A_{FB} in semileptonic decays at Belle II

Anomalies and Precision in the Belle II Era

Session on $b \to c\ell\nu$ transitions

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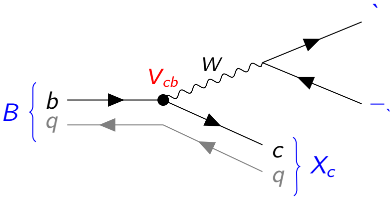
$b \to c$ transitions: Beyond the $|V_{cb}|$

Probing the $b \to c$ transitions with different semileptonic decays: $B \to X_c \ell \nu$, $B \to D \ell \nu$, $B \to D^{\prime} \ell \nu$, etc.



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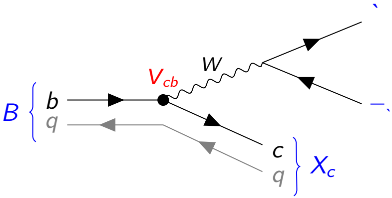

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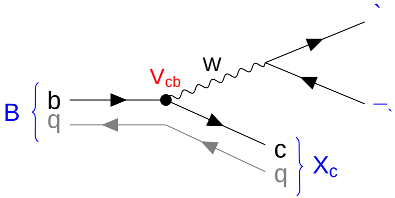
Existence of new physics with no effect on $|V_{cb}|$, but on other observables?

b ! c transitions: Beyond the jV_{cb}j

Probing the b ! c transitions with di erent semileptonic decays B ! X_c` `,
B ! D ` `, B ! D^0` `, etc.



- A well-known anomaly: jV_{cb}j tension between exclusive and inclusive measurements
- Existence of new physics with no e ect on jV_{cb}j, but on other observables?

B^0 ! D $^{+}$` `

- Large potential: Many observables
- Flavour tagging by slow pion
- Can probe the physics Beyond the Standard Model (BSM)

B^0 ! D $^{+}$` `
↳ D^0 $^{+}_{s}$
↳ K $^{+}$

Full angular distribution in $B^0 \to D^{*+}\ell^-\bar{\nu}_\ell$

[doi:10.1103/PhysRevD.90.074013]

Angular dependency of the semileptonic width:

$$\frac{d^4\Gamma^{(\ell)}}{dq^2\, d\cos\theta_\ell\, d\cos\theta_D\, d\chi} = \frac{3}{8\pi}\sum_i J_i^{(\ell)}(q^2)\, f_i(\cos\theta_\ell, \cos\theta_D, \chi) \quad (1)$$

12 terms

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Two-lepton invariant mass, q:

$$q^2 = (p_\ell + p_\nu)^2 = \overset{0}{m_\ell^2} + \overset{0}{m_\nu^2} + 2(E_\ell E_\nu - \vec{p}_\ell \cdot \vec{p}_\nu) \quad (2)$$

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Angular dependency of the semileptonic width:

$$\frac{d^4\Gamma^{(\ell)}}{dq^2\, d\cos\theta_\ell\, d\cos\theta_D\, d\chi} = \frac{3}{8}\sum_i J_i^{(\ell)}(q^2) f_i(\cos\theta_\ell, \cos\theta_D, \chi) \quad (1)$$

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Two-lepton invariant mass, q:

$$q^2 = (p_` + p)^2 = m_`^2 + m^2 + 2(E_` E \quad p \; p) \quad (2)$$

After integration over one variable, q^2:

$$\frac{d^3 \, (`)}{d\cos \, ` \, d\cos \, _D \, d} = \frac{3}{8} \sum_i \left\langle J_i^{(`)} \right\rangle f_i(\cos \, `; \cos \, _D; \;) \quad (3)$$

! 12 angular observables $J_i^{(`)}$

! Their respective (linearly independent) angular coe cient functions f_i

Angular distributions - cont'd

The number of observables can be reduced by:

- Binned CP-averaging (! b(`))
- Integration over angles

Angular distributions - cont'd

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- Binned CP-averaging ($\rightarrow$ $\bar{\Gamma}(\ell)$)
- Integration over angles

$$\frac{1}{\bar{\Gamma}(\ell)}\frac{d\,\bar{\Gamma}(\ell)}{d\cos_{\ell}} = \frac{1}{2} + \left\langle A_{FB}^{(\ell)} \right\rangle \cos_{\ell} + \frac{1}{4}\left(1 - 3\left\langle \tilde{F}_{L}^{(\ell)} \right\rangle\right)\frac{3\cos^2_{\ell} - 1}{2} \quad (4)$$

$$\frac{1}{\bar{\Gamma}(\ell)}\frac{d\,\bar{\Gamma}(\ell)}{d\cos_{D}} = \frac{3}{4}\left(1 - \left\langle F_{L}^{(\ell)} \right\rangle\right)\sin^2_{D} + \frac{3}{2}\left\langle F_{L}^{(\ell)} \right\rangle \cos^2_{D} \quad (5)$$

$$\frac{1}{\bar{\Gamma}(\ell)}\frac{d\,\bar{\Gamma}(\ell)}{d} = \frac{1}{2} + \frac{2}{3}\left\langle S_{3}^{(\ell)} \right\rangle \cos 2 + \frac{2}{3}\left\langle S_{9}^{(\ell)} \right\rangle \sin^2 \quad (6)$$

CP-averaged value vanishes

Angular distributions - cont'd

The number of observables can be reduced by:

- Binned CP-averaging (! b(`))
- Integration over angles

$$\frac{1}{b(`)}\frac{d\,b(`)}{d\cos `} = \frac{1}{2} + D\, A_{FB}^{(`)}\, E \cos ` + \frac{1}{4}\; 1 \quad 3\; D\, \tilde{F}_L^{(`)}\, E \; \frac{3\cos^2 ` \quad 1}{2} \tag{4}$$

$$\frac{1}{b(`)}\frac{d\,b(`)}{d\cos D} = \frac{3}{4}\; 1 \quad D\, F_L^{(`)}\, E \sin^2 D + \frac{3}{2} D\, F_L^{(`)}\, E \cos^2 D \tag{5}$$

$$\frac{1}{b(`)}\frac{d\,b(`)}{d} = \frac{1}{2} + \frac{2}{3} D\, S_3^{(`)}\, E \cos 2 + \frac{2}{3} D\, S_9^{(`)}\, E \sin^2 \tag{6}$$

CP-averaged value vanishes

4 independent angular observables that have sensitivity to BSM physics:

- $A_{FB}^{(`)}$: lepton forward-backward asymmetry
- $F_L^{(`)}$: D longitudinal polarization factor
- $\tilde{F}_L^{(`)}$ and $S_3^{(`)}$: two further angular observables

Generic $b \to c$ model

Effective Field Theory: (dim. 6)

Wilson coefficient (unknown) — operator (known)

$$\mathcal{L}(b \to c \ell \nu) = \frac{4G_F}{\sqrt{2}} V_{cb} \sum_i \sum_{\ell'} C_i^{\ell\ell'} O_i^{\ell\ell'} + \text{h.c.} \tag{7}$$

5 terms — sum over neutrino flavour

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4 angular observables

Belle analysis of B ! D ` `

Why Belle (II)? B ! D angular analysis needs high-precision measurements!

[arXiv:1809.03290]

Belle analysis of B ! D ` `

Why Belle (II)? B ! D angular analysis needs high-precision measurements!

ANALYSIS OVERVIEW:

- Aim: to measure $|V_{cb}|$
- Belle sample: 711 fb^{1}
- Untagged analysis
- 3D Binned Maximum Likelihood t:
  - cos BY
  - M: mass di erence D D^{0}
  - Lepton momentum
- Separates electron and muon channel
- Signal yields: 90000 for each channel

[arXiv:1809.03290]

Belle analysis of $B \to D^* \ell \nu$

Why Belle (II)? $B \to D^* \ell \nu$ angular analysis needs high-precision measurements!

ANALYSIS OVERVIEW:

Aim: to measure $|V_{cb}|$

Belle sample: $711\,\mathrm{fb}^{-1}$

Untagged analysis

3D Binned Maximum Likelihood fit:

- $\cos\theta_{BY}$
- ΔM: mass difference $D^* - D^0$
- Lepton momentum

Separates electron and muon channel

Signal yields: $\approx$ 90000 for each channel

θ_{BY}: Angle between directions of the B-meson and the $D^* \ell$ (Y) system

$$\cos\theta_{BY} = \frac{2E_B E_Y - M_B^2 - m_Y^2}{2 p_B p_Y} \quad (8)$$

[arXiv:1809.03290]

Belle analysis

Next step: Extraction of observables, sensitive to BSM physics

[arXiv:2104.02094v1]

Belle analysis

Next step: Extraction of observables, sensitive to BSM physics

discrepancy of 3.9

A_{FB} A_{FB} A^{e}_{FB}

[arXiv:2104.02094v1]

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Correlation matrices of the statistical uncertainties are incorrect

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Measurements of observables

- Stable with respect to the type of t and the systematic correlations
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- ? Beyond the Standard Model physics scenario
- ? Wrong assumptions But why no discrepancy in other parameters?
- Further studies are needed
- e= avours should be studied separately

Belle II Studies of $B^0 \to D^{*+} \ell \nu_\ell$

Main objectives

Measurements of $|V_{cb}|$ and A_{FB}

Analysis overview:

- Similar to Belle analysis
- Untagged approach
- Fitting variable: $\cos\theta_{BY}$
- Separation between e and μ channel
- Measurements of several observables, like q^2 and angle distributions

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Data samples

- Belle II data collected in the years 2019 and 2020 equivalent to 62.8 fb^{-1}
- Background and signal are modeled by Monte Carlo sample of 300 fb^{-1}

Untagged analysis: B rest frame reconstruction

Belle II reconstruction framework uses dedicated algorithms to improve B rest frame reconstruction.

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DIAMOND FRAME

- B-mesons generated perpendicularly to the direction of the (4S) in (4S) ! B B
- Self-consistent coordinate system is computed
- Constant opening angle of constructed B vector: in nite amount of possibilities
- Four azimuthal angles for the weighted average (compromise between computing and precision)

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Rest-Of-Event (ROE) FRAME

- Estimate momentum p_{incl} of non-signal B-meson
- Choose direction of cone based on p_{incl}

$B^0 \to D^{*-} \ell^+ \nu_\ell$: Fitting procedure

- Binned Likelihood Fit of $\cos\theta_{BY}$
- Three MC templates (shapes) are used:
  - Signal events
  - $B\bar{B}$ backgrounds
  - Continuum ($e^+e^- \to q\bar{q}$)

$$\cos\theta_{BY} = \frac{2E_B E_Y - M_B^2 - m_Y^2}{2p_B p_Y}$$

Branching fraction

$$\mathcal{B}(B^0 \rightarrow D^{+}\ell \quad {}_{\ell}) = \frac{N^{\ell}_{sig}}{N_{B^0} \quad {}_{B^0}\ \mathcal{B}(D^{+} \rightarrow D^0 \ {}^{+}_{s})\ \mathcal{B}(D^0 \rightarrow K \quad {}^{+})} \quad (9)$$

N^{ℓ}_{sig} ... number of signal events

N_{B^0} ... the number of B^0 mesons in the data sample

${}_{B^0}$ ... the total signal selection e ciency

Branching fraction

$$\mathcal{B}(B^0 \to D^{*-} \ell^+ \nu_\ell) = \frac{N_{sig}^{\ell}}{N_{B^0}\,\varepsilon_{B^0}\,\mathcal{B}(D^{*+} \to D^0 \pi_s^+)\,\mathcal{B}(D^0 \to K^- \pi^+)} \quad (9)$$

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N_{B^0} ... the number of B^0 mesons in the data sample
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Combined $\mathcal{B}$:

- Weighted average of fractions
- Statistical uncertainty from fit
- Systematics: determined individually and propagated

Branching fraction

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CombinedB:

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Lepton universality:

- Probed by ratio of $\mathcal{B}_e/\mathcal{B} = 1.001 \quad 0.016$

Back to A_{FB} ...

- Besides the three angles ($\cos\theta_\ell$; $\cos\theta_D$; χ) and q^2, we define one more variable, w:

$$q^2 = M_{\ell\nu}^2 = 2(E_\ell E_\nu - \vec{p}_\ell \cdot \vec{p}_\nu) \tag{10}$$

$$w = \frac{p_B \cdot p_D}{m_B m_D} = \frac{m_B^2 + m_D^2 - q^2}{2 m_B m_D} \tag{11}$$

- Different theories use either q^2 or w as an input
- Limits restricted by kinematics: $q^2 \in [0; 10.69]$ GeV^2 and $w \in [1; 1.504]$

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q^2 resolution

w resolution

cos D resolution

cos ` resolution

resolution

cos $_D$ resolution

cos $_{`}$ resolution

resolution

RESOLUTIONS

	Belle	Belle II
w	0.025	0.026
cos $_D$	0.050	0.060
cos $_{`}$	0.049	0.044
	13.48	0.288 rad

0:235 rad

Belle: 141 fb ^{1}, Belle II: 300 fb ^{1}

(di erent methods for resolution determinations)

Summary & Outlook

BELLE RESULTS

4 discrepancy between data and SM for A_{FB}

Physics beyond SM? Issues in model assumptions? Further studies are needed!

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BELLE II PROSPECTS

Branching ratios, obtained with 628 fb ^{1} of Belle II data, are in good agreement with the current world averages

$$B(B^0 \to D^{+\ell}\ \ell) = (4.82 \quad 0.04_{stat} \quad 0.29_{sys})\%$$

$$R(e/\ ) = 1.00 \quad 0.02_{stat}$$

Observables for A_{FB} determination were measured

New measurements with larger data sample will be used for A_{FB} extraction

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BELLE RESULTS

- 4 discrepancy between data and SM for A_{FB}
- Physics beyond SM? Issues in model assumptions? Further studies are needed!

BELLE II PROSPECTS

- Branching ratios, obtained with 62.8 fb ^{1} of Belle II data, are in good agreement with the current world averages

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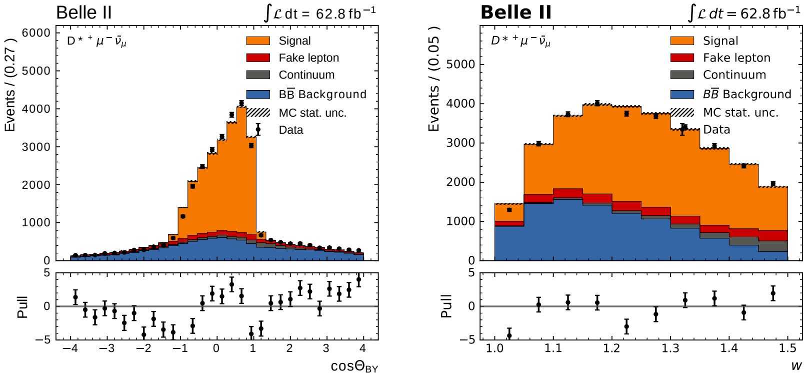
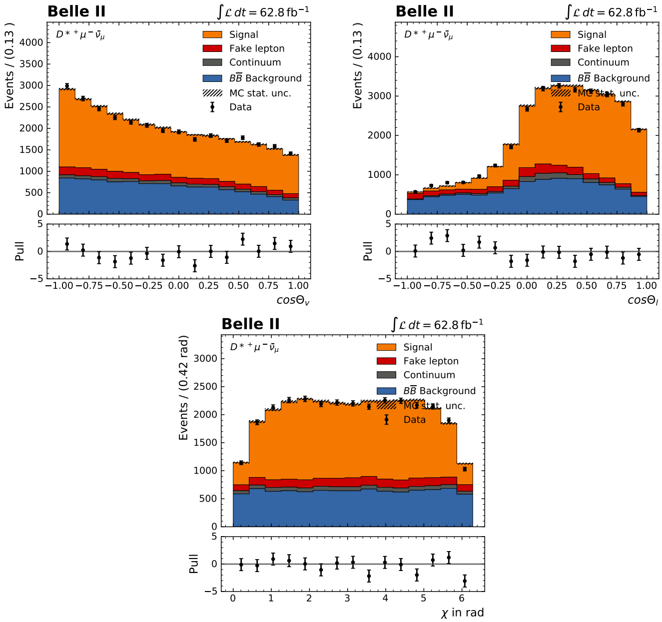
We plan to obtain A_{FB} with Belle II data soon! :)

BACKUP

Distributions of observables – mode




Belle II
$\int \mathcal{L}\,dt = 62.8\,\mathrm{fb}^{-1}$
$D^{*+}\mu^-\bar{\nu}_\mu$
Signal
Fake lepton
Continuum
$B\bar{B}$ Background
MC stat. unc.
Data
Events / (0.13)
Pull
$\cos\Theta_V$
$\cos\Theta_l$
Events / (0.42 rad)
χ in rad