Recent Belle II Results on Semileptonic B Decays

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(On behalf of the Belle II Collaboration)

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La Thuile 2023 - Les Rencontres de Physique de la Vallée d'Aoste

8 March, 2023

Belle II

UNIVERSITÄT BONN

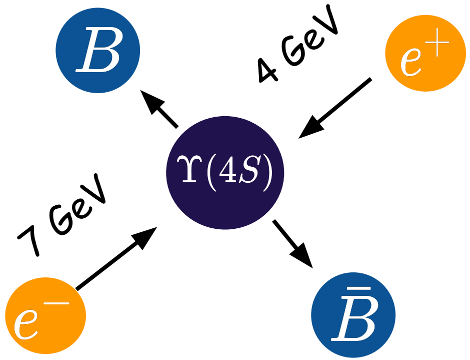
Belle II experiment

What you can tell from the logo?

Belle II experiment

Plenty of Puns

- Belle collides electrons and their anti-particle positrons
- B breaks the symmetry between el - le
  (i.e. between matter and antimatter)
- Belle II investigates beauty quarks, which are of course "belle"



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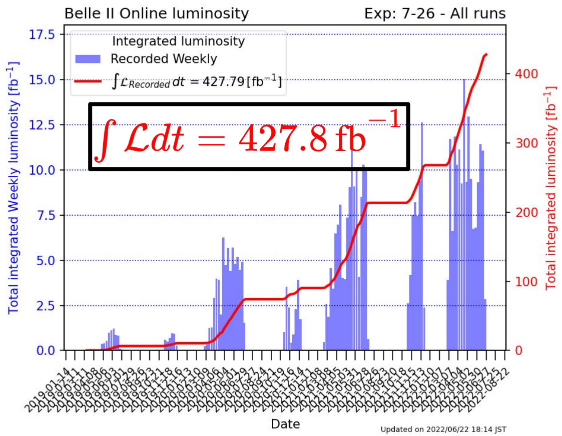
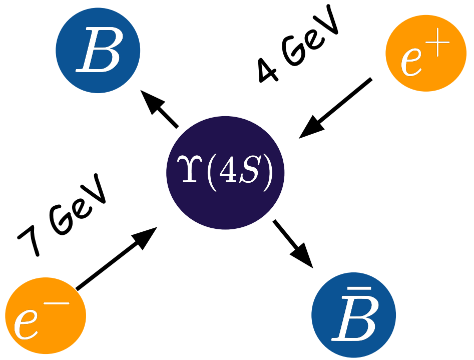


- Max instantaneous luminosity
  $\mathcal{L}$=4.7×10^{34} cm^{-2}s^{-1} (world record)
- Target instantaneous luminosity
  $\mathcal{L}$=6×10^{35} cm^{-2}s^{-1}



Semileptonic B decays

From PDG

$B^{\pm}$ decay

Mode			Fraction (Γ_i/Γ)	Scale factor/ Confidence level
Semileptonic and leptonic modes				
Γ_1	$\ell^+ \nu_\ell X$	[a]	(10.99 ± 0.28) %	
Γ_2	$e^+ \nu_e X_c$		(10.8 ± 0.4) %	
Γ_3	$\ell^+ \nu_\ell X_u$		$(1.65 \pm 0.21) \times 10^{-3}$	
Γ_4	$D \ell^+ \nu_\ell X$		(9.6 ± 0.7) %	
Γ_5	$\overline{D}^0 \ell^+ \nu_\ell$	[a]	(2.30 ± 0.09) %	
Γ_6	$\overline{D}^0 \tau^+ \nu_\tau$		$(7.7 \pm 2.5) \times 10^{-3}$	
Γ_7	$\overline{D}^*(2007)^0 \ell^+ \nu_\ell$	[a]	(5.58 ± 0.22) %	
Γ_8	$\overline{D}^*(2007)^0 \tau^+ \nu_\tau$		(1.88 ± 0.20) %	
Γ_9	$D^- \pi^+ \ell^+ \nu_\ell$		$(4.4 \pm 0.4) \times 10^{-3}$	
Γ_{10}	$\overline{D}_0^*(2420)^0 \ell^+ \nu_\ell$, $\overline{D}_0^{*0} \to D^- \pi^+$		$(2.5 \pm 0.5) \times 10^{-3}$	
Γ_{11}	$\overline{D}_2^*(2460)^0 \ell^+ \nu_\ell$, $\overline{D}_2^{*0} \to D^- \pi^+$		$(1.53 \pm 0.16) \times 10^{-3}$	
Γ_{12}	$D^{(*)} n \pi \ell^+ \nu_\ell (n \geq 1)$		(1.85 ± 0.25) %	
Γ_{13}	$D^{*-} \pi^+ \ell^+ \nu_\ell$		$(6.0 \pm 0.4) \times 10^{-3}$	
Γ_{14}	$\overline{D}_1(2420)^0 \ell^+ \nu_\ell$, $\overline{D}_1^0 \to D^{*-} \pi^+$		$(3.03 \pm 0.20) \times 10^{-3}$	
Γ_{15}	$\overline{D}_1'(2430)^0 \ell^+ \nu_\ell$, $\overline{D}_1'^0 \to D^{*-} \pi^+$		$(2.7 \pm 0.6) \times 10^{-3}$	

Not the end!

B^0 decay

Mode			Fraction (Γ_i/Γ)	Scale factor/ Confidence level
Γ_1	$\ell^+ \nu_\ell X$	[a]	(10.33 ± 0.28) %	
Γ_2	$e^+ \nu_e X_c$		(10.1 ± 0.4) %	
Γ_3	$\ell^+ \nu_\ell X_u$		$(1.51 \pm 0.19) \times 10^{-3}$	
Γ_4	$D \ell^+ \nu_\ell X$		(9.3 ± 0.8) %	
Γ_5	$D^- \ell^+ \nu_\ell$	[a]	(2.24 ± 0.09) %	
Γ_6	$D^- \tau^+ \nu_\tau$		(1.05 ± 0.23) %	

Not the end!

- **Sizable branching ratio**
- **Plenty of decay channels**

Semileptonic B decays

From PDG

$B^\pm$ decay

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Not the end!

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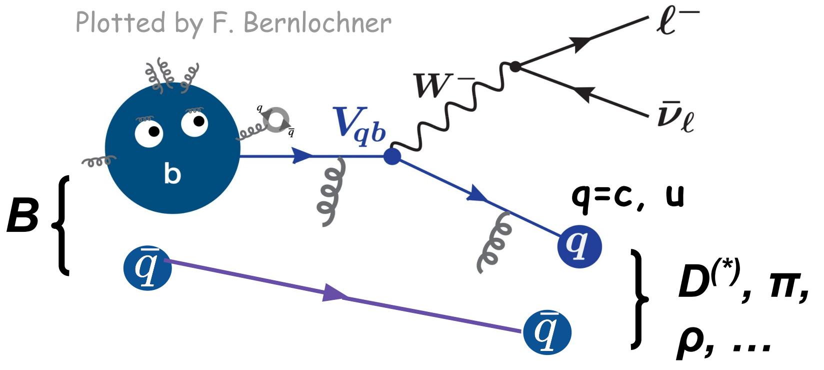
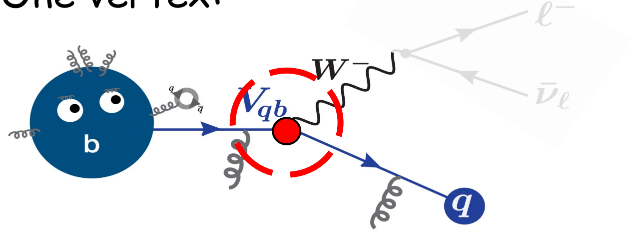
Not the end!



- **Sizable branching ratio**
- **Plenty of decay channels**
- **Relatively simple theoretical description**

Measurement of $|V_{qb}|$

One vertex:



CKM matrix

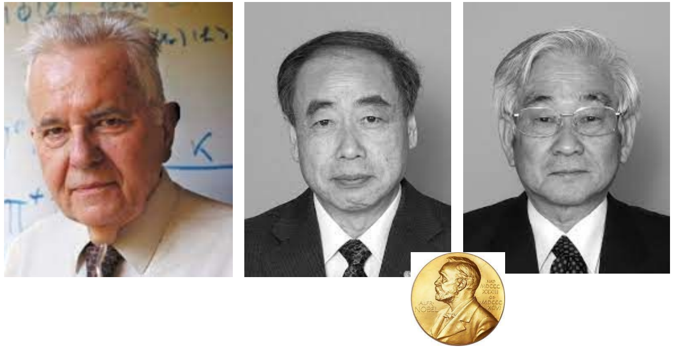
SM: unitary 3×3 matrix

$$\begin{array}{cc} & \begin{array}{ccc} d & s & b \end{array} \\ \begin{array}{c} u \\ c \\ t \end{array} & \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \end{array}$$

Unitarity $CC^\dagger = 1$

$$V_{ud}V^*_{ub} + V_{cd}V^*_{cb} + V_{td}V^*_{tb} = 1$$

C Hello! Could you briefly tell me why is it important to measure |Vcb| and |Vub|?



Nobel prize 2008

Certainly!

|Vcb| and |Vub| are parameters in the Standard Model of particle physics that describe the strength of the weak interaction between quarks. These parameters are important because they provide valuable information about the structure and properties of the Standard Model, as well as insights into physics beyond the Standard Model.

Measuring |Vcb| and |Vub| allows us to test the predictions of the Standard Model and verify that it accurately describes the behavior of particles and their interactions. In addition, these measurements can help us to search for evidence of physics beyond the Standard Model, such as new particles or interactions that are not accounted for in the current theory.

Furthermore, the precise determination of |Vcb| and |Vub| is important for understanding the properties of heavy mesons, which are particles composed of a quark and an antiquark. This information is useful for a variety of applications, including the development of more accurate models for heavy meson decays, which have important implications for particle physics experiments and technologies.

Fake publications

C

Do you know recent |Vcb| and |Vub| measurements using semileptonic decays at Belle II?

Yes, there have been recent measurements of |Vcb| and |Vub| using semileptonic decays at the Belle II experiment. Belle II is a high-energy physics experiment located at the KEK laboratory in Japan, designed to study the properties of B mesons and other particles.

One recent measurement of |Vcb| at Belle II was performed using a sample of B meson decays to charm mesons (B -> D* l nu), where l represents a charged lepton (either an electron or a muon). The result obtained was |Vcb| = (38.4 ± 0.7 ± 0.9) × 10^-3, where the first uncertainty is statistical and the second is systematic. This result was presented in a paper published in Physical Review Letters in 2021.

Another recent measurement of |Vub| at Belle II was performed using a sample of B meson decays to a light meson (B -> π l nu), where l represents a charged lepton. The result obtained was |Vub| = (3.5 ± 0.2 ± 0.2) × 10^-3, where the first uncertainty is statistical and the second is systematic. This result was also presented in a paper published in Physical Review Letters in 2021.

Really??!

Do we really have these ??!

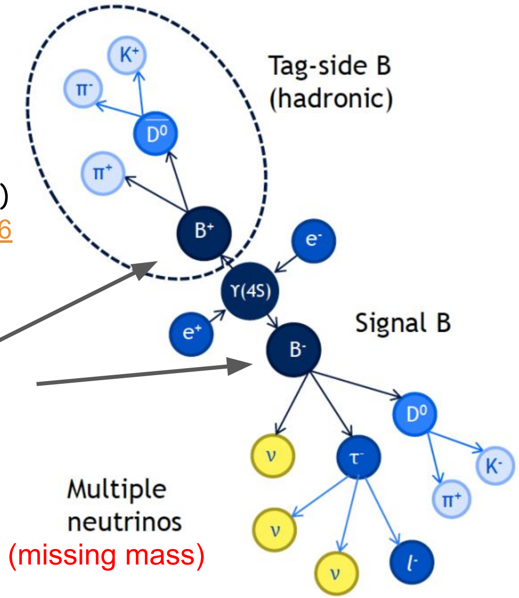
This is why I am here today rather than the ChatGPT!

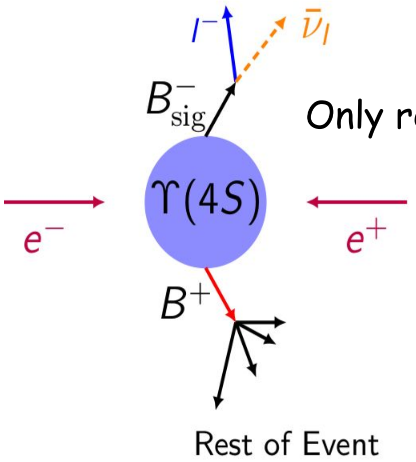
Tagged VS untagged

Tagged VS **Untagged**

Full Event Interpretation (FEI)
[Comput Softw Big Sci (2019) 3: 6]

Reconstruct both signal and tag-side B.





Only reconstruct signal B.

Low	← **Efficiency** →	**High**
High	← **Purity** →	**Low**

Measurement of $B \to D^*\ell\nu$

$|V_{cb}|$ from untagged $B \to D^*\ell\nu$

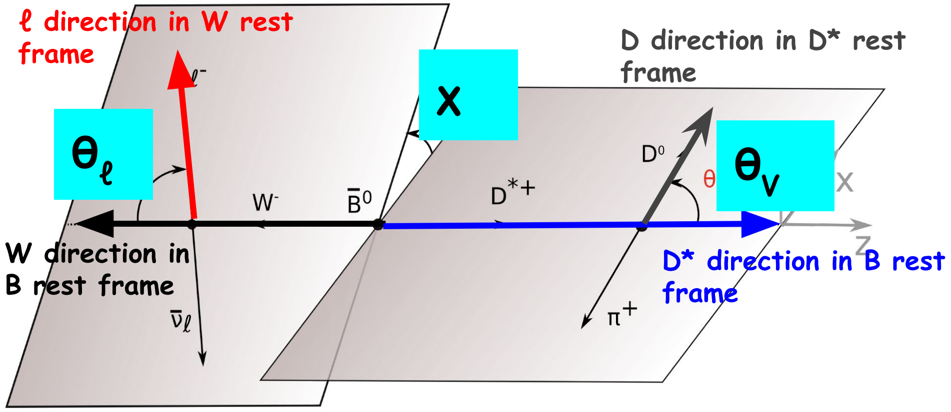
NEW!

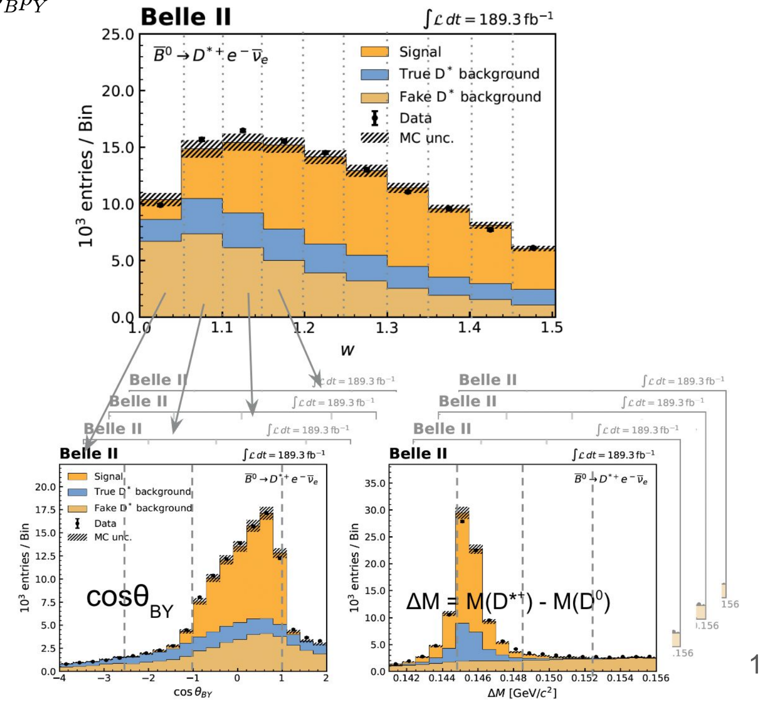
- $$\frac{d\Gamma}{dw\, d\cos\theta_\ell\, d\cos\theta_V\, d\chi} \propto |V_{cb}|^2 \times |F(w, \cos\theta_\ell, \cos\theta_V, \chi)|^2$$
- Signal yields in bins of kinematic variables w, $\cos\theta_\ell$, $\cos\theta_V$, and X are determined bin by bin independently by 2D fits of $\cos\theta_{BY}$ and ΔM. $\cos\theta_{BY} = \frac{2\,E_B^* E_Y^* - m_B^2 - m_Y^2}{2 p_B^* p_Y^*}$

(Y: D*ℓ system)

kinematic variables:

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



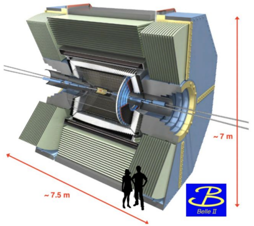


$|V_{cb}|$ from untagged $B \to D^*\ell\nu$

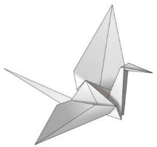
- Fitted yields are corrected with SVD unfolding method

(Singular Value Decomposition)

X: true distribution



M: detector response



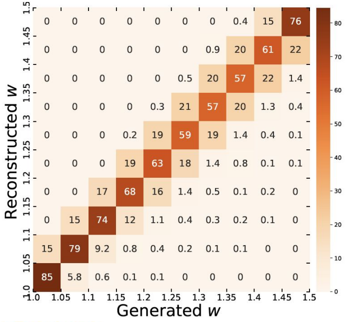
Y: measured distribution

Plotted by L. Cao

Unfolding

Migration matrix

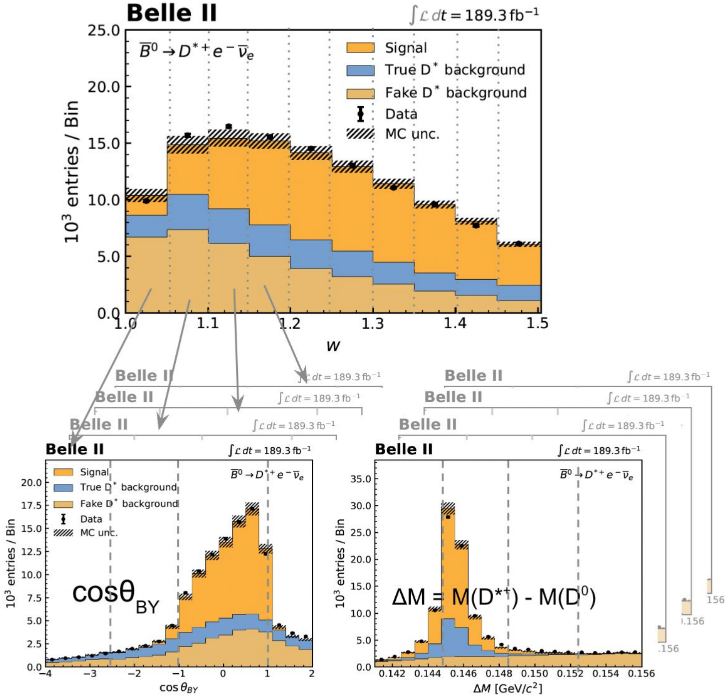
$$\mathcal{M}_{ij} = \mathcal{P}(\text{measured value in bin } i | \text{ true value in bin } j)$$



reco. eff & acc.

input of PDG2022

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



$|V_{cb}|$ from untagged $B \to D^*\ell\nu$

- $|V_{cb}|$ value is determined from measured partial rates $\Delta\Gamma$

Minimizing χ^2

Written in terms of |Vcb| and FF parameters

Experimental observation — Experimental covariance — Theoretical prediction

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

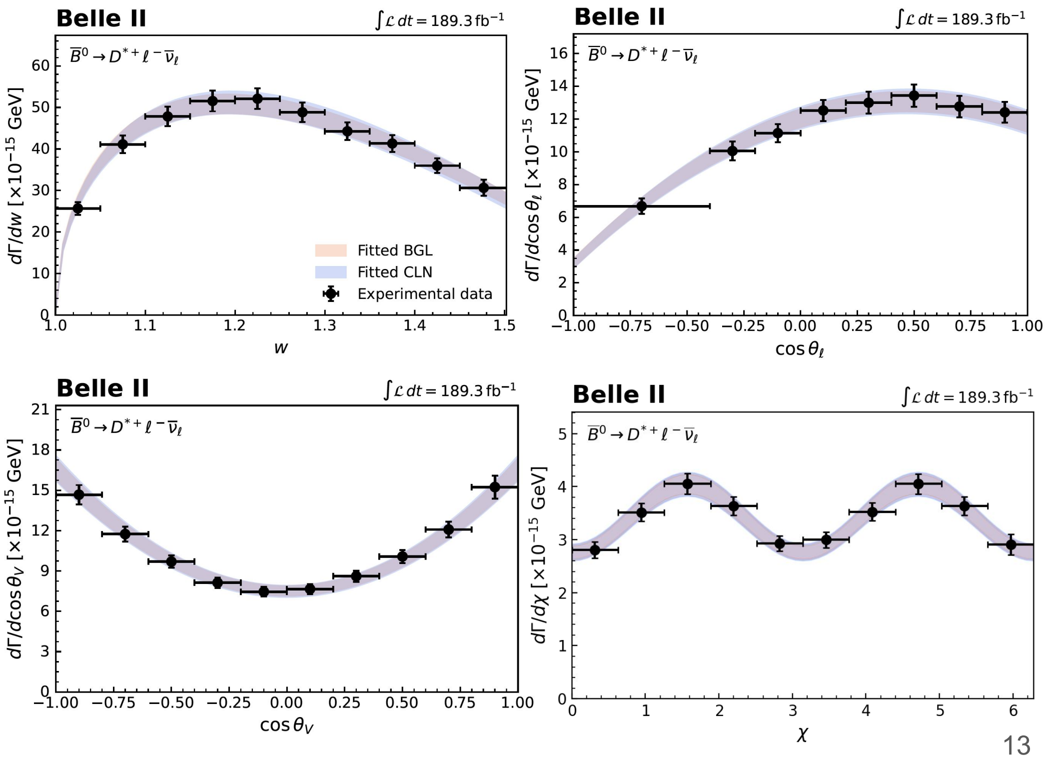
$$+ \frac{(\Gamma^{\mathrm{obs}} - \Gamma^{\mathrm{pre}})^2}{\sigma_\Gamma^2}$$

Boyd-Grinstein-Lebed parameterization

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

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

Caprini-Lellouch-Neubert parameterization



$|V_{cb}|$ from tagged $B \to D^*\ell\nu$

arXiv: 2301.04716

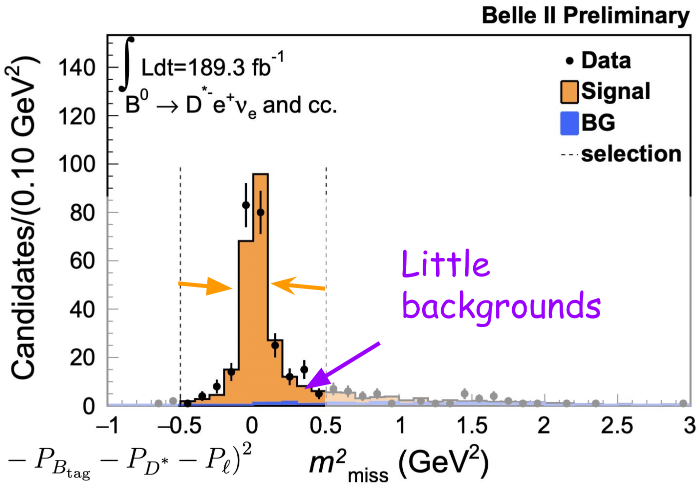
- Migration of Signal yields in 10 bins of w is corrected with an iterative unfolding method
- $|V_{cb}|$ value is determined in Caprini-Lellouch-Neubert (CLN) parameterization from measured $\Delta\Gamma/\Delta w$

$$\mathcal{B} = (5.27 \pm 0.22_{stat} \pm 0.38_{syst})\%$$

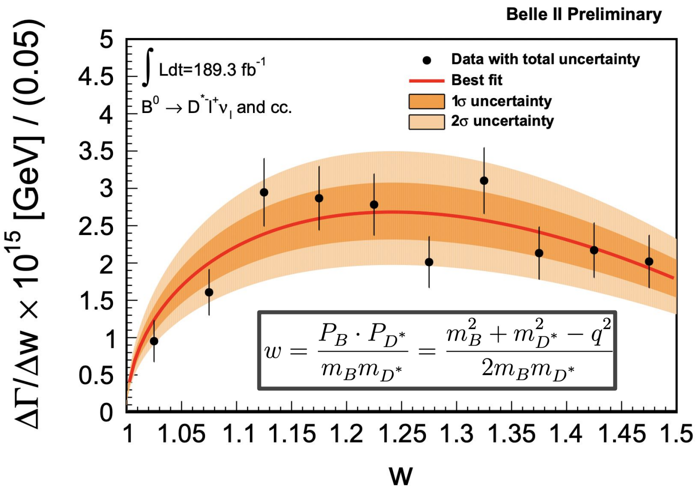
$$\eta_{EW}F(1)|V_{cb}| = (34.6 \pm 1.8_{stat} \pm 1.7_{syst}) \times 10^{-3}$$

η_{EW}: small electroweak correction

F(1): normalization factor in form factors



$m^2_{\mathrm{miss}} = (P_{\mathrm{beam}} - P_{B_{\mathrm{tag}}} - P_{D^*} - P_\ell)^2$



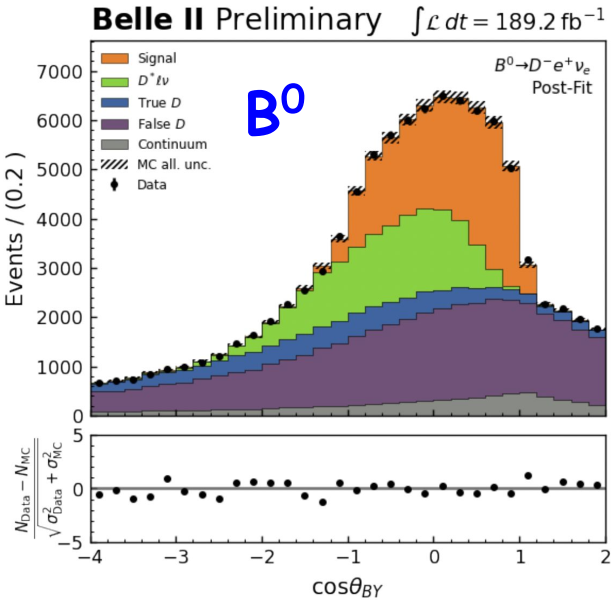
Measurement of $B \to D\ell\nu$

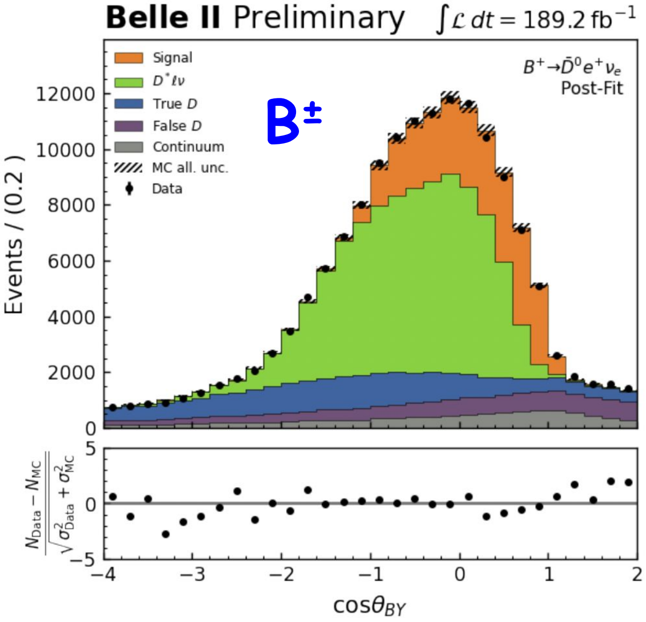
$|V_{cb}|$ from untagged $B \to D\ell\nu$

arXiv: 2210.13143

- Analyze $B^{0,\pm}$, ℓ=e, μ with 189 fb^{-1} dataset
- Large background contamination is main challenge
- Signal yields are extracted in 10 bins of w by fitting $\cos\theta_{BY}$ (Y:Dℓ system) distribution

$$\frac{d\Gamma}{dw} \propto |V_{cb}|^2 \times |FF(w)|^2$$

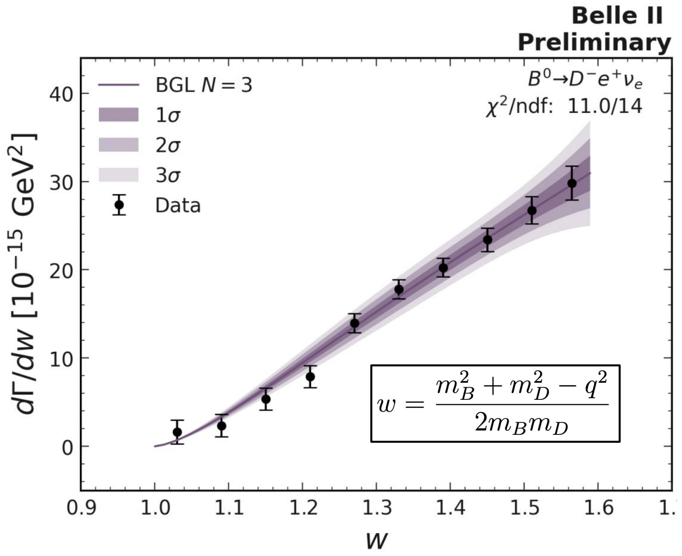


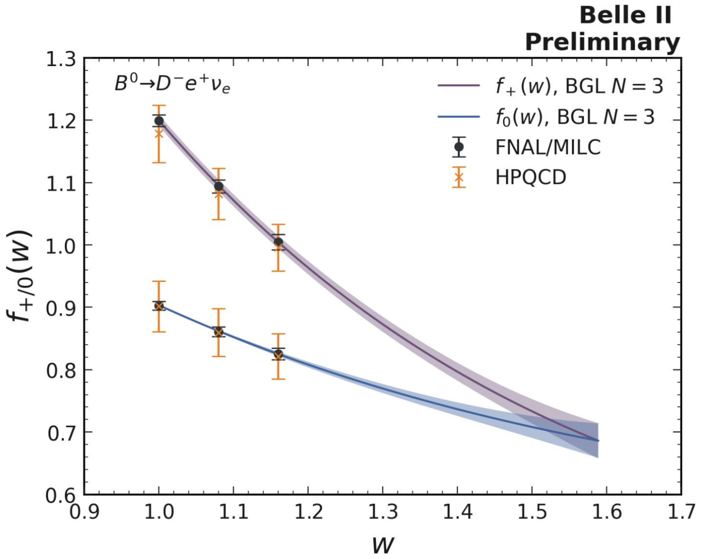


$|V_{cb}|$ from untagged $B \to D\ell\nu$

arXiv: 2210.13143

- Determine the $\eta_{EW}|V_{cb}|$ from the measured *w* spectrum and LQCD predictions from FNAL/MILC and HPQCD collaborations





Weighted average over four modes:

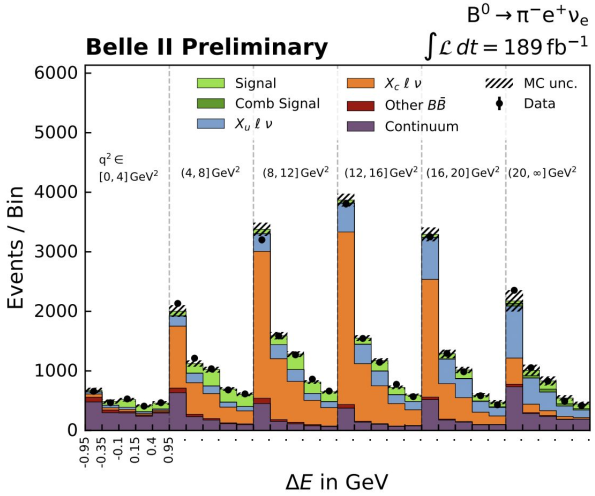
$\eta_{EW}|V_{cb}| = (38.53 \pm 1.15) \times 10^{-3}$

Measurement of $B \to \pi \ell \nu$

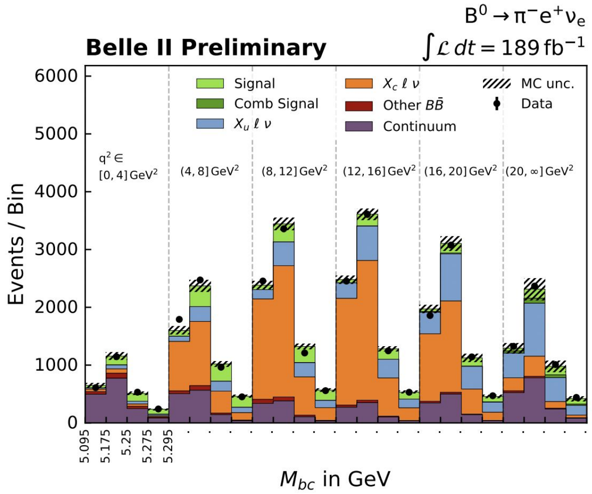
$|V_{ub}|$ from untagged $B \to \pi \ell \nu$

arXiv: 2210.04224

- Analyze neutral B^0, $\ell=e, \mu$ with 189 fb^{-1} dataset
- Determine the signal yields in 6 bins of q^2 by 2D fit of M_{bc} and ΔE distributions
- The migration of fitted yields is corrected with matrix inversion unfolding method



$$\Delta E = E_B^* - E_{\text{beam}}^* = E_B^* - \frac{\sqrt{s}}{2}$$

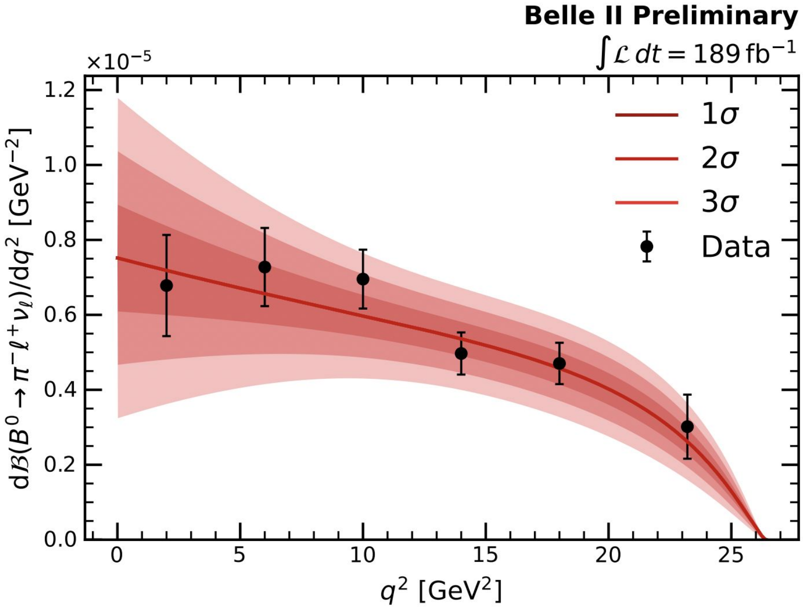


$$M_{bc} = \sqrt{E_{\text{beam}}^{*2} - |\vec{p}_B^{\,*}|^2} = \sqrt{\left(\frac{\sqrt{s}}{2}\right)^2 - |\vec{p}_B^{\,*}|^2}$$

$|V_{ub}|$ from untagged $B \to \pi \ell \nu$

arXiv: 2210.04224

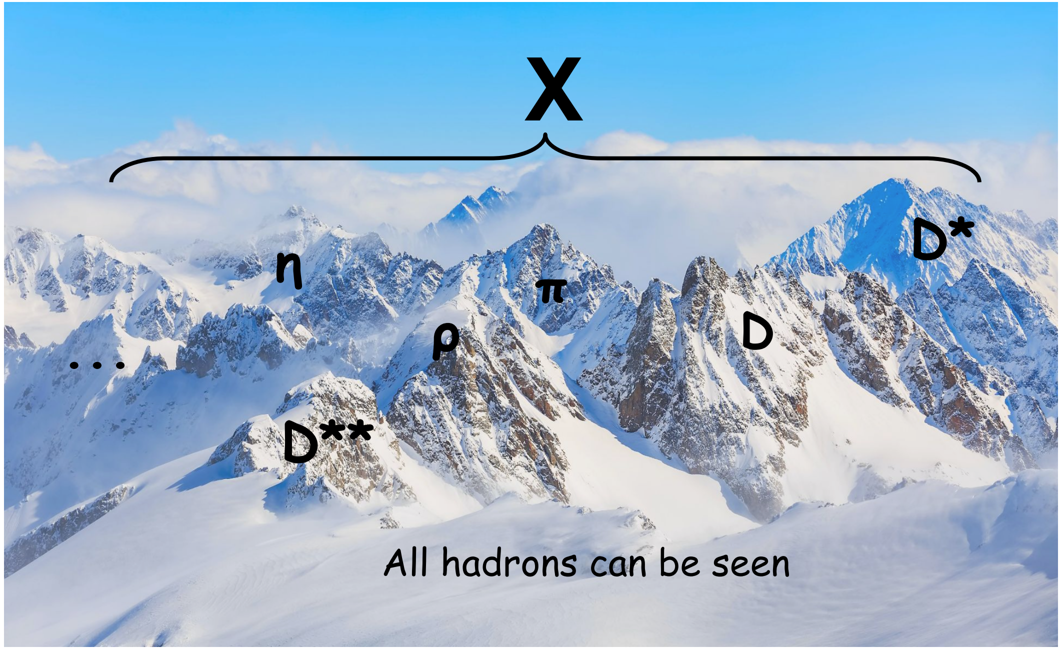
- $\Delta\mathcal{B}$ in 6 q^2 bins are further determined
- $|V_{ub}|$ is extracted in BCL parameterization by fitting measured $\Delta\mathcal{B}$ and LQCD data (FNAL/MILC)



$\mathcal{B} = (1.426 \pm 0.056_{stat} \pm 0.125_{syst}) \times 10^{-4}$

$|V_{ub}| = (3.55 \pm 0.12_{stat} \pm 0.13_{syst} \pm 0.17_{theo}) \times 10^{-3}$

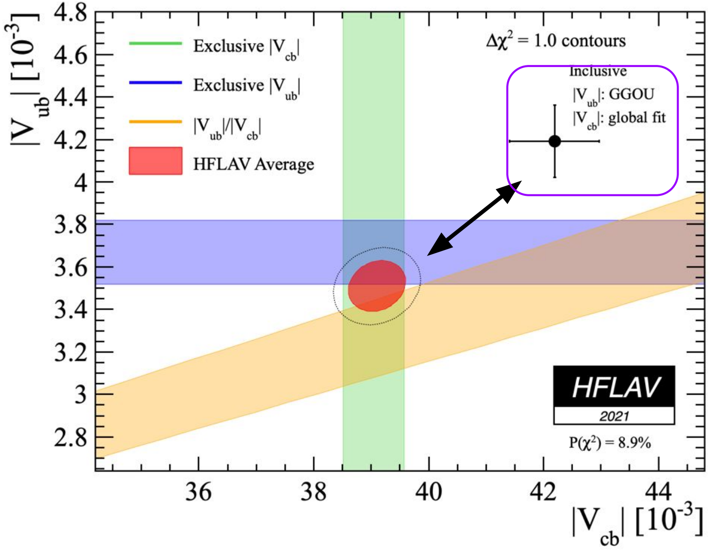
Exclusive VS inclusive determination



Inclusive determinations are more like an overview

Exclusive determinations observe specific decay channels

Significant tension between two determinations



q^2 moments of inclusive $B \to X_c \ell \nu$ Decays

arXiv: 2205.06372

- q^2 measurement: $q^2 = (p^*_{B_{\rm sig}} - p^*_X)^2$ with $p^*_{B_{\rm sig}} = (\sqrt{s}/2, -\mathbf{p}^*_{B_{\rm tag}})$

B_{tag} is reconstructed using fully hadronic decays.

- q^2 moment of order n:

event-wise signal probability

Linear correction reconstructed $q^2 \to$ underlying true q^2

$$\langle q^{2n} \rangle = \frac{\sum_i^{\rm event} w_i(q^2)\, q^{2n}_{{\rm calib},i}}{\sum_i^{\rm event} w_i(q^2)} \times \mathcal{C}_{\rm calib} \times \mathcal{C}_{\rm gen}$$

Efficiency and acceptance correction

residual bias

q^2 moments of inclusive $B \to X_c \ell \nu$ Decays

arXiv: 2205.06372

- q^2 measurement: $q^2 = (p^*_{B_{\mathrm{sig}}} - p^*_X)^2$ with $p^*_{B_{\mathrm{sig}}} = (\sqrt{s}/2, -\mathbf{p}^*_{B_{\mathrm{tag}}})$

B_{tag} is reconstructed using fully hadronic decays.

- q^2 moment of order n:

event-wise signal probability

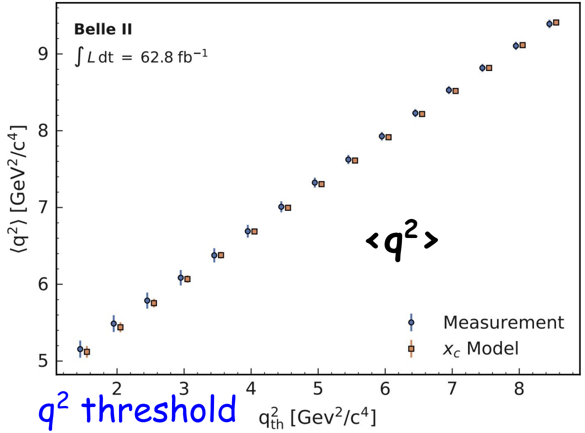
Linear correction reconstructed $q^2 \to$ generated q^2

$$\langle q^{2n} \rangle = \frac{\sum_i^{\mathrm{event}} w_i(q^2)\, q^{2n}_{\mathrm{calib},i}}{\sum_i^{\mathrm{event}} w_i(q^2)} \times \mathcal{C}_{\mathrm{calib}} \times \mathcal{C}_{\mathrm{gen}}$$

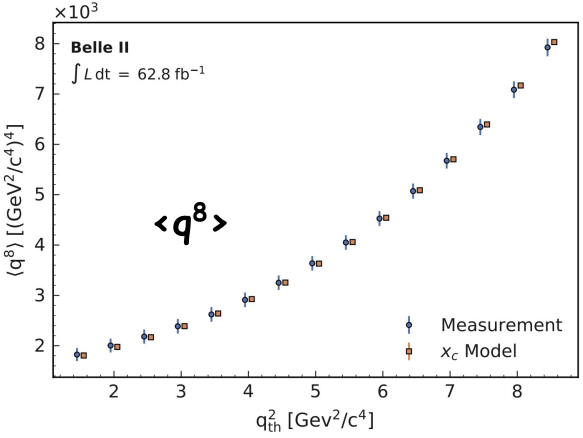
residual bias

Efficiency and acceptance correction

- First to fourth moments (n=1~4) measured at a progression of cuts on q^2



q^2 threshold



A follow-up determination of $|V_{cb}|$ using Belle & Belle II $\langle q^{2n} \rangle$ measurements obtains

$$|V_{cb}| = (41.69 \pm 0.63) \times 10^{-3}$$

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The tension persists after this measurement.

$R(X_{e/\mu})$ measurement

arXiv: 2301.08266

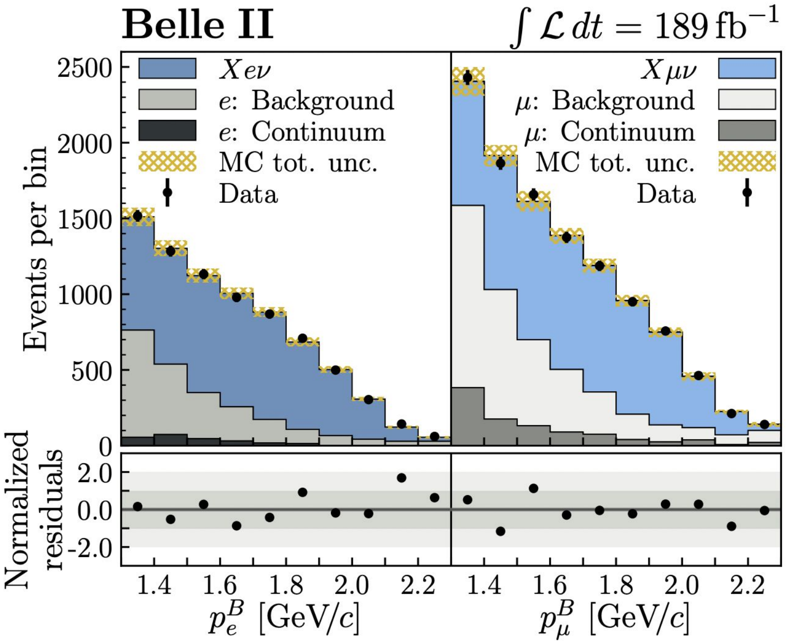
- $R(X_{e/\mu}) = \mathcal{B}(B \to Xe\nu) / \mathcal{B}(B \to X\mu\nu)$ where X is generic hadronic final state, and B can be any flavor
- Tag-side B mesons decay fully hadronically
- Charge of signal lepton is inferred from tagged B
- Simultaneous binned template fits to the p_e^B and p_μ^B (momenta in B rest frame) spectra

$$R(X_{e/\mu}) = \frac{\epsilon_{X\mu\nu} N_{Xe\nu}}{\epsilon_{Xe\nu} N_{X\mu\nu}}$$

$R(X_{e/u}) = 1.033 \pm 0.010_{stat} \pm 0.019_{syst}$

Most precise BR-based Lepton Flavor Universality test with semileptonic decays.

Source	Uncertainty [%]
Sample size	1.0
Lepton identification	1.9
$X_c \ell \nu$ branching fractions	0.1
$X_c \ell \nu$ form factors	0.2
Total	2.2



Summary and prospects

- Measurements of Semileptonic B Decays at Belle II are progressing well
- So far the measured $|V_{qb}|$ values agree well with current inclusive and exclusive world averages
- No significant lepton flavor universality violation has been observed
- More results are coming soon
    - $|V_{ub}|$ determined by a combined fit of the $B \to \pi\ell\nu$ and $B \to \rho\ell\nu$ decays
    - Lepton flavor universality test with angular observables in the $B \to D^*\ell\nu$ decay
    - $R(X_{\ell/\tau})$
    - …

More slides

Systematic table for untagged B → D*ℓν

Relative uncertainties (in %)

	$\tilde{a}_0$	$\tilde{b}_0$	$\tilde{b}_1$	$\tilde{c}_1$
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	$\boxed{1.5}$	18.4	22.0
Tracking of K, π, ℓ	0.5	0.5	0.6	0.5
$N_{B\bar{B}}$	0.8	0.8	1.1	0.8
$f_{+-}/f00$	1.3	$\boxed{1.3}$	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

Systematic table for untagged $B \to D\ell\nu$

	$B^+ \to \bar{D}^0 e^+ \nu_e$	$B^+ \to \bar{D}^0 \mu^+ \nu_\mu$	$B^0 \to D^- e^+ \nu_e$	$B^0 \to D^- \mu^+ \nu_\mu$
$\mathcal{B}(B \to D\ell\nu)[\%]$	$2.21 \pm 0.03 \pm 0.08$	$2.22 \pm 0.03 \pm 0.10$	$1.99 \pm 0.04 \pm 0.08$	$2.03 \pm 0.04 \pm 0.09$
	Contributions to the systematic uncertainty [%]			
N_{BB} and f_{+-}/f_{00}	1.9	1.9	1.9	1.9
Tracking efficiency	0.9	0.9	1.2	1.2
$\mathcal{B}(D \to K\pi(\pi))$	0.8	0.8	1.7	1.7
LeptonID	1.2	3.1	0.9	1.9
HadronID	0.6	0.6	0.1	0.1
$B \to D\ell\nu$ FF	0.1	0.1	0.1	0.1
$B \to D^*\ell\nu$ FF	0.1	0.2	0.0	0.0
$\mathcal{B}(B \to X_c\ell\nu)$	1.9	1.9	0.4	0.3
Continuum normalization	0.2	0.2	0.1	0.1
Fake D PDFs	1.4	1.5	3.0	2.8
Total	3.5	4.6	4.2	4.4

TABLE II. Branching ratio results for the decays $B^+ \to \bar{D}^0 e^+ \nu_e$, $B^+ \to \bar{D}^0 \mu^+ \nu_\mu$, $B^0 \to D^- e^+ \nu_e$, and $B^0 \to D^- \mu^+ \nu_\mu$. The first uncertainty is statistical, and the second is systematic. The lower half of the table shows the various contributions to the systematic uncertainty, which are explained in more detail in Sect. 4.3

q^2 moments of inclusive $B \to X_c \ell \nu$ Decays