Highlights of LHCb Physics

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for the LHCb collaboration

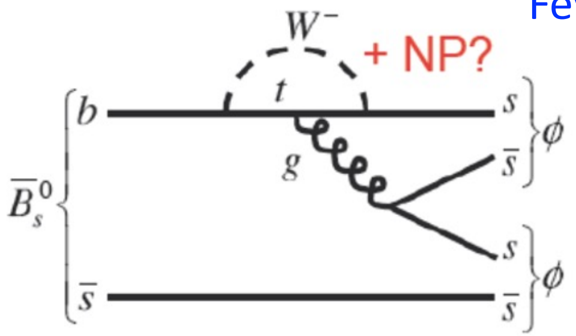
CERN – Ukraine 2024

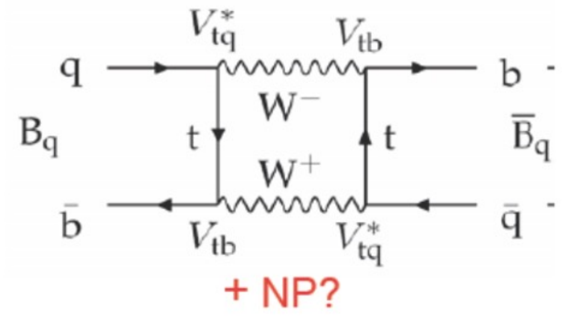
Past – Present – Future

Kyiv, 28th May 2024

“Indirect” searches for New Physics at LHCb

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





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

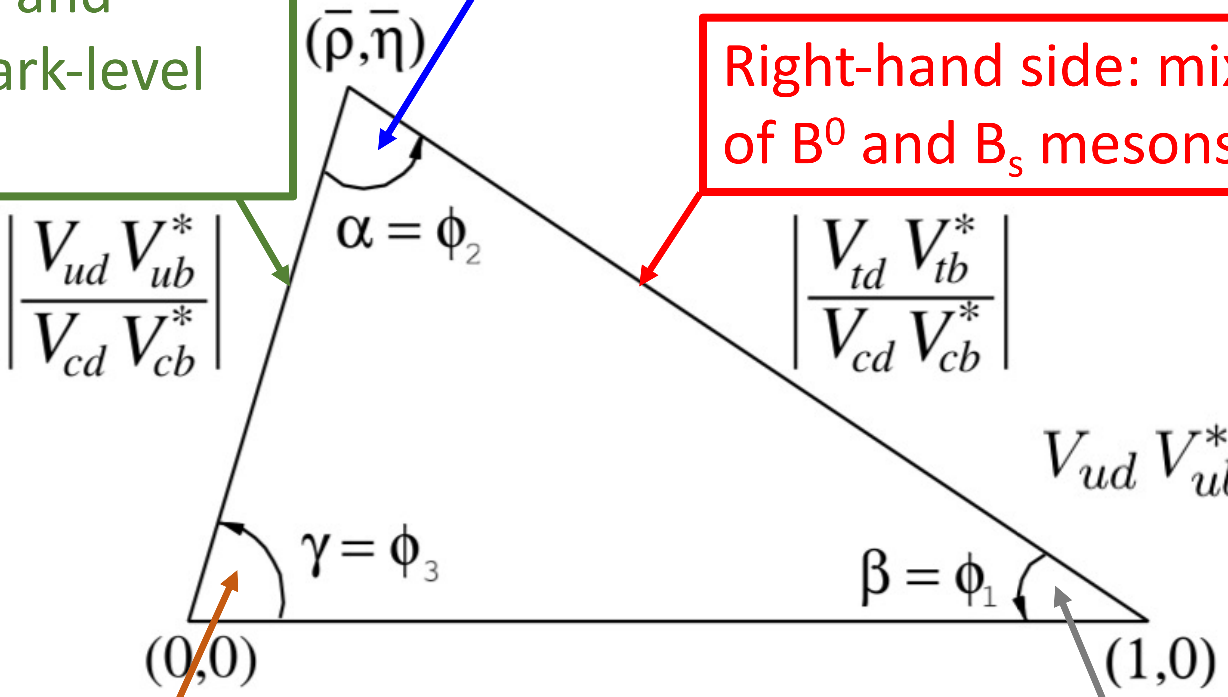
- General decomposition of a transition amplitude in terms of couplings and scales
- New-physics virtual particles of arbitrarily large mass can enter loops in Feynman diagrams and produce observable effects → the existence of particles with much larger masses than the energy made available by the LHC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

Measuring the unitarity triangle (UT)

Left-hand side: rates of decays mediated by $b \to u l \nu$ and $b \to c l \nu$ quark-level processes

Angle α: decay rates and *CP* violation in $B \to \pi\pi$, $B \to \rho\pi$, $B \to \rho\rho$ decays

Right-hand side: mixing rate of B^0 and B_s mesons



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

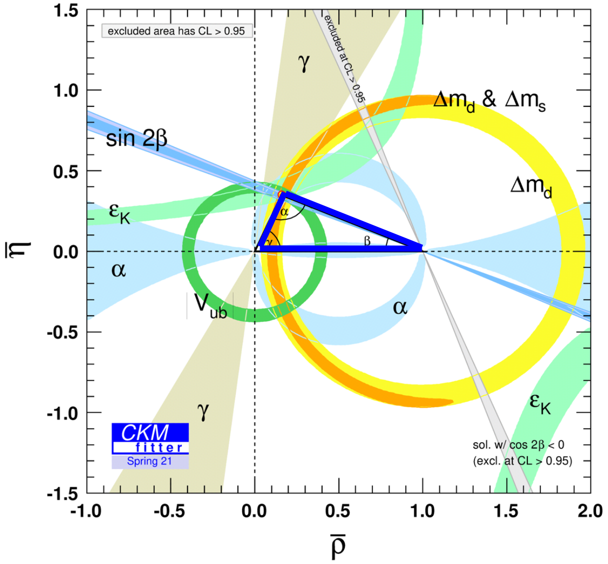
Angle γ: *CP* violation in $B \to DK$, $B \to D\pi$ decays

Angle β: *CP* violation in $B \to c\bar{c}K_S$, $B \to c\bar{c}K_L$ decays

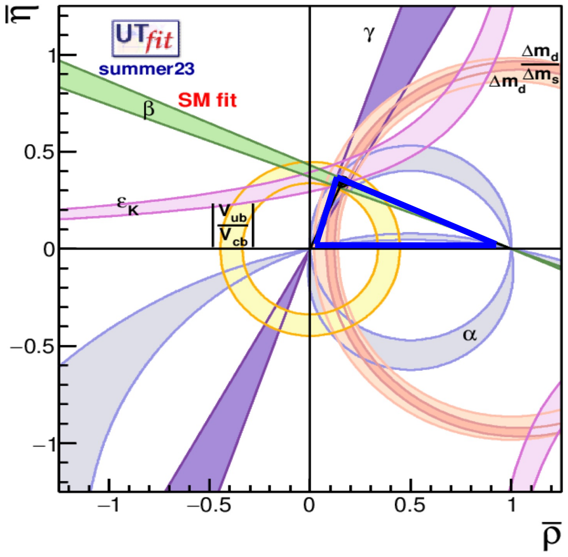
Consistency of global CKM fits

- Each coloured band defines the allowed region of the apex of the unitarity triangle according to the measurement of a specific process

http://ckmfitter.in2p3.fr

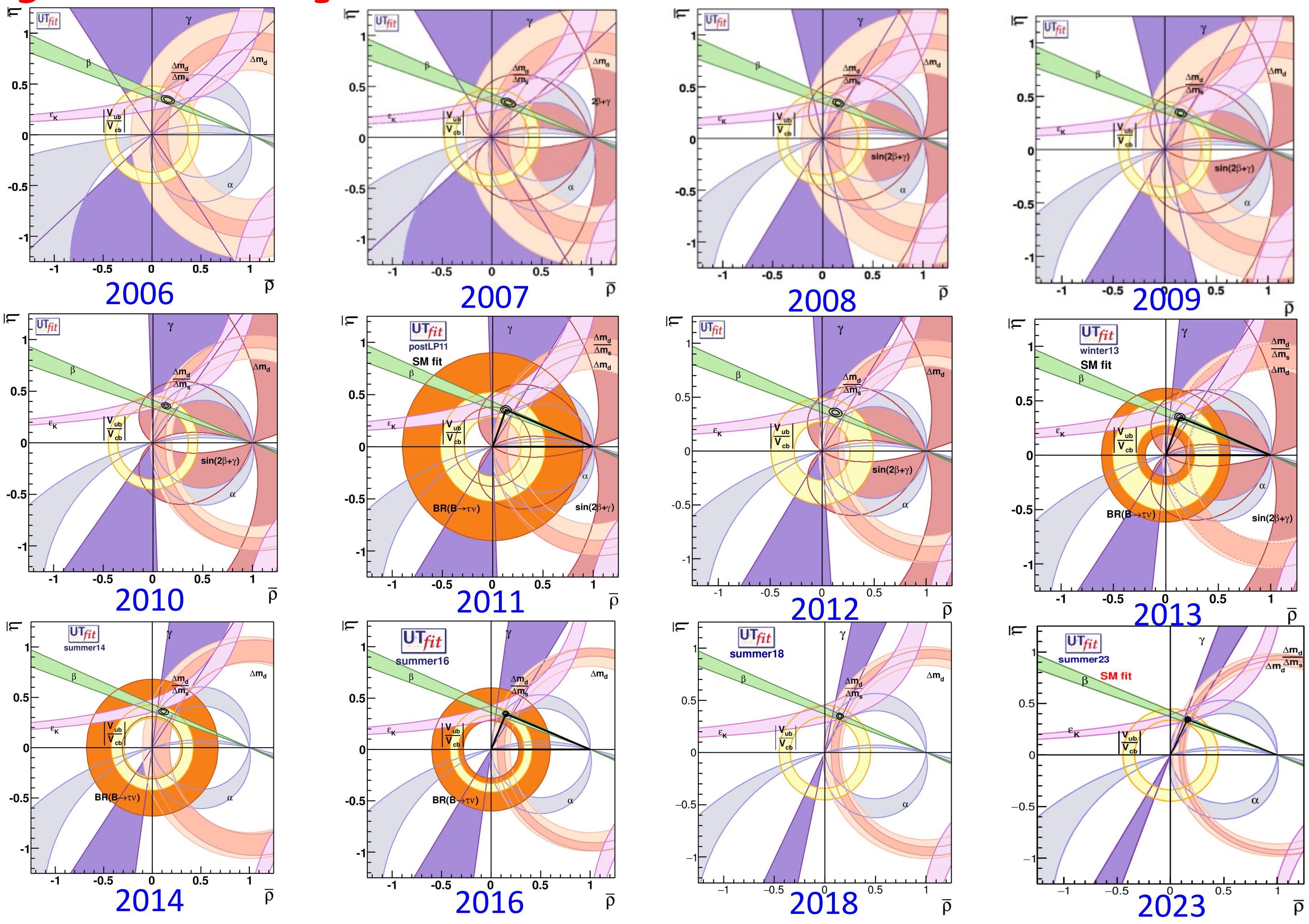


http://www.utfit.org

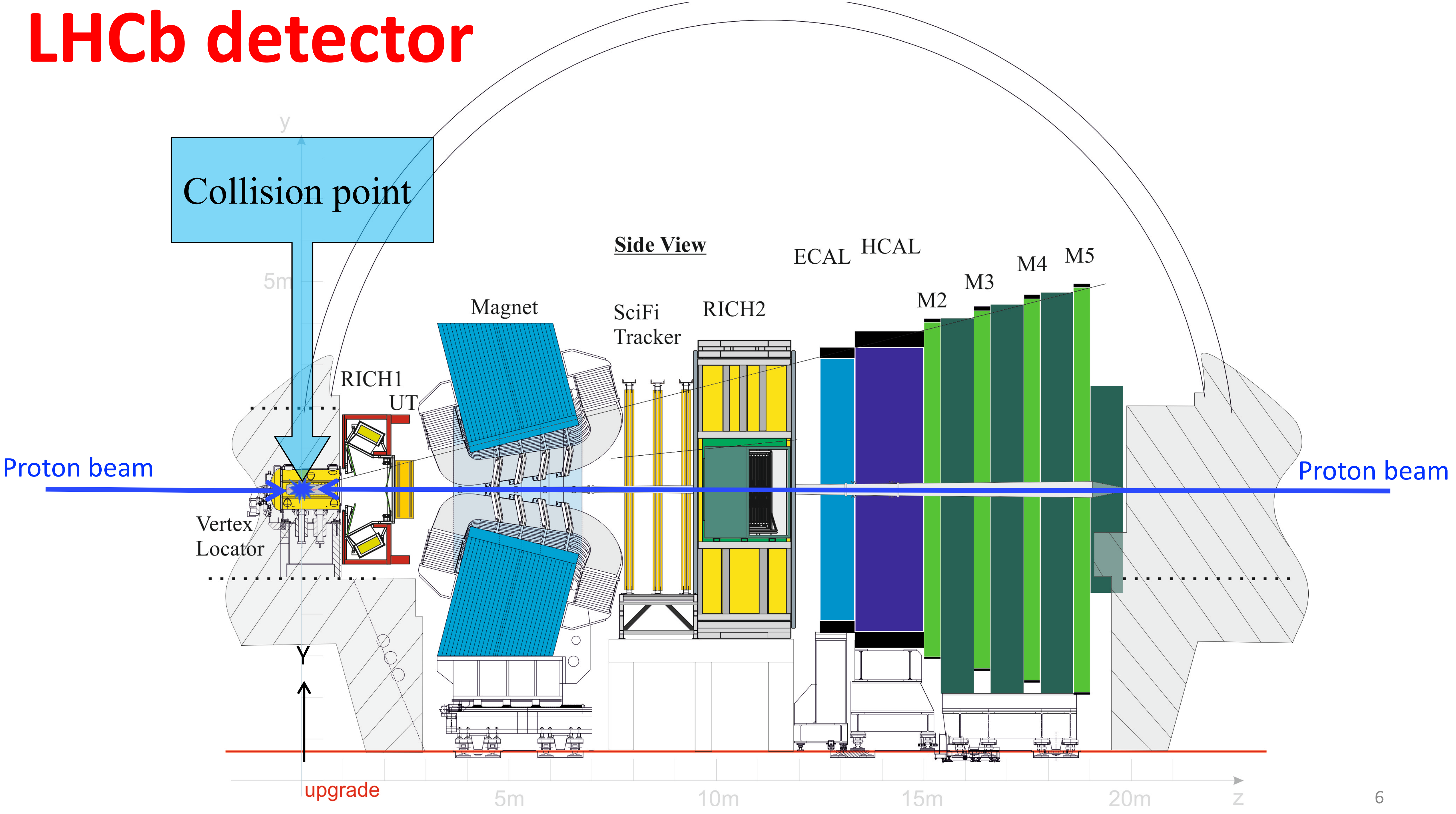


- Tremendous success of the CKM paradigm!
  - All of the available measurements agree in a highly profound way to the current level of precision
  - In presence of new physics affecting the measurements, the various contours would not cross each other into a single point
- The quark flavour sector is generally well described by the CKM mechanism, but there's still room for new physics contributions at the ~10% level

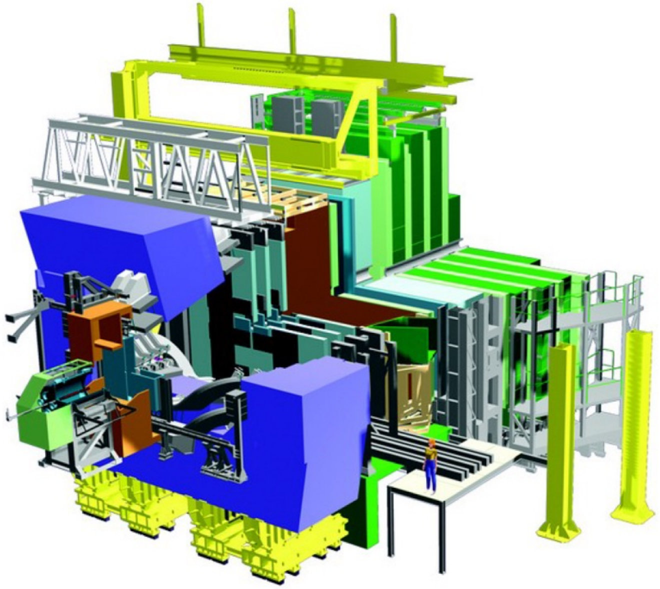
Long journey to reach here…



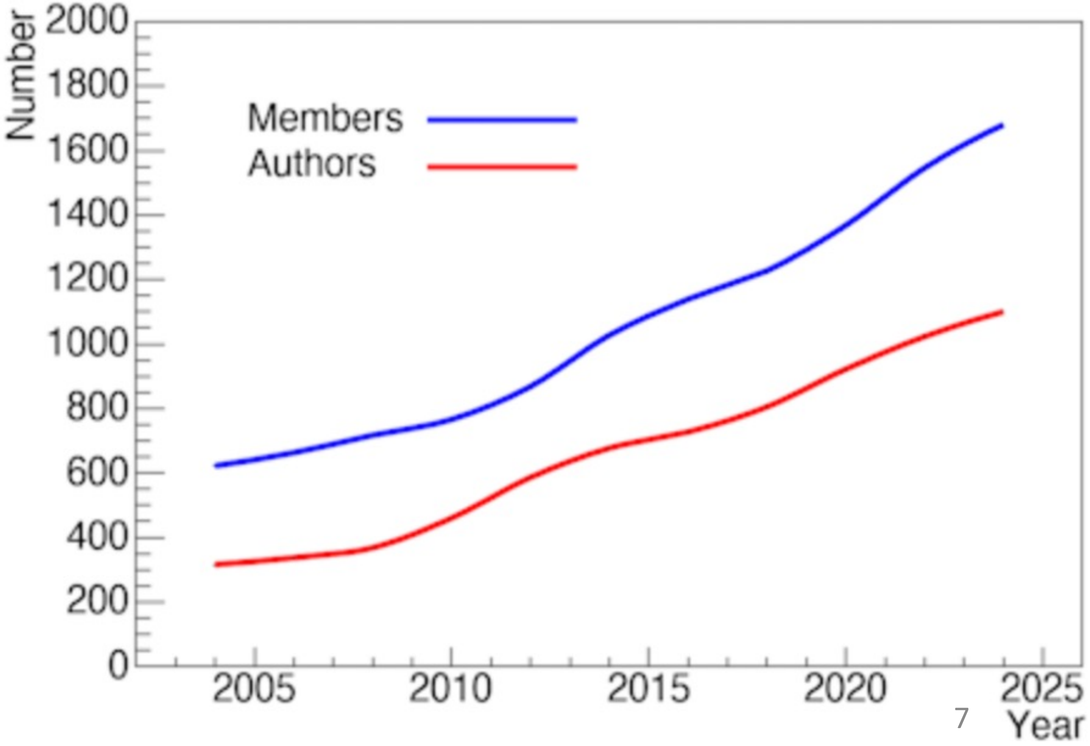
LHCb detector



LHCb collaboration

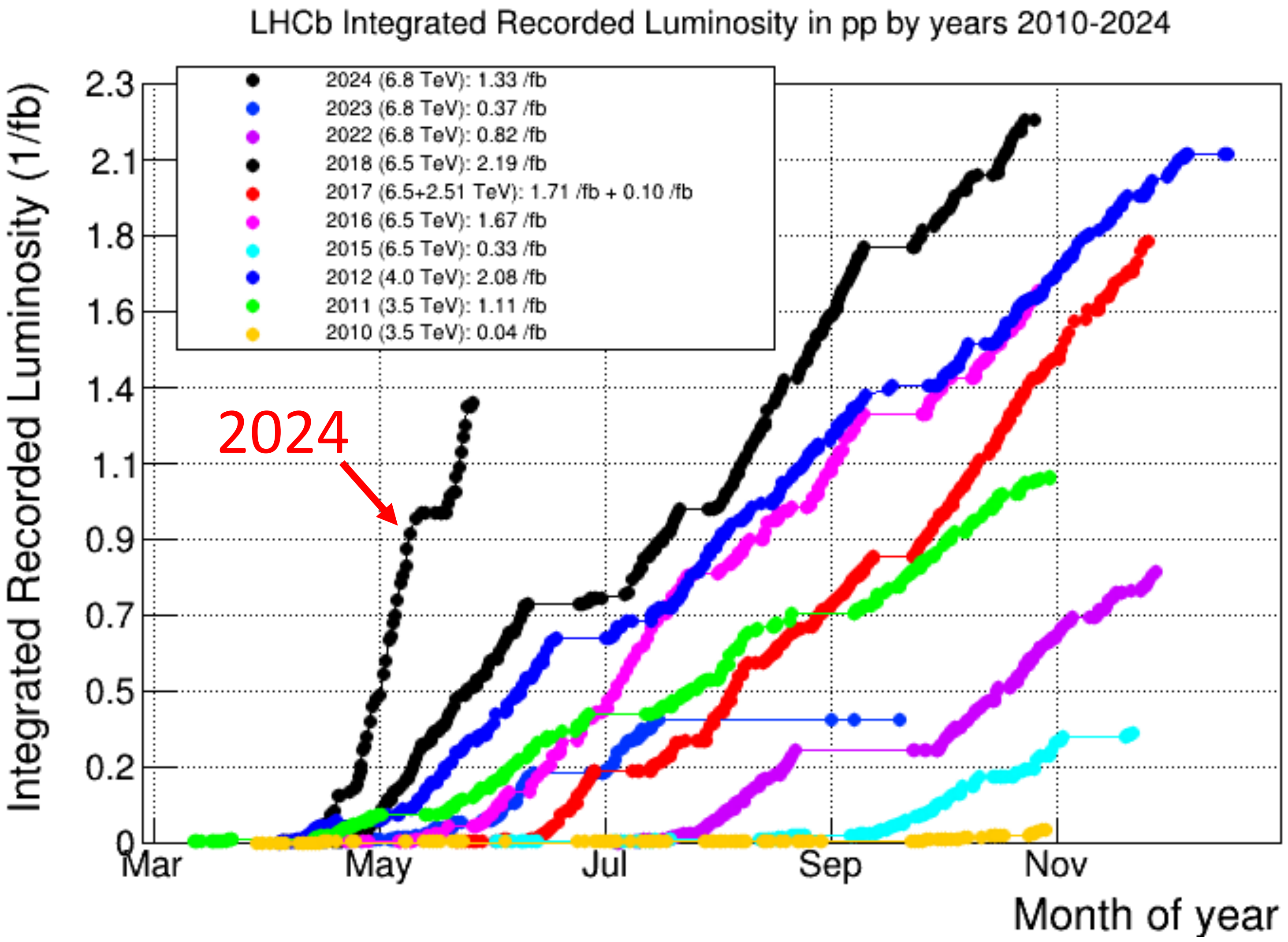


- As of today, 1720 members from 100 institutes in 22 countries
- Including 1140 authors

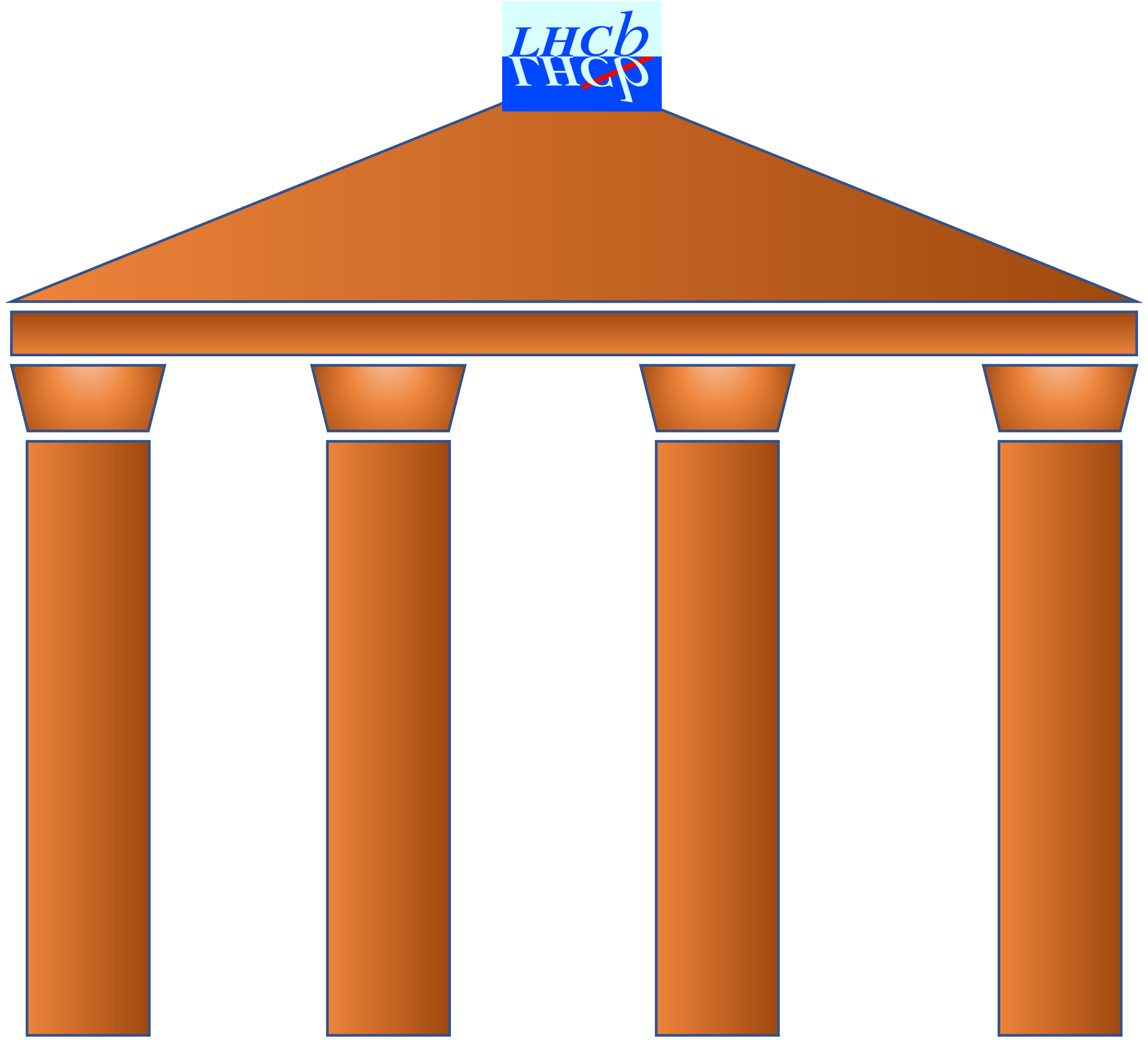


LHCb data

- The experiment recorded about 9 fb^{-1} of luminosity in Run-1 and Run-2
- Run-3 prospects are to surpass in a single year the statistics of all previous runs!



The pillars of LHCb physics



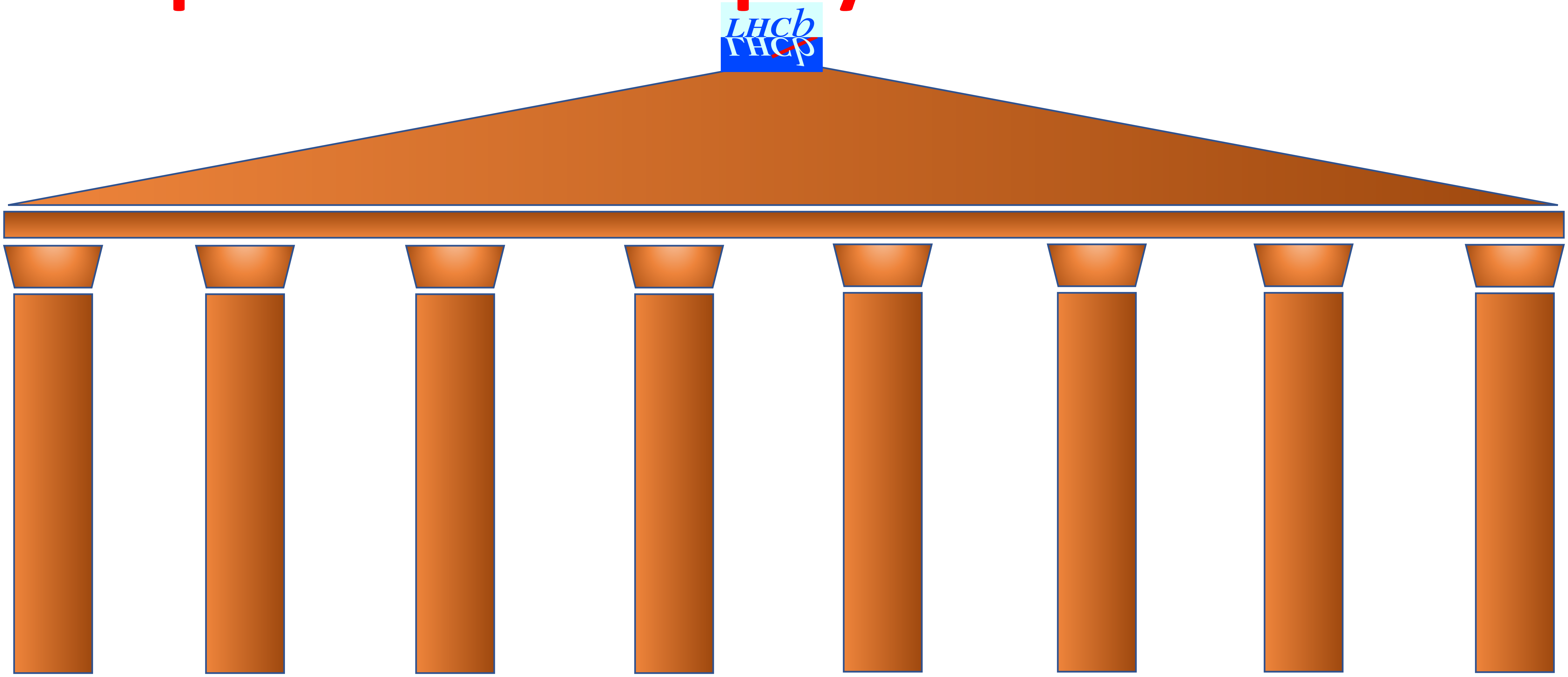
CPV in beauty

Rare decays in beauty, charm (and strange)

CPV in charm

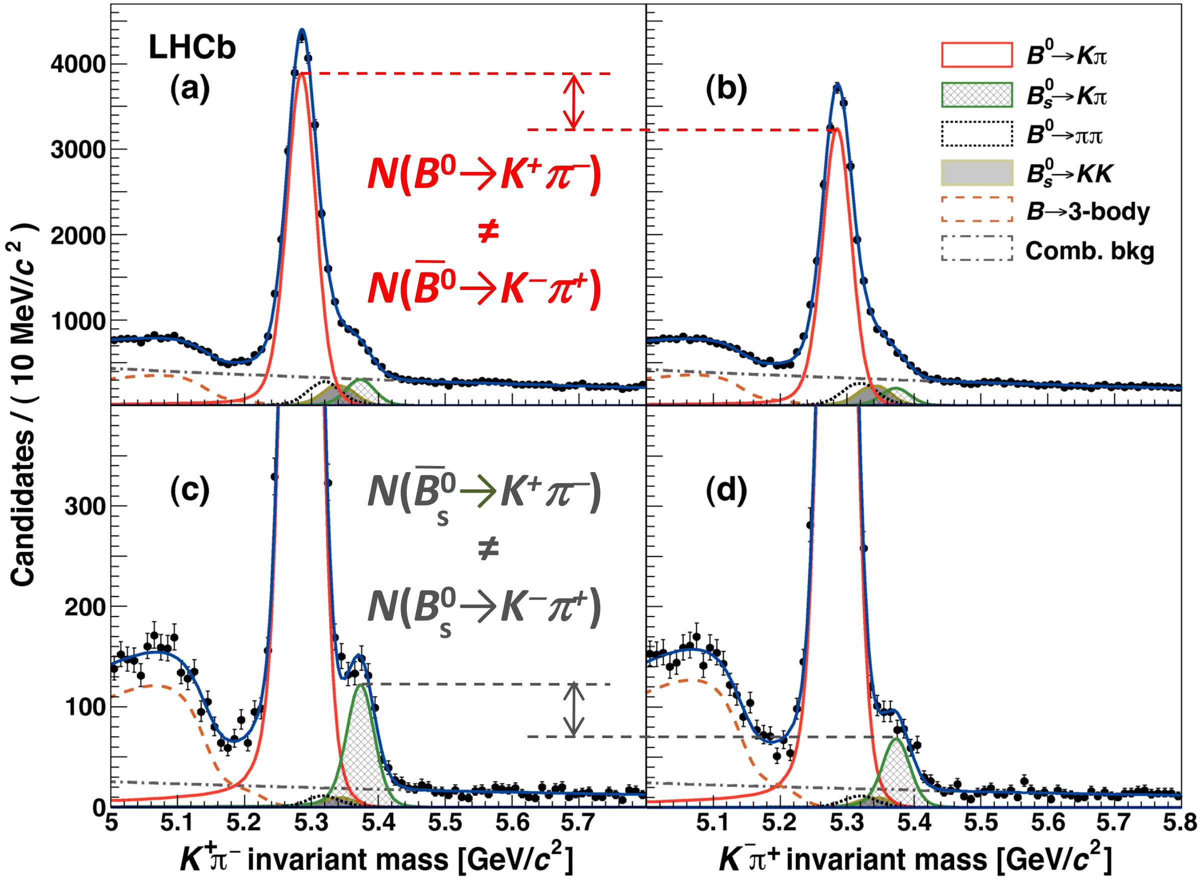
Heavy flavour production and spectroscopy

The pillars of LHCb physics



Textbook example: *CP* asymmetry in $B \to K\pi$ decays

Phys. Rev. Lett. 110 (2013) 221601



- Count the number of decays $B \to f$, and compare with the *CP* conjugate $\overline{B} \to \overline{f}$ by measuring the time-integrated *CP* asymmetry

$$A_{CP} = \frac{\Gamma(\overline{B}^0_{(s)} \to \overline{f}) - \Gamma(B^0_{(s)} \to f)}{\Gamma(\overline{B}^0_{(s)} \to \overline{f}) + \Gamma(B^0_{(s)} \to f)}$$

- $A_{CP} \neq 0 \to$ direct *CP* violation

- If we start with a symmetric number of B and $\overline{B}$ mesons, we end up with more positive kaons than negative kaons, and viceversa for pions

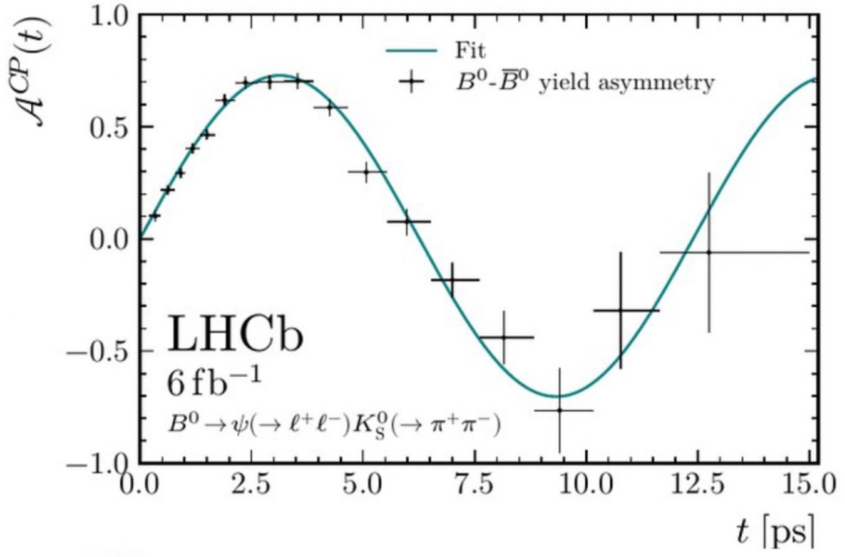
World's best measurement of sin2β

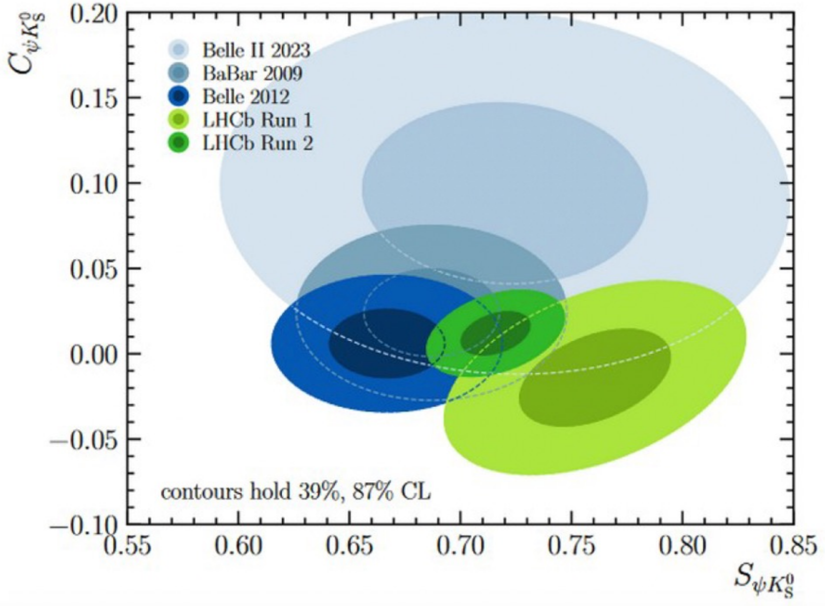
Phys. Rev. Lett. 132 (2024) 021801

- Golden mode that led to the construction of *B* factories
- Interference between B^0 mixing and decay graphs
- Precision from LHCb now much better than that of measurements from *B* factories

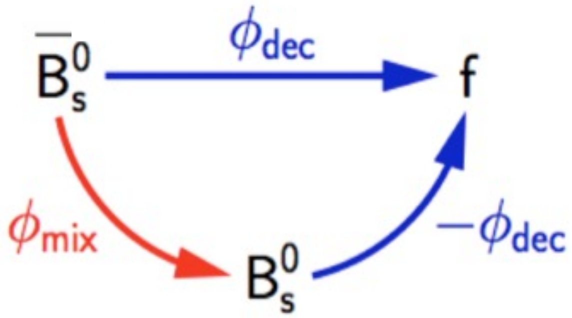
$$S^{\text{Run }1+2}_{J/\psi K^0_S} = 0.724 \pm 0.014\,(\text{stat+syst})$$

- Measurement still dominated by statistical uncertainties → lots of room for improvements with Run-3 data

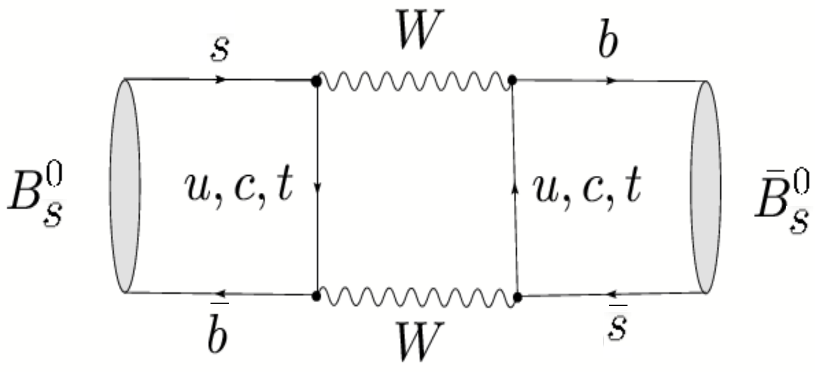


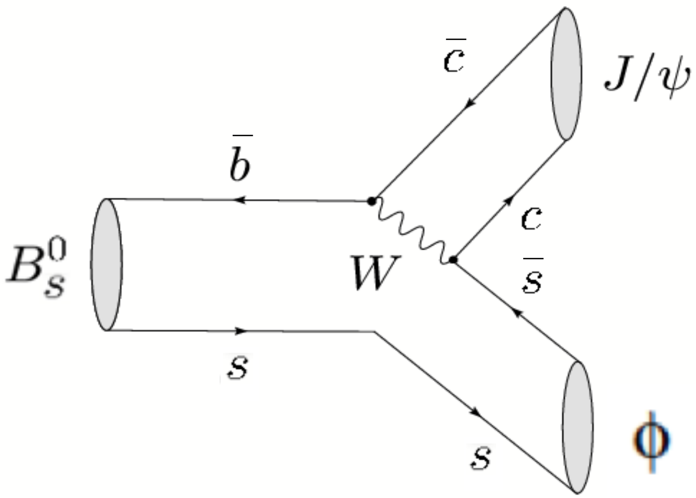


Measurement of *CP* violation in $B_s \rightarrow J/\psi\phi$ decays



- Analogue to $B^0 \rightarrow J/\psi K_S$ but with an initial B_s meson
- Interference between B_s mixing and decay graphs

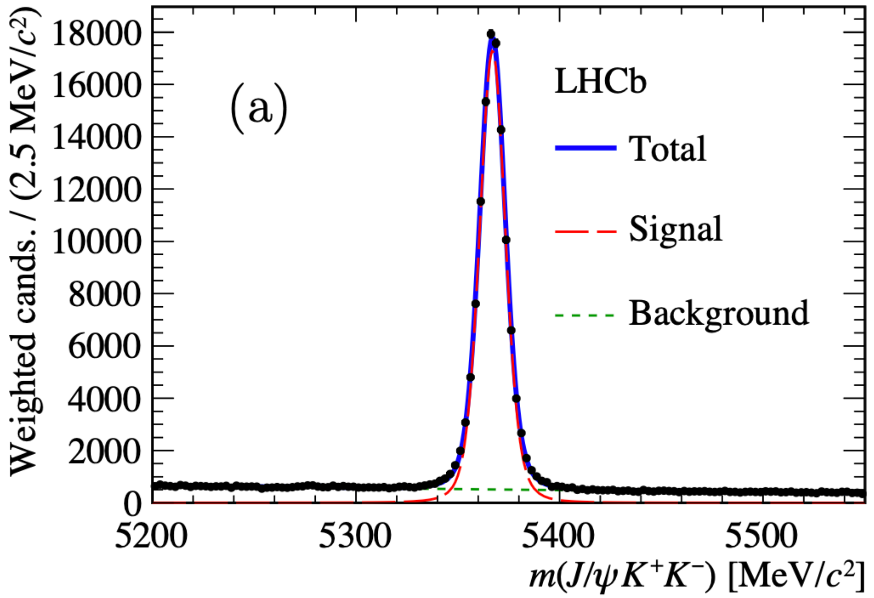




- One measures the phase-difference ϕ_s between the two diagrams, precisely predicted in the Standard Model to be $\phi_s = -2\lambda^2\eta = -37.4 \pm 0.7$ mrad → very small *CP* violation in the Standard Model
- Additional contributions from new physics can modify this value → need precise experimental measurement

Measurement of *CP* violation in $B_s \rightarrow J/\psi\phi$ decays

- Conceptually similar to measuring sin(2β), but now we have a pseudoscalar to vector-vector decay
- The final state is not a *CP* eigenstate, but a mixture of *CP*=+1 and *CP*=-1 eigenstates
  - Angular analysis of decay products is needed to disentangle the two eigenstates
- Furthermore, for a B_s meson the decay width difference $\Delta\Gamma_s$ is not negligible, and needs to be measured



Eur. Phys. J. C 79 (2019) 706

Measurement of *CP* violation in $B_s \rightarrow J/\psi\phi$ decays

Simultaneous fit to decay time and three helicity angles

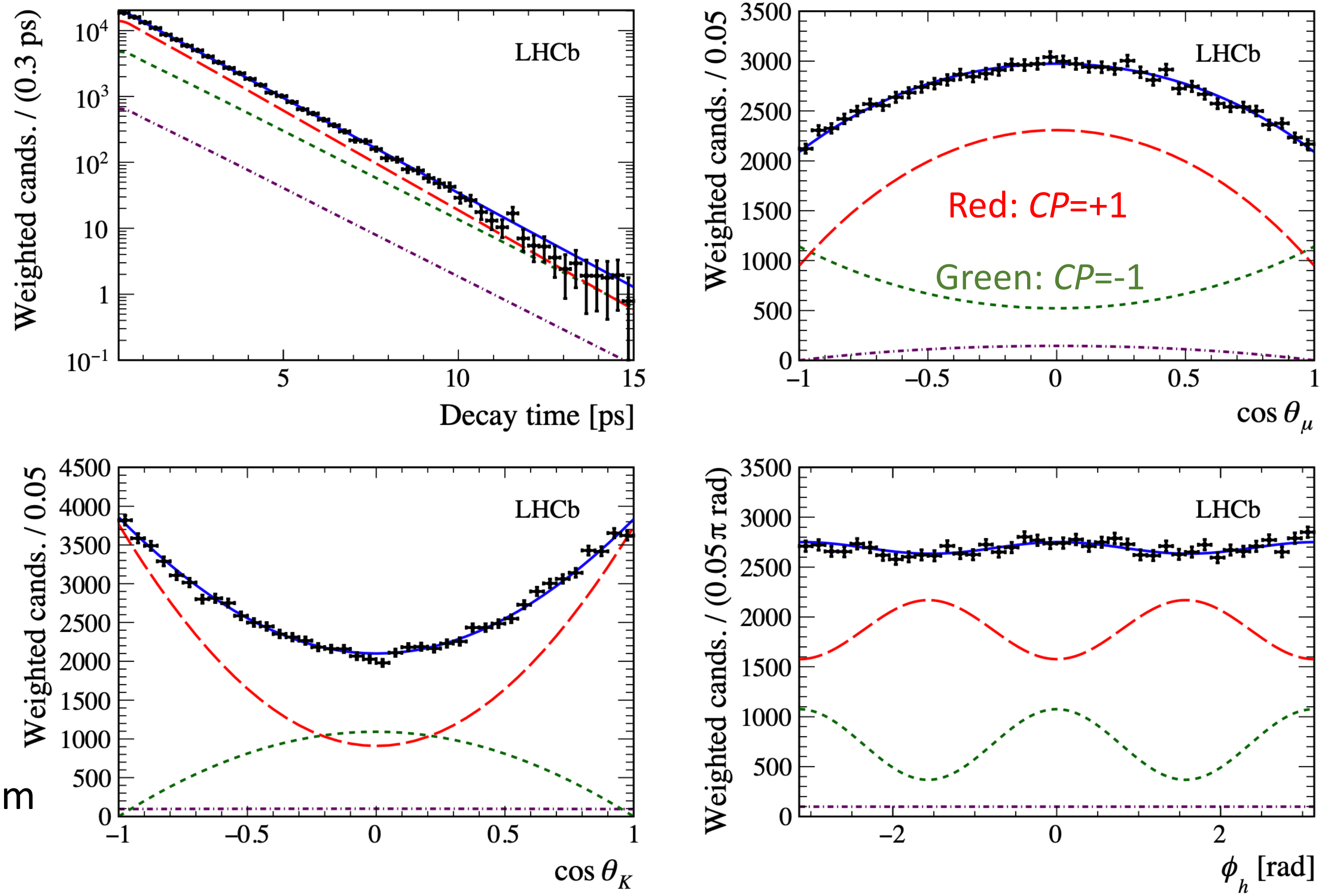
Latest result published by LHCb

$$\phi_s = -0.081 \pm 0.032\,\mathrm{rad}$$

To be compared with Standard Model prediction

$\phi_s = -0.0374 \pm 0.007$ rad

Not yet incompatible, but large room for experimental improvement



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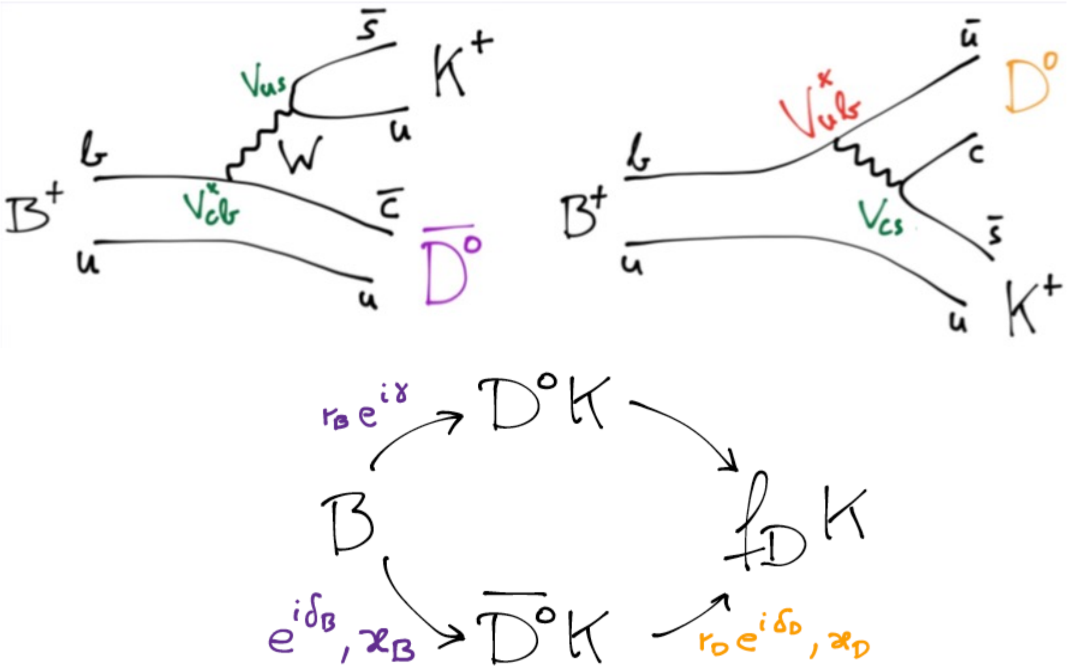
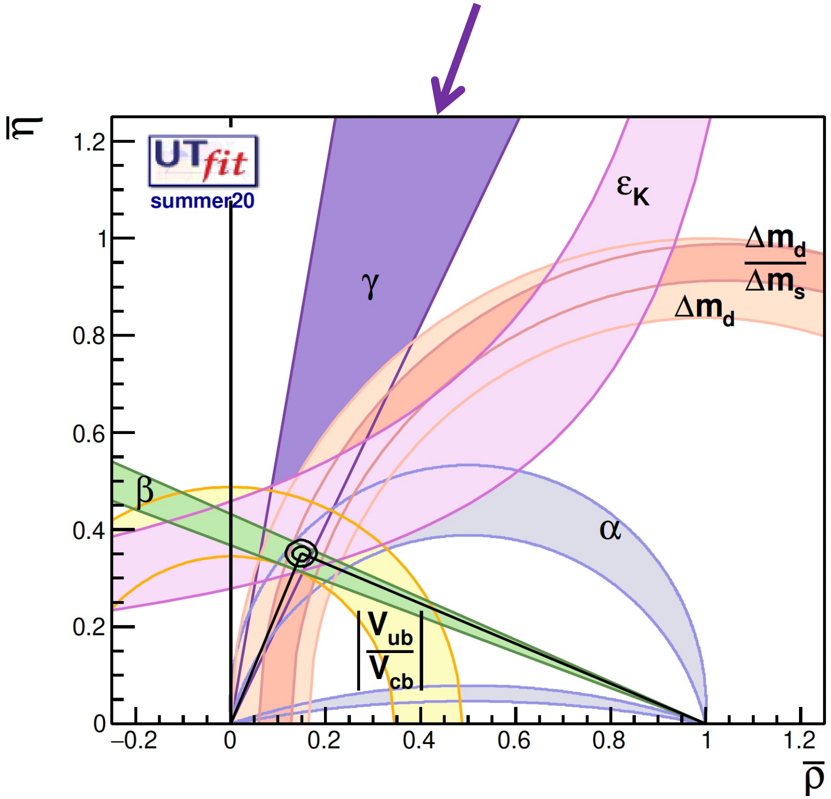
Measurement of the CKM angle γ

- γ has been for long time the least known angle of the unitarity triangle
- It is measured via the interference between *b*→*c* and *b*→*u* tree-level quark transitions





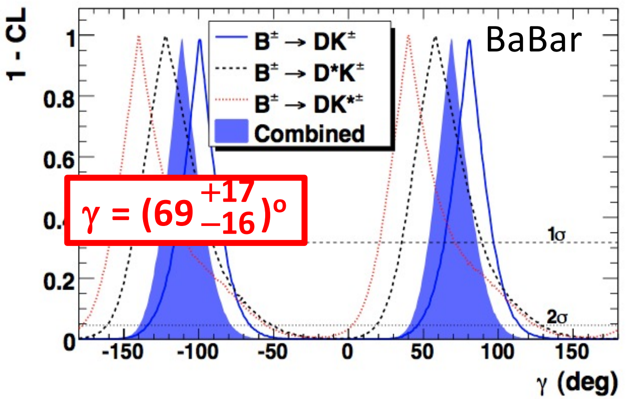
- Simple and clean theoretical interpretation, but statistically very challenging

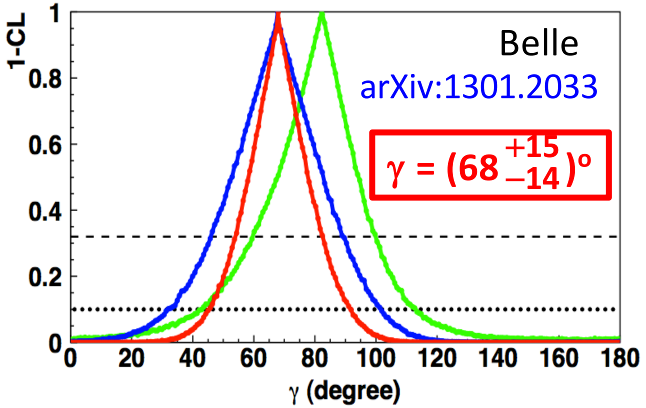
Measurement of the CKM angle γ

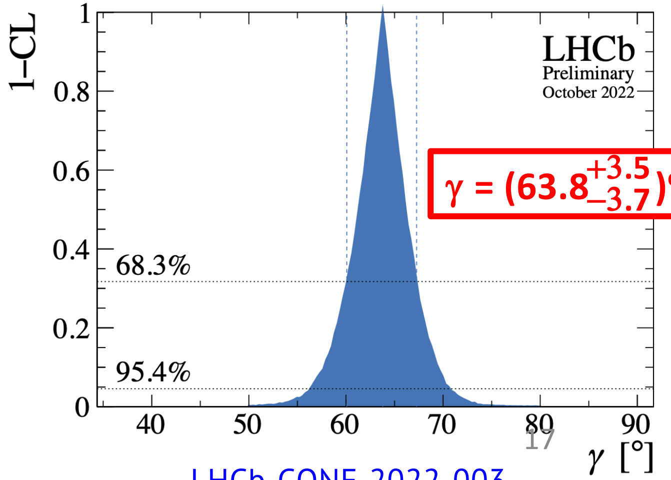
- A plethora of independent measurements exploiting different methods and decays
- LHCb precision significantly better than that of previous results from the *B*-factories and undergoing continuous improvements

B decay	D decay
$B^\pm \to Dh^\pm$	$D \to h^+h^-$
$B^\pm \to Dh^\pm$	$D \to h^+\pi^-\pi^+\pi^-$
$B^\pm \to Dh^\pm$	$D \to K^\pm\pi^\mp\pi^+\pi^-$
$B^\pm \to Dh^\pm$	$D \to h^+h^-\pi^0$
$B^\pm \to Dh^\pm$	$D \to K^0_S h^+h^-$
$B^\pm \to Dh^\pm$	$D \to K^0_S K^\pm\pi^\mp$
$B^\pm \to D^*h^\pm$	$D \to h^+h^-$
$B^\pm \to DK^{*\pm}$	$D \to h^+h^-$
$B^\pm \to DK^{*\pm}$	$D \to h^+\pi^-\pi^+\pi^-$
$B^\pm \to Dh^\pm\pi^+\pi^-$	$D \to h^+h^-$
$B^0 \to DK^{*0}$	$D \to h^+h^-$
$B^0 \to DK^{*0}$	$D \to h^+\pi^-\pi^+\pi^-$
$B^0 \to DK^{*0}$	$D \to K^0_S\pi^+\pi^-$
$B^0 \to D^\mp\pi^\pm$	$D^+ \to K^-\pi^+\pi^+$
$B^0_s \to D_s^\mp K^\pm$	$D_s^+ \to h^+h^-\pi^+$
$B^0_s \to D_s^\mp K^\pm\pi^+\pi^-$	$D_s^+ \to h^+h^-\pi^+$

Phys. Rev. **D87** (2013) 052015





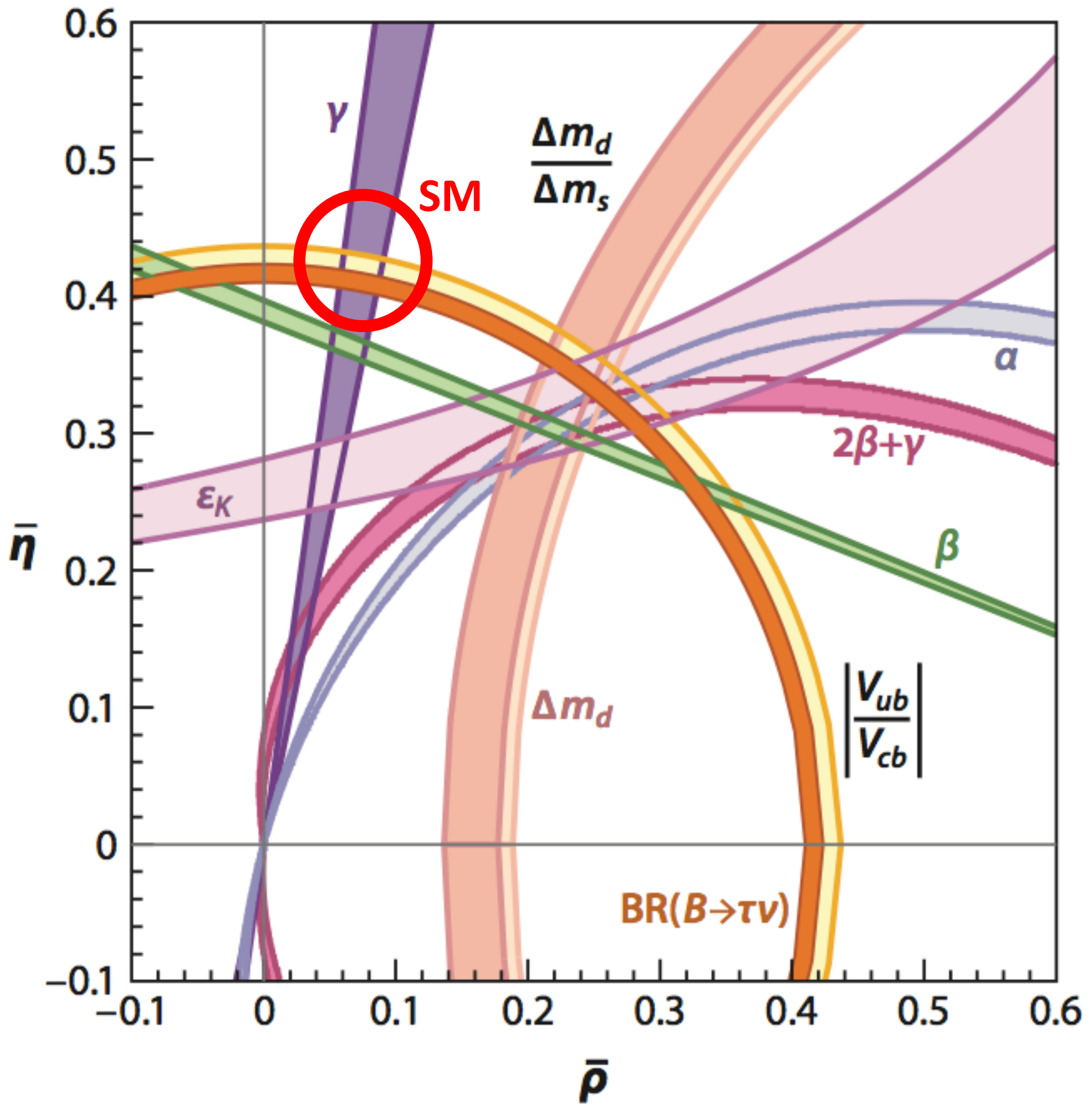


LHCb-CONF-2022-003

Why do we care so much?

Importance of γ

- As the dominant SM diagrams are at tree-level, γ is expected to be mostly insensitive to new physics
- Exactly for this reason, it is a crucial reference to interpret the various constraints of the unitarity triangle, allowing for a reference Standard Model point to be established and looking for discrepancies with other measurements from loop-mediated processes



Dream scenario, for illustration only

Observation of *CP* violation in charm

Phys. Rev. Lett. 122 (2019) 211803

$$\Delta A_{CP} \equiv A_{CP}(K^-K^+) - A_{CP}(\pi^-\pi^+)$$

$$A_{\rm raw}(f) = \frac{N(D^0 \to f) - N(\bar{D}^0 \to f)}{N(D^0 \to f) + N(\bar{D}^0 \to f)}$$

$D^{*+} \to D^0(\to K^+K^-)\pi_s^+$	$D^{*+} \to D^0(\to \pi^+\pi^-)\pi_s^+$

$$A_{\rm raw}(f) \simeq A_{CP}(f) + A_{\rm D}(f) + A_{\rm D}(\pi_s) + A_{\rm P}(D^{*+})$$

- $A_{CP}(f)$: Physical *CP* asymmetry
- $A_{\rm D}(f)$: D^0 detection asymmetry ➔ equal to zero, since K^-K^+ and $\pi^-\pi^+$ are symmetric final states
- $A_{\rm D}(\pi_s)$: π_s detection asymmetry → Independent on the final state
- $A_{\rm P}(D^{*+})$: D^* production asymmetry → Independent on the final state

- If the kinematics of the D^{*+} and π_s for the two decay modes are equal

$$\Rightarrow A_{CP}(K^-K^+) - A_{CP}(\pi^-\pi^+) = A_{\rm raw}(K^-K^+) - A_{\rm raw}(\pi^-\pi^+)$$

- Production and detection asymmetries are cancelled
- Very robust measurement against systematic uncertainties

Results for ΔA_{CP}

Phys. Rev. Lett. 122 (2019) 211803

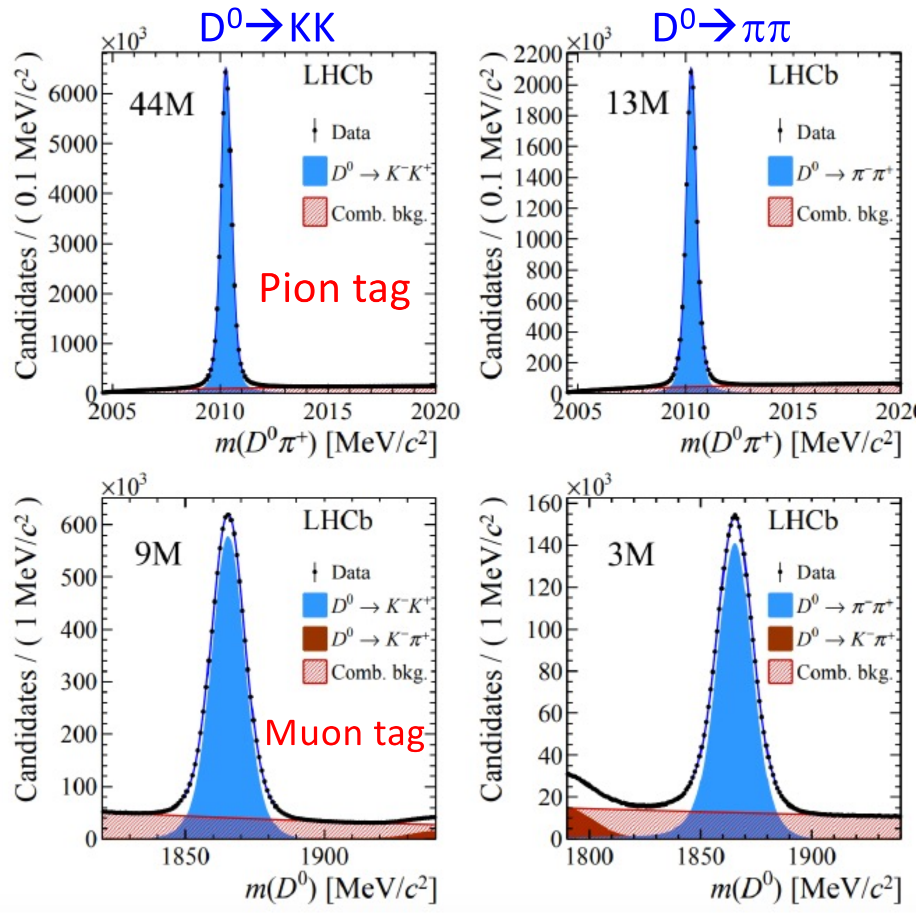
$$\Delta A_{CP}^{\pi\text{-tagged}} = [-18.2 \pm 3.2\,(\text{stat.}) \pm 0.9\,(\text{syst.})] \times 10^{-4}$$

$$\Delta A_{CP}^{\mu\text{-tagged}} = [-9 \pm 8\,(\text{stat.}) \pm 5\,(\text{syst.})] \times 10^{-4}$$

- Run-2 results well compatible with previous LHCb results and world average
- Combination of Run-1 and Run-2 data gives

$$\Delta A_{CP} = (-15.4 \pm 2.9) \times 10^{-4}$$

- *CP* violation observed at 5.3σ
  - Not discussed here today, but more recent LHCb measurement also disentangled the individual *CP* asymmetries in the difference



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 mechanisms

Measurement of $B \rightarrow \mu^+\mu^-$ 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

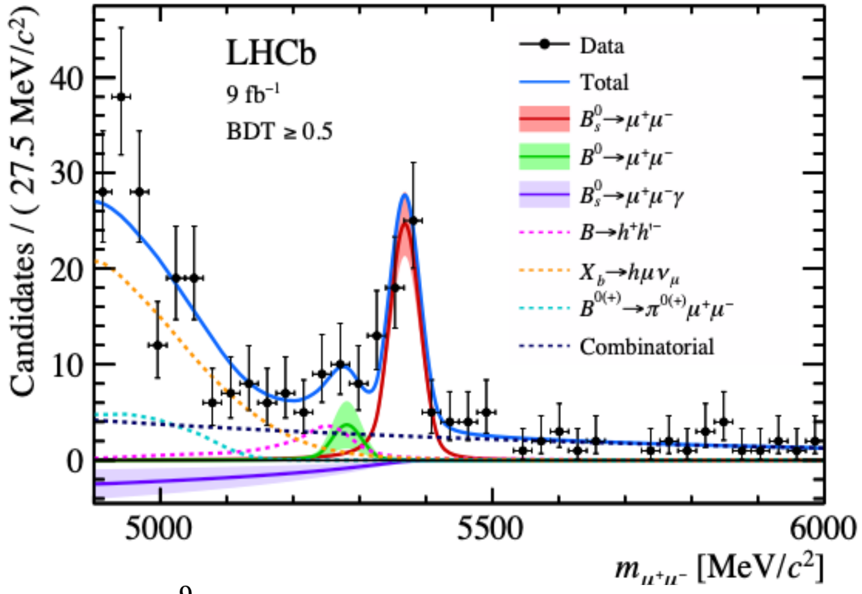
- Latest LHCb results

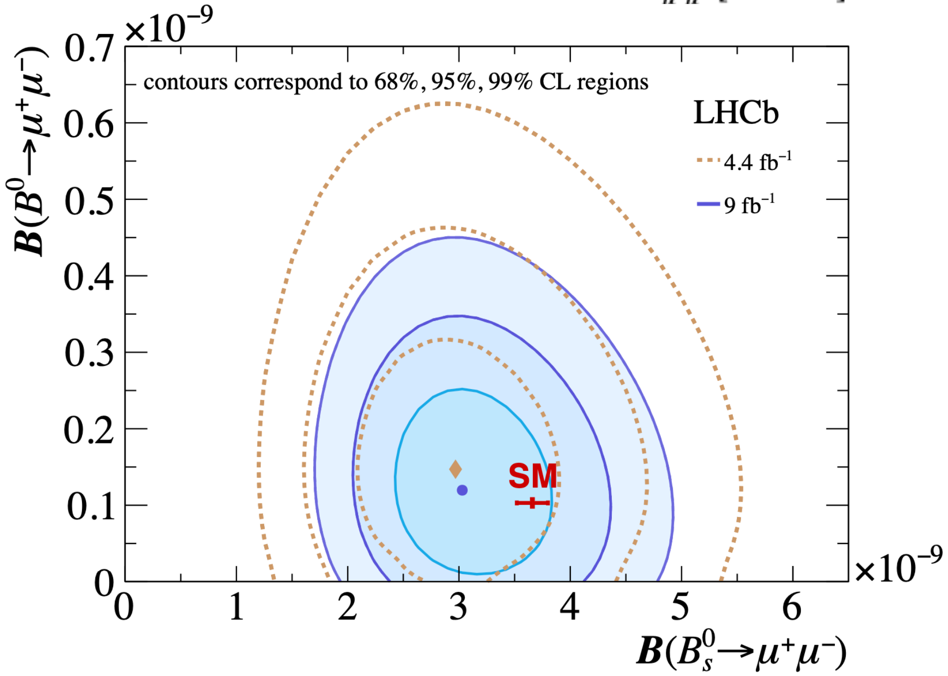
$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (3.09\,^{+0.46}_{-0.43}\,^{+0.15}_{-0.11}) \times 10^{-9}$$
$$\mathcal{B}(B^0 \to \mu^+\mu^-) < 2.6 \times 10^{-1} \text{at } 95\% \text{ CL}$$

Sensitivity approaching SM uncertainty

- Great prospects with Run-3 data!

LHCb-PAPER-2021-007





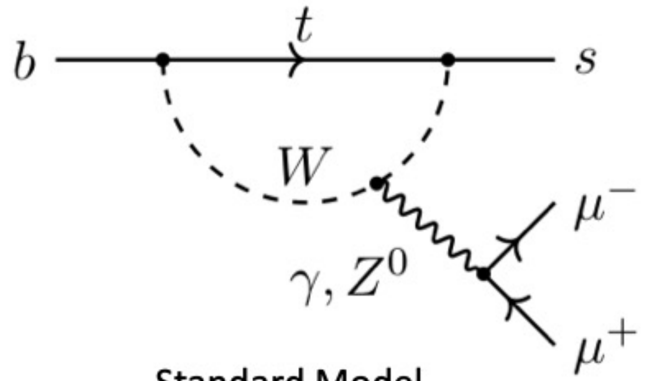
$b \rightarrow s\ell^+\ell^-$ transitions and LFU tests

- 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

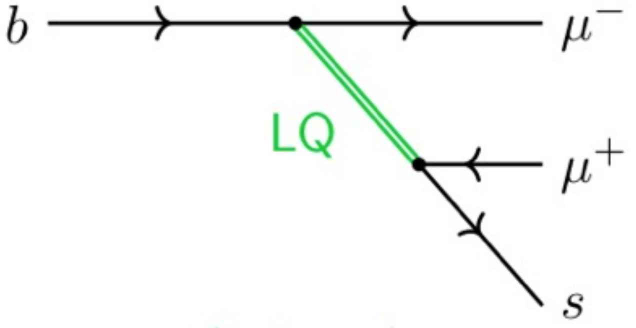
  $R_K = \mathfrak{B}(B^+ \rightarrow K^+\mu^+\mu^-) \,/\, \mathfrak{B}(B^+ \rightarrow K^+e^+e^-)$

  $R_{K*} = \mathfrak{B}(B^0 \rightarrow K^{*0}\mu^+\mu^-) \,/\, \mathfrak{B}(B^0 \rightarrow K^{*0}e^+e^-)$
- 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!

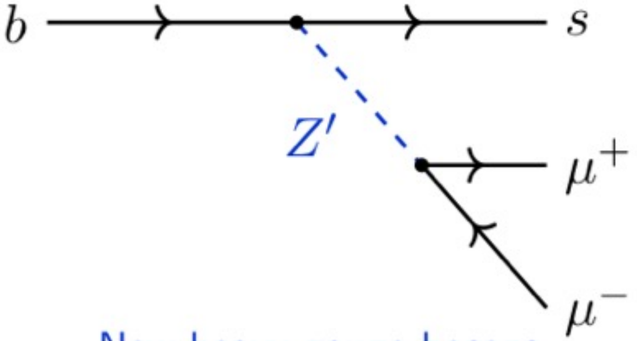
$$R_H = \frac{\int_{q^2_{\min}}^{q_{\max}} \frac{d\mathcal{B}(B \to H\mu^+\mu^-)}{dq^2}\, dq^2}{\int_{q^2_{\min}}^{q_{\max}} \frac{d\mathcal{B}(B \to He^+e^-)}{dq^2}\, dq^2} \overset{\text{SM}}{\cong} 1$$



Standard Model



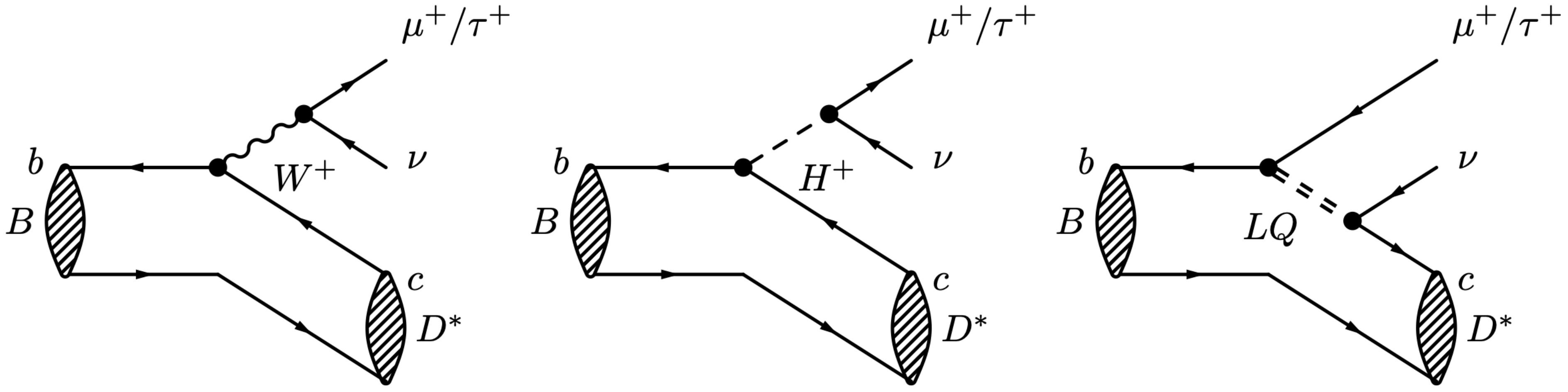
Leptoquarks



New heavy gauge bosons

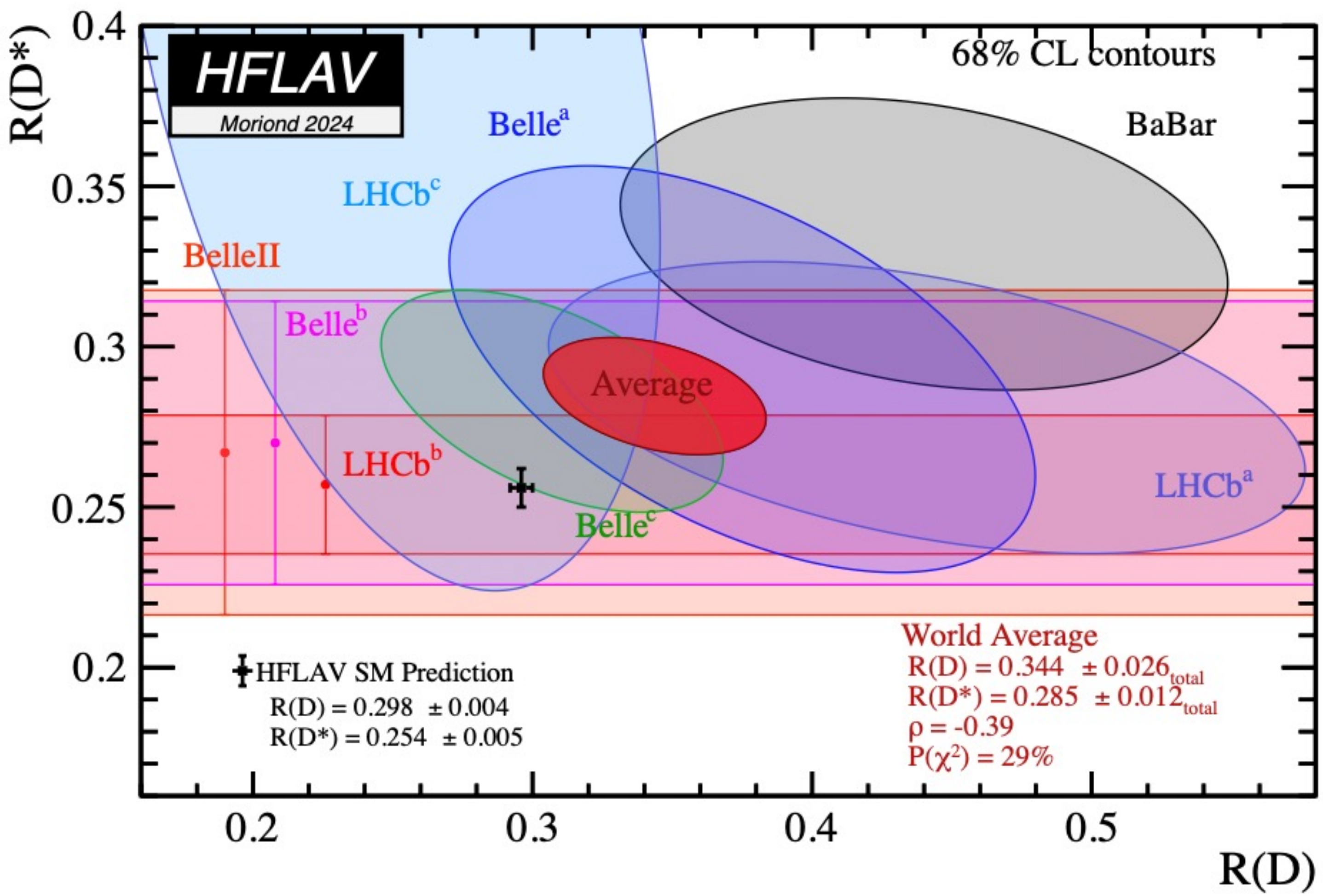
Semileptonic anomalies

- In the Standard Model, the only difference between $\overline{B} \to D^{(*)}\tau^-\overline{\nu}_\tau$ and $\overline{B} \to D^{(*)}\mu^-\overline{\nu}_\mu$ is the mass of the charged lepton
  - Form factors mostly cancel in the ratio of rates
- Ratio $\mathrm{R}(D^{(*)}) = \mathcal{B}(\overline{B} \to D^{(*)}\tau^-\overline{\nu}_\tau) \;/\; \mathcal{B}(\overline{B} \to D^{(*)}\mu^-\overline{\nu}_\mu)$ is sensitive to e.g charged Higgs, leptoquarks



Semileptonic anomalies

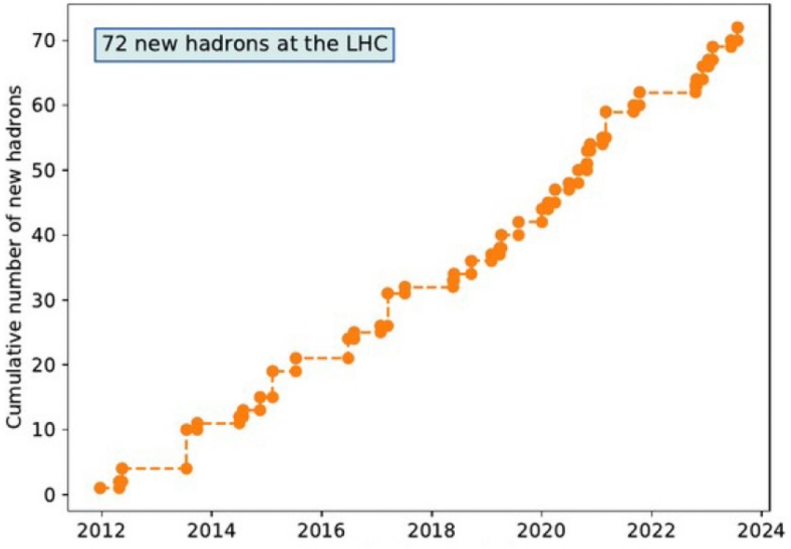
- Combining all measurements for BaBar, Belle and LHCb, world average at 3.2σ from the Standard Model
- Need further data to clarify the experimental picture

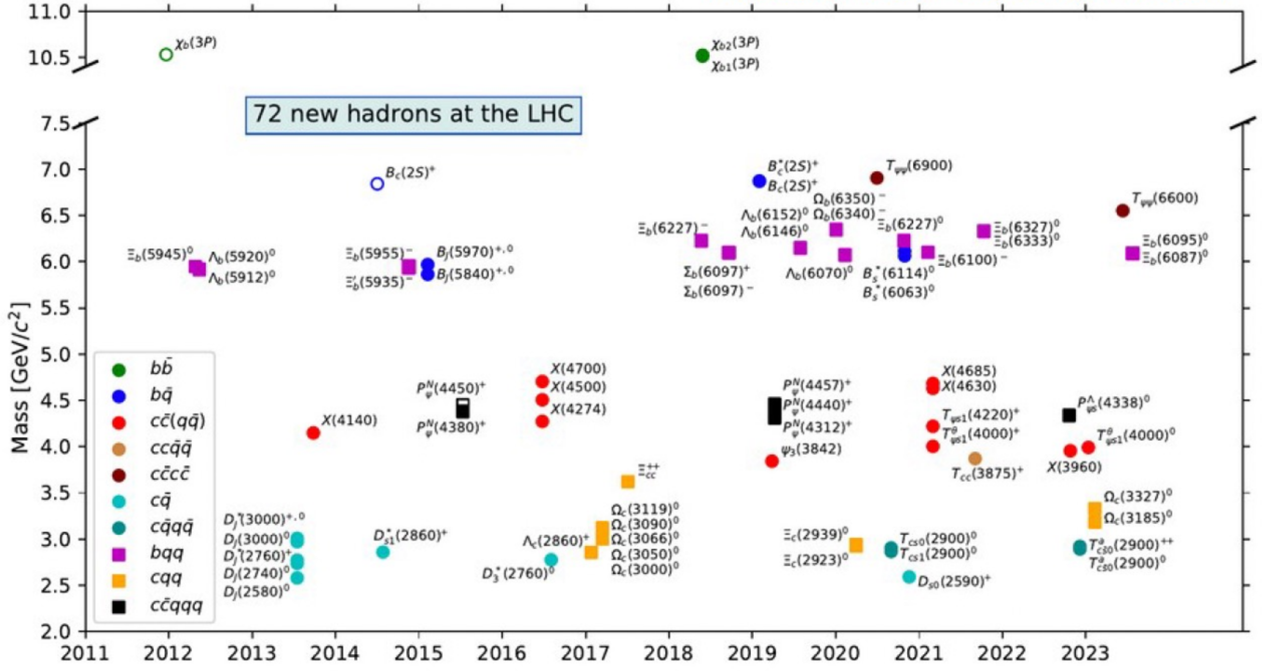


Spectroscopy

- 72 new hadrons observed at the LHC so far, amongst which 64 from LHCb, including several tetra- and penta-quarks!

https://www.nikhef.nl/~pkoppenb/particles.html

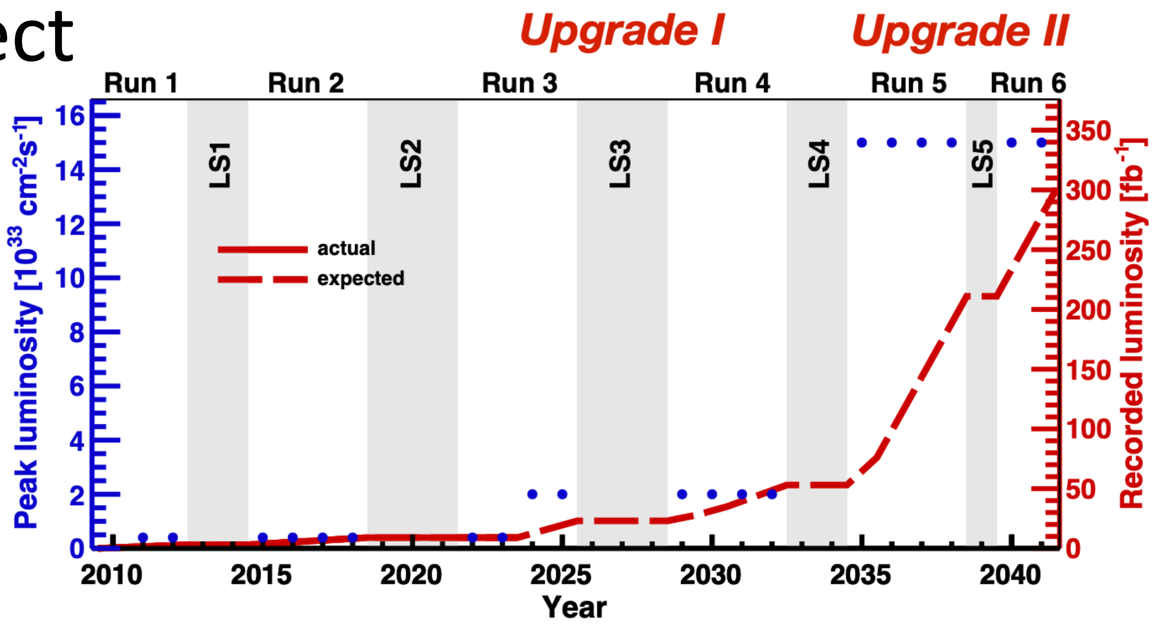




- LHCb measurements are inspiring lots of work from the rich theory community involved in this sector

Future prospects

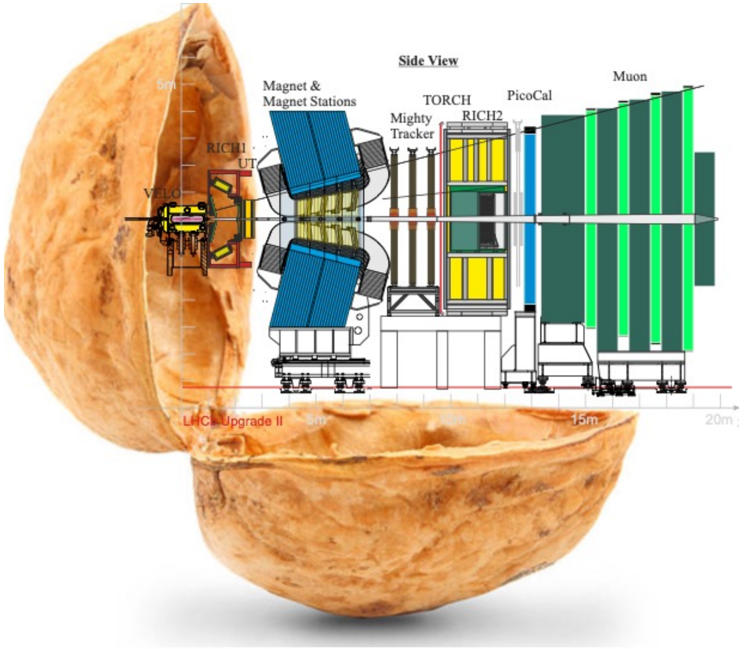
- European Strategy Update 2020: "The full physics potential of the LHC and the HL-LHC, including the study of flavour physics, ... should be exploited"
- LHCb Upgrade I was designed to collect 50 fb^{-1} by end of Run 4, but there is the opportunity to operate the experiment until the end of HL-LHC
  - 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 is an extremely rich laboratory to look for physics beyond the SM
- After the era of the *B* factories, with data from the first two runs of the LHC, LHCb published several interesting results spanning a wide physics programme, in about 730 publications so far
  - Only a few results shown today → the LHCb physics spectrum is much larger
- 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, hoping that new physics will eventually show up
- Looking forward to continue the collaboration with our Ukrainian institutes in Kyiv and Karkhiv towards the 2040s!