Flavor Physics and the Belle II Experiment

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Belle II Collaboration

International Conference
on the Physics of the Two Infinities

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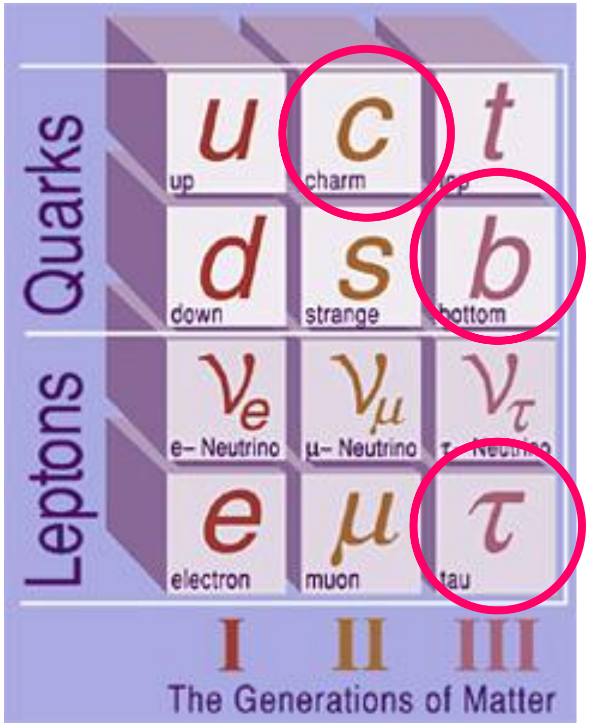
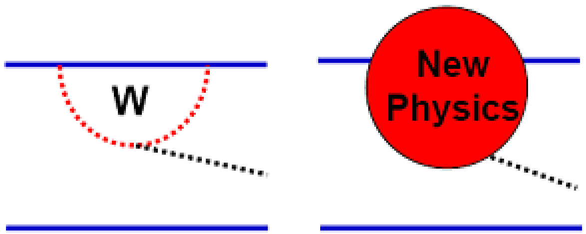
Flavor Physics



c : ~ 1.3 GeV
b : ~ 4.2 GeV
τ : 1.78 GeV

- Flavor = species of the quarks and leptons
- Only weak interaction changes the species of the quarks and leptons.
- Heavy flavor: c, b, τ
  - ✓ Hadrons with c, b: D, D_s, B, B_s, …
  - ✓ Many kinds of decay modes.
- Precise measurements of the decays can provide information of the physics beyond the Standard Model (SM).
  - ✓ Loop diagrams: New Physics (NP) particles can virtually contribute to the decays
  - ✓ Observables (branching fraction etc.) to be compared with the SM expectation.



penguin diagram

Flavor Physics Experiments

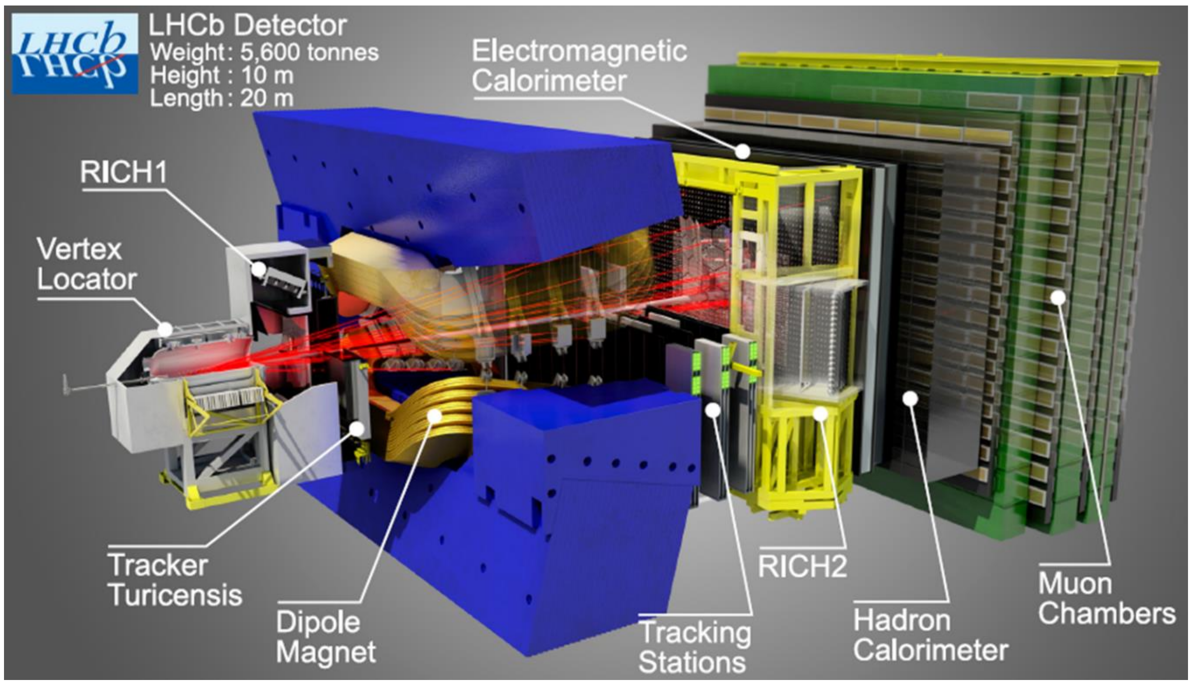
Two flavor physics experiments (producing b quarks) : LHCb and Belle II

- ✓ BESIII (e^+e^- collider for charm) …

- Huge cross section of b.
- Many particles at collision.
- Neutral particles reconstruction not trivial.

LHCb @ LHC, CERN : pp collision

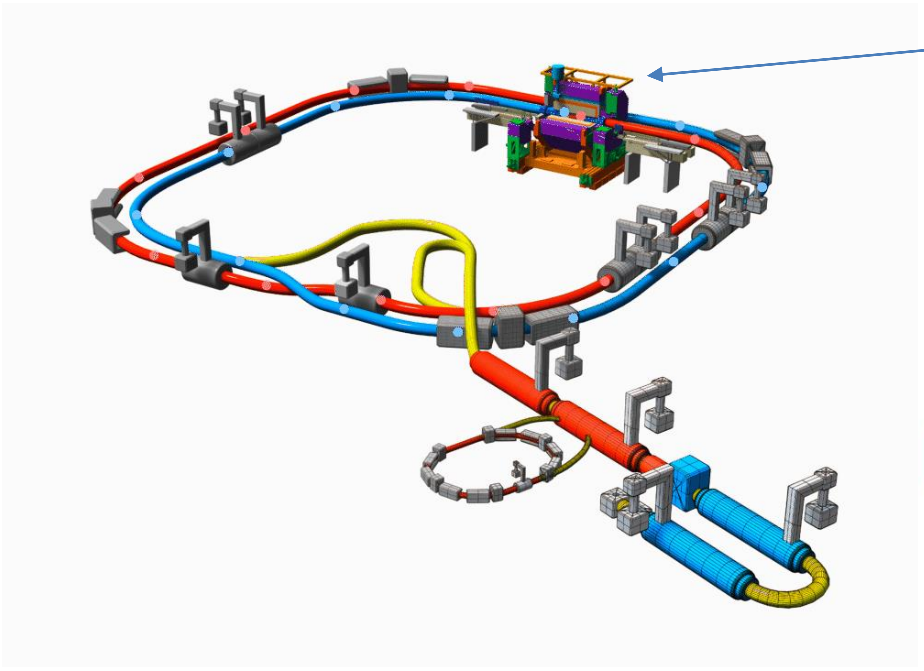
Forward detector optimized for b and c studies.

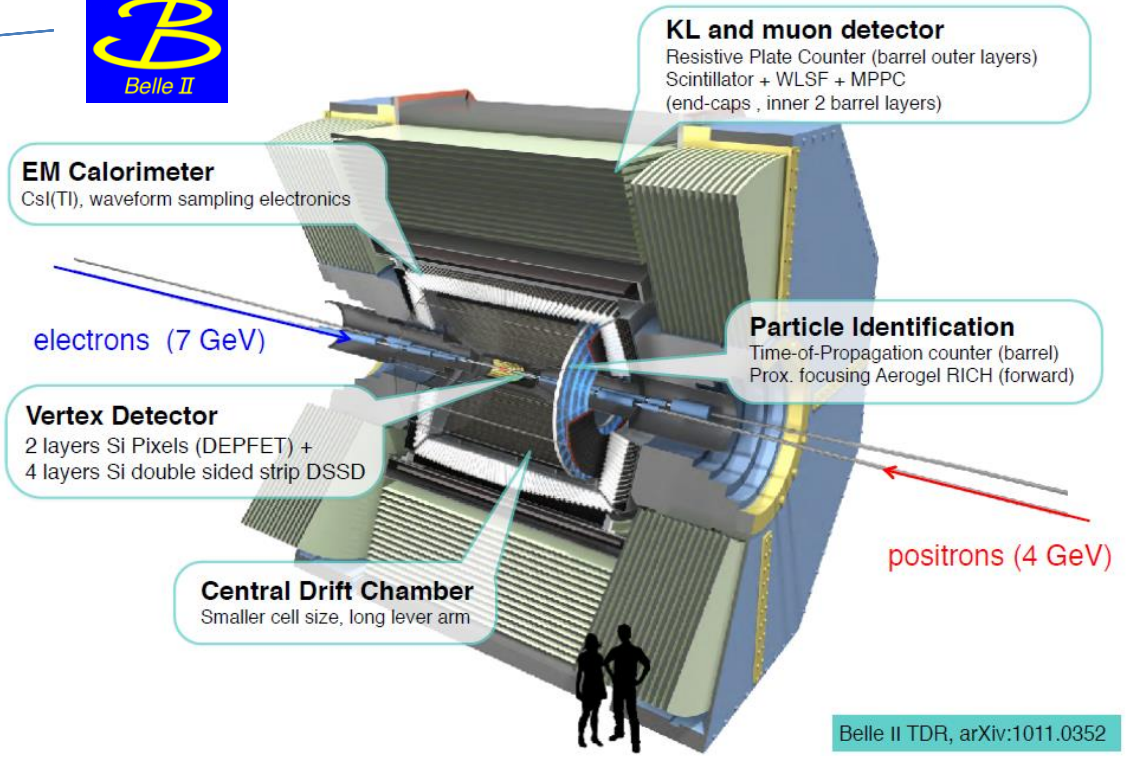


Detector for Run 1-2

- Excellent vertex resolution to separate b, c (weak) decays.
- Particle identification (PID).
- Run 1-2 (2010-2018)
  - ✓ 9 fb^{-1} data accumulated.
- Run 3 started in 2022 with an upgrade of the LHCb detector.

Belle II



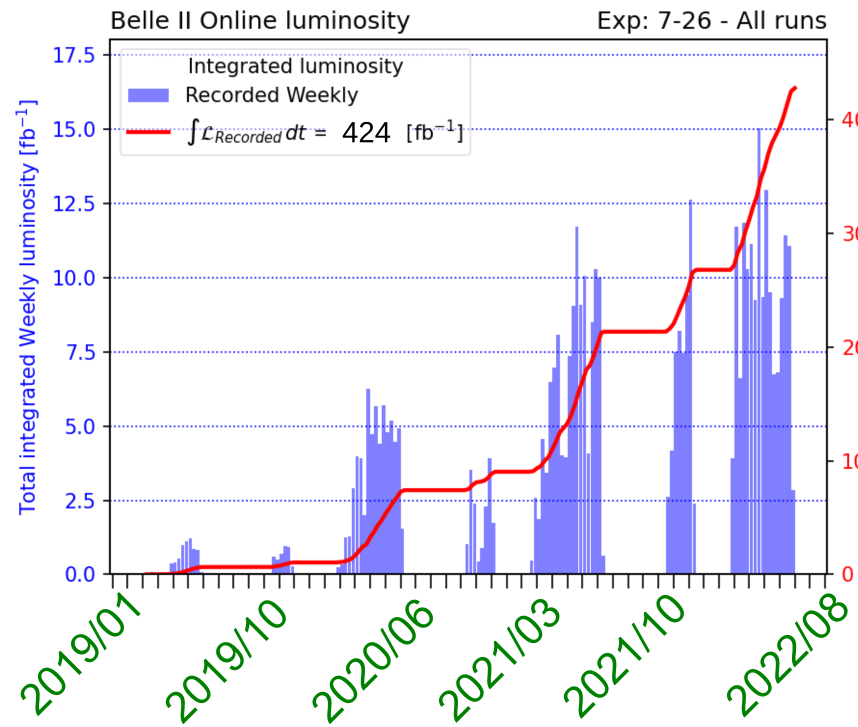


$e^+e^- \to \Upsilon(4S) \to B\bar{B}$

- Belle II experiment at KEK: flavor physics experiment, successor of Belle.
- SuperKEKB asymmetric electron-positron collider: 4 GeV e^+ + 7 GeV e^-.
- Nano beam scheme to achieve high luminosity.
- General purpose Belle II detector: 4π coverage
  - ✓ Key components: vertex detector, particle identification.

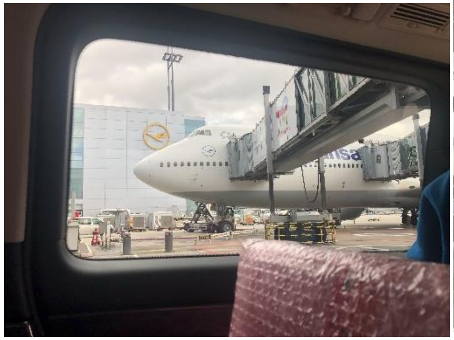
Belle II

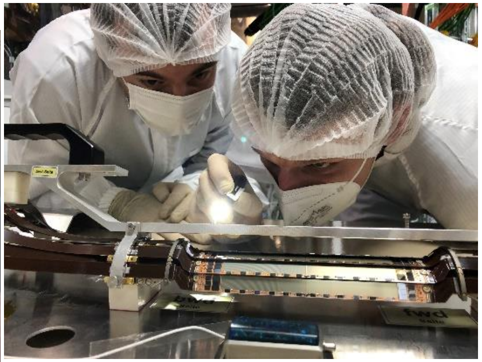
- Operation with full detector started in 2019.
- Luminosity $4.7 \times 10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ achieved (Jun 8, 2022).
  - ✓ World record (~ ×2 of KEKB)
  - ✓ Aiming one order higher.
- $424\ \mathrm{fb}^{-1}$ of data accumulated so far.
  - ✓ Belle: $1\ \mathrm{ab}^{-1}$ (= $1000\ \mathrm{fb}^{-1}$) in 11 years' operation.
  - ✓ Belle II target: O(10) of Belle.



- Long shutdown (LS) 1 starts from summer 2022 to fully install the PXD detector.
- Operation will be resumed around the end of 2023.

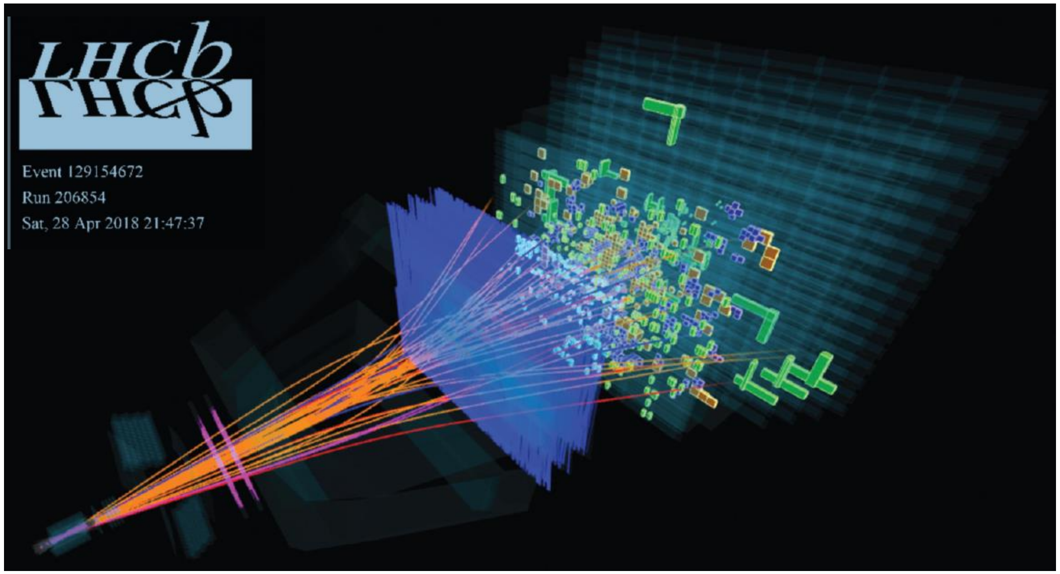
PXD just arrived at KEK from DESY





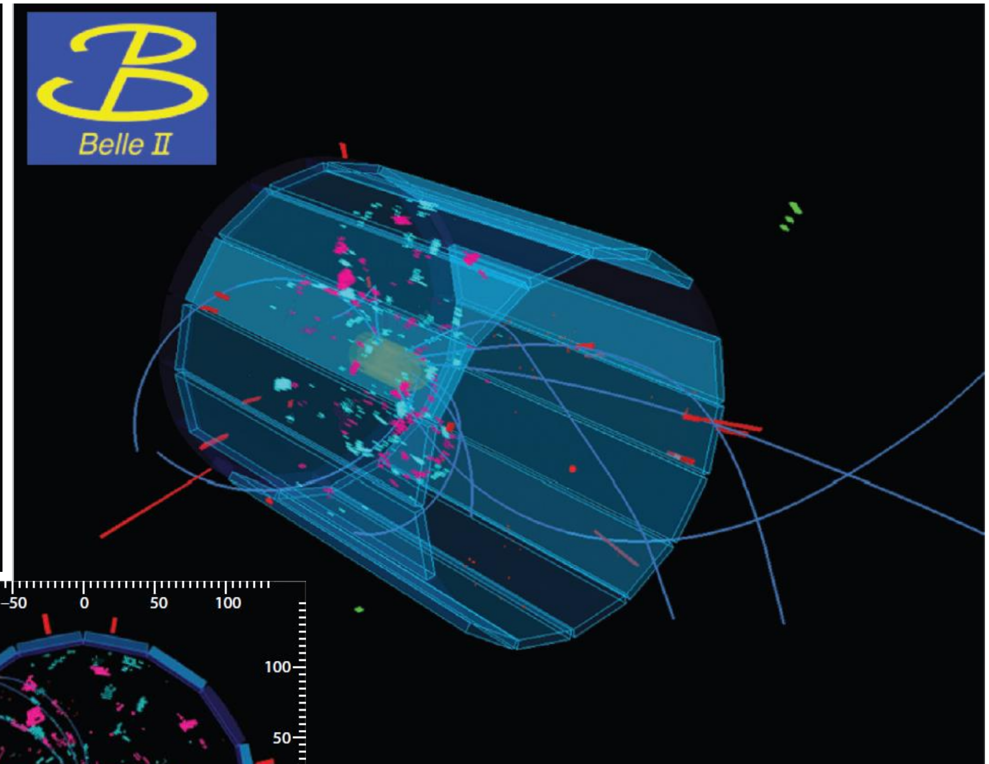
Event Display

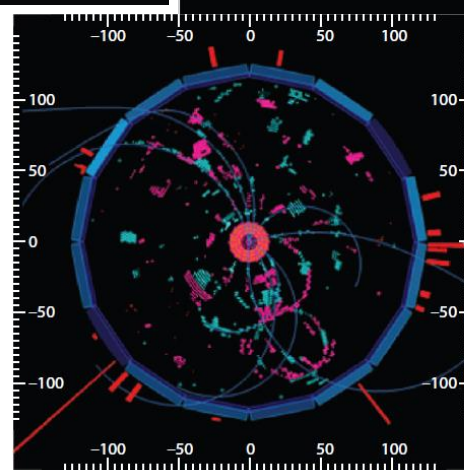
LHCb



pp collision

Belle II



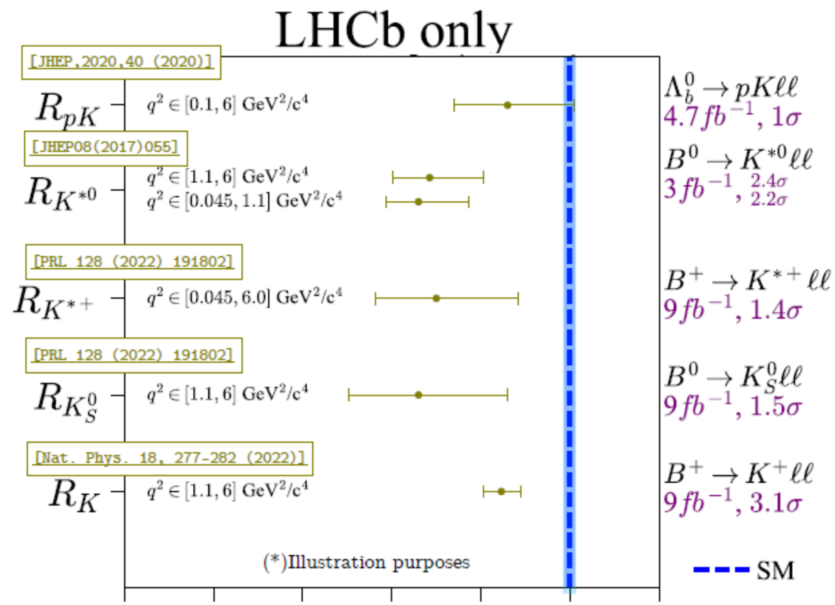


e^+e^- collision

"B Anomaly"

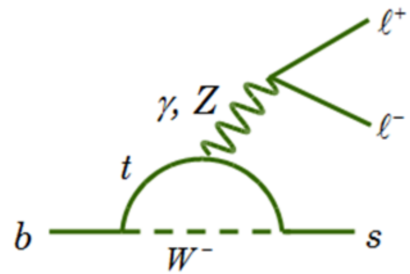
- A few "anomalies" have been found in B meson decays.
  - ✓ The SM prediction and measurement have some discrepancy.

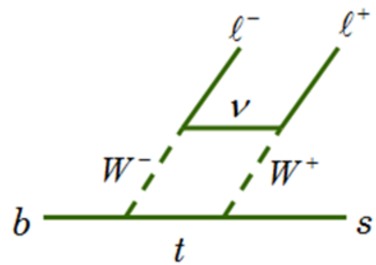
- Lepton Flavor Universality (LFU)
  - ✓ In the SM, the coupling of EW interaction does not depend on the lepton flavor.
  - ✓ B.F. to e, μ, τ should be the same except for the effect of different mass.
- ~3σ discrepancy from the SM prediction
  - ✓ LFU in $B \to K^{(*)}e^+e^-$, $K^{(*)}\mu^+\mu^-$
  - ✓ LFU in $B \to D^{(*)}\tau^+\nu$, $D^{(*)}l^+\nu$ (l=e, μ)
  - ✓ Angular observables in $B \to K^*\mu^+\mu^-$



$$R_X = \frac{\mathcal{B}(b \to s\mu^+\mu^-)}{\mathcal{B}(b \to se^+e^-)}$$

Signature of the New Physics (?)





LFU Test of $B \to K^{(*)} l^+ l^-$

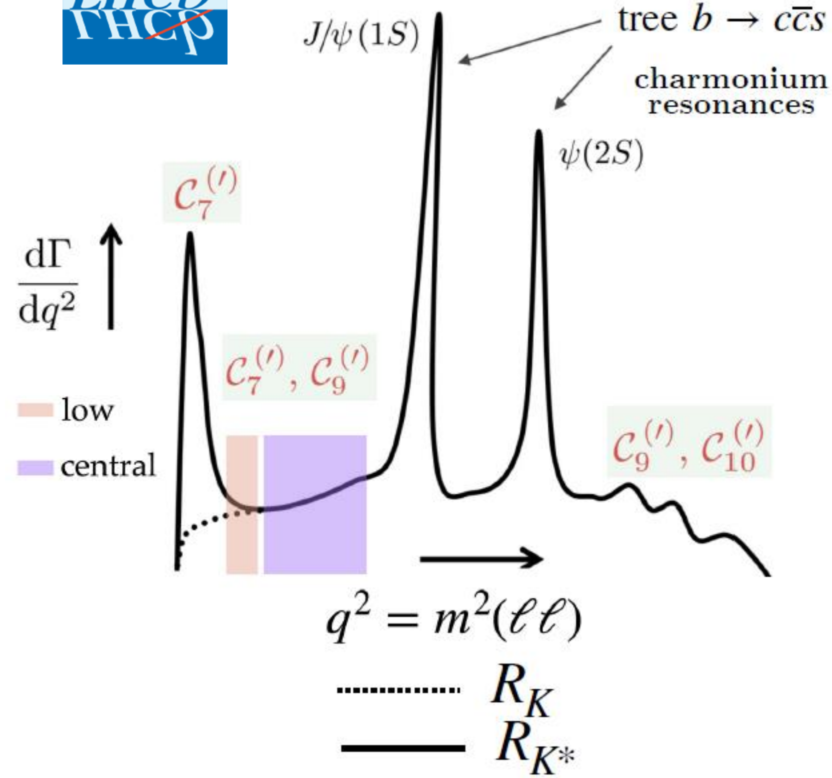
[arXiv:2212.09152, 2212.09153]

- New results with LHCb full dataset (9 fb^{-1}) on R_K and R_{K^*}.

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

$b \to s$ process

$$R_{K,K^*}(q_a^2, q_b^2) = \frac{\int_{q_a^2}^{q_b^2} \frac{\mathrm{d}\Gamma(B^{(+,0)} \to K^{(+,*0)}\mu^+\mu^-)}{\mathrm{d}q^2}\mathrm{d}q^2}{\int_{q_a^2}^{q_b^2} \frac{\mathrm{d}\Gamma(B^{(+,0)} \to K^{(+,*0)}e^+e^-)}{\mathrm{d}q^2}\mathrm{d}q^2}$$



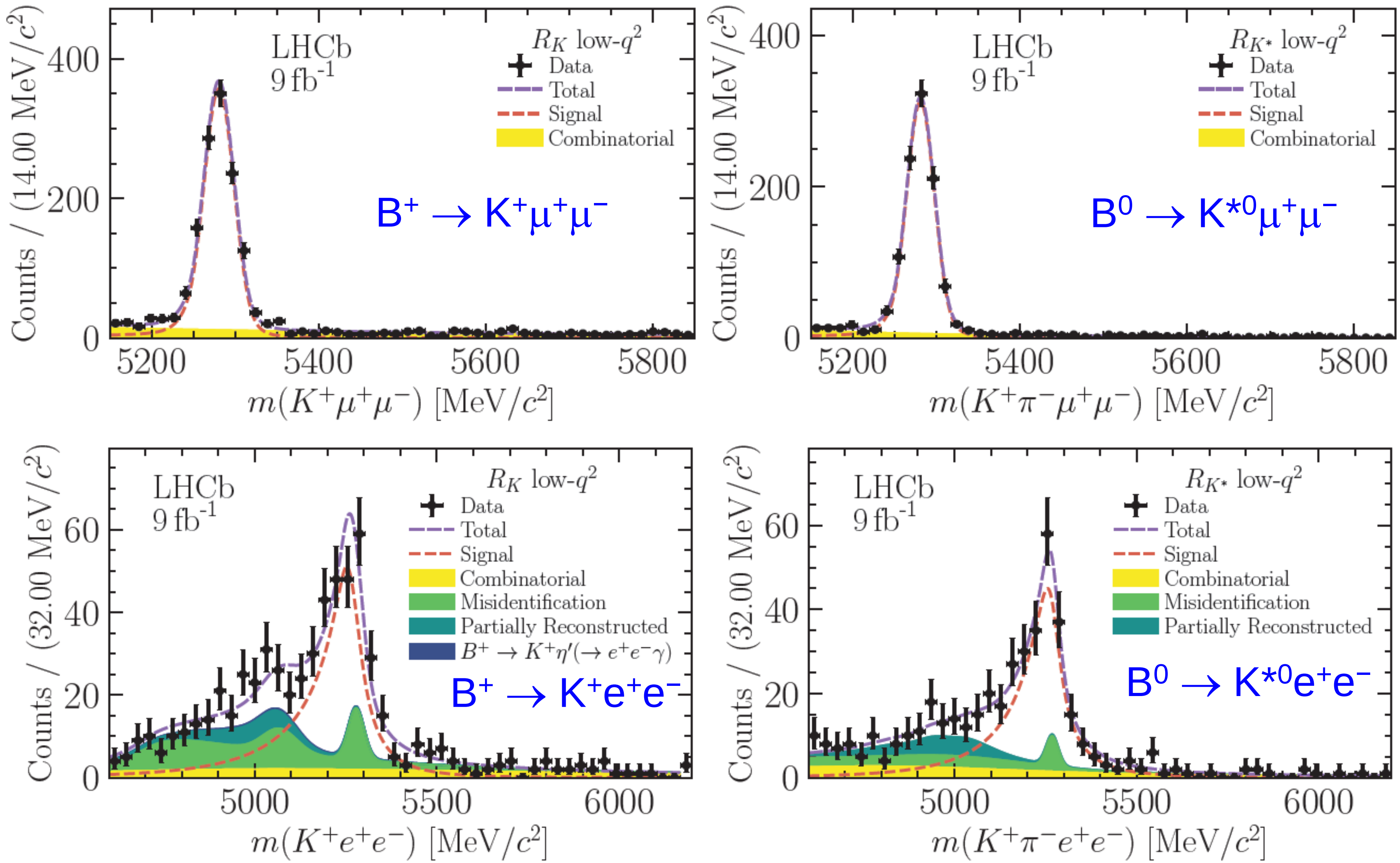
- Simultaneous fit to the K^+, K^{*0} modes.
- Take double ratio with $B \to K^{(*)} J/\psi$.
  - ✓ Cancel out the detector efficiency, systematic uncertainty.

$$R_{(K,K^*)} \equiv \frac{\frac{\mathcal{N}}{\varepsilon}(B^{(+,0)} \to K^{(+,*0)}\mu^+\mu^-)}{\frac{\mathcal{N}}{\varepsilon}(B^{(+,0)} \to K^{(+,*0)}J/\psi(\to \mu^+\mu^-))} \Big/ \frac{\frac{\mathcal{N}}{\varepsilon}(B^{(+,0)} \to K^{(+,*0)}e^+e^-)}{\frac{\mathcal{N}}{\varepsilon}(B^{(+,0)} \to K^{(+,*0)}J/\psi(\to e^+e^-))}$$

LFU Test of $B \to K^{(*)} l^+ l^-$

LHCb

(low-q^2 region)



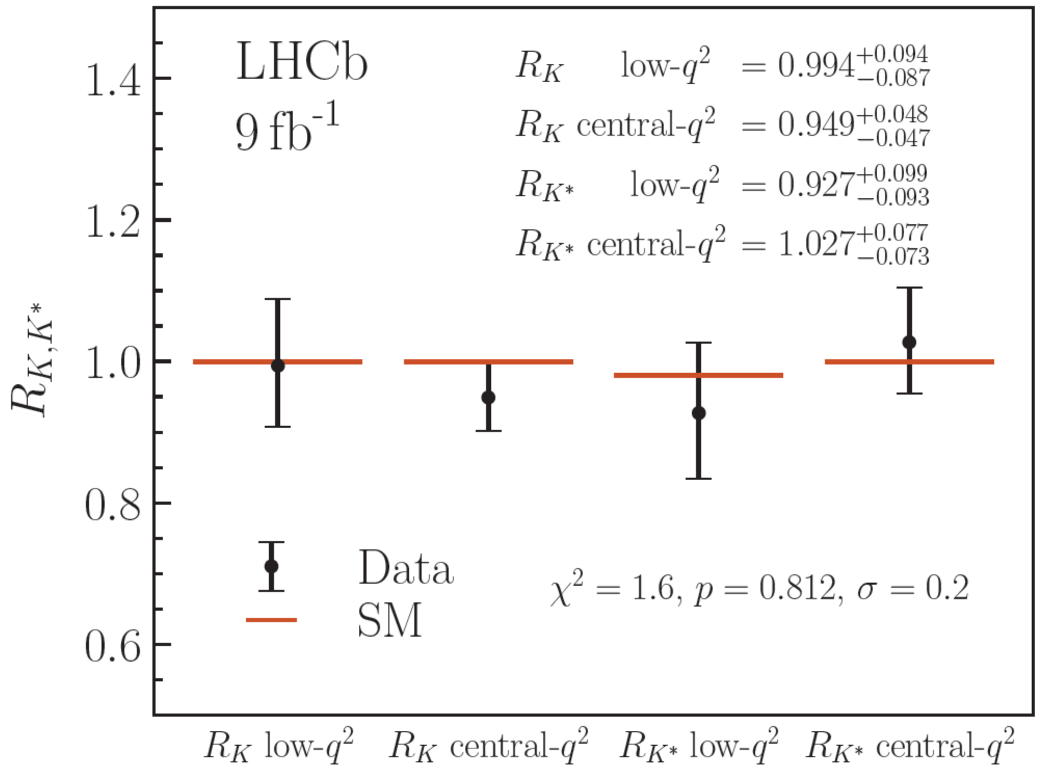
LFU Test of $B \to K^{(*)} l^+ l^-$

LHCb

- low-q^2 : $q^2 \in [0.1, 1.1]\,\mathrm{GeV}^2/c^4$
- central-q^2 : $q^2 \in [1.1, 6.0]\,\mathrm{GeV}^2/c^4$

$$\text{low-}q^2 \begin{cases} R_K = 0.994\,^{+0.090}_{-0.082}\,(\text{stat})\,^{+0.029}_{-0.027}\,(\text{syst}), \\ R_{K^*} = 0.927\,^{+0.093}_{-0.087}\,(\text{stat})\,^{+0.036}_{-0.035}\,(\text{syst}), \end{cases}$$

$$\text{central-}q^2 \begin{cases} R_K = 0.949\,^{+0.042}_{-0.041}\,(\text{stat})\,^{+0.022}_{-0.022}\,(\text{syst}), \\ R_{K^*} = 1.027\,^{+0.072}_{-0.068}\,(\text{stat})\,^{+0.027}_{-0.026}\,(\text{syst}). \end{cases}$$

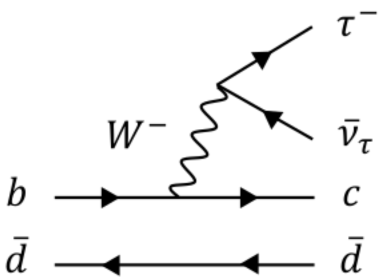


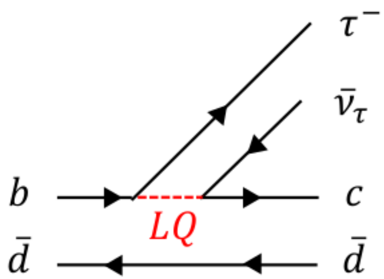
- Most precise LFU test.
- Four measurements are consistent with the SM (at 0.2σ).
  - ✓ SM prediction (0.98-1.00) with uncertainty of ~0.01 .
- The anomaly looks gone.

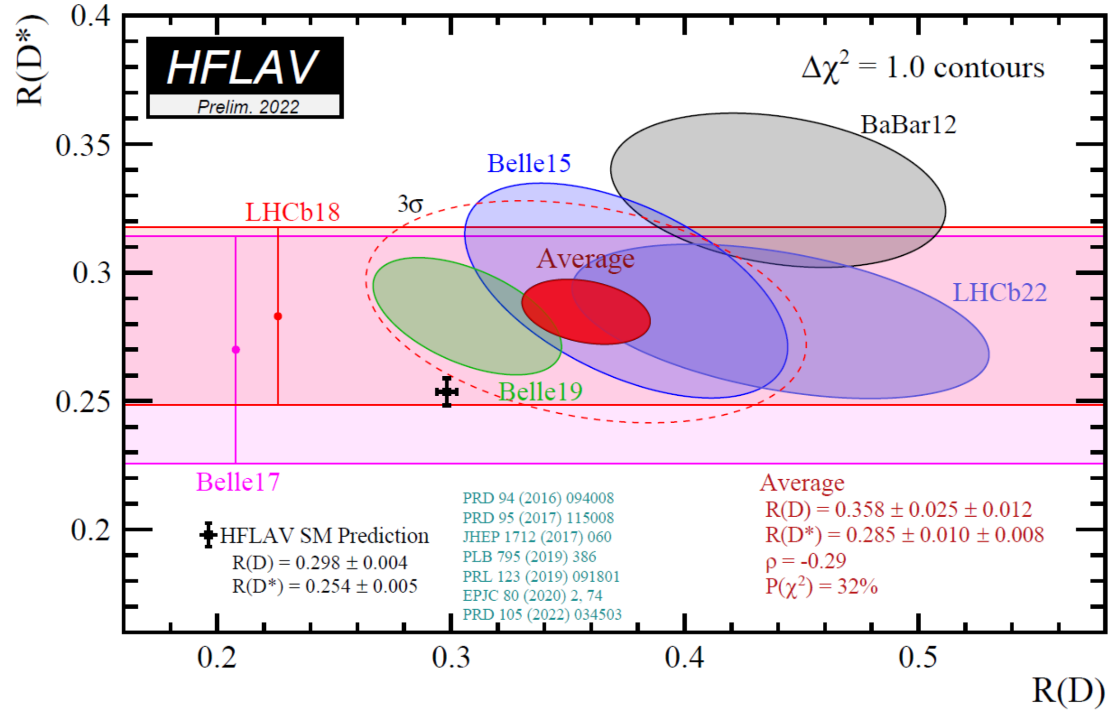
LFU in B → $D^{(*)}l^+\nu$

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

$$(\ell = e \text{ or } \mu)$$







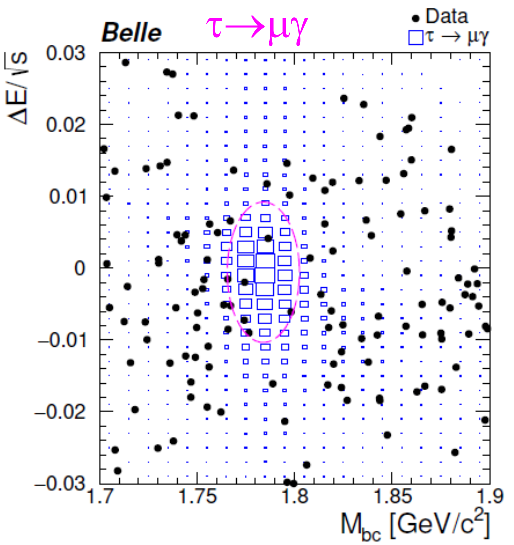
- Possible contributions of NP particles (leptoquark, charged Higgs) in tree diagram.
- 3σ tension between the SM and measurements so far.
  - ✓ LHCb reported a new $R(D^{(*)})$ measurement with hadronic τ decays.
- Analysis at Belle II is going on.
- Belle II reported measurements of LFU test between e and μ in B → $D^{(*)} l^+\nu$, Xc $l^+\nu$.
  - ✓ See K.Kozima's talk on 29th (parallel talk)

Lepton Flavor Violation Decays

- Lepton Flavor Violation (LFV) : clear signature of the NP.
- Searches for LFV decays in B, B_s, τ … are intensively going on at LHCb, Belle II etc.
- A few results from Belle.

$\tau \to l\gamma$ [JHEP10(2021)019]

982 fb^{-1} : 912 M $\tau\tau$



$B(\tau \to \mu\gamma) < 4.2\times10^{-8}$

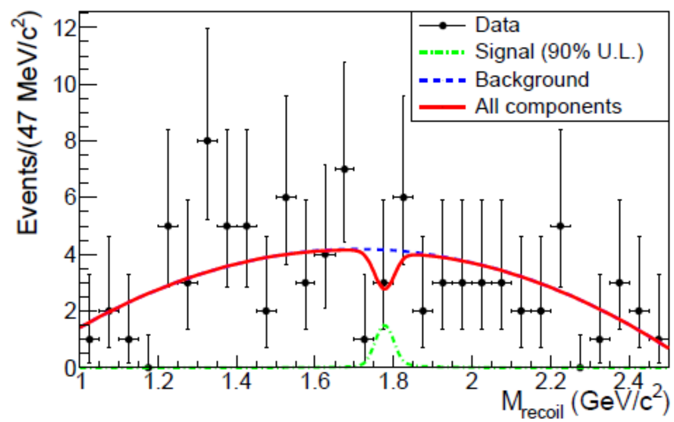
$B(\tau \to e\gamma) < 5.6\times10^{-8}$

most stringent limit of $\tau \to \mu\gamma$

$B \to K\tau l$ [arXiv:2212.04128]

711 fb^{-1} : 772 M BB

- Look at τ recoil mass



$B(B^+ \to K^+\tau^+\mu^-) < 0.59\times10^{-5}$

$B(B^+ \to K^+\tau^+e^-) < 1.51\times10^{-5}$

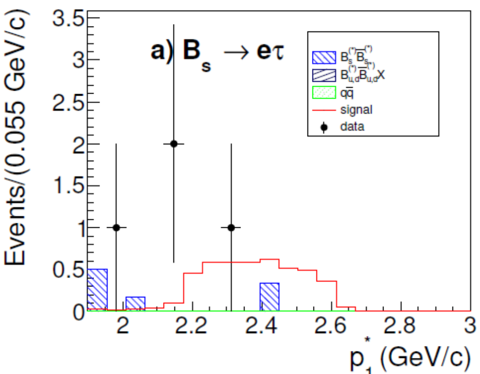
$B(B^+ \to K^+\tau^-\mu^+) < 2.45\times10^{-5}$

$B(B^+ \to K^+\tau^-e^+) < 1.53\times10^{-5}$

$B_s \to l\tau$ [arXiv:2301.10989]

121 fb^{-1}@Υ(5S) : 16 M B_sB_s

- Tag B_s with $B_s \to D_sXl\nu$



$B(B_s \to e\tau) < 14.1\times10^{-4}$

$B(B_s \to \mu\tau) < 7.3\times10^{-4}$

- First measurement of $B_s \to e\tau$
- $B(B_s \to \mu\tau) < 3.4\times10^{-5}$ @LHCb [PRL 123, 211801(2019)]

Kobayashi-Maskawa Theory

Kobayashi-Maskawa (KM) theory

Complex phase in the quark mixing matrix

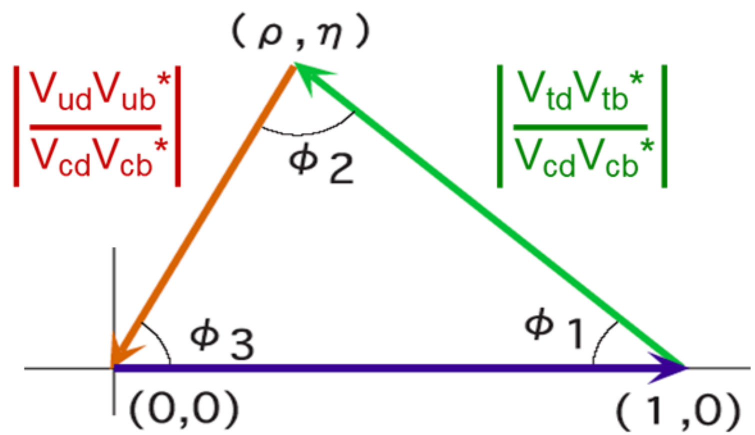
→ CP violation in the Standard Model (SM)

CKM (Cabibbo-Kobayashi-Maskawa) Matrix

$$V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

From the unitarity of the matrix:

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



$\phi_1 = \beta$
$\phi_2 = \alpha$
$\phi_3 = \gamma$

CP Violation in B Meson

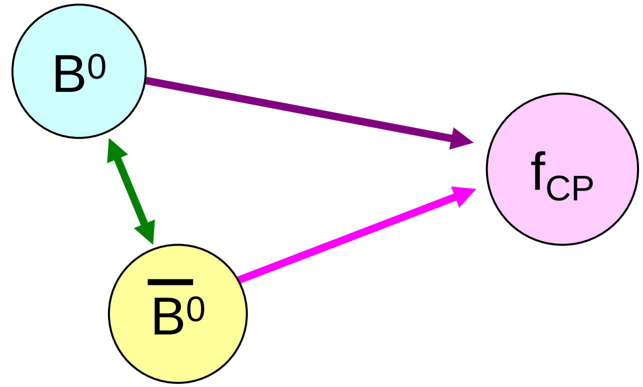
Mixing-induced CP asymmetry of B mesons

- B^0 and $\overline{B}^0$ decay to a common CP eigenstate f_{CP}.
- CP violation appears as a decay time difference.

$$A_{CP}(\Delta t) = \frac{\Gamma(\overline{B}^0(\Delta t) \to f_{CP}) - \Gamma(B^0(\Delta t) \to f_{CP})}{\Gamma(\overline{B}^0(\Delta t) \to f_{CP}) + \Gamma(B^0(\Delta t) \to f_{CP})}$$

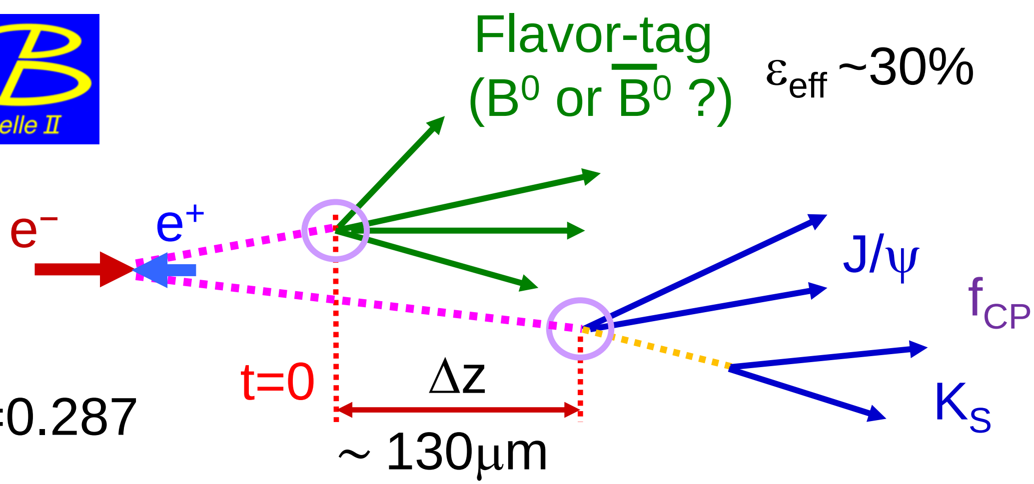
$$= S \sin(\Delta m \Delta t) + A \cos(\Delta m \Delta t)$$

$S = -\xi \sin(2\phi_1)$ for $B \to J/\psi\, K_S$ $\quad(\phi_1 = \beta)$

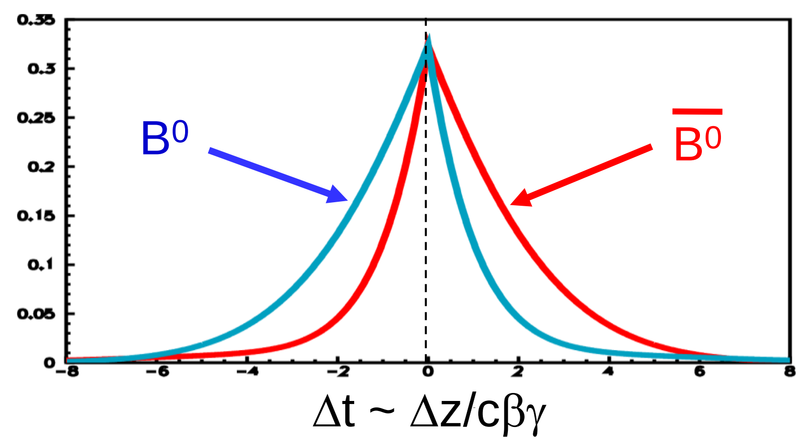


S : mixing induced CPV

A : direct CPV (=−C)



measure position instead of time



CP Violation in B Meson

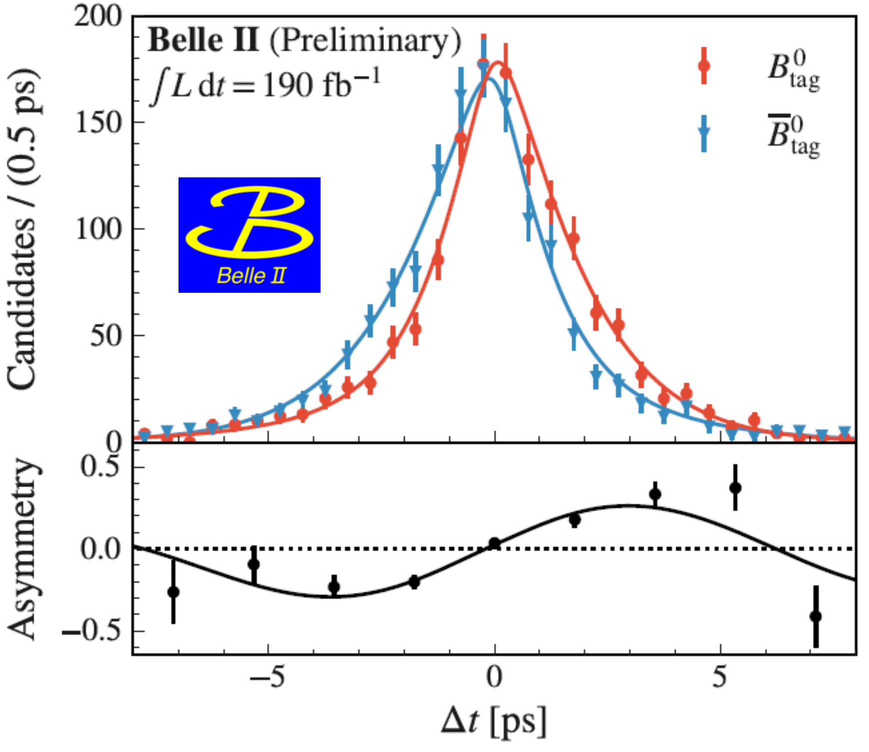
In 2001, BaBar and Belle observed the CP violation in B mesons.
$\rightarrow$ Verification of the KM theory.

Belle result (771 fb^{-1})

[PRL 108, 171802 (2012)]

$\sin(2\phi_1) = 0.667 \pm 0.023 \pm 0.012$
$A = 0.006 \pm 0.016 \pm 0.012$

2008 Nobel Prize



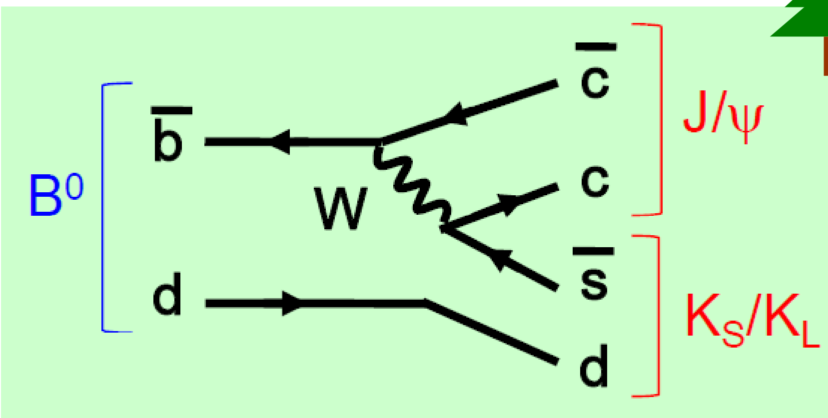
[arXiv:2302.12898]

- First measurement by Belle II is done with 190 fb^{-1}.
- Statistically limited.

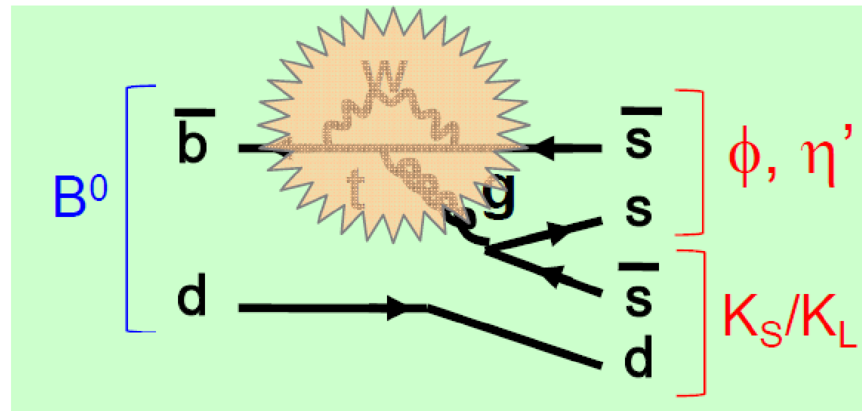
$\sin(2\phi_1) = 0.720 \pm 0.062 \pm 0.016$
$A = 0.094 \pm 0.044 \,^{+0.047}_{-0.017}$

CP Violation in $b \to s$

$b \to c$ ($B \to J/\psi\, K^0$)



$b \to s$ ($B \to \phi K^0$, $\eta' K^0$)



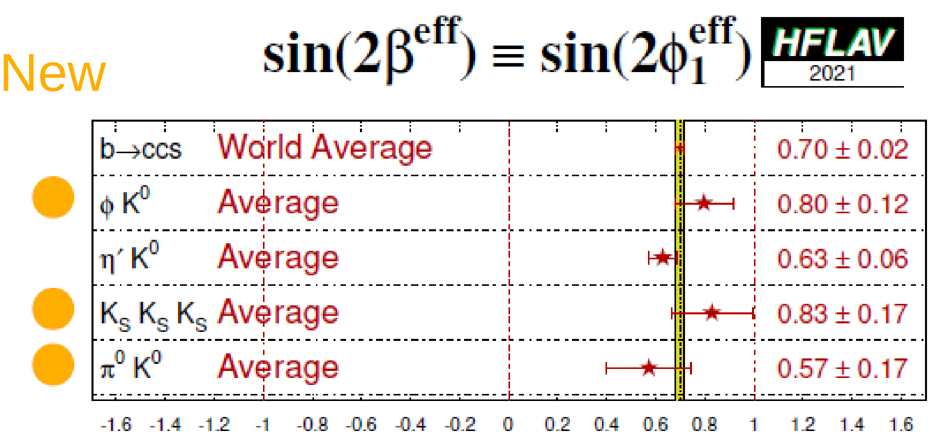
In the SM,

$S = -\xi \sin(2\phi_1)$

for $b \to s$ processes. NP contribution can make a discrepancy.

- The theoretical uncertainty (within SM) depends on the final states.
- $B \to K^0K^0K^0$, ϕK^0, $\eta' K^0$ are the cleanest modes (δS_{theory} ~a few %).

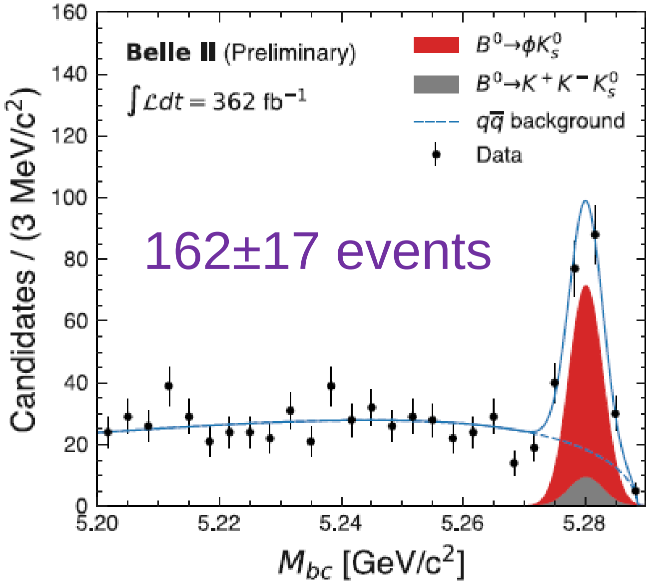
New



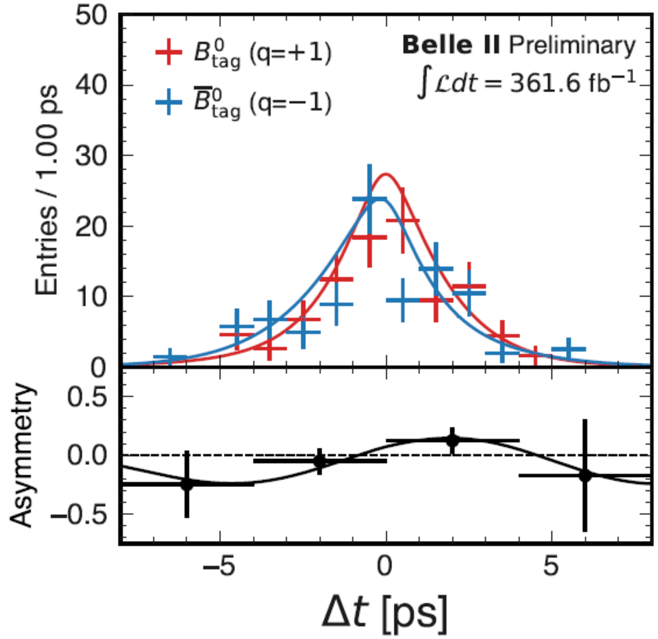
CP Violation in $B \to \phi K_S$

$B^0 \to \phi K_S$

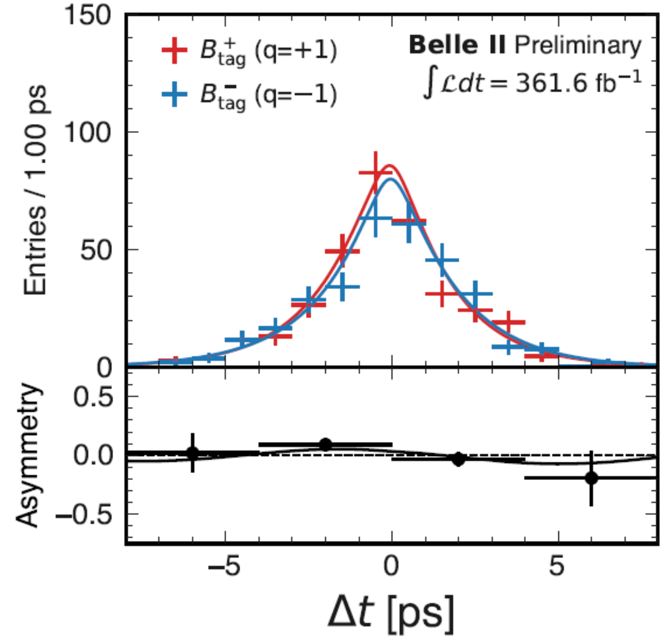
387 M $B\bar{B}$



$B^0 \to \phi K_S$



$B^+ \to \phi K^+$



- Compatible with world average.
- Most precise determination of A_{CP}.

$S = 0.54 \pm 0.26 ^{+0.06}_{-0.08}$

$A = 0.31 \pm 0.20 ^{+0.05}_{-0.06}$

HFLAV $S = 0.74 ^{+0.11}_{-0.13}$

$A = -0.01 \pm 0.14$

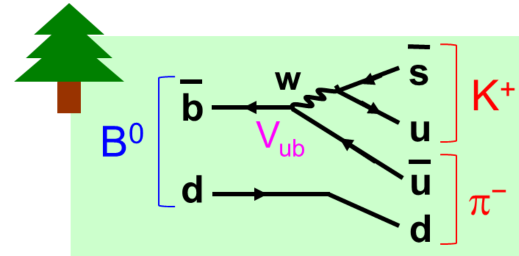
$S = -0.09 \pm 0.12$
$A = 0.12 \pm 0.10$
(control sample)

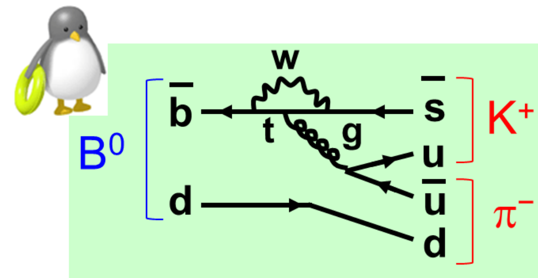
$B \to K\pi$

$B \to K\pi$

- Rare decay, but relatively high branching fraction ($\sim 10^{-5}$)
- Tree diagram (with V_{ub}) + penguin diagram
  - ✓ Direct CP violation is possible (observed)
- The sum-rule provides precise prediction of the relation of the branching fractions and A_{CP}.

[M.Gronau, PLB627 (2005) 82]

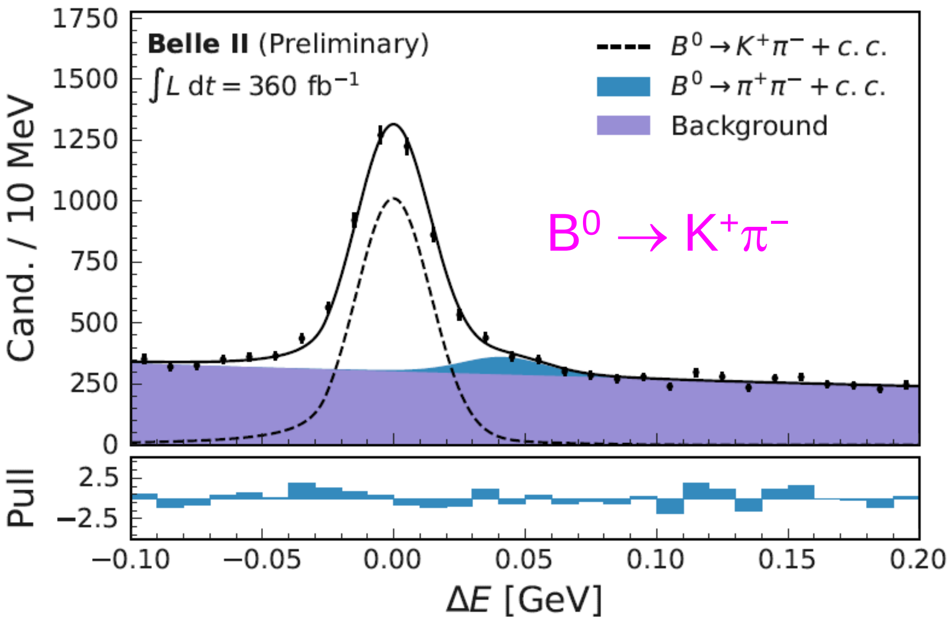


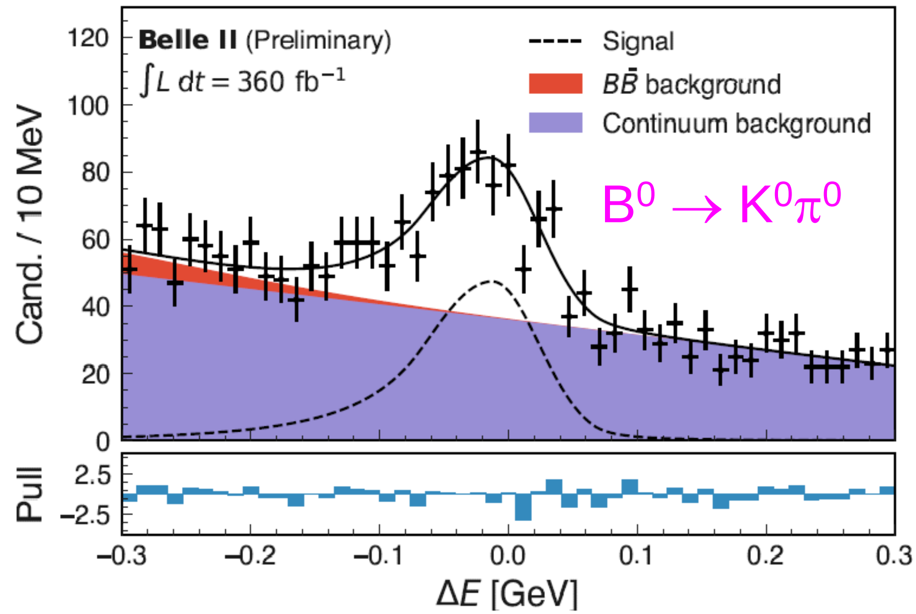


$$I_{K\pi} = \mathcal{A}_{CP}^{K^+\pi^-} + \mathcal{A}_{CP}^{K^0\pi^+} \frac{\mathcal{B}_{K^0\pi^+}}{\mathcal{B}_{K^+\pi^-}} \frac{\tau_{B^0}}{\tau_{B^+}} - 2\mathcal{A}_{CP}^{K^+\pi^0} \frac{\mathcal{B}_{K^+\pi^0}}{\mathcal{B}_{K^+\pi^-}} \frac{\tau_{B^0}}{\tau_{B^+}} - 2\mathcal{A}_{CP}^{K^0\pi^0}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

- $I_{K\pi}$ is predicted to be 0 within 1%
- Belle II can measure all the observables.

$B \to K\pi$





$\mathcal{B}(B^0 \to K^+\pi^-) = (20.7 \pm 0.4 \pm 0.6) \times 10^{-6}$

$A_{CP}(B^0 \to K^+\pi^-) = -0.07 \pm 0.02 \pm 0.01$

$\mathcal{B}(B^0 \to K^0\pi^0) = (10.16 \pm 0.65 \pm 0.65) \times 10^{-6}$

$A_{CP}(B^0 \to K^0\pi^0) = -0.06 \pm 0.15 \pm 0.05$

from the time-integrated analysis. This is combined with the time-dependent analysis.

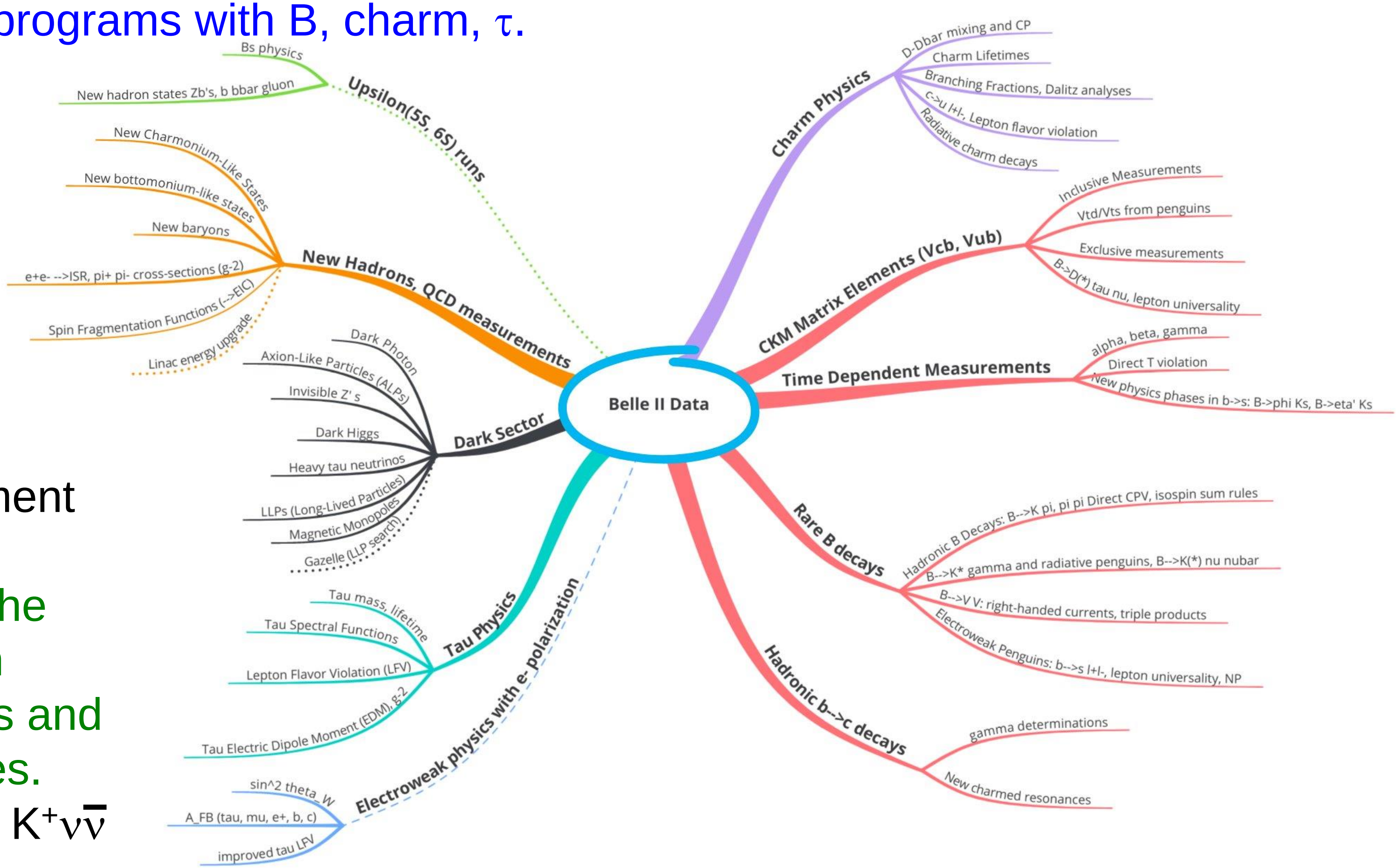
$I_{K\pi} = -0.03 \pm 0.13 \pm 0.05$

- Consistent with the SM prediction (null).
- Competitive with world average (-0.13 ± 0.11)

even with smaller dataset than Belle

Physics at Belle II

- Intensity frontier experiment: Search for New Physics with precise measurements.
- Rich physics programs with B, charm, τ.



- Clean environment (e^+e^- collider) : advantage for the final states with neutral particles and missing particles.
  - ✓ e.g. $B^+ \to K^+\nu\bar{\nu}$

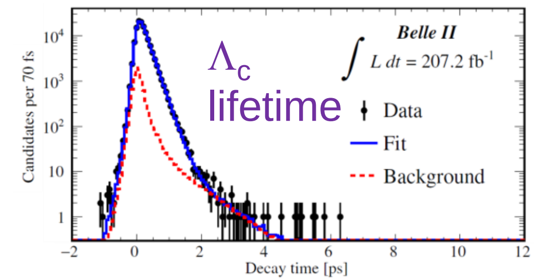
Physics at Belle II

With half of the Belle dataset, Belle II already have many world best or competing measurements.

T. Fillinger's talk on recent Belle II results on 29th (parallel)

New hadron (bottomonium) energy scan run at 10.75 GeV

Precise measurement of D, Λ_c, Ω_c lifetime



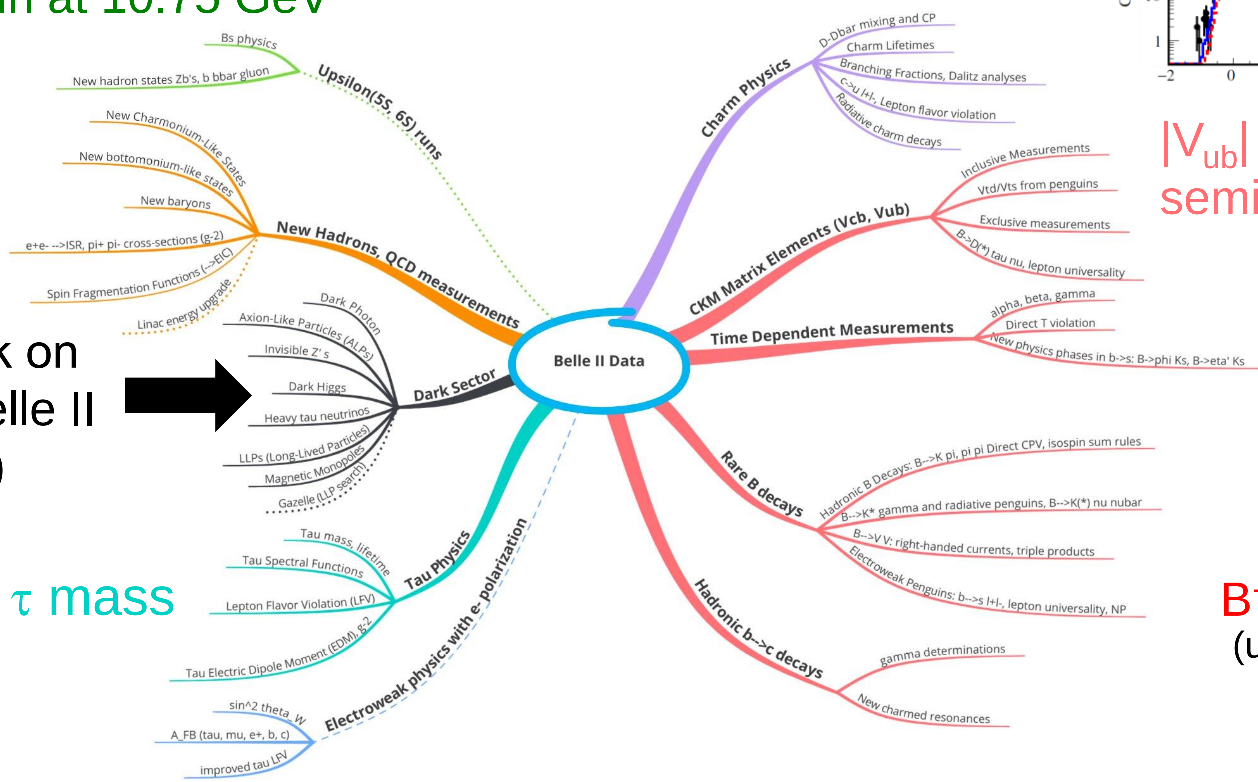
$|V_{ub}|$ and $|V_{cb}|$ from semi-leptonic B decays

ϕ_3 from time-dependent Dalitz Analysis

A. Ishikawa's talk on dark sector at Belle II on 29th (parallel)

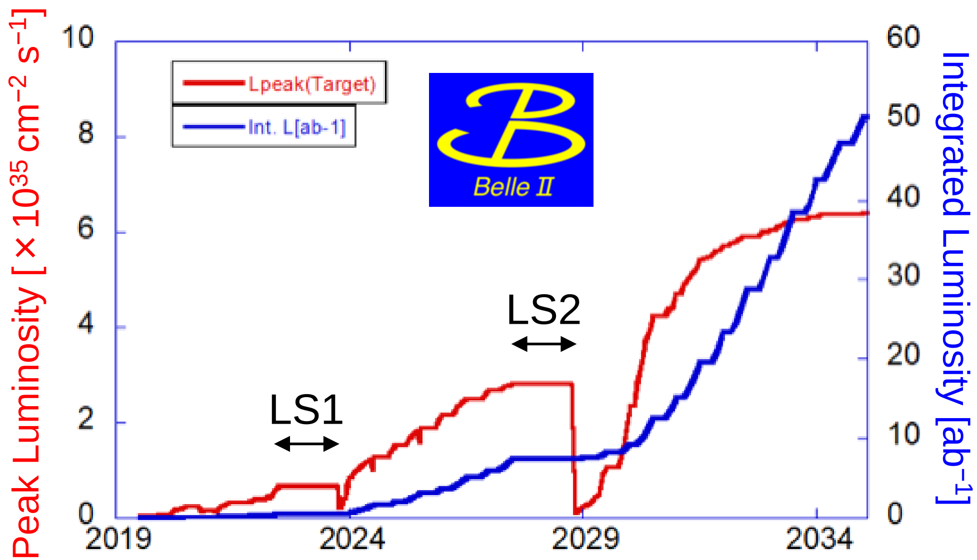
τ mass

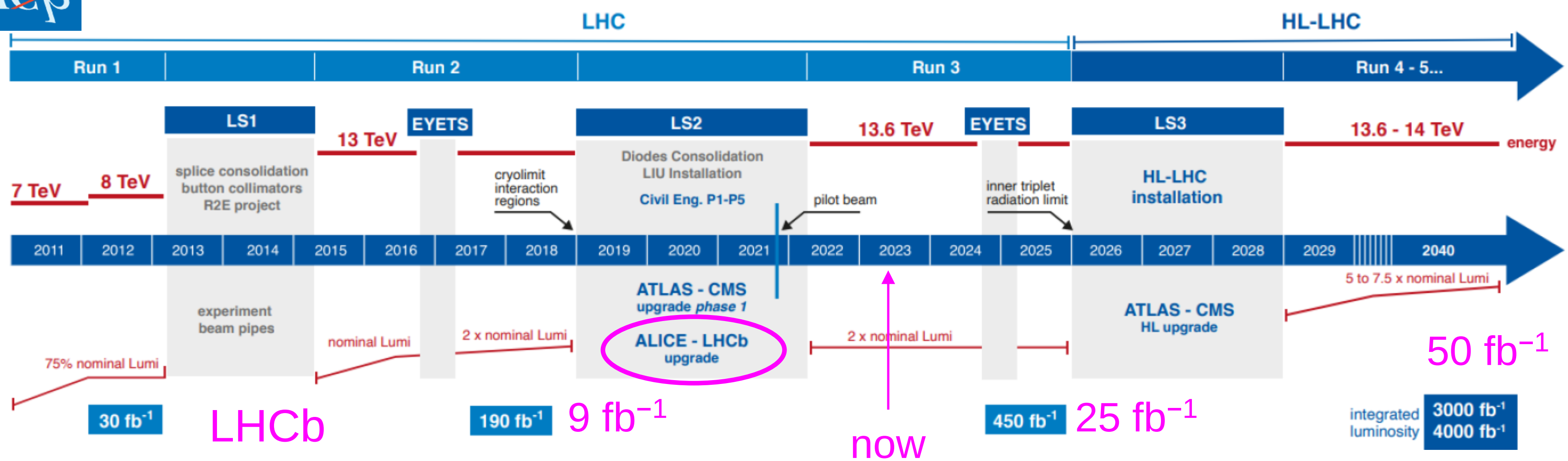
$B^+ \to K^+\nu\nu$
(update comes soon)



Plan

- SuperKEKB and Belle II are now in Long Shutdown1 (LS1). Operation will be resumed around the end of 2023.
  - ✓ Accumulate an order magnitude larger dataset than BaBar/Belle.
- LHCb started Run3 operation.
- Many new results are expected to come.

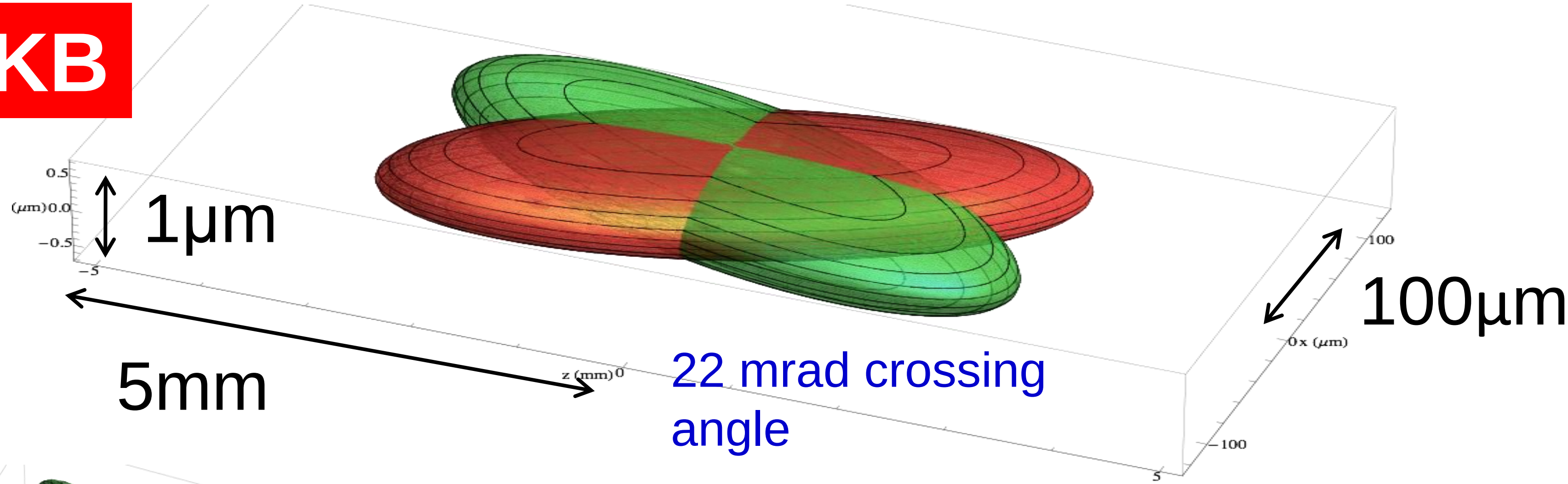




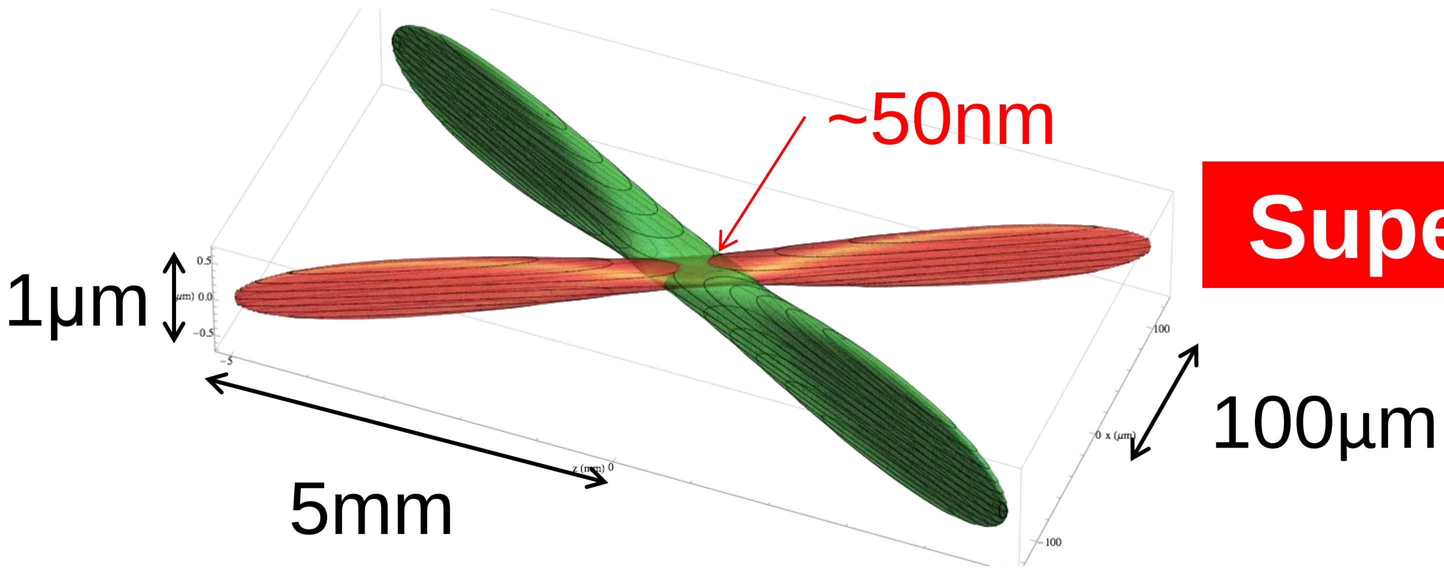
Backup

SuperKEKB

KEKB



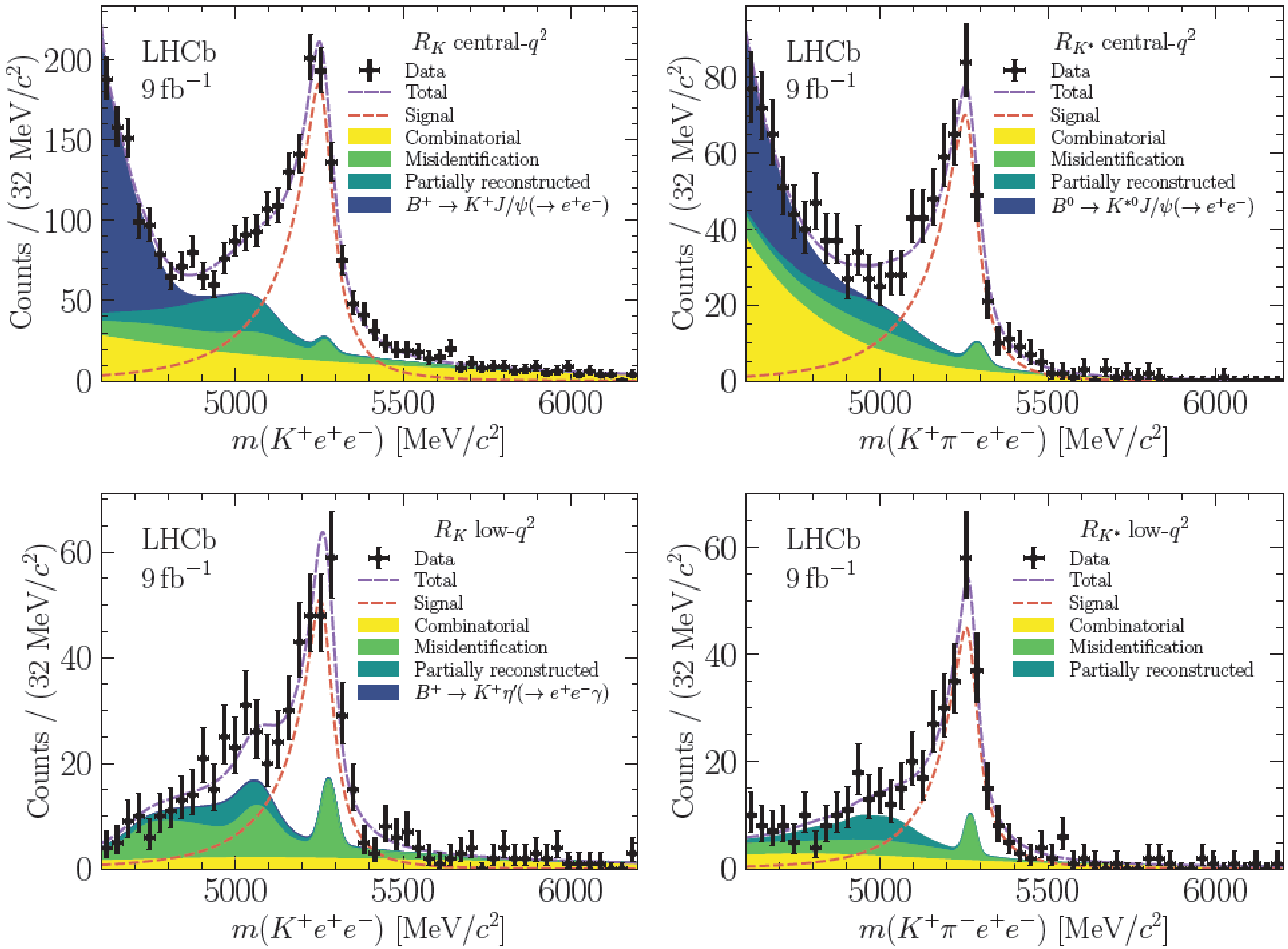
22 mrad crossing angle



SuperKEKB

83 mrad crossing angle

LFU Test of $B \to K^{(*)}l^+l^-$



LFU Test of $B \to K^{(*)}l^+l^-$

LHCb

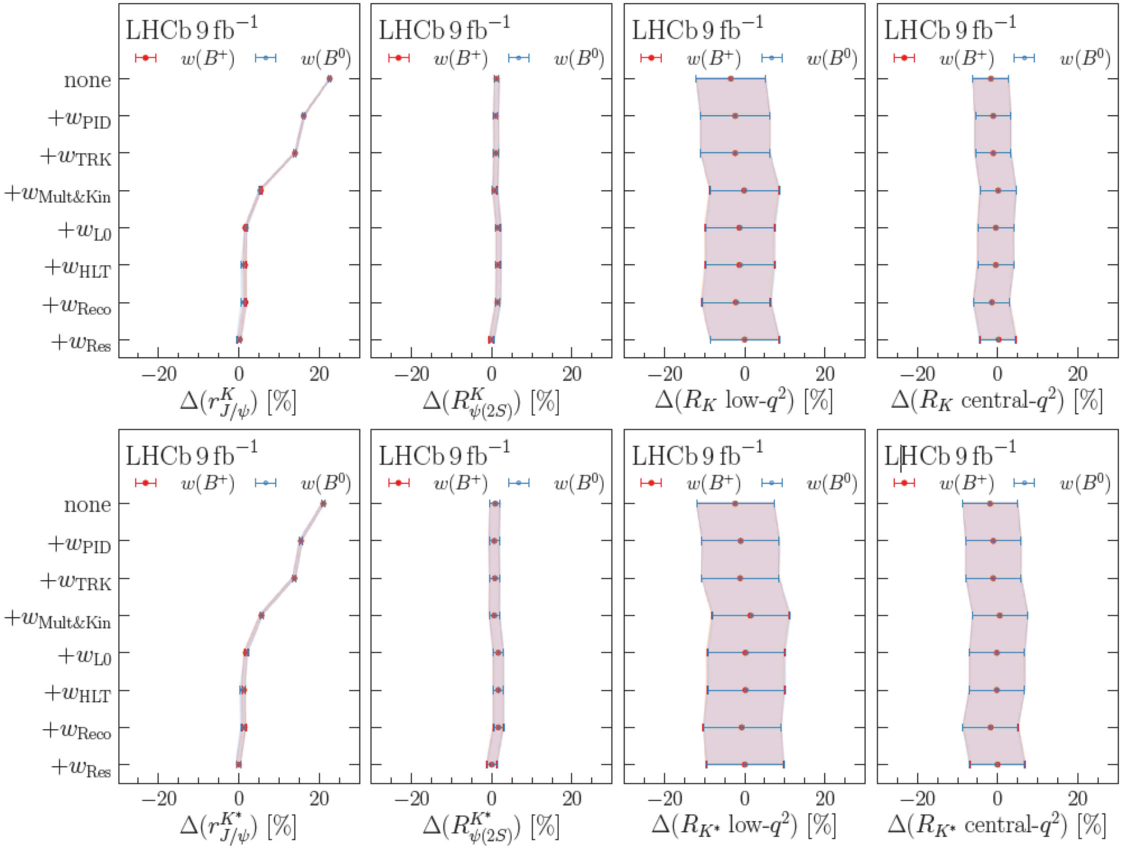
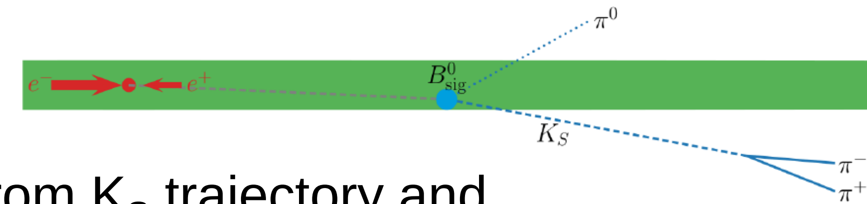


Table 11: SM predictions and uncertainties from the `flavio` software package [69].

	R_K low-q^2	R_K central-q^2	R_{K^*} low-q^2	R_{K^*} central-q^2
SM prediction	0.9936	1.0007	0.9832	0.9964
SM uncertainty	0.0003	0.0003	0.0014	0.0006

CP Violation in b→s

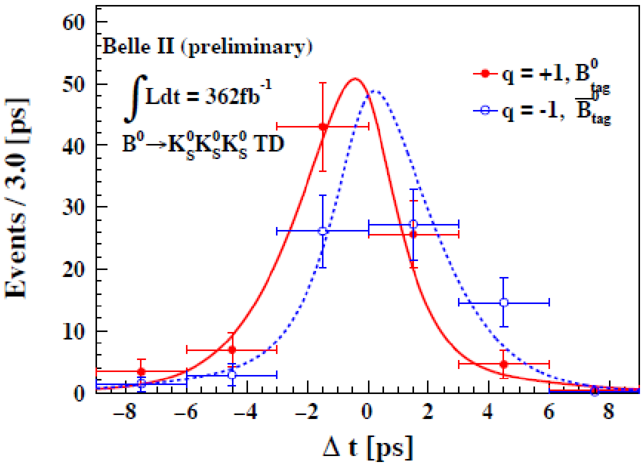
$B^0 \to K_S K_S K_S$

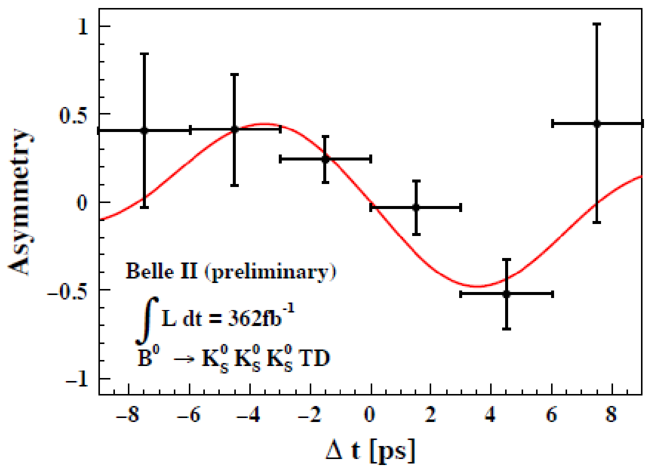


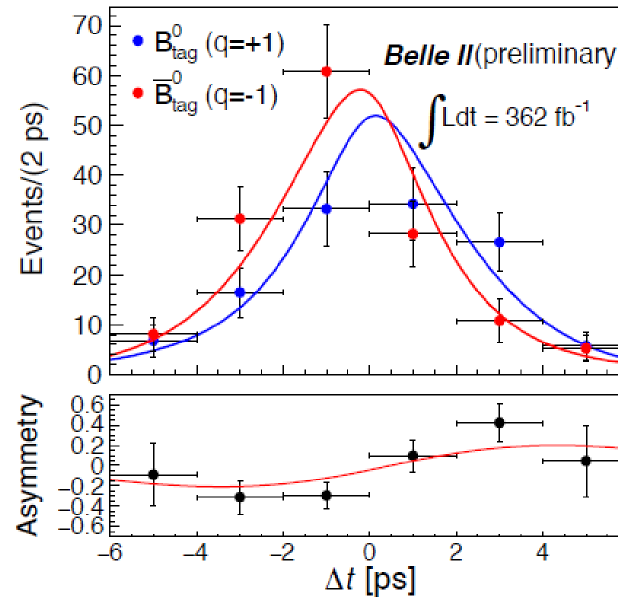
387 M $B\bar{B}$

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

- Decay vertex from K_S trajectory and profile of the interaction point.







$$A_{CP} = 0.07^{+0.15}_{-0.20} \pm 0.02$$
$$S_{CP} = -1.37^{+0.35}_{-0.45} \pm 0.03$$

HFLAV: S = 0.83±0.17, A = 0.15±0.12

$$A_{CP} = 0.04 \pm 0.15 \pm 0.05$$
$$S_{CP} = 0.75^{+0.20}_{-0.23} \pm 0.04$$

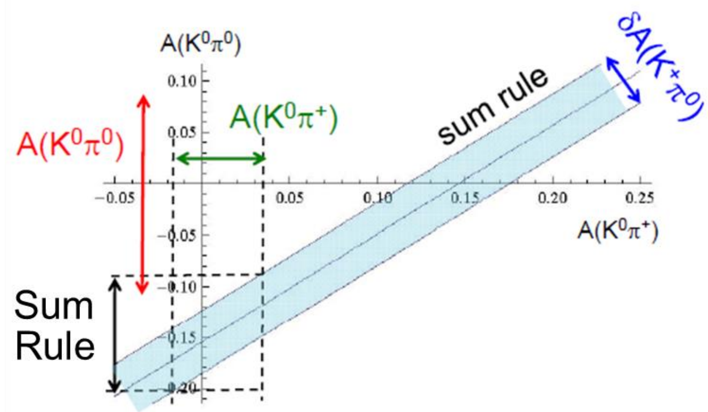
HFLAV: S = 0.57±0.17, A = -0.01±0.10

- More precise test of NP with b→s penguin in near future.

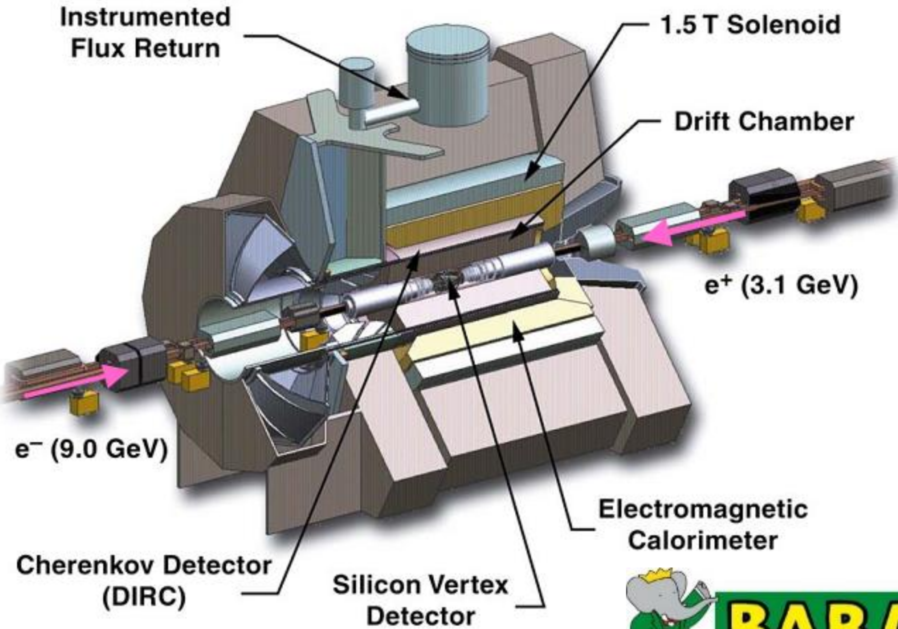
$B \to K\pi$

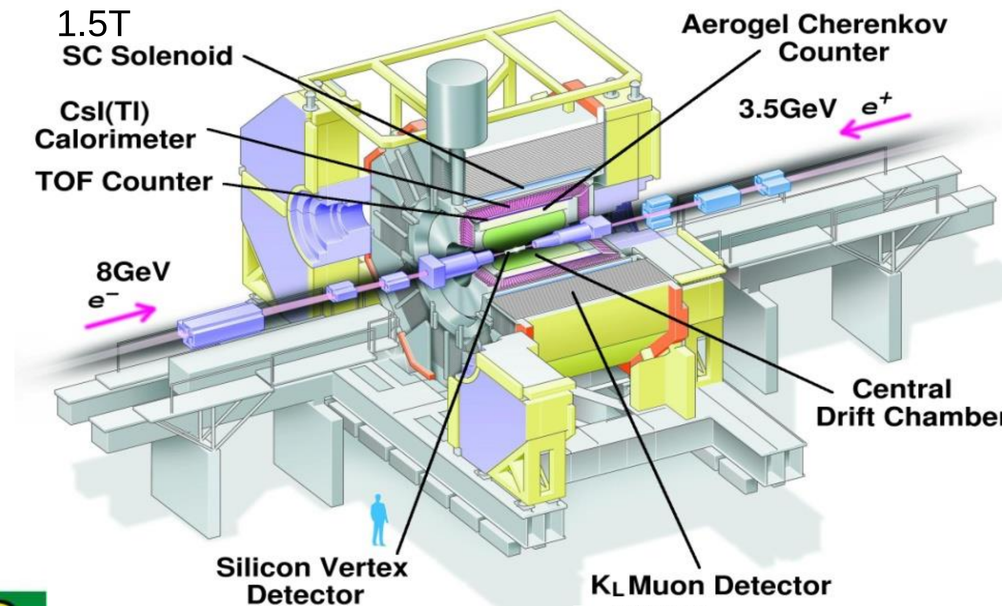
Decay	Signal yield	Feed-across yield	Signal ϵ [%]	Feed-across ϵ [%]	$\mathcal{B}$ [10^{-6}]	$\mathcal{A}_{CP}$
$B^0 \to K^+\pi^-$	3868 ± 71	880 ± 16	52.42	9.67	$20.67 \pm 0.37 \pm 0.62$	$-0.072 \pm 0.019 \pm 0.007$
$B^0 \to \pi^+\pi^-$	1187 ± 43	327 ± 8	56.42	13.11	$5.83 \pm 0.22 \pm 0.17$	–
$B^+ \to K^+\pi^0$	2070 ± 57	362 ± 10	37.47	5.30	$14.21 \pm 0.38 \pm 0.85$	$0.013 \pm 0.027 \pm 0.005$
$B^+ \to \pi^+\pi^0$	786 ± 44	113 ± 6	38.22	5.50	$5.02 \pm 0.28 \pm 0.31$	$-0.082 \pm 0.054 \pm 0.008$
$B^+ \to K^0\pi^+$	1547 ± 45	–	15.89	–	$24.4 \pm 0.71 \pm 0.86$	$0.046 \pm 0.029 \pm 0.007$
$B^0 \to K^0\pi^0$ (this analysis)	502 ± 32	–	12.67	–	$10.16 \pm 0.65 \pm 0.65$	$-0.06 \pm 0.15 \pm 0.05$
$B^0 \to K^0\pi^0$ (combination with Ref. [9])	–	–	–	–	$10.50 \pm 0.62 \pm 0.65$	$-0.01 \pm 0.12 \pm 0.05$

Situation around 2010



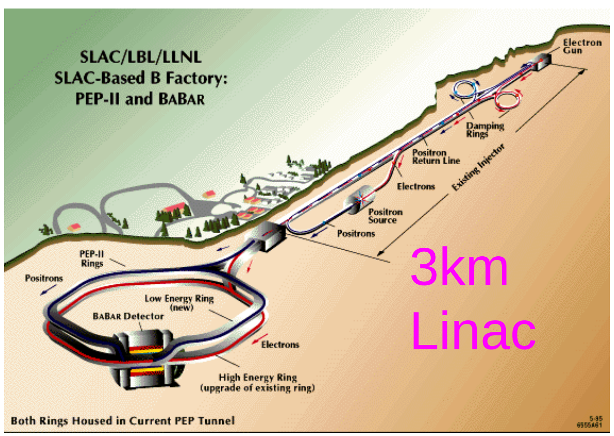
Two B Factories





BaBar @ PEP-II

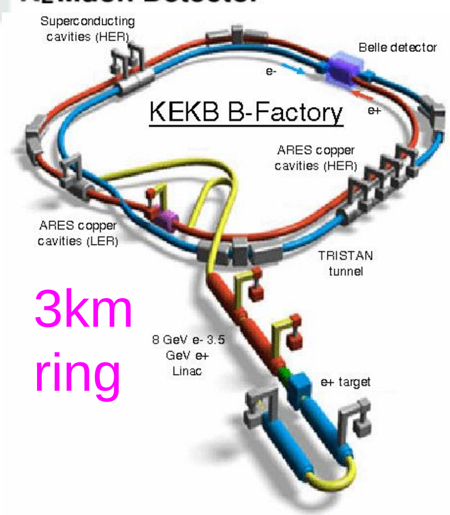
Belle @ KEKB



3km
Linac

9 GeV e^- +
3.1 GeV e^+

8 GeV e^- +
3.5 GeV e^+



3km
ring

Abstract

Belle II is a flavor physics experiment at the asymmetric e+e- collider SuperKEKB in Japan. Belle II aims to record an order of magnitude more data than the previous Belle experiment. Belle II started operation in 2019 and has accumulated 430 fb-1 of data to date. I will present the status and plans of the Belle II experiment, and review its recent results, including those on rare B meson decays, CP violation and lepton flavor violation. This talk also covers other flavor physics programs, including that of LHCb at CERN.