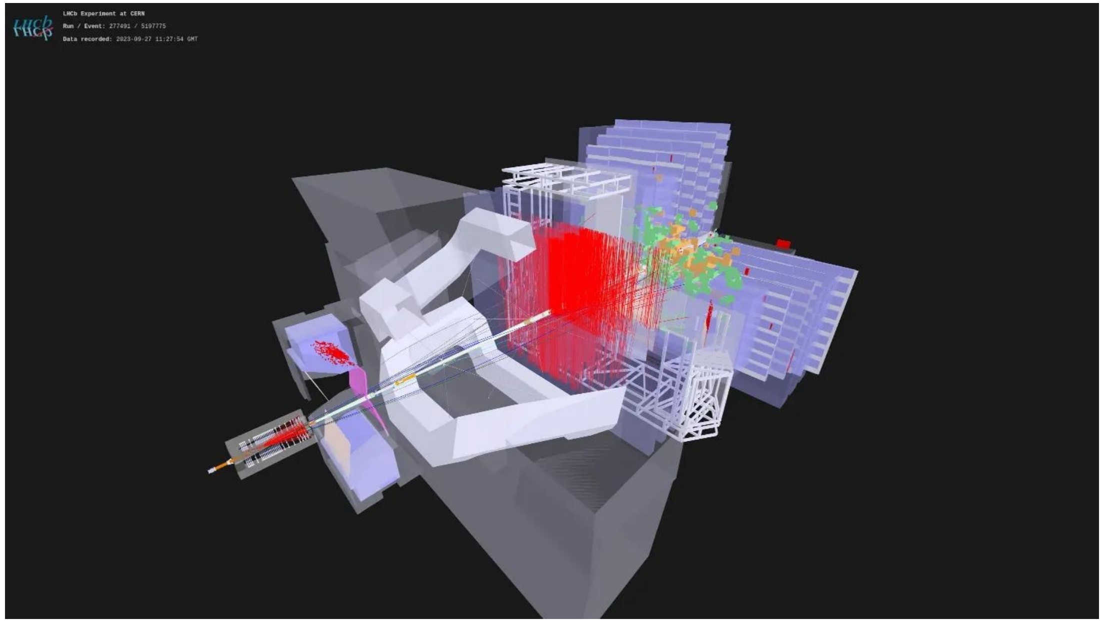


LHCb Status and Overview

A story in three chapters

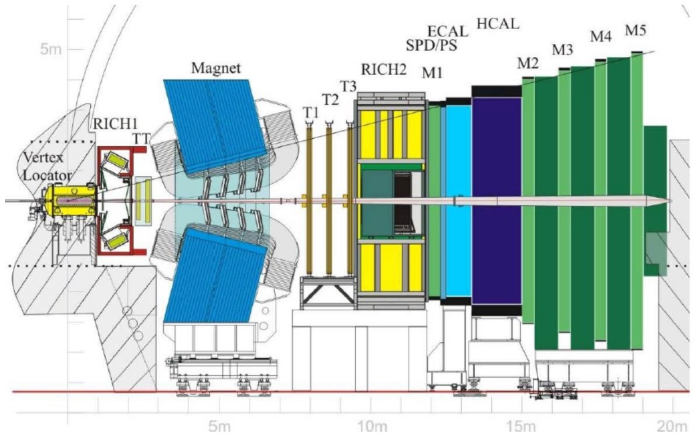
Marina Artuso, Syracuse University

On behalf of the LHCb collaboration

The LHCb trilogy

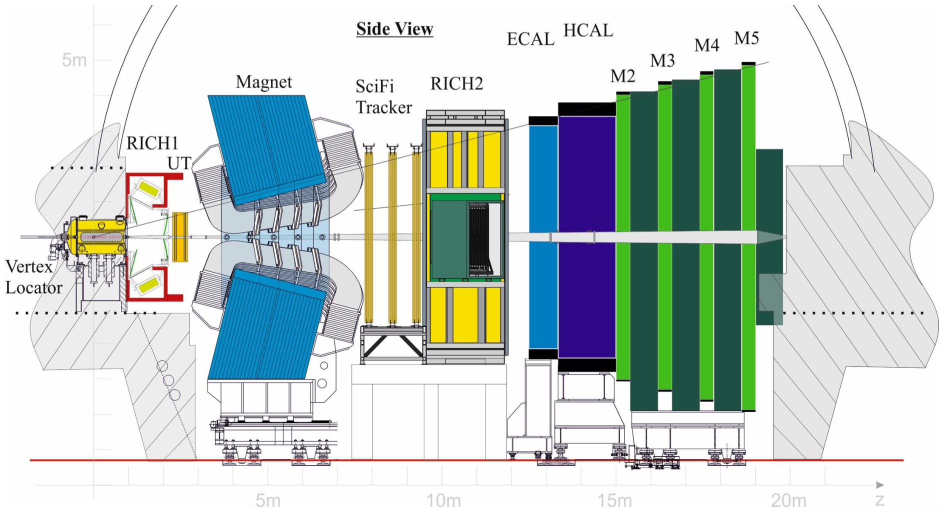
LHCb: Phase I

(an ever-growing physics scope)



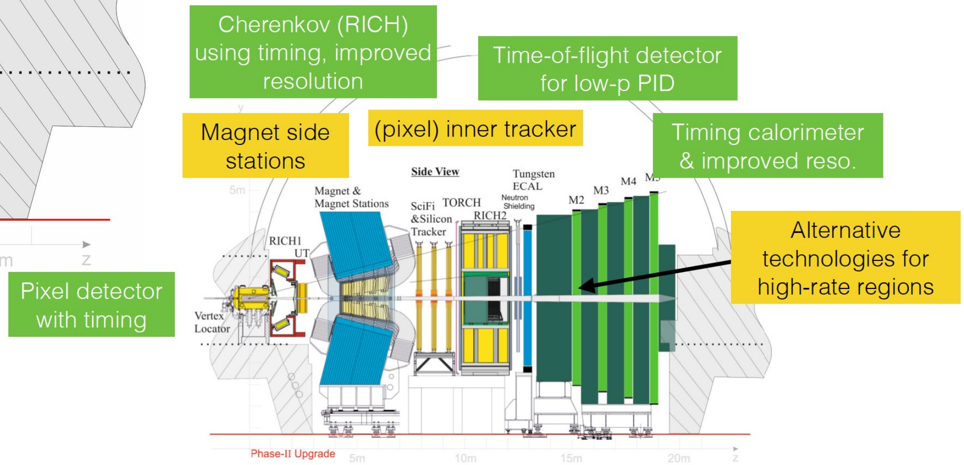
LHCb Upgrade I

(the software trigger edition)



LHCb Upgrade II

(exploiting timing to reach the highest sensitivity)



Chapter I – Physics Highlights from Run I & II

LHCb physics: beauty, charm and beyond

New leaves are still growing on this rich "tree of knowledge"

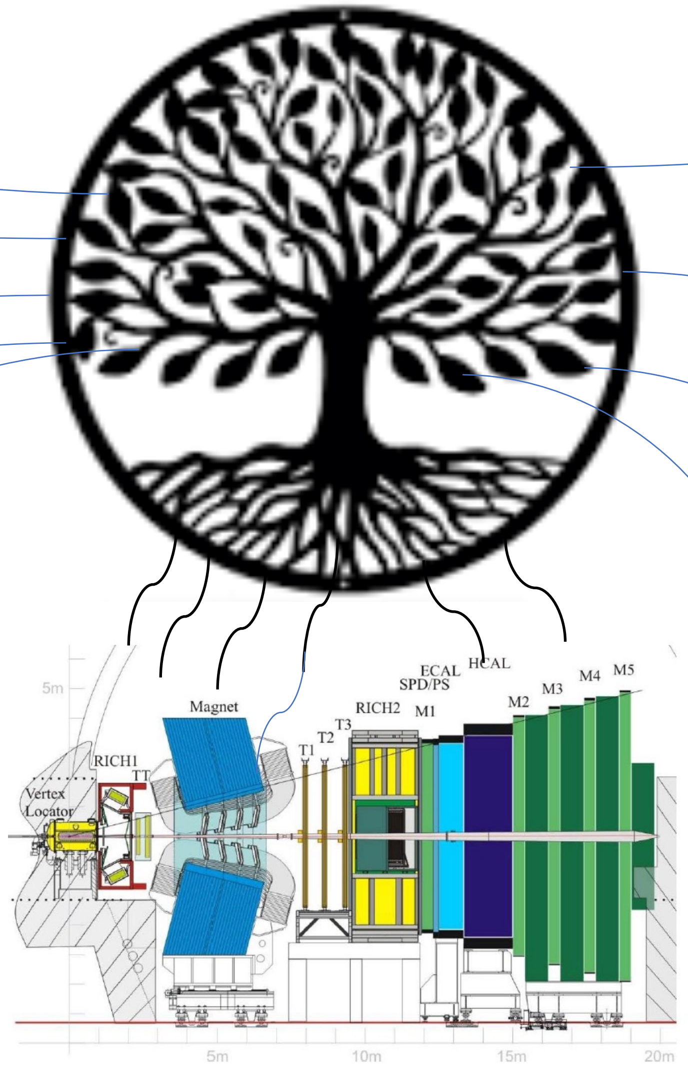
CP Violation in charm and beauty decays

Magnitude of quark mixing angles

Rare b and c decays

Neutral meson oscillations

Lepton flavor universality



Conventional and exotic spectroscopy

Search for exotic new particles, axions, dark sector ..

Electroweak physics in the forward direction

Heavy ion physics

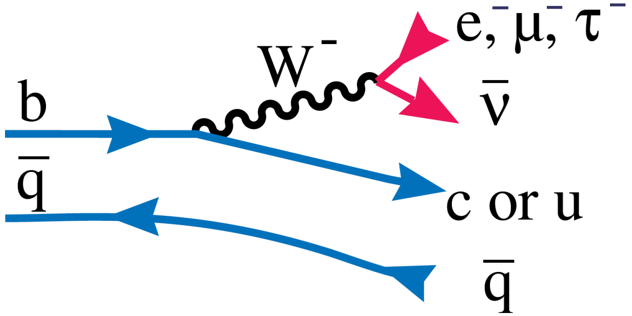
The origin story: beauty as a tool for discovery

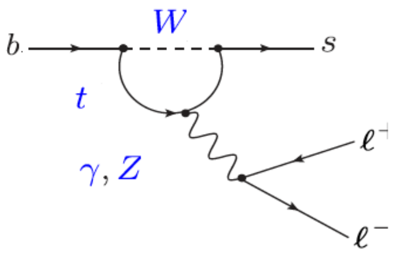
E. Smith Experimental status of b->sll and b->clν

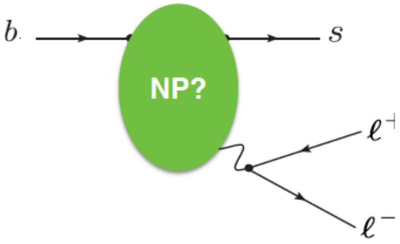
F. Gallego Rare & forbidden decays

L. Hartmann Anomaly detection

G. Pietrzyk Flavor anomalies

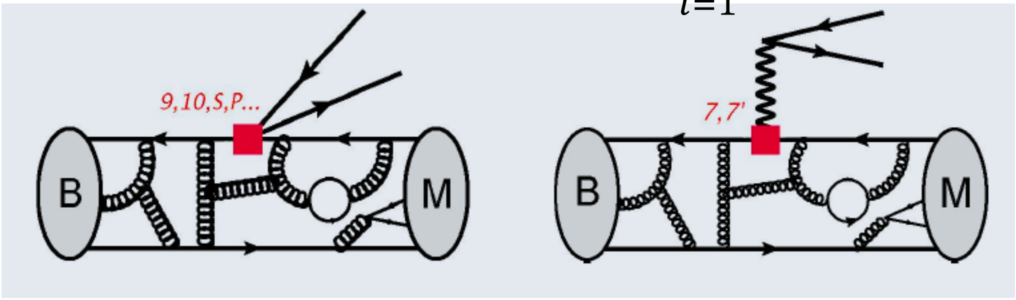




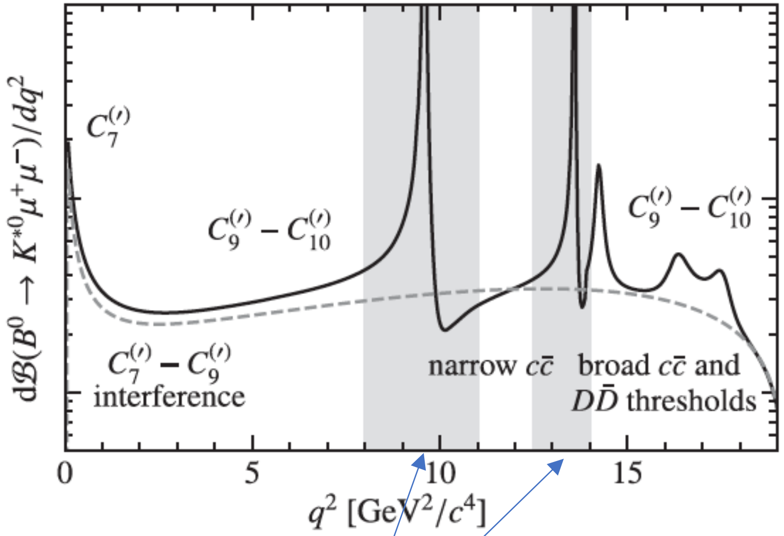


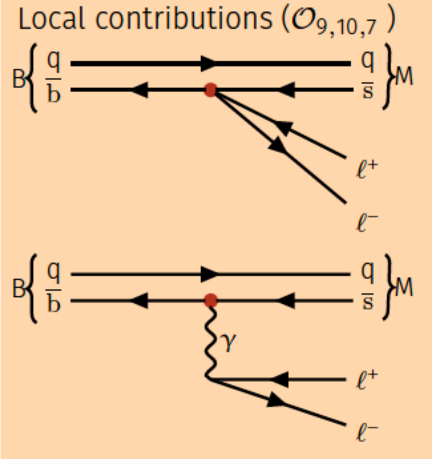
- ❑ Old paradigm: tree diagrams are dominated by Standard Model processes, and loops can unveil new physics manifestations through interference with new particles (maybe not the whole story)
- ❑ Also: things are more complicated: we observe hadron decays ➡️ effective Hamiltonian

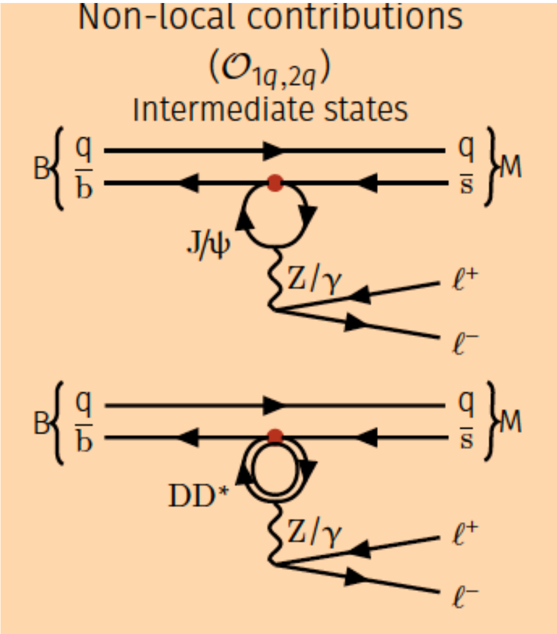
$$\mathcal{H}(b \to s\ell^+\ell^-) = -\frac{4G_F}{\sqrt{2}} V_{tb}V_{ts}^* \sum_{i=1}^{10} \mathcal{C}_i(\mu)\mathcal{O}_i(\mu)$$

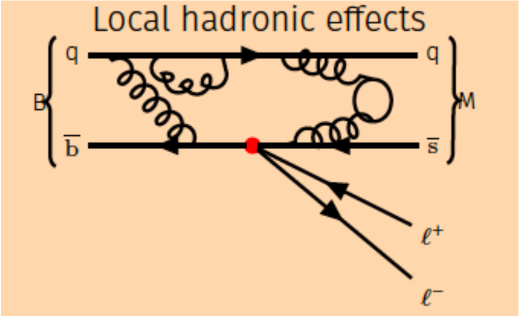


The long and winding road: disentangle the amplitudes contributing to these decays









Old approach: exclude regions where non-local effects expected to be dominant

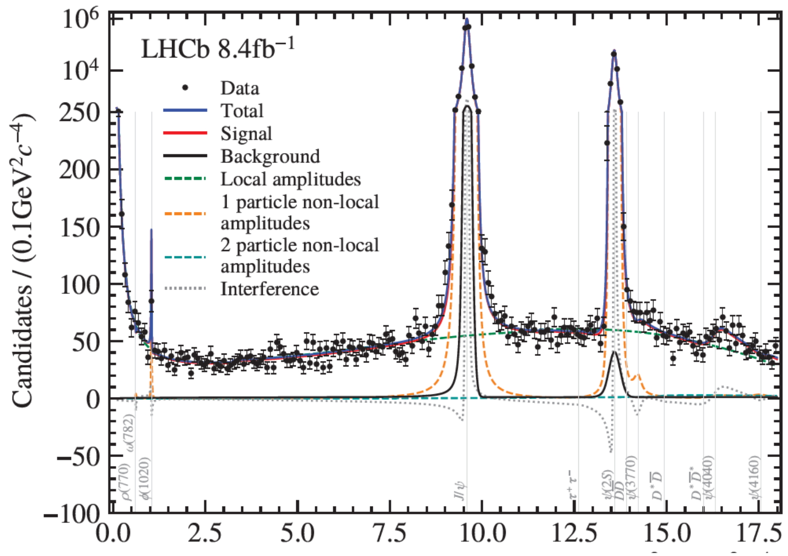
$$\mathcal{A}_\lambda^{L,R}(B \to M_\lambda \ell\ell) = N_\lambda \left\{ (C_9 \mp C_{10})\mathcal{F}_\lambda(q^2) - 16\pi^2 \frac{M_B}{m_b} \mathcal{H}_\lambda(q^2) \right\}$$

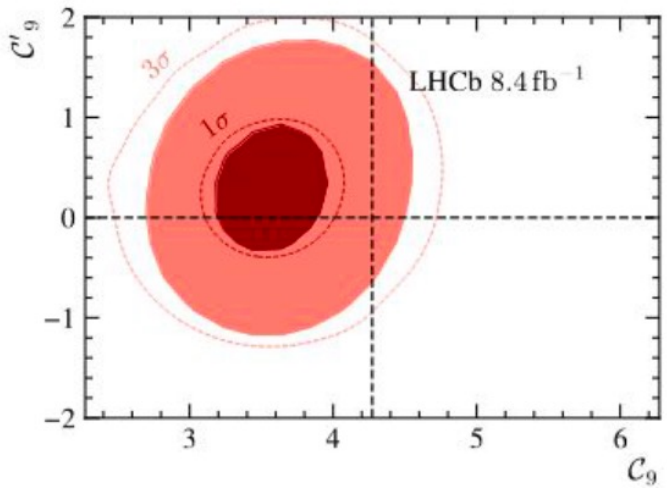
Local form factors

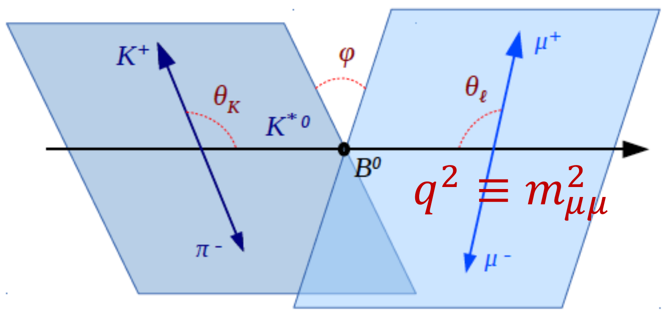
Non-local form factors

Experimental study of local and non-local amplitudes

LHCb-PAPER-2024-011, in preparation







- Full q^2 range of $B^0 \to K^{*0}\mu^+\mu^-$ used in the fit
- Fit model encompasses signal (local, one and two-particle non-local amplitudes & interference terms) & gives:

Wilson Coefficient results	
$\mathcal{C}_9$	$3.56 \pm 0.28 \pm 0.18$
$\mathcal{C}_{10}$	$-4.02 \pm 0.18 \pm 0.16$
$\mathcal{C}'_9$	$0.28 \pm 0.41 \pm 0.12$
$\mathcal{C}'_{10}$	$-0.09 \pm 0.21 \pm 0.06$
$\mathcal{C}_{9\tau}$	$(-1.0 \pm 2.6 \pm 1.0)\times 10^{-2}$

$B^0 \to K^{*0}[\tau^+\tau^- \to \mu^+\mu^-]$ rescattering

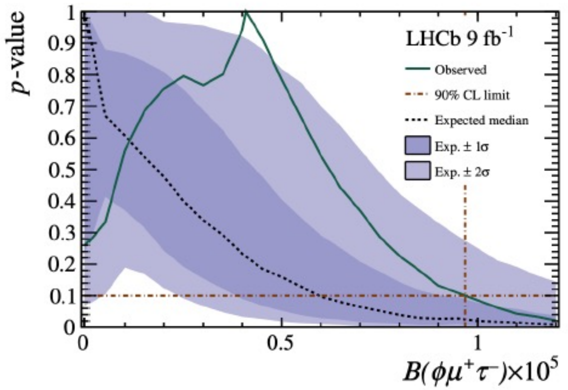
Lepton flavor violation

LHCb-PAPER-2024-114

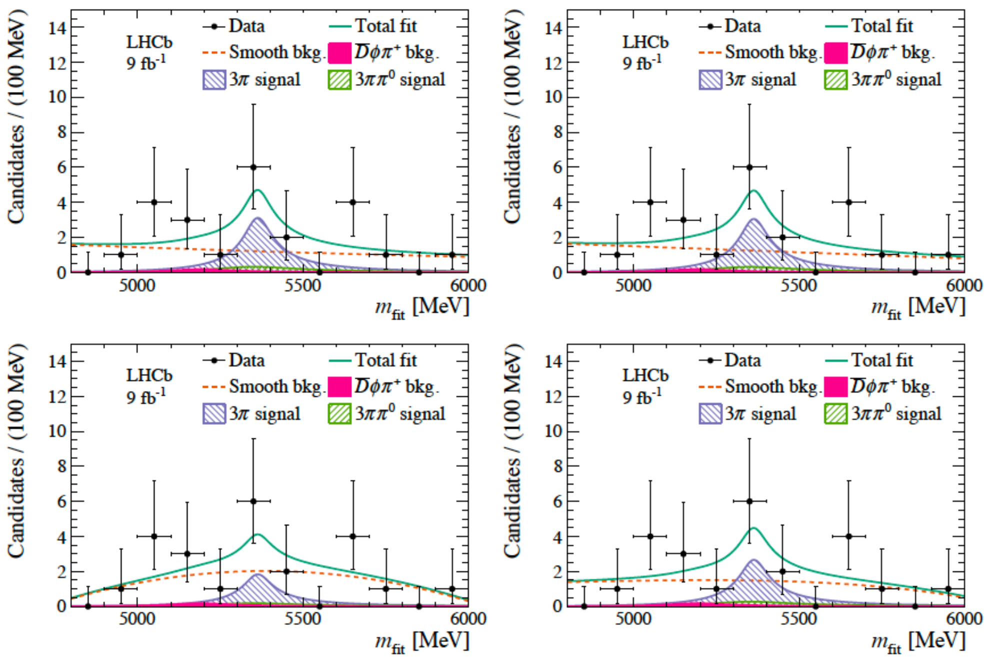
First limit of this lepton flavor violating decay

- Lepton flavor is conserved in decays mediated by the Standard Model
- New physics models predict deviations especially involving the 3rd family ⇒ it is important to look!

$$\mathcal{B}(B_s^0 \to \phi\mu^+\tau^-) < 1.0 \times 10^{-5} \text{ at } 90\% \text{ CL},$$
$$\mathcal{B}(B_s^0 \to \phi\mu^+\tau^-) < 1.1 \times 10^{-5} \text{ at } 95\% \text{ CL}.$$



No significant excess is observed

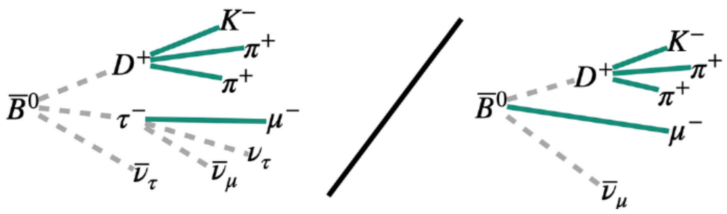


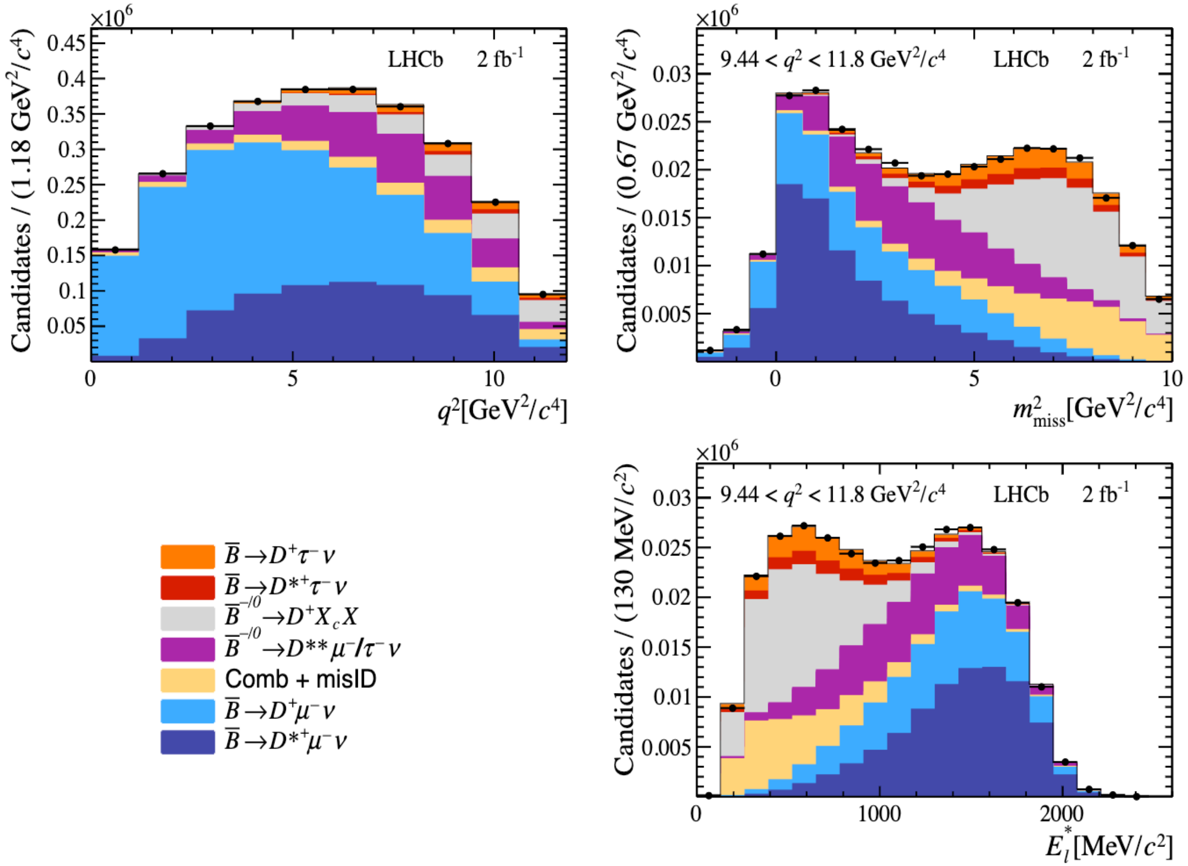
Lepton flavor universality – the tauonic semileptonic story

LHCb-PAPER-2024-007 in preparation

- ❑Would require new physics at tree level
- ❑Most recent example: simultaneous measurement of $\mathcal{R}(D^{+})$ and $\mathcal{R}(D^{*+})$
- ❑Challenging measurement: multi ν in the final state!

R(D⁺) =





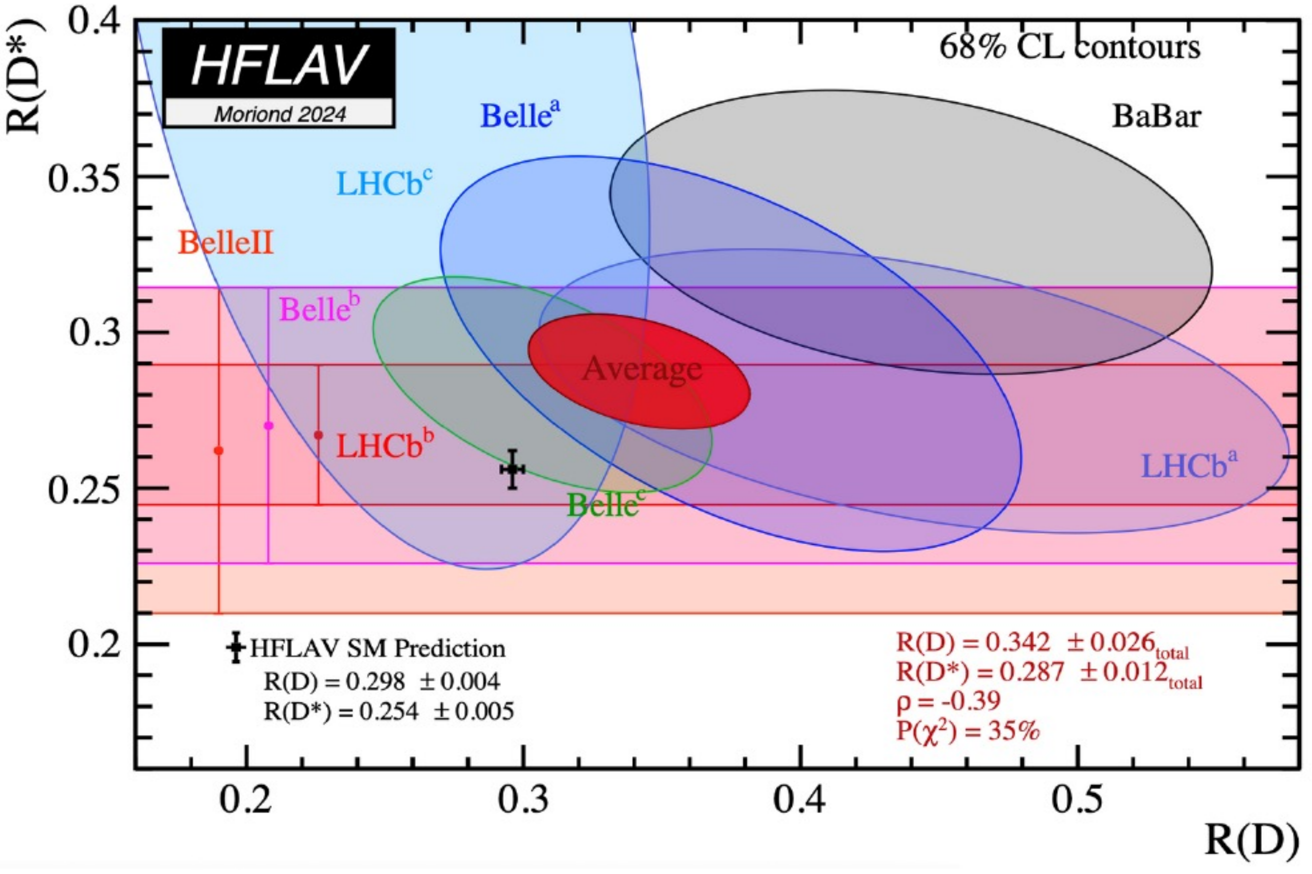
- ❑Complex template 3D fit in $q^2, m^2_{miss}, E^*_\ell$ gives

$$R(D^+) = 0.249 \pm 0.043 \pm 0.047$$
$$R(D^{*+}) = 0.402 \pm 0.081 \pm 0.085$$

- ❑Correlation coefficient -0.39

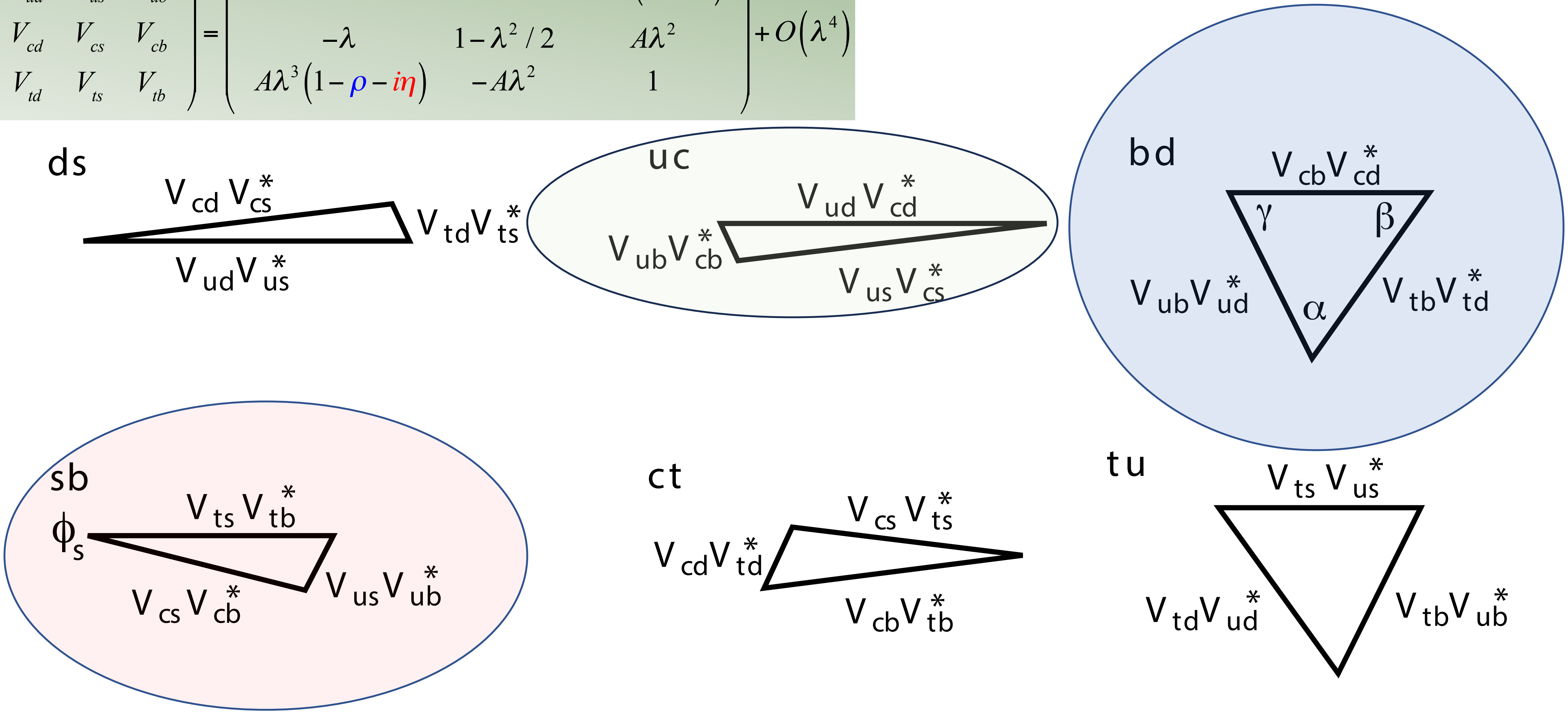
Where are we now?

- ❑The result shown is 0.78σ from SM and 1.09σ from the world average
- ❑The combined average is 3.3σ tension with the Standard Model



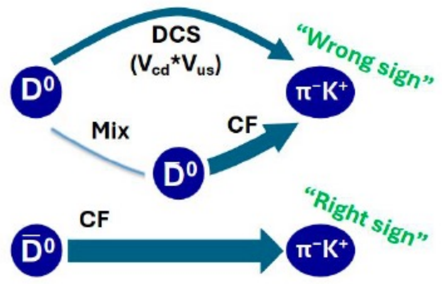
Unitarity constraints: the triangles

$$V_{\left(\frac{2}{3},-\frac{1}{3}\right)} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3\left(\rho - i\eta\right) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3\left(1-\rho-i\eta\right) & -A\lambda^2 & 1 \end{pmatrix} + O\left(\lambda^4\right)$$



Mixing and CP Violation in $D^0 \to K^+\pi^-$ decays

- Analysis using Run II data set (6fb^{-1})
- Fit time-dependent ratios $R^{+}_{K\pi}(t) \equiv \frac{\Gamma(D^0(t)\to K^+\pi^-)}{\Gamma(\bar{D}^0(t)\to K^+\pi^-)}$ & $R^{-}_{K\pi}(t) \equiv \frac{\Gamma(\bar{D}^0(t)\to K^-\pi^+)}{\Gamma(D^0(t)\to K^-\pi^+)}$



CPV in decay

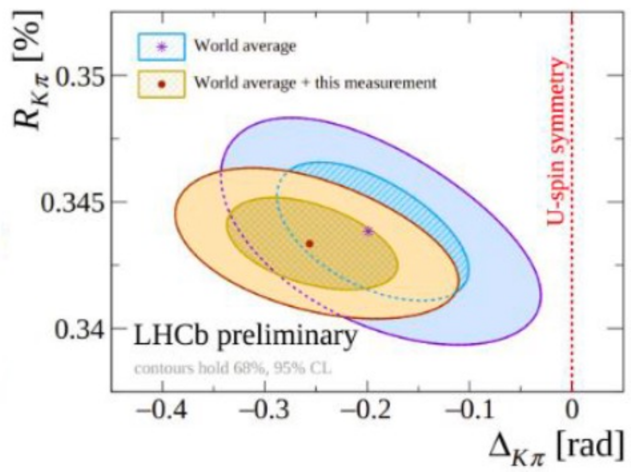
CPV in mixing

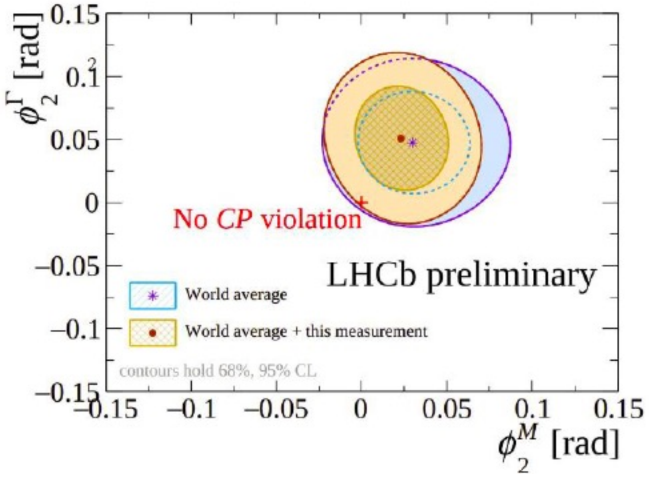
$$R^{\pm}_{K\pi}(t) \approx R_{K\pi}(1\pm A_{K\pi}) + \sqrt{R_{K\pi}(1\pm A_{K\pi})}(c_{K\pi}\pm\Delta c_{K\pi})\frac{t}{\tau_{D^0}} + (c'_{K\pi}\pm\Delta c'_{K\pi})\left(\frac{t}{\tau_{D^0}}\right)^2$$

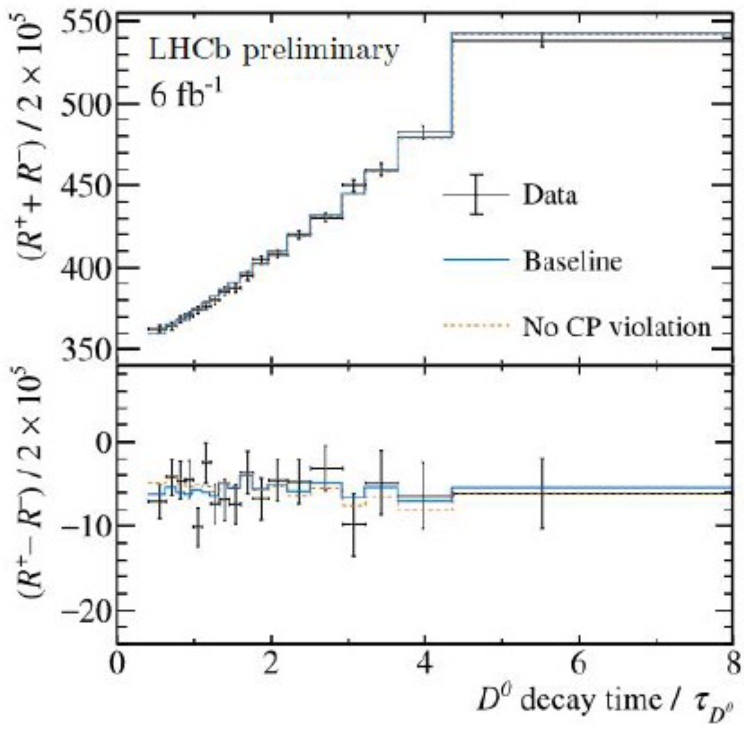
DCS

Interference

Mixing







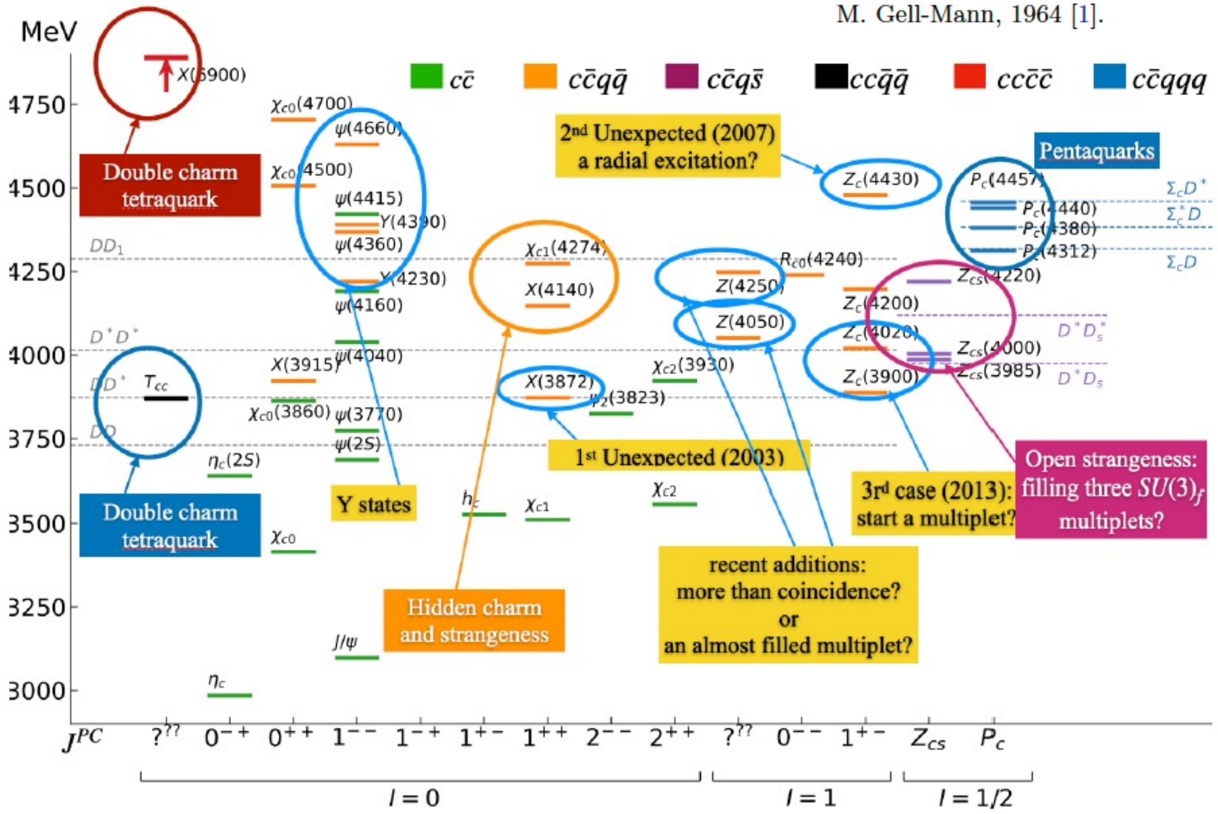
P. Gandini Heavy Flavor spectroscopy

T. Martin Precision QCD (LHCb, Atlas, CMS)

QCD @ work

L. Maiani, A. Pilloni, GGI Lectures on exotic mesons

> Baryons can now be constructed from quarks by using the combinations qqq, $qqqq\bar{q}$, etc., while mesons are constructed out of $q\bar{q}$, $qq\bar{q}\bar{q}$, etc.
>
> M. Gell-Mann, 1964 [1].



Q1:Can we organize the zoo of known hadrons into a well-motivated structures $(q\bar{q}, qqq, q\bar{q}q\bar{q}, qqqq\bar{q}..)$ with specific quantum numbers and masses consistent with a theoretical model?

Q2: Study manifestations of QCD in collective nuclear phenomena

Q3: Validate effective theories based on QCD (or lattice QCD calculations) to extract fundamental SM parameters

Q3: how well do the predictive tools in-hand work?

LHCb-PAPER-2024-010

- Heavy quark expansion has been crucial to the extraction of quark mixing parameters from inclusive measurements, determination of flavor oscillation parameters
- Lifetime measurements have been one of the important testing ground of HQE predictions
- Measure ratio R(t) with respect to $\Lambda_b^0 \longrightarrow \Lambda_c^+ \pi^-$

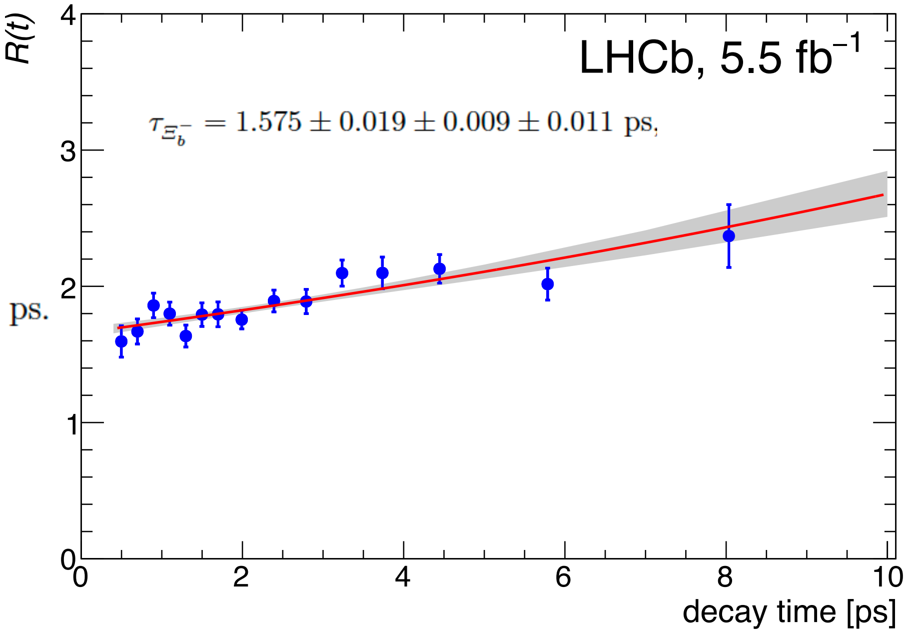
$$R(t) \equiv \frac{N[\Xi_b^- \to \Xi_c^0 \pi^-](t)}{N[\Lambda_b^0 \to \Lambda_c^+ \pi^-](t)} \cdot \frac{\varepsilon[\Lambda_b^0 \to \Lambda_c^+ \pi^-](t)}{\varepsilon[\Xi_b^- \to \Xi_c^0 \pi^-](t)} = R_0 \exp(\lambda t).$$

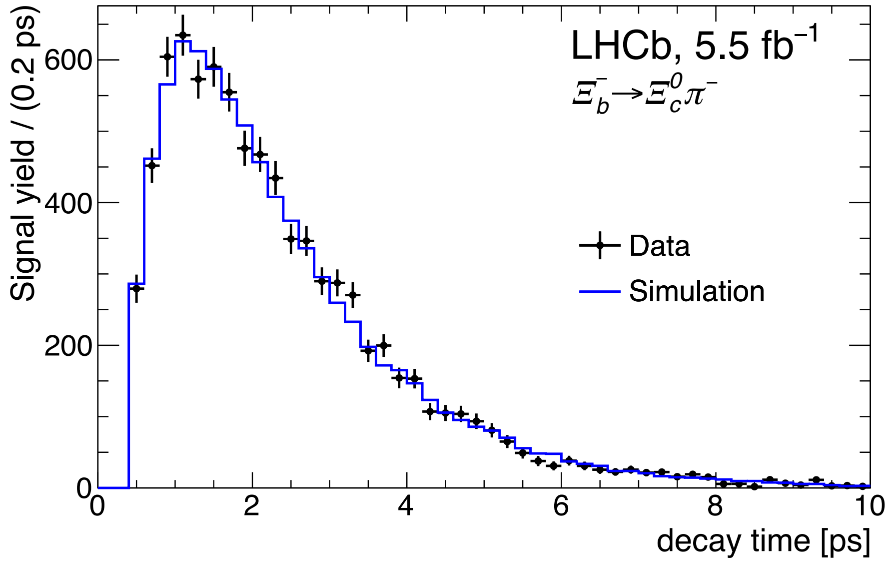
$$\lambda \equiv \frac{1}{\tau_{\Lambda_b^0}} - \frac{1}{\tau_{\Xi_b^-}}$$

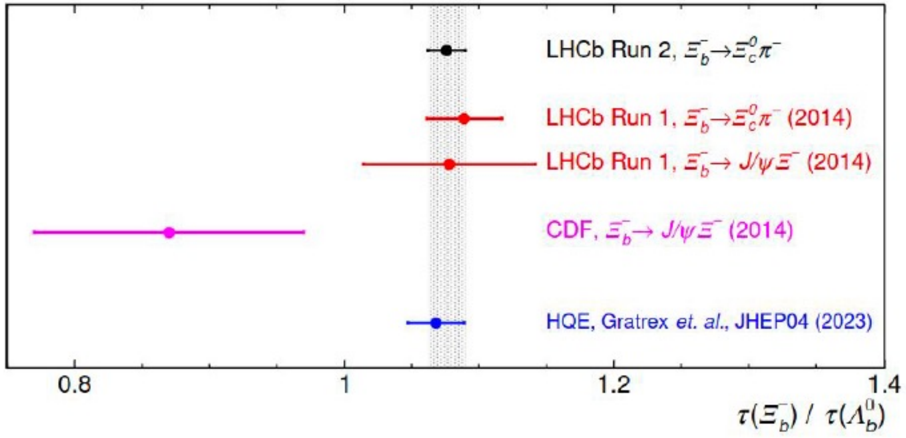
RUN I-II average:

$$r_\tau = 1.078 \pm 0.012 \pm 0.007,$$

$$\tau_{\Xi_b^-} = 1.578 \pm 0.018 \pm 0.010 \pm 0.011 \text{ ps.}$$

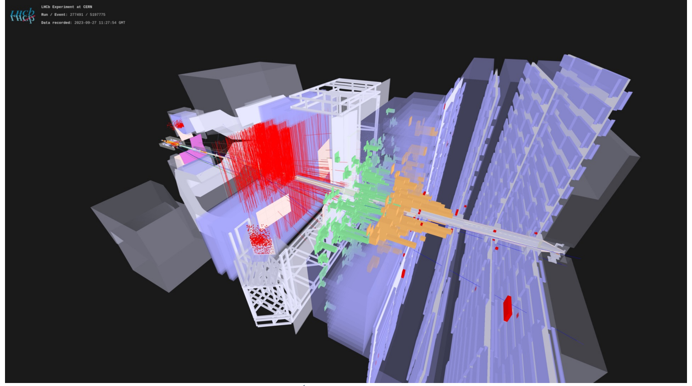






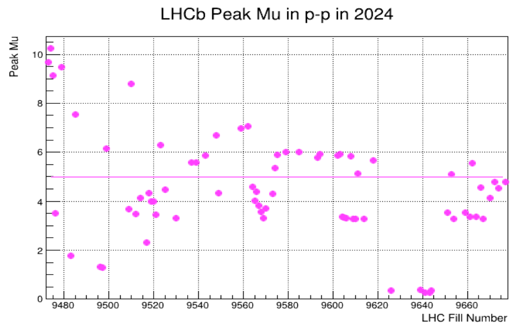
Chapter II

The software trigger edition

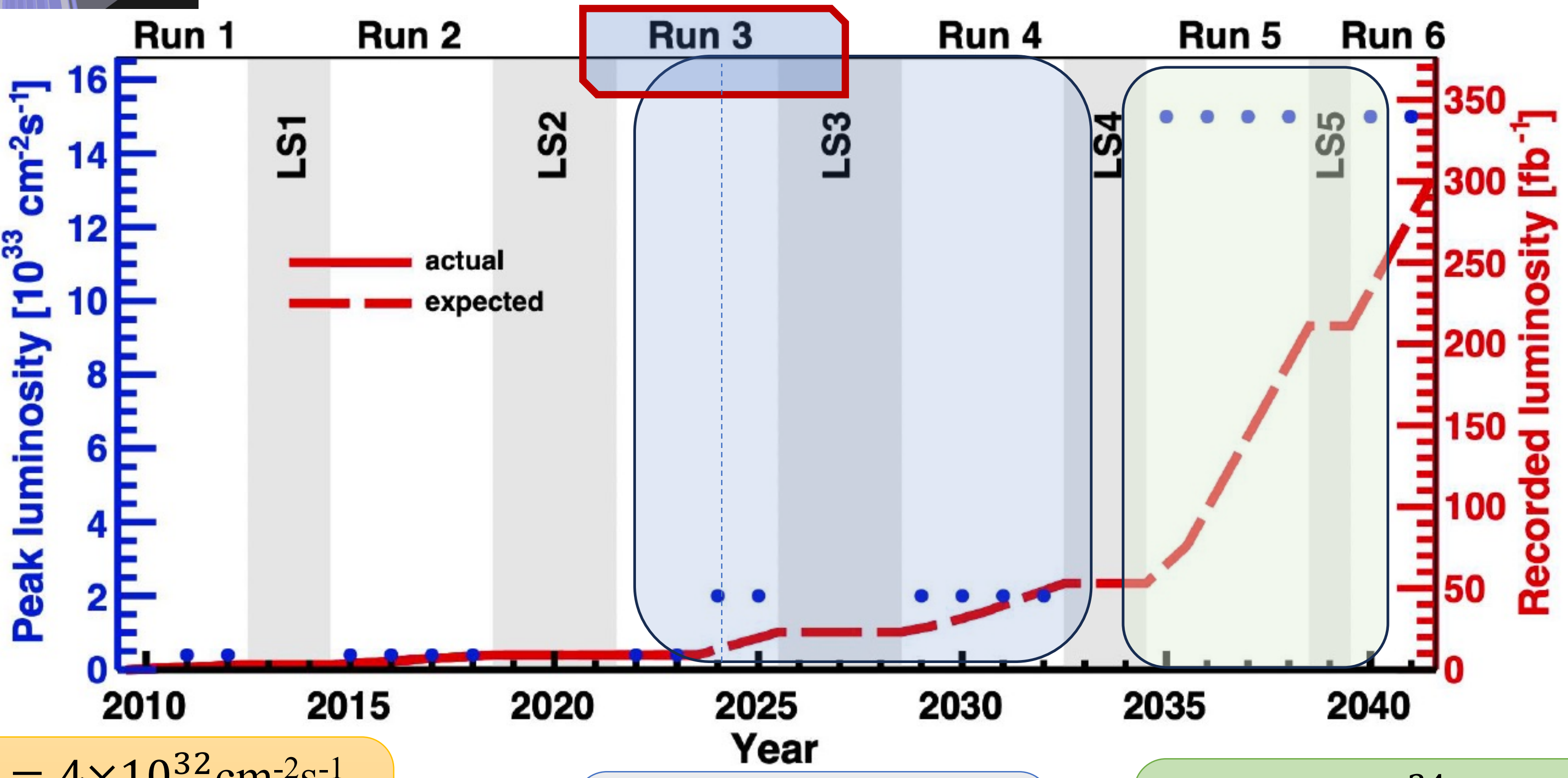


RUN 3 & 4

Now



40 MHz readout Software trigger



Upgrade I Goals: higher luminosity (~×5) + higher sensitivity

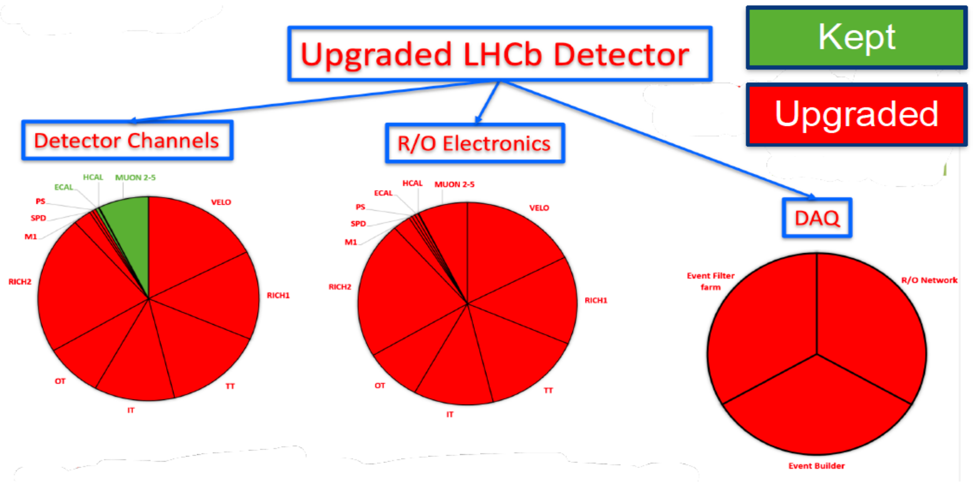
$\mathcal{L} = 4\times10^{32}\text{cm}^{-2}\text{s}^{-1}$
$\mathcal{L}_{int} = 9\ \text{fb}^{-1}$
$\mu \approx 1$

$\mathcal{L} = 2\times10^{33}\text{cm}^{-2}\text{s}^{-1}$
$\mathcal{L}_{int} = 50\ \text{fb}^{-1}$
$\mu \approx 5$

$\mathcal{L} = 1.5\times10^{34}\text{cm}^{-2}\text{s}^{-1}$
$\mathcal{L}_{int} = 300\ \text{fb}^{-1}$
$\mu \approx 40$

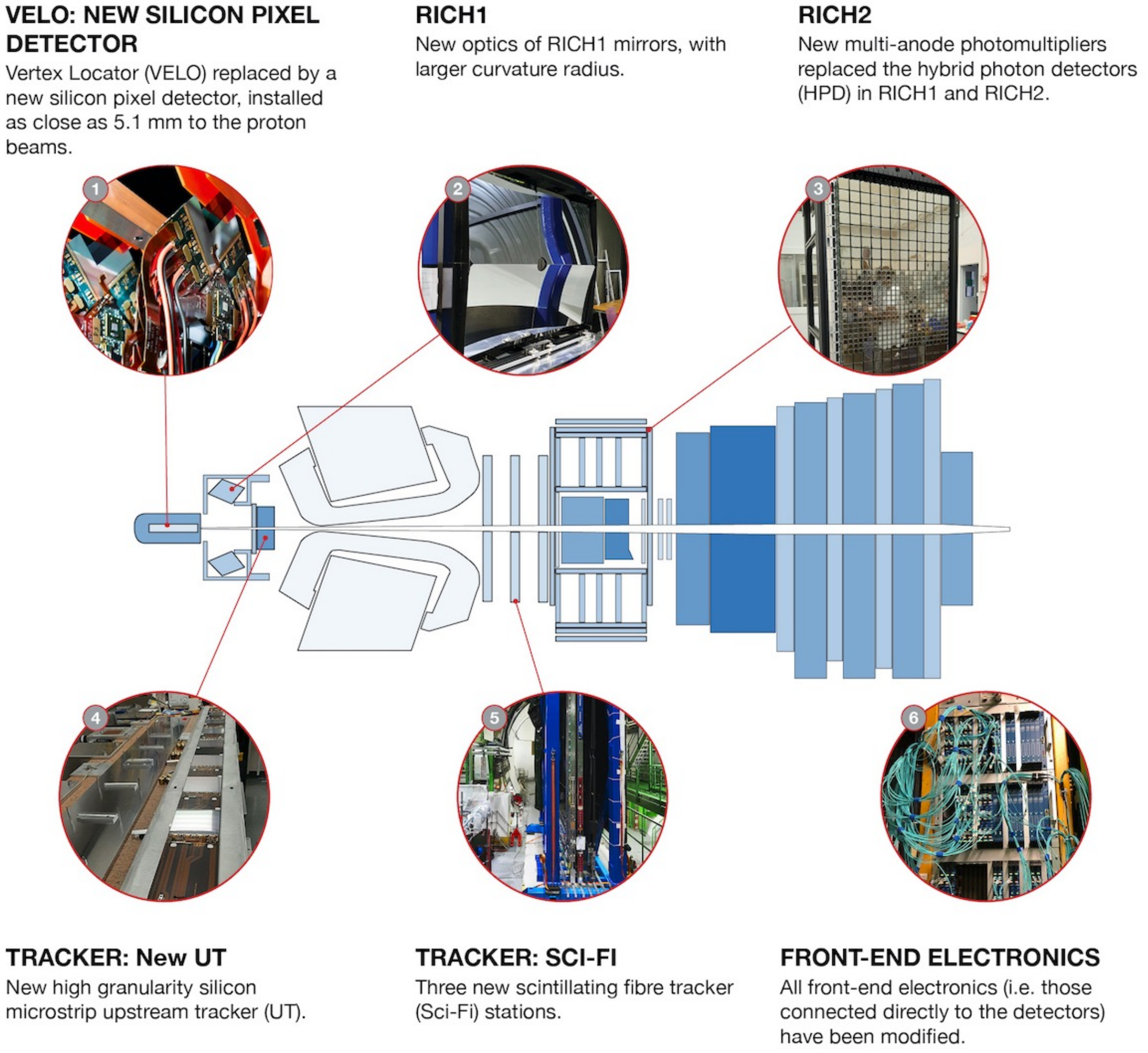
[LHCb Upgrade I paper]

A new detector!



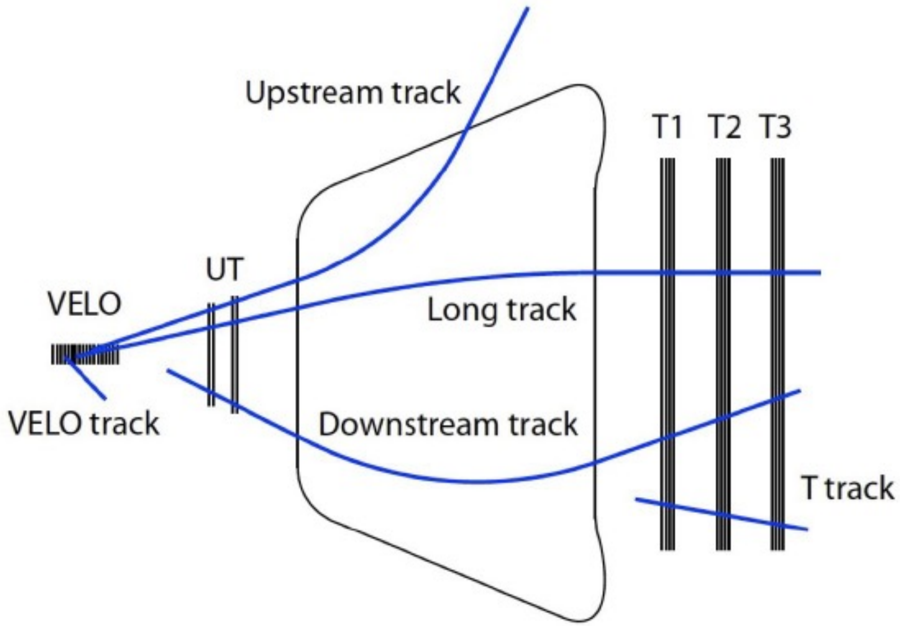
Highlights:

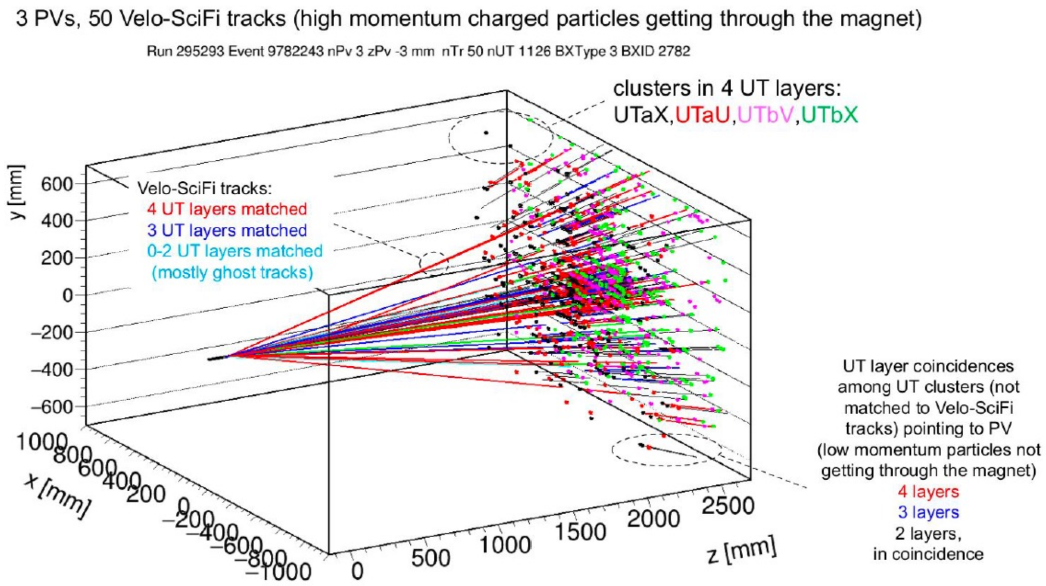
1. New Tracking system: pixel-based VELO closer to the beam pipe (8.2mm→ 5.1mm) + Upstream tracker with higher granularity + New SciFi
2. RICH with new mechanics, optics and PMT readout
3. New luminometer (PLUME)
4. New SMOG2 system for fixed target physics



The tracking system

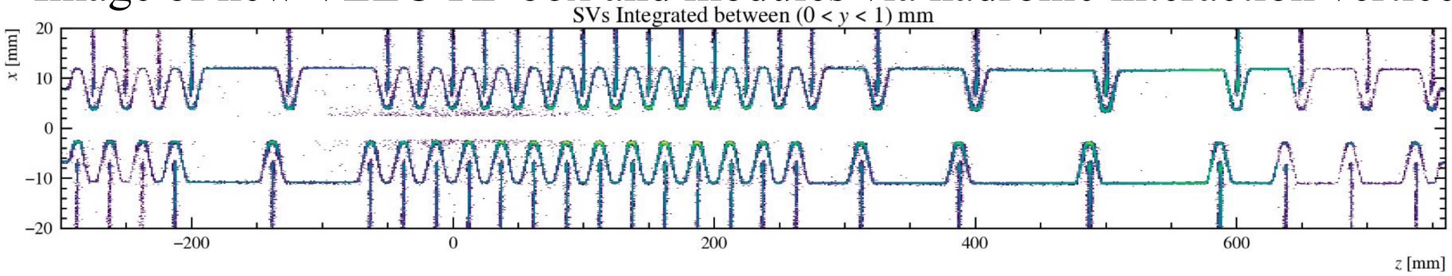
For PID see [M. Atzeni PID at LHCb]

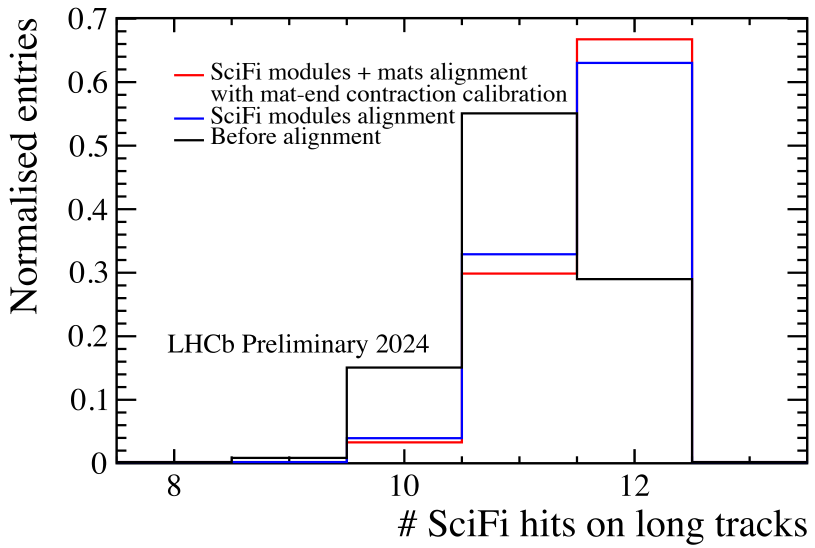




[C. Trippl SciFi Tracker]

Image of new VELO RF box and modules via hadronic interaction vertices

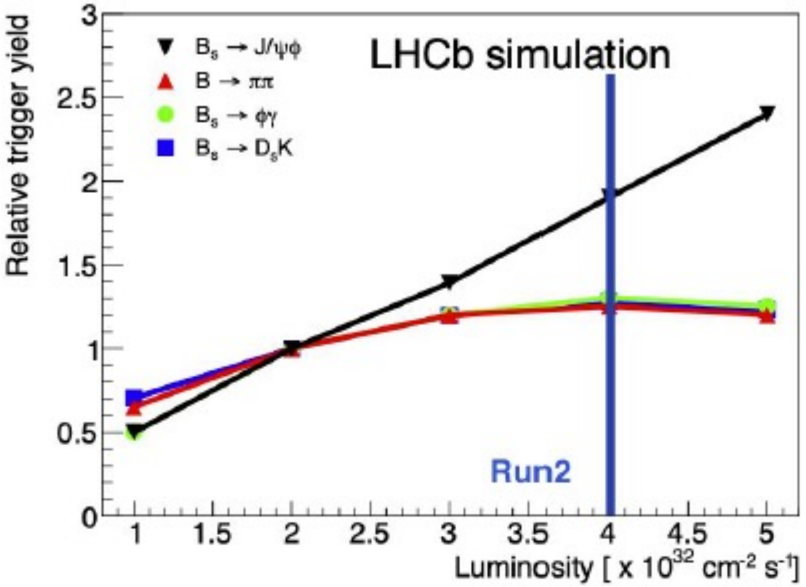




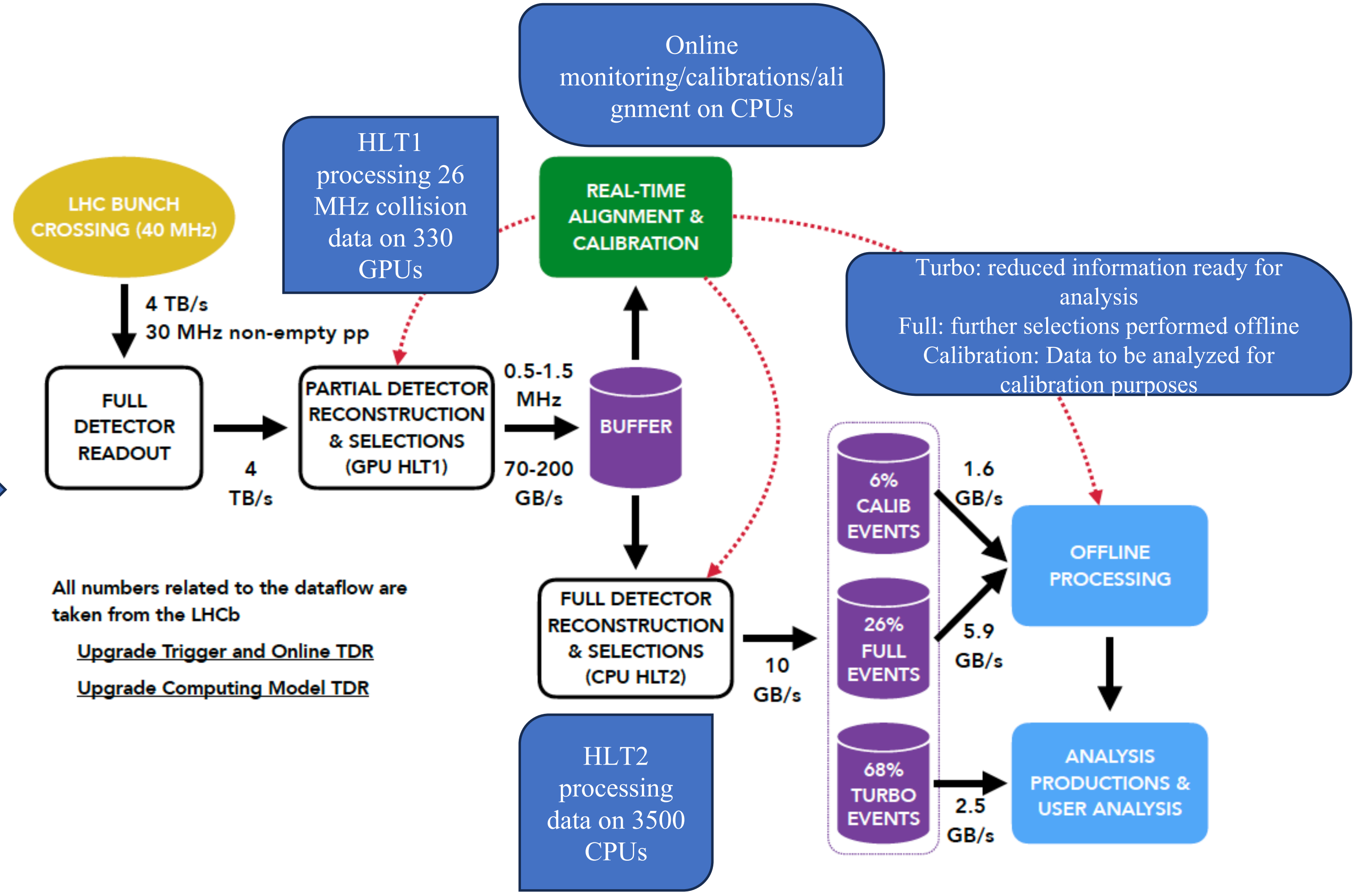
https://arxiv.org/abs/1903.01360

K. Richardson Real time Analysis

The Software Trigger



To exploit a higher luminosity, we needed to get rid of the hardware first level trigger (hadron, calorimeter objects and muon threshold



Write ~10GB/s at 1 MHz

New opportunities in search for exotic particles

M. Ramos Pernas Electroweak Measurements

B.R. Delaney Axion searches

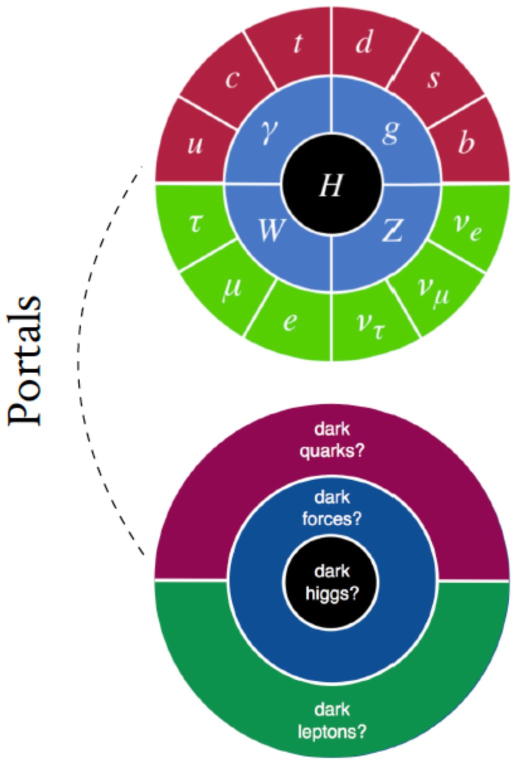
Louis Henry - HLNs@LHCb

F.M. Vidal Unstable long-lived particles

- Probing the dark sector:

Software trigger offers the opportunity to enhance sensitivity

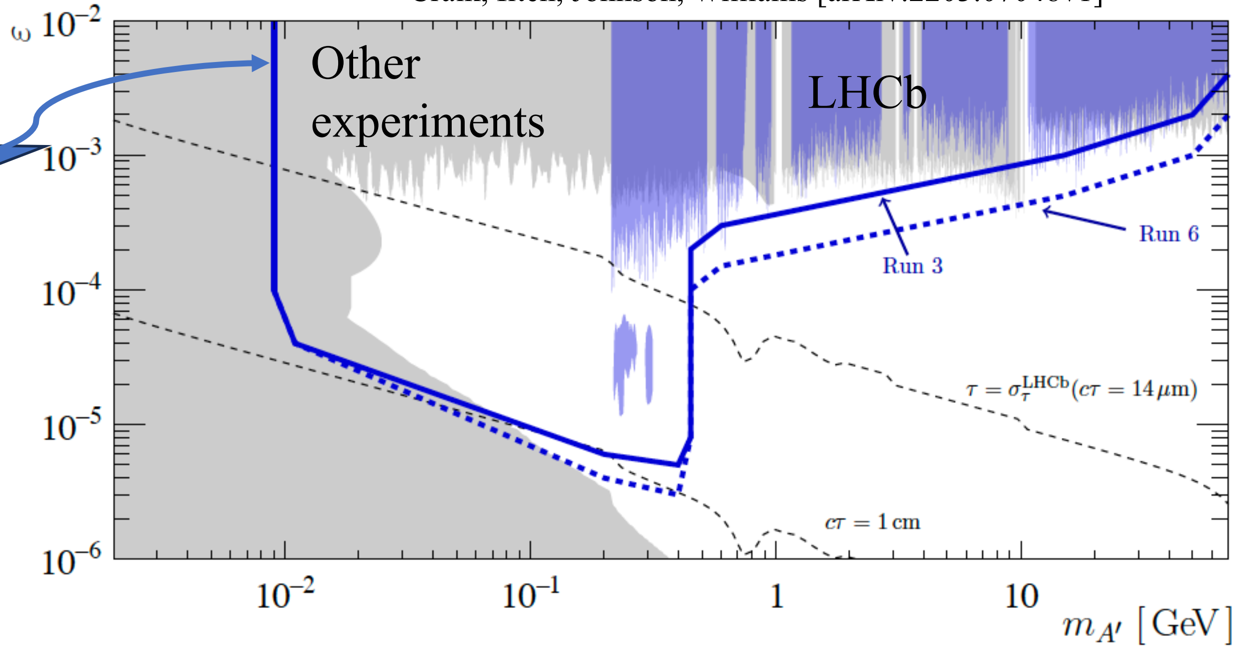
Dark sector physics at high-intensity experiments



Electron ID in the HLT

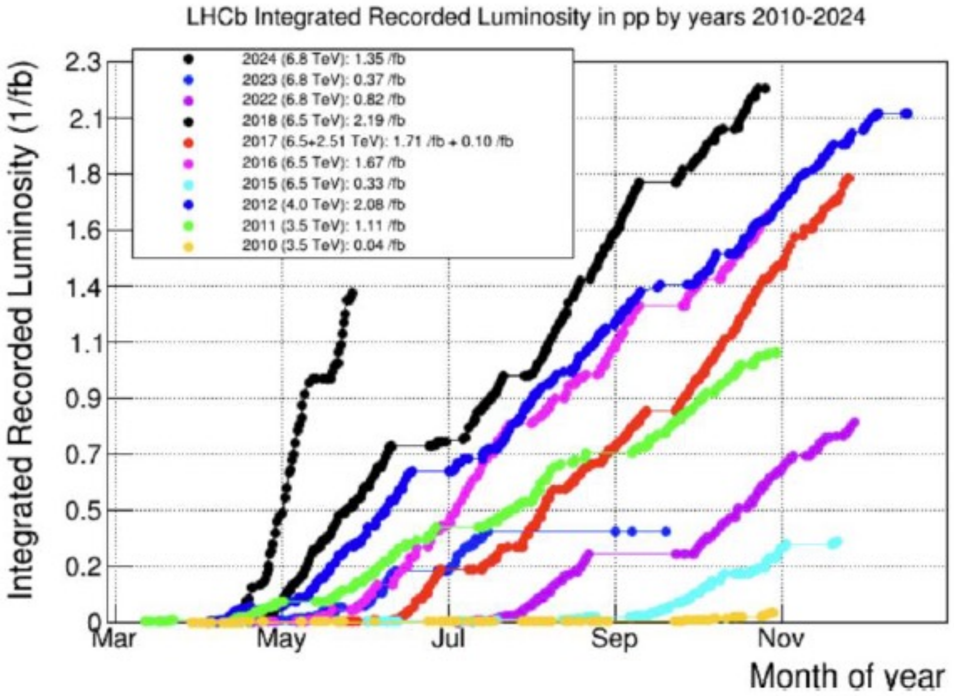
Sensitivity projections for dark photon

Craik, Ilten, Johnson, Williams [arXiv:2203.07048v1]

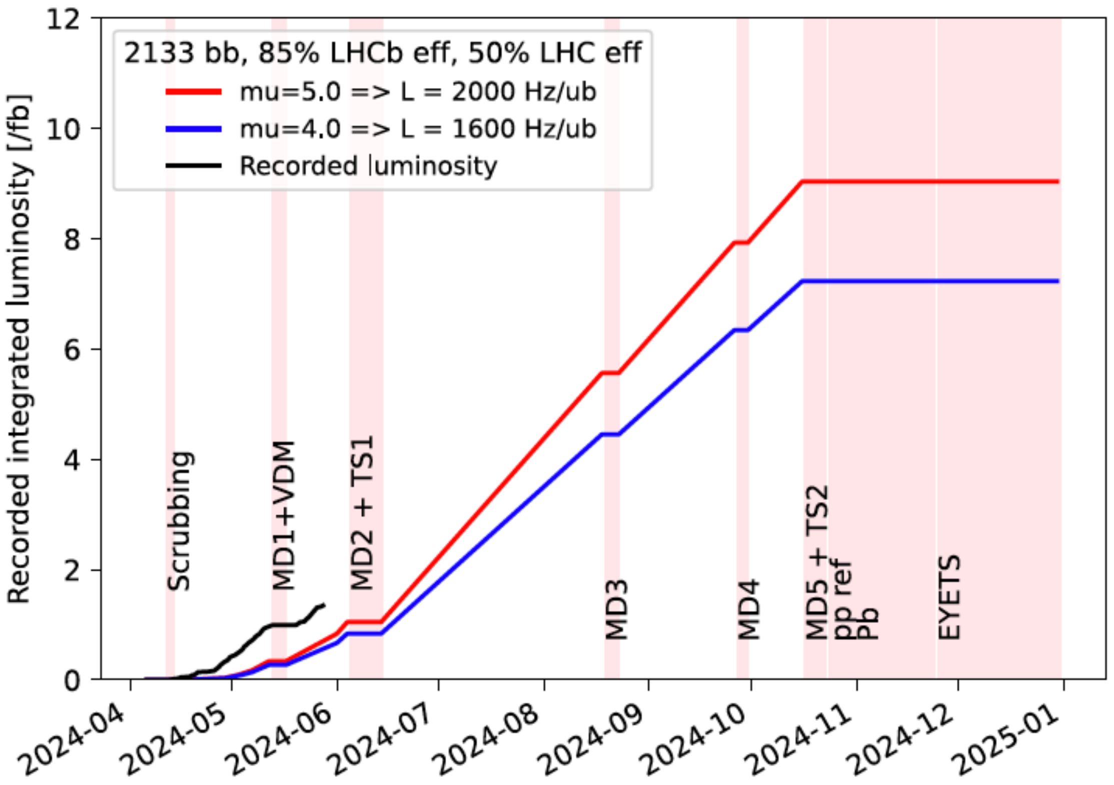


Moving towards the integrated luminosity goals

Integrated luminosity over the years

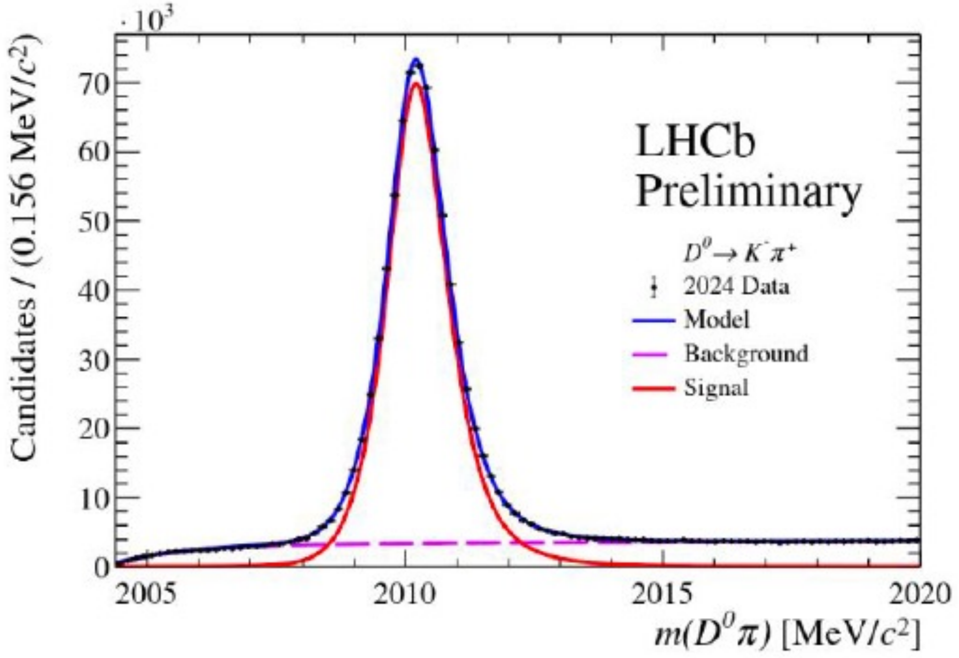


This year's plans

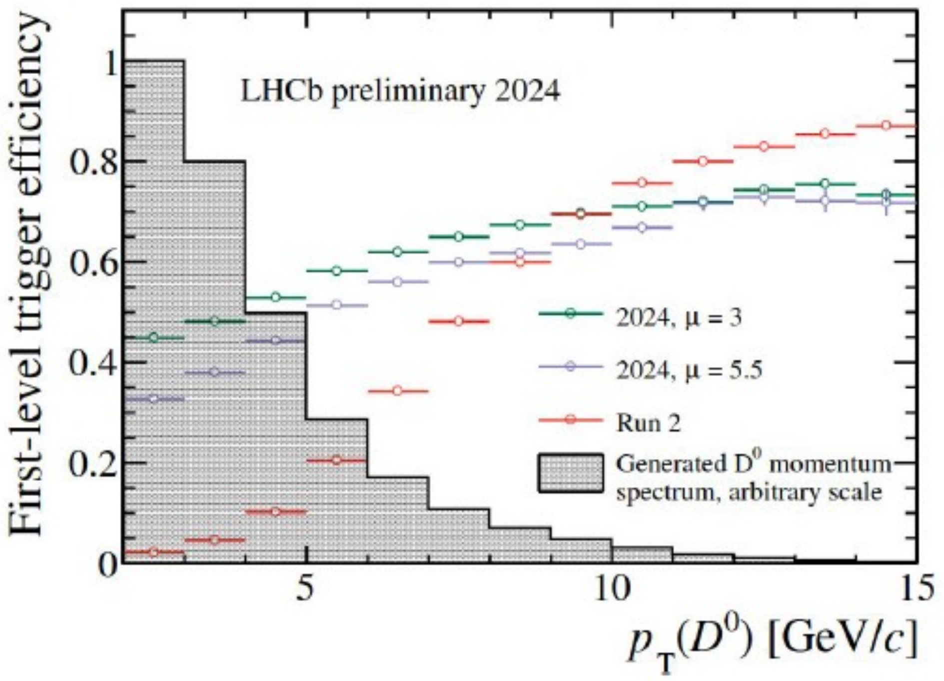


Software trigger at work

- ❑Removing the L0 trigger selection improves charm reconstruction efficiency



LHCb-FIGURE-2024-006

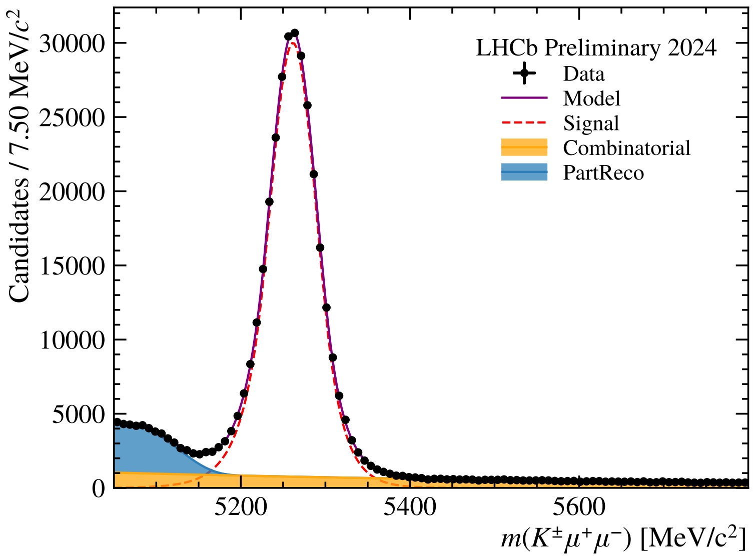


LHCb-FIGURE-2024-007

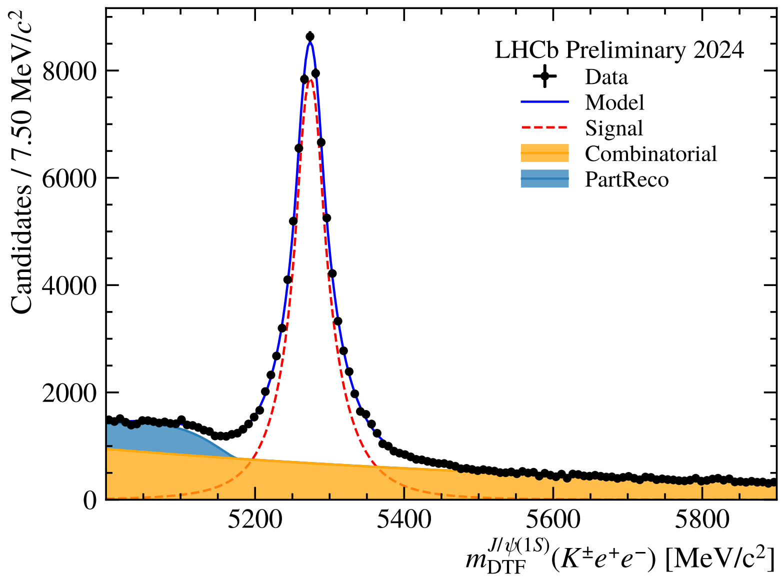
B decays in 2024 data

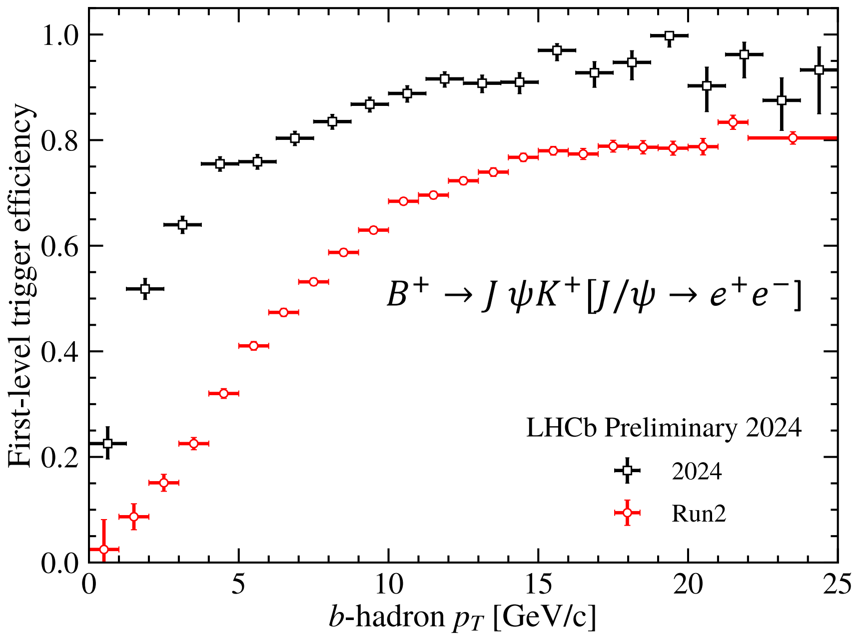
Trigger improvement also in hadronic B decays with electrons in the final state

$B^+ \to J\,\psi K^+[J/\psi \to \mu^+\mu^-]$



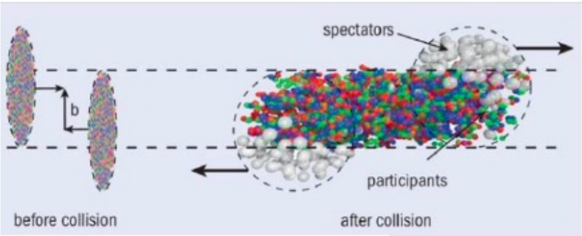
$B^+ \to J\,\psi K^+[J/\psi \to e^+e^-]$

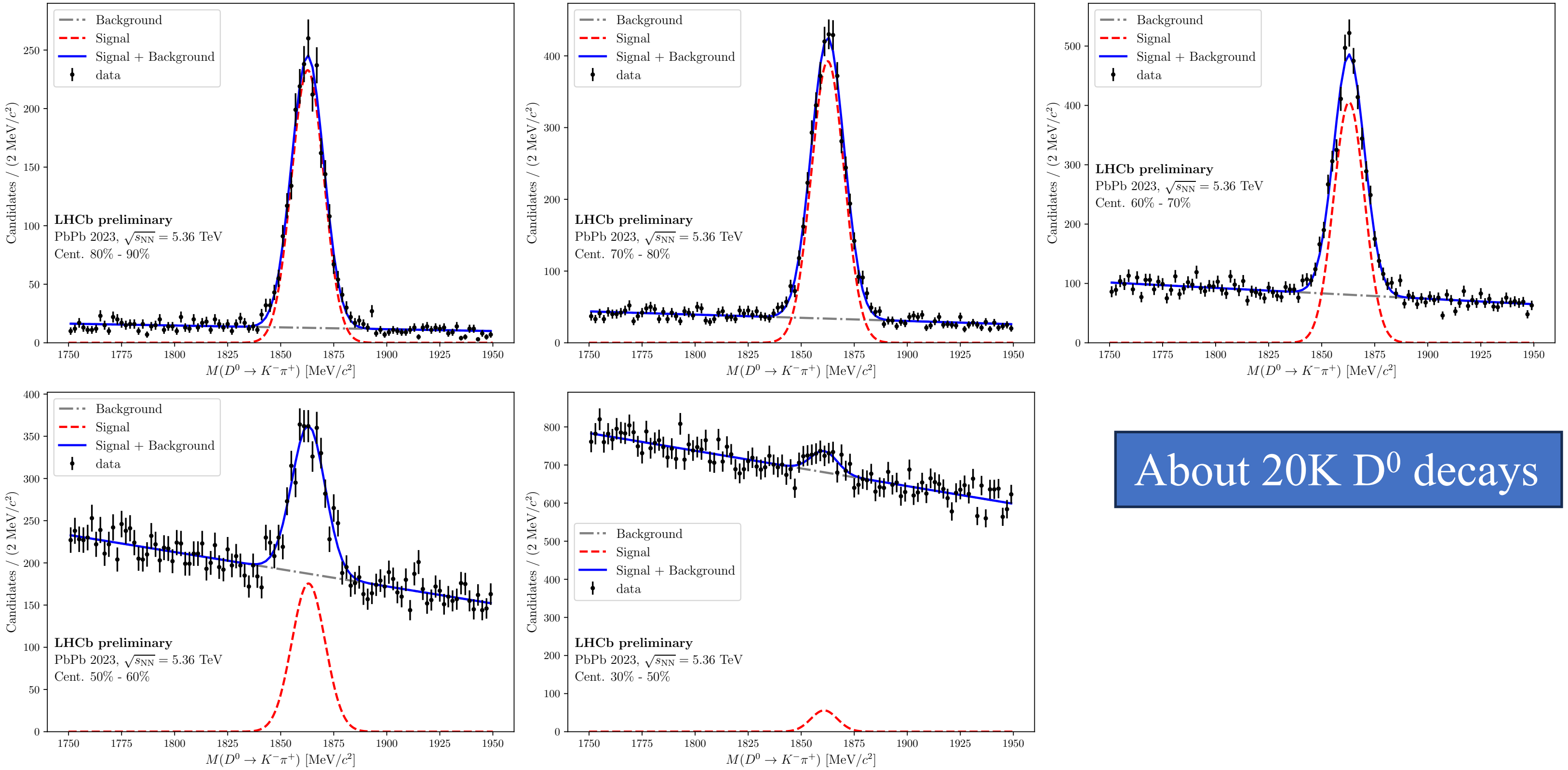




Heavy ion program: 2023 PbPb data

- ❑VELO in open position and no UT reached **30% centrality** (70% saturation in Run II)





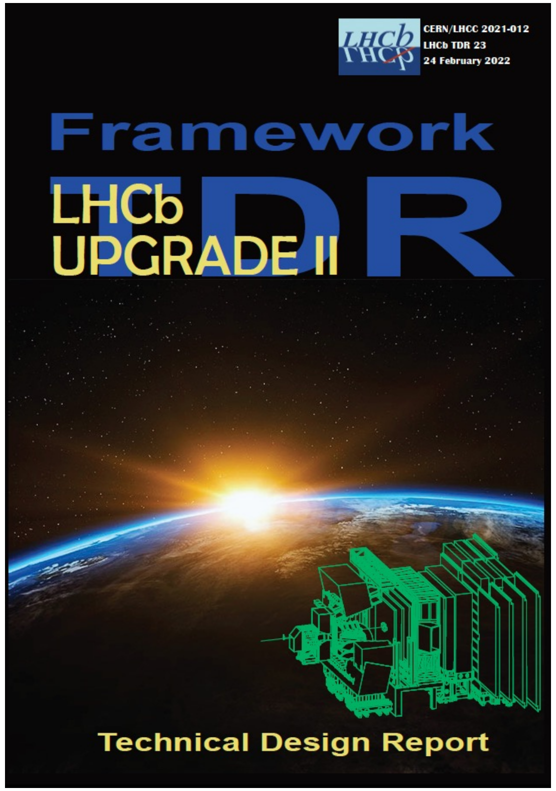
About 20K D^0 decays

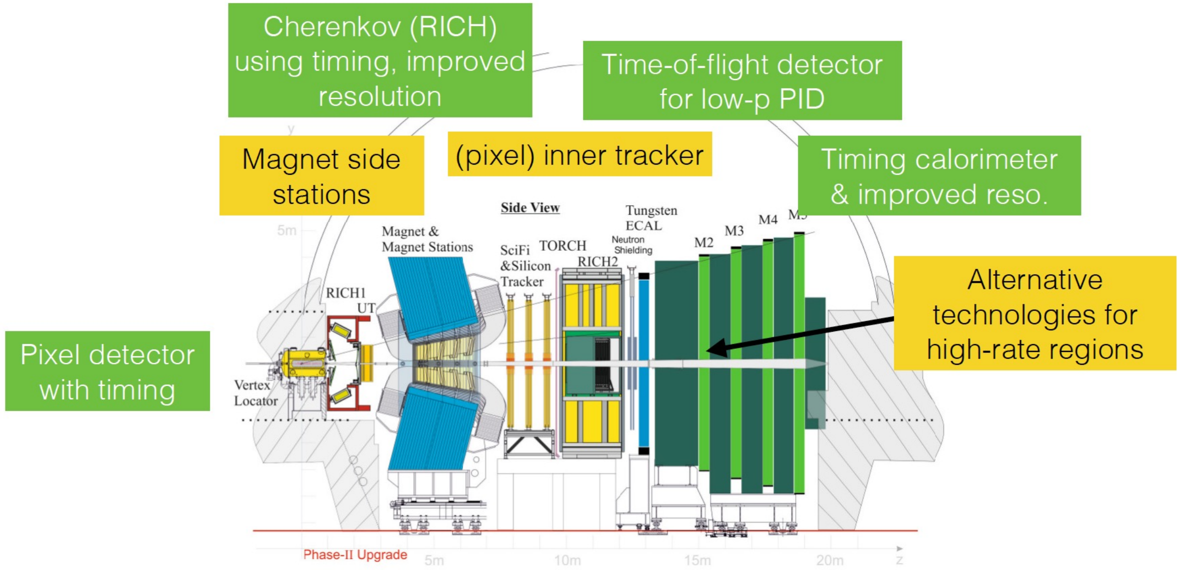
Chapter III:
LHCb Upgrade 2

Tackling the challenge of the high luminosity (operation at high pile-up)

The LHCb upgrade II

E. Niel LHCb Upgrades

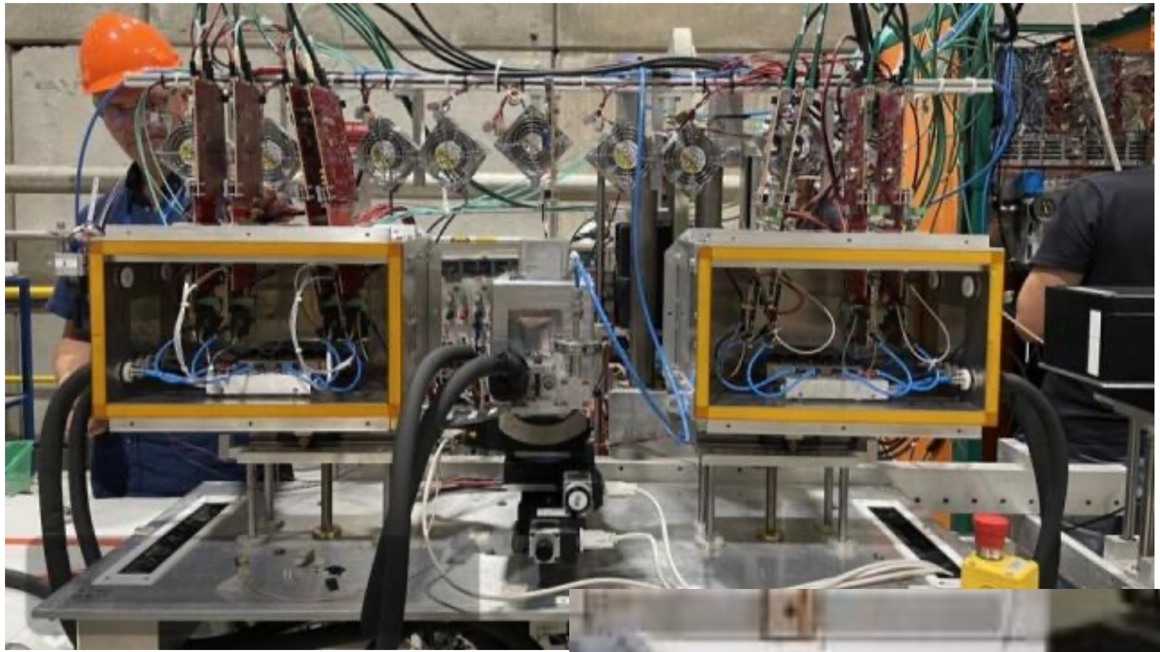




- ❑Use $\mathcal{O}$(10 ps) timing in vertex reconstruction and particle identification to mitigate pile-up
- ❑Increase granularity in UT & add MAPs sectors to the SCIFI
- ❑Add tracking stations in the magnet to increase efficiency for low-momentum tracks

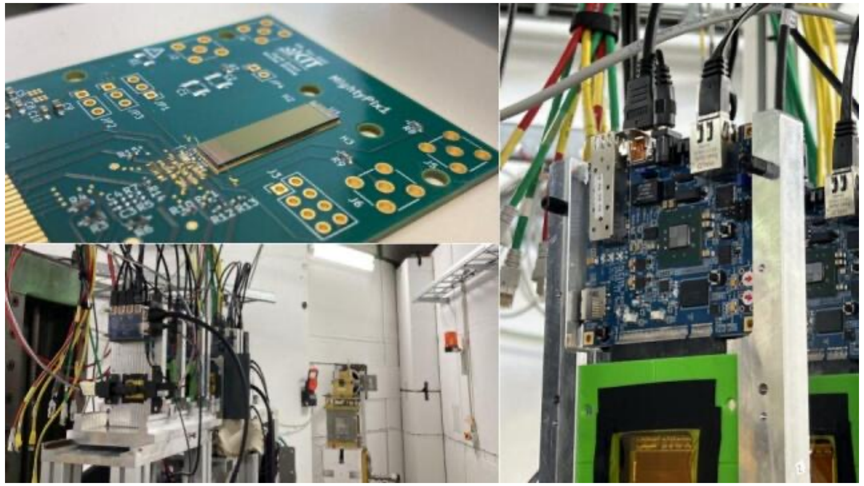
Detector R&D

Timepix4 telescope : studies of per hit time resolution



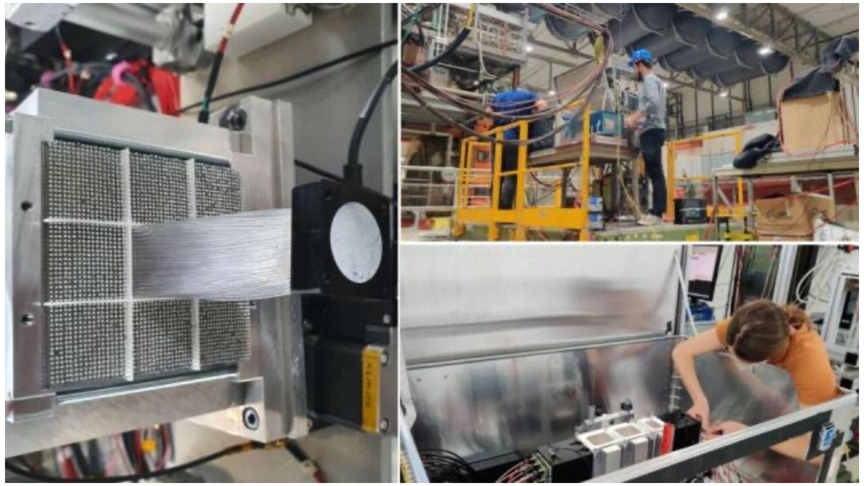
TORCH prototype
test beam

Test beam Mighty Tracker prototype



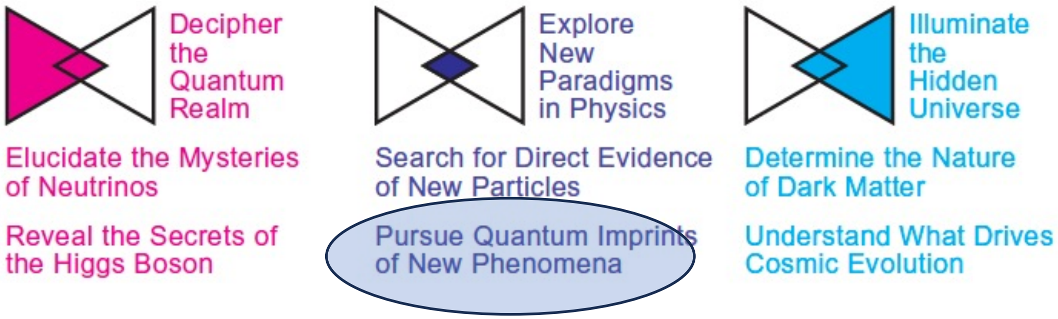
SPACAL technology for the
innermost section of the ECAL
being studied in test beams

[D. Manuzzi PicoCAL](#)



arXiV:1808.08865

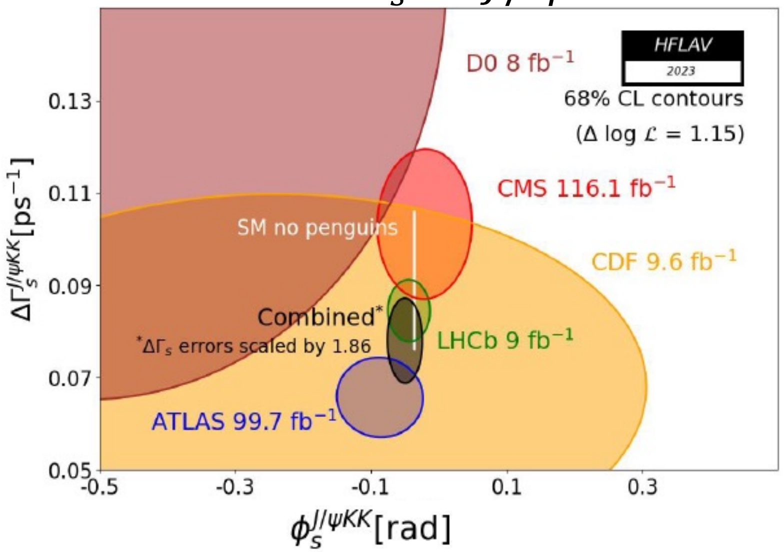
Physics opportunities

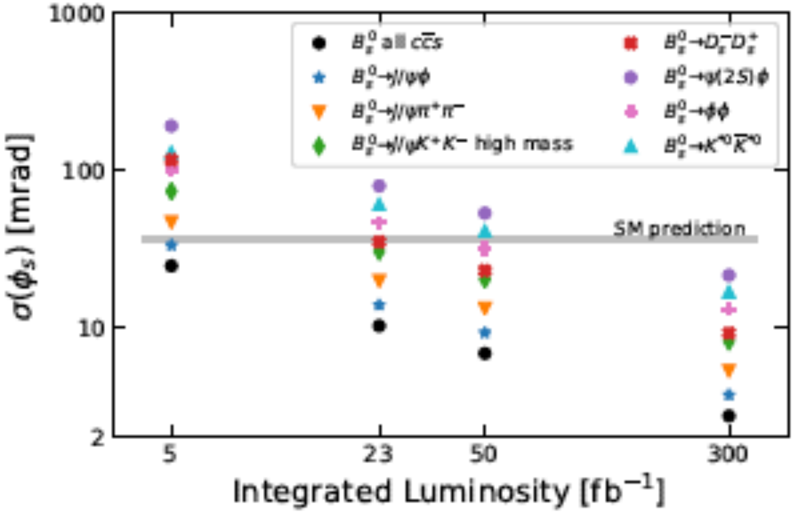


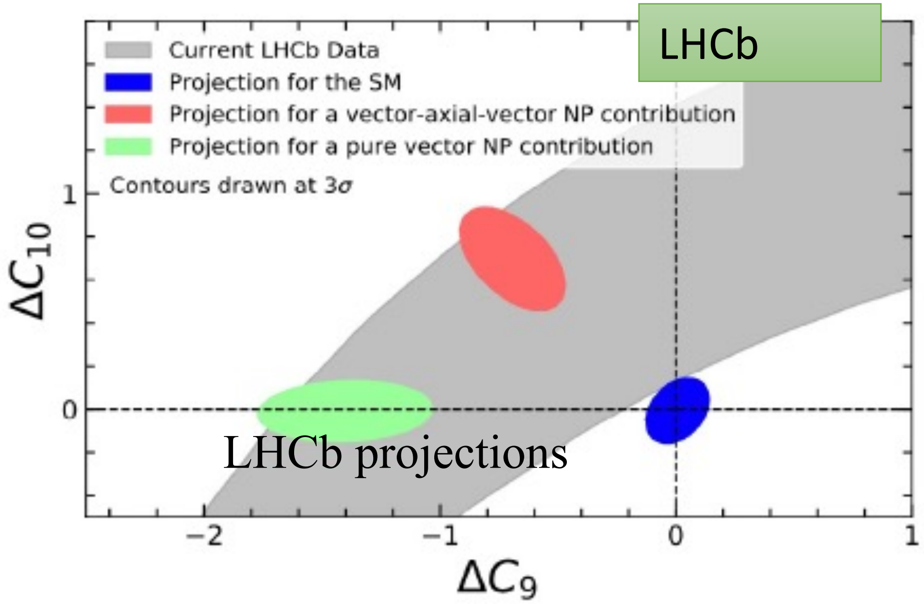
Our goal is to fully exploit the HL-LHC discovery potential using flavor as a probe of quantum imprints of new phenomena and, more broadly, LHCb as a general-purpose detector in the forward direction exploiting a trigger strategy that can adapt the experiment strategy to the lesson learned in the course of the data taking, well aligned with one of the science drivers emerging from the Snowmass community study and cited in the P5 report

Future prospects: CP violation and rare decays will probe **subtle deviations from SM expectations**

CP violation in $B_s^0 \to J/\psi\, KK$







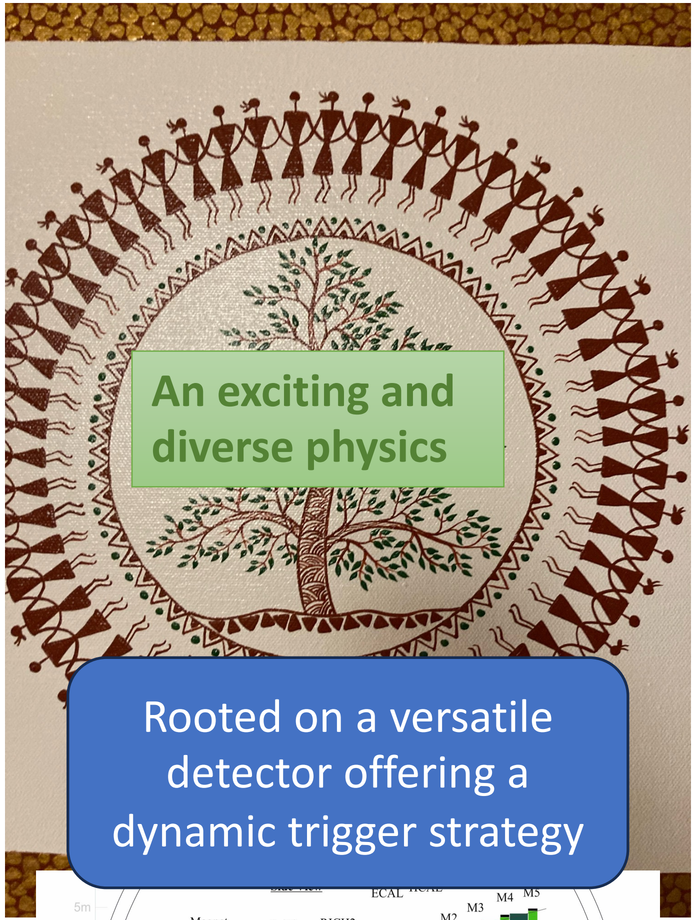
Integrated Luminosity	$3\ \text{fb}^{-1}$	$23\ \text{fb}^{-1}$	$300\ \text{fb}^{-1}$
R_K and R_{K^*} measurements			
$\sigma(C_9)$	0.44	0.12	0.03
$\Lambda^{\text{tree generic}}$ [TeV]	40	80	155
$\Lambda^{\text{tree MFV}}$ [TeV]	8	16	31
$\Lambda^{\text{loop generic}}$ [TeV]	3	6	12
$\Lambda^{\text{loop MFV}}$ [TeV]	0.7	1.3	2.5
$B^0 \to K^{*0}\mu^+\mu^-$ angular analysis			
$\sigma^{\text{stat}}(S_i)$	0.034–0.058	0.009–0.016	0.003–0.004
$\sigma(C'_{10})$	0.31	0.15	0.06
$\Lambda^{\text{tree generic}}$ [TeV]	50	75	115
$\Lambda^{\text{tree MFV}}$ [TeV]	10	15	23
$\Lambda^{\text{loop generic}}$ [TeV]	4	6	9
$\Lambda^{\text{loop MFV}}$ [TeV]	0.8	1.2	1.9

Sensitivity projections

Current LHCb

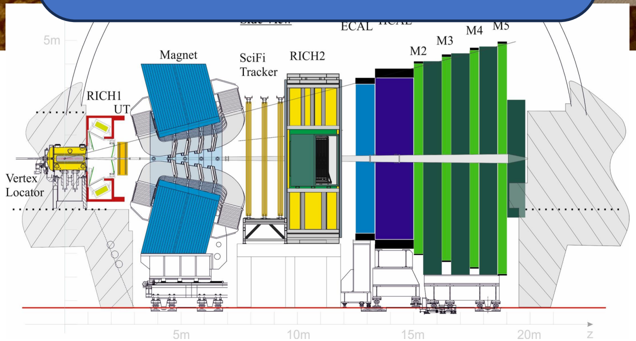
Observable	~~Current~~ LHCb (up to $9\,\mathrm{fb}^{-1}$)		Upgrade I ($23\,\mathrm{fb}^{-1}$)	($50\,\mathrm{fb}^{-1}$)	Upgrade II ($300\,\mathrm{fb}^{-1}$)
CKM tests					
γ ($B \to DK$, *etc.*)	$4°$	[9, 10]	$1.5°$	$1°$	$0.35°$
ϕ_s ($B_s^0 \to J/\psi\phi$)	32 mrad	[8]	14 mrad	10 mrad	4 mrad
$\|V_{ub}\|/\|V_{cb}\|$ ($\Lambda_b^0 \to p\mu^-\overline{\nu}_\mu$, *etc.*)	6%	[29, 30]	3%	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
$A_{\mathrm{T}}^{(2)}$ ($B^0 \to K^{*0}e^+e^-$)	0.10	[52]	0.060	0.043	0.016
$A_{\mathrm{T}}^{\mathrm{Im}}$ ($B^0 \to K^{*0}e^+e^-$)	0.10	[52]	0.060	0.043	0.016
$\mathcal{A}_{\phi\gamma}^{\Delta\Gamma}(B_s^0 \to \phi\gamma)$	$^{+0.41}_{-0.44}$	[51]	0.124	0.083	0.033
$S_{\phi\gamma}(B_s^0 \to \phi\gamma)$	0.32	[51]	0.093	0.062	0.025
$\alpha_\gamma(\Lambda_b^0 \to \Lambda\gamma)$	$^{+0.17}_{-0.29}$	[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



An exciting and diverse physics

Rooted on a versatile detector offering a dynamic trigger strategy



A story in progress

Fueled by a dedicated and vibrant community

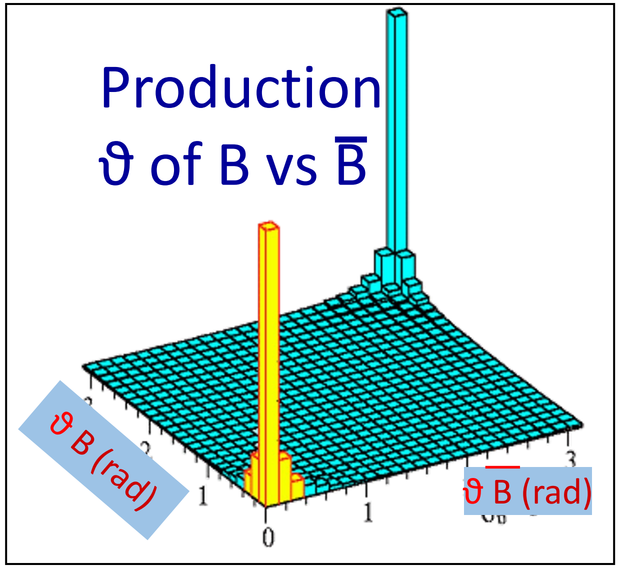
Thank you for your attention!

The end

Back-up material follows

LHCb Methodology: study b and c in the forward direction at the LHC

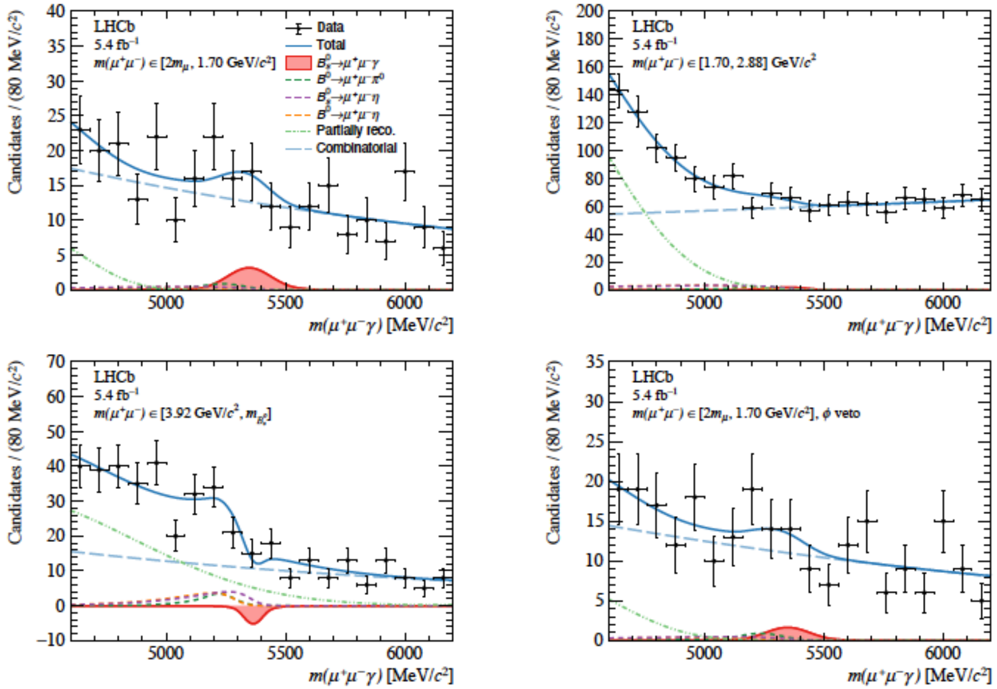
- In the forward region at LHC the $b\bar{b}$ production σ is large
- The hadrons containing the b & b quarks are both likely to be in the acceptance. Essential for "flavor tagging"
- LHCb uses the forward direction where the B's are moving with considerable momentum ~100 GeV, thus minimizing multiple scattering
- At $\mathcal{L}$=2x10^{32}/cm^2/s, we get 10^{12} B hadrons in 10^7 sec

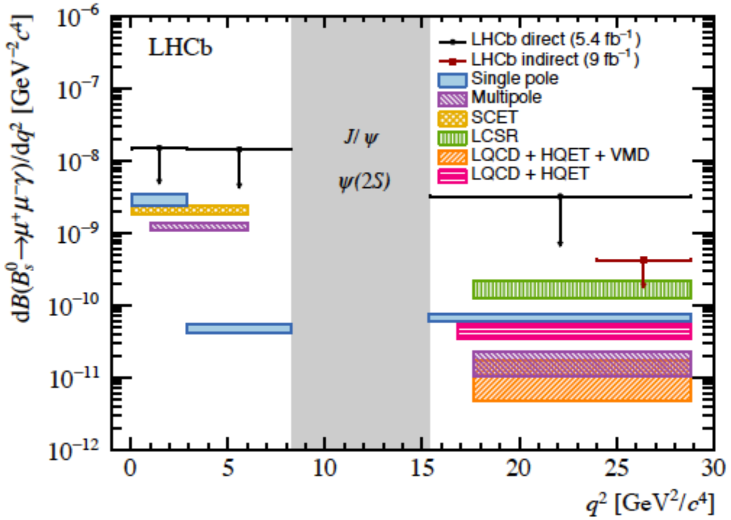


$B^0_{(s)} \to \mu^+\mu^-(\gamma)$

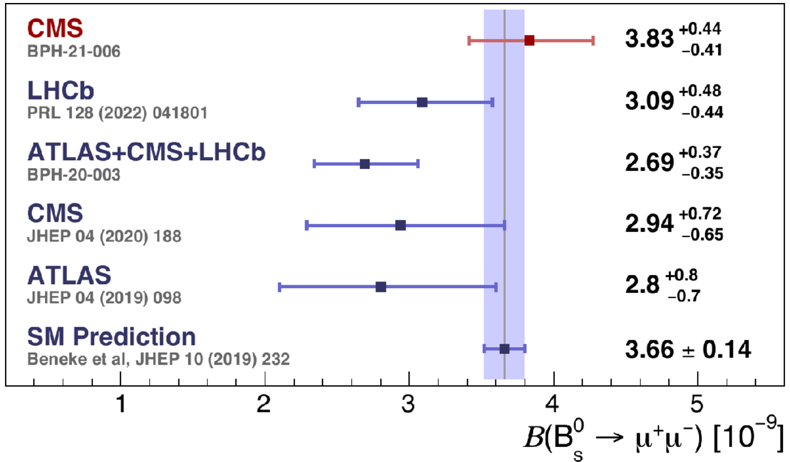
LHCb-PAPER-2023-045

A γ in the final state adds complexity to the reconstruction but also new opportunities (e.g. sensitivity to additional Wilson coefficients). nThis is the first search with full reconstruction of the final state in different q^2 (i.e. $m^2_{\mu\mu}$) intervals.





$B^0_s \to \mu^+\mu^-$, the well-studied "golden mode"

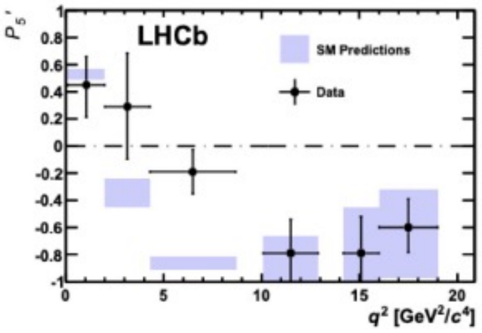


Several tensions currently reported in $B \to K^{(*)}\mu^+\mu^-$

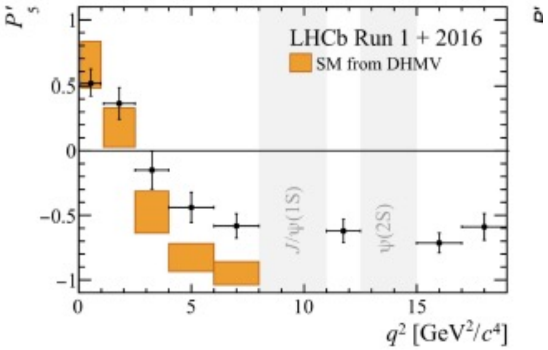
Angular distribution $B^0 \to K^{*0}\mu^+\mu^-$

Nicola Serra's talk

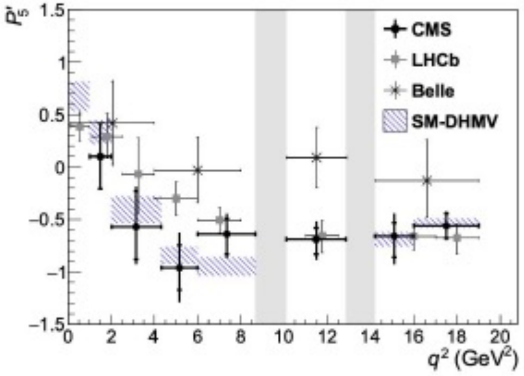
$$R_K = \frac{BR(B^+ \to K^+\mu^+\mu^-)}{BR(B^+ \to K^+e^+e^-)}$$



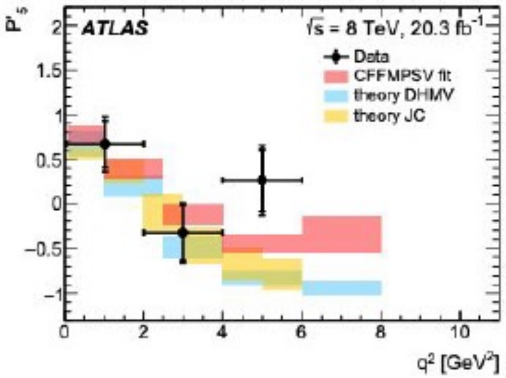
Phys.Rev.Lett. 111 (2013) 191801



Phys.Rev.Lett. 125 (2020) 1, 011802

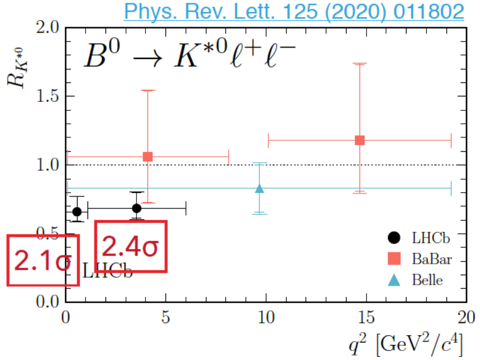


Phys.Lett.B 781 (2018) 517-541

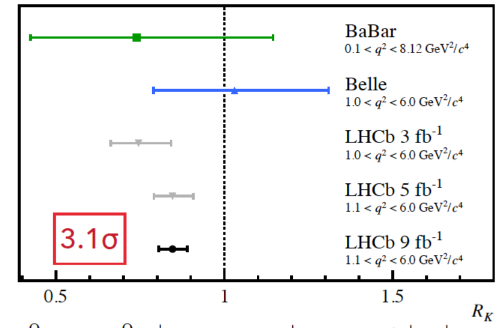


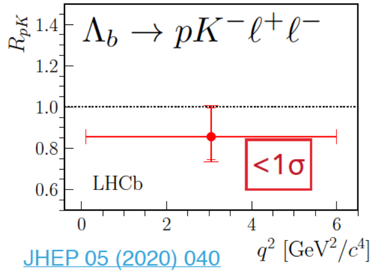
JHEP 10 (2018) 047

Phys. Rev. Lett. 125 (2020) 011802



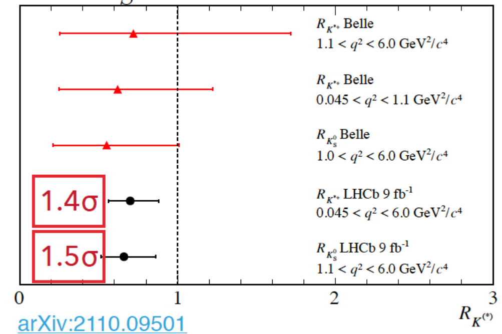
$B^+ \to K^+\ell^+\ell^-$ arXiv:2103.11769





JHEP 05 (2020) 040

$B^0 \to K^0_S\ell^+\ell^-$ $B^+ \to K^{*+}\ell^+\ell^-$

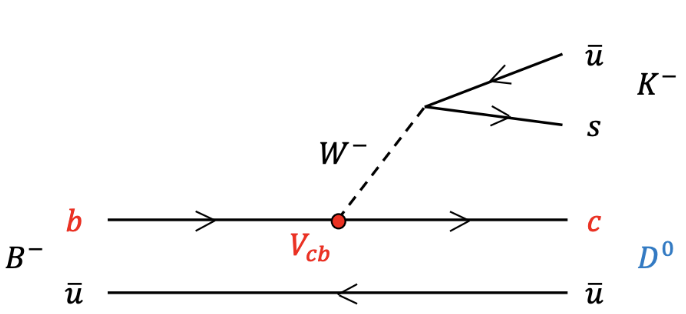


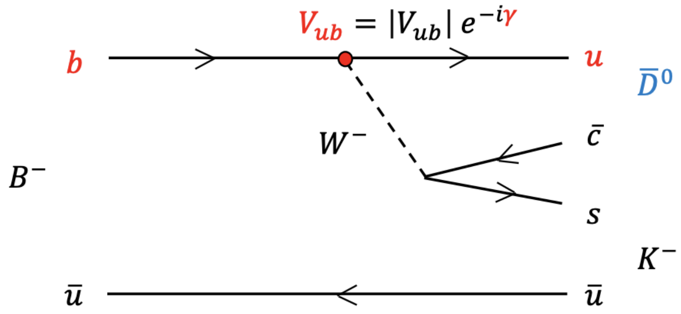
arXiv:2110.09501

The angle γ

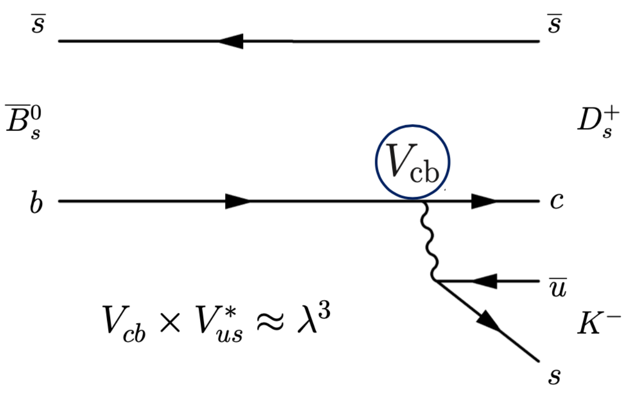
- Accessible from tree level processes (good Standard Model probe)
- Negligible theoretical uncertainty [Brod-Zupan,arXiV:1308.5663]

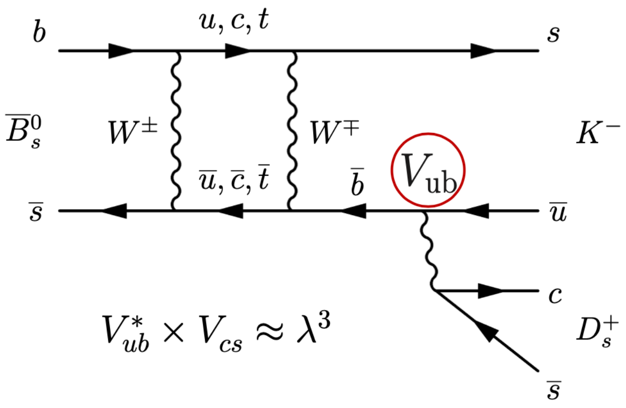
Key processes in charged B decays





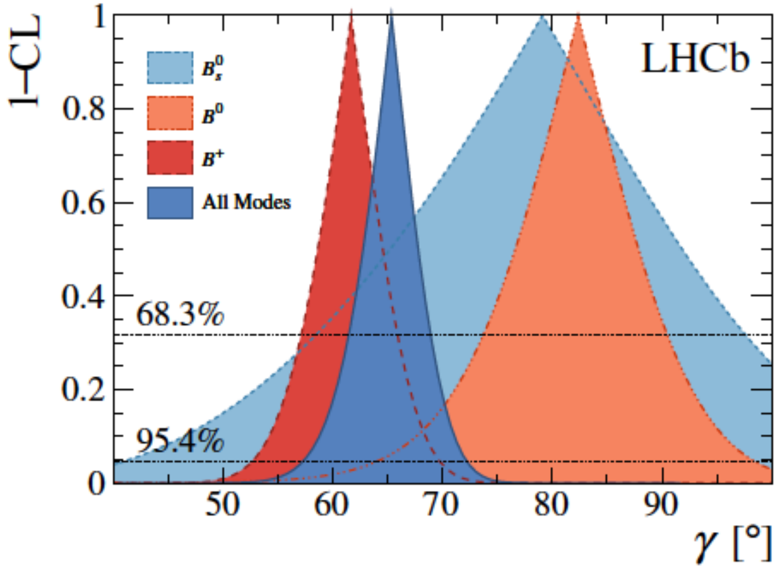
Key processes in B^0 decays





More details in D. Manuzzi's talk

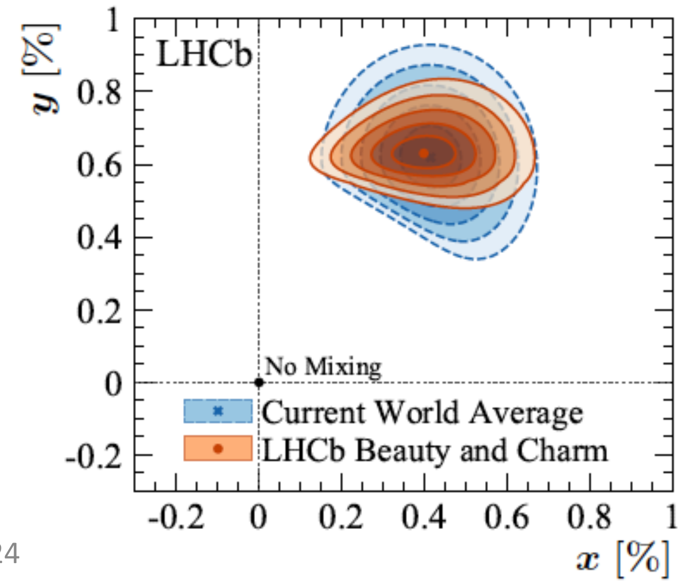
LHCb average:

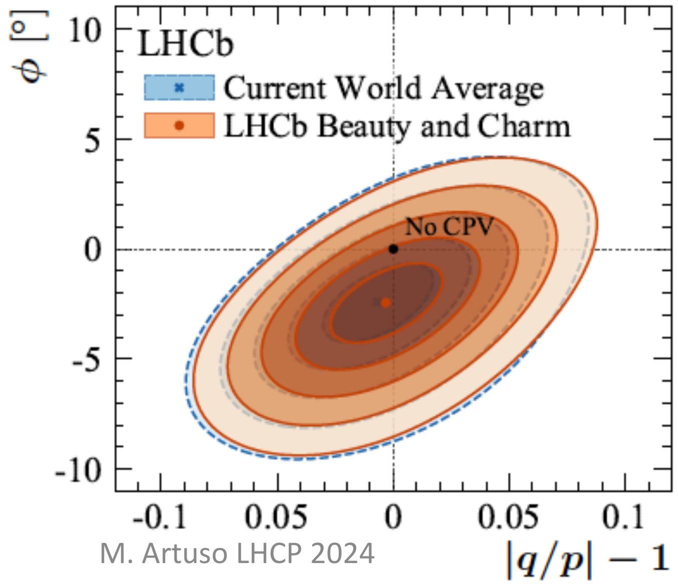


Species	Value [°]	68.3% CL		95.4% CL	
		Uncertainty	Interval	Uncertainty	Interval
B^+	61.7	$^{+4.4}_{-4.8}$	[56.9, 66.1]	$^{+8.6}_{-9.5}$	[52.2, 70.3]
B^0	82.0	$^{+8.1}_{-8.8}$	[73.2, 90.1]	$^{+17}_{-18}$	[64, 99]
B_s^0	79	$^{+21}_{-24}$	[55, 100]	$^{+51}_{-47}$	[32, 130]

$$\gamma = (65.4^{+3.8}_{-4.2})^\circ$$

Average of all the measurements





$$x \equiv \frac{\Delta M}{\Gamma} = 0.400^{+0.052}_{-0.053}$$

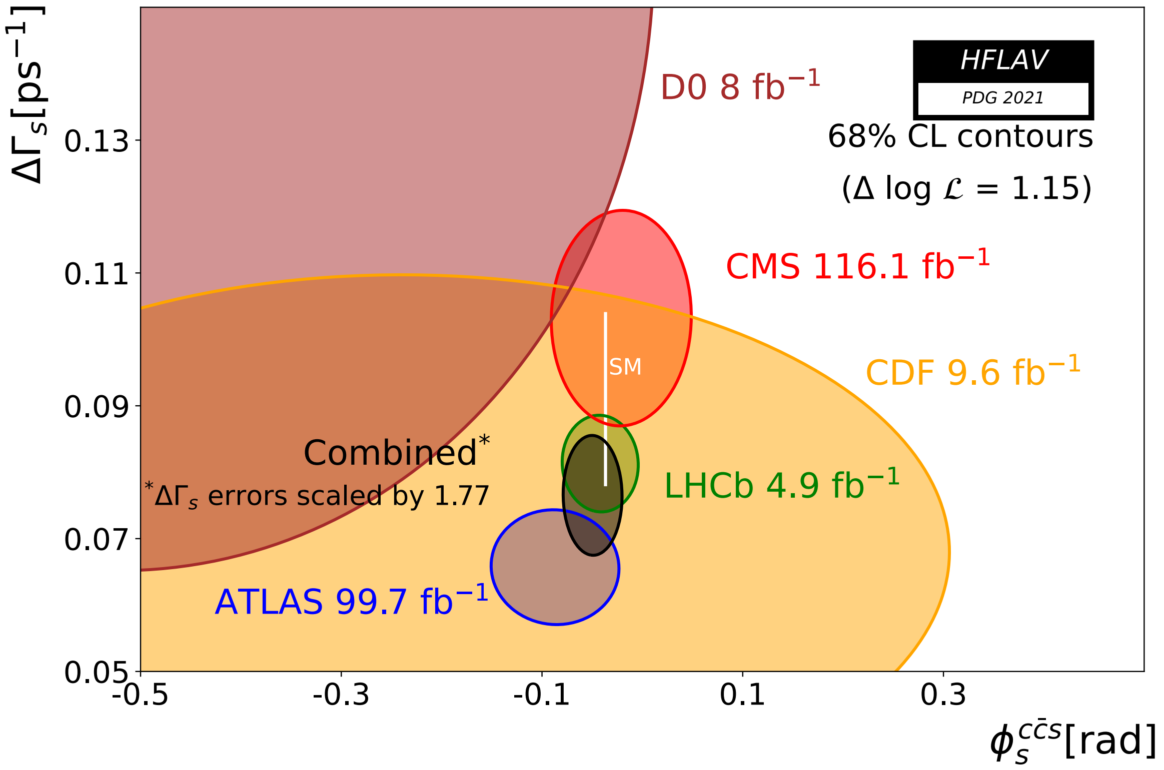
$$y \equiv \frac{\Delta\Gamma}{2\Gamma} = (0.630^{+0.033}_{-0.030})\%$$

$$\left|\frac{q}{p}\right| = 0.997 \pm 0.016$$

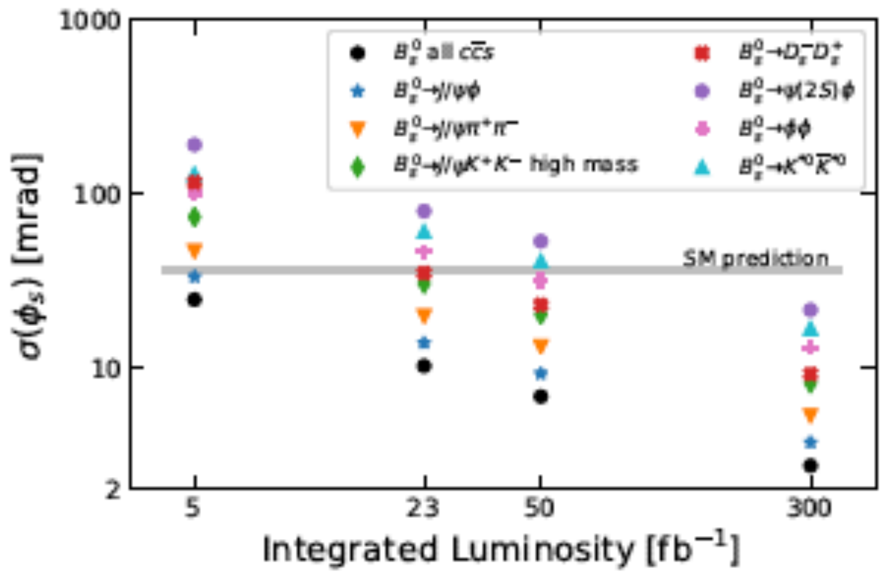
The B_s^0 triangle

CPV in B_s^0 $b \to [c\bar{c}s]$ decays

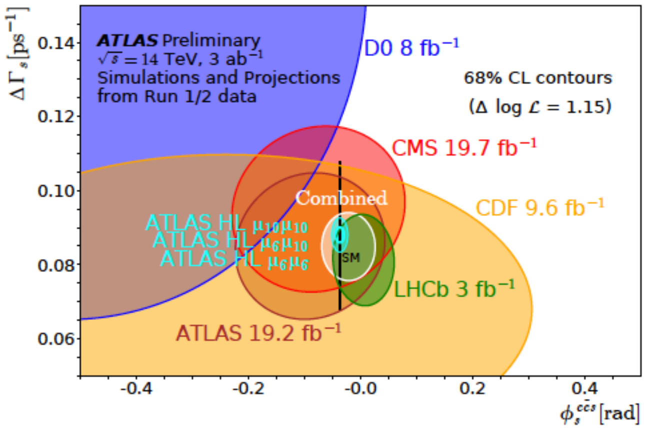
Current status

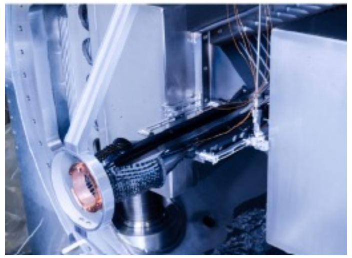


LHCb-TDR-023

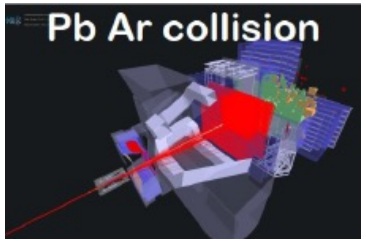


ATL-PHYS-PUB-2018-041

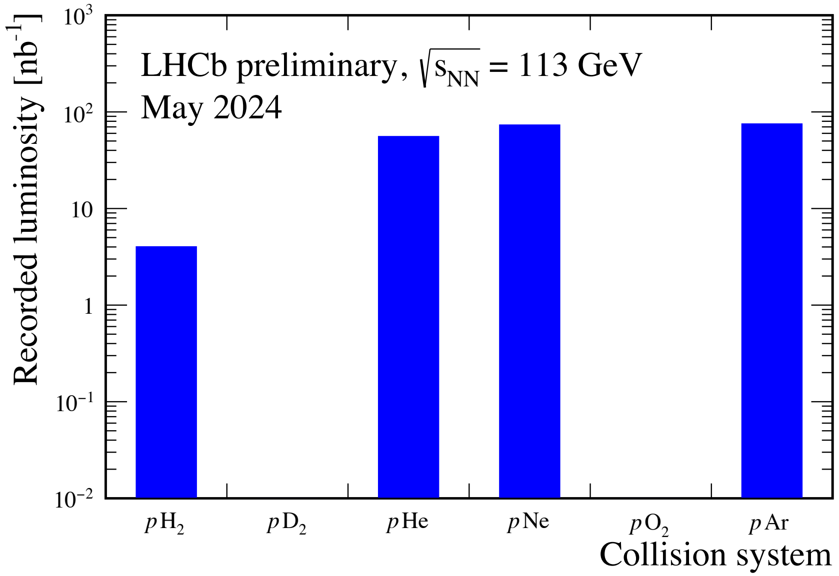




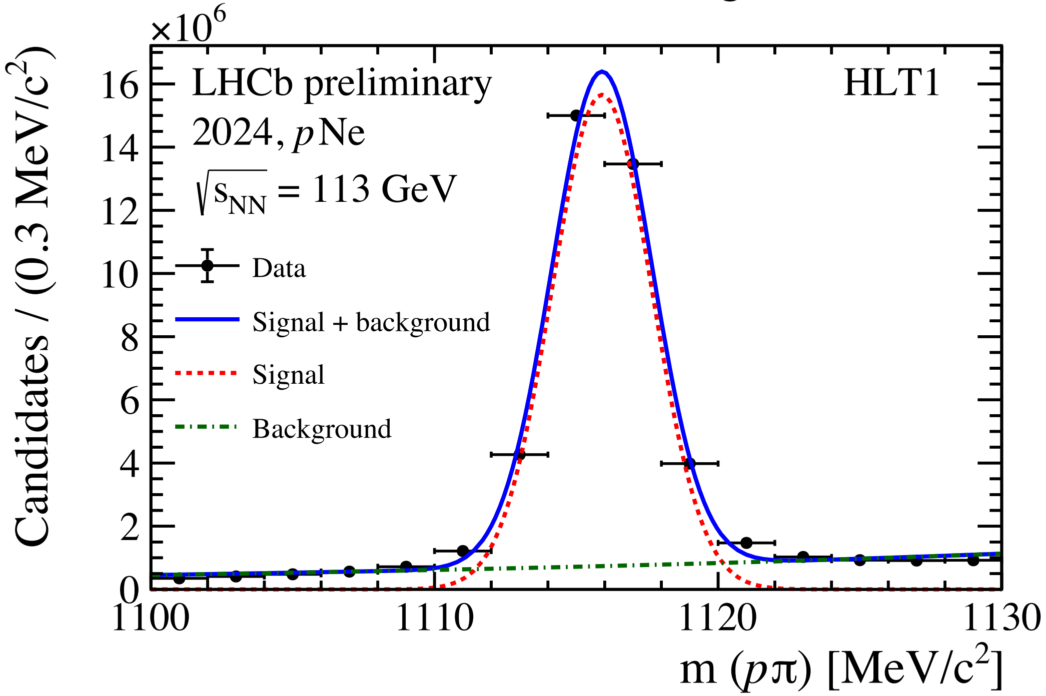
Fixed target program at LHCb



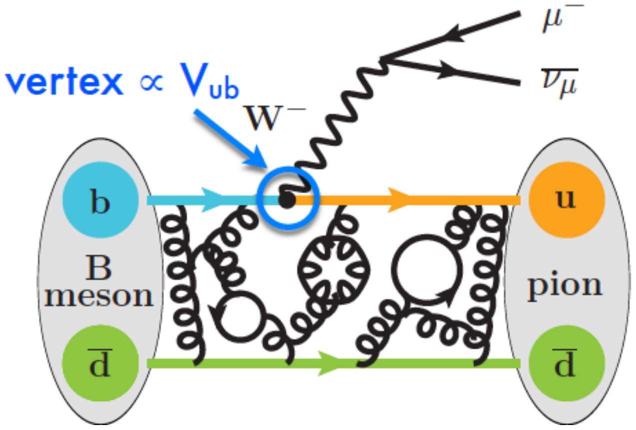
SMOG detector allows pursuit of [fixed target]program: gas injection system (H_2,He,Ne…)



LHCb-Figure-2024-005

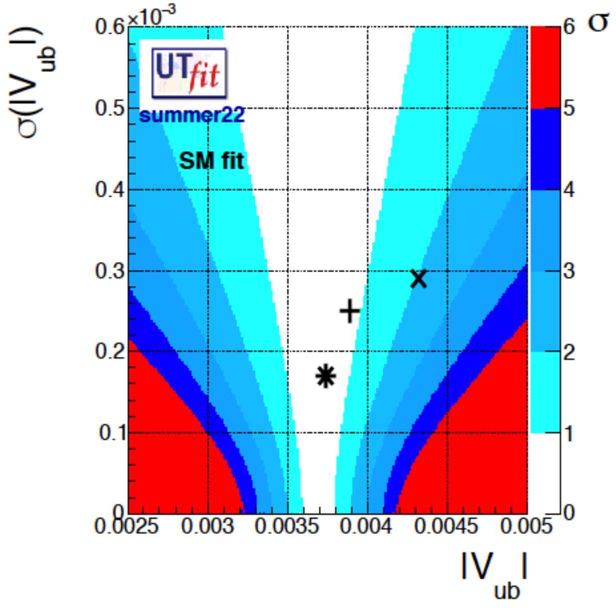


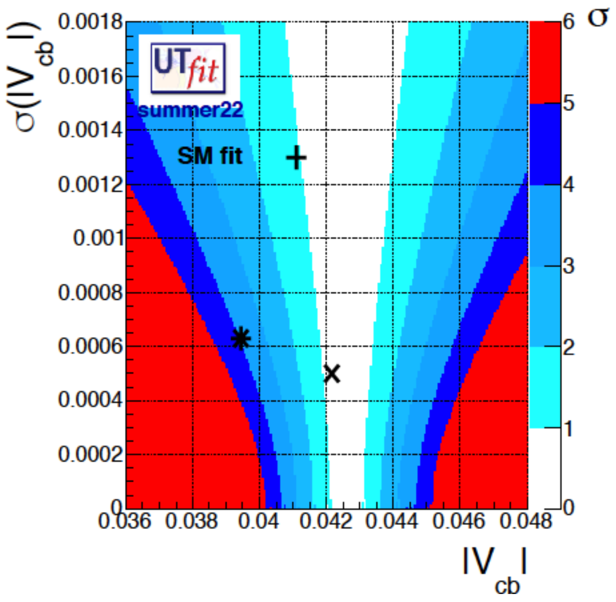
CKM: the sides – old tensions to be resolved



Inclusive: reconstruct a physical property integrated over hadronic final states

Exclusive: reconstruct the hadron in the final state





- A multidecade puzzle: both $|V_{ub}|$ and $|V_{cb}|$ determination encompass a persisting tension between the values extracted from **inclusive** or **exclusive** final state

$x = |V_{ub}|_{incl} \times 10^3 = 4.32 \pm 0.29$
$* = |V_{ub}|_{excl} \times 10^3 = 3.74 \pm 0.19$
$+ = |V_{ub}|_{ave} \times 10^3 = 3.89 \pm 0.25$

$x = |V_{cb}|_{incl} \times 10^3 = 42.16 \pm 0.50$
$* = |V_{cb}|_{excl} \times 10^3 = 39.44 \pm 0.63$
$+ = |V_{cb}|_{ave} \times 10^3 = 41.1. \pm 1.3$