

# INTRODUCTION TO THE IMPLICATIONS WORKSHOP

- Looking back
- Upgrade I
- Upgrade II



On behalf of the LHCb collaboration

23/10/2024 — Implications Workshop  
[indico]

Patrick Koppenburg

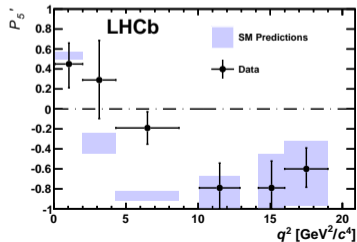
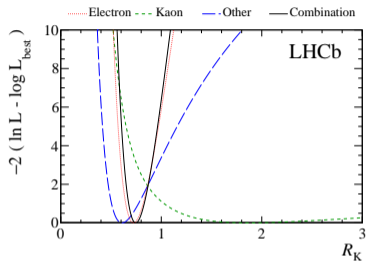
[[@pkoppenburg.bsky.social](https://bsky.app/profile/pkoppenburg.bsky.social)] [[@pkoppenburg](https://twitter.com/pkoppenburg)] [[patrick.koppenburg@nikhef.nl](mailto:patrick.koppenburg@nikhef.nl)]



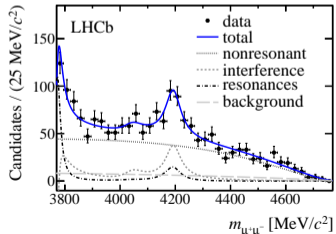
Nikhef

# $R_K$ AND $P'_5$ AND $c\bar{c}$

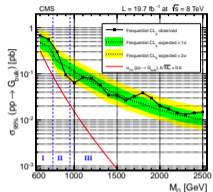
Patrick Koppenburg  
October 2014  
Tomorrow Morning



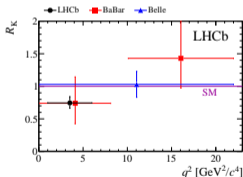
- $R_K$   $2.6\sigma$  from SM [PRL 113 (2014) 151601]
- $P'_5$   $3.7\sigma$  away in one bin [PRL 111 (2013) 191801]
- Leptophobic  $Z'$ ? [Altmannshofer, PRD 89 (2014) 095033]
- But how well do we control  $c\bar{c}$ ? [PRL 111 (2013) 112003]



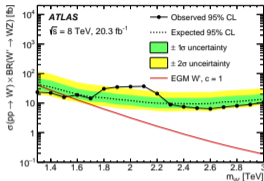
# ARE WE ALREADY SEEING NEW PHYSICS?



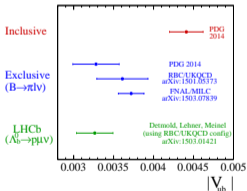
Excess at 2 TeV [CMS, JHEP 08 (2014) 174]



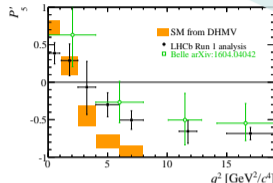
Lepton universality [PRL 113 (2014) 151601]



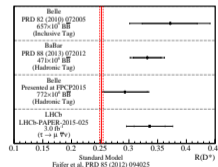
Excess at 2 TeV [ATLAS, JHEP 12 (2015) 55]



$V_{ub}$  puzzle [Nature Phys. 11 (2015) 743]



$P_5'$  in  $B \rightarrow K^* \mu^+ \mu^-$  [JHEP 02 (2016) 104]



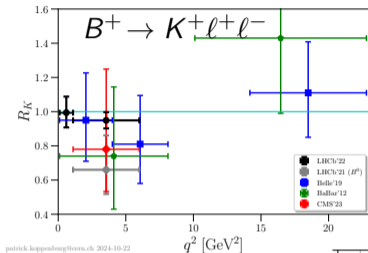
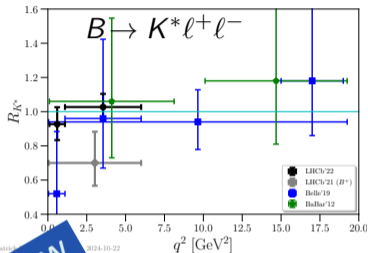
$B \rightarrow D^* \tau \nu$  [PRD 92 (2015) 011102(R)]

There's a handful of intriguing 3–4 $\sigma$  anomalies



# ALL $R_X \sim 1$

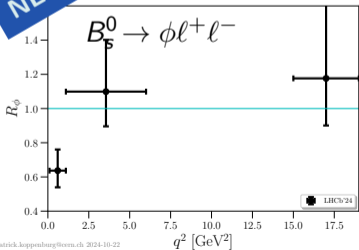
Sara Celani,  
tomorrow



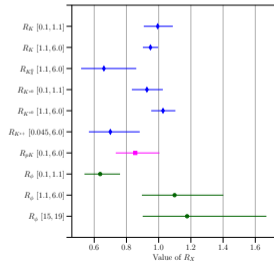
patrick.koppenburg@cern.ch 2024-10-22

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NEW

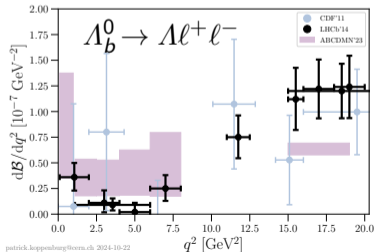
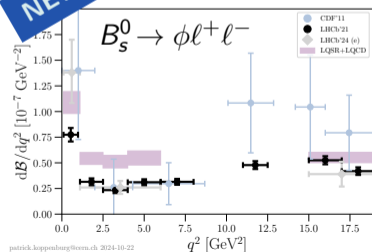
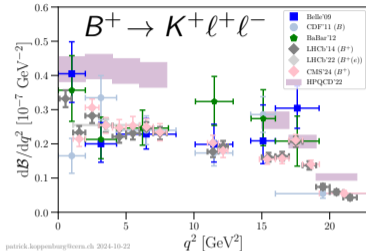
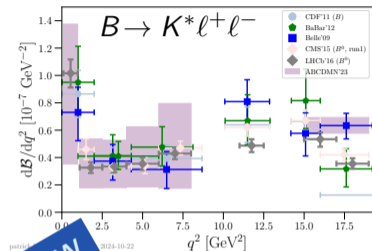


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# BFs TOO LOW IN $b \rightarrow sl^+l^-$ DECAYS



**NEW**

# BFs TOO LOW IN $b \rightarrow sl^+l^-$ DECAYS



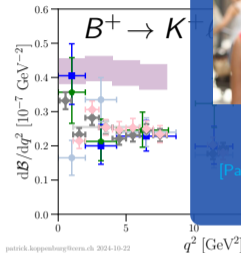
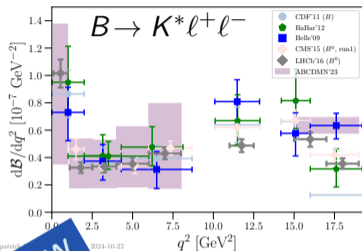
Lattice

Sum Rules

$4.2\sigma$  for  $B \rightarrow K\mu^+\mu^-$

[Parrott, Bouchard, Davies (HPQCD), PRD

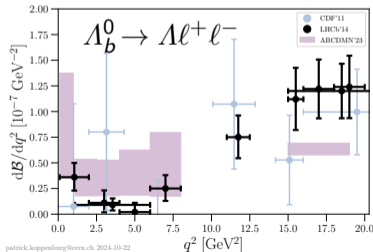
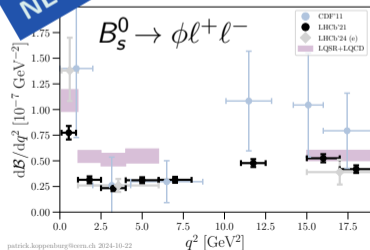
107 (2023) 119903]



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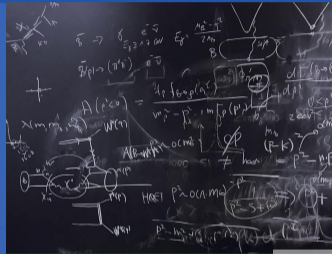
NEW



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# BFs TOO LOW IN $b \rightarrow sl^+l^-$ DECAYS



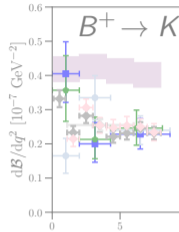
## Hadron Form Factors

From Basic Phenomenology to QCD Sum Rules

Alexander Khodjamirian

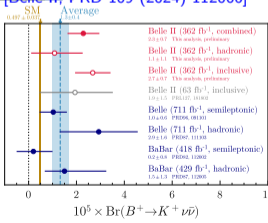


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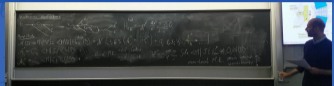


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[Belle II, PRD 109 (2024) 112006]



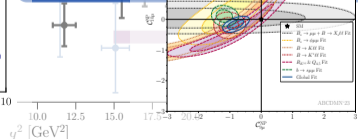
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## Nonlocal $c\bar{c} \rightarrow \gamma^*$ operators



[Algueró et al., arXiv:2304.07330]



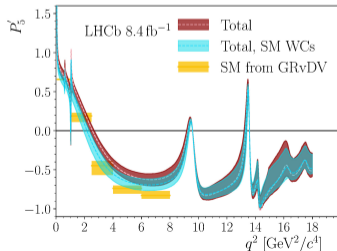
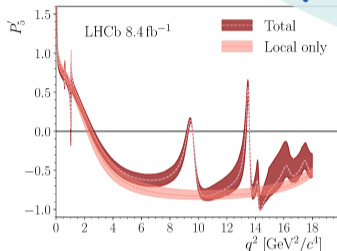


UNBINNED  $B^0 \rightarrow K^{*0} \mu^+ \mu^-$ 

Use all data without charmonium veto to determine local and nonlocal contributions.

Determine Wilson coefficients and nonlocal contributions from fit

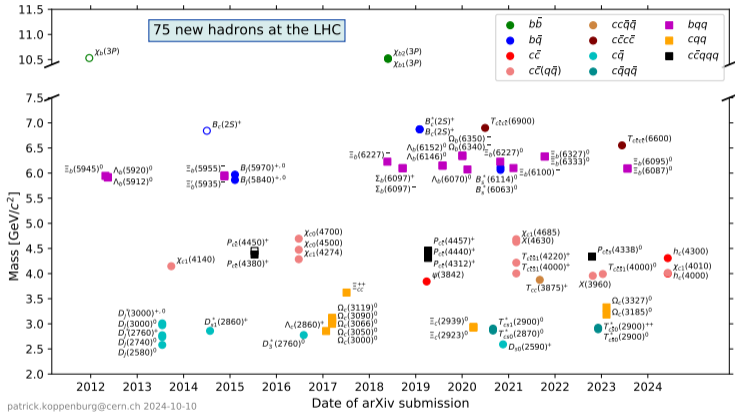
Nonlocal operators play a role, but the tension in Wilson coefficients persists.





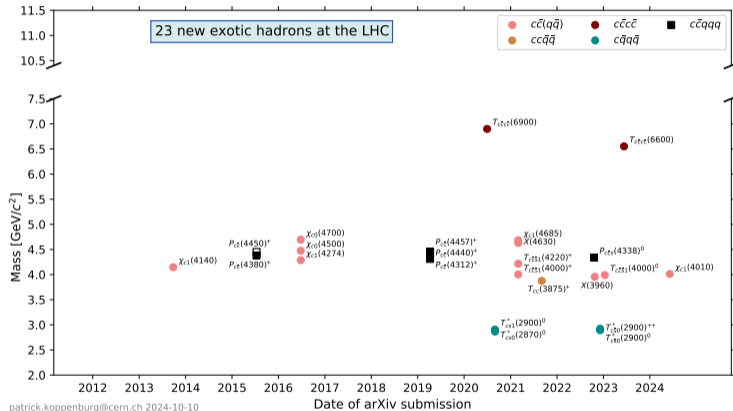
Yuhao Wang,  
Da Yu Tou,  
Linxuan Zhu,  
tomorrow

# ALL HADRONS FOUND AT THE LHC



All resonances observed at the LHC in a mass versus submission date plot. Hollow markers indicate superseded states.

## ALL EXOTIC HADRONS FOUND AT THE LHC

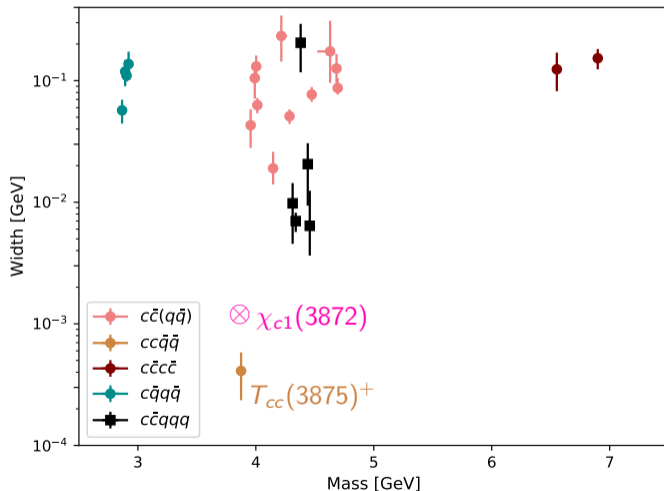


All exotic resonances observed at the LHC in a mass versus submission date plot. Hollow markers indicate superseded states.

# MASSES AND WIDTHS



All exotic resonances observed at the LHC in a width versus mass plot.

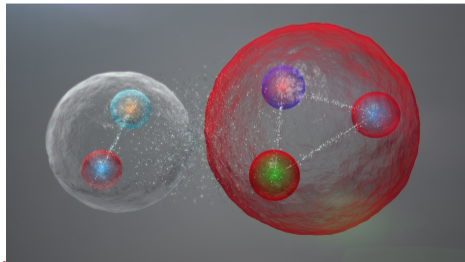
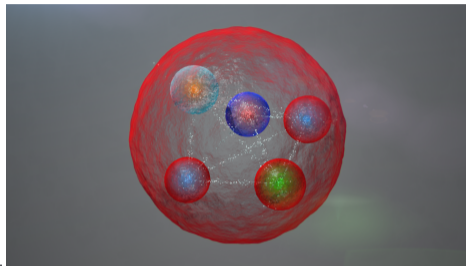


patrick.koppenburg@cern.ch 2024-10-10

# EXTREME CONFIGURATIONS

## Tightly bound pentaquark

Each quark sees the colour charge of every other quark



## Loosely bound molecule

Two colour singlets interacting by light meson exchange

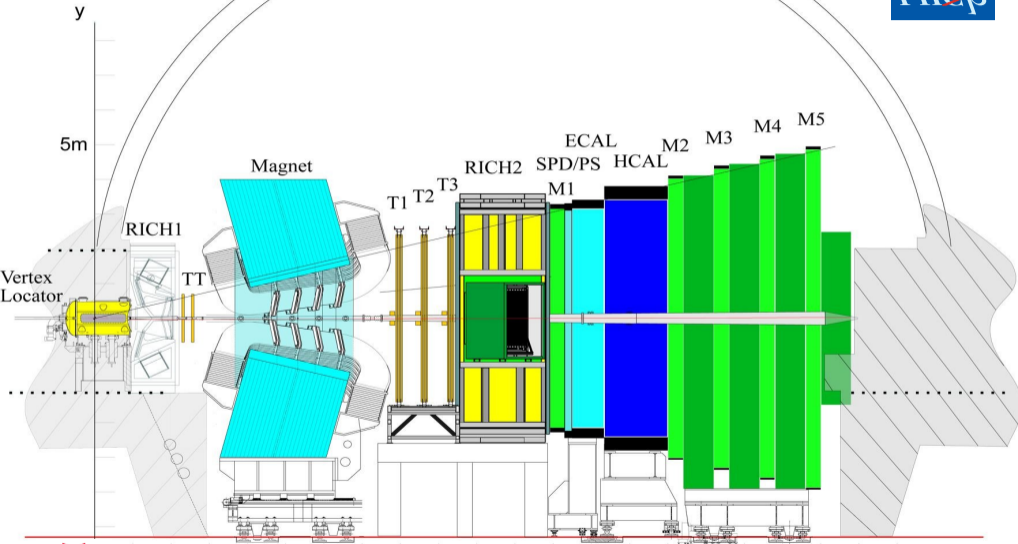


# LHCb

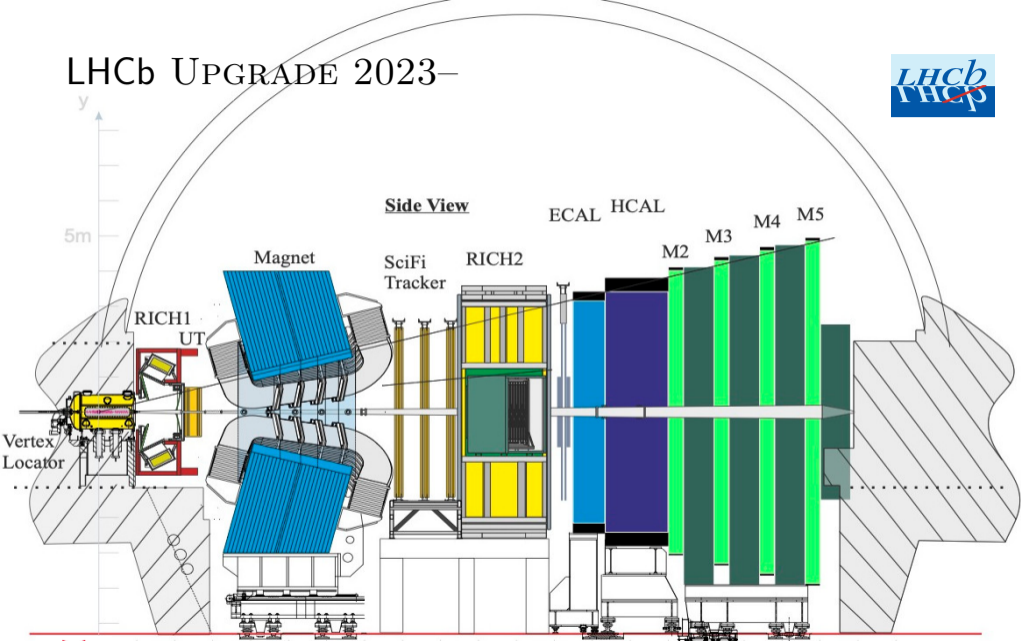
No Visitors  
Aucun visiteur autorisé  
Pas de Visiteurs  
No visitors allowed



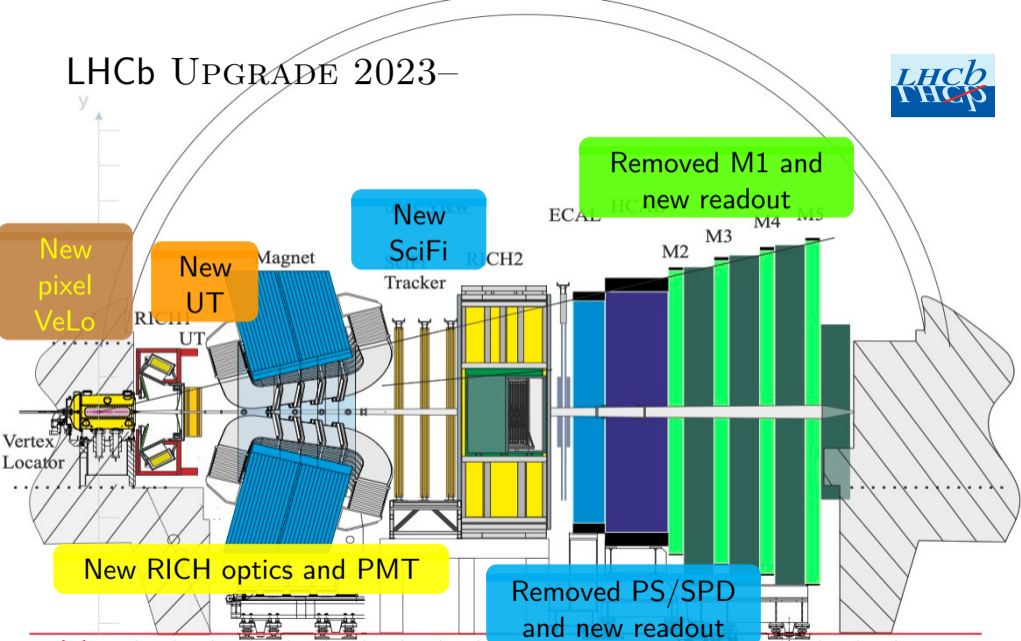
# LHCb LEGACY 2009–2018



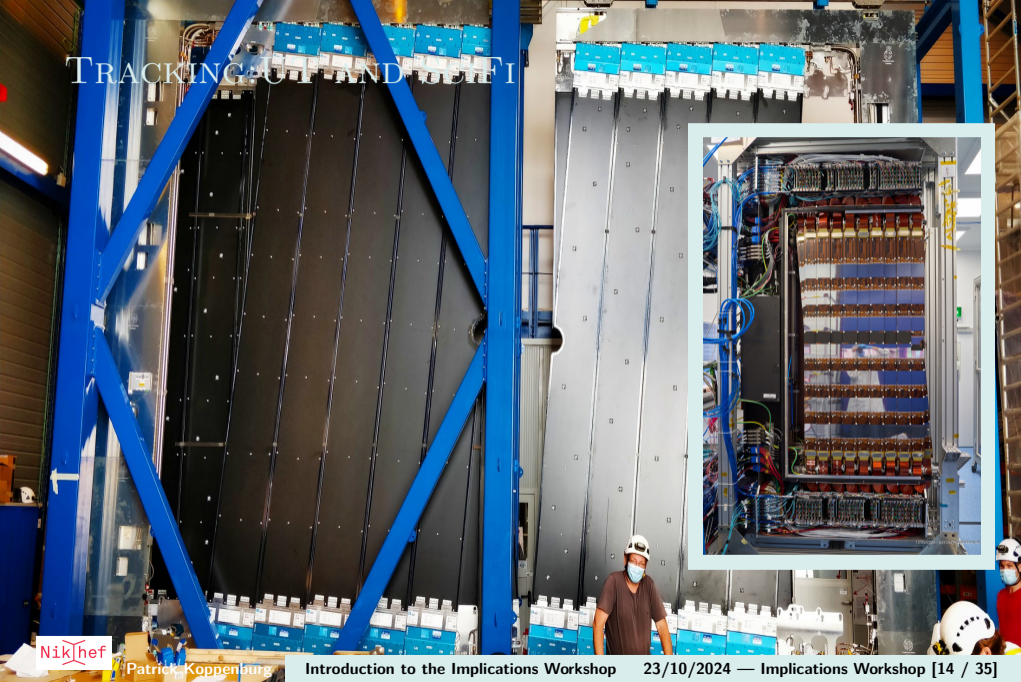
# LHCb UPGRADE 2023



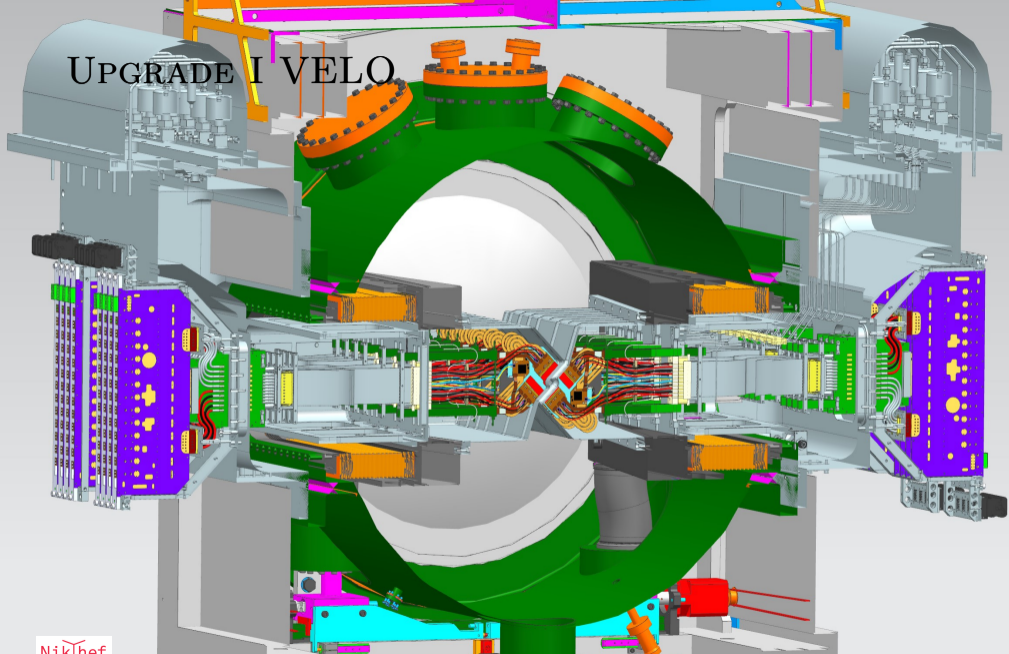
# LHCb UPGRADE 2023



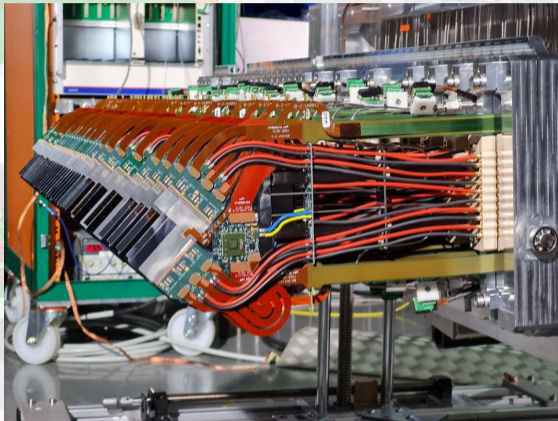
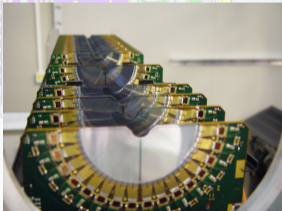
# TRACKING: UI AND UDFI



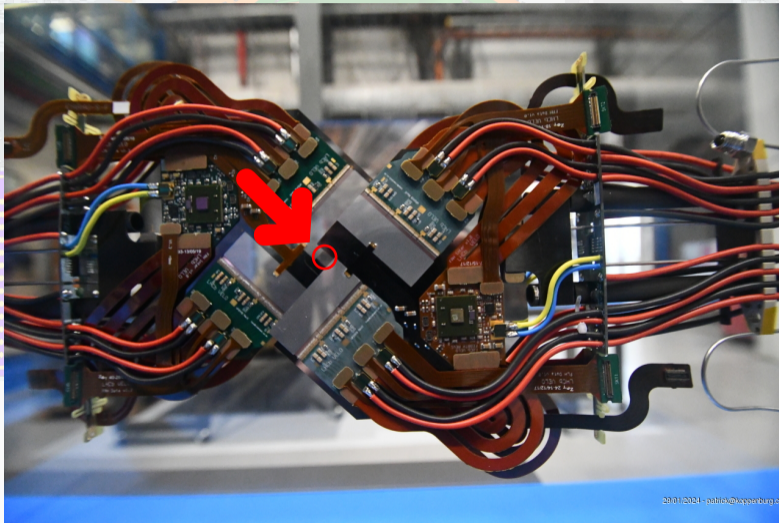
# UPGRADE I VELO



# UPGRADE I VELO



# UPGRADE I VELO

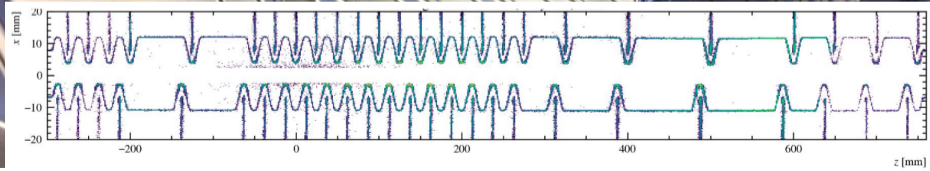
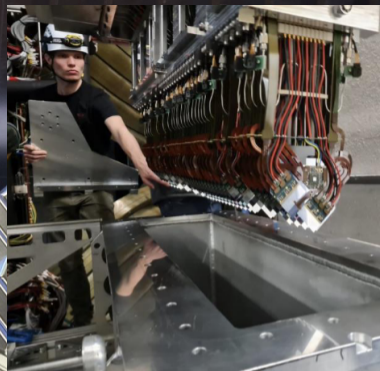


29/11/2024 - patrick.koppenburg.ch

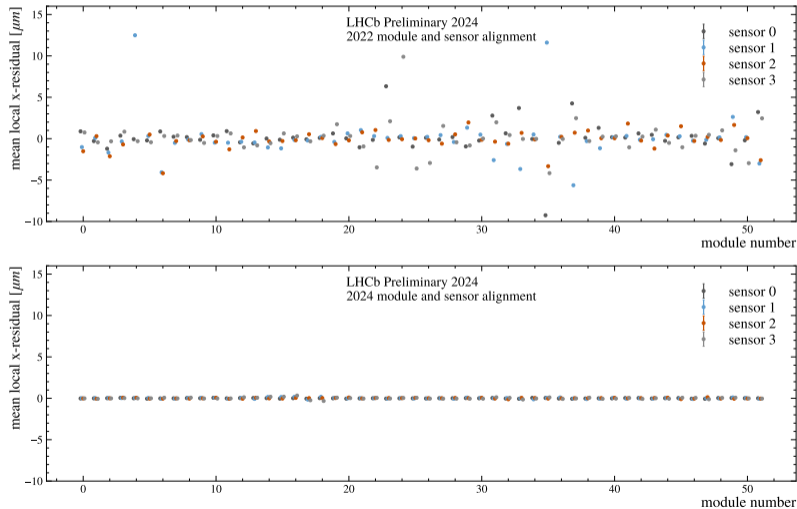
# VELO INCIDENT



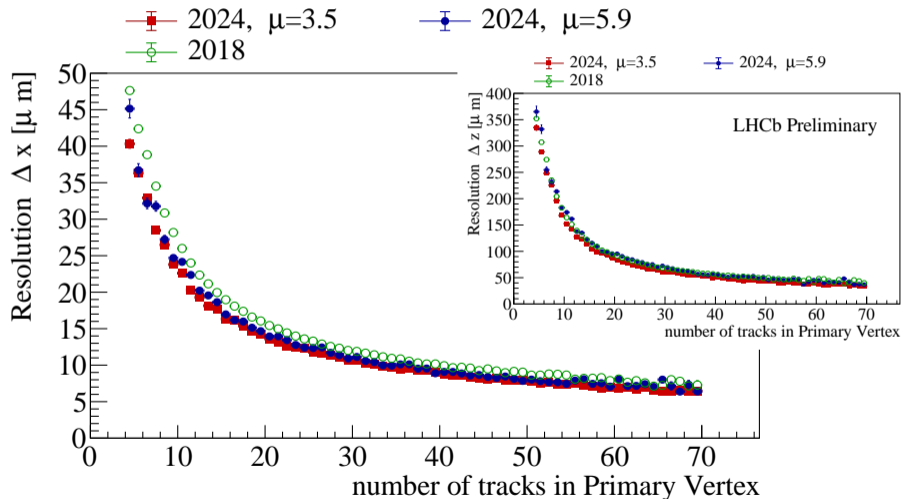
# VELO INCIDENT



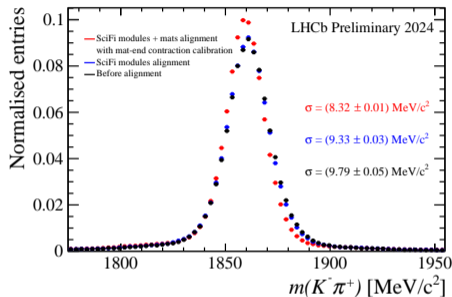
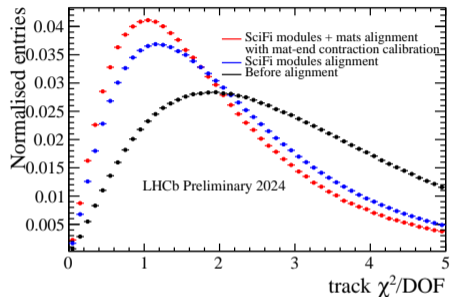
## RUN 3 FIGURES: VELO ALIGNMENT



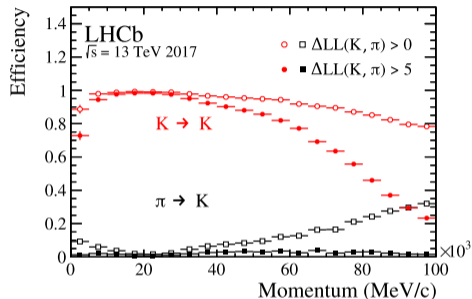
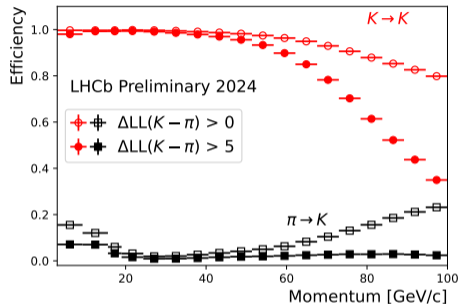
# RUN 3 FIGURES: PV RESOLUTION



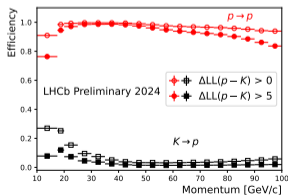
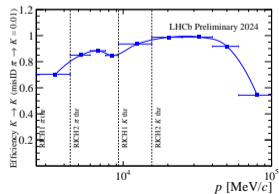
# RUN 3 FIGURES: ALIGNMENT



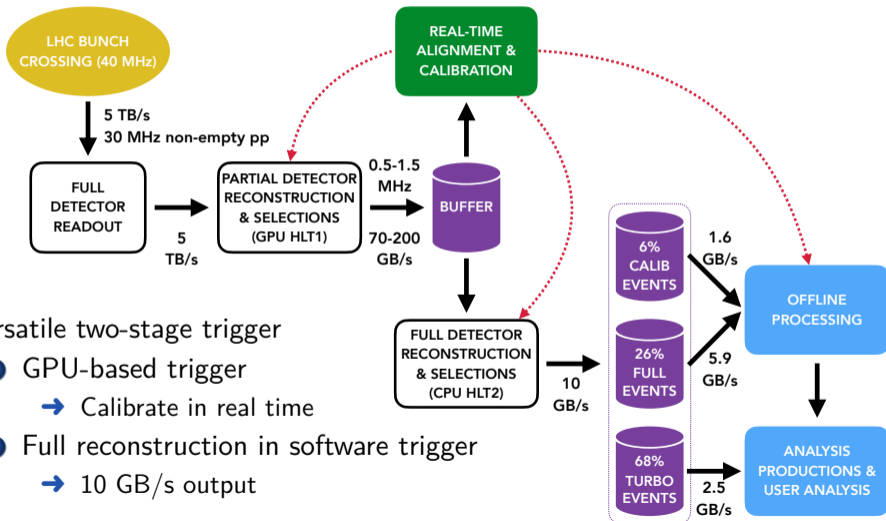
# RUN 3 FIGURES: PID



[LHCb-DP-2021-004, arXiv:2205.13400]



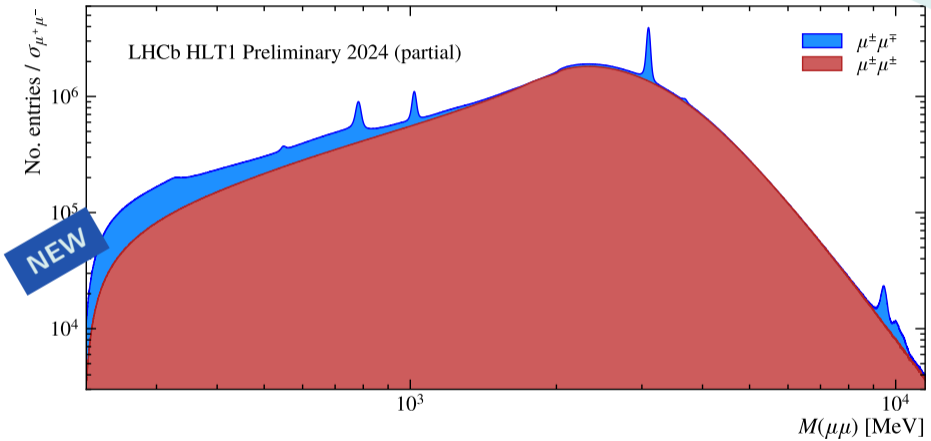
# LHCb DATAFLOW IN RUN 3

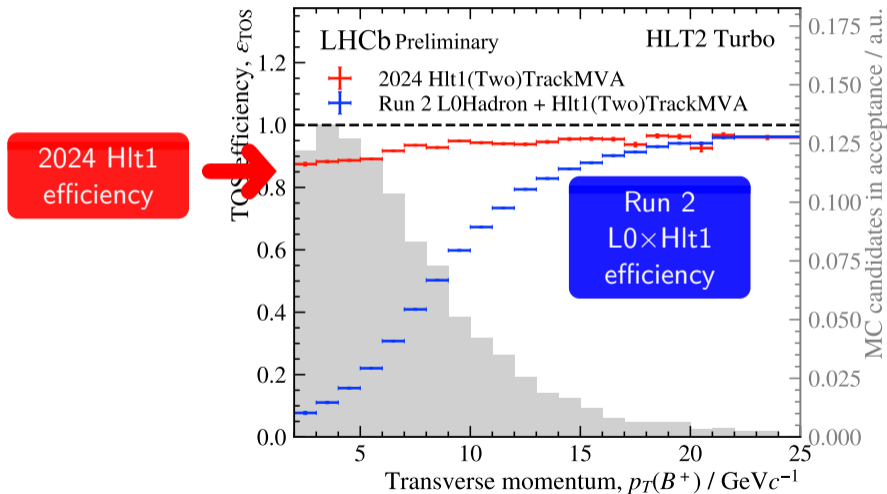


Versatile two-stage trigger

- 1 GPU-based trigger
  - Calibrate in real time
- 2 Full reconstruction in software trigger
  - 10 GB/s output

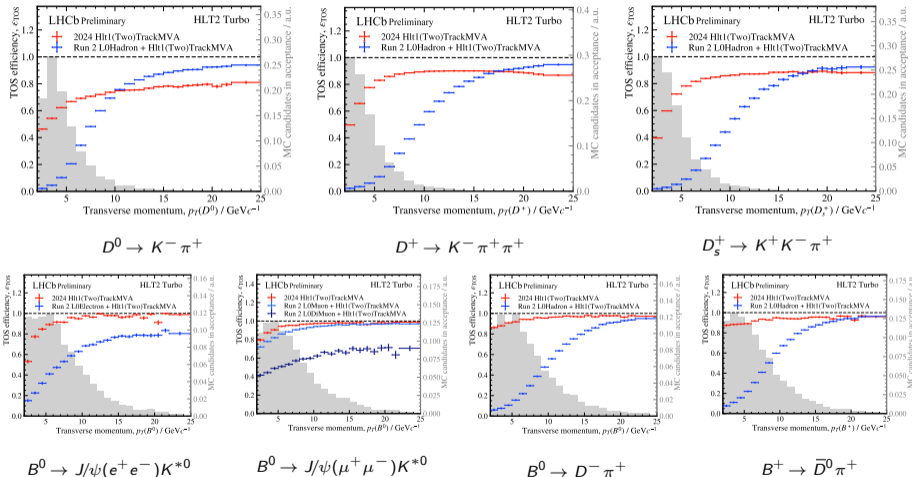
## RUN 3 FIGURES: HLT1 DIMUONS



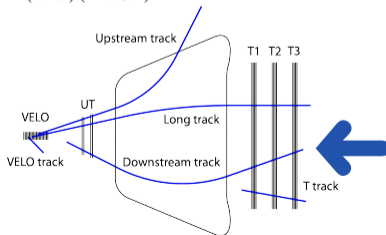
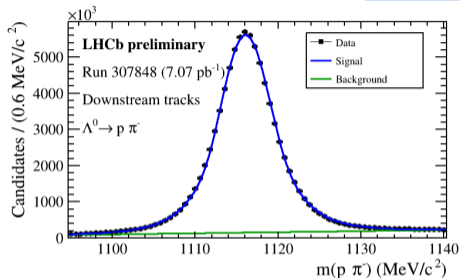
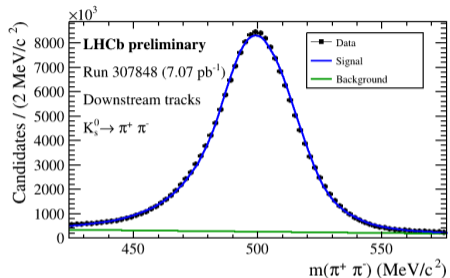
HLT1 EFFICIENCIES FOR  $B^+ \rightarrow \bar{D}^0 \pi^+$ 



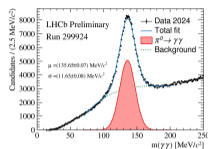
# HLT1 EFFICIENCIES



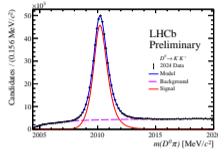
# HLT1 DOWNSTREAM TRACKING



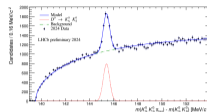
# RUN 3 FIGURES: MASS PLOTS



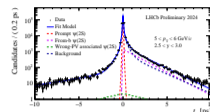
$\pi^0 \rightarrow \gamma\gamma$   
[FIGURE-2024-017]



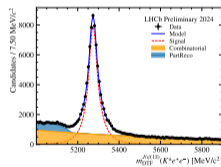
$D^{*0} \rightarrow D^0(K^+K^-)\pi^+$   
[FIGURE-2024-006]



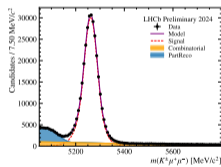
$D^0 \rightarrow K_S^0 K_S^0$   
[FIGURE-2024-008]



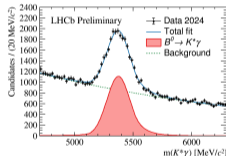
$\psi(2S)$  pseudo-lifetime  
[FIGURE-2024-024]



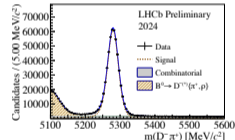
$B^+ \rightarrow J/\psi(e^+e^-)K^+$   
[FIGURE-2024-007]



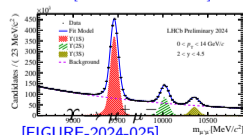
$B^+ \rightarrow J/\psi(\mu^+\mu^-)K^+$   
[FIGURE-2024-007]



$B^0 \rightarrow K^{*0} \gamma$   
[FIGURE-2024-017]



$B^0 \rightarrow D^- \pi^+$   
[FIGURE-2024-021]

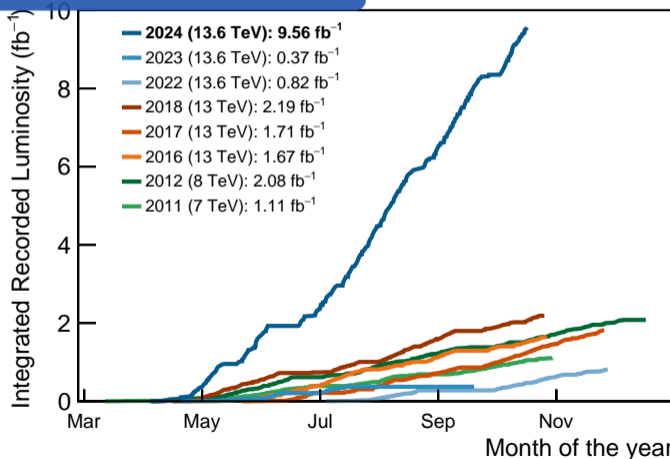


[FIGURE-2024-025]

# RUN 3



## The one plot to remember from this talk

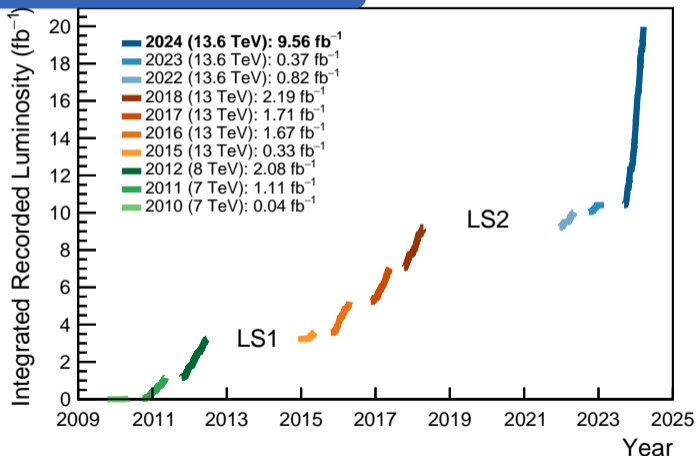


2010 not even listed.  
We need a log scale.

## RUN 3



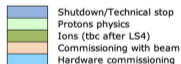
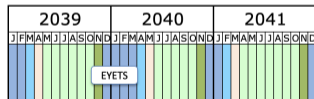
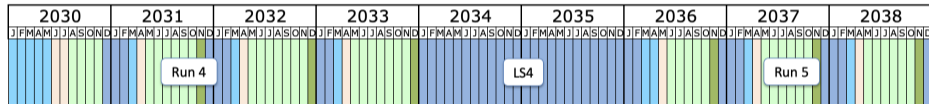
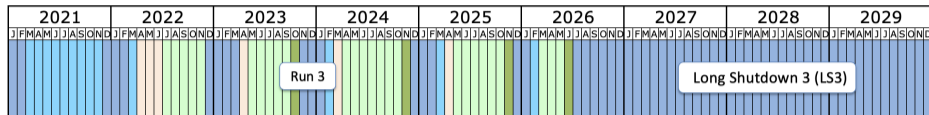
The one plot to remember from this talk





[3]

# LHC SCHEDULE (OCT 2024)



Last update: September 24



# Upgrade II

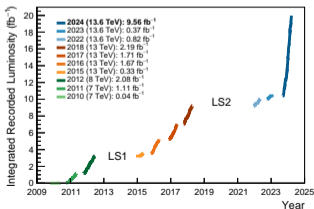
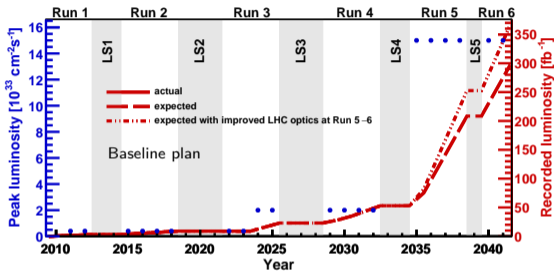


# UPGRADE II

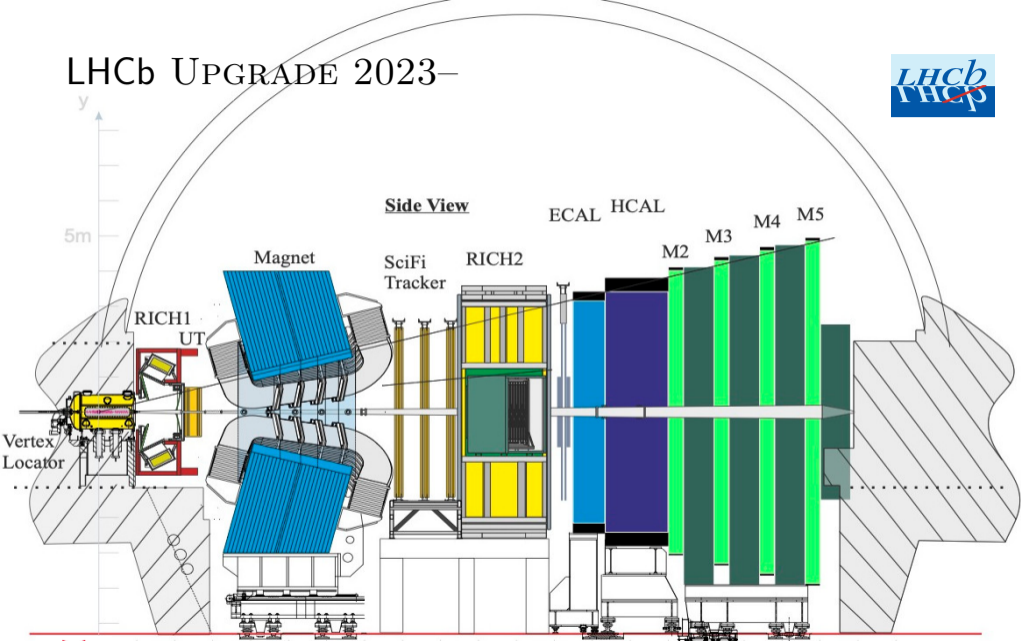


The baseline plan is to record  $300 \text{ fb}^{-1}$  by the end of Run 5.

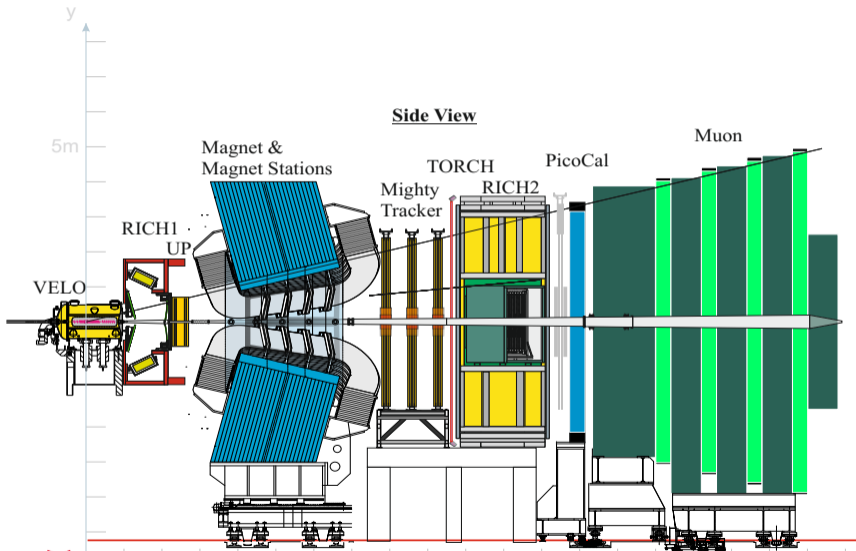
- 1 Eol [CERN-LHCC-2017-003]
- 2 Physics case [LHCb U2  
Physics case, arXiv:1808.08865]
- 3 Framework TDR  
[LHCb-TDR-023]
- 4 Scoping document  
[LHCb-TDR-026] (with LHCC —  
will be public soon)



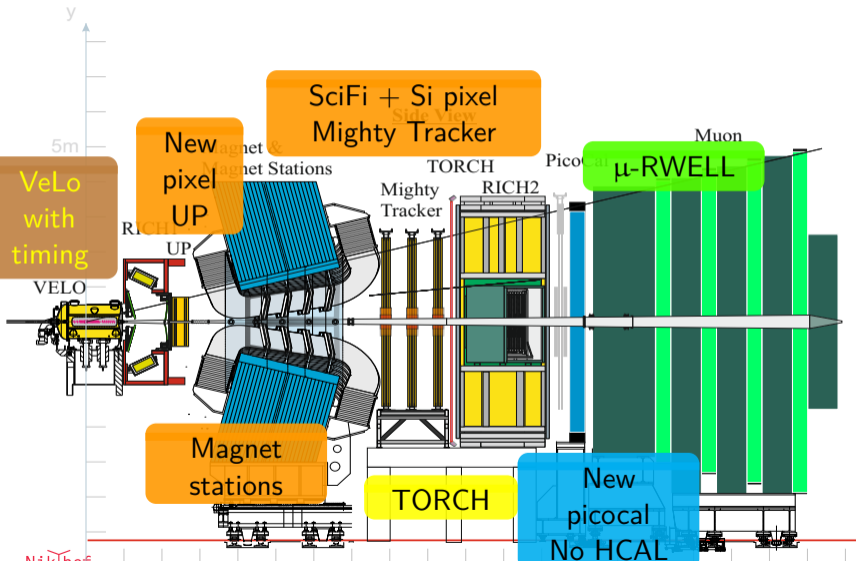
# LHCb UPGRADE 2023



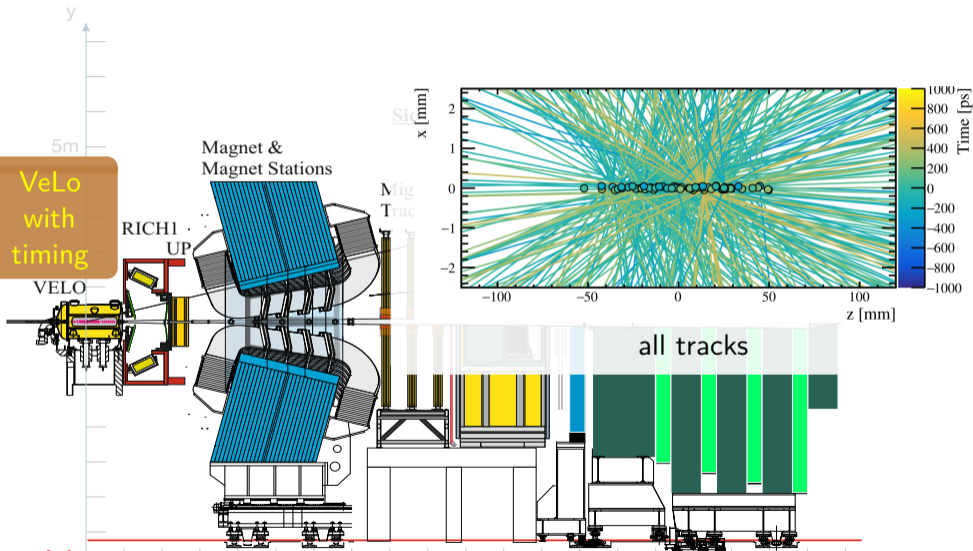
# LHCb UPGRADE II



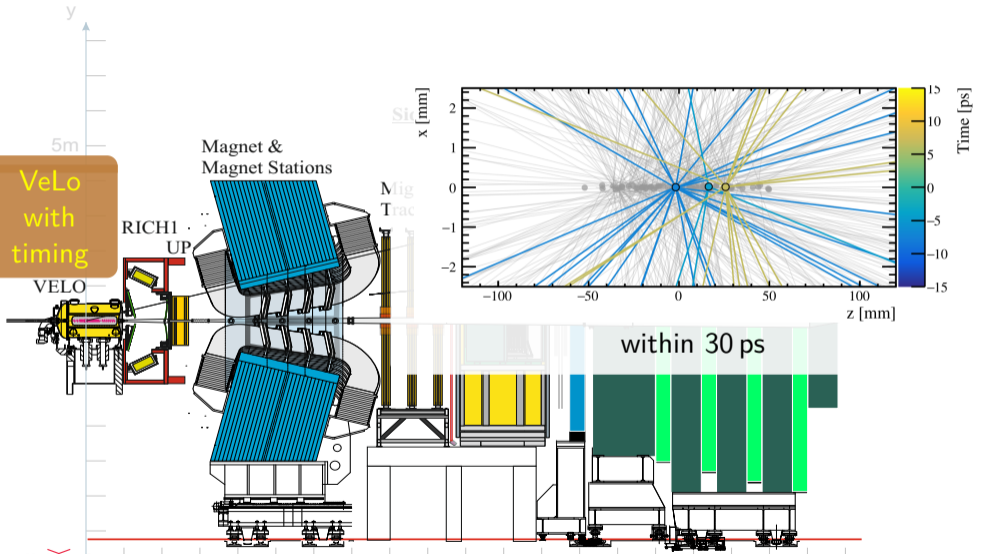
## LHCb UPGRADE II



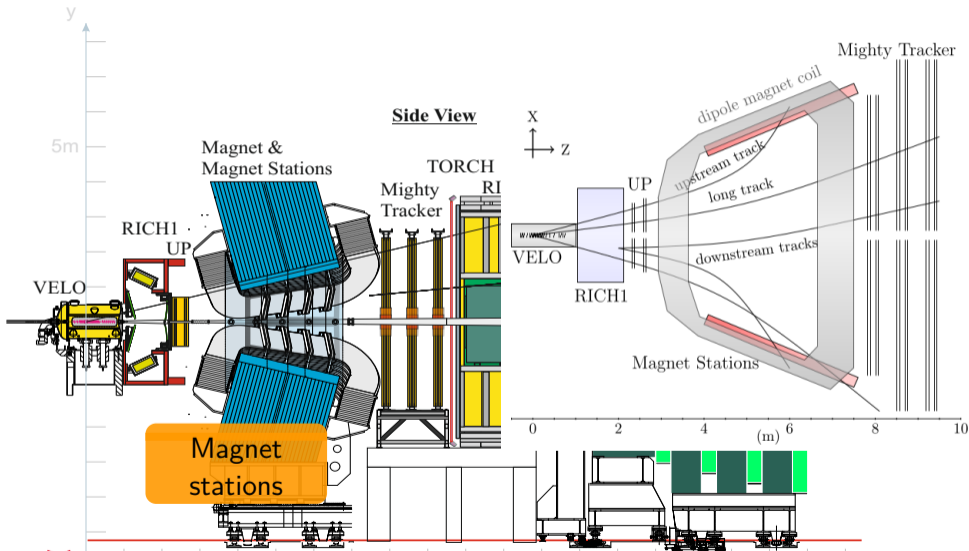
## LHCb UPGRADE II



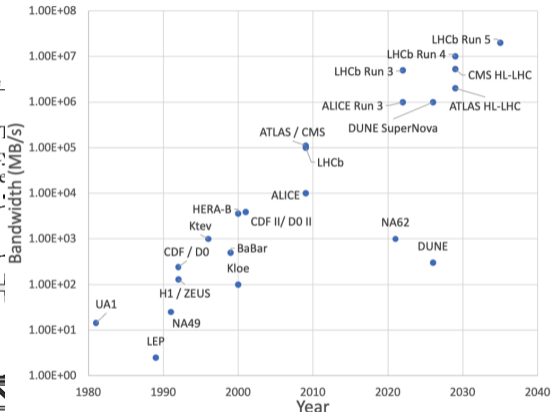
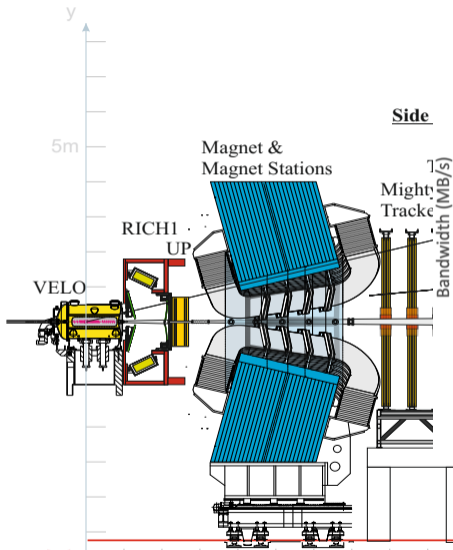
# LHCb UPGRADE II



# LHCb UPGRADE II



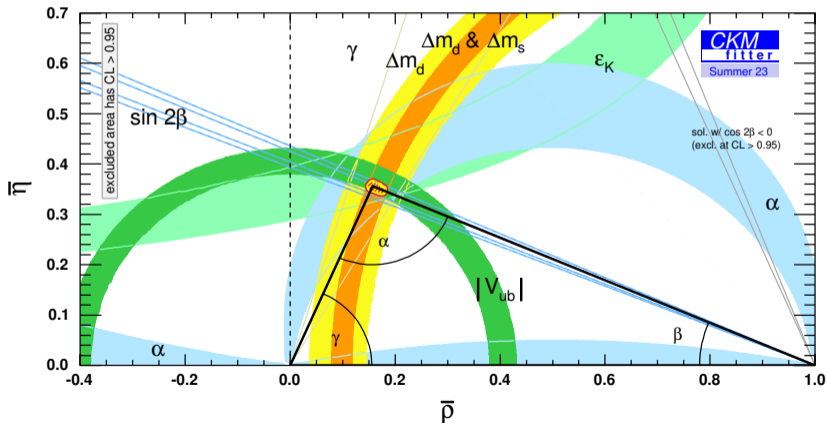
# LHCb UPGRADE II



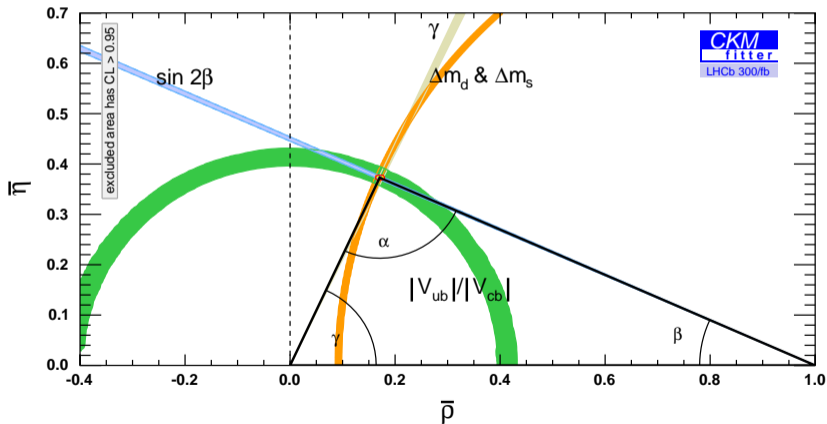




# UNITARITY TRIANGLE



# UNITARITY TRIANGLE



# SOME RESULTS YOU'LL BE FIRST TO SEE

LHCb-PAPER-

2024-030 Photon polarisation with low- $q^2$   $e^+e^-$

2024-046 More  $b \rightarrow s\ell^+\ell^-$  lepton universality

2024-047  $D \rightarrow h^+h^-e^+e^-$

2024-037  $B^- \rightarrow D^{*0}\tau^- \nu$  decays

2024-031 Direct  $CPV$  in  $b \rightarrow J/\psi X$

2024-043, 2024-048  $CPV$  in baryons (with an evidence, finally!)

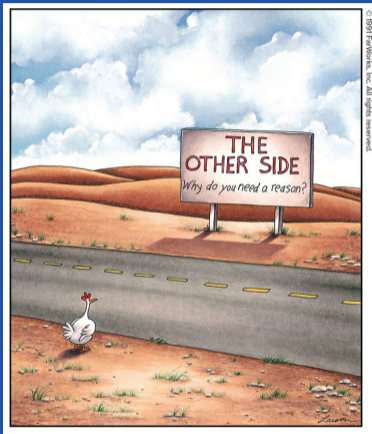
2024-044 Mixing and  $CPV$  in charm

2024-033 Likely two new tetraquarks, but we are not sure

2024-040 A known tetraquark in another decay mode

# Conclusion

Enjoy the workshop!



# Backup

## LHCb UPGRADE II PERFORMANCE

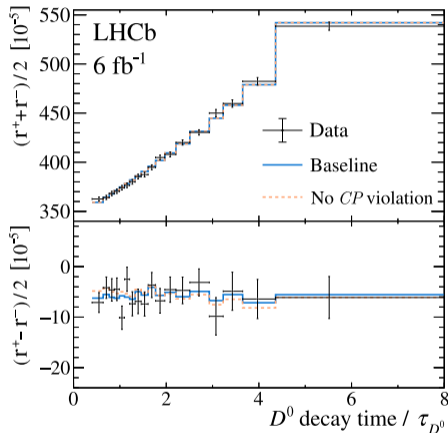
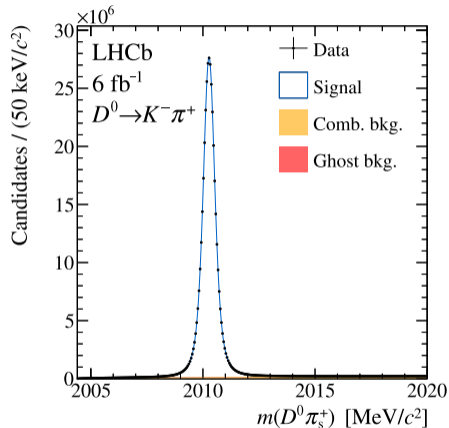


Observable	Legacy (9 fb <sup>-1</sup> )		Upgrade I (23 fb <sup>-1</sup> )   (50 fb <sup>-1</sup> )		U2 (300 fb <sup>-1</sup> )
	$\sin 2\beta$ , with $B^0 \rightarrow J/\psi K_S^0$	0.015	<a href="#">[PRL 132 (2024) 021801]</a>	0.011	
$\varphi_s$ , with $B_s^0 \rightarrow J/\psi K^+ K^-$ [mrad]	20	<a href="#">[PRL 132 (2024) 051802]</a>	12	8	3
$\varphi_s^{\bar{s}s}$ , with $B_s^0 \rightarrow \phi\phi$ [mrad]	80	<a href="#">[PRL 131 (2023) 171802]</a>	39		11
$\gamma$	4°	<a href="#">[LHCb-CONF-2024-004]</a>	1.5°	1.0°	0.35°
$ V_{ub} / V_{cb} $	6%	<a href="#">[Nature Phys. 11 (2015) 743]</a>	3%	2%	1%
$\mathcal{R}_{\mu^+\mu^-}$	69%	<a href="#">[PRL 128 (2022) 041801]</a>	41%	27%	11%
$R_K (1 < q^2 < 6 \text{ GeV}^2/c^4)$	0.1	<a href="#">[PRD 108 (2023) 032002]</a>	0.025		0.007
$A_T^{(2)}(B \rightarrow K^* e^+ e^-)$	0.1	<a href="#">[JHEP 12 (2020) 081]</a>	0.06	0.04	0.016
$S_{\phi\gamma}(B_s^0 \rightarrow \phi\gamma)$	0.32	<a href="#">[PRL 123 (2019) 081802]</a>	0.09	0.06	0.025
$R(D^*)$	0.022	<a href="#">[PRD 108 (2023) 012018]</a>	0.007		0.002
$\Delta A_{CP}(D^0 \rightarrow KK, \pi\pi)$ [10 <sup>-5</sup> ]	29	<a href="#">[PRL 122 (2019) 211803]</a>	13	8	3.3
$A_\Gamma(D^0 \rightarrow KK, \pi\pi)$ [10 <sup>-5</sup> ]	11	<a href="#">[PRD 104 (2021) 072010]</a>	5	3.2	1.2



# Mixing and $\bar{C}PV$

# D MIXING WITH $D \rightarrow K^- \pi^+$



In  $B$  CPV in mixing came before direct CPV. In  $D$  CPV in mixing is still missing. With Runs 1&2 measure  $A_{K\pi} = (-6.6 \pm 5.7) \times 10^{-3}$ .

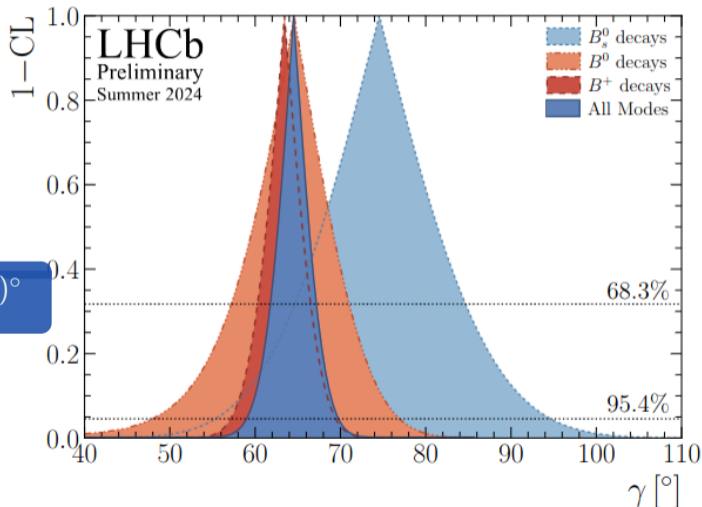


$\gamma$  COMBINATION MATRIX

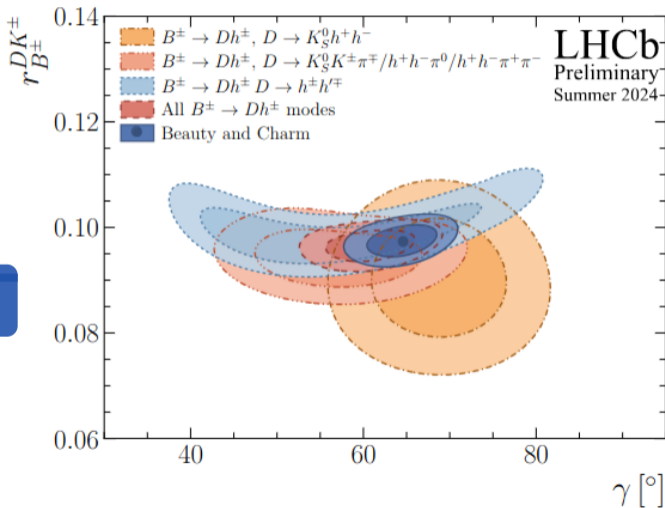
	Time-integrated measurements					
Final states	$Dh^+$	$D^{*0}h^+$	$DK_S^0\pi^+$	$DK^+\pi^-$	$DK^+\pi^-\pi^-$	$DK^{*+}$
$h^+h^-$	[9 fb <sup>-1</sup> ]	[9 fb <sup>-1</sup> ]	[5 fb <sup>-1</sup> ]	[9 fb <sup>-1</sup> ]	[3 fb <sup>-1</sup> ]	[9 fb <sup>-1</sup> ]
$h^+\pi^-\pi^+\pi^-$	[3 fb <sup>-1</sup> ][9 fb <sup>-1</sup> ]	[9 fb <sup>-1</sup> ]	[5 fb <sup>-1</sup> ]	[9 fb <sup>-1</sup> ]		
$h^+h^-\pi^+\pi^-$	[9 fb <sup>-1</sup> ]					[9 fb <sup>-1</sup> ]
$h^+h^-\pi^0$	[9 fb <sup>-1</sup> ]					
$K^\mp\pi^\pm$						
$K^\mp\pi^\pm\pi^0$						
$K_S^0h^+h^-$	[9 fb <sup>-1</sup> ]	[9 fb <sup>-1</sup> ][9 fb <sup>-1</sup> ]		[9 fb <sup>-1</sup> ]		[9 fb <sup>-1</sup> ]
$K_S^0K^+\pi^-$	[9 fb <sup>-1</sup> ]					

	Time-dependent measurements		
Final states	$D^\mp\pi^\pm$	$B_s^0 \rightarrow D_s^\mp K^\pm$	$D_s^\mp K^\pm\pi^+\pi^-$
$K^\pm h^+ h^-$	[3 fb <sup>-1</sup> ]	N/A	N/A
$h^\pm h^\mp \pi^\pm$	N/A	[9 fb <sup>-1</sup> ]	[9 fb <sup>-1</sup> ]

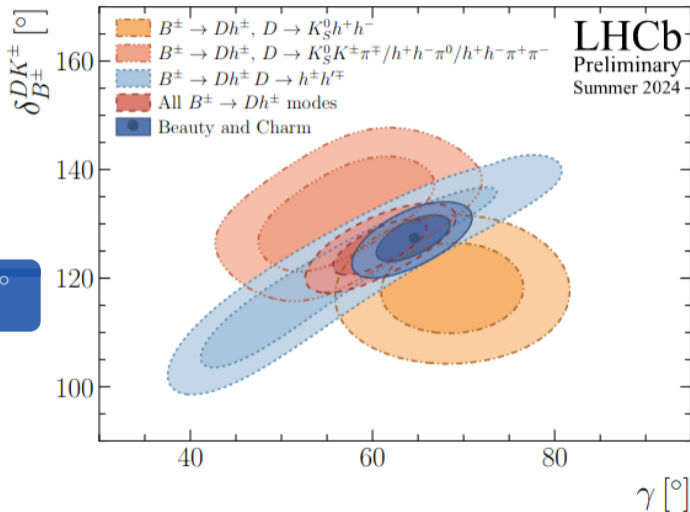
Click on lumi to get reference. Last updated with [\[LHCb-CONF-2024-004\]](#).

2024  $\gamma$  COMBINATION

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

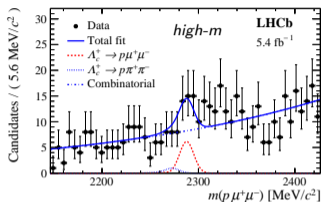
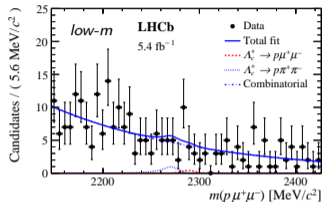
2024  $\gamma$  COMBINATION

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

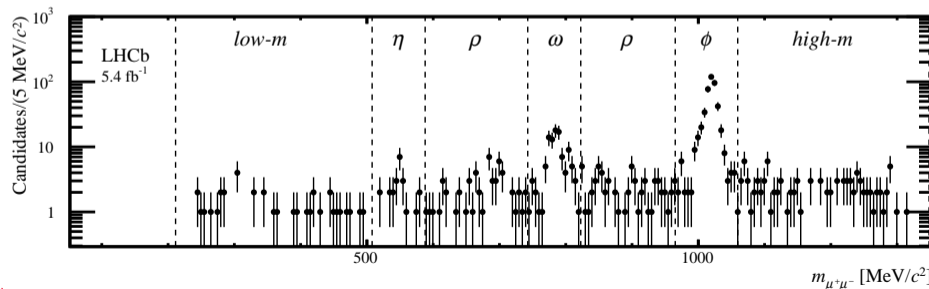
2024  $\gamma$  COMBINATION

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



SEARCH FOR  $\Lambda_c^+ \rightarrow p\mu^+\mu^-$ 

$$\mathcal{B}(\Lambda_c^+ \rightarrow p\mu^+\mu^-) < 8.2 \times 10^{-8} \text{ (95\% CL)}$$



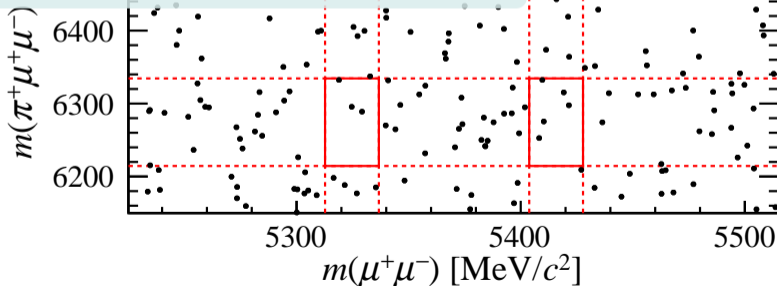
$B_{(s)}^{*0} \rightarrow \mu^+ \mu^-$  IN  $B_c^+$  DECAYS

No excess seen

LHCb 9 fb<sup>-1</sup>

$$\frac{\mathcal{B}(B_c^+ \rightarrow B^{*0} \pi^+) \times \mathcal{B}(B^{*0} \rightarrow \mu^+ \mu^-)}{\mathcal{B}(B_c^+ \rightarrow J/\psi \pi^+)} < 3.8 \times 10^{-5} \text{ (90\%)}$$

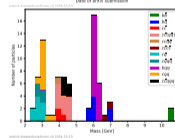
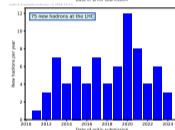
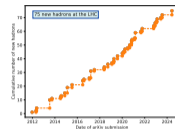
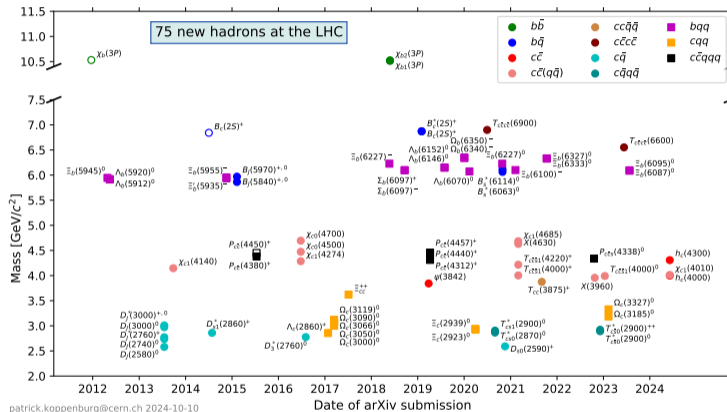
$$\frac{\mathcal{B}(B_c^+ \rightarrow B_s^{*0} \pi^+) \times \mathcal{B}(B_s^{*0} \rightarrow \mu^+ \mu^-)}{\mathcal{B}(B_c^+ \rightarrow J/\psi \pi^+)} < 5.0 \times 10^{-5} \text{ (90\%)}$$



# Spectroscopy

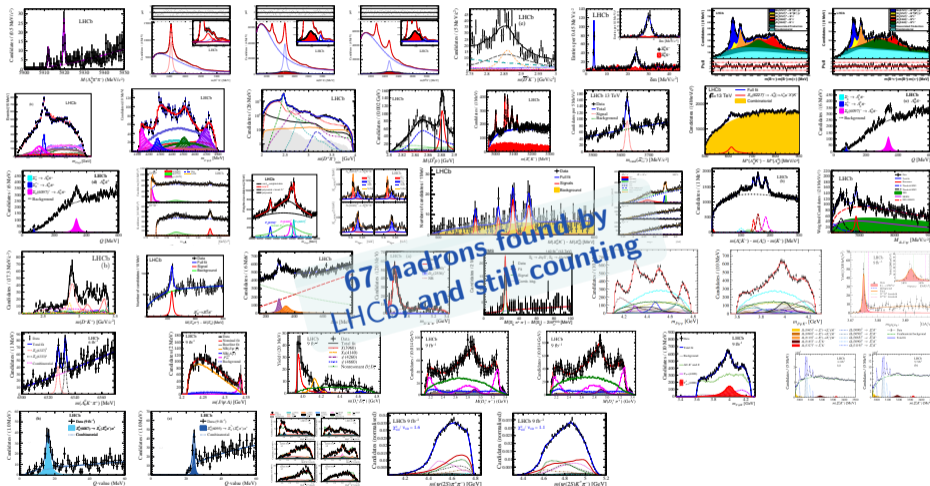


# ALL HADRONS FOUND AT THE LHC

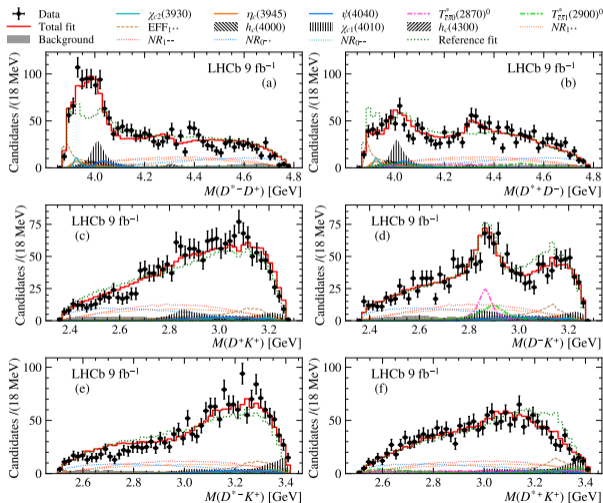


All resonances observed at the LHC in a mass versus submission date plot. Hollow markers indicate superseded states.

# NEW HADRONS FOUND AT LHCb



# NEW STATES IN $B^+ \rightarrow D^{*\pm} D^\mp K^+$



$\eta_c(3945)$  agrees with  $X(3940)$  state found by Belle [PRL 98 (2007) 082001] in  $D^*\bar{D}$  and recoiling against  $J/\psi$ . Could be  $\eta_c(3S)$ .

$h_c(4000)$  candidate for  $h_c(2P)$ . Similar to state by BESIII in  $D^*\bar{D}^*$  [PRL 115 (2015) 182002]

$\chi_{c1}(4010)$  has quantum numbers of  $\chi_{c1}(3872)$  and other  $\chi_{c1,2}$ . Could be exotic.

$h_c(4300)$  candidate for  $h_c(2P)$  and  $h_c(3P)$ . State at 4274 has different parity [PRL 127 (2021) 082001].

Also confirm  $T_{cs0}^*(2900)^0$  and  $T_{cs1}^*(2900)^0$  in another decay mode [PRL 125 (2020) 242001].

OBSERVATION OF  $\Lambda_b^0 \rightarrow \Sigma_c^{(*)++} D^{(*)-} K^-$ 

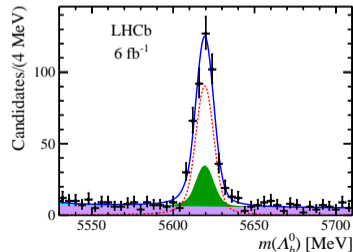
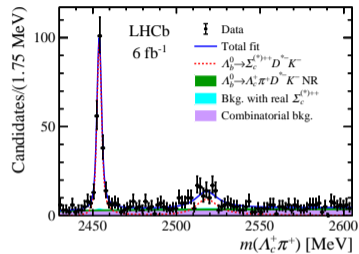
$P_{c\bar{c}}$  pentaquarks are 10 MeV below  $\Sigma_c \bar{D}^*$  threshold.

Hence look for  $\Lambda_b^0 \rightarrow \Sigma_c \bar{D}^* K^-$  decays.

Specifically,  $\Lambda_b^0 \rightarrow \Sigma_c^{(*)++} D^{(*)-} K^-$  with  $\Sigma_c^{(*)++} \rightarrow \Lambda_c^+ \pi^+ \pi^+$  or  $D^{*-} \rightarrow D^0 \pi^-$  or  $D^- \rightarrow K^+ \pi^- \pi^-$ . So a  $p3K4\pi$  final state.

Not enough data to look for pentaquarks, but with more data we'll get there.

- $\Lambda_b^0 \rightarrow \Sigma_c^{(*)++} D^- K^-$  ( $480 \pm 25 \Sigma_c$ ,  $279 \pm 26 \Sigma_c^{(*)}$ )
- $\Lambda_b^0 \rightarrow \Sigma_c^{(*)++} D^{*-} K^-$  ( $243 \pm 17 \Sigma_c$ ,  $116 \pm 15 \Sigma_c^{(*)}$ )





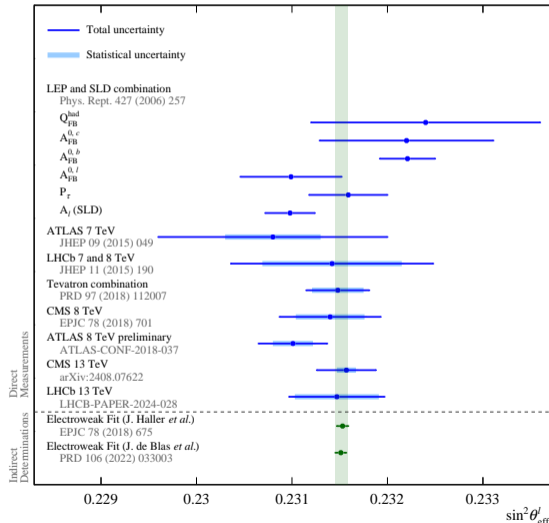
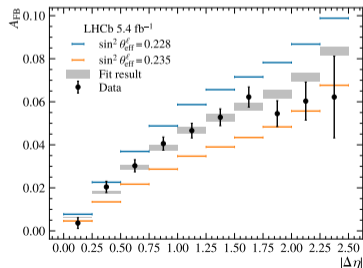
# EW and exotics


# $\sin^2 \theta_{\text{EFF}}^{\ell}$ FROM $Z \rightarrow \mu^+ \mu^-$ $A_{\text{FB}}$



Using data in  $66 < m_{\mu^+ \mu^-} < 116 \text{ GeV}/c^2$  with  $5.4 \text{ fb}^{-1}$  13 TeV data (2016–18).

$\sin^2 \theta_{\text{eff}}^{\ell}$  from fit to asymmetry of muon pseudorapidities,  $A_{\text{FB}}$ , vs their absolute difference





# Other stuff

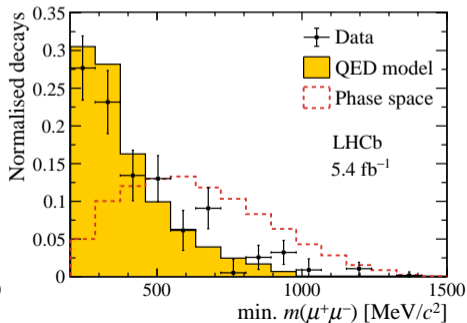
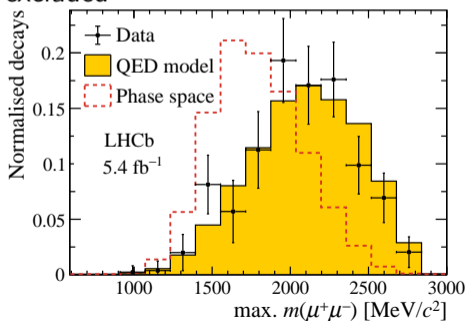


$$J/\psi \rightarrow \mu^+ \mu^- \mu^+ \mu^-$$

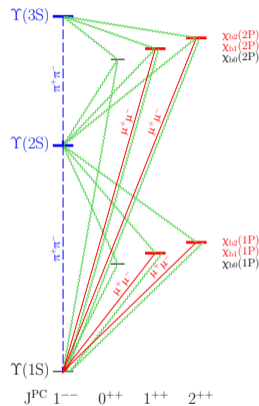
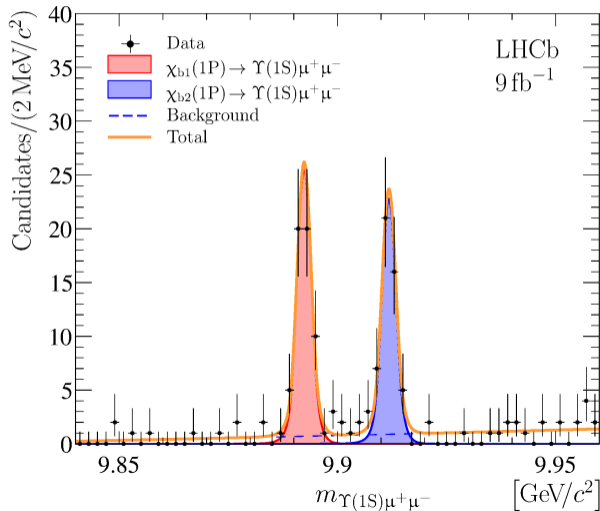
Using  $5 \text{ fb}^{-1}$  2016–18 data get

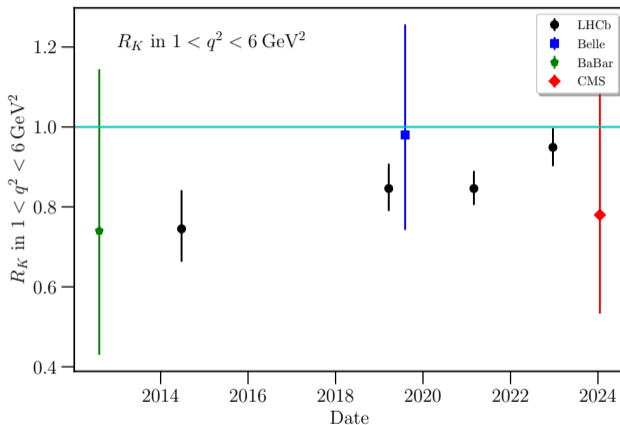
$$\mathcal{B}(J/\psi \rightarrow \mu^+ \mu^- \mu^+ \mu^-) = (1.13 \pm 0.10 \pm 0.05 \pm 0.01) \times 10^{-6}$$

The phase-space model assumed by CMS [CMS, PRD 109 (2024) L111101, arXiv:2403.11352] is excluded





DALITZ DECAY OF  $\chi_b$ 

$R_K$  VERSUS TIME

patrick.koppenburg@cern.ch 2024-10-22

[BaBar, PRD 86 (2012) 032012] [PRL 113 (2014) 151601] [PRL 122 (2019) 191801] [Belle, PRL 126 (2021) 161801] [PRD 108 (2023) 032002] [CMS, Rep. Prog. Phys. 87 (2024) 077802]