Belle/Belle II measurements of $B \to D^{(*)}\ell\nu$

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on behalf of Belle II collaboration

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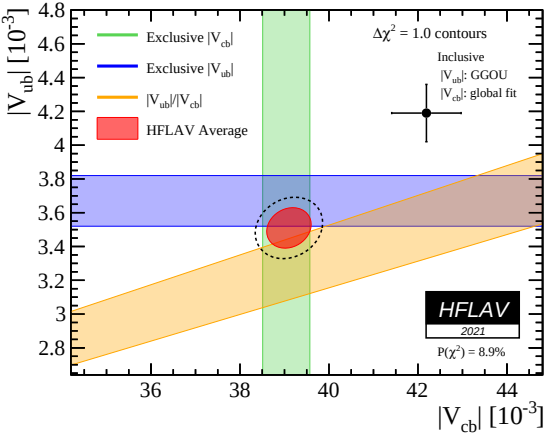
19th April 2022

Ongoing $b \to c$ analyses at Belle II

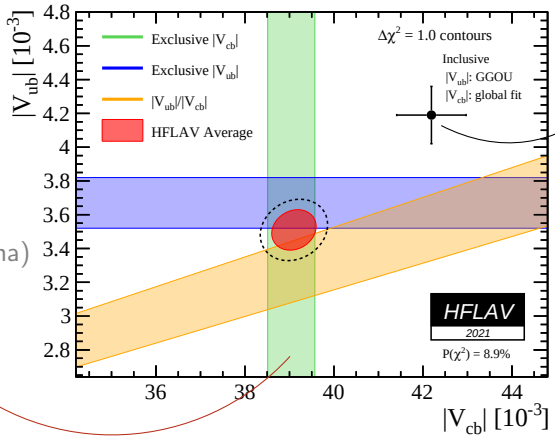


Ongoing $b \to c$ analyses at Belle II

Tagged and untagged
$B \to D^{**}\ell\nu_\ell$
(Göttingen, McGill)

Tagged and untagged
$B \to D^{*}\ell\nu_\ell$
(KEK, McGill, Bonn, Vienna)

Untagged
$B \to D\ell\nu_\ell$
(Vienna, Bonn)



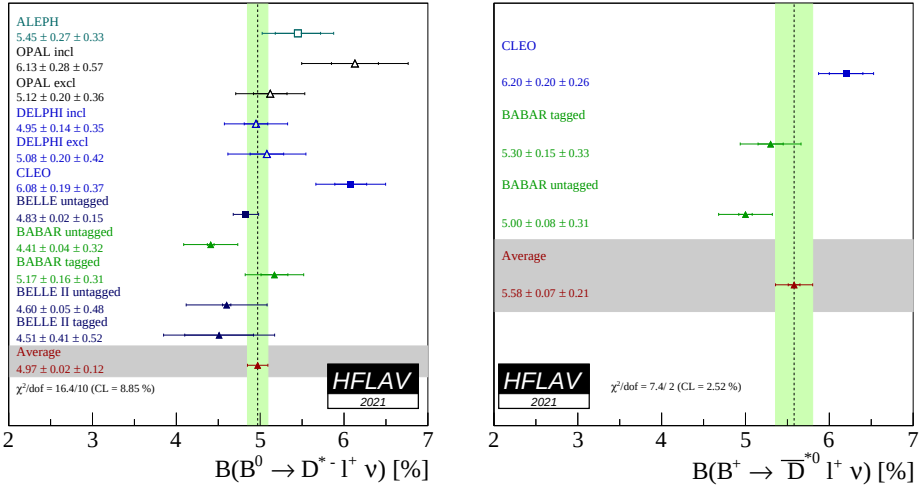
Tagged and untagged
$B \to X_c\ell\nu_\ell$
Ray's talk on Wed.

Untagged: only **signal** B **meson** is reconstructed

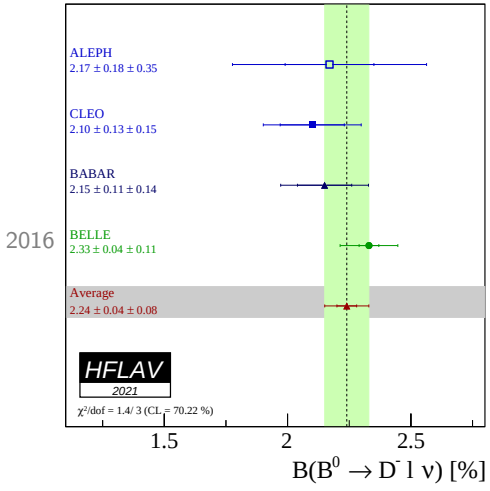
Tagged: **both** B **mesons** are reconstructed

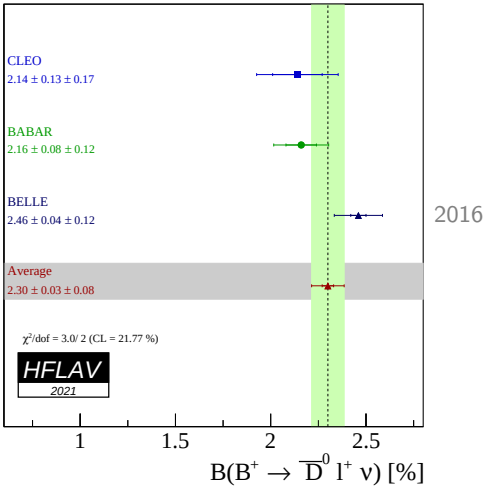
Branching fractions of $B \to D^* \ell \nu$

2020



Branching fractions of $B \to D\ell\nu$





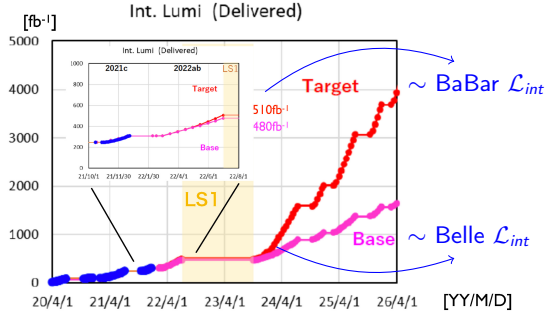
Belle II Experiment & Exclusive $b \to c$ Milestones

- **Feb 2018** — Detector commissioning phase
- **Feb 2019** — First physics runs
- **Aug 2020** — First untagged $\mathcal{B}(\bar{B}^0 \to D^{*+}\ell^-\bar{\nu}_\ell)$ measurements with $34.6\,\text{fb}^{-1}$ of data [arXiv:2008.07198, arXiv:2008.10299]
- **Oct 2021** — First untagged $\mathcal{B}(B^- \to D^0\ell^-\bar{\nu}_\ell)$ measurement with $62.8\,\text{fb}^{-1}$ of data [arXiv:2110.02648]
- **Mar 2022** — First $|V_{cb}|$ measurements from tagged $B^0 \to D^{*-}\ell^+\nu_\ell$ with $189.3\,\text{fb}^{-1}$ of data [Moriond22]
- **$\sim$2024/25** — Surpassing Belle integrated luminosity

Projection of integrated luminosity delivered by SuperKEKB to Belle II

Target scenario: extrapolation from 2021 run including expected improvements.

Base scenario: conservative extrapolation of SuperKEKB parameters from 2021 run

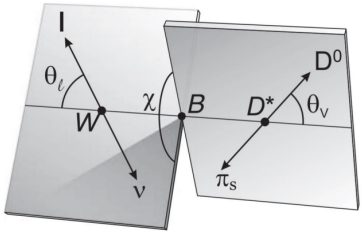


- We start long shutdown 1 (LS1) from summer 2022 for 15 months to replace VXD. There will be other maintenance/improvement works of machine and detector.
- We resume physics running from Fall 2023.
- A SuperKEKB International Taskforce (aiming to conclude in summer 2022) is discussing additional improvements.
- An LS2 for machine improvements could happen on the time frame of 2026-2027

Belle 2018 study: $B^0 \to D^{*-}\ell^+\nu_\ell$ [arXiv:1809.03290]

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

- Aim to measure $|V_{cb}|$
- Belle sample: $711\,\text{fb}^{-1}$
- Untagged analysis – only D^* and ℓ are reconstructed
- Signal extracted in bins of w, θ_ℓ, θ_v, χ^2



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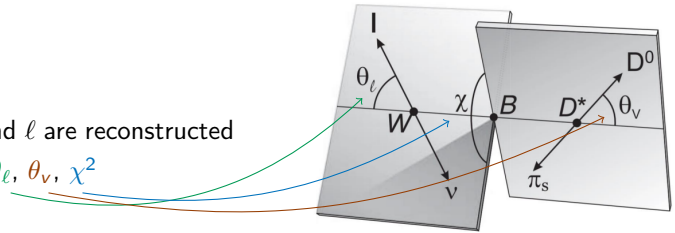

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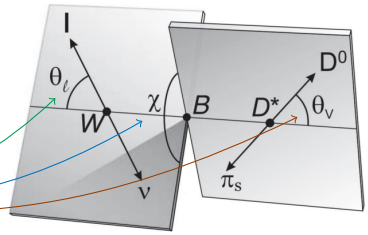

$$w = \frac{p_B \cdot p_{D^*}}{m_B m_{D^*}} = \frac{m_B^2 + m_{D^*}^2 - q^2}{2 m_B m_{D^*}}$$

$$q^2 = (p_\ell + p_\nu)^2 = 2(E_\ell E_\nu - \vec{p_\ell} \cdot \vec{p_\nu}); \quad p_\nu = (|p_{\text{miss}}|, \vec{p}_{\text{miss}})$$

Belle 2018 study: $B^0 \to D^{*-}\ell^+\nu_\ell$ [arXiv:1809.03290]

- 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
- Signal extracted in bins of w, θ_ℓ, θ_ν, χ^2 $\to$ Statistically correlated samples!

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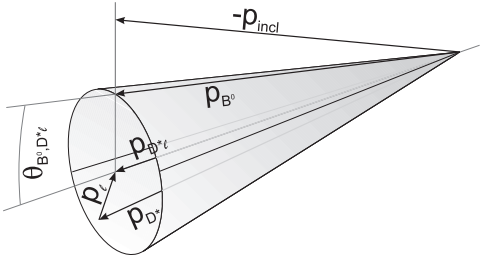
θ_{BY}: Angle between directions of the B-meson and the $D^*\ell$ (Y) system

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



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Measurements

- CLN parameterisation:
  - $\mathcal{F}(1)\eta_{EW}|V_{cb}| = (35.06 \pm 0.15 \pm 0.56) \times 10^3$
  - $\rho^2 = 1.106 \pm 0.031 \pm 0.007$
  - $R_1(1) = 1.229 \pm 0.028 \pm 0.009$
  - $R_2(1) = 0.852 \pm 0.021 \pm 0.006$
- BGL parameterisation:
  - $\mathcal{F}(1)\eta_{EW}|V_{cb}| = (34.93 \pm 0.23 \pm 0.59) \times 10^3$
- Branching ratio: $\mathcal{B}(B^0 \to D^{*-}\ell^+\nu_\ell) = (4.90 \pm 0.02 \pm 0.16) \times 10^{-3}$
- Lepton flavor universality: $R_{e/\mu} = \frac{B^0 \to D^{*-} e^+ \nu_e}{B^0 \to D^{*-} \mu^+ \nu_\mu} = 1.01 \pm 0.01 \pm 0.03$

$|V_{cb}|$ from $B^0 \to D^{*-}\ell^+\nu_\ell$ (2021)

[doi:10.1103/PhysRevD.103.073005]

- Preliminary tagged $B^0 \to D^{*-}\ell^+\nu_\ell$ study in 2017 [arXiv:1702.01521] indicated that $|V_{cb}|$ measurement depends on parametrisation (CLN/BGL) $\to$ Motivation for more studies
- **Based on 2018 Belle untagged study**: fits for $\{H_\pm, H_0\}$ defined in both CLN and BGL parameterisations

$$\frac{d^4\Gamma(B^0 \to D^{*-}\ell^+\nu_\ell)}{dw\, d(\cos\theta_\ell)\, d(\cos\theta_V)\, d\chi} = \frac{6 m_B m_{D^*}^2}{8(4\pi)^4}\sqrt{w^2-1}$$
$$(1-2wr+r^2)G_F^2|V_{cb}|^2\{(1-\cos\theta_\ell)^2\sin^2\theta_V H_+^2(w)$$
$$+(1+\cos\theta_\ell)^2\sin^2\theta_V H_-^2(w)+4\sin^2\theta_\ell\cos^2\theta_V H_0^2(w)$$
$$-2\sin^2\theta_\ell\sin^2\theta_V\cos 2\chi H_+(w)H_-(w)$$
$$-4\sin\theta_\ell(1-\cos\theta_\ell)\sin\theta_V\cos\theta_V\cos\chi H_+(w)H_0(w)$$
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- New LQCD developments provide calculations of form factors at non-zero hadronic recoil:
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- Consistency of several models was checked

$$\frac{d^4\Gamma(B^0 \to D^{*-}\ell^+\nu_\ell)}{dw\, d(\cos\theta_\ell)\, d(\cos\theta_V)\, d\chi} = \frac{6 m_B m_{D^*}^2}{8(4\pi)^4}\sqrt{w^2-1}$$
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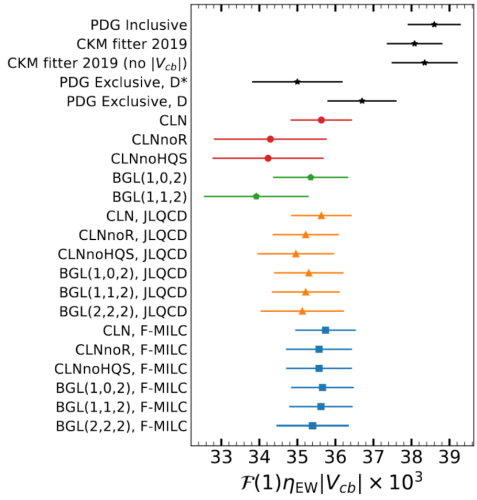
$|V_{cb}|$ from $B^0 \to D^{*-}\ell^+\nu_\ell$ (2021)

Conclusions

- **Model-independent results**
- Results using new Fermilab-MILC and JLQCD inputs are consistent



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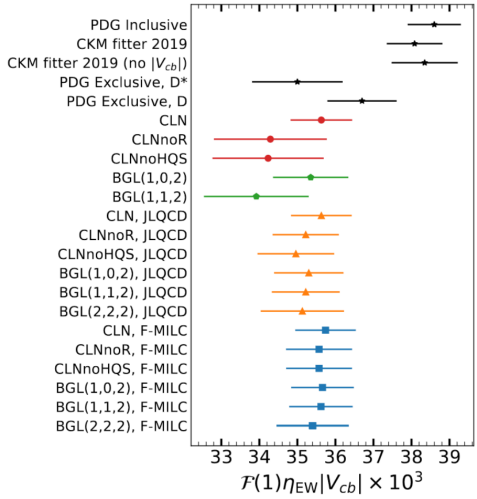

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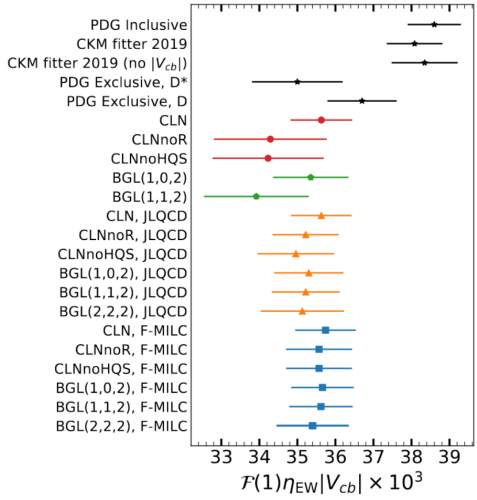
Conclusions

- **Model-independent results**
- Results using new Fermilab-MILC and JLQCD inputs are consistent
- **Inclusive-exclusive tension remains with higher confidence**
- Future studies: use these LQCD calculations to tighten systematic uncertainties on exclusive $|V_{cb}|$, $R(D^{(*)})$ and hadronic factorisation
- Waiting for results from tagged analysis

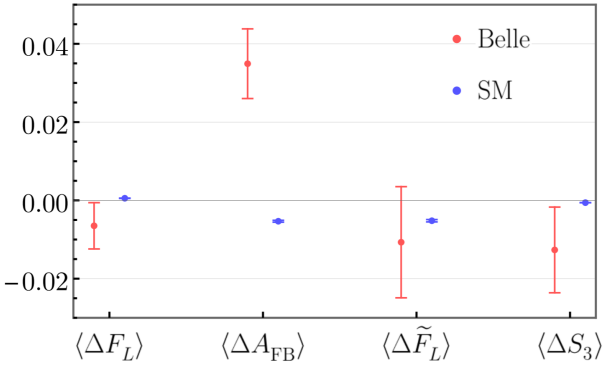
[doi:10.1103/PhysRevD.103.073005]



A_{FB} from $B^0 \to D^{*-}\ell^+\nu_\ell$ (2021)

[arXiv:2104.02094v1]

Theory paper based on Belle 2018 analysis: Calculation of BSM–sensitive angular observables



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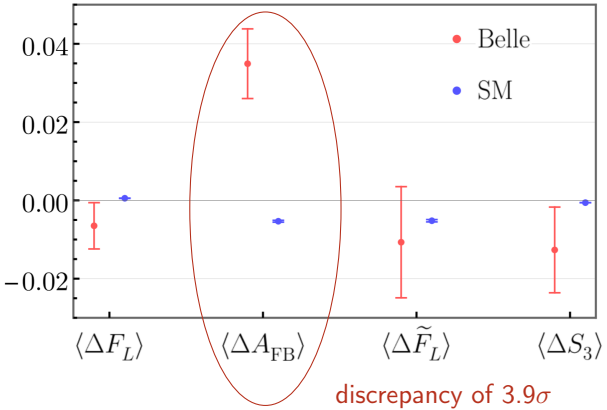

$$\Delta A_{FB} \equiv A_{FB}^{\mu} - A_{FB}^{e}$$

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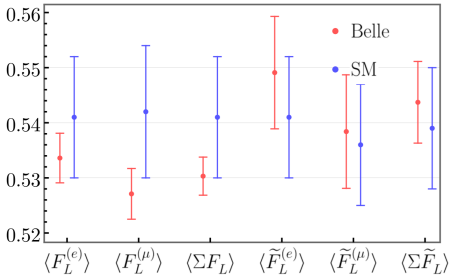

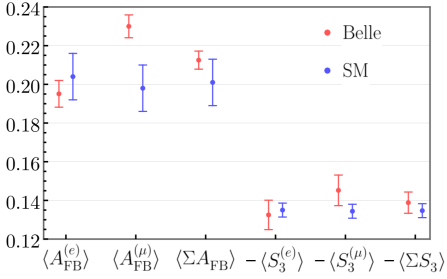

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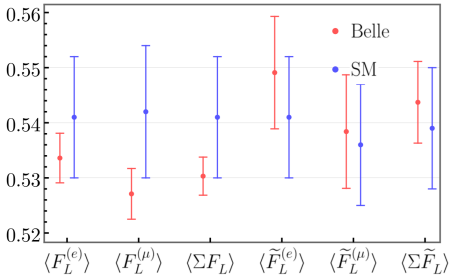

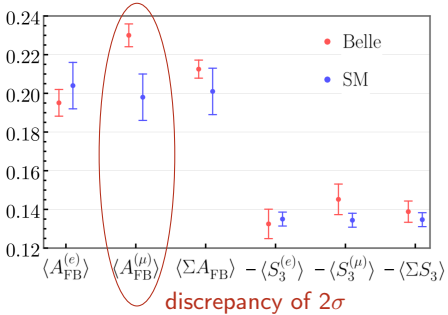

discrepancy of 2σ

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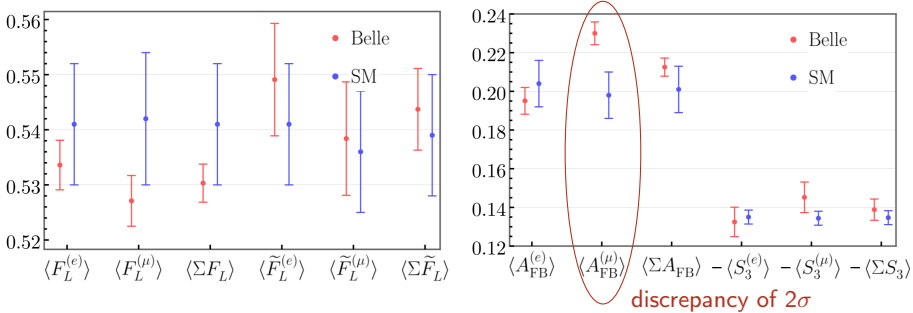

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- Correlation matrices of the statistical uncertainties are incorrect

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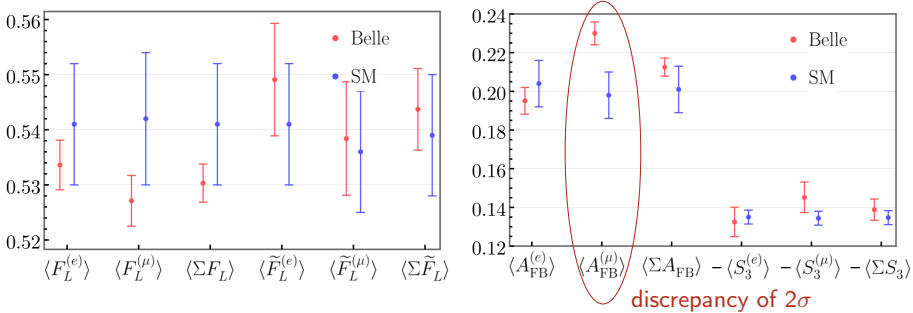

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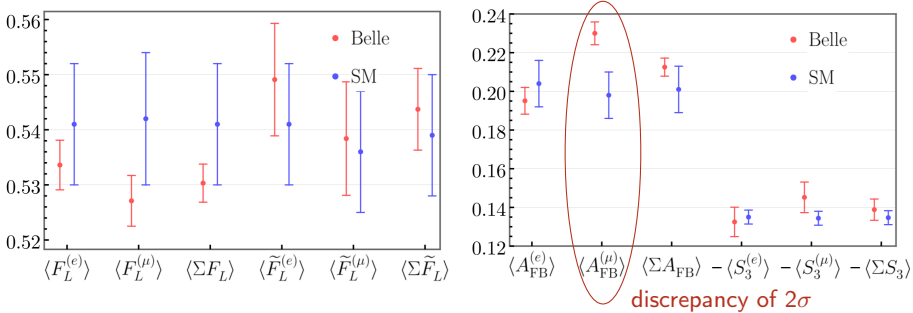

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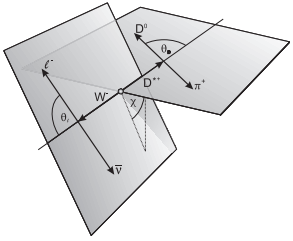
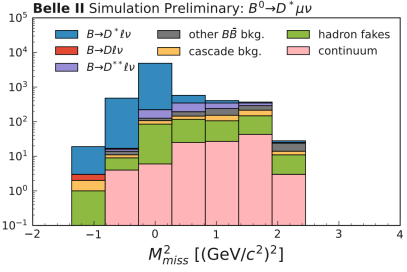
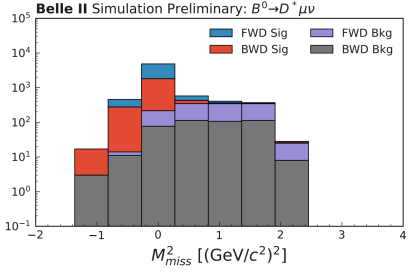
- **Further studies are needed**
- **e/μ flavours should be studied separately**

A_{FB} at Belle II

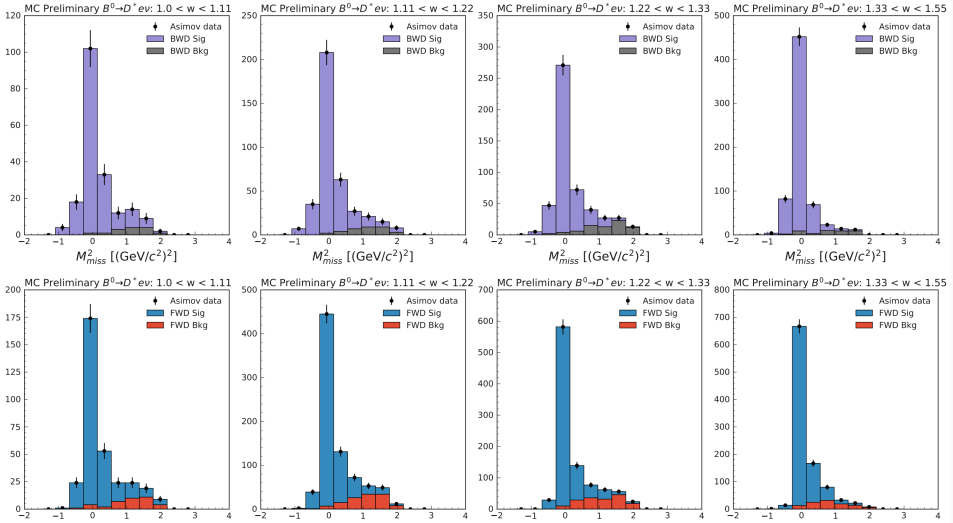
- Aim: to analyse tagged and untagged $B \to D^* \ell \nu_\ell$
- Signal extraction via asimov fits in M^2_{miss} in 4 bins of w
- Theory suggests measuring $A_{FB}(q^2)$ [arXiv:2203.07189]
- Results:
  - ◇ Expected for summer conferences
  - ◇ Calculate average ΔA_{FB} from tagged and untagged analyses







A_{FB} at Belle II: Asimov fits



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

[arXiv:2008.07198]

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- Signal and background separation in $\cos\theta_{BY}$ in 5 bins of w
- Signal yield: almost 10000 for each lepton mode

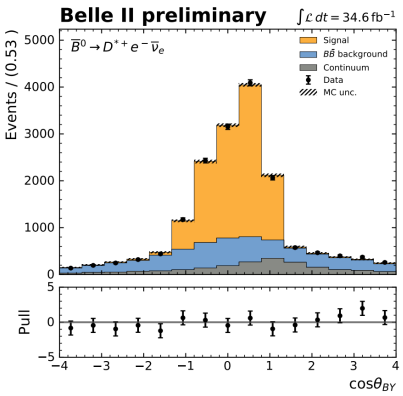

Figure: The fitted $\cos\theta_{BY}$ distribution for the electron candidates.

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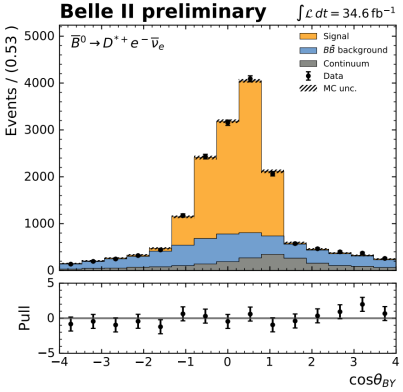
Results:

- Distributions of $\cos\theta_{BY}$ and hadronic recoil parameter w



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- Signal and background separation in $\cos\theta_{BY}$ in 5 bins of w
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Results:

- Distributions of $\cos\theta_{BY}$ and hadronic recoil parameter w
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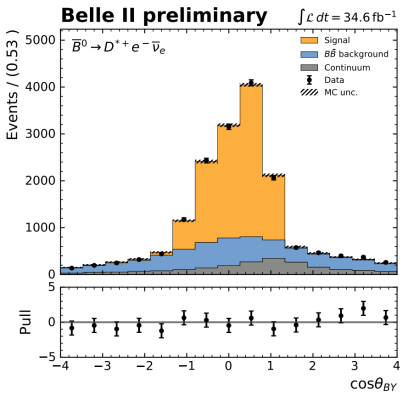

Figure: The fitted $\cos\theta_{BY}$ distribution for the electron candidates.

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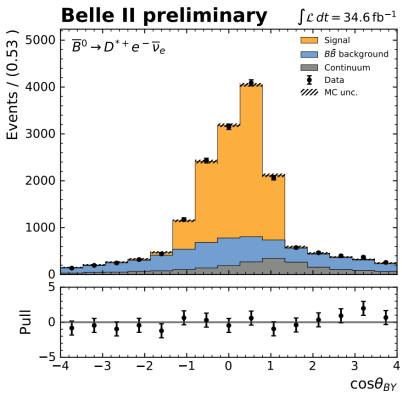

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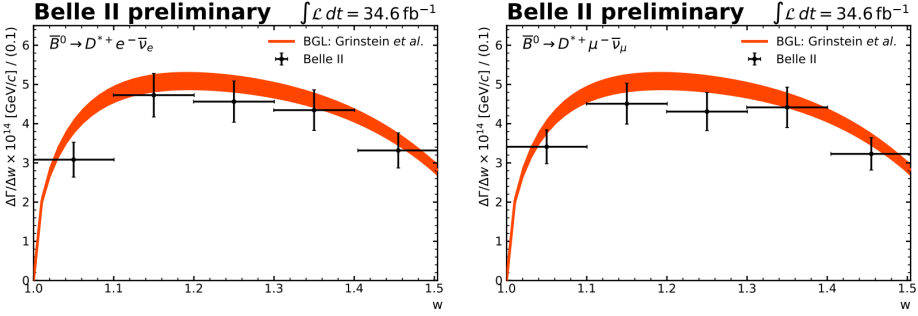

Figure: The measured partial decay rates for electrons and muons are compared to the BGL form factor parameters of Refs. [arXiv:1703.08170] and [arXiv:1703.06124].

Leading uncertainty: slow pion (∼10 %)

$B^- \to D^0 \ell^- \bar{\nu}_\ell$ studies at Belle II

[arXiv:2110.02648]

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- Signal and background separation in $\cos\theta_{BY}$
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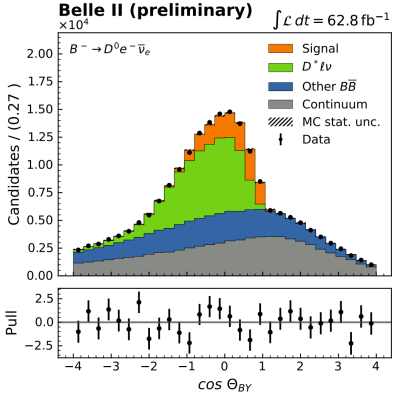

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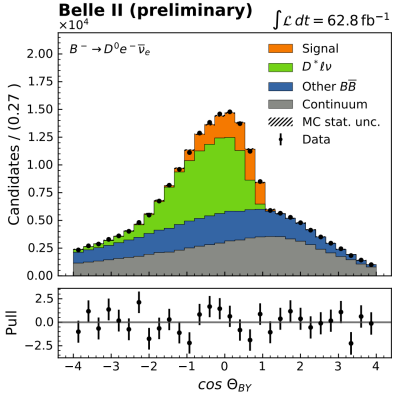

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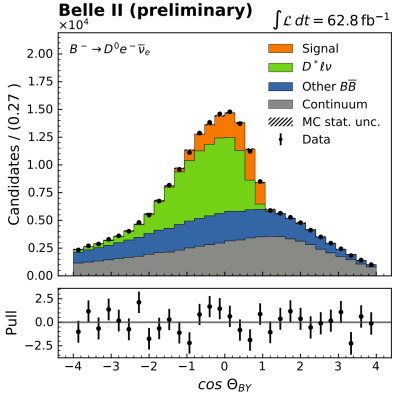

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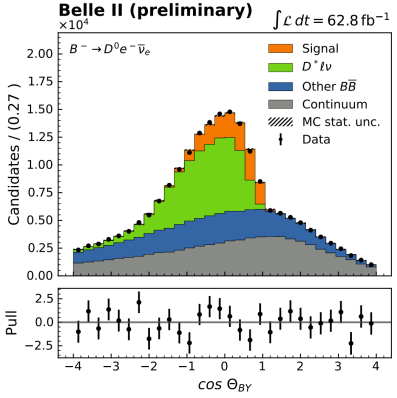

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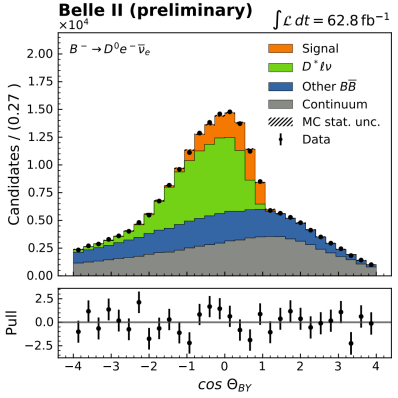
- Leading systematic uncertainties: tracking and lepton identification



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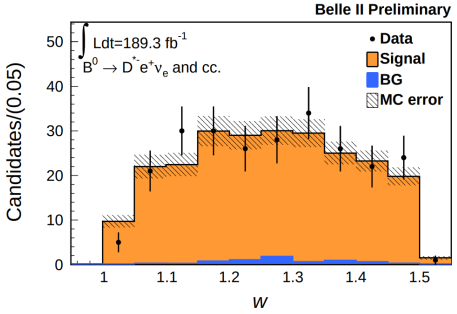
$|V_{cb}|$ from $B^0 \to D^{*-}\ell^+\nu_\ell$ studies at Belle II [Moriond22]

- New tagged analysis → Results presented at Moriond22
- Belle II data sample of $189.3\,\text{fb}^{-1}$



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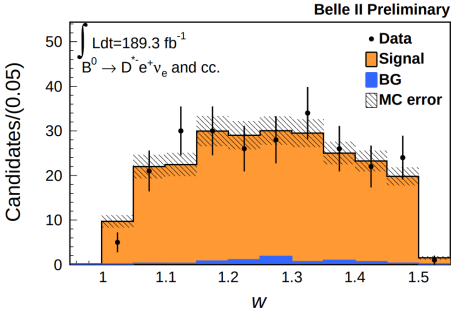
- CLN paramterization assumed [arXiv:hep-ph/9712417]
- Measured: $\eta_{EW} F(1) |V_{cb}|$
- Looking into w distribution to determine signal yields



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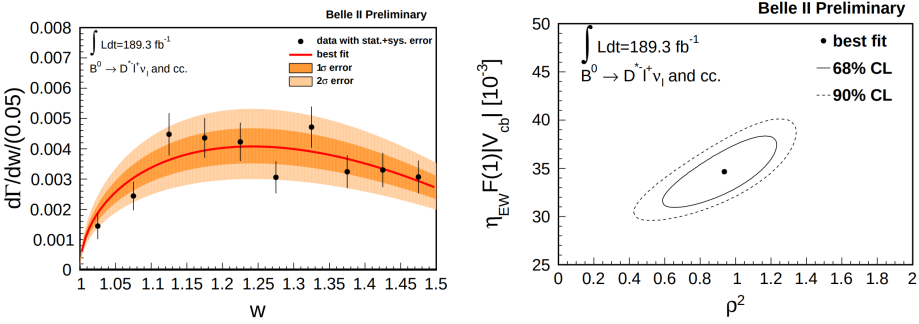

Figure: Left: Measured $d\Gamma/dw(B^0 \to D^{*-}\ell^+\nu_\ell)$. Right: Measured $\eta_{EW}F(1)|V_{cb}|$ and ρ^2. Both results are presented with 1σ contour (solid line), 2σ contour (dashed line) and the best fit function or point.

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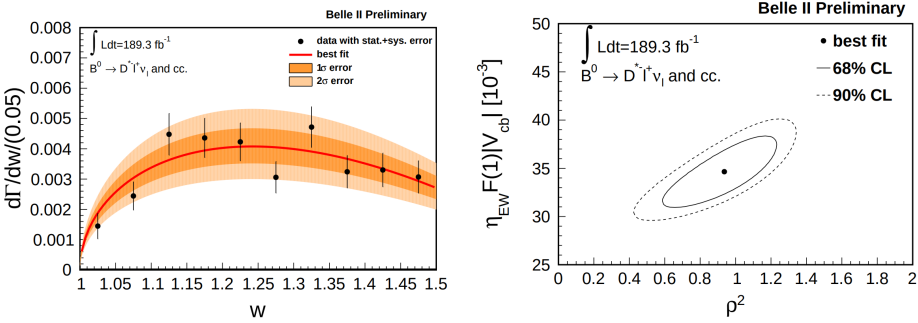

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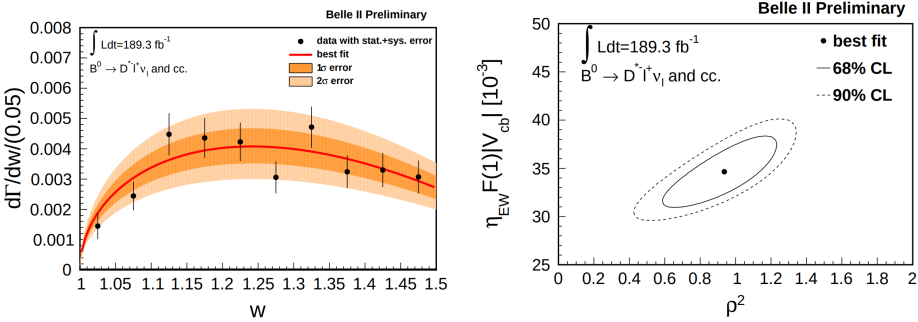

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Results

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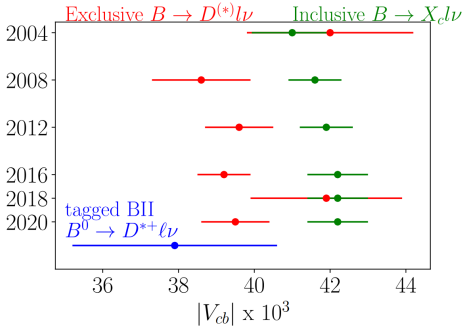
- $|V_{cb}| = (37.9 \pm 2.7_{(stat.+syst.)}) \times 10^{-3}$
- The first Belle II tagged determination of $|V_{cb}|$ is statistically limited
- Dominant uncertainties: slow pion and Full Event Interpretation (hadronic tagging) efficiency
- We expect higher precision soon with untagged determinations



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- Results are in agreement with world averages, but not competitive yet
- Main uncertainty originates from slow pion $\to$ In latest measurements uncertainty went from $\sim 10\%$ down to $\sim 3\%$ $\to$ We expect $\sim 2\%$ uncertainty on measured $|V_{cb}|$
- We expect more (competitive) results in summer $\to$ Stay tuned!