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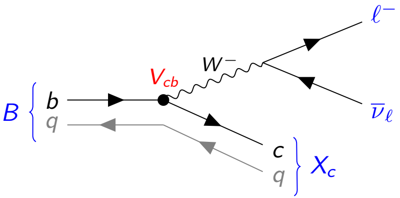
$b \to c$ transitions: Beyond the $|V_{cb}|$

Probing the $b \to c$ transitions with different semileptonic decays: $B \to X_c \ell \nu_\ell$, $B \to D^* \ell \nu_\ell$, $B \to D^0 \ell \nu_\ell$, etc.



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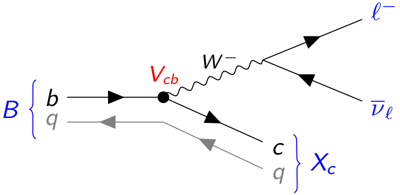

- A well-known anomaly: $|V_{cb}|$ tension between exclusive and inclusive measurements
- Existence of new physics with no effect on $|V_{cb}|$, but on other observables?

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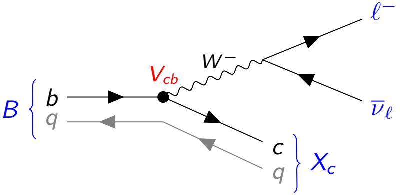

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$\bar{B}^0 \to D^{*+} \ell^- \bar{\nu}_\ell$

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

$$\bar{B}^0 \to D^{*+} \ell^- \bar{\nu}_\ell$$
$$\hookrightarrow D^0 \pi_s^+$$
$$\hookrightarrow K^- \pi^+$$

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

[doi:10.1103/PhysRevD.90.074013]

Angular dependency of the semileptonic width:

$$\frac{d^4\Gamma^{(\ell)}}{dq^2 d\cos\theta_\ell d\cos\theta_D d\chi} = \frac{3}{8\pi} \underbrace{\sum_i}_{\text{12 terms}} J_i^{(\ell)}(q^2) f_i(\cos\theta_\ell, \cos\theta_D, \chi) \quad (1)$$

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

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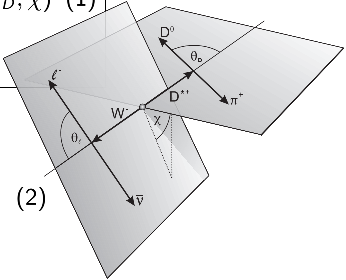

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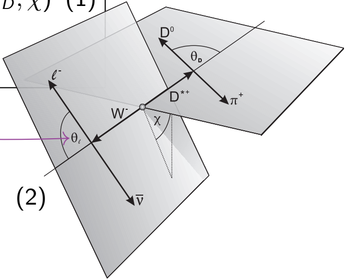

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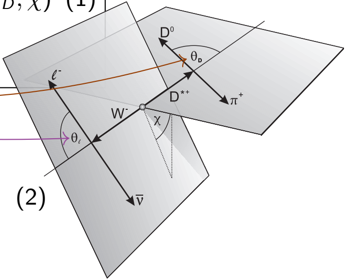

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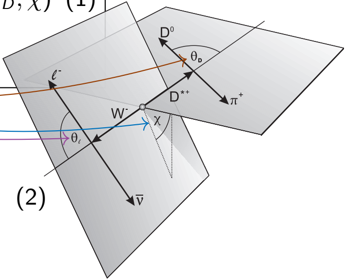

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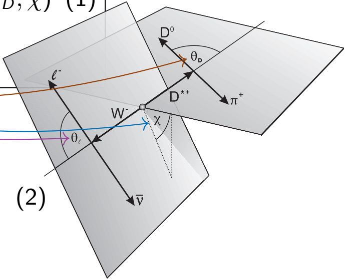

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After integration over one variable, q^2:

$$\frac{d^3\Gamma^{(\ell)}}{d\cos\theta_\ell d\cos\theta_D d\chi} = \frac{3}{8\pi}\sum_i \left\langle J_i^{(\ell)}\right\rangle f_i(\cos\theta_\ell, \cos\theta_D, \chi) \quad (3)$$

→ 12 angular observables $J_i^{(\ell)}$

→ Their respective (linearly independent) angular coefficient functions f_i

Angular distributions - cont'd

The number of observables can be reduced by:

- Binned CP-averaging ($\Gamma \to \widehat{\Gamma}^{(\ell)}$)
- Integration over angles

Angular distributions - cont'd

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- Binned CP-averaging ($\Gamma \to \widehat{\Gamma}^{(\ell)}$)
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$$\frac{1}{\widehat{\Gamma}^{(\ell)}} \frac{\mathrm{d}\,\widehat{\Gamma}^{(\ell)}}{\mathrm{d}\cos\theta_\ell} = \frac{1}{2} + \left\langle A_{\mathrm{FB}}^{(\ell)} \right\rangle \cos\theta_\ell + \frac{1}{4}\left(1 - 3\left\langle \widetilde{F}_L^{(\ell)} \right\rangle\right) \frac{3\cos^2\theta_\ell - 1}{2} \tag{4}$$

$$\frac{1}{\widehat{\Gamma}^{(\ell)}} \frac{\mathrm{d}\,\widehat{\Gamma}^{(\ell)}}{\mathrm{d}\cos\theta_D} = \frac{3}{4}\left(1 - \left\langle F_L^{(\ell)} \right\rangle\right) \sin^2\theta_D + \frac{3}{2}\left\langle F_L^{(\ell)} \right\rangle \cos^2\theta_D \tag{5}$$

$$\frac{1}{\widehat{\Gamma}^{(\ell)}} \frac{\mathrm{d}\,\widehat{\Gamma}^{(\ell)}}{\mathrm{d}\chi} = \frac{1}{2\pi} + \frac{2}{3\pi}\left\langle S_3^{(\ell)} \right\rangle \cos 2\chi + \frac{2}{3\pi}\left\langle S_9^{(\ell)} \right\rangle \sin^2\chi \tag{6}$$

CP-averaged value vanishes

Angular distributions - cont'd

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CP-averaged value vanishes

4 independent angular observables that have sensitivity to BSM physics:

- $\left\langle A_{FB}^{(\ell)}\right\rangle$: lepton forward-backward asymmetry
- $\left\langle F_L^{(\ell)}\right\rangle$: D^* longitudinal polarization factor
- $\left\langle \widetilde{F}_L^{(\ell)}\right\rangle$ and $\left\langle S_3^{(\ell)}\right\rangle$: two further angular observables

Generic $b \to c$ model

Wilson coefficient (unknown) operator (known)

Effective Field Theory:
(dim. 6)

$$\mathcal{L}(b \to c\ell\bar{\nu}_\ell) = \frac{4G_F}{\sqrt{2}} V_{cb} \sum_i \sum_{\ell'} \mathcal{C}_i^{\ell\ell'} \mathcal{O}_i^{\ell\ell'} + \text{h.c.} \quad (7)$$

5 terms sum over neutrino flavour

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Wilson coefficients

J_i observables

Observable	$\lvert C_A\rvert^2$	$\lvert C_V\rvert^2$	$\lvert C_P\rvert^2$	$\lvert C_T\rvert^2$	$\mathrm{Re}(C_AC_V^*)$	$\mathrm{Re}(C_AC_P^*)$	$\mathrm{Re}(C_AC_T^*)$	$\mathrm{Re}(C_VC_P^*)$	$\mathrm{Re}(C_VC_T^*)$	$\mathrm{Re}(C_PC_T^*)$
$J_{1c} = V_1^0$	✓	–	✓	✓	–	(m)	(m)	–	–	–
$J_{1s} = V_1^T$	✓	✓	–	✓	–	–	(m)	–	(m)	–
$J_{2c} = V_2^0$	✓	–	–	✓	–	–	–	–	–	–
$J_{2s} = V_2^T$	✓	✓	–	✓	–	–	–	–	–	–
$J_3 = V_4^T$	✓	✓	–	✓	–	–	–	–	–	–
$J_4 = V_1^{0T}$	✓	–	–	✓	–	–	–	–	–	–
$J_5 = V_2^{0T}$	(m^2)	–	–	(m^2)	✓	(m)	(m)	–	(m)	✓
$J_{6c} = V_3^0$	(m^2)	–	–	–	–	(m)	(m)	–	–	✓
$J_{6s} = V_3^T$	–	–	–	(m^2)	✓	–	(m)	–	(m)	–
$d\Gamma/dq^2$	✓	✓	✓	✓	–	(m)	(m)	–	(m)	–
num(A_{FB})	(m^2)	–	–	(m^2)	✓	(m)	(m)	–	(m)	✓
num(F_L)	✓	–	✓	✓	–	(m)	(m)	–	–	–
num$(F_L$-$1/3)$	✓	✓	✓	✓	–	(m)	(m)	–	(m)	–
num$(\widetilde{F}_L)$	✓	(m^2)	✓	✓	–	(m)	(m)	–	(m)	–
num$(\widetilde{F}_L$-$1/3)$	✓	✓	–	✓	–	–	–	–	–	–
num(S_3)	✓	✓	–	✓	–	–	–	–	–	–
Observable	–	–	–	–	$\mathrm{Im}(C_AC_V^*)$	$\mathrm{Im}(C_AC_P^*)$	$\mathrm{Im}(C_AC_T^*)$	$\mathrm{Im}(C_VC_P^*)$	$\mathrm{Im}(C_VC_T^*)$	$\mathrm{Im}(C_PC_T^*)$
$J_7 = V_3^{0T}$					(m^2)	–	(m)	(m)	–	✓
$J_8 = V_4^{0T}$					✓	–	–	–	–	–
$J_9 = V_5^T$					✓	–	–	–	–	–

TABLE I. The dependence of angular observables on combinations of Wilson coefficients. An entry of ✓ denotes the presence of

Generic $b \to c$ model

Effective Field Theory: (dim. 6)

Wilson coefficient (unknown)

operator (known)

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

5 terms

sum over neutrino flavour

Wilson coefficients

J_i observables

4 angular observables

Observable	$\lvert C_A\rvert^2$	$\lvert C_V\rvert^2$	$\lvert C_P\rvert^2$	$\lvert C_T\rvert^2$	$\mathrm{Re}(C_A C_V^*)$	$\mathrm{Re}(C_A C_P^*)$	$\mathrm{Re}(C_A C_T^*)$	$\mathrm{Re}(C_V C_P^*)$	$\mathrm{Re}(C_V C_T^*)$	$\mathrm{Re}(C_P C_T^*)$
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$J_{2s} = V_2^T$	✓	✓	–	✓	–	–	–	–	–	–
$J_3 = V_4^T$	✓	✓	–	✓	–	–	–	–	–	–
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$J_5 = V_2^{0T}$	(m^2)	–	–	(m^2)	✓	(m)	(m)	–	(m)	✓
$J_{6c} = V_3^0$	(m^2)	–	–	–	–	(m)	(m)	–	–	✓
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$d\Gamma/dq^2$	✓	✓	✓	✓	–	(m)	(m)	–	(m)	–
$\mathrm{num}(A_{\mathrm{FB}})$	(m^2)	–	–	(m^2)	✓	(m)	(m)	–	(m)	✓
$\mathrm{num}(F_L)$	✓	–	✓	✓	–	(m)	(m)	–	–	–
$\mathrm{num}(F_L\text{-}1/3)$	✓	✓	✓	✓	–	(m)	(m)	–	(m)	–
$\mathrm{num}(\widetilde{F}_L)$	✓	(m^2)	✓	✓	–	(m)	(m)	–	(m)	–
$\mathrm{num}(\widetilde{F}_L\text{-}1/3)$	✓	✓	–	✓	–	–	–	–	–	–
$\mathrm{num}(S_3)$	✓	✓	–	✓	–	–	–	–	–	–
Observable	–	–	–	–	$\mathrm{Im}(C_A C_V^*)$	$\mathrm{Im}(C_A C_P^*)$	$\mathrm{Im}(C_A C_T^*)$	$\mathrm{Im}(C_V C_P^*)$	$\mathrm{Im}(C_V C_T^*)$	$\mathrm{Im}(C_P C_T^*)$
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Belle analysis of $\bar{B} \to D^* \ell \bar{\nu}_\ell$

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

[arXiv:1809.03290]

Belle analysis of $\bar{B} \to D^* \ell \bar{\nu}_\ell$

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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: $\sim$ 90000 for each channel

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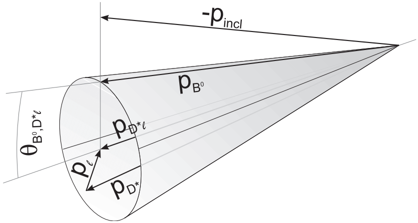
θ_{BY}: Angle between directions of the B-meson and the $D^*\ell$ (Y) system

$$\cos\theta_{BY} = \frac{2E_B^* E_Y^* - 2M_B^2 - m_Y^2}{2p_B^* p_Y^*} \tag{8}$$



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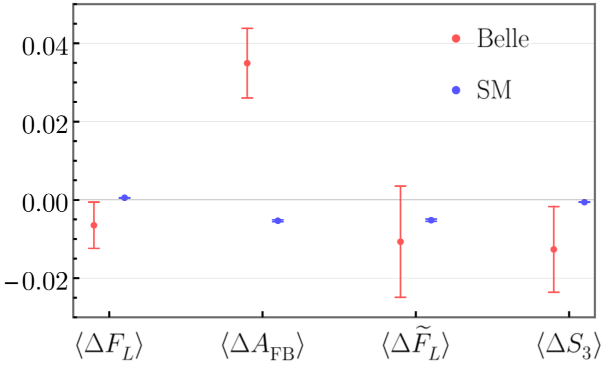
Belle analysis

Next step: Extraction of observables, sensitive to BSM physics



[arXiv:2104.02094v1]

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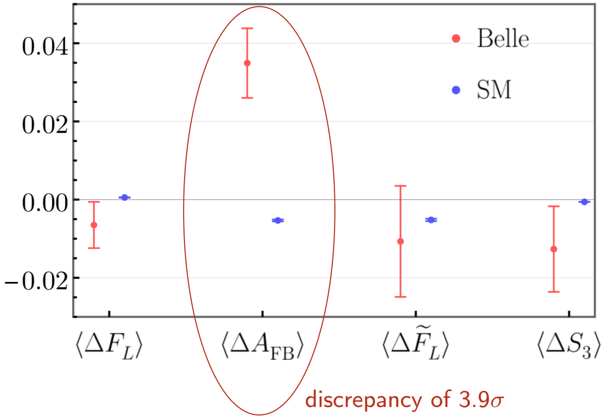
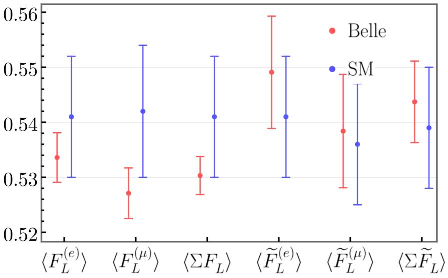
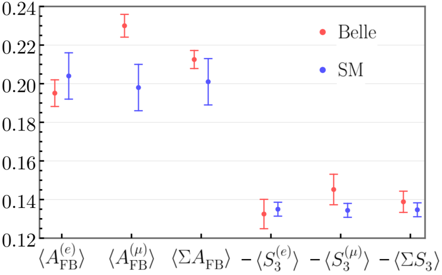


$$\Delta A_{FB} \equiv A^{\mu}_{FB} - A^{e}_{FB}$$

[arXiv:2104.02094v1]

Measurements of observables





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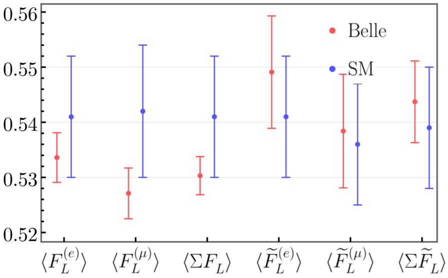

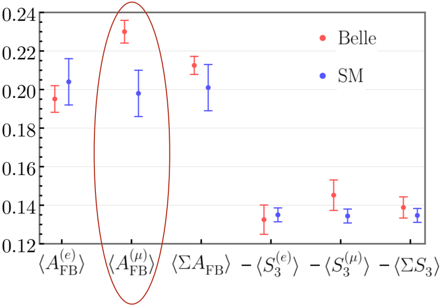

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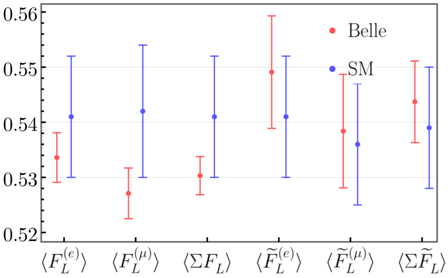

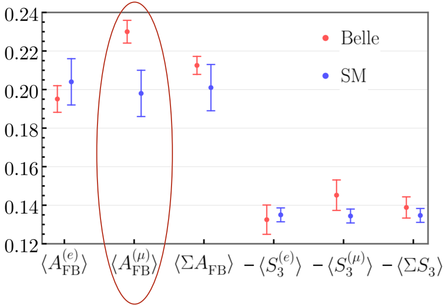

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- Correlation matrices of the statistical uncertainties are incorrect

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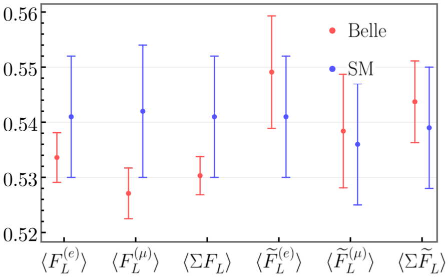

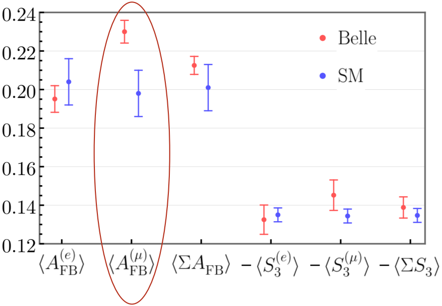

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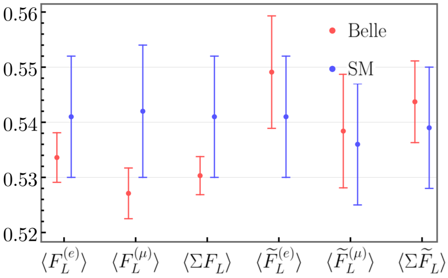
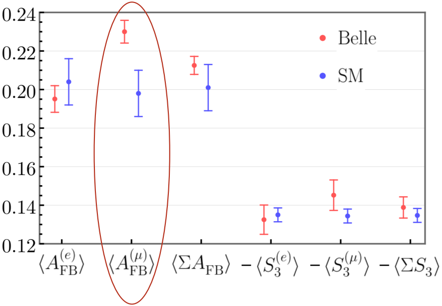
? Beyond the Standard Model physics scenario

? Wrong assumptions → But why no discrepancy in other parameters?

Measurements of observables





- Stable with respect to the type of fit and the systematic correlations
- Correlation matrices of the statistical uncertainties are incorrect

? Beyond the Standard Model physics scenario

? Wrong assumptions $\rightarrow$ But why no discrepancy in other parameters?

- **Further studies are needed**
- **e/μ flavours should be studied separately**

Belle II Studies of $\bar{B}^0 \to D^{*+}\ell^-\bar{\nu}_\ell$

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

Belle II Studies of $\bar{B}^0 \to D^{*+}\ell^-\bar{\nu}_\ell$

HEPHY Institut für Hochenergiephysik

[arXiv:2008.07198]

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Event	nTracks ≥ 3 $E^*_{Vis} > 4$ GeV FoxWolframR2 < 0.3
Tracking	$\lvert z_0\rvert < 2$ cm $\lvert d_0\rvert < 0.5$ cm Θ in CDC acceptance
Brems-Photon	$0.05 \le E \le 0.15$ GeV
Leptons	ℓID > 0.9 $1.2 < p^*_\ell < 2.4$ GeV
Slow pions	$p^*_{\pi s} < 0.4$ GeV
D mesons	$1.85 < m_D < 1.88$ GeV $0.144 < \Delta m_D < 0.148$ GeV $p^*_{D^*} < 2.5$ GeV
$\cos\Theta_{BY}$	$\lvert\cos\Theta_{BY}\rvert \le 4$
For kinematic variables only	$w \le 1.5$

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cosΘ$_{BY}$	$\lvert\cos\Theta_{BY}\rvert$ ≤ 4
For kinematic variables only	w ≤ 1.5

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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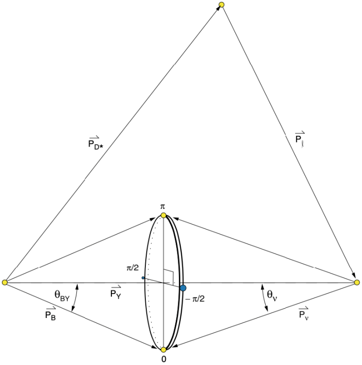
DIAMOND FRAME

- B-mesons generated perpendicularly to the direction of the $\Upsilon(4S)$ in $\Upsilon(4S) \to B\bar{B}$
- Self-consistent coordinate system is computed
- Constant opening angle of constructed B vector: infinite amount of possibilities
- Four azimuthal angles ϕ for the weighted average (compromise between computing and precision)



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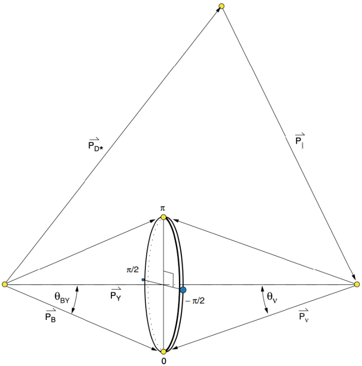
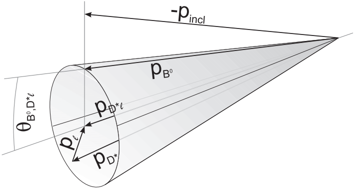


Rest-Of-Event (ROE) FRAME

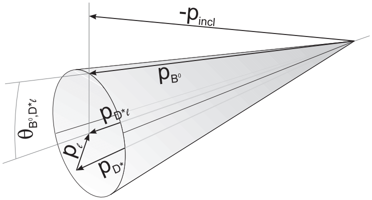
- Estimate momentum $\vec{p}_{\text{incl}}$ of non-signal B-meson
- Choose direction of cone based on $\vec{p}_{\text{incl}}$

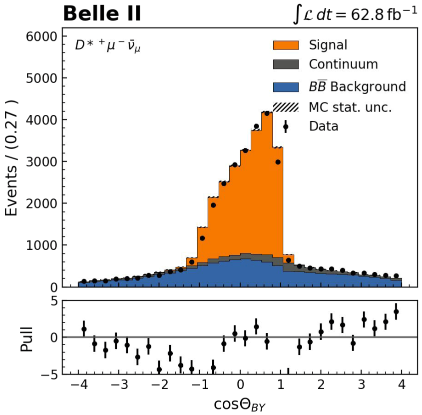


$B^0 \to D^{*-}\ell^+\nu_\ell$: Fitting procedure

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

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





Branching fraction

$$\mathcal{B}(\bar{B}^0 \to D^{*+}\ell^-\bar{\nu}_\ell) = \frac{N_{\text{sig}}^{\ell}}{N_{B^0} \times \epsilon_{B^0} \times \mathcal{B}(D^{*+} \to D^0\pi_s^+) \times \mathcal{B}(D^0 \to K^-\pi^+)} \tag{9}$$

N_{sig}^{ℓ} ... number of signal events
$N_{\bar{B}^0}$ ... the number of B^0 mesons in the data sample
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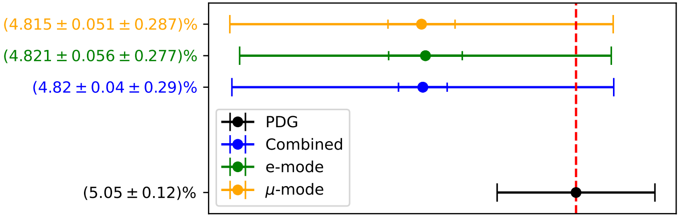
Combined $\mathcal{B}$:

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



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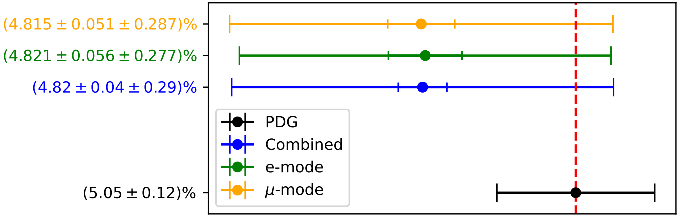
Lepton universality:

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



Back to A_{FB}...

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

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

$$w = \frac{p_B \cdot p_{D^*}}{m_B m_{D^*}} = \frac{m_B^2 + m_{D^*}^2 - q^2}{2 m_B m_{D^*}} \tag{11}$$

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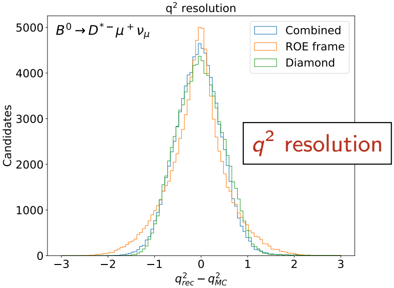
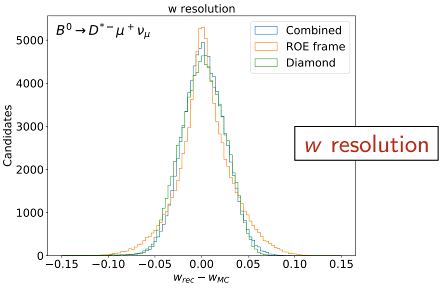
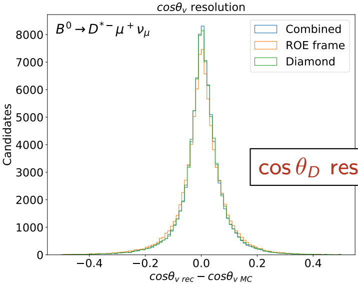
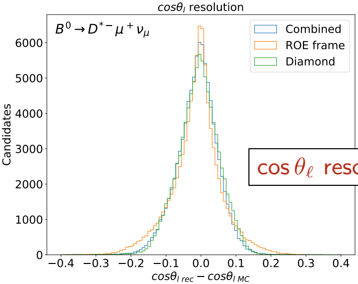


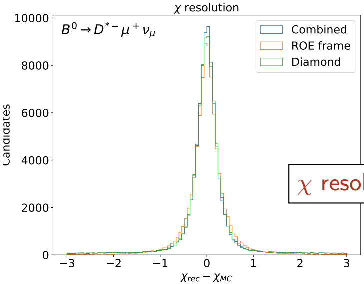




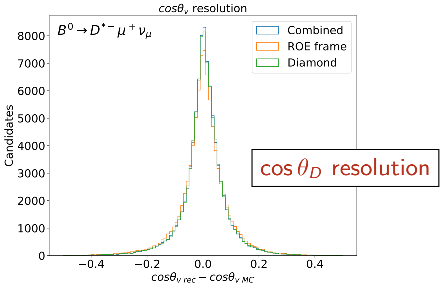
$\cos\theta_D$ resolution

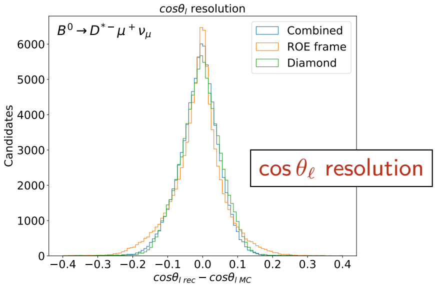


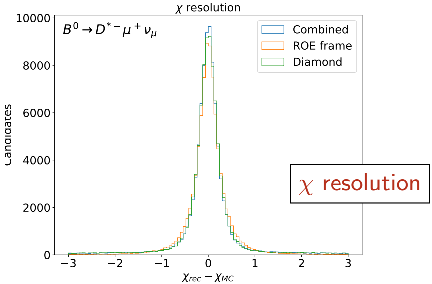
$\cos\theta_\ell$ resolution



χ resolution







RESOLUTIONS

	Belle	Belle II
w	0.025	0.026
$\cos\theta_D$	0.050	0.060
$\cos\theta_\ell$	0.049	0.044
χ	13.48° *	0.288 rad

* ~ 0.235 rad

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

(different methods for resolution determinations)

Summary & Outlook

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- Physics beyond SM? Issues in model assumptions? $\rightarrow$ Further studies are needed!

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

$$\mathcal{B}(\bar{B}^0 \rightarrow D^{*+}\ell^-\bar{\nu}_\ell) = (4.82 \pm 0.04_{\mathrm{stat}} \pm 0.29_{\mathrm{sys}})\%$$

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

- Observables for A_{FB} determination were measured
- New measurements with larger data sample will be used for A_{FB} extraction

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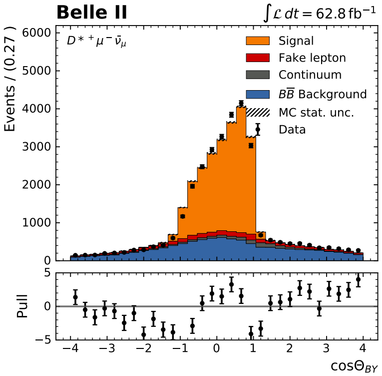
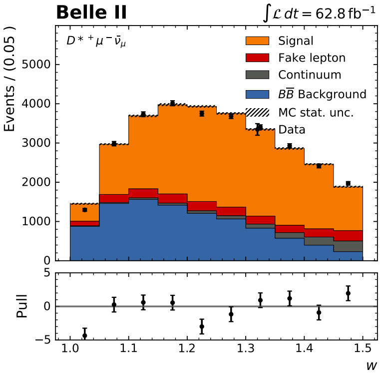
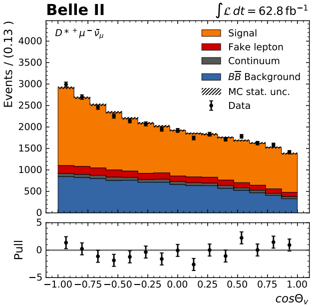
We plan to obtain A_{FB} with Belle II data soon! :)

BACKUP

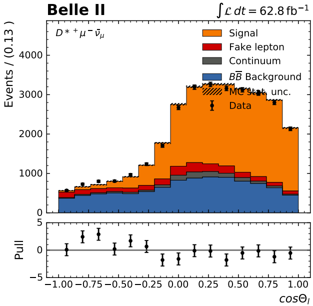
Distributions of observables – μ mode



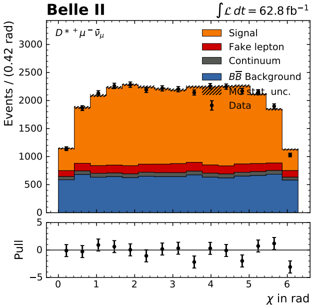




Belle II
$\int \mathcal{L}\,dt = 62.8\,\mathrm{fb}^{-1}$
$D^{*+}\mu^-\bar{\nu}_\mu$
Signal
Fake lepton
Continuum
$B\bar{B}$ Background
MC stat. unc.
Data
Events / (0.13)
Pull
$cos\Theta_V$



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
$cos\Theta_l$



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 / (0.42 rad)
Pull
χ in rad

Different methods were tried:

- Fit with one gaussian distributions
- Fit with two gaussian distributions
- Integrating over $\mu \pm 1\sigma$

	Belle		Belle II	
	σ_1	σ_2	σ_1	σ_2
$\cos\theta_D$	0.033	0.086	0.026	0.080
$\cos\theta_\ell$	0.028	0.095	0.024	0.082
χ	0.055	0.175	0.142	0.403