Semileptonic B hadron decays

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On behalf of the Belle and Belle II Collaborations,
With results from LHCb collaboration
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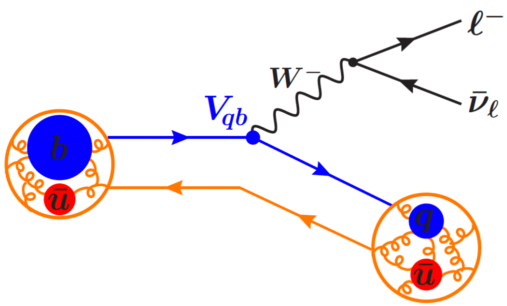
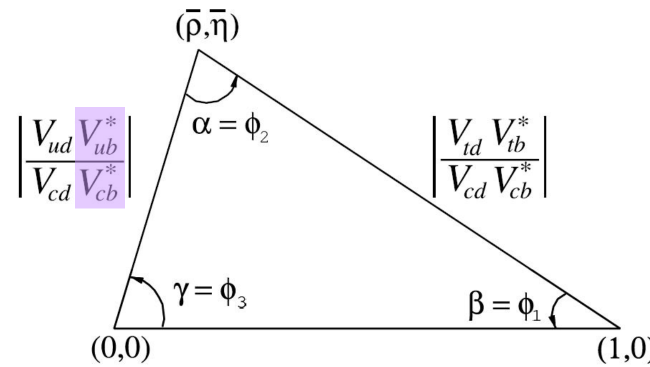
Motivation

- Decay of $B \to Xl\nu$: measure CKM matrix-elements $|V_{cb}|$ and $|V_{ub}|$
  - ✓ Test CKM unitarity triangle
  - ✓ Impact on the SM prediction of rate for rare Kaon decay: $K \to \pi\nu\bar{\nu}$

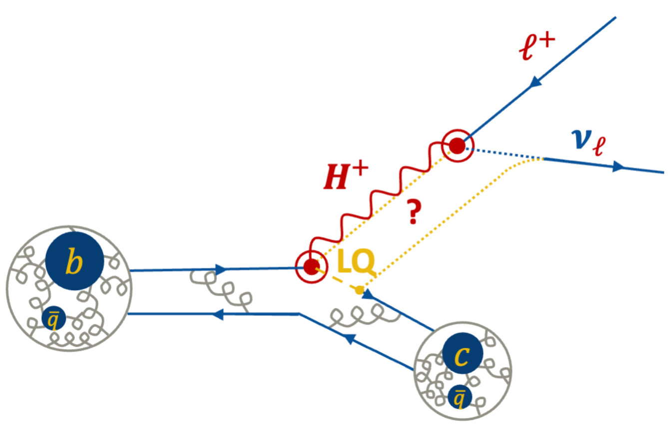


$$\begin{bmatrix} d' \\ s' \\ b' \end{bmatrix} = \begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix} \begin{bmatrix} d \\ s \\ b \end{bmatrix}$$



$$d\Gamma \propto G_F^2 |V_{qb}|^2 |L^\mu \langle X|\bar{q}\gamma_\mu P_L b\rangle|^2$$

- Probe the universality of the lepton couplings, $g_l(l = e, \mu, \tau)$, to the EW gauge boson
  - ✓ Lepton universality is challenged by several current measurements.
  - ✓ Deviation would be a clean sign of new physics (NP) beyond the standard model (SM)



$$R_{D^{(*)}} = \frac{\mathcal{B}(B \to D^{(*)}\tau\nu)}{\mathcal{B}(B \to D^{(*)}\ell\nu)}$$

$$R_{X_{e/\mu}} = \frac{\mathcal{B}(B \to Xe\nu)}{\mathcal{B}(B \to X\mu\nu)}$$

Outline of the talk

- Recent measurements of V_{cb} and V_{ub} from Belle & Belle II experiments
  - ✓ $|V_{cb}|$ measurements using $B \to Dl\nu$ [Belle & Belle II]
  - ✓ $|V_{cb}|$ measurements using $B \to X_c l\nu$ [Belle II]
  - ✓ $|V_{ub}|$ measurements using $B \to \pi l\nu$ [Belle II]
  - ✓ Simultaneous Determination of Inclusive and exclusive $|V_{ub}|$ [Belle]
  - ✓ Simultaneous Determinations of $|V_{ub}|$ and $|V_{cb}|$ [Belle, LHCb]

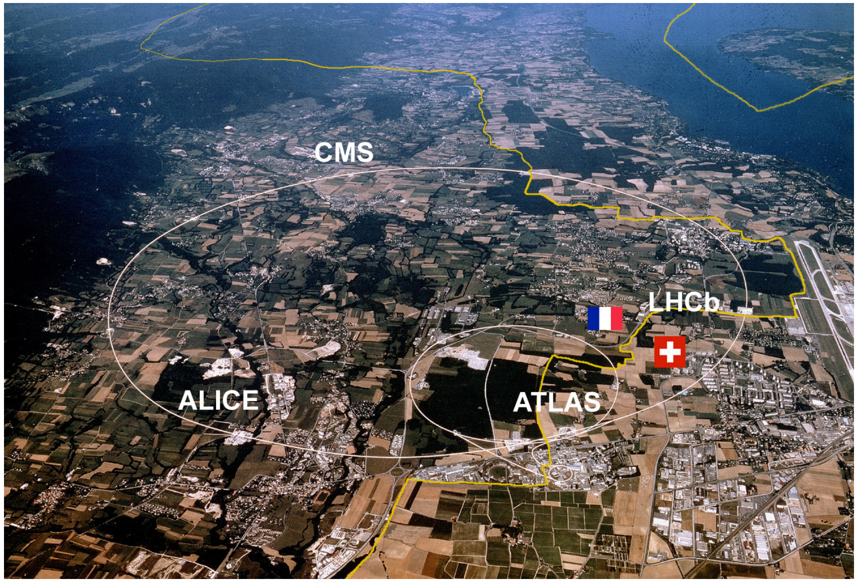
- Tests of lepton universality
  - ✓ Measurement of $R^{(*)}$ [LHCb, Belle II]
  - ✓ Muon-electron universality test in inclusive decays [Belle II]
  - ✓ Angular asymmetries in $B^0 \to D^{*+} l\nu$ [Belle II]

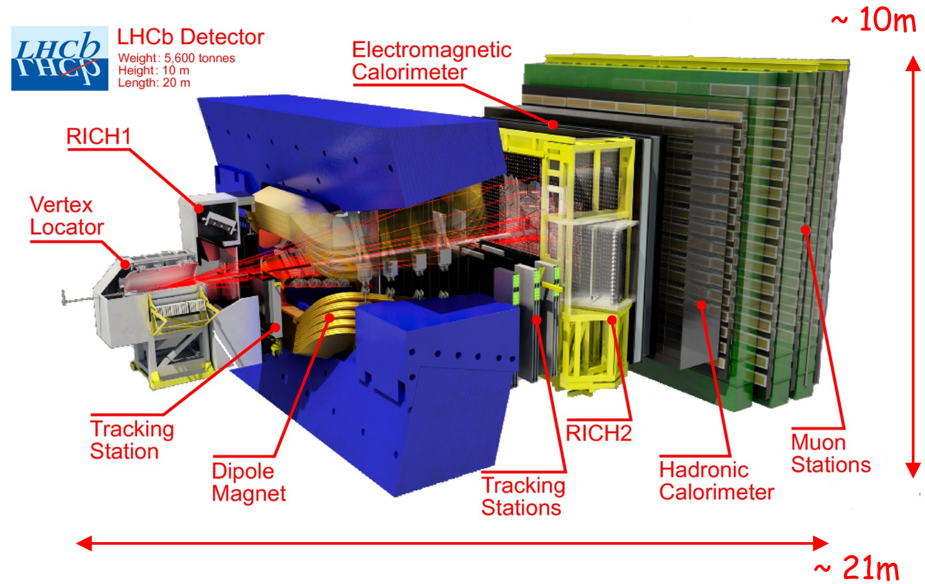
- Comparison to previous measurements and outlook in the future

- Only cover some selected recent semileptonic b-hadron decay results

- Will not cover many experimental analysis details
  - ✓ Some more details in parallel talk by: Kazuki Kojima

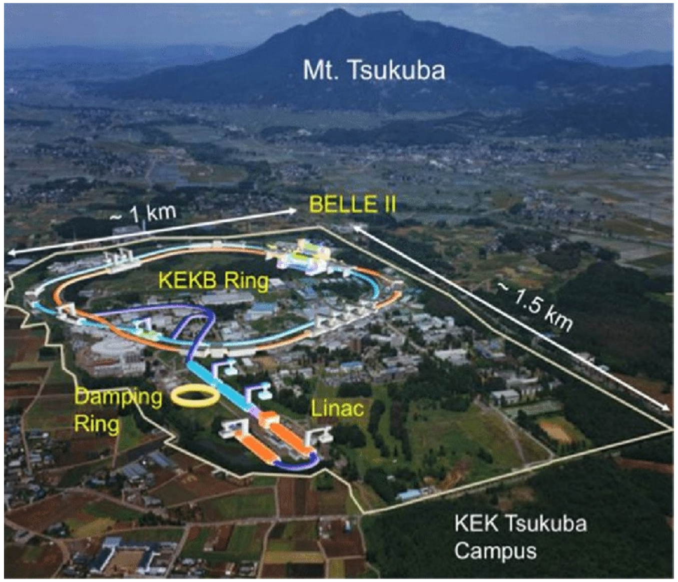
LHCb experiment

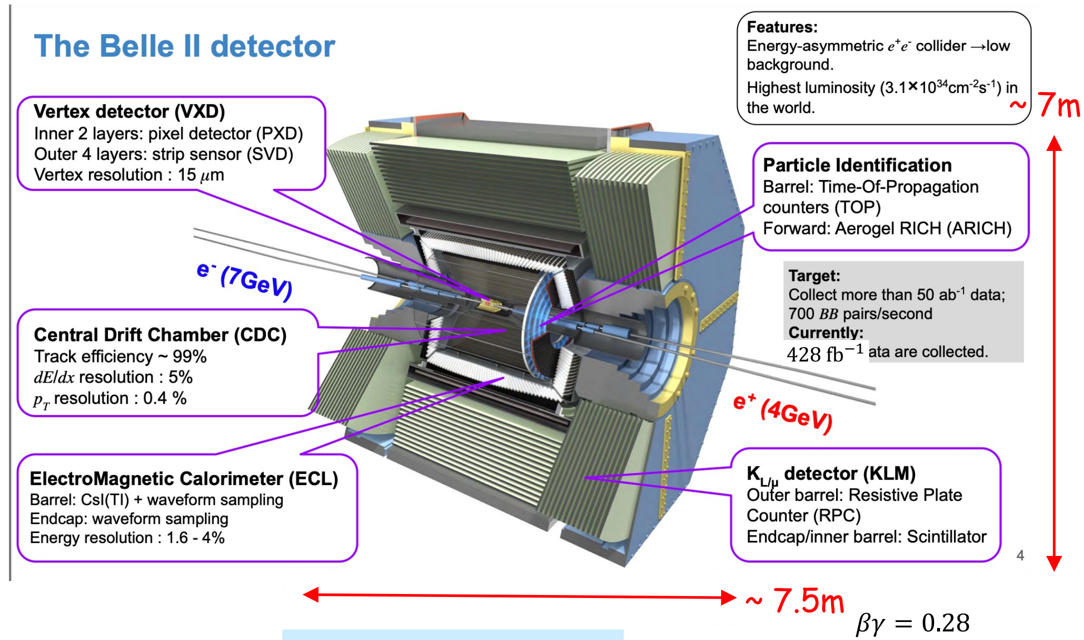




- Large $pp \to b\bar{b}X$ production cross section $\sim 72(144)\mu b$ at $7(13)$ TeV pp collisions
- Forward detector optimized for measurements of b and c-hadrons
  - ✓ Excellent vertex resolution and charged particle identification
  - ✓ High multiplicity event (high background) and neutral reconstruction is difficult
  - ✓ High precision measurement for selected final states
- $9\ \text{fb}^{-1}$ data accumulated during Run 1-2 (2010-2018)
  - ✓ Run 3 started in 2022 with an upgraded LHCb detector
  - ✓ Goal: $300\ \text{fb}^{-1}$ data by the end of HL-LHC

Belle and Belle II experiments





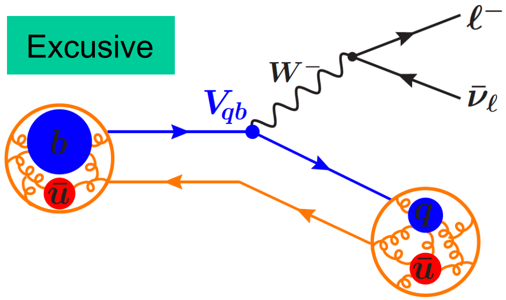
Belle II TDR: arXiv:1011.0352

- Asymmetric $e^+e^- \to \Upsilon(4S) \to B\bar{B}$ with production cross section $\sim 1.1nb$
  - ✓ Belle → Belle II: $e^+(3.5\text{ GeV})e^-(8\text{ GeV}) \to e^+(4\text{ GeV})e^-(7\text{ GeV})$
  - ✓ Belle II has smaller boost but improved vertex resolution
- Belle and Belle II are general purpose 4π detectors
  - ✓ Low background and inclusive trigger ($\sim 100\%$ efficiency for all final states)
  - ✓ Knowledge of initial state: stringent kinematic constraints for signal reconstruction
- Belle II collected $428\ \text{fb}^{-1}$ data so far with record peak luminosity $4.7\times10^{34}cm^{-2}s^{-1}$
  - ✓ Goal: 50 ab^{-1} data and peak luminosity at $6.5\times10^{35}cm^{-2}s^{-1}$

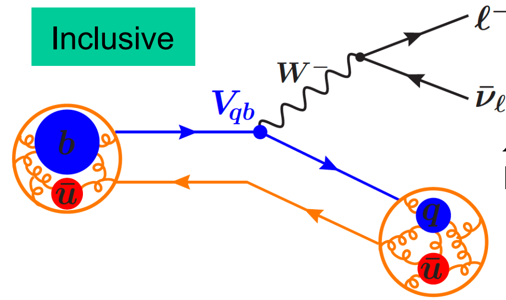
$|V_{cb}|$ and $|V_{ub}|$ Measurement

$|V_{cb}|$ and $|V_{ub}|$ Measurement

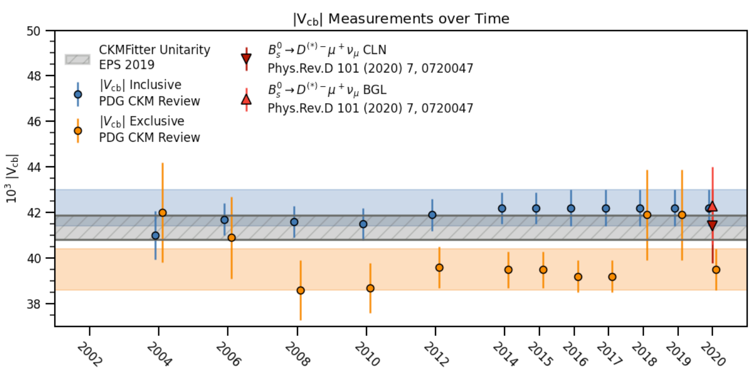
- Two approaches to measure $|V_{qb}|$ using decay $B \to (X_c/X_u)l\nu$
  - ✓ Use theory/lattice transform branch fraction or moments into $|V_{cb}|$ & $|V_{ub}|$
  - ✓ Different method based on how to reconstruct the neutrino (untagged/tagged)



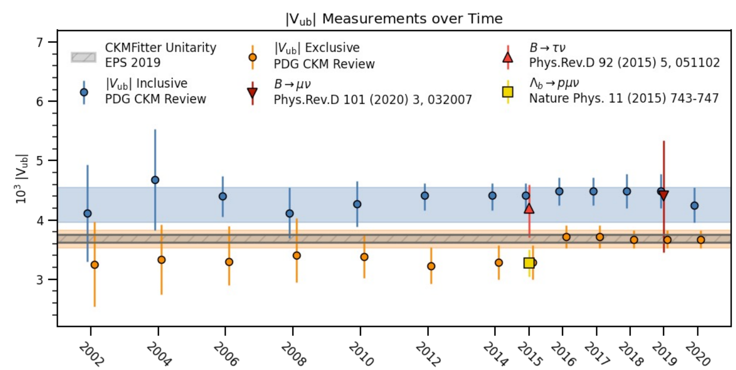
$X_c = D^{(*)}$
$X_u = \pi, \rho, \cdots$



X_c / X_u:
No explicit reconstruction



$|V_{cb}| = (39.10 \pm 0.50)\times 10^{-3}$ (exclusive)
$|V_{cb}| = (42.19 \pm 0.78)\times 10^{-3}$ (inclusive)



$|V_{ub}| = (3.51 \pm 0.12)\times 10^{-3}$ (exclusive)
$|V_{ub}| = (4.19 \pm 0.17)\times 10^{-3}$ (inclusive)

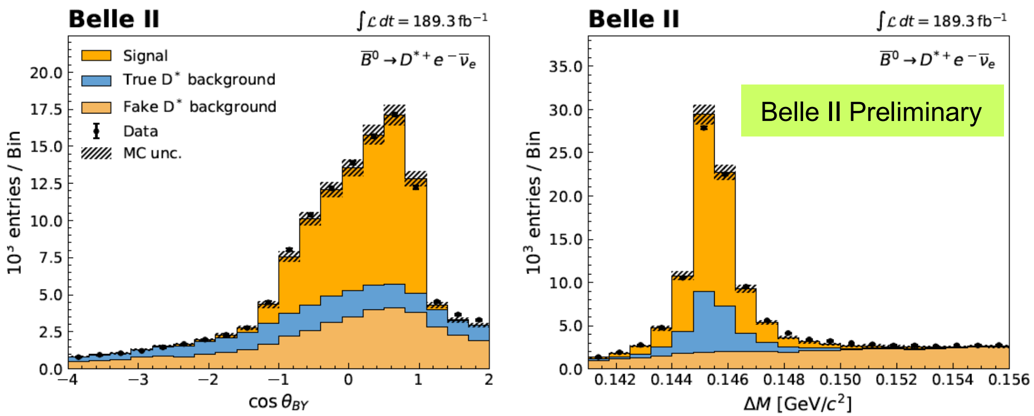
HFLAV: PRD107.052008 (2022) [arXiv:2206.07501]

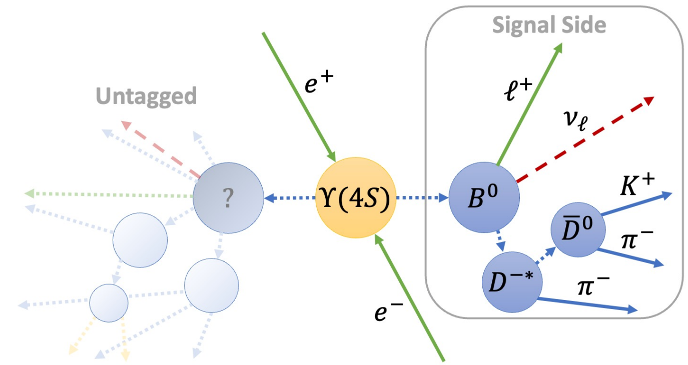
- Inclusive and exclusive Measurements of $|V_{cb}|/|V_{ub}|$ have 3 σ discrepancy
  - ✓ Small statistical uncertainty, comparable systematic and theory uncertainty

Exclusive $|V_{cb}|$ from $B^0 \to D^{*-} l^+ \nu$ (Untagged)

- Extract signal using cleanest Experimental mode

$$\cos\theta_{BY} = (2E_B E_Y - m_B^2 c^4 - m_Y^2) \,/\, 2p_B p_Y. \quad Y = D + l$$



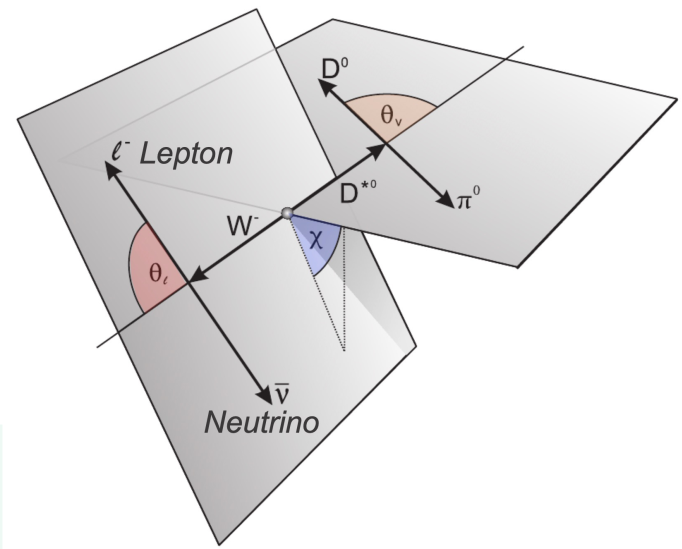


Recoiled parameter $w = \frac{m_B^2 + m_{D^*}^2 - q^2}{2 m_B m_{D^*}}$

- Extract signal using cleanest Experimental mode

$$\frac{d^4\Gamma}{dw\, d\cos\vartheta_l\, d\cos\vartheta_V\, d\chi} \propto |V_{cb}|^2 \times F^2(w, \cos\theta_l, \cos\theta_V, \chi)$$

3 form factors as functions of w parametrize the non-perturbative physics



- Need to know B_{sig} direction (neutrino reconstruction)
  - ✓ Inclusive information of the other untagged B
  - ✓ (Similar to missing momentum in hadron collider)
  - ✓ Constraint of $\cos\theta_{BY}$
  - ✓ Constraint of angular distribution of $\Upsilon(4S) \to B\bar{B}$ w.r.t. the beam axis

Exclusive $|V_{cb}|$ from $B^0 \to D^{*-} l^+ \nu$ (Untagged)

- Belle II Results: $189.3\ \mathrm{fb}^{-1}$ Belle II Preliminary

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

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

LQCD input used for
Normalization at zero recoil
FNAL/MILC PRD 89,114504 (2014)

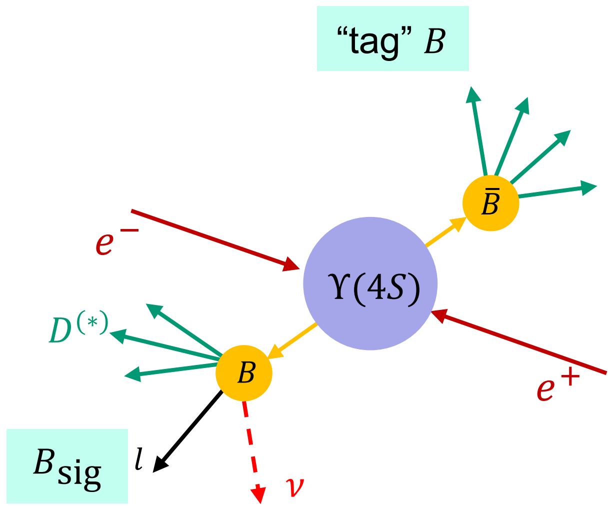
- Consistent with exclusive and inclusive world average
  - ✓ Not conclusive statement due to large experimental uncertainty

- Experimental systematic uncertainty can be significantly reduced
  - ✓ Detector related: data driven
  - ✓ External inputs: more difficult but feasible, need more data and additional measurements

TABLE VI. Composition of the relative uncertainties (in percent) for the CLN form factors in a combined fit of the $\overline{B}^0 \to D^{*+}\ell^-\bar{\nu}_\ell$ decay. The uncertainties originating from tracking efficiency, the number of B^0 mesons, the B^0 lifetime, and the charm branching fractions only affect the overall normalization but do not contribute to the parameters related to the shape.

	ρ^2	$R_1(1)$	$R_2(1)$	$\lvert V_{cb}\rvert$
Statistical	2.8	3.7	2.9	0.6
Finite MC samples	2.5	3.3	2.4	0.6
Signal modelling	2.7	3.2	2.1	0.4
Background subtraction	1.5	1.3	1.4	0.3
Lepton ID efficiency	0.2	1.5	0.3	0.3
Slow pion efficiency	1.1	0.6	0.8	1.5
Tracking of K, π, ℓ	-	-	-	0.5
$N_{B\overline{B}}$	-	-	-	0.8
$f_{+-}/f00$	-	-	-	1.3
$\mathcal{B}(D^{*+} \to D^0\pi^+)$	-	-	-	0.4
$\mathcal{B}(D^0 \to K^-\pi^+)$	-	-	-	0.4
B^0 lifetime	-	-	-	0.1
Total	5.0	6.2	4.7	2.5

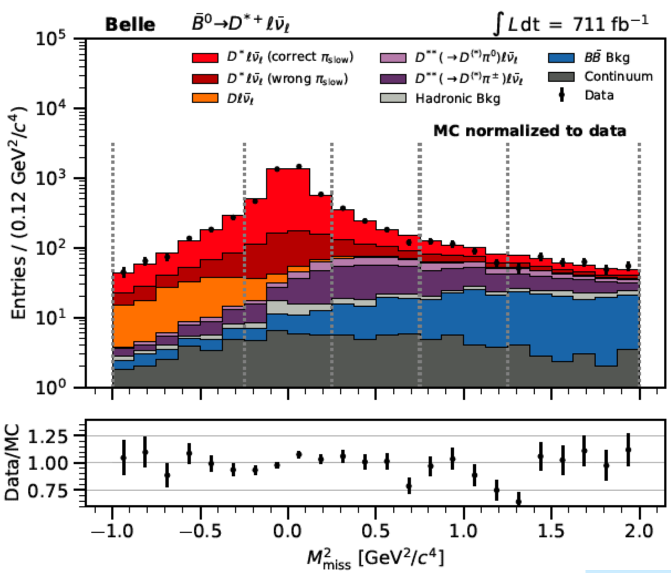
Exclusive $|V_{cb}|$ from $B^0 \to D^{*-} l^+ \nu$ (Tagged)

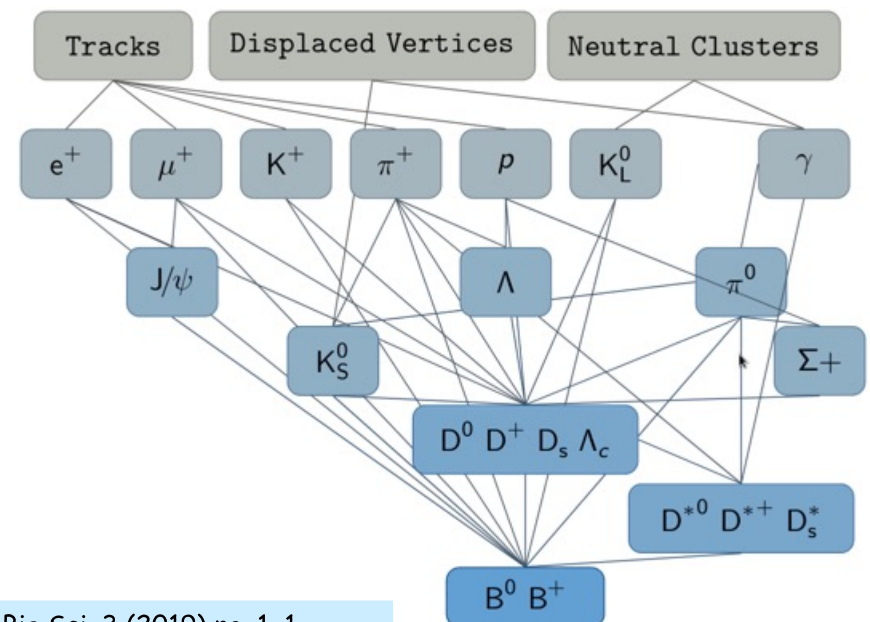


- Fully reconstruct "tag" B:

$$\vec{p}_\nu = \vec{p}_{miss} = \vec{p}_{e^+e^-} - \vec{p}_{tag} - \vec{p}_{D^{(*)}} - \vec{p}_l$$

- Better measurement of B_{sig} Kinematic variables
- Small tag efficiency but significantly reduce background
- Full-Event-Interpretation (FEI) at Belle II
  - ✓ Multivariate classification using BDT
  - ✓ 50% tag efficiency improvement vs Belle





$$M^2_{miss} = p^2_{miss}$$

Comput. Softw. Big Sci. 3 (2019) no. 1, 1, [arXiv:1807.08680] & Belle II, arXiv: 2008.06096

Exclusive $|V_{cb}|$ from $B^0 \to D^{*-} l^+ \nu$ (Tagged)

- Belle II Results: 189.3 fb^{-1}

  $$|V_{cb}|_{\text{CLN}} = (37.9 \pm 2.0^{\text{stat}} \pm 1.9^{\text{syst}} \pm 0.5^{\text{theo}}) \times 10^{-3}$$

  Belle II, arXiv: 2301.04716

- Belle Result: 711 fb^{-1}
  - ✓ Analyze the data using FEI developed at Belle II

  $$|V_{cb}|_{\text{CLN}} = (40.6 \pm 0.9^{\text{exp}}) \times 10^{-3}$$
  $$|V_{cb}|_{\text{BGL}} = (40.1 \pm 0.9^{\text{exp}}) \times 10^{-3}$$

  Belle, arXiv: 2301.07529

- Consistent with exclusive world average
  - ✓ Belle central value shift up slightly
  - ✓ Slightly reduce the tension between Exclusive and inclusive V_{cb} measurements

- Belle II Experimental statistical and systematic uncertainty can be significantly reduced with more data

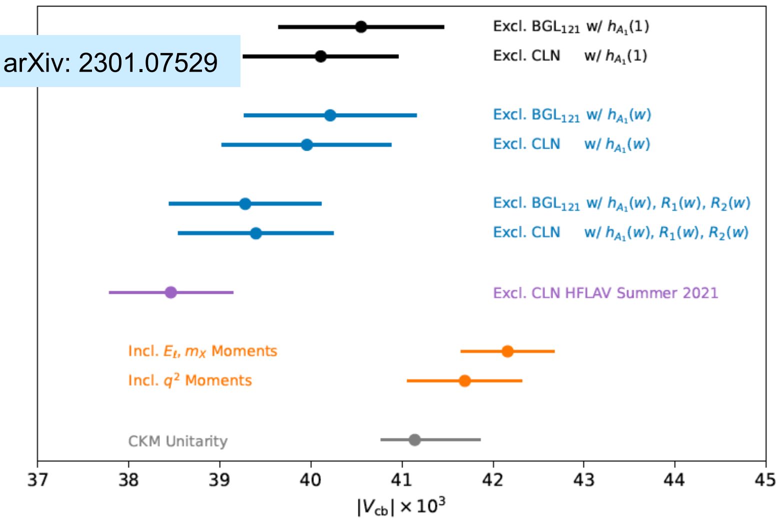
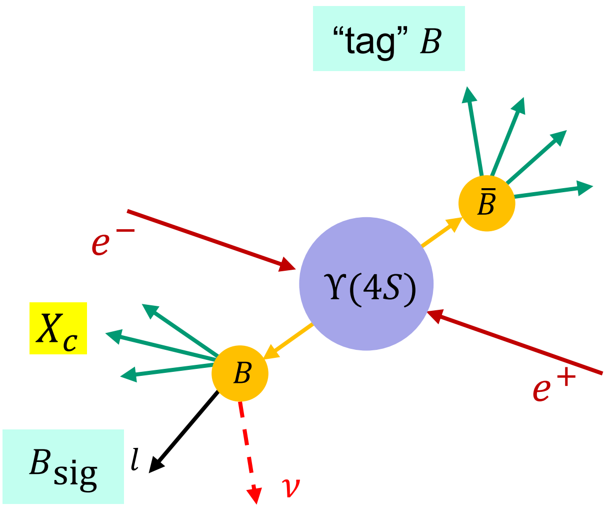


FIG. 11. Our extracted $|V_{cb}|$ values using the lattice input from Ref. [17] (black) and Ref. [16] (blue), together with the latest exclusive HFLAV average [43] (purple), determinations from inclusive approaches [8, 9] (orange), and from CKM unitarity (grey).

Inclusive $|V_{cb}|$ from $B \to X_c l\nu$ (Tagged)



- No explicit reconstruction of $D^{(*)}$ in the event
- All remaining particles in the event added to X_c
- Measurement dominated by theory uncertainty
- Theory uncertainty can be reduced with measurements of lepton mass squared moments

$$q^2 = (p_l + p_\nu)^2 = (p_B - p_{X_c})^2$$

$$\vec{p}_\nu = \vec{p}_{miss} = \vec{p}_{e^+e^-} - \vec{p}_{tag} - \vec{p}_{X_c} - \vec{p}_l$$

- A kinematic fit to improve moment measurement
- Belle II inclusive $|V_{cb}|$ extraction not available yet
  - ✓ Interpretation with Belle result by some physicists

F.Bernlocher, et.al, JHEP10(2022)068
Belle PRD104,112011(2021)

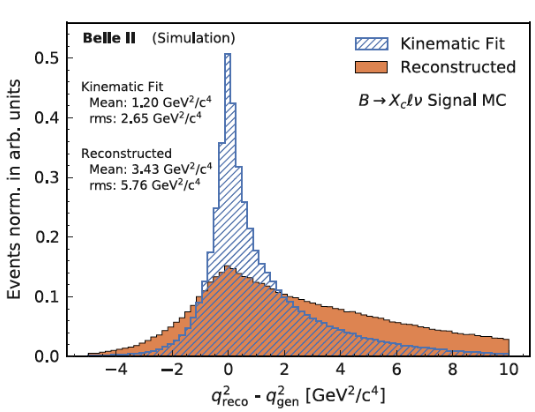
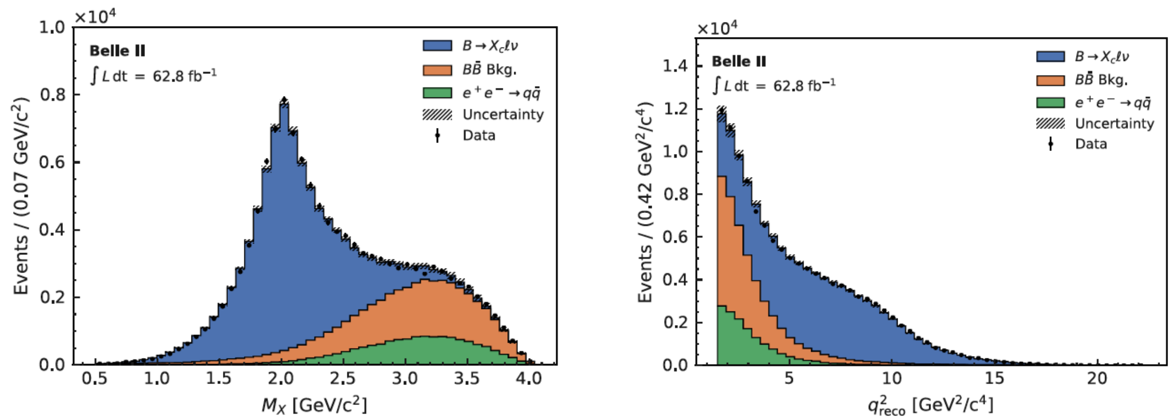
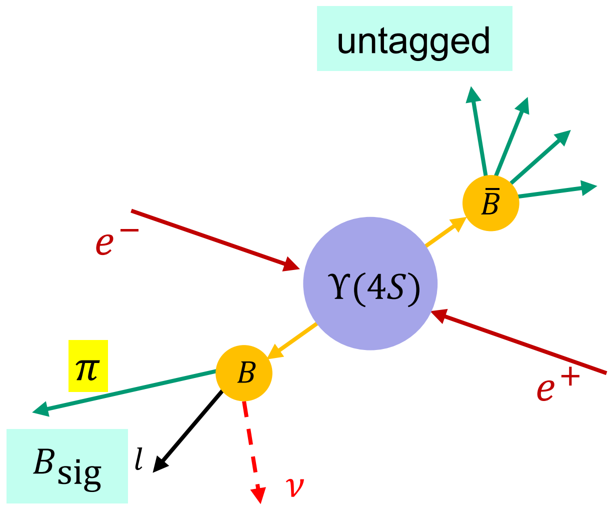


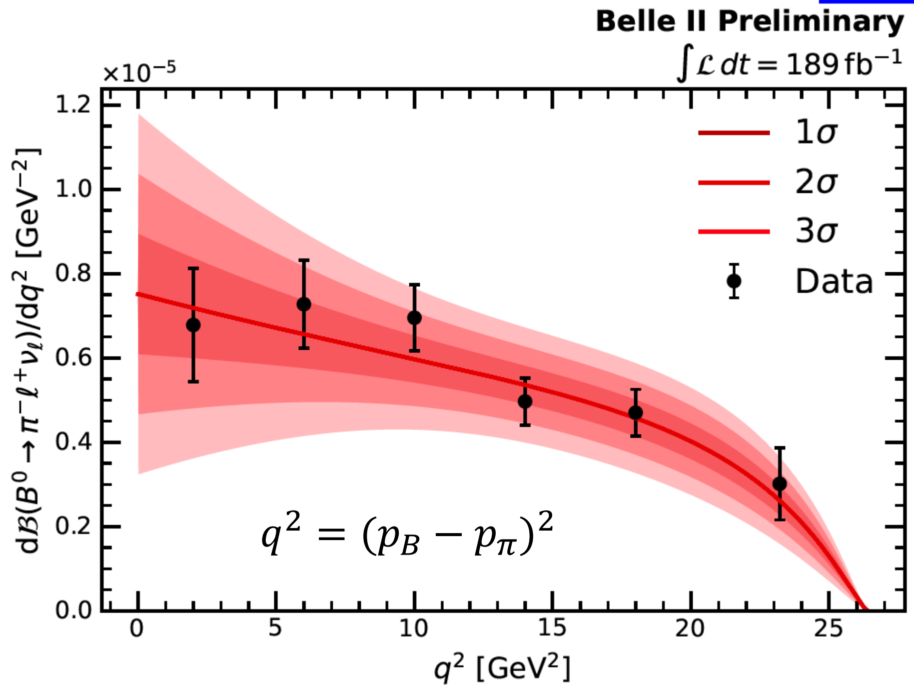
FIG. 3. Comparison of reconstructed, fitted, and generated q^2 for $B \to X_c \ell \bar{\nu}_\ell$. The residuals are the difference of estimated ("reco") and generated ("gen") values.



Belle II, PRD107,072002(2023) [arXiv: 2301.04716]

Exclusive $|V_{ub}|$ from $B^0 \to \pi l \nu$ (Untagged)





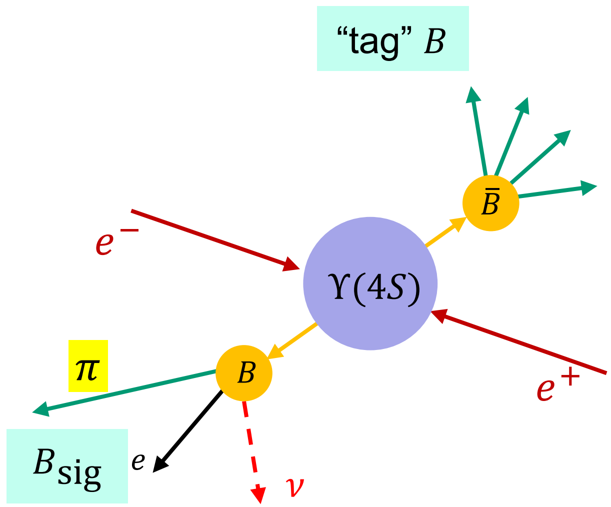
- Similar analysis technique as untagged $B \to D^{(*)} l \nu$
  - ✓ Significant background from $B \to X_c l \nu$
- Extract V_{ub} using measured differential decay rate as a function of $q^2 = (p_B - p_\pi)^2$

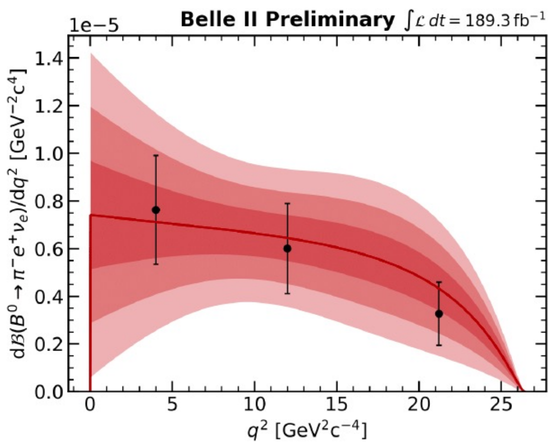
$$|V_{ub}| = (3.55 \pm 0.12^{\text{stat}} \pm 0.13^{\text{syst}} \pm 0.17^{\text{theo}}) \times 10^{-4}$$

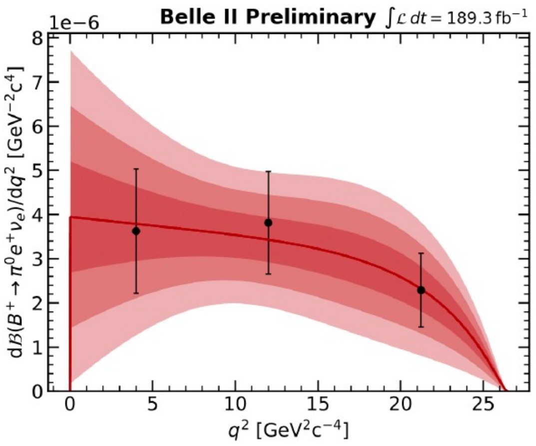
- Consistent with the world averaged of $|V_{ub}|$
  - ✓ Systematic uncertainty dominated by the $e^+e^- \to q\bar{q}$ continuum bg estimate
  - ✓ Will be greatly reduced with more off-resonance data taking

Belle II, [arXiv: 2210.04224]

Exclusive $|V_{ub}|$ from $B \to \pi e \nu$ (Tagged)







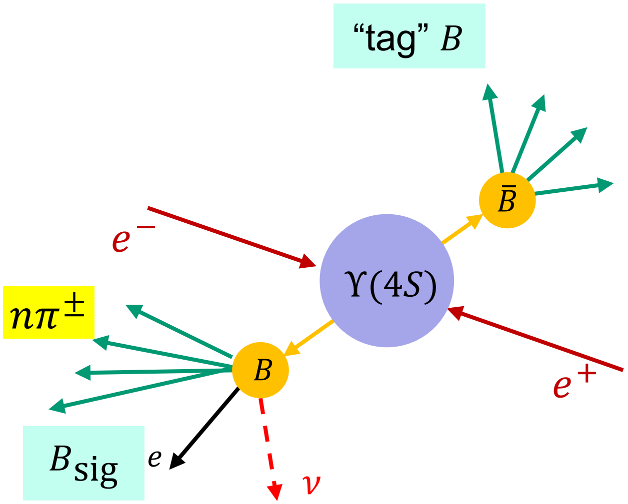
- Similar analysis technique as "tagged" $B \to Dl\nu$ using FEI
  - ✓ Smaller signal statistics but significantly reduce background from $B \to X_c l\nu$
- Extract V_{ub} using measured differential decay rate as a function of $q^2 = (p_B - p_\pi)^2$

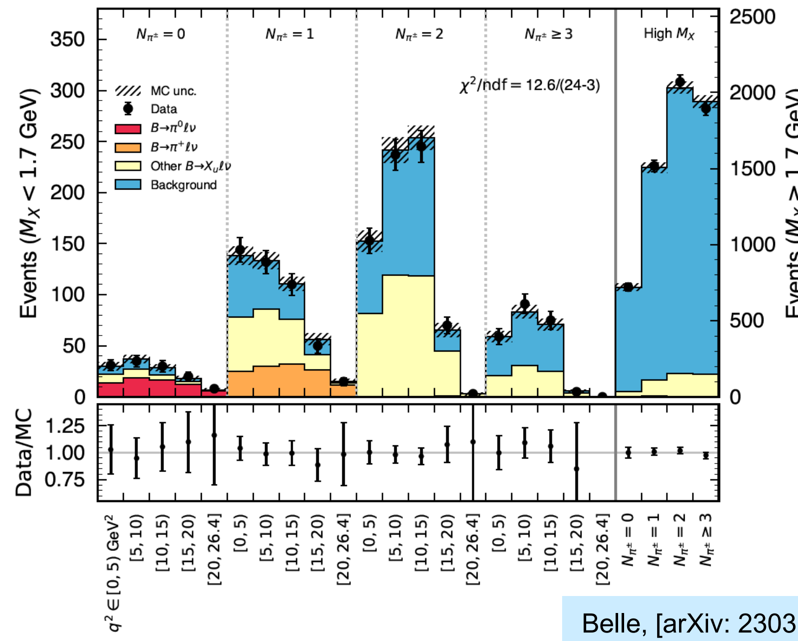
$$|V_{ub}| = (3.88 \pm 0.45^{\text{exp}}) \times 10^{-4}$$

- Consistent with the world averaged of $|V_{ub}|$
  - ✓ Dominated by statistical uncertainty
  - ✓ Systematic uncertainty is half of the one in "untagged" exclusive measurement
    - ✓ Primarily due to FEI calibration and π^0 efficiency determination
    - ✓ Both are data driven and will be reduced with more Belle II data

Belle II, [arXiv: 2206.08102]

Simultaneous meas. exclusive & Inclusive $|V_{ub}|$

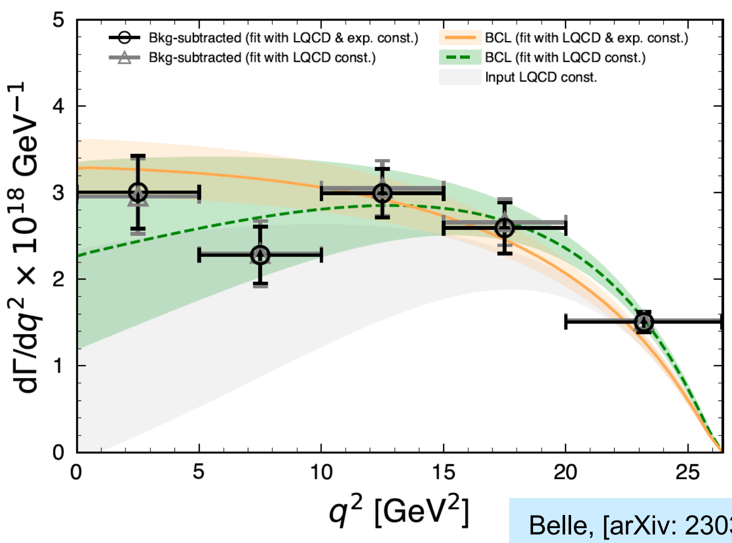




Belle, [arXiv: 2303.17309]

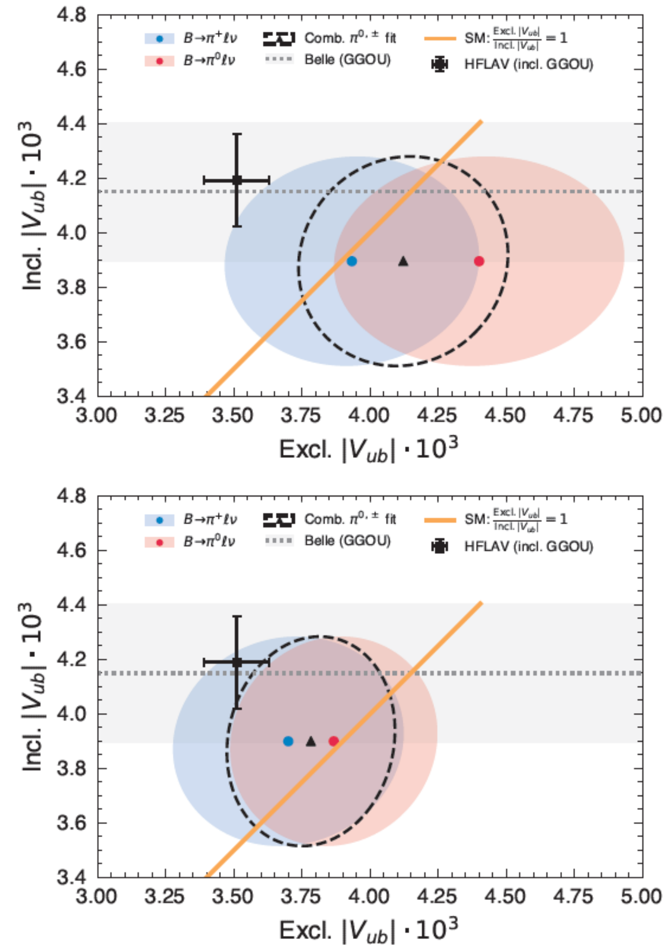
- Belle measurement $711\ \text{fb}^{-1}$
- Identifical all $\pi^\pm$ associated with lepton to form X_u system
  - ✓ BDT rejects >98% $B \to X_c l\nu$ with signal efficiency $\sim 18.5/\%$
    - Decay vertex probability, M^2_{miss}, number of $K^\pm$ and K_S mesons near lepton
  - ✓ Signal extraction: 2D fit of $q^2 = (p_B - p_X)^2$ and $N_{\pi^\pm}$
- Extract $|V_{ub}|$ using measured differential decay rate as function of q^2
- Large systematic uncertainty (comparable to statistical error)
  - ✓ Exclusive: tagging efficiency calibration (4.0%), $B \to X_u l\nu$ modeling (3.5%)
  - ✓ Inclusive: $B \to X_u l\nu$ modeling (12.1%), $b \to X_u$ fragmentation (5.3%).

Simultaneous meas. exclusive & Inclusive $|V_{ub}|$



Belle, [arXiv: 2303.17309]

FIG. 3. The q^2 spectra of $\overline{B}^0 \to \pi^+\ell^-\bar{\nu}_\ell$ obtained from the fit of the combined LQCD and experimental information (orange, solid) and from the fit to LQCD only (green, dashed)



$$|V_{ub}^{\text{excl.}}| = (3.78 \pm 0.23^{\text{stat}} \pm 0.16^{\text{syst}} \pm 0.14^{\text{theo}}) \times 10^{-3}$$

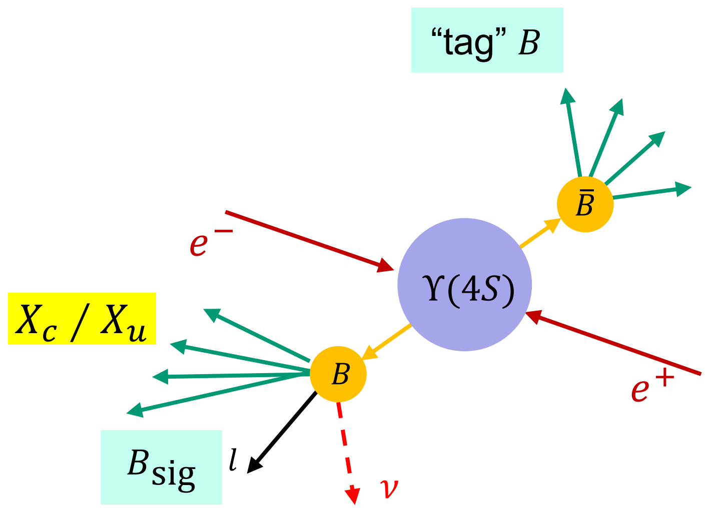
$$|V_{ub}^{\text{incl.}}| = (3.90 \pm 0.20^{\text{stat}} \pm 0.32^{\text{syst}} \pm 0.09^{\text{theo}}) \times 10^{-3}$$

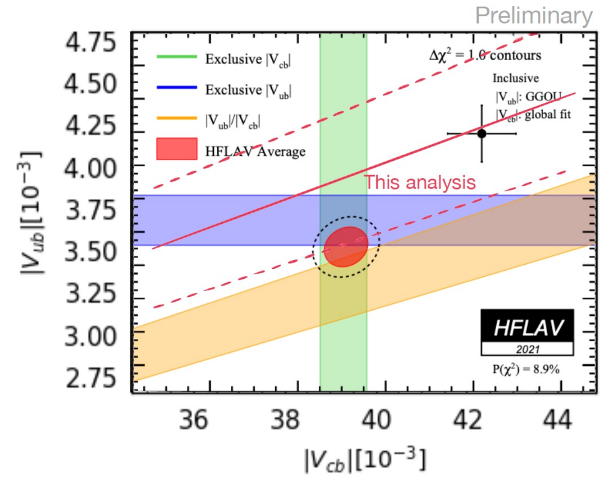
Correlation = 0.10

$$|V_{ub}^{\text{excl.}}| \,/\, |V_{ub}^{\text{incl.}}| = 0.97 \pm 0.12^{\text{exp}}$$

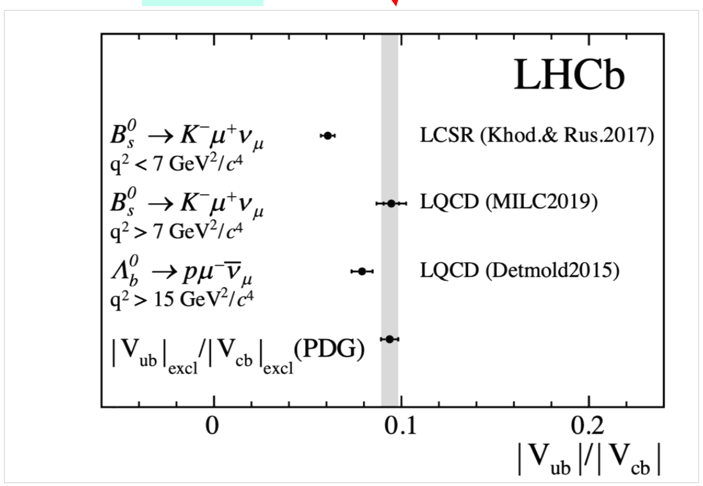
FIG. 2. The $|V_{ub}|$ values obtained with the fits using (top) LQCD or (bottom) LQCD and experimental constraints for the $\overline{B}^0 \to \pi^+\ell^-\bar{\nu}_\ell$ form factor are shown. The inclusive $|V_{ub}|$ value is based on the decay rate from the GGOU calculation. The values obtained from the previous Belle measurement [9] (grey band) and the world averages from Ref. [1] (black marker) are also shown. The shown ellipses correspond to 39.3% confidence levels ($\Delta\chi^2 = 1$).

Measurement of $|V_{ub}|/|V_{cb}|$





Belle Preliminary
711 fb^{-1}



- Belle: inclusive $|V_{ub}|$ measurement complicated
  - ✓ Large "bg" contribution from $B \to X_c l\nu$
- Treat $B \to X_c l\nu$ as part of signal
  - ✓ Simultaneously measure $|V_{ub}|$ & $|V_{ub}|$
  - ✓ $B \to X_u l\nu$ dominate (>86%) in high p_l^B bins

$$|V_{ub}|/|V_{cb}|(\text{low}) = 0.0607 \pm 0.0015(\text{stat}) \pm 0.0013(\text{syst}) \pm 0.0008\,(D_s) \pm 0.0030\,(\text{FF}),$$

$$|V_{ub}|/|V_{cb}|(\text{high}) = 0.0946 \pm 0.0030(\text{stat})^{+0.0024}_{-0.0025}(\text{syst}) \pm 0.0013\,(D_s) \pm 0.0068\,(\text{FF}),$$

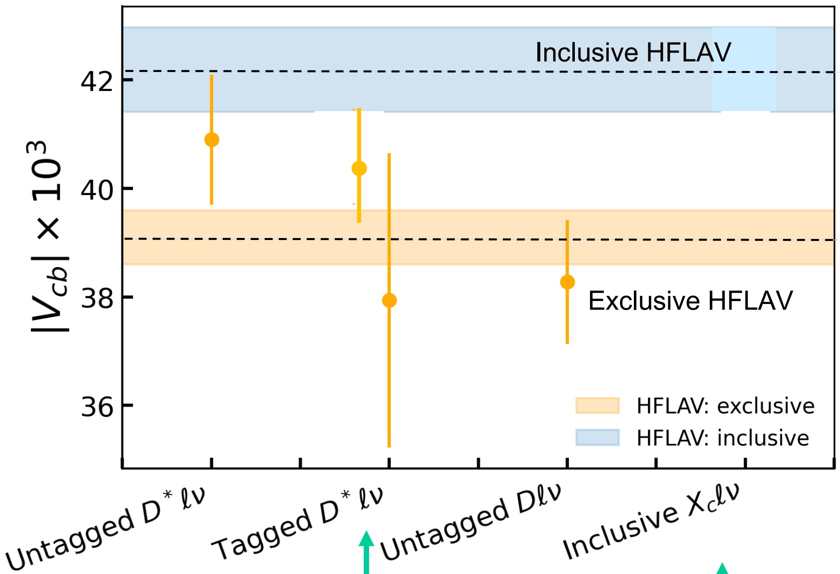
- LHCb: 2 fb^{-1}data at 8 pp collisions
- Observation of $B_s^0 \to K^-\mu^+\nu_\mu l$
  - ✓ Branching fraction measurement

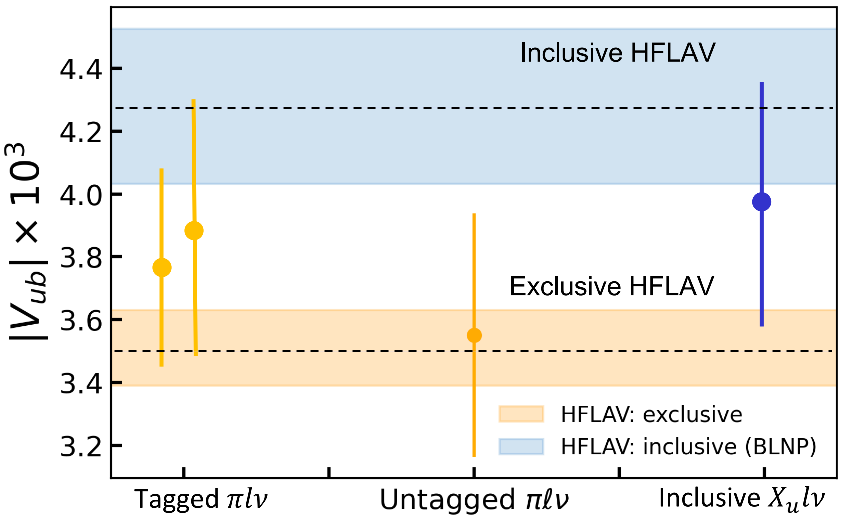
$$R_{\rm BF} = \frac{\mathcal{B}(B_s^0 \to K^-\mu^+\nu_\mu)}{\mathcal{B}(B_s^0 \to D_s^-\mu^+\nu_\mu}$$

  - ✓ Determination of $|V_{ub}|$ / $|V_{ub}|$ in low/high q^2 bins

LHCb, PRL126.081804(2021), [arXiv: 2303.17309]

Belle & Belle II recent $|V_{cb}|$ & $|V_{ub}|$ Summary





Belle, [arXiv: 2301.07529]

BelleII, [arXiv:2301.04716]

BelleII, [arXiv:2210.13143]

Belle II, PRD107,072002(2023) [arXiv: 2301.04716]
Moment measurement only, extraction of V_{cb} with Belle result
Belle PRD104,112011(2021) by F.Bernlocher, et.al,
JHEP10(2022)068

BelleII, [arXiv:2206.08102]

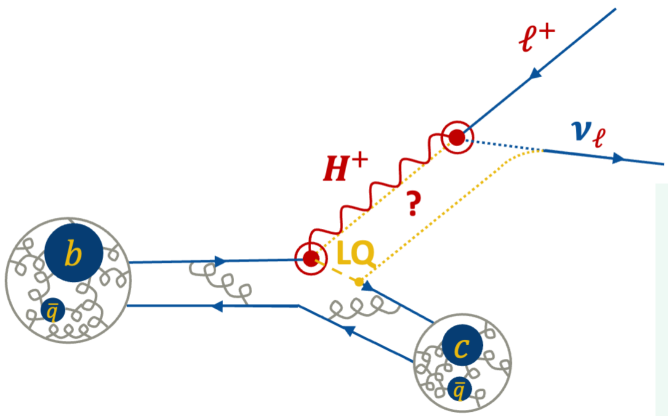
Belle, [arXiv: 2303.17309]
Simultaneous determination of
Exclusive and inclusive V_{ub}

BelleII, [arXiv:2210.04224]

Belle, [arXiv: 2303.17309]
Simultaneous determination of
Exclusive and inclusive V_{ub}

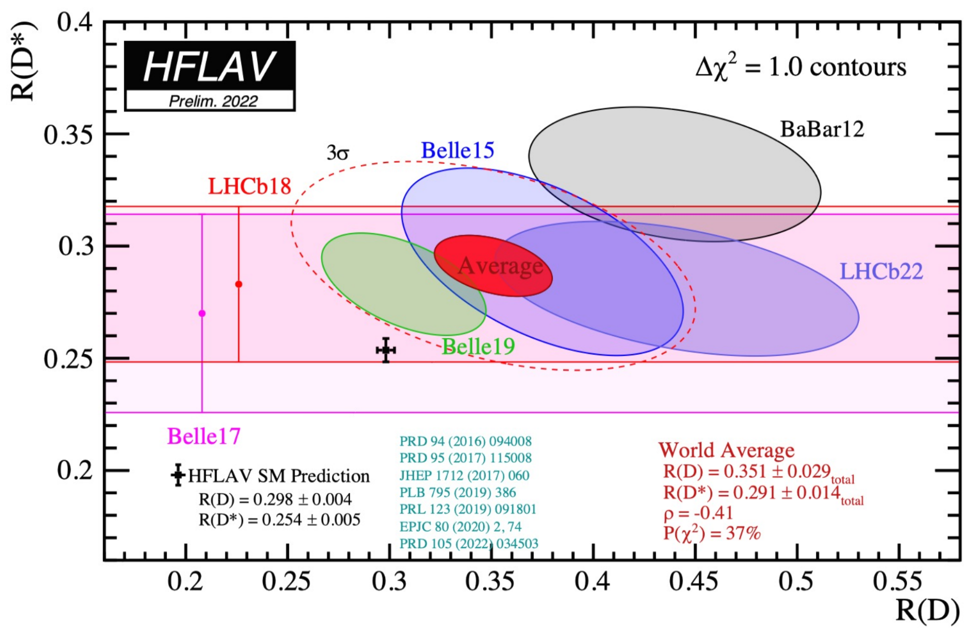
Lepton Flavour Universality tests

Measurements of R_{D^*} and R_D



$$R_{D^*} = \frac{\mathcal{B}(B \to D^* \tau \nu)}{\mathcal{B}(B \to D^* l \nu)} \qquad R_D = \frac{\mathcal{B}(B \to D \tau \nu)}{\mathcal{B}(B \to D l \nu)}$$

- Uncertainty from form factor and V_{cb} drop out
  - ✓ Small uncertainty for the SM prediction
- Ratios test lepton universality
  - ✓ NP change rate, angular and q^2 distributions
- Measured values consistent above the SM prediction



Measurement of R_D and R_{D^*} exceed the SM predictions by 1.82σ & 2.49σ, respectively, for 2-degree of freedom, deviation above the SM is 3.5σ. [End of 2022]

Including result from a recent LHCb simultaneous measurement of R_{D^*} (closer to the SM value) and R_{D^0} (Further away from the SM prediction), which are at a combined 1.9σ above the SM value [arXiv:2302.02886, submitted to PRL]

All LHCb measurements here are based 3 fb^{-1}data at 7 and 8 TeV pp collisions

Measurements of $R_{D^{*-}}$

- LHCb measurement using $2\ \mathrm{fb}^{-1}$ data at 13TeV pp collisions
  - ✓ $pp \to b\bar{b}X$ cross section at 13TeV twice of the one at 7/8 TeV & improved trigger
  - ✓ More than 40% more signal candidates than previous analysis ($3\ \mathrm{fb}^{-1}$ at 7/8 TeV)
- Hadronic $\tau^+ \to \pi^+\pi^-\pi^+\nu, \pi^+\pi^-\pi^+\pi^0\nu$ final states
  - ✓ Reconstruction of two neutrinos: 6 unknowns with 6 Kinematic constraints
    - B meson and τ lepton directions using vertex positions
    - B meson and τ lepton mass constraints
- Branching fraction measurement: using normalization mode with similar topology

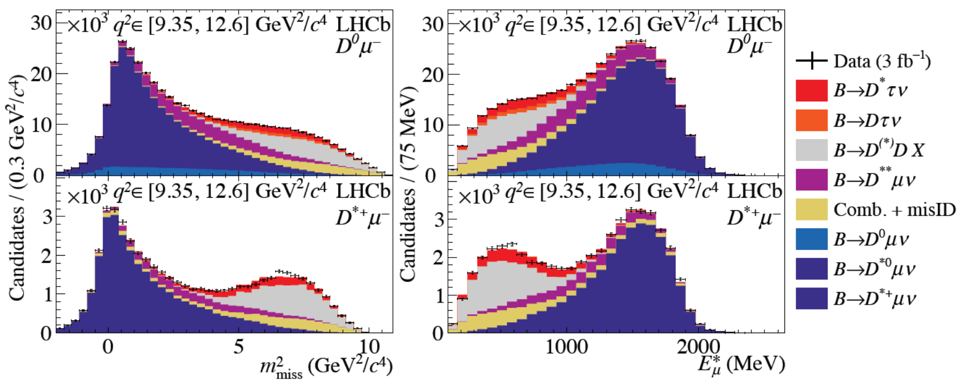
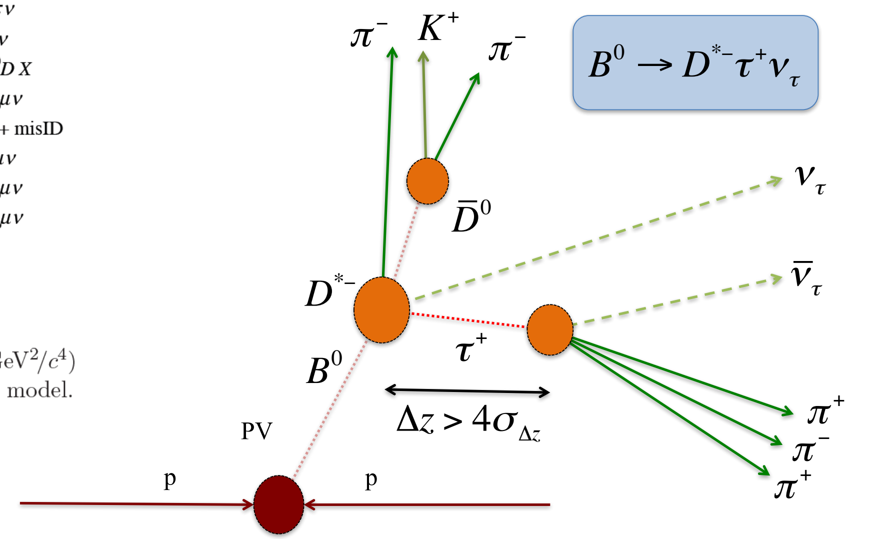


Figure 1: Distributions of (left) m^2_{miss} and (right) E^*_μ in the highest q^2 bin (above $9.35\,\mathrm{GeV}^2/c^4$) of the (top) $D^0\mu^-$ and (bottom) $D^{*+}\mu^-$ signal data, overlaid with projections of the fit model.

LHCb, [arXiv: 2305.01463]

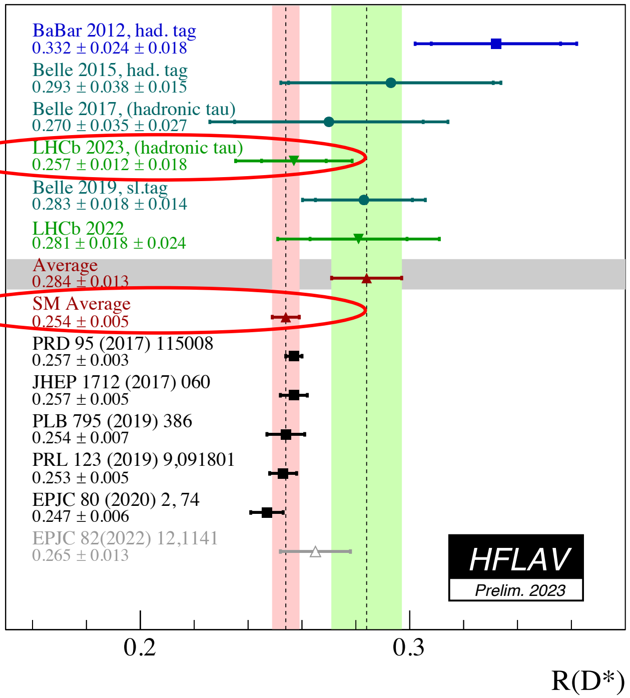


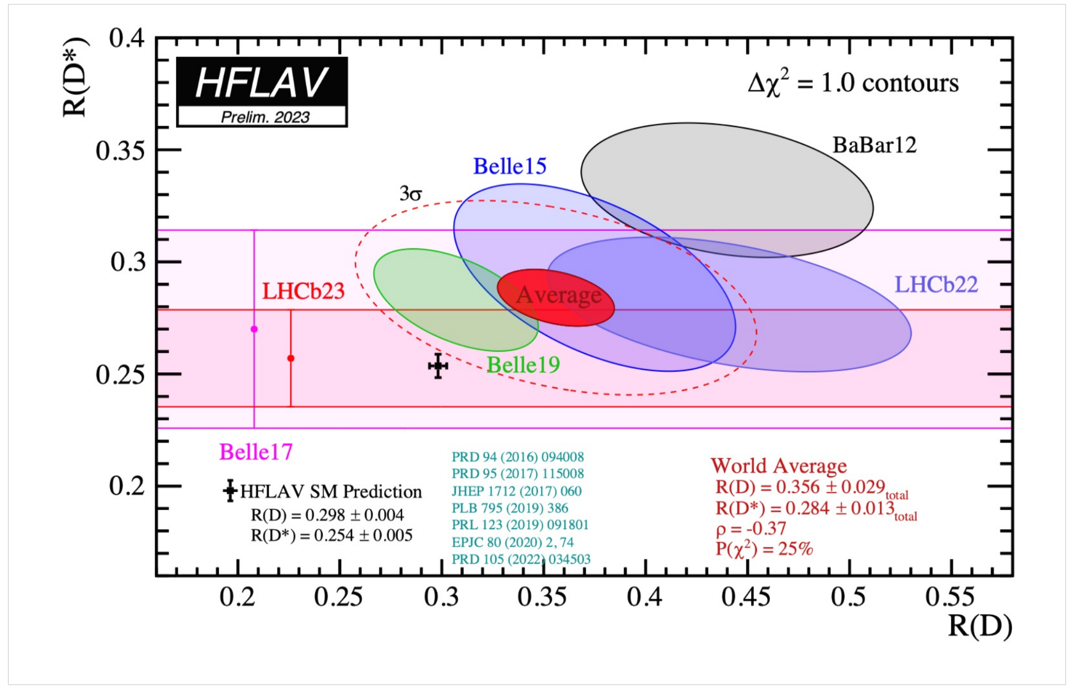
$$R_{\text{BF}} = \frac{\mathcal{B}(B^0 \to D^{*-}\tau^+\nu_\tau)}{\mathcal{B}(B^0 \to D^{*-}\pi^+\pi^-\pi^+)} = (1.97 \pm 0.13^{\text{stat}} \pm 0.18^{\text{syst}})\%$$

$$R_{D^{*-}} = \frac{\mathcal{B}(B^0 \to D^{*-}\tau^+\nu_\tau)}{\mathcal{B}(B^0 \to D^{*-}\mu^+\nu_\mu)} = (0.247 \pm 0.015^{\text{stat}} \pm 0.015^{\text{syst}} \pm 0.012^{\text{ext}})$$

Status of R_{D^*} and R_D

Including the latest LHCb result: [arXiv: 2305.01463], before the LP2023



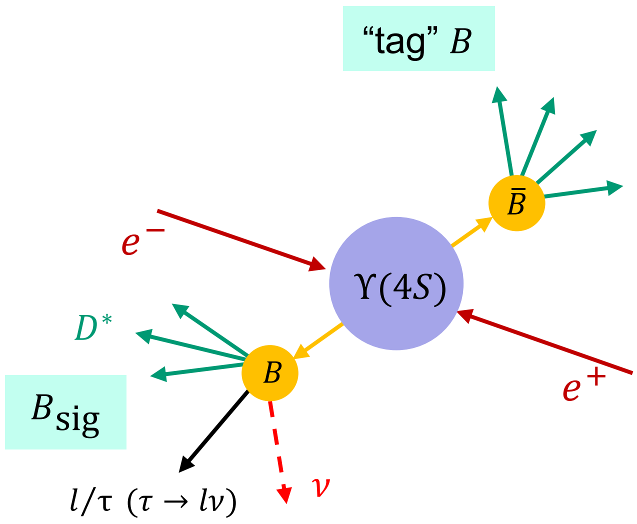


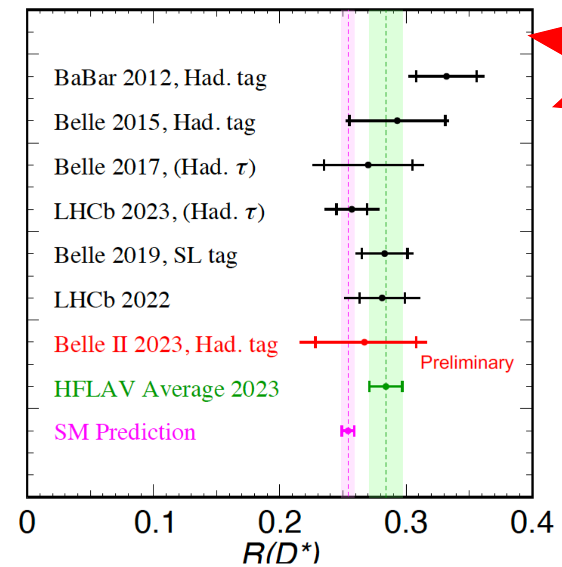
Very good agreement with the SM value, reduce tension $2.49\sigma \rightarrow 2.15\sigma$

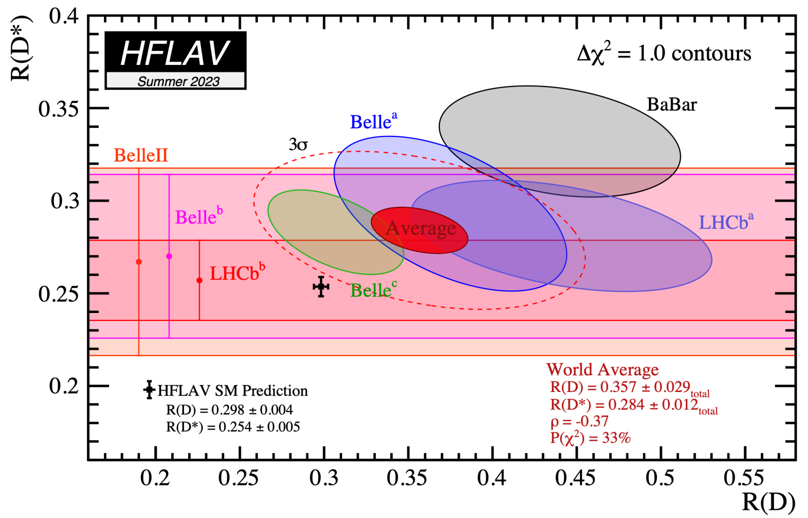
Measurement of R_D and R_{D^*} exceed the SM predictions by 1.98σ & 2.15σ, respectively, for 2-degree of freedom, the deviation above the SM is 3.2σ [Reduce from previous 3.5σ].

Latest Status of R_{D^*}

New For LP2023







- Belle II preliminary: 189 fb^{-1}data

$$R_{D^*} = 0.267^{+0.041}_{-0.039}(\text{stat.})^{+0.028}_{-0.033}(\text{syst.})$$

- Consistent with SM prediction and HFLAV Average due to large uncertainties (dominant systematic due to MC statistics and E_{ECL} can be reduced with more data)
- Slightly increase the deviation above the SM: $3.2\sigma \to 3.3\sigma$
- Future measurement as a function of q^2 and angular distributions

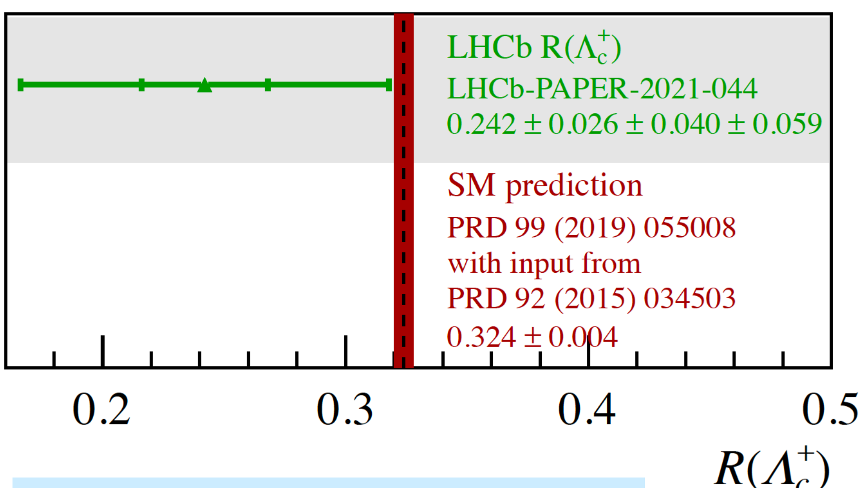
See more details in K.Kojima's talk at LP2023
https://indico.cern.ch/event/1114856/sessions/457254/#20230718

Test lepton universality using $b-$baryon

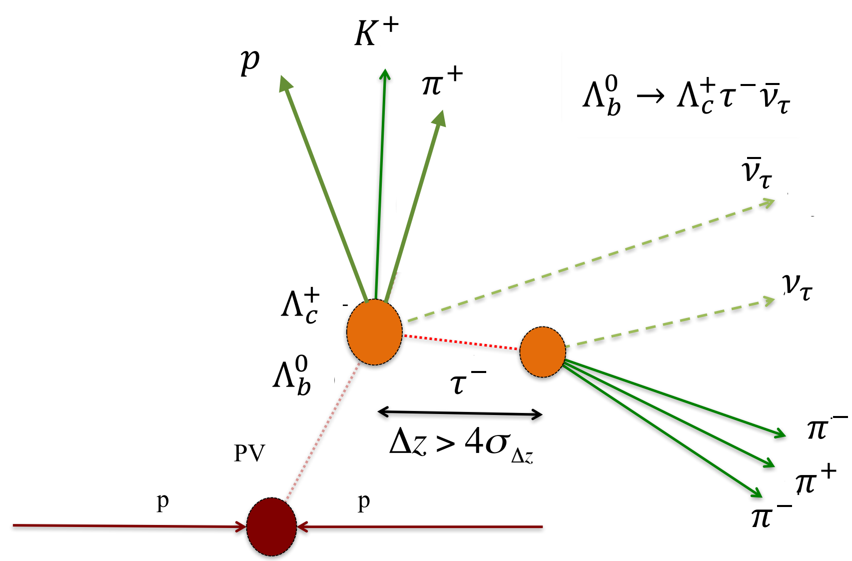
- LHCb measurement using 3 fb^{-1}data at 13TeV pp collisions

$$R_{\Lambda_c^+} \equiv \frac{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ \tau^- \bar{\nu}_\tau)}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ \mu^- \bar{\nu}_\mu)}$$

- Similar analysis techniques as the recent R_{D^*} measurement
  - ✓ Hadronic $\tau^+ \to \pi^+\pi^-\pi^+\nu, \pi^+\pi^-\pi^+\pi^0\nu$ final states
  - ✓ Reconstruction of two neutrinos: 6 unknowns with 6 Kinematic constraints
    - Λ_b^0 baryon and τ lepton directions using vertex positions
    - Λ_b^0 baryon and τ lepton mass constraints
  - ✓ Using normalization mode $(\Lambda_b^0 \to \Lambda_c^+\pi^-\pi^+\pi^-)$ with similar topology

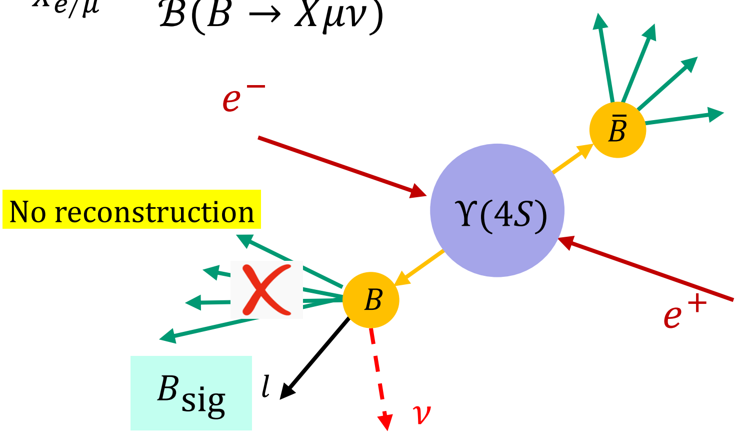


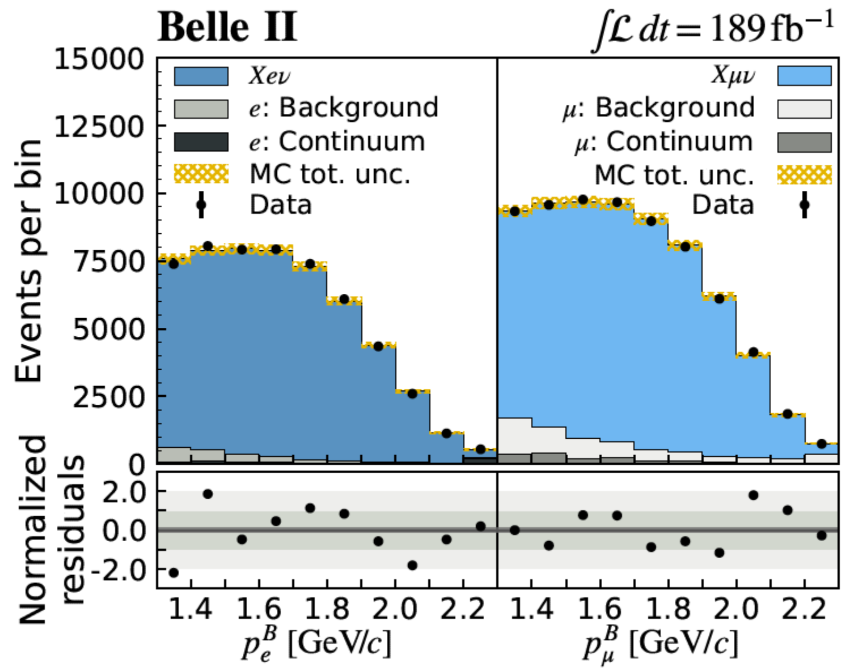
LHCb, PRL128,191803(2022) [arXiv: 2305.01463]



Muon-electron universality: inclusive

$$R_{X_{e/\mu}} = \frac{\mathcal{B}(B \to Xe\nu)}{\mathcal{B}(B \to X\mu\nu)}$$





- Sample composition fit to lepton momentum spectrum in signal and control regions
  - ✓ Using "tag" B (FEI) and flavor correlation to greatly reduce the background
- First and most precise test of LFU in light leptons using semileptonic decays

$$R_{X_{e/\mu}}(p_l^B > 1.3\text{GeV}) = 1.005 \pm 0.009^{\text{stat}} \pm 0.019^{\text{syst}}$$

Belle II, [arXiv: 2301.08226], submitted to PRL

Dominated by lepton efficiency (data driven calibration)

- Consistent with the SM prediction of 1.006 ± 0.001.
  - ✓ Need more statistics to reduce experimental uncertainty

[M.Rahimi,K.K.Vos, JHEP 11,007(2022)[arXiv:2207.03432].

Muon-electron universality: exclusive

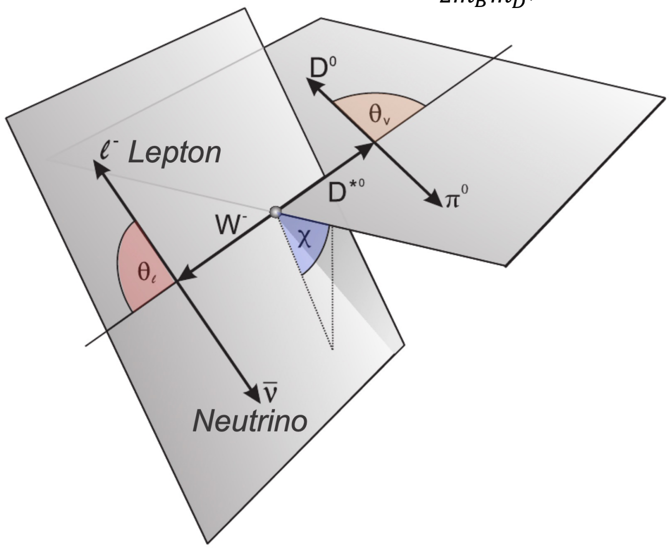
- A recent claim of 4σ deviation from SM in the angular distribution of $B \to D^{(*)} l\nu$
  - ✓ Reinterpretation of public Belle result (1-D projection plot) by theorists

C. Bobet, et, al, Eur.Phys.J.C 81(2021)11,984: arXiv 2104.02094

- Measure five angular asymmetries of e and μ using $B^0 \to D^{*-} l^+ \nu$

$$\mathcal{A}_x(w) = \left(\frac{d\Gamma}{dw}\right)^{-1} \Big[\underbrace{\int_0^1}_{+} - \underbrace{\int_{-1}^0}_{-}\Big] dx \frac{d^2\Gamma}{dw dx}$$

Recoiled parameter $w = \frac{m_B^2 + m_{D^*}^2 - q^2}{2 m_B m_{D^*}}$



Highly sensitive to lepton universality violation

$A_{FB}(w)$: $dx = d(\cos\theta_\ell)$

$S_3(w)$: $dx = d(\cos 2\chi)$

$S_5(w)$: $dx = d(\cos\chi \cos\theta_V)$

Less sensitive or insensitive to NP. Control tests of the analysis method

$S_7(w)$: $dx = d(\sin\chi \cos\theta_V)$

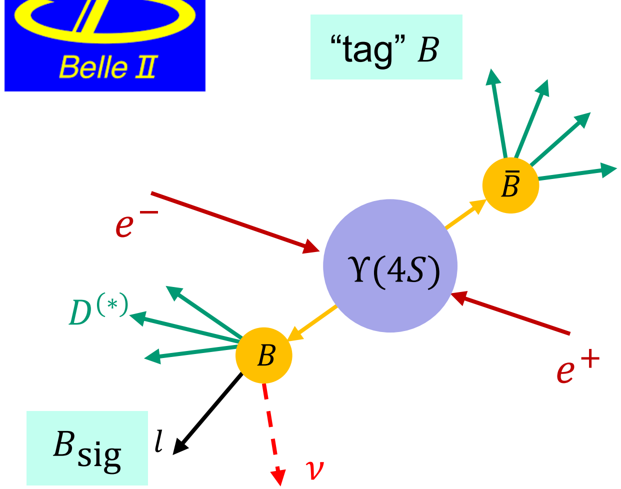
$S_9(w)$: $dx = d(\sin 2\chi)$

B.Bhattacharya, et, al, PRD107,015011(2023): arXiv 2206.11283

- The difference of those asymmetries between e and μ sensitive to interactions that violate LU

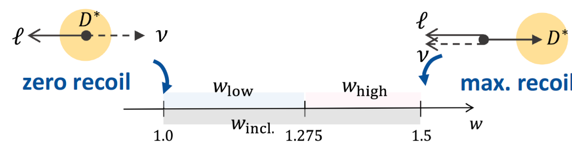
$$\Delta A_x(w) \equiv A_x^\mu(x) - A_x^e(x) = \frac{N_x^+(w) - N_x^-(w)}{N_x^+(w) + N_x^-(w)}$$

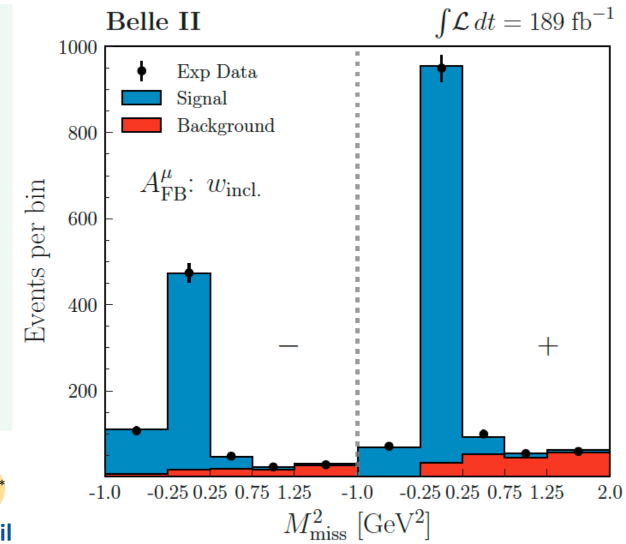
Muon-electron universality: exclusive

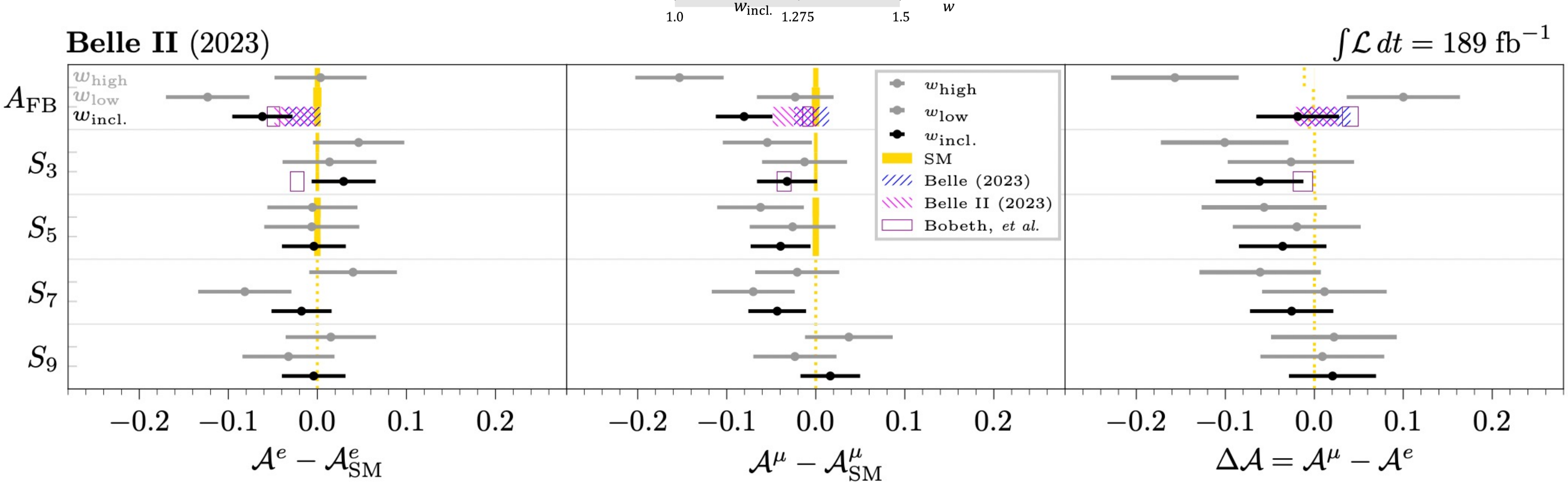


Similar to $|V_{cb}|$ measurement using $B^0 \to D^{*-} l^+ \nu$. Using "tagged" B (FEI) allow better neutrino reconstruction to calculate kinematic variables
Reduce background

Simultaneous determine all symmetries in different w bins







All consistent with the SM within 5-7% uncertainties (statistically limited)

Summary and Conclusion

- A few selected recent measurements from Belle(II) and LHCb experiments
  - ✓ Measurements of $|V_{cb}|$ & $|V_{ub}|$
  - ✓ Tests of lepton universality
- Discrepancies $(> 3\sigma)$ of measured $|V_{cb}|$ and $|V_{ub}|$ between inclusive and exclusive final states remains
  - ✓ Measurements not limited by statistical precision
  - ✓ Better design analysis choice to reduce systematic uncertainties
  - ✓ Many systematic uncertainties can be reduced with more data
  - ✓ Important to improve precision of theoretical calculations
- Deviation of measured $R_{D^{(*)}}$ from the SM prediction remains $(> 3\sigma)$
  - ✓ More precise measurement expected with more coming data
  - ✓ Measurements as a function of q^2 and angular distributions
- Test muon and electron universality: inclusive and angular distributions
  - ✓ Systematic uncertainties that will further be reduced with more data
- **Semileptonic b-hadron offer reach opportunities to look for NP, expect new results soon**

Backup