LHCb Status Report

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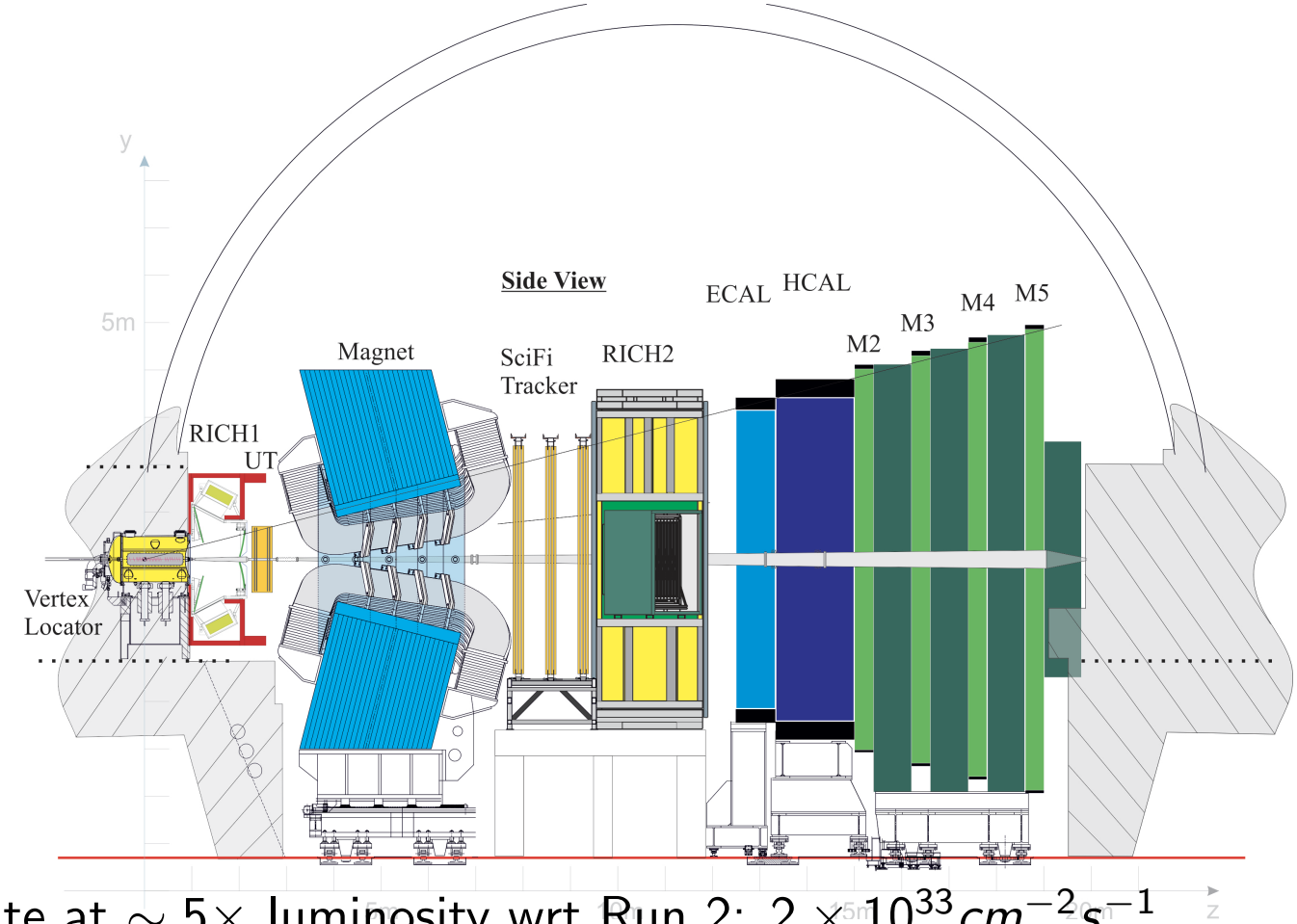
on behalf of the LHCb collaboration

145$^{\text{th}}$ LHCC Open Session 2021/03/03

University of Glasgow

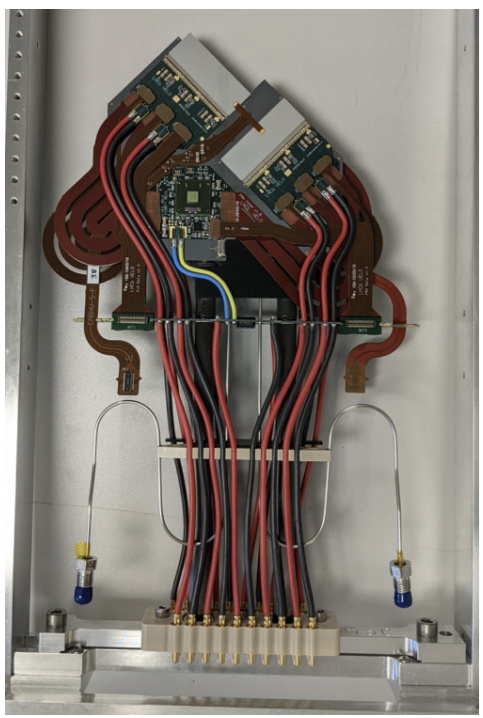
Outline

Anatomy of the Upgrade



- Operate at $\sim 5\times$ luminosity wrt Run 2: $2 \times 10^{33} cm^{-2} s^{-1}$
- Full detector readout at 40 MHz:
  - Allows more efficient, full software trigger
  - Upgrade ~90% of detector channels & 100% of readout electronics & DAQ

Vertex Locator (VELO)



Installation:

- Beam pipe section 1 & exit window
- Downstream wake field suppressor

Production:

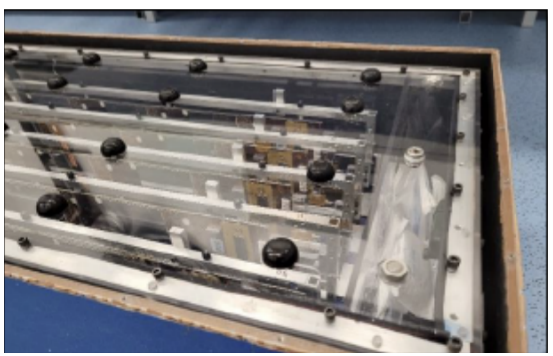
- Major progress but significant delays due to COVID (and Brexit to a lesser extent)
- 52 microchannels produced since CERN reopening - first ones shipped successfully to assembly sites by air rather than land due to COVID
- Module production in steady state, $\sim$1/week - 1/4 of production finalised

Next steps:

- Assemble C-side half, transport & install in Nov 2021
- A-side half installation Jan 2022
- Tight schedule with limited commissioning time

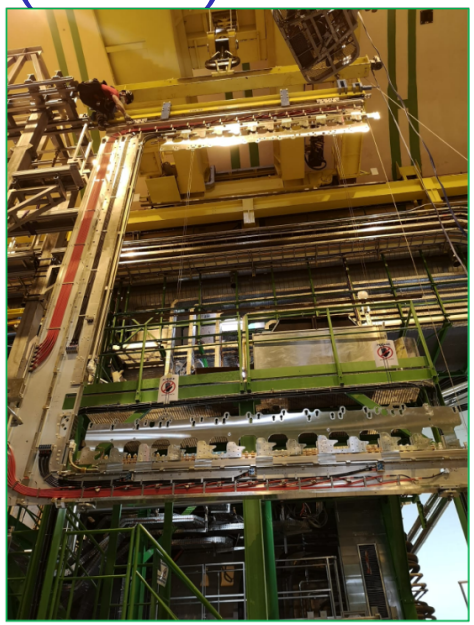
Upstream Tracker (UT)

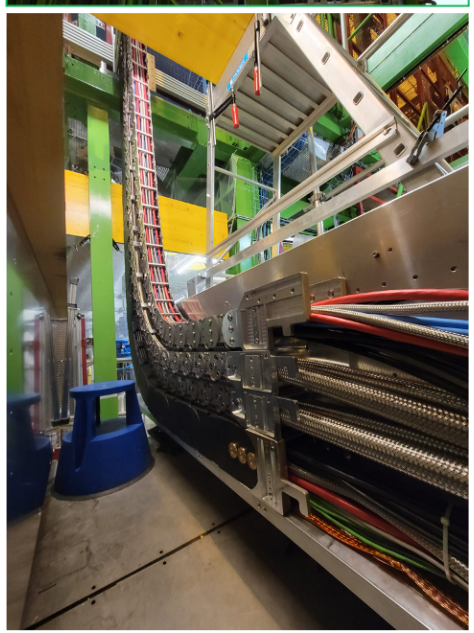
- $\sim$ 95% of modules & 100% of electronics boards ready (excluding spares)
- Produced & tested $\sim$20 staves
  - need 26/half + spares
- Clean room for assembly at P8 completed after COVID delays
- First fully instrumented staves delivered to CERN
- Detector assembly over spring & summer
- Installation in autumn 2021



Scintillating Fibre Tracker (SciFi)

- C-frame assembly stopped due to COVID
- Significant effort to organise restart - aim for end of March
- Many thanks to the CERN directorate & HSE for their support in planning!
- Four C-frames fully assembled & commissioned - need six per half
- Prioritise next two for installation of one full half ahead of beam pipe installation
- Successful dry run of C-frame installation
- Successful test run of filling cable chains for full C-frame

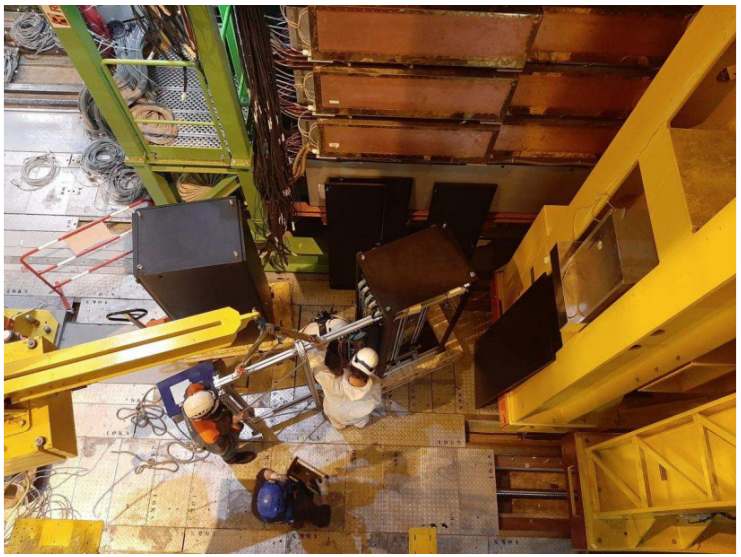




RICH1&2

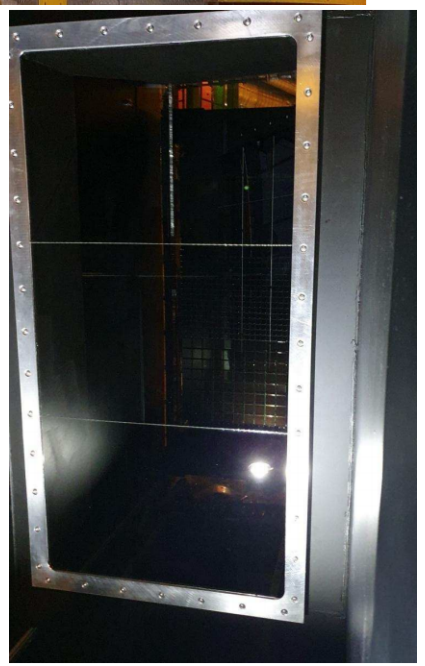
RICH1:

- Gas enclosure & seal to VELO installed
- Next install exit window (spring), mirrors (Oct), & MaPMT columns (Oct)



RICH2:

- A-side MaPMT columns installed
- Controls live in the Control Room
- First new element of Upgrade-I to go live!
- Next install C-side columns (March)



Calorimeters & Muon Chambers

CALO:

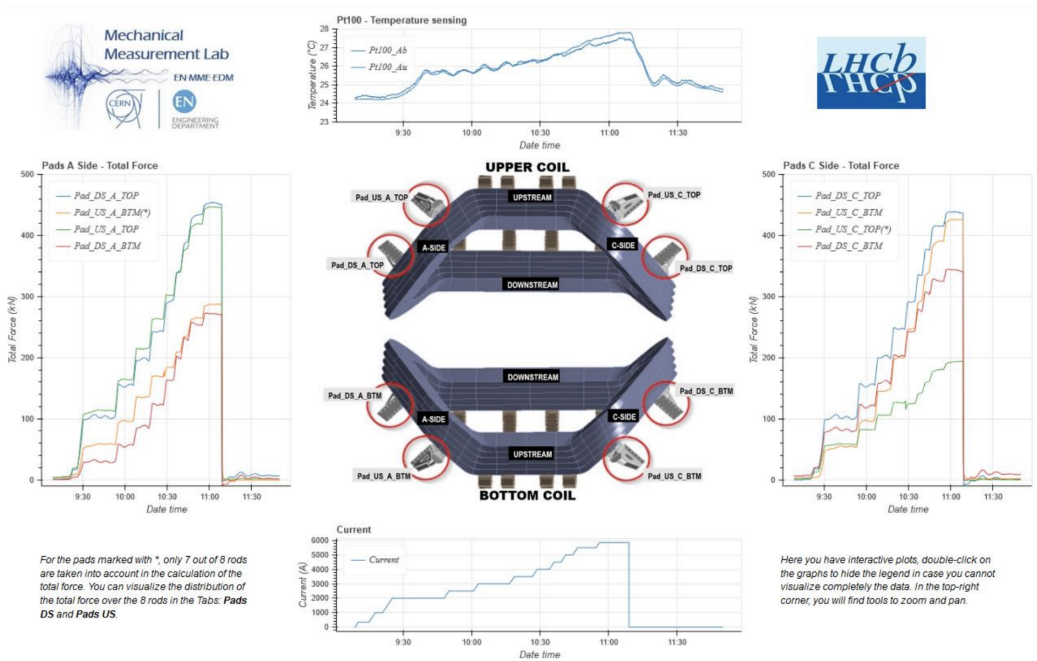
- Front-end electronics in full production after COVID delays, start of installation in April 2021
- Completed maintenance of movement system
- Upgrade of movement control system in spring

Muon:

- All readout electronics installed!
- HCAL shielding & tungsten shielding in place
- Next install M2 beam plug
- Commissioning ongoing alongside preparation for new chambers - foreseen for installation in very inner regions of M2&M3 during Run 3

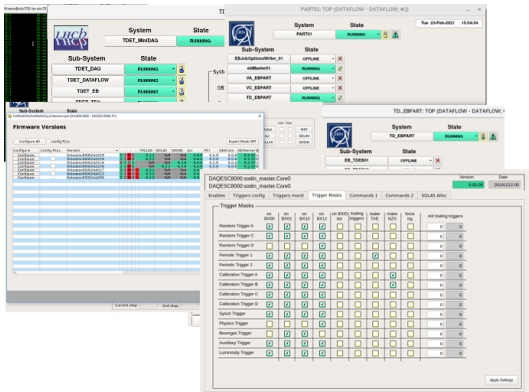
Dipole magnet

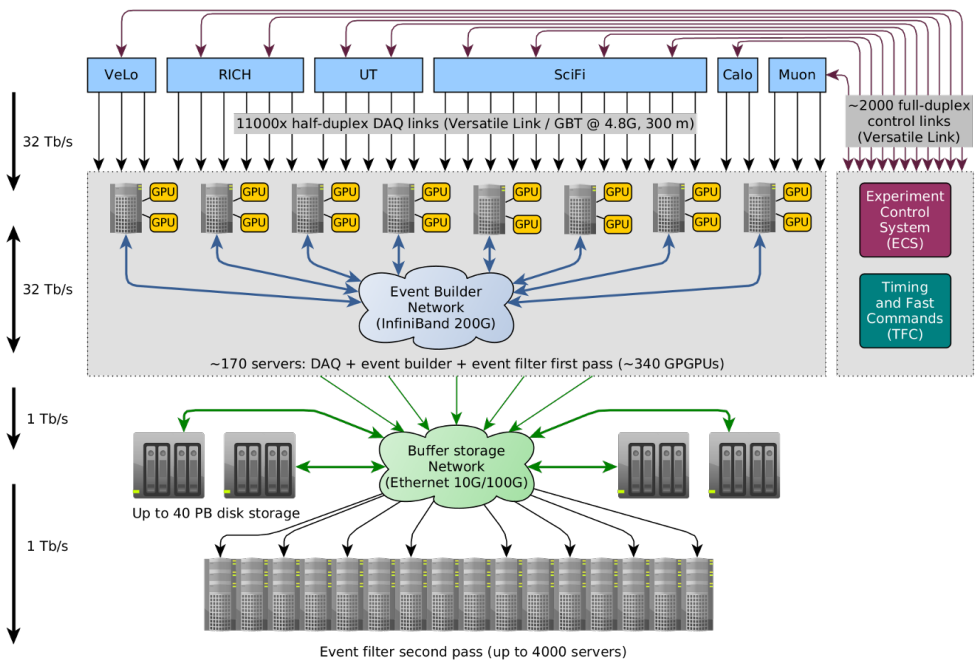
- Now fully operational - many thanks to EN/MME and EP/DT for their help!
- New support structure & repair of broken clamps
- New strain monitoring system
- Magnetic field mapping performed



Online

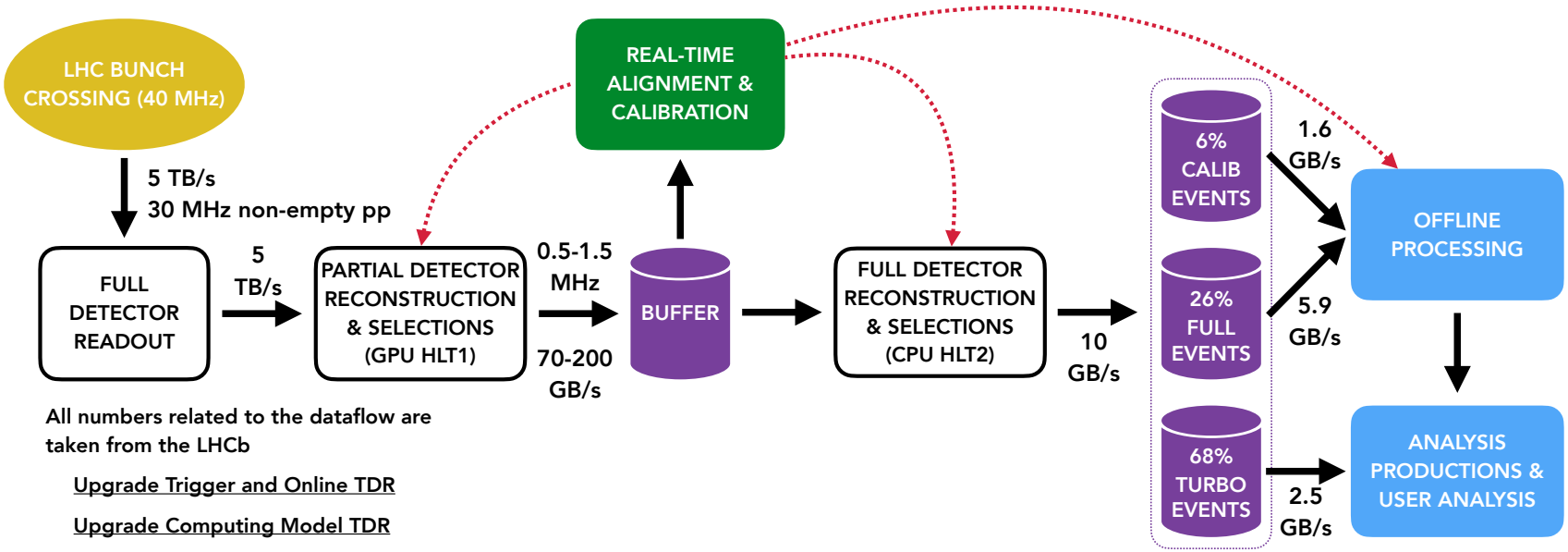
- Commissioning has started!
- Experiment Control System (ECS) taking charge of all new components in DAQ, fast- and slow-control
- Full stack (soft and firmware) releases setting the pace
- The largest ever DAQ is taking shape!
- 68 Tbit/s installed bandwidth, ∼400 FPGA cards, ∼15000 fibres, 1000s of cables, 10,000s of labels!





[LHCB-TDR-016]
[LHCB-TDR-017]
[LHCB-TDR-021]
[LHCB-FIGURE-2020-016]

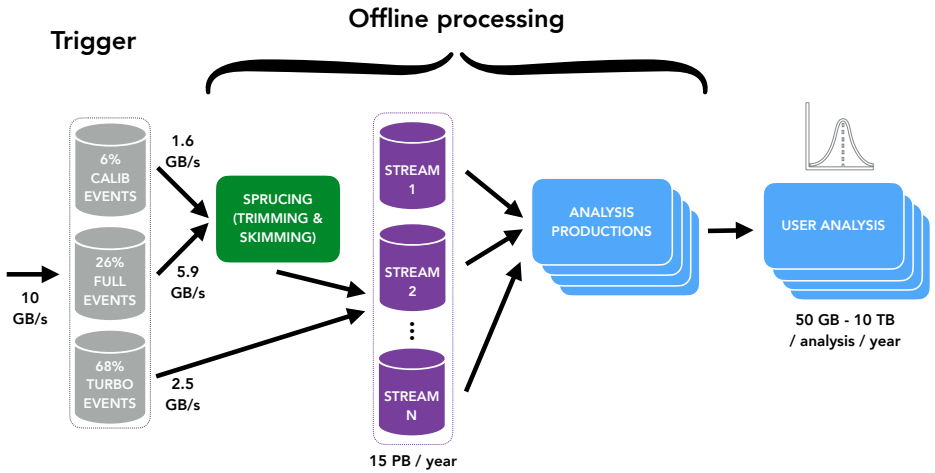
Real Time Analysis (RTA)



- HLT1 GPU implementation: current throughput meets requirements with generous safety margins
- HLT2 CPU implementation:
  - Reconstruction throughput now also within requirements
  - Begin populating selections using vectorised framework in preparation for Full Experiment System Test (FEST) in June
- Good progress in real-time alignment, calibration, & monitoring

[LHCB-TDR-017]
[LHCB-TDR-018]
[LHCB-FIGURE-2020-016]

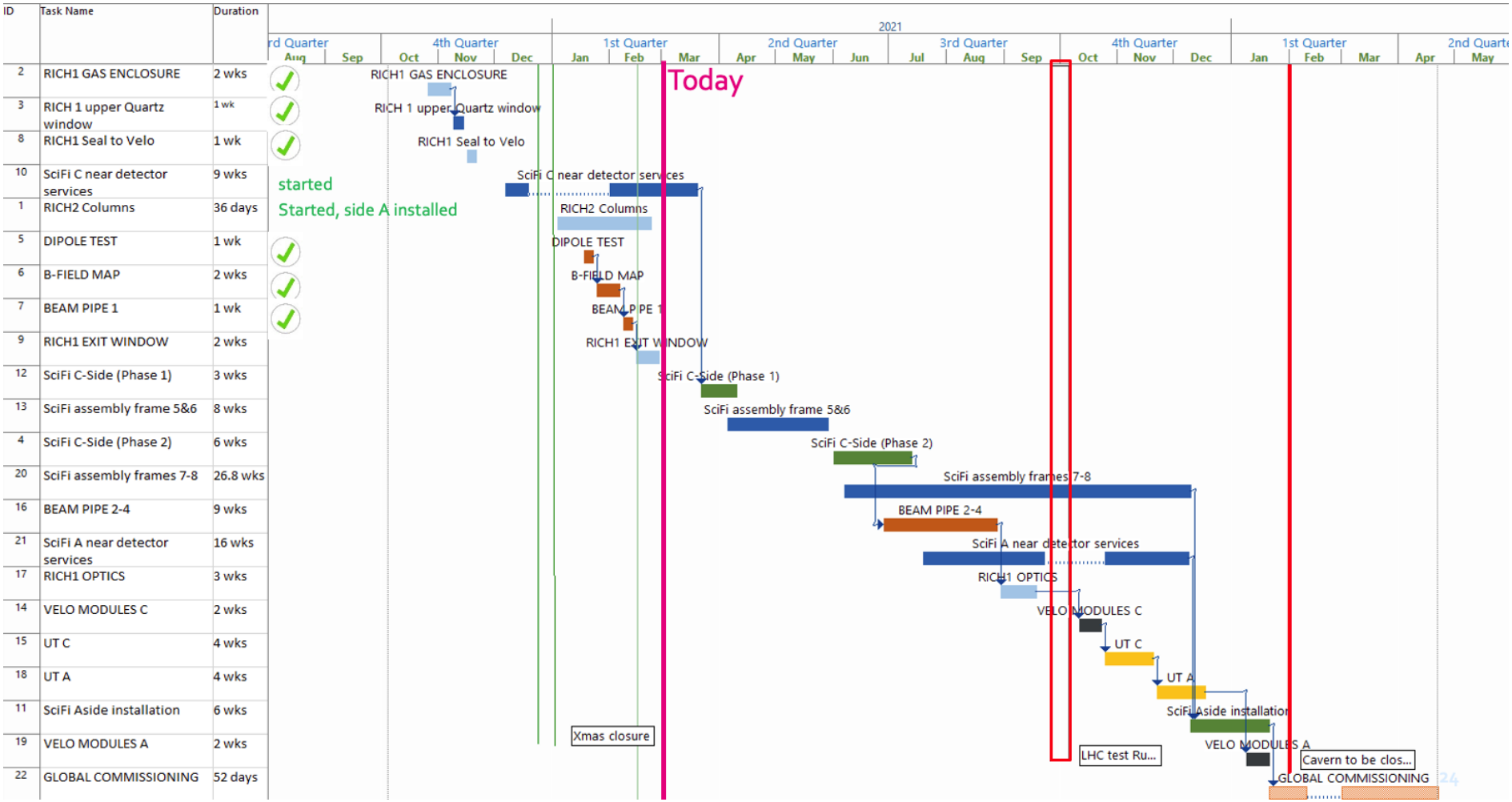
Data Processing & Analysis



- WP1 - Sprucing
- WP2 - Analysis Productions
- WP3 - Offline Analysis Tools
- WP4 - Innovative Analysis Techniques
- WP5 - Legacy Software & Data
- WP6 - Analysis Preservation & Open Data

- WP1 - share of application & selection framework between HLT2 and offline, focus on persistency aspects
- WP2 - used daily by LHCb for Run I & II analyses, proving ground for Run III
- WP3 - share as much as possible the software stack with online, focus on a modern design & friendly configuration
- WP4 - first proof-of-concept work on Quantum Computing techniques for b-jet tagging
- WP5 - re-processing of Run I & II data
- WP6 - (new since last LHCC) focus on release of Run I data to the Open Data portal, guidelines & tools for analysis preservation

Installation Schedule

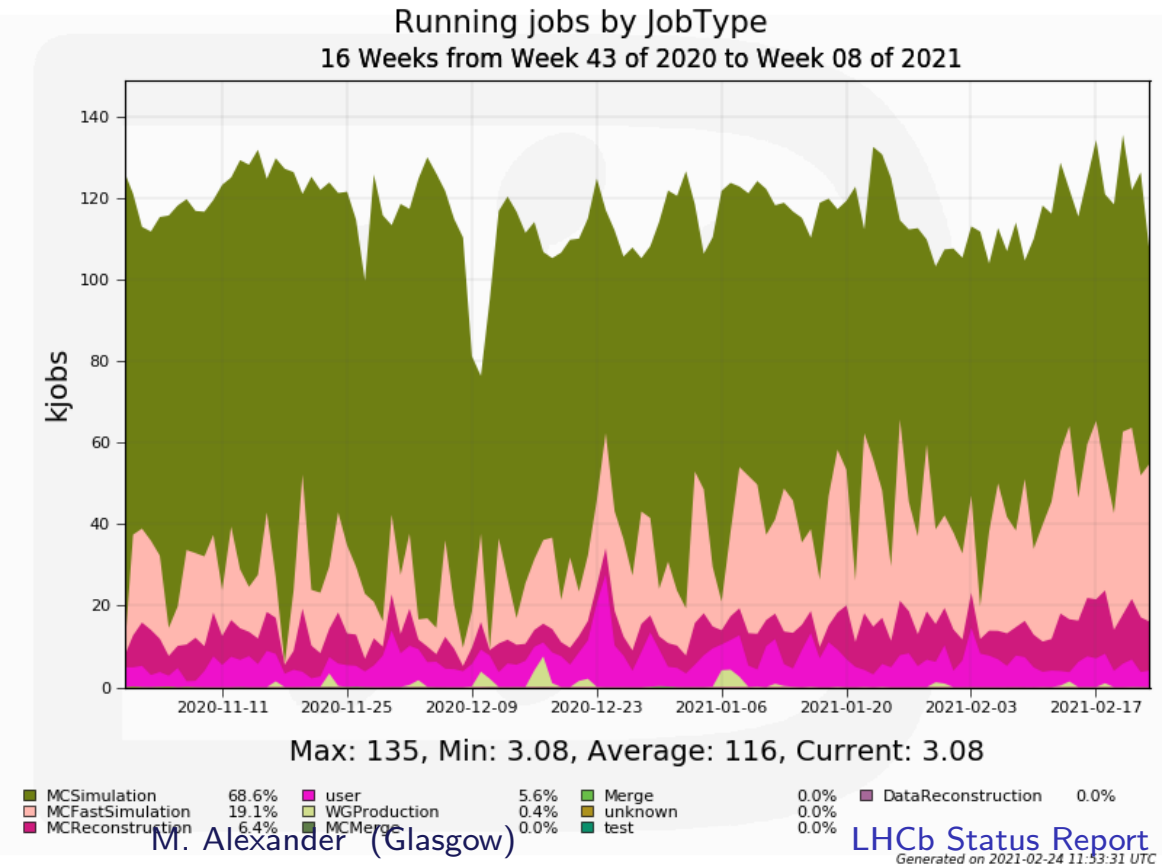


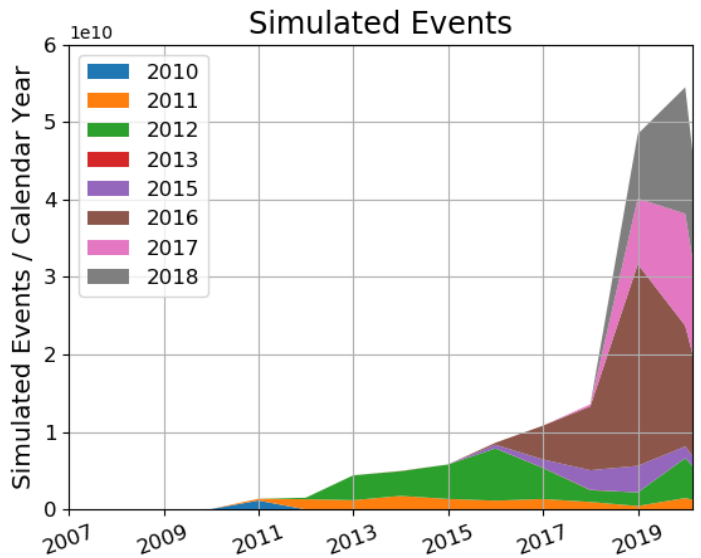
Very tight with little contingency, but still feasible provided all goes to plan

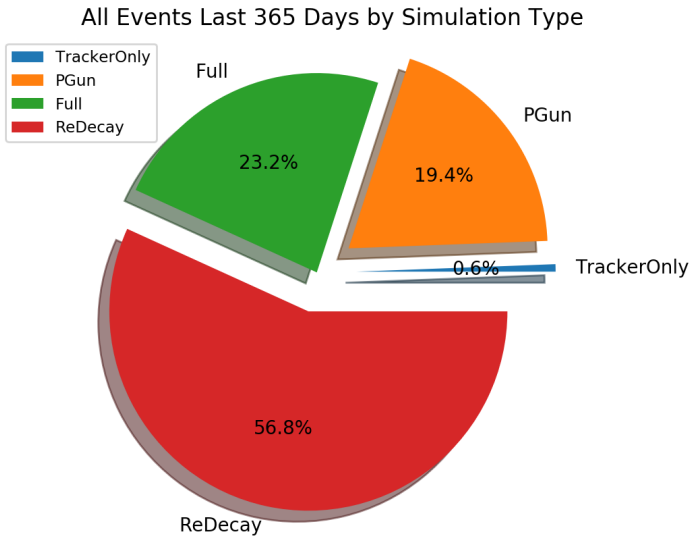
Outline

Operations

- Smooth operations
- Work dominated by MC production
- ∼3/4 of events generated using faster simulation (mostly ReDecay)
- Preparation for partial re-processing of Run II data to be performed within the year (DPA WP5)







Preparation for Run 3

Full Experiment System Test campaign, a joint effort from all the software groups:

- New data processing scheme - aim to commission as much software infrastructure as possible as early as possible
- Run simulated data through the whole Online and Offline chain to verify readiness of data processing
  - Injection of MC into HLT1, through HLT2
  - Test alignment & monitoring
  - Test data transfer & offline processing
- Integration test run as commissioning week at P8 (including "Run meeting" to verify check points)
- First campaign during the first week of June
- Second campaign in Autumn, avoiding clash with LHC beam test
- Complementary test will be performed during LHC beam test in September:
  - Switch on as many sub-detectors as possible
  - Acquire data in pass-through for reprocessing
  - Early time alignment test

Outline

New results since last LHCC

Submitted to journal:

- [PAPER-2020-033] Search for the rare decay $B^0 \to J/\psi\,\phi$
- [PAPER-2020-034] **Observation of a new excited D_s^+ meson in $B^0 \to D^+D^-K^+\pi^-$ decays**
- [PAPER-2020-030] Measurement of the CKM angle γ and B_s^0-$\bar{B}_s^0$ mixing frequency with $B_s^0 \to D_s^\mp h^\pm\pi^\pm\pi^\mp$ decays
- [PAPER-2020-028] **Observation of the $\Lambda_b^0 \to \Lambda_c^+K^+K^-\pi^-$ decay**
- [PAPER-2020-027] Search for long-lived particles decaying to $e^\pm\mu^\mp\nu$
- [PAPER-2020-037] Observation of the $B_s^0 \to D^{*\pm}D^\mp$ decay
- [PAPER-2020-038] First observation of the decay $B_s^0 \to K^-\mu^+\nu_\mu$ and measurement of $|V_{ub}|/|V_{cb}|$
- [PAPER-2020-036] Measurement of *CP* observables in $B^\pm \to D^{(*)}K^\pm$ and $B^\pm \to D^{(*)}\pi^\pm$ decays using two-body D final states
- [PAPER-2020-039] Evidence of a $J/\psi\Lambda$ structure and observation of excited Ξ^- states in the $\Xi_b^- \to J/\psi\Lambda K^-$ decay
- [PAPER-2020-040] Measurement of CP violation in the decay $B^+ \to K^+\pi^0$
- **Brand new:** [PAPER-2020-044] Observation of new resonances decaying to $J/\psi K^+$ and $J/\psi\phi$

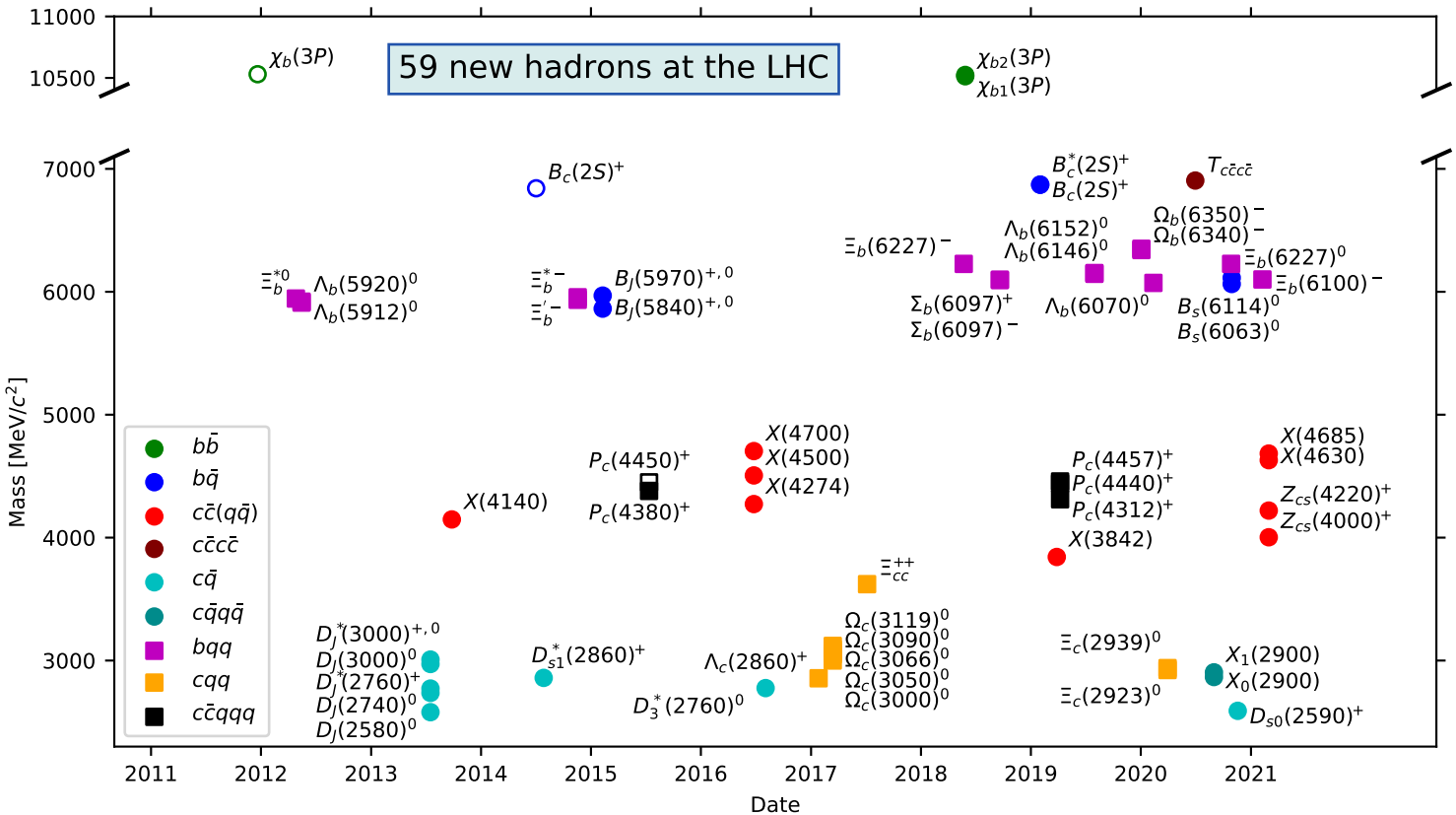
Newly approved:

- [PAPER-2020-048] Measurement of prompt cross-section ratio $\sigma(\chi_{c2})/\sigma(\chi_{c1})$ in pPb collisions at $\sqrt{s_{NN}} = 8.16$ TeV
- [PAPER-2020-045] **Search for time-dependent *CP* violation in $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$ decays**
- [PAPER-2020-047] **Measurement of CP asymmetry in $D^0 \to K_S^0K_S^0$ decays**
- [PAPER-2021-001] **Search for CP violation in $D_{(s)}^+ \to h^+\pi^0$ and $D_{(s)}^+ \to h^+\eta$ decays**

Plus many new results coming for winter conferences!

[LHCB-FIGURE-2021-001]
[LHCB-PAPER-2020-044]

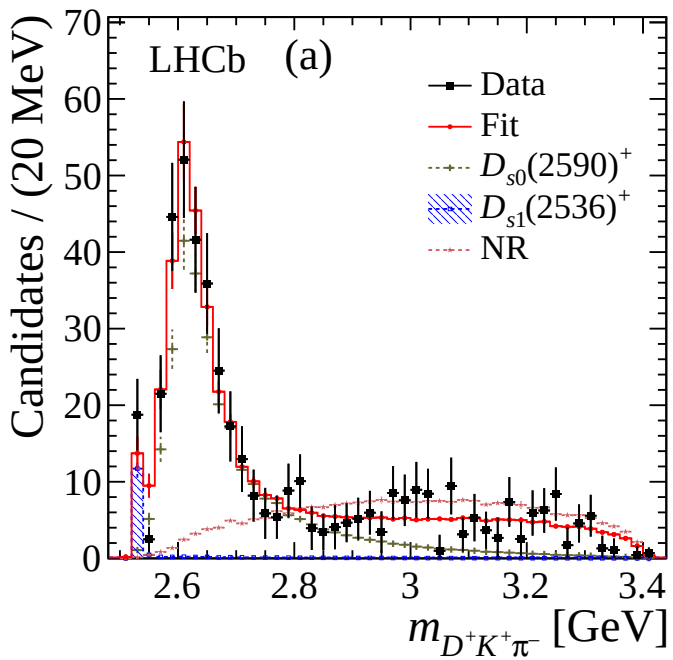
Expanding the zoo



The LHC has had great success in discovering new hadrons, now 59 in total.
Most recently, four new exotics from LHCb - to be presented in full at La Thuile!

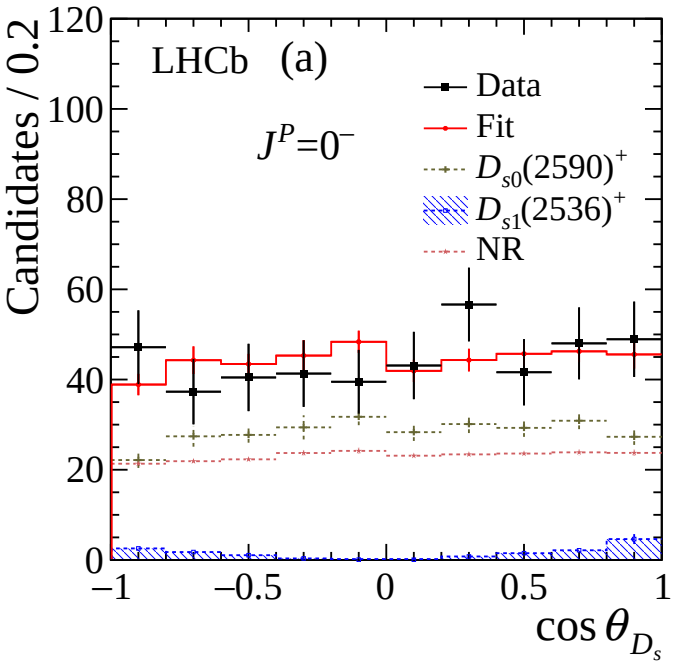
Discovery of $D_{s0}(2590)^+$

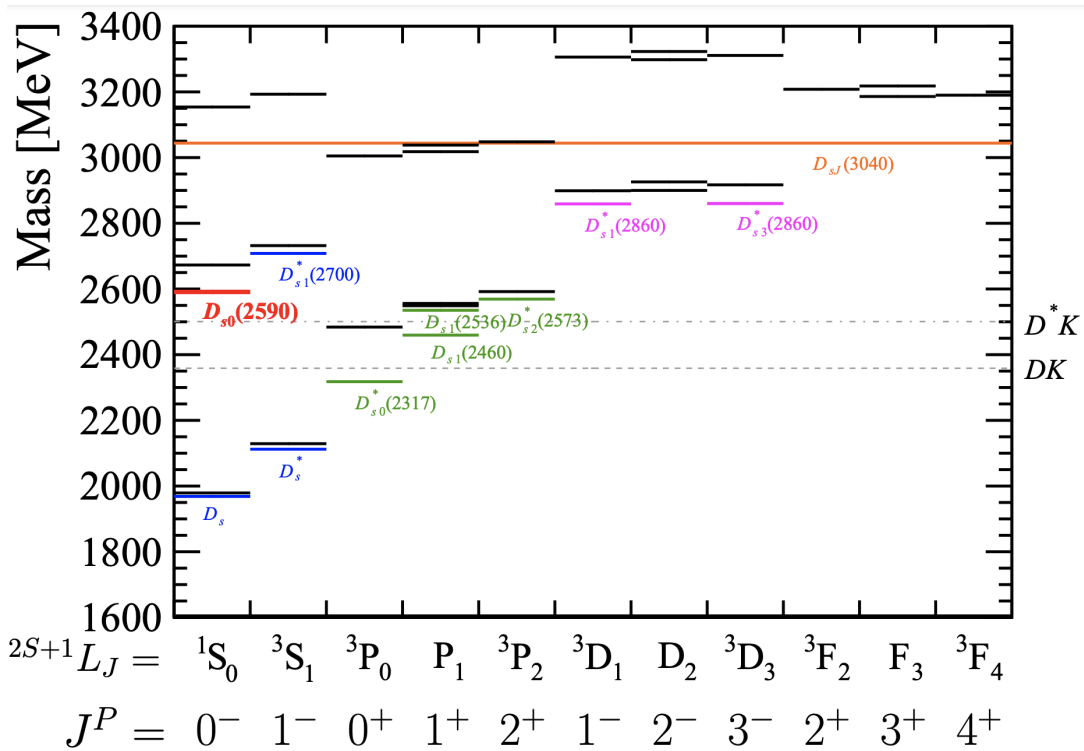
- Many puzzling charm-strange resonances observed, and many predicted but as yet unobserved
- Search for states with unnatural spin-parity decaying to $D^+K^+\pi^-$ by selecting $B^0 \to D^+D^-K^+\pi^-$ candidates with non-resonant $K^+\pi^-$, $m(K^+\pi^-) < m(K^*(892)^0)$
- **Amplitude analysis finds new resonance with:**
  $m_R = 2591 \pm 6 \pm 7\,\mathrm{MeV}$, $\Gamma_R = 89 \pm 16 \pm 12\,\mathrm{MeV}$



Discovery of $D_{s0}(2590)^+$

- Angular distribution consistent with $J^P = 0^-$ and excludes $J^P = 1^+, 2^-$ at $> 10\sigma$
- New state is strong candidate to be the $D_s(2^1S_0)^+$ state - radial excitation of D_s^+



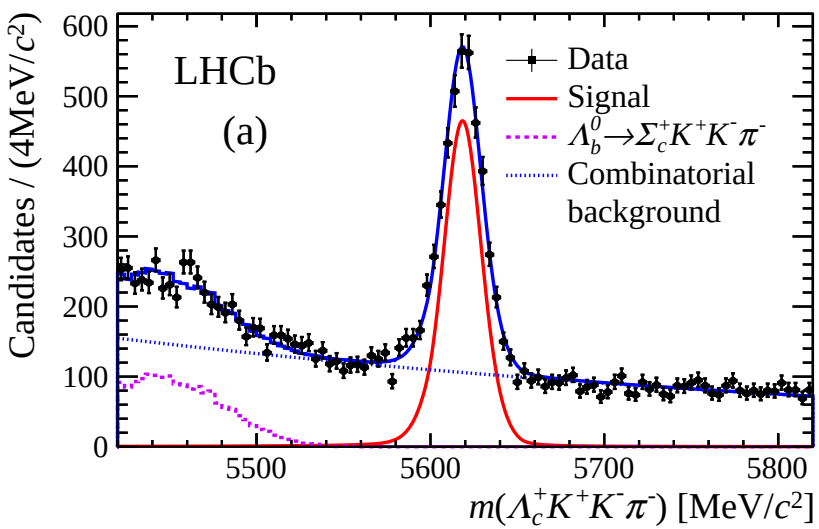


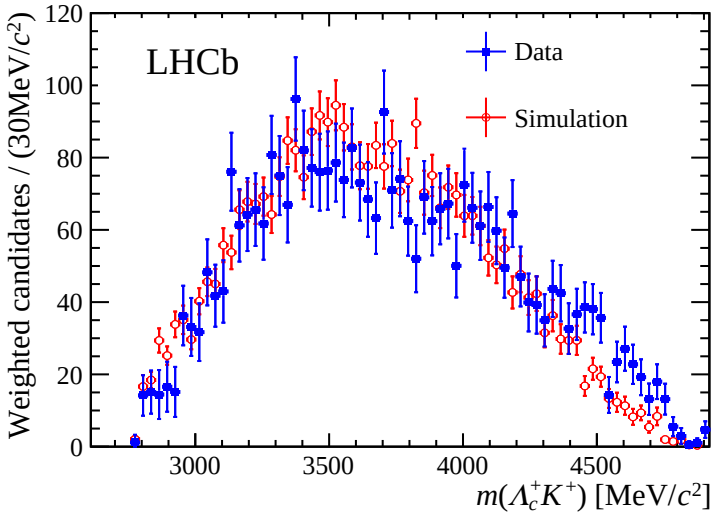
Search for open-charm pentaquarks

- Following discovery of narrow pentaquarks with $c\bar{c}uud$ content, search for $c\bar{s}uud$ pentaquarks in previously unobserved $\Lambda_b^0 \to \Lambda_c^+ K^+ K^- \pi^-$ decays
- **New decay mode observed with high significance, finding**

$$\frac{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ K^+ K^- \pi^-)}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ D_s^-)} = (9.26 \pm 0.29 \pm 0.46 \pm 0.26) \times 10^{-2}$$

  where uncertainties are stat., syst., and from $\sigma(\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ D_s^-))$.
- However, **no structures observed in** $m(\Lambda_c^+ K^+)$



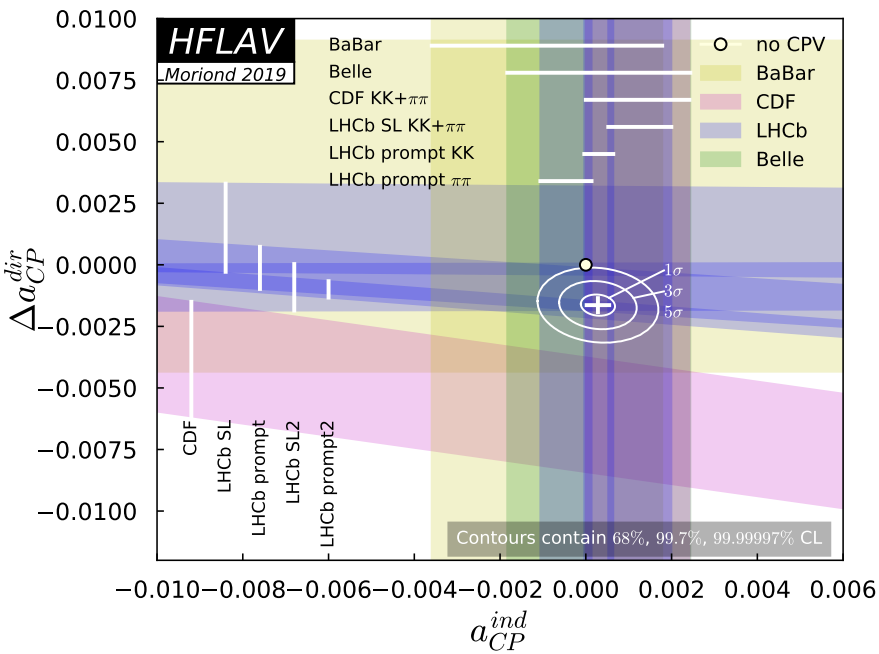


[PRL 122 (2019) 211803]
[HFLAV]

Searches for CP violation in charm

- Discovery of direct CP violation in $D^0 \to K^+K^-, \pi^+\pi^-$ decays in 2019 marked a milestone in flavour physics
- Searches continue in many complementary decay modes in hopes of more discoveries

- Aim to over-constrain the system as for CPV in B decays, understand its nature, and test for inconsistencies
- Time-integrated and time-dependent studies probe different facets of the phenomenology

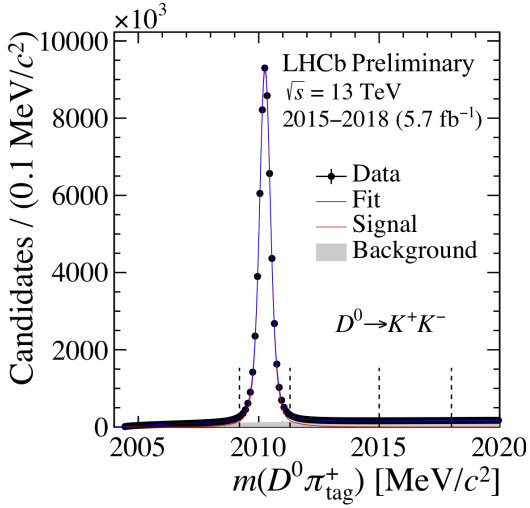


Search for time-dependent CP violation in charm

- Direct CP violation recently observed in charm, but time-dependent CPV remains unseen
- Measurement of CP asymmetry vs time in $D^0 \to K^+K^-, \pi^+\pi^-$ provides high precision probe for new physics, complementary to direct CPV discovery

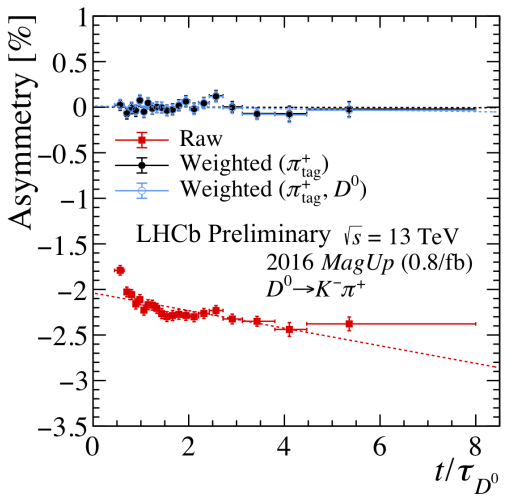
$$A_{CP}(f,t) \approx a_f^d + \Delta Y_f \frac{t}{\tau_{D^0}},$$

$$\Delta Y_f \approx -x_{12} \sin\phi_f^M + y_{12} a_f^d \; (\approx -A_f^\Gamma)$$



- Requires precise control of detection asymmetries
- **Analysis of full Run II sample finds**

$$\Delta Y_{K^+K^-} = (-2.3 \pm 1.5 \pm 0.3) \times 10^{-4},$$
$$\Delta Y_{\pi^+\pi^-} = (-4.0 \pm 2.8 \pm 0.4) \times 10^{-4},$$



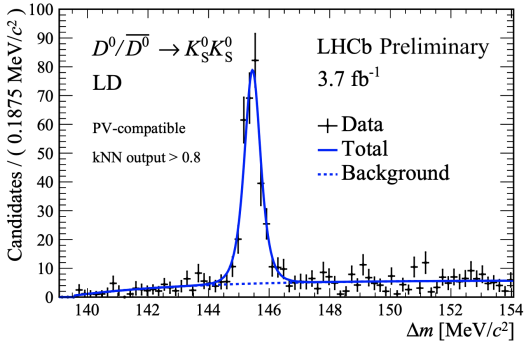
- **No evidence for CPV but $\sim 2\times$ improvement in world average precision**

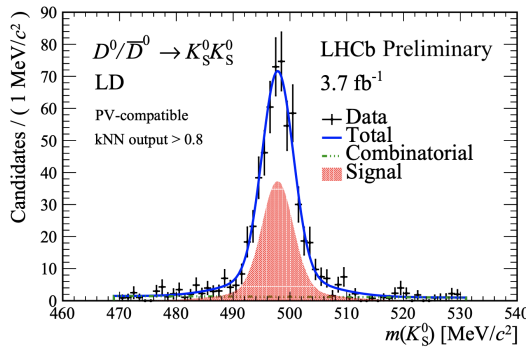
Measurement of CP asymmetry in $D^0 \to K^0_S K^0_S$

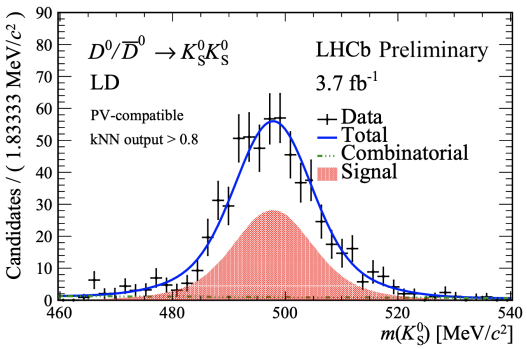
- Decays proceed only via loop-suppressed amplitudes & exchange diagrams - interference can enhance CPV
- Challenging analysis due to long lifetime of K^0_S
- 3D fit to $m(K^0_{S\,1})$, $m(K^0_{S\,2})$ and $\Delta m \equiv m(D^{*+}) - m(D^0)$ required to control backgrounds
- **Analysis of full Run II data finds:**

$$\mathcal{A}_{CP}(D^0 \to K^0_S K^0_S) = (-3.1 \pm 1.2 \pm 0.5 \pm 0.2)\%$$

- **Most precise determination to date, compatible with no CPV at 2.4σ**



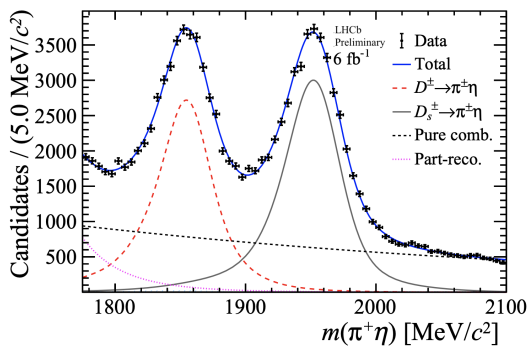


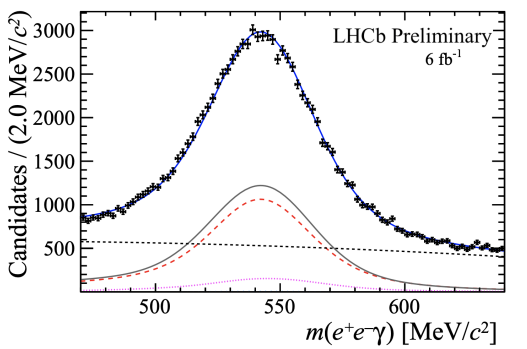


Search for CP violation in $D^+_{(s)} \to h^+ h^0$

- Precise theory predictions afford strong tests of the SM
- Challenging reconstruction: exploit $\pi^0, \eta \to e^+e^-\gamma$ and $\pi^0, \eta \to \gamma(\to e^+e^-)\gamma$ to obtain $D^+_{(s)}$ decay vertex - first analysis to use these modes
- Detection asymmetries controlled using $D^+_{(s)} \to K^0_S h^+$
- **Using Run I (π^0 only) & Run II (π^0 & η) data, find**

$$\mathcal{A}_{CP}(D^+ \to \pi^+\pi^0) = (-1.3 \pm 0.9 \pm 0.6)\%,$$
$$\mathcal{A}_{CP}(D^+ \to K^+\pi^0) = (-3.2 \pm 4.7 \pm 2.1)\%,$$
$$\mathcal{A}_{CP}(D_s^+ \to K^+\pi^0) = (-0.8 \pm 3.9 \pm 1.2)\%,$$
$$\mathcal{A}_{CP}(D^+ \to \pi^+\eta) = (-0.2 \pm 0.8 \pm 0.4)\%,$$
$$\mathcal{A}_{CP}(D_s^+ \to \pi^+\eta) = (0.8 \pm 0.7 \pm 0.5)\%,$$
$$\mathcal{A}_{CP}(D^+ \to K^+\eta) = (-6 \pm 10 \pm 4)\%,$$
$$\mathcal{A}_{CP}(D_s^+ \to K^+\eta) = (0.9 \pm 3.7 \pm 1.1)\%,$$

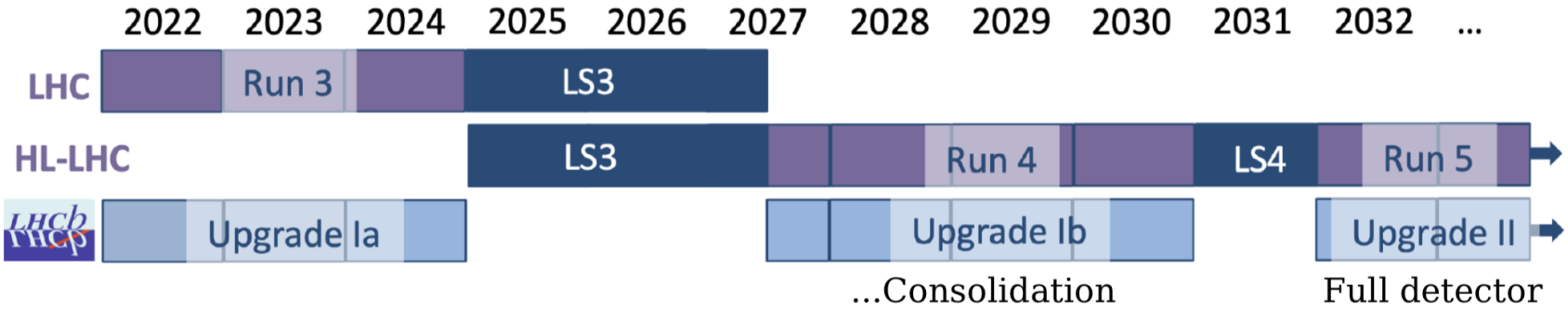




- **No evidence of CPV but most precise measurements to date in these modes**

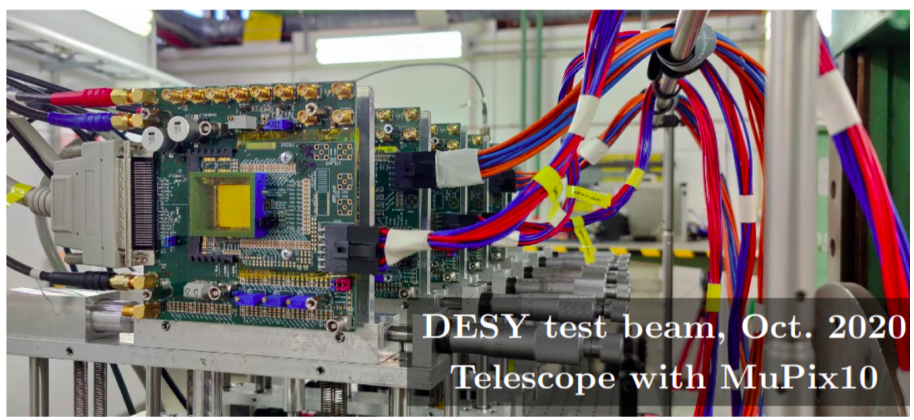
Outline

Upgrade-II



- Installed in LS4 to operate at 1-2$\times 10^{34} cm^{-2} s^{-1}$ and collect $\sim$300 fb^{-1}
- Significant challenges include $\sim$50 ps timing, radiation hardness, & high granularity
- Framework TDR in preparation, to submit to LHCC later this year
- Extensive R&D underway, promising test beam results for ECAL, Mighty Tracker, & VELO

- Preliminary results from test beams with new CMOS chip presented at 9$^{\text{th}}$ Beam Telescopes and Test Beams Workshop



Outline

[LHCB-PAPER-2020-034]
[LHCB-PAPER-2020-045]

Outlook

- Good progress on Upgrade-I construction & installation despite delays due to COVID, however, schedule is tight
- LHCb continues to push the boundaries of flavour physics
  - Wealth of new hadrons discovered
  - CP violation in charm approaching 1×10^{-4} precision
  - Many new results to come for winter conferences
- Upgrade-II will go further by orders of magnitude in the quest to break the SM
- Exciting and challenging times ahead!