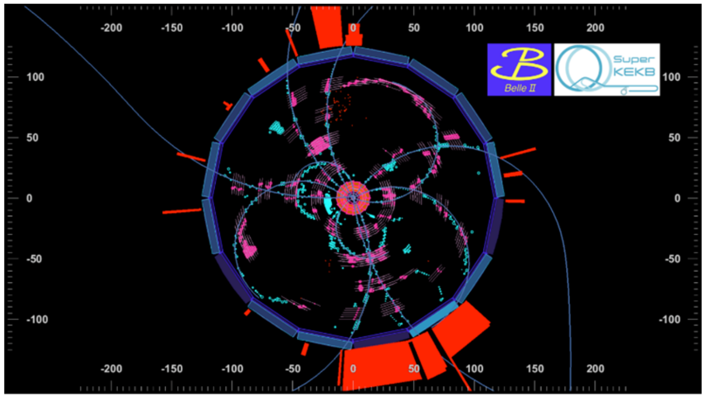
Belle II at SuperKEKB – Status and Plans



Peter Križan

University of Ljubljana and J. Stefan Institute

Belle II

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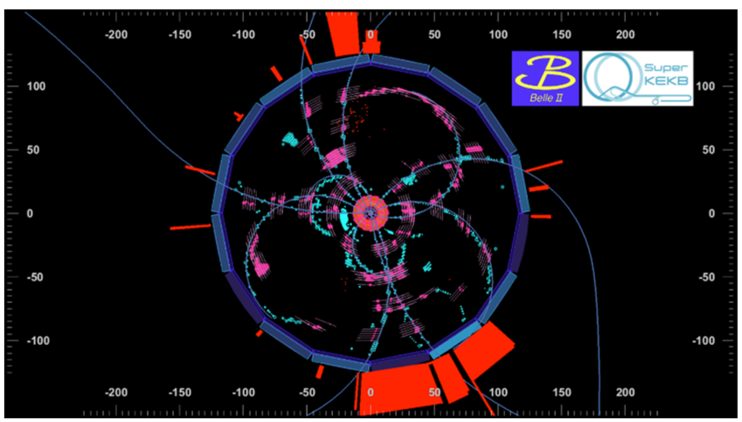
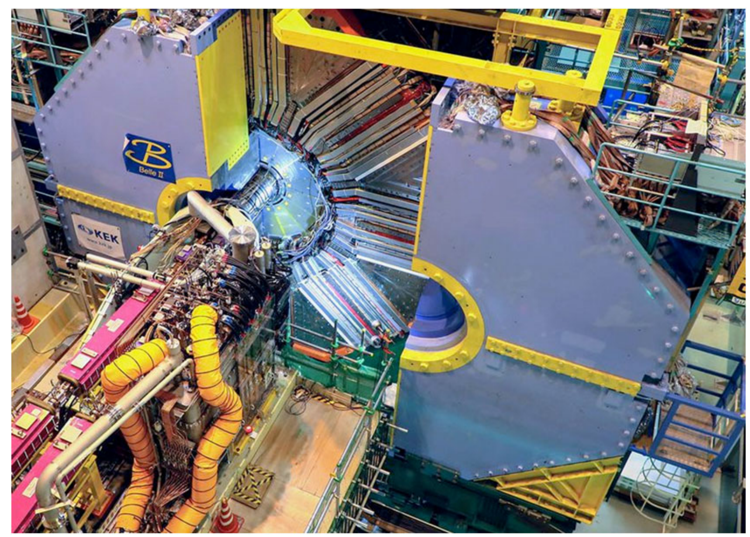




Flavour Physics in 2022

The standard model of particle physics is in a great shape, after decades of deep investigation and precision measurements, all phenomena happening at colliders are accounted for.

However, in the past years, hints that the SM is not the full story have been accumulating:

➔ hints of violation of Lepton Flavor Universality;

➔ (partial) branching fractions and angular observables of B decays dominated by loop amplitudes;

➔ $(g\text{-}2)_\mu$

Many of the anomalies have been detected by the LHCb experiment, which is currently the main actor on the scene.

Taken one by one, these anomalies are not striking, but they seem to paint a consistent picture...

→ Talks by Damir Becirevic, Renato Quagliani

Flavor physics at an e^+e^- collider

- Clear disadvantage against the LHC in terms of cross sections, but:

- Many of the interesting modes (not only for flavor physics) are unique to B Factories:

➔ channels with π^0, K_L, $\eta(')$, … ;

➔ final states with one or more ν's;

➔ modes affected by "difficult" backgrounds, where the full knowledge of the kinematics in the event is the only way to control them;

➔ a variety of inclusive measurements can be performed.

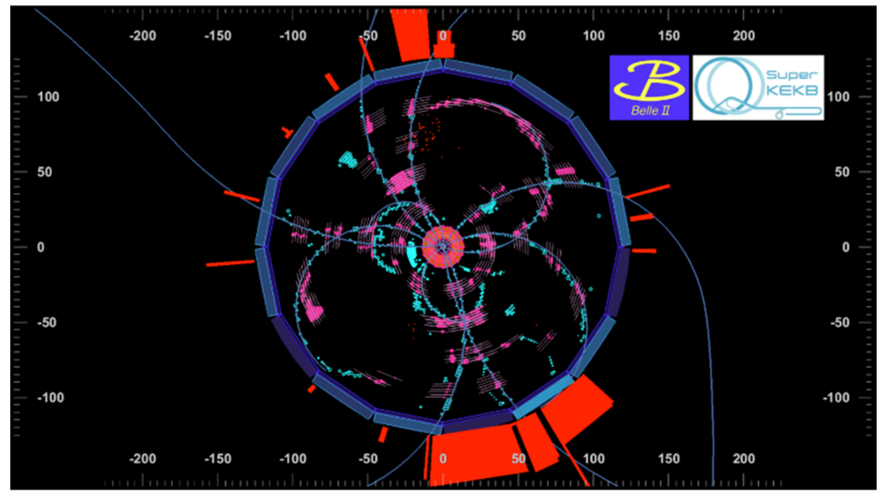
- In general: a wider spectrum of measurements allows for a better understanding (or highlights our lack of…).

- And extraordinary claims require extraordinary evidence: we need an independent confirmation for as many modes as possible.

A B factory in the LHC era

Fantastic performance of LHCb with many interesting results!

Still, an e^+e^- machine running at (or near) Y(4S) is complementary to LHCb in several aspects.



Unique capabilities of a B factory:

→ Exactly two B mesons produced
→ High flavour tagging efficiency
→ Detection of gammas, π^0s, K_Ls
→ Very clean detector environment (decays with several neutrinos in the final state, tau physics, dark sector)

Physics potential summarized in Belle II Theory Interface Platform (B2TiP) 'physics book' PTEP 2019 (2019) 123C01, arXiv:1808.10567

<u>However, need a two-orders-of-magnitude larger data sample!</u>

<u>→ Increase by 30x the luminosity of a world record accelerator</u>

How to increase the luminosity?

$$L = \frac{\gamma_{e\pm}}{2er_e}\left(1+\frac{\sigma_y^*}{\sigma_x^*}\right)\left(\frac{I_{e\pm}\xi_y^{e\pm}}{\beta_y^*}\right)\left(\frac{R_L}{R_{\xi_y}}\right)$$

Lorentz factor

Beam current

Beam-beam parameter

Classical electron radius

Beam size ratio@IP
1 ~ 2 % (flat beam)

Vertical beta function@IP

Lumi. reduction factor (crossing angle)&
Tune shift reduction factor (hour glass effect)
0.8 ~ 1
(short bunch)

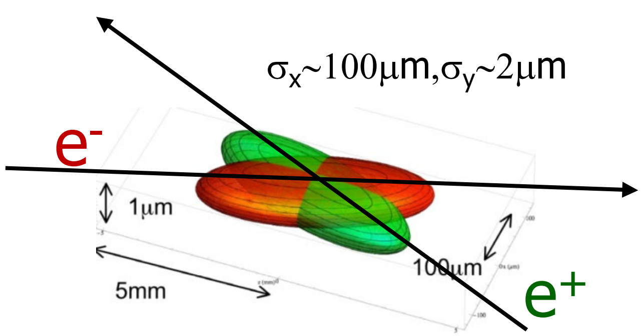
(1) Smaller β_y^*

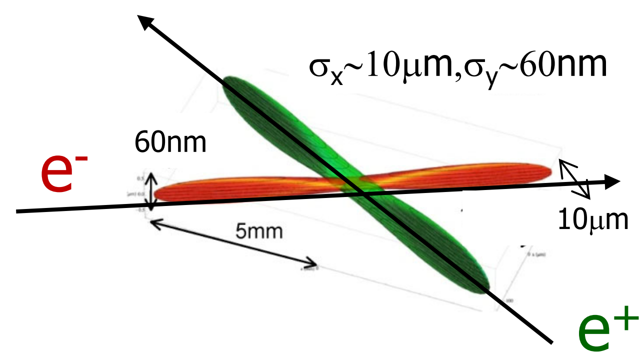
(2) Increase beam currents

(3) Increase ξ_y

"Nano-Beam" scheme

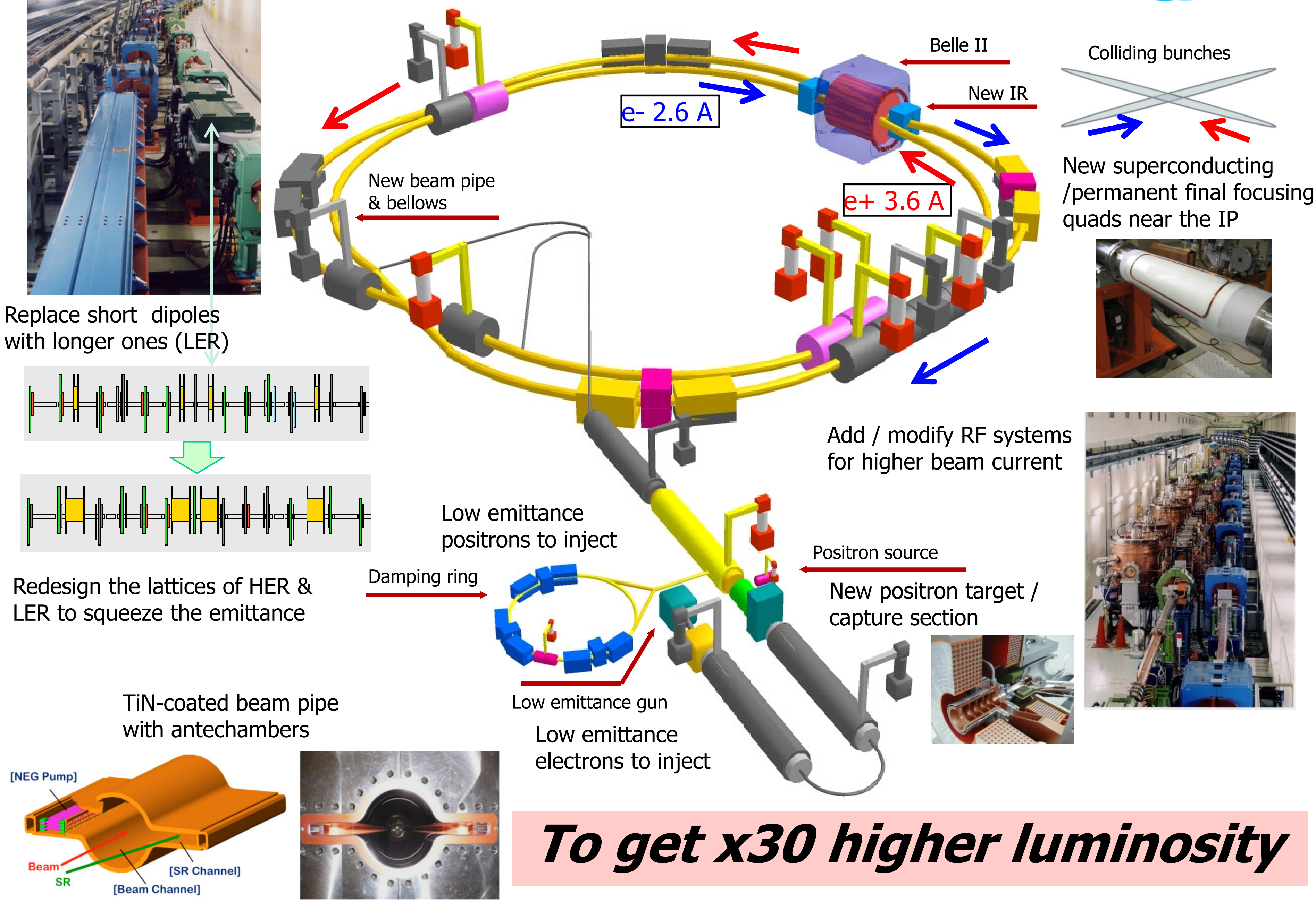
Invented by Pantaleo Raimondi for SuperB





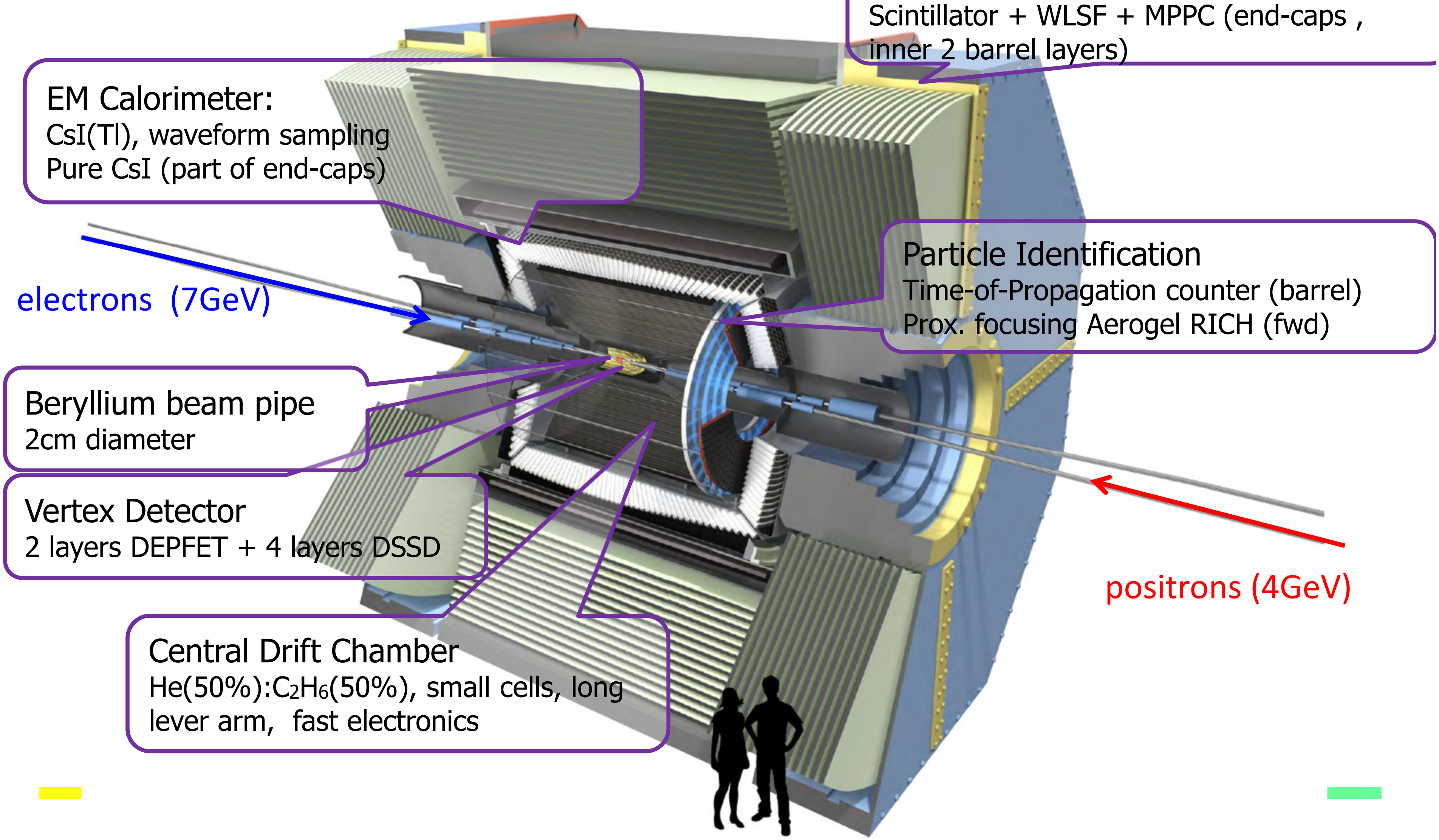
In KEKB, colliding electron and positron beams were already much thinner than a human hair...
... For a 30x increase in intensity you have to make the beam as thin as a few x100 atomic layers!

KEKB → SuperKEKB



Detector: Belle → Belle II

It looks like Belle, but practically
it is a brand new detector!



SuperKEKB/Belle II phases

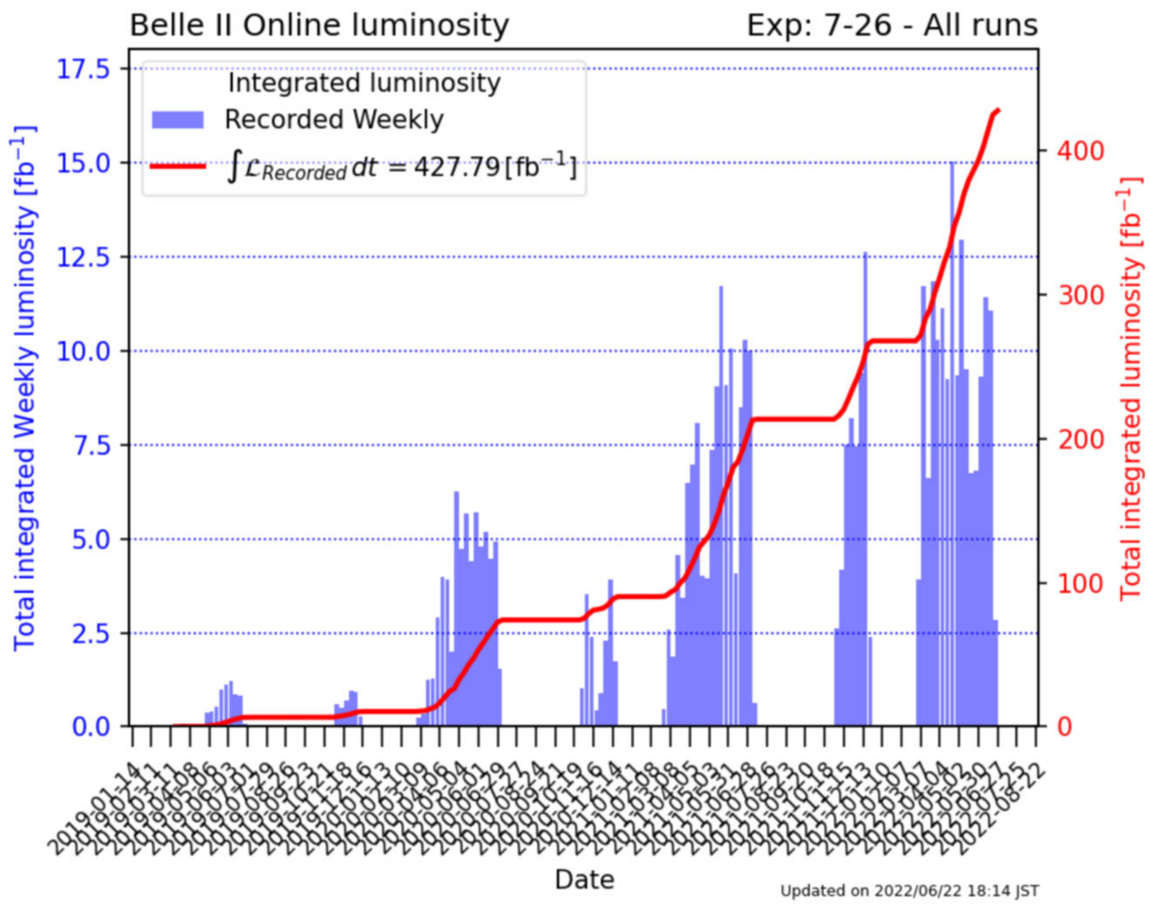
- Phase 1(2016): no detector, no collision, test the rings, baking the 3km of the accelerator vacuum chambers

- Phase 2 (2018): first collisions with complete accelerator
  - Incomplete detector: Vertex detector replaced by dedicated background detector (Beast 2)

- Phase 3 (2019-): luminosity run with complete detector
  - Pixel Detector (PXD): layer 1 + partly equipped layer 2
  - Full 4-layers strip detector (SVD)
  - First physics paper appeared in January 2020

- New and difficult accelerator. Additional operational complexity during the pandemic
- Record peak luminosity 4.7×10^{34} cm^{-2} s^{-1}
- Path to reach 2×10^{35} cm^{-2} s^{-1} identified.
- More effort needed to reach the target peak luminosity of 6×10^{35} cm^{-2} s^{-1}

Belle II and SuperKEKB



Very successful data taking throughout the pandemic

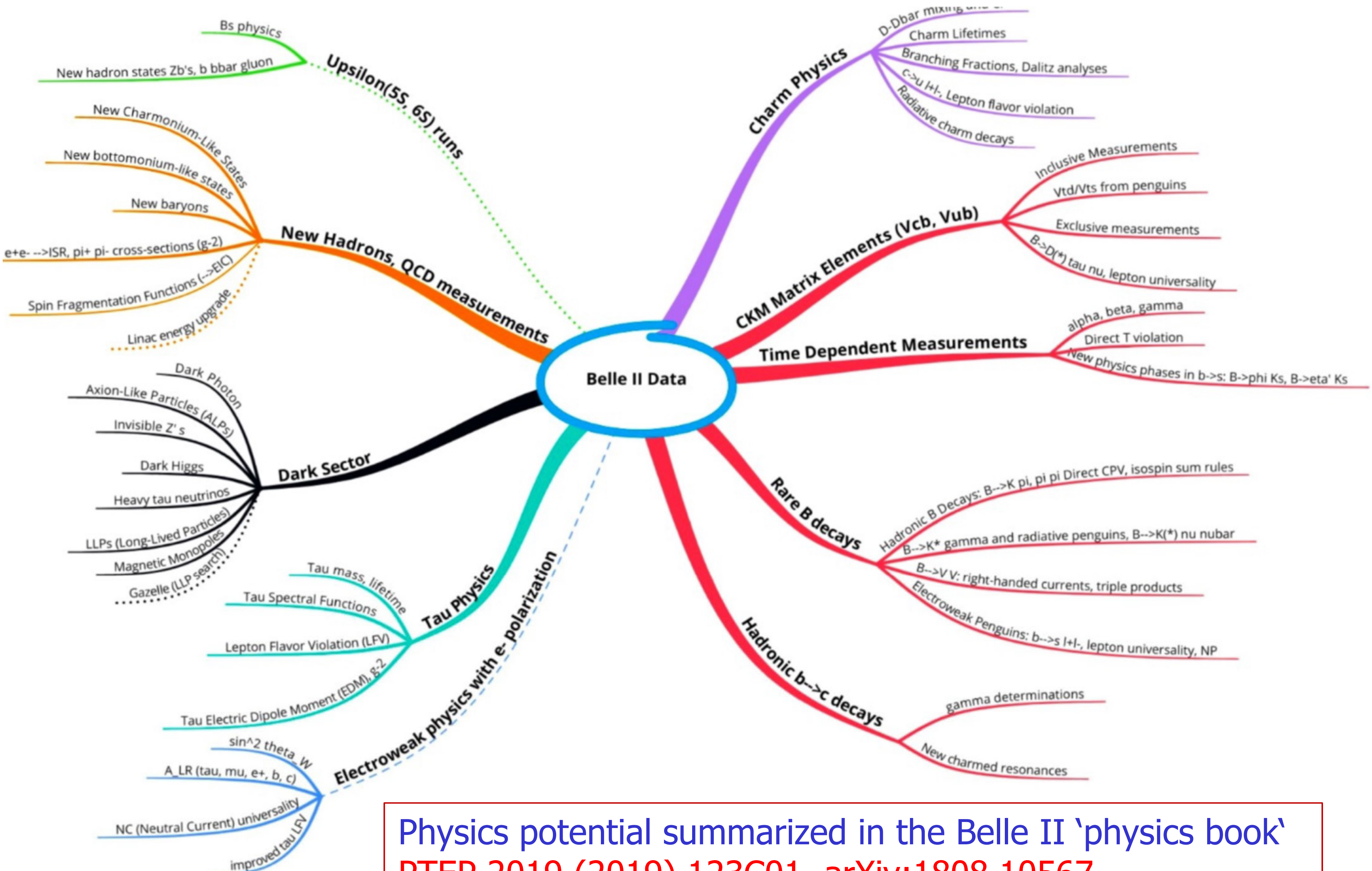
-overall data taking efficiency of 89.5%

-reached world record instantaneous luminosity: $4.7 \times 10^{34}\ cm^{-2}\ s^{-1}$, collected up to $15\ fb^{-1}$ per week: Super-B factory mode

-recorded luminosity at Belle II: $428\ fb^{-1}$ (Belle $988\ fb^{-1}$, BaBar $513\ fb^{-1}$)

Ultimate goal: reach $50\ ab^{-1}$ by operating at the instantaneous luminosity of $6 \times 10^{35}\ cm^{-2}\ s^{-1}$

Physics program



Physics potential summarized in the Belle II ‘physics book‘
PTEP 2019 (2019) 123C01, arXiv:1808.10567

Recent results – selected topics

This talk - a subselection of recent results:

- Lifetimes of charmed hadrons
- Measurements to help understand the long standing tension between inclusive and exclusive V_{xb} determinations.
- Test of Lepton Flavour Universality: $B^0 \to X e^- \nu_e$ vs $B^0 \to X \mu^- \nu_\mu$
- Searches for new physics in rare decays of the type b → s: $B \to X_S \ell\ell$, $B^\pm \to K^\pm \nu\nu$, $b \to s\gamma$ transitions, $K\pi$ puzzle

This talk: results based on an integrated luminosity of up to ~190 fb^{-1}

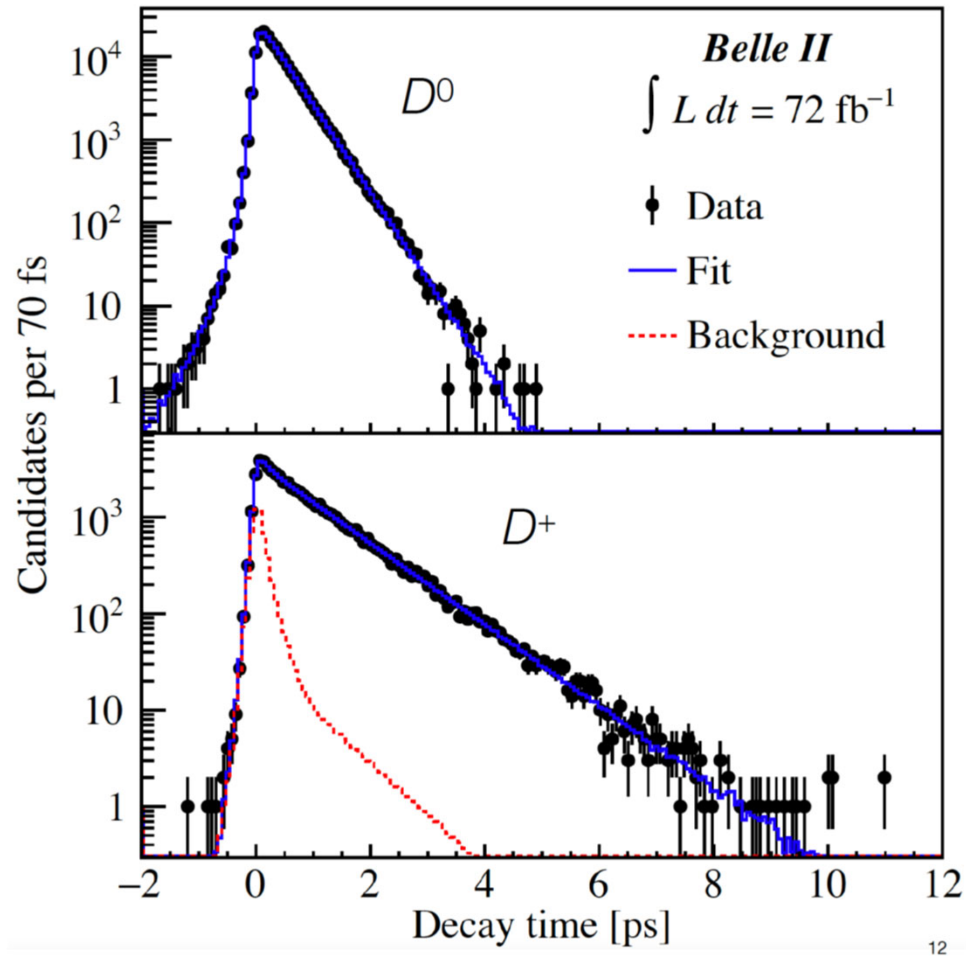
Recorded luminosity at Belle II: 428 fb^{-1} (Belle 988 fb^{-1}, BaBar 513 fb^{-1})

D^0 and D^+ lifetime measurements

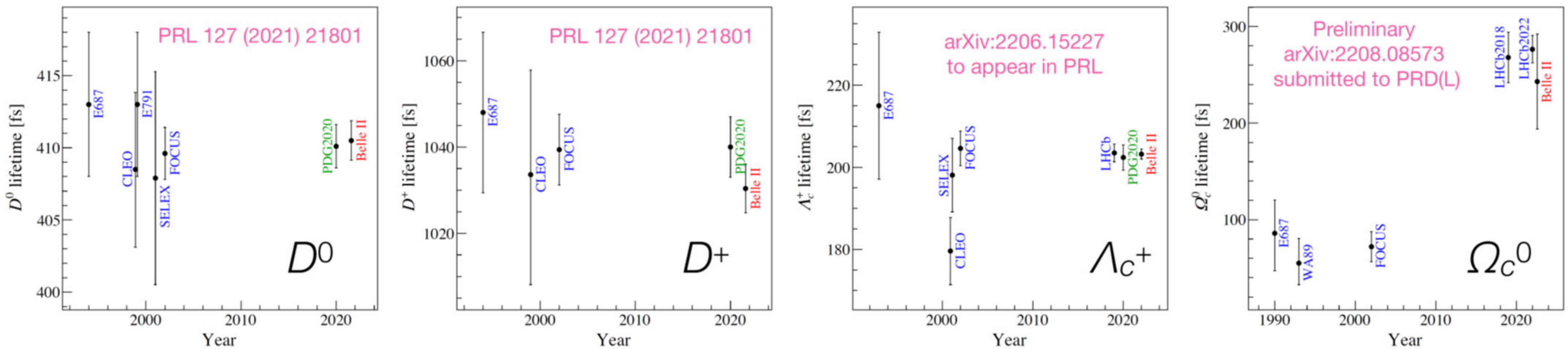
Example of improved performance of Belle II vs Belle: time-dependent capabilities in D lifetime measurements.

The addition of a pixel vertex detector (with a 1cm radius beam pipe) gives a *factor of two improvement* in proper time resolution for charm lifetime measurements compared to Belle. Alignment systematics are much improved.

PRL 127 (2021) 21801



Lifetimes of charmed hadrons



Used early Belle II data to measure lifetimes of charm hadrons

- World-best D^0, D^+ and Λ_c^+ lifetimes (first Belle II precision measurements)
- Confirmation of LHCb result indicating that the Ω_c^0 is not the shortest-lived weakly decaying charmed baryon

Tiny systematic uncertainties (e.g., 2‰ for D^0) demonstrate excellent performance and understanding of the Belle II detector, never achieved at previous B factories

sin(2ϕ_1) / sin(2β) from B → J/ψ K_s

- Full time dependent analysis of the most sensitive (almost background free) of the golden channels;
- Using the same resolution function developed for the lifetime and mixing analysis, and determining common parameters from $B^0 \to D(*)^- h^+$ modes;
- Results:

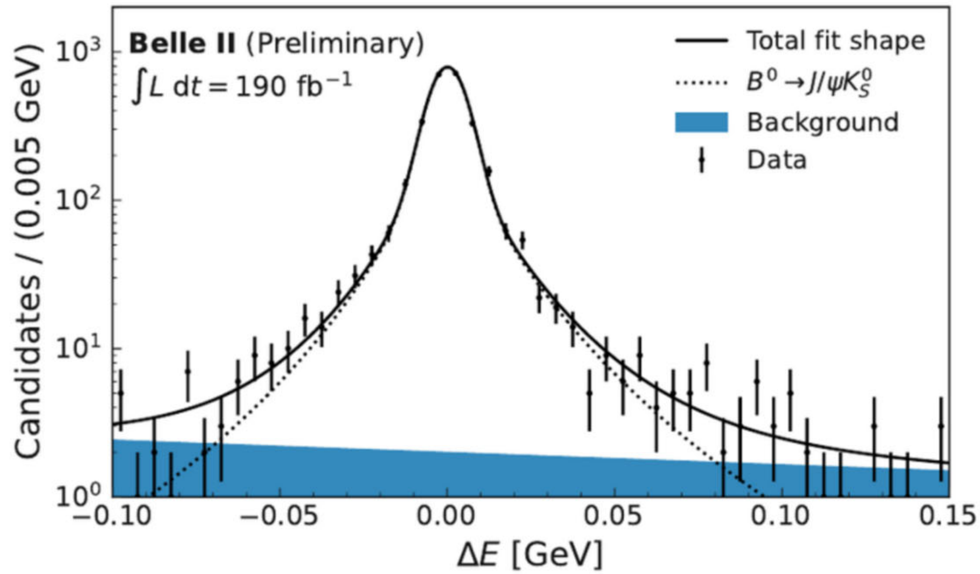
$$S_{CP} = 0.720 \pm 0.062(\text{stat}) \pm 0.016(\text{syst})$$

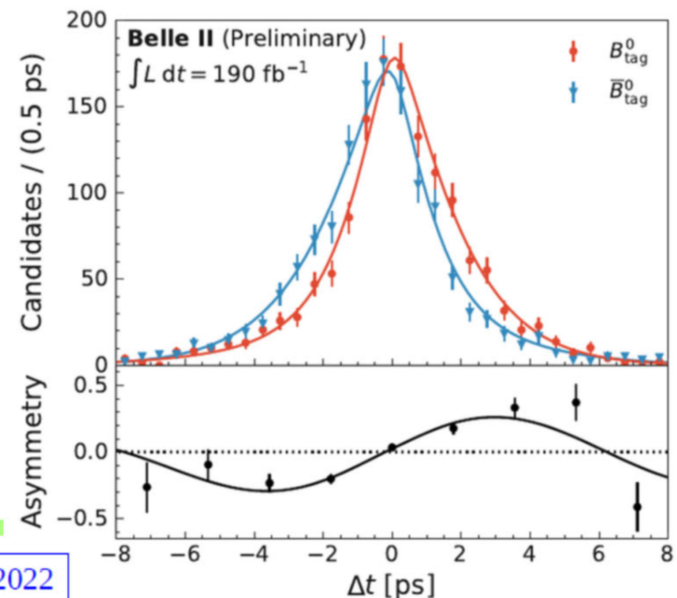
$$A_{CP} = 0.094 \pm 0.044(\text{stat})^{+0.042}_{-0.017}(\text{syst})$$

World average (K_S mode only):

S_{CP} = 0.695 ± 0.019

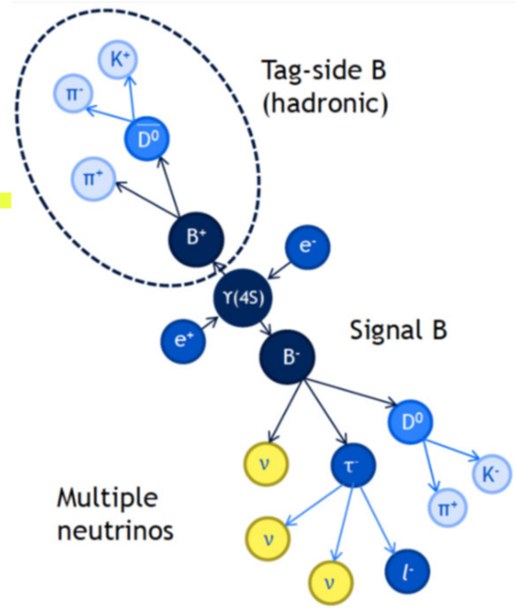
A_{CP} = 0.000 ± 0.020





- In the near future we will add the K_L and other cc resonances;
- Still very far from being limited by the systematics!

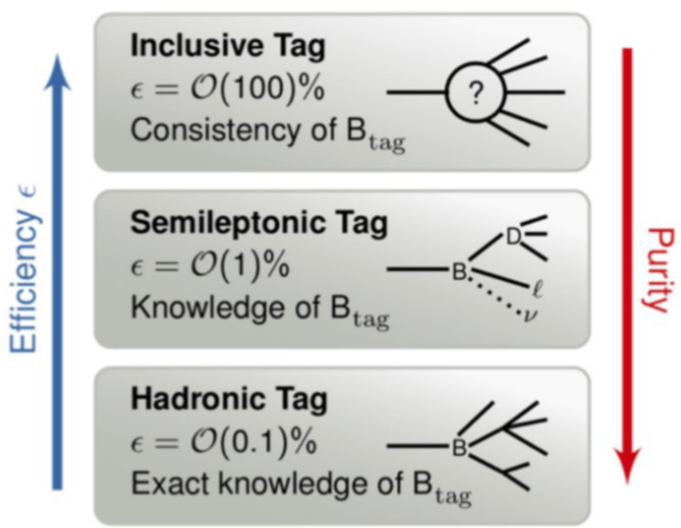
Hadronic taging at Belle II

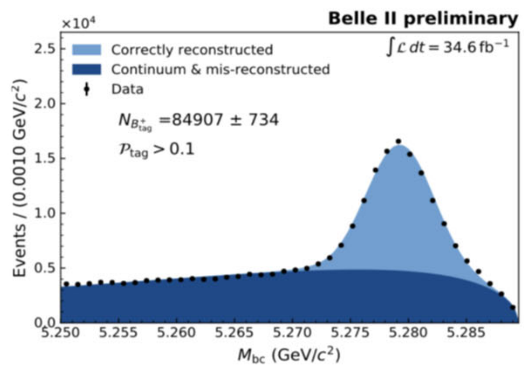


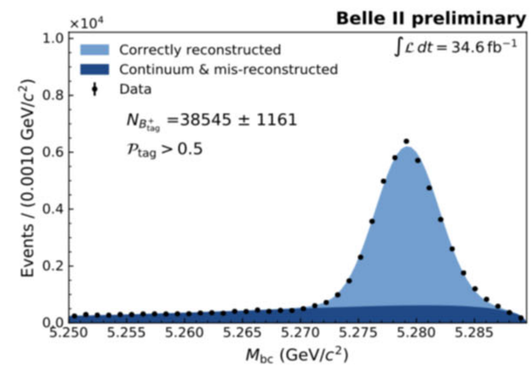
Profit from the fact that exactly two B mesons are produced in e^+e^- collisions

→Full Event Interpretation (FEI)

- hierarchical multivariate technique (>200 BDTs) to reconstruct the B-tag side (semi-leptonic or hadronic) through $O(10^3)$ different decay modes
- results in a significantly increased tagging efficiency compared to Belle



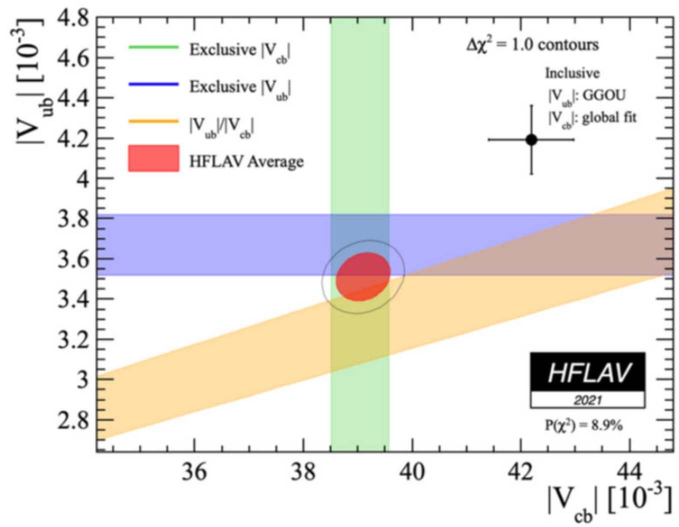




$$M_{bc} = \sqrt{s/4 - p_{cm}^2 c^2}$$

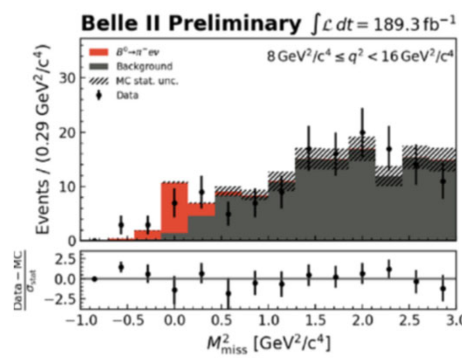
V_{ub} matrix element with exclusive decays

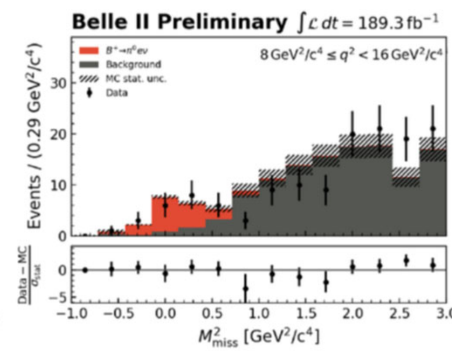
Long standing tension between inclusive and exclusive V_{xb} determinations.



Belle II: exclusive and inclusive measurements of V_{cb} and V_{ub} with tagged and untagged methods.

Tagged V_{ub} study: using the FEI, we can measure the $B \to \pi\, l\, \nu$ branching ratios with much less background, and tackle the more challenging $B \to \rho\, l\, \nu$





$$\mathcal{B}(B^0 \to \pi^- e^+ \nu_e) = (1.43 \pm 0.27(\text{stat}) \pm 0.07(\text{syst})) \times 10^{-4}$$

$$\mathcal{B}(B^+ \to \pi^0 e^+ \nu_e) = (8.33 \pm 1.67(\text{stat}) \pm 0.55(\text{syst})) \times 10^{-5}$$

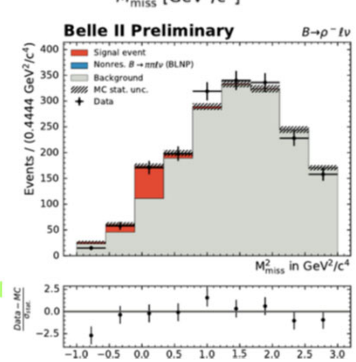
$$|V_{ub}| = (3.88 \pm 0.45) \times 10^{-3}$$

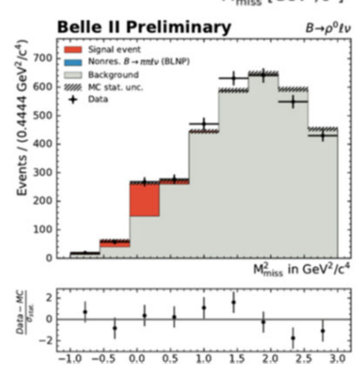
arXiv:2206.08102 [hep-ex]

$$\mathcal{B}(B^0 \to \rho^- \ell^+ \nu_\ell) = (4.12 \pm 0.64_{\text{stat}} \pm 1.16_{\text{sys}}) \times 10^{-4}$$

$$\mathcal{B}(B^+ \to \rho^0 \ell^+ \nu_\ell) = (1.77 \pm 0.23_{\text{stat}} \pm 0.36_{\text{sys}}) \times 10^{-4}$$

T. Koga @ ICHEP 2022

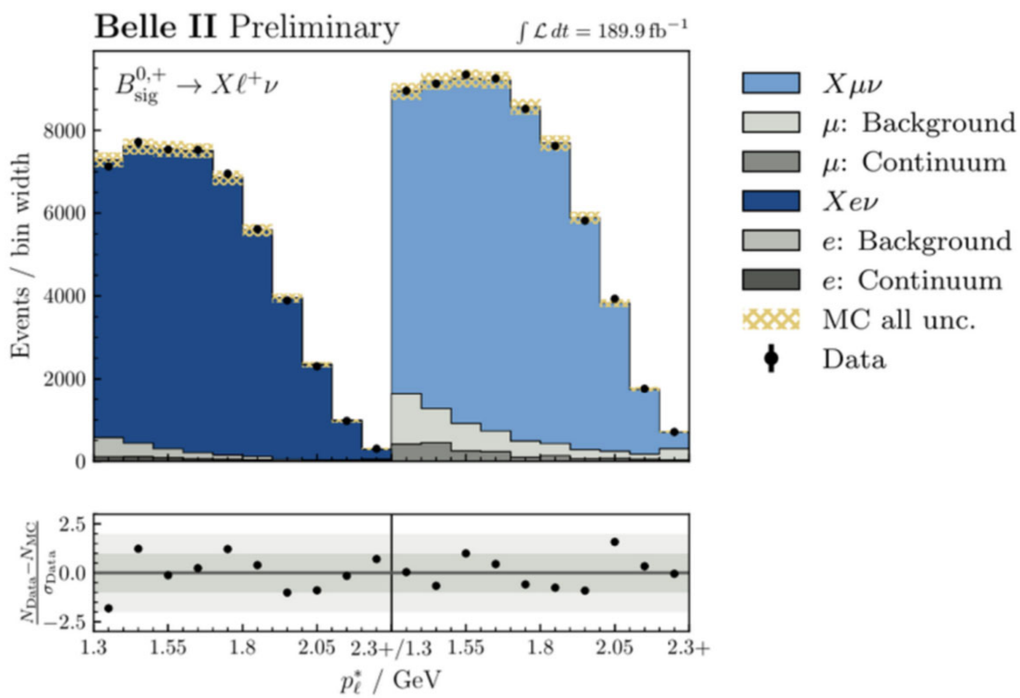




Preparation for the R(D*) measurement

Test of Lepton Flavour Universality: measure $R(X_{e/\mu}) = B(B^0 \to Xe^-\nu_e)/B(B^0 \to X\mu^-\nu_\mu)$

Template fit on CM frame lepton momentum p_l^*, with $p_l^* > 1.3$ GeV



Two main sources of background:
1) continuum, constrained with off-resonance data;
2) other B decays (fake leptons, leptons arising from decay of charmed hadrons, …), constrained from background enriched control regions.

$R(X_{e/\mu}) = 1.033 \pm 0.010 \pm 0.020$

H. Junkerkalefeld @ ICHEP 2022

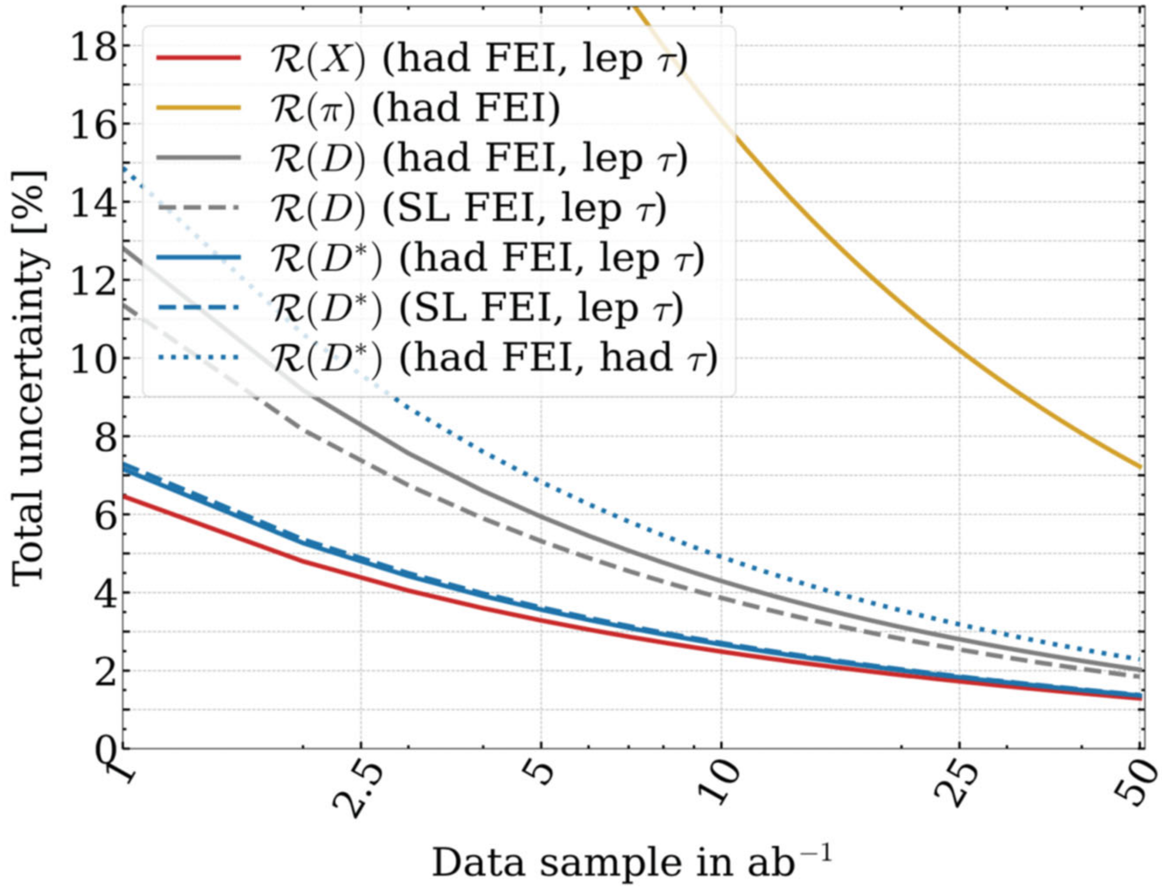
To date the most precise measurement, in good agreement with the SM. Dominant systematic uncertainty from lepton identification (1.8%).

This paves the way to the first measurement of $$R(X) = \frac{\mathcal{B}(B \to X\tau\nu)}{\mathcal{B}(B \to X\ell\nu)}$$

Belle II: prospects for the R(D*), R(D), R(X), R(π) measurements

$$R(D, D^*, X) = \frac{\mathscr{B}(B \to D, D^*, X\tau\nu)}{\mathscr{B}(B \to D, D^*, X\ell\nu)}$$

with ℓ a light lepton



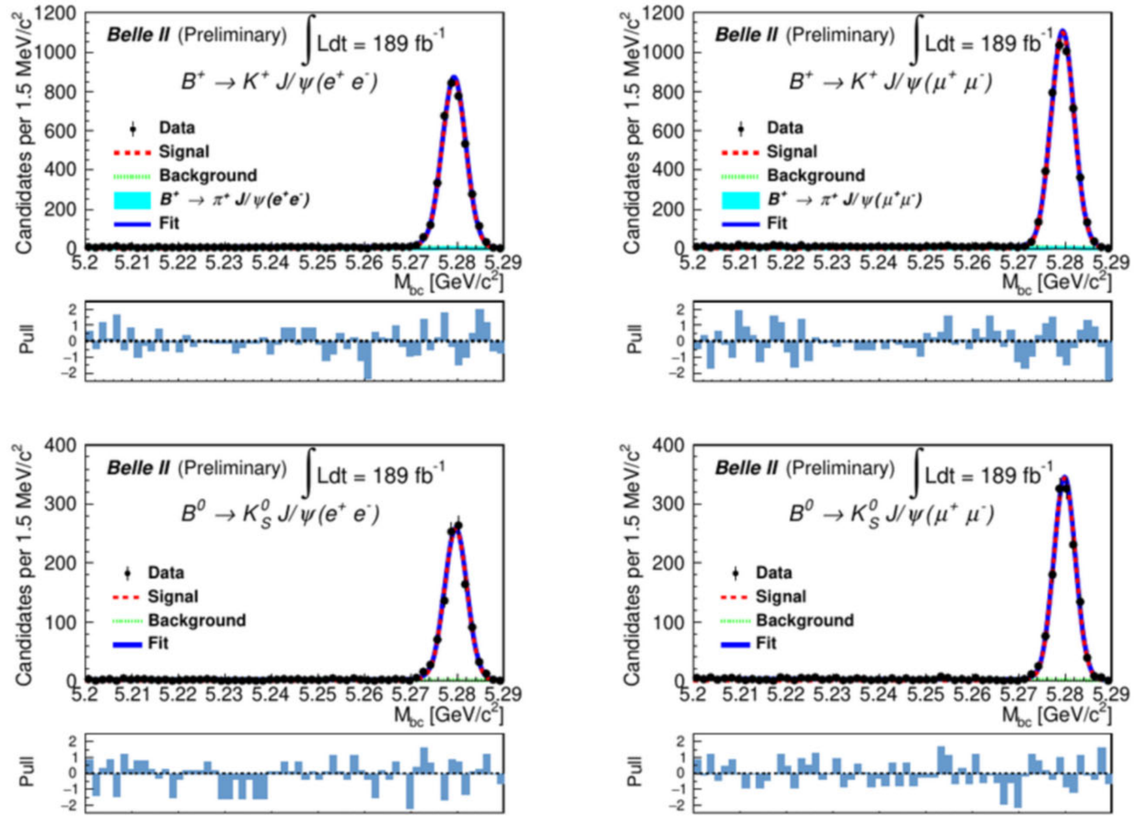
From: Snowmass white paper "Belle II physics reach and plans for the next decade and beyond"
https://www.slac.stanford.edu/~mpeskin/ Snowmass2021/ BelleIIPhysicsforSnowmass.pdf

R(K) in B → J/ψ K

Hot topic: potential LFU violation in $B \to K^{(*)} l^+ l^-$ decays that proceed through loop diagrams.

Approaching step: measure R(K) in B → J/ψ K decays (tree level process, no LFU violation is expected)

$$R_K(J/\psi) = \frac{\mathcal{B}(B \to J/\psi(\mu^+\mu^-)K)}{\mathcal{B}(B \to J/\psi(e^+e^-)K)}$$



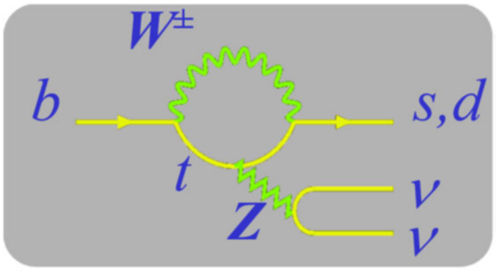
- Results:

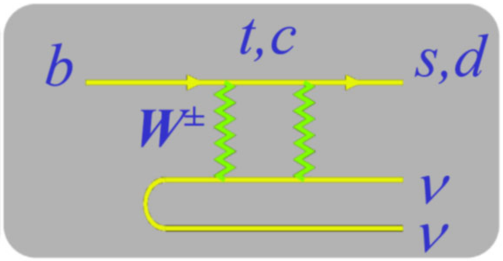
$$R_{K^+}(J/\psi) = 1.009 \pm 0.022 \pm 0.008$$
$$R_{K^0}(J/\psi) = 1.042 \pm 0.042 \pm 0.008$$

arXiv:2207.11275 [hep-ex]

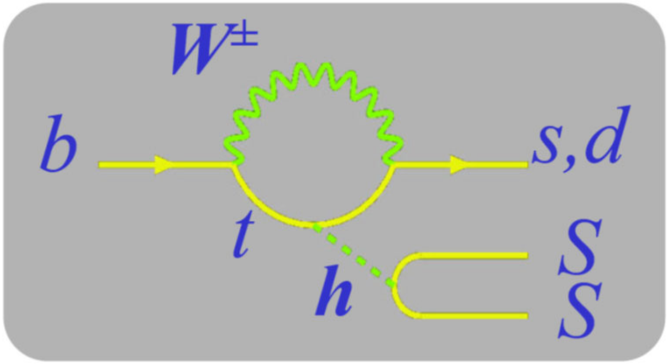
Search for $B^\pm \to K^\pm \nu\bar{\nu}$

SM: penguin + box diagrams





Look for deviations from the expected values → information on anomalous couplings C^ν_L and C^ν_R compared to the SM value $(C^\nu_L)^{SM}$, coming from the loop or from processes like



Flavour-Changing Neutral Current process that has not yet been observed

-no photon contribution/much cleaner theoretical prediction

$\mathcal{B}(B^\pm \to K^\pm \nu\nu) = (4.6 \pm 0.5) \times 10^{-6}$

Previous searches based on tagged analyses

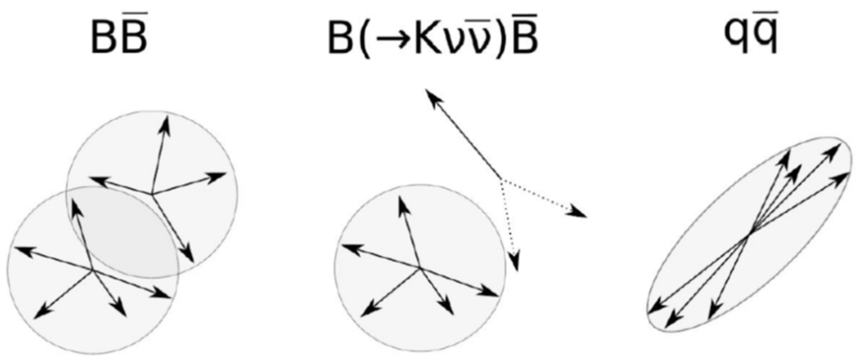
-semi-leptonic tag: $\varepsilon_{sig} \sim 0.2\%$ (Belle)

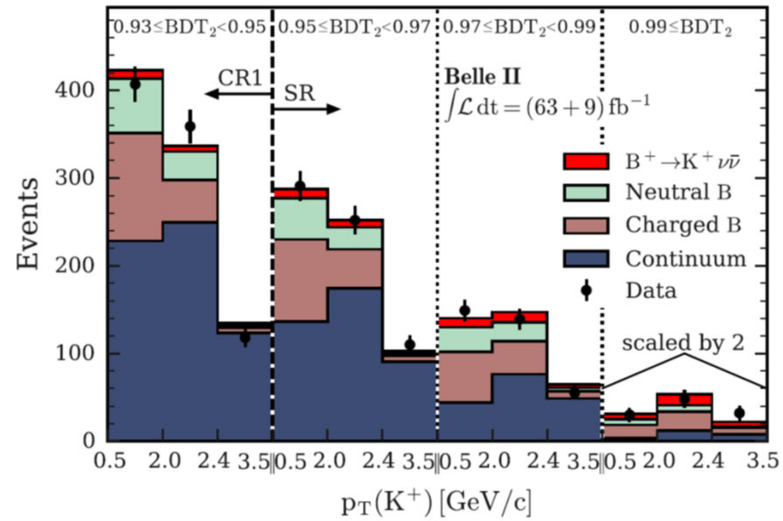
-hadronic tag: $\varepsilon_{sig} \sim 0.04\%$ (BaBar)

New approach by Belle II based on an inclusive tag

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

PRL 127 (2921)18, 121202





New approach by Belle II based on an inclusive tag

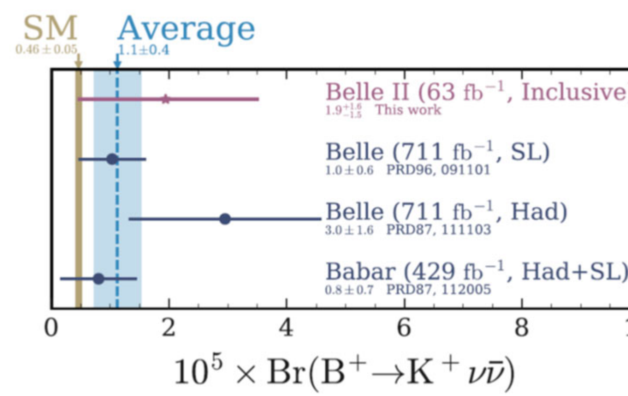
-no explicit reconstruction of the second B-meson

-use BDTs to exploit distinctive topological features of $B^\pm \to K^\pm \nu\bar{\nu}$

-much higher efficiency of $\varepsilon_{sig} \sim 4.3\%$ resulting in increased sensitivity per luminosity

Further improvements are underway

- more data (already have 6x more on tape)
- additional channels ($B^0 \to K^{*0}\nu\bar{\nu}$, $B^0 \to K_S^0\nu\bar{\nu}$…)
- improved/extended classifiers (neural networks)



Events of different tagging methods are to a large degree statistically independent and can be combined, details are under study.

$B^0 \rightarrow \pi^0\pi^0$

Most elusive of the $\pi\pi$ modes, extremely difficult at LHCb.

Machine learning is applied to improve the purity of the candidate photons for $\pi^{\mathbf{0}} \rightarrow \gamma\gamma$ reconstruction;

Using $B^0 \rightarrow D^0\,(K^+\,\pi^-\,\pi^0)\,\pi^0$ as calibration channel;

Signal yields are extracted from a fit to M_{bc}, ΔE, and the output of the continuum suppression BDT;

The Flavor Tagger is used to extract the direct CP asymmetry.

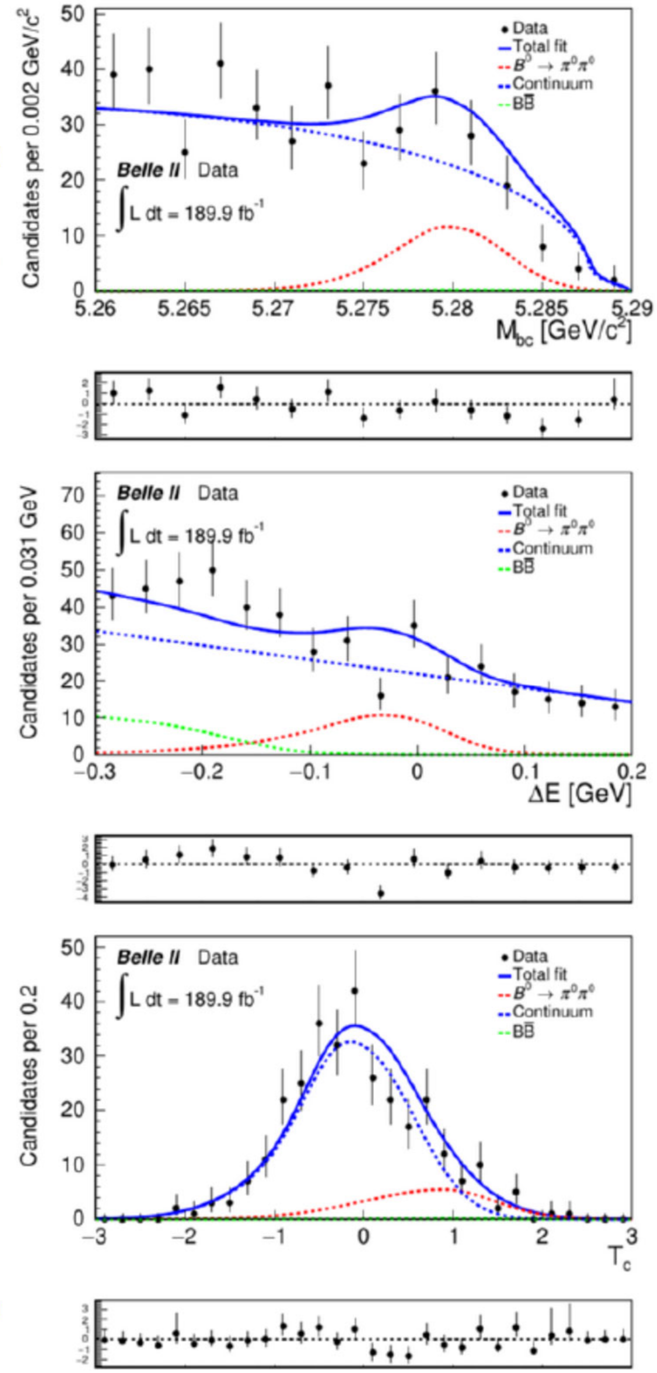
Results:

nSig = 93 ± 18 (7.5σ significance)

$$\mathcal{B}(B^0 \rightarrow \pi^0\pi^0) = (1.27 \pm 0.25 \pm 0.17) \times 10^{-6}$$

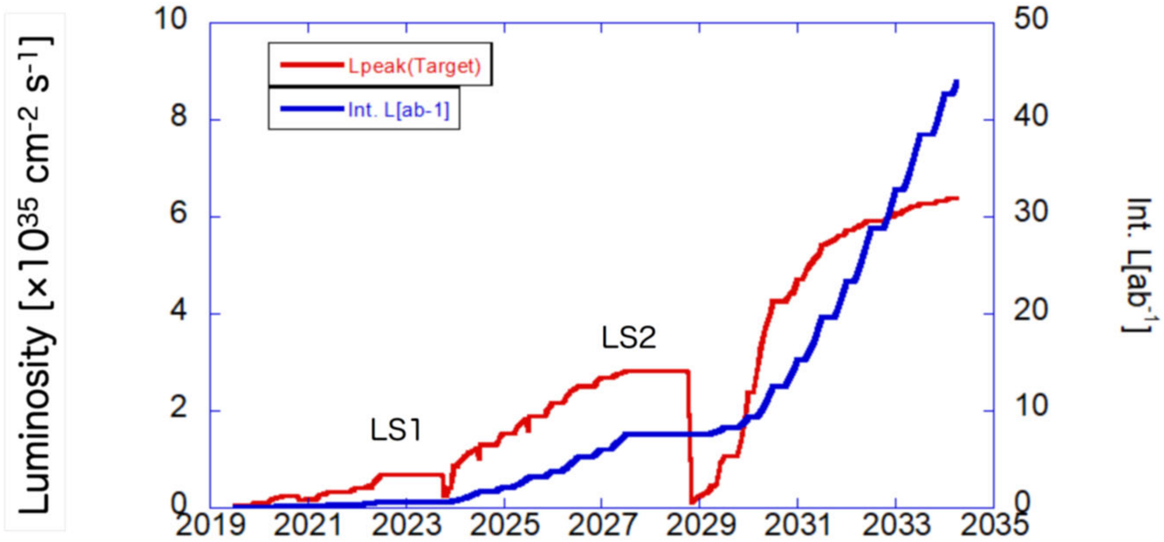
$$\mathcal{A}_{CP} = +0.14 \pm 0.46 \pm 0.07$$

Close to Belle's sensitivity with ~1/4 data.



J. Skorupa @ ICHEP 2022

Outlook



Ultimate goal: reach 50/ab by operating at the design luminosity of 6 x 10^{35} cm^{-2} s^{-1}

Current working plan follows the KEK Roadmap2020
-LS1 in 2022-23 for the full pixel vertex detector (PXD) installation & partial replacement of MCP-PMTs in TOP
-options for an interaction region upgrade (LS2) ≳2026 under study
→https://arxiv.org/abs/2203.11349

Beyond: discussions of physics and detector options with an upgraded accelerator to reach an even larger data sample of ~250/ab

Summary

- Physics of b and c hadrons and τ leptons has contributed substantially to our present understanding of elementary particles and their interactions
- B, D and τ decays have been and continue being a very hot topic in searches for new physics. Intriguing phenomena that have been seen in recent years make this research area one of the most interesting in particle physics.
- Belle II has entered the super-B-factory regime.
- Expect a new, exciting era of discoveries, and a friendly competition and complementarity of Belle II and LHCb, as well ATLAS and CMS

Additional slides

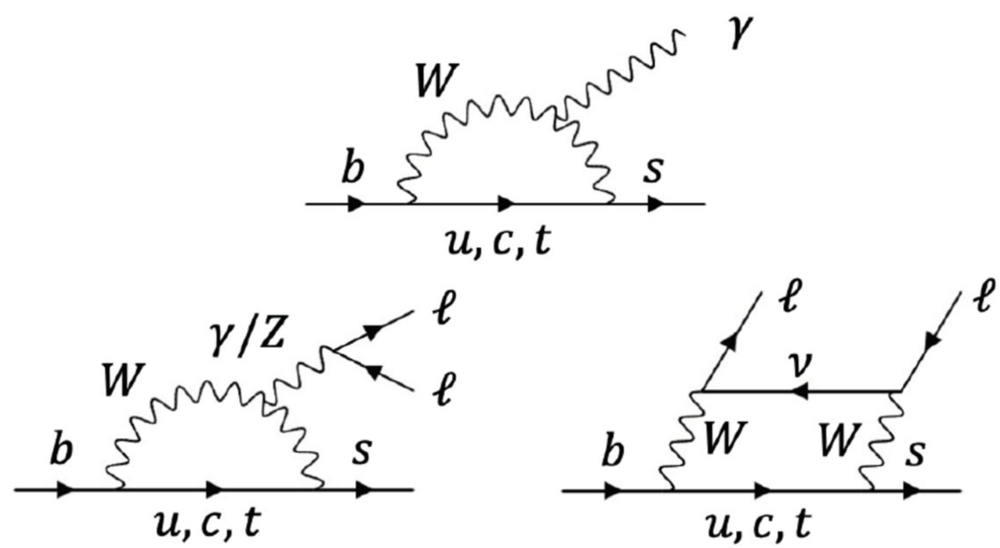
More on rare decays with b→s transitions

Most significant anomaly as observed by LHCb is in $B \to K^{(*)}e^+e^-$ vs $B \to K^{(*)}\mu^+\mu^-$ (a b→s transition)

→ More searches for new physics in rare decays of the type b → s

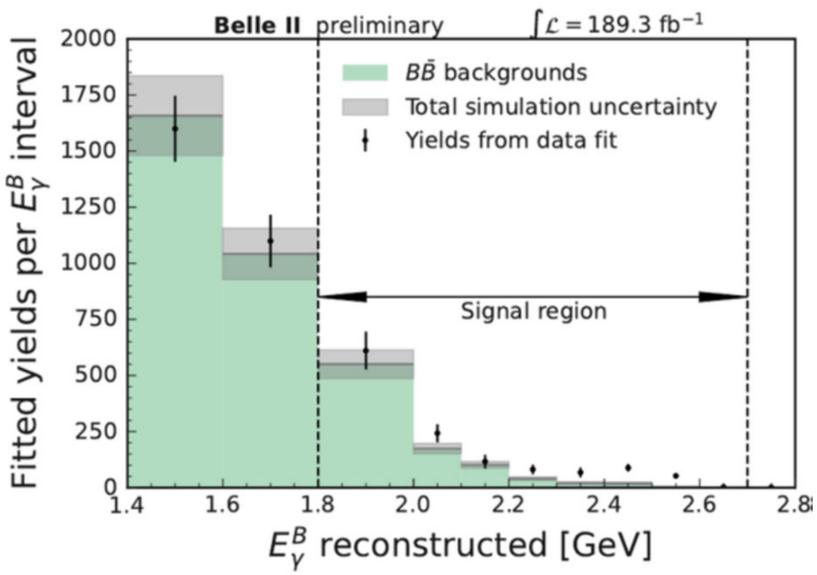
- R(K) in $B \to J/\psi\ K$ as a preparation for the R(K) and R(K*) measurements
- $B^\pm \to K^\pm \nu\nu$ with the inclusive tag
- $b \to s\gamma$ inclusive
- $K\pi$ puzzle

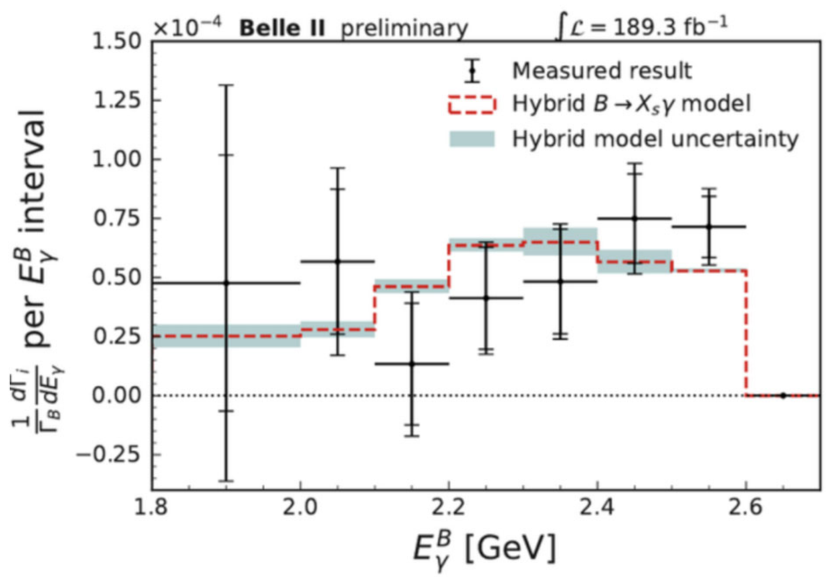
b → s - loop and box diagrams in SM, new physics could be leptoquarks, new particles in loops/boxes, new particles in the final state instead of neutrino pairs



Inclusive $b \to s\gamma$

E. Ganiev @ ICHEP 2022





Analysis performed in the recoil of FEI reconstructed hadronic B's;
Signal B rest frame is determined by the Btag
reconstruction. The signal g is the highest energy g in the event;
Signal region: $1.8 < E\gamma^B < 2.7$ GeV;
Two-step fitting procedure:
1) fit the tag side M_{bc} for correctly reconstructed tags;
2) use the MC to estimate the BB background events with a good B_{tag}.

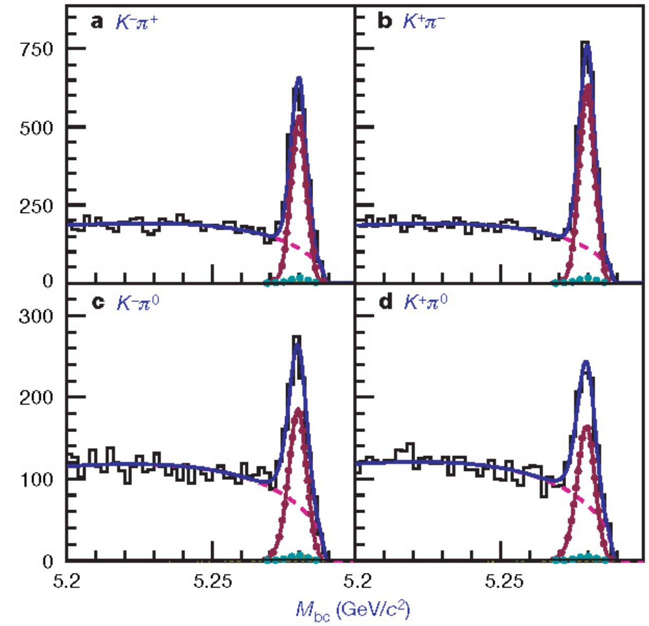
E_γ^B threshold [GeV]	$\mathcal{B}(B \to X_s\gamma)(10^{-4})$
1.8	3.54 ± 0.78 (stat.) ± 0.83 (syst.)
2.0	3.06 ± 0.56 (stat.) ± 0.47 (syst.)
2.1	2.49 ± 0.46 (stat.) ± 0.35 (syst.)

Already competitive with BaBar's hadronic tag measurement!

Expected impact of Belle II on the longstanding $K\pi$ puzzle (another b → s transition)

Belle, Nature 452, 332 (2008)

A significant difference is seen between direct CP asymmetry in $B^0 \to K^+\pi^-$ and $B^+ \to K^+\pi^0$ decays:
$\Delta A_{CP} = 0.124 \pm 0.021$



An Isospin sum rule has been proposed as a sensitive null-test: PLB 627 (2005) 82

$$I_{K\pi} = \mathcal{A}_{K^+\pi^-} + \mathcal{A}_{K^0\pi^+}\frac{\mathcal{B}(K^0\pi^+)}{\mathcal{B}(K^+\pi^-)}\frac{\tau_{B^0}}{\tau_{B^+}} - 2\mathcal{A}_{K^+\pi^0}\frac{\mathcal{B}(K^+\pi^0)}{\mathcal{B}(K^+\pi^-)}\frac{\tau_{B^0}}{\tau_{B^+}} - 2\mathcal{A}_{K^0\pi^0}\frac{\mathcal{B}(K^0\pi^0)}{\mathcal{B}(K^+\pi^-)}$$

- a violation of the sum rule would be evidence for New Physics
- precision on $A_{CP}^{K^0\pi^0}$ is the most limiting input for the test of the sum rule

Expected impact of Belle II on the longstanding Kπ puzzle (another b → s transition)

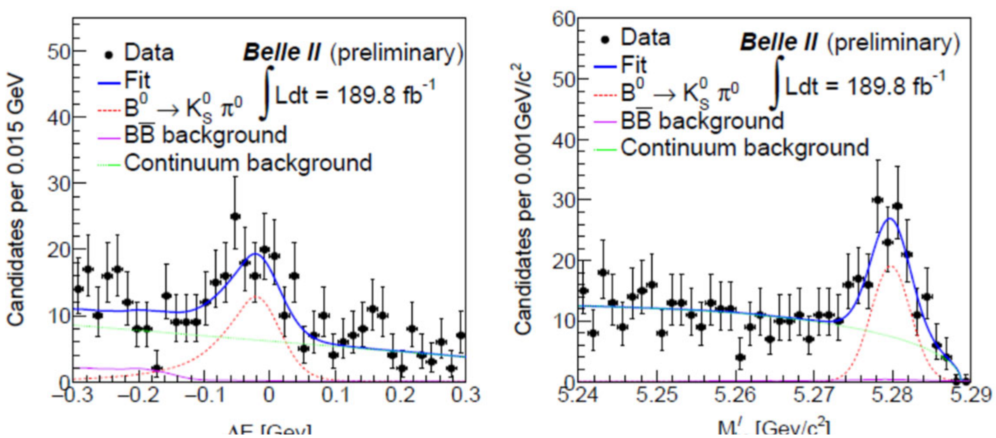
$$I_{K\pi} = \mathcal{A}_{K^+\pi^-} + \mathcal{A}_{K^0\pi^+}\frac{\mathcal{B}(K^0\pi^+)}{\mathcal{B}(K^+\pi^-)}\frac{\tau_{B^0}}{\tau_{B^+}} - 2\mathcal{A}_{K^+\pi^0}\frac{\mathcal{B}(K^+\pi^0)}{\mathcal{B}(K^+\pi^-)}\frac{\tau_{B^0}}{\tau_{B^+}} - 2\mathcal{A}_{K^0\pi^0}\frac{\mathcal{B}(K^0\pi^0)}{\mathcal{B}(K^+\pi^-)}$$

- precision on $A_{CP}^{K^0\pi^0}$ is the most limiting input for the test of the sum rule

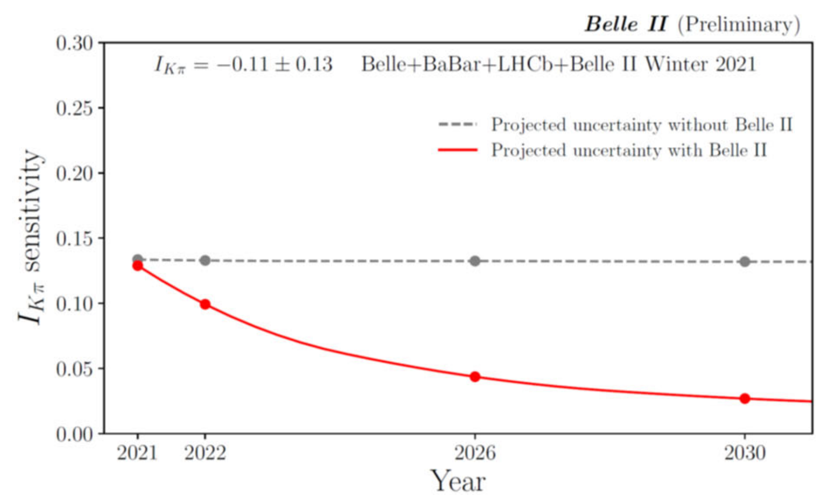
$$\mathcal{B}(B^0 \to K^0\pi^0) = [11.0 \pm 1.2(\text{stat}) \pm 1.0(\text{syst})] \times 10^{-6}$$

$$\mathcal{A}_{CP}(B^0 \to K^0\pi^0) = -0.41^{+0.30}_{-0.32}(\text{stat}) \pm 0.09(\text{syst})$$

arxiv.org/abs/2206.07453



Belle II: expected precision on $I_{K\pi}$



Belle II: recorded data set

Recorded in total **~424 fb^{-1}**, of which:

➔ **~362 fb^{-1}** taken at a CM energy of 10.58 GeV, corresponding to the mass of the Υ(4S), which dominantly decays to BB;

➔ **~42 fb^{-1}** taken 60 MeV below the Υ(4S) peak (for continuum background studies);

➔ **~19 fb^{-1}** taken around 10.75 GeV for exotic hadron searches.