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

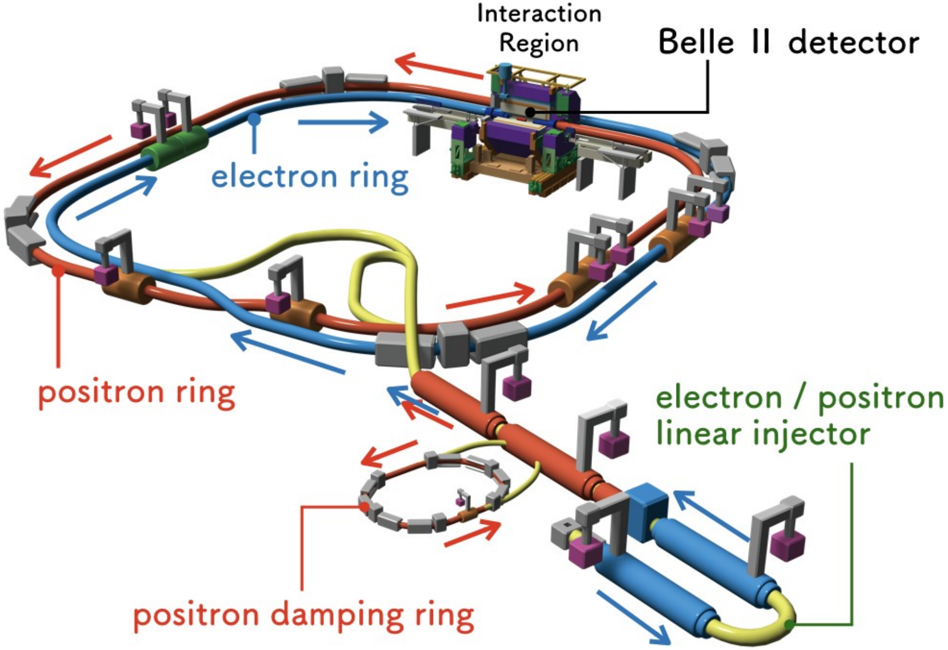
Outline

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

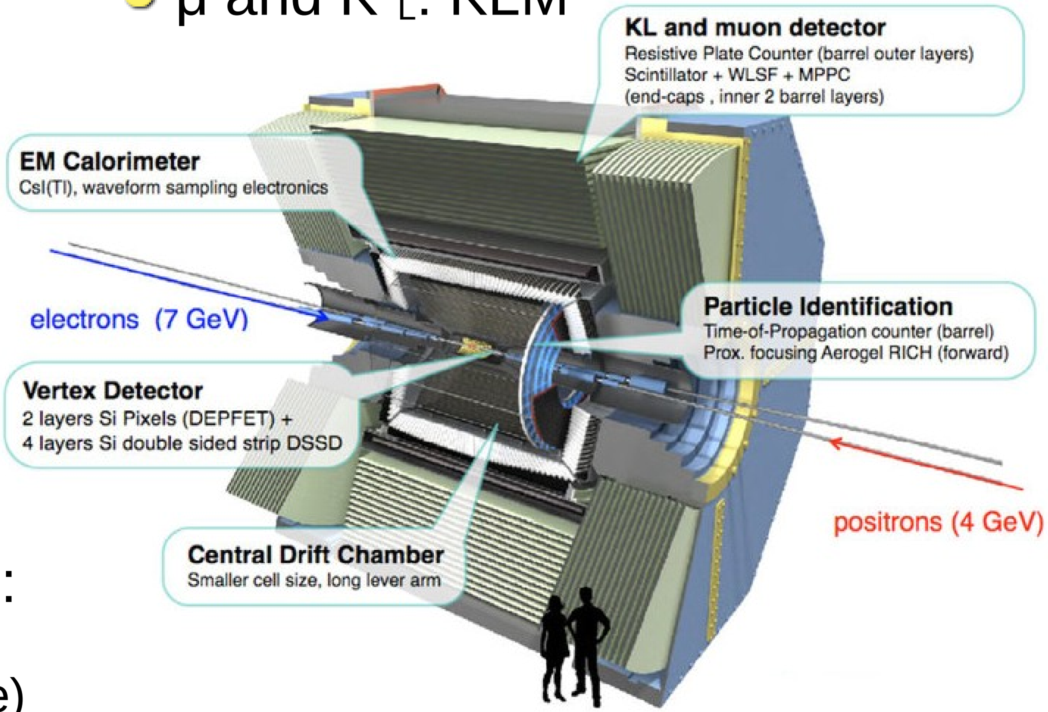
B Mesons

- Light enough to be produced abundantly
- Heavy enough to have many decays
- Myriad of final states and interactions to probe from
- Well known Standard Model predictions
- One of the main missions of B factories is to perform searches for physics beyond SM in rare B decays
- Rare B decay: branching fractions $< 5 \times 10^{-5}$
- Flavour changing neutral currents (FCNC) decays of B mesons
  - Forbidden at tree level, allowed at loop level
  - Standard Model (SM) contribution is small, sensitive to beyond SM
  - BSM particles can contribute in the loop (eg. charged Higgs) or mediate the process at the tree level (eg leptoquarks).

B Factories



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



- βγ ~ 0.284
- BR(Υ(4S) → $B\bar{B}$) > 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

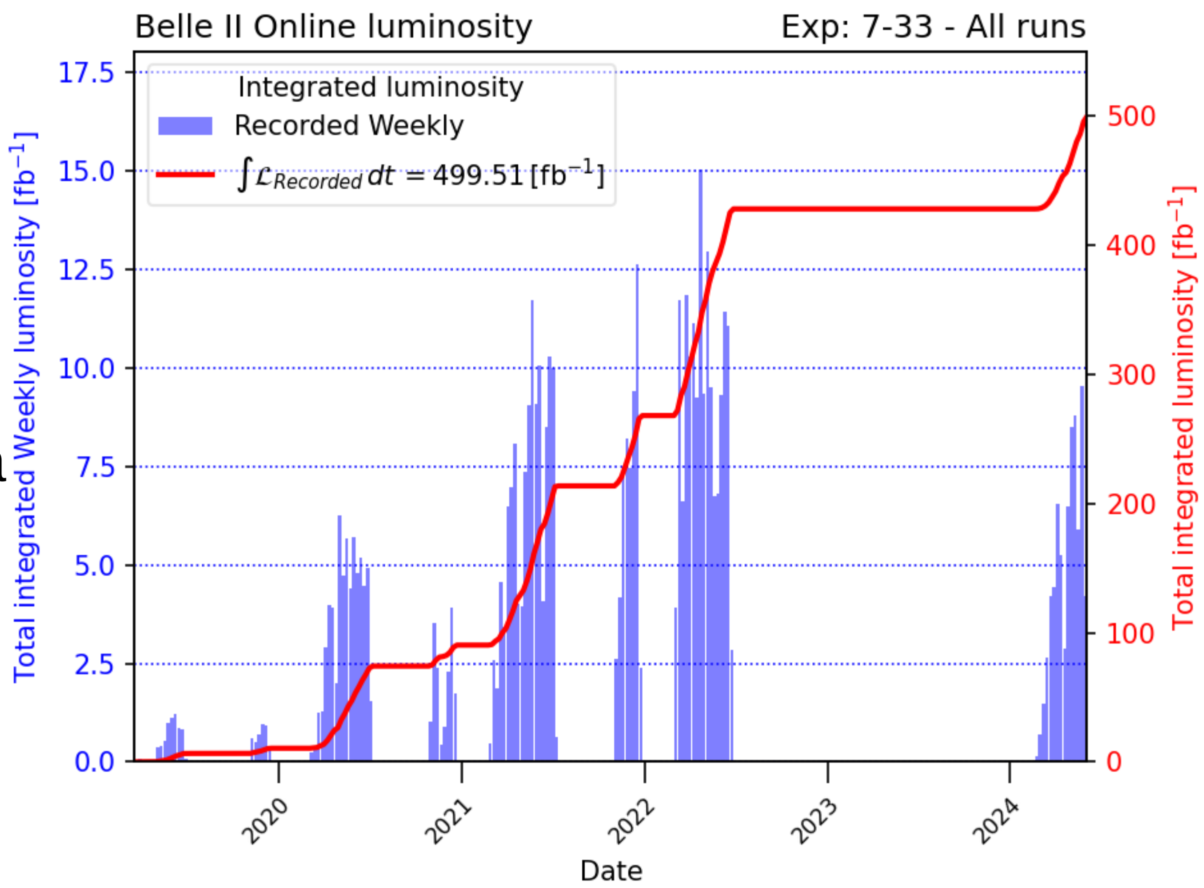
SuperKEKB + Belle II@KEK, Tsukuba

- 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+

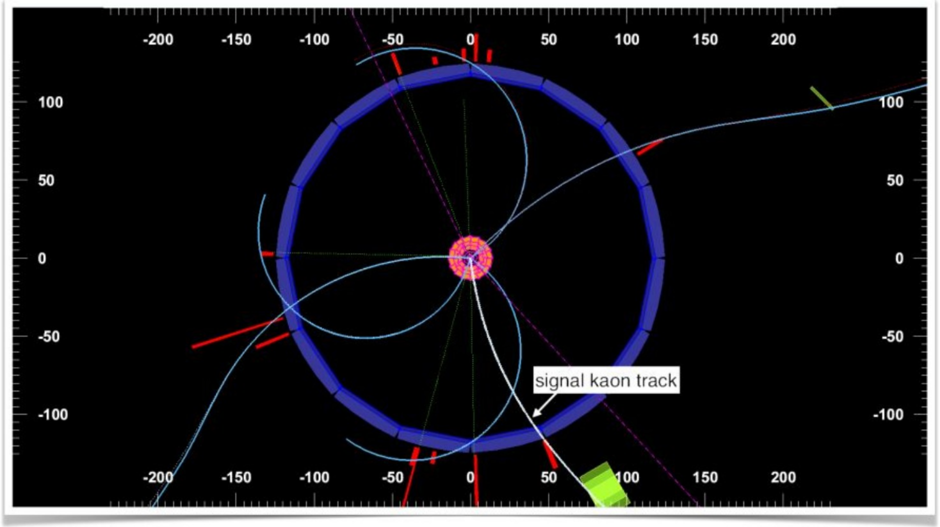
KEK status and luminosity

Belle II collected:

- xxx fb^{-1} at Y(4S)
  - equivalent to BaBar and ~1/2 of Belle
  - current results: 362 fb^{-1}
- 42 fb^{-1} of off-resonance data [60 MeV below Y(4S)]
  - compared to ~90 fb^{-1} from Belle



Events at the B Factories:



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

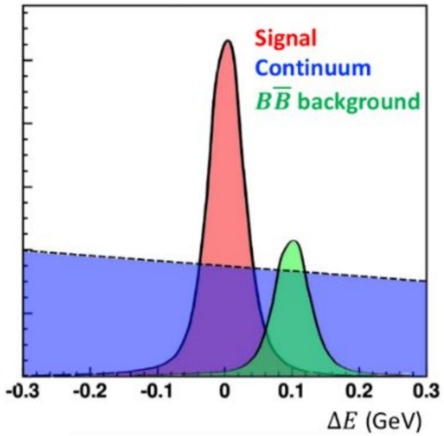
$$\begin{aligned}\sigma(e^+e^-) \to \Upsilon(4S) &= 1.1 \text{ nb}\\ \sigma(e^+e^-) \to c\bar{c}(g) &= 1.6 \text{ nb}\\ \sigma(e^+e^-) \to u\bar{u}(\gamma) &= 1.3 \text{ nb}\end{aligned}$$

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

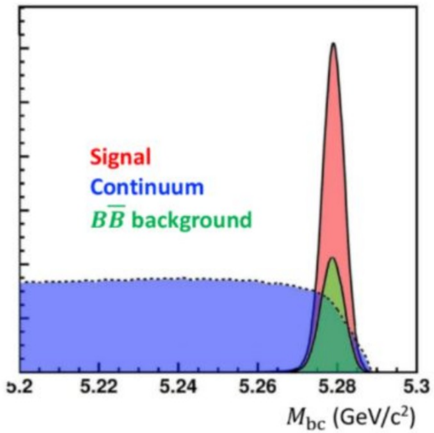
- Principal background from light quark (continuum)
- Near 100% efficiency for B decays

Events Kinematics:

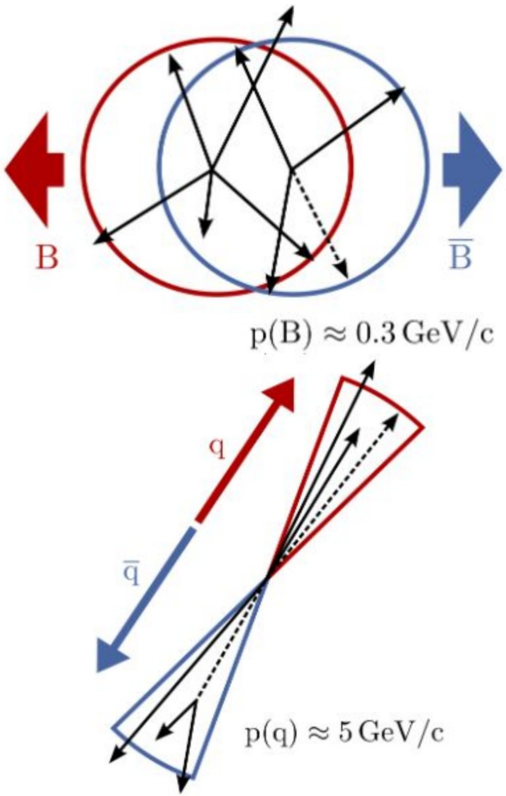
$$\Delta E = E_B^* - \sqrt{s}/2 \qquad M_{bc} = \sqrt{(\sqrt{s}/2)^2 - |\vec{p}_B^{*2}|}$$



Expected $\Delta E \simeq 0$

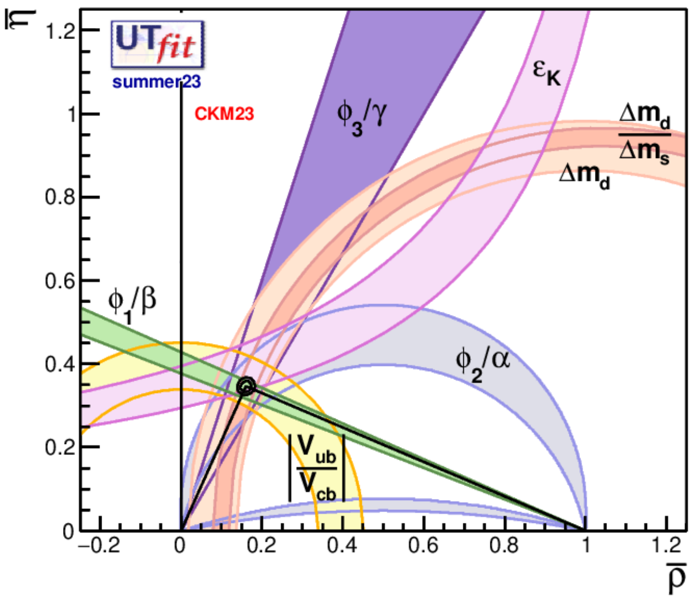


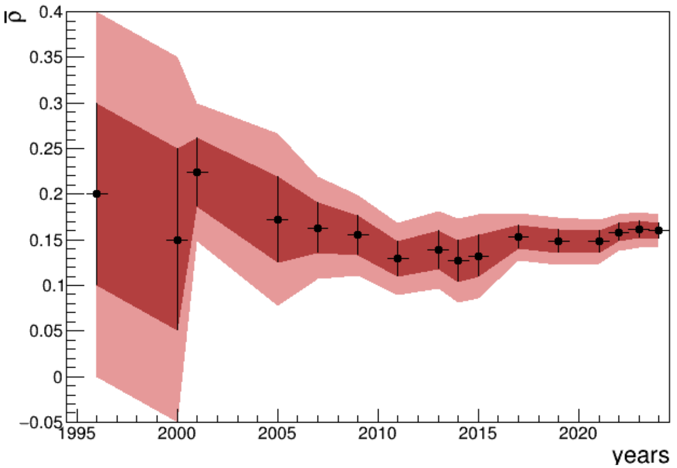
Expected $M_{bc} \simeq m_B$

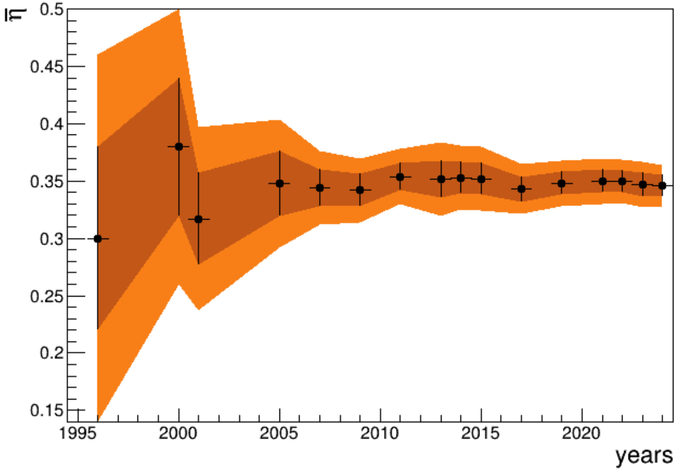


- B-factory-specific variables
  to exploit information on initial kinematics
- Different event shape to separate B events
  from continuum background

CKM and CP violation

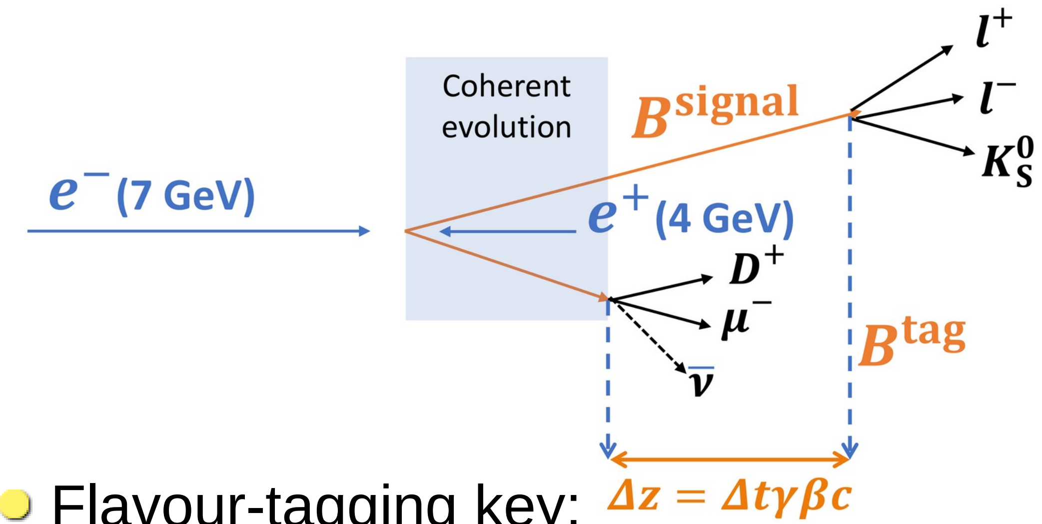


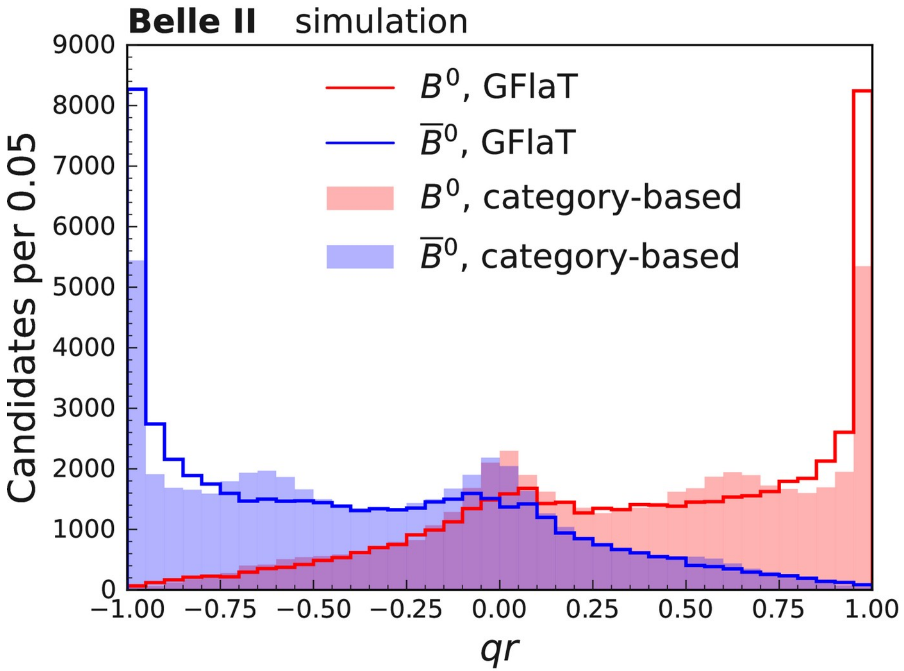




Flavour Tagging improvement:

arXiv:2402.17260 [hep-ex]





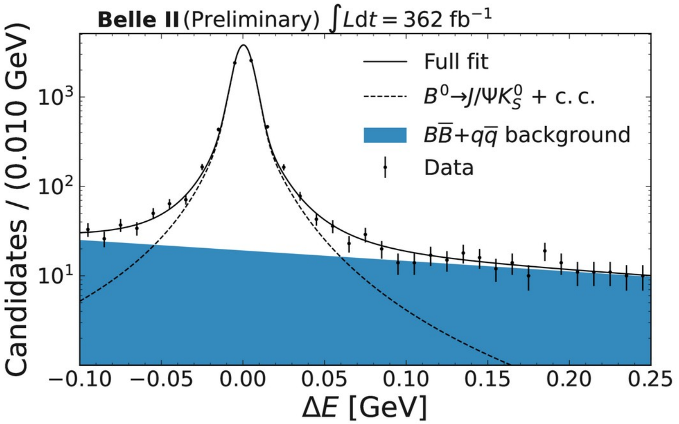
- Flavour-tagging key:
  - leptons, kaons, high momentum tracks etc
- Parameters:
  - ε is the tagging efficiency
  - w is the probability to wrongly determine flavour

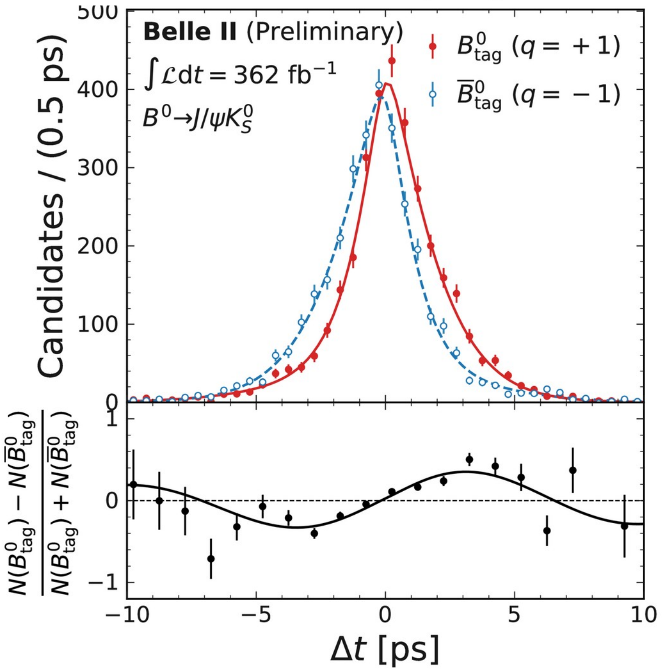
Graph-neural-network approach has improved tagging by 18%
$\varepsilon(1 - 2\omega) = 37.4$ %

$\sin(2\phi_1/\beta)$ from $B \to J/\varphi K_S$

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
  - **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

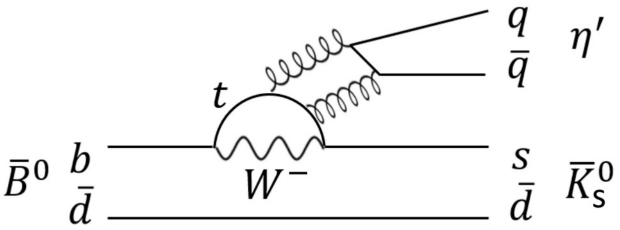


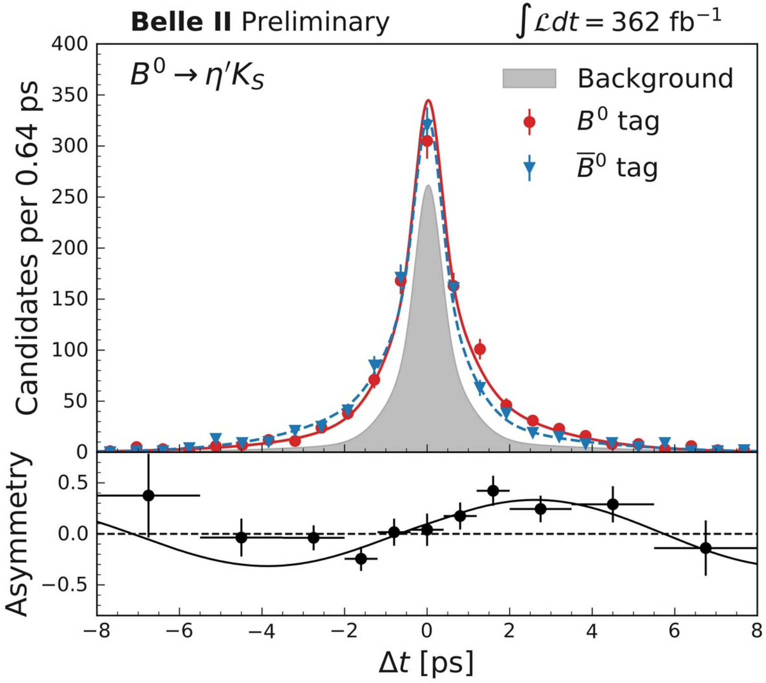


Time-dependent CP violation: $B^0 \rightarrow \eta K_S$

arXiv:2402.03713 [hep-ex]

- 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





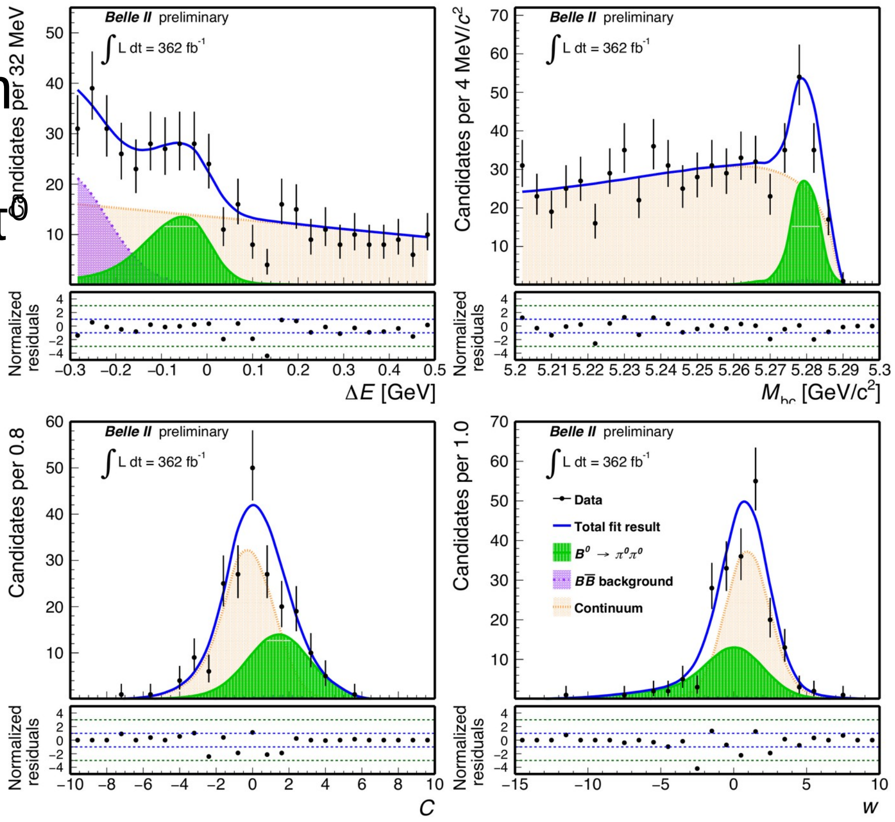
Towards ϕ_2/α : $B^0 \rightarrow \pi^0\pi^0$

New for FPCP

- Update on BR and A_{CP} using full Run-1 statistics:
- Improved selections, new flavour tagger (GflaT), reduction of systematics
  - Background dominated by continuum
  - then $B\bar{B}$:
    $B^+ \rightarrow \rho^+(\rightarrow \pi^+\pi^0)\,\pi^0$, $B^0 \rightarrow K^0_S(\rightarrow \pi^0\pi^0)\,\pi^0$
  - 4D fit including M_{bc}, ΔE, cont. suppression (C), and w (wrong tag probability - unbinned)
- Results:
  - $\mathcal{B} = (1.26 \pm 0.20 \pm 0.11) \times 10^{-6}$
  - $A_{CP} = 0.06 \pm 0.30 \pm 0.06$

World-best B determination.
ACP on par with world best

126±20 signal events

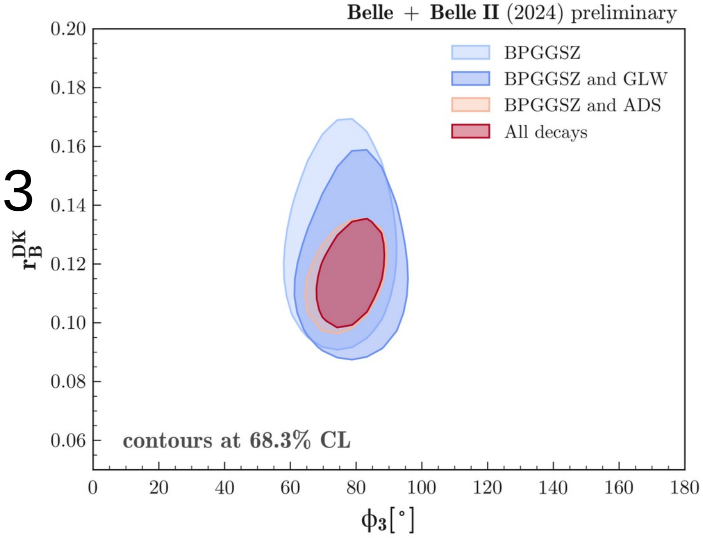


ϕ_3/γ: Belle/Belle II combined results

arXiv [2404.12817]

- Several methods used
  - GLW $B^\pm \to D^0_{CP}K^\pm$: arXiv:2308.05048 [hep-ex]
    - 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 $D^0 \to K_S K\pi$: JHEP 09(2023)146
- Likelihood with 60 input observables
  - including 15 auxiliary inputs (D-decay)
  - 16 free parameters
  - $r_B(\delta_B)$ with little high fluctuation

$\phi_3=(78.6\pm7.3)°$



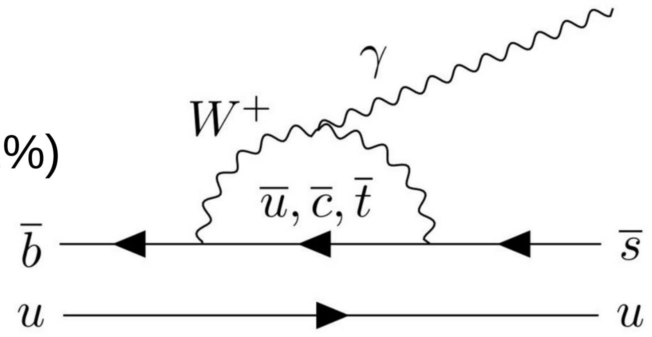
LHCb: $\phi_3=(63.8\pm3.6)°$ (LHCb-CONF-2022-003)
Few ab^{-1} needed for similar statistical result

First measurement of B →K*(892)ɣ

- 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 $B \to K^*(892)\gamma$

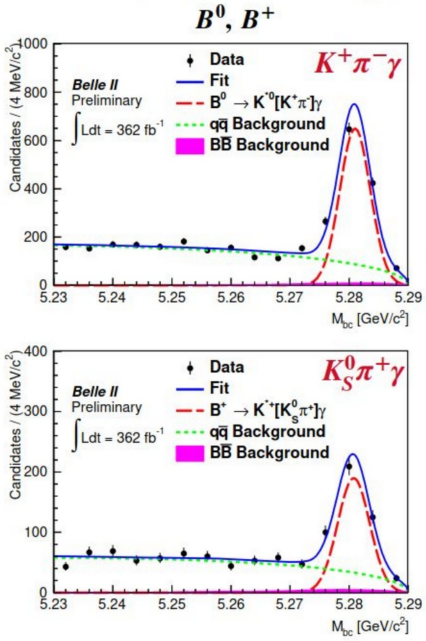
- Analysis based on Run-1 data (362 fb^{-1})
- Reconstruct $K^* \to K^+ \pi^-$, $K^0_S \pi^0$, $K^+ \pi^0$, $K^0_S \pi^-$
- Combine K^* with a prompt photon to get B candidate

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)



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

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

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

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

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

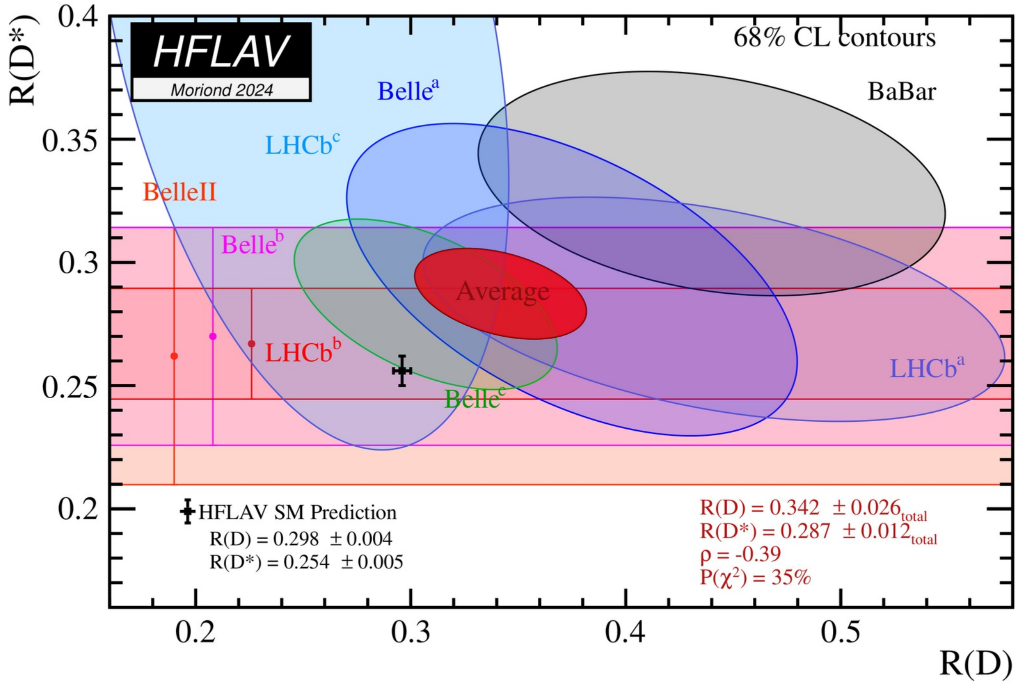
$$\Delta_{0+} = (5.1 \pm 2.0 \pm 1.0 \pm 1.1)\%$$

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

CKM matrix element Vcb abd Vub:

- Long standing tension between inclusive and exclusive measurements:
  -

Lepton flavour/universality violation and rare decays



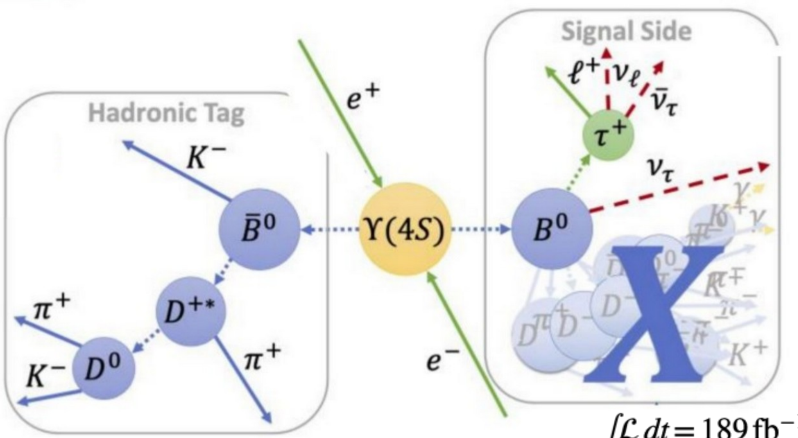
Measurement of R(X)

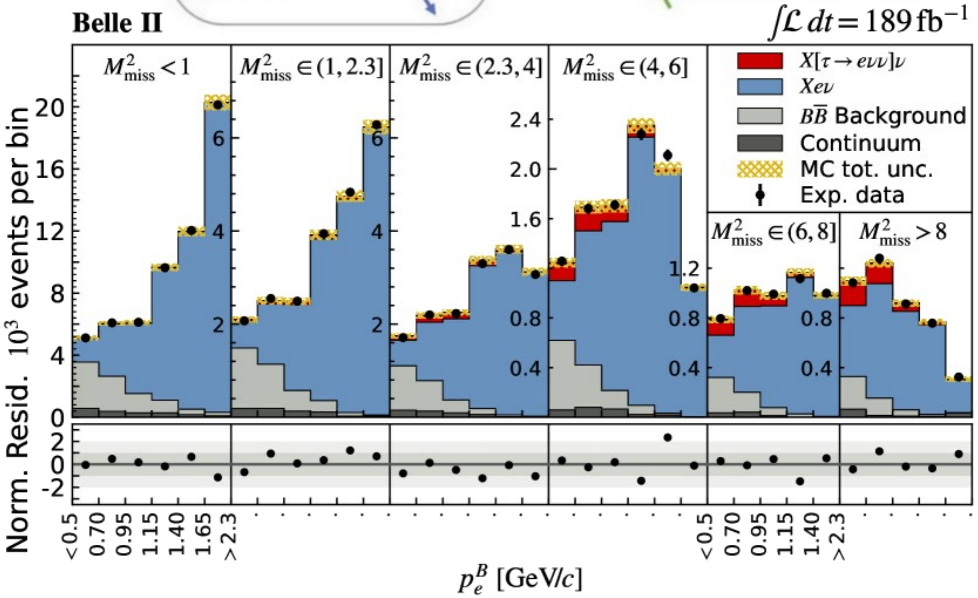
arXiv:2311.07248 [hep-ex]

- 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 lepton momentum to isolate signal above B→Xℓν background
- Background templates calibrated to control samples and sidebands

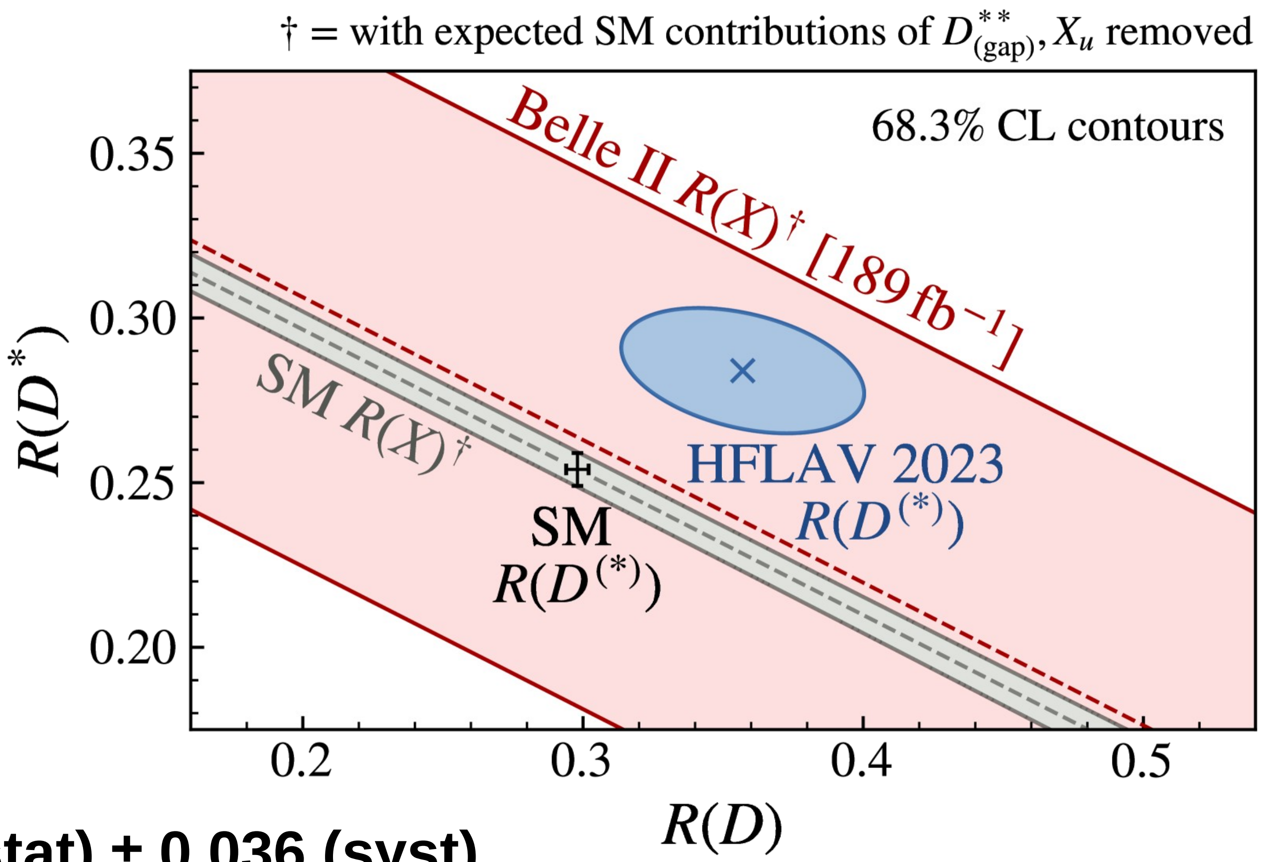




Measurement of R(X)

arXiv:2311.07248 [hep-ex]

- Systematics dominated by control sample reweighting procedures
- First at B factories
- Agrees with SM prediction and the WA R(D(*)) values

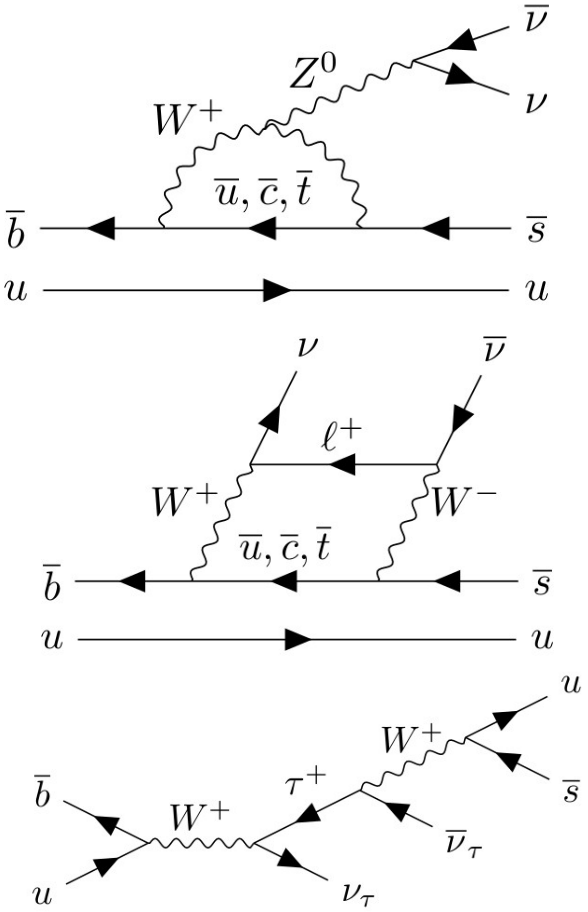


R(X)=0.228 ± 0.016 (stat) ± 0.036 (syst)

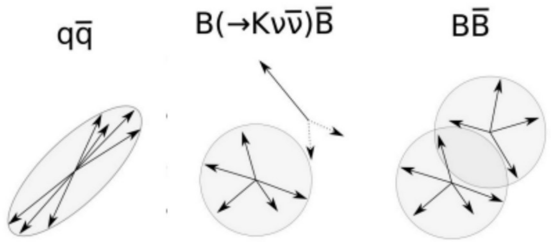
Probing $B^+ \to K^+ \nu\bar{\nu}$

arXiv:2311.14647 [hep-ex]
Accepted PRD

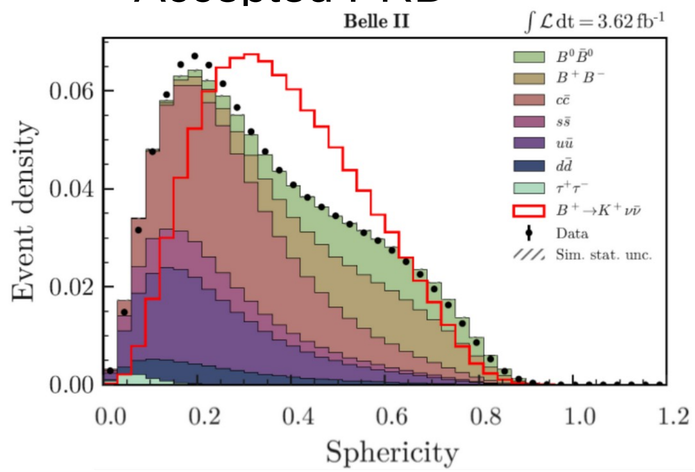
- Well known in SM but very sensitive to BSM enhancements – 3rd gen
  - $B(B^+ \to K^+ \nu\nu) = (5.6 \pm 0.4) \times 10^{-6}$ [arXiv:2207.13371]
- Challenging experimentally
  - Low branching fraction with large background
  - No peak – two neutrinos leads to no good kinematic constraint
- Advantages 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



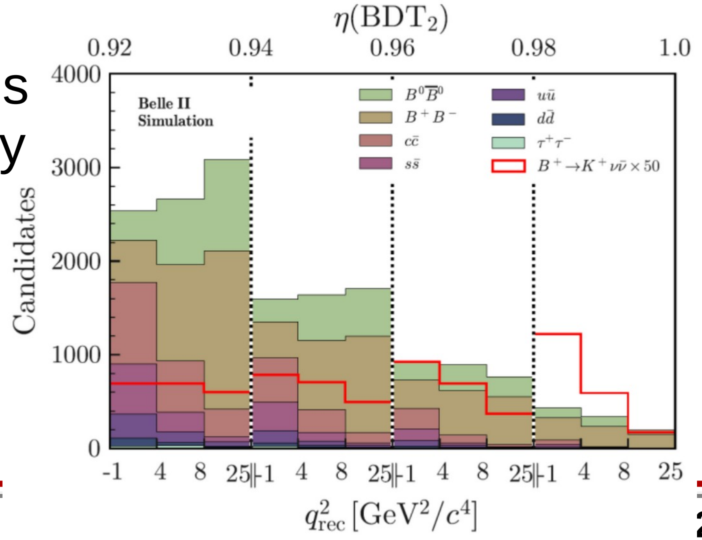
$B^+ \to K^+\nu\bar{\nu}$ analysis strategy



arXiv:2311.14647 [hep-ex]
Accepted PRD



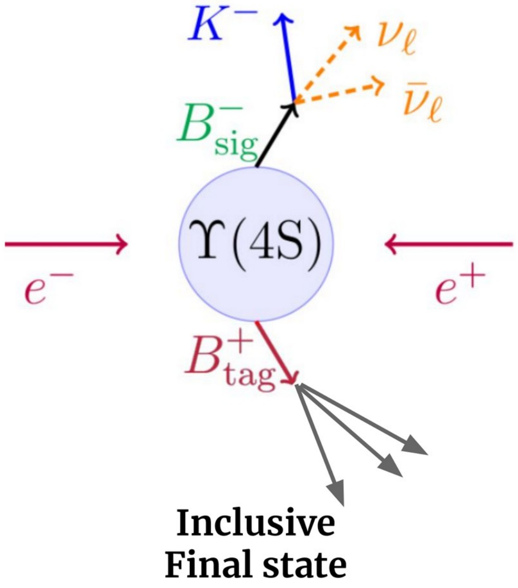
- Two methods: an inclusive tag and conventional hadronic tag
  - many common features except tag
- Inclusive event variables to suppress background
  - preselect events where missing momentum and signal kaon well reconstructed
  - First boosted decision tree (BDT1): 12 variables
  - Second BDT2: 35 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 [hep-ex]
Accepted PRD

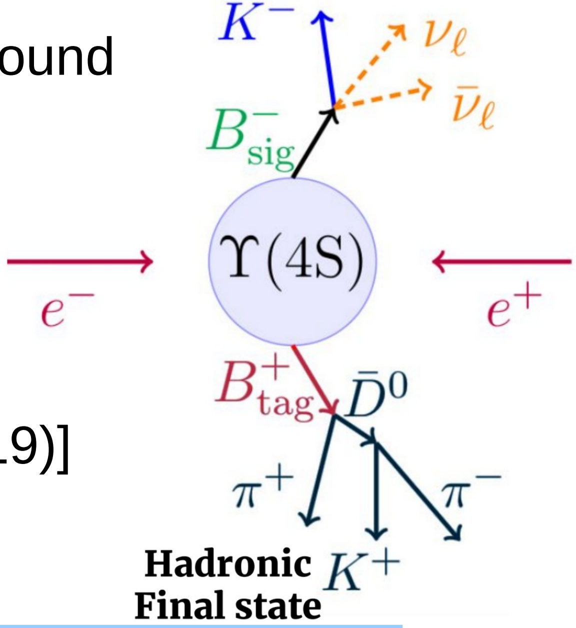
Two methods: an inclusive tag and conventional hadronic tag



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

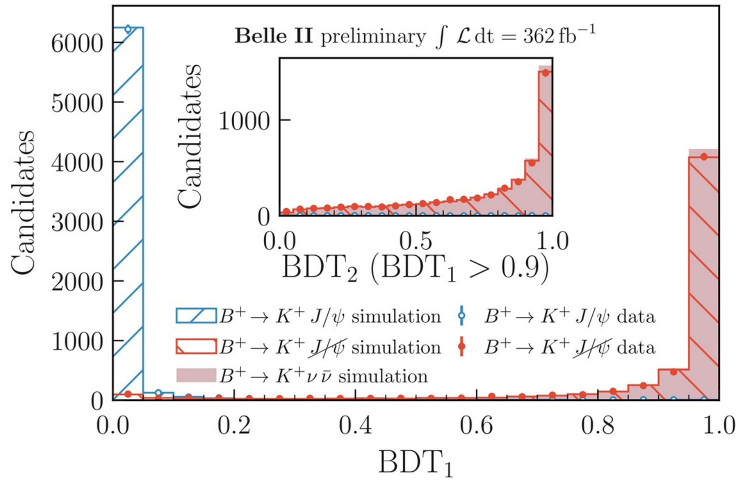


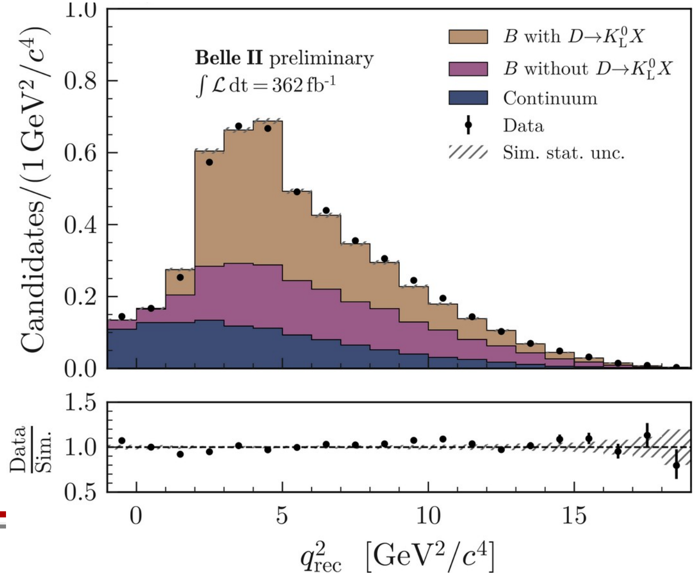
HTA: signal efficiency = 0.4%
purity = 3.5%

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

arXiv:2311.14647 [hep-ex] Accepted PRD

- Signal efficiency checked with signal-embedded $B \rightarrow K\, J/\psi(\rightarrow \mu\mu)$
  - Remove J/ψ and correct the kaon kinematics to match that of signal
- Continuum validated with off-resonance
- $B \rightarrow X_c(\rightarrow K^0_L)$ validated from pion-enriched sideband
- Signal like $B \rightarrow K^+ K^0_L K^0_L$ checked with $B \rightarrow K^+ K^0_S K^0_S$ [PRD 85 112010]
- Similar treatment for $B \rightarrow K^+ K^0_S K^0_S$ and $B \rightarrow K^+ nn$
- Closure test: $BR(K^0 \pi^+) = (2.5 \pm 0.5) \times 10^{-5}$ compatible with the WA: $(2.38 \pm 0.08) \times 10^{-5}$





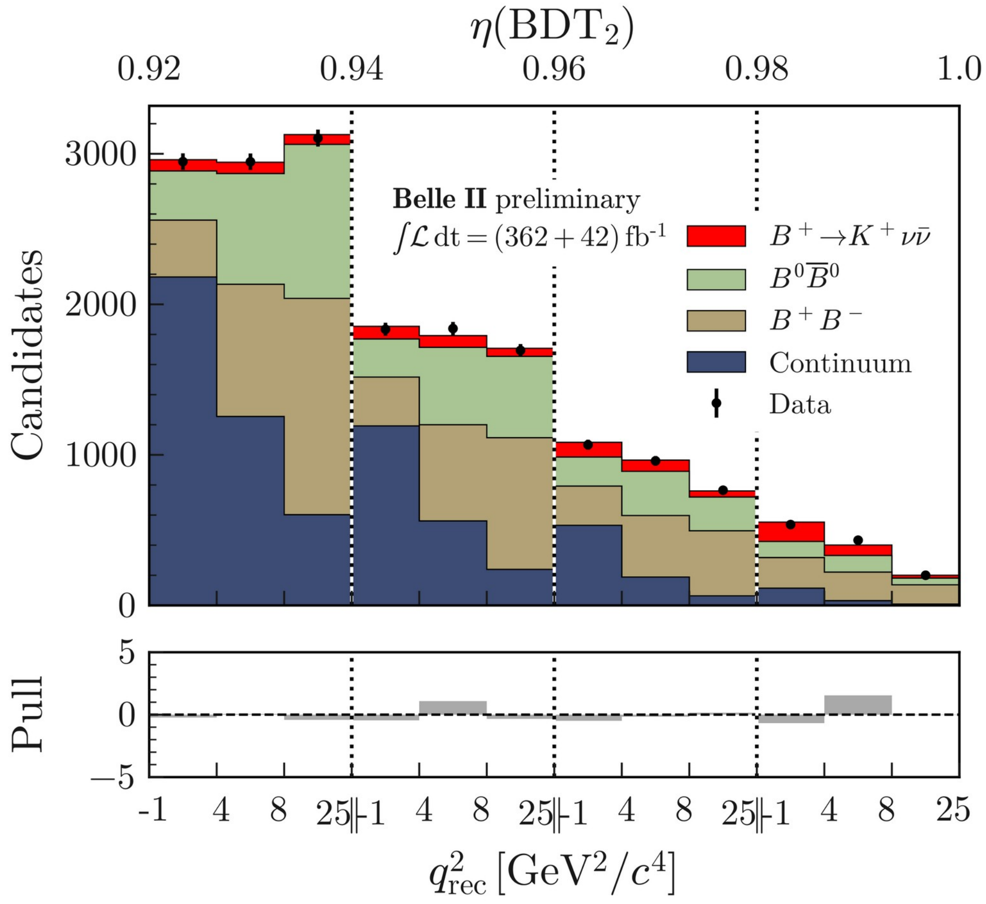
$B^+ \to K^+ \nu\bar{\nu}$ results

arXiv:2311.14647 [hep-ex] 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

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

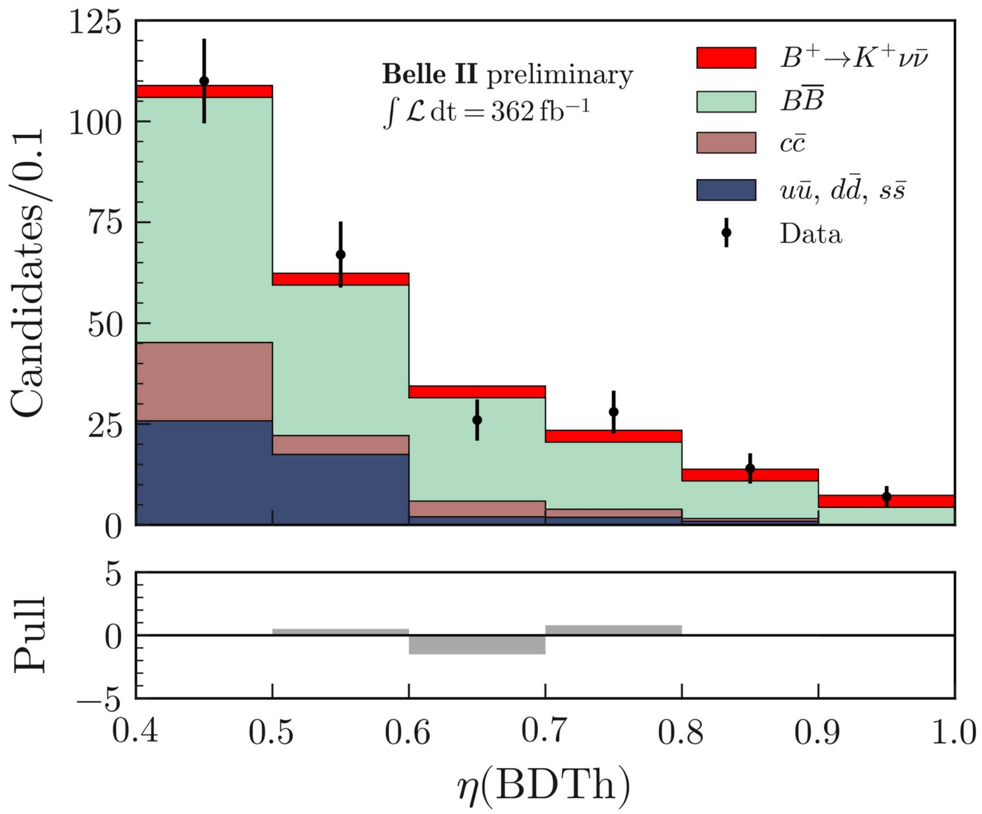
$BR(B^+ \to K^+\nu\nu) = (2.7 \pm 0.5 \pm 0.5) \times 10^{-5}$

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

  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

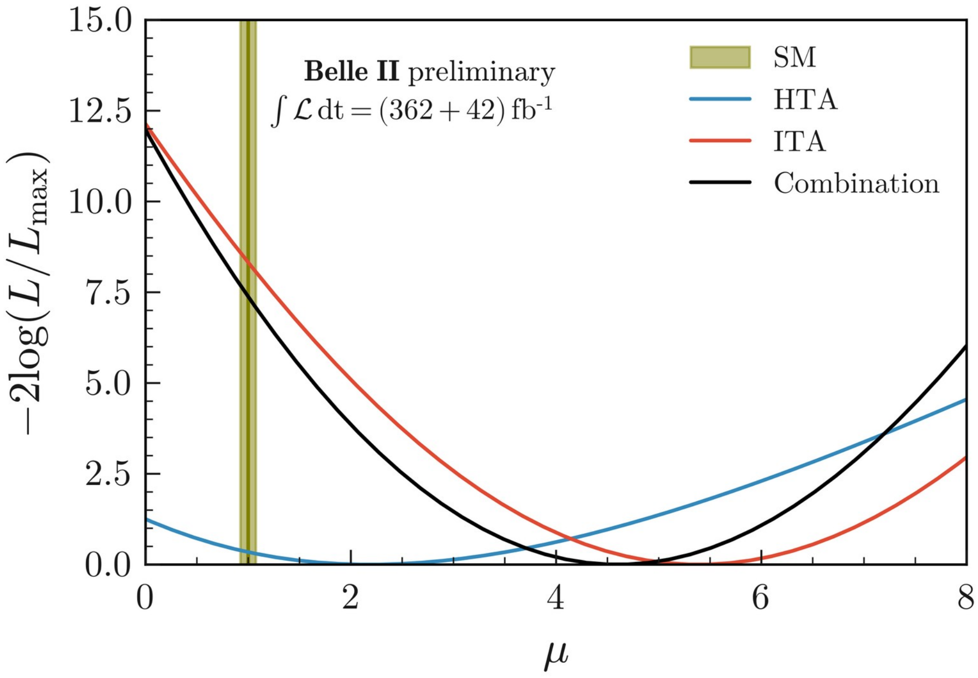
arXiv:2311.14647 [hep-ex] Accepted PRD

- 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%



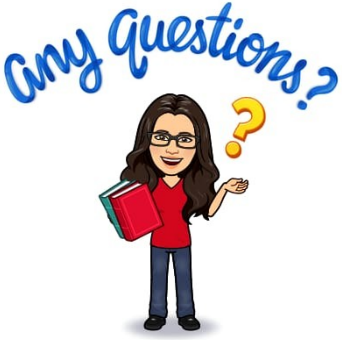
Goals with current data to a few inverse ab^{-1}

- Semileptonic decay:
  - Vcb: 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 is the most up to date prospects document

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
    - 37 papers and 10 preliminary results with a paper in preparation [to be updated]
    - 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