Workshop on Muon Physics at the Intensity and Precision Frontiers (MIP 2024)

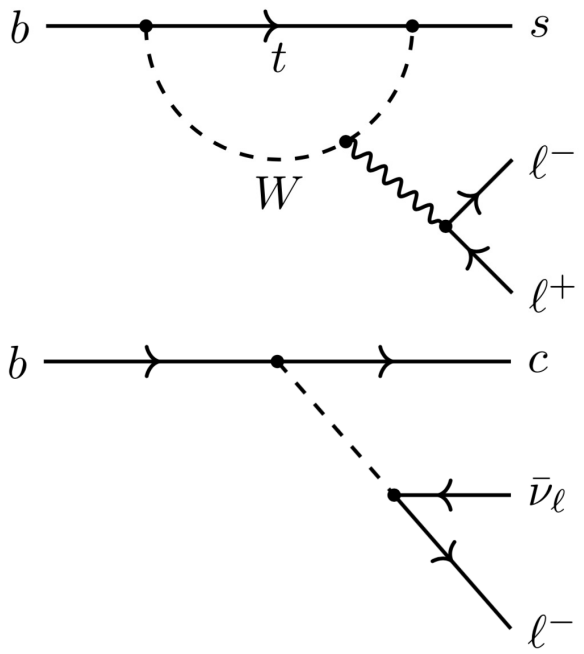
19–22 Apr 2024
Peking University
Asia/Shanghai timezone

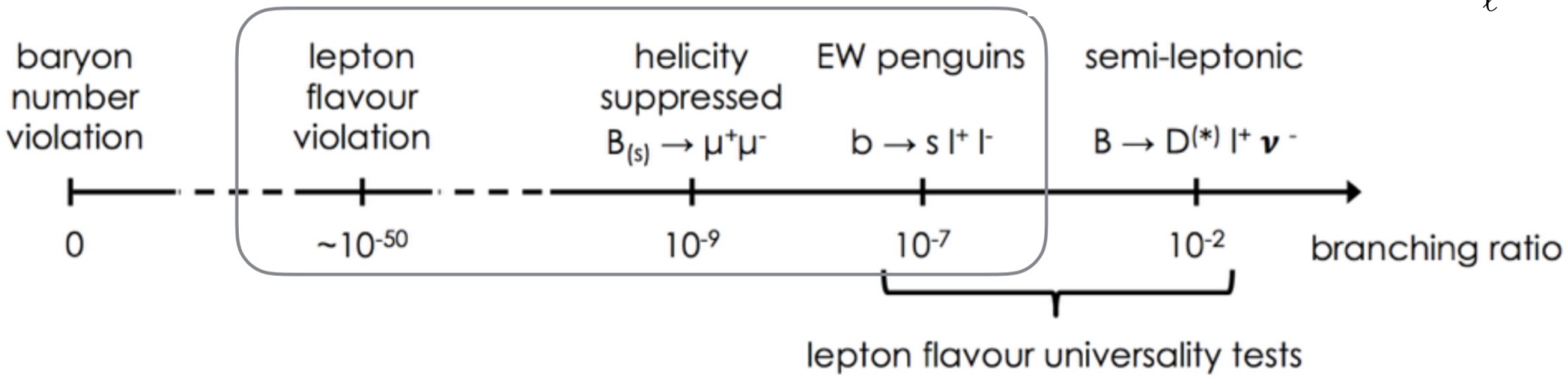
Muons in Beauty/Charm decays at LHCb

Jibo HE/何吉波(UCAS)

Introduction

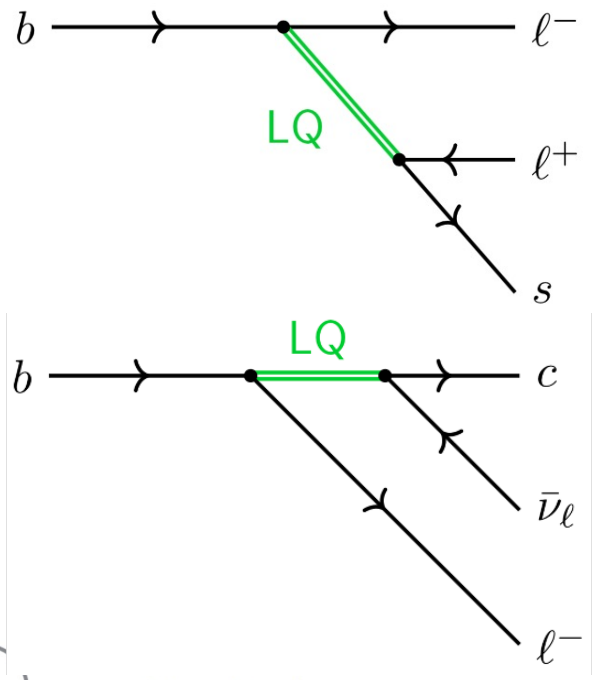
- Indirect search for new physics via measurements of *b*-decays
  - Semi-leptonic
  - FCNC (Flavour Changing Neutral Current)
  - CLFV (Charged Lepton Flavour Violation)
  - …

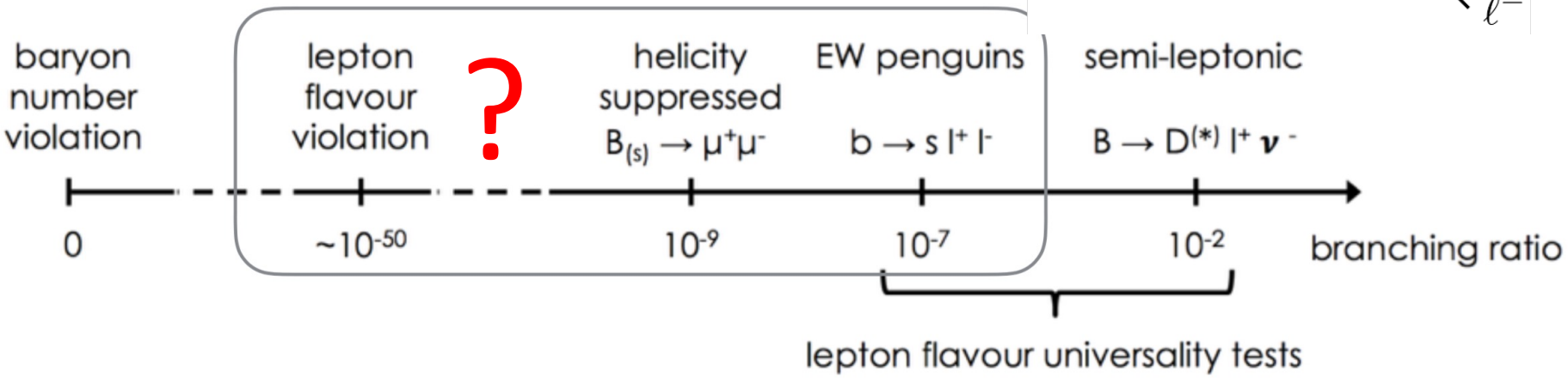




Effects of New Physics

- New Physics can change
  - Branching fraction
  - Angular distributon
  - Lepton flavour universality





Large Hadron Collider

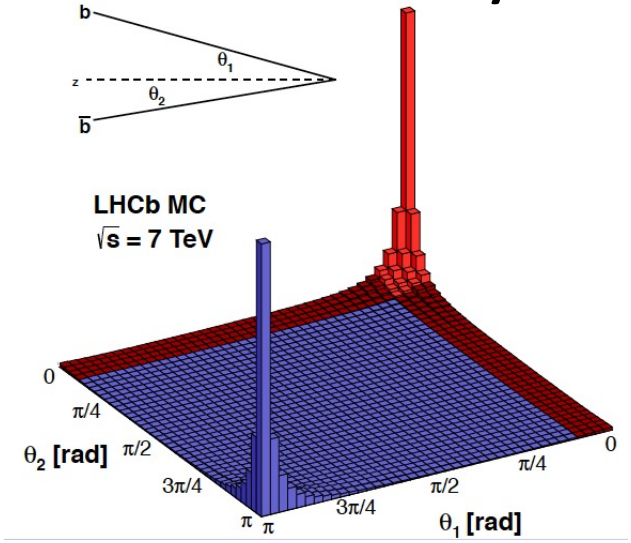
Proton energy: up to 7 TeV (10^{12} eV)
speed: 0.999999991 c

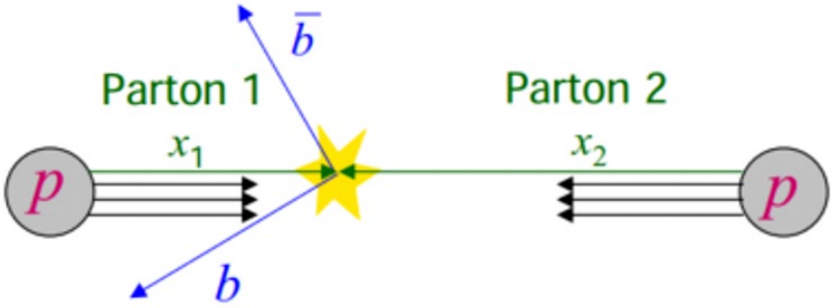
Beauty/charm production

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

} Flavour factory!

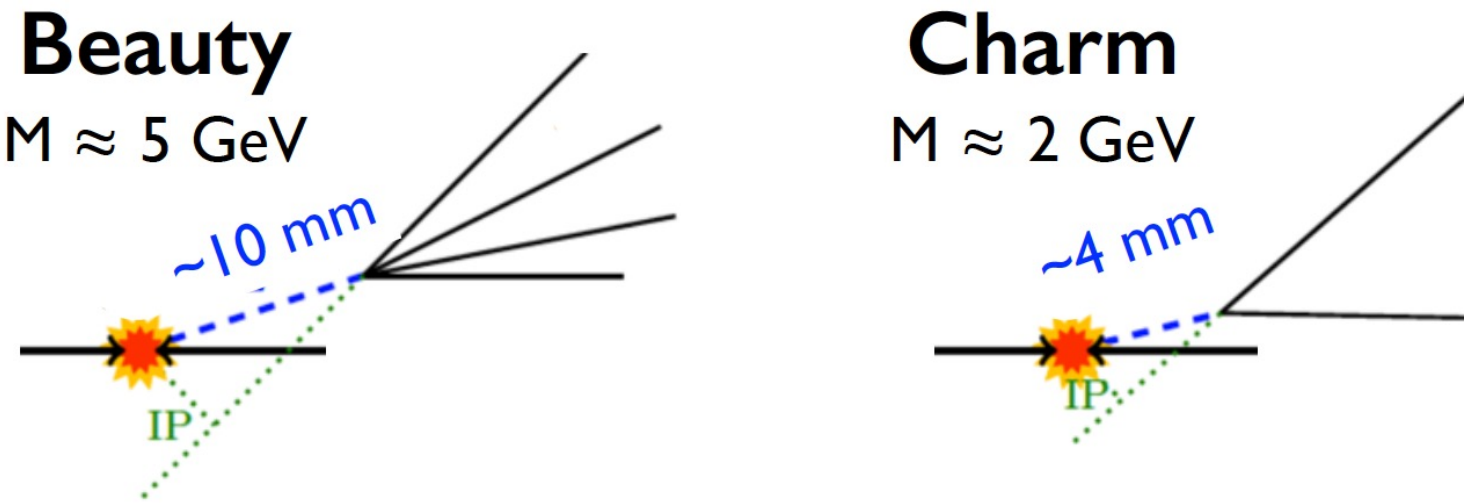
- Predominantly in forward/backward cones





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

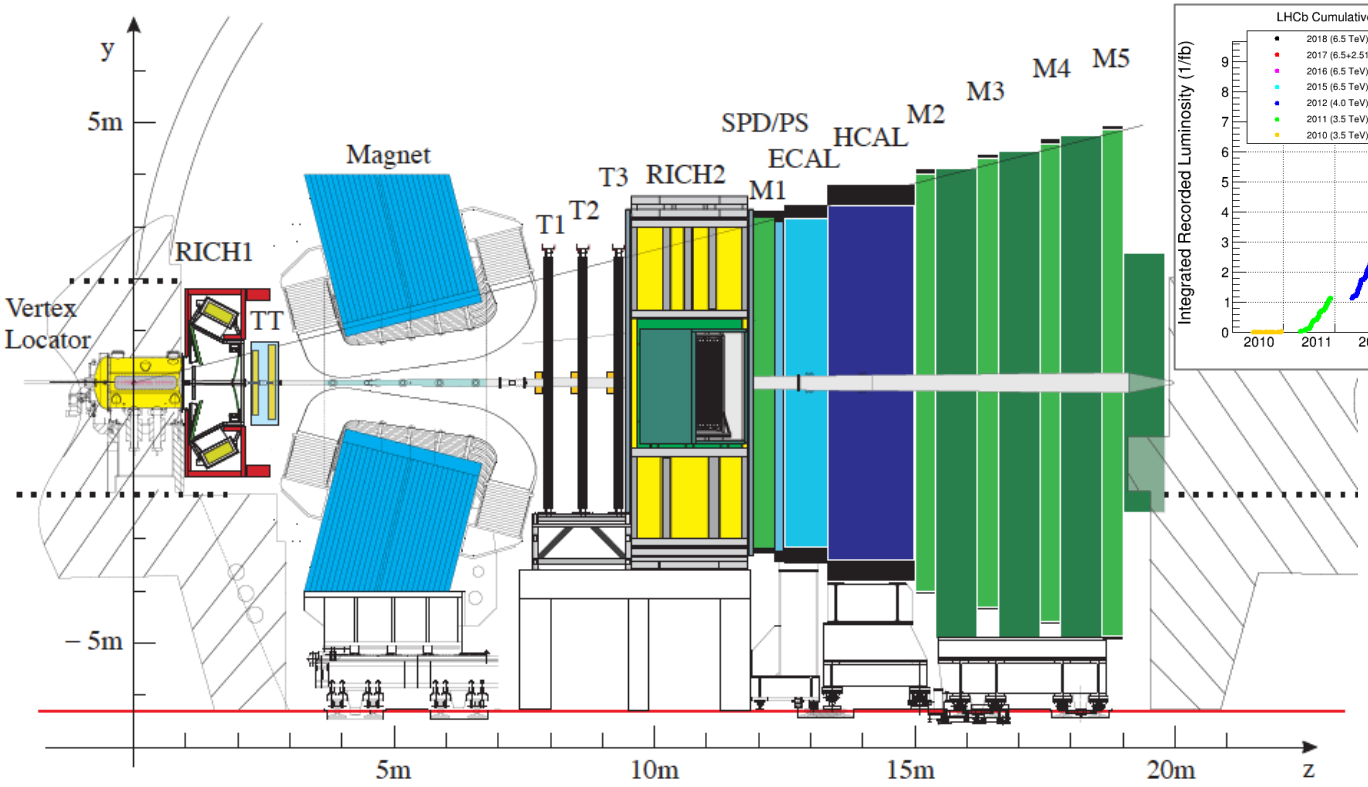
Beauty/charm signature

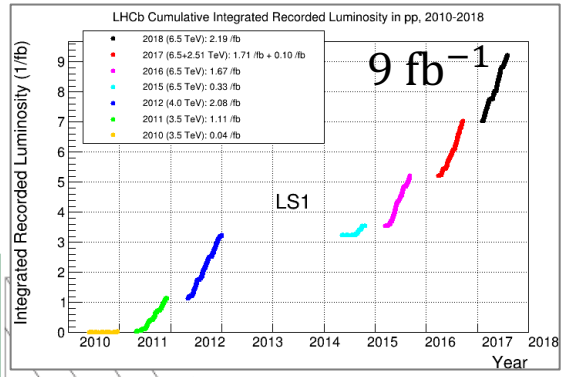


- Compared to minimum bias (background)
  - Relatively high mass → high *transverse momentum*
  - Relatively long lifetime → large impact parameter (IP)
- Requires excellent vertexing, tracking, particle-identification

The LHCb experiment

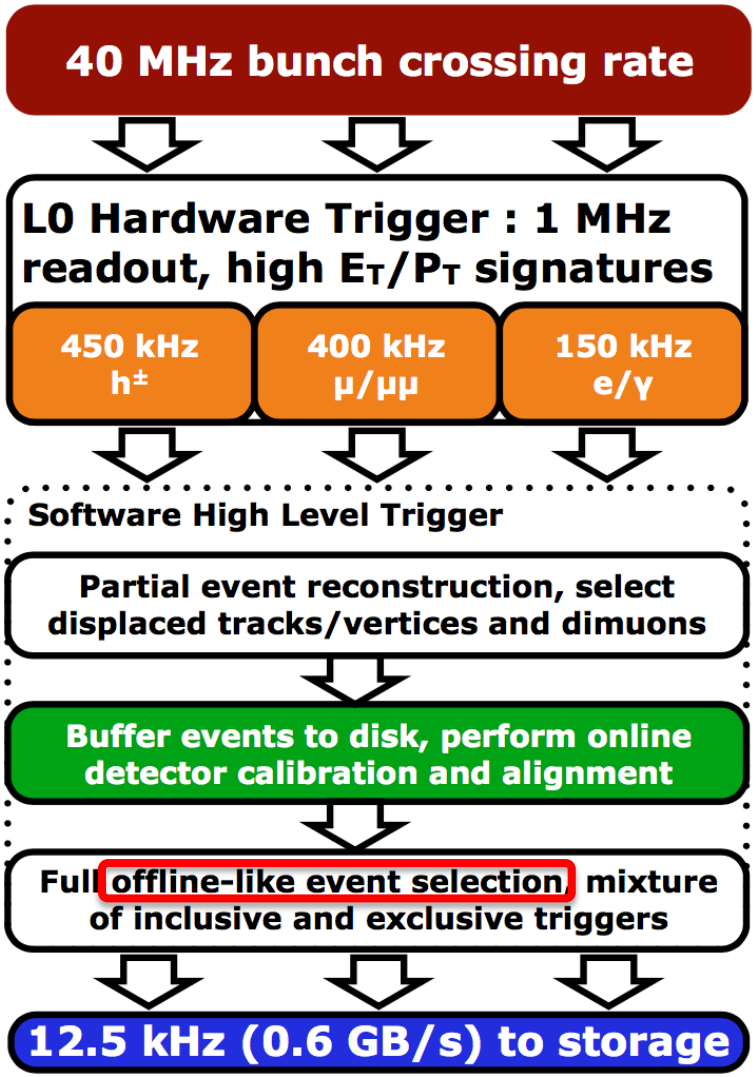
[JINST 3 (2008) S08005]





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)

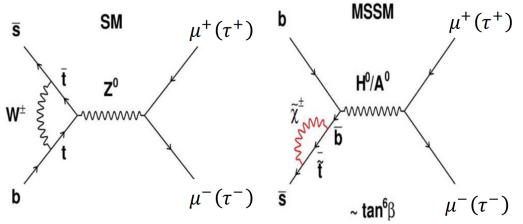
The LHCb trigger (2018)

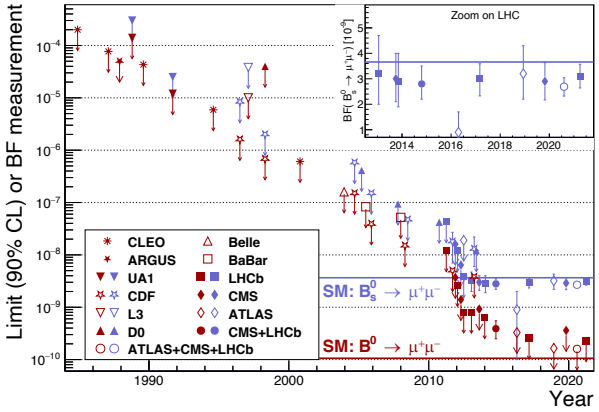


- L0, Hardware
  - $p_{\mathrm{T}}(\mu_1)\times p_{\mathrm{T}}(\mu_2) >$ (1.5 GeV)^2
  - $p_{\mathrm{T}}(\mu) >$ 1.8 GeV
  - $E_{\mathrm{T}}(e) >$ 2.4 GeV
  - $E_{\mathrm{T}}(\gamma) >$ 3.0 GeV
  - $E_{\mathrm{T}}(h) >$ 3.7 GeV
- High Level Trigger
  - Stage1, p_{T}, IP
  - Stage2, full selection

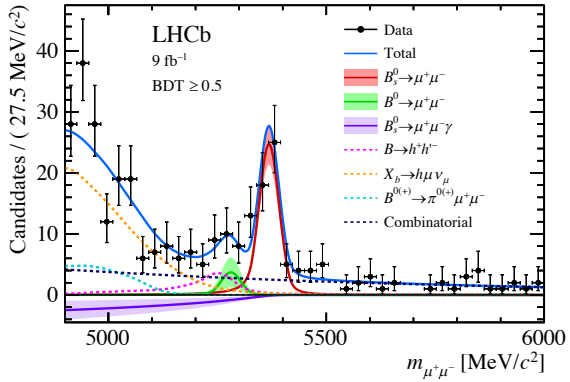
$B^0_{(s)} \to \mu^+\mu^-$

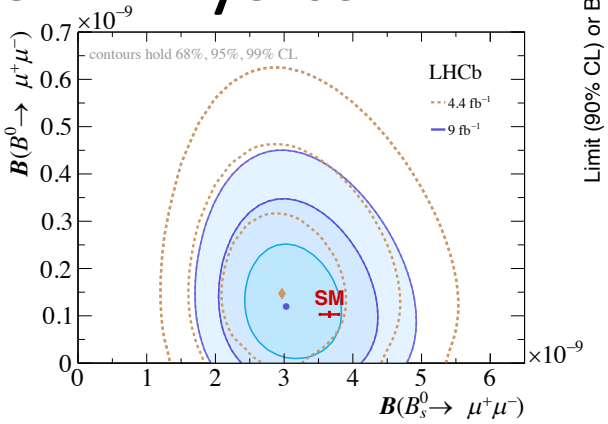
- Suppressed in SM, could be enhanced by New Physics

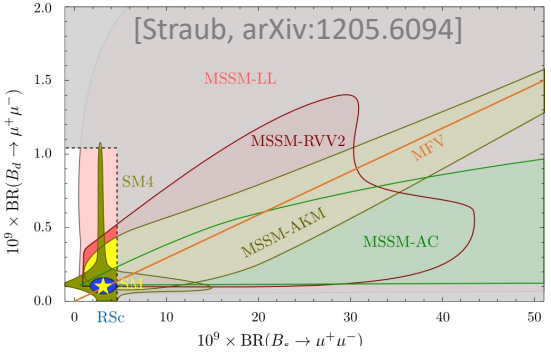




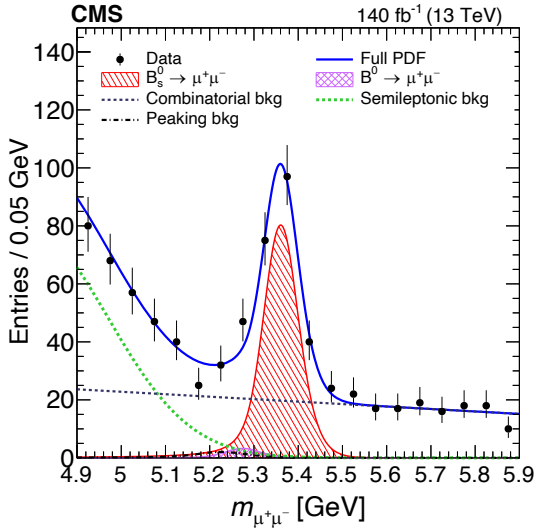
PRL 128 (2022) 041801

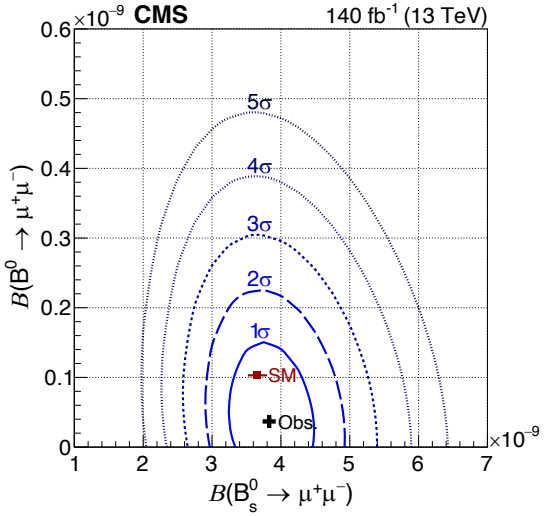


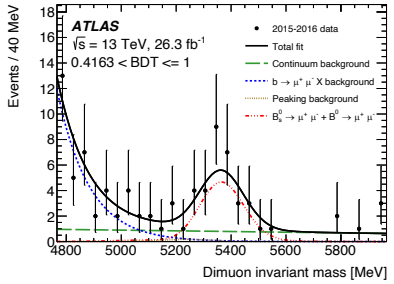




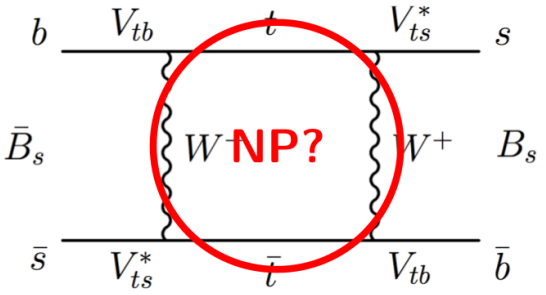
PLB 842 (2023) 137955







$B_s^0 \to \mu^+\mu^-$ eff. τ

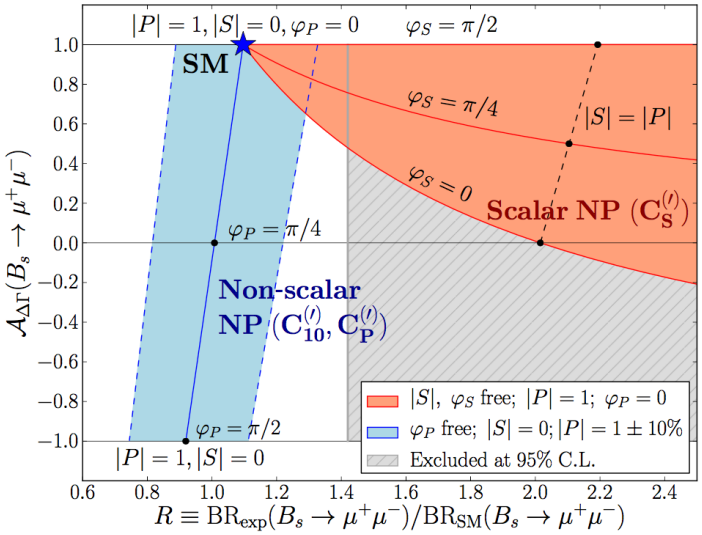


- B_s^0 mixing ⇒ effective τ

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

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

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



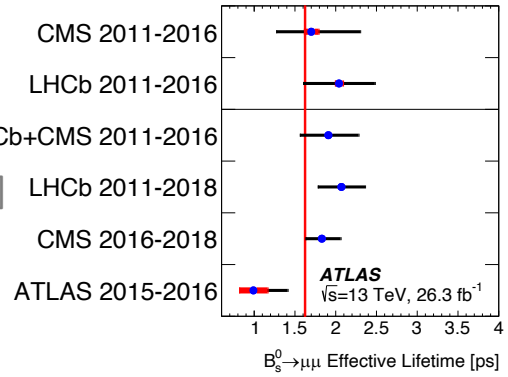
[De Bruyn *et al.*, PRL 109 (2012) 041801]

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

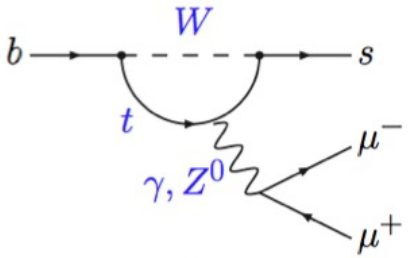
$\tau_{\mu\mu} = 2.07 \pm 0.29 \pm 0.03$ ps [LHCb, PRL 128 (2022) 041801]

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

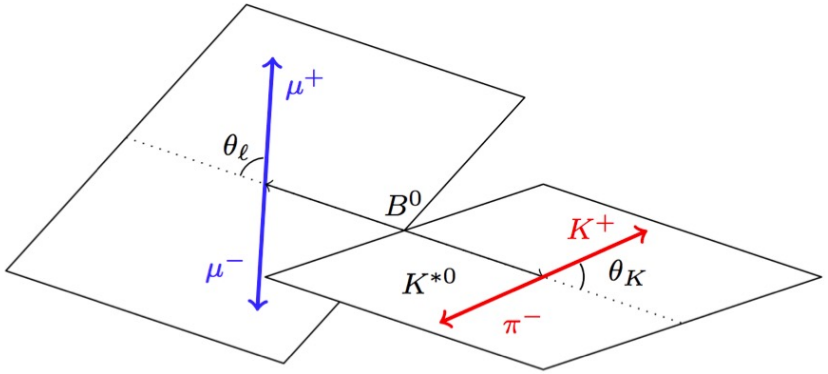
$0.99^{+0.42}_{-0.07} \pm 0.17$ ps [ATLAS, JHEP 09 (2023) 199]



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



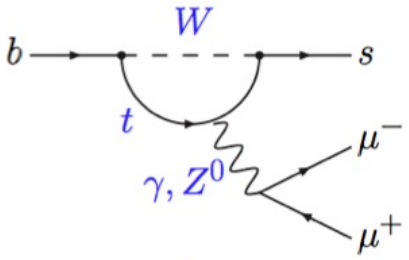
- "Poster-child" decay of $b \to s\mu^+\mu^-$
- Described by $q^2 = m^2(\ell^+\ell^-)$ and $\theta_\ell, \theta_K, \phi$
- Many observables!

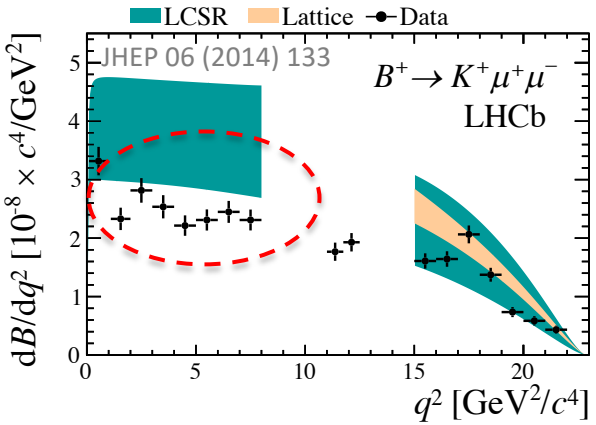


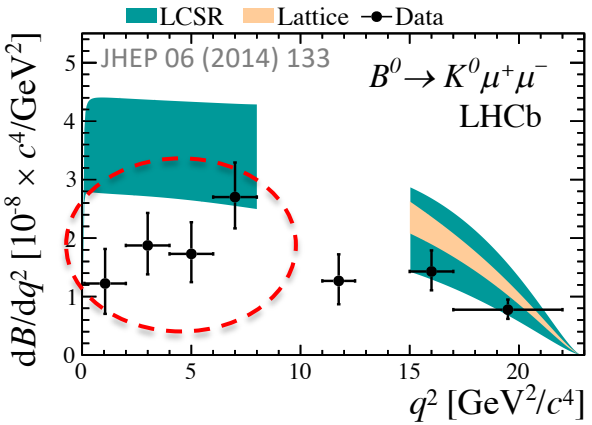
$$\frac{1}{\mathrm{d}(\Gamma+\bar{\Gamma})/\mathrm{d}q^2}\frac{\mathrm{d}^3(\Gamma+\bar{\Gamma})}{\mathrm{d}\vec{\Omega}} = \frac{9}{32\pi}\Big[\tfrac{3}{4}(1-F_\mathrm{L})\sin^2\theta_K + F_\mathrm{L}\cos^2\theta_K + \tfrac{1}{4}(1-F_\mathrm{L})\sin^2\theta_K\cos 2\theta_\ell$$
$$- F_\mathrm{L}\cos^2\theta_K\cos 2\theta_\ell + S_3\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi$$
$$+ S_4\sin 2\theta_K\sin 2\theta_\ell\cos\phi + S_5\sin 2\theta_K\sin\theta_\ell\cos\phi$$
$$+ \tfrac{4}{3}A_\mathrm{FB}\sin^2\theta_K\cos\theta_\ell + S_7\sin 2\theta_K\sin\theta_\ell\sin\phi$$
$$+ S_8\sin 2\theta_K\sin 2\theta_\ell\sin\phi + S_9\sin^2\theta_K\sin^2\theta_\ell\sin 2\phi\Big]$$

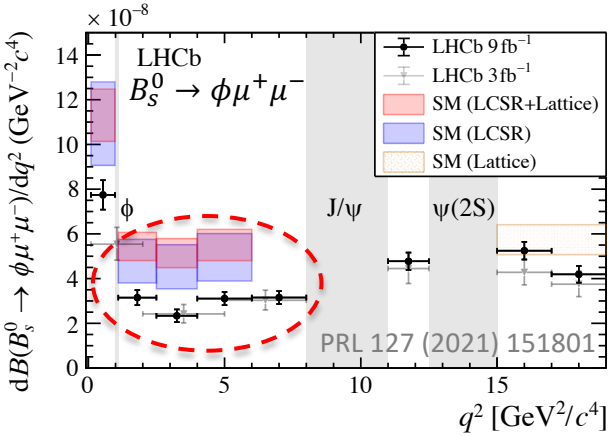
Branching fraction of $b \to s\mu^+\mu^-$

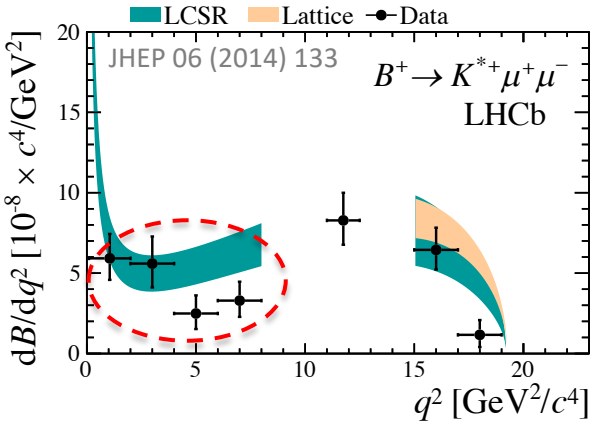
- Pattern of tensions seen, theoretical uncertainty?

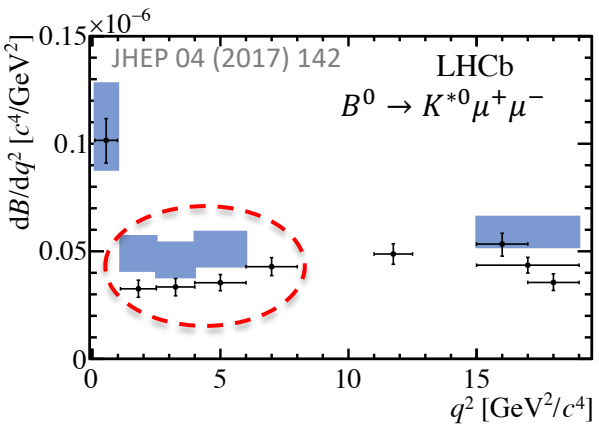


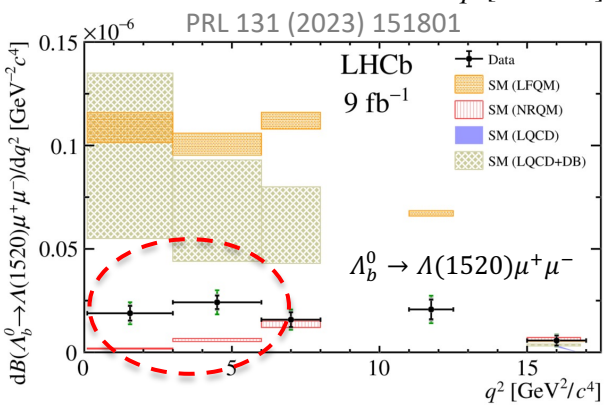












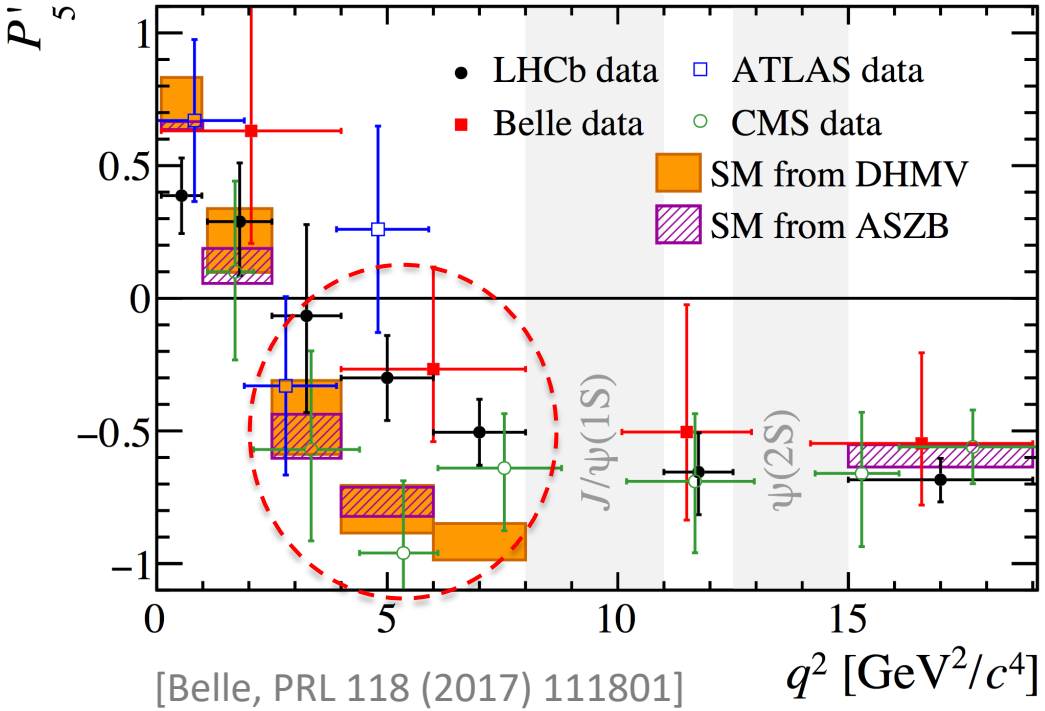
P_5' with $B^0 \to K^{*0}\mu^+\mu^-$

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

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

- Also measured by Belle, ATLAS, CMS

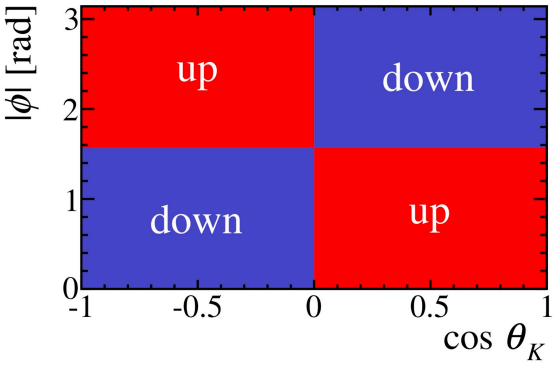
[PRL 125 (2020) 011802]

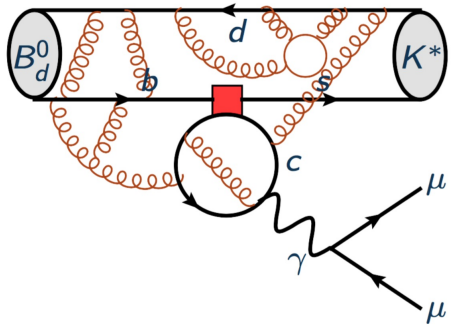


[Belle, PRL 118 (2017) 111801]
[ATLAS, JHEP 10 (2018) 047]
[CMS, PLB 781 (2018) 517]

Count blue minus red

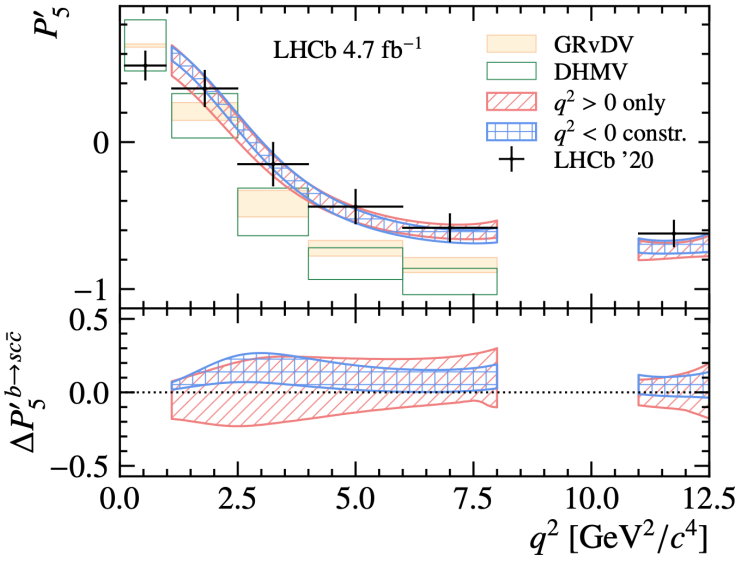
[P. Koppenburg, arXiv:1606.00999]

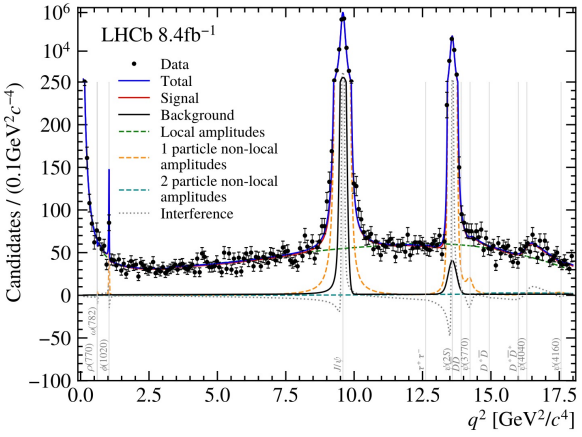


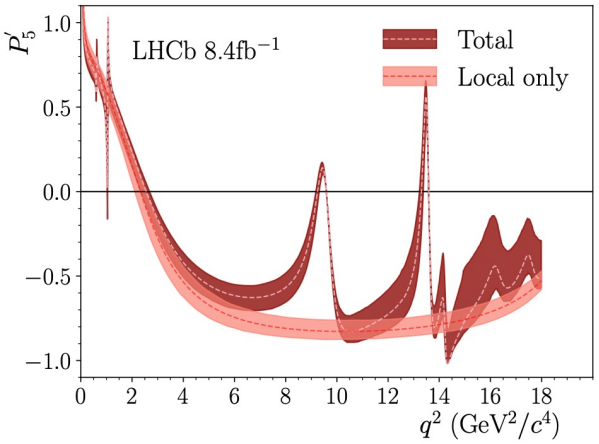


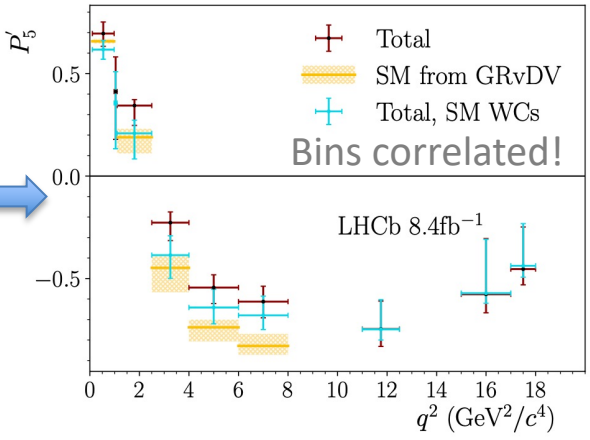
Impact of charm loop

- Model of local and nonlocal contributions to extract Wilson co-efficiency [PRL 132 (2024) 131801]
- Model of both 1-(2-) particle amplitudes, whole dimuon region [LHCb-Paper-2024-011, in preparation]



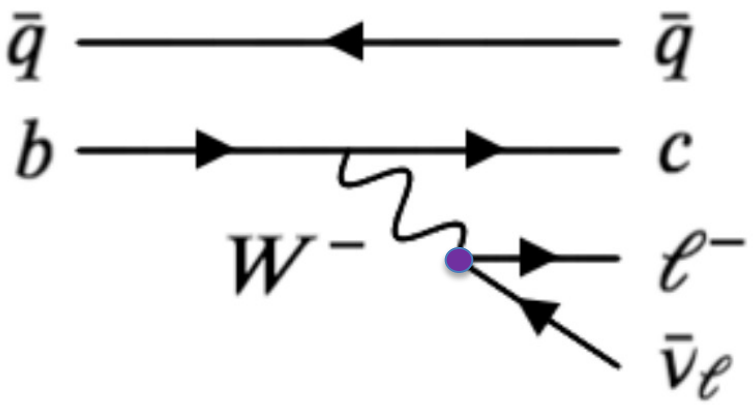


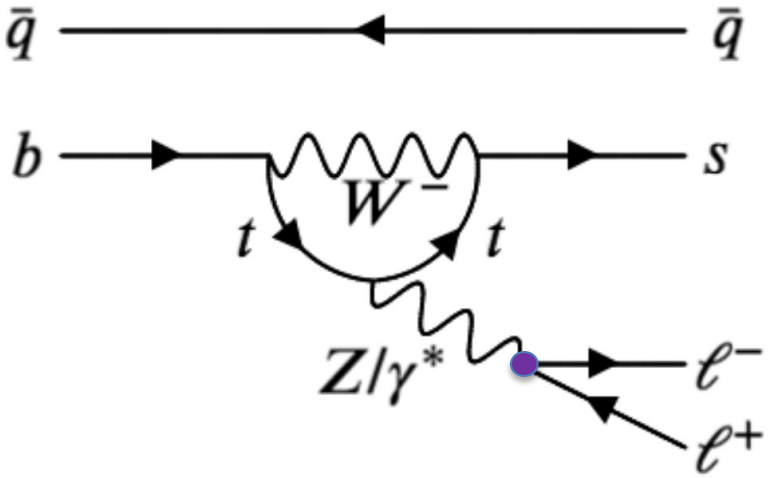




Lepton flavour universality

- In SM, three lepton families (e, μ, τ) have identical couplings to the gauge bosons





  - which means, e.g.,

$$R_K = \frac{\mathcal{B}(B^+ \to K^+ \mu^+ \mu^-)}{\mathcal{B}(B^+ \to K^+ e^+ e^-)} \cong 1$$

$\mathcal{O}(10^{-4})$ uncertainty
[C. Bobeth *et al.*, JHEP 12 (2007) 040]

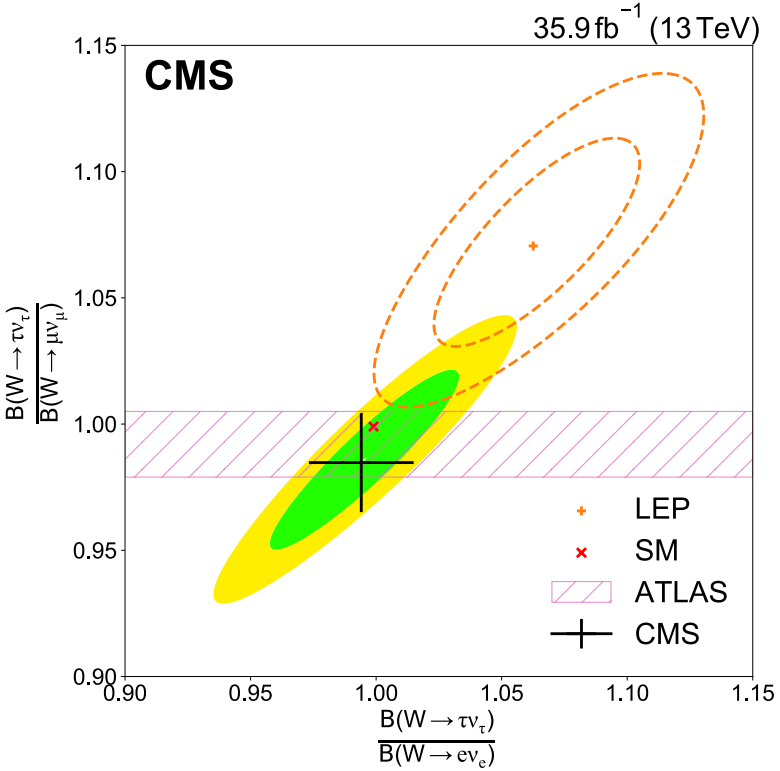
$\mathcal{O}(1\%)$ QED correction
[M. Bordone *et al.*, EJPC 76 (2016) 440]

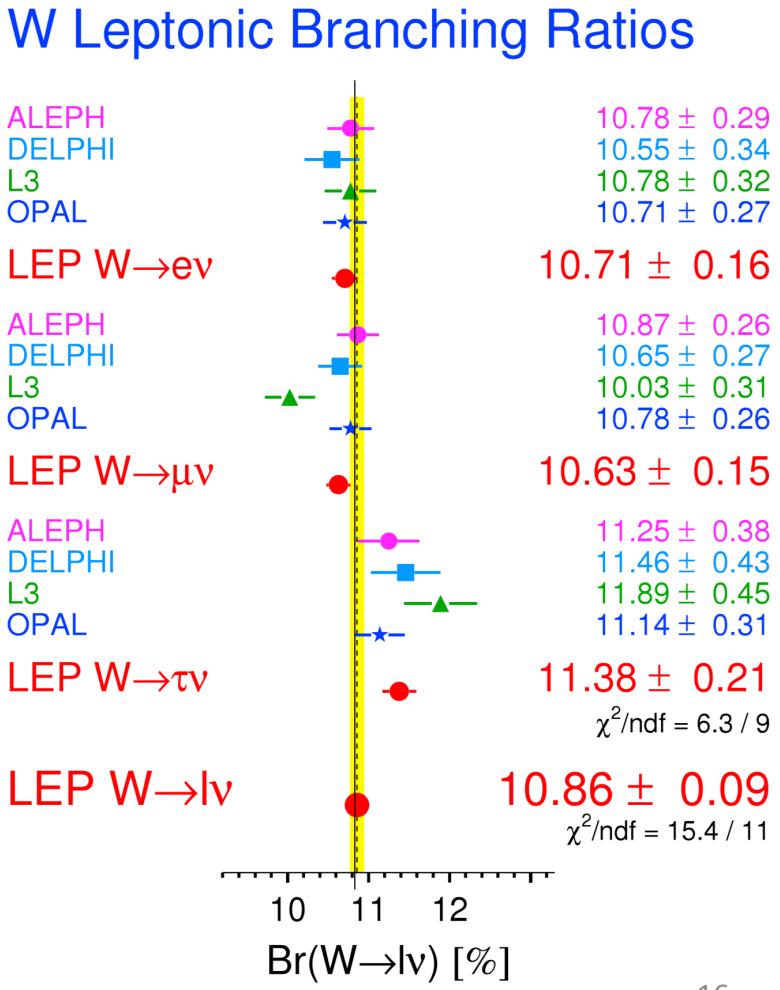
- Lepton flavour universality violation? New Physics!

Experimental test of LFU

- Well established in SM, e.g. $W \to \ell\nu$
  - Some tension at LEP, addressed by ATLAS/CMS

[ATLAS, NP 17 (2021) 813; CMS, PRD 105 (2022) 072008]

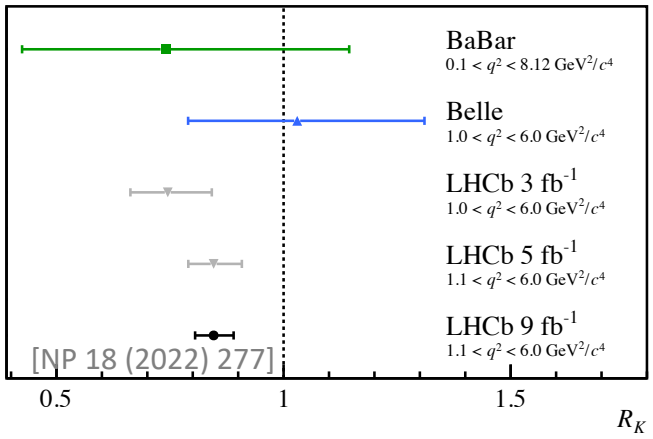


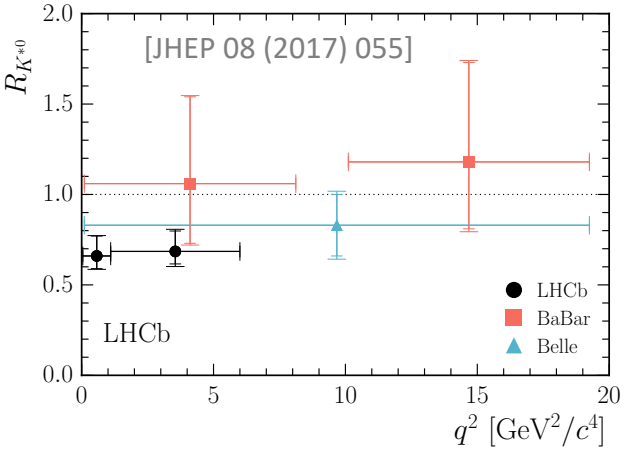


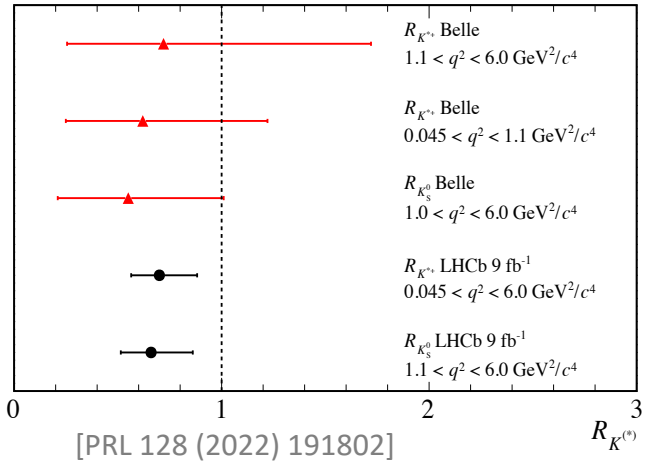
LFU in $b \to s\ell^+\ell^-$ decays

before Dec 2022

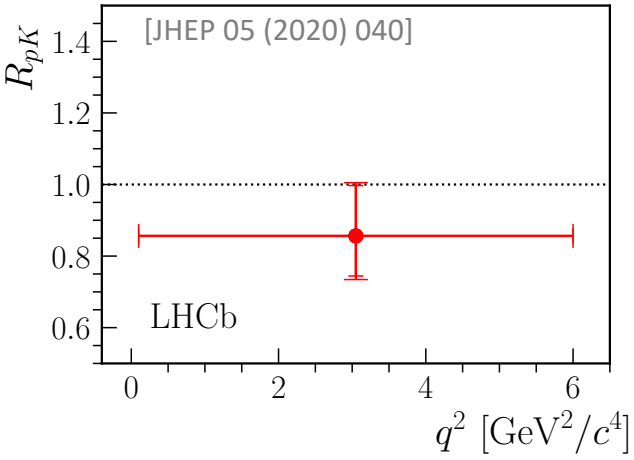
- Deviations from SM seen by LHCb

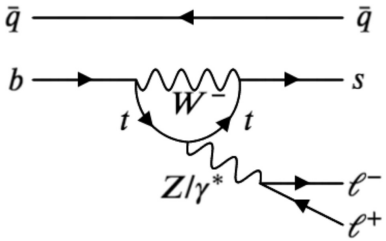




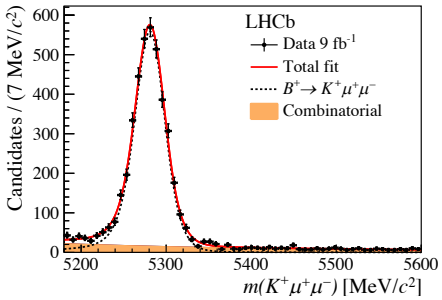


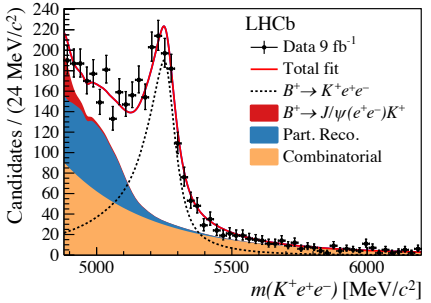
[PRL 128 (2022) 191802]





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

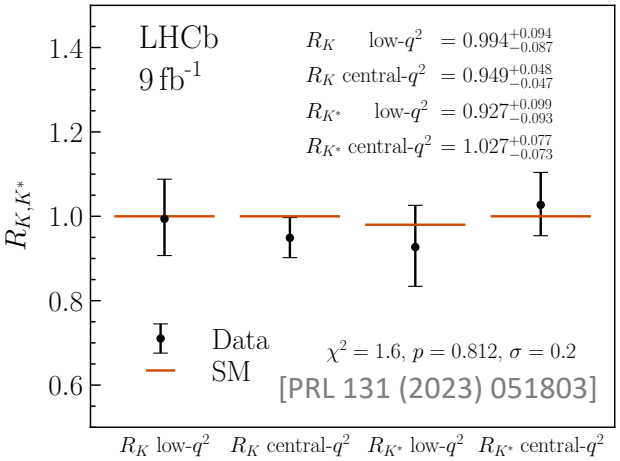




LFU in $b \to s\ell^+\ell^-$ decays

after Dec 2022

- Deviations mostly gone



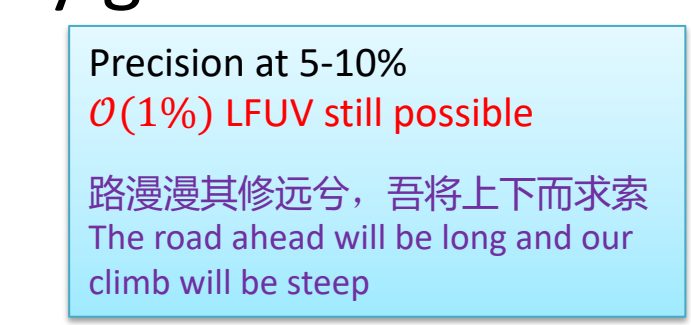
[PRL 131 (2023) 051803]

Precision at 5-10%

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

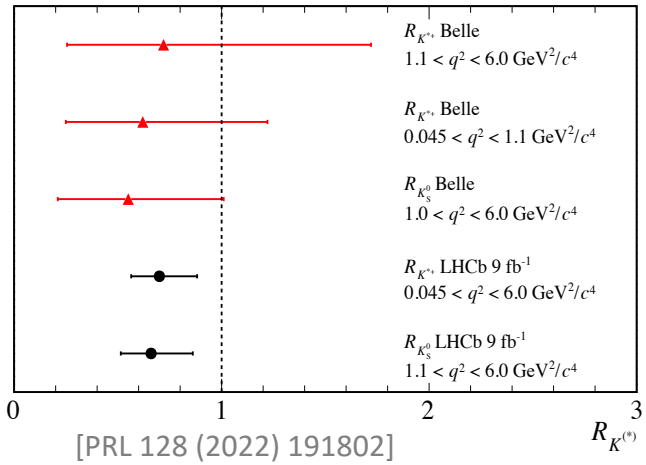
路漫漫其修远兮，吾将上下而求索

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

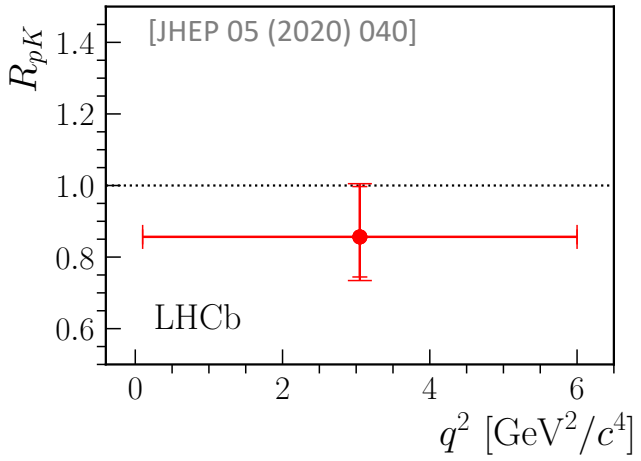


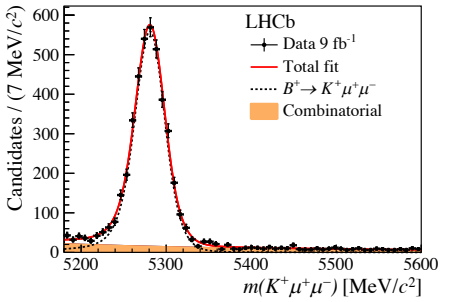
$R_K = 0.78^{+0.46\,+0.09}_{-0.23\,-0.05}$ [CMS, BPH-22-005-PAS]

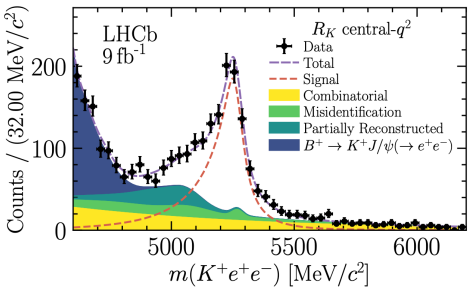
$$R_X = \frac{\mathcal{B}(H_b \to X\mu^+\mu^-)}{\mathcal{B}(H_b \to Xe^+e^-)}$$



[PRL 128 (2022) 191802]

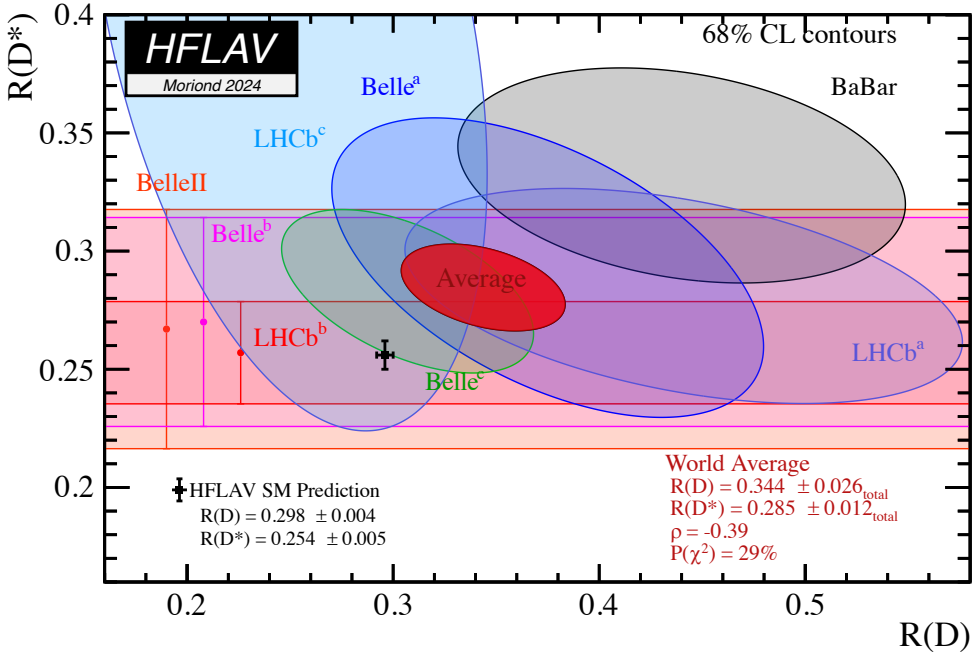


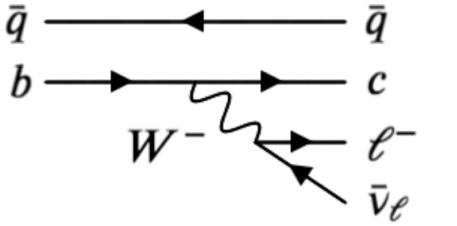




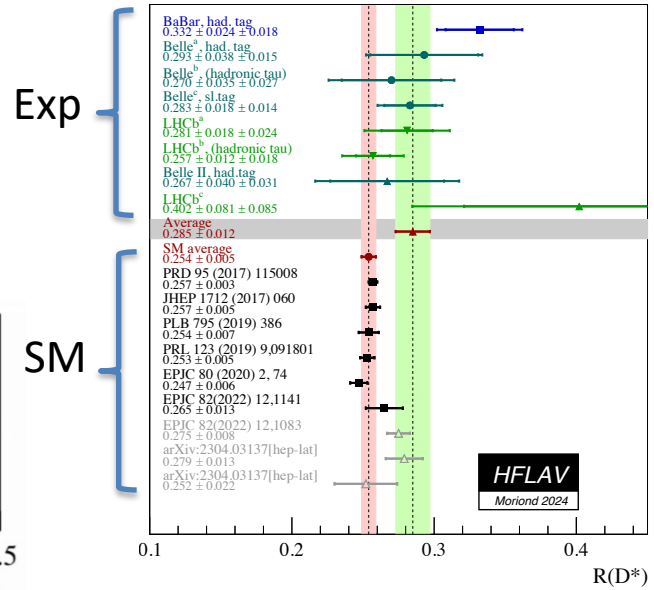
LFU in $b \to c\ell\nu$ decays

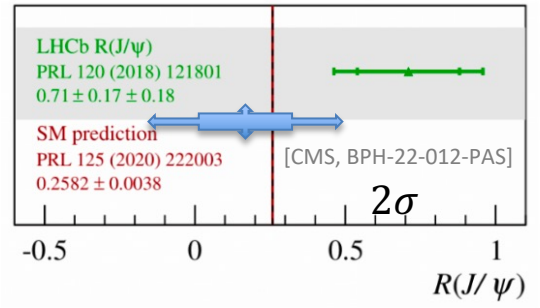
- Deviations from SM seen by Babar/Belle/LHCb

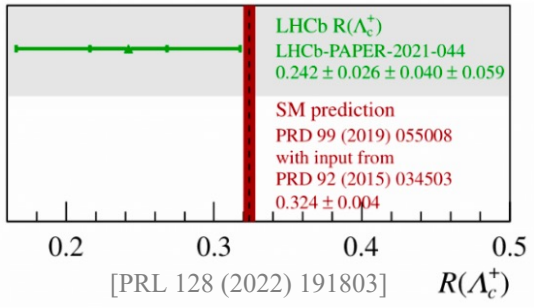




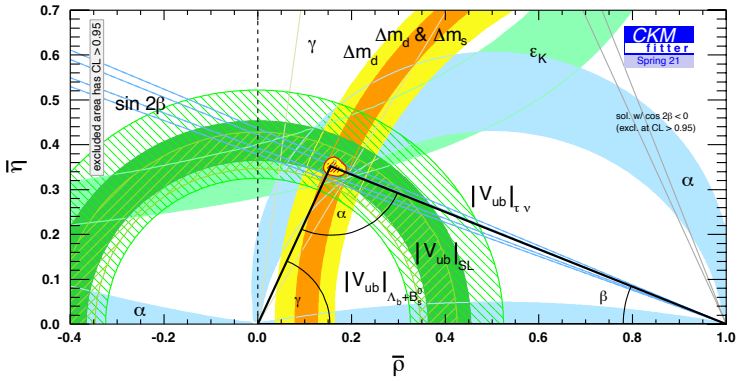
$$R(H_c) = \frac{\mathcal{B}(H_b \to H_c \tau^- \bar{\nu}_\tau)}{\mathcal{B}(H_b \to H_c \mu^- \bar{\nu}_\mu)}$$



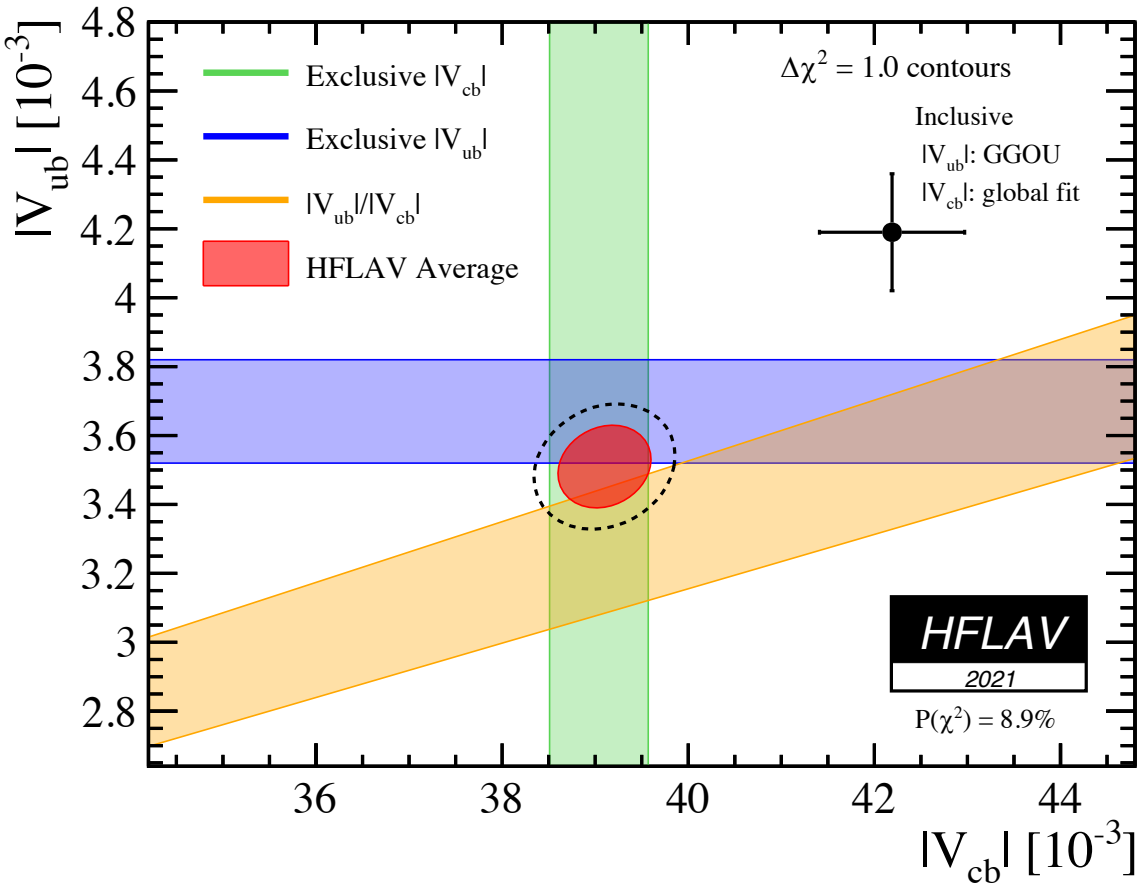


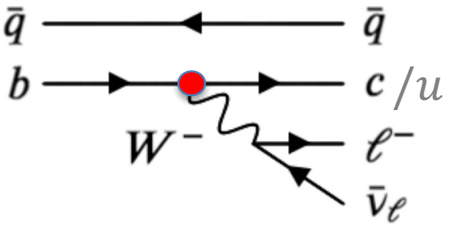


V_{cb}, V_{ub}



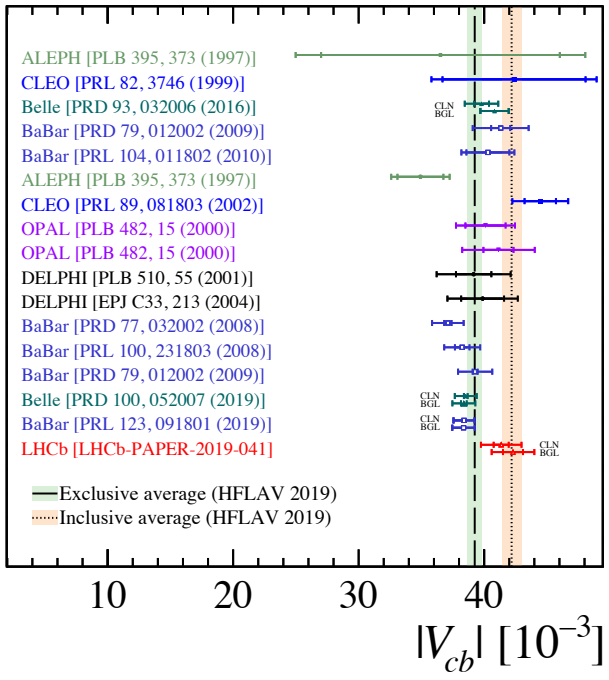
- Some tension between exclusive/inclusive



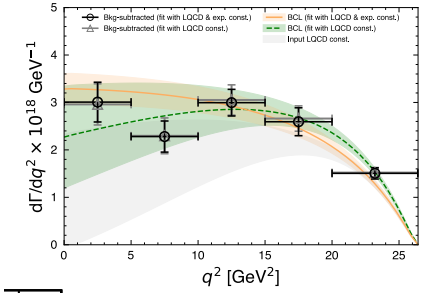


$$d\Gamma \propto |V_{cb}|^2 |f_H|^2$$

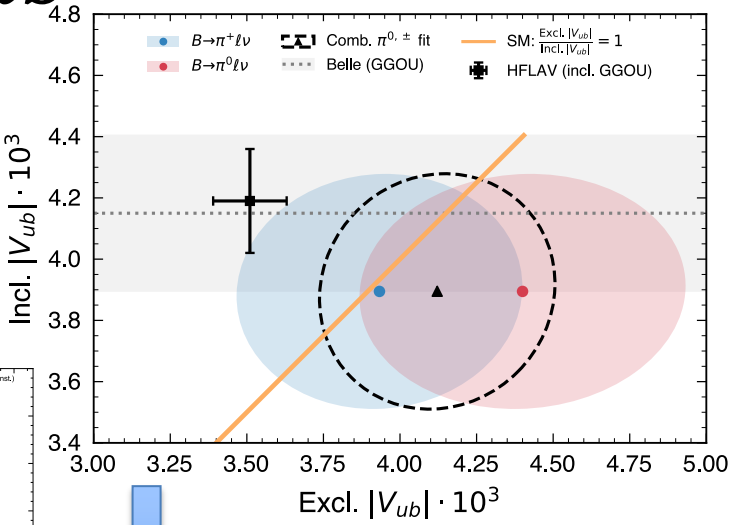
V_{cb}, V_{ub}



[PRD 101 (2020) 072004]

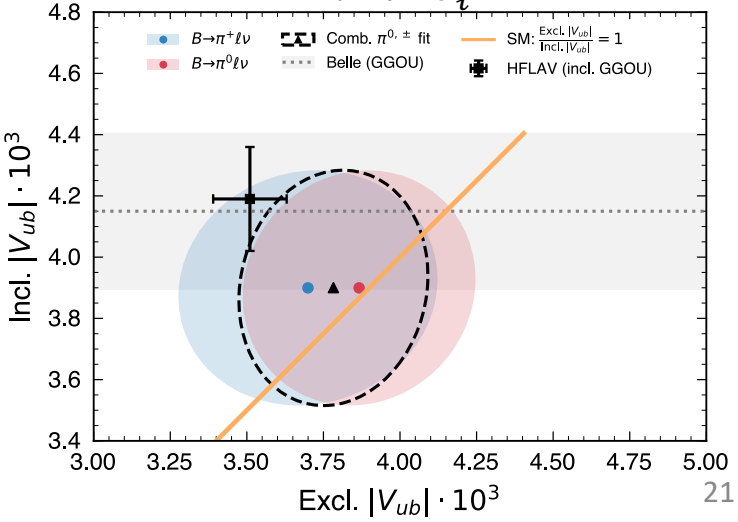


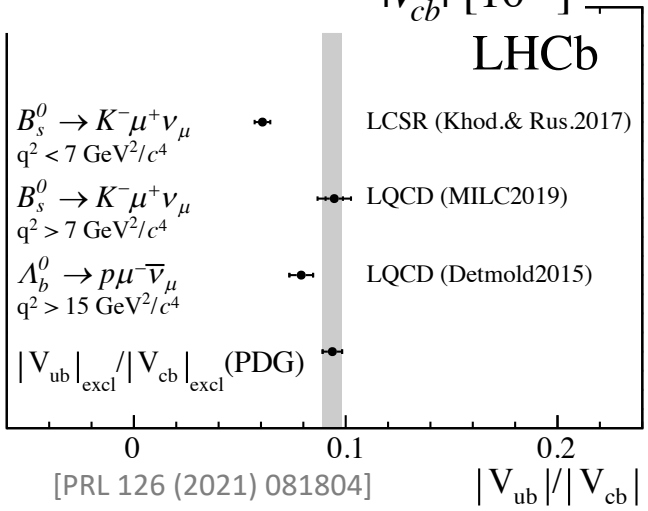
[Belle, PRL 131 (2023) 211801]



+

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

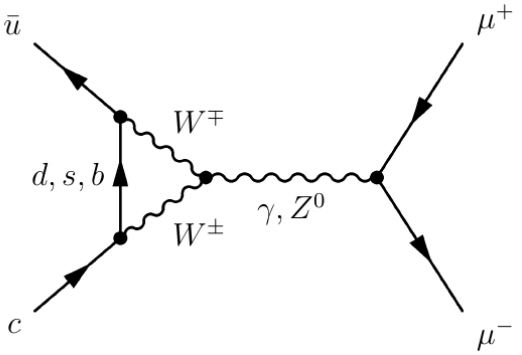


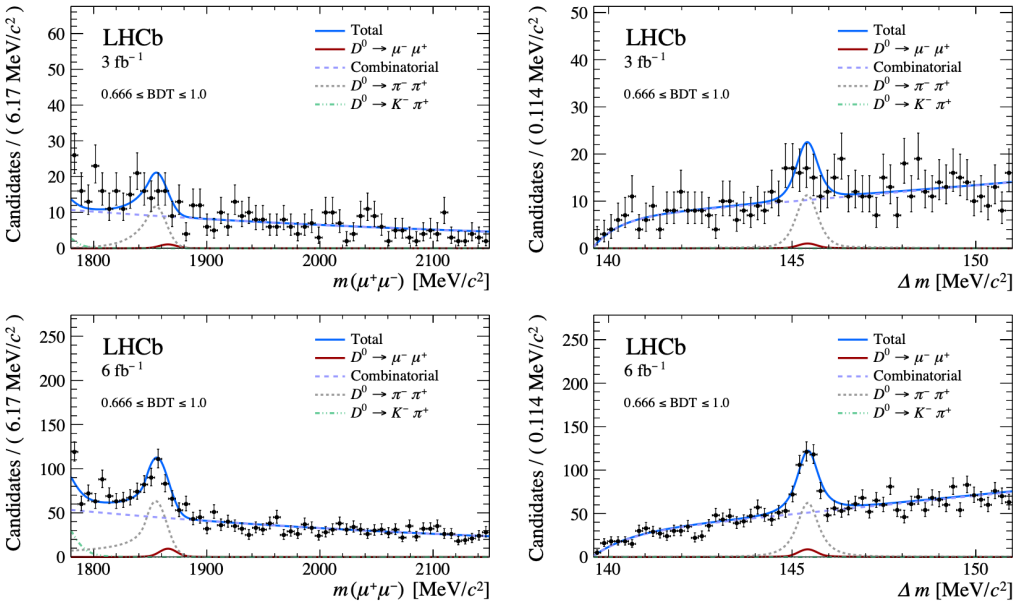


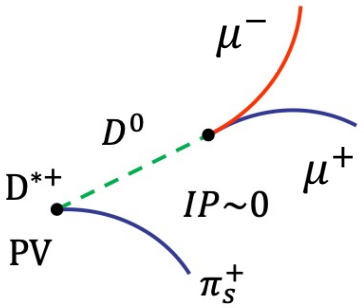
[PRL 126 (2021) 081804]

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

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







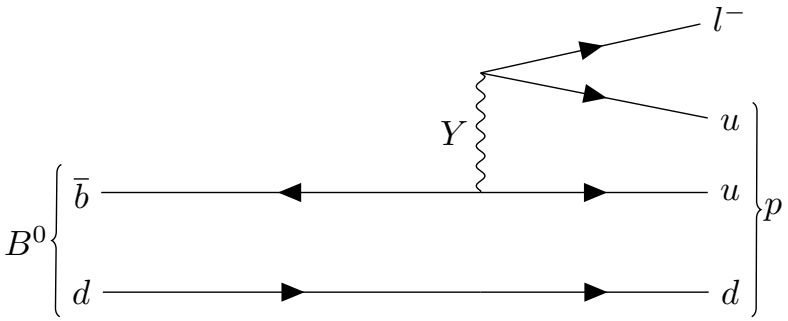
$\mathcal{B}(D^0 \to \mu^+\mu^-) < 3.1{\times}10^{-9}$ @ 90% CL

[PRL 131 (2023) 041804]

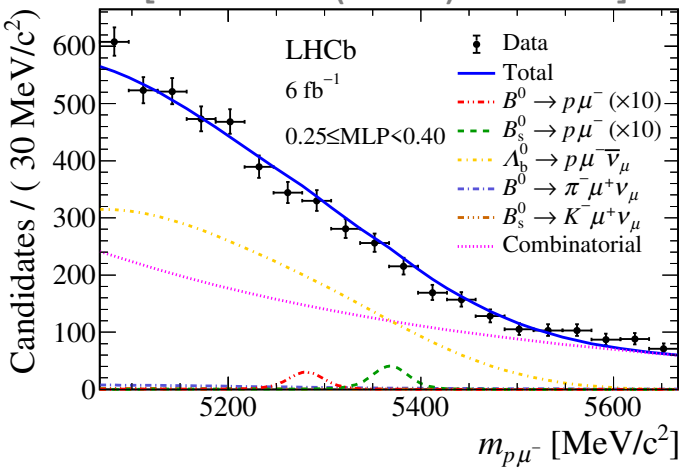
Charged Lepton Flavour Violation

- $B^0 \to p\mu^-$

$\mathcal{B} < 2.6\times10^{-9}$ @ 90% CL



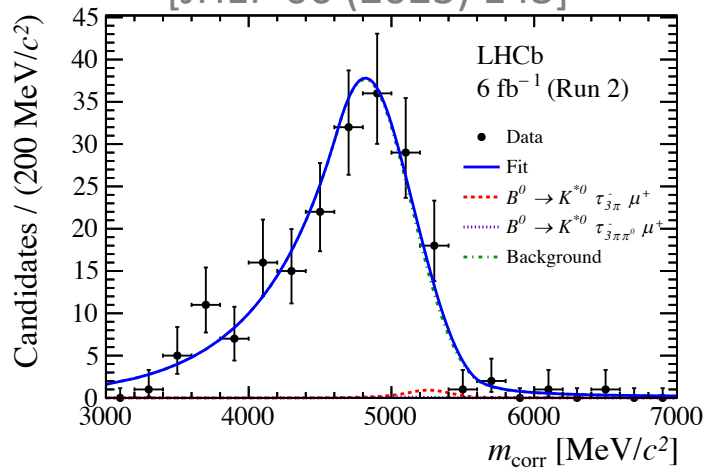
[PRD 108 (2023) 012021]



- $B^0 \to K^{*0}\tau^\pm\mu^\mp$

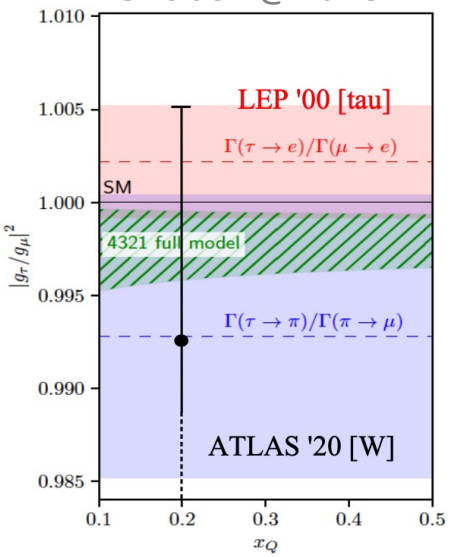
$\mathcal{B} < 8.2\times10^{-6}$ @ 90% CL

[JHEP 06 (2023) 143]

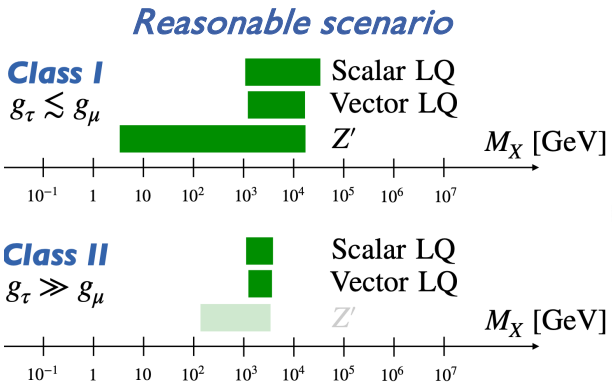


Implications?

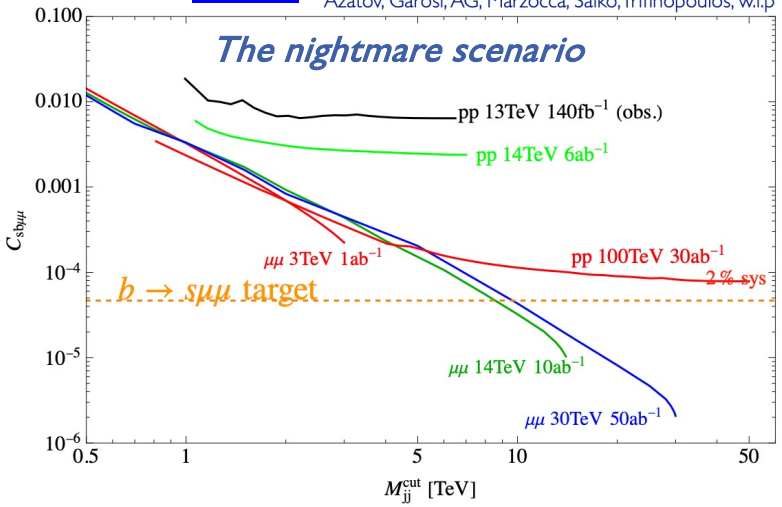
G. Isidori @ NJNU



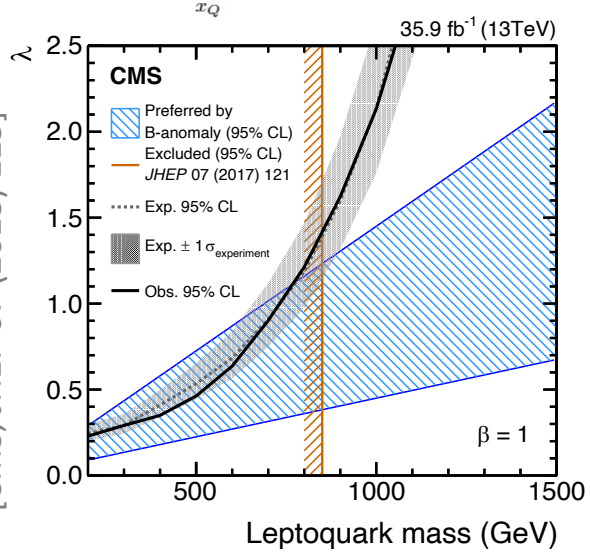
A. Greljo @ LHCb implication 2021 [slides]

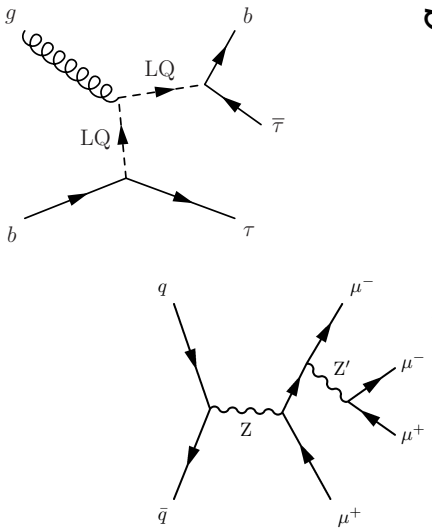


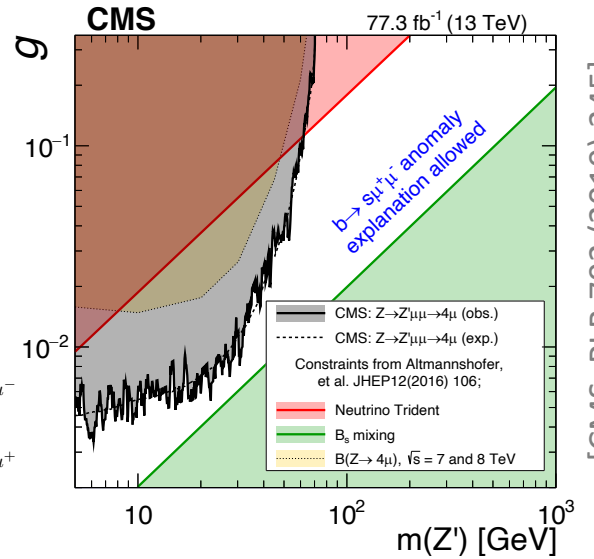
Azatov, Garosi, AG, Marzocca, Salko, Trifinopoulos; w.i.p



[CMS, JHEP 07 (2018) 115]

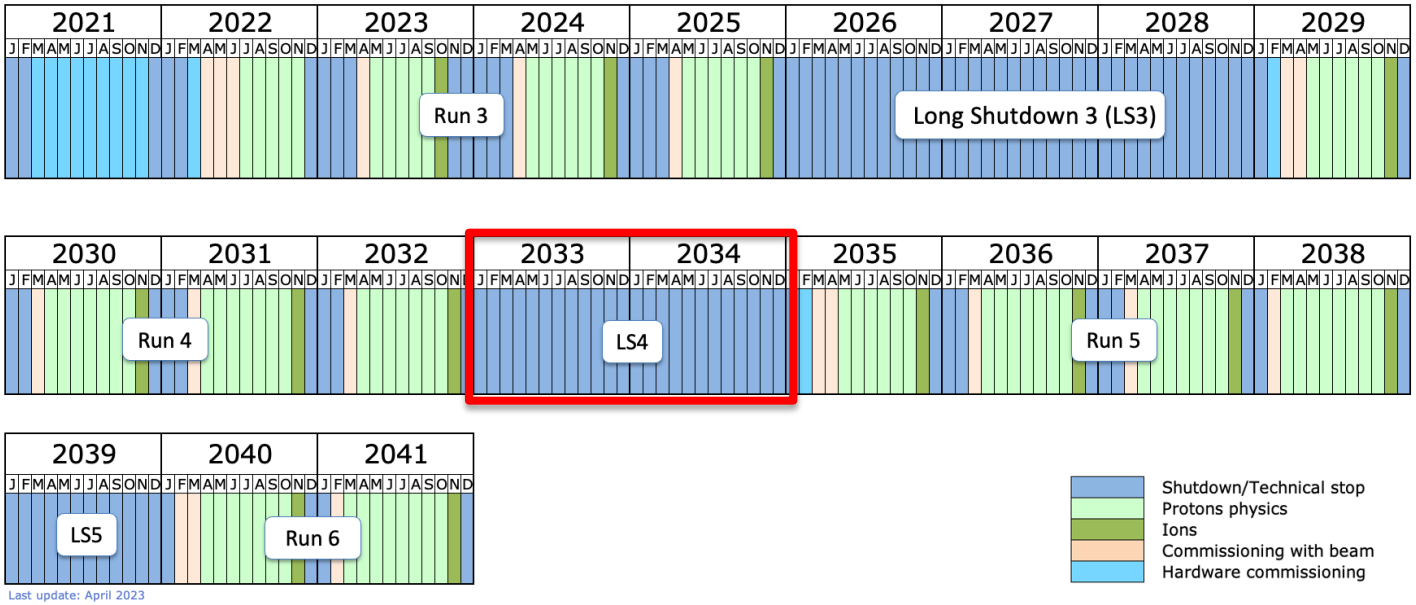




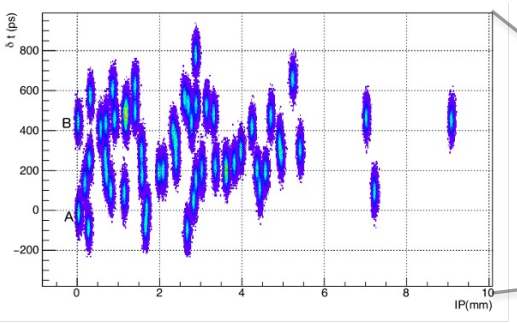


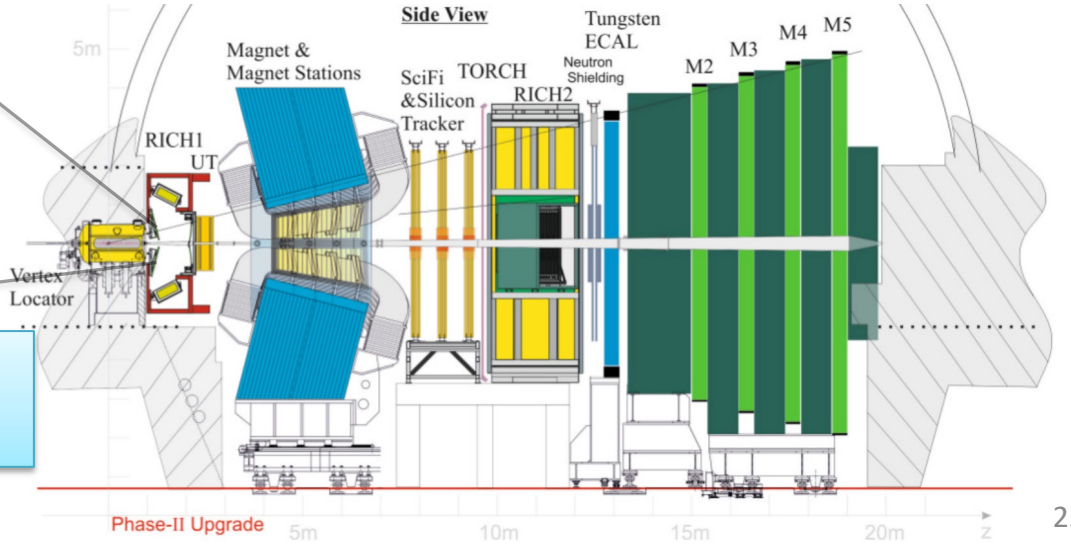
[CMS, PLB 792 (2019) 345]

The LHCb upgrades



[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]

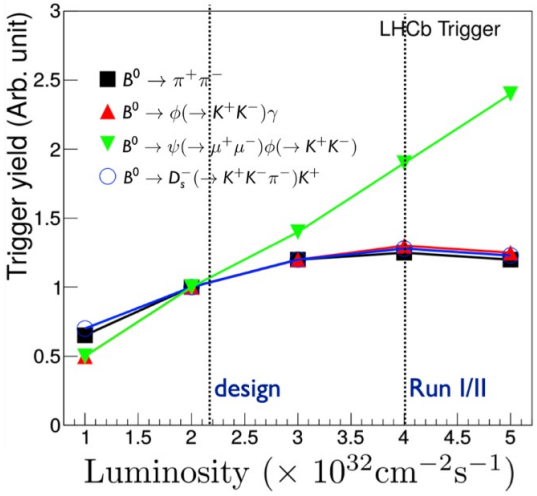
Observable	Current LHCb	LHCb 2025	Belle II	Upgrade II	ATLAS & CMS
EW Penguins					
R_K $(1 < q^2 < 6\,\mathrm{GeV}^2c^4)$	0.1 [274]	0.025	0.036	0.007	–
R_{K^*} $(1 < q^2 < 6\,\mathrm{GeV}^2c^4)$	0.1 [275]	0.031	0.032	0.008	–
R_ϕ, R_{pK}, R_π	–	0.08, 0.06, 0.18	–	0.02, 0.02, 0.05	–
CKM tests					
γ, with $B_s^0 \to D_s^+ K^-$	$(^{+17}_{-22})^\circ$ [136]	4°	–	1°	–
γ, all modes	$(^{+5.0}_{-5.8})^\circ$ [167]	1.5°	1.5°	0.35°	–
$\sin 2\beta$, with $B^0 \to J/\psi K_S^0$	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_{sl}^s	33×10^{-4} [211]	10×10^{-4}	–	3×10^{-4}	–
$\lvert V_{ub}\rvert/\lvert V_{cb}\rvert$	6% [201]	3%	1%	1%	–
$B_s^0, B^0 \to \mu^+\mu^-$					
$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	90% [264]	34%	–	10%	21% [609]
$\tau_{B_s^0 \to \mu^+\mu^-}$	22% [264]	8%	–	2%	–
$S_{\mu\mu}$	–	–	–	0.2	–
$b \to c\ell^-\bar{\nu}_l$ 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}	$(K_S^0\pi\pi)$ 1.2×10^{-4}	$(K3\pi)$ 8.0×10^{-6}	–

Summary

- The Flavour anomalies are still there
  - $b \to s\mu^+\mu^-$, BR, P_5'
  - $\mathcal{R}_{D^{(*)}}$
  - V_{cb}, V_{ub}
- Efforts from both theoretical and experimental sides needed to understand whether they are
  - Sign of New Physics?
  - QCD effects?
- Muon collider may be needed to find NP directly

Backup

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

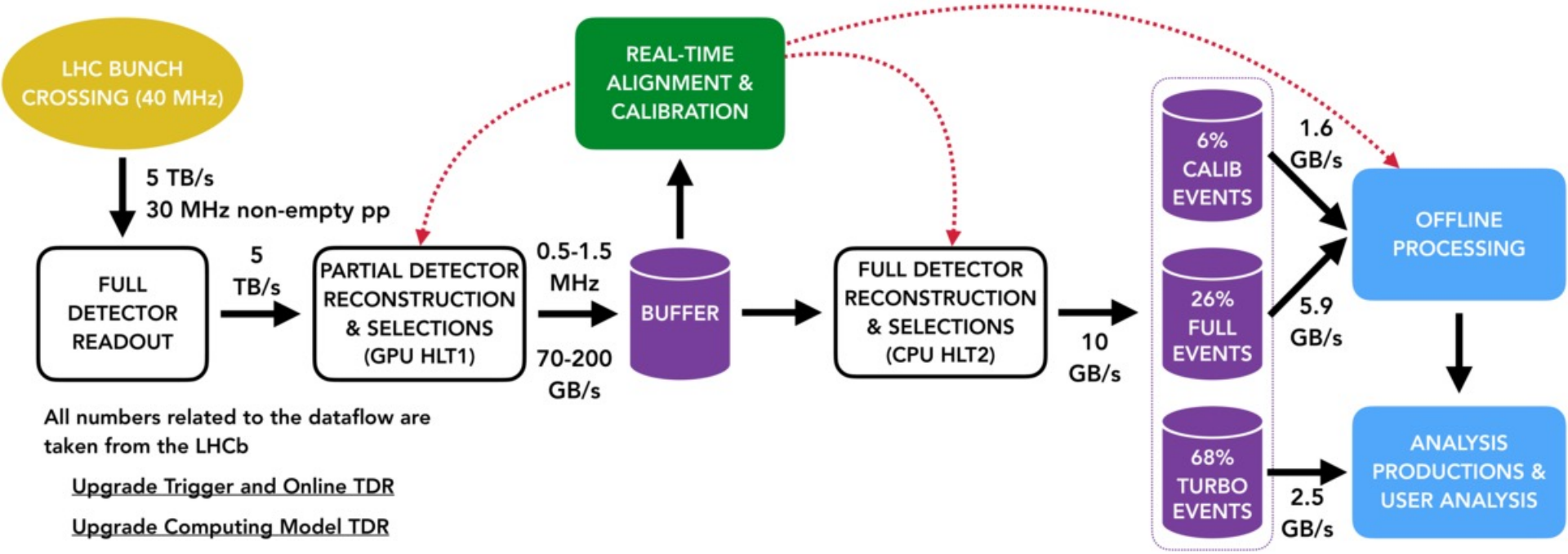
Buffer events to disk, perform online detector calibration and alignment

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

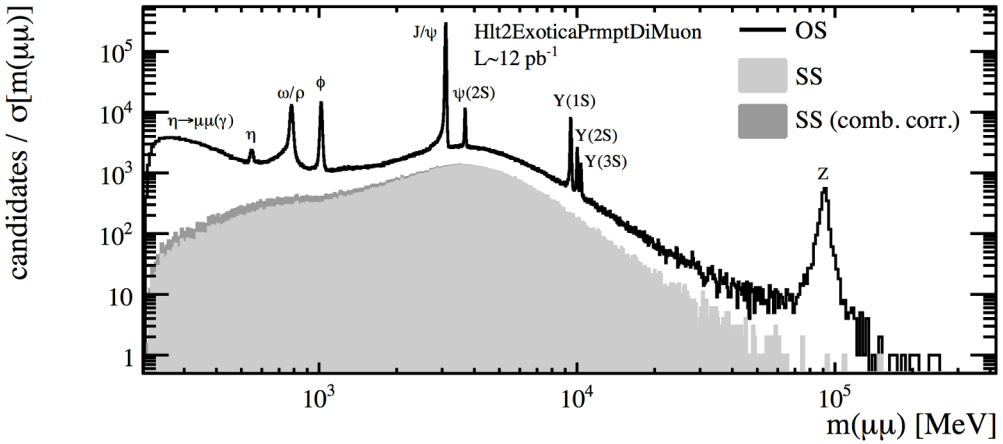
The turbo stream



All numbers related to the dataflow are taken from the LHCb

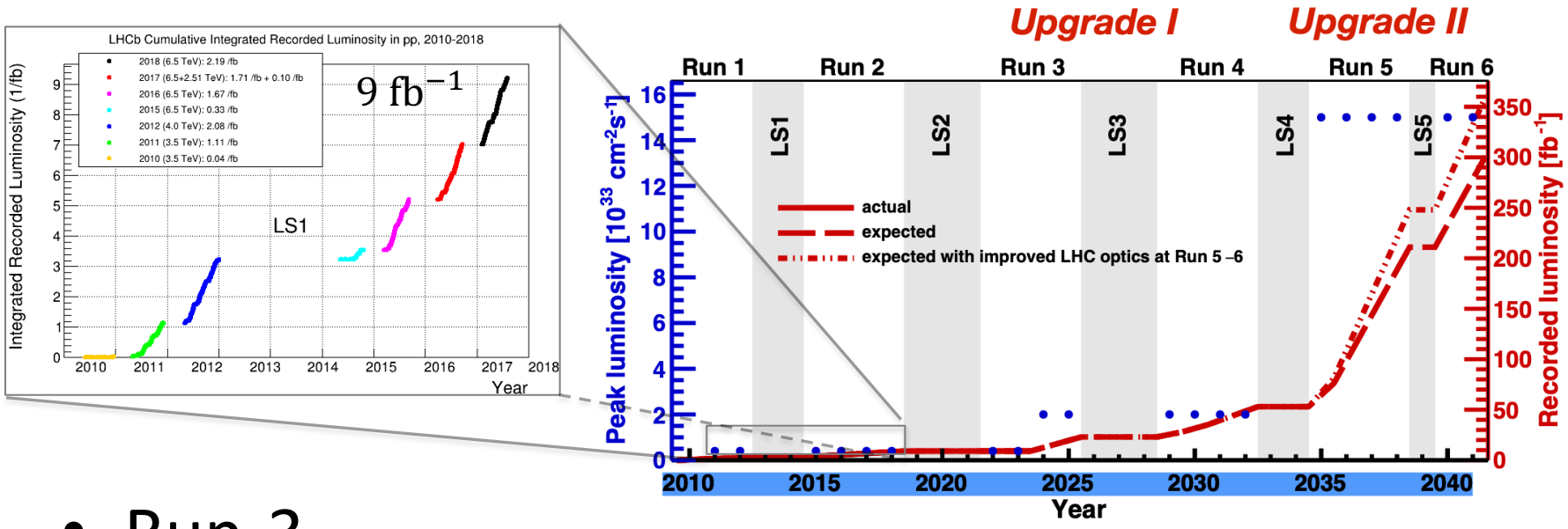
Upgrade Trigger and Online TDR

Upgrade Computing Model TDR



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

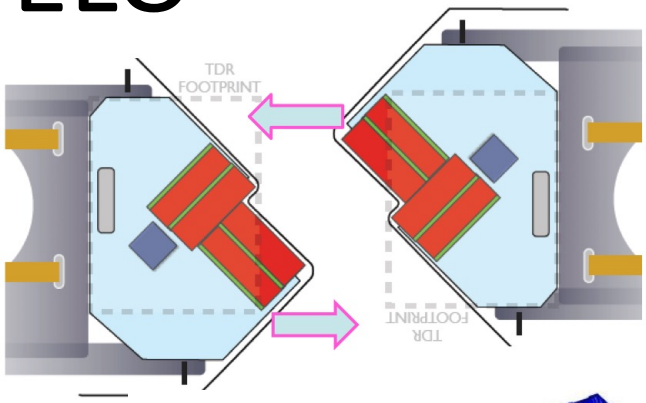
LHCb luminosity prospects



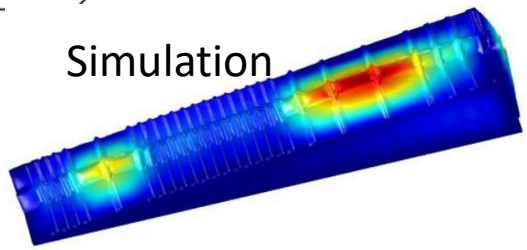
- Run-3
  - Luminosity: 7 fb^{-1} (2024) + 7 fb^{-1} (2025)
  - Yields, compared to Run 1+2
    - Muon modes ~2
    - Hadronic modes ~4 (2 x 2 due to higher trigger eff.)

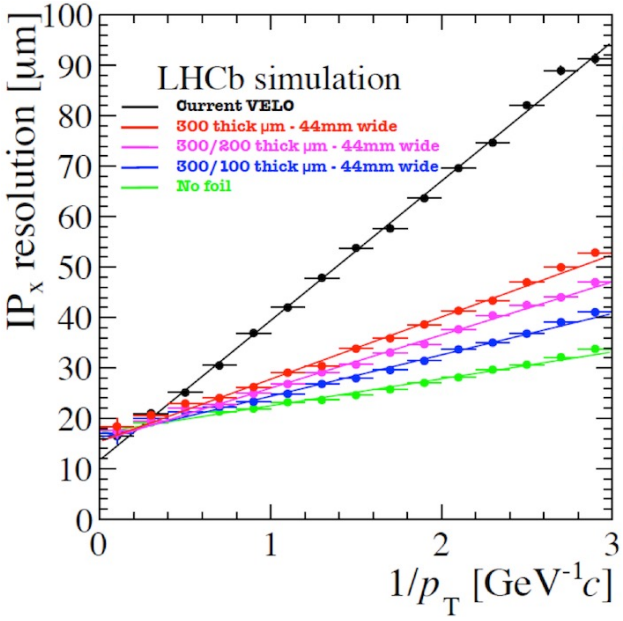
The upgraded VELO

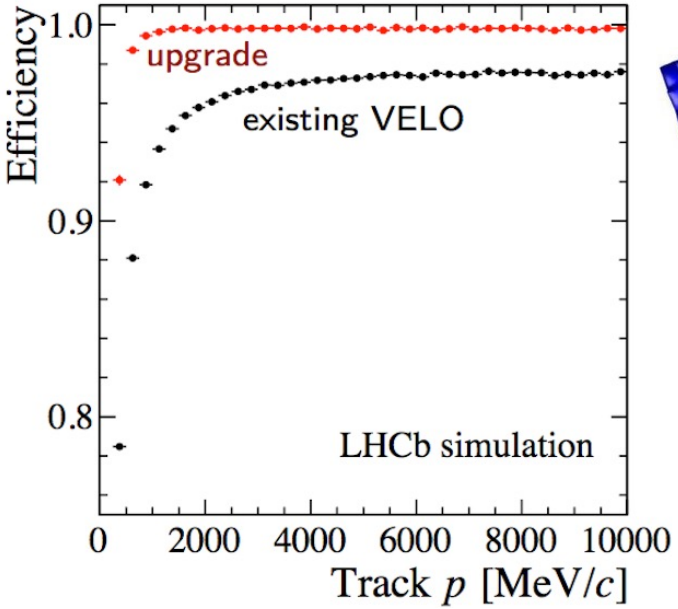
- Hybrid silicon pixel (55 x 55 μm^2)
  - Thinner RF foil, 185 μm
  - Inner aperture reduced from 5.5→3.5 mm
- Incident in 2023, RF foil replaced now



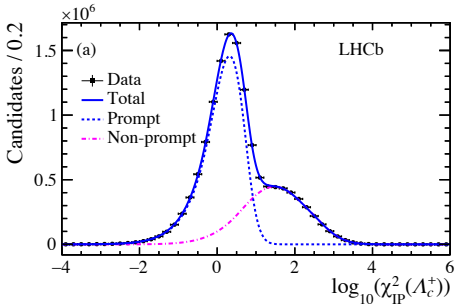
Simulation







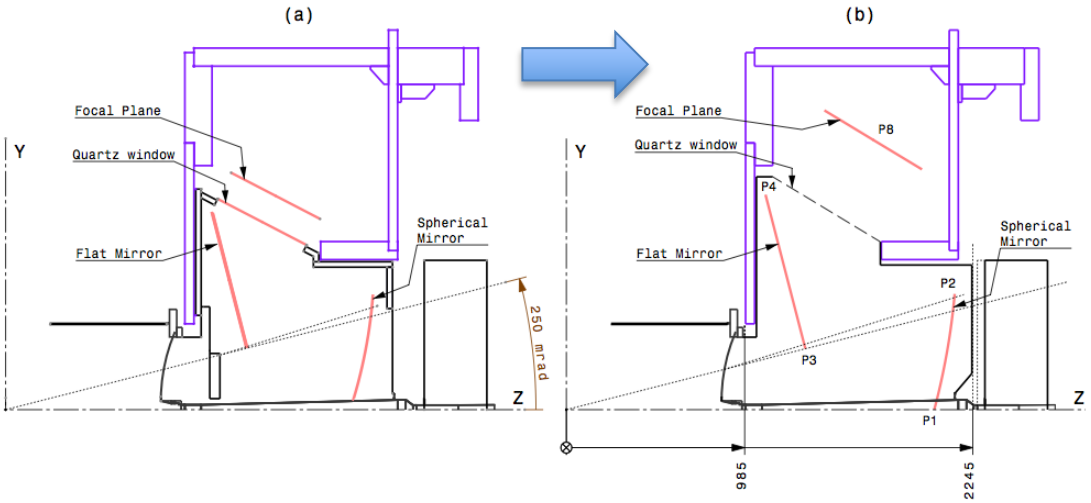
Importance of IP resolution

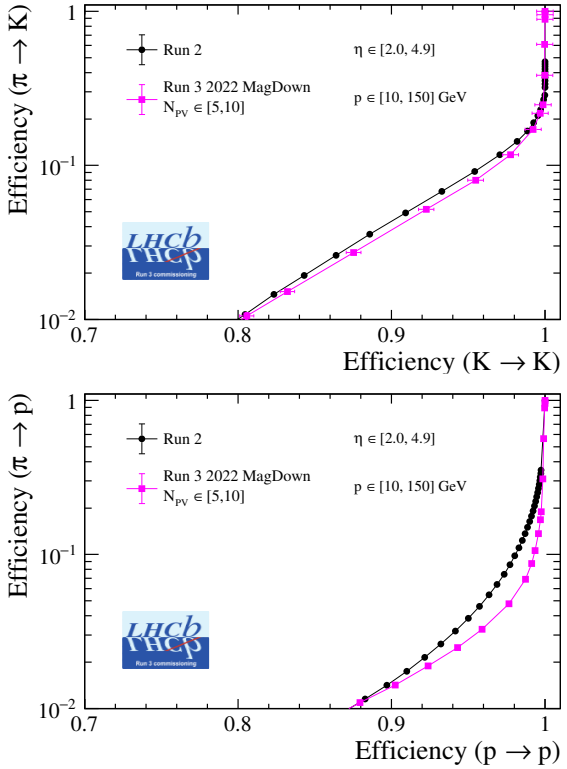


The upgraded RICH

- 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

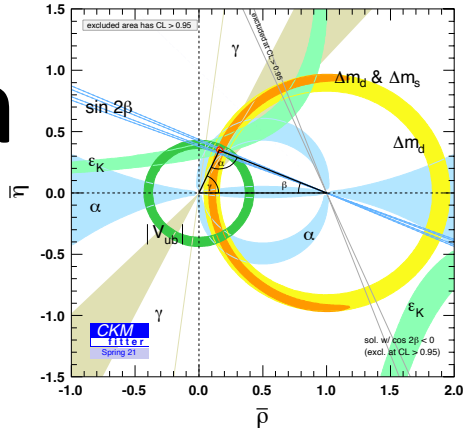
[LHCb-FIGURE-2023-019]

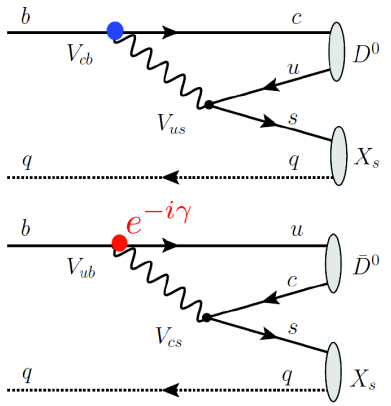




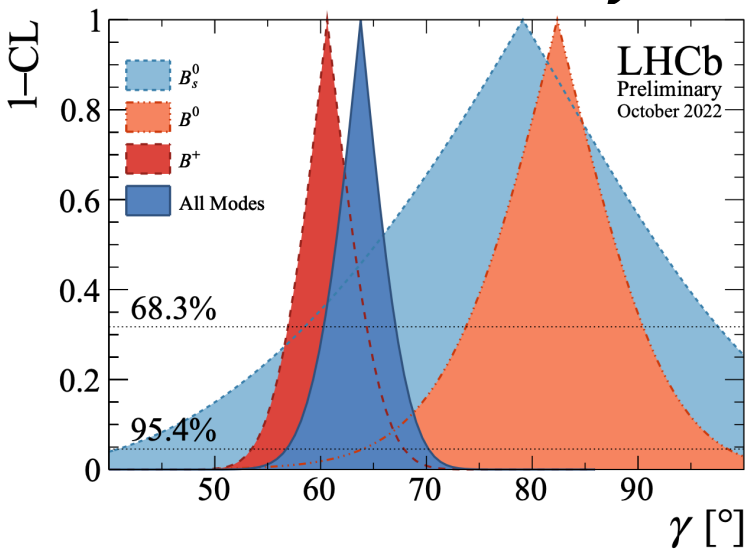
CKM-γ combination

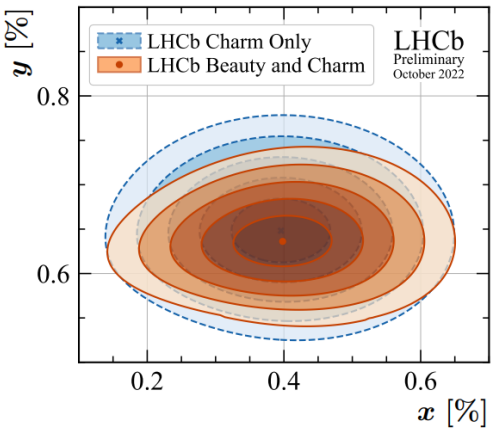
- Simultaneous determination of CKM-γ & charm mixing parameters
  - CKM $\gamma = \left(63.8^{+3.5}_{-3.7}\right)°$
  - Charm mixing $x = \left(0.398^{+0.050}_{-0.049}\right)\%$,
    $y = \left(0.636^{+0.020}_{-0.019}\right)\%$

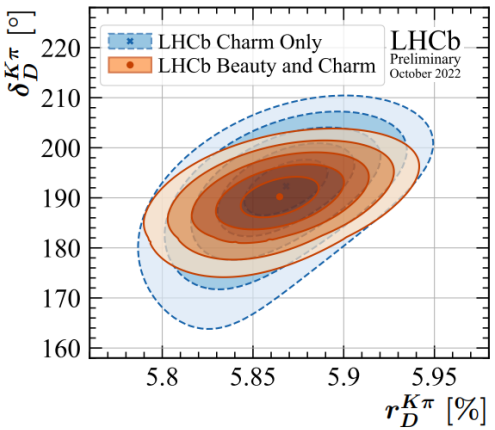




[LHCb-Conf-2022-003]

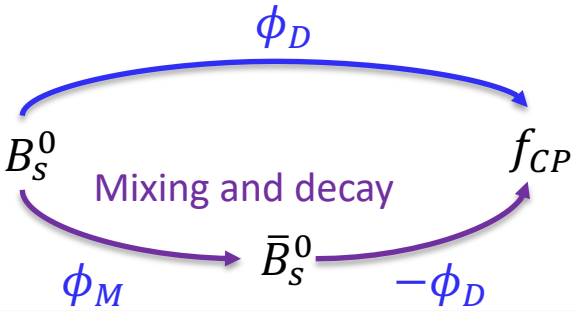


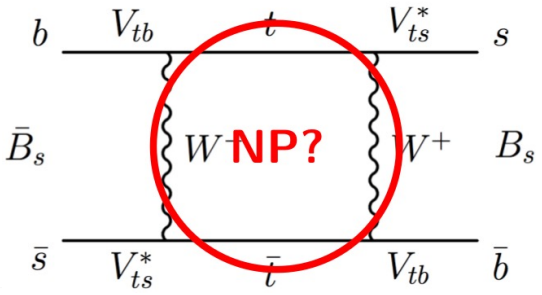




CPV in mixing

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





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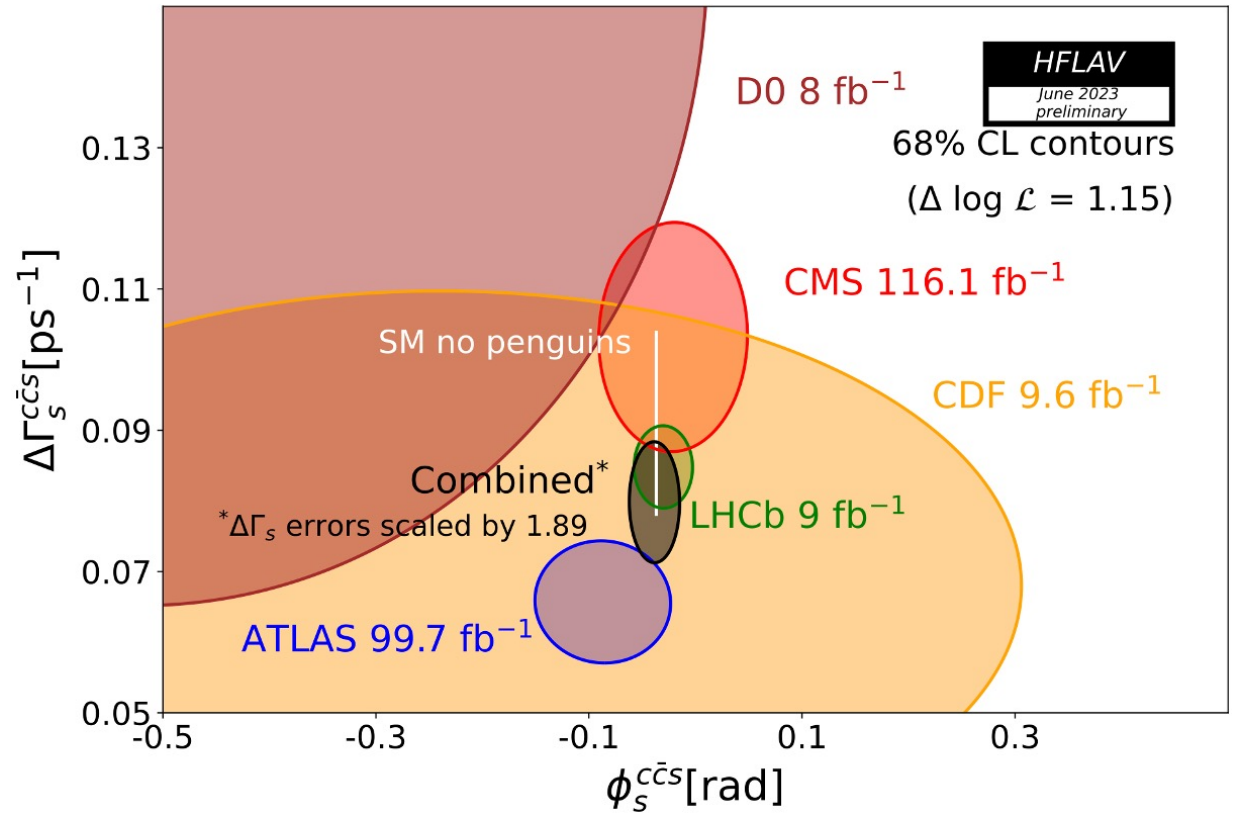

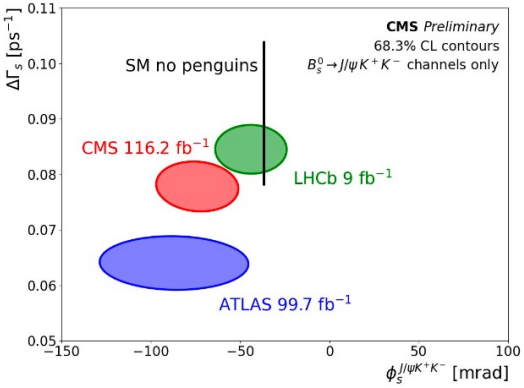

Flavour tagging?