LHCb and its upgrades

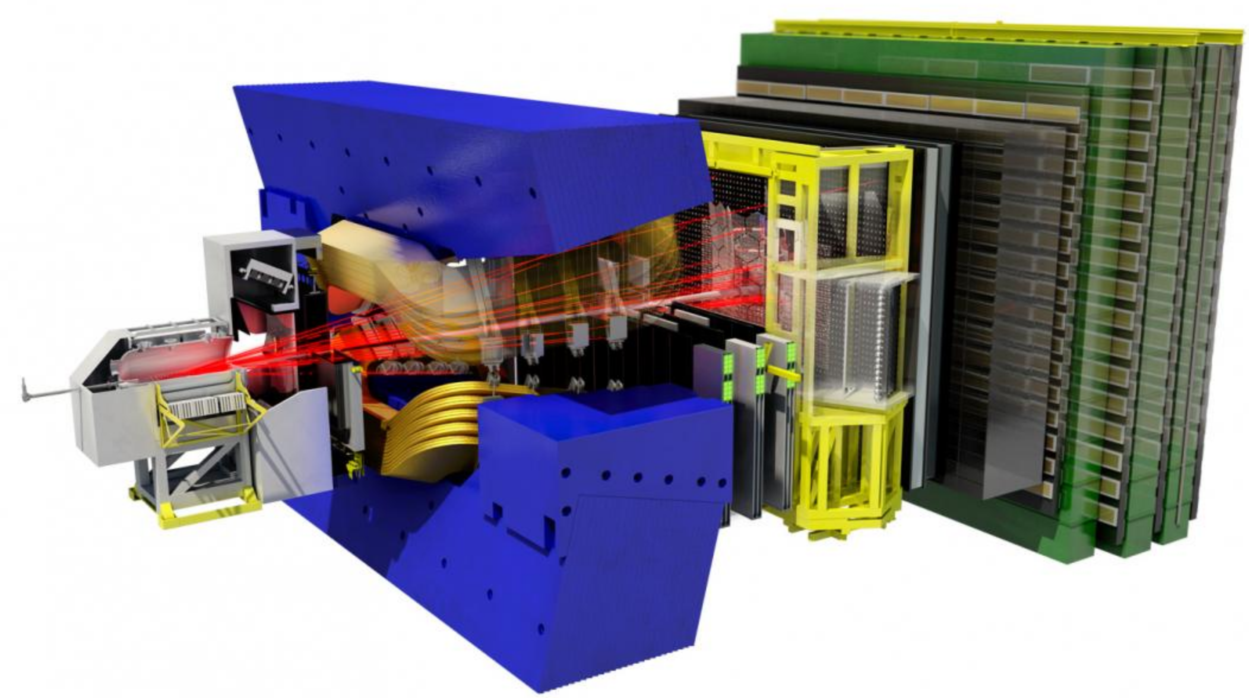
Mika Vesterinen, Oxford

LHCb-UK: University of Birmingham, University of Bristol, University of Cambridge, University of Edinburgh, University of Glasgow, Imperial College London, University of Liverpool, University of Manchester, University of Oxford, Rutherford Appleton Laboratory, University of Warwick.

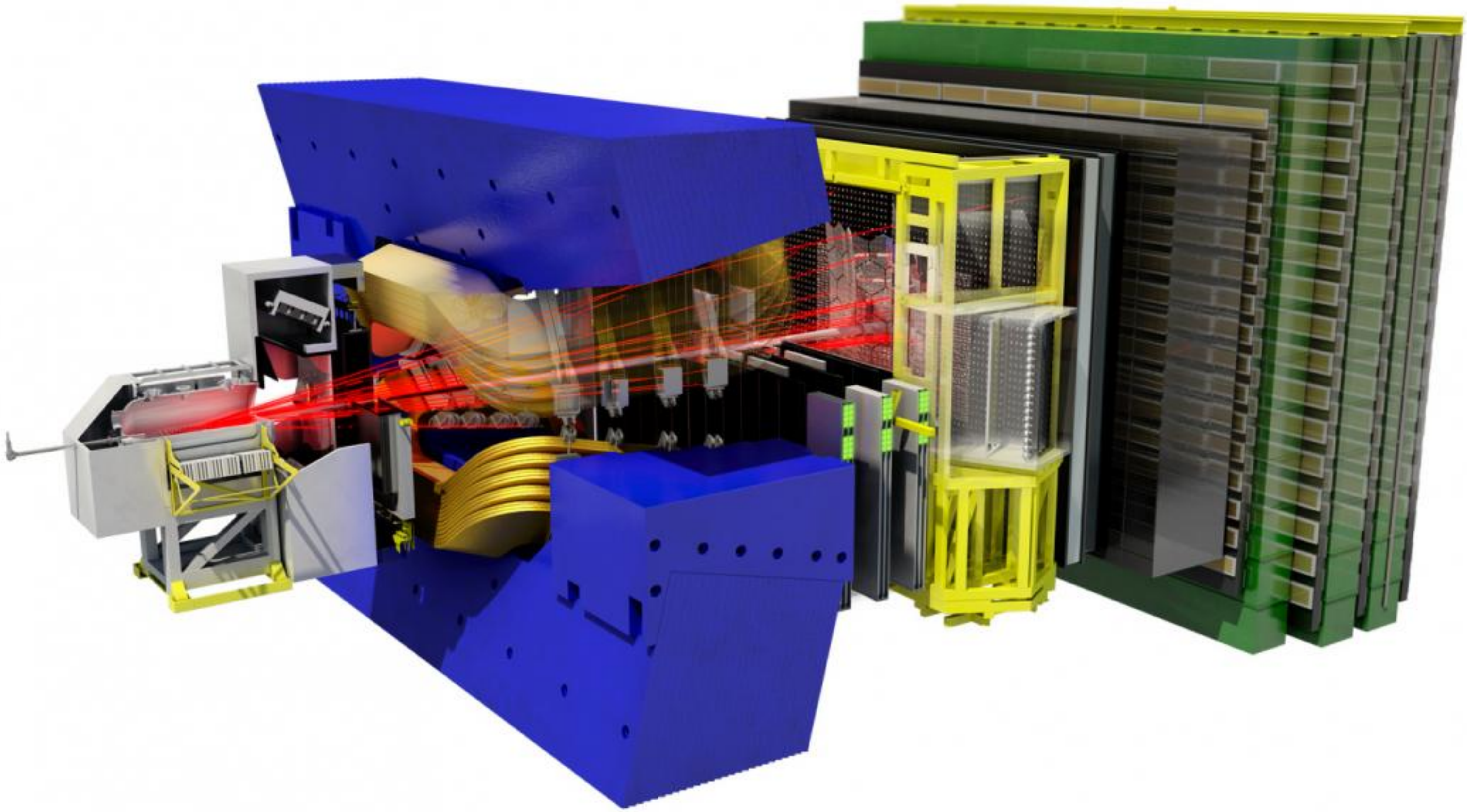
PPAP meeting 20–21/7/2017

Outline

- LHCb introduction
- Recent physics highlights
- The LHCb phase-I upgrade
- Phase-Ib and Phase-II upgrades



Our goal is to expose BSM physics through precision studies of quark flavour violating processes, exploiting the enormous heavy flavour production of the LHC.



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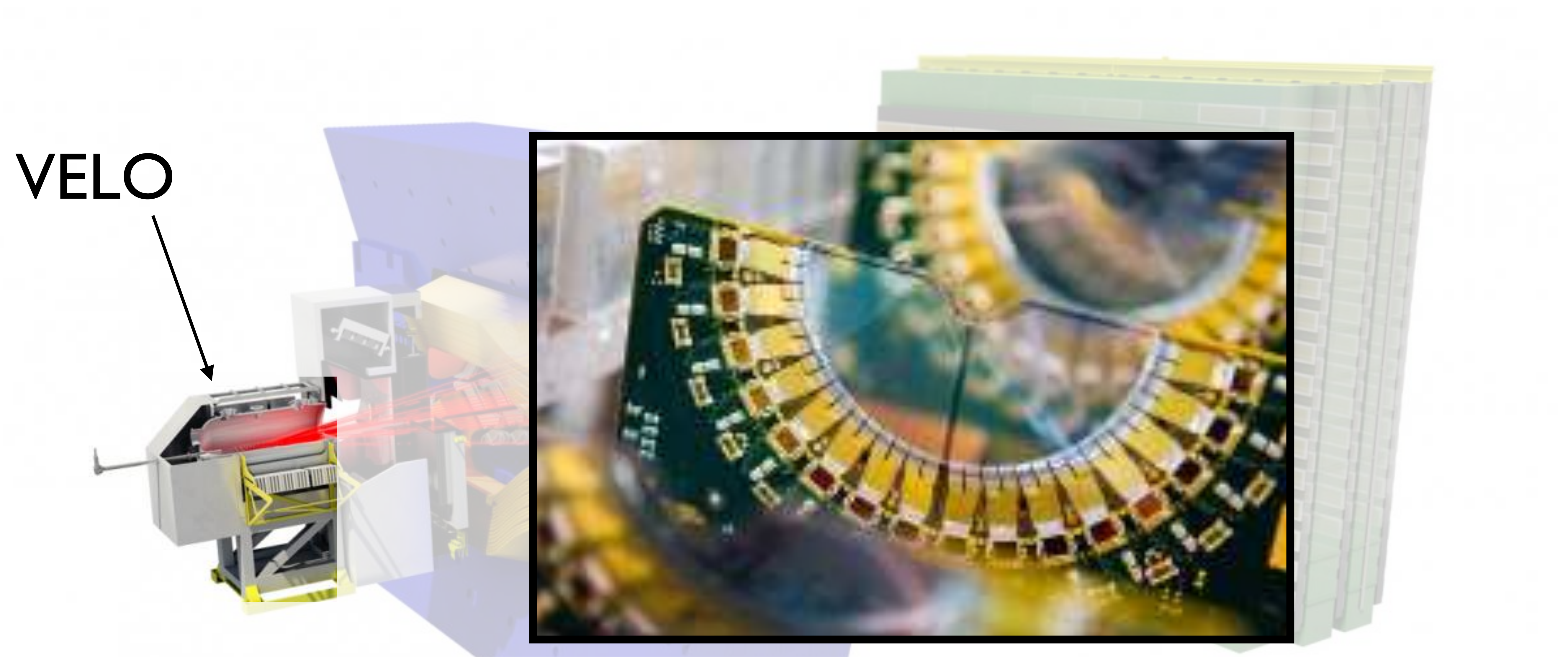

Our core **VELO** sub-detector was primarily designed and constructed by UK groups, and we continue to lead the maintenance, operations and upgrade development.

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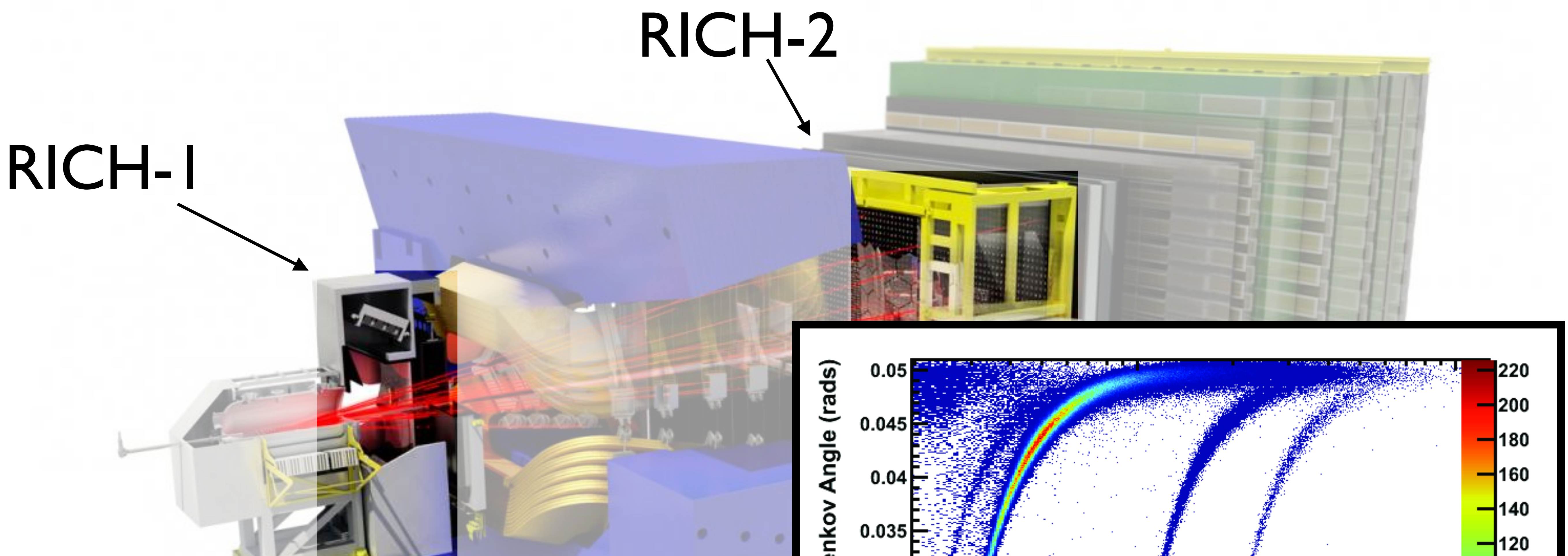
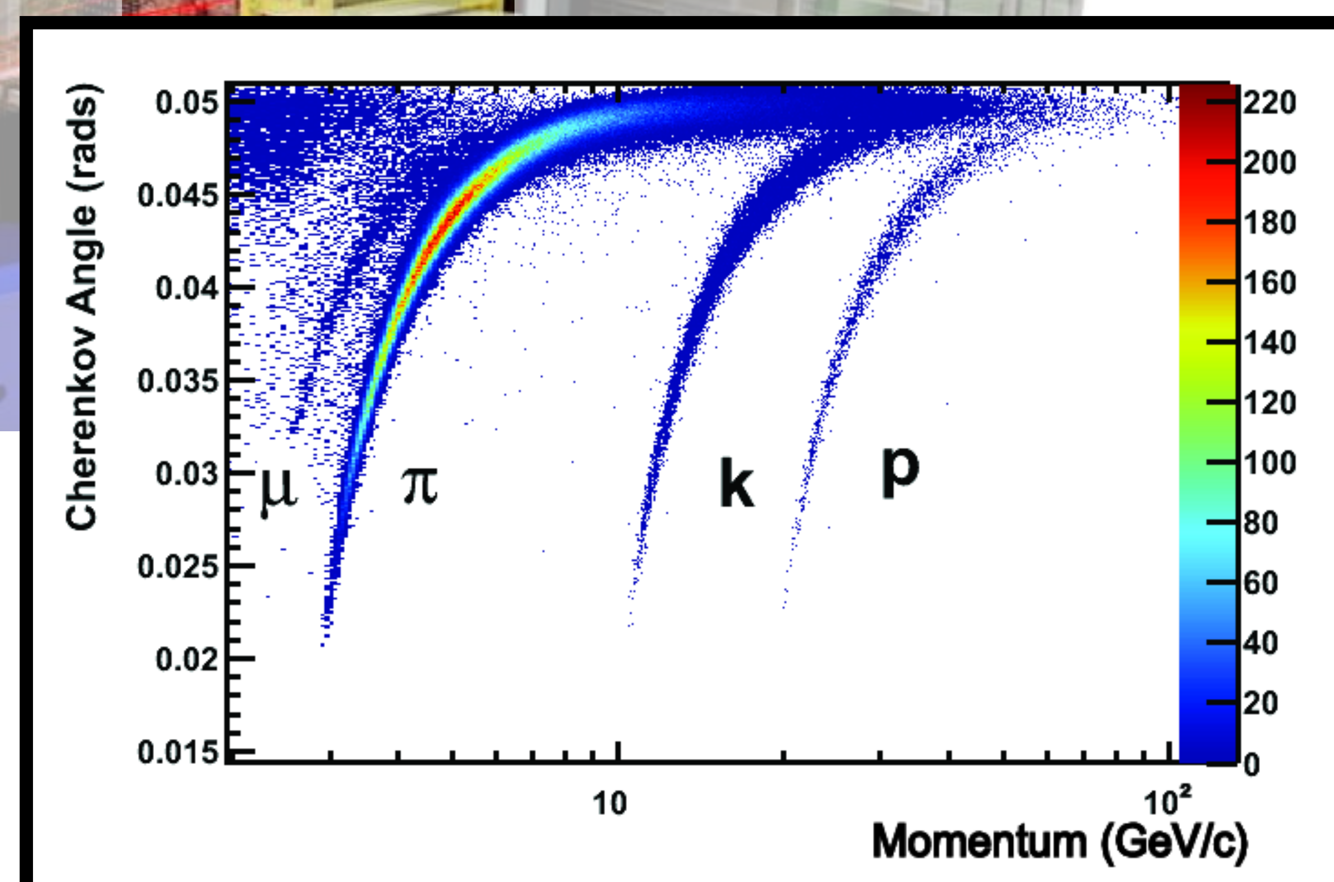




Likewise for the **RICHes**, whose particle-ID capabilities are central to our capabilities in precision flavour physics.

LHCb-UK prominence

International leadership:

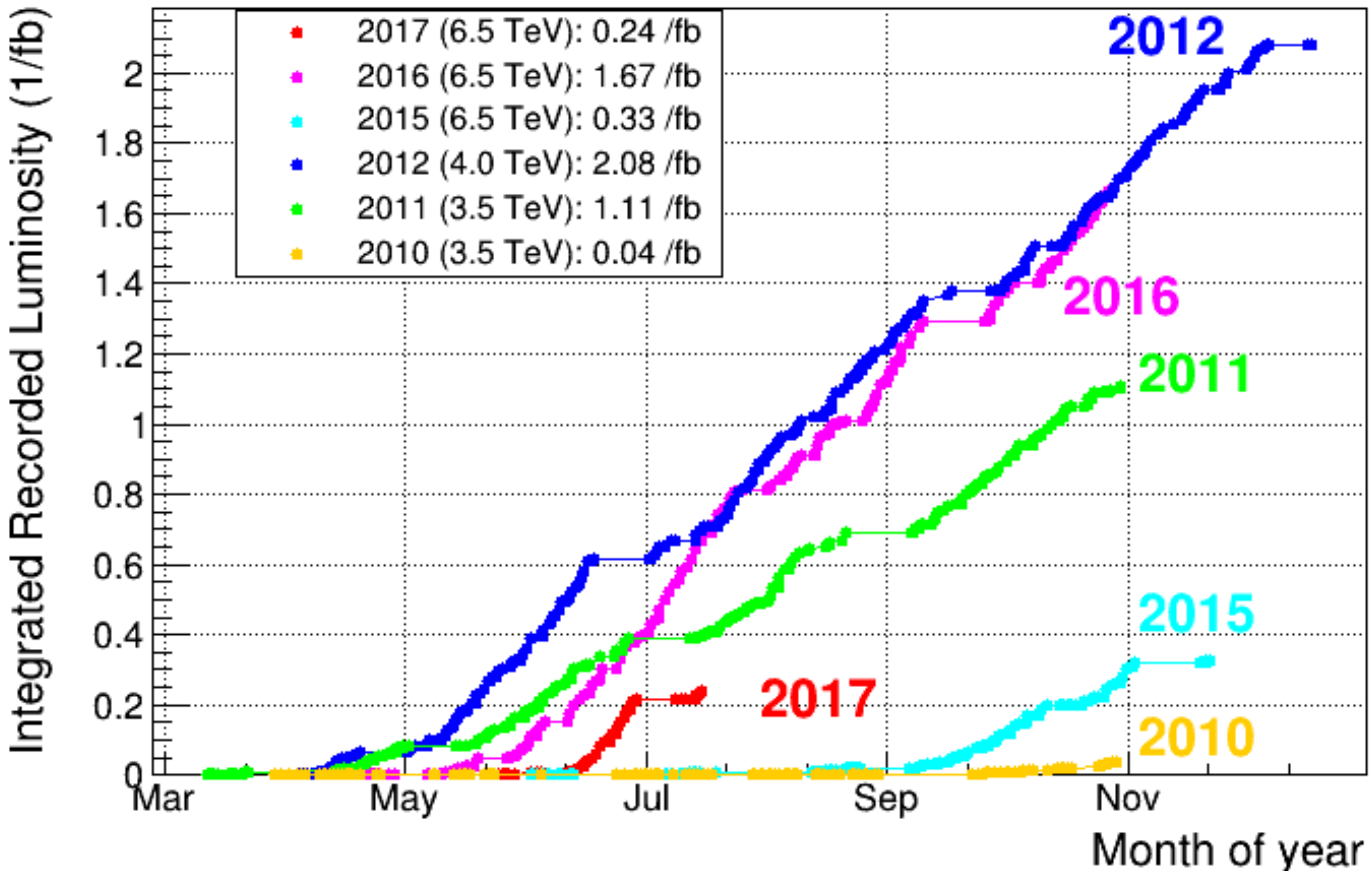
Spokesperson	**G. Passaleva** (Italy) and deputy **C. Parkes** (UK)
Collaboration Board	Chaired by **Val Gibson** (UK)
Editorial Board	Chaired by **Fergus Wilson** (UK)
Speakers Bureau	Chaired by **Marco Gersabeck** (UK)

Many other notable appointments, e.g. **A. Papanestis** as RICH P.L., **A. McNab** as computing deputy P.L., **S.Borghi** as operations coordinator…

High achieving LHCb-UK students, e.g:

- Winning two (O. Lupton, A. Pearce) of the three 2017 LHCb thesis awards!
- Eight (of nineteen) current top-level physics WG convenors are recent LHCb-UK students!

LHCb run status

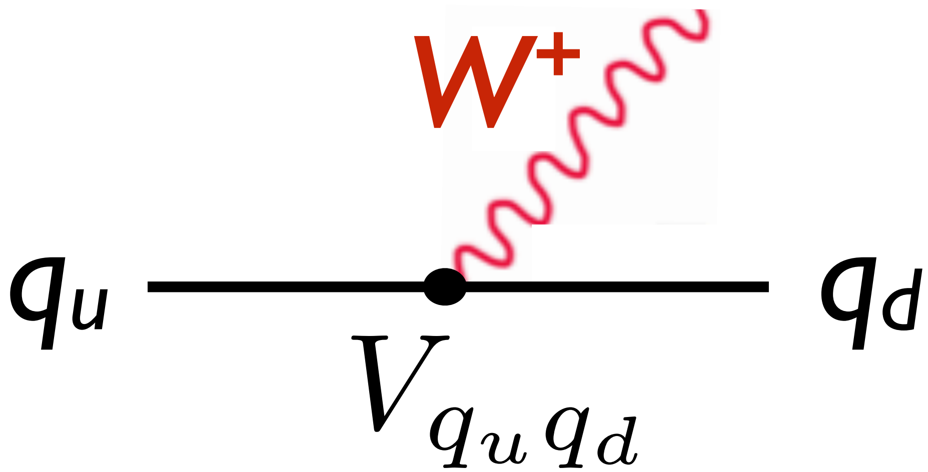


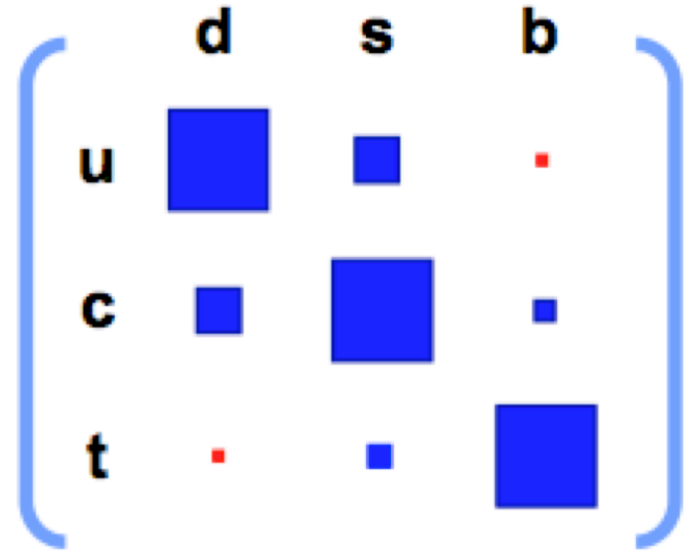
Some recent physics highlights…

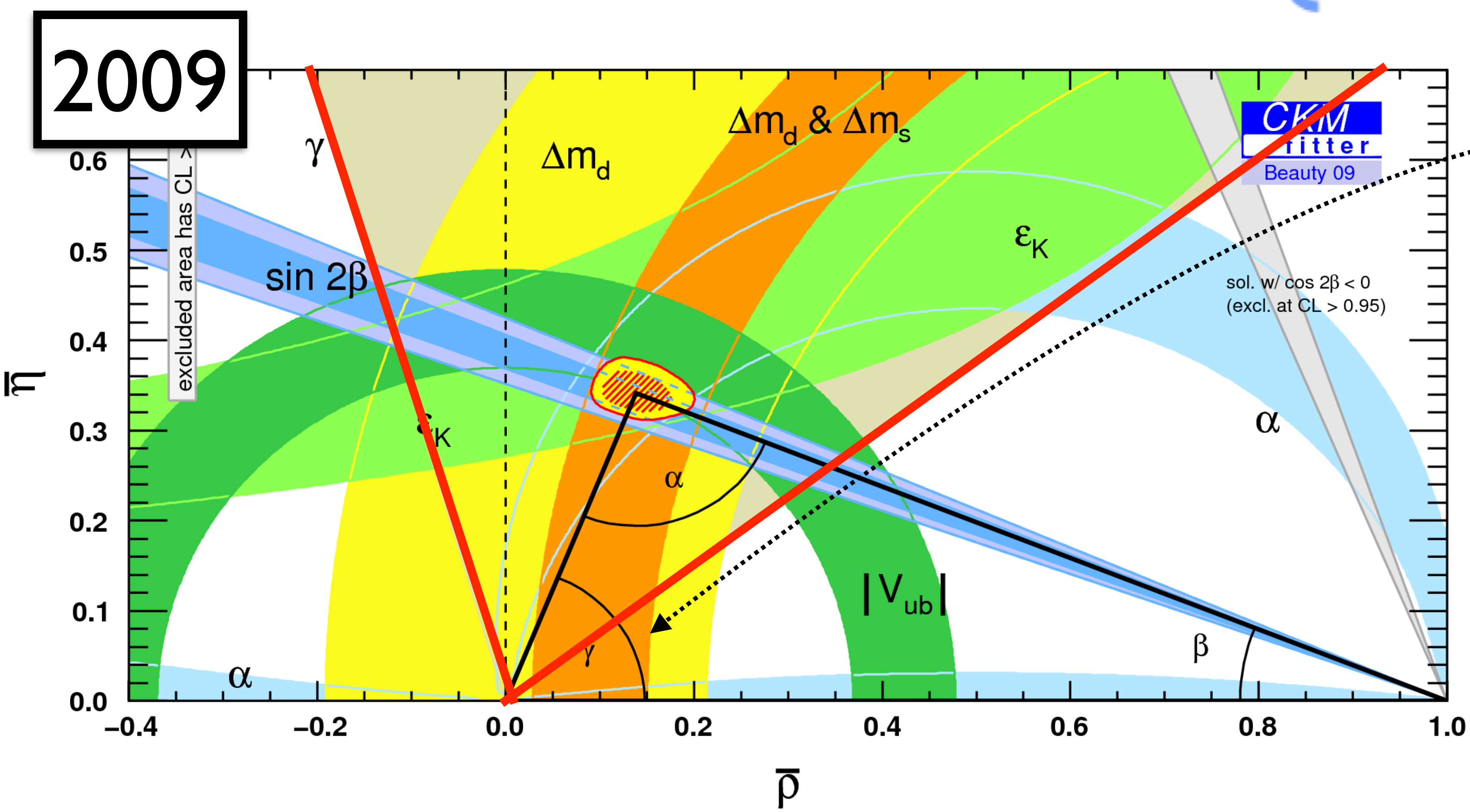
Unless otherwise stated, the following work has major involvement by LHCb-UK groups

Full listing of public results here:
http://lhcbproject.web.cern.ch/lhcbproject/Publications/LHCbProjectPublic/Summary_all.html

Unitarity of the CKM matrix

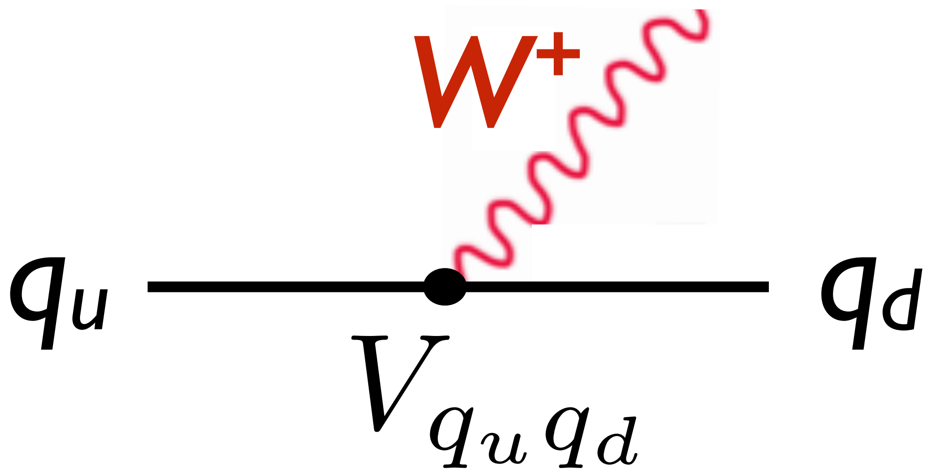


$V =$ 



$$\gamma = \arg\left(\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right)$$

Unitarity of the CKM matrix



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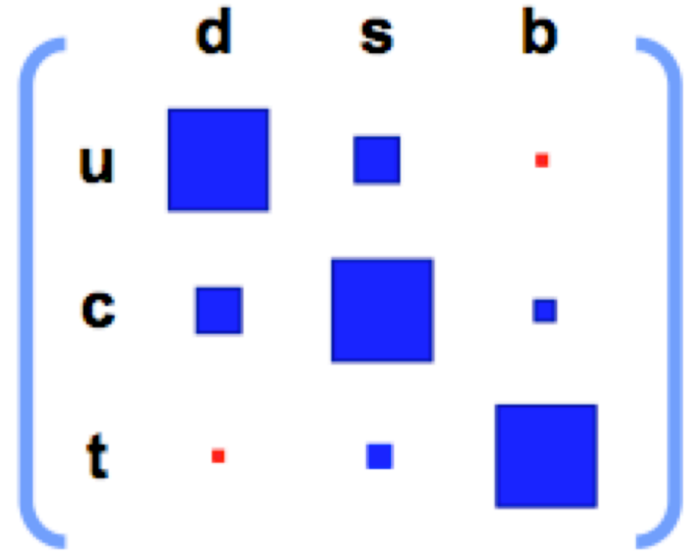
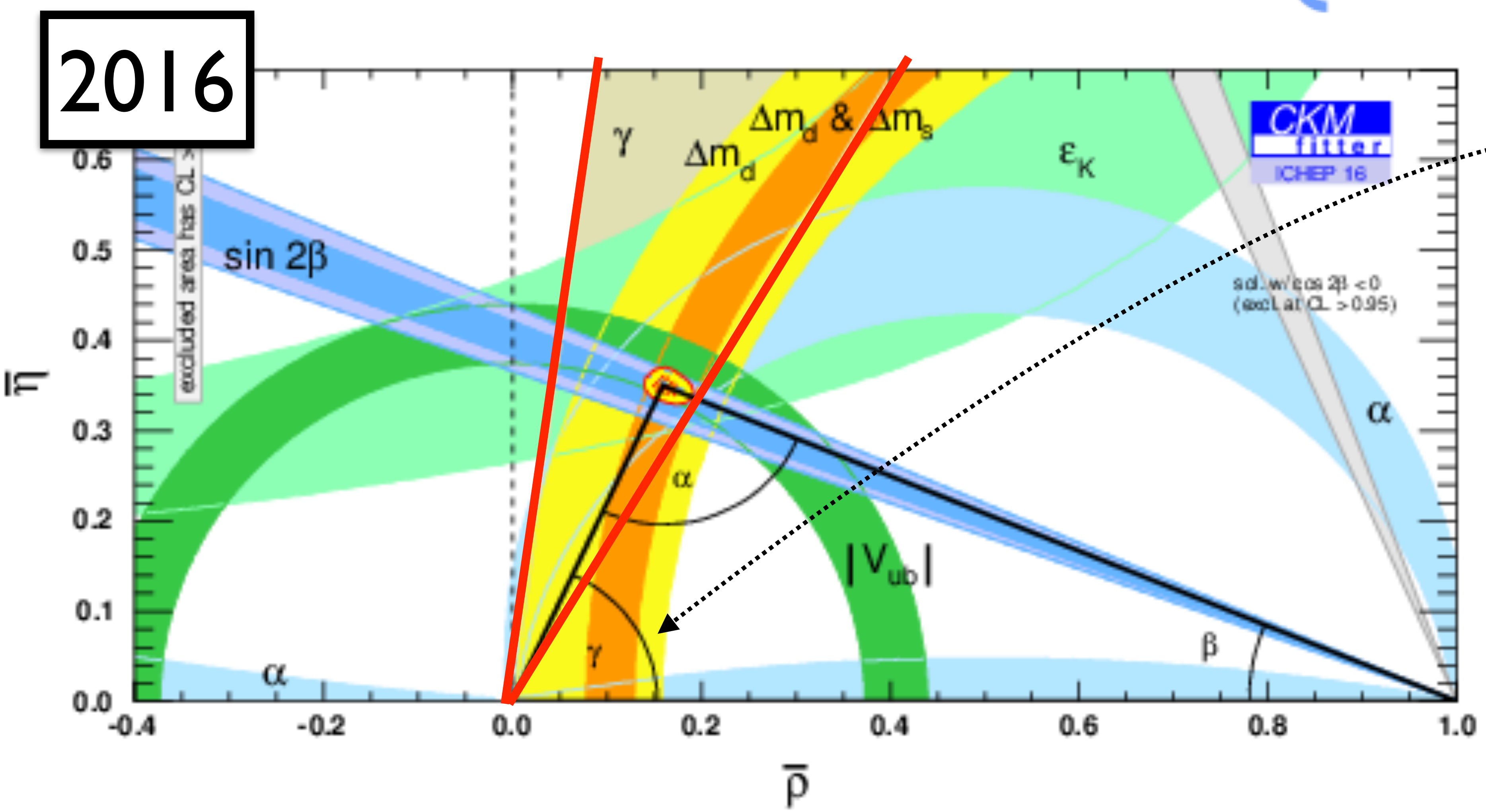
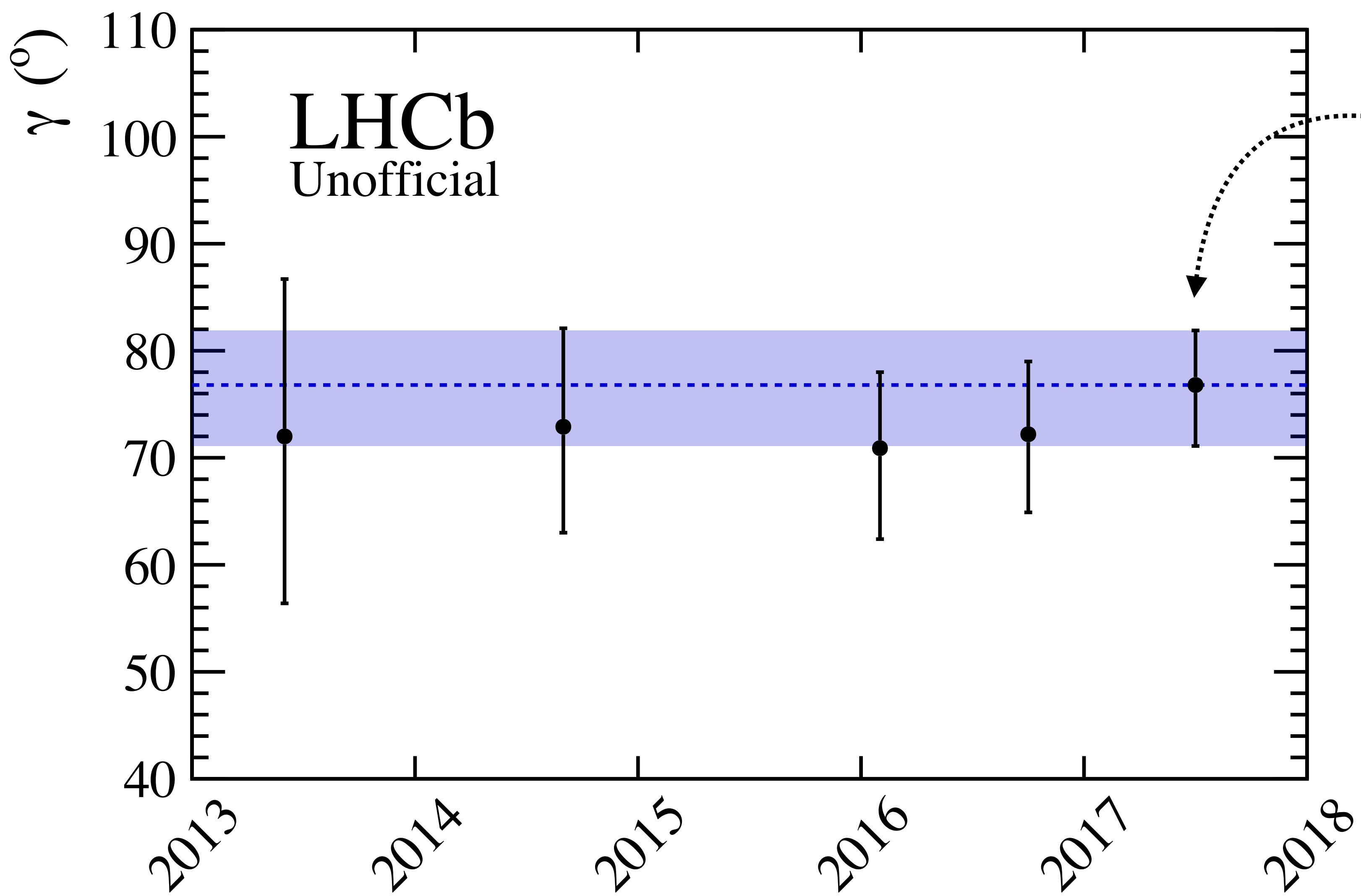




$$\gamma = \arg\left(\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right)$$

New LHCb γ determination

A combination of 13 analyses, almost all of which were performed by LHCb-UK groups (as was the combination itself).

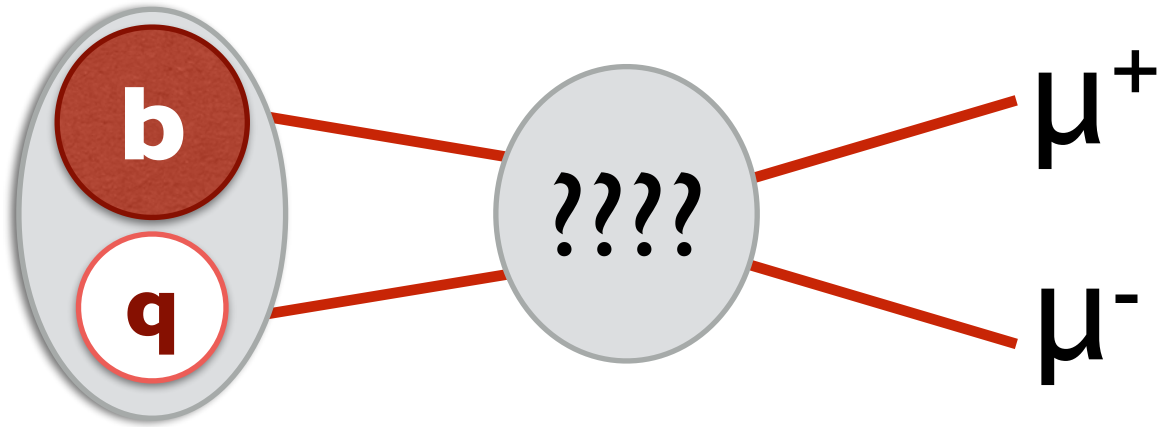


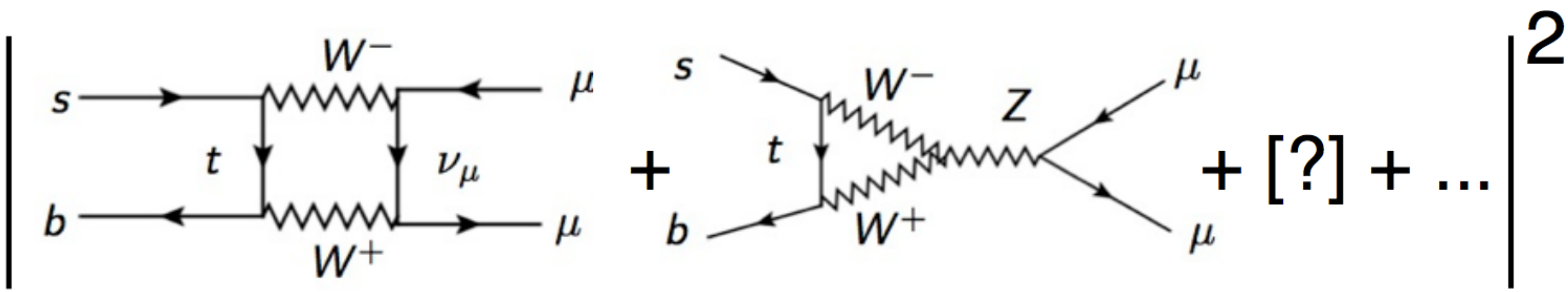
LHCb
EPS 2017

$$\gamma = \left(76.8^{+5.1}_{-5.7}\right)^\circ$$

Now approach 5° precision!

The golden suppressed *B* decay



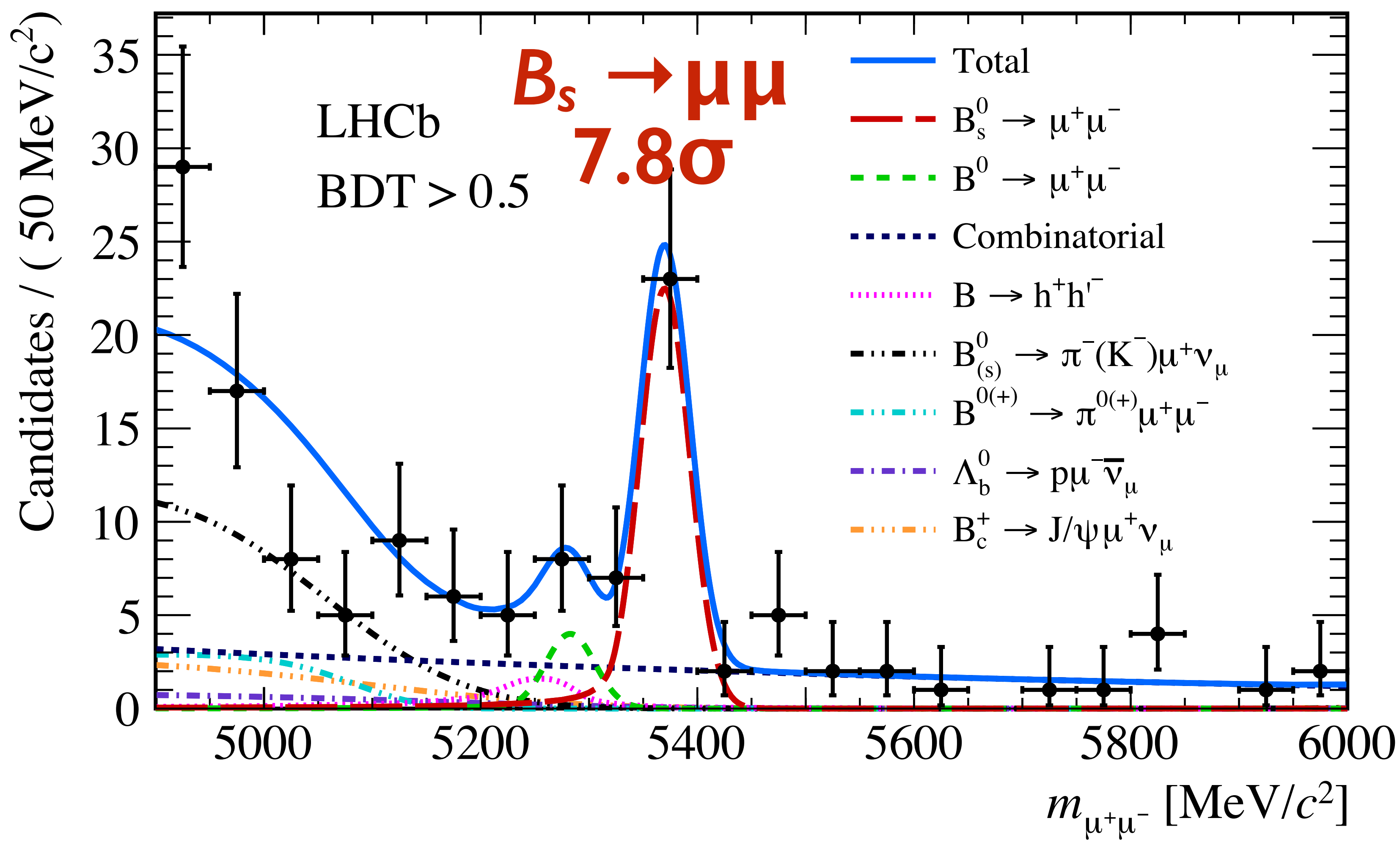


If only SM amplitudes:

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (3.66 \pm 0.23) \times 10^{-9}$$
$$\mathcal{B}(B^0 \to \mu^+\mu^-) = (1.06 \pm 0.09) \times 10^{-10}$$

Bobeth *et al.*, PRL 112, 101801 (2014)

First single-experiment observation

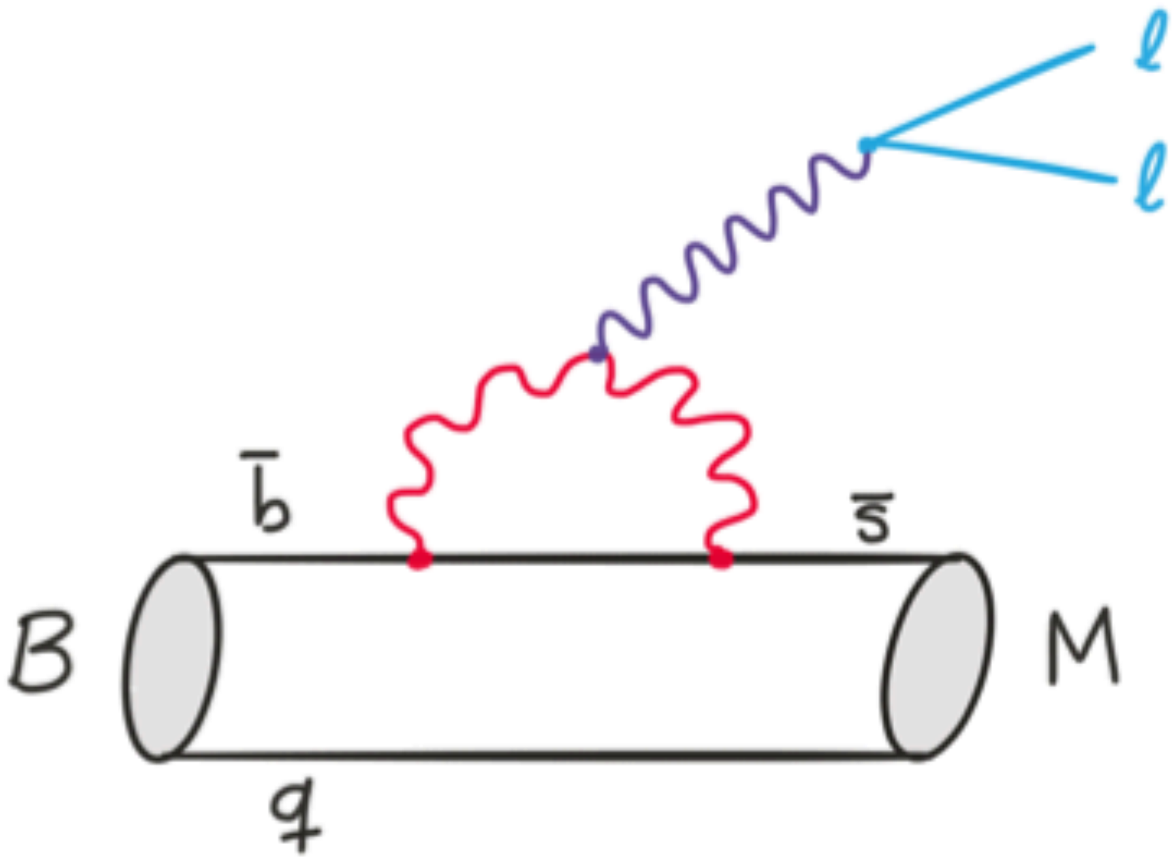


BR measured to ~20% precision and in agreement with the SM prediction, which is particularly constraining on scalar BSM physics.

First measurement of the effective lifetime.

With more luminosity we will become sensitive to $B_d \to \mu\mu$.

Semi-leptonic decays

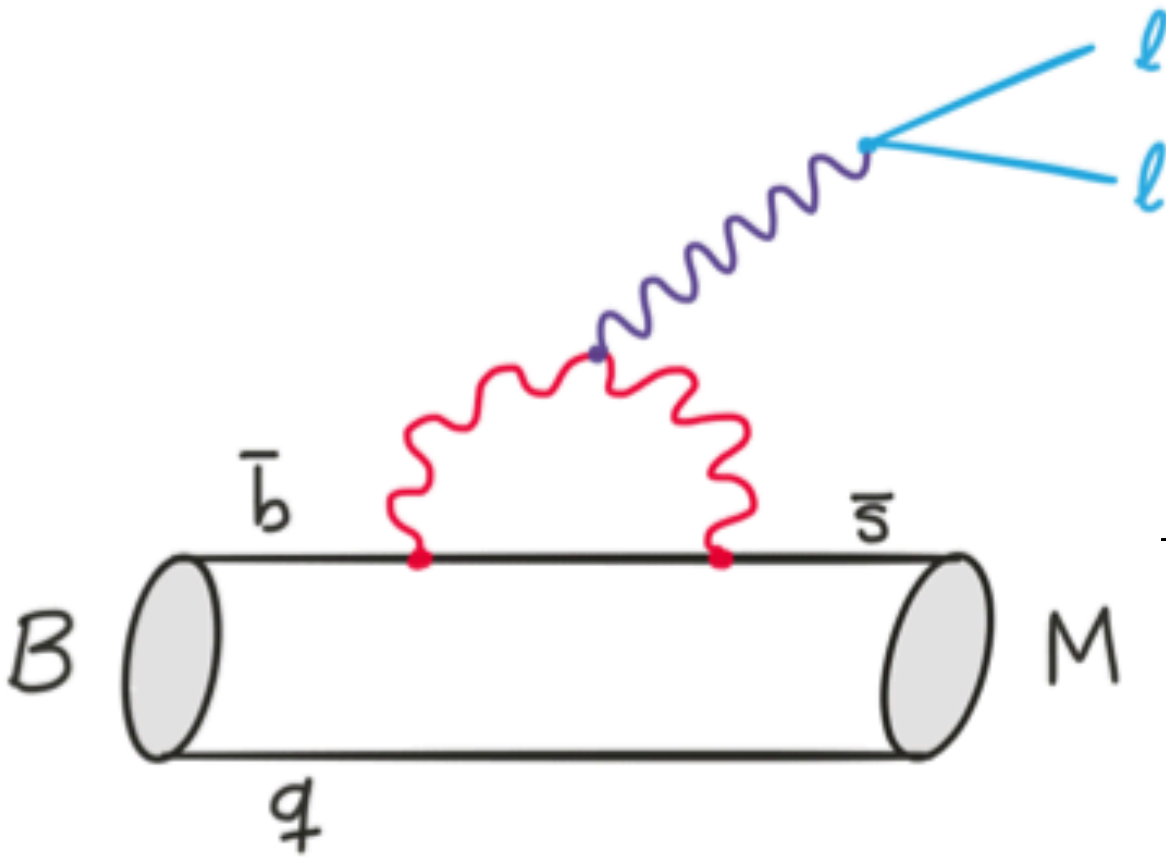


Complementary probe of similar physics to $B_s \to \mu\mu$.

Intriguing >3σ anomalies seen in the decay rates and angular distributions (P_5').

Much debate about the **theory uncertainties**…

Semi-leptonic decays



Observable(s) with almost no theory uncertainty whatsoever!

$$R(K) = \frac{B(B \to K\mu^+\mu^-)}{B(B \to Ke^+e^-)}$$

Complementary probe of similar physics to $B_s \to \mu\mu$.

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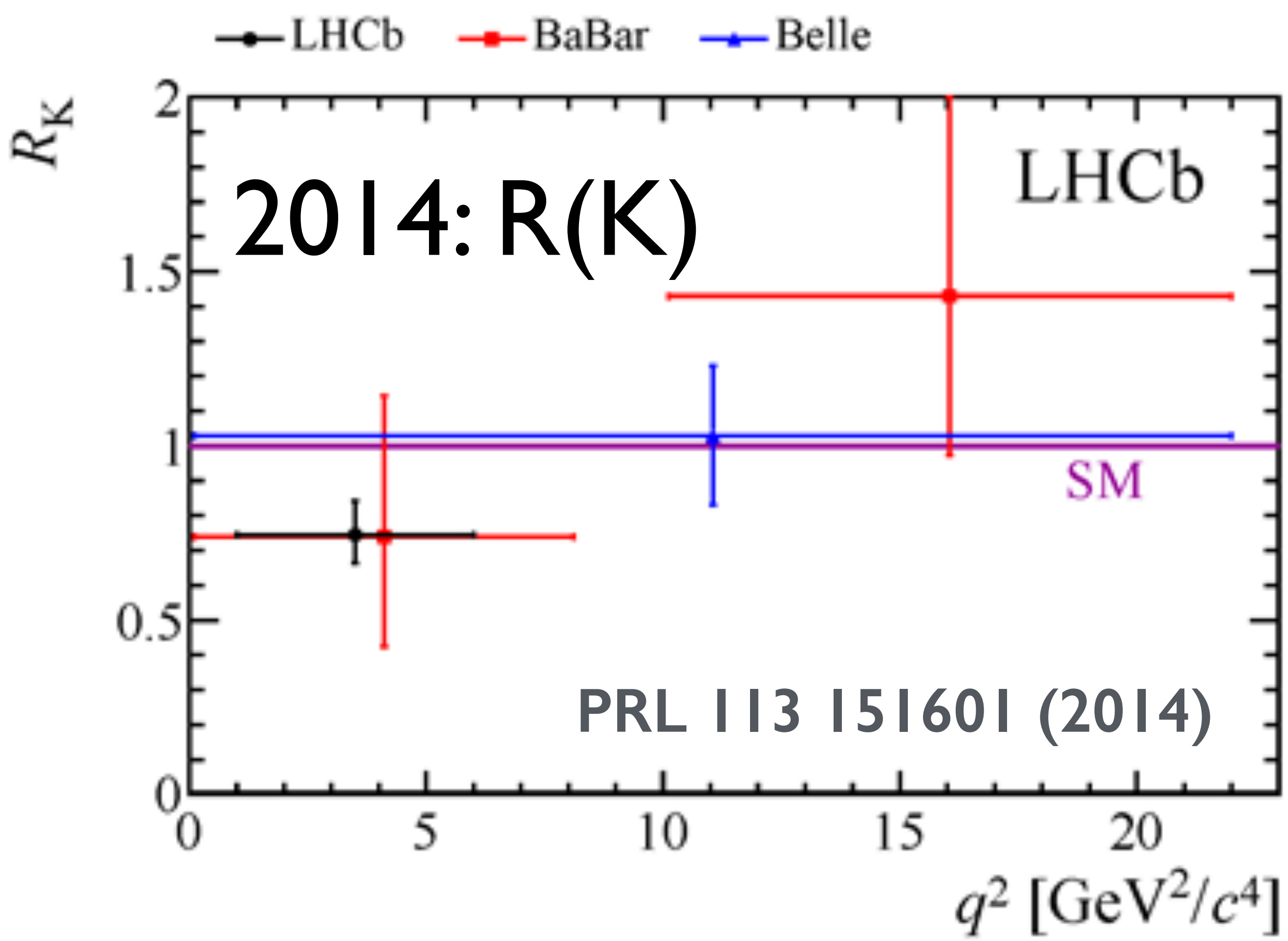
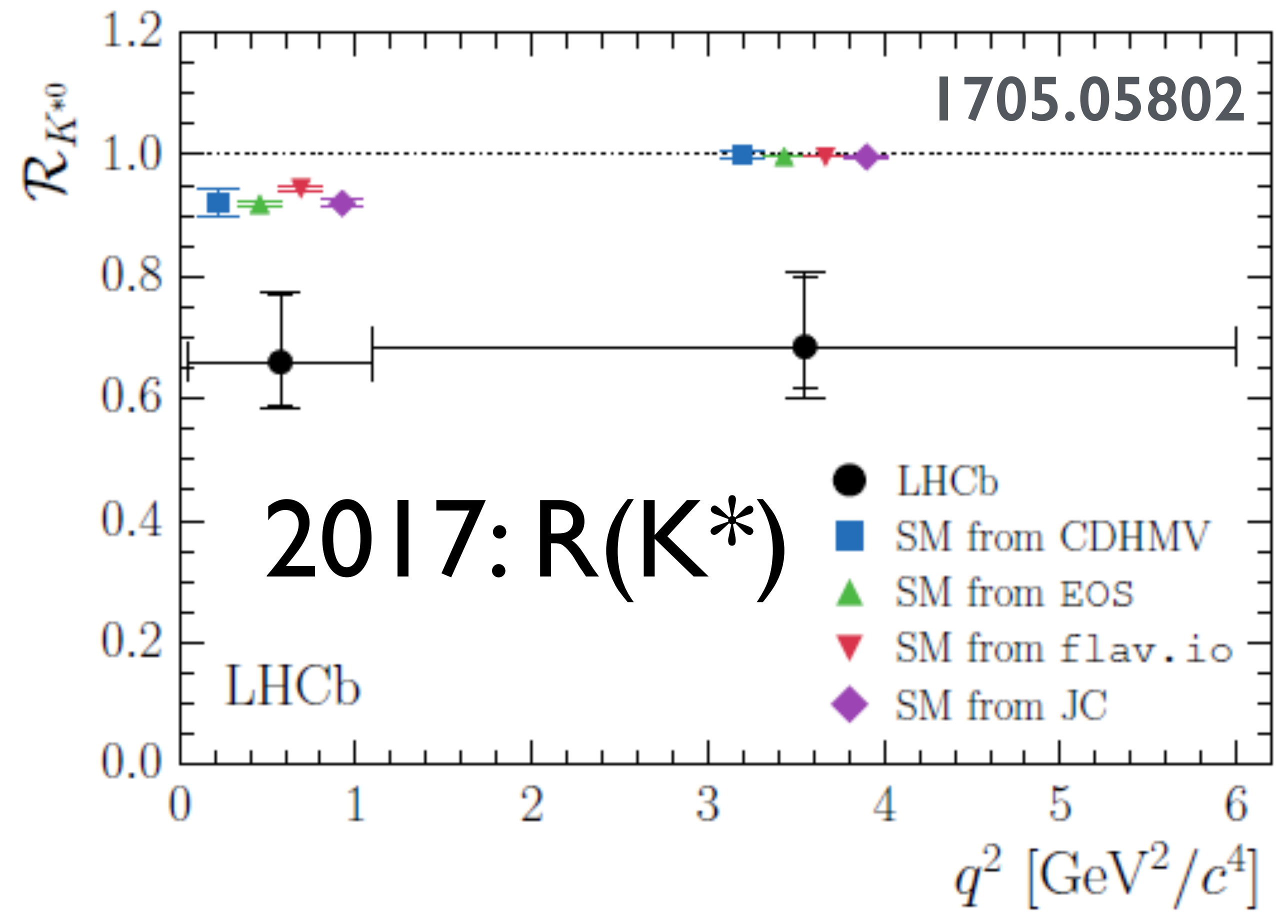
Much debate about the **theory uncertainties**…

Lepton universality tests

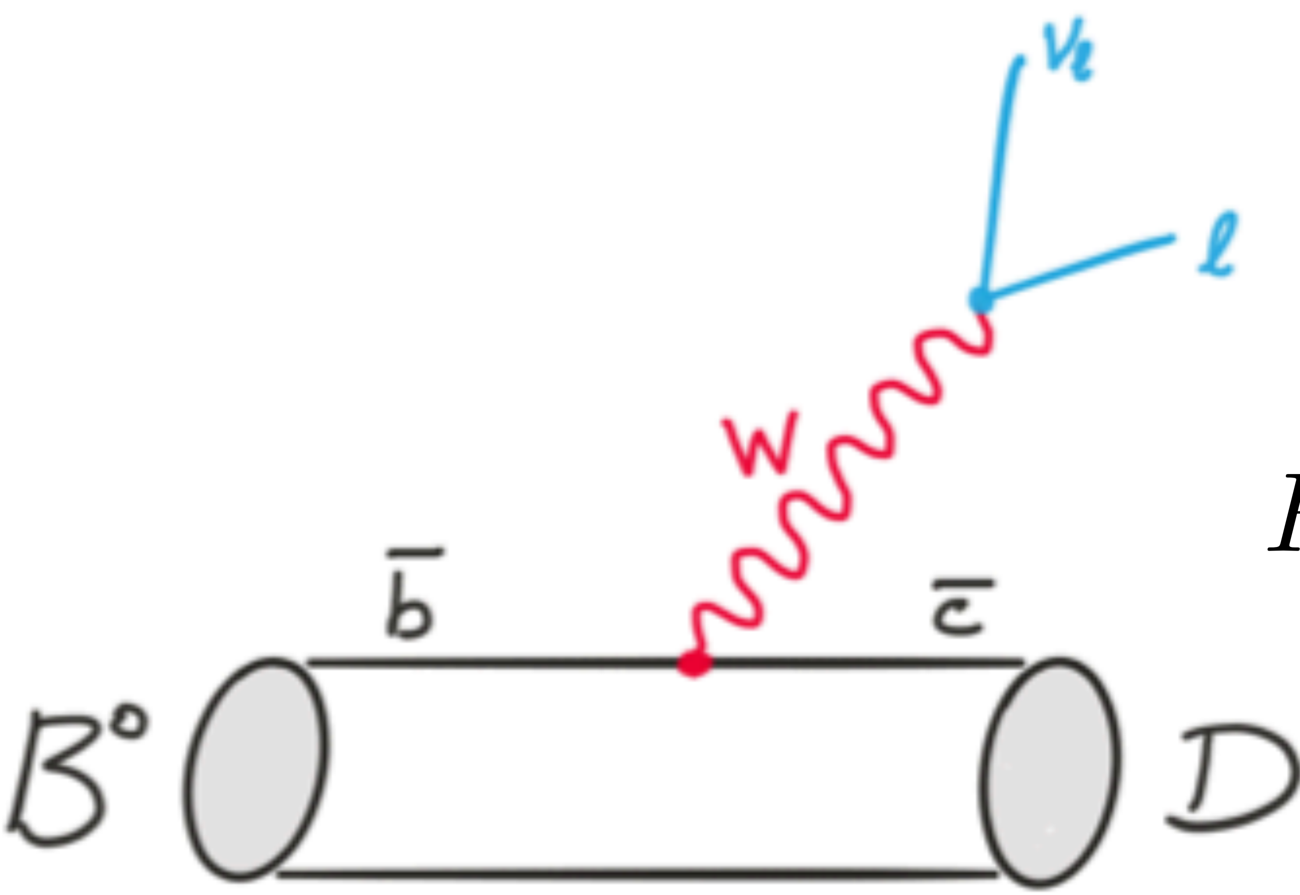




An intriguing pattern of anomalies in related observables, but not statistically conclusive.

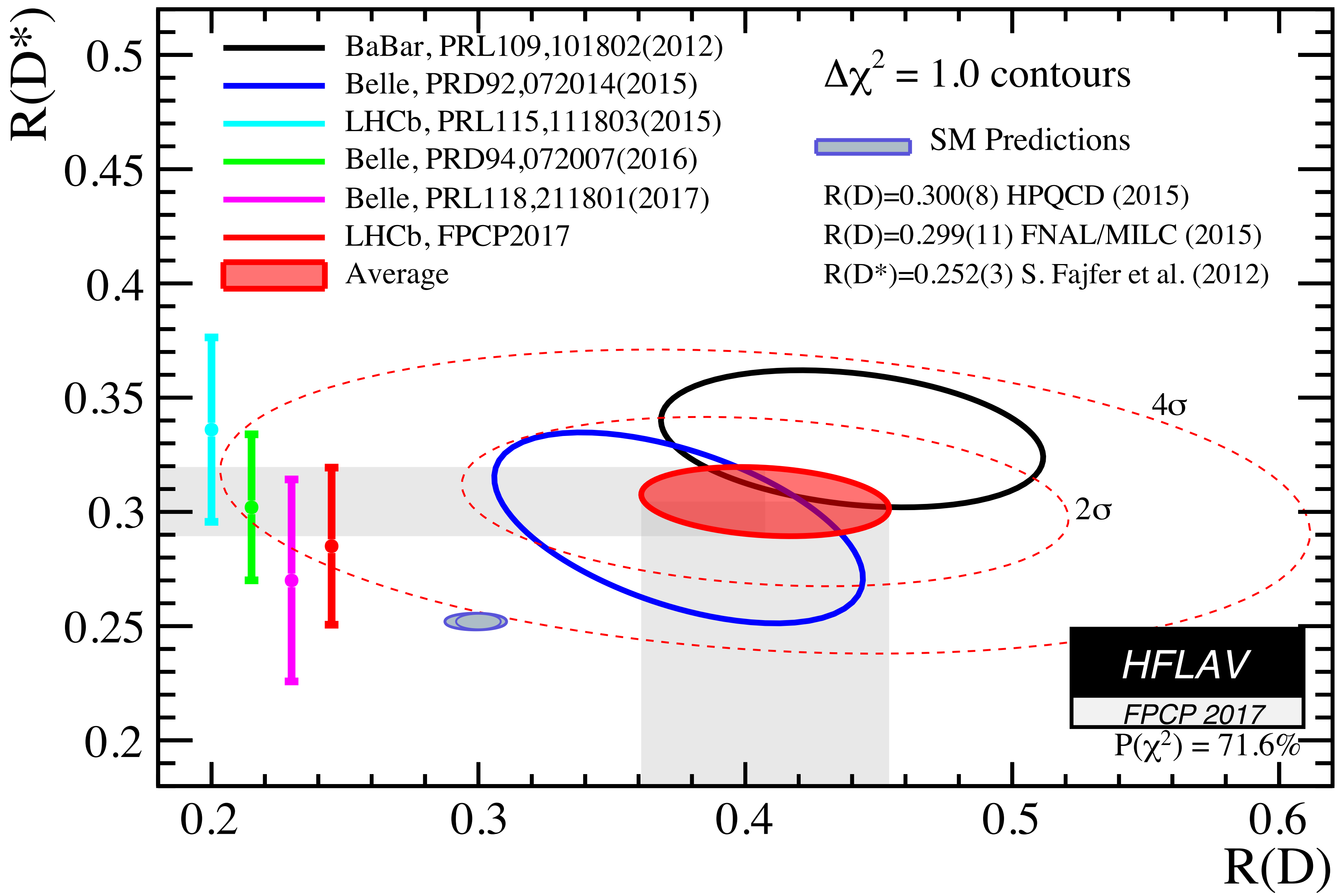
The analysis of Run-II data will be exciting indeed!

LFU tests with trees



$$R(D^{(*)}) = \frac{B(B \to D^{(*)}\tau\nu)}{B(B \to D^{(*)}\mu\nu)}$$

LFU tests with trees



Combined $R(D,D^*)$ is ~4σ from SM

LHCb, recently: first with 3-prong decay of τ!

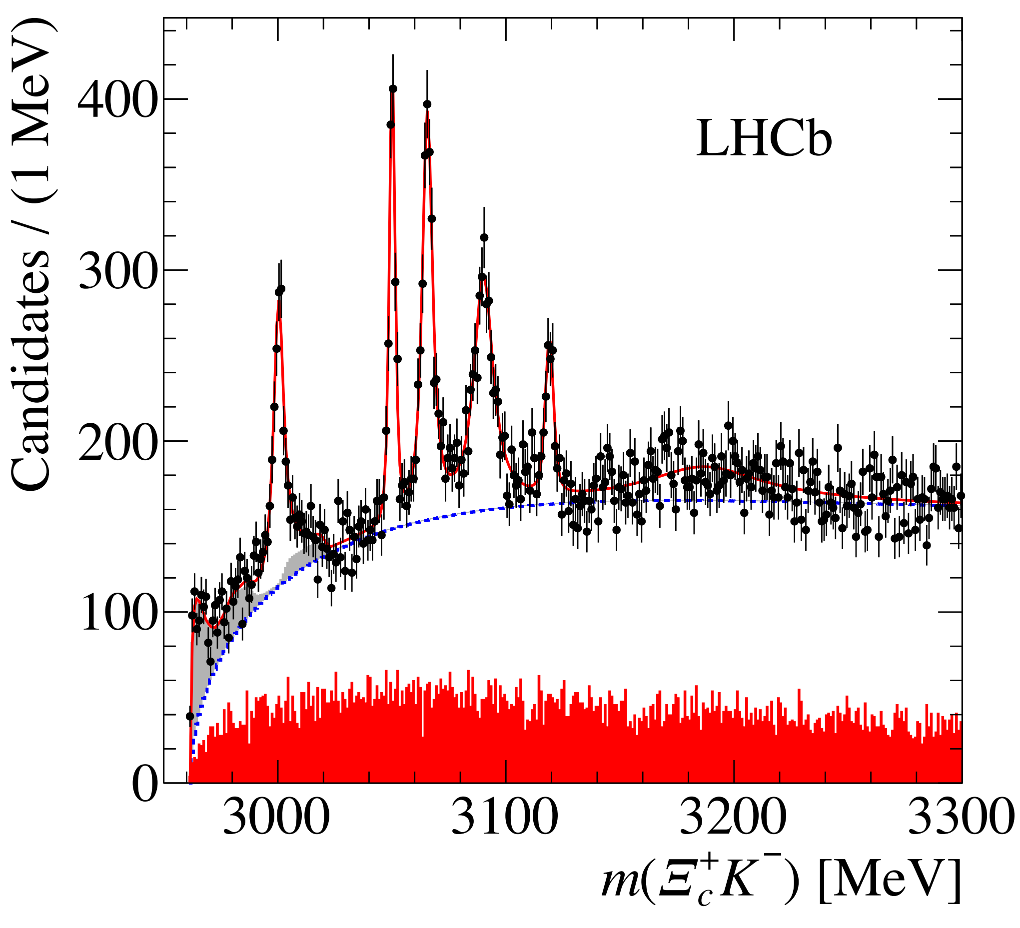
Watch out for: first measurements of new $b \to c$ observables with b species that can only be studied by LHCb!

And preliminary work towards tests with $b \to u$ decays!

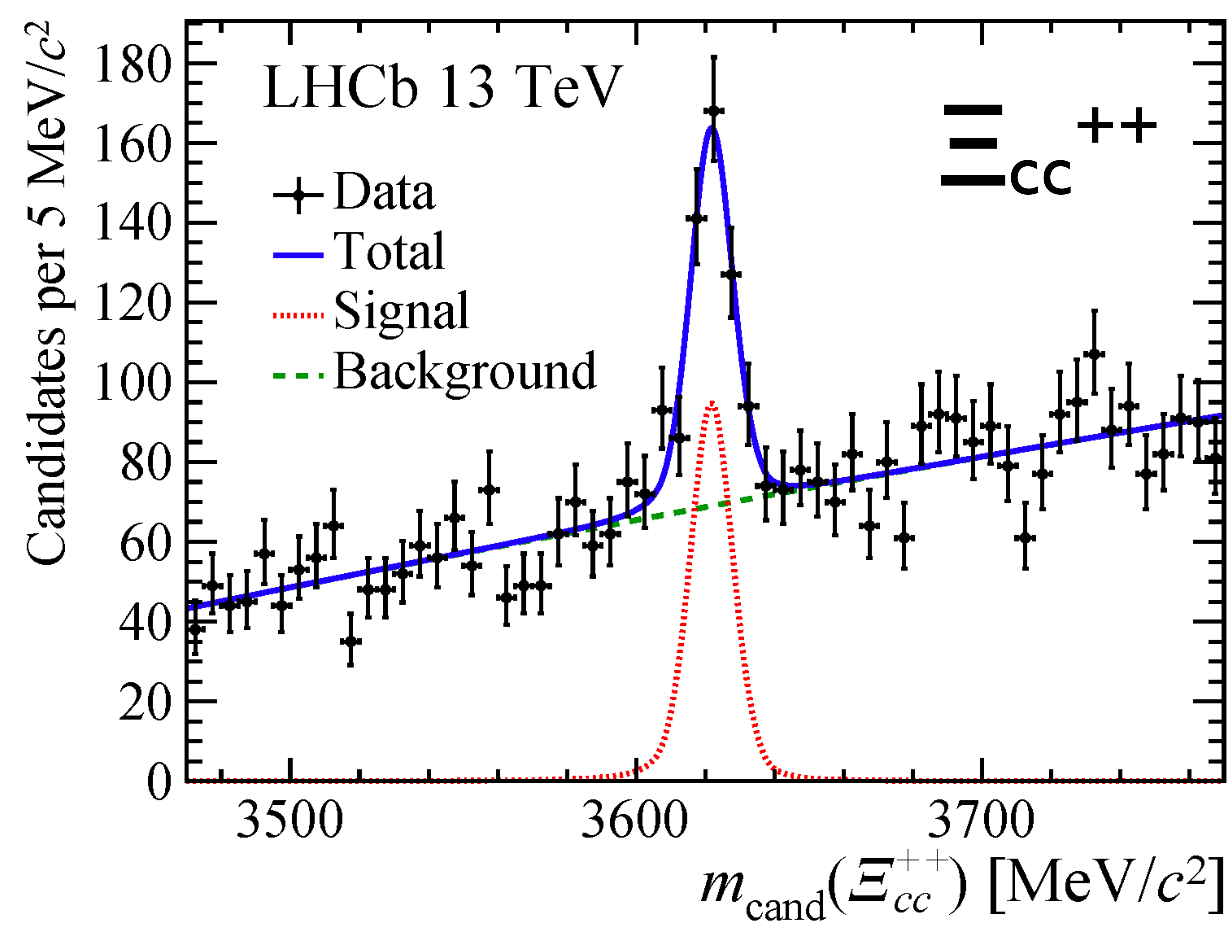
QCD and confinement

Recall that LHCb discovered the first five-quark states, and gave the first indisputable confirmation of previous claims of four-quark states. Some more recent highlights in this area:

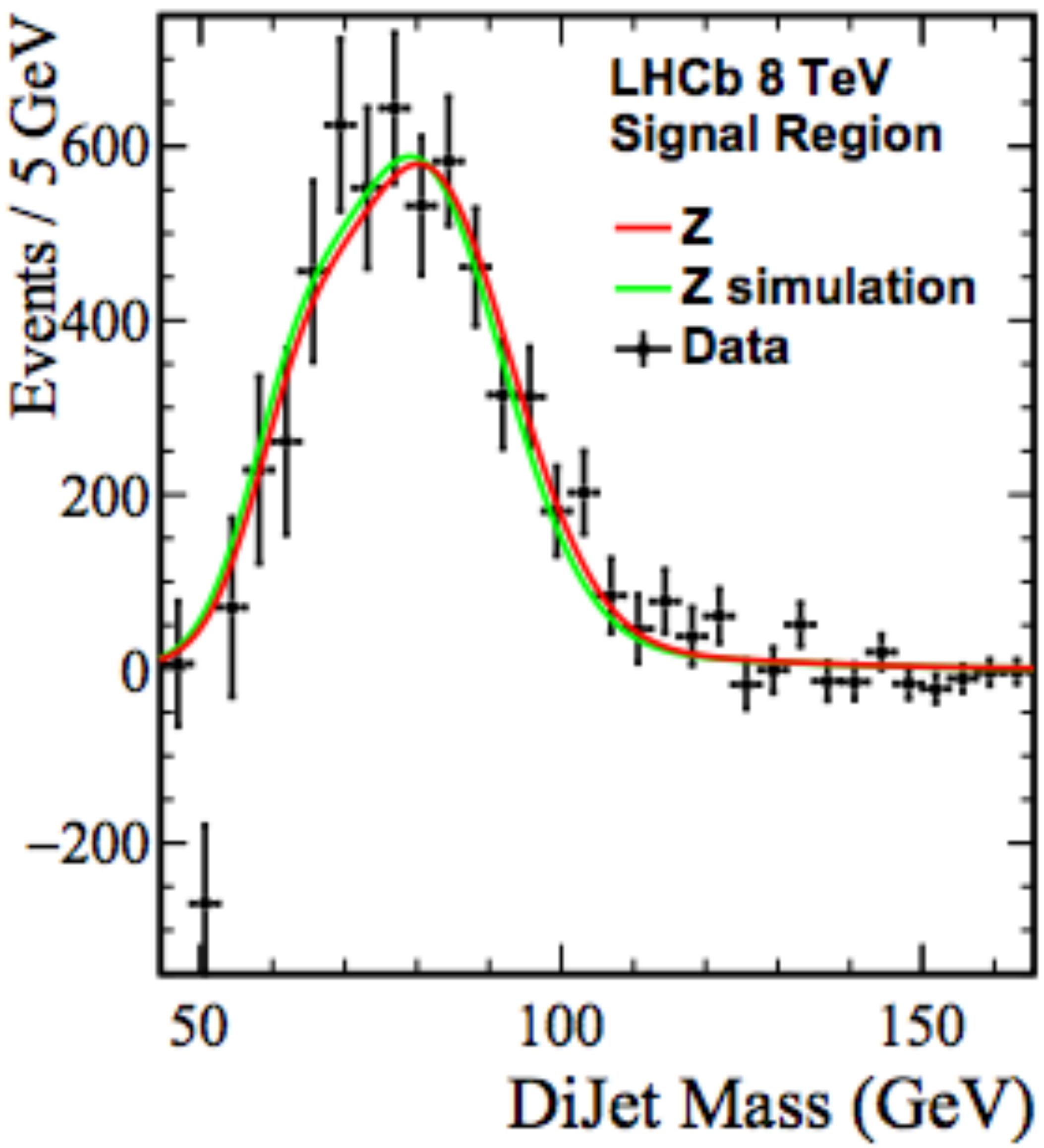
Five new (*css*) states



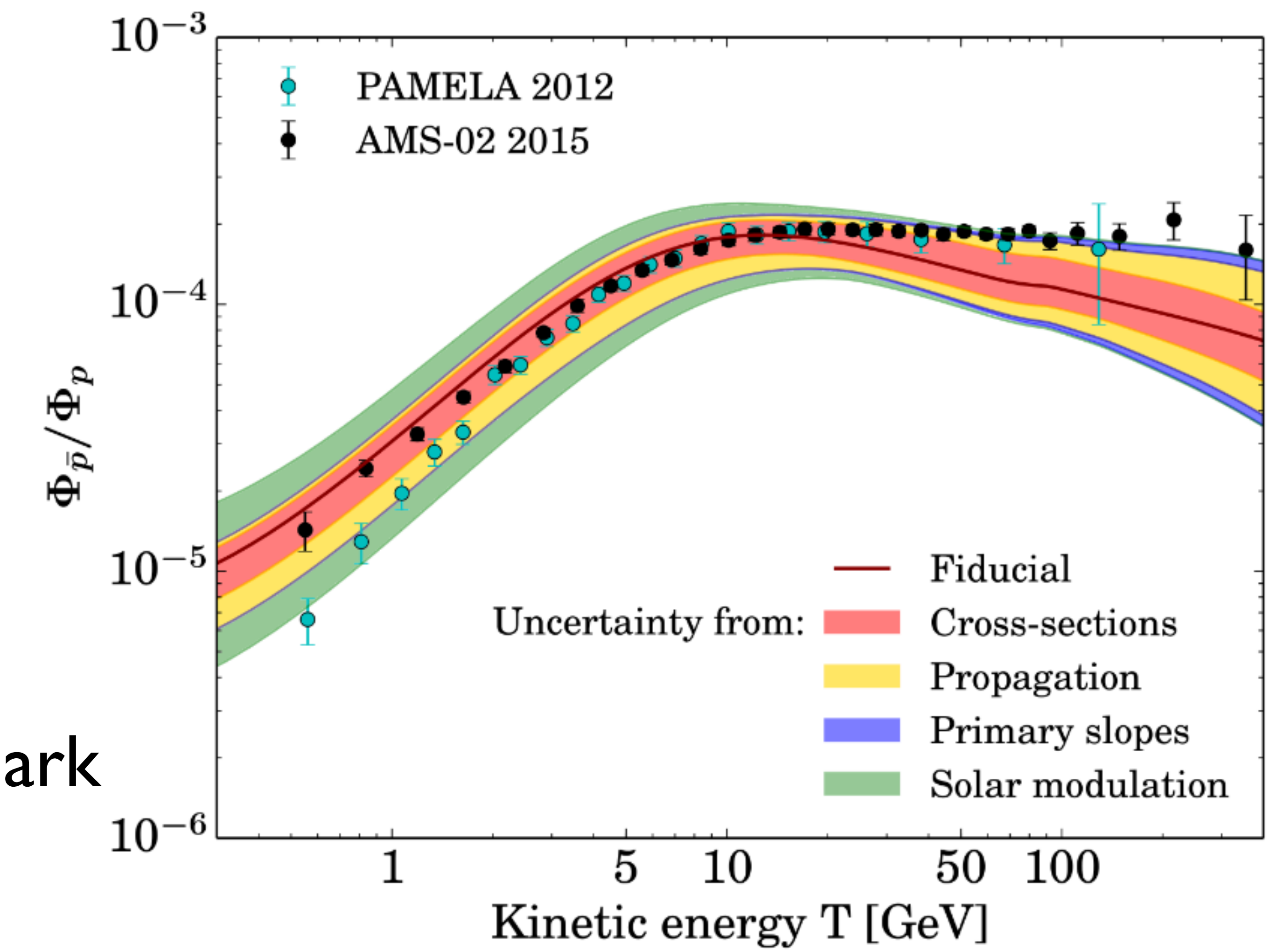
First "doubly heavy" baryon (*ccu*)



Examples beyond flavour



First measurements of anti-proton* production in pHe will crucially constrain models of secondary production to help with the interpretation of AMS data.



Study of *Z*→*bb* presents, e.g., a benchmark for sensitivity in searches for exotic signatures decaying to *b*-jets.

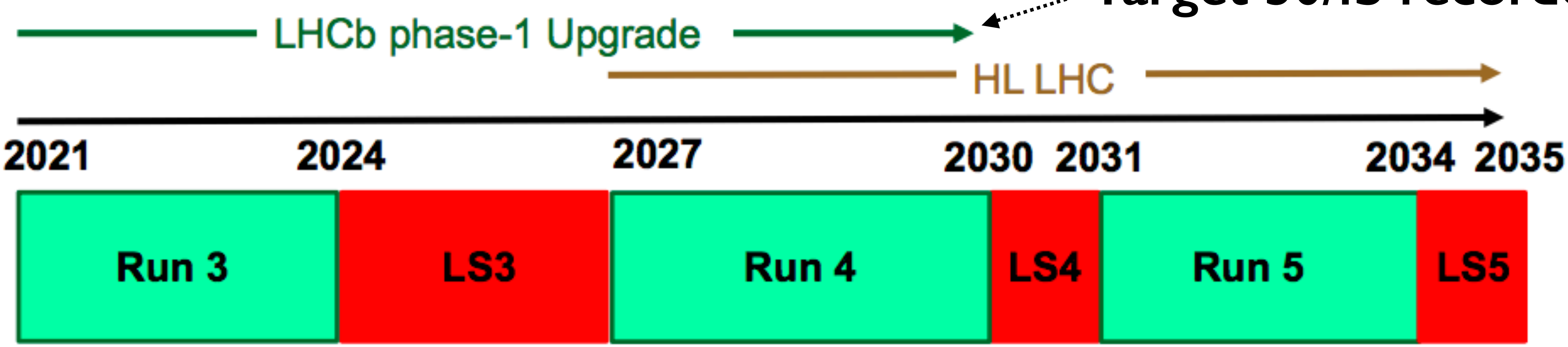
*This measurement would be impossible were it not for the charged-hadron-ID performance of our LHCb-UK-led RICH detectors.

LHCb Phase-I upgrade

1. Replace our hardware trigger with a fully software-based trigger, which gives us higher efficiency and flexibility. This requires a trigger-less readout, creating the world's highest throughput DAQ system.

2. Five-fold luminosity increase to $2{\times}10^{33}$ $cm^{-2}s^{-1}$, which requires the re-design of several sub-detectors.

Target 50/fb recorded



Software trigger: factor of two* higher efficiency for hadronic *b* decays.

*We will actually see far larger (up to ×10!) gains in trigger efficiency for our programs in e.g. charm and rare kaon decays.

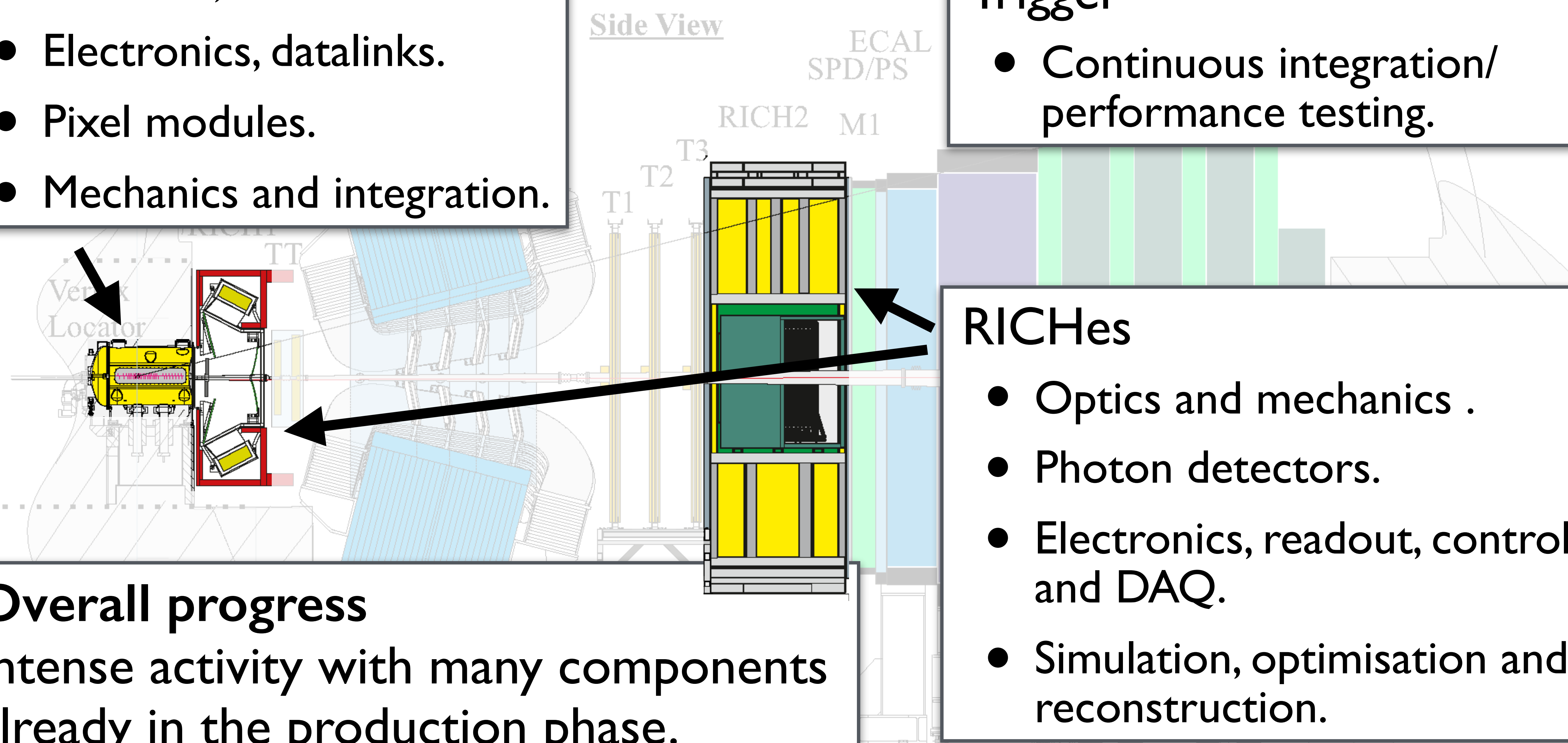
The LHCb-UK contributions

VELO

- Software, firmware.
- Electronics, datalinks.
- Pixel modules.
- Mechanics and integration.

Computing & High Level Trigger

- Continuous integration/ performance testing.



RICHes

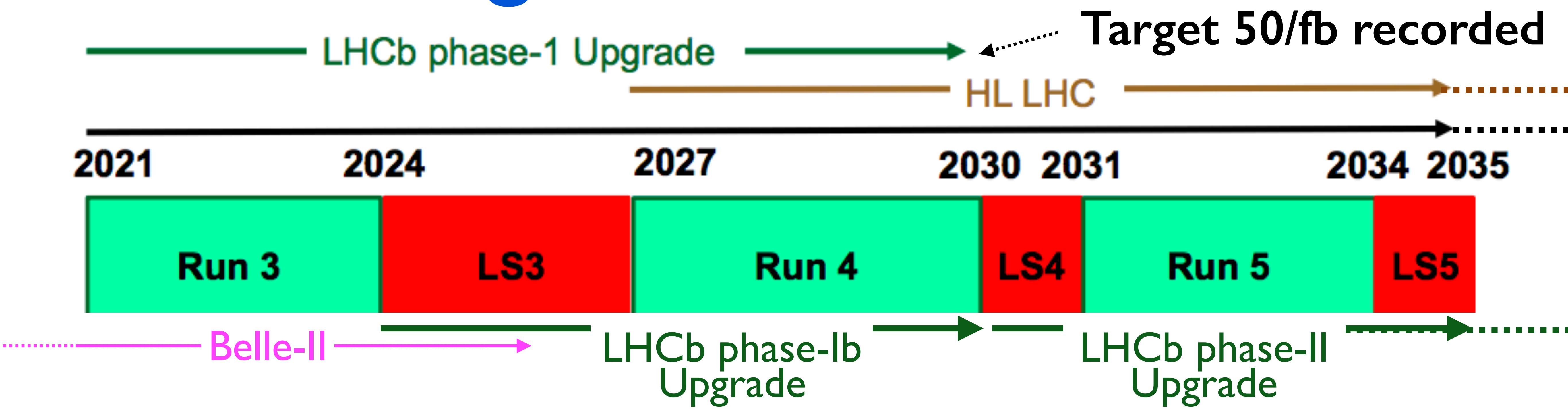
- Optics and mechanics .
- Photon detectors.
- Electronics, readout, controls and DAQ.
- Simulation, optimisation and reconstruction.

Overall progress

Intense activity with many components already in the production phase.

A tight schedule, but well on-track to complete installation during LS3.

Extending our vision for flavour



The LHCb phase-I Upgrade and Belle-II will greatly advance our knowledge of the flavour sector. However, our key theoretically clean observables will still be limited by experimental statistical uncertainties, and others will remain statistically out of reach.

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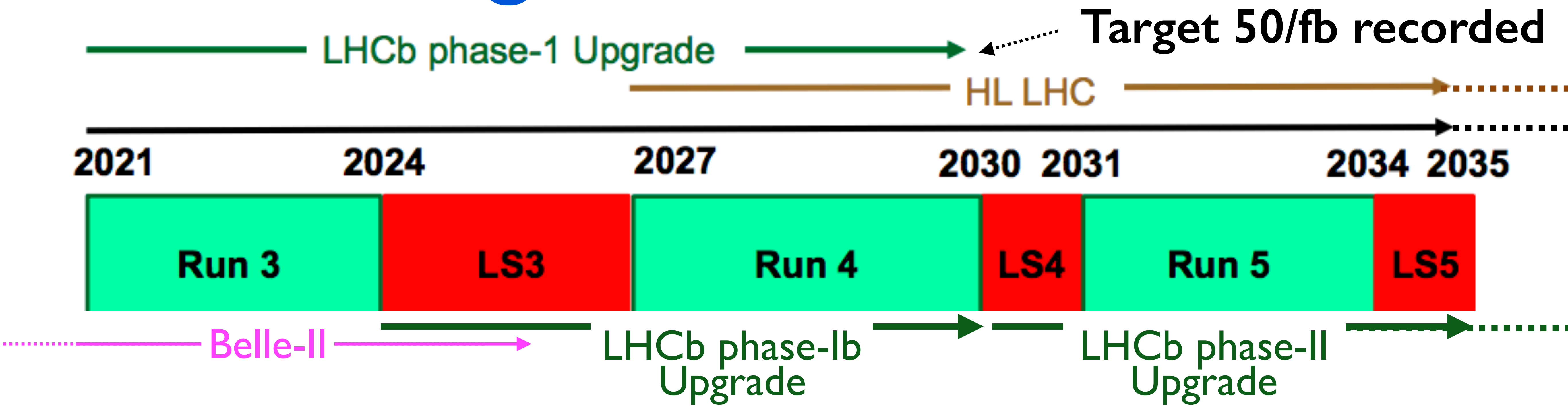

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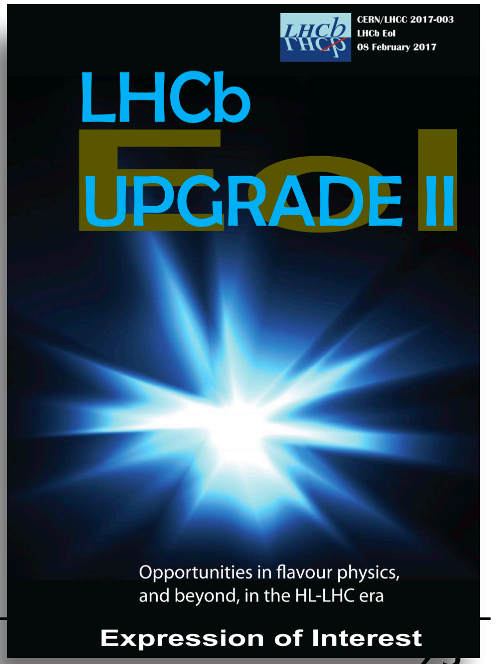
Beyond LS4 a luminosity increase is required. We present a proposal upgrade our detector during LS4, to operate at 1-2×10^{34} cm^{-2}s^{-1}, allowing us to accumulate 300/fb during runs 5-6.

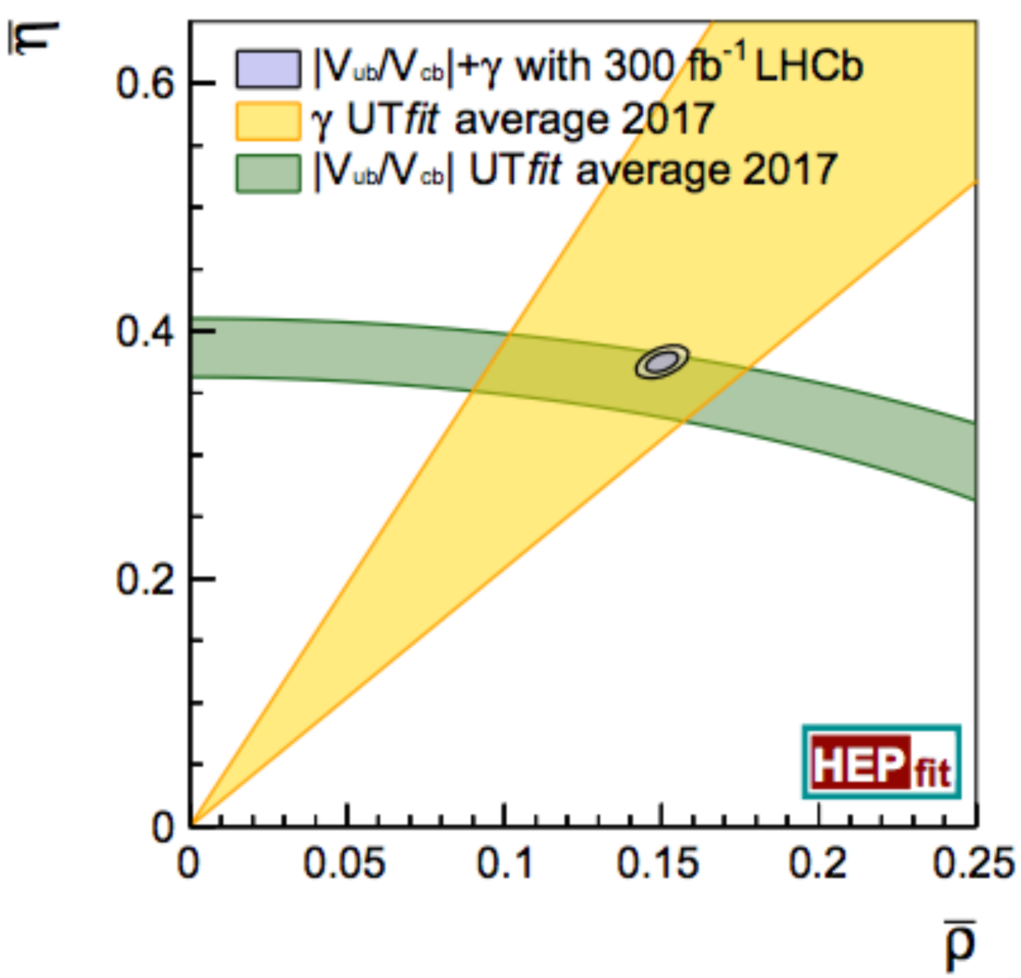
The length of LS3 presents an opportunity to enhance our capabilities for Run-4 with the phase-Ib upgrade.



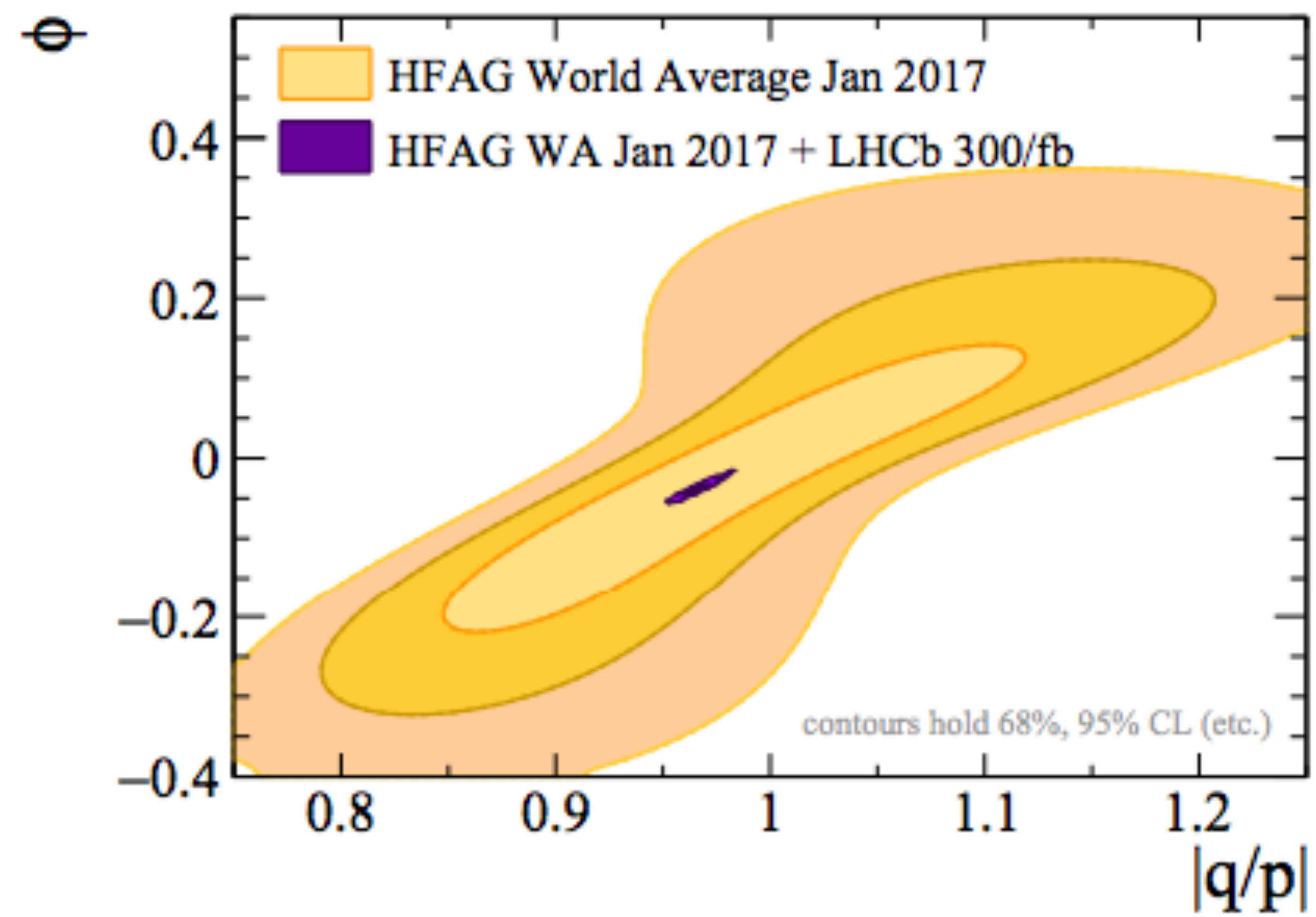
LHCb Phase-II physics potential

Capability to perform a broad spectrum of flavour physics measurements. A few key examples:

Ultra-precise theoretically-clean tests of CKM unitarity.



Charm CP-violation at the 10^{-5} level!



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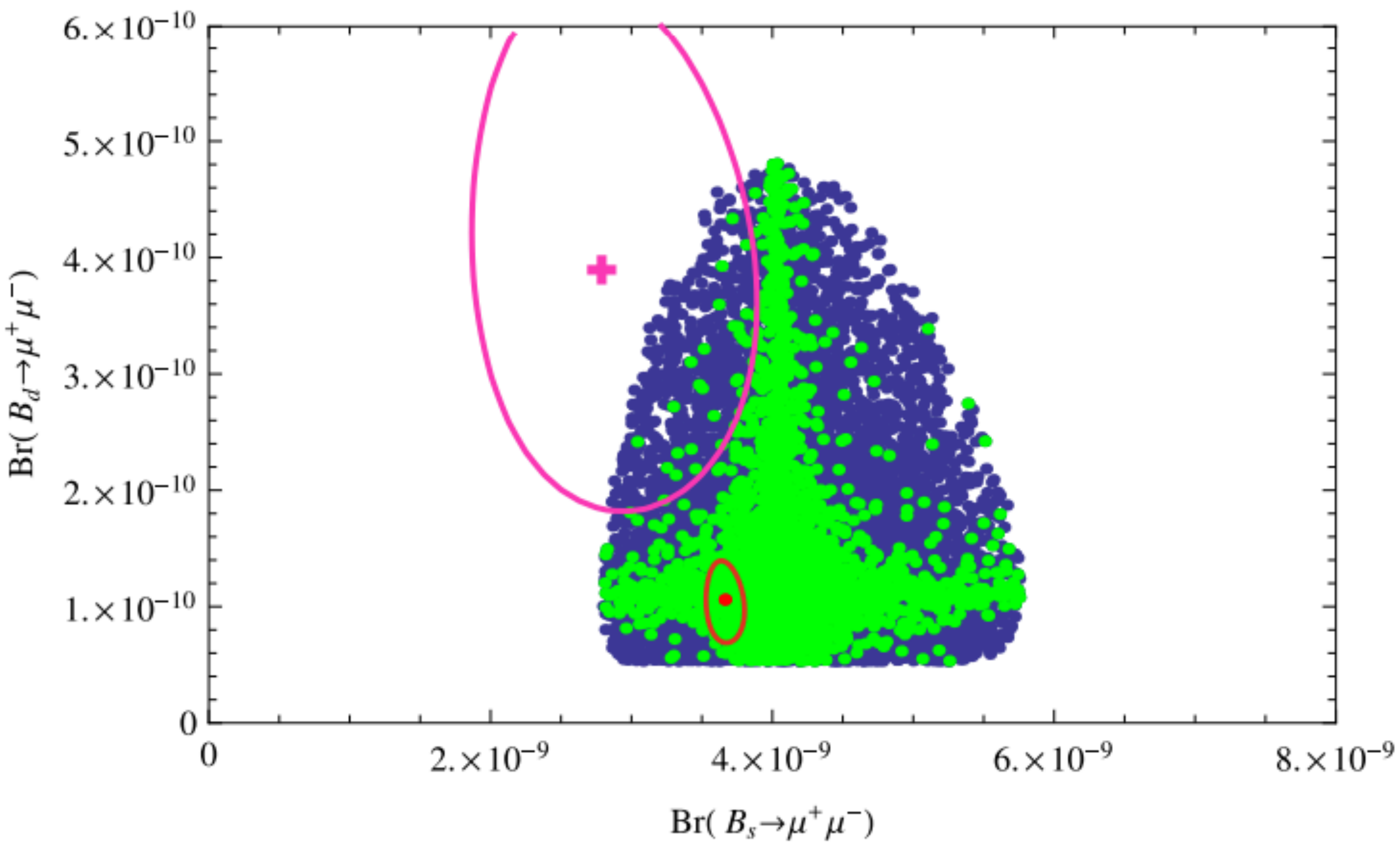
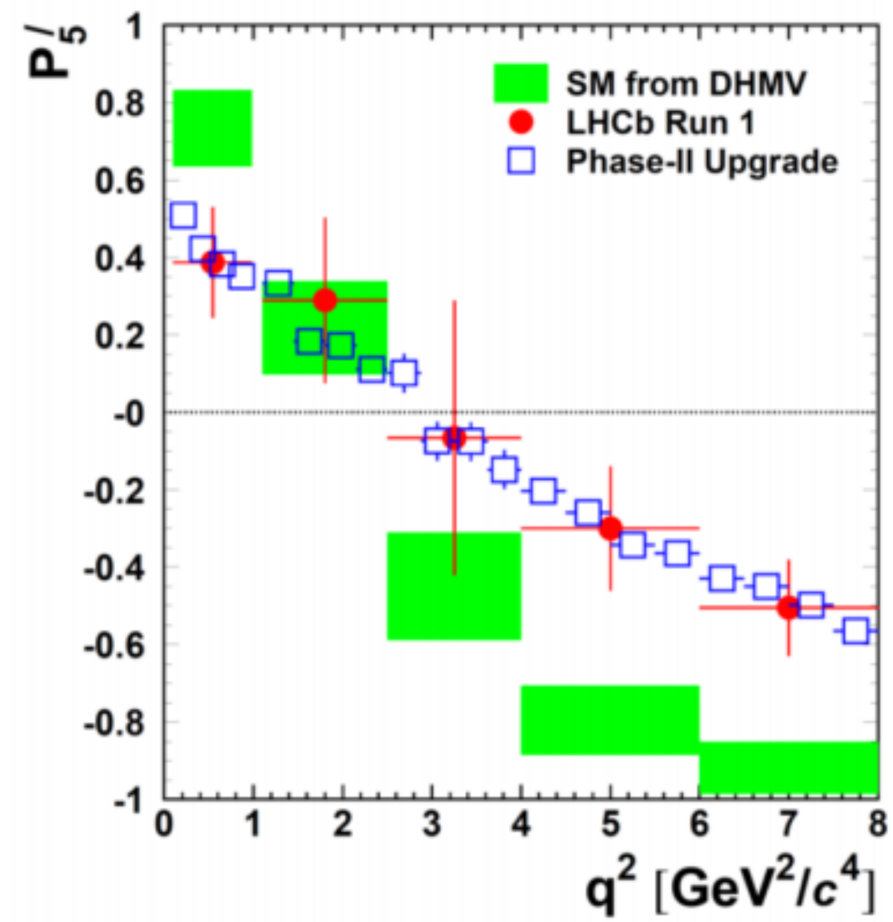
Precisely compare B_d versus B_s decays to $\mu^+\mu^-$.



Semileptonic decays with e, μ and b→s,d.



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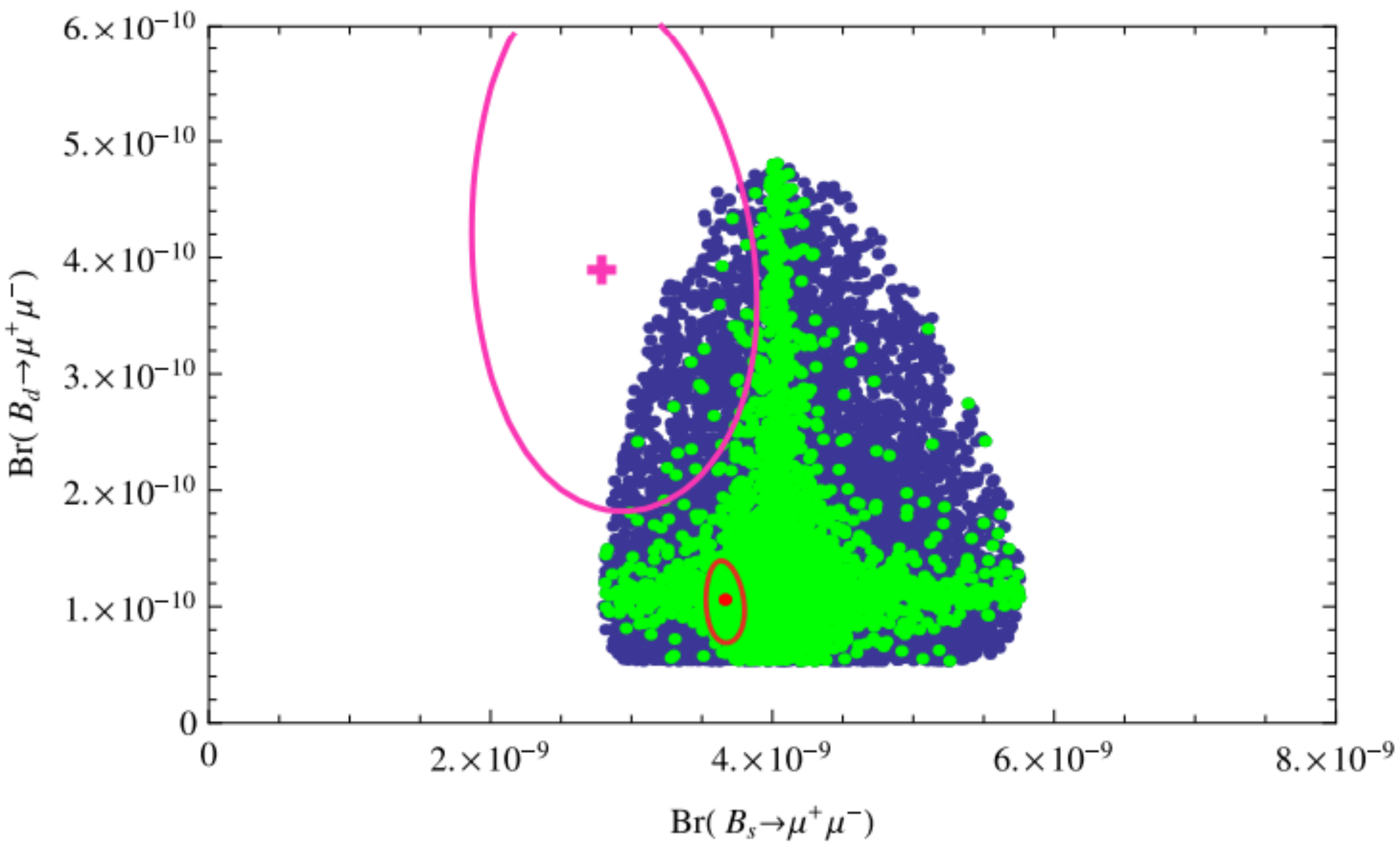

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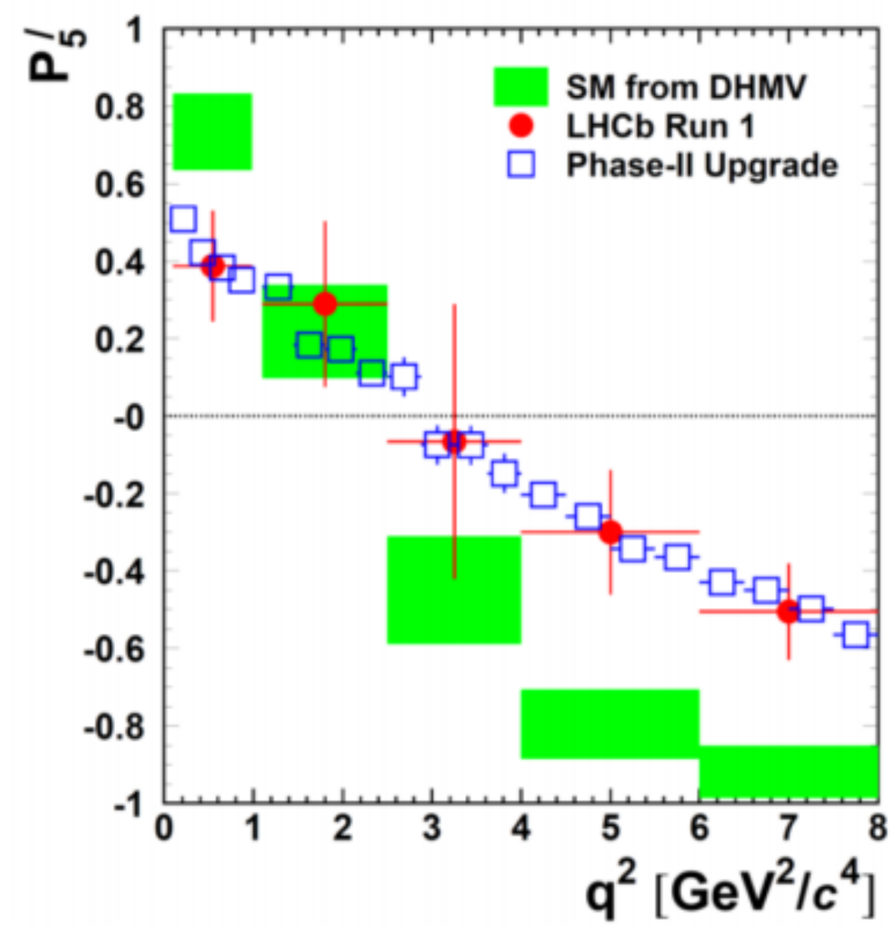
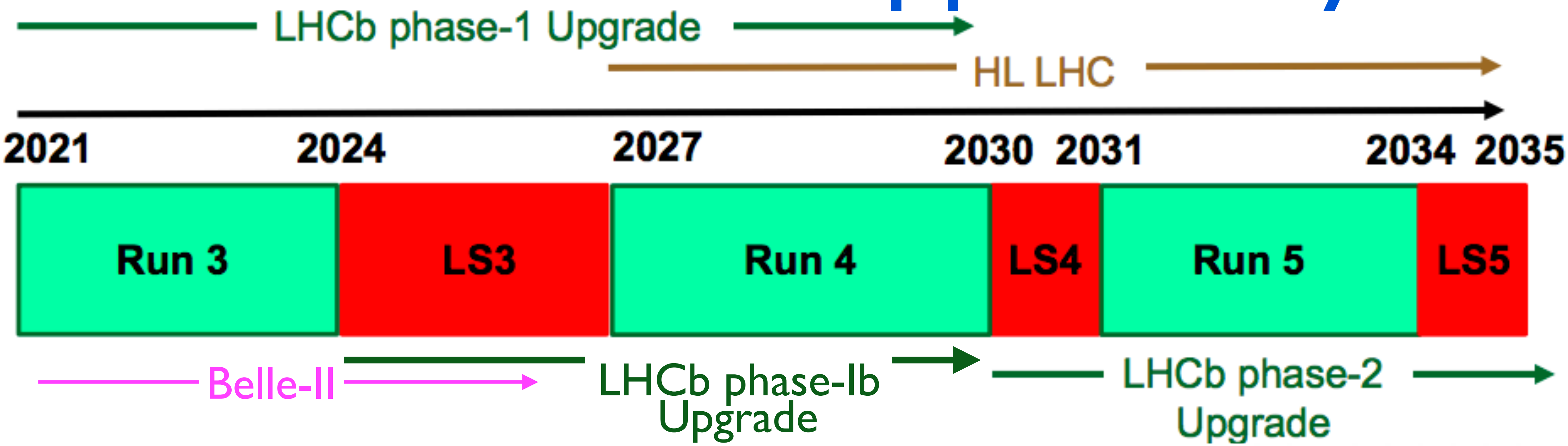


Also expect major discoveries in spectroscopy, and unique programme of physics beyond flavour.

The Phase-Ib opportunity



Side-chambers within dipole magnet.

Novel TORCH detector (UK-led R&D project).

Inner silicon tracker (UK CMOS interest).

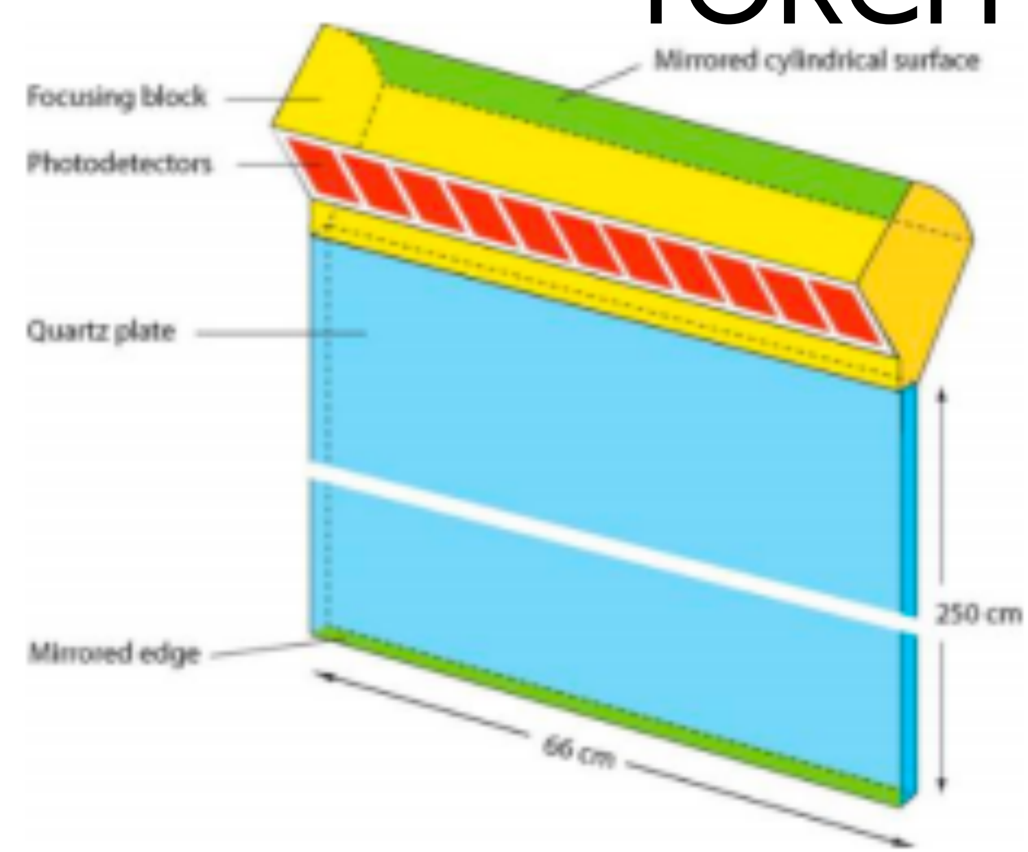
New RICH1 photodetectors in central region.

Upgraded ECAL technology in inner region.

HCAL replaced with Fe shield, and new μ detectors in highest rate regions.

….

TORCH



Phase-II machine considerations

Raising the luminosity requires a smaller β^* at LHCb, which is challenging since it wasn't in the HL-LHC baseline.

Great progress from our accelerator friends — already a range of scenarios in which it is realistic to record 300 fb^{-1} during the HL-LHC lifetime, with minimal impact on ATLAS/CMS luminosity.

300 fb^{-1} is considered as a baseline since that is the limit for the inner-triplets at our IP.

Phase-II detector solutions

Our EOI presents candidate solutions to the challenge of performing precision flavour physics at $1\text{-}2\times10^{33}\text{cm}^{-2}\text{s}^{-1}$.

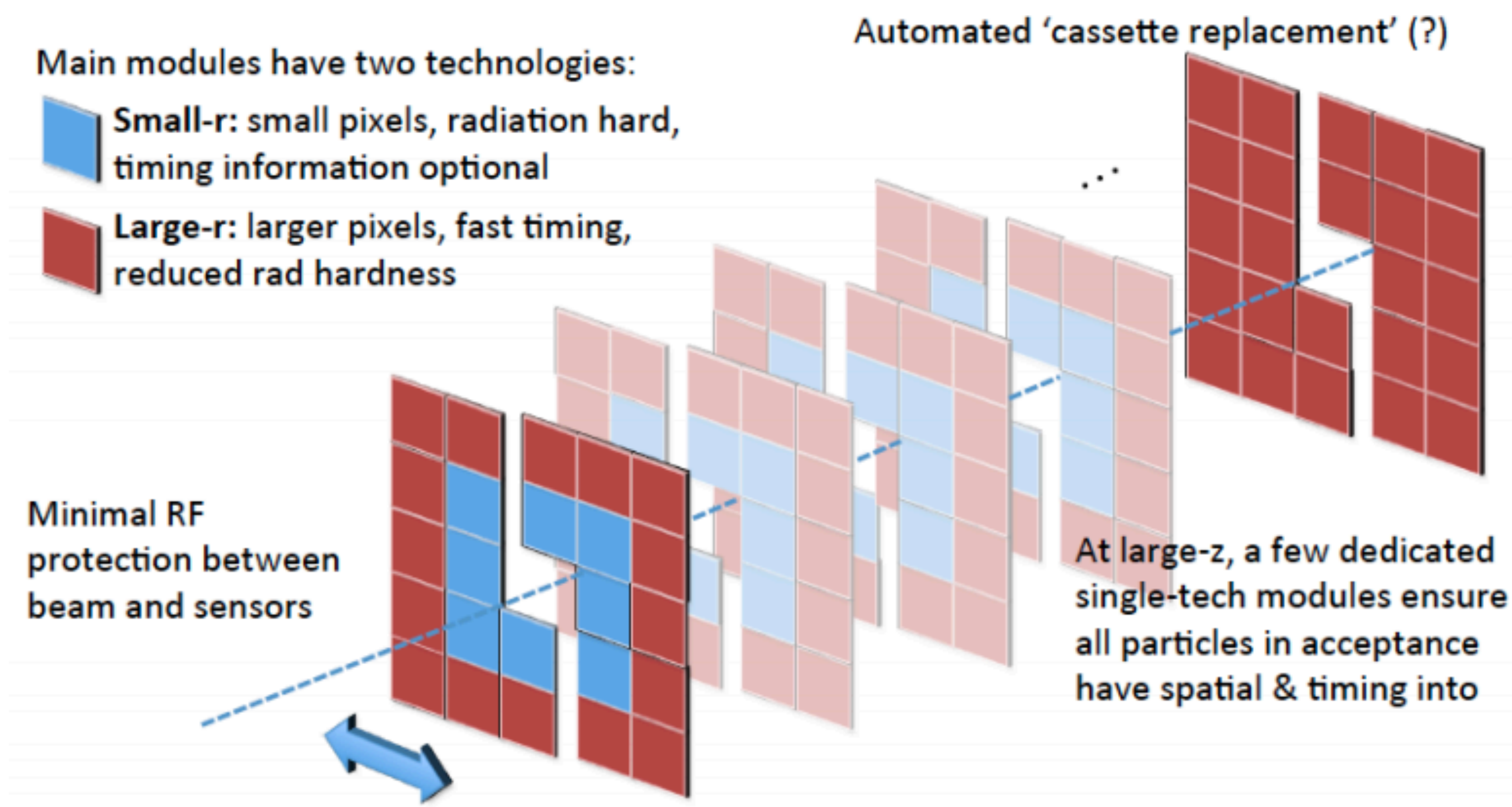
Common to ATLAS/CMS and LHCb is an increase in pileup, which must be mitigated by fast-timing detectors.

Despite the considerable synergy with ATLAS/CMS R&D, significant developments will be required.

Aim to maintain reconstruction performance in some key areas and to improve in others.

The VELO example

↑ Occupancy	Smaller pixels
↑ Pileup	Fast timing
↑ Radiation	Automated cassette replacement

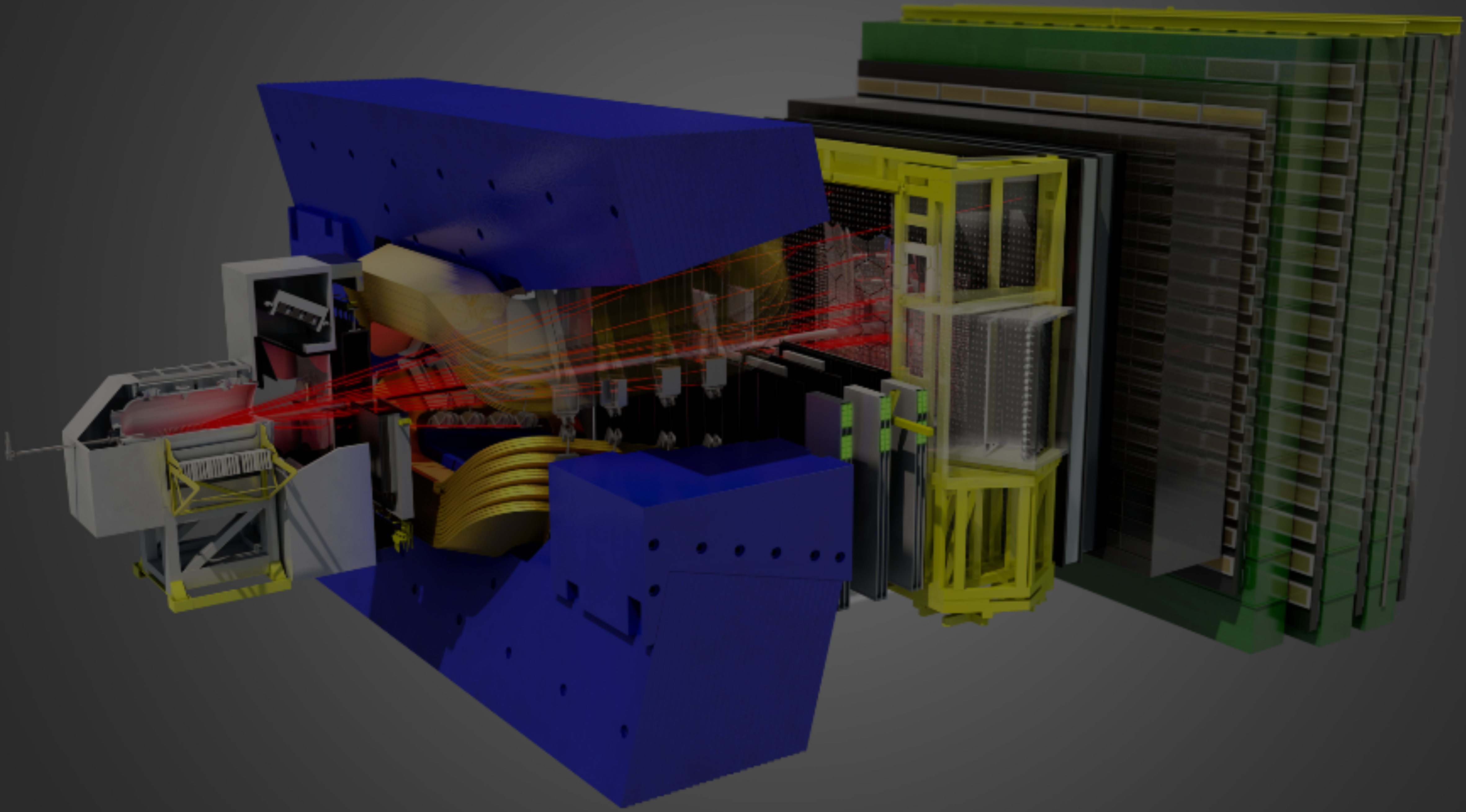


A challenging, but realistic and exciting R&D program awaits us!

Summary

The current LHCb experiment performs exceptionally well, delivering its promised core studies, and many unexpected results in a diverse programme.

We are on-track with Phase-I upgrade preparations, and we now present a clear vision to exploit the precision flavour physics potential of the HL-LHC.



Backup slides start here...

Phase-Ib,II hardware

Table 5.1: Summary of the modifications under consideration for LS3, and those for Phase-II (LS4). Priorities will be assigned for the LS3 activities after further studies.

Detector	LS3	Phase-II
VELO	Deployment of prototype modules	New detector with fast timing
Tracking	Insert silicon IT, modify SciFi; install MS	Silicon UT and IT, SciFi OT
RICH	New photodetectors for selected regions; use of timing information	New optics; full replacement of photodetectors
TORCH	Installation for low-p hadron identification	Higher granularity photodetectors
CALO	Tungsten sampling modules installed in inner region	New modules in middle and outer regions
Muon	Replace HCAL with iron shielding; installation of high-rate chambers	Complete chamber installation
Trigger and data processing	Adiabatic software improvements; review of offline processing; installation of downstream track-finding processor	Expansion/replacement of links, readout boards and servers

Phase-II flavour reach

Table 2.1: Summary of prospects for Phase-II measurements of selected flavour observables.

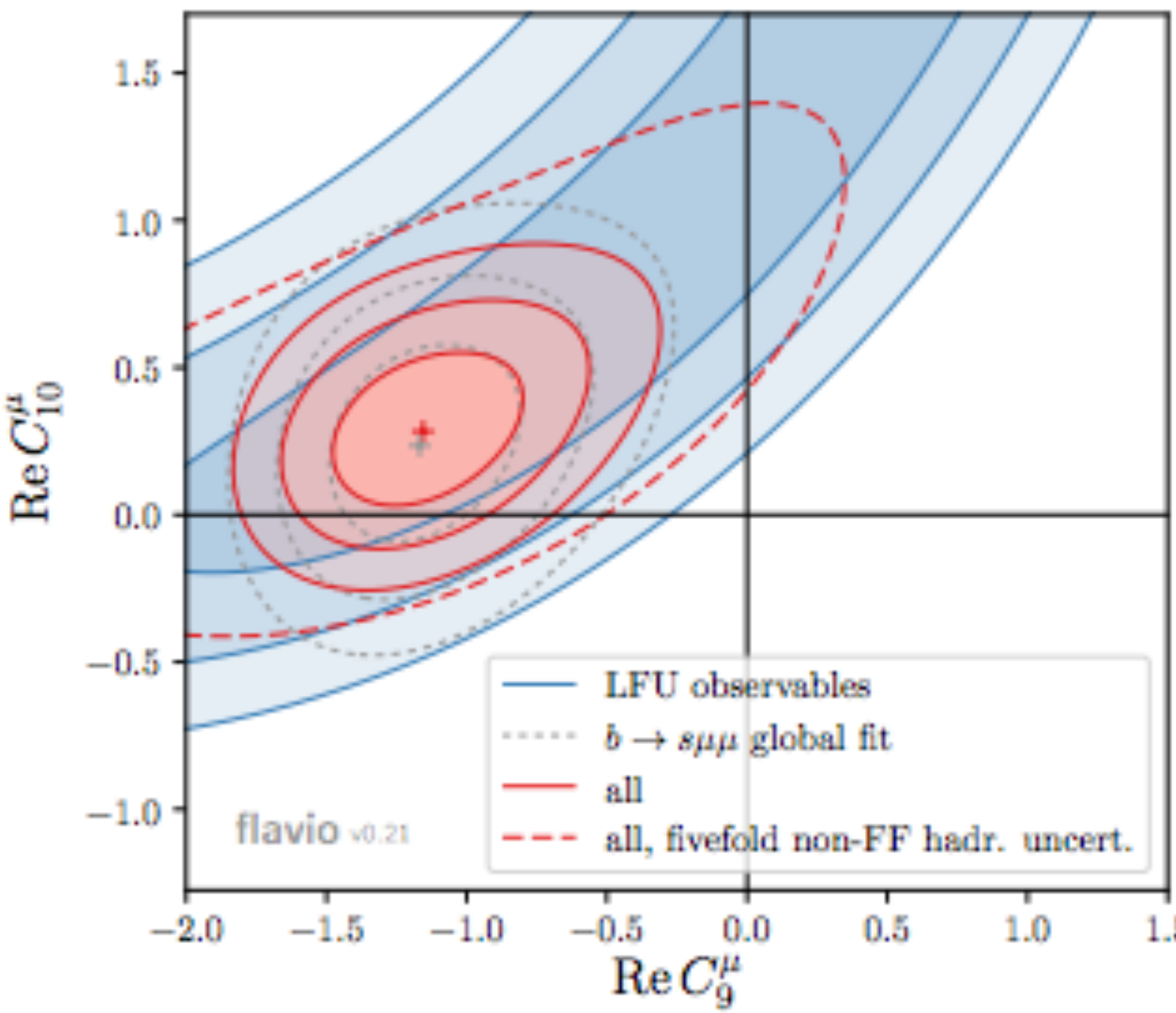
Topics and observables	Experimental reach	Remarks
EW Penguins		
Global tests in many $b \to s\mu^+\mu^-$ modes with full set of precision observables; lepton universality tests; $b \to dl^+l^-$ studies	*e.g.* 440k $B^0 \to K^*\mu^+\mu^-$ & 70k $\Lambda_b^0 \to \Lambda\mu^+\mu^-$; Phase-II $b \to d\mu^+\mu^-$ $\approx$ Run-1 $b \to s\mu^+\mu^-$ sensitivity.	Phase-II ECAL required for lepton universality tests.
Photon polarisation		
$\mathcal{A}^{\Delta}$ in $B_s^0 \to \phi\gamma$; $B^0 \to K^*e^+e^-$; baryonic modes	Uncertainty on $\mathcal{A}^{\Delta} \approx 0.02$; $\sim 10k$ $\Lambda_b^0 \to \Lambda\gamma$, $\Xi_b \to \Xi\gamma$, $\Omega_b^- \to \Omega\gamma$	Strongly dependent on performance of ECAL.
$b \to cl^-\bar{\nu}_l$ lepton-universality tests		
Polarisation studies with $B \to D^{(*)}\tau^-\bar{\nu}_\tau$; τ^-/μ^- ratios with B_s^0, Λ_b^0 and B_c^+ modes	*e.g.* 8M $B \to D^*\tau^-\bar{\nu}_\tau$, $\tau^- \to \mu^-\bar{\nu}_\mu\nu_\tau$ & $\sim 100k$ $\tau^- \to \pi^-\pi^+\pi^-(\pi^0)\nu_\tau$	Additional sensitivity expected from low-p tracking.
B_s^0, $B^0 \to \mu^+\mu^-$		
$R \equiv \mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$; $\tau_{B_s^0 \to \mu^+\mu^-}$; *CP* asymmetry	Uncertainty on $R \approx 20\%$; Uncertainty on $\tau_{B_s^0 \to \mu^+\mu^-} \approx 0.03\,\mathrm{ps}$	
LFV τ decays		
$\tau^- \to \mu^+\mu^-\mu^-$, $\tau^- \to h^+\mu^-\mu^-$, $\tau^- \to \phi\mu^-$	Sensitive to $\tau^- \to \mu^+\mu^-\mu^-$ at 10^{-9}	Phase-II ECAL valuable for background suppression.
CKM tests		
γ with $B^- \to DK^-$, $B_s^0 \to D_s^+K^-$ *etc.*	Uncertainty on $\gamma \approx 0.4°$	Additional sensitivity expected
ϕ_s with $B_s^0 \to J/\psi K^+K^-$, $J/\psi\pi^+\pi^-$	Uncertainty on $\phi_s \approx 3\,\mathrm{mrad}$	in *CP* observables from Phase-II
$\phi_s^{s\bar{s}s}$ with $B_s^0 \to \phi\phi$	Uncertainty on $\phi_s^{s\bar{s}s} \approx 8\,\mathrm{mrad}$	ECAL and low-p tracking.
$\Delta\Gamma_d/\Gamma_d$	Uncertainty on $\Delta\Gamma_d/\Gamma_d \sim 10^{-3}$	Approach SM value.
Semileptonic asymmetries $a_{\rm sl}^{d,s}$	Uncertainties on $a_{\rm sl}^{d,s} \sim 10^{-4}$	Approach SM value for $a_{\rm sl}^{d}$.
$\lvert V_{ub}\rvert/\lvert V_{cb}\rvert$ with Λ_b^0, B_s^0 and B_c^+ modes	*e.g.* 120k $B_c^+ \to D^0\mu^-\bar{\nu}_\mu$	Significant gains achievable from thinning or removing RF-foil.
Charm		
CP-violation studies with $D^0 \to h^+h^-$, $D^0 \to K_S^0\pi^+\pi^-$ and $D^0 \to K^\mp\pi^\pm\pi^+\pi^-$	*e.g.* 4×10^9 $D^0 \to K^+K^-$; Uncertainty on $A_\Gamma \sim 10^{-5}$	Access *CP* violation at SM values.
Strange		
Rare decay searches	Sensitive to $K_S^0 \to \mu^+\mu^-$ at 10^{-12}	Additional sensitivity possible with downstream trigger enhancements.

Phase-II machine scenarios

β^* [m]	Maximum $\mathcal{L}$ [$\times 10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$] −	+	Target levelling $\mathcal{L}$ [$\times 10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$]	Fill length [h] −	+	Levelling time [h] −	+	$\int \mathcal{L}\,dt$ [fb^{-1}/yr] −	+
3	1.04	0.78	0.20	8.1	8.1	8.1	8.1	10	10
2	1.53	1.04	1.00	7.7	7.8	2.8	0.4	39	31
2	1.53	1.04	/	7.6	7.8	/	/	43	31
1	2.90	1.66	1.00	7.5	7.6	6.0	3.5	48	42
1	2.90	1.66	2.00	7.3	7.5	2.3	0	73	48
1	2.90	1.66	/	7.2	7.5	/	/	80	48

Example Wilson coefficient fit

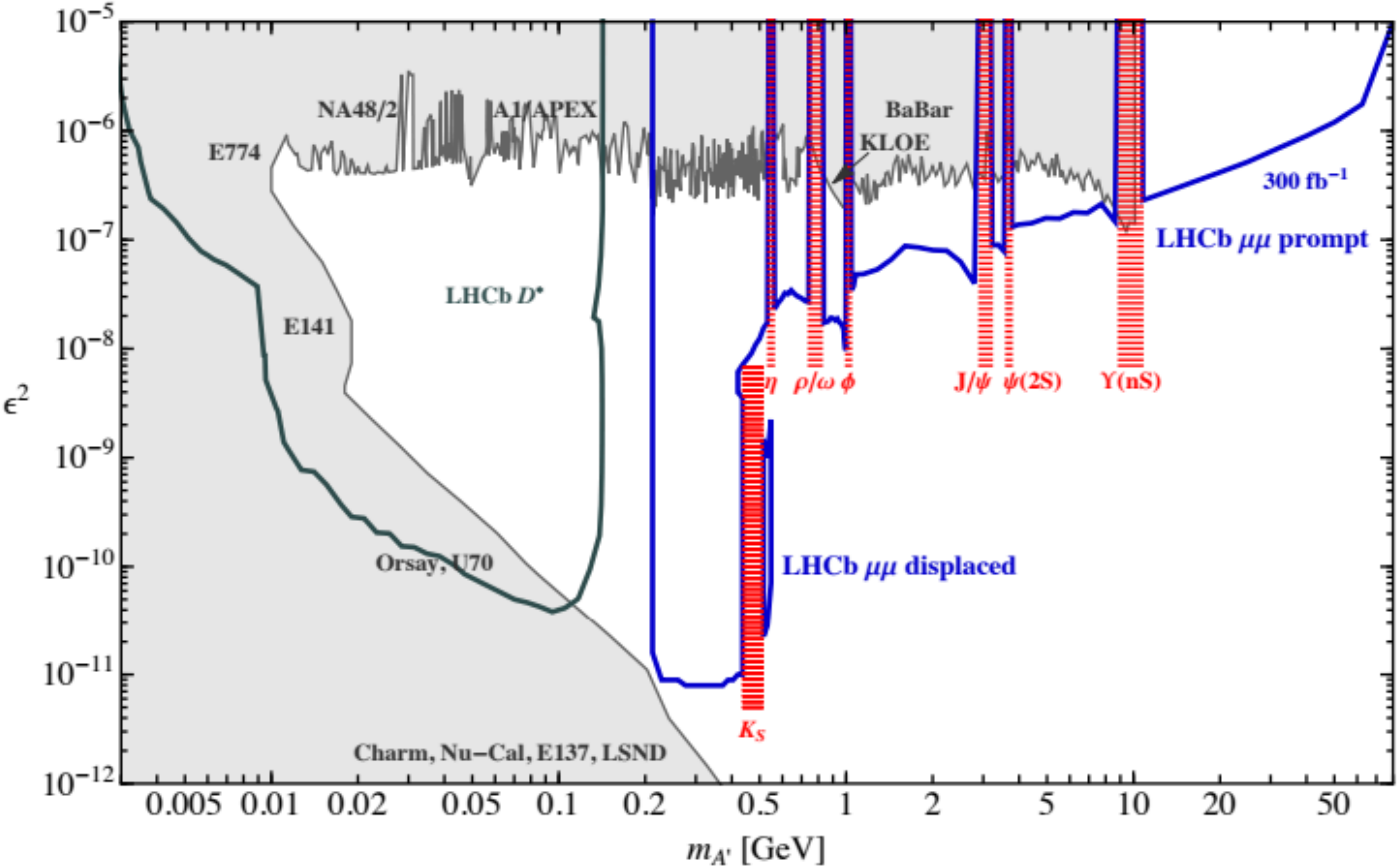
Altmannshofer et al., 1704.05435



$$O_9^{\ell} = (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \ell)\,,$$

$$O_{10}^{\ell} = (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \gamma_5 \ell)$$

Example beyond flavour



LHCb Phase-I upgrade