17th International Conference on
Interconnections between Particle Physics and Cosmology (PPC 2024)
14 to 18 Oct, IIT Hyderabad, India

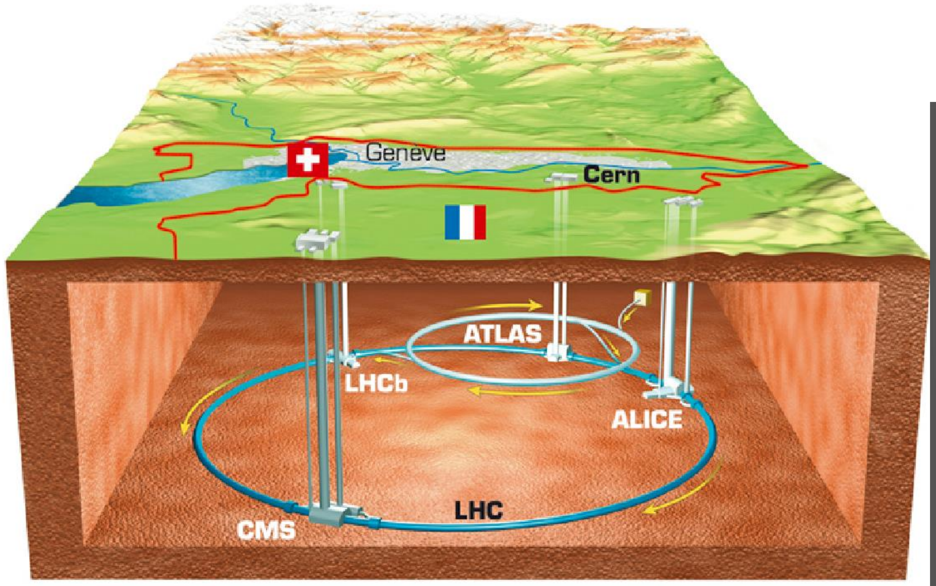
LHCb Highlights

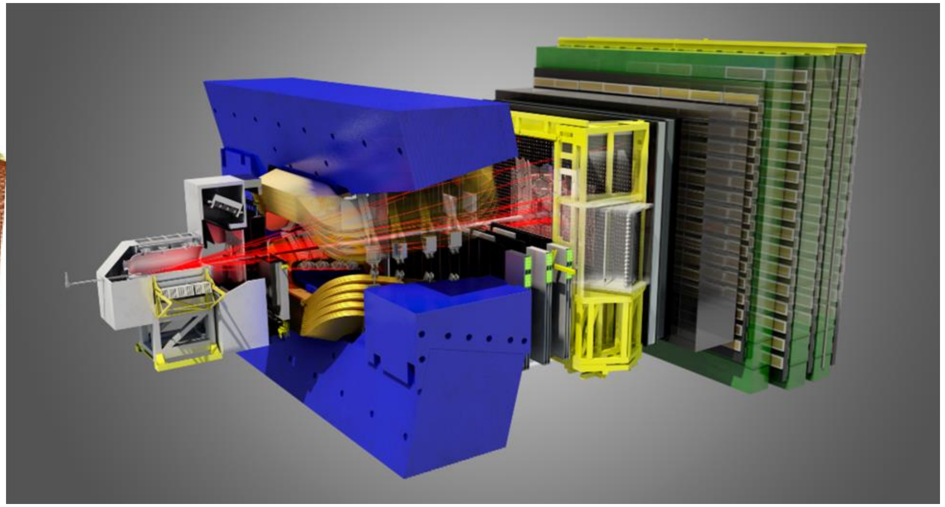
Brij Kishor Jashal
IFIC, U. Valencia, TIFR Mumbai and RAL Oxford.

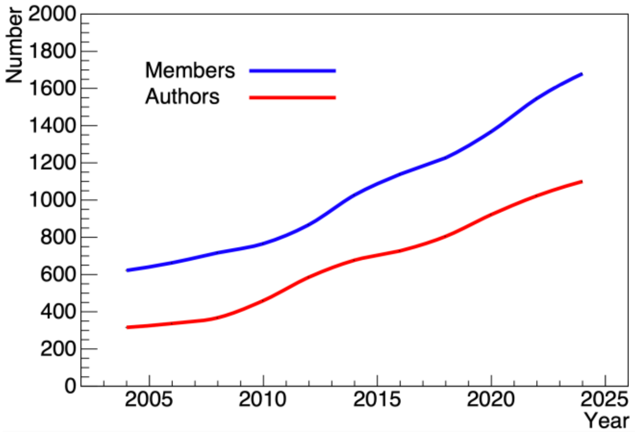
On behalf of The LHCb collaboration

Introduction

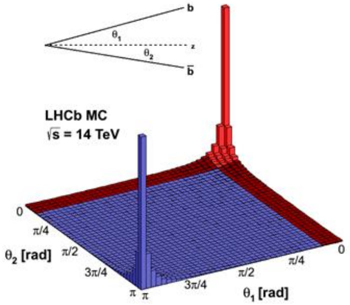
LHCb: a general purpose spectrometer in the forward direction (2<η<5), optimized for high-precision heavy--flavour physics.





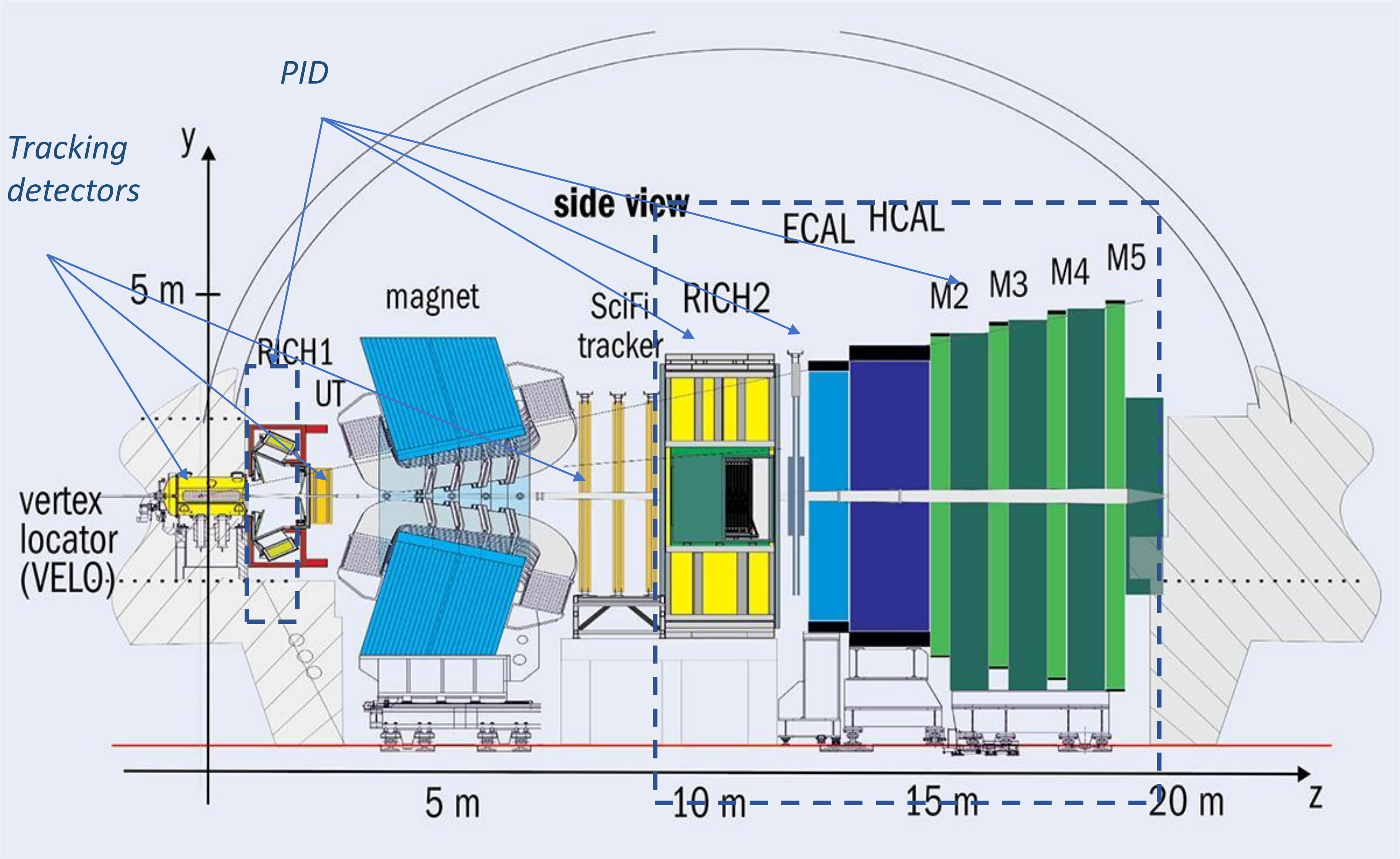


103 institutes & 1766 members



~ 4% of the solid angle (2 < η < 5),
~30% of the *b* hadron production

Introduction



Tracking:

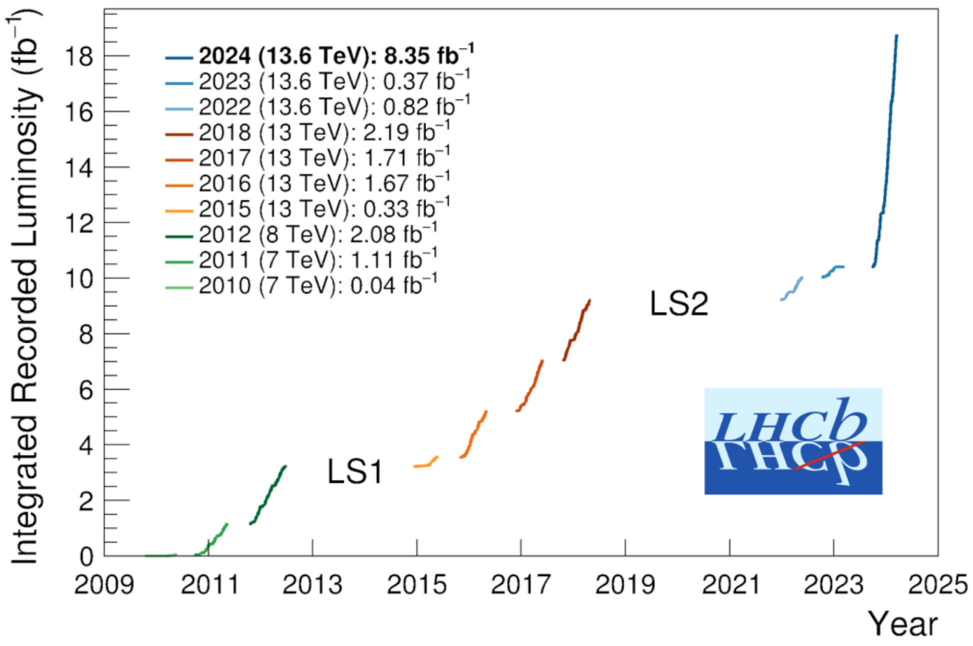
- VELO – Silicon Pixel: 52 planes, 41 million channels.
- UT – Silicon strip: 4 planes
- SciFi – Scintillating Fibres: (12 planes of 2x2.5 m)

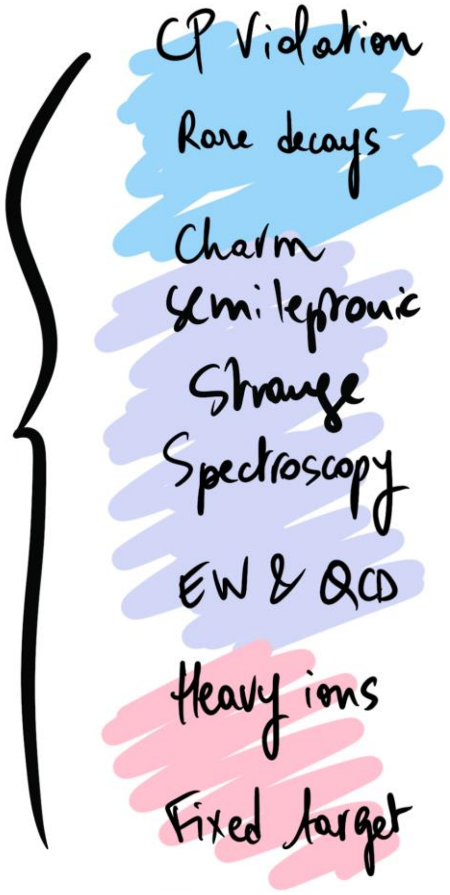
PID:

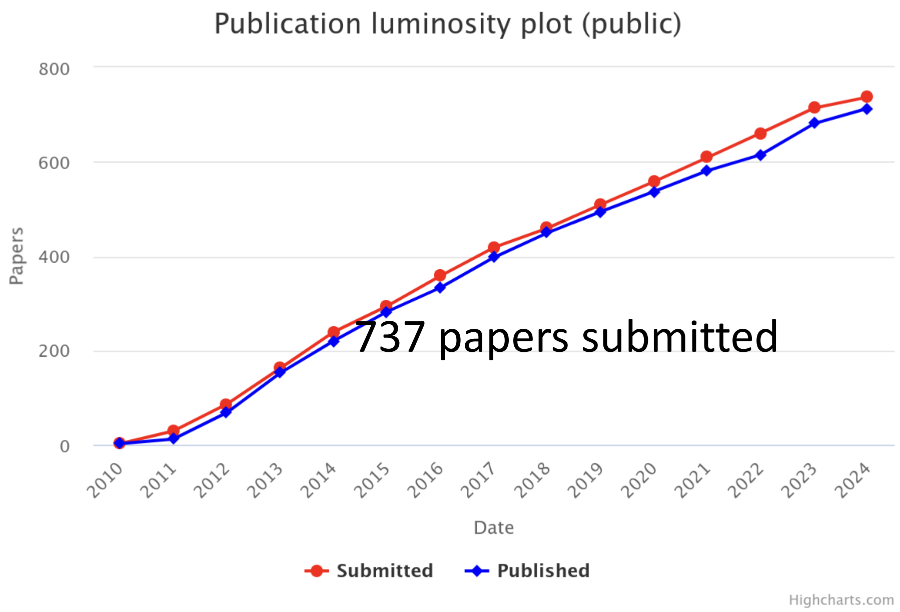
- RICH1 and 2
- Calorimeters,
- Muon chambers
- Dipole magnet with 4 TM

Introduction

LHCbs physics programme has evolved and grown a lot in the last years.



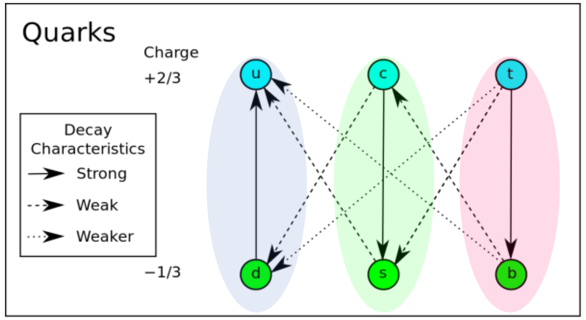


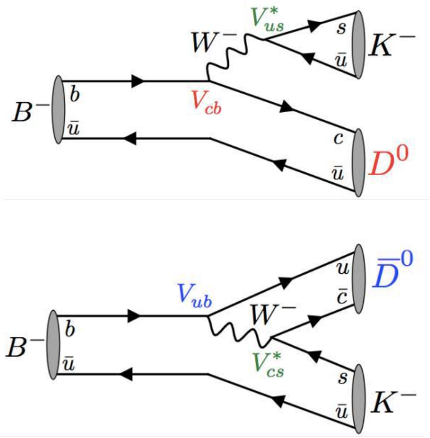


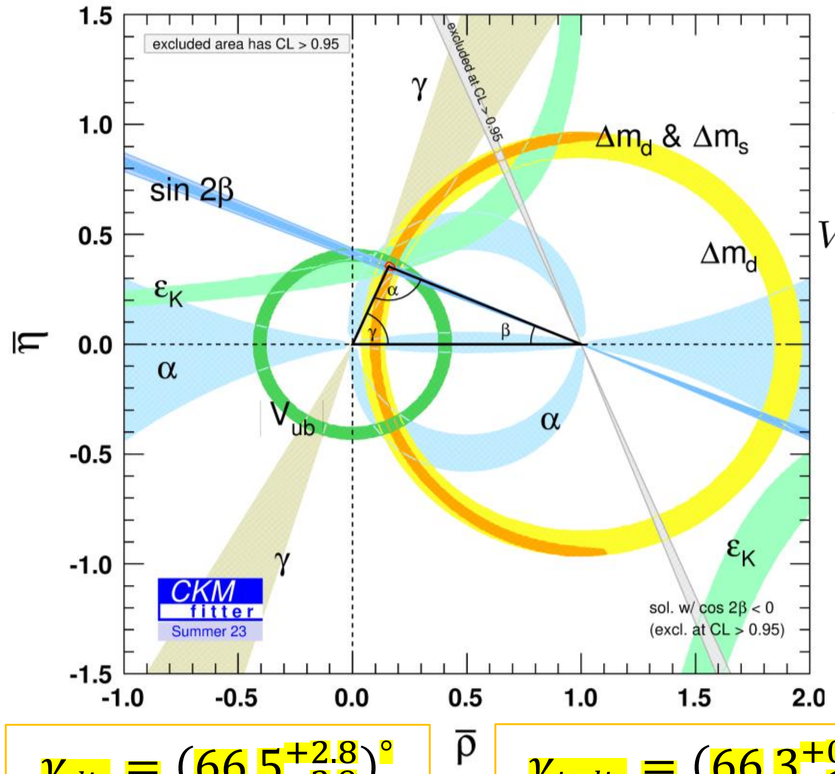
Run 1+2: 9 fb^{-1} of pp collisions (+ pPb, PbPb, fixed-target mode)
And about ~9 fb^{-1} in 2024 only so far

Improved determination of the CKM angle γ

[LHCb-CONF-2024-004]







$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

$$\gamma = \arg\left(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right)$$

$$\beta = \arg\left(-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right)$$

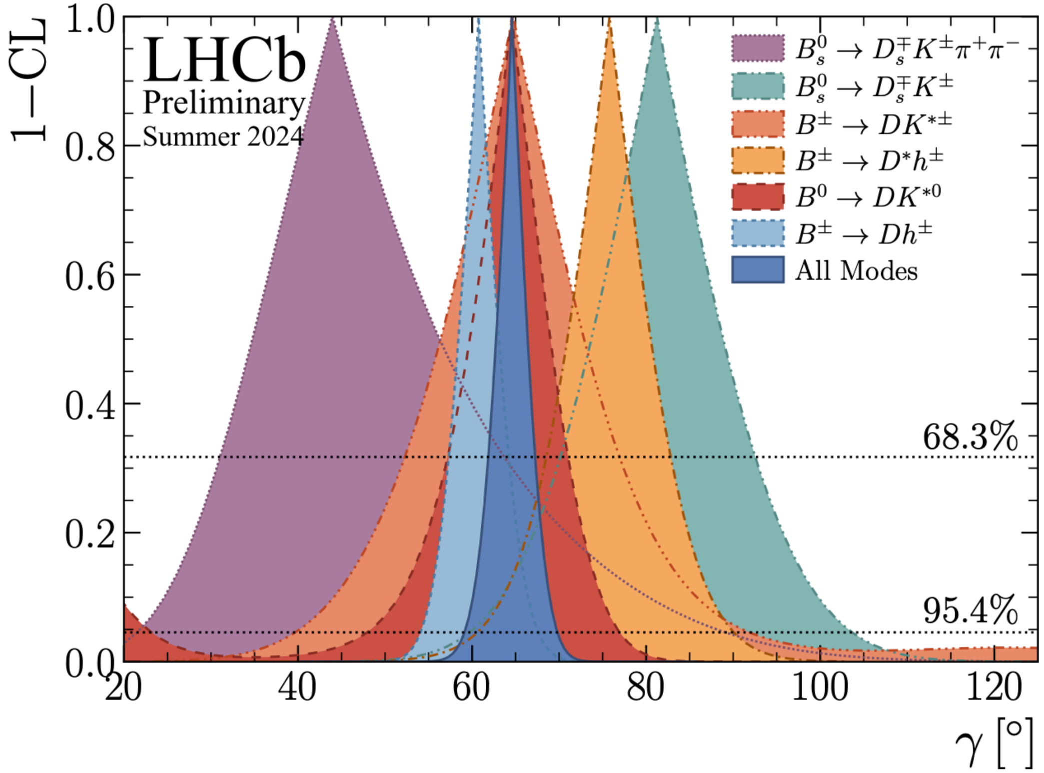
$$\alpha = \arg\left(-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right)$$

$\gamma_{dir} = (66.5^{+2.8}_{-2.9})^\circ$

$\gamma_{indir} = (66.3^{+0.7}_{-1.9})^\circ$

$\gamma = (64.6 \pm 2.8)^\circ$

- Combination of
  - 19 LHCb *B* decay results
  - 11 LHCb *D* decay results
  - 4 new and few updated measurements
  - 198 input observables to determine 53 parameters

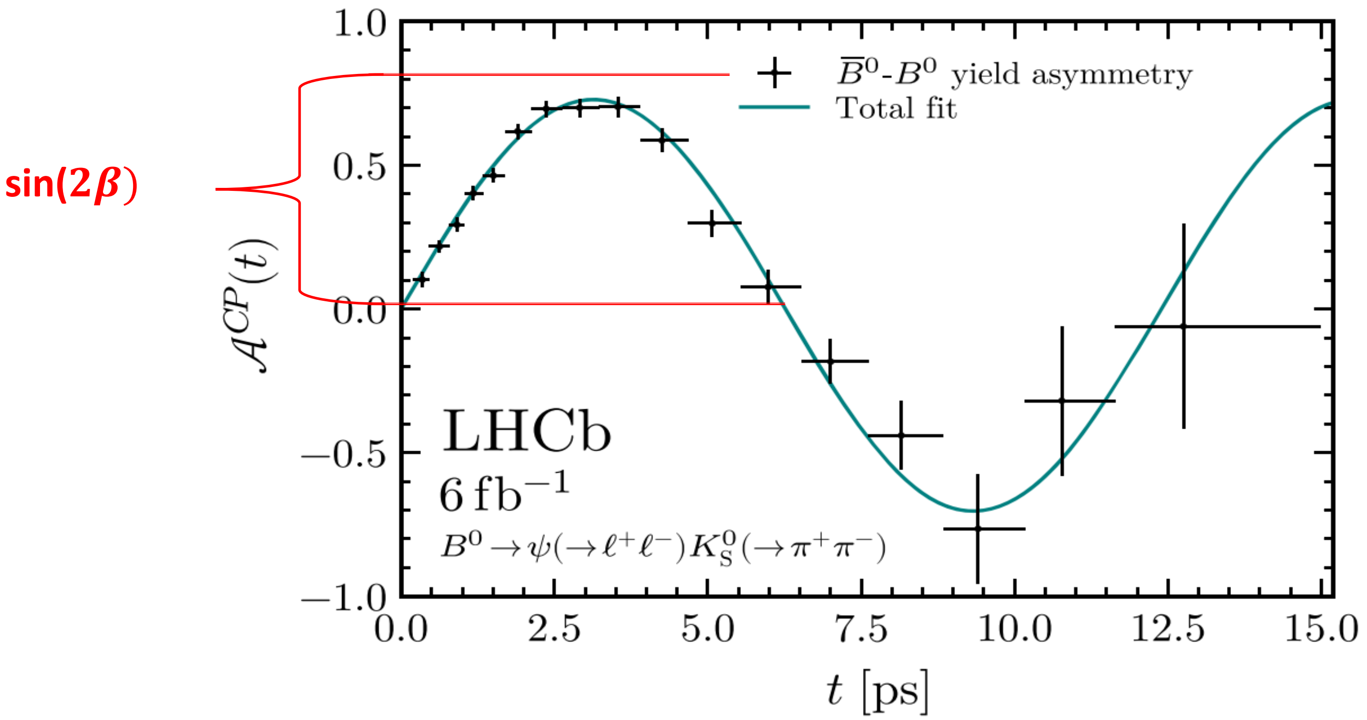


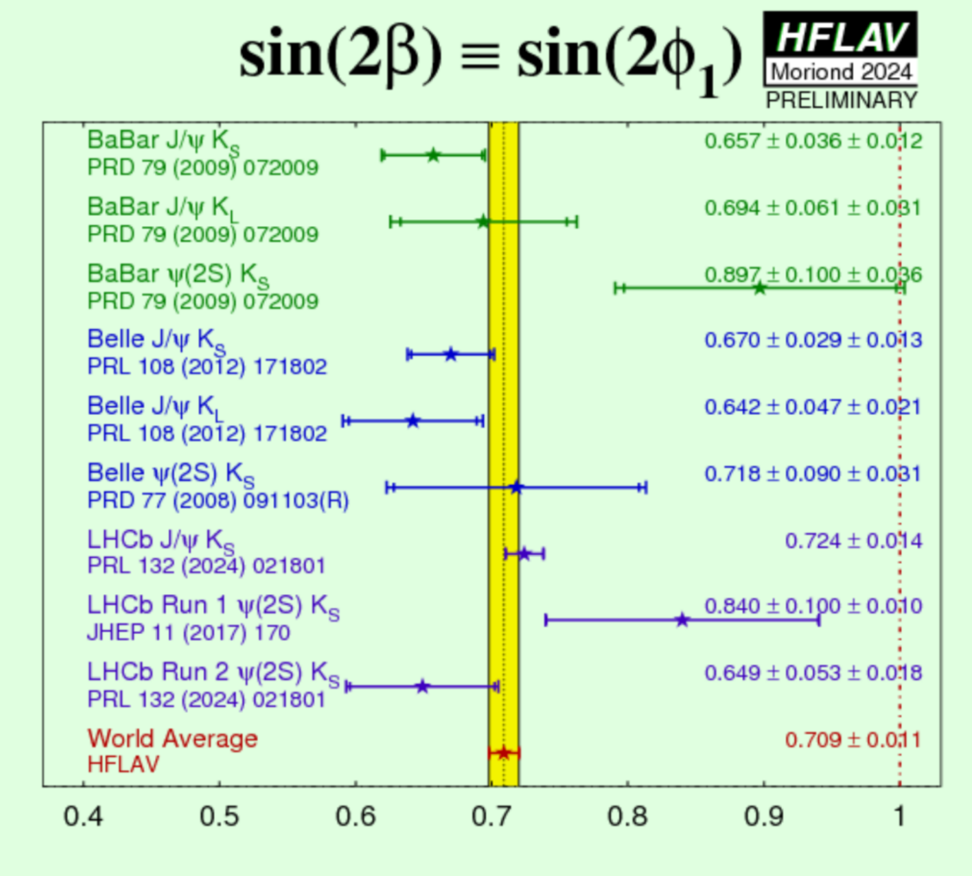
Improved determination of the CKM angle $\sin(2\beta)$

[Phys. Rev. Lett. 132 (2024) 021801]

- Most precise single measurement of $\sin(2\beta)$ to date

$$\sin(2\beta) = 0.716 \pm 0.013\,(\text{stat.}) \pm 0.008\,(\text{syst.})$$





CPV in charm sector: $D^0 \to K^+\pi^-$ and $D^0 - \bar{D}^0$ Mixing

[LHCb-PAPER-2024-008]
[arXiv: 2407.18001]

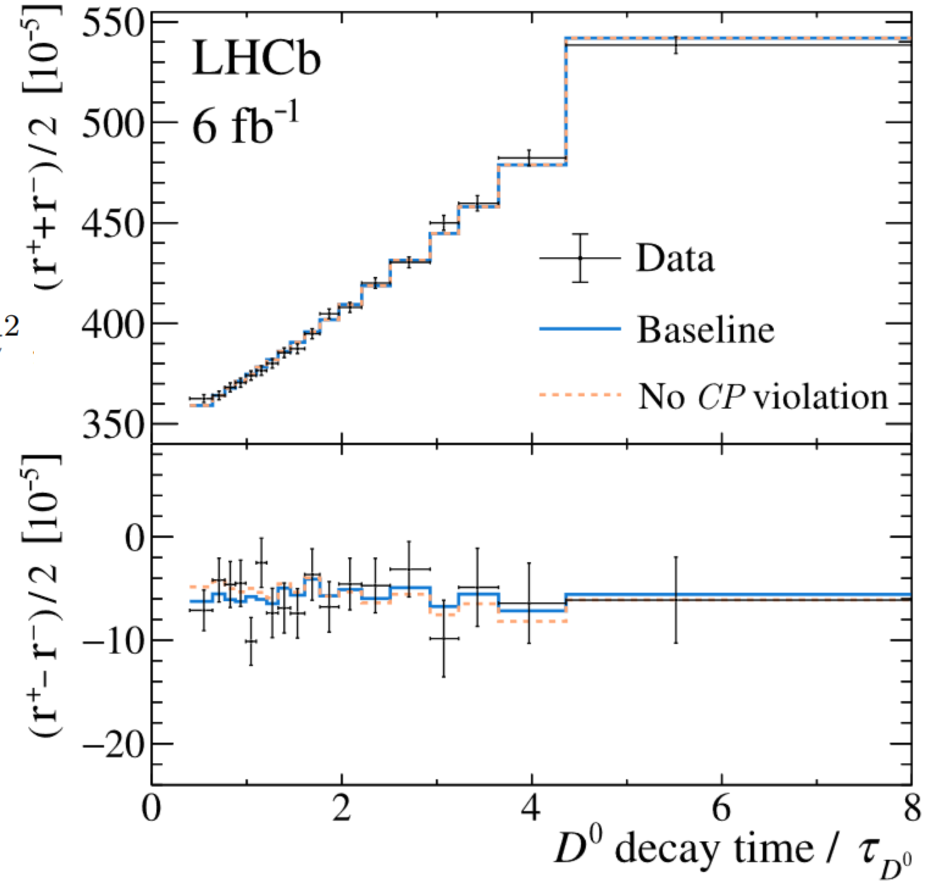
- In SM, charm CPV effects are predicted to be very small, $\mathcal{O}(10^{-4} - 10^{-3})$
- Direct CPV in charm has been observed by LHCb in $D^0 \to h^+h^-$, $A_{CP}(K^+K^-) - A_{CP}(\pi^+\pi^-) \neq 0$ [1]
- $D^0 \to K^+\pi^-$ allows us to measure mixing and all types of CPV
- Measure the time dependence of WS/RS yield ratio

$$R^+_{K\pi}(t) \equiv \frac{\Gamma(D^0(t) \to K^+\pi^-)}{\Gamma(\bar{D}^0(t) \to K^+\pi^-)} \qquad R^-_{K\pi}(t) \equiv \frac{\Gamma(\bar{D}^0(t) \to K^-\pi^+)}{\Gamma(D^0(t) \to K^-\pi^+)}$$

$$R^{\pm}_{K\pi}(t) \approx R_{K\pi}(1 \pm A_{K\pi}) + \sqrt{R_{K\pi}(1 \pm A_{K\pi})}(c_{K\pi} \pm \Delta c_{K\pi})\, t + (c'_{K\pi} \pm \Delta c'_{K\pi})\, t^2$$

$R_{K\pi}$	$(343.1 \pm 2.0) \times 10^{-5}$
$c_{K\pi}$	$(51.4 \pm 3.5) \times 10^{-4}$
$c'_{K\pi}$	$(13.1 \pm 3.7) \times 10^{-6}$

$A_{K\pi}$	$(-7.1 \pm 6.0) \times 10^{-3}$
$\Delta c_{K\pi}$	$(3.0 \pm 3.6) \times 10^{-4}$
$\Delta c'_{K\pi}$	$(-1.9 \pm 3.8) \times 10^{-6}$



[1] PRL 122 (2019) 211803

CPV in charm sector: $D^+ \to K^-K^+\pi^+$

[arXiv:2409.01414]

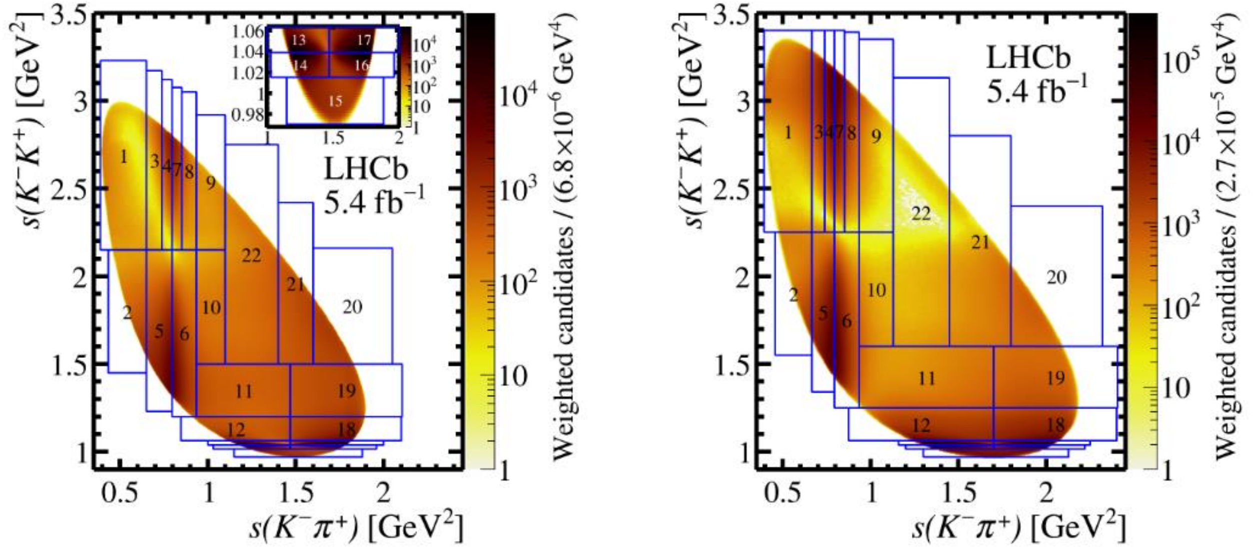
- A search for CPV in $D^+ \to K^-K^+\pi^+$ decays using binned model-independent technique to compare the D^+ and D^- phase-space distributions with instrumental asymmetries subtracted using the $D_s{}^+ \to K^-K^+\pi^+$ decay as a control channel.

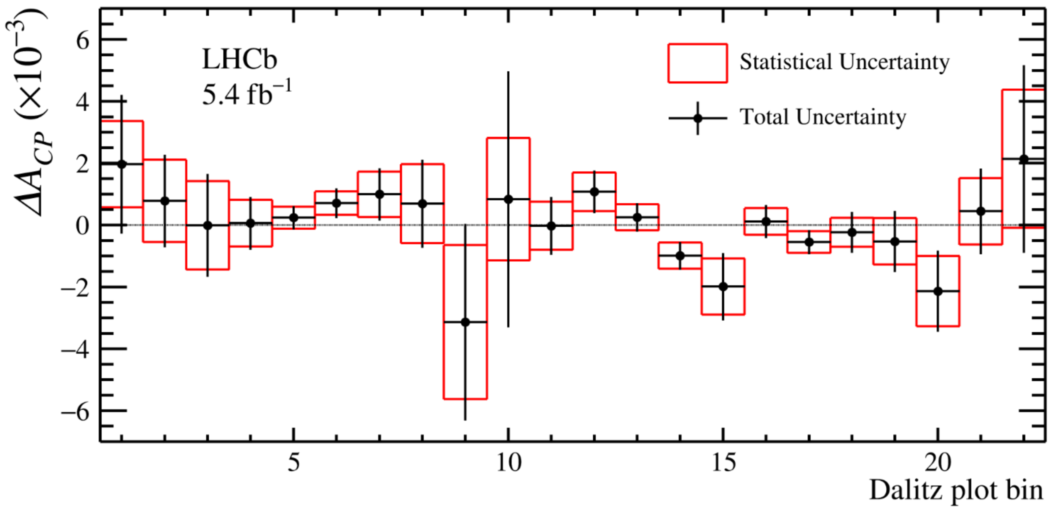
- In addition, Measurements of the CP asymmetry in the phase-space region dominated by $D^+ \to \phi\pi^+$, with $\phi \to K^-K^+$

$$A^{\phi\pi^+}_{CP|S} = (0.95 \pm 0.43_{\rm stat} \pm 0.26_{\rm syst}) \times 10^{-3}$$

$$A^{\overline{K}^{*0}K^+}_{CP|S} = (-0.26 \pm 0.56_{\rm stat} \pm 0.18_{\rm syst}) \times 10^{-3}$$

- No evidence of CP violation and represent the most sensitive search performed through the phase space of a multibody decay.



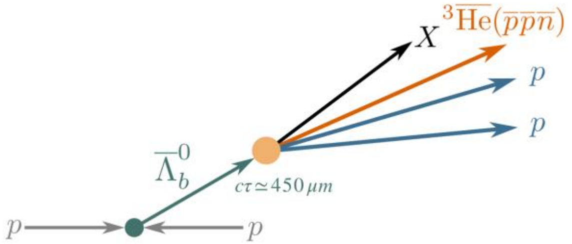


Antihelium production in $\overline{\Lambda}_b^0$ decays: Dark matter annihilation

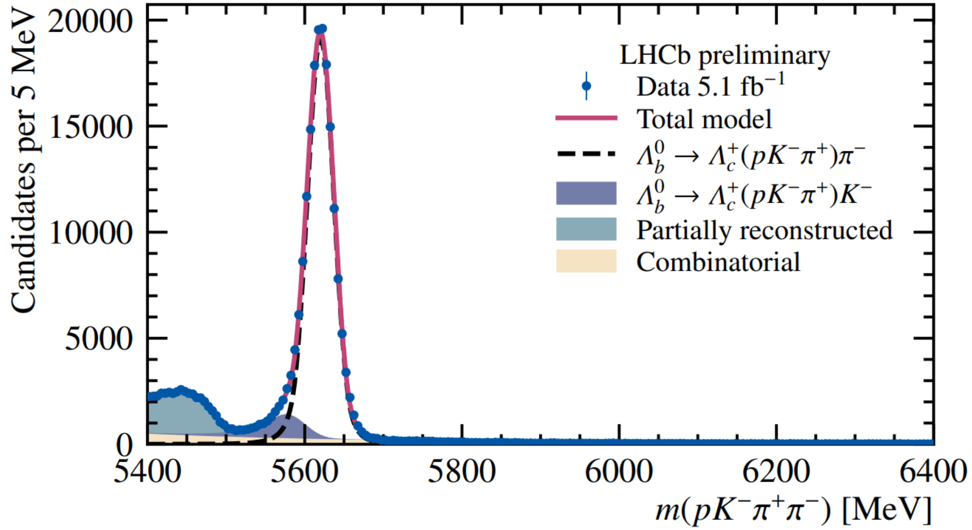
First results on (anti)helium production in $\bar{\Lambda}_b^0$ decays.

$\sim \mathcal{O}(10^{11})$ Λ_b^0 produced at 13TeV

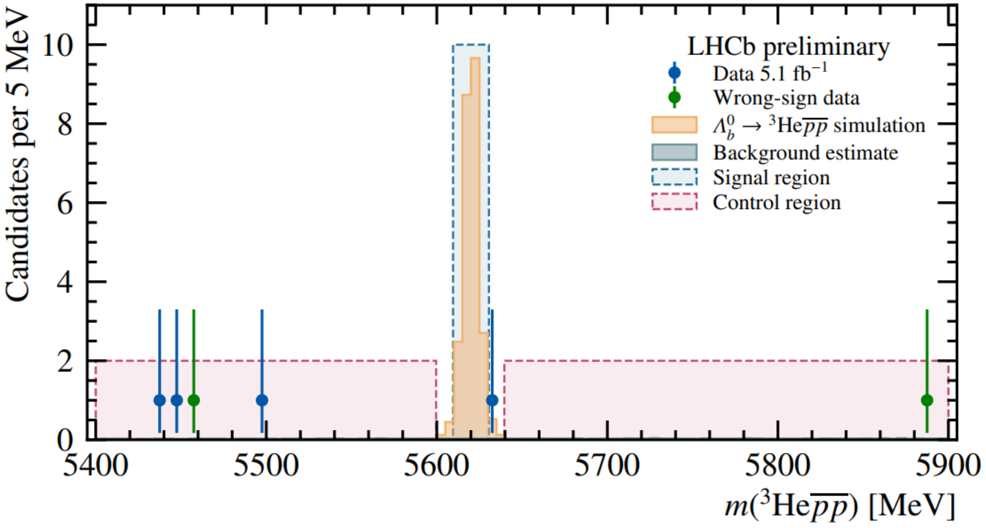
$\Rightarrow$ measure Λ_b^0 branching fraction down to $\mathcal{O}(10^{-8})$

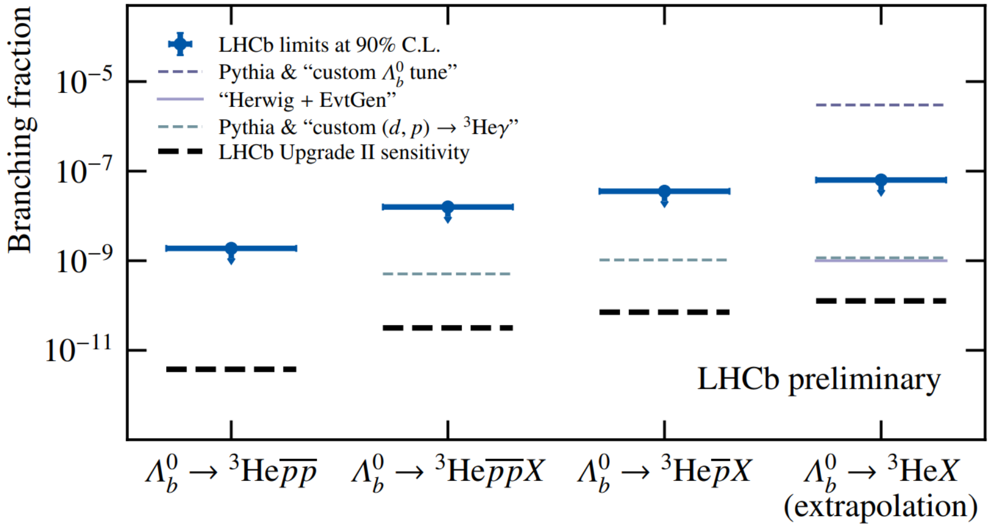


$$\mathcal{B}(\overline{\Lambda}_b^0 \to {}^3\overline{\mathrm{He}}pp) < 1.9 \times 10^{-9} \text{ at } 90\% \text{ CL},$$
$$\mathcal{B}(\overline{\Lambda}_b^0 \to {}^3\overline{\mathrm{He}}ppX) < 1.6 \times 10^{-8} \text{ at } 90\% \text{ CL},$$
$$\mathcal{B}(\overline{\Lambda}_b^0 \to {}^3\overline{\mathrm{He}}pX) < 3.6 \times 10^{-8} \text{ at } 90\% \text{ CL}.$$



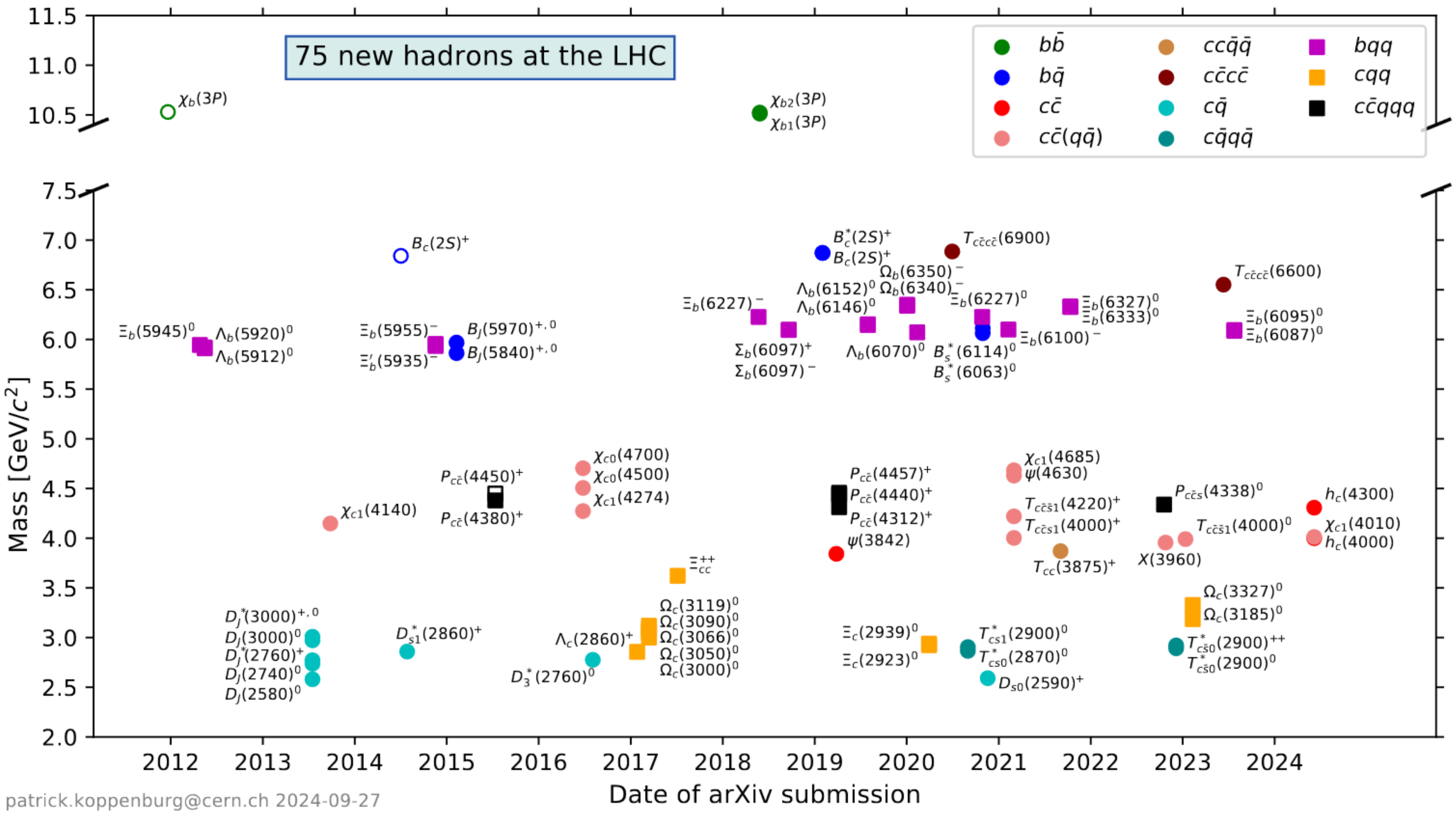
He3 identified with correlated measurements of charge between VELO and Silicon Strips Tracker





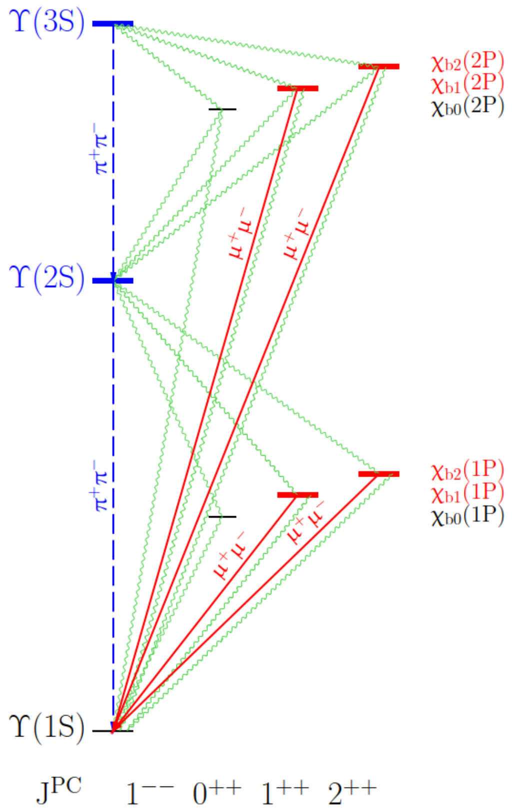
Pioneer of hadron spectroscopy

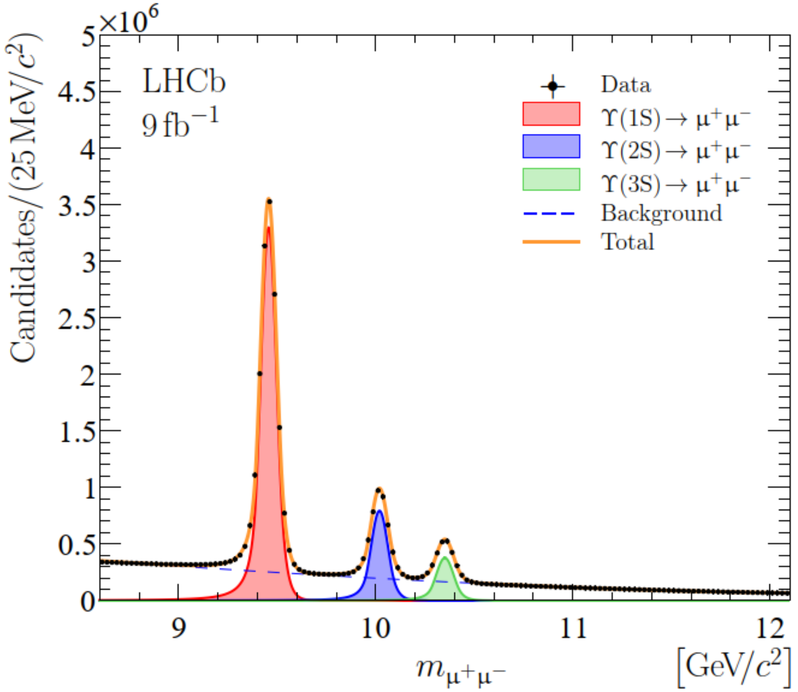
What a pleasure to make contributions to text book physics

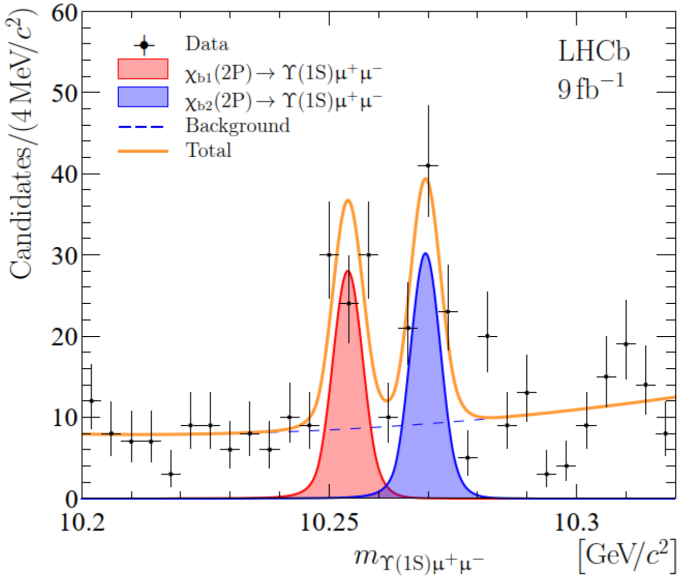


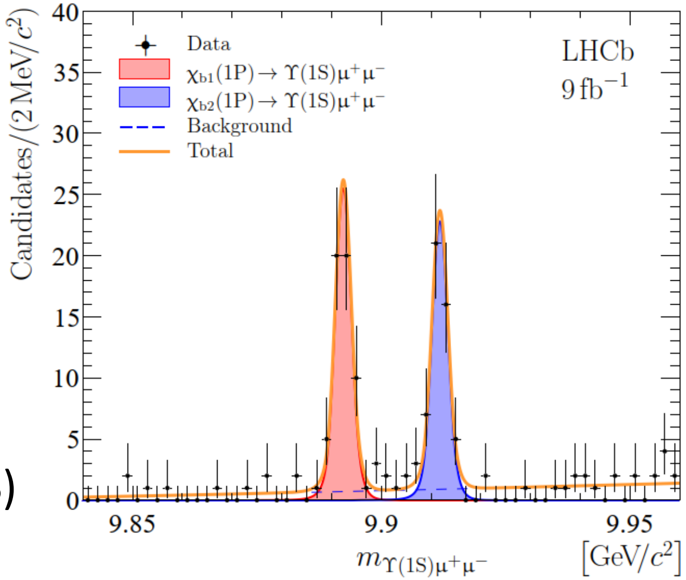
First observation of muonic Dalitz decays of χ_b mesons

$\chi_{b1}(1P)$, $\chi_{b2}(1P)$, $\chi_{b1}(2P)$ and $\chi_{b2}(2P)$ mesons to the Υ(1S)









Previous e^+e^- experiments relied on the photon energy of the Υ(2S) and Υ(3S)

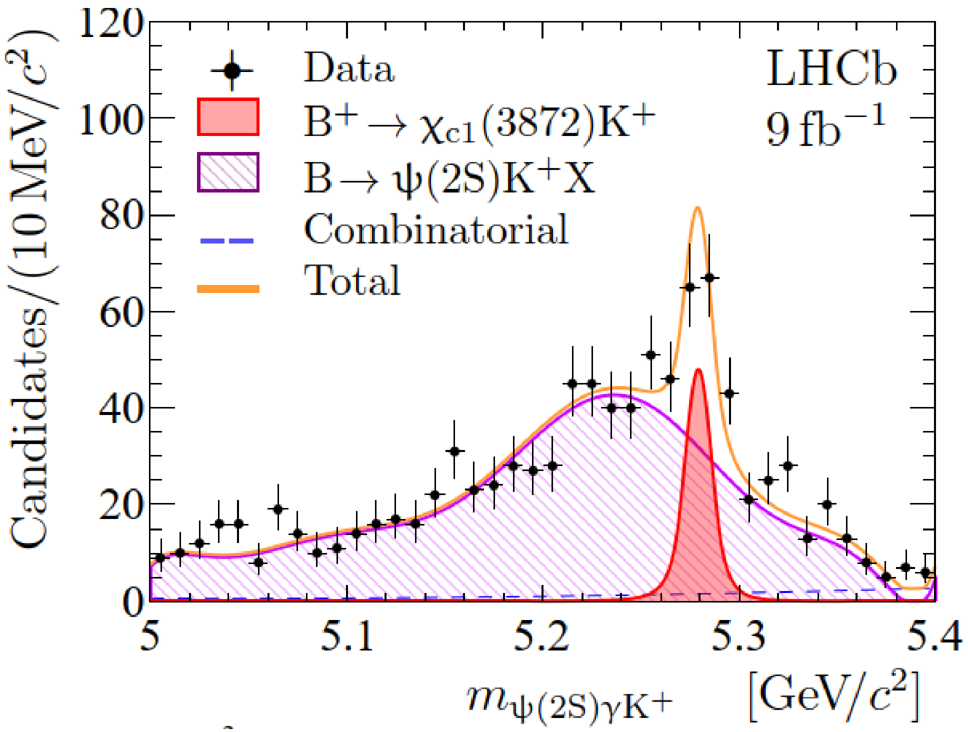
Probing the nature of the mysterious $\chi_{c1}(3872)$

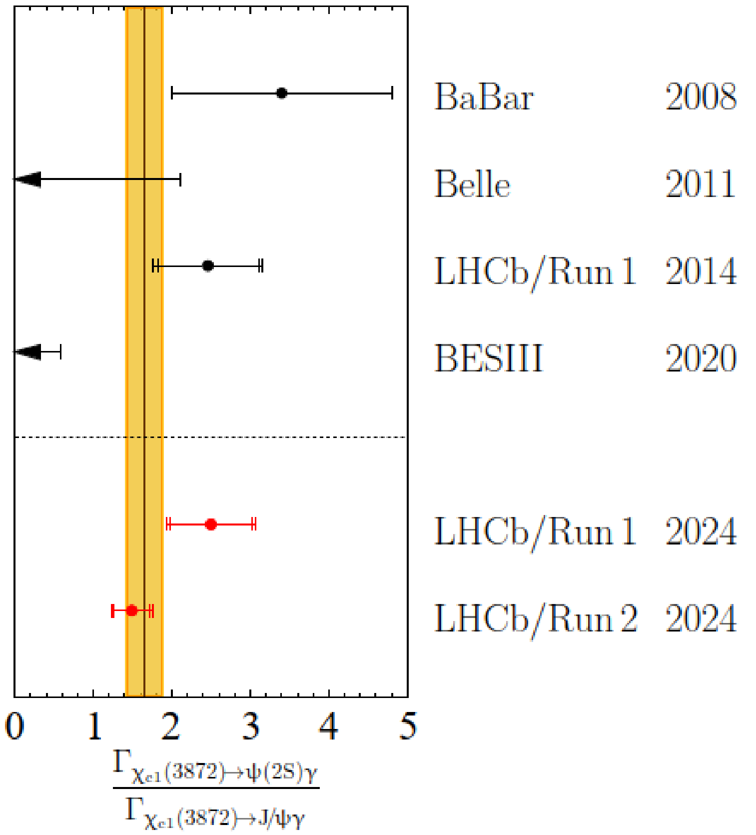
[arXiv: 2406.17006]

- The radiative decays $\chi c1(3872) \rightarrow \psi(2S)\gamma$ and $\chi c1(3872) \rightarrow J/\psi\gamma$ are used to probe the nature of the $\chi c1(3872)$
- Using the $B^+ \rightarrow \chi c1(3872)K^+$ decay, the $\chi c1(3872) \rightarrow \psi(2S)\gamma$ process is observed for the first time and the ratio of its partial width to that of the $\chi c1(3872) \rightarrow J/\psi\gamma$ decay is measured to be

$$\frac{\Gamma_{\chi_{c1}(3872)\to\psi(2S)\gamma}}{\Gamma_{\chi_{c1}(3872)\to J/\psi\gamma}} = 1.67 \pm 0.21 \pm 0.12 \pm 0.04\,,$$

- Likely sign of conventional $c\bar{c}$ charmonium OR $c\bar{c}q\bar{q}$ tetraquark molecules

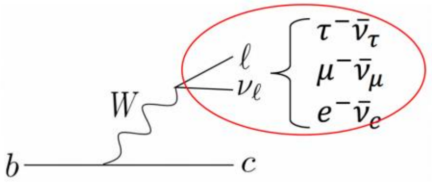


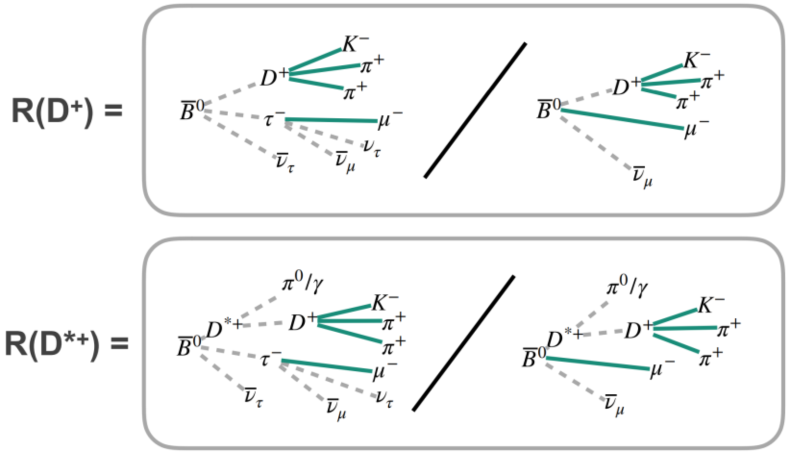


New LHCb measurement of $R(D^{(*)+})$

[arXiv: 2406. 03387]

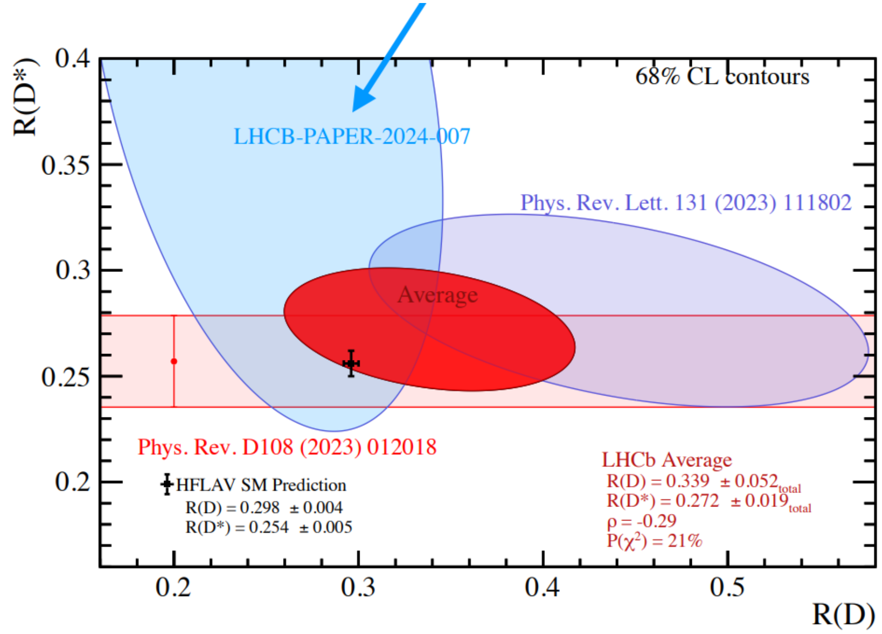
- First LHCb measurement using the D^+ ground state with $D^+ \to K^-\pi^+\pi^+$, muonic-tau decay
  - Primary goal is to measure $\boldsymbol{R(D^+)}$
  - Feed down from $\boldsymbol{D^{*+} \to D^+\pi^0/\gamma}$ with not reconstructed π^0/γ gives also access to $\boldsymbol{R(D^{*+})}$ in the same final state





- Data sample: 2 fb^{-1} at 13TeV

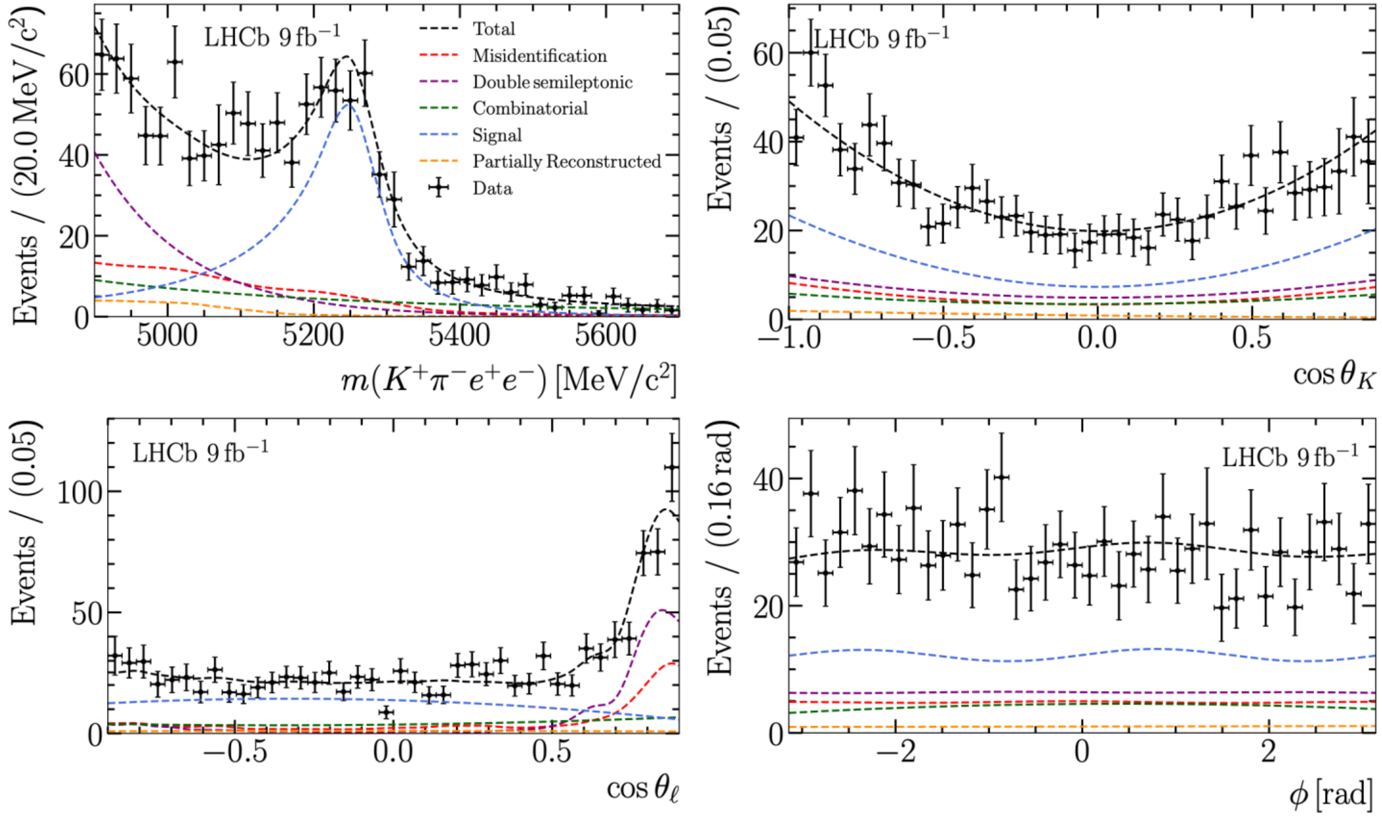
$$R(D^+) = 0.249 \pm 0.043\,(\text{stat.}) \pm 0.047\,(\text{syst.})$$
$$R(D^{*+}) = 0.402 \pm 0.081\,(\text{stat.}) \pm 0.085\,(\text{syst.})$$

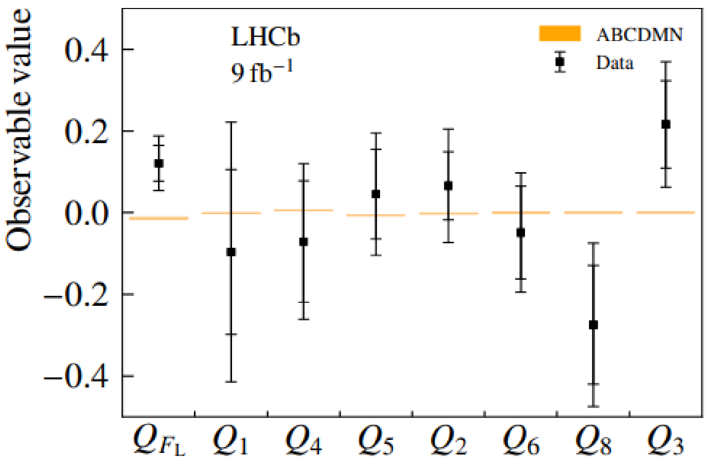


- Compatible with the SM at the 0.78 σ level
- Compatible with the (previous) W.A. at the 1.09 σ level

Angular analysis of $B \to K^{*}e+e-$

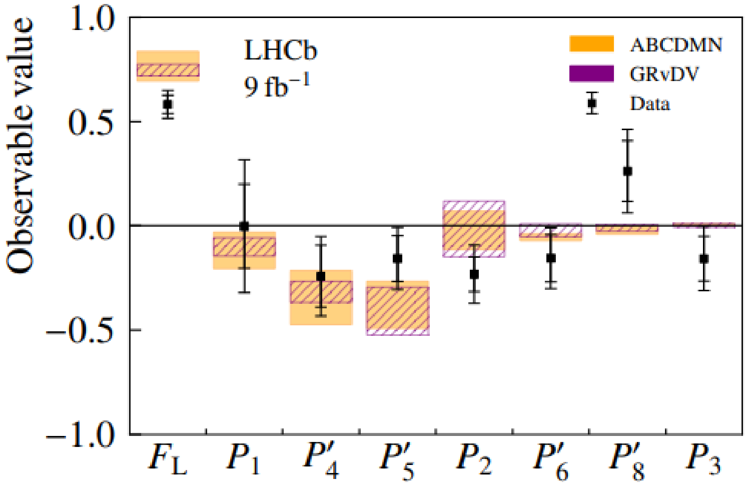
Allows the extraction of the angular observable in the central q² region





F_L: the fraction of longitudinally polarized

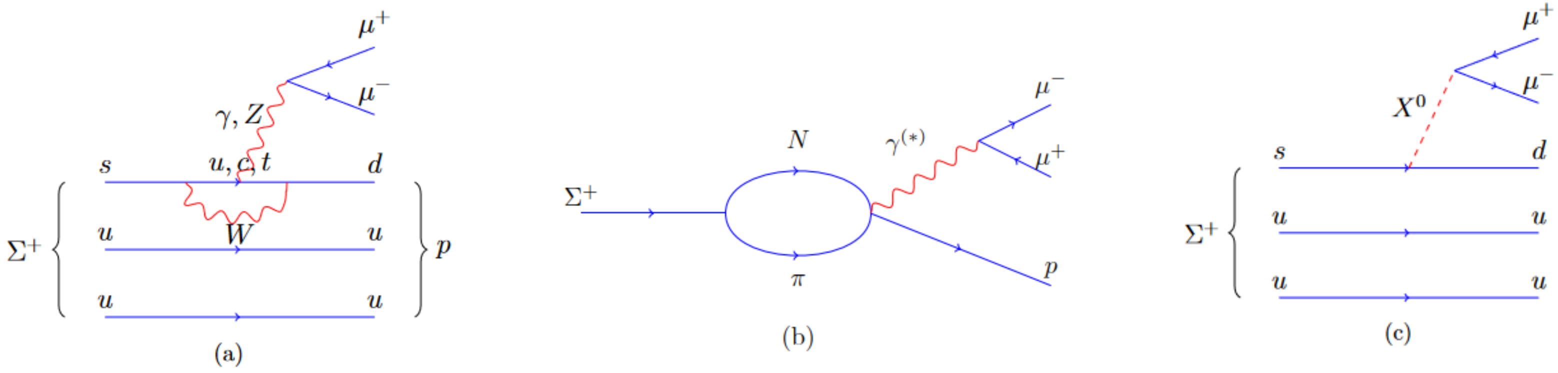
P: P-basis angular observables

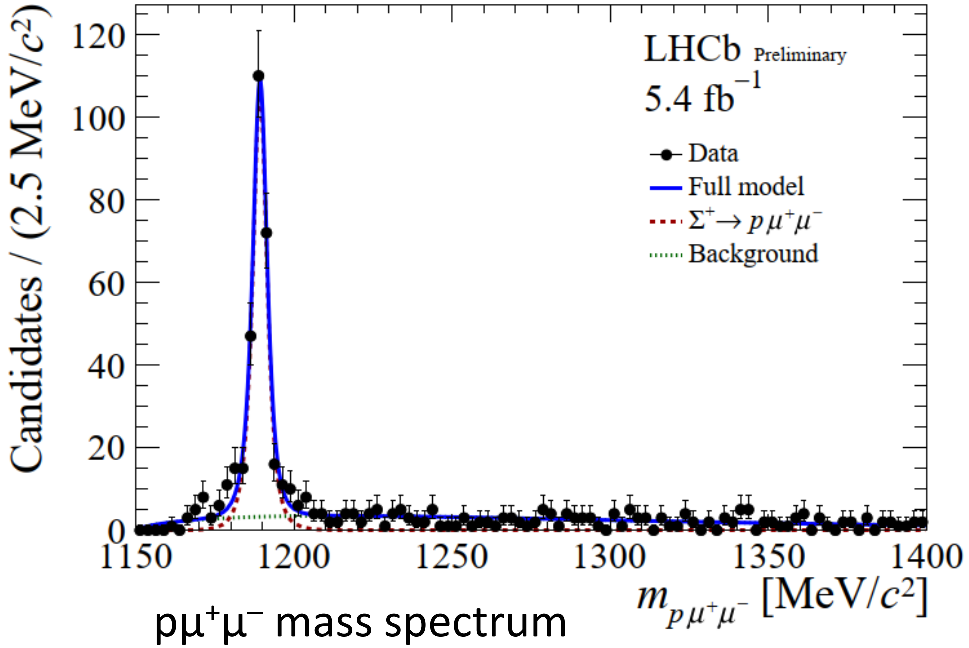


- Most precise determination of angular observables and no sign of lepton flavour violating effects are observed

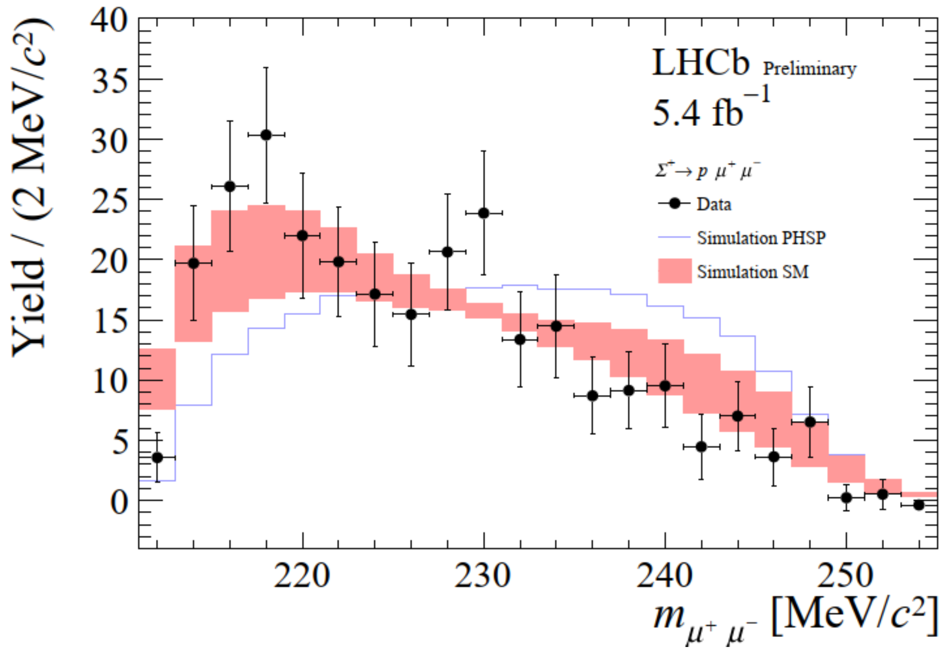
Observation of the rare $\Sigma^+ \to p\mu^+\mu^-$ decay

LHCb-CONF-2024-002





$p\mu^+\mu^-$ mass spectrum



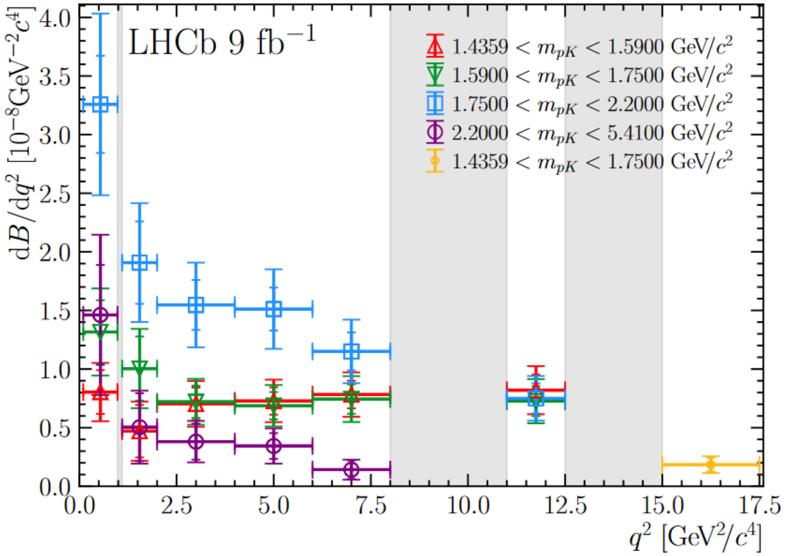
background-subtracted $\mu^+\mu^-$ mass spectrum

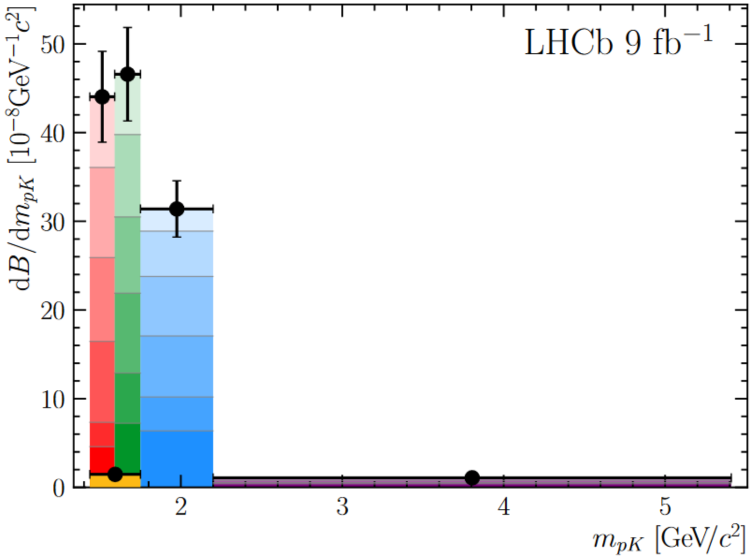
Analysis of $\Lambda^0_b \to pK^-\mu^+\mu^-$ decays

[arXiv:2409.12629v1]

Measurement of the branching fraction, and a first measurement of the angular distribution, of $\mathbf{\Lambda^0_b \to pK^-\mu^+\mu^-}$ decays

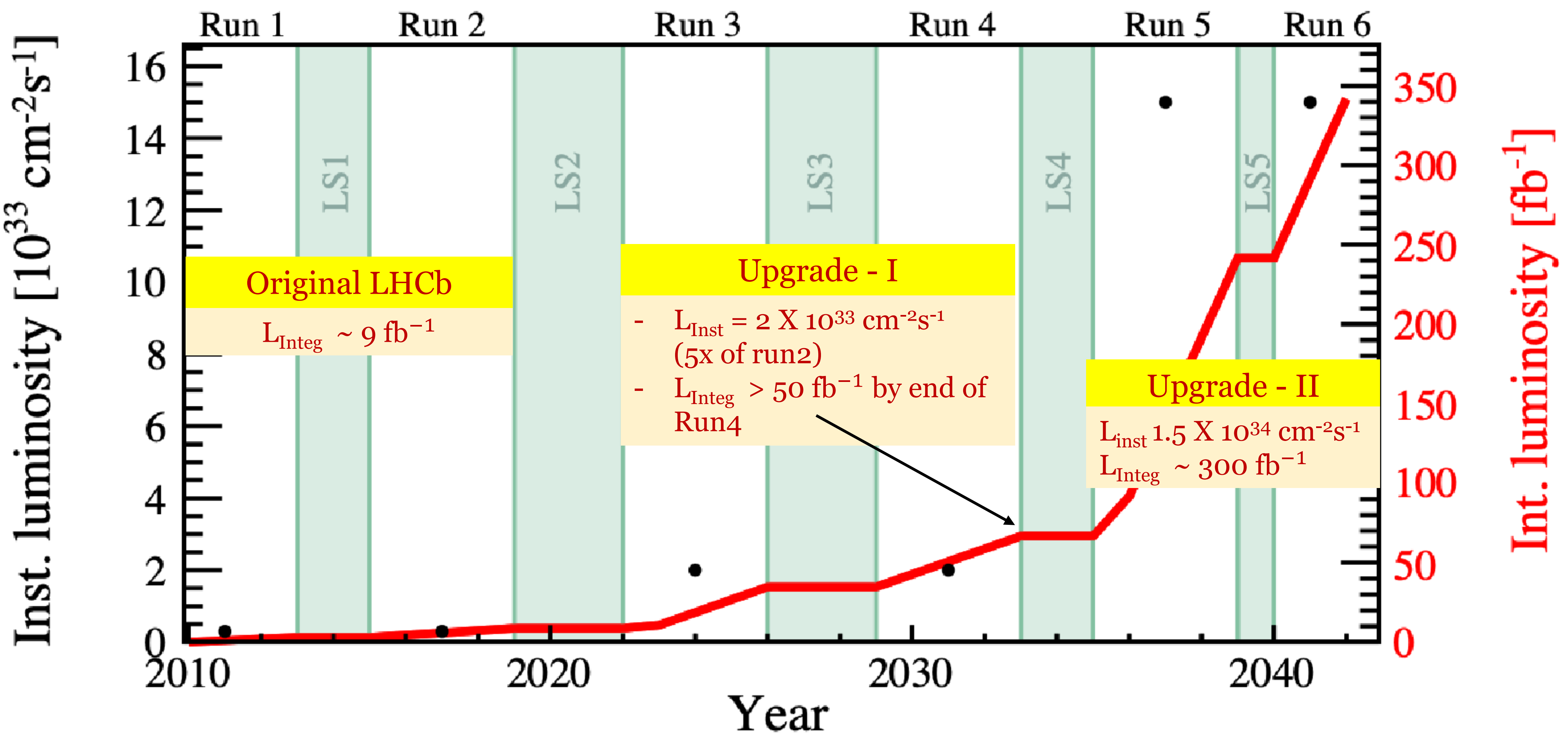
$$\Lambda_b^0 \to pK^-\mu^+\mu^- \qquad \frac{\mathrm{d}^2\mathcal{B}(\Lambda_b^0 \to pK^-\mu^+\mu^-)}{\mathrm{d}q^2\mathrm{d}m_{pK}^2} = \frac{N_{\Lambda_b^0\to pK^-\mu^+\mu^-}}{N_{\Lambda_b^0\to J/\psi pK^-}} \frac{\mathcal{B}(\Lambda_b^0 \to J/\psi pK^-)\mathcal{B}(J/\psi \to \mu^+\mu^-)}{\Delta(q^2, m_{pK}^2)},$$





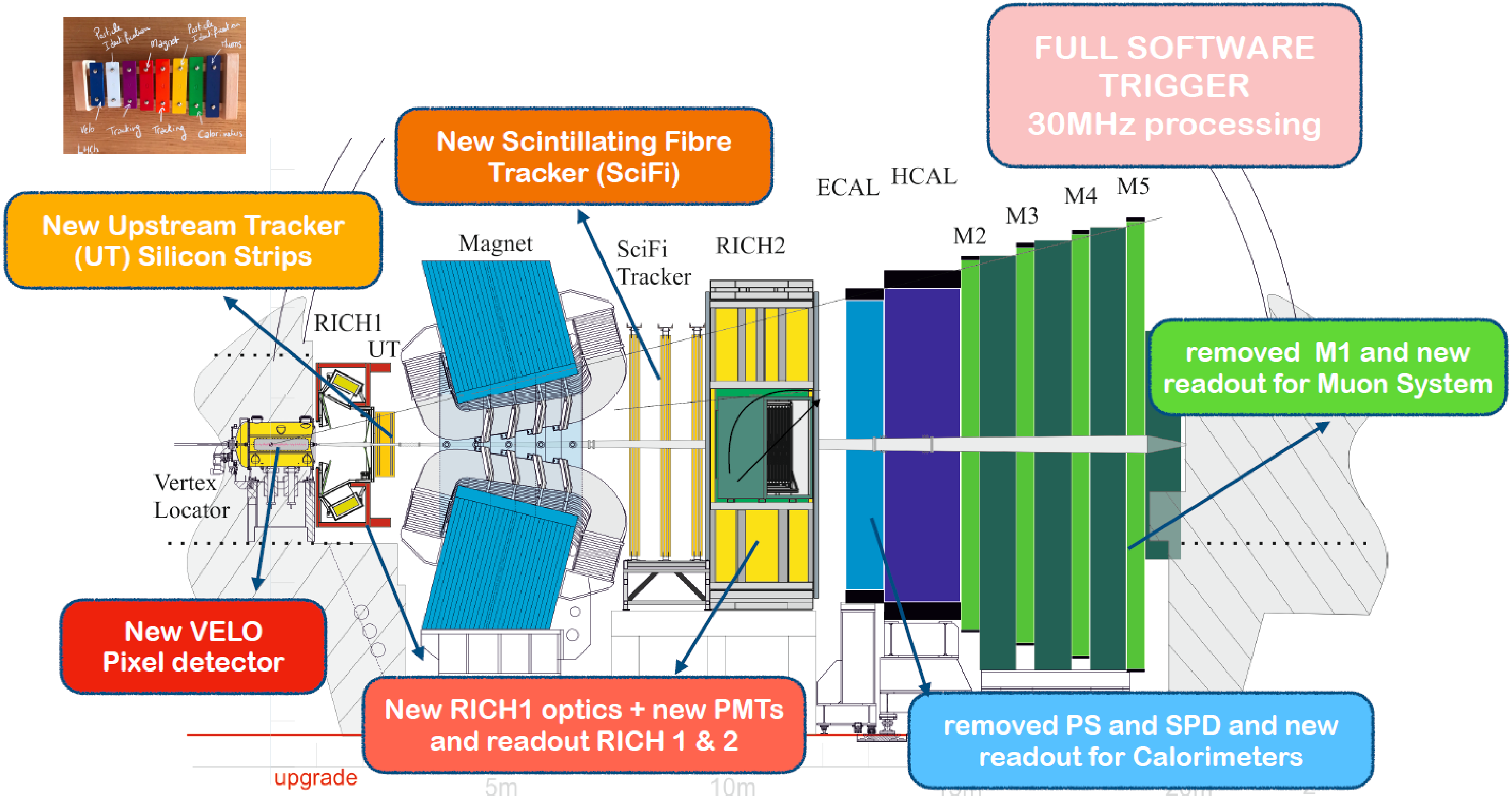
q^2 \ m_{pK}	[1.4359, 1.5900]	[1.59, 1.75]	[1.75, 2.20]	[2.20, 5.41]
[0.10, 0.98]	$5.22 \pm 1.21 \pm 0.43 \pm 0.98$	$8.22 \pm 1.69 \pm 0.38 \pm 1.54$	$7.24 \pm 0.92 \pm 0.52 \pm 1.36$	$0.46 \pm 0.13 \pm 0.14 \pm 0.09$
[1.1, 2.0]	$3.05 \pm 1.45 \pm 0.51 \pm 0.57$	$6.27 \pm 1.71 \pm 0.40 \pm 1.18$	$4.24 \pm 0.78 \pm 0.16 \pm 0.80$	$0.16 \pm 0.09 \pm 0.02 \pm 0.03$
[2.0, 4.0]	$4.56 \pm 0.90 \pm 0.26 \pm 0.86$	$4.50 \pm 0.86 \pm 0.21 \pm 0.84$	$3.44 \pm 0.47 \pm 0.08 \pm 0.64$	$0.12 \pm 0.05 \pm 0.02 \pm 0.02$
[4.0, 6.0]	$4.72 \pm 0.76 \pm 0.15 \pm 0.89$	$4.29 \pm 0.73 \pm 0.20 \pm 0.81$	$3.36 \pm 0.41 \pm 0.07 \pm 0.63$	$0.11 \pm 0.03 \pm 0.02 \pm 0.02$
[6.0, 8.0]	$5.08 \pm 0.76 \pm 0.12 \pm 0.95$	$4.65 \pm 0.79 \pm 0.34 \pm 0.87$	$2.56 \pm 0.36 \pm 0.05 \pm 0.48$	$0.04 \pm 0.02 \pm 0.01 \pm 0.01$
[11, 12.5]	$5.32 \pm 0.86 \pm 0.20 \pm 1.00$	$4.53 \pm 0.80 \pm 0.16 \pm 0.85$	$1.67 \pm 0.28 \pm 0.03 \pm 0.31$	—
[15.0, 17.5]	$0.59 \pm 0.19 \pm 0.07 \pm 0.11$		—	—

Timeline:


Run 1
Run 2
Run 3
Run 4
Run 5
Run 6
LS1
LS2
LS3
LS4
LS5
Inst. luminosity [10^{33} cm^{-2}s^{-1}]
Int. luminosity [fb^{-1}]
Year
0
2
4
6
8
10
12
14
16
0
50
100
150
200
250
300
350
2010
2020
2030
2040
Original LHCb
L_{Integ} ~ 9 fb^{-1}
Upgrade - I
- L_{Inst} = 2 X 10^{33} cm^{-2}s^{-1} (5x of run2)
- L_{Integ} > 50 fb^{-1} by end of Run4
Upgrade - II
L_{inst} 1.5 X 10^{34} cm^{-2}s^{-1}
L_{Integ} ~ 300 fb^{-1}

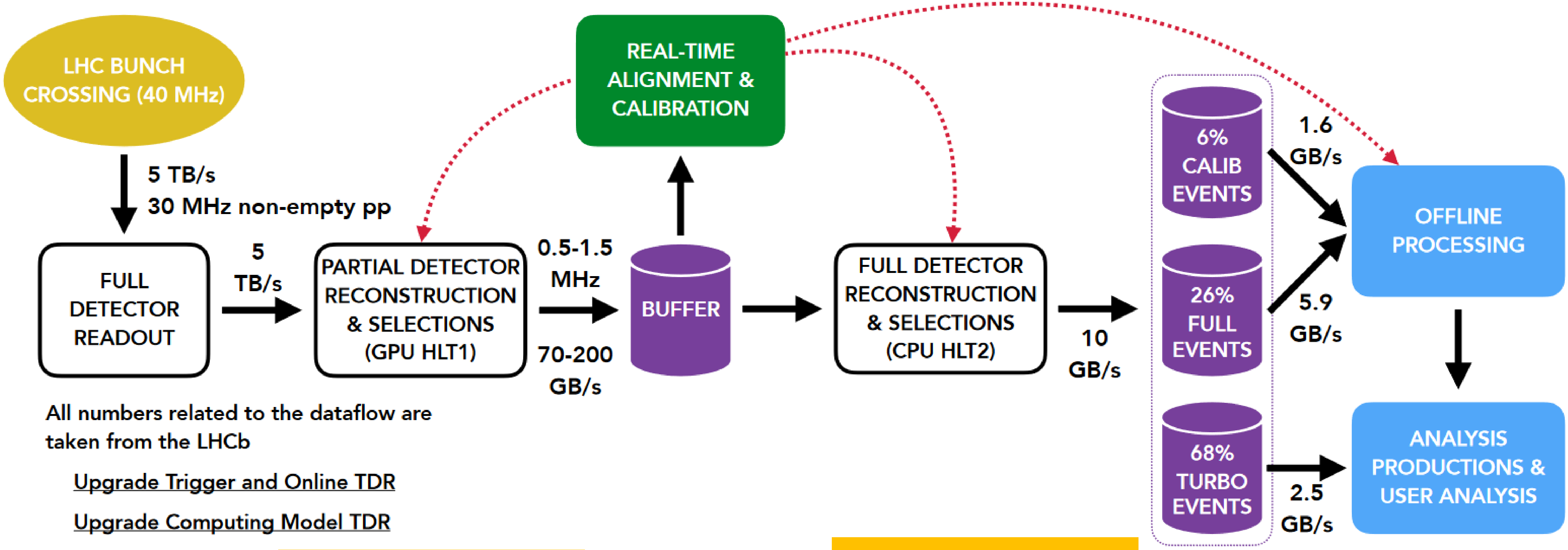
Upgrade I

[arXiv.2305.10515]



Upgrade I - Trigger and online system

10.17181/CERN.QDVA.5PIR



All numbers related to the dataflow are taken from the LHCb

Upgrade Trigger and Online TDR

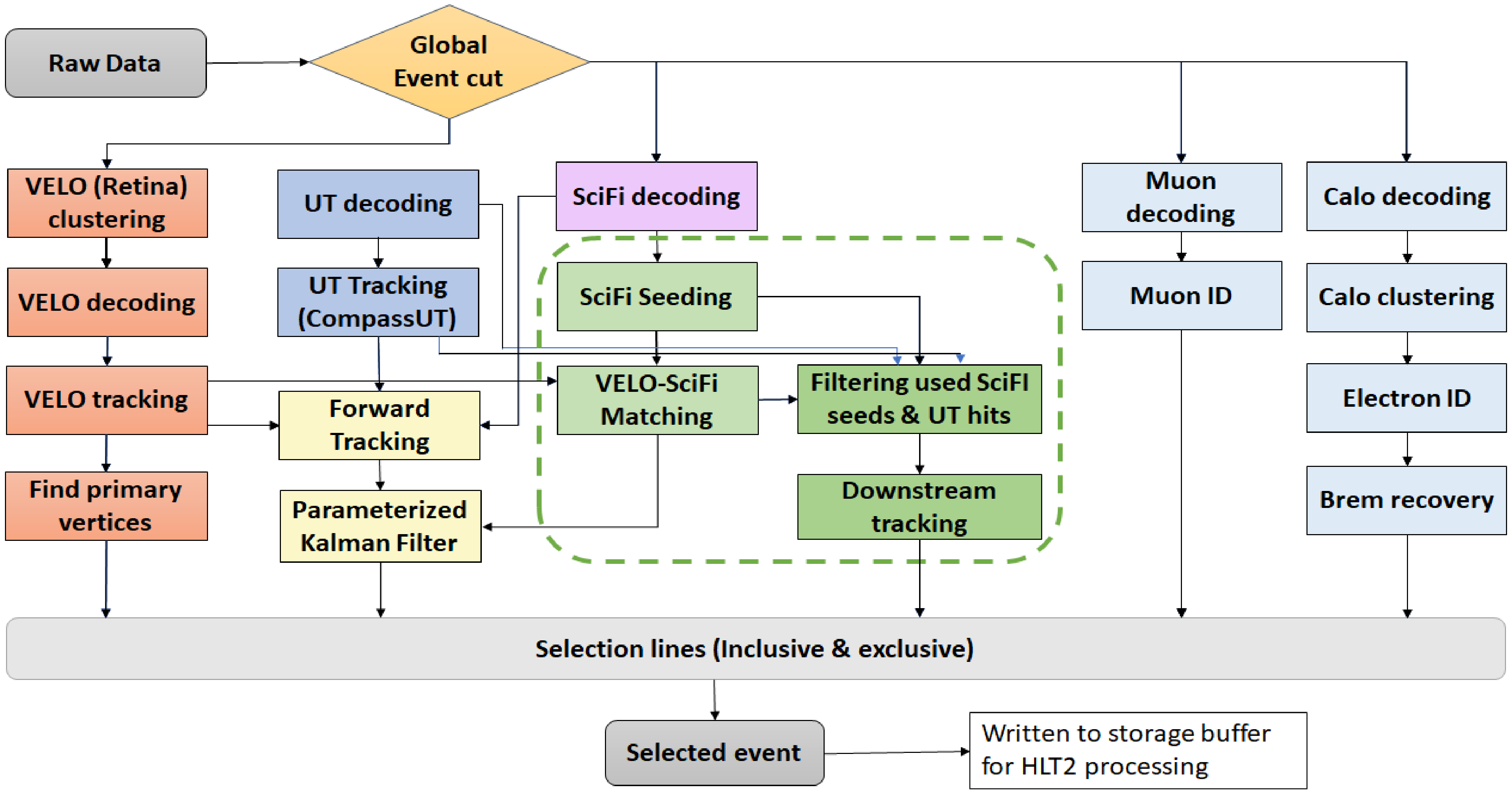
Upgrade Computing Model TDR

HLT1 Data reduction of factor of ~ 20 - 40

HLT2 Data reduction of Factor of ~400

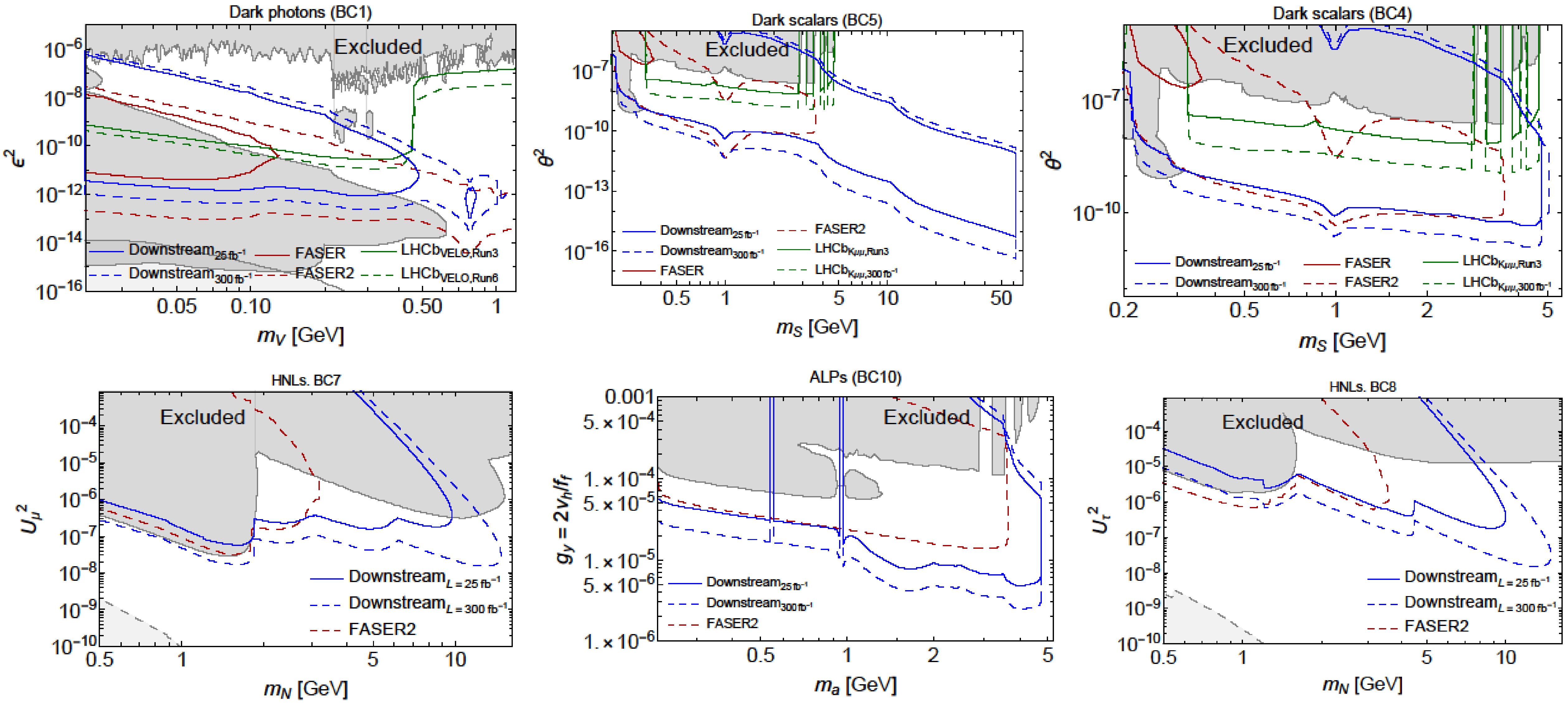
Upgrade I – HLT1 sequence

[Allen, Com. Softw Big Sci 4, 7 ('20)]
[CERN-THESIS-2023-249]

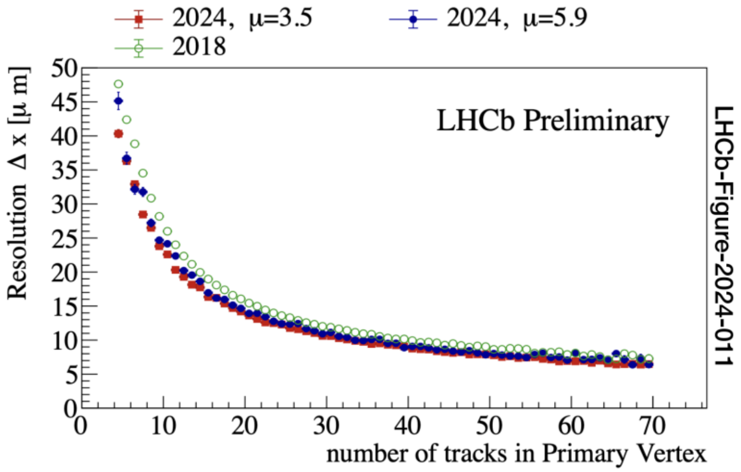


Upgrade-I LHCb as lifetime frontier experiment

Eur.Phys.J.C 84 (2024) 6, 608

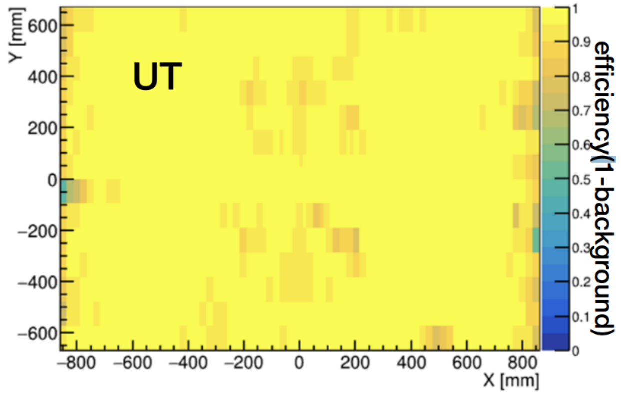


Upgrade I – Performance



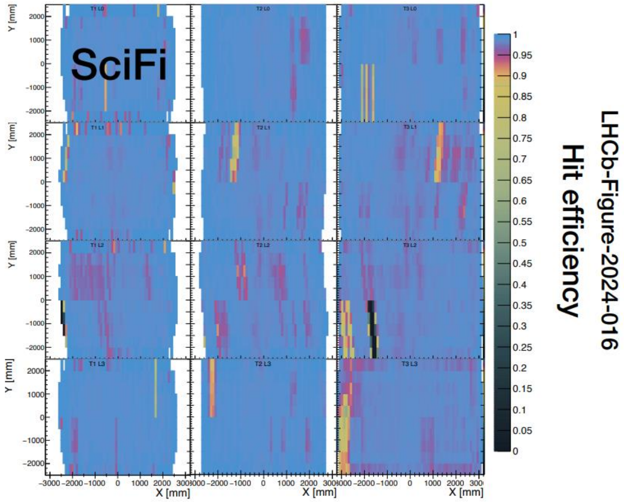
LHCb – FIGURE – 2024 – 011

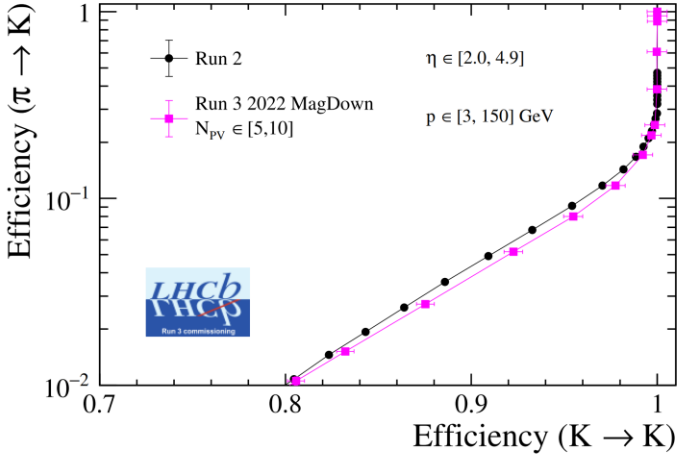
Tracking detectors



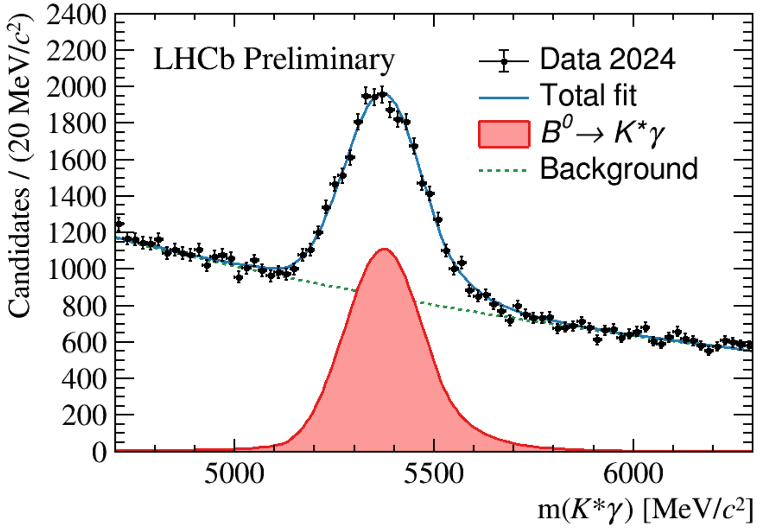
LHCb – FIGURE – 2024 – 016

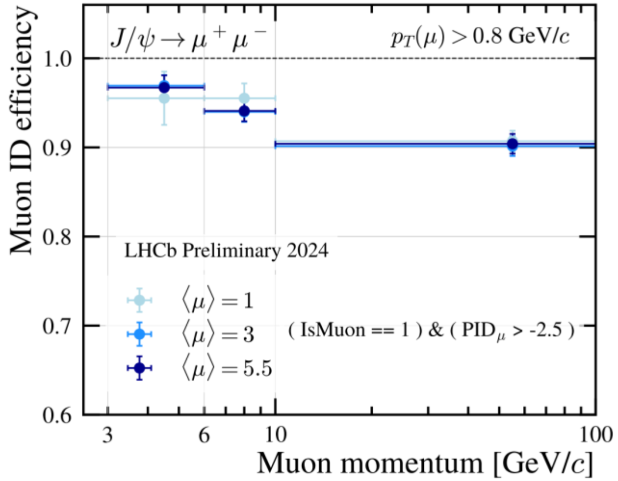
LHCb – FIGURE – 2024 – 016





LHCb-Figure-2023-019



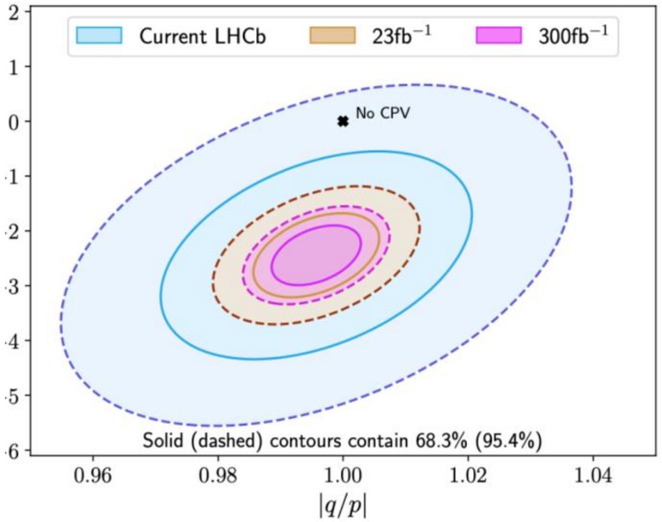


Particle Identification

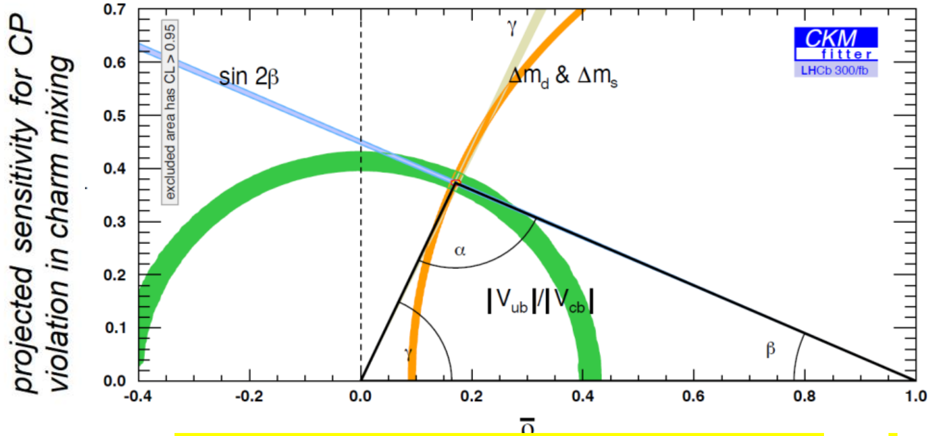
LHCb-Figure-2024-010

Upgrade-II: Physics case: ultimate precision

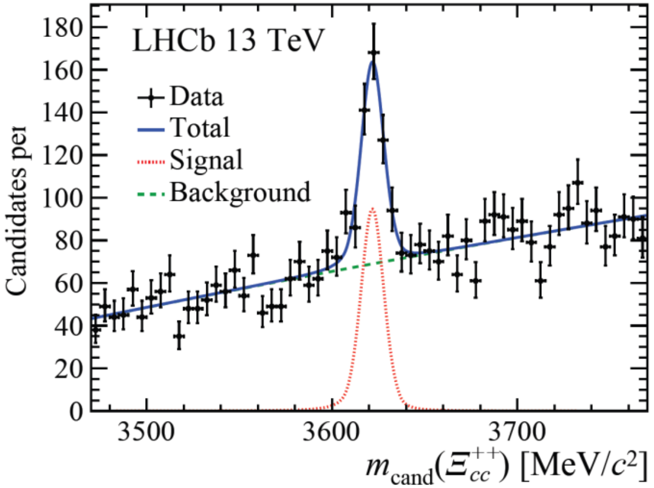
Observable	Current LHCb (up to 9 fb^{-1})		Upgrade I (23 fb^{-1})	Upgrade I (50 fb^{-1})	Upgrade II (300 fb^{-1})
CKM tests					
γ ($B \to DK$, *etc.*)	$4°$	[9, 10]	$1.5°$	$1°$	$0.35°$
ϕ_s ($B_s^0 \to J/\psi\phi$)	32 mrad	[8]	14 mrad	10 mrad	4 mrad
$\lvert V_{ub}\rvert/\lvert V_{cb}\rvert$ ($\Lambda_b^0 \to p\mu^-\overline{\nu}_\mu$, *etc.*)	6%	[29, 30]	3%	2%	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]	13×10^{-5}	8×10^{-5}	3.3×10^{-5}
A_Γ ($D^0 \to K^+K^-, \pi^+\pi^-$)	11×10^{-5}	[38]	5×10^{-5}	3.2×10^{-5}	1.2×10^{-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					
$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	69%	[40, 41]	41%	27%	11%
$S_{\mu\mu}$ ($B_s^0 \to \mu^+\mu^-$)	—		—	—	0.2
$A_{\text{T}}^{(2)}$ ($B^0 \to K^{*0}e^+e^-$)	0.10	[52]	0.060	0.043	0.016
A_{T}^{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^*} ($B^0 \to K^{*0}\ell^+\ell^-$)	0.12	[61]	0.034	0.022	0.009
$R(D^*)$ ($B^0 \to D^{*-}\ell^+\nu_\ell$)	0.026	[62, 64]	0.007	0.005	0.002

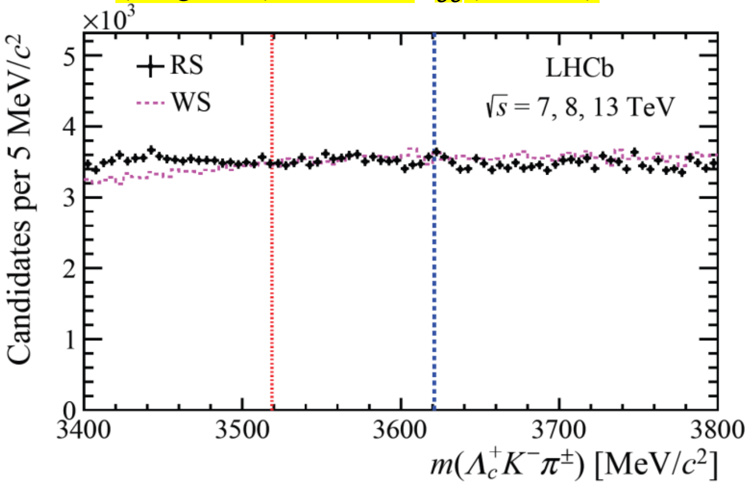


LHCb will test the CKM paradigm with unprecedented accuracy
arXiv:1808.08865.



VELO performance enough to separate Ξ_{cc}^{++} (~250 fs) but not Ξ_{cc}^{+}(~80 fs)



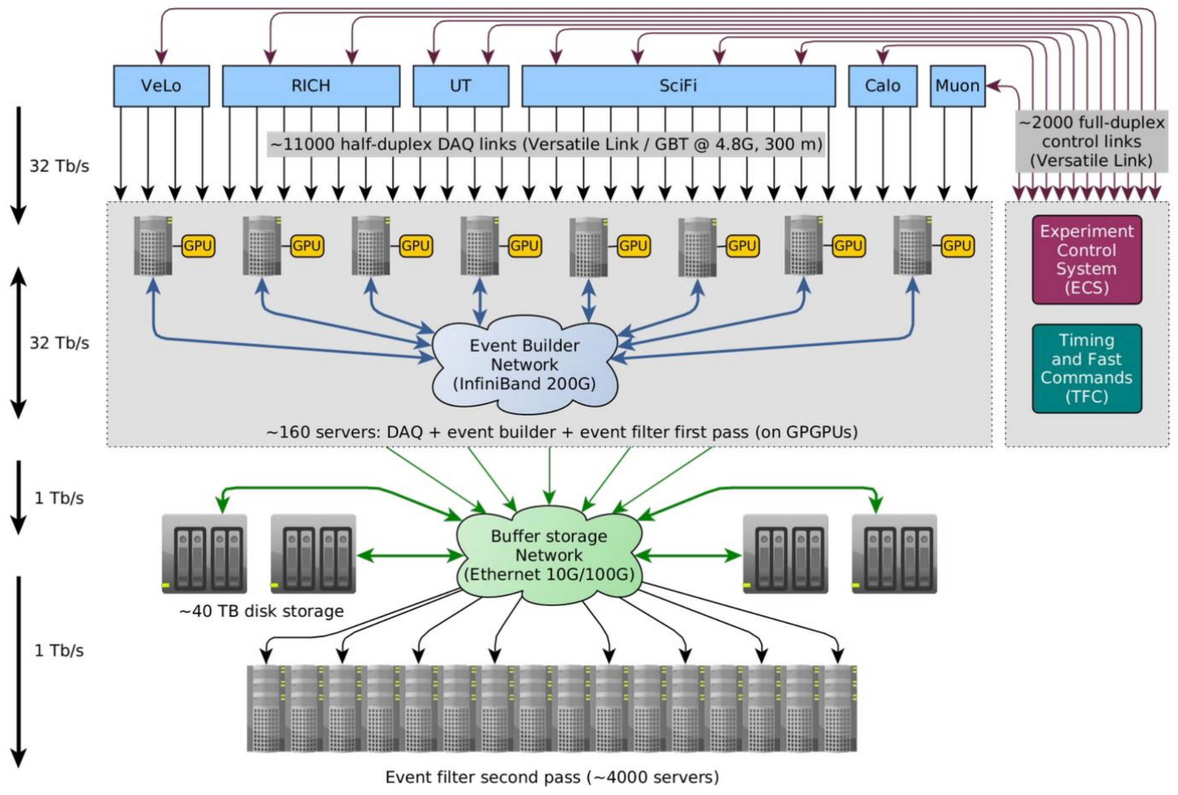


Data Acquisition and Triggering

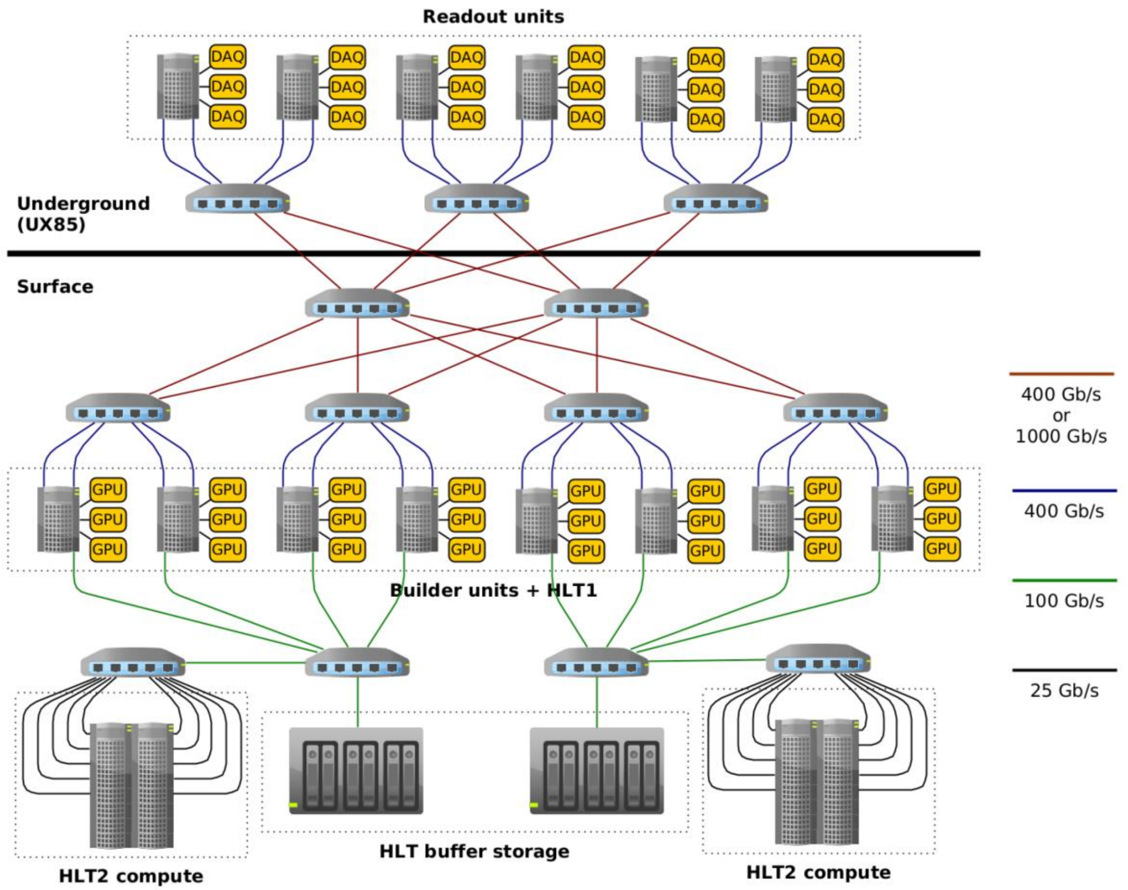
[CERN-LHCC-2021-012]

Architecture

Run3



Run 5



- Much more data
  - 3x data links 11000 (x5 Gbps) to 30000(x10 Gbps)
  - 5x readout throughput ~ 32 to 160 Tbps
  - 5x output to tape 80 → 400 Gbps

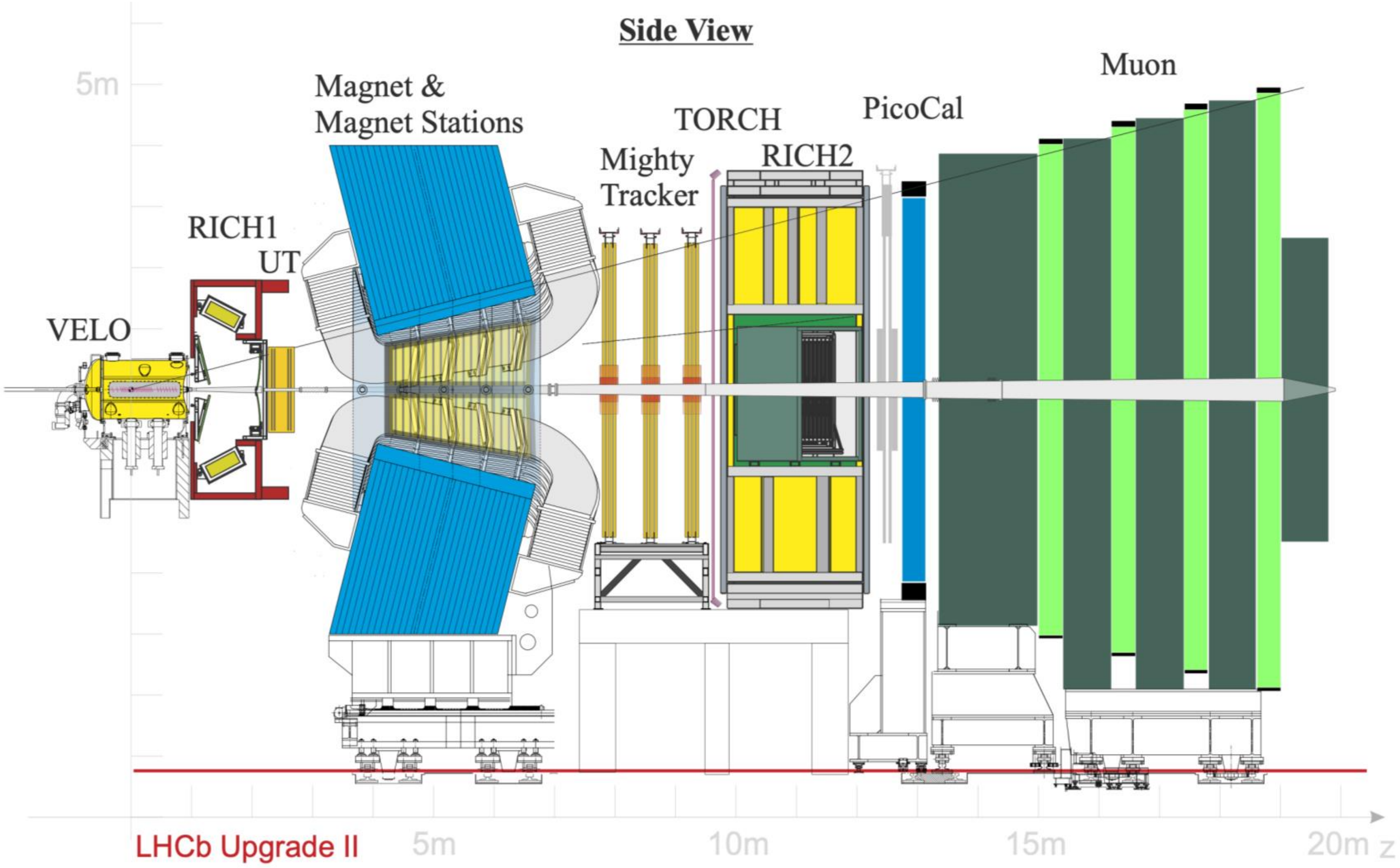
- Need to split EB and move underground (link limitations)
- FPGA ((PCIe400) based read-out boards to interface Front-end with event-building

Upgrade-I Trigger and online system

[CERN-LHCC-2021-012]

Targeting same performance as in Run 3, but with ~7 times the pileup of Run3

[CERN-LHCC-2021-012]



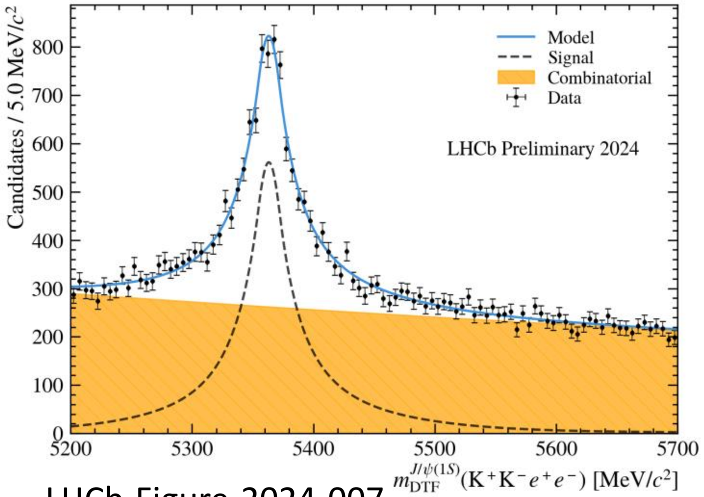
Conclusion

- Wrapped up a number of legacy measurements with Run 1/2
- The LHCb programme is in constant evolution
- Detector stably operating, expected improvements of trigger efficiencies covering wide range of physics.
- Already preparing Upgrade II

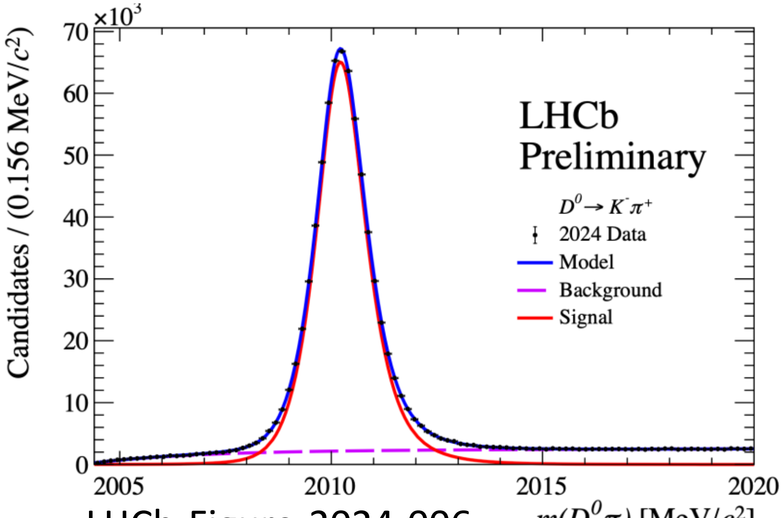
Thank you

Backup

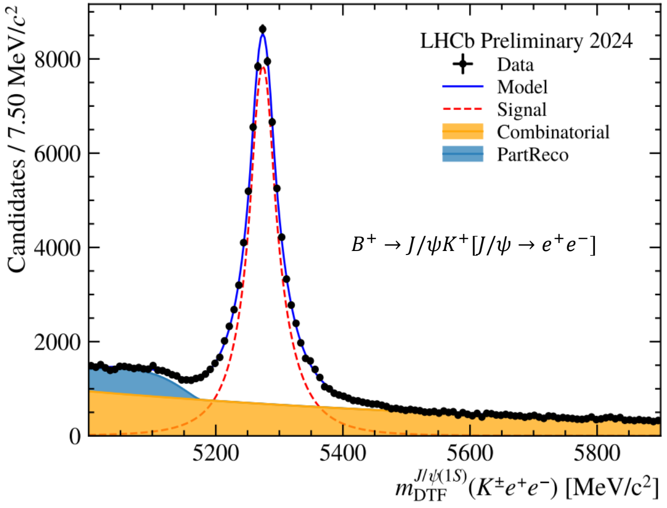
Upgrade I – Performance

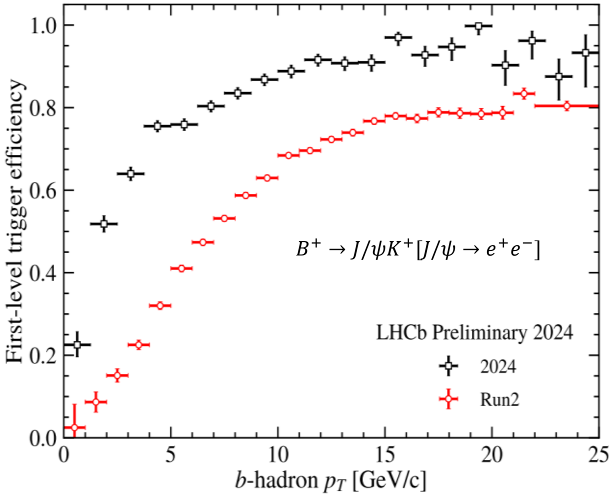


LHCb-Figure-2024-007

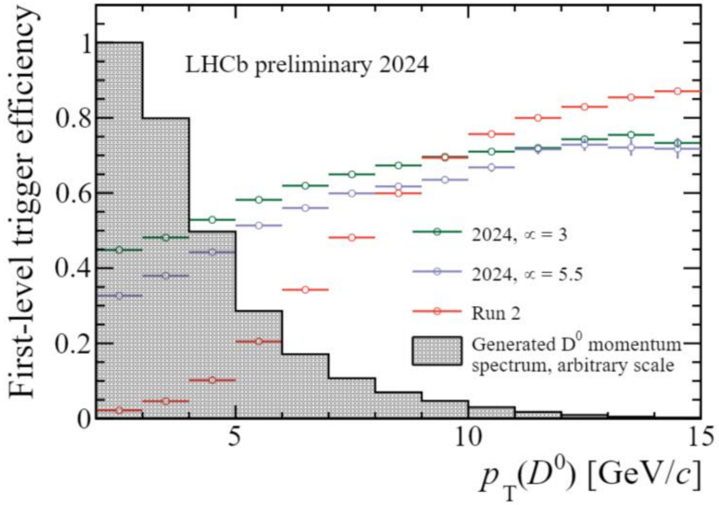


LHCb-Figure-2024-006





LHCb-Figure-2024-007



LHCb-Figure-2024-006

$b \to s l^+ l^-$ decays

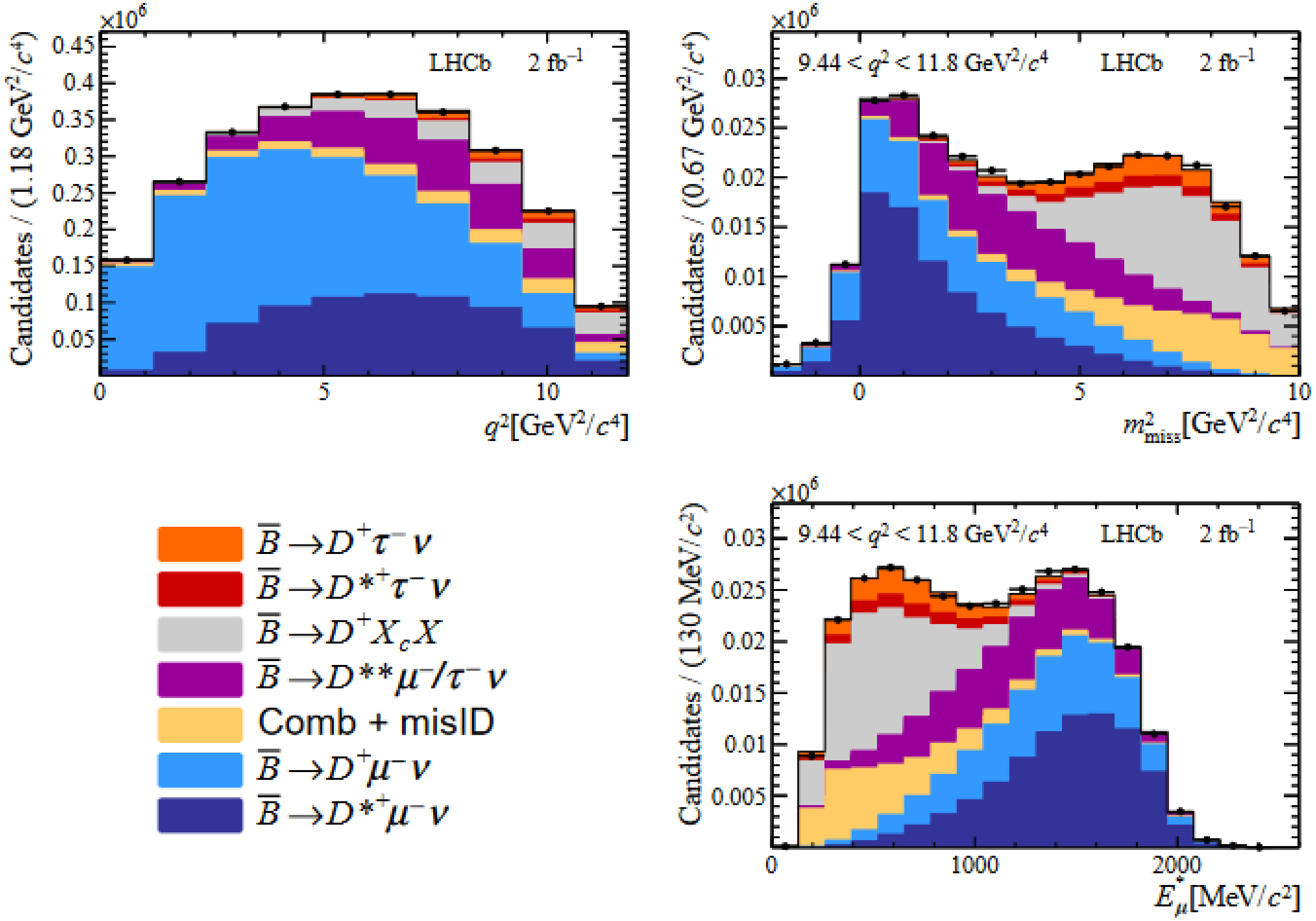
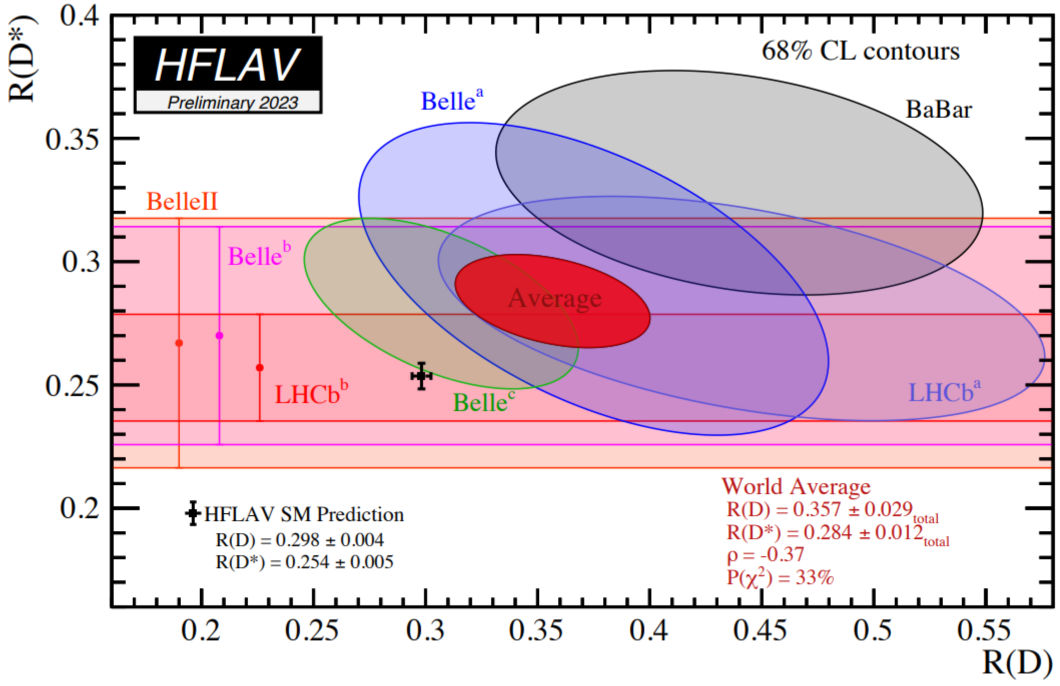


Figure 1: Distributions of the three kinematic variables in the signal isolation region, with the fit result overlaid. The q^2 distribution is shown over the full fit range whereas m^2_{miss} and E^*_μ are only shown in the range $9.44 < q^2 < 11.8\,\text{GeV}^2/c^4$.

New $R(D^{(*)})$ W.A.

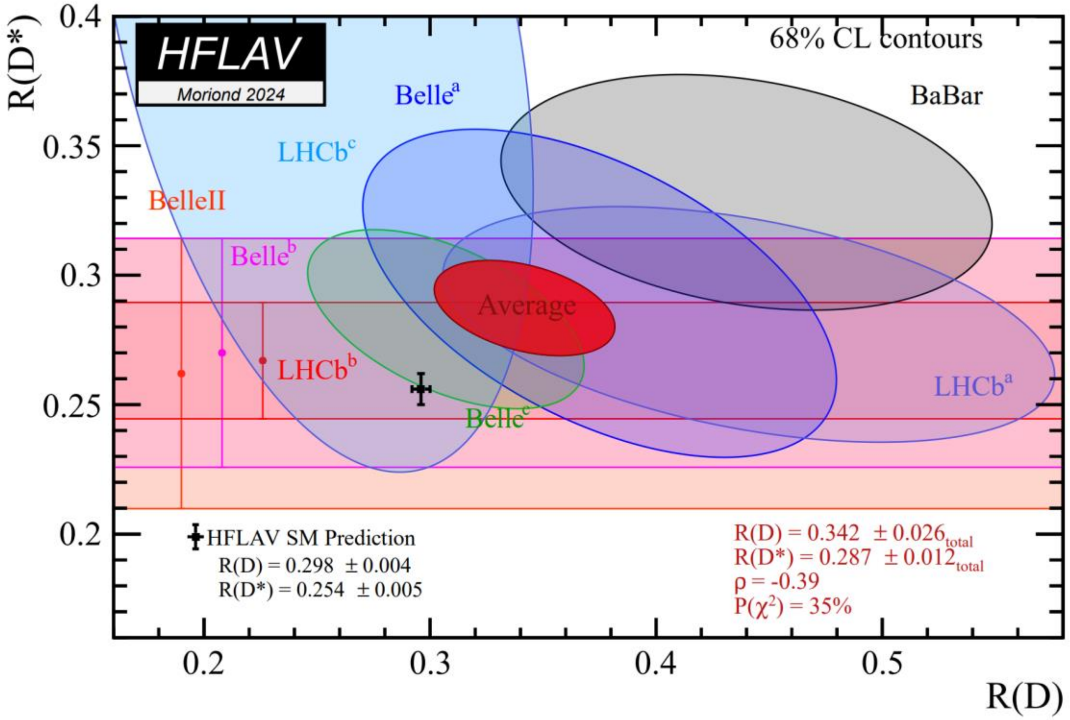
HFLAV



Previous W.A.

Tension with SM at the level of 3.34 σ

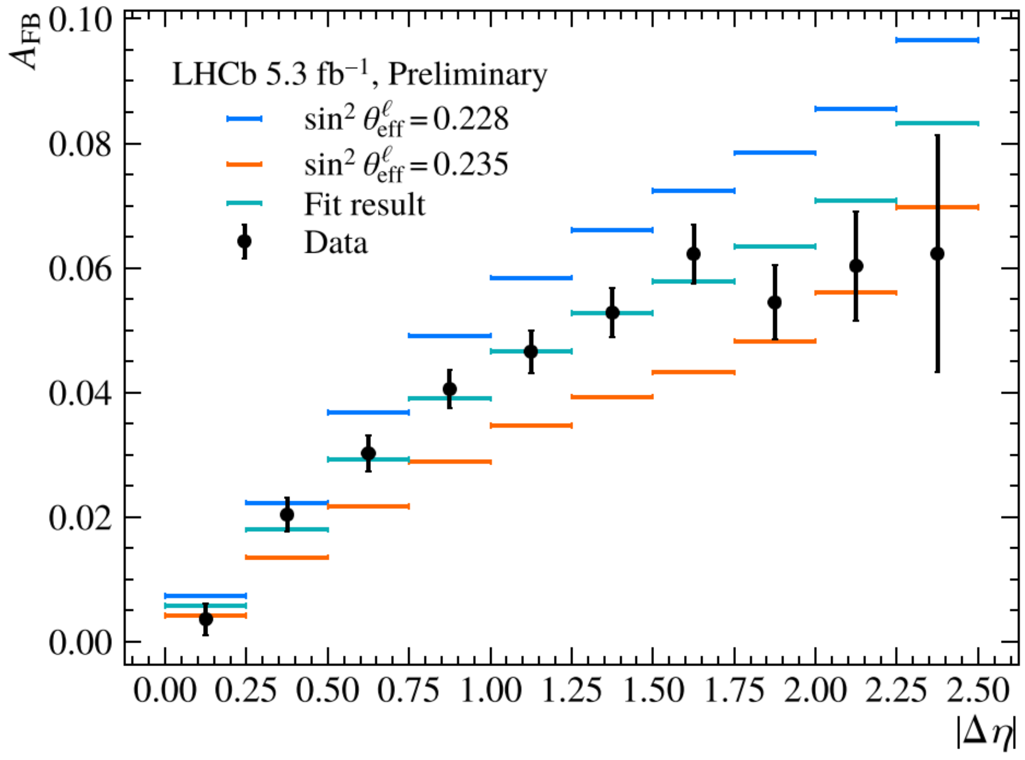
HFLAV



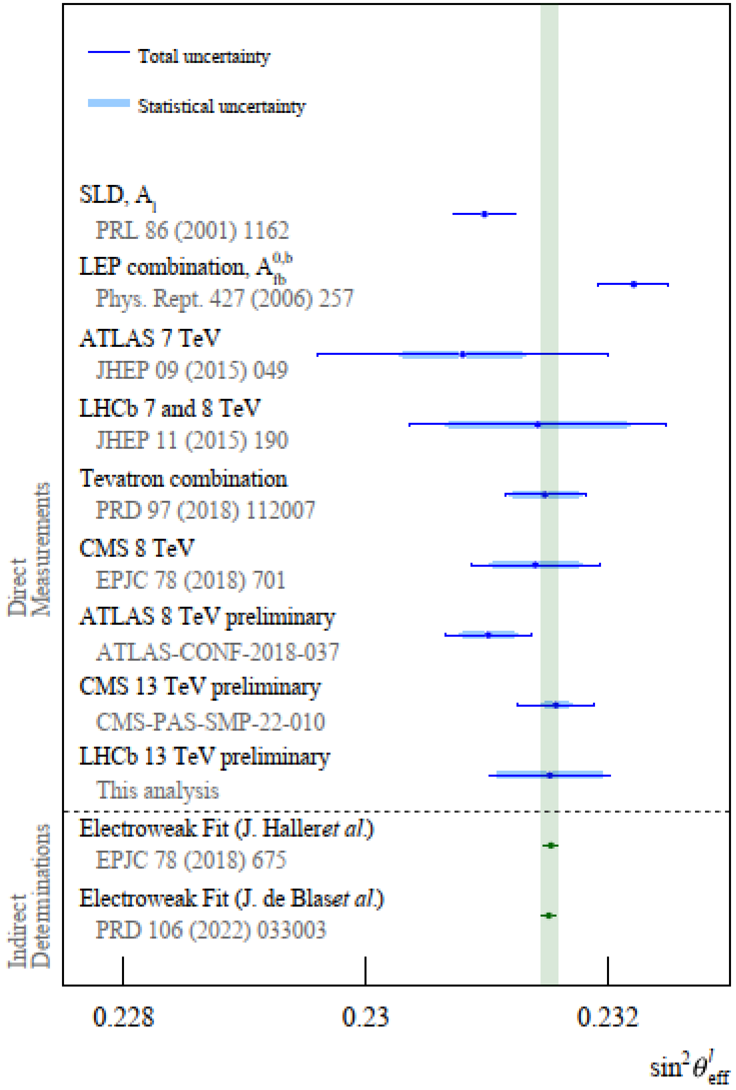
New W.A.

Tension with SM at the level of 3.17 σ

Measurement of the effective leptonic weak mixing angle



$$\sin^2\theta^{\ell}_{eff} = 0.23152 \pm 0.00044 \pm 0.00005 \pm 0.00022$$



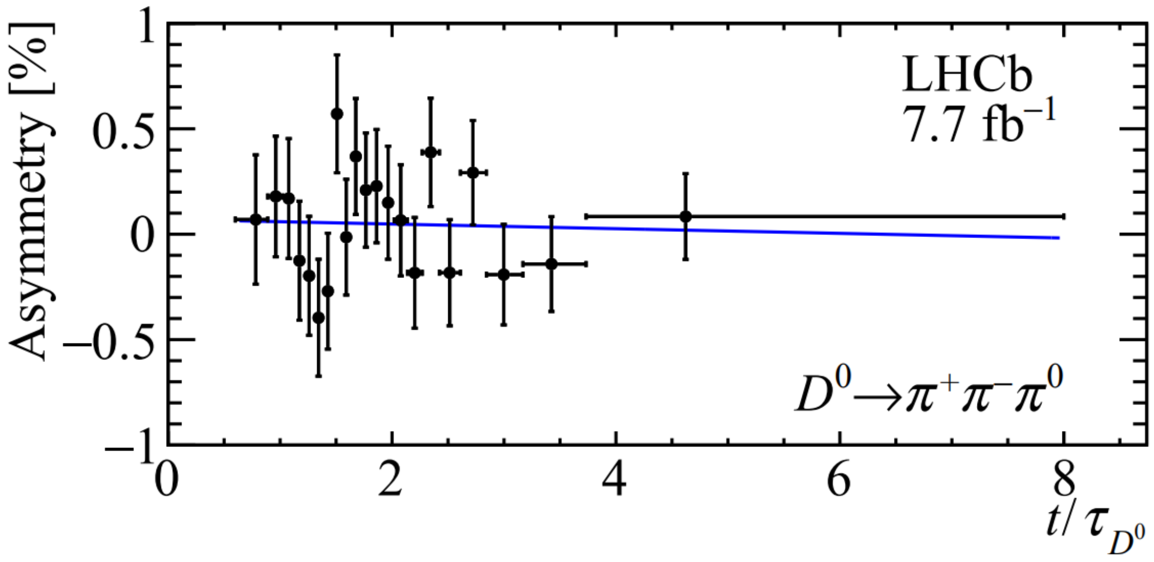
CPV in charm sector: $D^0 \to \pi^+\pi^-\pi^0$

[Phys. Rev. Lett. 133 (2024) 101803]

- A search for time-dependent CPV in $D^0 \to \pi^+\pi^-\pi^0$ decays
- The initial flavor of each D^0 candidate is determined from the charge of the pion produced in the $D^*(2010)^+ \to D^0\pi^+$ decay
- Control channel $D^0 \to K^+\pi^+\pi^0$
- The gradient of the time-dependent CP asymmetry is measured to be $\Delta Y = (-1.3 \pm 6.3 \pm 2.4) \times 10^{-4}$,

Consistent with W.A, no CPV

$$A_{CP}(f_{CP}, t) \equiv \frac{\Gamma_{D^0\to f_{CP}}(t) - \Gamma_{\bar{D}^0\to f_{CP}}(t)}{\Gamma_{D^0\to f_{CP}}(t) + \Gamma_{\bar{D}^0\to f_{CP}}(t)} \approx a^{\mathrm{dir}}_{f_{CP}} + \Delta Y_{f_{CP}} \frac{t}{\tau_{D^0}},$$



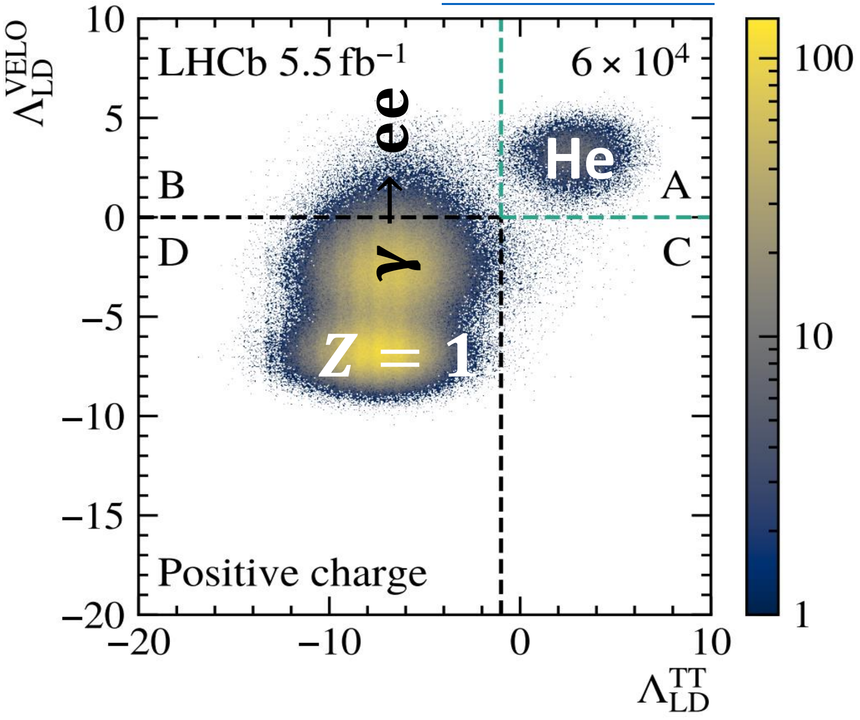
[1] 10.1016/j.physletb.2015.05.043

New area of physics

[LHCb-DP-2023-003]
[LHCb-CONF-2023-002]

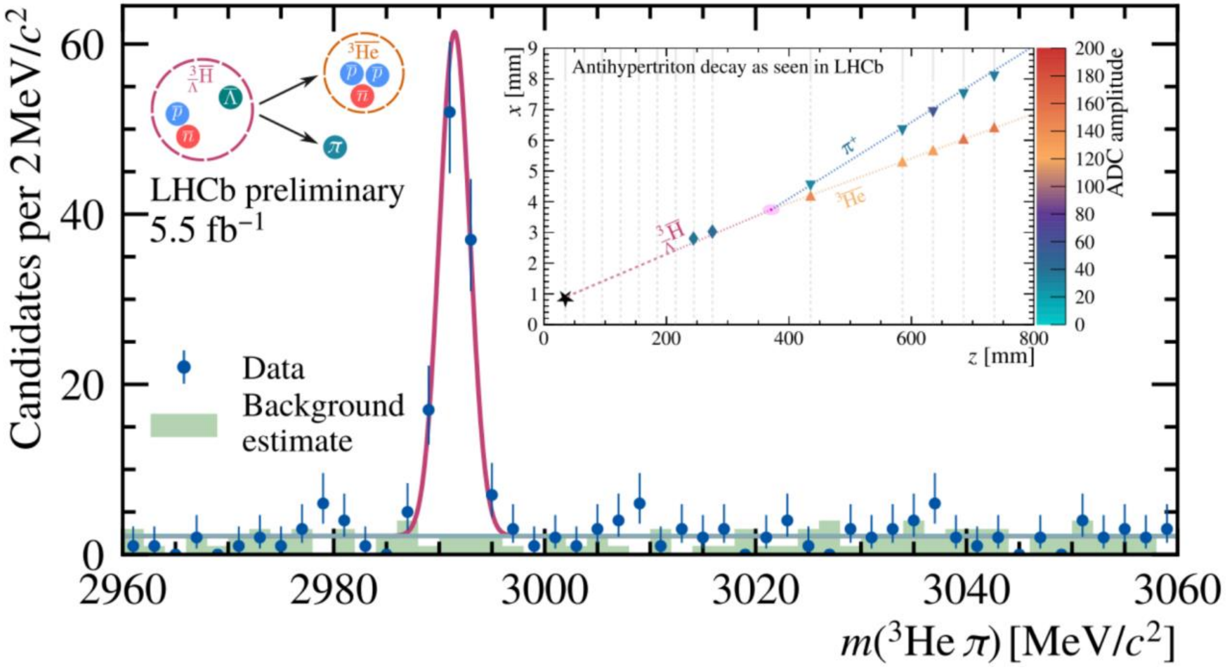
- The observation of antihelium in Cosmic Rays could be a signature of physics BSM
- LHCb can measure helium production in the forward region that is unexplored by other experiments

LHCb-DP-2023-002



Clean identification of He !

PoS EPS-HEP2023 (2024) 254



Observation of anti-hypertritons