Latest results on rare *B* decays from Belle II and LHCb

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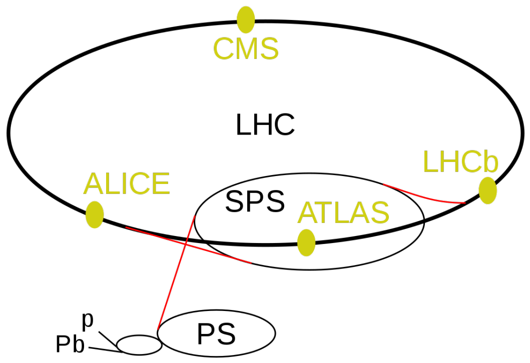
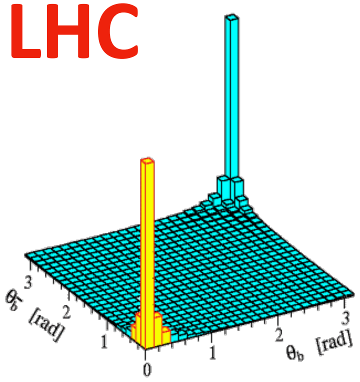
INFN Bologna and CERN

Vulcano Workshop 2024
Frontier Objects in Astrophysics and Particle Physics

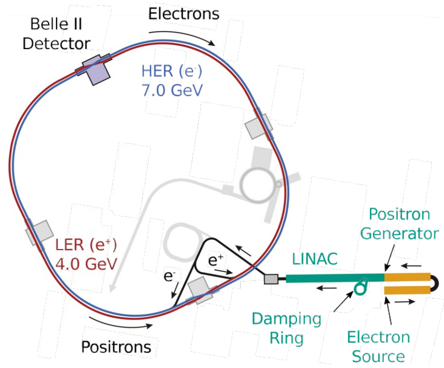
Two very different accelerators

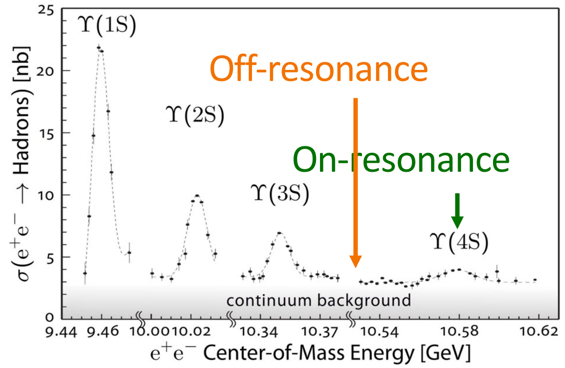


LHC



SuperKEKB



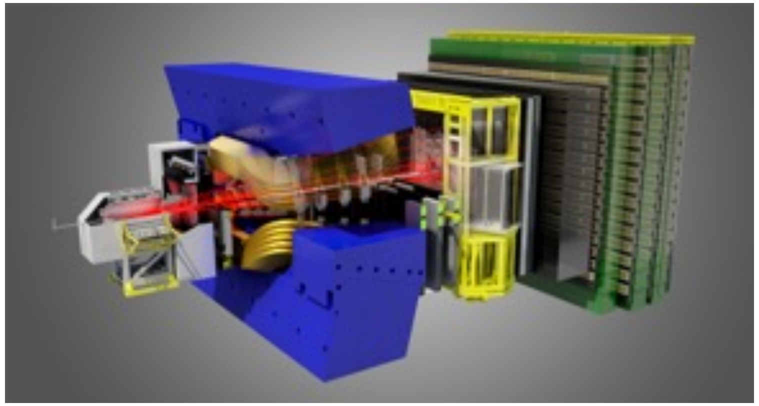


- pp collisions at 13 TeV
- b-quarks produced by gluon fusion
- Highly boosted topology
- σ_{bb} = 100 μb

- e^+e^- energy-asymmetric collisions at 10.58 GeV
- $B\bar{B}$ produced via Υ(4S)
- Asymmetric beam energy to boost to B mesons
- σ_{bb} = 1.1 nb

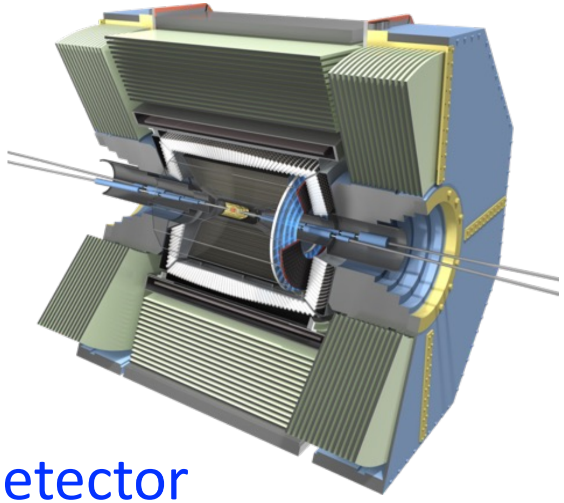
Two very different experiments with same goal

LHCb



- Forward spectrometer
- Taking data since 2010, collecting ~10 fb^{-1} so far
  - 4×10^{12} $b\bar{b}$ pairs
  - B_u (40%), B_d(40%), B_s(10%), B_c and b-baryons (10%)

Belle II

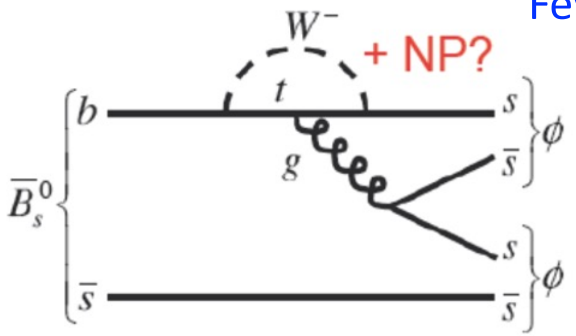


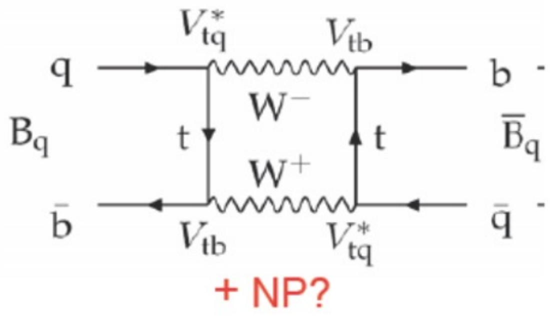
- 4π detector
- Taking data since 2019, collecting ~360 fb^{-1} in Run 1
  - 370 million $B\bar{B}$ pairs
- Resumed data-taking this year after ~1.5y long shut-down

Roughly 1 fb^{-1} LHCb = 1000 fb^{-1} Belle II

"Indirect" searches for New Physics

Feynman diagrams with closed loops within: new-physics virtual particles can circulate





$$A = A_0 \left[c_{SM} \frac{1}{M_W{}^2} + c_{NP} \frac{1}{\Lambda^2} \right]$$

- General decomposition of a transition amplitude in terms of couplings and scales
- New-physics virtual particles of arbitrarily large mass can enter loops in Feynman diagrams and produce observable effects → the existence of particles with much larger masses than the energy made available by the LHC could be unveiled

Why studying rare decays?

- Decays characterised by tiny branching fractions in the SM are excellent laboratories to look for new-physics effects

$$A = A_0 \left[c_{SM} \frac{1}{M_W{}^2} + c_{NP} \frac{1}{\Lambda^2} \right]$$

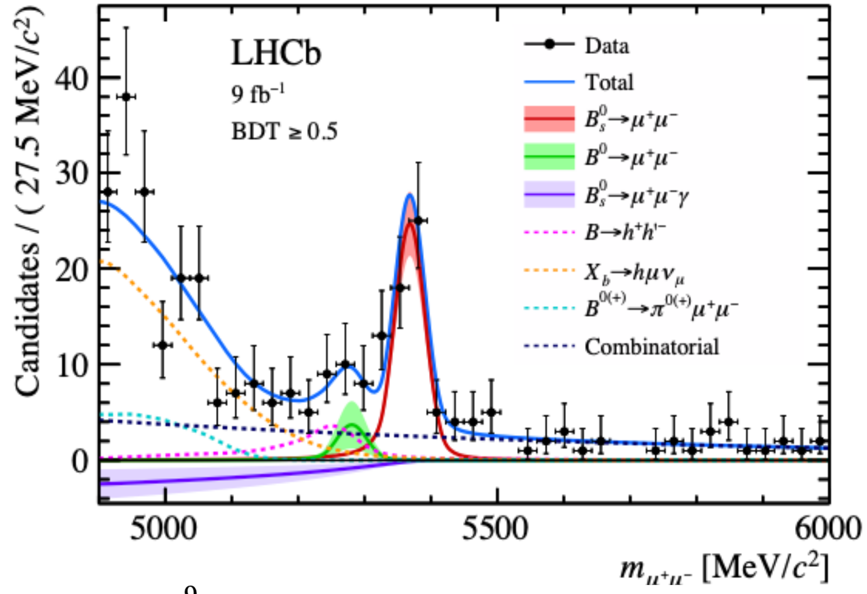
- In particular, flavour-changing neutral-current (FCNC) processes cannot proceed at tree level in the SM, hence higher order diagrams are needed → strong suppression
  - And further suppressions may arise from additional dynamical mechanisms

Classics: measurement of $B \to \mu^+\mu^-$ decays

- Highly suppressed in the SM
  - FCNC- and helicity-suppressed, proceed via Z penguin and W box → precise SM prediction

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (3.66 \pm 0.14) \times 10^{-9}$$
$$\mathcal{B}(B^0 \to \mu^+\mu^-) = (1.03 \pm 0.05) \times 10^{-10}$$

JHEP 10 (2019) 232

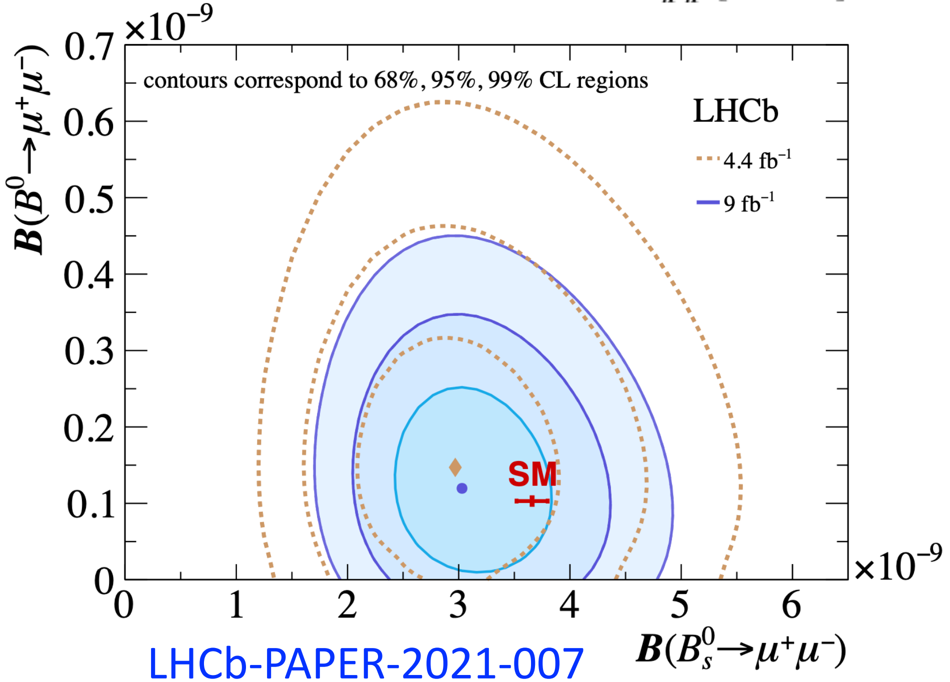


- Latest results

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (3.09\,^{+0.46}_{-0.43}\,^{+0.15}_{-0.11}) \times 10^{-9}$$
$$\mathcal{B}(B^0 \to \mu^+\mu^-) < 2.6 \times 10^{-1} \text{at } 95\% \text{ CL}$$

Sensitivity approaching SM uncertainty

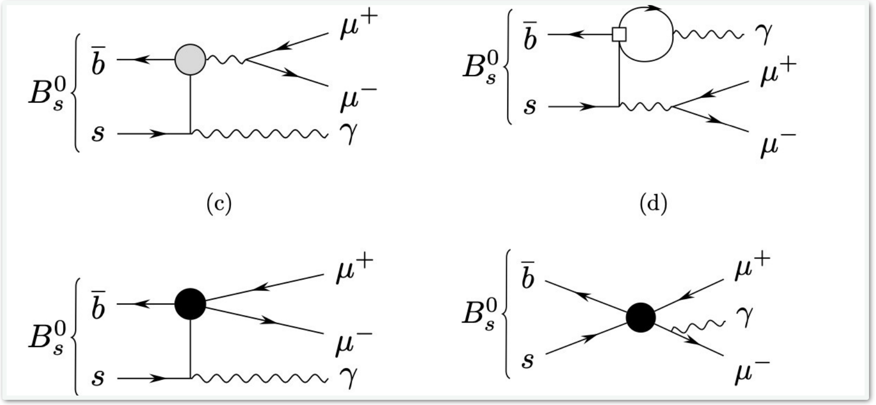
- Great prospects with Run-3 data!



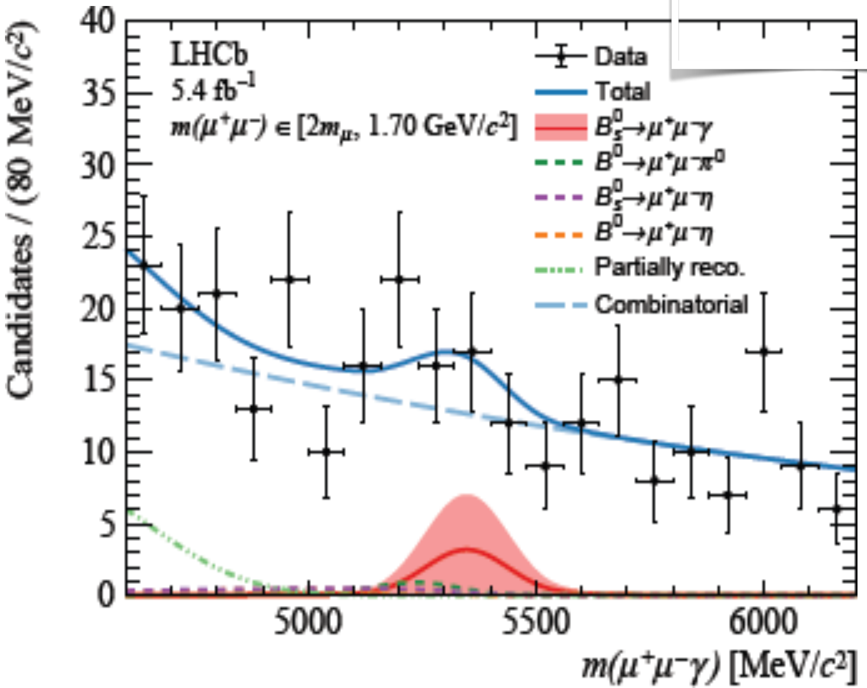
LHCb-PAPER-2021-007

Search for the $B_s^0 \to \mu^+\mu^-\gamma$ decay

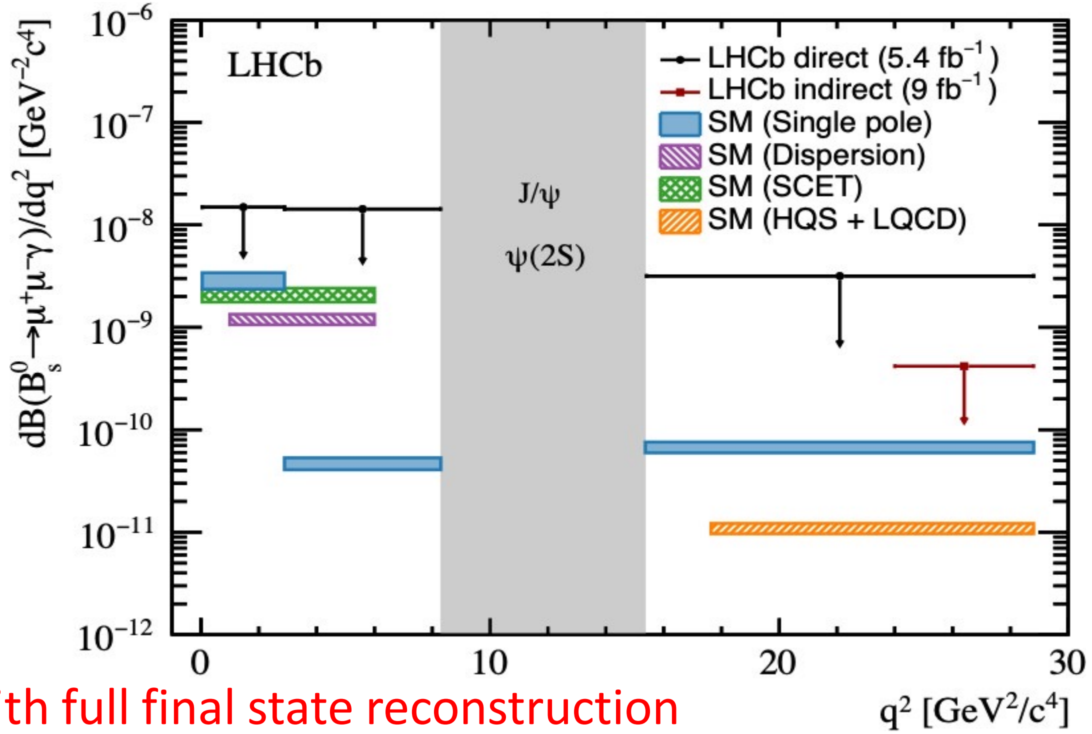
LHCb-PAPER-2023-045



Photon reconstructed in the final state.
Analysis performed in bins of q^2 using Run 2 data



- Loop suppressed $b \to s\mu^+\mu^-$ transitions are sensitive to new particles
- The photon in the final state lifts the helicity suppression



- First limits with full final state reconstruction and the first limit at low dimuon mass

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-\gamma) < 4.22 \times 10^{-8},\ m(\mu^+\mu^-) \in [m_\mu,\ 1700]\ \mathrm{MeV}/c^2,$$
$$\mathcal{B}(B_s^0 \to \mu^+\mu^-\gamma) < 7.73 \times 10^{-8},\ m(\mu^+\mu^-) \in [1700,\ 2880]\ \mathrm{MeV}/c^2,$$
$$\mathcal{B}(B_s^0 \to \mu^+\mu^-\gamma) < 4.24 \times 10^{-8},\ m(\mu^+\mu^-) \in [3920,\ m_{B_s^0}]\ \mathrm{MeV}/c^2,$$

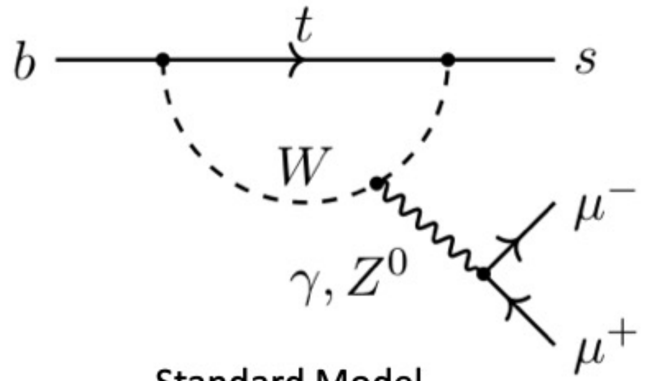
$b \to s\ell^+\ell^-$ transitions and LFU tests

- Measure ratios of decay rates to muons and electrons: LFU test
- Theoretically very clean in the SM
  - Observation of non-LFU would be a clear sign of new physics
- Mostly measured with the ratios

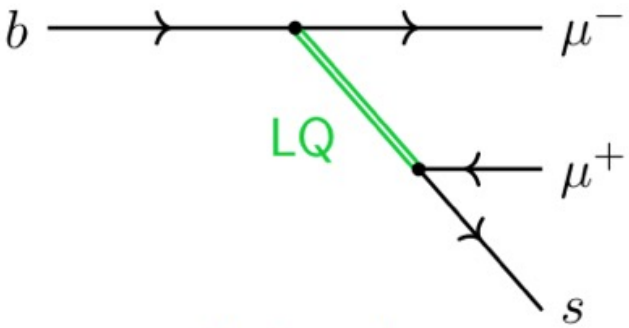
  $R_K = \mathfrak{B}(B^+ \to K^+\mu^+\mu^-)\ /\ \mathfrak{B}(B^+ \to K^+e^+e^-)$

  $R_{K^*} = \mathfrak{B}(B^0 \to K^{*0}\mu^+\mu^-)\ /\ \mathfrak{B}(B^0 \to K^{*0}e^+e^-)$
- 3σ-ish level from SM not long ago triggered wide interest in the theory community, but later reabsorbed
- Still, very interesting physics playing a central role in the quark-flavour physics programme!

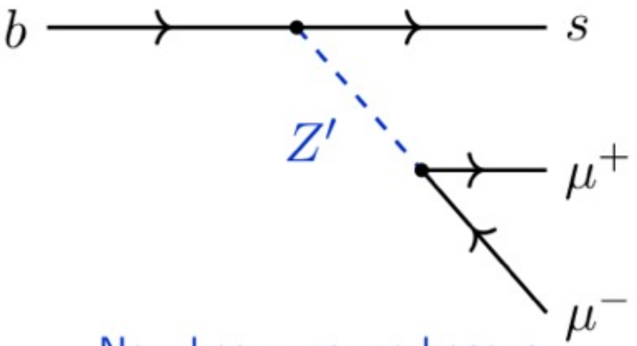
$$R_H = \frac{\int_{q^2_{\min}}^{q_{\max}} \frac{\mathrm{d}\mathcal{B}(B \to H\mu^+\mu^-)}{\mathrm{d}q^2}\,\mathrm{d}q^2}{\int_{q^2_{\min}}^{q_{\max}} \frac{\mathrm{d}\mathcal{B}(B \to He^+e^-)}{\mathrm{d}q^2}\,\mathrm{d}q^2} \overset{\text{SM}}{\cong} 1$$



Standard Model



Leptoquarks



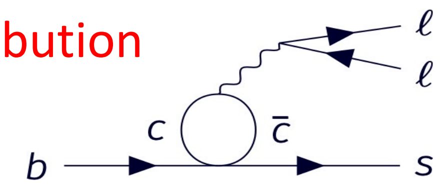
New heavy gauge bosons

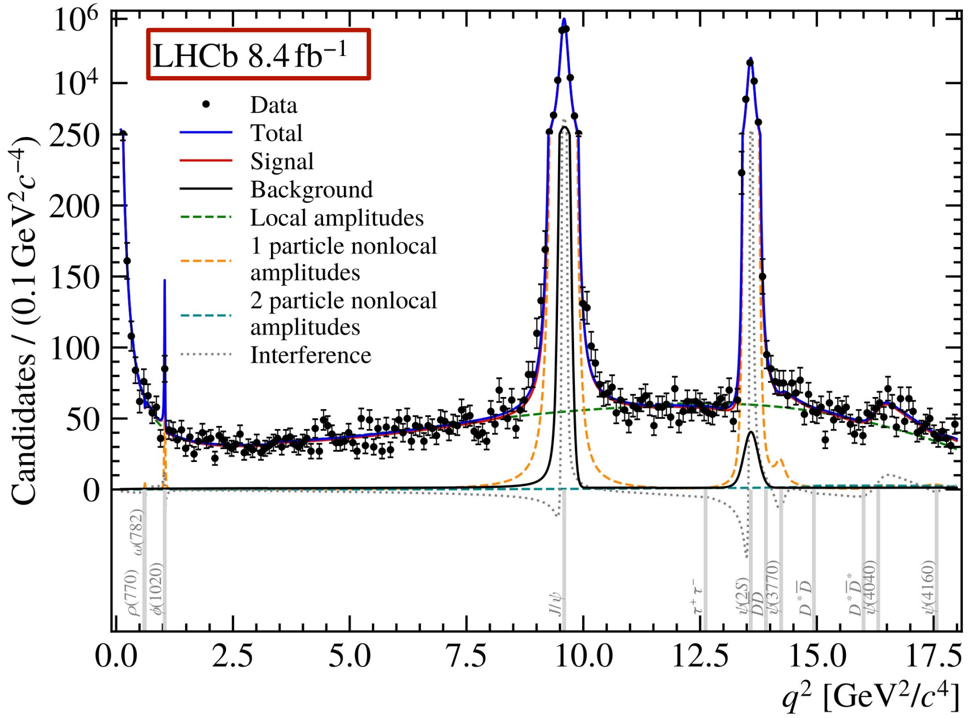
Comprehensive analysis of local and nonlocal amplitudes in the $B^0 \to K^{*0}\mu^+\mu^-$ decay

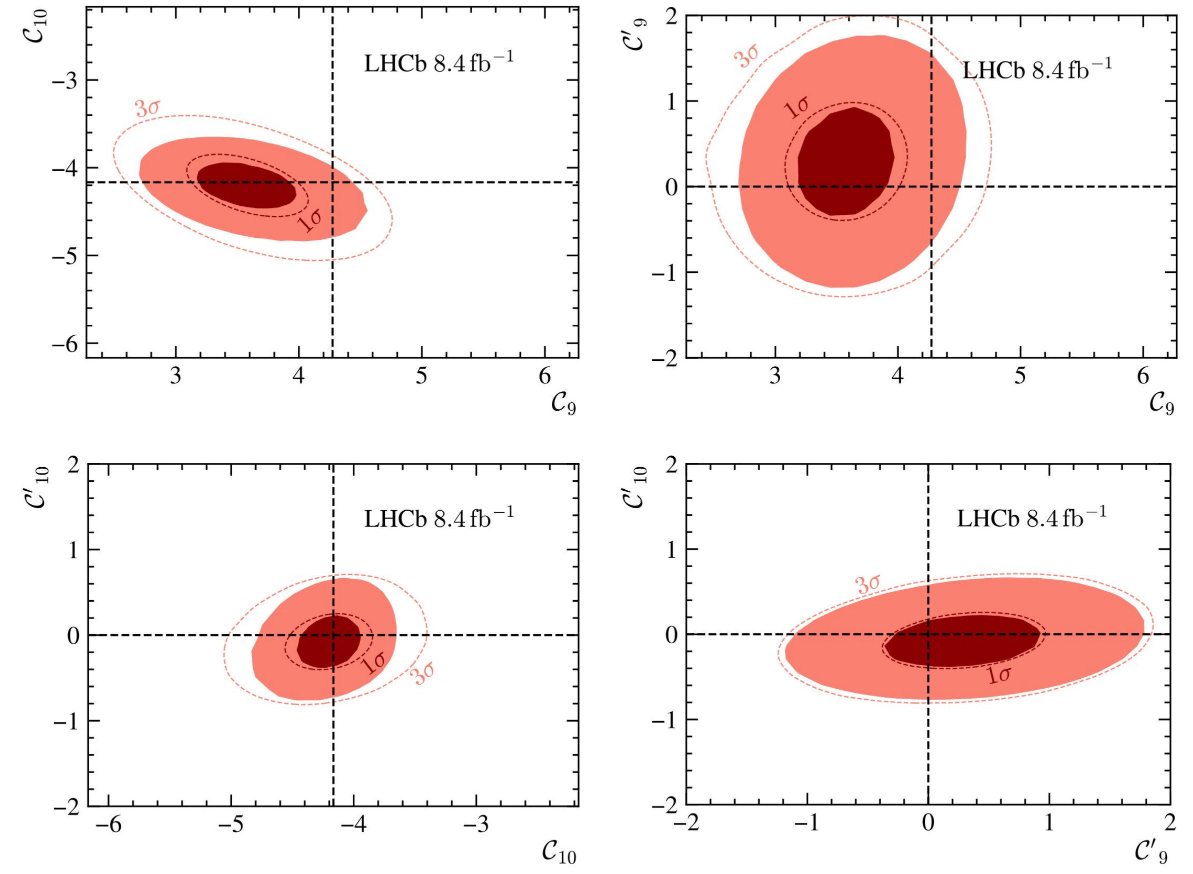
LHCb-PAPER-2024-011
arXiv:2405.17347

$$\mathcal{H}_{\rm WET} = \frac{-4G_F}{\sqrt{2}} V_{ts}^* V_{tb} \sum_i \mathcal{C}_i^{(\prime)}(\mu)\mathcal{O}_i^{(\prime)}(\mu),$$

- Fit model that combines the local and nonlocal amplitudes across the full q^2 spectrum
- Model includes all known vector resonances and two-particle contribution from $D^{(*)}\bar{D}^{(*)}$ and $\tau^+\tau^-$ loops





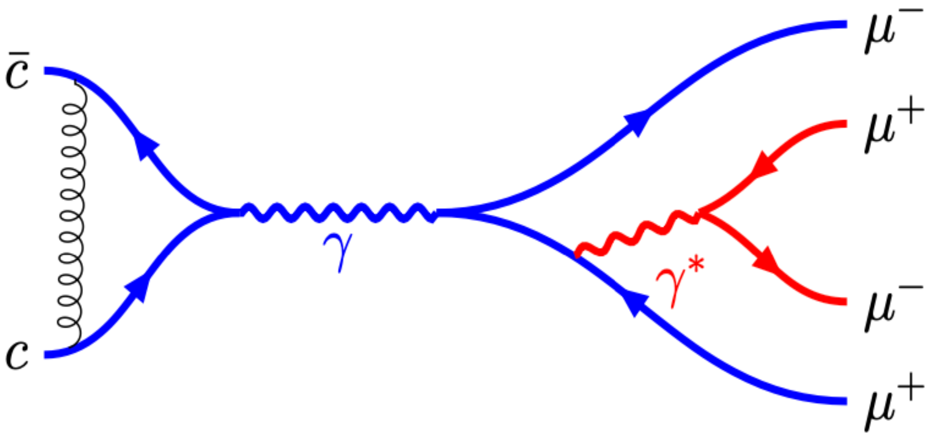


There is a preference for a value of C_9 shifted from the SM expectation; no deviation in C_{10}

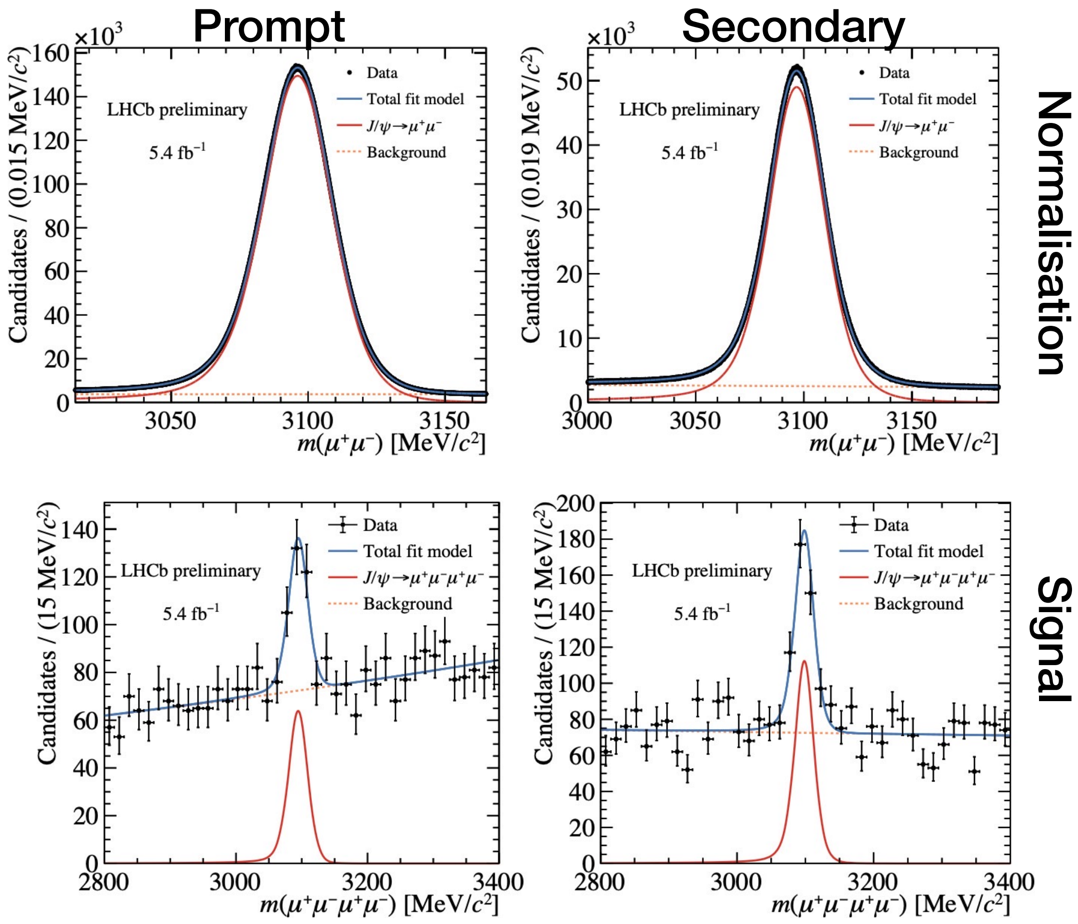
Observation of the rare decay $J/\psi \to \mu^+\mu^-\mu^+\mu^-$

LHCb-CONF-2024-001

- Decay dominantly through final-state radiation of a virtual photon



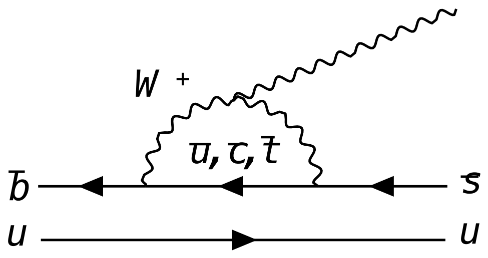
- Limit from BES III, measurement from CMS with handful of signal events
- Most precise measurement by LHCb with hundreds of signals



$$\mathcal{B}(J/\psi \to \mu^+\mu^-\mu^+\mu^-) = (1.13 \pm 0.10 \pm 0.05 \pm 0.01) \times 10^{-6},$$

$B \to K^*\gamma$

FCNC $b \to s\gamma$ transition



- First radiative penguin to be measured at Belle II
- Branching fractions $\mathcal{B}$ have large theoretical uncertainties (~20%)
- CP (A_{CP}) and isospin (Δ_{+0}) asymmetries theoretically clean (cancellation of form factors)

$$A_{CP} = \frac{\Gamma(\bar{B} \to \overline{K^*}\gamma) - \Gamma(B \to K^*\gamma)}{\Gamma(\bar{B} \to \overline{K^*}\gamma) + \Gamma(B \to K^*\gamma)}$$

SM prediction: A_{CP} is small (~1%)

$$\Delta A_{CP} = A_{CP}(B^0 \to K^{*0}\gamma) + A_{CP}(B^+ \to K^{*+}\gamma)$$

$$\Delta_{+0} = \frac{\Gamma(B^0 \to K^{*0}\gamma) - (B^+ \to K^{*+}\gamma)}{\Gamma(B^0 \to K^{*0}\gamma) + (B^+ \to K^{*+}\gamma)}$$

SM prediction: $\Delta_{+,0}$ range from 2-8% with an uncertainty ~2%

$B \to K^*\gamma$

Branching fractions

$\mathcal{B}[B^0 \to K^{*0}\gamma] = (4.16 \pm 0.10 \pm 0.11) \times 10^{-5}$

$\mathcal{B}[B^+ \to K^{*+}\gamma] = (4.04 \pm 0.13 \pm 0.13) \times 10^{-5}$

$\mathcal{B}[B \to K^*\gamma] = (4.12 \pm 0.08 \pm 0.11) \times 10^{-5}$

A_{CP}

$A_{CP}[B^0 \to K^{*0}\gamma] = (-3.2 \pm 2.4 \pm 0.4)\,\%$

$A_{CP}[B^+ \to K^{*+}\gamma] = (-1.0 \pm 3.0 \pm 0.6)\,\%$

$A_{CP}[B \to K^*\gamma] = (-2.3 \pm 1.9 \pm 0.3)\,\%$

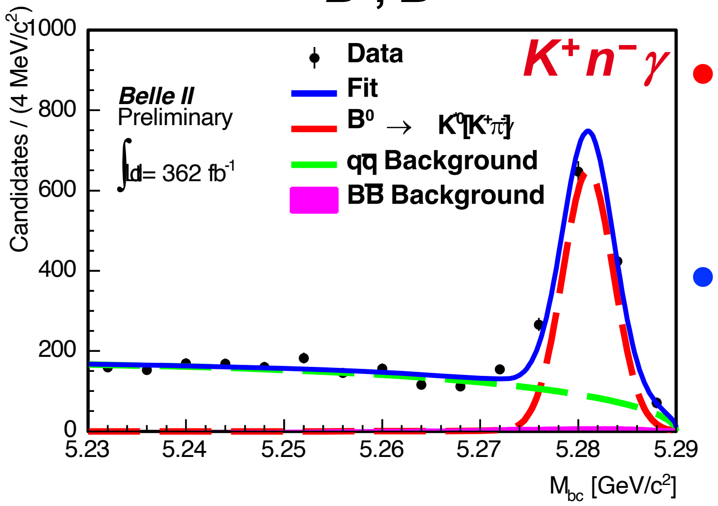
Asymmetries

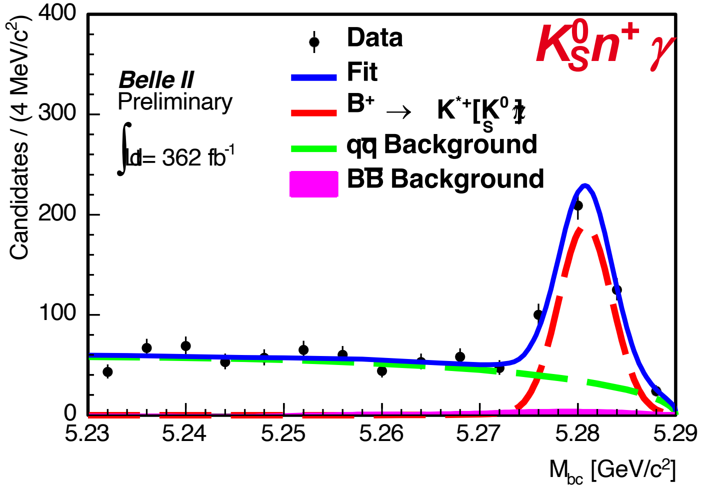
$\Delta A_{CP} = (2.2 \pm 3.8 \pm 0.7)\,\%$

$\Delta_{+0} = (5.1 \pm 2.0 \pm 1.0 \pm 1.1)\,\%$ ($f^{\pm}/f^{00}$)

Fit projections to M_{bc}

B^0, B^+



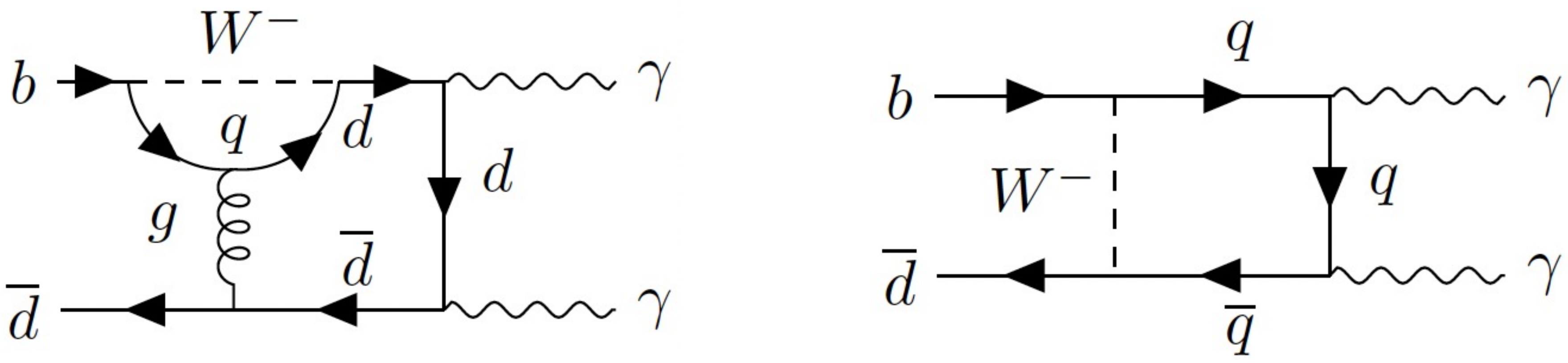


- Consistent with previous measurements and SM
- Similar sensitivity to Belle due to improved K_s efficiency and ΔE resolution

$B^0 \to \gamma\gamma$

FCNC $b \to d\gamma$ transition

Theoretically the $\mathcal{B}$ of this decay mode is expected to be $(1.4^{+1.4}_{-0.8}) \times 10^{-8}$



Previous measurements

Experiment	Integrated Luminosity ($\int \mathcal{L}\, dt$)	Limit @ 90 C.L.
L3	73 pb^{-1}	3.9×10^{-5}
Belle	104 fb^{-1}	6.2×10^{-7}
Babar	426 fb^{-1}	3.2×10^{-7}

$B^0 \to \gamma\gamma$

Results

$11.0^{+6.5}_{-5.5}$ signal events corresponding to 2.5σ significance

Since no significant signal set 90% C.L. limits

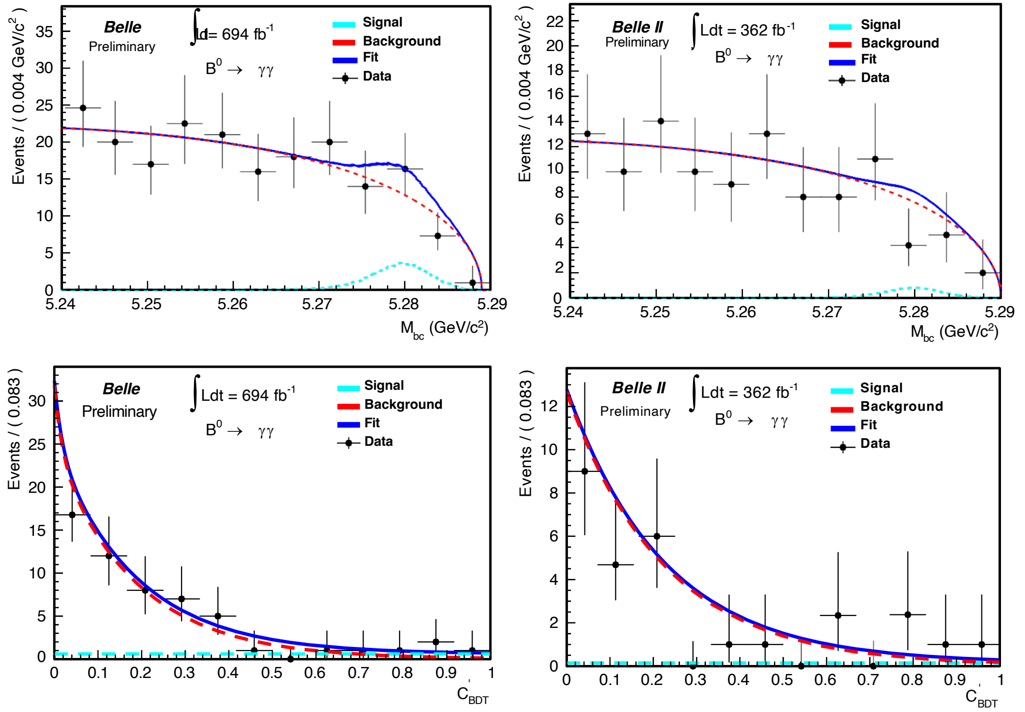
Really close to SM expectation

best upper limit with Belle II data

	$\mathcal{B}(B^0 \to \gamma\gamma)$	$\mathcal{B}(B^0 \to \gamma\gamma)$ (at 90% CL)
Belle	$(5.4^{+3.3}_{-2.6} \pm 0.5) \times 10^{-8}$	$< 9.9 \times 10^{-8}$
Belle II	$(1.7^{+3.7}_{-2.4} \pm 0.3) \times 10^{-8}$	$< 7.4 \times 10^{-8}$
Combined	$(3.7^{+2.2}_{-1.8} \pm 0.7) \times 10^{-8}$	$< 6.4 \times 10^{-8}$

- 5 x improvement in limit with respect to BaBar (previous best result) BaBar had upward fluctuation

Fit projections on M_{bc} and C'_{BDT}



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

arxiv: 2311.14647

Belle II

FCNC $b \to s$ transition

precise SM prediction: $\mathcal{B}(B^+ \to K^+\nu\bar{\nu}) = (5.58 \pm 0.37) \times 10^{-6}$

NP scenarios

Light: axions PRD 102 (2020) 015023

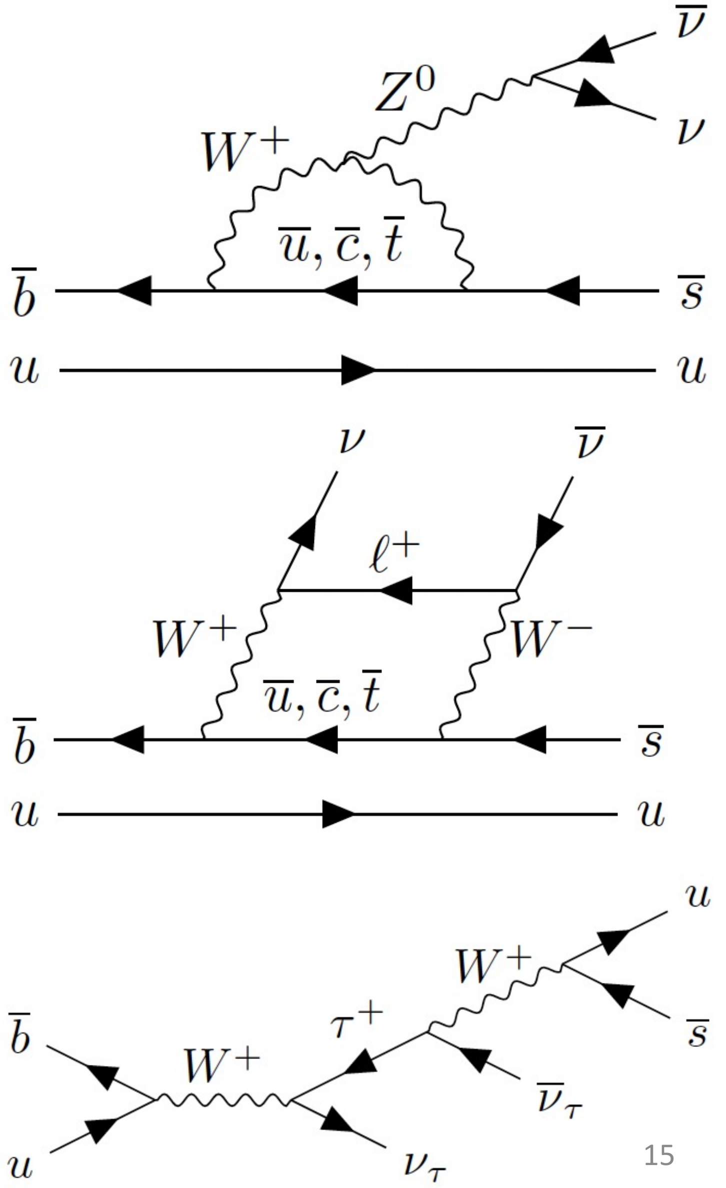
dark scalars PRD 101 (2020) 095006

axion-like particles JHEP 04 (2023) 131

Heavy: Z' PLB 821 (2021) 136607

leptoquarks PRD 98 (2018) 055003

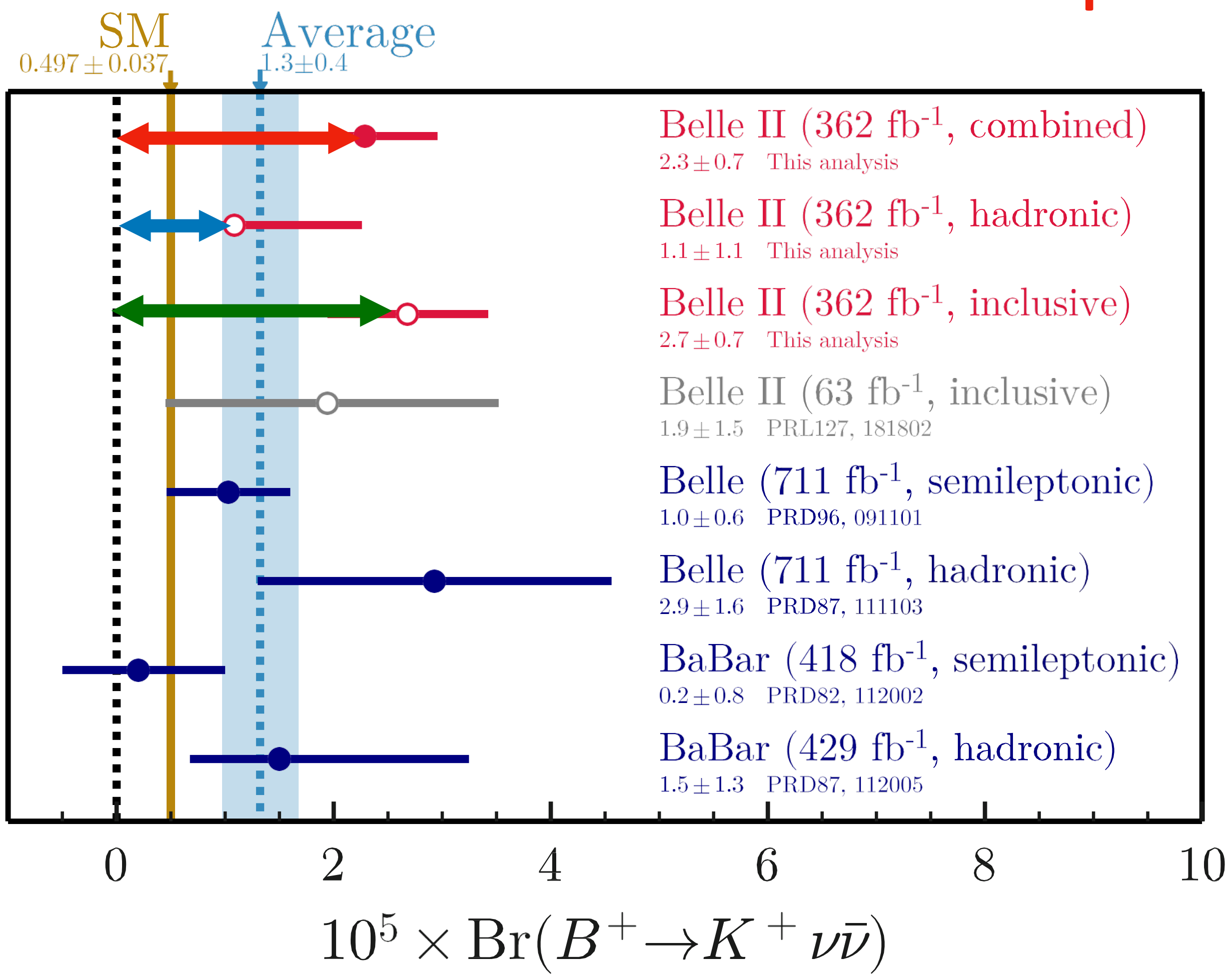
Previous limits one order of magnitude above SM expectation



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

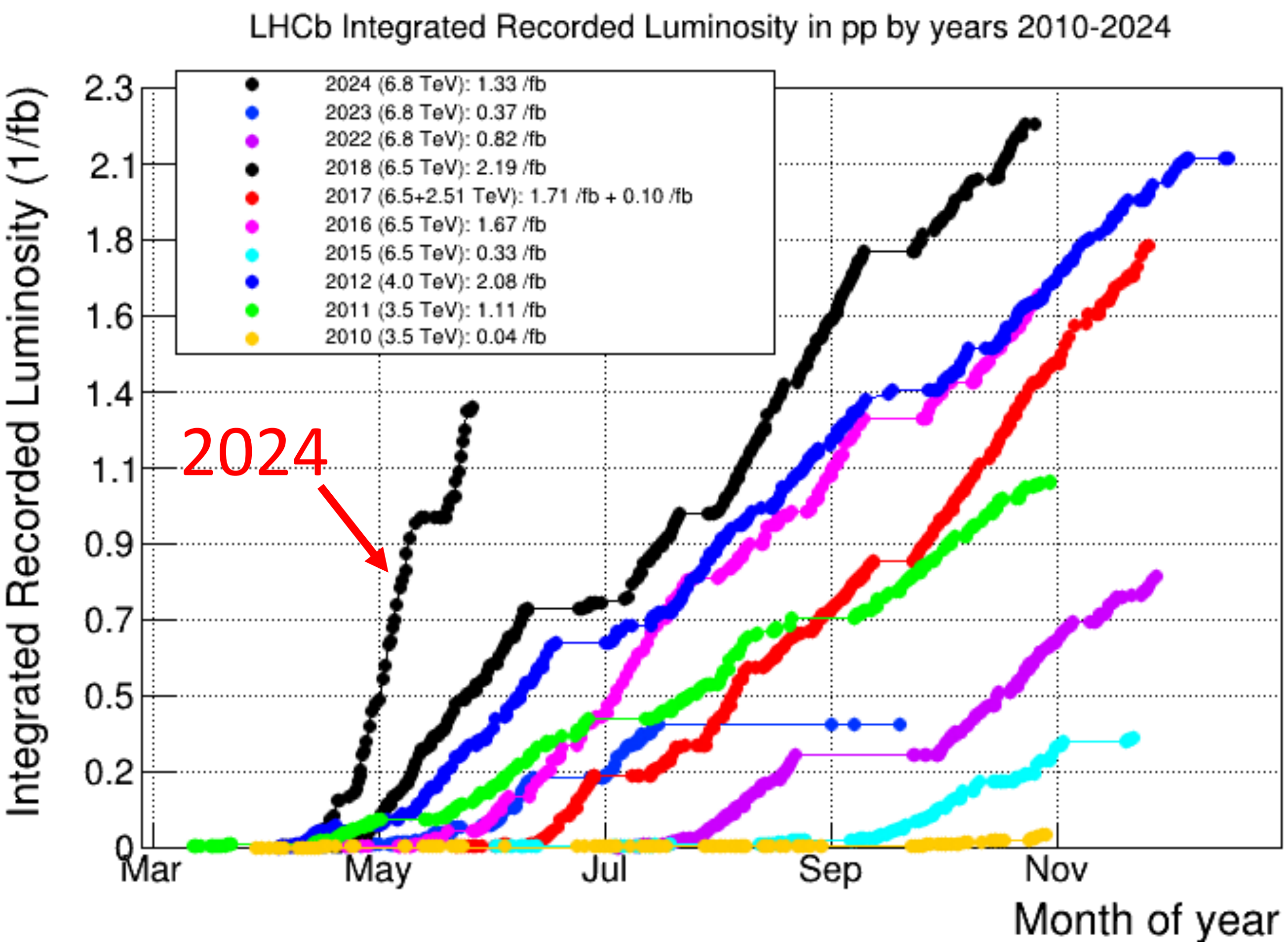
arxiv: 2311.14647

First evidence of the $B^+ \to K^+\nu\bar{\nu}$ process



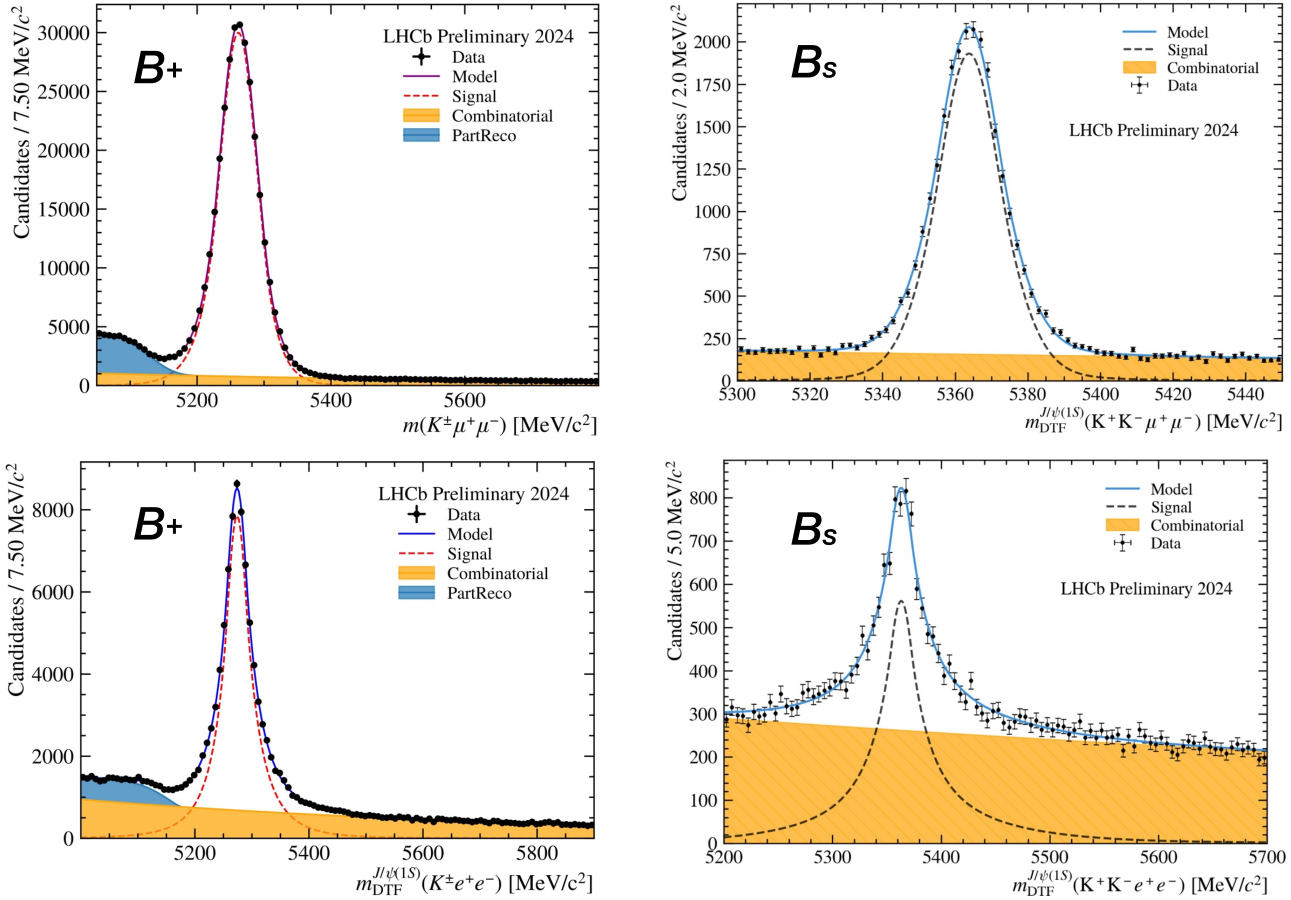
LHCb 2024

- The experiment recorded about 9 fb^{-1} of luminosity in Run-1 and Run-2, and already 1.4 fb^{-1} in the first few weeks of 2024 (Run-3), thanks to much higher instantaneous luminosity
- Run-3 prospects are to surpass in a single year the statistics of all previous runs!



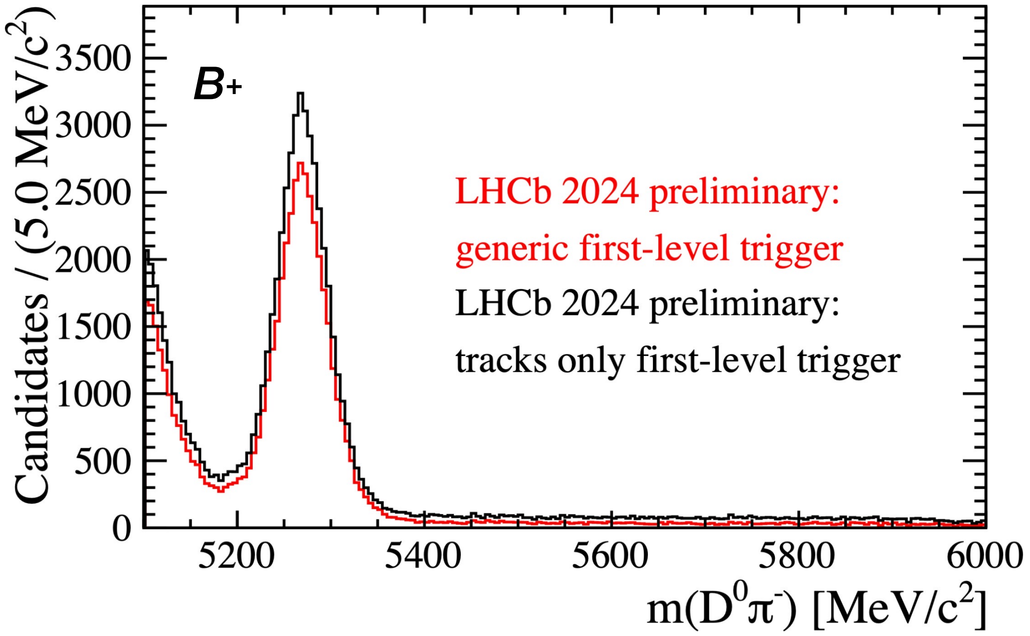
2024 data: *b*-decays with leptons and fully hadronic

LHCb-FIGURE-2024-007



18

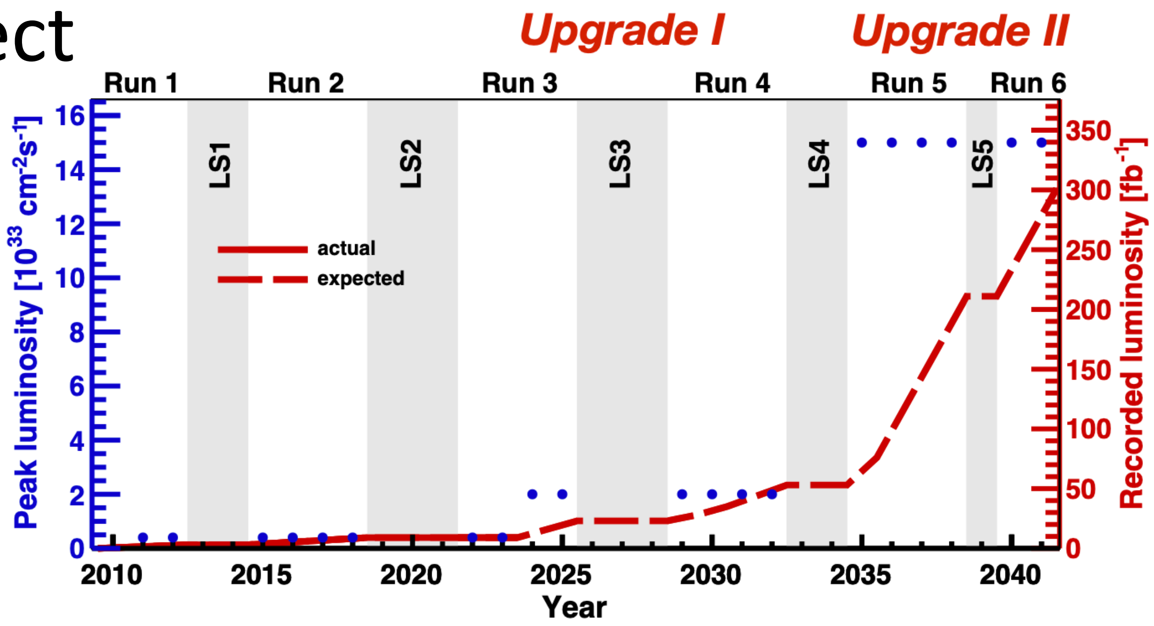
LHCb-FIGURE-2024-014



- Also new purely software trigger in Run-3, with much improved efficiencies!

Future prospects

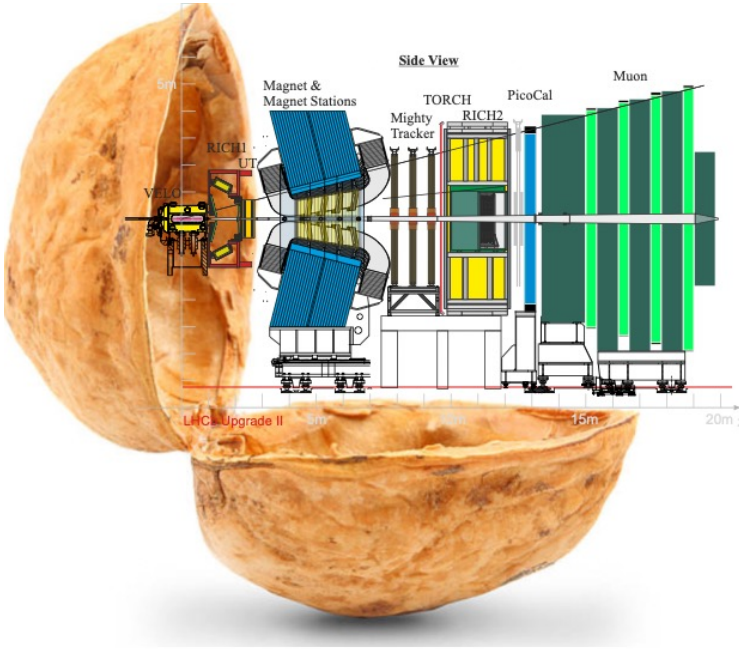
- European Strategy Update 2020: "The full physics potential of the LHC and the HL-LHC, including the study of flavour physics, ... should be exploited"
- LHCb Upgrade I was designed to collect 50 fb^{-1} by end of Run 4, but there is the opportunity to operate the experiment until the end of HL-LHC
  - With this in mind, the LHCb Upgrade II detector is being designed to accumulate the maximum possible integrated luminosity



- The proposed baseline is to achieve 50 fb^{-1} per year and reach at least 300 fb^{-1} at the end of Run-6

LHCb Upgrade II in a nutshell

- Unique scientific programme with BSM discovery potential using unprecedented samples of *B* and *D* decays
- Furthermore, broad programme on spectroscopy, EWK precision measurements, top and Higgs physics, dark sector searches, heavy ions and fixed target, all made with a unique and fully instrumented forward acceptance



- Technology-wise, it provides an exciting technology roadmap with novel detectors and electronics

In conclusion

- Quark-flavour physics and rare decays are an extremely rich laboratory to look for physics beyond the SM
- LHCb is still analysing data from Run-1 and Run-2, and Belle II started significant analyses with Run-1 data
- Now the LHCb collaboration is focusing on Run-3, and the plan in 2024-25 is to integrate a luminosity that will triple the statistics from Run-1 and Run-2, and even more for hadronic decay modes
- A further upgrade of LHCb is planned for Run-5, increasing the luminosity by another order of magnitude, with the aim of squeezing the LHC to release all flavour physics results up to the next accelerator