Charm physics at LHCb

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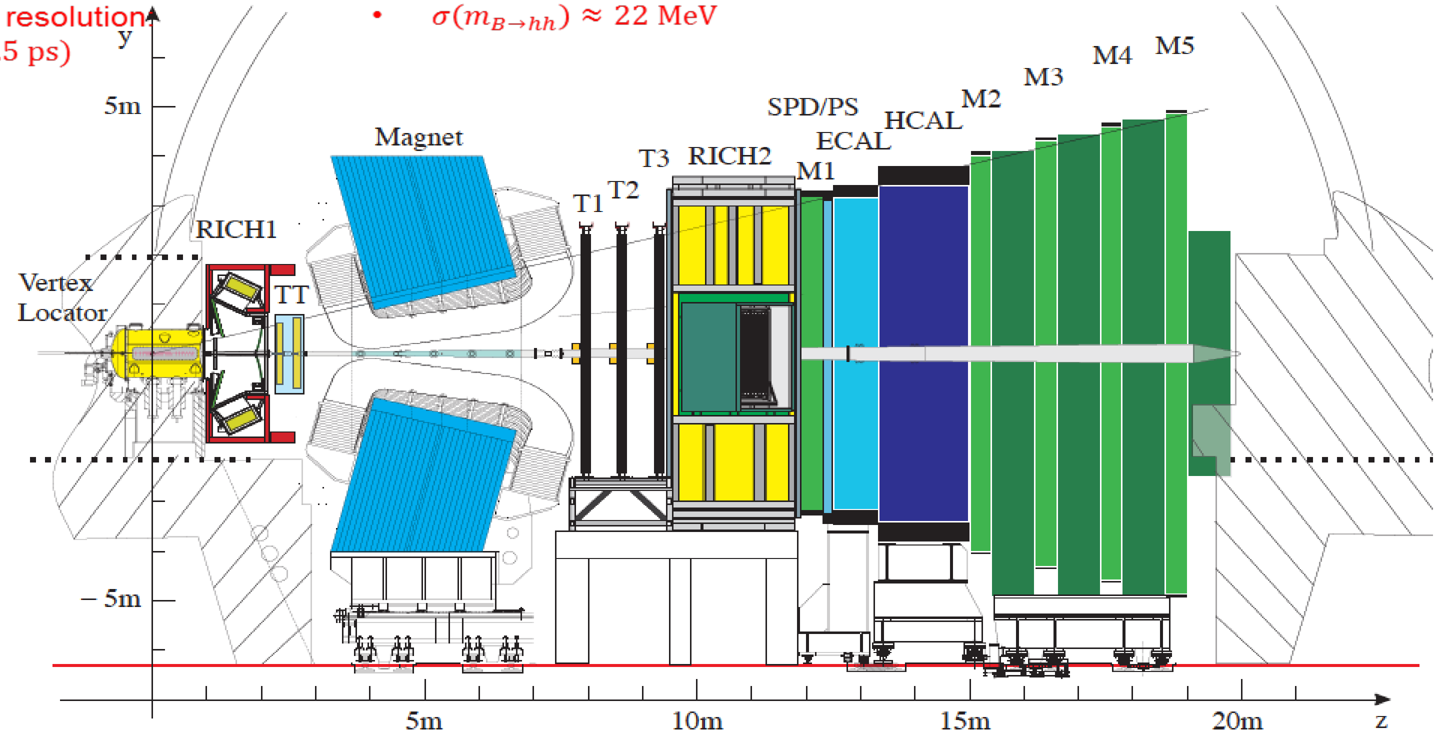
LHCb detector Run 1 + 2

- 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 (τ_B~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



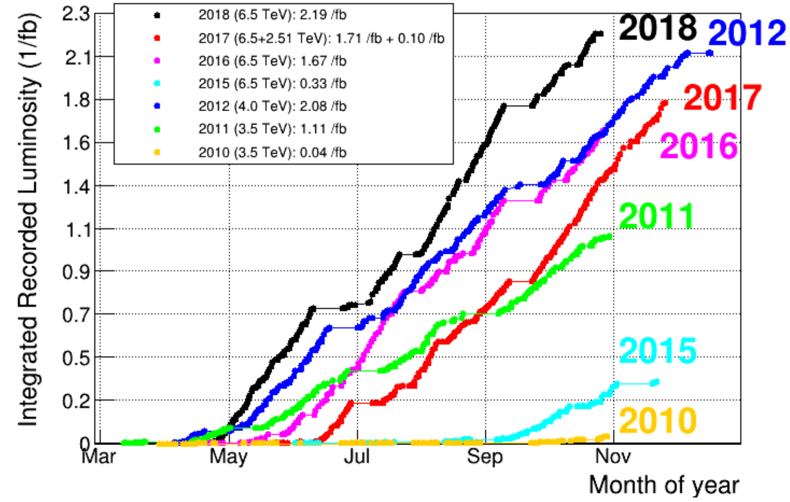
RICH: particle ID
- $\varepsilon(K \to K)$ ~95%
- Mis-ID: $\varepsilon(\pi \to K)$ ~5%

Magnet
- Bending power: 4 Tm

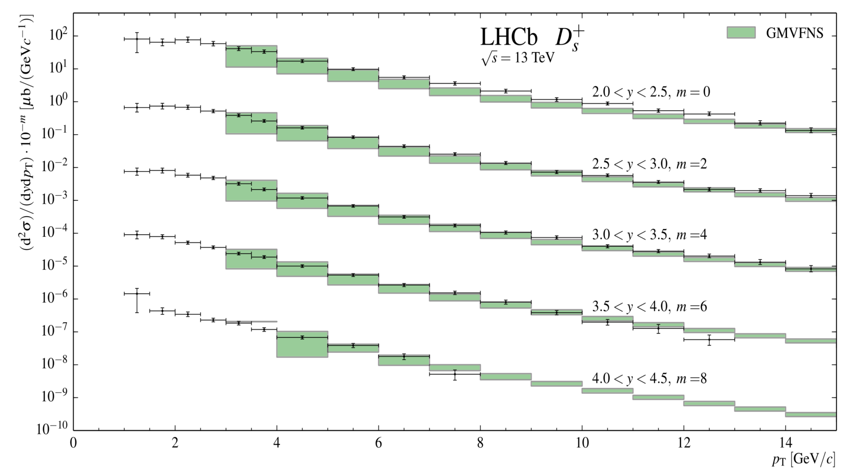
Muon system
- μ ID: $\varepsilon(\mu \to \mu)$ ~97%
- Mis-ID: $\varepsilon(\pi \to \mu)$ ~1-3%

Luminosity and 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}



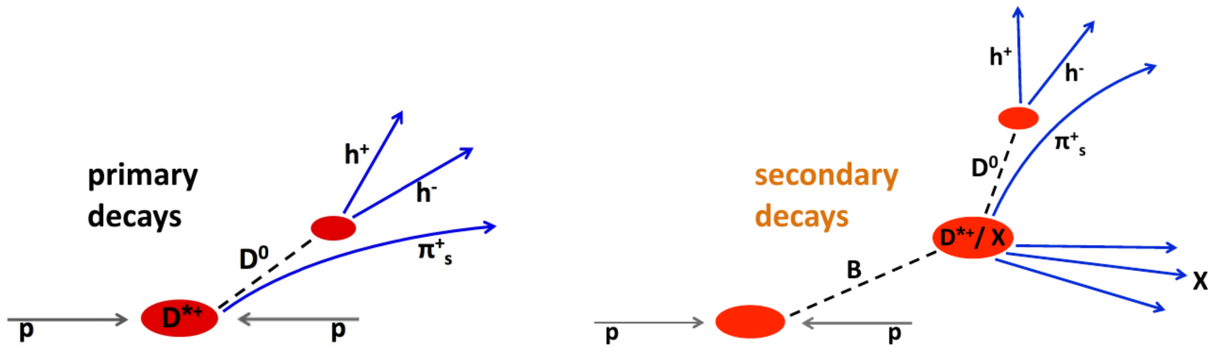
- Largest recorded sample of charmed hadrons
  - σ(pp -> ccX, 7 TeV) ~ 1.4 mb
  - σ(pp -> ccX, 13 TeV) ~ 2.4 mb
- LHCb is the most efficient for charged decay modes and decays with muons
- Increasing amount of studies involving neutral particles such as π^0 and gamma



JHEP 05 074 (2017)

Production modes and asymmetries

- LHCb has an access to both promptly produced charm and secondary production from b-decays
  - Prompt production: higher signal yield, lower purity
  - From-b production: lower signal yield, better discriminating of combinatorial background



- Due to the nature of LHC as pp collider, particles and antiparticles are not produced equally
  - Must be treated accordingly in order not to bias any CPV observables
  - Using a known values, extracting via suitable control channel, ...
- Detection asymmetries
  - Different interaction cross-section between the detector material and particles / antiparticles

Charm physics at LHCb

- Very broad physics programme in Charm sector, can be divided into three main categories:
  - CPV studies
  - Production measurements
  - Rare decays
- Predominantly focusing on charmed mesons, however number of analyses with baryons is increasing
- All results available at public LHCb webpage
- Due to a limited time this talk will focus only on selected set of some (very) recent results

- Selected CPV results:
  - Search for CP violation in $D_{(s)}^+ \to K^- K^+ K^+$ decays [2303.04062]
  - Measurement of the time-integrated CP asymmetry in $D^0 \to K^- K^+$ decays [2209.03179]
- Selected rare charm decays:
  - Search for $D^*(2007)^0 \to \mu^+\mu^-$ in $B^- \to \pi^-\mu^+\mu^-$ [2304.01981]
  - Search for rare decays of D^0 mesons into two muons [2212.11203]
- Selected production measurements:
  - Observation of new Ω_c^0 states decaying to the $\Xi_c^+ K^-$ final state [2302.04733]
  - Proposed naming convention for exotic states [2206.15233v1]

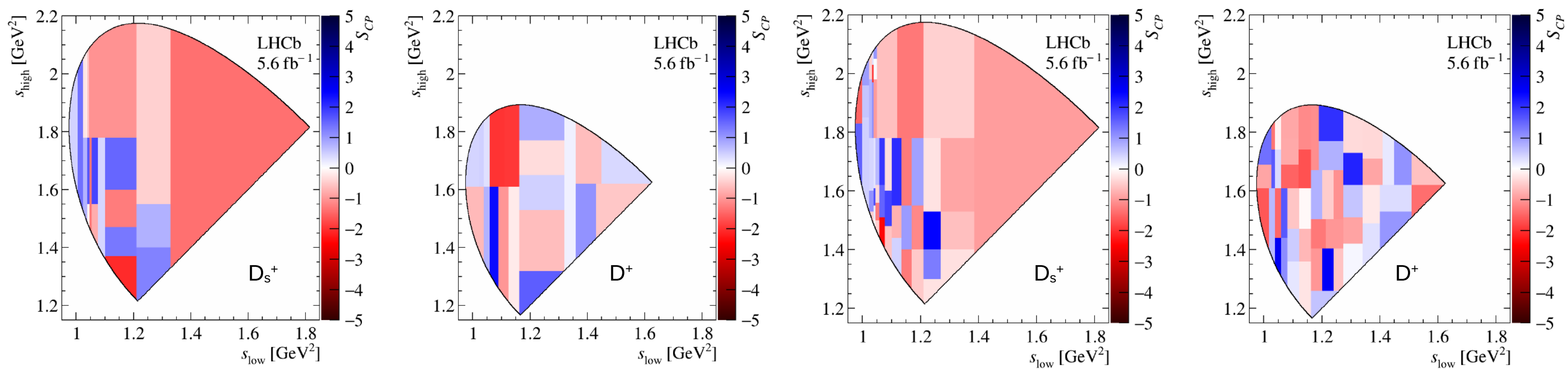
CP violation studies

Search for CP violation in $D_{(s)}^+ \to K^-K^+K^+$ decays

arXiv: 2303.04062

- Search for a direct CP violation using 2016-2018 data based on model-independent binned method
- First search for CP violation in DCS $D^+ \to K^-K^+K^+$ and CS $D_s^+ \to K^-K^+K^+$ at LHCb
- 0.97 million and 1.27 million promptly produced D_s^+ and D^+ decays, respectively
- Dalitz plot of $D_{(s)}^+$ and $D_{(s)}^-$ are compared in bins and significance of difference between $D_{(s)}^+$ and $D_{(s)}^-$ is computed
  - Two schemes: 21 and 50 bins; significance calculated as: $\mathcal{S}_{CP}^i = \frac{N^i(D_{(s)}^+) - \alpha N^i(D_{(s)}^-)}{\sqrt{\alpha(\delta^2_{N^i(D_{(s)}^+)} + \delta^2_{N^i(D_{(s)}^-)})}}$, with $\alpha = \frac{\sum_i N^i(D_{(s)}^+)}{\sum_i N^i(D_{(s)}^-)}$,

- Obtained results show no CP violation for both binning schemes



- First analysis in a series of studies focusing on three-body $D_{(s)}^+$ decays

Time-integrated CP asymmetry in $D^0 \to K^-K^+$ decays

arXiv: 2209.03179

- Based on 2016-2018 data, D^0 tagged from the promptly produced D^{*+}
- Time-integrated CP asymmetry is defined as:

$$f = K^-K^+/\pi^-\pi^+$$

$$\mathcal{A}_{CP}(f) \equiv \frac{\int \mathrm{d}t\, \epsilon(t) \left[\Gamma(D^0 \to f)(t) - \Gamma(\overline{D}^0 \to f)(t)\right]}{\int \mathrm{d}t\, \epsilon(t) \left[\Gamma(D^0 \to f)(t) + \Gamma(\overline{D}^0 \to f)(t)\right]} \approx a_f^d + \frac{\langle t \rangle_f}{\tau_D} \cdot \Delta Y_f$$

- Complex method to cancel experimental asymmetries applied, depending on set of CF modes
  - C_{D+} procedure (used in Run 1) uses $D^{*+} \to D^0(\to K^-\pi^+)\pi^+$, $D^+ \to K^-\pi^+\pi^+$, $D^+ \to \overline{K}^0\pi^+$
  - C_{Ds+} procedure (new for Run 2) uses $D^{*+} \to D^0(\to K^-\pi^+)\pi^+$, $D_s^+ \to \phi(\to K^-K^+)\pi^+$, $D_s^+ \to \overline{K}^0 K^+$

$$\mathrm{C}_{D^+}: \mathcal{A}_{CP}(K^-K^+) = A(K^-K^+) - A(K^-\pi^+) + A(K^-\pi^+\pi^+) - A(\overline{K}^0\pi^+) + A(\overline{K}^0),$$

$$\mathrm{C}_{D_s^+}: \mathcal{A}_{CP}(K^-K^+) = A(K^-K^+) - A(K^-\pi^+) + A(\phi\pi^+) - A(\overline{K}^0K^+) + A(\overline{K}^0).$$

$$A(K^-\pi^+) \approx A_{\mathrm{P}}(D^{*+}) - A_{\mathrm{D}}(K^+) + A_{\mathrm{D}}(\pi^+) + A_{\mathrm{D}}(\pi^+_{\mathrm{tag}}),$$

$$A(K^-\pi^+\pi^+) \approx A_{\mathrm{P}}(D^+) - A_{\mathrm{D}}(K^+) + A_{\mathrm{D}}(\pi^+_1) + A_{\mathrm{D}}(\pi^+_2),$$

$$A(\overline{K}^0\pi^+) \approx A_{\mathrm{P}}(D^+) + A(\overline{K}^0) + A_{\mathrm{D}}(\pi^+),$$

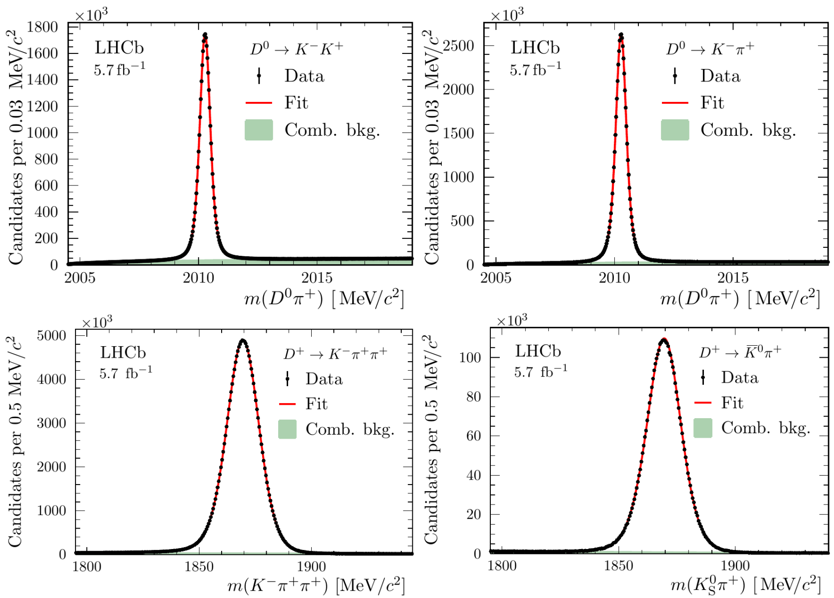
$$A(\phi\pi^+) \approx A_{\mathrm{P}}(D_s^+) + A_{\mathrm{D}}(\pi^+),$$

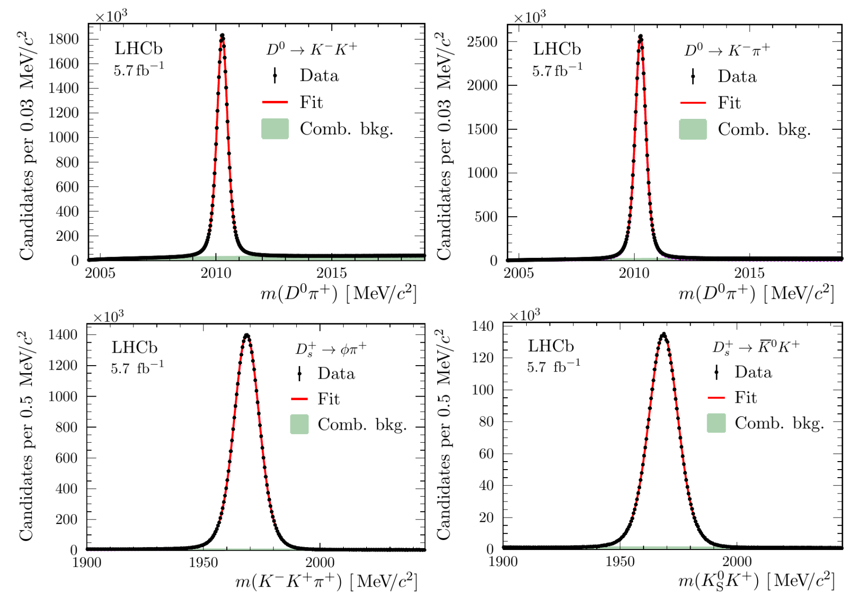
$$A(\overline{K}^0K^+) \approx A_{\mathrm{P}}(D_s^+) + A(\overline{K}^0) + A_{\mathrm{D}}(K^+).$$

Time-integrated CP asymmetry in $D^0 \to K^- K^+$ decays

arXiv: 2209.03179

- Invariant mass plots
  - Modes used in C_{D+} method (left) and C_{Ds+} method (right)





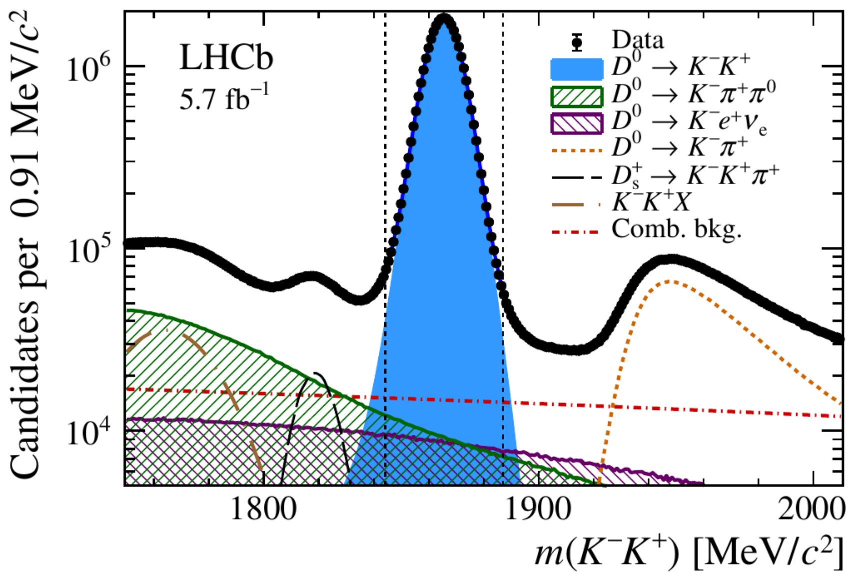
- Reduction factors correspond to the statistical power of each data sample after weighting
- Large reduction in case of different phase space between various decay modes

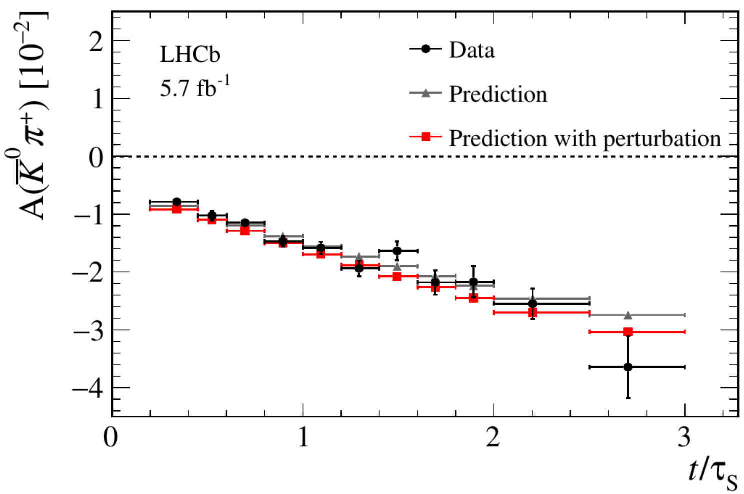
Decay mode	Signal yield [10^6]		Red. factor	
	C_{D^+}	$C_{D_s^+}$	C_{D^+}	$C_{D_s^+}$
$D^0 \to K^-K^+$	37	37	0.75	0.75
$D^0 \to K^-\pi^+$	58	56	0.35	0.75
$D^+ \to K^-\pi^+\pi^+$	188	–	0.25	–
$D^+ \to \bar{K}^0\pi^+$	6	–	0.25	–
$D_s^+ \to \phi\pi^+$	–	43	–	0.55
$D_s^+ \to \bar{K}^0K^+$	–	5	–	0.70

Time-integrated CP asymmetry in $D^0 \to K^-K^+$ decays

arXiv: 2209.03179

- Systematic uncertainties well under the control and below statistic uncertainty
- Dominated by the fit model and kinematic weighting procedure
- Fit model evaluated by generating pseudoexperiments according to the baseline fit models (Johnson S_u + Gaussian) and fitting alternative models to those samples
- Asymmetry due to neutral kaon evaluated by a separate sample decaying outside VELO





Source	C_{D^+} $[10^{-4}]$	$C_{D_s^+}$ $[10^{-4}]$	Corr.
Fit model	1.1	1.0	0.05
Peaking backgrounds	0.3	0.4	0.74
Secondary decays	0.6	0.3	–
Kinematic weighting	0.8	0.4	–
Neutral kaon asymmetry	0.6	1.3	1.00
Charged kaon asymmetry	–	1.0	–
Total	1.6	2.0	0.28

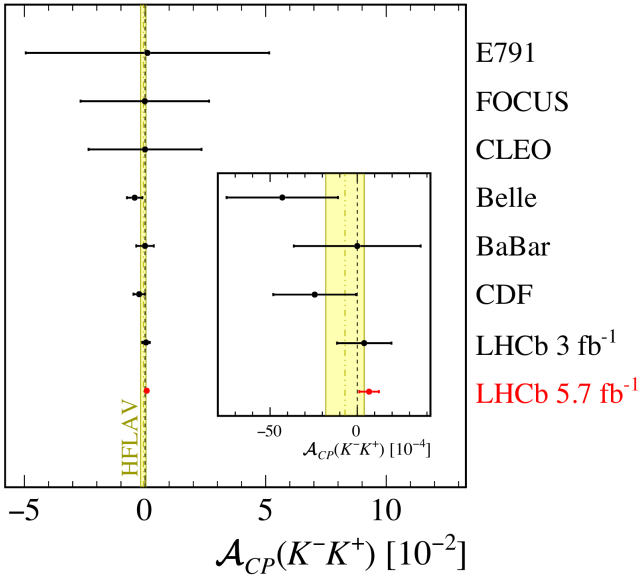
Time-integrated CP asymmetry in $D^0 \to K^-K^+$ decays

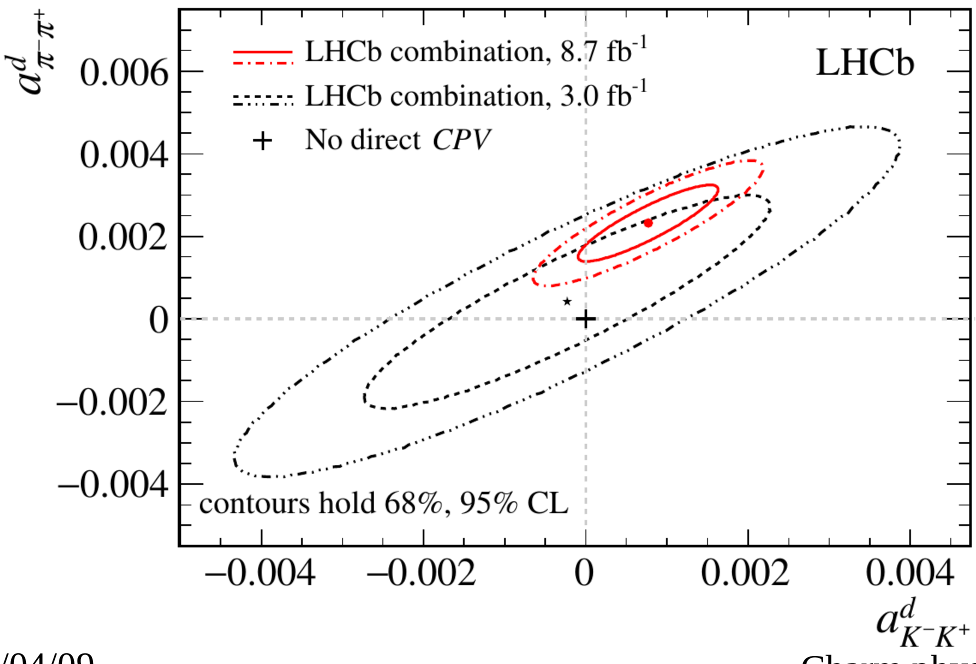
arXiv: 2209.03179

- Obtained results:

$$C_{D^+}: \mathcal{A}_{CP}(K^-K^+) = [13.6 \pm 8.8\,(\text{stat}) \pm 1.6\,(\text{syst})] \times 10^{-4}$$
$$C_{D_s^+}: \mathcal{A}_{CP}(K^-K^+) = [\ 2.8 \pm 6.7\,(\text{stat}) \pm 2.0\,(\text{syst})] \times 10^{-4}$$

$$\mathcal{A}_{CP}(K^-K^+) = [6.8 \pm 5.4\,(\text{stat}) \pm 1.6\,(\text{syst})] \times 10^{-4}$$





- When combined with previous LHCb measurements of ΔA_{CP}:

$$a^d_{K^-K^+} = (\ 7.7 \pm 5.7) \times 10^{-4}$$
$$a^d_{\pi^-\pi^+} = (23.2 \pm 6.1) \times 10^{-4}$$
$$\rho(a^d_{KK}, a^d_{\pi\pi}) = 0.88$$

- Which is the first evidence for CPV in a single charm-meson decay as 3.8σ
- Additionally this implies U-spin symmetry violation at level of 2.7σ

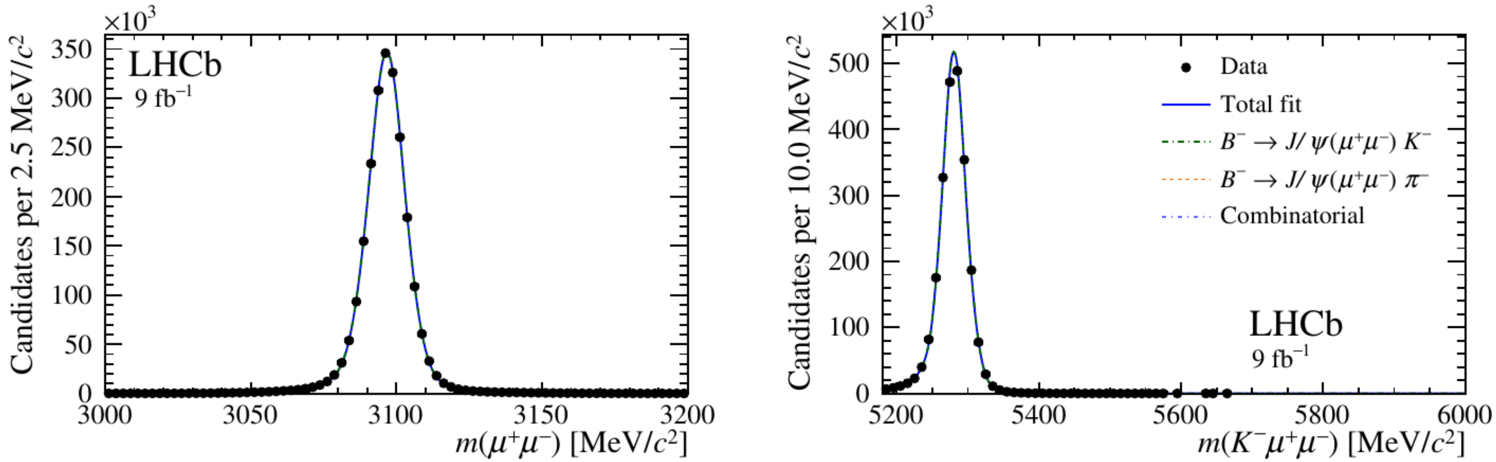
Rare decays

Search for $D^*(2007)^0 \to \mu^+\mu^-$ in $B^- \to \pi^-\mu^+\mu^-$ decays

arXiv: 2304.01981

- Decays of B mesons don't have to be used only for the tagging D^{*+}/D^0 mesons but can be utilized in searches for rare decays of D mesons as well
- $V \to \mu^+\mu^-$ decays probe same operators as pseudo-scalar decays, but not helicity suppressed
- Predicted BR 10^{-19}, expected LHCb sensitivity with a full data-set: 10^{-8}
  - Not possible to observe but still can rule out several BSM models
- Using $B^- \to J/\psi K^-$ as the control channel resulting Branching fraction can be computed as:

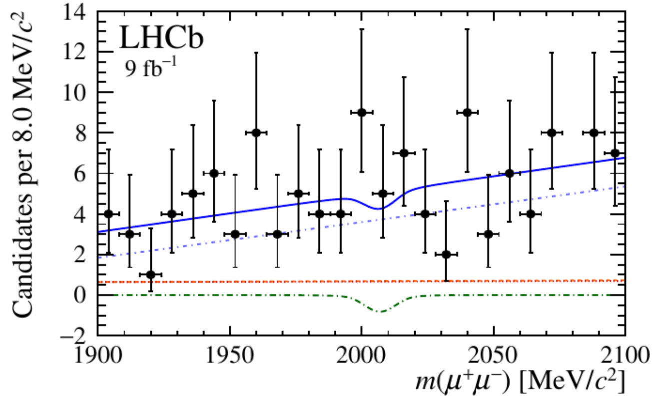
$$\mathcal{B}\left(D^{*0} \to \mu^+\mu^-\right) = \frac{N_{D^{*0}\pi^-}}{N_{J/\psi K^-}} \cdot \frac{\varepsilon_{J/\psi K^-}}{\varepsilon_{D^{*0}\pi^-}} \cdot \frac{\mathcal{B}\left(B^- \to J/\psi K^-\right)}{\mathcal{B}\left(B^- \to D^{*0}\pi^-\right)} \cdot \mathcal{B}\left(J/\psi \to \mu^+\mu^-\right)$$

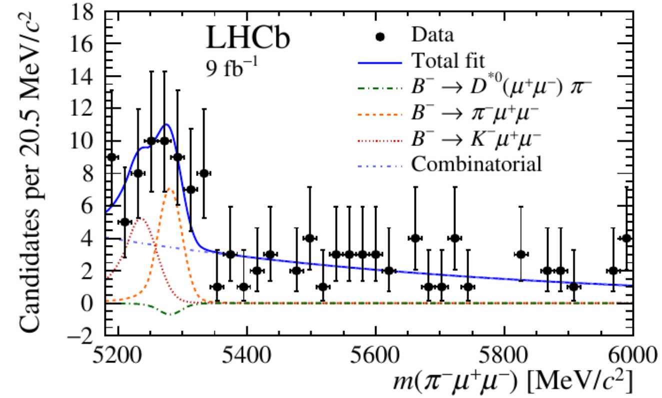


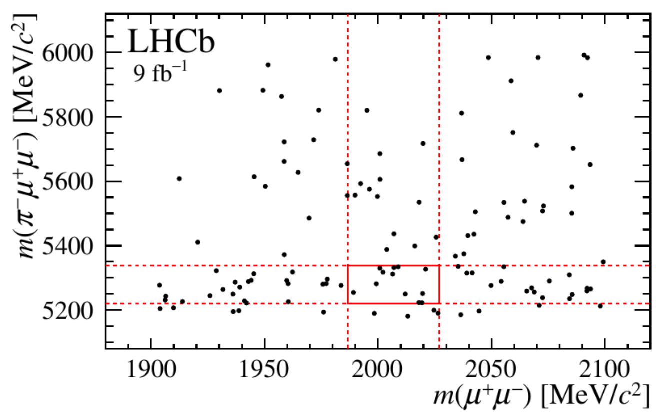
Search for $D^*(2007)^0 \to \mu^+\mu^-$ in $B^- \to \pi^-\mu^+\mu^-$ decays

arXiv: 2304.01981

- Signal fit to $B^- \to D^{*0}(\mu^+\mu^-)\pi^-$ is performed as 2D unbinned fit to the $m(\mu^+\mu^-)$ and $m(\pi^-\mu^+\mu^-)$ distributions
- Four components included: signal $B^- \to D^{*0}\pi^-$, non-resonant $B^- \to \mu^+\mu^-\pi^-$ decays, misidentified $B^- \to \mu^+\mu^-K^-$ decays and combinatorial background.







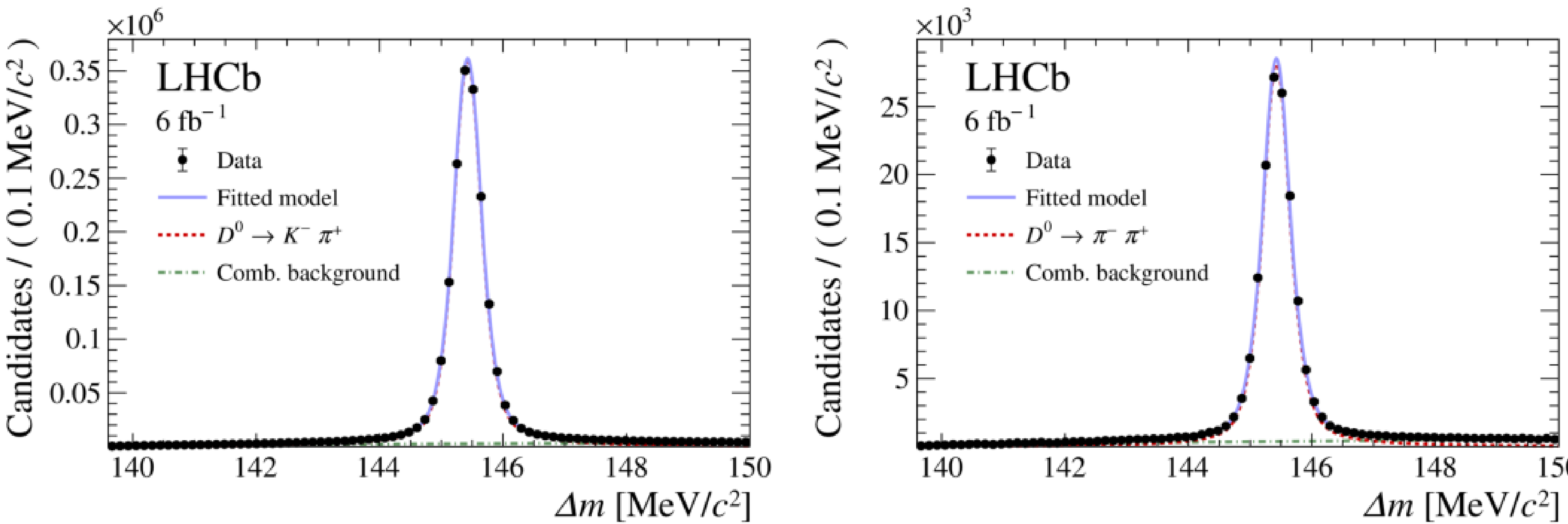
- Upper limit set as: $\mathcal{B}(D^{*0} \to \mu^+\mu^-) < 2.6\,(3.4) \times 10^{-8}$ at 90 (95)% CL

Search for rare decays of D^0 mesons into two muons

arXiv: 2212.11203

- FCNC c -> ull transition, mediated through a short-distance, BF ~ 10^{-18}, a long-distance, BF < 10^{-13}, contributions
- Possible enhancements from BSM models
- Previous LHCb results based on Run 1 data: $B(D^0 \to \mu^+\mu^-) < 7.6 \times 10^{-9}$ at 95% CL

- New analysis based on full Run 1 + Run 2 dataset
- D^0 -> Kπ and ππ used as a control channel $\mathcal{B}(D^0 \to \mu^+\mu^-) = \frac{N_{D^0\to\mu^+\mu^-}}{N_{D^0\to h^+h^-}} \cdot \frac{\varepsilon_{h^+h^-}}{\varepsilon_{\mu^+\mu^-}} \cdot s \cdot \mathcal{B}(D^0 \to h^+h^-) \equiv \alpha N_{D^0\to\mu^+\mu^-}$



Search for rare decays of D^0 mesons into two muons

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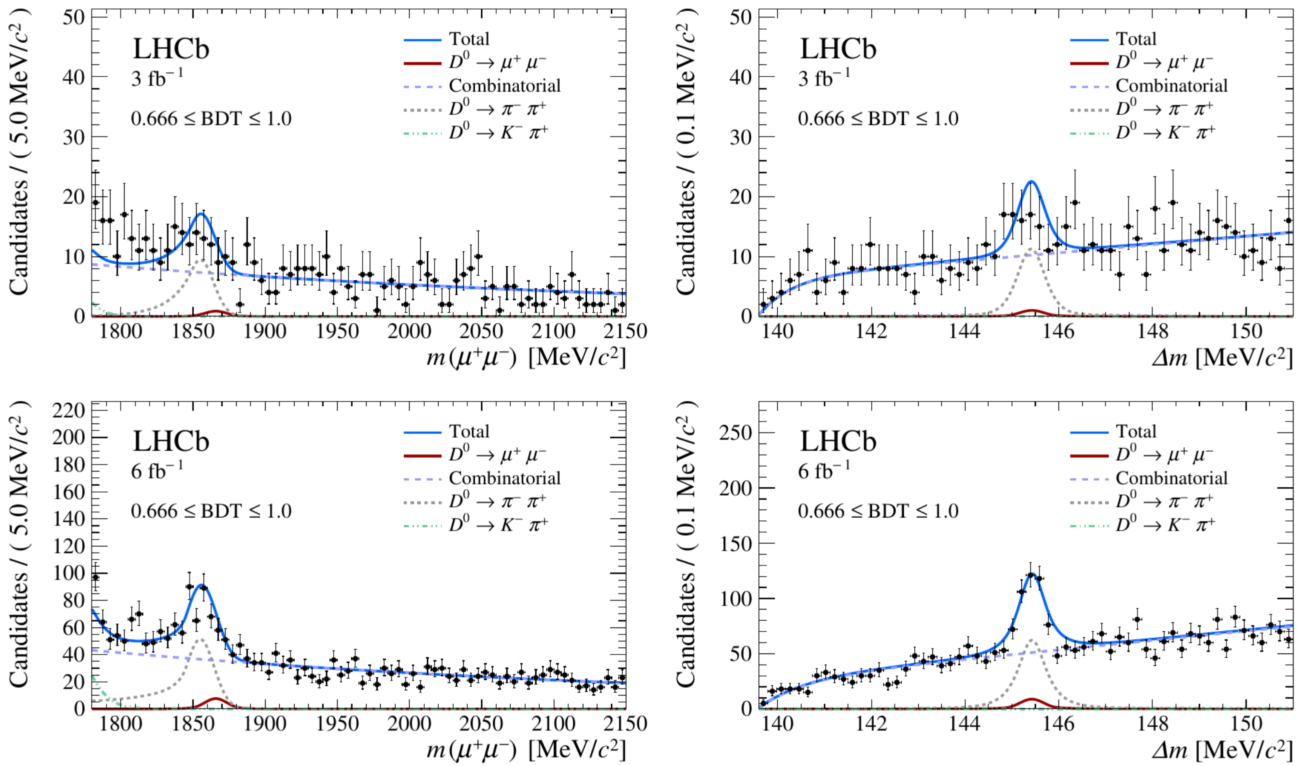
- Final fit to the data:



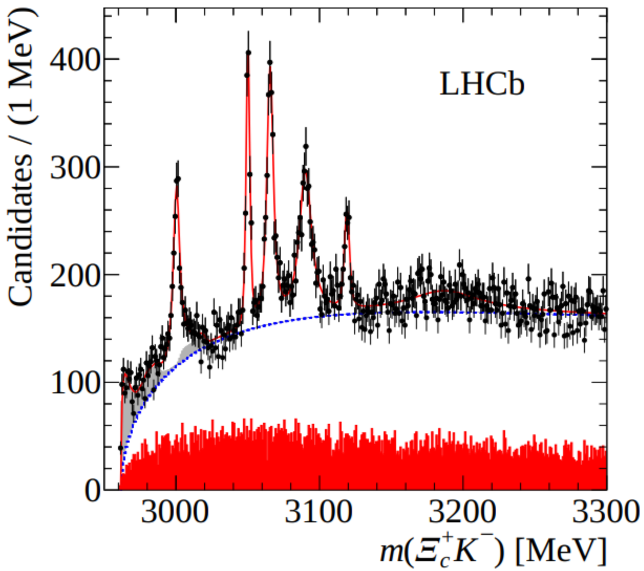
- Signal yield: 79 ± 45
- Upper limit set as $\mathcal{B}(D^0 \to \mu^+\mu^-) < 3.1\,(3.5) \times 10^{-9}$ at 90 (95)% CL

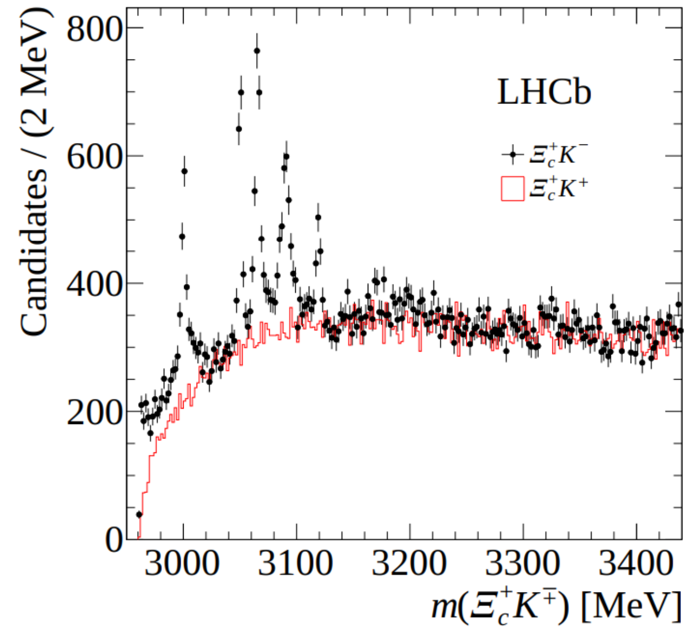
Spectroscopy

Observation of new Ω_c^0 states decaying to the $\Xi_c^+ K^-$ final state

arXiv: 2302.04733

- In 2017 LHCb studied $\Xi_c^+ K^-$ spectrum up to 3450 MeV using 3.3 fb^{-1} of data [PRL 118 (2017) 182001]





- Five new Ω_c^0 states observed:
  - $\Omega_c(3000)^0$, $\Omega_c(3050)^0$, $\Omega_c(3066)^0$, $\Omega_c(3090)^0$, $\Omega_c(3119)^0$
  - Hint on another broad structure around 3200 and 3300 MeV

Observation of new Ω_c^0 states decaying to the $\Xi_c^+K^-$ final state

arXiv: 2302.04733

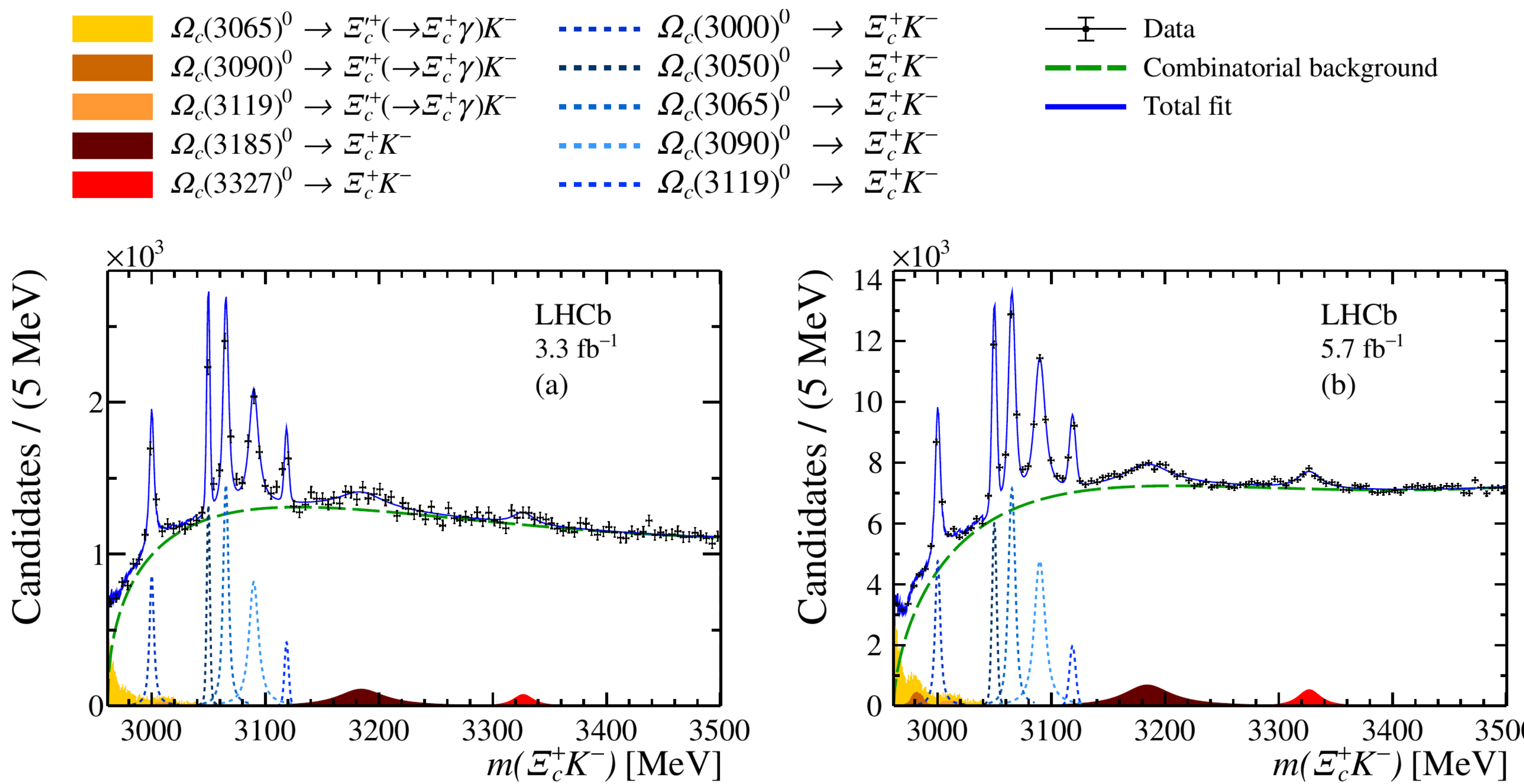
- New states can be described by heavy quark effective theory
- However large difference in predictions for masses and quantum numbers diverges in different models
  - lattice quantum chromodynamics predicts invariant-mass spectrum with D or F–wave excited states [PRL 119 042001]
  - baryon-meson molecular (quasi-bound) states interpretation for $\Omega_c(3050)^0$ and $\Omega_c(3090)^0$ [PRD 97 (2018) 094035 , EPJ. A54 (2018) 64, Few Body Syst. 61 (2020) 34]
  - interpretation as pentaquark states [PRD96 (2017) 034012, CTP 73 (2021) 035201]

- New study is based on a full LHCb data-set of 9 fb^{-1}
- Data are split into two samples contained previously analysed data (3.3 fb^{-1}) and newly added 2016-2018 data (5.7 fb^{-1})
  - Higher instantaneous luminosity and improved trigger result into five times large data set
  - Dedicated selection and BDT training per sample
- BDT trained with a special focus not to favour any particular excited state
- $\Omega_c(X)^0$ candidates are described by S-wave relativistic Breit–Wigner functions convolved with a Gaussian resolution function

Observation of new Ω_c^0 states decaying to the $\Xi_c^+K^-$ final state

arXiv: 2302.04733

- In total 7 states are reported, including two new states $\Omega_c(3185)^0$ and $\Omega_c(3327)^0$
- Several checks performed to confirm the existence of new states:
  - Splitting data into subsamples based on data-taking conditions, charge combination ($\Xi_c^+K^-$ or $\Xi_c^-K^+$) and different kinematic regions of pT(K^-) and pT(Ξ_c^+)



Proposed naming convention for exotic states

arXiv: 2206.15233v1

- A new exotic hadron naming convention proposed: 2206.15233v1
- Following properties:
  - T for tetraquark, P for pentaquark
  - superscript: based on existing symbols, to indicate isospin, parity and G-parity
  - subscript: heavy quark content

T states zero net S, C, B

(P,G)	$I=0$	$I=1$
$(-,-)$	ω	π
$(-,+)$	η	ρ
$(+,+)$	f	b
$(+,-)$	h	a

T states non-zero net S, C, B

(P)	$I=0$	$I=\frac{1}{2}$	$I=1$
$(-)$	η	τ	π
$(+)$	f	θ	a

P states

$I=0$	$I=\frac{1}{2}$	$I=1$	$I=\frac{3}{2}$
Λ	N	Σ	Δ

Minimal quark content	Current name	$I^{(G)}$, $J^{P(C)}$	Proposed name	Reference
$c\bar{c}$	$\chi_{c1}(3872)$	$I^G=0^+$, $J^{PC}=1^{++}$	$\chi_{c1}(3872)$	[24, 25]
$c\bar{c}u\bar{d}$	$Z_c(3900)^+$	$I^G=1^+$, $J^P=1^+$	$T^b_{\psi 1}(3900)^+$	[26–28]
$c\bar{c}u\bar{d}$	$X(4100)^+$	$I^G=1^-$	$T_\psi(4100)^+$	[29]
$c\bar{c}u\bar{d}$	$Z_c(4430)^+$	$I^G=1^+$, $J^P=1^+$	$T^b_{\psi 1}(4430)^+$	[30, 31]
$c\bar{c}(s\bar{s})$	$\chi_{c1}(4140)$	$I^G=0^+$, $J^{PC}=1^{++}$	$\chi_{c1}(4140)$	[32–35]
$c\bar{c}u\bar{s}$	$Z_{cs}(4000)^+$	$I=\frac{1}{2}$, $J^P=1^+$	$T^\theta_{\psi s1}(4000)^+$	[7]
$c\bar{c}u\bar{s}$	$Z_{cs}(4220)^+$	$I=\frac{1}{2}$, $J^P=1^?$	$T_{\psi s1}(4220)^+$	[7]
$c\bar{c}c\bar{c}$	$X(6900)$	$I^G=0^+$, $J^{PC}=?^{?+}$	$T_{\psi\psi}(6900)$	[4]
$cs\bar{u}\bar{d}$	$X_0(2900)$	$J^P=0^+$	$T_{cs0}(2900)^0$	[5, 6]
$cs\bar{u}\bar{d}$	$X_1(2900)$	$J^P=1^-$	$T_{cs1}(2900)^0$	[5, 6]
$cc\bar{u}\bar{d}$	$T_{cc}(3875)^+$		$T_{cc}(3875)^+$	[8, 9]
$b\bar{b}u\bar{d}$	$Z_b(10610)^+$	$I^G=1^+$, $J^P=1^+$	$T^b_{\Upsilon 1}(10610)^+$	[36]
$c\bar{c}uud$	$P_c(4312)^+$	$I=\frac{1}{2}$	$P^N_\psi(4312)^+$	[3]
$c\bar{c}uds$	$P_{cs}(4459)^0$	$I=0$	$P^\Lambda_{\psi s}(4459)^0$	[20]

Start of LHCb Run 3

Prospects for LHCb Run 3

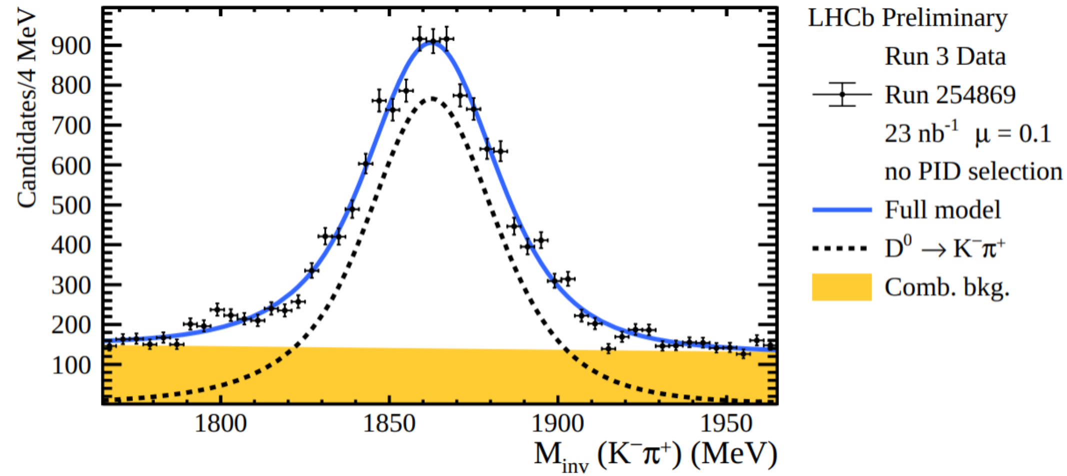
CERN-LHCC-2012-007 /
LHCb-TDR-12

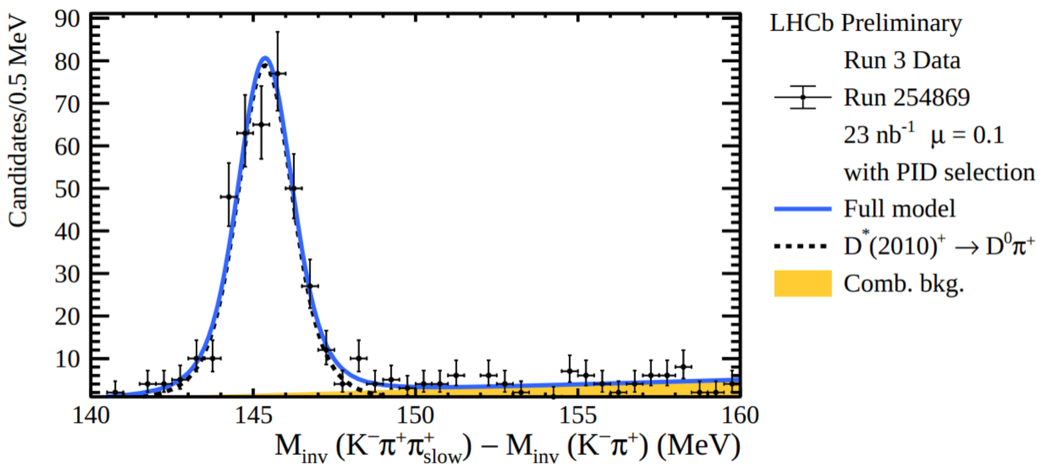
- Claimed prospects for LHCb Run 3

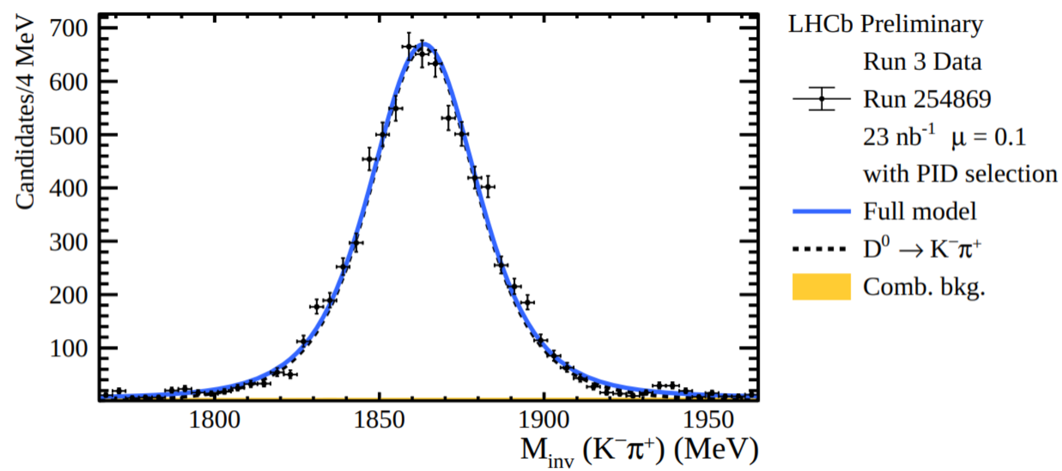
Type	Observable	Current precision	LHCb 2018	**Upgrade** ($50\,\mathrm{fb}^{-1}$)	Theory uncertainty
B^0_s mixing	$2\beta_s$ ($B^0_s \to J/\psi\ \phi$)	0.10 [9]	0.025	0.008	~ 0.003
	$2\beta_s$ ($B^0_s \to J/\psi\ f_0(980)$)	0.17 [10]	0.045	0.014	~ 0.01
	$A_{\mathrm{fs}}(B^0_s)$	6.4×10^{-3} [18]	0.6×10^{-3}	0.2×10^{-3}	0.03×10^{-3}
Gluonic penguin	$2\beta^{\mathrm{eff}}_s(B^0_s \to \phi\phi)$	–	0.17	0.03	0.02
	$2\beta^{\mathrm{eff}}_s(B^0_s \to K^{*0}\bar{K}^{*0})$	–	0.13	0.02	< 0.02
	$2\beta^{\mathrm{eff}}(B^0 \to \phi K^0_S)$	0.17 [18]	0.30	0.05	0.02
Right-handed currents	$2\beta^{\mathrm{eff}}_s(B^0_s \to \phi\gamma)$	–	0.09	0.02	< 0.01
	$\tau^{\mathrm{eff}}(B^0_s \to \phi\gamma)/\tau_{B^0_s}$	–	5 %	1 %	0.2 %
Electroweak penguin	$S_3(B^0 \to K^{*0}\mu^+\mu^-; 1 < q^2 < 6\,\mathrm{GeV}^2/c^4)$	0.08 [14]	0.025	0.008	0.02
	$s_0\ A_{\mathrm{FB}}(B^0 \to K^{*0}\mu^+\mu^-)$	25 % [14]	6 %	2 %	7 %
	$A_{\mathrm{I}}(K\mu^+\mu^-; 1 < q^2 < 6\,\mathrm{GeV}^2/c^4)$	0.25 [15]	0.08	0.025	~ 0.02
	$\mathcal{B}(B^+ \to \pi^+\mu^+\mu^-)/\mathcal{B}(B^+ \to K^+\mu^+\mu^-)$	25 % [16]	8 %	2.5 %	~ 10 %
Higgs penguin	$\mathcal{B}(B^0_s \to \mu^+\mu^-)$	1.5×10^{-9} [2]	0.5×10^{-9}	0.15×10^{-9}	0.3×10^{-9}
	$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B^0_s \to \mu^+\mu^-)$	–	~ 100 %	~ 35 %	~ 5 %
Unitarity triangle angles	γ ($B \to D^{(*)}K^{(*)}$)	$\sim$ 10–12° [19, 20]	4°	0.9°	negligible
	γ ($B^0_s \to D_s K$)	–	11°	2.0°	negligible
	β ($B^0 \to J/\psi\ K^0_S$)	0.8° [18]	0.6°	0.2°	negligible
Charm CP violation	A_Γ	2.3×10^{-3} [18]	0.40×10^{-3}	0.07×10^{-3}	–
	ΔA_{CP}	2.1×10^{-3} [5]	0.65×10^{-3}	0.12×10^{-3}	–

Start of LHCb Run 3

- First data of the upgraded LHCb already recorded in 2022
- New tracker detectors and upgraded electronic of remaining detectors
- Fully software trigger is especially beneficial for hadronic decays and allows to record larger statistics while keeping efficiency similar to Run 2
- LHCb is getting ready for a nominal Run 3 data taking







Thank you for the attention

Spare slides

Time-integrated CP asymmetry in $D^0 \to K^-K^+$ decays

- Based on 2016-2018 data, tagged from promptly produced D*
- Time-integrated CP asymmetry is defined as:

$$f = K^-K^+/\pi^-\pi^+$$

$$\mathcal{A}_{CP}(f) \equiv \frac{\int \mathrm{d}t\, \epsilon(t)\left[\Gamma(D^0 \to f)(t) - \Gamma(\overline{D}^0 \to f)(t)\right]}{\int \mathrm{d}t\, \epsilon(t)\left[\Gamma(D^0 \to f)(t) + \Gamma(\overline{D}^0 \to f)(t)\right]} \approx a_f^d + \frac{\langle t \rangle_f}{\tau_D} \cdot \Delta Y_f$$

- Complex method to cancel experimental asymmetries applied, depending on set of CF modes

$$A_{CP}(f) = \frac{\int \epsilon(t)[\Gamma(D^0 \to f)(t) - \Gamma(\bar{D}^0 \to \bar{f})(t)]\mathrm{d}t}{\int \epsilon(t)[\Gamma(D^0 \to f)(t) + \Gamma(\bar{D}^0 \to \bar{f})(t)]\mathrm{d}t} = a_f^d + \frac{<t>_f}{\tau_{D^0}} \Delta Y_f$$

- $\epsilon(t)$ is the time-dependent reconstruction efficiency
- ΔY_f is related to charm mixing and related CPV parameters $\approx x\phi - y\left(\left|\frac{q}{p}\right| - 1\right)$
- $< t >_f$ is the average acceptance-dependent decay time of the D^0 mesons in the reconstructed sample

$$A_{CP}(D \to f) = \frac{\Gamma(D \to f) - \Gamma(\overline{D} \to \bar{f})}{\Gamma(D \to f) + \Gamma(\overline{D} \to \bar{f})}$$

- Direct CP violation when $|A_f|^2 \neq |\bar{A}_{\bar{f}}|^2$

$$i\frac{d}{dt}\begin{pmatrix} D^0(t) \\ \overline{D}^0(t) \end{pmatrix} = \left(\boldsymbol{M} - \frac{i}{2}\boldsymbol{\Gamma}\right)\begin{pmatrix} D^0(t) \\ \overline{D}^0(t) \end{pmatrix}$$

- For oscillating neutral mesons, mass eigenstates $|D_{1,2}\rangle = p|D^0\rangle \pm q|\overline{D}^0\rangle$
  - CP violation in mixing when $|q/p| \neq 1$
  - CP violation in decay-mixing interference when $\phi_f \equiv \arg[(q\bar{A}_f)/(pA_f)] \neq 0$

Phenomenological parametrisation

$$x \equiv \frac{2(m_1 - m_2)}{\Gamma_1 + \Gamma_2}, \quad y \equiv \frac{\Gamma_2 - \Gamma_1}{\Gamma_1 + \Gamma_2}, \quad \left|\frac{q}{p}\right| - 1$$

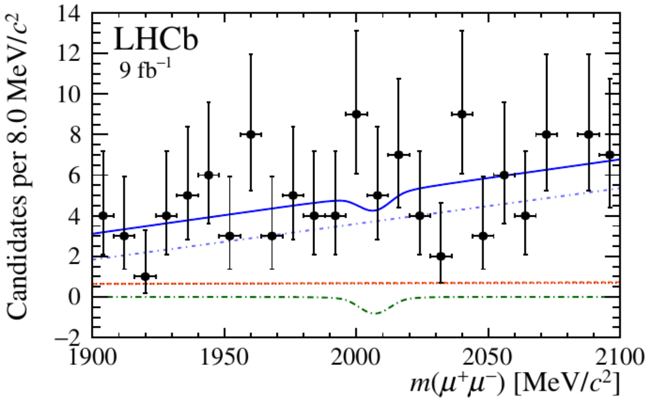
Theoretical parametrisation

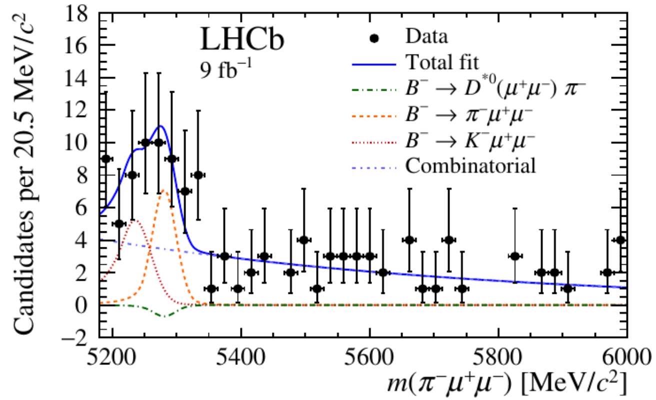
$$x_{12} \equiv \frac{2|M_{12}|}{\Gamma_1 + \Gamma_2}, \quad y_{12} \equiv \frac{|\Gamma_{12}|}{\Gamma_1 + \Gamma_2}, \quad \phi_{12} \equiv \arg\left(\frac{M_{12}}{\Gamma_{12}}\right)$$

$$x^2 - y^2 = x_{12}^2 - y_{12}^2,$$
$$xy = x_{12}y_{12}\cos\phi_{12},$$
$$\left|\frac{q}{p}\right|^{\pm 2}(x^2 + y^2) = x_{12}^2 + y_{12}^2 \pm 2x_{12}y_{12}\sin\phi_{12}$$

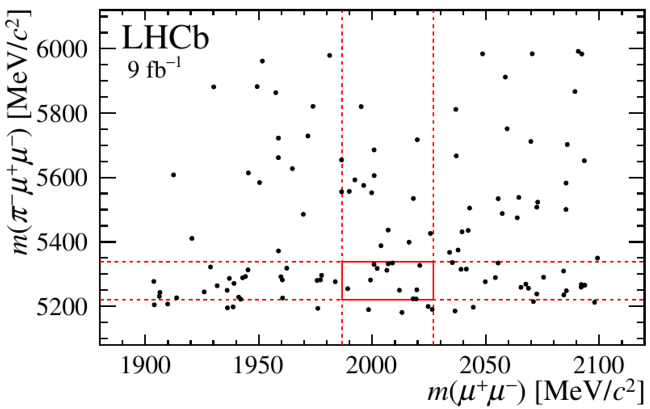
PRL 103 (2009) 071602
PRD 80 (2009) 076008
PRD 103 (2021) 053008

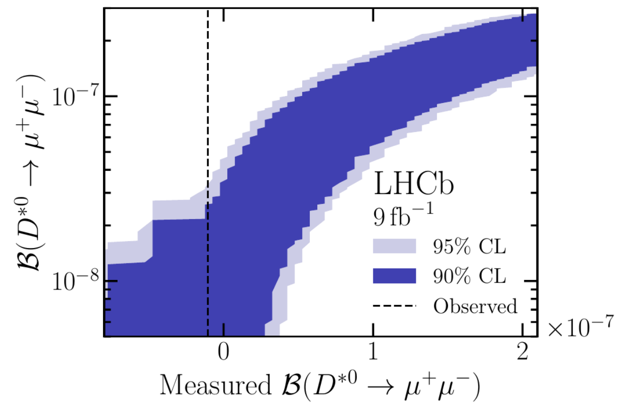
Search for $D^*(2007)^0 \to \mu^+\mu^-$ in $B^- \to \pi^-\mu^+\mu^-$ decays





Parameter	Value
$\mathcal{B}(B^- \to J/\psi K^-)$	$(10.20 \pm 0.19) \times 10^{-4}$ [25]
$\mathcal{B}(B^- \to D^{*0}\pi^-)$	$(4.90 \pm 0.17) \times 10^{-3}$ [25]
$\mathcal{B}(J/\psi \to \mu^+\mu^-)$	$(59.61 \pm 0.33) \times 10^{-3}$ [25]
$\varepsilon_{J/\psi K^-}/\varepsilon_{D^{*0}\pi^-}$	1.21 ± 0.03
$N_{J/\psi K^-}$	$(2316 \pm 8) \times 10^3$





Component	Yield
$B^- \to D^{*0}(\mu^+\mu^-)\,\pi^-$	-2 ± 3
$B^- \to \pi^-\mu^+\mu^-$	17 ± 7
$B^- \to K^-\mu^+\mu^-$	17 ± 8
Combinatorial bkg.	90 ± 13

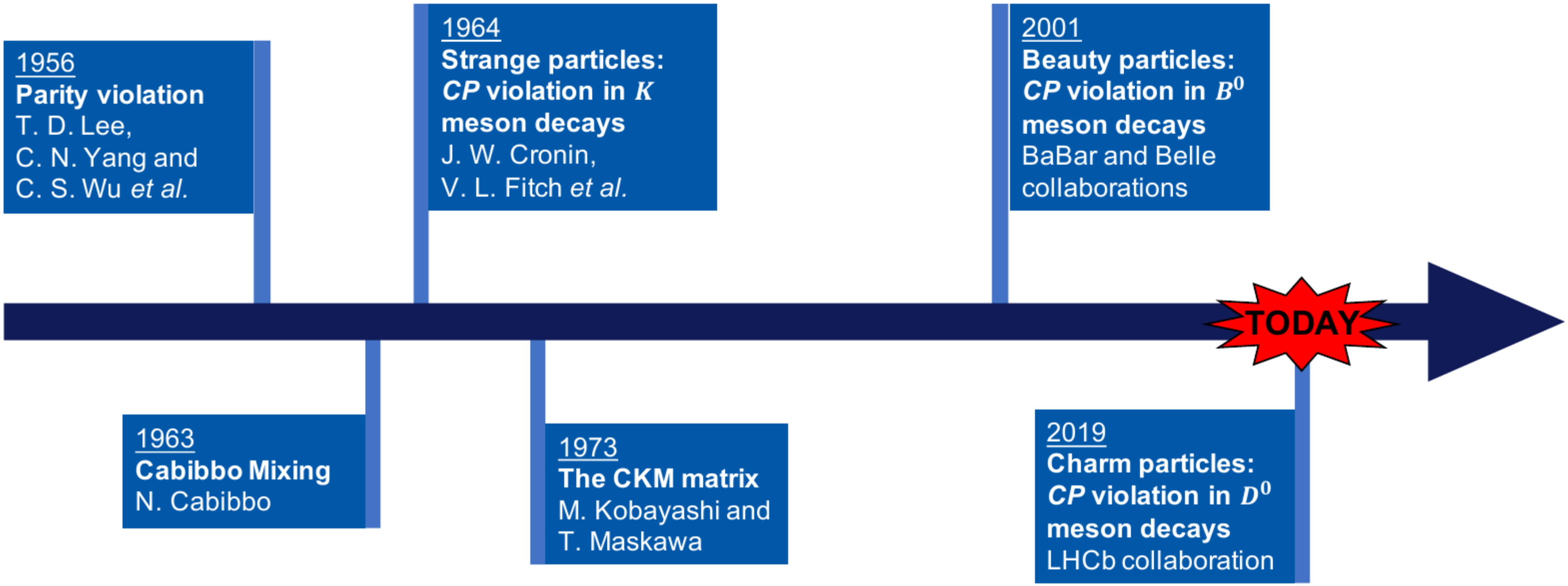
$$\mathcal{B}(D^{*0} \to \mu^+\mu^-) < 2.6\,(3.4) \times 10^{-8} \text{ at } 90\ (95)\% \text{ CL}$$

Observation of new Ω_c^0 states decaying to the $\Xi_c^+K^-$ final state

- New study is based on a full LHCb data-set of 9 fb^{-1}
- Data are split into two samples contained previously analysed data (3.3 fb^{-1}) and newly added 2016-2018 data (5.7 fb^{-1})
  - Higher instantaneous luminosity and improved result result into five times large data set
  - Dedicated selection and BDT for both samples
- BDT trained with a special focus not to favour any particular excited state
- To improve the mass resolution, the variable $m(\Xi_c^+K^-)$ is defined as the difference between the invariant mass of the $\Omega_c(X)^0$ and Ξ_c^+ candidates
- $\Omega_c(X)^0$ candidates are described S-wave relativistic Breit–Wigner functions convolved with a Gaussian

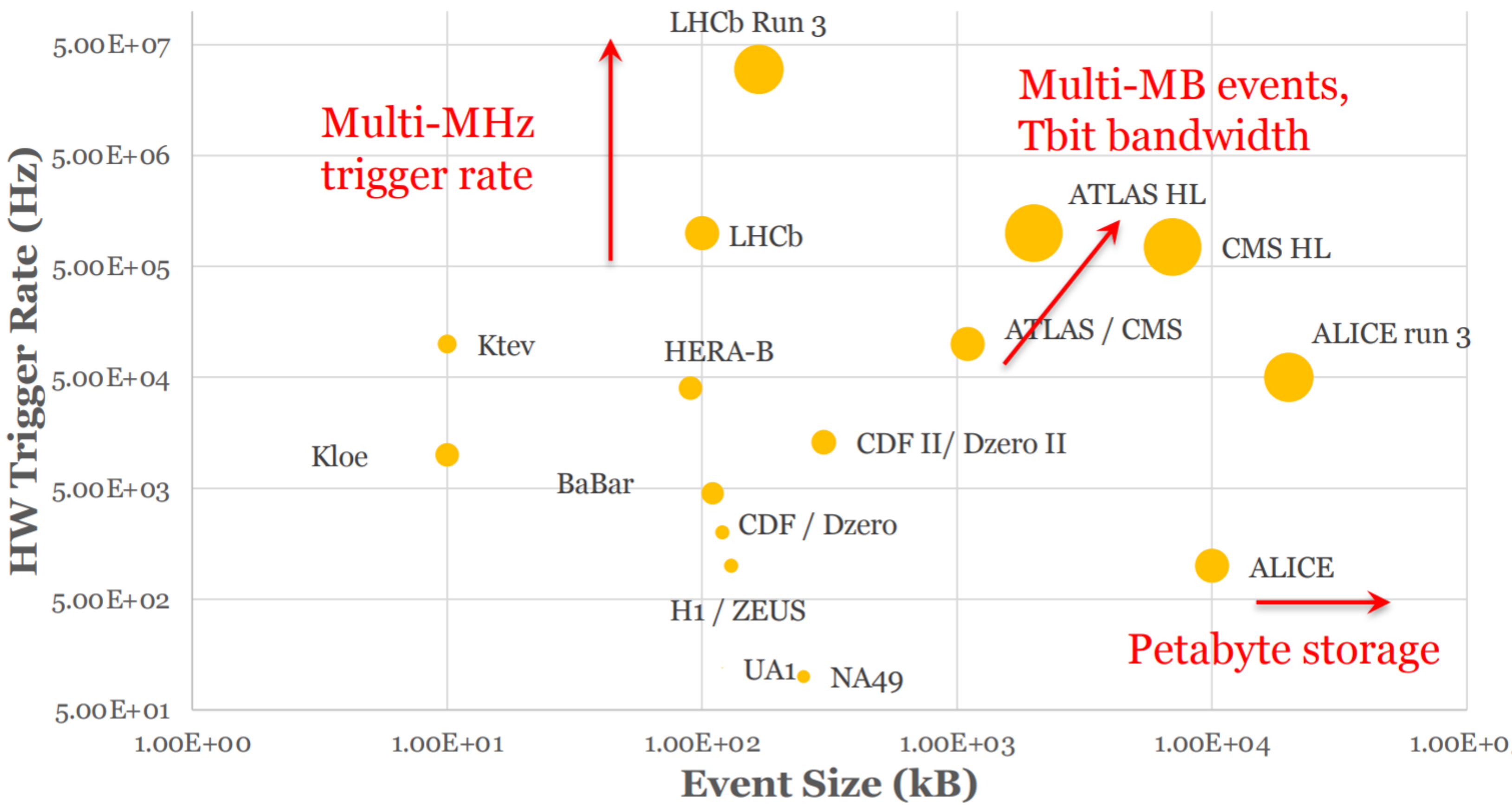
Resonance	m (MeV)	Γ (MeV)
$\Omega_c(3000)^0$	$3000.44 \pm 0.07\ ^{+0.07}_{-0.13} \pm 0.23$	$3.83 \pm 0.23\ ^{+1.59}_{-0.29}$
$\Omega_c(3050)^0$	$3050.18 \pm 0.04\ ^{+0.06}_{-0.07} \pm 0.23$	$0.67 \pm 0.17\ ^{+0.64}_{-0.72}$
		$< 1.8\,\text{MeV}, 95\%$ C.L.
$\Omega_c(3065)^0$	$3065.63 \pm 0.06\ ^{+0.06}_{-0.06} \pm 0.23$	$3.79 \pm 0.20\ ^{+0.38}_{-0.47}$
$\Omega_c(3090)^0$	$3090.16 \pm 0.11\ ^{+0.06}_{-0.10} \pm 0.23$	$8.48 \pm 0.44\ ^{+0.61}_{-1.62}$
$\Omega_c(3119)^0$	$3118.98 \pm 0.12\ ^{+0.09}_{-0.23} \pm 0.23$	$0.60 \pm 0.63\ ^{+0.90}_{-1.05}$
		$< 2.5\,\text{MeV}, 95\%$ C.L.
$\Omega_c(3185)^0$	$3185.1 \pm 1.7\ ^{+7.4}_{-0.9} \pm 0.2$	$50 \pm 7\ ^{+10}_{-20}$
$\Omega_c(3327)^0$	$3327.1 \pm 1.2\ ^{+0.1}_{-1.3} \pm 0.2$	$20 \pm 5\ ^{+13}_{-1}$

Type	Observable	Current precision	LHCb 2018	**Upgrade** ($50\,\text{fb}^{-1}$)	Theory uncertainty
B_s^0 mixing	$2\beta_s$ ($B_s^0 \to J/\psi\ \phi$)	0.10 [9]	0.025	0.008	~ 0.003
	$2\beta_s$ ($B_s^0 \to J/\psi\ f_0(980)$)	0.17 [10]	0.045	0.014	~ 0.01
	$A_{\text{fs}}(B_s^0)$	6.4×10^{-3} [18]	0.6×10^{-3}	0.2×10^{-3}	0.03×10^{-3}
Gluonic penguin	$2\beta_s^{\text{eff}}(B_s^0 \to \phi\phi)$	–	0.17	0.03	0.02
	$2\beta_s^{\text{eff}}(B_s^0 \to K^{*0}\bar{K}^{*0})$	–	0.13	0.02	< 0.02
	$2\beta^{\text{eff}}(B^0 \to \phi K_S^0)$	0.17 [18]	0.30	0.05	0.02
Right-handed currents	$2\beta_s^{\text{eff}}(B_s^0 \to \phi\gamma)$	–	0.09	0.02	< 0.01
	$\tau^{\text{eff}}(B_s^0 \to \phi\gamma)/\tau_{B_s^0}$	–	5 %	1 %	0.2 %
Electroweak penguin	$S_3(B^0 \to K^{*0}\mu^+\mu^-; 1 < q^2 < 6\,\text{GeV}^2/c^4)$	0.08 [14]	0.025	0.008	0.02
	$s_0\, A_{\text{FB}}(B^0 \to K^{*0}\mu^+\mu^-)$	25 % [14]	6 %	2 %	7 %
	$A_{\text{I}}(K\mu^+\mu^-; 1 < q^2 < 6\,\text{GeV}^2/c^4)$	0.25 [15]	0.08	0.025	~ 0.02
	$\mathcal{B}(B^+ \to \pi^+\mu^+\mu^-)/\mathcal{B}(B^+ \to K^+\mu^+\mu^-)$	25 % [16]	8 %	2.5 %	~ 10 %
Higgs penguin	$\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	1.5×10^{-9} [2]	0.5×10^{-9}	0.15×10^{-9}	0.3×10^{-9}
	$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	–	~ 100 %	~ 35 %	~ 5 %
Unitarity triangle angles	γ ($B \to D^{(*)}K^{(*)}$)	~ 10–$12°$ [19, 20]	4°	0.9°	negligible
	γ ($B_s^0 \to D_s K$)	–	11°	2.0°	negligible
	β ($B^0 \to J/\psi\, K_S^0$)	0.8° [18]	0.6°	0.2°	negligible
Charm *CP* violation	A_Γ	2.3×10^{-3} [18]	0.40×10^{-3}	0.07×10^{-3}	–
	ΔA_{CP}	2.1×10^{-3} [5]	0.65×10^{-3}	0.12×10^{-3}	–


1956
Parity violation
T. D. Lee,
C. N. Yang and
C. S. Wu *et al.*
1963
Cabibbo Mixing
N. Cabibbo
1964
Strange particles:
CP violation in K
meson decays
J. W. Cronin,
V. L. Fitch *et al.*
1973
The CKM matrix
M. Kobayashi and
T. Maskawa
2001
Beauty particles:
CP violation in B^0
meson decays
BaBar and Belle
collaborations
2019
Charm particles:
CP violation in D^0
meson decays
LHCb collaboration
TODAY

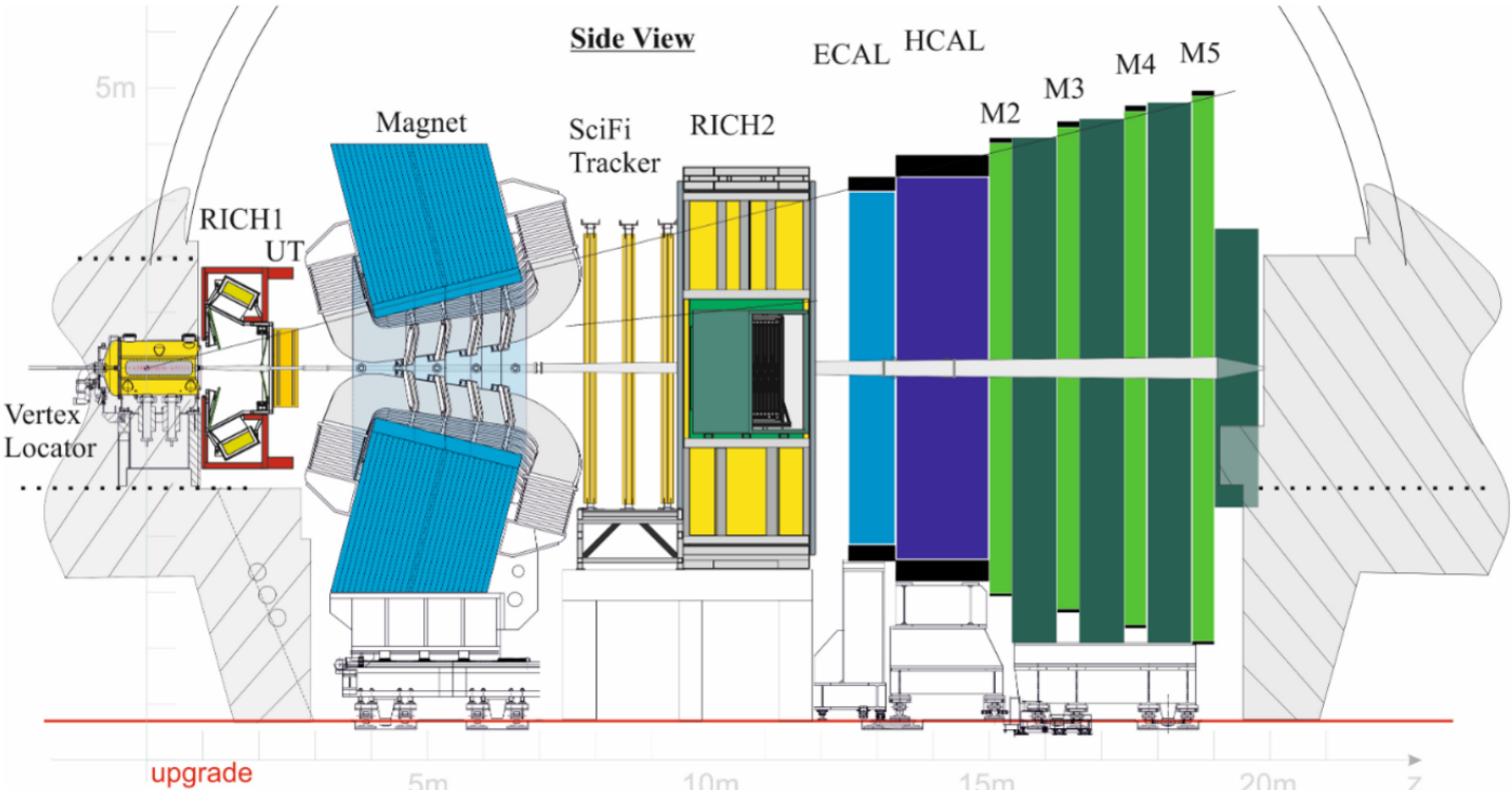
Trigger strategies

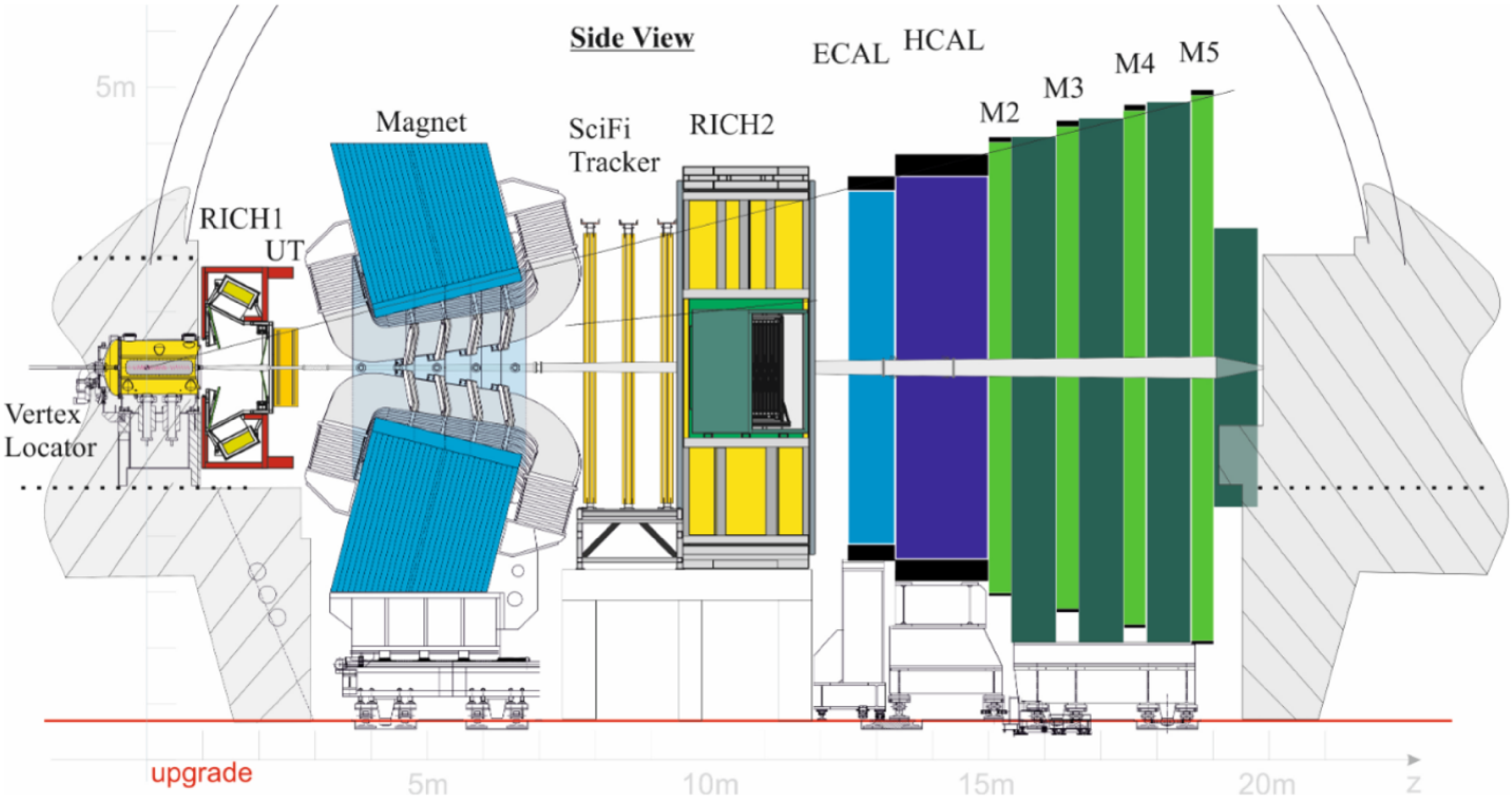
- Luminosity of 2x10^{33} cm^{-2}s^{-1}, √s = 13.6 TeV, visible collisions per bunch μ ~ 5
  - Almost all events will produce heavy quarks (*b*, *c*)
- Hard constrains: Bandwidth [GB/s] ≈ Accept Rate [kHz] × Event size [kB]



Prospects for LHCb Run 3

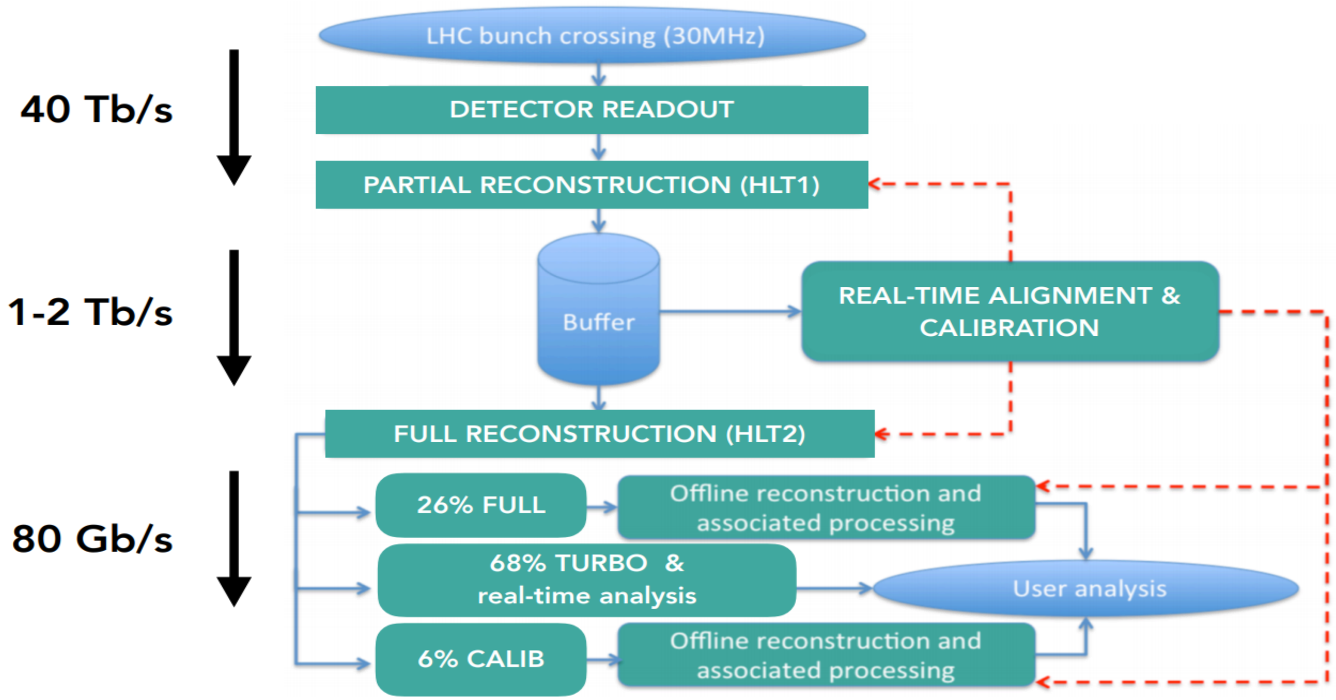
- Luminosity of 2×10^{33} $cm^{-2}s^{-1}$, $\sqrt{s}$ = 13.6 TeV, visible collisions per bunch $\mu \sim 5$
  - New tracker detectors, upgraded electronics, fully software trigger, ...
- A new detector at LHC



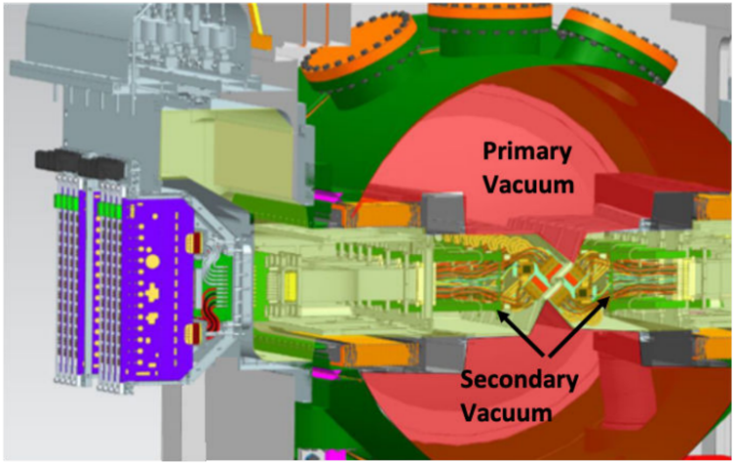

Side View
ECAL
HCAL
M2
M3
M4
M5
Magnet
SciFi
Tracker
RICH2
RICH1
UT
Vertex
Locator
5m
upgrade
5m
10m
15m
20m
z

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



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

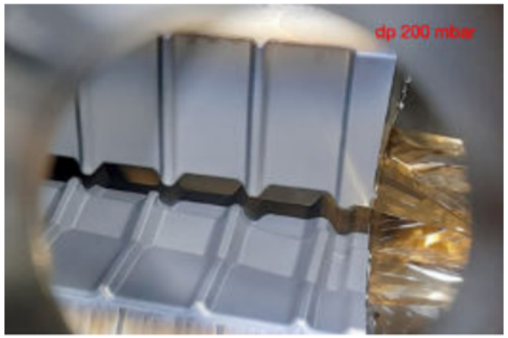
On 10th January 2023, during a VELO warm up in Neon, there was a loss of control of the protection system. A relay failed and damaged a power supply, leading to multiple equipment failures and a pumping action on the primary volume. The safety valve didn't open at the designed ΔP = 10 mbar, and a pressure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

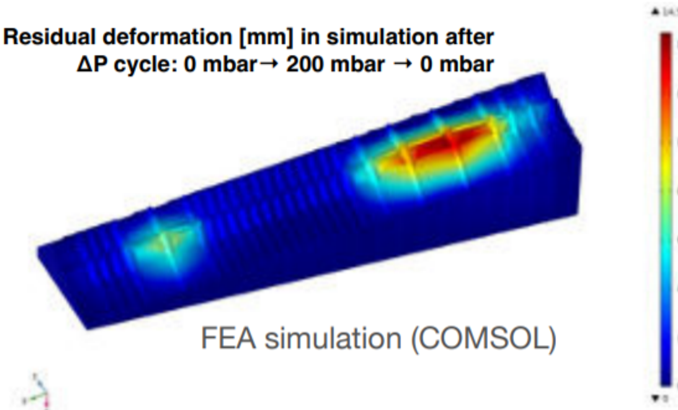
VELO incident

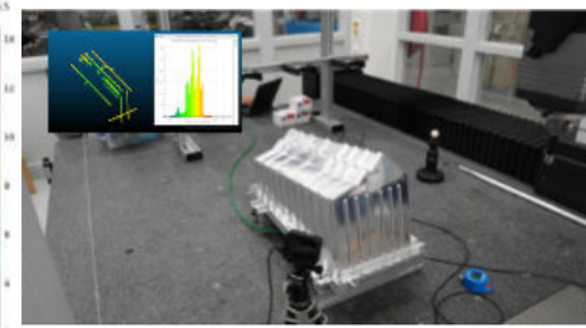
The deformation of the RF foil has been simulated, and the results have been benchmarked against measurements on a 1/2 scale prototype box.



Visualisation through viewing port

Residual deformation [mm] in simulation after ΔP cycle: 0 mbar→ 200 mbar → 0 mbar


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