Karlsruhe Institute of Technology

Belle II

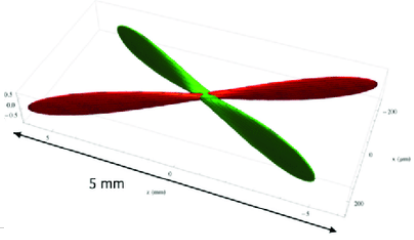
# Status and prospects for $|V_{ub}|$ and $|V_{cb}|$ at Belle II

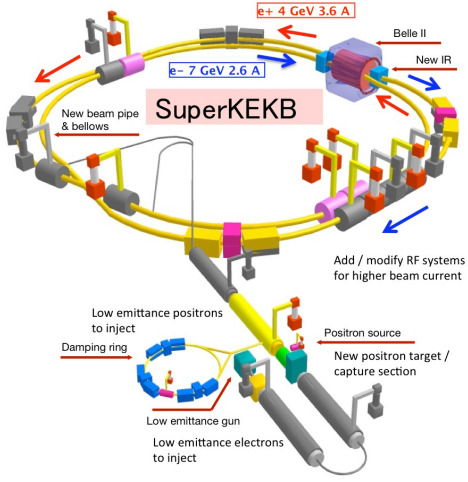
**14th Annual Meeting of the Helmholtz Alliance "Physics at the Terascale"**

Moritz Bauer | 23. November 2021

# World record luminosity: SuperKEKB accelerator

- $e^+e^-$ collider with $\sqrt{s} \approx 10.6\,\text{GeV}$ ($\Upsilon(4S)$ resonance)
- Peak luminosity (June 22): $3.1 \times 10^{34}\,\text{cm}^{-2}\,\text{s}^{-1}$ (+50% vs. KEKB)
  - In part thanks to nano-beam scheme.



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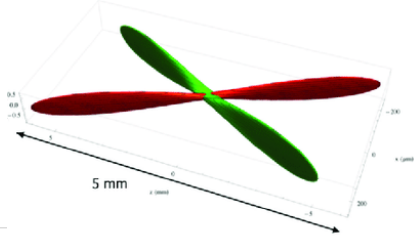
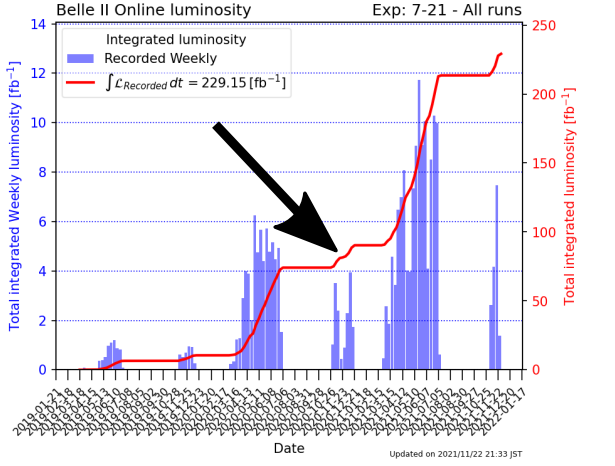
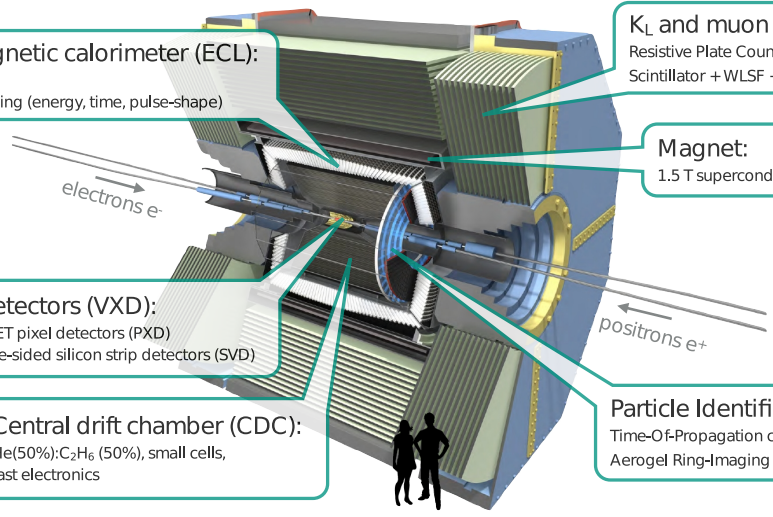
  - In part thanks to nano-beam scheme.
- Current recorded dataset: $\approx 229\,\text{fb}^{-1}$
  - Newest published analyses use $\approx 70\,\text{fb}^{-1}$.
  - Aiming for 50x of Belle's dataset ($50\,\text{ab}^{-1}$)



# The Belle II detector

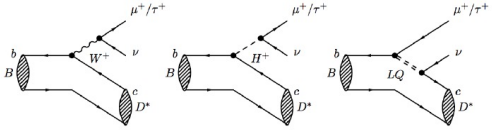


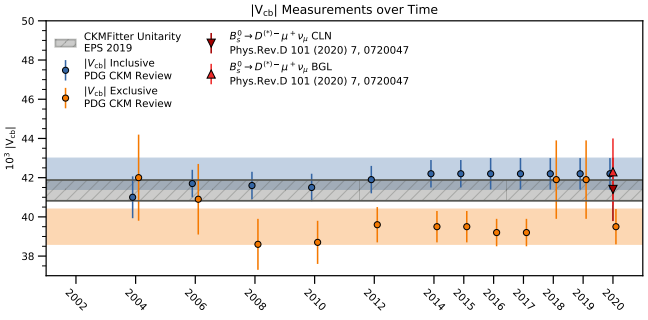

DEPFET: depleted p-channel field-effect transistor
WLSF: wavelength-shifting fiber
MPPC: multi-pixel photon counter

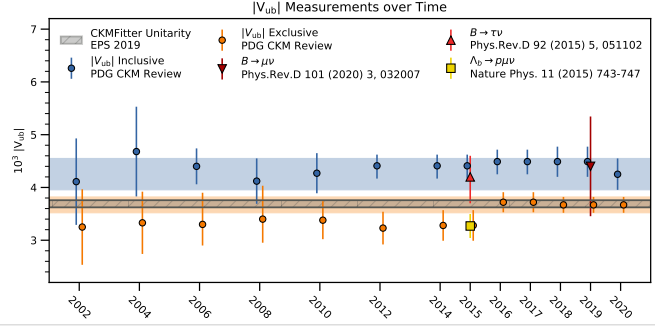
# $|V_{ub}|$ and $|V_{cb}|$

- Tension ($\approx 3.3\sigma$) between
  - **incl. (all B $\rightarrow$ X$\ell\bar{\nu}_\ell$)** and
  - **excl. (one b $\rightarrow$ x process)**

  measurements of $|V_{ub}|/|V_{cb}|$.
- $|V_{cb}|$ sensitive to charged Higgs in 2HD models or leptoquarks.



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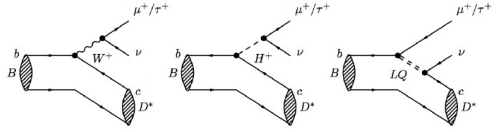
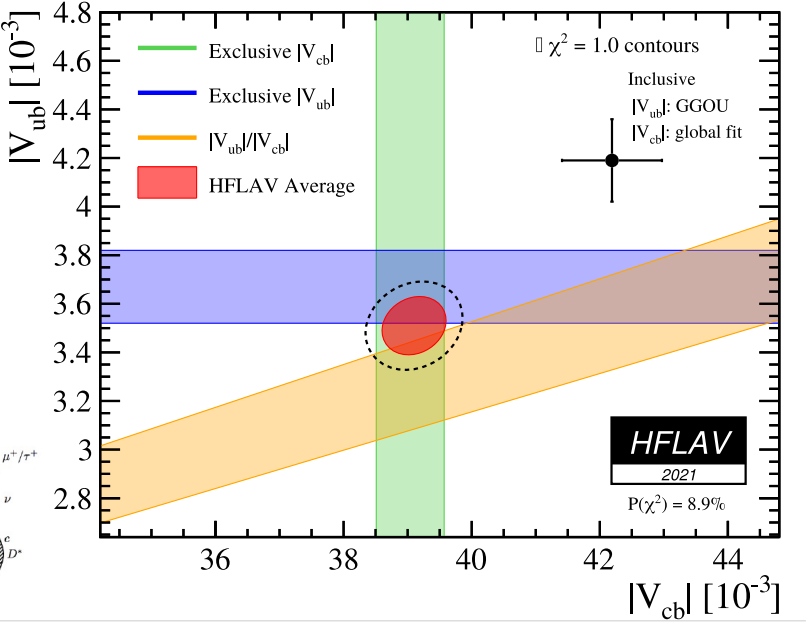
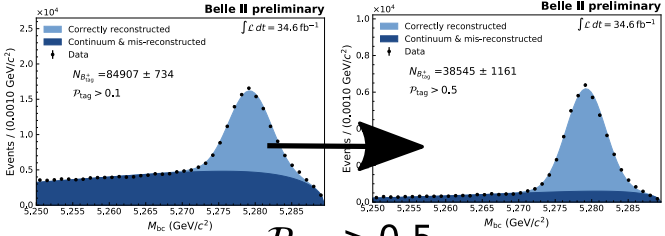


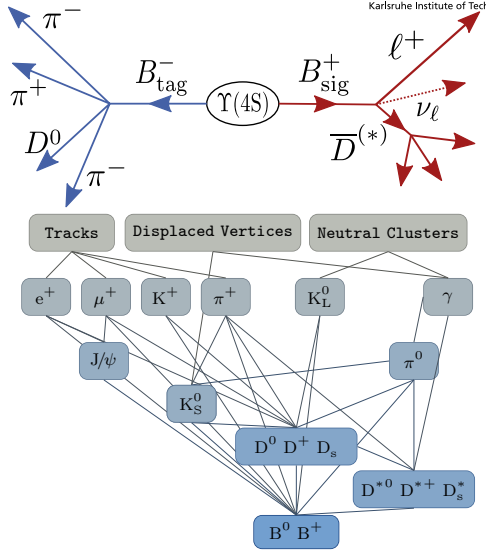



# Experimental techniques

- $e^-e^+$ collisions “clean” compared to pp.
- Tagging: Use 2nd B ($B_{tag}$) e.g. with Full Event Interpretation (FEI). Keck, T. et al. Comput Softw Big Sci 3, 6




$\mathcal{P}_{tag} > 0.5$ arXiv:2008.06096




- Alternative: Untagged with potentially all events.
  - Exclusive analyses can combine all non-signal particle candidates into “inclusive tag”.
  - Smaller systematic uncertainties can compete already (see $B^+ \to K^+ \nu\bar{\nu}$; PRL 127, 181802).

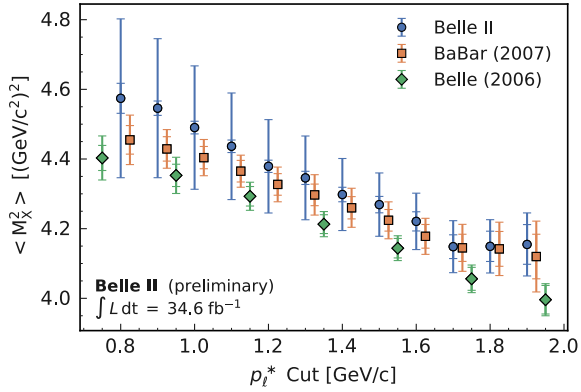
# Tagged inclusive B $\rightarrow X_c \ell \nu$

arXiv:2009.04493

- Measurement of first six mass moments $\langle M_X^n \rangle$ of the hadronic system.

- Background is subtracted with weight $\omega_i(M_X)$.
- To avoid unfolding, calibration between true and reconstructed mass is needed.
- Main systematic uncertainty from calibration factors influenced by $X_c$ composition.
- Next: $|V_{cb}|$ from $q^2$ moments (novel approach!).

Momentum transfer squared: $q^2 = (p_B - p_X)^2$



# Untagged inclusive B $\rightarrow X_c \ell \nu$

arXiv:2111:09405

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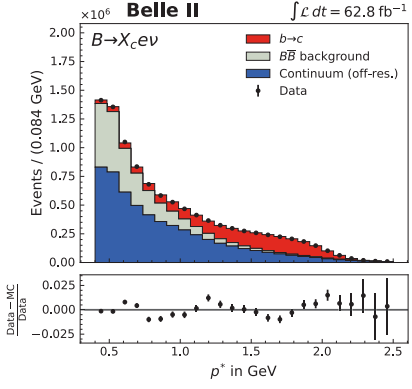
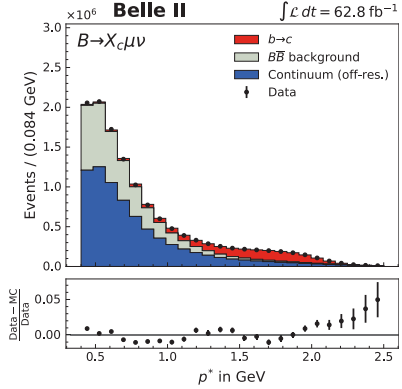
- Only signature: single (well identified) lepton.
  - Use missing mass/momentum and event charge to reject events with >1 neutrino.

- $e^- e^+ \rightarrow q\bar{q}$ modelled with separate off-resonance sample.
- Signal extraction in $p^*_{lep}$, from 0.4 GeV to 2.5 GeV.
- BF result: $(9.75 \pm 0.03_{stat} \pm 0.47_{sys})\%$
- Dominant sys. uncert. from $B \rightarrow X_c \ell \nu$ composition.
- Next: $|V_{cb}|$ from $q^2$ moments



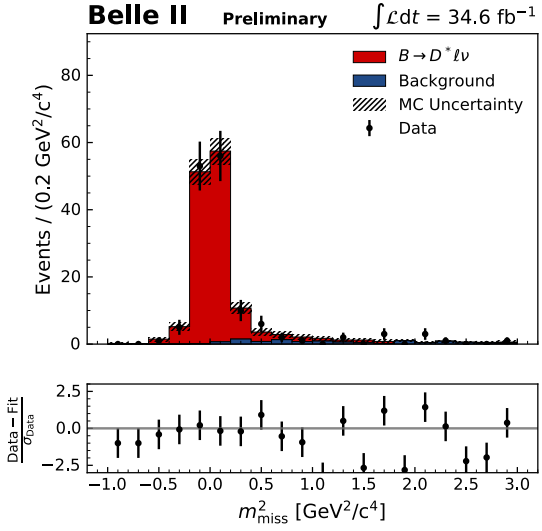
# Tagged exclusive $\overline{B}^0 \to D^{*+}(\to D^0\pi_s)\ell\nu$

arXiv:2008.10299

- Little background with $m_{D^*}$, $m_D$, $p_l^* > 1$ GeV and extra track cuts.
- Signal extraction in $M^2_{miss}$.

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

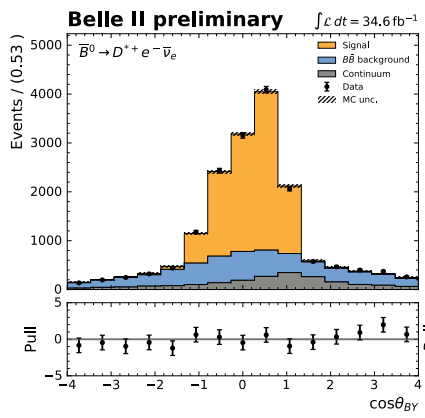
- BF: $(4.51 \pm 0.41_{stat} \pm 0.27_{syst} \pm 0.45_{\pi_s})\%$
  - In agreement with world average but not competitive yet.
- Main systematic: "slow" pion from $D^*$ and MC modelling.

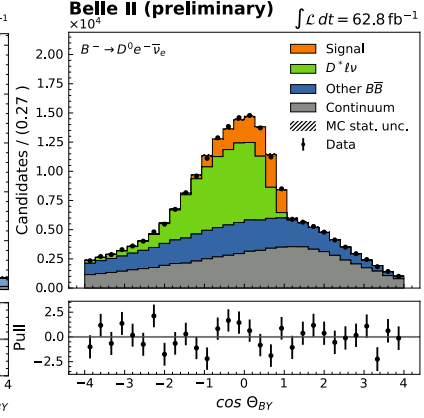


# Untagged exclusive B $\rightarrow$ D$^{(*)}\ell\nu$

arXiv:2008.07198

- Signal extraction in $\cos(\theta_{BY})$, the angle between D$^0\ell$ system and B meson from beam 4-momentum.
- BF (D): $(2.29 \pm 0.05_{\text{stat}} \pm 0.08_{\text{sys}})\%$
  - Consistent (and competitive!) with world average.
  - Next: $|V_{cb}|$ from partial BF in bins of $q^2$.



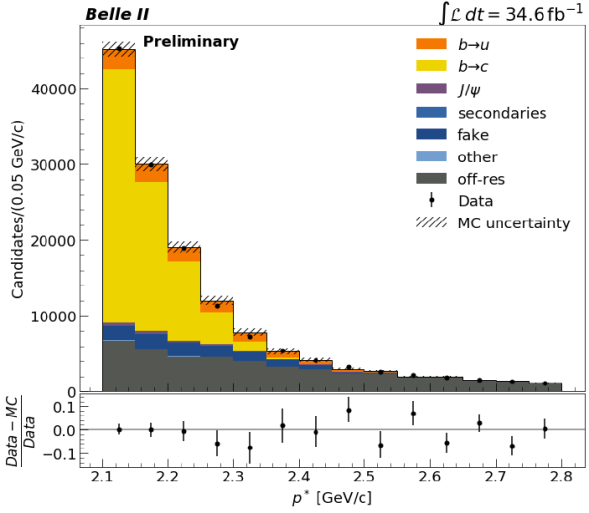



# Untagged inclusive B $\rightarrow X_u \ell \nu$

arXiv:2103.02629

- Signal extraction in electron momentum in center-of-mass frame $p^*$.
- Signature also only a single well identified lepton (like $B \rightarrow X_c \ell \nu$).

  $\rightarrow$ go to $p^*$ endpoint (2.1 GeV to 2.8 GeV).
- $B \rightarrow X_u \ell \nu$ observed with $\approx 3\sigma$.



# Tagged exclusive B $\to X_u \ell\nu$, $X_u = \{\pi^+, \pi^0, \rho^+, \rho^0\}$

arXiv:2111.00710

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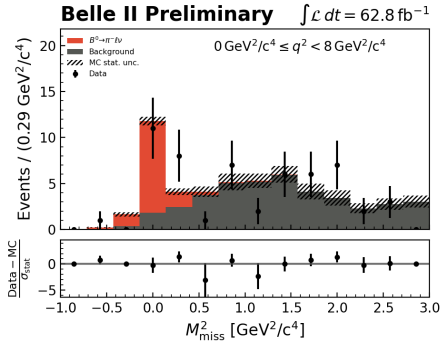
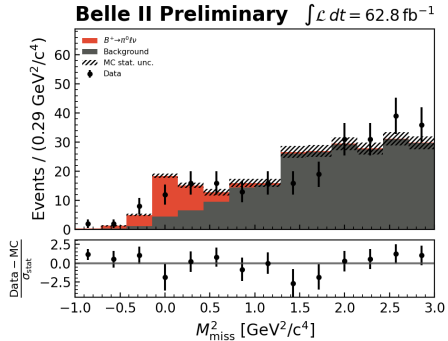
- $\mathcal{B}(B \to \pi^0 \ell\nu) = (8.29 \pm 1.99_{stat} \pm 0.46_{sys}) \times 10^{-5}$

- $B \to \pi^{+,0} \ell\nu$ re-discovered with $> 6\sigma$.
- $\mathcal{B}(B \to \pi^+ \ell\nu)$ in bins of $q^2$.
- Next: $|V_{ub}|$.
- Also first (stat. limited) results for $B \to \rho \ell\nu$.




$B \to \pi^+ \ell\nu$ in first $q^2$ bin

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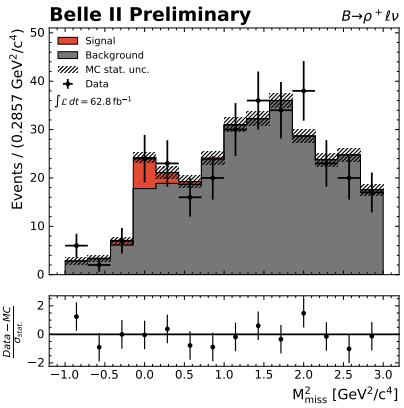


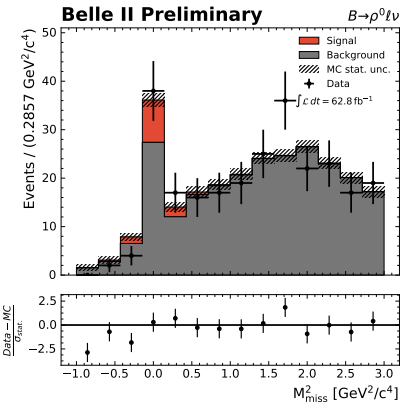

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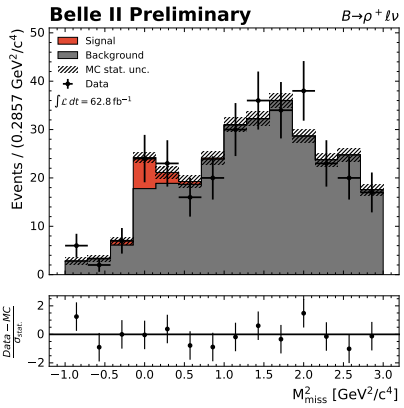
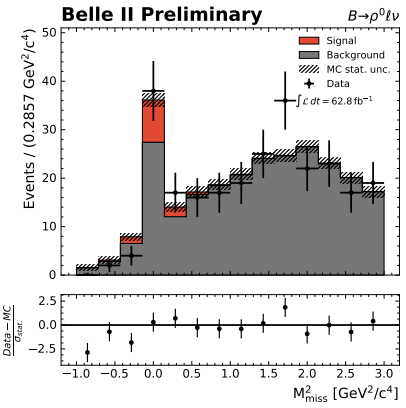
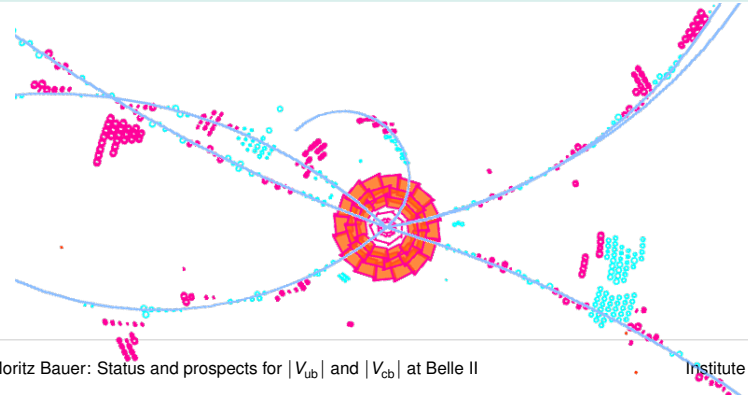
- $\mathcal{B}(B \to \pi^+ \ell\nu)$ in bins of $q^2$.
- Next: $|V_{ub}|$.
- Also first (stat. limited) results for $B \to \rho \ell\nu$.
- Untagged excl. measurement of $|V_{ub}|$ in progress.



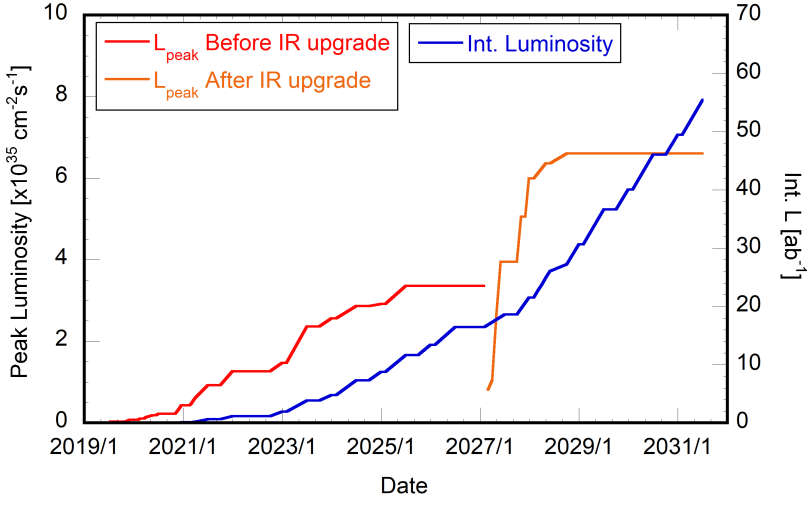
# Summary

- Shown today: 6 analyses
  - Using up to 1/4 of currently recorded dataset.
  - Untagged BF measurements already competitive thanks to new techniques.
  - Tagged measurements need some more data but more competitive thanks to FEI.
- Soon, Belle II should be able to address the tension in $|V_{cb}|$ and $|V_{ub}|$ measurements.



# Backup

# Luminosity projection

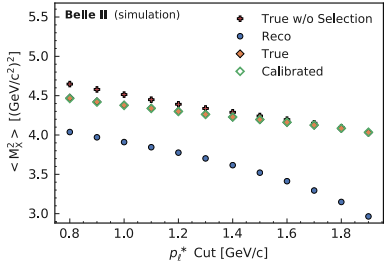


# Tagged inclusive B $\rightarrow X_c \ell \nu$ in detail

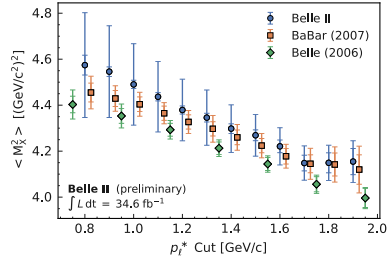
- Measurement of first six mass moments $\langle M_X^n \rangle$ of the hadronic system arXiv:2009.04493

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

- Background is subtracted with weight $\omega_i(M_X)$.
- To avoid unfolding, calibration between true and reconstructed mass is needed.
- Main systematic uncertainty from bias correction $\mathcal{C}_{true}$.
- $|V_{cb}|$ from $q^2$ moments (novel approach!) ongoing.




$M_X$ calibration




$M_X^2$ results