Recent Belle II results on semileptonic B decays and LFU tests

LAU Tak-Shun (IJC lab)
on behalf of the Belle II Colleboration

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The semileptonic B decays

- Semileptonic (SL) B decays are studied to determine the CKM elements $|V_{ub}|$ and $|V_{cb}|$.

  In Standard Model(SM), the CKM matrix is unitary. The measurement of the $|V_{ub}|$ and $|V_{cb}|$ provide the global constraint power on the Unitary Triangle (UT) fit.

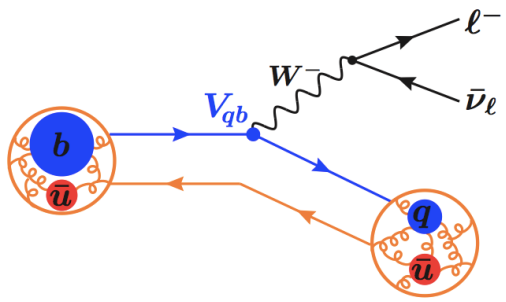
- The measurements can be either :

  "Exclusive" – reconstruct through specific single final state. Examples : $B \to \pi \ell \nu$, $B \to D \ell \nu$, $B \to D^* \ell \nu$

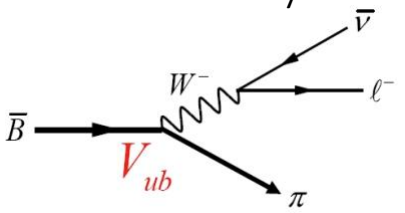
  "Inclusive " – reconstruct other particles than a lepton inclusively into X. Examples : $B \to X_u \ell \nu$

	Experiment	Theory
Exclusive	1. Lower signal efficiency 2. Lower background	Lattice QCD
Inclusive	1. Higher signal efficiency 2. Higher background	Heavy Quark Effective Theory (HQET)

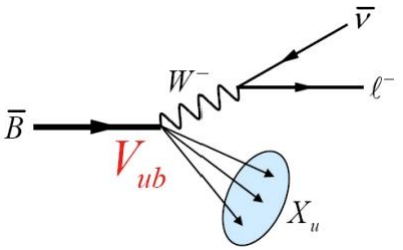
Semileptonic B decays:



Exclusive decay:



Inclusive decay:

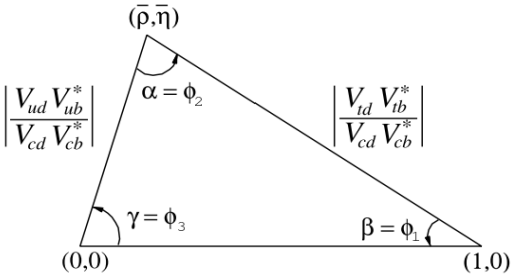


CKM Matrix:

$$V_{\mathrm{CKM}} = \begin{pmatrix} V_{\mathrm{ud}} & V_{\mathrm{us}} & V_{\mathrm{ub}} \\ V_{\mathrm{cd}} & V_{\mathrm{cs}} & V_{\mathrm{cb}} \\ V_{\mathrm{td}} & V_{\mathrm{ts}} & V_{\mathrm{tb}} \end{pmatrix} \begin{matrix} \mathrm{u} \\ \mathrm{c} \\ \mathrm{t} \end{matrix}$$

d s b

Unitary Triangle:



$$V_{ud}\,V_{ub}^* + V_{cd}\,V_{cb}^* + V_{td}\,V_{tb}^* = 0$$

Experimental Status

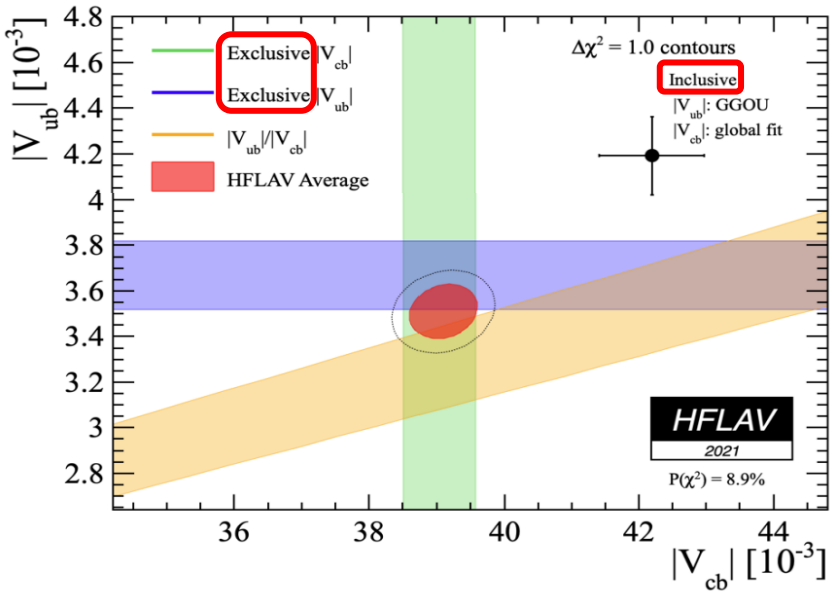
- There are 2 anomalies in the SL B decays.

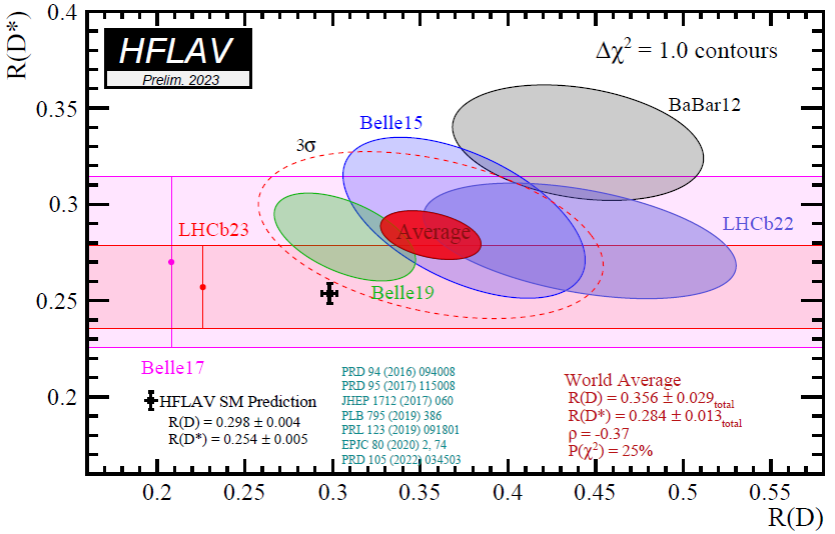
- The first one, the exclusive measurement on $|V_{cb}|$ and $|V_{ub}|$ shows a discrepancy from the inclusive one.

- The SL B decays can also be used as a Lepton Flavour Universality (LFU) test. The ratio between the branching ratios(BR) of different flavour can be measured.

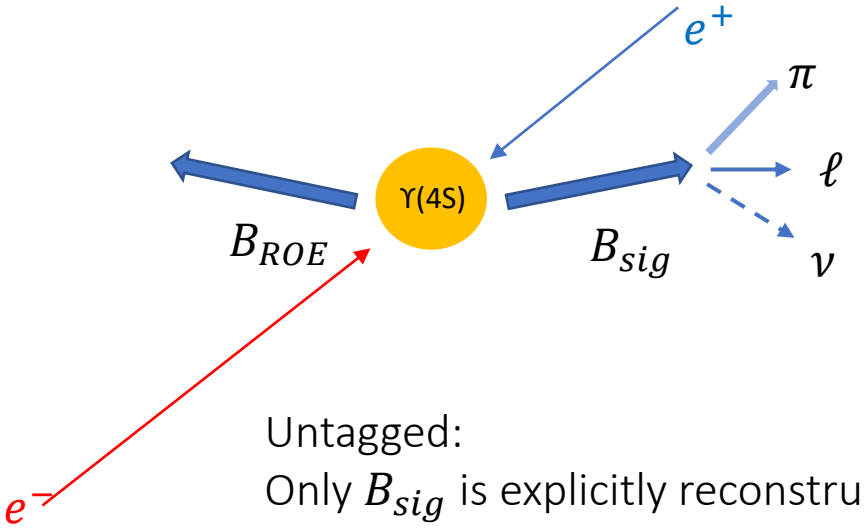
  For example :
  $R(D^*_{\tau/\ell}) = \frac{BR(B \to D^* \tau \nu)}{BR(B \to D^* \ell \nu)}$.

  Here comes the second anomalies. The LFU is violated.



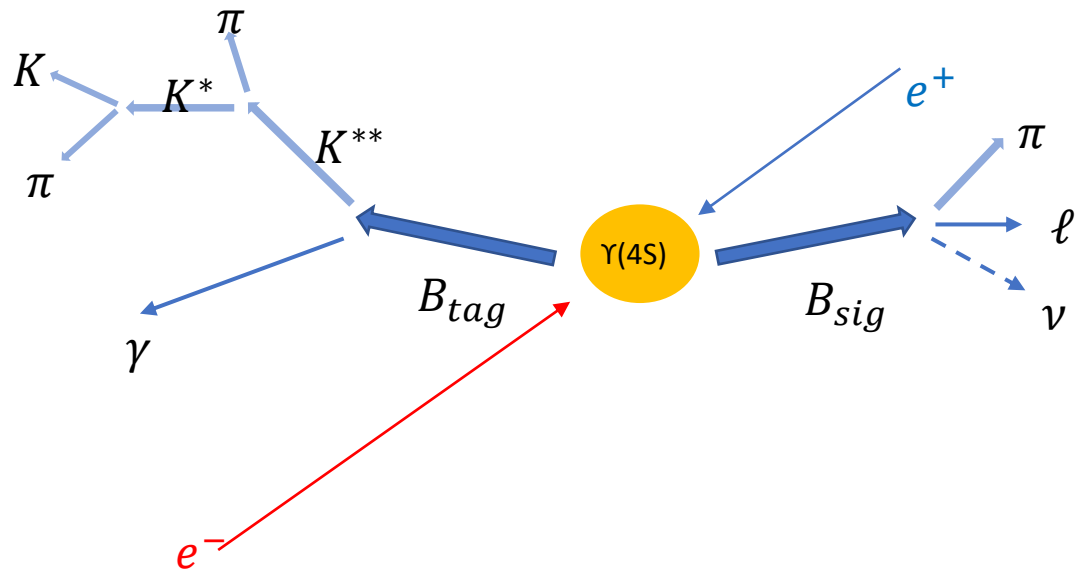


Experimental Methods



Untagged:
Only B_{sig} is explicitly reconstructed.

	Tagged	Untagged
Signal Yield	Low	High
Backgrounds	Low	High
Neutrino Reconstruction	Good	Poor
Tag calibration	Yes	No



Tagged (Full Event Interpretation*):
Both B_{sig} and B_{tag} are both explicitly reconstructed.

* Comp. and Soft. For Big Sci. 3, 6 (2019)

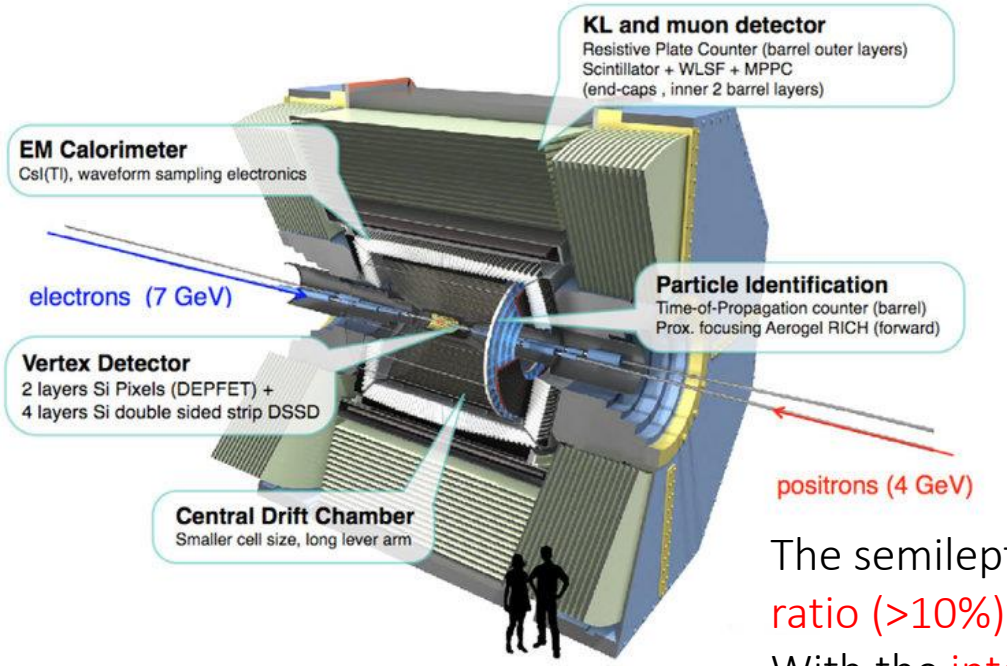
Super KEKB and Belle II

- Super KEKB :

  e^+e^- collider at 10.58 GeV, the ϒ(4S) resonance.

  The peak luminosity is $4.7 \times 10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$.

- Belle II:



The semileptonic decay from B meson has the highest branching ratio (>10%) for both neutral mode and charged mode.
With the integrated luminosity $189.3\ \mathrm{fb}^{-1}$ data recorded by the Belle II detector, some interesting result was observed.

Outline of Measurements

- Exclusive measurements of $|V_{cb}|$:
  1. untagged $\overline{B}^0 \to D^{*+}\ell^-\overline{\nu}_\ell$ (to be submitted to PRD)
  2. tagged $B^0 \to D^{*-}\ell^+\nu_\ell$ (arXiv : 2301.04716)
  3. untagged $B \to D\ell\nu_\ell$ (arXiv : 2210.13143)

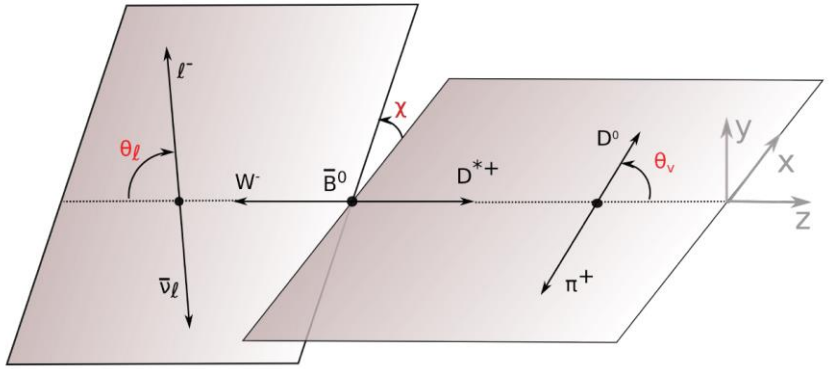
- Exclusive measurements of $|V_{ub}|$:
  4. untagged $B^0 \to \pi^-\ell^+\nu_\ell$ (arXiv : 2210.04224)
  5. tagged $B \to \pi e\nu_e$ (arXiv : 2206.08102)

- Exclusive measurements of LFU:
  6. Test of Angular asymmetries with tagged $B^0 \to D^{*-}\ell^+\nu_\ell$ (to be submitted to PRL)

- Inclusive measurements of LFU:
  7. Measurement of $R(X_{e/\mu})$. (arXiv : 2301.08266)

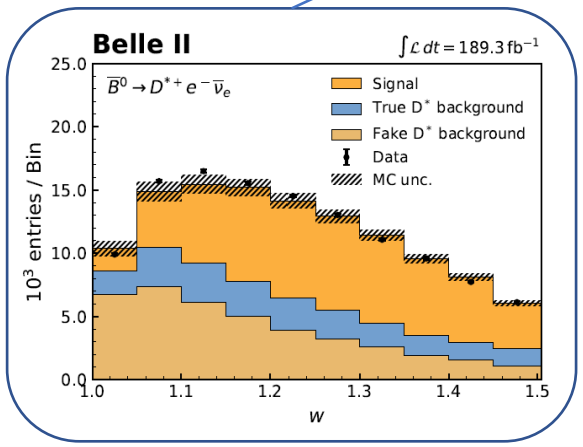
- Other Semileptonic Measurments

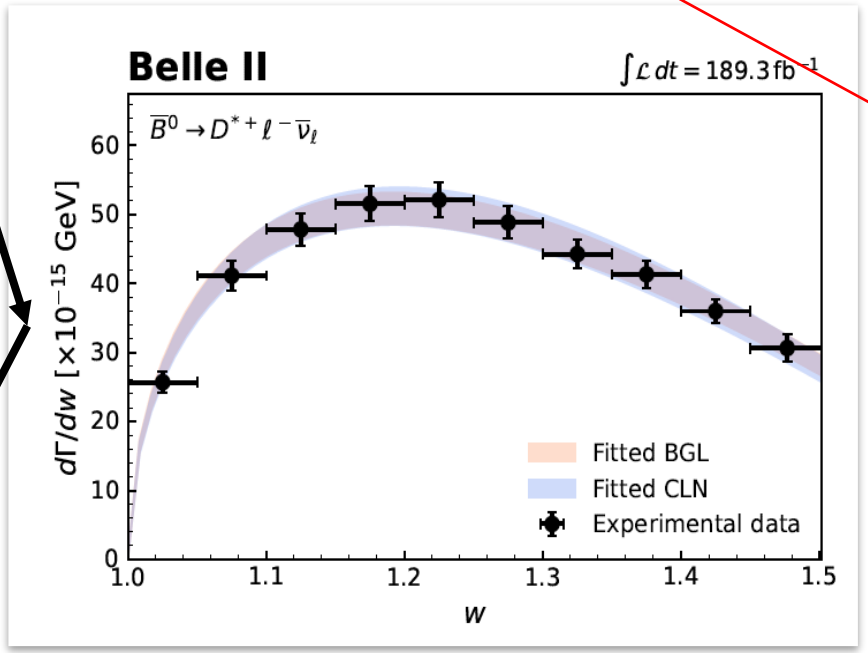
Untagged $\overline{B}^0 \to D^{*+}\ell^-\overline{\nu}_\ell$



- There are 4 main observables, including 3 angular observables θ_ℓ, θ_{v}, and χ. While the remaining observable w, is defined as $w = \left(\frac{p_B}{m_B}\right) \cdot \left(\frac{p_{D^*}}{m_{D^*}}\right)$.
- The differential cross-section is then :

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





$$|V_{cb}|_{\mathrm{BGL}} = (40.9 \pm 0.3 \pm 1.0 \pm 0.6) \times 10^{-3}$$
$$|V_{cb}|_{\mathrm{CLN}} = (40.4 \pm 0.3 \pm 1.0 \pm 0.6) \times 10^{-3}$$

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

BGL parameterization
Phys. Rev. D56, 6895 (1997)

$$h_{A_1}(z) = h_{A_1}(w=1)\Big(1 - 8\rho^2 z + (53\rho^2 - 15)z^2 - (231\rho^2 - 91)z^3\Big).$$

CLN parameterization
Nucl. Phys. B530, 153 (1998)

~~Untagged~~ Tagged $B^0 \to D^{*-}\ell^+\nu_\ell$

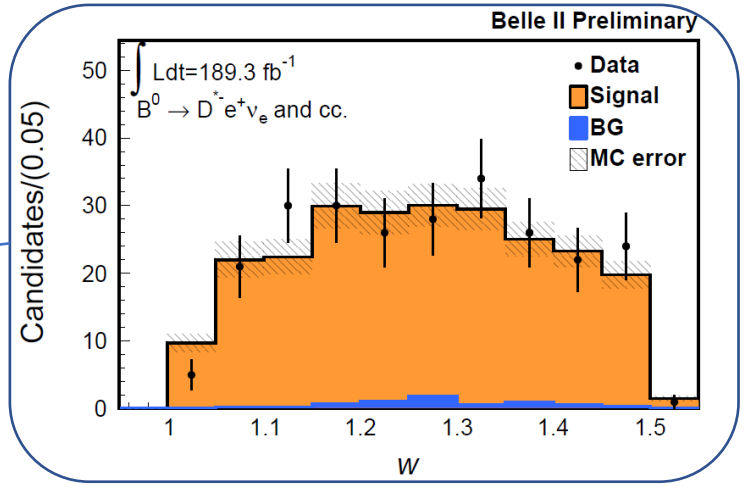
- Tagged events analysis allows a more precise understanding of $B^0 \to D^{*-}\ell^+\nu_\ell$, which is a stepping stone for the future measurement of $R(D^*_{\tau/\ell})$.
- The differential cross-section is :

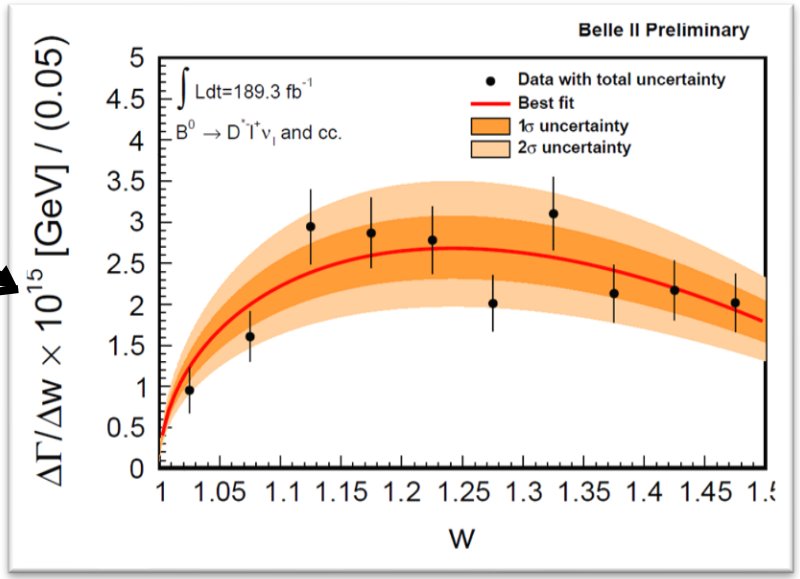
$$\frac{d\Gamma}{dw} = \frac{\eta_{EW}^2 G_F^2}{48\pi^3} m_{D^*}^3 (m_B - m_{D^*})^2 g(w) F^2(w) |V_{cb}|^2 \quad ,$$

$\eta_{EW} = 1.00662 \pm 0.00016$*,
and $F(1) = 0.906 \pm 0.004(\text{stat}) \pm 0.012(\text{syst})$*.

- CLN parameterization was used to parametrize the phase space factor and the form factor.
- RESULT : $\eta_{EW} F(1)|V_{cb}| \times 10^3 = 34.6 \pm 1.8 \ (\text{stat}) \pm 1.7 \ (\text{syst})$

(arXiv : 2301.04716)





* Phys. Rev. D 89 (2014) no. 11, 114504

Untagged $B \to D\ell\nu_\ell$

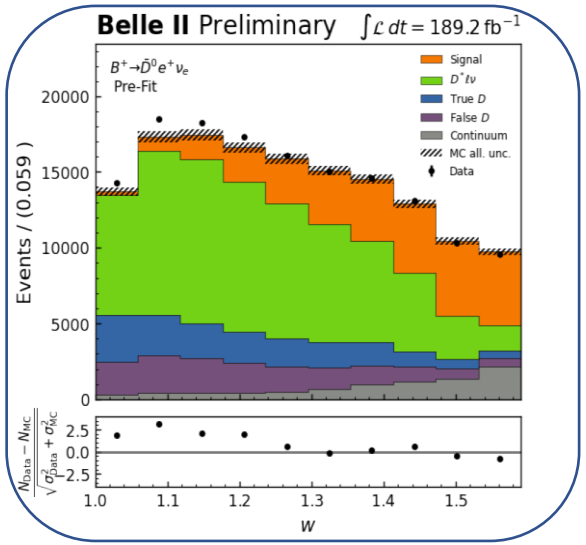
- Both the neutral mode $B^0 \to D^-\ell^+\nu_\ell$ and the charged mode $B^+ \to \overline{D}^0\ell^+\nu_\ell$ were studied.

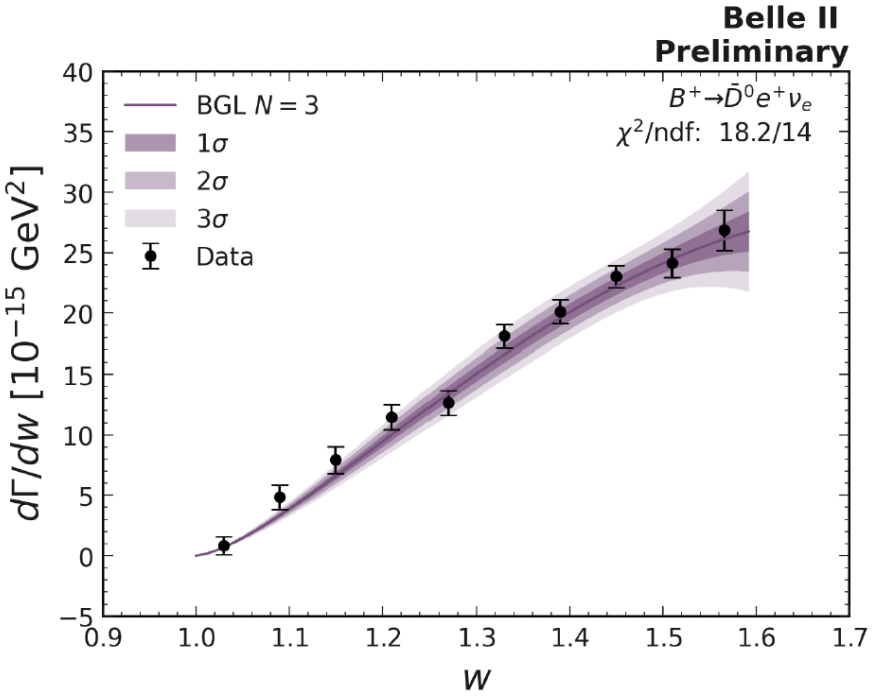
- Untagged sample was used to maximize the statistical power, but large combinatorial background from $B \to D^*\ell\nu$ were also included.

- The differential cross-section $d\Gamma/dw$ was studied, which is directly proportional to $|V_{cb}|^2$ and the square of form factor. BGL parametrization was used.

- The fit result is : $\eta_{\mathrm{EW}}|V_{cb}| = (38.53 \pm 1.15) \times 10^{-3}$

(arXiv : 2210.13143)





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  6. Test of Angular asymmetries with tagged $B^0 \to D^{*-}\ell^+\nu_\ell$ (to be submitted to PRL)

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  7. Measurement of $R(X_{e/\mu})$. (arXiv : 2301.08266)

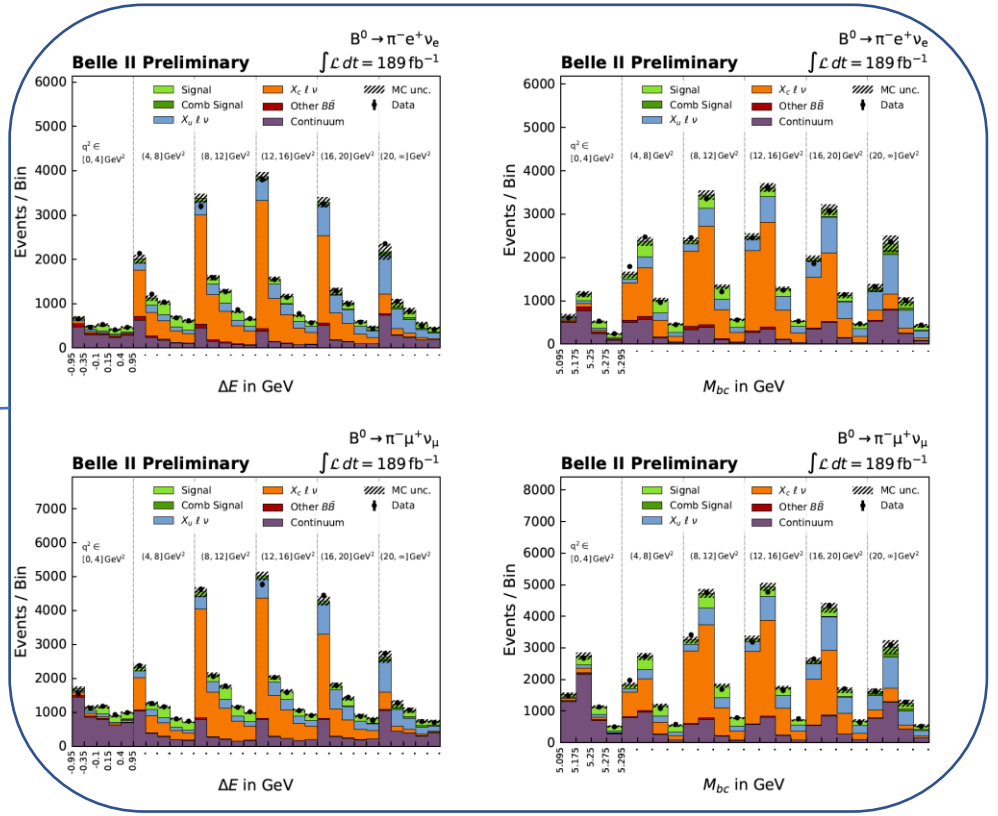
- Other Semileptonic Measurments

Untagged $B^0 \to \pi^- \ell^+ \nu_\ell$

- The differential cross-section $d\Gamma/dq^2$ with form factor provided by "Phys. Rev. D 92, 014024 (2015)" is used, where $q^2 = (p_B - p_\pi)^2$

$$\frac{d\Gamma(B \to \pi \ell \nu)}{dq^2} = \frac{G_F^2 |V_{ub}|^2}{24\pi^3} |\boldsymbol{p}_\pi|^3 |f_+(q^2)|^2$$

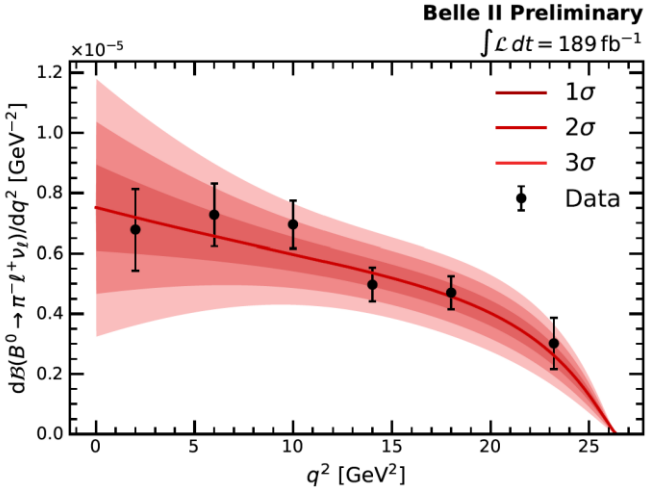
- To obtain the q^2 distributions, $M_{bc} = \sqrt{\left(\frac{\sqrt{s}}{2}\right)^2 - \left|\overrightarrow{p_B^*}\right|^2}$, and $\Delta E = E_B^* - \frac{\sqrt{s}}{2}$ was used. The 2 observables were plotted into 6 different q^2 bins.



- Results:

$$|V_{ub}|_{B^0 \to \pi^- e^+ \nu_e} = (3.60 \pm 0.18(\text{stat}) \pm 0.14(\text{syst}) \pm 0.18(\text{theo})) \times 10^{-3}$$
$$|V_{ub}|_{B^0 \to \pi^- \mu^+ \nu_\mu} = (3.71 \pm 0.16(\text{stat}) \pm 0.15(\text{syst}) \pm 0.17(\text{theo})) \times 10^{-3}$$
$$|V_{ub}|_{B^0 \to \pi^- \ell^+ \nu_\ell} = (3.55 \pm 0.12(\text{stat}) \pm 0.13(\text{syst}) \pm 0.17(\text{theo})) \times 10^{-3}$$

(arXiv : 2210.04224)



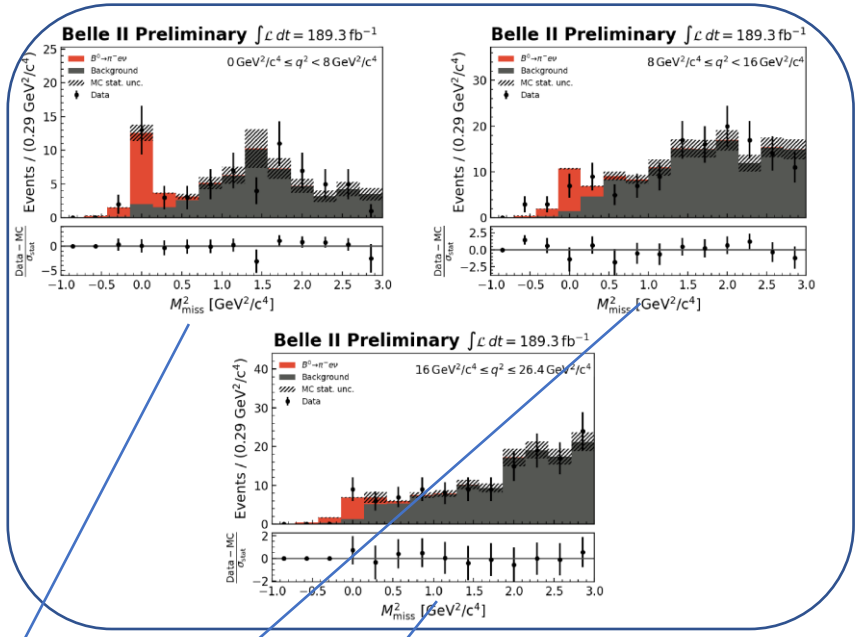
~~Untagged~~ Tagged $B \to \pi e \nu$

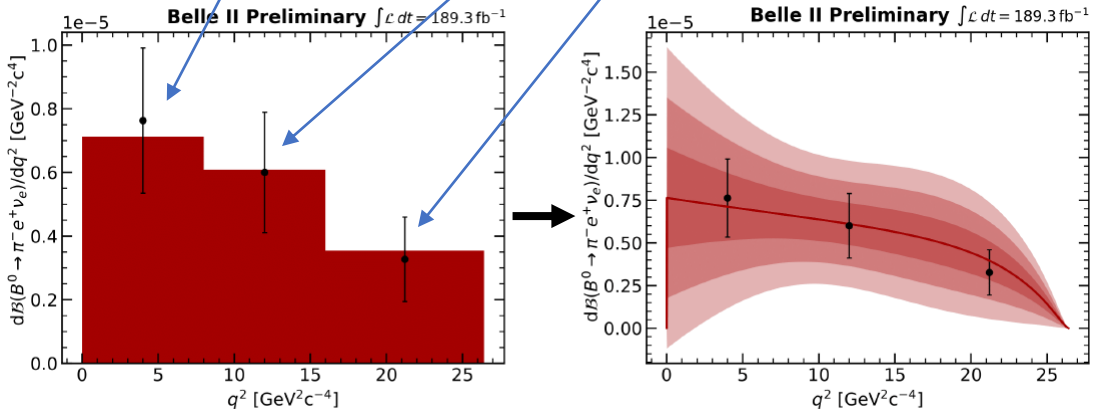
- Both neutral mode B^0 and charged mode $B^{\pm}$ were studied.
- Similarly as the untagged one, The differential cross-section $d\Gamma/dq^2$ was used.
- Due to the limited sample size, only 3 q^2 bins were used.
- To obtain the q^2 distributions, M^2_{miss} was used, where $M^2_{\mathrm{miss}} = p^2_{\mathrm{miss}}$, $p_{\mathrm{miss}} = p_{B_{sig}} - p_Y$, and Y represented the electron-pion system. Also, $p_{B_{sig}} = (\frac{\sqrt{s}}{2}, -\vec{p}_{B_{tag}})$.
- The fit result is :

Decay mode	Fitted $\lvert V_{\mathrm{ub}}\rvert$
$B^0 \to \pi^- e^+ \nu_e$	$(3.71 \pm 0.55) \times 10^{-3}$
$B^+ \to \pi^0 e^+ \nu_e$	$(4.21 \pm 0.63) \times 10^{-3}$
Combined fit	$(3.88 \pm 0.45) \times 10^{-3}$

(arXiv : 2206.08102)

Neutral mode B^0 bins 1-3:





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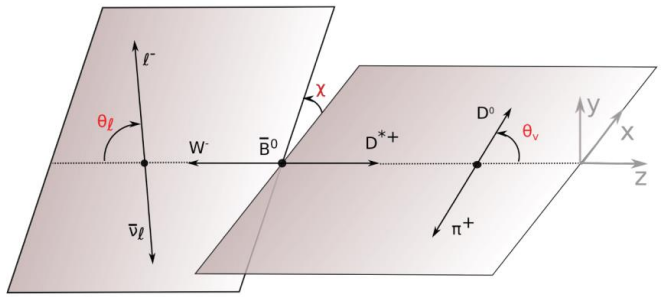
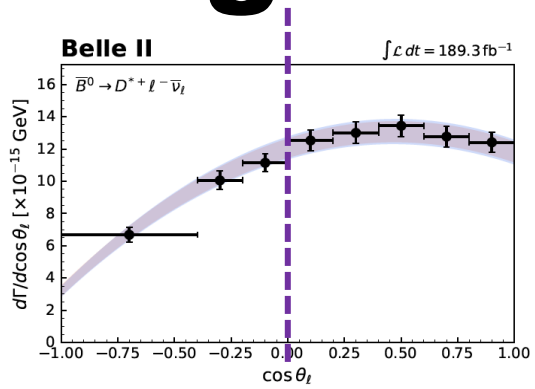
  7. Measurement of $R(X_{e/\mu})$. (arXiv : 2301.08266)

- Other Semileptonic Measurments

$\overline{B}^0 \to D^{*+}\ell^-\overline{\nu}_\ell$ Angular Asymmetries





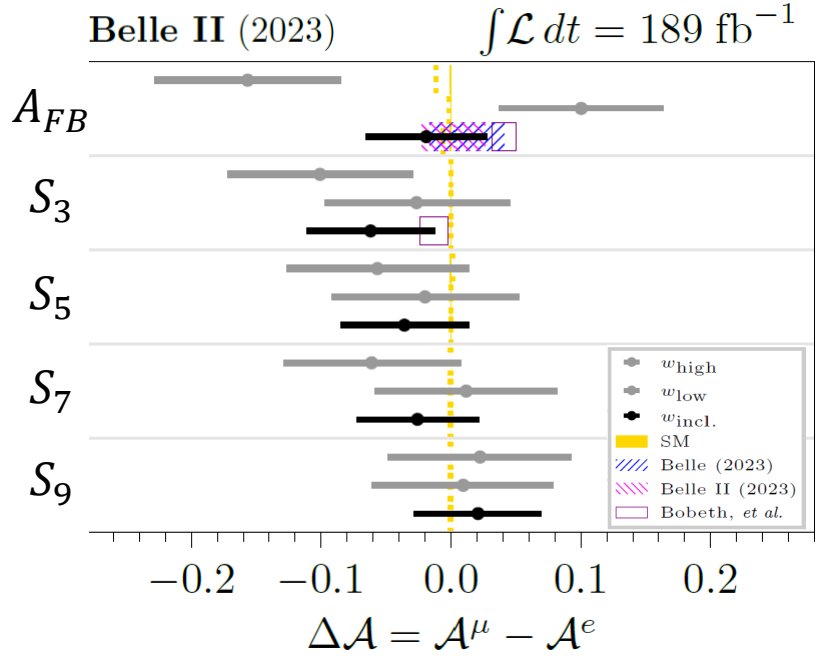
- The asymmetry A_x is defined $\mathcal{A}_x(w) \equiv \left(\frac{\mathrm{d}\Gamma}{\mathrm{d}w}\right)^{-1}\left[\int_0^1 - \int_{-1}^0\right]\mathrm{d}x\frac{\mathrm{d}^2\Gamma}{\mathrm{d}w\mathrm{d}x}$

- There were 5 observables defined, $x = \cos(\theta_\ell)$, $\cos(2\chi)$, $\cos(\chi)\cos(\theta_\mathrm{v})$, $\sin(\chi)\cos(\theta_\mathrm{v})$, and $\sin(2\chi)$. They are labelled as A_{FB}, S_3, S_5, S_7, and S_9 respectively.

- The asymmetries were studied in 3 different w ranges,which are $w_\mathrm{low} < 1.275$, $w_\mathrm{high} > 1.275$, and w_incl .

- The asymmetries were studied separately for electrons A^e and muons A^μ. The results were then compared by $\Delta A = A^\mu - A^e$.

Result :



The observables are in agreement with the Standard Model.

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

- The ratio is defined as $R(X_{e/\mu}) = \frac{BR(\overline{B}\to Xe^{-}\overline{\nu})}{BR(\overline{B}\to X\mu^{-}\overline{\nu})}$, where X is generic hardonic final state, and B can be any flavour.

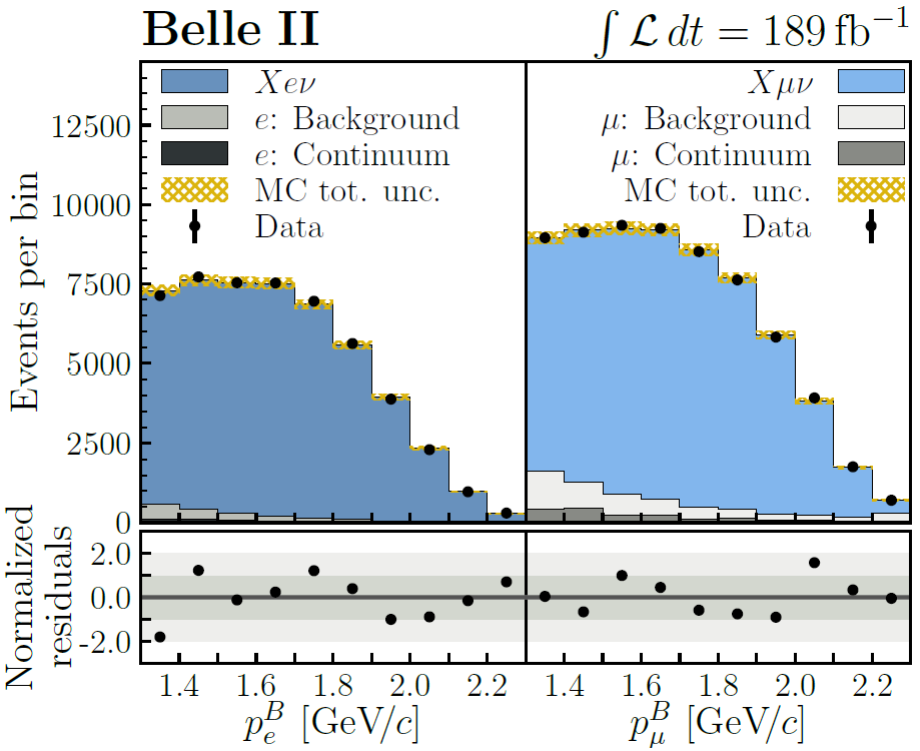
- To increase the signal purity, full event interpretation was used. Fully hadronic B-mesons were tagged. To reduce the fakes and secondary leptons, p_ℓ^B >1.3GeV was required.

- Experimentally, the ratio is obtained by

$$R(X_{e/\mu}) = \frac{N_e^{\text{meas}}}{N_\mu^{\text{meas}}} \cdot \frac{N_\mu^{\text{sel}}}{N_e^{\text{sel}}} \cdot \frac{N_e^{\text{gen}}}{N_\mu^{\text{gen}}}$$

, where N_ℓ^{sel} was the selected signal yield, N_ℓ^{gen} was the generated events in the full space, and N_ℓ^{meas} was obtained from the fit on signal region data. The signal yields were extracted with simultaneous binned maximum likelihood template fits to p_e^B and p_μ^B.

- The result is consistent with the SM.



And the final result :

$$R(X_{e/\mu}) = 1.007 \pm 0.009(\text{stat}) \pm 0.019(\text{stat})$$

(arXiv : 2301.08266), while the result in arXiv is not updated.

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- Other Semileptonic Measurments

Other Measurement

- The inclusive measurement $B \to X_c \ell \overline{\nu}_\ell$ decays was performed. (arXiv : 2205.06372)

  In this measurement, the spectral moments of the lepton mass squared $< q^{2n} >$, where $n = 1,2,3,$ and 4, were the observables. "The simultaneous analysis of these moments can determine the non-perturbative matrix elements as their contributions vary with the q2 threshold." *

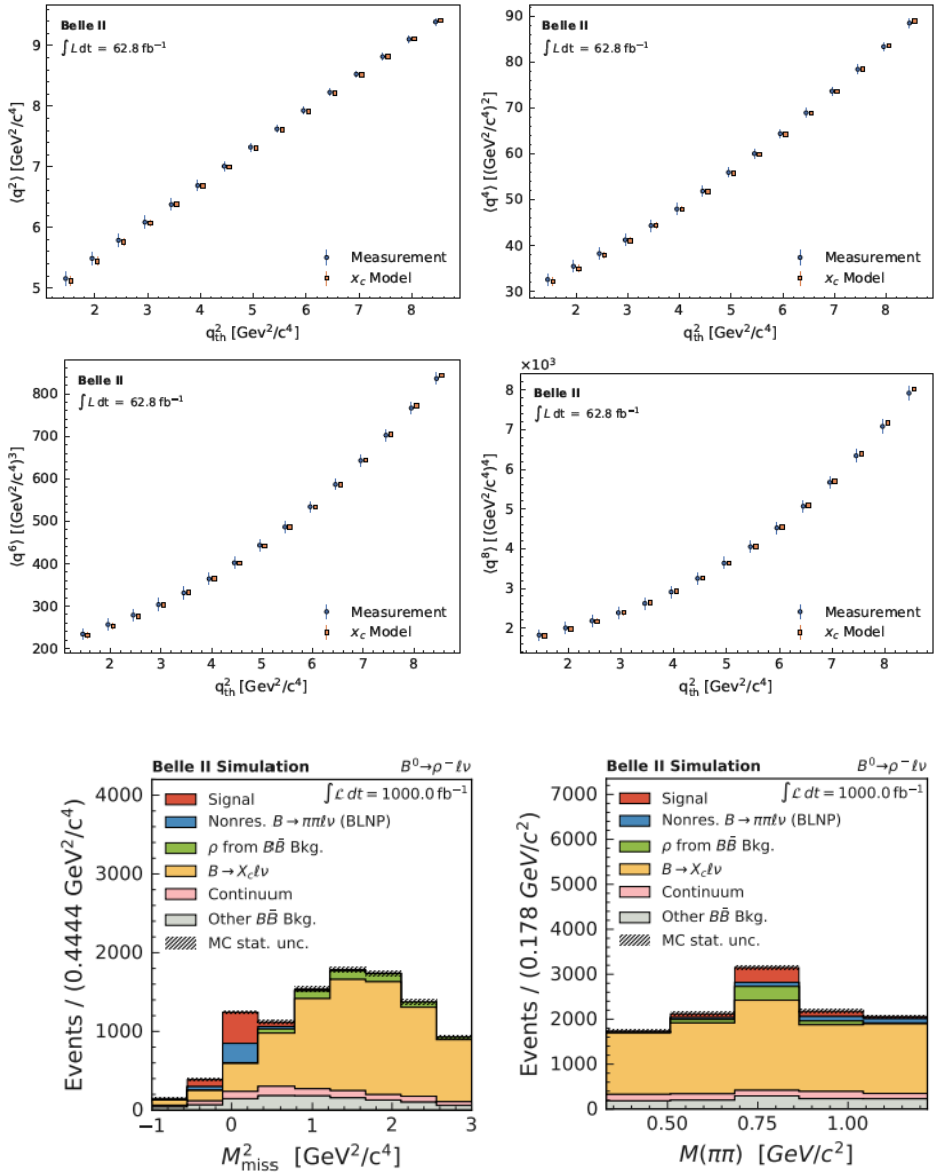
  $|V_{cb}|$ was not measured in this paper directly, but there is another paper using the same method and using both Belle and Belle II data. (arXiv : 2205.10274)

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

- Branching ratio (BR) of TAGGED $B \to \rho \ell \nu_\ell$ decays was measured. (arXiv : 2211.15270)

  Both neutral mode and charged mode were measured.
  The signal yield was fitted by using the M^2_{miss} and $M(\pi\pi)$ distribution.
  $|V_{ub}|$ was not measured in this paper, while the BR is :

$$\mathcal{B}(B^0 \to \rho^- \ell^+ \nu_\ell) = (4.12 \pm 0.64(\text{stat}) \pm 1.16(\text{syst})) \times 10^{-4}$$
$$\mathcal{B}(B^+ \to \rho^0 \ell^+ \nu_\ell) = (1.77 \pm 0.23(\text{stat}) \pm 0.36(\text{syst})) \times 10^{-4}$$



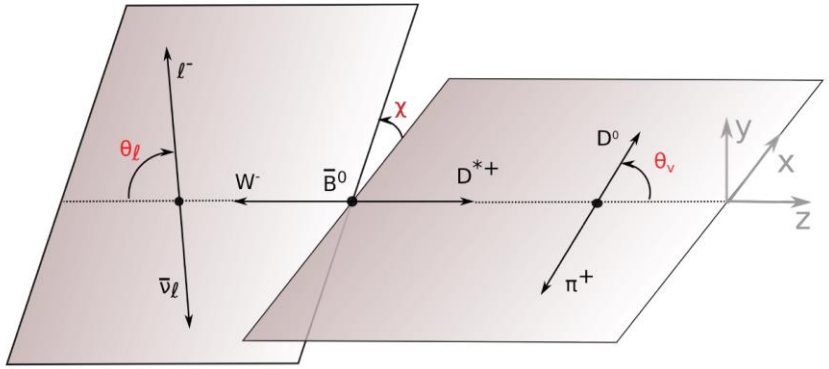
* JHEP 01, 147 (2014)

Summary

- Belle-II performed both exclusive and inclusive measurements of $|V_{cb}|$ and $|V_{ub}|$.
- The discrepancy between exclusive and inclusive results still exists.
- No significant LFU violation has been observed.
- With new data samples, more exciting results are expected.

Back up

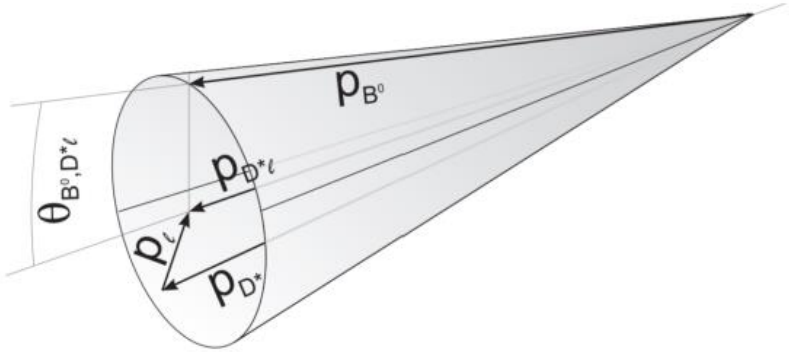
Untagged $\overline{B}^0 \to D^{*+}\ell^-\overline{\nu}_\ell$



- To reconstruct the 4 main observables, w, θ_ℓ, θ_v, and χ, other variables were needed.

- B meson :

  $E_B^* = \frac{E_{\mathrm{beam}}^*}{2}$, $|\vec{p}_B^{\,*}| = \sqrt{\left(E_{\mathrm{beam}}^*\right)^2 - m_B^2}$



- From the reconstruction of ℓ and D^* :

  $\cos(\theta_{BY}) = \frac{2E_B^*E_Y^* - m_B^2 - m_Y^2}{2|\vec{p}_B^{\,*}||\vec{p}_Y^{\,*}|}$, where Y is the combined $D^*$and ℓ system.

Back up
Some data from Particle data group*

- $|V_{cb}| = (42.2 \pm 0.8) \times 10^{-3}$ (inclusive)
- $|V_{cb}| = (39.4 \pm 0.8) \times 10^{-3}$ (exclusive)
- $|V_{cb}| = (40.8 \pm 1.4) \times 10^{-3}$ (average)

- $|V_{ub}| = \left(4.13 \pm 0.12^{+0.13}_{-0.14} \pm 0.18\right) \times 10^{-3}$ (inclusive)
- $|V_{ub}| = (3.70 \pm 0.10 \pm 0.12) \times 10^{-3}$ (exclusive)
- $|V_{ub}| = (3.82 \pm 0.20) \times 10^{-3}$

* https://pdg.lbl.gov/2022/reviews/rpp2022-rev-vcb-vub.pdf