# A novel analysis of $B \to D\ell\nu$ and $B \to D^*\ell\nu$ decays at Belle II

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**on behalf of the Belle II Collaboration**

**Challenges in Semileptonic B decays**
**Vienna, Sept 24, 2024**

# Overview

I will show 3 different approaches to measure $|V_{cb}|$, form factors and branching fractions using exclusive $B$ decays at Belle II:

1. $B^0 \to D^{*-}\ell^+\nu$ analysis with 189 $fb^{-1}$ [PRD 108, 092013 (2023)].

2. $B \to D\ell\nu$ analysis: preliminary result with 189 $fb^{-1}$ [arXiv: 2210.13143].
   Update to 362 $fb^{-1}$ ongoing.

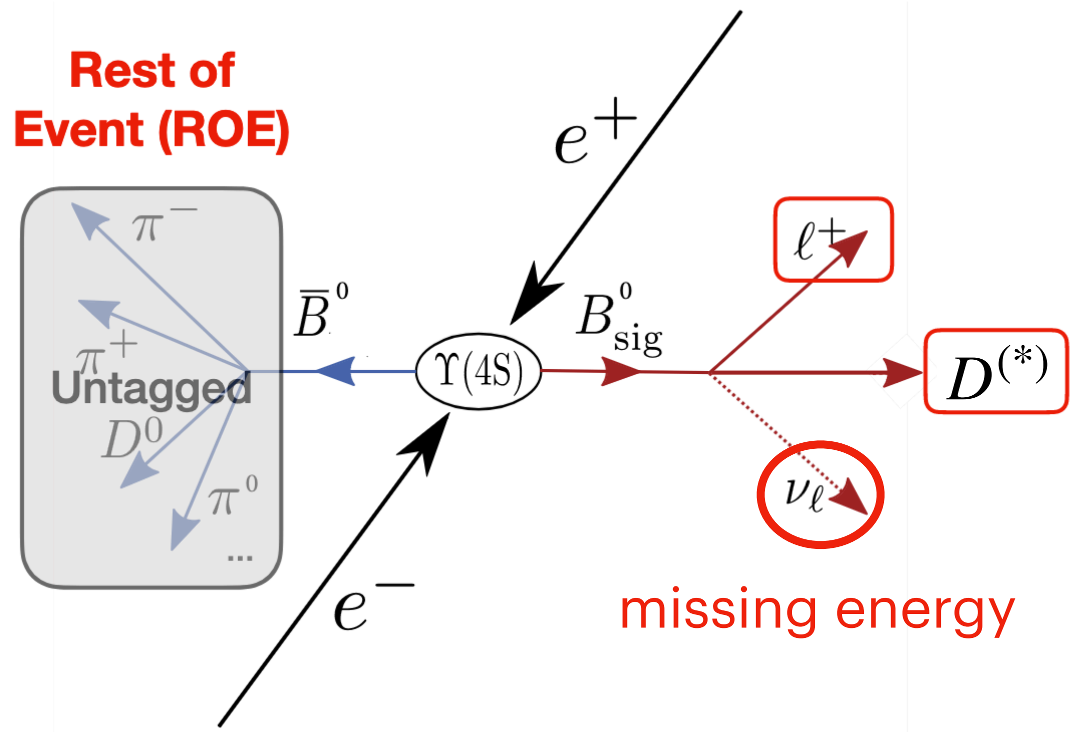
3. New global analysis of $B \to D^*\ell\nu$ and $B \to D\ell\nu$ decays: a study with simulation for an ongoing analysis.

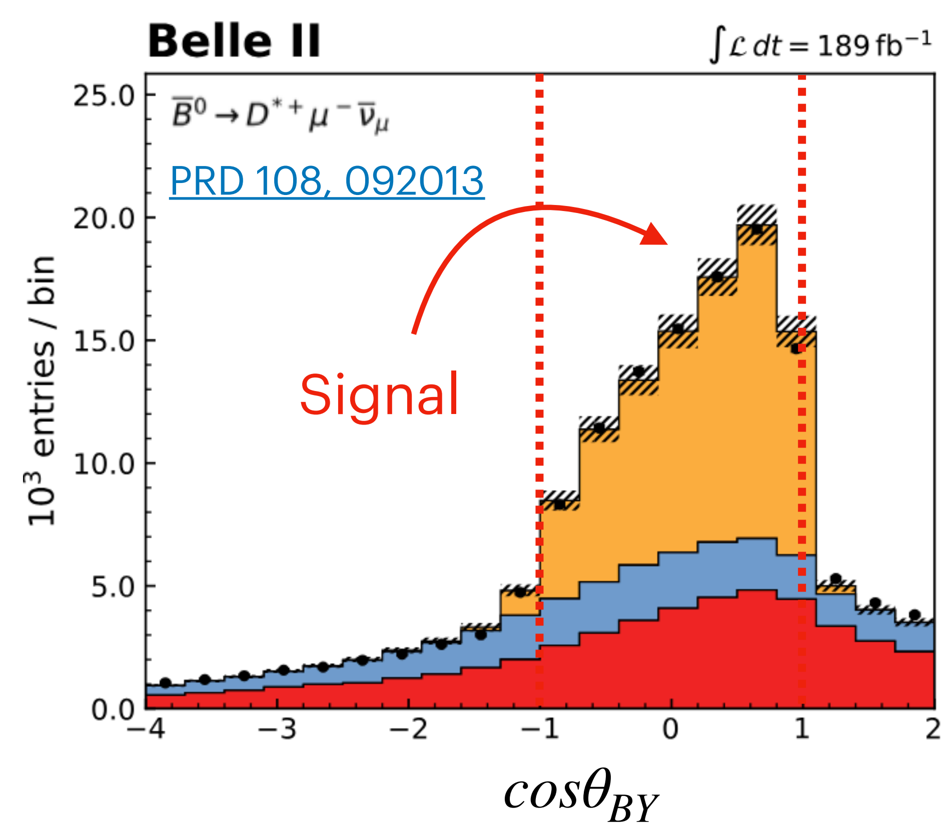
# Dealing with missing energy

All analyses covered here are UNTAGGED:

- No systematic related to $B$ tagging efficiency, important for BR and $|V_{cb}|$.
- High efficiency compensate for low resolution of approximated $B$ kinematics.
- No discriminating $B$ peak for signal.
  - Leverage $M(D)$ and $\Delta M = M(D^*) - M(D)$ narrow peaks.
  - Use available kinematic constraint:

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



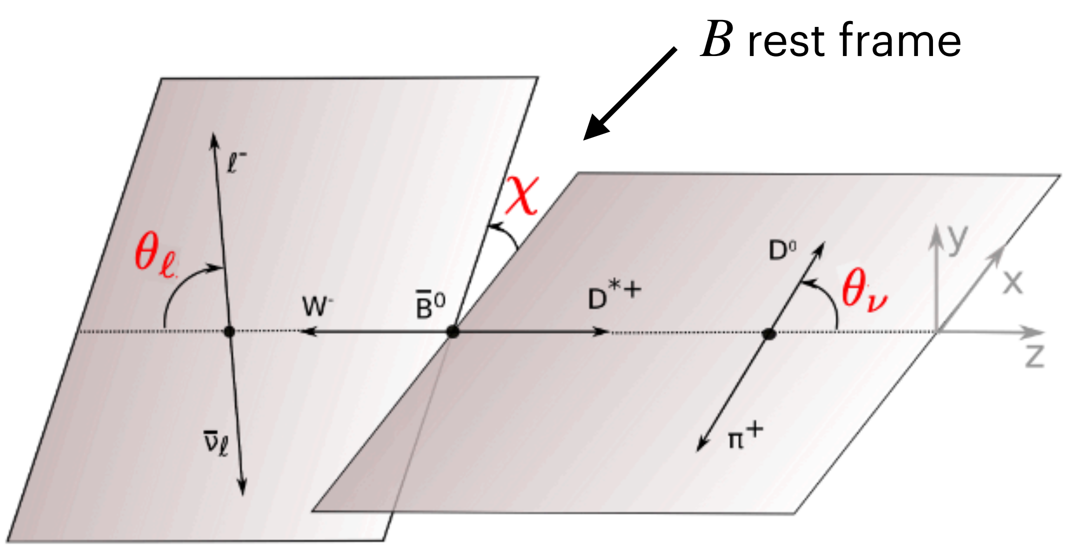
# $B \to D^*\ell\nu$ measurement

[PRD 108, 092013 (2023), 189 $fb^{-1}$]

# In a nutshell

Rich phenomenology due to different decay amplitudes encoded in angular distributions.

Reconstruct $B^0 \to D^{*+}\ell^-\nu$, with $D^{*+} \to D^0[\to K^-\pi^+]\pi^+_{soft}$.




Reconstruct the kinematic variables:

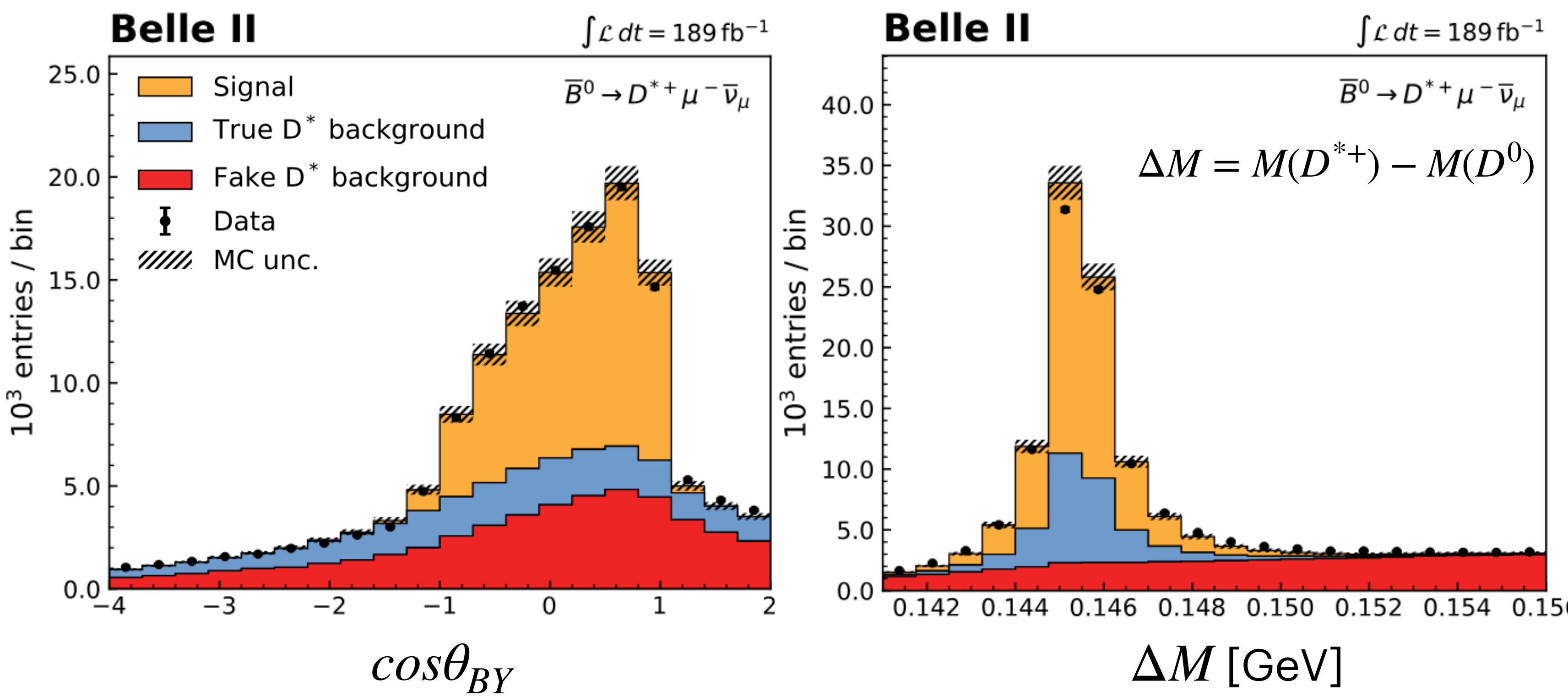
$w$ and 3 helicity angles, $cos\theta_\ell$, $cos\theta_v$ and $\chi$.

$w = E_{D^*}/M_D^*$

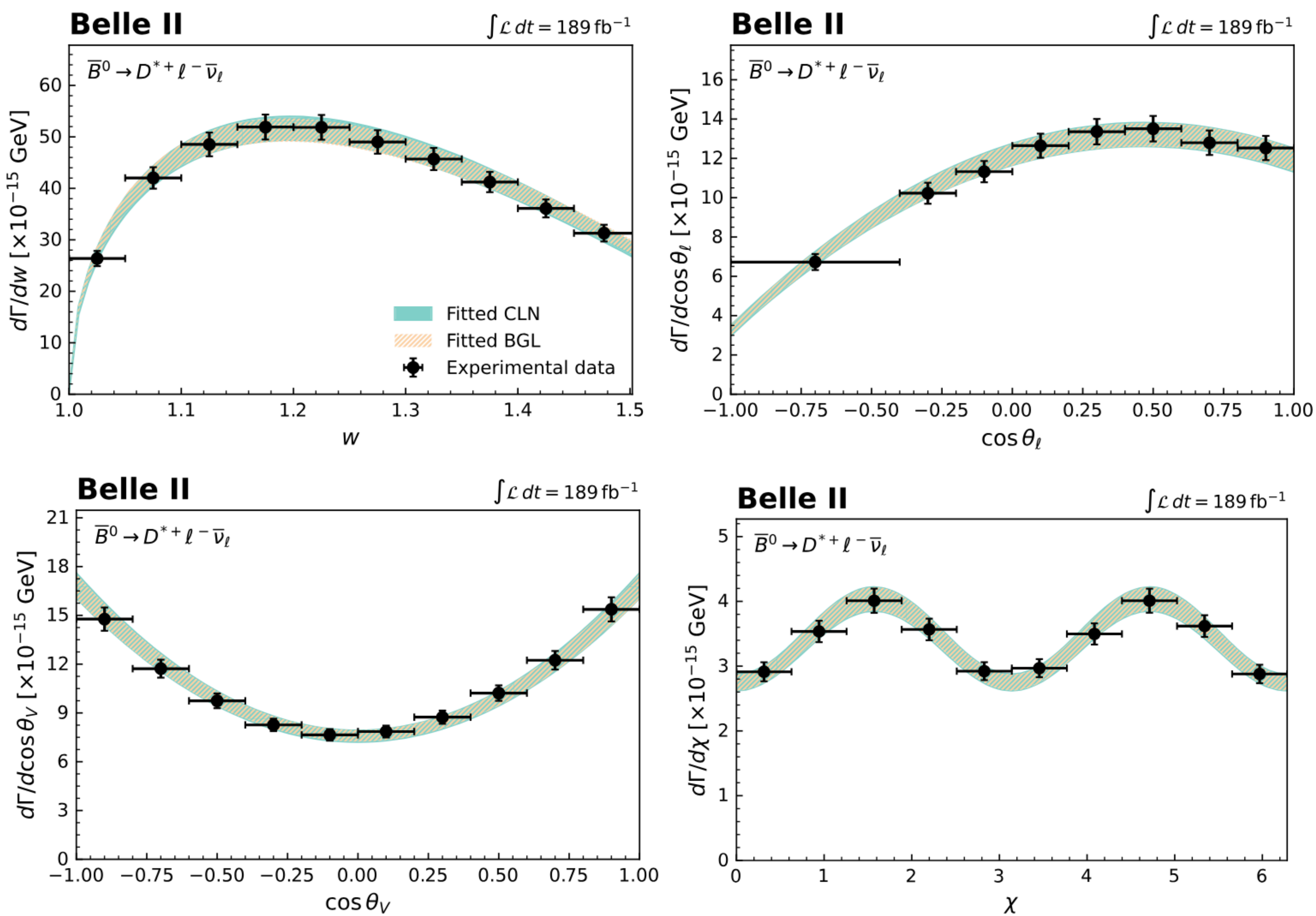
Extract the signal yields with fit to $cos\theta_{BY}$ and $\Delta M$

in bins of $w$, $cos\theta_\ell$, $cos\theta_v$ and $\chi$, to reconstruct 1D signal distributions.

Unfold the reconstructed distributions from experimental effects (efficiencies and resolutions).



# Unfolded distributions




Fit the unfolded distributions with different form-factor model to obtain $|V_{cb}|$.

# Results

$\mathcal{B}(\bar{B}^0 \to D^{*+}\ell^-\bar{\nu}_\ell)$ : $(4.922 \pm 0.023(stat) \pm 0.220(syst))$ %

Compatible with the current WA: $(4.97 \pm 0.12)$ %

$$|V_{cb}|_{BGL} = (40.57 \pm 0.31(stat) \pm 0.95(syst) \pm 0.58(th)) \cdot 10^{-3}$$

Compatible with the exclusive (inclusive) WA: 1.5$\sigma$ (1.3$\sigma$)

$$|V_{cb}|_{CLN} = (40.13 \pm 0.27(stat) \pm 0.93(syst) \pm 0.58(th)) \cdot 10^{-3}$$

Compatible with the exclusive (inclusive) WA: 1.1$\sigma$ (1.6$\sigma$)

Use FNAL/MILC lattice QCD data at zero recoil ($w = 1$) for normalisation. BGL truncated using nested hypothesis test: BGL(1,2,2).

LFU test by comparing separated results for electrons and muons:

$$R_{e/\mu} = 0.998 \pm 0.009(stat) \pm 0.020(syst)$$

$$\Delta A_{FB} = (-17 \pm 16(stat) \pm 16(syst)) \cdot 10^{-3}$$

$$\Delta F_L = (0.006 \pm 0.007(stat) \pm 0.005(syst)) \cdot 10^{-3}$$

No deviations observed from the SM.

Dominant systematic sources:

1) slow-pion reconstruction efficiency $\to$ 1.5% on $|V_{cb}|$

2) $f_{+0} = \dfrac{\mathcal{B}(\Upsilon(4S) \to B^+B^-)}{\mathcal{B}(\Upsilon(4S) \to B^0\bar{B}^0)} \to$ 1.3% on $|V_{cb}|$

# $B \to D\ell\nu$ measurement

[arXiv: 2210.13143, 189 $fb^{-1}$]

# Preliminary results

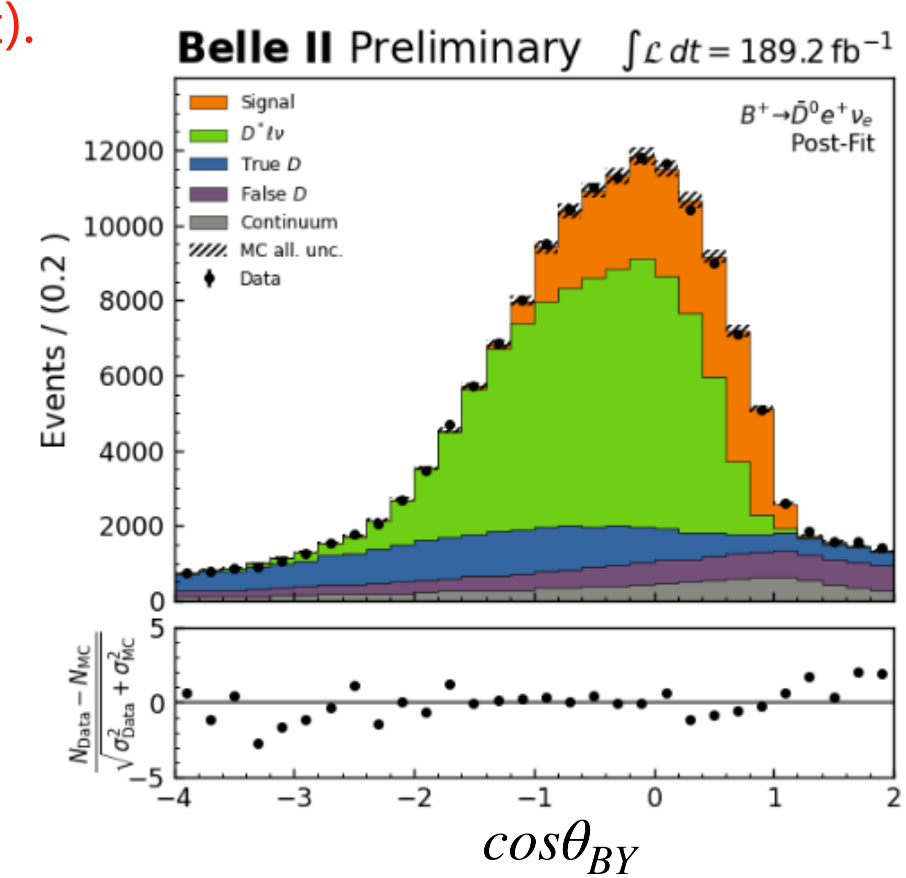
More simpler on theoretical side: only 1 form factor (massless limit).

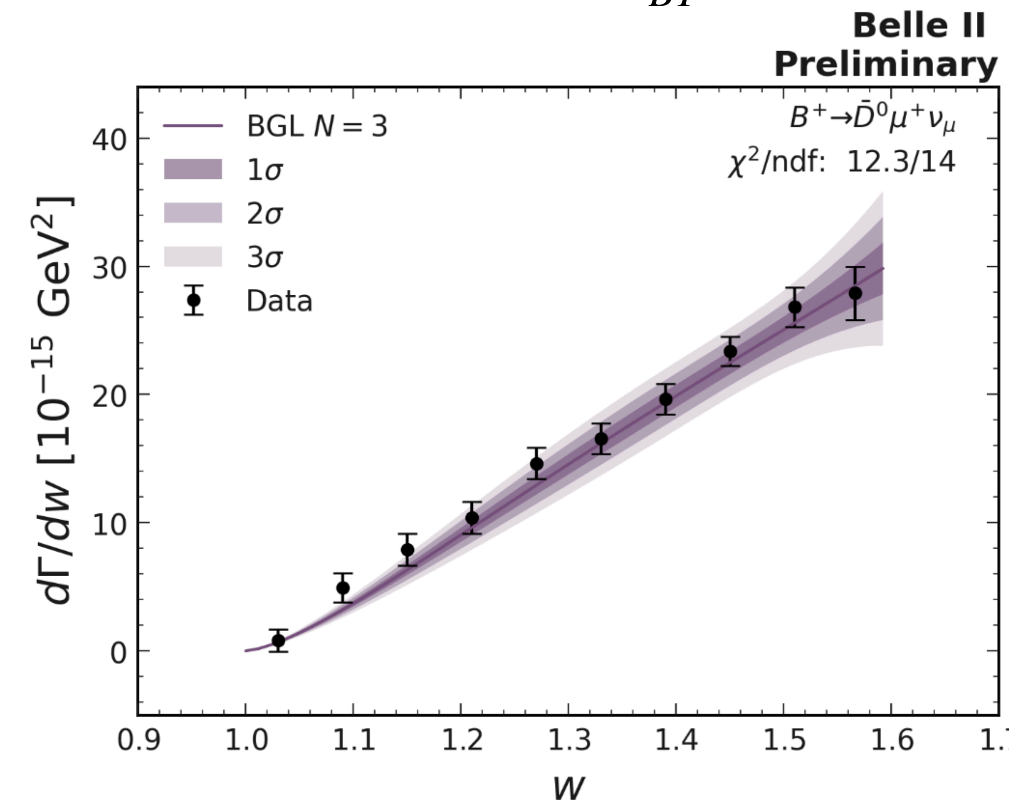
Reconstruct both $B^0$ and $B^+$ decays from $D^0 \to K\pi$ and $D^- \to K\pi\pi$ final states.

Exploit isospin symmetry to analyse $B^0$ and $B^+$decays simultaneously and reduce experimental uncertainties.

Extract signal yields from fit to the $cos\theta_{BY}$ in 10 bins of $w$.

Unfold the reconstructed $w$ distribution of the signal.




Preliminary result

$$|V_{cb}|_{BGL} = (38.28 \pm 1.16) \cdot 10^{-3}$$

Obtain a total uncertainty on $|V_{cb}|$ of ~ 3%.

# Update to 362 $fb^{-1}$ ongoing

An analysis on the full data set collected by Belle II between 2019 and 2022 is ongoing.
Improved selection and better control of systematic uncertainties:

| | $\|V_{cb,BGL}\|$ [%] | $\|V_{cb,BCL}\|$ [%] |
|---|---|---|
| Stat. Error | 0.7 | 0.6 |
| MC Stat. Error | 0.4 | 0.3 |
| $N_{bb}$ | 0.8 | 0.8 |
| $f_{00}/f_{+-}$ | $< 0.1$ | $< 0.1$ |
| $\mathcal{B}(D \to K\pi(\pi))$ | 0.4 | 0.4 |
| Selection | 0.2 | 0.2 |
| $\mathcal{B}(B \to X_c \ell\nu)$ | 0.2 | 0.1 |
| LeptonID | 0.1 | 0.1 |
| KaonID | 0.4 | 0.4 |
| Tracking efficiency | 0.5 | 0.5 |
| $B \to D\ell\nu_\ell$ form factor | 0.8 | 0.4 |
| $B \to D^*\ell\nu_\ell$ form factor | 0.1 | 0.1 |
| $\cos\theta_{BY}$ background modelling | 0.2 | 0.2 |
| $w$ background modelling | 0.5 | 0.4 |
| $\tau_{B^0/\pm}$ | 0.1 | 0.1 |
| Total systematic | 1.5 | 1.4 |
| Theory PRD 79, 013008, PRD 93, 119906 | 1.3 | 1.2 |
| Total | 2.1 | 1.9 |

The uncertainty on $f_{+-}/f_{00}$ cancel out by assuming isospin symmetry between $B^0$ and $B^+$ samples.

Theory contribution: lattice point at non-zero recoil lattice QCD calculations.

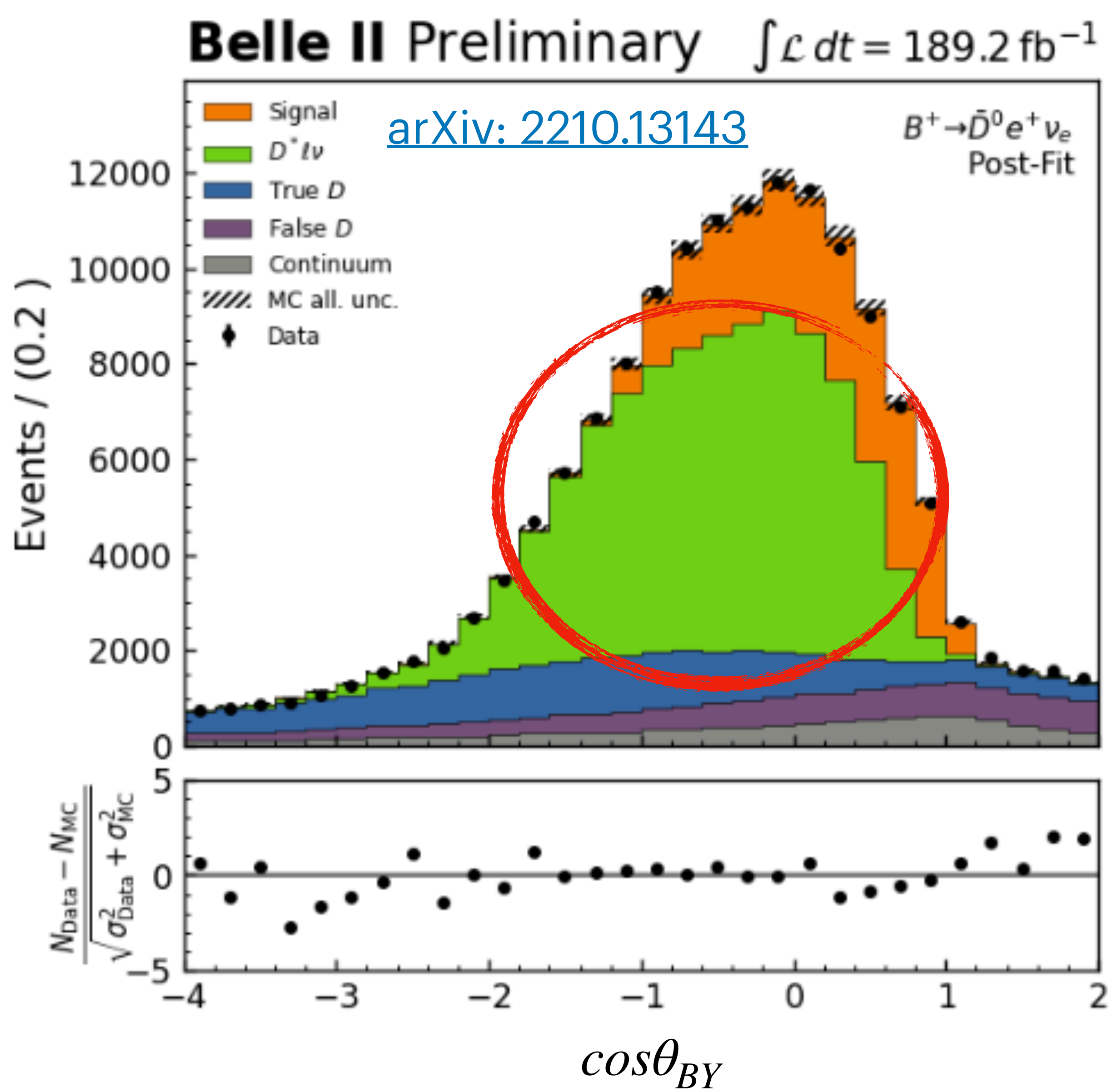
Expected competitive result on $|V_{cb}|$ with a total uncertainty of ~ 2%.

Expected also competitive result on the branching-fraction measurements.

Can we combine them?
A global analysis of
$B \to D^* \ell \nu$ and $B \to D \ell \nu$ decays

# New approach

The $B \to D\ell\nu$ sample features a large feed-down contribution from $B \to D^*\ell\nu$ decays, usually treated as a background.




Can we analyse $B \to D^*\ell\nu$ and $B \to D\ell\nu$ together?

[inspired by a BaBar analysis from 2008 (**PRD 79, 012002**)]

# Simultaneous analysis at Belle II

- By reconstructing $D\ell\nu$ final states, perform a simultaneous analysis of $B \to D\ell\nu$ and $B \to D^*\ell\nu$ where $D^*$ is partially reconstructed:

1. Get rid of major systematic uncertainty on $B \to D^*\ell\nu$ analysis (slow pion efficiency).

2. Analyse both $B^0$ and $B^+$ decays. Can exploit isospin symmetry to:

   - reduce total uncertainty budget
   - determine also $f_{+-}/f_{00}$

   at the cost of an uncertainty on isospin breaking (Coulomb factor*).

- An alternative approach to the ongoing measurements, affected by different sources of systematic uncertainties.

*Coulomb factor: difference between $B^0$ and $B^+$ decays due to possible QED interactions in $D^{*-}\ell^+$ and not in $D^{*0}\ell^+$.

Contribute a (conservative) uncertainty of ~ 1% on the BR.

# Model-independent observables

Measure observables that allow interpretation of results with any form-factor model.

$D\ell\nu$, measure the differential rate as a function of $w$:

$$\frac{d\Gamma}{dw} \propto \Gamma_0(w)\underbrace{|V_{cb}|^2 |G(w)|^2}$$

$G'(w)$, measured in 7 bins of $w$

$D^*\ell\nu$, measure the squared helicity amplitudes as a function of $w$:

$$\frac{d^2\Gamma}{dwdcos\theta_\ell} \propto \Gamma_0(w)|V_{cb}|^2 \Big\{ \overbrace{H_+^2(w) + H_-^2(w) + 2H_0^2(w)}^{a(w)}$$

$$+ \overbrace{2[H_-^2(w) - H_+^2(w)]}^{b(w)} cos\theta_\ell$$

$$+ \overbrace{[H_+^2(w) + H_-^2(w) - 2H_0^2(w)]}^{c(w)} cos^2\theta_\ell \Big\}$$

$a'(w), b'(w), c'(w)$, measured in 5 bins of $w$

# Results from these observables

From the measured values of $G', a', b', c'$ in bins of $w$, can determine:

1. $\mathscr{B}(B \to D\ell\nu)$ , $\mathscr{B}(B \to D^*\ell\nu)$ and their ratio.

2. $|V_{cb}|$ and form factors: $f_+(w)$ for $D\ell\nu$ and $f(w)$, $g(w)$, $\mathscr{F}_1(w)$ for $D^*\ell\nu$.
   Can use any model and reinterpret the measurement using any theoretical advancement.

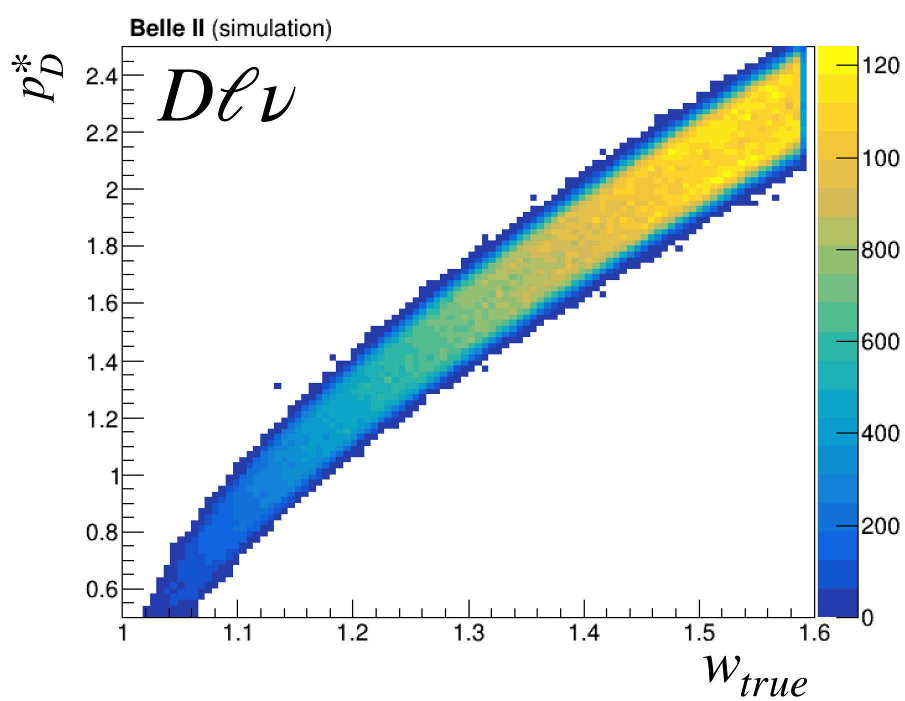
3. Forward-backward asymmetry $A_{FB}$ and longitudinal polarisation $F_L^{D^*}$ in bins of $w$:

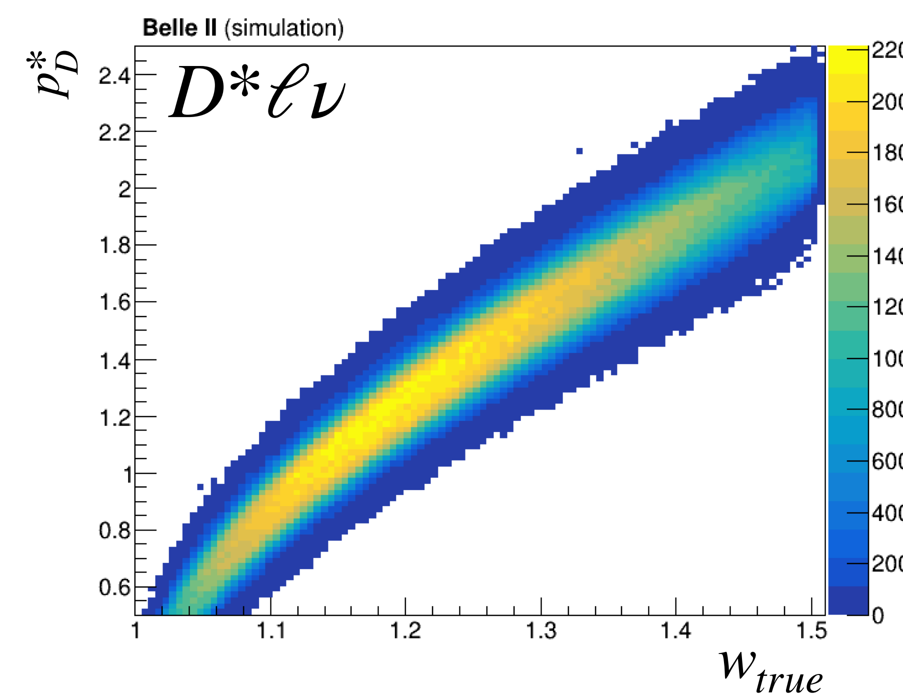
$$A_{FB}(w) = \frac{3b'(w)}{6a'(w) + 2c'(w)} \qquad F_L^{D^*}(w) = \frac{a'(w) - c'(w)}{3a'(w) + c'(w)}$$

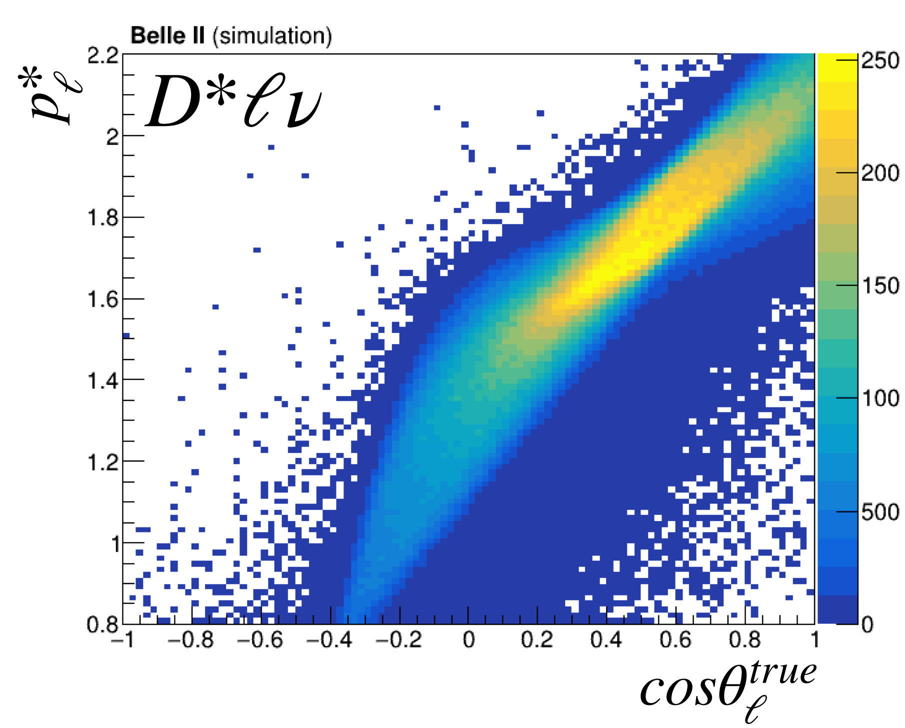
Can also do measurements separately for electrons and muons to test LFU.

# How?

- $p_D^*$, momentum of the $D$ in the CMS, encapsulates $w$ for both $D\ell\nu$ and $D^*\ell\nu$.
- $p_\ell^*$, momentum of the lepton in the CMS, encapsulates $cos\theta_\ell$ for $D^*\ell\nu$.
- Their 2D distribution is highly sensitive to the $D\ell\nu$ and $D^*\ell\nu$ differential decay rates.



# Analysis strategy

**Selection**

Reconstruct both electron and muon samples.
Tight selection to have clean samples. Minimise uncertainties from background.

**Sample composition**

Study in detail all possible sources of background and categorise them in components for the fit.

**Measurement of model-independent observables**

Make a 3D $\chi^2$ fit using $p_D^*$ and $p_\ell^*$ to access the differential decay rate, and $cos\theta_{BY}$ to enhance signal-to-bkg separation. Assess systematic uncertainties.

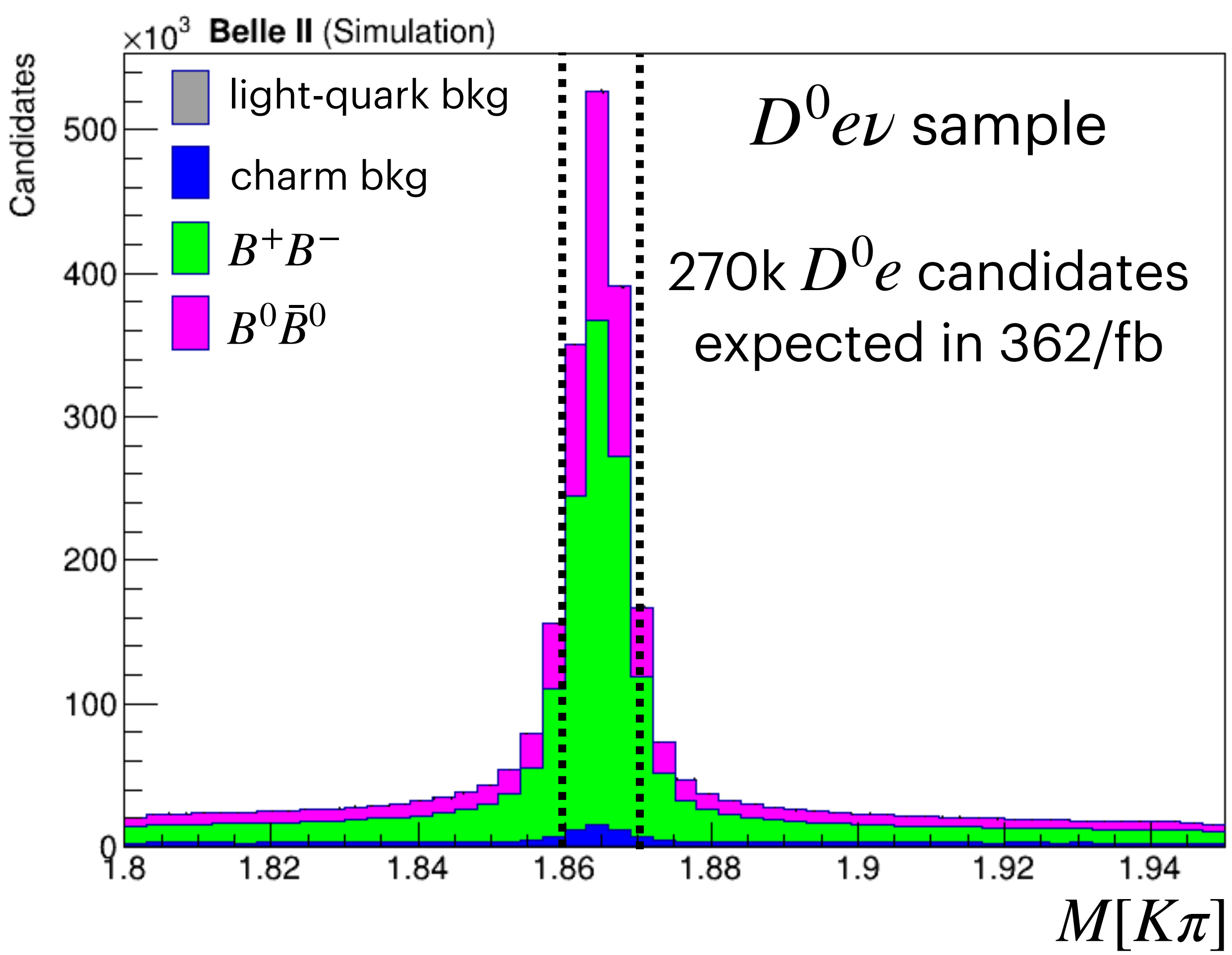
**Interpretation of the measurement**

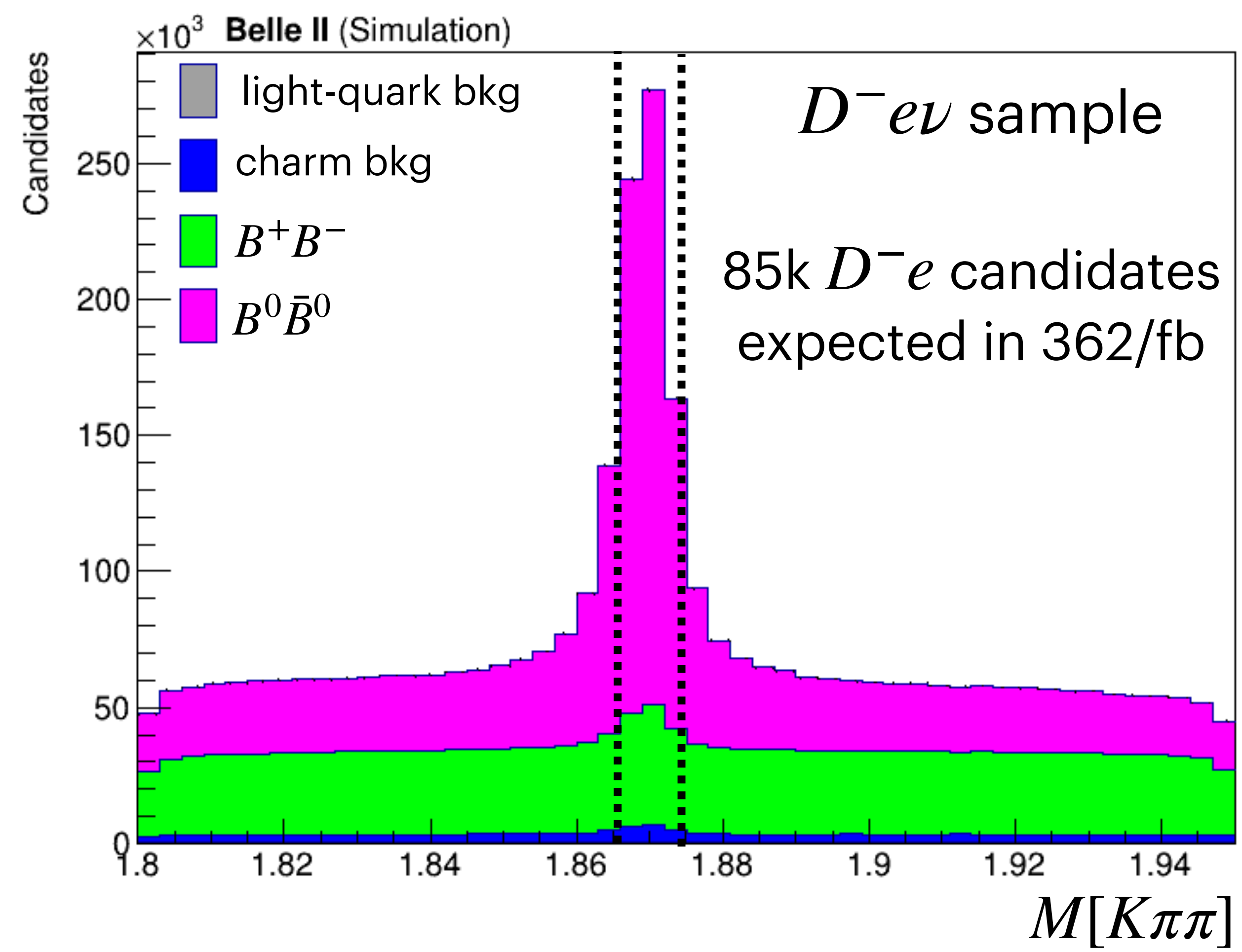
Determine BR, $|V_{cb}|$, form factors, $A_{FB}$ and $F_L^{D^*}$ from the measured values of $G', a', b', c'$ and their covariance.

Full analysis tested with realistic Belle II simulation of 362 $fb^{-1}$ sample.

# Selection

- Three or four tracks of good quality. Apply leptonID and KaonID.
- Suppress continuum with total energy in the event, shape variables and kinematic bounds.
- Minimum thresholds on momentum for leptons and $D$ mesons.
- Tight cut around narrow $D$ mesons peaks.

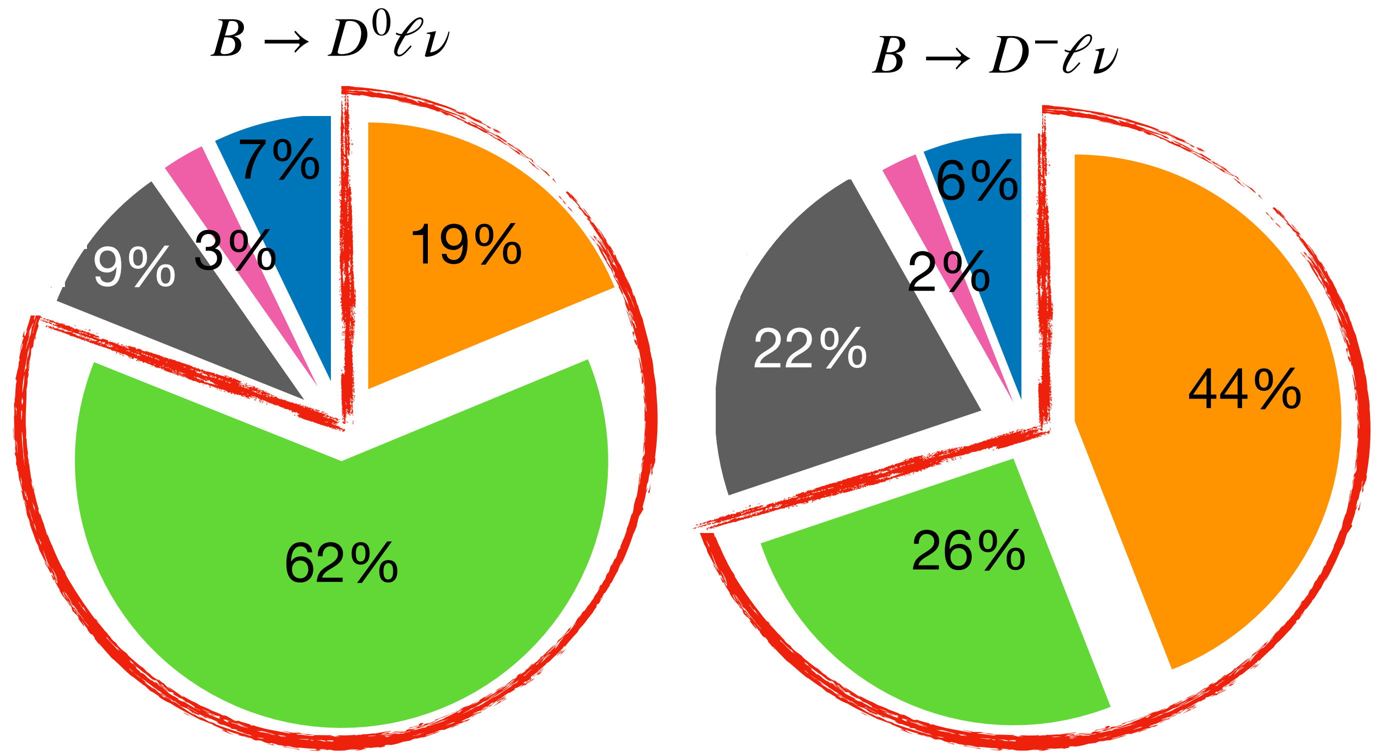



Similar proportion for the muon samples.

# Sample composition

Divide $B \to D\ell\nu$ samples in 6 components:




1. $B \to D^*\ell\nu$
2. $B \to D\ell\nu$

] **signal**

3. Fake D: a random $K\pi/K\pi\pi$ combination + lepton (real or fake)
4. Continuum: background from $e^+e^- \to q\bar{q}$, $q \in [u, d, c, s]$

] **constrained from data: using D mass sideband + off-resonance data**

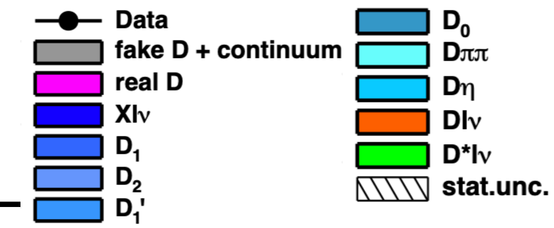
5. $B \to X\ell\nu$ + gap modes, where $X$ is $D^{**}$ (include also $D^{(*(*))}\tau\nu$) ] **Constrained from data using a control region**

6. Real D: real D + lepton (real or fake) ] **Most of the B-hadronic decays unknown. Take into account as systematics uncertainty.**

# Fit configuration

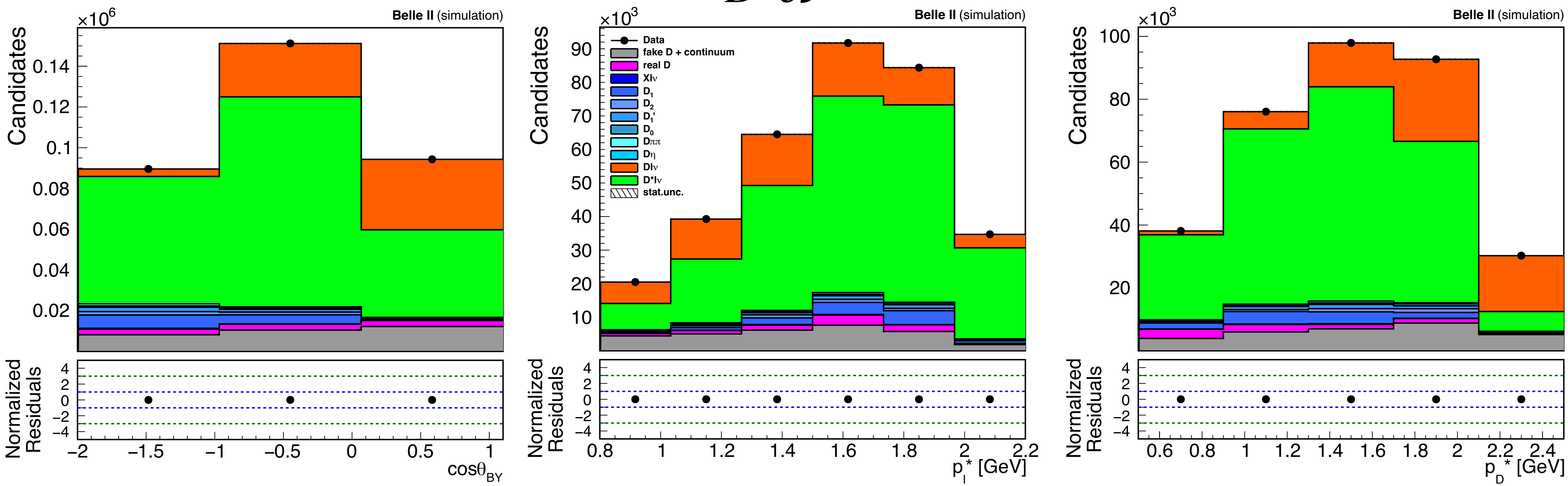
- Fit 3D data distribution of $(cos\theta_{BY}, p^*_\ell, p^*_D)$ using templates from simulation or data sideband.
- Signal templates and yields depend on the parameters $G', a', b', c'$.
- Assume isospin symmetry: $G', a', b', c'$ parameters in common between $B^0$ and $B^+$ decays.
- Total of 37 physics parameters:
  - 22 for signal (model-independent observables)
  - $f_{+-}/f_{00}$
  - 14 parameters for the background modelling
- Fit simultaneously electron and muon samples.
- Fit simultaneously to a control region to constrain $D^{**}$ backgrounds.

# Projections: signal region

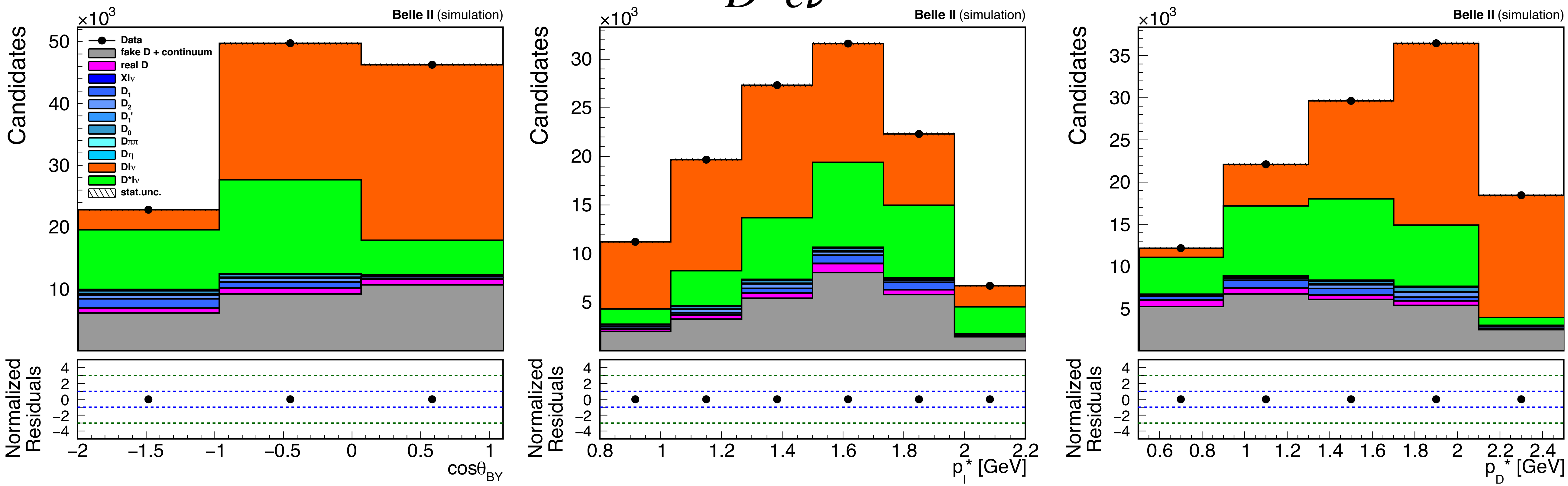



Other projections in backup

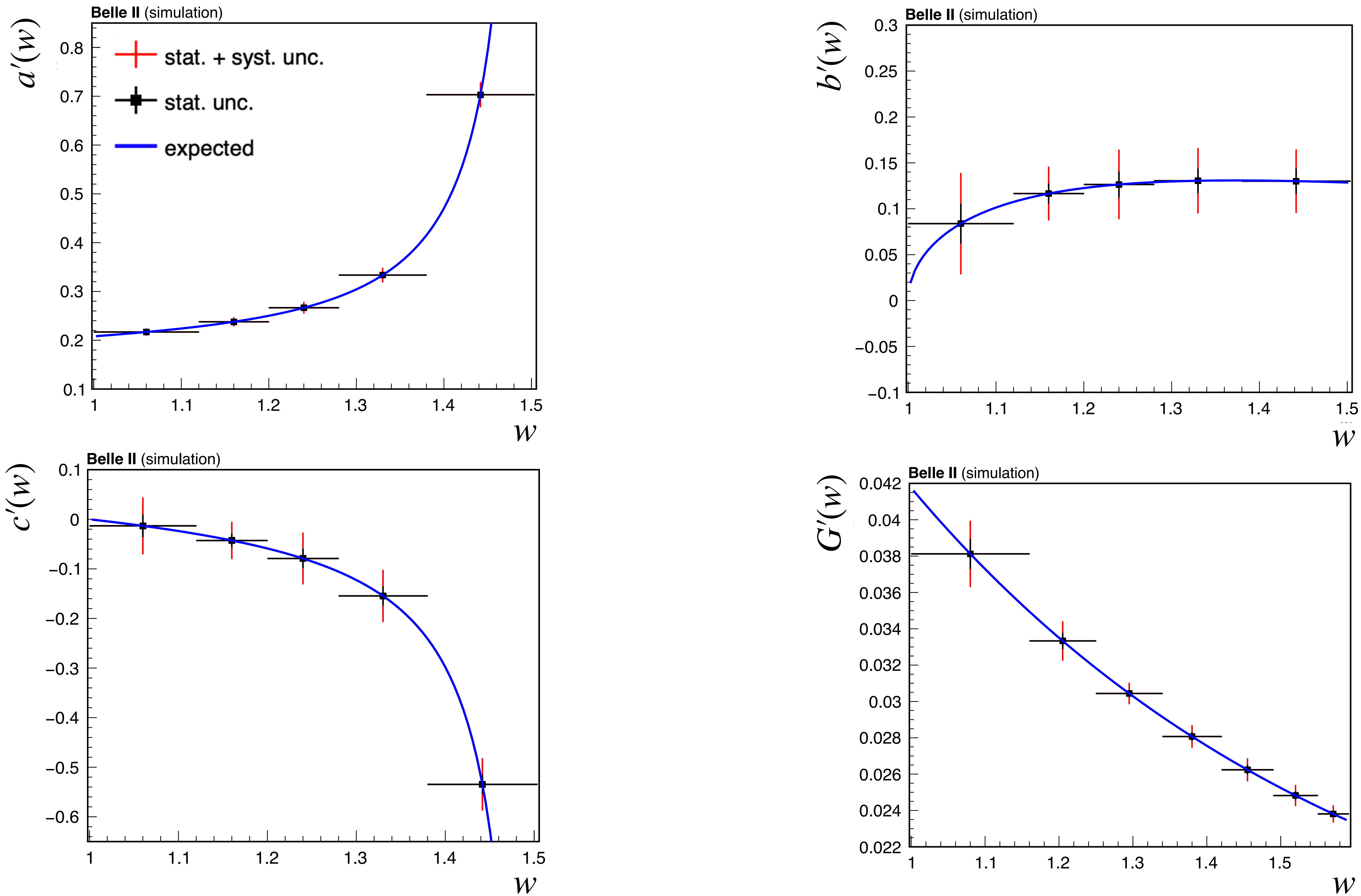
$D^0 e\nu$




$D^- e\nu$



# Model-independent observables




Measurement limited by systematic uncertainties.

Dominant uncertainties correlated through the bins as they concern the normalisation (e.g.BB pairs).

# BR and $f_{+-}/f_{00}$ expected uncertainties

Measure the $\mathscr{B}(B \to D\ell\nu)$ and $\mathscr{B}(B \to D^*\ell\nu)$ by integrating over all the $w$ range the differential branching fractions obtained from our model-independent observables in each $w$ bins.

| | Relative uncertainties [%] on $\mathscr{B}(B \to D\ell\nu)$ | Relative uncertainties [%] on $\mathscr{B}(B \to D^*\ell\nu)$ | Relative uncertainties [%] on $f_{+-}/f_{00}$ |
|---|---|---|---|
| **NBB** | 1.5 | 1.5 | $< 0.1$ |
| **BR(D decays)** | 1.0 | 0.7 | 1.9 |
| **Lifetime ratio** | 0.2 | 0.2 | 0.4 |
| **track efficiency** | 0.8 | 0.8 | 0.2 |
| **BR(D** + gap)** | 1.3 | 1.2 | 1.1 |
| **Backgrounds modelling** | 0.6 | 0.3 | 1.0 |
| **MC stat** | 0.1 | 0.1 | 0.1 |
| **Coulomb factor (th. unc.)** | 1.0 | 1.1 | 2.3 |
| **TOTAL SYST** | 2.0 (syst) + 1.0 (th.) | 1.9 (syst) + 1.1 (th.) | 2.0 (syst) + 2.3 (th.) |
| **Stat** | 0.3 | 0.2 | 0.3 |

# BR and $f_{+-}/f_{00}$ expected uncertainties

Compare the uncertainties of $\mathscr{B}(B \to D\ell\nu)$, $\mathscr{B}(B \to D^*\ell\nu)$ and $f_{+-}/f_{00}$ with the best measurements.

| | Expected results | Best measurements |
|---|---|---|
| $\mathscr{B}(B^- \to D^0\ell\nu)$ | $(XXX \pm 0.01(stat) \pm 0.05(syst) \pm 0.02(th)) \cdot 10^{-2}$ | BaBar<br>$(2.34 \pm 0.03(stat) \pm 0.13(syst)) \cdot 10^{-2}$<br>Phys.Rev.D 79 (2009) 012002 |
| $\mathscr{B}(B^- \to D^{*0}\ell\nu)$ | $(XXX \pm 0.01(stat) \pm 0.11(syst) \pm 0.06(th)) \cdot 10^{-2}$ | BaBar<br>$(5.40 \pm 0.02(stat) \pm 0.21(syst)) \cdot 10^{-2}$<br>Phys.Rev.D 79 (2009) 012002 |
| $f_{+-}/f_{00}$ | $XXX \pm 0.003(stat) \pm 0.021(syst) \pm 0.024(th)$ | Belle<br>$1.065 \pm 0.012(stat) \pm 0.019(syst) \pm 0.047(th)$<br>Phys. Rev. D 107, L031102 |

Th. uncertainty from Coulomb factor.

Measurements competitive with the world's best.

# FF and $|V_{cb}|$

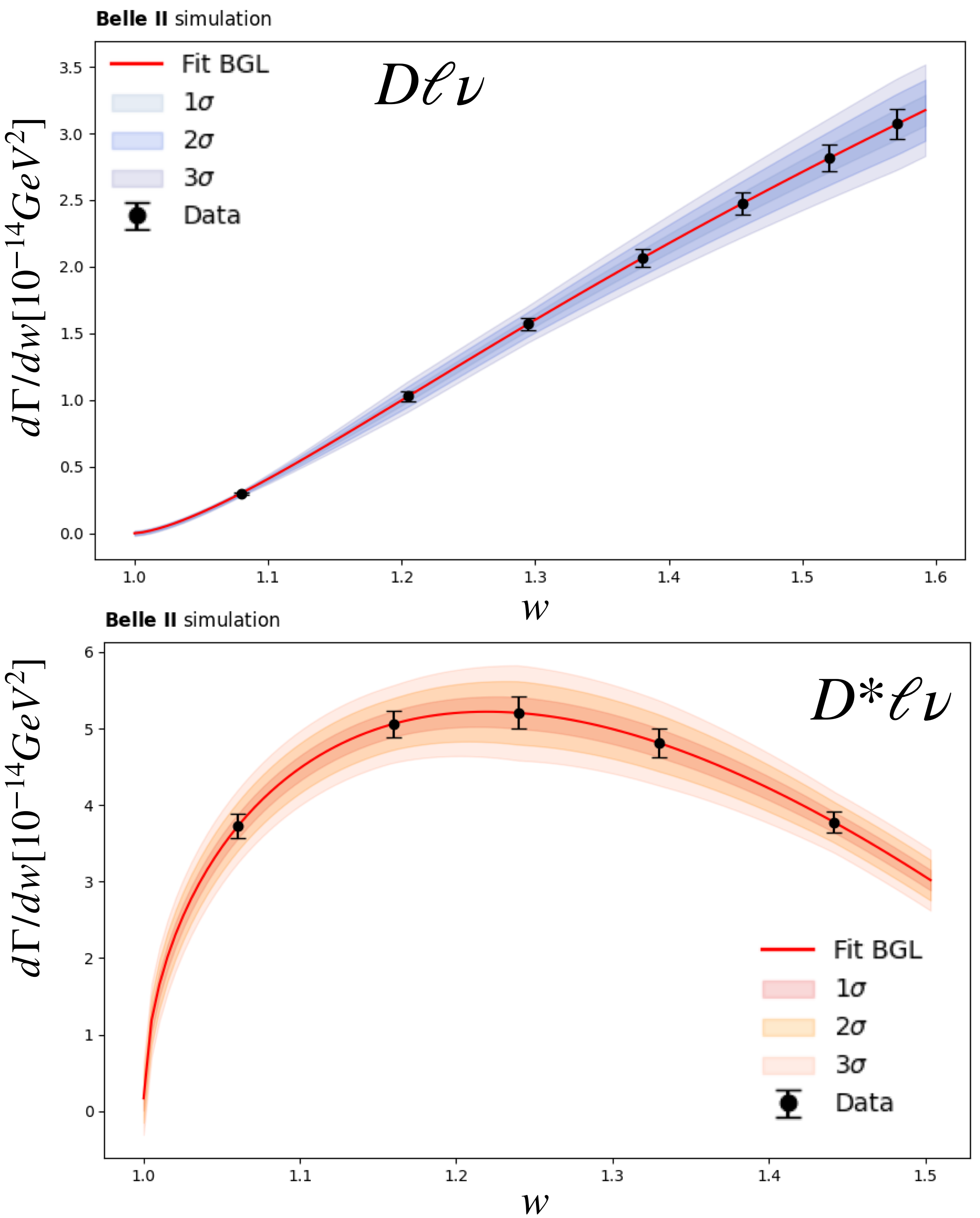
Fit a-posteriori the model-independent observables with BGL at order 1 as an example.

Use only lattice points at $w = 1$

$G(1) : 1.029 \pm 0.009$ for $D\ell\nu$

$h_{A_1}(1) : 0.904 \pm 0.013$ for $D^*\ell\nu$.

| | Generator values | Fit a-posteriori |
|---|---|---|
| $a_1$ | -0.094 | -0.0940 +- 0.0005 |
| $a_0^g$ | 0.02596 | 0.02596 +- 0.00049 |
| $a_1^g$ | -0.06049 | -0.06053 +- 0.01635 |
| $a_1^f$ | 0.01713 | 0.01713 +- 0.00461 |
| $a_1^F$ | 0.00753 | 0.00753 +- 0.00017 |
| $G(1)$ | 1.029 +- 0.009 | 1.029 +- 0.008 |
| $h_{A_1}(1)$ | 0.904 +- 0.013 | 0.904 +- 0.007 |
| $\lvert V_{cb}\rvert [10^{-3}]$ | 38.72 | 38.72 +- 0.3 |



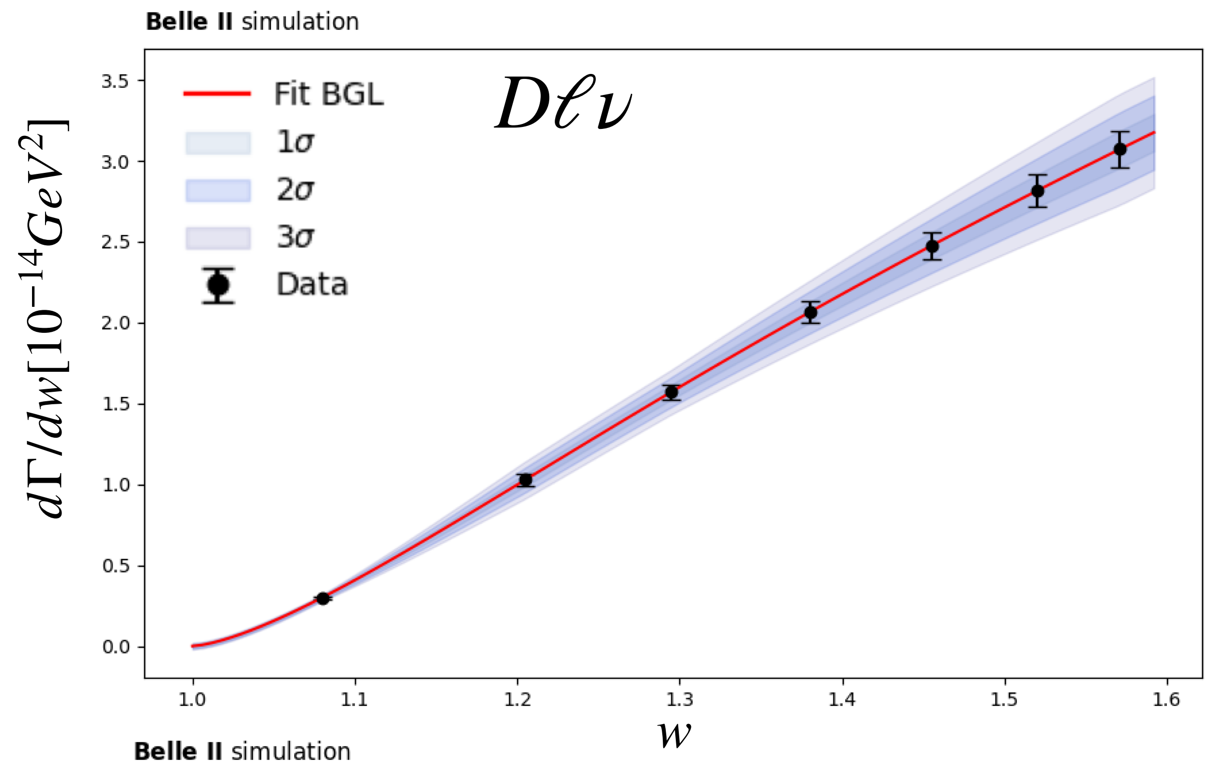

Obtain the same generator values. Data can provide information on $h_{A_1}(1)$.

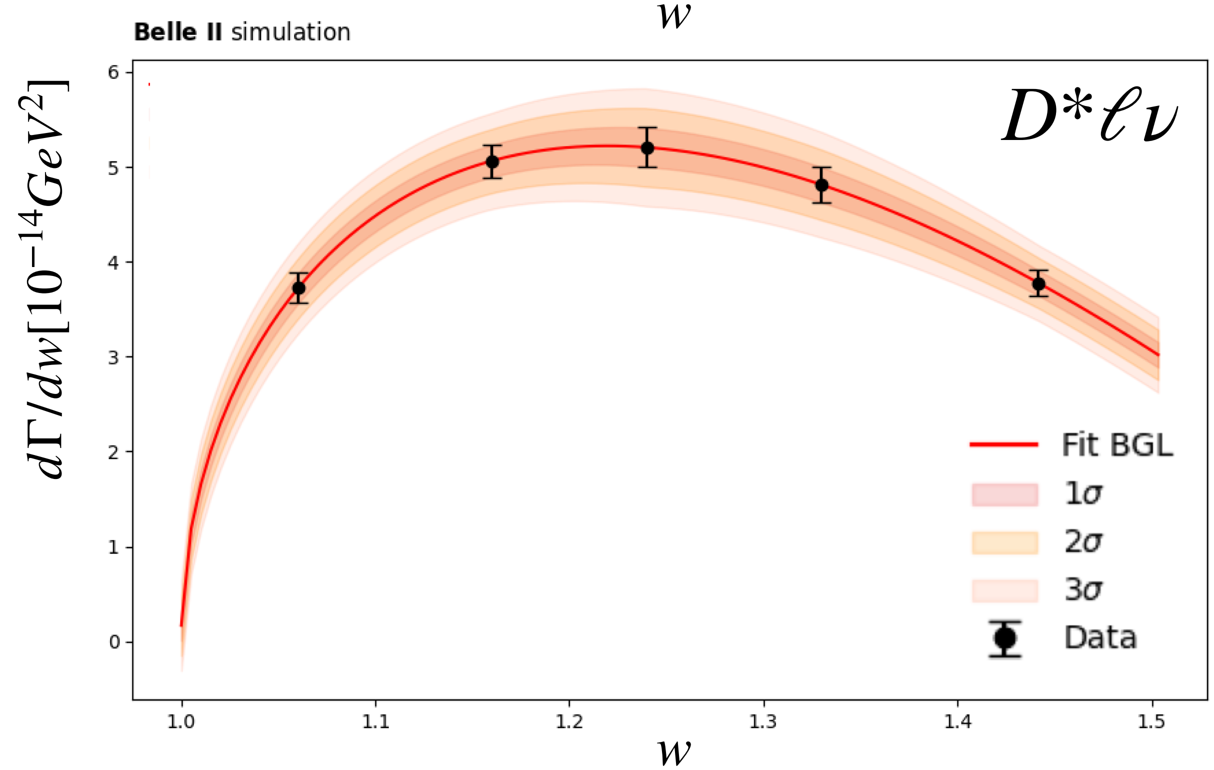
# Bonus

Simultaneous analysis of $D\ell\nu$ and $D^*\ell\nu$, data provides information to improve $h_{A_1}(1)$.

Try to fit model-independent observables by Gaussian constraining only $G(1)$.

| | Generator values | Fit a-posteriori |
|---|---|---|
| $a_1$ | -0.094 | -0.0940 +- 0.0005 |
| $a_0^g$ | 0.02596 | 0.02596 +- 0.00050 |
| $a_1^g$ | -0.06049 | -0.06053 +- 0.01652 |
| $a_1^f$ | 0.01713 | 0.01713 +- 0.00463 |
| $a_1^F$ | 0.00753 | 0.00753 +- 0.00017 |
| $G(1)$ | 1.029 +- 0.009 | 1.029 +- 0.009 |
| $h_{A_1}(1)$ | 0.904 +- 0.013 | 0.904 +- 0.009 |
| $\|V_{cb}\|[10^{-3}]$ | 38.72 | 38.72 +- 0.4 |




Can measure FF w/o assuming any lattice inputs for $D^*\ell\nu$ with a small impact on $V_{cb}$.

# Expected uncertainties on FF and $|V_{cb}|$

| | Rel. unc. [%] on | Uncertainty $[10^{-2}]$ on | | | | |
|---|---|---|---|---|---|---|
| | $\lvert V_{cb}\rvert$ | $a_1$ | $a_0^g$ | $a_1^g$ | $a_1^f$ | $a_1^F$ |
| **NBB** | 0.69 | 0.002 | 0.004 | 0.130 | 0.036 | 0.002 |
| **BR(D decays)** | 0.64 | 0.020 | 0.011 | 0.373 | 0.078 | 0.006 |
| **Lifetime ratio** | 0.09 | 0.001 | 0.001 | 0.028 | 0.008 | $< 0.001$ |
| **track efficiency** | 0.35 | 0.004 | 0.003 | 0.108 | 0.031 | 0.001 |
| **BR(D** + gap)** | 0.60 | 0.010 | 0.015 | 0.516 | 0.087 | 0.012 |
| **Backgrounds modelling** | 0.56 | 0.120 | 0.220 | 2.270 | 1.170 | 0.050 |
| **MC stat** | 0.13 | 0.020 | 0.025 | 0.725 | 0.233 | 0.009 |
| **Coulomb factor (th. unc.)** | 0.48 | 0.002 | 0.003 | 0.090 | 0.024 | 0.001 |
| **TOTAL SYST** | 1.18 (syst) + 0.48 (th) | 0.118 (syst) + 0.002 (th) | 0.127 (syst) + 0.003 (th) | 4.234 (syst) + 0.090 (th) | 1.164 (syst) + 0.024 (th) | 0.054 (syst) + 0.001 (th) |
| **Stat** | 0.24 | 0.039 | 0.043 | 1.340 | 0.413 | 0.015 |

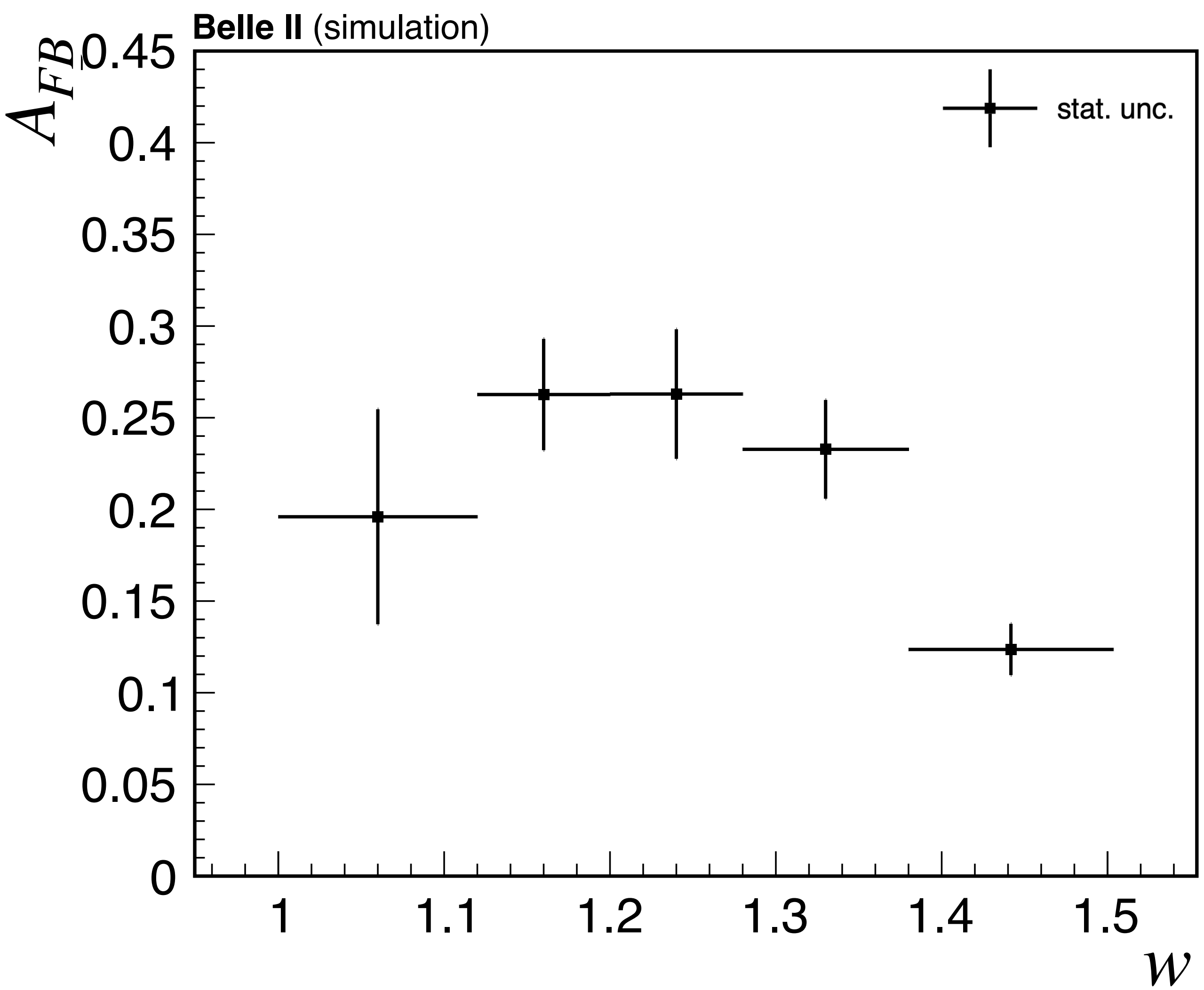
Competitive with world best: $|V_{cb}| = (XXX \pm 0.1(stat) \pm 0.5(syst) \pm 0.2(th))10^{-3}$.

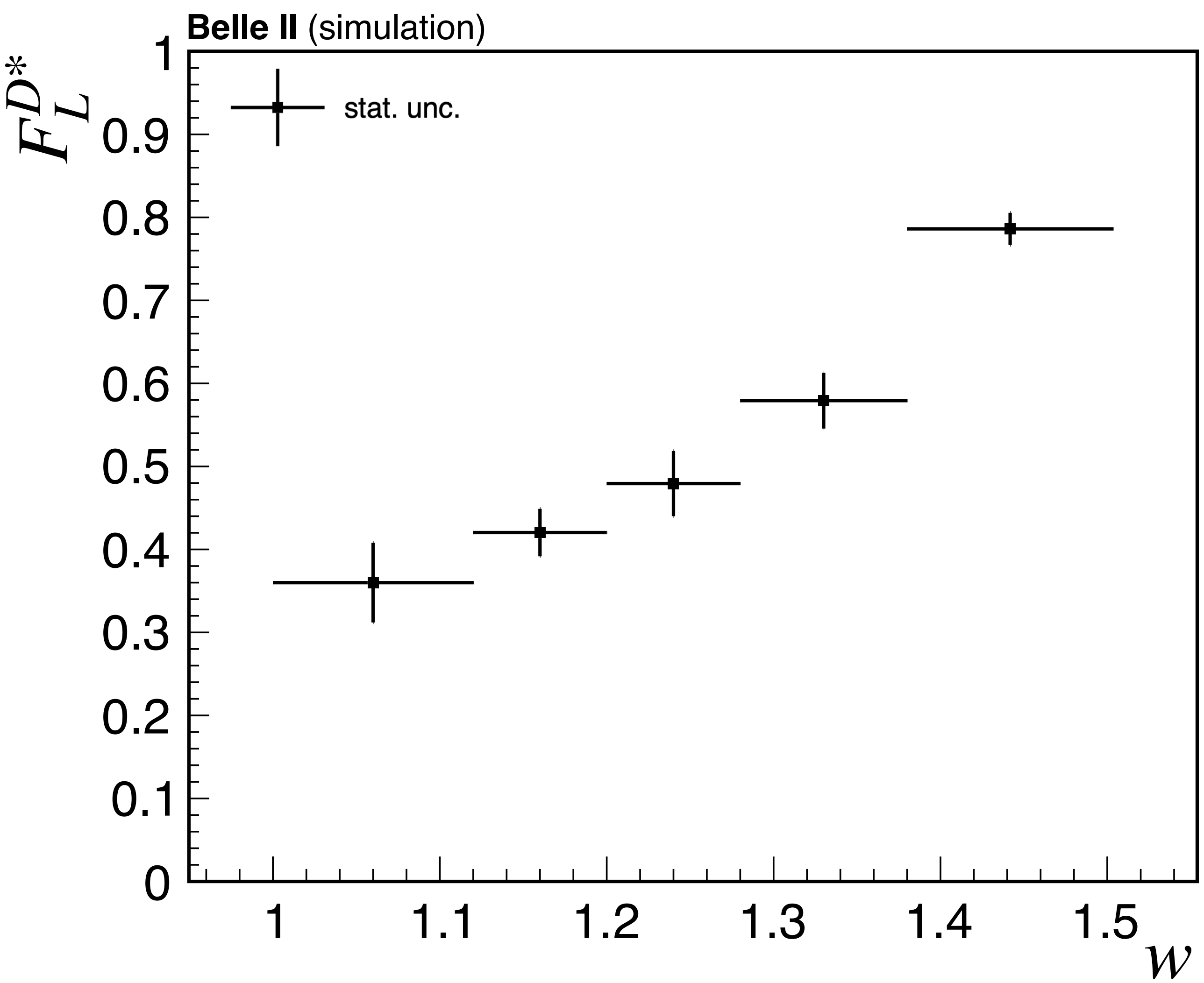
Th. uncertainty from Coulomb factor only (unc. on lattice points not included here).

# $A_{FB}$ and $F_L^{D^*}$

$$A_{FB}(w) = \frac{3b'(w)}{6a'(w) + 2c'(w)}$$

$$F_L^{D^*}(w) = \frac{a'(w) - c'(w)}{3a'(w) + c'(w)}$$




Only statistical uncertainty shown, systematic uncertainty calculation ongoing.

Can also measure separately for electron and muon for LFU.

# Global analysis: potential

From a development of the analysis in simulation can expect:

$$\mathscr{B}(B^- \to D^0 \ell \nu) = (XXX \pm 0.01(stat) \pm 0.05(syst) \pm 0.02(th))\,\%$$

$$\mathscr{B}(B^- \to D^{*0} \ell \nu) = (XXX \pm 0.01(stat) \pm 0.11(syst) \pm 0.06(th))\,\%$$

$$f_{+-}/f_{00} = XXX \pm 0.003(stat) \pm 0.021(syst) \pm 0.024(th)$$

Results competitive with world's best measurements.

Model-independent observables can be reinterpret with any form-factor model:

$$|V_{cb}|_{BGL} = (XXX \pm 0.1(stat) \pm 0.5(syst) \pm 0.2(th))10^{-3}$$

Competitive with world's best measurement.

Ratio of branching fractions, $A_{FB}$ and $F_L^{D*}$ are ongoing:

expected also measurements competitive with world's best.

# Summary

Presented the exclusive measurements at Belle II:

- $B \to D^*\ell\nu$ measurement [PRD 108, 092013 (2023)]: compatible results with the WA.

  Limited by systematic uncertainties.

- $B \to D\ell\nu$ preliminary measurement [arXiv: 2210.13143].

  Updated analysis is ongoing with a promising and competitive results.

- New approach: first simultaneous analysis of $B \to D\ell\nu$ and $B \to D^*\ell\nu$:
  - New measurement of $f_{+-}/f_{00}$.
  - Model-independent observables sensitive to the form-factors and $|V_{cb}|$.

    Important key measurements are derived from these observables.
  - Obtain form factors and $|V_{cb}|$ by fitting a-posteriori the measurements assuming any model.
  - Expected competitive results with the world's best measurements.