Exclusive semileptonic decays at Belle II

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on behalf of the Belle II collaboration

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Open LHCb Workshop on semileptonic exclusive $b \to c$ decays

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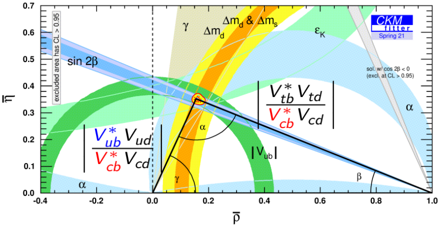
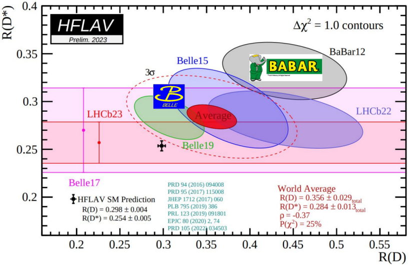
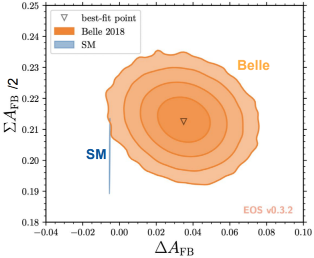
Der Wissenschaftsfonds.

Semileptonic decays

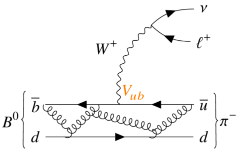
- SM precision measurements
  - Measure SM parameters such as $|V_{cb}|$ and $|V_{ub}|$
- Potential probes of new physics
  - $R(D^{(*)}) = \frac{\mathcal{B}(B\to D^{(*)}\tau\nu_\tau)}{\mathcal{B}(B\to D^{(*)}\ell\nu_\ell)}$ $(\ell = \mu, e)$
  - $\Delta\mathcal{A}_{fb}$ in $B \to D^*\ell\nu$

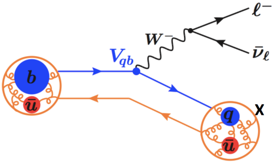






Status of $|V_{cb}|$ and $|V_{ub}|$



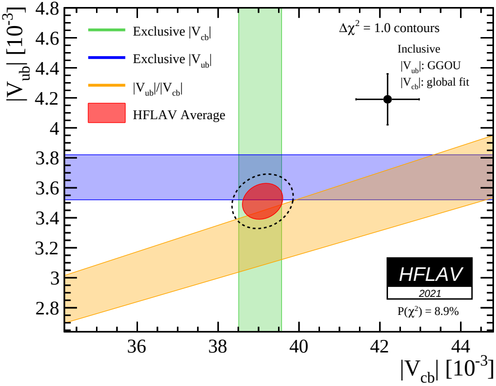


- **Exclusive**: Reconstruct specific final states
  - Measure all visible final state particles
- *i.e.:*
  - $|V_{cb}|$: $B \to D^{(*)}\ell\nu$
  - $|V_{ub}|$: $B \to \pi\ell\nu$
- Theory: Lattice QCD

- **Inclusive**: Measure general $X\ell\nu$ decay
  - Measure some particles in decay
  - Assign remaining unmeasured parts to X
- *i.e.:*
  - $|V_{cb}|$: $B \to X_c\ell\nu$
  - $|V_{ub}|$: $B \to X_u\ell\nu$
- Theory: HQET

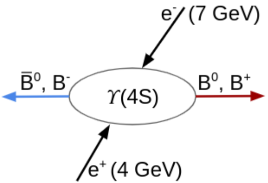
Status of $|V_{cb}|$ and $|V_{ub}|$

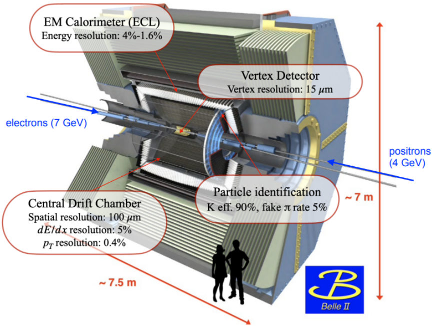
- $\sim 3\sigma$ discrepancy between inclusive and exclusive $|V_{cb}|$ and $|V_{ub}|$ measurements



SuperKEKB and Belle II

- **SuperKEKB:**
  - e^+e^- collider at 10.58 GeV, the $\Upsilon(4S)$ resonance
  - Peak luminosity reached: $4.7 \times 10^{34} \text{cm}^{-2}\text{s}^{-1}$
    - World record!
    - $>$ 100% increase over KEKB (Belle)

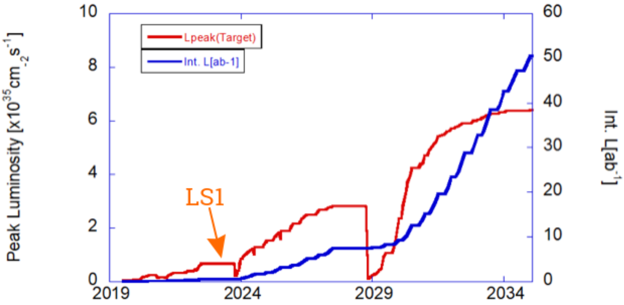




[Belle II TDR: arXiv:1011.0352]

- **Belle II:**
  - Hermetic detector
    - 3-dimensional missing momentum measurements
    - Important for studying events with missing energy
  - Particle identification
    - Excellent particle identification
    - μ ID superior to Belle
  - high γ detection efficiency

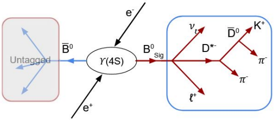
Luminosity



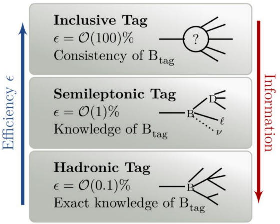
- Data-taking since 2019
- With June 2022 went into Long Shutdown 1
- Recorded data up until LS1 @ $\Upsilon(4S)$: **362 fb^{-1}**
  - (BaBar: 425 fb^{-1}, Belle: 711 fb^{-1})
- Results presented today: $\mathcal{L} = 189$ fb^{-1}

Untagged vs Tagged

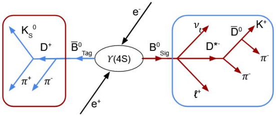
Untagged



- Reconstruct only B_{sig}
- High efficiency, high backgrounds



Tagged



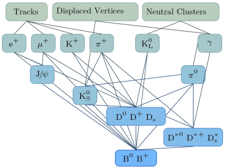
- B_{sig} and B_{tag} are reconstructed
- Tag can be hadronic or semileptonic
- Precisely determine missing neutrino momentum

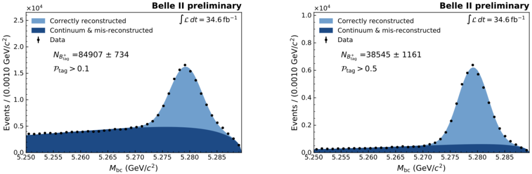
Terminology

- **Untagged - Tagged**
  - Only one or both B mesons reconstructed per event
- **Exclusive - Inclusive**
  - Reconstruction of $B_{sig} \to$ specific decay or $B_{sig} \to X\ell\nu$

Full Event Interpretation

- Full Event Interpretation algorithm [Comput Softw Big Sci 3, 6 (2019)] to reconstruct B_{tag}
  - Reconstruct B candidate with all combinations of daughters
  - Multivariate classifiers
  - Calculate signal probability





$$M_{bc} = \sqrt{E^2_{beam}/4 - (p^{\mathrm{cm}}_{B_{\mathrm{tag}}})^2} > 5.27\ \mathrm{GeV}/c^2$$

- Hadronic FEI
  - Over 200 BDTs to reconstruct $\mathcal{O}(10000)$ distinct decay chains
  - $\epsilon_{B+} \approx 0.5\%$, $\epsilon_{B^0} \approx 0.3\%$ at $\sim 15\%$ purity
    - $\sim 50\%$ increase over Belle tag

Analyses

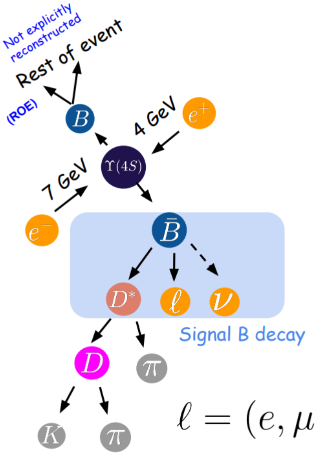
Featured analyses with 189 fb^{-1}

- 

$|V_{cb}|$ from untagged $B \to D^*\ell\nu$ (2023)
- $|V_{cb}|$ from tagged $B \to D^*\ell\nu$ (2022)
- $|V_{cb}|$ from untagged $B \to D\ell\nu$ (2022)

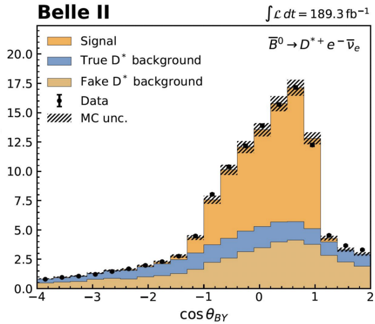
Reconstruction

[to be submitted to Phys. Rev. D]



$$\ell = (e, \mu)$$

- Reconstruct neutral B mode $B^0 \to D^{*+}\ell^-\nu$
- Clean sample by reducing background with cut on $M(D^*(K\pi\pi_s)) - M(D(K\pi))$

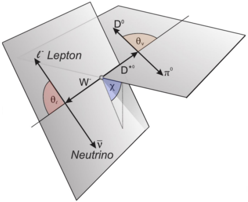


$$\cos\theta_{BY} = \frac{2\,E_B^* E_Y^* - m_B^2 - m_Y^2}{2 p_B^* p_Y^*}$$

Kinematics

Kinematic variables

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



$$\frac{d^4\Gamma}{dw\, d\cos\theta_\ell\, d\cos\theta_V\, d\chi} \propto |V_{cb}|^2 F^2(w, \cos\theta_\ell, \cos\theta_V, \chi)$$

Measurement of fully differential rate challenging $\rightarrow$ measure partially differential rates

Form factors

- Boyd, Grinstein, Lebed (BGL) [Phys. Rev. D56, 6895 (1997)]

$$g(z) = \frac{1}{P_g(z)\phi_g(z)} \sum_{n=0}^{n_a-1} a_n z^n,$$
$$f(z) = \frac{1}{P_f(z)\phi_f(z)} \sum_{n=0}^{n_b-1} b_n z^n,$$
$$\mathcal{F}_1(z) = \frac{1}{P_{\mathcal{F}_1}(z)\phi_{\mathcal{F}_1}(z)} \sum_{n=0}^{n_c-1} c_n z^n,$$
$$z = \frac{\sqrt{w+1} - \sqrt{2}}{\sqrt{w+1} + \sqrt{2}}$$

- Caprini, Lellouch, Neubert (CLN) [Nucl. Phys. B530, 153 (1998)]

$$h_{A_1}(z) = h_{A_1}(w=1)\left(1 - 8\rho^2 z + (53\rho^2 - 15)z^2 - (231\rho^2 - 91)z^3\right)$$
$$R_1(w) = R_1(1) - 0.12(w-1) + 0.05(w-1)^2$$
$$R_2(w) = R_2(1) + 0.11(w-1) - 0.06(w-1)^2$$

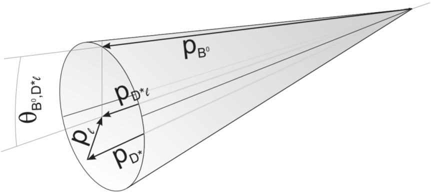
Kinematic variable construction

- How to reconstruct $w, \theta_\ell, \theta_V, \chi$?
- What we know about B:

$$E_B^* = \frac{E_{Beam}^*}{2} \qquad |\vec{p}_B^*| = \sqrt{(E_{Beam}^*)^2 - m_{B^0}^2}$$

- From reconstructed ℓ and D^*:

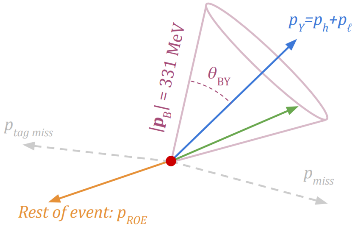
$$\cos\theta_{BY} = \frac{2\,E_B^* E_Y^* - m_B^2 - m_Y^2}{2|p_B^*||p_Y^*|},\ Y = \text{Combined } D^*\ \ell \text{ system}$$



- For kinematic variables, need direction on this cone

Kinematic variable construction

- Novel approach : (extension of BaBar's diamond frame [Phys. Rev. D 74, 092004])



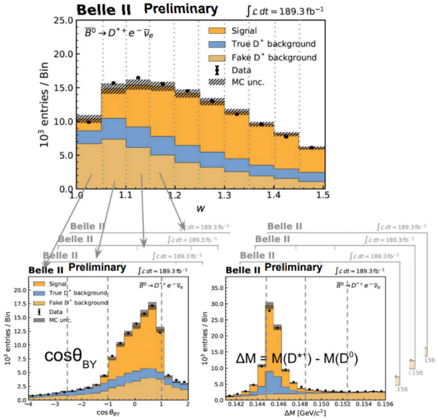
- Calculate $\cos\theta_{BY}$ from reconstructed D^* and ℓ
- $B\overline{B}$ production: angularly distributed according to $\sin^2\theta_B$
- Sum up left-over tracks and clusters as Rest-of-Event (ROE) and calculate momentum p^*_{ROE}
- Likely direction on $\cos\theta_{BY}$ cone: Back-to-back with ROE

- Weighted average over 10 uniformly distributed vectors on cone
- Each vector has weight combining ROE and kinematic information:

$$\frac{1}{2}(1 - \hat{p}_{\mathrm{ROE}} \cdot \hat{p}_{\mathrm{B}})\ \sin^2\theta_B$$

↪ Improved resolution compared to previous methods!

Signal extraction



- 2-dimensional fit in $\cos\theta_{BY}$ and $\Delta M = M(K\pi\pi_s) - M(K\pi)$
- Independent fits in 10 (8) bins of w, θ_V, χ (θ_ℓ)
- Template fit with 3 components
- Systematic uncertainties included as correlated shape variations
- Bin-to-bin migration is corrected with SVD unfolding [arXiv:hep-ph/9509307]

- Partial decay rates are determined from the unfolded yields

reco. eff & acc. — input of PDG2022

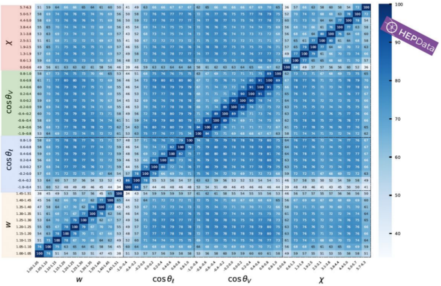
$$\Delta\Gamma_i = \frac{y_i^{\text{unfolded}}}{\epsilon_i N_{B^0} \mathcal{B}(D^{*+} \to D^0\pi^+)\mathcal{B}(D^0 \to K^-\pi^+)\tau_{B^0}}$$

$|V_{cb}|$ extraction

- Minimize

$$\chi^2 = \sum_{i,j}^{34} \left(\frac{\Delta\Gamma_i^{\text{obs}}}{\Gamma^{\text{obs}}} - \frac{\Delta\Gamma_i^{\text{pre}}}{\Gamma^{\text{pre}}} \right) C_{ij}^{-1} \left(\frac{\Delta\Gamma_j^{\text{obs}}}{\Gamma^{\text{obs}}} - \frac{\Delta\Gamma_j^{\text{pre}}}{\Gamma^{\text{pre}}} \right) + \frac{(\Gamma^{\text{obs}} - \Gamma^{\text{pre}})^2}{\sigma_\Gamma^2}$$

Full experimental correlation C_{ij}



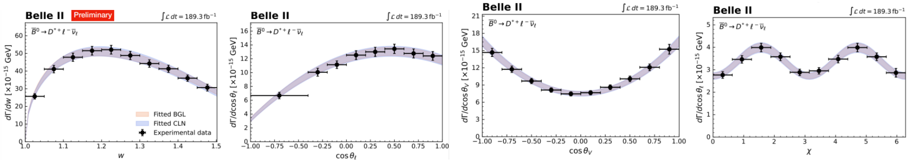
- $|V_{cb}|$ extraction is performed with:
  - Including lattice QCD information for zero-recoil $w = 1$
  - Including LQCD beyond $w = 1$

$|V_{cb}|$ extraction

- BGL truncation order from Nested Hypothesis Test [Phys. Rev. D100, 013005 (2019)]
  - Expand BGL order by one if χ^2 decreases by at least 1
  - Reject if maximum correlation between 2 parameters > 0.95

(n_a, n_b, n_c)	$\lvert V_{cb}\rvert \times 10^3$	χ^2	Ndf	$\rho_{\max}$
$(1,1,2)$	40.3 ± 1.1	41.4	32	0.3
$(2,1,2)$	40.2 ± 1.1	38.4	31	0.97
$(1,2,2)$	**40.9 ± 1.2**	**39.8**	**31**	**0.56**
$(1,1,3)$	40.2 ± 1.1	40.5	31	0.97
$(2,2,2)$	40.1 ± 1.3	38.4	30	0.99
$(1,3,2)$	39.7 ± 1.4	37.4	30	0.98
$(1,2,3)$	40.7 ± 1.2	39.5	30	0.97

BGL fit results (LQCD at $w = 1.0$)



$$|V_{cb}|_{\text{BGL}} = (40.9 \pm 0.3_{\text{stat}} \pm 1.0_{\text{sys}} \pm 0.6_{\text{theo}}) \times 10^{-3}$$

World-average exclusive $D^*\ell\nu$: [arXiv:2206.07501]

$$(38.46 \pm 0.40_{\text{exp}} \pm 0.55_{\text{th}}) \times 10^{-3}$$

$|V_{cb}|$ extraction

Fitted BGL parameters

	Values	Correlations				χ^2/ndf
$\tilde{a}_0 \times 10^3$	0.89 ± 0.05	1.00	0.26	−0.27	0.07	40/31
$\tilde{b}_0 \times 10^3$	0.54 ± 0.01	0.26	1.00	−0.41	−0.46	
$\tilde{b}_1 \times 10^3$	-0.44 ± 0.34	−0.27	−0.41	1.00	0.56	
$\tilde{c}_1 \times 10^3$	-0.05 ± 0.03	0.07	−0.46	0.56	1.00	

Preliminary

Systematics

Relative uncertainty (%) Preliminary

	$\tilde{a}_0$	$\tilde{b}_0$	$\tilde{b}_1$	$\tilde{c}_1$
Statistical	3.3	0.7	44.8	35.4
Finite MC samples	3.0	0.7	39.4	33.0
Signal modelling	3.0	0.4	40.0	30.8
Background subtraction	1.2	0.4	24.8	18.1
Lepton ID efficiency	1.5	0.3	3.1	2.5
Slow pion efficiency	1.5	1.5	18.4	22.0
Tracking of K, π, ℓ	0.5	0.5	0.6	0.5
$N_{B\overline{B}}$	0.8	0.8	1.1	0.8
$f_{+-}/f00$	1.3	1.3	1.7	1.3
$\mathcal{B}(D^{*+} \to D^0\pi^+)$	0.4	0.4	0.5	0.4
$\mathcal{B}(D^0 \to K^-\pi^+)$	0.4	0.4	0.5	0.4
B^0 lifetime	0.1	0.1	0.2	0.1
Total	6.1	2.5	78.3	64.1

BGL fit with LQCD $w > 1.0$

LQCD constraints on $h_{A_1}(w)$ at $w = 1.03, 1.10, 1.17$
[Eur. Phys. J. C 82, 1141 (2022)]

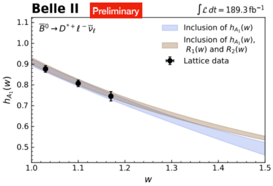
Preliminary

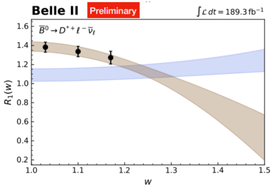
	Values	Correlations					
$\lvert V_{cb} \rvert \times 10^3$	40.4 ± 1.2	1	-0.31	-0.57	-0.1	0.02	-0.26
$a_0 \times 10^3$	22.0 ± 1.4	-0.31	1	0.27	0.1	-0.18	0.31
$b_0 \times 10^3$	13.2 ± 0.2	-0.57	0.27	1	-0.18	0.13	-0.12
$b_1 \times 10^3$	9.0 ± 14.5	-0.1	0.1	-0.18	1	-0.88	0.52
b_2	-0.5 ± 0.4	0.02	-0.18	0.13	-0.88	1	-0.36
$c_1 \times 10^3$	-0.7 ± 0.8	-0.26	0.31	-0.12	0.52	-0.36	1

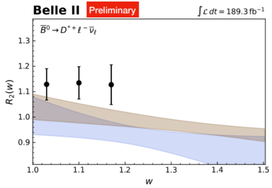
LQCD constraints on $h_{A_1}(w)$, $R_1(w)$ and $R_2(w)$ at $w = 1.03, 1.10, 1.17$
[Eur. Phys. J. C 82, 1141 (2022)]

Preliminary

	Values	Correlations						
$\lvert V_{cb} \rvert \times 10^3$	40.0 ± 1.2	1	-0.16	0.02	-0.09	-0.61	-0.17	0.1
$a_0 \times 10^3$	28.3 ± 1.0	-0.16	1	-0.08	-0.19	0.17	0.12	-0.03
$a_1 \times 10^3$	-31.5 ± 66.6	0.02	-0.08	1	-0.85	-0.04	-0.07	0.11
a_2	-5.8 ± 2.5	-0.09	-0.19	-0.85	1	0.1	0.1	-0.13
$b_0 \times 10^3$	13.3 ± 0.2	-0.61	0.17	-0.04	0.1	1	0.11	-0.13
$c_1 \times 10^3$	-3.2 ± 1.4	-0.17	0.12	-0.07	0.1	0.11	1	-0.9
$c_2 \times 10^3$	59.1 ± 31.1	0.1	-0.03	0.11	-0.13	-0.13	-0.9	1







Other results

- Other extractable results from this analysis:

$$|V_{cb}|_{\text{CLN}} = (40.4 \pm 0.3_{\text{stat}} \pm 1.0_{\text{sys}} \pm 0.6_{\text{theo}}) \times 10^{-3}$$

$$\mathcal{B}(B^0 \to D^{*+}\ell^-\nu) = (4.94 \pm 0.02_{\text{stat}} \pm 0.22_{\text{sys}})\%$$

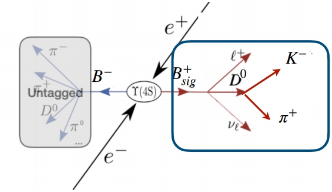
HFLAV average: $(4.97 \pm 0.12)\%$ [arXiv:2206.07501]

$$\mathcal{R}_{e/\mu} = 1.001 \pm 0.009_{\text{stat}} \pm 0.021_{\text{sys}}$$
$$\Delta\mathcal{A}_{fb} = (-4 \pm 16_{\text{stat}} \pm 18_{\text{sys}}) \times 10^{-3}$$

→ Look forward to Belle II talks tomorrow for more $\Delta\mathcal{A}_{fb}$ results!

Untagged $|V_{cb}|$ via $B \to D\ell\nu$

[arXiv:2210.13143]

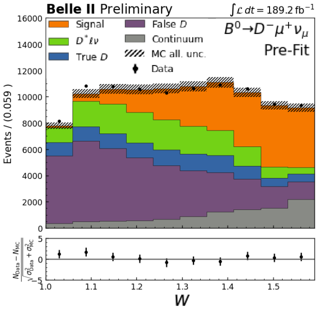


- Reconstruct both charged and neutral B modes
- $D^0 \to K^-\pi^+$ and $D^+ \to K^-\pi^+\pi^+$

Key differences to $D^*\ell\nu$

- Scalar meson, one form factor and one kinematic variable w
- Larger signal yields due to higher branching ratio
- No slow π dependence
- Much more background contamination
  - Particularly down-feed from $D^*\ell\nu$

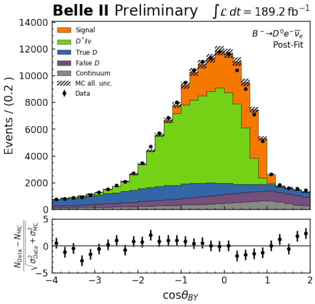
B^0 mode



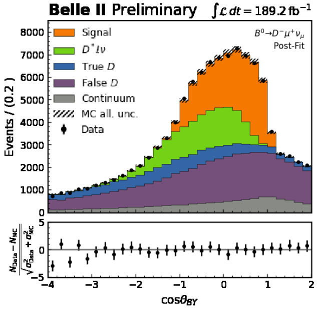
Veto

- Active veto of $B \to D^{*+}\ell^-\nu$ decays
  - Combine reconstructed D candidate with potential slow pion candidates
  - If $\Delta M = M(D\pi) - M(D) \in [0.14, 0.15]$ GeV $\to$ veto event
  - Removes $\sim 70\%$ of $D^{*+}\ell^-\nu$ down-feed while retaining 98% of signal
- Most of remaining down-feed $D^{*0}\ell\nu$

Charged B

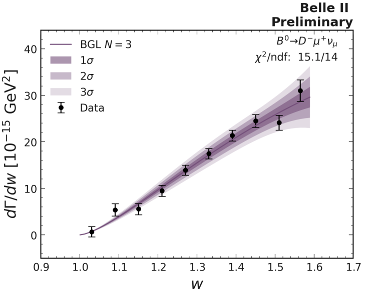


Neutral B



Untagged $|V_{cb}|$ via $B \to D\ell\nu$

- Signal yields from independent fits to $\cos\theta_{BY}$ in 10 w bins
- Fit BGL form factors up to $N = 3$ to partial decay rates
- FNAL/MILC [Phys. Rev. D 92, 034506] and HPQCD Lattice QCD [Phys. Rev. D 92, 054510 (2015)] as nuisance parameters



$$|V_{cb}| = (38.3 \pm 1.2) \times 10^{-3}$$

World-average exclusive $D\ell\nu$: [arXiv:2206.07501]

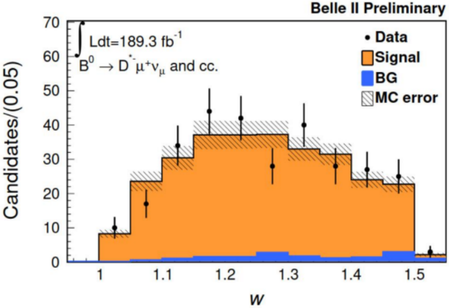
$(39.14 \pm 0.92_{\text{exp}} \pm 0.36_{\text{th}}) \times 10^{-3}$

- Consistent with the exclusive world average
- $\sim 3\%$ error, comparable to the past measurements

Tagged $|V_{cb}|$ via $B \to D^*\ell\nu$

[arXiv:2301.04716]

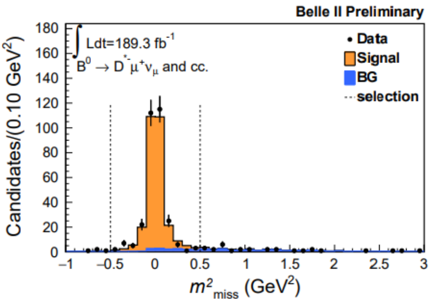
- Tagged measurement of $B^0 \to D^{*\pm}\ell\nu$ with $\ell = (e, \mu)$

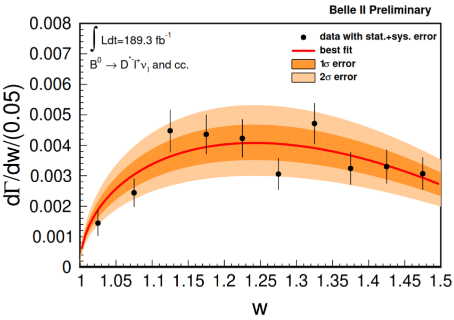


- Tag side B meson fully reconstructed in hadronic final states
- Improved purity, w resolution compared to untagged analysis
- $\mathcal{O}(1\%)$ of untagged signal yields

Tagged $|V_{cb}|$ via $B \to D^*\ell\nu$

- Fit m^2_{miss} in 10 bins of w
- Fit CLN parametrized form factor [NPB530, 153 (1998)] to differential decay rates





$$|V_{cb}| = (37.9 \pm 2.7) \times 10^{-3}$$

World-average exclusive $D^*\ell\nu$: [arXiv:2206.07501]

$$(38.46 \pm 0.40_{\text{exp}} \pm 0.55_{\text{th}}) \times 10^{-3}$$

- Major systematic errors: slow π efficiency and tag calibration

Summary

- Improved measurements of $|V_{cb}|$ and $|V_{ub}|$ are essential to increase the constraining power of the Unitarity triangle fit
- First exclusive measurements of $|V_{cb}|$ at Belle II with 189 fb^{-1}
- Results are quickly approaching previous best precisions

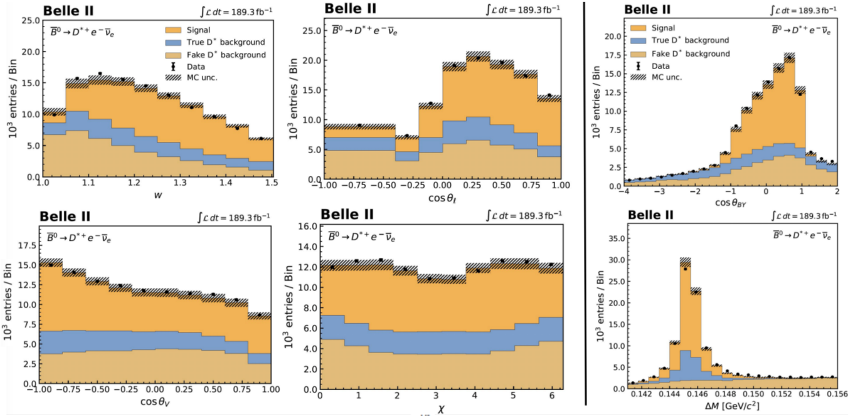
- Related talks:
  - Michael Hedges: Measurements of LFU in $B \to D^{(*)}\ell\nu$ at B–Factories
  - Florian Bernlochner: Measurements and prospects for $B \to D^*\ell\nu$ angular analysis at Belle/Belle II decays
  - Frank Meier: $B \to D^{**}$ decays experimental status @ Belle

Backup

$D^*\ell\nu$ Data-MC comparison

- e mode

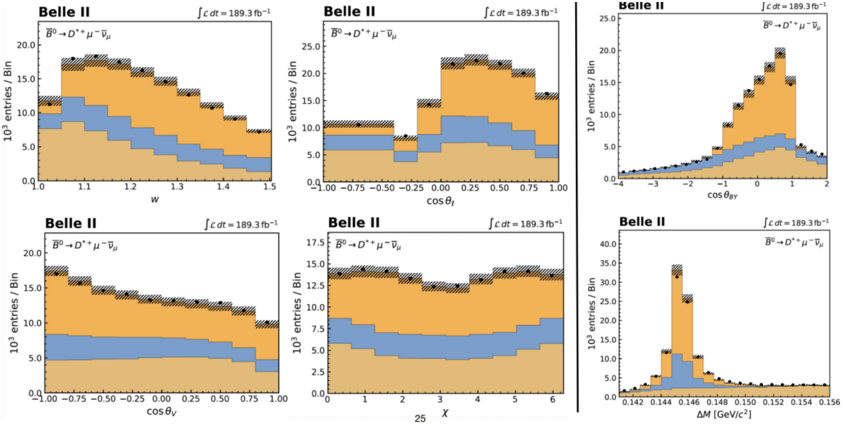
Preliminary



$D^*\ell\nu$ Data-MC comparison

- μ mode

Preliminary



$D^*\ell\nu$ kinematic variable resolutions

Variable	Bias	Resolution
w	0.001	0.04
$\cos\theta_\ell$	-0.005	0.10
$\cos\theta_V$	0.004	0.13
χ [rad]	0.0004	0.58