Present and future of LHCb Physics

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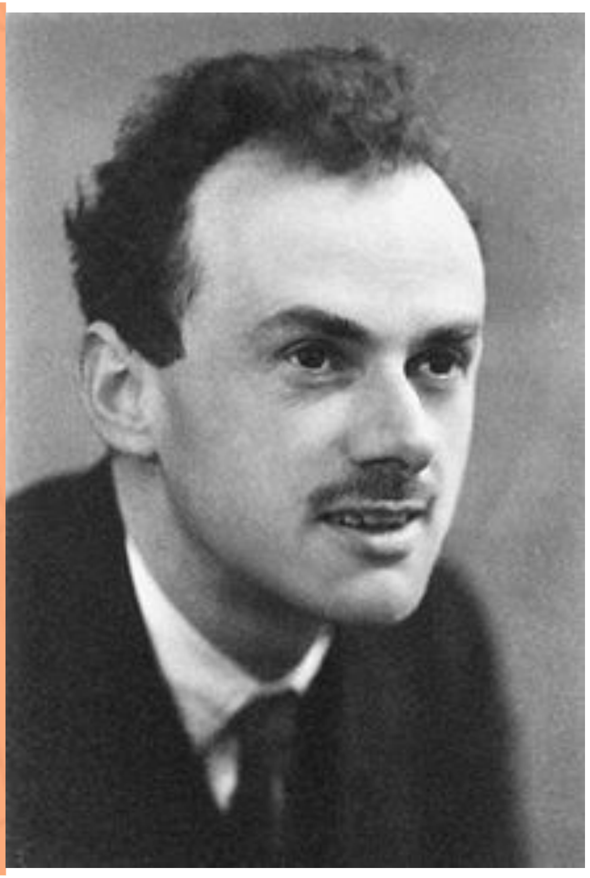
Standard Model: how stubborn is it?

- Why three generations of leptons and quarks?
- Why different masses of fundamental particles?
  - Spanning several orders of magnitude
- What's the origin of the structure of flavour couplings?
- What's dark matter made of?
  - And even worse, what's dark energy?
- Why the universe is made of "matter" and not "antimatter" ?
  - Baryon asymmetry of the universe (BAU)
- What about gravity?
  - Why so weak with respect to the other interactions?
  - How to develop a consistent theory of quantum gravity?
- …

The Standard Model is not the ultimate theory, but certainly it's incredibly stubborn

First thoughts on BAU: Dirac dixit…

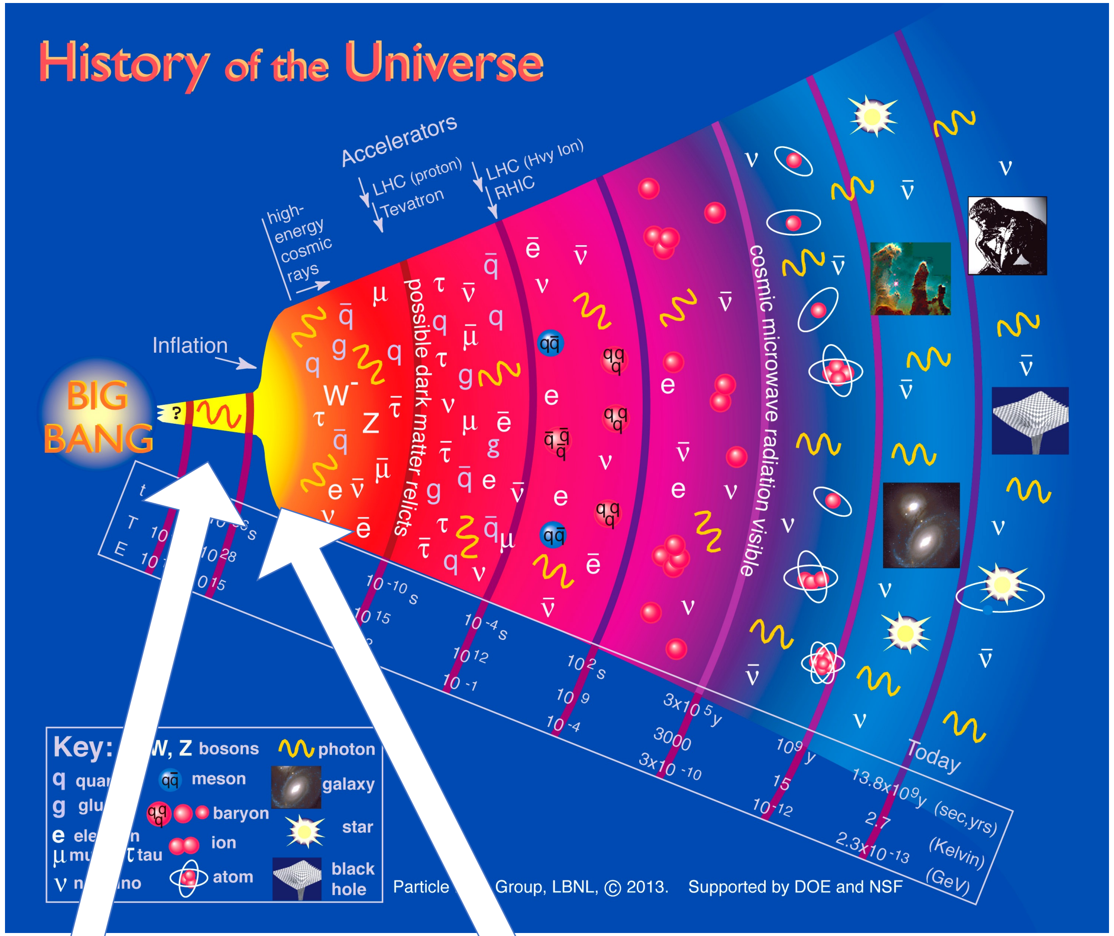
> “If we accept the view of complete symmetry between positive and negative electric charge so far as concerns the fundamental laws of Nature, we must regard it rather as an accident that the Earth (and presumably the whole solar system), contains a preponderance of negative electrons and positive protons. It is quite possible that for some of the stars it is the other way about, these stars being built up mainly of positrons and negative protons. In fact, there may be half the stars of each kind. The two kinds of stars would both show exactly the same spectra, and there would be no way of distinguishing them by present astronomical methods.”



- Excerpt of Dirac’s Nobel lecture in 1933
- At the time we were starting to wonder where had antimatter gone…

Matter-dominated universe

- We observe that there's no evidence of primary antimatter on the scale of the observable universe today
- What led to the disappearance of antimatter assuming an initial symmetric state?
- How big the asymmetry should have been to lead to what we observe?

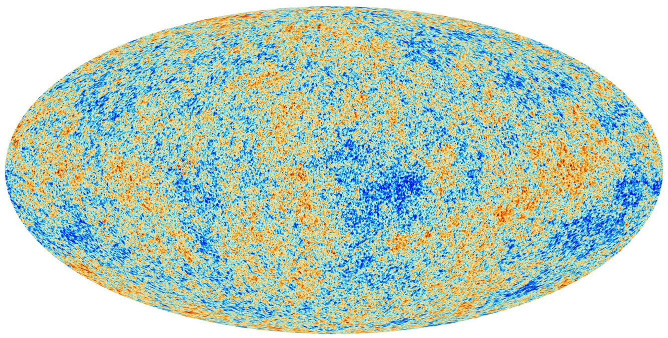


Symmetric matter-antimatter initial state?

Symmetry broken right after inflation?

Mainstream explanation

- Antimatter and matter particles annihilated massively in the early universe, but a tiny fraction of matter was left over



Planck data

- The radiation produced by the initial annihilation is what we see today as the big bang afterglow: the cosmic microwave background (CMB)
  - By measuring CMB photon and baryon number densities in the universe we can determine how much matter survived the annihilation with respect to matter-antimatter annihilations

Mainstream explanation

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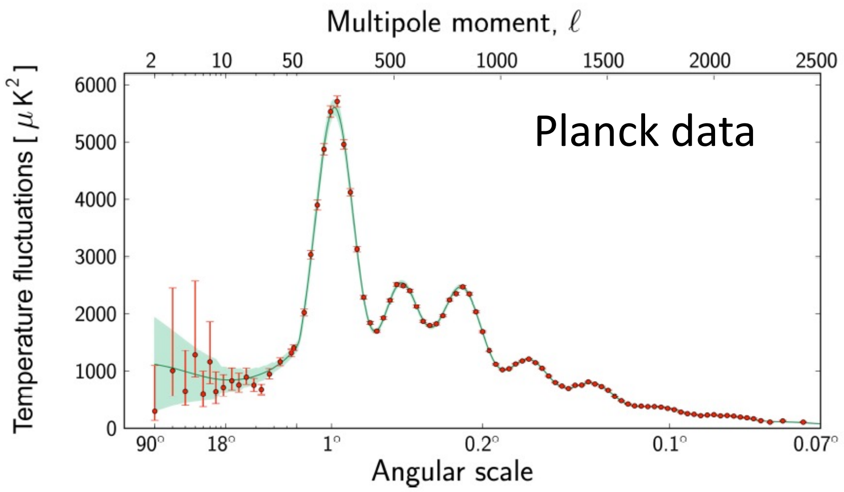


- The ratio of baryon to CMB-photon number densities is nowadays very well known, precisely measured in the framework of ΛCDM cosmological model

Every 10^{10} particle-antiparticle annihilations only a handful of matter particle survived

$$\eta = (6.04 \pm 0.08) \times 10^{-10}$$

Can we explain the asymmetry by Standard Model physics?

- Qualitatively: yes
  - The Standard Model in principle contains all the necessary ingredients
- It is possible to derive an expression of the ratio η

$$\eta = \frac{n_B}{n_\gamma} \sim \frac{(m_t^2 - m_u^2)(m_t^2 - m_c^2)(m_c^2 - m_u^2)(m_b^2 - m_d^2)(m_b^2 - m_s^2)(m_s^2 - m_d^2)\,2J}{M^{12}}$$

where $J \approx 3\times10^{-5}$ is the Jarlskog invariant* quantifying the size of *CP* violation in the Standard Model and M≈100 GeV is the electroweak scale at which the baryon asymmetry freezes out

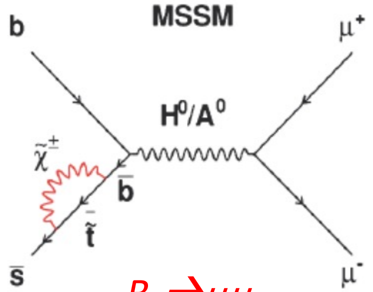
*Phys. Rev. Lett. 55 (1985) 1039

Can we explain the asymmetry by Standard Model physics?

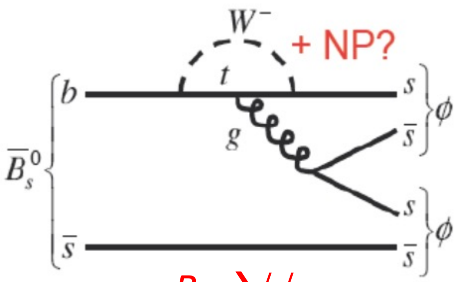
- Quantitatively: no
- The previous equation gives $\eta \approx 10^{-19}$, which is off by 10 orders of magnitude with respect to the experimental observation
- *CP* violation in the Standard Model is too small
- Are there new sources of *CP* violation in some beyond-the-SM physics?

New physics searches in the flavour sector

- Look for indirect effects of new particles to low energy processes

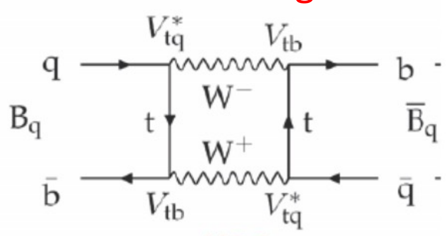


$B_s \to \mu\mu$



$B_s \to \phi\phi$

B-$\bar{B}$ mixing



+ NP?

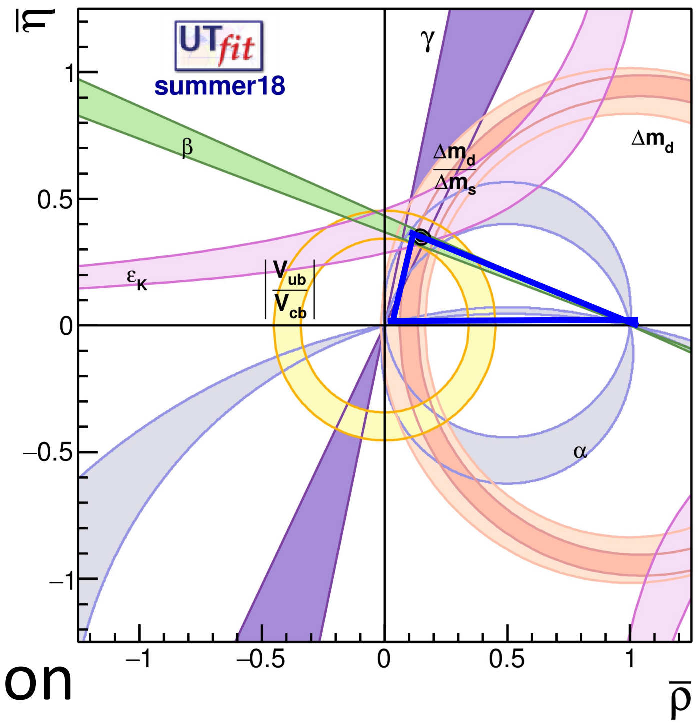
- General amplitude decomposition in terms of couplings and scales

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

- Fundamental tasks
  - Look for new sources of *CP* violation
  - Identify new symmetries (and their breaking) beyond the SM
  - Probe mass scales not directly accessible directly at energy frontier

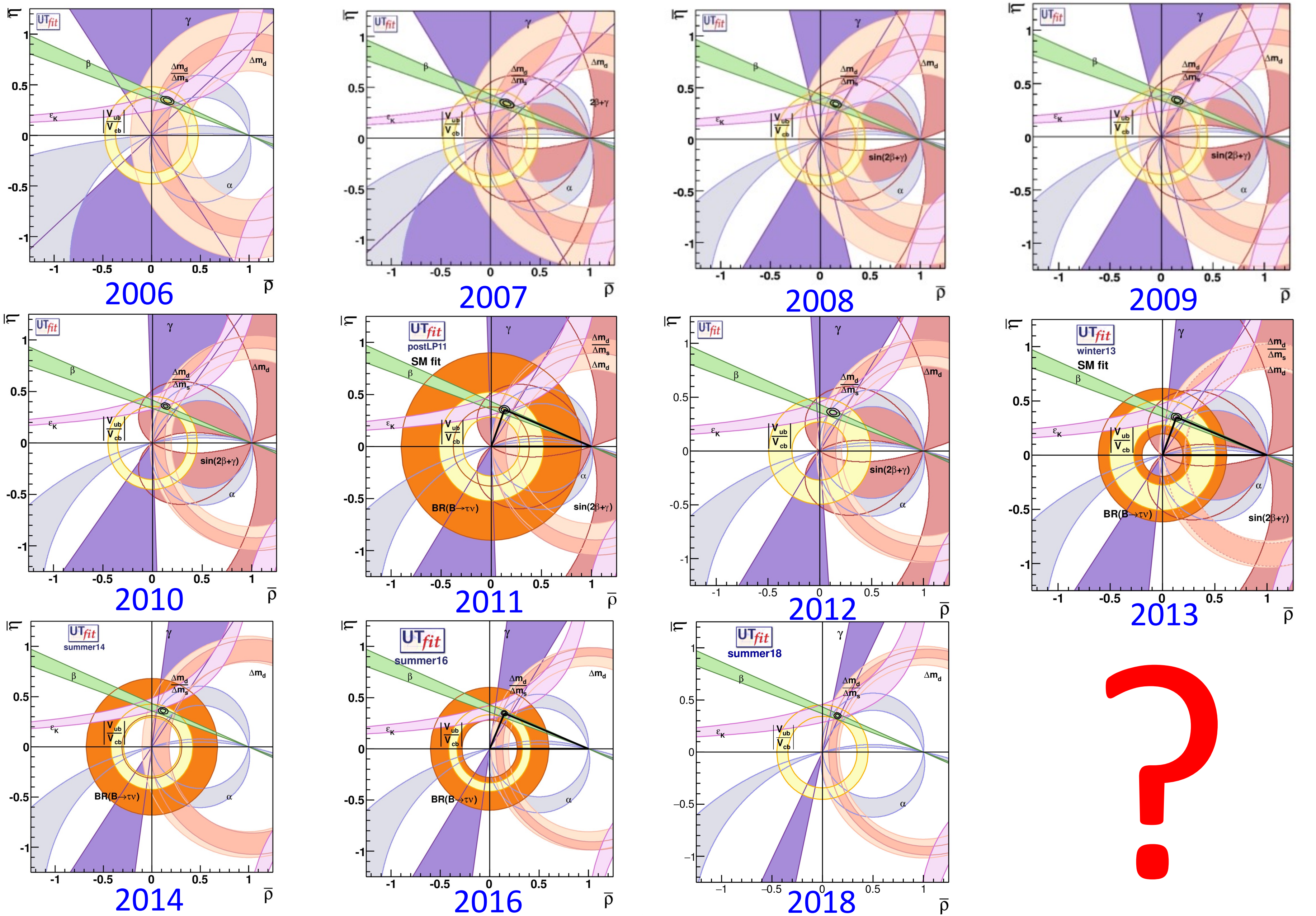
Consistency of global CKM fits on Unitarity Triangle

http://www.utfit.org



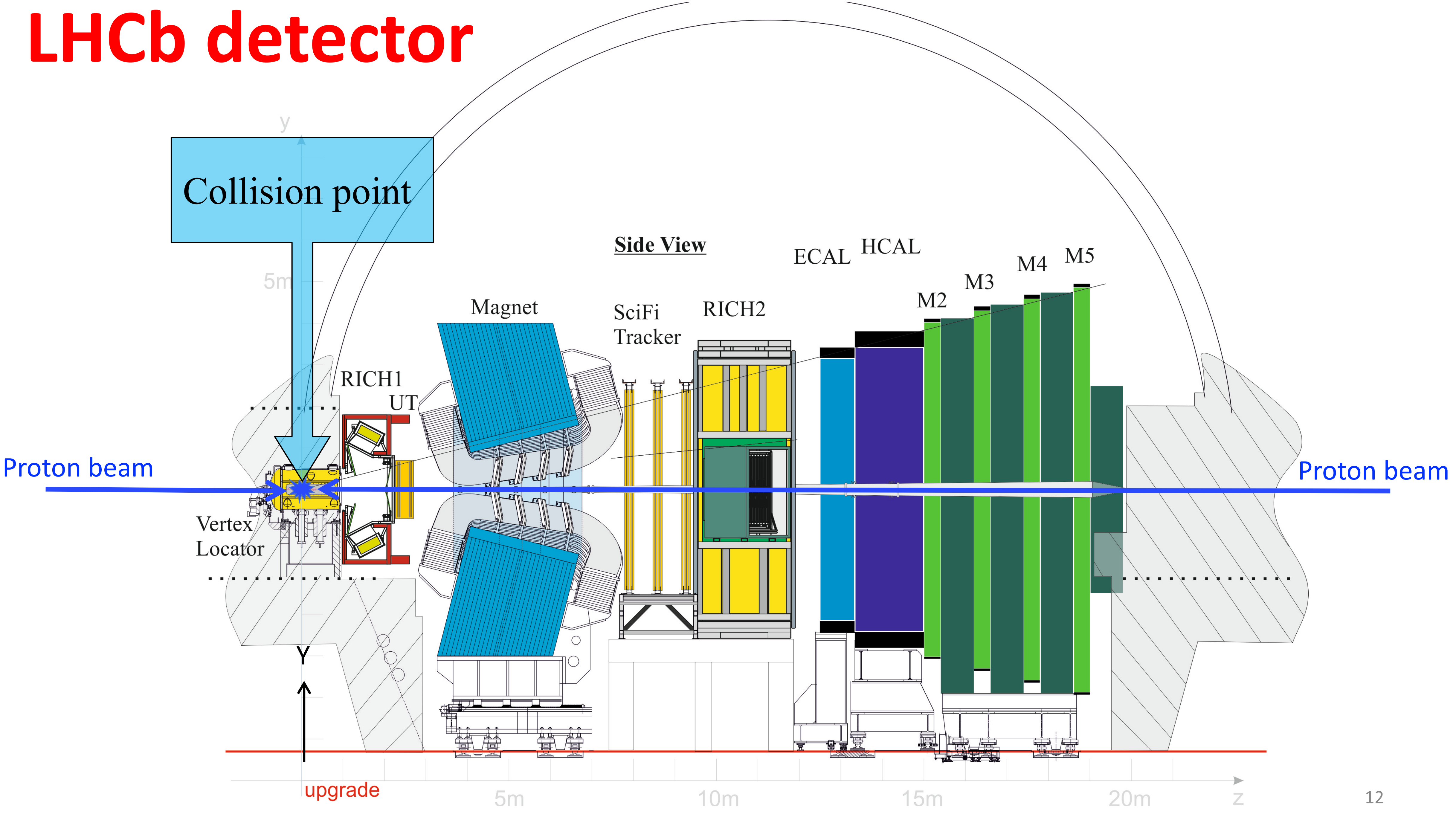
- Each coloured band defines the allowed region of the apex of the unitarity triangle according to the measurement of a specific process
- Tremendous success of the CKM paradigm!
  - All of the available measurements agree in a highly profound way to the current level of precision
  - In presence of new physics affecting some of 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 new physics can manifest as small discrepancies

Long journey to reach here...



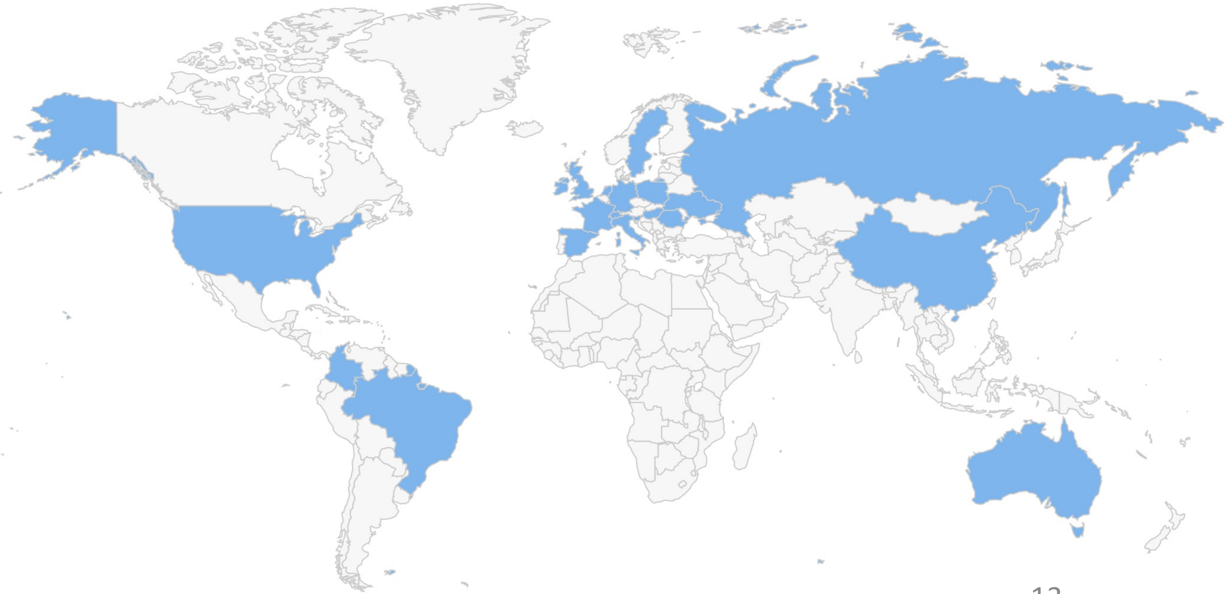
?

LHCb detector

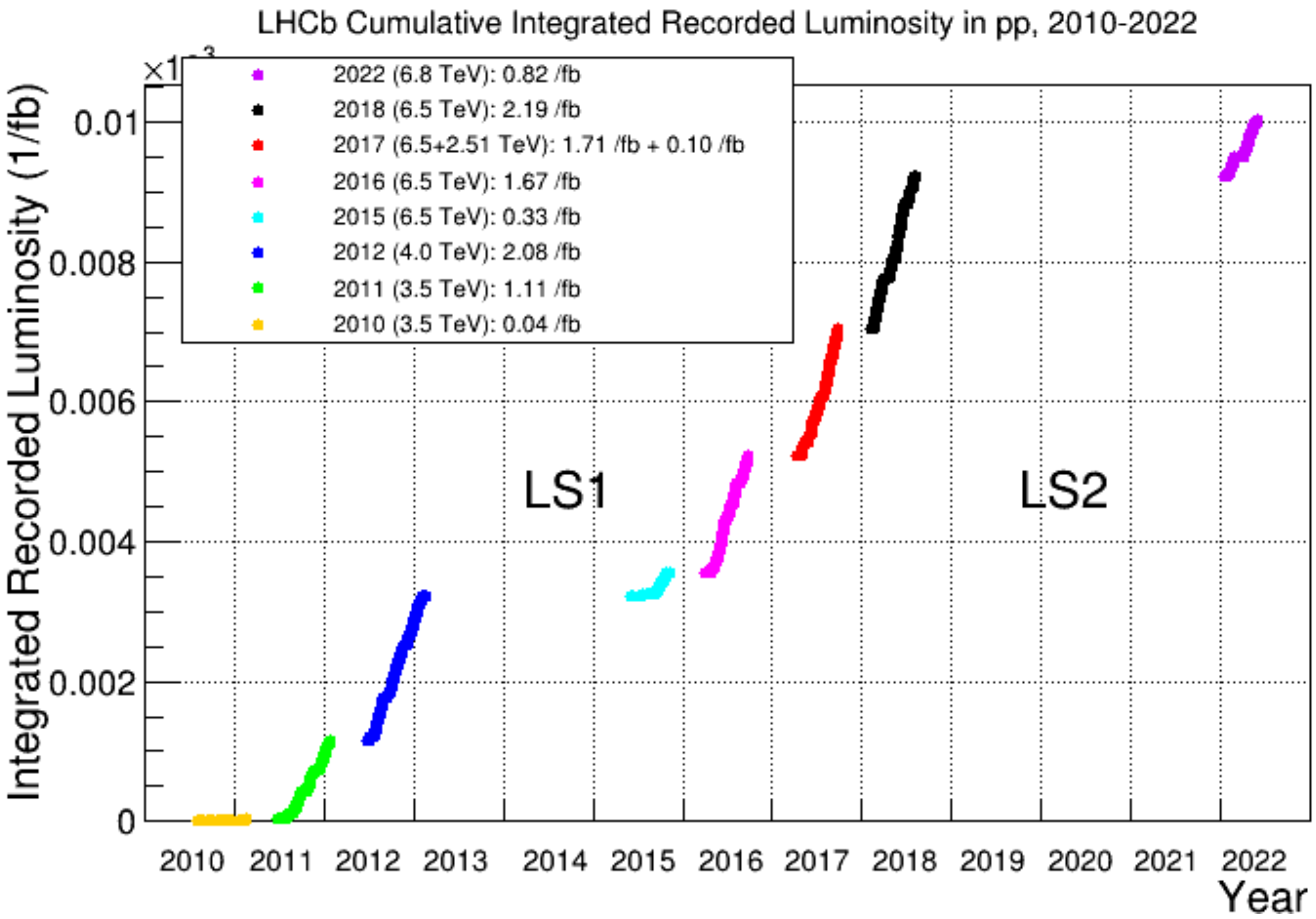


LHCb people

- As of today, 1540 members from 95 institutes in 20 Countries

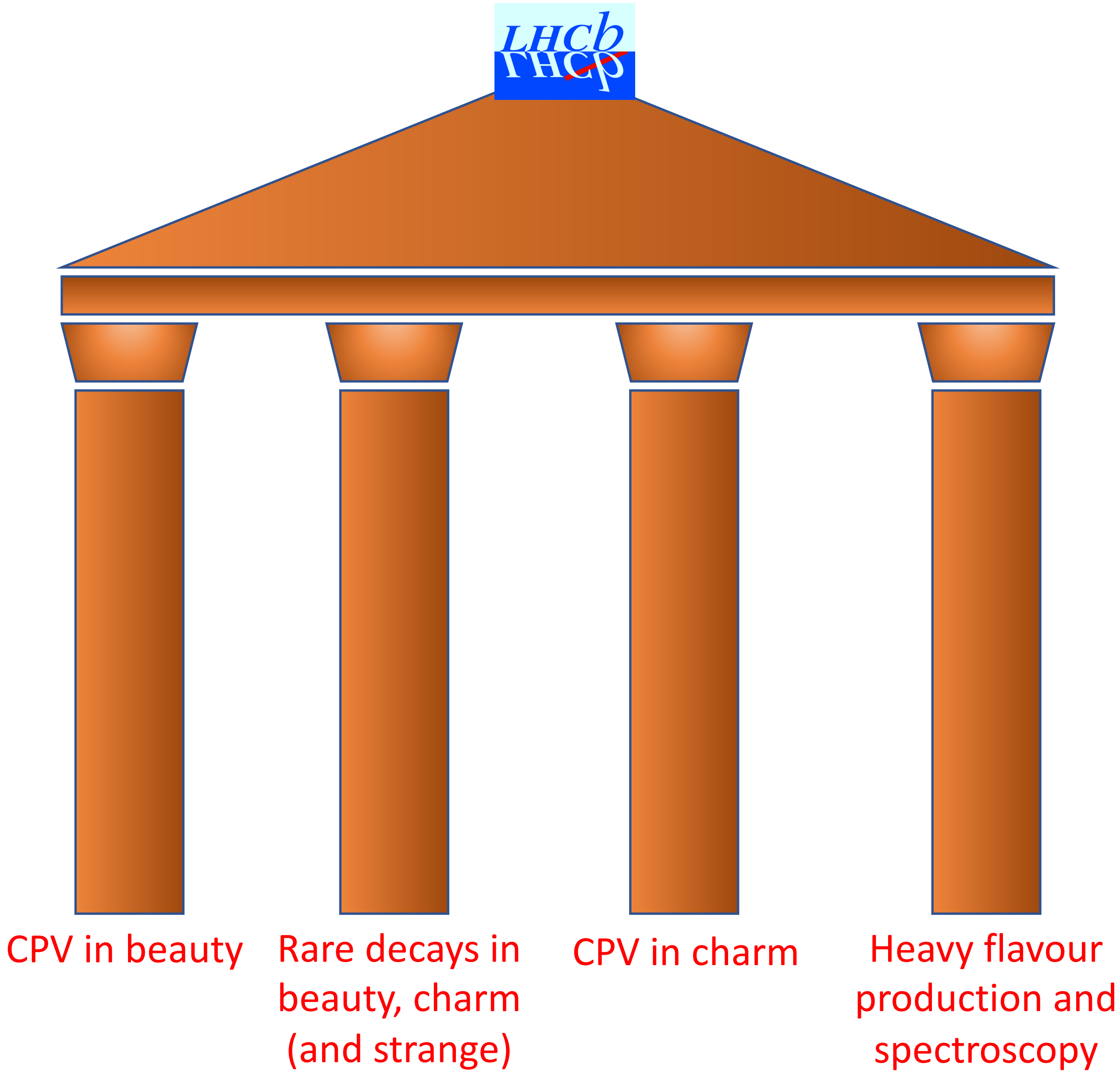


LHCb data

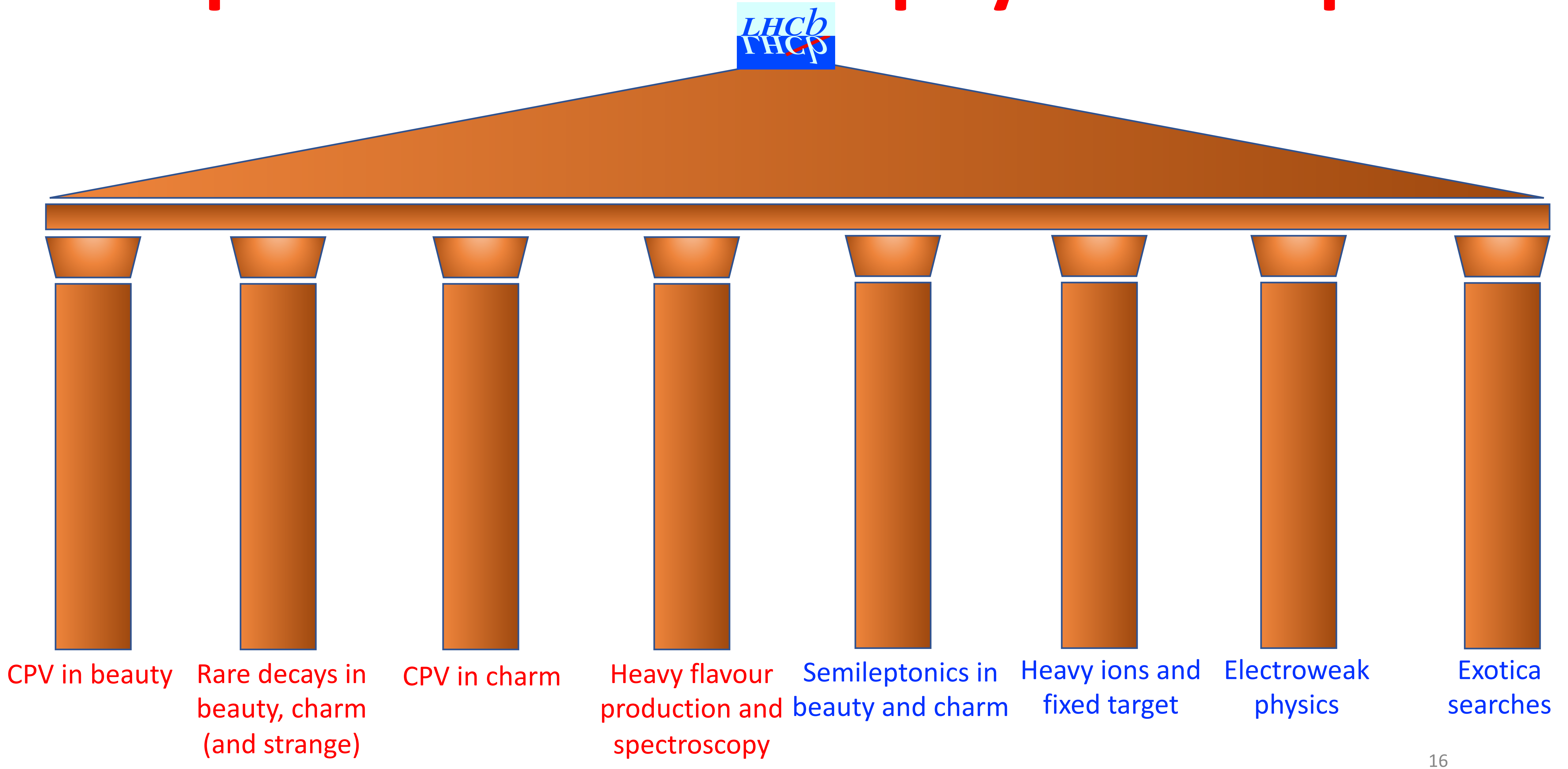


LHCb Cumulative Integrated Recorded Luminosity in pp, 2010-2022
×10⁻³
2022 (6.8 TeV): 0.82 /fb
2018 (6.5 TeV): 2.19 /fb
2017 (6.5+2.51 TeV): 1.71 /fb + 0.10 /fb
2016 (6.5 TeV): 1.67 /fb
2015 (6.5 TeV): 0.33 /fb
2012 (4.0 TeV): 2.08 /fb
2011 (3.5 TeV): 1.11 /fb
2010 (3.5 TeV): 0.04 /fb
Integrated Recorded Luminosity (1/fb)
0.01
0.008
0.006
0.004
0.002
0
LS1
LS2
2010 2011 2012 2013 2014 2015 2016 2017 2018 2019 2020 2021 2022
Year

The pillars of the LHCb physics temple

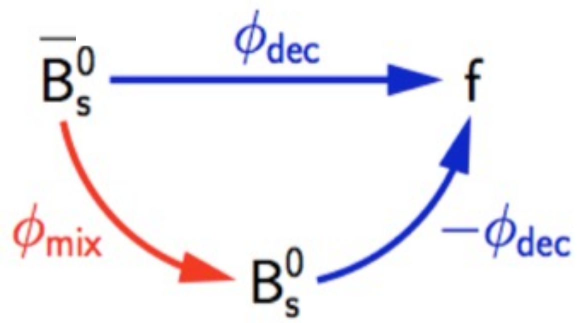


The pillars of the LHCb physics temple

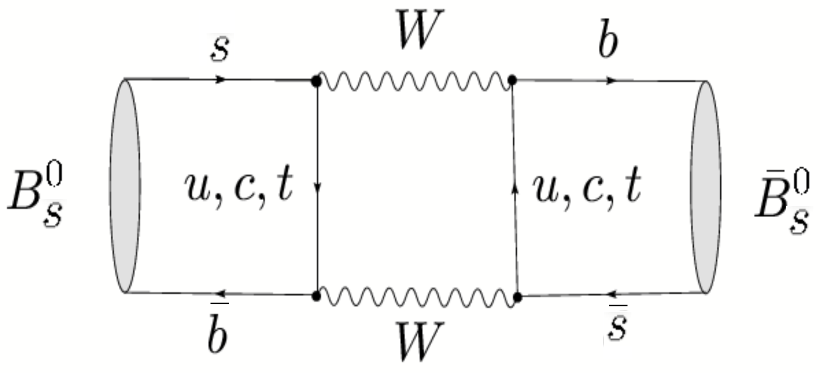


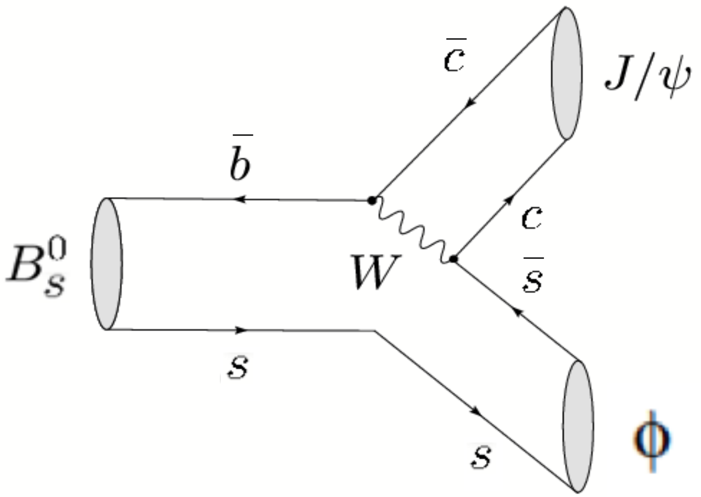
A glimpse of present LHCb physics

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

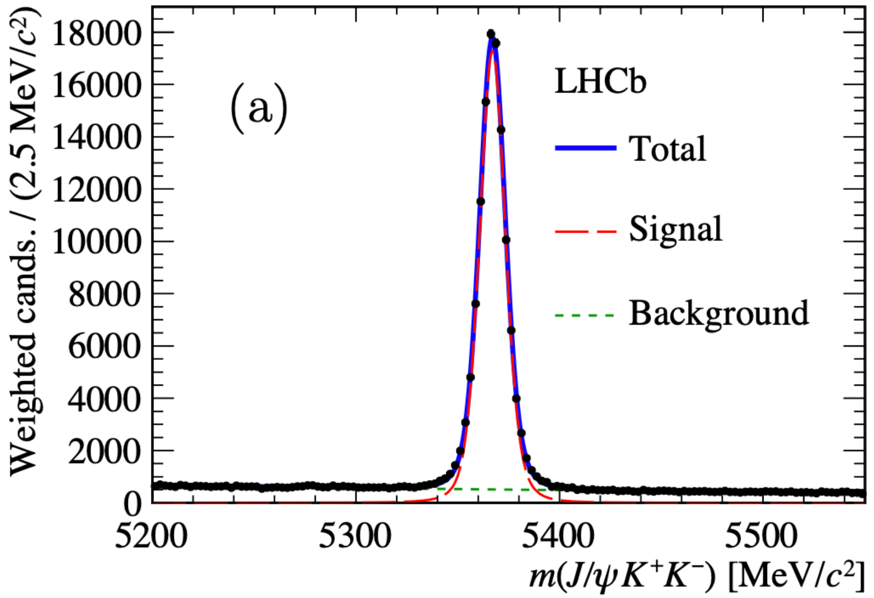




- One measures the phase-difference ϕ_s between the two diagrams, precisely predicted in the Standard Model to be $\phi_s = -2\lambda^2\eta = -37.4 \pm 0.7$ mrad → very small *CP* violation in the Standard Model
- Additional contributions from new physics can modify this value → need precise experimental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

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

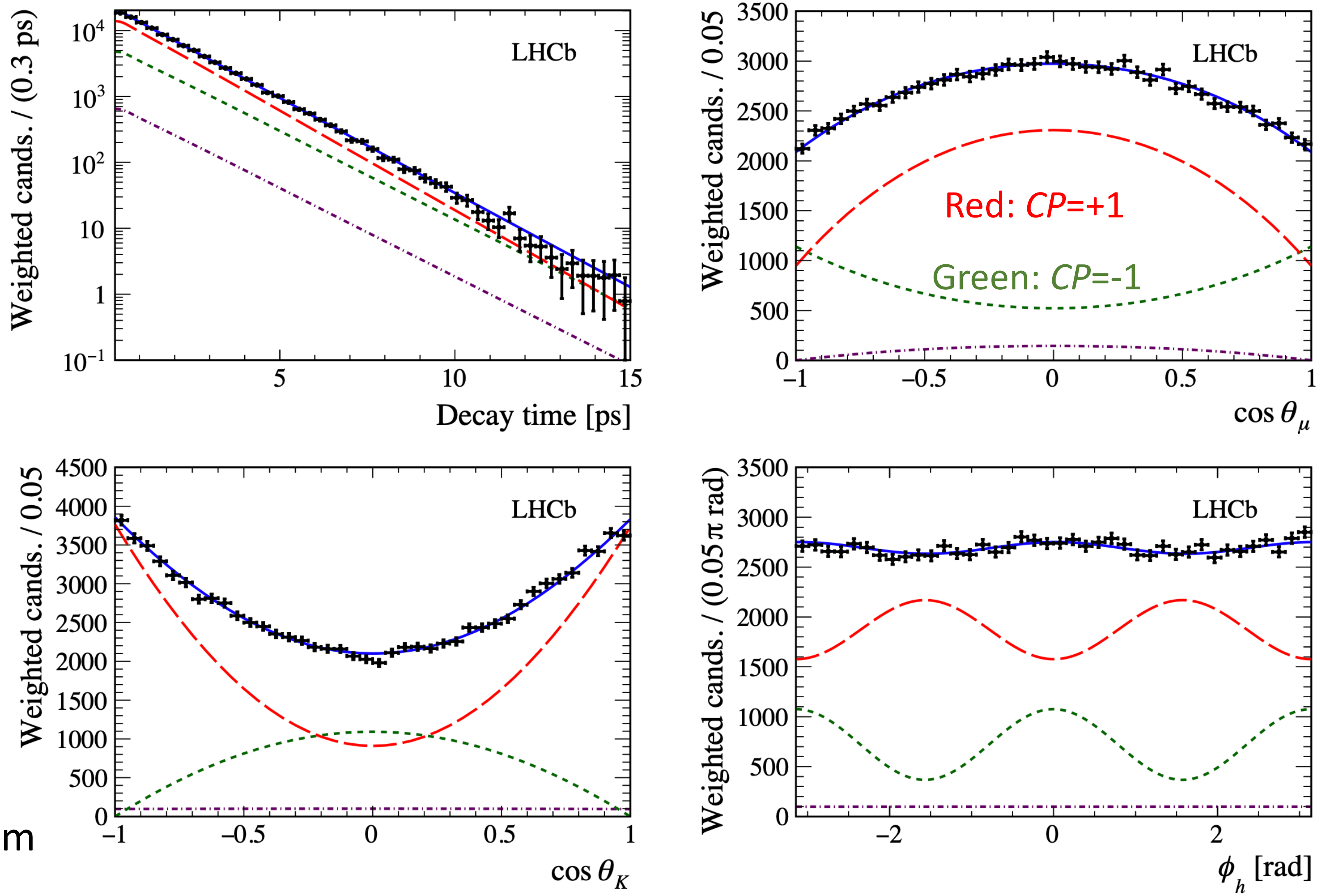
- Conceptually similar to measuring sin(2β), but now we have a pseudoscalar to vector-vector decay
- The final state is not a *CP* eigenstate, but a mixture of *CP*=+1 and *CP*=-1 eigenstates
  - Angular analysis of decay products is needed to disentangle the two eigenstates
- Furthermore, for a B_s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

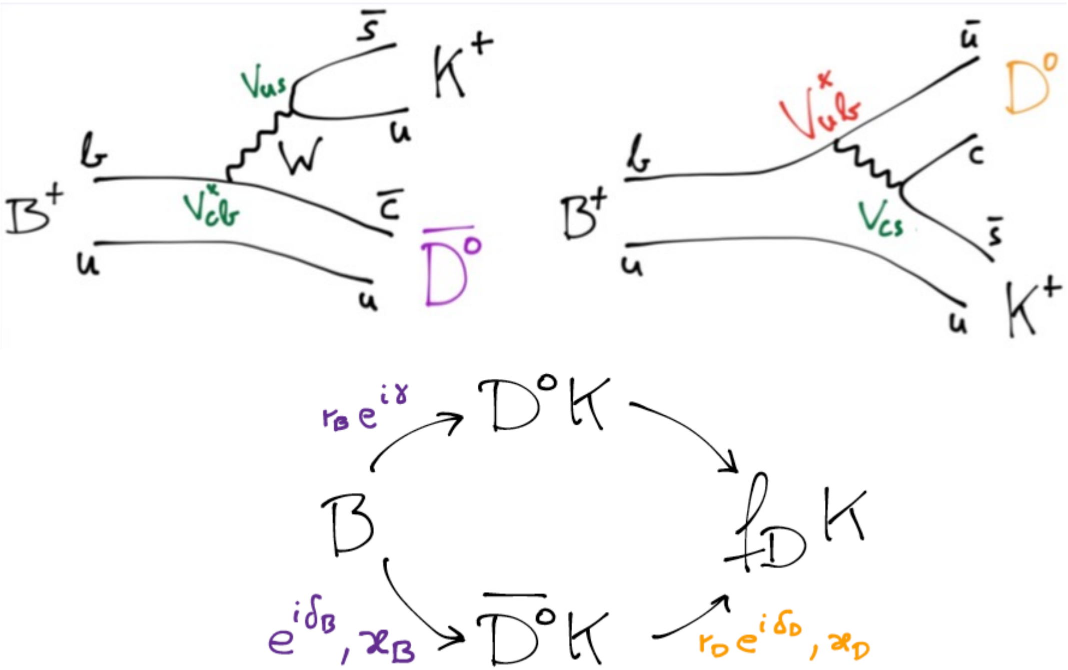
$$\phi_s = -0.0374 \pm 0.007\ \mathrm{rad}$$

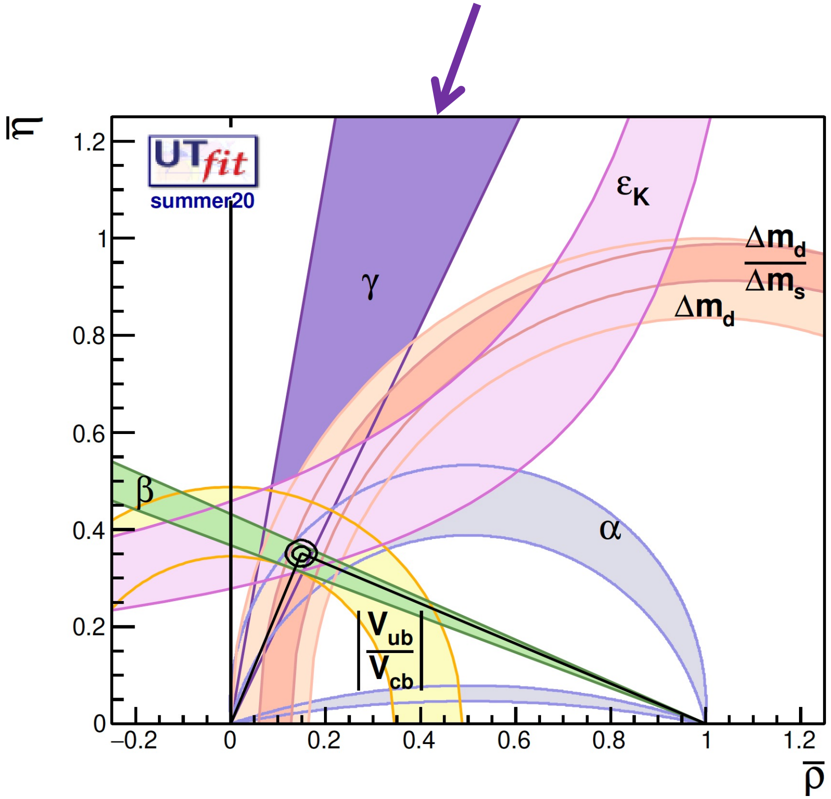
Not yet incompatible, but large room for experimental improvement

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

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





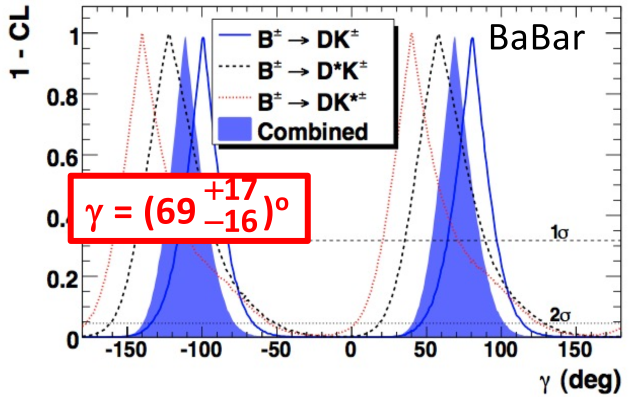
- Simple and clean theoretical interpretation, but statistically very challenging

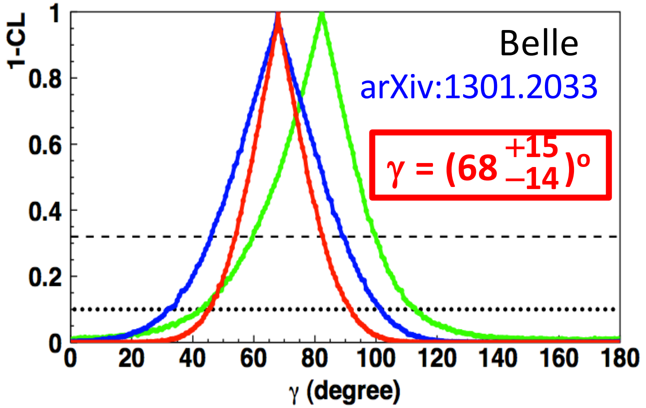
Measurement of the CKM angle γ

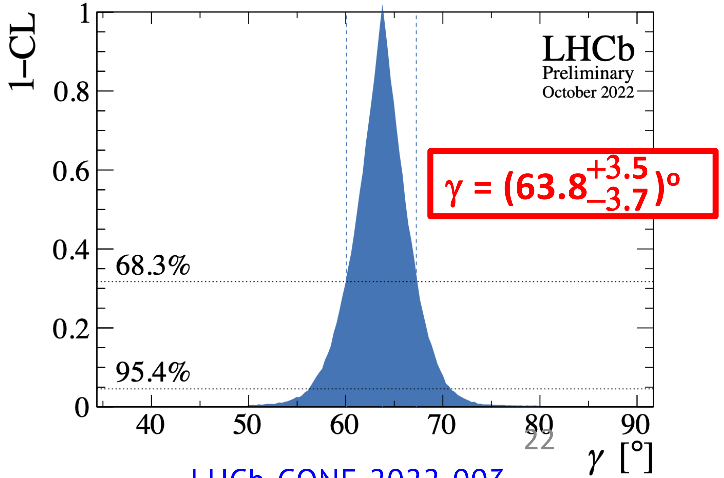
- A plethora of independent measurements exploiting different methods and decays
- LHCb precision significantly better than that of previous results from the *B*-factories and undergoing continuous improvements

B decay	D decay
$B^{\pm} \to Dh^{\pm}$	$D \to h^{+}h^{-}$
$B^{\pm} \to Dh^{\pm}$	$D \to h^{+}\pi^{-}\pi^{+}\pi^{-}$
$B^{\pm} \to Dh^{\pm}$	$D \to K^{\pm}\pi^{\mp}\pi^{+}\pi^{-}$
$B^{\pm} \to Dh^{\pm}$	$D \to h^{+}h^{-}\pi^{0}$
$B^{\pm} \to Dh^{\pm}$	$D \to K^{0}_{S}h^{+}h^{-}$
$B^{\pm} \to Dh^{\pm}$	$D \to K^{0}_{S}K^{\pm}\pi^{\mp}$
$B^{\pm} \to D^{*}h^{\pm}$	$D \to h^{+}h^{-}$
$B^{\pm} \to DK^{*\pm}$	$D \to h^{+}h^{-}$
$B^{\pm} \to DK^{*\pm}$	$D \to h^{+}\pi^{-}\pi^{+}\pi^{-}$
$B^{\pm} \to Dh^{\pm}\pi^{+}\pi^{-}$	$D \to h^{+}h^{-}$
$B^{0} \to DK^{*0}$	$D \to h^{+}h^{-}$
$B^{0} \to DK^{*0}$	$D \to h^{+}\pi^{-}\pi^{+}\pi^{-}$
$B^{0} \to DK^{*0}$	$D \to K^{0}_{S}\pi^{+}\pi^{-}$
$B^{0} \to D^{\mp}\pi^{\pm}$	$D^{+} \to K^{-}\pi^{+}\pi^{+}$
$B^{0}_{s} \to D^{\mp}_{s}K^{\pm}$	$D^{+}_{s} \to h^{+}h^{-}\pi^{+}$
$B^{0}_{s} \to D^{\mp}_{s}K^{\pm}\pi^{+}\pi^{-}$	$D^{+}_{s} \to h^{+}h^{-}\pi^{+}$

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





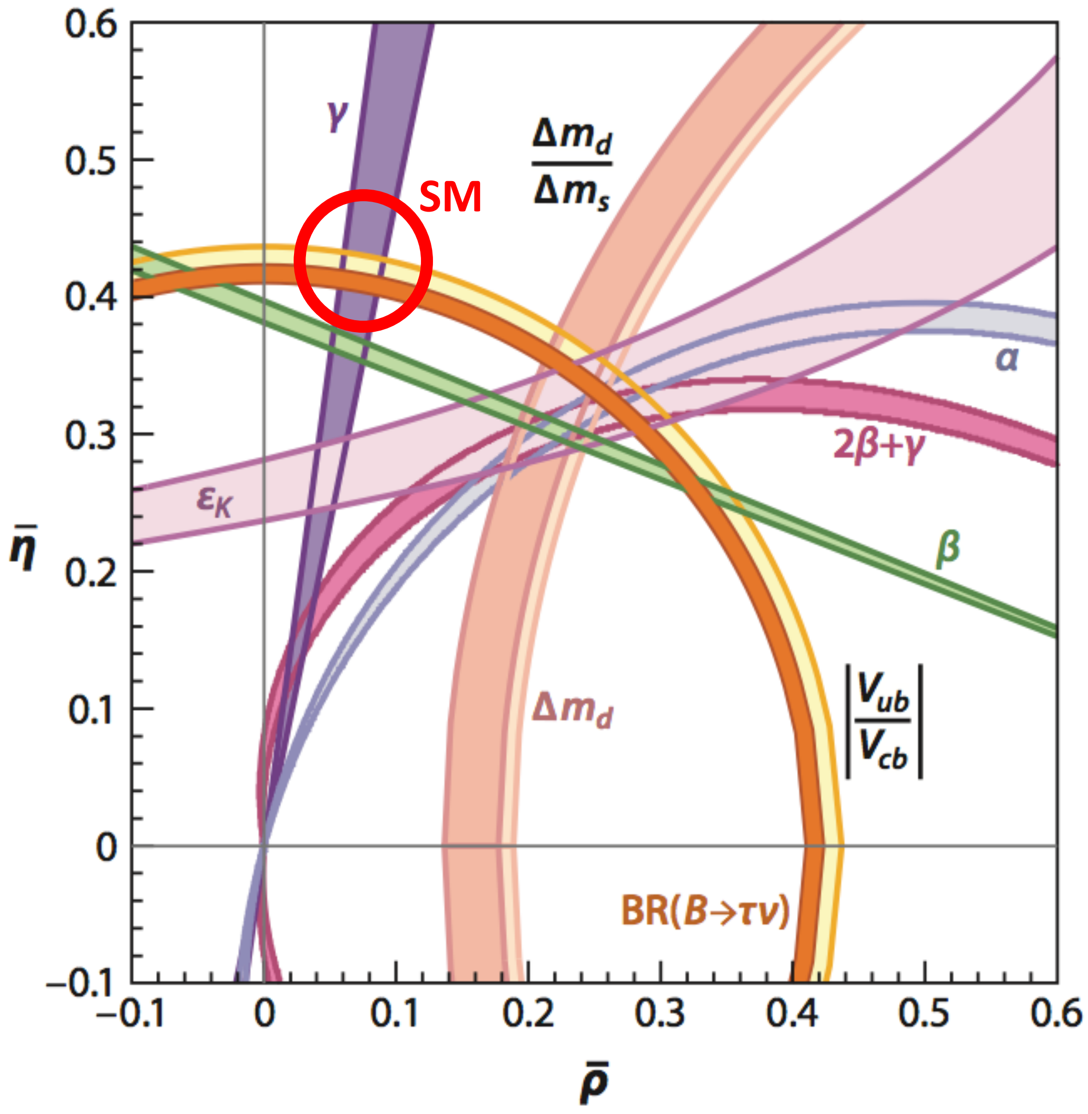


LHCb-CONF-2022-003

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

Why studying rare decays?

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

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

- For example, 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

LHCb-PAPER-2021-007

- 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

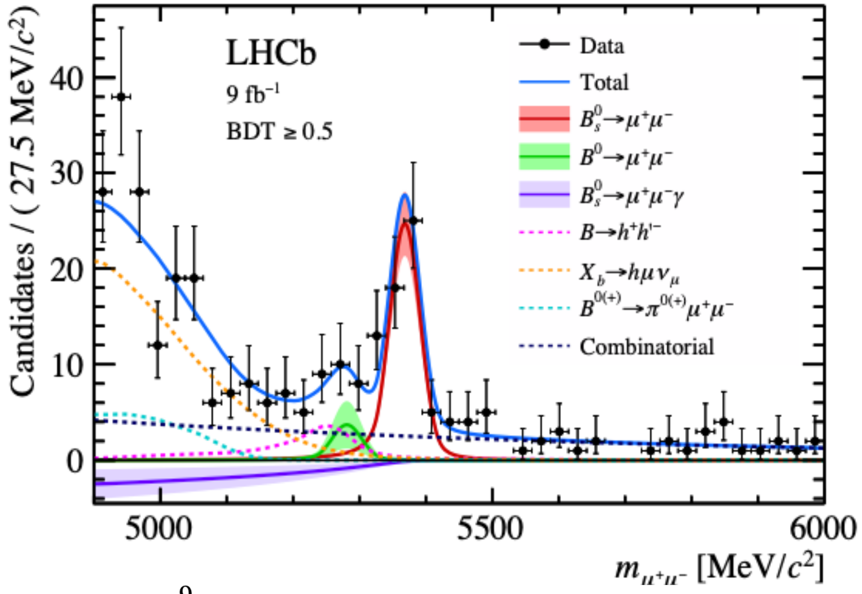
- Latest LHCb results

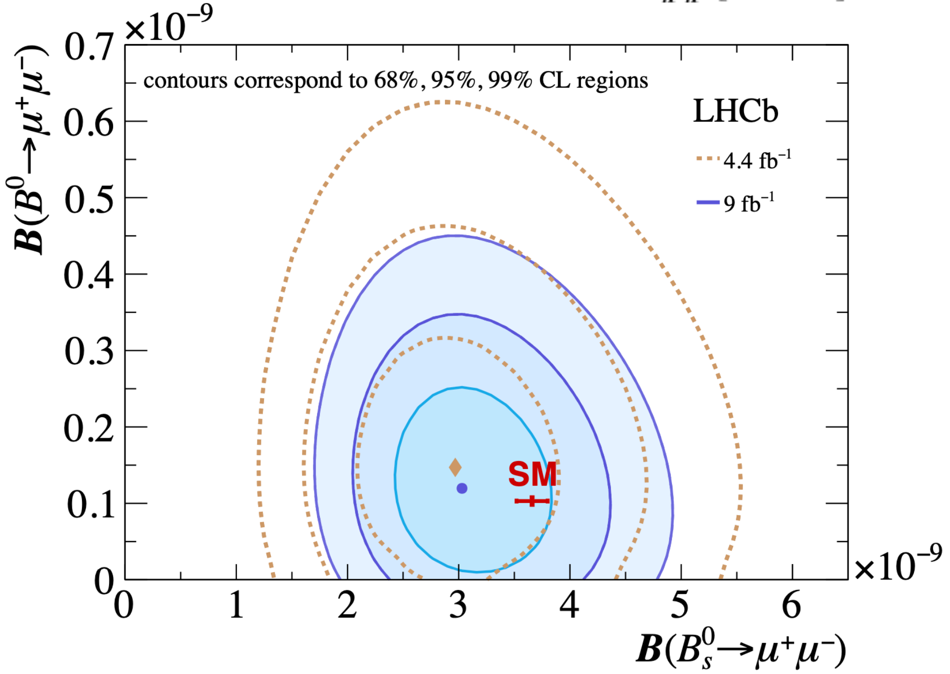
$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (3.09\,^{+0.46}_{-0.43}\,^{+0.15}_{-0.11}) \times 10^{-9}$$
$$\mathcal{B}(B^0 \to \mu^+\mu^-) < 2.6 \times 10^{-10} \text{ at 95\% CL}$$

Sensitivity approaching SM uncertainty

- Significant results from ATLAS and CMS, the latter in particular reached the same precision of LHCb with their latest measurement
  - LHC average from Summer 2020

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (2.69\,^{+0.37}_{-0.35}) \times 10^{-9}$$
$$\mathcal{B}(B^0 \to \mu^+\mu^-) < 1.9 \times 10^{-10} \text{ at 95\% CL}$$





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

- Measure ratios of decay rates to muons and electrons: LFU test

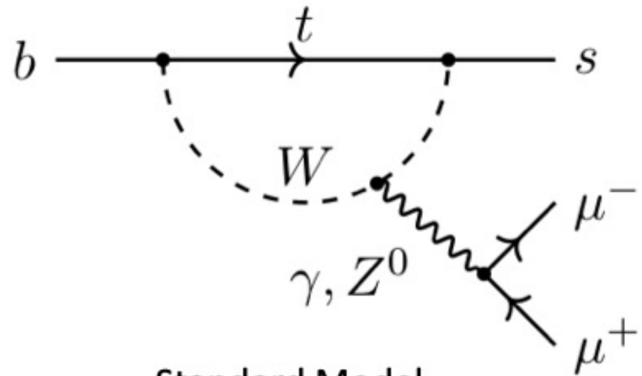
$$R_H = \frac{\int_{q^2_{\min}}^{q_{\max}} \frac{d\mathcal{B}(B \to H\mu^+\mu^-)}{dq^2}\, dq^2}{\int_{q^2_{\min}}^{q_{\max}} \frac{d\mathcal{B}(B \to He^+e^-)}{dq^2}\, dq^2} \overset{\text{SM}}{\cong} 1$$

- Theoretically very clean in the SM
  - Observation of non-LFU would be a clear sign of new physics
- Initially measured with the ratios

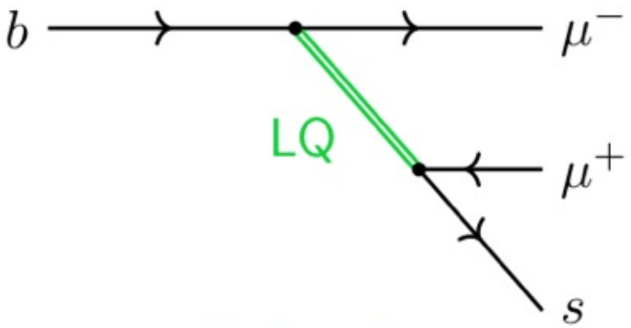
$R_K = \mathcal{B}(B^+ \to K^+\mu^+\mu^-) / \mathcal{B}(B^+ \to K^+e^+e^-)$

$R_{K*} = \mathcal{B}(B^0 \to K^{*0}\mu^+\mu^-) / \mathcal{B}(B^0 \to K^{*0}e^+e^-)$

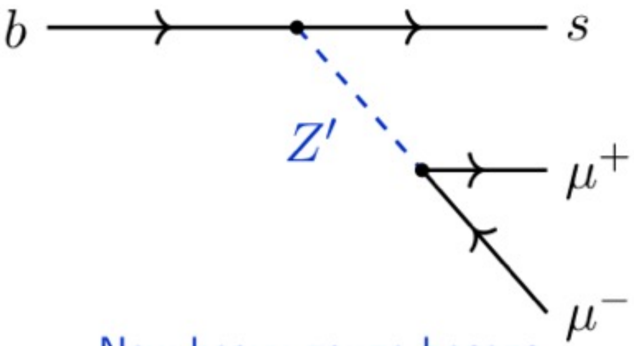
- 3σ-ish level from SM triggered wide interest on the subject
- Recently updated with new measurement



Standard Model



Leptoquarks



New heavy gauge bosons

Anomalies in $b \to s\ell^+\ell^-$ LFU

- $B^0 \to K^{*0}\ell^+\ell^-$ with 3 fb^{-1} JHEP 08 (2017) 055

$$R_{K^{*0}} = 0.66^{+0.11}_{-0.07}(\text{stat}) \pm 0.03(\text{syst}) \text{ in } [0.045, 1.1] \text{ GeV}^2$$
$$R_{K^{*0}} = 0.69^{+0.11}_{-0.07}(\text{stat}) \pm 0.05(\text{syst}) \text{ in } [1.1, 6.0] \text{ GeV}^2$$

- $\Lambda_b \to pK\ell^+\ell^-$ with 4.7 fb^{-1} JHEP 05 (2020) 040

$$R_{pK^-} = 0.86^{+0.14}_{-0.11}(\text{stat}) \pm 0.05(\text{syst}) \text{ in } [0.1, 6.0] \text{ GeV}^2$$

- $B^+ \to K^+\ell^+\ell^-$ with 9 fb^{-1} Nature Physics 18 (2022) 277

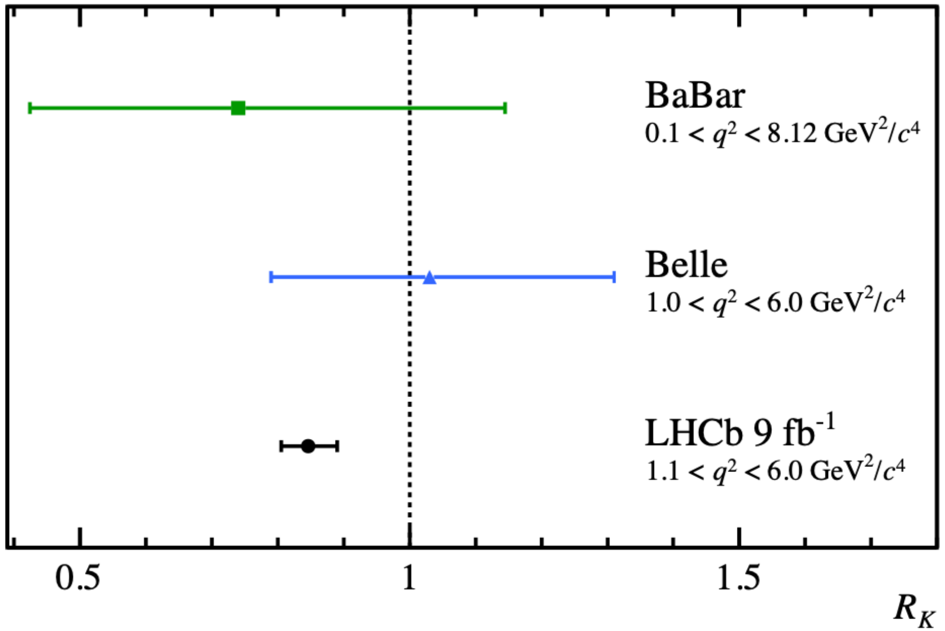
$$R_{K^+} = 0.846^{+0.042}_{-0.039}(\text{stat})^{+0.013}_{-0.012}(\text{syst}) \text{ in } [1.1, 6.0] \text{ GeV}^2$$

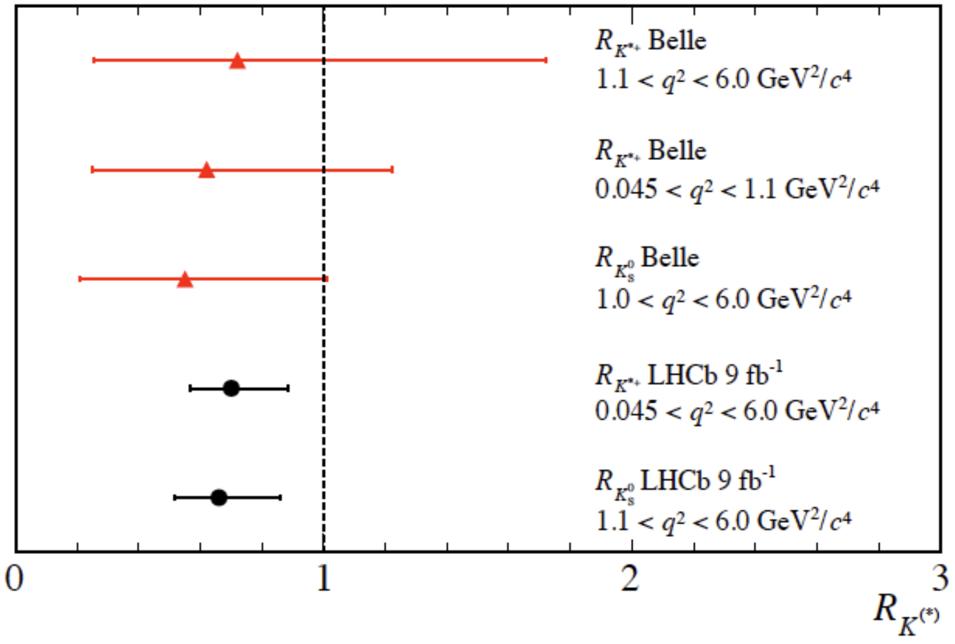
- $B^0 \to K^0_S\ell^+\ell^-$ with 9 fb^{-1} Phys. Rev. Lett. 128 (2022) 191802

$$R_{K^0_S} = 0.66^{+0.20}_{-0.14}(\text{stat.})^{+0.02}_{-0.04}(\text{syst.}) \text{ in } [1.1, 6.0] \text{ GeV}^2$$

- $B^+ \to K^{*+}\ell^+\ell^-$ with 9 fb^{-1} Phys. Rev. Lett. 128 (2022) 191802

$$R_{K^{*+}} = 0.70^{+0.18}_{-0.13}(\text{stat.})^{+0.03}_{-0.04}(\text{syst.}) \text{ in } [0.045, 6.0] \text{ GeV}^2$$





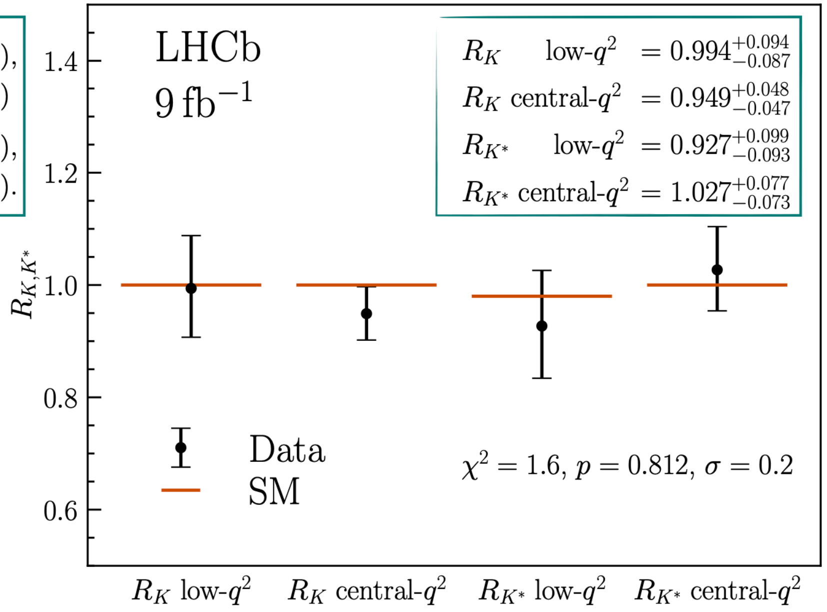
Breaking news!

LHCb-PAPER-2022-045 arXiv:2212.09153
LHCb-PAPER-2022-046 arXiv:2212.09152

$$\text{low-}q^2 \begin{cases} R_K &= 0.994 \,^{+0.090}_{-0.082}\,(\text{stat})\,^{+0.027}_{-0.029}\,(\text{syst}), \\ R_{K^*} &= 0.927 \,^{+0.093}_{-0.087}\,(\text{stat})\,^{+0.034}_{-0.033}\,(\text{syst}) \end{cases}$$

$$\text{central-}q^2 \begin{cases} R_K &= 0.949 \,^{+0.042}_{-0.041}\,(\text{stat})\,^{+0.023}_{-0.023}\,(\text{syst}), \\ R_{K^*} &= 1.027 \,^{+0.072}_{-0.068}\,(\text{stat})\,^{+0.027}_{-0.027}\,(\text{syst}). \end{cases}$$

- Most precise and accurate LFU test in $b \to s\ell\ell$ transition
- Compatible with SM with a simple χ^2 test on 4 measurement at 0.2 σ

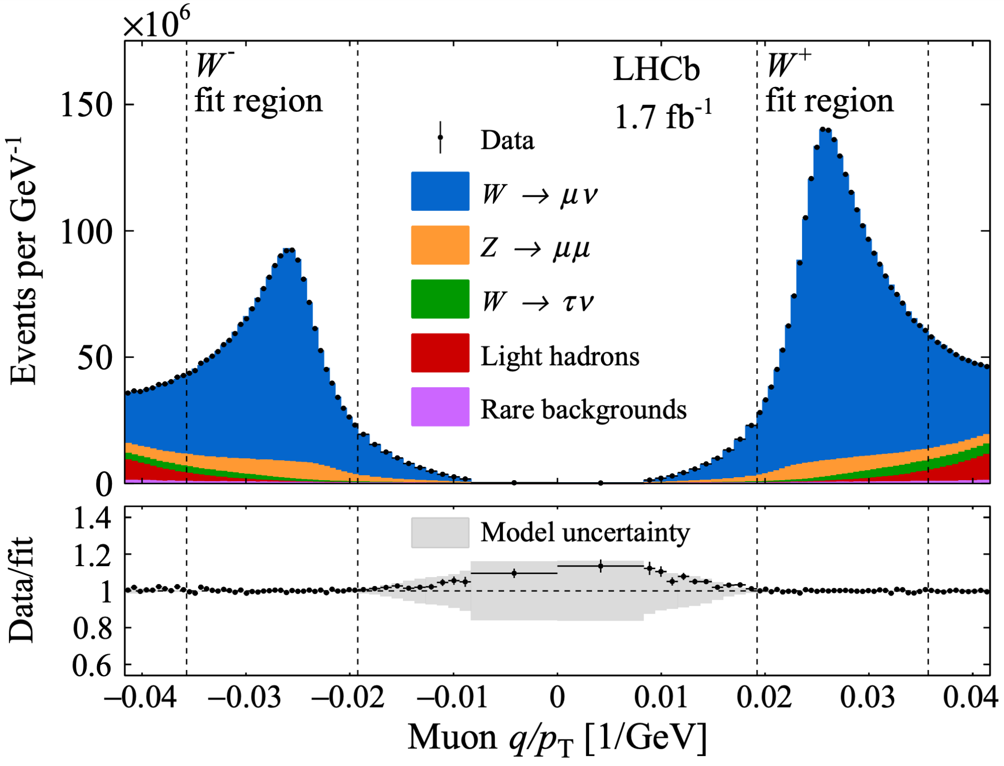


$$R_{K,K^*}(q_a^2, q_b^2) = \frac{\displaystyle\int_{q_a^2}^{q_b^2} \frac{\mathrm{d}\Gamma(B^{(+,0)} \to K^{(+,*0)}\mu^+\mu^-)}{\mathrm{d}q^2}\mathrm{d}q^2}{\displaystyle\int_{q_a^2}^{q_b^2} \frac{\mathrm{d}\Gamma(B^{(+,0)} \to K^{(+,*0)}e^+e^-)}{\mathrm{d}q^2}\mathrm{d}q^2}$$

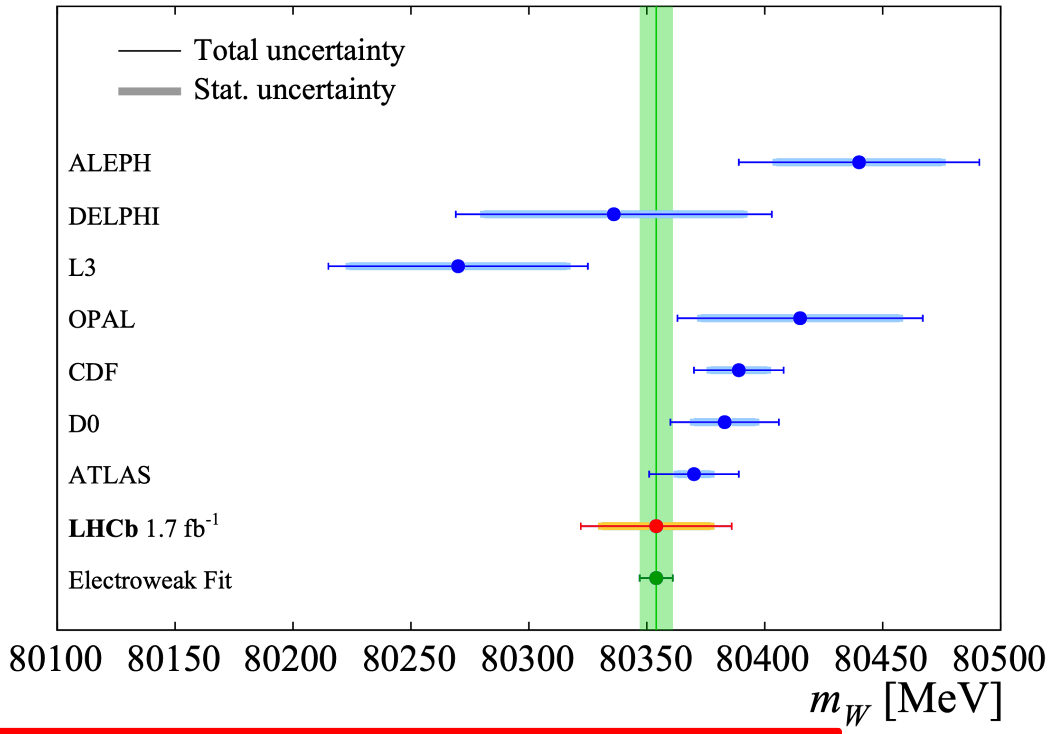
- **q^2 ranges:**
  - low-q^2 : $q^2 \in [0.1, 1.1]\,\text{GeV}^2/c^4$
  - central-q^2 : $q^2 \in [1.1, 6.0]\,\text{GeV}^2/c^4$
- **For R_{K*}**
  K^{*0} : $m(K^+\pi^-) \in [792, 992]\,\text{MeV}/c^2$

- Simultaneous measurement of R_K and R_{K^*} with full Run-1 and Run-2 data
- Better understanding of misidentification background
- Two bins in q^2
- Well in agreement with Standard Model

LHCb$_{GPD}$: W mass measurement



LHCb-PAPER-2021-024



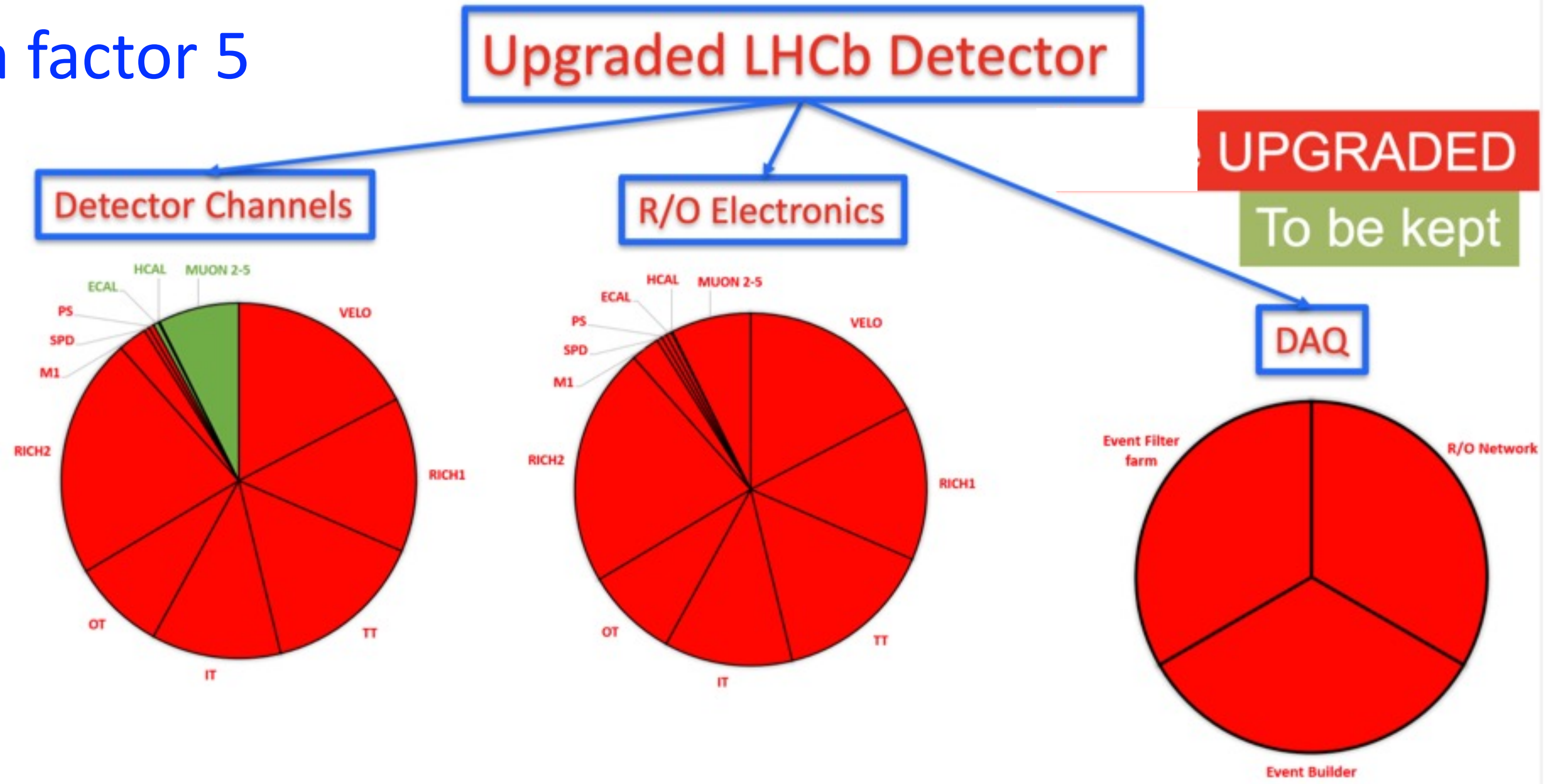
$$m_W = 80354 \pm 23_{\text{stat}} \pm 10_{\text{exp}} \pm 17_{\text{theory}} \pm 9_{\text{PDF}}\ \text{MeV}$$

- LHCb is nowadays a general purpose detector in the forward region
- Hot topic due to recent CDF measurement (m_W = 80433 ± 9 MeV)!

LHCb future

LHCb Upgrade-1 (Run-3 e Run-4)

- Increase in luminosity by a factor 5 (to 2 x 10^{33} cm^{-2}s^{-1})
- The detector has been renewed almost entirely
- All readout electronics moved to 40 MHz

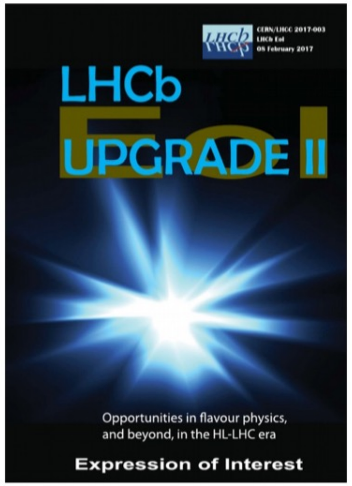


- Expect increase by a factor 5 in yield for muonic *B*-decay channels and a factor 10 for hadronic channels, owing to a new trigger system entirely software-based GPU/CPU hybrid

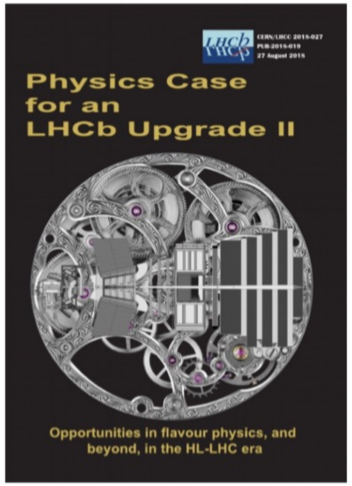
LHCb Upgrade 2: advanced design phase

	LHC era			HL-LHC era	
	Run 1	Run 2	Run 3	Run 4	Run 5+
LHCb $\int \mathcal{L} dt$	3 fb^{-1}	9 fb^{-1}	23 fb^{-1}	50 fb^{-1}	300 fb^{-1}

- Further upgrade proposed to increase the luminosity by another factor 10 (up to 1.5 x 10^{34} $cm^{-2}s^{-1}$) in Run 5
- Framework TDR published last year
- Now working towards the sub-detector TDRs to be ready in ~3 years



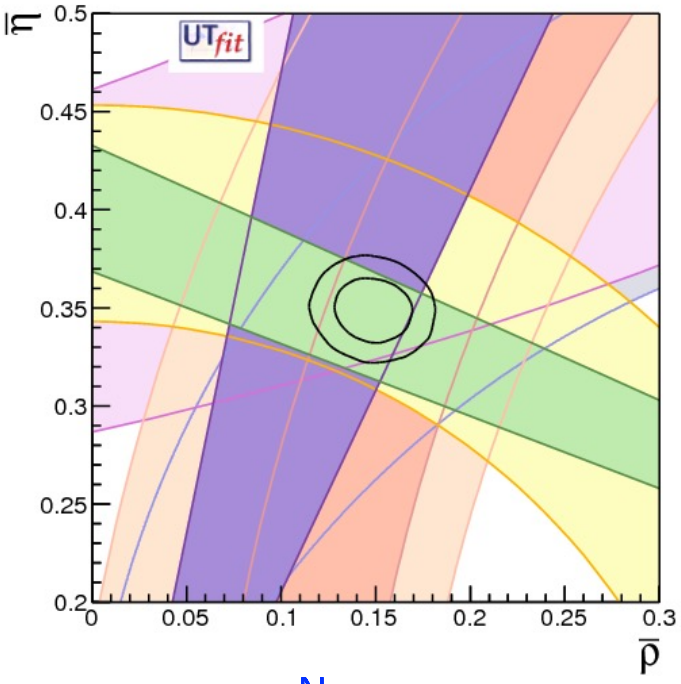
CERN-LHCC-2017-003



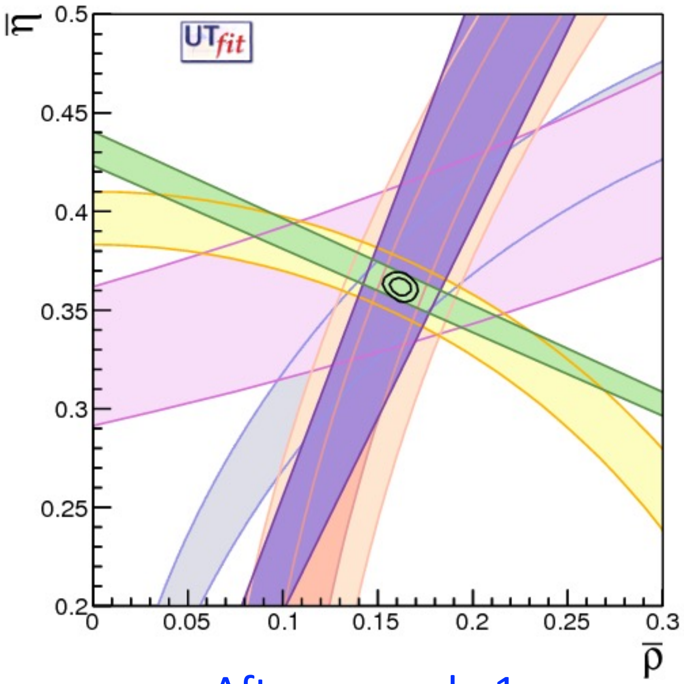
CERN-LHCC-2018-027
arXiv:1808.08865

CERN-LHCC-2021-012

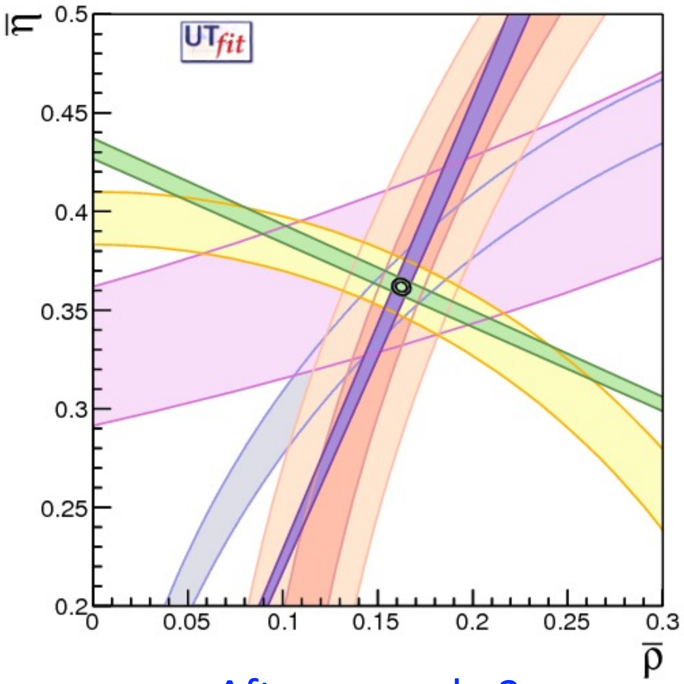
Evolution of Unitarity Triangle precision



Now



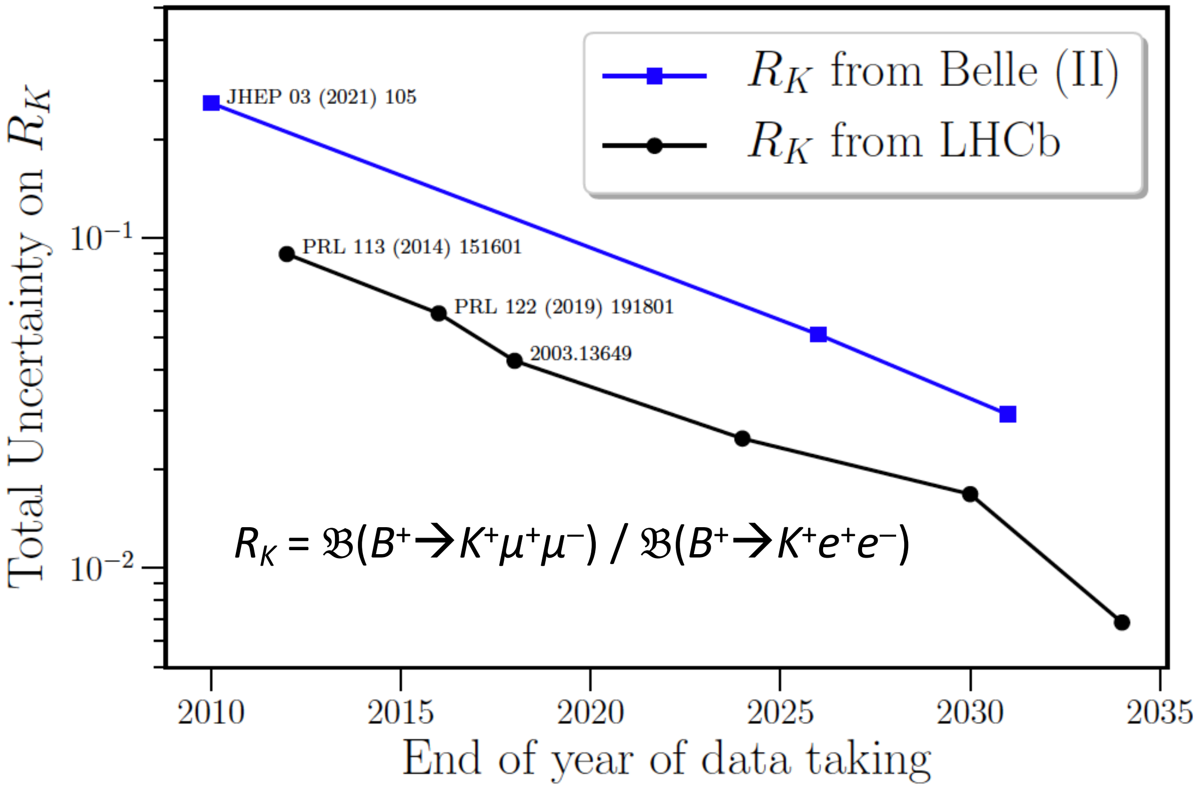
After upgrade 1

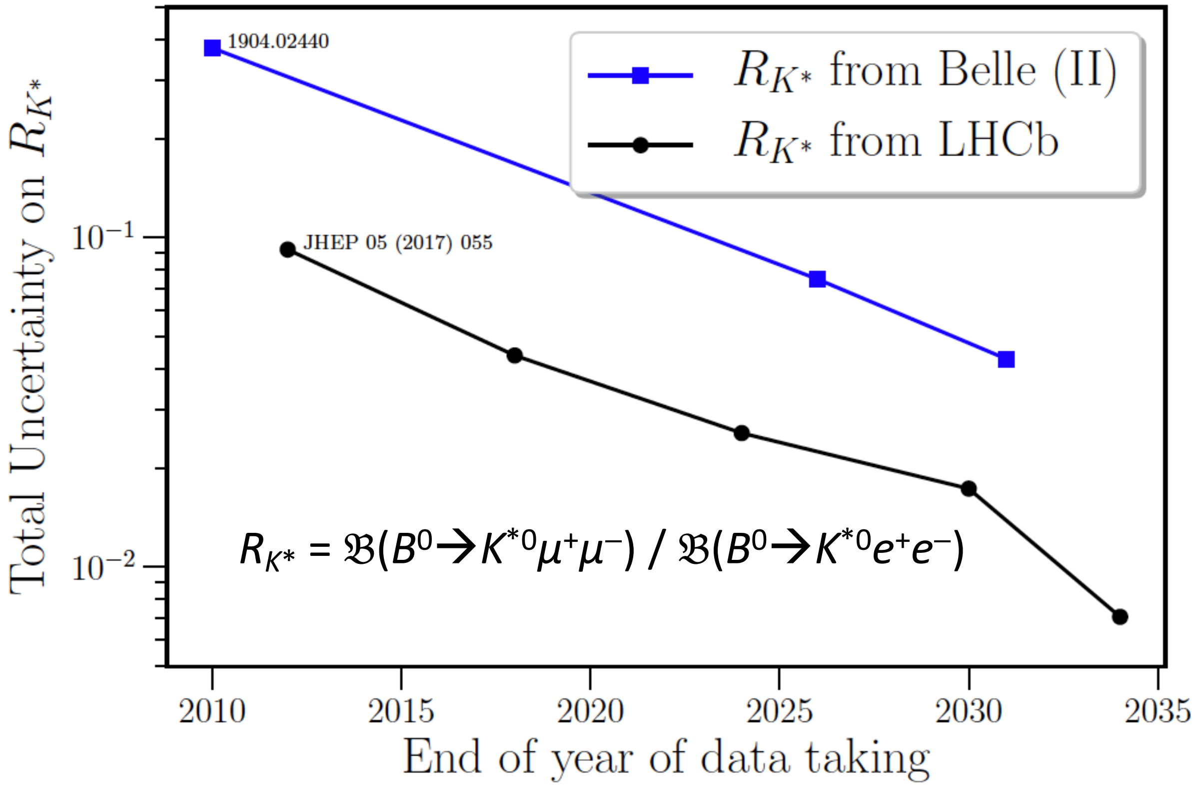


After upgrade 2

	λ	$\bar{\rho}$	$\bar{\eta}$	A	$\sin 2\beta$	γ	α	β_s
Current	0.12%	9%	3%	1.5%	4.5%	3%	2.5%	3%
Phase 1	0.12%	2%	0.8%	0.6%	0.9%	0.9%	0.7%	0.8%
Phase 2	0.12%	1%	0.6%	0.5%	0.6%	0.8%	0.4%	0.5%

Prospects with $b \to s\ell^+\ell^-$ LFU in LHCb upgrades



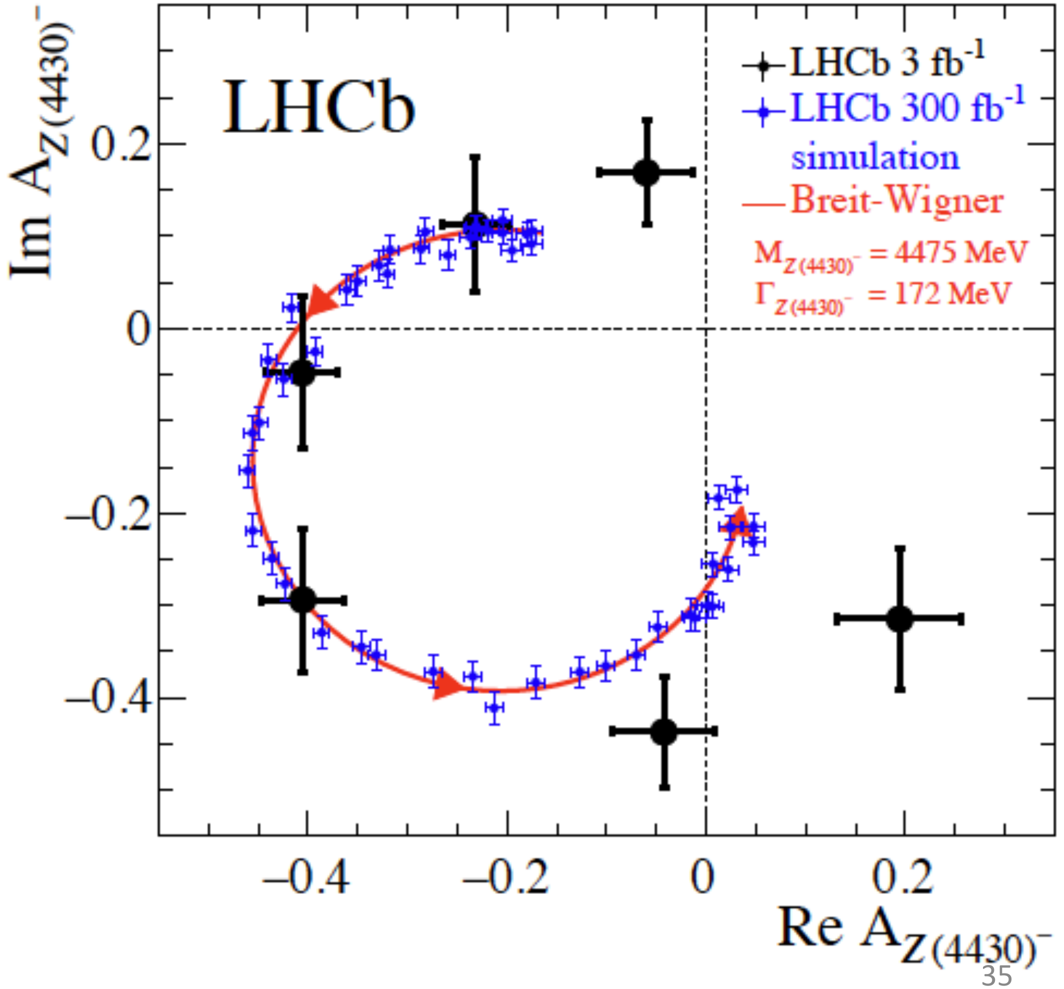


- And not only bringing $b \to s\ell^+\ell^-$ measurements to an unprecedented level of accuracy, but LHCb will also tackle even $b \to d\ell^+\ell^-$ transitions

One shot on spectroscopy in LHCb upgrades

- Puzzling charged exotic meson candidates, e.g. $Z(4430)^+$ decaying to J/ψ, $\psi(2S)$ or χ_{c1} plus a charged pion, have been observed in *B* decays
  - Some of them are broad, and none can be satisfactorily explained by any of the available phenomenological models
- The determination of their properties, or even claim for their existence, relies on amplitude analyses, which allow the exotic contributions to be separated from the (typically) dominant non-exotic components
- The large data set collected during LHCb Upgrade runs would allow the resonant character of such states to be tested with unprecedented precision

Argand diagram of the $Z(4430)^+$ amplitude in bins of $m^2_{\psi(2S)\pi}$ from $B^0 \rightarrow \psi(2S)K^+\pi^-$ decays



In conclusion

- In the first two runs of the LHC, LHCb published several interesting results spanning a wide physics programme (650+ physics papers so far)
    - Today we use to call LHCb a “general purpose detector in the forward region”
    - Only a few results shown today → the LHCb physics spectrum is much larger
- Now the collaboration is focusing on commissioning the new upgraded detector, whose completion is expected next year
    - Increase of a factor 5 in luminosity, with an effective increment of a factor 5 in statistics for muonic modes and up to a factor 10 for hadronic modes of *B* decays
- A further upgrade of LHCb is planned for Run-5, increasing the luminosity by another factor 10, with the aim of squeezing the LHC to release all flavour physics results up to the next era of accelerator machines