Recent results on inclusive semileptonic B decays at Belle and Belle II

Frank Meier
on behalf of Belle and Belle II

14th Conference on the Intersections of Particle and Nuclear Physics
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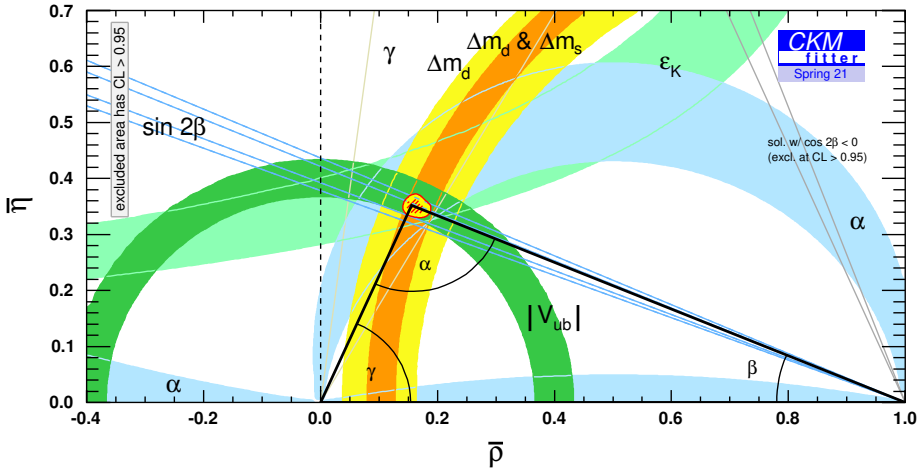
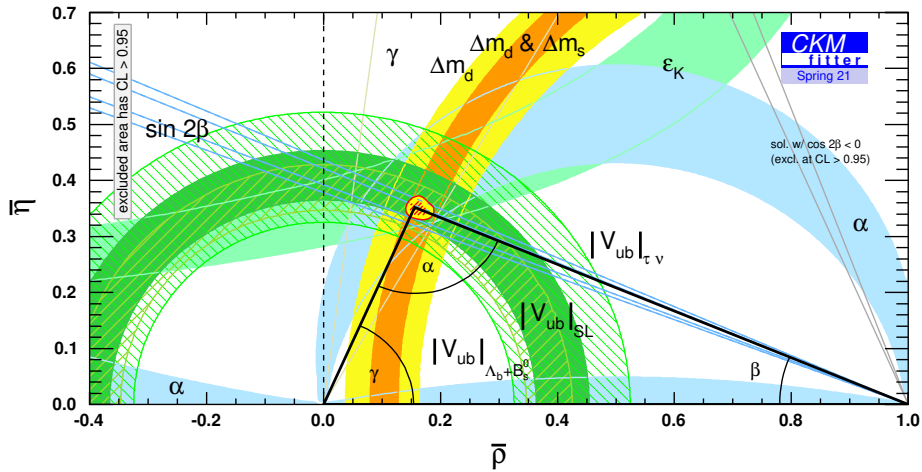
Research supported by

CKM triangle



- precise measurements of $|V_{ub}|$ and $|V_{cb}|$ crucial to constrain CKM triangle

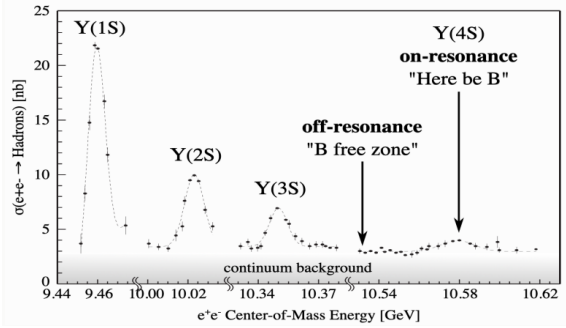
CKM triangle



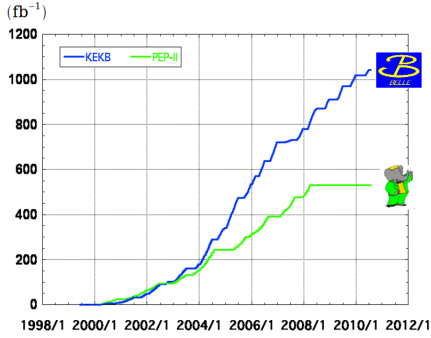
- precise measurements of $|V_{ub}|$ and $|V_{cb}|$ crucial to constrain CKM triangle

Data-taking at the B factories

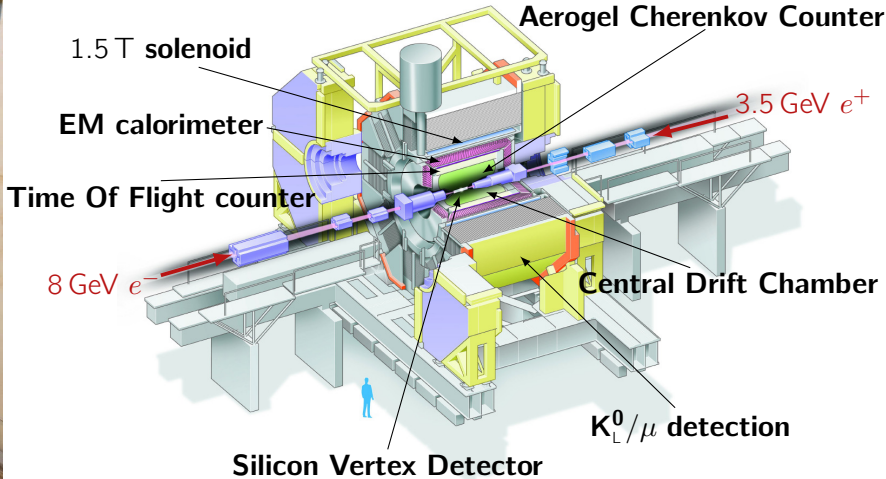
- asymmetric collision of e^+e^-, mostly at a center-of-mass energy of the $\Upsilon(4S)$ resonance
- $\Upsilon(4S) \to B^+B^-$ (∼51.5 %), $\Upsilon(4S) \to B^0\overline{B}^0$ (∼48.5 %)
- Belle collected ∼772M $B\overline{B}$ pairs over the course of 10 years



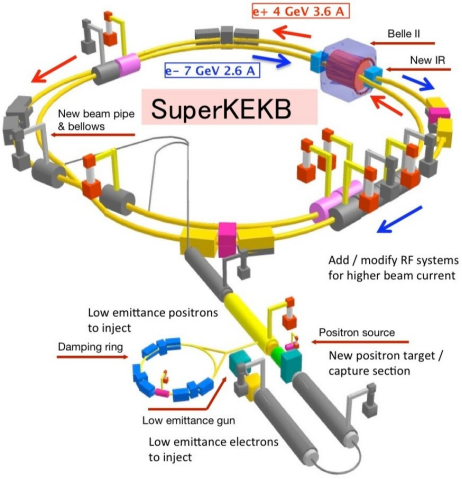
Integrated luminosity of B factories

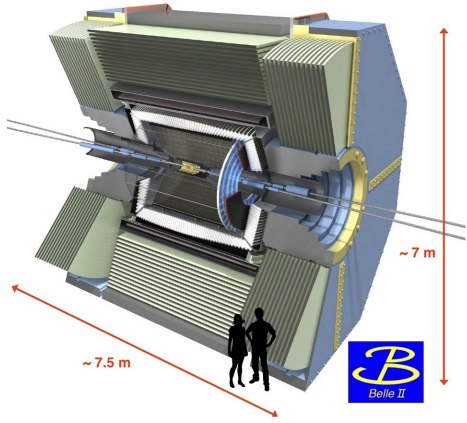


Belle detector



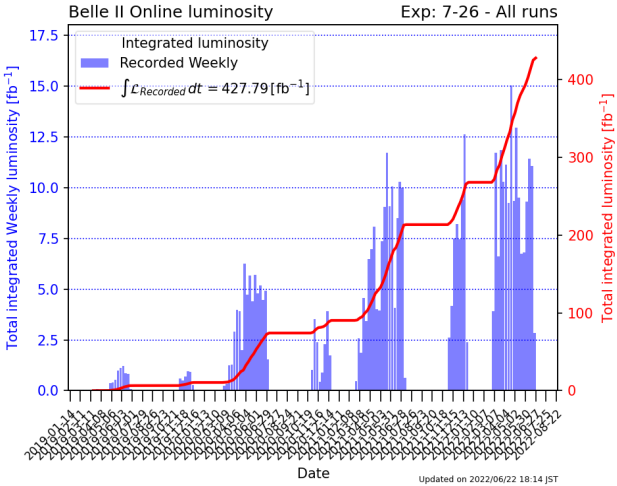
Changes from KEKB to SuperKEKB and from Belle to Belle II





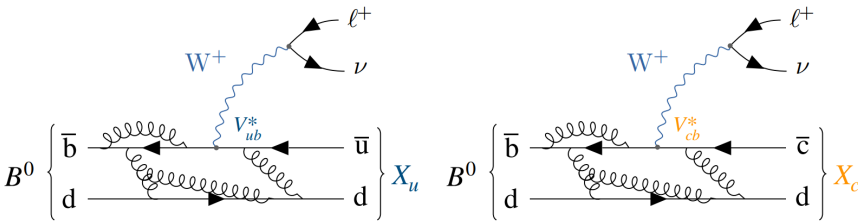
- higher instantaneous luminosity, but also more background
- improved inner detector
- new electronics at many places

Data-taking at Belle II



- new luminosity world record of $4.7 \cdot 10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$

Semileptonic B decays



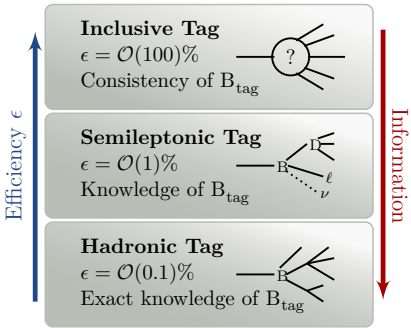
- make use of kinematic constraint
- signal extraction via fit of
  - missing mass distribution
  - lepton momentum spectrum
  - hadronic mass spectrum
  - four-momentum-transfer squared distribution
  - angle in CMS between measured momentum and nominal direction

$$\cos\theta_{\mathrm{BY}} = \frac{2E_B^{\mathrm{CM}}E_{Xl}^{\mathrm{CM}} - m_B^2 - m_{Xl}^2}{2p_B^{\mathrm{CM}}p_{Xl}^{\mathrm{CM}}}$$

Tagged vs untagged measurement

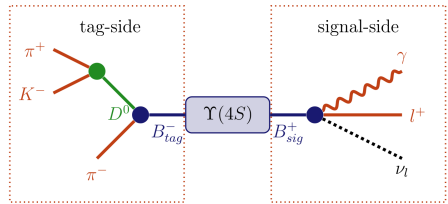
Tagged approach

- reconstruct $\Upsilon(4S)$ from signal and tag side
- lower efficiency
- higher purity



Untagged approach

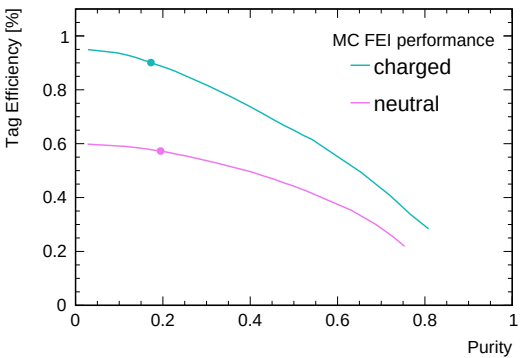
- reconstruct only signal side
- higher signal efficiency
- lower purity
  $\Rightarrow$ suppression and / or proper description of background more important

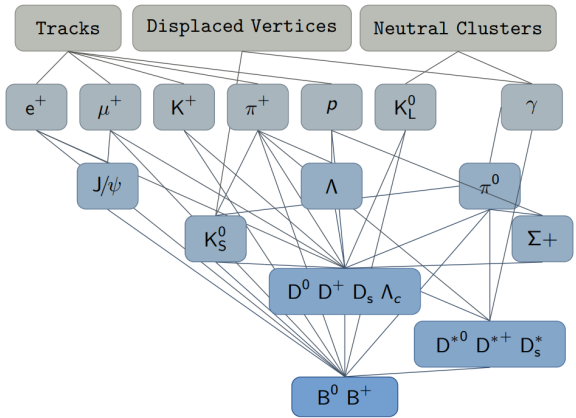


Full Event Interpretation

Comput. Softw. Big Sci. 3 (2019)

- fully reconstruct one of the B mesons (tag-side) in many exclusive modes
- hadronic and semileptonic version:
  trade-off between efficiency and purity
- train BDT for each stage
  $\Rightarrow$ signal probability





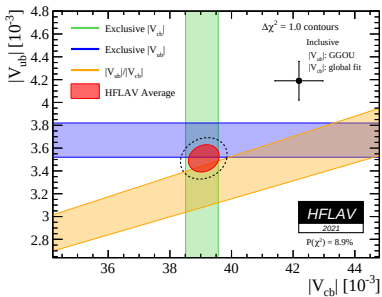
Exclusive vs inclusive analysis technique

Exclusive approach

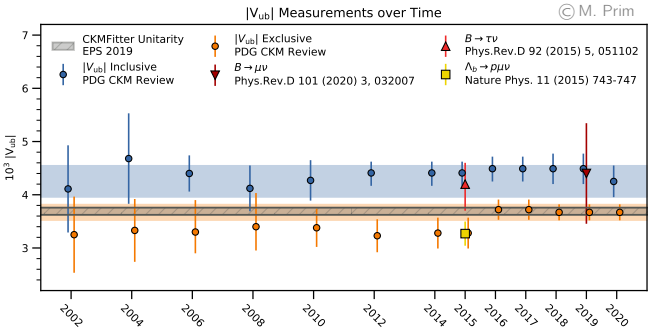
- fully reconstruct final state
  - $B \to D^{(*)} \ell \nu_\ell$
  - $B \to \pi \ell^+ \nu_\ell$
- theory: lattice QCD
- Belle II results in HF session on Saturday by Philipp Horak

Inclusive approach

- partial reconstruction
  - $B \to X_c \ell^+ \nu_\ell$
  - $B \to X_u \ell^+ \nu_\ell$
- theory: Heavy Quark Effective Theory
- covered in this talk



Measurements of V_{ub}

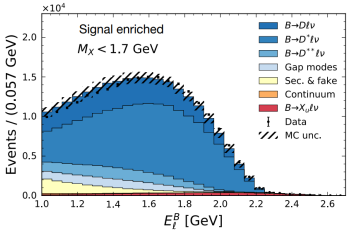


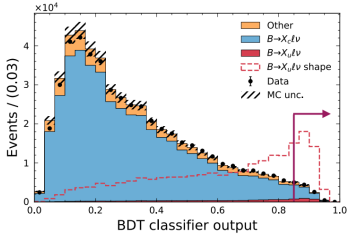
- $b \to u$ transitions CKM suppressed $\Rightarrow$ large background contributions from $b \to c$ transitions
- clean measurement only possible in certain kinematic regions (lepton endpoint or low M_X)

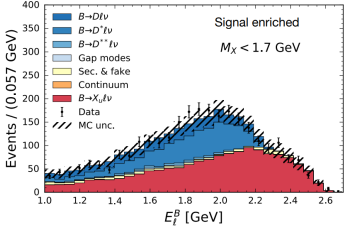
$$|V_{ub}| = \sqrt{\frac{\Delta\mathcal{B}(B \to X_u \ell^+ \nu_\ell)}{\tau_B \Delta\Gamma(B \to X_u \ell^+ \nu_\ell)}}$$

Measurements of Partial Branching Fractions of Inclusive $B \to X_u \ell^+ \nu_\ell$ Decays with Hadronic Tagging PRD 104, 012008 (2021)

- BDTs trained to reduce $B \to X_c \ell \nu_\ell$ (background rejection of 98.7 % at 18.5 % signal retention)
- inclusion of gap modes major improvement







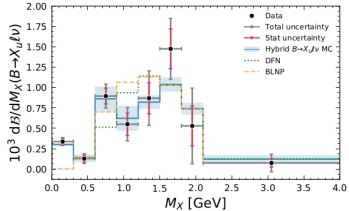
- extract signal yield from fits to
  - hadronic mass M_X
  - four-momentum-transfer squared q^2
  - lepton energy E_ℓ^B in B rest frame
- partial branching fraction in 3 phase-space regions
  - $M_X < 1.7\,\text{GeV}/c^2$
  - $M_X < 1.7\,\text{GeV}/c^2$ + $q^2 > 8\,\text{GeV}^2$
  - $E_\ell^B > 1\,\text{GeV}$

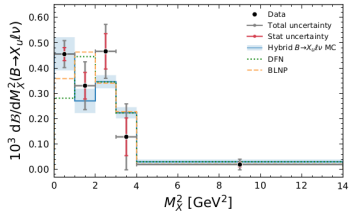
$$|V_{ub}| = \left(4.10 \pm 0.09\,(\text{stat}) \pm 0.22\,(\text{syst}) \pm 0.15\,(\text{theo})\right) \cdot 10^{-3}$$

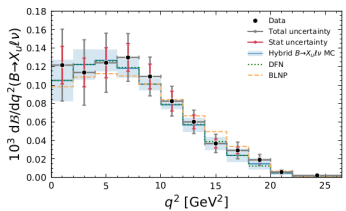
Measurement of Differential Branching Fractions of Inclusive $B \to X_u \ell^+ \nu_\ell$ Decays

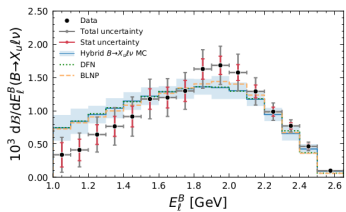
PRL 127, 261801 (2021)

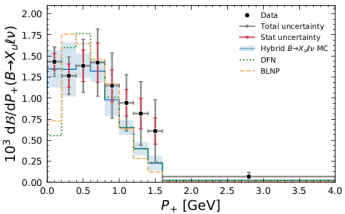
- selection and reconstruction analogous to partial branching fraction measurement
- distributions corrected for det. resolution and efficiency effects and unfolded to phase space of $E_\ell^B > 1\,\text{GeV}$

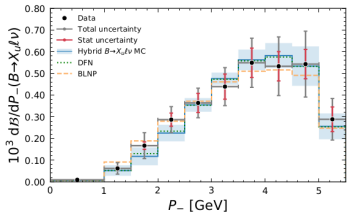






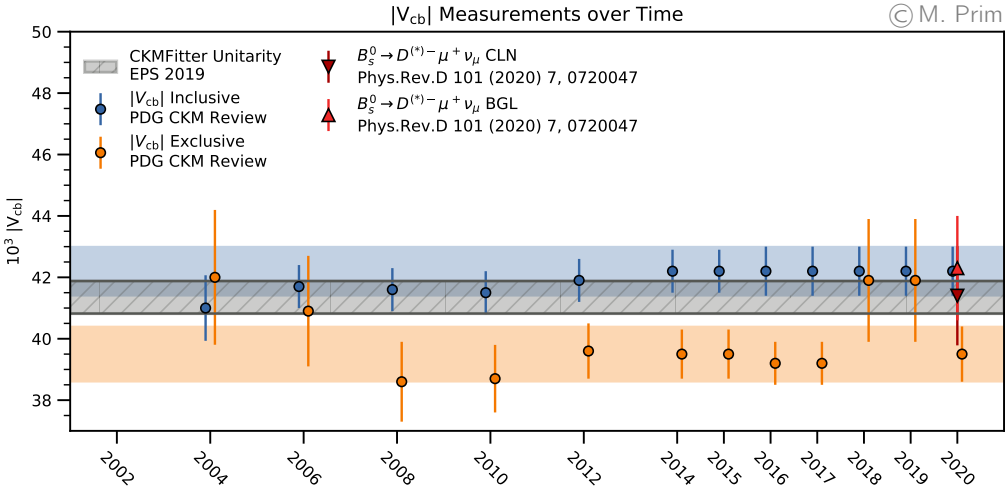






- fair agreement of data to hybrid model and inclusive predictions

Measurements of V_{cb}

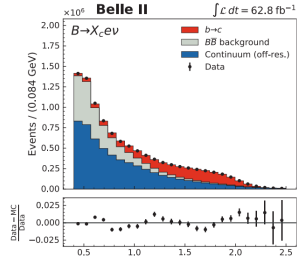


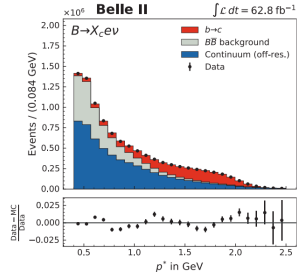
Measurement of $\mathcal{B}\,(B \to X_c \ell^+ \nu_\ell)$ arXiv:2111.09405

- first shown in summer last year on reduced data set of 62.8 fb^{-1}
- one well-identified signal lepton required
- background rejected using missing mass and momentum distributions
- signal yield extracted via binned likelihood fit of p_ℓ^*
- $N_{\text{sig}}^{X_c e} = (1.932 \pm 0.006) \cdot 10^6$
- $N_{\text{sig}}^{X_c \mu} = (1.501 \pm 0.007) \cdot 10^6$

$$\mathcal{B}(B \to X_c \ell^+ \nu_\ell) = \frac{N_{\text{sig}}^{\ell}\,\tau}{2N_{B\overline{B}}\left(f_+ \epsilon^\ell(B^+)\tau(B^+) + f_0 \epsilon^\ell(B^0)\tau(B^0)\right)}$$
$$= (9.75 \pm 0.03\,(\text{stat}) \pm 0.47\,(\text{syst}))\,\%$$

- leading systematic: branching fractions of $B \to X_c \ell^+ \nu_\ell$ components and lepton ID corrections





Extracting $|V_{cb}|$ from inclusive $B \to X_c \ell \nu_\ell$ decays

$$\Gamma = \frac{G_F^2 m_b^5}{192\pi^3} |V_{cb}|^2 \left(1 + \frac{c_5(\mu) O_5(\mu)}{m_b^2} + \frac{c_6(\mu) O_6(\mu)}{m_b^3} + \mathcal{O}\left(\frac{1}{m_b^4}\right) + \dots\right)$$

- Operator Product Expansion (OPE)
  - non-perturbative hadronic matrix elements O_i
  - perturbative coefficients c_i

Order	HQE parameters
$\mathcal{O}(1)$	m_b, m_c
$\mathcal{O}(1/m_b^2)$	μ_π^2, μ_G^2
$\mathcal{O}(1/m_b^3)$	ρ_D^3, ρ_{LS}^3

- precision depends on order of expansion
- higher order of expansion requires more matrix elements
- solution: reparametrization invariance arXiv:1812.07472
  - works for q^2 moments

q^2 moments

- q^2: squared four-momentum-transfer $(p_\ell + p_{\nu_\ell})^2$

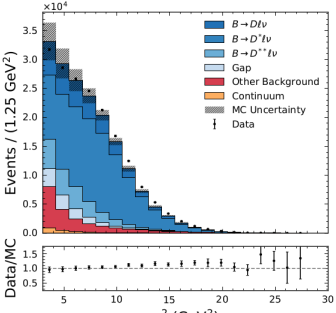
$$\langle q^{2n} \rangle = \frac{\sum w_i(q^2)(q^{2n}_{\text{calib},i})}{\sum w_i(q^2)} \times \mathcal{C}_{\text{cal}} \times \mathcal{C}_{\text{acc}}$$

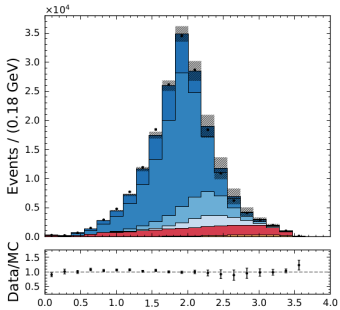
- $w_i(q^2)$ signal probability weights
- calibrate reconstructed moments using MC: $q^2_{\text{calib},i} = \left(q^2_{\text{reco},i} - c\right)/m$ with c & m parameters of linear fit
- $\mathcal{C}_{\text{cal}}$ corrects for small residual calibration bias
- $\mathcal{C}_{\text{acc}}$ corrects selection bias

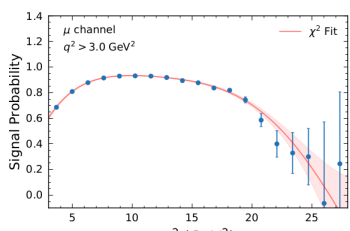
- using q^2 moments reduces number of necessary HQE parameters from 13 to 8 at $\mathcal{O}(1/m_b^4)$

Measurements of q^2 Moments of Inclusive $B \to X_c \ell^+ \nu_\ell$ Decays with Hadronic Tagging PRD 104, 112011 (2021) arXiv:2109.01685

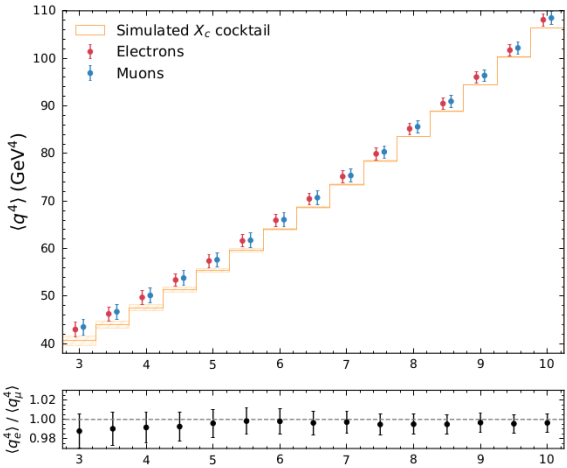
- using full Belle data sample
- one B meson reconstructed in fully hadronic decay modes (Full Reconstruction, not FEI)
- signal characterized by single lepton
- background statistically subtracted via event weights from fit of M_X distribution followed by polynomial fit of signal probability







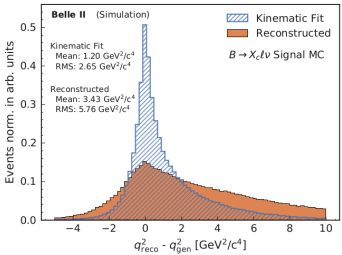
Measurements of q^2 Moments of Inclusive $B \to X_c \ell^+ \nu_\ell$ Decays with Hadronic Tagging PRD 104, 112011 (2021) arXiv:2109.01685

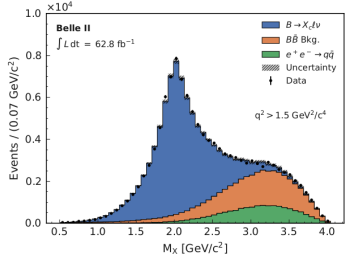


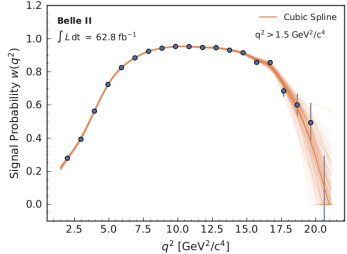
- first to fourth moment of q^2 spectrum determined
- no deviation between electron and muon mode observed
- moments for low q^2 slightly higher than simulated cocktail sample
  - indicating necessity to better understand contributions from heavier charmed final states and high multiplicity decays
  - currently covered by systematic uncertainties

Measurement of lepton mass squared moments in $B \to X_c \ell \nu_\ell$ decays with the Belle II experiment arXiv:2205.06372 (submitted to PRD)

- raw and central moments for $q^2 > 1.5\,\mathrm{GeV}^2/c^4$ up to $q^2 > 8.5\,\mathrm{GeV}^2/c^4$
- first measurement in range $[1.5,2.5]\,\mathrm{GeV}^2/c^4$
- exploit FEI for reconstruction of tag B meson (two times higher efficiency than Belle's algorithm)



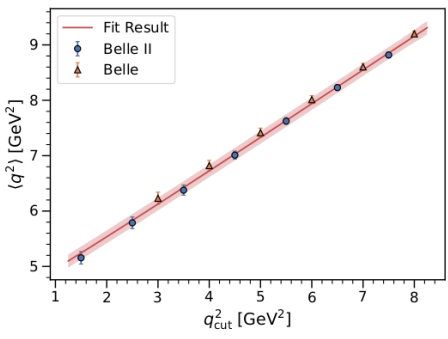


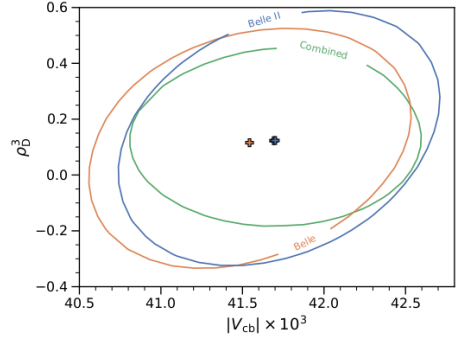


- kinematic fit significantly improves q^2 resolution
- signal probability fit with cubic spline

First extraction of inclusive V_{cb} from q^2 moments arXiv:2205.10274

- input: q^2 moment spectra of Belle and Belle II
- use $\mathcal{B}\,(B \to X_c \ell \nu_\ell) = (10.48 \pm 0.13)\,\%$
- HQE parameters and $|V_{cb}|$ determined in simultaneous χ^2 fit





- fit result: $|V_{cb}| = (41.69 \pm 0.63) \cdot 10^{-3}$

Prospects for semileptonic measurements

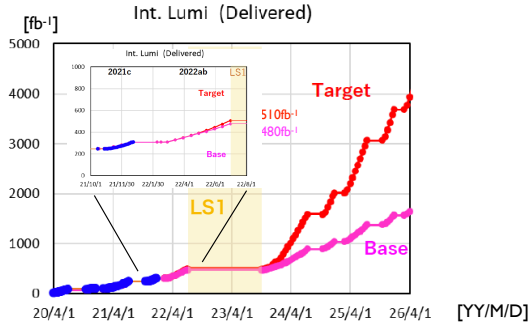
	Process	Observable	Theory	Sys. dom. (Discovery) [ab^{-1}] vs LHCb	vs Belle	Anomaly	NP
●	$B \to \pi \ell \nu_\ell$	$\lvert V_{ub} \rvert$	⋆⋆⋆	10-20	⋆⋆⋆	⋆⋆⋆	⋆⋆	⋆
●	$B \to X_u \ell \nu_\ell$	$\lvert V_{ub} \rvert$	⋆⋆	2-10	⋆⋆⋆	⋆⋆	⋆⋆⋆	⋆
●	$B \to \tau \nu$	$Br.$	⋆⋆⋆	>50 (2)	⋆⋆⋆	⋆⋆⋆	⋆	⋆⋆⋆
●	$B \to \mu \nu$	$Br.$	⋆⋆⋆	>50 (5)	⋆⋆⋆	⋆⋆⋆	⋆	⋆⋆⋆
●	$B \to D^{(*)} \ell \nu_\ell$	$\lvert V_{cb} \rvert$	⋆⋆⋆	1-10	⋆⋆⋆	⋆⋆	⋆⋆	⋆
●	$B \to X_c \ell \nu_\ell$	$\lvert V_{cb} \rvert$	⋆⋆⋆	1-5	⋆⋆⋆	⋆⋆	⋆⋆	⋆⋆
●	$B \to D^{(*)} \tau \nu_\tau$	$R(D^{(*)})$	⋆⋆⋆	5-10	⋆⋆	⋆⋆⋆	⋆⋆⋆	⋆⋆⋆
●	$B \to D^{(*)} \tau \nu_\tau$	P_τ	⋆⋆⋆	15-20	⋆⋆⋆	⋆⋆⋆	⋆⋆	⋆⋆⋆
●	$B \to D^{**} \ell \nu_\ell$	$Br.$	⋆	-	⋆⋆	⋆⋆⋆	⋆⋆	-

- $R(X)$: ratio of inclusive $\mathcal{B}$ ($B \to X \tau \nu$) to lower-mass lepton counterparts

Projection of integrated luminosity delivered by SuperKEKB to Belle II

Target scenario: extrapolation from 2021 run including expected improvements.

Base scenario: conservative extrapolation of SuperKEKB parameters from 2021 run



- We start long shutdown 1 (LS1) from summer 2022 for 15 months to replace VXD. There will be other maintenance/improvement works of machine and detector.
- We resume physics running from Fall 2023.
- A SuperKEKB International Taskforce (aiming to conclude in summer 2022) is discussing additional improvements.
- An LS2 for machine improvements could happen on the time frame of 2026-2027

Conclusion

- study of semileptonic decays reveals some tensions with SM
  - mystery about difference between inclusive and exclusive determination of V_{ub} and V_{cb}
  - deviation of $R(D/D^*)$ from SM expectation
- measurement of q^2 moments provide important input for global fit of inclusive $|V_{cb}|$
- inclusive measurement of $R\big(X_{e/\mu}\big)^{p_\ell^* > 1.3\ \mathrm{GeV}/c}$ will be presented by Koji Hara in joint HI/HF session on Saturday
- stay tuned for new results with more data collected by Belle II

Conclusion

- study of semileptonic decays reveals some tensions with SM
  - mystery about difference between inclusive and exclusive determination of V_{ub} and V_{cb}
  - deviation of $R(D/D^*)$ from SM expectation
- measurement of q^2 moments provide important input for global fit of inclusive $|V_{cb}|$
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Thanks for your attention!