High Statistics B Decays

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Pres:
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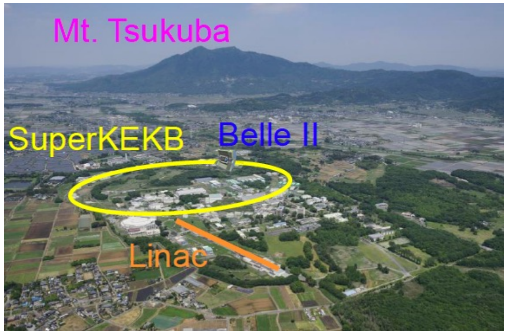
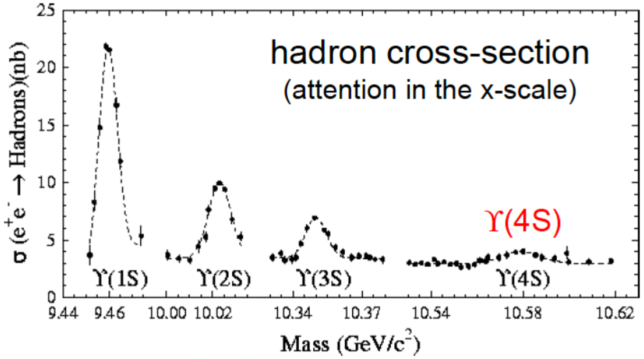
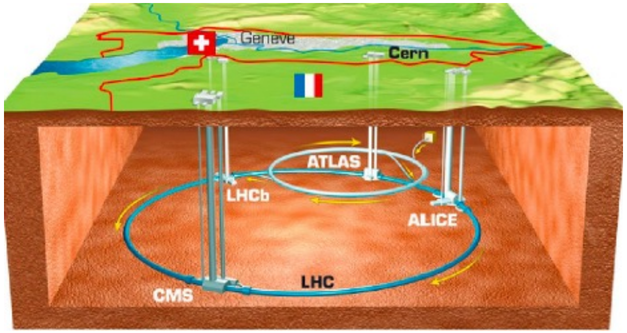
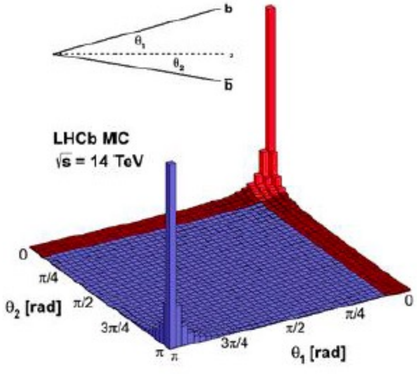
Story of two players...

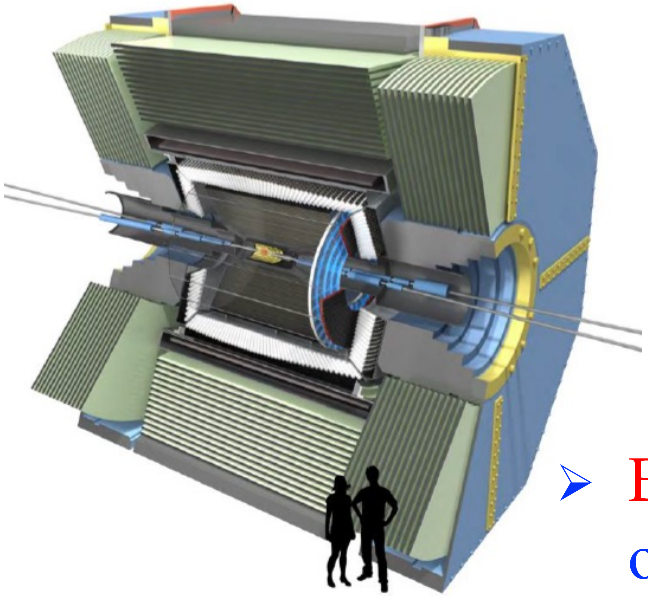


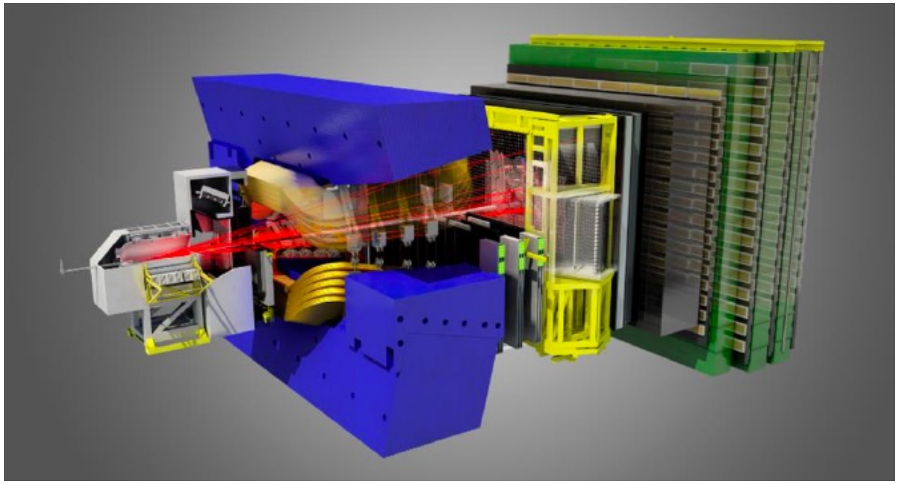
- LHCb: a general-purpose spectrometer in the forward direction at the LHC, optimized for precision flavor physics







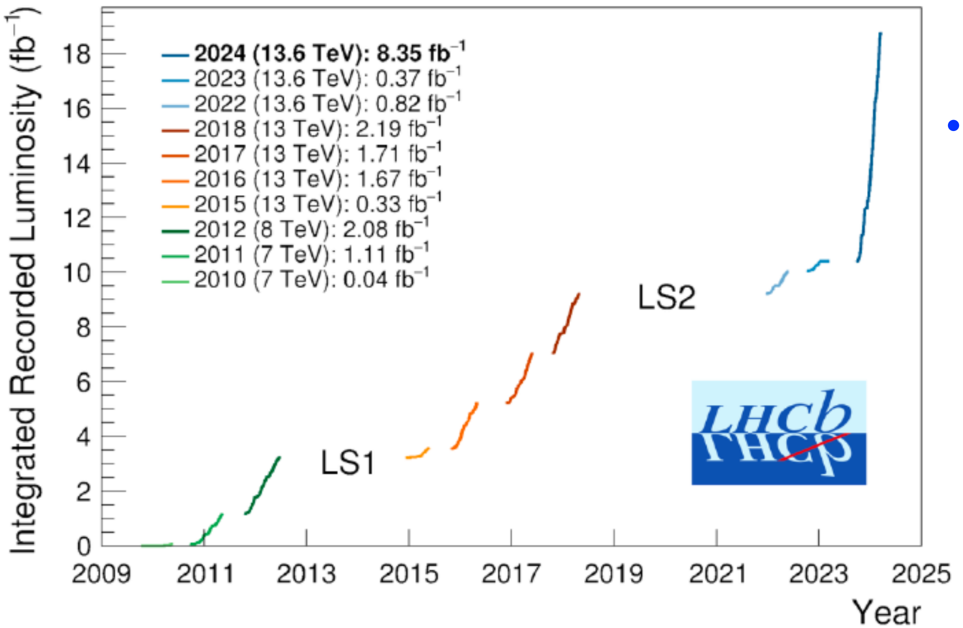




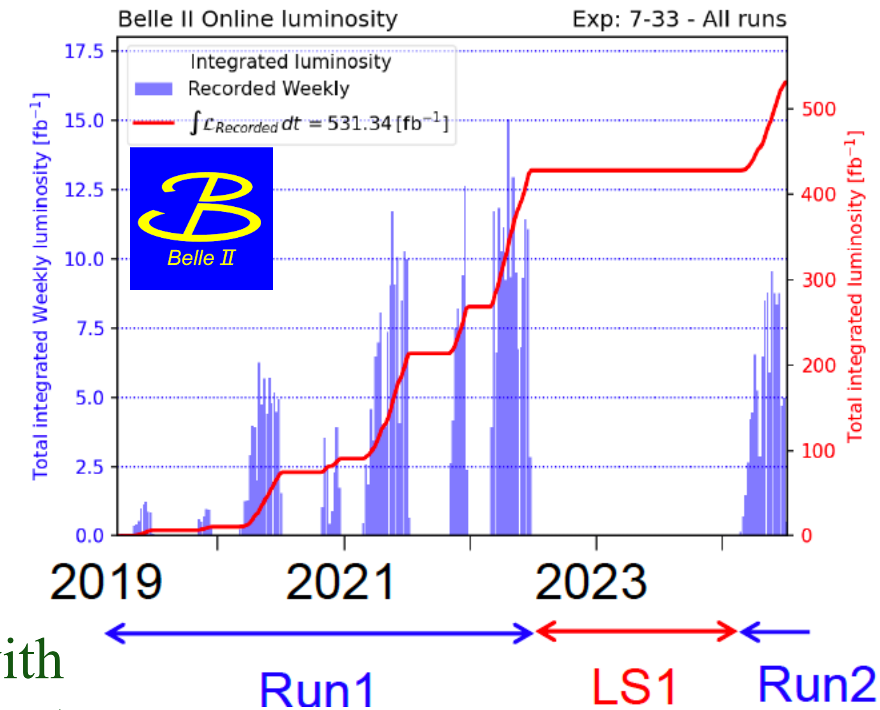
- Belle II: second-generation e^+e^- flavor factory operating near the $\Upsilon(4S)$ resonance

In their kitty, they have got

- Integrated luminosity: 9 fb^{-1} of pp collisions (+ pPb, PbPb, fixed target mode) until 2024
- Recorded ~8 fb^{-1} in 2024 alone!



- Peak luminosity: $4.7\times10^{34}\text{cm}^{-2}\text{s}^{-1}$
  - World record (~ ×2 of KEKB)
  - Aiming an order higher
- Integrated luminosity: 530 fb^{-1}
  - Similar to BABAR data set and half of what Belle recorded in 11 years
- Target: 50 ab^{-1}



👉 Roughly, 1 fb^{-1} of LHCb corresponds to 1 ab^{-1} of Belle II

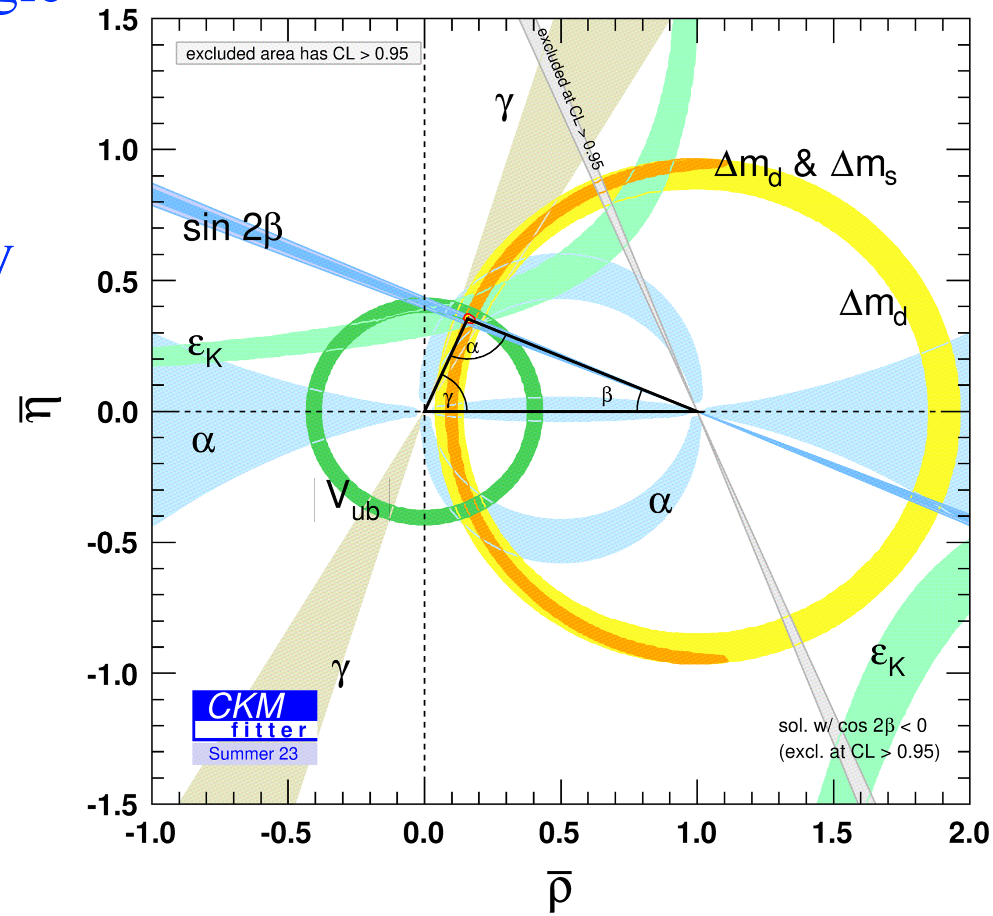
👉 Belle II has advantage for final states with neutrals (γ, π^0) and missing particles (ν…)

Their main goals

1) Precision test of the standard model (SM): measure the angles and sides of CKM Unitarity Triangle

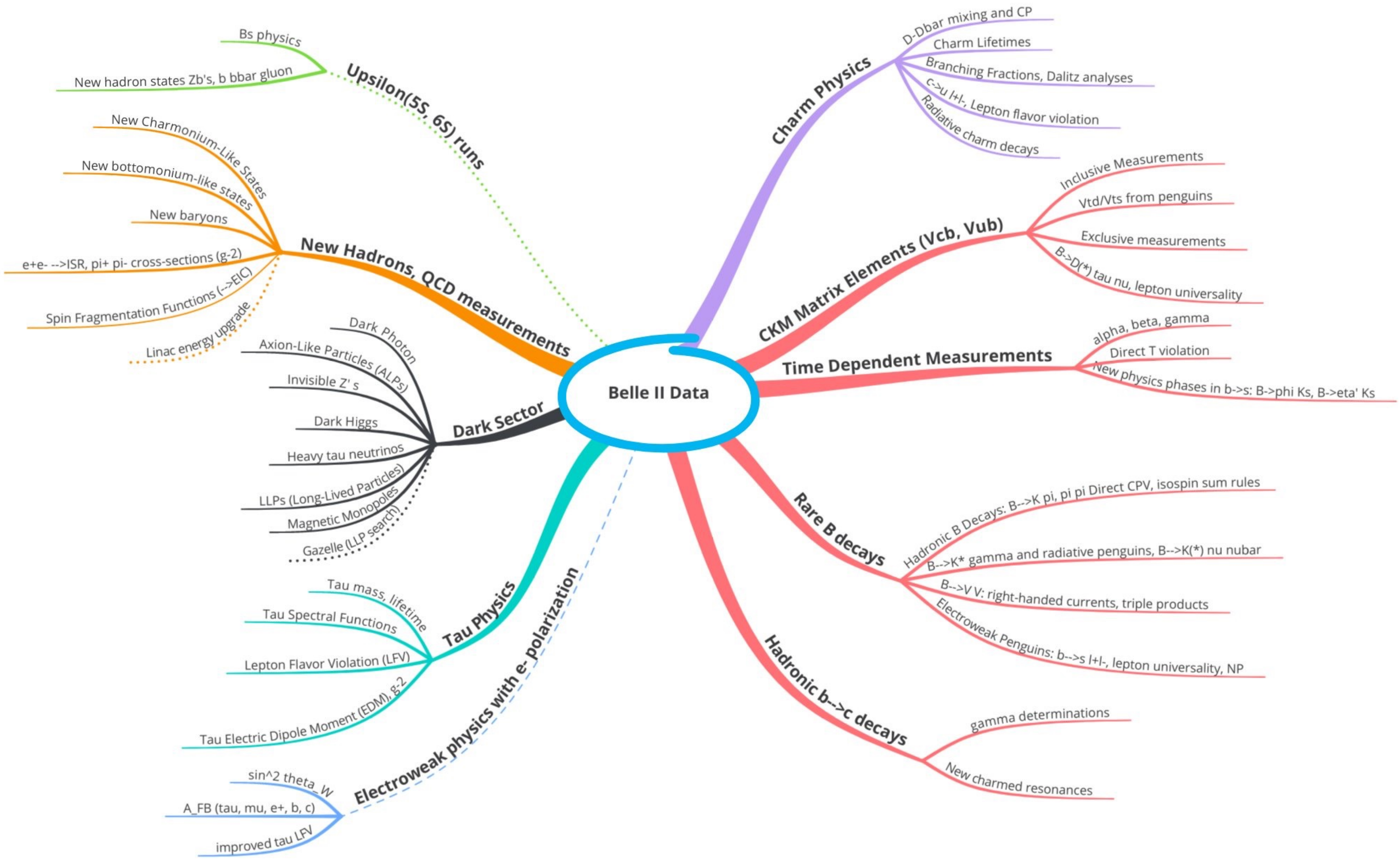
2) Indirect searches for beyond-the-SM (BSM) physics mostly in loop dominated decays

   👉 See the talk by C. Kar



Alternative notation $\beta \equiv \phi_1$, $\alpha \equiv \phi_2$, and $\gamma \equiv \phi_3$ exists

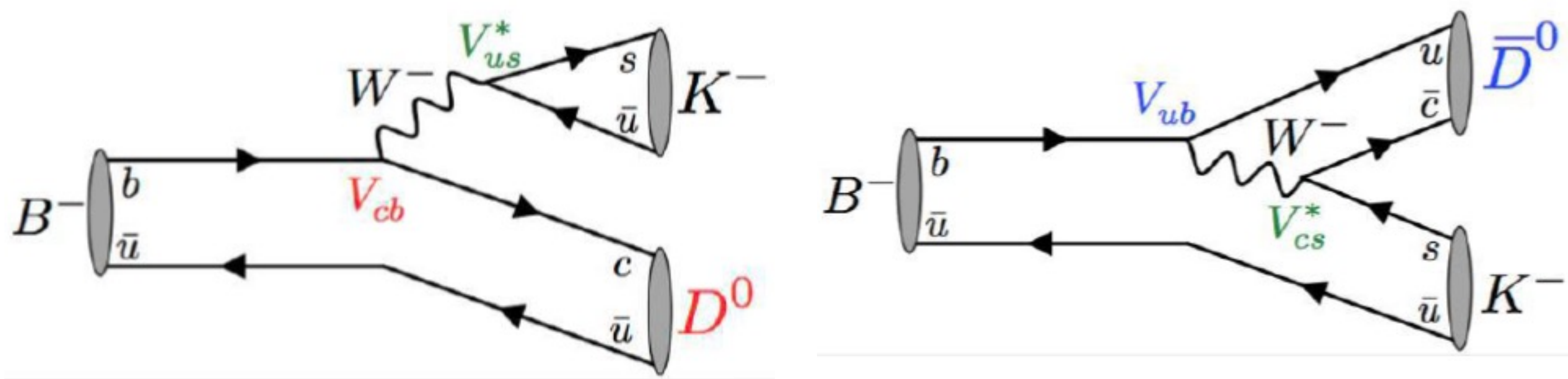
They do much more



👉 LHCb has access to all kinds of heavy hadrons: B^0, B^+, B_s^0, B_c^+, Λ_b ...

Checking an SM candle: γ/ϕ_3

- The CKM angle γ can be measured directly by exploiting the interference between tree-level $b \to c\bar{u}s$ and $b \to u\bar{c}s$ transition amplitudes involving the exchange of a single W boson
  - Theoretically clean with uncertainty $\mathcal{O}(10^{-7})$ JHEP 01 (2014) 051



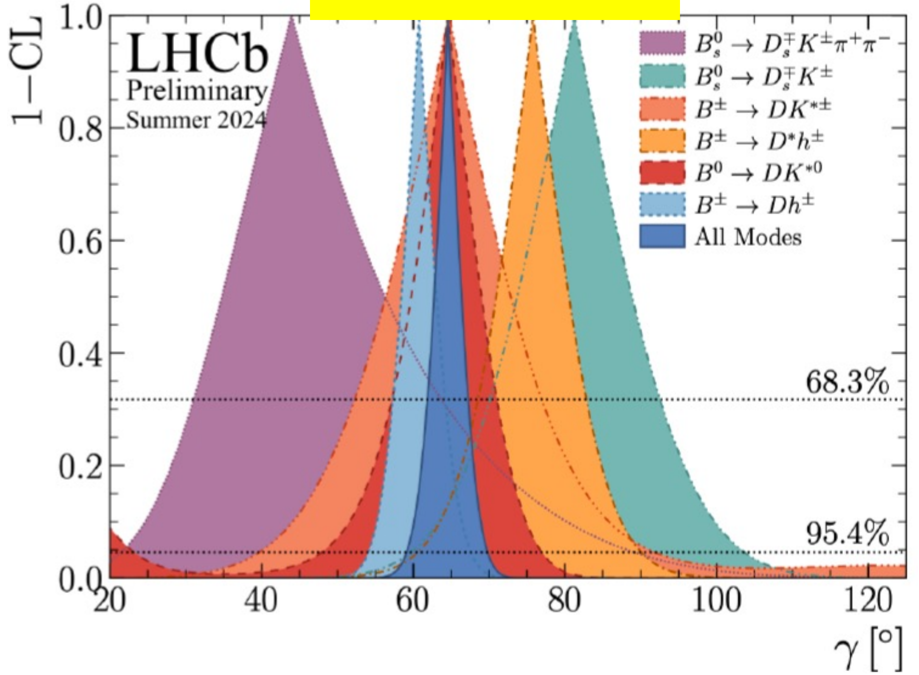
- Deviations between its direct measurements and indirect determinations from the global CKM fits would be a clear indication of BSM physics

Checking an SM candle: γ/ϕ_3

- Combination of measurements of the angle γ as well as of mixing and CP violation in the charm sector, including nine new measurements published by LHCb during 2023–2024

- In particular, combination used:
  - 19 B decay results
  - 11 D decay results
  - 4 new and few updated results
  - 198 input observables to determine 53 parameters

LHCb-CONF-2024-004



$$\gamma = (64.6 \pm 2.8)^\circ$$

👉 Most precise determination from direct measurements to date

Checking an SM candle: γ/ϕ_3

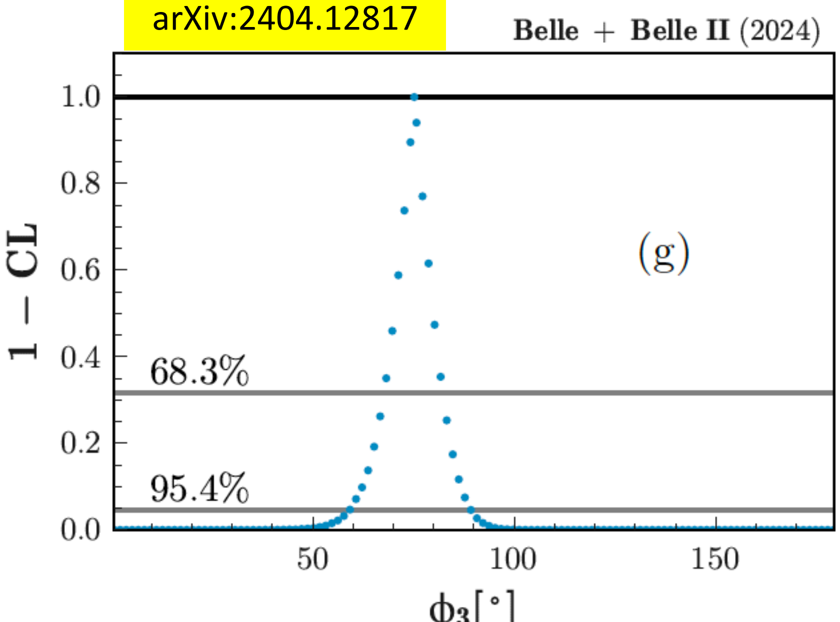
- Combine measurements based on data (771 fb^{-1}) from Belle with those based on data (up to 362 fb^{-1}) from Belle II

B decay	D decay	Method	Data set (Belle + Belle II)[fb^{-1}]
$B^+ \to Dh^+$	$D \to K_S^0\pi^0, K^-K^+$	GLW	711 + 189
$B^+ \to Dh^+$	$D \to K^+\pi^-, K^+\pi^-\pi^0$	ADS	711 + 0
$B^+ \to Dh^+$	$D \to K_S^0K^-\pi^+$	GLS	711 + 362
$B^+ \to Dh^+$	$D \to K_S^0h^-h^+$	BPGGSZ (m.i.)	711 + 128
$B^+ \to Dh^+$	$D \to K_S^0\pi^-\pi^+\pi^0$	BPGGSZ (m.i.)	711 + 0
$B^+ \to D^*K^+$	$D^* \to D\pi^0, D \to K_S^0\pi^0, K_S^0\phi, K_S^0\omega, K^-K^+, \pi^-\pi^+$	GLW	210+0
$B^+ \to D^*K^+$	$D^* \to D\pi^0, D\gamma, D \to K_S^0\pi^-\pi^+$	BPGGSZ (m.d.)	605 + 0

- 4 methods: GLW (CP eigenstates), ADS (doubly Cabibbo suppressed modes), GLS (Cabibbo suppressed modes), and BPGGSZ aka Dalitz

$$\phi_3 = (75.2 \pm 7.6)^\circ$$

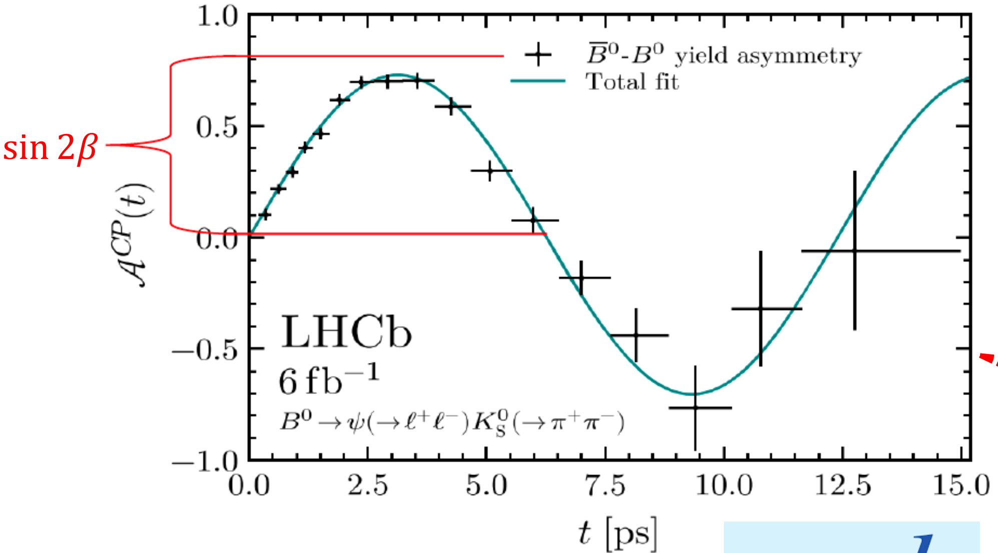
arXiv:2404.12817

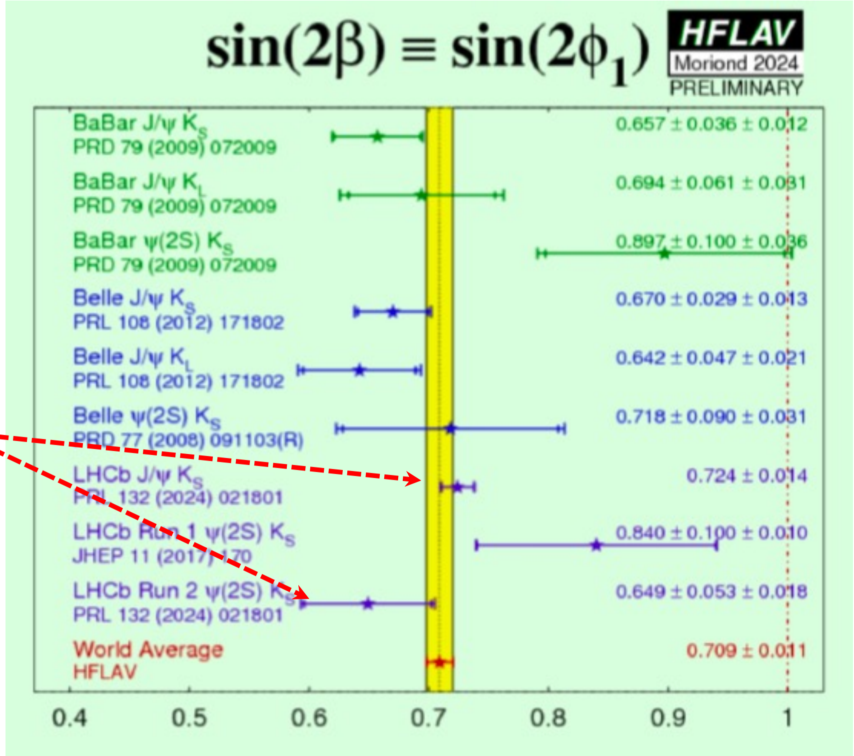


Improved determination of $\sin 2\beta$

- Flagship measurements from first-generation e^+e^- flavor factories (Belle and BaBar) confirmed the Kobayashi-Maskawa theory for CP violation

- LHCb performed the measurement in $B^0 \to \psi[J/\psi, \psi(2S)]K_S^0$ decays





PRL 132 (2024) 021801

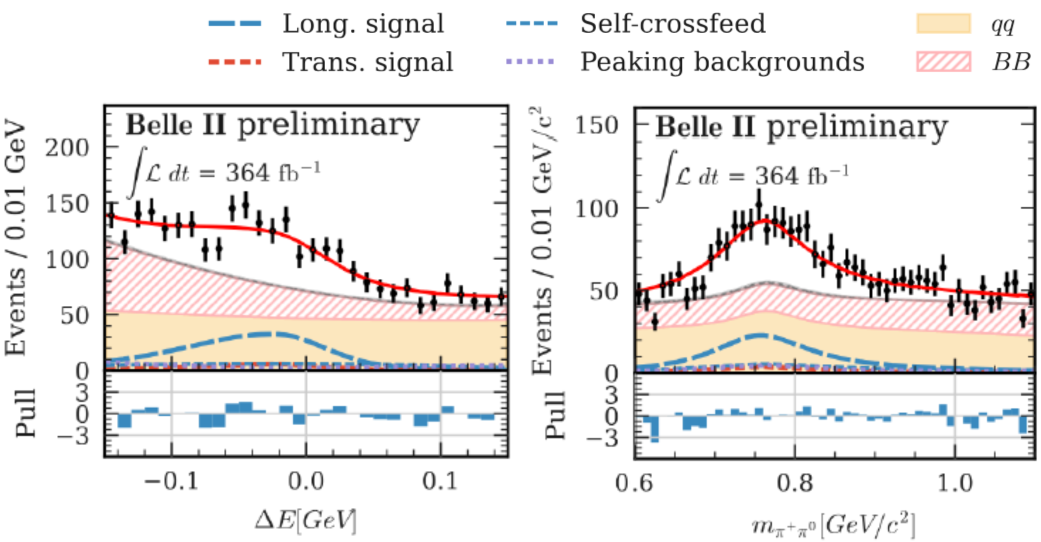
$$\sin 2\beta = 0.717 \pm 0.013(\text{stat}) \pm 0.008(\text{syst})$$

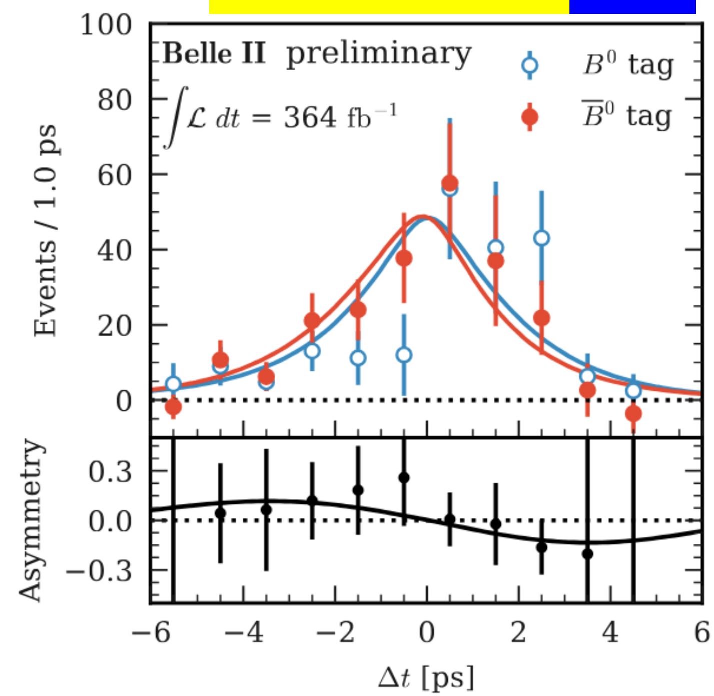
👉 Most precise single measurement of $\sin 2\beta$ to date

What about the angle ϕ_2?

- Challenging measurement of $B^0 \to \rho^+\rho^-$
  - ➢ P → VV decay (requires angular analysis)
  - ➢ Two soft neutral pions from ρ mesons
  - ➢ Large continuum and $B\bar{B}$ backgrounds

Paper in preparation





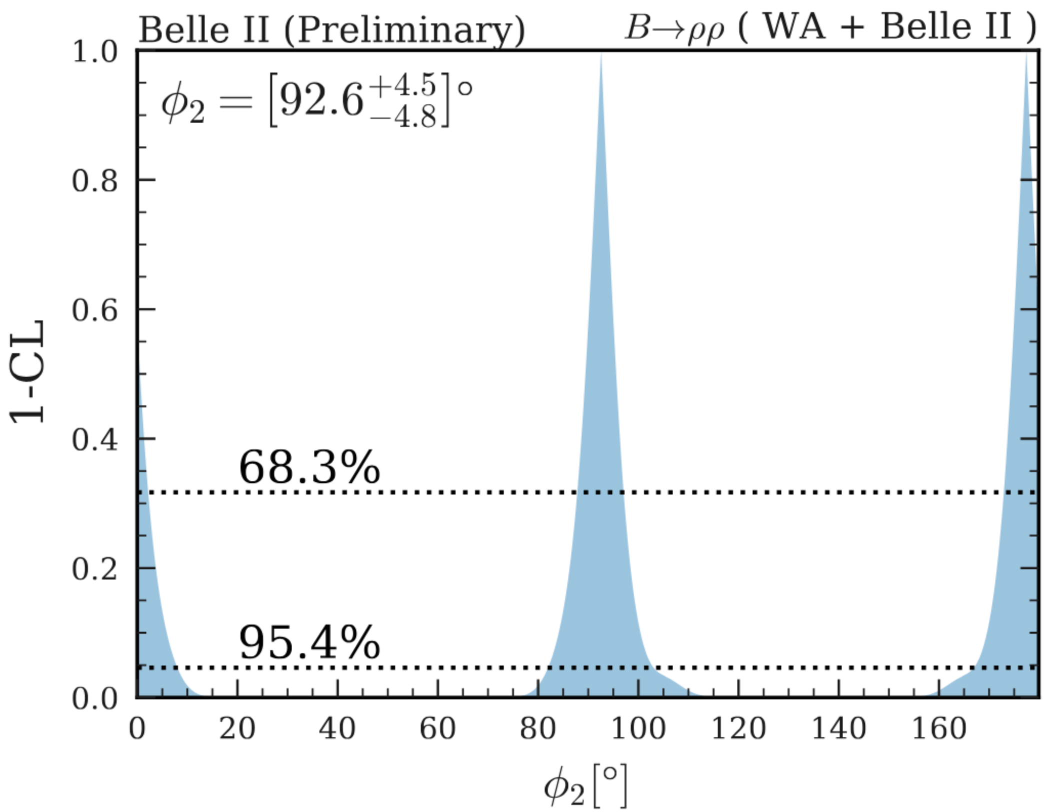
Experiment	$\mathcal{S}$	$\mathcal{C}$	$N_{B\bar{B}}$
Belle II	$-0.26 \pm 0.19 \pm 0.08$	$-0.02 \pm 0.12^{+0.06}_{-0.05}$	388×10^6
Belle	$-0.13 \pm 0.15 \pm 0.05$	$0.00 \pm 0.10 \pm 0.06$	772×10^6
BABAR	$-0.17 \pm 0.20^{+0.05}_{-0.06}$	$0.01 \pm 0.15 \pm 0.06$	384×10^6

👉 Agree with previous e^+e^- experiments (will be difficult for LHCb)

What about the angle ϕ_2?

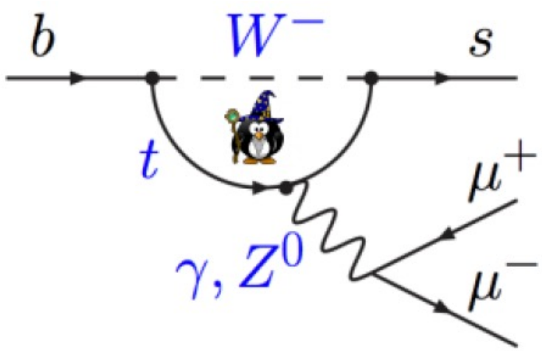
- Inclusion of the Belle II $B^0 \rightarrow \rho^+\rho^-$ result yields 6% improvement in the world average

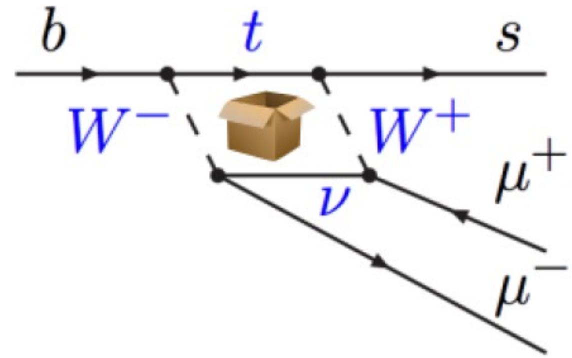
$$\phi_2 = \left(92.6^{+4.5}_{-4.8}\right)^\circ$$



From CKM angles to anomalies

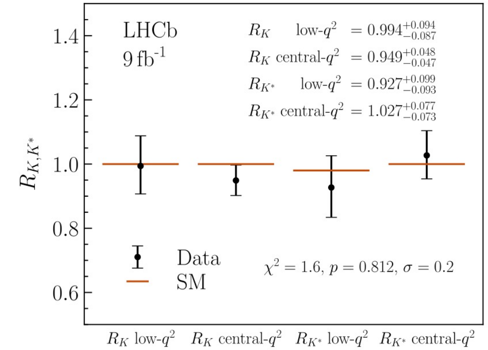
- Two types: first one in decays mediated by the flavor-changing neutral current $b \to s\ell^+\ell^-$ transition





- Tensions of 2-3 standard deviations (σ) in branching fractions and angular distributions $\Rightarrow$ remember the famous p_5'
  - ➢ Potential long-distance contributions weaken these tensions

- Lepton flavor universality (LFU) violation in the $R(K^*, K)$ ratios died off around 2022 Christmas
  - ➢ Details in PRD 108 (2022) 032002

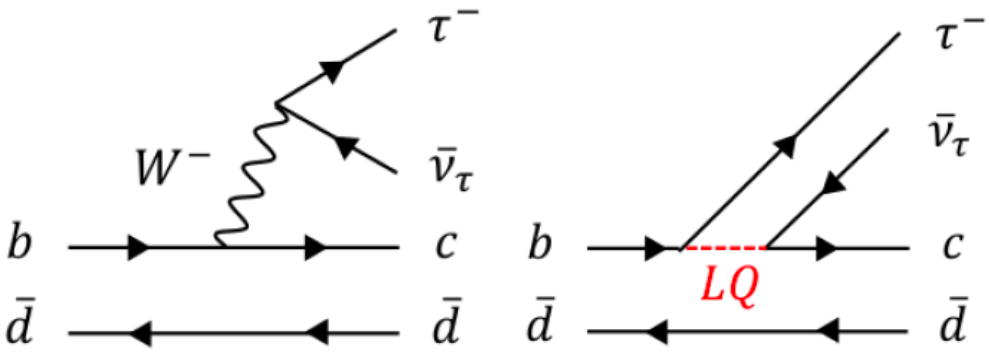


There is another one →

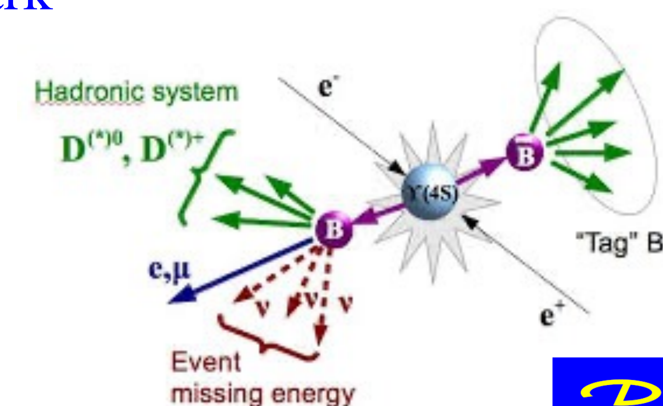
R(D^(*)): subject of great interest

- Measure the LFU ratio:

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



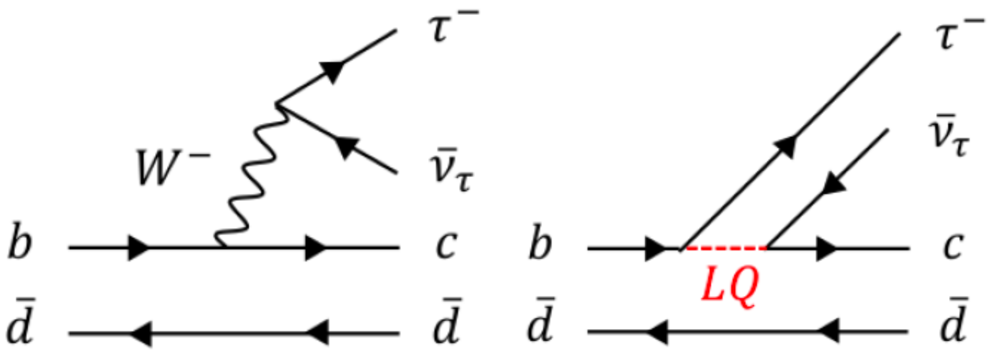
- Sensitive to BSM contribution, e.g., leptoquark
- First $R(D^*)$ Belle II result (189 fb^{-1}) based on the hadronic B tagging method



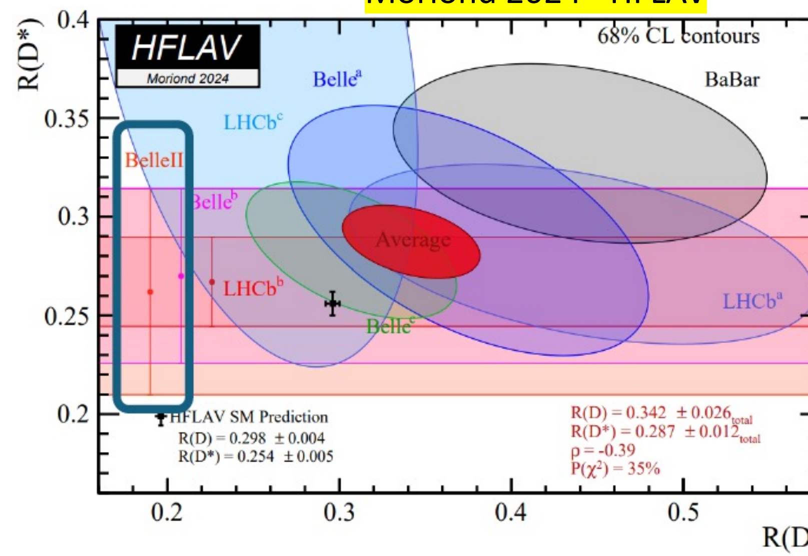
R(D$^{(*)}$): subject of great interest

- Measure the LFU ratio:

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



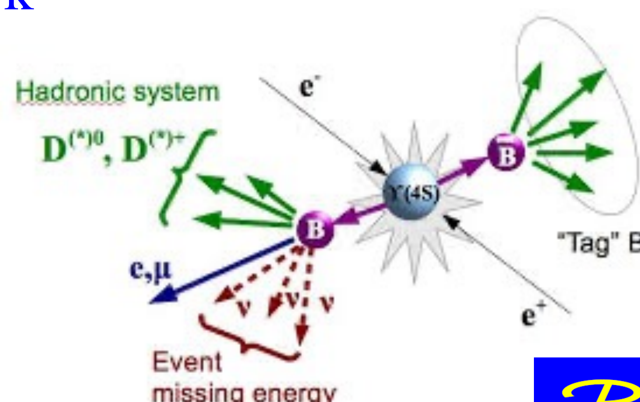
Moriond 2024 - HFLAV



- Sensitive to BSM contribution, e.g., leptoquark
- First $R(D^*)$ Belle II result (189 fb^{-1}) based on the hadronic B tagging method

arXiv:2401.02840

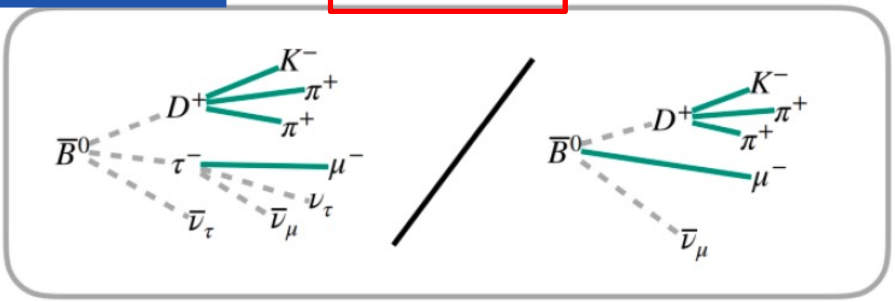
$$R(D^*) = 0.262\ ^{+0.041}_{-0.039}(\text{stat})\ ^{+0.035}_{-0.032}(\text{syst})$$

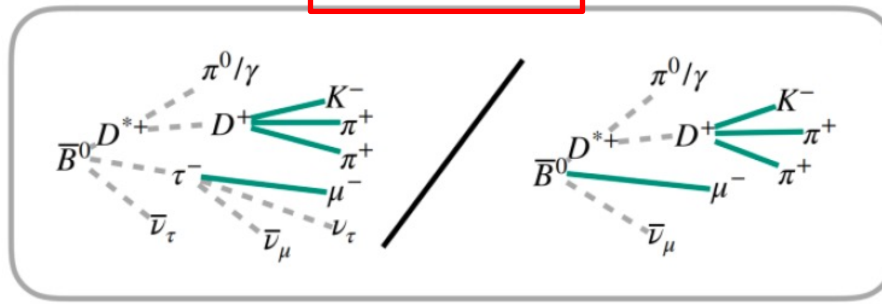


- Control sample statistics is the main source of systematic uncertainty
  - 👉 Comparable statistical precision as Belle with only ¼ the data due to the use of a new B tagging algorithm and an optimized selection

What does LHCb say?

$R(D^+)$ | $R(D^{*+})$



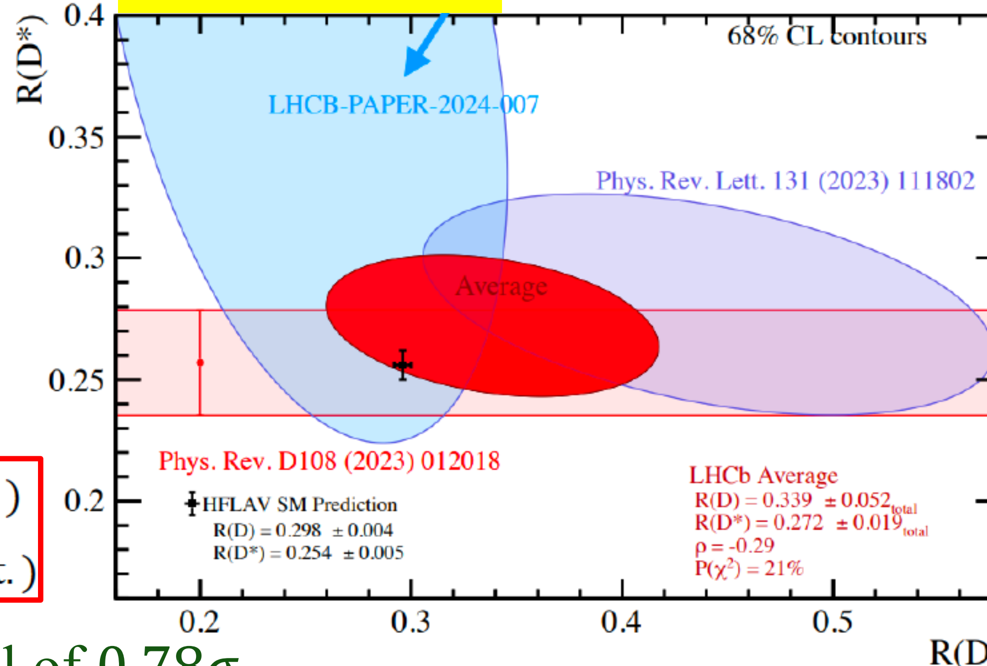


- At one point, I was bit unsure if LHCb could really do this measurement involving multiple neutrinos...
- Reconstruct the final state in all cases by combining $D^+ \to K^-\pi^+\pi^+$ with $\tau^- \to \mu^-\bar{\nu}_\mu\nu_\tau$
- Fit to four-momentum transfer squared, muon energy in B rest frame & missing mass squared

$R(D^+) = 0.249 \pm 0.043\,(\text{stat.}) \pm 0.047\,(\text{syst.})$

$R(D^{*+}) = 0.402 \pm 0.081\,(\text{stat.}) \pm 0.085\,(\text{syst.})$

LHCB-PAPER-2024-007



👉 Compatible with SM at the level of 0.78σ

A related observable: $R(X)$

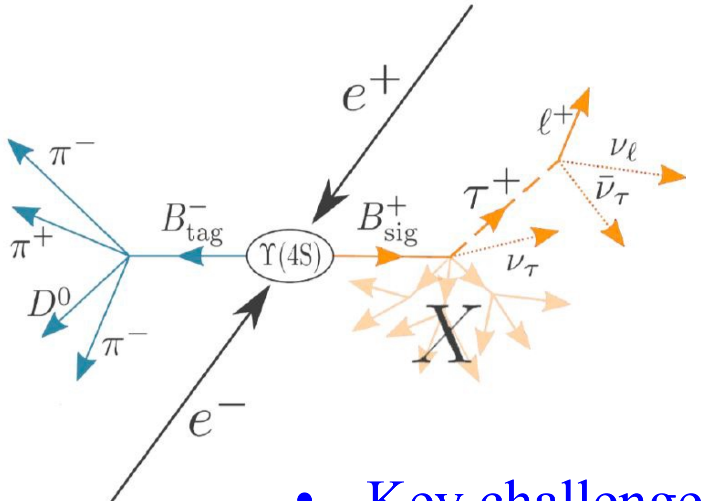
- Using Run 1 data (189 fb^{-1}) Belle II measured the inclusive LFU ratio:

$$R(H_{\tau/l}) = \frac{\mathcal{B}(B \to H\tau\nu_\tau)}{\mathcal{B}(B \to Hl\nu_l)}$$

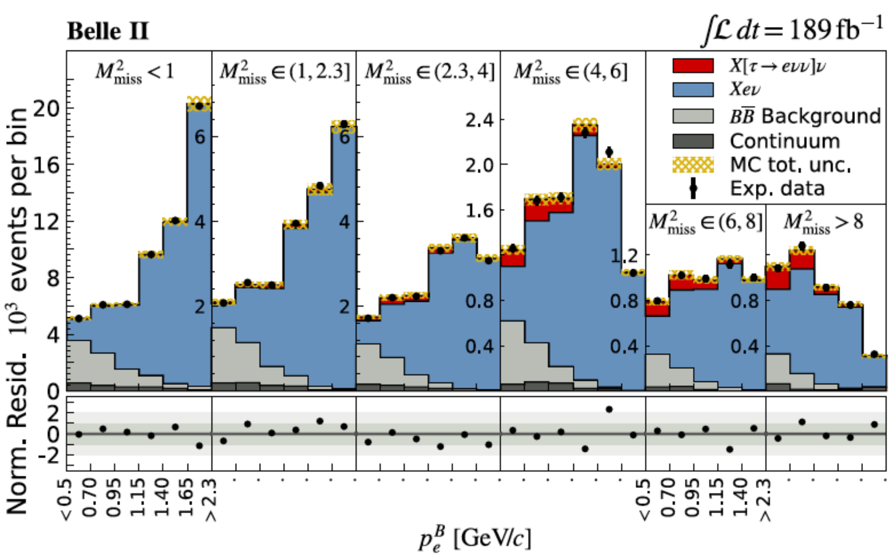
Where $H = D, D^*, X, \pi, etc.$ and $l = e, \mu$

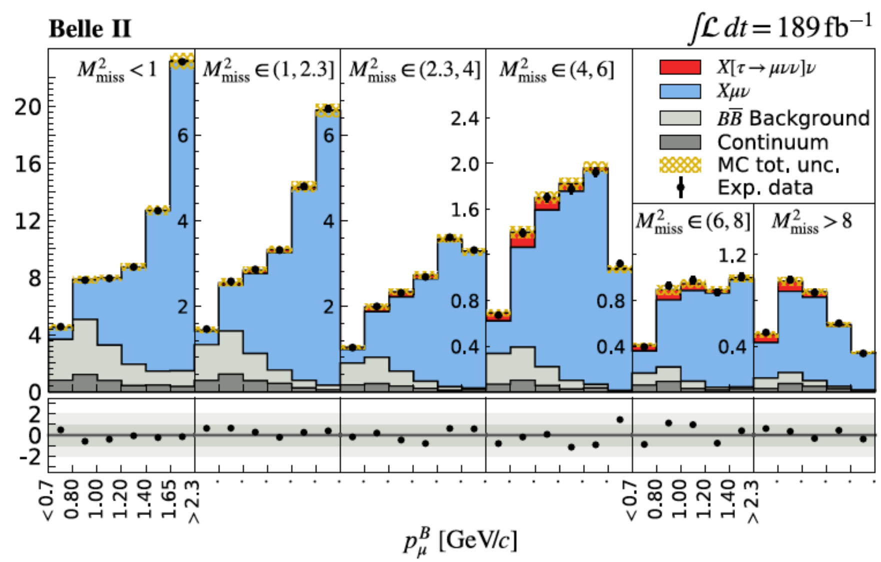
"Traditional" modes
Tension of $R(D^{(*)})$ with SM ~3σ

New



- Exploit the hadronic tagging method
- Use missing mass squared and $B_{\rm sig}$ momentum to extract the signal
- Key challenge: accurate modeling of backgrounds
  - ➢ Their templates calibrated with control samples and sidebands





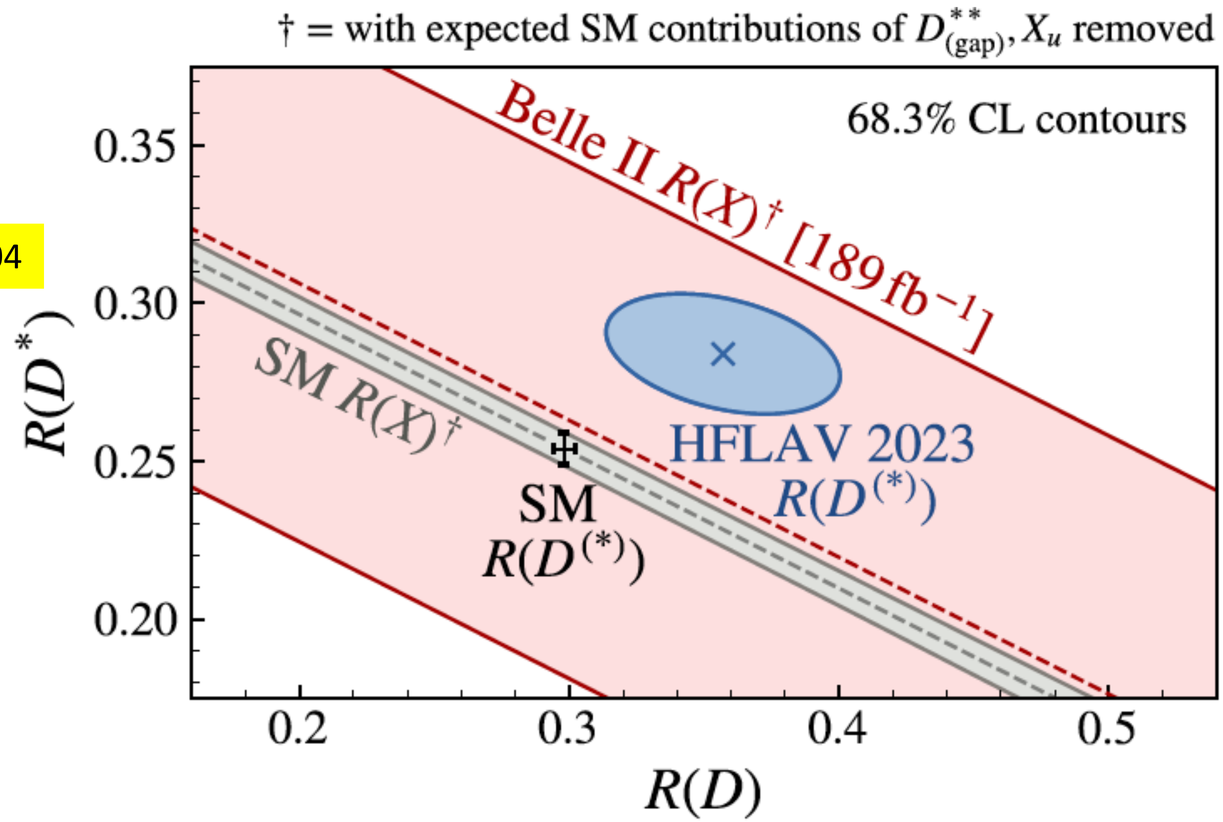
A related observable: $R(X)$

Combined

$$R(X_{\tau/\ell}) = 0.228 \pm 0.016(\text{stat}) \pm 0.036(\text{syst})$$

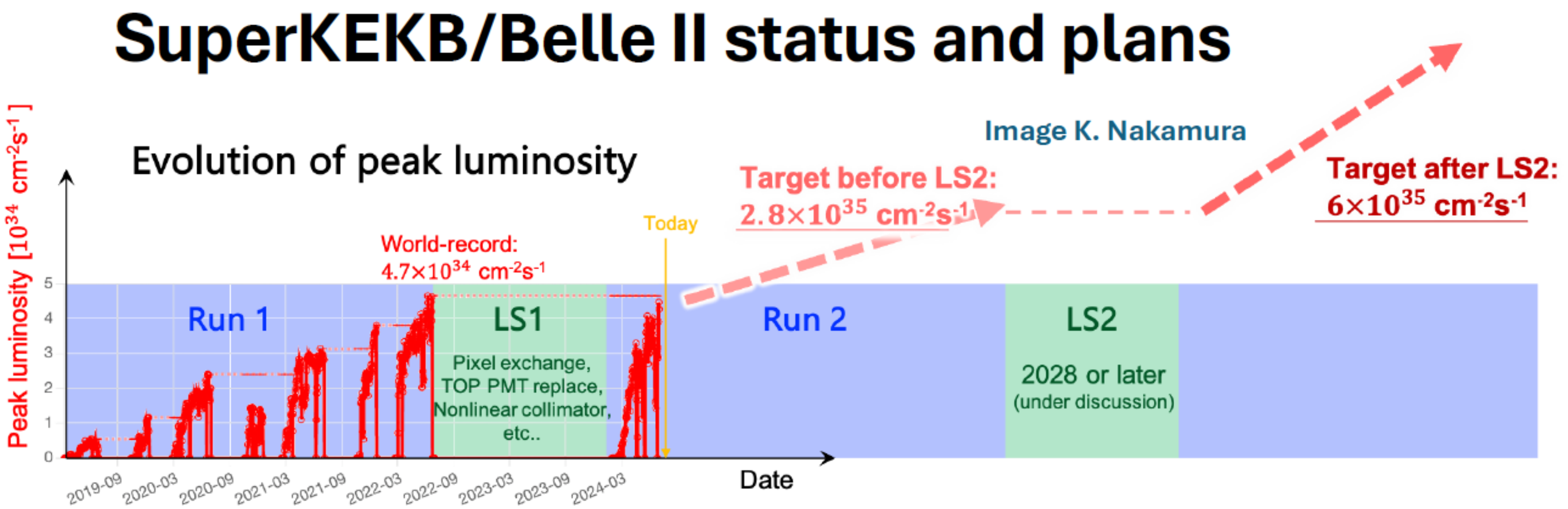
- Result agrees with the prediction $R(X)_{\text{SM}} = 0.223 \pm 0.005$ JHEP 11 (2022) 007

PRL 132 (2024) 211804



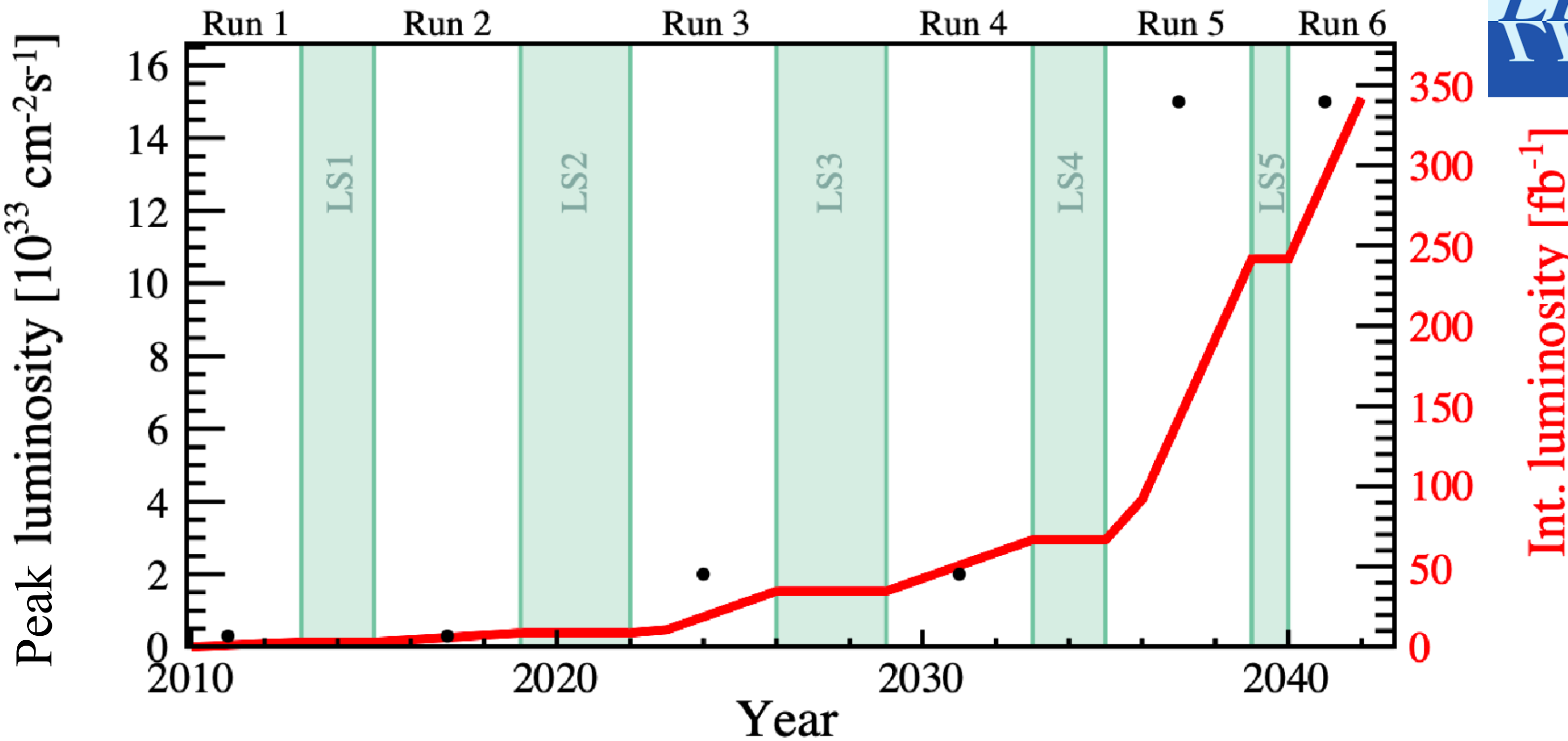
👉 Above plot tells us that the result is also consistent with world averages of $R(D^{(*)})$

What future holds for Belle II?



- Run 2 is expected to be long (may be end 2028 or later)
  - ➢ Steady integration at a peak luminosity of $\sim 2\times10^{35}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ for several ab^{-1} data
  - ➢ After Run 2, go for upgrade to reach the design luminosity ($6\times10^{35}\mathrm{cm}^{-2}\mathrm{s}^{-1}$) and accumulate tens of ab^{-1}

What about LHCb upgrade?



- Phase-I upgrade during LS2 for Run 3+4
  - Full software trigger and read out all detectors at 40 MHz
  - Replace vertex and tracking detectors as well as PID system; consolidate PID, tracking and ECAL during LS3
  - Target for $\mathcal{L}_{\rm peak} \sim 2\times10^{33}{\rm cm}^{-2}{\rm s}^{-1}$ and $\mathcal{L}_{\rm int} > 50\ {\rm fb}^{-1}$ by end of Run 4
- Phase-II upgrade during LS4 beyond Run 4 (for 300 $\rm fb^{-1}$)
  - New detector technologies and timing towards $\mathcal{L}_{\rm peak} \sim 1.5\times10^{34}{\rm cm}^{-2}{\rm s}^{-1}$

Summary

- ❑ Focus on some of the recent analyses from Belle II and LHCb related to the Unitarity Triangle and LFU test
- ❑ Number of interesting studies that I have been unable to cover in this talk can be accessed from the Belle II and LHCb publication pages:
  - https://www.belle2.org/research/physics/publications
  - https://lbfence.cern.ch/alcm/public/analysis
- ❑ Much more to come from these flavor frontier experiments

➢ Stay tuned …