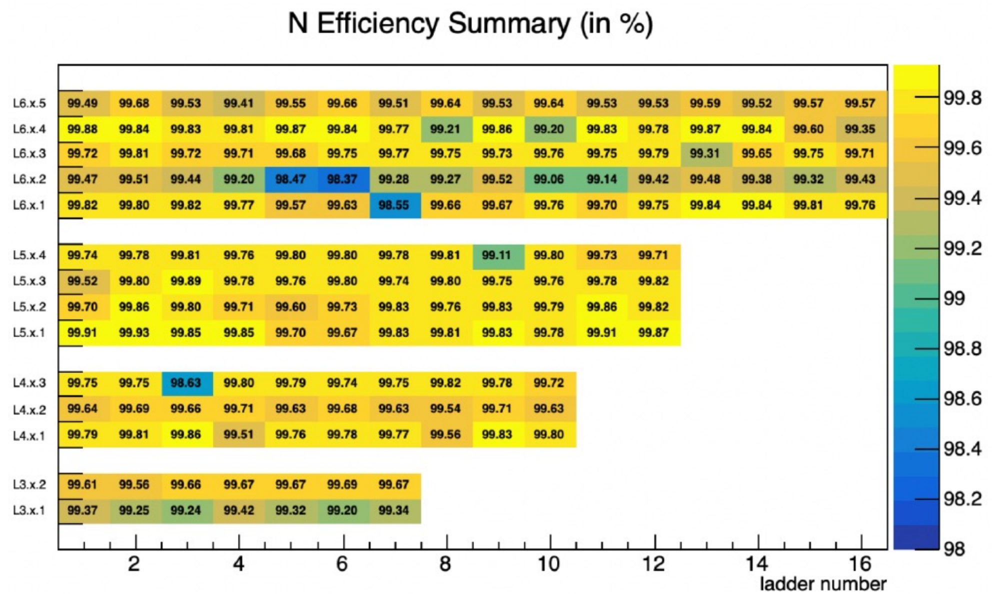
Highlight of Belle (II) Activities

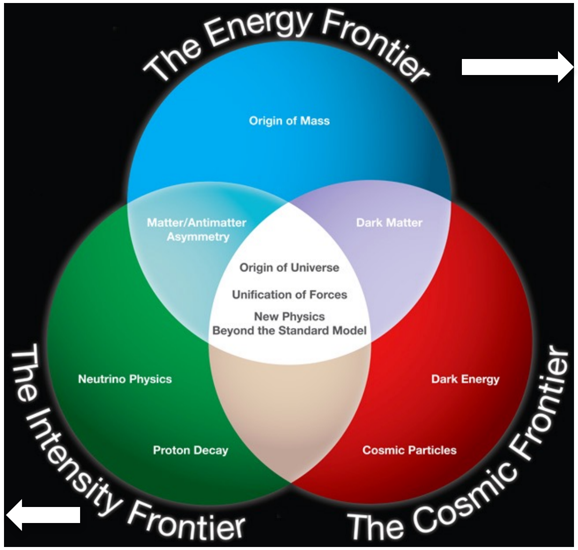


K. Rao, P. Shingade (Eng.), S. Mayekar, R. Thomas (Tech.)
PhD student: S. Halder, S. Hazra, R. Tiwary
Master student: R. Mehta

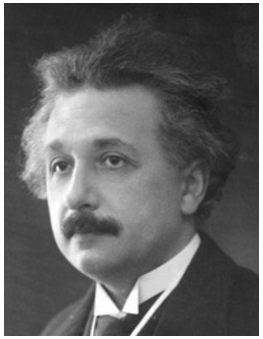
DHEP Annual Meeting
May 4-6, 2022

Probing one of the three frontiers

$\Delta m . \Delta t \sim 1$



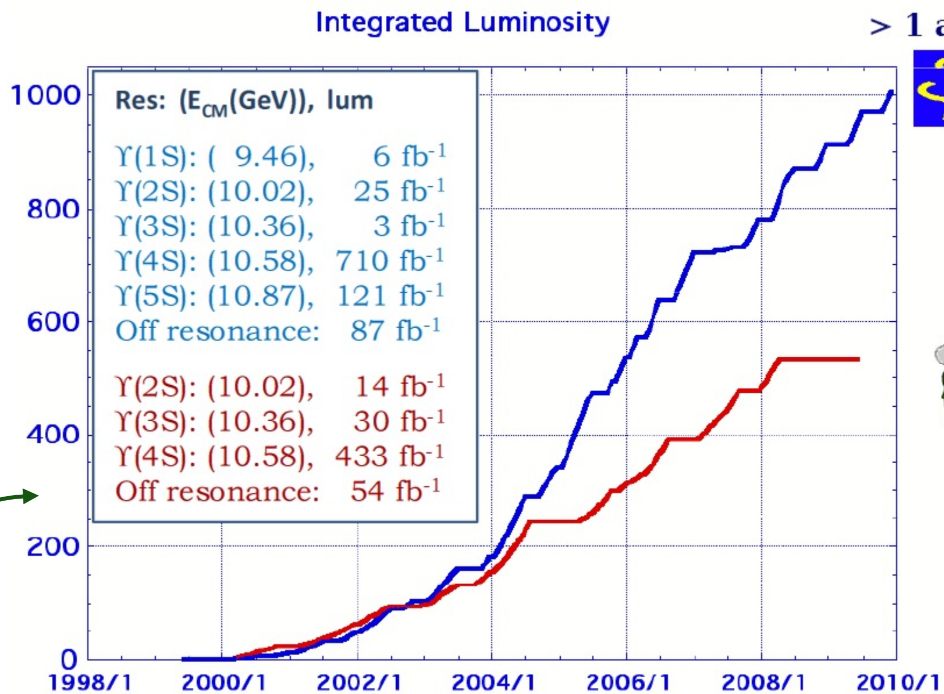
$E \sim m$



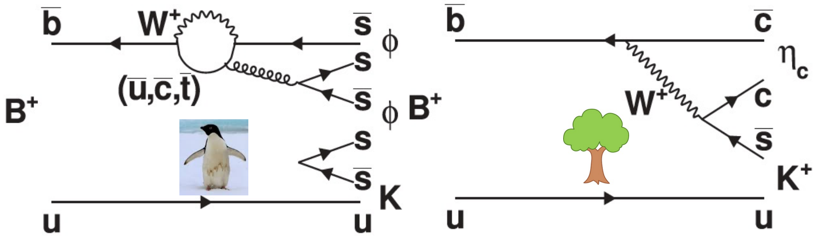
- Experiments at the Intensity Frontier indirectly probe new physics (NP) by studying the suppressed decays of subatomic particles like beauty and charm mesons as well as tau leptons

- Belle and BaBar were earlier flag bearers, and now the baton is passed to LHCb and Belle II

$> 1\ ab^{-1}$!

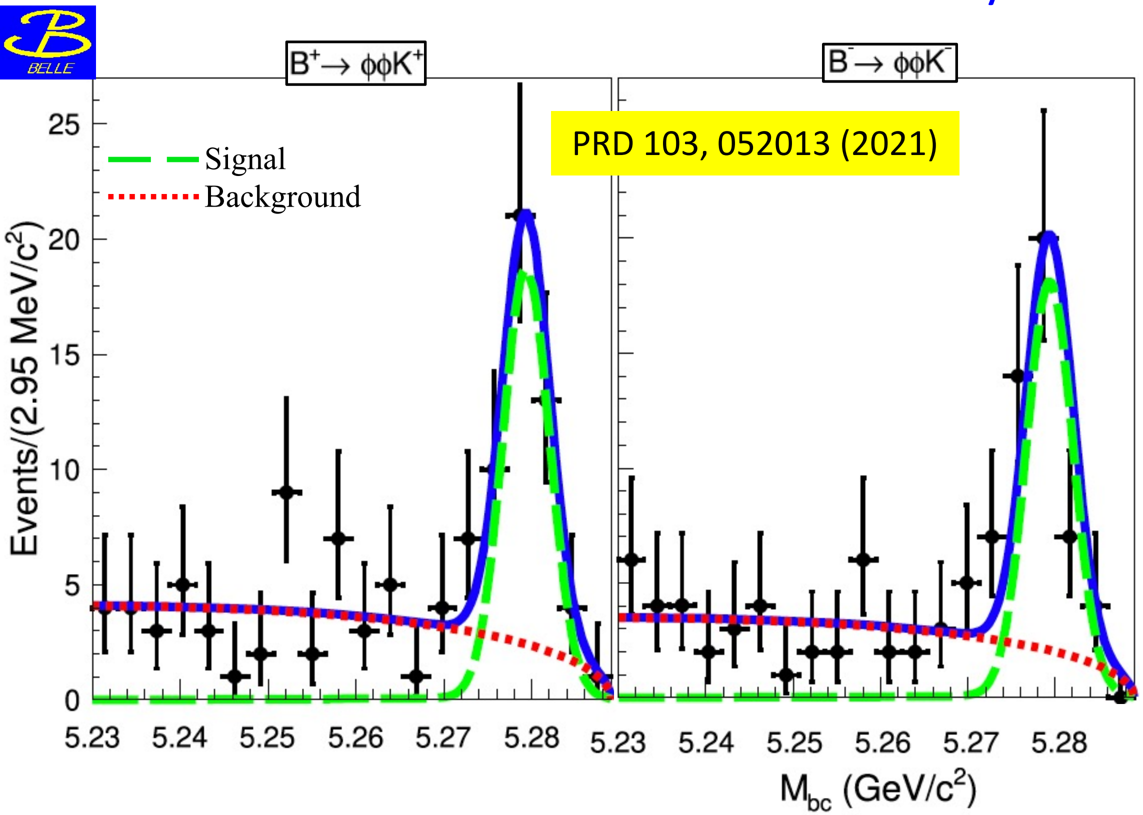


Study of $B \to \phi\phi K$ decays



- Expect no CP violation from the interference btw penguin and tree ($\eta_c \to \phi\phi$) diagrams
- NP contributions in the loop can enhance CP asymmetry to the level of 40%

PLB 583, 285 (2004)



- BF and CP asymmetry measured below the η_c threshold ($m_{\phi\phi} < 2.85\ \mathrm{GeV}/c^2$):

$$\mathcal{B}(B^\pm \to \phi\phi K^\pm) = (3.43^{+0.48}_{-0.46} \pm 0.22)\times 10^{-6}$$
$$A_{CP}(B^\pm \to \phi\phi K^\pm) = -0.02 \pm 0.11 \pm 0.01$$

- CP asymmetry in the η_c region ($m_{\phi\phi} \in [2.94, 3.02]\ \mathrm{GeV}/c^2$):

$$A_{CP}(B^\pm \to \phi\phi K^\pm) = -0.12 \pm 0.12 \pm 0.01$$

is consistent with no CP violation

- Measured BF for the $B^0 \to \phi\phi K^0$ decay is $(3.02^{+0.75}_{-0.66} \pm 0.20)\times 10^{-6}$
- Consistent with theory prediction that lies in the range $(1.3\text{–}4.3)\times 10^{-6}$

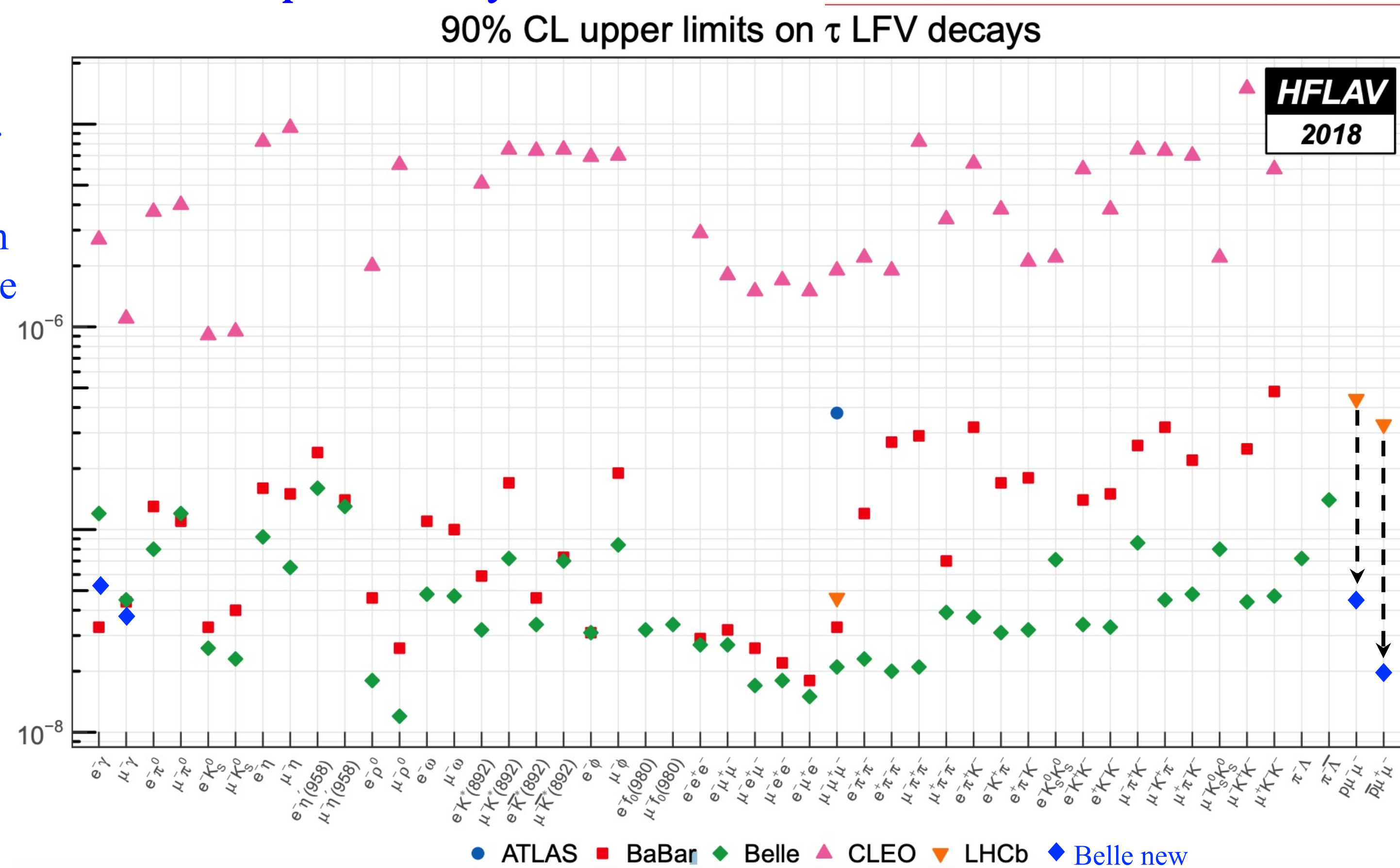
PRD 69, 114020 (2004) PRD 70, 054006 (2004)

Searching for baryon number violation

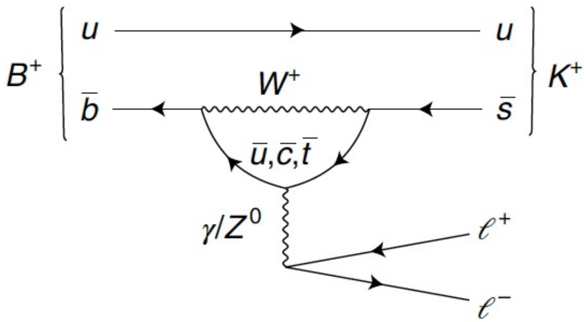
- Tau is the only lepton that can decay to hadrons
- Can potentially give rise to baryon number violating decays $\tau \to p\ell\ell'$ $[\ell^{(\prime)} = e, \mu]$; such processes will be a signature for NP e.g., supersymmetry, GUT or models with black holes
- Performed a search for $\tau \to p\ell\ell'$ decays
  - No evidence for a signal is found
  - Set 90% CL upper limits, improving LHCb limits by an order of magnitude in two channels
  - Brand new limits set for four other decay channels

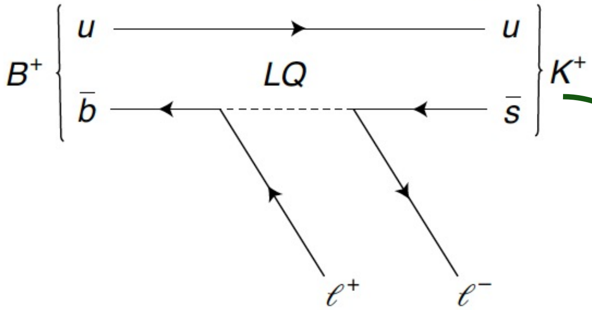
PRD 102, 111101(R) (2020)

All channels	$\epsilon(\%)$	$N_{\rm sig}^{\rm UL}$	$\mathcal{B}\,(\times 10^{-8})$
$\tau^- \to \overline{p}e^+e^-$	7.8	3.9	< 3.0
$\tau^- \to pe^-e^-$	8.0	4.1	< 3.0
$\tau^- \to \overline{p}e^+\mu^-$	6.5	2.2	< 2.0
$\tau^- \to \overline{p}e^-\mu^+$	6.9	2.1	< 1.8
$\tau^- \to p\mu^-\mu^-$	4.6	3.1	< 4.0
$\tau^- \to \overline{p}\mu^-\mu^+$	5.0	1.5	< 1.8



Talk of the town





- If one keeps mass terms aside, the SM does not distinguish between leptons of different flavor
- The ratio:

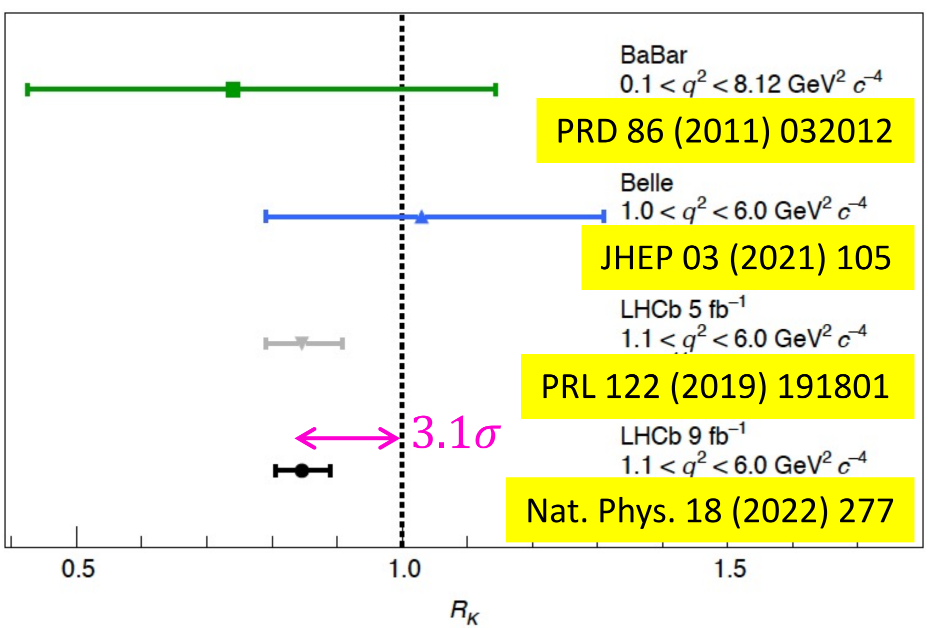
$$R(K^{(*)}) = \frac{\mathcal{B}(B \to K^{(*)}\mu\mu)}{\mathcal{B}(B \to K^{(*)}ee)}$$

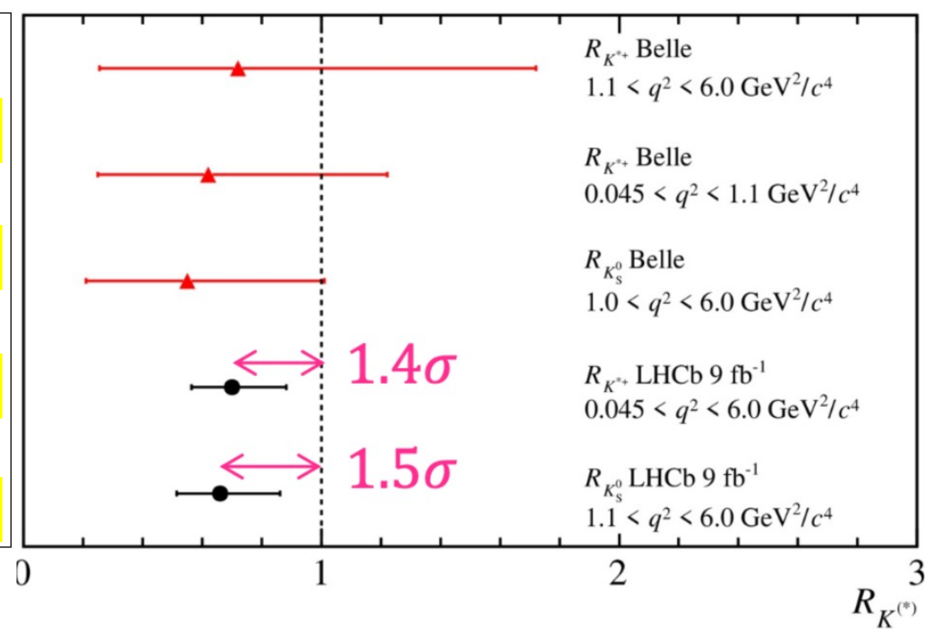
is expected to be one to an accuracy of $\mathcal{O}(10^{-2})$

⇒ lepton flavor universality (LFU)

- New physics can affect these observables

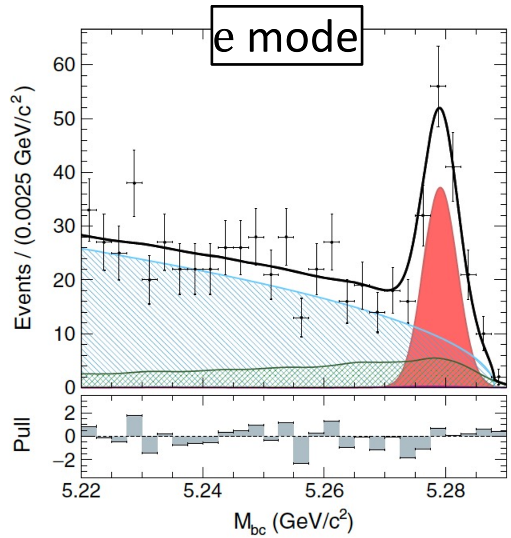
✓ LHCb finds evidence for LFU violation

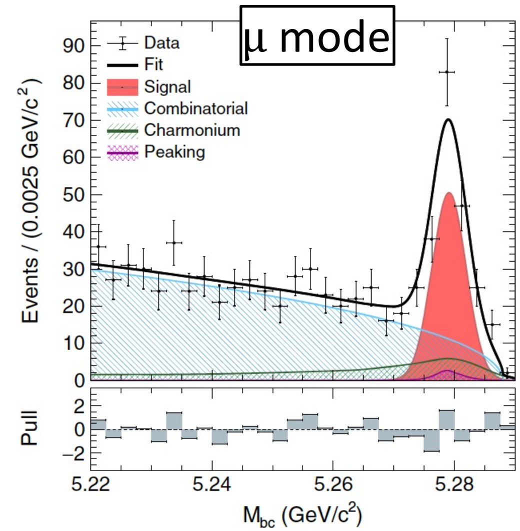




Measurement of R_{K^*} at Belle

- Test the LFU by measuring the ratio of $\mathcal{B}(B \to K^*\mu^+\mu^-)$ and $\mathcal{B}(B \to K^*e^+e^-)$, with the K^{*+} reconstructed in final states of $K^+\pi^0$ and $K_S^0\pi^+$ and the K^{*0} in $K^+\pi^-$ and $K_S^0\pi^0$

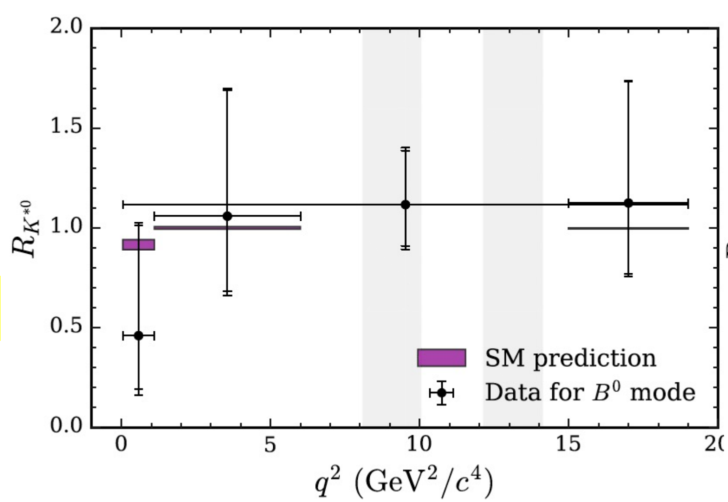




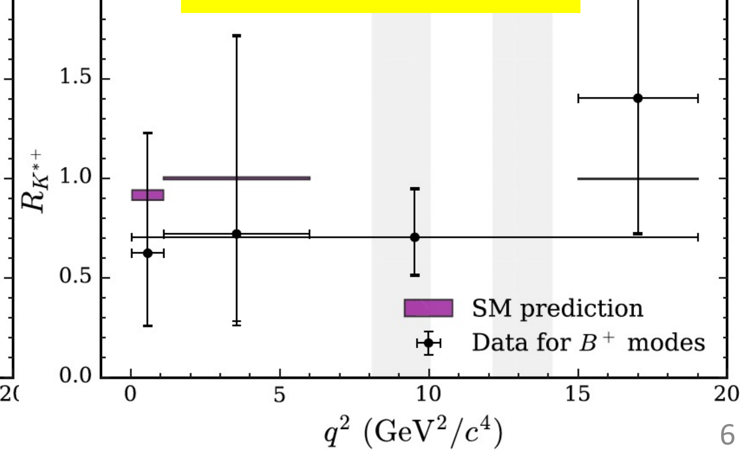
- Measured R_{K^*} in a number of q^2 bins including the one up to 19 GeV^2/c^4
- Similar performance for electron and muon mode (103 vs. 140 signal evt)
- $R_{K^{*+}}$ is measured for the first time

☞ Results consistent with SM predictions with largest deviation found in the lowest q^2 bin, where LHCb reports an $R_{K^{*0}}$ value differing from the SM expectation

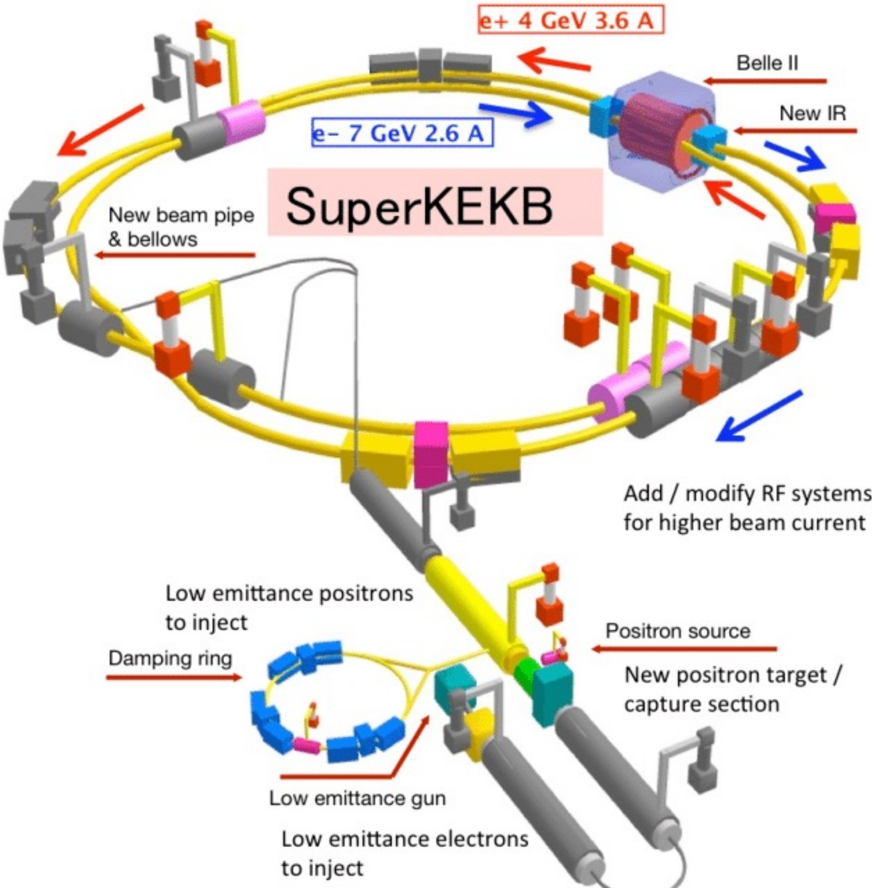
JHEP 08 (2017) 055

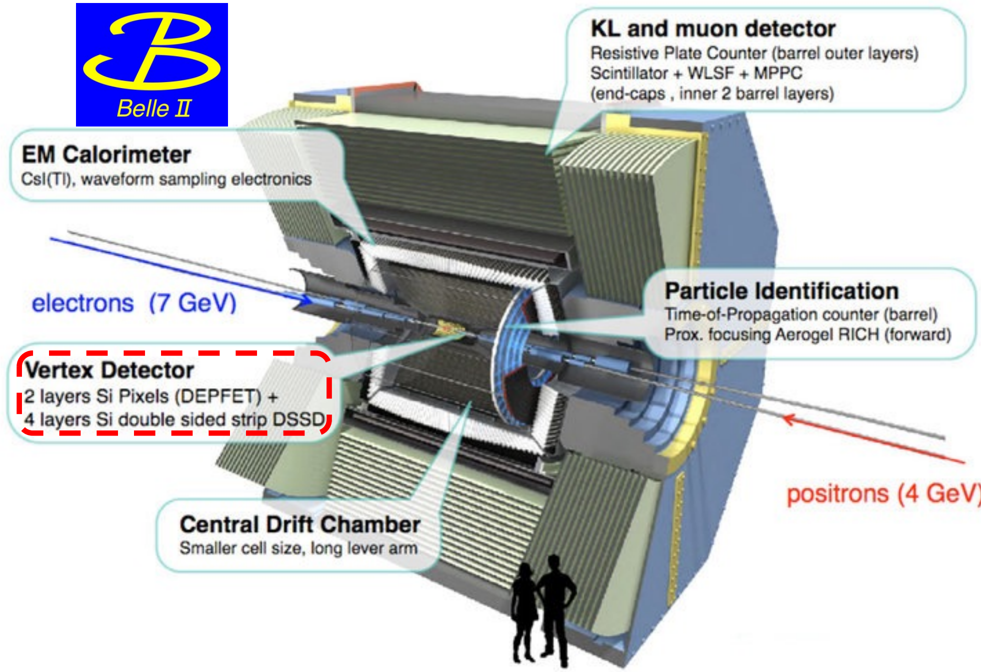


PRL 126, 161801 (2021)



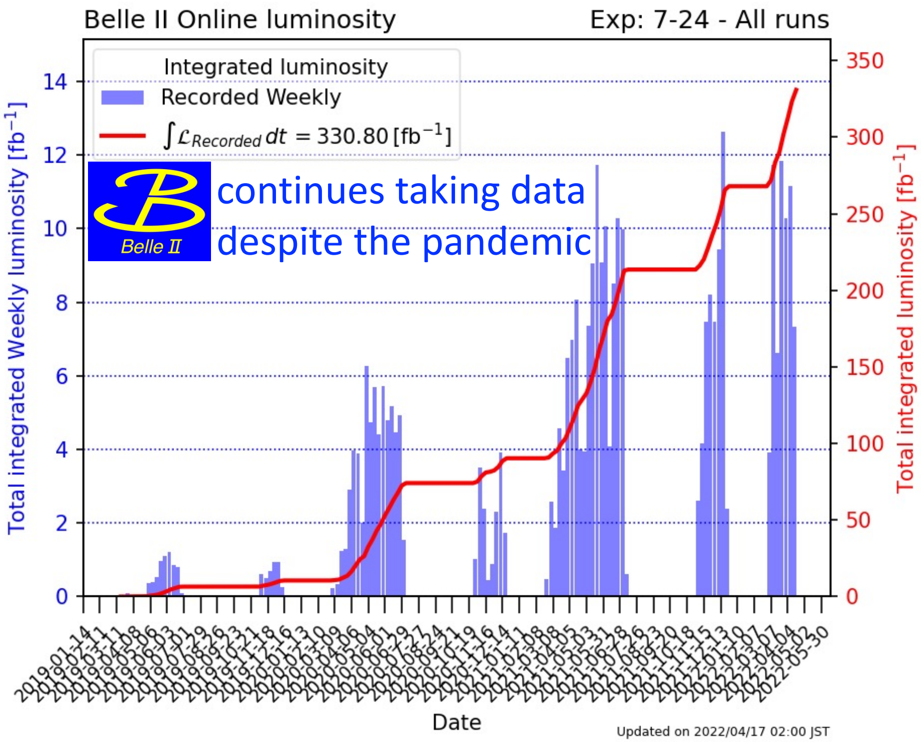
Move to Belle II





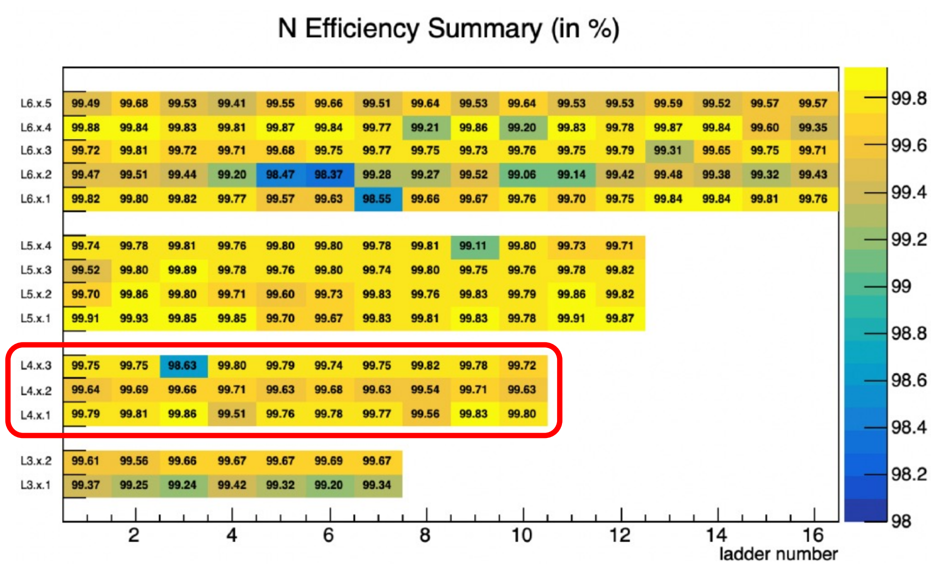
- ❑ Mega collaboration ≈1100 researchers, 123 institutions, 26 nations
- ❑ Our participation encompasses:
  - a) Computing ⇒ Please refer to Prashant's talk
  - b) SVD operation, performance and upgrade ⇒ Tomorrow Sagar will talk about it
  - c) Physics analysis ⇒ Soumen will provide a glimpse tomorrow

Dataset and performance



- ❑ Peak luminosity: $3.8\times10^{34}\text{cm}^{-2}\text{s}^{-1}$ (world record)
- ❑ Data recorded: 330 fb^{-1} of which a maximum of 190 fb^{-1} is analysed
- ❑ Path to reach $2.0\times10^{35}\text{cm}^{-2}\text{s}^{-1}$ has been defined
- ❑ Still large factors to arrive at target peak luminosity ($6.0\times10^{35}\text{cm}^{-2}\text{s}^{-1}$)

➢ Performance of SVD where our group played a leading role (and continues to do so)



☞ Details will be in Sagar's talk

An example decay where VXD is the key

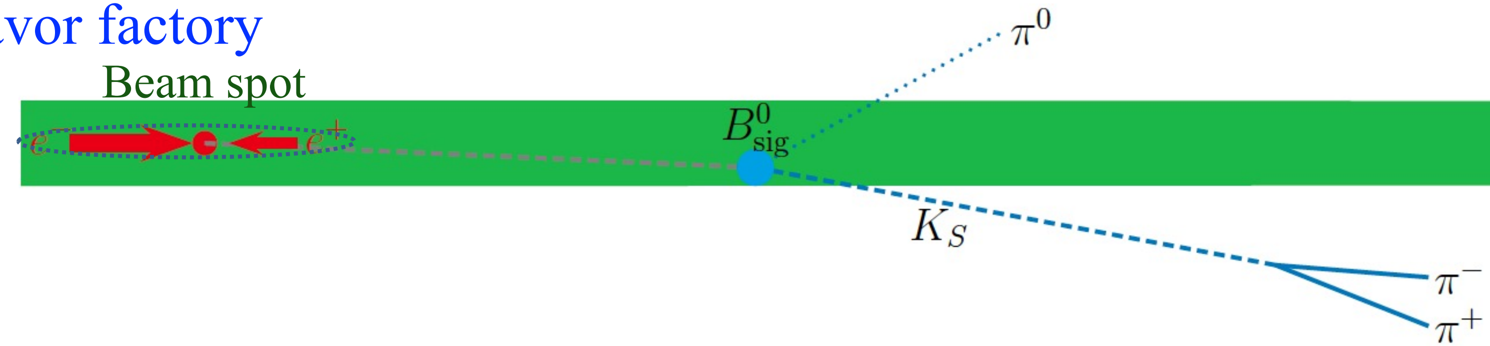
- Perform a time-dependent study to measure the branching fraction and direct CP asymmetry in charmless $B^0 \to K^0\pi^0$ decays

$$\mathcal{P}(\Delta t) = \frac{e^{-|\Delta t|/\tau_{B^0}}}{4\tau_{B^0}}[1 + q\{\mathcal{A}_{CP}\cos(\Delta m_d \Delta t) + \mathcal{S}_{CP}\sin(\Delta m_d \Delta t)\}]$$

- In the SM, $\mathcal{A}_{CP} \approx 0$ and $\mathcal{S}_{CP} \approx \sin 2\beta$
- Further, branching fraction and $\mathcal{A}_{CP}$ are inputs to an isospin sum rule proposed in PLB 627, 82 (2005) $\Rightarrow$ null test for new physics

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

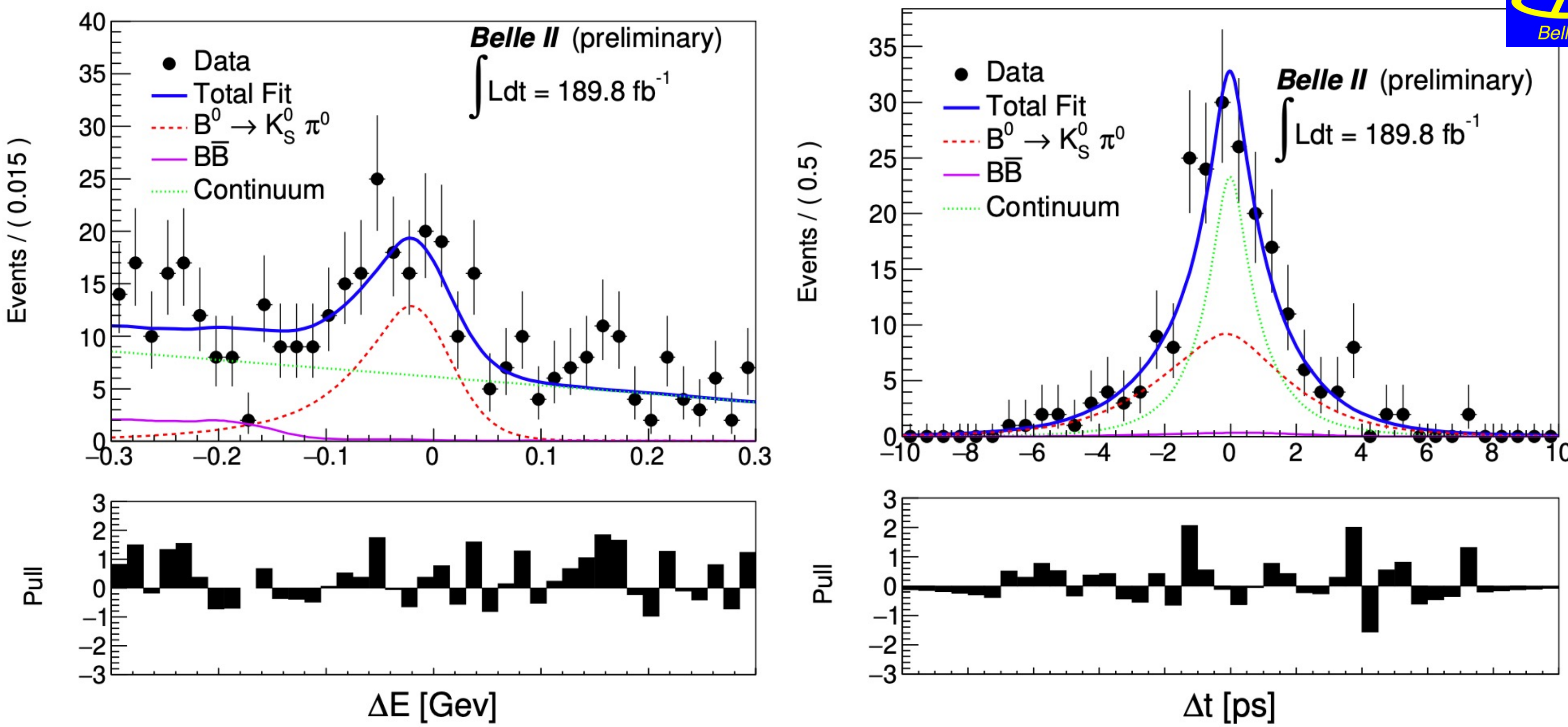
- Time-dependent study in a decay without any primary charged particle coming from B_{sig} is challenging and likely the sole preserve of an e^+e^- flavor factory



✓ Need good performance with neutrals and beam-spot constraint

Results on $\mathcal{B}$ and $\mathcal{A}_{CP}$ for $B^0 \to K^0\pi^0$

- 4D fit comprising M_{bc}, ΔE, continuum suppression output, and Δt
- Use $B^0 \to J/\psi(\mu^+\mu^-)K_S^0$ as the control channel
- Fix the $\mathcal{S}_{CP}$ value to current world average in order to maximize the precision on $\mathcal{A}_{CP}$



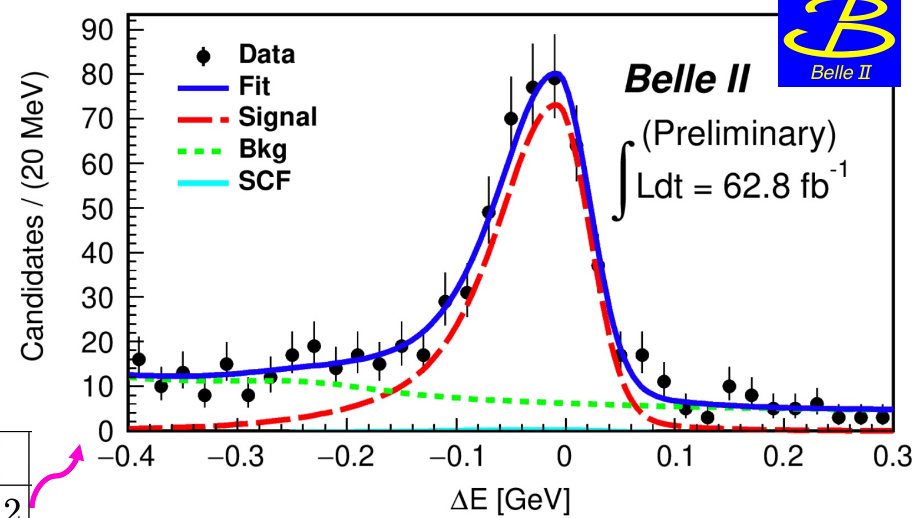
$$\mathcal{A}_{CP} = -0.41^{+0.30}_{-0.32}(\text{stat}) \pm 0.09(\text{syst})$$

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

Moving to radiative penguin decays

Branching fractions for $B \to K^*\gamma$ with $K^* \to K^+\pi^-$, $K_S^0\pi^0$, $K^+\pi^0$ and $K_S^0\pi^0$

- Extract the signal yield from an unbinned maximum-likelihood fit to the ΔE distribution

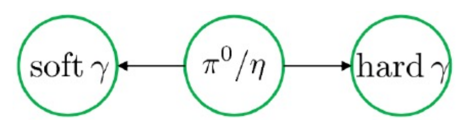


- Branching fractions are in fair agreement with world averages

Mode	Signal yield	Efficiency (%)	$\mathcal{B}_{\rm meas}$ $[10^{-5}]$
$B^0 \to K^{*0}[K^+\pi^-]\gamma$	454 ± 28	15.22 ± 0.03	$4.5 \pm 0.3 \pm 0.2$
$B^0 \to K^{*0}[K_S^0\pi^0]\gamma$	50 ± 10	1.73 ± 0.01	$4.4 \pm 0.9 \pm 0.6$
$B^+ \to K^{*+}[K^+\pi^0]\gamma$	169 ± 18	4.84 ± 0.02	$5.0 \pm 0.5 \pm 0.4$
$B^+ \to K^{*+}[K_S^0\pi^+]\gamma$	160 ± 17	4.23 ± 0.02	$5.4 \pm 0.6 \pm 0.4$

arXiv:2110.08219

- Major systematic sources: fit model, mis-modeling of π^0/η veto, and selection variables in simulation (depending on the channel)



(hard photon from asymmetric π^0/η faking signal γ)

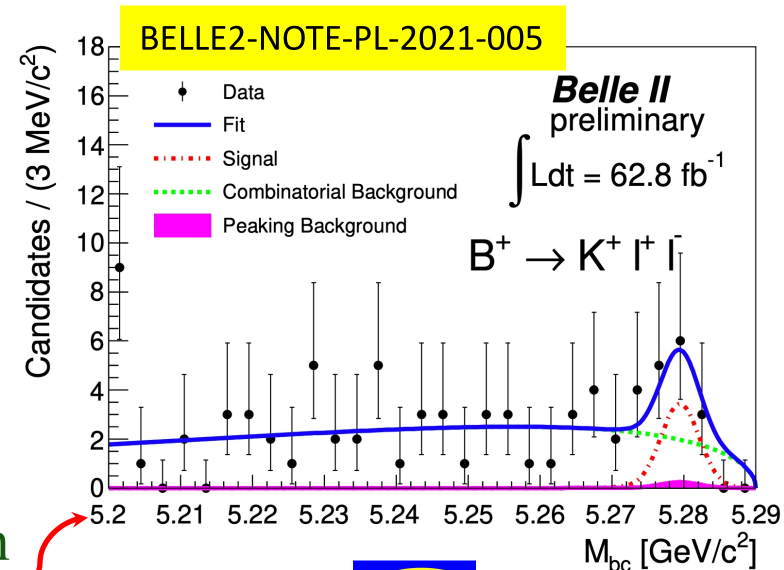
✓ Update with full available dataset is ongoing to measure the branching fraction, CP violation and isospin asymmetry; may be noted that Belle has observed 3.1σ evidence for isospin violation PRL 119 (2017) 191802

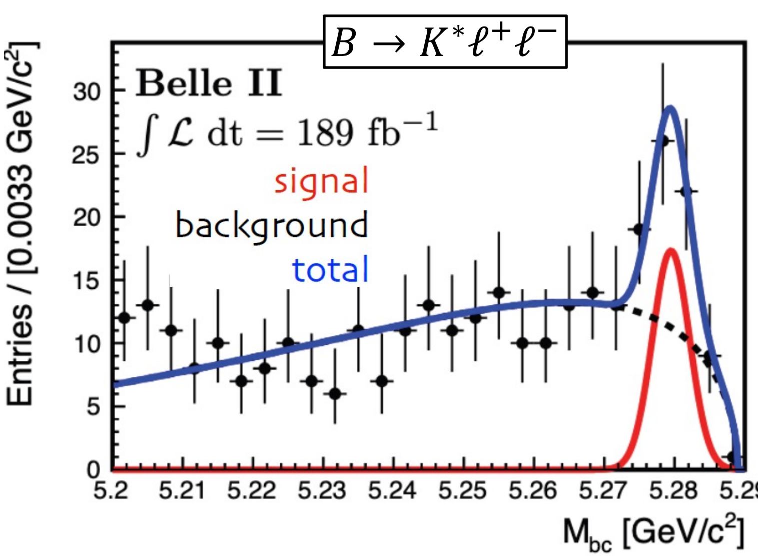
What is the status of LFU?

USP: Belle II can

a) provide essential independent checks of $R(K^{(*)})$ anomalies with few ab^{-1} data
b) measure $R(X_s)$ for inclusive B decays
c) provide independent measurements of absolute branching fractions for e and μ modes

- ❑ 2021 prelim results for $B^+ \to K^+\ell^+\ell^-$ with only 63 fb^{-1}: 2.7σ significance for signal





PDG $\mathcal{B} \times 10^6$

$$\mathcal{B}(B \to K^*\mu^+\mu^-) = (1.19 \pm 0.31^{+0.08}_{-0.07}) \times 10^{-6}$$ 0.94±0.05

$$\mathcal{B}(B \to K^*e^+e^-) = (1.42 \pm 0.48 \pm 0.09) \times 10^{-6}$$ 1.03±.19

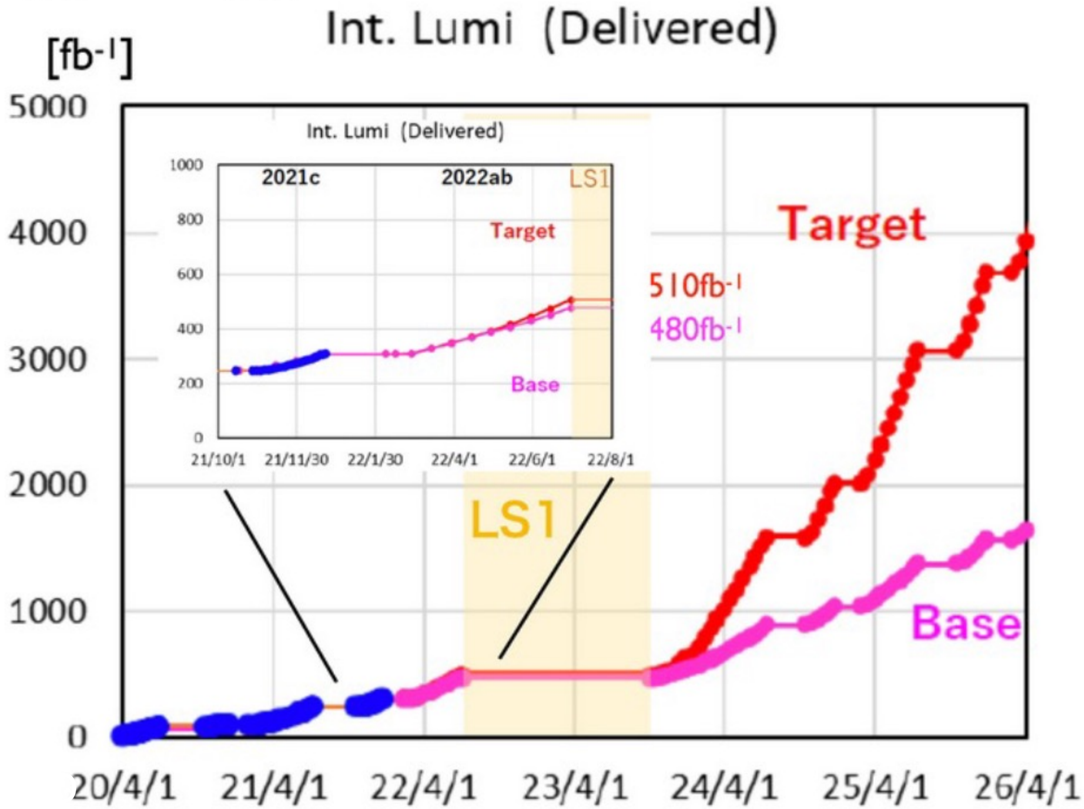
$$\mathcal{B}(B \to K^*\ell^+\ell^-) = (1.25 \pm 0.30^{+0.08}_{-0.07}) \times 10^{-6}$$ 0.99±0.12

- ❑ Limited by the sample size
- ❑ Precision of both electron and muon modes in the same ballpark
- ❑ Electron mode is off by 2.5σ wrt PDG; we expect it to be competitive with 1 ab^{-1}

What does future hold?

PTEP 2019 (2019) 12, 123C01

Observables	Belle $0.71\ ab^{-1}$	Belle II $5\ ab^{-1}$	Belle II $50\ ab^{-1}$
R_K ([1.0, 6.0] GeV^2)	28%	11%	3.6%
R_K (>14.4 GeV^2)	30%	12%	3.6%
R_{K^*} ([1.0, 6.0] GeV^2)	26%	10%	3.2%
R_{K^*} (>14.4 GeV^2)	24%	9.2%	2.8%
R_{X_s} ([1.0, 6.0] GeV^2)	32%	12%	4.0%
R_{X_s} (>14.4 GeV^2)	28%	11%	3.4%



- By 2026 we would have got 5 ab^{-1} of data that would allow us to probe LFU to $\mathcal{O}(10\%)$

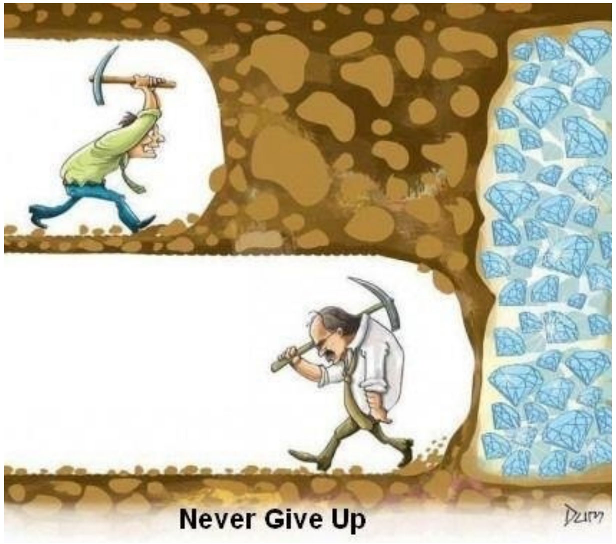
Summary

- Focus on some recent analyses from Belle (II) where our group has played a major role

- A number of interesting studies that I have been unable to cover in this talk can be accessed from the following two links:
  https://belle.kek.jp/bdocs/b_journal.html
  https://confluence.desy.de/pages/viewpage.action?pageId=138001973

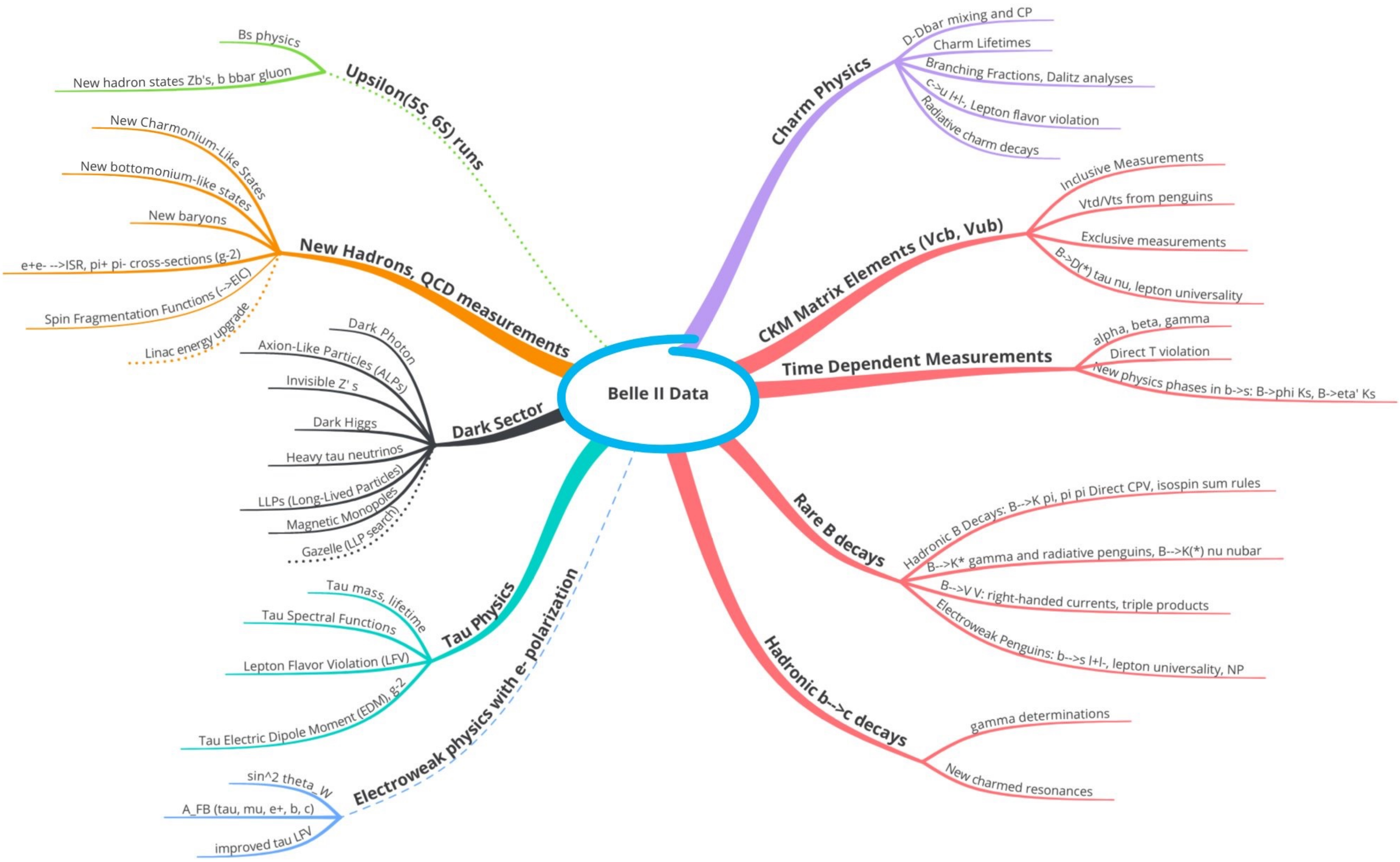
- Much more to come from these exciting experiments at Intensity Frontier

➢ Stay tuned …



Thanks very much for your attention

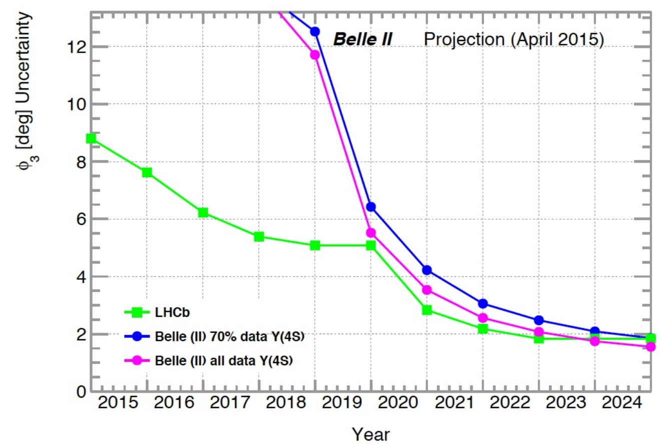
Belle II mind map

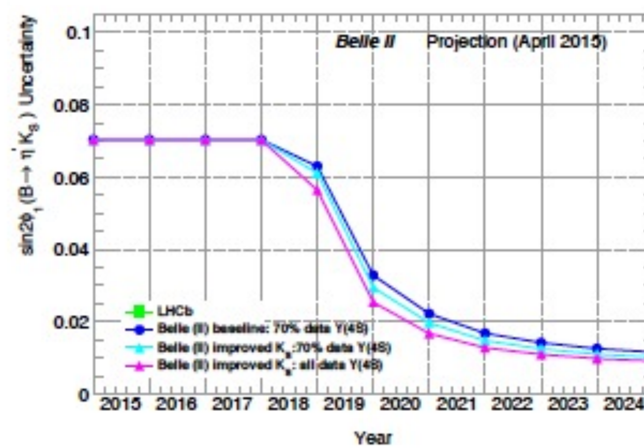


Belle II vs. LHCb

Observable	Expected th. accuracy	Expected exp. uncertainty	Facility
CKM matrix			
$\lvert V_{us}\rvert$ $[K \to \pi \ell \nu]$	**	0.1%	K-factory
$\lvert V_{cb}\rvert$ $[B \to X_c \ell \nu]$	**	1%	Belle II
$\lvert V_{ub}\rvert$ $[B_d \to \pi \ell \nu]$	*	4%	Belle II
$\sin(2\phi_1)$ $[c\bar{c}K^0_S$	***	$8 \cdot 10^{-3}$	Belle II/LHCb
ϕ_2		1.5°	Belle II
ϕ_3	***	3°	LHCb
CPV			
$S(B_s \to \psi\phi)$	**	0.01	LHCb
$S(B_s \to \phi\phi)$	**	0.05	LHCb
$S(B_d \to \phi K)$	***	0.05	Belle II/LHCb
$S(B_d \to \eta' K)$	***	0.02	Belle II
$S(B_d \to K^*(\to K^0_S\pi^0)\gamma))$	***	0.03	Belle II
$S(B_s \to \phi\gamma))$	***	0.05	LHCb
$S(B_d \to \rho\gamma))$		0.15	Belle II
A^d_{SL}	***	0.001	LHCb
A^s_{SL}	***	0.001	LHCb
$A_{CP}(B_d \to s\gamma)$	*	0.005	Belle II
rare decays			
$\mathcal{B}(B \to \tau\nu)$	**	3%	Belle II
$\mathcal{B}(B \to D\tau\nu)$		3%	Belle II
$\mathcal{B}(B_d \to \mu\nu)$	**	6%	Belle II
$\mathcal{B}(B_s \to \mu\mu)$	***	10%	LHCb
zero of $A_{FB}(B \to K^*\mu\mu)$	**	0.05	LHCb
$\mathcal{B}(B \to K^{(*)}\nu\nu)$	***	30%	Belle II
$\mathcal{B}(B \to s\gamma)$		4%	Belle II
$\mathcal{B}(B_s \to \gamma\gamma)$		$0.25 \cdot 10^{-6}$	Belle II (with 5 ab^{-1})
$\mathcal{B}(K \to \pi\nu\nu)$	**	10%	K-factory
$\mathcal{B}(K \to e\pi\nu)/\mathcal{B}(K \to \mu\pi\nu)$	***	0.1%	K-factory
charm and τ			
$\mathcal{B}(\tau \to \mu\gamma)$	***	$3 \cdot 10^{-9}$	Belle II
$\lvert q/p\rvert_D$	***	0.03	Belle II
$arg(q/p)_D$	***	1.5°	Belle II

- Great for neutral and missing energy modes
- Inclusive measurement: OK
- Excellent flavor tagging and K_S reconstruction





Something to keep in mind

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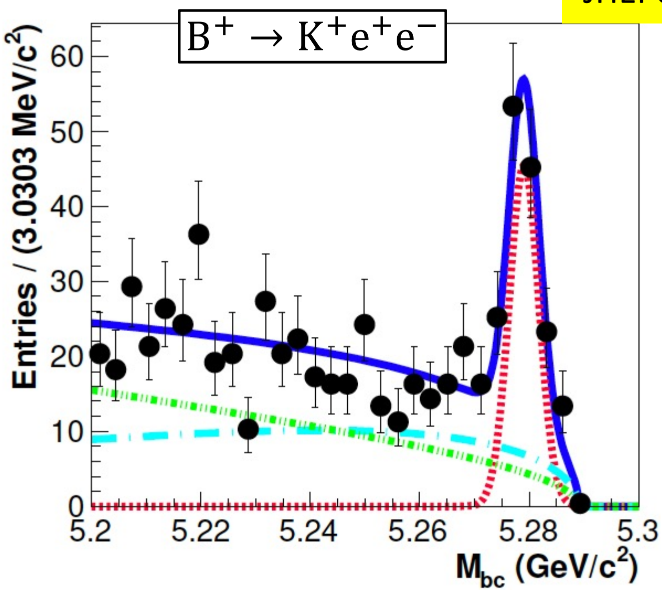

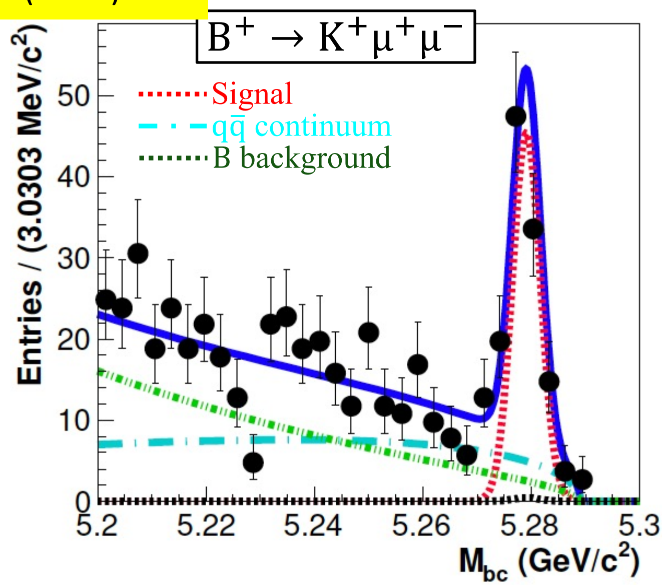

- ❑ Belle (II) has got similar sensitivity both for electron and muon modes
- ❑ Electron mode is not as clean as the muon for LHCb (lower two plots)

Nat. Phys. 18 (2022) 277