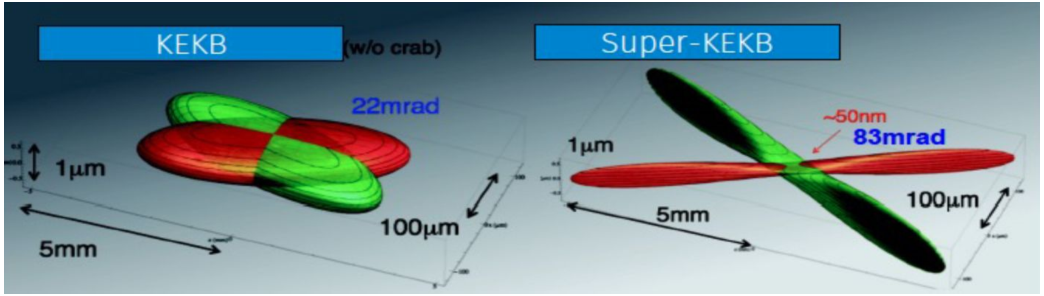
Recent result from LHCb is in excellent agreement with the SM expectations.

The uncertainties reach **10%** to **5%** level.

→most accurate measurement at the moment, sets the precision target.

SuperKEKB





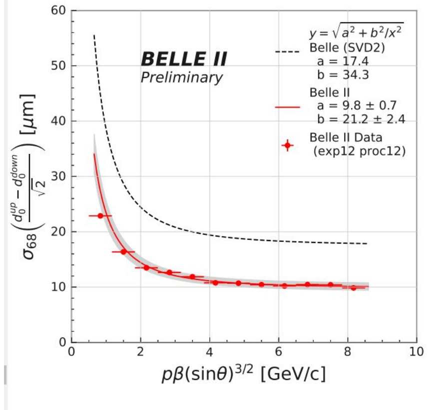
- Nano-beam collision scheme leading to highest specific luminosity, employed for the first time
- First physics data from 2018
- Design luminosity of **$6.5 \times 10^{35} \mathrm{cm}^{-2}\mathrm{s}^{-1}$**
- Achieved world-record peak luminosity of **$4.7 \times 10^{34}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$**
- Expected total integrated luminosity of **50 ab^{-1}**, (x50 Belle), to be collected over decade.
- Collected currently: **0.4 ab^{-1}**

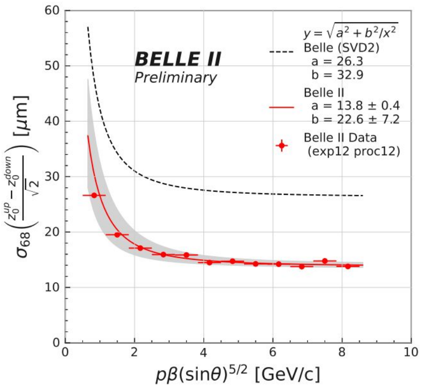
Future of high-intensity e^+e^- colliders relies on success of SuperKEKB

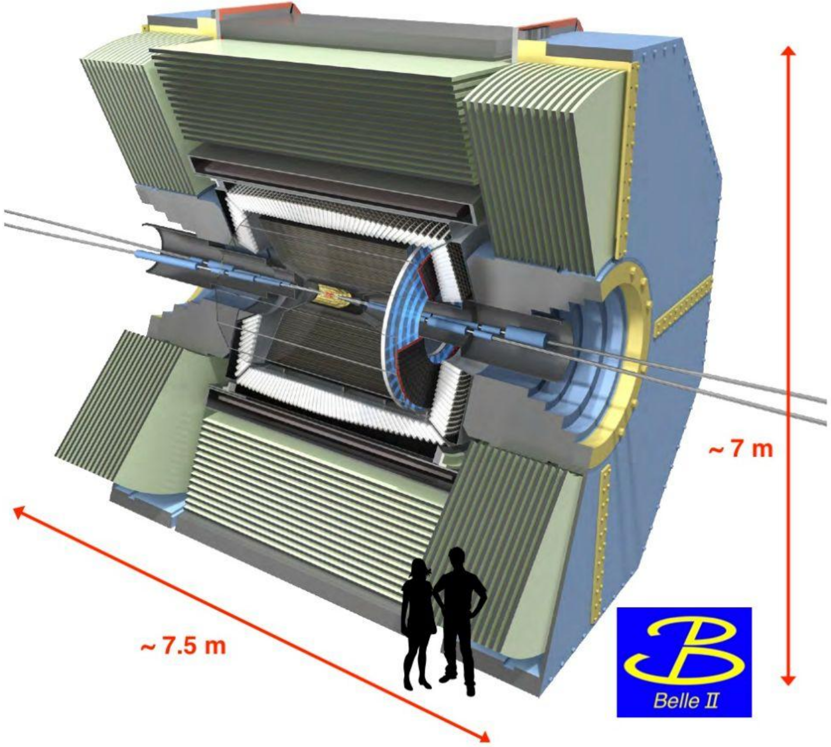
Belle II detector

Collected at Y(4S):	360 fb^{-1}, about 0.4 x 10^{9} BB
Expected:	50 ab^{-1}, about 50 x 10^{9} BB

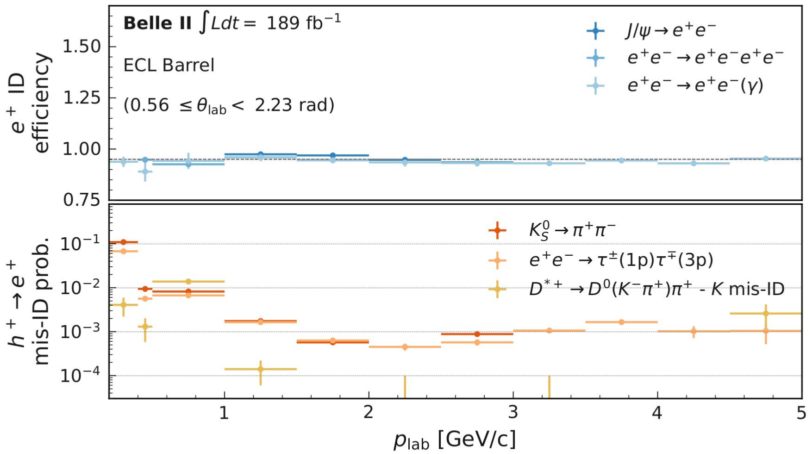
- Nearly 4π detector
- Tracking, PID, and photon reconstruction capabilities
- Similar performance for **electrons** and **muons**
- Well-suited to measure decays with missing energy, π^0 in the final state, inclusive measurements
- Comparable or better performance vs its predecessor Belle.

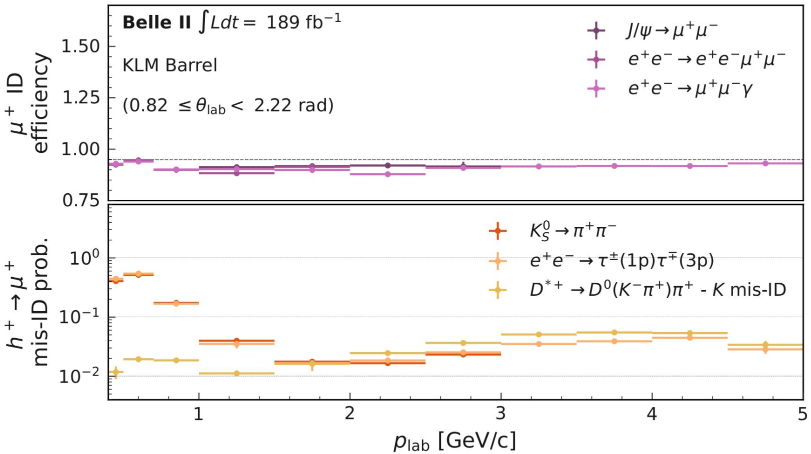


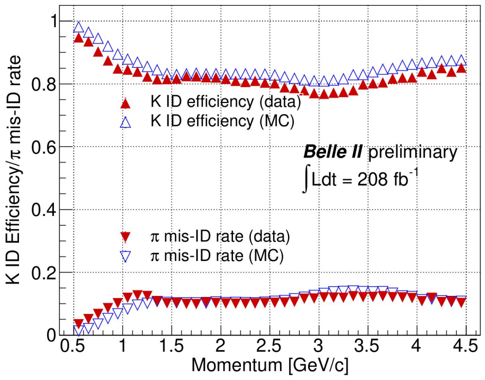




Key experimental inputs for measurement of $B \to K^{(*)} ll$

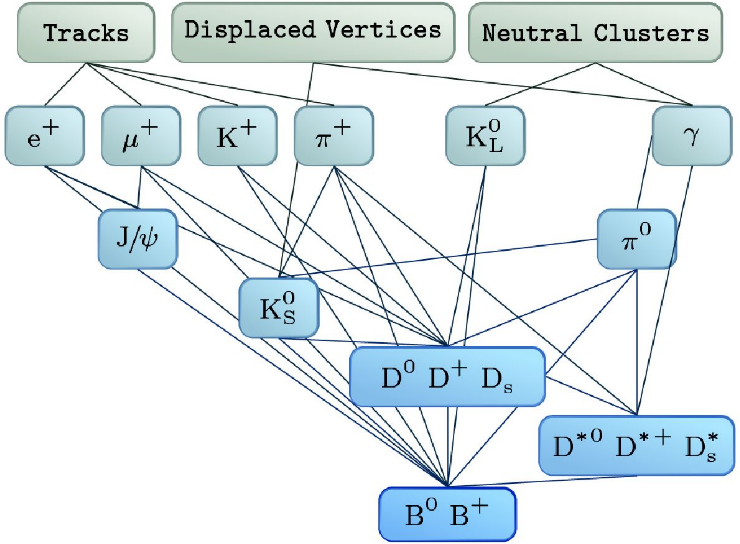


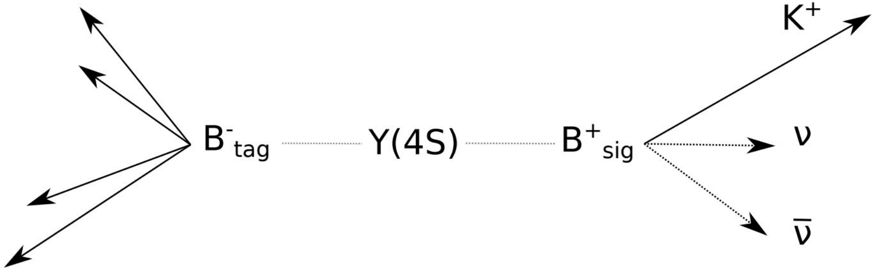




Main ingredients for accurate **$B \to K^{(*)} l^+ l^-$** measurements are efficient tracking, high momentum resolution, good lepton ID and K-π separation.

Reconstruction methods at Belle II



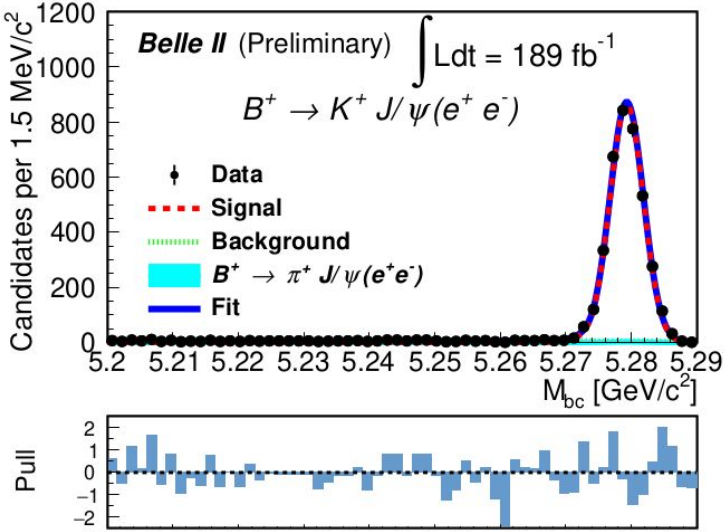


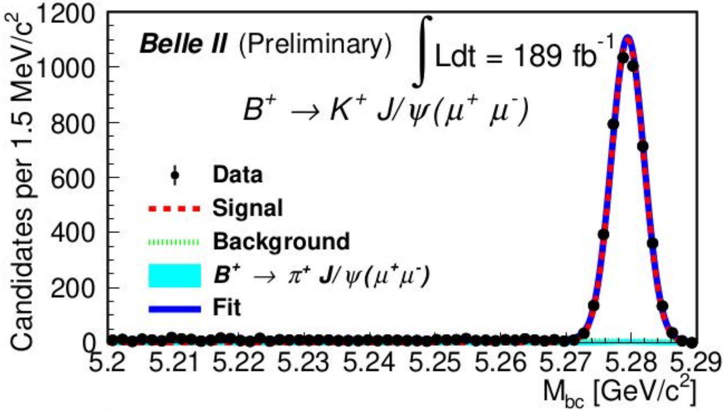
$$\Delta E = E_B^* - \sqrt{s}/2 \qquad M_{bc} = \sqrt{s/4 - {p_B^*}^2}$$

- The second “tag” B in Y(4S) → BB decays can be used to constrain kinematics, reduce continuum background.
- Explicit reconstruction of the tag in hadronic or semileptonic modes and inclusive tagging provide different working points in terms of efficiency/purity.
- Fully reconstructed modes usually do not require hadronic/semileptonic tagging

Towards R(K): measurements of $B^{+,0} \rightarrow K^{+,0}_S J/\psi(ll)$

https://arxiv.org/pdf/2207.11275.pdf



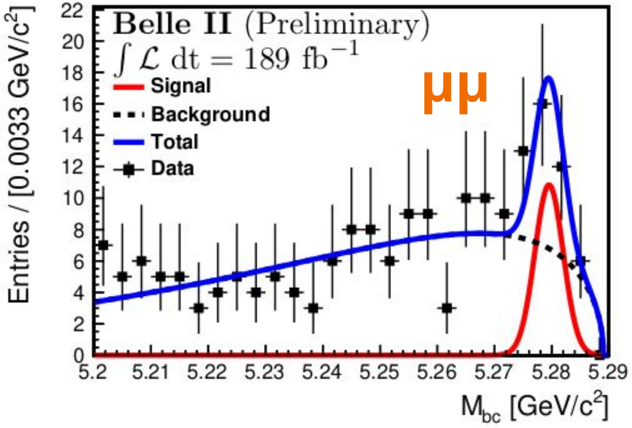


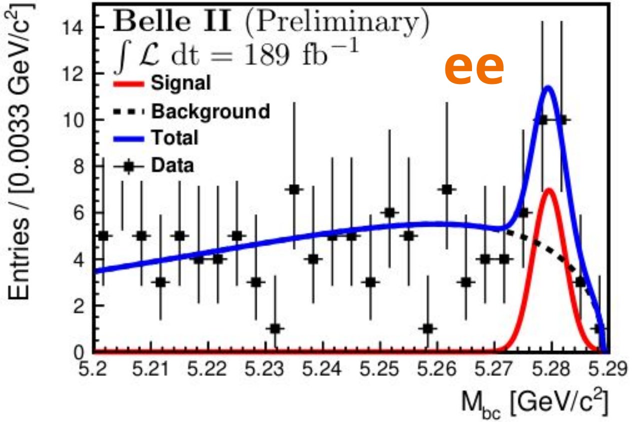
$R_{K^+}\ (J/\psi)$	$1.009 \pm 0.022 \pm 0.008$
$R_{K^0_S}\ (J/\psi)$	$1.042 \pm 0.042 \pm 0.008$

- Precision measurement of branching fractions, $R_K(J/\psi)$ in neutral and charged channel
- **Systematic uncertainties (lepton ID)** below **1%**.
- Check of performance, useful normalization channel.

R(K^*) status

https://arxiv.org/abs/2206.05946





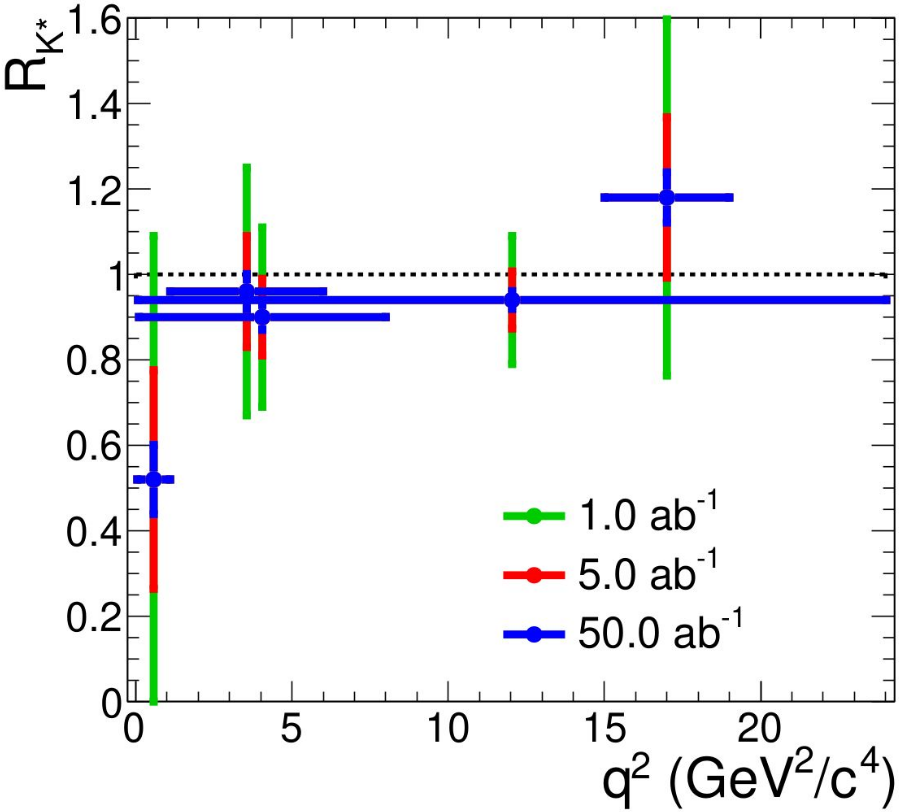
- $B^{0,+} \rightarrow K^{*0,+} ll$ decays reconstructed (with veto on charmonium, low q^2 resonances)
- Similar performance for **μμ** and ee channels. Efficiency between **6-16%**

$$\mathcal{B}(B \to K^* \mu^+ \mu^-) = (1.19 \pm 0.31^{+0.08}_{-0.07}) \times 10^{-6},$$
$$\mathcal{B}(B \to K^* e^+ e^-) = (1.42 \pm 0.48 \pm 0.09) \times 10^{-6},$$
$$\mathcal{B}(B \to K^* \ell^+ \ell^-) = (1.25 \pm 0.30^{+0.08}_{-0.07}) \times 10^{-6}.$$

- Considering smaller luminosity, similar performance to Belle (PRL 126, 161801 (2021)).

R(K$^{(*)}$) perspective

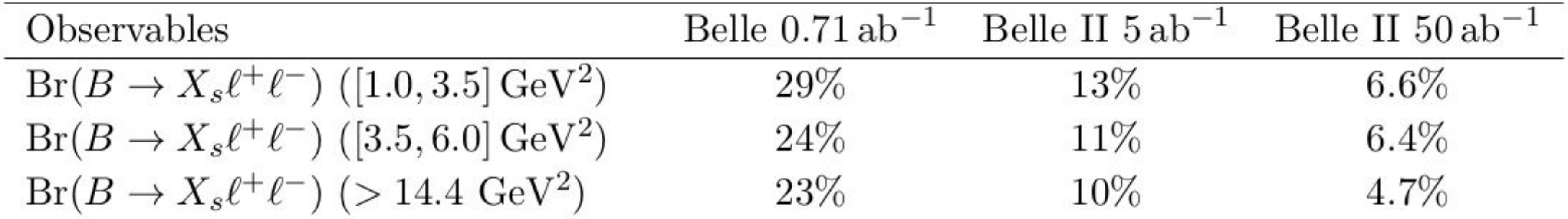
Based on Belle PRL 126, 161801 (2021)



- Belle and Belle II performance for R(K) and R(K*) is similar
- Uncertainties are dominated by statistics
- Scaling uncertainties to different luminosities, about **3%** precision is possible for q^2 bin [1-6] GeV^2/c^4 for 50 ab^{-1} data sample.

Perspectives for B → Xs l^+l^-

arXiv:1808.10567

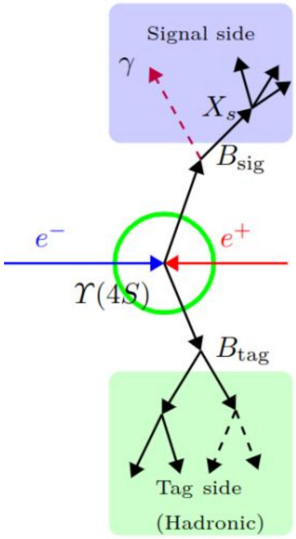


Observables	Belle 0.71 ab^{-1}	Belle II 5 ab^{-1}	Belle II 50 ab^{-1}
$\text{Br}(B \to X_s \ell^+ \ell^-)$ $([1.0, 3.5]\ \text{GeV}^2)$	29%	13%	6.6%
$\text{Br}(B \to X_s \ell^+ \ell^-)$ $([3.5, 6.0]\ \text{GeV}^2)$	24%	11%	6.4%
$\text{Br}(B \to X_s \ell^+ \ell^-)$ $(> 14.4\ \text{GeV}^2)$	23%	10%	4.7%

- Belle II is ideally suited to perform inclusive measurements
- Can be performed as “sum of exclusive” branching fractions, **K+nπ**
- Already with **5 ab^{-1} 10%** accuracy is expected
- Other observables include FB and CP asymmetries

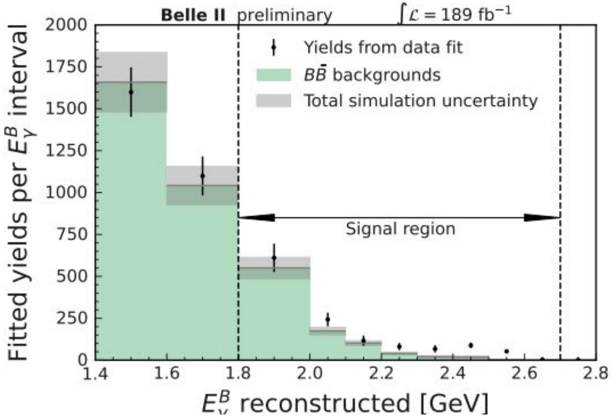
arXiv:2210.10220

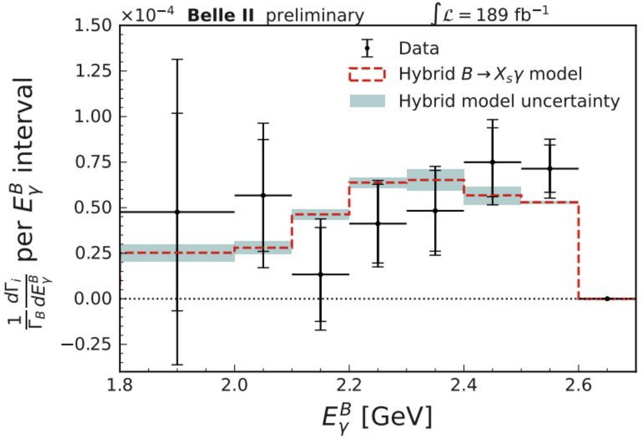
Measurement of B →Xs gamma with hadronic tag



- Hadronic tagging allows to:
    - Suppress background
    - Precisely define Xs
    - Accurately reconstruct **$E^*\gamma$**
- Measurement differential in **$E^*\gamma$,** high purity for high **E*ɣ**
- Unfolded result has uncertainties comparable to other hadronic tag measurements, agrees well with the expectations

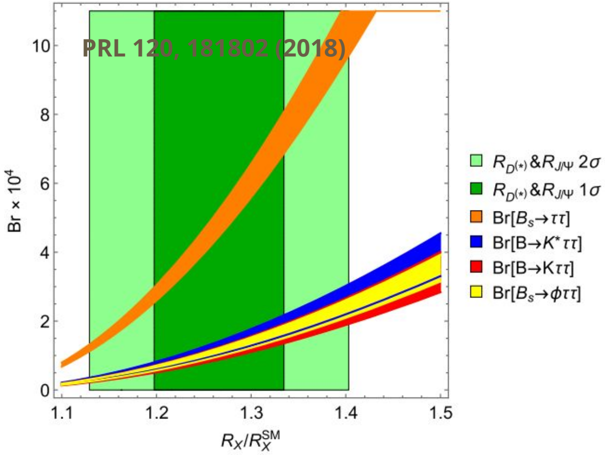
E_γ^B threshold [GeV]	$\mathcal{B}(B \to X_s\gamma)$ $[10^{-4}]$
1.8	3.54 ± 0.78 (stat.) $\pm$ 0.83 (syst.)
2.0	3.06 ± 0.56 (stat.) $\pm$ 0.47 (syst.)
2.1	2.49 ± 0.46 (stat.) $\pm$ 0.35 (syst.)

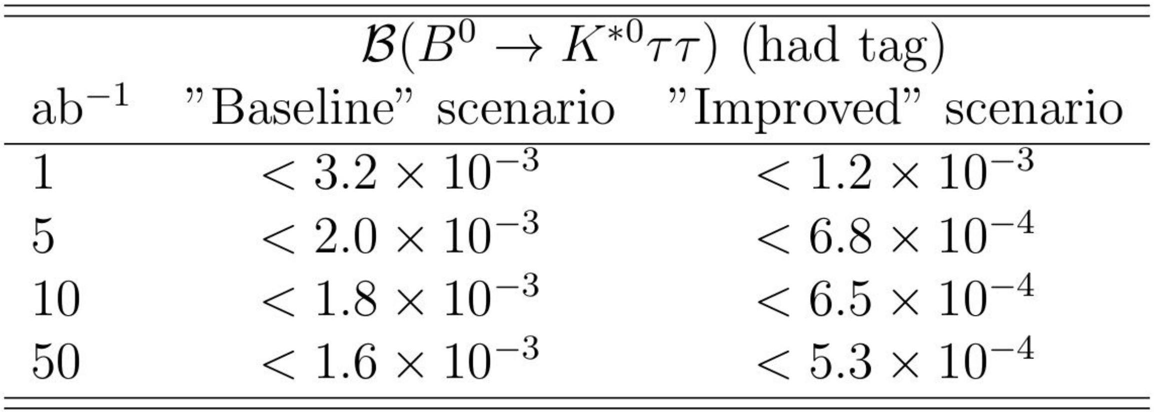




Prospects for $B^0 \to K^{*0}\tau\tau$

https://arxiv.org/pdf/2207.06307.pdf

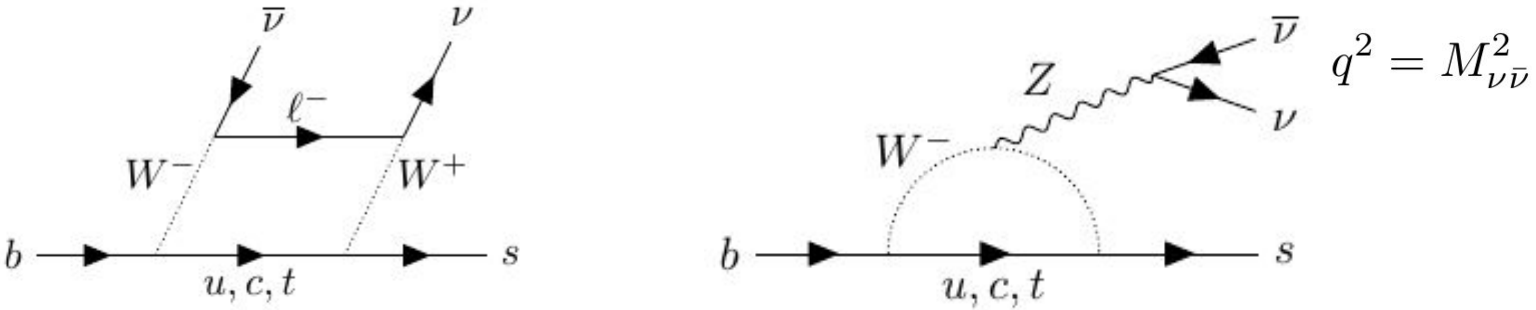




	$\mathcal{B}(B^0 \to K^{*0}\tau\tau)$ (had tag)	
ab^{-1}	"Baseline" scenario	"Improved" scenario
1	$< 3.2 \times 10^{-3}$	$< 1.2 \times 10^{-3}$
5	$< 2.0 \times 10^{-3}$	$< 6.8 \times 10^{-4}$
10	$< 1.8 \times 10^{-3}$	$< 6.5 \times 10^{-4}$
50	$< 1.6 \times 10^{-3}$	$< 5.3 \times 10^{-4}$

- **$B\to K^{(*)}\tau\tau$** decays are complementary to $B \to K^{(*)}ll$ and highly sensitive to NP models. B_{SM} is around **10^{-7}**, while the current limit for $B \to K^*\tau\tau$ is **$< 2\ 10^{-3}$** at 90% CL [arXiv:2110.03871].
- "Baseline" sensitivity projections based on hadronic tag and leptonic decays of τ, "improved" consider other decay modes which improve sensitivity.
- Further improvements possible with $B^+\to K^{*+}\tau\tau$ channel.
- Similar case for $B^+ \to K^+\tau\tau$

B → K νν SM predictions



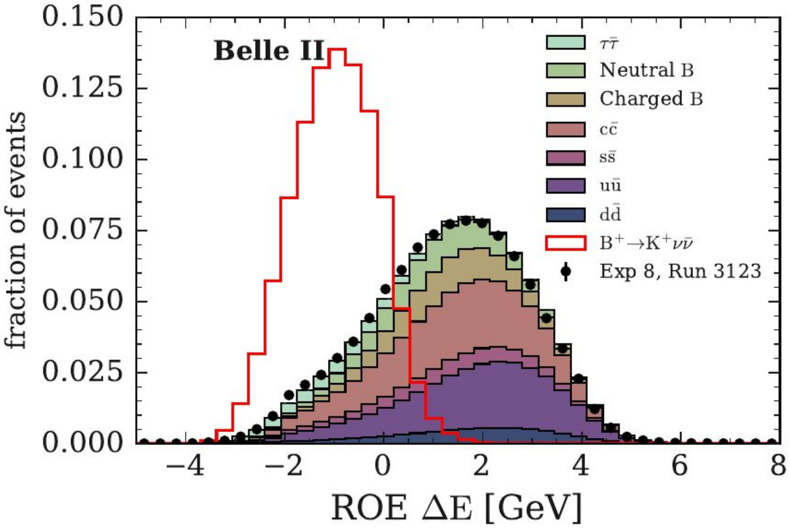
$$\frac{d\mathrm{BR}(B^+ \to K^+ \nu\bar{\nu})}{dq^2} = \tau_{B^+} 3|N|^2 \frac{X_t^2}{s_w^4} \rho_K(q^2) \qquad N = V_{tb} V_{ts}^* \frac{G_F \alpha}{16\pi^2} \sqrt{\frac{m_B}{3\pi}}$$

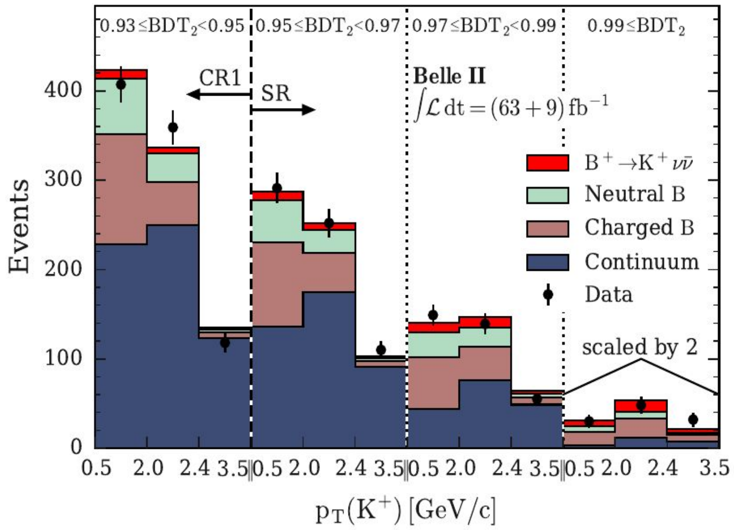
$$\mathrm{BR}_{\mathrm{SM}} = (5.67 \pm 0.38) \times 10^{-6} \quad [\mathrm{arXiv{:}2207.13371}]$$

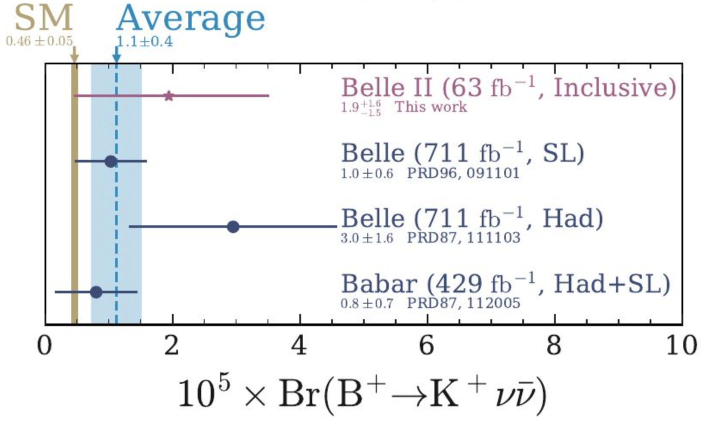
- The B → $K^{(*)}$ νν processes are known with high accuracy in the SM
- Extensions beyond SM may lead to **O(50%)** rate increase (often via ν_τ)
- Very challenging experimentally, not yet observed

$B^+ \to K^+ \nu\nu$ status

Phys.Rev.Lett. 127 (2021) 18, 181802





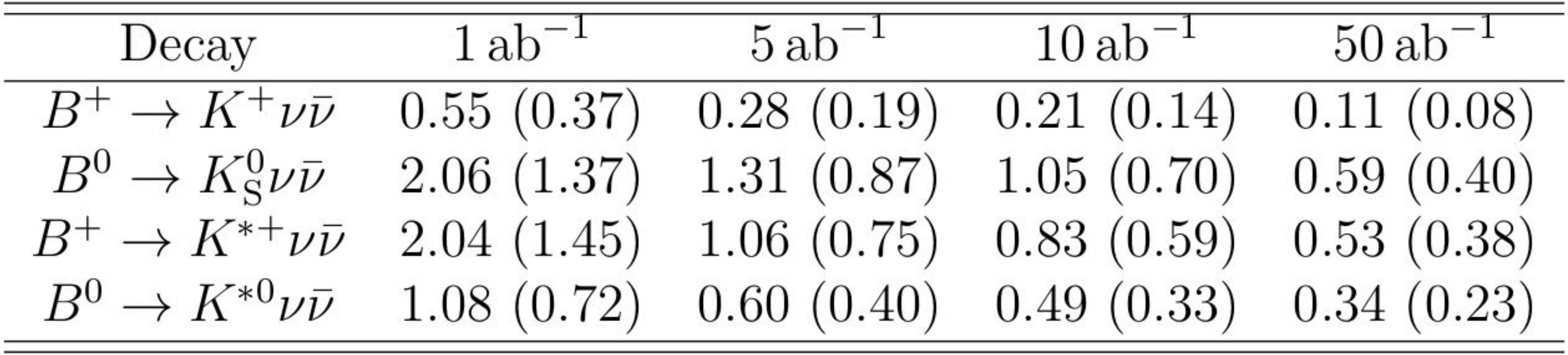


- Analysis using inclusive tag, exploiting distinct topological features of the decay.
- Competitive performance with a small 63 fb^{-1} data sample

$B \to K^{(*)} \nu\nu$ perspectives

https://arxiv.org/pdf/2207.06307.pdf

Uncertainties on **B(measured)/B(SM)**

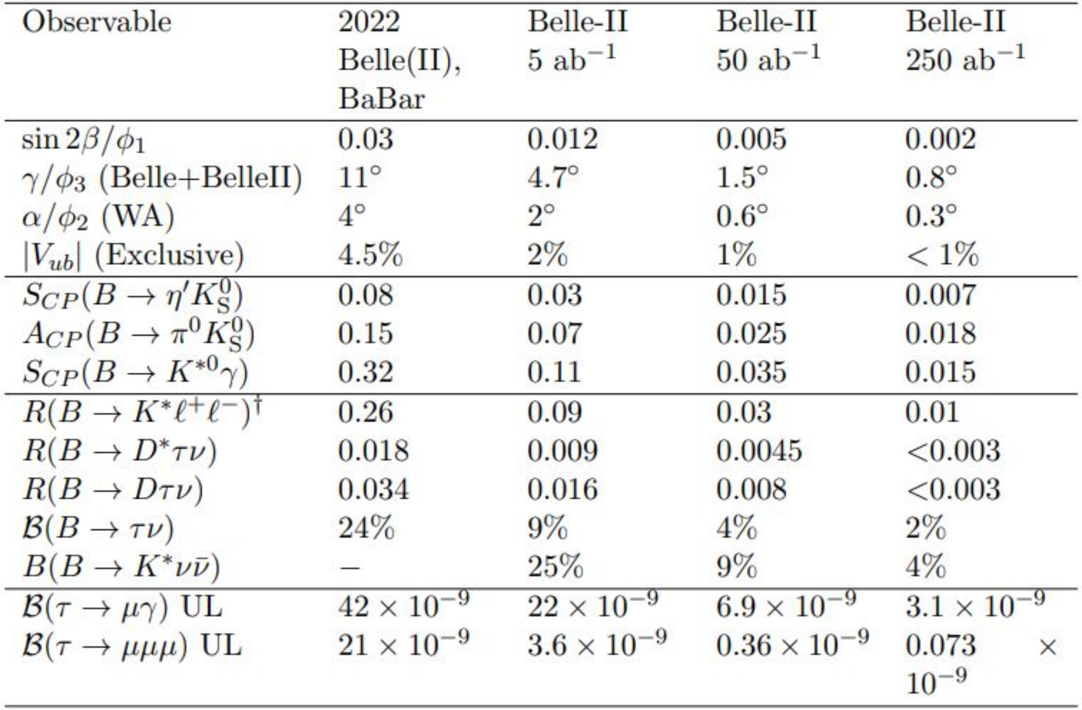


Decay	$1\,\mathrm{ab}^{-1}$	$5\,\mathrm{ab}^{-1}$	$10\,\mathrm{ab}^{-1}$	$50\,\mathrm{ab}^{-1}$
$B^+ \to K^+\nu\bar{\nu}$	0.55 (0.37)	0.28 (0.19)	0.21 (0.14)	0.11 (0.08)
$B^0 \to K^0_S\nu\bar{\nu}$	2.06 (1.37)	1.31 (0.87)	1.05 (0.70)	0.59 (0.40)
$B^+ \to K^{*+}\nu\bar{\nu}$	2.04 (1.45)	1.06 (0.75)	0.83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

- Projections based on published analysis plus updated MC studies
- Baseline (improved) scenarios considers improved background normalization uncertainty (improved signal efficiency) by using additional variables, combining tagging methods
- Can establish $B^+ \to K^+\nu\nu$ decay at 5 sigma with 5 ab^{-1} sample

https://arxiv.org/pdf/2203.11349.pdf

Belle II upgrade



Observable	2022 Belle(II), BaBar	Belle-II 5 ab^{-1}	Belle-II 50 ab^{-1}	Belle-II 250 ab^{-1}
$\sin 2\beta/\phi_1$	0.03	0.012	0.005	0.002
γ/ϕ_3 (Belle+BelleII)	11°	4.7°	1.5°	0.8°
α/ϕ_2 (WA)	4°	2°	0.6°	0.3°
$\lvert V_{ub}\rvert$ (Exclusive)	4.5%	2%	1%	$< 1\%$
$S_{CP}(B \to \eta' K^0_S)$	0.08	0.03	0.015	0.007
$A_{CP}(B \to \pi^0 K^0_S)$	0.15	0.07	0.025	0.018
$S_{CP}(B \to K^{*0}\gamma)$	0.32	0.11	0.035	0.015
$R(B \to K^* \ell^+ \ell^-)^\dagger$	0.26	0.09	0.03	0.01
$R(B \to D^* \tau \nu)$	0.018	0.009	0.0045	<0.003
$R(B \to D \tau \nu)$	0.034	0.016	0.008	<0.003
$\mathcal{B}(B \to \tau \nu)$	24%	9%	4%	2%
$B(B \to K^* \nu \bar{\nu})$	–	25%	9%	4%
$\mathcal{B}(\tau \to \mu\gamma)$ UL	42×10^{-9}	22×10^{-9}	6.9×10^{-9}	3.1×10^{-9}
$\mathcal{B}(\tau \to \mu\mu\mu)$ UL	21×10^{-9}	3.6×10^{-9}	0.36×10^{-9}	0.073×10^{-9}

- Near- and long-term Belle II upgrade is under consideration
- Benchmark studies assuming x5 data sample (250 x 10^9 BB events)
- Significant increase of sensitivity for key channels
- Requirements to SuperKEKB accelerator need to be investigated

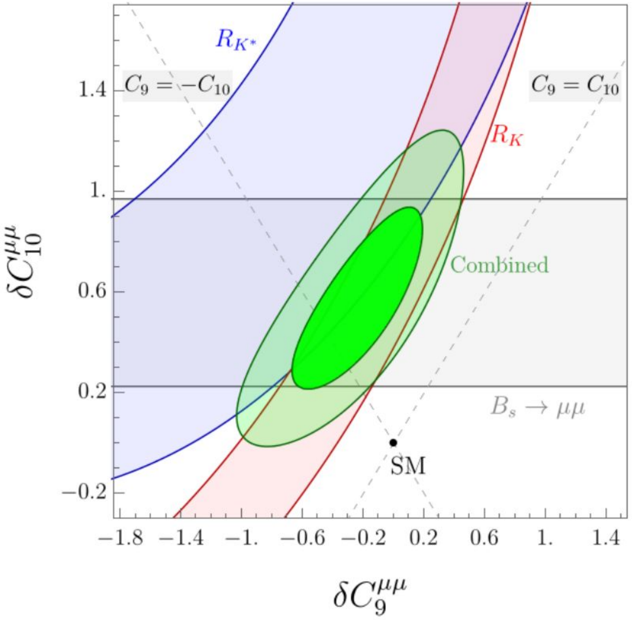
Summary

- Success of SuperKEKB is essential for future high-luminosity e^+e^- colliders.
- $R(K^{(*)})$ from Belle II becomes competitive with larger data samples.
- $B \rightarrow K \nu\nu$ should be established by Belle II, if it is consistent with SM
- $B \rightarrow K^{(*)} \tau\tau$ has a lot of potential to search for new physics.
- Long-term upgrade of Belle II is under consideration, with an option to x5 the Belle II data sample.

BACKUP

BSM models to explain anomalies.

https://arxiv.org/pdf/2103.12504.pdf
https://arxiv.org/pdf/2110.13270.pdf



$$\mathcal{L}_{\rm nc} \supset \frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_i C_i\, \mathcal{O}_i + \text{h.c.}\,,$$

$$\mathcal{O}_9^{\ell_1\ell_2} = \frac{e^2}{(4\pi)^2} (\bar{s}\gamma_\mu P_L b)(\bar{\ell}_1 \gamma^\mu \ell_2)\,,$$

$$\mathcal{O}_{10}^{\ell_1\ell_2} = \frac{e^2}{(4\pi)^2} (\bar{s}\gamma_\mu P_L b)(\bar{\ell}_1 \gamma^\mu \gamma^5 \ell_2)\,,$$

- EFT analysis suggests modification of $\mathbf{C_{10}}$ and $\mathbf{C_9}$ effective couplings
- A number of models which can generate these modifications: W’, Z’, LP
- Some models can prediction both R_K and R_D anomalies at the same time, e.g. vector U_1 leptoquark
- Many but not all models predict large effects for loop decays involving taus, sometimes with LFV, e.g. B →Kμτ
- UV completion requires presence of extra particles at high energies.