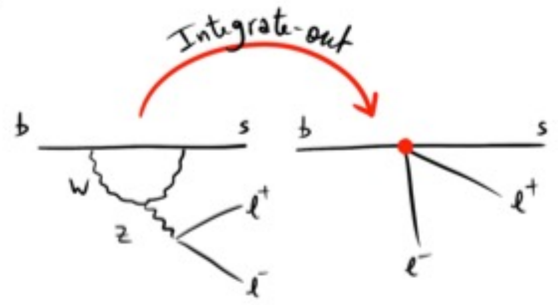
Indirect search for New Physics at LHCb

Jibo HE/何吉波(UCAS)

第十二届新物理研讨会

2023年7月23-29日

Indirect search for New Physics



- Measure FCNC transitations, and compare to predictions

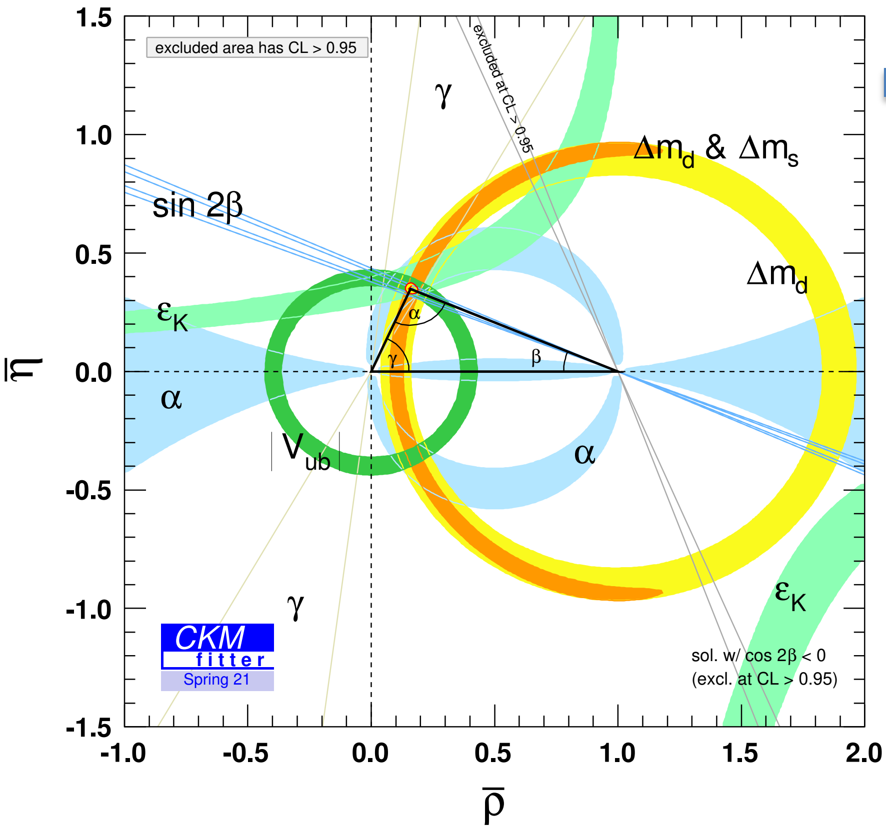
- Operator product expansion (OPE) of $b \to s\ell^+\ell^-$

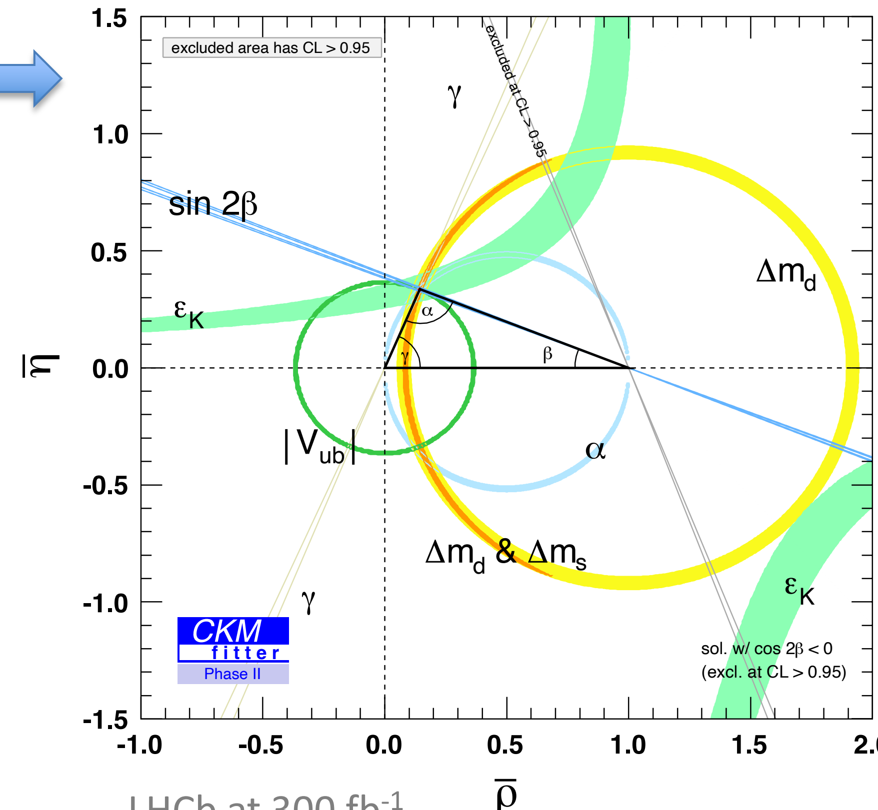
$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \frac{e^2}{16\pi^2} \sum_i (C_i O_i + C_i' O_i') + h.c.$$

  - 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

Indirect search for NP (cont.)

- Overconstrain the CKM triangle





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

Large Hadron Collider

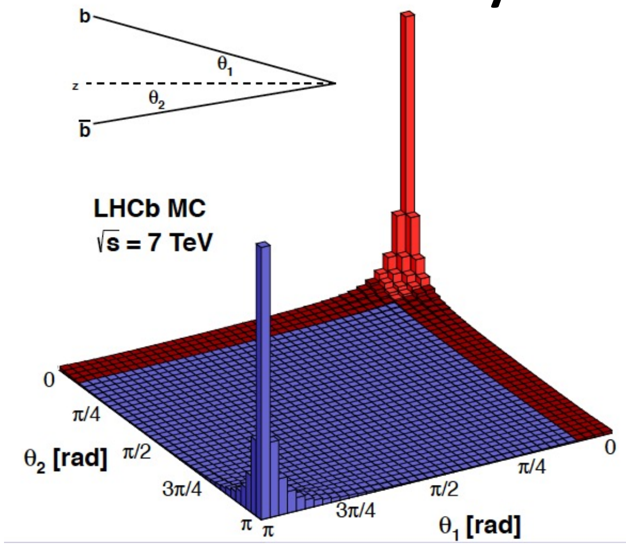
Proton energy: up to 7 TeV (10^{12} eV)
speed: 0.999999991 c

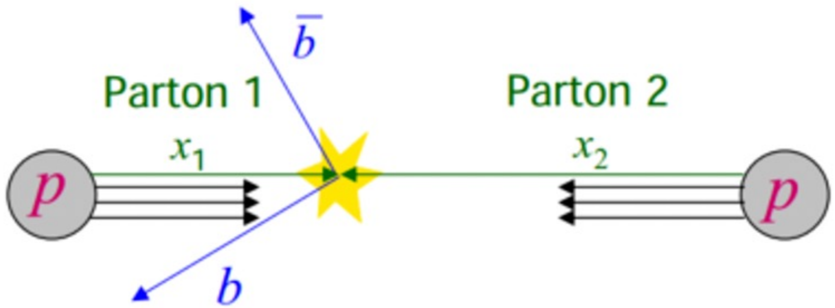
Beauty/charm production

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

Flavour factory!

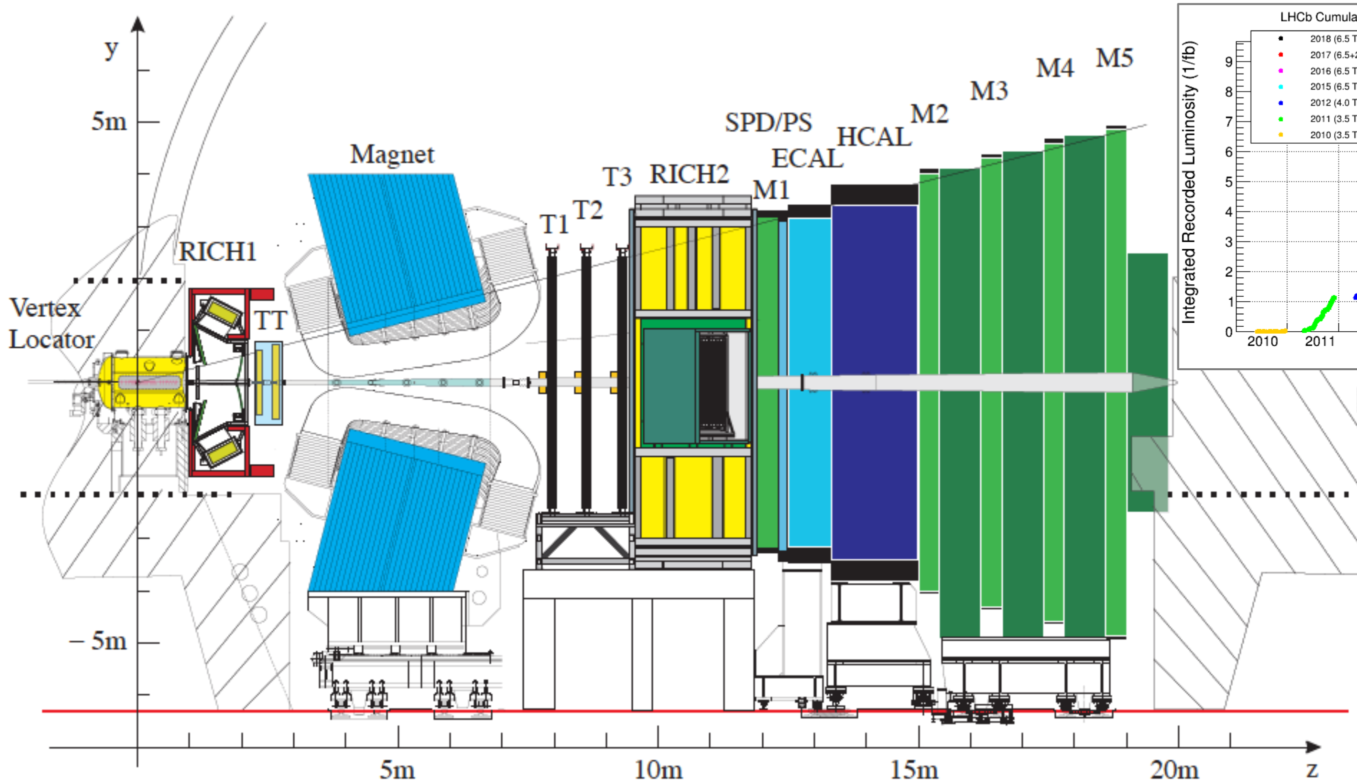
- Predominantly in forward/backward cones

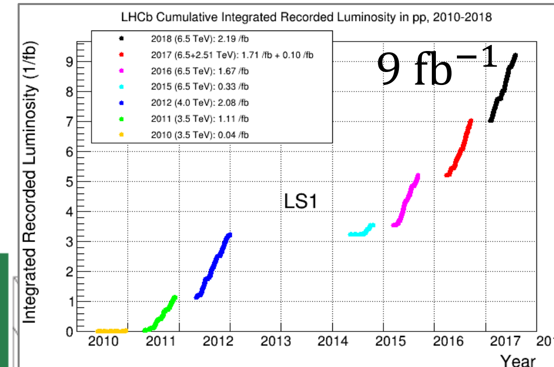




Initial energy of $b\bar{b}$ not known

The LHCb experiment

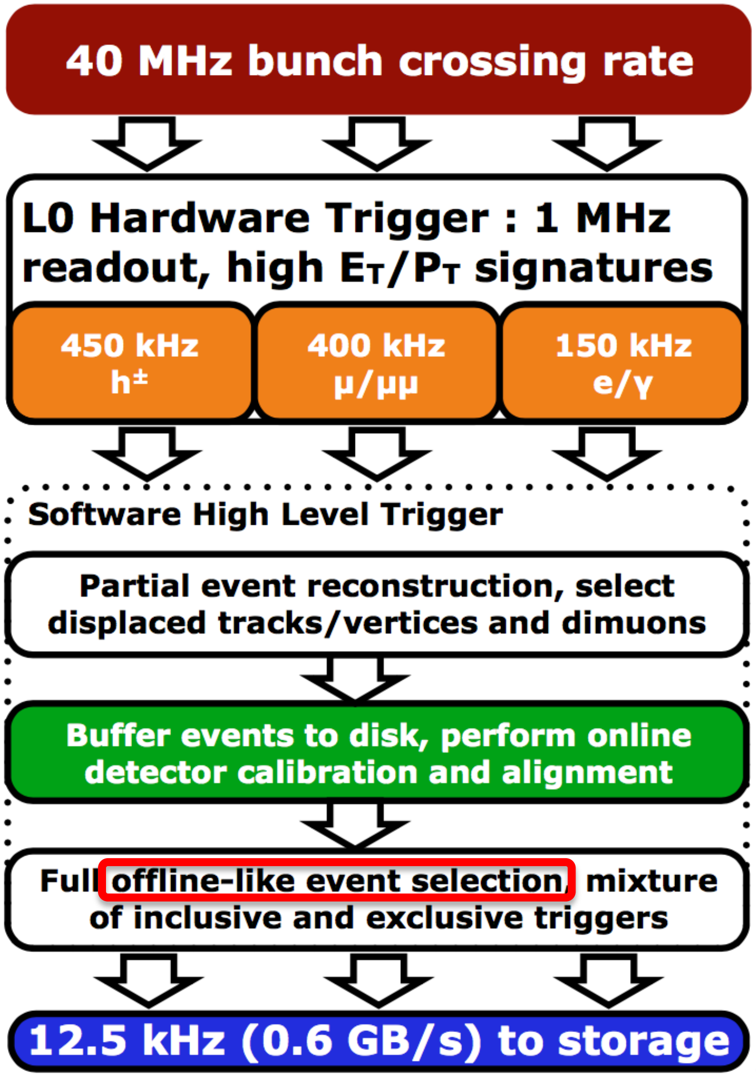




[JINST 3 (2008) S08005]

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)

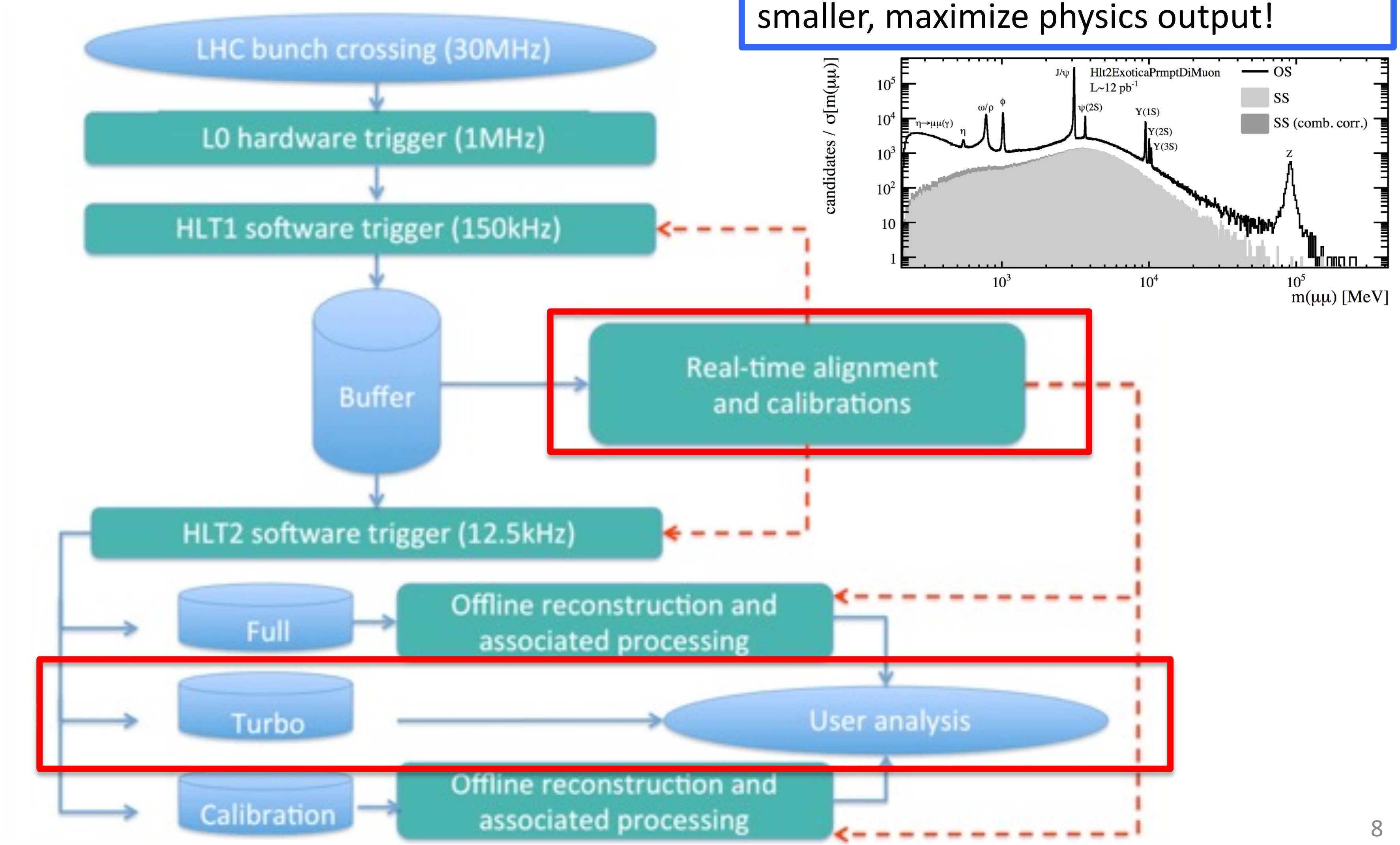
The LHCb trigger (2018)



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

The turbo stream

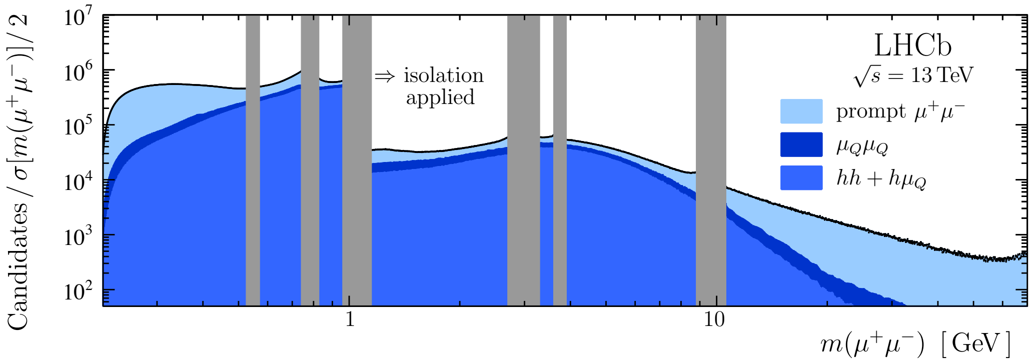
Turbo stream, μDST, event size 10 times smaller, maximize physics output!

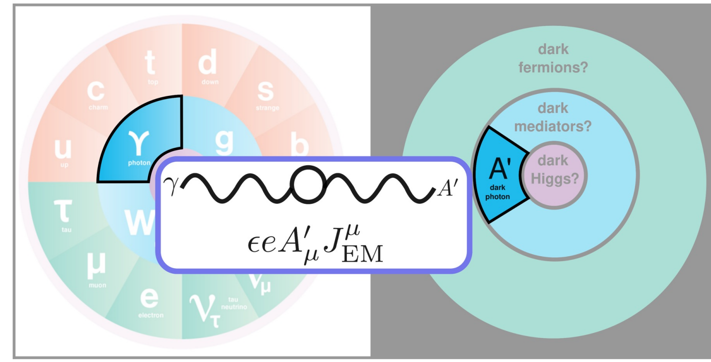


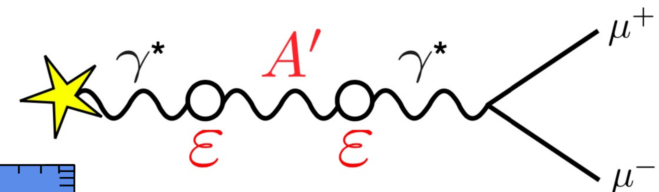
Dark photon

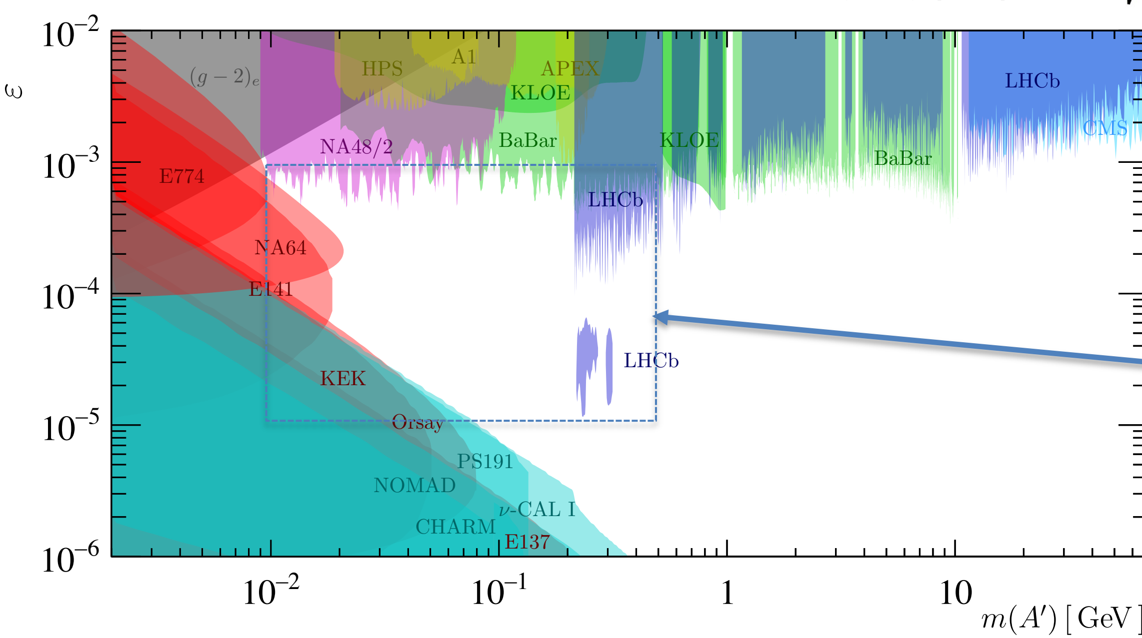
- Searched in $m(\mu\mu)$

[PRL 124 (2020) 041801]







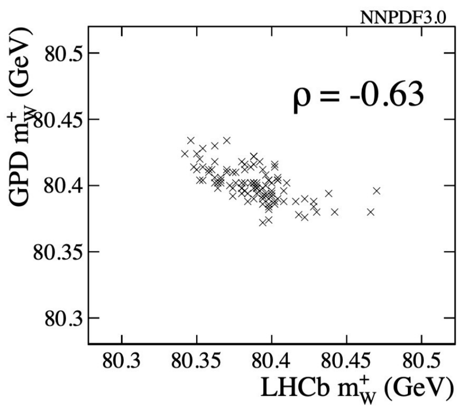


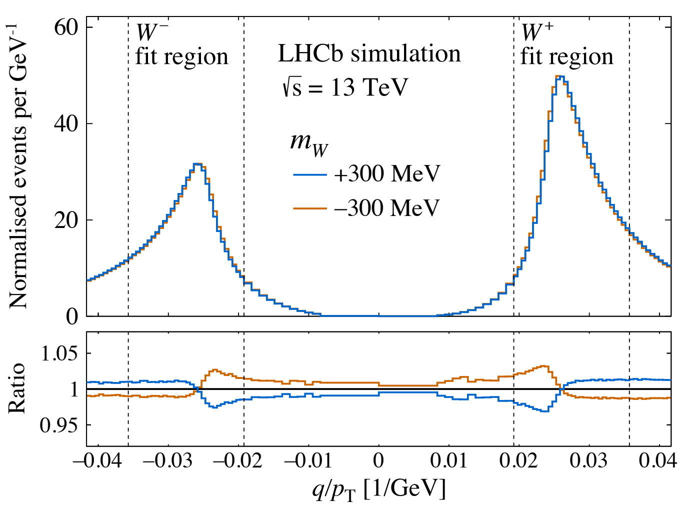
Proposed to cover this with $D^*(2007)^0 \to D^0 A'(\to e^+e^-)$
[Iten *et al.*, PRD 92 (2015) 115017]

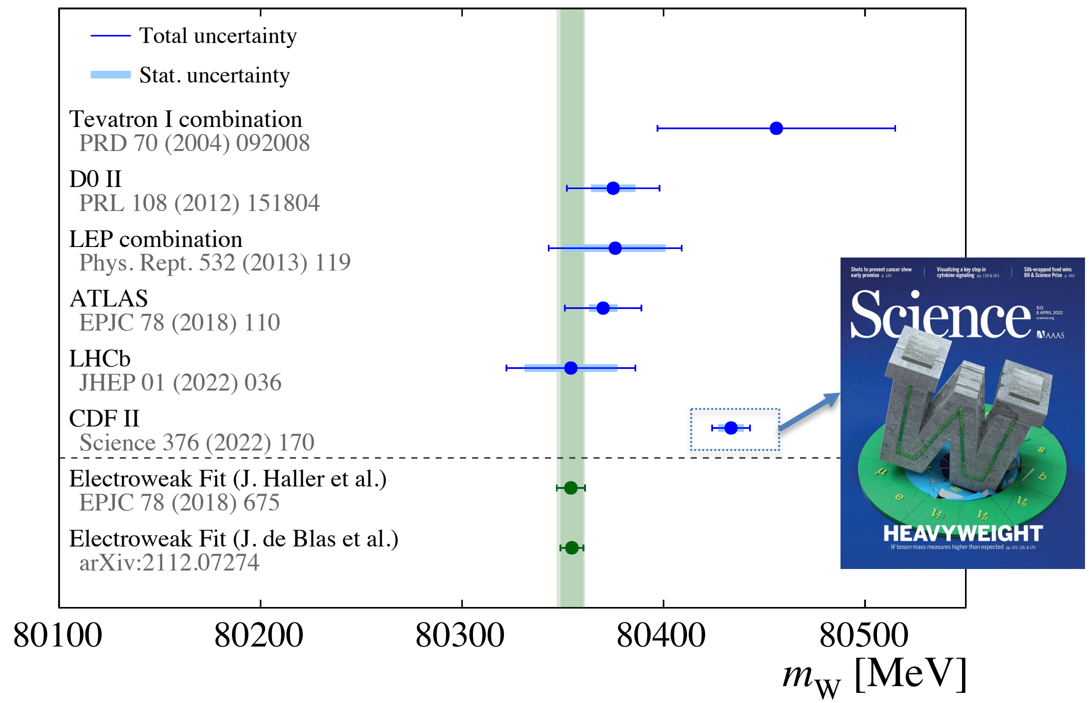
W mass

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

[JHEP 01 (2022) 036]

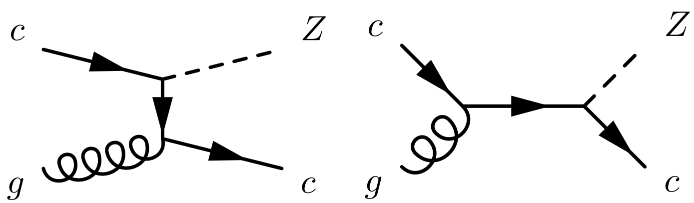






Intrinsic charm?

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



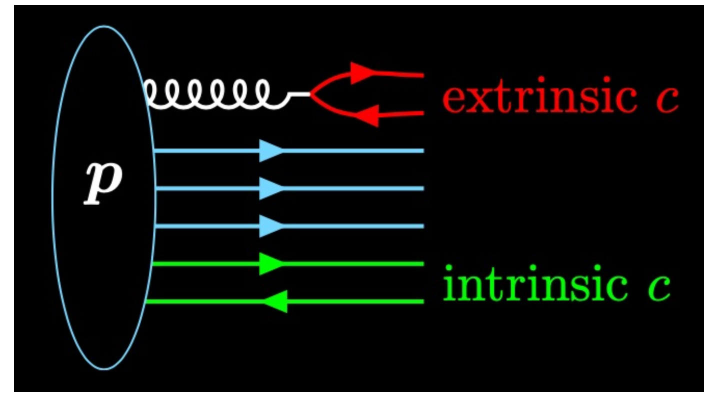
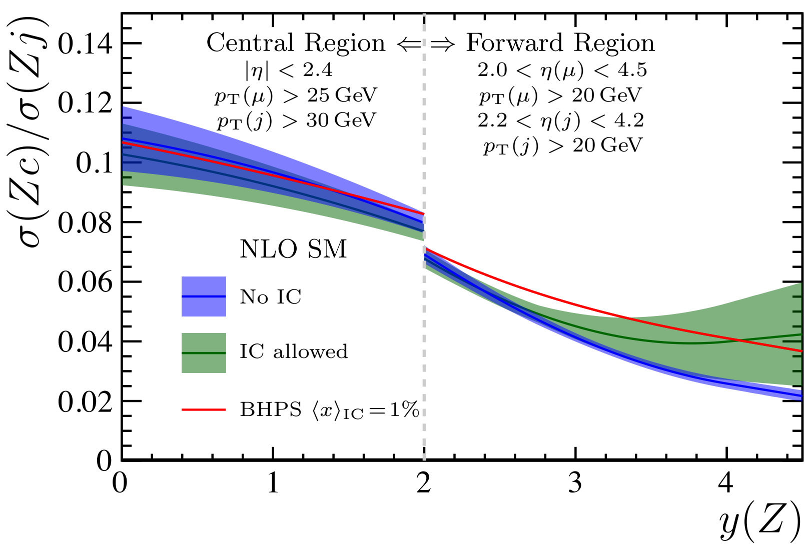
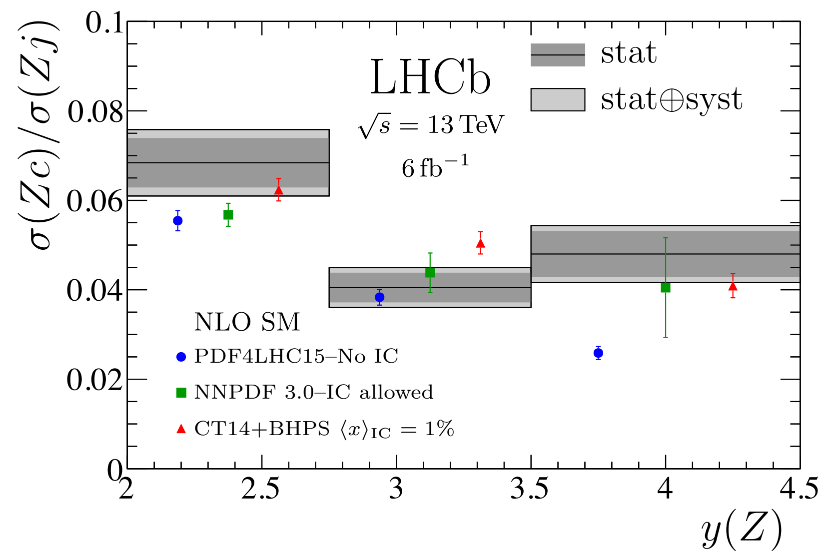


Image: D. Craik

[PRL 128 (2022) 082001]





ΔA_{CP} in charm

[PRL 122 (2019) 211803]

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

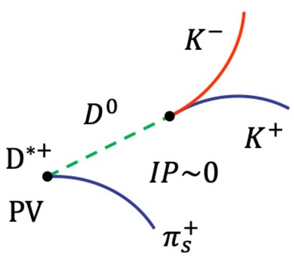
$$\Delta A_{CP} \equiv A_{CP}(K^-K^+) - A_{CP}(\pi^-\pi^+)$$

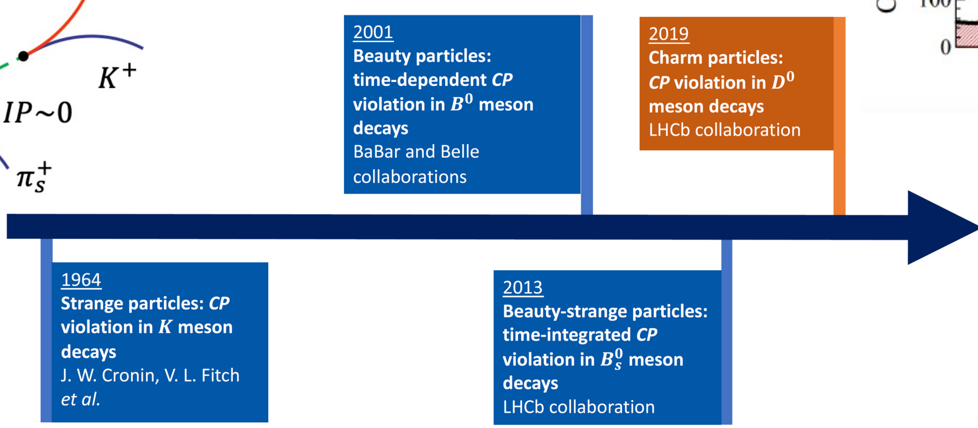
$$\Delta A_{CP}^{\pi\text{-tagged}} = [-18.2 \pm 3.2\,(\text{stat.}) \pm 0.9\,(\text{syst.})] \times 10^{-4},$$

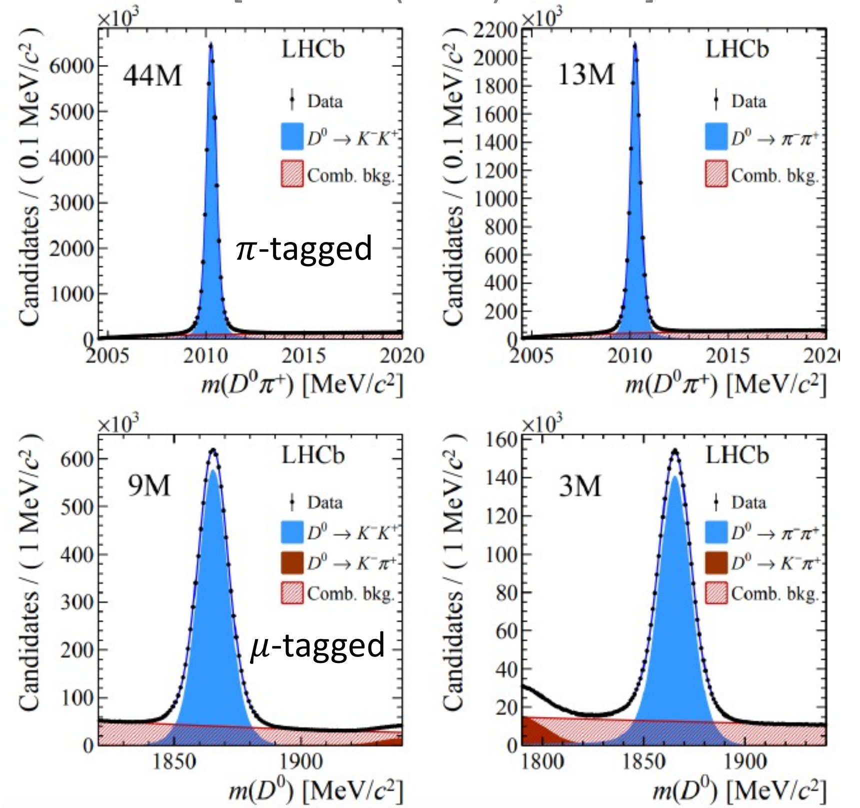
$$\Delta A_{CP}^{\mu\text{-tagged}} = [-9 \pm 8\,(\text{stat.}) \pm 5\,(\text{syst.})] \times 10^{-4}.$$

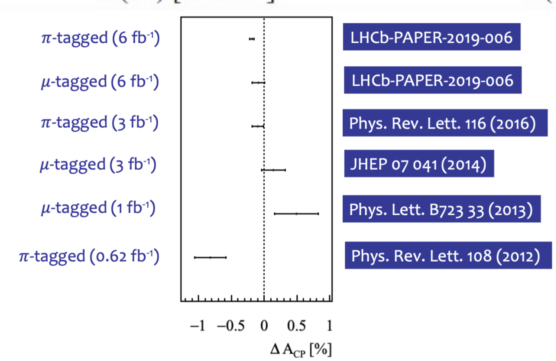
Combined one:

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

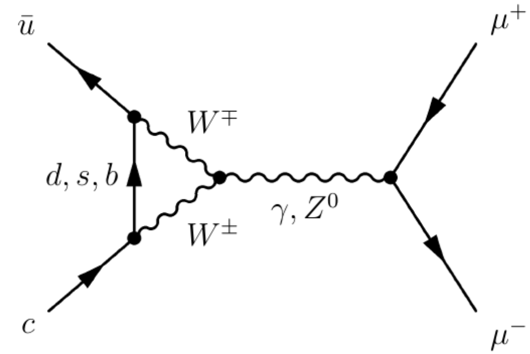






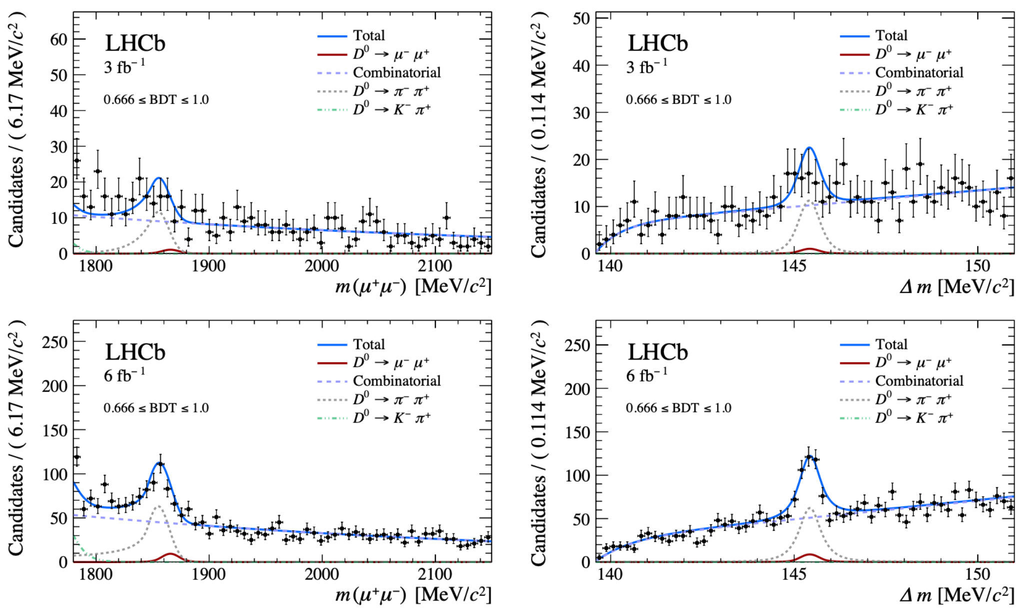


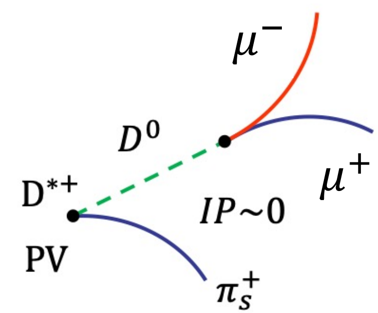
$D^0 \to \mu^+\mu^-$



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

[arXiv:2212.11203]





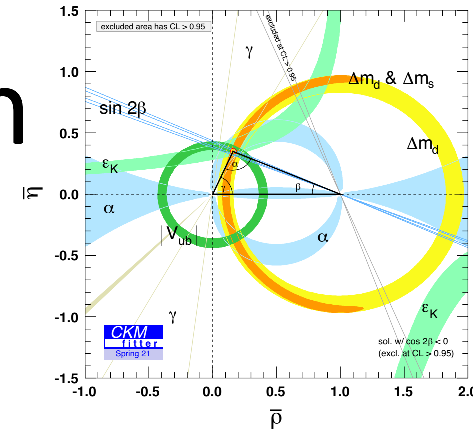
$\mathcal{B}(D^0 \to \mu^+\mu^-) < 2.9 \times 10^{-9}$ @ 90% CL

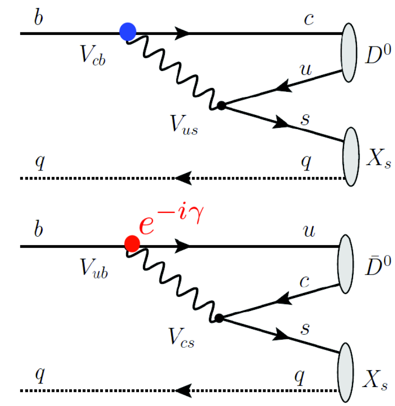
CKM-γ combination

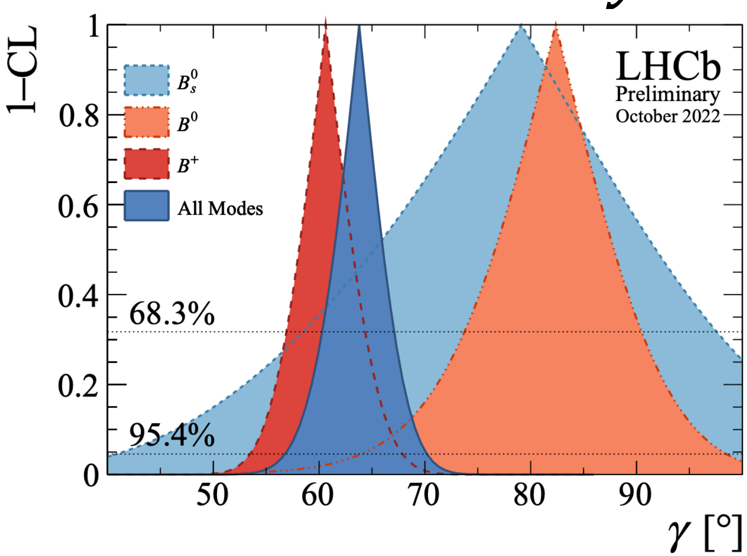
- Simultaneous determination of CKM-γ & charm mixing parameters
  - CKM $\gamma = \left(63.8^{+3.5}_{-3.7}\right)^\circ$
  - Charm mixing $x = \left(0.398^{+0.050}_{-0.049}\right)\%$,

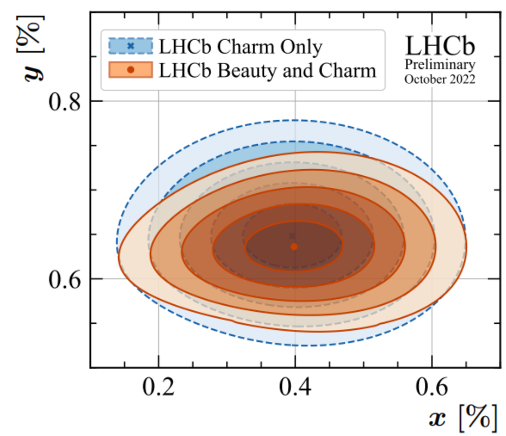
    $y = \left(0.636^{+0.020}_{-0.019}\right)\%$

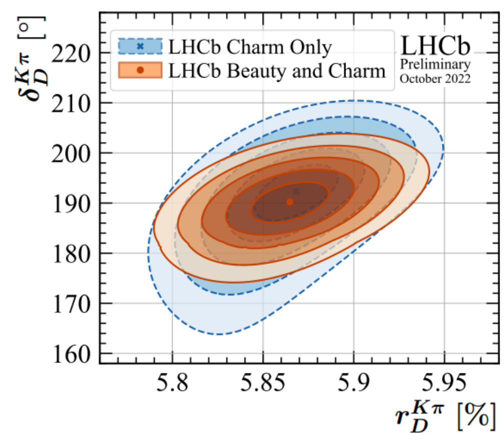
[LHCb-Conf-2022-003]





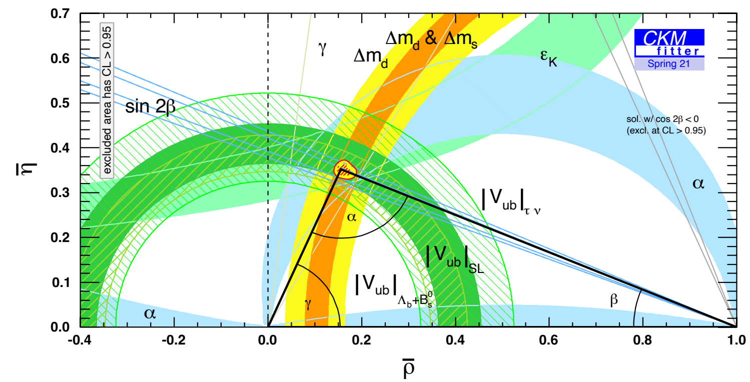


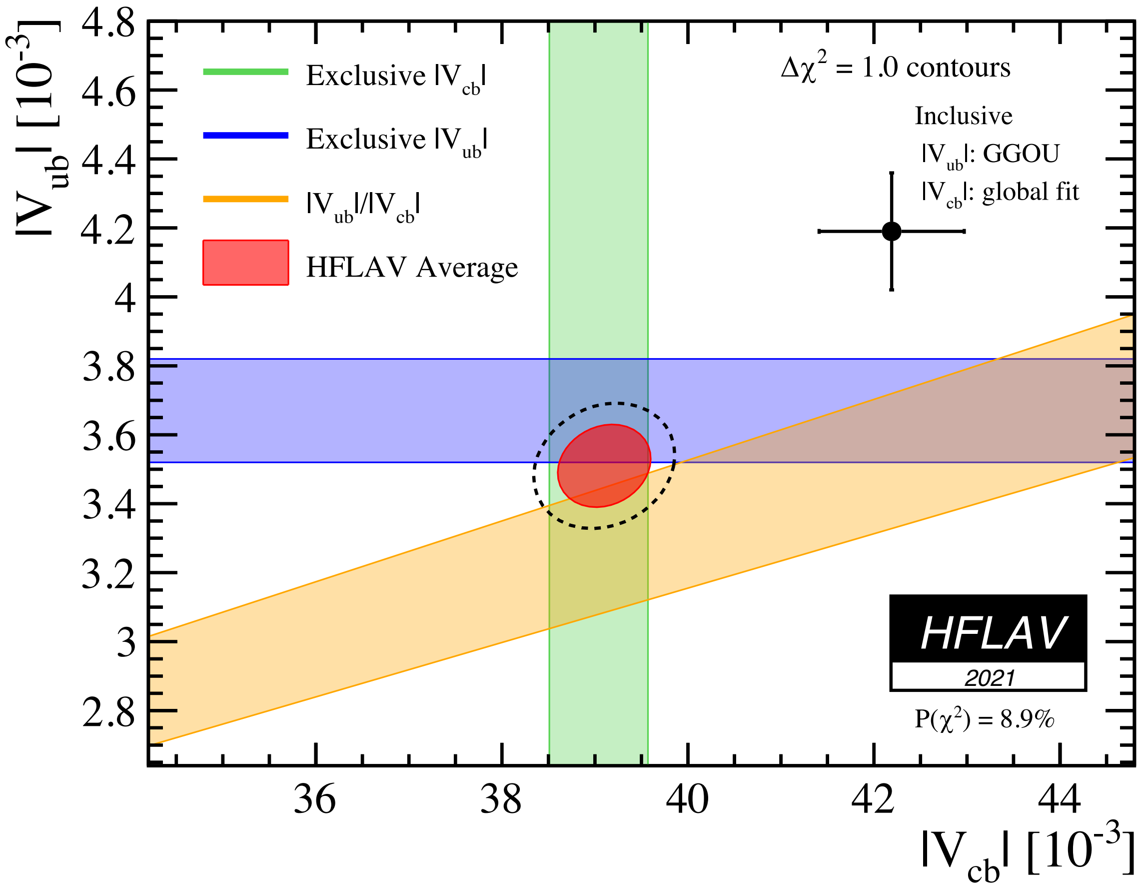


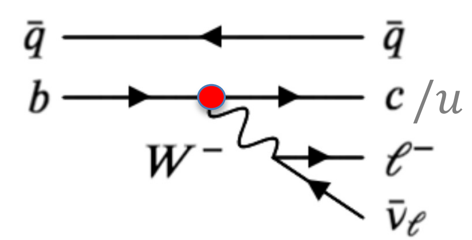


V_{cb}, V_{ub}

- Some tension between exclusive/inclusive

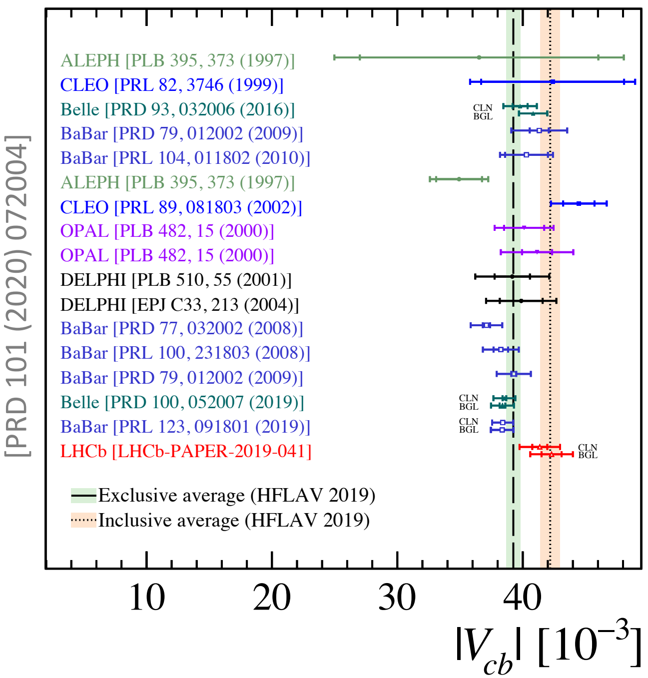


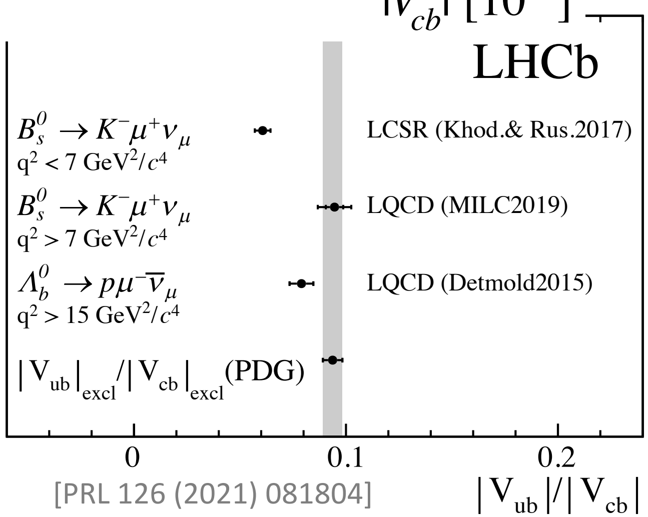




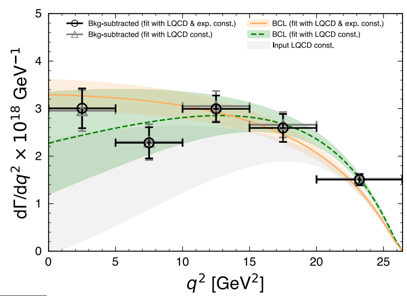
$$d\Gamma \propto |V_{cb}|^2 |f_H|^2$$

V_{cb}, V_{ub}

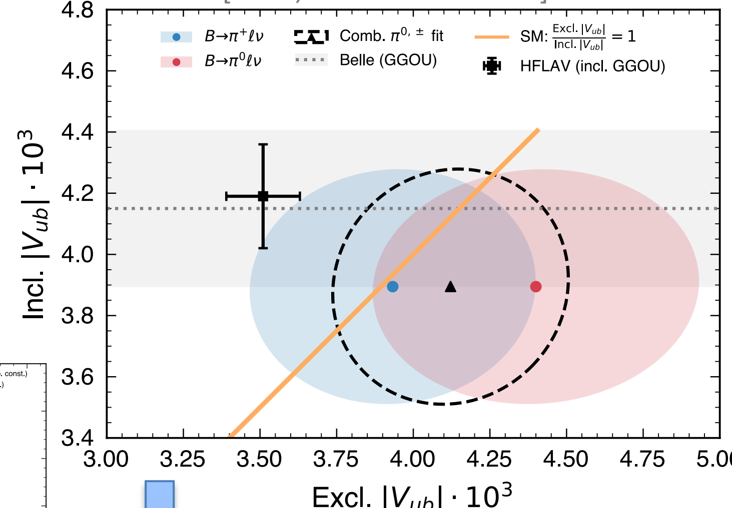




[PRL 126 (2021) 081804]

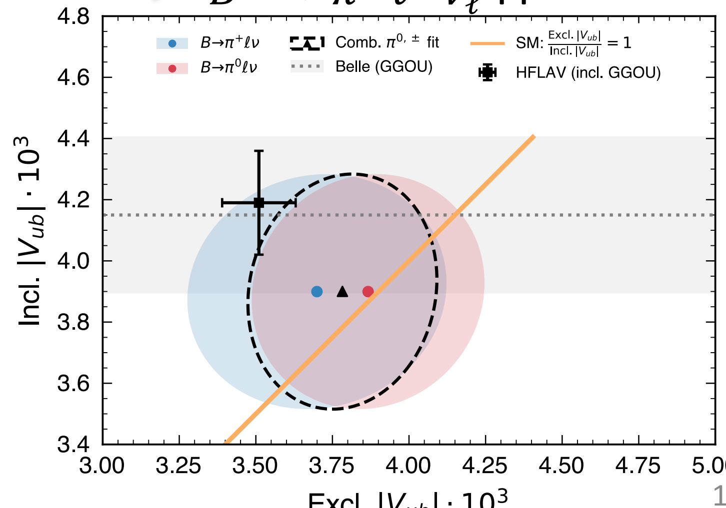


[Belle, arXiv:2303.17309]



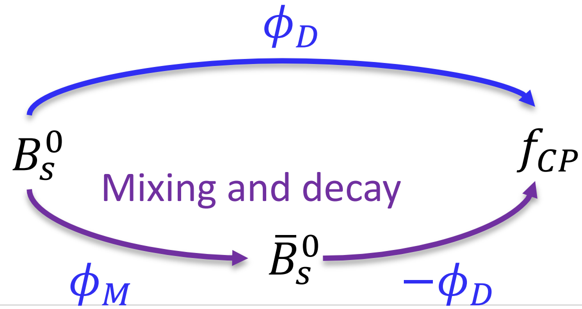
+

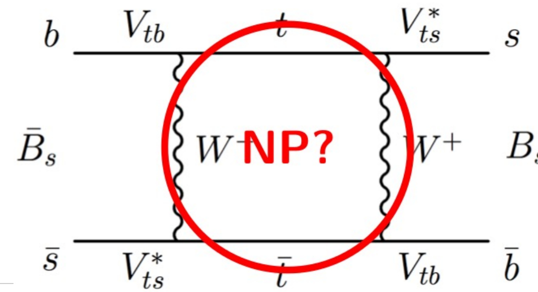
w/ exp constraint for $\bar{B}^0 \to \pi^+ \ell^- \bar{\nu}_\ell$ FF



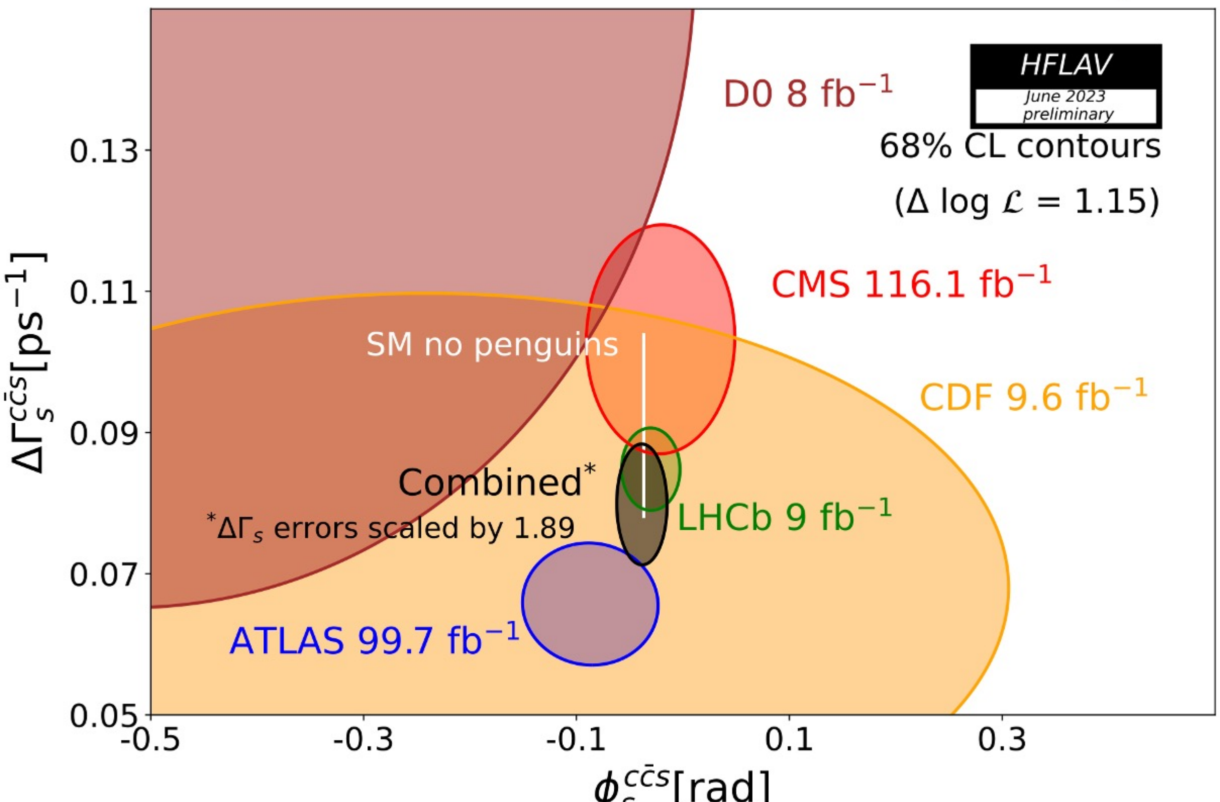
CPV in mixing

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





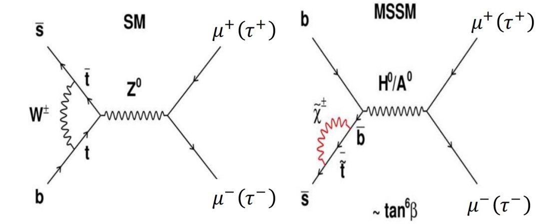
[LHCb-Paper-2023-016]

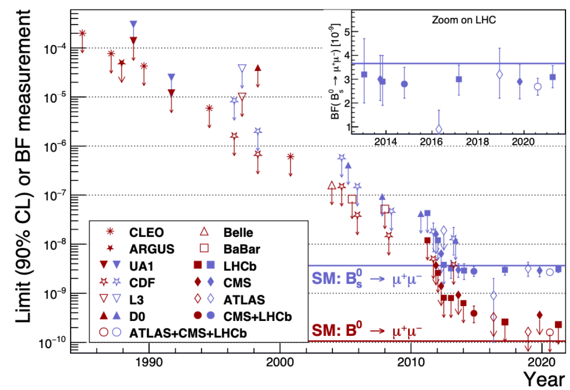


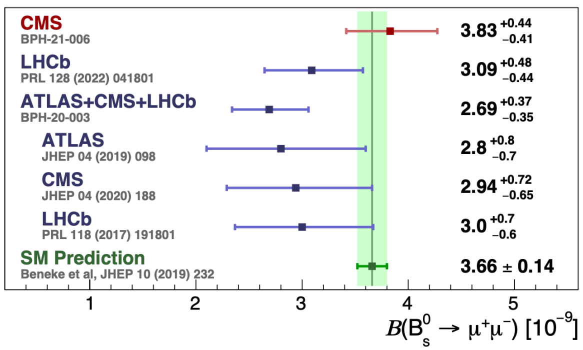
$B^0_{(s)} \to \mu^+\mu^-$

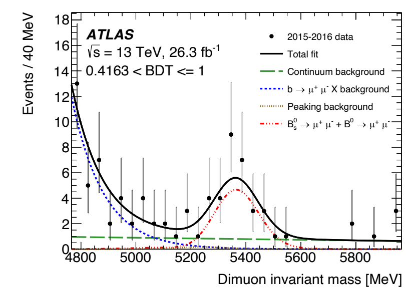
- Suppressed in SM, could be enhanced by New Physics

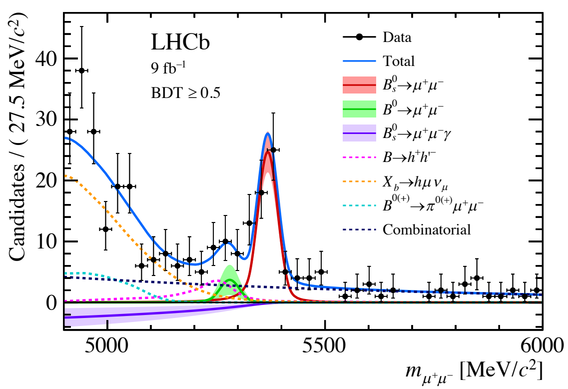
[PRL 128 (2022) 041801]

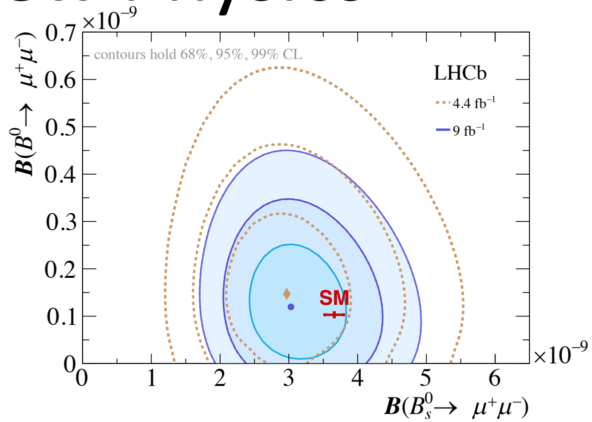


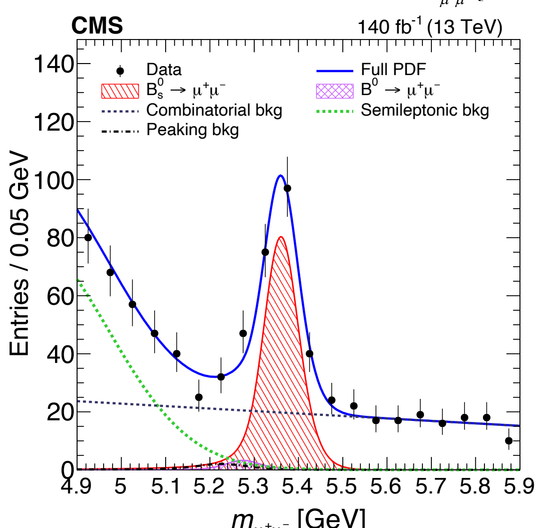


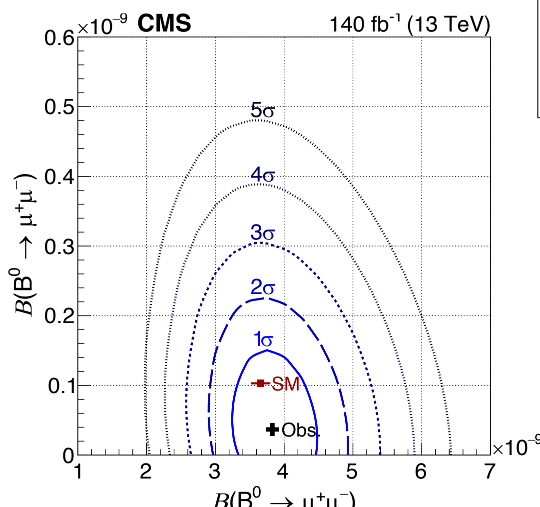












$B_s^0 \to \mu^+\mu^-$ eff. τ

- B_s^0 mixing $\Rightarrow$ 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

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

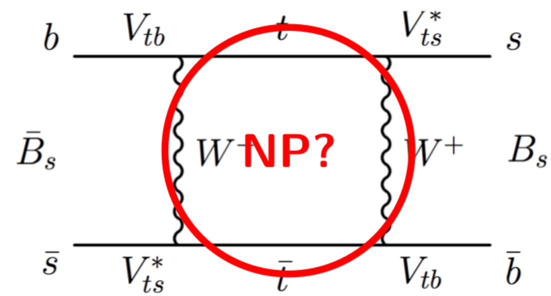
- Measured by LHCb/CMS, not yet sensitive to $A_{\Delta\Gamma}$

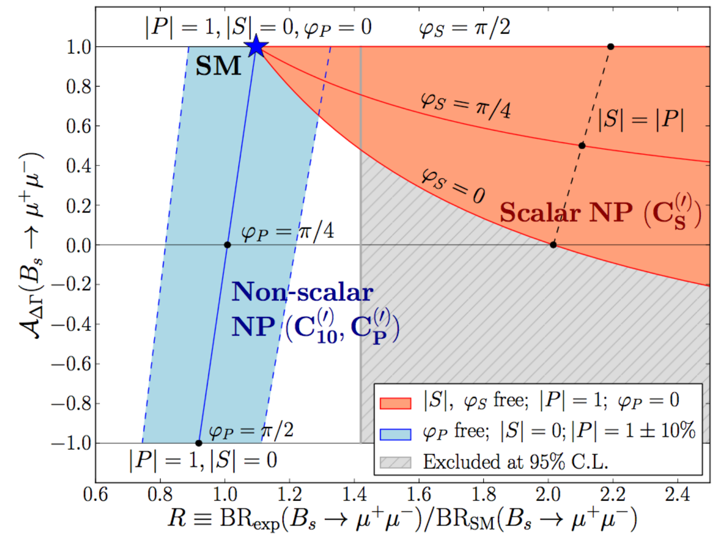
$$\boxed{\tau_{\mu\mu} = 2.07 \pm 0.29 \pm 0.03 \text{ ps}}$$

[PRL 128 (2022) 041801]

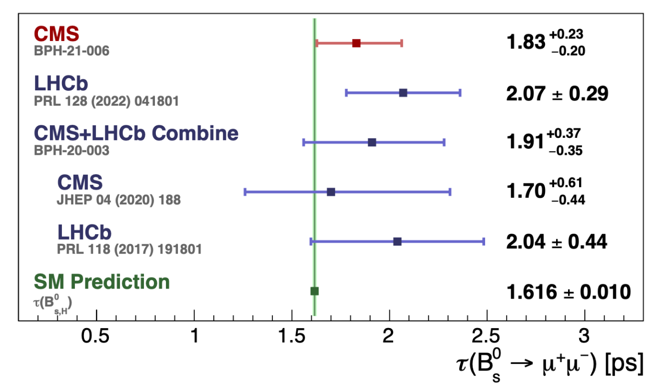
$$1.83\ {}^{+0.23}_{-0.20}\ {}^{+0.04}_{-0.04}\ \text{ps}$$

[CMS, PLB 842 (2023) 137955]

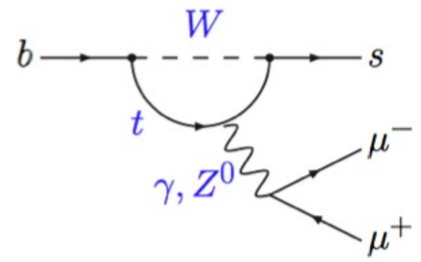




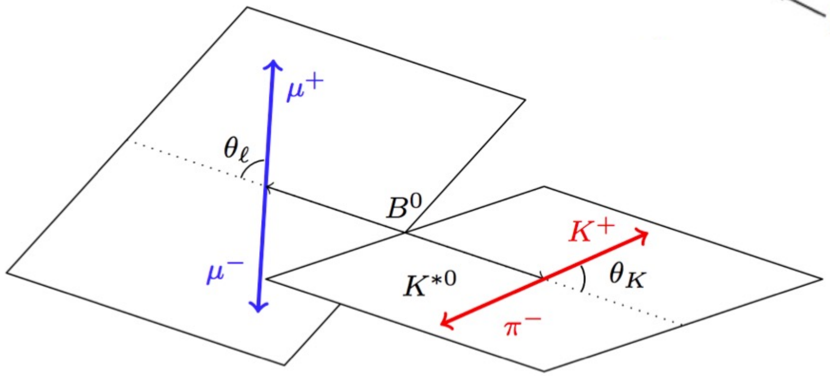
[De Bruyn *et al.*, PRL 109 (2012) 041801]



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



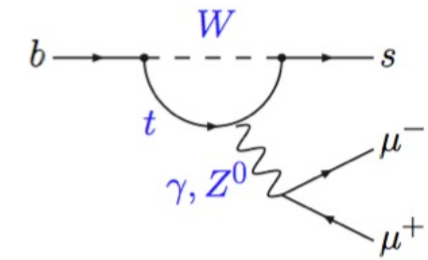
- Described by $q^2 = m^2(\ell^+\ell^-)$ and $\theta_\ell, \theta_K, \phi$
- Many observables!

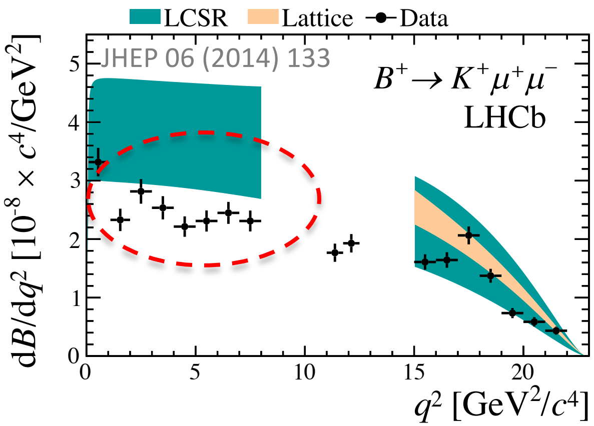


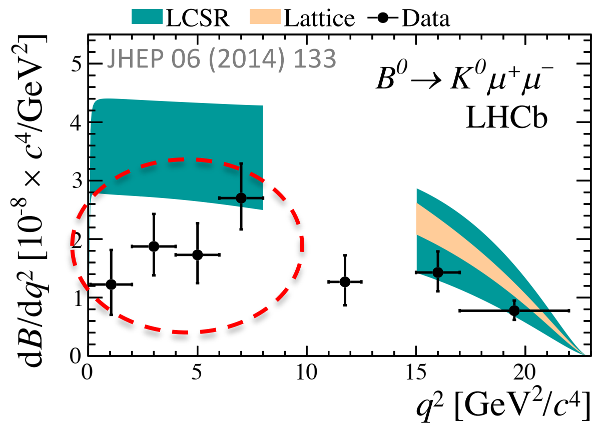
$$\frac{1}{\mathrm{d}(\Gamma+\bar{\Gamma})/\mathrm{d}q^2}\frac{\mathrm{d}^3(\Gamma+\bar{\Gamma})}{\mathrm{d}\vec{\Omega}} = \frac{9}{32\pi}\Big[\tfrac{3}{4}(1-F_{\mathrm{L}})\sin^2\theta_K + F_{\mathrm{L}}\cos^2\theta_K + \tfrac{1}{4}(1-F_{\mathrm{L}})\sin^2\theta_K\cos 2\theta_\ell$$
$$- F_{\mathrm{L}}\cos^2\theta_K\cos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

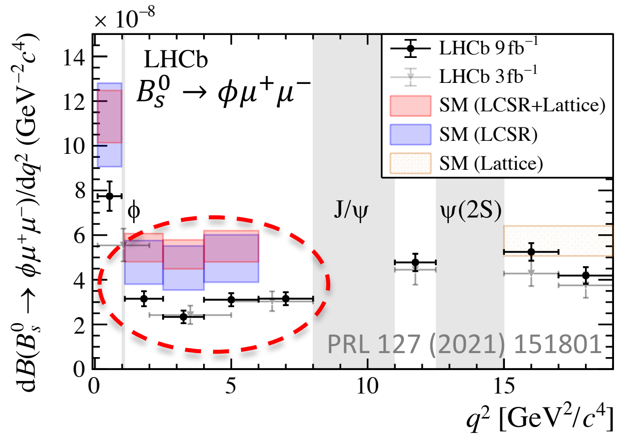
Branching fraction of $b \to s\mu^+\mu^-$

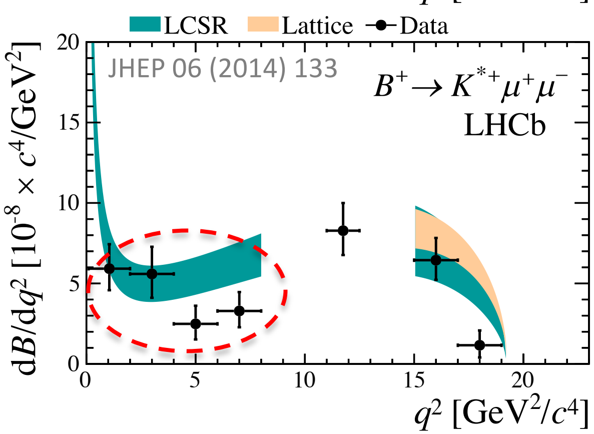
- Pattern of tensions seen, theoretical uncertainty?

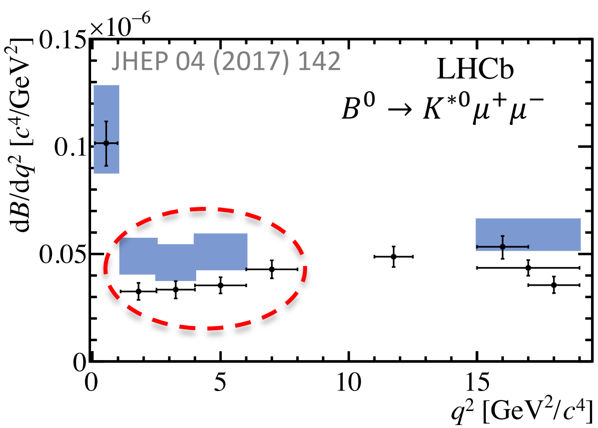


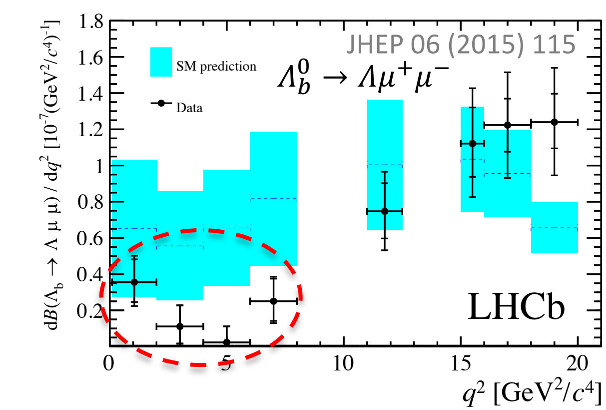








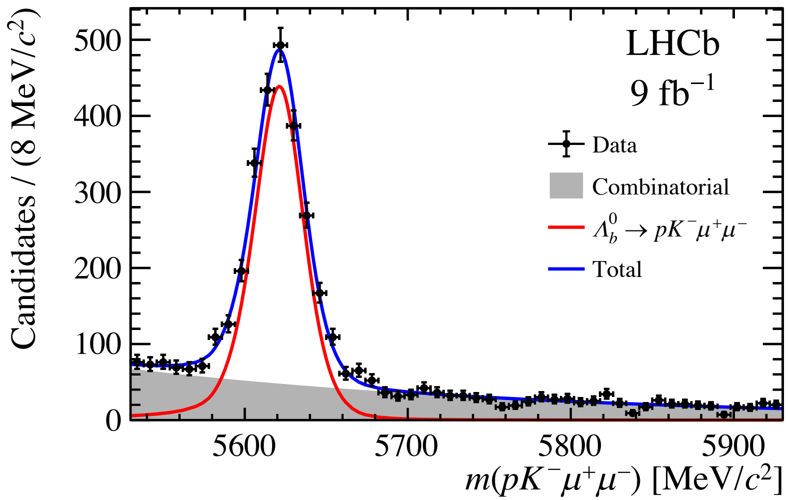


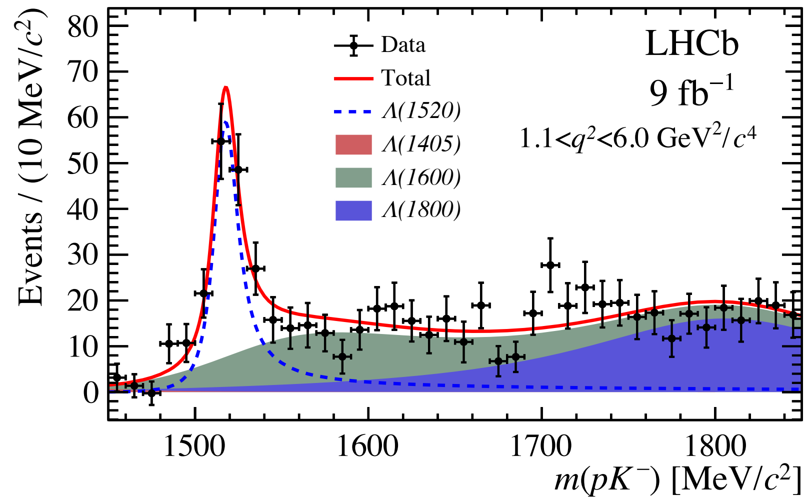


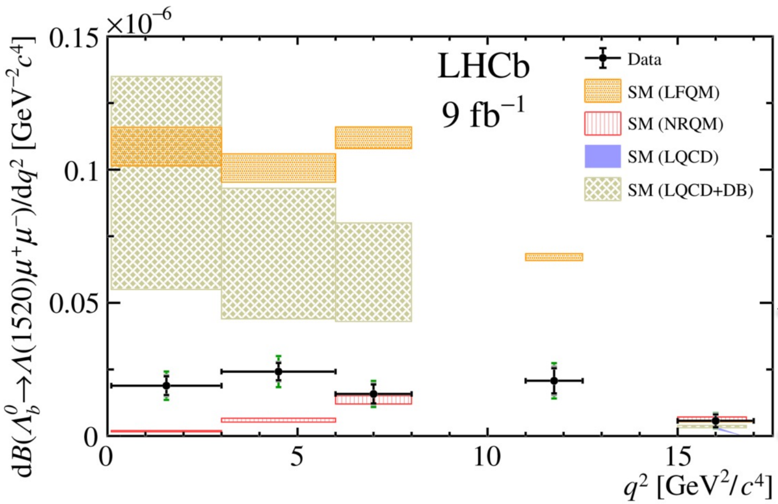
BR of $\Lambda_b^0 \to \Lambda(1520)\mu^+\mu^-$

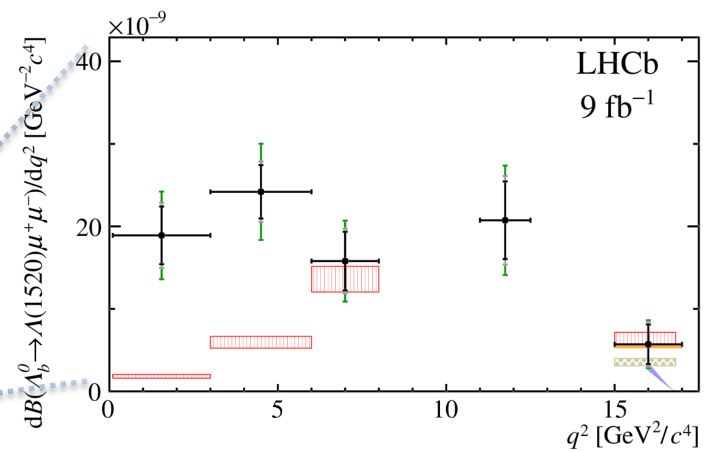
- First measurement, w/ all data

[arXiv:2302.08262]









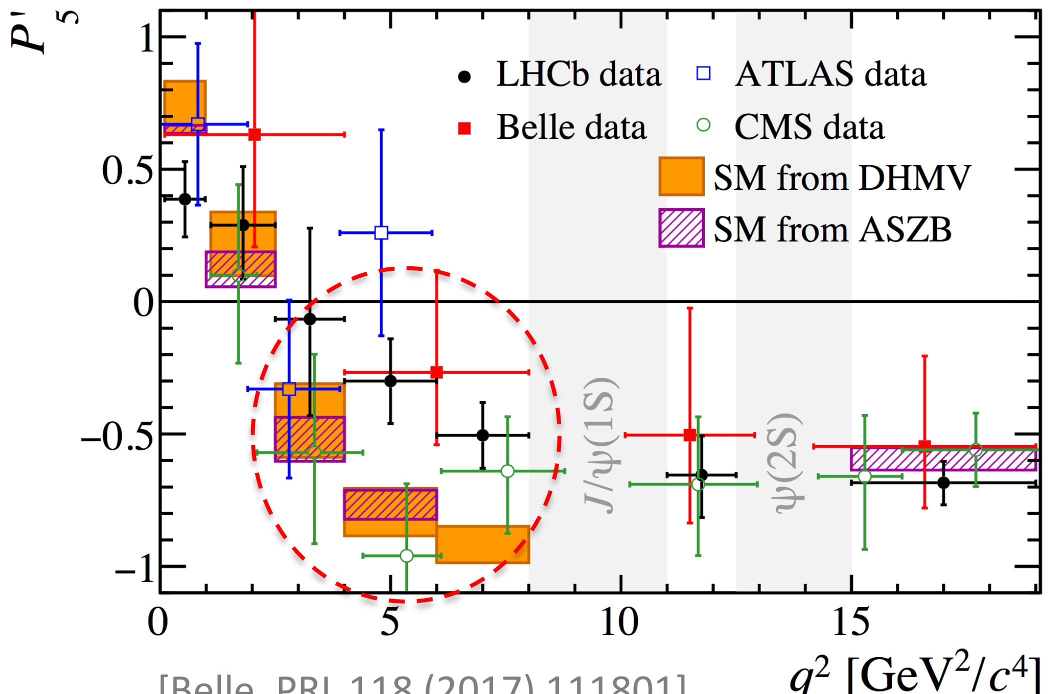
P_5' with $B^0 \to K^{*0}\mu^+\mu^-$

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

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

- Also measured by Belle, ATLAS, CMS

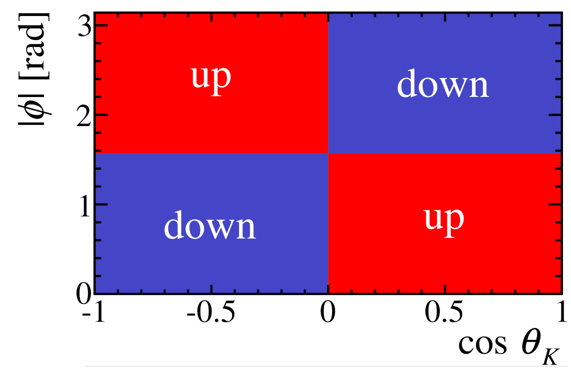
[PRL 125 (2020) 011802]

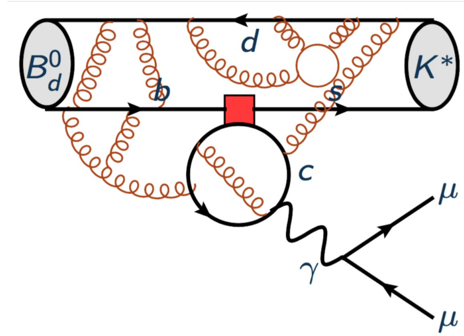


[Belle, PRL 118 (2017) 111801]
[ATLAS, JHEP 10 (2018) 047]
[CMS, PLB 781 (2018) 517]

Count blue minus red

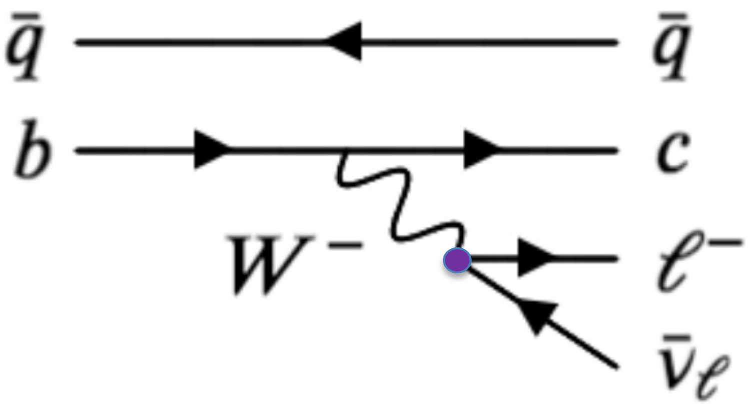
[P. Koppenburg, arXiv:1606.00999]

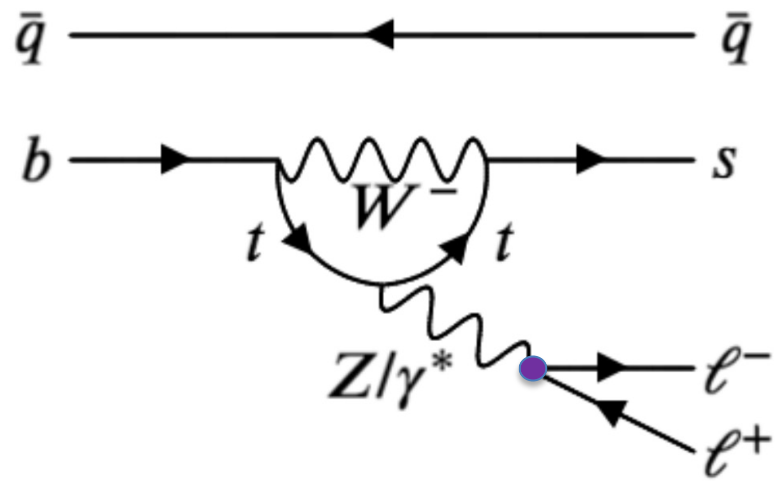




Lepton flavour universality

- 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]

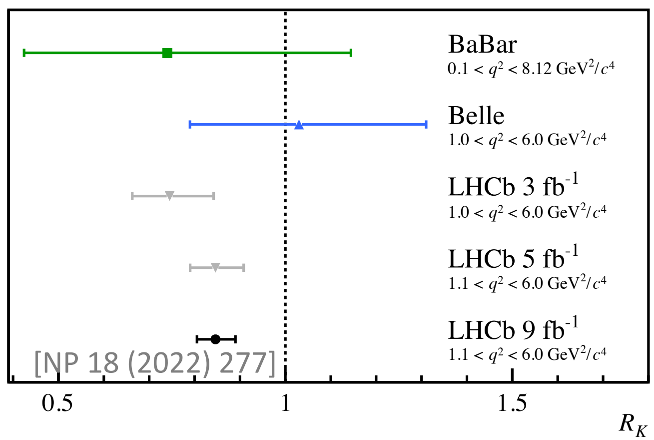
$\mathcal{O}(1\%)$ QED correction
[M. Bordone *et al.*, EJPC 76 (2016) 440]

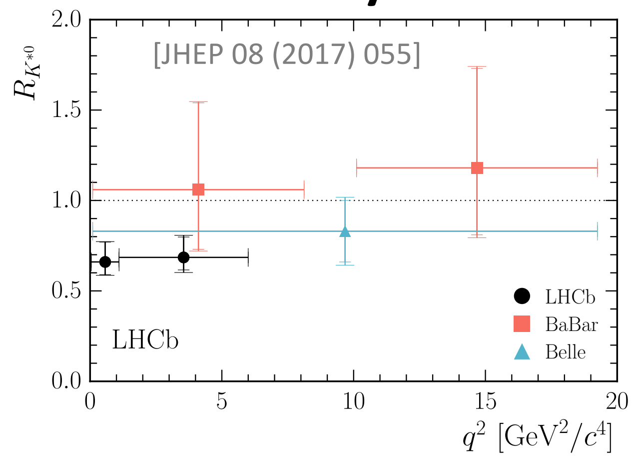
- Lepton flavor universality violation? New Physics!

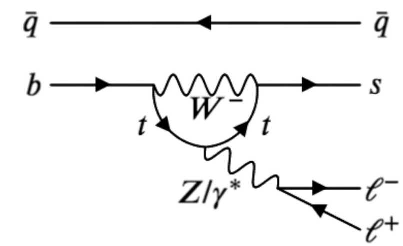
LFU in $b \to s\ell^+\ell^-$ decays

before Dec 2022

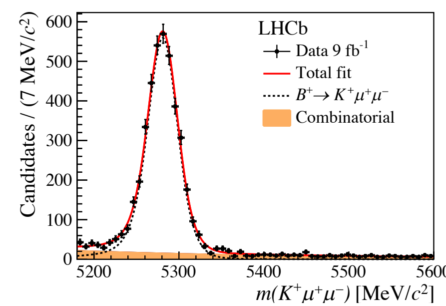
- Deviations from SM seen by LHCb

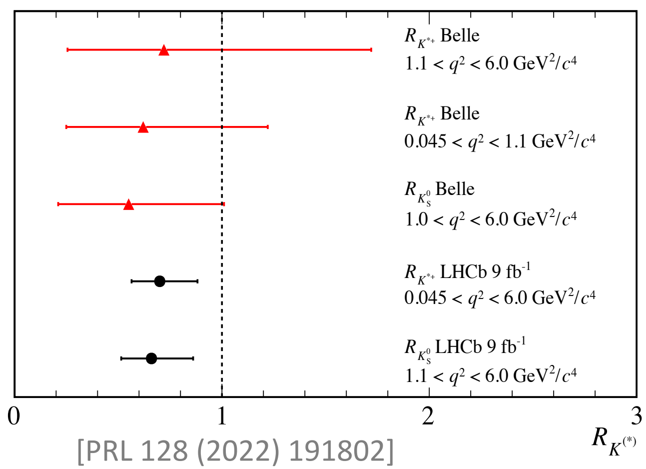


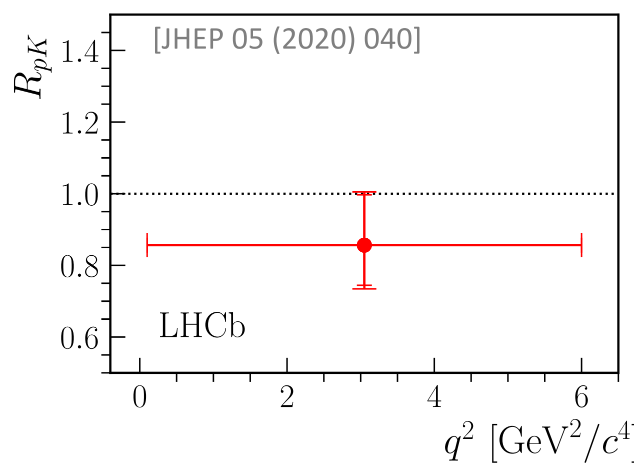


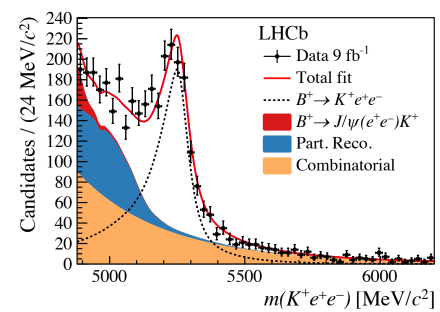


$$R_{X} = \frac{\mathcal{B}(H_b \to X\mu^+\mu^-)}{\mathcal{B}(H_b \to Xe^+e^-)}$$





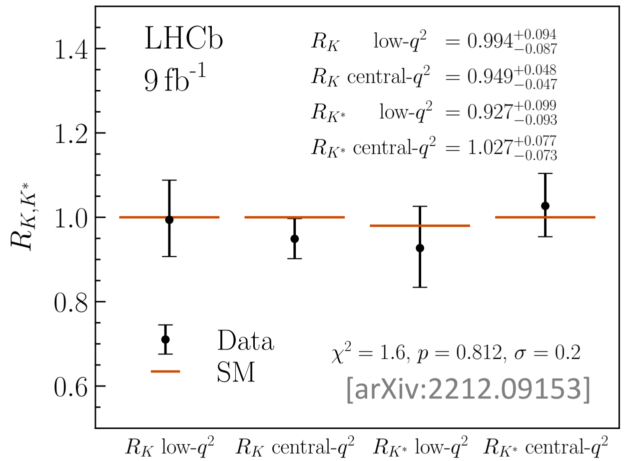




LFU in $b \to s\ell^+\ell^-$ decays

after Dec 2022

- Deviations mostly gone

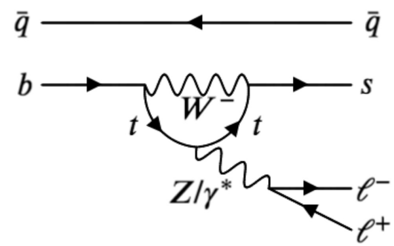


Precision at 5-10%

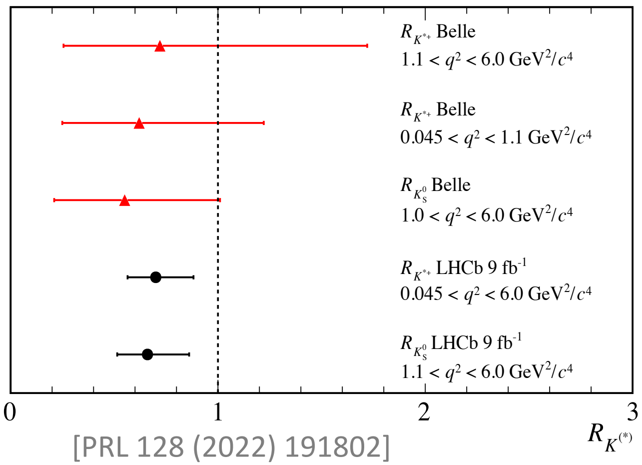
$\mathcal{O}(1\%)$ LFUV still possible

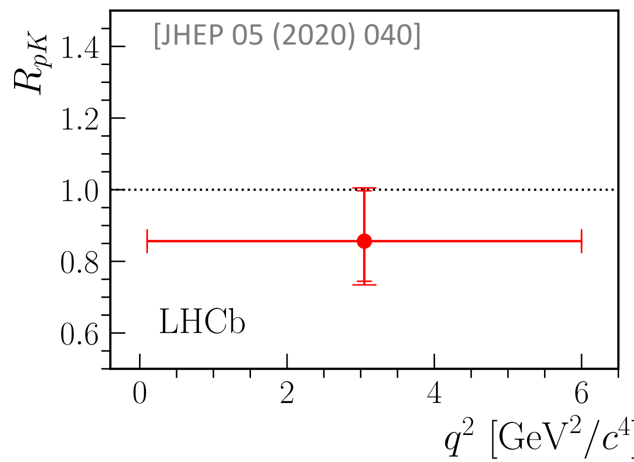
路漫漫其修远兮，吾将上下而求索

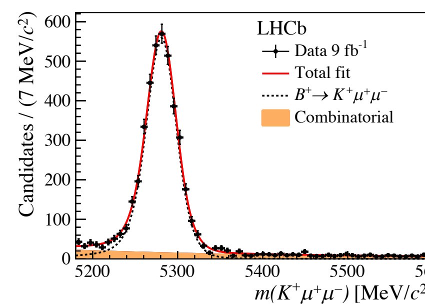
The road ahead will be long and our climb will be steep

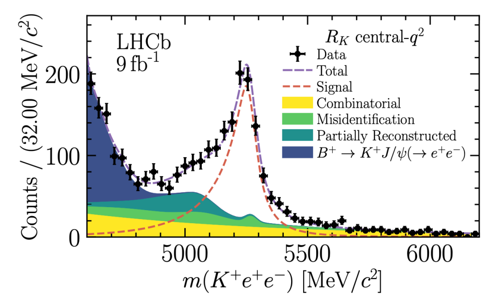


$$R_X = \frac{\mathcal{B}(H_b \to X\mu^+\mu^-)}{\mathcal{B}(H_b \to Xe^+e^-)}$$



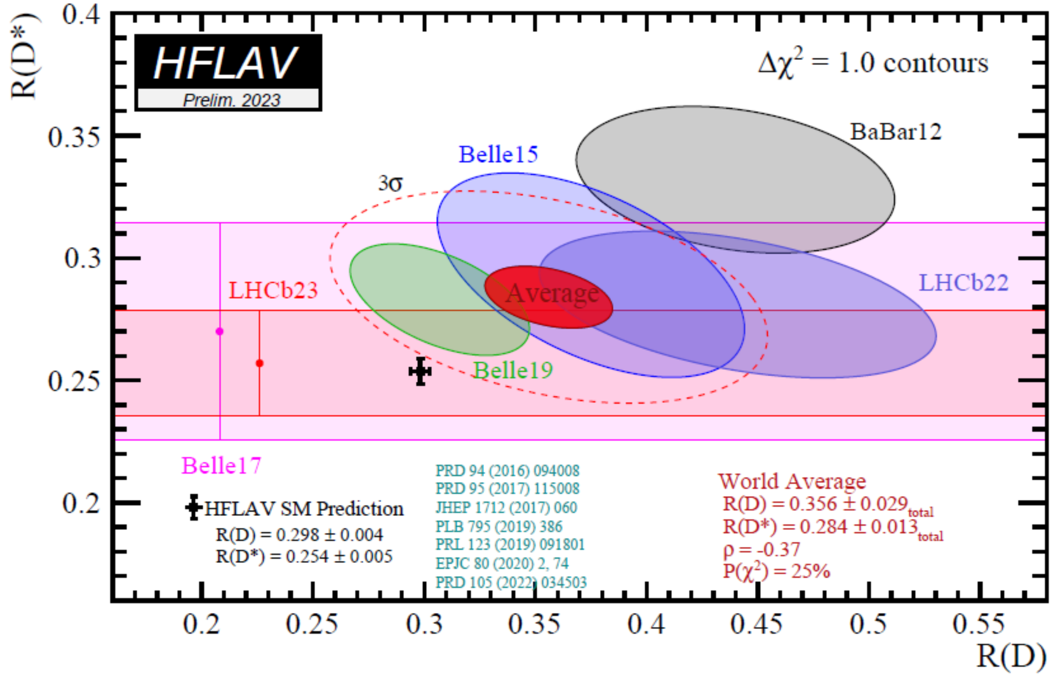


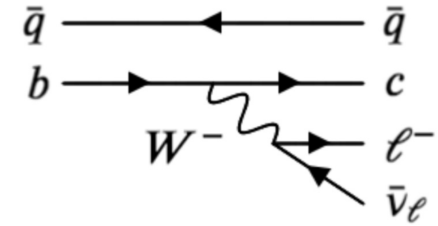




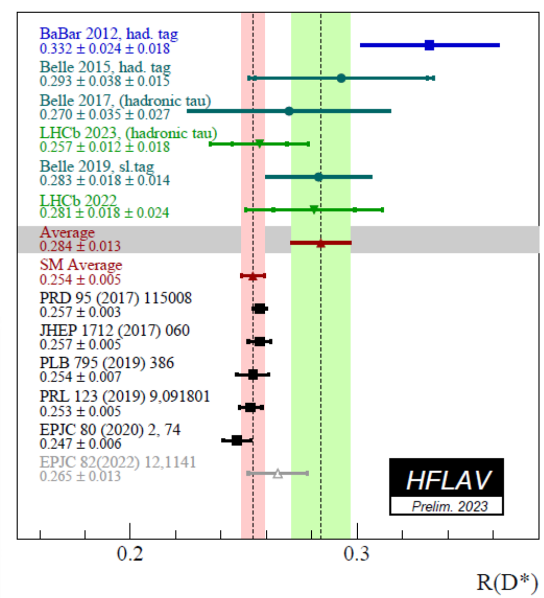
LFU in $b \to c\ell\nu$ decays

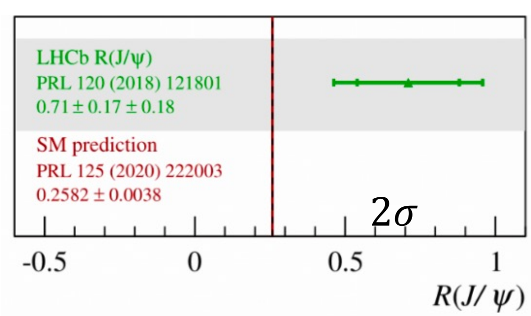
- Deviations from SM seen by Babar/Belle/LHCb

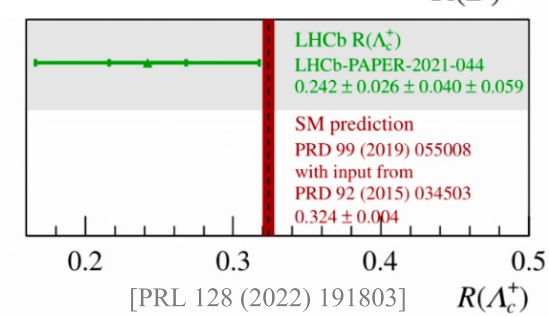




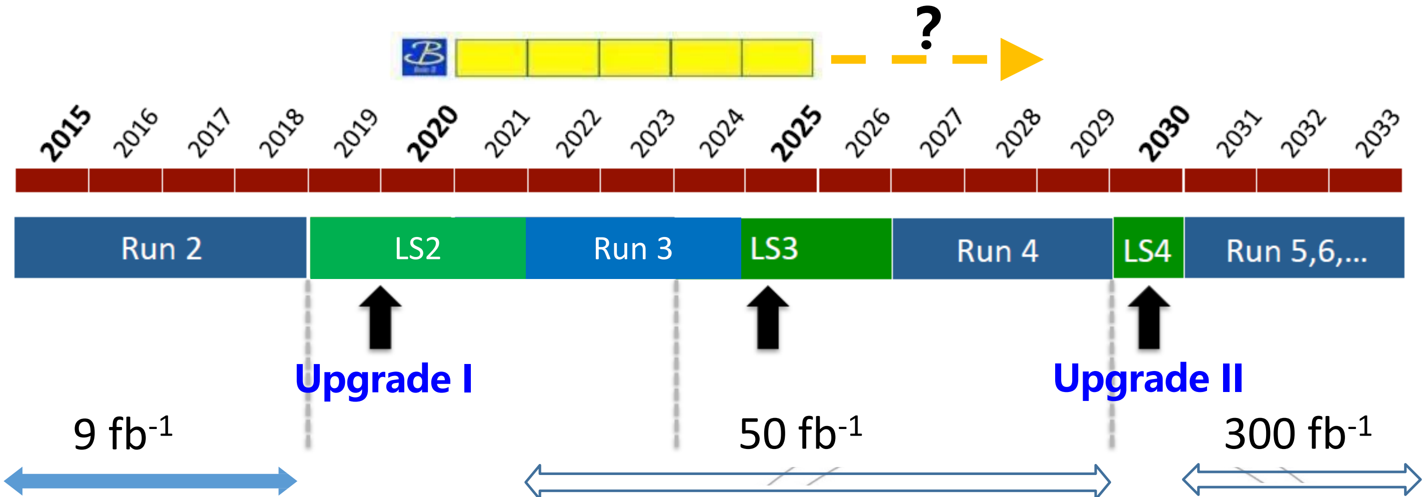
$$R(H_c) = \frac{\mathcal{B}(H_b \to H_c \tau^- \bar{\nu}_\tau)}{\mathcal{B}(H_b \to H_c \mu^- \bar{\nu}_\mu)}$$



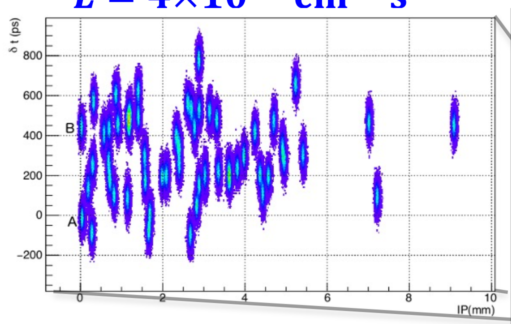


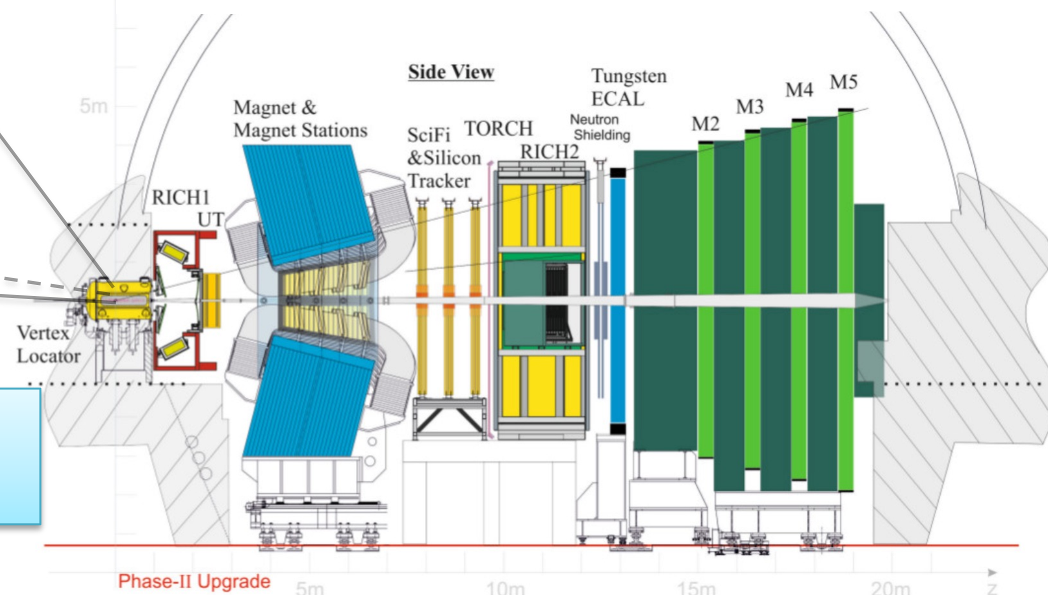


The LHCb upgrades



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





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 $B^0 \to J/\psi K_S^0$	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]
$a_{\rm sl}^s$	33×10^{-4} [211]	10×10^{-4}	–	3×10^{-4}	–
$\lvert V_{ub}\rvert/\lvert V_{cb}\rvert$	6% [201]	3%	1%	1%	–
$\boldsymbol{B_s^0, B^0 \to \mu^+\mu^-}$					
$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	90% [264]	34%	–	10%	21% [609]
$\tau_{B_s^0 \to \mu^+\mu^-}$	22% [264]	8%	–	2%	–
$S_{\mu\mu}$	–	–	–	0.2	–
$\boldsymbol{b \to c\ell^-\bar{\nu}_l}$ **LUV studies**					
$R(D^*)$	0.026 [215, 217]	0.0072	0.005	0.002	–
$R(J/\psi)$	0.24 [220]	0.071	–	0.02	–
Charm					
$\Delta A_{CP}(KK - \pi\pi)$	8.5×10^{-4} [610]	1.7×10^{-4}	5.4×10^{-4}	3.0×10^{-5}	–
A_Γ $(\approx x \sin\phi)$	2.8×10^{-4} [240]	4.3×10^{-5}	3.5×10^{-4}	1.0×10^{-5}	–
$x \sin\phi$ from $D^0 \to K^+\pi^-$	13×10^{-4} [228]	3.2×10^{-4}	4.6×10^{-4}	8.0×10^{-5}	–
$x \sin\phi$ from multibody decays	–	$(K3\pi)$ 4.0×10^{-5}	$(K_S^0\pi\pi)$ 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, $\phi_s, \gamma, \Delta A_{CP}$
  - 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?

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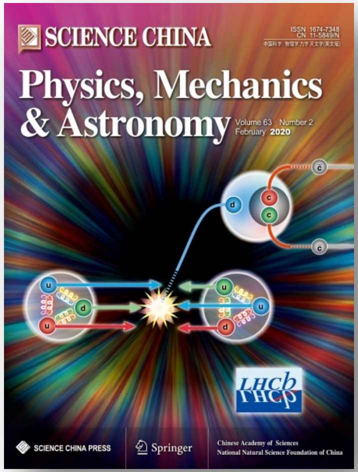

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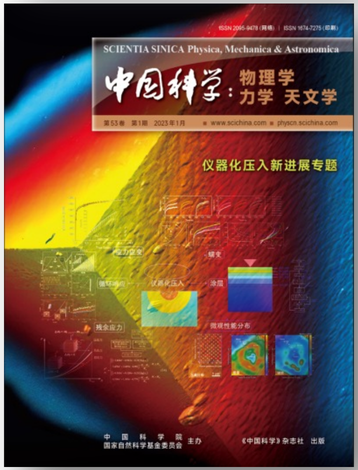

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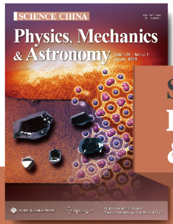

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