Latest results from Belle II

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on behalf of the Belle II collaboration

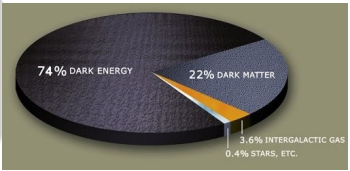
XXXV^{e} Rencontres de
Physique de la Vallée d'Aoste

The big picture

- Standard Model successful yet incomplete
- Promising to search for New Physics at the intensity frontier: precise tests of the Standard Model can probe energy scales inaccessible to direct production

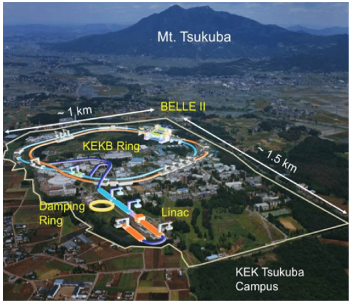
Belle II main goals

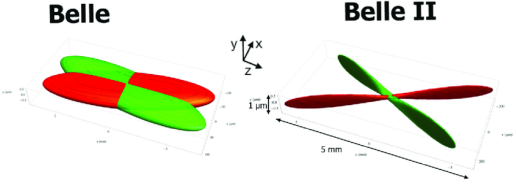
- New physics search in B, D and τ decays
- Direct search for light new particles
- Precise measurement of Standard Model
- Hadron physics



Belle II @ SuperKEKB

- Multi-purpose detector successor of Belle @ KEKB
- Beams of electrons and positrons with asymmetric energy (7 and 4 GeV): boost $\beta\gamma = 0.28$
- Collisions at the $\Upsilon(4S)$ mass (10.58 GeV)
- Will collect 50 times more data than Belle

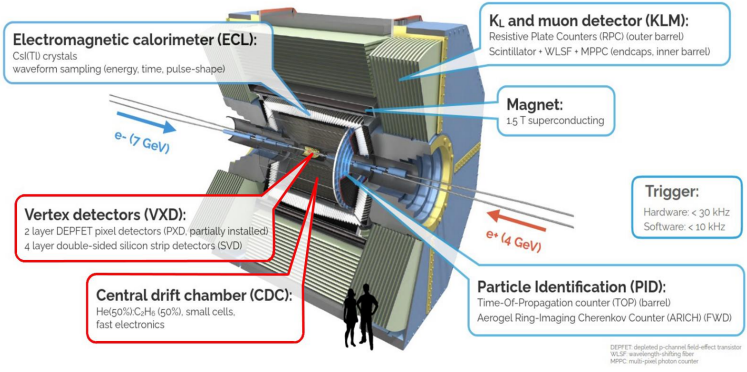


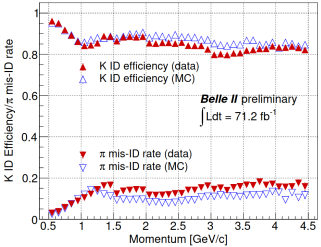


- Planned x30 increase of instantaneous luminosity
- Mainly by x20 reduction of interaction reagion
- Already World record luminosity: $3.8 \times 10^{34}\text{cm}^{-2}\text{s}^{-1}$ (June 15^{th} 2020) with lower currents than KEKB

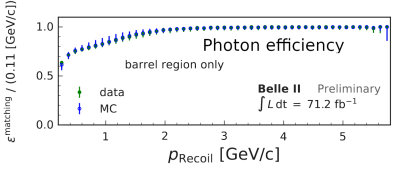
Belle II

Ensure equal/better performance than Belle (tracking, vertexing, PID, calorimeter resolution) in an harsher environment (higher beam background, higher trigger rate: 0.5 kHz → 30 kHz)





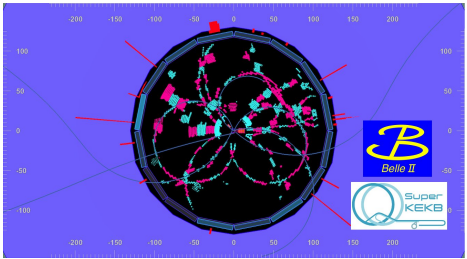
[BELLE2-NOTE-PL-2020-024]

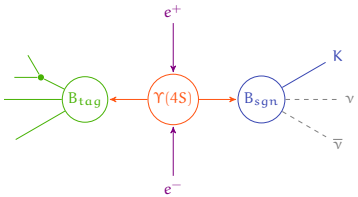


[BELLE2-NOTE-PL-2021-008]

Life in a $e^+ e^-$ flavour factory

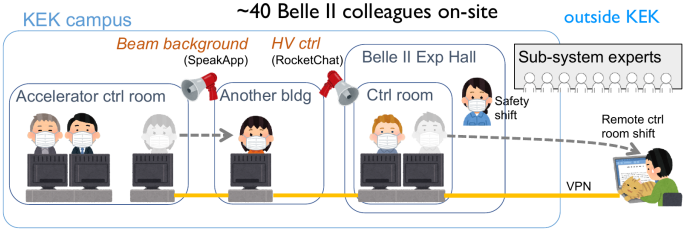
- Cross section for beauty, charm and tau events $\sim$ 1 nb each
- Clean environment (average 11 tracks per event)
  - efficient detection of neutrals (γ, π^0, η, ...)
- Quantum correlated $B^0\bar{B}^0$ pairs
  - High effective flavour tagging efficiency ($\sim$ 34%)
- Good hermeticity
- Full Event interpretation
  - possible to fully reconstruct events with invisible particles
- Good complementarity with LHCb
  - Different strengths and different systematics
  - Essential independent check if common discovery of New Physics

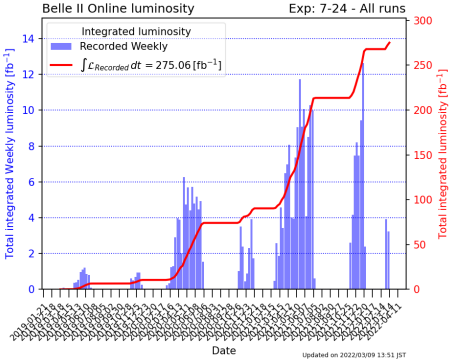




Data taking so far

- Started data taking in 2019 (commissioning run in 2018 with only a fraction of the vertex detector)
- Collected about 270 fb^{-1} (results presented in this talk use $\sim$60 fb^{-1})
- Data taking continued minimising risk of covid-19 infection



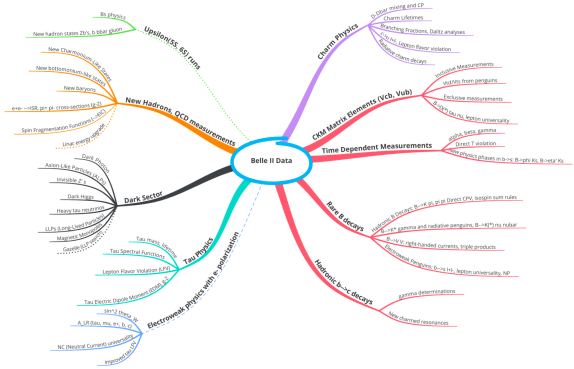


- $\sim$90% data taking efficiency
- 1-2 fb^{-1}/day
- 10 fb^{-1}/week

Belle II physics program

Belle II has unique/world-leading reach in dozens of measurements that are key to probe non-SM, involving for example

- CKM elements ($|V_{xb}|$) and phases (α/ϕ_2 through $\rho\rho$)
- Rare decays ($B \to K^{(*)}\nu\overline{\nu}$, $B \to K^{(*)}ll'$)
- LFUV processes ($R(D)$, $R(D^*)$)
- Phenomenological relationships (isospin sum rules in $B \to K\pi$)
- CPV in B (ϕK^0, $\eta' K^0$)
- Charm ($D^+ \to \pi^+\pi^0$, $D^0 \to K^0_S K^0_S$)
- Low-mass dark sectors
- Will dominate tau physics for the next decade



First physics results

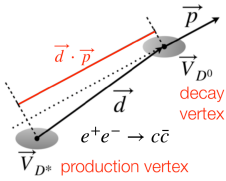
- Published five physics's papers
  - Two on dark matter searches (using 2018 commissioning data)
  - Search for $B^+ \to K^+ \nu\bar{\nu}$ using an inclusive tagging method
  - World leading measurement of the D^0 and D^+ lifetimes
  - Combined analysis of Belle and Belle II data to determine the CKM angle α/ϕ_3 using $B^+ \to D(K^0_S h^- h^+) h^+$ decays
- Many conference papers posted on arXiv
- For the full list: `https://arxiv.org/search/?query=Belle+II&searchtype=author`
- In this talk only a limited and personal selection
  - D lifetime
  - CKM matrix elements
  - $b \to s$ transitions

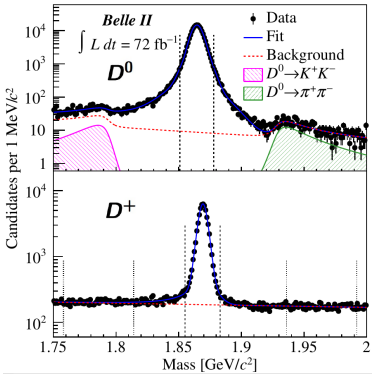
D lifetime

D lifetime measurement

[PRL 127, 211801 (2021)]

- Lifetime measurements test of non-perturbative QCD
- Lifetime of other charm hadrons (D_s, Λ_c, Ξ_c, Ω_c) dominated by LHCb but all relative to $\tau(D)$
- High precision measurement: good test of resolutions of production and decay vertices
- Reconstruct $D^0 \to K^-\pi^+$ and $D^+ \to K^-\pi^+\pi^+$ from $D^{*+} \to D^{0/+}\pi^{+/-}$ decay
- Avoid bias from secondary D (from B decays) asking high momentum (D^{*+})

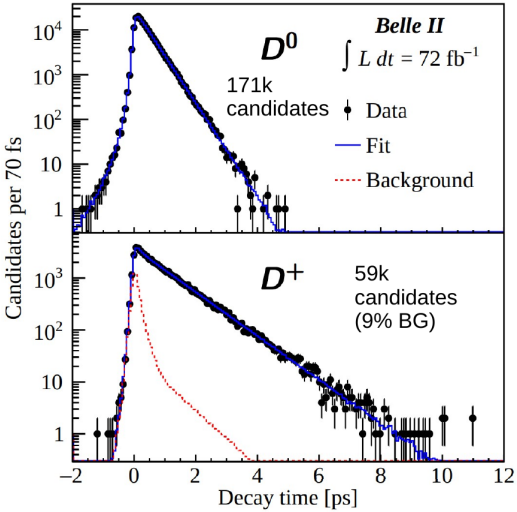




D lifetime measurement

[PRL 127, 211801 (2021)]

- Unbinned maximum fit on decay time and its error
  - Fit with exponential convoluted with resolution function
  - All parameters are determined from data
  - D^+ separate components for signal and 9% bkg contamination
  - D^0 ignore 0.2% bkg contamination



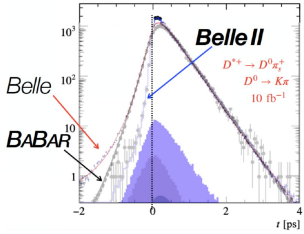
D lifetime measurement

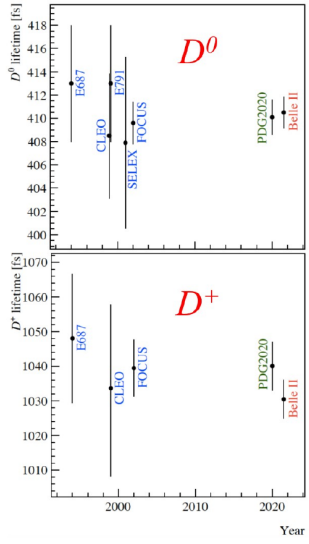
[PRL 127, 211801 (2021)]

- Results more precise than the World average

$$\tau(D^0) = 410.5 \pm 1.1 \pm 0.8\,\text{fs}$$
$$\tau(D^+) = 1030.4 \pm 4.7 \pm 3.1\,\text{fs}$$
$$\tau(D^+)/\tau(D^0) = 2.510 \pm 0.013 \pm 0.007\,\text{fs}$$

- Proof of excellent vertexing performances: will guarantee improved precision of other time-dependent measurements

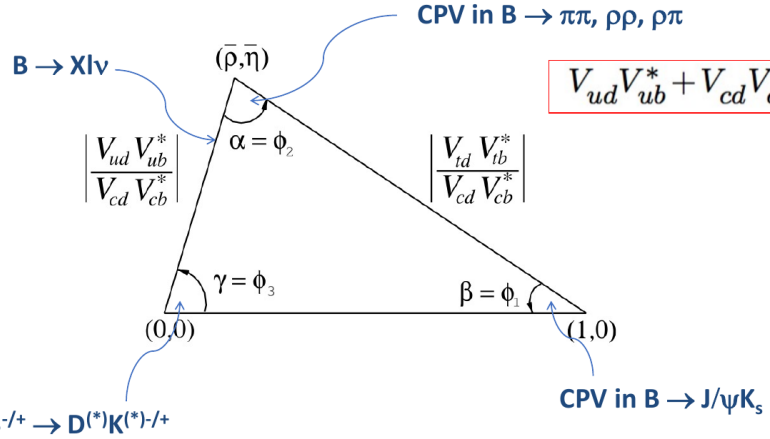




CKM matrix elements

Measurement of CKM paramenters

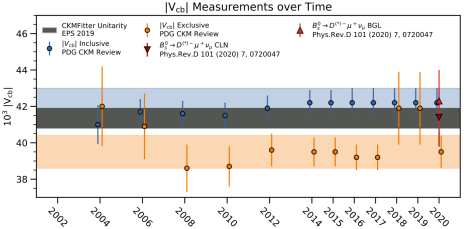
- In Standard model CP violation arises via a non zero phase of the CKM matrix
- Over-constraining unitarity triangle measuring both sides and angles is formidable test of Standard Model

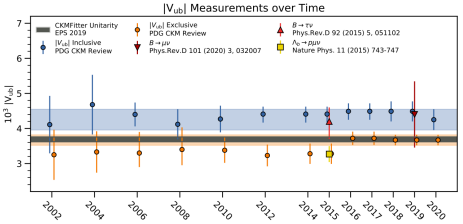


$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$$

Toward the determination of $|V_{cb}|$ and $|V_{ub}|$

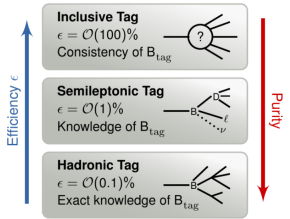
- $|V_{cb}|$ and $|V_{ub}|$ can be determined via inclusive decays $B \to Xl\nu$ or exclusive decays
- Long-standing tension between the two determinations





Tagging strategies

- Inclusive tag: signal B_{sgn} is reconstructed first and remaining particles are assigned to the B_{tag}
- Exclusive tag: explicit reconstruction of the B_{tag} in a semileptonic or an hadronic decay



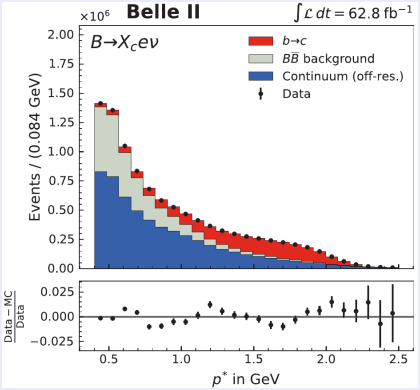
Toward the determination of $|V_{cb}|$

[arXiv:2111.09405]

Different strategies may help resolve the inclusive/exclusive tension in $b \to c l \nu$ and $b \to u l \nu$

Inclusive measurement of $B \to X_c l \nu$

- Inclusive tag analysis on 62.8 fb^{-1}
- Require one well identified lepton
- Exploit missing mass and momentum to reject background
- Dominant systematic from continuum modelling, lepton ID and signal shape
- Measure the branching fraction $\mathcal{B}(B \to X_c l \nu) = (9.5 \pm 0.03 \pm 0.47)\%$
- Consistent $\mathcal{B}$ between electron and muon modes
- Next goal: $|V_{cb}|$ from q^2 moments



Toward the determination of $|V_{cb}|$

[arXiv:2110.02648]

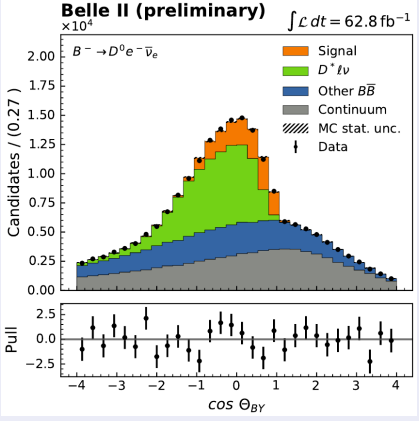
Different strategies may help resolve the inclusive/exclusive tension in $b \to c l \nu$ and $b \to u l \nu$

Measurement of $\mathcal{B}(B \to D^0 l^- \overline{\nu}_l)$

- Inclusive tag analysis on 62.8 fb^{-1}
- Reconstruct $D^0 \to K^- \pi^+$ + a lepton
- Main challenge from feeddown from $B \to D^{*0} l^- \overline{\nu}_l$
- Discriminate signal and background with $cos\vartheta_{BY}$

$$cos\vartheta_{BY} = \frac{2E_B^* E_{D^0 l^-}^* - m_B^2 - m_{D^0 l^-}^2}{2p_B^* p_{D^0 l^-}^*}$$

- Measure the branching fraction $\mathcal{B}(B \to D^0 l^- \overline{\nu}_l) = (2.29 \pm 0.05 \pm 0.08)\%$
- Consistent $\mathcal{B}$ between electron and muon modes



Toward the determination of $|V_{ub}|$

[arXiv:2111.00710]

Different strategies may help resolve the inclusive/exclusive tension in $b \to c l \nu$ and $b \to u l \nu$

Exclusive measurement of $B \to \pi l \nu_l$

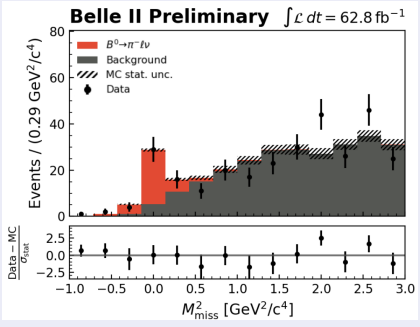
- Exclusive tag analysis on 62.8 fb^{-1}
- Golden modes for $|V_{ub}|$
- Measured on the recoil of fully reconstructed B mesons

$$\mathcal{B}(B^0 \to \pi^- l^+ \nu_l) = (1.47 \pm 0.29 \pm 0.05) \times 10^{-4}$$
$$\mathcal{B}(B^+ \to \pi^0 l^+ \nu_l) = (8.28 \pm 1.99 \pm 0.46) \times 10^{-5}$$

- Main systematics from calibration of efficiencies of B_{tag} and π^0
- Hints also of $B \to \rho l \nu_l$ ($\sim 1.5\sigma$ significance)

$$p_{B_{sgn}} = \left(\frac{m_{\Upsilon(4S)}}{2}, -\vec{p}_{B_{tag}} \right)$$

$$M^2_{\text{miss}} = (p_{B_{sgn}} - p_\pi - p_l)^2$$



Toward the determination of α/ϕ_2

[arXiv:2107.02373, arXiv:2109.11456]

- Unique Belle II capability to study all $B \to \pi\pi$, $\rho\rho$ needed to determine CKM angle α/ϕ_2
- Reconstruct also challenging decays with only neutrals

$B \to \pi^0\pi^0$

- Four photons in final states: dedicated MVA for photon selection
- Main background from continuum π^0

$$N(B \to \pi^0\pi^0) = 14^{+6.8}_{-5.6}, \quad \mathcal{B}(B \to \pi^0\pi^0) = 1.09^{+0.50}_{-0.41} \pm 0.27$$

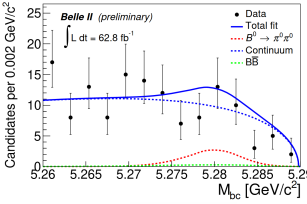
$B \to \rho^+\rho^0$

- Main background due to ρ mass width

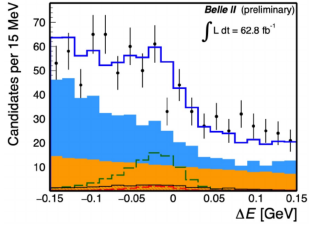
$$N(B \to \rho^+\rho^0) = 104 \pm 16, \quad \mathcal{B}(B \to \rho^+\rho^0) = 20.6 \pm 3.2 \pm 4.0$$

$$M_{bc} = \sqrt{E^2_{\text{beam}} - p^{*2}_B}$$

$$\Delta E = E^*_B - E_{\text{beam}}$$



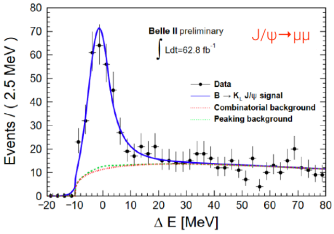
$B^+ \to \rho^+\rho^0$



Toward the determination of β/ϕ_1

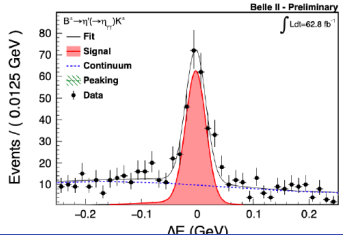
[arXiv:2104.06224, arXiv:2106.13547]

- Extracted from measurement of time-dependent asymmetries
- β/ϕ_1 can be measured in modes dominated by tree (like $B^0 \to J/\psi K_S^0$) or by loop (like $B^0 \to \eta' K_S^0$) sensitive to New Physics



$B^0 \to J/\psi K_L^0$

- Channel complementary to golden mode $B^0 \to J/\psi K_S^0$ (opposite CP eigenvalue) but harder to reconstruct
- For now just first reconstruction ($N = (7.3 \pm 0.4)/\,\text{fb}^{-1}$ consistent with expectations from Belle)



$B^0 \to \eta' K_S^0$

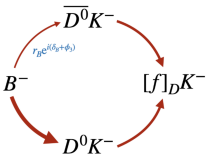
- Dominated by loop → sensitive to New Physics
- For now just first reconstruction ($\mathcal{B} \sim 7 \times 10^{-5}$)

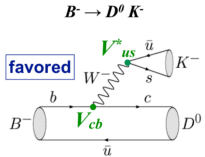
First hint of time-dependent CPV in [BELLE2-NOTE-PL-2020-011]

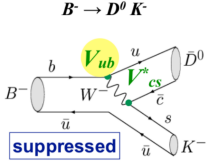
Measurement of γ/ϕ_3

[JHEP 02, 063 (2022)]

- Use golden channel $B^- \to \overset{(--)}{D^0} K^-$
- Interference between favoured and suppressed mode gives access to phase



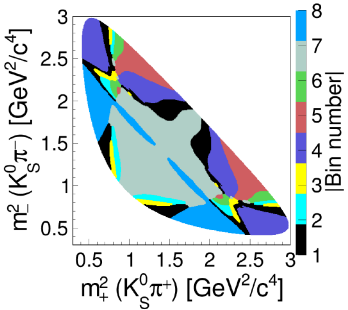




$$r_B e^{i(\delta_B+\gamma/\phi_3)} = \frac{\mathcal{A}^{\text{suppr.}}(B^- \to \overline{D}^0 K^-)}{\mathcal{A}^{\text{favor.}}(B^- \to D^0 K^-)}$$

r_B: magnitude ratio of amplitudes, δ_B: strong phase difference

- $\overset{(--)}{D^0}$ reconstructed from $K^0_S\pi^+\pi^-$ and $K^0_S K^+ K^-$
- Use binned model independent method: D strong phase parameters from CLEO [PRD 82, 112006 (2010)] and BESIII [PRD 101, 112002 (2020), PRD 102, 052008 (2020)]



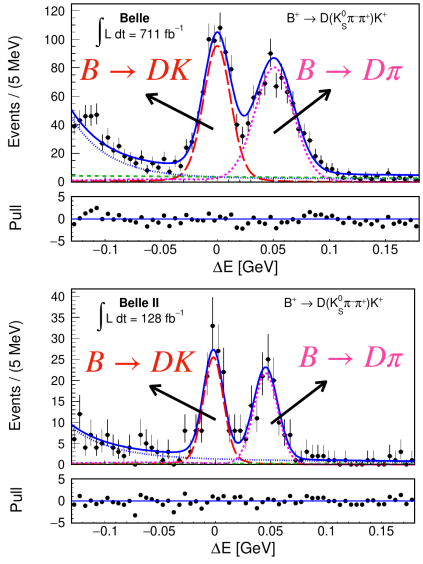
Measurement of γ/ϕ_3

[JHEP 02, 063 (2022)]

- Combine Belle and Belle II dataset (711+128) fb^{-1}
- Unbinned fit to ΔE and MVA output (with event shape variables)

$$\gamma/\phi_3 = (78.4 \pm 11.4 \pm 0.5 \pm 1.0(\text{ext. input}))^\circ$$

  - 30% improvement on stat. err. with 20% more data
  - Systematic err $4^\circ \to 0.5^\circ$
  - Ext. input syst. $4^\circ \to 1^\circ$
- Many improvements wrt [Belle, PRD 85, 112014 (2012)]
  - Added $K^0_S K^+ K^-$ mode
  - Multivariate K^0_S selection
  - Improved background rejection
  - New fitting strategy exploiting constraints from more abundant $B^- \to \overset{(--)}{D}{}^0 \pi^-$
  - New strong phase inputs (BESIII)



$b \to s$ transitions

$b \to s\gamma$ and $b \to sll$ searches

[arXiv:2110:08219, BELLE2-NOTE-PL-2021-005]

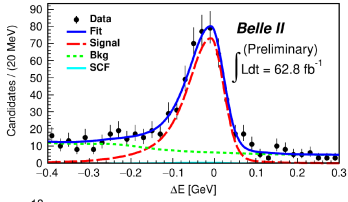
First reconstruction of $b \to s$ decays potentially sensitive to new physics in the light of the anomalies

$B \to K^*\gamma$

- Measured branching fraction in agreement with World averages
- First step before measurement of CP and isospin asymmetries

Mode	$\mathcal{B}_{\text{meas}}$ $[10^{-5}]$	$\mathcal{B}_{\text{PDG}}$ $[10^{-5}]$
$B^0 \to K^{*0}\gamma$	$4.5 \pm 0.3 \pm 0.2$	4.18 ± 0.25
$B^+ \to K^{*+}\gamma$	$5.2 \pm 0.4 \pm 0.3$	3.92 ± 0.22

$B^0 \to K^{*0}(\to K^+\pi^-)\gamma$



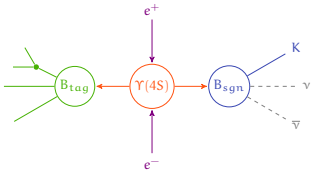
$B^+ \to K^+l^+l^-$

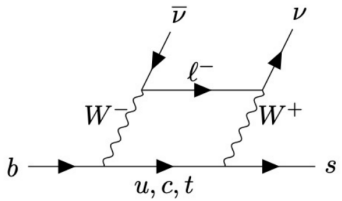
- First hint: $N = 8.6^{+4.3}_{-3.9} \pm 0.4$
- Would need more than 5 ab^{-1} to provide significant information on $R(K)$

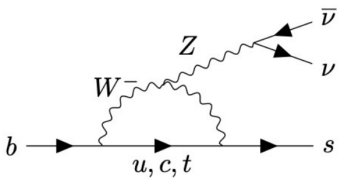
Search for $B^+ \to K^+ \nu\overline{\nu}$

[PRL 127, 181802 (2021)]

- $B^+ \to K^+ \nu\overline{\nu}$ suppressed in the Standard Model and not yet observed
- Best upper limit from BaBar $\mathcal{B} < 1.6 \times 10^{-5}$ using exclusive tag approach
- $\mathcal{B}_{SM} \sim 5 \times 10^{-6}$ and
  - Clean SM computation (no charm loop contributions)
  - Possible impact from New Physics linked to $b \to sll$ anomalies [arXiv:2005.03734]
- Possible to recast to look for $B^+ \to K^+ X_{dark}$



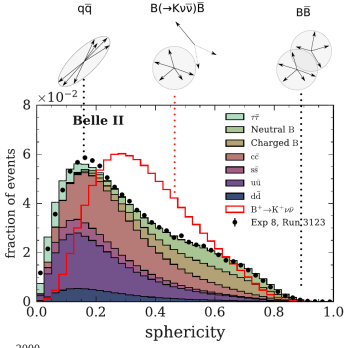




Search for $B^+ \to K^+ \nu\bar{\nu}$

[PRL 127, 181802 (2021)]

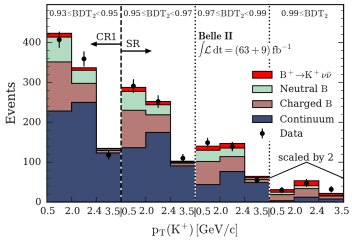
- Use inclusive tag approach on 63 fb^{-1}
- Consider as the signal K^+ the highest p_T track in the event (right 78% of the times)
- Two nested BDTs to suppress background using specific signal topology (event topology, missing energy, signal kinematic, ...)
- Factor 20 higher efficiency wrt exclusive tag approach ($\sim$ 4% vs $\sim$ 0.2%)
- Validation with control channel $B^+ \to K^+ J/\psi\,(\to \mu^+\mu^-)$ by removing the J/ψ



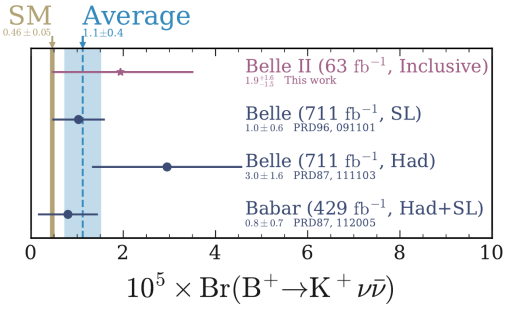
Search for $B^+ \to K^+ \nu\bar{\nu}$

[PRL 127, 181802 (2021)]

- Binned simultaneous fit to $p_T(K^+)$ and output second BDT
- No significant signal observed
- $\mathcal{B} < 4.1 \times 10^{-5}$ @ 90% CL



- Competitive sensitivity with 10 times less data than previous searches
- Combined analysis with inclusive + exclusive tag reconstruction could lead to faster observation



Conclusion

Belle II will have an unique reach in dozens of measurement that could unveil new physics, fist steps undertaken toward that goal

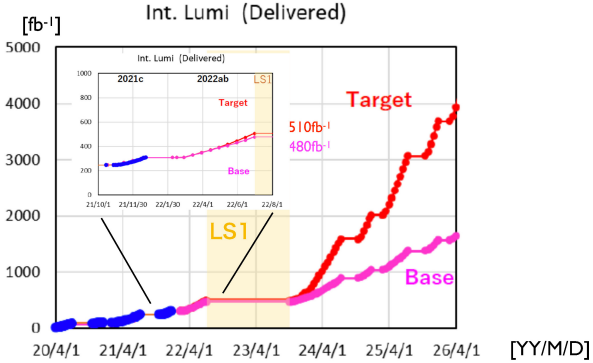
- World record instantaneous luminosity (with lower currents than previous record holders)
- Established excellent vertexing performance with World's best D lifetime measurement
- Proved good overall performances (PID, flavour tagger, momentum and energy resolutions ...)
- A pletora of re-observation of known decays and performance studies to pave the way to a broad physics program
- First physics papers with new analyses techniques to optimal exploit current dataset and capitalising to unique advantages
- More than 200 fb^{-1} on tape expected to double by this summer, stay tuned

BACKUP

Projection of integrated luminosity delilivered 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

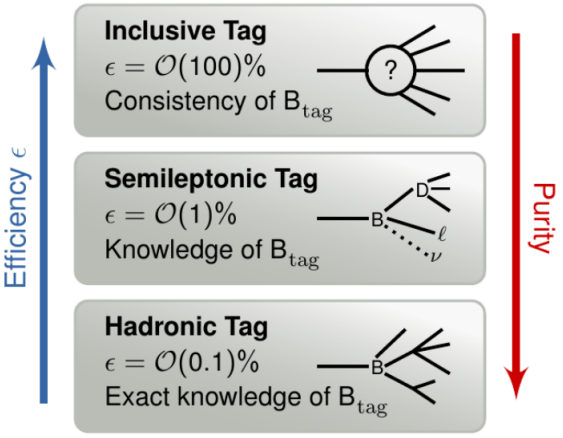
D lifetime measurement, systematics

[PRL 127, 211801 (2021)]

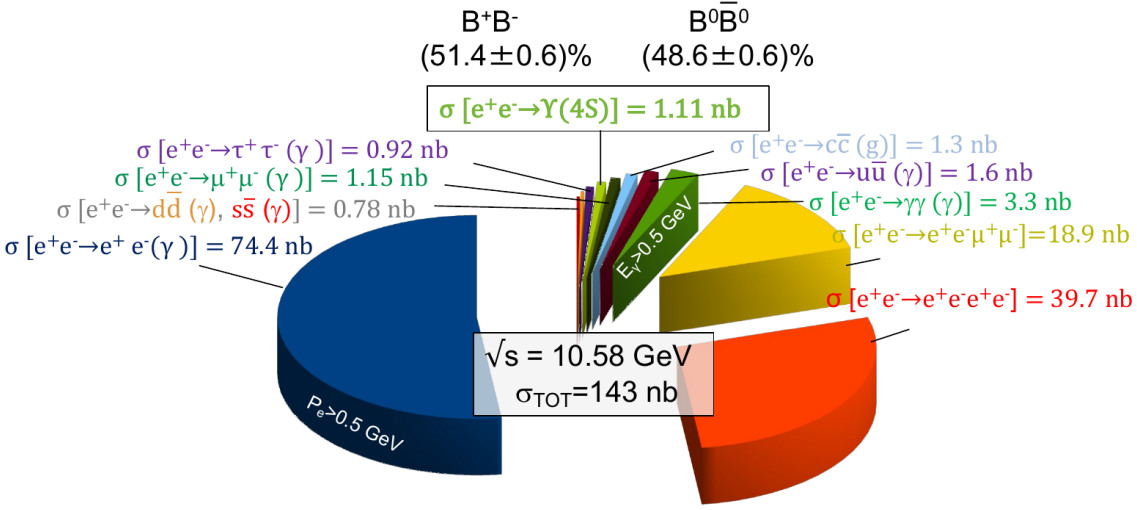
$$\tau(D^0) = 410.5 \pm 1.1 \pm 0.8 \text{ fs} \quad (0.3\%)$$
$$\tau(D^+) = 1030.4 \pm 4.7 \pm 3.1 \text{ fs} \quad (0.5\%)$$
$$\tau(D^+)/\tau(D^0) = 2.510 \pm 0.015 \quad (0.6\%)$$

Source	Uncertainty (fs)	
	$D^0 \to K^-\pi^+$	$D^+ \to K^-\pi^+\pi^+$
Resolution model	0.16	0.39
Backgrounds	0.24	2.52
Detector alignment	0.72	1.70
Momentum scale	0.19	0.48
Input charm masses	0.01	0.03
Total systematic	0.8	3.1
Statistical	1.1	4.7

Tagging strategies



Cross sections at the $\Upsilon(4S)$

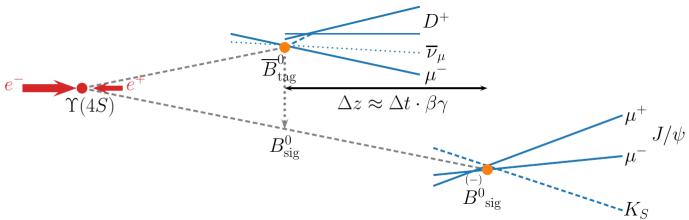


Measurement of β/ϕ_1

[BELLE2-NOTE-PL-2020-011]

- First measurement with golden channel $B^0 \to J/\psi K_S^0$ with $34.6\,\text{fb}^{-1}$
- Time dependent measurement

$$\sin(2\beta/\phi_1) \propto \frac{N(B^0_{tag}) - N(\bar{B}^0_{tag})}{N(B^0_{tag}) + N(\bar{B}^0_{tag})}(\Delta t)$$



- Reconstruct $B^0 \to J/\psi K_S^0$ with $J/\psi \to \mu^+\mu^-, e^+e^-$
- Key ingredients: Δt resolution and flavour tagger
- Belle II already able to see first 2.7σ hint for time-dependent CPV

$$sin(2\beta/\phi_1) = 0.55 \pm 0.21 \pm 0.04$$

(PDG value: $0.670 \pm 0.029 \pm 0.013$)