第五届粒子物理前沿研讨会

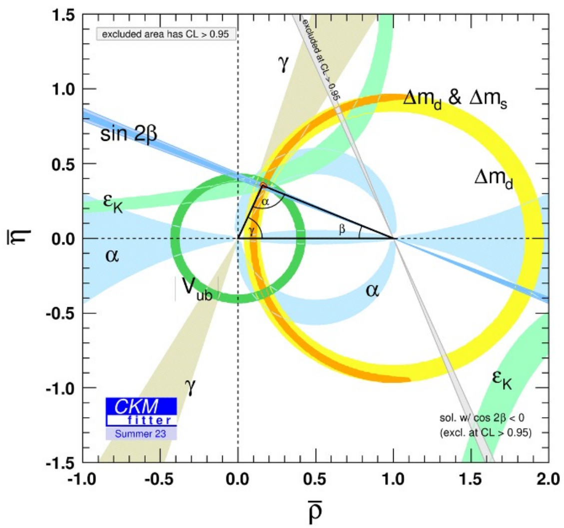
The Fifth Workshop on Frontiers of Particle Physics

Indirect search for New Physics at LHCb

Jibo HE/何吉波(UCAS)

Introduction

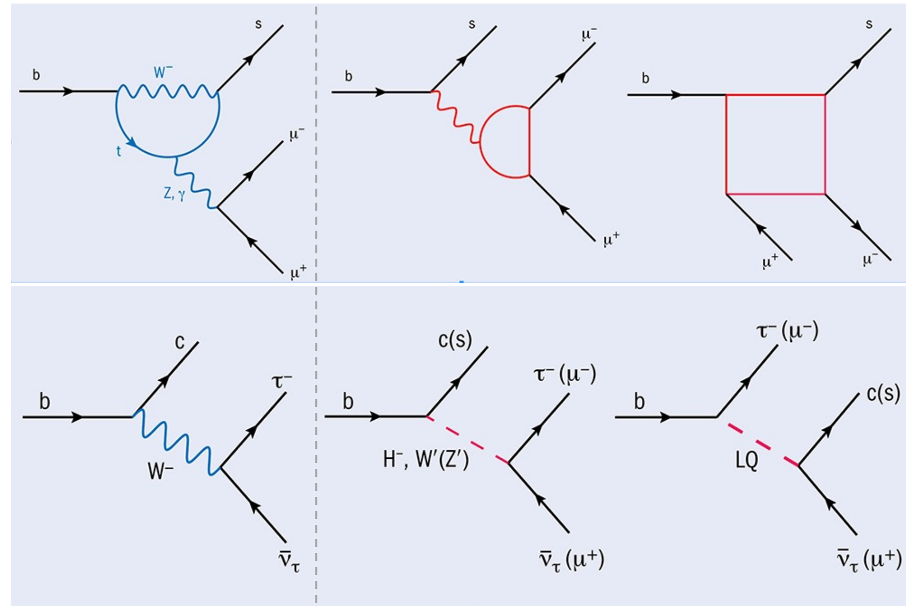
- Flavour-Changing NC
- Flavour-Changing CC

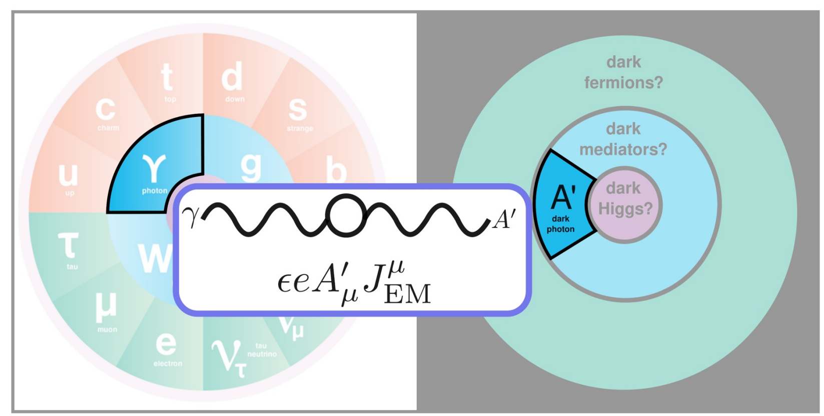


- CPV
- Dark sector

SM

NP





Large Hadron Collider

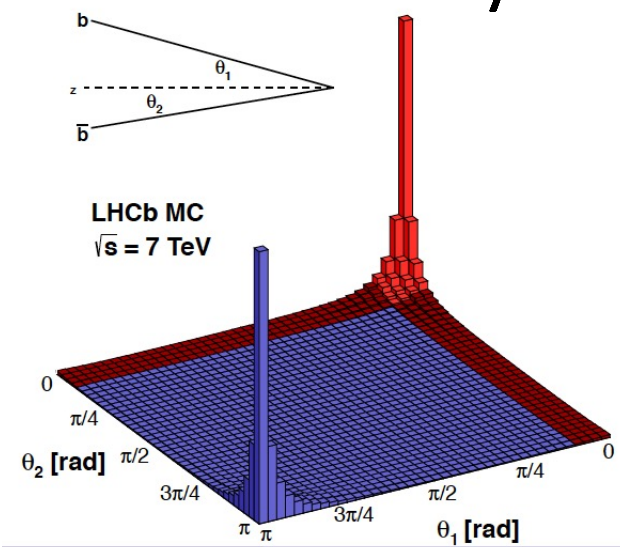
Proton energy: up to 7 TeV (10^{12} eV)
speed: 0.999999991 c

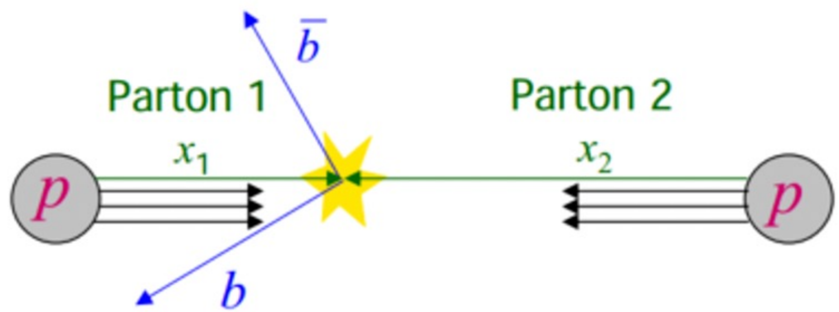
Beauty/charm production

- 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

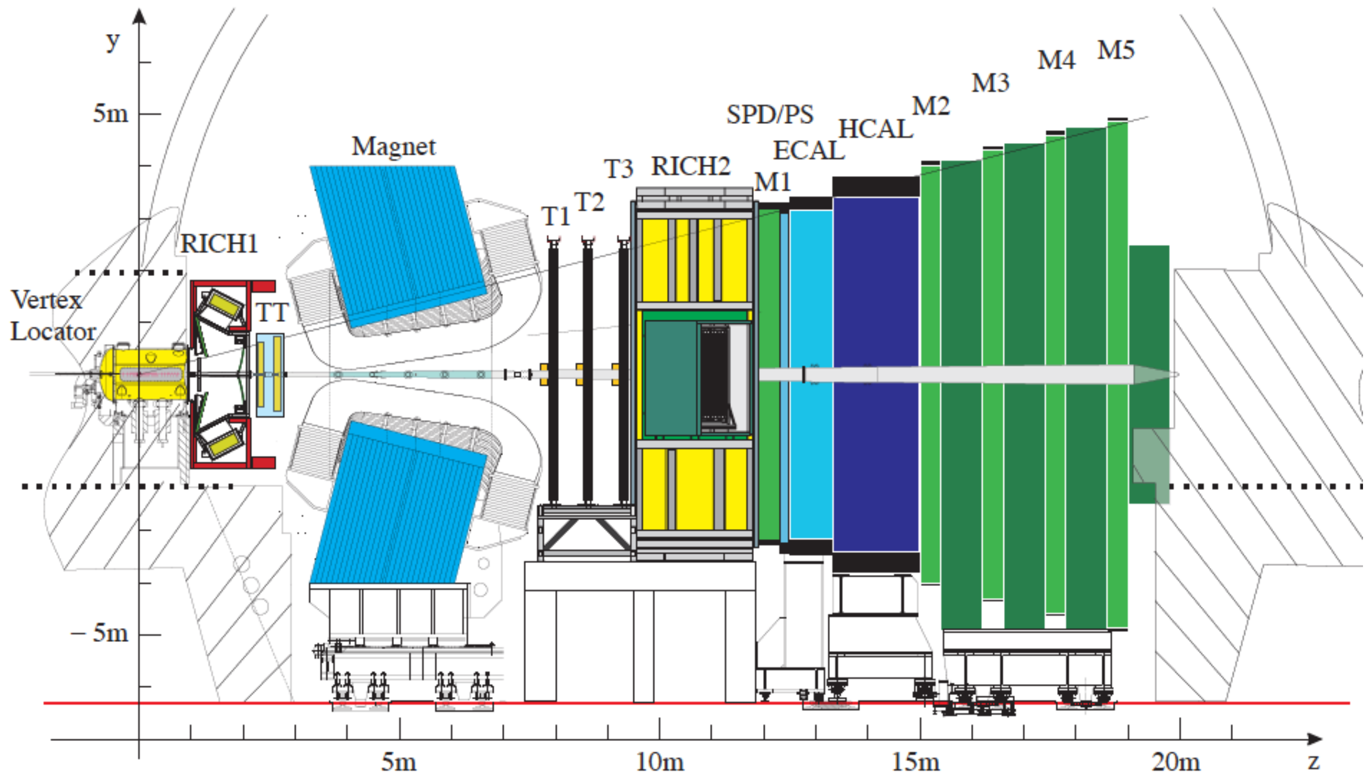




Initial energy of $b\bar{b}$ not known

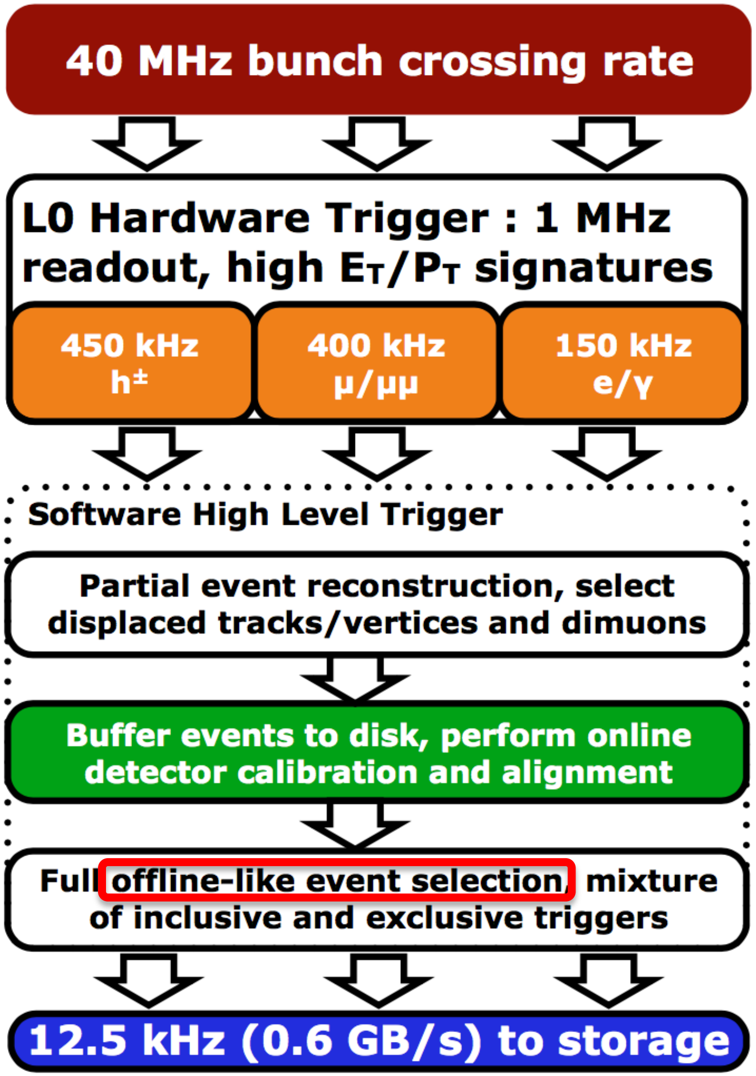
The LHCb experiment

[JINST 3 (2008) S08005]



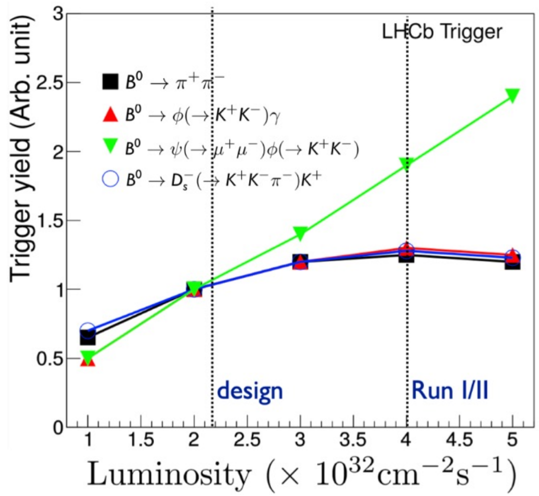
Vertex Locator	$\sigma_{\mathrm{PV},x/y} \sim 10\ \mu\mathrm{m}$, $\sigma_{\mathrm{PV},z} \sim 60\ \mu\mathrm{m}$
Tracking (TT, T1-T3)	$\Delta p/p$: 0.4% at 5 GeV/c, to 0.6% at 100 GeV/c
RICHs	$\varepsilon(K \to K) \sim 95\%$, mis-ID rate $(\pi \to K) \sim 5\%$
Muon system (M1-M5)	$\varepsilon(\mu \to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

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

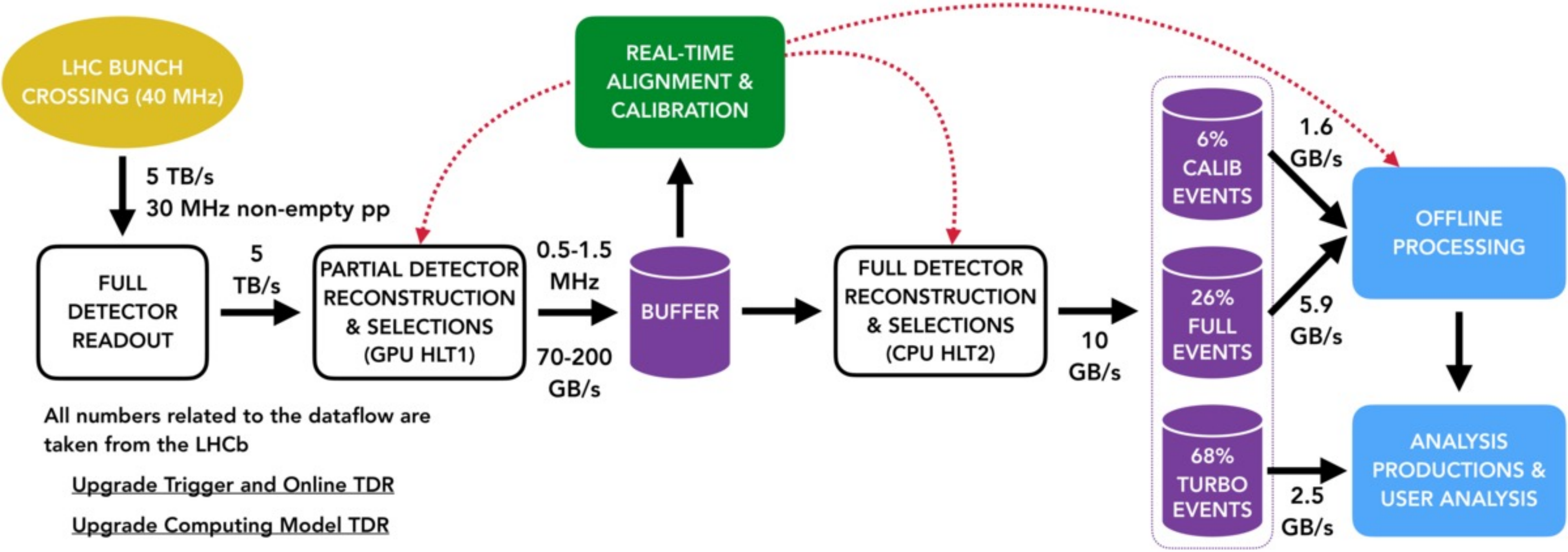
Buffer events to disk, perform online detector calibration and alignment

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

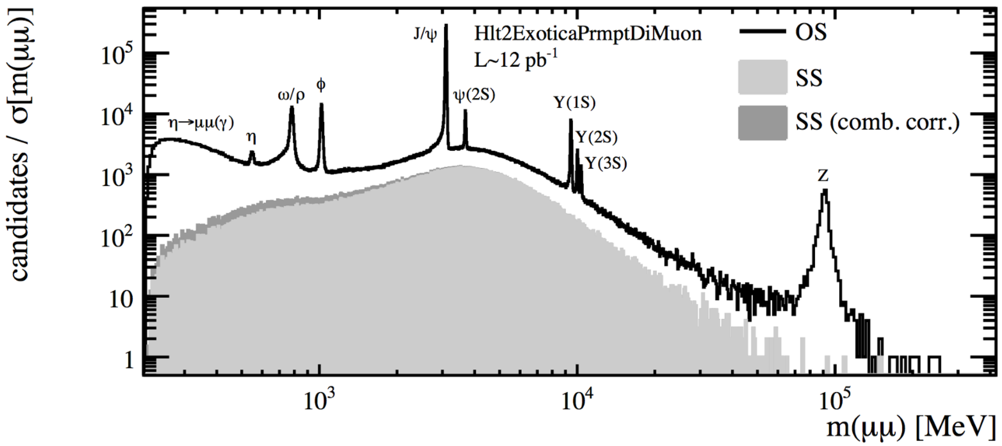
The turbo stream



All numbers related to the dataflow are taken from the LHCb

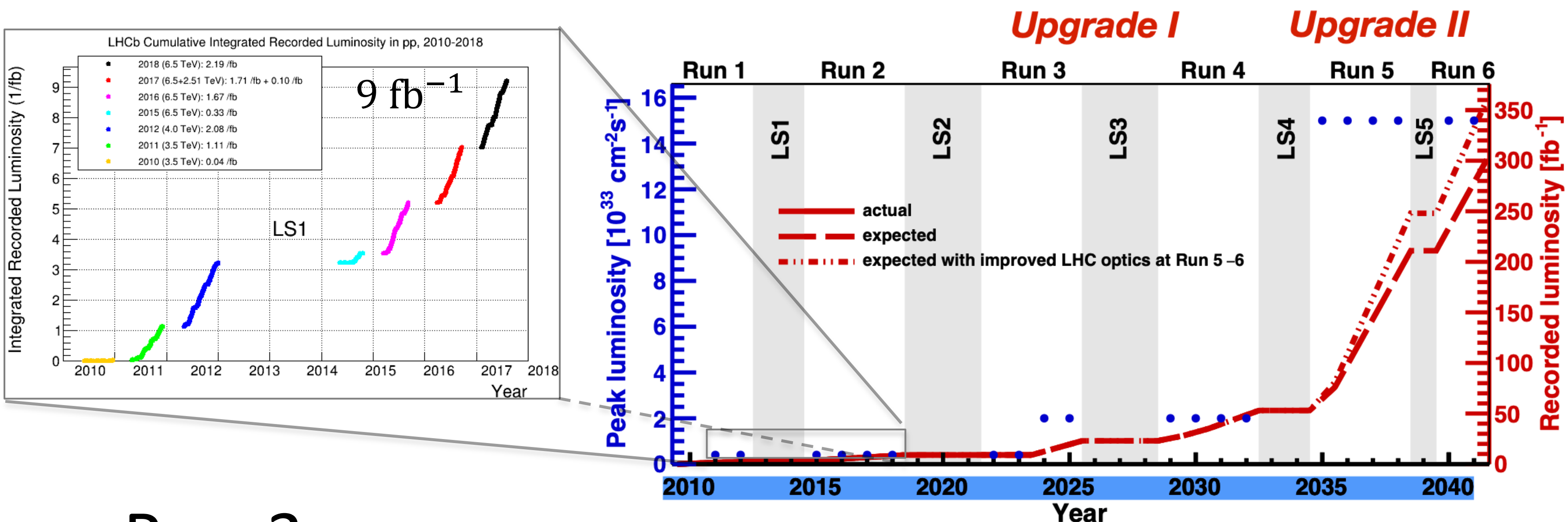
[Upgrade Trigger and Online TDR]

[Upgrade Computing Model TDR]



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

LHCb luminosity prospects

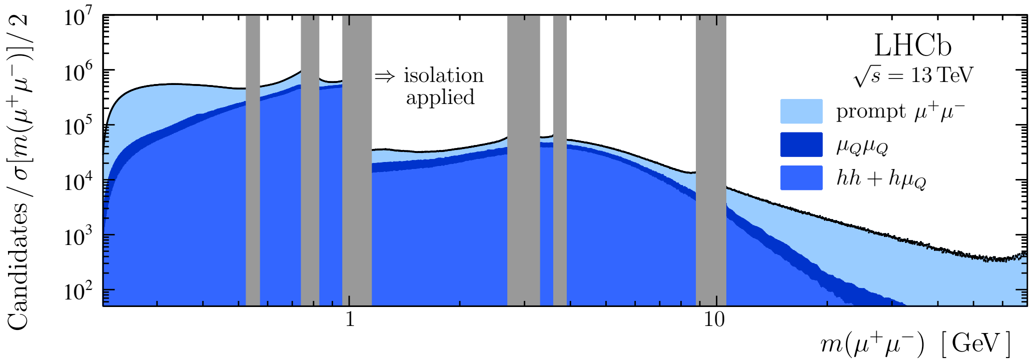


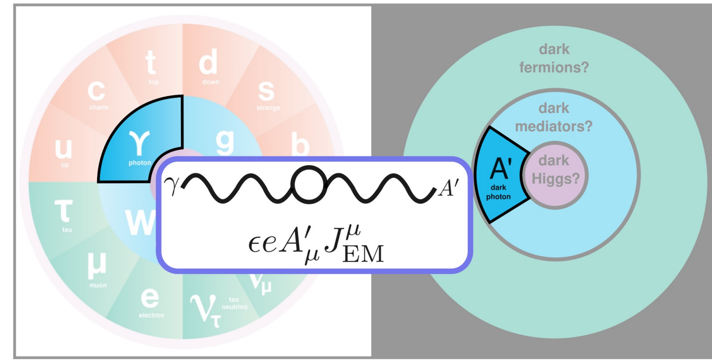
- Run-3
  - Luminosity: 7 fb^{-1} (2024) + 7 fb^{-1} (2025)
  - Yields, compared to Run 1+2
    - Muon modes ~2
    - Hadronic modes ~4 (2 x 2 due to higher trigger eff.)

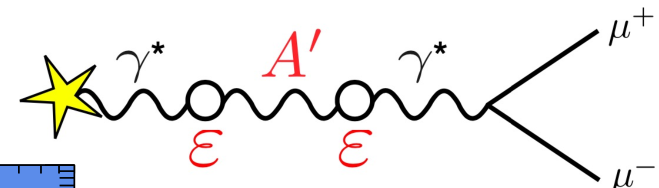
Dark photon

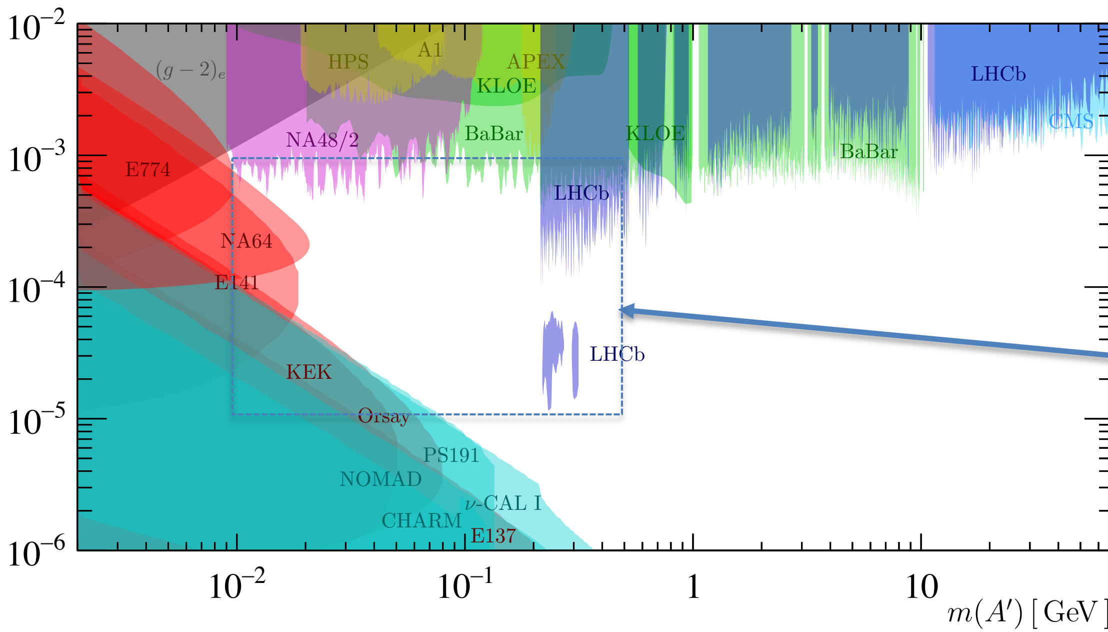
- Searched in $m(\mu\mu)$

[PRL 124 (2020) 041801]







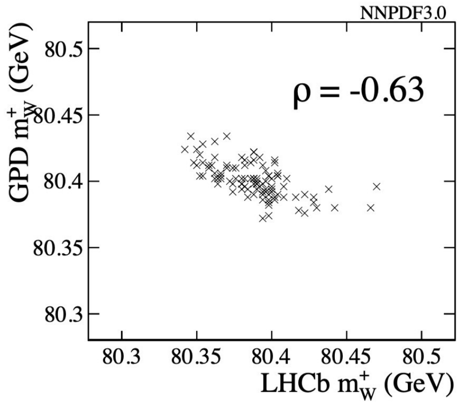


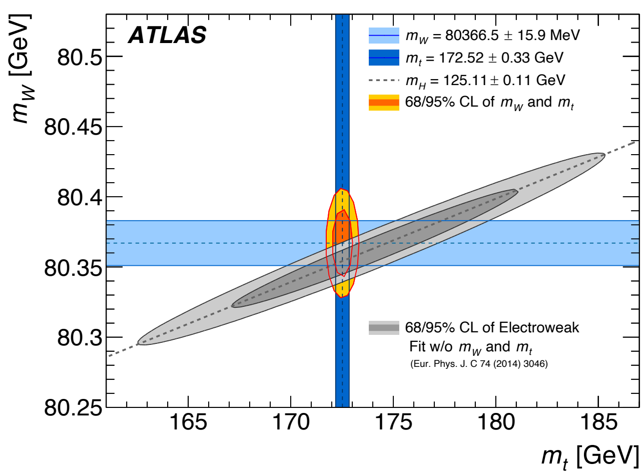
Proposed to cover this with $D^*(2007)^0 \to D^0 A'(\to e^+e^-)$

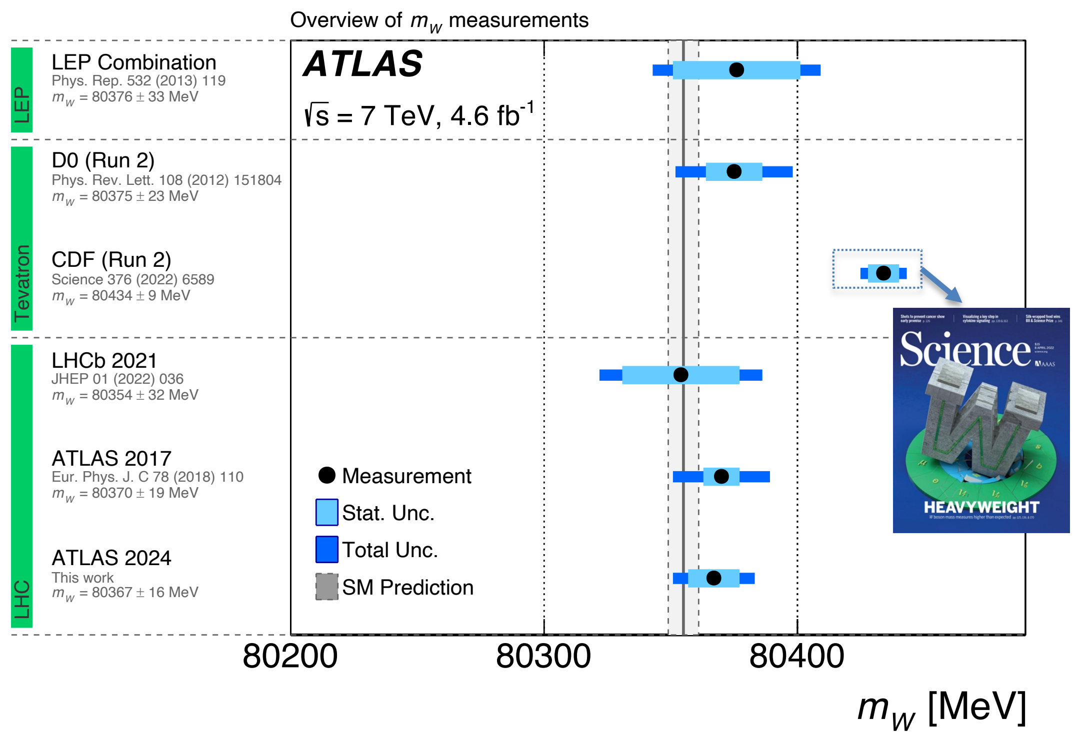
[Iten *et al.*, PRD 92 (2015) 115017]

W mass

- CDF results demand more measurements at LHC
- Anti-correlation of PDF at GPD/LHCb helps



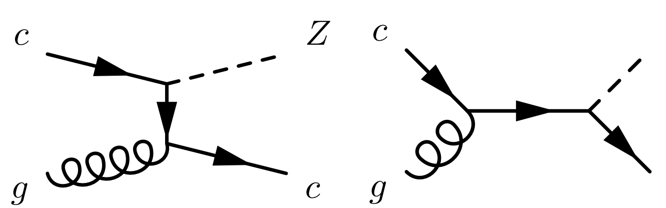




[ATLAS, arXiv:2403.15085]

Intrinsic charm?

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



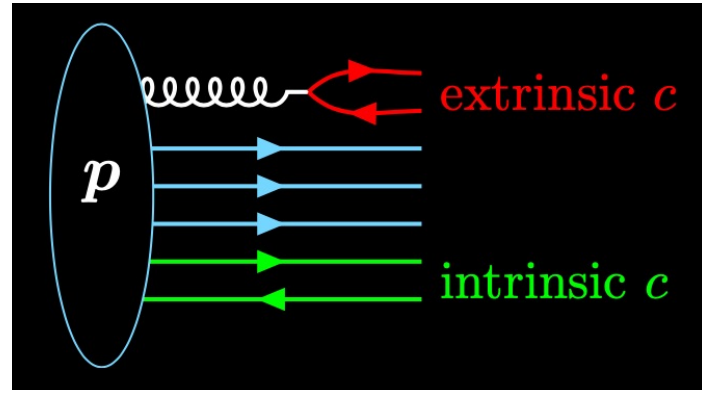
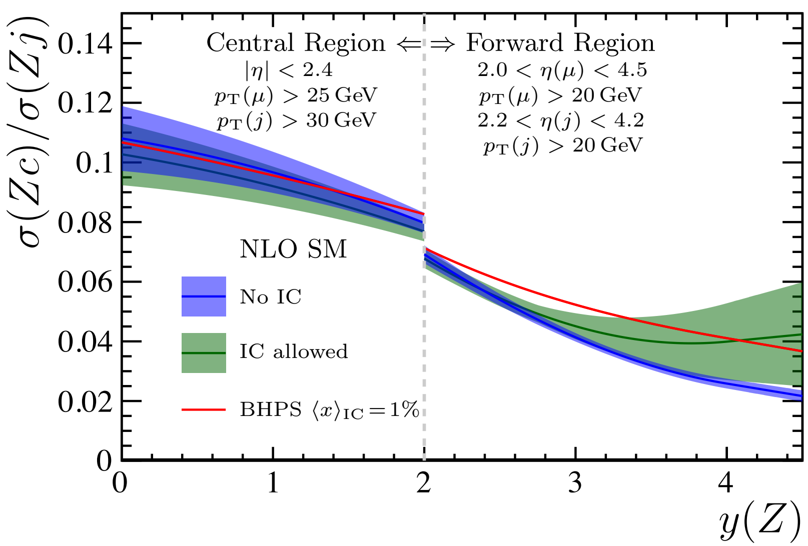
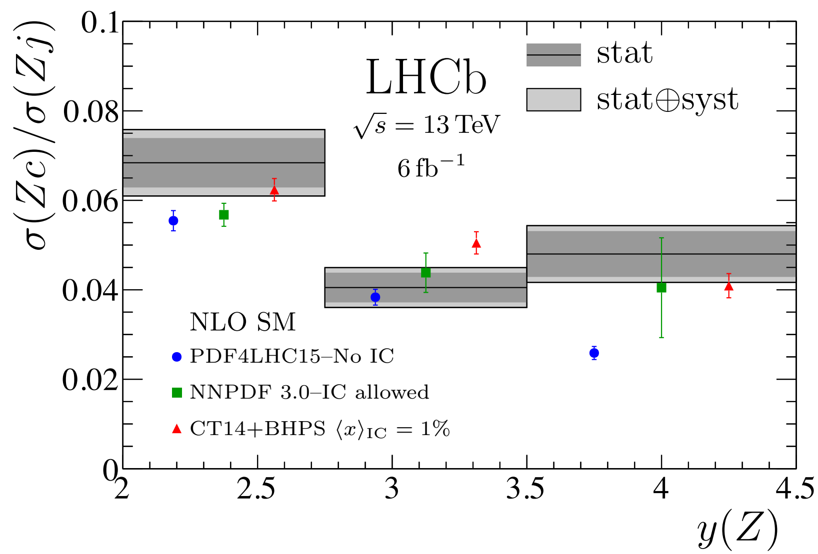


Image: D. Craik

[PRL 128 (2022) 082001]





ΔA_{CP} in charm

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

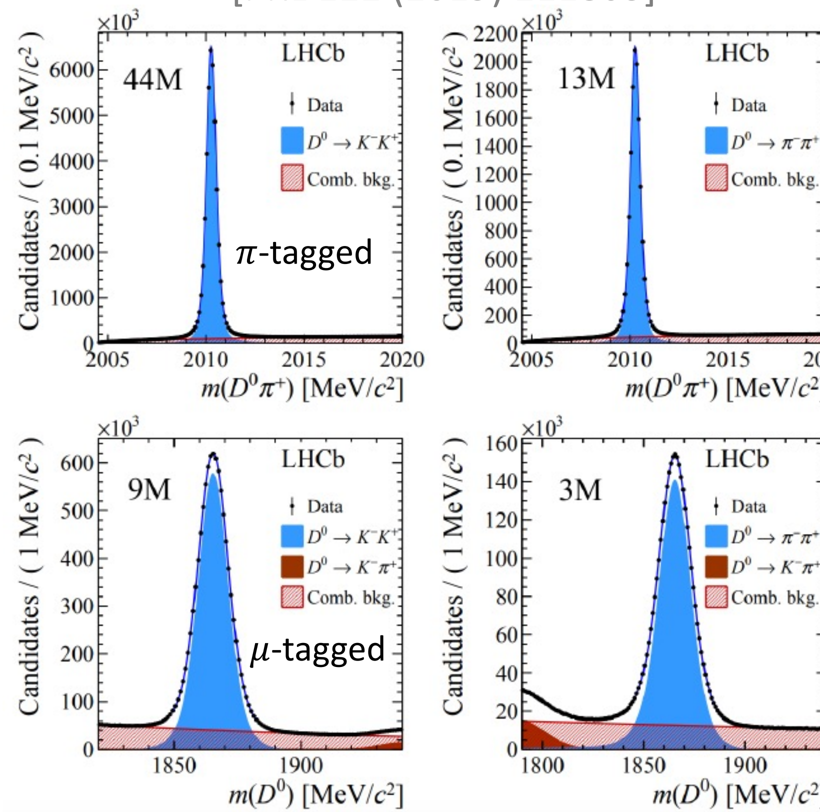
$$\Delta A_{CP} \equiv A_{CP}(K^-K^+) - A_{CP}(\pi^-\pi^+)$$

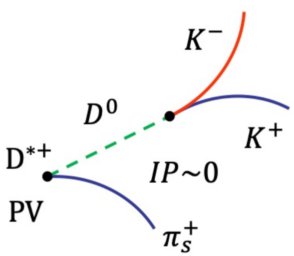
$$\Delta A_{CP}^{\pi\text{-tagged}} = [-18.2 \pm 3.2\,(\text{stat.}) \pm 0.9\,(\text{syst.})] \times 10^{-4},$$
$$\Delta A_{CP}^{\mu\text{-tagged}} = [-9 \pm 8\,(\text{stat.}) \pm 5\,(\text{syst.})] \times 10^{-4}.$$

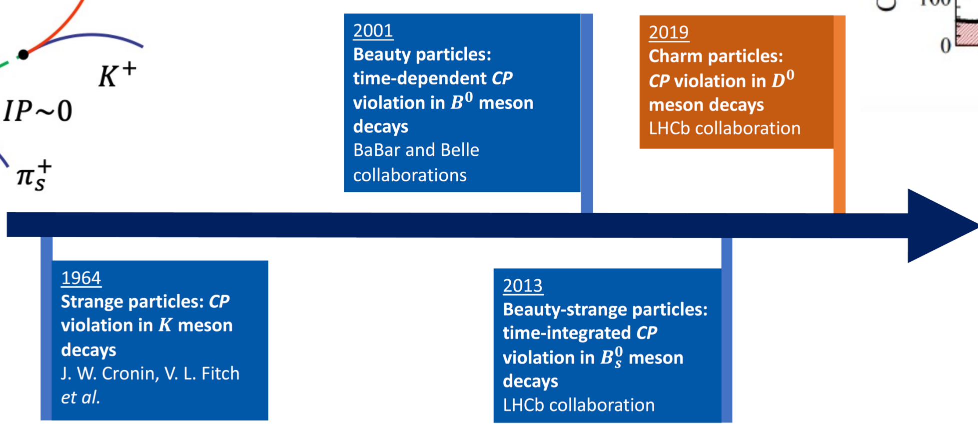
Combined one:

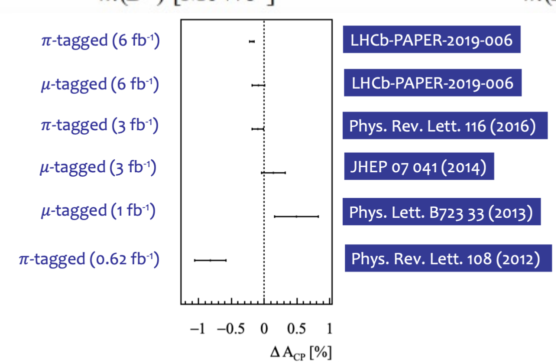
$$\Delta A_{CP} = (-15.4 \pm 2.9)\times 10^{-4}$$

[PRL 122 (2019) 211803]



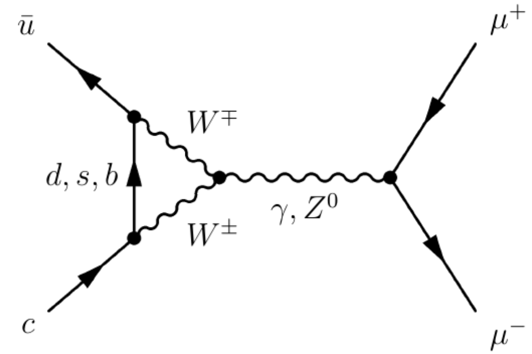


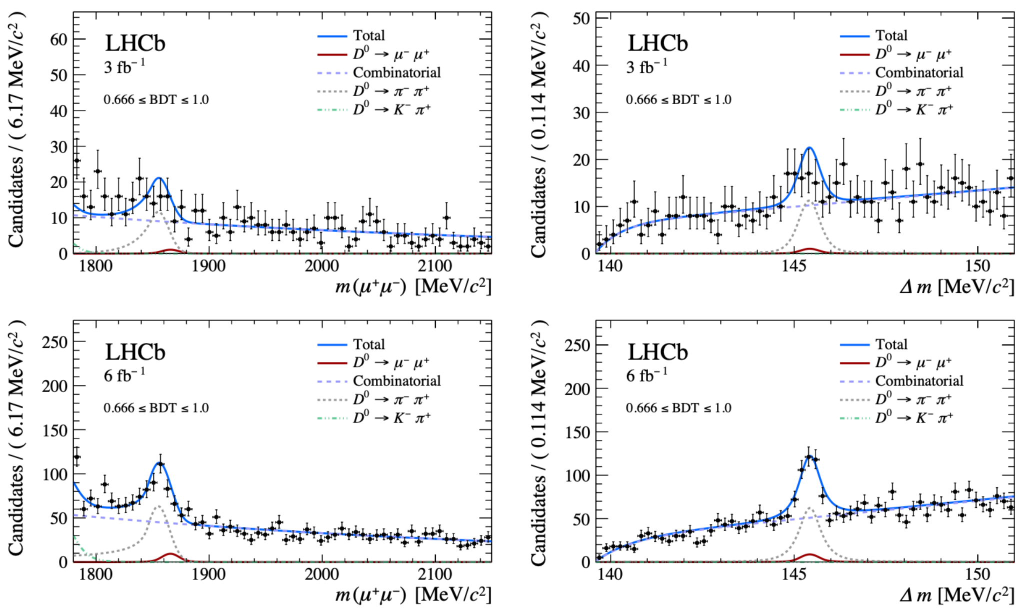


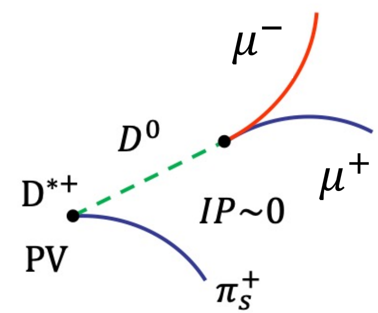


$D^0 \to \mu^+\mu^-$

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



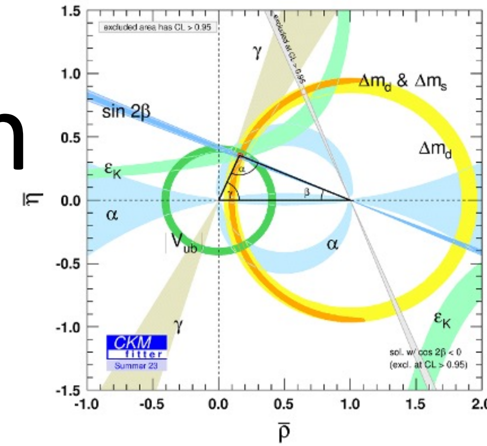




$\boxed{\mathcal{B}(D^0 \to \mu^+\mu^-) < 3.1\times10^{-9} \text{ @ 90\% CL}}$

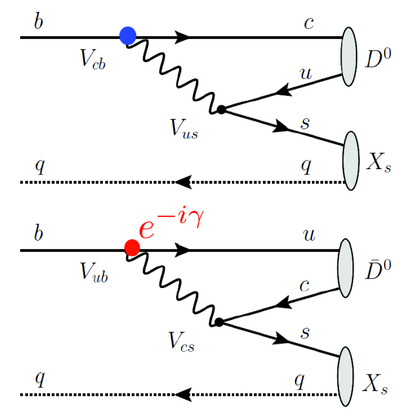
[PRL 131 (2023) 041804]

CKM-γ combination

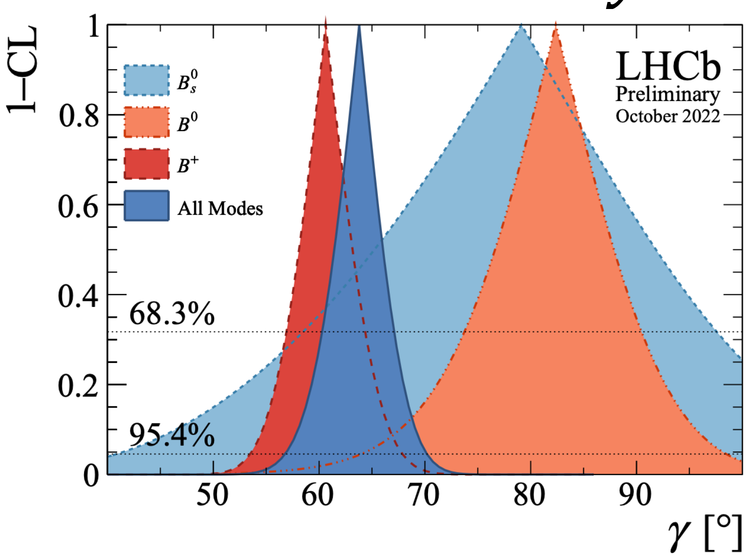


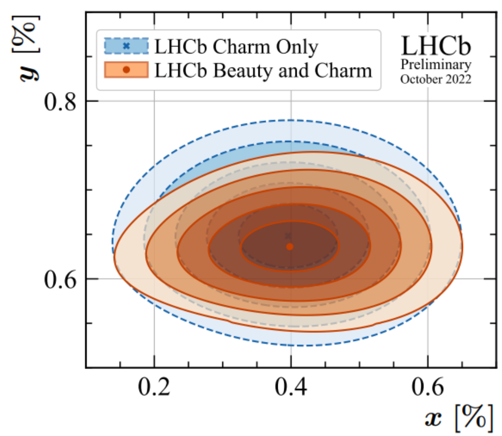
- Simultaneous determination of CKM-γ & charm mixing parameters
  - CKM $\gamma = \left(63.8^{+3.5}_{-3.7}\right)^\circ$
  - Charm mixing $x = \left(0.398^{+0.050}_{-0.049}\right)\%$,

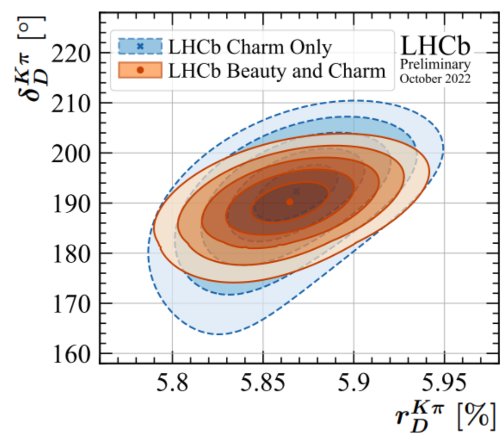
    $y = \left(0.636^{+0.020}_{-0.019}\right)\%$



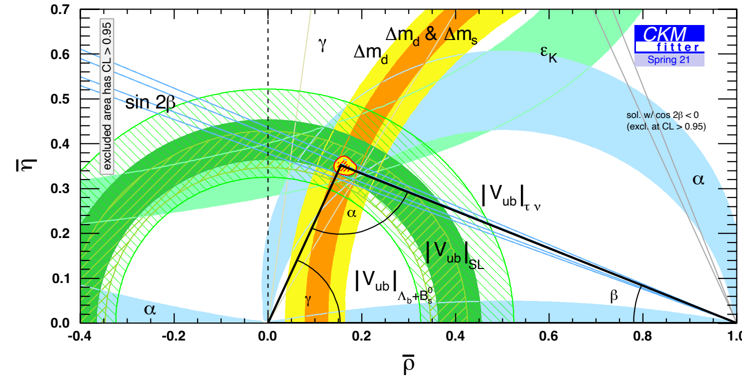
[LHCb-Conf-2022-003]



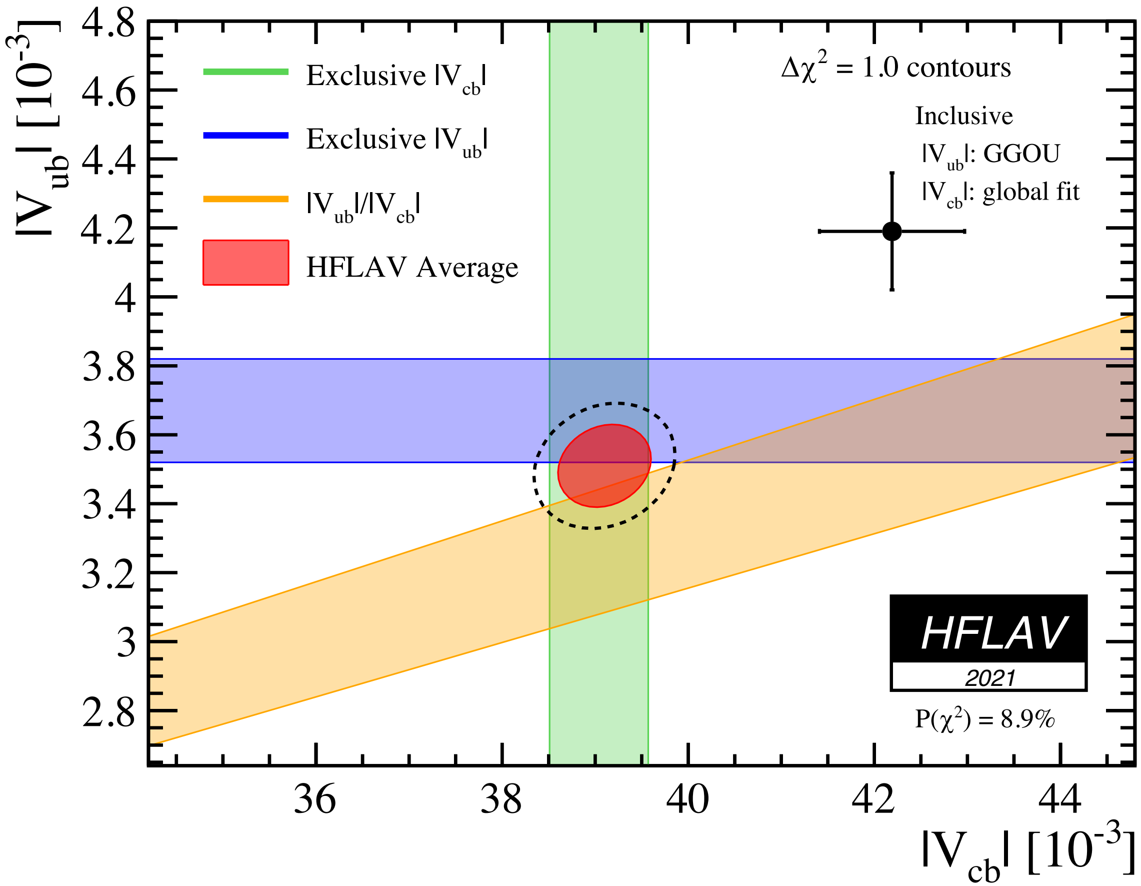


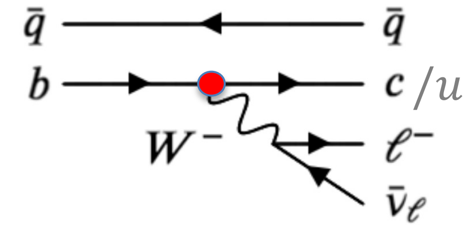


V_{cb}, V_{ub}



- Some tension between exclusive/inclusive

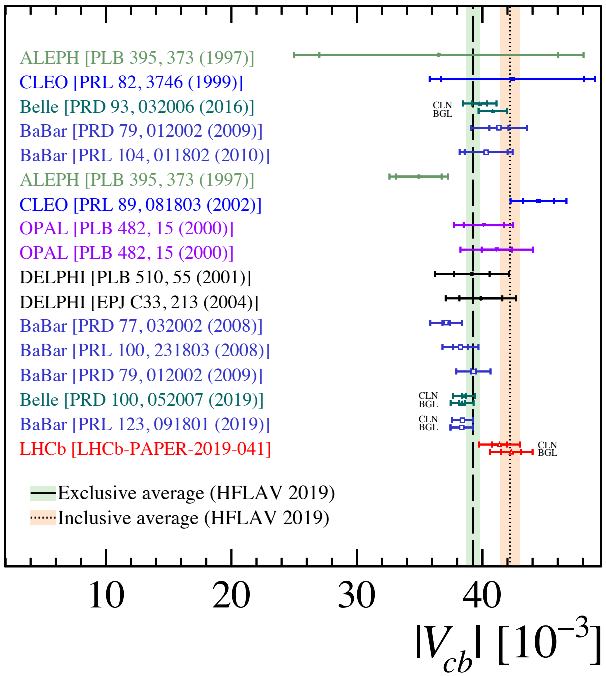


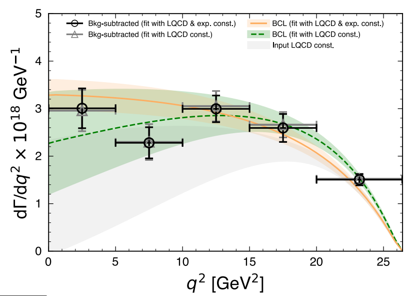


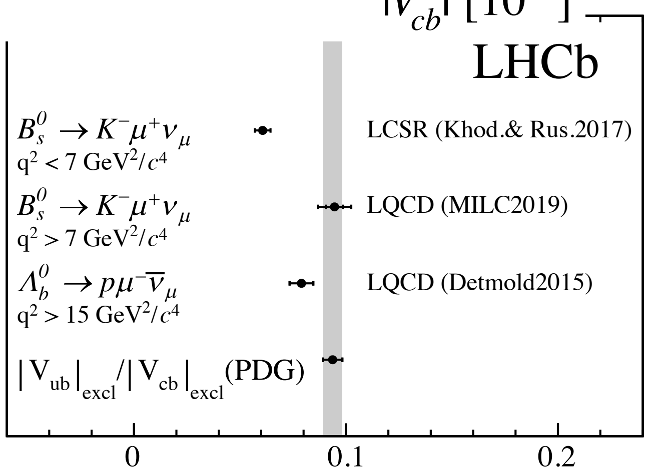
$$d\Gamma \propto |V_{cb}|^2 |f_H|^2$$

V_{cb}, V_{ub}

[PRD 101 (2020) 072004]

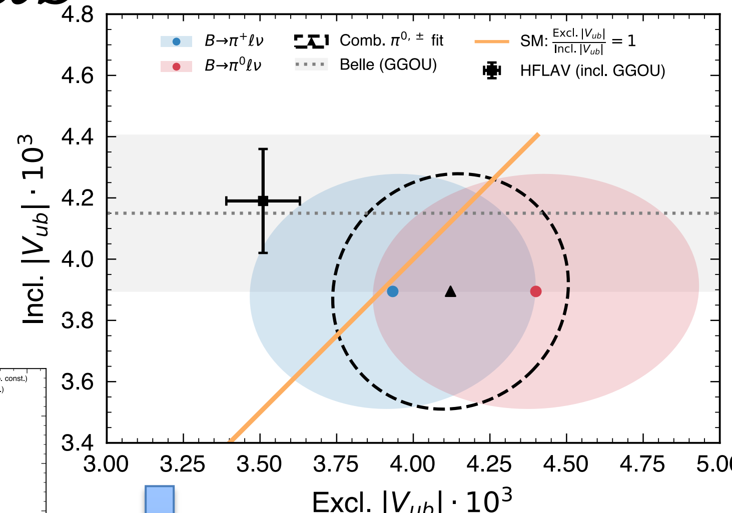






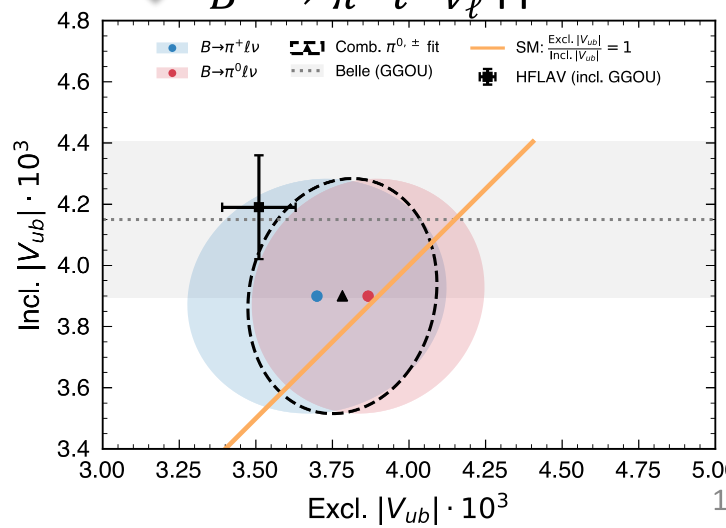
[PRL 126 (2021) 081804]

[Belle, PRL 131 (2023) 211801]



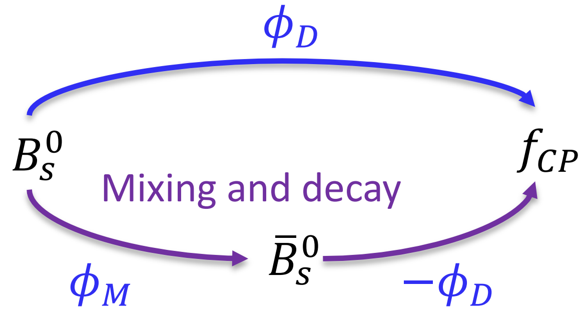
+

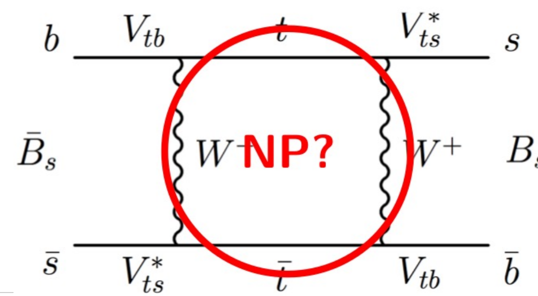
w/ exp constraint for $\bar{B}^0 \to \pi^+\ell^-\bar{\nu}_\ell$ FF



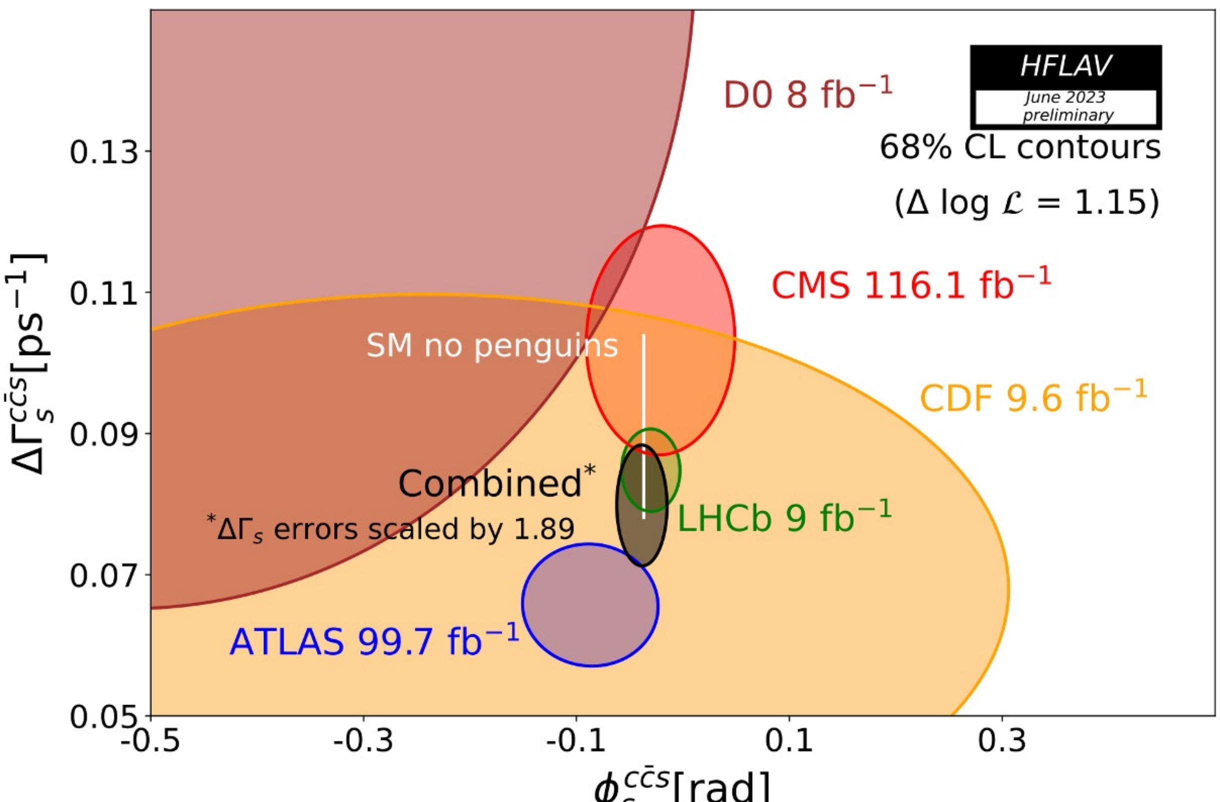
CPV in mixing

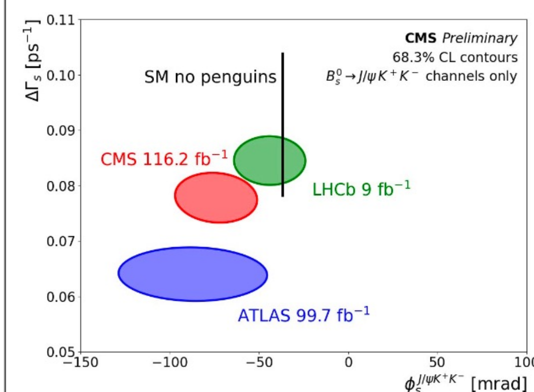
- $\phi_s = \phi_M - 2\phi_D$, small in SM
- $B_s^0 \to J/\psi h^+ h^-$





[PRL 132 (2024) 051802]

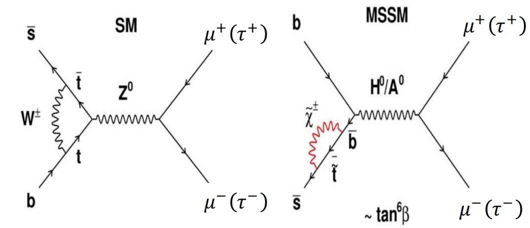


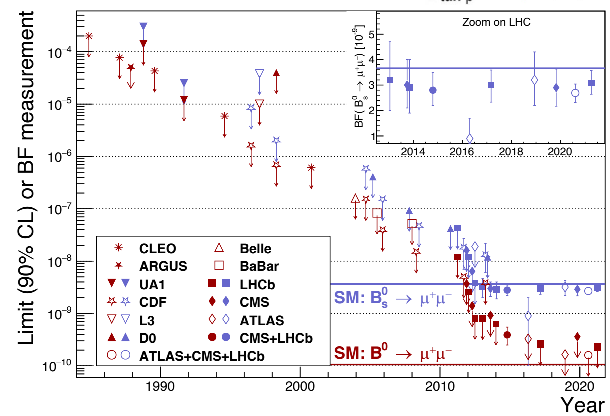


Flavour tagging?

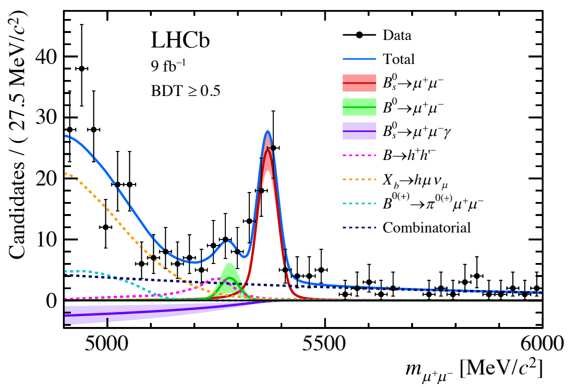
$B^0_{(s)} \to \mu^+\mu^-$

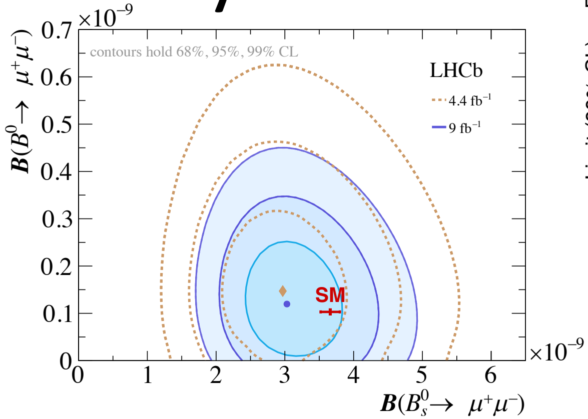
- Suppressed in SM, could be enhanced by New Physics

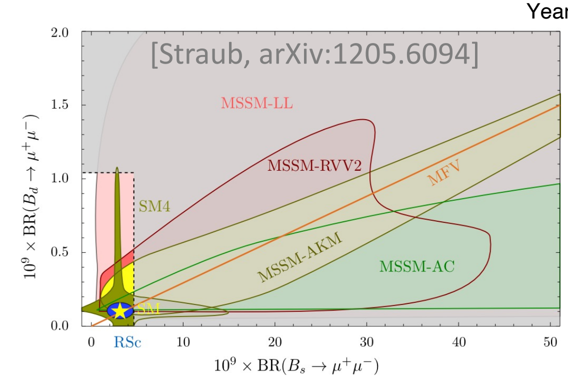




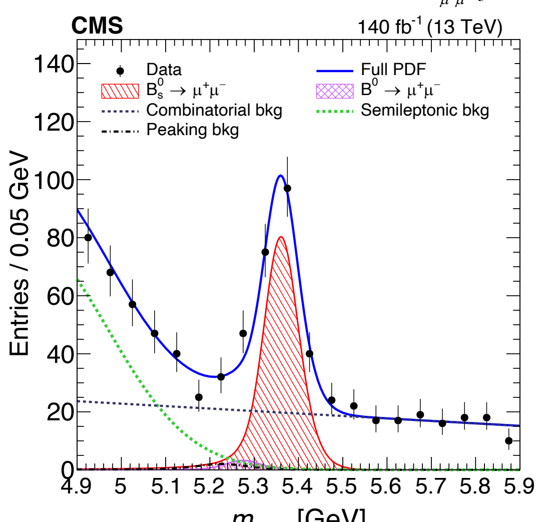
PRL 128 (2022) 041801

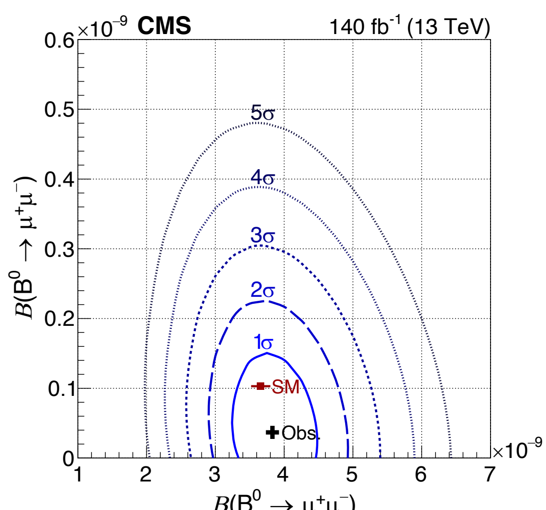


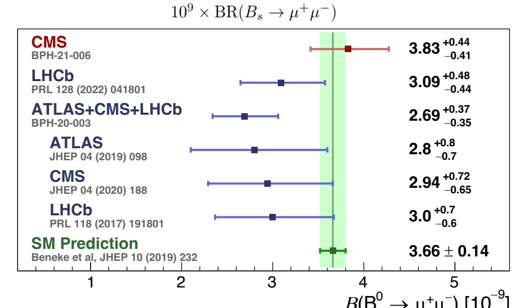




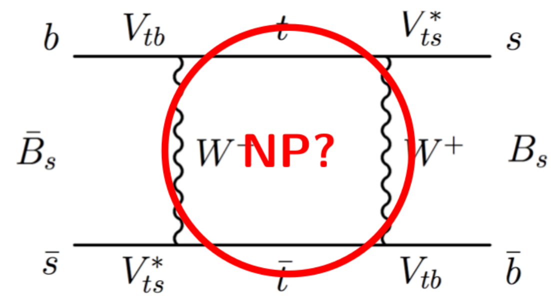
PLB 842 (2023) 137955







$B_s^0 \to \mu^+\mu^-$ eff. τ



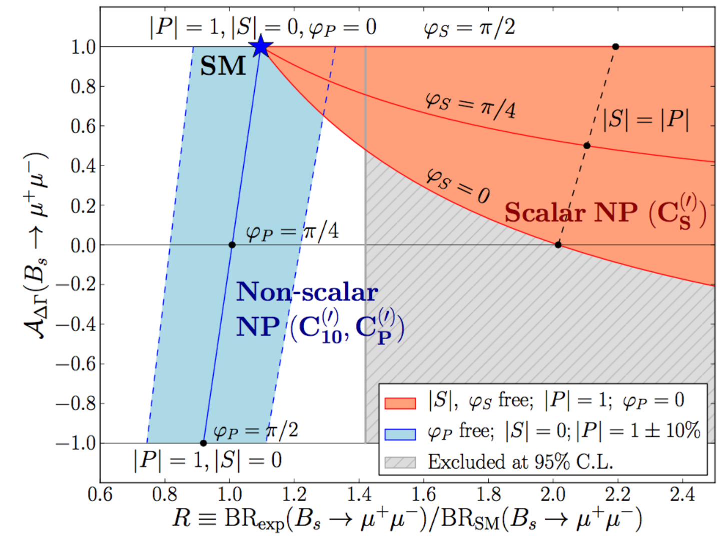
- B_s^0 mixing ⇒ effective τ

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

$$A_{\Delta\Gamma}^{\mu^+\mu^-} \equiv \frac{R_H^{\mu^+\mu^-}-R_L^{\mu^+\mu^-}}{R_H^{\mu^+\mu^-}+R_L^{\mu^+\mu^-}}$$

$A_{\Delta\Gamma}$=1 in SM

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



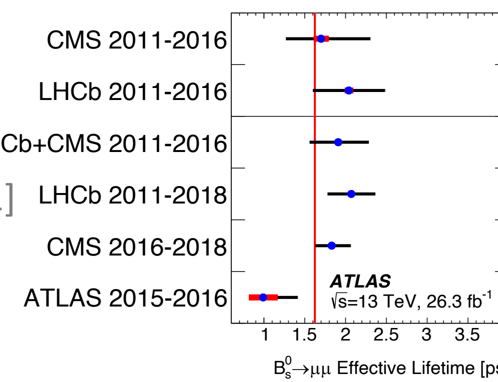
[De Bruyn *et al.*, PRL 109 (2012) 041801]

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

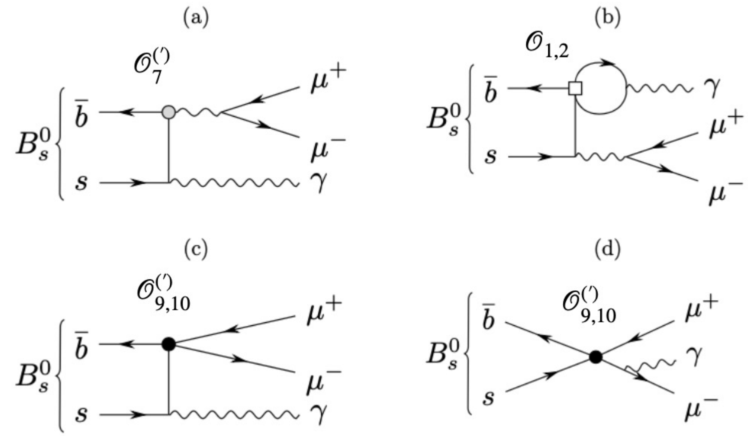
$\boxed{\tau_{\mu\mu} = 2.07 \pm 0.29 \pm 0.03 \text{ ps}}$ [LHCb, PRL 128 (2022) 041801]

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

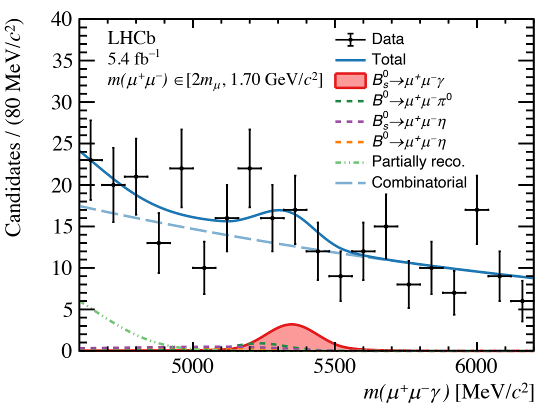
$0.99^{+0.42}_{-0.07} \pm 0.17$ ps [ATLAS, JHEP 09 (2023) 199]

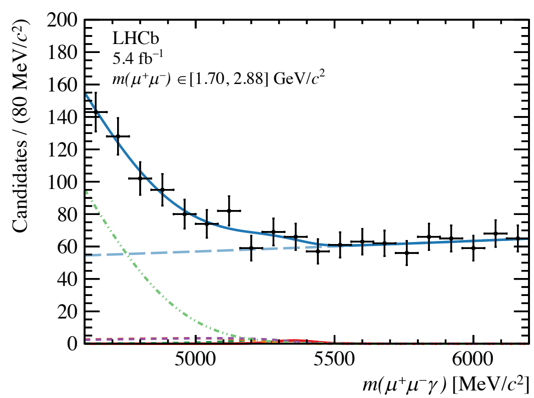


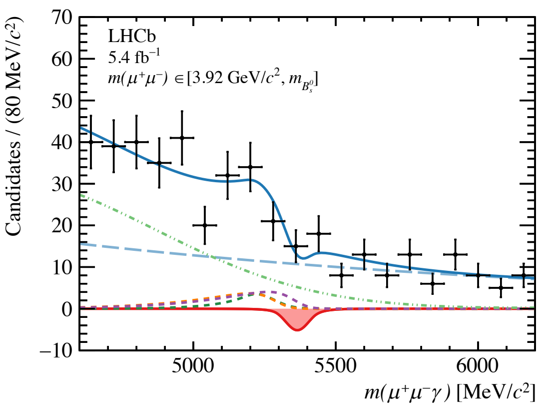
$B_s^0 \to \mu^+\mu^-\gamma$



- Less chiral suppressed, but w/ $B_s^0 \to \gamma$ form factor

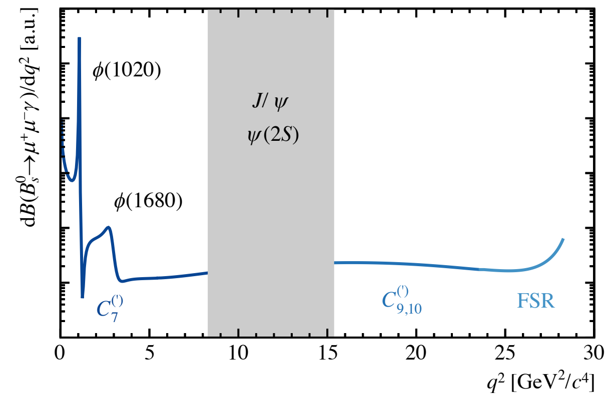


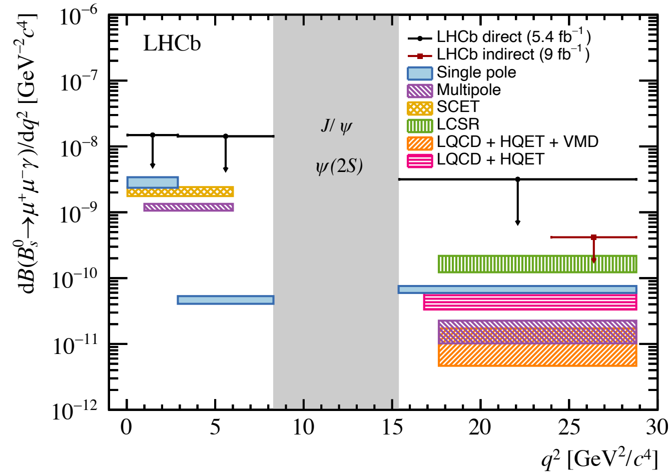




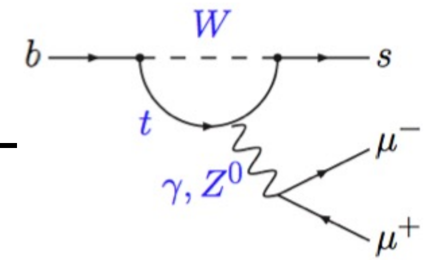
$$\mathcal{B}(B_s^0 \to \mu^+\mu^-\gamma)_{\mathrm{I}} < 3.6\,(4.2) \times 10^{-8}$$
$$\mathcal{B}(B_s^0 \to \mu^+\mu^-\gamma)_{\mathrm{II}} < 6.5\,(7.7) \times 10^{-8}$$
$$\mathcal{B}(B_s^0 \to \mu^+\mu^-\gamma)_{\mathrm{III}} < 3.4\,(4.2) \times 10^{-8}$$
$$\mathcal{B}(B_s^0 \to \mu^+\mu^-\gamma)_{\mathrm{I,\ with}\ \phi\ \mathrm{veto}} < 2.9\,(3.4) \times 10^{-8}$$
$$\mathcal{B}(B_s^0 \to \mu^+\mu^-\gamma)_{\mathrm{comb.}} < 2.5\,(2.8) \times 10^{-8}$$

[arXiv: 2404.03375]

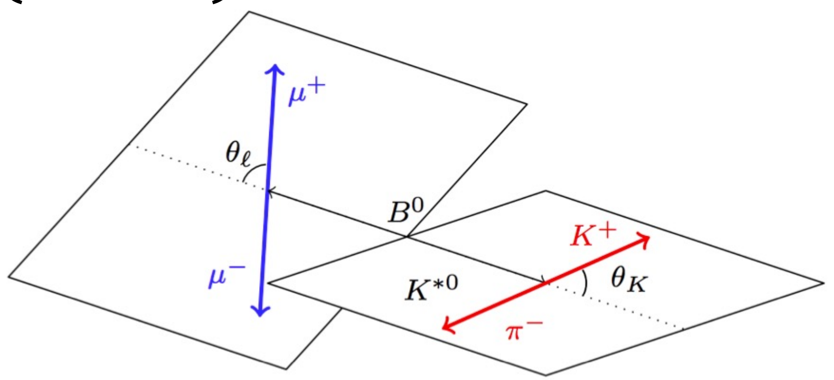




$B^0 \to K^{*0}\mu^+\mu^-$



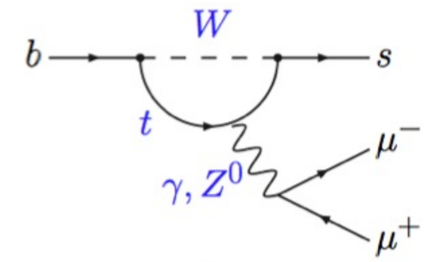
- "Poster-child" decay of $b \to s\mu^+\mu^-$
- Described by $q^2 = m^2(\ell^+\ell^-)$ and $\theta_\ell, \theta_K, \phi$
- Many observables!

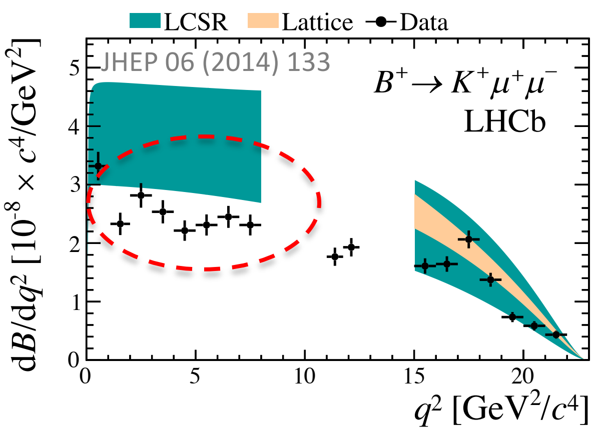


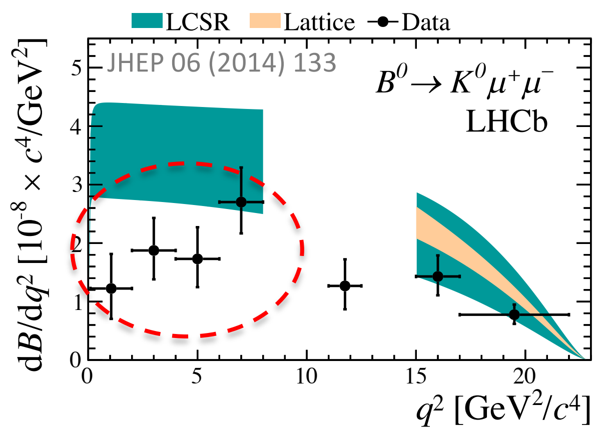
$$\frac{1}{\mathrm{d}(\Gamma+\bar{\Gamma})/\mathrm{d}q^2}\frac{\mathrm{d}^3(\Gamma+\bar{\Gamma})}{\mathrm{d}\vec{\Omega}} = \frac{9}{32\pi}\Big[\tfrac{3}{4}(1-F_\mathrm{L})\sin^2\theta_K + F_\mathrm{L}\cos^2\theta_K + \tfrac{1}{4}(1-F_\mathrm{L})\sin^2\theta_K\cos 2\theta_\ell$$
$$- F_\mathrm{L}\cos^2\theta_K\cos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

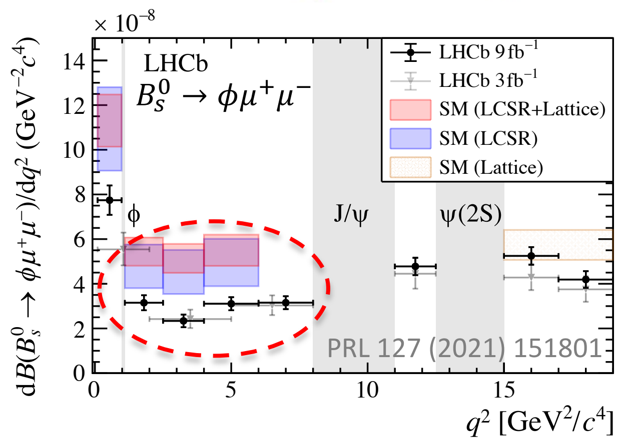
Branching fraction of $b \to s\mu^+\mu^-$

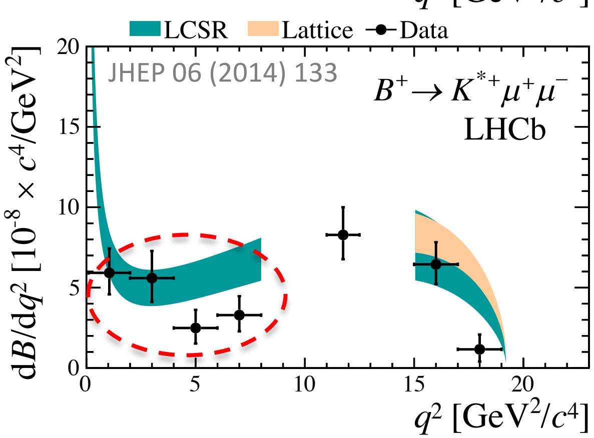
- Pattern of tensions seen, theoretical uncertainty?

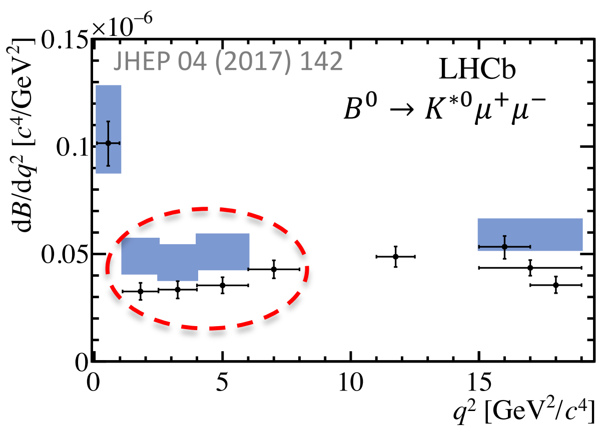


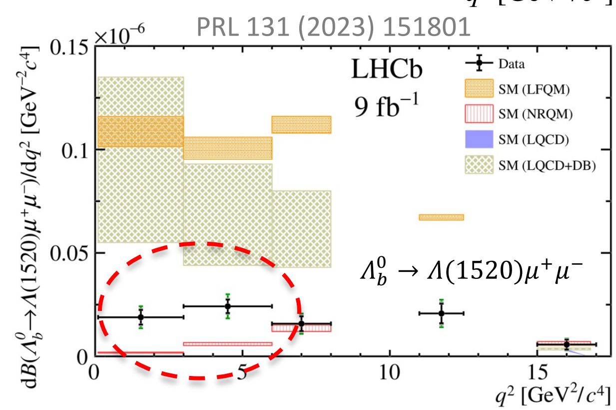












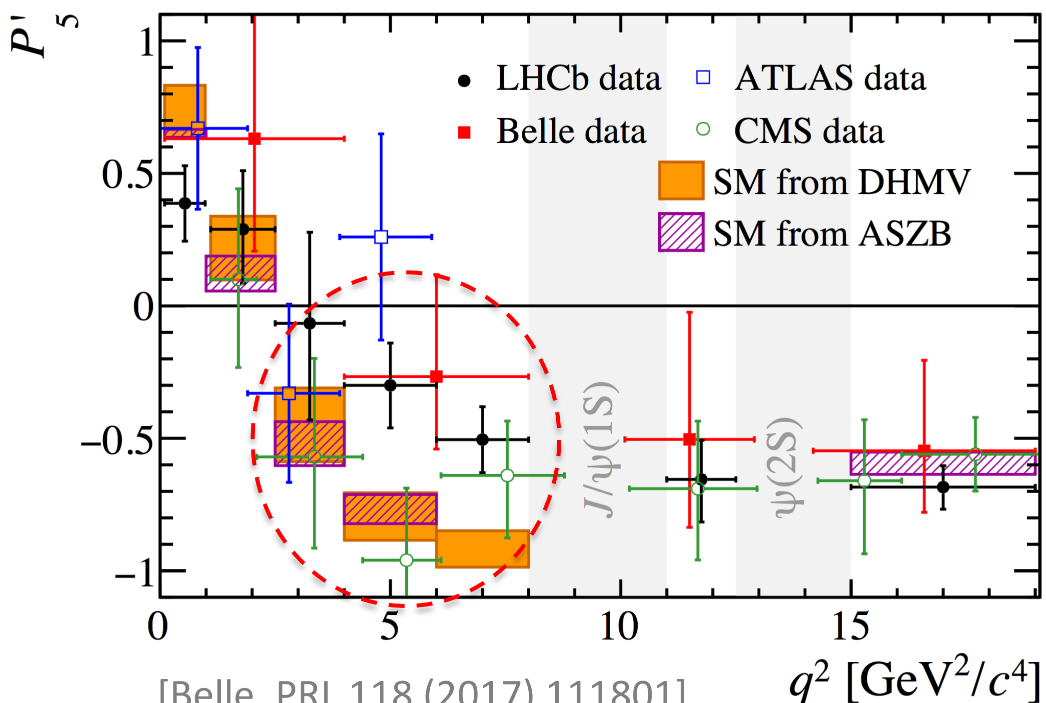
P_5' with $B^0 \to K^{*0}\mu^+\mu^-$

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

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

- Also measured by Belle, ATLAS, CMS

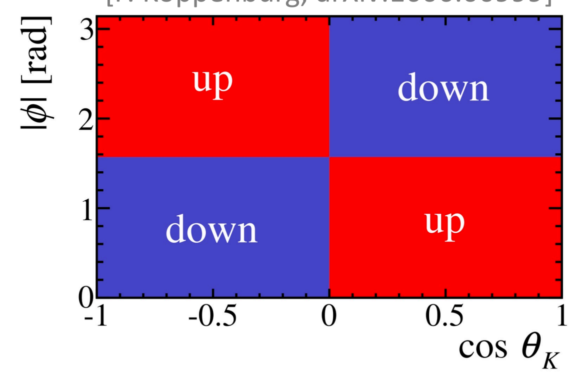
[PRL 125 (2020) 011802]

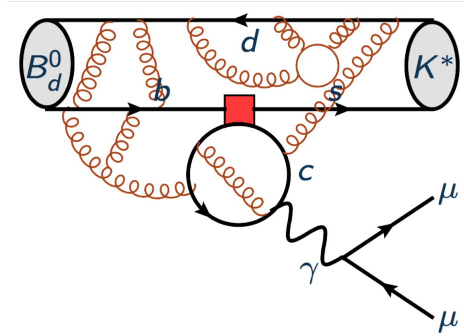


[Belle, PRL 118 (2017) 111801]
[ATLAS, JHEP 10 (2018) 047]
[CMS, PLB 781 (2018) 517]

Count blue minus red

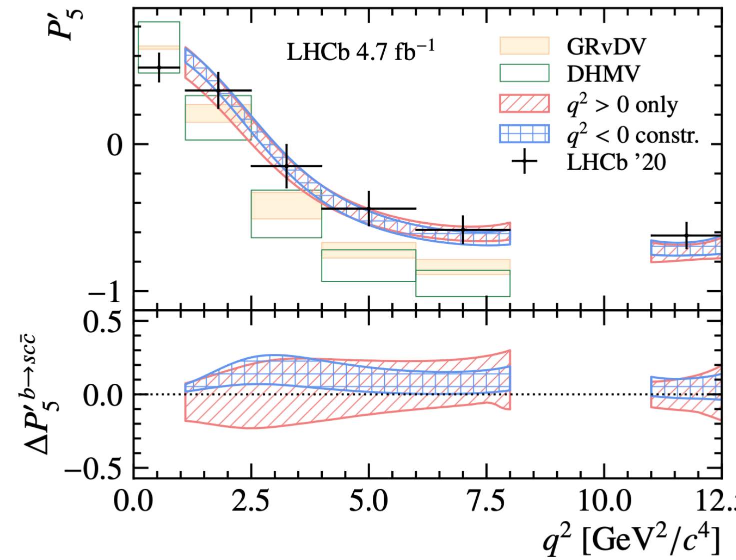
[P. Koppenburg, arXiv:1606.00999]

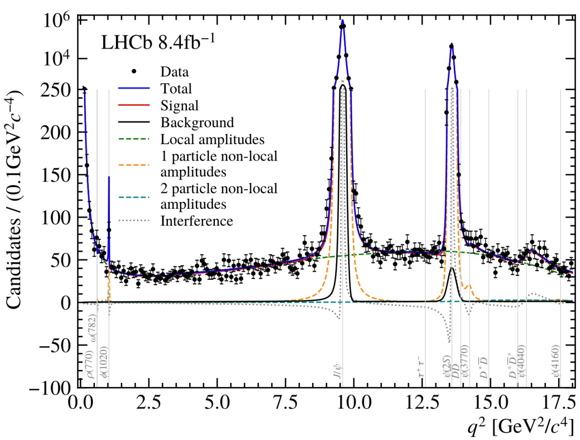


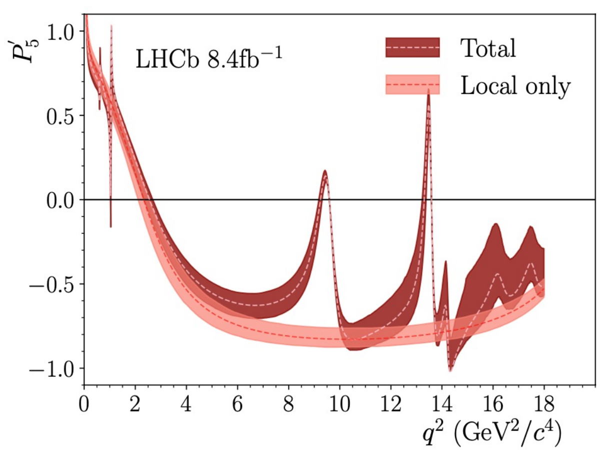


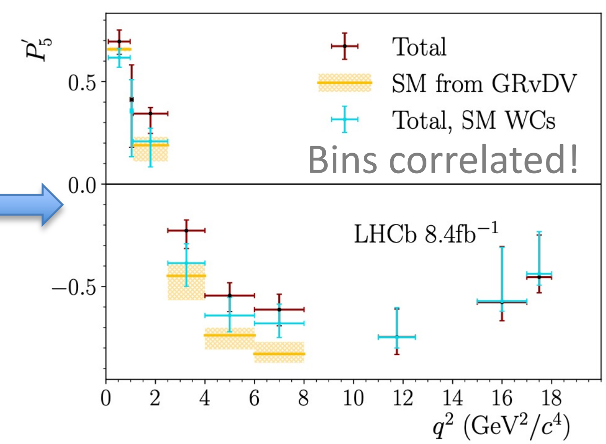
Impact of charm loop

- 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]



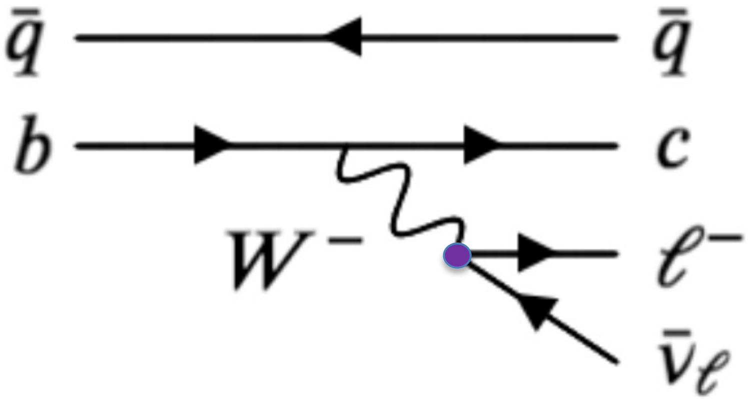


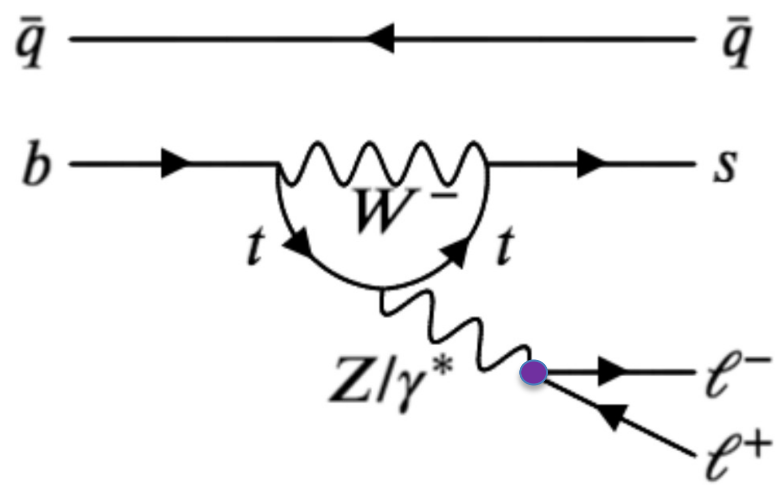




Lepton flavour universality

- 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]

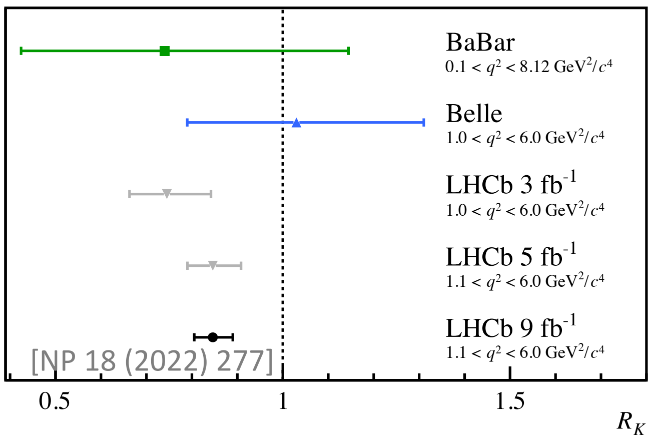
$\mathcal{O}(1\%)$ QED correction
[M. Bordone *et al.*, EJPC 76 (2016) 440]

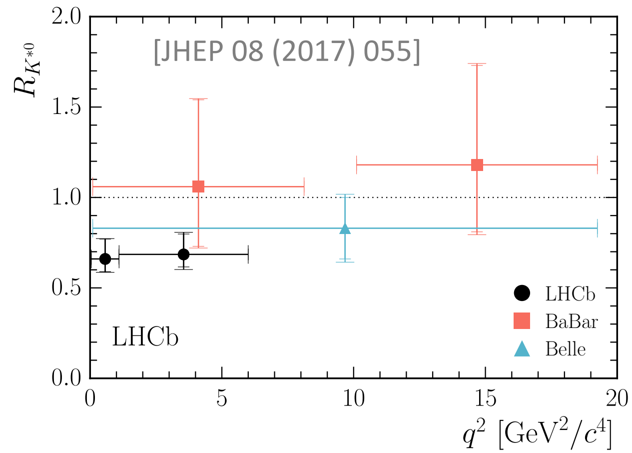
- Lepton flavour universality violation? New Physics!

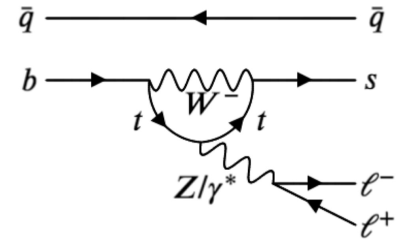
LFU in $b \to s\ell^+\ell^-$ decays

before Dec 2022

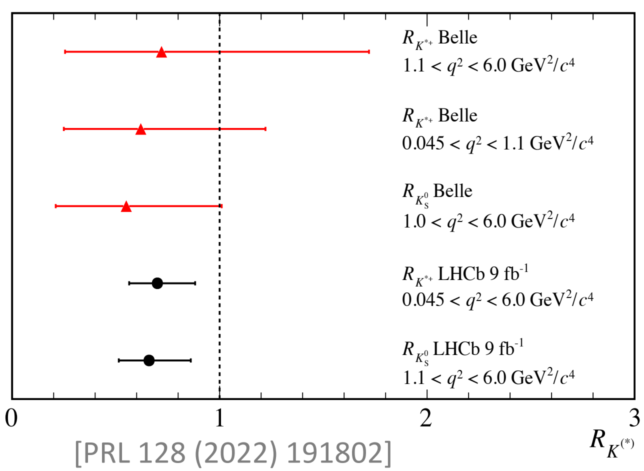
- Deviations from SM seen by LHCb

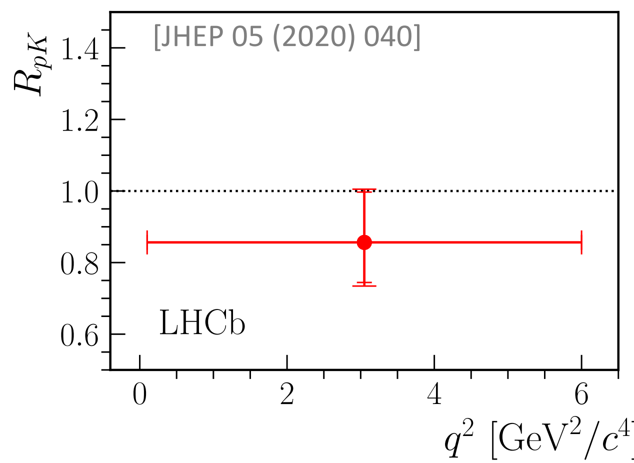


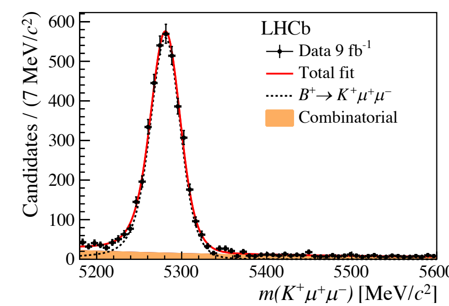


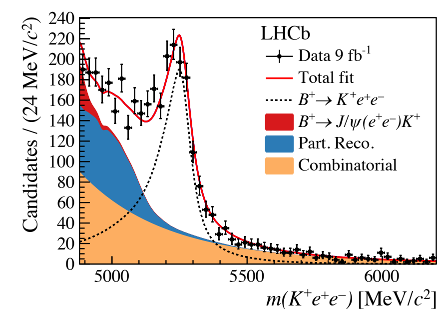


$$R_X = \frac{\mathcal{B}(H_b \to X\mu^+\mu^-)}{\mathcal{B}(H_b \to Xe^+e^-)}$$





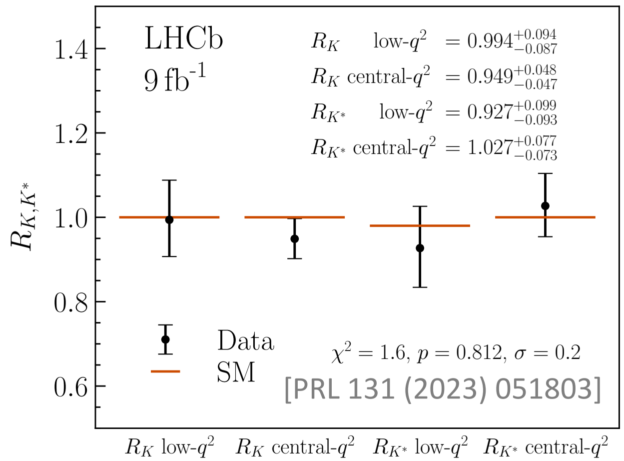




LFU in $b \to s\ell^+\ell^-$ decays

after Dec 2022

- Deviations mostly gone



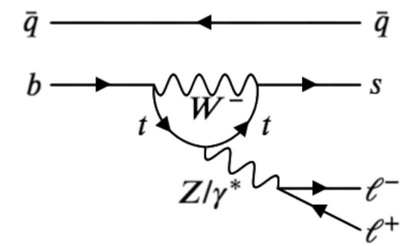
Precision at 5-10%

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

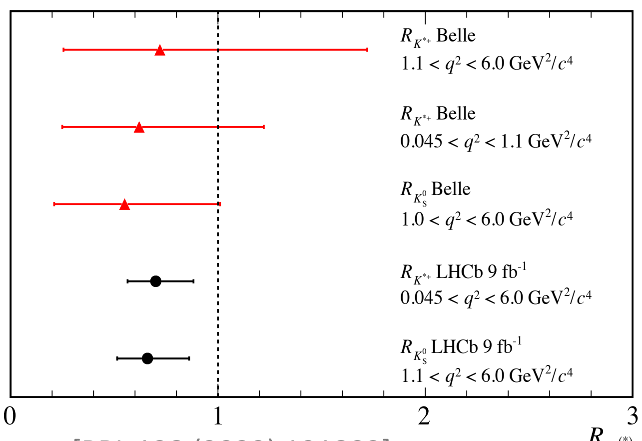
路漫漫其修远兮，吾将上下而求索

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

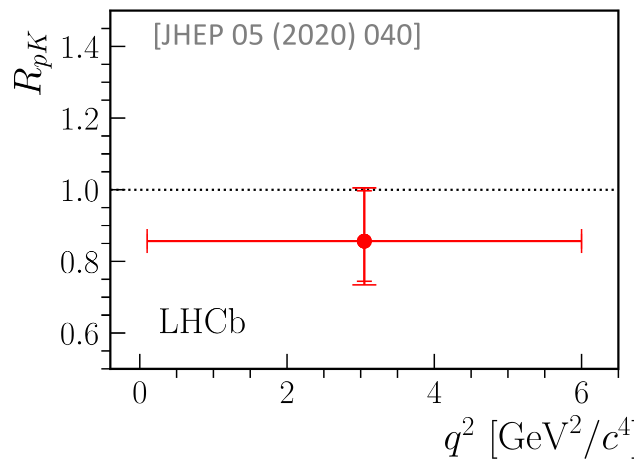
$$R_K = 0.78^{+0.46}_{-0.23}{}^{+0.09}_{-0.05}$$ [CMS, BPH-22-005-PAS]

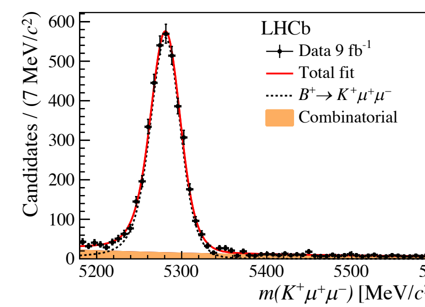


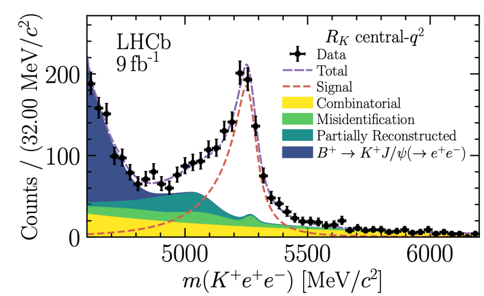
$$R_X = \frac{\mathcal{B}(H_b \to X\mu^+\mu^-)}{\mathcal{B}(H_b \to Xe^+e^-)}$$



[PRL 128 (2022) 191802]

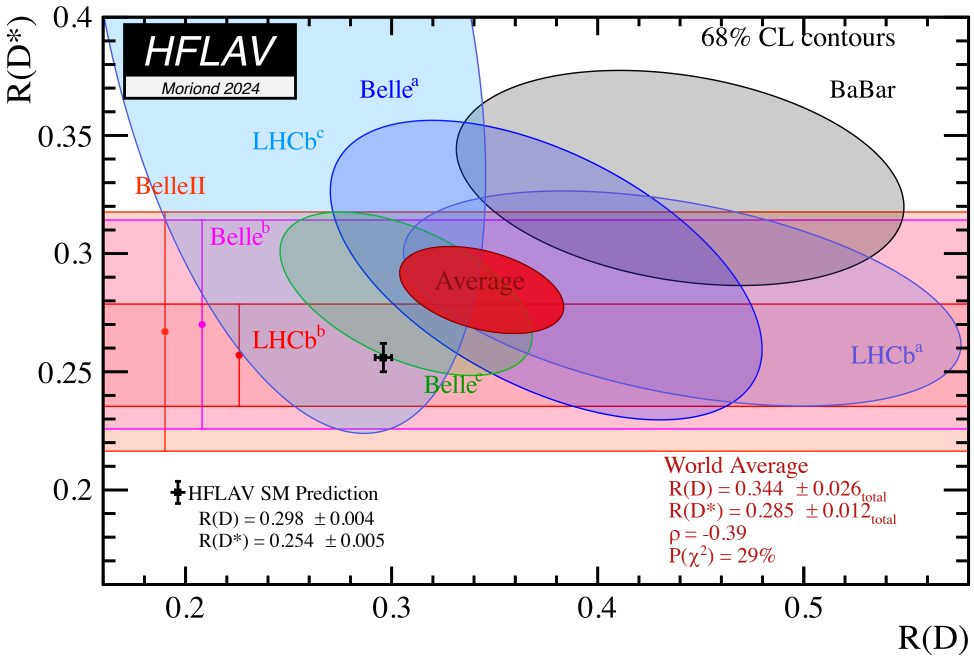


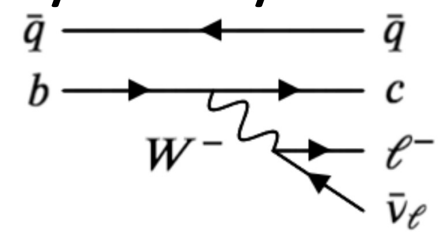




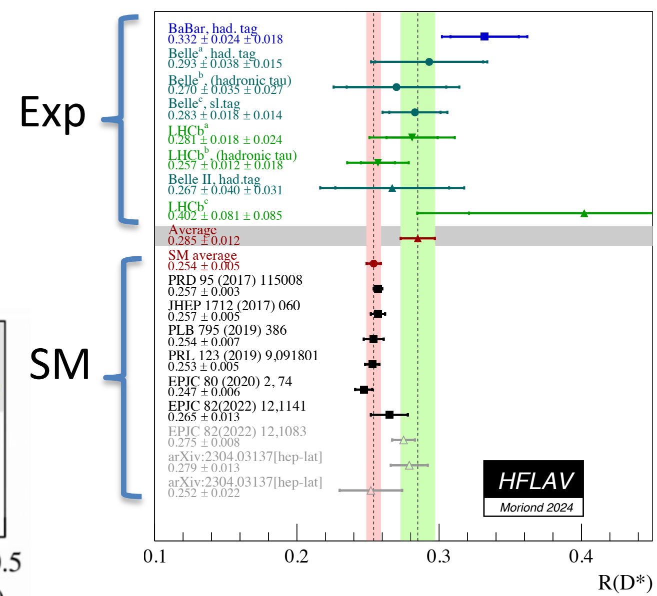
LFU in $b \to c\ell\nu$ decays

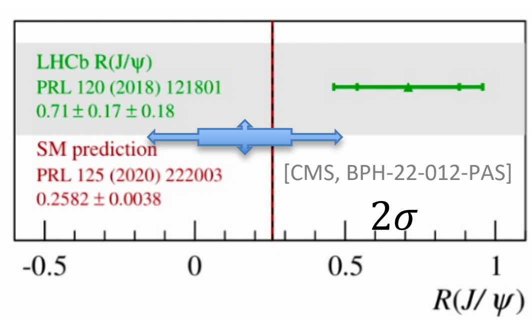
- Deviations from SM seen by Babar/Belle/LHCb

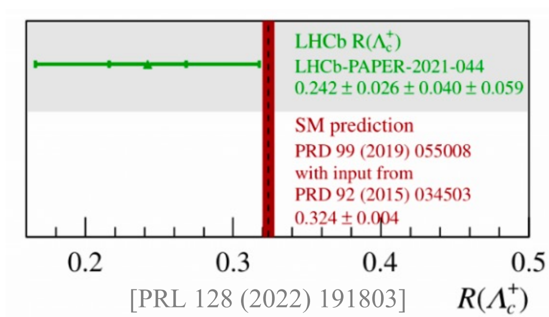




$$R(H_c) = \frac{\mathcal{B}(H_b \to H_c \tau^- \bar{\nu}_\tau)}{\mathcal{B}(H_b \to H_c \mu^- \bar{\nu}_\mu)}$$

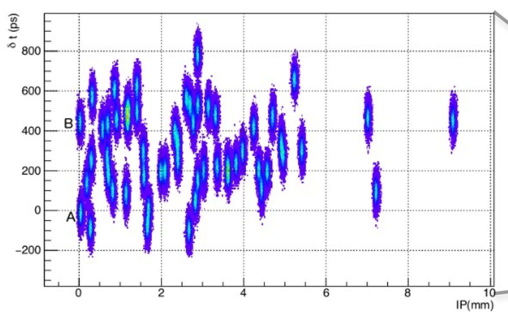


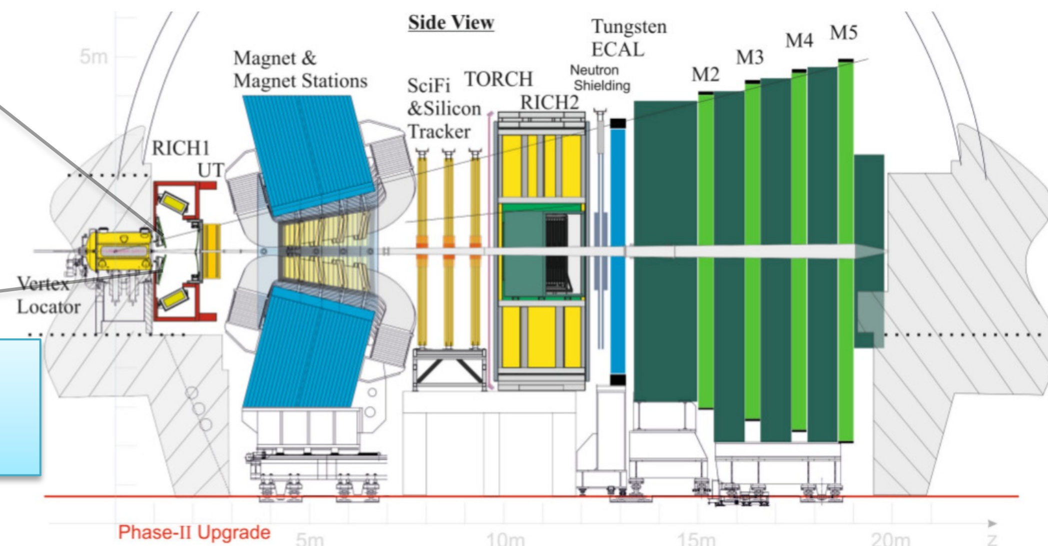




The LHCb upgrade II

[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 $(1 < q^2 < 6\,\mathrm{GeV}^2 c^4)$	0.1 [274]	0.025	0.036	0.007	–
R_{K^*} $(1 < q^2 < 6\,\mathrm{GeV}^2 c^4)$	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

- Many interesting results from LHCb
  - Electroweak, A', W mass, intrinsic charm
  - CP Violation, CKM triangle, ϕ_s, γ, ΔA_{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 continued and strong supports appreciated!
  - Form factors, non-form-factor contributions
  - New observables?