LHCb recent results of b baryons

Miroslav Saur
(Peking University)
on behalf of the LHCb collaboration

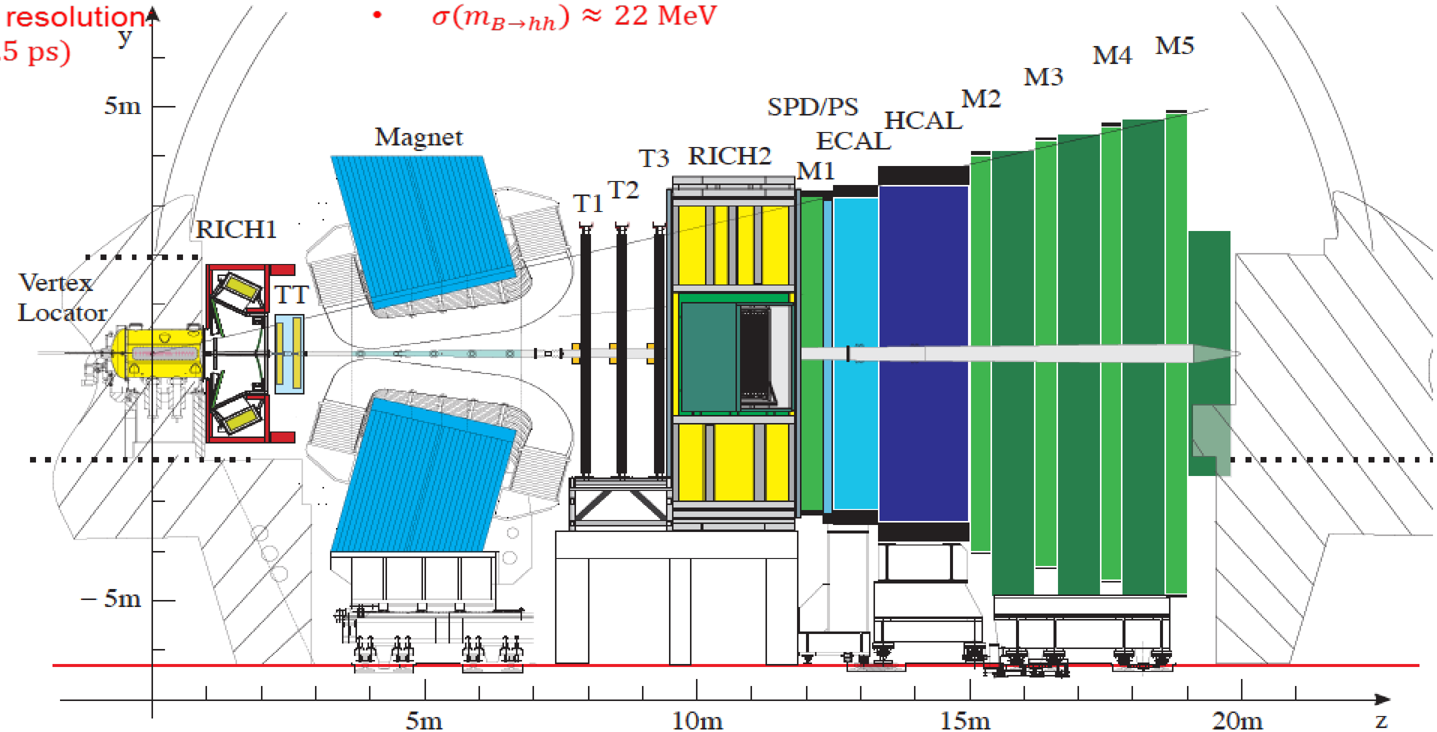
第五届粒子物理天问论坛，长沙
2023/11/12

LHCb detector Run 1 + 2

- General purpose detector in forward region with a special focus on heavy flavour physics
- Successful operation in Run 1 (2010-2012) and 2 (2015-2018), upgraded for Run 3 (2022-2025)

Vertex Locator(vertex reconstruction)
- Impact parameter resolution: 20 µm
- Decay time resolution: 45 fs ($\tau_B \sim 1.5$ ps)

Tracking system(particle reconstruction)
- ϵ(Tracking) ~96%
- $\delta p/p$ ~0.5%-1%(5-200 GeV)
- $\sigma(m_{B\to hh}) \approx 22$ MeV



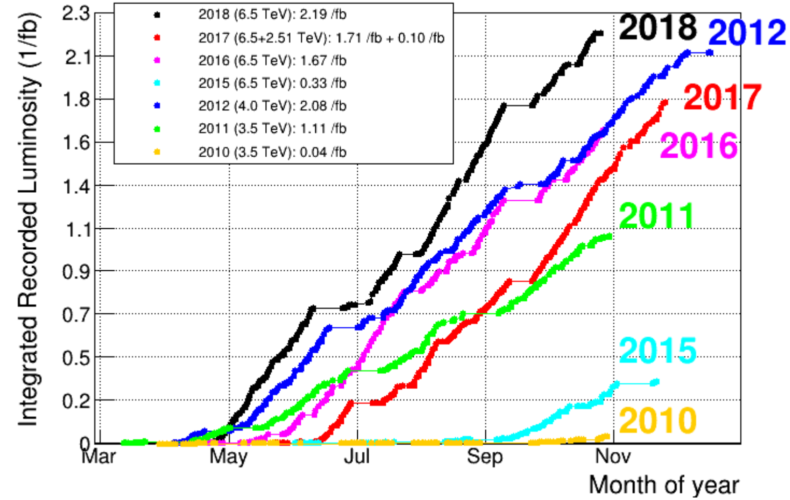
RICH: particle ID
- $\varepsilon(K \to K)$ ~95%
- Mis-ID: $\varepsilon(\pi \to K)$ ~5%

Magnet
- Bending power: 4 Tm

Muon system
- μ ID: $\varepsilon(\mu \to \mu)$ ~97%
- Mis-ID: $\varepsilon(\pi \to \mu)$ ~1-3%

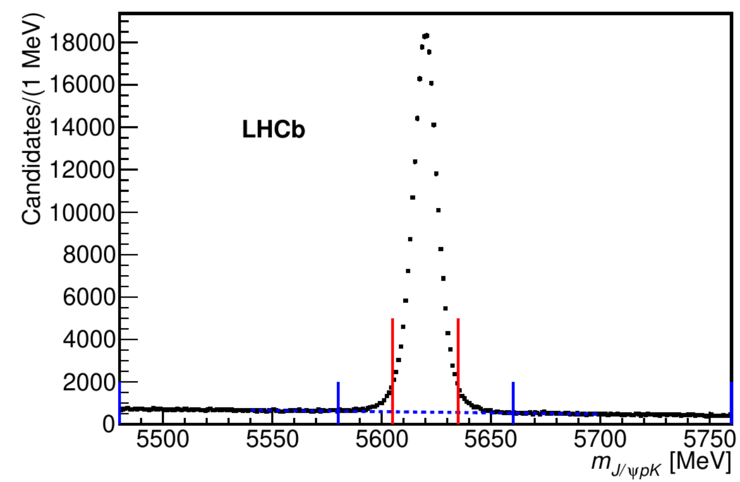
LHCb data

- Successful operation in Run 1 and Run 2
- Annual data-taking efficiency above 90 %
- Various collision systems:
  - pp, p-Pb, Pb-Pb, SMOG (fixed target-like)
- Recorded substantial amount of data
  - Run 1: ~ 3 fb^{-1}
  - Run 2: ~ 6 fb^{-1}



- Largest recorded sample of heavy flavour hadrons
- LHCb historically focused mostly on decays with charged hadrons or muons in the final state
  - Increasing amount of studies involving neutral particles such as π^0 and gamma
  - Progress on electron PID and bremsstrahlung corrections allowing wider usage of electron modes
  - Better understanding o relatively long-lived particles decaying outside of VELO (K^0, Λ^0, ...)

280k $\Lambda_b^0 \to J/\psi p K^-$ (Run1+Run2)



b-baryons at LHCb

- Historically LHCb mainly focused on mesons but interest in baryons is steadily growing
- Broad physics programme involving b-baryons which can be divided into three main categories:
  - Spectroscopy and production measurements
  - Electroweak penguin-governed and rare decays
  - CP violation measurements
- All results available at public LHCb webpage
- Due to a limited time this talk will focus only on a selected set of some (relatively) recent results

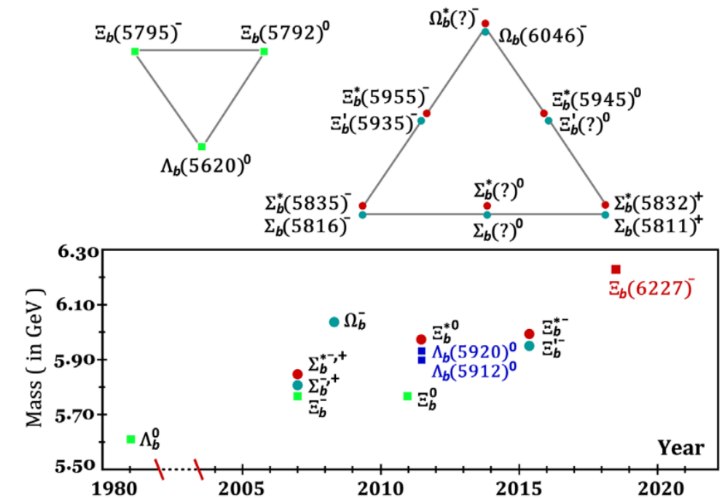
- Selected spectroscopy measurements:
  - Observation of New Baryons in the $\Xi_b^- \pi^+ \pi^-$ and $\Xi_b^0 \pi^+ \pi^-$ Systems [PRL 131 (2023) 171901]
  - Measurement of the mass difference and relative production rate of the Ω_b^- and Ξ_b^- baryons [2305.15329]
- Selected EW and rare decays:
  - Measurement of the $\Lambda_b^0 \to \Lambda(1520)\mu^+\mu^-$ Differential Branching Fraction [PRL 131 (2023) 151801]
  - Measurement of the photon polarization in $\Lambda_b^0 \to \Lambda^0\gamma$ decays [PRD 105 (2022) L051104]
- Selected CP violation measurements:
  - Observation of the suppressed $\Lambda_b^0 \to DpK^-$ decay with $D^0 \to K^+\pi^-$ and measurement of its CP asymmetry [PRD 104 (2021) 112008]
  - Search for CP violation in $\Xi_b^- \to pK^-K^-$ decays [PRD 104 (2021) 052010]

Spectroscopy measurements

Observation of New Baryons in the $\Xi_b^-\pi^+\pi^-$ and $\Xi_b^0\pi^+\pi^-$

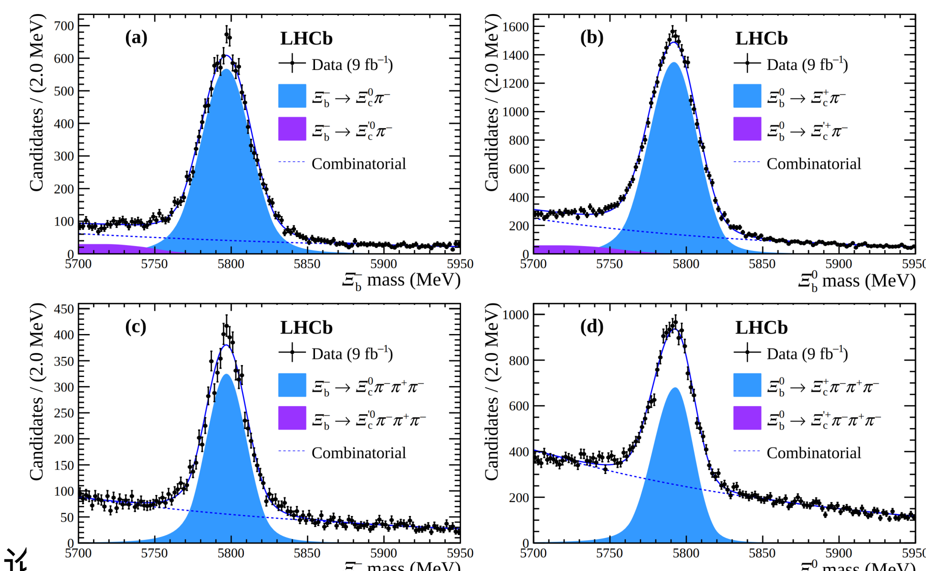
PRL 131 (2023) 171901

- $\Xi_b^{0/-}$ baryons form an isospin doublet (bsu, bsd)
  - The ground states have L=0 between b-quark and lighter sq diquark
  - Three isospin doublets of such non-excited states are expected
  - $\Xi_b'^0$ still unobserved (possibly below $\Xi_b^-\pi^+$ threshold)



PRD 98 (2018) 031502

- First investigation in LHCb of the final states $\Xi_b^-\pi^+\pi^-$ and $\Xi_b^0\pi^+\pi^-$
  - Based on full Run 1 + Run 2 LHCb data set
  - Ξ_b^0 reconstructed as $\Xi_c^+\pi^-$ or $\Xi_c^+\pi^-\pi^+\pi^-$
  - Ξ_b^- reconstructed as $\Xi_c^0\pi^-$ or $\Xi_c^0\pi^-\pi^+\pi^-$

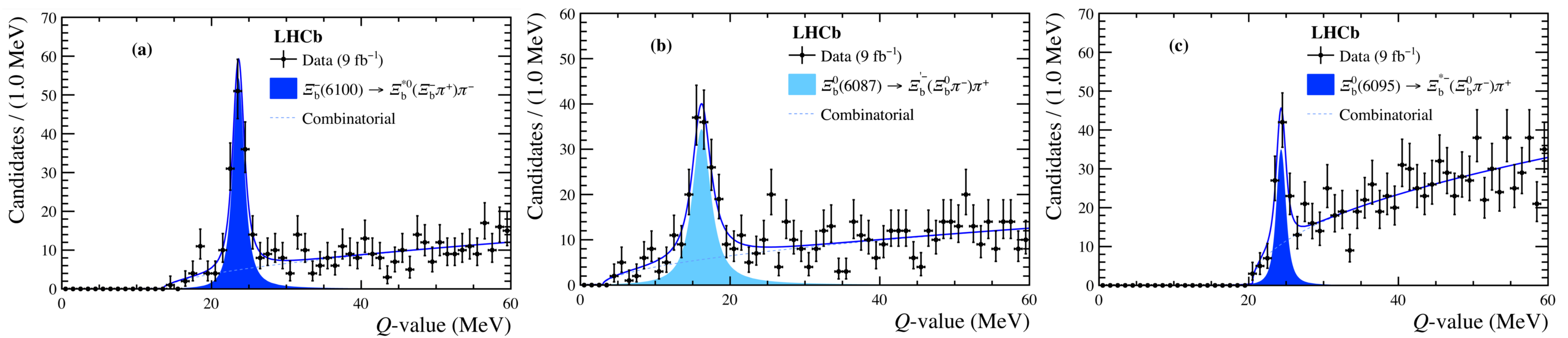


PRL 131 (2023) 171901

Observation of New Baryons in the $\Xi_b^-\pi^+\pi^-$ and $\Xi_b^0\pi^+\pi^-$

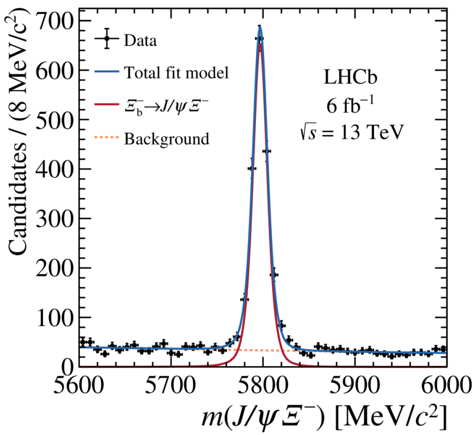
- Two new narrow states observed in $\Xi_b^-\pi^+\pi^-$ and $\Xi_b^0\pi^+\pi^-$ spectrum
  - Ξ_b^0 (6087) and Ξ_b^0(6095)
  - Ξ_b^- (6100) confirmed (first observation by CMS)
- Mass difference (Q value) fitted in order to cancel resolution effects
  - Signal model consists of Double Crystall Ball and relativistic BW
  - Partially reconstructed candidates from possible higher-mass resonances taken into account
- Analysis is statistically dominated, improvement expected with Run 3 data

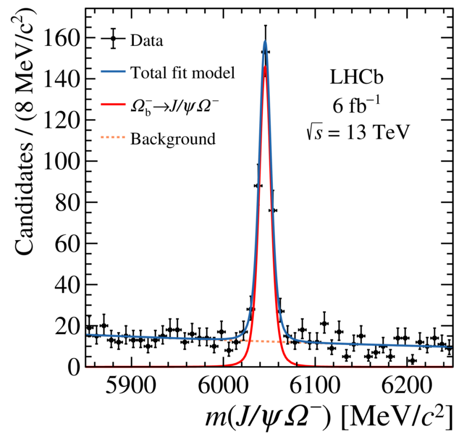
State	Observ.	Value (MeV)
$\Xi_b(6100)^-$	Q_0	$23.6 \pm 0.11 \pm 0.02$
	Γ	$0.94 \pm 0.30 \pm 0.08$
	m_0	$6099.74 \pm 0.11 \pm 0.02 \pm 0.6\ (\Xi_b^-)$
$\Xi_b(6087)^0$	Q_0	$16.20 \pm 0.20 \pm 0.06$
	Γ	$2.43 \pm 0.51 \pm 0.10$
	m_0	$6087.24 \pm 0.20 \pm 0.06 \pm 0.5\ (\Xi_b^0)$
$\Xi_b(6095)^0$	Q_0	$24.32 \pm 0.15 \pm 0.03$
	Γ	$0.50 \pm 0.33 \pm 0.11$
	m_0	$6095.36 \pm 0.15 \pm 0.03 \pm 0.5\ (\Xi_b^0)$



Relative production rate of the Ω_b^- and Ξ_b^- baryons

- From the weakly-decaying ground states of b-baryons, the Ω_b^- baryon is the least studied
  - Relative production rate measured at Tevatron, had to be updated for LHCb
- Measurement based on Run 2 data
- Very clean signal sample obtained for both studied channels: $\Xi_b^- \to J/\psi \Xi^-$, $\Omega_b^- \to J/\psi \Omega^-$





Source	Uncertainty [%]
Size of simulated samples	0.3
Calibration of simulation	5.5
Selection criteria	0.1
Lifetimes of b baryons	3.1
Material interactions	0.7
Fit model	0.8
External input ($\mathcal{B}$)	1.0
Total	6.5

- Production ratio defined as: $R \equiv \frac{f_{\Omega_b^-}}{f_{\Xi_b^-}} \times \frac{\mathcal{B}(\Omega_b^- \to J/\psi \Omega^-)}{\mathcal{B}(\Xi_b^- \to J/\psi \Xi^-)} \approx R = \frac{N(\Omega_b^- \to J/\psi \Omega^-)}{N(\Xi_b^- \to J/\psi \Xi^-)} \times \frac{\epsilon(\Xi_b^- \to J/\psi \Xi^-)}{\epsilon(\Omega_b^- \to J/\psi \Omega^-)} \times \frac{\mathcal{B}(\Xi^- \to \Lambda \pi^-)}{\mathcal{B}(\Omega^- \to \Lambda K^-)}$
  - Limited knowledge of $f_{\Omega_b^-}/f_{\Xi_b^-}$, further theoretical input needed
  - Large differences in BFs predictions [PRD56 2799, PRD98 074011, PRD105 056015]
- Obtained ratio: $R = 0.120 \pm 0.008\,(\text{stat}) \pm 0.008\,(\text{syst})$
  - Slightly below previous Tevatron results: $R = 0.27 \pm 0.12\,(\text{stat}) \pm 0.01\,(\text{syst})$ [PRD 80 072003]

arXiv: 2305.15329

Mass difference between the Ω_b^- and Ξ_b^- baryons

- Using full Run 1 + Run 2 data
- Mass difference between the Ω_b^- and Ξ_b^- baryons used to reduce systematic uncertainties
- LHCb measurement of Ξ_b^- mass used: $m(\Xi_b^-) = 5797.33 \pm 0.24 \pm 0.29\,\mathrm{MeV}/c^2$ [PRD 103 012004]
- Obtained results:

$$m(\Omega_b^-) - m(\Xi_b^-) = 248.54 \pm 0.51\,(\mathrm{stat}) \pm 0.38\,(\mathrm{syst})\,\mathrm{MeV}/c^2$$

$$m(\Omega_b^-) = 6045.9 \pm 0.5\,(\mathrm{stat}) \pm 0.6\,(\mathrm{syst})\,\mathrm{MeV}/c^2$$

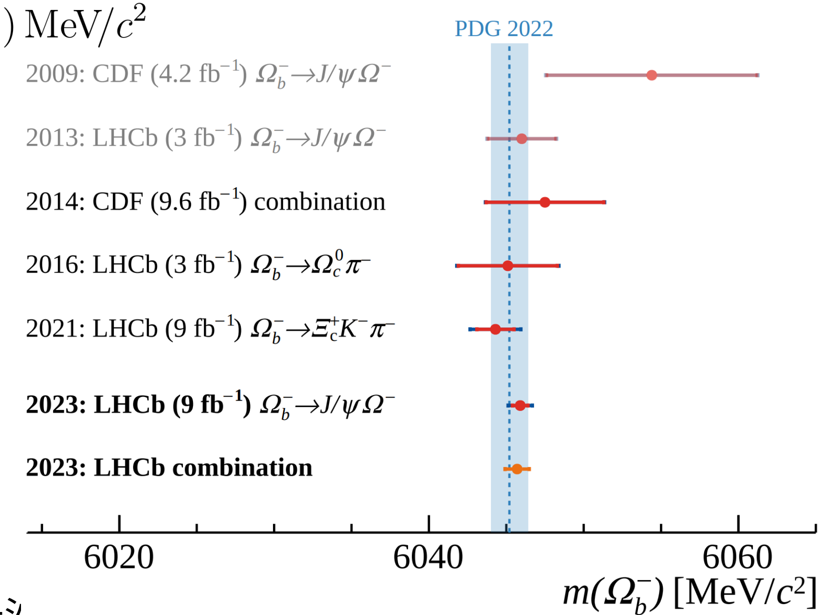
Source	Uncertainty [MeV/c^2]
Momentum scale	0.09
dE/dx correction	0.01
Hyperon mass	0.35
$\Lambda_b^0 \to J/\psi \Lambda$ background	0.10
Fit bias	0.06
Full fit model	0.01
Total	0.38

- Mass difference combined with previous LHCb results [PRD 93 092007]:

$$[m(\Omega_b^-) - m(\Xi_b^-)]_{\mathrm{LHCb\ comb}} = 248.50 \pm 0.51\,(\mathrm{stat}) \pm 0.37\,(\mathrm{syst})\,\mathrm{MeV}/c^2$$

- Full LHCb combination on Ω_b^- mass

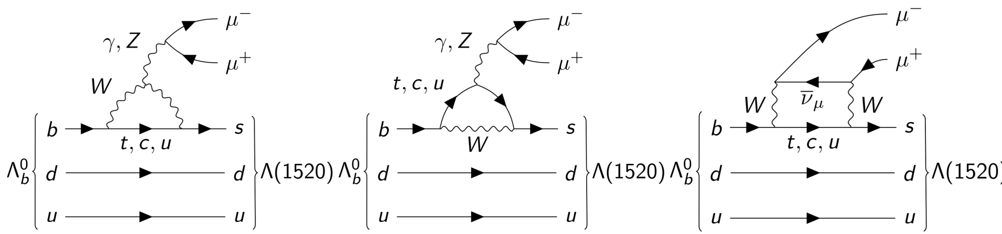
$$m(\Omega_b^-)_{\mathrm{LHCb\ comb}} = 6045.7 \pm 0.5\,(\mathrm{stat}) \pm 0.6\,(\mathrm{syst})\,\mathrm{MeV}/c^2$$



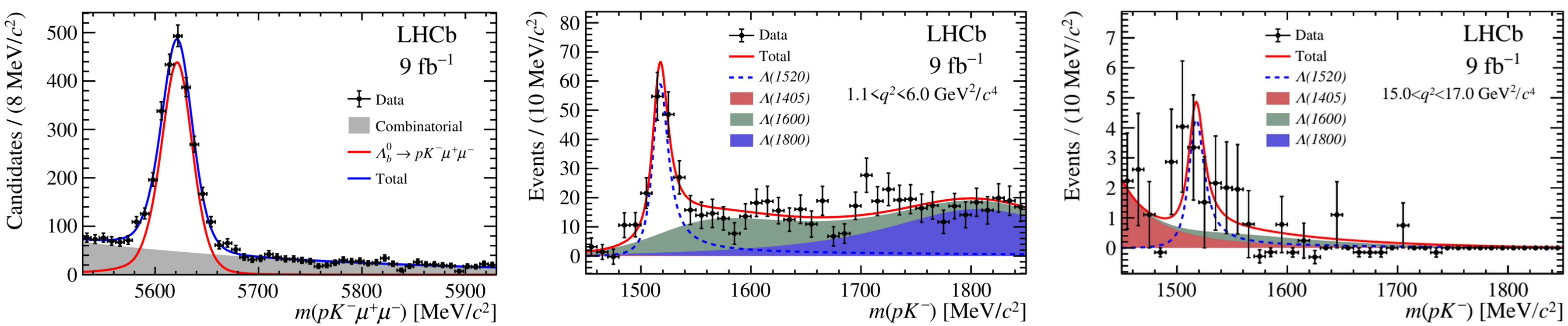
EW and rare decays

Λ_b^0 -> $\Lambda(1520)\mu^+\mu^-$ Differential Branching Fraction

- Rise of b-anomalies in decays of B mesons prompted to check baryonic decays as well
  - Due to non-zero spin, baryon decays carry additional helicity information
- Λ_b^0 -> $\Lambda(1520)\mu^+\mu^-$ is an example of Flavour Changing Neutral Current (FCNC) b -> sll process
  - Governed by a electroweak loop in SM, high sensitivity for various BSM models expected

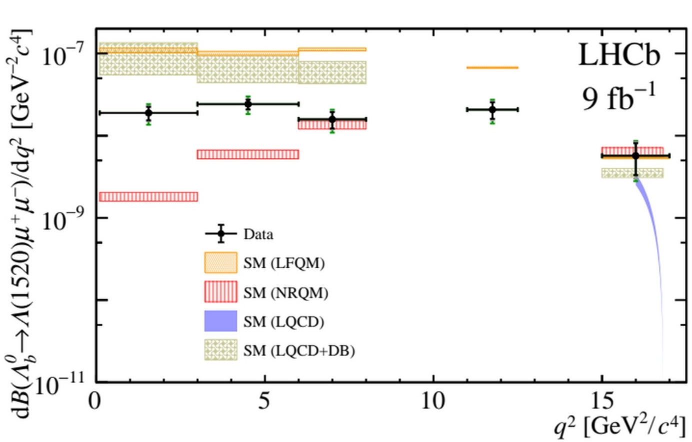


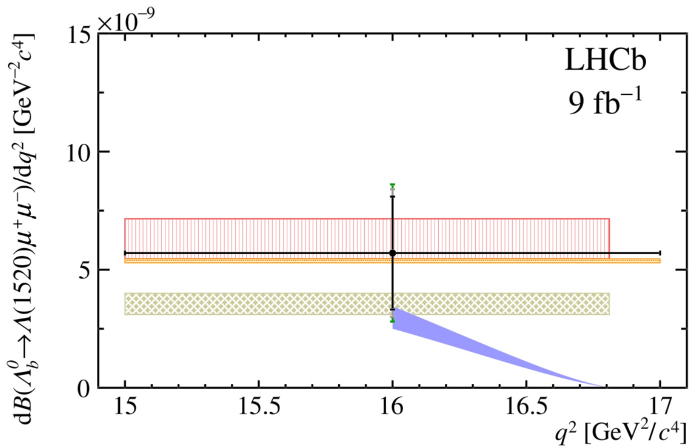
- Study based on full Run 1 + Run 2 data sample
- Several q2 bins studied: [0.1-3.0], [3.0-6.0], [6.0-8.0], [11.0-12.5], [15.0-17.0], [1.1-6.0]

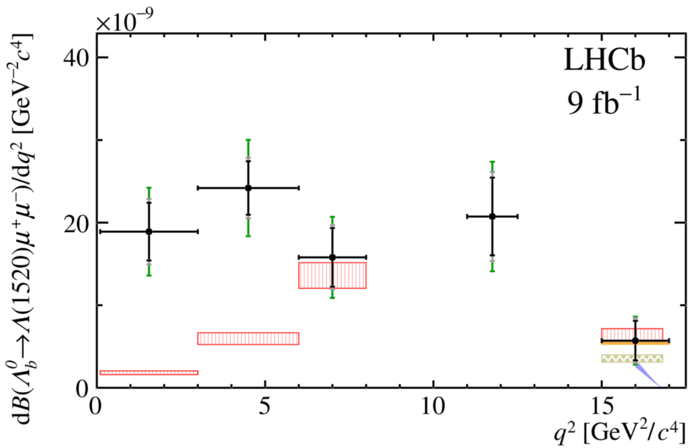


$\Lambda_b^0 \to \Lambda(1520)\mu^+\mu^-$ Differential Branching Fraction

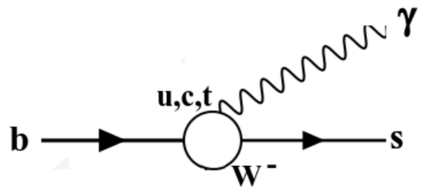
- Obtained differential branching fraction compared with various theory predictions:
  - Light-front quark model (LQFM) [PRD 107 (2023) 093003]
  - SM with nonrelativistic quark model form factor unc. (NRQM) JHEP 06 (2019) 136
  - Lattice QCD (LQCD), available only for $q^2 > 16$ GeV^2/c^4 [PRD 105 (2022) 054511]
  - Joint lattice QCD and dispersive bound (LQCD+DB) [J. High Energ. Phys. 2023, 10]
- Bin at $q^2 > 15$ GeV^2/c^4 has the lowest model-dependency and results are consistent with the theory
- Results at lower q^2 bins are inconclusive due to very large spread of SM predictions



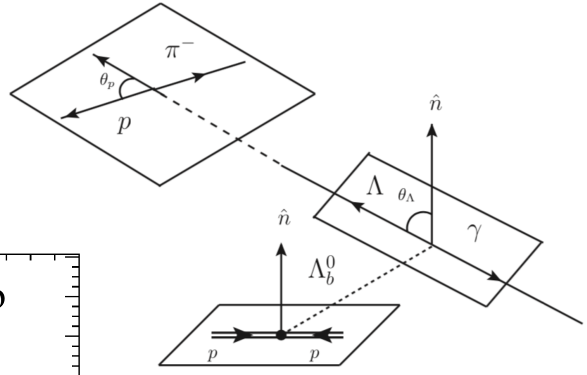


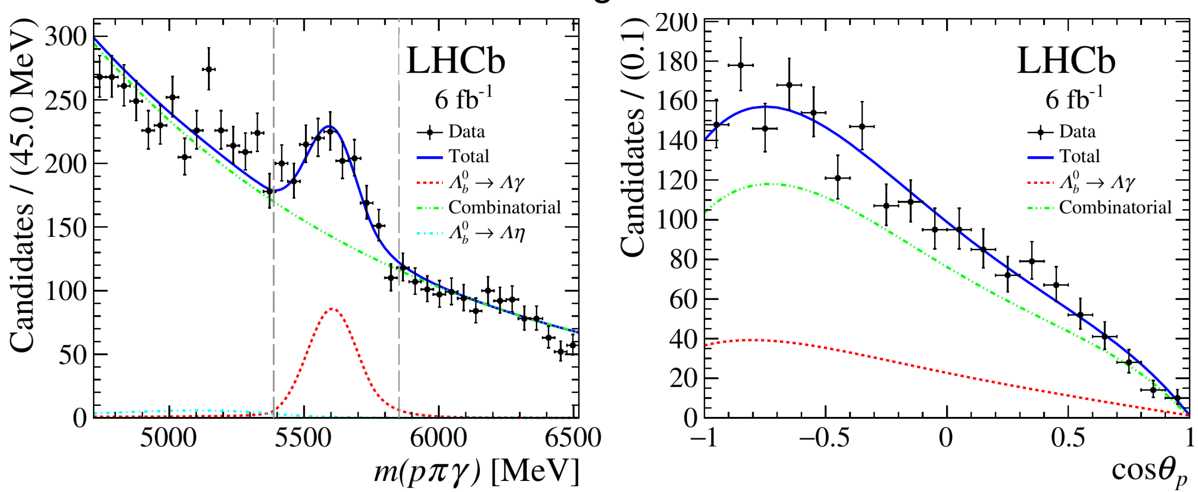


Photon polarization in $\Lambda_b^0 \to \Lambda^0\gamma$ decays



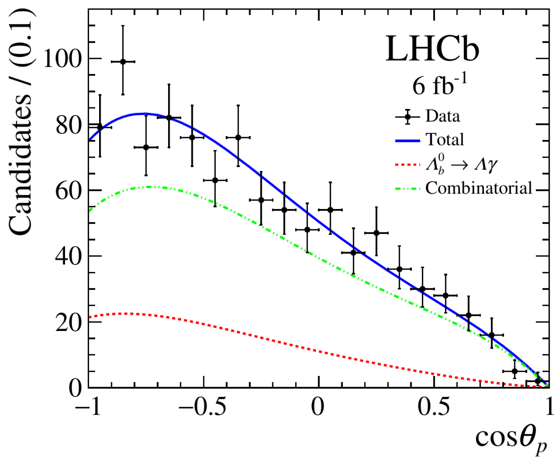
- Another example of FCNC process is a radiative transition b -> sγ
  - Photons expected to be predominantly left-handed in the SM (photons from b-bar would be right-handed, possible to check CP asymmetry)
  - Dedicated study thus could probe the existence of right-handed currents
- Beneficial to study in baryons compared to spinless mesons
- The value of interest is the photon polarization asymmetry (α_γ) defined as: $\alpha_\gamma = \frac{\gamma_L - \gamma_R}{\gamma_L + \gamma_R}$
  - Asymmetry expected to be equal to 1 within SM
- The observable distribution is then given as: $\frac{d\Gamma}{d(\cos\theta_p)} \propto 1 - \alpha_\gamma \alpha_\Lambda \cos\theta_p$
  - Λ_b^0 is expected to be unpolarised at LHC
- Analysis is based on Run 2 data: 440 ± 40 signal candidates

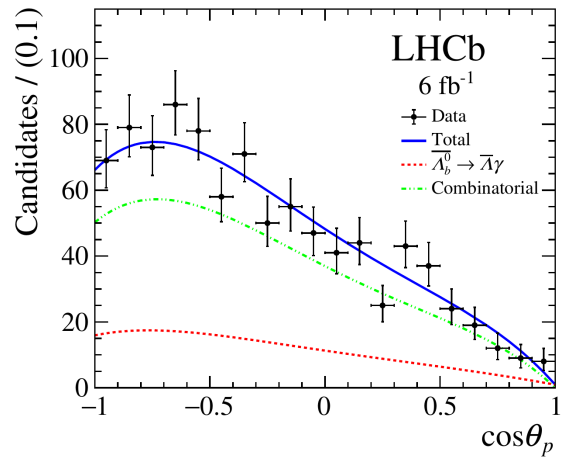




Photon polarization in $\Lambda_b^0 \to \Lambda^0\gamma$ decays

- Angular distribution for Λ_b^0 and for Λ_b^0-bar



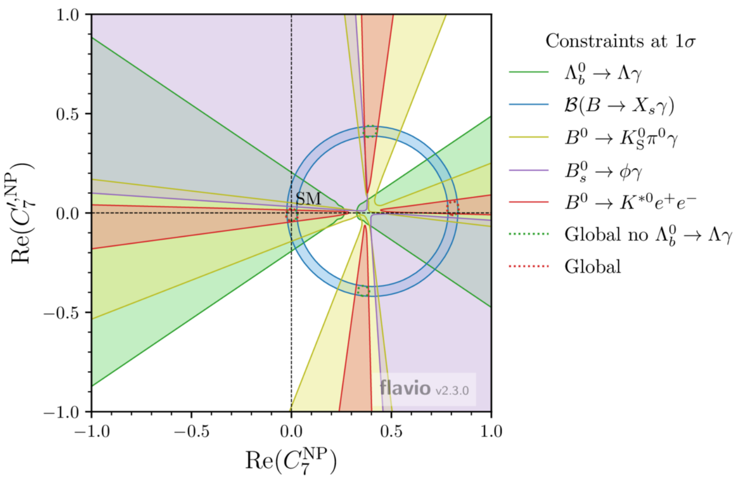


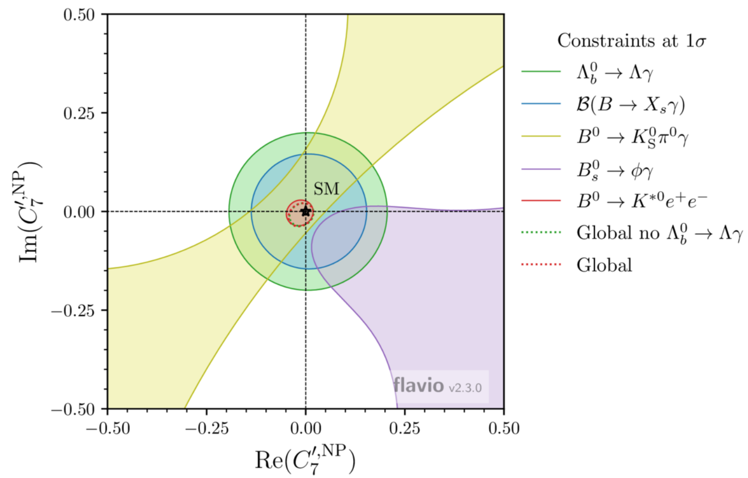
$$\alpha_\gamma = 0.82\,^{+0.17}_{-0.26}\,(\text{stat.})\,^{+0.04}_{-0.13}\,(\text{syst.})$$

$$\alpha_\gamma^- > 0.56\ (0.44)\ \text{at}\ 90\%\ (95\%)\ \text{CL}$$

$$\alpha_\gamma^+ = -0.56\,^{+0.36}_{-0.33}\,(\text{stat.})\,^{+0.16}_{-0.09}\,(\text{syst.})$$

- Additionally, Wilson coefficients C_7 and C'_7 can be constrained

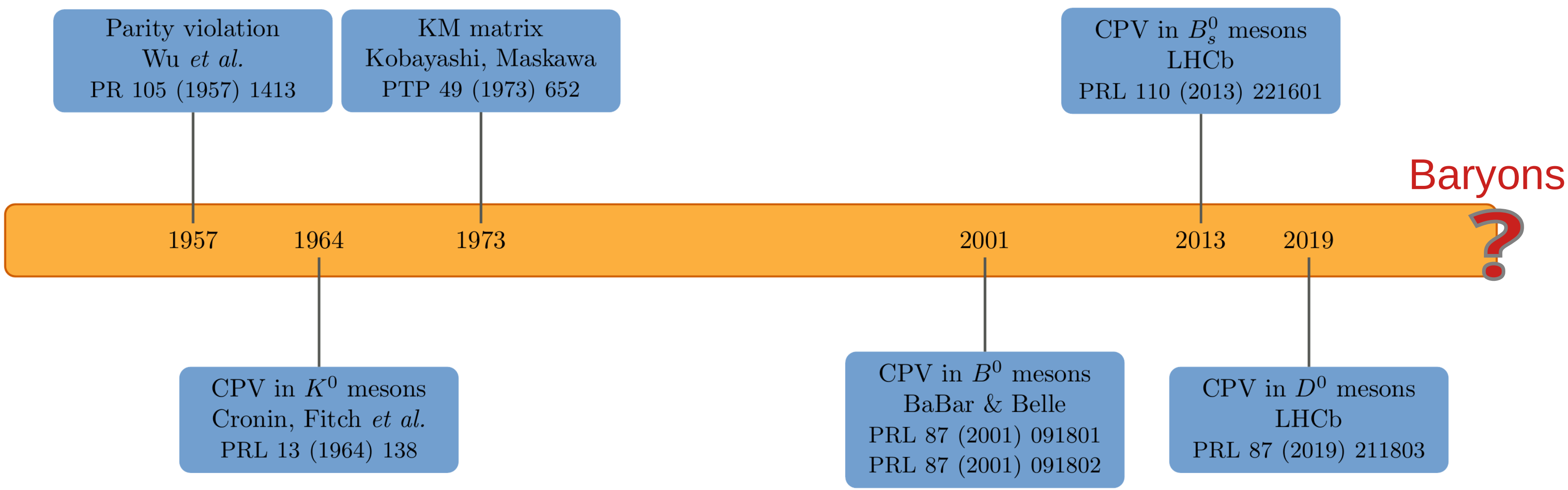




CP violation measurements

Search for CP asymmetry in baryon sector at LHCb

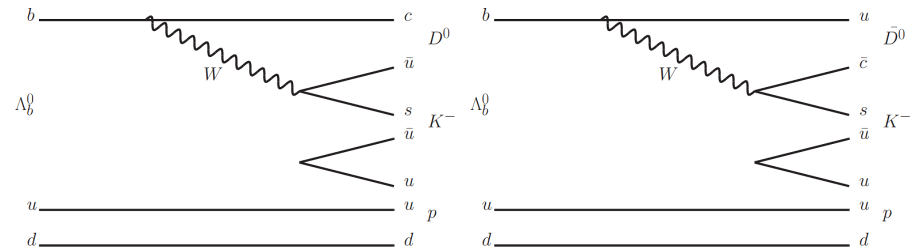
- The question of CP violation in baryon sector remains one of the main open question within SM
- Required for Baryonic asymmetry of Universe but never experimentally observed!
  - First evidence of CP violation in difference of $\Lambda_b^0 \to p\pi^+\pi^-\pi^-$ and $\Lambda_b^0 \to p\pi^- K^- K^+$ [Nature Physics 13 (2017) 391] not confirmed with additional data
  - So far only P-violation observed in decays of $\Lambda_b^0 \to p\pi^+\pi^-\pi^-$ [PRD 102 (2020) 051101]
- Practically all searches are statistically limited
  - Especially problematic for methods looking for a local asymmetries

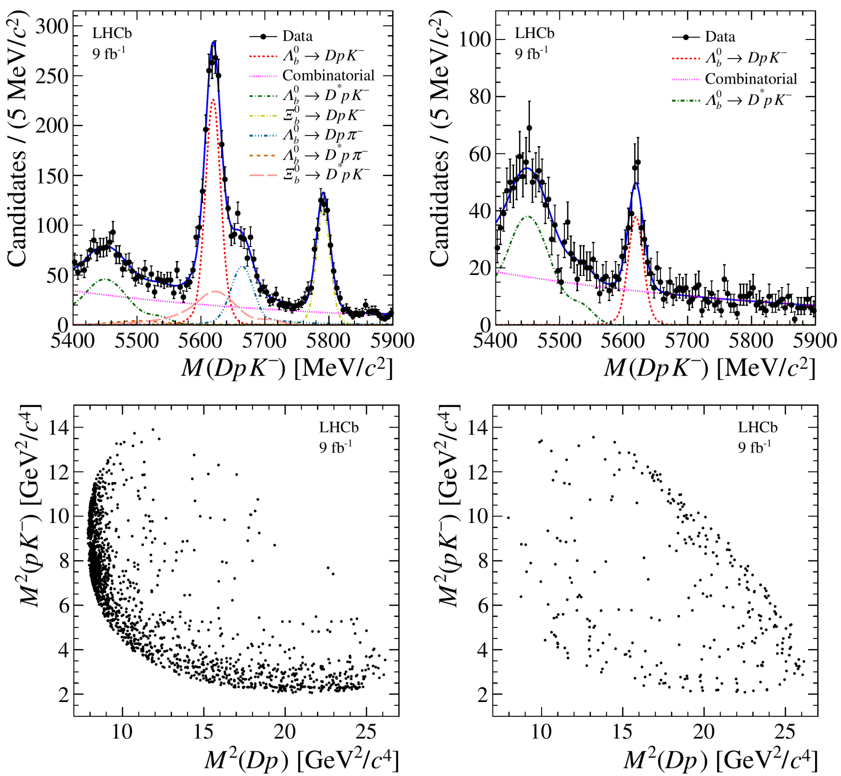


PRD 104 (2021) 112008

Observation of the Λb0 -> DpK⁻ decay and CP asymmetry

- The main goal of analysis is to study Λb0 -> $p[K^+\pi^-]_D K^-$ relative to $\Lambda_b^0 \to p[K^-\pi^+]_D K^-$ as ratio R
  - Analysis based on full Run 1 + Run 2 data sample
- Suppressed Λb0 -> $p[K^+\pi^-]_D K^-$ observed for the first time





$$R = 7.1 \pm 0.8\,(\text{stat.})^{+0.4}_{-0.3}\,(\text{syst.})$$

- CP asymmetry is defined as

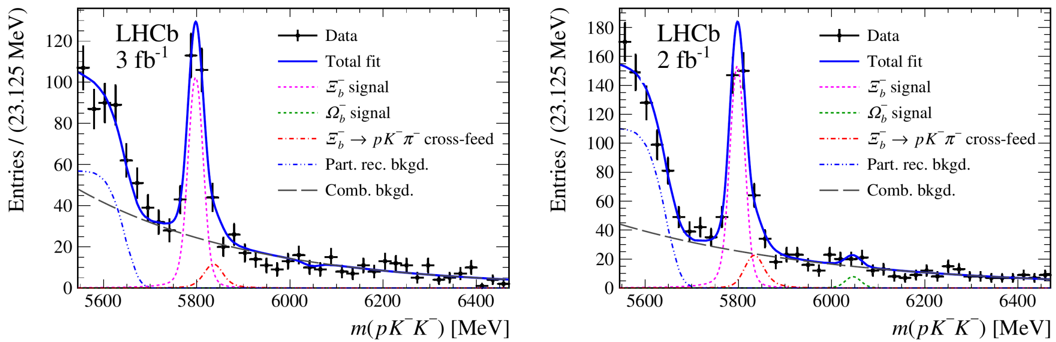
$$A = \frac{\mathcal{B}(\Lambda_b^0 \to [K^+\pi^-]_D p K^-) - \mathcal{B}(\bar{\Lambda}_b^0 \to [K^-\pi^+]_D \bar{p} K^+)}{\mathcal{B}(\Lambda_b^0 \to [K^+\pi^-]_D p K^-) + \mathcal{B}(\bar{\Lambda}_b^0 \to [K^-\pi^+]_D \bar{p} K^+)}$$

- Studied in a full phase space and M(pK) < 5 GeV²/c⁴ where larger sensitivity to angle γ is expected
- Full phase space: $A = 0.12 \pm 0.09\,(\text{stat.})^{+0.02}_{-0.03}\,(\text{syst.})$
- Restricted phase space: $A = 0.01 \pm 0.16\,(\text{stat.})^{+0.03}_{-0.02}\,(\text{syst.})$
- Compatible with no CP asymmetry in both cases
- Measurement is statistically limited and it is not possible to extract angle γ

PRD 104 (2021) 052010

Search for CP violation in $\Xi_b^- \to pK^-K^-$ decays

- Charmless decays are considered to be the most promising place where to search for CP violation
- The first amplitude analysis of $\Xi_b^- \to pK^-K^-$ based on combined data from Run 1 and 2015+2016

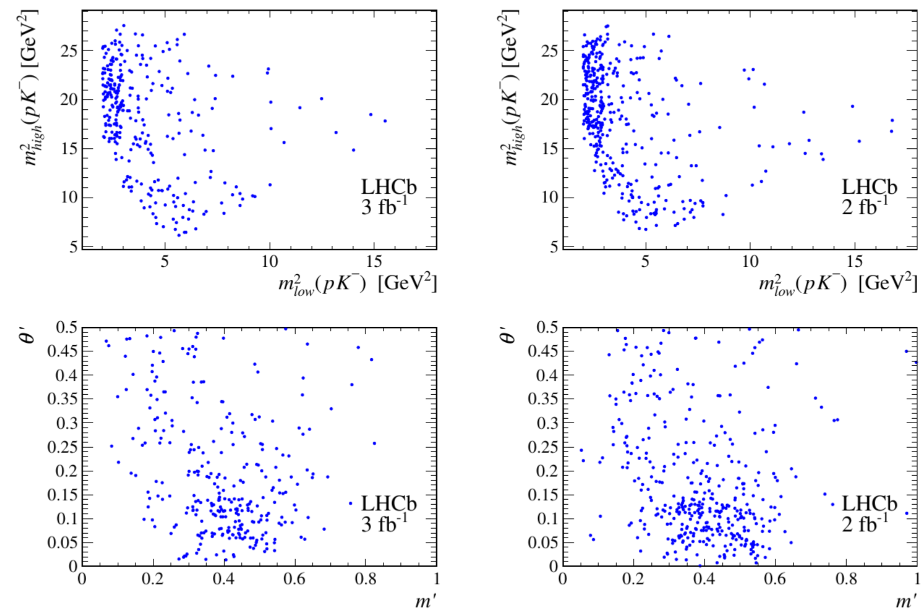


Parameter	Run 1	Run 2
$\Xi_b^- \to pK^-K^-$ yield	193 ± 21	297 ± 23
$\Omega_b^- \to pK^-K^-$ yield	-4 ± 6	15 ± 9
Partially reconstructed background yield	231 ± 34	442 ± 36
Combinatorial background yield	721 ± 50	775 ± 51

- For amplitude analysis is useful to use so-called "square" Dalitz plot variables defined as:

$$\theta' = \frac{1}{\pi}\theta(K^-K^-)$$

$$m' = \frac{1}{\pi}\arccos\left(2\frac{m(K^-K^-) - m_{\min}(K^-K^-)}{m_{\max}(K^-K^-) - m_{\min}(K^-K^-)}\right)$$



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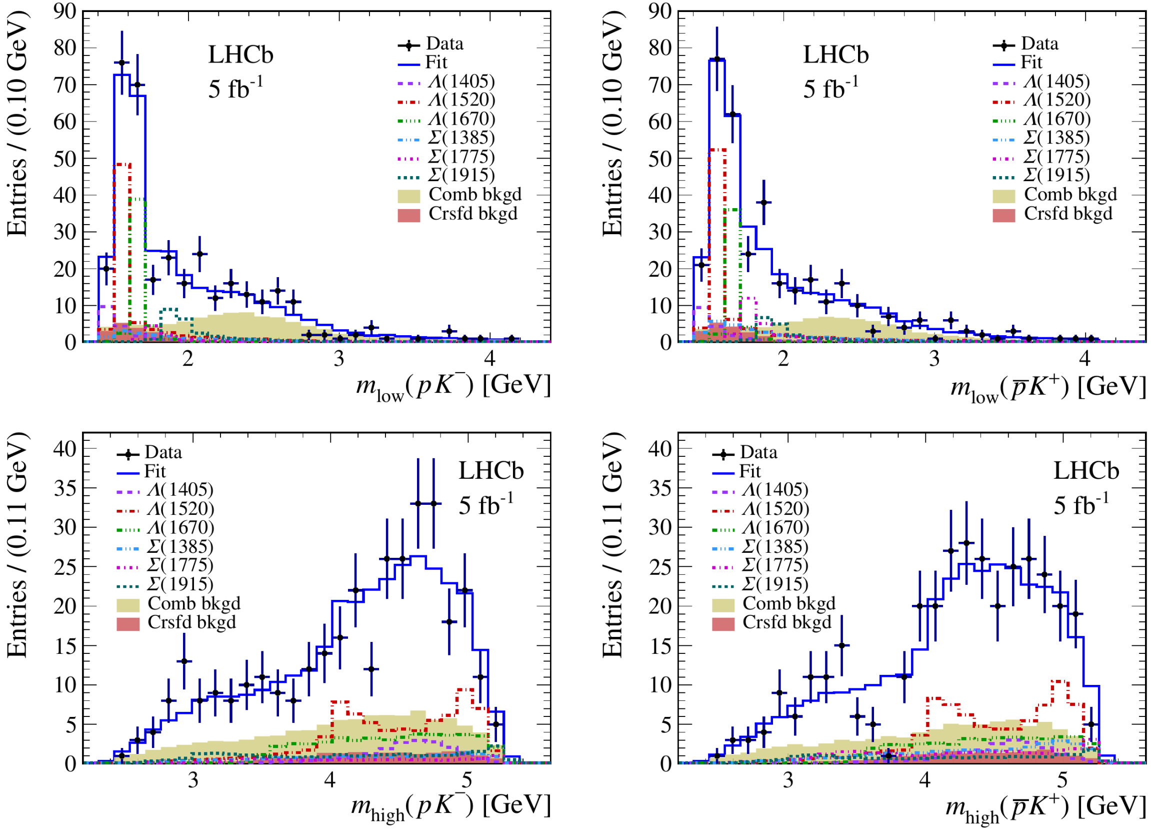


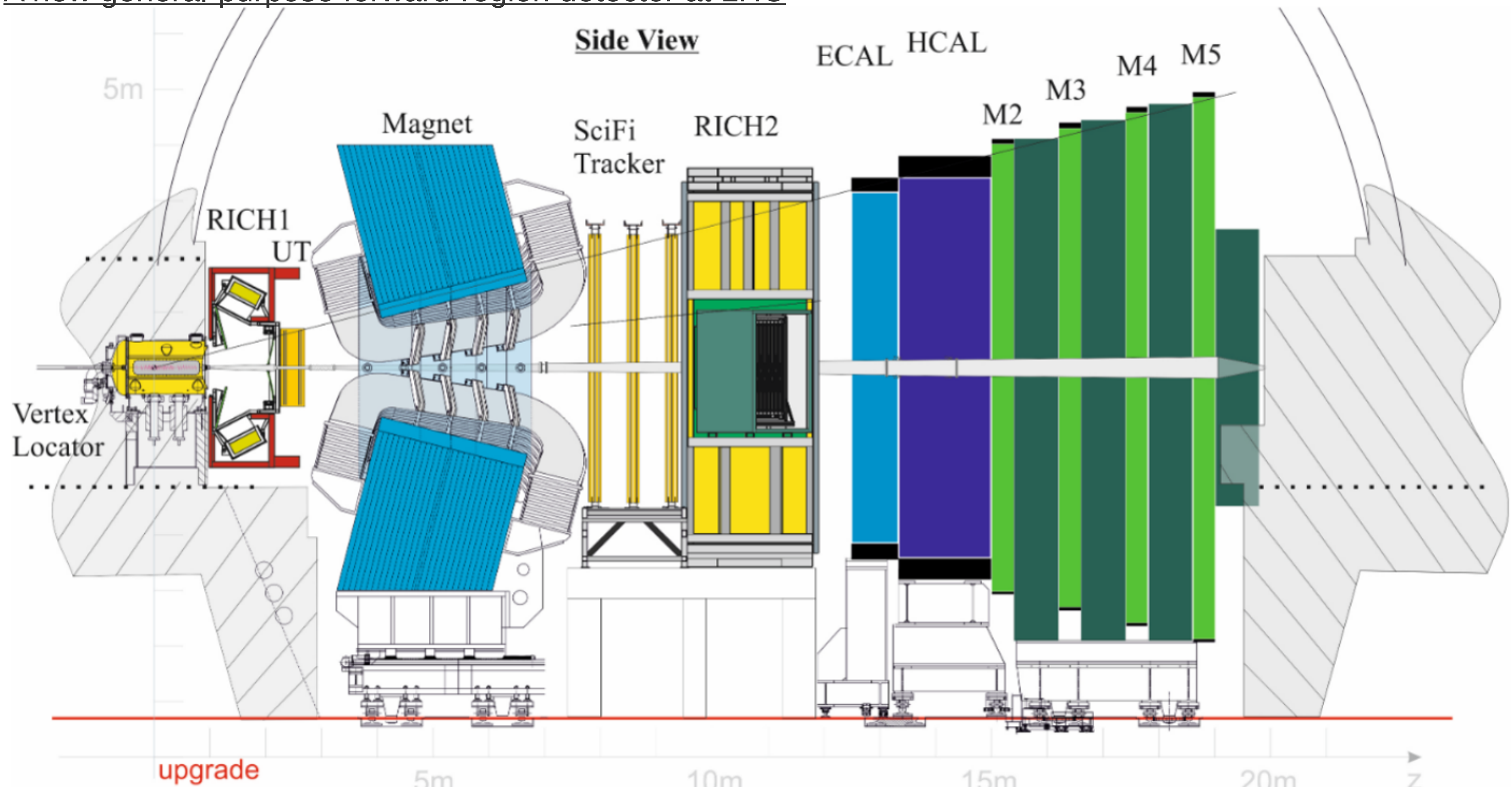
	Name	J^P	Mass (MeV)	Width (MeV)	Main decay channels
			****		
†	$\Lambda(1405)$	$\frac{1}{2}^-$	$1405.1^{+1.3}_{-1.0}$	50.5 ± 2.0	$\Sigma\pi$
†	$\Lambda(1520)$	$\frac{3}{2}^-$	1518 to 1520	15 to 17	$N\bar{K}$, $\Sigma\pi$
†	$\Lambda(1670)$	$\frac{1}{2}^-$	1660 to 1680	25 to 50	$N\bar{K}$, $\Sigma\pi$, $\Lambda\eta$
	$\Lambda(1690)$	$\frac{3}{2}^-$	1685 to 1695	50 to 70	$N\bar{K}$, $\Sigma\pi$, $\Lambda\pi\pi$, $\Sigma\pi\pi$
	$\Lambda(1820)$	$\frac{5}{2}^+$	1815 to 1825	70 to 90	$N\bar{K}$
	$\Lambda(1830)$	$\frac{5}{2}^-$	1810 to 1830	60 to 110	$\Sigma\pi$
	$\Lambda(1890)$	$\frac{3}{2}^+$	1850 to 1910	60 to 200	$N\bar{K}$
†	$\Sigma(1385)$	$\frac{3}{2}^+$	1383.7 ± 1	36 ± 5	$\Lambda\pi$, $\Sigma\pi$
	$\Sigma(1670)$	$\frac{3}{2}^-$	1665 to 1685	40 to 80	$\Sigma\pi$
†	$\Sigma(1775)$	$\frac{5}{2}^-$	1770 to 1780	105 to 135	$N\bar{K}$, $\Lambda^{(*)}\pi$
†	$\Sigma(1915)$	$\frac{5}{2}^+$	1900 to 1935	80 to 160	not clear
			***		
	$\Lambda(1600)$	$\frac{1}{2}^+$	1560 to 1700	50 to 250	$N\bar{K}$, $\Sigma\pi$
	$\Lambda(1800)$	$\frac{1}{2}^-$	1720 to 1850	200 to 400	$N\bar{K}^{(*)}$, $\Sigma\pi$, $\Lambda\eta$
	$\Lambda(1810)$	$\frac{1}{2}^+$	1750 to 1850	50 to 250	$N\bar{K}^{(*)}$, $\Sigma\pi$, $\Lambda\eta$, ΞK
	$\Lambda(2110)$	$\frac{5}{2}^+$	2090 to 2140	150 to 250	$N\bar{K}^{(*)}$, $\Sigma\pi$, $\Lambda\Omega$
	$\Sigma(1660)$	$\frac{1}{2}^-$	1630 to 1690	40 to 200	$N\bar{K}$, $\Sigma\pi$, $\Lambda\pi$
	$\Sigma(1750)$	$\frac{1}{2}^-$	1730 to 1800	60 to 160	$N\bar{K}$, $\Sigma\pi$, $\Lambda\pi$, $\Sigma\eta$
	$\Sigma(1940)$	$\frac{3}{2}^-$	1900 to 1950	150 to 300	$N\bar{K}$, $\Sigma\pi$, $\Lambda\pi$
	$\Sigma(2250)$	$?^?$	2210 to 2280	60 to 150	$N\bar{K}$, $\Sigma\pi$, $\Lambda\pi$

Component	A^{CP} (10^{-2})
$\Sigma(1385)$	-27 ± 34 (stat) ± 73 (syst)
$\Lambda(1405)$	-1 ± 24 (stat) ± 32 (syst)
$\Lambda(1520)$	-5 ± 9 (stat) ± 8 (syst)
$\Lambda(1670)$	3 ± 14 (stat) ± 10 (syst)
$\Sigma(1775)$	-47 ± 26 (stat) ± 14 (syst)
$\Sigma(1915)$	11 ± 26 (stat) ± 22 (syst)

Outlook for Run 3 and 4

LHCb experiment in Run 3

- LHCb conditions in Run 3: luminosity of 2×10^{33} $cm^{-2}s^{-1}$, $\sqrt{s}$ = 13.6 TeV, visible collisions per bunch $\mu \sim 5$
- New tracker detectors, upgraded electronics, fully software trigger, ...
- A new general-purpose forward-region detector at LHC

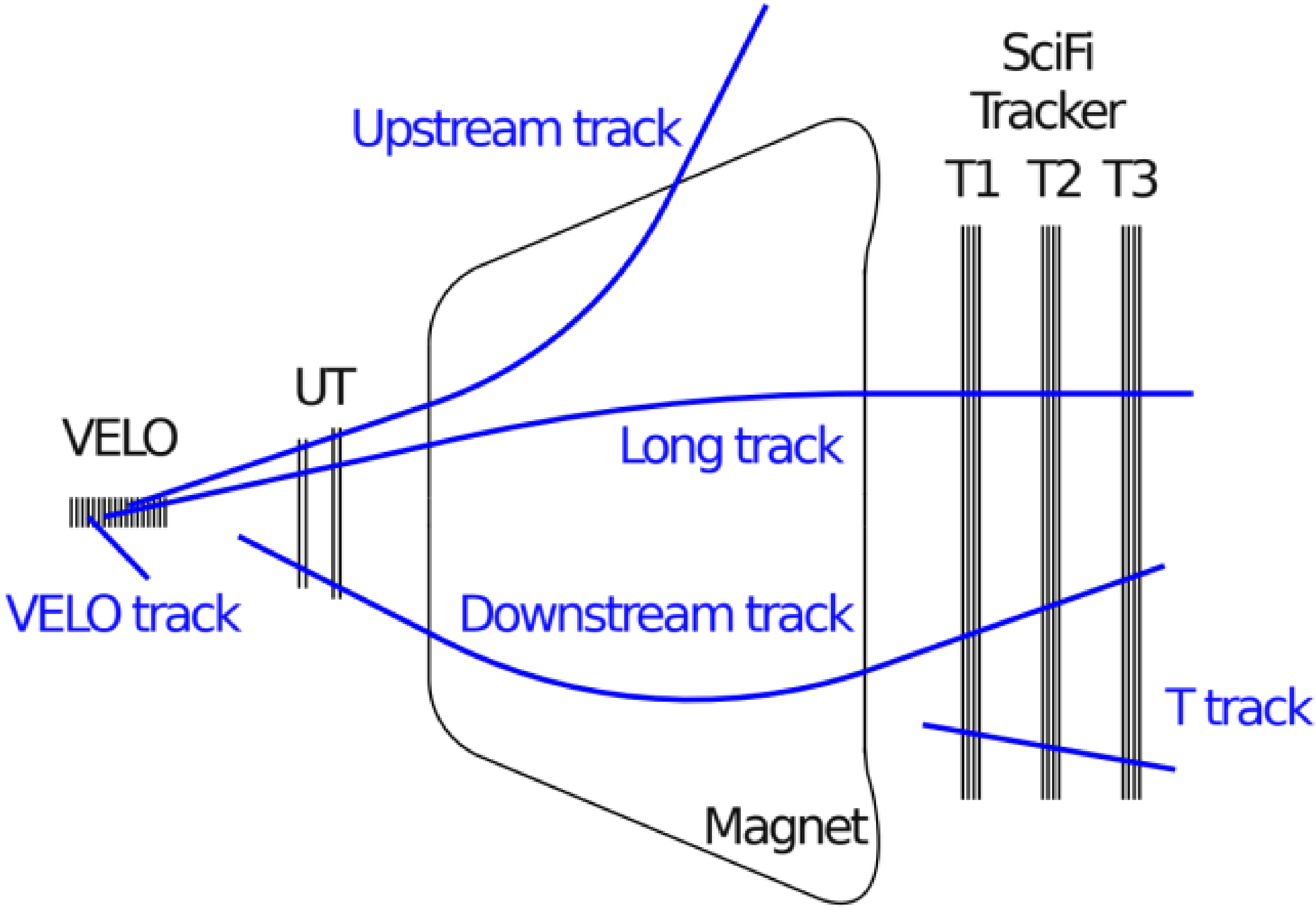


Baryons in Run 3 and 4

- Heavy baryons are a rather unexplored area compared to mesons
  - Possibility of many complementary studies but also many unique possibilities
- Limited knowledge of beauty baryons decays even for a ground states
- LHCb is the only experiment which can achieve needed precision for various studies
  - Access to doubly-heavy baryons, exotic baryons, CPV, polarisation, ...
- Run 2 data should already include reasonable statistics for many decays but never properly investigated
  - Lower BF, often high background, lacking theory predictions, …
  - Several studies using Run 2 data still ongoing
- In Run 3 the largest benefit from the new trigger system is expected to be for hadronic modes
  - Especially hadronic modes with a soft particles such as charm and beauty multi-body decays
- Various new ideas for baryons in last few years, to name a few:
  - proposal to measure angle ɣ using $\Lambda_b^0 \to \Lambda^0 D^0$ [2112.12954]
  - new observables allowing a better access to CPV observables as generalised two-dimensional angular distribution [Phys. Rev. D. 107 L011301] or partial-wave CP analysis [JHEP07 (2021) 177]
- Both experimental and theory progress needed to effectively probe baryonic sector

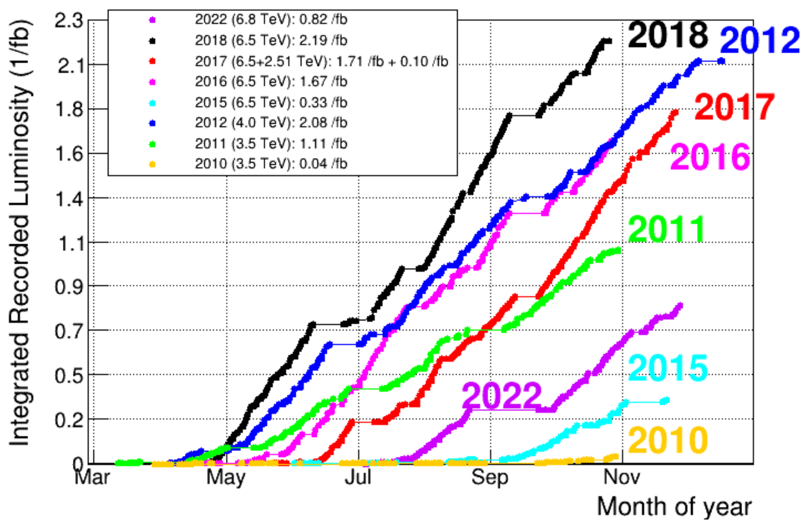
Thank you for the attention

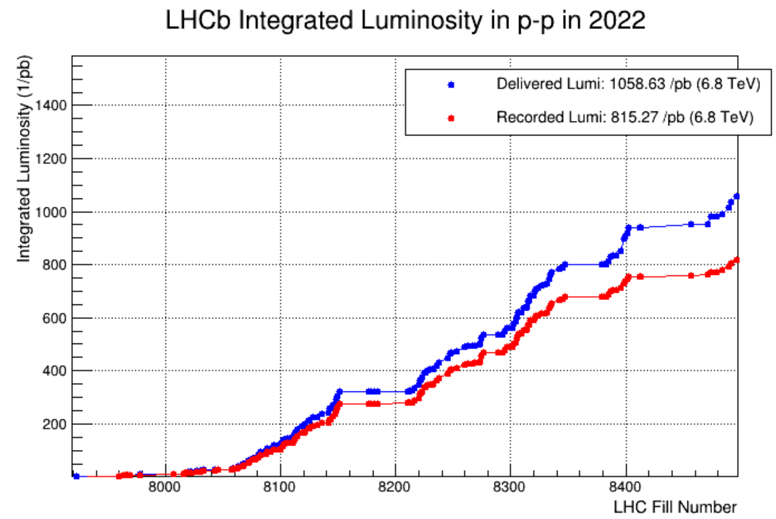
Spare slides


Upstream track
SciFi
Tracker
T1 T2 T3
UT
VELO
Long track
VELO track
Downstream track
T track
Magnet

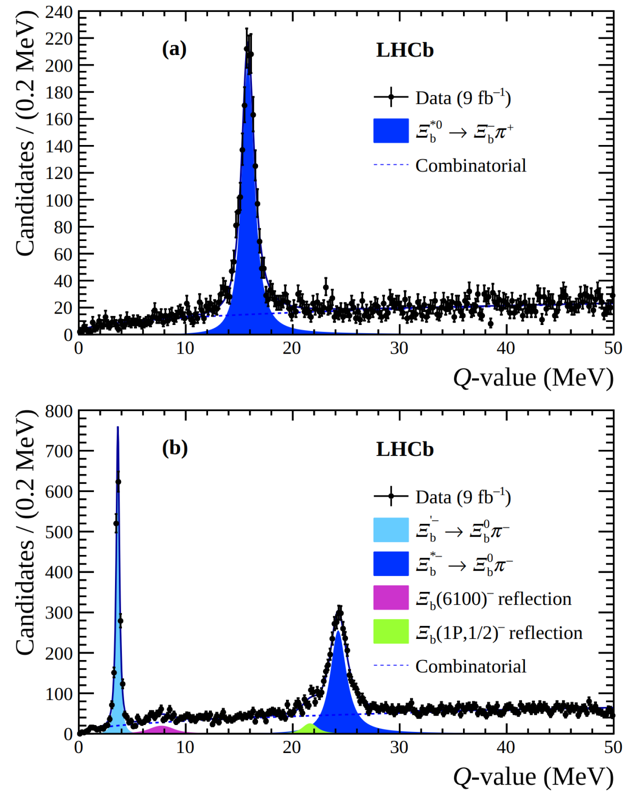
LHCb 2022 operations

- Operations in 2022



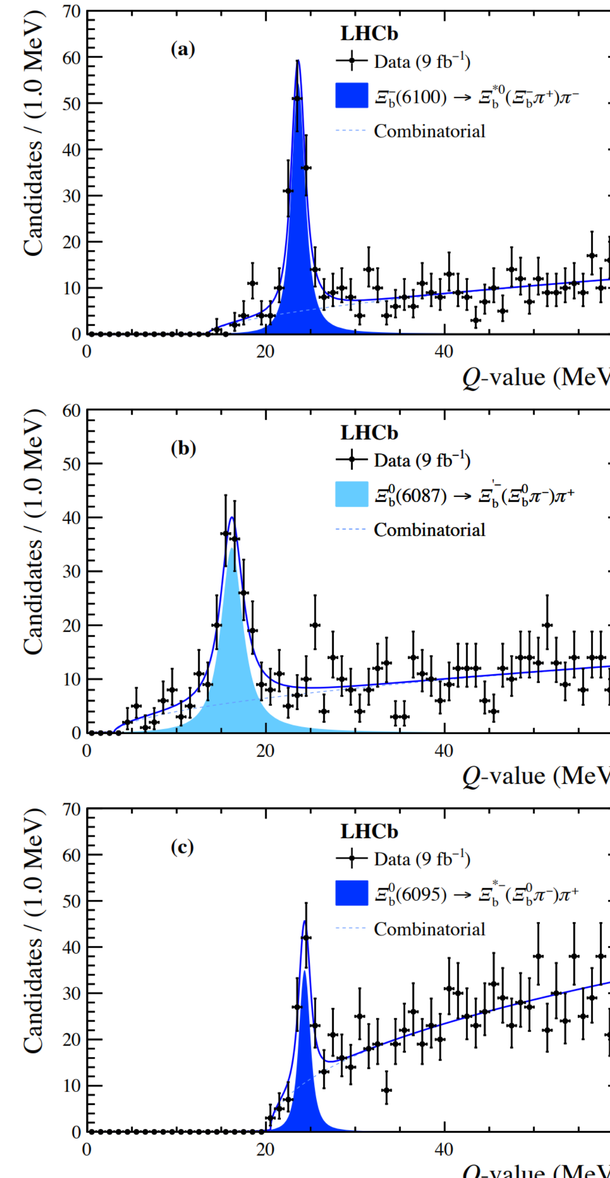


Observation of New Baryons in the $\Xi_b^- \pi^+ \pi^-$ and $\Xi_b^0 \pi^+ \pi^-$



Source	Ξ_b^{*0} Q_0	Ξ_b^{*0} Γ	$\Xi_b^{'-}$ Q_0	$\Xi_b^{'-}$ Γ	Ξ_b^{*-} Q_0	Ξ_b^{*-} Γ
Momentum scale	0.006	0.001	0.001	0.001	0.008	0.001
Background	0.003	0.029	0.000	0.006	0.004	0.073
Reflections			0.000	0.000	0.002	0.007
Resolution	0.001	0.038	0.002	0.027	0.000	0.033
BW param.	0.001	0.001	0.000	0.000	0.001	0.002
Total	0.007	0.048	0.002	0.028	0.010	0.081

Source	$\Xi_b(6100)^-$ Q_0	$\Xi_b(6100)^-$ Γ	$\Xi_b(6087)^0$ Q_0	$\Xi_b(6087)^0$ Γ	$\Xi_b(6095)^0$ Q_0	$\Xi_b(6095)^0$ Γ
Momentum scale	0.008	0.002	0.007	0.001	0.009	0.006
Background	0.004	0.035	0.022	0.089	0.023	0.025
Resolution	0.004	0.054	0.001	0.035	0.006	0.073
BW param.	0.016	0.050	0.056	0.007	0.001	0.079
Total	0.019	0.081	0.060	0.096	0.026	0.111

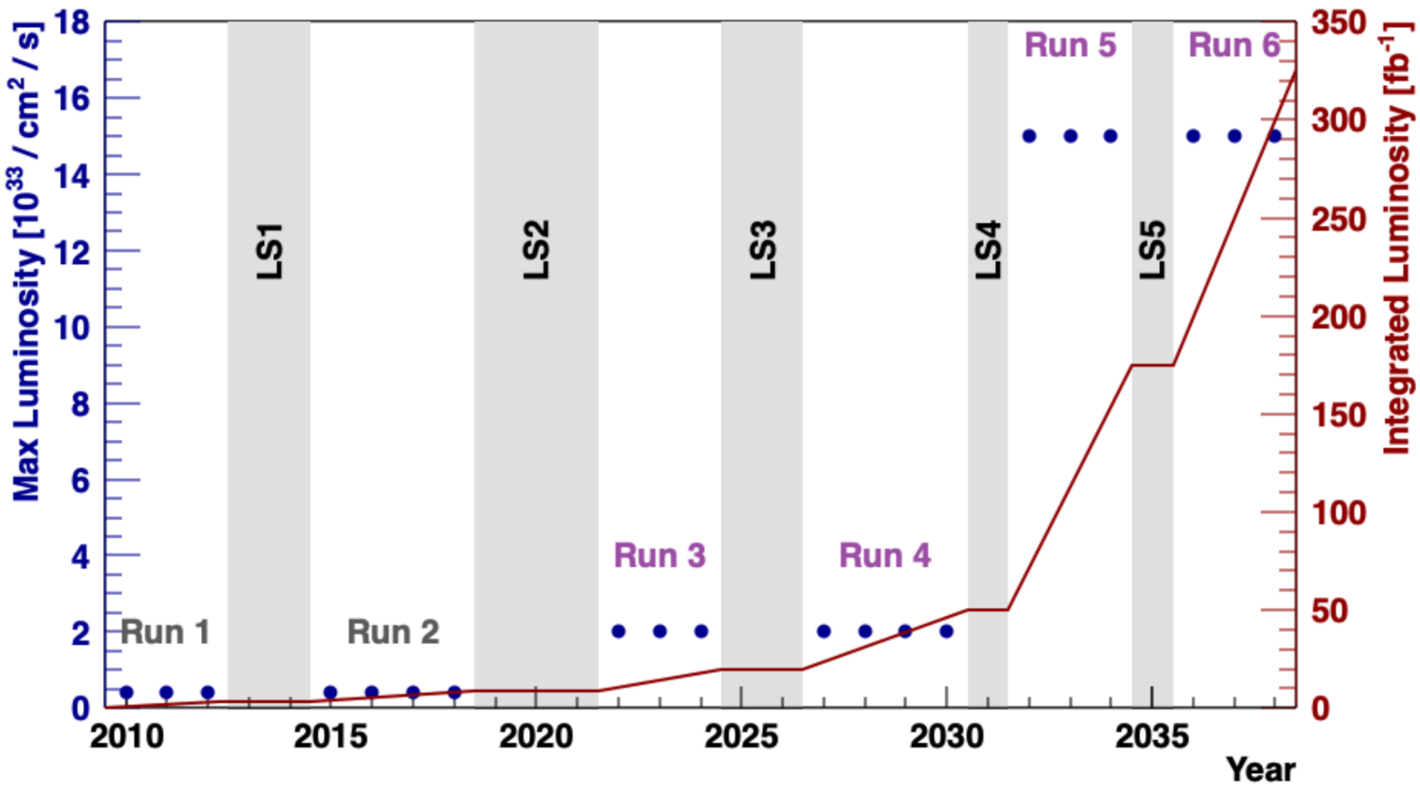


Uprade 2 precision

Observable	Current LHCb (up to $9\,\mathrm{fb}^{-1}$)		Upgrade I ($23\,\mathrm{fb}^{-1}$)	($50\,\mathrm{fb}^{-1}$)	Upgrade II ($300\,\mathrm{fb}^{-1}$)
CKM tests					
γ ($B \to DK$, *etc.*)	4°	[9, 10]	1.5°	1°	0.35°
ϕ_s ($B_s^0 \to J/\psi\phi$)	49 mrad	[8]	14 mrad	10 mrad	4 mrad
$\|V_{ub}\|/\|V_{cb}\|$ ($\Lambda_b^0 \to p\mu^-\overline{\nu}_\mu$, *etc.*)	6%	[29, 30]	3%	—	1%
a_{sl}^d ($B^0 \to D^-\mu^+\nu_\mu$)	36×10^{-4}	[34]	8×10^{-4}	5×10^{-4}	2×10^{-4}
a_{sl}^s ($B_s^0 \to D_s^-\mu^+\nu_\mu$)	33×10^{-4}	[35]	10×10^{-4}	7×10^{-4}	3×10^{-4}
Charm					
ΔA_{CP} ($D^0 \to K^+K^-, \pi^+\pi^-$)	29×10^{-5}	[5]	17×10^{-5}	—	3.0×10^{-5}
A_Γ ($D^0 \to K^+K^-, \pi^+\pi^-$)	13×10^{-5}	[38]	4.3×10^{-5}	—	1.0×10^{-5}
Δx ($D^0 \to K_S^0\pi^+\pi^-$)	18×10^{-5}	[37]	6.3×10^{-5}	4.1×10^{-5}	1.6×10^{-5}
Rare Decays					
$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	71%	[40, 41]	34%	—	10%
$S_{\mu\mu}$ ($B_s^0 \to \mu^+\mu^-$)	—		—	—	0.2
$A_{\mathrm{T}}^{(2)}$ ($B^0 \to K^{*0}e^+e^-$)	0.10	[52]	0.060	0.043	0.016
$A_{\mathrm{T}}^{\mathrm{Im}}$ ($B^0 \to K^{*0}e^+e^-$)	0.10	[52]	0.060	0.043	0.016
$\mathcal{A}_{\phi\gamma}^{\Delta\Gamma}$($B_s^0 \to \phi\gamma$)	$^{+0.41}_{-0.44}$	[51]	0.124	0.083	0.033
$S_{\phi\gamma}$($B_s^0 \to \phi\gamma$)	0.32	[51]	0.093	0.062	0.025
α_γ($\Lambda_b^0 \to \Lambda\gamma$)	$^{+0.17}_{-0.29}$	[53]	0.148	0.097	0.038
Lepton Universality Tests					
R_K ($B^+ \to K^+\ell^+\ell^-$)	0.044	[12]	0.025	0.017	0.007
R_{K^*} ($B^0 \to K^{*0}\ell^+\ell^-$)	0.10	[61]	0.031	0.021	0.008
$R(D^*)$ ($B^0 \to D^{*-}\ell^+\nu_\ell$)	0.026	[62, 64]	0.007	—	0.002

LHCb Upgrade 2

- A significant challenge
- Many new detector technologies needed



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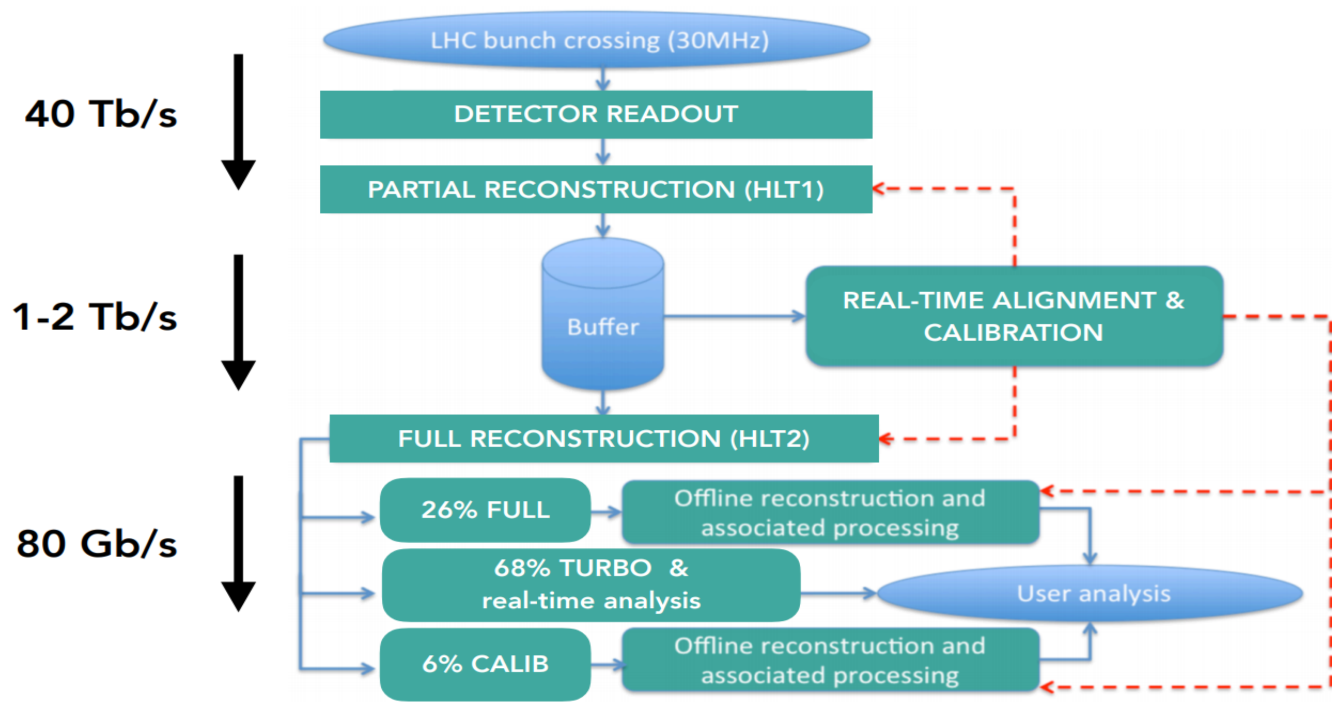
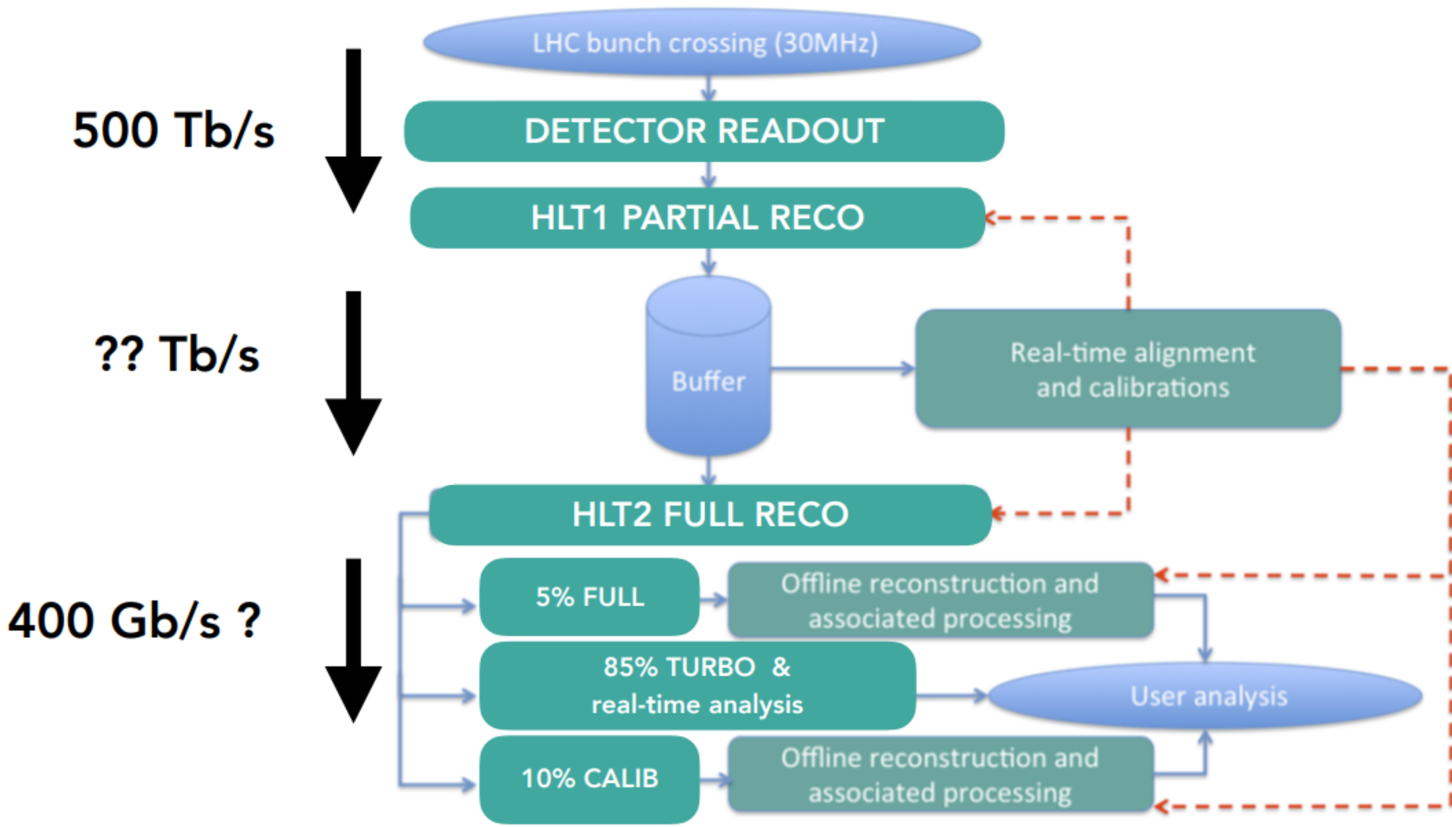
LHCb Upgrade I

- Real-Time Analysis – efficient decision about data in the full online mode
- Keeping only a signal and suppress any unnecessary information about event
- Continuous readout, full software trigger at visible collision rate of 30 MHz



LHCb Upgrade II

- Real-Time Analysis – efficient decision about data in the full online mode
- Run 5 – at least 5 times more data than in Run 3
- An evolution or Run 3 trigger scheme or a revolution needed?



Baryons in Run 3 and 4

- Heavy baryons are a rather unexplored area and portal to study the Baryonic Asymmetry of the Universe
  - Substantial studies on charmed baryons by BESIII and Belle (II)
- Limited knowledge of beauty baryons even a decays of ground states
- LHCb is the only experiment which can record enough statistics for various studies
  - Access to doubly-heavy baryons, exotic baryons, CPV, polarisation, ...

- Run 2 data should already include reasonable statistics for many decays but never properly investigated
  - Lower BF, often high background, lacking theory predictions, ...
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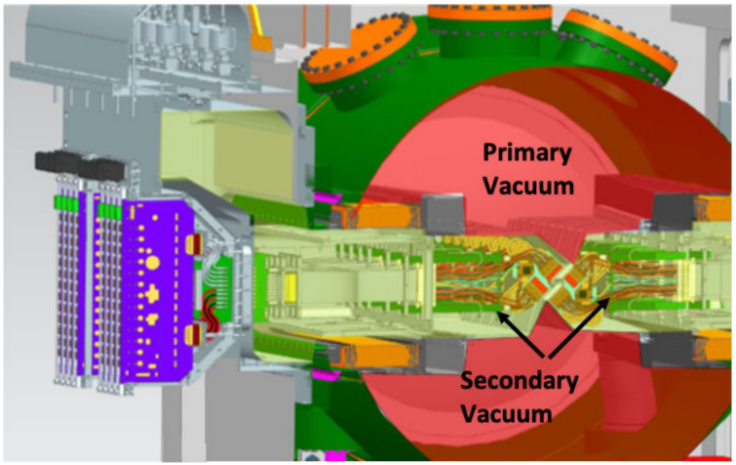
VELO incident

The VELO detector is installed in a secondary vacuum inside the LHC primary vacuum. The primary and secondary volumes are separated by two thin walled (180 μm) Aluminium boxes, the RF foils. The LHC vacuum control system protects against pressure differentials, both during vacuum operation and during technical stops, when all volumes are sometimes filled with Neon.




RF foils before installation

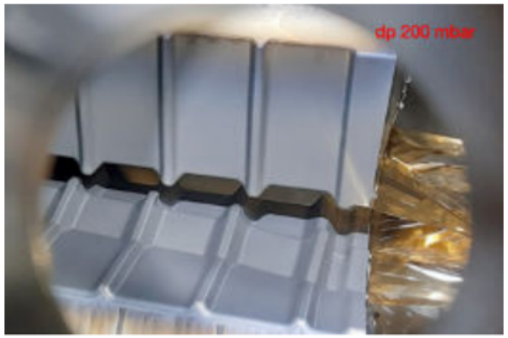
On 10th January 2023, during a VELO warm up in Neon, there was a loss of control of the protection system. A relay failed and damaged a power supply, leading to multiple equipment failures and a pumping action on the primary volume. The safety valve didn't open at the designed ΔP = 10 mbar, and a pressure differential of 200 mbar built up between the two volumes, whereas the foils are designed to withstand 10 mbar only.

The system has been returned to a safe situation and VELO modules are not damaged and operational:

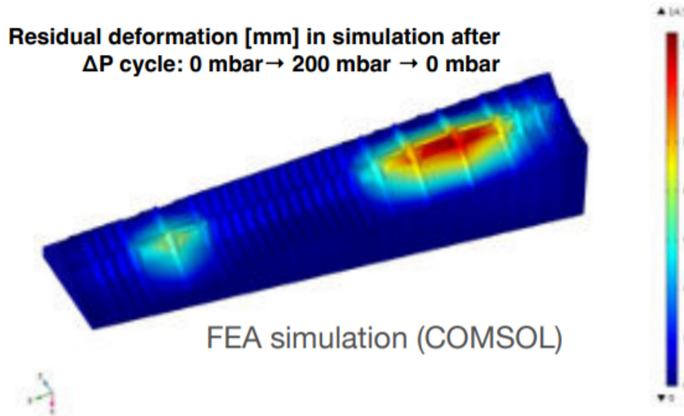
- correct leakage current measured in silicon sensors
- silicon microchannels show no leaks

VELO incident

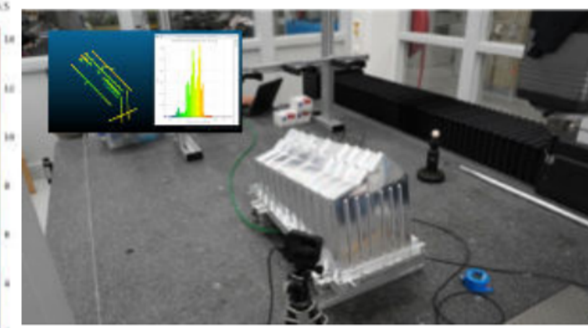
The deformation of the RF foil has been simulated, and the results have been benchmarked against measurements on a 1/2 scale prototype box.



Visualisation through viewing port



FEA simulation (COMSOL)



Benchmarking simulation/measurement

- Plastic deformation of the foils of up to 14 mm expected
  - to be validated with tomography with beam
- detector and vacua brought back to a safe state (thanks to the LHC vacuum group for their crucial help)
- commissioning of VELO and other subdetectors can continue
- VELO cannot be fully closed
- foil needs to be replaced in next YETS (~13 weeks intervention)

Physics programme in 2023 will be significantly affected: lower acceptance; slightly worse IP resolution, similar to Run 2; lower integrated luminosity — targeting ~1 fb^{-1}

- could still provide world-best measurements in some areas thanks to the new flexible software-only high-bandwidth trigger