Prospects of LHCb Run-3

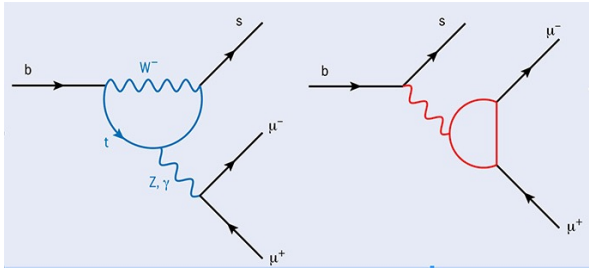
Jibo HE/何吉波(UCAS)

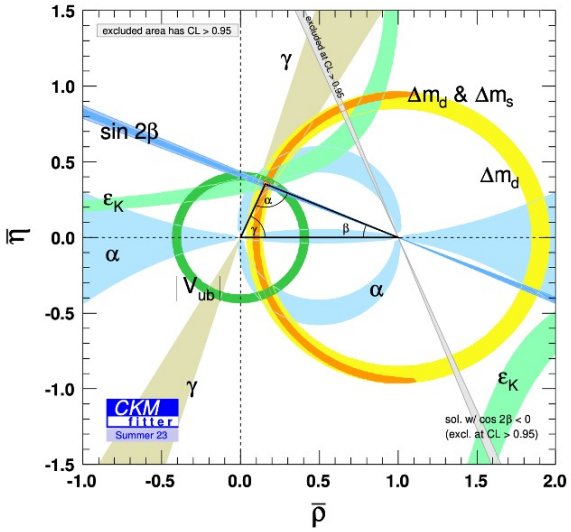
第三届强子与重味物理理论与实验联合研讨会

2024年4月5-9日@华中科技大学

Introduction

- Indirect search for New physics
  - Rare decays
  - CP violation
- QCD
  - Spectroscopy
  - Production
- Electroweak

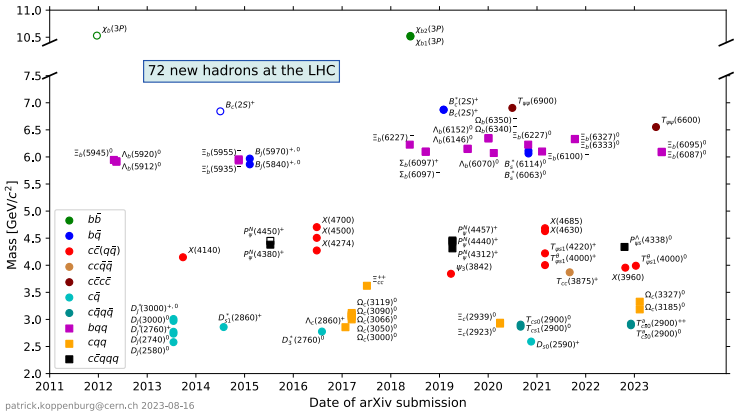




谢跃红，Opportunities to probe CP in rare B decays, 14h30, 8 April

钱文斌，Exotic states in B decays, 14h00, 7 April

俞洁晟，Study of Bc physics at LHCb, 16h00, 7 April



Large Hadron Collider

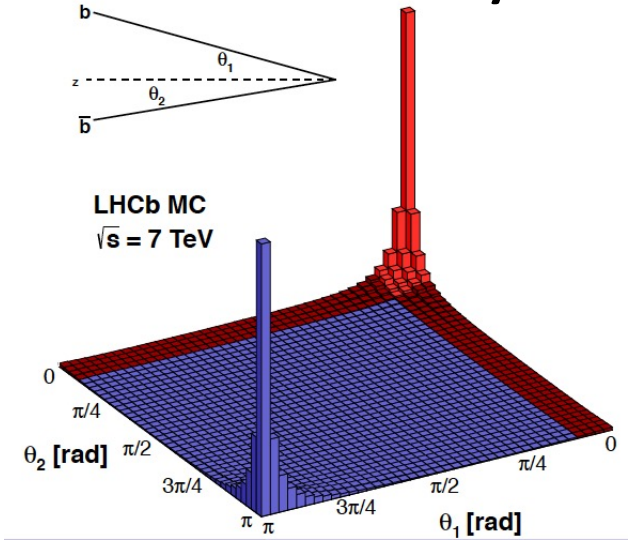
Proton energy: up to 7 TeV (10^{12} eV)
speed: 0.999999991 c

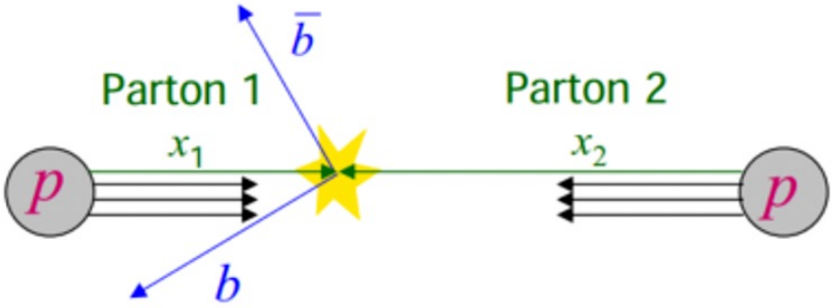
Beauty/charm production

- Large production cross-section @ 7 TeV
  - Minibias ~60 mb
  - Charm ~6 mb
  - Beauty ~0.3 mb **c.f. 1nb @$\Upsilon(4S)$**

} Flavour factory!

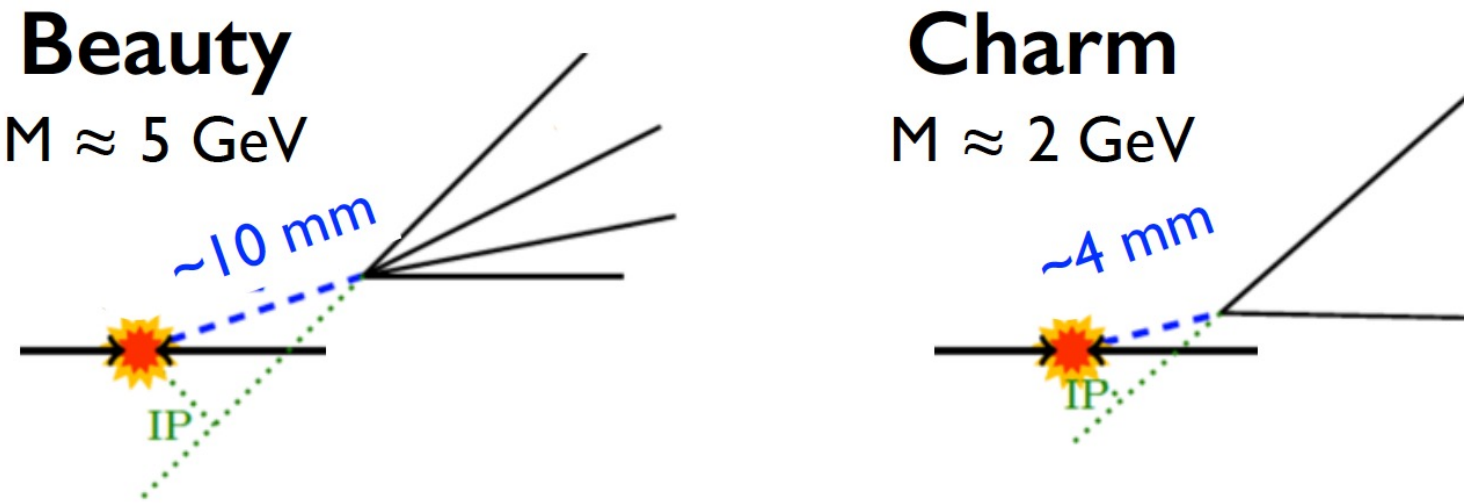
- Predominantly in forward/backward cones





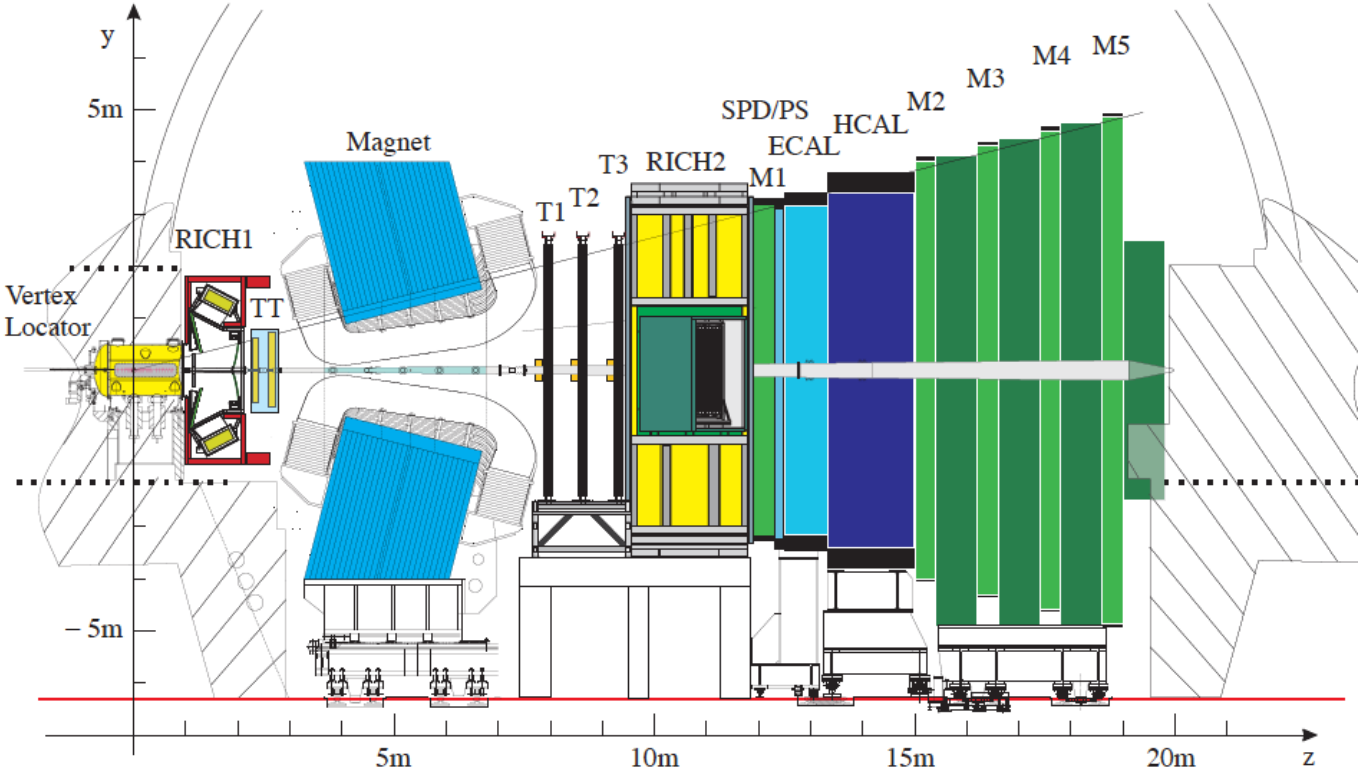
Initial energy of $b\bar{b}$ not known

Beauty/charm signature



- Compared to minimum bias (background)
  - Relatively high mass → high *transverse momentum*
  - Relatively long lifetime → large impact parameter (IP)
- Requires excellent vertexing, tracking, particle-identification

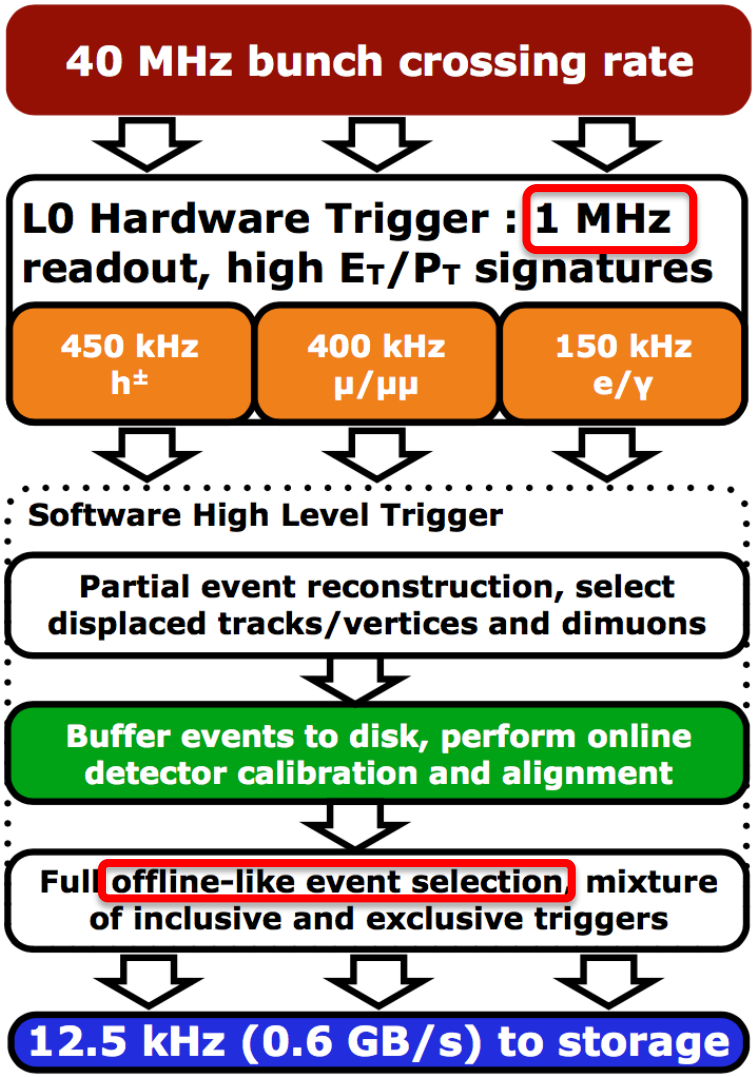
The LHCb experiment



[JINST 3 (2008) S08005]

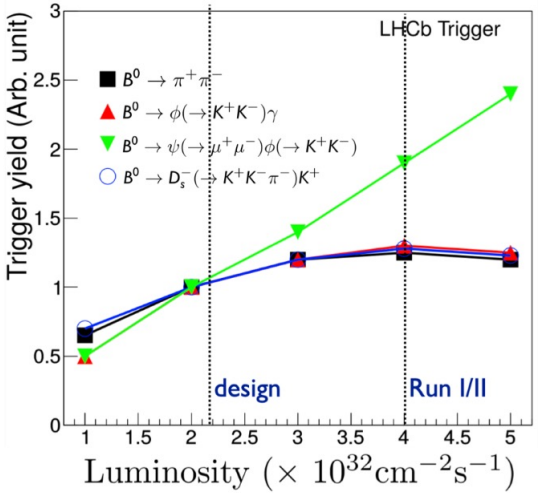
Vertex Locator	$\sigma_{PV,x/y} \sim 10\ \mu m$, $\sigma_{PV,z} \sim 60\ \mu m$
Tracking (TT, T1-T3)	$\Delta p/p$: 0.4% at 5 GeV/c, to 0.6% at 100 GeV/c
RICHs	$\varepsilon(K \to K) \sim 95\%$, mis-ID rate $(\pi \to K) \sim 5\%$
Muon system (M1-M5)	$\varepsilon(\mu \to \mu) \sim 97\%$, mis-ID rate $(\pi \to \mu) = 1 - 3\%$
ECAL	$\sigma_E/E \sim 10\%/\sqrt{E} \oplus 1\%$ (E in GeV)
HCAL	$\sigma_E/E \sim 70\%/\sqrt{E} \oplus 10\%$ (E in GeV)

The LHCb trigger (2018)



- L0, Hardware
  - $p_{\mathrm{T}}(\mu_1)\times p_{\mathrm{T}}(\mu_2) > (1.5\ \mathrm{GeV})^2$
  - $p_{\mathrm{T}}(\mu) > 1.8$ GeV
  - $E_{\mathrm{T}}(e) > 2.4$ GeV
  - $E_{\mathrm{T}}(\gamma) > 3.0$ GeV
  - $E_{\mathrm{T}}(h) > 3.7$ GeV
- High Level Trigger
  - Stage1, p_{T}, IP
  - Stage2, full selection

The LHCb trigger (Run3)



Software High Level Trigger

Partial event reconstruction, select displaced tracks/vertices and dimuons

Buffer events to disk, perform online detector calibration and alignment

Full offline-like event selection, mixture of inclusive and exclusive triggers

12.5 kHz (0.6 GB/s) to storage

30 MHz inelastic event rate (full rate event building)

Software High Level Trigger

Full event reconstruction, inclusive and exclusive kinematic/geometric selections

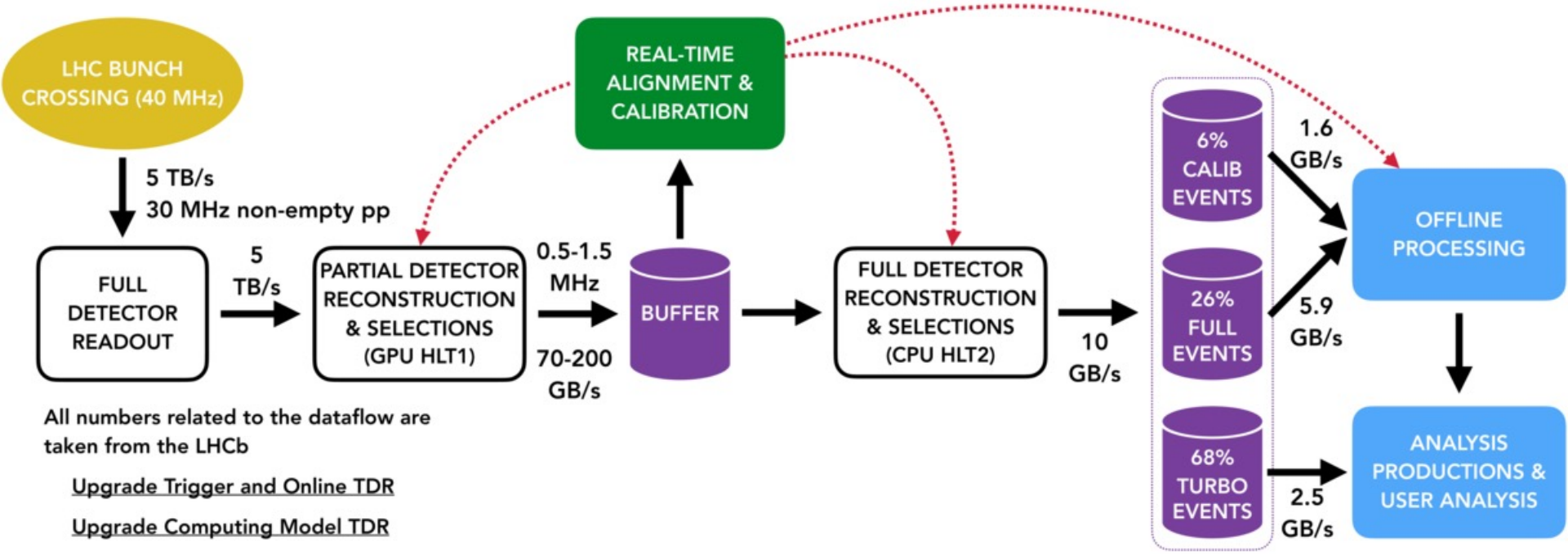
Buffer events to disk, perform online detector calibration and alignment

Add offline precision particle identification and track quality information to selections

Output full event information for inclusive triggers, trigger candidates and related primary vertices for exclusive triggers

2-5 GB/s to storage

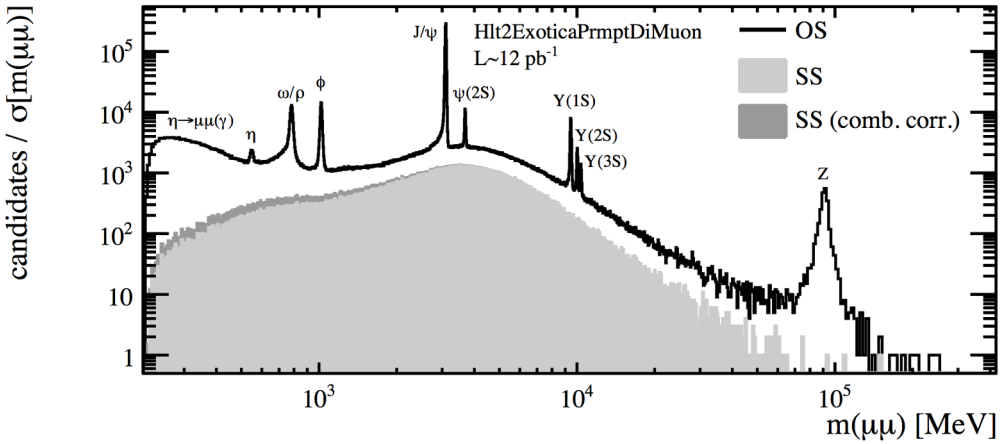
The turbo stream



All numbers related to the dataflow are taken from the LHCb

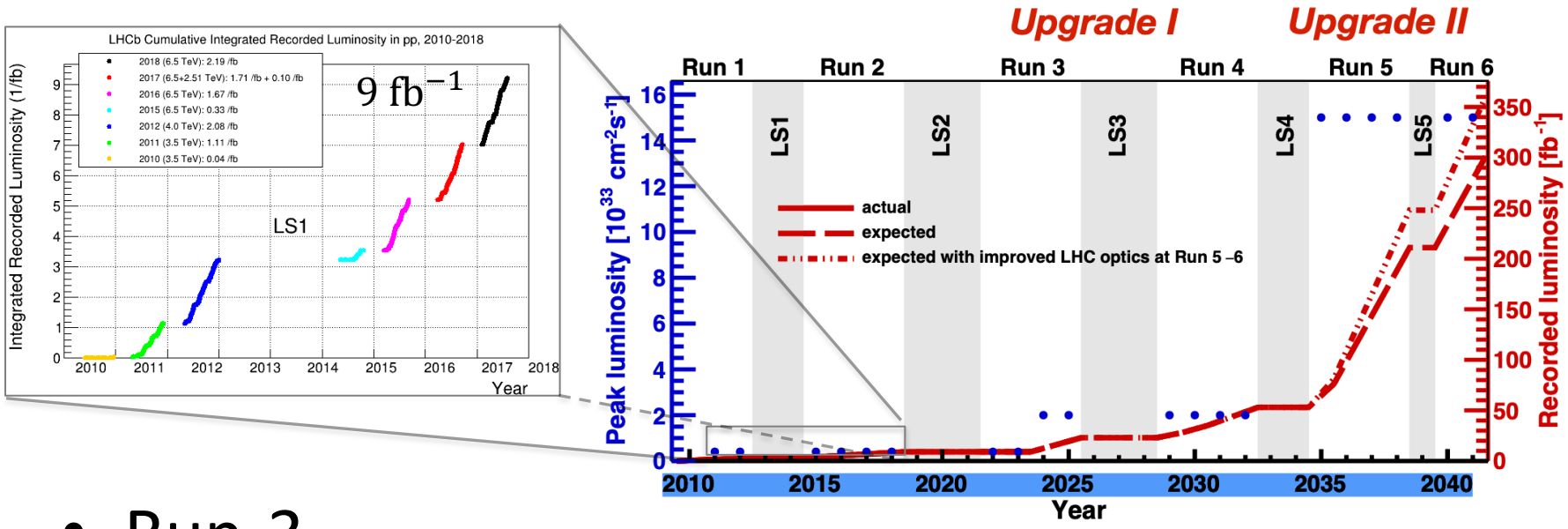
Upgrade Trigger and Online TDR

Upgrade Computing Model TDR



Turbo stream, μDST, event size 10 times smaller, maximize physics output!

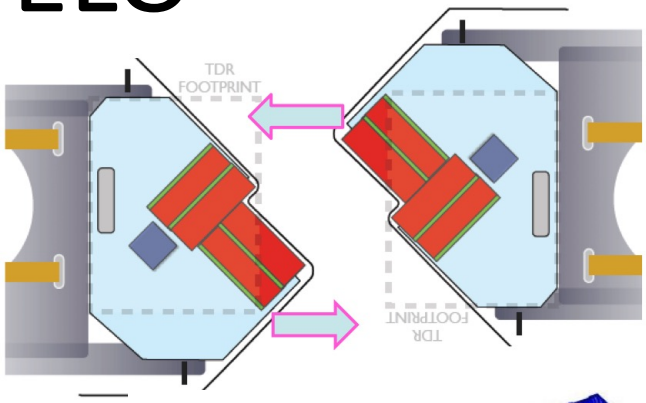
LHCb luminosity prospects



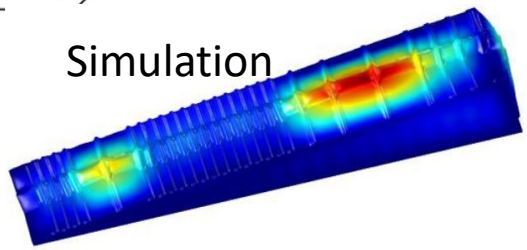
- Run-3
  - Luminosity: 7 fb^{-1} (2024) + 7 fb^{-1} (2025)
  - Yields, compared to Run 1+2
    - Muon modes ~2
    - Hadronic modes ~4 (2 x 2 due to higher trigger eff.)

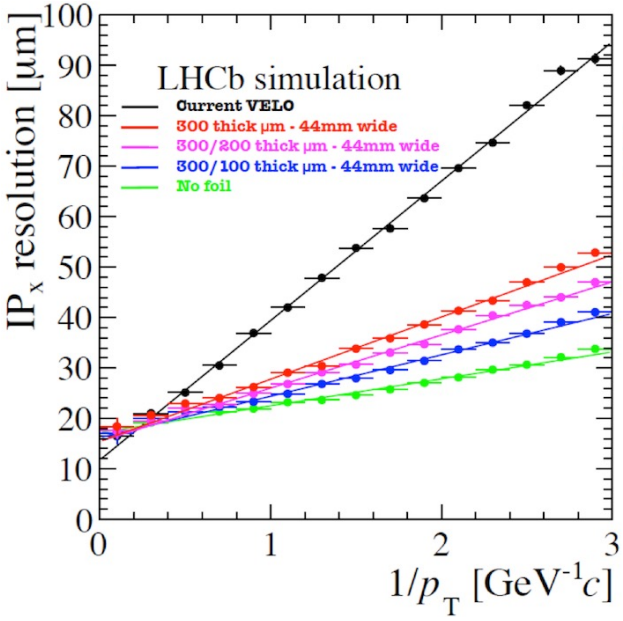
The upgraded VELO

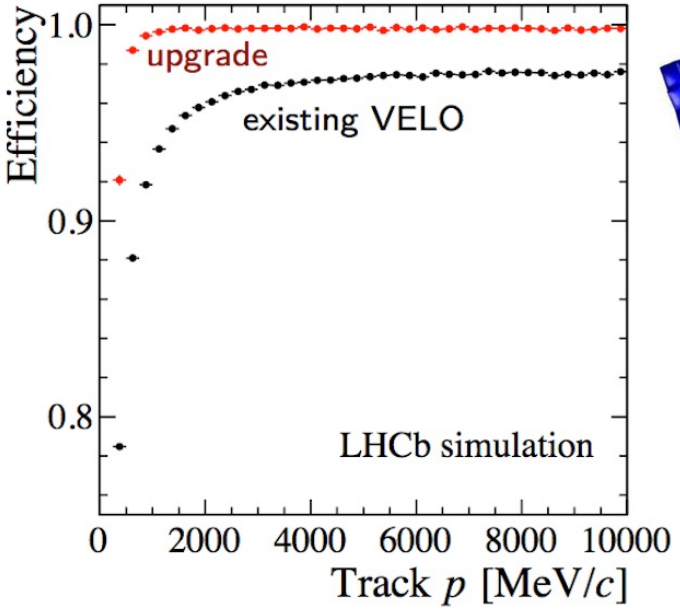
- Hybrid silicon pixel (55 x 55 μm^2)
  - Thinner RF foil, 185 µm
  - Inner aperture reduced from 5.5→3.5 mm
- Incident in 2023, RF foil replaced now



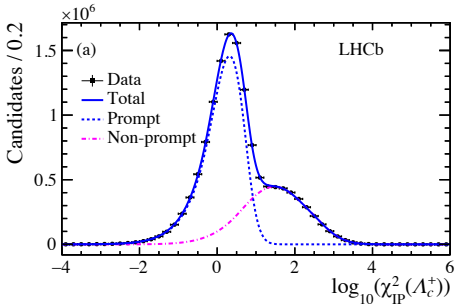
Simulation







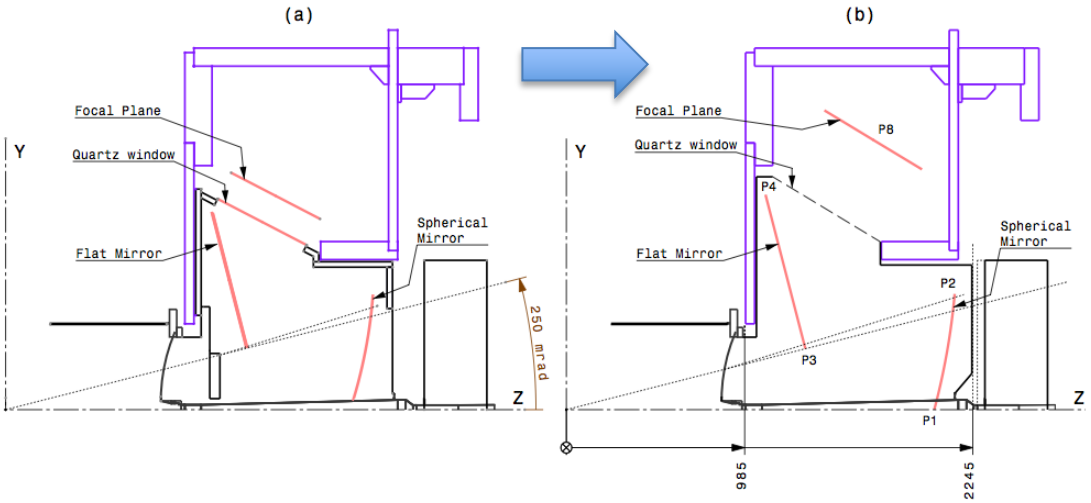
Importance of IP resolution

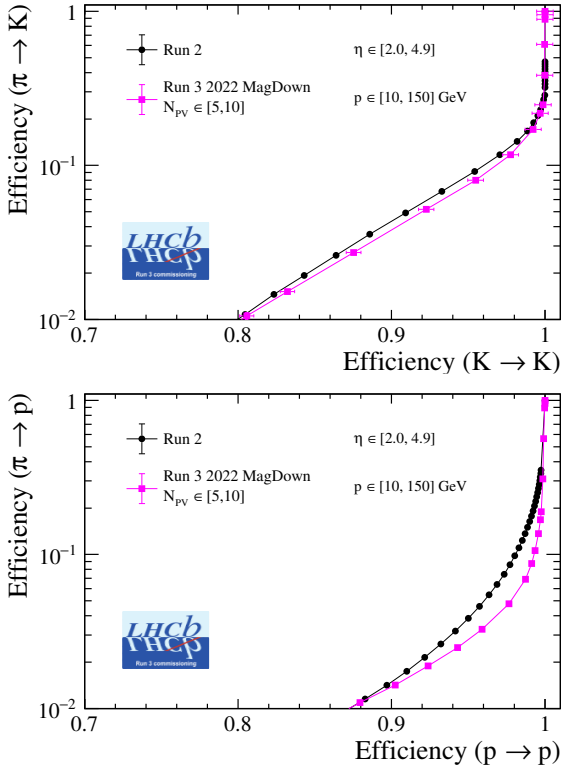


The upgraded RICH

- RICH-1, Aerogel removed; RoC of Spherical mirror increased
  - Cherenkov angle resolution improved
  - Radiator length increased => increased photon yields
- Performance in data
  - Note 2022 required to have higher pile-up
  - Alignment/calibration not-yet the best

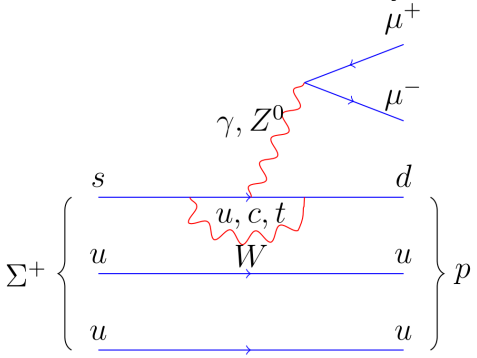
[LHCb-FIGURE-2023-019]

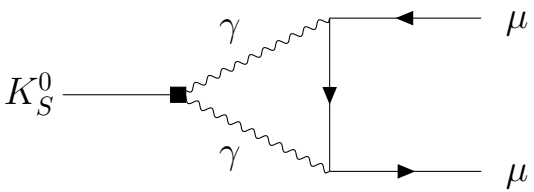


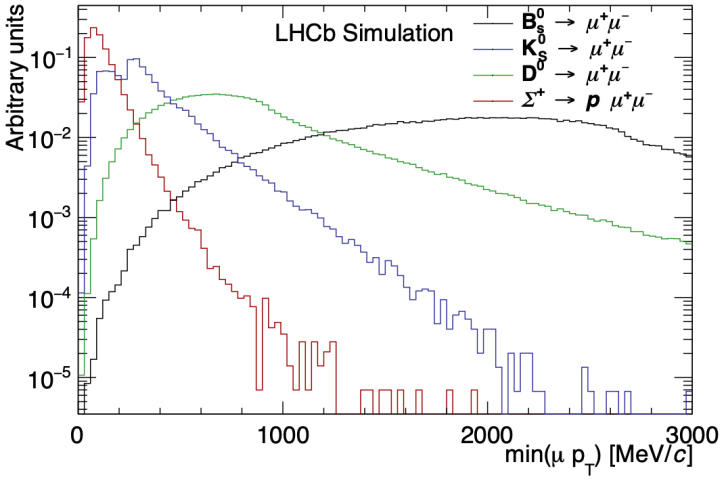


Rare strange decays

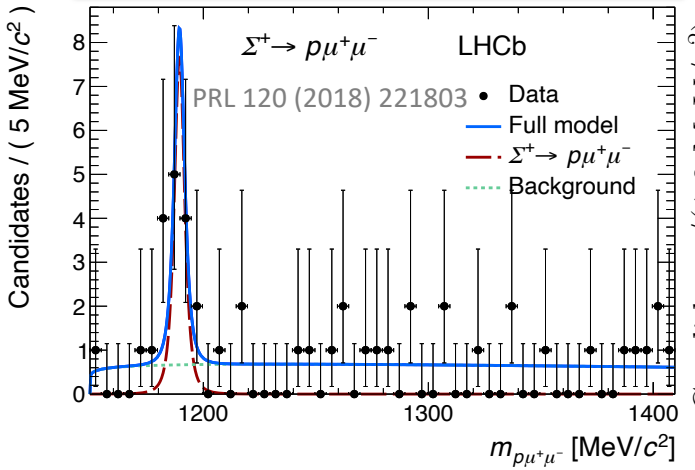
- $\Sigma^+ \to p\mu^+\mu^-, K_S^0 \to \mu^+\mu^-,$ muon soft, L0 was a bottleneck



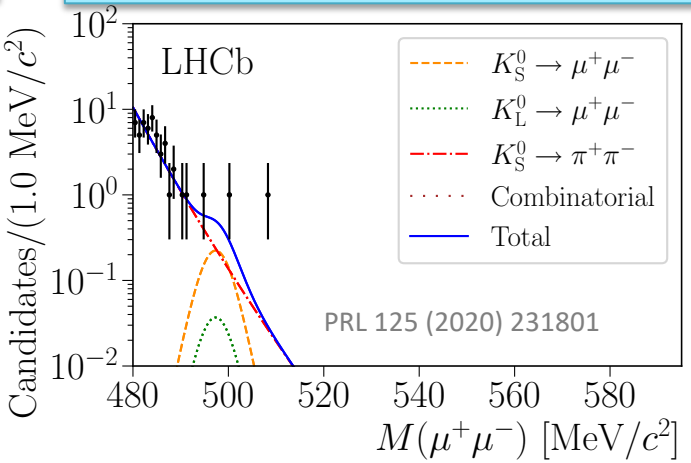


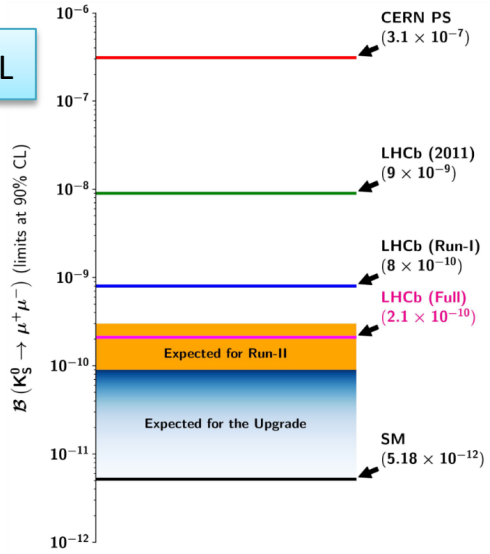


$\mathcal{B}(\Sigma^+ \to p\mu^+\mu^-) = (2.2^{+1.8}_{-1.3})\times10^{-10}$



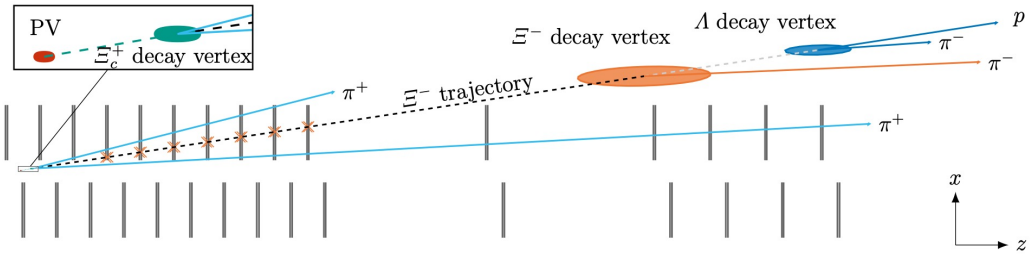
$\mathcal{B}(K_S^0 \to \mu^+\mu^-) < 2.1\times10^{-10}$ @ 90% CL

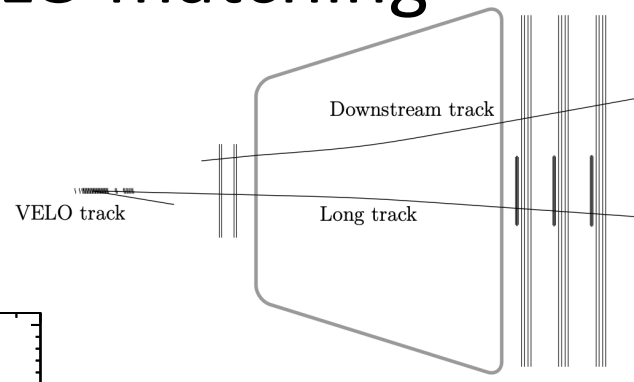


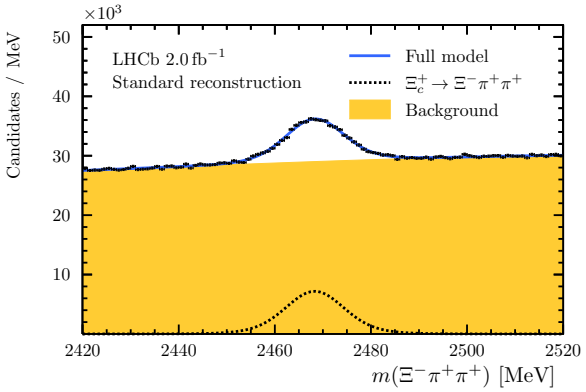


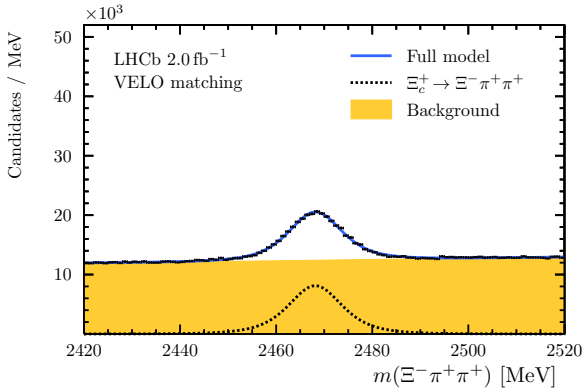
Particle with long lifetime, $\mathcal{O}$(ns)

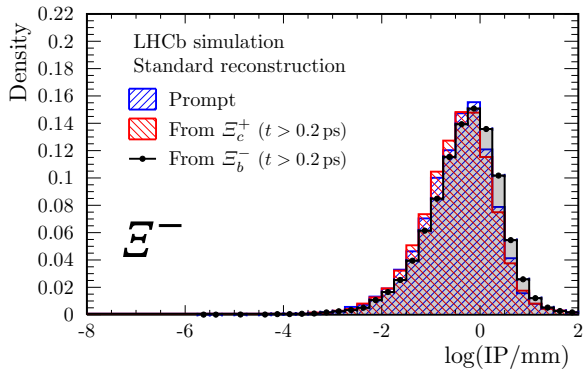
- Reconstruction improved w/ VELO matching

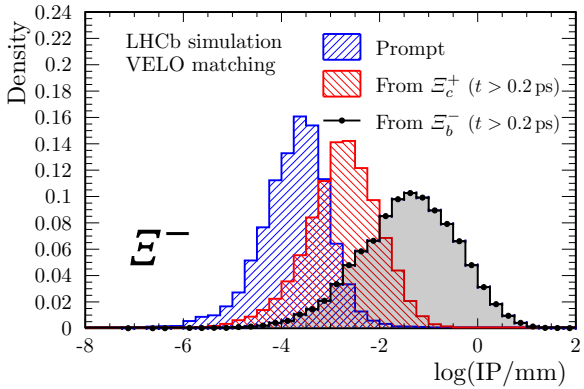












[arXiv:2403.09483]

ΔA_{CP} in charm

[PRL 122 (2019) 211803]

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

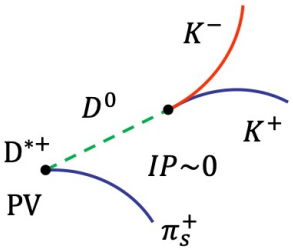
$$\Delta A_{CP} \equiv A_{CP}(K^-K^+) - A_{CP}(\pi^-\pi^+)$$

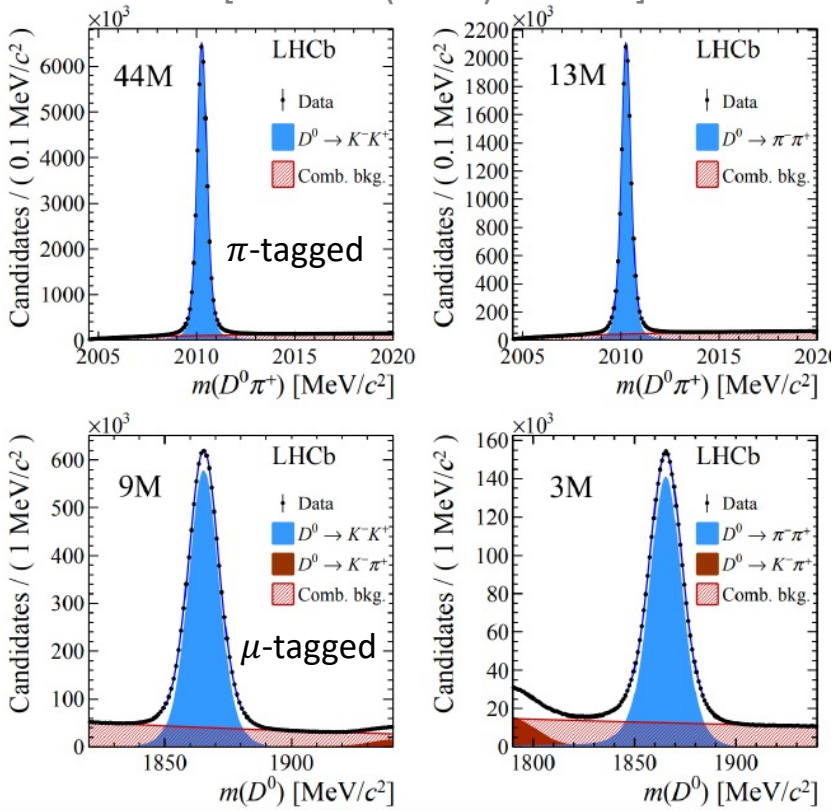
$$\Delta A_{CP}^{\pi\text{-tagged}} = [-18.2 \pm 3.2\,(\text{stat.}) \pm 0.9\,(\text{syst.})] \times 10^{-4},$$

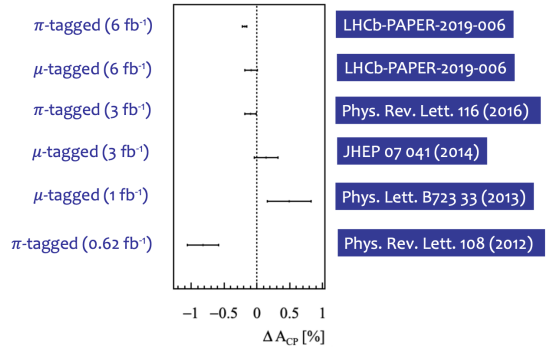
$$\Delta A_{CP}^{\mu\text{-tagged}} = [-9 \pm 8\,(\text{stat.}) \pm 5\,(\text{syst.})] \times 10^{-4}.$$

Combined one:

$$\Delta A_{CP} = (-15.4 \pm 2.9) \times 10^{-4}$$







1964
Strange particles: *CP* violation in K meson decays
J. W. Cronin, V. L. Fitch *et al.*

2001
Beauty particles: time-dependent *CP* violation in B^0 meson decays
BaBar and Belle collaborations

2013
Beauty-strange particles: time-integrated *CP* violation in B_s^0 meson decays
LHCb collaboration

2019
Charm particles: *CP* violation in D^0 meson decays
LHCb collaboration

Charm mixing

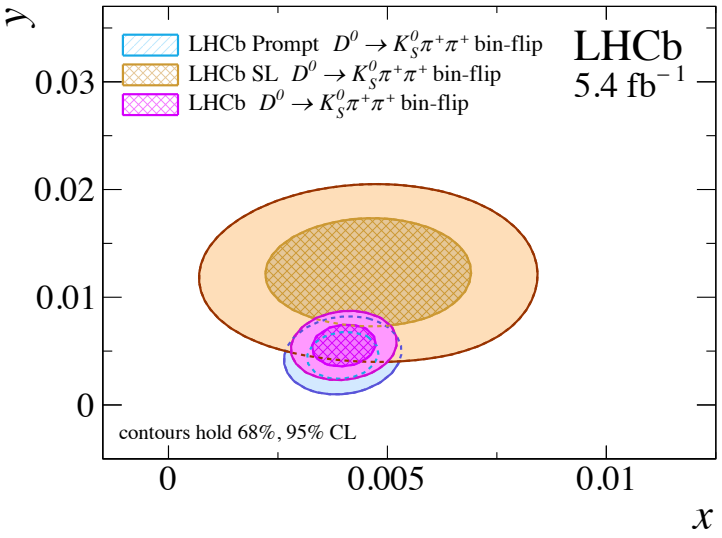
- Mass eigen., superpositions of flavour eigen.

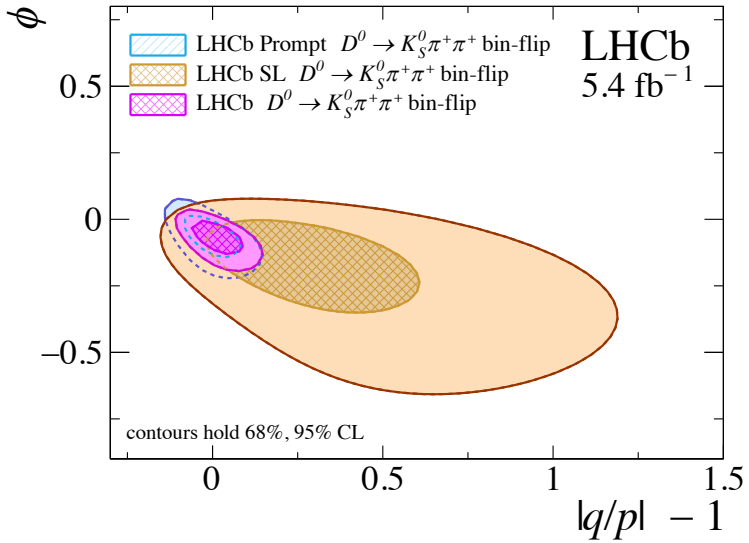
$$|D_{1,2}\rangle = p\,|D_0\rangle \pm q\,|\overline{D}_0\rangle$$

- Oscillations dynamics defined by

$$x = \frac{m_1 - m_2}{\Gamma}, y = \frac{\Gamma_1 - \Gamma_2}{2\Gamma}, \text{ where } \Gamma = \frac{\Gamma_1 + \Gamma_2}{2}$$

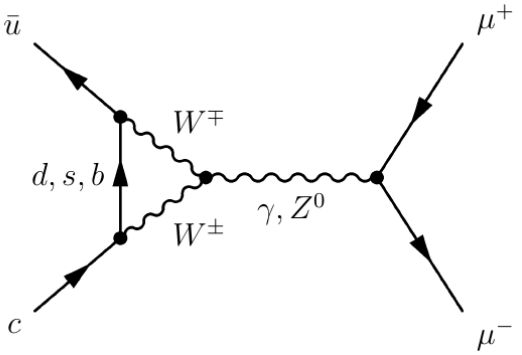
[PRD 108 (2023) 052005]

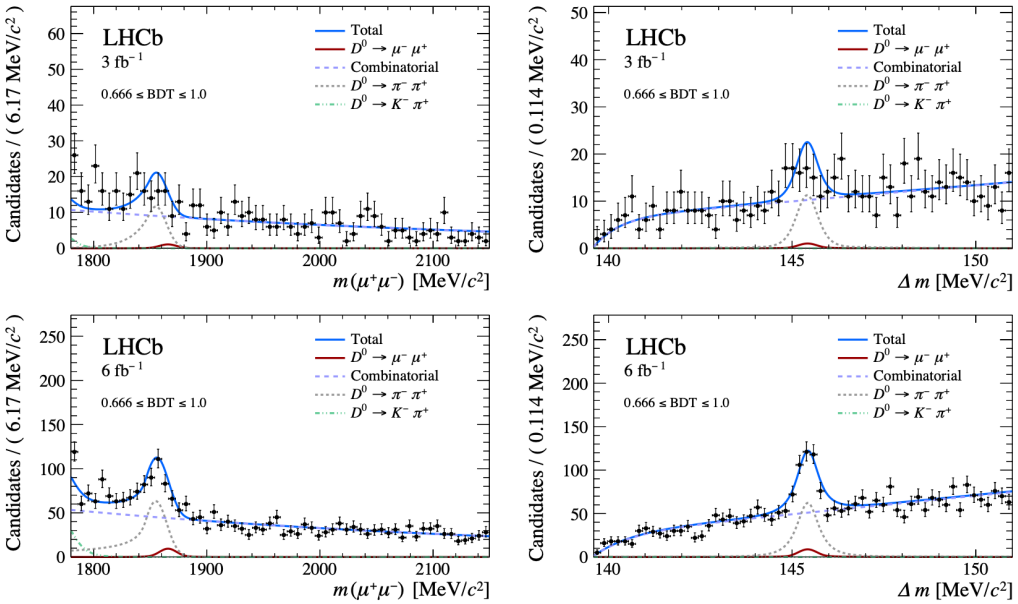


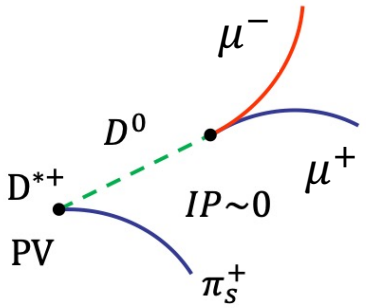


$D^0 \to \mu^+\mu^-$

- Very rare decay: FCNC+helicity suppression, contributions in SM
  - SD, $\mathcal{B}(D^0 \to \mu^+\mu^-) \sim 10^{-18}$
  - LD, $\mathcal{B}(D^0 \to \mu^+\mu^-) \sim 10^{-11}$





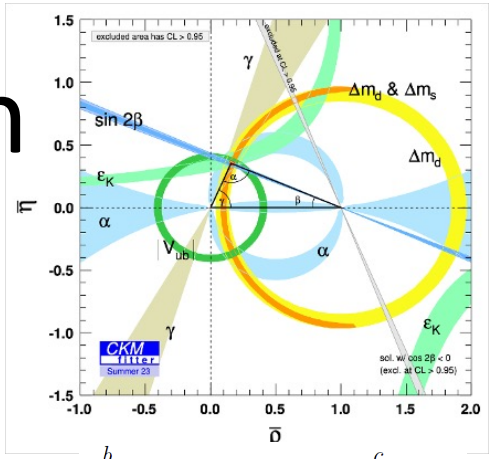


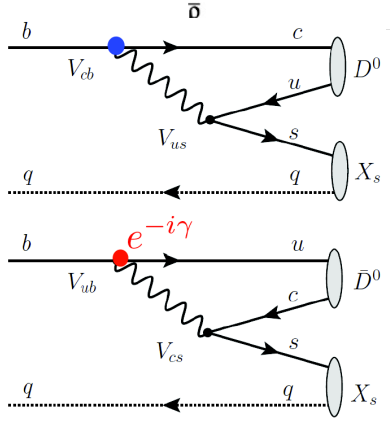
$\mathcal{B}(D^0 \to \mu^+\mu^-) < 3.1{\times}10^{-9}$ @ 90% CL

[PRL 131 (2023) 041804]

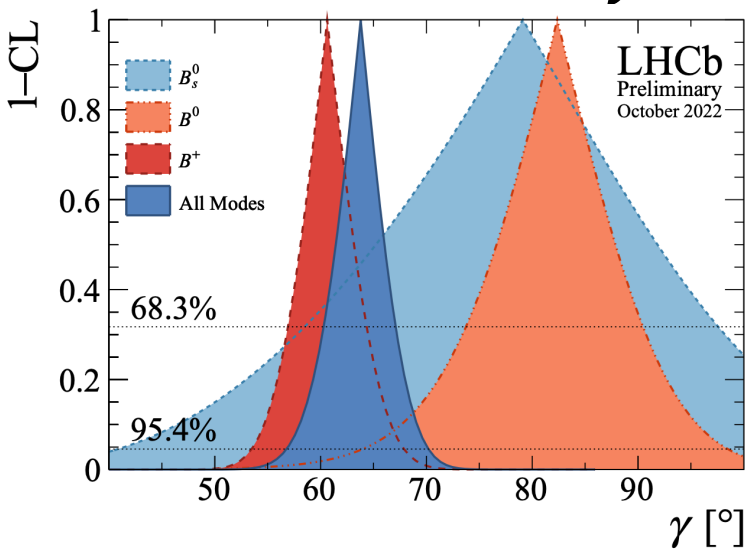
CKM-γ combination

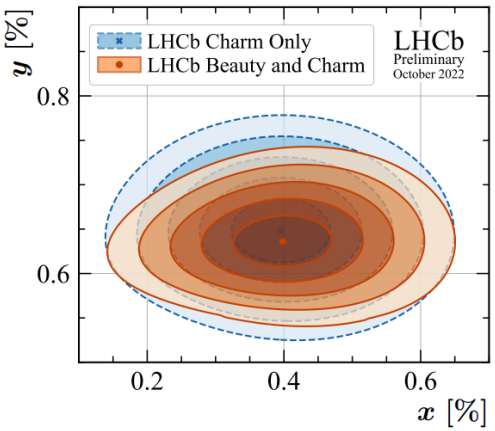
- Simultaneous determination of CKM-γ & charm mixing parameters
  - CKM $\gamma = \left(63.8^{+3.5}_{-3.7}\right)°$
  - Charm mixing $x = \left(0.398^{+0.050}_{-0.049}\right)\%$,
    $y = \left(0.636^{+0.020}_{-0.019}\right)\%$

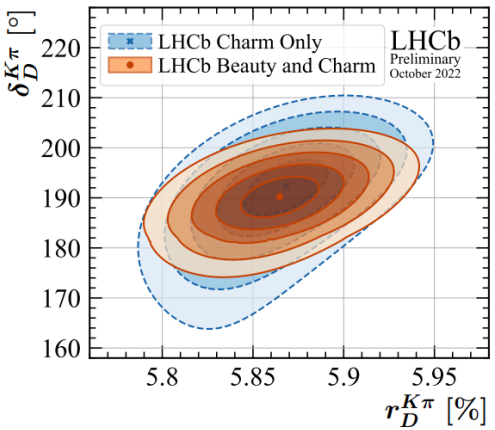




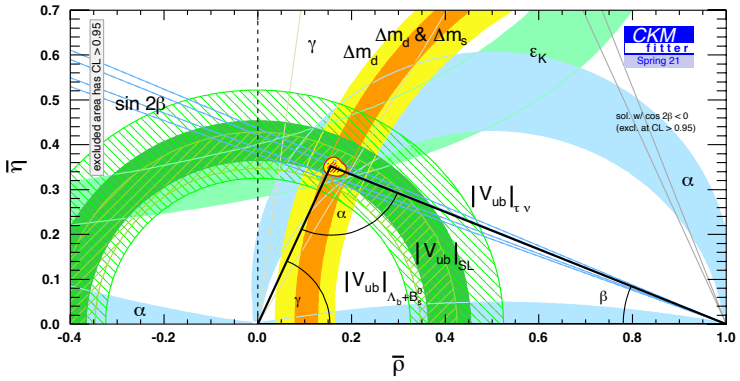
[LHCb-Conf-2022-003]



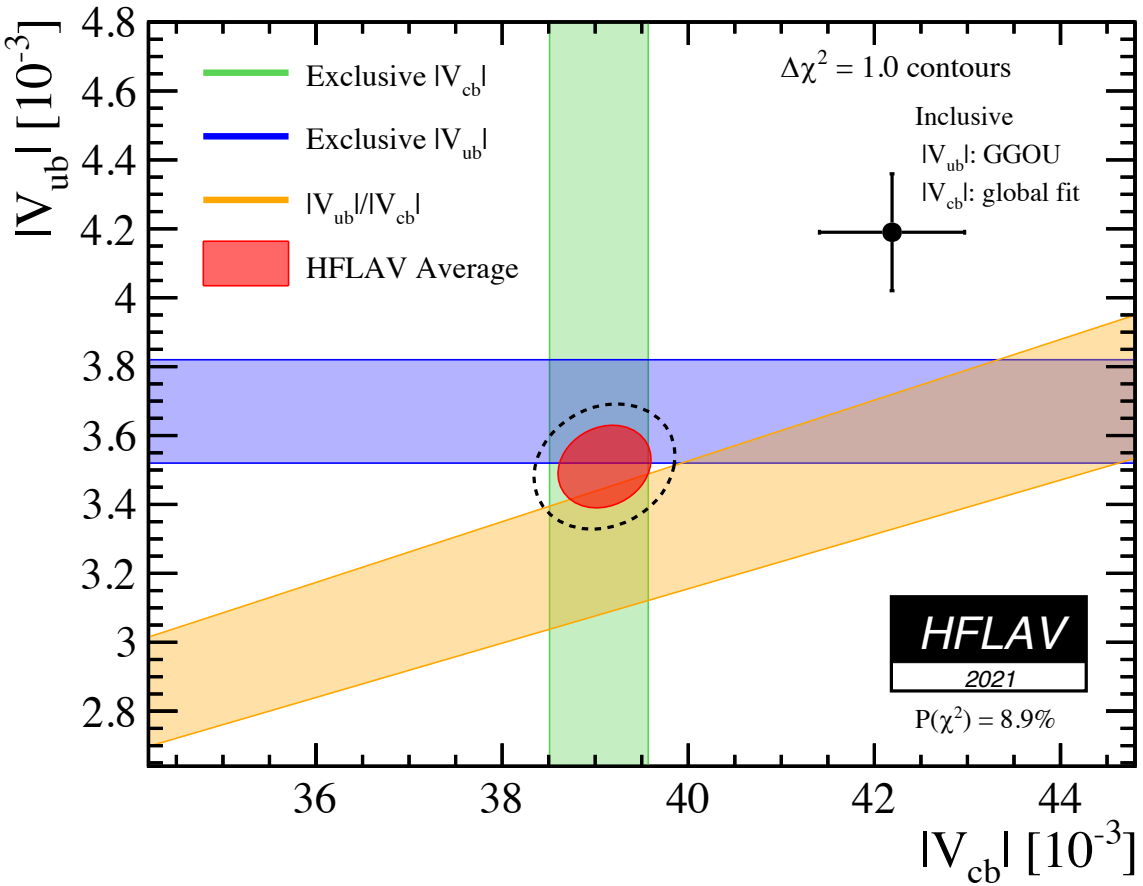


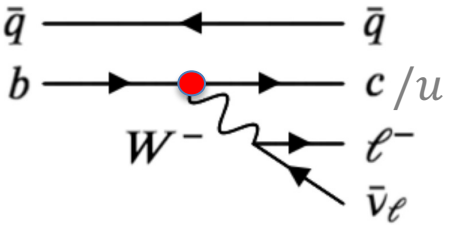


V_{cb}, V_{ub}



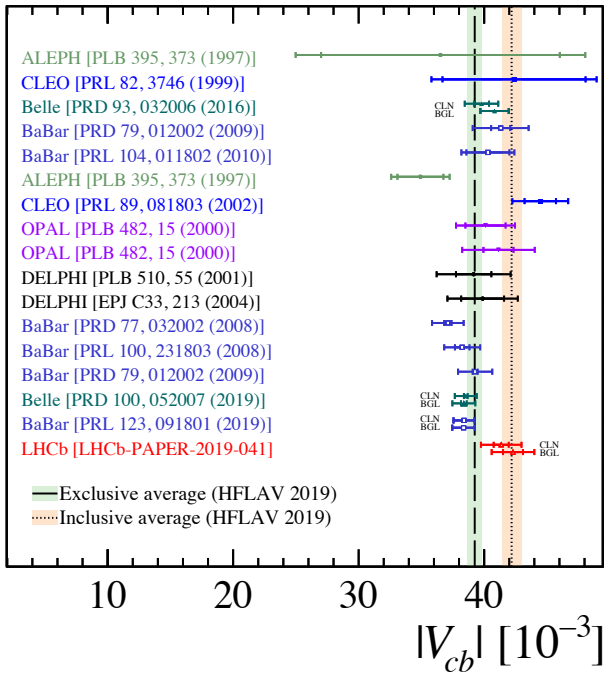
- Some tension between exclusive/inclusive



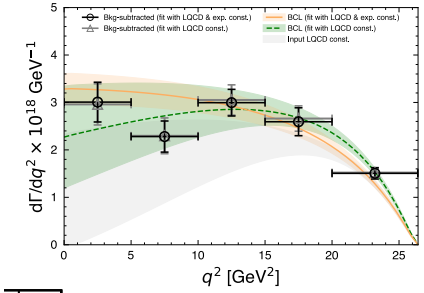


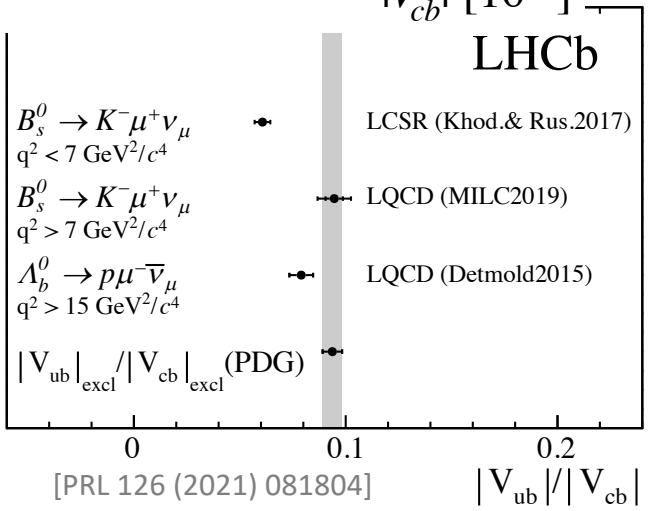
$$d\Gamma \propto |V_{cb}|^2 |f_H|^2$$

V_{cb}, V_{ub}



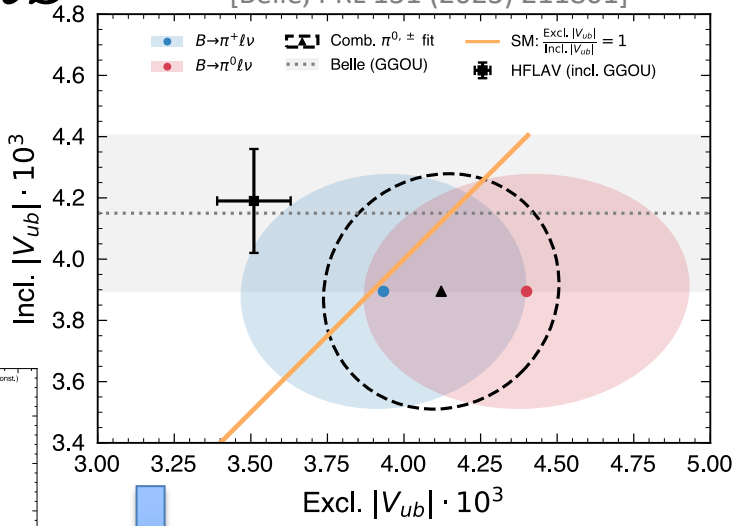
[PRD 101 (2020) 072004]





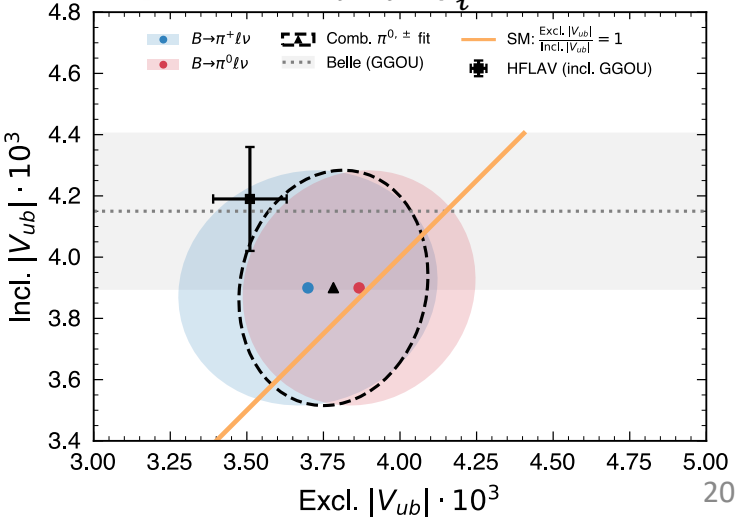
[PRL 126 (2021) 081804]

[Belle, PRL 131 (2023) 211801]



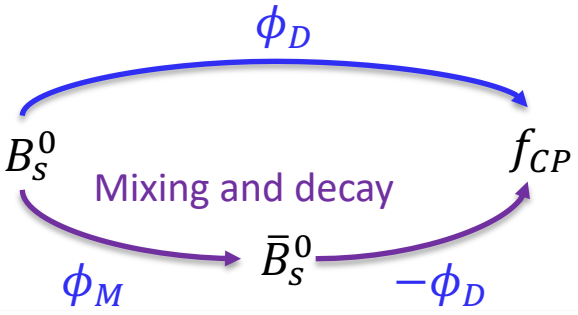
+

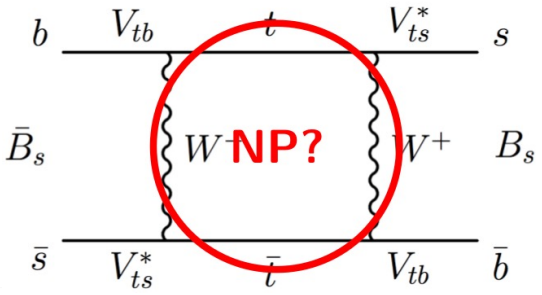
w/ exp constraint for
$\bar{B}^0 \to \pi^+\ell^-\bar{\nu}_\ell$ FF



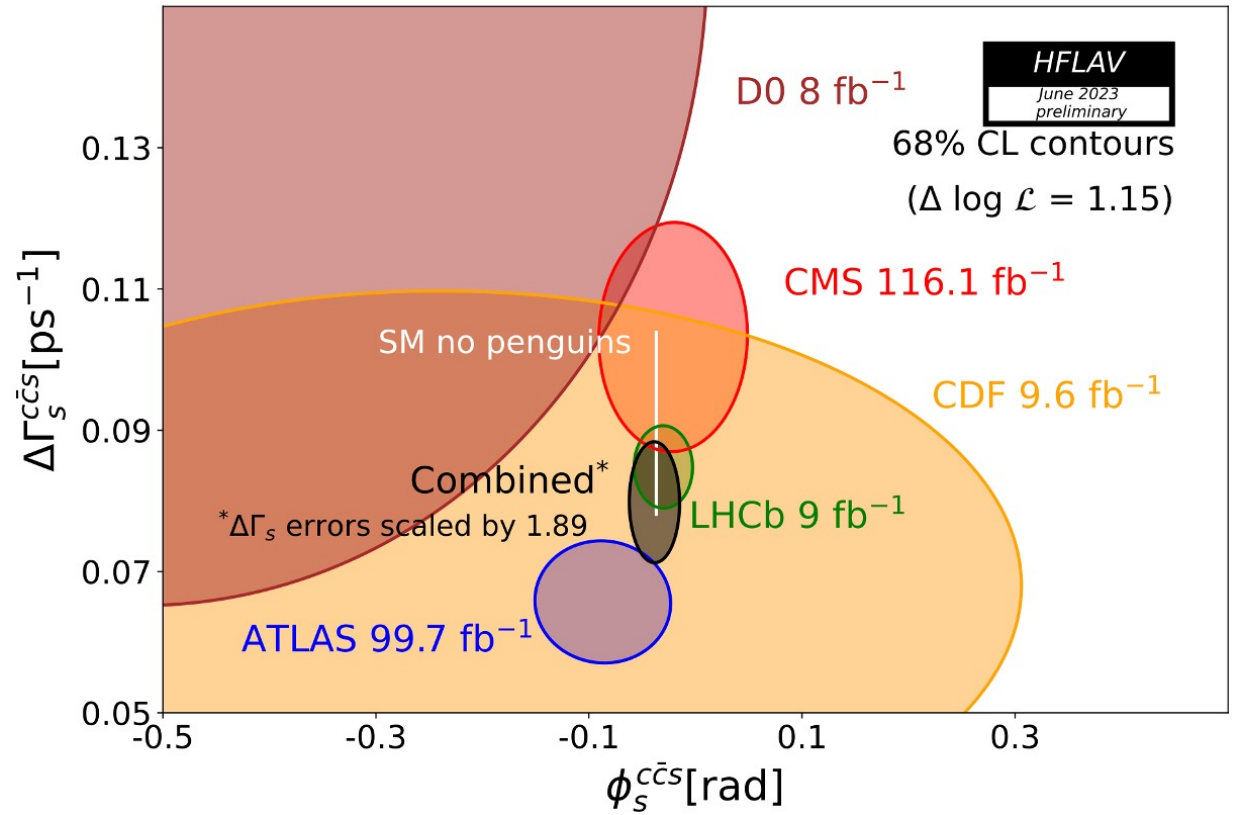
CPV in mixing

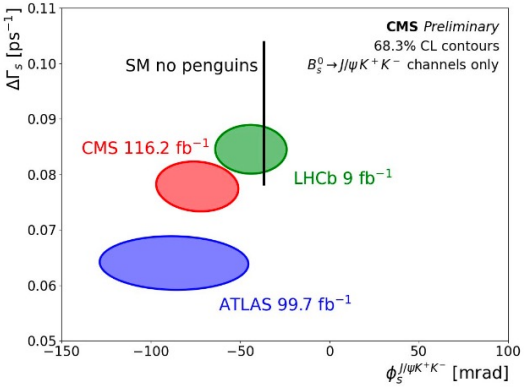
- $\phi_s = \phi_M - 2\phi_D$, small in SM
- $B_s^0 \to J/\psi h^+ h^-$





[PRL 132 (2024) 051802]

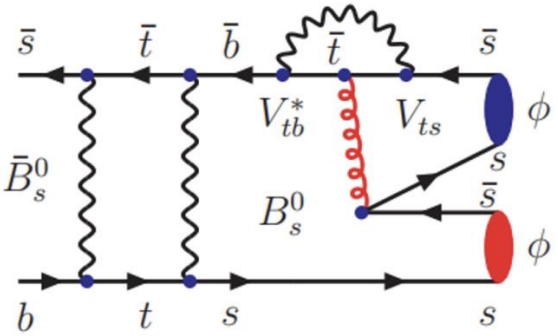




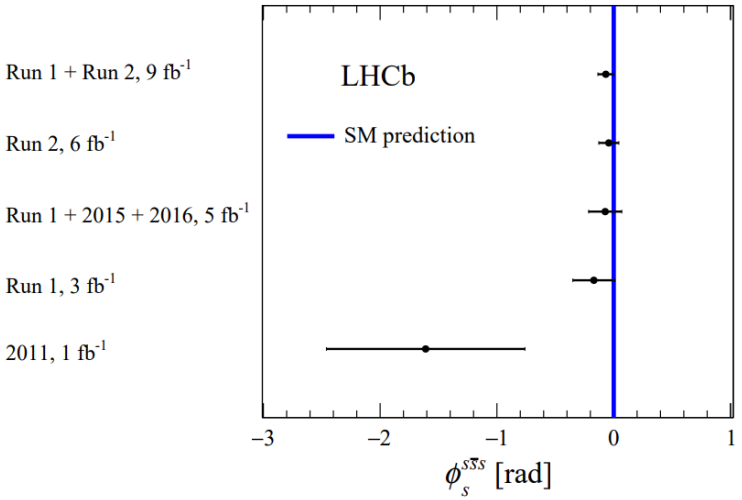
Flavour tagging?

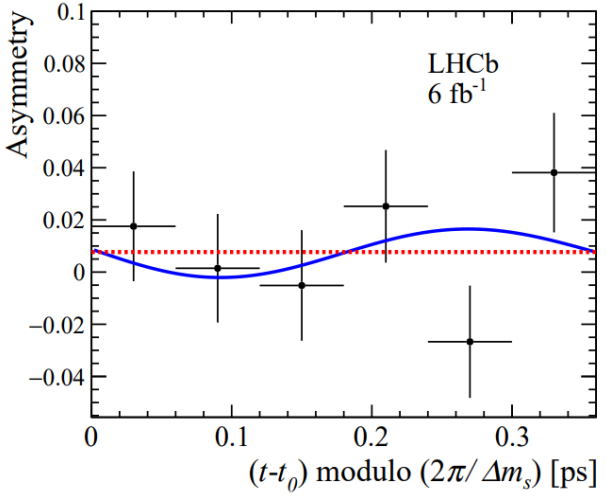
CPV in $B_s^0 \to \phi\phi$

- Probe NP in mixing & penguin
- Tiny CPV expected in SM:
  $\phi_s^{s\bar{s}s} = 0.00 \pm 0.02$ rad
- New LHCb results: $\phi_s^{s\bar{s}s} = -0.074 \pm 0.069$ rad,
  No sign of CPV & results consistent with SM



[PRL 131 (2023) 171802]

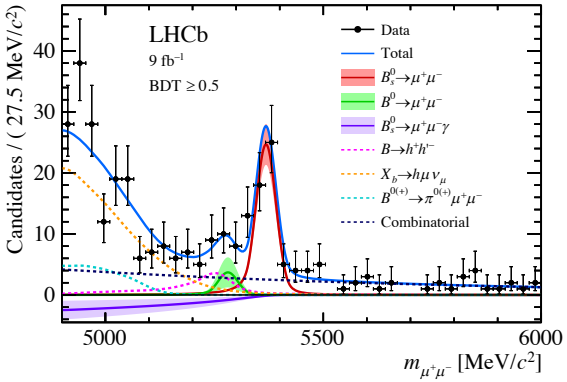


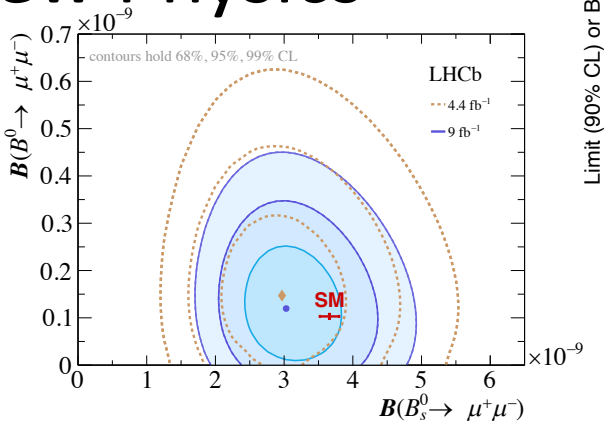


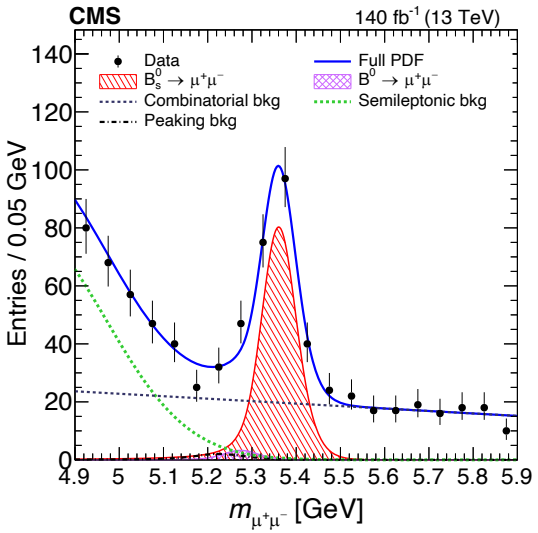
$B^0_{(s)} \to \mu^+\mu^-$

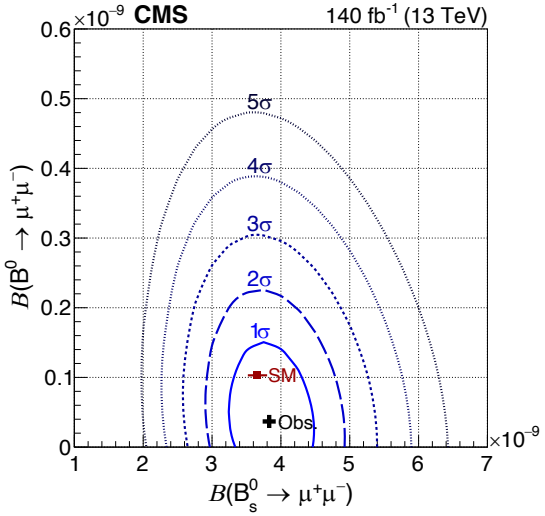
- Suppressed in SM, could be enhanced by New Physics

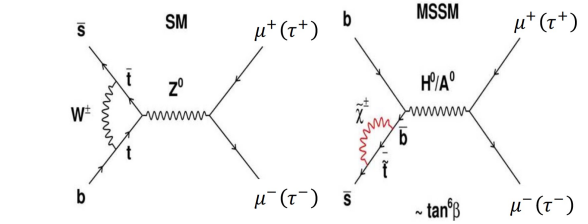
[PRL 128 (2022) 041801]

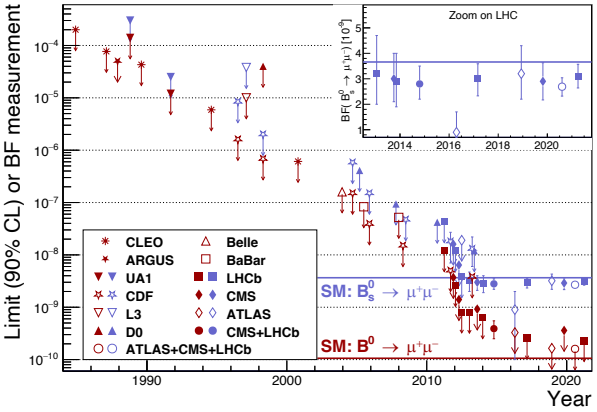


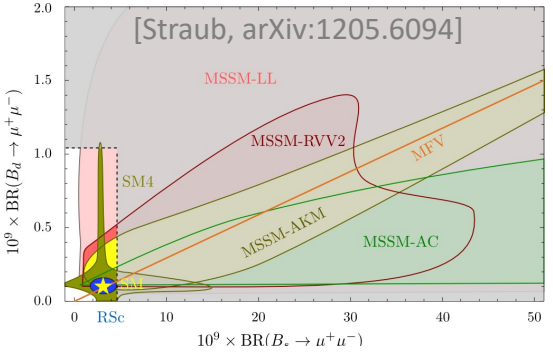


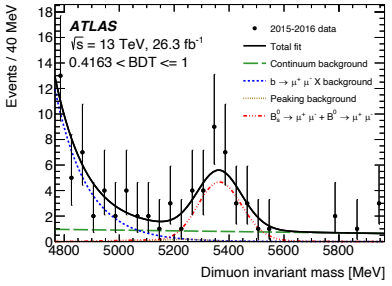












$B_s^0 \to \mu^+\mu^-$ eff. τ

- B_s^0 mixing ⇒ effective τ

$$\tau_{\mu^+\mu^-} = \frac{\tau_{B_s}}{1-y_s^2}\left[\frac{1+2A_{\Delta\Gamma}^{\mu^+\mu^-}y_s+y_s^2}{1+A_{\Delta\Gamma}^{\mu^+\mu^-}y_s}\right]$$

$$A_{\Delta\Gamma}^{\mu^+\mu^-} \equiv \frac{R_H^{\mu^+\mu^-}-R_L^{\mu^+\mu^-}}{R_H^{\mu^+\mu^-}+R_L^{\mu^+\mu^-}} \qquad A_{\Delta\Gamma}=1 \text{ in SM}$$

$$y_s = \frac{\Delta\Gamma_s}{2\Gamma_s}$$

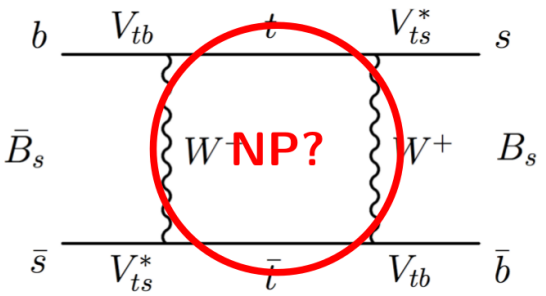
- Measured by LHCb, CMS, ALTAS, not-yet sensitive to $A_{\Delta\Gamma}$

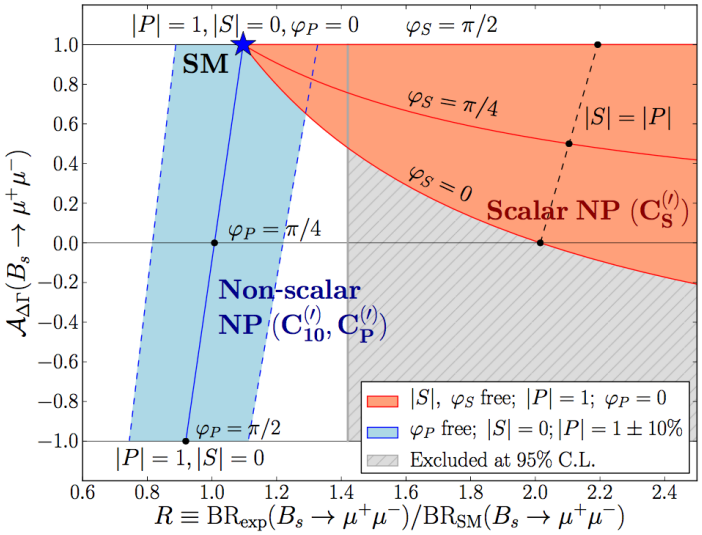
$\tau_{\mu\mu} = 2.07 \pm 0.29 \pm 0.03$ ps

$1.83^{+0.23}_{-0.20} \pm 0.04$ ps [CMS, PLB 842 (2023) 137955]

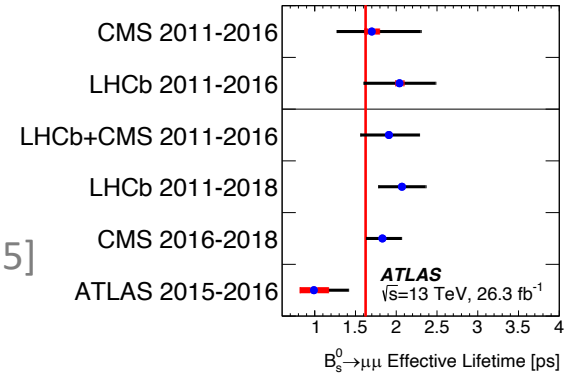
$0.99^{+0.42}_{-0.07} \pm 0.17$ ps [ATLAS, JHEP 09 (2023) 199]

[PRL 128 (2022) 041801]



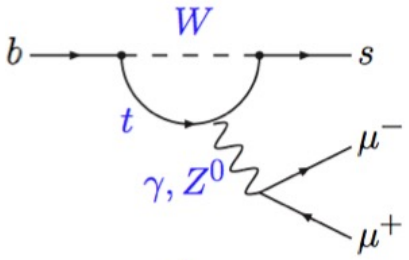


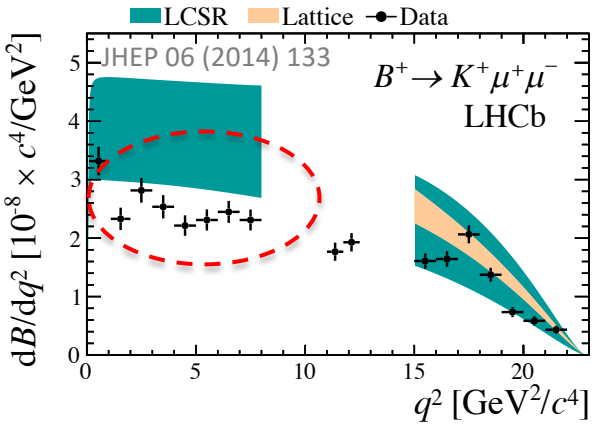
[De Bruyn *et al.*, PRL 109 (2012) 041801]

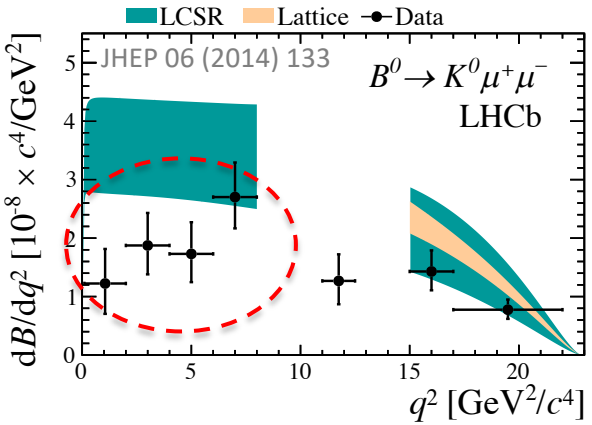


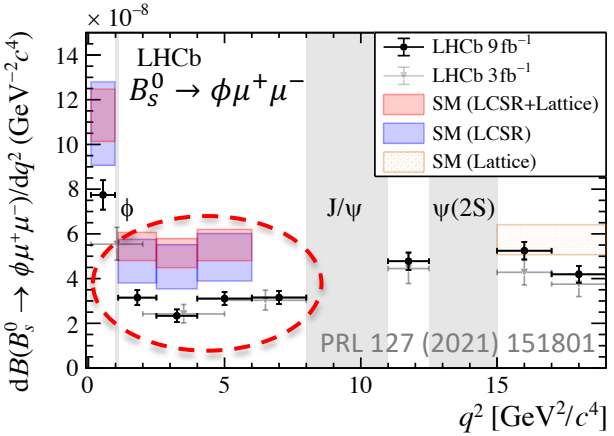
Branching fraction of $b \to s\mu^+\mu^-$

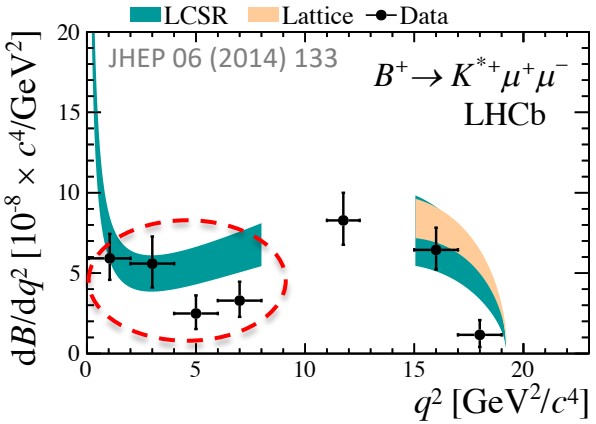
- Pattern of tensions seen, theoretical uncertainty?

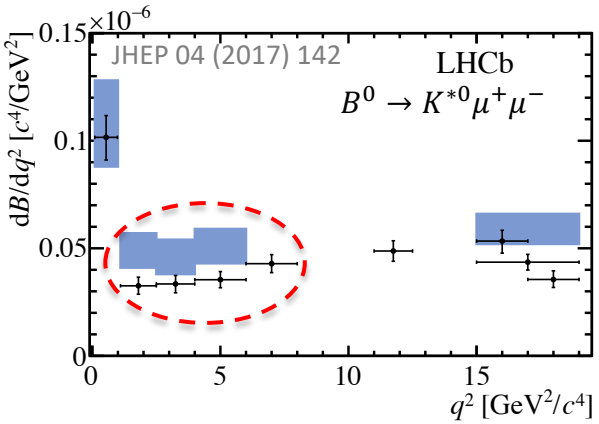


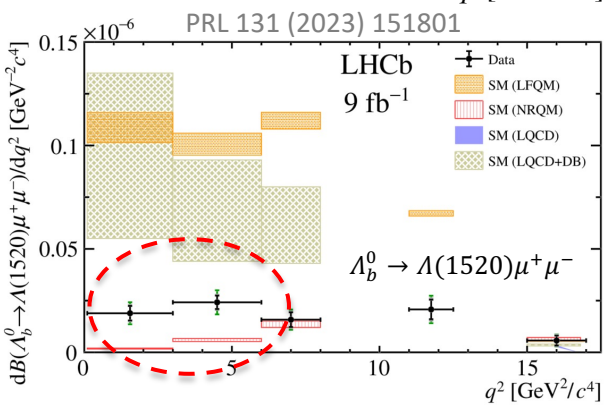












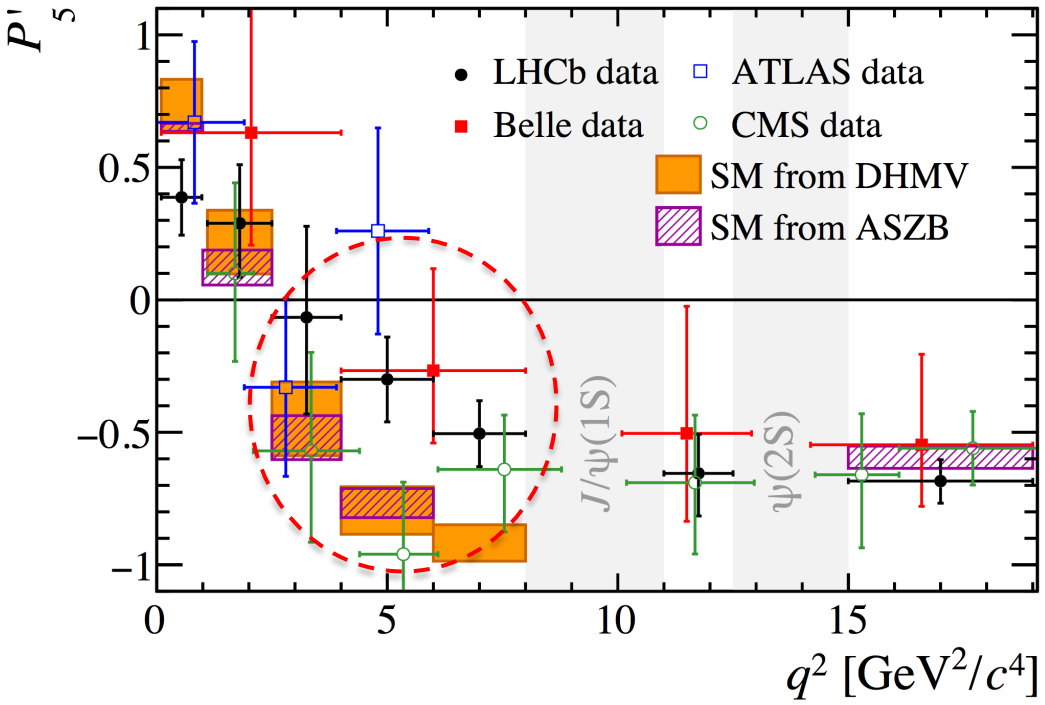
P_5' with $B^0 \to K^{*0}\mu^+\mu^-$

- $P_5' = \frac{S_5}{\sqrt{F_L(1-F_L)}}$, less form-factor dependent

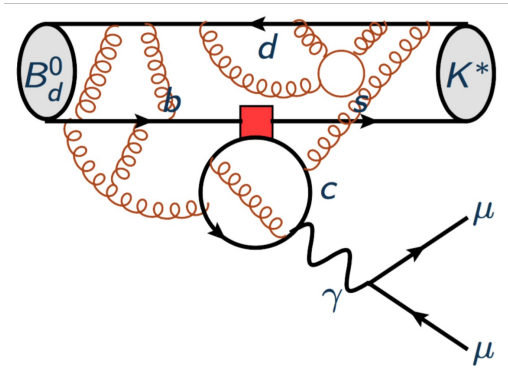
[S. Descotes-Genon, *et al.*, JHEP 01 (2013) 048]

- Also measured by Belle, ATLAS, CMS

[PRL 125 (2020) 011802]



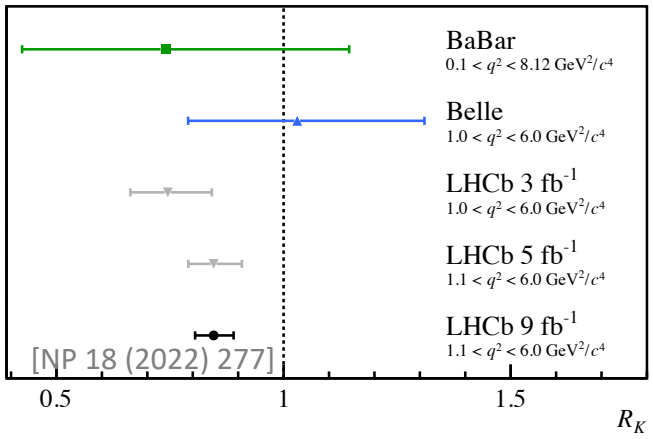
[Belle, PRL 118 (2017) 111801]
[ATLAS, JHEP 10 (2018) 047]
[CMS, PLB 781 (2018) 517]

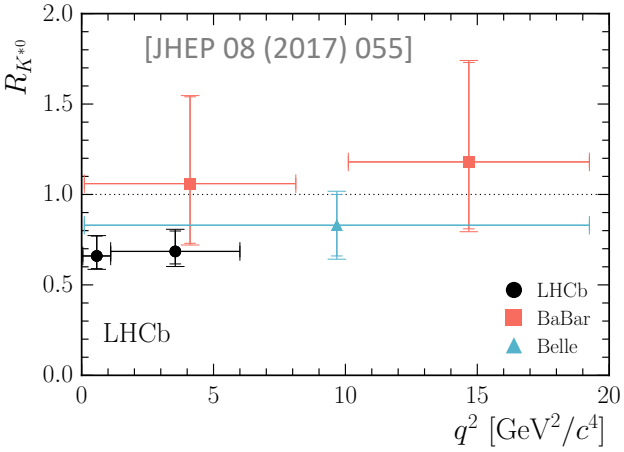


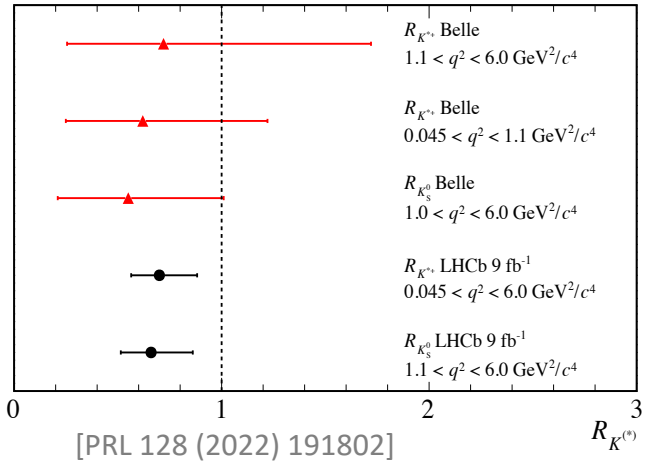
LFU in $b \to s\ell^+\ell^-$ decays

before Dec 2022

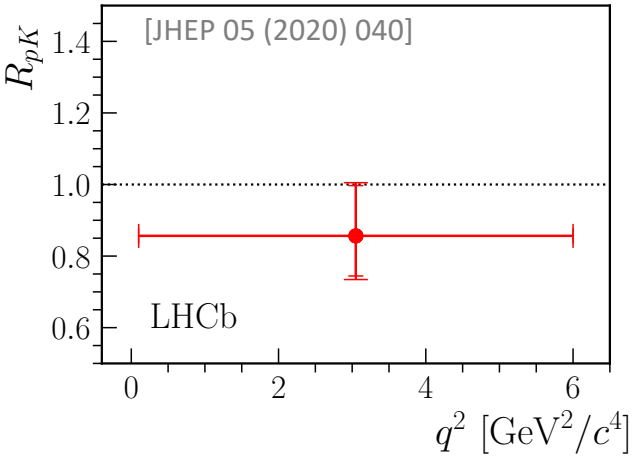
- Deviations from SM seen by LHCb

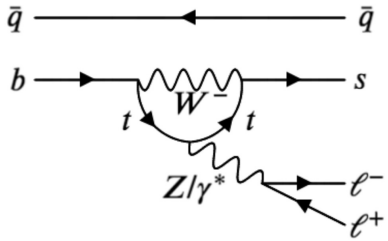




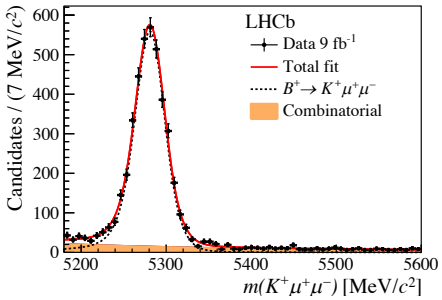


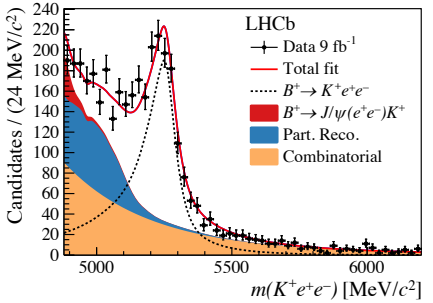
[PRL 128 (2022) 191802]





$$R_X = \frac{\mathcal{B}(H_b \to X\mu^+\mu^-)}{\mathcal{B}(H_b \to Xe^+e^-)}$$

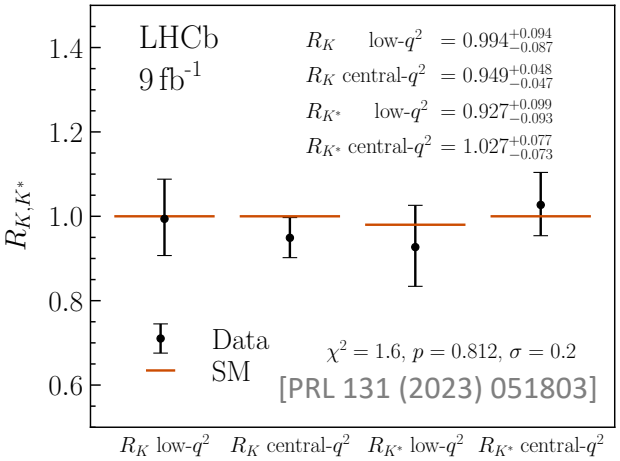




LFU in $b \to s\ell^+\ell^-$ decays

after Dec 2022

- Deviations mostly gone



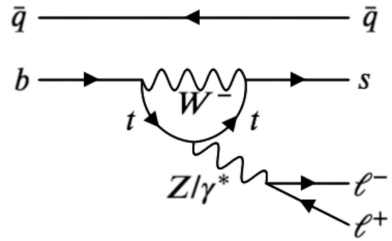
[PRL 131 (2023) 051803]

Precision at 5-10%

$\mathcal{O}(1\%)$ LFUV still possible

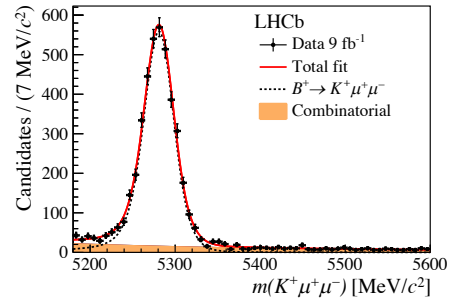
路漫漫其修远兮，吾将上下而求索

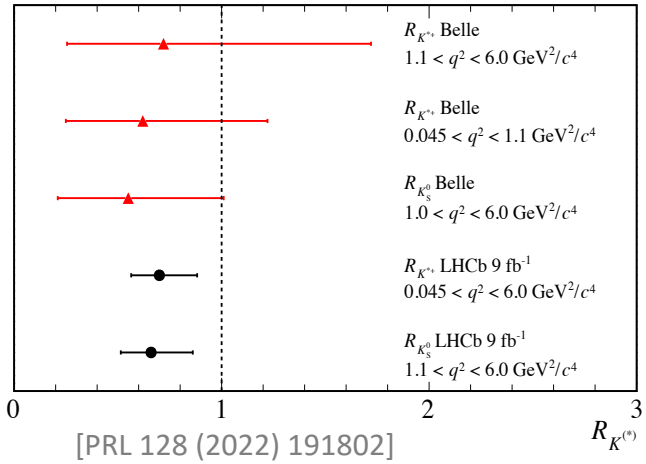
The road ahead will be long and our climb will be steep



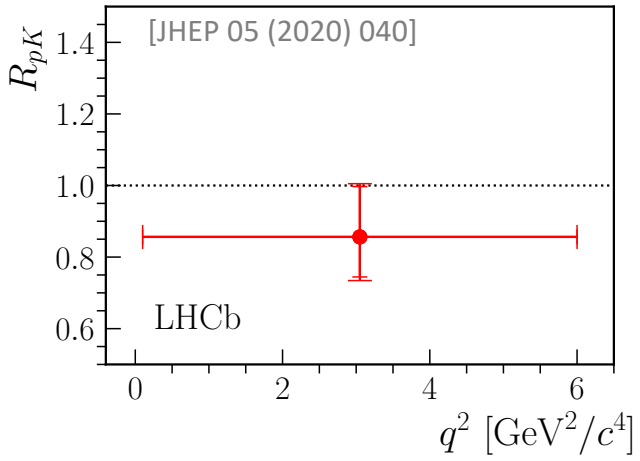
$$R_X = \frac{\mathcal{B}(H_b \to X\mu^+\mu^-)}{\mathcal{B}(H_b \to Xe^+e^-)}$$

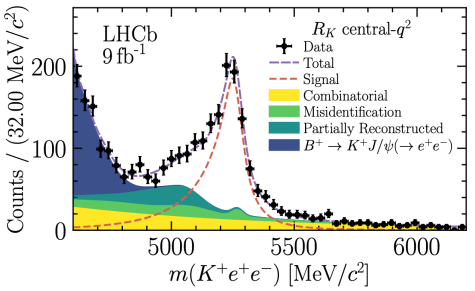
$R_K = 0.78^{+0.46\,+0.09}_{-0.23\,-0.05}$ [CMS, BPH-22-005-PAS]





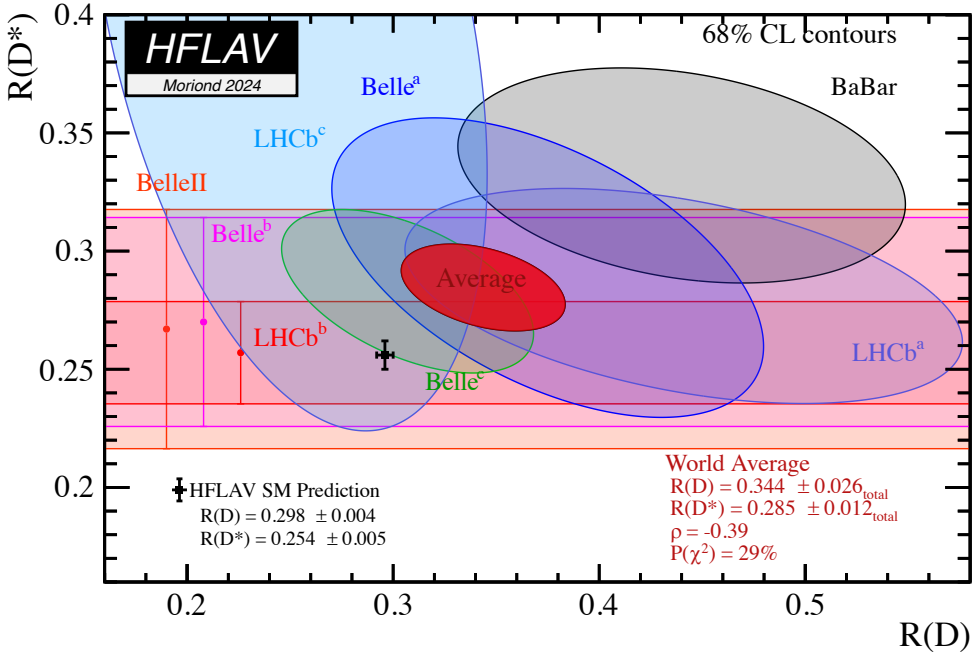
[PRL 128 (2022) 191802]

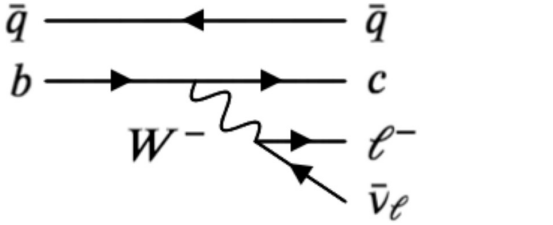




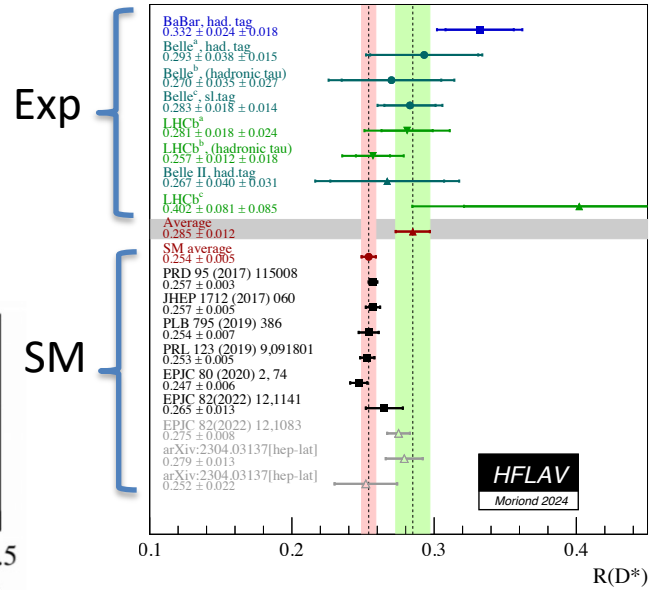
LFU in $b \to c\ell\nu$ decays

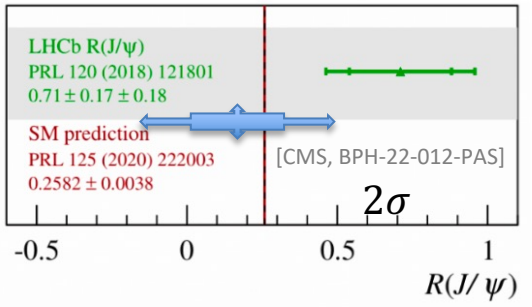
- Deviations from SM seen by Babar/Belle/LHCb

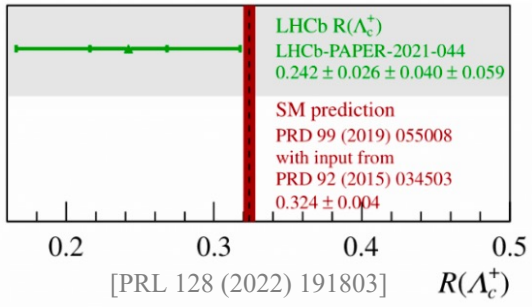




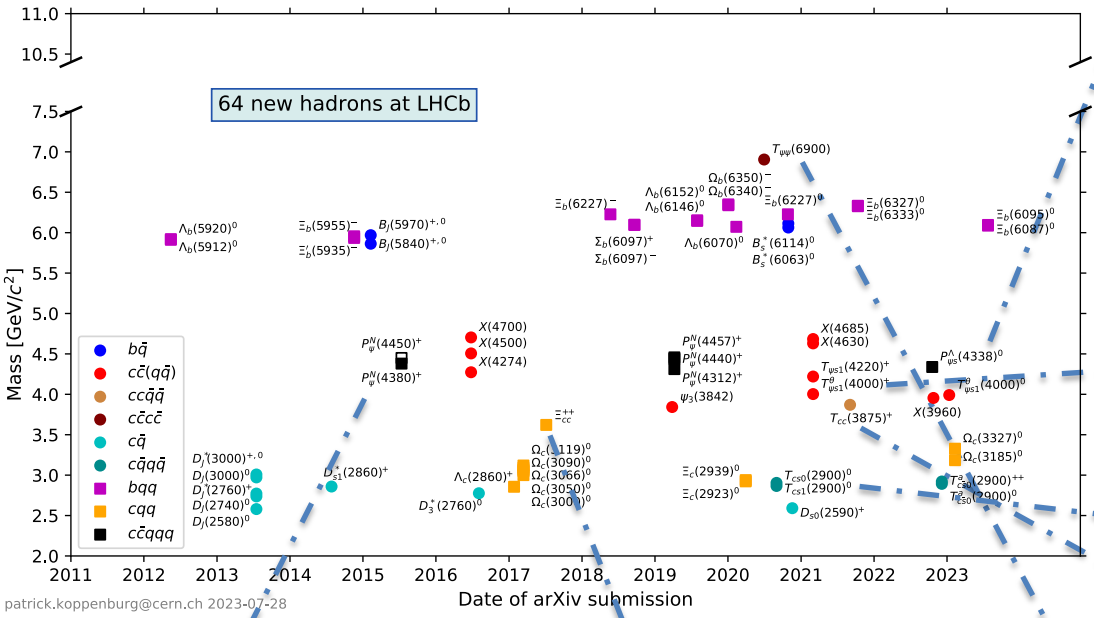
$$R(H_c) = \frac{\mathcal{B}(H_b \to H_c \tau^- \bar{\nu}_\tau)}{\mathcal{B}(H_b \to H_c \mu^- \bar{\nu}_\mu)}$$

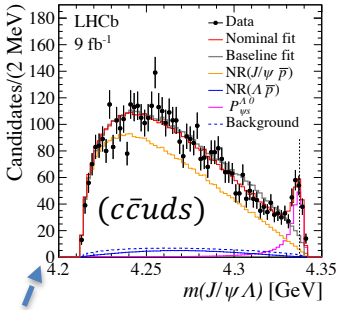


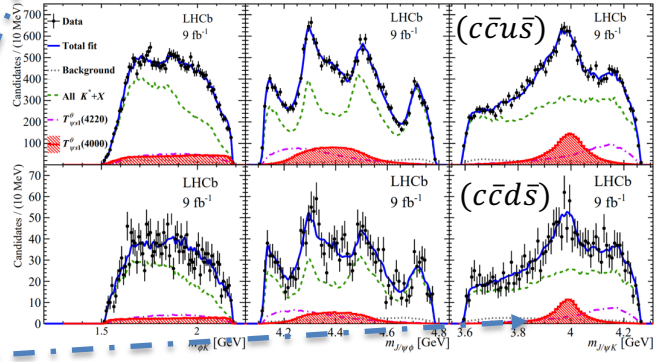


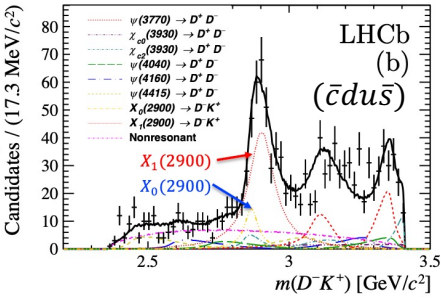


Spectroscopy at LHCb

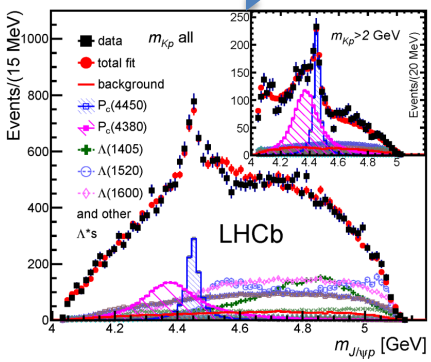








(cc̄uud)



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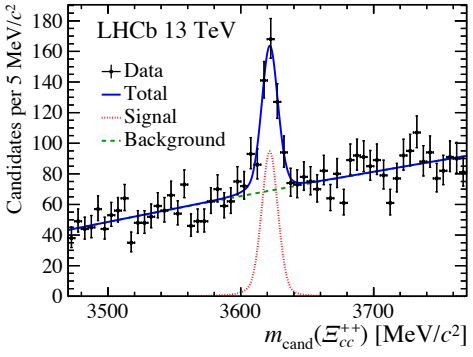

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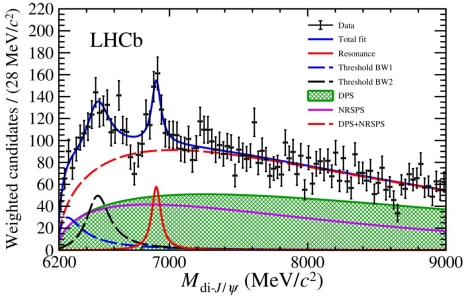
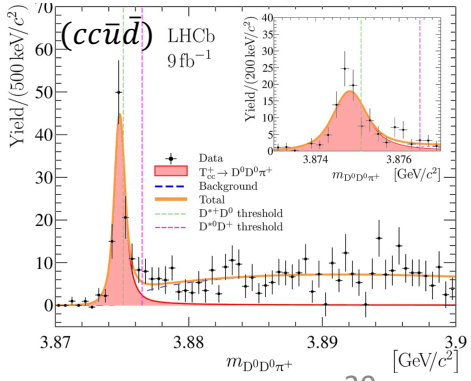
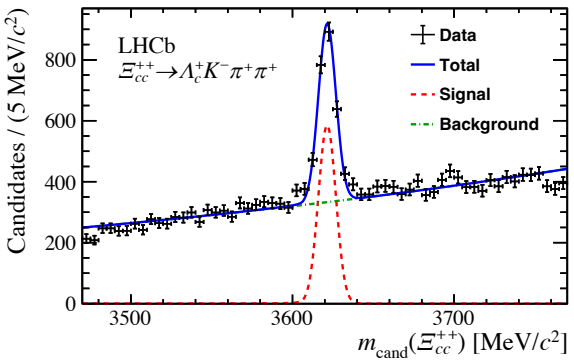
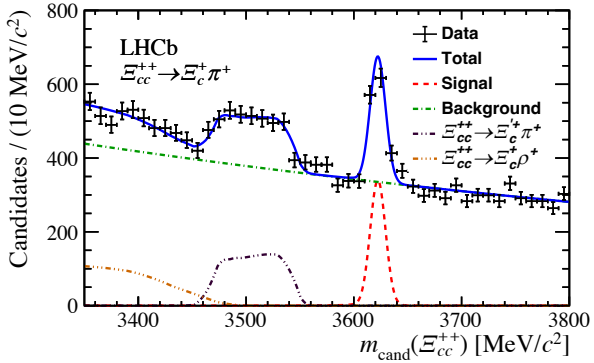




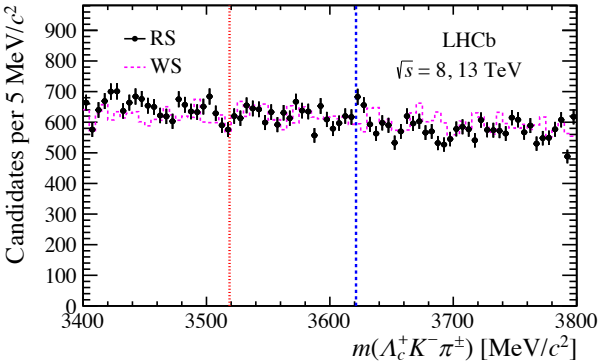
Experimental status of DHB

$\Xi_{cc}^{++}(ccu)$





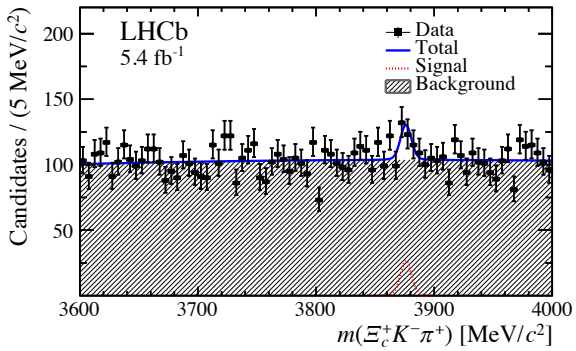
$\Xi_{cc}^{+}(ccd)$



PRL 119 (2017) 112001, PRL 121 (2018) 052002, PRL 121 (2018) 162002, CPC 44 (2020) 022001, JHEP 02 (2020) 049, JHEP 05 (2022) 038

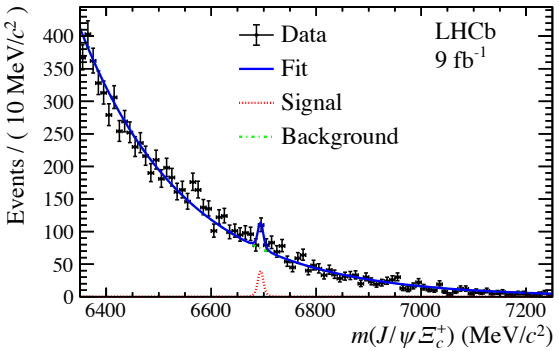
SCPMA 63 (2020) 221062

$\Omega_{cc}^{+}(ccs)$



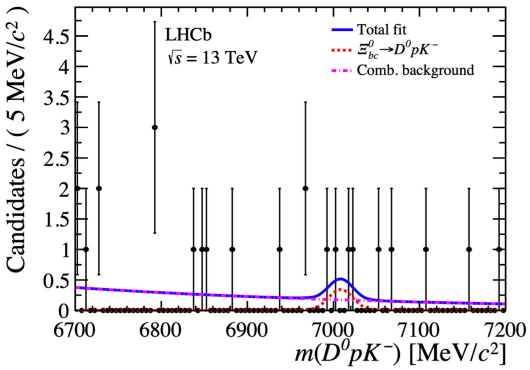
SCPMA 64 (2021) 101062

$\Xi_{bc}^{+}(bcu)$



CPC 47 (2023) 093001

$\Xi_{bc}^{0}(bcd)$



JHEP 11 (2020) 095

Intrinsic charm?

- Bound to valence quarks, longer time scales
- *Z* associated with charm

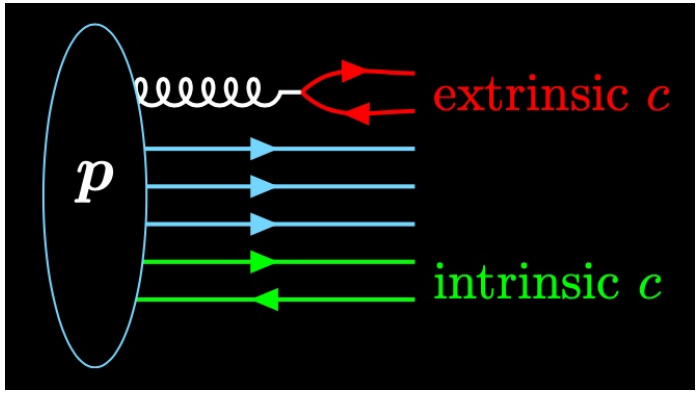
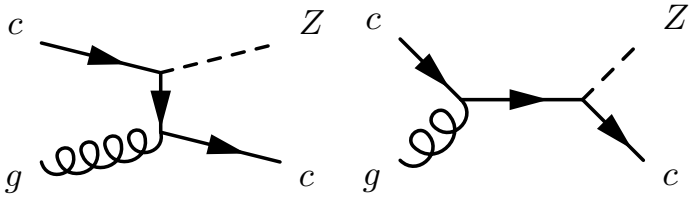
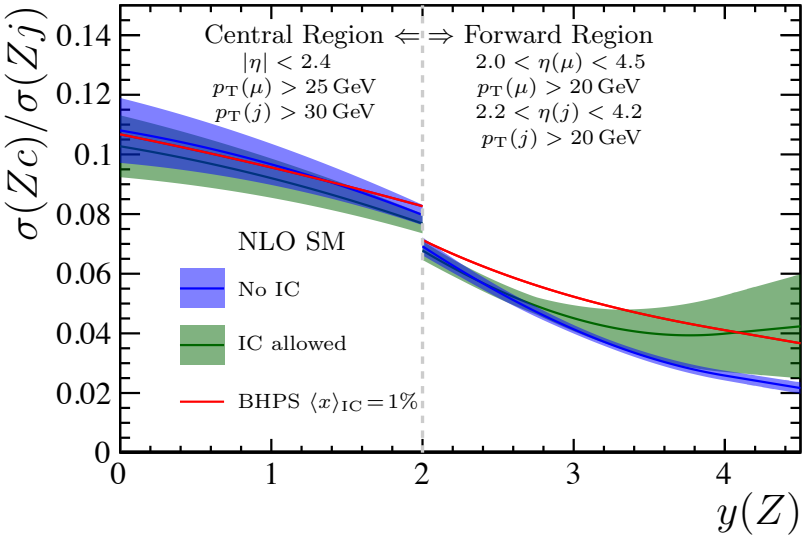
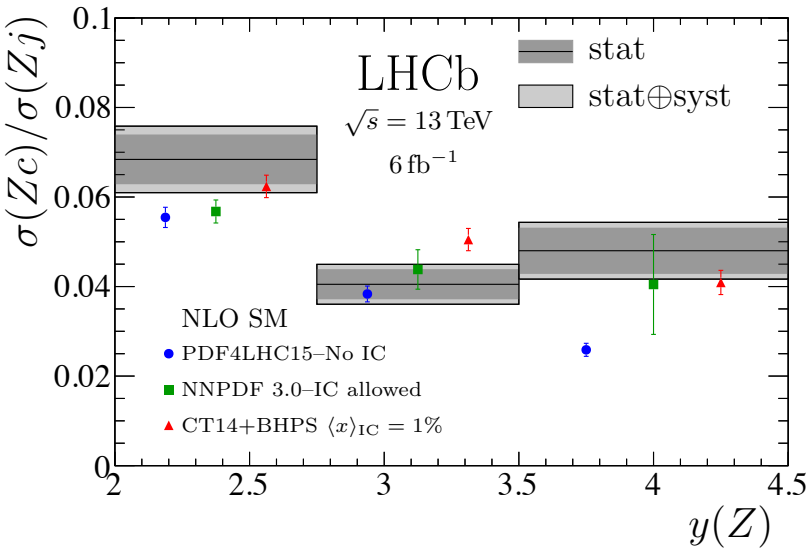


Image: D. Craik

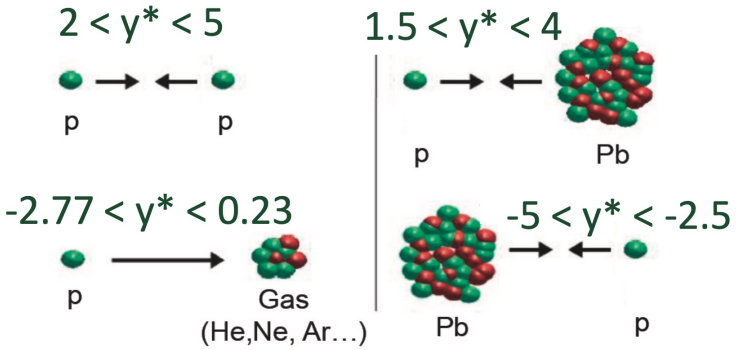


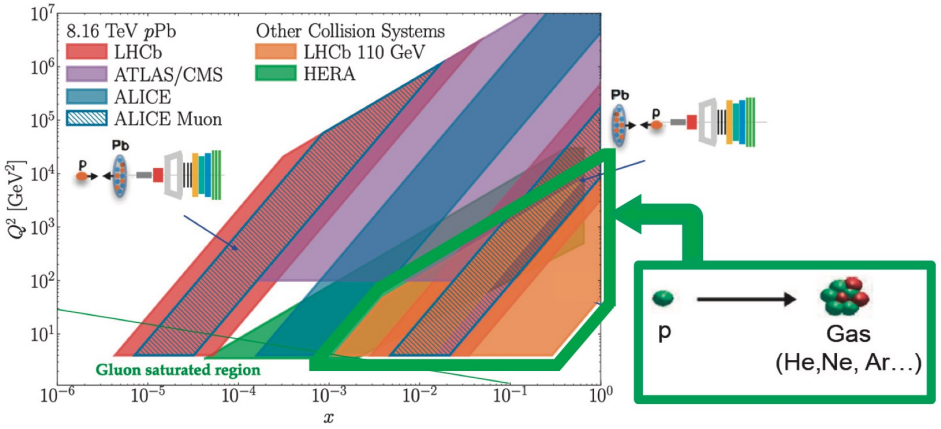




[PRL 128 (2022) 082001]

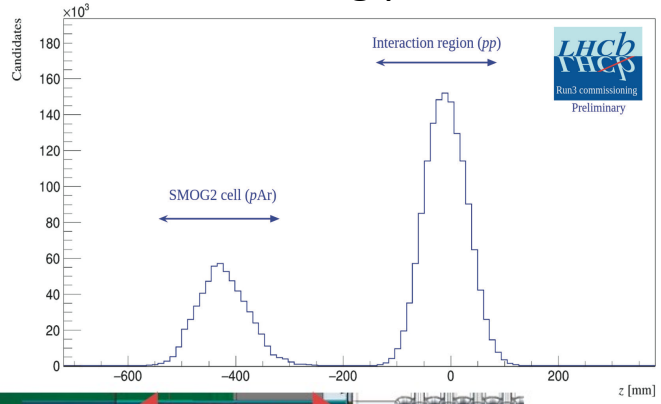
SMOG (System for Measuring Overlap with Gas)

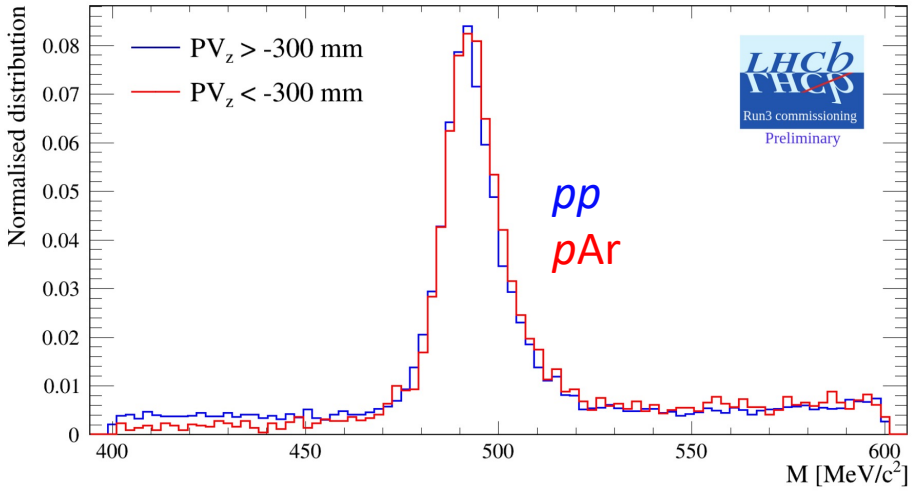


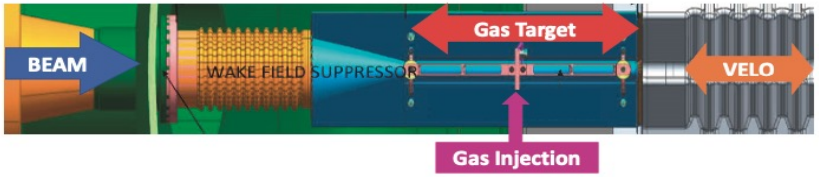


[LHCb-Figure-2023-008]

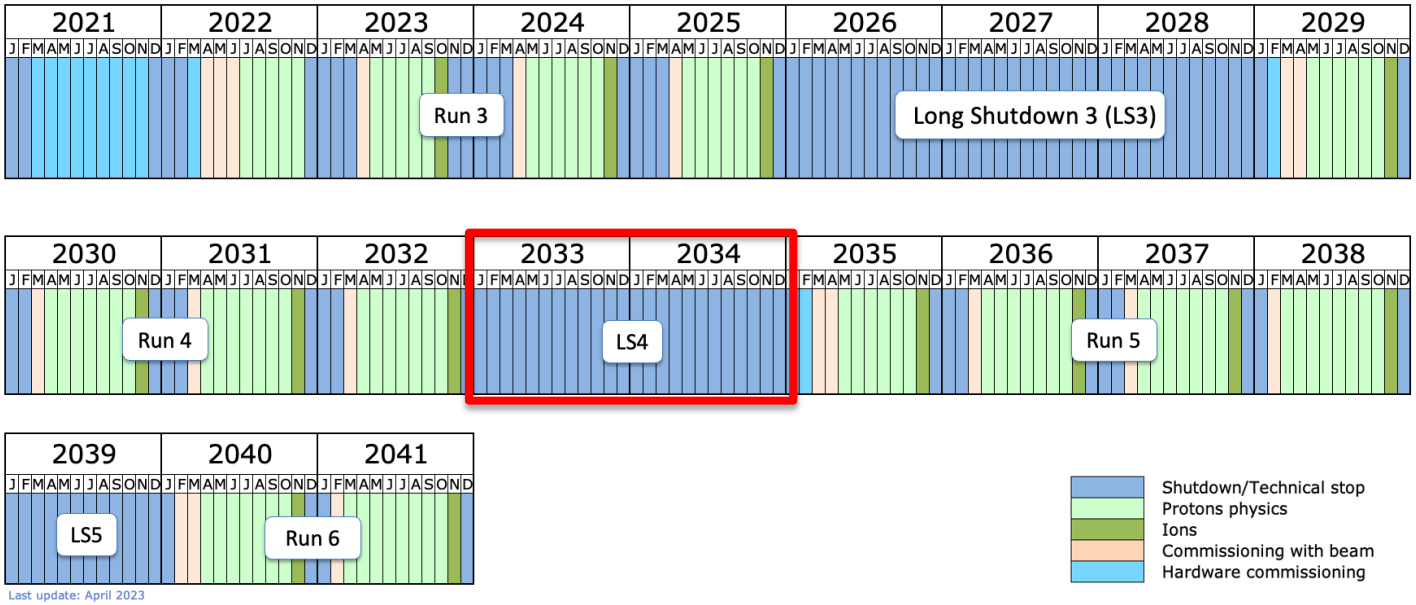
Simultaneous data-taking possible



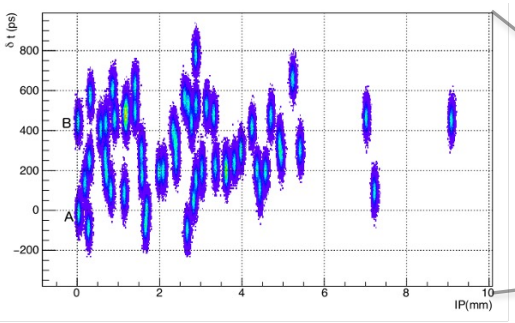


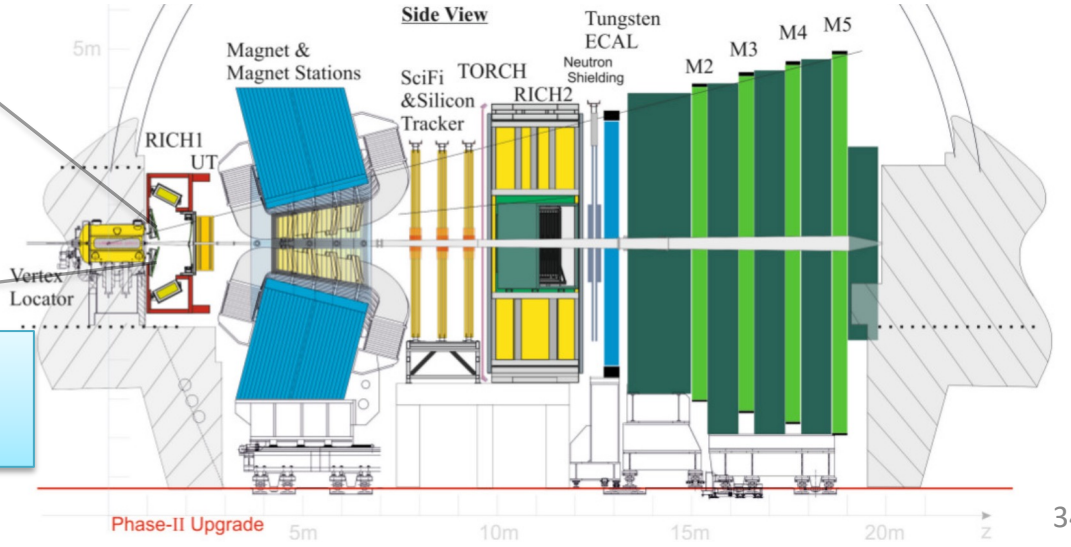


The LHCb upgrade II



[CERN-LHCC-2018-027, 2021-012]





Upgrade II, 4D detector
Timing, $\mathcal{O}(10\ \text{ps})$, is essential

Prospects

- LHCb upgrades
  (2025: 23 fb^{-1}, Upgrade-II: 300 fb^{-1})

[CERN-LHCC-2018-027, 2021-012]

Observable	Current LHCb	LHCb 2025	Belle II	Upgrade II	ATLAS & CMS
EW Penguins					
R_K $(1 < q^2 < 6\,\mathrm{GeV}^2c^4)$	0.1 [274]	0.025	0.036	0.007	–
R_{K^*} $(1 < q^2 < 6\,\mathrm{GeV}^2c^4)$	0.1 [275]	0.031	0.032	0.008	–
R_ϕ, R_{pK}, R_π	–	0.08, 0.06, 0.18	–	0.02, 0.02, 0.05	–
CKM tests					
γ, with $B_s^0 \to D_s^+ K^-$	$(^{+17}_{-22})^\circ$ [136]	4°	–	1°	–
γ, all modes	$(^{+5.0}_{-5.8})^\circ$ [167]	1.5°	1.5°	0.35°	–
$\sin 2\beta$, with $B^0 \to J/\psi K^0_S$	0.04 [606]	0.011	0.005	0.003	–
ϕ_s, with $B_s^0 \to J/\psi\phi$	49 mrad [44]	14 mrad	–	4 mrad	22 mrad [607]
ϕ_s, with $B_s^0 \to D_s^+ D_s^-$	170 mrad [49]	35 mrad	–	9 mrad	–
$\phi_s^{s\bar{s}s}$, with $B_s^0 \to \phi\phi$	154 mrad [94]	39 mrad	–	11 mrad	Under study [608]
a^s_{sl}	33×10^{-4} [211]	10×10^{-4}	–	3×10^{-4}	–
$\lvert V_{ub}\rvert/\lvert V_{cb}\rvert$	6% [201]	3%	1%	1%	–
$\boldsymbol{B^0_s, B^0 \to \mu^+\mu^-}$					
$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B^0_s \to \mu^+\mu^-)$	90% [264]	34%	–	10%	21% [609]
$\tau_{B^0_s \to \mu^+\mu^-}$	22% [264]	8%	–	2%	–
$S_{\mu\mu}$	–	–	–	0.2	–
$\boldsymbol{b \to c\ell^-\bar{\nu}_l}$ **LUV studies**					
$R(D^*)$	0.026 [215, 217]	0.0072	0.005	0.002	–
$R(J/\psi)$	0.24 [220]	0.071	–	0.02	–
Charm					
$\Delta A_{CP}(KK - \pi\pi)$	8.5×10^{-4} [610]	1.7×10^{-4}	5.4×10^{-4}	3.0×10^{-5}	–
A_Γ $(\approx x \sin\phi)$	2.8×10^{-4} [240]	4.3×10^{-5}	3.5×10^{-4}	1.0×10^{-5}	–
$x \sin\phi$ from $D^0 \to K^+\pi^-$	13×10^{-4} [228]	3.2×10^{-4}	4.6×10^{-4}	8.0×10^{-5}	–
$x \sin\phi$ from multibody decays	–	$(K3\pi)$ 4.0×10^{-5}	$(K^0_S\pi\pi)$ 1.2×10^{-4}	$(K3\pi)$ 8.0×10^{-6}	–

Summary

- LHCb is almost ready for Run-3 data-taking, and will continue delivering world-leading measurements on
  - Rare decays
  - CP violation
  - Spectroscopy …
- Your continued and strong support always appreciated