Flavour Physics with Electroweak-Penguin and Semileptonic Decays at Belle II

Kazuki Kojima (Nagoya University)
on behalf of the Belle II collaboration

Light Cone 2021: Physics of Hadrons on the Light Front
Nov. 30th, 2021

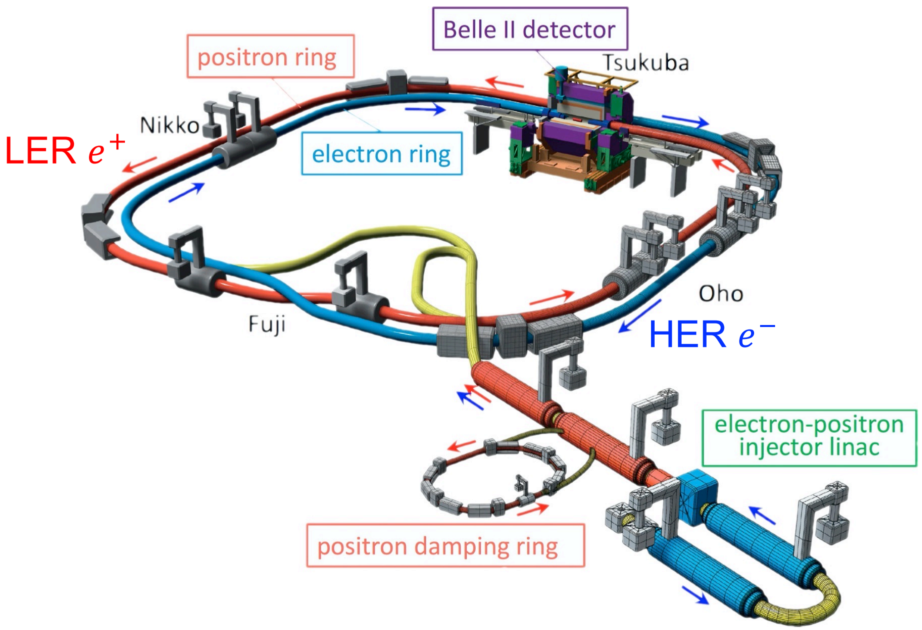
The SuperKEKB/Belle II Experiment

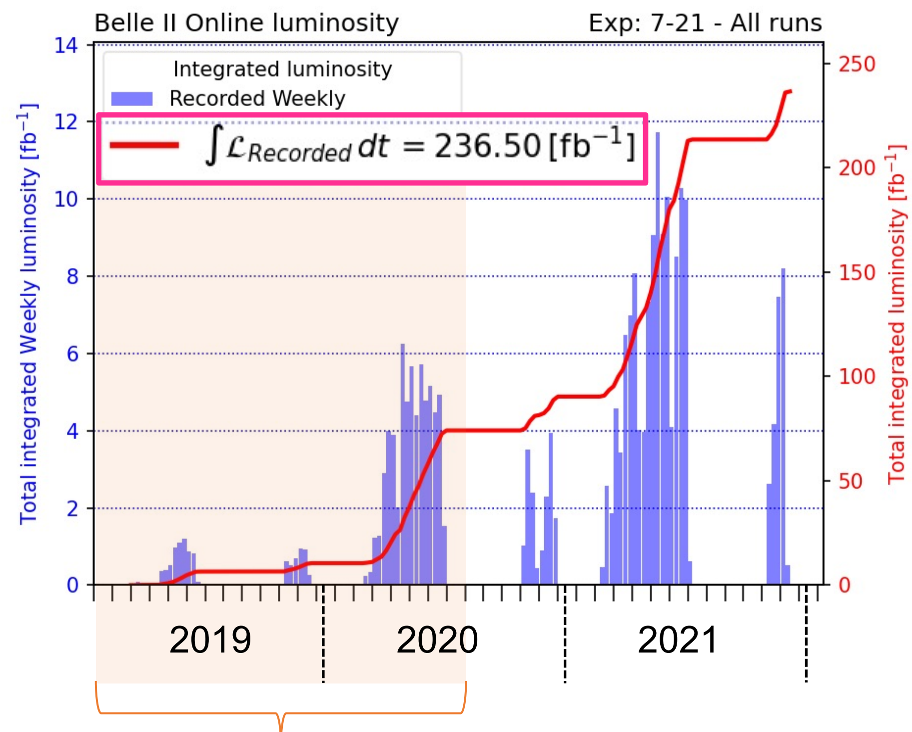
Electron-positron collider at a center of mass energy of the $\Upsilon(4S)$ resonance or around.

The world's highest instantaneous luminosity: $\mathbf{3.1 \times 10^{34}\ cm^{-2}s^{-1}}$

$12\ \mathrm{fb}^{-1}/\mathrm{week},\ 40.3\ \mathrm{fb}^{-1}/\mathrm{month}$

(KEKB record: $2.1 \times 10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1},\ 8\ \mathrm{fb}^{-1}/\mathrm{week},\ 29.4\ \mathrm{fb}^{-1}/\mathrm{month}$)





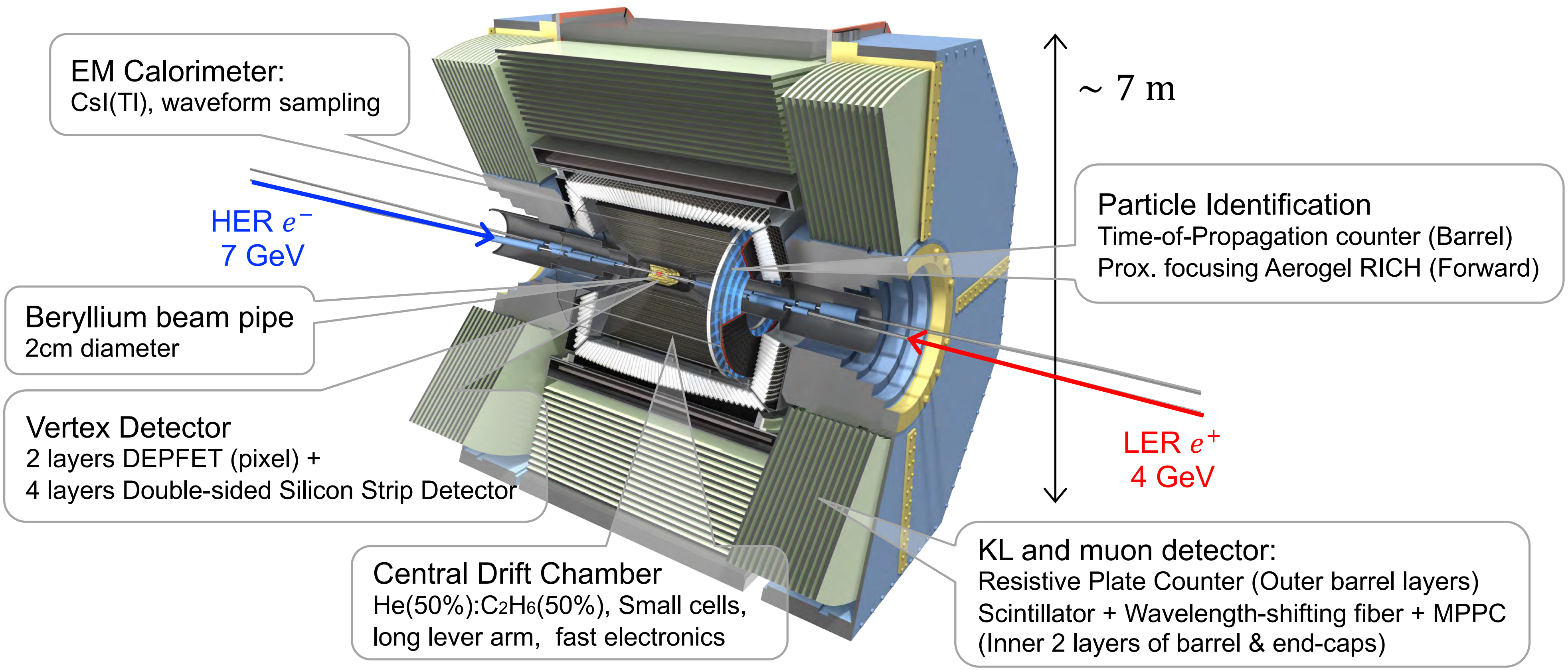
Today's results: $34.6\ \mathrm{fb}^{-1}$ or $62.8\ \mathrm{fb}^{-1}$ at $\Upsilon(4S)$

Belle II Luminosity
https://confluence.desy.de/display/BI/Belle+II+Luminosity

The Belle II Detector

Substantially upgraded from the Belle detector
except for calorimeter crystal and superconducting magnet

Equivalent or improved performances under higher beam background and event rate conditions.
e.g. vertex resolution, K_S^0 reconstruction, K/π identification, trigger system, …



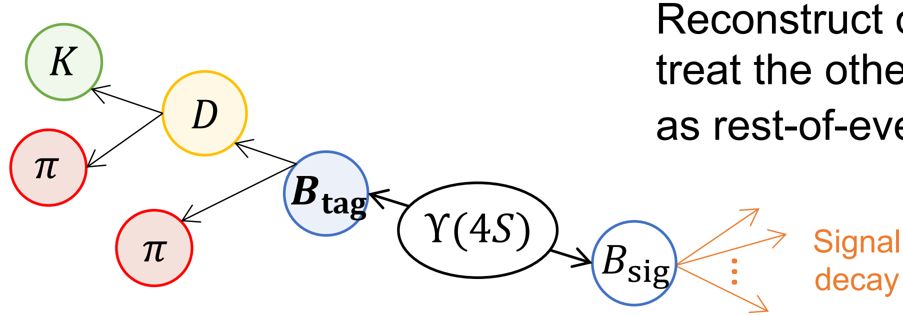
B Decay Reconstruction: Tagged Analysis

1. Tagged Analysis

One B meson from $\Upsilon(4S)$ decay is exclusively reconstructed to tag $B\bar{B}$ events.

2. Untagged Analysis (Inclusive Tagged Analysis)

Reconstruct only signal B decay and treat the other particles not in B_{sig} as rest-of-event information.



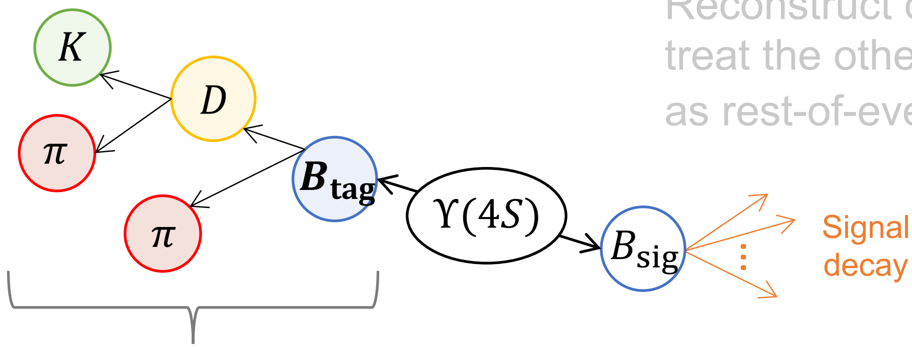
B Decay Reconstruction: Tagged Analysis

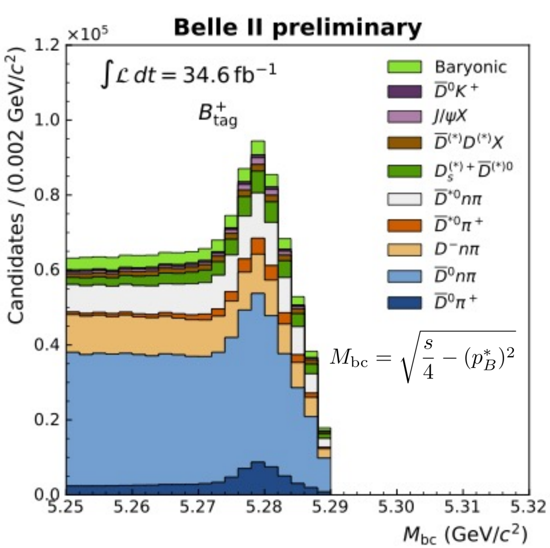
1. Tagged Analysis

One B meson from $\Upsilon(4S)$ decay is exclusively reconstructed to tag $B\bar{B}$ events.

2. Untagged Analysis
(Inclusive Tagged Analysis)

Reconstruct only signal B decay and treat the other particles not in B_{sig} as rest-of-event information.



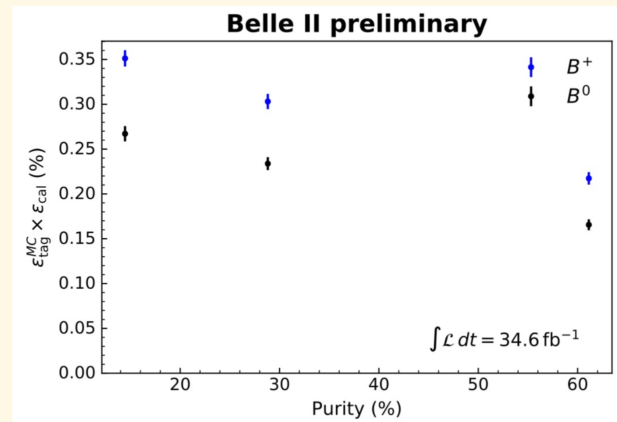


Full Event Interpretation (FEI): Comp. and Soft. For Big Sci. **3**, 6 (2019)
Multivariate algorithm for exclusive tagging of one B meson in a $\Upsilon(4S)$ decay using hierarchal approach.

Over 100 B meson decay channels and over 10,000 decay cascades

Improved effiiciency up to 50% relatively with respect to conventional approaches!

arXiv:2008.06096



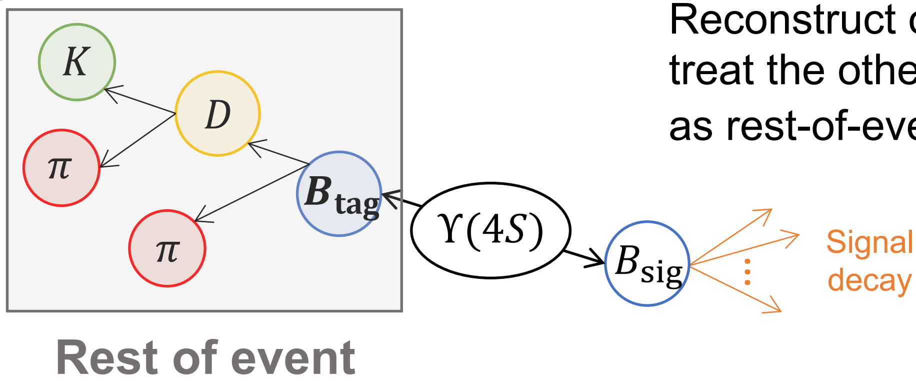
B Decay Reconstruction: Untagged Analysis

1. Tagged Analysis

One B meson from $\Upsilon(4S)$ decay is exclusively reconstructed to tag $B\bar{B}$ events.

2. Untagged Analysis
(Inclusive Tagged Analysis)

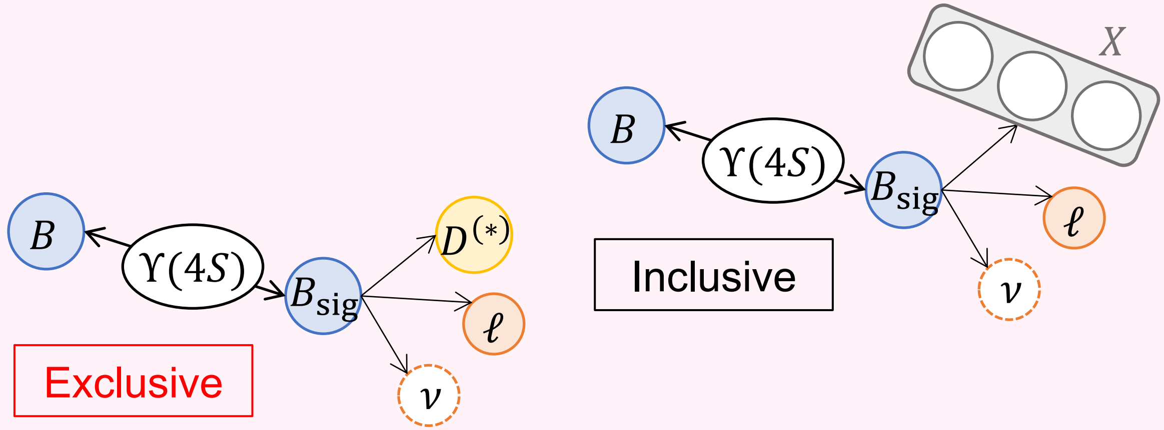
Reconstruct only signal B decay and treat the other particles not in B_{sig} as rest-of-event information.

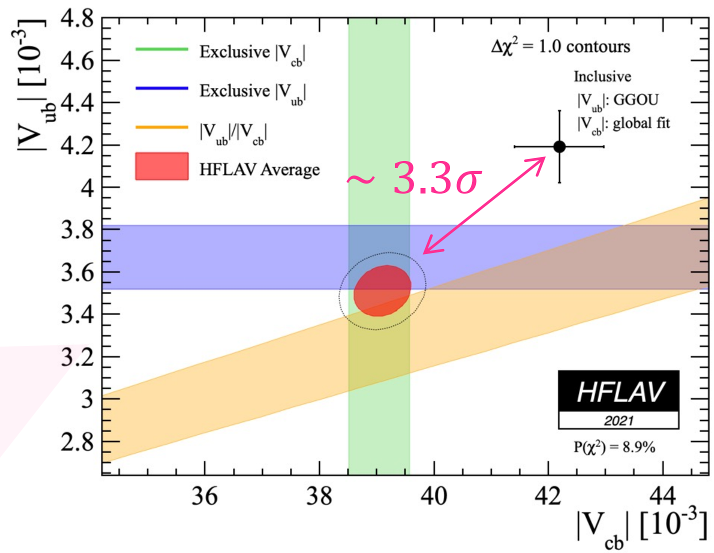


Semileptonic Decays

Tensions in Semileptonic Decay Measurements

Long standing tension ($\sim 3.3\sigma$) between inclusive and exclusive measurements of $|V_{cb}|$ and $|V_{ub}|$

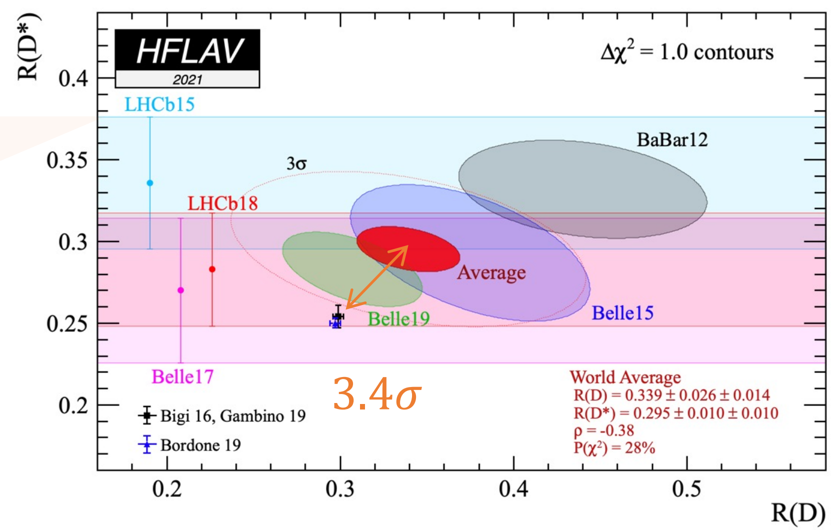




Anomalies (LFUV) in semitauonic decays:

3.4σ deviation from the SM expectation of

$$R(D^{(*)}) = \frac{\mathcal{B}(B \to \bar{D}^{(*)}\tau\nu)}{\mathcal{B}(B \to \bar{D}^{(*)}\ell\nu)}, \ (\ell = e, \ \mu)$$

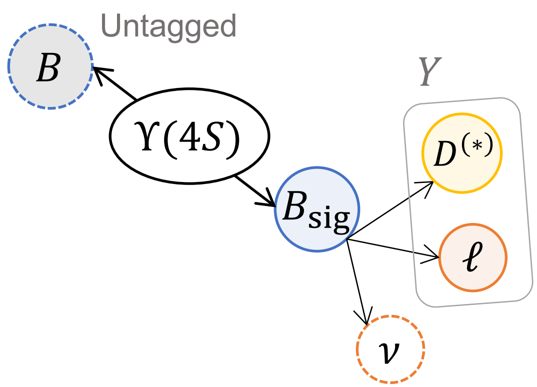


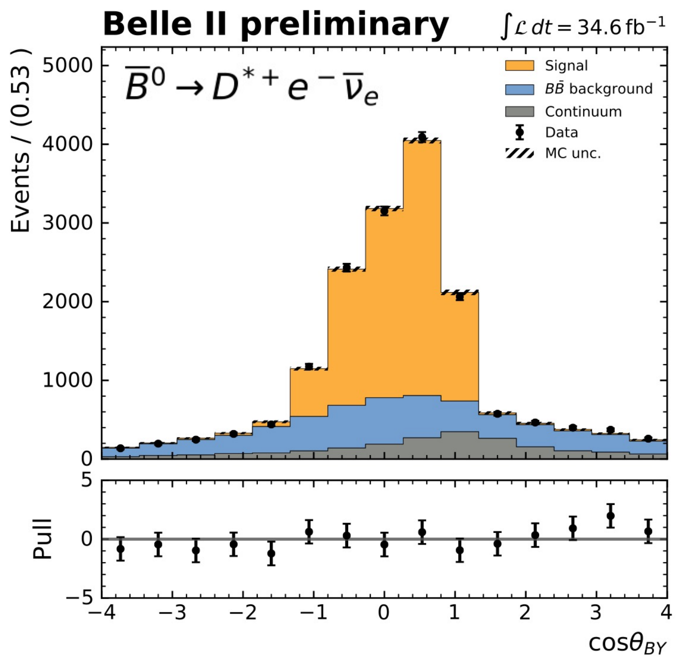
Untagged Exclusive $|V_{cb}|$ Measurements: $B \to D^{(*)}\ell\nu$

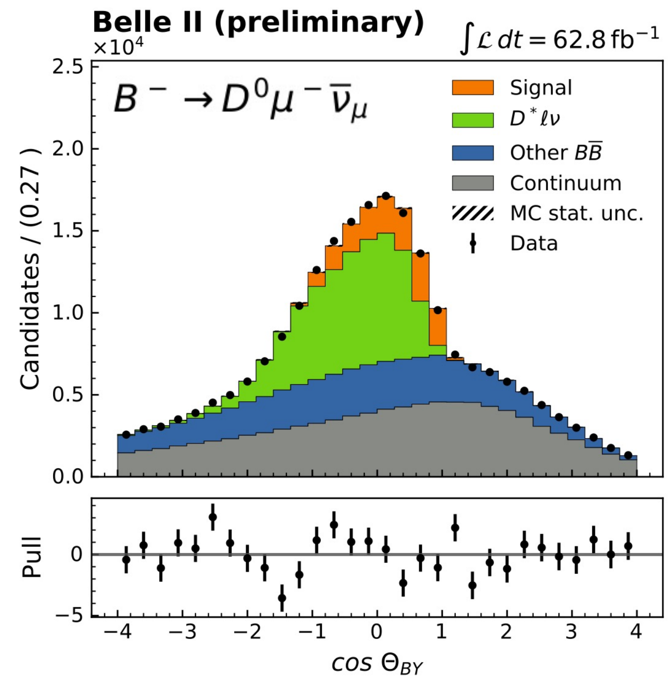
Measured branching ratios of $B^0 \to \bar{D}^{(*)}\ell\nu$. arXiv:2008.07198, arXiv:2110.02648

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

Angle between nominal B meson and $Y (= D^{(*)}\ell)$ system







	Measured	PDG Values
$\mathcal{B}(\bar{B}^0 \to D^{*+}\ell^-\bar{\nu}_\ell)$	$(4.60 \pm 0.05_{\text{stat}} \pm 0.17_{\text{syst}} \pm 0.45_{\pi_{\text{slow}}})\%$	$(5.05 \pm 0.14)\%$
$\mathcal{B}(\bar{B}^0 \to D^0\ell^-\bar{\nu}_\ell)$	$(2.29 \pm 0.05_{\text{stat}} \pm 0.08_{\text{syst}})\%$	$(2.35 \pm 0.09)\%$

Consistent within 1σ

Competitive accuracy!

In progress $|V_{cb}|$ measurement from differential BR in bins of hadron recoil parameter w

Untagged Exclusive $|V_{cb}|$ Measurements: $B \to D^{(*)}\ell\nu$

Measured branching ratios of $B^0 \to \bar{D}^{(*)}\ell\nu$.

arXiv:2008.07198, arXiv:2110.02648

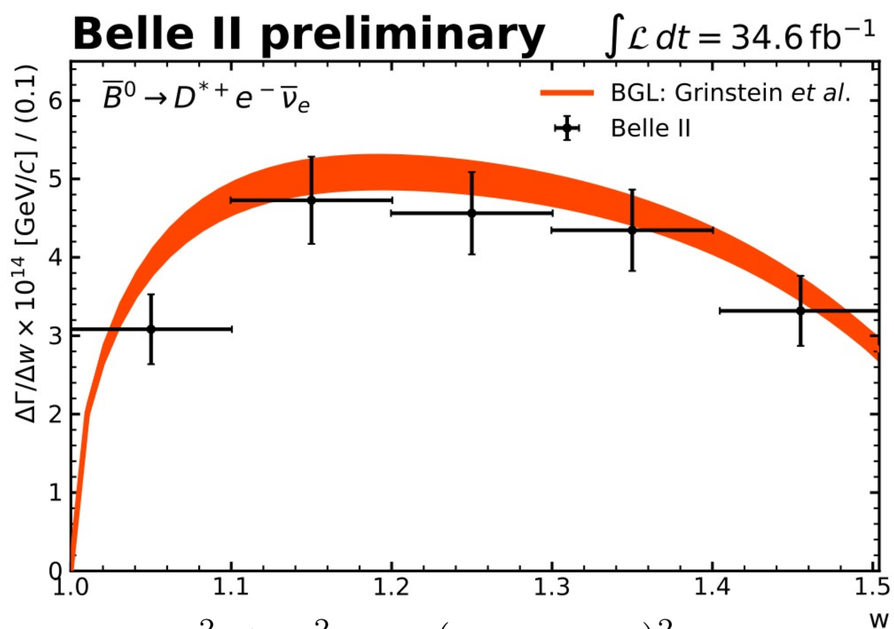
In progress $|V_{cb}|$ measurement from differential BR in bins of hadron recoil parameter w

Form factor parameters will be extracted with partial decay rates:

$$\Delta\Gamma_i = \frac{\overline{N}^{\text{unfoloded}}_{\text{signal},i} \times \tau_{B^0}}{\epsilon_i \times N_{B^0} \times \mathcal{B}(D^{*+} \to D^0\pi^+) \times \mathcal{B}(D^0 \to K^-\pi^+)}$$

Unfolded signal yield; B^0 meson lifetime; ϵ_i: Reconstruction efficiency and acceptance

∗ Not fit yet

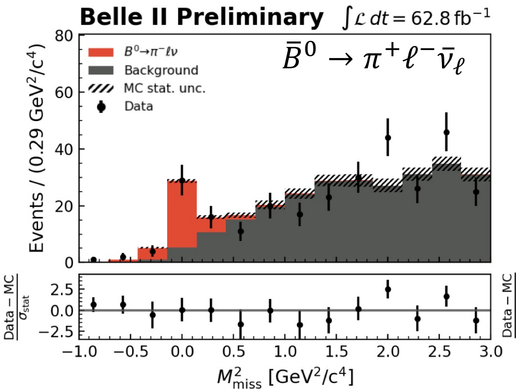


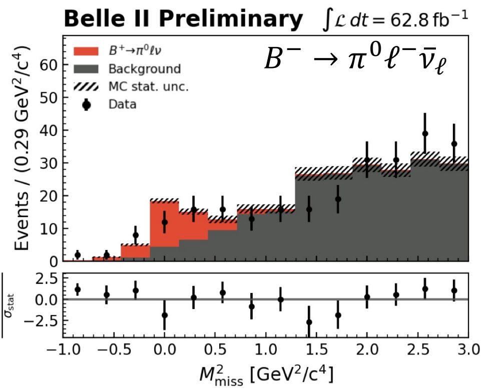
$$w = \frac{m_B^2 + m_{D^{*+}}^2 - (p_B - p_{D^{*+}})^2}{2 m_B m_{D^{*+}}} = v_B \cdot v_{D^{*+}}$$

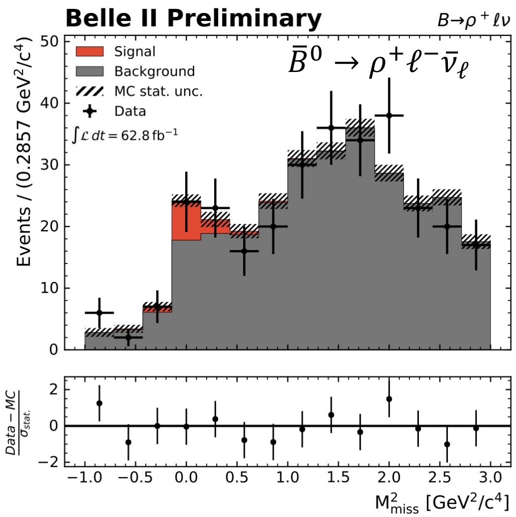
Tagged Exclusive $|V_{ub}|$ Measurements: $B \to \pi\ell\nu/\rho\ell\nu$

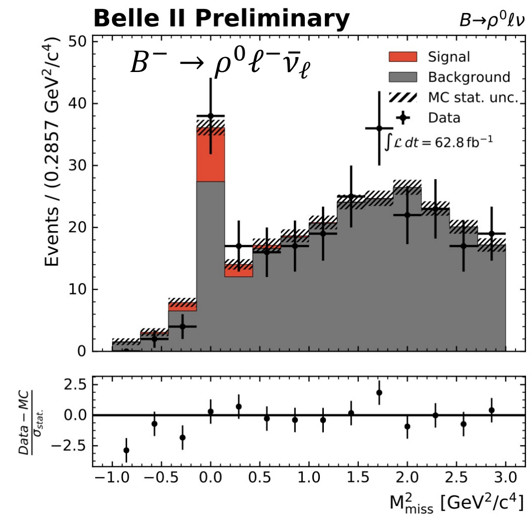
The branching fractions of four $B \to \pi\ell\nu/\rho\ell\nu$ channels were measured. arXiv:2111.00710

$$M^2_{\text{miss}} = (p_{e^+e^-} - p_{B_{\text{tag}}} - p_{\pi/\rho} - p_\ell)^2$$





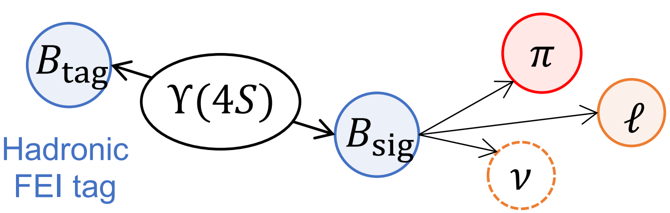




	Measured	Significance	PDG Values
$\mathcal{B}(\bar{B}^0 \to \pi^+\ell^-\bar{\nu}_\ell)$	$(1.47 \pm 0.29_{\text{stat}} \pm 0.05_{\text{syst}})\times10^{-4}$ (*)	6.2σ	$(1.50 \pm 0.06)\times10^{-4}$
$\mathcal{B}(B^- \to \pi^0\ell^-\bar{\nu}_\ell)$	$(8.29 \pm 1.99_{\text{stat}} \pm 0.46_{\text{syst}})\times10^{-5}$	7.7σ	$(7.80 \pm 0.27)\times10^{-4}$
$\mathcal{B}(\bar{B}^0 \to \rho^+\ell^-\bar{\nu}_\ell)$	$(9.26 \pm 6.33_{\text{stat}} \pm 0.38_{\text{syst}})\times10^{-5}$ Upper limit: $< 3.37\times10^{-4}$ (95% CL)	1.4σ	$(2.94 \pm 0.21)\times10^{-4}$
$\mathcal{B}(B^- \to \rho^0\ell^-\bar{\nu}_\ell)$	$(1.51 \pm 1.13_{\text{stat}} \pm 0.09_{\text{syst}})\times10^{-5}$ Upper limit: $< 1.97\times10^{-4}$ (95% CL)	1.5σ	$(1.58 \pm 0.11)\times10^{-4}$

(*) Sum of three q^2 bins

Consistent with the world average

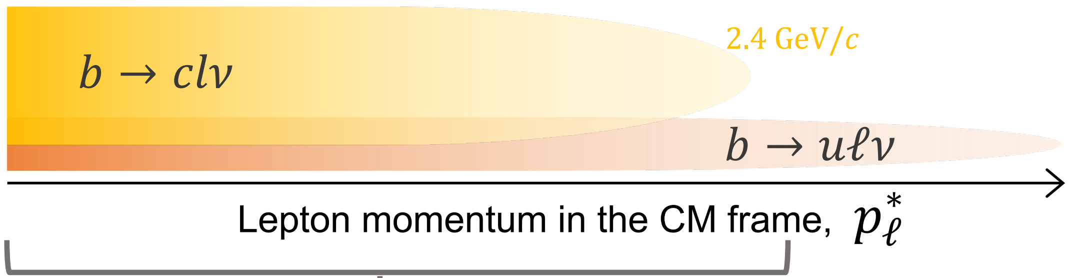


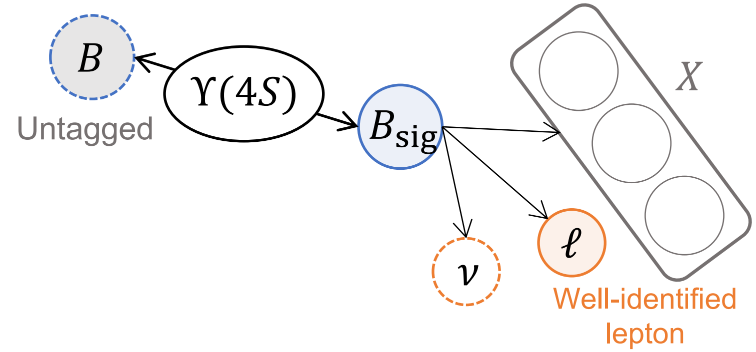
In progress: $|V_{ub}|$ measurement in q^2 bins, untagged exclusive measurement

Untagged Inclusive $|V_{cb}|$, $|V_{ub}|$ Measurement: $B \to X\ell\nu$

Only a charged lepton is reconstructed explicitly and $X_{u,d}\ell\nu$ yields are extracted by fitting a p_ℓ^* distribution.

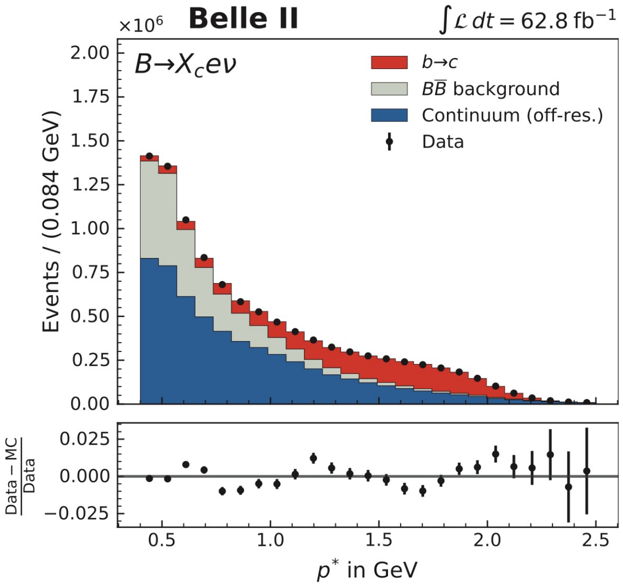
arXiv:2111.09405, arXiv:2103.02629





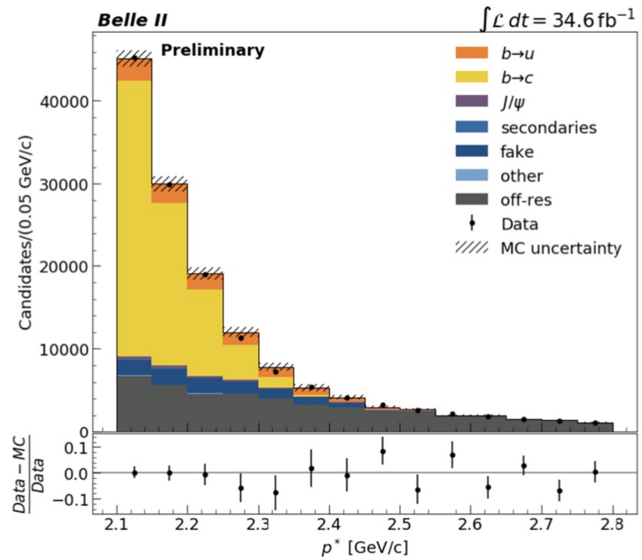
0.4 - 2.5 GeV/c $\boldsymbol{B \to X_c\ell\nu}$

2.1 - 2.8 GeV/c $\boldsymbol{B \to X_u e\nu}$



Measured branching ratio:

$$\mathcal{B}(B \to X_c\ell\nu) = (9.75 \pm 0.03_{\text{stat}} \pm 0.47_{\text{syst}})\%$$



$B \to X_u e\nu$ excess at 3σ level

In progress

Developing MVA to distinguish $b \to u$ and $b \to c$ events based on M_X and rest-of-event information

Prospects of $R\left(D^{(*)}\right)$ Measurements

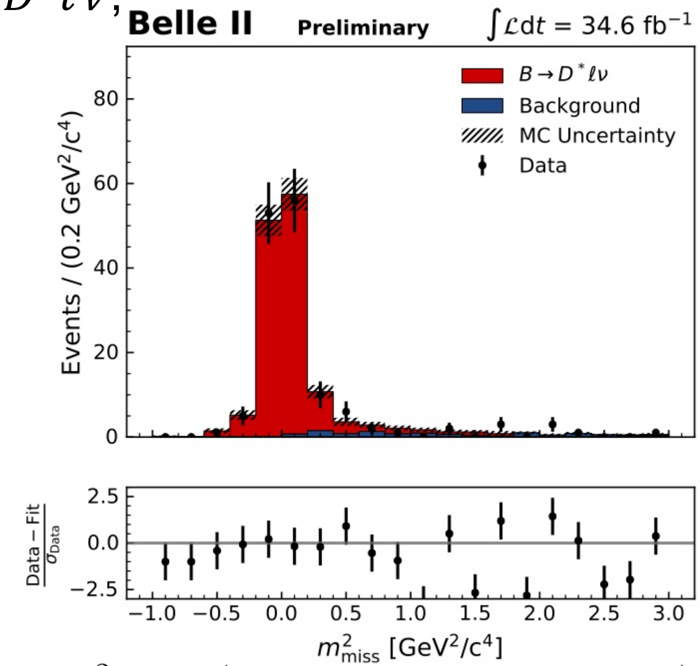
Realized the measurement of branching fractions of $B \to D^* \ell \nu$, one of the normalization modes for

$$R(D^{(*)}) = \frac{\mathcal{B}(B \to \bar{D}^{(*)}\tau\nu)}{\mathcal{B}(B \to \bar{D}^{(*)}\ell\nu)},\ (\ell = e,\ \mu)$$, at Belle II.

Hadronic FEI tag

$$\mathcal{B}\left(\bar{B}^0 \to D^{*+}\ell^-\bar{\nu}_\ell\right) = \left(4.60 \pm 0.41_{\text{stat}} \pm 0.27_{\text{syst}} \pm 0.45_{\pi_{\text{slow}}}\right)\%$$

arXiv:2008.10299



$$M^2_{\text{miss}} = \left(p_{e^+e^-} - p_{B_{\text{tag}}} - p_{D^*} - p_\ell\right)^2$$

In progress

The analysis of $R\left(D^{(*)}\right)$ with multiple channels

- Hadronic FEI tag, leptonic τ decays
  → First results by 2022 summer
- Hadronic FEI tag, hadronic τ decays
- Semileptonic FEI tag, leptonic τ decays

Inclusive $R(X) = \frac{\mathcal{B}(B \to X\tau\nu)}{\mathcal{B}(B \to X\ell\nu)}$ measurement

Unique measurement with hadronic FEI tag at Belle II !

→ First results in 2022

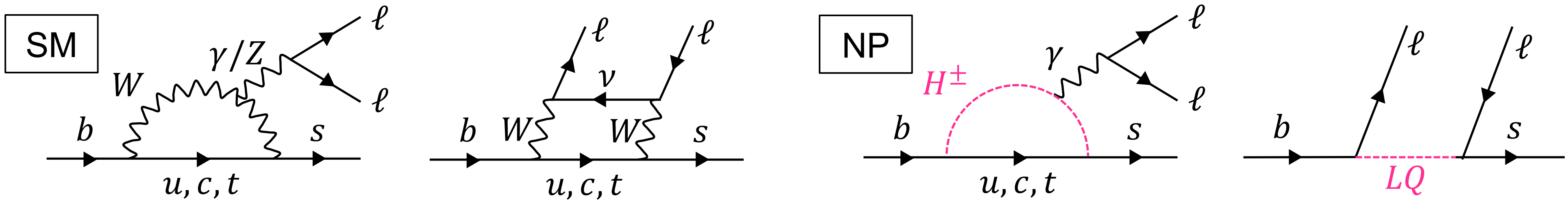
Observable	Uncertainties at 5 ab^{-1}
$R(D^*)$	$\left(\pm 3.0_{\text{stat}} \pm 2.5_{\text{syst}}\right)\%$
$R(D)$	$\left(\pm 6.0_{\text{stat}} \pm 3.9_{\text{syst}}\right)\%$

Prog. Theor. Exp. Phys., 2019, 12, (2019) 123C01

Electroweak-Penguin Decays

Electroweak-Penguin Decays & $R(K^{(*)})$ Anomalies

Electroweak penguin decays have flavor-changing neutral current (FCNC).
→ Sensitive to new physics (NP) beyond SM that contributes to FCNC process, suppressed in SM with one-loop diagrams.



Recently the LHCb experiment report new results of lepton flavor universality test in $b \to s\ell\ell$.

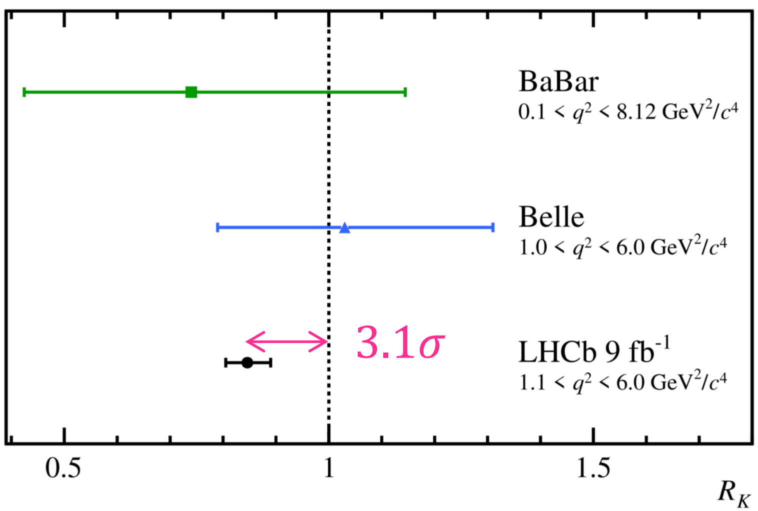
arXiv:2103.11769, arXiv:2110.09501

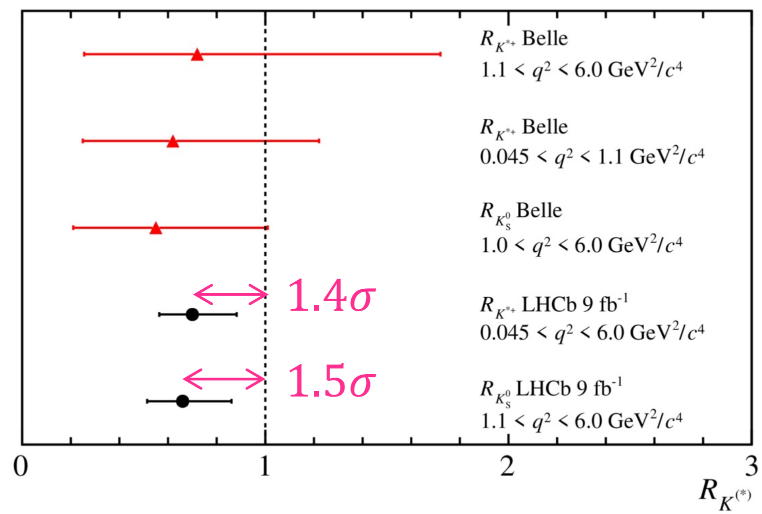
SM

$$R(K^{(*)}) = \frac{\mathcal{B}(B \to K^{(*)}\mu^+\mu^-)}{\mathcal{B}(B \to K^{(*)}e^+e^-)} = 1 \pm \mathcal{O}(10^{-2})$$

$q^2 \in [1(1.1), 6]$ for $R(K^{(*)})$

JHEP 2018, 93 (2018)





Independent tests at Belle II are highly demanded!

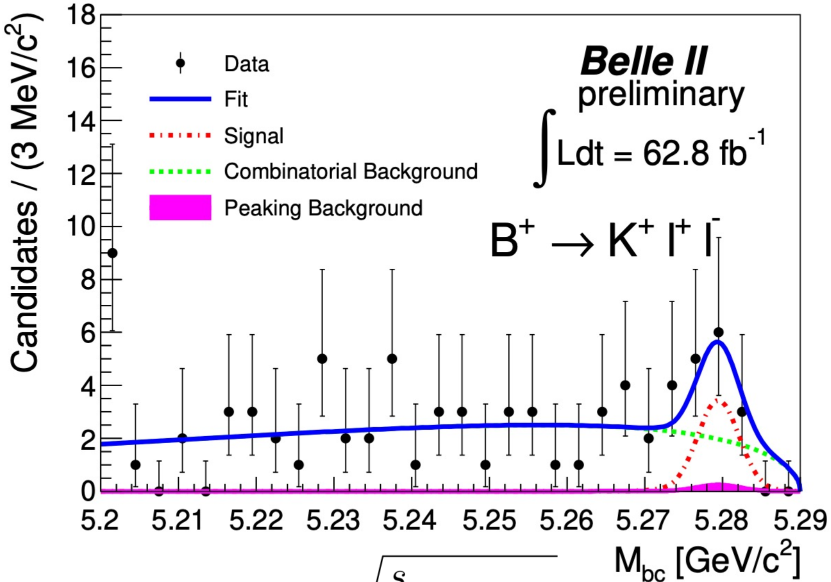
Preliminary Result of $B \to K\ell\ell$ at Belle II

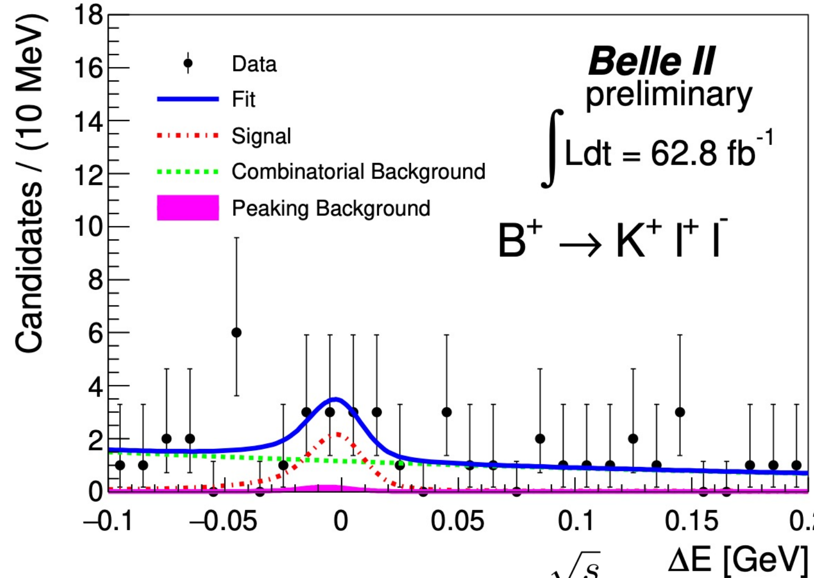
$B \to K\ell\ell$ is studied toward the $R(K)$ measurements at Belle II.

- Electron can be reconstructed at an equivalent efficiency to muon at Belle II with a high purity.
- Momentum can be measured in the same way both for electrons and muons.

Signal yield : $8.6^{+4.3}_{-3.9}{}_{\text{stat}} \pm 0.4_{\text{syst}}$

BELLE2-NOTE-PL-2021-005





$$M_{\rm bc} = \sqrt{\frac{s}{4} - (p_B^*)^2} \qquad \Delta E = E_B^* - \frac{\sqrt{s}}{2}$$

In progress

The measurement of $R(K^{(*)}) = \dfrac{\mathcal{B}(B \to K^{(*)}\mu^+\mu^-)}{\mathcal{B}(B \to K^{(*)}e^+e^-)}$ and $R(X_s) = \dfrac{\mathcal{B}(B \to X_s\mu^+\mu^-)}{\mathcal{B}(B \to X_s e^+e^-)}$

Not competitive to LHCb, but will be capable of independent check of the anomalies with $>$ 5-10 ab^{-1}

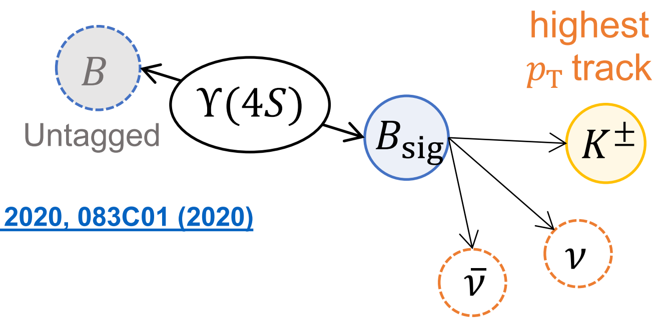
Search for $B^+ \to K^+\nu\bar{\nu}$ with an Inclusive Tagging Method

$b \to s\nu\bar{\nu}$ offers a complementary probe of new physics to explain the anomalies in $b \to s\ell\ell$.

$b \to s\nu\bar{\nu}$ decays are not observed yet.

SM : $\mathcal{B}(B^+ \to K^+\nu\bar{\nu}) = (4.6 \pm 0.5)\times 10^{-6}$
Upper limit: $\mathcal{B}(B^+ \to K^+\nu\bar{\nu}) < 1.6\times 10^{-5}$

arXiv:1409.4557
Prog. Theor. Exp. Phys. 2020, 083C01 (2020)



Belle II performed the search for $B^+ \to K^+\nu\bar{\nu}$ with an inclusive tagging method for the first time!

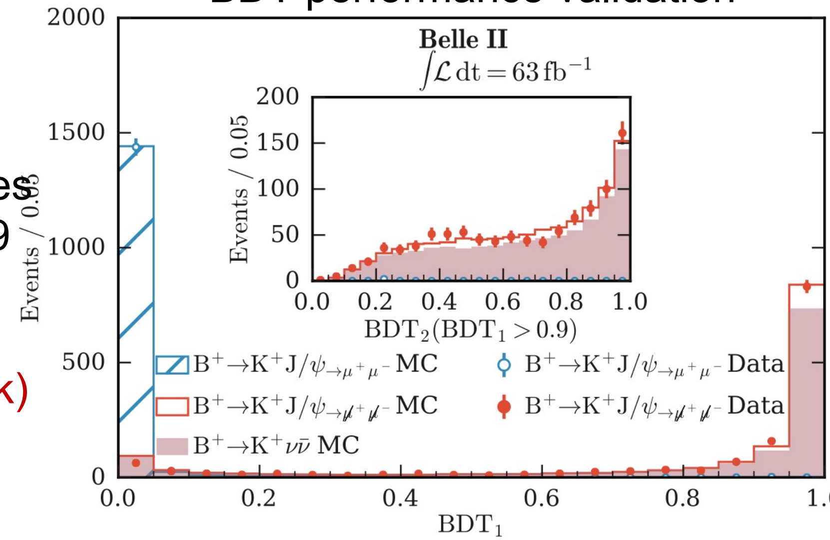
Phys. Rev. Lett. 127, 181802 (2021)

Train two BDTs in cascade to suppress backgrounds using event shape and rest-of-event information.

> BDT_1 … Discriminate signals mainly by topological features
> BDT_2 … Improve purity of signals in events with $\text{BDT}_1 > 0.9$
> → 35% increase at 4% signal efficiency

$B^+ \to K^+J/\psi \to K\cancel{\mu^+}\cancel{\mu^-}$: Signal-like events (with dimuon mask)
$B^+ \to K^+J/\psi \to K\mu^+\mu^-$: Background-like events

BDT performance validation

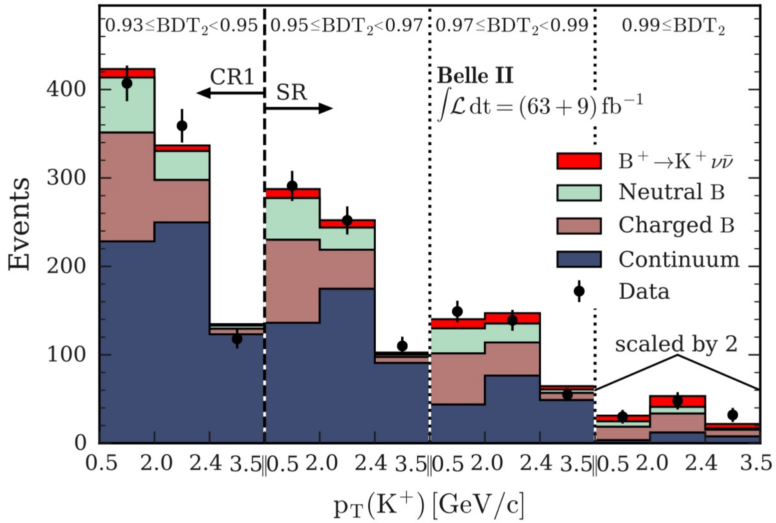


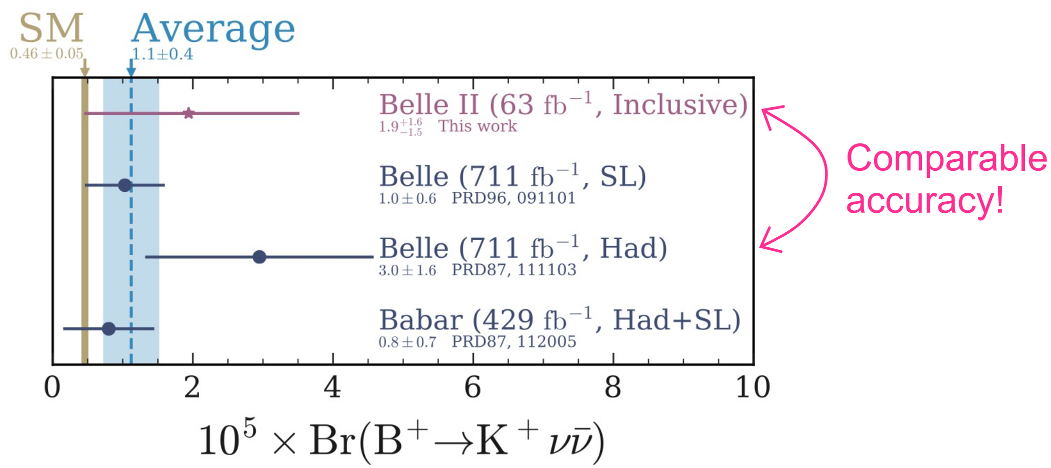
Search for $B^+ \to K^+\nu\bar{\nu}$ with an Inclusive Tagging Method

Observed branching fraction:

Phys. Rev. Lett. 127, 181802 (2021)

$$\mathcal{B}(B^+ \to K^+\nu\bar{\nu}) = \left(1.9\,^{+1.3}_{-1.3}{}_{\text{stat}}\,^{+0.8}_{-0.7}{}_{\text{syst}}\right)\times 10^{-6}$$





Observed (expected) upper limit on the branching fraction:

$$\mathcal{B}(B^+ \to K^+\nu\bar{\nu}) < 4.1\ (2.3)\times 10^{-5}\ (90\%\ \text{CL})$$

In progress

Update of the $B^+ \to K^+\nu\bar{\nu}$ analysis with more data,
Application of the inclusive tagging method e.g. to $B \to K^*\nu\bar{\nu}/K_S^0\nu\bar{\nu}$, $B^+ \to \tau^+\nu$

Competitive when the integrated luminosity is scaled to the previous results'!
20% and 350% improvement from the semileptonic and hadronic tagging method, respectively

Summary

Preliminary results are reported at early stage of Belle II with 34.6 or 62.8 fb-1 dataset for flavor physics studies with semileptonic decays and electroweak-penguin decays.

Semileptonic decays:

The analysis for $|V_{cb}|$ and $|V_{ub}|$ determination is ongoing.

Branching ratios of $B \to D^{(*)}\ell\nu$, $B \to \pi\ell\nu$, and $B \to \rho\ell\nu$ (exclusive) and $X_c\ell\nu$ (inclusive)

The inclusive and exclusive $|V_{cb}|$ and $|V_{ub}|$ tension will be addressed in the next years.

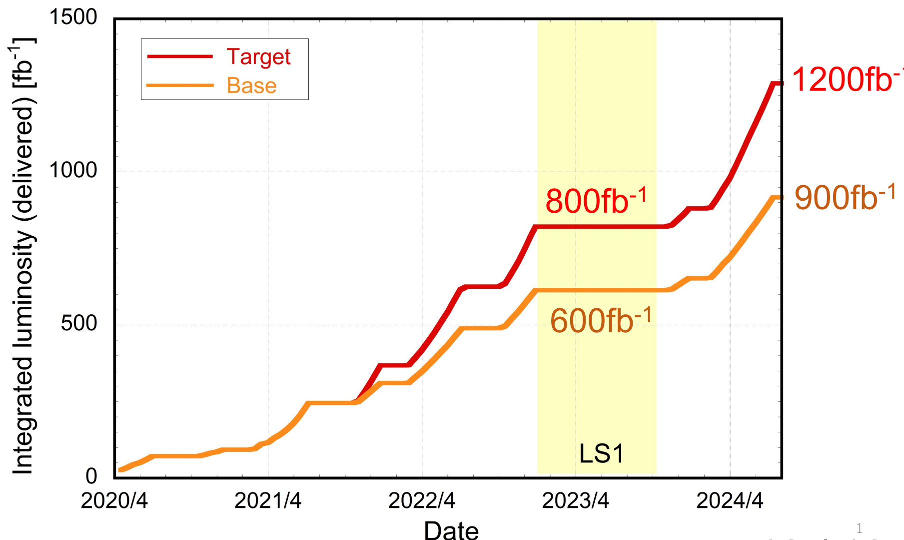
Electroweak penguin decays:

New inclusive tagged approach in $B^+ \to K^+\nu\bar{\nu}$ shows high capability of the analysis.

Observed (expected) upper limit: $\mathcal{B}(B^+ \to K^+\nu\bar{\nu}) < 4.1\ (2.3)\times 10^{-5}$ (90% CL)

Working on the measurement of $R(D^{(*)})$, $R(X)$, $R(K^{(*)})$ and $R(X_s)$ to test lepton flavor universality in SM at Belle II.

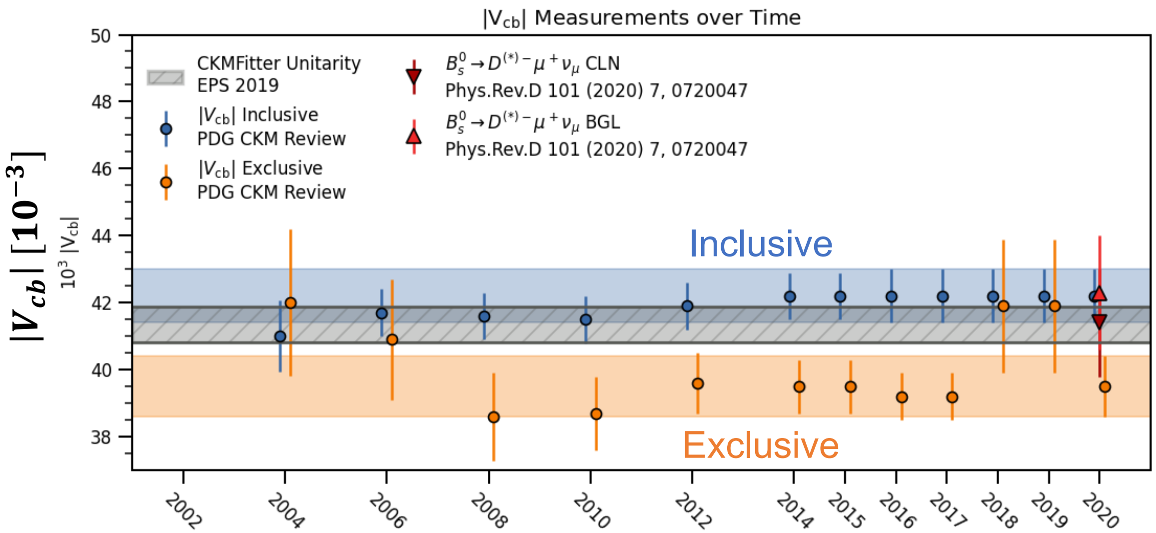
Aiming for $\sim 800\ \mathrm{fb}^{-1}$ by long shutdown in 2023 and $50\ \mathrm{ab}^{-1}$ over ~10 years.

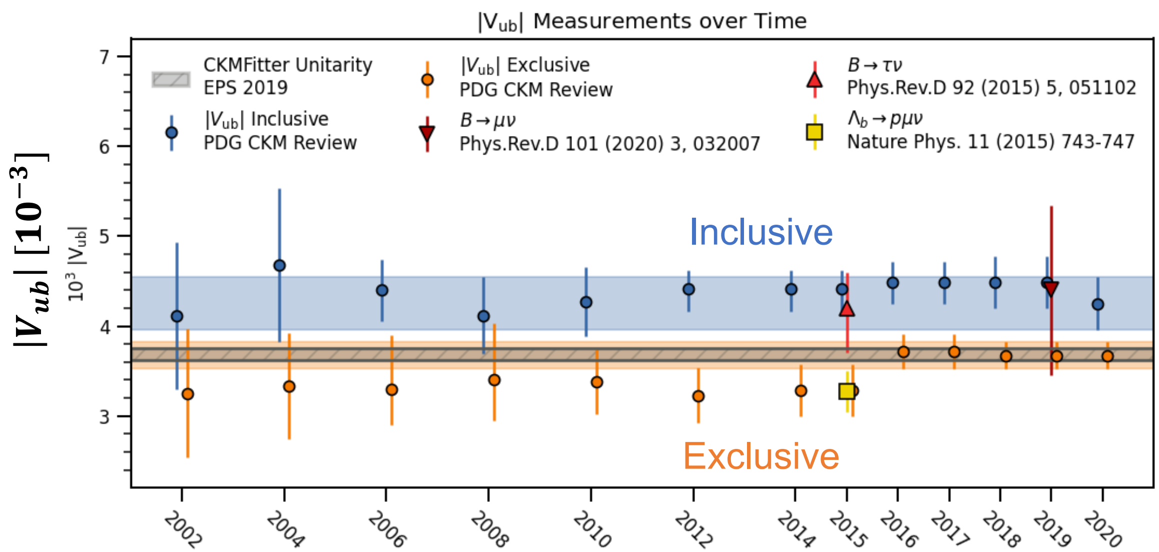


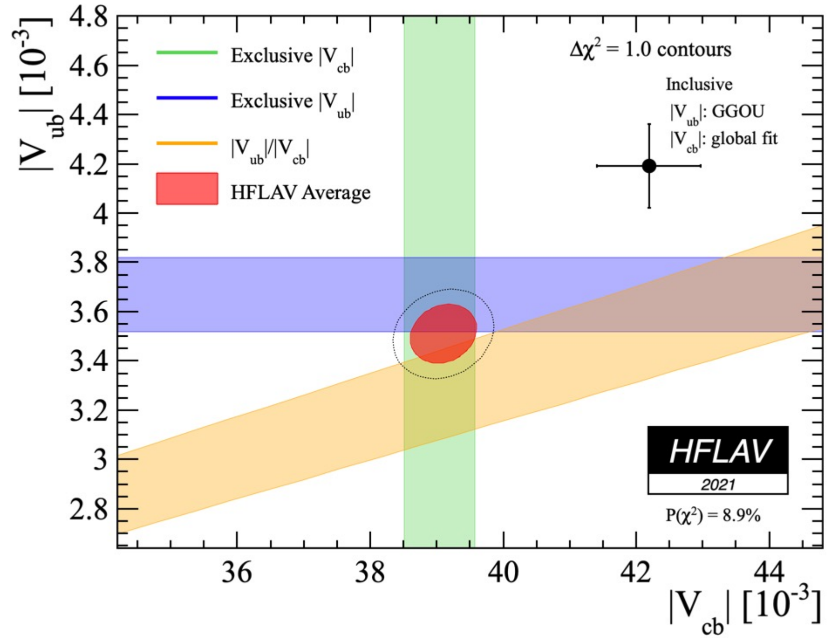
Appendix

$|V_{cb}|$ & $|V_{ub}|$ Puzzle

Long standing tensions ($\sim 3.3\sigma$) between inclusive and exclusive measurements of $|V_{cb}|/|V_{ub}|$



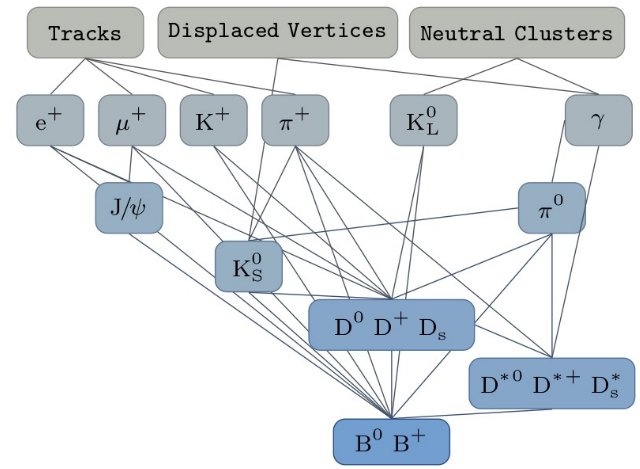




Full Event Interpretation

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

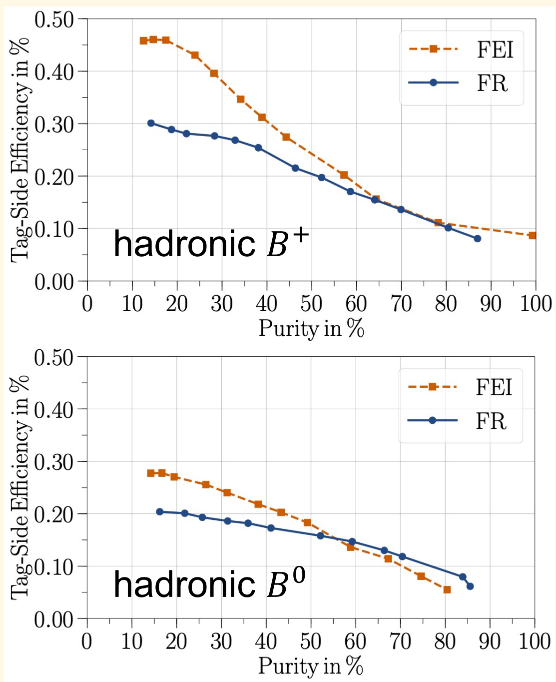
Multivariate algorithm for exclusive tagging of one B meson in a $\Upsilon(4S)$ decay using hierarchal approach with six stages of objects.



Over 100 B meson decay channels and over 10,000 decay cascades

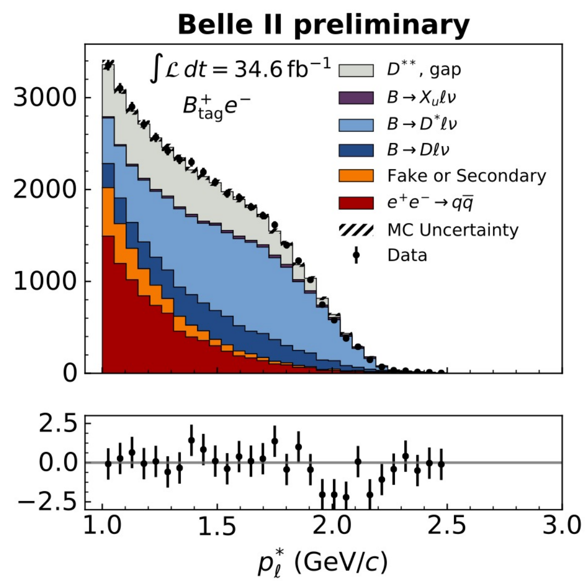
Tagging efficiency of B^+/B^0 at 10% purity in Belle MC

Tagging Algorithm	Hadronic	Semileptonic
Full Reconstruction	0.28%/0.18%	0.67%/0.63%
FEI	0.78%/0.46%	1.80%/2.04%



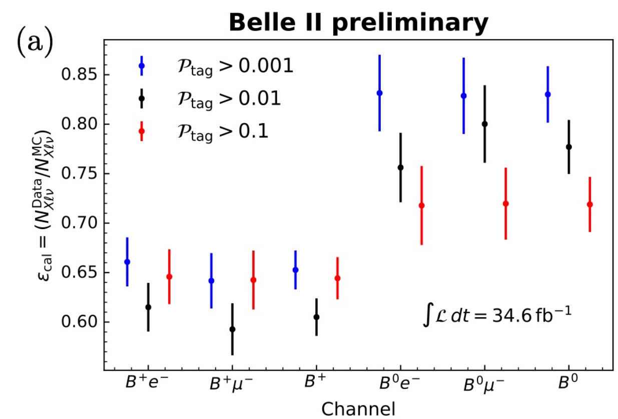
The performance calibration is made with $B \to X\ell\nu$

[arXiv:2008.06096]



$N_{X\ell\nu}$ is determined by the fit on p^*_ℓ distribution both in data and in MC.

→ The calibration factor $\epsilon_{\text{cal}} = N^{\text{data}}_{X\ell\nu}/N^{\text{MC}}_{X\ell\nu}$



FEI Tag Mode List

Hadronic tag	Reconstructing B meson through B^+/B^0modes and their daughter modes in the table
Semileptonic tag	Reconstructing B meson through $B \to D^{(*)}\ell\nu$ or $B \to D^{(*)}\pi\ell\nu$ with $D^{(*)}$ modes in the table

Same as Full Reconstruction method in Belle

B^+ modes	B^0 modes
$B^+ \to \bar{D}^0\pi^+$	$B^0 \to D^-\pi^+$
$B^+ \to \bar{D}^0\pi^+\pi^0$	$B^0 \to D^-\pi^+\pi^0$
$B^+ \to \bar{D}^0\pi^+\pi^0\pi^0$	$B^0 \to D^-\pi^+\pi^+\pi^-$
$B^+ \to \bar{D}^0\pi^+\pi^+\pi^-$	$B^0 \to D_s^+D^-$
$B^+ \to D_s^+\bar{D}^0$	$B^0 \to D^{*-}\pi^+$
$B^+ \to \bar{D}^{*0}\pi^+$	$B^0 \to D^{*-}\pi^+\pi^0$
$B^+ \to \bar{D}^{*0}\pi^+\pi^0$	$B^0 \to D^{*-}\pi^+\pi^+\pi^-$
$B^+ \to \bar{D}^{*0}\pi^+\pi^+\pi^-$	$B^0 \to D^{*-}\pi^+\pi^+\pi^-\pi^0$
$B^+ \to \bar{D}^{*0}\pi^+\pi^+\pi^-\pi^0$	$B^0 \to D_s^{*+}D^-$
$B^+ \to D_s^{*+}\bar{D}^0$	$B^0 \to D_s^+D^{*-}$
$B^+ \to D_s^+\bar{D}^{*0}$	$B^0 \to D_s^{*+}D^{*-}$
$B^+ \to \bar{D}^0K^+$	$B^0 \to J/\psi K_S^0$
$B^+ \to D^-\pi^+\pi^+$	$B^0 \to J/\psi K^+\pi^+$
$B^+ \to J/\psi K^+$	$B^0 \to J/\psi K_S^0\pi^+\pi^-$
$B^+ \to J/\psi K^+\pi^+\pi^-$	
$B^+ \to J/\psi K^+\pi^0$	

Newly added in FEI

B^+ modes	B^0 modes
$B^+ \to D^-\pi^+\pi^+\pi^0$	$B^0 \to D^-\pi^+\pi^0\pi^0$
$B^+ \to \bar{D}^0\pi^+\pi^+\pi^-\pi^0$	$B^0 \to D^-\pi^+\pi^+\pi^-\pi^0$
$B^+ \to \bar{D}^0D^+$	$B^0 \to \bar{D}^0\pi^+\pi^-$
$B^+ \to \bar{D}^0D^+K_S^0$	$B^0 \to D^-D^0K^+$
$B^+ \to \bar{D}^{*0}D^+K_S^0$	$B^0 \to D^-D^{*0}K^+$
$B^+ \to \bar{D}^0D^{*+}K_S^0$	$B^0 \to D^{*-}D^0K^+$
$B^+ \to \bar{D}^{*0}D^{*+}K_S^0$	$B^0 \to D^{*-}D^{*0}K^+$
$B^+ \to \bar{D}^0D^0K^+$	$B^0 \to D^-D^+K_S^0$
$B^+ \to \bar{D}^{*0}D^0K^+$	$B^0 \to D^{*-}D^+K_S^0$
$B^+ \to \bar{D}^0D^{*0}K^+$	$B^0 \to D^-D^{*+}K_S^0$
$B^+ \to \bar{D}^{*0}D^{*0}K^+$	$B^0 \to D^{*-}D^{*+}K_S^0$
$B^+ \to \bar{D}^{*0}\pi^+\pi^0\pi^0$	$B^0 \to D^{*-}\pi^+\pi^0\pi^0$

Same as Full Reconstruction method in Belle

D^+, D^{*+}, D_s^+ modes	D^0,D^{*0} modes
$D^+ \to K^-\pi^+\pi^+$	$D^0 \to K^-\pi^+$
$D^+ \to K^-\pi^+\pi^+\pi^0$	$D^0 \to K^-\pi^+\pi^0$
$D^+ \to K^-K^+\pi^+$	$D^0 \to K^-\pi^+\pi^+\pi^-$
$D^+ \to K^-K^+\pi^+\pi^0$	$D^0 \to \pi^-\pi^+$
$D^+ \to K_S^0\pi^+$	$D^0 \to \pi^-\pi^+\pi^0$
$D^+ \to K_S^0\pi^+\pi^0$	$D^0 \to K_S^0\pi^0$
$D^+ \to K_S^0\pi^+\pi^+\pi^-$	$D^0 \to K_S^0\pi^+\pi^-$
$D^{*+} \to D^0\pi^+$	$D^0 \to K_S^0\pi^+\pi^-\pi^0$
$D^{*+} \to D^+\pi^0$	$D^0 \to K^-K^+$
$D_s^+ \to K^+K_S^0$	$D^0 \to K^-K^+K_S^0$
$D_s^+ \to K^+\pi^+\pi^-$	$D^{*0} \to D^0\pi^0$
$D_s^+ \to K^+K^-\pi^+$	$D^{*0} \to D^0\gamma$
$D_s^+ \to K^+K^-\pi^+\pi^0$	
$D_s^+ \to K^+K_S^0\pi^+\pi^-$	
$D_s^+ \to K^-K_S^0\pi^+\pi^+$	
$D_s^+ \to K^+K^-\pi^+\pi^+\pi^-$	
$D_s^+ \to \pi^+\pi^+\pi^-$	
$D_s^{*+} \to D_s^+\pi^0$	

Newly added in FEI

D^+, D^{*+}, D_s^+ modes	D^0,D^{*0} modes
$D^+ \to \pi^+\pi^0$	$D^0 \to K^-\pi^+\pi^0\pi^0$
$D^+ \to \pi^+\pi^+\pi^-$	$D^0 \to K^-\pi^+\pi^+\pi^-\pi^0$
$D^+ \to \pi^+\pi^+\pi^-\pi^0$	$D^0 \to \pi^-\pi^+\pi^+\pi^-$
$D^+ \to K^+K_S^0K_S^0$	$D^0 \to \pi^-\pi^+\pi^0\pi^0$
$D^{*+} \to D^+\gamma$	$D^0 \to K^-K^+\pi^0$
$D_s^+ \to K_S^0\pi^+$	
$D_s^+ \to K_S^0\pi^+\pi^0$	
$D_s^{*+} \to D_s^+\pi^0$	

$R\left(D^{(*)}\right)$ Measurement with FEI at Belle

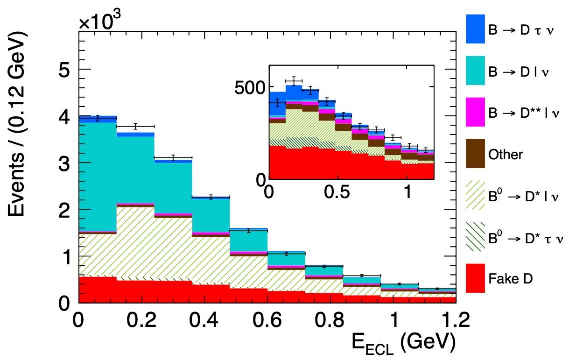
Measurement of $R(D^{(*)}) = \dfrac{\mathcal{B}(B \to \bar{D}^{(*)}\tau\nu)}{\mathcal{B}(B \to \bar{D}^{(*)}\ell\nu)}$, $(\ell = e,\ \mu)$ at Belle. Phys. Rev. Lett. 124, 161803 (2020)

with the semileptonic tag of $B \to D^{(*)}\ell\nu$ channels by Full Event Interpretation and leptonic τ decays.

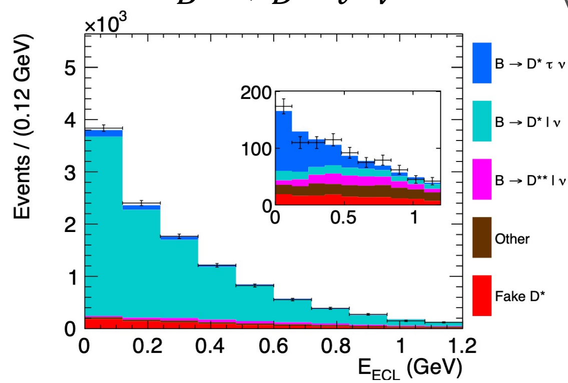
Extracted the yields of signal and normalization modes from a two-dimensional extended maximum likelihood fit to the variables E_{ECL} and $\mathcal{O}_{\mathrm{classfier}}$.

XGBoost with three input variables:
$\cos\theta_{B,D^{(*)}\ell}$,
the approximate missing mass squared
$m_{miss}^2 = \left(E_{e^+e^-} - E_{D^{(*)}} - E_\ell\right)^2 - \left(\vec{p}_{D^{(*)}} - \vec{p}_\ell\right)^2$,
and the visible energy $E_{vis} = \sum_i E_i$

$\bar{B}^0 \to D^+\ell^-\nu$



$\bar{B}^0 \to D^{*+}\ell^-\nu$

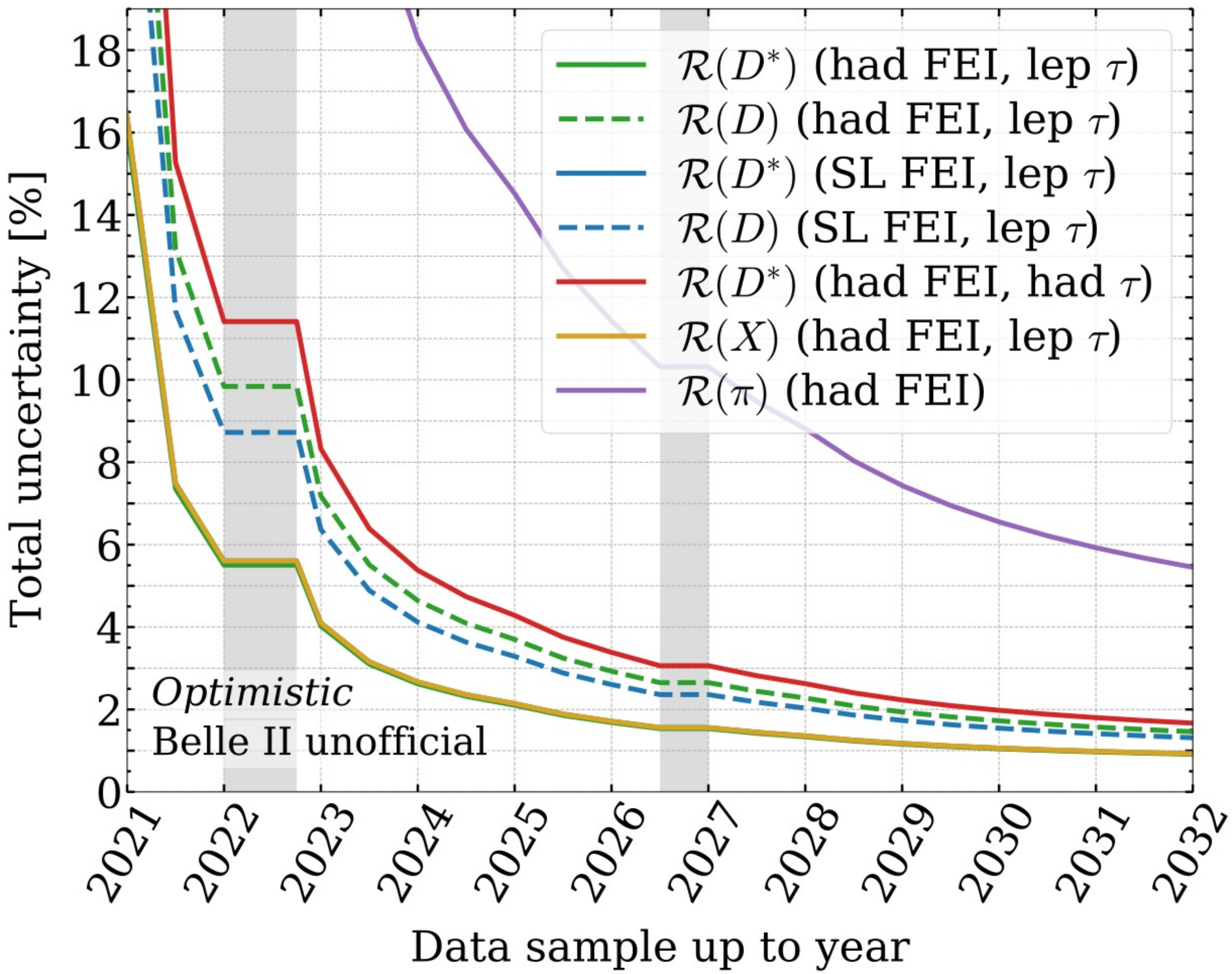


E_{ECL} (sum of extra energy not used for the reconstruction) distributions with $\mathcal{O}_{\mathrm{classfier}} > 0.9$

Observable	Measured	SM Prediction	Deviation	
$R(D^*)$	$\left(0.283 \pm 0.018_{\mathrm{stat}} \pm 0.014_{\mathrm{syst}}\right)\%$	$(0.258 \pm 0.003)\%$	1.1σ	0.8σ
$R(D)$	$\left(0.307 \pm 0.037_{\mathrm{stat}} \pm 0.016_{\mathrm{syst}}\right)\%$	$(0.299 \pm 0.003)\%$	0.2σ	

$R(D^{(*)})$ and $R(X)$ Projection [Unofficial]

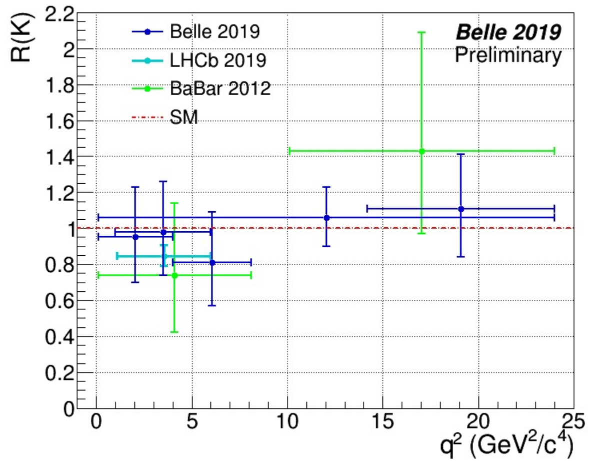
arXiv:2101.08326

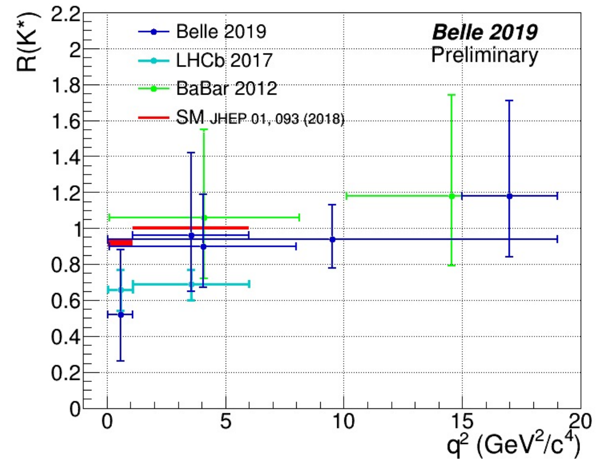


An irreducible systematic uncertainty of 0.5% for the optimistic one is assumed.
The optimistic scenario also assumes 50% increase in the reconstruction efficiency of the exclusive tagging algorithms.

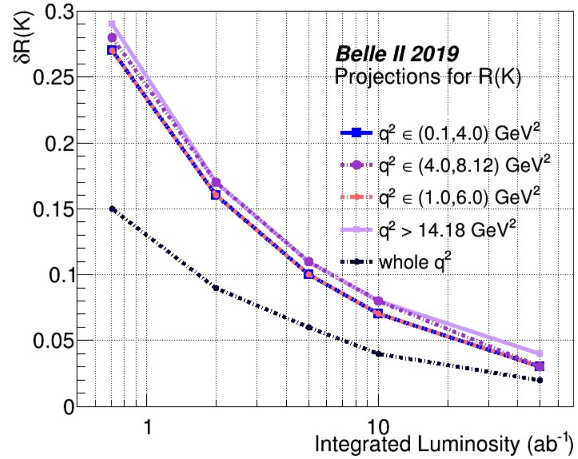
$R(K^{(*)})$ Status & Projection

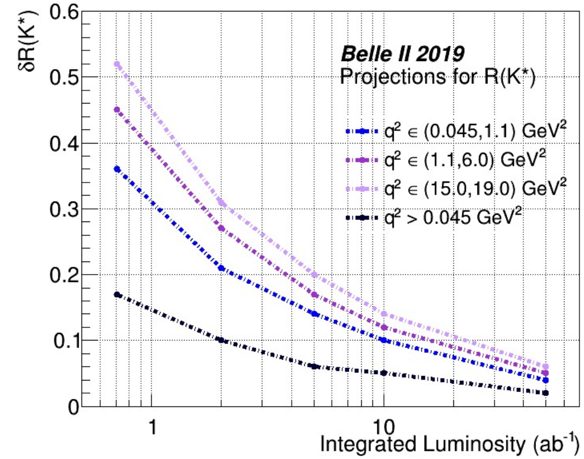
Status in 2019





Belle II Projection





LHCb Projection
arXiv:1808.08865

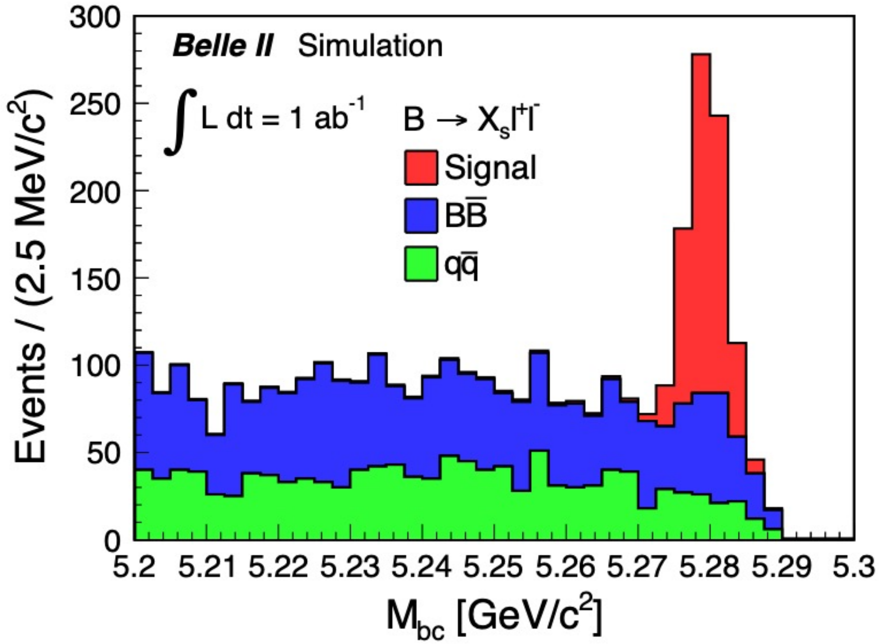
$1.1 < q^2 < 6.0\ \mathrm{GeV}^2/c^4$

R_X precision	Run 1 result	$9\,\mathrm{fb}^{-1}$	$23\,\mathrm{fb}^{-1}$	$50\,\mathrm{fb}^{-1}$	$300\,\mathrm{fb}^{-1}$
R_K	$0.745 \pm 0.090 \pm 0.036$ [274]	0.043	0.025	0.017	0.007
$R_{K^{*0}}$	$0.69 \pm 0.11 \pm 0.05$ [275]	0.052	0.031	0.020	0.008
R_ϕ	–	0.130	0.076	0.050	0.020
R_{pK}	–	0.105	0.061	0.041	0.016
R_π	–	0.302	0.176	0.117	0.047

$R(X_s)$ Projection

BELLE2-NOTE-PL-2020-007

$$R(X_s) = \frac{\mathcal{B}(B \to X_s \mu^+ \mu^-)}{\mathcal{B}(B \to X_s e^+ e^-)}$$



Observables	Belle $0.71\,\mathrm{ab}^{-1}$	Belle II $5\,\mathrm{ab}^{-1}$	Belle II $50\,\mathrm{ab}^{-1}$
R_{X_s} $([1.0, 6.0]\,\mathrm{GeV}^2)$	32%	12%	4.0%
R_{X_s} $(> 14.4\,\mathrm{GeV}^2)$	28%	11%	3.4%

New Physics Constraint by $B \to K^{(*)}\nu\nu$ Measurement

JHEP 2021, 050 (2021)

A spin-1 $SU(2)_L$ singlet leptoquark U_1 with one loop and Z' exchange at tree level can be considered as new physics contributions in the transition of $b \to s\nu\nu$.

Effective Lagrangian of $b \to s\nu\nu$:

$$\mathcal{L}_{b\to s\nu\bar{\nu}} = -\frac{4G_F}{\sqrt{2}} V_{ts}^* V_{tb} \mathcal{C}_\nu^{\alpha\beta} (\bar{s}_L\gamma_\mu b_L)(\bar{\nu}_L^\alpha \gamma^\mu \nu_L^\beta)$$

Due to the underlying $\mathrm{U}(2)^5$ flavor structure, NP effects are dominant in the Wilson coefficient involving the third family,

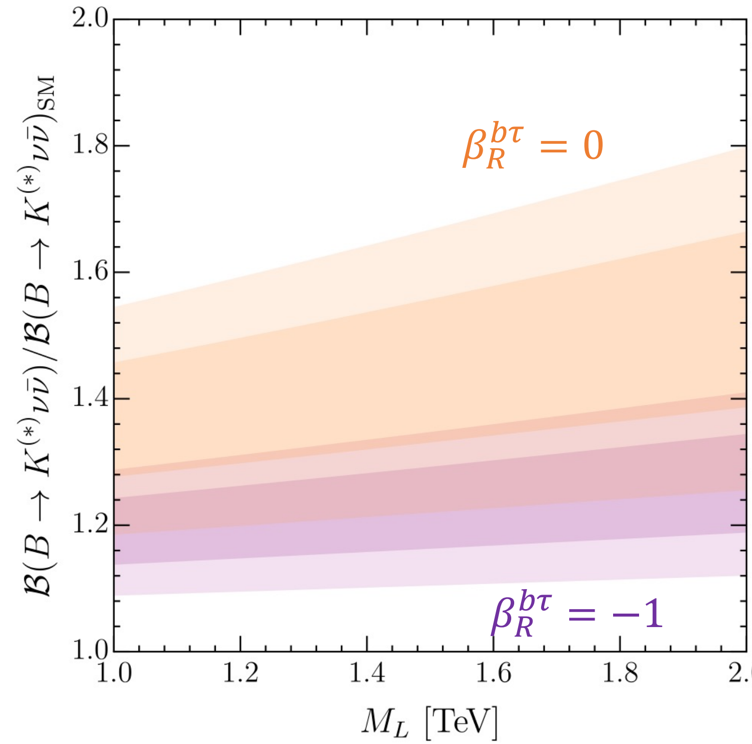
$$\mathcal{C}_{\nu,\mathrm{NP}}^{\tau\tau} = \mathcal{C}_{\nu,Z'}^{\tau\tau} + \mathcal{C}_{\nu,U}^{\tau\tau}\,.$$

The NP correction to the $B \to K^{(*)}\nu\bar{\nu}$ branching ratio:

$$\frac{\mathcal{B}(B\to K^{(*)}\nu\bar{\nu})}{\mathcal{B}(B\to K^{(*)}\nu\bar{\nu})_{\mathrm{SM}}} \approx \frac{2}{3} + \frac{1}{3}\left|\frac{\mathcal{C}_{\nu,\mathrm{NP}}^{\tau\tau} + \mathcal{C}_{\nu,\mathrm{SM}}}{\mathcal{C}_{\nu,\mathrm{SM}}}\right|^2$$

Current experimental limits:

$$\frac{\mathcal{B}(B\to K\nu\bar{\nu})}{\mathcal{B}(B\to K\nu\bar{\nu})_{\mathrm{SM}}} = 2.4 \pm 0.9, \frac{\mathcal{B}(B\to K^*\nu\bar{\nu})}{\mathcal{B}(B\to K^*\nu\bar{\nu})_{\mathrm{SM}}} < 3.2\ (95\%\ \mathrm{CL})$$



Mass of additional vector-like fermions with left-handed lepton quantum numbers that mix with the third and second generation left-handed leptons

$$\beta_L^{sL}\beta_L^{bL^*} \approx -\beta_L^{s\tau} \leftrightarrow \mathcal{C}_U \leftrightarrow \beta_R^{b\tau}; R(D^{(*)})$$

$\beta_R^{b\tau}$: the U_1 coupling to b and τ

Systematics on Untagged Exclusive $B \to D^{(*)}\ell\nu$

arXiv:2008.07198

Source	Relative uncertainty (%)	
	$\overline{B}^0 \to D^{*+}e^-\overline{\nu}_e$	$\overline{B}^0 \to D^{*+}\mu^-\overline{\nu}_\mu$
PDF shape uncertainties	0.7	0.6
$\mathcal{B}(\bar{B} \to D^{**}\ell\bar{\nu})$	0.1	< 0.1
Lepton-ID	0.4	1.9
MC statistics, efficiency	< 0.1	< 0.1
Tracking of K, π, ℓ	2.4	2.4
Tracking of π_s	9.9	9.9
N_{B^0}	2.0	2.0
Charm branching fractions	1.1	1.1
$\overline{B}^0 \to D^{*+}\ell^-\overline{\nu}_l$ Form Factors	1.1	1.1
Total	10.5	10.7

arXiv:2110.02648

Source	Relative uncertainty [%]	
	$B^- \to D^0e^-\overline{\nu}_e$	$B^- \to D^0\mu^-\overline{\nu}_\mu$
$N_{B^\pm}$	1.61	1.61
$\mathcal{B}(D^0 \to K^-\pi^+)$	0.78	0.78
Tracking	2.07	2.07
Lepton identification	1.41	2.38
MC efficiency (statistical)	0.09	0.09
$D\ell\nu$ form factor	0.15	0.15
$D^*\ell\nu$ form factor	0.44	0.44
Continuum shape	0.37	0.37
Sum	3.14	3.68

The uncertainties on $N_{B^{0/\pm}}$, lepton ID, tracking, continuum shape will be reducible by evaluation with more data.

- $N_{B^{0/\pm}}$: BELLE2-NOTE-PL-2019-017
- Lepton ID performance: BELLE2-CONF-PH-2021-002
- Tracking: BELLE2-NOTE-PL-2020-014

Systematics on Tagged Exclusive $B \to \pi\ell\nu/\rho\ell\nu$

arXiv:2111.00710

Source	% of $\mathcal{B}(B^0 \to \pi^- \ell^+ \nu_\ell)$	% of $\mathcal{B}(B^+ \to \pi^0 \ell^+ \nu_\ell)$	% of $\mathcal{B}(B^0 \to \rho^- \ell^+ \nu_\ell)$	% of $\mathcal{B}(B^+ \to \rho^0 \ell^+ \nu_\ell)$
FEI calibration	2.8	2.5	2.8	2.5
$N_{B\bar{B}}$		1.1		
f_{+0}		1.2		
Reconstruction efficiency ϵ	0.5	0.5	0.6	0.6
Tracking	1.4	0.7	1.4	2.1
Lepton ID	1.5	1.5	1.1	1.1
Pion ID	0.6	-	0.8	1.5
π^0 efficiency	-	4.4	4.4	—
Total	3.9	5.6	5.8	4.1

Source	% of $\Delta\mathcal{B}_i(B^0 \to \pi^- \ell^+ \nu_\ell)$		
	$0 \le q^2 < 8\mathrm{GeV}^2/c^4$	$8 \le q^2 < 16\mathrm{GeV}^2/c^4$	$16 \le q^2 \le 26.4\mathrm{GeV}^2/c^4$
f_{+0}		1.2	
FEI calibration		2.8	
$N_{B\bar{B}}$		1.1	
Tracking		1.4	
Recon. efficiency ϵ_i	0.8	0.8	0.9
Lepton ID	1.7	1.3	1.6
Pion ID	0.7	0.6	0.6
Total	4.0	3.9	4.0

For $B \to \pi\ell\nu$ decays, the systematic uncertainties from the modeling of $B \to X_u\ell\nu$ are expected to be small compared to other systematic uncertainties.

For $B \to \rho\ell\nu$ decays, the uncertainty on the non-resonant model cannot be quantified with the currently available dataset, but is expected to be small compared to the statistical uncertainties.

Additional systematic uncertainties on the efficiencies of various selection criteria are not included, as these are expected to be considerably small in comparison to other systematic effects.

Systematics on Untagged Inclusive $B \to X_c \ell \nu$

arXiv:2111.09405

Contribution	Relative uncertainty [%] Electron mode	Muon mode
Tracking	0.69	0.69
$N_{B\bar{B}}$	1.1	1.1
Lepton ID corrections	1.64	2.33
f_0/f_+, B lifetime	1.2	1.2
$B \to X_c \ell \nu_\ell$ branching fractions	2.65	2.15
$B \to X_c \ell \nu_\ell$ form factors	1.11	1.11
$B\bar{B}$ background model	0.24	0.34
Off-resonance data model	0.34	2.91
Sum	3.77	4.79

Each branching fraction of 30 separate decay mode in inclusive samples is varied by $\pm 1\sigma$ of the current average branching fraction at the fit. The full modeling uncertainty is calculated by adding the separate contributions in quadrature.

The form factor uncertainty is estimated by assuming the Caprini, Lellouch and Neubert (CLN) parameterization for the $B \to D^* \ell \nu$ and $B \to D \ell \nu$ decays and varying the form factor parameters within their ranges of uncertainty

Systematics on Tagged Exclusive $B \to D^{(*)}\ell\nu$

arXiv:2008.10299

Source	Relative uncertainty (%)
Tracking of π_s	10%
MC modeling	5%
FEI Calibration	3%
Tracking of K, π, ℓ	3%
N_{B^0}	2%
f_{+0}	1%
Charm branching fractions	1%
Lepton ID	1%
Total	12%

← MC sample size $100\ \mathrm{fb}^{-1}$

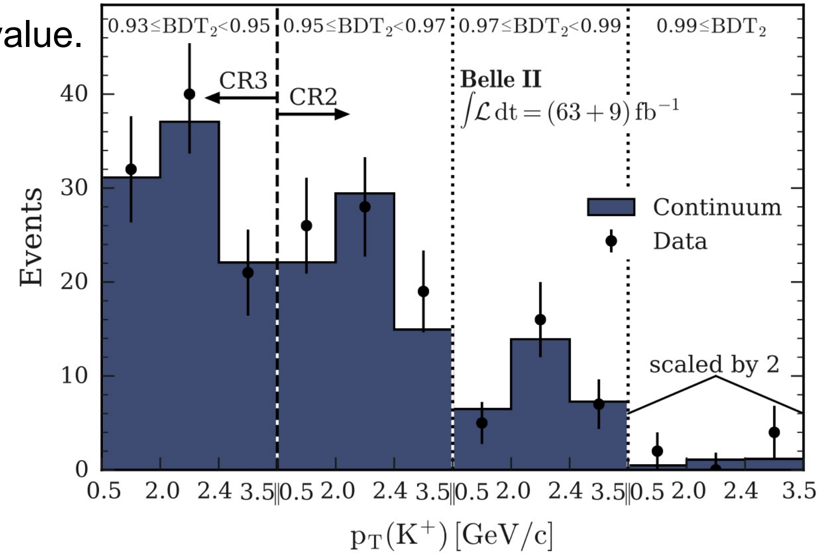
Systematics on $B^+ \to K^+\nu\nu$

Phys. Rev. Lett. 127, 181802 (2021)

The leading systematic uncertainty is the normalization uncertainty on the background yields.

- Each of background yields is constrained assuming a normal constraint, centered at the expected background yield obtained from simulation
- The background yields can be varied in the fit within a standard deviation corresponding to 50% of the central value.

a global normalization difference of $(40 \pm 12)\%$ between the off-resonance data and simulation in the control regions CR2 and CR3
+
the uncertainty on the sample luminosity



- The branching fractions of the leading B meson decays
- The PID correction
- The SM form factors

Three nuisance parameters each to model correlations between the individual SR and CR bins)

- The energy miscalibration of hadronic and beam-background calorimeter energy deposits
- The tracking inefficiency

One nuisance parameter each)

- The systematic uncertainty due to the limited size of simulated samples

One nuisance parameter per bin per background category

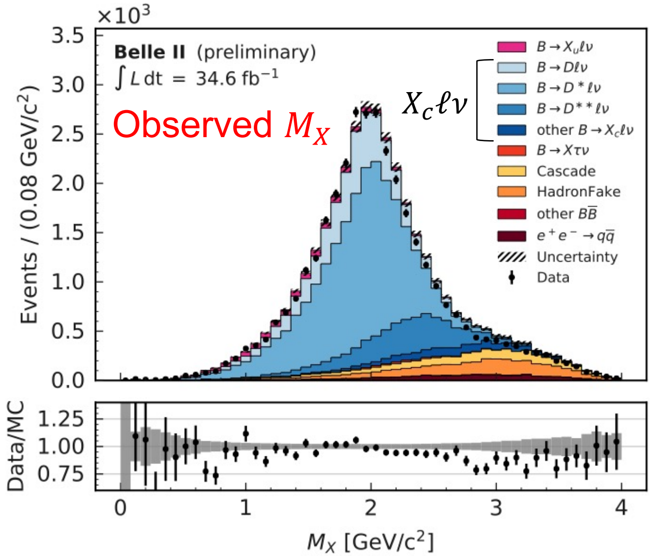
→ 175 nuisance parameters in total

Tagged Inclusive $|V_{cb}|$ Measurement: $B \to X_c \ell \nu$

[arXiv:2009.04493]

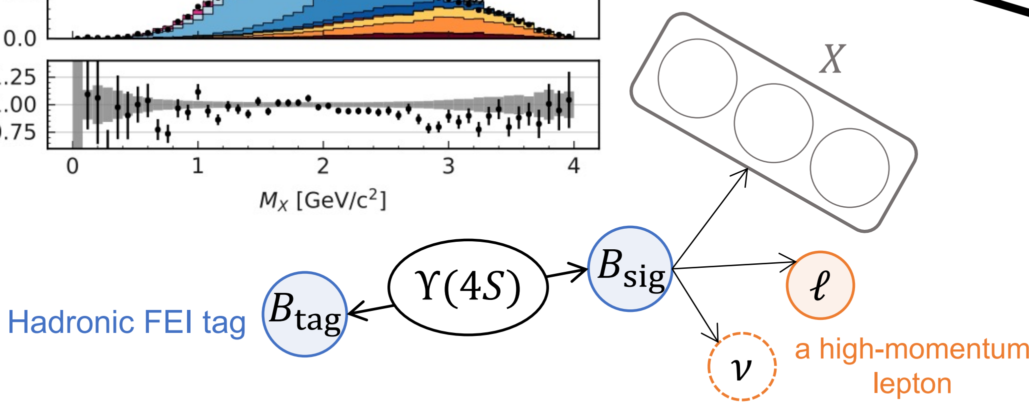
$|V_{cb}|$ is extracted using the branching fraction as well as spectral moments based on the Heavy Quark Expansion (HQE) up to $\mathcal{O}(1/m_b^3)$.

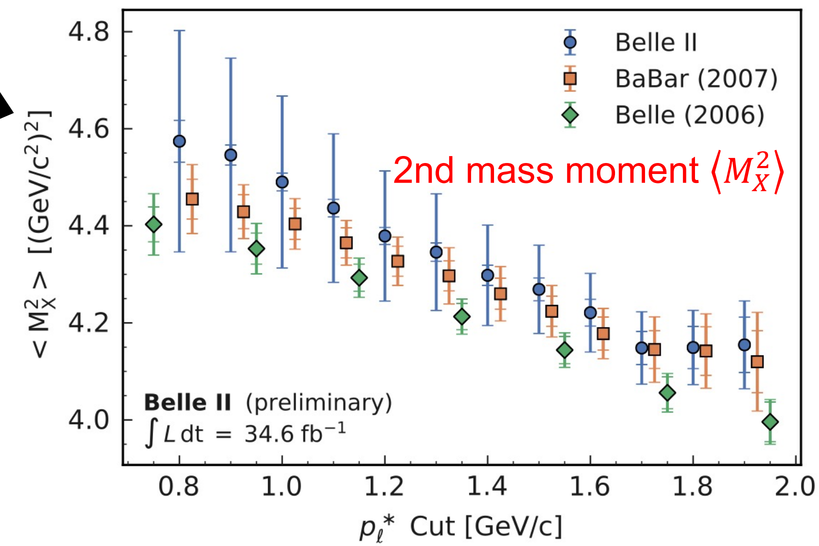
Measured the first six hadronic mass moments, $\langle M_X \rangle$ to $\langle M_X^6 \rangle$, with the hadronic FEI tag.



$$\langle M_X^n \rangle = \frac{\sum_i w_i(M_X) M_{X,\mathrm{calib}\,i}^{\;n}}{\sum_i w_i(M_X)} \times \mathcal{C}_{\mathrm{calib}} \times \mathcal{C}_{\mathrm{true}}$$

signal weight; Calibration bias; Reconstruction bias





In progress The analysis of leptonic invariant mass (q^2) spectrum

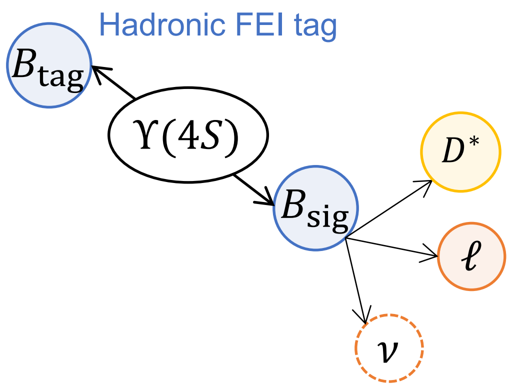
→ Fully data-driven $|V_{cb}|$ determination up to $\mathcal{O}(1/m_b^4)$ with a novel approach [JHEP02(2019)177].

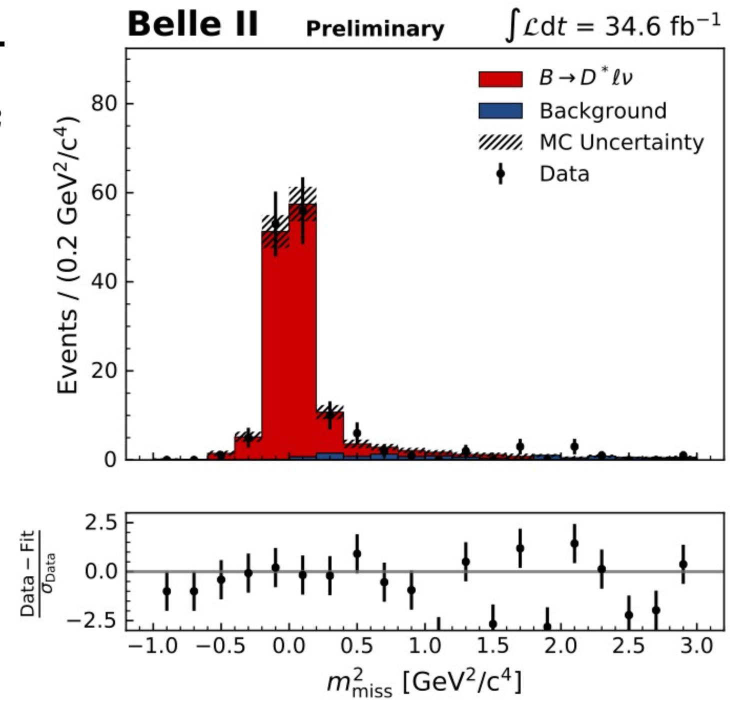
Tagged Exclusive $|V_{cb}|$ Measurements: $B \to D^* \ell \nu$

Measured branching fractions of $B \to D^* \ell \nu$.

[arXiv:2008.10299](https://arxiv.org/abs/2008.10299)

$$M^2_{\mathrm{miss}} = \left(p_{e^+e^-} - p_{B_{\mathrm{tag}}} - p_{D^*} - p_\ell\right)^2$$





$\mathcal{B}(\overline{B}^0 \to D^{*+} \ell^- \overline{\nu}_\ell)$	Measured	PDG Values
Had. FEI tagged	$(4.60 \pm 0.41_{\mathrm{stat}} \pm 0.27_{\mathrm{syst}} \pm 0.45_{\pi_{\mathrm{slow}}})\%$	$(5.05 \pm 0.14)\%$
Untagged	$(4.60 \pm 0.05_{\mathrm{stat}} \pm 0.17_{\mathrm{syst}} \pm 0.45_{\pi_{\mathrm{slow}}})\%$	

In progress $|V_{cb}|$ measurement from differential BR in bins of hadron recoil parameter w

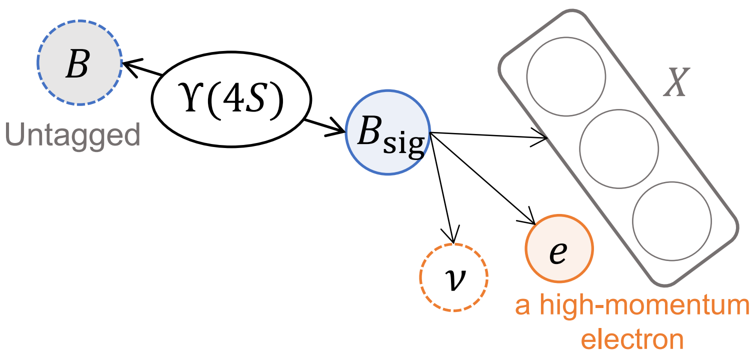
This analysis mode is used as a normalization mode of $R(D^{(*)}) = \dfrac{\mathcal{B}(B \to \bar{D}^{(*)} \tau \nu)}{\mathcal{B}(B \to \bar{D}^{(*)} \ell \nu)}, \ (\ell = e,\ \mu)$

Untagged Inclusive $|V_{ub}|$ Measurement: $B \to X_u e\nu$

arXiv:2103.02629

Challenging due to large background from $X_c \ell \nu$.
→ Exploit the endpoint of the electron momentum, p^*.

The $b \to c$ component becomes negligible above $2.4\ \mathrm{GeV}/c$.



Observed $B \to X_u e\nu$ excess at 3σ level.

In progress

Developing MVA
to distinguish $b \to u$ from $b \to c$ events
based on M_X and rest-of-event information

→ Capable of measuring $|V_{ub}|$ with more data.