LHCb and its upgrades

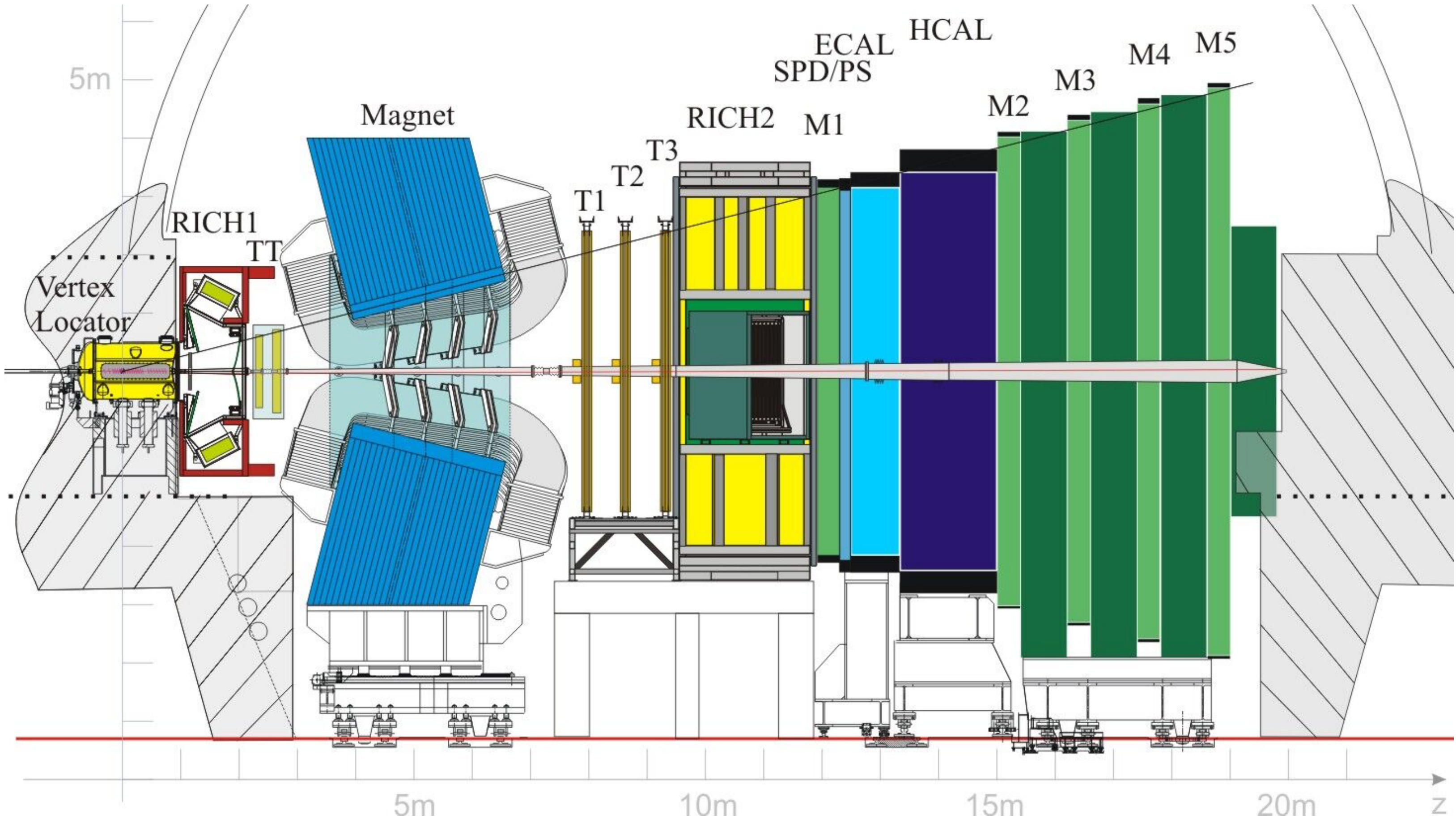
Mark Whitehead

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 community meeting 2020

LHCb Detector

- Flavour physics at the LHC
  - Precise tests of the SM to reveal possible new physics effects



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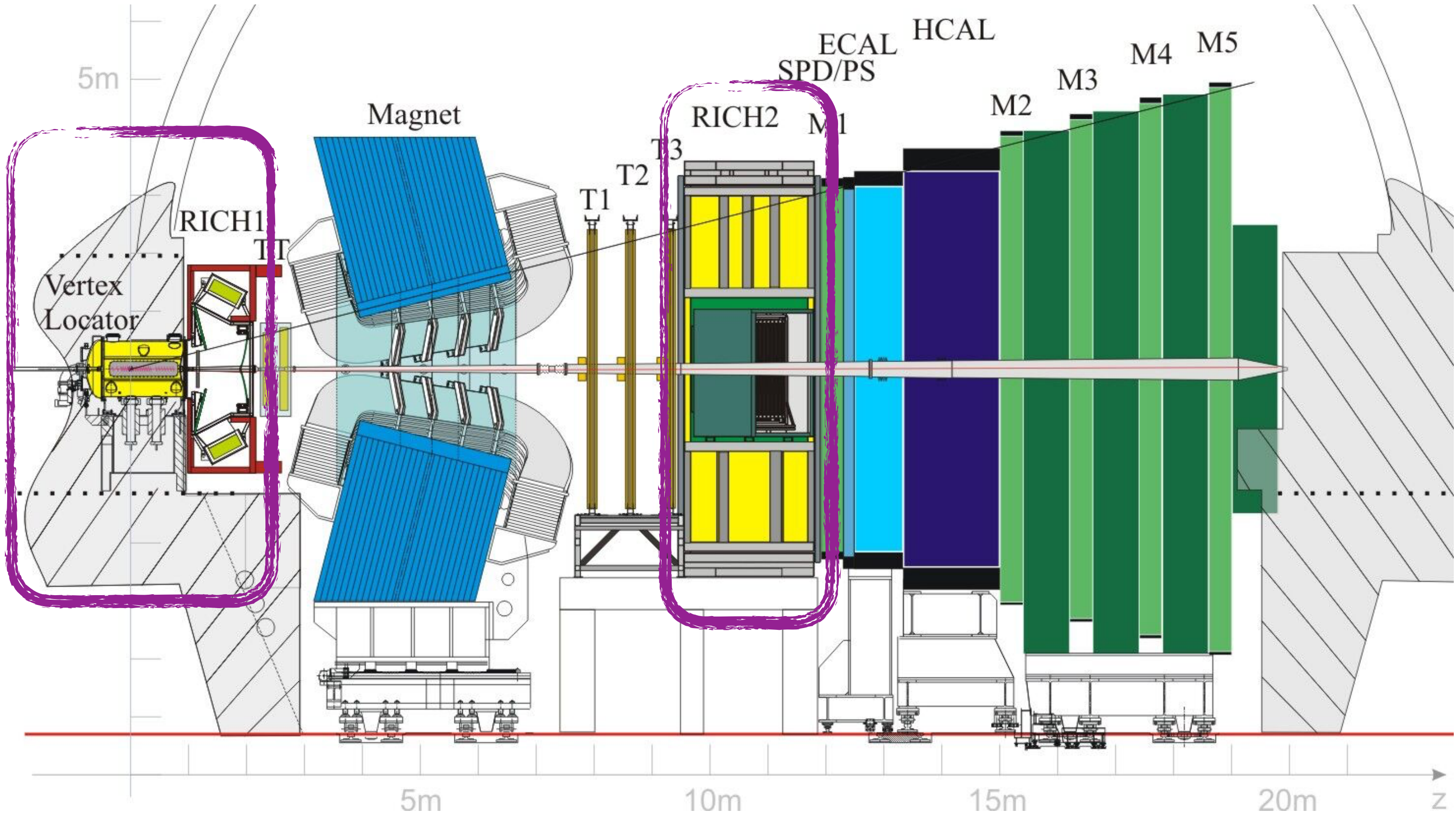
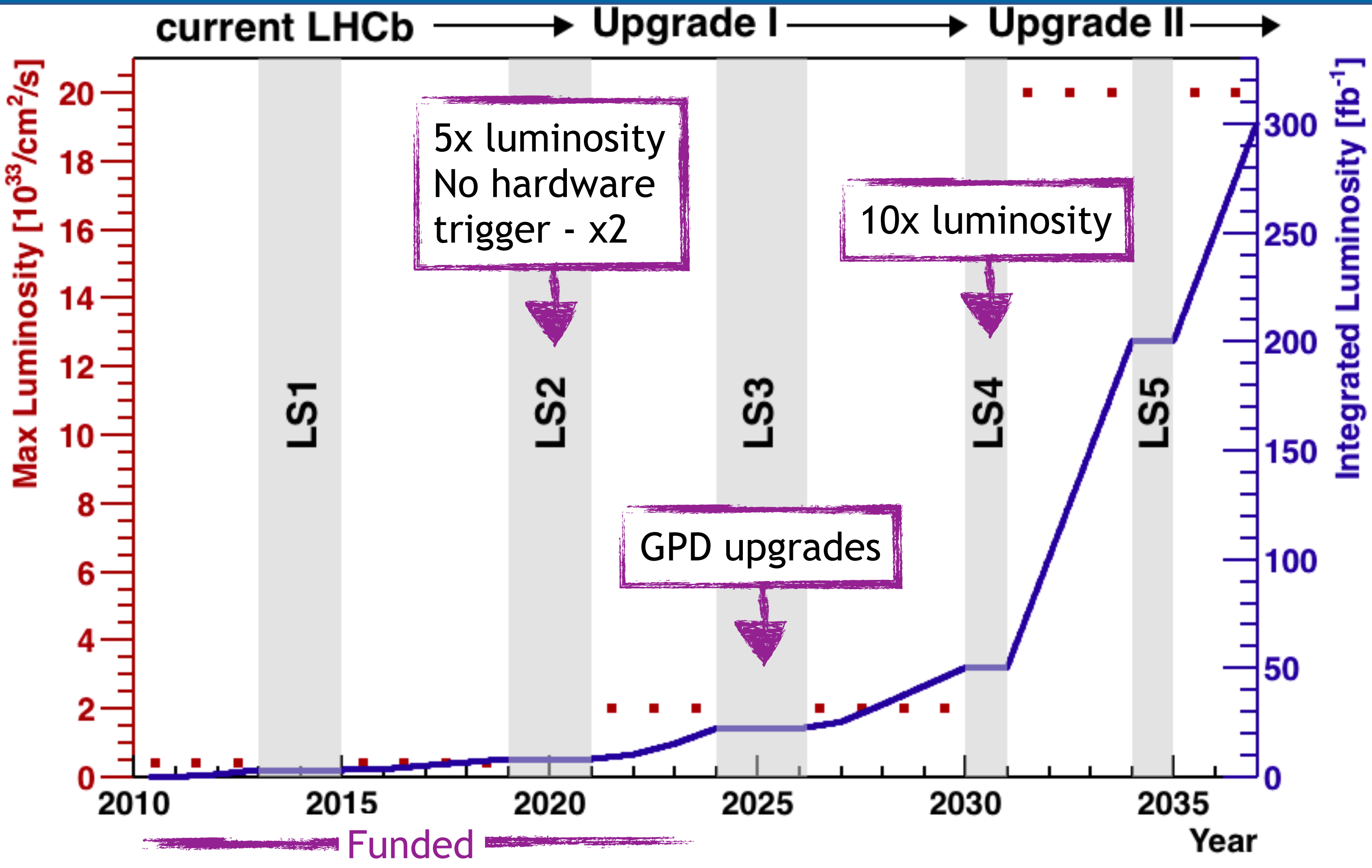


- Large UK contributions
  - VELO
  - RICH 1 and 2
  - Offline computing

Timelines



current LHCb
Upgrade I
Upgrade II
Max Luminosity [10^33/cm^2/s]
Integrated Luminosity [fb^-1]
20
18
16
14
12
10
8
6
4
2
0
300
250
200
150
100
50
0
LS1
LS2
LS3
LS4
LS5
5x luminosity
No hardware
trigger - x2
10x luminosity
GPD upgrades
2010
2015
2020
2025
2030
2035
Year
Funded

UK prominence within the collaboration

- LHCb consists of 87 institutes (11 from UK) from 18 countries

Strong presence in **senior** management positions

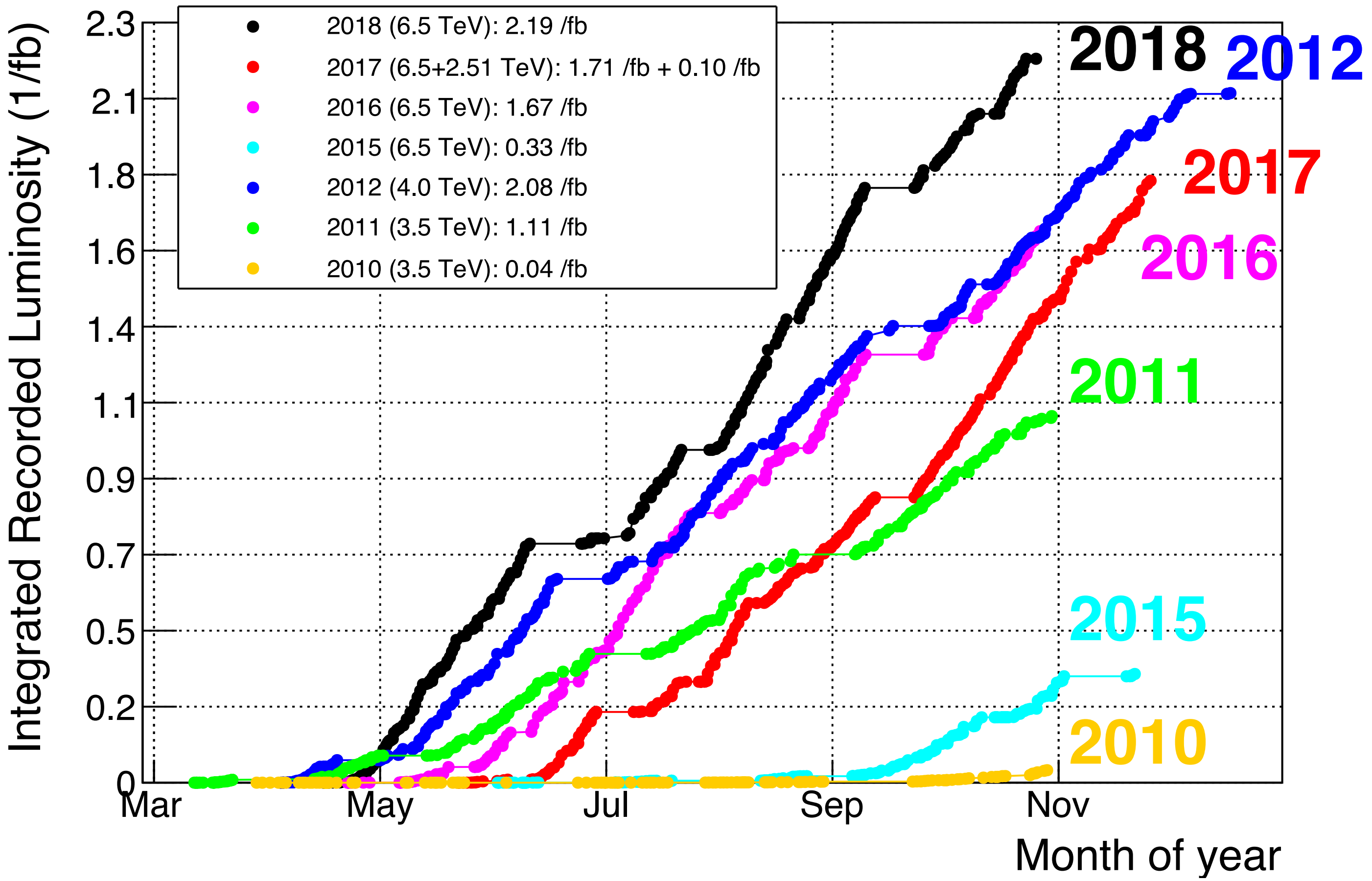
- **Spokesperson** - Chris Parkes
- **Collaboration board chair** - Val Gibson
- **Operations coordinator** - Silvia Gambetta
- **Editorial board chair** - Franz Muheim
- **Speakers bureau chair** - Stefania Ricciardi

- Leading ~**half** of the **physics** and **operations** working groups

The UK continually maintains strong leadership positions across the collaboration

Recent results

- Total data sample from LHCb Run 1 and 2
  - ~9 fb^{-1} good for physics
- Focus today on a few recent UK-led results
  - UK interests cover most of the physics programme of LHCb



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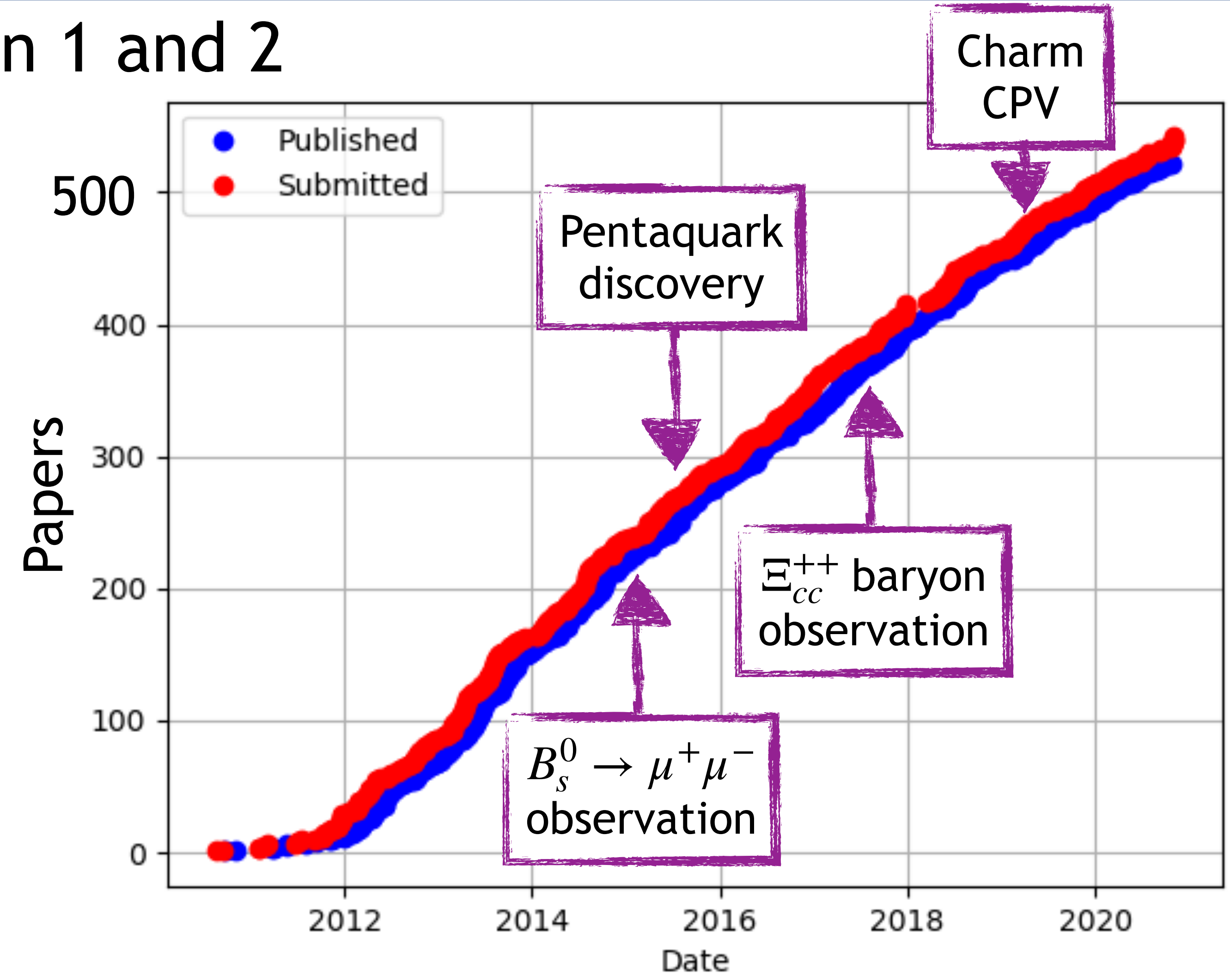
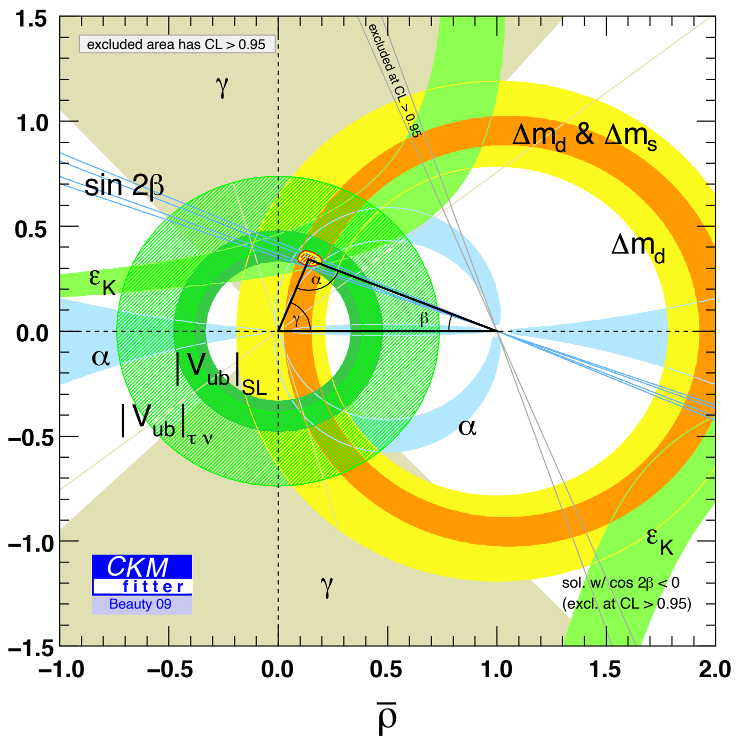
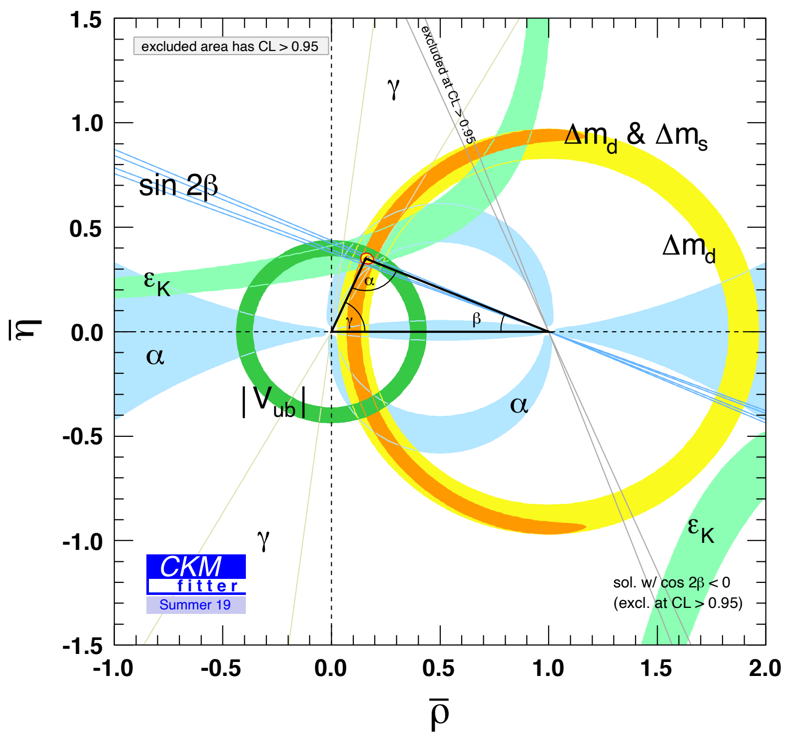


CP violation

- Huge progress in recent years primarily by LHCb
  - Measurements of the CKM matrix and unitarity triangle
  - First observation of CP violation in the charm sector

2009





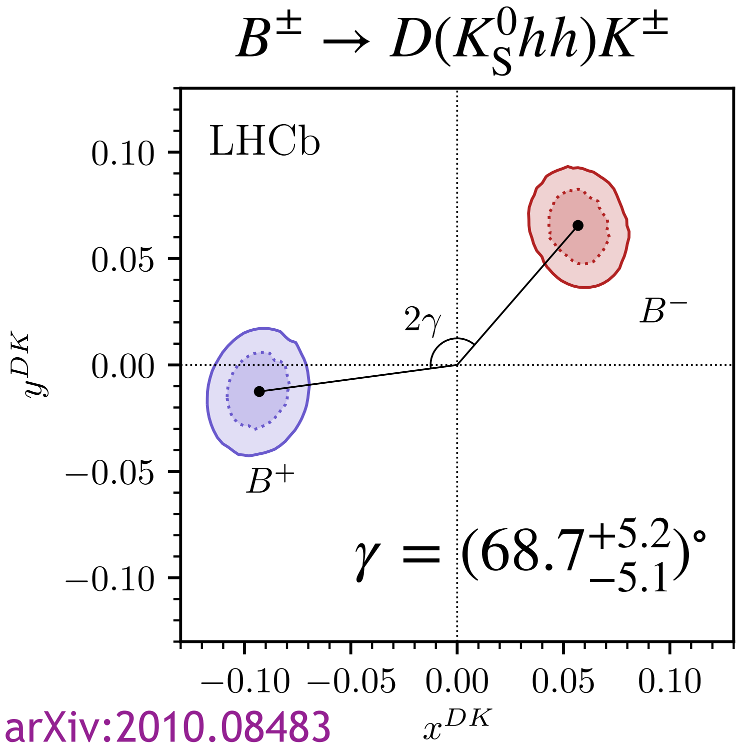
2019

CP violation

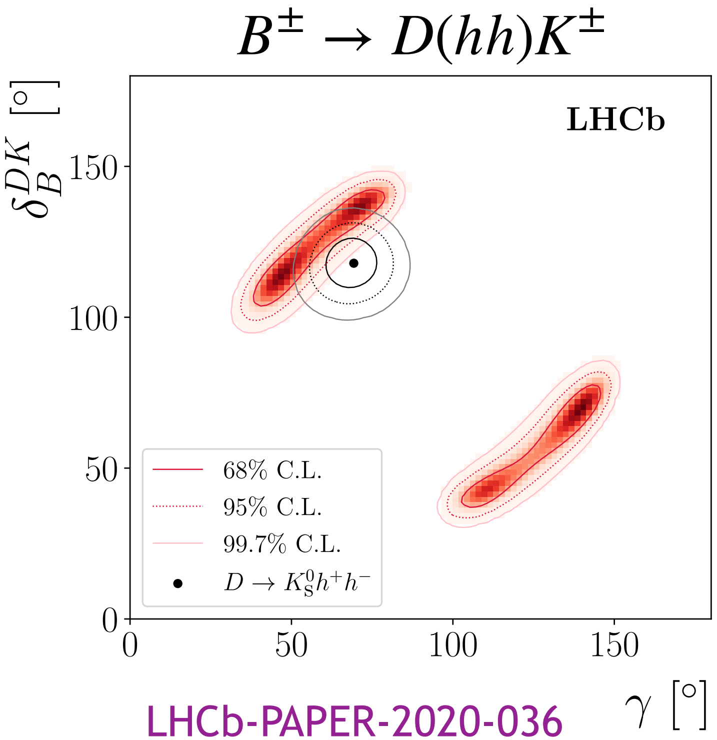
UK led

- New measurements this year of the CKM angle γ
  - Led by contributions from UK institutes
  - Run 2 target precision of 4º achieved, with more to come

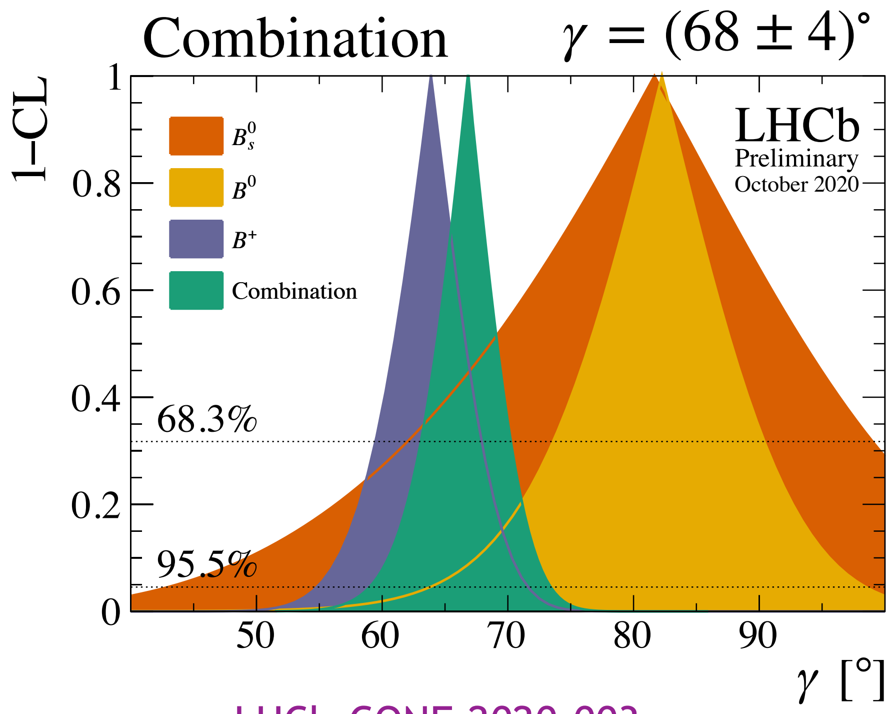
Area of synergy with BES III experiment



arXiv:2010.08483



LHCb-PAPER-2020-036

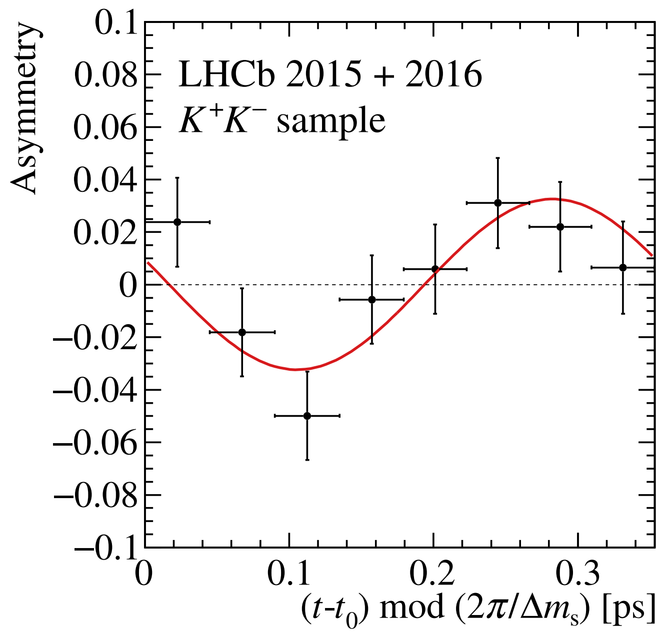


LHCb-CONF-2020-003

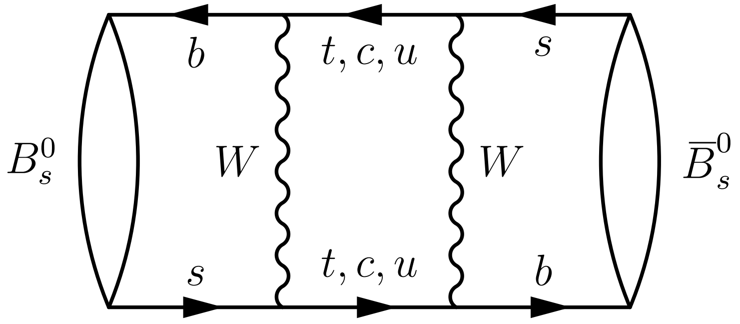
CP violation

- Time-dependent CP violation in $B_s^0 - \bar{B}_s^0$ meson decays
  - First observation and ~instant confirmation of this phenomenon!

$B_s^0 \to K^+K^-$

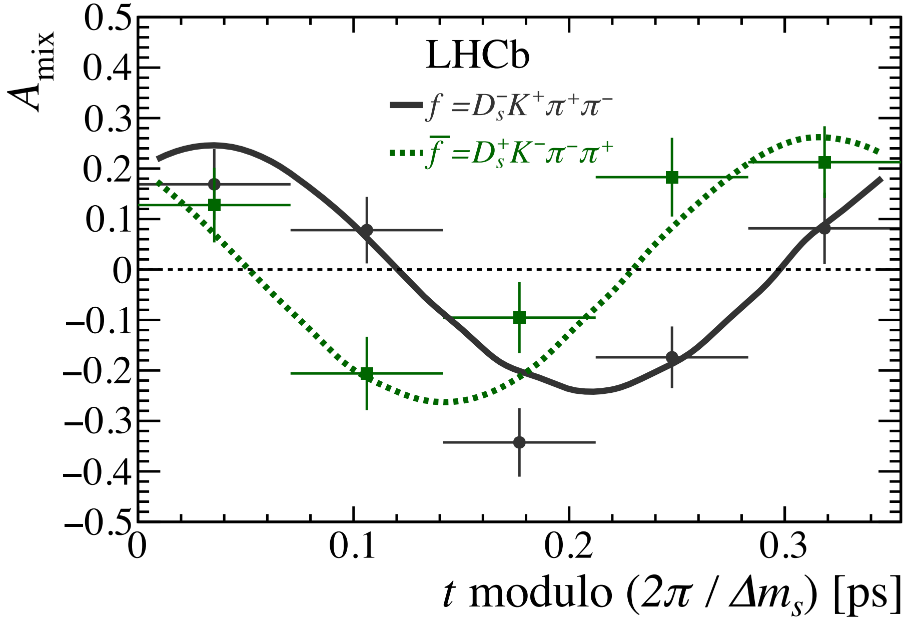


LHCb-PAPER-2020-029



$B_s^0 \to D_s^{\mp}K^{\pm}\pi^{\pm}\pi^{\mp}$

Also measures γ and Δm_s



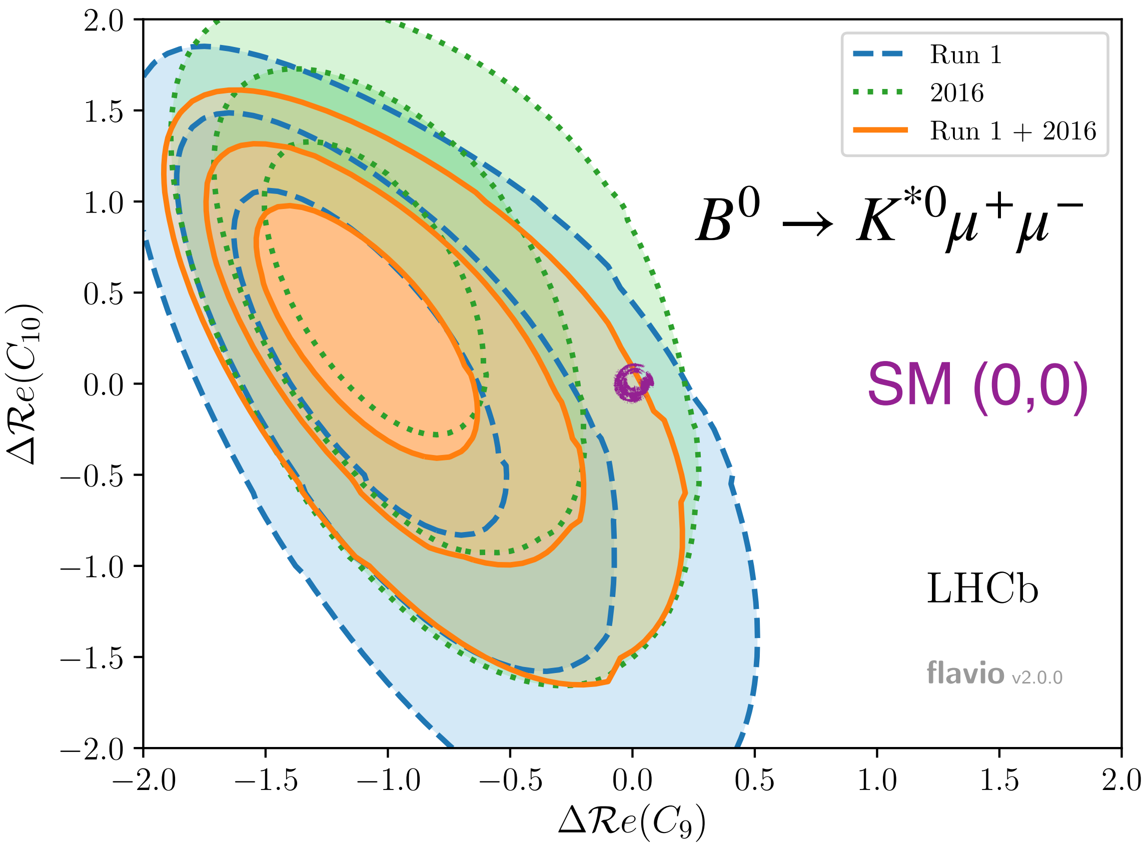
LHCb-PAPER-2020-030

Flavour anomalies

UK led

- Tensions between measurements and the standard model
  - Most prevalent in rare and semi-leptonic B meson decays
- Update from $B^0 \to K^{*0}\mu^+\mu^-$ decays
  - Added the 2016 data sample
  - Tension with the standard model increased slightly but still around 3σ
  - More to come - 2017 and 2018 data!
- Similar picture in $B^+ \to K^{*+}\mu^+\mu^-$
  - Full run 1+2 analysis
  - Similar 3σ tension with the SM

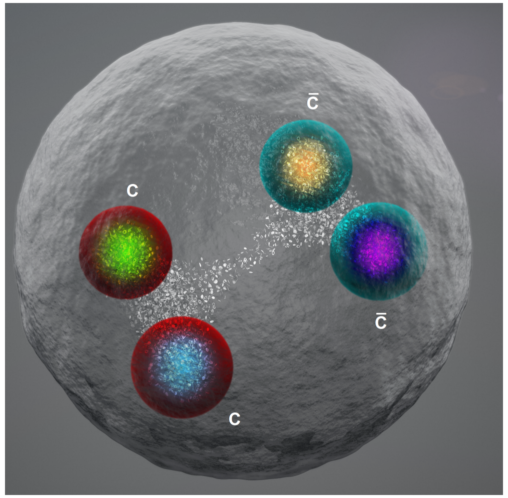
PRL 125 (2020) 011802



Discovering new states

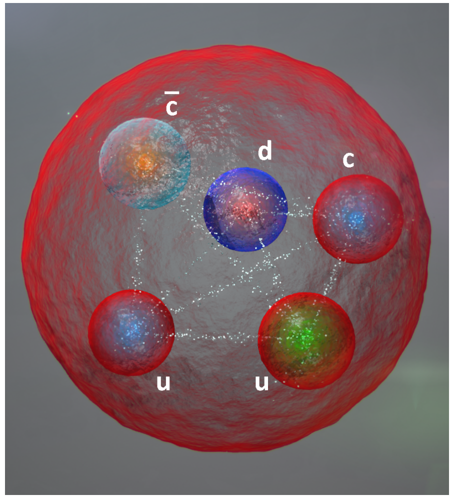
- Unique LHCb dataset has created a new golden age of spectroscopy
  - All kinds of beauty and charm hadrons produced at the LHC
  - Pre LHCb - quarks in **twos** and **threes**, now also in **fours** and **fives**

4 charm quarks



Science Bulletin 2020 65(23)1983-1993

5 quarks



Phys. Rev. Lett. 122, 222001 (2019)

- As well as
  - Many charm mesons
  - Many charm baryons
  - Beauty mesons
  - Beauty baryons

- Around 50 first observations of new states

Discovering new states

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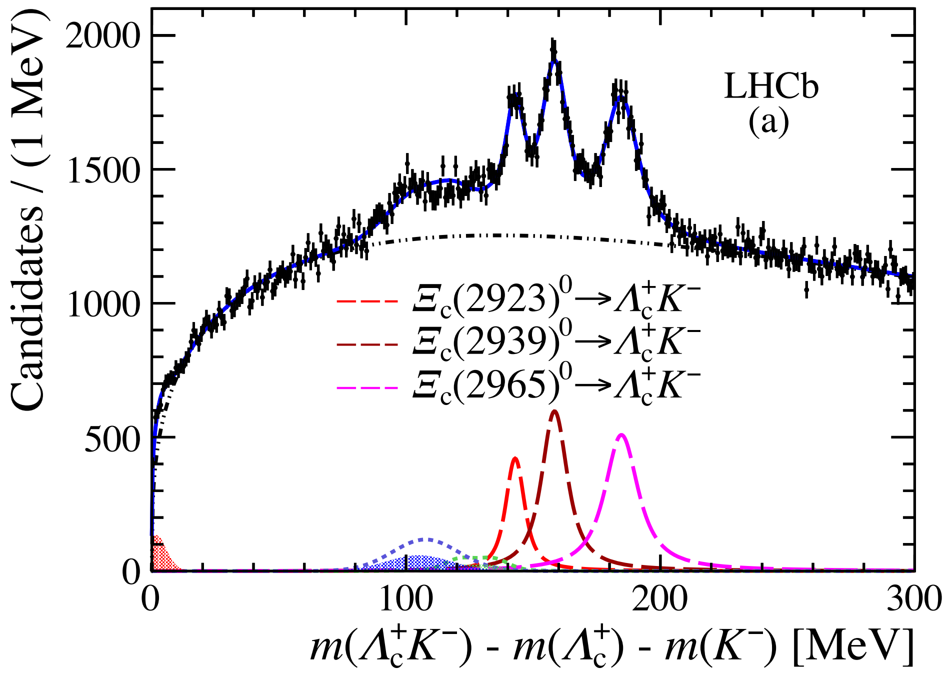

- $\Lambda_c^+ K^-$ spectrum
  - Two first observations $\Xi_c(2923)^0$, $\Xi_c(2939)^0$
  - State at 2965 MeV close to an existing state, though masses and widths don't agree well

PRL 124 (2020) 222001

Discovering new states

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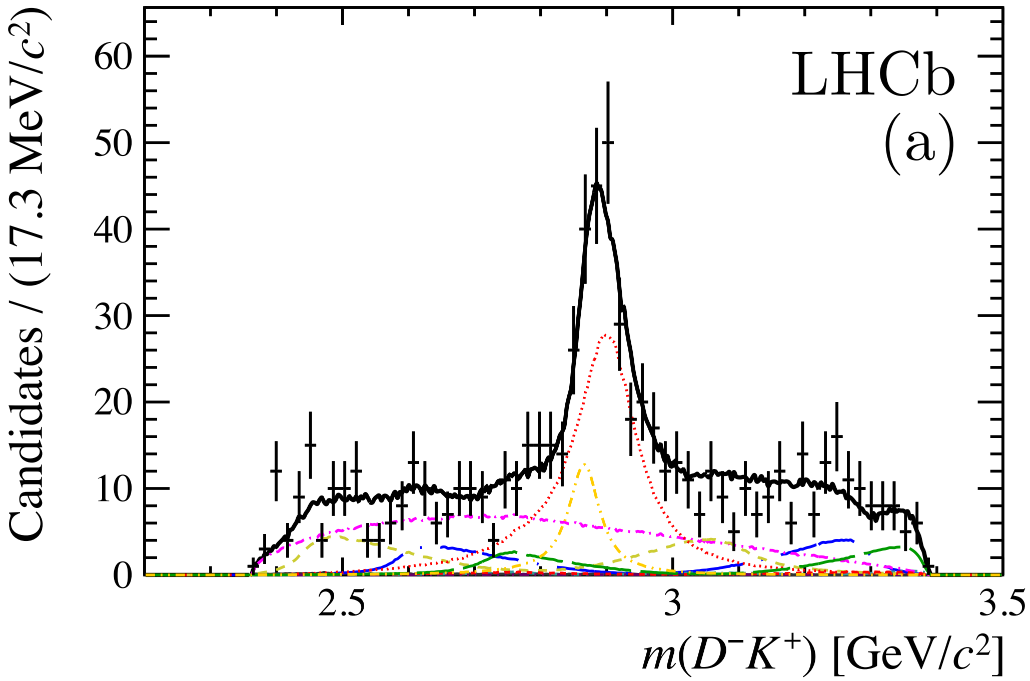
  - All kinds of beauty and charm hadrons produced at the LHC



arXiv:2009.00025, arXiv:2009.00026

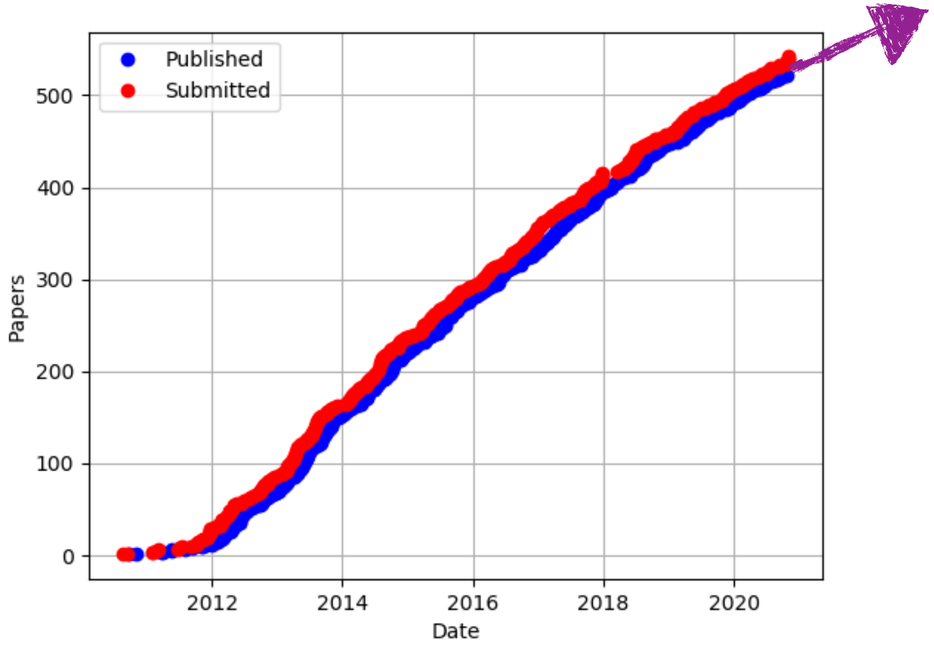
- $B^+ \to D^+D^-K^+$ decays
  - Large, unexpected peak in $m(D^-K^+)$
  - Quark content $\bar{c}d\bar{s}u$ – must be exotic
  - Best fit requires two new states

Will appear in PRL & PRD very soon
with a PRD Editor's Suggestion

… and much, much more

- Plenty of results to come with strong UK involvement
  - Lepton flavour universality tests
  - Lepton flavour violation tests
  - Charm mixing and time-dependent CP violation
  - Electroweak physics
  - Top physics
  - Higgs physics
  - Exotica

LHCb has become a GPD in the forward region



Moving forwards

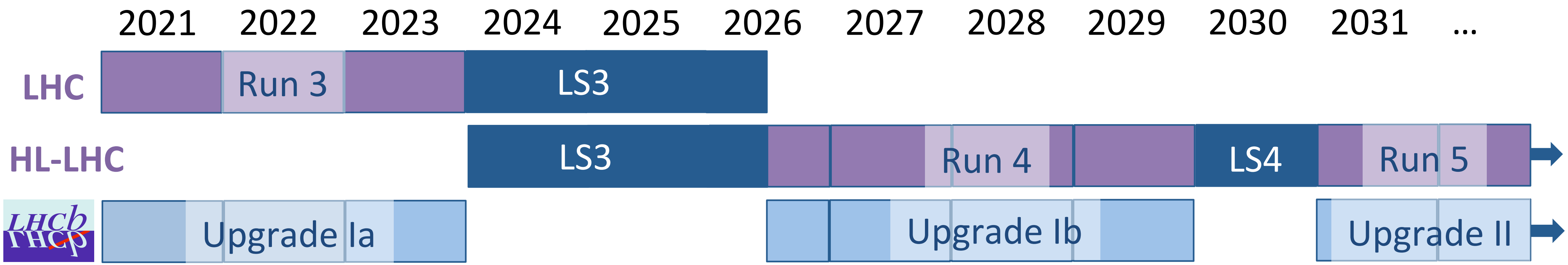
- LHCb was a huge success
  - **Surpassed** core physics programme **goals** and measured things **no one expected**
  - Time to **double** our data sample is now too long - must **upgrade** the detector

Observable	Current LHCb ($5\,\mathrm{fb}^{-1}$)	Upgrade Ia ($23\,\mathrm{fb}^{-1}$)	Upgrade Ib ($50\,\mathrm{fb}^{-1}$)	Upgrade II ($300\,\mathrm{fb}^{-1}$)
CKM tests				
γ	4°	1.5°	1°	0.35°
ϕ_s	49 mrad	14 mrad	10 mrad	4 mrad
$\lvert V_{ub}\rvert/\lvert V_{cb}\rvert$	6%	3%	—	1%
Charm				
ΔA_{CP}	2.9×10^{-4}	1.7×10^{-4}	—	3.0×10^{-5}
A_Γ	2.8×10^{-4}	4.3×10^{-5}	—	1.0×10^{-5}
Rare Decays				
$S_{\mu\mu}$	—	—	—	0.2
R_K	0.1	0.025	0.017	0.007
R_{K^*}	0.1	0.031	0.021	0.008

Excellent upgrade detectors will allow us to do even more

Timelines

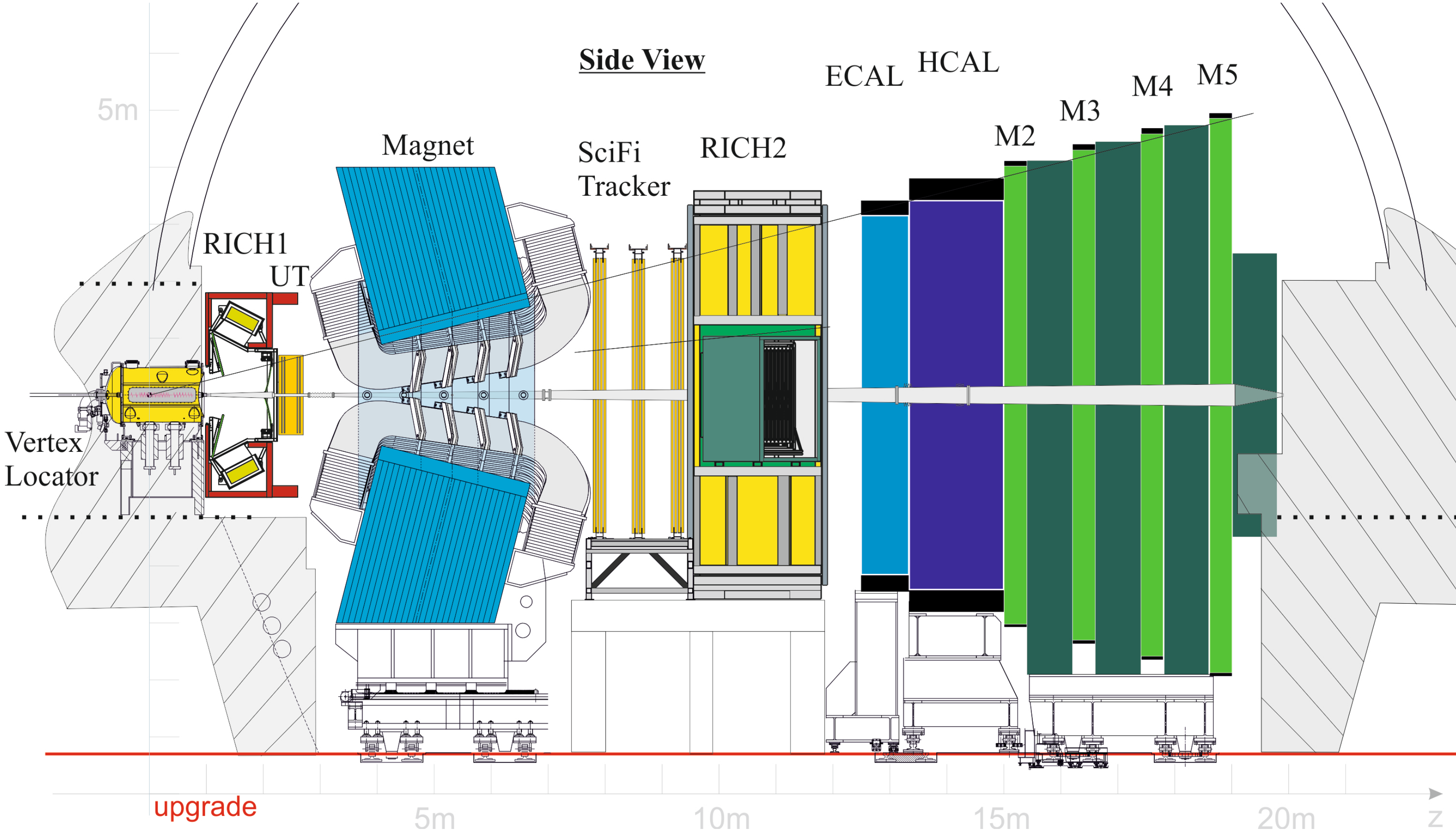
- The pre-pandemic plan…



- … and now?
  - Now expect Run 3 to begin in early 2022
  - Run 3 extended to include the full year of 2024
  - LHCb is currently on schedule to meet this new timeline
  - The situation (LHC, LHCb) is subject to change in the coming months

LHCb upgrade I

- Looks similar to LHCb…
  - This is a major detector upgrade
  - New tracking detectors
  - Full readout replacement
  - Remove hardware trigger
  - Run at 5x higher lumi



- UK focus
  - Vertex Locator (VELO)
  - PID (RICH 1 and 2)
  - Offline computing

LHCb upgrade I - VELO

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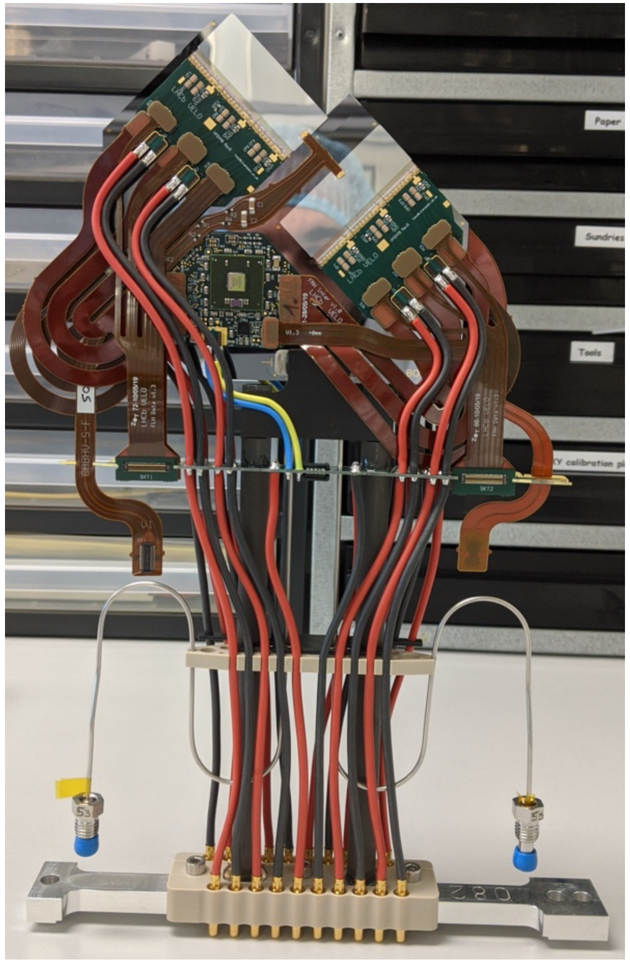
- New silicon pixel detector
  - Closer to the beam - 5.1mm compared to 8.1mm
  - Improved IP resolution
  - Strips → 41 million pixels
  - Micro-channel cooling
  - 40MHz readout

- On track to be ready
  - Module shown from Manchester post lockdown



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- RICH 1
  - New optics
  - New photon detectors
- RICH 2
  - New photon detectors
  - Associated support mechanics
- On track
  - New electronics tested during Run 2

LHCb future upgrade II

- Upgrade I just the beginning
  - Support from CERN and the new European strategy for flavour physics in the HL-LHC era and beyond
- Submitted funding request for UK involvement
  - PPRP request for 3 years R&D funding
  - Followed by construction, installation, commissioning and operation

Current involvement and R&D from individual grants and small amounts of CG effort

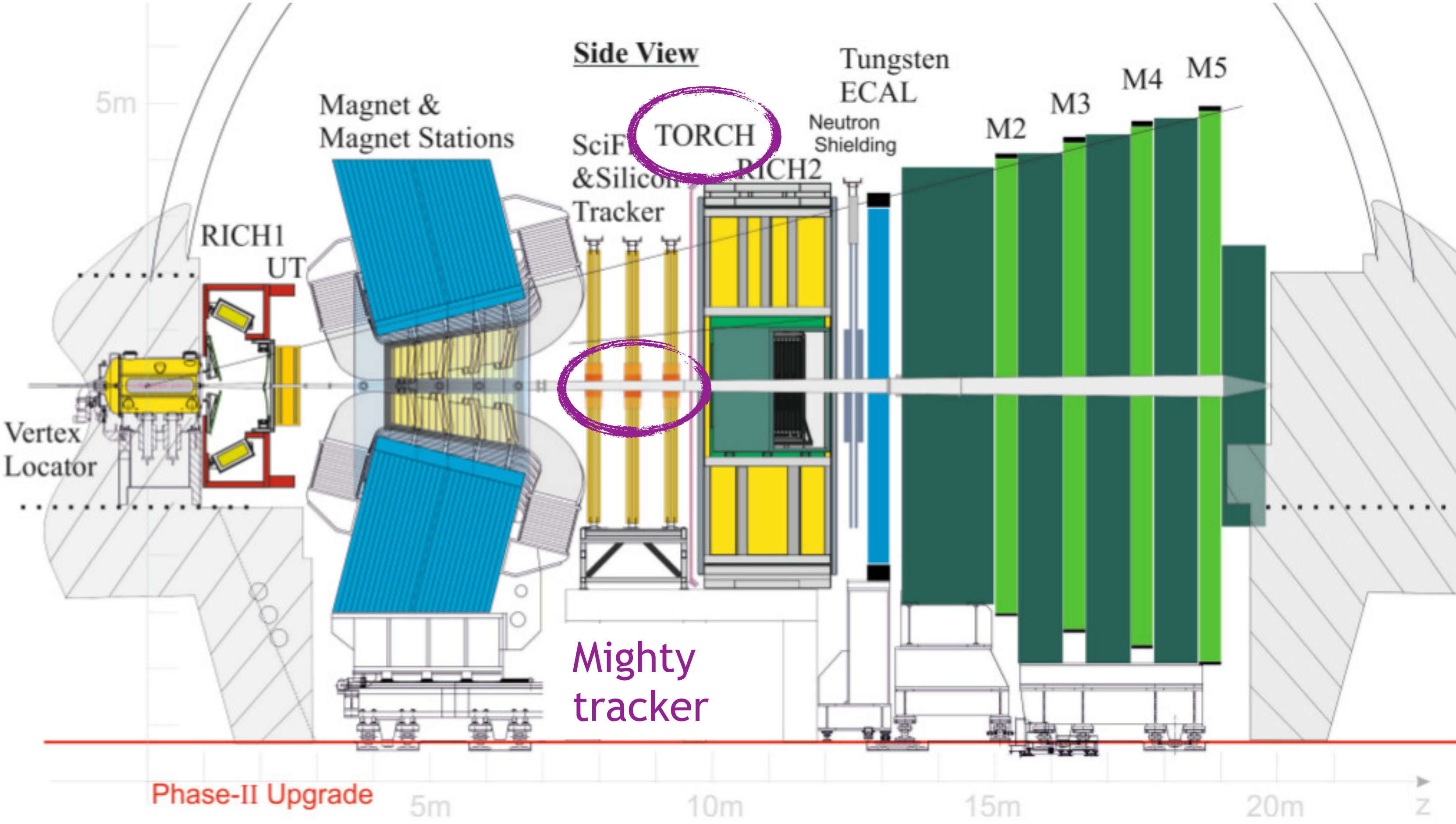
1

Major developments from the 2013 Strategy

A. Since the recommendation in the 2013 Strategy to proceed with the programme of upgrading the luminosity of the LHC, the HL-LHC project, was approved by the CERN Council in June 2016 and is proceeding according to plan. In parallel, the LHC has reached a centre-of-mass energy of 13 TeV, exceeded the design luminosity, and produced a wealth of remarkable physics results. Based on this performance, coupled with the innovative experimental techniques developed at the LHC experiments and their planned detector upgrades, a significantly enhanced physics potential is expected with the HL-LHC. The required high-field superconducting Nb_3Sn magnets have been developed. ***The successful completion of the high-luminosity upgrade of the machine and detectors should remain the focal point of European particle physics, together with continued innovation in experimental techniques. The full physics potential of the LHC and the HL-LHC, including the study of flavour physics and the quark-gluon plasma, should be exploited.***

LHCb future upgrade II

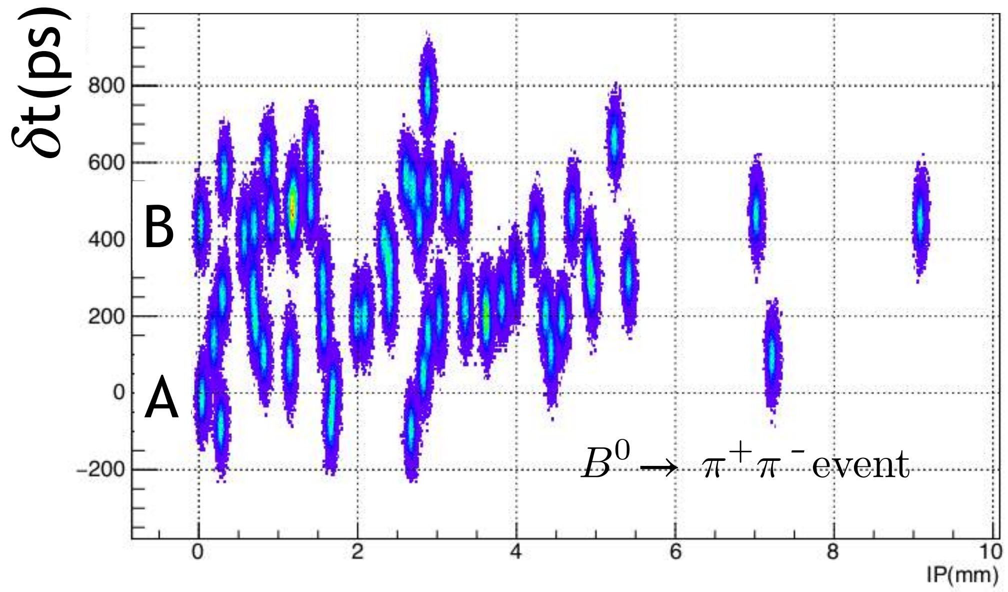
- Strong UK involvement
  - VELO, RICH
  - TORCH, Mighty tracker
  - Data processing
  - Management
- Upgrade II
  - Increase luminosity by a further factor of 10

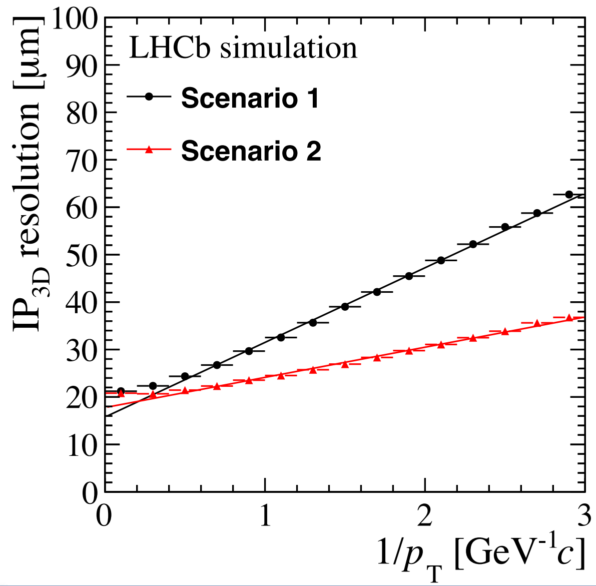


LHCb future upgrades - VELO

UK led

- Huge challenge with ~50 interactions per bunch crossing
  - Use timing information to assign tracks to the correct primary vertex
  - Precision of <50ps can reduce 20% mis-association to ~5%
  - LGAD technology under study in partnership with Micron Semiconductors (UK)
  - Remove or reduce the RF foil - improve resolution and limit material interactions





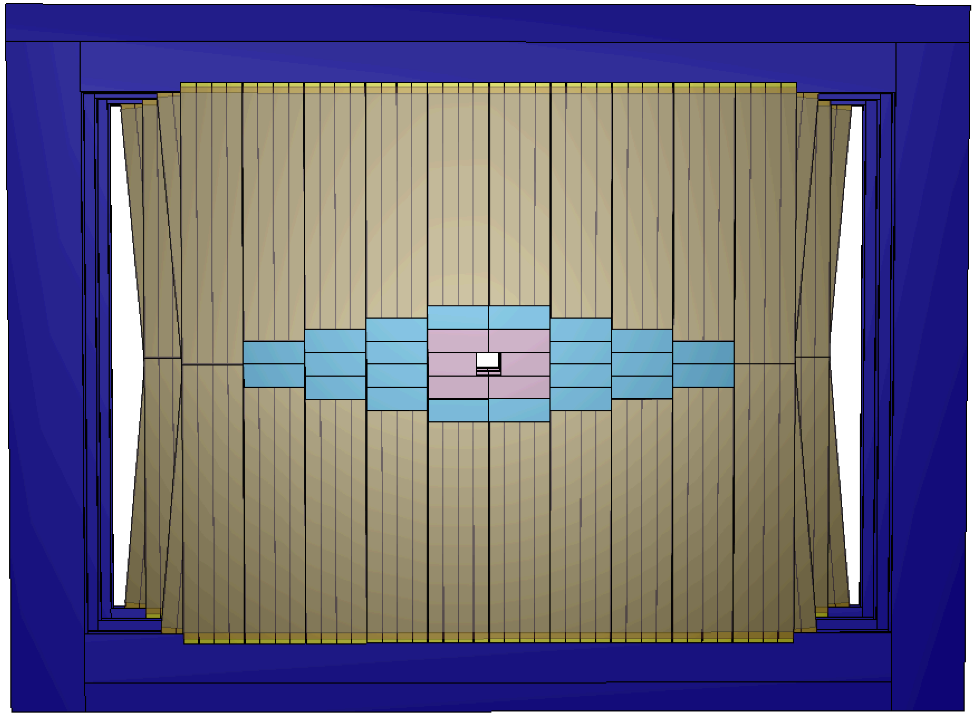
With foil

Without foil

LHCb future upgrades - Mighty tracker

UK led

- Two stages foreseen
  - Inner tracker in pre-upgrade II (LS3), middle tracker in upgrade II (LS4)
  - Improve tracking performance and reduce occupancy in the SciFi
- Inner tracker
  - 6 layers of pixels (HV CMOS), can be relatively large ~100 x 300 microns
  - Each layer ~0.7m², ~4m² in total
  - Combine with SciFi with minimum material
- Middle Tracker
  - Expand pixel coverage to 3m² per layer

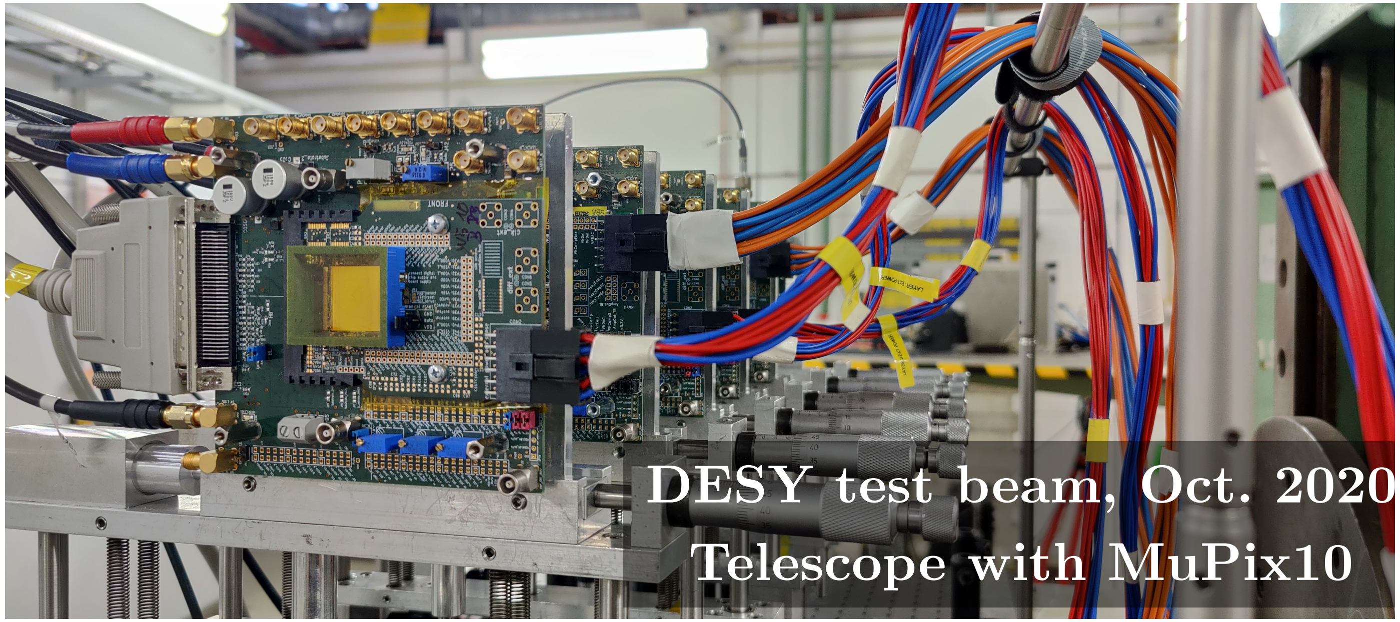


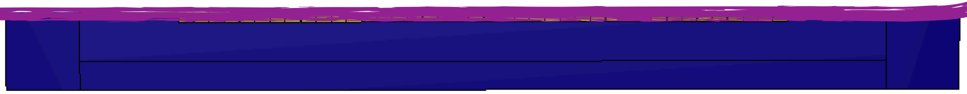
LHCb future upgrades - Mighty tracker

UK led

- Two stages foreseen
  - Inner tracker in pre-upgrade II (LS3), middle tracker in upgrade II (LS4)

- Recent team beam at DESY
  - First MightyPix HVCMOS chips
  - Despite COVID, we were able to take data
  - Data analysis ongoing and led by UK groups



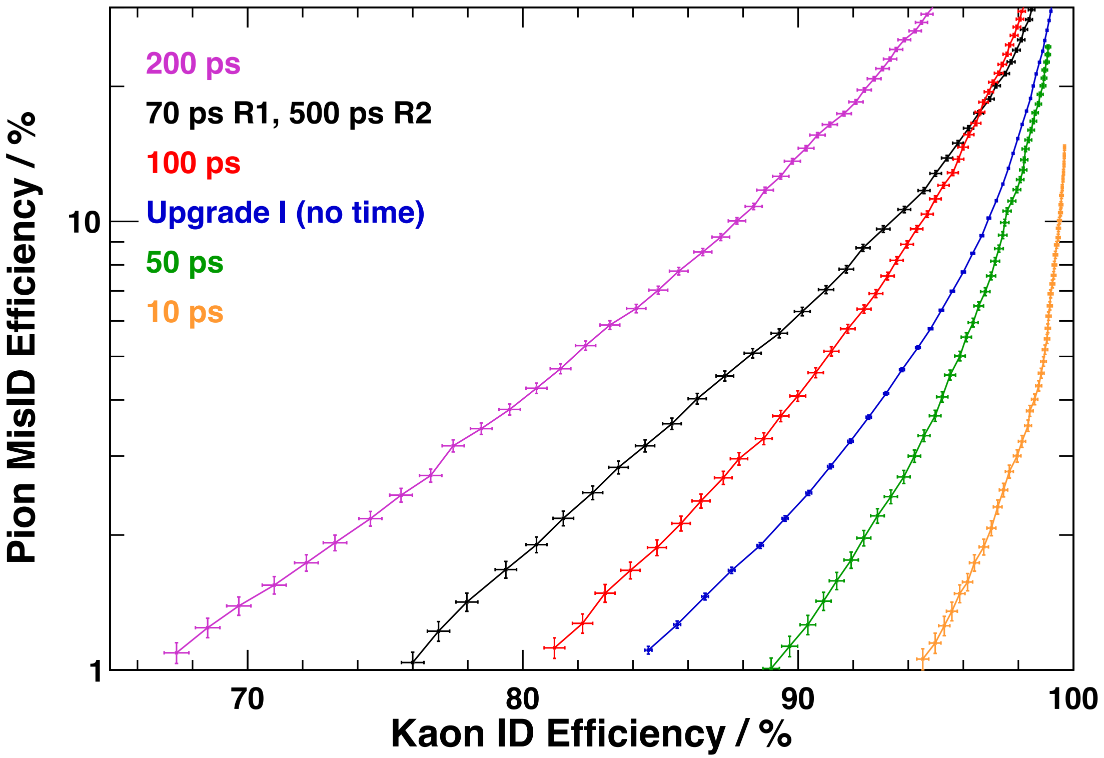


- Expand pixel coverage to $3m^2$ per layer

LHCb future upgrades - RICH

UK led

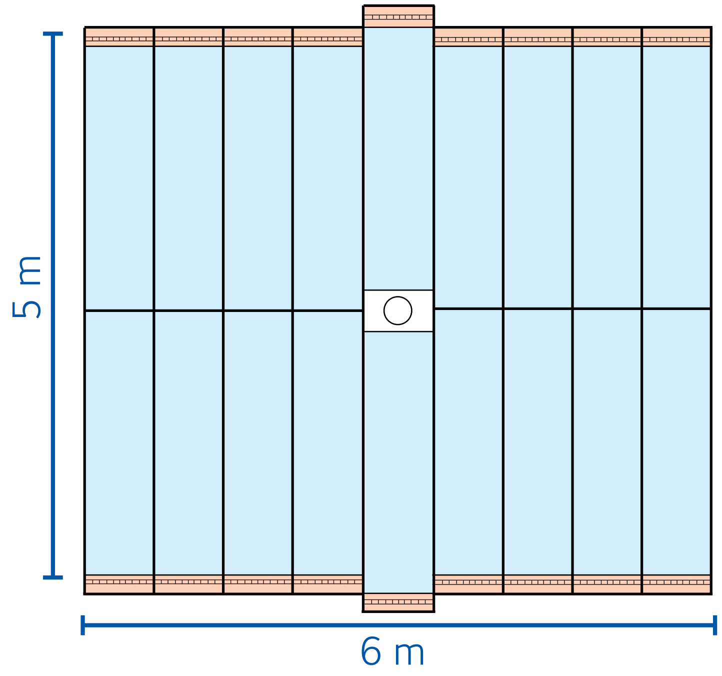
- PID a crucial part to enable the future LHCb physics programme
  - Use timing information to recover upgrade I performance
  - Improvement from better assignment of hits to tracks
  - Can also reduce the pixel size
- R&D well underway
  - Choice of photon detectors
  - Choice of radiator material
  - Electronics

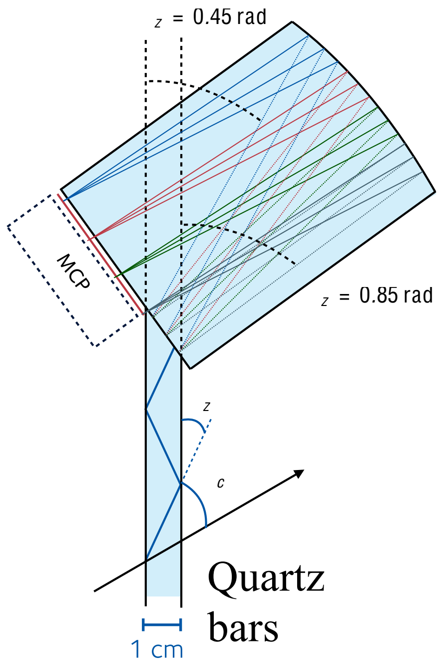


LHCb future upgrades - TORCH

UK led

- PID information for tracks in the 2-20 GeV range
  - Novel time of flight detector using quartz bars
  - Provide information below the Cherenkov threshold of RICH
  - Improve proton identification and PID for low momentum tracks
- Precise timing
  - Aim for 15ps resolution per track
- UK led project
  - Fast timing detectors (MCP) under development by a UK company (Photek)





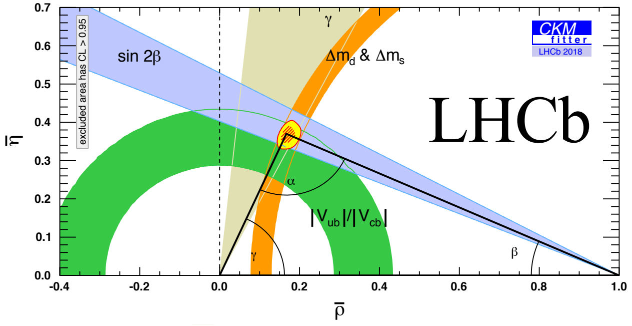
LHCb future upgrades - Data processing

- Build on LHCb's innovative approach to data processing
  - Real-time alignment and calibration scheme
  - Flexible real-time analysis model
  - Full GPU based first level trigger in upgrade I
  - For upgrade II, even greater challenges must be met

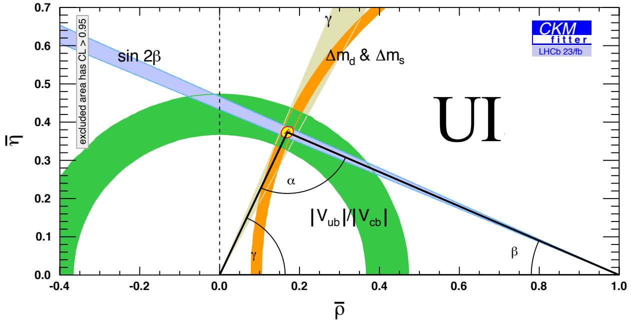
- Need for speed
  - R&D for new architectures
  - Four dimensional event reconstruction
  - Detailed simulations

Summary

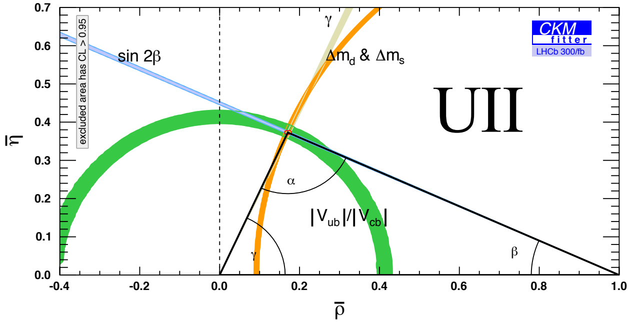
- Lots to look forward to!
  - High profile results, many with UK involvement, are still rolling in



- Upgrade I on track for 2022 startup
  - Installation going well
  - Exciting time for commissioning and first physics



- Long term plans - Upgrade II
  - Supported by CERN and the European strategy
  - UK leading in many areas, let’s keep it that way



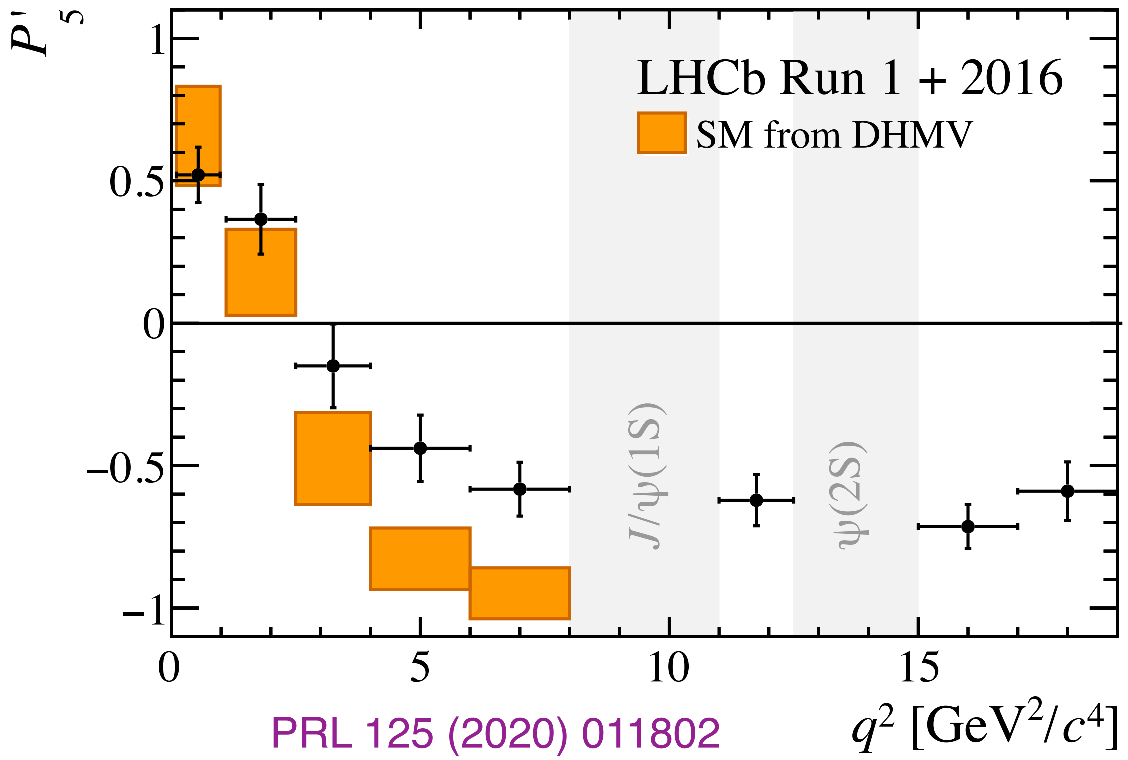
Backup

Flavour anomalies

- Tensions between measurements and the standard model
  - Most prevalent in rare and semi-leptonic B meson decays

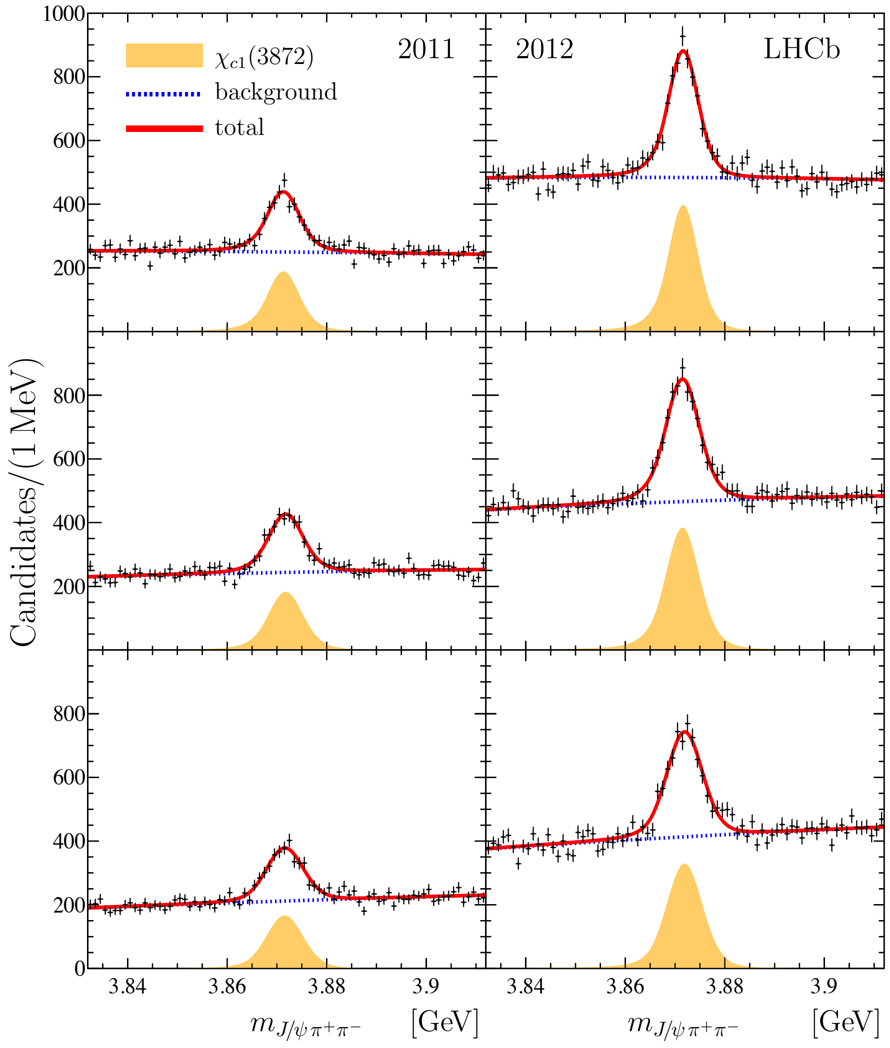
- Update from $B^0 \to K^{*0}\mu^+\mu^-$ decays
  - Added the 2016 data sample
  - Tension with the standard model increased slightly but still around 3σ
  - More to come - 2017 and 2018 data!

- UK also involved in R(D(*)) decays
  - New results hotly anticipated



PRL 125 (2020) 011802

Spectroscopy



- $\chi_{c1}(3872)$ (a.k.a. $X(3872)$)
  - Two measurements this year to study the lineshape of the resonance
  - What is the nature of the state?
  - Non-zero natural width seen for the first time

$$\Gamma_{\mathrm{BW}} = 1.39 \pm 0.24 \pm 0.10\,\mathrm{MeV}$$

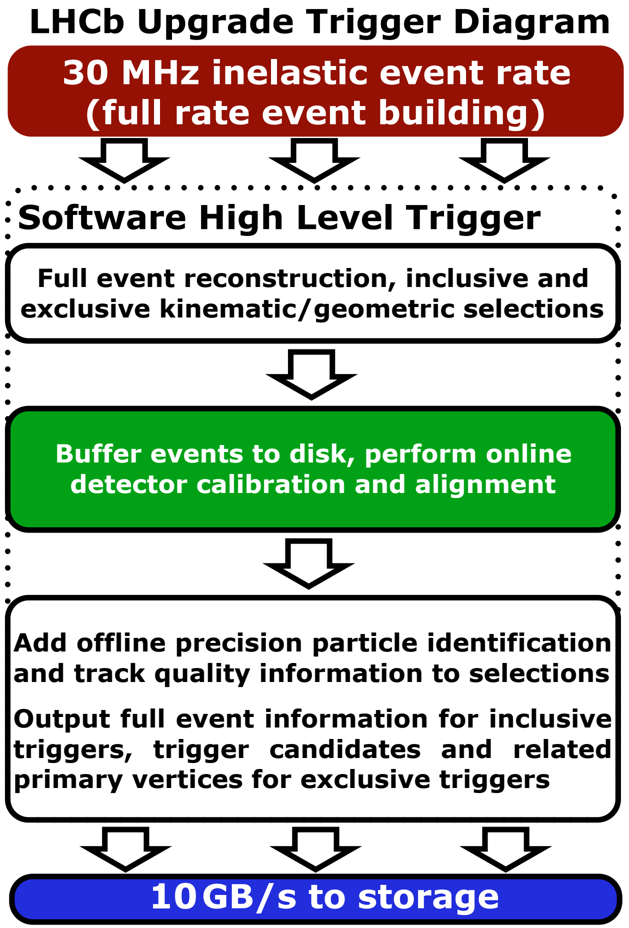
  - assuming a Breit-Wigner function applies
  - Other models also employed, which prefer a narrow width.
  - Lineshapes are important!

JHEP 08 (2020) 123, LHCb-PAPER-2020-008

LHCb upgrade I - Trigger

- Looks similar to LHCb…
  - This is a major detector upgrade
  - New tracking detectors
  - Full readout replacement
  - Remove hardware trigger
  - Run at 5x higher lumi
- UK focus
  - Vertex Locator (VELO)
  - PID (RICH 1 and 2)
  - Offline computing

- Software trigger
  - First level will run on GPU
  - 30 MHz rate can already be handled
- Alignment and calibration
  - Strong UK involvement
- Physics selections
  - Second level to use CPU
  - Selections under way



LHCb upgrade I - Physics

Type	Observable	LHC Run 1	LHCb 2018	**LHCb upgrade**	Theory
B_s^0 mixing	$\phi_s(B_s^0 \to J/\psi\,\phi)$ (rad)	0.049	0.025	**0.009**	~ 0.003
	$\phi_s(B_s^0 \to J/\psi\, f_0(980))$ (rad)	0.068	0.035	**0.012**	~ 0.01
	$A_{\rm sl}(B_s^0)$ (10^{-3})	2.8	1.4	**0.5**	0.03
Gluonic penguin	$\phi_s^{\rm eff}(B_s^0 \to \phi\phi)$ (rad)	0.15	0.10	**0.018**	0.02
	$\phi_s^{\rm eff}(B_s^0 \to K^{*0}\bar{K}^{*0})$ (rad)	0.19	0.13	**0.023**	< 0.02
	$2\beta^{\rm eff}(B^0 \to \phi K_S^0)$ (rad)	0.30	0.20	**0.036**	0.02
Right-handed currents	$\phi_s^{\rm eff}(B_s^0 \to \phi\gamma)$ (rad)	0.20	0.13	**0.025**	< 0.01
	$\tau^{\rm eff}(B_s^0 \to \phi\gamma)/\tau_{B_s^0}$	5%	3.2%	**0.6%**	0.2 %
Electroweak penguin	$S_3(B^0 \to K^{*0}\mu^+\mu^-; 1 < q^2 < 6\,{\rm GeV}^2/c^4)$	0.04	0.020	**0.007**	0.02
	$q_0^2\, A_{\rm FB}(B^0 \to K^{*0}\mu^+\mu^-)$	10%	5%	**1.9%**	$\sim 7\%$
	$A_{\rm I}(K\mu^+\mu^-; 1 < q^2 < 6\,{\rm GeV}^2/c^4)$	0.09	0.05	**0.017**	~ 0.02
	$\mathcal{B}(B^+ \to \pi^+\mu^+\mu^-)/\mathcal{B}(B^+ \to K^+\mu^+\mu^-)$	14%	7%	**2.4%**	$\sim 10\%$
Higgs penguin	$\mathcal{B}(B_s^0 \to \mu^+\mu^-)$ (10^{-9})	1.0	0.5	**0.19**	0.3
	$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	220%	110%	**40%**	$\sim 5\,\%$
Unitarity triangle angles	$\gamma(B \to D^{(*)}K^{(*)})$	7°	4°	**0.9°**	negligible
	$\gamma(B_s^0 \to D_s^{\mp}K^{\pm})$	17°	11°	**2.0°**	negligible
	$\beta(B^0 \to J/\psi\, K_S^0)$	1.7°	0.8°	**0.31°**	negligible
Charm *CP* violation	$A_\Gamma(D^0 \to K^+K^-)$ (10^{-4})	3.4	2.2	**0.4**	–
	ΔA_{CP} (10^{-3})	0.8	0.5	**0.1**	–

Many measurements will still be statistically limited - we will need even more data!