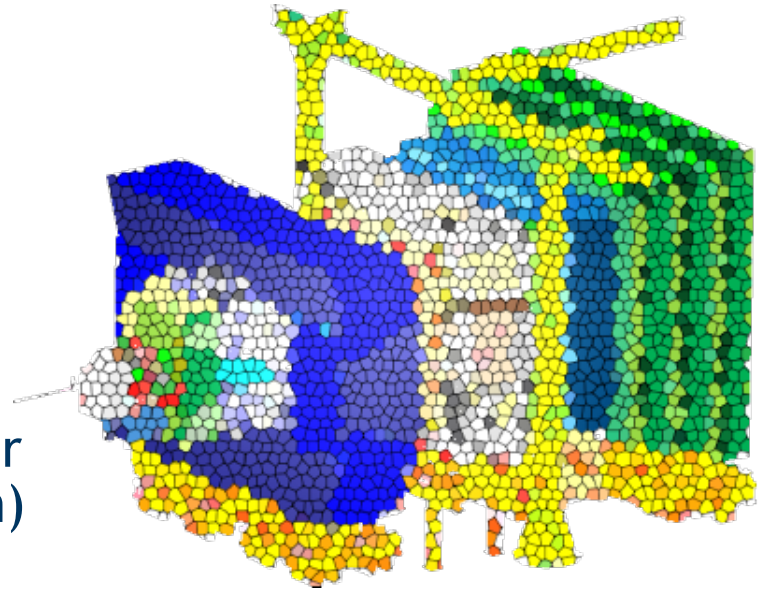
Flavour Physics potential with LHCb Upgrade II

LHCb	Original
	2009-2018
LHCb	Upgrade I
	2022-2032
LHCb	Upgrade II
	2033-

Mark Whitehead

On behalf of the LHCb collaboration

The 2023 International Workshop on Circular Electron Positron Collider (European Edition)

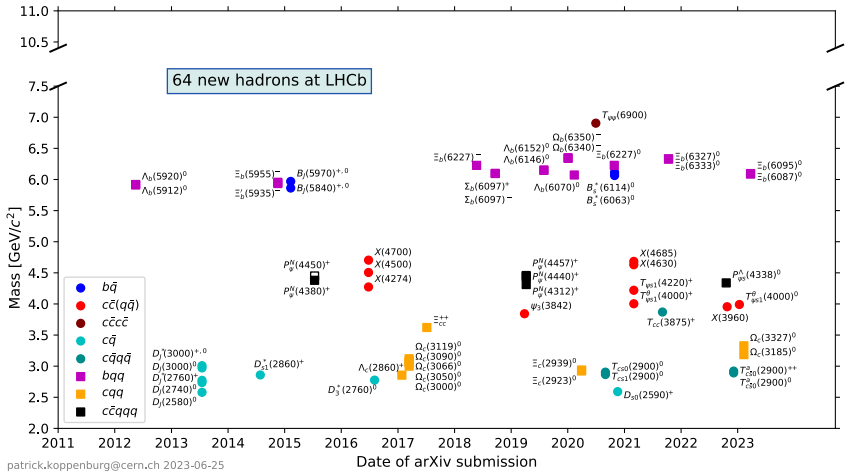


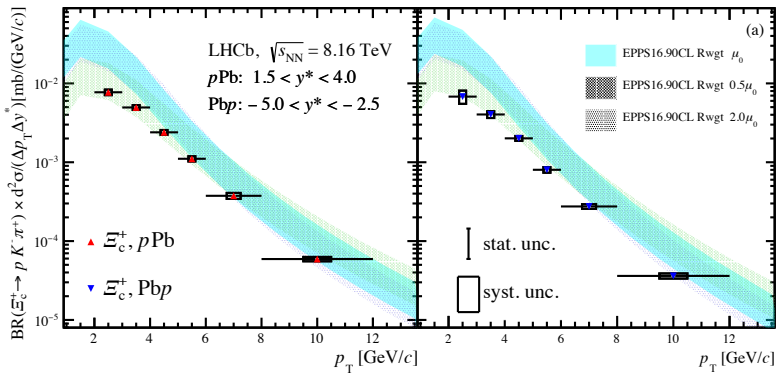
Science and Technology Facilities Council

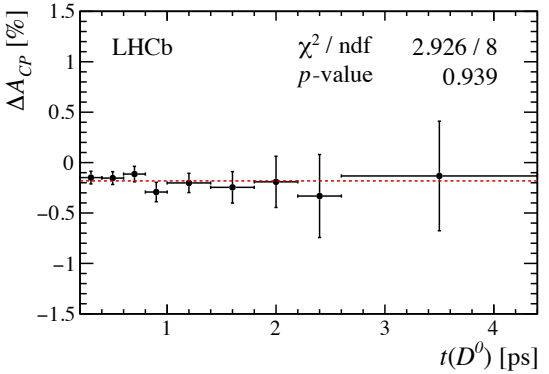
University of Glasgow

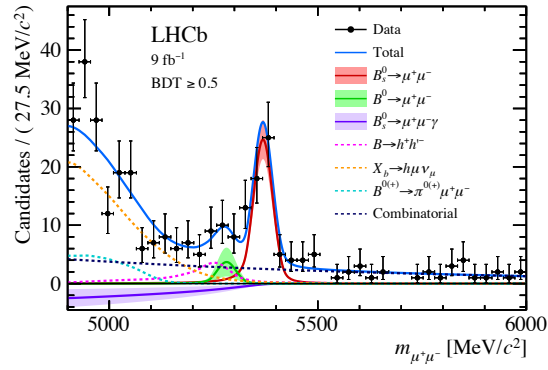
LHCb Original

- Hugely successful experiment, > 600 publications
- Significant discoveries
  - CPV observed in new systems
  - Rare decays
  - 64 of 72 new hadrons discovered at the LHC
- Broad physics programme
  - World leading for core topics, but also
    - Heavy ions
    - Fixed target
    - Electroweak
    - Dark Sector





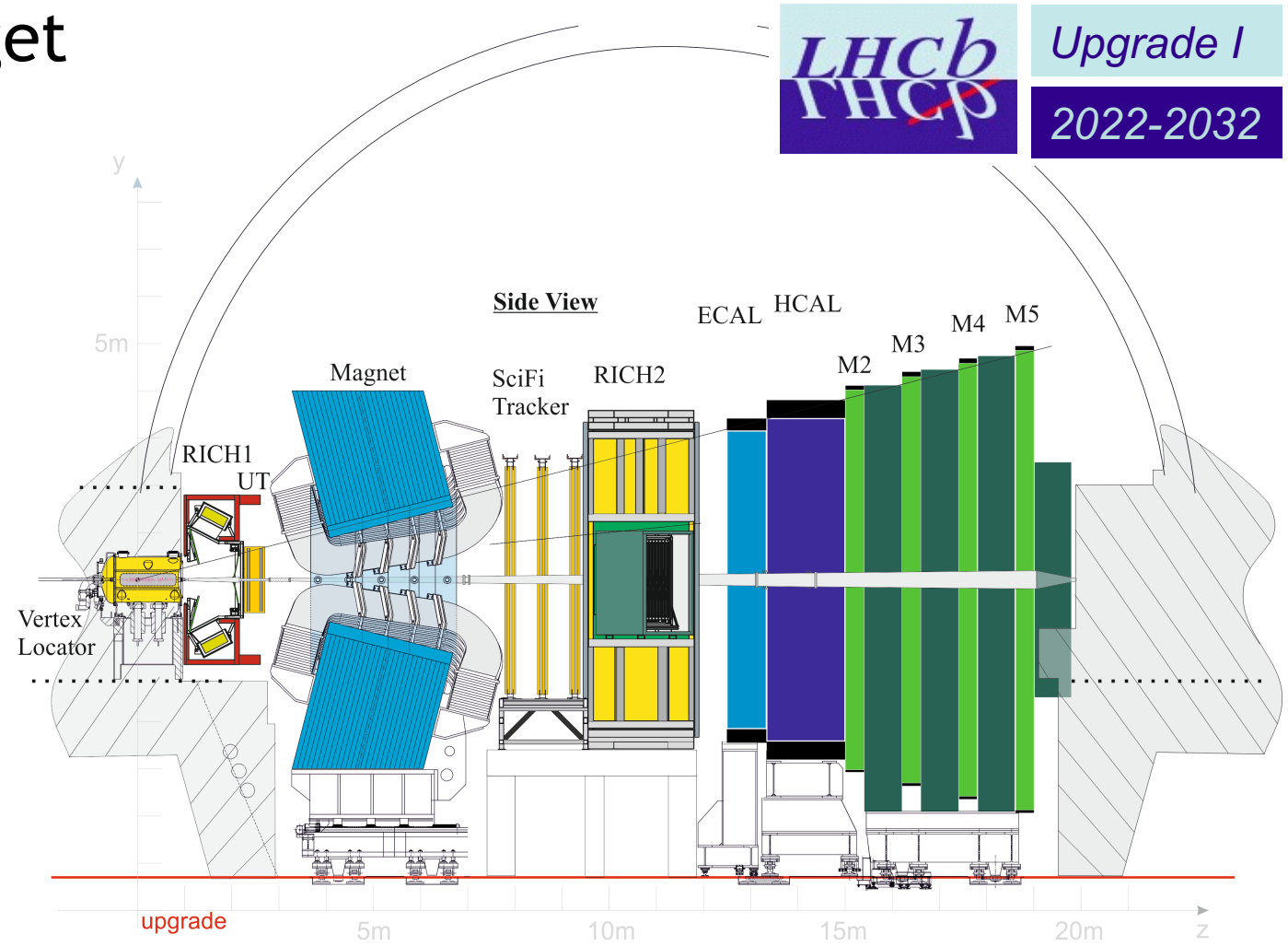




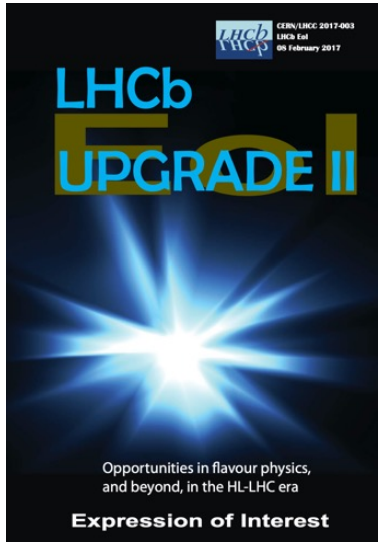
LHCb Upgrade I

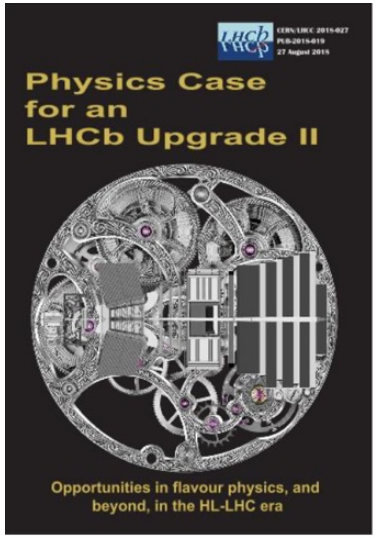
- Major project achieved on budget
  - All sub detectors installed
  - Commissioning to detector and dataflow ongoing
  - Detector performance studies underway
  - 90% of channels upgraded
  - Replaced readout electronics
  - Operate at 30 MHz
  - Peak luminosity x5 w.r.t. Run 1

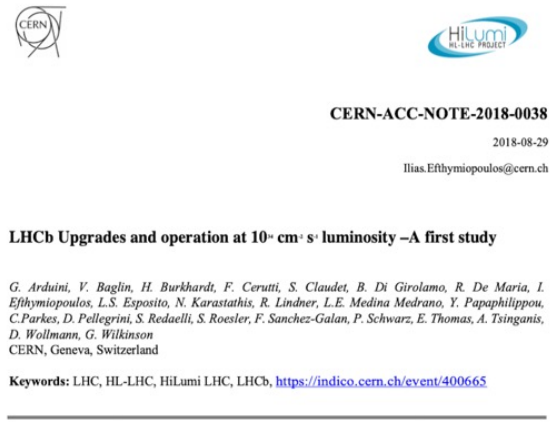
$$2 \times 10^{33}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$$



LHCb Upgrade II







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2018-08-29

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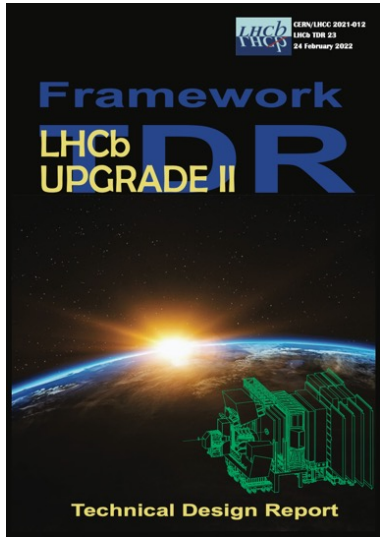
LHCb Upgrades and operation at 10³⁴ cm⁻² s⁻¹ luminosity –A first study

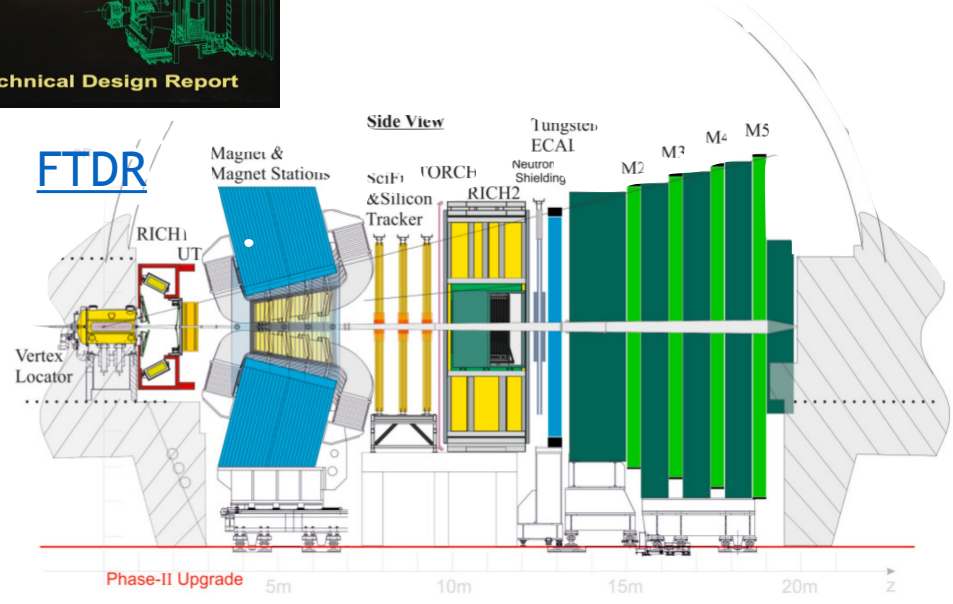
G. Arduini, V. Baglin, H. Burkhardt, F. Cerutti, S. Claudet, B. Di Girolamo, R. De Maria, I. Efthymiopoulos, L.S. Esposito, N. Karastathis, R. Lindner, L.E. Medina Medrano, Y. Papaphilippou, C.Parkes, D. Pellegrini, S. Redaelli, S. Roesler, F. Sanchez-Galan, P. Schwarz, E. Thomas, A. Tsinganis, D. Wollmann, G. Wilkinson
CERN, Geneva, Switzerland

Keywords: LHC, HL-LHC, HiLumi LHC, LHCb, https://indico.cern.ch/event/400665



LHCb Upgrade II 2033-

[EOI](#) [Physics case](#) [Accelerator study](#) [FTDR](#)



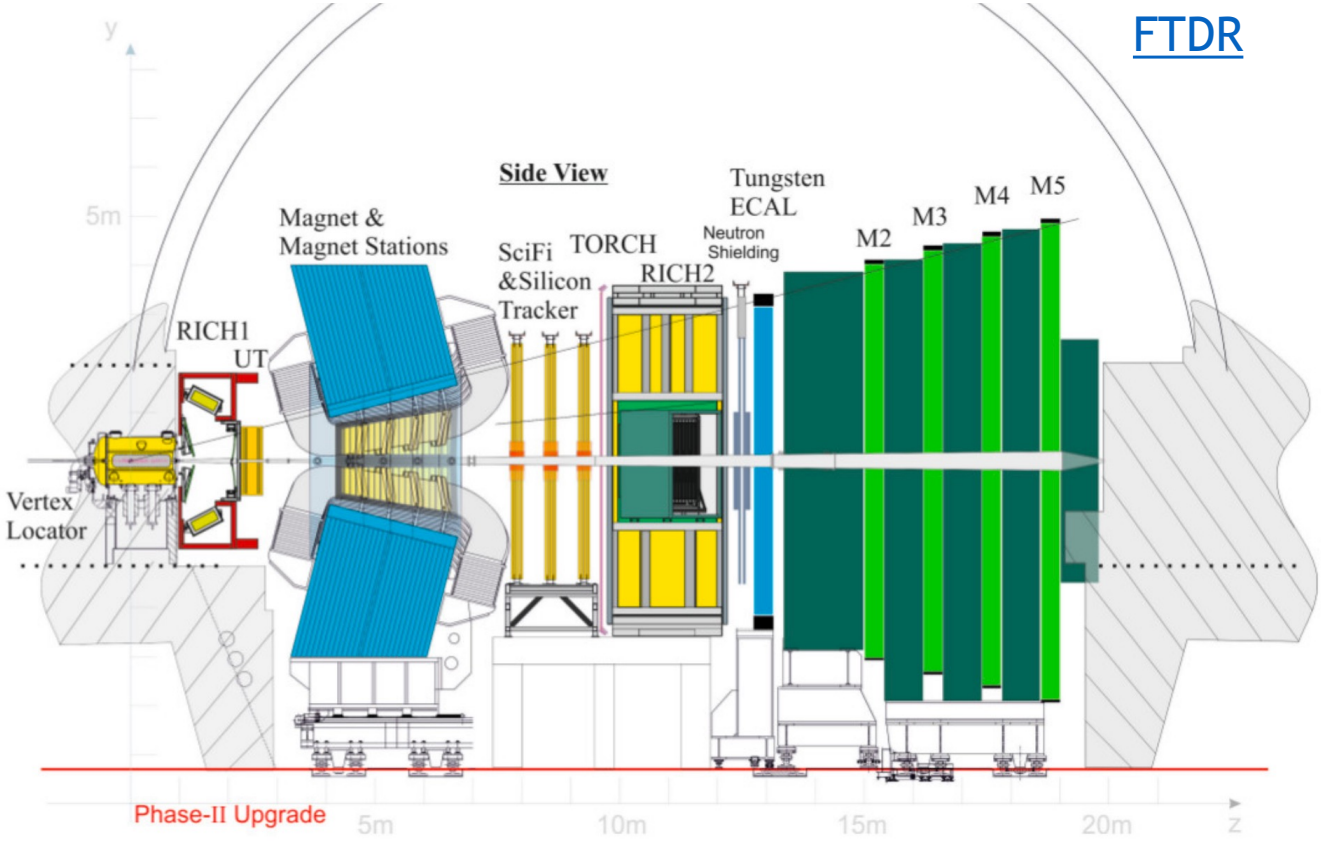
- European strategy Update 2020:
  - The full potential of the LHC and the HL-LHC, including the study of flavour physics, should be exploited
- Approved March 2022

LHCb Upgrade II

- Complete new detector required
  - Vertexing: Pixel detector with timing
  - Hadron PID: RICH with timing and better resolution, TORCH for low momentum tracks
  - Tracking: New magnet stations and pixel mighty tracker
  - Calorimeter: Better resolution and timing information
  - Muon system: New technologies for high occupancy regions

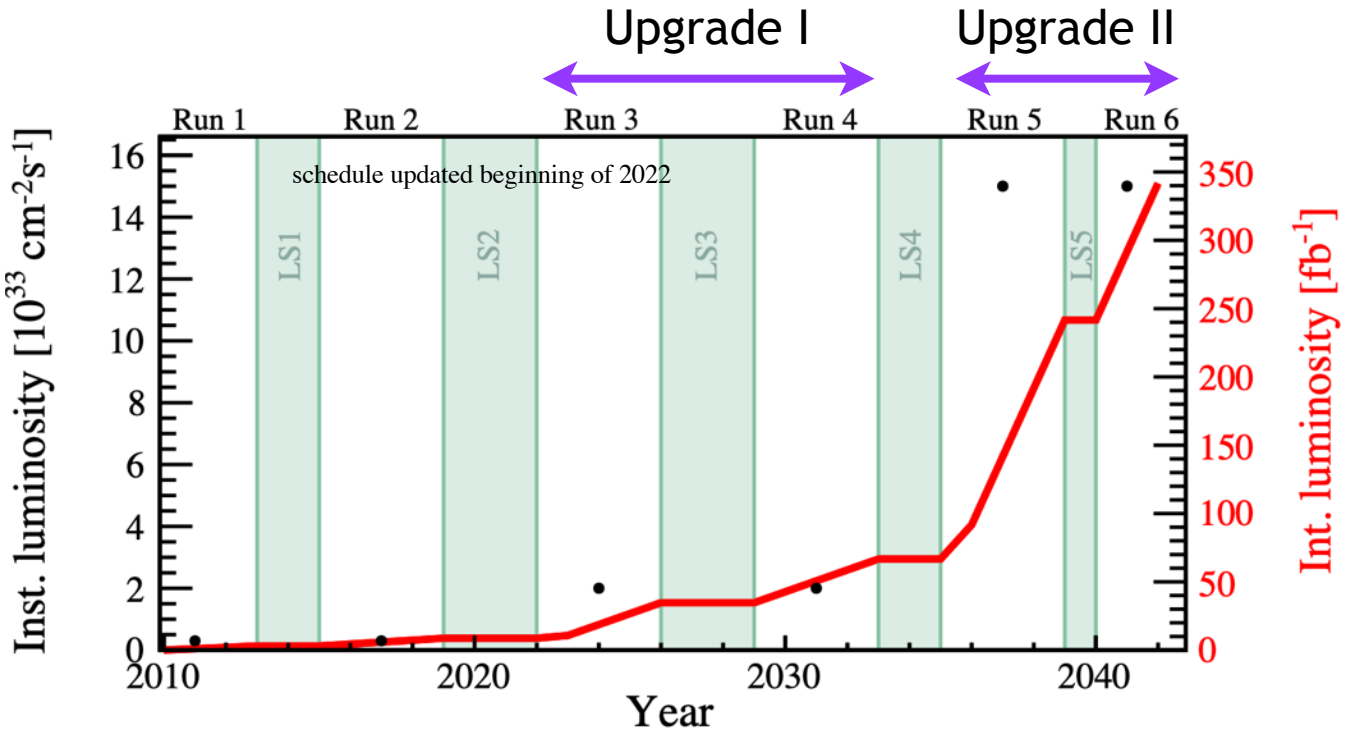
LHCb Upgrade II 2033-

FTDR



LHCb Upgrade II

- LHCb physics programme not limited by the LHC
  - Ambitious future upgrades plan



LHCb Upgrade II 2033-

- Peak luminosity - $1.5 \times 10^{34}\,\mathrm{cm^{-2}s^{-1}}$
- Integrated luminosity ~ $300\,\mathrm{fb^{-1}}$
  - For Run 5 + 6
- Install during LS4
- Smaller detector consolidation and enhancements during LS3

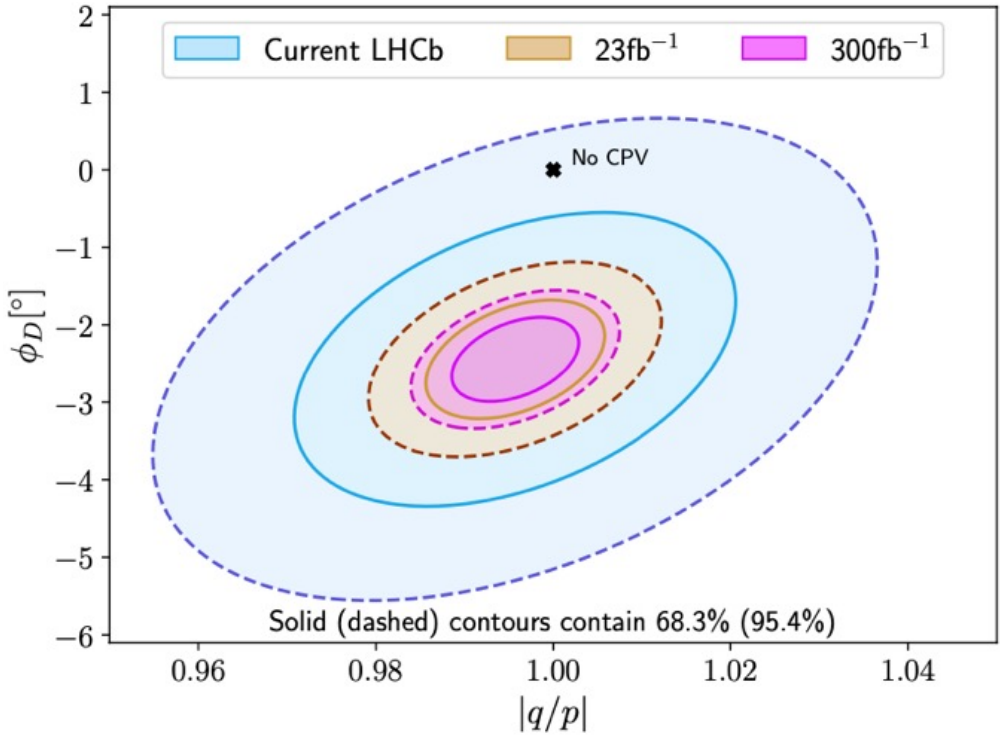
Summary of golden modes

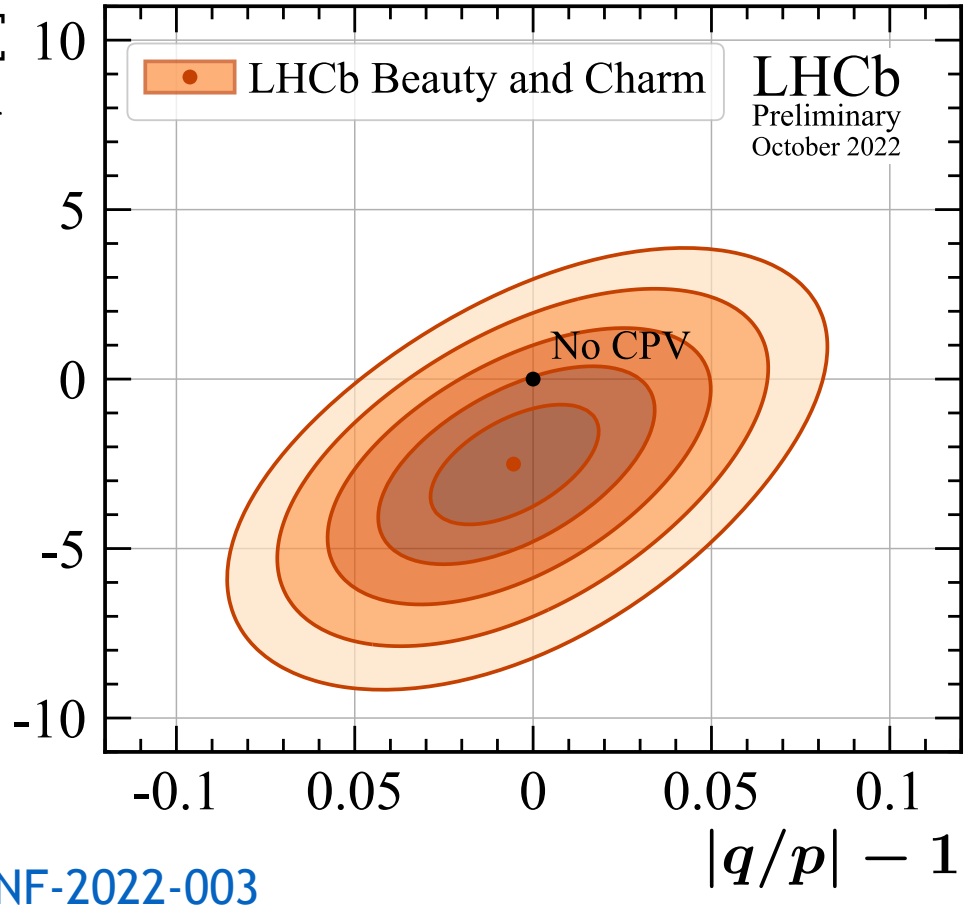
Observable	Current LHCb	LHCb 2025	Belle II	Upgrade II	ATLAS & CMS
EW Penguins					
R_K $(1 < q^2 < 6\,\mathrm{GeV}^2c^4)$	0.1 [274]	0.025	0.036	0.007	–
R_{K^*} $(1 < q^2 < 6\,\mathrm{GeV}^2c^4)$	0.1 [275]	0.031	0.032	0.008	–
R_ϕ, R_{pK}, R_π	–	0.08, 0.06, 0.18	–	0.02, 0.02, 0.05	–
CKM tests					
γ, with $B_s^0 \to D_s^+ K^-$	$(^{+17}_{-22})^\circ$ [136]	4°	–	1°	–
γ, all modes	$(^{+5.0}_{-5.8})^\circ$ [167]	1.5°	1.5°	0.35°	–
$\sin 2\beta$, with $B^0 \to J/\psi K^0_S$	0.04 [609]	0.011	0.005	0.003	–
ϕ_s, with $B_s^0 \to J/\psi\phi$	49 mrad [44]	14 mrad	–	4 mrad	22 mrad [610]
ϕ_s, with $B_s^0 \to D_s^+ D_s^-$	170 mrad [49]	35 mrad	–	9 mrad	–
$\phi_s^{s\bar{s}s}$, with $B_s^0 \to \phi\phi$	154 mrad [94]	39 mrad	–	11 mrad	Under study [611]
a^s_{sl}	33×10^{-4} [211]	10×10^{-4}	–	3×10^{-4}	–
$\lvert V_{ub}\rvert/\lvert V_{cb}\rvert$	6% [201]	3%	1%	1%	–
$\boldsymbol{B^0_s, B^0 \to \mu^+\mu^-}$					
$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	90% [264]	34%	–	10%	21% [612]
$\tau_{B_s^0 \to \mu^+\mu^-}$	22% [264]	8%	–	2%	–
$S_{\mu\mu}$	–	–	–	0.2	–
$\boldsymbol{b \to c\ell^-\bar{\nu}_l}$ **LUV studies**					
$R(D^*)$	0.026 [215, 217]	0.0072	0.005	0.002	–
$R(J/\psi)$	0.24 [220]	0.071	–	0.02	–
Charm					
$\Delta A_{CP}(KK - \pi\pi)$	8.5×10^{-4} [613]	1.7×10^{-4}	5.4×10^{-4}	3.0×10^{-5}	–
A_Γ $(\approx x \sin\phi)$	2.8×10^{-4} [240]	4.3×10^{-5}	3.5×10^{-4}	1.0×10^{-5}	–
$x \sin\phi$ from $D^0 \to K^+\pi^-$	13×10^{-4} [228]	3.2×10^{-4}	4.6×10^{-4}	8.0×10^{-5}	–
$x \sin\phi$ from multibody decays	–	$(K3\pi)$ 4.0×10^{-5}	$(K^0_S\pi\pi)$ 1.2×10^{-4}	$(K3\pi)$ 8.0×10^{-6}	–

Physics case

Charm mixing and CPV

- Charm mixing observed and CPV in decay observed by LHCb original
  - How far can we go with LHCb Upgrade II?
  - CPV in mixing consistent with 0 at 2σ level



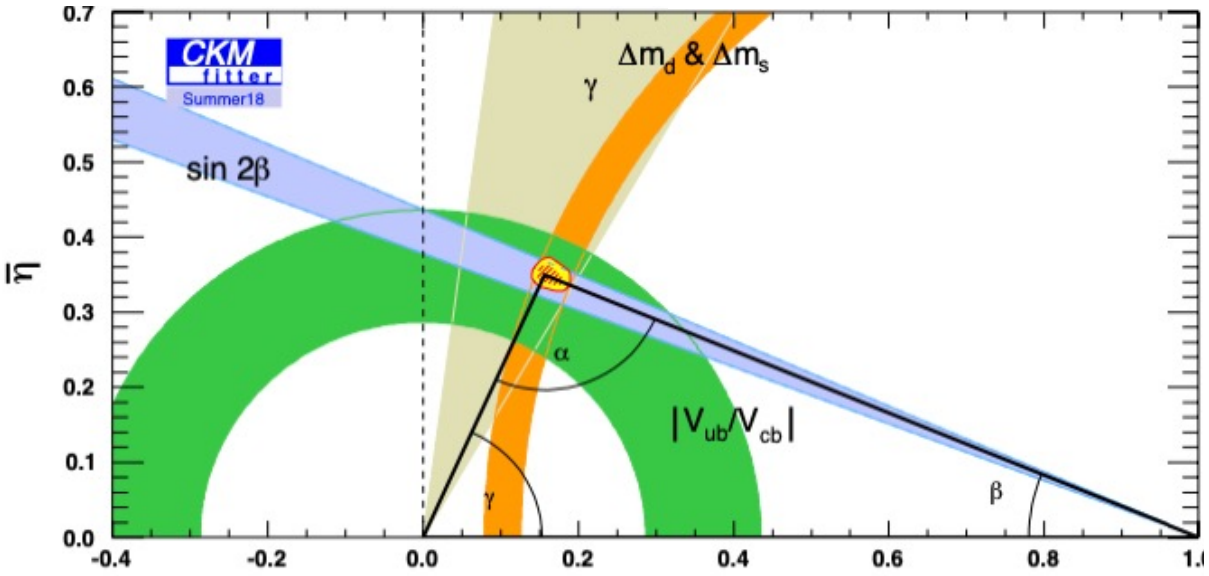


LHCb-CONF-2022-003

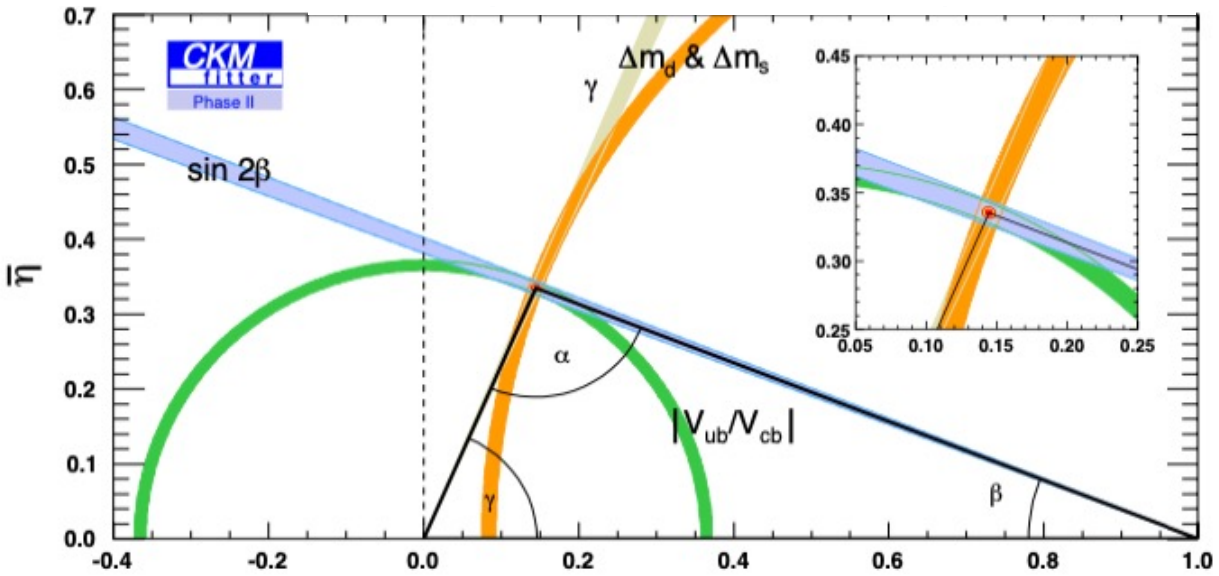
Unitarity triangle

- Picture remains consistent at the moment, need better precision

LHCb only, end of 2018



LHCb Upgrade II with LQCD improvement



- Many key observables have negligible theoretical uncertainties
- Flavour physics still one of the more promising areas to find a paradigm shifting discovery at HL-LHC

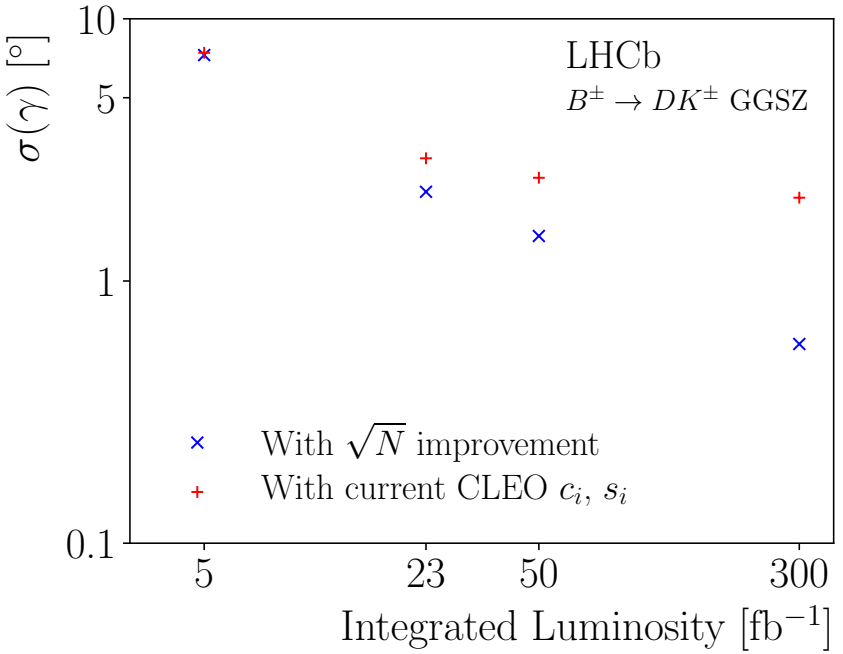
CKM Fitter Physics case

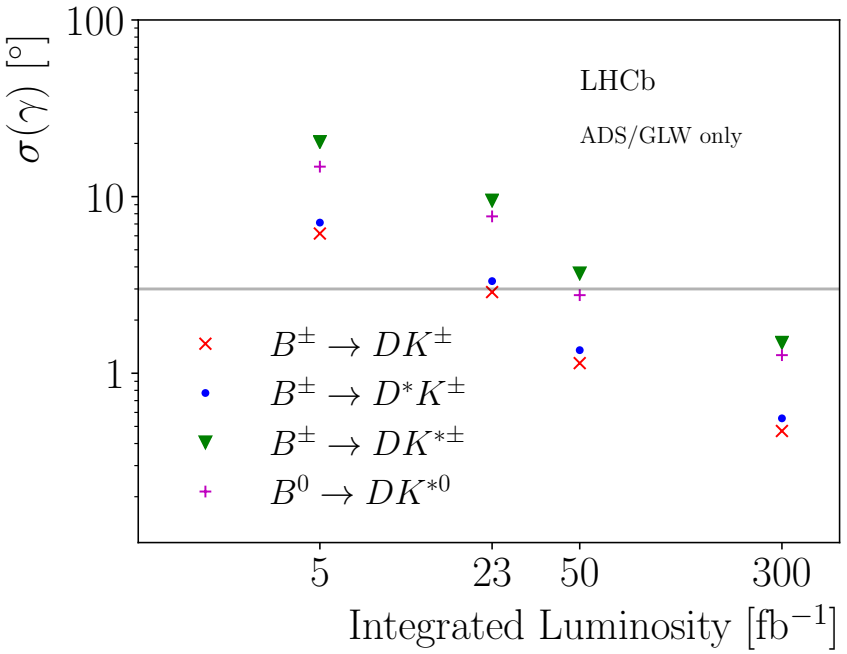
CKM angle γ

- Already outperforming our estimates for LHCb original
  - Charm mixing parameters also determined simultaneously
  - In the SM, irreducible theory uncertainty $|\delta_\gamma/\gamma| \leq 10^{-7}$
  - Expect to reach a precision of 0.35°
  - Will be interesting to compare B meson species and decay modes to look for NP effects in tree-level decays!

$$\gamma = \left(63.8^{+3.5}_{-3.7}\right)^\circ$$

LHCb-CONF-2022-003

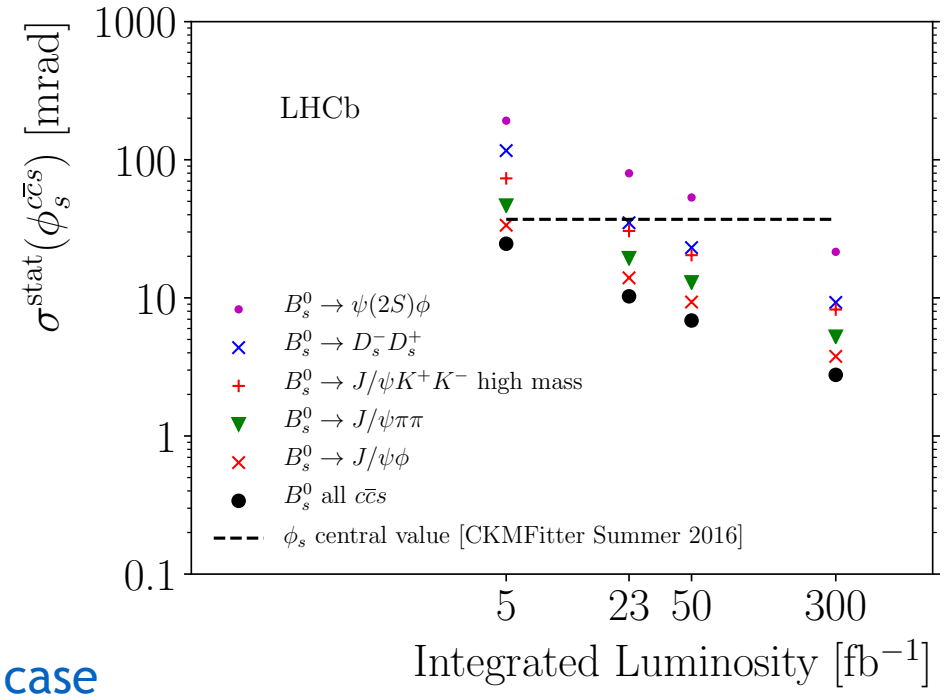




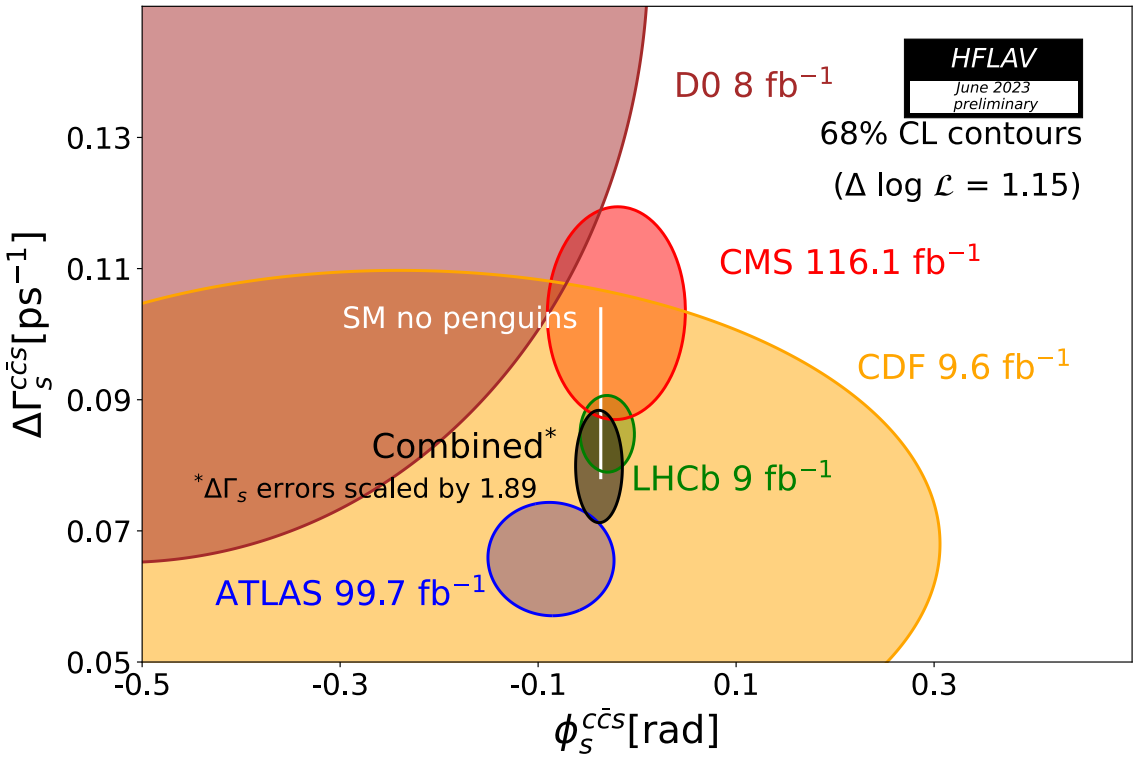
Physics case

B_s^0 mixing phase ϕ_s

- Complementary area for LHCb, ATLAS and CMS
  - World average $-0.039 \pm 0.016\,\text{rad}$ is statistically limited
  - Will remain so even after LHCb Upgrade II, with precision of $< 3\,\text{mrad}$



Includes brand new preliminary result from LHCb



Physics case

$B^0_{(s)} \to \mu^+\mu^-$

- Golden mode for NP searches, precise SM predictions

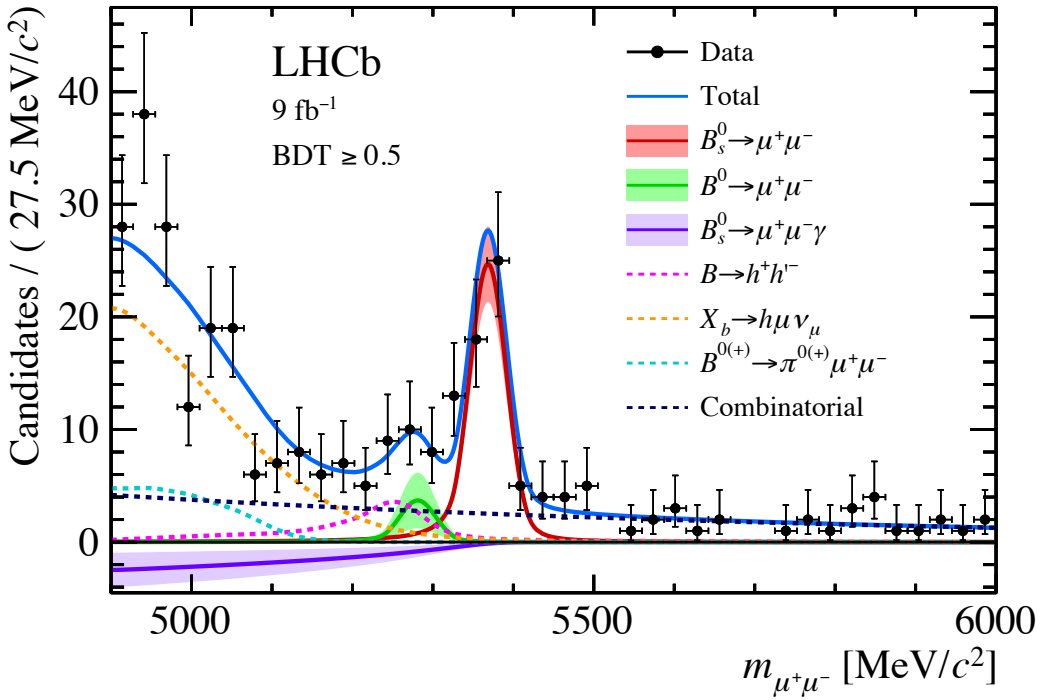
LHCb-PAPER-2021-007

  - Current LHCb results $\mathcal{B}(B^0_s \to \mu^+\mu^-) = (3.09^{+0.46+0.15}_{-0.43-0.11}) \times 10^{-9}$

$\mathcal{B}(B^0 \to \mu^+\mu^-) = (1.2^{+0.8}_{-0.7} \pm 0.1) \times 10^{-10}$

- Current precision of the B^0_s mode is 15%
  - Expect to reach 1.8% with Upgrade II
  - Experimental systematics should scale
  - Hard to predict uncertainty of f_s/f_d
  - Expect to reach 10% for the B^0 mode

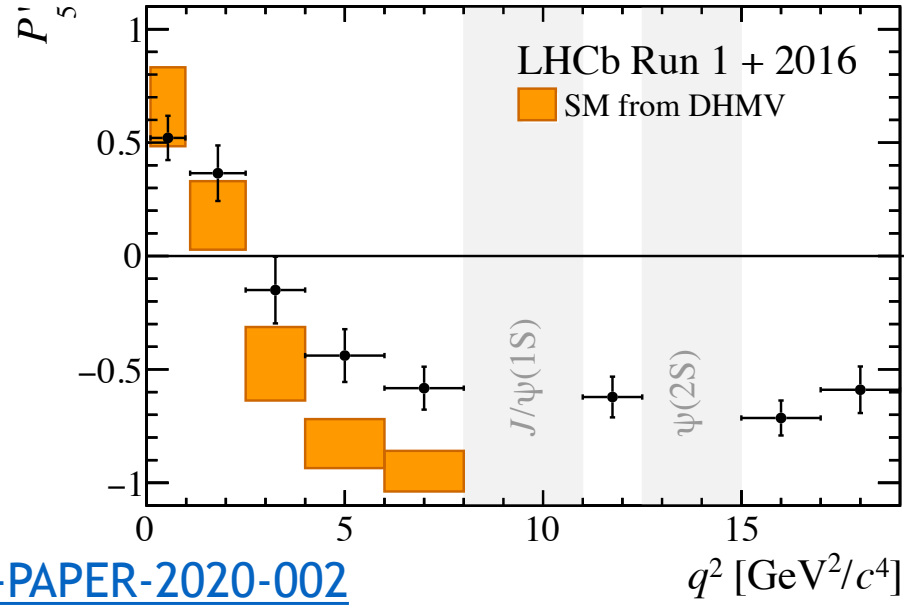
- Effective lifetime (2%) and CPV (10-20%) also within reach



$B^0 \to K^{*0}\mu^+\mu^-$

- Exhibits rich angular structure, including the famous P_5' discrepancy
  - Expected >400k signal events with Upgrade II
  - Cleanly discriminate between NP scenarios and the SM
  - Need to understand charm loops and SM contributions!

scenario	$C_9^{\rm NP}$	$C_{10}^{\rm NP}$	C_9'	C_{10}'
I	-1.4	0	0	0
II	-0.7	0.7	0	0
III	0	0	0.3	0.3
IV	0	0	0.3	-0.3



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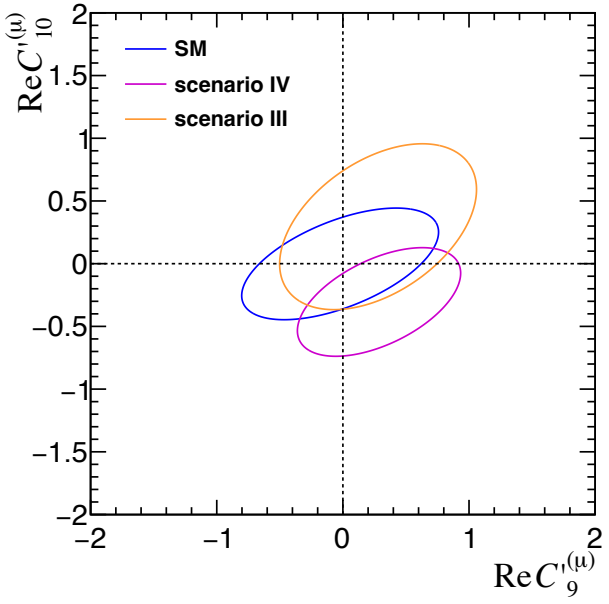
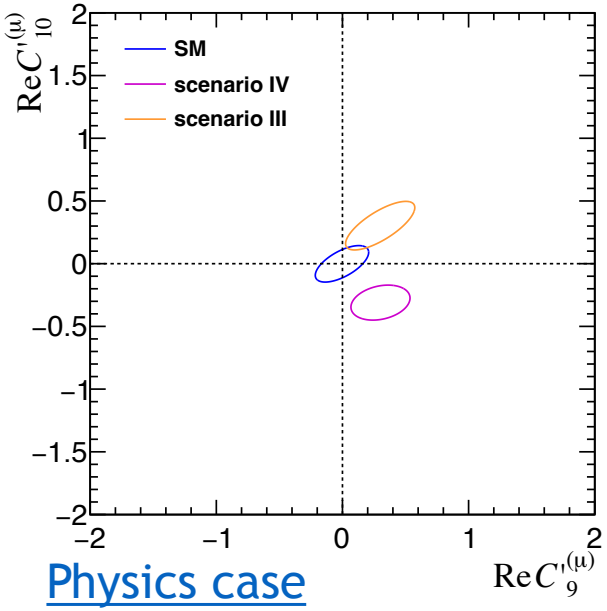
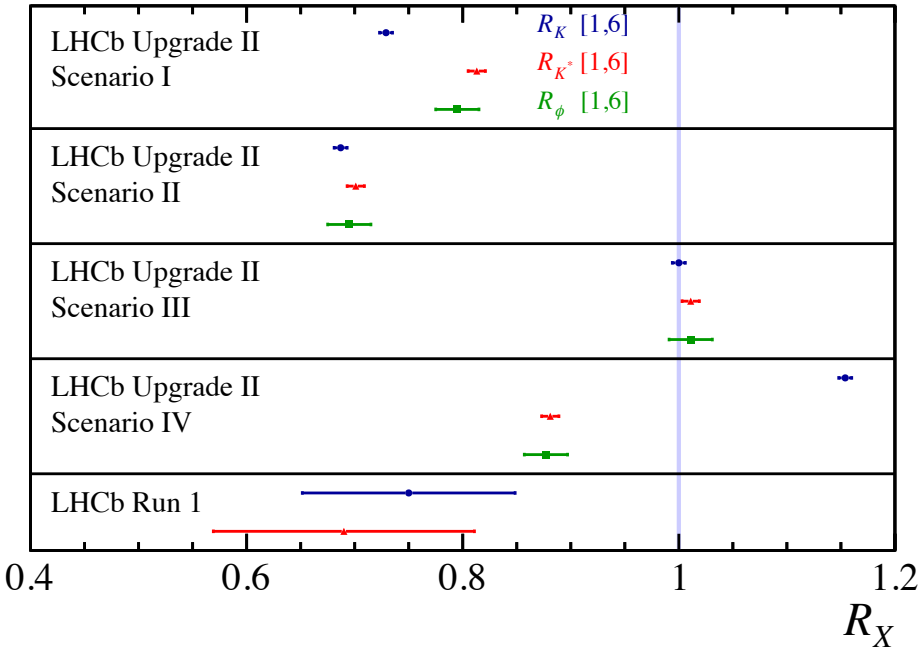




Physics case

Lepton Universality: $R(K^{(*)})$

- Latest results from LHCb now consistent with the SM — LHCb-PAPER-2022-045
  - Nevertheless these ratios remain interesting to follow-up in Upgrade II
  - If NP appears, will have sensitivity to distinguish between different options



Physics case

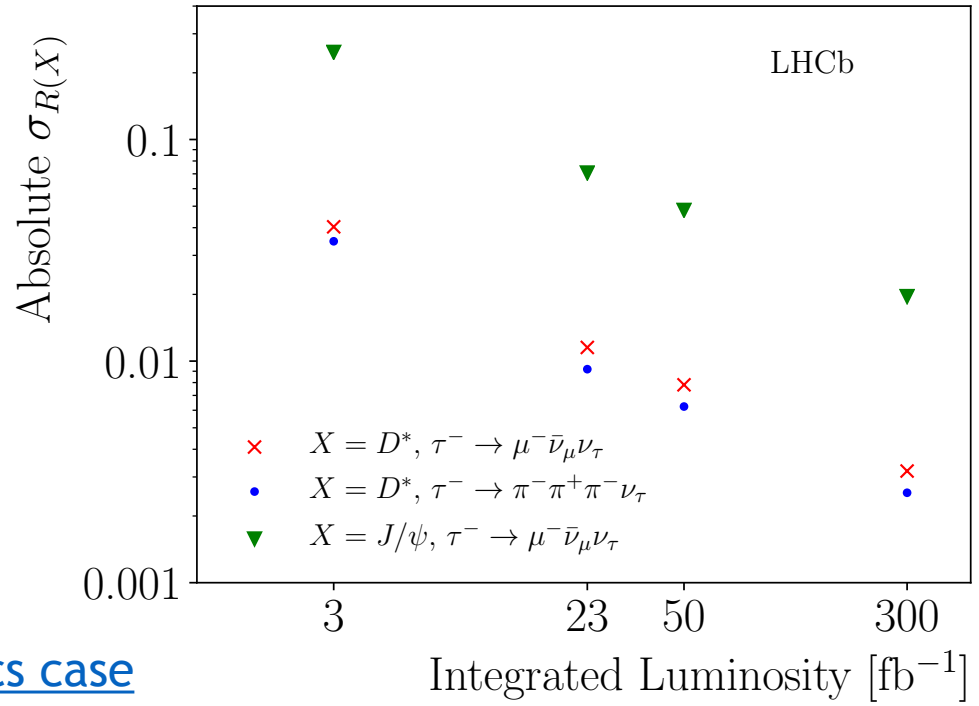
Yield	Run 1 result	$9\,\text{fb}^{-1}$	$23\,\text{fb}^{-1}$	$50\,\text{fb}^{-1}$	$300\,\text{fb}^{-1}$
$B^+ \to K^+e^+e^-$	254 ± 29 [274]	1 120	3 300	7 500	46 000
$B^0 \to K^{*0}e^+e^-$	111 ± 14 [275]	490	1 400	3 300	20 000
$B_s^0 \to \phi e^+e^-$	–	80	230	530	3 300
$\Lambda_b^0 \to pKe^+e^-$	–	120	360	820	5 000
$B^+ \to \pi^+e^+e^-$	–	20	70	150	900
R_X precision	Run 1 result	$9\,\text{fb}^{-1}$	$23\,\text{fb}^{-1}$	$50\,\text{fb}^{-1}$	$300\,\text{fb}^{-1}$
R_K	$0.745 \pm 0.090 \pm 0.036$ [274]	0.043	0.025	0.017	0.007
$R_{K^{*0}}$	$0.69 \pm 0.11 \pm 0.05$ [275]	0.052	0.031	0.020	0.008
R_ϕ	–	0.130	0.076	0.050	0.020
R_{pK}	–	0.105	0.061	0.041	0.016
R_π	–	0.302	0.176	0.117	0.047

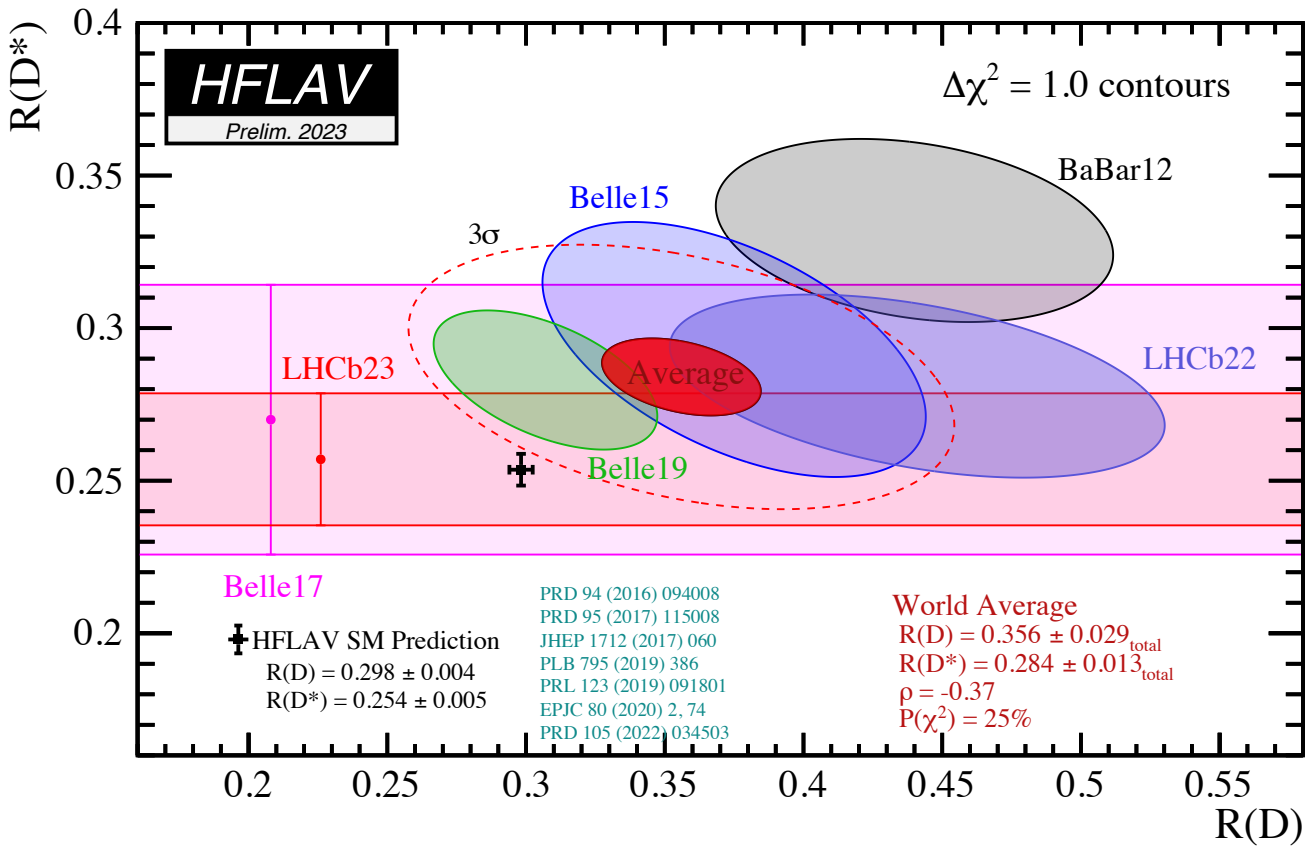
Lepton Universality: $R(D^{(*)})$

- Latest results still in about 3σ tension with SM predictions
  - Two new results from LHCb in the last year didn't change the picture

LHCb-PAPER-2022-039 LHCb-PAPER-2022-052

$$R(X_c) = \frac{\mathcal{B}(X_b \to X_c \tau^+ \nu_\tau)}{\mathcal{B}(X_b \to X_c \ell^+ \nu_\ell)}$$

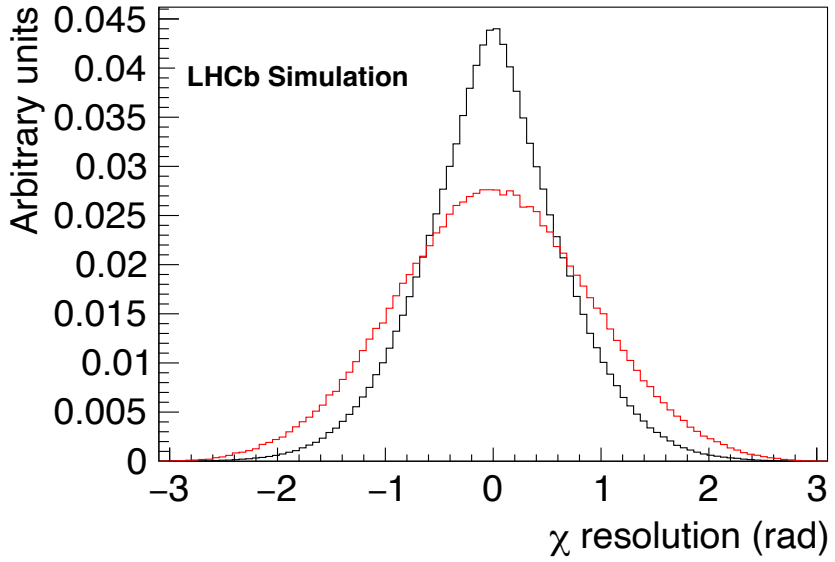


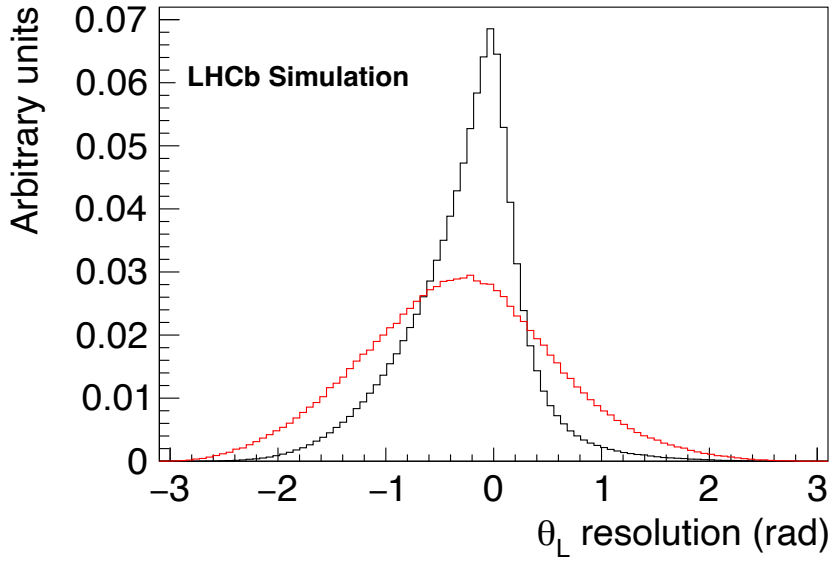


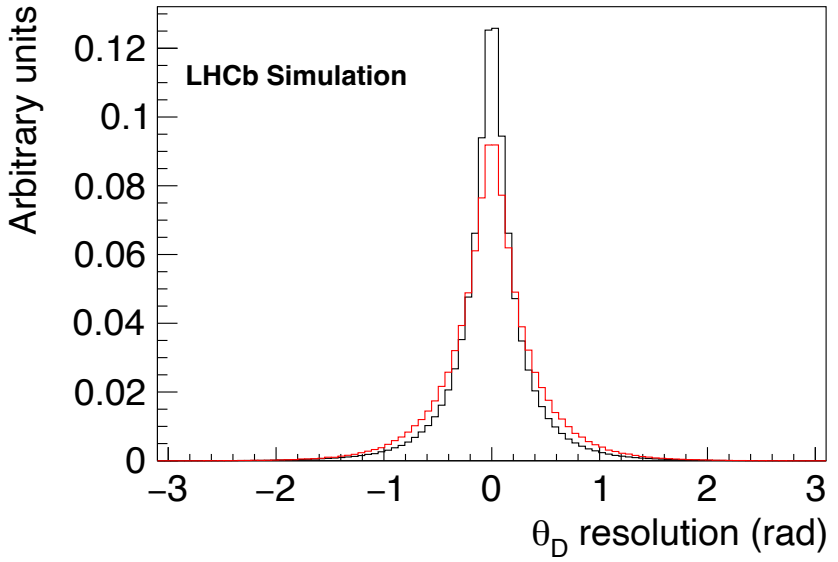
Physics case

Lepton Universality: $R(D^{(*)})$

- Important to also go beyond these simple ratios
  - Angular variables sensitive to spin structure of the decay processes
  - Can distinguish between different new physics models
  - Proof of principle measurements underway with Run 2 data







Physics case

Angular resolution for simulated $B \to D^*\mu\nu$ and $B \to D^*\tau\nu$ decays

Spectroscopy

- Hugely successful area for LHCb original
  - 64 particle discoveries to date! Many of them appear to be exotic
  - Many conventional particles are waiting to be found, just a question of statistics:

$\Sigma_b^0\,(udb)$

$\Omega_{cc}^+\,(scc)$

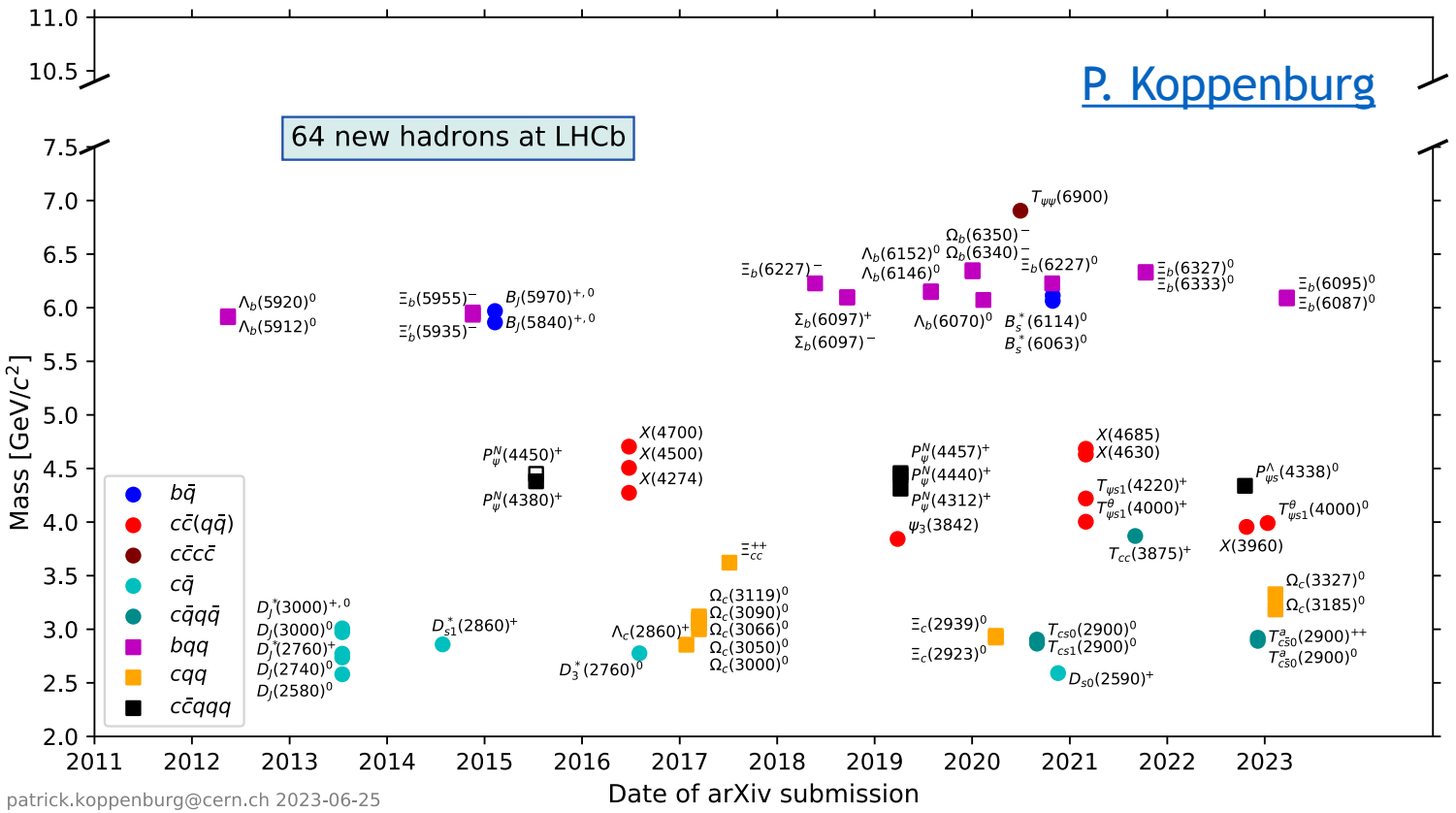
$\Omega_{ccc}^{++}\,(ccc)$

$\Omega_{bb}^-\,(bbs)$

$\Omega_{bc}^0\,(bcs)$

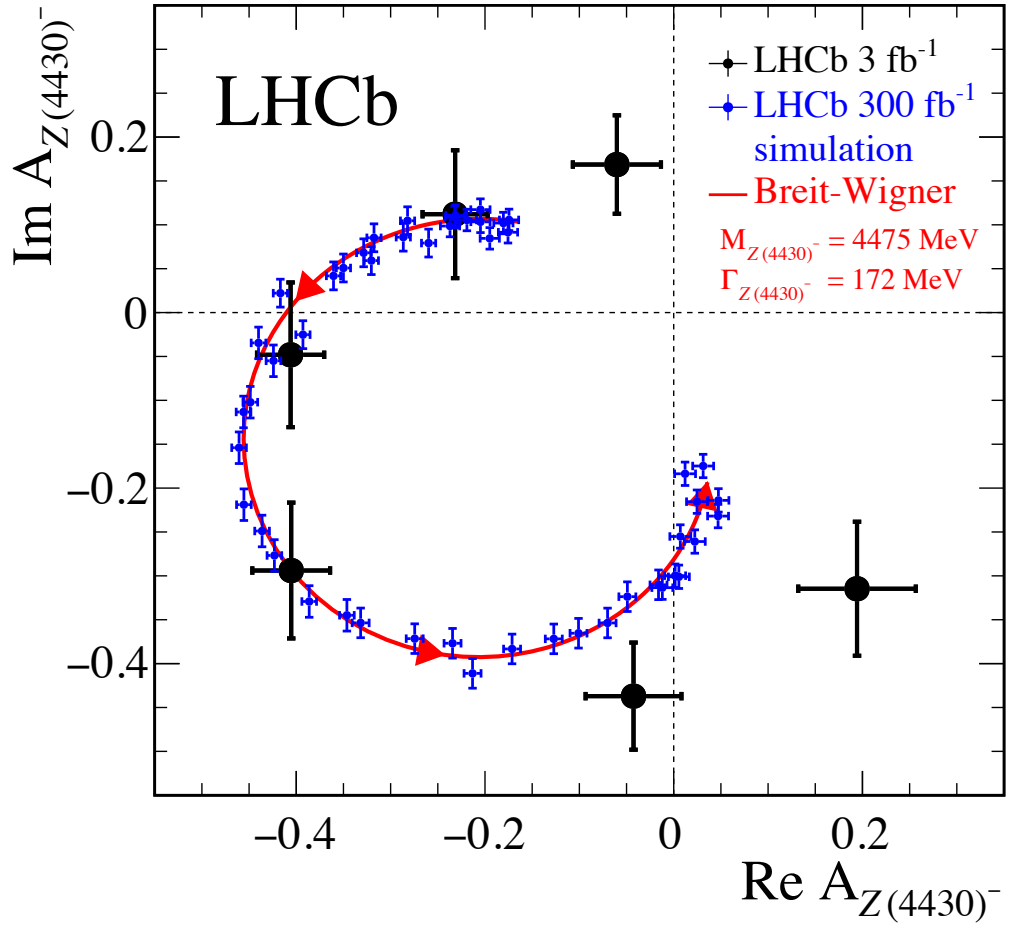
$\Xi_{bc}^+\,(bcu)$

$\Xi_{bb}^0\,(bbu)$



Spectroscopy

- Hugely successful area for LHCb original
  - Explore the nature of 4 and 5 quark states
  - Look for new decay modes and look for their partners
- Where are the hexaquarks?
- With enormous data samples, can we compete for some nuclear resonances?

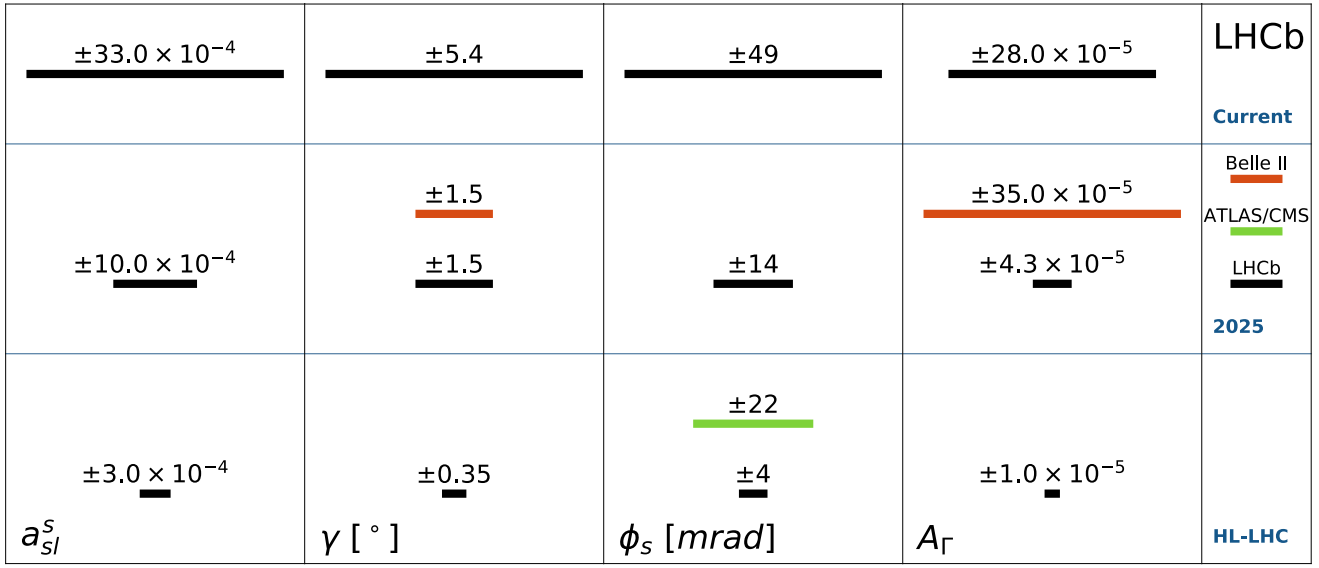


Physics case

Summary

- Majority of the LHCb physics programme is statistically limited
  - We do not, yet, run at the maximum peak luminosity of the LHC
  - Upgrade II will allow us to take full advantage of the HL-LHC

- Haven't covered prospects for non-flavour topics
  - See physics document for more details



Physics case

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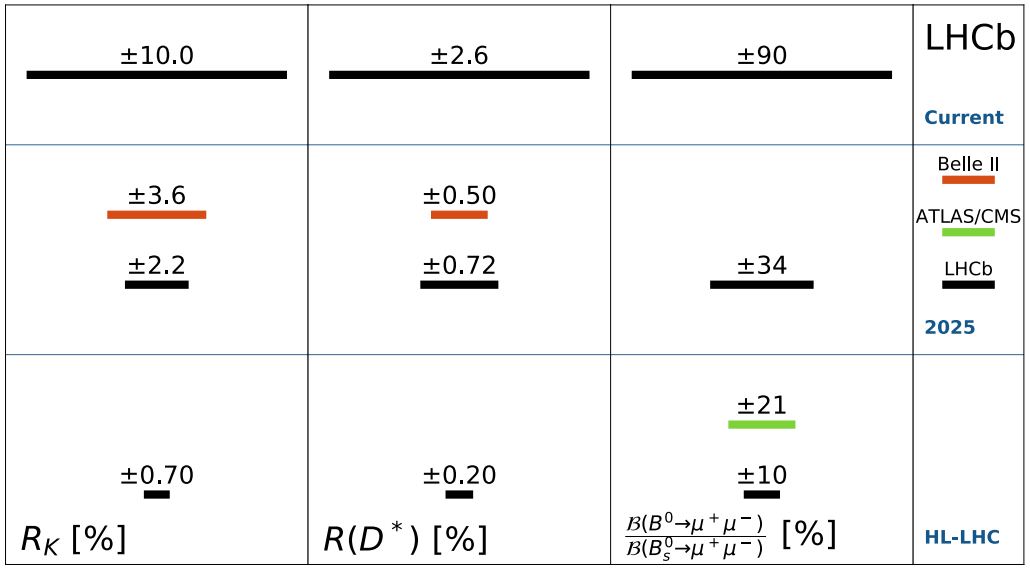
- Haven't covered prospects for non-flavour topics
  - See physics document for more details



Physics case