B Physics at Belle II: Status and Prospecs

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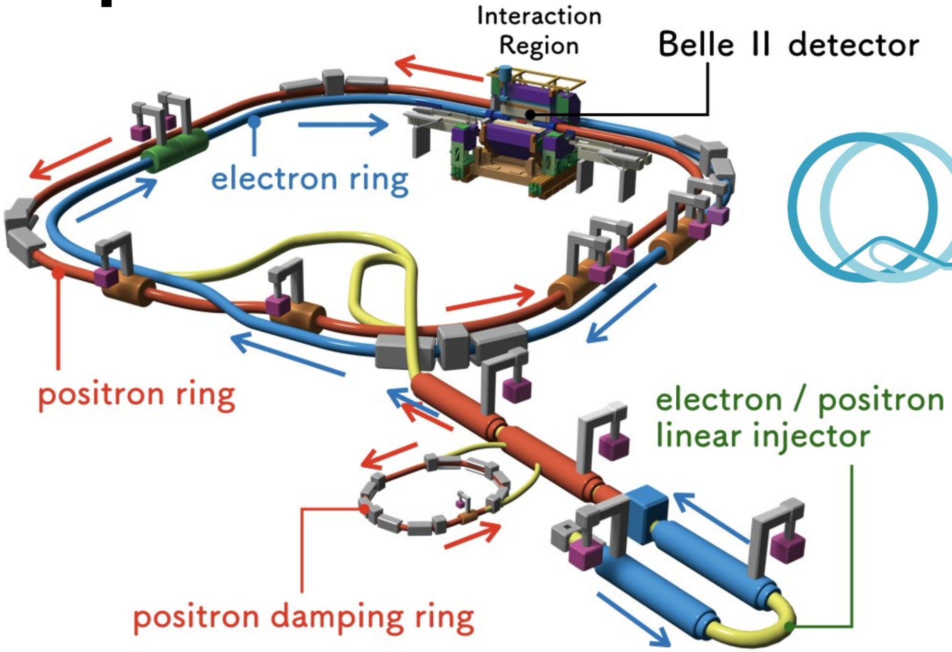
on behalf of the Belle II collaboration

The Flavour Path to New Physics
University of Zurich
05/06/2024

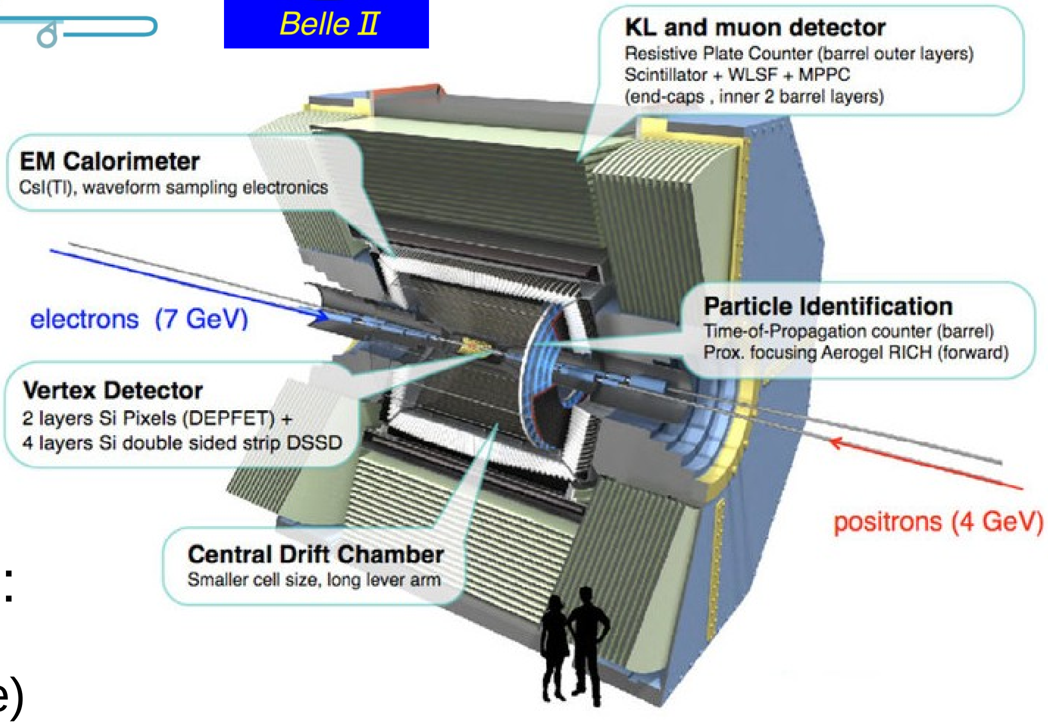
Outline

- Beautiful B factories
- B physics highlights
  - CKM and CP violation
  - Tests of lepton-flavour universality and rare decays
  - Evidence for $B^+ \to K^+ \nu\bar{\nu}$
- Prospects

Super KEKB and Belle II



- Vertexing: PXD+SVD
- Tracking: CDC
- K and π: RICH + TOP
- γ and e: ECL
- μ and K^0_L: KLM



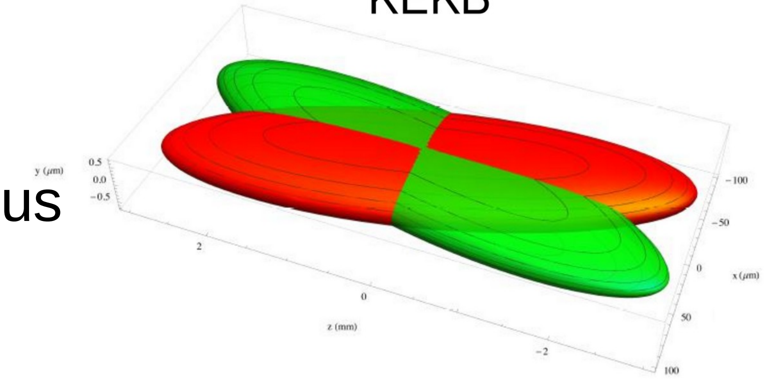
- $\beta\gamma \sim 0.284$
- $BR(\Upsilon(4S) \rightarrow B\bar{B}) > 96\%$
- coherent B-meson pair production:
  - one B to determine flavour (tag side)
  - other B for CP measurement (CP side)

Super KEKB and Belle II

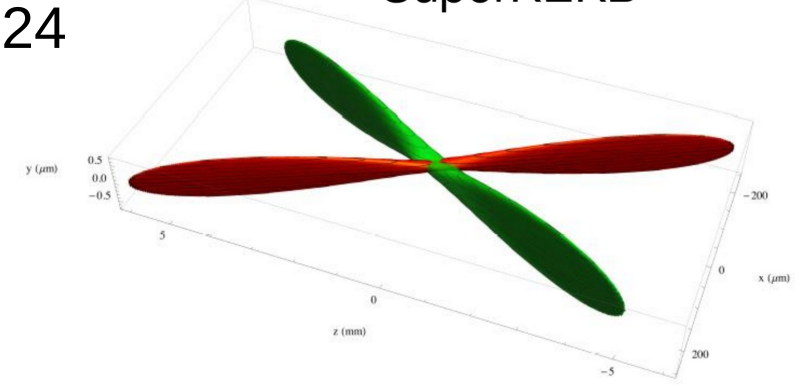
SuperKEKB + Belle II@KEK, Tsukuba

- nanobeam scheme to increase instantaneous luminosity by factor 30
  - to collect multi-ab^{-1} sample
  - world record 4.7×10^{34} cm^{-2}s^{-1}
- Shutdown from summer 2022 until Feb 2024
  - for accelerator upgrades to mitigate background and increase luminosity
- Detector upgrades too
  - two-layer pixel detector installed
- Path to 2×10^{35} cm^{-2}s^{-1}
  - but new final focus to go beyond
  - proposed upgrade from 2028+

KEKB



SuperKEKB



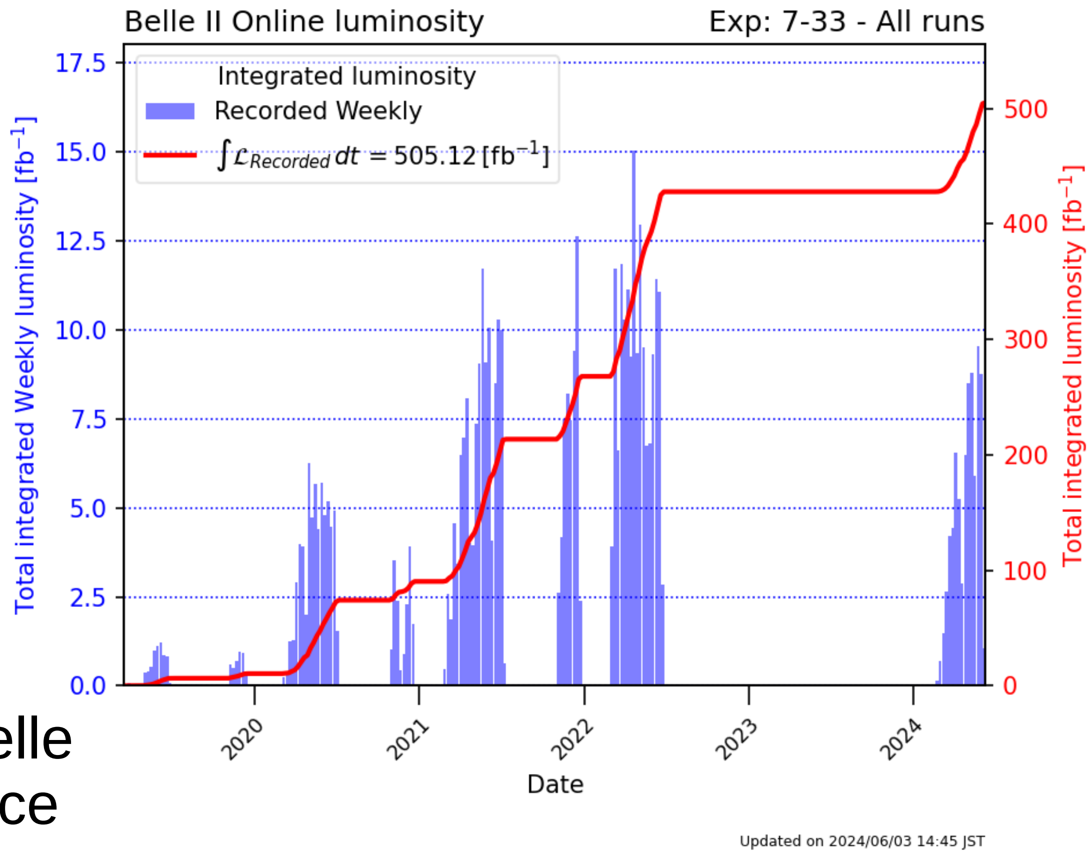
KEK status and luminosity

Belle II collected:

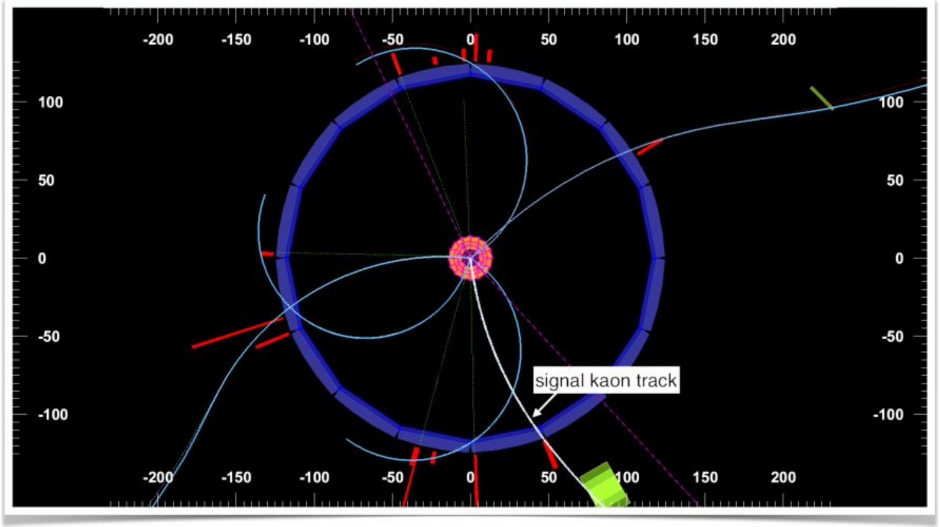
- 505 fb^{-1} up to Monday
  - Run 1 + Run 2

Belle II Run 1 is:

- 362 fb^{-1} at Υ(4S)
  - equivalent to BaBar and ~1/2 of Belle
  - current results on this
- 42 fb^{-1} of off-resonance data [60 MeV below Υ(4S)]
  - compared to ~90 fb^{-1} from Belle
- 19 fb^{-1} above the Υ(4S) resonance



Events at the B Factories:



$$B^+B^-(51.4\pm0.6)\%, \quad B^0\overline{B}^0(48.6\pm0.6)\%$$

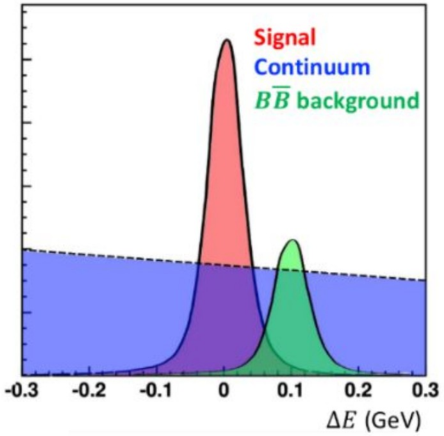
$$\sigma(e^+e^-) \to \Upsilon(4S) = 1.1 \text{ nb}$$
$$\sigma(e^+e^-) \to c\bar{c} = 1.6 \text{ nb}$$
$$\sigma(e^+e^-) \to u\bar{u} = 1.3 \text{ nb}$$

- Clean environment with on average ~10-15 tracks, 3-4 π^0
- Known initial state kinematics

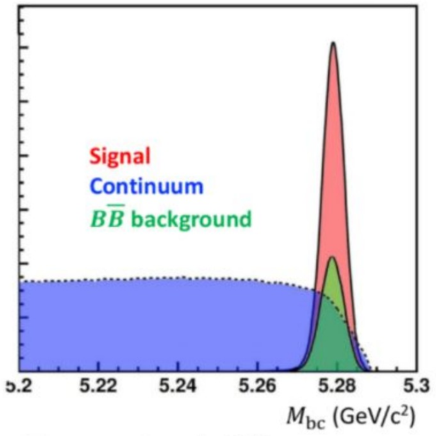
- Principal background from light quark (continuum)
- Near 100% efficiency for B decays

Events Kinematics:

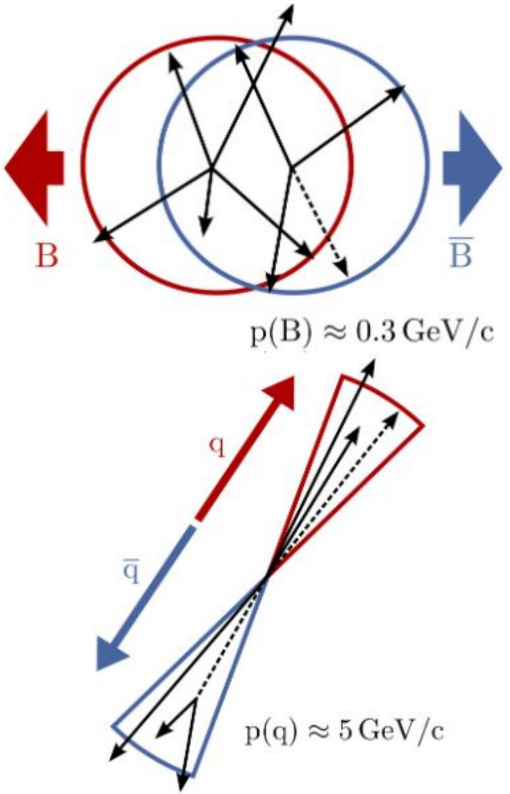
$$\Delta E = E_B^* - \sqrt{s}/2 \qquad M_{bc} = \sqrt{(\sqrt{s}/2)^2 - |\vec{p}_B^{\,*}|^2}$$



Expected ΔE = 0

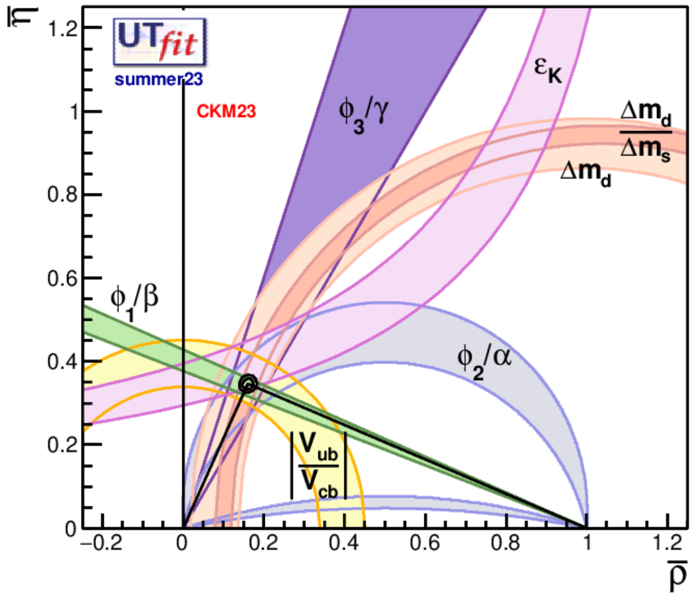


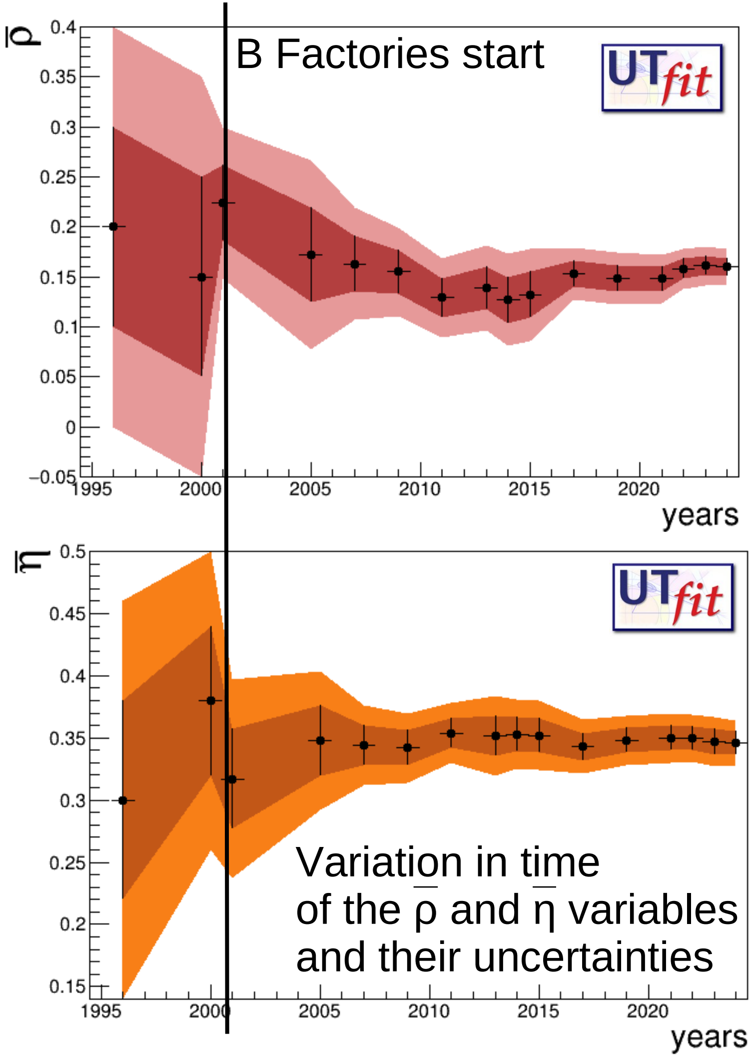
Expected $M_{bc} = m_B$



- B-factory-specific variables to exploit information on initial kinematics
- Different event shape to separate B events from continuum background

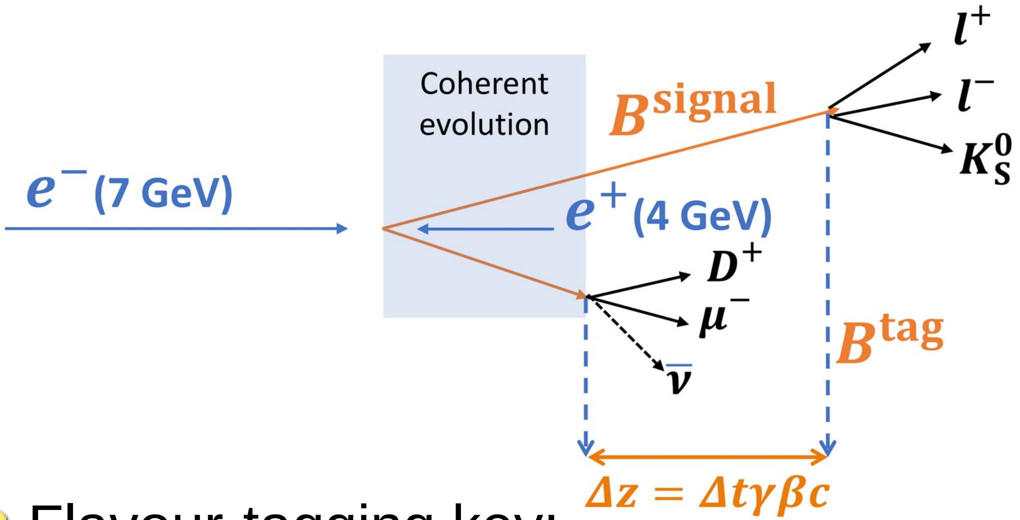
CKM and CP violation

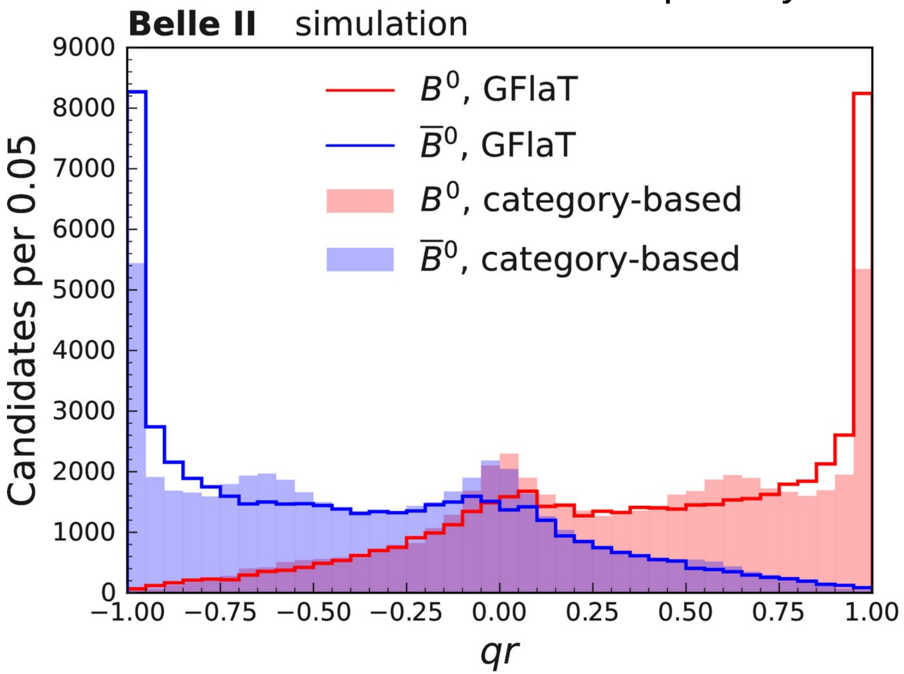




Flavour Tagging improvement:

arXiv:2402.17260
Accepted by PRD





- Flavour-tagging key:
  - leptons, kaons,
    high momentum tracks, etc

Graph-neural-network approach has improved tagging efficiency by 18% relative to the previous approach: effective efficiency = 37.4 %

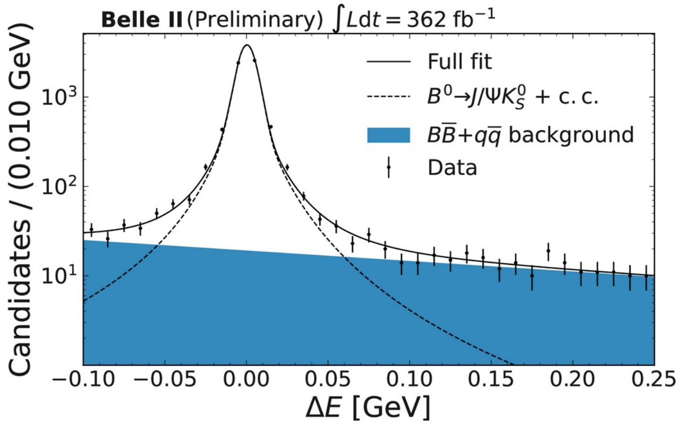
sin(2ϕ₁/β) from B → J/φKs

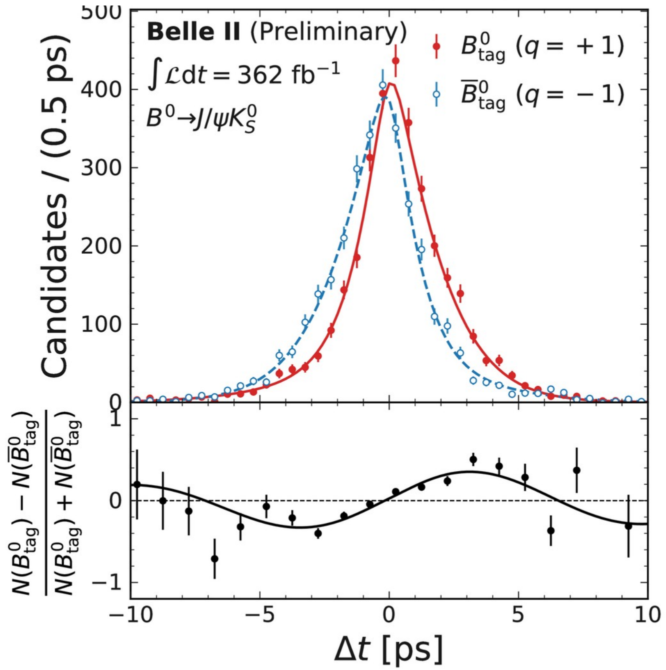
arXiv:2402.17260
Accepted by PRD

- Exploited this new tagging to update the golden channel
- Fit ΔE distribution to subtract background
- Fit background-subtracted Δt distribution to extract CPV parameters

$$\mathcal{A}(\Delta t) = S\sin(\Delta m_d \Delta t) - C\cos(\Delta m_d \Delta t)$$

  - S = 0.724 ± 0.035 ± 0.014
  - C = − 0.035 ± 0.026 ± 0.013
- To be compared to WA:
  - S = 0.695 ± 0.019
  - C = 0.000 ± 0.020
- **Statistical uncertainties 8% smaller than with category-based Flavour Tagger**

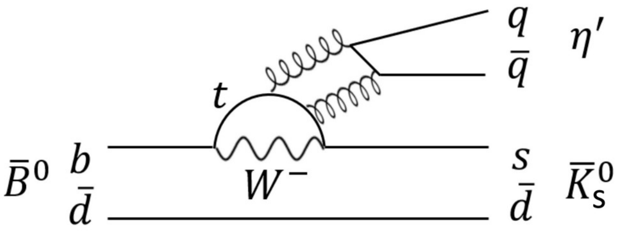




Time-dependent CP violation: $B^0 \rightarrow \eta' K_S$

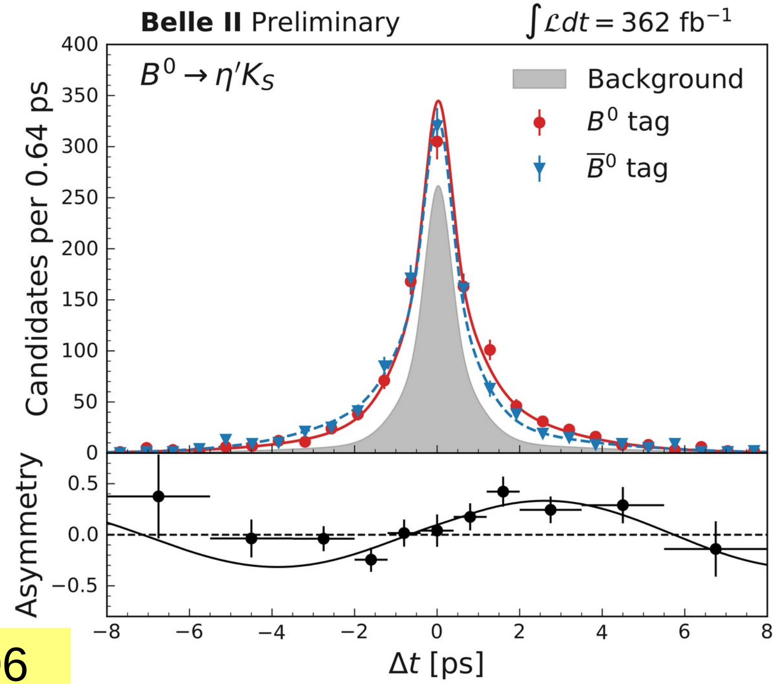
arXiv:2402.03713

- Decay may also have a BSM phase as it is a gluonic penguin
  - alter the value of ϕ_1 from the $b \rightarrow c\bar{c}s$ transitions such as $B0 \rightarrow J/\varphi K_S^0$



- Reconstructing $\eta' \rightarrow \eta(\gamma\gamma)\pi^+\pi^-$ and $\eta' \rightarrow \rho(\pi^+\pi^-)\gamma$
  - we select 829 ± 35 events in 362 fb^{-1}
  - 3D fit to ΔE, M_{bc} and continuum suppression output

- **$\sin 2\phi'_1 = 0.67 \pm 0.10 \pm 0.04$**
- Consistent with current HFLAV average and that from $b \rightarrow c\bar{c}s$ result



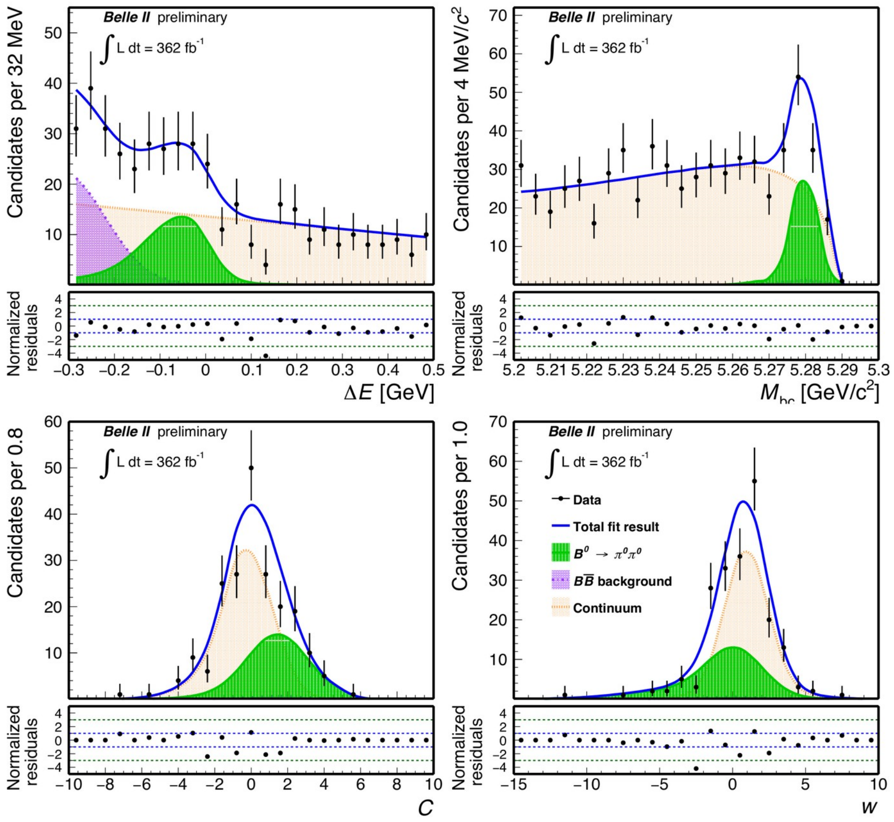
$\sin 2\phi'_1$ (HFLAV) = 0.63 ± 0.06

Towards ϕ_2/α : $B^0 \to \pi^0\pi^0$

New for FPCP
Paper in preparation

- Only possible at a B factory!
- Update on BR and A_{CP}
  - full Run-1 statistics
- Improved selections, new flavour tagger (GFlaT), reduction of systematics
  - 4D fit including M_{bc}, ΔE, continuum suppression (C), and w (wrong tag probability - unbinned)
- Results:
  - BR = $(1.26 \pm 0.20 \pm 0.11) \times 10^{-6}$
  - $A_{CP} = 0.06 \pm 0.30 \pm 0.06$

126±20 signal events



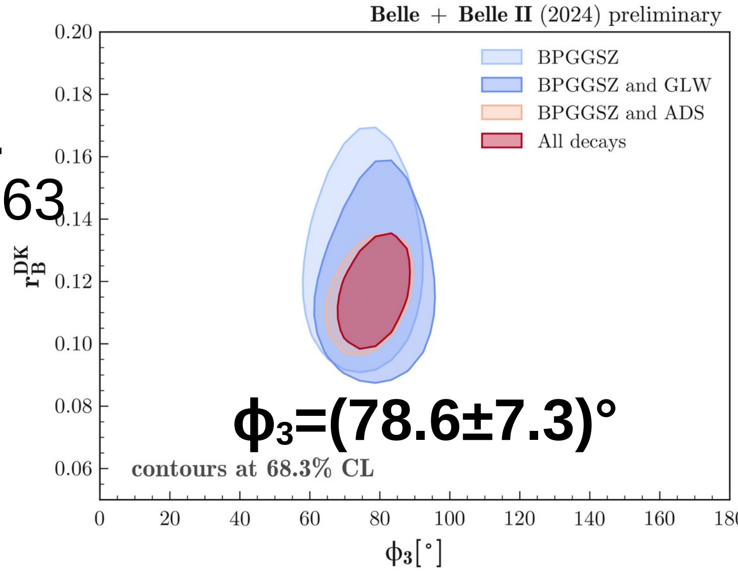
World-best BR determination
A_{CP} on par with world best

ϕ_3/γ: Belle/Belle II combined results

arXiv:2404.12817

- Several methods used
  - GLW $B^\pm \to D^0_{CP}K^\pm$: arXiv:2308.05048
    - Use **CP eigenstates of D meson**
  - ADS: PRL 78 (1997) 3257
    - Enhancement of CP violation by using **doubly Cabibbo suppressed decays**.
  - BPGGSZ $D^0 \to K_S h^+ h^-$: JHEP 2022(2022), 63
    - Different amplitude and strong phase in different region of **Dalitz plot**.
  - GLS $\mathbf{D^0 \to K_S K\pi}$: JHEP 09(2023)146
    - Singly Cabibbo-suppressed D decays
- Likelihood with 60 input observables
  - including 15 auxiliary inputs (D-decay)
  - 16 free parameters

LHCb: $\phi_3=(63.8\pm3.6)°$ (LHCb-CONF-2022-003)
Few ab^{-1} needed at Belle II for similar statistical result



$\phi_3=(78.6\pm7.3)°$

Some level of discrepancy in correlated parameters r_B (2.2σ) and δ_B (4.0σ) wrt WA

First measurement of B →K*(892)ɣ

Paper in preparation

- Flavour changing neutral current decays sensitive to new physics
- First observed FCNC decay [PRL 71 (1993) 674]
- CP (A_{CP}) and isospin (Δ_{+0}) asymmetries are theoretically clean thanks to form factor cancellations
- Asymmetries are ideal for BSM searches
  - PRD 88 (2013) 094004, PRL 106 (2011) 141801
- Belle measurement found evidence of isospin asymmetry at 3.1σ
  - PRL 119 (2017) 191802

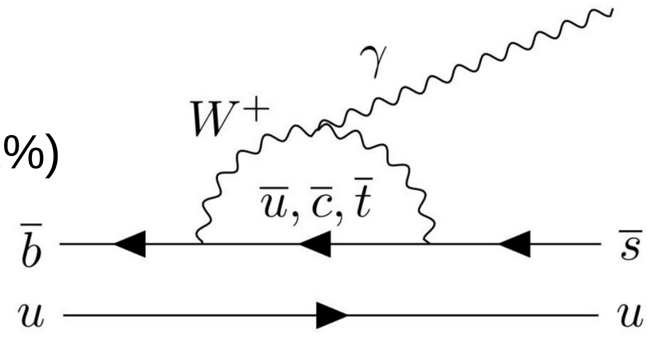
$$A_{CP} = \frac{\Gamma(\bar{B} \to \overline{K^*}\gamma) - \Gamma(B \to K^*\gamma)}{\Gamma(\bar{B} \to \overline{K^*}\gamma) + \Gamma(B \to K^*\gamma)}$$

SM prediction is small (~1%)

$$\Delta A_{CP} = A_{CP}(B^0 \to K^{*0}\gamma) - A_{CP}(B^+ \to K^{*+}\gamma)$$

$$\Delta_{+0} = \frac{\Gamma(B^0 \to K^{*0}\gamma) - (B^+ \to K^{*+}\gamma)}{\Gamma(B^0 \to K^{*0}\gamma) + (B^+ \to K^{*+}\gamma)}$$

SM prediction: 4.9 ± 2.6%
[PRD 88 (2013) 094004]



First measurement of B → K*(892)γ

- Analysis based on Run-1 data (362 fb^{-1})
- Reconstruct $K^* \rightarrow K^+ \pi^-$, $K^0_S \pi^0$, $K^+ \pi^0$, $K^0_S \pi^-$
- Combine K* with a prompt photon to get B candidate

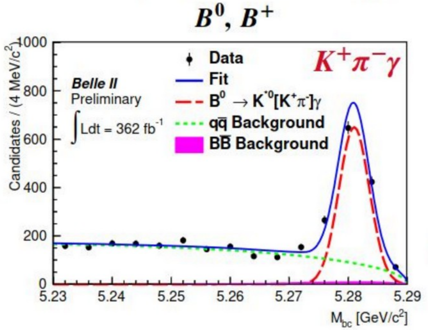
Fit strategy

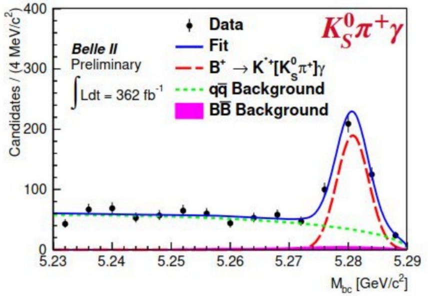
- Perform 2D fit to ΔE and M_{bc} to extract signal yield

Results:

- Consistent with world average and SM
- Asymmetries are statistically limited
- Similar sensitivity to Belle result despite half the data
  - Thanks to improved K^0_S efficiency, continuum suppression, and addition of ΔE to fit model)

Paper in preparation





$$\mathcal{B}[B^0 \rightarrow K^{*0}\gamma] = (4.16 \pm 0.10 \pm 0.11) \times 10^{-5},$$

$$\mathcal{B}[B^+ \rightarrow K^{*+}\gamma] = (4.04 \pm 0.13 \pm 0.13) \times 10^{-5},$$

$$\mathcal{A}_{CP}[B^0 \rightarrow K^{*0}\gamma] = (-3.2 \pm 2.4 \pm 0.4)\%,$$

$$\mathcal{A}_{CP}[B^+ \rightarrow K^{*+}\gamma] = (-1.0 \pm 3.0 \pm 0.6)\%,$$

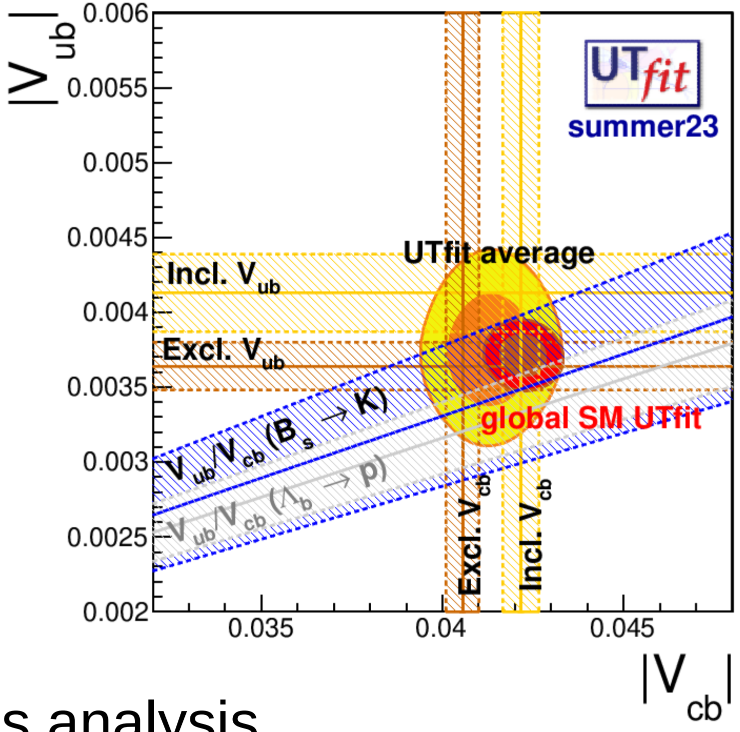
$$\Delta\mathcal{A}_{CP} = (2.2 \pm 3.8 \pm 0.7)\%,$$

$$\Delta_{0+} = (5.1 \pm 2.0 \pm 1.0 \pm 1.1)\%$$

Uncertainty:
stat. + sys. + f_{+-}/f_{00} (for Δ_{0+})

CKM matrix element V_{cb} abd V_{ub}:

- Long standing tension between inclusive and exclusive measurements
- Extracted from BF measurement of beauty hadron semi-leptonic decays:
  - With exclusive decays:
    - $BR(B \to H_q \ell \nu) \leftarrow |V_{qb}|2\ FF(q2)$
    - Theory input: Form factors
  - Or with inclusive decays:
    - $BR(B \to X_q \ell \nu) \leftarrow |V_{qb}|2\ (1+..)$
    - Theory input: OPE expansion



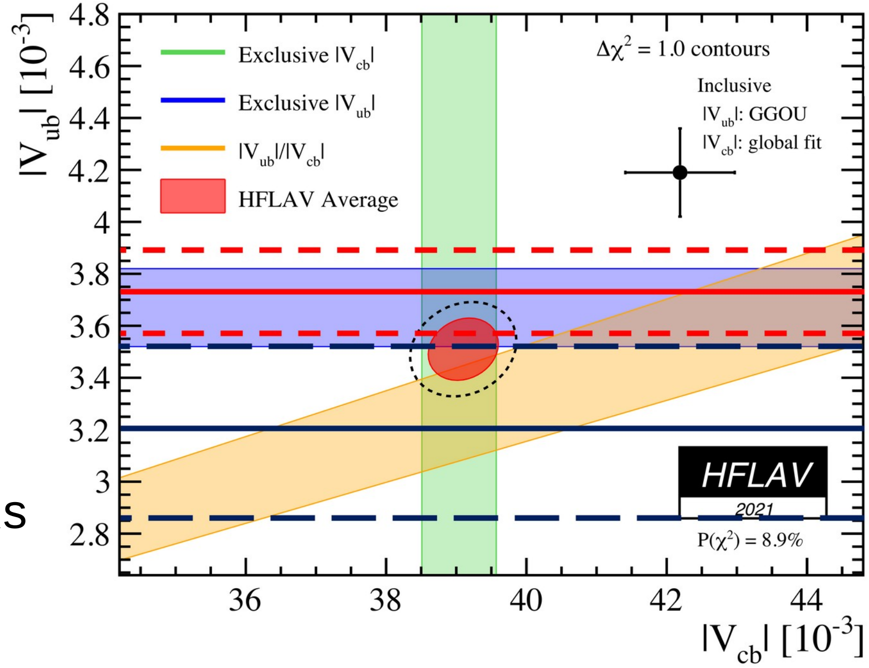
- Latest from Belle II:
  - $|V_{ub}|$ from exclusive decays:
    - From $B \to \pi \ell \nu$ and $B \to \rho \ell \nu$ simultaneous analysis
    - Belle II new result at Moriond 2024

CKM matrix element V_{cb} abd V_{ub}:

new at Moriond
Paper in preparation

$|V_{ub}|$ from $B \to \pi \ell \nu$ and $B \to \rho \ell \nu$ simultaneous analysis

- On full Run-1 dataset of 364 fb^{-1}
- Untagged reconstruction of $B \to \pi \ell \nu$ and $B \to \rho \ell \nu$
- Extract signal yields with simultaneous 3D fit in $(13 + 10) \times 4 \times 6$ bins of $q^2 \times M_{bc} \times \Delta E$
  - include signal cross-feeds and correlations with backgrounds
- Partial branching ratios from fitted yield in each q^2 bin and reconstruction efficiency
  - Total branching ratio: sum of all the partial BRs
- Estimate $|V_{ub}|$ from the partial BRs along with theoretical calculations of the form factors



$$B^0 \to \pi^+ l\nu : |V_{ub}|_{LQCD} = (3.93 \pm 0.09_{stat} \pm 0.13_{syst} \pm 0.19_{theo})\times 10^{-4}$$

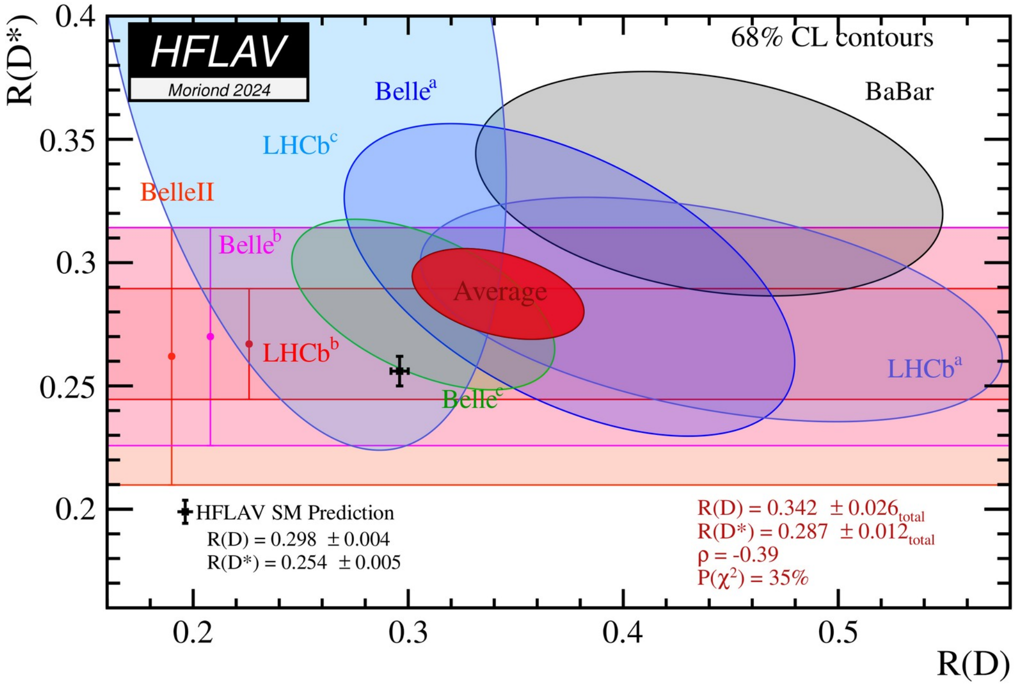
$$|V_{ub}|_{+LCSR} = (3.73 \pm 0.07_{stat} \pm 0.07_{syst} \pm 0.16_{theo})\times 10^{-4}$$

$$B^+ \to \rho^0 l\nu : |V_{ub}|_{LCSR} = (3.19 \pm 0.12_{stat} \pm 0.17_{syst} \pm 0.26_{theo})\times 10^{-4}$$

HFLAV = $(3.67 \pm 0.15) \times 10^{-3}$
$B \to \pi \ell \nu$ = $(3.73 \pm 0.16) \times 10^{-3}$
$B \to \rho \ell \nu$ = $(3.19 \pm 0.33) \times 10^{-3}$

To be compared with:
$|V_{ub}|$ *(incl)* = $(4.13 \pm 0.26)\ 10^{-3}$

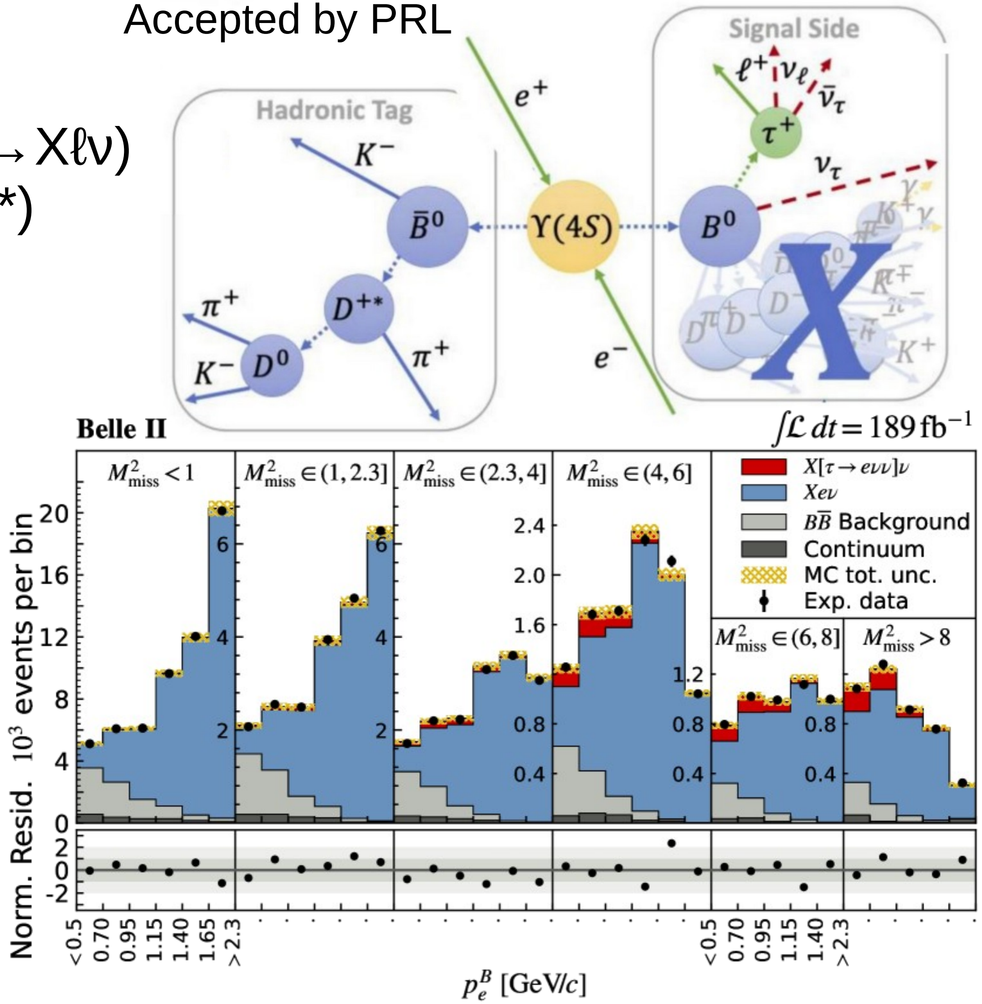
Lepton flavour/universality violation and rare decays



Measurement of R(X)

arXiv:2311.07248
Accepted by PRL

- Inclusive ratio R(X) = BR(B→Xτν)/BR(B→Xℓν)
  - A complementary alternative to R(D(*))
- Hadronic-tagging method with 189 fb−1
  - Hadronic tag pioneered by BaBar
    PRL 92 071802
  - MVA version at Belle II
    Comput. Softw. Big Sci. 3 (2019) 1, 6
- Use missing-mass squared and
  B candidate momentum to extract signal
- Background templates calibrated
  to control samples and sidebands

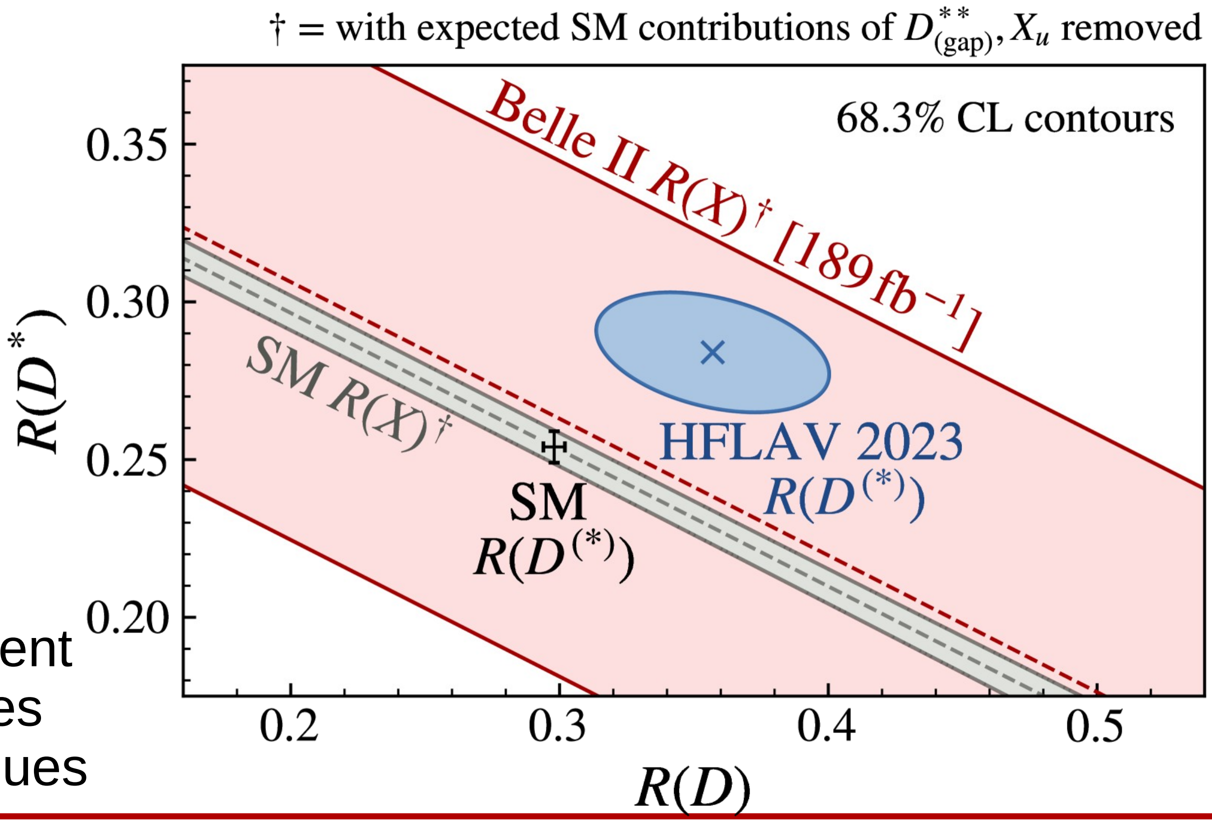


Measurement of R(X)

arXiv:2311.07248
Accepted by PRL

- Result agrees with SM prediction
  - $R(X)_{SM} = 0.223 \pm 0.005$
- Constraints inferred on R(D(*)) are weak, but:
  - Statistics-dominated, with <0.4% of target dataset.
  - Also systematics are statistics-dominated
  - Independent of R(D*) measurement: ~0.4% of statistical overlap, different theory description and different observable
- Belle II developed an independent new test of the $b \rightarrow c\tau\nu$ anomalies driven by new inclusive techniques

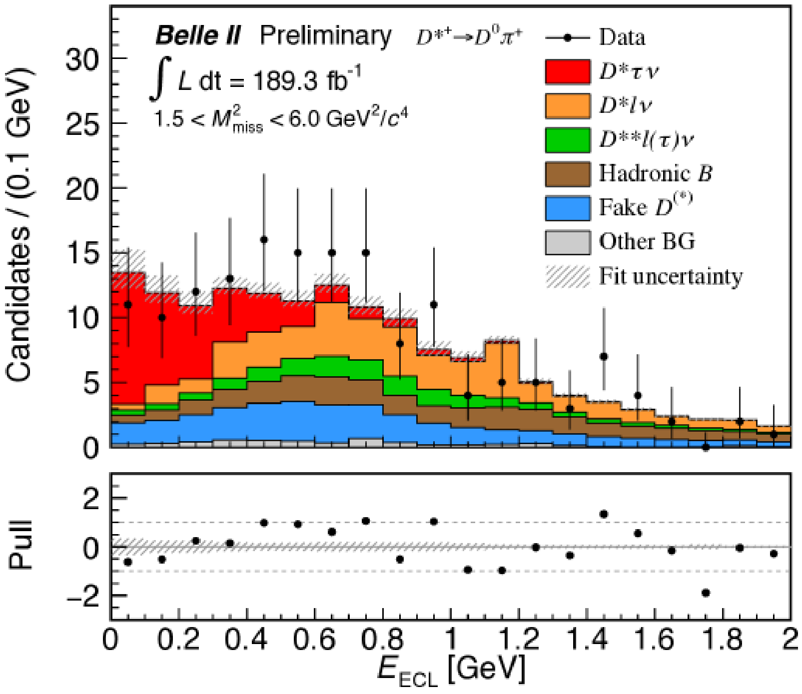
R(X)=0.228 ± 0.016 (stat) ± 0.036 (syst)



Measurement of R(D*)

arXiv:2401.02840

- Consider three signal modes: $D^{*+} \rightarrow D^0\pi^+$ and $D^+\pi^-$, $D^{*0} \rightarrow D^0\pi^0$
- Identify lepton from $\tau \rightarrow \ell\nu\bar{\nu}$
- Completeness constraint require no additional tracks or π^0 candidates.
- Main challenge:
  - poorly known $B \rightarrow D^{**}\ell\nu$ background
  - data-driven validation of background
  - and signal modelling based on sidebands.
- Extract signal with 2D fit to residual energy in the calorimeter E_{ECL} and mass of undetected neutrinos $M^2_{miss} = (p_{ee} - p_{Btag} - p_{D*} - p_\ell)^2$



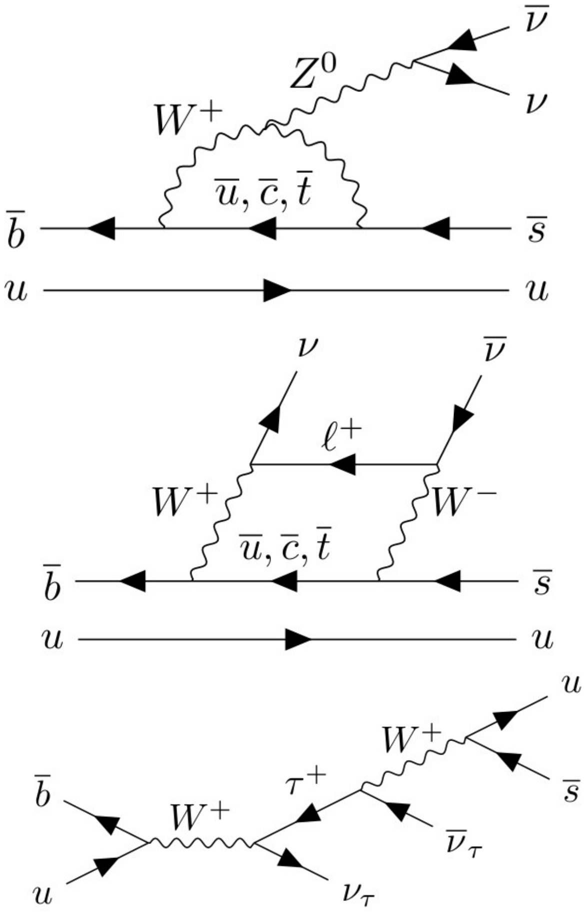
$$R(D^*) = 0.262\ ^{+0.041}_{-0.039}(\text{stat})\ ^{+0.035}_{-0.032}(\text{syst})$$

HFLAV 23: $R(D^*) = 0.284 \pm 0.013$
Eur. Phys. J. C 81, 226 (2021)

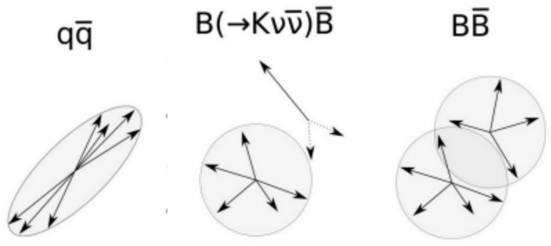
Probing $B^+ \to K^+\nu\bar{\nu}$

arXiv:2311.14647
Accepted PRD

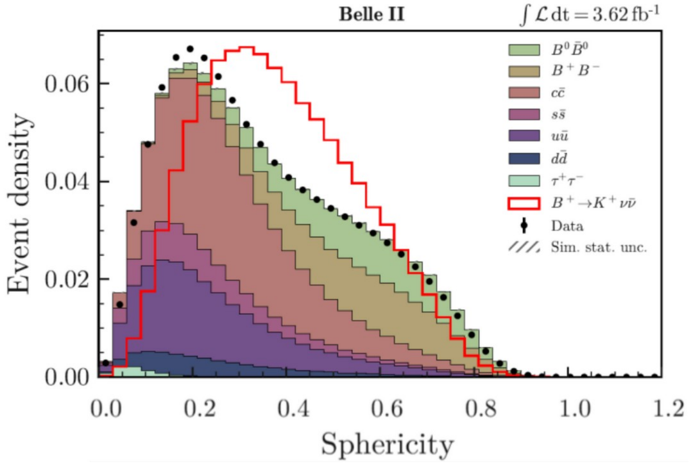
- Well known in SM but very sensitive to BSM enhancements – 3rd gen
  - $B(B^+ \to K^+\nu\nu) = (5.6 \pm 0.4) \times 10^{-6}$ [arXiv:2207.13371]
- Challenging experimentally
  - Low branching fraction with large background
  - No peak – two neutrinos leads to no good kinematic constraint
- Advantages at Belle II:
  - Constraints from initial state kinematics;
  - Lower average multiplicity at the Υ(4S) compared to hadronic collisions.
- NP scenarios:
  - Light: axions, dark scalars, axion-like particles
  - Heavy: Z’, leptoquarks



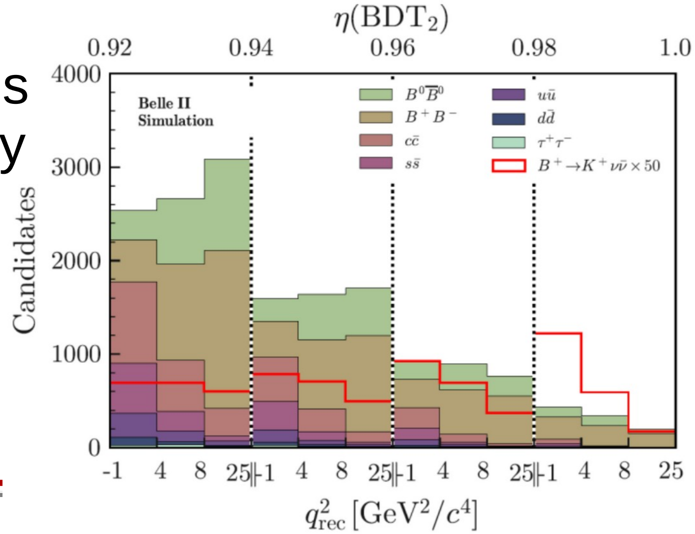
$B^+ \to K^+ \nu\bar{\nu}$ analysis strategy



arXiv:2311.14647
Accepted PRD



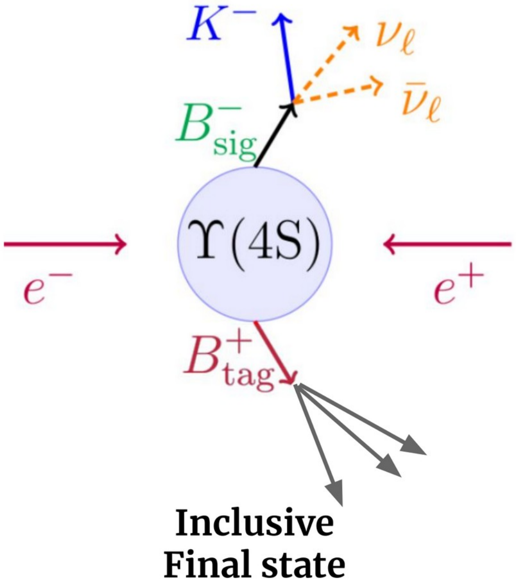
- Two methods: an inclusive tag and conventional hadronic tag
    - many common features except tag
- Inclusive event variables to suppress background
    - preselect events where missing momentum and signal kaon well reconstructed
    - First boosted decision tree (BDT1): 12 variables
    - Second BDT2: 35 variables – 3 times sensitivity
    - BDT2 fit extraction variable in bins of mass-squared– q2
- Many systematic studies with data-driven corrections and checks with control samples



$B^+ \to K^+\nu\bar{\nu}$ reconstruction

arXiv:2311.14647
Accepted PRD

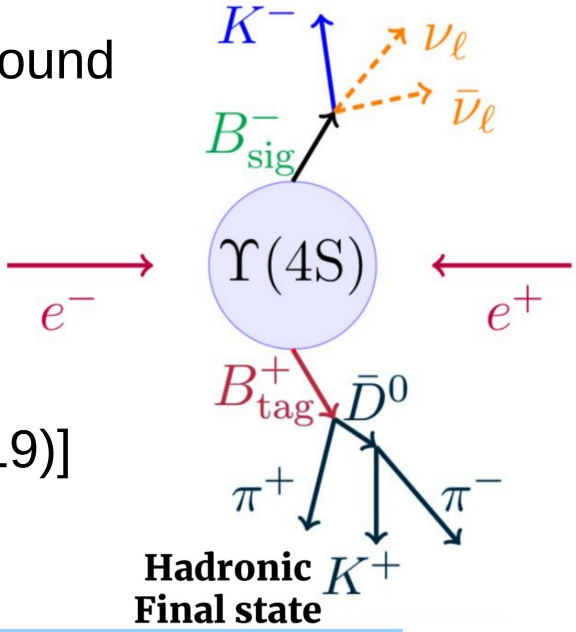
Two methods: an inclusive tag and conventional hadronic tag



- Inclusive tag analysis (ITA)
  - Select first signal kaon that minimizes $q^2_{\rm rec}$ (computed as K^+ recoil)
  - Nested BDT to suppress background
  - Fit $q^2_{\rm rec}$ and BDT output

ITA: signal efficiency = 8%
purity = 0.9%

- Hadronic tag analysis (HTA)
  - Select first tag B decaying hadronically [Comput Softw Big Sci 3, 6 (2019)]
  - Single BDT to suppress background
  - Fit BDT output



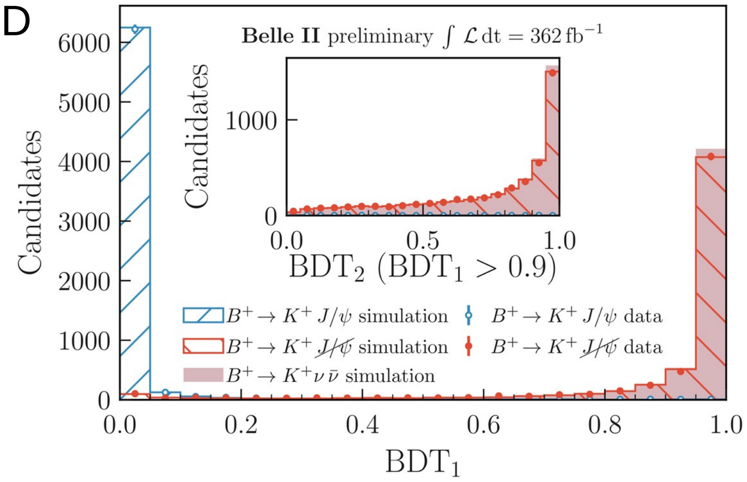
HTA: signal efficiency = 0.4%
purity = 3.5%

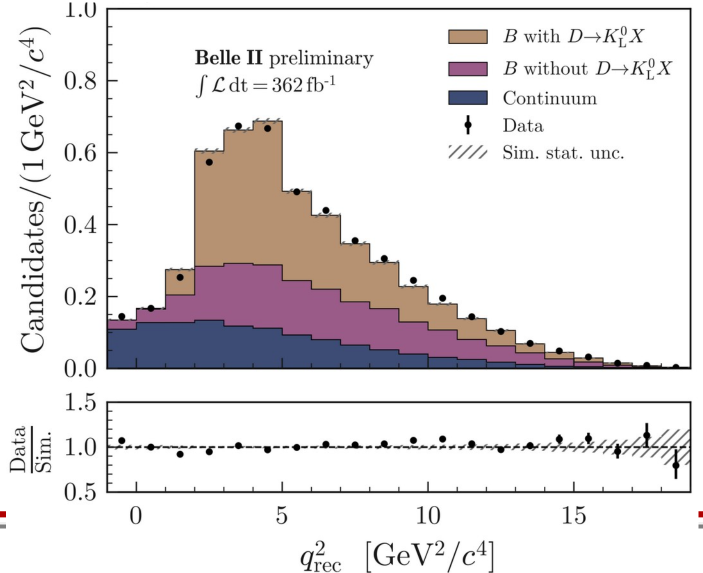
$B^+ \to K^+ \nu \bar{\nu}$ validation

arXiv:2311.14647
Accepted PRD

- Signal efficiency checked with signal-embedded $B \to K\, J/\psi(\to \mu\mu)$
  - Remove J/ψ and correct the kaon kinematics to match that of signal

- Continuum validated with off-resonance
- $B \to X_c(\to K^0_L)$ validated from pion-enriched sideband
- Signal like $B \to K^+ K^0_L K^0_L$ checked with $B \to K^+ K^0_s K^0_s$ [PRD 85 112010]
- Similar treatment for $B \to K^+ K^0_L K^0_s$ and $B \to K^+ nn$
- Closure test: BR($K^0 \pi^+$) = $(2.5 \pm 0.5) \times 10^{-5}$ compatible with the WA: $(2.38 \pm 0.08) \times 10^{-5}$





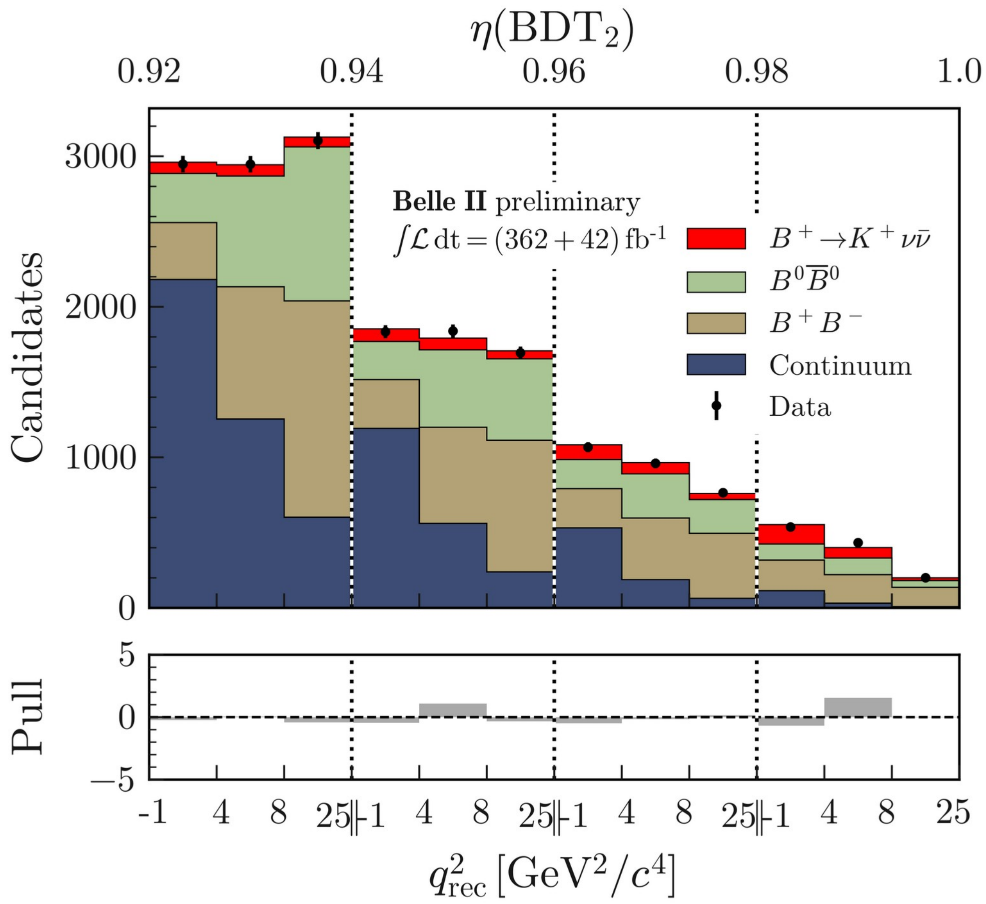
$B^+ \to K^+\nu\bar{\nu}$ results

arXiv:2311.14647
Accepted PRD

- ITA:
  - $\mu = 5.4 \pm 1.0$ (stat) ± 1.1 (syst)
  - corresponds to

$BR(B^+ \to K^+\nu\nu) = (2.7 \pm 0.5 \pm 0.5) \times 10^{-5}$

  - 3.5σ compatibility wrt bkg only
  - 2.9σ compatibility wrt the SM



$B^+ \to K^+\nu\bar{\nu}$ results

arXiv:2311.14647
Accepted PRD

- ITA:
  - $\mu = 5.4 \pm 1.0$ (stat) ± 1.1 (syst)
  - corresponds to

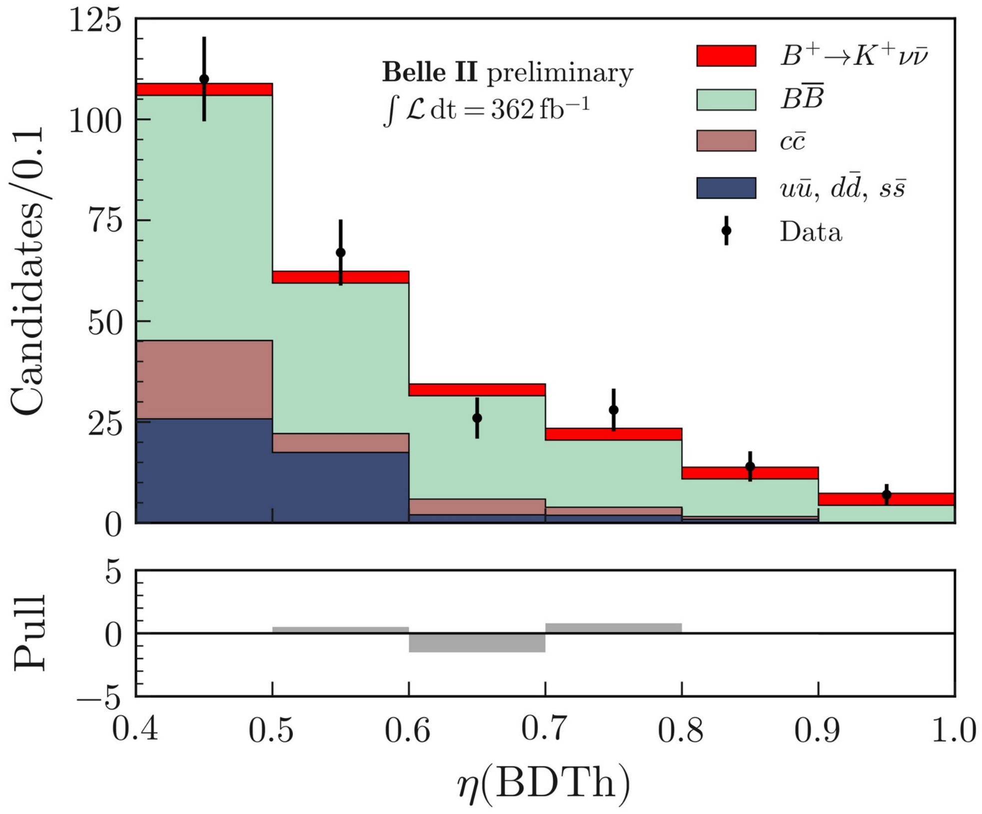
$BR(B^+ \to K^+\nu\nu) = (2.7 \pm 0.5 \pm 0.5) \times 10^{-5}$

  - 3.5σ compatibility wrt bkg only
  - 2.9σ compatibility wrt the SM
- HTA:
  - $\mu = 2.2\,^{+1.8}_{-1.7}$ (stat) $^{+1.6}_{-1.1}$ (syst)

    corresponds to

$BR(B^+ \to K^+\nu\nu) = (1.1\,^{+0.9}_{-0.8}\,^{+0.8}_{-0.5}) \times 10^{-5}$

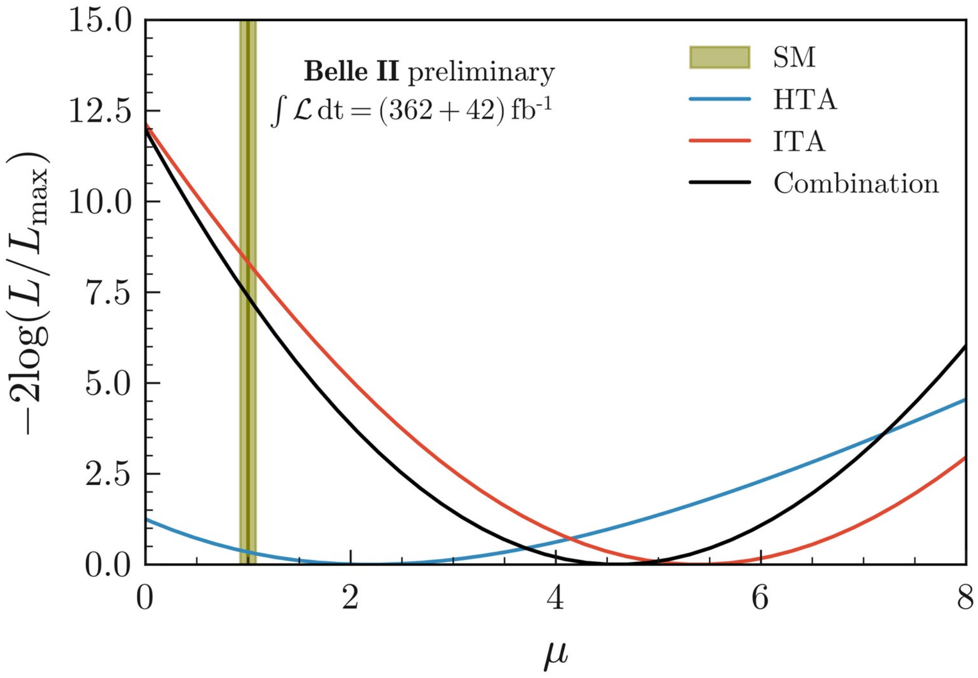
  - 1.1σ compatibility wrt bkg only
  - 0.6σ compatibility wrt the SM



$B^+ \to K^+\nu\bar{\nu}$ results

arXiv:2311.14647
Accepted PRD

- ITA:
  $BR(B^+ \to K^+\nu\nu) = (2.7 \pm 0.5 \pm 0.5) \times 10^{-5}$
- HTA:
  $BR(B^+ \to K^+\nu\nu) = (1.1\,^{+0.9}_{-0.8}\,^{+0.8}_{-0.5}) \times 10^{-5}$
- Combination:
  $BR(B^+ \to K^+\nu\nu) = (2.7 \pm 0.5\,^{+0.5}_{-0.4}) \times 10^{-5}$
  - 3.5σ compatibility wrt bkg only
  - 2.7σ compatibility wrt the SM
  - Combination improves the ITA-only precision by 10%



$B^+ \rightarrow K^+\nu\bar{\nu}$ results

arXiv:2311.14647
Accepted PRD

- ITA:
  $BR(B^+ \rightarrow K^+\nu\nu) = (2.7 \pm 0.5 \pm 0.5) \times 10^{-5}$
- HTA:
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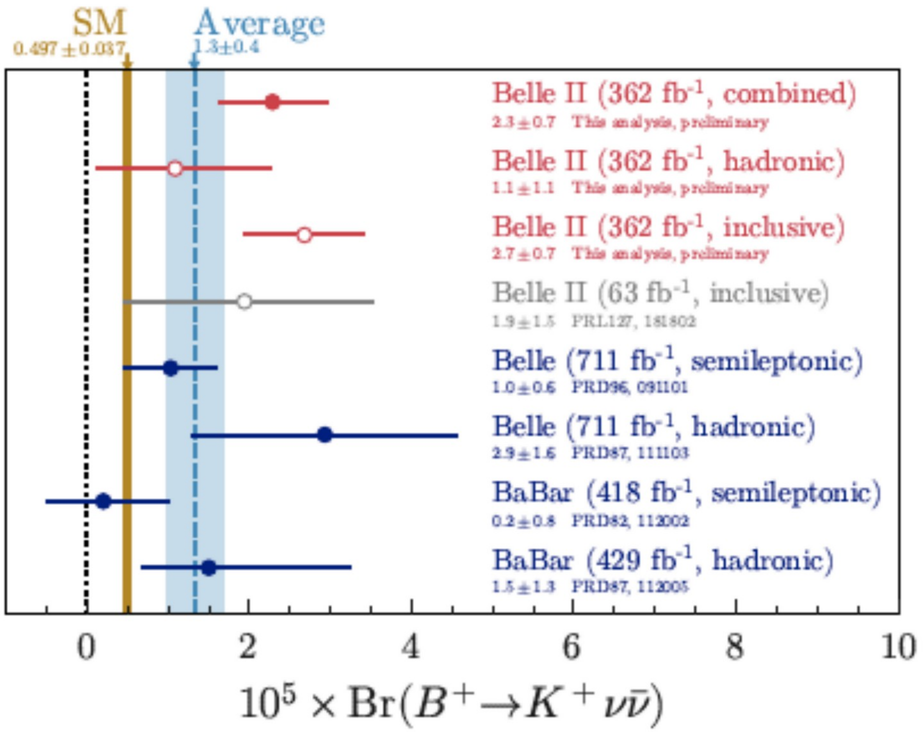
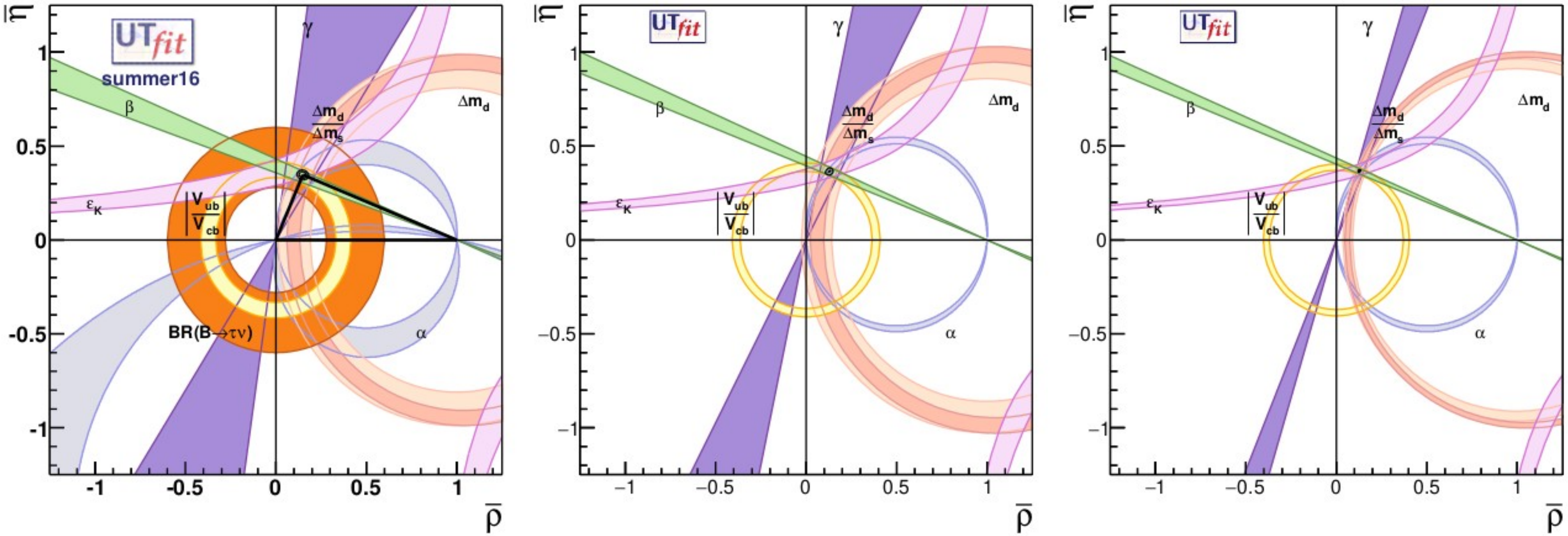


Prospects



arXiv:1808.10567

Goals with current data to a few inverse ab^{-1}

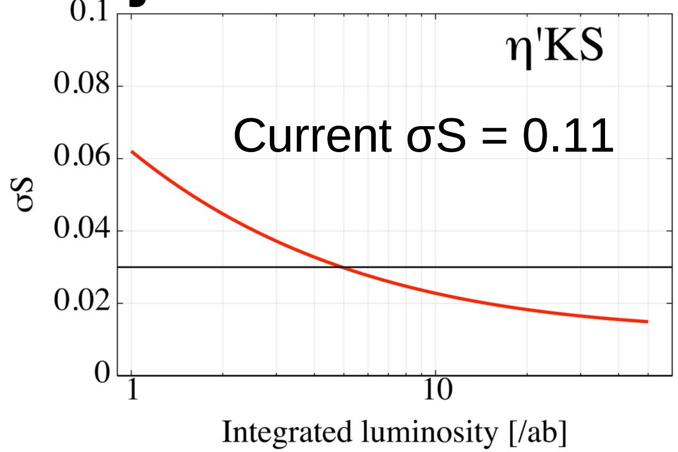
- Semileptonic decay:
  - V_{cb}: can we make progress on the inclusive vs. exclusive tension → KEK report in preparation
  - R(D)-R(D*)
- Electroweak penguin
  - Missing energy modes like $B \to K\tau\tau$ and $K\nu\nu$
- CP violation
  - α and the gluonic penguins
- tau
  - LFV and precision
- Charm
  - final states with neutrals, e.g., $D \to \pi^0\pi^0$
- Quarkonium
  - Y(10753) scan and isospin partners (ISR and B decay)
- Dark sector and low multiplicity
  - dark photon and $e^+e^- \to \pi^+\pi^-$

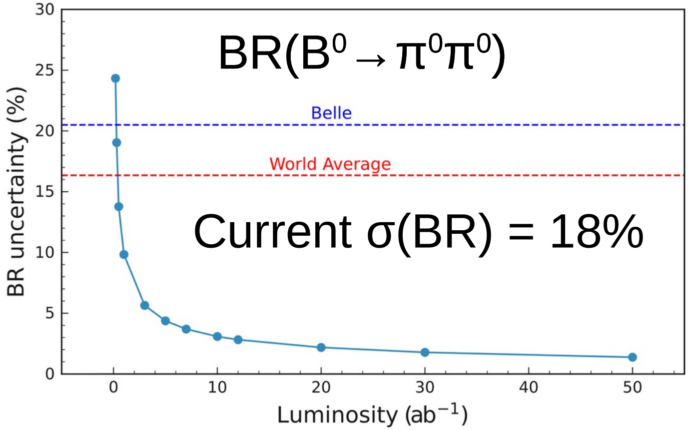
Snowmass submission [arXiv:2207.06307] is the most up to date prospects document

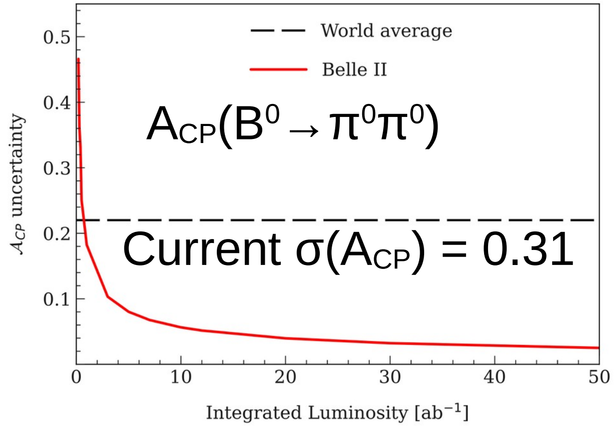
Projections:

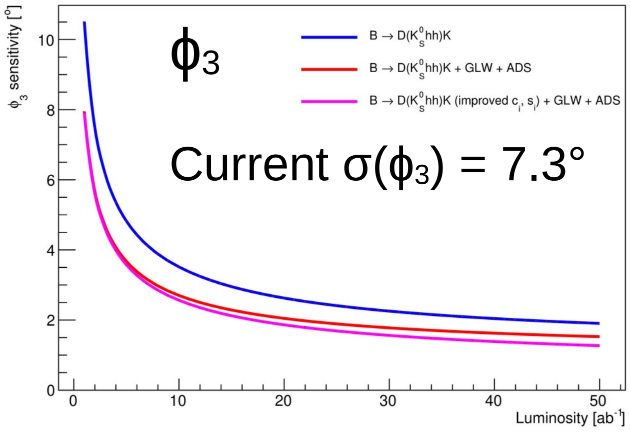
In this slide: current == Belle II in this talk

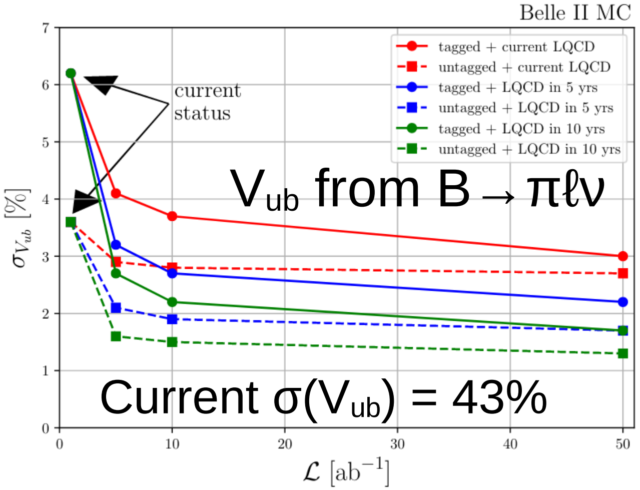
arXiv:2207.06307

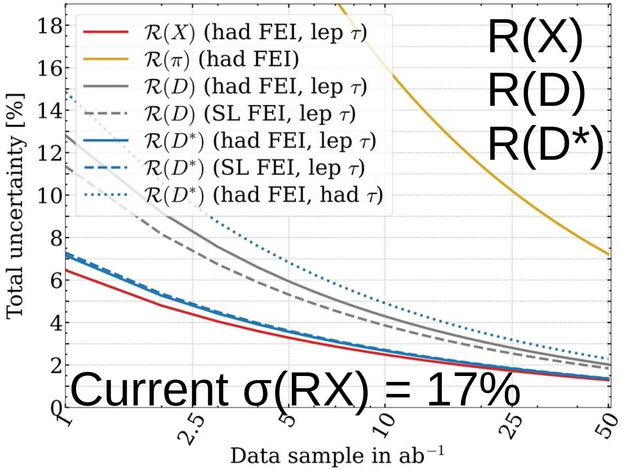










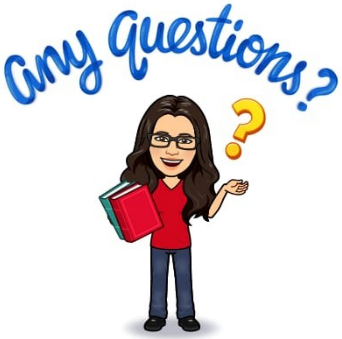


Current σ(BR) = 0.71

Decay	$1\,ab^{-1}$	$5\,ab^{-1}$	$10\,ab^{-1}$	$50\,ab^{-1}$
$B^+ \to K^+\nu\bar{\nu}$	0.55 (0.37)	0.28 (0.19)	0.21 (0.14)	0.11 (0.08)

Conclusions

- e^+e^- has an important role to play in the future of flavour
  - Belle II is catching up to first generation sample size, producing competitive and exciting results
    - 54 physics papers/preliminary results
      - 44 published or submitted
      - 10 preliminary results with a paper in preparation
    - More before the summer with the Run-1 data
  - A lot more to come once we enter the "10^{35} era" of Run 2 which is just starting



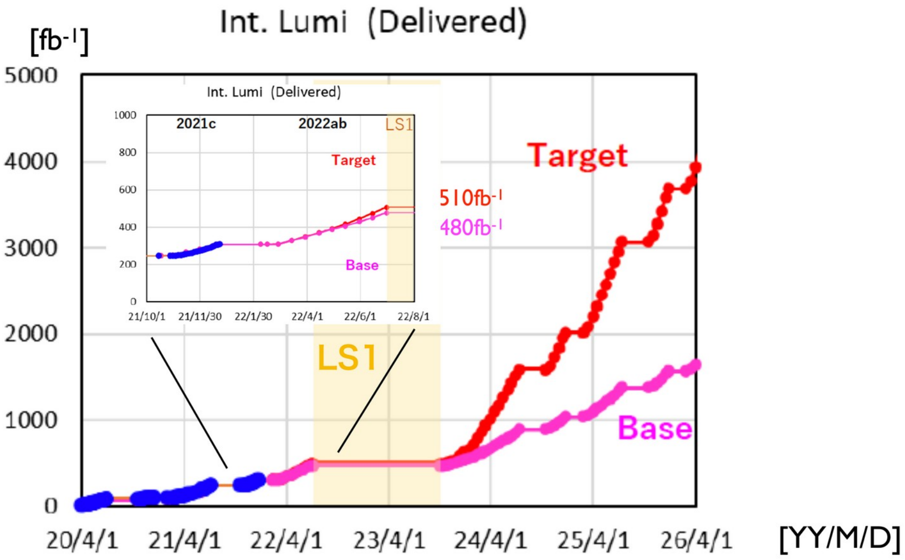
back-up slides

Projected Luminosity

Projection of integrated luminosity delivered by SuperKEKB to Belle II

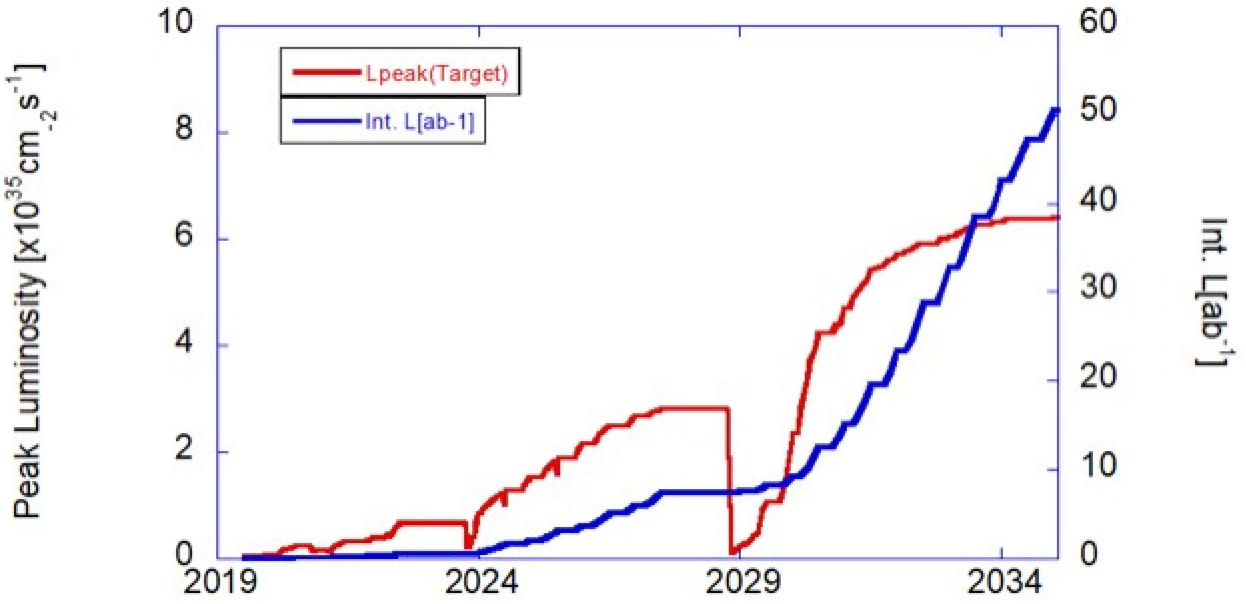
Target scenario: extrapolation from 2021 run including expected improvements.

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

Projected Luminosity



SuperKEK and Belle II status

We are back to the conditions of end of Run 1 with instantaneous luminosity close to 4×10^{34} with LER/HER currents above 1A (LER), but we are still suffering from sudden beam loss events, with sometimes large doses at IR (happened few times in 3 months).

This is why we have decided to turn off PXD for now until we understand better the origin for these events. The PXD is still operating well, with 98% of the channels live. However, to preserve this high level of performance we have decided to turn it off for now until the sudden beam loss events are understood and beam operations stabilise, as Run 2 will be long.