# Recent results on lepton universality and flavor violation from Belle II

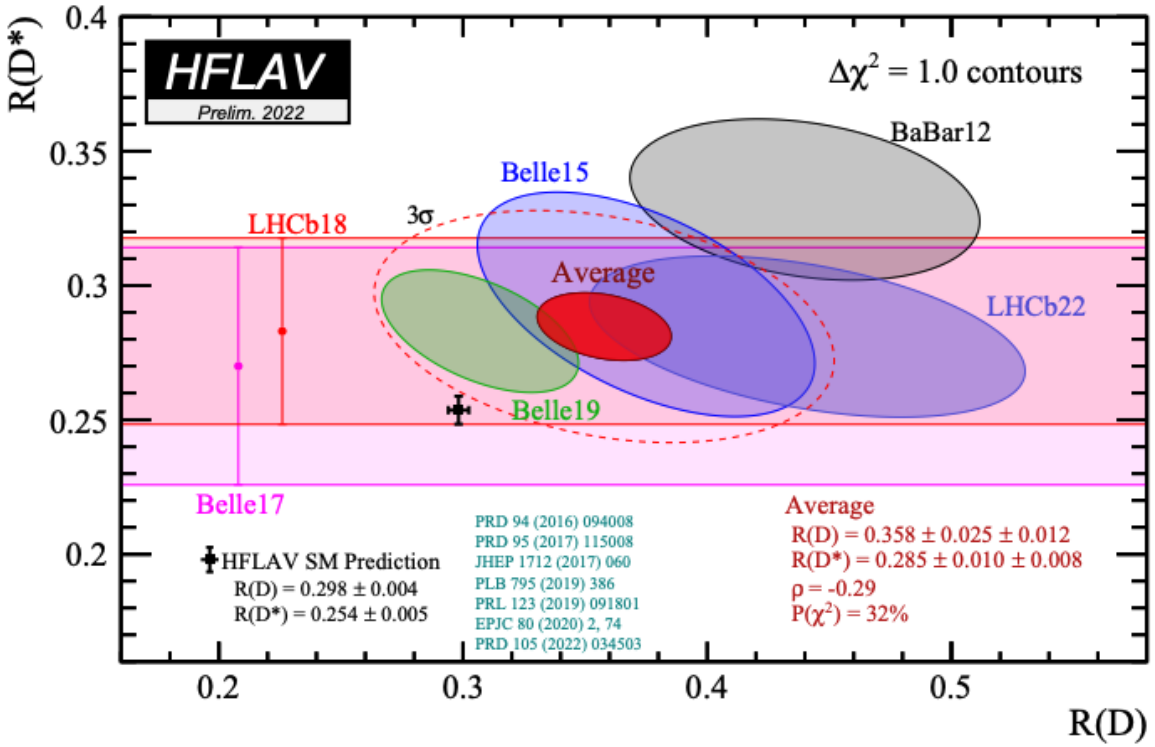
Marcel Hohmann on behalf of the Belle II Collaboration

DISCRETE 2022, 08.11.22

# Where we stand

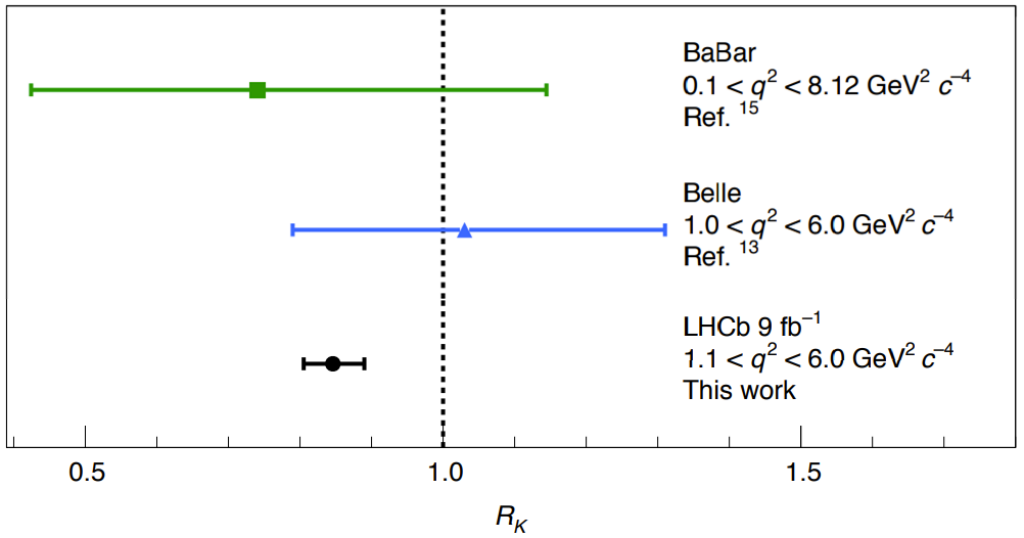
- ~$3\sigma$ anomalies in tests of Lepton Flavor Universality observed at LHCb, Belle, and BaBar.

$$R\left(D^{(*)}\right) = \frac{B(B\to D^{(*)}\tau\nu)}{B(B\to D^{(*)}\ell\nu)}$$




$$R(K) = \frac{B(B\to Kee)}{B(B\to K\mu\mu)}$$

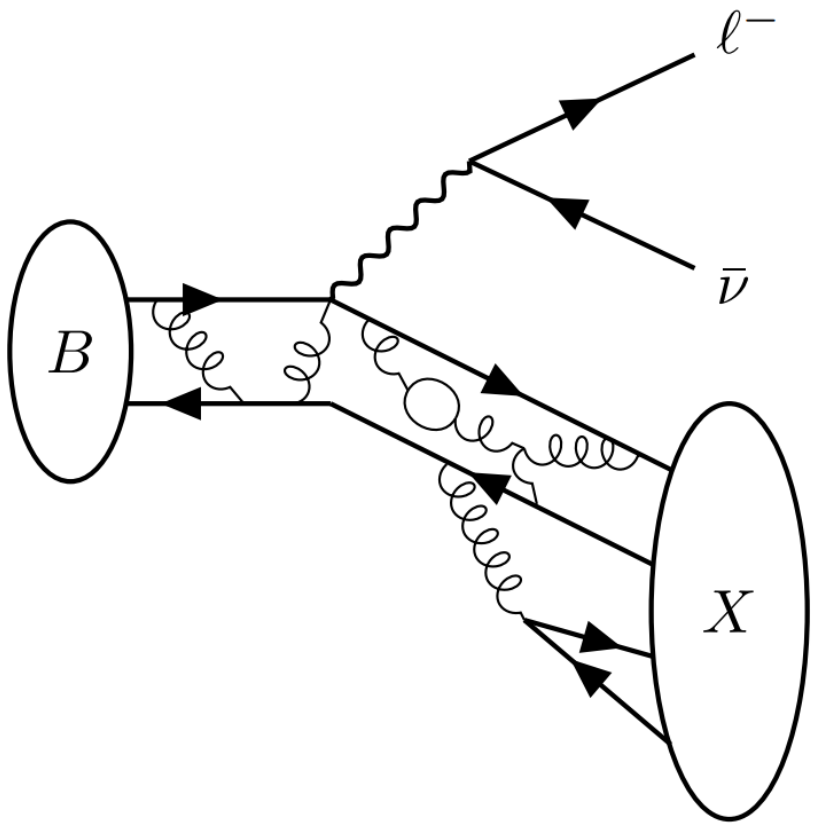
+ angular observables



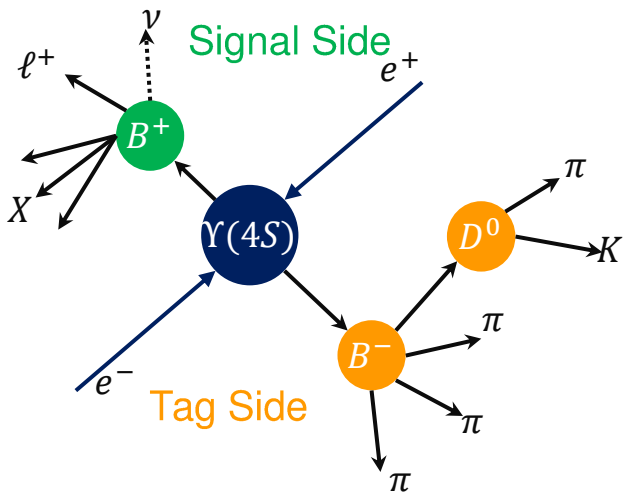

BaBar, PRD 86, 032012 (2012)
Belle, JHEP 2021, 105 (2021)
LHCb, Nat.Phys. 18 (2022) 27

- What about Belle II?

# Tree Level



# $R(X_{e/\mu})$



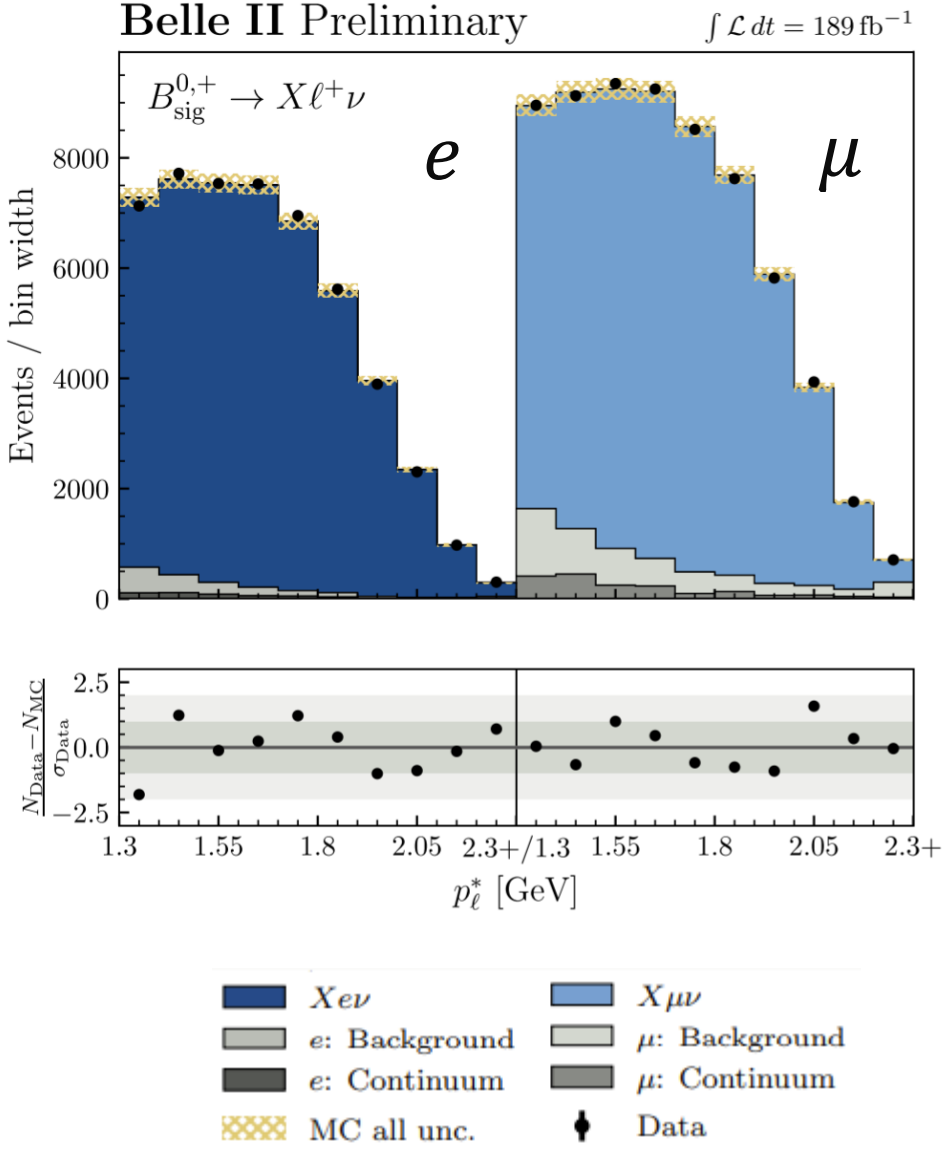

- Test light lepton universality in inclusive semi-leptonic B decays.

- Reconstruct companion B as a *tag* in $O(10\,000)$ hadronic channels via Full Event Interpretation[1].
- Select well identified lepton on signal side.
- Challenge: Keeping sample composition under control.

- $X\ell\nu$ signal yields extracted in 10 bins of $p_\ell$ in B-frame.
  - Constrain secondary lepton, fake lepton and continuum contributions from sidebands.

[1]: Comput.Softw.Big Sci. 3 (2019) 1, 6

Belle II, H. Junkerkalefeld ICHEP2022



# $R(X_{e/\mu})$

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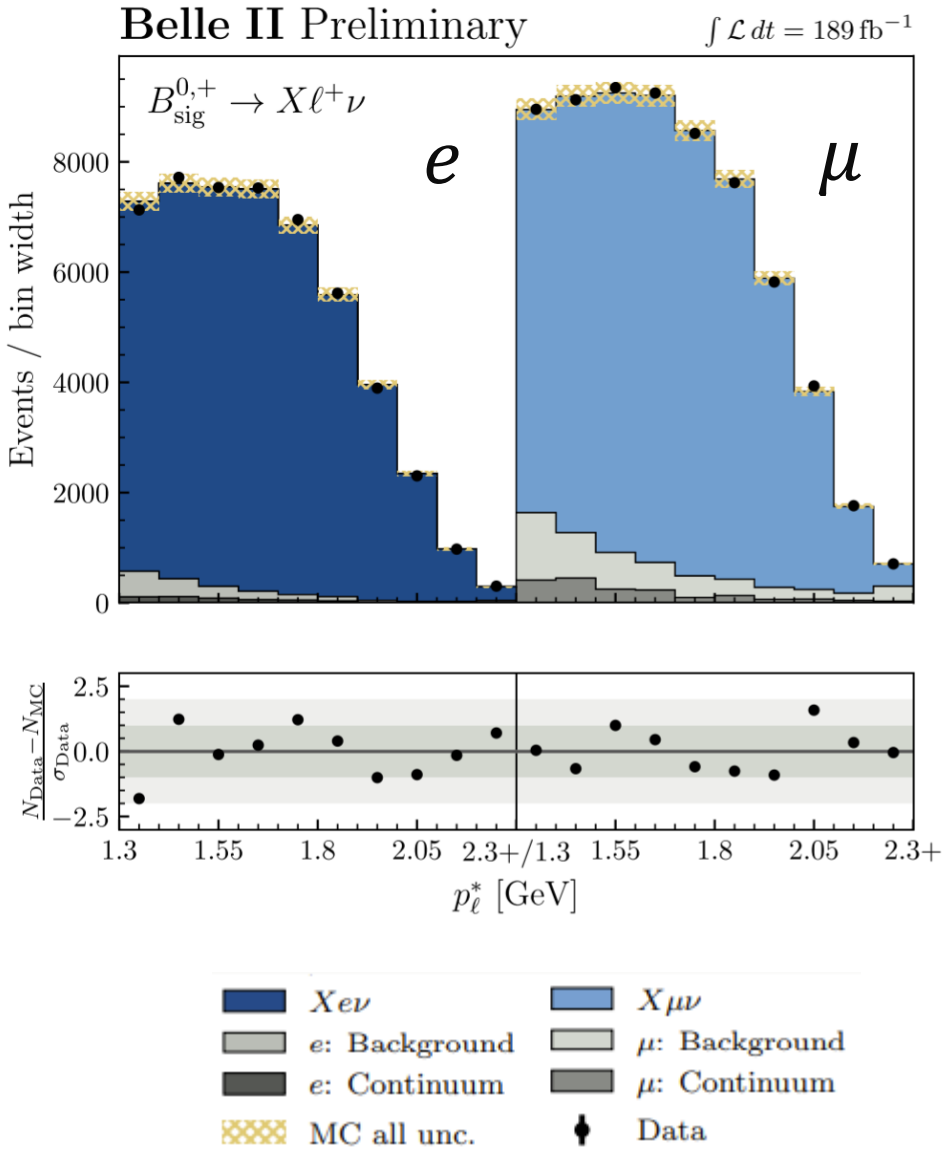
$$R(X_{e/\mu}) = \frac{B(B \to Xe\nu)}{B(B \to X\mu\nu)} = \frac{\epsilon_{X\mu\nu} N_{Xe\nu}}{\epsilon_{Xe\nu} N_{X\mu\nu}}$$

$$R(X_{e/\mu})^{p^*_\ell > 1.3\,\mathrm{GeV}} = 1.033 \pm 0.010^{\mathrm{stat.}} \pm 0.020^{\mathrm{syst.}}$$

- Most precise LFU test with semi-leptonic B decays!
- Compatible with SM at $1.2\sigma$[1].
- Agreement with $R(D^*_{e/\mu})$ from Belle at $0.6\sigma$[2].

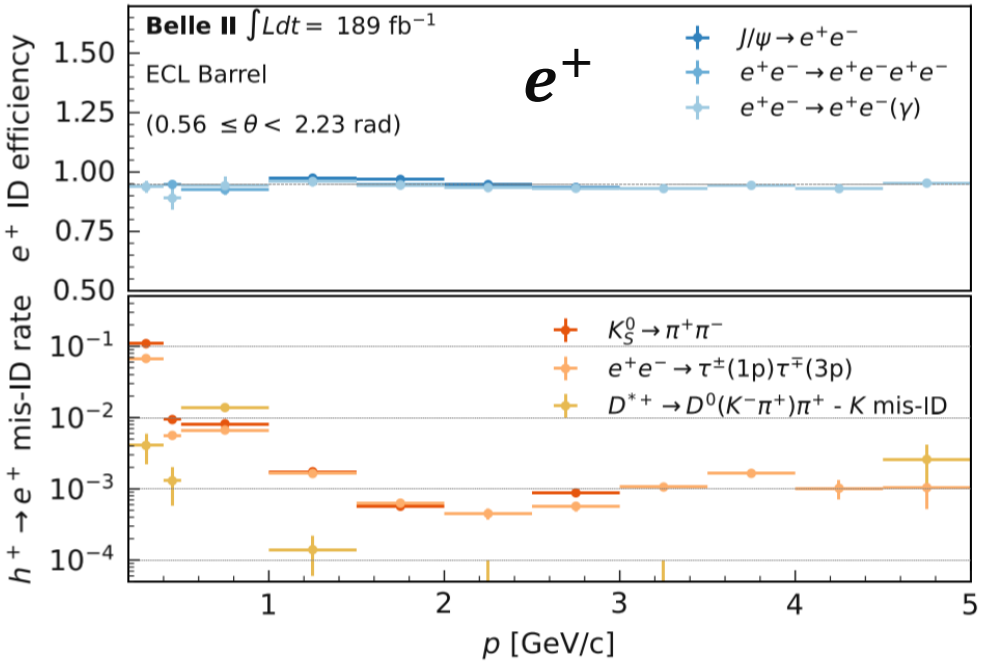
| Source of uncertainty | Lepton ID | $X_c\ell\nu$ BFs | $X_c\ell\nu$ FFs | Statistical | Total |
|---|---|---|---|---|---|
| Rel. unc. of $R(X_{e/\mu})$ | 1.8% | 0.1% | 0.2% | 1.0% | 2.2% |

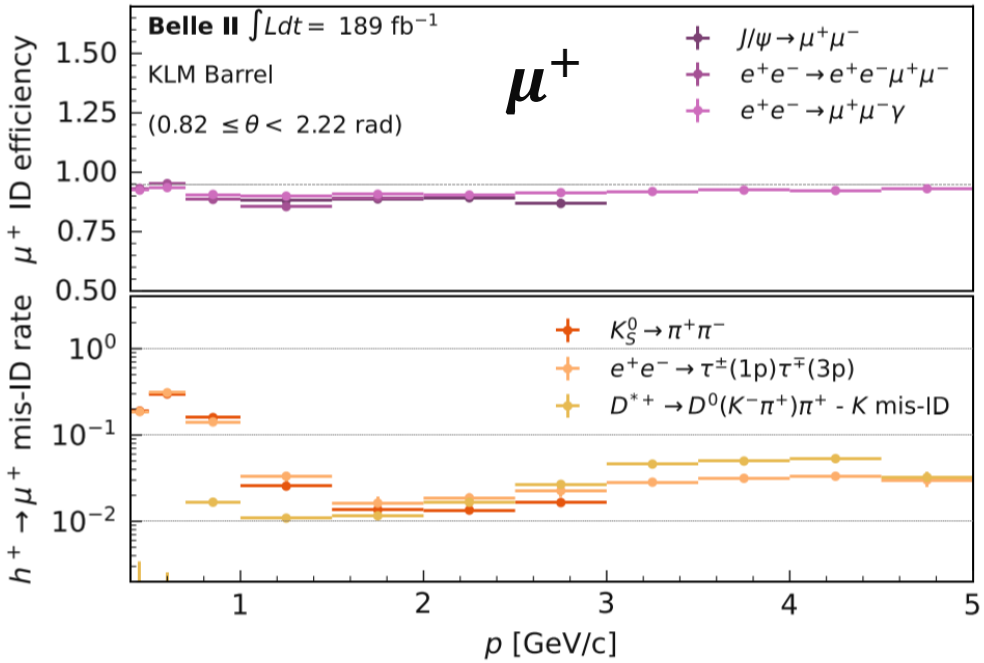



[1]: Rahimi, Voss, arXiv: 2207.03432, [2]: Belle, PRD 100 (2019) 052007

# Key performance driver: LeptonID

- Control of lepton identification crucial to all LFU tests.
- Calibrated in several well understood control channels. ⇒ corrections are close to $1.0$ and measured to $O(0.1-2\%)$ for electrons and muons. ~Approaching Belle precision.

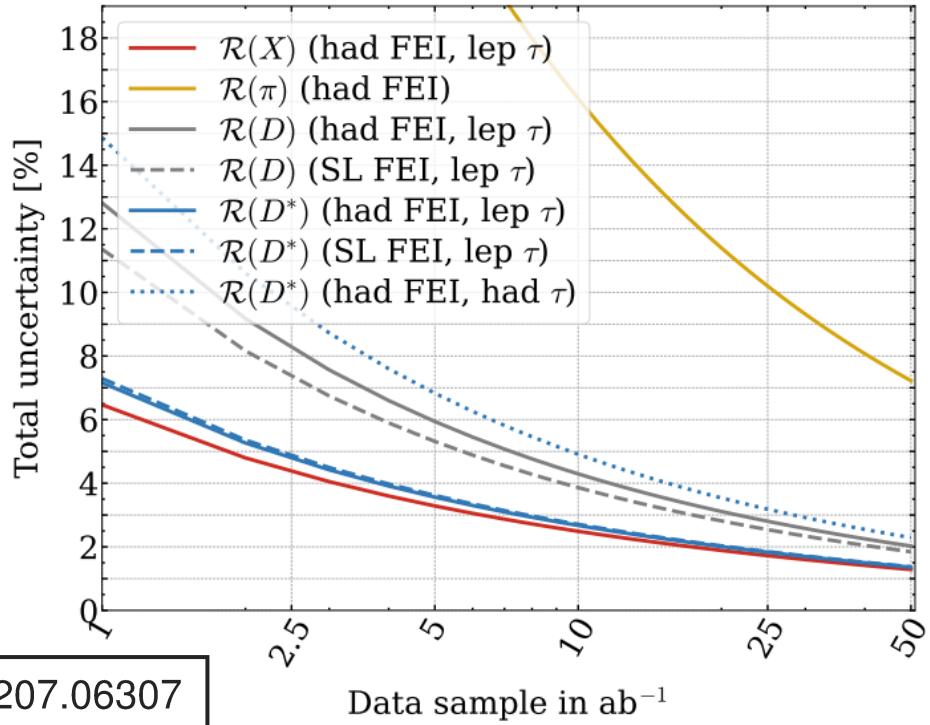


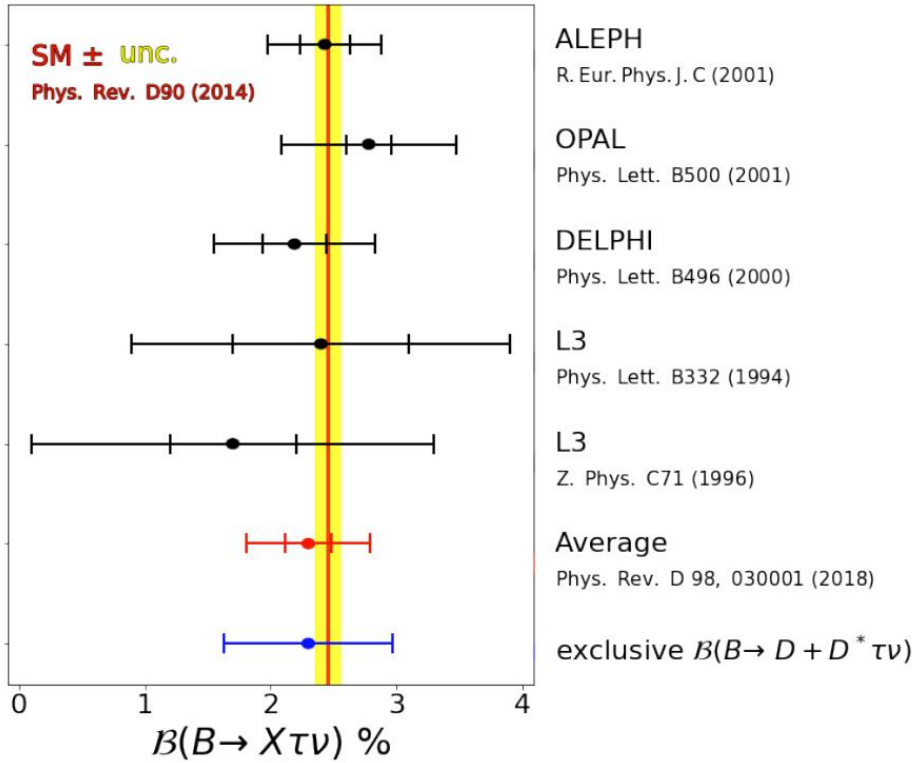




- Constantly improving our understanding.
- Expect lepton identification uncertainties to decrease!

# $R(D), R(D^*), R(X)$ – Prospects

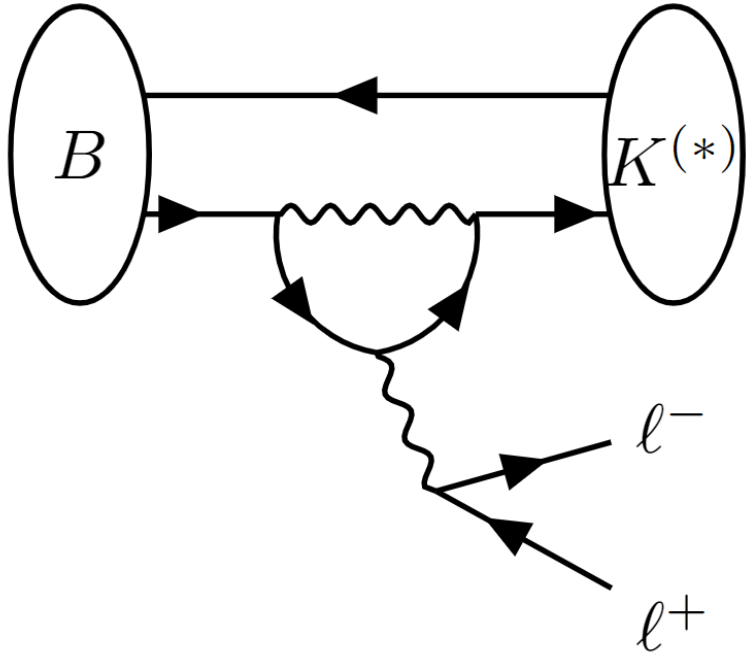
- Expect the first competitive results for $R(D)$ and $R(D^*)$ soon, precisions reaching $4\%\ R(D^*), 6\%\ R(D)$ with $5\text{ab}^{-1}$.
- Unique capability for an inclusive measurement: $R(X)$. Expect 10-20% precision with current sample ($424\ \text{fb}^{-1}$).
- Last measured at LEP, no input from Belle or BaBar.




Belle II, arXiv: 2207.06307

# Electroweak Penguins

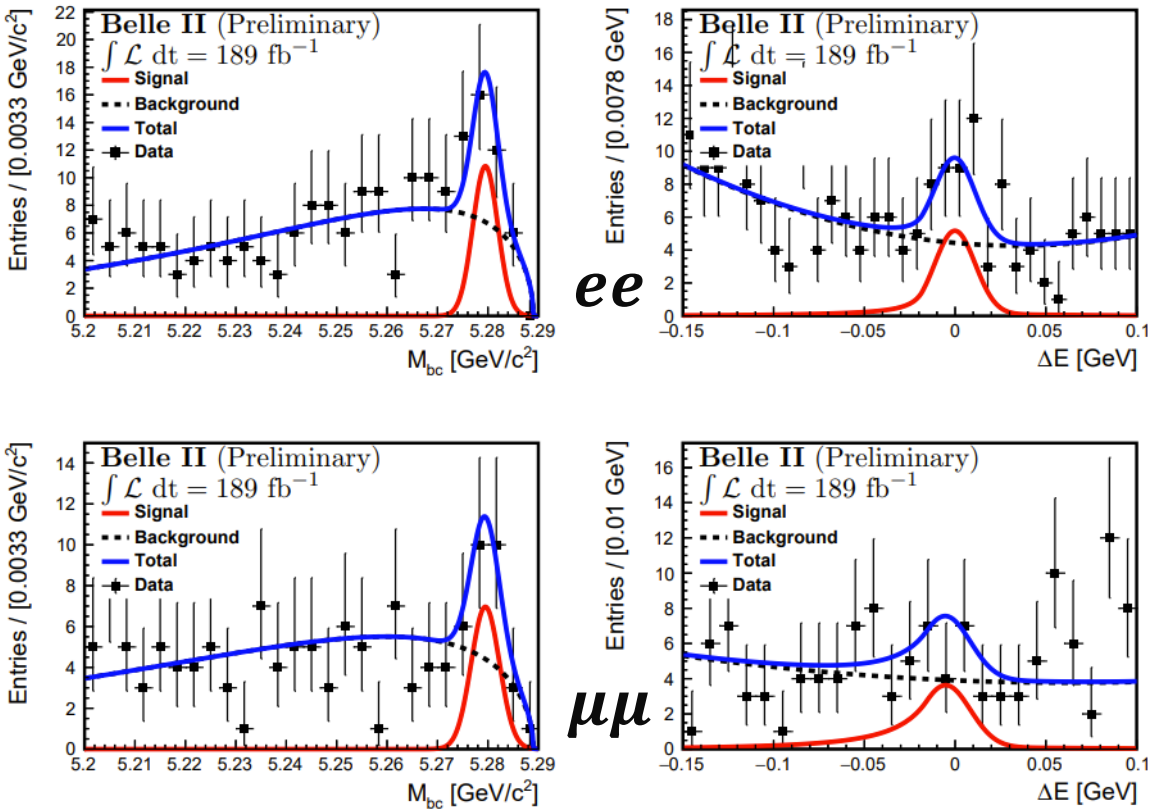


# Preparing for $R(K^{(*)})$

Belle II, arXiv: 2206.05946

- Search for $B \to K^*(892)\ell\ell$ in three modes:
  $B^0 \to K^{*0}(K^+\pi^-)\ell\ell$
  $B^+ \to K^{*+}(K^+\pi^0, K_S^0\pi^+)\ell\ell$
- Continuum and $B\overline{B}$ backgrounds vetoed via BDT on event shape, kinematics and vertex quality.
- Signal extracted in 2D unbinned fit to $M_{bc}, \Delta E$.
- Integrated measurement over $q^2$ range with vetoes around photon conversion and charmonium resonances ($J/\psi$, $\psi(2S)$).
- Equivalent performance in electron and muon modes.

$$M_{\mathrm{bc}} = \sqrt{E_{\mathrm{beam}}^2 - p_B^{*\,2}} \qquad \Delta E = E_B^* - E_{\mathrm{beam}}$$




| Mode | Observed Events | Branching Fraction | PDG2020 Branching Fraction |
|---|---|---|---|
| $B \to K^* ee$ | $22 \pm 6$ | $1.42 \pm 0.48 \pm 0.09$ | $1.19 \pm 0.20$ |
| $B \to K^* \mu\mu$ | $18 \pm 6$ | $1.19 \pm 0.31^{+0.08}_{-0.07}$ | $1.06 \pm 0.09$ |

# Preparing for $R(K^{(*)})$: $R_K(J/\psi)$

Belle II, arXiv: 2207.11275

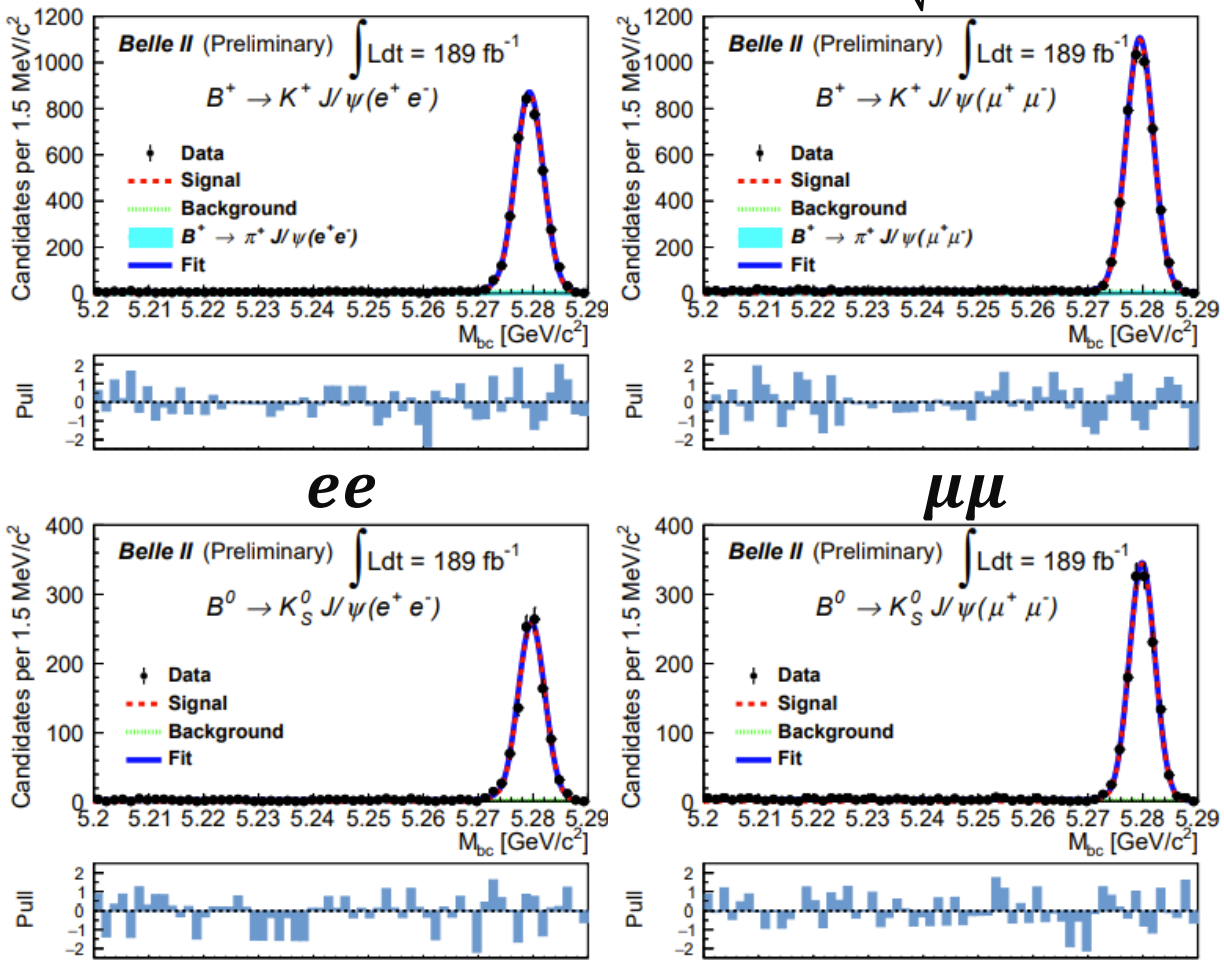
- $R_K(J/\psi) = \frac{B(B \to K J/\psi(\to ee))}{B(B \to K J/\psi(\to \mu\mu))}$
- Highly pure, high statistics normalisation channel for $R(K)$.
- Tree level - expected to be free from NP effects.
- $J/\psi$ known to respect LFU within 0.31%.

- Signal extracted in 2D unbinned fit to $M_{bc}, \Delta E$.

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

- Take lepton ID corrections from inclusive $J/\psi$ sample.

$$M_{\mathrm{bc}} = \sqrt{E_{\mathrm{beam}}^2 - p_B^{*2}}$$



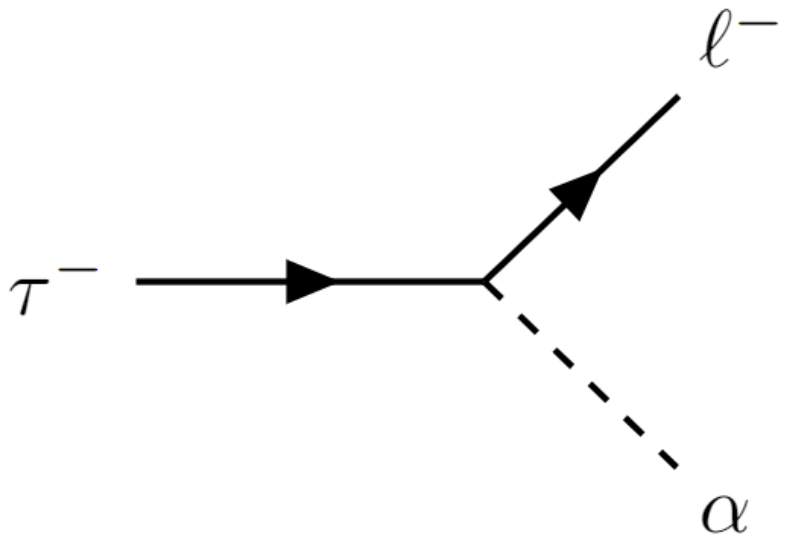
# $R(K^{(*)})$ Prospects

- Heavily limited by sample size.
- Belle II will provide competitive and independent checks of $R(K^{(*)})$ anomalies with a few $\mathrm{ab}^{-1}$.

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

Belle II , PTEP 2019 (2019) 12, 123C01

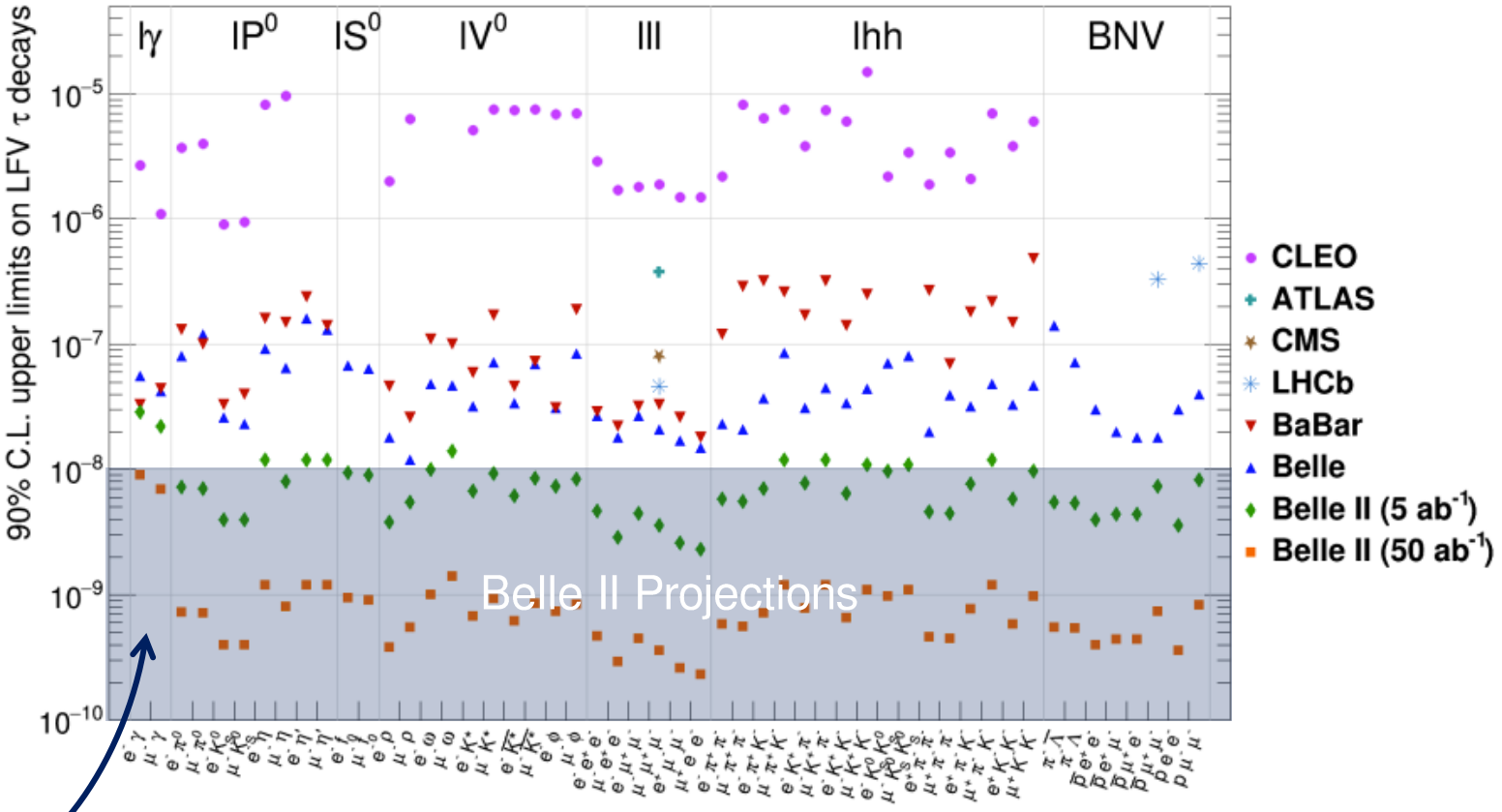
# Tau Sector



# Searches for LFV in the $\tau$ sector

- SuperKEKB is not only a $B$ factory but also a $\tau$ factory.
- $\sigma(\Upsilon(4S)) = 1.05\text{nb}$
  $\sigma(\tau\tau) = 0.92\text{nb}$
- $\sim$1 million $\tau$ pairs per $\text{fb}^{-1}$.
- Several dedicated low multiplicity triggers at Belle II.
- Rich possibility to search for LFV effects in 52+ channels!

Banerjee et al., arXiv:2203.14919

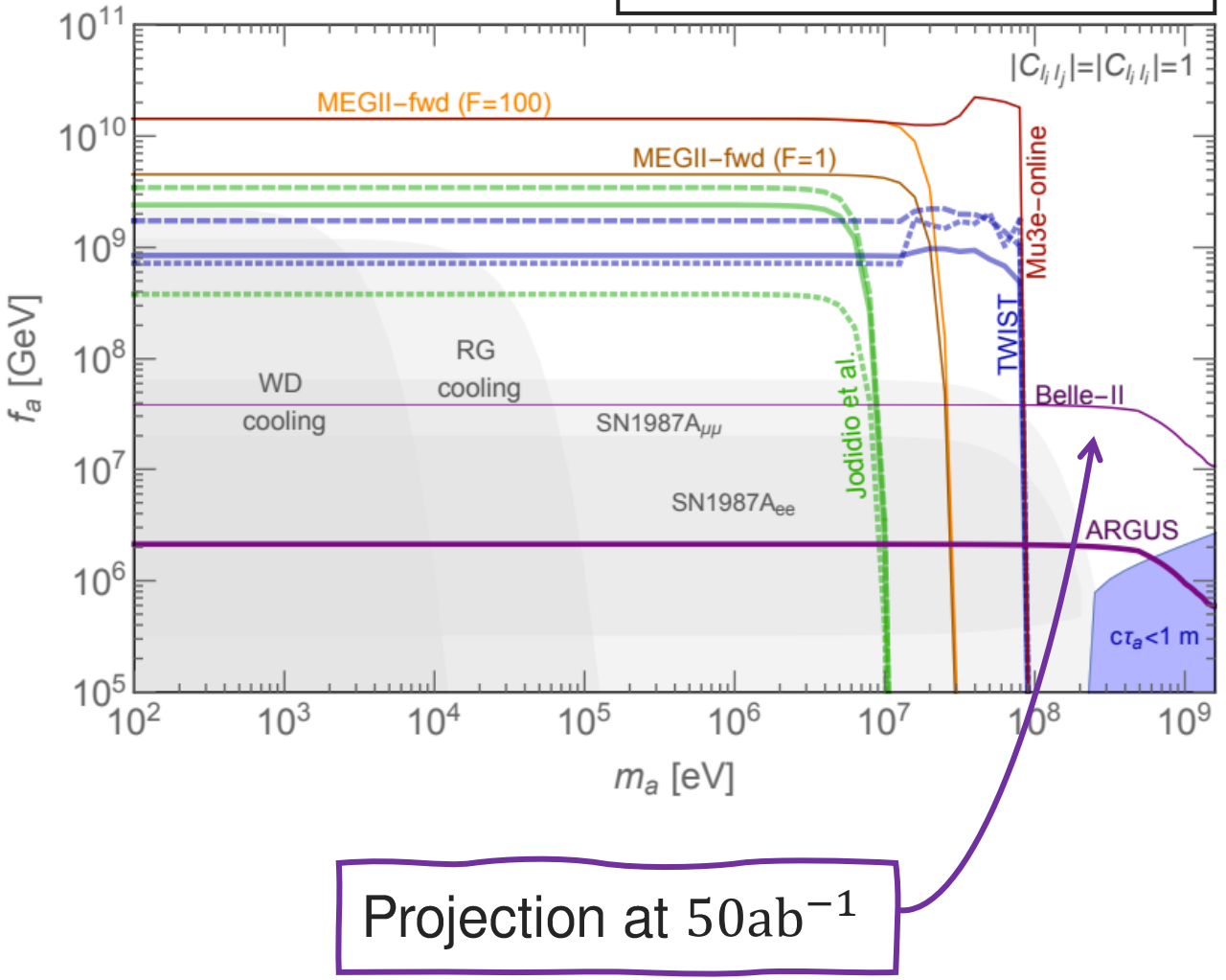



Region expected to be sensitive to new physics.

# $\tau \to \ell\alpha$ (invisible)

- Can enter from new physics models such as light long-lived ALP.
- Best limits $\mathrm{m}_\alpha \in [0.1 - 1.6]\mathrm{GeV}$ range from ARGUS $(476\ \mathrm{pb}^{-1})$, no studies at Belle or BaBar.
- $B(\tau \to \ell\alpha) \propto {}^{1}/_{f_a^2}$.

Calibbi et al., JHEP 09 (2021) 17




Projection at $50\mathrm{ab}^{-1}$

# $\tau \to \ell\alpha$ (invisible): Strategy

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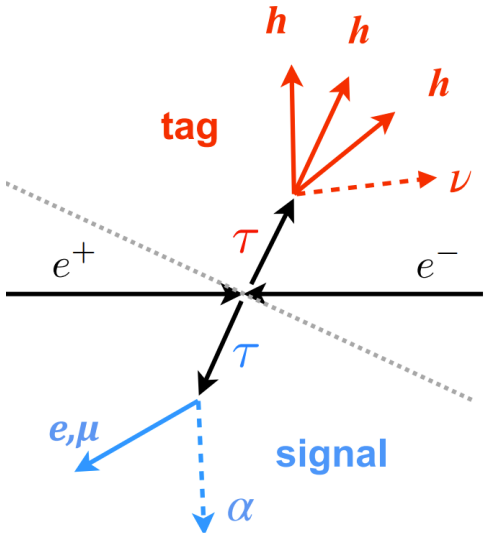
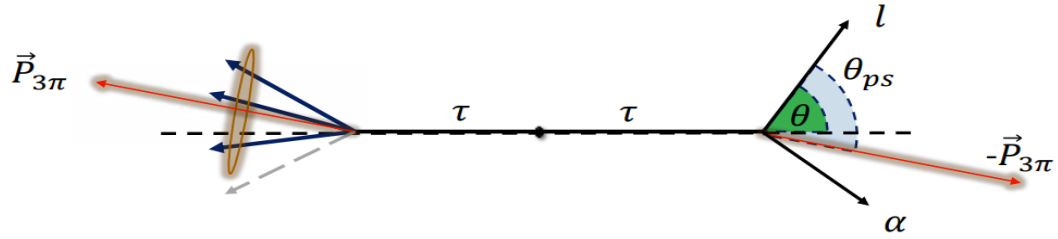
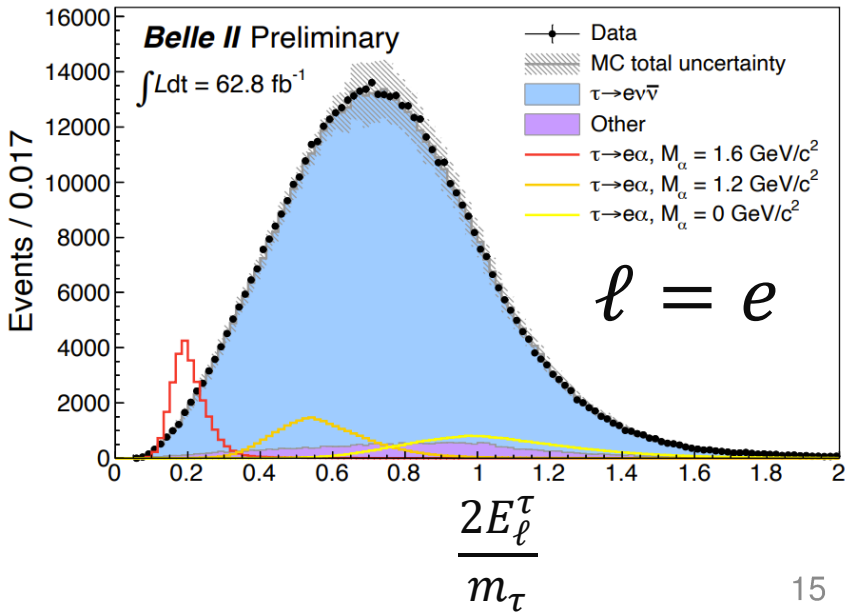
- Require exactly 4 tracks.
  - Signal lepton
  - 3-prong tag: $\tau^+ \to \pi^+\pi^+\pi^-\nu$
- Veto neutrals $(\gamma, \pi^0)$




- Suppress reducible background $(q\bar{q}, \ell\ell, \ell\ell\ell\ell, \ell\ell hh, \tau \to h\nu)$ via selection criteria optimised on $\tau \to \ell\nu\bar{\nu}$ (irreducible background with same signature).

- Signal Extraction in energy of lepton in $\tau$ pseudo rest frame: $E_\tau = \sqrt{s}/2$, $\hat{p}_\tau = -\hat{p}_{3\pi}$



# $\tau^+ \to \ell^+ \alpha$ (invisible): Result

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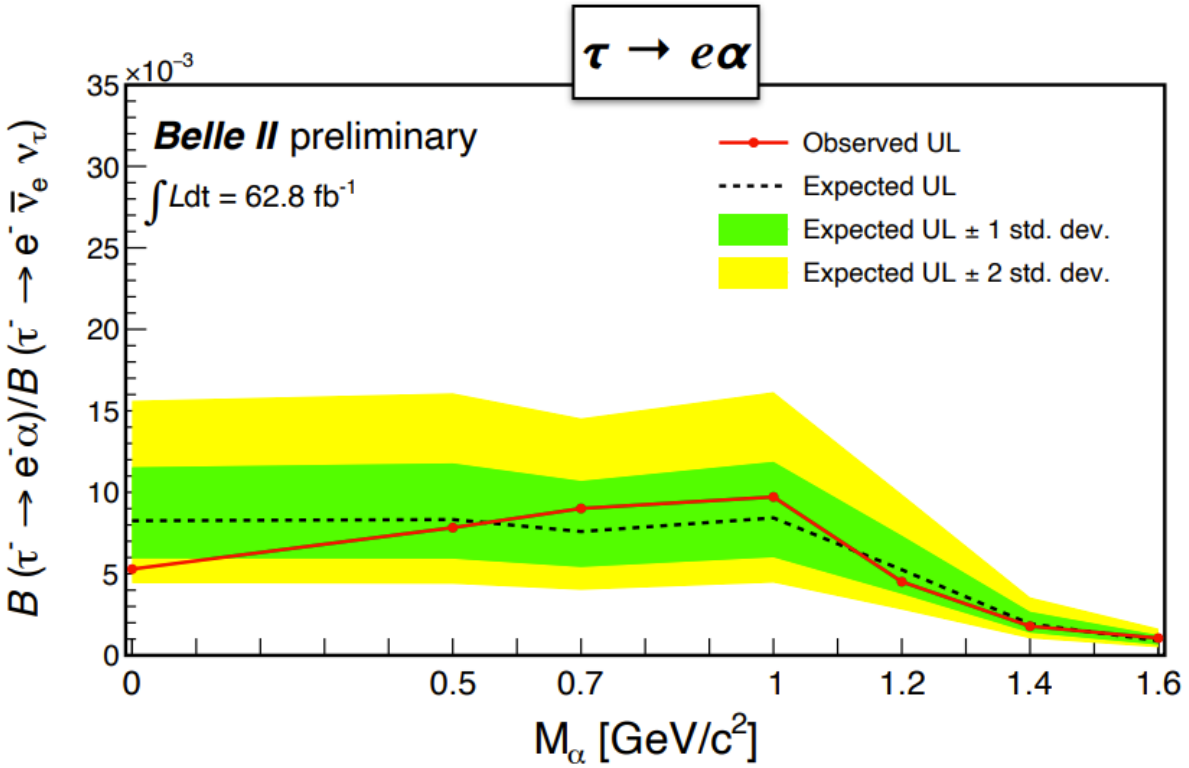
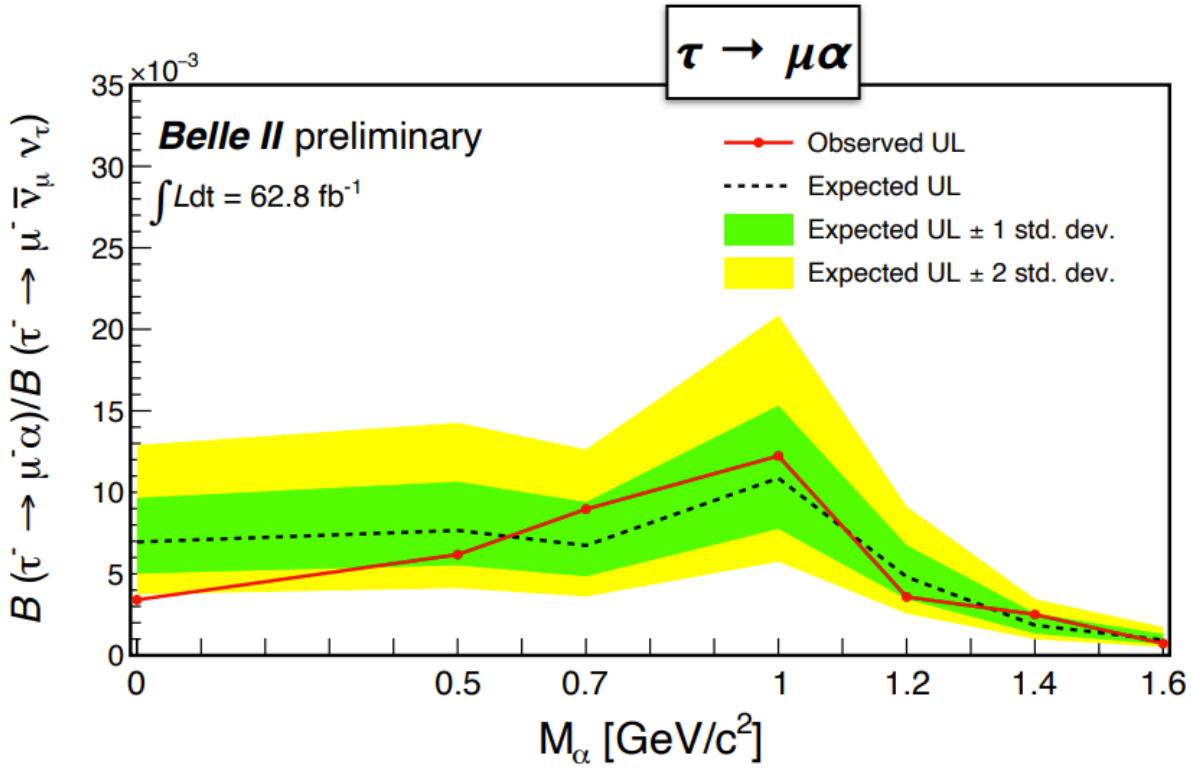
- 95% C.L. upper limit using the CLs method.
- No significant excess found in $62.8\text{fb}^{-1}$.
- 2.2 to 14 times better limit than ARGUS ($m_\alpha$ and $\ell$ channel dependent).



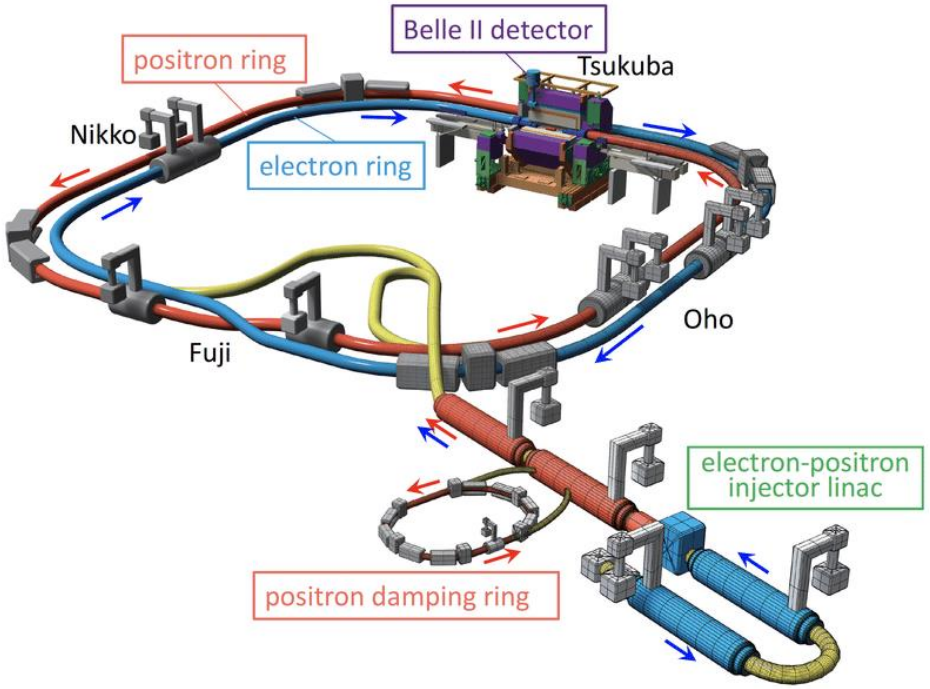
# Conclusion

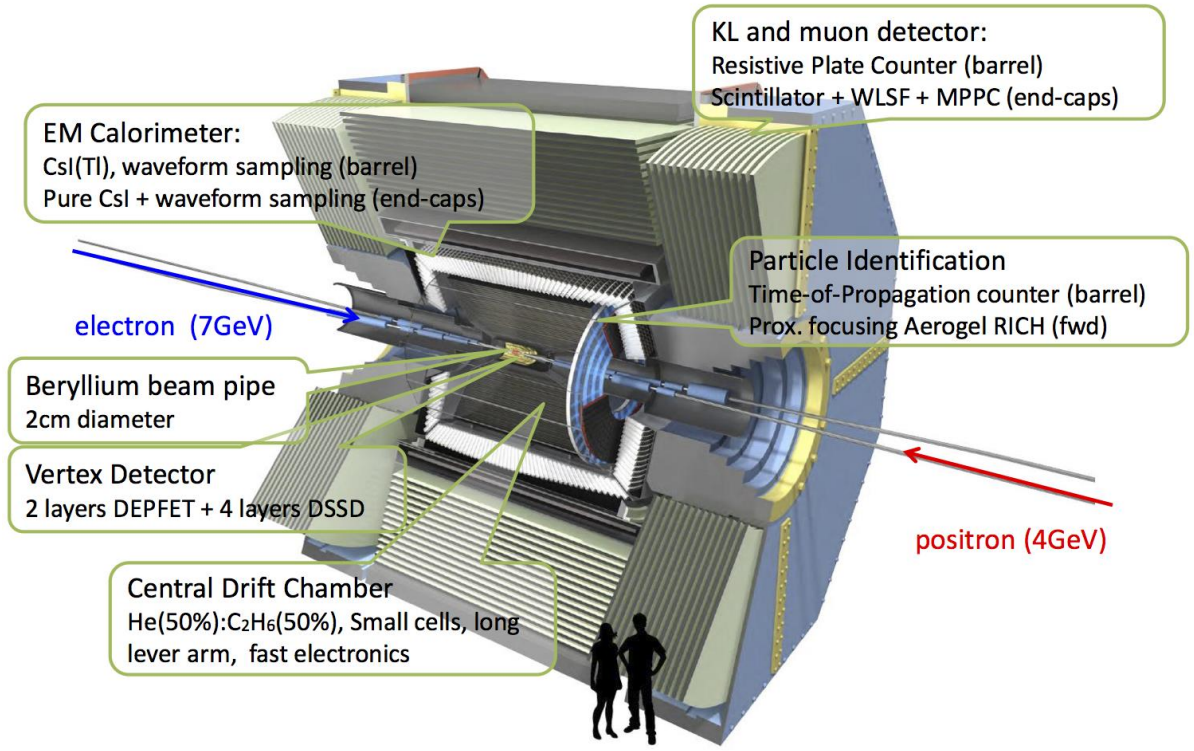
- Recent Belle II results related to lepton flavor universality:
  - $R(X_{e/\mu})$ ⇒ Precise LFU test. First step to $R(X)$
  - $B \to K^* \ell\ell$
  - $B \to K\, J/\psi$ ⇒ Preparation for $R(K^{(*)})$
  - $\tau \to \ell\alpha$ ⇒ Most stringent limit.

- Our understanding of lepton identification is constantly improving → expect a decrease in the systematics associated with lepton ID.
- Belle II will provide input to $R(D^{(*)}), R(X)$ soon.
- Larger sample needed before weighing in on $R(K^{(*)})$.
- A rich possibility to search for LFV in the $\tau$ sector.
  Will push sensitivity into the region exposed to new physics as we head towards $50\,\mathrm{ab}^{-1}$.

# Backup

# SuperKEKB and Belle II




- Nanobeam collision scheme.
- World record luminosity $4.65 \times 10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$
  - 2 times Belle record.
  - Aiming another order of magnitude higher.

- Nearly $4\pi$ coverage.
- Excellent charged particle identification and neutral particle reconstruction.

# Data Collection

- Now in Long Shutdown 1 to replace Pixel Detector and other maintenance.
- $424\ \mathrm{fb}^{-1}$ collected before Long Shutdown 1.
  - $363\ \mathrm{fb}^{-1}$ at $\sqrt{s} = m_{\Upsilon(4S)} = 10.58\mathrm{GeV}$
  - $42\ \mathrm{fb}^{-1}$ at $10.52\mathrm{GeV}$ (off-resonance)
  - $19\ \mathrm{fb}^{-1}$ at $10.75\mathrm{GeV}$ for exotic hadron searches
- Matches BaBar $(550\mathrm{fb}^{-1})$ and challenges Belle $(1\mathrm{ab}^{-1})$ due to improved reconstruction performance.