Flavor Anomalies at Belle II
Status and Prospects

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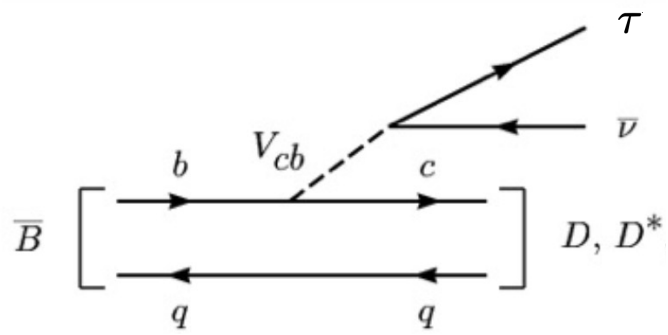
On behalf of the Belle II Collaboration

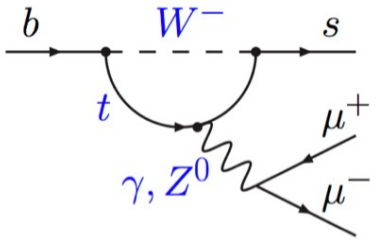
The “Flavor Anomalies”

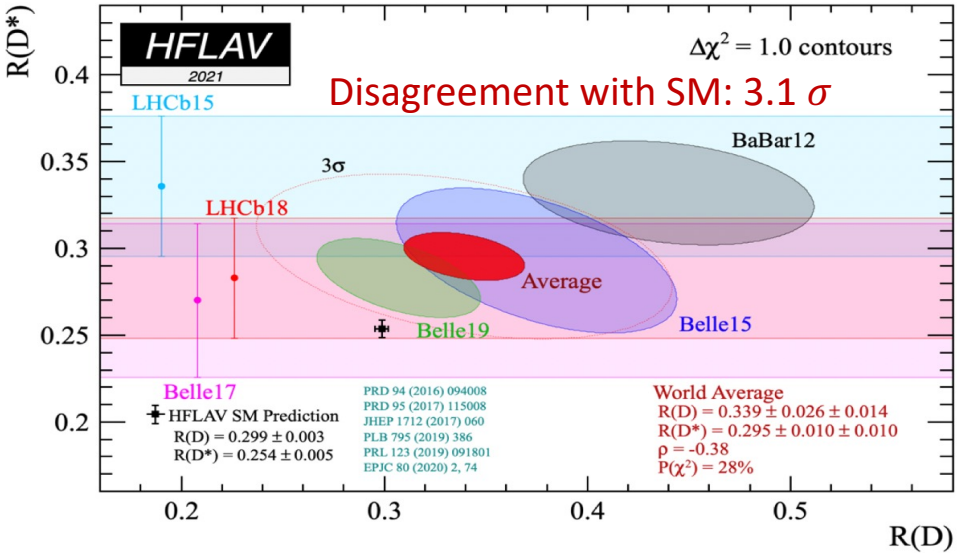
Interesting flavor anomalies seen in B decays at LHCb, Belle and BaBar

Lepton Flavor Universality (LFU)
in semileptonic decays B ⟶ D/D*$\tau\nu$

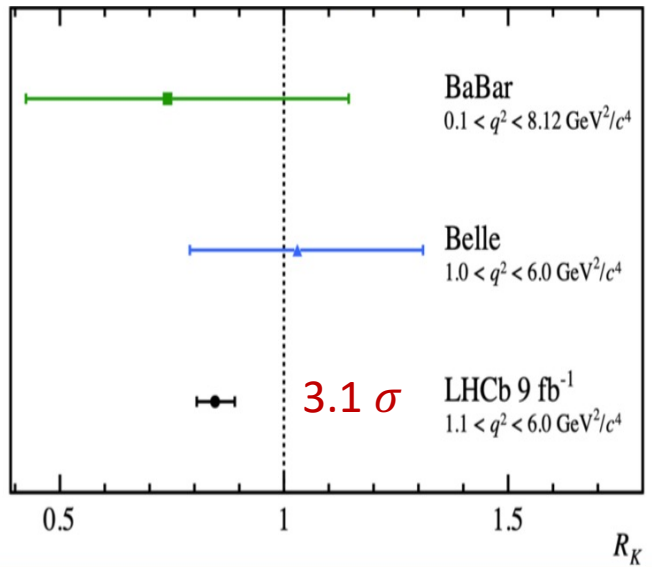


LFU and angular distributions
in electroweak penguin decays





LHCb, Nature Physics 18 (2022) 277



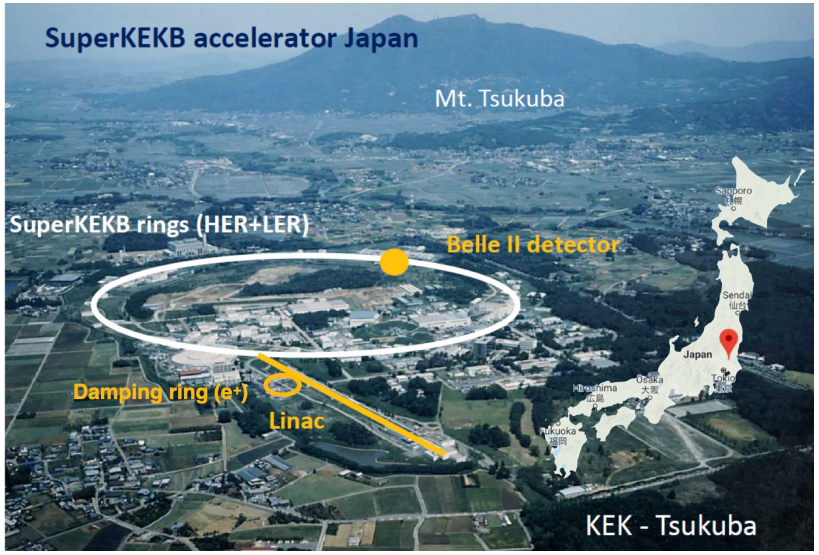
❖ Where do we stand with analyses related to flavor anomalies in Belle II?

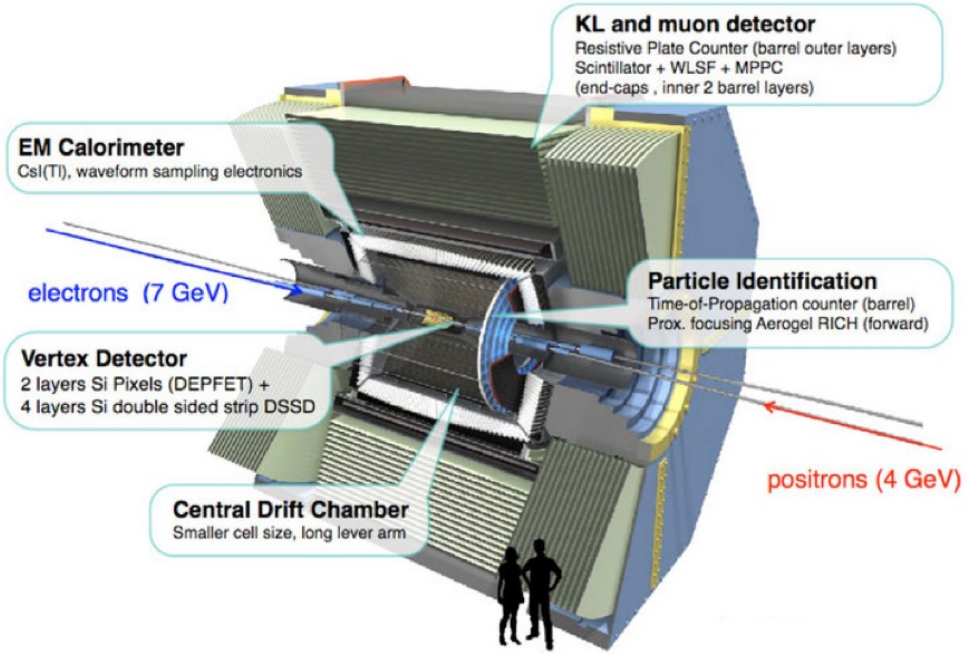
Outline

- LFU test with semileptonic B decays
  - $R(X_{e/\mu})$ from inclusive $B \longrightarrow Xl\nu$
  - Prospects
- Electroweak and radiative B decays
  - $B \longrightarrow K^{*}l^{+}l^{-}$
  - $R(K_{J/\psi})$ from $B \longrightarrow J/\psi K$
  - Inclusive $B \longrightarrow X_s\gamma$
  - Prospects

New preliminarly Belle II measurements with **189 fb^{-1}**

Belle II and SuperKEKB





SuperKEKB

$$L = \frac{\gamma_\pm}{2er_e}\left(1+\frac{\sigma_y^*}{\sigma_x^*}\right)\frac{R_L}{R_\xi}\frac{I_\pm \xi_{y\pm}}{\beta^*_{y\pm}}$$

beam current x1.5

beam-beam param. x1

vertical beta function x 1/20

Instantaneous luminosity: ~ 6×10^{35} $cm^{-2}s^{-1}$

Integrated luminosity: ~ 50 ab^{-1}

Belle II

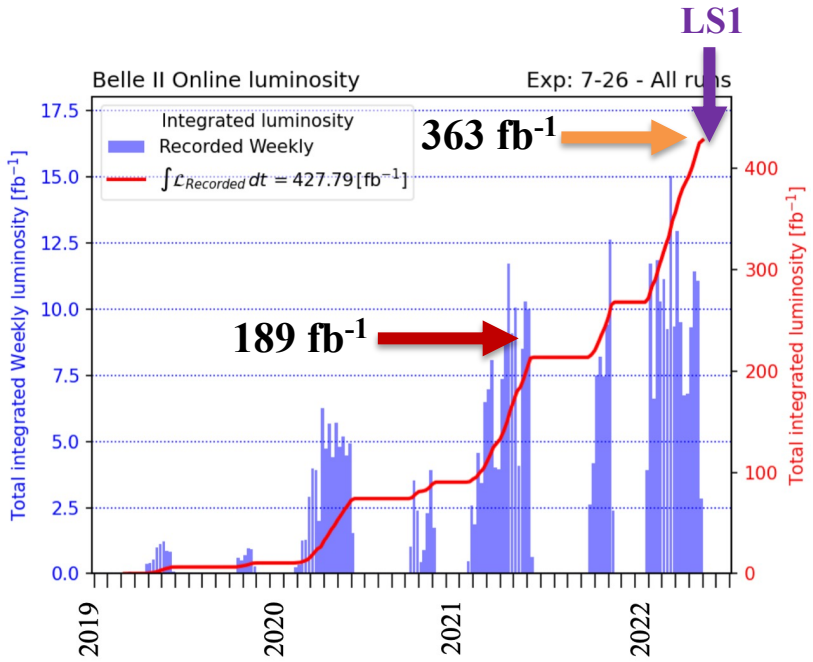
- Nearly-hermetic 4π detector coverage ⇒ **inclusive** final states, **neutrinos**
- Excellent neutral particle reconstruction (γ, π^0, K_S)

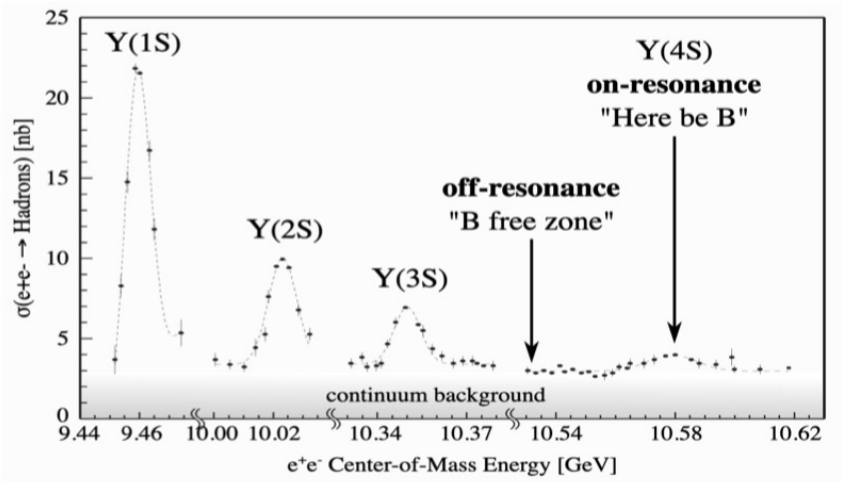
Status of data taking

- SuperKEKB set **luminosity world record** on June 22, 2022:

  $L = 4.71 \times 10^{34}\ cm^{-2}s^{-1}$ (> 2 × KEKB record) ⇒ entering "Super B-factory" regime

- **Integrated luminosity: 424 fb^{-1}** (2019-2022)
  - 363 fb^{-1} at √s = 10.58 GeV = Υ(4S) mass [BaBar: 420 fb^{-1}, Belle: 700 fb^{-1}]
  - 42 fb^{-1} off-resonance, 60 MeV below Υ(4S) mass
  - 19 fb^{-1} at √s = 10.75 GeV for exotic hadron searches



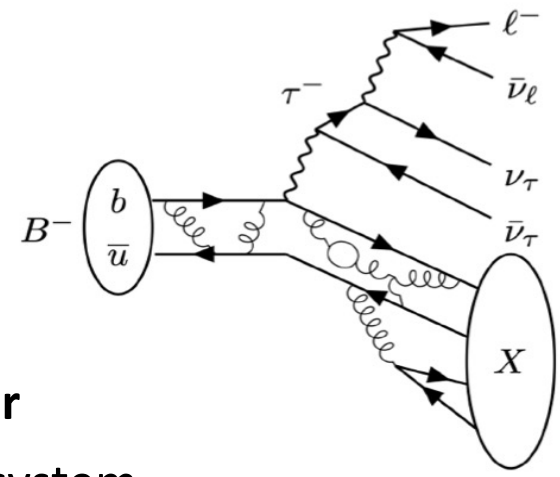


- **Currently:** Long Shutdown 1 (15 mos.) for detector upgrades and beam-pipe improvement

LFU in inclusive semileptonic B decays

- **Inclusive** cross-check of R_D , R_{D^*} anomaly:

$$R(X) = \frac{\mathcal{B}(B \to X\tau\nu)}{\mathcal{B}(B \to X\ell\nu)}$$

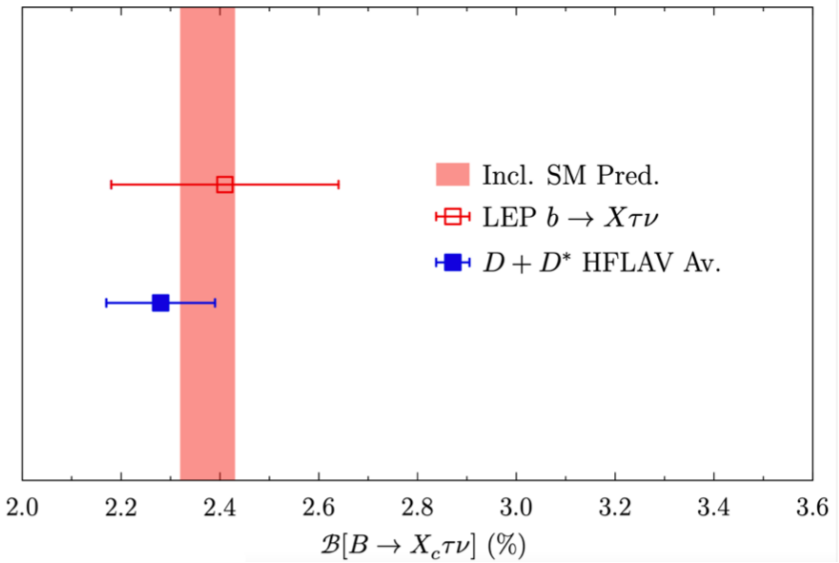


- **So far, no R(X) measurement from Belle or BaBar**
  - Large background due to less constrained X system
  - Modeling of B ⟶ X$\tau\nu$ with X ⟶ … difficult

- **New Belle II measurement** of **light-lepton ratio**:

$$R(X_{e/\mu}) = \frac{\mathcal{B}(B \to Xe\nu)}{\mathcal{B}(B \to X\mu\nu)}$$

b ⟶ X$\tau\nu$ from LEP

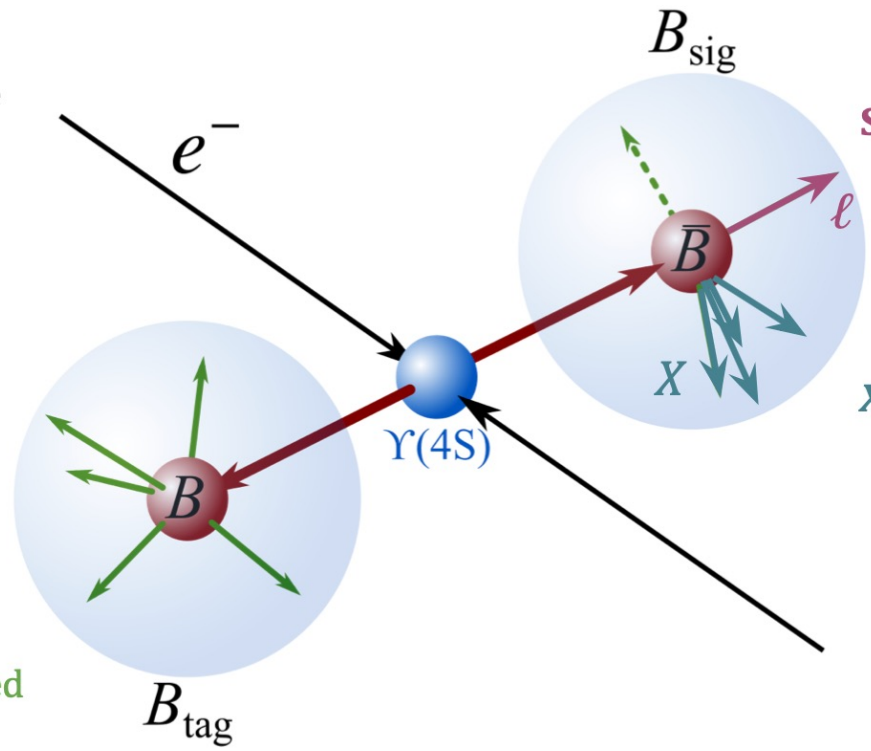


Reconstructing inclusive B ⟶ Xlν

H. Junkerkalefeld @ ICHEP 2022

Reconstruction of inclusive B ⟶ Xlν decays with hadronic B tagging

Full event
Shape variables used to reduce continuum background with machine learning



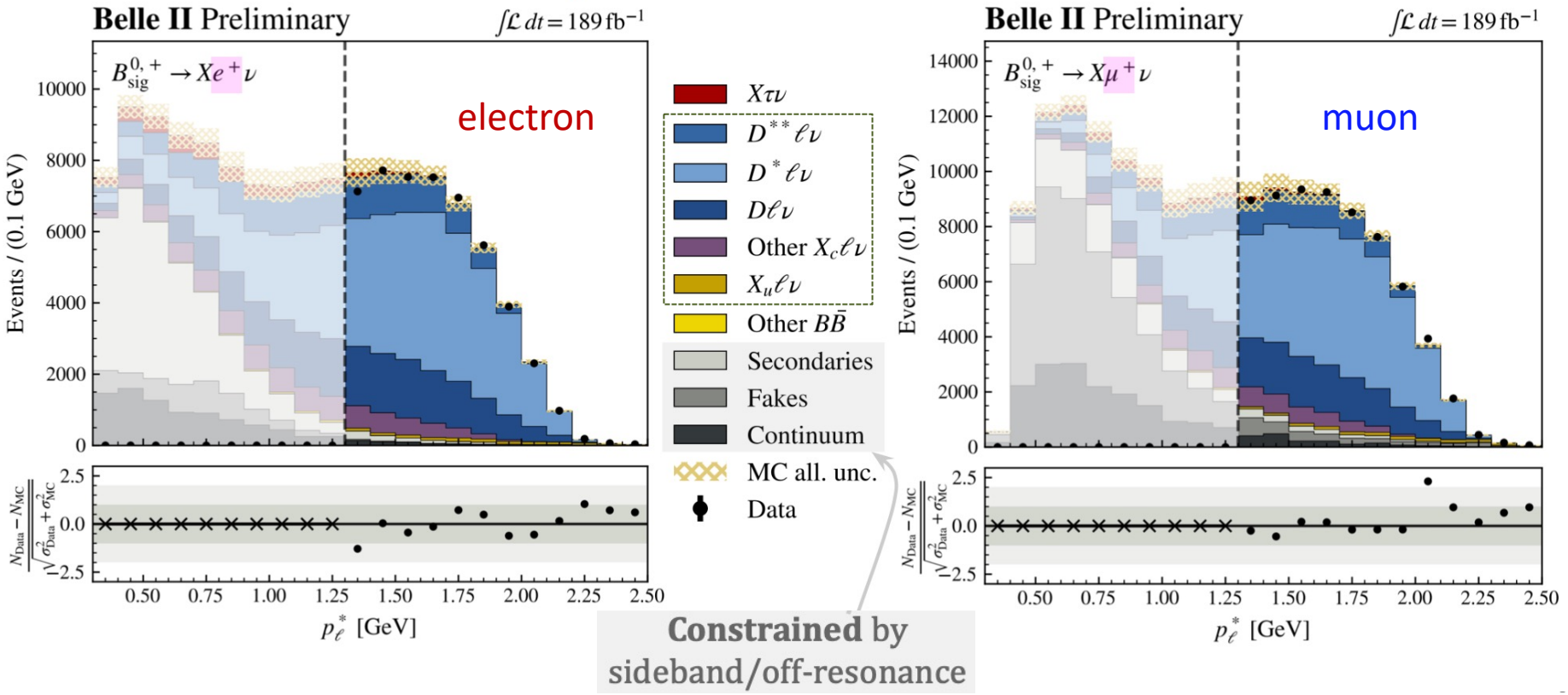
Signal lepton:
- $p^*_\ell > 1.3$ GeV
- High electron or muon likelihood

***X* system:**
- Everything else in the event…
- …passing quality criteria

Tag-side *B* meson
- Fully reconstructed (hadronic FEI)
- Tight tag quality selections

LFU in inclusive semileptonic B decays

- Signal yields for B ⟶ Xeν and B ⟶ X$\mu\nu$ extracted with fit in **10 bins of p_l^***



$N_{Xe\nu}$ = 48034 ± 286

ε = 0.114%

$N_{X\mu\nu}$ = 58569 ± 429

ε = 0.138%

LFU in inclusive semileptonic B decays

Result: $R(X_{e/\mu}) = 1.033 \pm 0.010^{\text{stat.}} \pm 0.020^{\text{syst.}}$

- Most precise BF-based LFU test with semileptonic B decays to date
- **Agrees with SM value of 1.006 ± 0.001 within 1.2σ** EPJ 81 (2021) 984
- Compatible within 0.6σ with exclusive Belle result: $R(D^*_{e/\mu}) = 1.01 \pm 0.01 \pm 0.03$

PRD 100 (2019) 052007

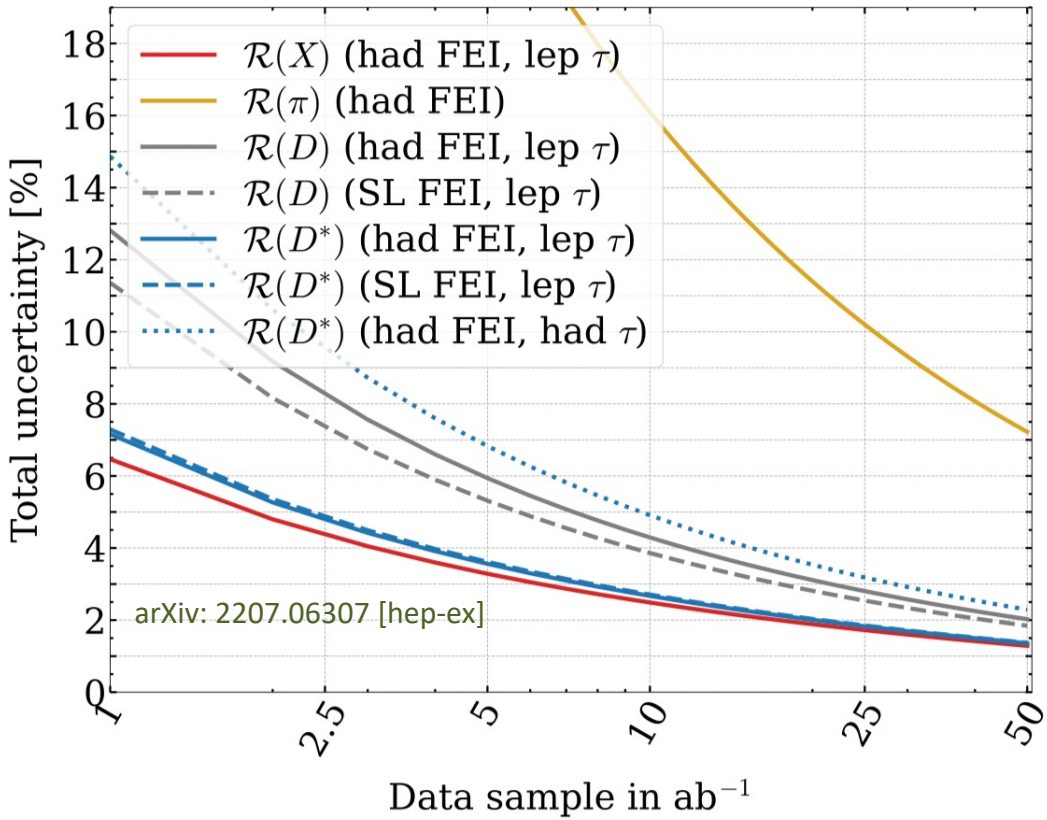
Source of uncertainty	Lepton ID	$X_c\ell\nu$ BFs	$X_c\ell\nu$ FFs	Statistical	Total
Uncertatinty of $R(X_{e/\mu})$	1.8%	0.1%	0.2%	1.0%	2.2%

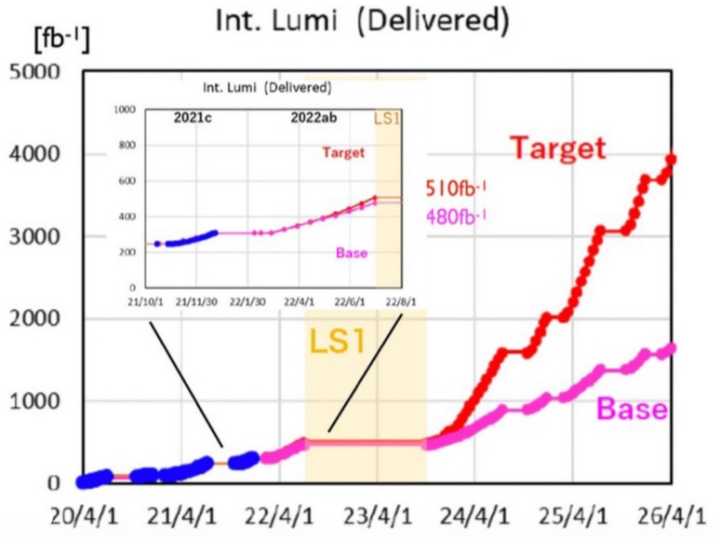
Next steps:

- Uncertainty dominated by lepton ID systematic ⇒ expected to further improve
- **Paves the way for inclusive R(X) measurement**

Prospects for LFU in semileptonic B decays

Belle II projections for R(D$^{(*)}$), R(X), R(π)



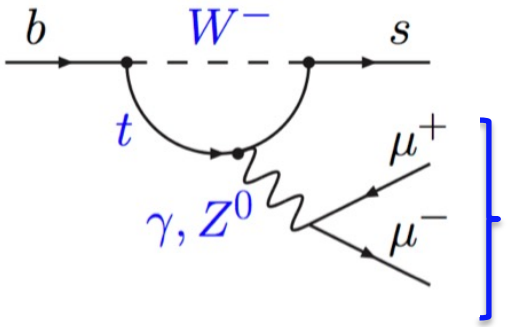


- R(X) from inclusive decays unique to Belle II
  Precision with current data set expected to be **~ 10-20%**

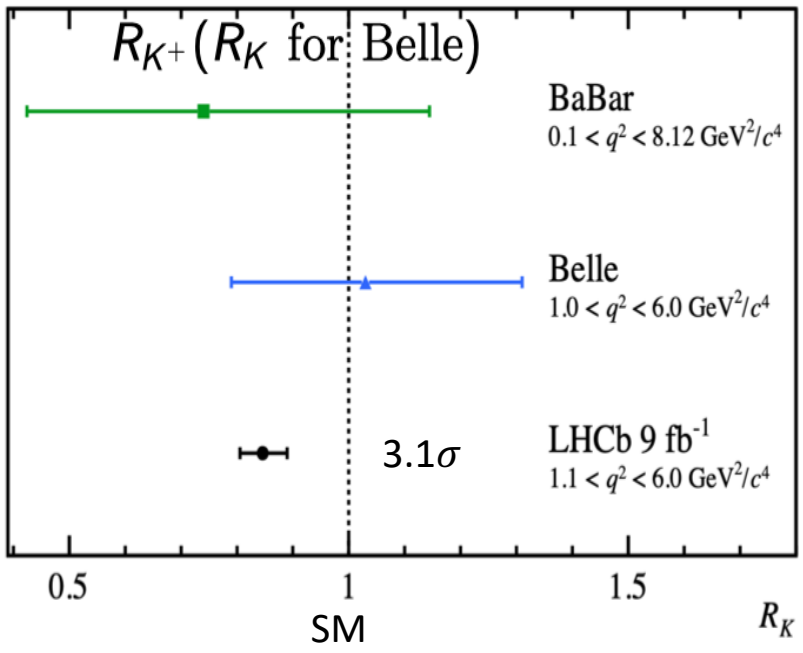
- Belle II will need **few ab^{-1}** (until ~ 2026) to clarify if R(D$^{(*)}$) anomaly has statistical or systematic origin

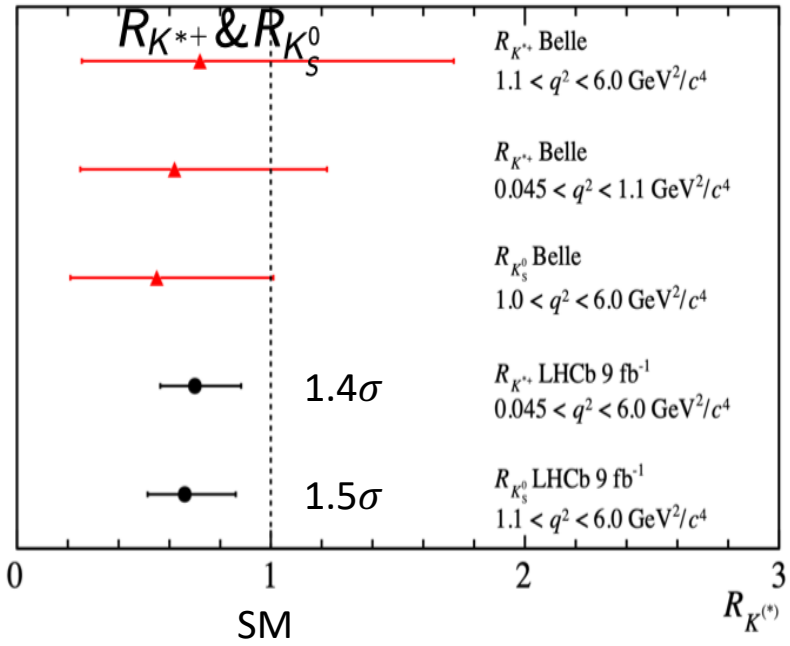
LFU in electroweak penguin decays

- Rare B decays with **b ⟶ s loop-level transitions** interesting LFU tests
- Measure LFU ratio: $R_{K^{(*)}} = \frac{\mathcal{B}(B \to K^{(*)}\mu\mu)}{\mathcal{B}(B \to K^{(*)}ee)}$



- Measurements for K^+, K^{+*}, K_S from **LHCb, BaBar, Belle**:





$B \longrightarrow K^* l^+ l^-$

arXiv: 2206.05946 [hep-ex]

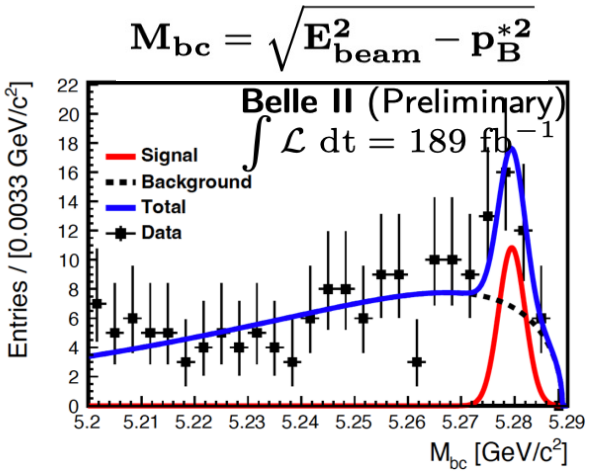
- **Decay modes:**

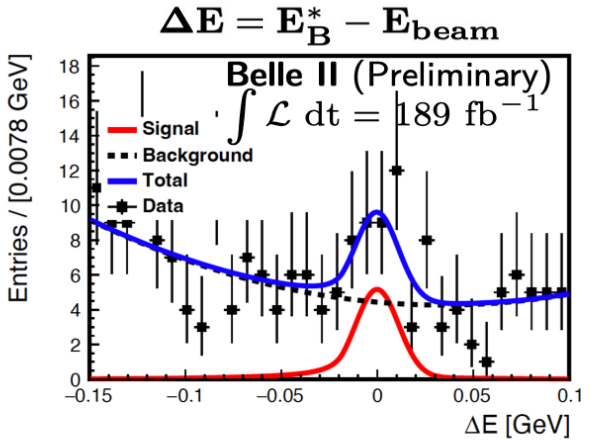
  $B^0 \to K^{*0}(K^+\pi^-)\ell\ell$ and $B^+ \to K^{*+}(K^+\pi^0, K^0_S\pi^+)\ell\ell$

- **Background suppression:**
  - $e^+e^- \longrightarrow q\bar{q}$ and $e^+e^- \longrightarrow B\bar{B}$ bkgs suppressed with BDT using event shape, vertex quality, kinematics

- Extract signal yields from **2D unbinned fit in M_{bc} and ΔE**

- Branching fractions measured over **entire q^2 range**, excluding low-mass region to reject $B \longrightarrow K^*\gamma\ (\longrightarrow e^+e^-)$ and regions of charmonium resonances





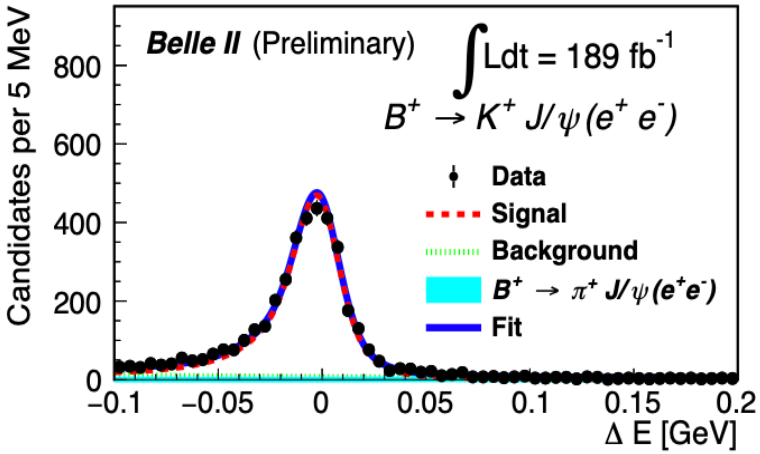
Mode	Observed events	Branching Fraction ($\times 10^{-6}$)	World average ($\times 10^{-6}$)
$B \to K^* e^+ e^-$	22 ± 6	$1.42 \pm 0.48 \pm 0.09$	1.19 ± 0.20
$B \to K^* \mu^+ \mu^-$	18 ± 6	$1.19 \pm 0.31^{+0.08}_{-0.07}$	1.06 ± 0.09

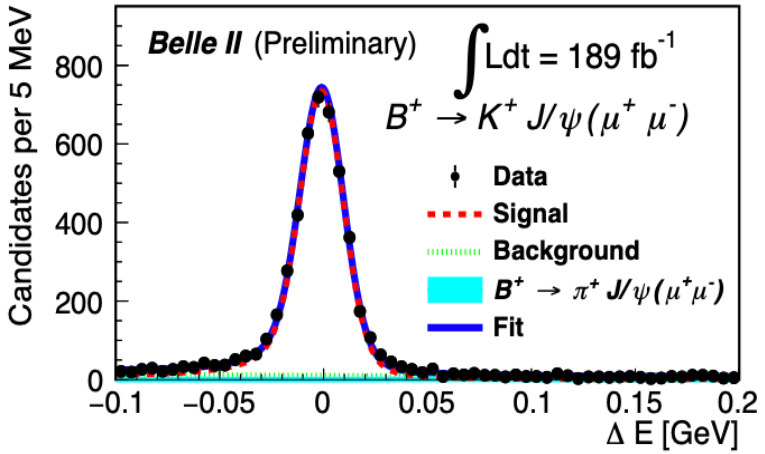
- ❖ Comparable precision for e and μ modes (~25-30%)
- ❖ BF measurement important first step towards R(K*) determination

$R_K(J/\psi)$

arXiv:2207.11275 [hep-ex]

- Decay channels: $B^+ \to J/\psi(\ell\ell)K^+$ and $B^0 \to J/\psi(\ell\ell)K^0$
- **Tree-level b ⟶ c transition**, serves as **control channel for R(K) measurement**
- Signal yields extracted from **2D unbinned fit in M_{bc} and ΔE**





Signal purity: 90-95%

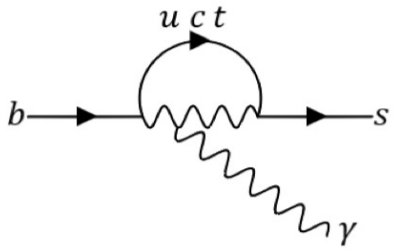
$$R_K(J/\psi) = \frac{\mathcal{B}(B \to J/\psi(\mu^+\mu^-)K)}{\mathcal{B}(B \to J/\psi(e^+e^-)K)}$$

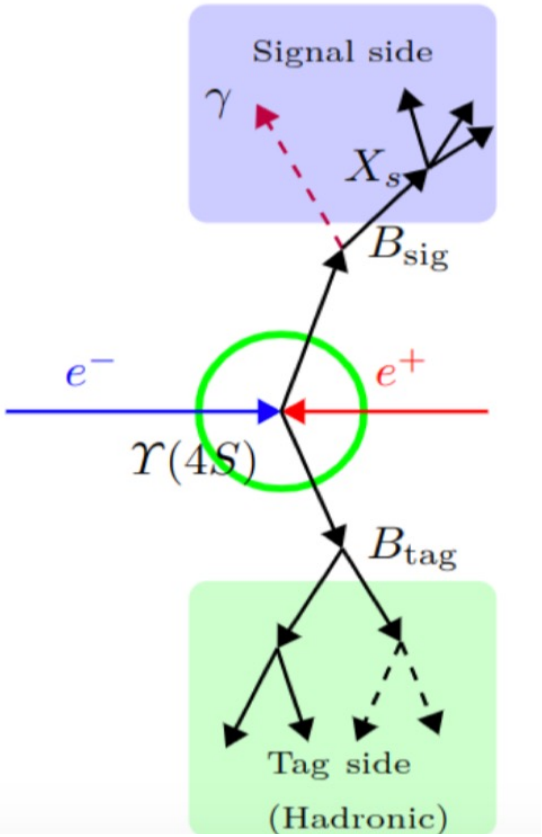
Observable	Belle II	Belle (2021)
$R_{K^+}(J/\Psi)$	$1.009 \pm 0.022 \pm 0.008$	$0.0994 \pm 0.011 \pm 0.010$
$R_{K^0_S}(J/\Psi)$	$1.042 \pm 0.042 \pm 0.008$	$0.0993 \pm 0.015 \pm 0.010$

- ❖ Results **agree with previous Belle and LHCb measurements**
- ❖ **Reduced systematics** compared with most-precise Belle result

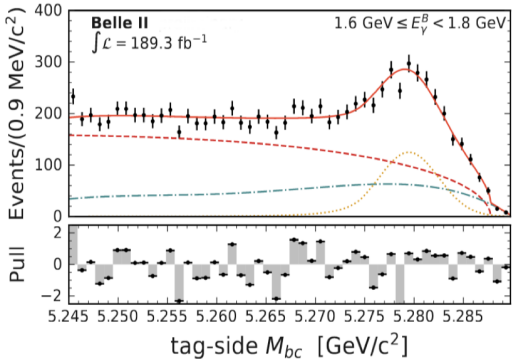
Inclusive B $\longrightarrow X_s\gamma$

- B $\longrightarrow X_s\gamma$ has **higher rate** than B $\longrightarrow X_s l^+ l^-$ and in addition to NP sensitivity, **measurement of E_γ** facilitates determination of:
  - b-quark mass
  - shape function (b-quark motion inside B meson)



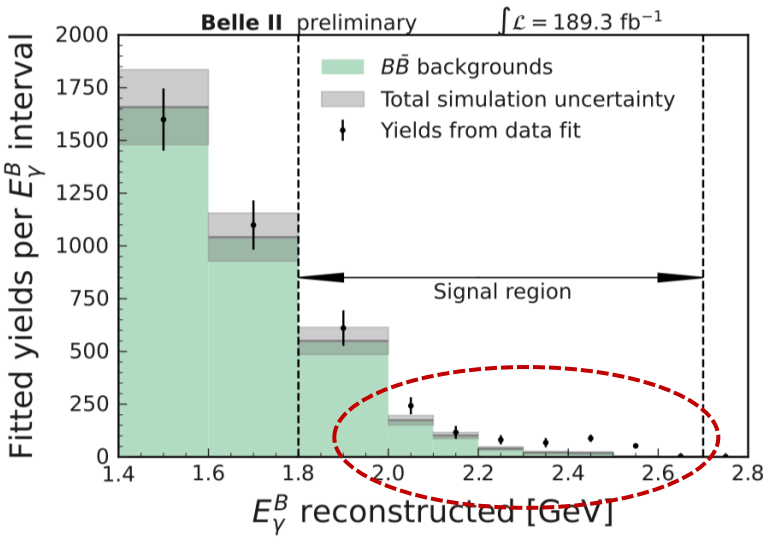


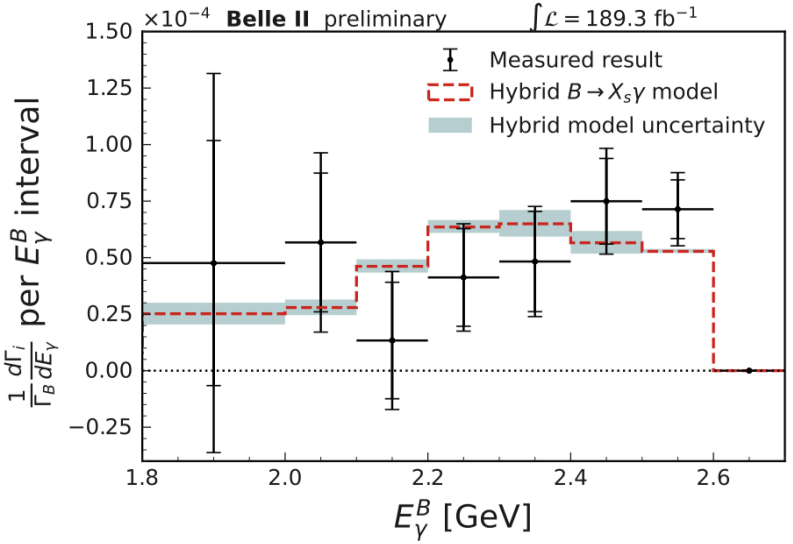
- **Hadronic-tag** measurement (high purity)
  - Reconstruct **photon energy in B rest frame** (E_γ^B)
- **Inclusive** measurement (all X_s states):
  - Only photon reconstructed on signal side
  - Signal photon = highest-E photon with $E_\gamma^B > 1.4$ GeV
- Large backgrounds challenging to suppress without sacrificing "inclusiveness"
- **Tag-side M_{bc} fit in bins of E_γ^B** to determine **correct tags**



Estimate **BB bkg** with good B_{tag} from simulation

Inclusive B $\longrightarrow X_s\gamma$





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

- **Consistent with world average**: $(3.49 \pm 0.19) \times 10^{-4}$ @ 1.8 GeV
- Comparable precision to BaBar hadronic-tag measurement with 210 fb^{-1}

Prospects for LFU in electroweak penguin decays

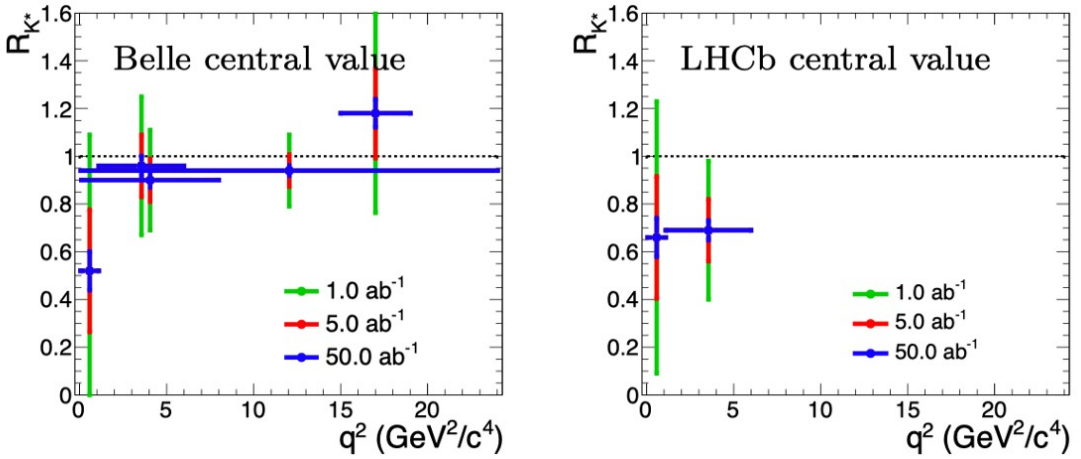
PTEP 2019 (2019) 12, 123C01

Observables	Belle $0.71\,ab^{-1}$	Belle II $5\,ab^{-1}$	Belle II $50\,ab^{-1}$
R_K ($[1.0, 6.0]\,GeV^2$)	28%	11%	3.6%
R_K ($>14.4\,GeV^2$)	30%	12%	3.6%
R_{K^*} ($[1.0, 6.0]\,GeV^2$)	26%	10%	3.2%
R_{K^*} ($>14.4\,GeV^2$)	24%	9.2%	2.8%
R_{X_s} ($[1.0, 6.0]\,GeV^2$)	32%	12%	4.0%
R_{X_s} ($>14.4\,GeV^2$)	28%	11%	3.4%

- Belle II can measure R_K, R_{K^*}, R_{Xs} over **full q^2 spectrum** with similar precison

- **Expected precision** with
  5 ab^{-1} : ~ 10%
  50 ab^{-1} : ~ 3 - 4%

R_{K^*} projections for Belle II



❖ Belle II can provide **competitive R(K), R(K*) measurements** to cross-check flavor anomalies with **few ab^{-1}**

Summary

- Belle II has now collected **424 fb^{-1}** of data – comparable to BaBar data set

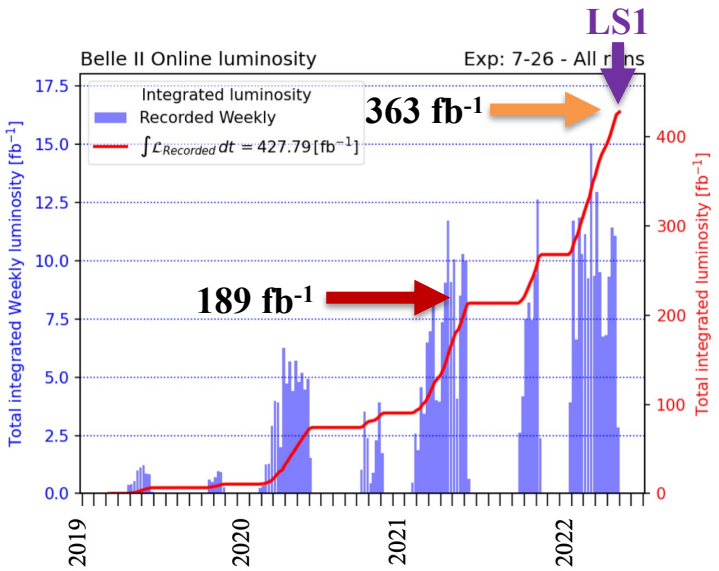
- **New preliminary Belle II measurements related to flavor anomalies:**
  - $R(X_{e/\mu})$ from inclusive $B \longrightarrow Xl\nu$ ⇒ Precise e/mu LFU test, first step towards R(X)
  - $B \longrightarrow K^{*}ll$
  - $B \longrightarrow J/\psi\, K$

  } ⇒ First step towards $R(K^{*})$

  - $B \longrightarrow X_s\gamma$ ⇒ First inclusive BF measurement from Belle II

- **Soon to come:**

  First Belle II measurement of **R(D*)** and **R(X)**

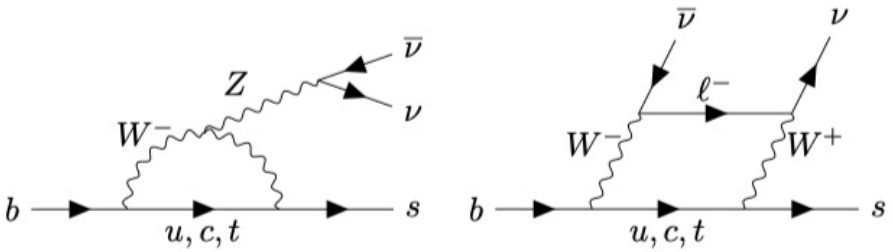


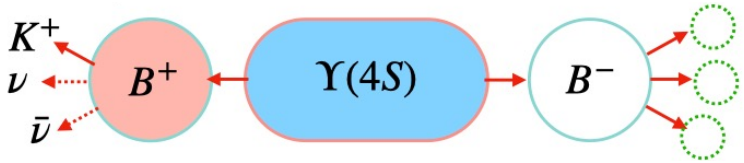
❖ **Stay tuned for new Belle II flavor-anomaly measurements with full dataset collected before the shutdown**

Backup

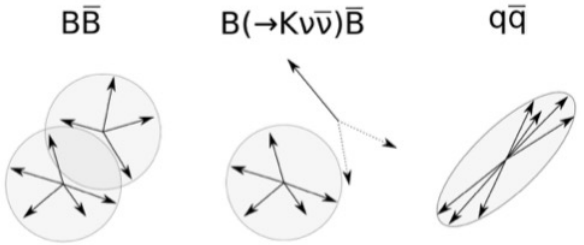
$B^+ \longrightarrow K^+\nu\nu$

PRL 127, 181802 (2021)



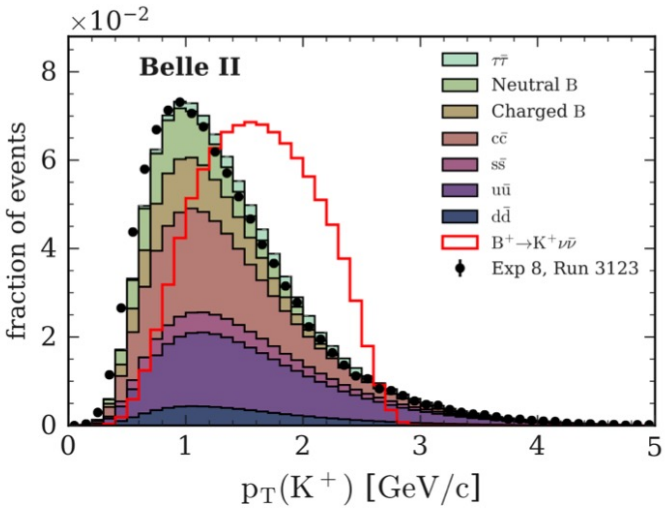


- **Complementary** to b ⟶ sll
- **Precise theory prediction** (no virtual γ contribution)
- Challenge: Final state with 2ν



- **Previous searches** based on **tagged** analyses:
  - Belle : semileptonic tag $\varepsilon_{sig} \approx 0.2\%$
  - BaBar: hadronic tag $\varepsilon_{sig} \approx 0.04\%$

- **New approach by Belle II** based on **inclusive tag**:
  - Signal kaon = track with hightest P_T
  - All remaining tracks/clusters associated with other B meson in event
  - Backgrounds suppressed by 2 sequential BDTs using topological, vertexing and kinematic variables
  - Much higher efficiency: 4.3%

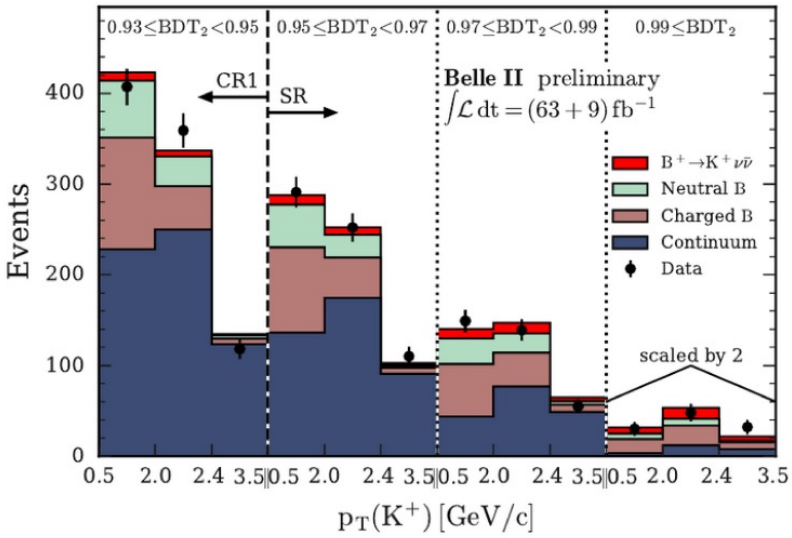


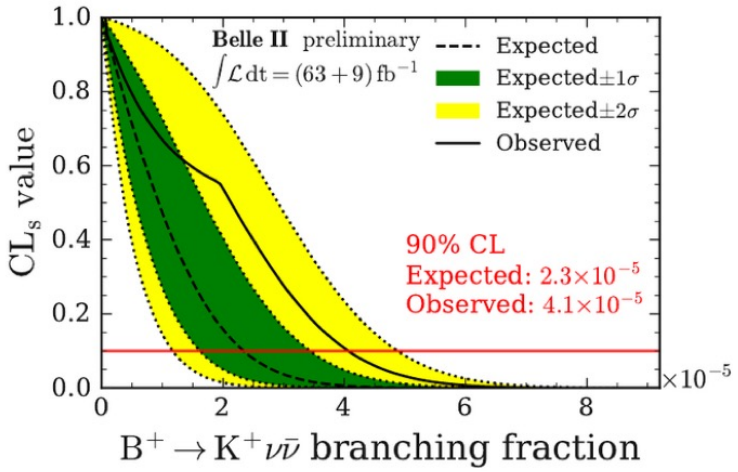
$B^+ \longrightarrow K^+\nu\nu$

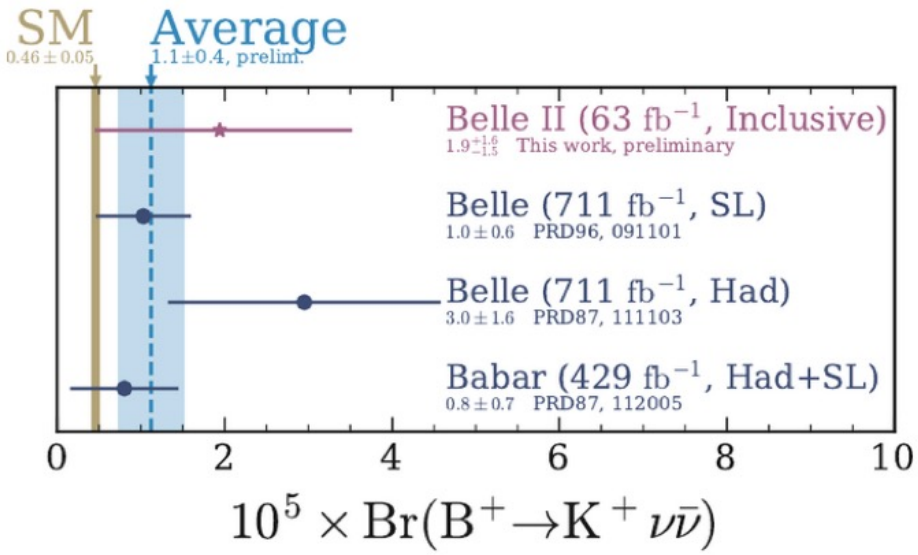
- Extract signal yield from **fit in bins of $P_T(K^+)$ and BDT score**

- No significant signal observed:
  BF($B \longrightarrow K\nu\nu$) < 4.1 × 10^{-5} @ 90% CL

- **Futher improvement underway:**
  - Update with 3× more data
  - Additional channels (K^*, K_S)
  - Improved classifiers (NN)







- ❖ **Inclusive methods** offers **large sensitivity improvement**
- ❖ Belle II will provide **world-leading measurement in the near future**