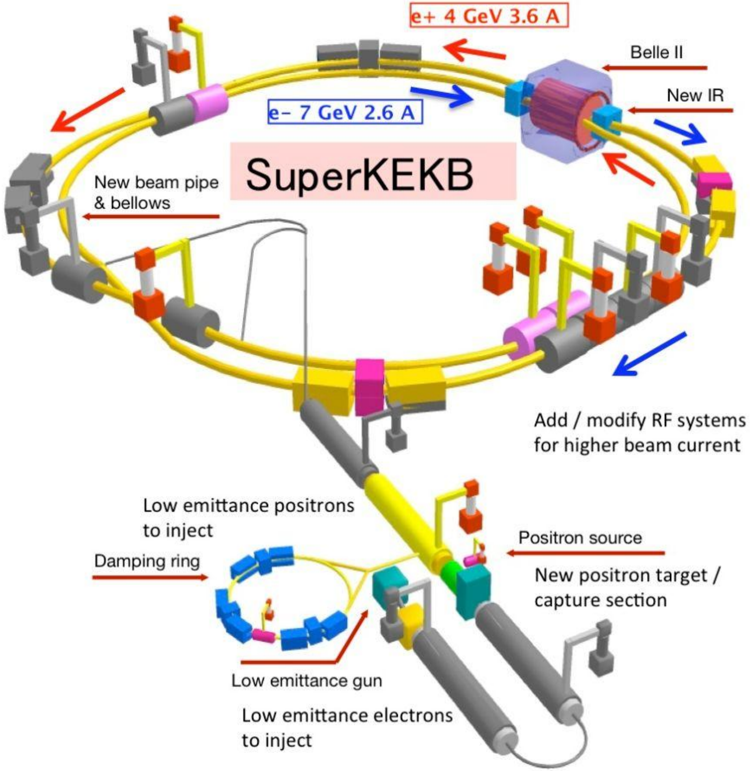
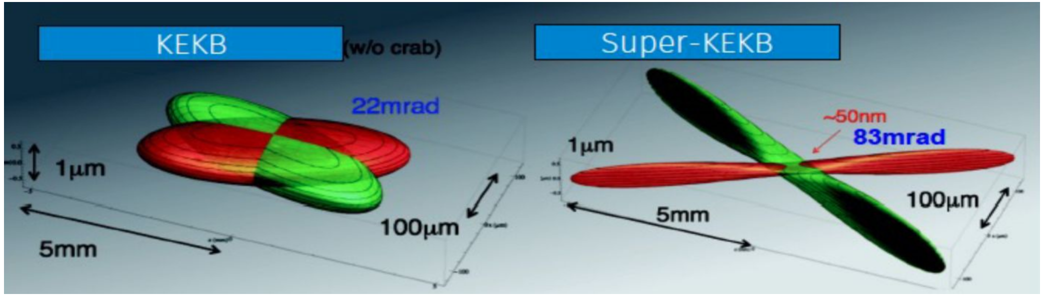

# Prospects for rare decays and flavour anomalies at Belle II

S. Glazov, ECFA workshop, DESY, Hamburg, 5 Oct 2022

# SuperKEKB



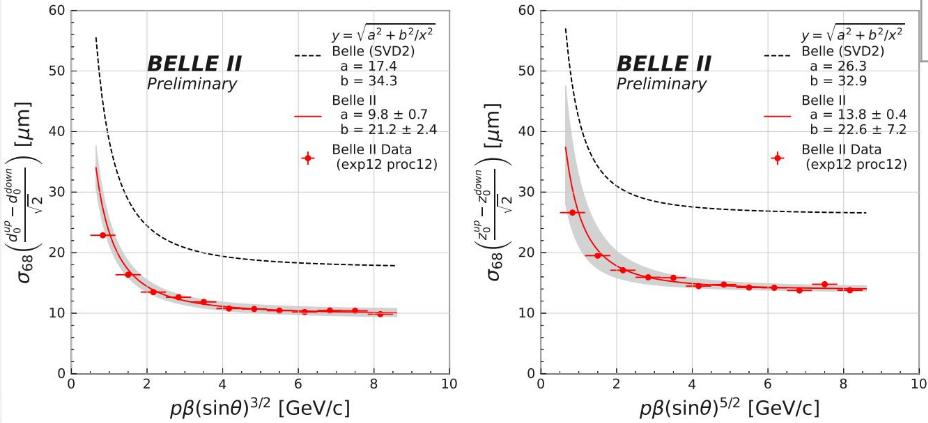



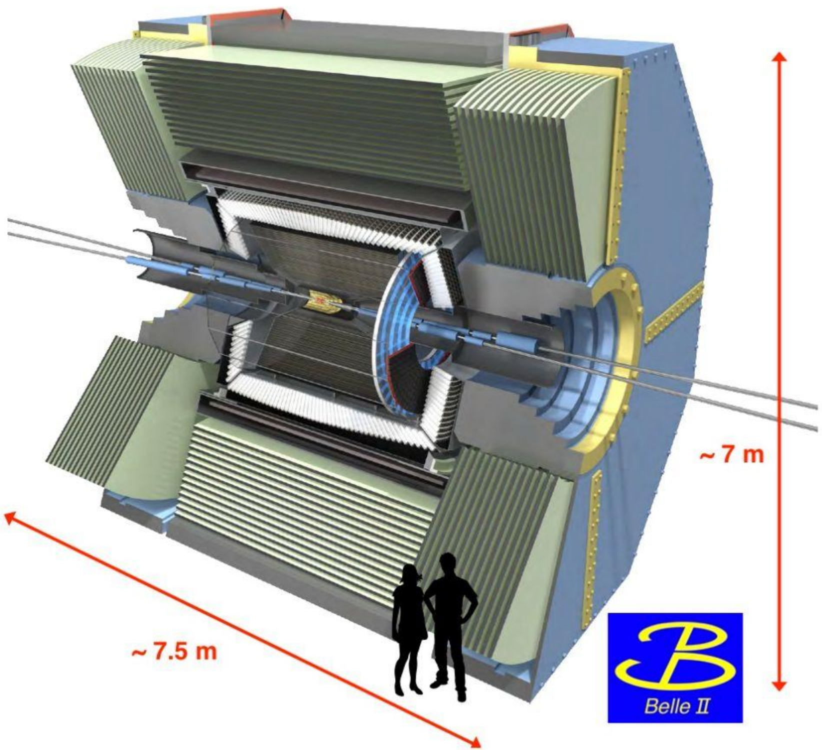

- Nano-beam collision scheme leading to highest specific luminosity, employed for the first time
- First physics data from 2018
- Design luminosity of **$6.5 \times 10^{35} cm^{-2}s^{-1}$**
- Achieved world-record peak luminosity of **$4.7 \times 10^{34}$ $cm^{-2}$ $s^{-1}$**
- Expected total integrated 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

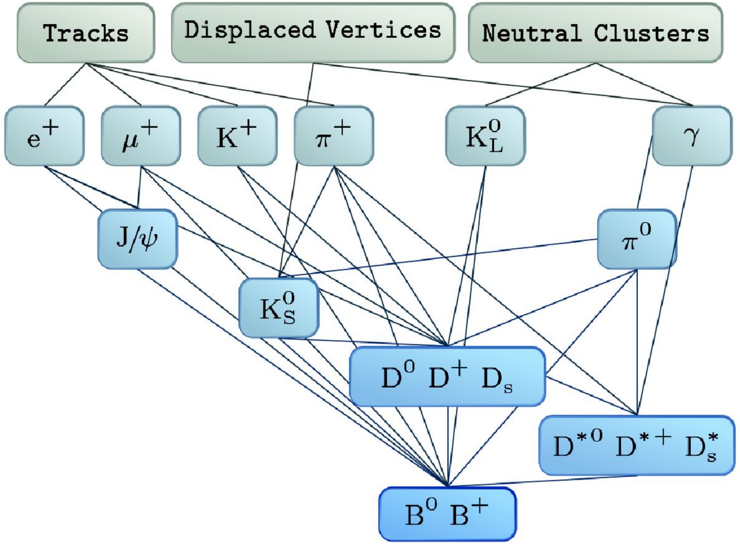
| Collected at Υ(4S): | 360 $fb^{-1}$, about 0.4 x $10^9$ BB |
|---|---|
| Expected: | 50 $ab^{-1}$, about 50 x $10^9$ BB |

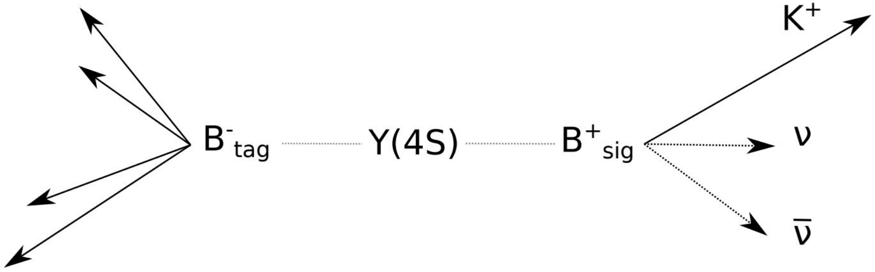



- Nearly 4π detector
- Tracking, PID, and photon reconstruction capabilities
- Similar performance for electrons and muons
- Well-suited to measure decays with missing energy, $\pi^0$ in the final state, inclusive measurements
- Comparable or better performance vs its predecessor Belle.

# Reconstruction methods at Belle II

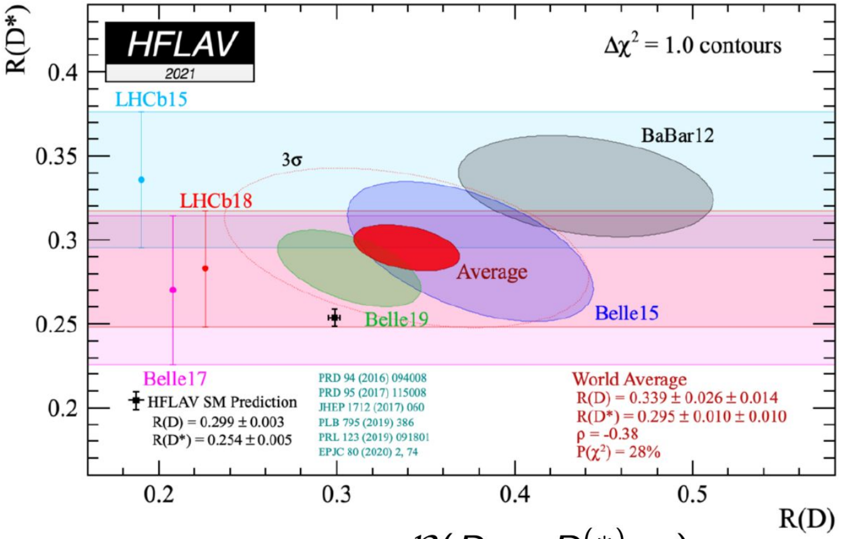


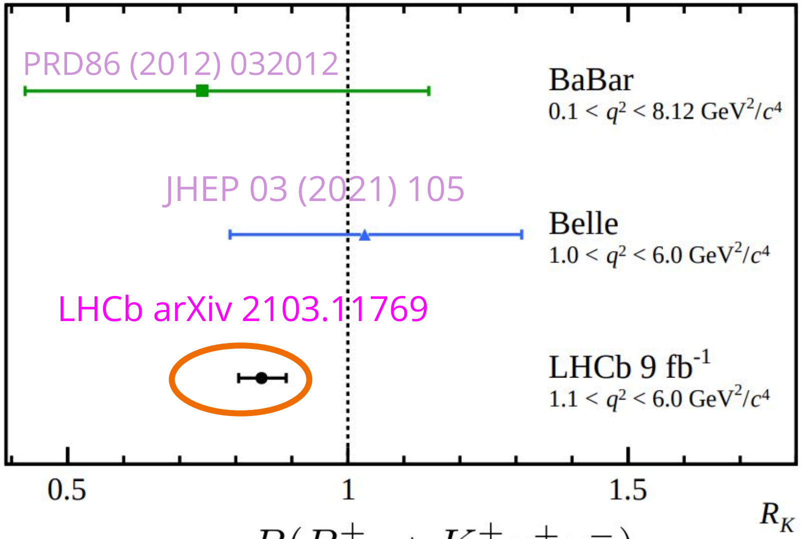




$$\Delta E = E^*_B - \sqrt{s}/2 \qquad M_{bc} = \sqrt{s/4 - {p^*_B}^2}$$

- 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.

# Flavour anomalies: R(D$^{(*)}$) and R(K$^{(*)}$) – status



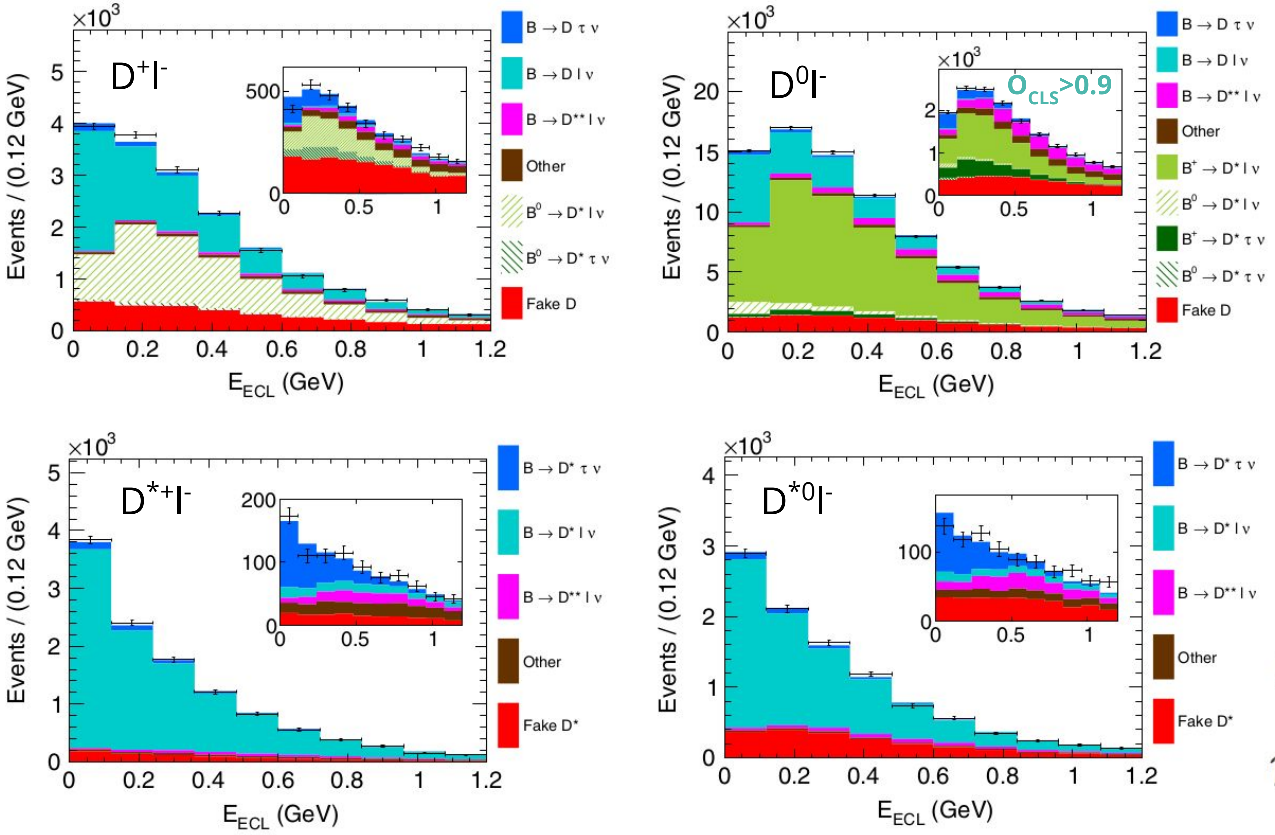

$$R_{D^{(*)}} = \frac{\mathcal{B}(B \to D^{(*)}\tau\nu)}{\mathcal{B}(B \to D^{(*)}\ell\nu)}$$

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

Potential signs of lepton-flavour universality violation in tree-level decays involving τ leptons, **R(D$^{(*)}$)**, and loop-level FCNC processes involving light leptons, **R(K$^{(*)}$)**.

# $R(D^{(*)})$ – last results from Belle

PRL 214, 161803 (2020)



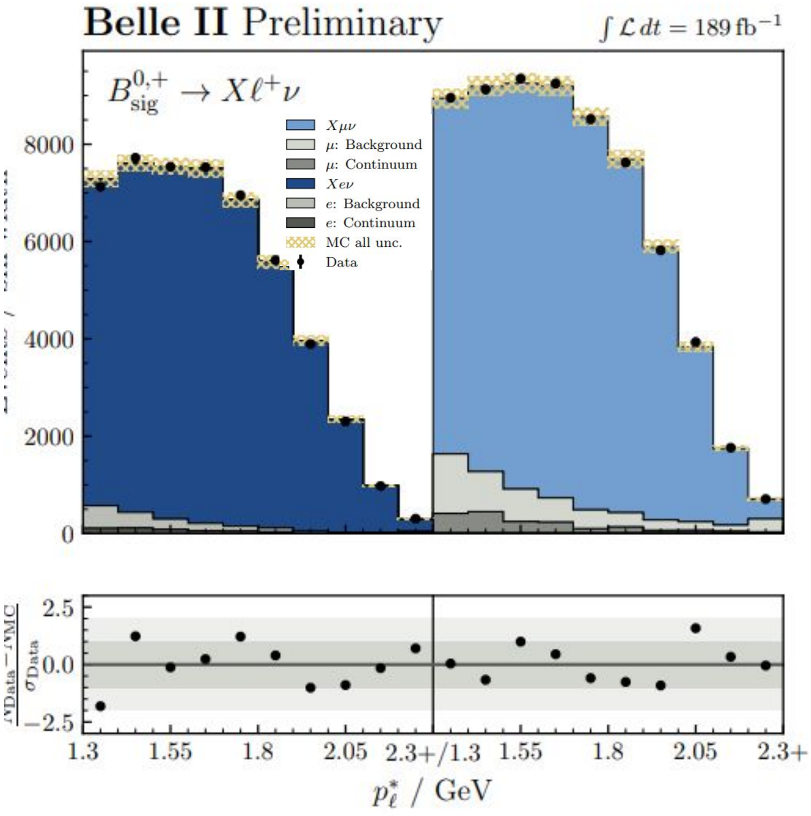

$E_{ECL}$ : sum of energy of "extra" neutral clusters in EM calorimeter

- Simultaneous determination of **R(D*)** and **R(D)** using semileptonic tagging (control over crossfeed contributions).
- Simultaneous fit in BDT output ($\mathbf{O_{cLs}}$) and $\mathbf{E_{ECL}}$
- Most precise determination up to date, consistent with SM at 0.2 σ and 1.1σ for **R(D)** and **R(D*)**, respectively

$$\mathcal{R}(D) = 0.307 \pm 0.037 \pm 0.016,$$

$$\mathcal{R}(D^*) = 0.283 \pm 0.018 \pm 0.014,$$

# Towards $R(X_{\tau/l})$: $R(X_{e/\mu})$ by Belle II

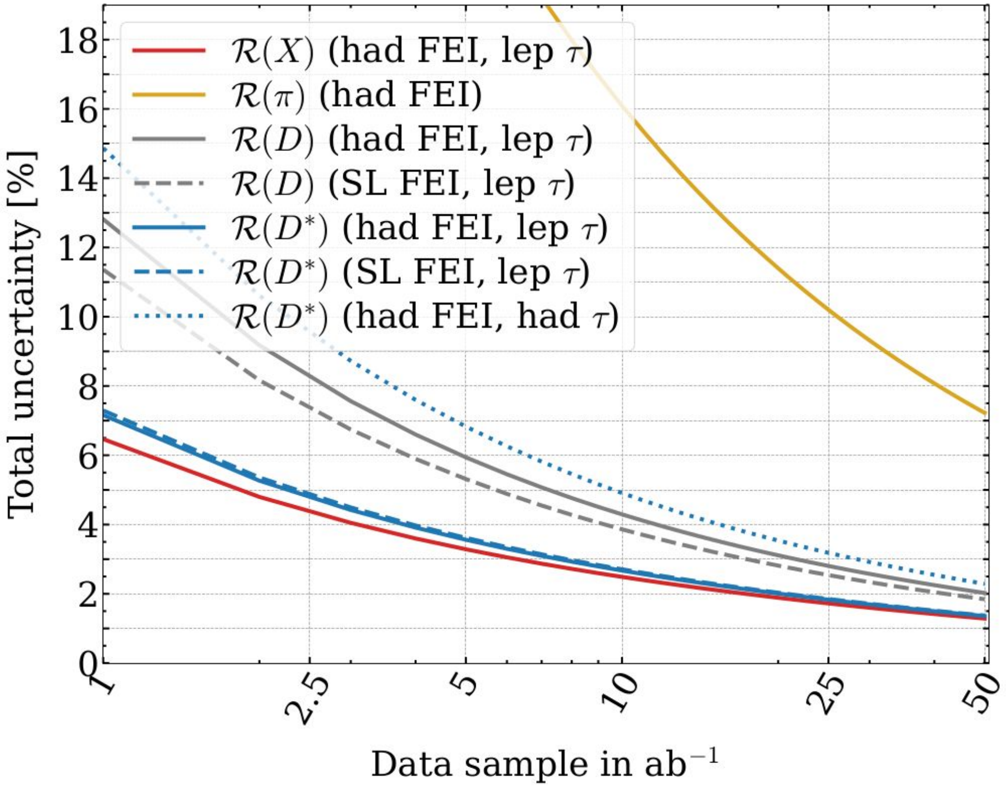



- Inclusive measurement of **$R(X_{e/\mu})$** using hadronic tag, that determines expected charge for the lepton
- Background from cascade decays is controlled using wrong charge combinations
- Simultaneous fit for e- and μ-channel in bins of $p^*_l > 1.3$ GeV/c

$$R(X_{e/\mu}) = 1.033 \pm 0.010 \pm 0.020$$

# R semi-taunic: perspectives

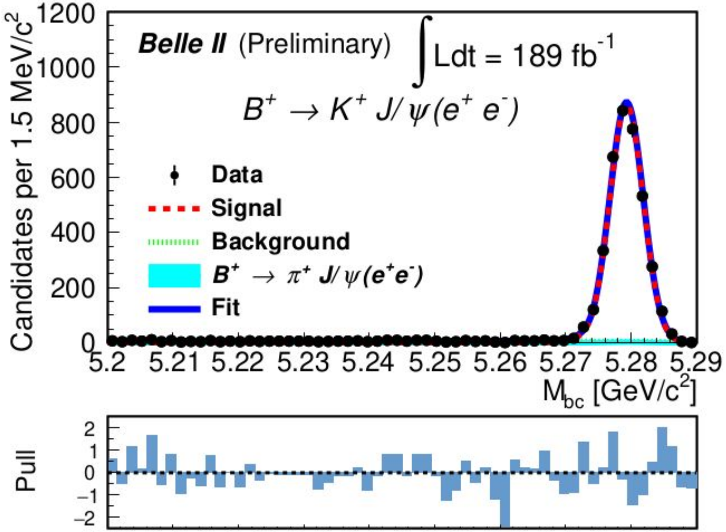
https://arxiv.org/pdf/2207.06307.pdf

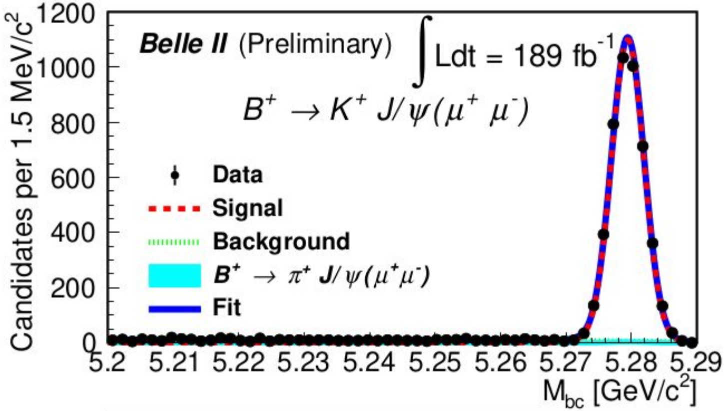



- Uncertainties on R(D) and R(D*) should be under 10% with few $ab^{-1}$
- Measurements of inclusive R(X) are unique for Belle II, can be performed with high accuracy
- b →u transitions B→πlν can be probed as well.
- Additional observables: D* and τ polarization.

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

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



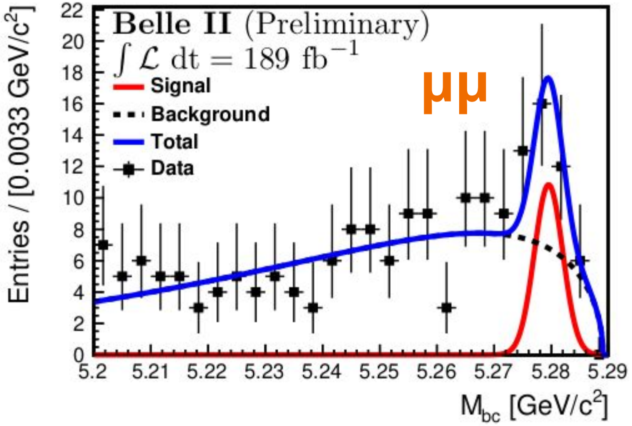



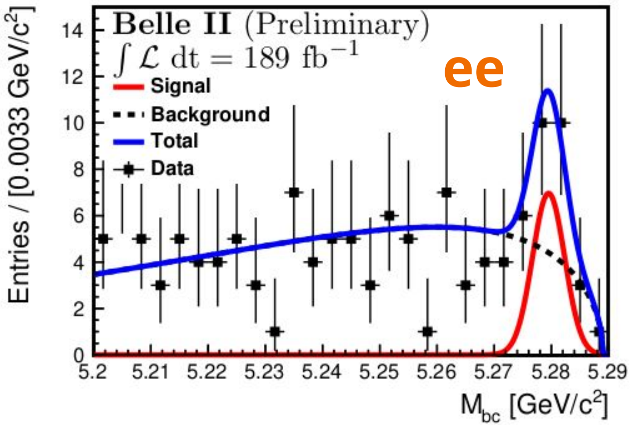

| | |
|---|---|
| $R_{K^+}(J/\psi)$ | $1.009 \pm 0.022 \pm 0.008$ |
| $R_{K^0_S}(J/\psi)$ | $1.042 \pm 0.042 \pm 0.008$ |

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

# R(K*) status

https://arxiv.org/abs/2206.05946



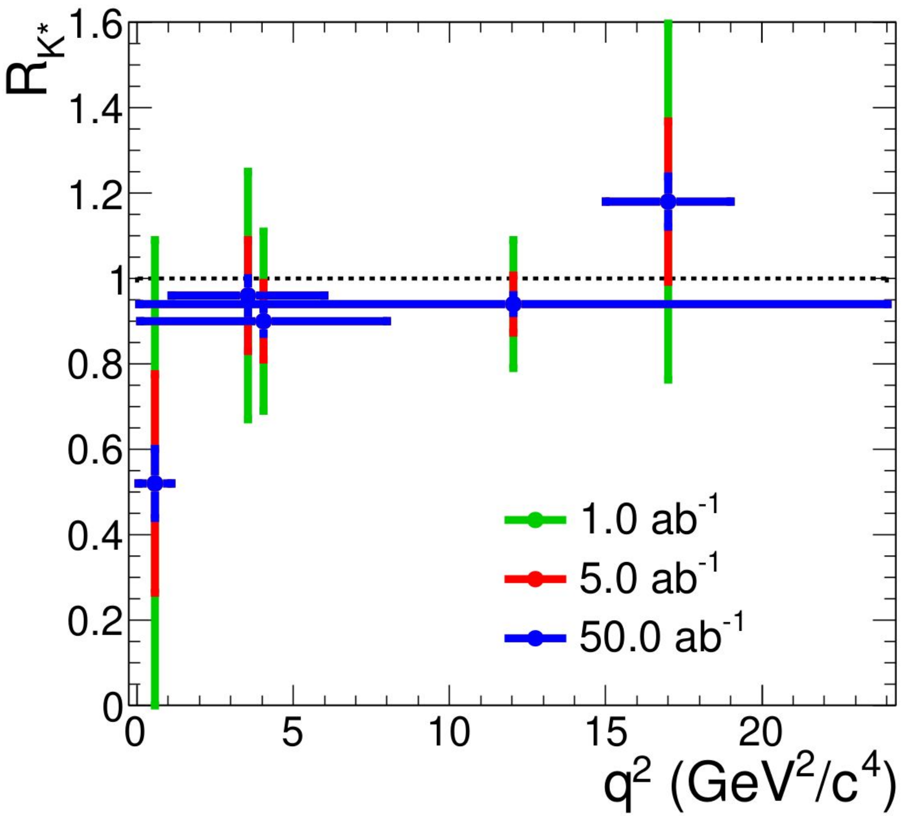

- $B^{0,+} \to K^{*0,+} ll$ decays reconstructed (with veto on charmonium, low $q^2$ resonances)
- Similar performance for **μμ** and ee channels.

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

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

Based on Belle PRL 126, 161801 (2021)

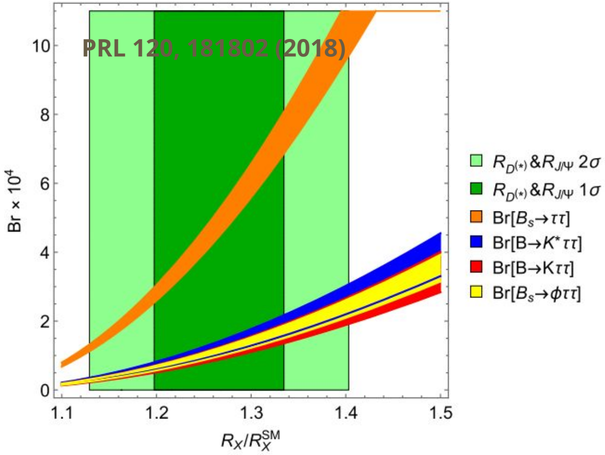
# $R(K^{(*)})$ perspective




- 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.

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

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

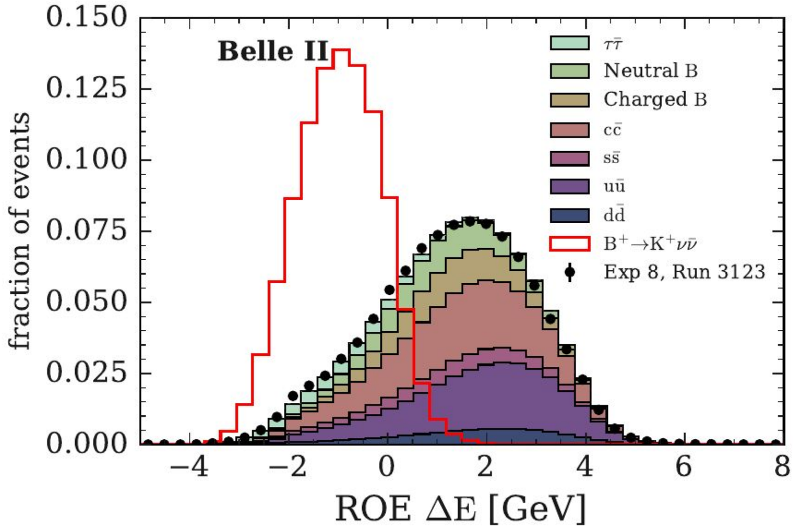


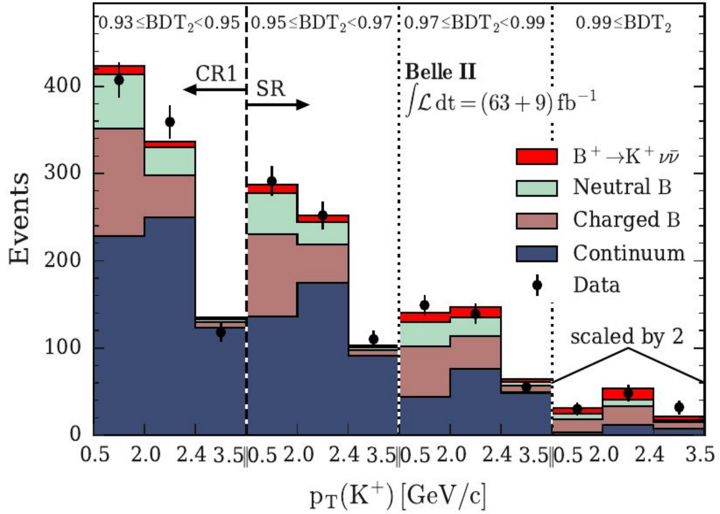

| $\mathcal{B}(B^0 \to K^{*0}\tau\tau)$ (had tag) | | |
|---|---|---|
| $ab^{-1}$ | "Baseline" scenario | "Improved" scenario |
| 1 | $< 3.2 \times 10^{-3}$ | $< 1.2 \times 10^{-3}$ |
| 5 | $< 2.0 \times 10^{-3}$ | $< 6.8 \times 10^{-4}$ |
| 10 | $< 1.8 \times 10^{-3}$ | $< 6.5 \times 10^{-4}$ |
| 50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

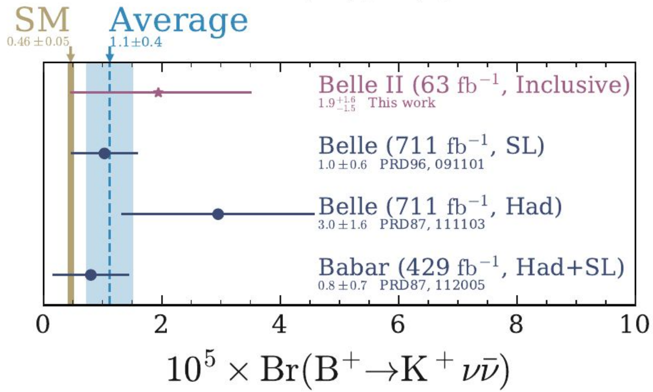
- **$B \to K^{(*)}\tau\tau$** decays are complementary to $B \to K^{(*)}ll$ and highly sensitive to NP models. B(SM) is around **$10^{-7}$**, while the current limit for $B \to K^*\tau\tau$ is **$< 2\ 10^{-3}$** at 90% CL [arXiv:2110.03871].
- "Baseline" sensitivity projections based on hadronic tag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

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

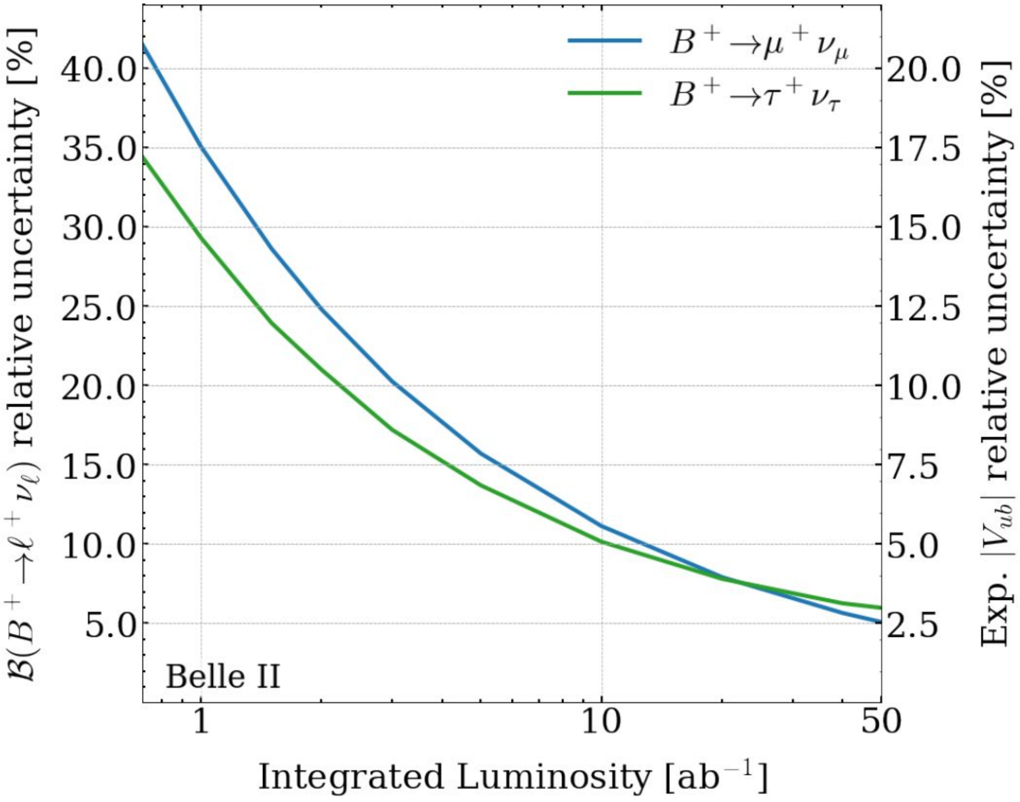
Uncertainties on **B(measured)/B(SM)**

| 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 $\mathrm{ab}^{-1}$ sample

# Leptonic B decays perspectives

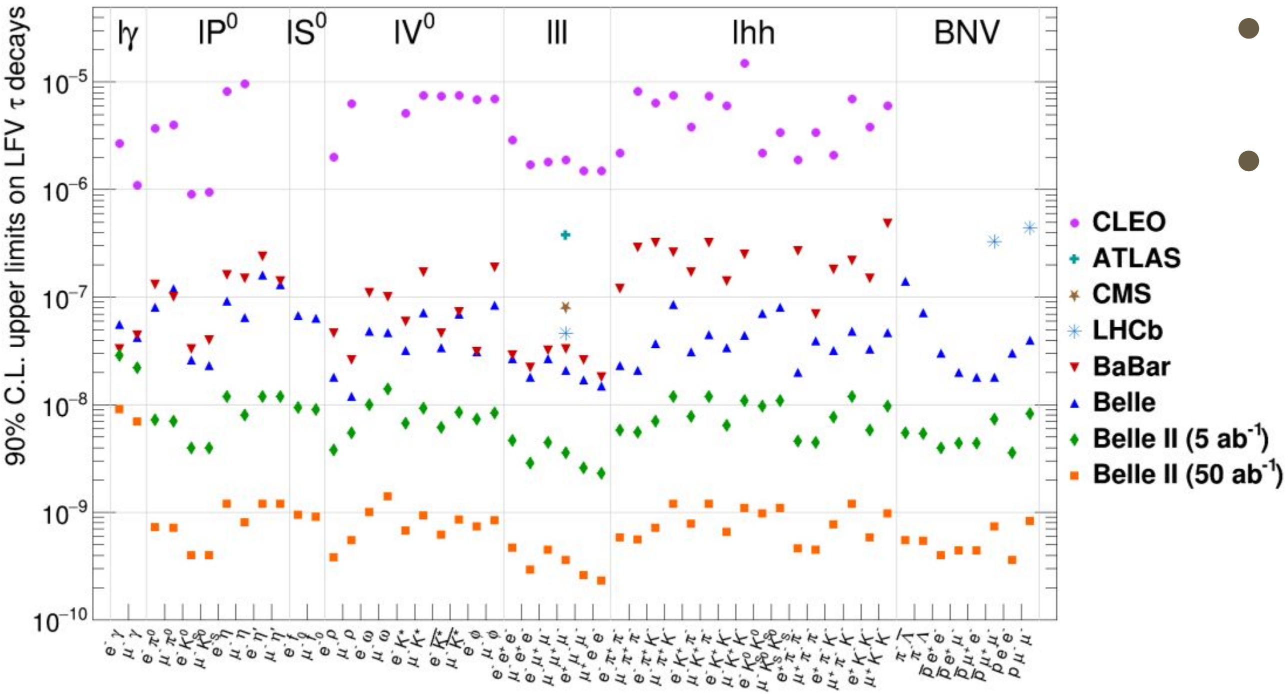
https://arxiv.org/pdf/2207.06307.pdf




- Leptonic decays $B^+ \to l^+ \nu$ are suppressed by $|V_{ub}|$ and helicity factor.
- Small theoretical uncertainty of 0.7%: clean probe of $|V_{ub}|$
- Currently, $B(B^+ \to \tau^+ \nu)$ is determined to about 20% accuracy.
- Belle II should observe $B^+ \to \mu^+ \nu$ with 5 $ab^{-1}$, measure $|V_{ub}|$ with 2.5% accuracy for the 50 ab-1 dataset.

# $\tau$ decays and lepton flavour violation

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




- SuperKEKB is not only B but also c-τ factory.
- Precision lepton universality check are possible with small data samples and searches for LFV can be performed with 5 $ab^{-1}$ already

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 |
| $\gamma/\phi_3$ (Belle+BelleII) | 11° | 4.7° | 1.5° | 0.8° |
| $\alpha/\phi_2$ (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 | $42 \times 10^{-9}$ | $22 \times 10^{-9}$ | $6.9 \times 10^{-9}$ | $3.1 \times 10^{-9}$ |
| $\mathcal{B}(\tau \to \mu\mu\mu)$ UL | $21 \times 10^{-9}$ | $3.6 \times 10^{-9}$ | $0.36 \times 10^{-9}$ | $0.073 \times 10^{-9}$ |

- 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.
- Belle II should provide additional information on $R(D^{(*)})$ anomalies already with samples of $5ab^{-1}$
- Clarification of $R(K^{(*)})$ anomalies is more challenging, larger data samples are required.
- $B \to K \nu\nu$ should be established by Belle II, if it is consistent with SM
- $B \to K^{(*)} \tau\tau$ is more challenging, leaves room for Z-factory
- Long-term upgrade of Belle II is under consideration, with an option to x5 the Belle II data sample.