Flavor Anomalies at Belle II
Status and Prospects

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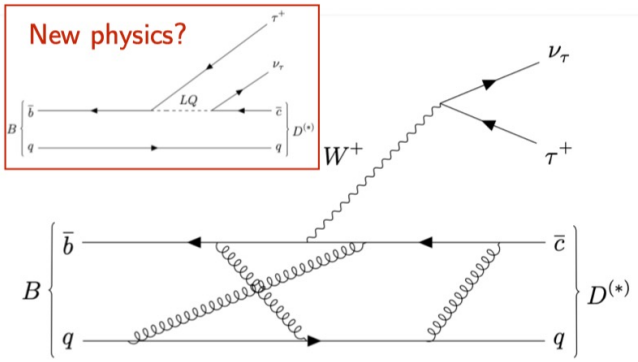
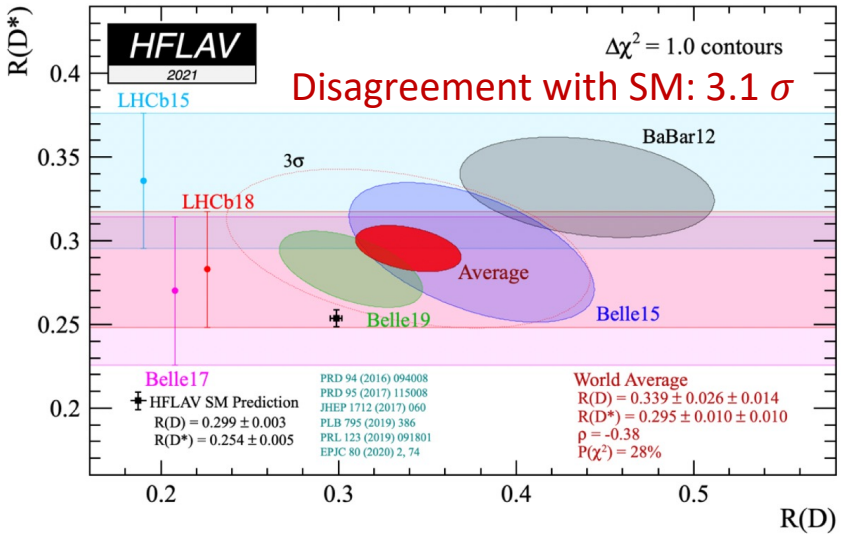
On behalf of the Belle II Collaboration

The “Flavor Anomalies”

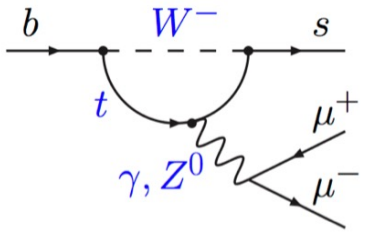
Interesting flavor anomalies seen in B decays at LHCb, Belle and BaBar

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

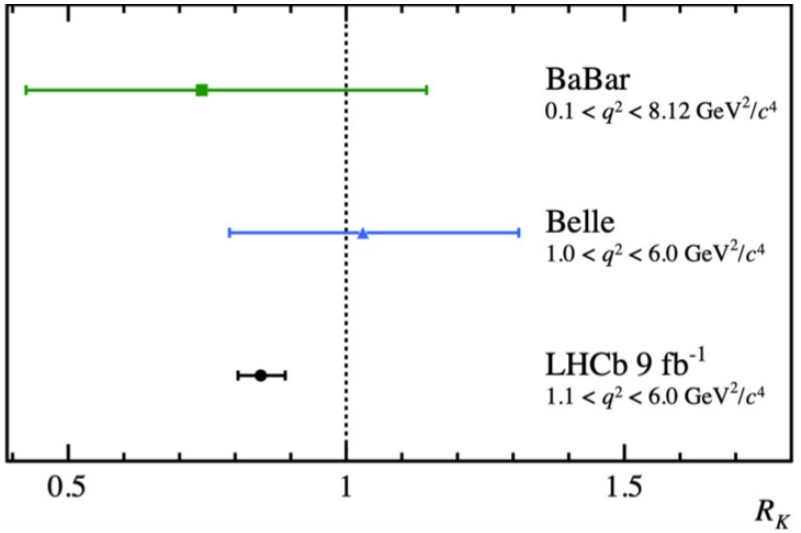




LFU and angular distributions in electroweak penguin decays



LHCb, Nature Physics 18 (2022) 277

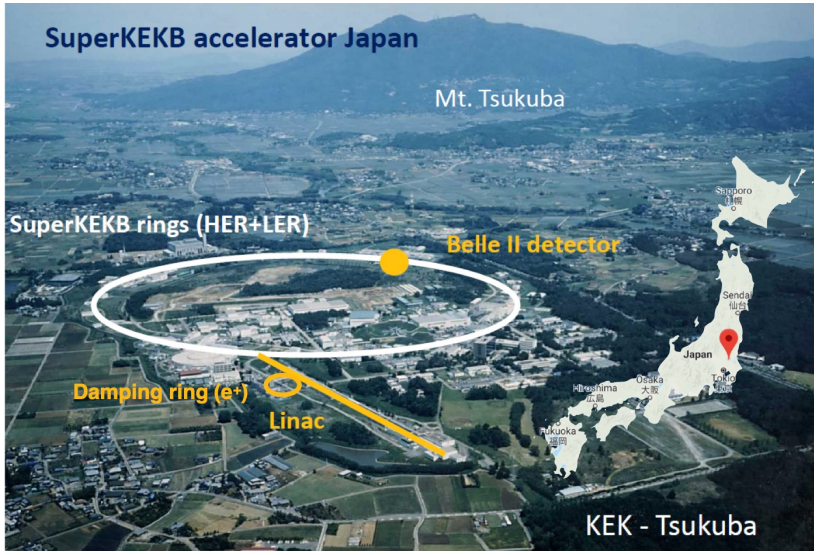


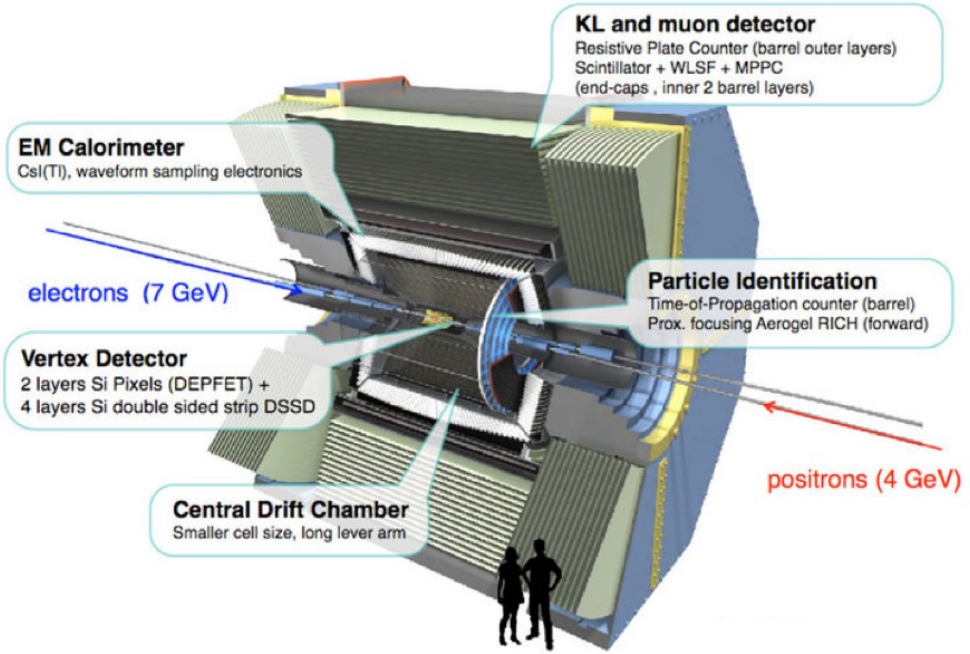
Where do we stand with analyses related to flavor anomalies in Belle II?

Measurements presented in this talk

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

Belle II and SuperKEKB





SuperKEKB

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

beam current x2 · beam-beam param. x1 · vertical beta function x 1/20

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

Integrated luminosity: ~ 50 ab^{-1}

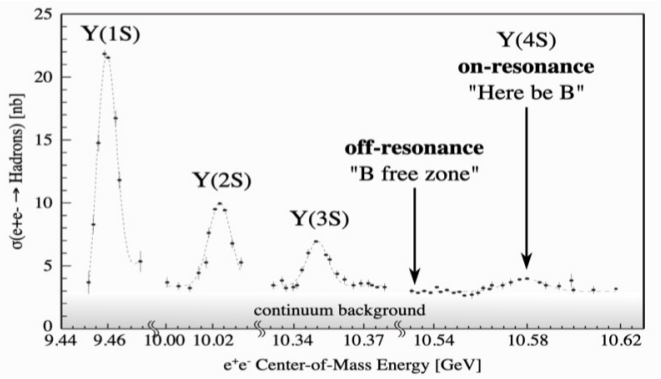
Belle II

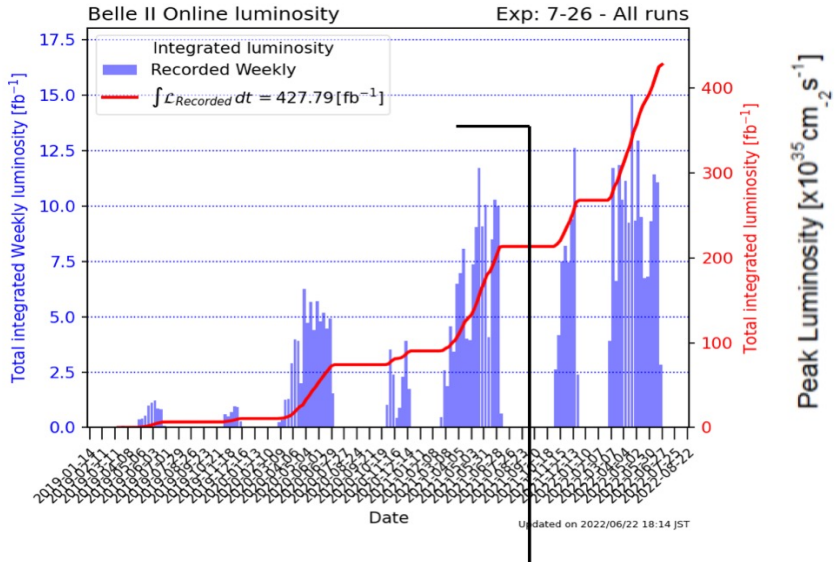
- Nearly-hermetic 4π detector coverage
  ⇒ inclusive final states, neutrinos
- Excellent neutral particle reco. (γ, π^0, K_S)
- Major detector upgrades w.r.t. Belle:
  - Improved vertexing resolution and K_S reconstruction
  - Improved K/π separation
  - New triggers for Dark Sector searches

Status of data taking

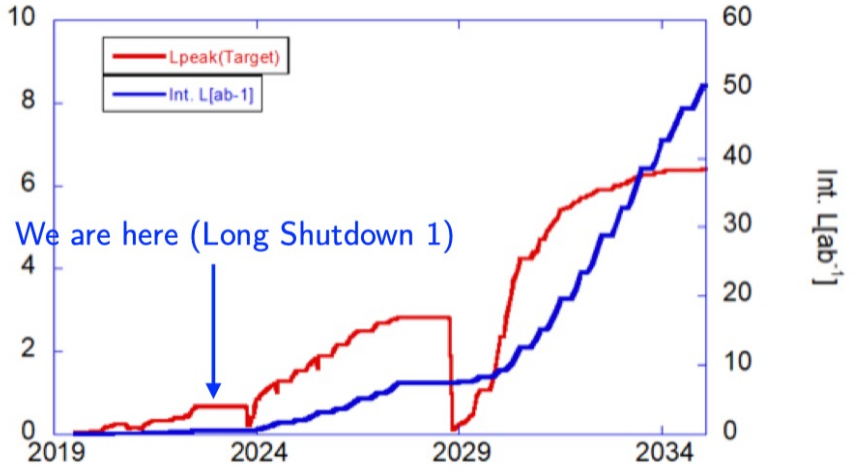
- SuperKEKB set **luminosity world record** on June 22, 2022:
  $L = 4.71 \times 10^{34}\ cm^{-2}s^{-1}$ (> 2 × KEKB record) ⇒ entering "Super B-factory" regime

- **Integrated luminosity: 424 fb^{-1}** (2019-2022)
  - 362 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





Results in this talk: up to 189 fb^{-1}

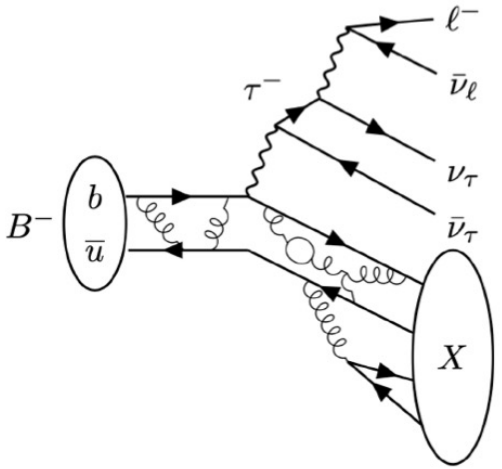


- **Currently: Long shutdown** for beampipe improvement and detector upgrades

LFU in inclusive semileptonic B decays

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

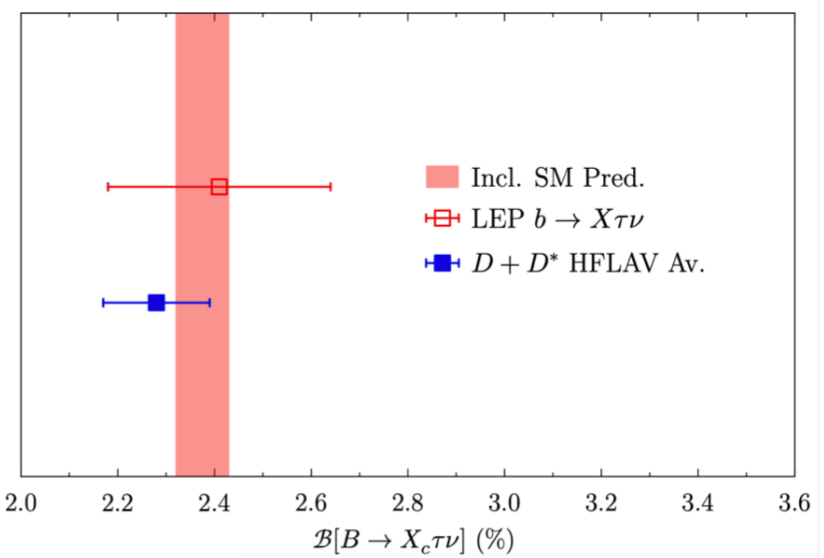
$$R(X) = \frac{\mathcal{B}(B \to X\tau\nu)}{\mathcal{B}(B \to X\ell\nu)}$$



- So far, no R(X) measurement from Belle or BaBar
  - Modeling of B ⟶ X$\tau\nu$ with X ⟶ … difficult
  - Larger background due to less constrained X system
- b ⟶ X$\tau\nu$ measurements at LEP
- First step towards R(X) measurement at Belle II:

Light-lepton ratio

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

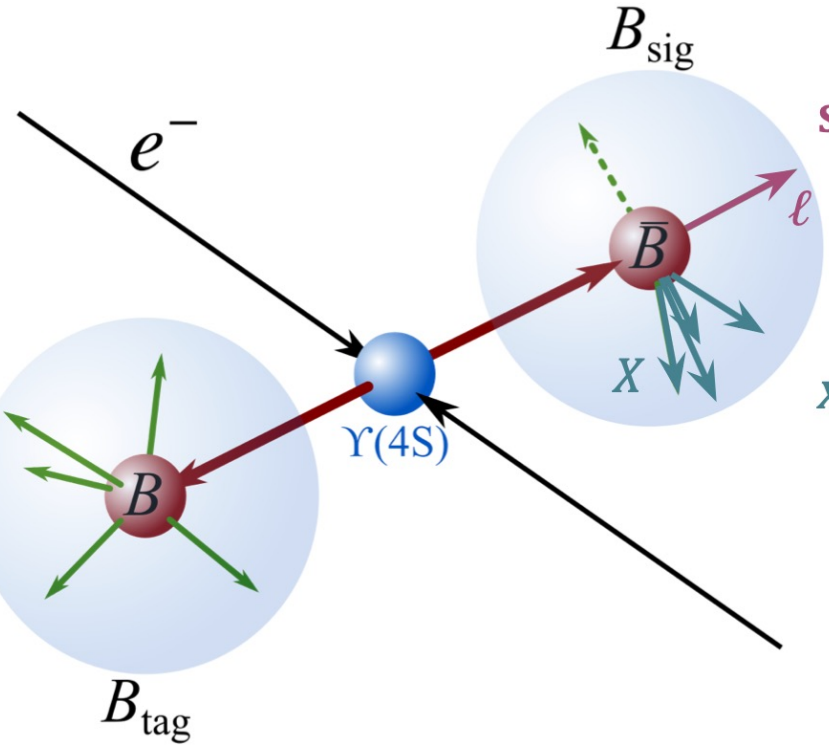


Reconstruction of inclusive B ⟶ Xlν

H. Junkerkalefeld @ ICHEP 2022

Reconstruction of B ⟶ Xlν decays

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



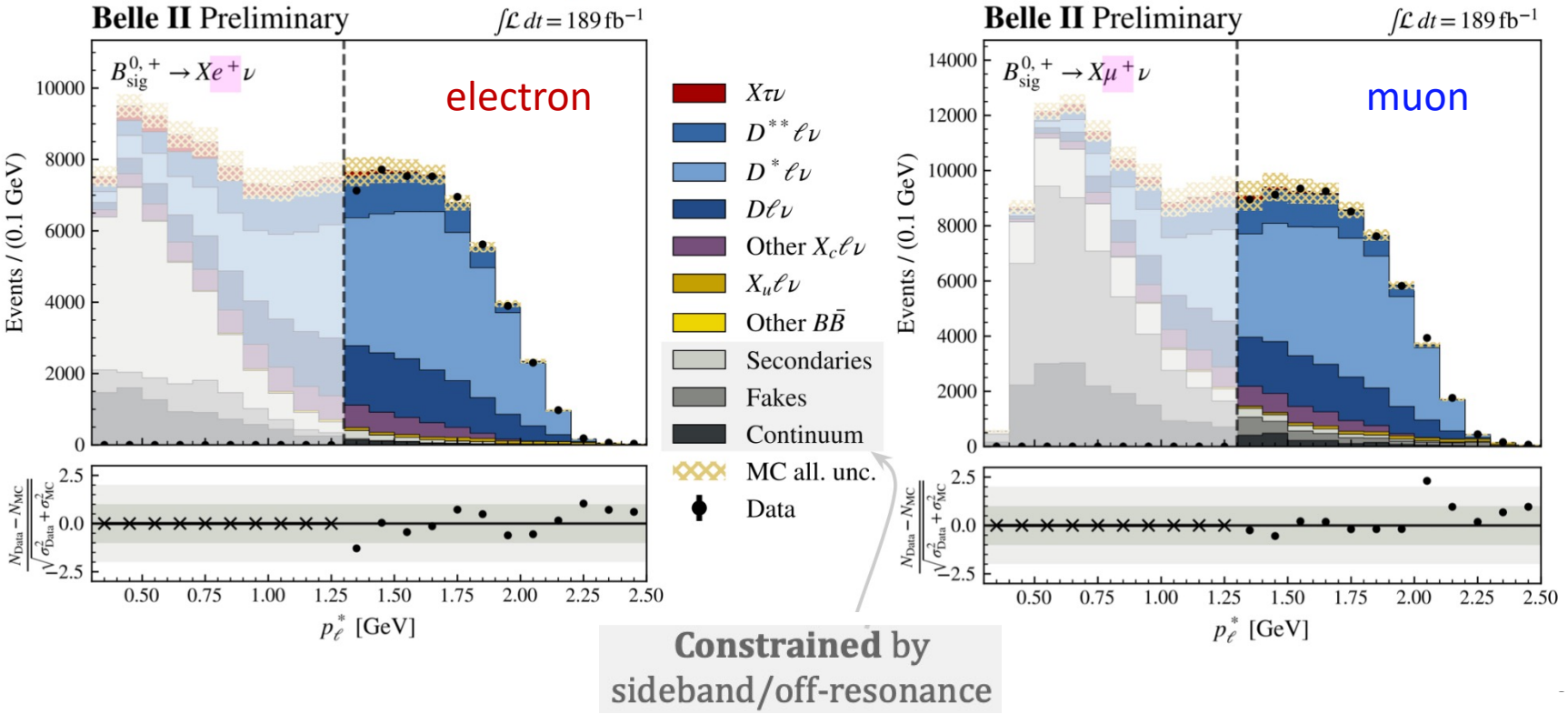
Signal lepton:
- $p^*_\ell > 1.3$ GeV
- High electron or muon likelihood

***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 in **10 bins of p_l^***
- Systematic uncertainties included as nuisance parameters in the fit



48034 ± 286 electron signal events

58569 ± 429 muon signal events

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: $R(D^*_{e/\mu}) = 1.01 \pm 0.01 \pm 0.03$

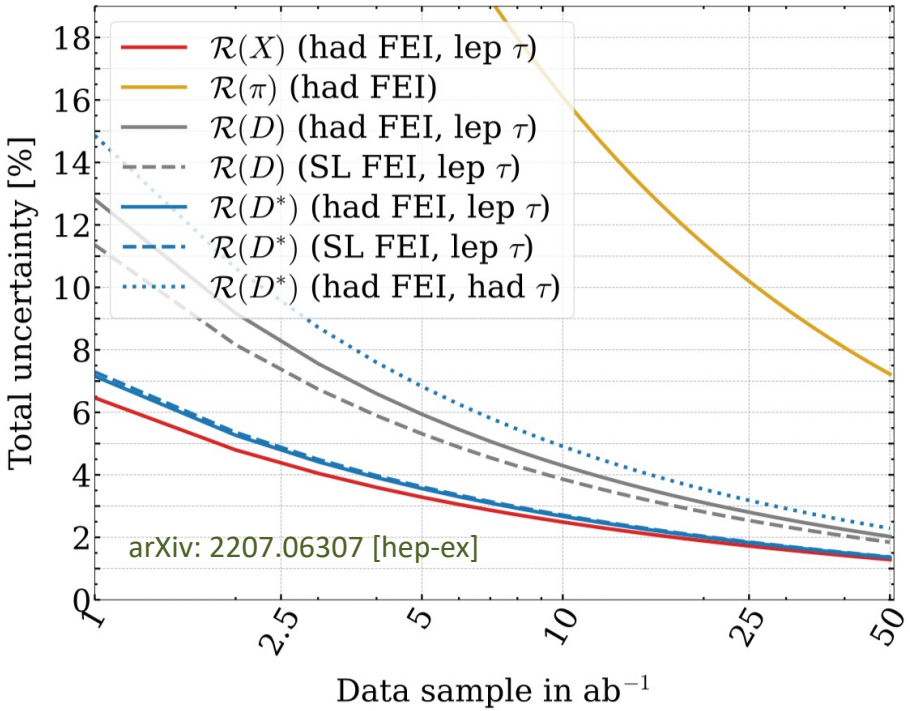
Source of uncertainty	Lepton ID	$X_c\ell\nu$ BFs	$X_c\ell\nu$ FFs	Statistical	Total
Uncertatinty of $R(X_{e/\mu})$	1.8%	0.1%	0.2%	1.0%	2.2%

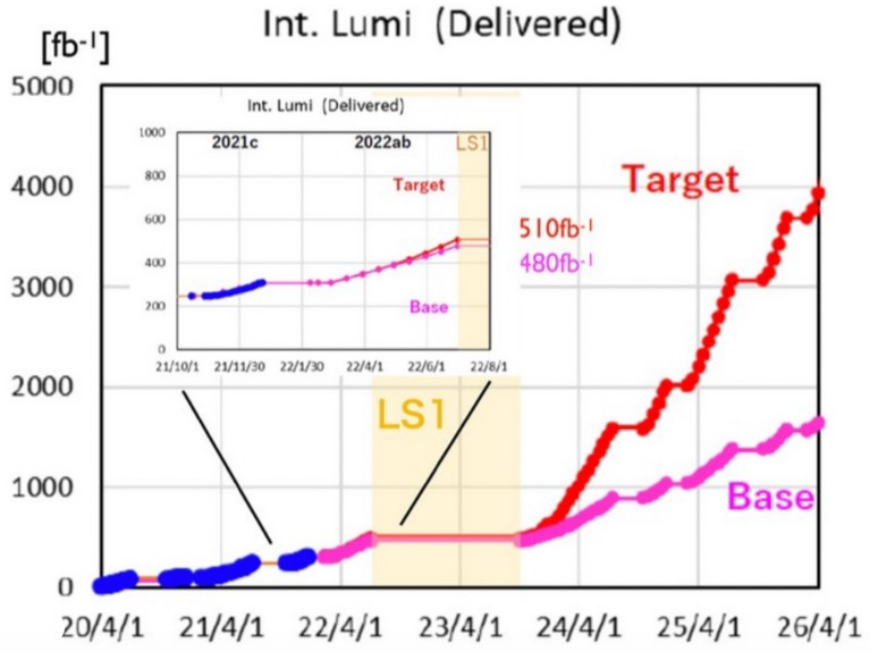
Next steps:

- Uncertainty dominated by lepton ID syst. ⇒ should improve over time
- Treatment of B ⟶ $X_c l\nu$ modeling variations **paves way to R(X)**:
  Expected sensitivity with current dataset is **10-20%**

Prospects for LFU in semileptonic B decays

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



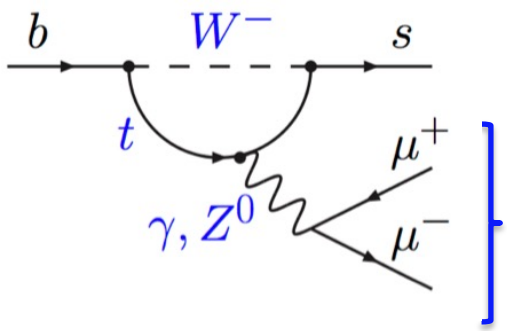


- R(X) from inclusive decays unique to Belle II
  Precision with current data set expected to be ~ **10-20%** (stat. + syst.)

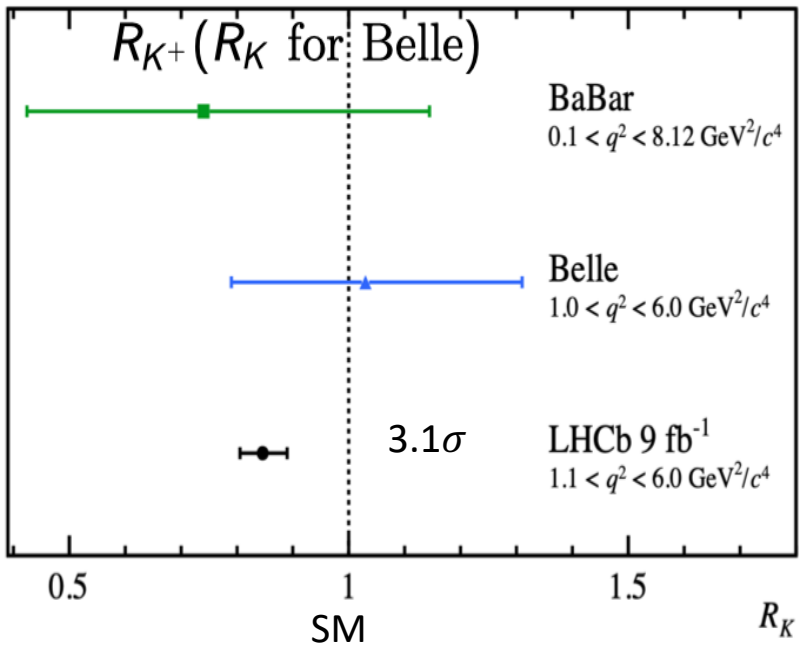
- Belle II will need **few ab^{-1}** (until ~ 2026) to clarify if R(D$^{(*)}$) anomaly has statistical or systematic origin

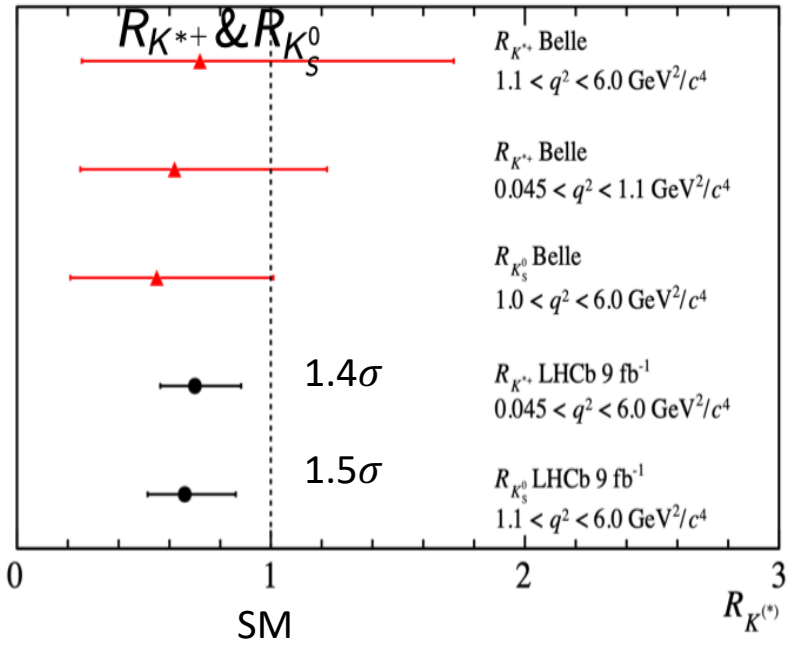
LFU in electroweak penguin decays

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



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





B ⟶ K*ll

PRL 126 (2021) 161801

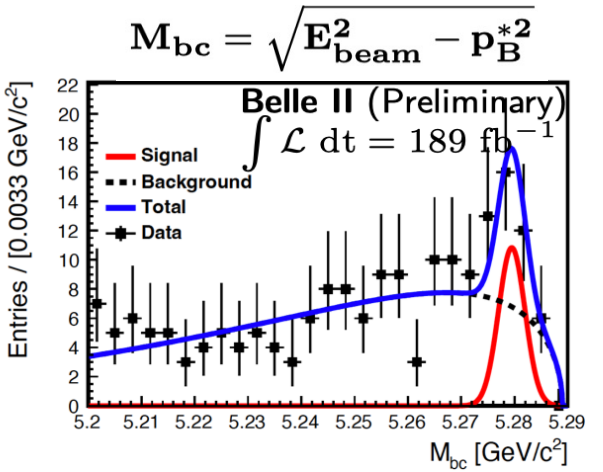
- **Decay modes:**

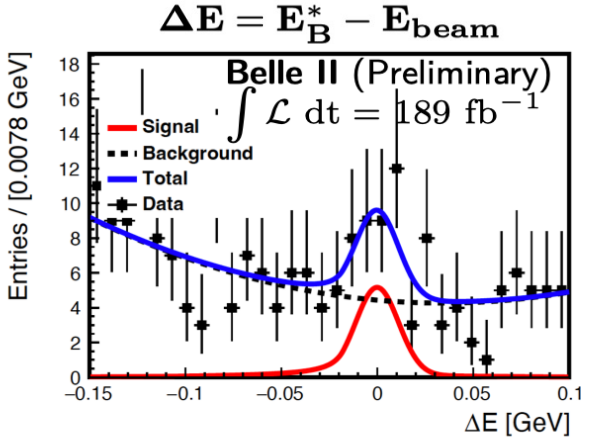
  $B^0 \to K^{*0}(K^+\pi^-)\ell\ell$ and $B^+ \to K^{*+}(K^+\pi^0, K^0_S\pi^+)\ell\ell$

- **Background suppression:**
  - $e^+e^- \longrightarrow qq$ and $e^+e^- \longrightarrow BB$ backgrounds suppressed with BDT using event shape, vertex quality, kinematic variables

- 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 $B \longrightarrow K^*\gamma\ (\longrightarrow e^+e^-)$





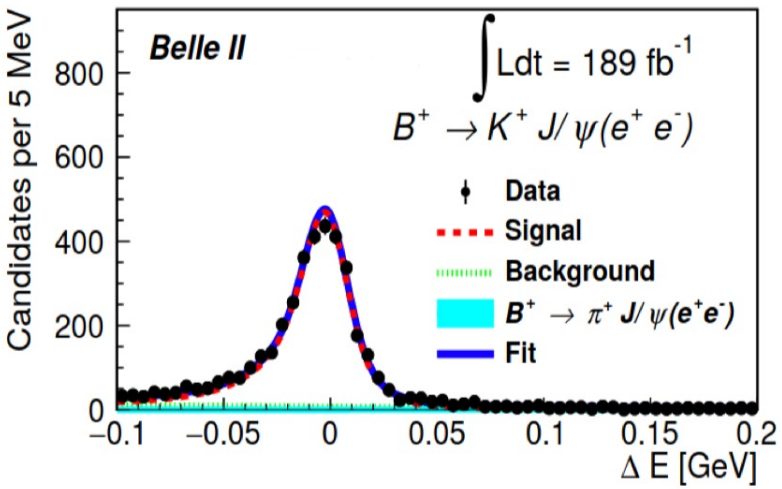
Mode	Observed events	Branching Fraction ($\times 10^{-6}$)	World average ($\times 10^{-6}$)
$B \to K^* e^+e^-$	22 ± 6	$1.42 \pm 0.48 \pm 0.09$	1.19 ± 0.20
$B \to K^* \mu^+\mu^-$	18 ± 6	$1.19 \pm 0.31^{+0.08}_{-0.07}$	1.06 ± 0.09

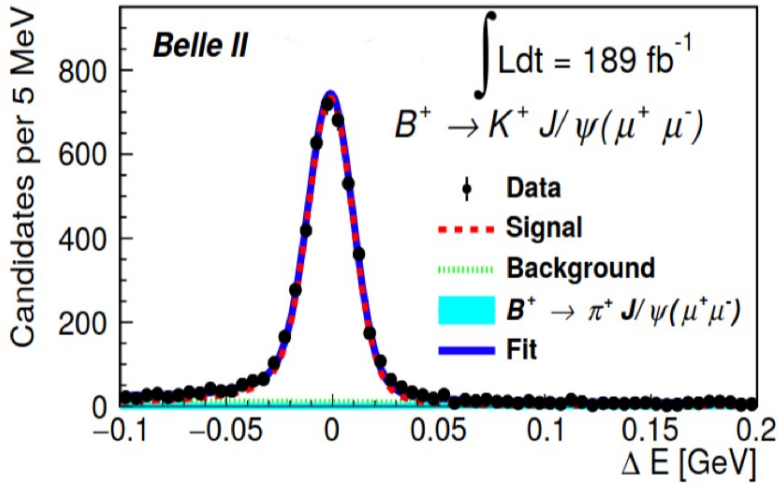
- ❖ Comparable precision for e and μ modes (25-30%)
- ❖ Belle II can provide **independent checks of R(K*)** with **few ab^{-1}**

$R_K(J/\psi)$

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**, but serves as **control channel** for b ⟶ s LFU tests
- Signal yields extracted from **2D unbinned fit in M_{bc} and ΔE**





Signal purity: 90-95%

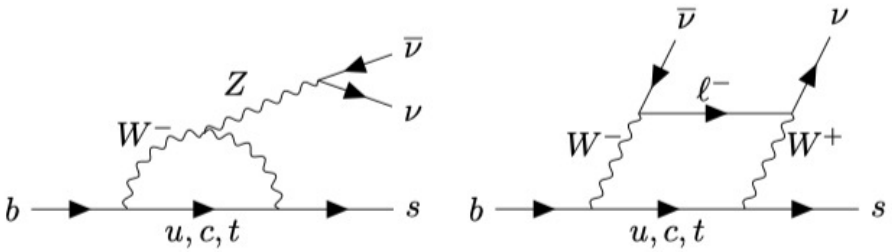
$$R_K(J/\psi) = \frac{\mathcal{B}(B \to J/\psi(\mu^+\mu^-)K)}{\mathcal{B}(B \to J/\psi(e^+e^-)K)}$$

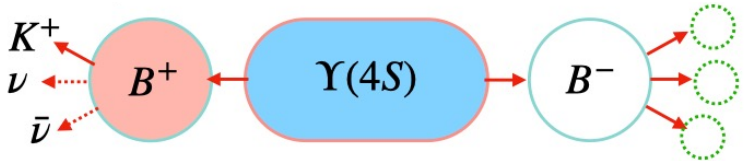
Observable	Belle II	Belle (2021)
$R_{K^+}(J/\Psi)$	$1.009 \pm 0.022 \pm 0.008$	$0.0994 \pm 0.011 \pm 0.010$
$R_{K^0_S}(J/\Psi)$	$1.042 \pm 0.042 \pm 0.008$	$0.0993 \pm 0.015 \pm 0.010$

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

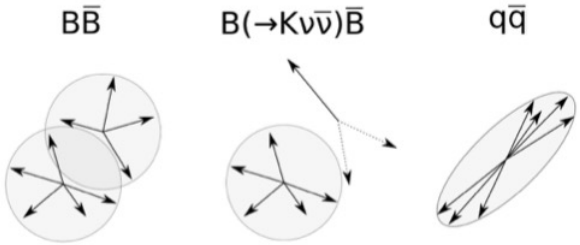
$B^+ \longrightarrow K^+\nu\nu$

PRL 127, 181802 (2021)



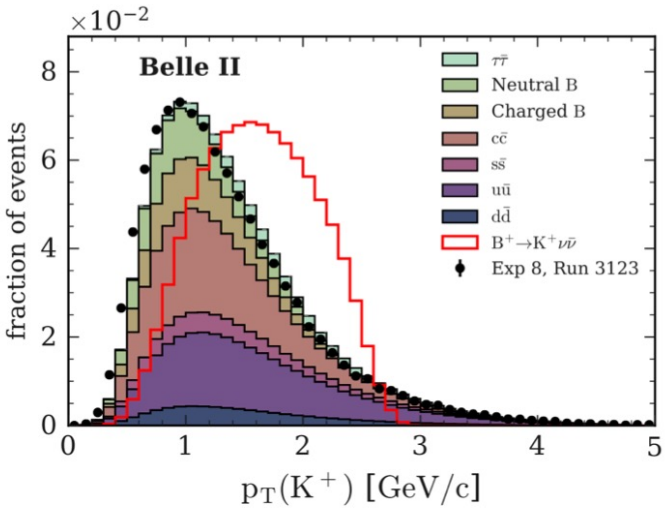


- **Complementary** to b ⟶ sll
- **Precise theory prediction** (no virtual γ contribution)
- Challenge: Final state with 2ν and very small rate



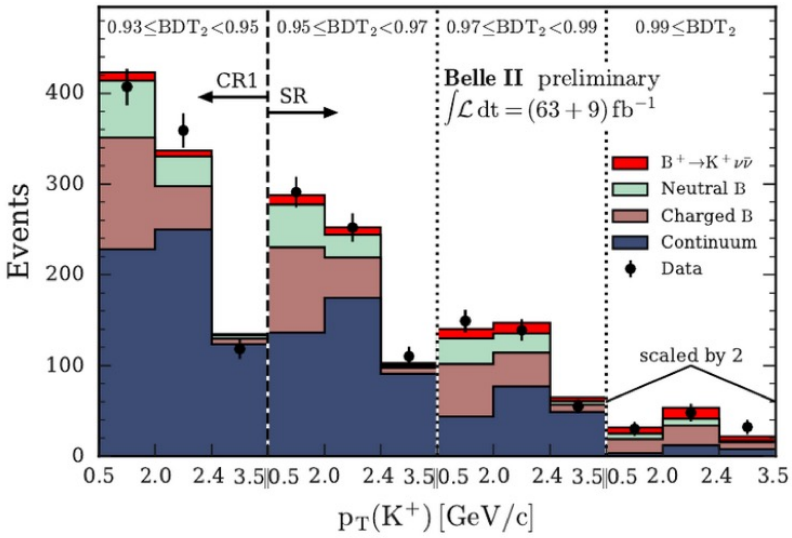
- **Previous searches** based on **tagged** analyses:
  - Belle : semileptonic tag $\varepsilon_{sig} \approx 0.2\%$
  - BaBar: hadronic tag $\varepsilon_{sig} \approx 0.04\%$

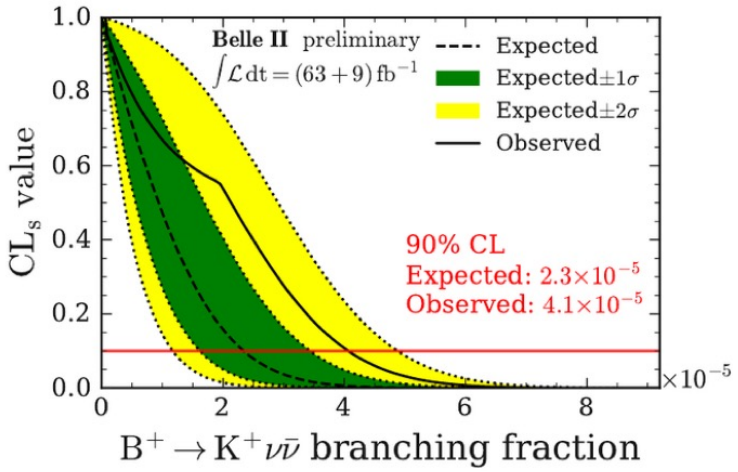
- **New approach by Belle II** based on **inclusive tag**:
  - Signal kaon = track with hightest P_T
  - All remaining tracks/clusters associated with other B meson in event
  - Backgrounds suppressed by 2 sequential BDTs using topological, vertexing and kinematic variables
  - Much higher efficiency: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

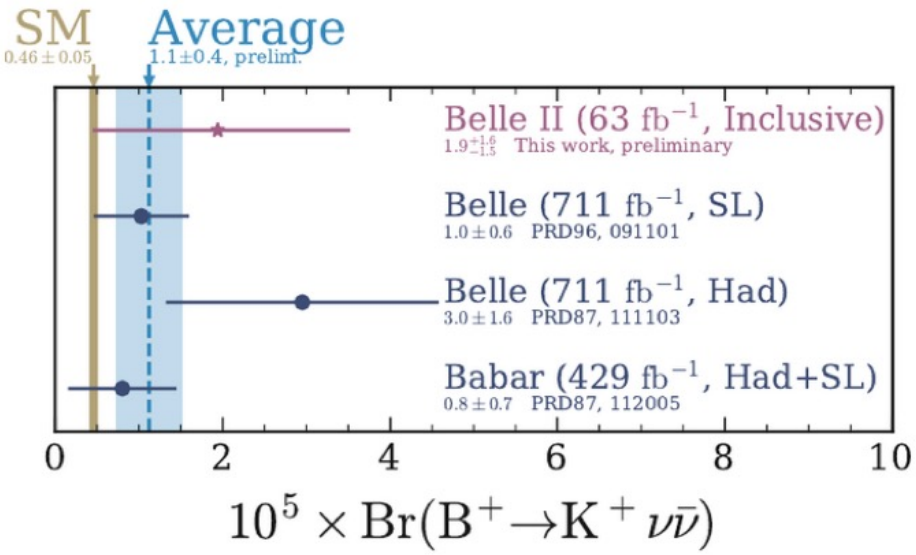


$B^+ \longrightarrow K^+\nu\nu$

- 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)





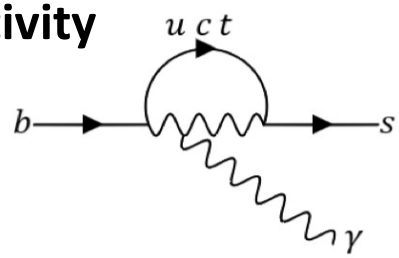


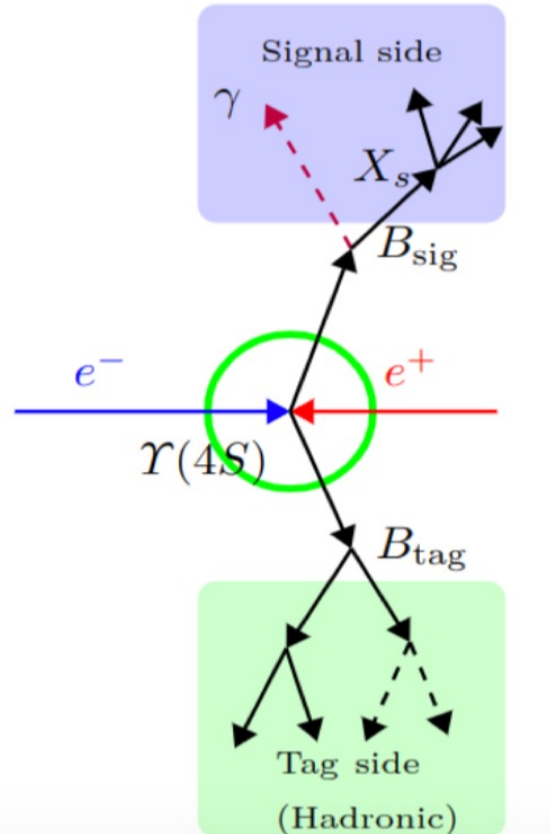
- ❖ **Inclusive methods** offers **large sensitivity improvement**
- ❖ Belle II will provide **world-leading measurement in the near future**

Inclusive B $\longrightarrow X_s\gamma$

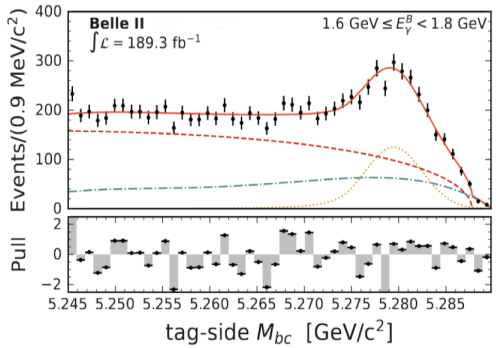
E. Ganiev @ ICHEP 2022

- B $\longrightarrow X_s\gamma$ has **higher rate** than B $\longrightarrow X_s\nu\nu$ and **different NP sensitivity**
- In addition to NP (e.g. charged Higgs, SUSY, …), measure:
  - b-quark mass
  - shape function (b-quark motion inside B meson)

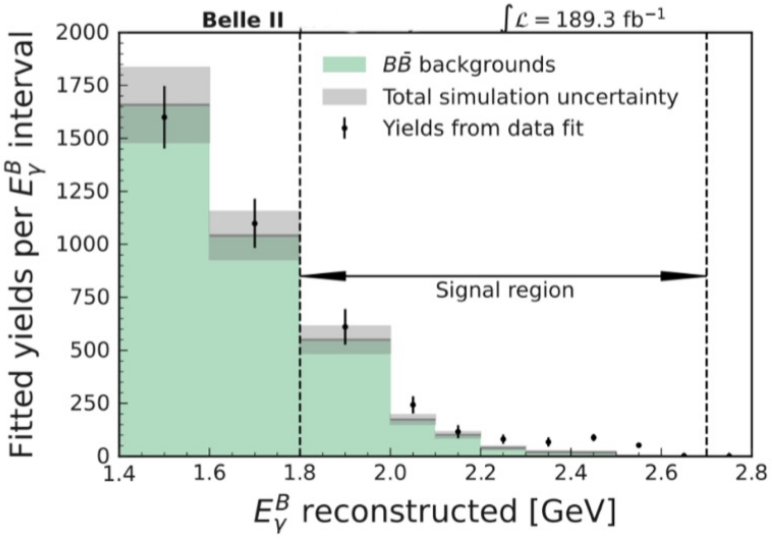


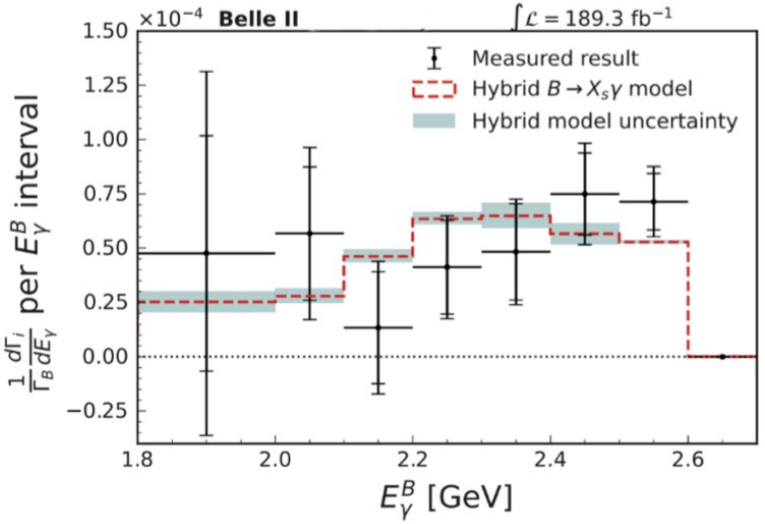


- **Hadronic-tag** measurement (high purity)
  - Reconstruct **photon energy in B rest frame** (E_γ^B)
- **Inclusive** measurement (all X_s states):
  - Only photon reconstructed on signal side
  - Signal photon = highest-E photon with $E_\gamma^B > 1.4$ GeV
- Large backgrounds challenging to suppress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



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}

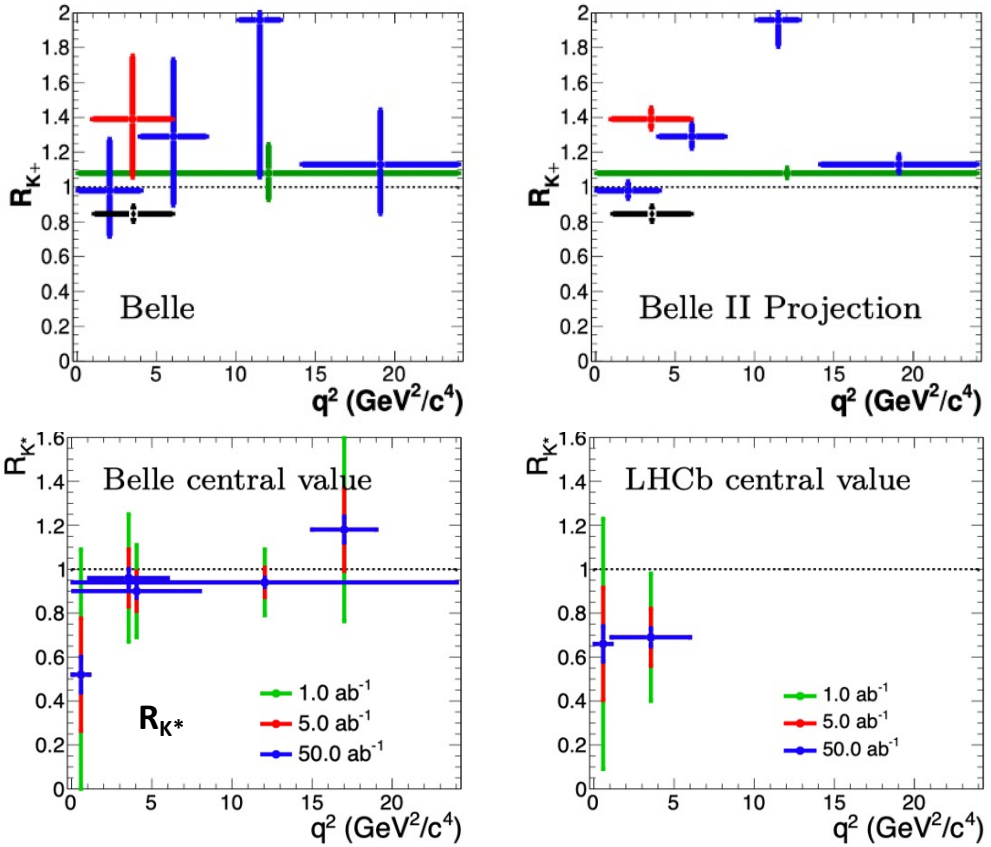
Prospects for LFU in electroweak penguin decays

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 and R_{K^*} over **full q^2 spectrum**
- Belle II can provide **competitive R(K), R(K*) measurements** to cross-check flavor anomalies with **few ab^{-1}**
- **Expected precision** with
  5 ab^{-1} : ~ 10%
  50 ab^{-1} : ~ 3 - 4%

Belle II projections for R(K) and R(K*)



Summary

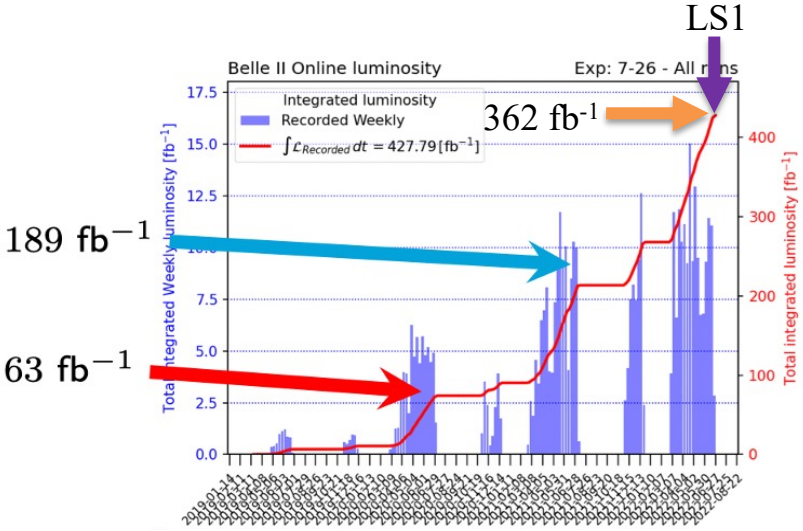
Belle II has now collected **424 fb^{-1}** of data (comparable to BaBar data set)

New/recent measurements related to flavor anomalies:

- R($X_{e/\mu}$) from inclusive $B \longrightarrow Xl\nu$ ⇒ First step towards R(X)
- $B \longrightarrow K^{*}ll$ and $B \longrightarrow J/\psi\, K$ ⇒ First step towards R(K^{*})
- $B^{+} \longrightarrow K^{+}\nu\nu$ ⇒ New approach, upper limit on BF
- $B \longrightarrow X_s\gamma$ ⇒ First inclusive BF measurement from Belle II

Soon to come:

First R(D*) and R(X) measurements from Belle II



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