LHCb上味物理的反常

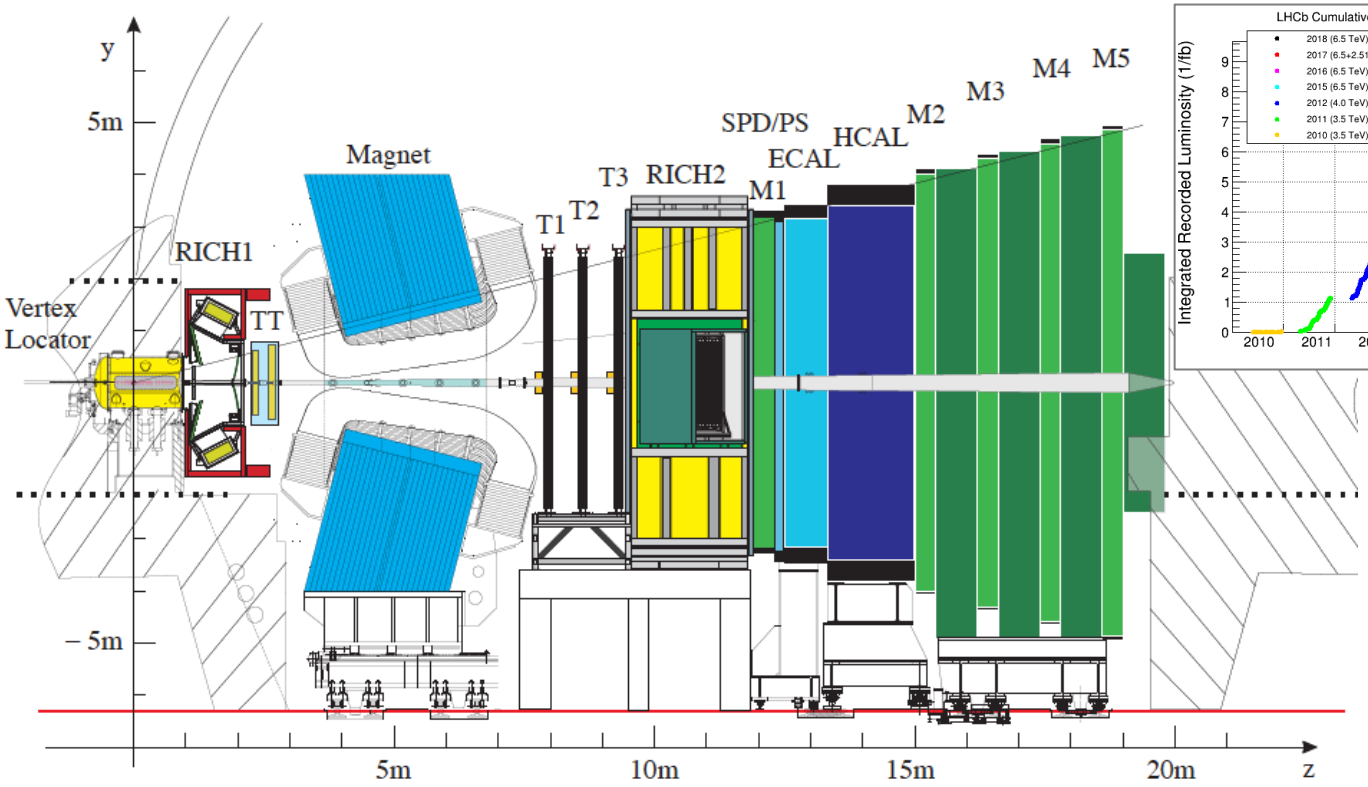
何吉波 (中国科学院大学)

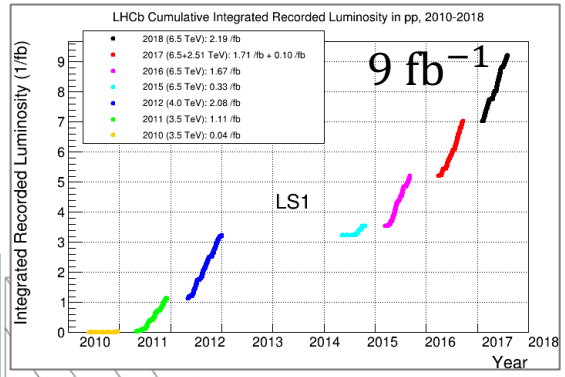
Large Hadron Collider

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

The LHCb experiment

[JINST 3 (2008) S08005]

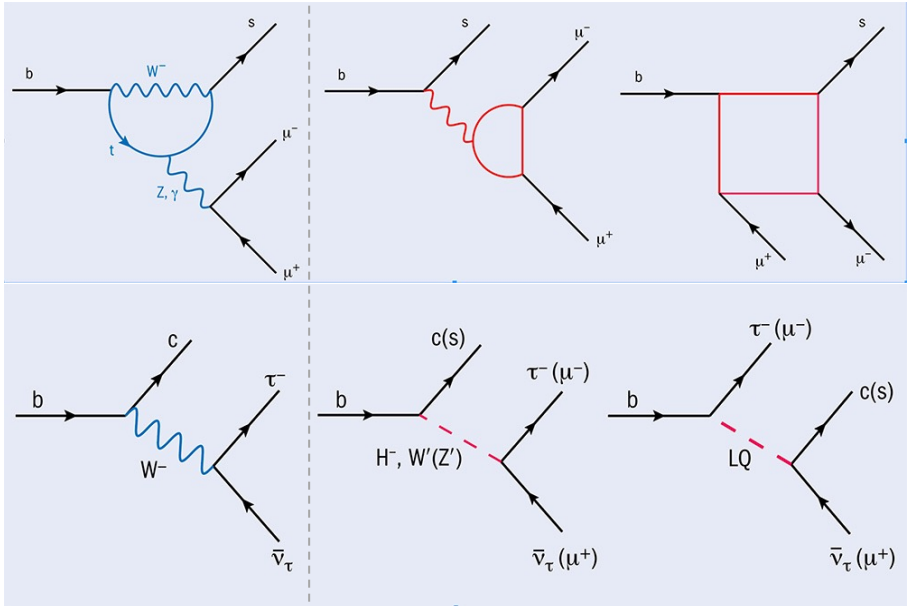


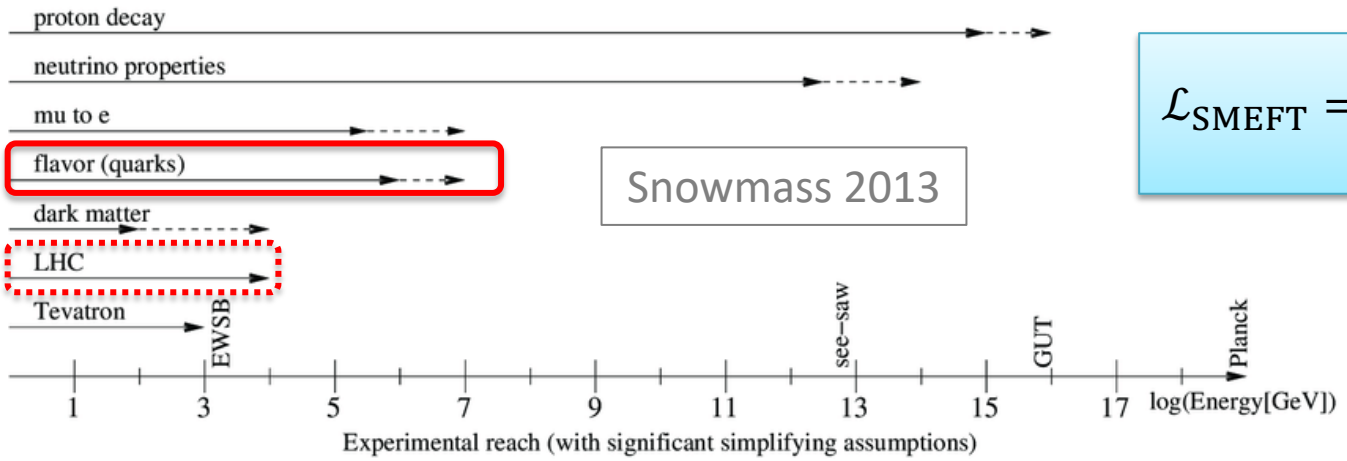


Vertex Locator	$\sigma_{PV,x/y} \sim 10\ \mu m$, $\sigma_{PV,z} \sim 60\ \mu m$
Tracking (TT, T1-T3)	$\Delta p/p$: 0.4% at 5 GeV/c, to 0.6% at 100 GeV/c
RICHs	$\varepsilon(K \to K) \sim 95\%$, mis-ID rate $(\pi \to K) \sim 5\%$
Muon system (M1-M5)	$\varepsilon(\mu \to \mu) \sim 97\%$, mis-ID rate $(\pi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

Indirect search for New Physics

- Precision measurement of heavy hadron decays
  - Flavour-Changing NC
  - Flavour-Changing CC
- Probe New Physics at high energy scale



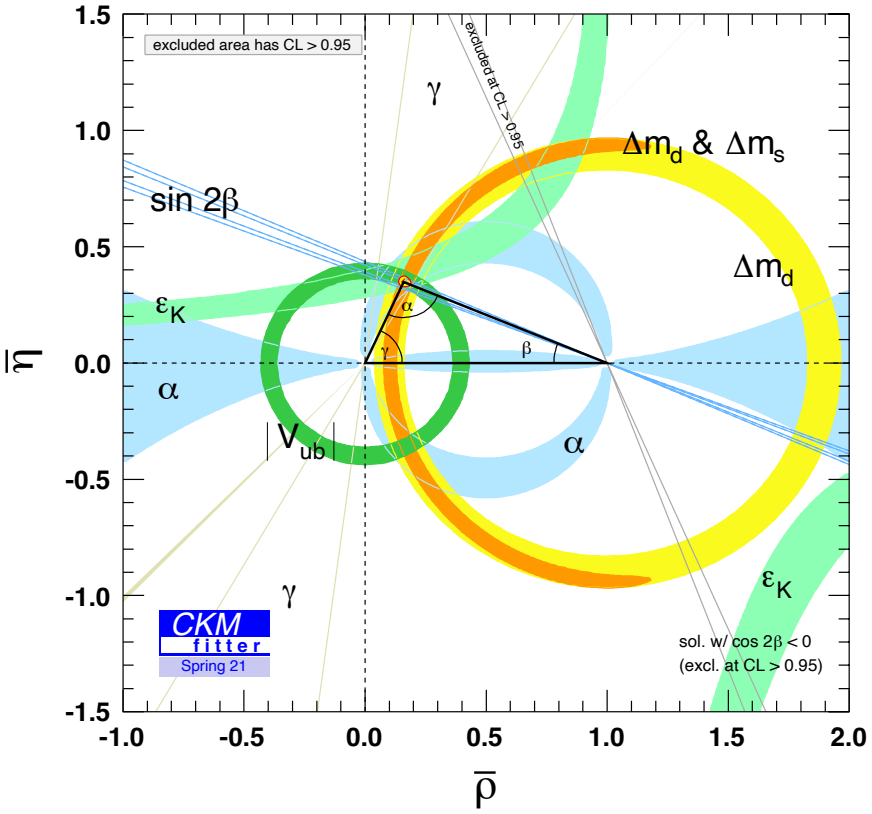


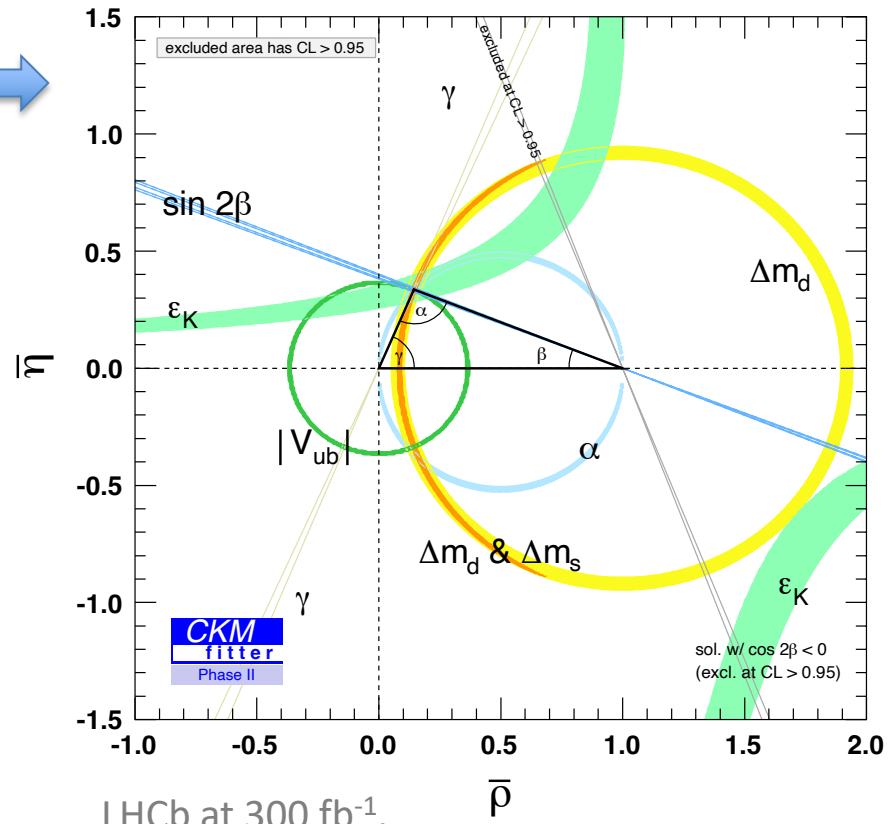
Snowmass 2013

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{C_i}{\Lambda^2}\mathcal{O}_i$$

Indirect search for NP (cont.)

- Overconstrain the CKM triangle

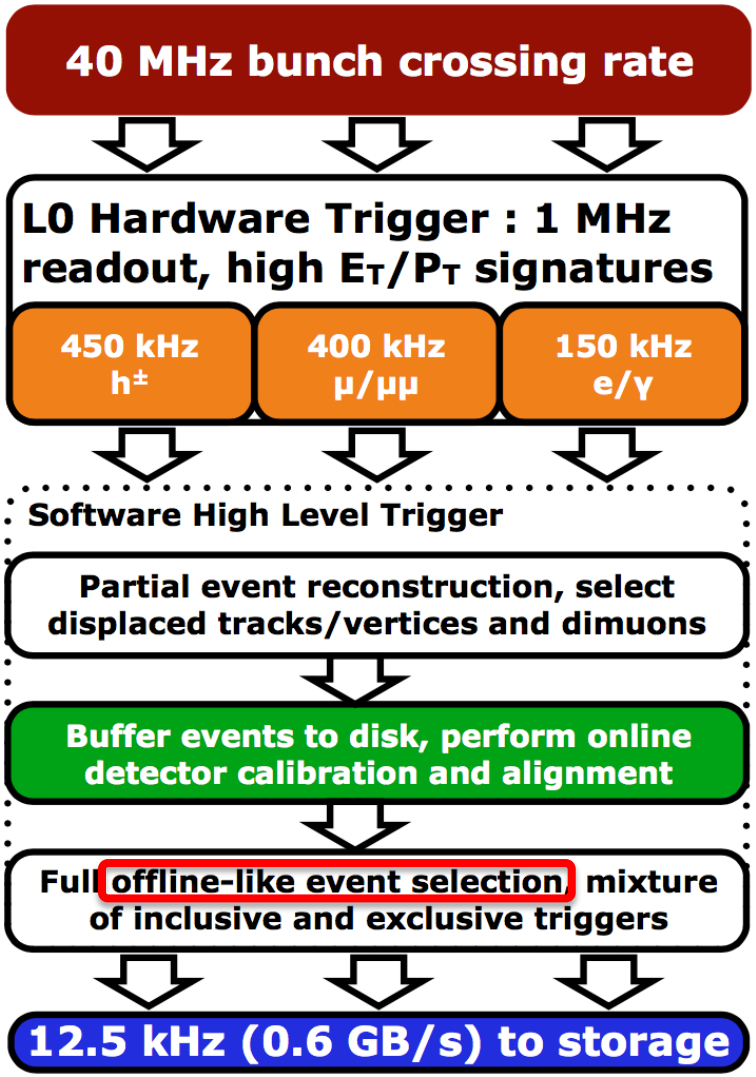




More in talks of J. Yu, L. Sun, S. Zhang

LHCb at 300 fb^{-1},
CMS/ATLAS at 3000 fb^{-1}, Belle II at 50 ab^{-1}.

The LHCb trigger (2018)

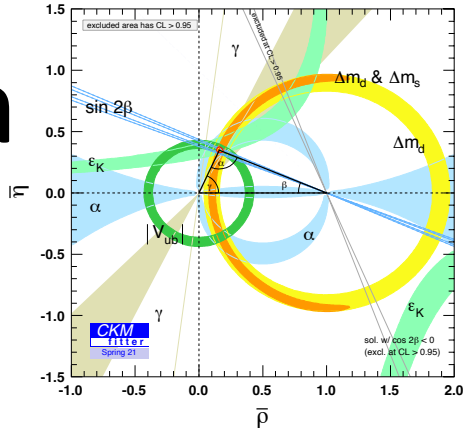


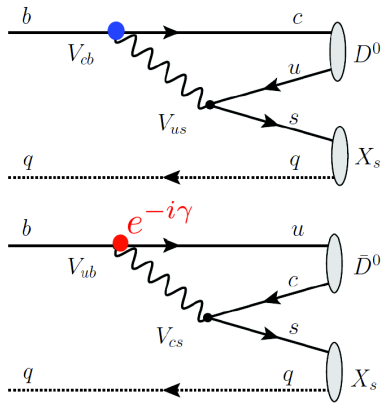
- L0, Hardware
  - $p_{\mathrm{T}}(\mu_1)\times p_{\mathrm{T}}(\mu_2) >$ (1.5 GeV)^2
  - $p_{\mathrm{T}}(\mu) >$ 1.8 GeV
  - $E_{\mathrm{T}}(e) >$ 2.4 GeV
  - $E_{\mathrm{T}}(\gamma) >$ 3.0 GeV
  - $E_{\mathrm{T}}(h) >$ 3.7 GeV
- High Level Trigger
  - Stage1, p_{T}, IP
  - Stage2, full selection

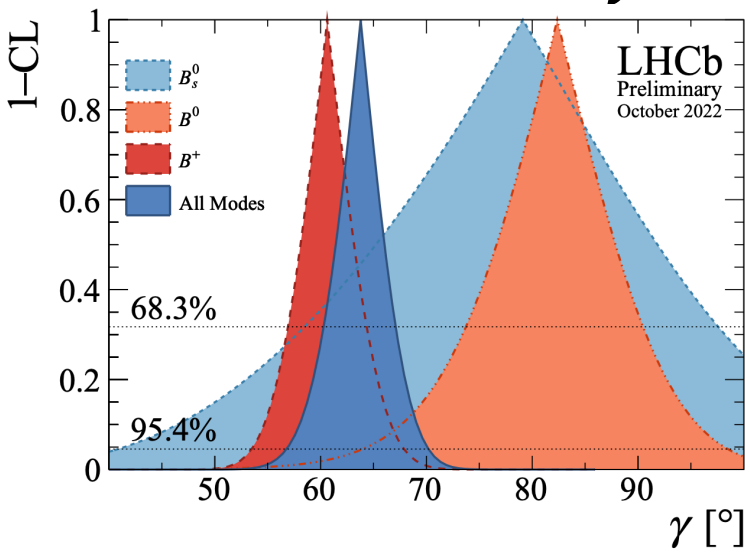
CKM-γ combination

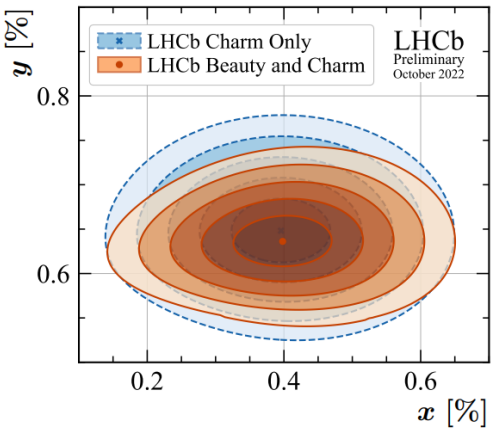
- Simultaneous determination of CKM-γ & charm mixing parameters
  - CKM $\gamma = \left(63.8^{+3.5}_{-3.7}\right)°$
  - Charm mixing $x = \left(0.398^{+0.050}_{-0.049}\right)\%$,
    $y = \left(0.636^{+0.020}_{-0.019}\right)\%$

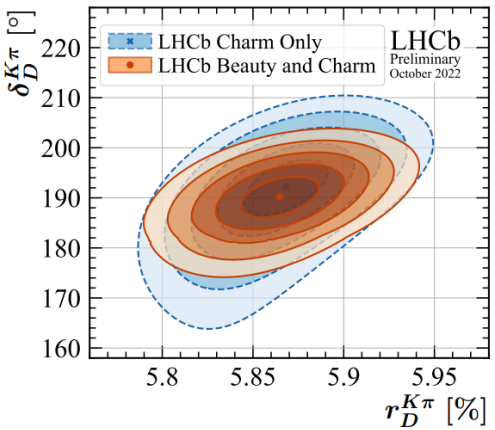
[LHCb-Conf-2022-003]





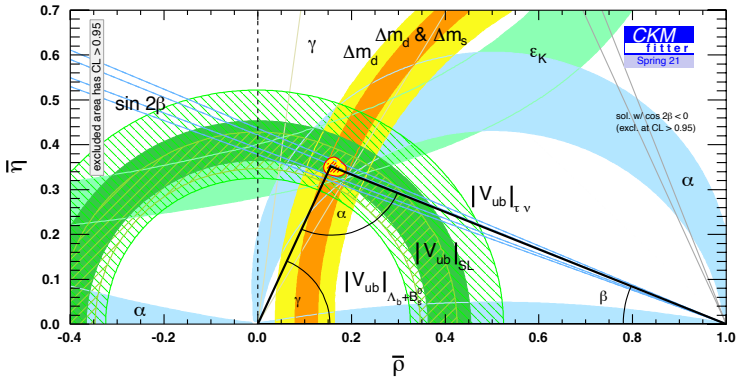


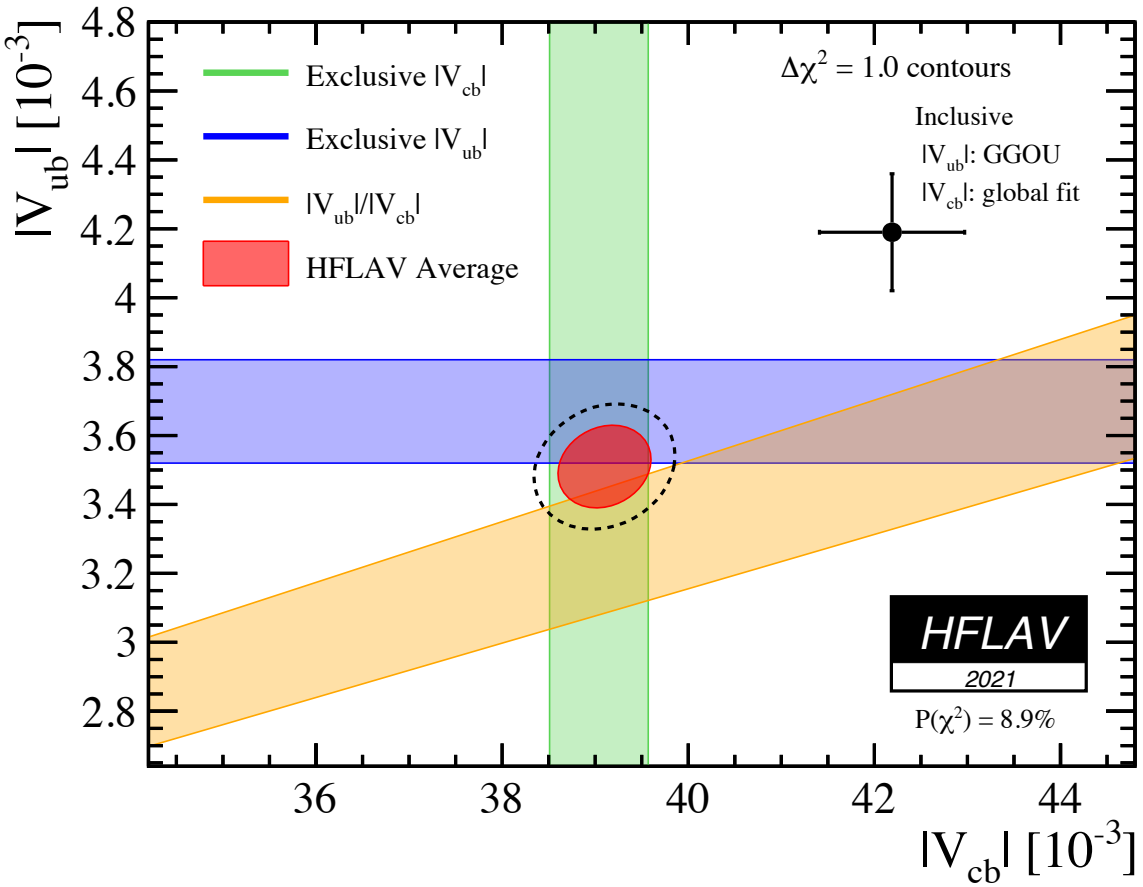


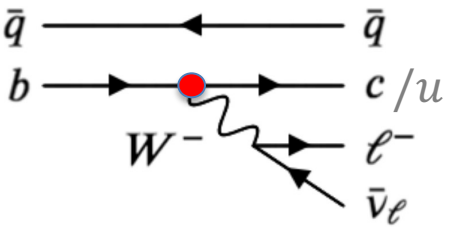


V_{cb}, V_{ub}

- Some tension between exclusive/inclusive

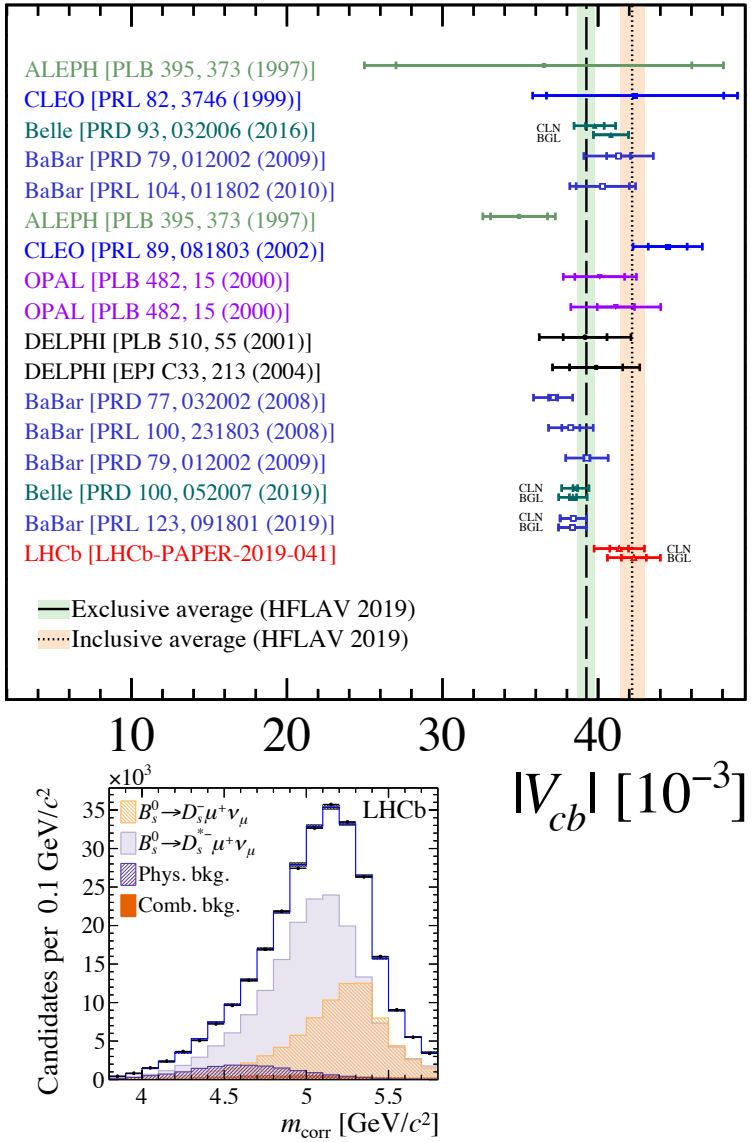




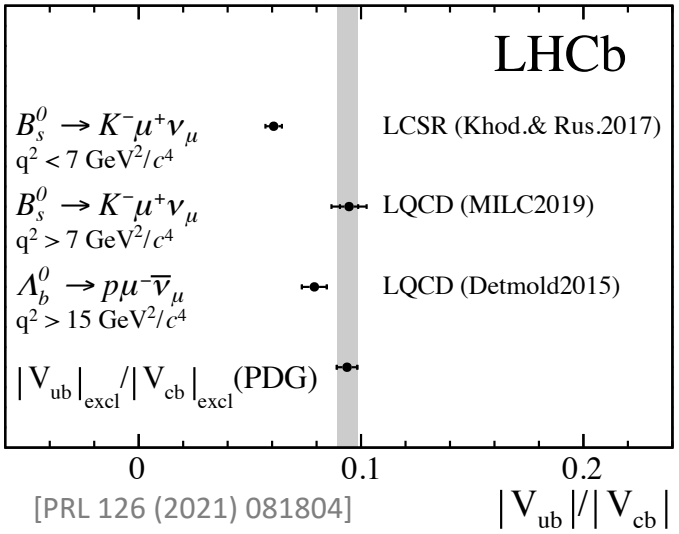


$$d\Gamma \propto |V_{cb}|^2 |f_H|^2$$

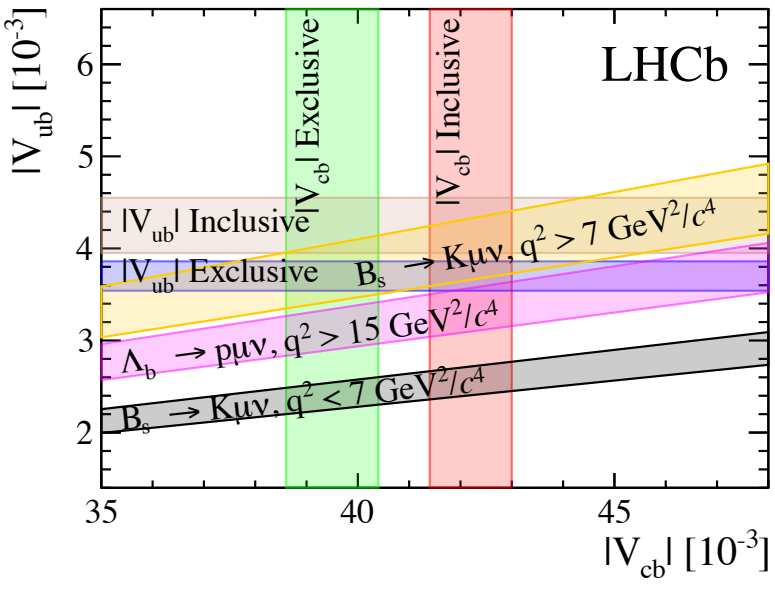
V_{cb}, V_{ub}



[PRD 101 (2020) 072004]



[PRL 126 (2021) 081804]



ΔA_{CP} in charm

[PRL 122 (2019) 211803]

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

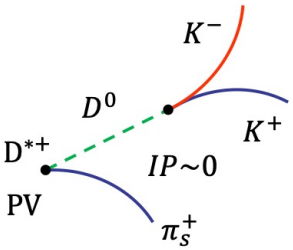
$$\Delta A_{CP} \equiv A_{CP}(K^-K^+) - A_{CP}(\pi^-\pi^+)$$

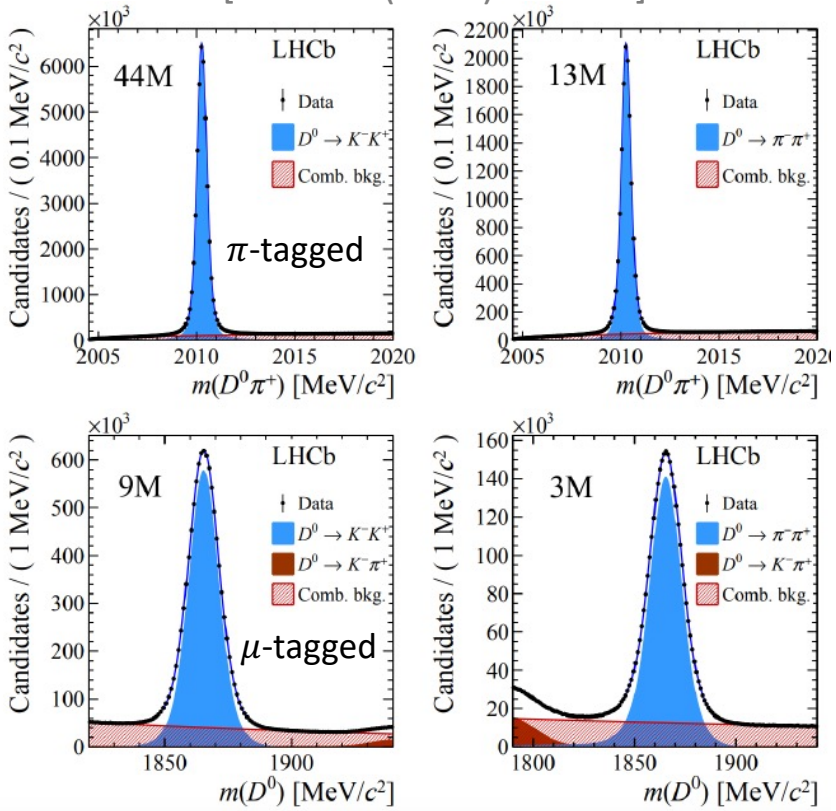
$$\Delta A_{CP}^{\pi\text{-tagged}} = [-18.2 \pm 3.2\,(\text{stat.}) \pm 0.9\,(\text{syst.})] \times 10^{-4},$$

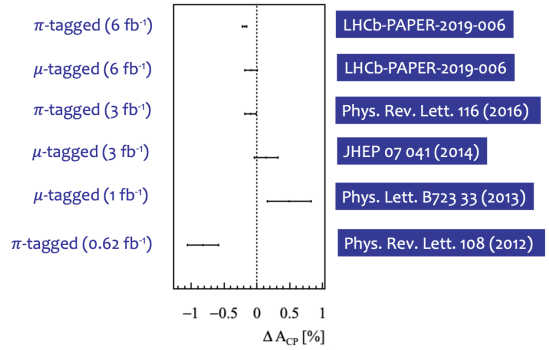
$$\Delta A_{CP}^{\mu\text{-tagged}} = [-9 \pm 8\,(\text{stat.}) \pm 5\,(\text{syst.})] \times 10^{-4}.$$

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.*

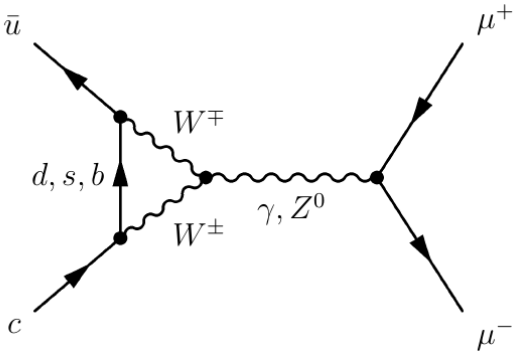
2001
Beauty particles: time-dependent *CP* violation in B^0 meson decays
BaBar and Belle collaborations

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

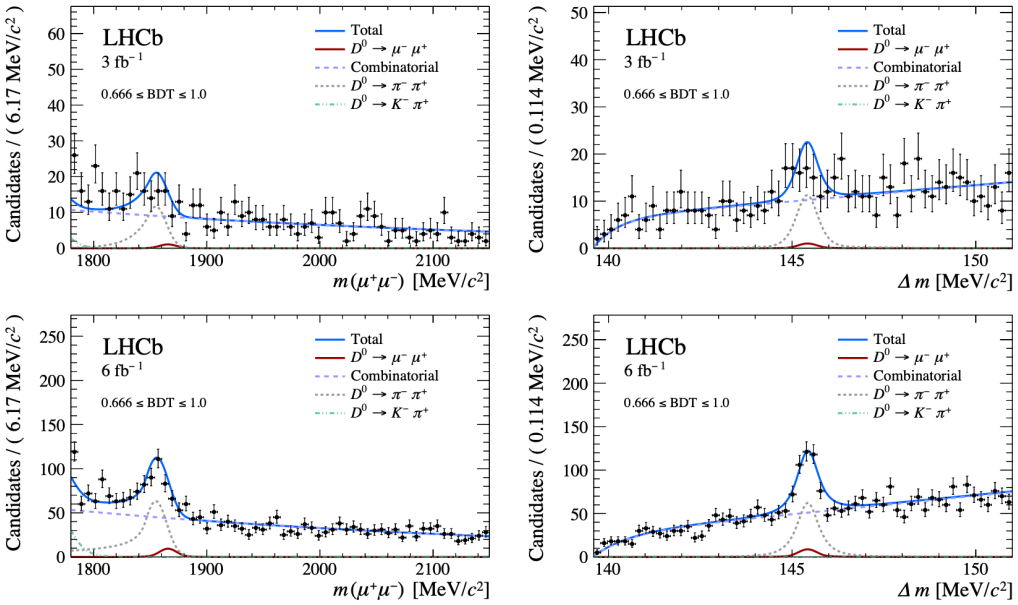
2019
Charm particles: *CP* violation in D^0 meson decays
LHCb collaboration

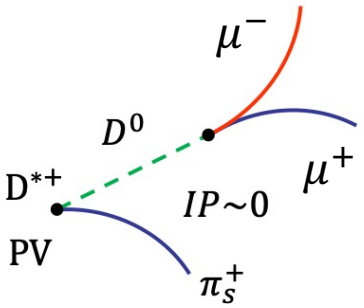
$D^0 \to \mu^+\mu^-$

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



[LHCb-Paper-2022-029]

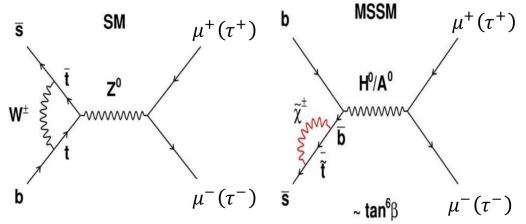


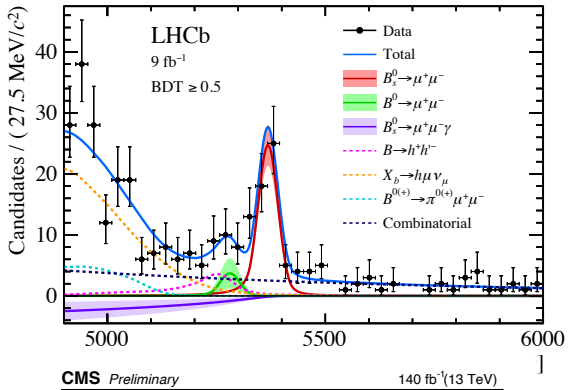


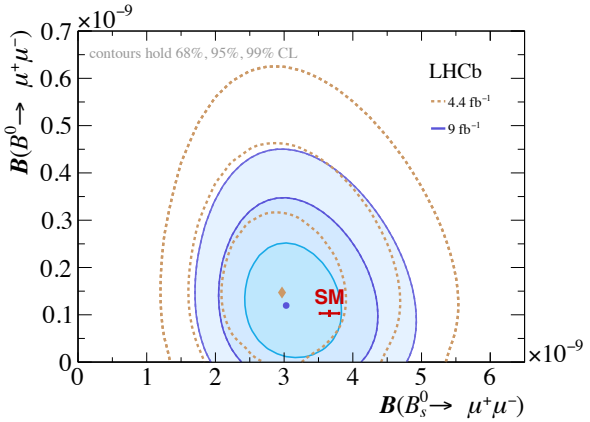
$\mathcal{B}(D^0 \to \mu^+\mu^-) < 2.9{\times}10^{-9}$ @ 90% CL

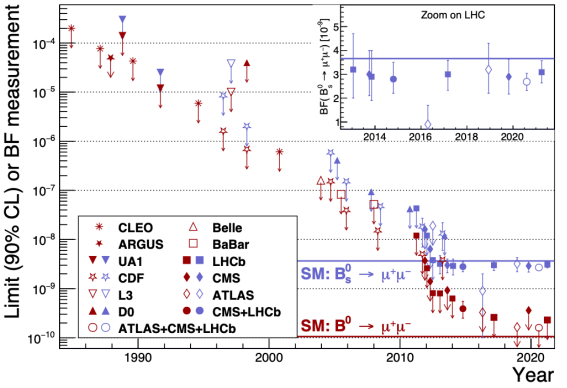
$B^0_{(s)} \to \mu^+\mu^-$

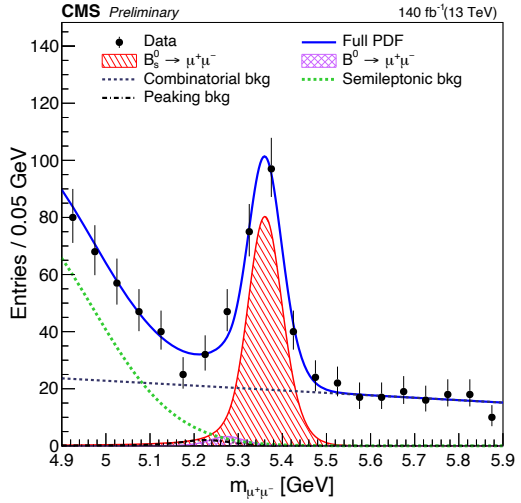
- Suppressed in SM, could be enhanced by New Physics

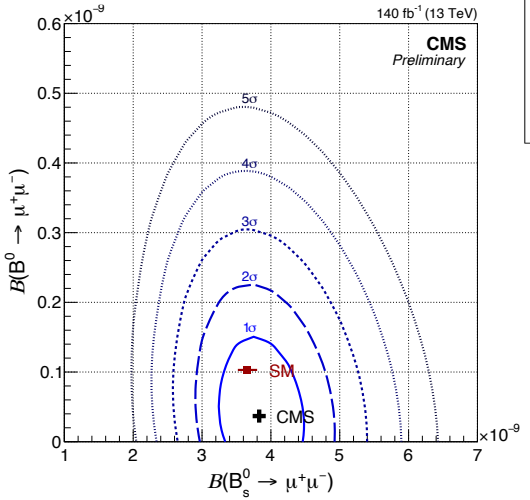


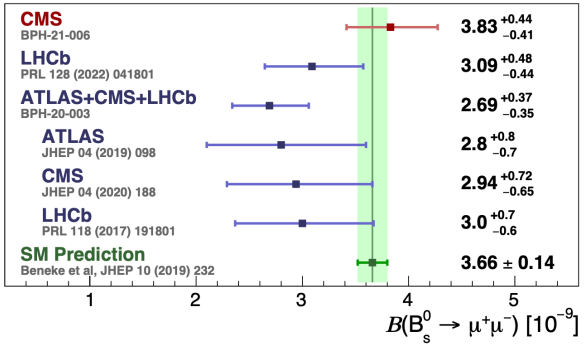


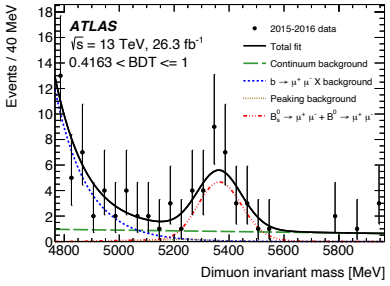












[PRL 128 (2022) 041801]

$B_s^0 \to \mu^+\mu^-$ effective lifetime

- B_s^0 mixing ⇒ effective τ

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

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

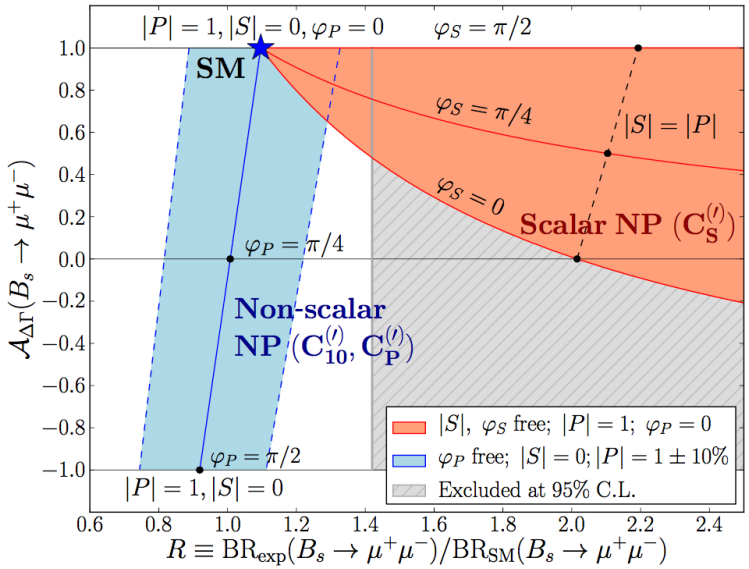
$$y_s = \frac{\Delta\Gamma_s}{2\Gamma_s}$$

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

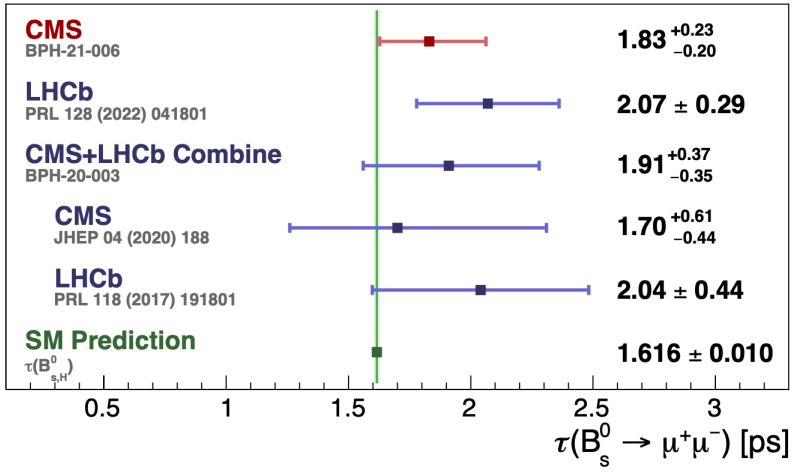
$$\tau_{\mu\mu} = 2.07 \pm 0.29 \pm 0.03 \text{ ps}$$

$$1.83\ ^{+0.23\ +0.04}_{-0.20\ -0.04} \text{ ps}$$

[CMS-PAS-BPH-21-006]



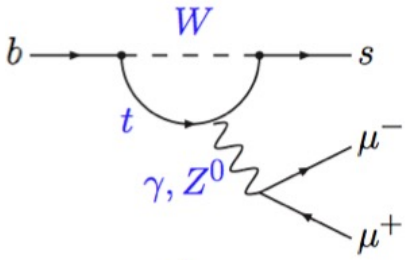
[De Bruyn *et al.*, PRL 109 (2012) 041801]

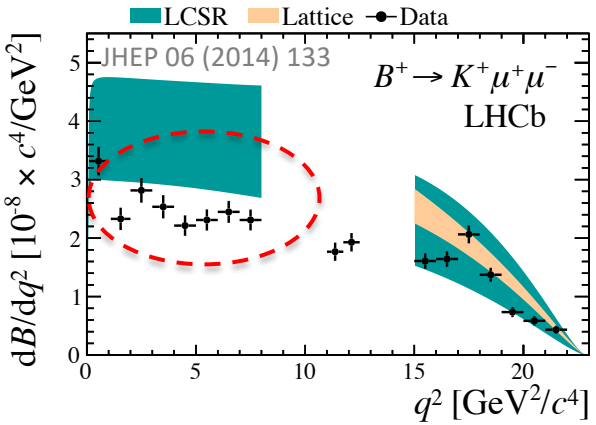


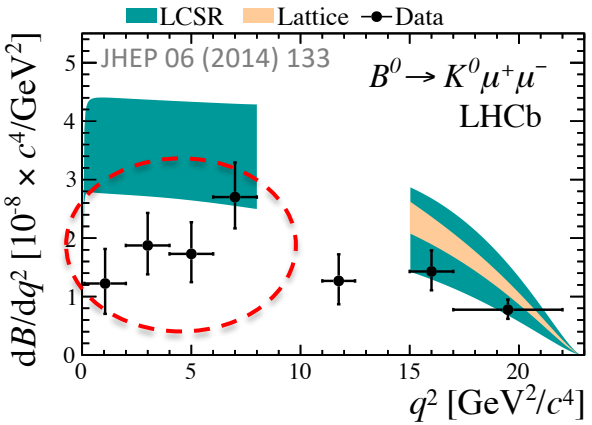
[PRL 128 (2022) 041801]

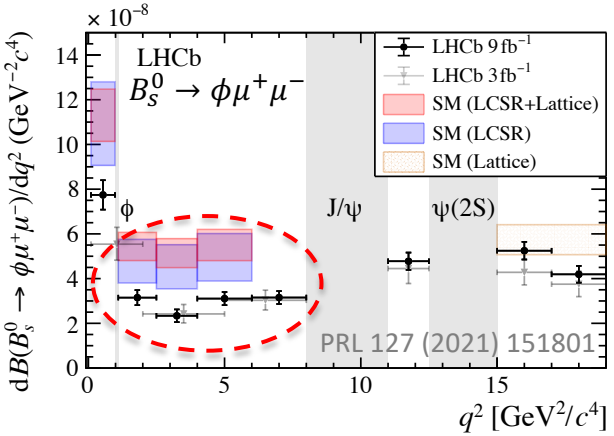
Branching fraction of $b \to s\mu^+\mu^-$

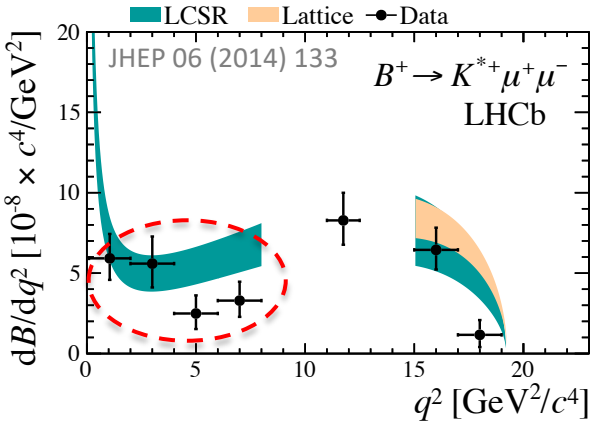
- Pattern of tensions seen, theoretical uncertainty?

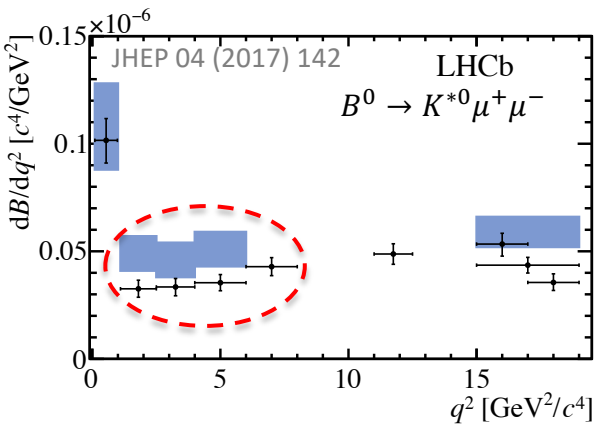


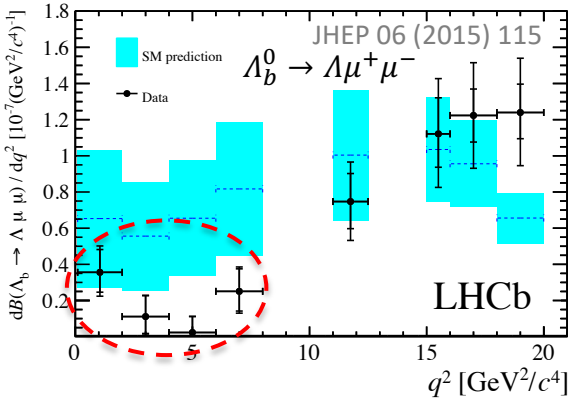












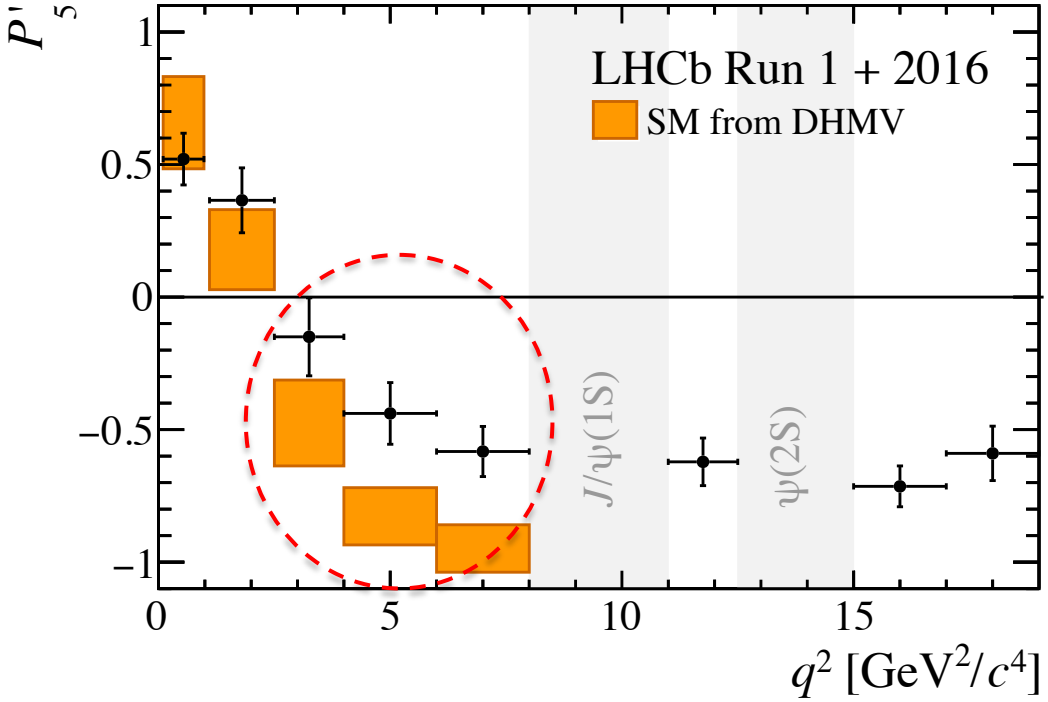
P_5' with $B^0 \to K^{*0}\mu^+\mu^-$

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

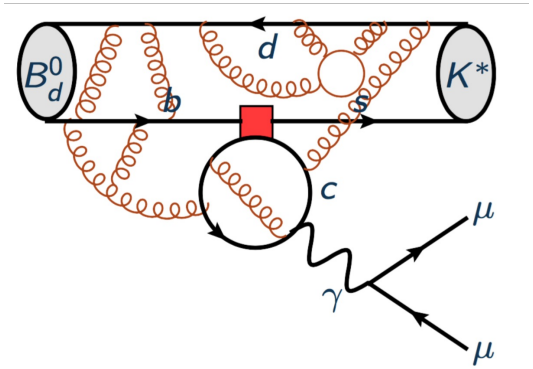
[S. Descotes-Genon, *et al.*, JHEP 01 (2013) 048]

- Also measured by Belle, ATLAS, CMS

[PRL 125 (2020) 011802]

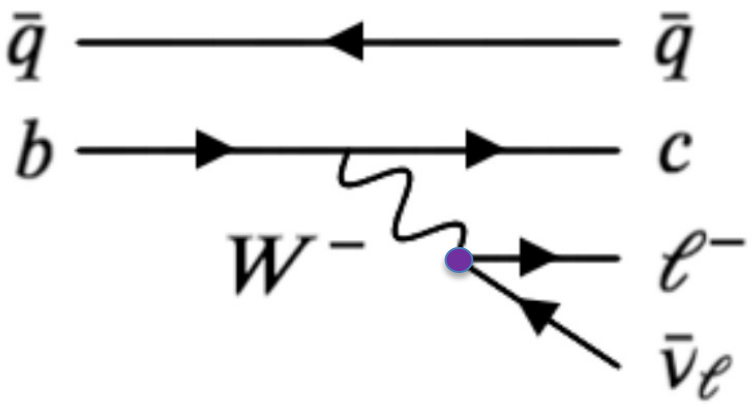


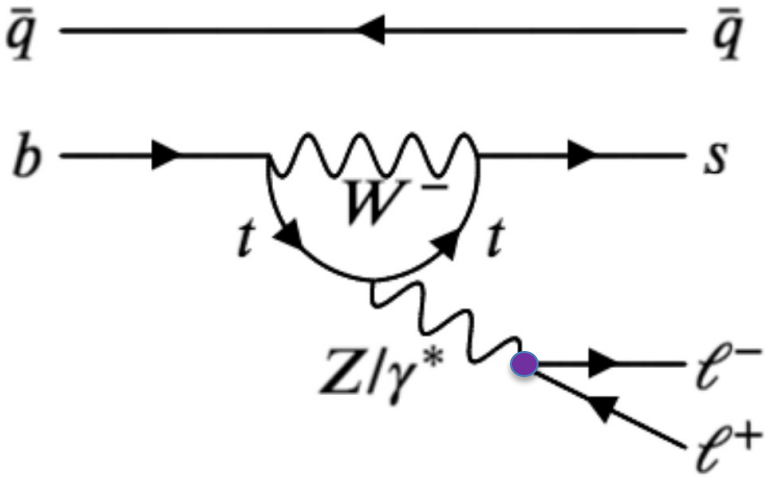
[Belle, PRL 118 (2017) 111801]
[ATLAS, JHEP 10 (2018) 047]
[CMS, PLB 781 (2018) 517]



Lepton flavour universality

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





  - which means, e.g.,

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

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

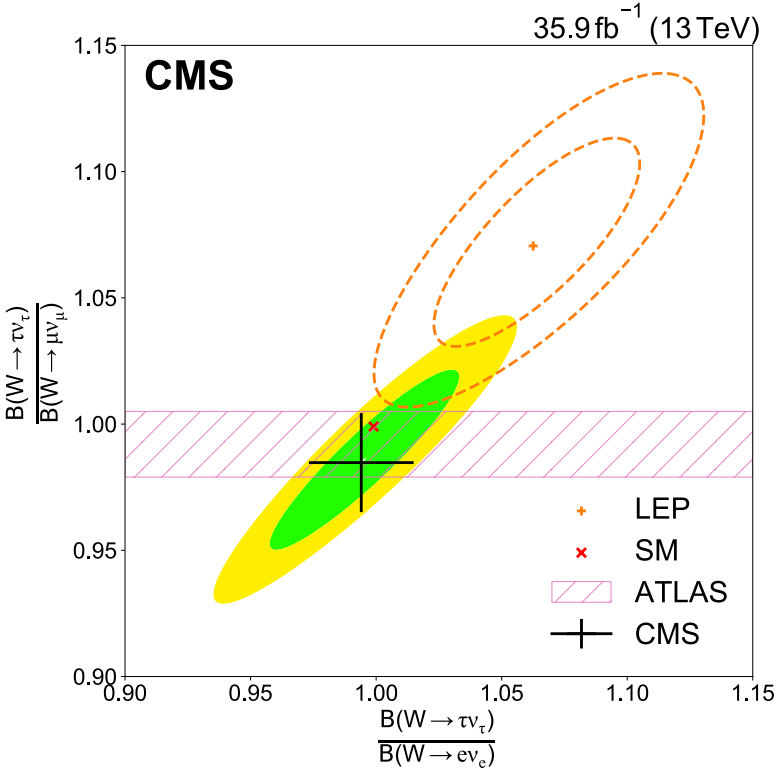
$\mathcal{O}(1\%)$ QED correction
[M. Bordone *et al.*, EJPC 76 (2016) 440]

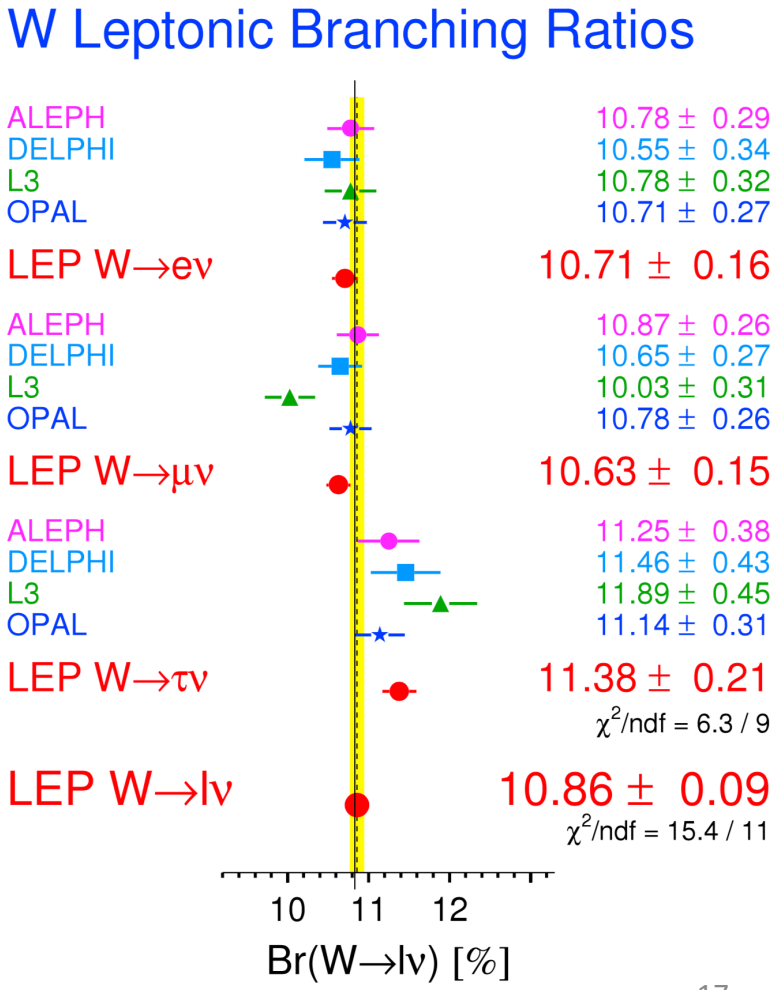
- Lepton flavor universality violation? New Physics!

Experimental test of LFU

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

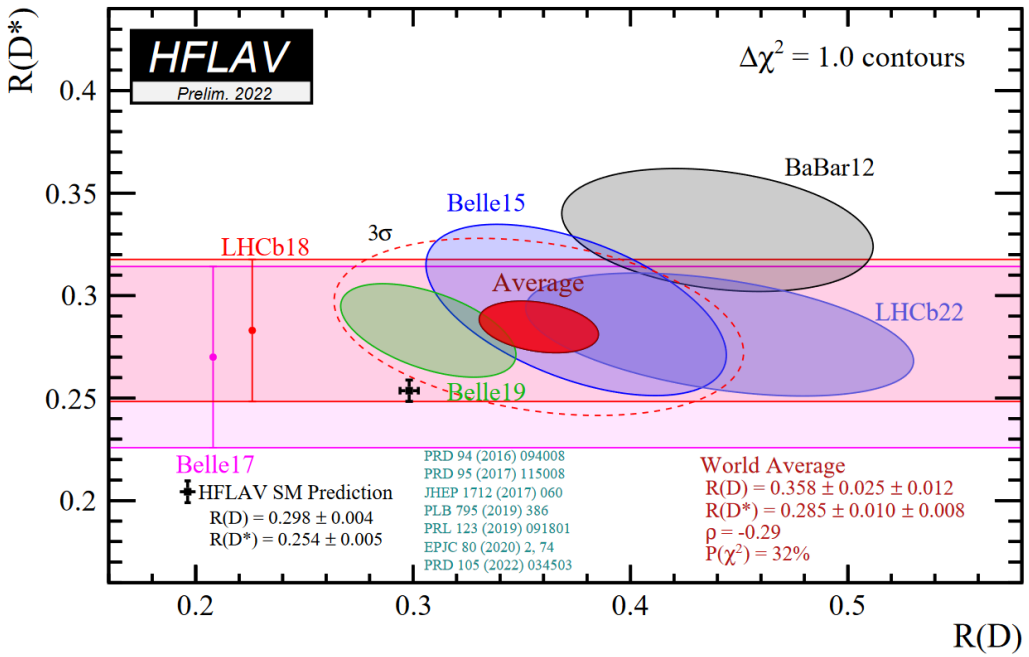
[ATLAS, NP 17 (2021) 813; CMS, PRD 105 (2022) 072008]

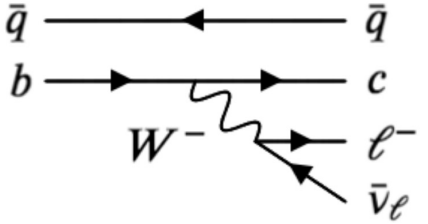




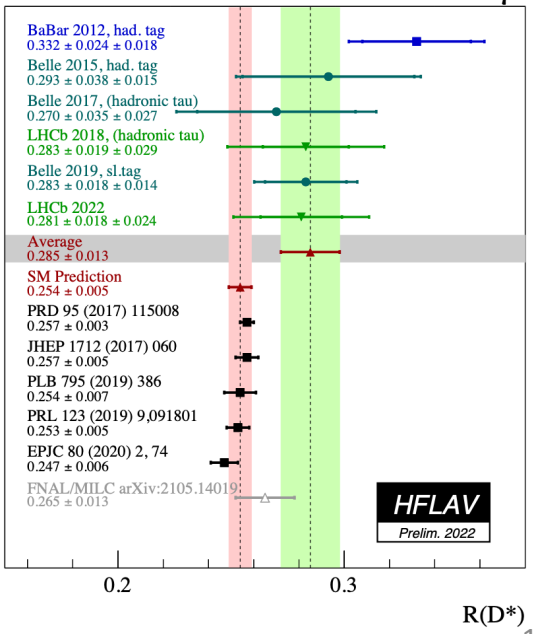
LFU in $b \to c\ell\nu$ decays

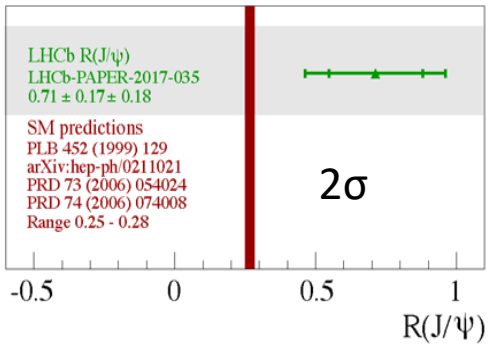
- Deviations from SM seen by Babar/Belle/LHCb



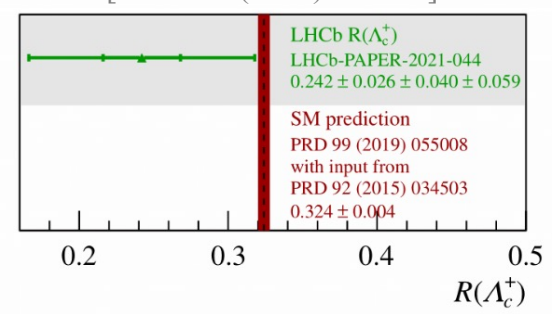


$$R(H_c) = \frac{\mathcal{B}(H_b \to H_c \tau^- \bar{\nu}_\tau)}{\mathcal{B}(H_b \to H_c \mu^- \bar{\nu}_\mu)}$$



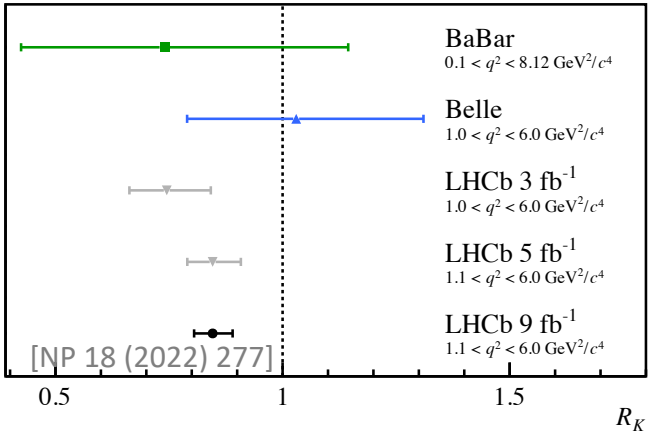


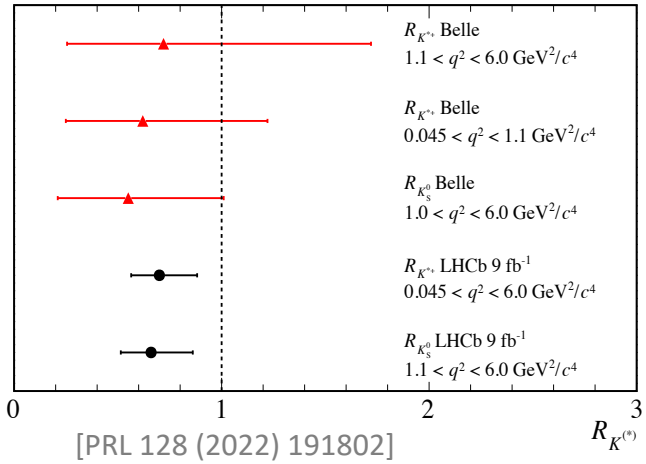
[PRL 128 (2022) 191803]



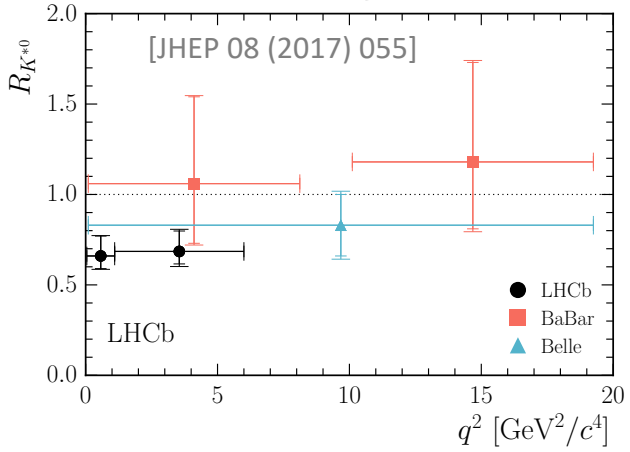
LFU in $b \to s\ell^+\ell^-$ decays

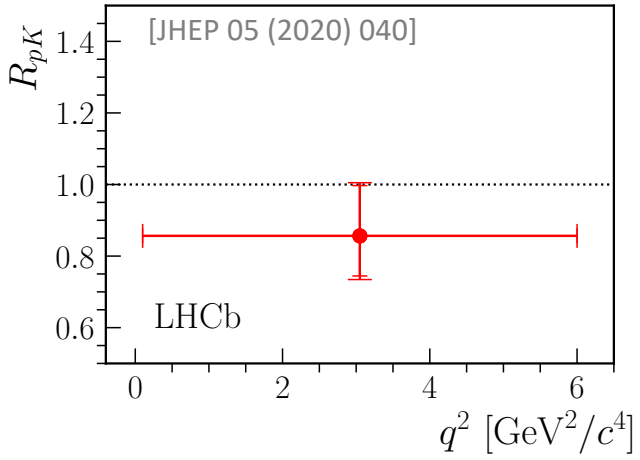
- Deviations from SM seen by LHCb

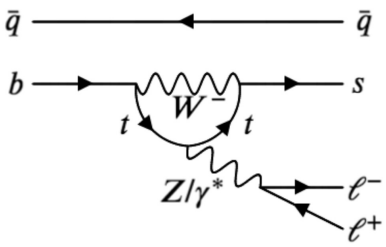




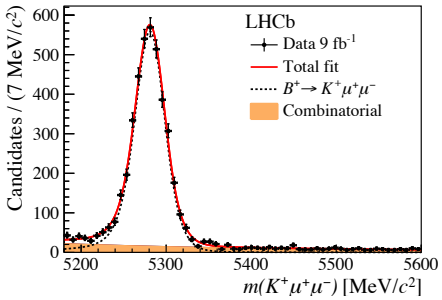
[PRL 128 (2022) 191802]

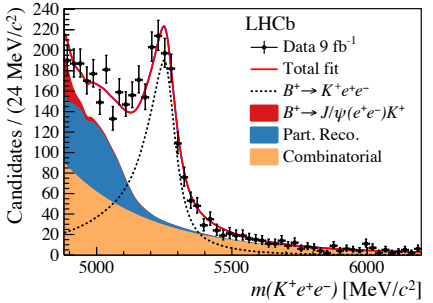




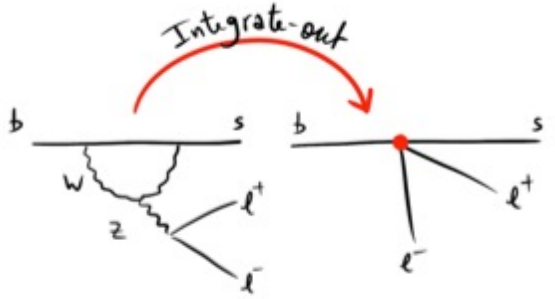


$$R_X = \frac{\mathcal{B}(H_b \to X\mu^+\mu^-)}{\mathcal{B}(H_b \to Xe^+e^-)}$$





Effective Field Theory of $b \to sll$



- Integrate out short-distance (high energy) interactions

- Operator production expansion

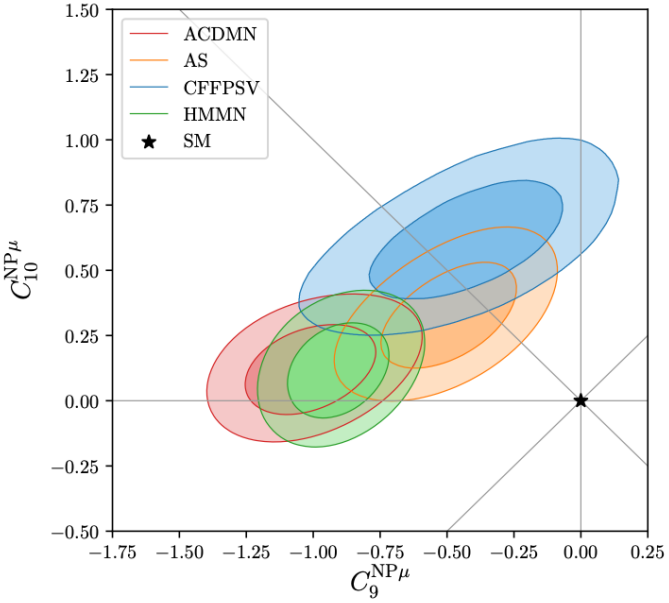
$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \frac{e^2}{16\pi^2} \sum_i (C_i O_i + C_i' O_i') + h.c.$$

  - Wilson coefficients $C_i^{(\prime)}$ encode short-distance physics
  - Operators $O_i^{(\prime)}$ describe low-enery QCD (using form factors), which have large theory uncertainties

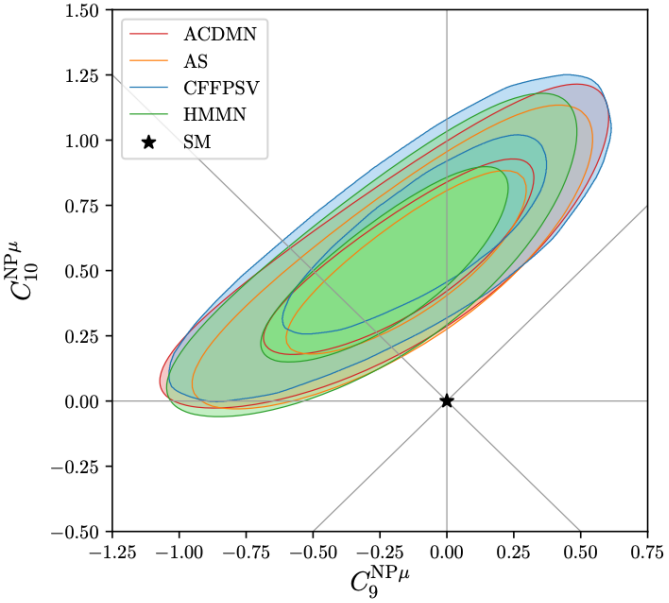
Global fit

- Different experimental inputs, form factors, assumptions about non-local matrix elements , statistical frameworks

B. Capdevila, M. Fedele, S. Neshatpour, P. Stangl @ LHCb implications 2021 [slides]



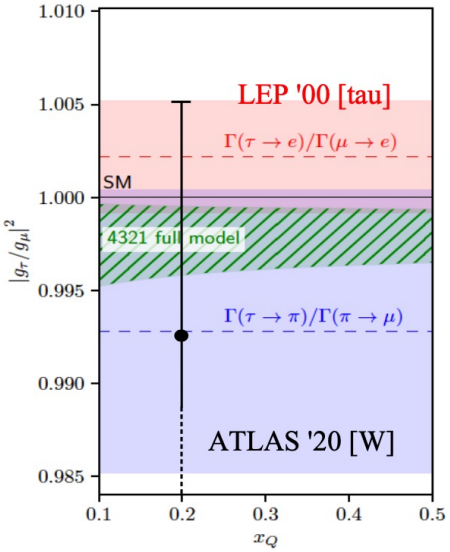
global fit



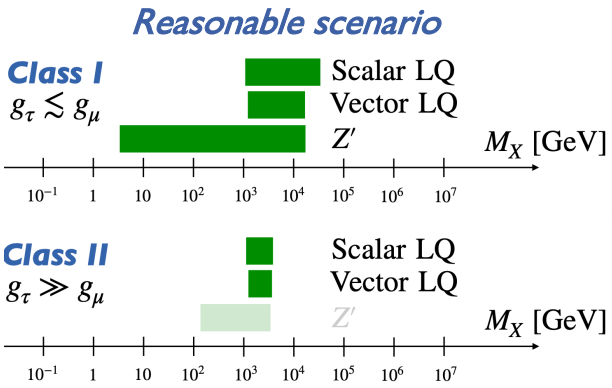
fit to LFU observables + $B_s \to \mu\mu$

Implications of Flavour anomalies?

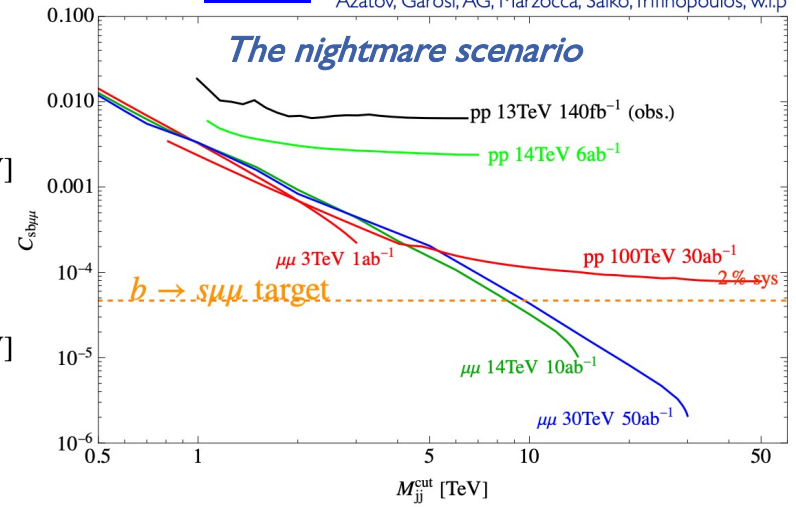
G. Isidori @ NJNU



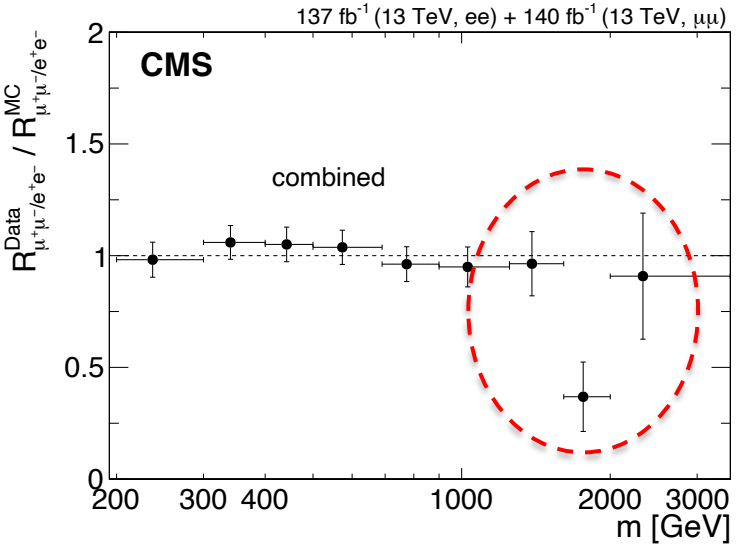
A. Greljo @ LHCb implication 2021 [slides]



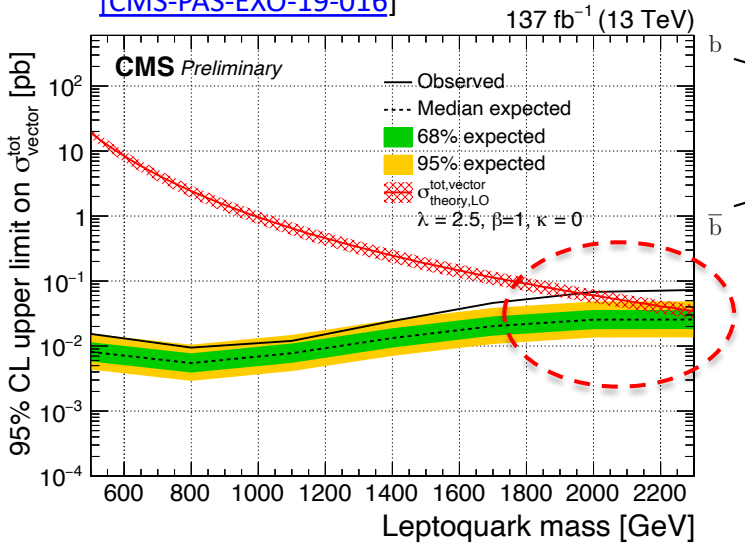
Azatov, Garosi, AG, Marzocca, Salko, Trifinopoulos; w.i.p

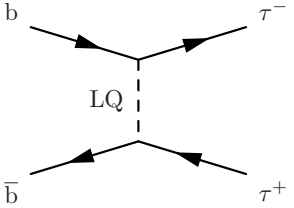


[CMS, JHEP 07 (2021) 208]



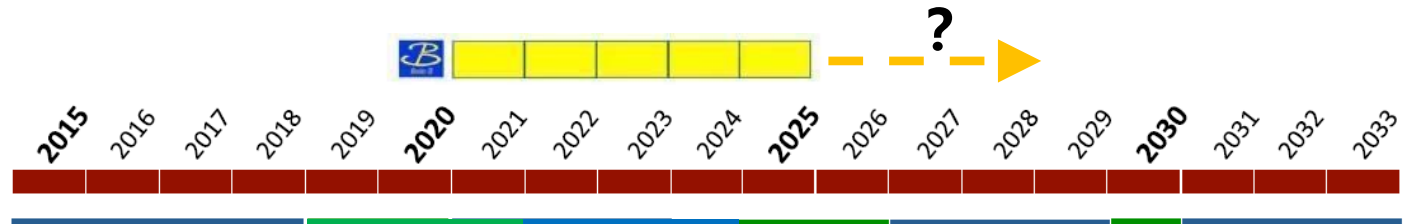
[CMS-PAS-EXO-19-016]





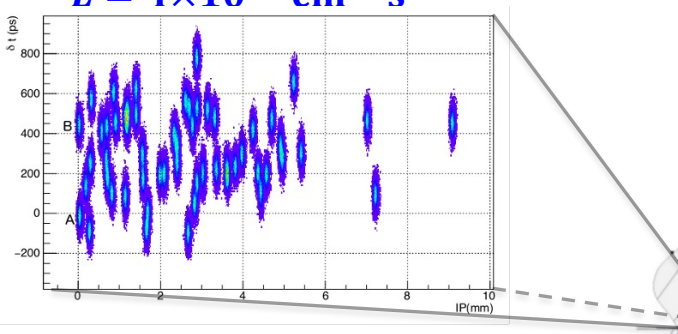
3.1-3.4σ

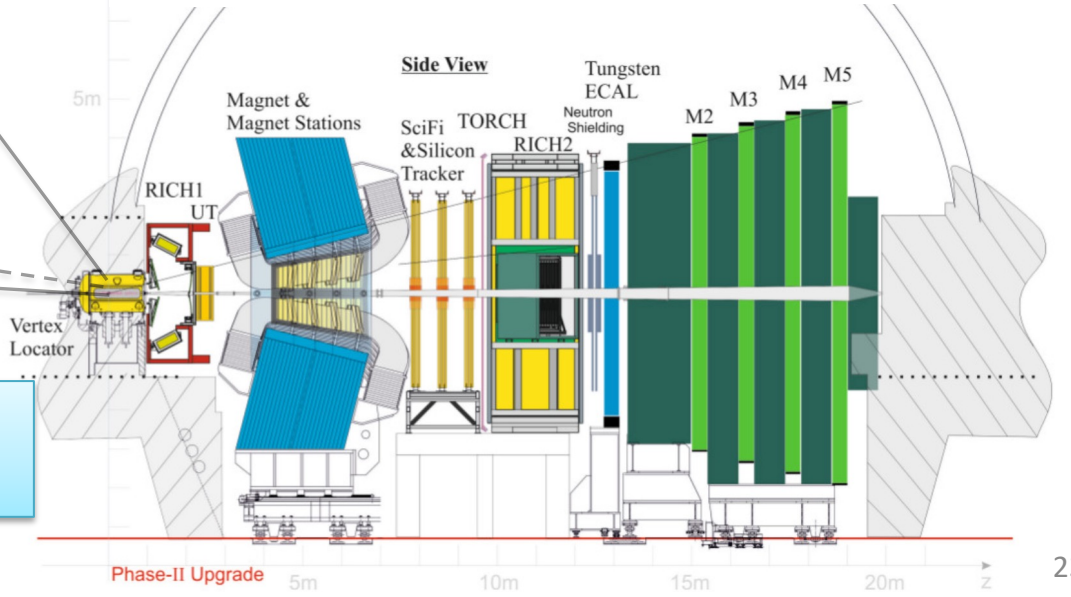
The LHCb upgrades



9 fb^{-1} | 50 fb^{-1} | 300 fb^{-1}

$L = 4\times10^{32}\ \mathrm{cm^{-2}s^{-1}}$ | $L = 2\times10^{33}\ \mathrm{cm^{-2}s^{-1}}$ | $L = 2\times10^{34}\ \mathrm{cm^{-2}s^{-1}}$



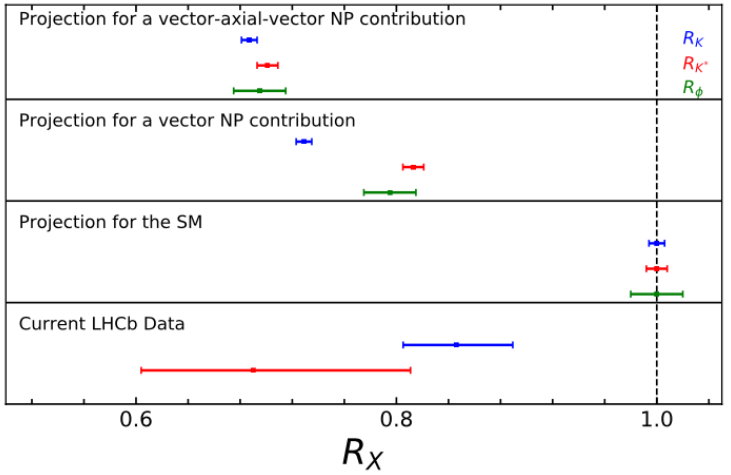


Upgrade II, 4D detector
Timing, $\mathcal{O}(10\ \mathrm{ps})$, is essential

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

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%	–
$B_s^0, B^0 \to \mu^+\mu^-$					
$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	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}	$(K^0_S\pi\pi)$ 1.2×10^{-4}	$(K3\pi)$ 8.0×10^{-6}	–

Summary

- Many interesting results from LHCb
  - CP Violation, CKM triangle, γ, $V_{ub}, V_{cb}, \Delta A_{CP}$
  - Flavour anomalies, $b \to s\mu^+\mu^-$ BR, P_5', $\mathcal{R}_{K^{(*0)}}, \mathcal{R}_{D^*}$, to be confirmed or refuted with more data
- With LHCb upgrade (50 fb^{-1}) & upgrade-II (300 fb^{-1}), much more will be done
- Your continuous and strong supports are always appreciated!
  - Form factors, non-form-factor contributions
  - New observables?