Recent Belle II results related to B anomalies

Yulan Fan (DESY)
On behalf of the Belle II Collaboration

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yulan.fan@desy.de

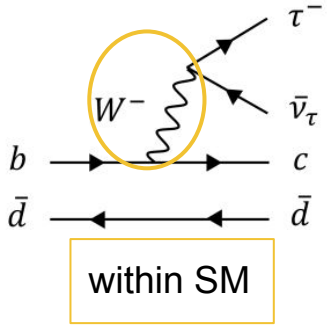
Outline

- Introduction
  - Lepton Flavour Universality
  - Belle II experiment
- Measurement of $R(X_{e/\mu})$ at Belle II
- Measurement of angular asymmetry in $B^0 \to D^* l \nu$

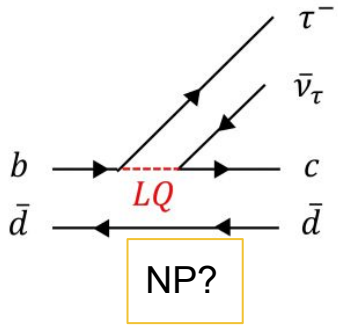
Lepton Flavour Universality

In SM, all charged leptons share the same electroweak coupling — Lepton Flavour Universality (LFU)

- Semileptonic B-meson decay involving the quark transition, e.g.
  $b \to c/s\ l\ \nu$, $b \to c/s\ l\ l$, ...
  are sensitive to probe (violation of) LFU



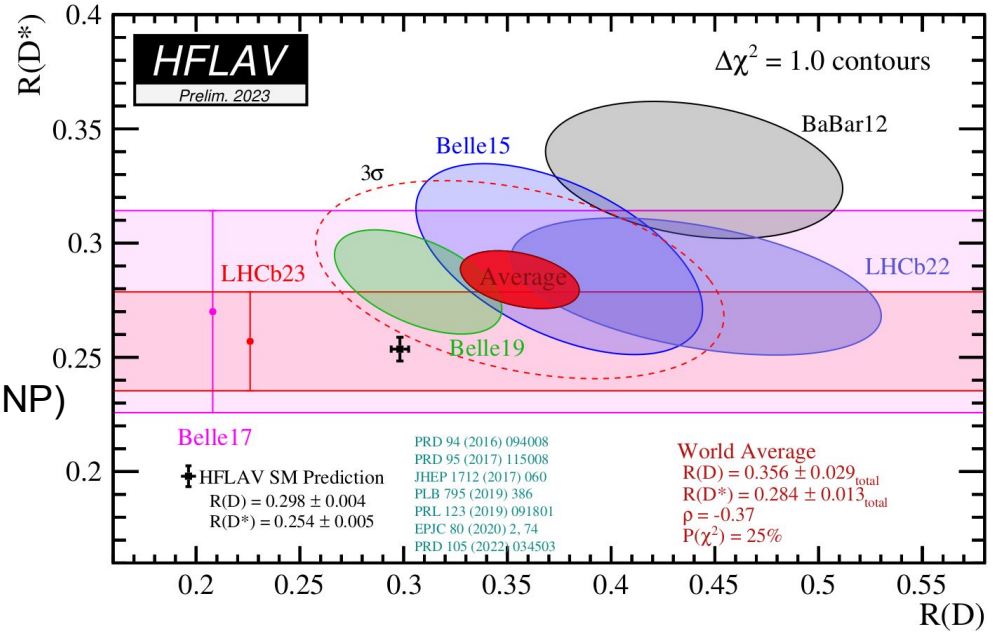
within SM



NP?

Tension in $R(D^*)$ could hint a possible new physics(NP)

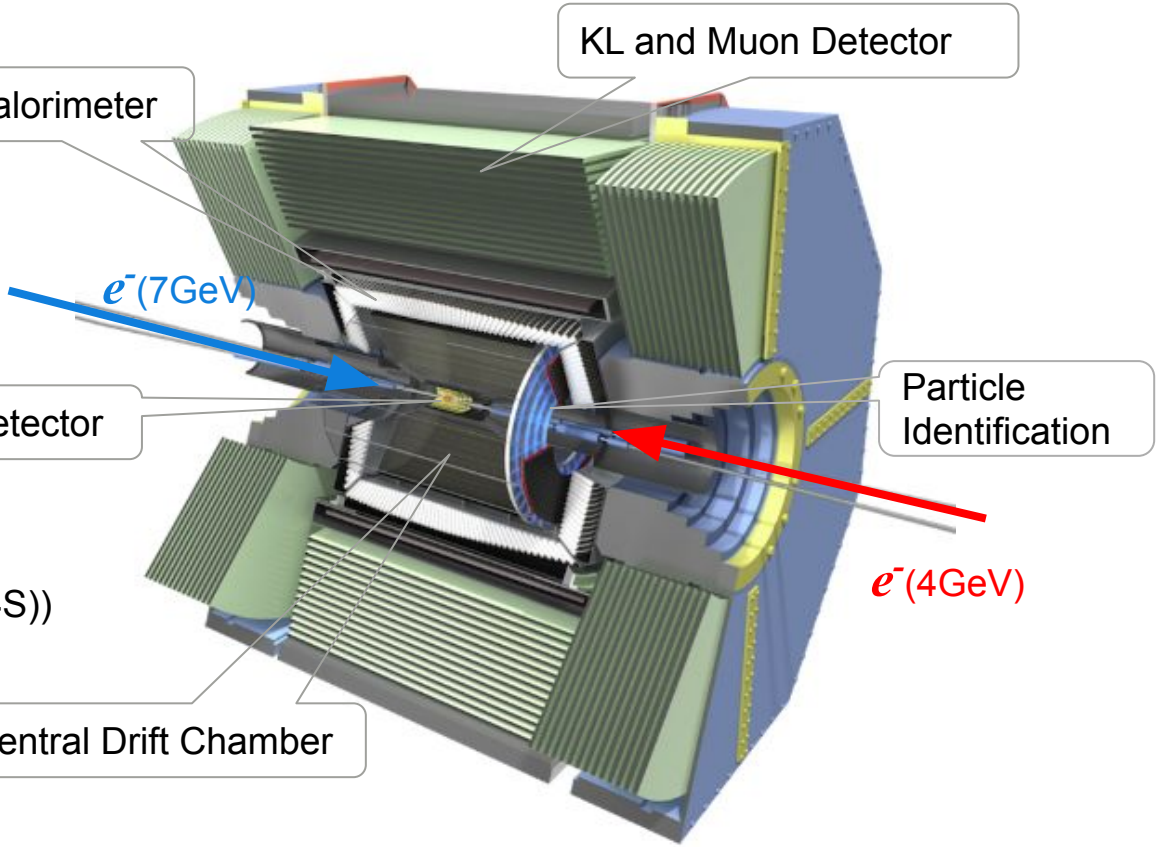
$$\mathcal{R}(D^{(*)}) = \frac{\mathcal{B}(B \to D^{(*)}\tau\nu)}{\mathcal{B}(B \to D^{(*)}\ell\nu)}$$



SuperKEKB and Belle II Experiment

- B-factory : electron-positron collider running @ $\Upsilon(4S)$ producing with $B\overline{B}$

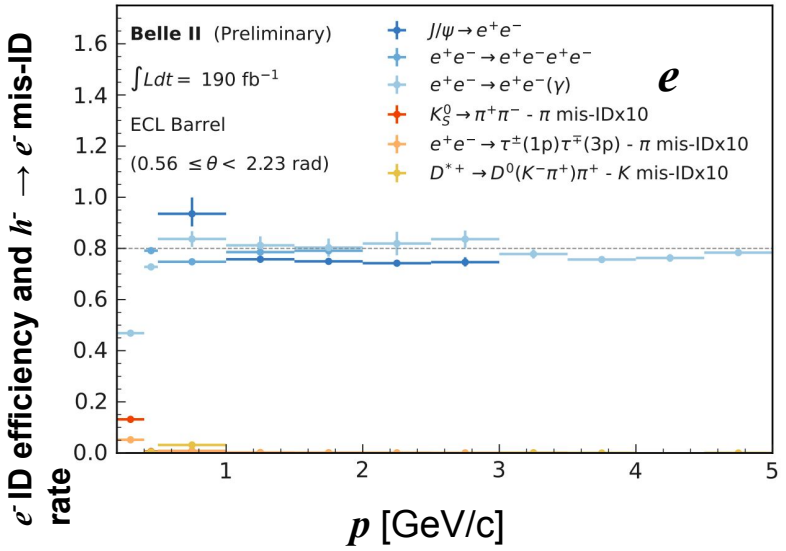
- Data collected so far: (2019-2022 summer)
  $\int \mathcal{L}\, dt$ = 362 fb^{-1} @ $\sqrt{s}$ = 10.58 GeV
  $\int \mathcal{L}\, dt$ = 42 fb^{-1} @ $\sqrt{s}$ = 10.52 GeV
  (60 MeV below $\Upsilon(4S)$)

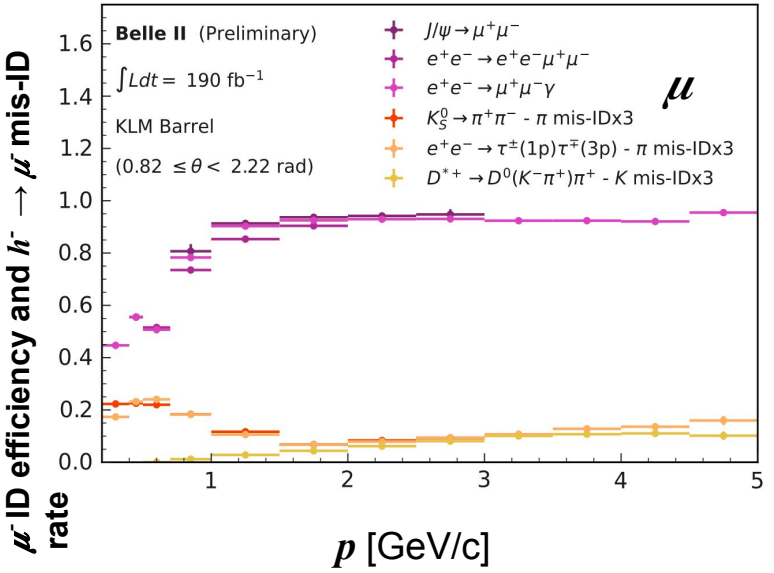


~ 4π Acceptance

BELLE2-CONF-PH-2022-003

Leptons can be reconstructed with high efficiency and low fake-rate





Similar performance at high momentum for e and μ

$R(X_{e/\mu})$ Measurement in $B \to X\, e/\mu\, \nu$

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

Preparation for measuring inclusive $R(X_{\tau/l})$

2301.08266v2 (accepted by PRL)

Event Reconstruction | $R(X_{e/\mu})$ Measurement in $B \to X\, e/\mu\, \nu$

X : generic hadronic final state of semi-leptonic decay with $b \to c/u\, l\, \nu$

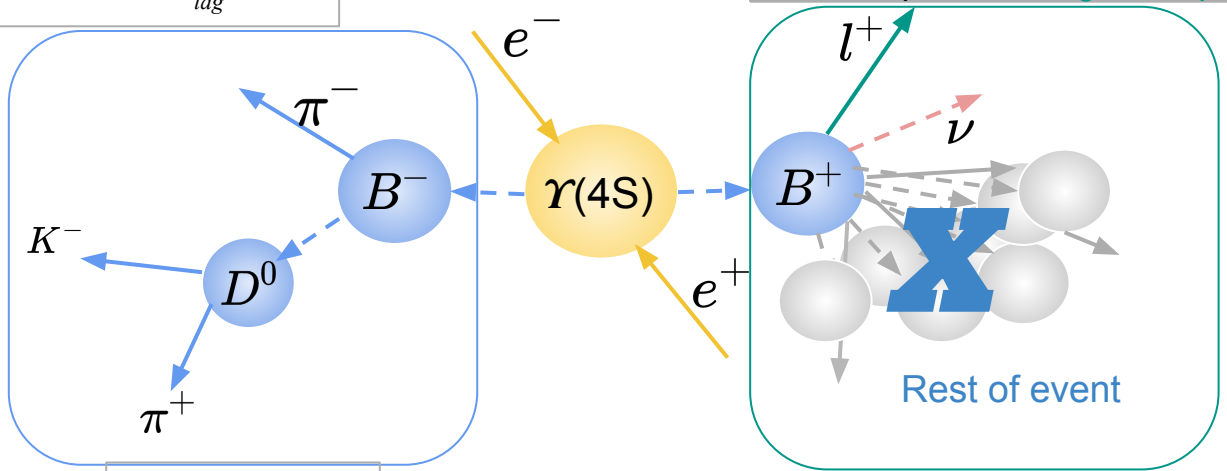
- Belle II data (2019-2021): **189 fb^{-1} @$\sqrt{s}$ = 10.58GeV**
  + 18 fb^{-1} @$\sqrt{s}$ = 10.52GeV
  (off-resonance data ~ 60 MeV below Υ(4S))

Lepton momentum in signal B rest-frame:
p_l^B > 1.3 GeV/c

- Reject most of $B \to X\, \tau\, \nu$ events
- Reduce fakes and secondaries

Opposite charge compared with B_{tag}
Select lepton with highest lepton-ID probability

Using Hadronic Full Event Interpretation (FEI) to reconstruct a B-meson : B_{tag}

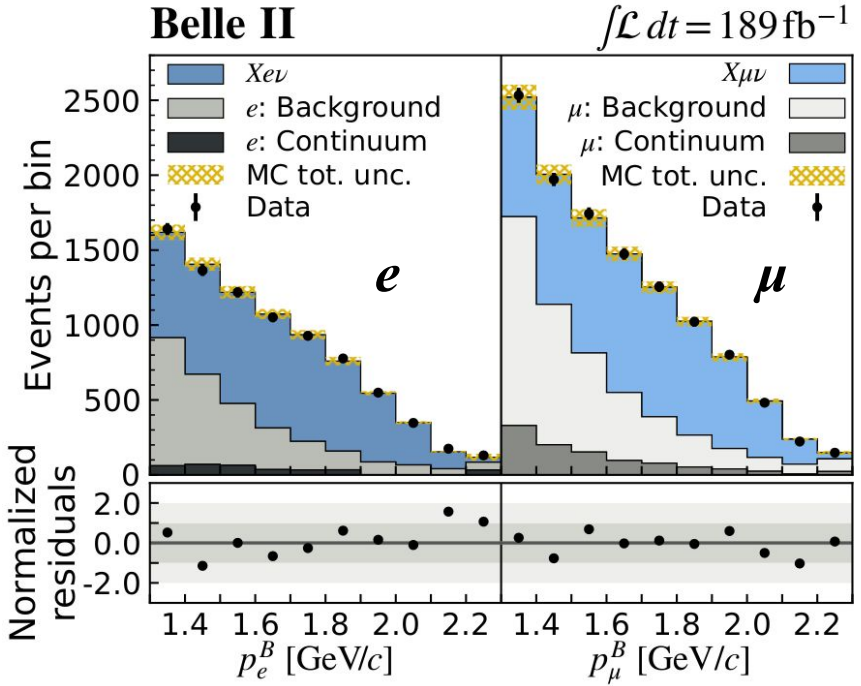


Hadronic Tag
$\epsilon = o(0.1\%)$

Signal Side

- Fit e and μ channels simultaneously in 10 p_l^B bins with binned maximum likelihood fit
- 3 templates for each channel:
  - "Continuum" (scaled to 'off-resonance data')
  - + "Background" (fakes + secondaries +...) (constraint yields from same charge control channel)
  - + $X\, e/\mu\, \nu$
- Systematics included as nuisance parameters

"same charge" control channel



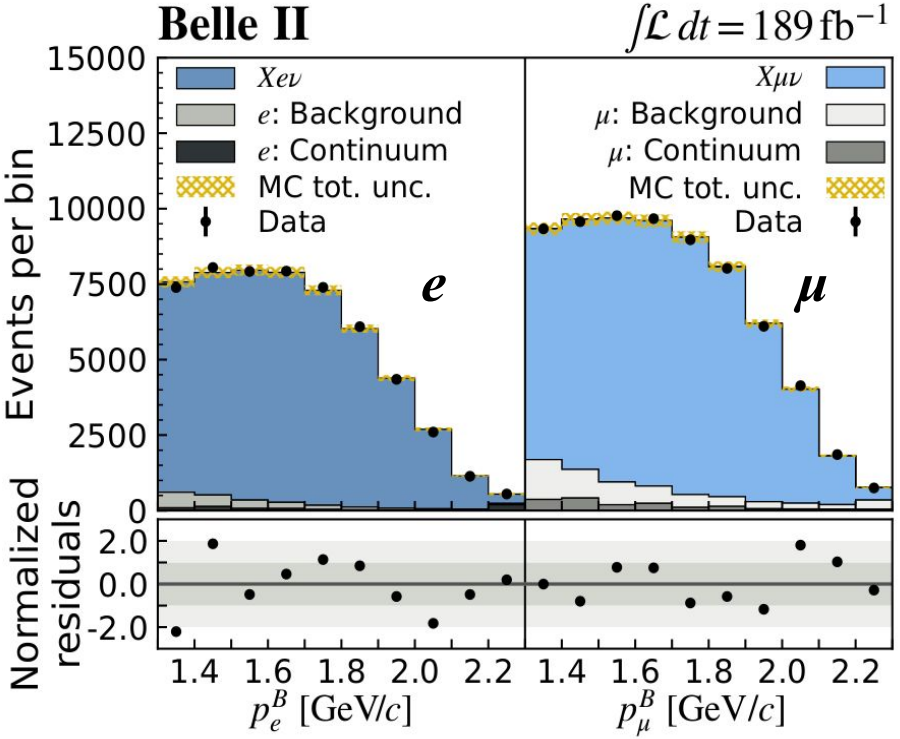
Signal Yields Extraction | $R(X_{e/\mu})$ Measurement in $B \to X\, e/\mu\, \nu$

Extracting signal yields N_l^{means} in each channel

$$R(X_{e/\mu}) = \frac{N_e^{meas}/\epsilon_e}{N_\mu^{meas}/\epsilon_\mu}$$

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

$$R(X_{e/\mu},\, p_l^B > 1.3\,GeV) = 1.005 \pm 0.009(stat.) \pm 0.019(syst.)$$



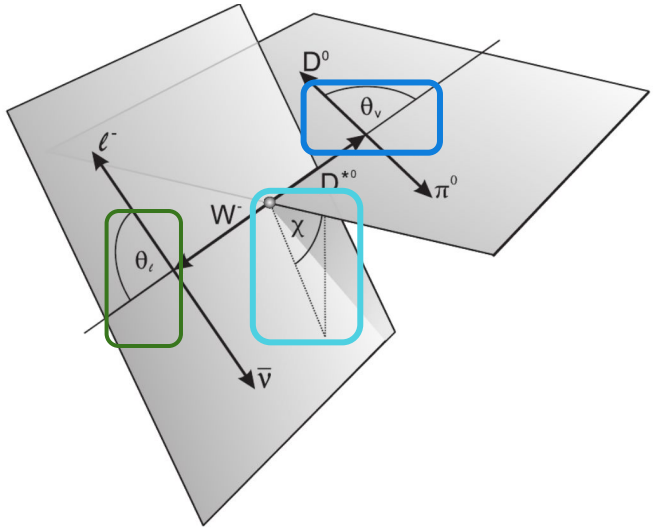
- Compatible with Belle measurements in $B \to D^* l\, \nu$ [Phys. Rev. D 100, 052007], [2301.07529v1]
- Most precise branching fraction based lepton universality test with semileptonic B decays
- **Good agreement with SM prediction** of [JHEP11(2022)007]

$$R(X_{e/\mu}) = 1.006 \pm 0.001$$

Angular Asymmetries of $B^0 \rightarrow D^* l \nu$

Tests of light-lepton universality

preliminary results



- **4 parameters to fully describe $B^0 \to D^* l \nu$ decay**:

  squared invariant mass of $l\,\nu$ system: $q^2 = (p_B - p_{D^*})^2$
  + 3 helicity angles θ_l , θ_V and χ

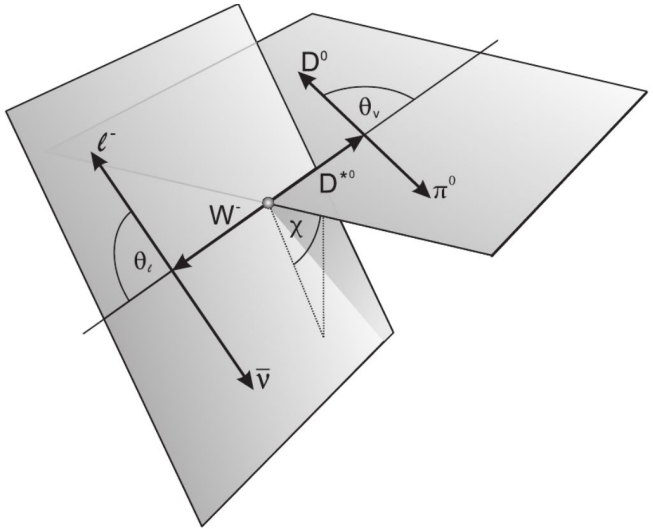
- **Properties of V-A coupling** are encoded in angular distribution

- Tension in differences of A_{FB} between e and μ is reported in a re-interpretation of Belle data
  [Phys. Rev. D 100, 052007 (2019)] in [Eur. Phys. J. C 81, 984 (2021)]

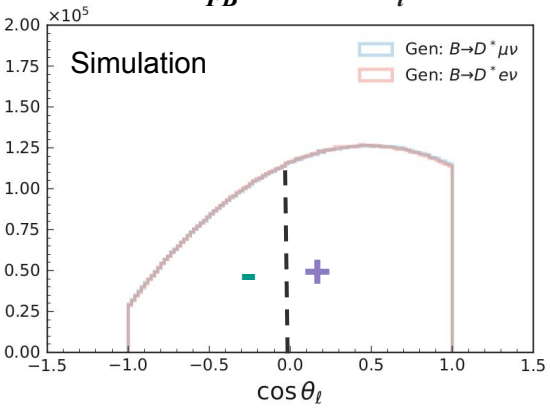
$$A_{FB}(q^2) = \left(\frac{d\Gamma}{dq^2}\right)^{-1} \left[\int_0^1 - \int_{-1}^0\right] d\cos\theta_\ell \frac{d^2\Gamma}{d\cos\theta_\ell dq^2}$$

$$A_x = \frac{\int_0^1 \frac{d\Gamma}{dx} dx - \int_{-1}^0 \frac{d\Gamma}{dx} dx}{\Gamma}$$

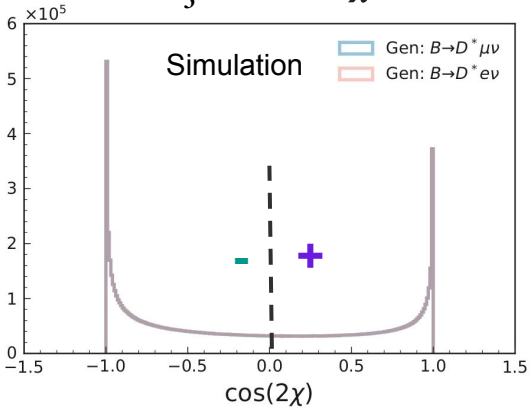
Define a set of 5 asymmetries for observables x



A_{FB}: $x = \cos\theta_l$



S_3: $x = \cos 2\chi$



$$A_x = \frac{N_x(x>0) - N_x(x<0)}{N_x(x>0) + N_x(x<0)}$$

S_5: $x = \cos\chi \cos\theta_V$
S_7: $x = \sin\chi \cos\theta_V$
S_9: $x = \sin 2\chi$

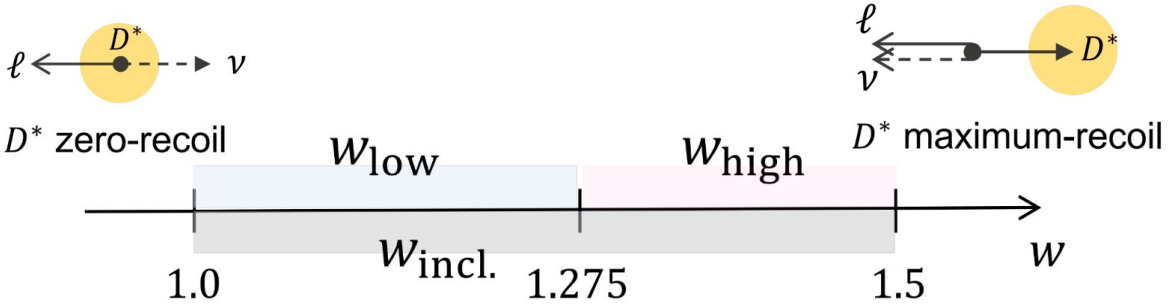
S_3, S_9: propensity in the alignment of $l\nu$ and D^* system

Test e/μ universality through the asymmetry difference

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

D^* recoiling parameter $$w = \frac{m_B^2 + m_{D^*}^2 + q^2c^2}{2m_B m_{D^*}}$$

- w_{low} < 1.275
- w_{high} > 1.275
- $w_{\text{incl.}}$: full phase-space



For each e and μ channel, measure asymmetry for each angular observable **versus** w

$$A_x(w) = \frac{N_x^+(w) - N_x^-(w)}{N_x^+(w) + N_x^-(w)}$$

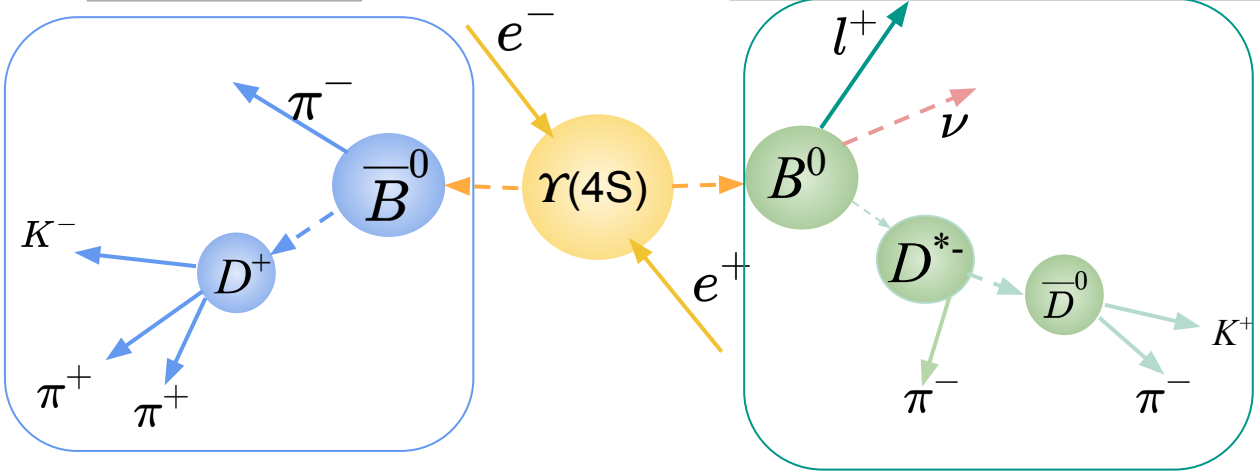
$$\Delta A_x(w) = A_x^\mu(w) - A_x^e(w)$$

Belle II data (2019-2021): **189 fb^{-1} @$\sqrt{s}$ = 10.58GeV**

- Reconstruct a lepton with Lab frame momentum: p_l > 1 GeV/c
- Reconstruct a D-meson with clean and abundant decay modes
- Reconstruct a D^* by combining a D and a slow π

Hadronic Tag
$\epsilon = o(0.1\%)$

Using Hadronic FEI to reconstruct a B-meson : B_{tag}



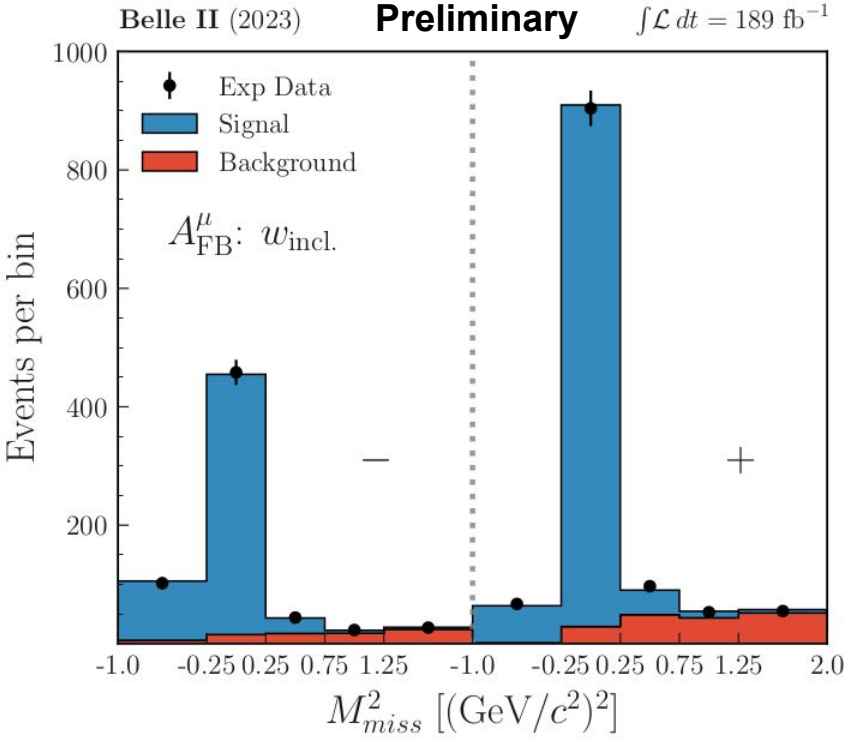
Signal Side Reconstruct exclusively by $B^0 \to D^* l \nu$

Extract signal yields:

- Binned maximum likelihood fit to M^2_{miss}

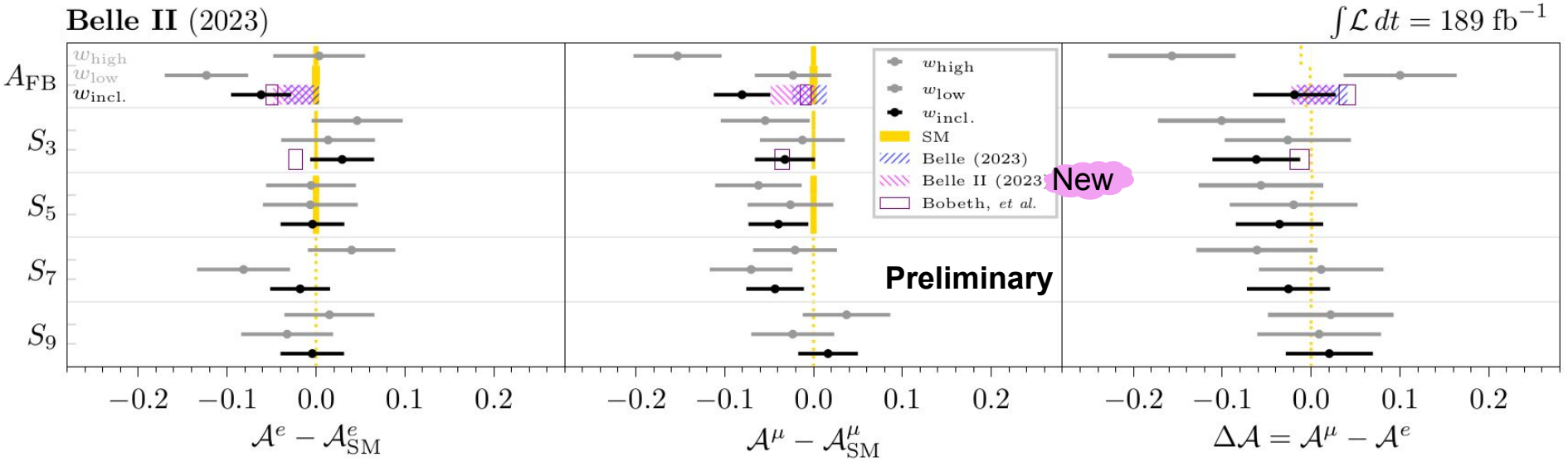
$$M^2_{miss} = p^2_{miss} = \left(p_{\gamma(4S)} - p_{B_{tag}} - p_{D^*} - p_l\right)^2$$

- Main background: $B^0 \to D^{**} l \nu$
- Signal is peaked at zero in M^2_{miss}



Results | Angular Analysis of $B^0 \to D^* l \nu$

e channel | μ channel | difference of e and μ channels



- Statistics dominated
- **All results agree well with SM expectation**

2301.07529v1 (Belle)
Eur. Phys. J. C 81, 984 (2021)

Summary

The Belle II experiment perform two light-lepton universality tests recently

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

  Preparation for measuring inclusive $R(X_{\tau/l})$

  Compatible with **exclusive** Belle measurements

  Good agreement with SM prediction

- Preliminary result on testing of LFU in angular asymmetry in $B^0 \to D^* l \nu$

  Comprehensive LFU test in angular distributions of semileptonic B decays

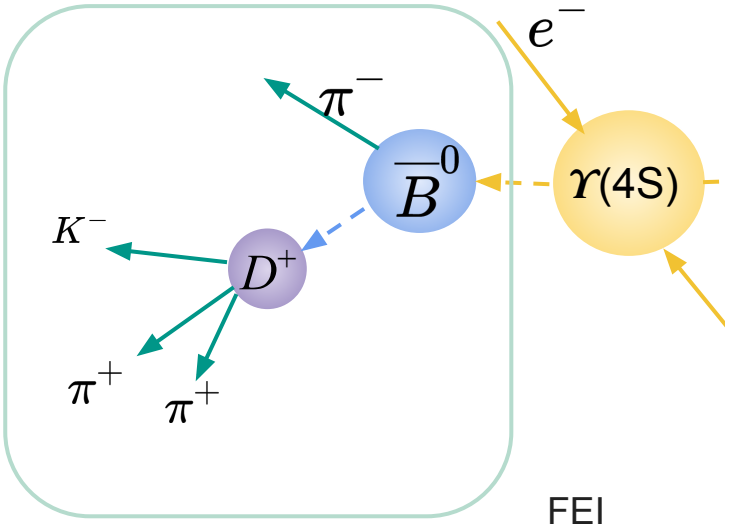
  Good consistency with SM prediction

backup

B-meson pair is produced with opposite flavours

BDT-based algorithm with a hierarchical approach :

- **Reconstruct tracks + clusters**
- **Reconstruct intermediate particles**
- **Reconstruct a B-meson**



	$B^{\pm}$ (%)	B^0 (%)
Hadronic		
FEI with FR channels	0.53	0.33
FEI	0.76	0.46
FR	0.28	0.18
SER	0.4	0.2
Semileptonic		
FEI	1.80	2.04
FR	0.31	0.34
SER	0.3	0.6

FEI

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

$$\epsilon_{Xlv} = \frac{N_{sel} \times \epsilon_{B_{tag}}^{Data/MC}}{2 \times N_{B\bar{B}} \times BR(B \to Xlv)}$$

$$\epsilon_{Xlv} = \frac{N_{sel} \times \epsilon_{B_{tag}}^{Data/MC}}{2 \times N_{B\bar{B}} \times BR\left(B \to Xlv,\, p_l^B > 1.3\,GeV\right)}$$

$$R\left(X_{e/\mu}\right)_{indep} = R\left(X_{e/\mu}\right) \times \frac{F_e^{p_l^B > 1.3GeV}}{F_\mu^{p_l^B > 1.3GeV}}$$

$$R\left(X_{e/\mu}\,,\, p_l^B > 1.3\,GeV\right) = 1.005 \pm 0.009(stat.) \pm 0.019(syst.)$$

Uncertainties estimation based on Asimov fits | $R(X_{e/\mu})$ Measurement in $B \to X\, e/\mu\, \nu$

Main Sources	sample size	**lepton identification**	$B \to X\, l\, \nu$ branching fraction	$B \to X_c\, l\, \nu$ form factors	**total**
Uncertainties(%)	0.9	**1.9**	0.2	0.1	**2.1**

completely correlated

completely uncorrelated

Validated by toy study

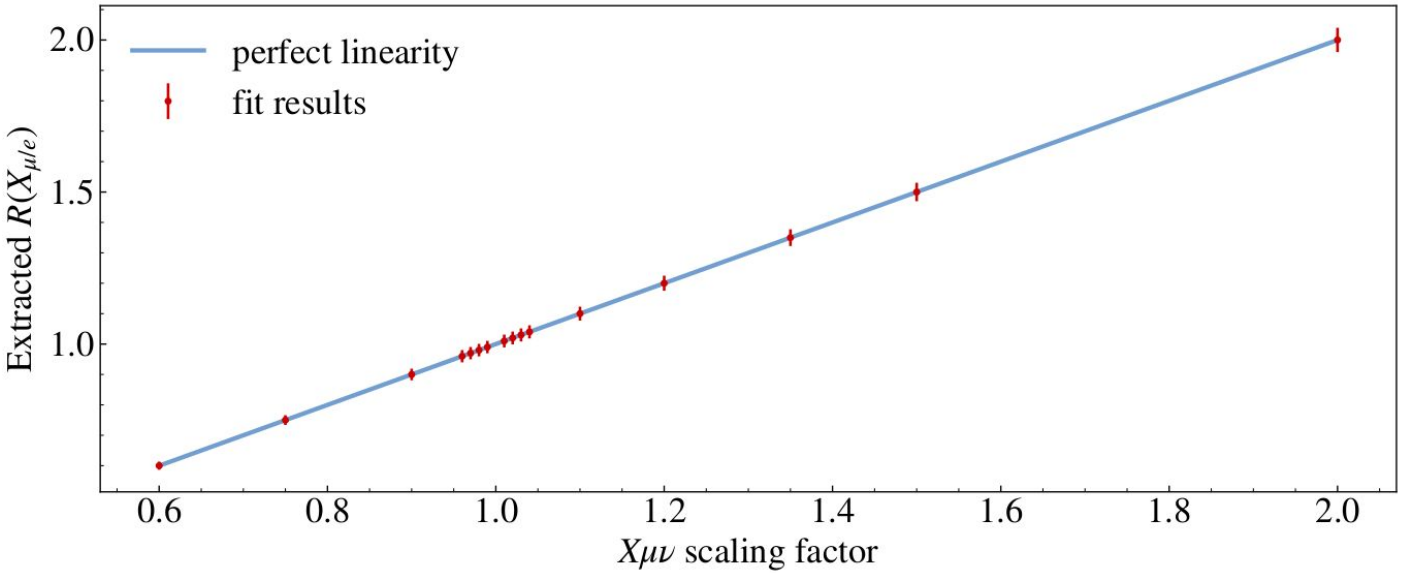
Error source	Combination Relative ratio of final uncertainty / %			
	Offres	Fakes, Other	$X\ell\nu$	$\mathcal{R}(X_{e/\mu})$
Total rel. Error	6.8	6.2	0.5	2.1
Statistical	96.0	69.9	79.3	22.0
"Fit"	2.1	19.3	12.4	2.4
PID	1.5	7.1	5.6	75.0
Track efficiency	0.0	0.0	0.0	0.0

FF $D\ell\nu$	0.0	0.0	0.0	0.0
FF $D^*\ell\nu$	0.3	1.2	1.0	0.1
FF $D^{**}\ell\nu$	0.7	4.5	3.5	0.6
FF GAP$\ell\nu$	1.0	5.0	4.0	0.2
FF $X_c\ell\nu$ corr.	-0.9	-4.3	-3.5	-0.1
FF $X_c\tau\nu$ total	0.0	0.0	0.0	0.0
FF $D\tau\nu$	0.0	0.0	0.0	0.0
FF $D^*\tau\nu$	0.0	0.0	0.0	0.0
FF $GAP\tau\nu$	0.0	0.0	0.0	0.0
FF $X_c\tau\nu$ corr.	-0.0	-0.0	-0.0	-0.0

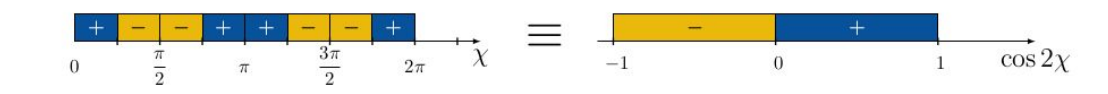
$\mathcal{B}(X_c\ell\nu)$ tot.	1.4	7.6	5.9	0.2
$\mathcal{B}(D\ell\nu)$	0.0	0.1	0.1	0.0
$\mathcal{B}(D^*\ell\nu)$	0.2	1.4	1.0	0.0
$\mathcal{B}(D^{**}\ell\nu)$	0.3	1.3	1.1	0.0
$\mathcal{B}(D^{(*)}\pi\pi\ell\nu)$	0.2	0.5	0.4	0.0
$\mathcal{B}(D^{(*)}\eta\ell\nu)$	1.4	6.4	5.2	0.2
$\mathcal{B}(D_sK\ell\nu)$	0.0	0.0	0.0	0.0
$\mathcal{B}(X_c\ell\nu)$ corr.	-0.7	-2.2	-1.9	-0.0
$\mathcal{B}(X_c\tau\nu)$ tot.	0.0	0.0	0.0	0.0
$\mathcal{B}(D\tau\nu)$	0.0	0.0	0.0	0.0
$\mathcal{B}(D^*\tau\nu)$	0.0	0.0	0.0	0.0
$\mathcal{B}(D^{**}\tau\nu)$	0.0	0.0	0.0	0.0
$\mathcal{B}(D^{(*)}\pi\pi\tau\nu)$	0.0	0.0	0.0	0.0
$\mathcal{B}(D^{(*)}\eta\tau\nu)$	0.0	0.0	0.0	0.0
$\mathcal{B}(X_c\tau\nu)$ corr.	-0.0	-0.0	-0.0	-0.0

Linearity Test | $R(X_{e/\mu})$ Measurement in $B \to X\, e/\mu\, \nu$

Fit sensitivity test



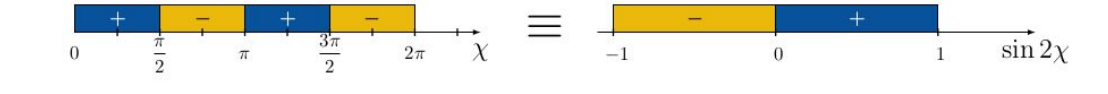
the extracted $R(X_{e/\mu})$ values perfectly follow the expected line



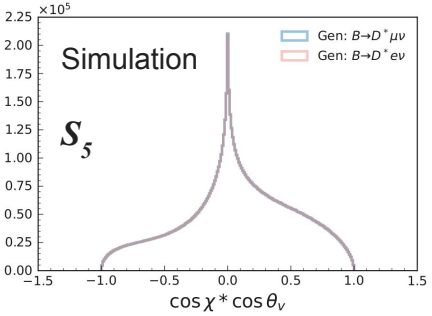
(a) S_3

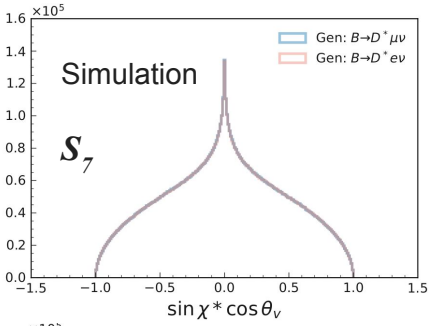
(b) S_5

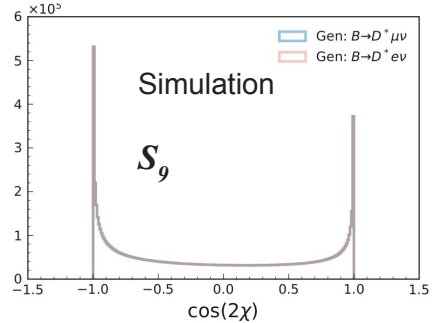
(c) S_7

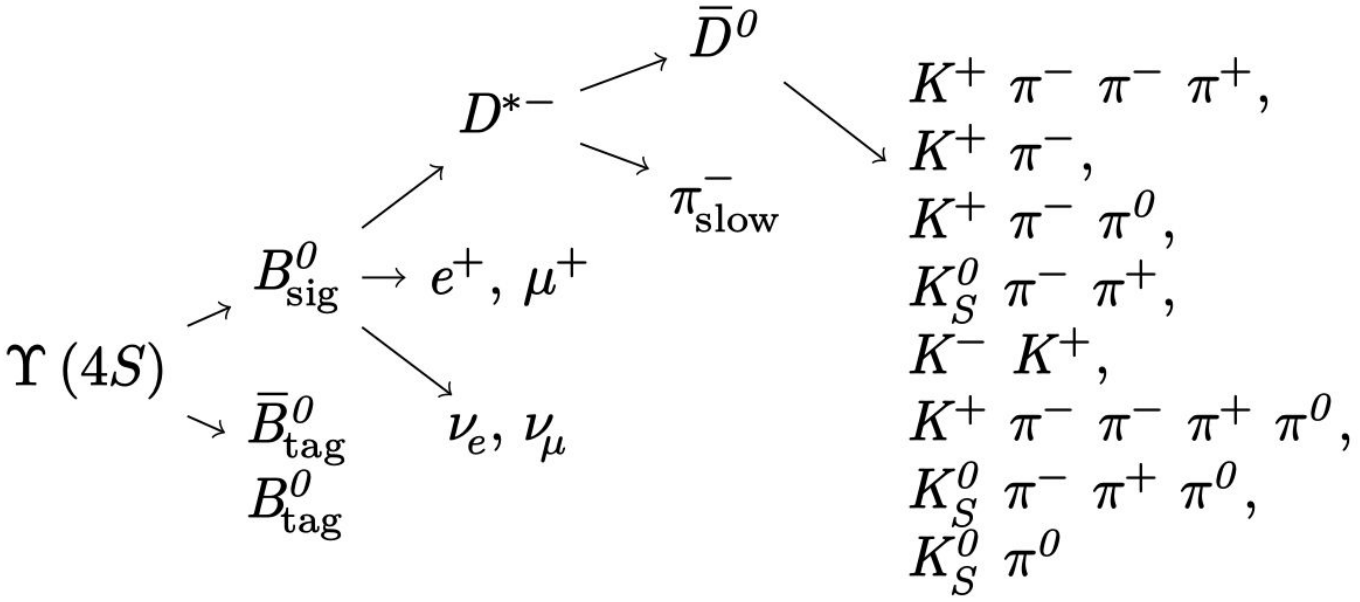


(d) S_9









Visualization of the reconstructed Υ(4S) decay chain, only reconstructed final states are shown explicitly

Results | Angular Analysis of $B^0 \to D^* l \nu$

Obs.	w bin	Measurement	SM$\times 10^5$
$\Delta A_{\rm FB}$	$w_{\rm low}$	0.099 ± 0.064	-104 ± 2
	$w_{\rm high}$	-0.168 ± 0.072	-1133 ± 9
	$w_{\rm incl.}$	-0.024 ± 0.046	-566 ± 7
ΔS_3	$w_{\rm low}$	-0.026 ± 0.071	28 ± 0.2
	$w_{\rm high}$	-0.101 ± 0.072	23 ± 1
	$w_{\rm incl.}$	-0.062 ± 0.049	18 ± 1
ΔS_5	$w_{\rm low}$	-0.019 ± 0.072	27 ± 0.3
	$w_{\rm high}$	-0.055 ± 0.07	107 ± 4
	$w_{\rm incl.}$	-0.035 ± 0.049	49 ± 2
ΔS_7	$w_{\rm low}$	0.011 ± 0.07	0 ± 0
	$w_{\rm high}$	-0.061 ± 0.068	0 ± 0
	$w_{\rm incl.}$	-0.026 ± 0.047	0 ± 0
ΔS_9	$w_{\rm low}$	0.009 ± 0.07	0 ± 0
	$w_{\rm high}$	0.022 ± 0.071	0 ± 0
	$w_{\rm incl.}$	0.02 ± 0.049	0 ± 0

w-Integrated	Central	Exp	Stat	MC shape	Unf. & eff.	Lep. ID	$\pi_{\rm slow}$ eff.	$\mathcal{B}(D^{**})$	K_S^0 eff.	form factors	SM
$A_{\rm FB}^{\mu}$	0.159		0.030	0.003	0.007	0.0017	0.0002	0.0000	0.0001	3.03×10^{-6}	0.0037
$A_{\rm FB}^{e}$	0.183		0.032	0.004	0.007	0.0032	0.0002	0.0000	0.0001	3.52×10^{-7}	0.0037
$\Delta A_{\rm FB}$	0.024		0.044	0.005	0.010	0.0036	0.0002	0.0000	0.0003	4.95×10^{-7}	0.0000
S_3^{μ}	0.142		0.032	0.003	0.008	0.0005	0.0002	0.0000	0.0001	5.48×10^{-6}	0.0020
S_3^{e}	0.080		0.034	0.004	0.008	0.0004	0.0002	0.0000	0.0001	5.27×10^{-6}	0.0020
ΔS_3	0.062		0.046	0.005	0.011	0.0006	0.0004	0.0000	0.0001	2.10×10^{-7}	0.0000
S_5^{μ}	0.155		0.032	0.003	0.008	0.0003	0.0003	0.0000	0.0001	4.20×10^{-6}	0.0035
S_5^{e}	0.190		0.034	0.004	0.008	0.0009	0.0008	0.0000	0.0001	5.50×10^{-6}	0.0036
ΔS_5	0.035		0.046	0.005	0.011	0.0010	0.0005	0.0000	0.0002	1.30×10^{-6}	0.0000
S_7^{μ}	0.043		0.031	0.003	0.008	0.0001	0.0001	0.0000	0.0001	4.69×10^{-7}	0.0000
S_7^{e}	0.018		0.032	0.004	0.008	0.0002	0.0001	0.0000	0.0001	1.02×10^{-7}	0.0000
ΔS_7	0.026		0.044	0.005	0.011	0.0003	0.0001	0.0000	0.0001	3.68×10^{-8}	0.0000
S_9^{μ}	0.016		0.032	0.004	0.008	0.0001	0.0002	0.0000	0.0001	2.12×10^{-7}	0.0000
S_9^{e}	0.004		0.034	0.003	0.008	0.0002	0.0001	0.0000	0.0001	3.39×10^{-7}	0.0000
ΔS_9	0.020		0.046	0.005	0.011	0.0003	0.0002	0.0000	0.0002	1.28×10^{-7}	0.0000