Recent Belle II results related to flavour anomalies

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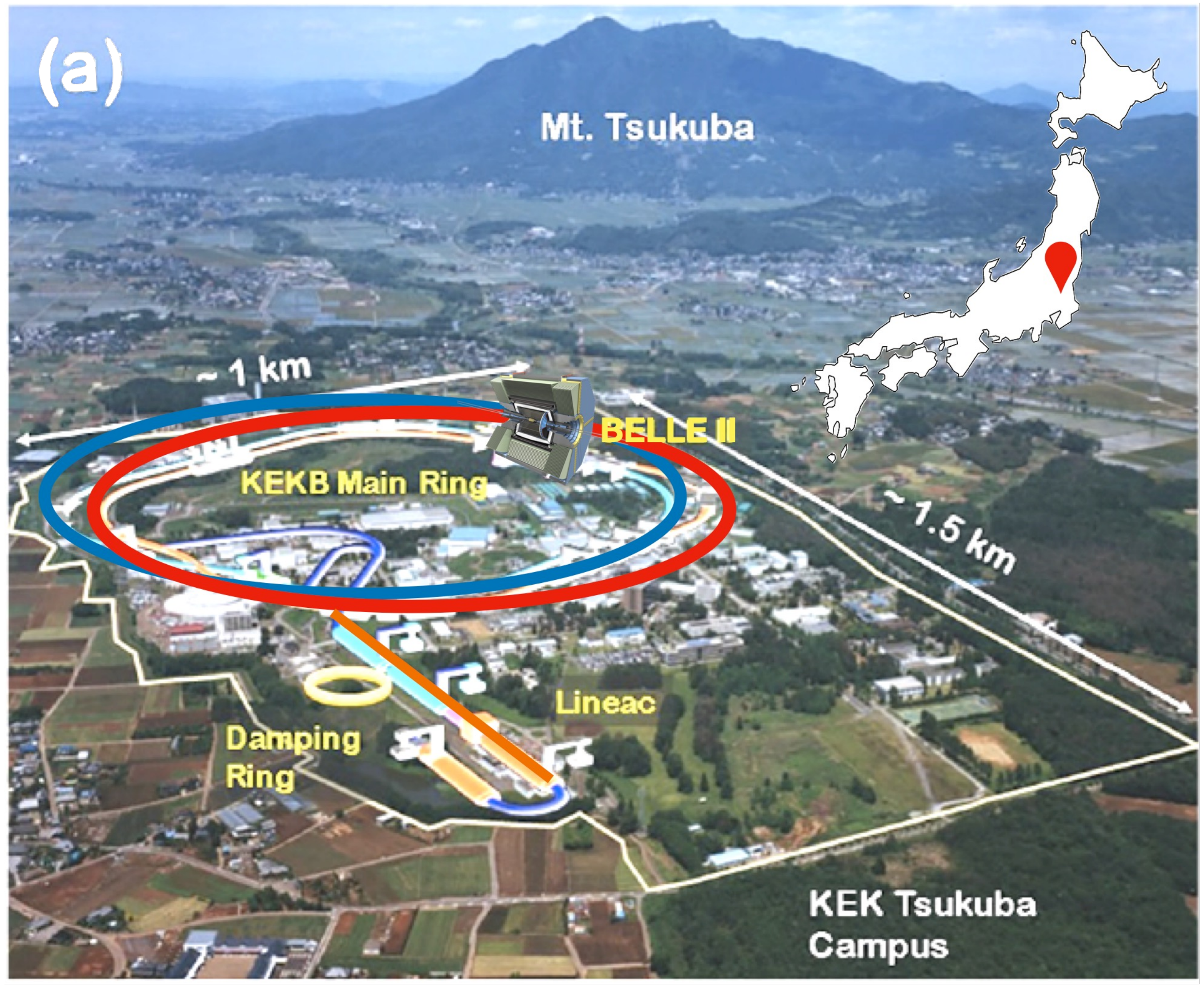
on behalf of the Belle II collaboration

30th Anniversary of the Rencontres du Vietnam

August 8th, 2023

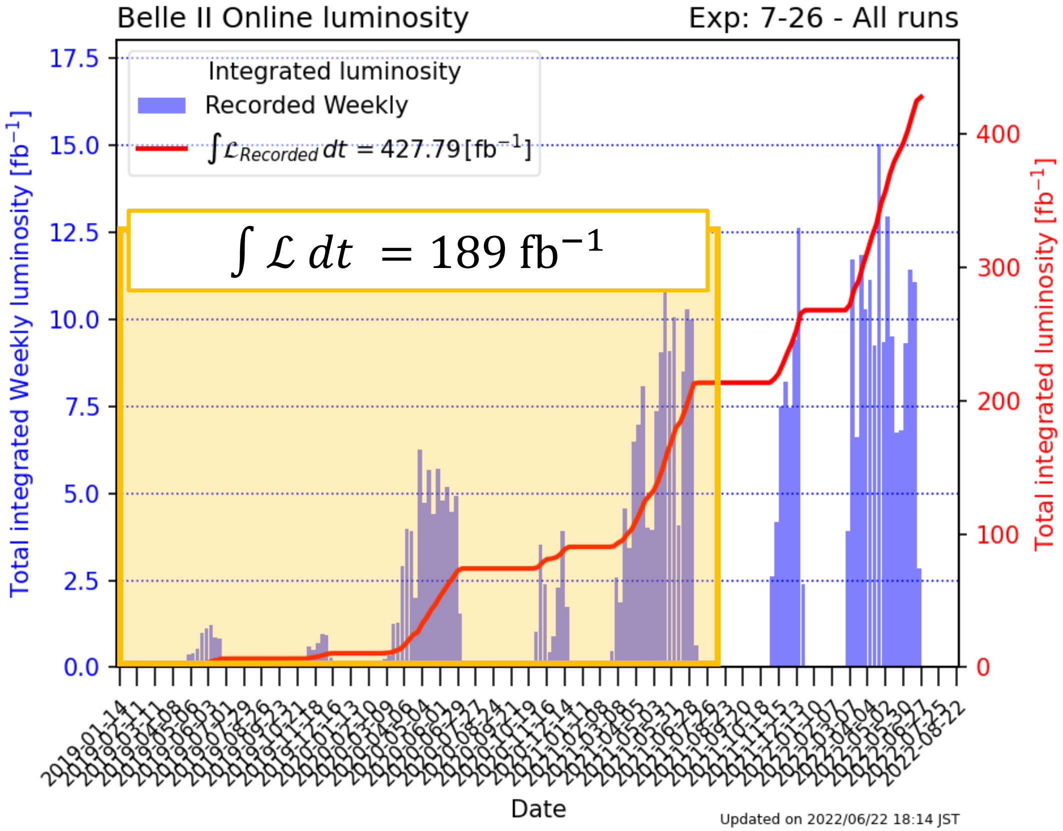
The Belle II experiment



- Electron-Positron (e^+e^-) collider

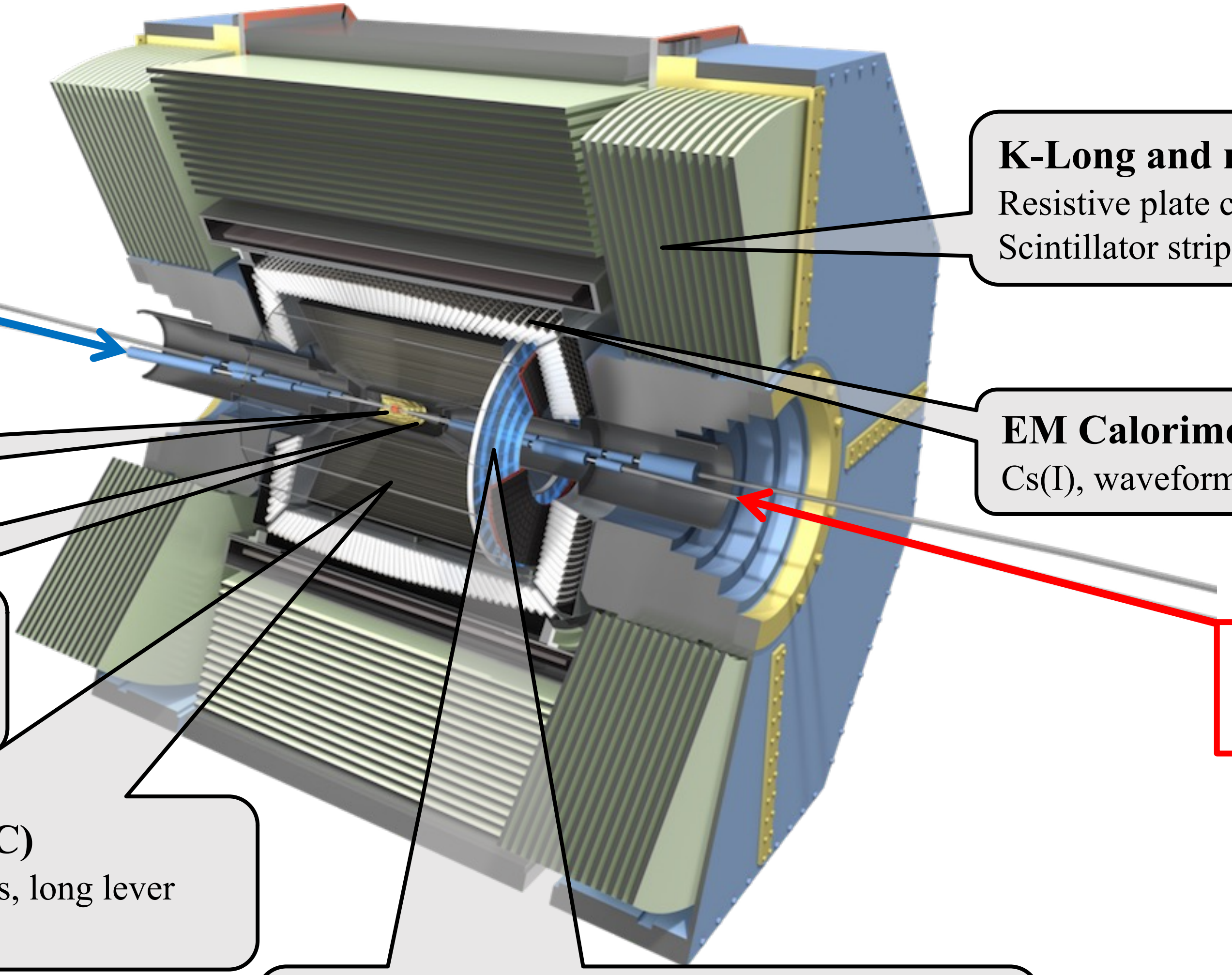
  e^- (7 GeV) $\rightarrow \leftarrow$ (4 GeV) e^+

- E_{CM} at $\Upsilon(4S)$ resonance (10.58 GeV)
- B-factory $\Upsilon(4S) \rightarrow B\bar{B}$ (*at least* 96%)



The following Belle II measurements are done at 189 fb^{-1}

The Belle II detector



4π coverage
More on this on talk by Doris Kim

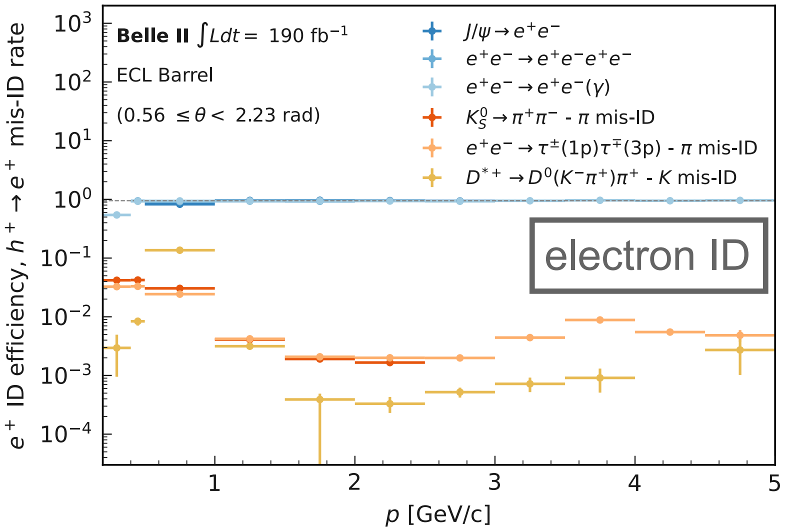
Lepton Identification

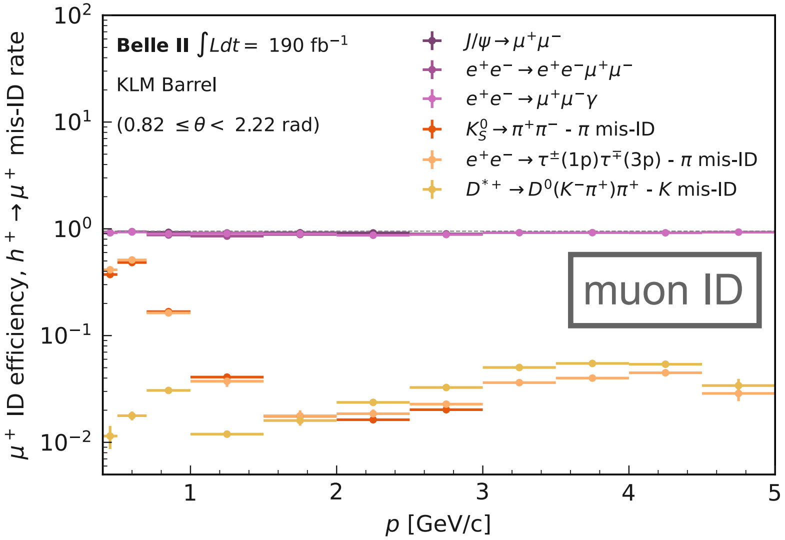
- Particle identification (PID) – identify "long-lived" particles passing through the detector by interacting with matter
- One of the most crucial part of determining the sensitivity of a measurement
- Lepton identification algorithm works based on likelihood ratio or BDT

$$\mathrm{ID}_{\mu} = \frac{\mathcal{L}_{\mu}}{\sum_{i}^{e,\,\mu,\,\pi,\,K,p,d} \mathcal{L}_{i}}$$

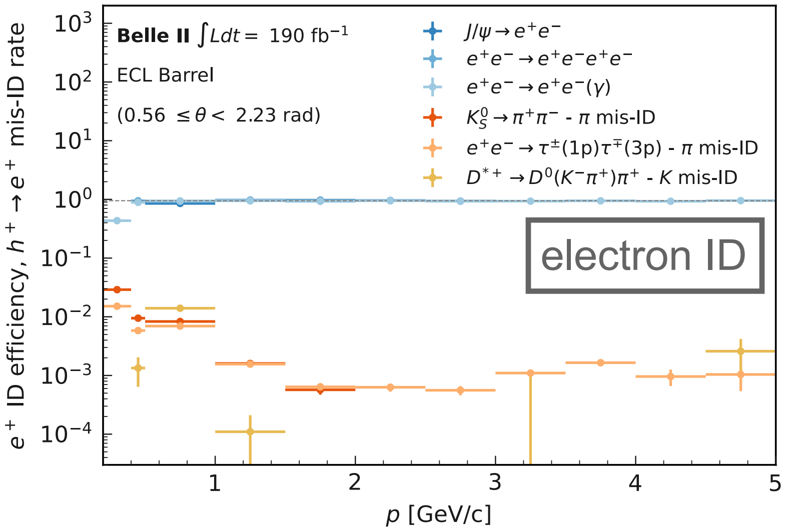
- New BDT-based lepton identification superior across the momentum spectrum, especially < 0.6 GeV/c
- Data/MC correction factors have associated systematics for the efficiency at the 0.5-1.5% level

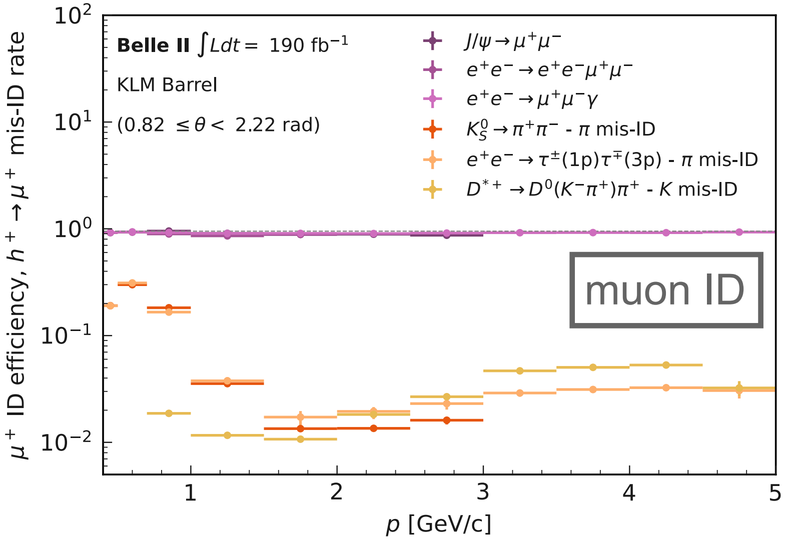
Likelihood Ratio





BDT-based



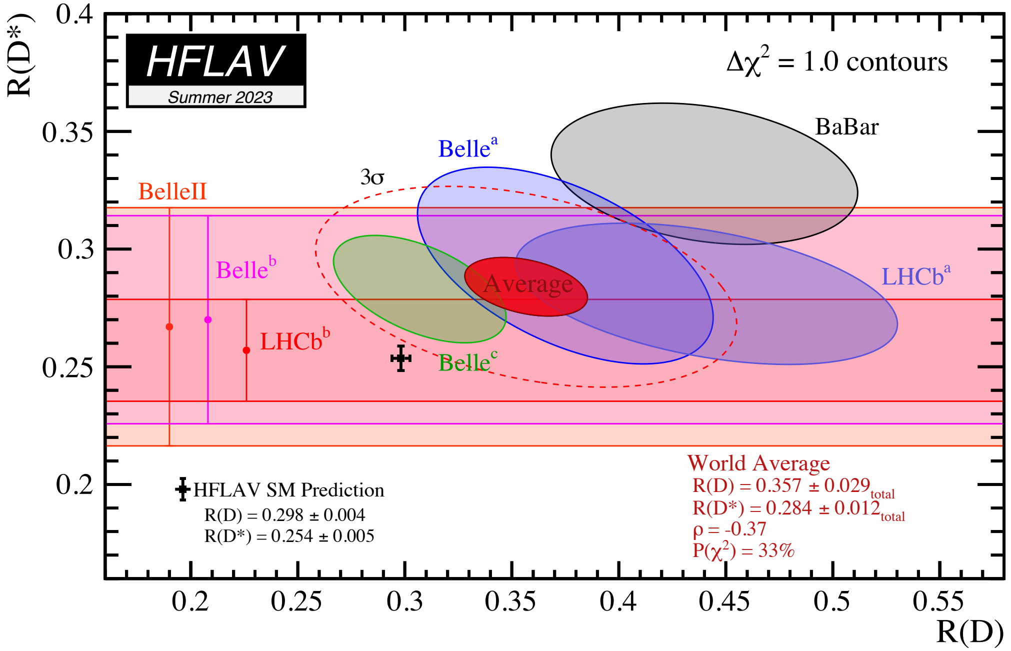


First $R(D^*)$ Measurement from Belle II

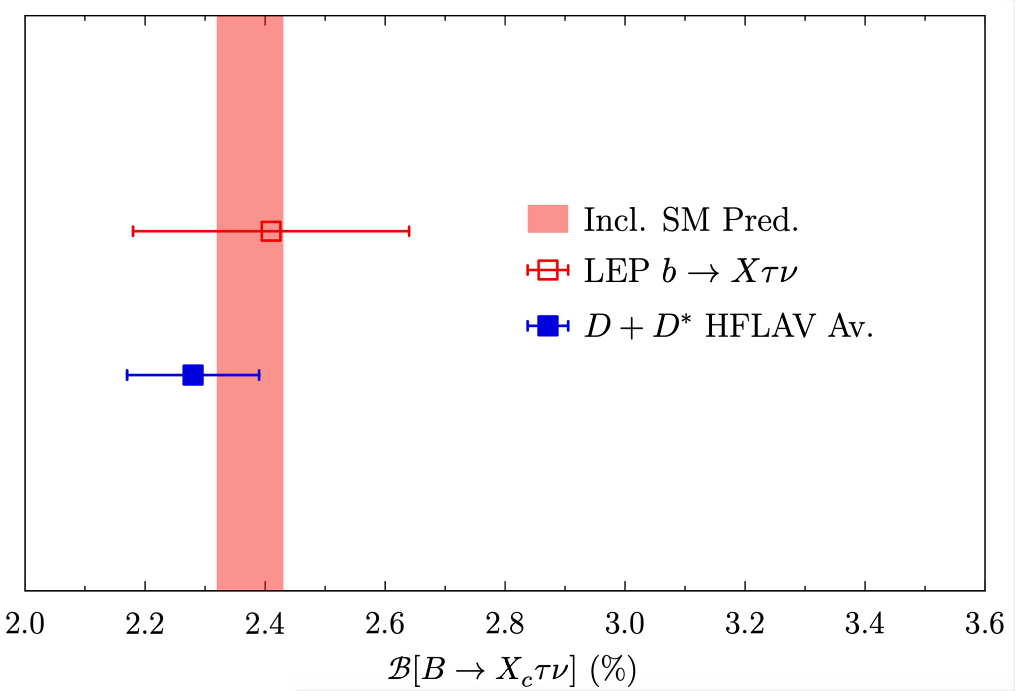
Introduction to flavour anomalies in $b \to c$ decays

- Flavour anomalies have been observed due to deviations from the Standard model in processes involving leptons
- New physics could introduce additional interactions with each lepton, affecting the predicted rate of $b \to c$ decays
- New interactions involving the $b \to c$ quark transition can probed in $R(D^{(*)})$ or $R(X_{\tau/\ell})$

$$R(D^{(*)}) = \frac{Br(B \to D^{(*)}\tau\nu)}{Br(B \to D^{(*)}\ell\nu)} \longleftrightarrow \ell \in \{e, \mu\} \longleftrightarrow R(X_{\tau/\ell}) = \frac{Br(B \to X\tau\nu)}{Br(B \to X\ell\nu)}$$



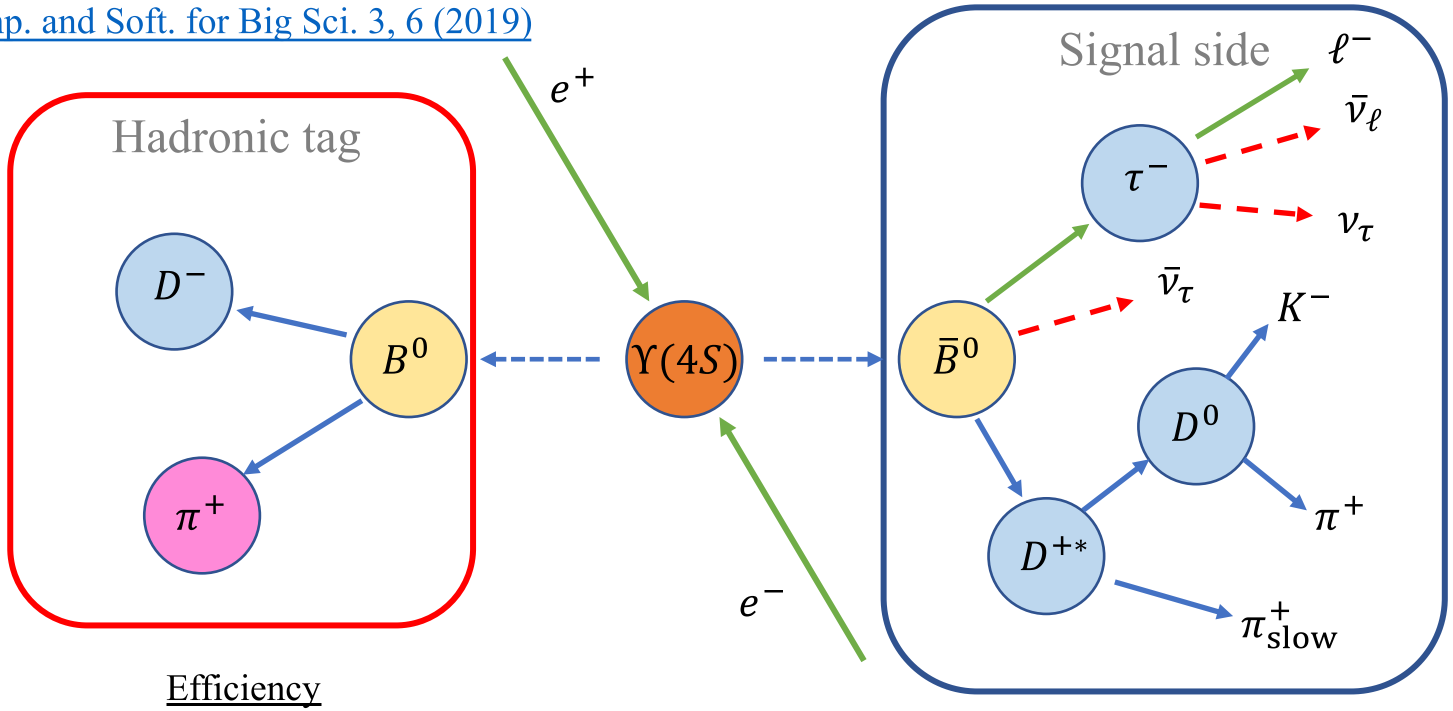
Tension with Standard model of $> 3\sigma$



Consistent with Standard Model expectation

$R(D^*)$ reconstruction

Hadronic B-tagging
(Full Event Interpretation)
Comp. and Soft. for Big Sci. 3, 6 (2019)



Efficiency
B^0: 0.27%, B^+: 0.35%
Belle II arXiv:2008.06096

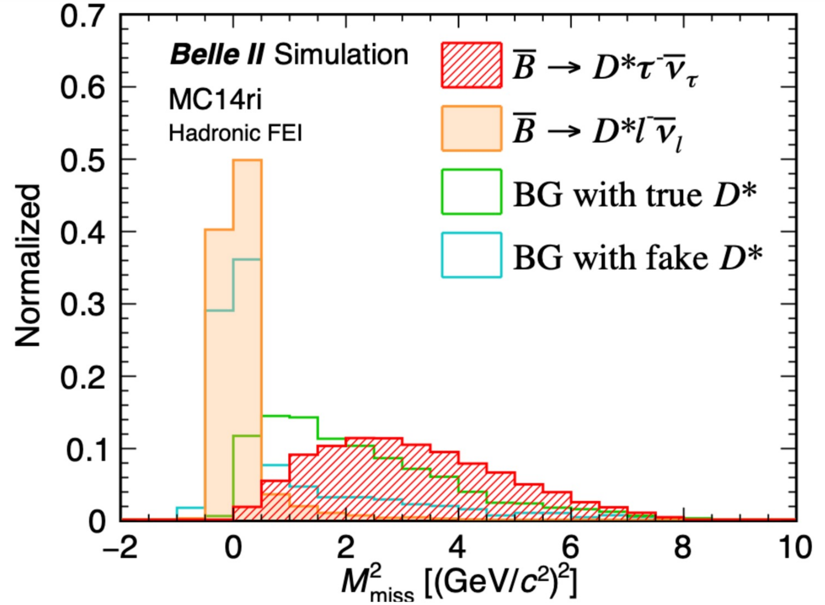
Precise knowledge of B_{tag} kinematics, strong kinematic reconstruction constraints for sig. side with 3 $\nu's$

Exclusive signal *B* modes
Reconstruct the signal-side *B* meson through specific decay channels

- Tag one B-meson from *hadronic* decays and analyse remaining B (**signal side**)
- Reconstruction of
  $\Rightarrow \overline{B^0} \rightarrow D^*\tau^- \bar{\nu}_\tau$
  $\Rightarrow \overline{B^0} \rightarrow D^*\ell^- \bar{\nu}_\ell, \quad \ell \in \{e, \mu\}$
- Leptonic τ decays
- Three D^* decay channels:
  $\Rightarrow D^{*+} \rightarrow D^0\pi^+$
  $\Rightarrow D^{*+} \rightarrow D^+\pi^0$
  $\Rightarrow D^{*0} \rightarrow D^0\pi^0$

$R(D^*)$ extraction

- 2D extended binned maximum likelihood fit to missing mass squared (M^2_{miss}) and extra ECL energy (E^{extra}_{ECL})



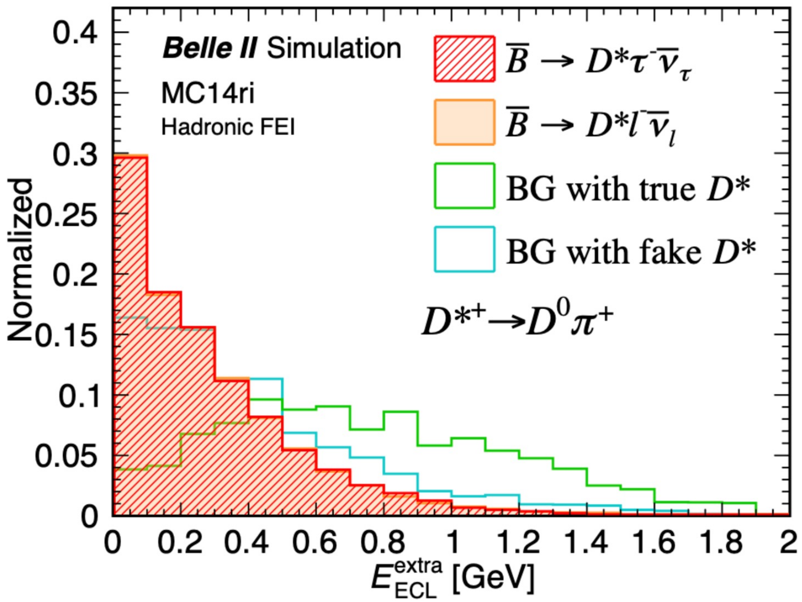
$$M^2_{miss} = \left(p_{e^+e^-} - p_{B_{tag}} - p_{D^*} - p_\ell\right)^2$$

M^2_{miss} distribution

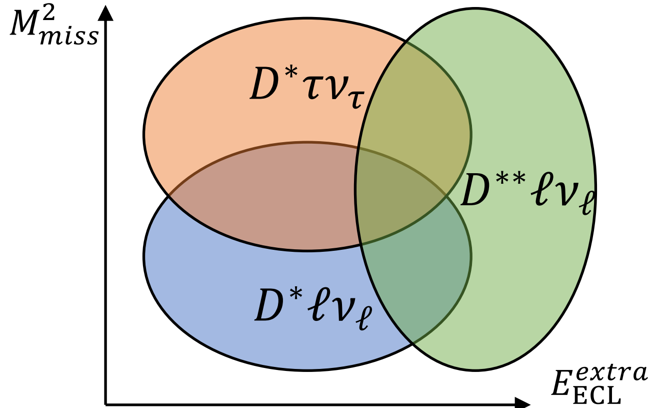
- $\bar{B} \to D^*\ell\nu$ events peak ~0 due to a single ν
- $\bar{B} \to D^*\tau\nu$ events larger M^2_{miss} due to multiple ν from $\bar{B}, \tau$
- Multiple ν causes broad peak $\bar{B} \to D^*\tau\nu$

E^{extra}_{ECL} distribution

- Background candidates have larger E^{extra}_{ECL} due to missing particles additional clusters



E^{extra}_{ECL}: Sum of cluster energy not used in reco.



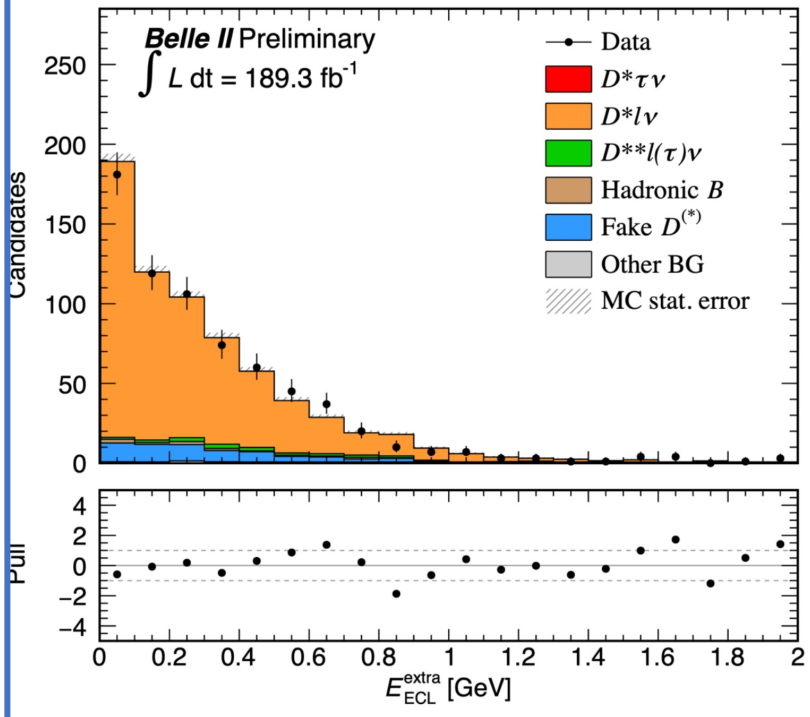
- Simultaneous fit the three D^* decays channels:
  - $\Rightarrow D^{*+} \to D^0\pi^+$
  - $\Rightarrow D^{*+} \to D^+\pi^0$
  - $\Rightarrow D^{*0} \to D^0\pi^0$
- $R(D^*)$ extracted from fit using $R(D^*) = \dfrac{N_{D^*\tau\nu}}{(N_{D^*\ell\nu}/2)} \cdot \dfrac{\varepsilon_{D^*\ell\nu}}{\varepsilon_{D^*\tau\nu}}$
  - N_χ: no. of χ events extracted from fit
  - ε_χ: reconstruction efficiency for χ events

Sample composition evaluation

$\bar{B} \to D^{*}\ell^{-}\bar{\nu}_{\ell}$ and major background contributions from $\bar{B} \to D^{**}\ell^{-}\bar{\nu}_{\ell}$ and fake D^{*} in three side-band regions are evaluated.

q^2 [GeV²/c²] side band for $\bar{B} \to D^{*}\ell^{-}\bar{\nu}_{\ell}$

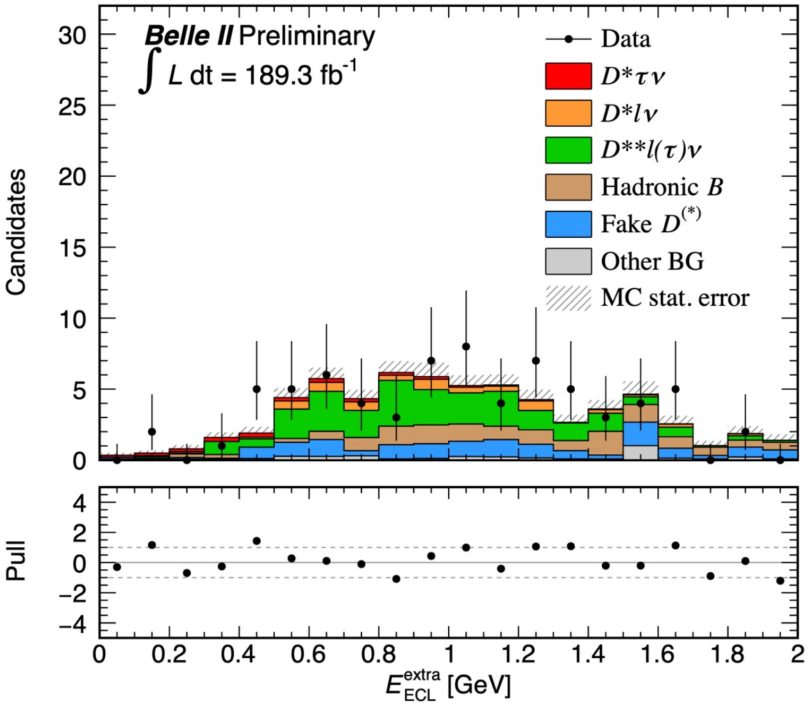
- $q^2 = (p_\ell + p_\nu)^2 < 3.5$ GeV
- Below m_τ threshold



$\bar{B} \to D^{**}\ell^{-}\bar{\nu}_{\ell}$ enhanced side band

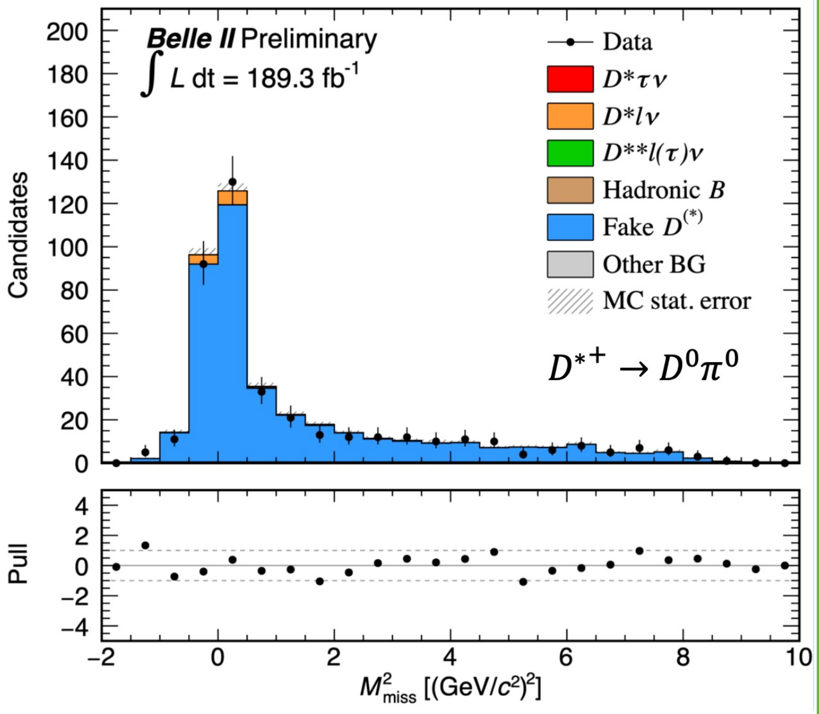
- An additional π^0 is required to $B\bar{B}$
- $\bar{B} \to D^{**}\ell^{-}\bar{\nu}_{\ell}$ have unknown rates and can mimic $\bar{B} \to D^{*}\tau^{-}\bar{\nu}_{\tau}$

$1.0 < M^2_{\mathrm{miss}} < 5.0\ (\mathrm{GeV}/c^2)^2$

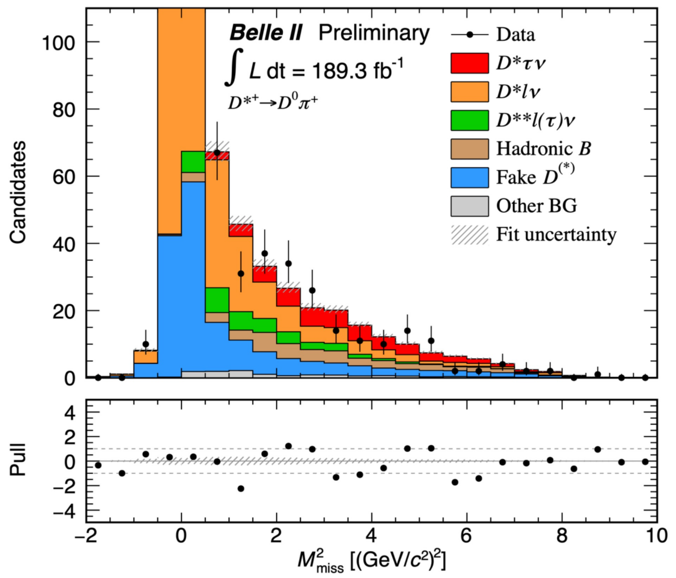


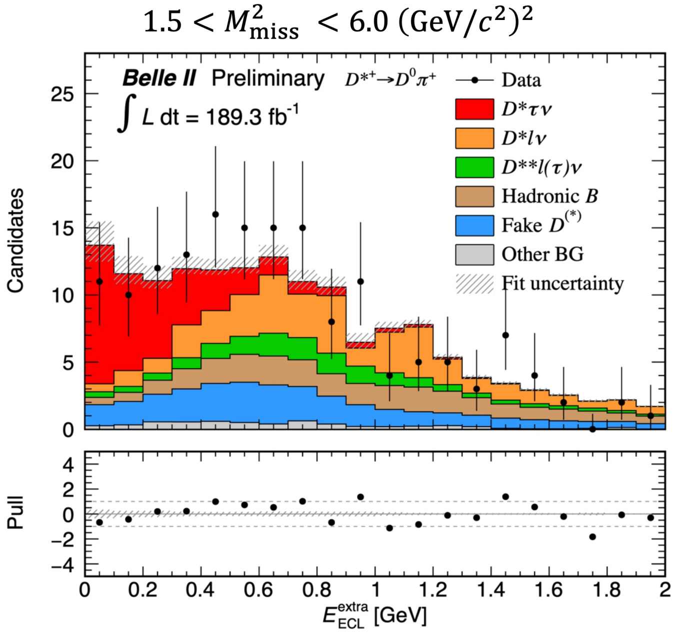
$\Delta M_{D^*} = (M_{D^*} - M_D)$ side bands for fake D^*

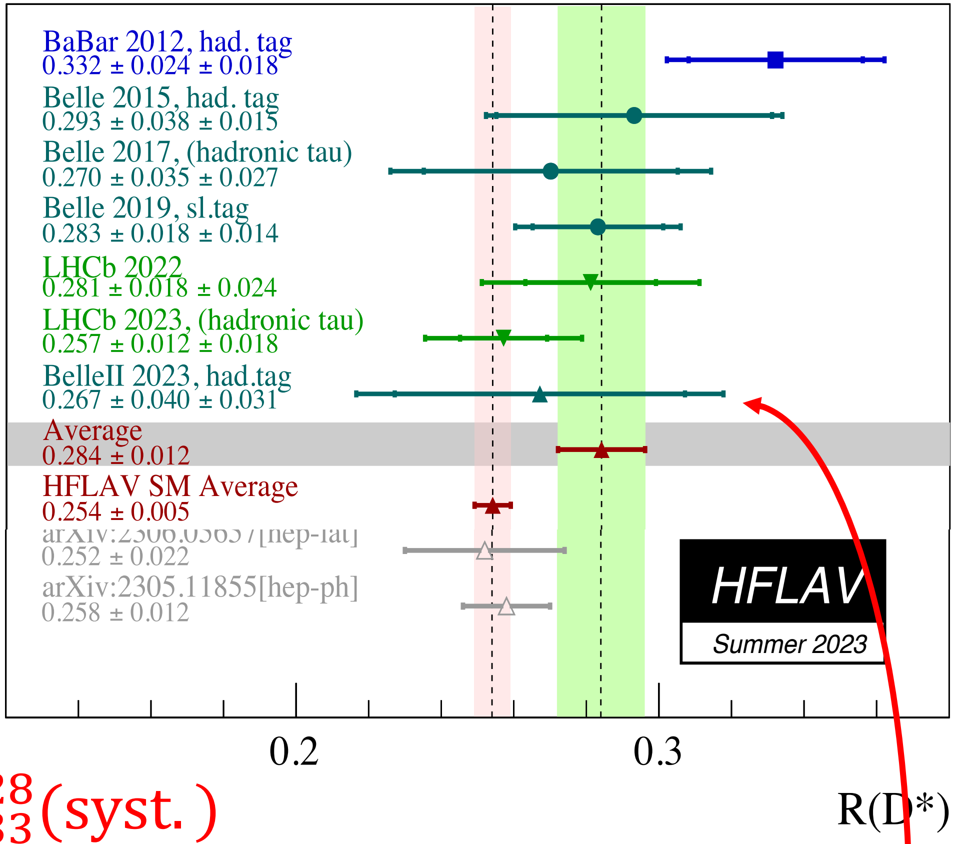
- Constrain the fake D^* yields in the signal regions with calibration factors at the ΔM_{D^*} side bands.



$R(D^*)$ post-fit results







This measurement

- First $R(D^*)$ result from Belle II

$$R(D^*) = 0.267^{+0.041}_{-0.039}(\text{stat.})\,^{+0.028}_{-0.033}(\text{syst.})$$

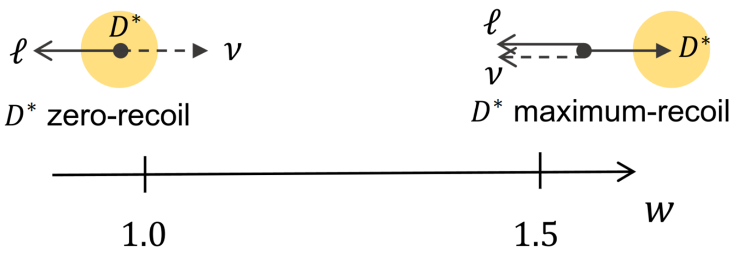
- 40% improvement in statistical precision over Belle result at the same sample size
- Systematic uncertainties dominated by PDF uncertainties and simulated sample size
- Result consistent with both SM prediction and HFLAV average

Light-lepton Universality test in angular asymmetries

Light-lepton flavour universality in $\bar{B} \to D^* \ell^- \bar{\nu}$

- Beyond the Standard Model effects in $R(D^{(*)})$ could affect angular asymmetries in $\bar{B} \to D^* \ell^- \bar{\nu}$ [Phys. Rev. D 106, 096015 (2022)]
- This effect could induce a violation of the light-lepton (e, μ) flavour universality
- Five angular asymmetries of e, μ in $\bar{B} \to D^* \ell^- \bar{\nu}$ are tested via the difference in angular observables:

$$\Delta\mathcal{A}_x(\mathrm{w}) = \mathcal{A}_x^e(\mathrm{w}) - \mathcal{A}_x^\mu(\mathrm{w})$$



Recoil parameter (w)

Angular Observable

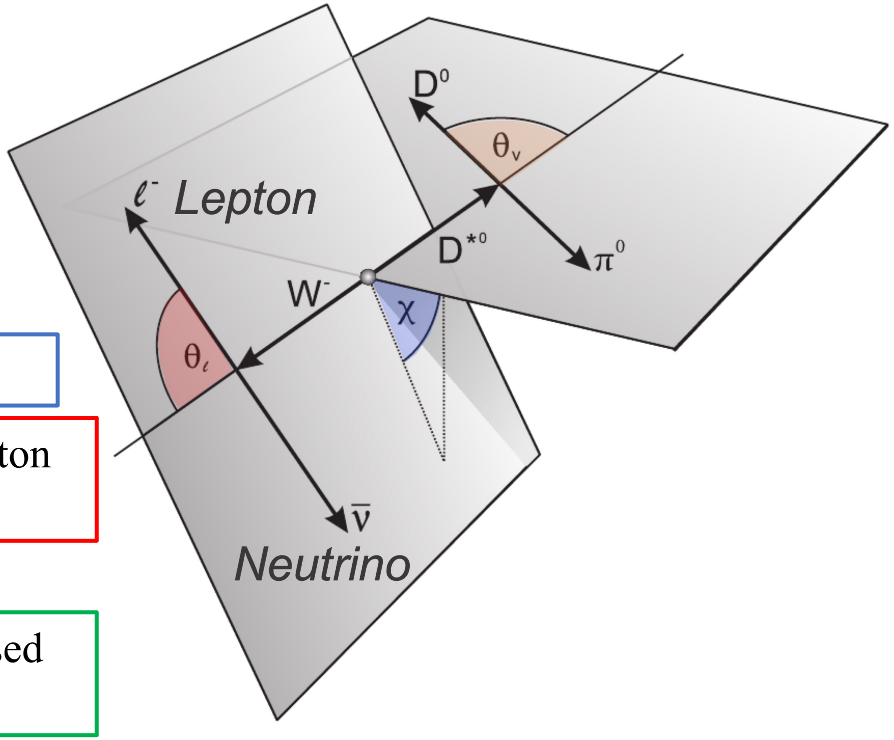
$$\mathcal{A}_x(w) = \left(\frac{d\Gamma}{dw}\right)^{-1} \left[\int_0^1 - \int_{-1}^0\right] dx \frac{d^2\Gamma}{dw dx} \qquad w = \frac{m_B^2 + m_{D^*}^2 - (p_B - p_{D^*})^2}{2 m_B m_{D^*}}$$

$\mathcal{A}_x(\mathrm{w})$	dx
$A_{FB}(w)$	$d(\cos\theta_\ell)$
$S_3(w)$	$d(\cos 2\chi)$
$S_5(w)$	$d(\cos\chi\cos\theta_V)$
$S_7(w)$	$d(\sin\chi\cos\theta_V)$
$S_9(w)$	$d(\sin 2\chi)$

Commonly analysed

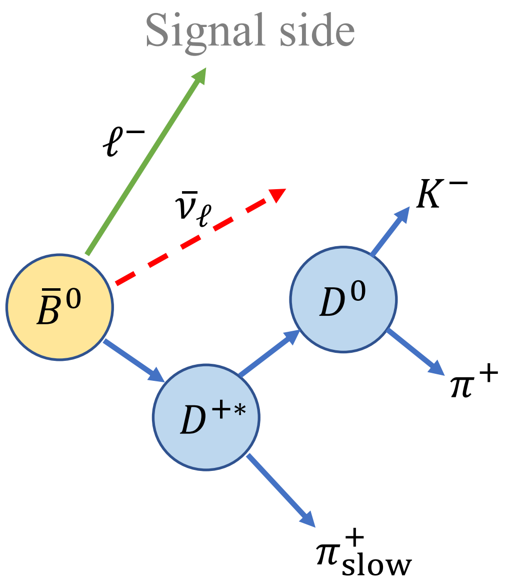
Highly sensitive to lepton flavour universality

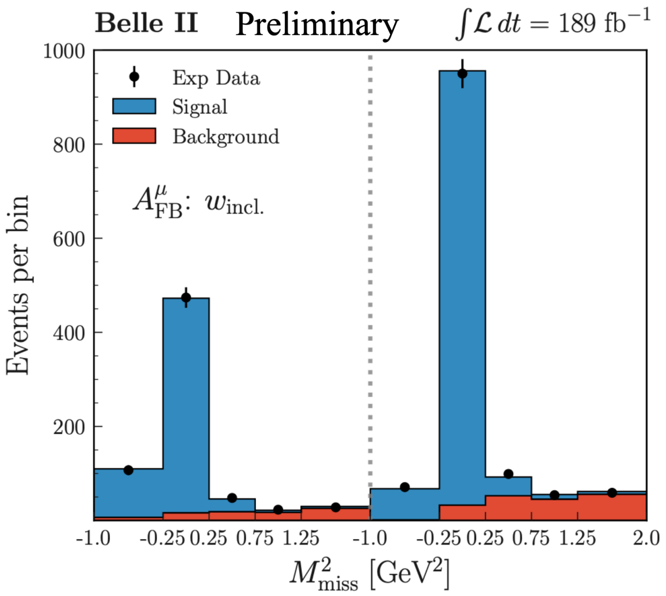
Reduced sensitivity, used as control



Helicity Angles ($\theta_\ell, \theta_V, \chi$)

$\bar{B} \to D^{*}\ell^{-}\bar{\nu}$ reconstruction





$\cos\theta_\ell \in [-1,0)$ $\cos\theta_\ell \in [0,1]$

- Tag one B-meson from *hadronic* decays – same as $R(D^*)$
- Analyse remaining B-meson(**signal side**)
- Reconstruction of

  $\Rightarrow \overline{B^0} \to (D^{*+} \to D^0\pi^+)\ell^-\bar{\nu}$
- Require momentum of lepton above 0.4 GeV
- No tracks remaining apart from the ones used in reconstruction
- Constrain mass of D^{*+} to be as close as possible to PDG value for each event

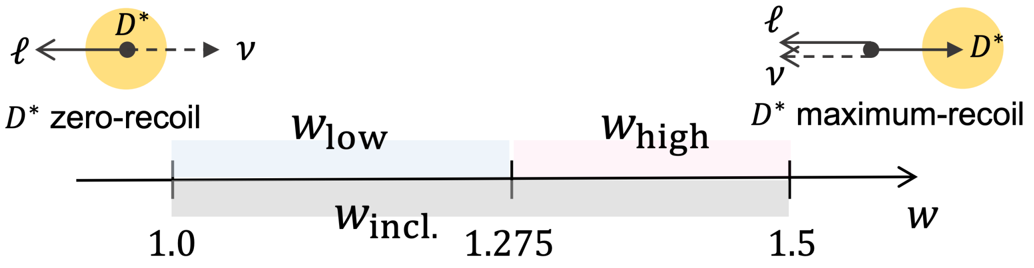
Angular Asymmetries extraction

- The first universality test using a full set of angular observables as function of recoil w
- 1D binned maximum-likelihood fit to missing mass squared (M^2_{miss})
- To maximise sensitivity to SM extensions, w separated into $w_{low}, w_{high}, w_{inc}$

$$\mathcal{A}_x(w) = \left(\frac{d\Gamma}{dw}\right)^{-1}\left[\int_0^1 - \int_{-1}^0\right] dx \frac{d^2\Gamma}{dwdx}$$

$$M^2_{miss} = \left(p_{e^+e^-} - p_{B_{tag}} - p_{D^*} - p_\ell\right)^2$$

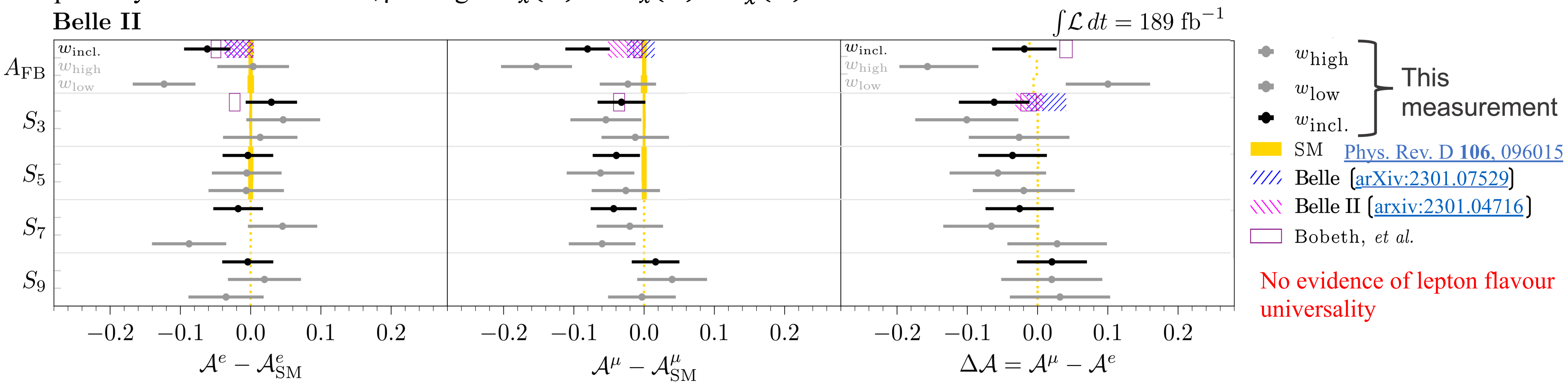
$$A_{FB}: dx = d(\cos\theta_\ell)$$



$\chi^2/N_{dof} = 2.0/3$ ($p = 0.57$) on A_{FB}, S_3, S_5 - w_{inc}

$\chi^2/N_{dof} = 10.2/6$ ($p = 0.13$) on A_{FB}, S_3, S_5 - $w_{high,low}$

- Compare asymmetries between e, μ using $\Delta\mathcal{A}_x(w) = \mathcal{A}^e_x(w) - \mathcal{A}^\mu_x(w)$



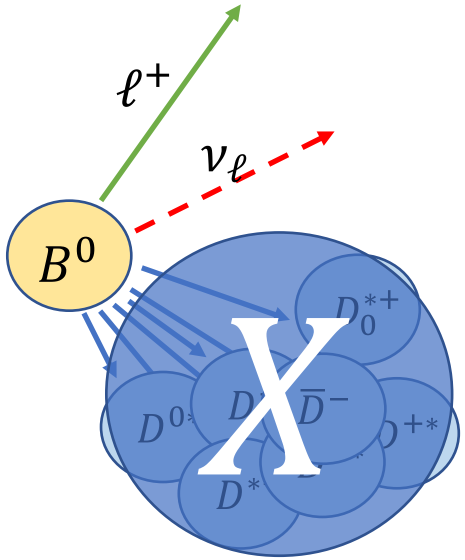
No evidence of lepton flavour universality

Light-lepton Universality test in $R(X_{e/\mu})$

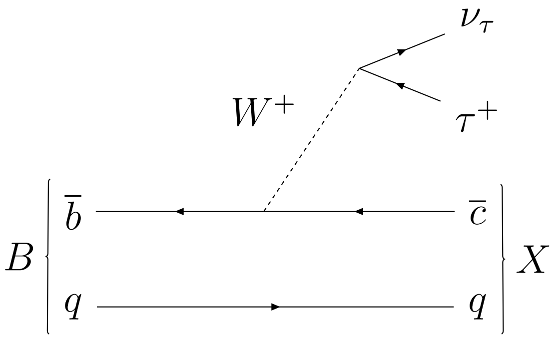
Light-lepton flavour universality in $R(X_{e/\mu})$

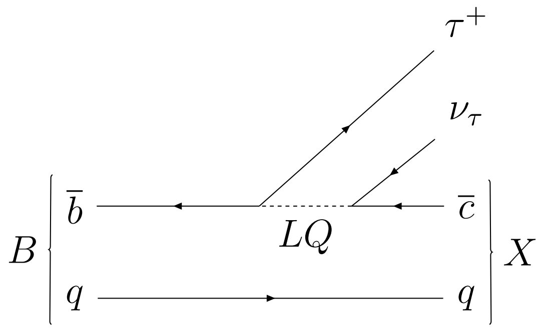
- As a first step towards measuring $R(X_{\tau/\ell})$, we measure $R(X_{e/\mu})$
- Beyond the Standard Model effects in $R(X_{\tau/\ell})$ could affect the light lepton ratio in $R(X_{e/\mu})$

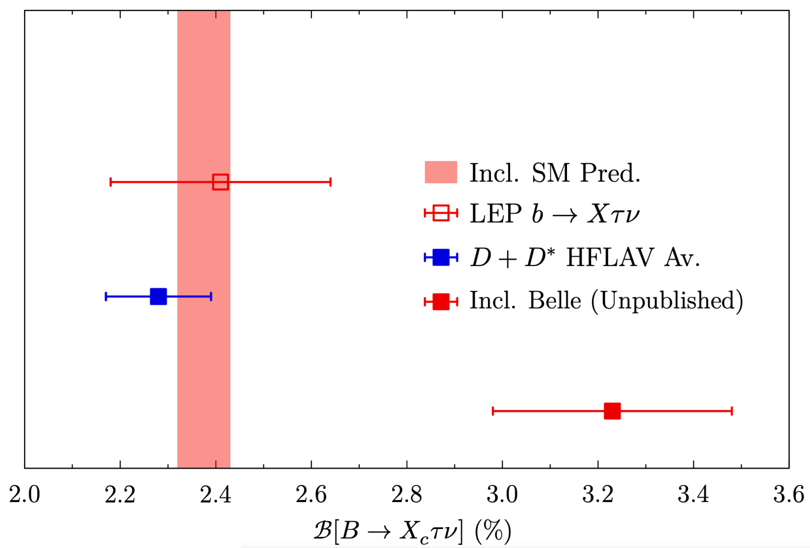
$$R(X_{e/\mu}) = \frac{Br(B \to Xe\nu)}{Br(B \to X\mu\nu)}$$



- X is the hadronic final state of semileptonic decay from $b \to c\ell\nu$, rarely $b \to u\ell\nu$
- Various leptoquark models have been presented to explain anomalies in $b \to c\ell\nu$







- Inclusive reconstruction of the charm system signal-side B
- $p_\ell^B > 1.3$ GeV/c to suppress background

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

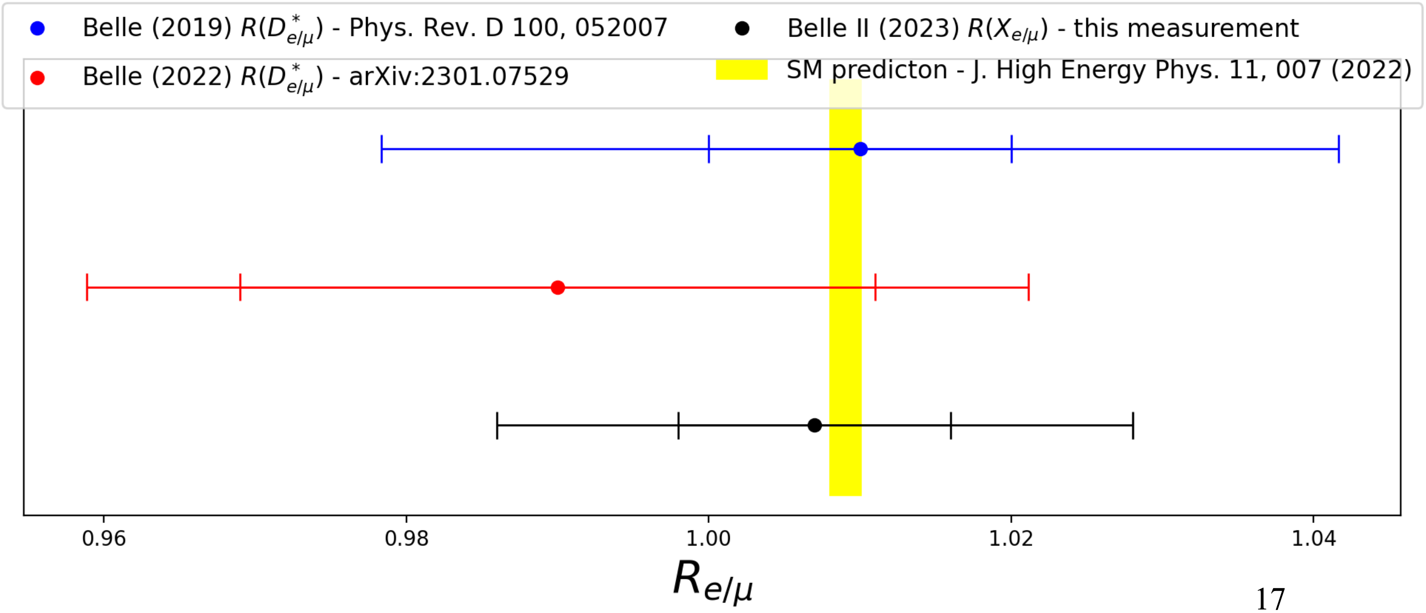
Phys. Rev. Lett. 131, 051804 (2023)

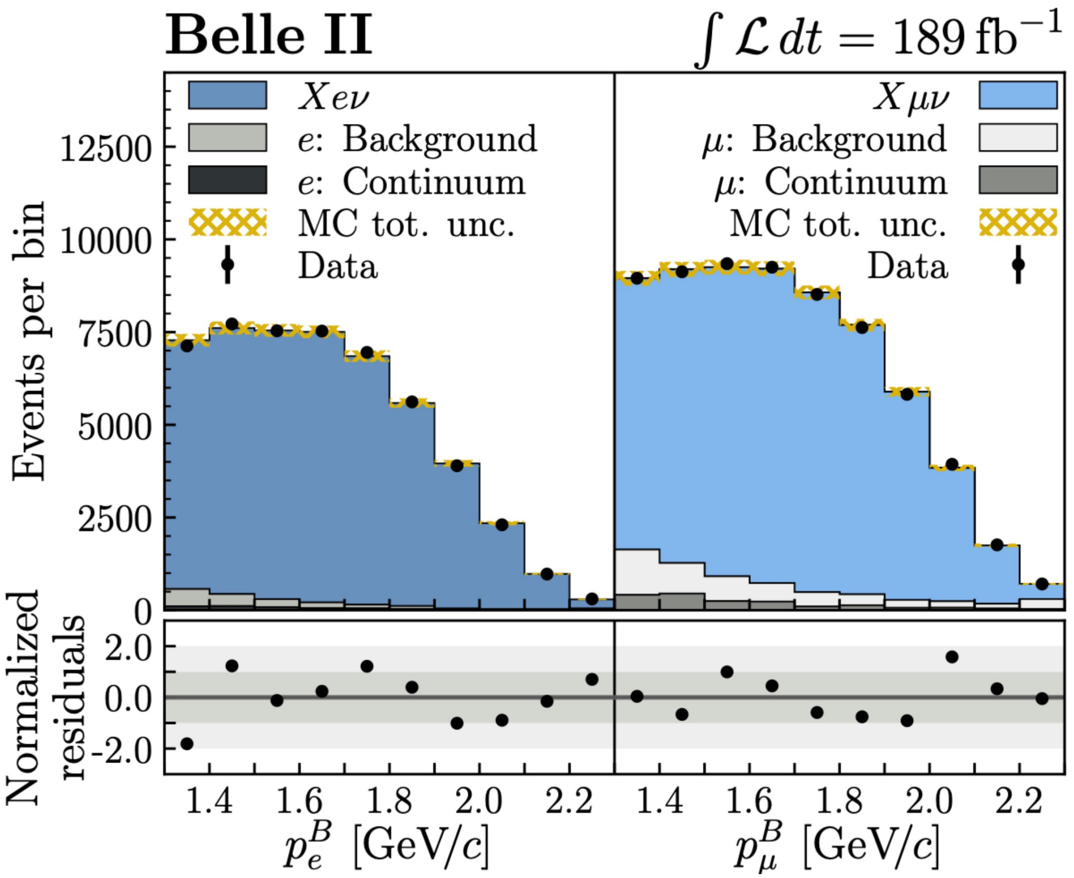
- 1D binned maximum-likelihood fit to lepton momentum of signal *B* rest-frame
- Control channel (B^0B^0/ B^+B^+) constrains background yield in signal channel ($B^0\bar{B}^0$/ B^+B^-) through simultaneous fit
- *e* and *μ* templates are fitted simultaneously in **10 p_ℓ^B bins** each

$$R(X_{e/\mu}) = 1.007 \pm 0.009\,(\text{stat.}) \pm 0.019\,(\text{sys.})$$

✓ **Most precise LFU test with semileptonic *B* decays to date!**

✓ Measurement systematically limited by lepton ID-based uncertainties





Signal channel ($B^0\bar{B}^0$/ B^+B^-) post-fit plot

Summary

Lepton Flavour Universality tests shed light on $b \to c$ decays anomalies.

Current deviations from the Standard Model expectations of $> 3\sigma$ characterise these anomalies.

Belle II performed three measurements to test lepton flavour universality:

- The first $R(D^*)$ result from Belle II

$$R(D^*) = 0.267^{+0.041}_{-0.039}(\text{stat.})^{+0.028}_{-0.033}(\text{syst.})$$

Consistent with both SM prediction and HFLAV average

- The first universality test using angular observables as function of recoil w

Consistent with Standard Model prediction

- The most precise Lepton Flavour Universality test with semileptonic B-decays to date

$$R(X_{e/\mu}) = 1.007 \pm 0.009\,(\text{stat.}) \pm 0.019\,(\text{sys.})$$

Consistent with Standard Model prediction