An *ALpine Particle physics Symposium*
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Recent Belle II results related to flavor anomalies

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On behalf of the Belle II collaboration

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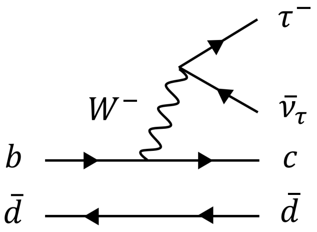
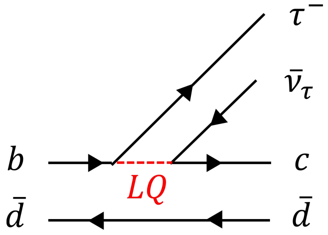
Anomalies in $b \to c$ decays

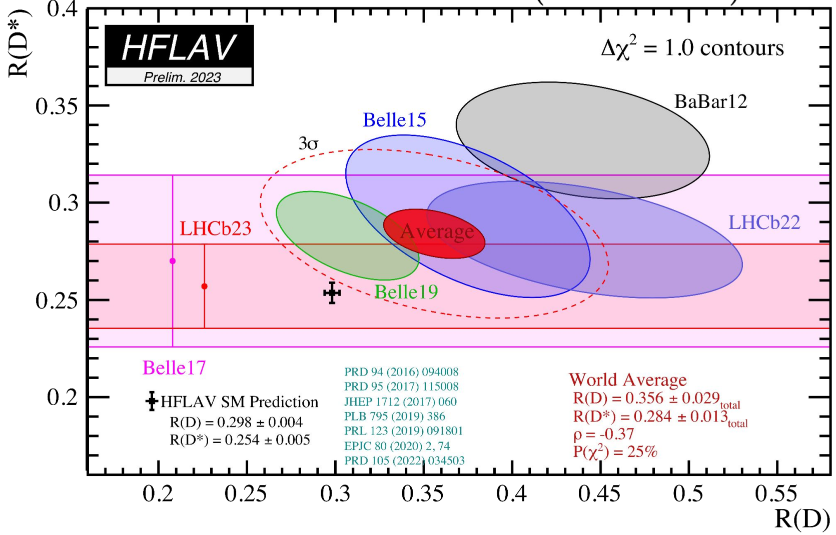
$$\mathcal{R}(D^{(*)}) = \frac{\mathcal{B}(B \to D^{(*)}\tau\nu)}{\mathcal{B}(B \to D^{(*)}\ell\nu)}$$

Standard Model assumes **lepton flavor universality** (LFU): $g_e = g_\mu = g_\tau$

- Observed ~3σ tension in $R(D^{(*)})$ could hint possible new physics scenarios





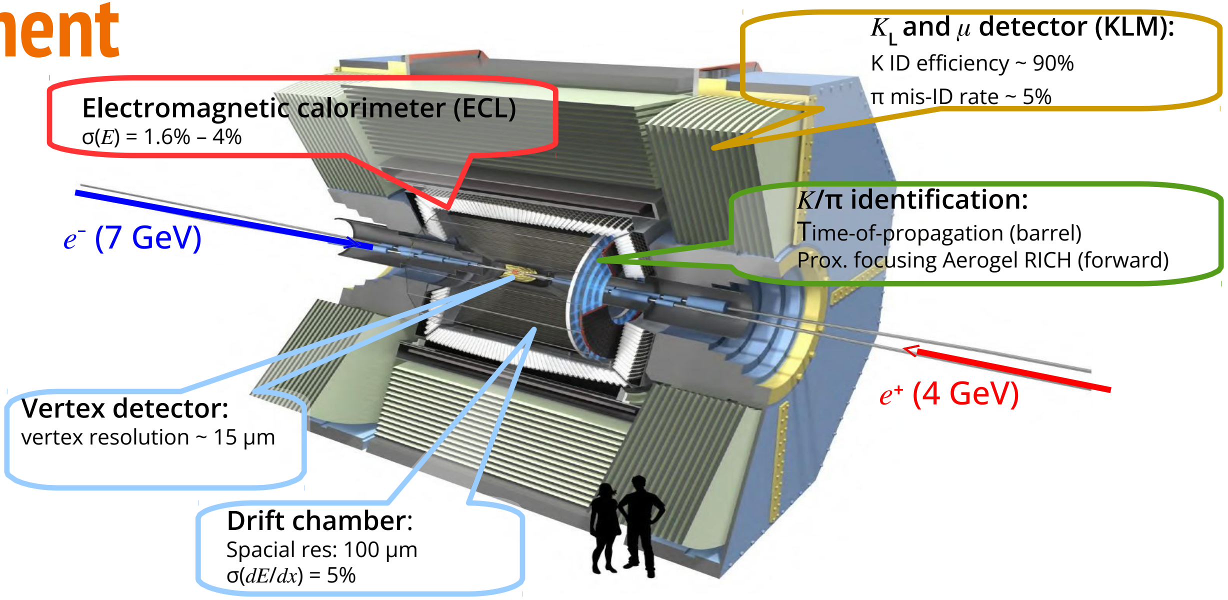


We present recent Belle II tests for LFU in **light leptons** (e/μ) for **semileptonic b decays**:

- Fully inclusive $\mathcal{R}(X_{e/\mu}) = \dfrac{\mathcal{B}(B \to Xe\nu)}{\mathcal{B}(B \to X\mu\nu)}$
- $B \to D^*\ell\nu$ angular asymmetries

The Belle II experiment

- Running at E_{CM}= 10.58 GeV
  $\Upsilon(4S) \rightarrow B\overline{B}$
- World-record instantaneous luminosity: **4.7 x 10^{34} $cm^{-2}s^{-1}$**
- By summer 2022:
  $\int \mathscr{L}\, dt$ = 424 fb^{-1}
  - 189 fb^{-1} in following analysis



- Multi purpose detector
- **Hermetic** (~ 4π acceptance)
  - combined with knowledge of initial collision → good reconstruction of missing neutrinos

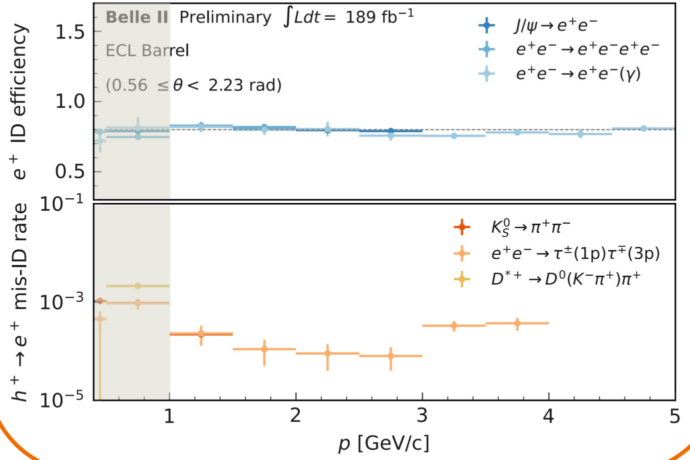
Lepton Identification

Crucial for any LFU test

- **Efficiencies** and **fake rates** measured on different well-known control channels [BELLE2-CONF-PH-2022-003]

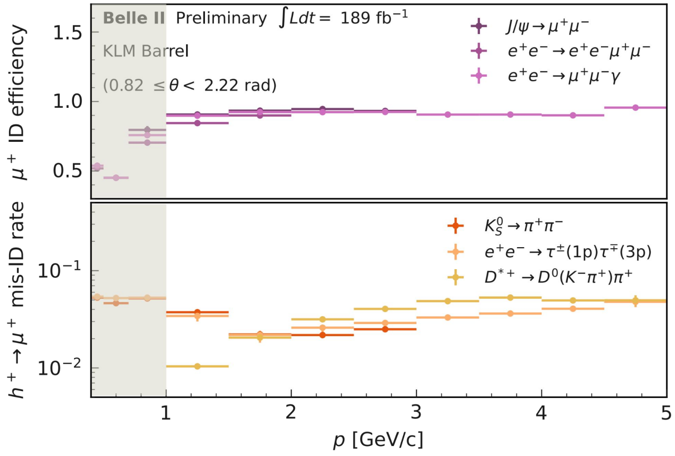
Electron ID

BDT exploiting **calorimeter** information

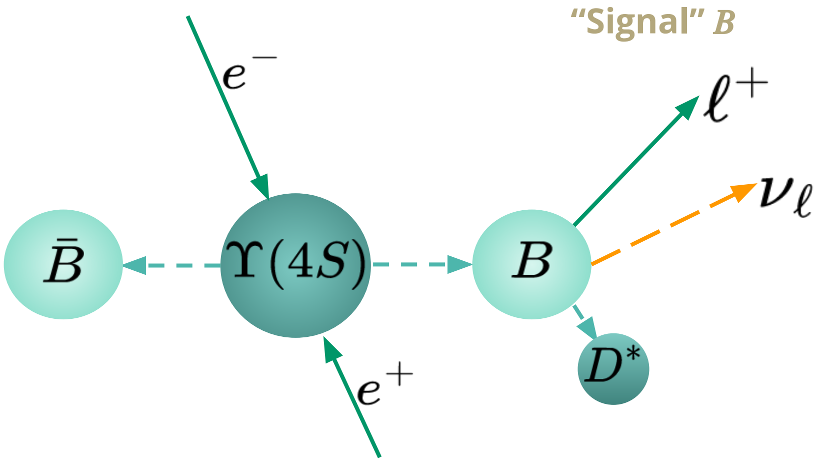


Muon ID

Combine likelihoods from **all sub-detectors** (calorimeter and μ detector are the most important)

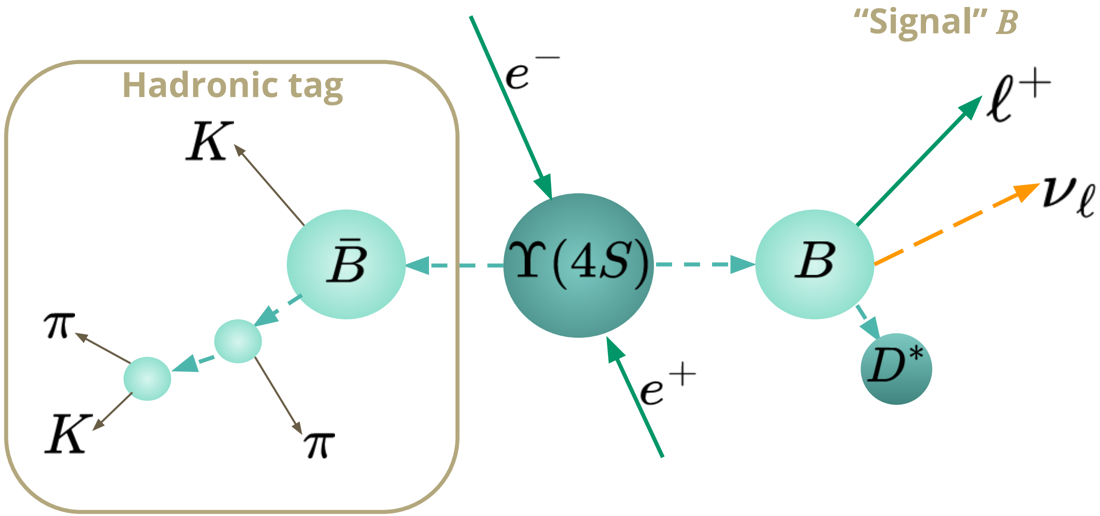


Event reconstruction



B-mesons are produced in pairs with opposite flavors

Event reconstruction



$\varepsilon_{tag} = \mathcal{O}(0.1\%)$

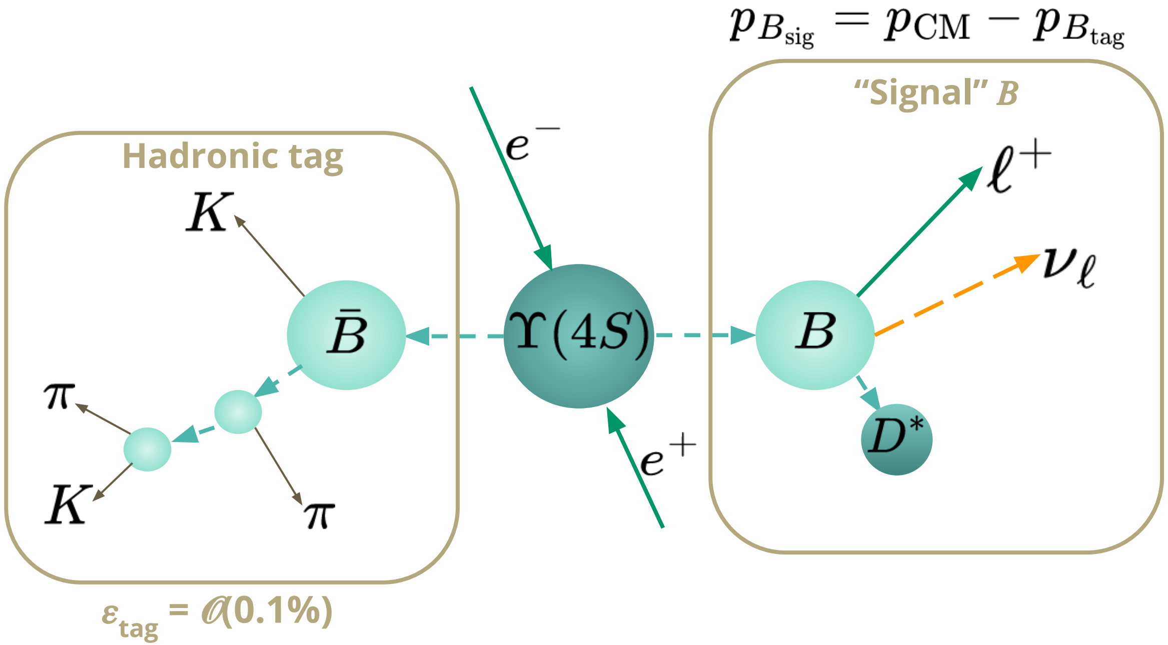
B-mesons are produced in pairs with opposite flavors

- Tag a B-meson (B_{tag}) in fully hadronic decays
  - $\mathcal{O}(0.1\%)$ efficiency of correctly reconstructed B_{tag}

BDT-based algorithm: **Full Event Interpretation** Comput Softw Big Sci 3, 6 (2019)

- B-tagging efficiency higher than Belle and BaBar algorithms

Event reconstruction



B-mesons are produced in pairs with opposite flavors

- Tag a B-meson (B_{tag}) in fully hadronic decays
  - $\mathcal{O}(0.1\%)$ efficiency of correctly reconstructed B_{tag}
- The other B-meson has well-defined energy and momentum

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

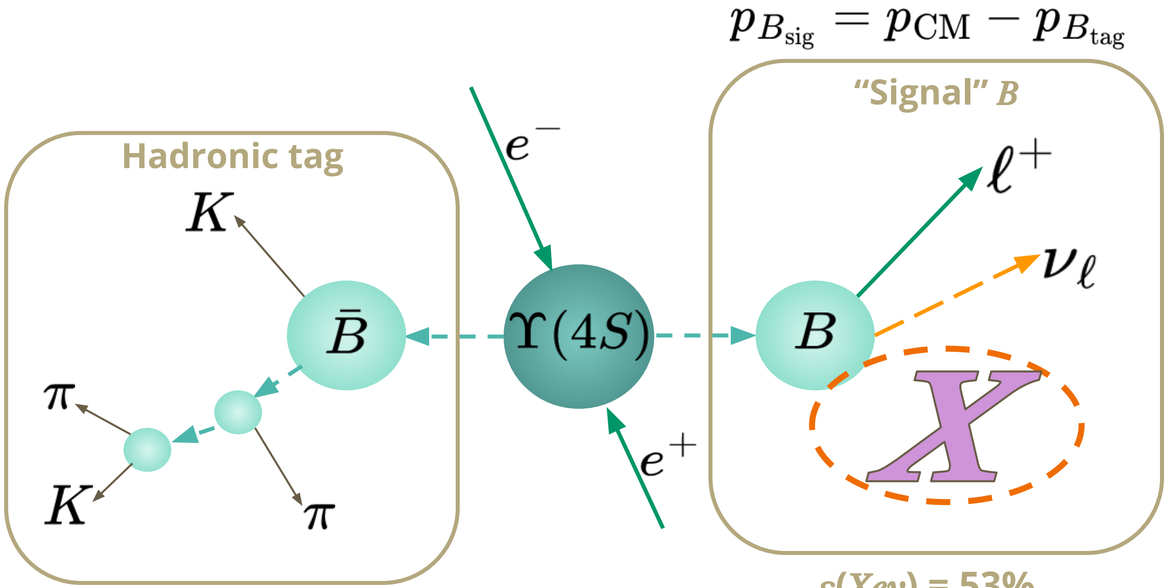
$R(X_{e/\mu})$

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

- Precise test of LFU for **light** leptons in semileptonic $b \to c\ell\nu$
- First fully inclusive $R(X_{e/\mu})$ measurement
- Preparation for measuring inclusive $R(X_{\tau/\ell})$ = ($B \to X\tau\nu$ / $B \to X\ell\nu$)

arXiv:2301.08266 (submitted to PRL)

$R(X_{e/\mu})$ event selection



$\varepsilon_{\rm tag} = \mathcal{O}(0.1\%)$

$\varepsilon(Xe\nu) = 53\%$
$\varepsilon(X\mu\nu) = 66\%$

- Tag a B-meson ($B_{\rm tag}$) in **fully hadronic** decays
- Lepton momentum in $B_{\rm sig}$ rest-frame: p_ℓ^B **> 1.3 GeV/*c***
  - reduce fakes and secondary leptons
  - suppress leptons from $B \to X\tau\nu$
  - if more leptons, keep the one with highest lepton-ID probability
- Rest of the event assigned to fully–inclusive X

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

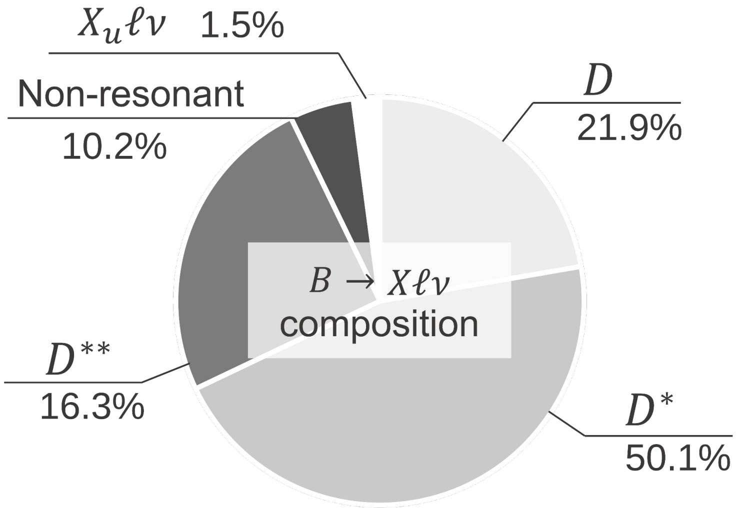
Extract signal yields N^{meas} by fit in 10 bins of p_ℓ^B (simultaneously for e and μ-channel)

- Maximize binned likelihood, systematics included as nuisance parameters
- 3 model templates (for e, μ separately)

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

Extract signal yields N^{meas} by fit in 10 bins of p_ℓ^B (simultaneously for e and μ-channel)

- Maximize binned likelihood, systematics included as nuisance parameters
- 3 model templates (for e, μ separately):
  - $X\ell\nu$ **signal**



Signal modelling:

- $B \to D^{(*)}\ell\nu$: BGL **form-factor** parametrization Phys. Rev. Lett. 74, 4603 (1995), Phys. Rev. D 103, 073005 (2021)
- $B \to D^{**}\ell\nu$: BLR model (form-factor) Phys. Rev. D 97, 075011(2018), Phys. Rev. D 95, 014022 (2017)
- **Non-resonant** "gap-modes" $B \to D^{(*)}\pi\pi\ell\nu$, $B \to D^{(*)}\eta\ell\nu$: treated as from $B \to D^{**}\ell\nu$

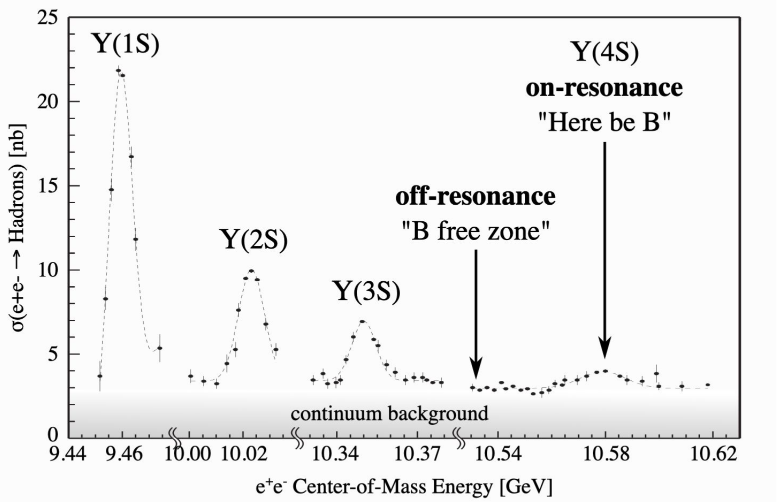
$R(X_{e/\mu})$ yields extraction

Extract signal yields N^{meas} by fit in 10 bins of p_ℓ^B (simultaneously for e and μ-channel)

- Maximize binned likelihood, systematics included as nuisance parameters
- 3 model templates (for e, μ separately):
  - $X\ell\nu$ signal
  - **continuum** background

Data-driven constraint:

- Use additional 18 fb^{-1} of **off-resonance** data: 60 MeV below $\Upsilon(4S) \Rightarrow$ no $B\bar{B}$
- Scale cross-section to account for CM energy difference



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

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- Maximize binned likelihood, systematics included as nuisance parameters
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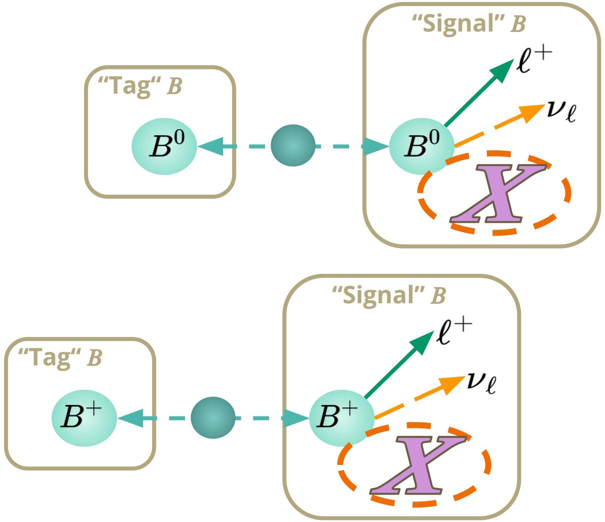
  - $X\ell\nu$ signal
  - continuum background
  - **other backgrounds** (fakes and secondaries)

Data-driven normalization:

- Exploit background-enriched **control channel**: same flavor for reconstructed B_{tag} and B_{sig}



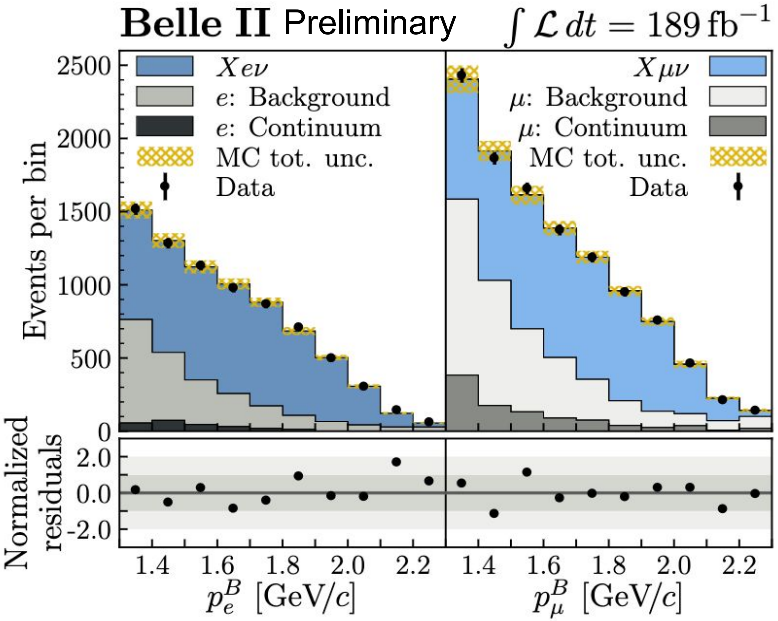
$R(X_{e/\mu})$ yields extraction

Extract signal yields N^{meas} by fit in 10 bins of $p_\ell{}^B$ (simultaneously for e and μ-channel)

- Maximize binned likelihood, systematics included as nuisance parameters
- 3 model templates (for e, μ separately):
  - $X\ell\nu$ signal
  - continuum background
  - **other backgrounds** (fakes and secondaries)

Data-driven normalization:

- Exploit background-enriched **control channel**: same flavor for reconstructed B_{tag} and B_{sig}
- Derive correction factors from **fit** to control channel



$R(X_{e/\mu})$ – results

Obtain N^{meas} by fit on signal-region data and evaluate $R(X)$, reweighting for signal efficiency:

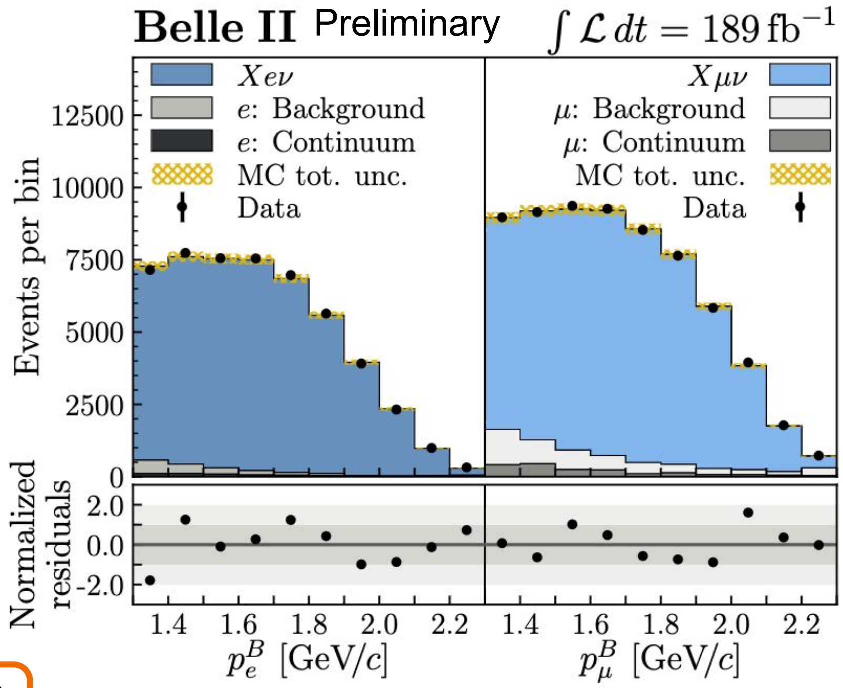
$$R(X_{e/\mu}) = \frac{N_e^{\text{meas}}}{N_\mu^{\text{meas}}} \cdot \frac{\varepsilon_\mu}{\varepsilon_e}$$

Signal **efficiency** ε for each channel (including B_{tag} efficiency) :

$$\varepsilon_\ell = \frac{N_\ell^{\text{sel}}}{N_\ell^{\text{gen}}} \qquad \begin{aligned} \varepsilon_e &= (1.62 \pm 0.03) \times 10^{-3} \\ \varepsilon_\mu &= (2.04 \pm 0.05) \times 10^{-3} \end{aligned}$$

- N^{sel} → signal yield extracted from simulation
- N^{gen} → total generated signal events

$$R(X_{e/\mu}) = 1.033 \pm 0.010(\text{stat}) \pm 0.019(\text{syst})$$



$R(X_{e/\mu})$ – systematics

Source	Uncertainty [%]
Sample size	1.0
Lepton identification	1.9
$X_c \ell \nu$ branching fractions	0.1
$X_c \ell \nu$ form factors	0.2
Total	2.2

- **Lepton-ID** efficiency and misidentification
- Other systematics mostly cancel in e/μ ratio:
  - form factor and BR uncertainties
  - B_{tag} efficiency corrections are the same for the two channels
- Check model-dependence recomputing efficiency with generated $p_\ell^B > 1.3$ GeV/c
  - result consistent with nominal one

$$R(X_{e/\mu}) = 1.033 \pm 0.010(\text{stat}) \pm 0.019(\text{syst})$$

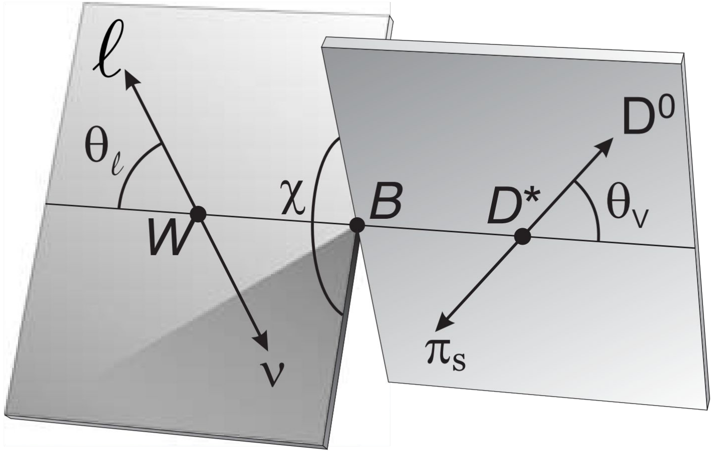
arXiv:2301.08266 (submitted to PRL)

SM JHEP11(2022)007	$R(X_{e/\mu})_{\text{SM}} = 1.006 \pm 0.001$

$B^0 \to D^* \ell \nu$ angular asymmetries

NEW

$B^0 \to D^* \ell \nu$ angular asymmetries

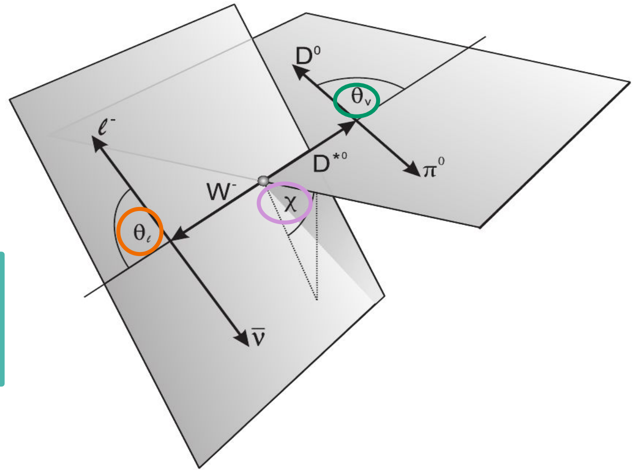


Study semileptonic B decays to D* vector

- **4 parameters** to fully describe $B \to D^* \ell \nu$ decay:
  - $\ell \nu$ invariant mass $q^2 = (p_B - p_{D^*})^2$
  - 3 helicity angles $\theta_\ell,\ \theta_V,\ \chi$
- Properties of $V - A$ **coupling** and **spin of virtual** W **boson** are encoded in angular distributions

We measure **asymmetries** of these **angular distributions** versus q^2

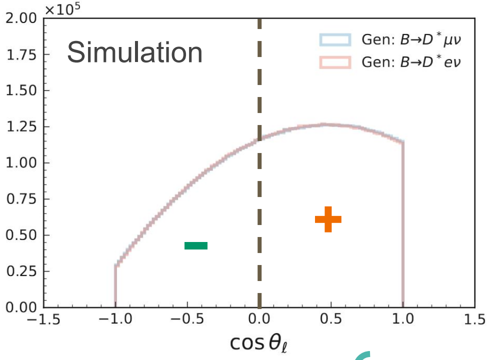
$B^0 \to D^* \ell \nu$ angular asymmetries



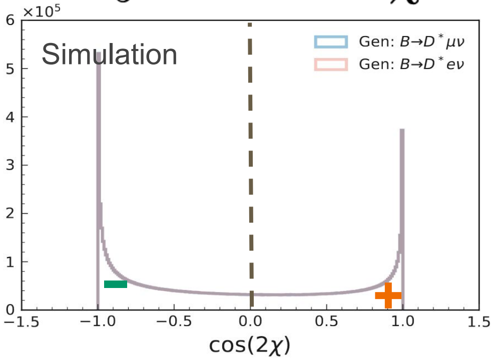
Define a set of 5 asymmetries for angular observables x

$$\mathcal{A}_x = \frac{\int_0^1 \frac{d\Gamma}{dx} dx - \int_{-1}^0 \frac{d\Gamma}{dx} dx}{\Gamma}$$

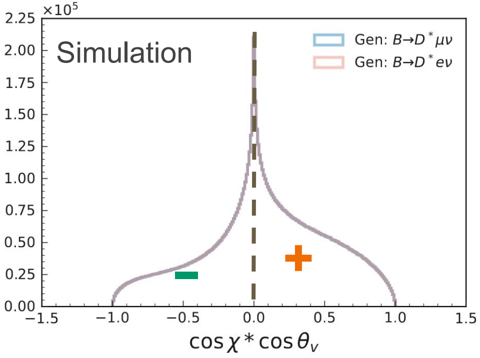
$$A_{\mathrm{FB}} : x = \cos\theta_\ell$$



$$S_3 : x = \cos 2\chi$$



$$S_5 : x = \cos\chi \cos\theta_V$$



Similarly, define:

$$S_7 : x = \sin\chi \cos\theta_V$$

$$S_9 : x = \sin 2\chi$$

LFU in $B^0 \to D^* \ell \nu$ angular asymmetries

[Phys. Rev. D 107, 015011 (2023)]

Test e/μ universality through the asymmetry difference:

$$\Delta\mathcal{A} = \mathcal{A}(B \to D^* \mu\nu) - \mathcal{A}(B \to D^* e\nu)$$

- Asymmetries $\mathscr{A}$ are **experimentally clean** (large cancellations of systematics)
- $\Delta\mathscr{A}$ difference is **theoretically well-known** (reduced form-factor uncertainty)

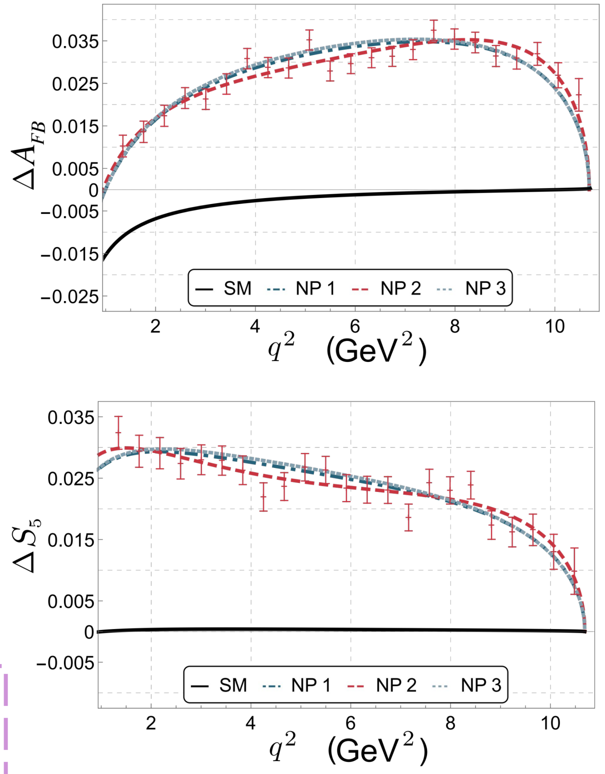
ΔA_{FB} ΔS_3 ΔS_5

sensitive to LFU violation

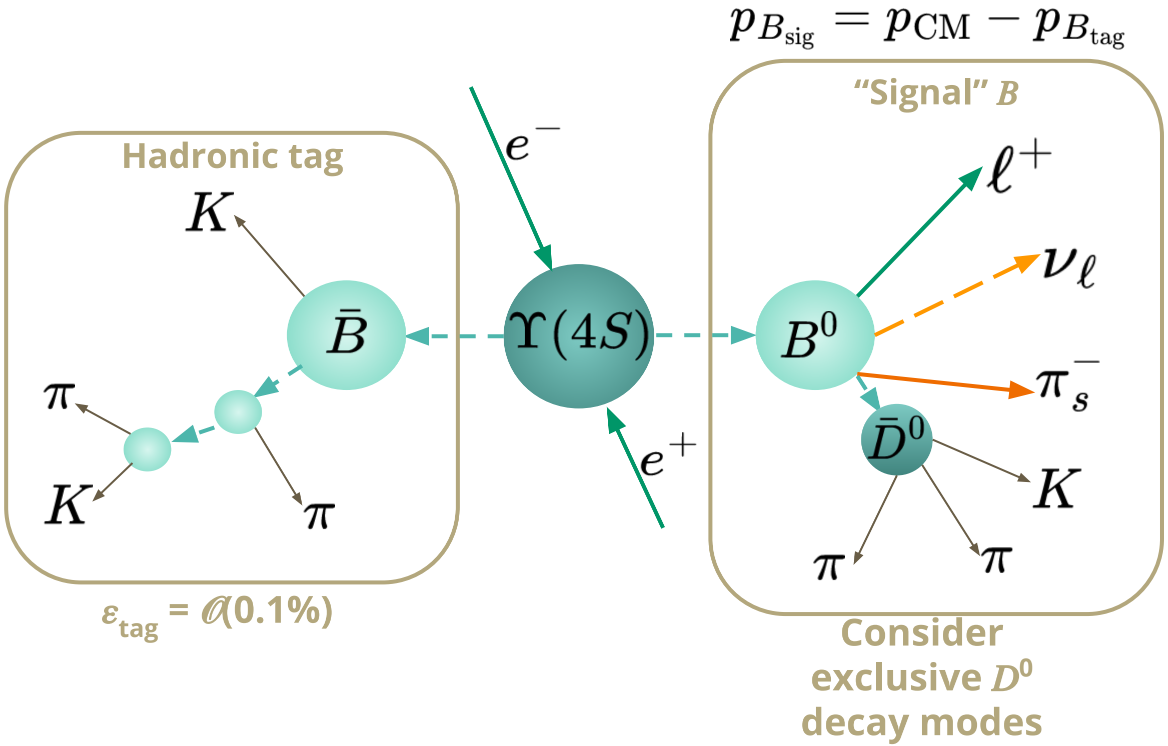
ΔS_7 ΔS_9

reduced or no sensitivity to new physics (used as cross-check)

~4σ deviation in ΔA_{FB} was claimed by theoretical reinterpretation of Belle data [Eur. Phys. J. C 81, 984 (2021), Phys. Rev. D 103, 079901 (2021)]



$B^0 \to D^* \ell \nu$ event selection



- Fully reconstruct a B-meson (B_{tag}) in **hadronic decay**
- Reconstruct signal-side $D^*\ell\nu$ **exclusively**
  - select one lepton with $p_\ell >$ 0.4 GeV/c
  - look for clean and abundant D^0 decay modes
  - combine with a charged slow pion: $D^* \to D^0\pi_s$

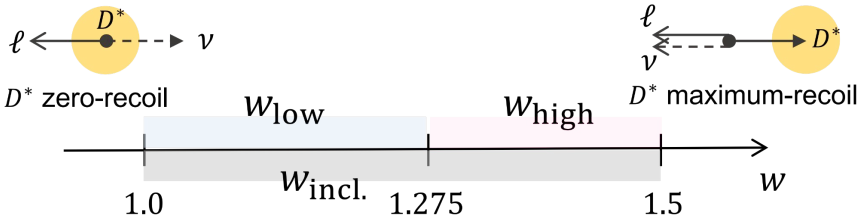
$B^0 \to D^* \ell \nu$ angular asymmetry measurement

Measure **asymmetry** for each angular observable and for each lepton ($\ell = e, \mu$)

$$\mathcal{A}_x = \frac{N_x(+) - N_x(-)}{N_x(+) + N_x(-)} \qquad x = \begin{cases} \cos\theta_\ell \\ \cos 2\chi \\ \cos\chi\cos\theta_V \\ \sin\chi\cos\theta_V \\ \sin 2\chi \end{cases} \qquad \begin{aligned} N_x(+) &= N(x > 0) \\ N_x(-) &= N(x < 0) \end{aligned}$$

Consider three q^2 **regions**:

- Use D^* **recoil parameter** w: product of B and D^* four-velocity (it is proportional to $-q^2$)
  - $w_{\text{low}} < 1.275$
  - $w_{\text{high}} > 1.275$
  - $w_{\text{incl.}} \to$ full phase-space



$$w = \frac{m_B^2 + m_{D_*}^2 - q^2}{2 m_B m_{D^*}}$$

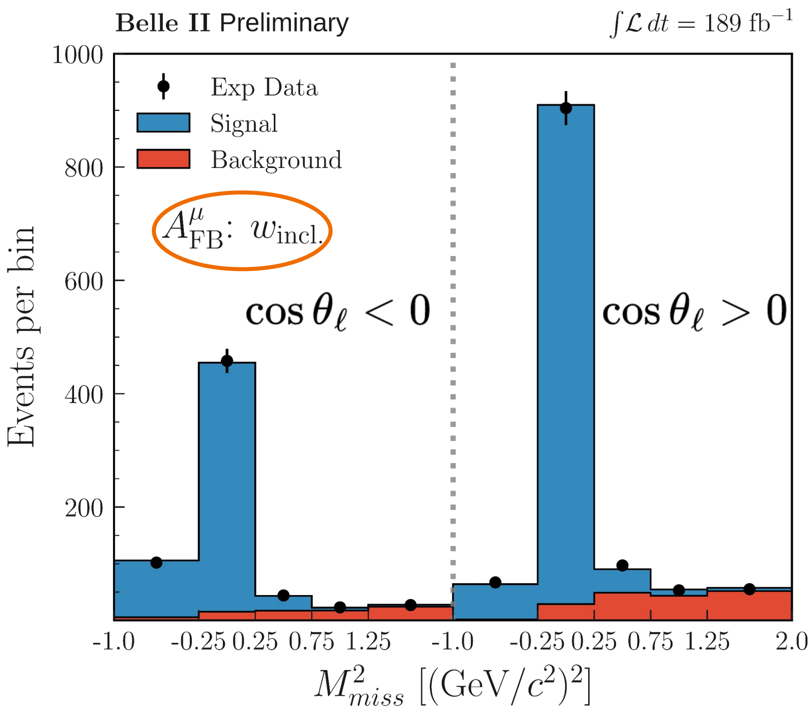
$B^0 \to D^* \ell \nu$ yields extraction

Fit M_{miss}^2 to **extract signal yields** $N(\pm)$

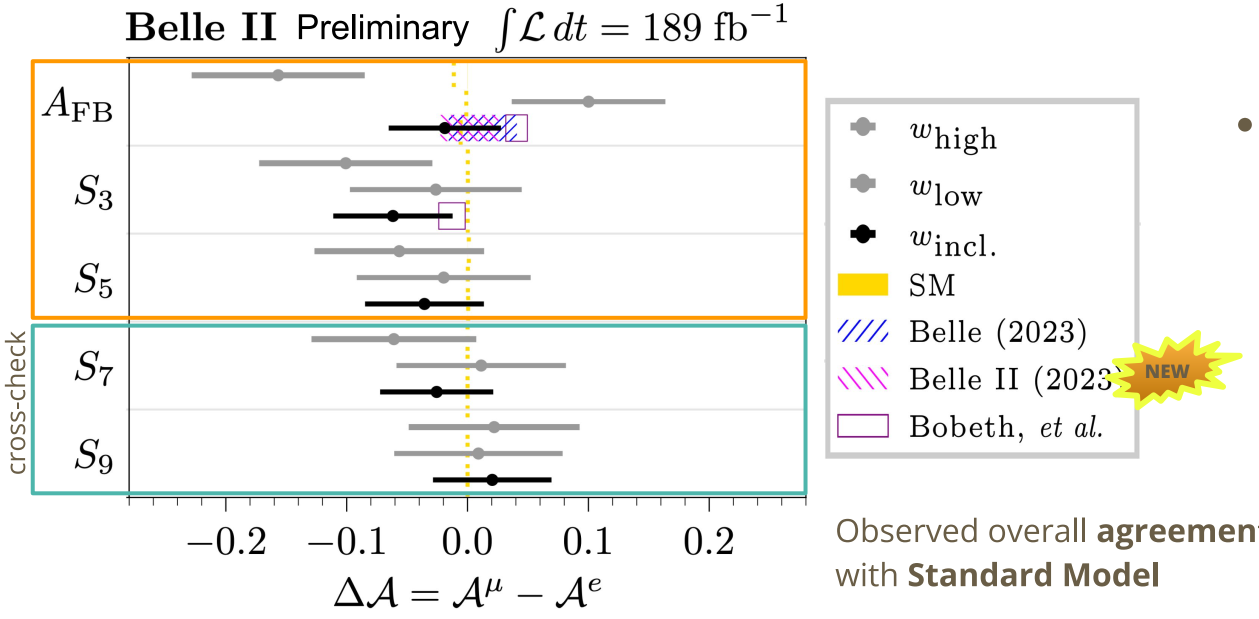
- Signal is peaked at zero M_{miss}^2
- Main background is from $B \to D^{**} \ell \nu$, with higher M_{miss}^2

Correct fitted yields for detector acceptance and efficiency

- Use detector response matrix (from simulation)
- Correct for migration of candidates between + − categories and different w-bins



LFU in $B^0 \to D^* \ell \nu$ angular asymmetries: results



Observed overall **agreement** with **Standard Model**

- **Statistical uncertainty** is dominant: ~one order of magnitude larger than systematics
- Limited size of sample to simulate detector response is the **main systematics**

Obs.	w bin	Total	Stat.	MC stat.	LID	π_{slow}
ΔA_{FB}	w_{low}	0.064	0.060	0.020	0.004	0.001
	w_{high}	0.072	0.067	0.024	0.004	0.001
	$w_{\text{incl.}}$	0.046	0.044	0.015	0.004	0.001
ΔS_3	w_{low}	0.071	0.067	0.024	0.001	0.000
	w_{high}	0.072	0.067	0.025	0.001	0.000
	$w_{\text{incl.}}$	0.049	0.046	0.017	0.001	0.000
ΔS_5	w_{low}	0.072	0.068	0.024	0.001	0.000
	w_{high}	0.070	0.066	0.023	0.001	0.000
	$w_{\text{incl.}}$	0.049	0.046	0.016	0.001	0.000
ΔS_7	w_{low}	0.070	0.066	0.023	0.001	0.001
	w_{high}	0.068	0.064	0.022	0.000	0.000
	$w_{\text{incl.}}$	0.047	0.044	0.016	0.000	0.000
ΔS_9	w_{low}	0.070	0.065	0.024	0.000	0.000
	w_{high}	0.071	0.067	0.024	0.001	0.001
	$w_{\text{incl.}}$	0.049	0.046	0.017	0.000	0.000

(*) arXiv:2301.07529
(**) Eur. Phys. J. C 81, 984 (2021) obtained in a slightly reduced $w \in [1, 1.5]$ range

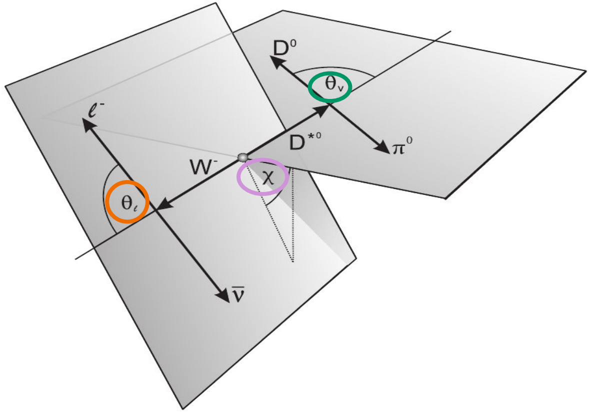
Summary

Belle II is playing a major role for LFU testing in semi-leptonic B decays

- First inclusive measurement of $R(X_{e/\mu})$ (arXiv:2301.08266 **submitted to PRL**)
  - most precise BF-based LFU e/μ test in semileptonic B-meson decays
  - consistent with Standard Model and with Belle $R(D^*_{e/\mu})$ measurements
  - $R(X_{e/\mu})$ is the first step towards $R(X_{\tau/\ell})$
- LFU in $B \to D^* \ell \nu$ angular asymmetries (**preliminary** result)
  - first comprehensive LFU test in angular distributions of semileptonic B decays
  - results agree well with Standard Model, no evidence of LFU
  - new promising method for testing LFU anomalies
  - demonstration of good experimental control. Still dominated by statistical uncertainty

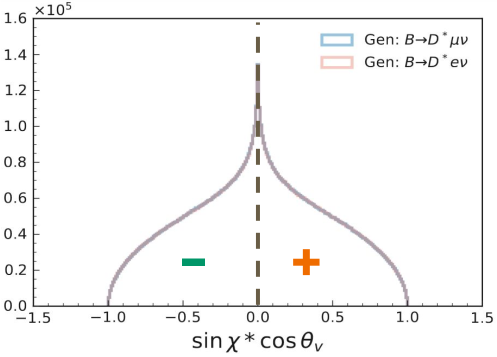
Backup

$B^0 \to D^* \ell \nu$ angular asymmetries (II)



$$\mathcal{A}_x = \frac{\int_0^1 \frac{d\Gamma}{dx} dx - \int_{-1}^0 \frac{d\Gamma}{dx} dx}{\Gamma}$$

$S_7 : x = \sin\chi \cos\theta_V$



$S_9 : x = \sin 2\chi$