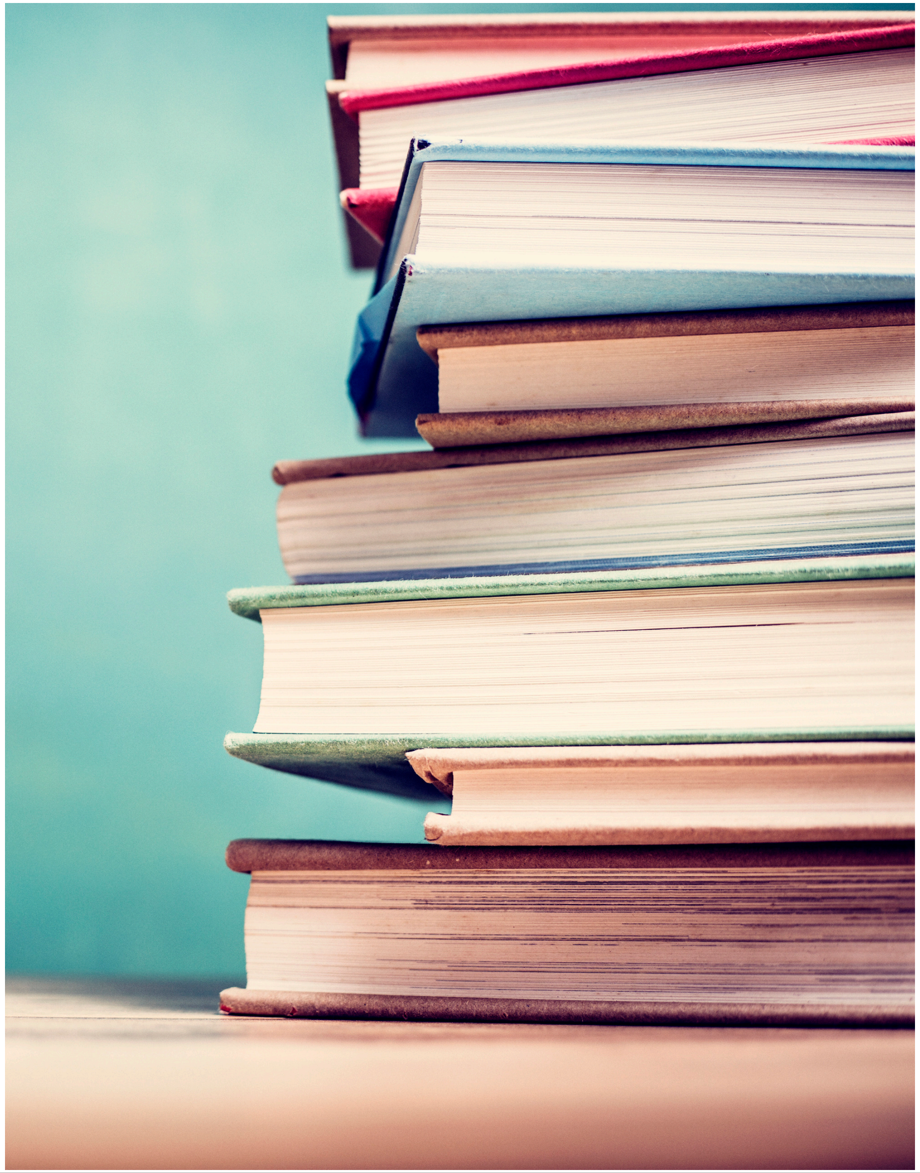


RECENT RESULTS FROM LHCb

Francesca Dordei (she/her), INFN - Cagliari (IT)
On behalf of the LHCb Collaboration

NuFACT 2023
Seoul, 26th August 2023

Flavour physics provide a wide range of Standard Model tests:

- CKM metrology and constraining the UT apex
- Spectroscopy
- Search for rare and forbidden decays
- Test of lepton-flavour universality and conservation

By comparing precise measurements with theoretical predictions the nature of new physics can be inferred

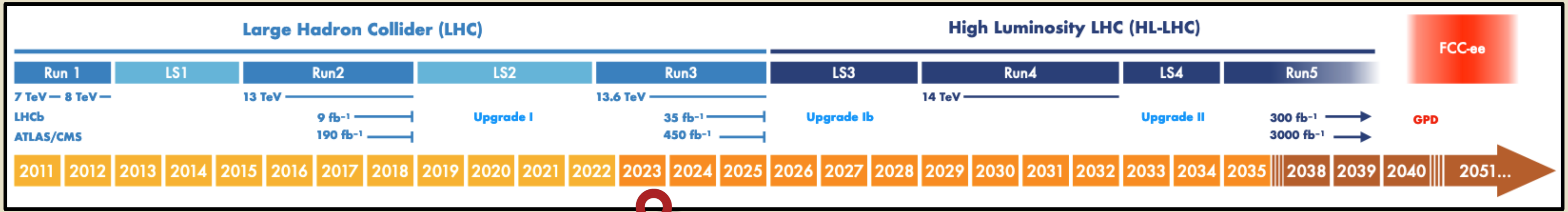
- Complementary to direct searches of new particles
- Not limited by the energy of collisions
- Requires inputs from theory

Many tools for discovery

The LHCb Collaboration

- About 1400 scientists, engineers and technicians
- 96 different universities and laboratories from 21 countries

The experimental scenario

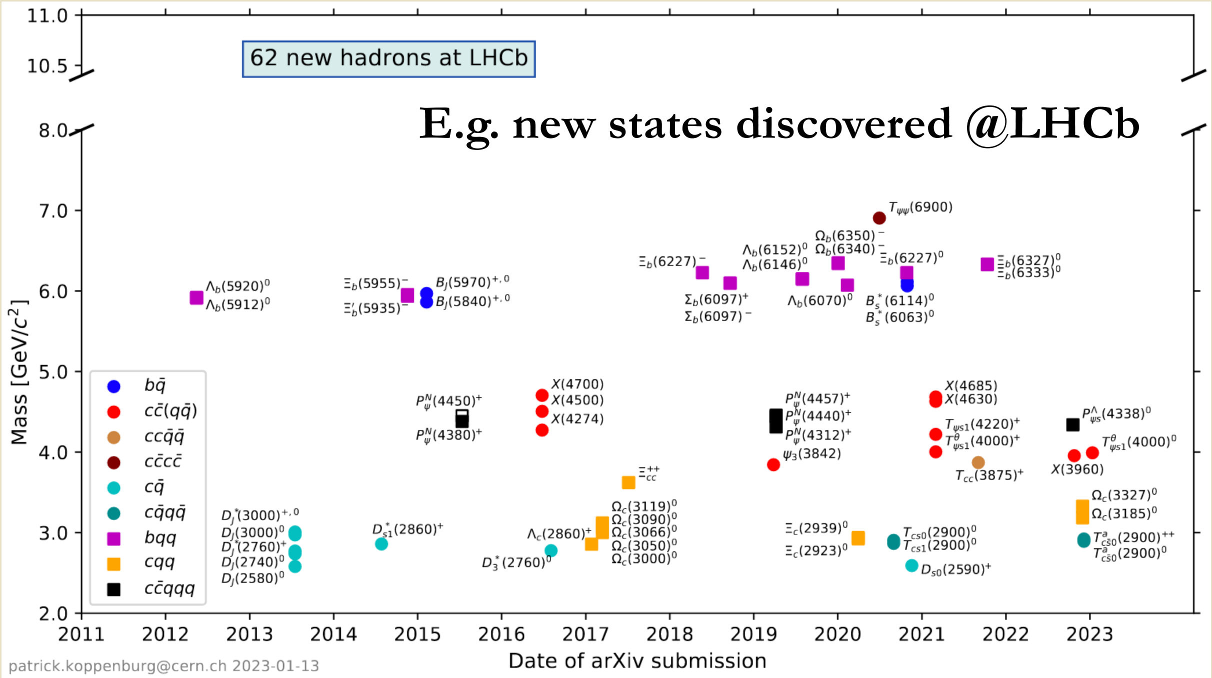


We are HERE

Run 1 + Run 2

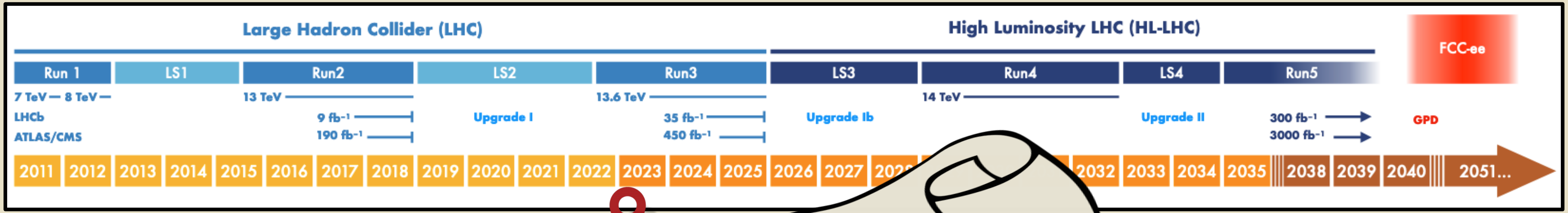
LBCb physics:

- **CP Violation + CKM**
- **Rare decays**
- **Charm** and **Strange**
- Spectroscopy
- Electroweak and QCD
- Dark sector
- Heavy ions
- Fixed target



Exemplifies the excellence in diversity!

The experimental scenario



Run 1 + Run 2

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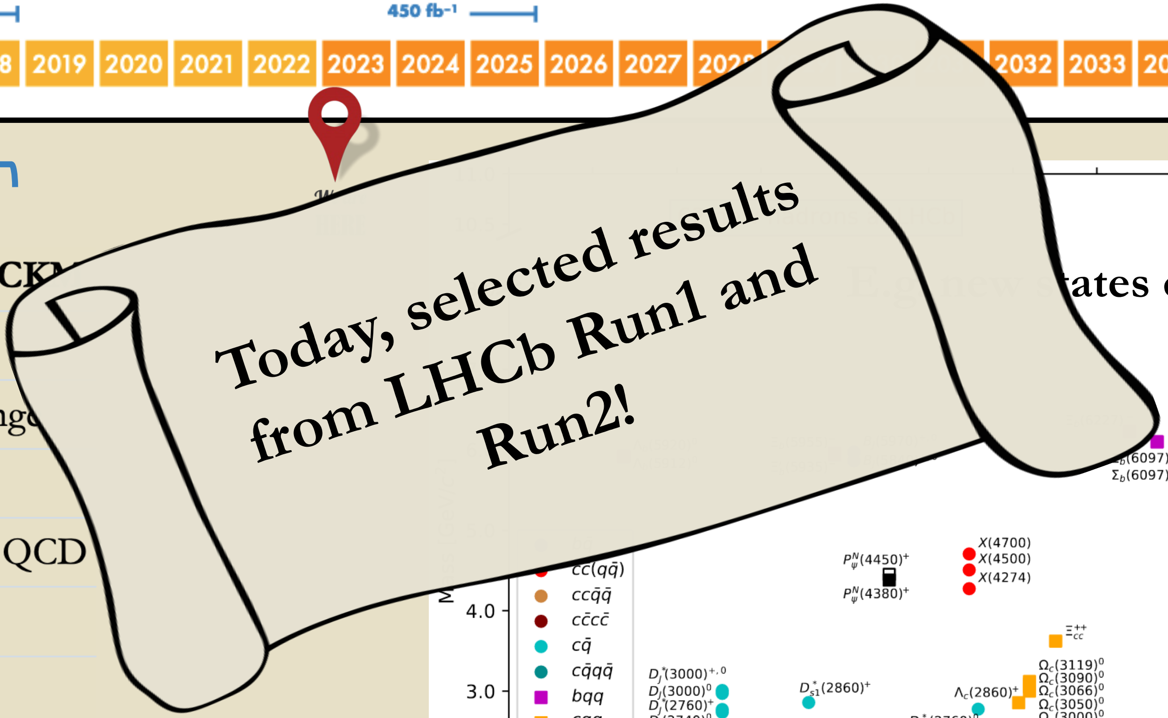
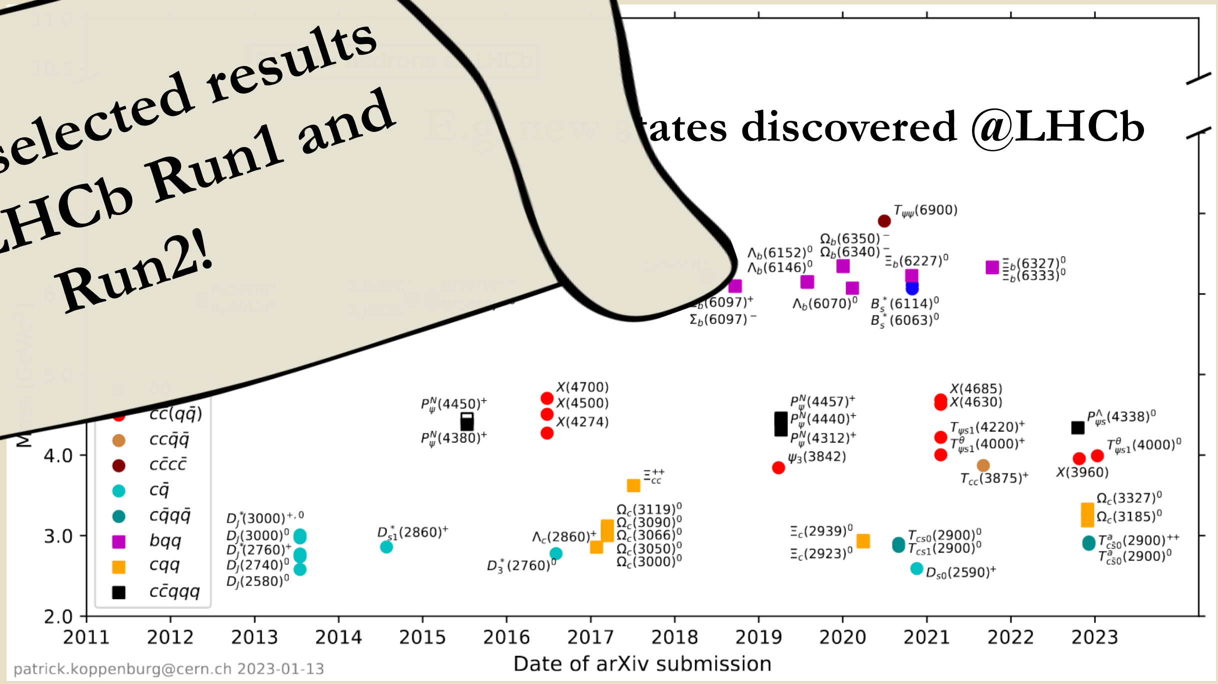
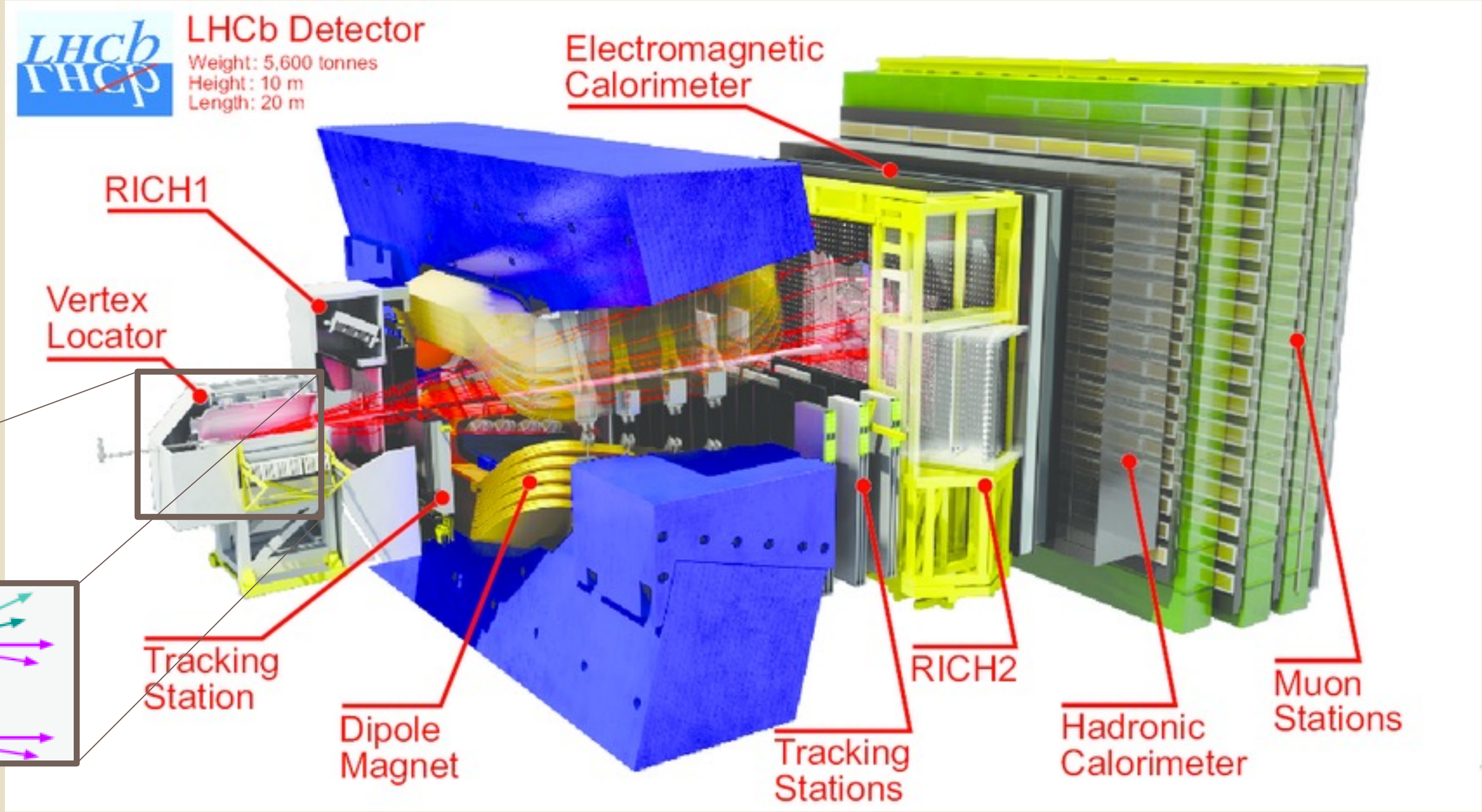


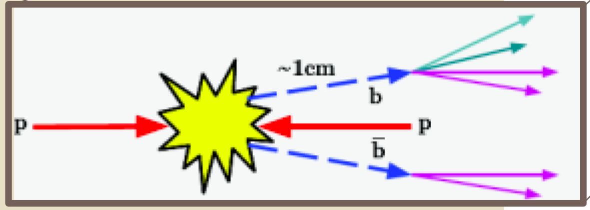


Exemplifies the excellence in diversity!

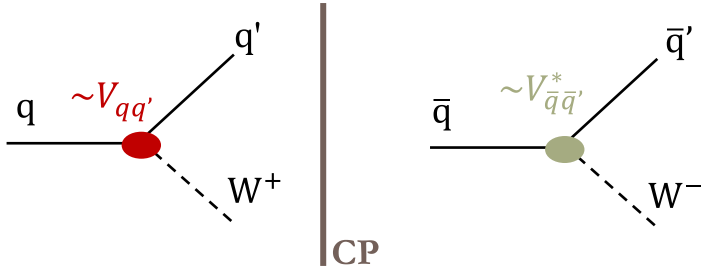
The LHCb detector in Run 1&2 (2011-2018)

- Single arm spectrometer designed for high precision flavour physics measurements
- Pseudorapidity range $\eta \in [2,5]$





LHCb Detector Performance
Int. J. Mod. Phys. A30 (2015)1530022



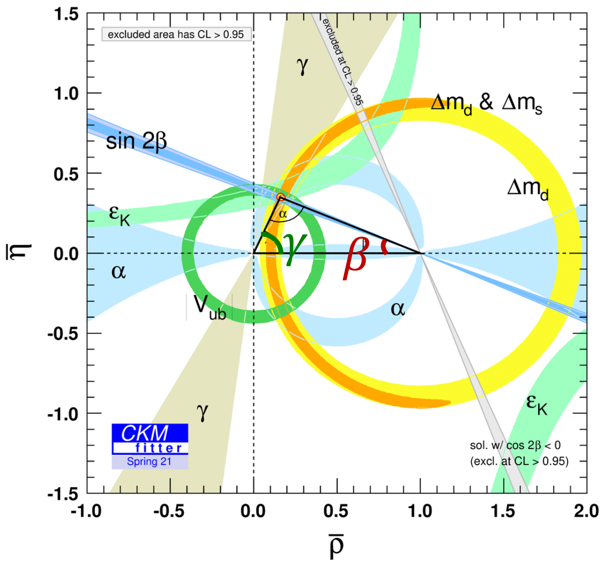
In the SM **quarks can change flavour**

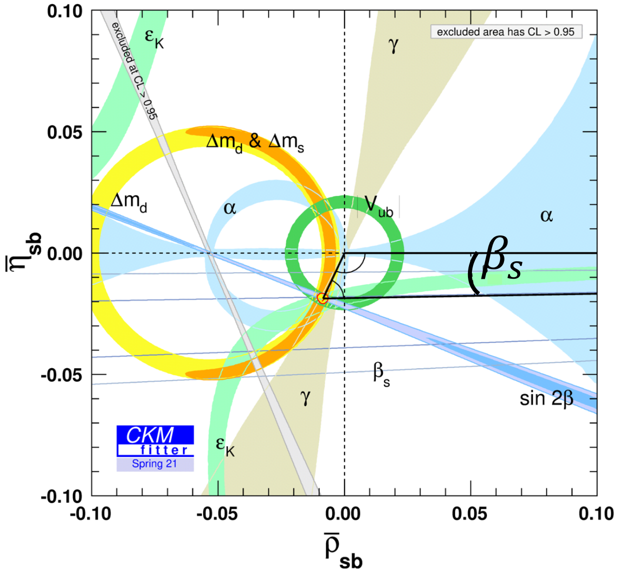
$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

Unitarity $V_{\text{CKM}} \cdot V_{\text{CKM}}^\dagger = I$ imposes several conditions which give rise to **"unitarity" triangles**

E.g. Unitarity condition from 2nd and 3rd columns:

$$V_{us}V_{ub}^* + V_{cs}V_{cb}^* + V_{ts}V_{tb}^* = 0$$



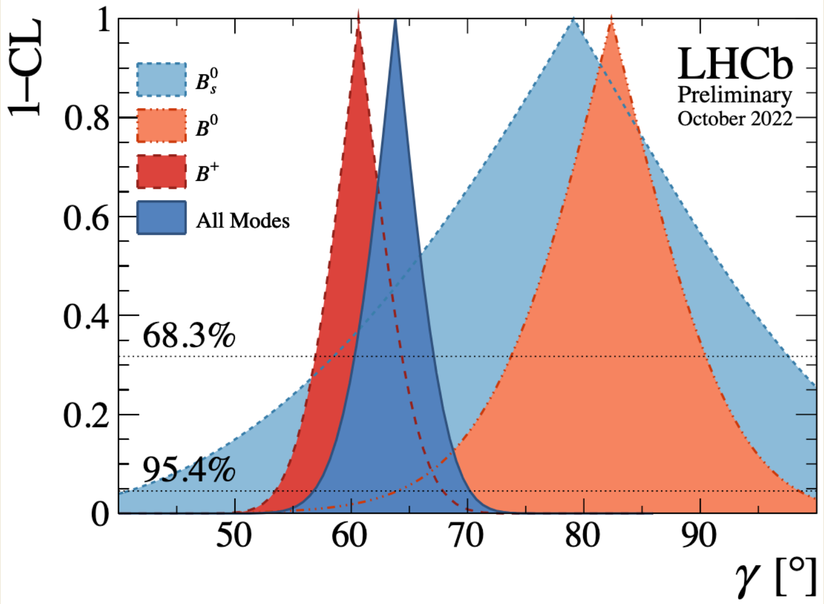


The CKM matrix

- The CKM matrix accommodates the **mixing between mass and flavour eigenstates** of quarks that arises from the electroweak symmetry breaking
- The SM works so remarkably well that we have to make **more and more precise measurements**
- **O(10-20%) NP contributions to most loop-level processes (FCNC) are still allowed**
  - See e.g. J. Charles at al arXiv:1309.2293 [hep-ph]
- Due to the CKM structure the **B system is favourable for CPV studies**. But important to investigate also the charm sector.

State of the art of γ

- Clean test of the SM: theoretical uncertainty is $\sim 10^{-7}$



LHCb combination
$\gamma = (63.8^{+3.5}_{-3.7})^\circ$

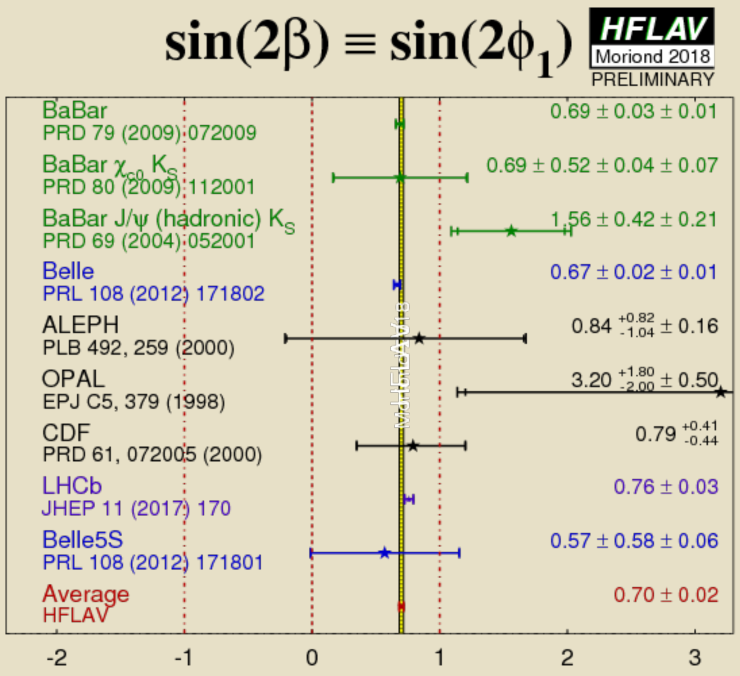
[LHCb-CONF-022-003]

- In agreement with previous and global averages $\gamma = (65.66^{+1.3}_{-1.2})^\circ$ [CKMFitter]
- Statistically limited, ample room for NP.

B decay	D decay	Ref.	Dataset	Status since Ref. [14]
$B^\pm \to Dh^\pm$	$D \to h^+h^-$	[29]	Run 1&2	As before
$B^\pm \to Dh^\pm$	$D \to h^+\pi^-\pi^+\pi^-$	[30]	Run 1	As before
$B^\pm \to Dh^\pm$	$D \to K^\pm\pi^\mp\pi^+\pi^-$	[18]	Run 1&2	**New**
$B^\pm \to Dh^\pm$	$D \to h^+h^-\pi^0$	[19]	Run 1&2	**Updated**
$B^\pm \to Dh^\pm$	$D \to K^0_S h^+h^-$	[31]	Run 1&2	As before
$B^\pm \to Dh^\pm$	$D \to K^0_S K^\pm\pi^\mp$	[32]	Run 1&2	As before
$B^\pm \to D^*h^\pm$	$D \to h^+h^-$	[29]	Run 1&2	As before
$B^\pm \to DK^{*\pm}$	$D \to h^+h^-$	[33]	Run 1&2(*)	As before
$B^\pm \to DK^{*\pm}$	$D \to h^+\pi^-\pi^+\pi^-$	[33]	Run 1&2(*)	As before
$B^\pm \to Dh^\pm\pi^+\pi^-$	$D \to h^+h^-$	[34]	Run 1	As before
$B^0 \to DK^{*0}$	$D \to h^+h^-$	[35]	Run 1&2(*)	As before
$B^0 \to DK^{*0}$	$D \to h^+\pi^-\pi^+\pi^-$	[35]	Run 1&2(*)	As before
$B^0 \to DK^{*0}$	$D \to K^0_S\pi^+\pi^-$	[36]	Run 1	As before
$B^0 \to D^\mp\pi^\pm$	$D^+ \to K^-\pi^+\pi^+$	[37]	Run 1	As before
$B^0_s \to D^\mp_s K^\pm$	$D^+_s \to h^+h^-\pi^+$	[38]	Run 1	As before
$B^0_s \to D^\mp_s K^\pm\pi^+\pi^-$	$D^+_s \to h^+h^-\pi^+$	[39]	Run 1&2	As before
D decay	**Observable(s)**	**Ref.**	**Dataset**	**Status since Ref. [14]**
$D^0 \to h^+h^-$	ΔA_{CP}	[24, 40, 41]	Run 1&2	As before
$D^0 \to K^+K^-$	$A_{CP}(K^+K^-)$	[16, 24, 25]	Run 2	**New**
$D^0 \to h^+h^-$	$y_{CP} - y_{CP}^{K^-\pi^+}$	[42]	Run 1	As before
$D^0 \to h^+h^-$	$y_{CP} - y_{CP}^{K^-\pi^+}$	[15]	Run 2	**New**
$D^0 \to h^+h^-$	ΔY	[43–46]	Run 1&2	As before
$D^0 \to K^+\pi^-$ (Single Tag)	$R^\pm$, $(x'^\pm)^2$, $y'^\pm$	[47]	Run 1	As before
$D^0 \to K^+\pi^-$ (Double Tag)	$R^\pm$, $(x'^\pm)^2$, $y'^\pm$	[48]	Run 1&2(*)	As before
$D^0 \to K^\pm\pi^\mp\pi^+\pi^-$	$(x^2+y^2)/4$	[49]	Run 1	As before
$D^0 \to K^0_S\pi^+\pi^-$	x, y	[50]	Run 1	As before
$D^0 \to K^0_S\pi^+\pi^-$	x_{CP}, y_{CP}, Δx, Δy	[51]	Run 1	As before
$D^0 \to K^0_S\pi^+\pi^-$	x_{CP}, y_{CP}, Δx, Δy	[52]	Run 2	As before
$D^0 \to K^0_S\pi^+\pi^-$ (μ^- tag)	x_{CP}, y_{CP}, Δx, Δy	[17]	Run 2	**New**

Frequentist approach, 173 observables, 52 parameters

State of the art of $\sin(2\beta)$



$S \equiv -\eta_{CP}\sin(2\beta) = 0.699 \pm 0.017$

[HFLAV 2018]

$S^{SM} \equiv \sin(2\beta) = 0.731^{+0.029}_{-0.016}$

[CKMfitter]

- Golden channel $B^0 \to J/\psi K_s^0$
- **New measurement using all Run 2 data**
- Averages including all charmonium ($J/\psi \to \mu\mu, ee; \psi(2S) \to \mu\mu$):

$B^0 \to (c\bar{c})K_S^0$	Signal (10^3) [with tag]	$\varepsilon_{tag}D^2$
$J/\psi \to \mu^+\mu^-$	306	4.71 ± 0.01
$J/\psi \to e^+e^-$	23.6	4.62 ± 0.04
$\psi(2S) \to \mu^+\mu^-$	42.7	6.48 ± 0.03

- The precision of the simultaneous fit to all channels is higher than the current world average as determined by the HFLAV group

LHCb:
  - $\boldsymbol{S = 0.7158 \pm 0.0133 \pm 0.0078}$ [LHCb-PAPER-2023-013]

Belle:
  - $\boldsymbol{S = 0.667 \pm 0.026}$ [PRL 108(2012) 171802]

Babar:
  - $\boldsymbol{S = 0.691 \pm 0.031}$ [PRD 79(2009) 072009]

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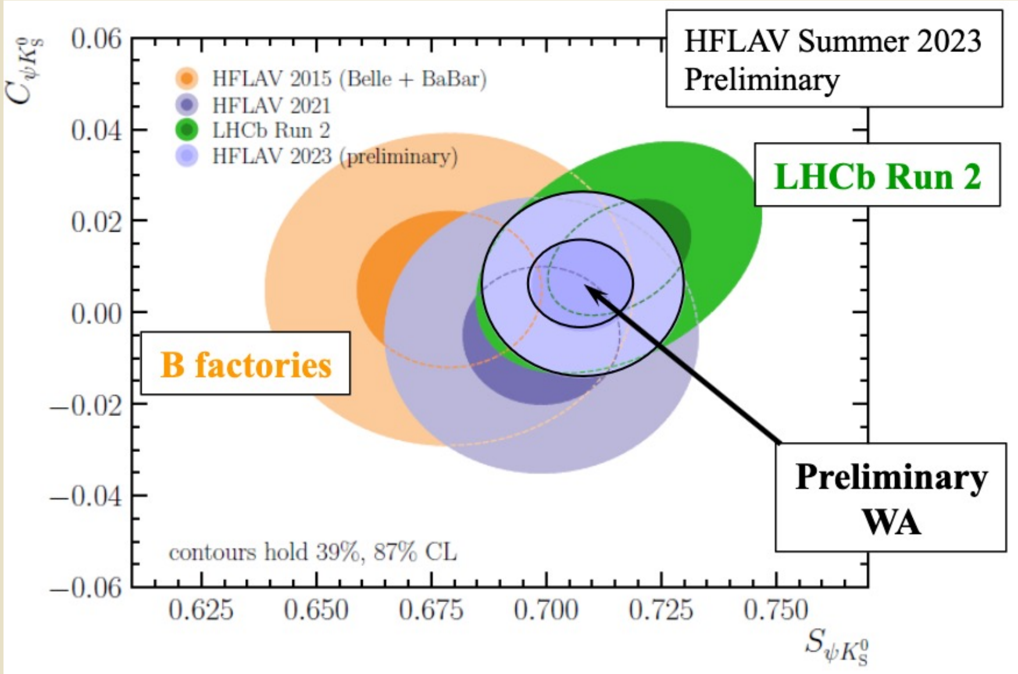

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$$S \equiv -\eta_{CP}\sin(2\beta) = 0.708 \pm 0.011$$

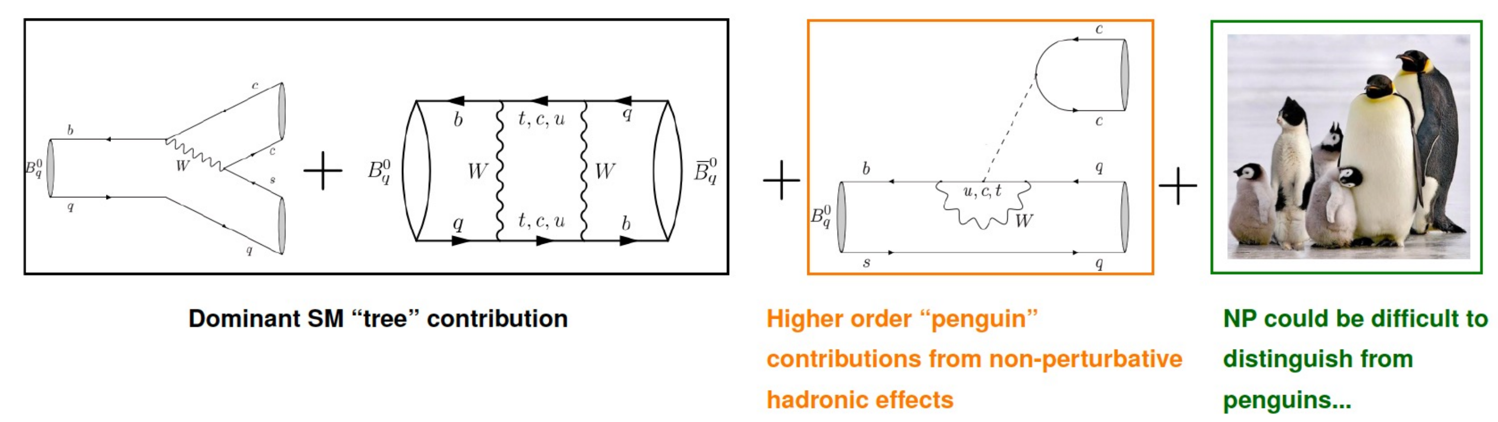
[HFLAV 2021]

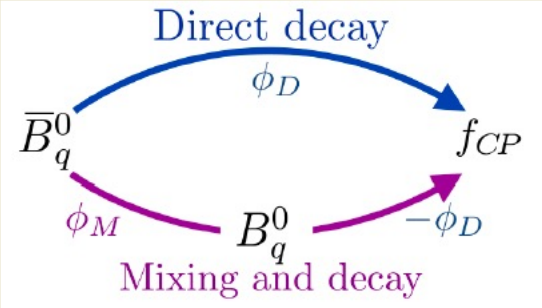
$$S^{SM} \equiv \sin(2\beta) = 0.731^{+0.029}_{-0.016}$$

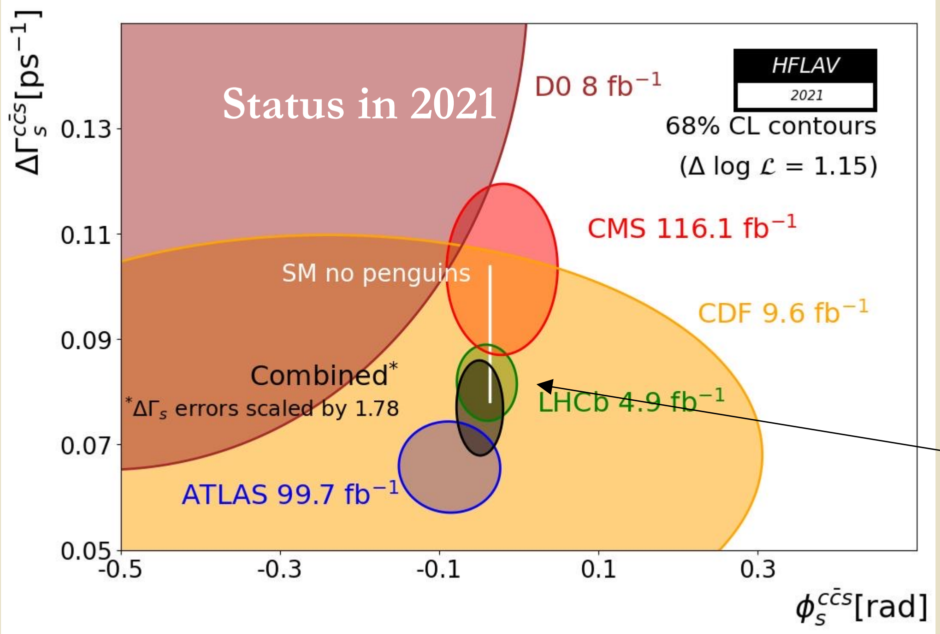
[CKMfitter]

Preliminary WA: 1.6% precision!

CP violation in B mixing and decay, φ_s







CP-violating phase arising from interference between mixing and decay.

- Precisely predicted by the SM: $\varphi_s^{SM} = -36.86^{+0.93}_{-0.67}$ mrad [CKMFitter]
- Golden channel exploited by LHCb, ATLAS, CMS: $B_s^0 \to J/\psi\phi$
- LHCb also measured many other channels

- World average (dominated by LHCb) consistent with predictions;
- Exp. uncertainty (19 mrad) almost a factor of 20 larger than uncert. of indirect determination when penguin pollution is ignored.

New φ_s result from LHCb

Using full Run 2 $B_s^0 \to J/\psi KK$

$$\varphi_s = -0.039 \pm 0.022 \pm 0.006 \text{ rad}$$
$$|\lambda| = 1.001 \pm 0.011 \pm 0.005$$
$$\Gamma_s - \Gamma_d = 0.0056^{+0.0013}_{-0.0015} \pm 0.0014 \text{ ps}^{-1}$$
$$\Delta\Gamma_s = 0.0845 \pm 0.0044 \pm 0.0024 \text{ ps}^{-1}$$

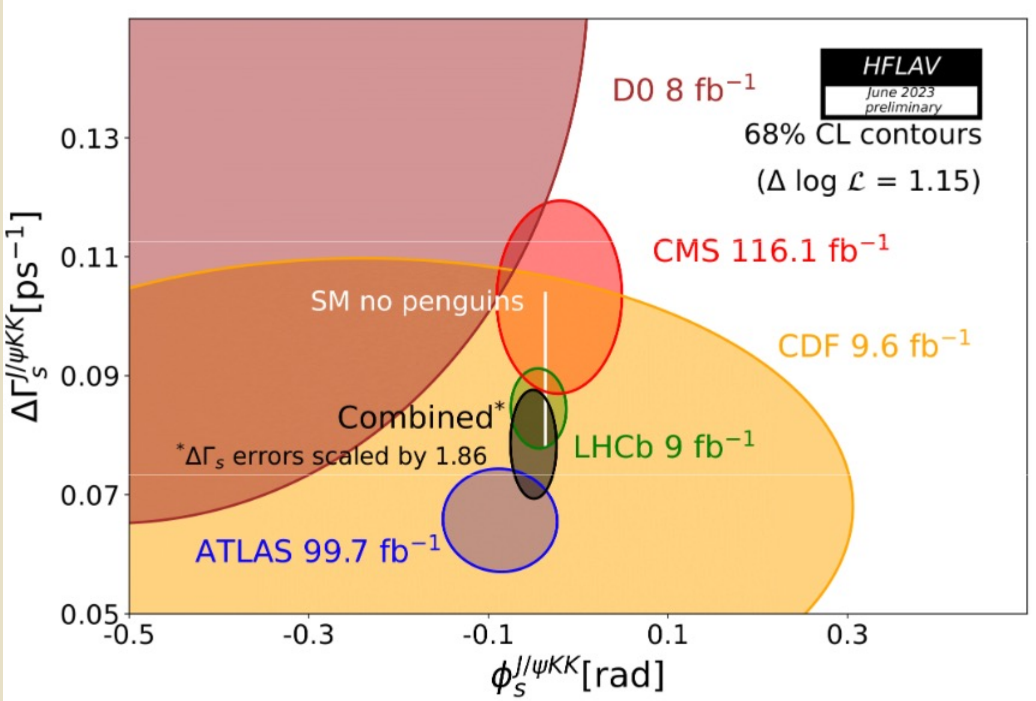
[LHCb-PAPER-2023-016, 2308.01468]

φ_s consistent with Standard Model

φ_s 1.7 σ away from 0
consistent with **no CPV in interference**

|λ| consistent with 1
consistent with no direct CPV

$\Gamma_s - \Gamma_d$ consistent with HQE prediction
[JHEP12 (2017) 068]



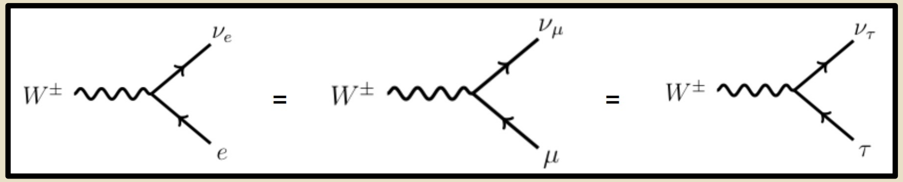
The new preliminary HFLAV combination is:

$$\varphi_s(2023) = -0.050 \pm 0.016 \text{ rad}$$
$$\varphi_s(2021) = -0.049 \pm 0.019 \text{ rad}$$

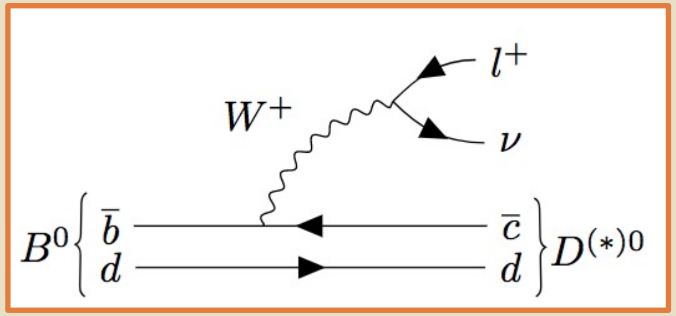
[HFLAV]

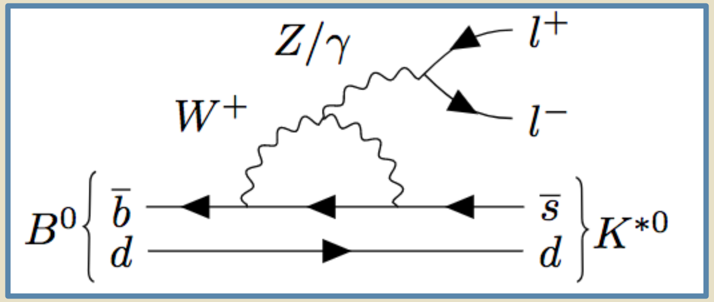
Lepton Flavour Universality

- Standard Model features **Lepton Flavour Universality (LFU)**: accidental symmetry of the SM
  - Equal electroweak coupling of gauge bosons to all charged leptons.
- Difference in dynamics driven solely by the **difference in the masses $m_e < m_\mu \ll m_\tau$**



- In this presentation: analysis of different b-hadron decays:

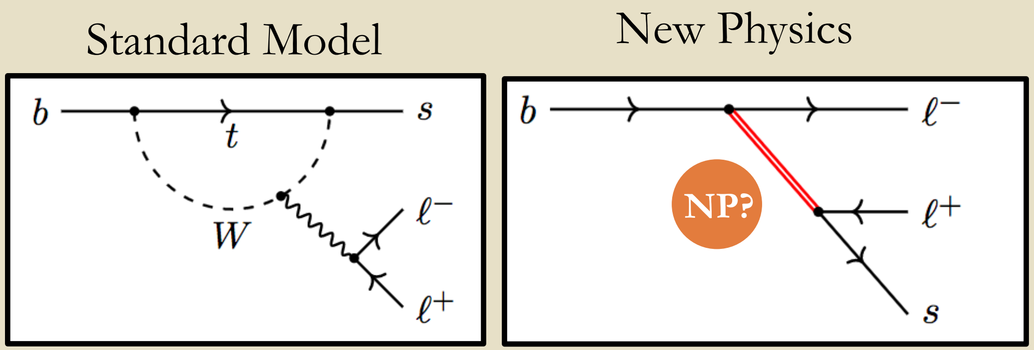




Flavour-changing CHARGED current $(b \to c\ell\bar{\nu})$ **Flavour-changing NEUTRAL current** $(b \to s(d)\ell^+\ell^-)$

Rare decays as probe for NP

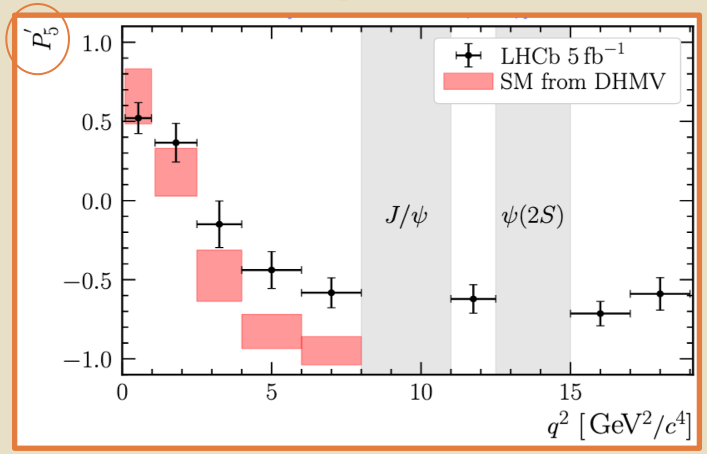
- Rare FCNC decays are **loop-suppressed** in the SM ($\mathcal{B} \sim 10^{-6} - 10^{-7}$ or less)
- New heavy particles (NP) can significantly contribute, affecting decay rates and angular distributions



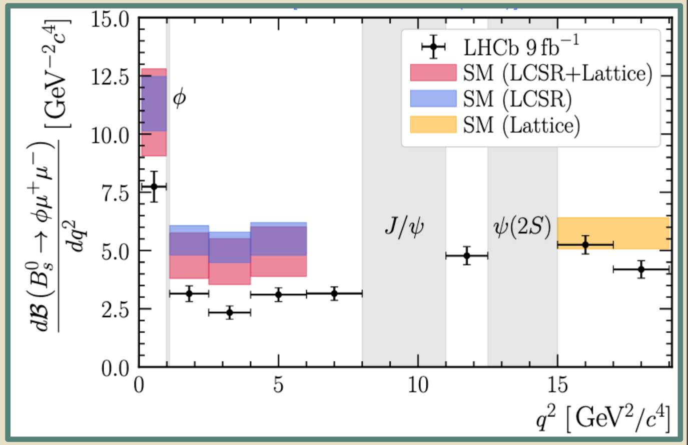
Intriguing **tensions** w.r.t. the SM, e.g.

- **Angular analyses**, e.g. $B^0 \to K^{*0}\mu^+\mu^-$ [PRL 125 011082 (2020)]
- **Branching fractions**, e.g. $B_s^0 \to \phi\mu^+\mu^-$ [PRL 127 151801 (2021)]
- **Tensions at 1-3 σ**
- **But**: sizeable **hadronic theory uncertainties** of SM predictions, more data always welcome

Less form-factor dependent observable



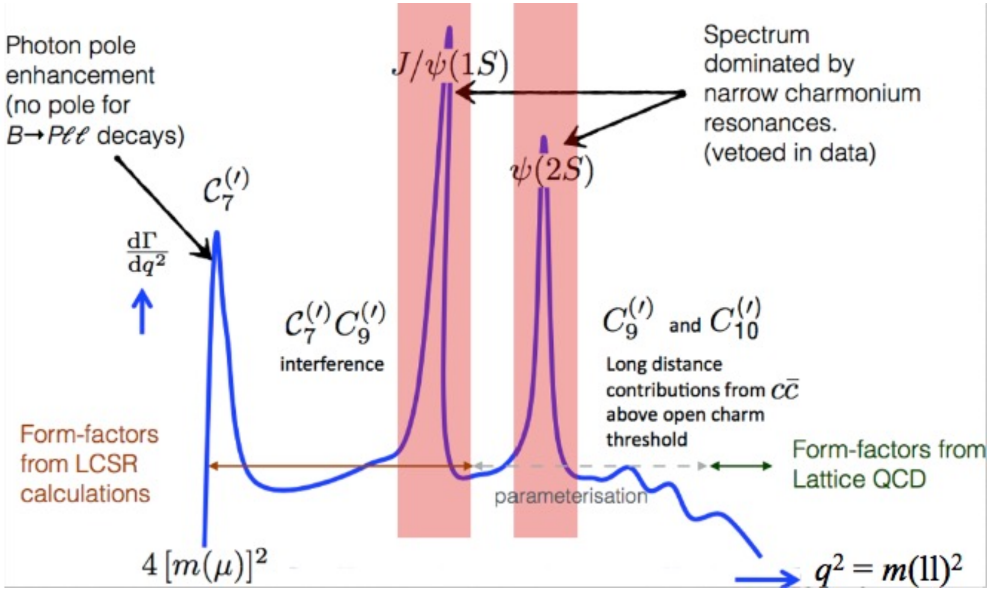
[PRL 125 011082 (2020)]



[PRL 127 151801 (2021)]

$$q^2 = m(\ell^+\ell^-)^2$$

Tests of LFU with RD



$q^2 = m(\ell^+\ell^-)^2$, inv. mass of di-lepton system

$C_i^{(\prime)}$ is the LH (RH) **Wilson coefficient** with:

i=1,2 Tree — ***i*=7 Photon penguin**

i=S,P (Pseudo)scalar penguin

i=3-6,8 Gluon Penguin — ***i*=9,10 EW penguin**

- Double ratio of the rare to the J/ψ reduces syst. unc. (LFU established at ‰ level [PDG 2022]):

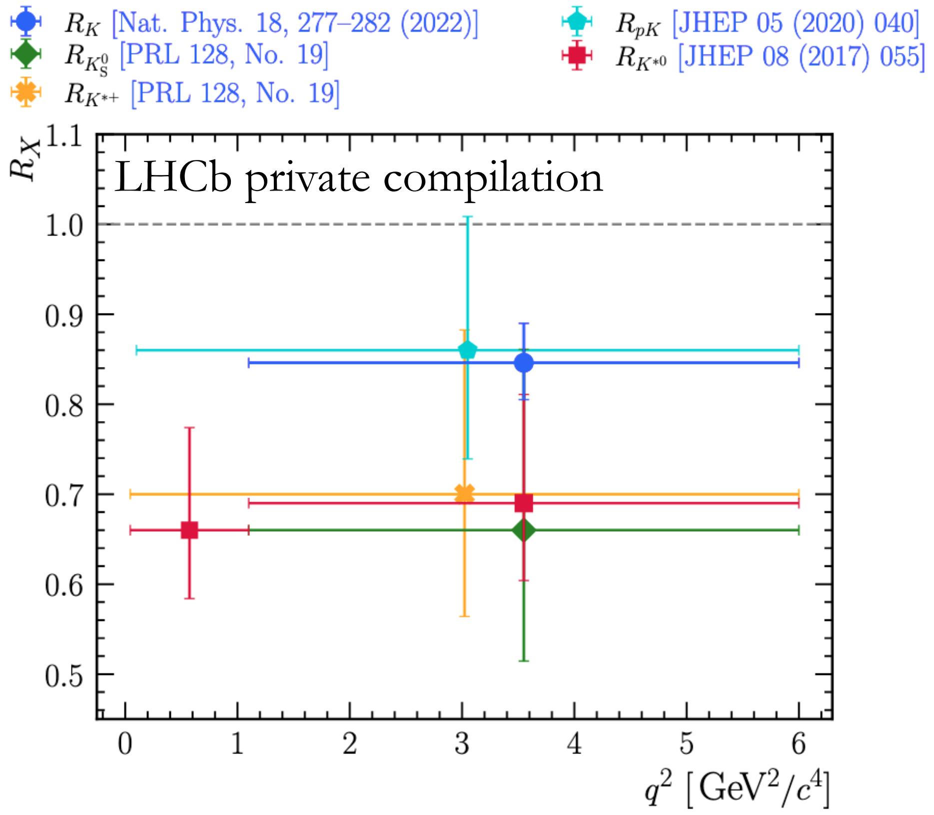
$$R_H = \frac{\mathcal{B}(B \to H_s\mu^+\mu^-)}{\mathcal{B}(B \to H_s e^+e^-)} \times \frac{\mathcal{B}(B \to H_s\, J/\psi(e^+e^-))}{\mathcal{B}(B \to H_s J/\psi(\mu^+\mu^-))}$$

$$= 1 \pm \mathcal{O}(1\%)$$ [Eur. Phys. J. C 76, 440 (2016)]

with $H_s = K^+, K^{*0}, K_S^0, K^{*+}, \ldots$

- In order to remove long distance effects (i.e. $b \to (c\bar{c} \to \ell^+\ell^-)s$) the narrow charm. resonances are vetoed and used to **validate the analysis**: $r_{J/\psi}$ - $R_{\psi(2S)}$
- **Hadronic uncertainties cancel in the ratio**
- **Main complexity**: muons and electrons behave very differently in the detector, but double ratio helps.
- Blind analyses

$b \to s\ell^+\ell^-$
2022 situation

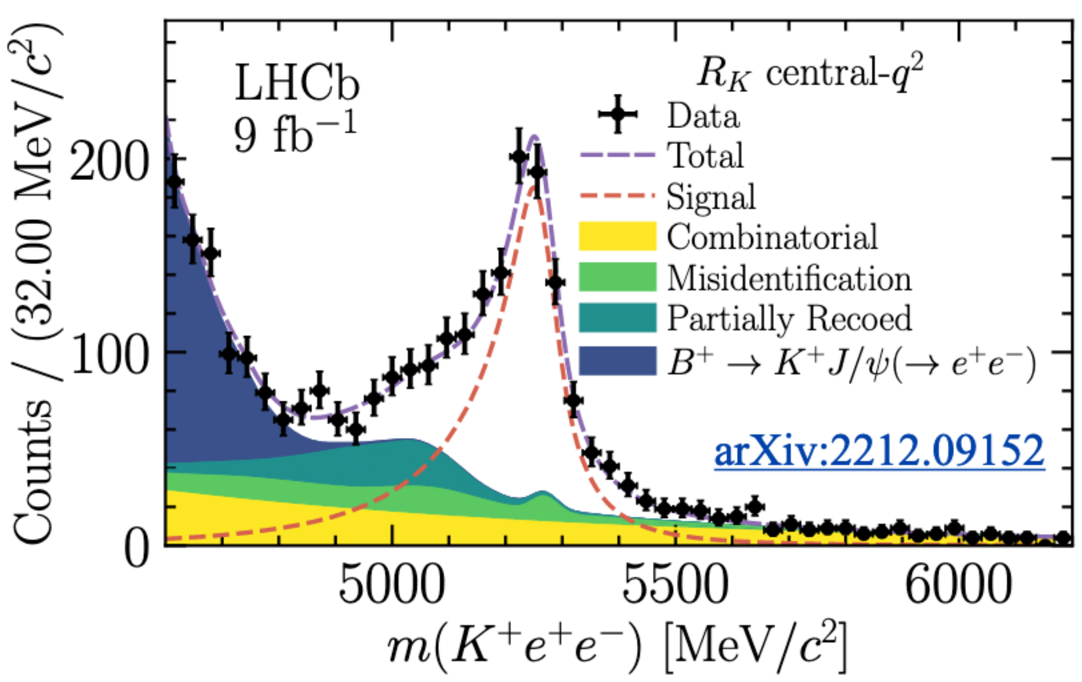


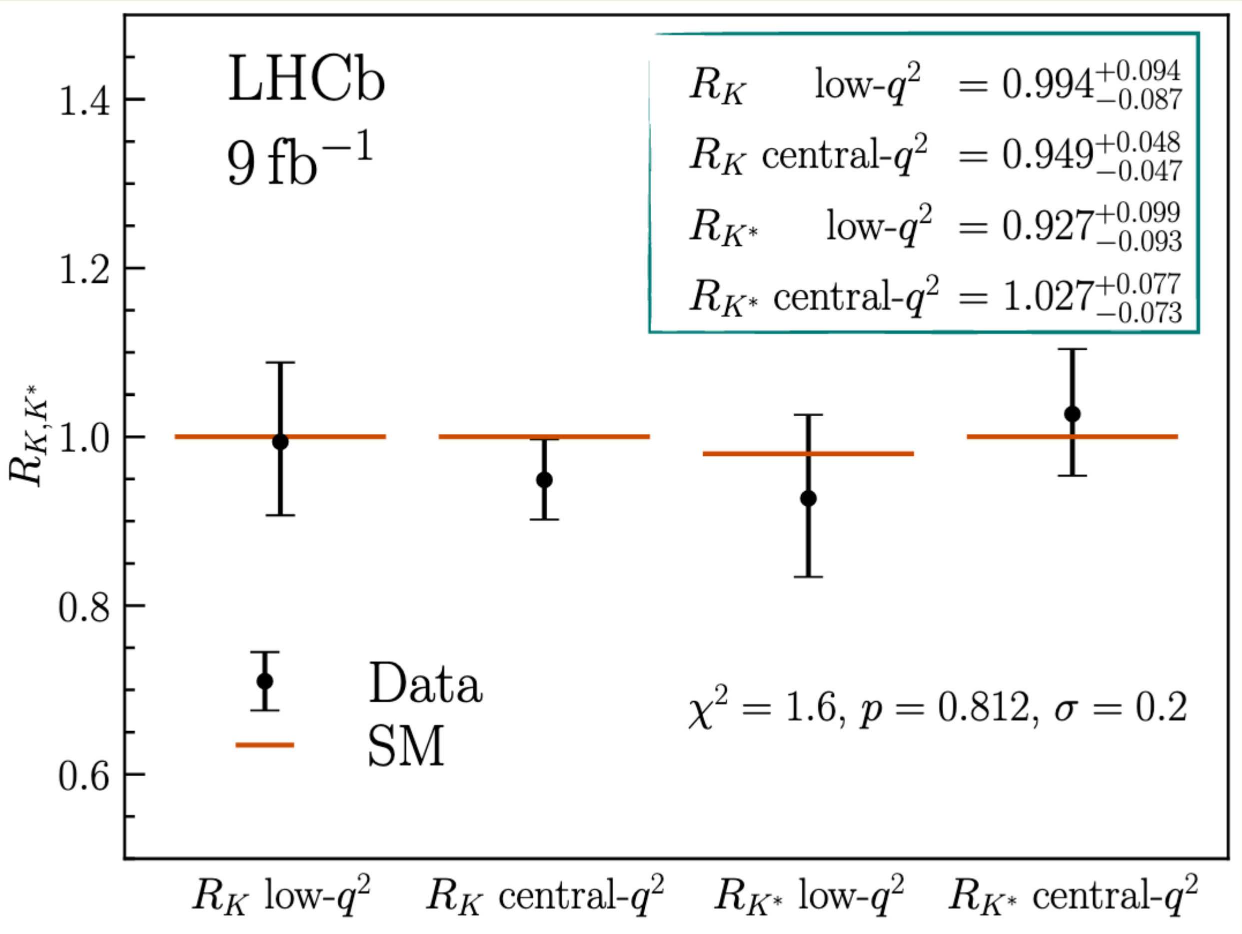
[S. Schmitt talk @ICHEP 2022]

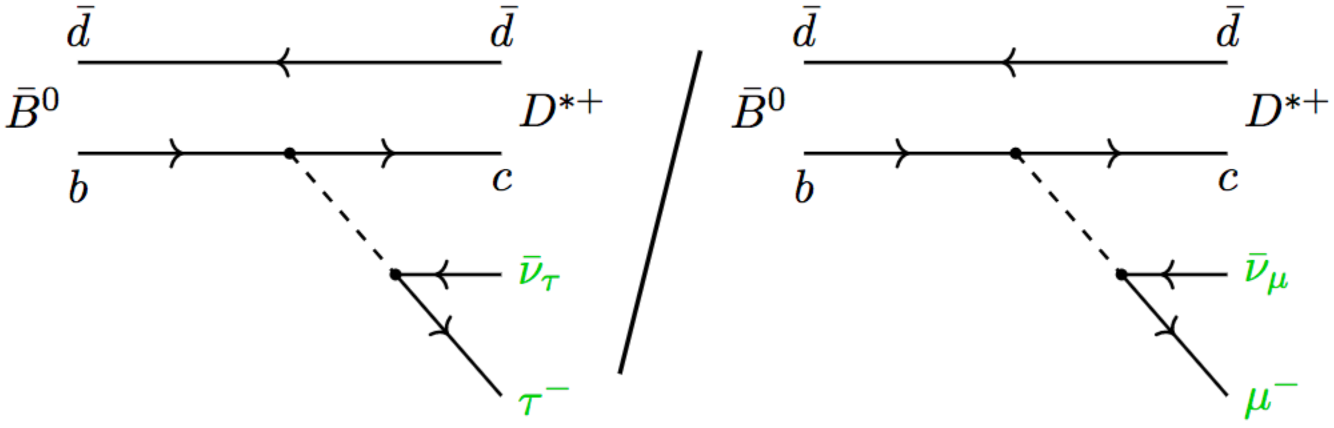
- Some tensions observed in some channels
- Most results from **partial LHCb dataset**
- Result of $\boldsymbol{R_{K^+}}$ was 3.1σ away from SM
- Since then, LHCb has focused on a **combined measurement of $\boldsymbol{R_{K^+}}$ and $\boldsymbol{R_{K^{*0}}}$** with the Run 1+2 legacy dataset
  - This lead to a deeper understanding of systematic effects which has been reflected in the final result.

New $R_{K^{(*)}}$ compatible with SM

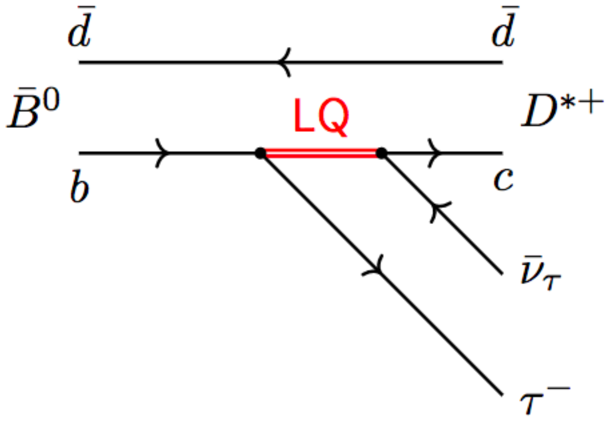
- Found PID-dependence on $R_{K^{(*)}}$
- Previous analysis has neglected the backgrounds:
  - Triple misID $B \to D(\to K_{\to e}\pi_{\to e})\pi_{\to K}$
  - Double misID $B \to K K_{\to e} K_{\to e}$
- Now estimates misID from control samples







Ratios sensitive to possible NP coupling mainly to the 3rd generation (e.g. Leptoquarks):
[PRL 116, 081801, PRD 94, 115201]



Tests of LFU with SLD

- LFU probed using the ratio:

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

with $H_c = \boldsymbol{D^{*+}}, D^0, D^+, D_s^+, \boldsymbol{\Lambda_c^+}, \boldsymbol{J/\psi}$ ... and $H_b = \boldsymbol{B^0}, B_s^0, \boldsymbol{B_{(c)}^+}, \boldsymbol{\Lambda_b}$ **,** but LHCb could also exploit Ξ_b, Ω_b, etc

- $B_s^0, B_{(c)}^+, \Lambda_b, \Xi_b, \Omega_b$ only at LHCb
- $\ell = \mu$ LHCb, $\ell = e/\mu$ B-factories

- **Neutrinos not detected, approximations used for signal reconstruction and large MCs needed for template shapes**
- Semileptonic decays theoretical predictions are precise (% level)
- Large branching ratios

Current experimental status $R(D) - R(D^*)$

LHCb has measured $R(D^*)$ and now also $R(D^0)$

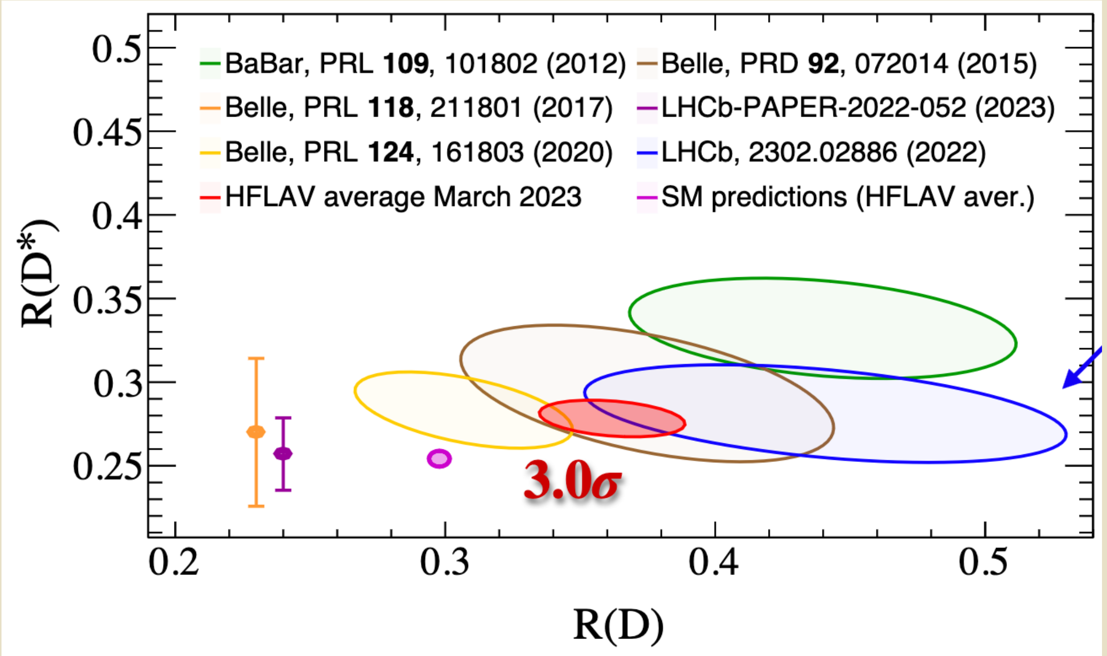
$$R(D^{0,*}) = \frac{\mathcal{B}(B^0 \to D^{0,*}\tau^+\nu_\tau)}{\mathcal{B}(B^0 \to D^{0,*}\mu^+\nu_\mu)}$$

NEW: using Run 1, first simultaneous determination of

- $R(D^*)$ with **muonic** $\tau^+ \to \mu^+\nu_\mu\bar{\nu}_\tau$
  $\boldsymbol{R(D^*) = 0.281 \pm 0.018 \pm 0.024}$
  [arXiv: 2302.02886 submitted to PRL]

- $R(D^0)$ with **muonic** $\tau^+ \to \mu^+\nu_\mu\bar{\nu}_\tau$ $\boldsymbol{R(D^0) = 0.441 \pm 0.060 \pm 0.066}$
  [arXiv: 2302.02886 submitted to PRL]

LHCb now a major player!



First measurement at hadron collider!

Deviation of $R(D)$ and $R(D^*)$ combination **from SM predictions ~3σ**

Overview of lepton-universality tests

- For each entry, the SM expectation (orange diamond) is set to zero, the experimental and theory uncertainties are summed in quadrature and their sum is normalised to unity.
- The experimental value is then shifted and scaled accordingly

Anomaly on $R(K^*)$ disappeared

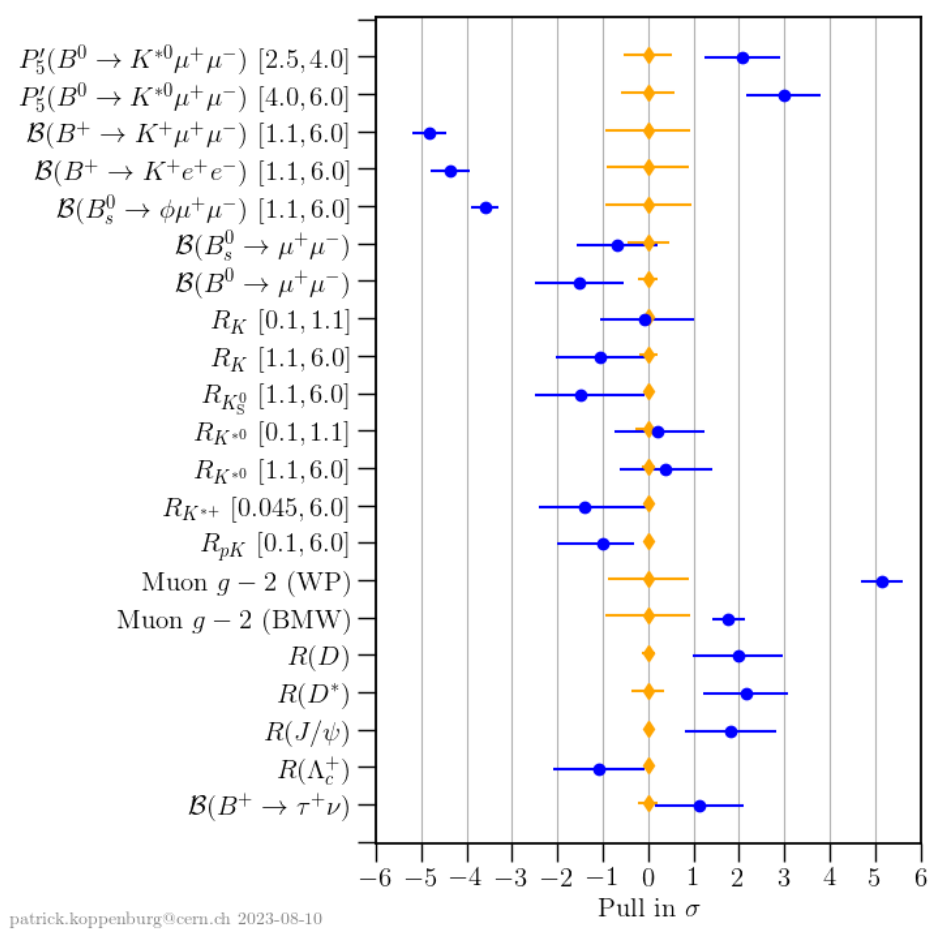
- ➢ Unaccounted-for misID backgrounds

Anomalies on BF/angular distributions of $b \to s\mu\mu$ remain

- ➢ Uncertain SM predictions
- ➢ Unbinned analysis may be able to measure all contributions

Anomalies on $b \to c\tau\nu$ remain

- ➢ Upgraded LHCb will allow us to characterize effects

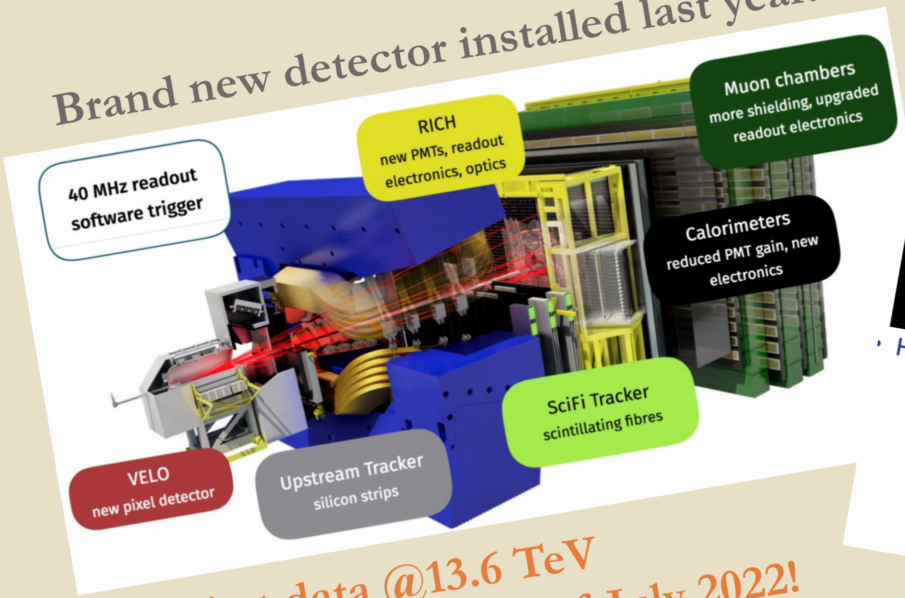


[https://www.nikhef.nl/~pkoppenb/anomalies.html]

The experimental scenario, this is not the end!

We are HERE

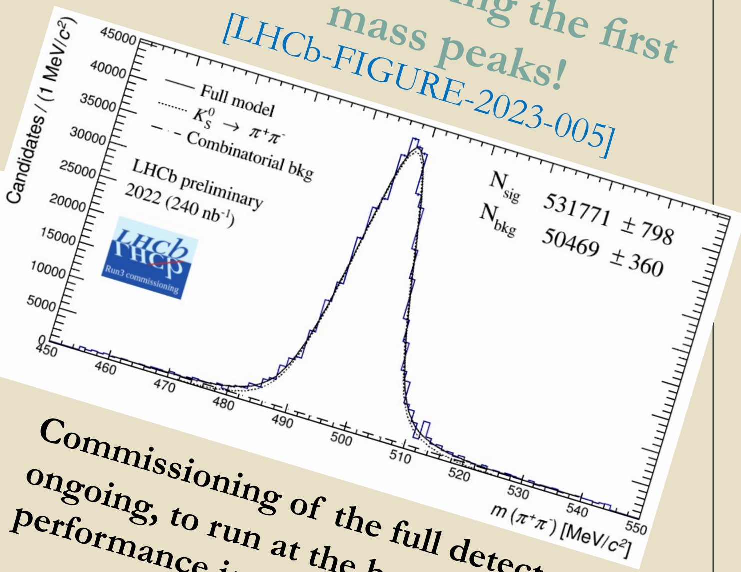
Brand new detector installed last year!



First data @13.6 TeV registered the 5th of July 2022!

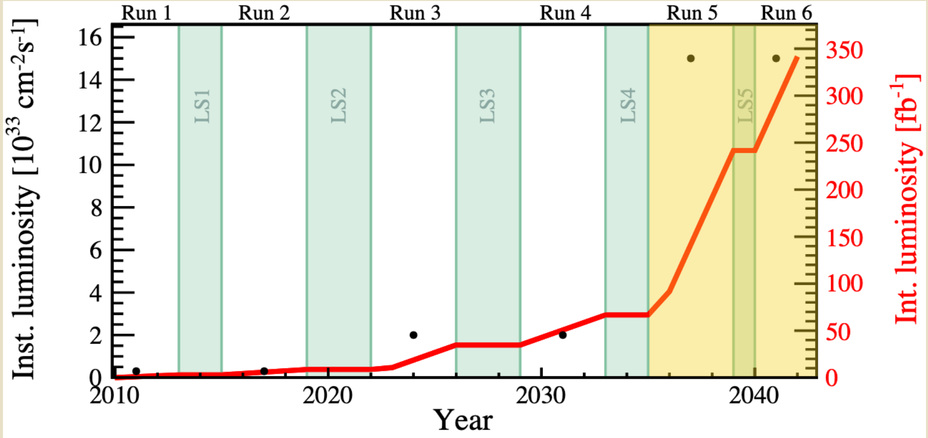
01/11/22 First fill with all subdetectors included…

… and seeing the first mass peaks! [LHCb-FIGURE-2023-005]



Commissioning of the full detector ongoing, to run at the best of the performance in 2024 and 2025!

Looking further into the future

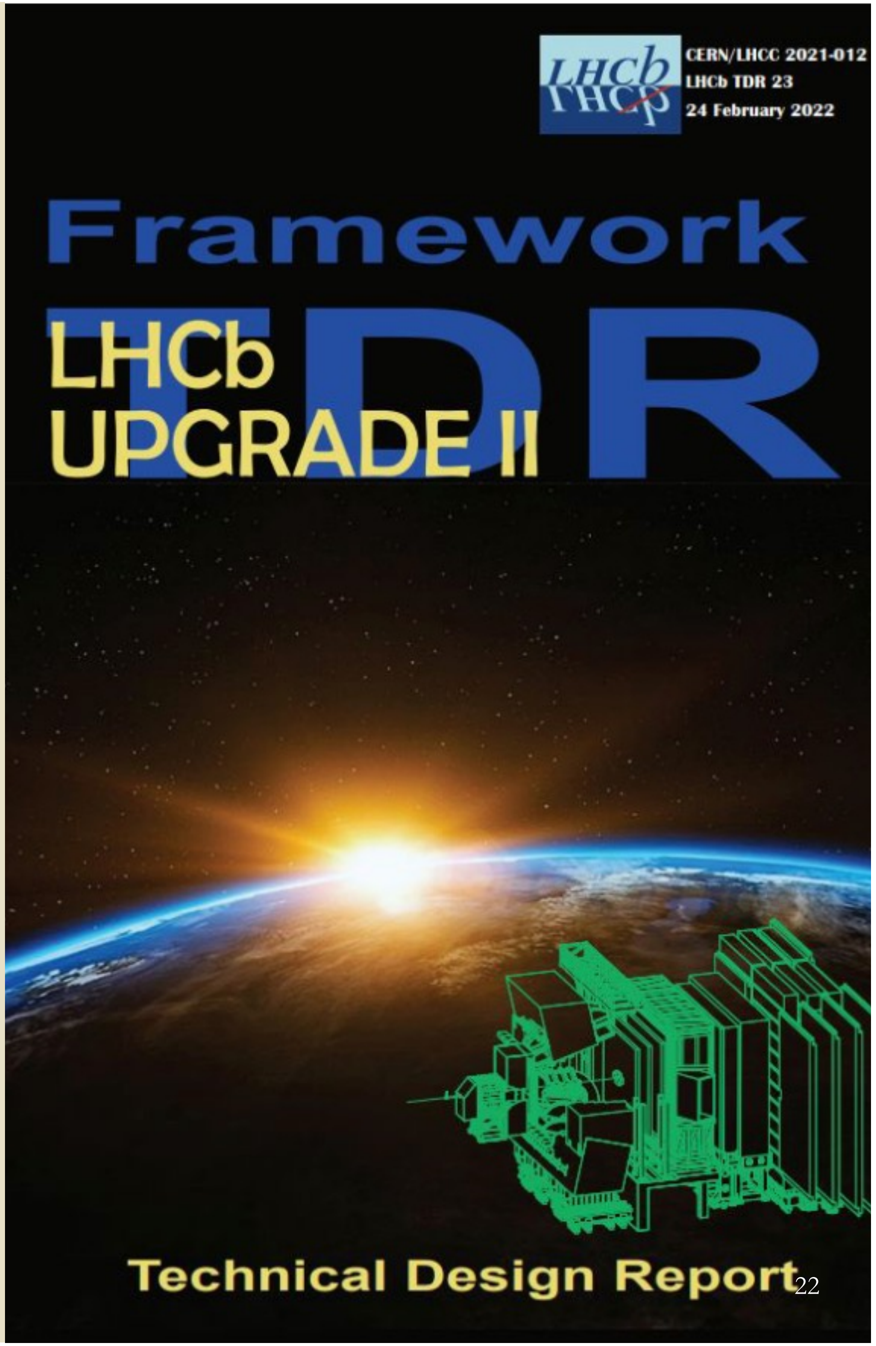


LHCb in Run 5&6?

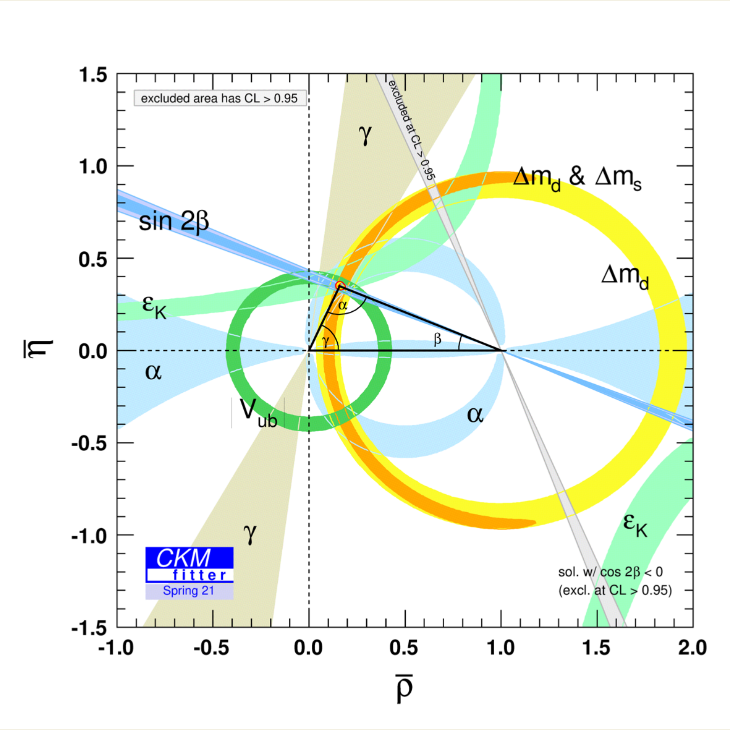
Target: ~300 fb^{-1}

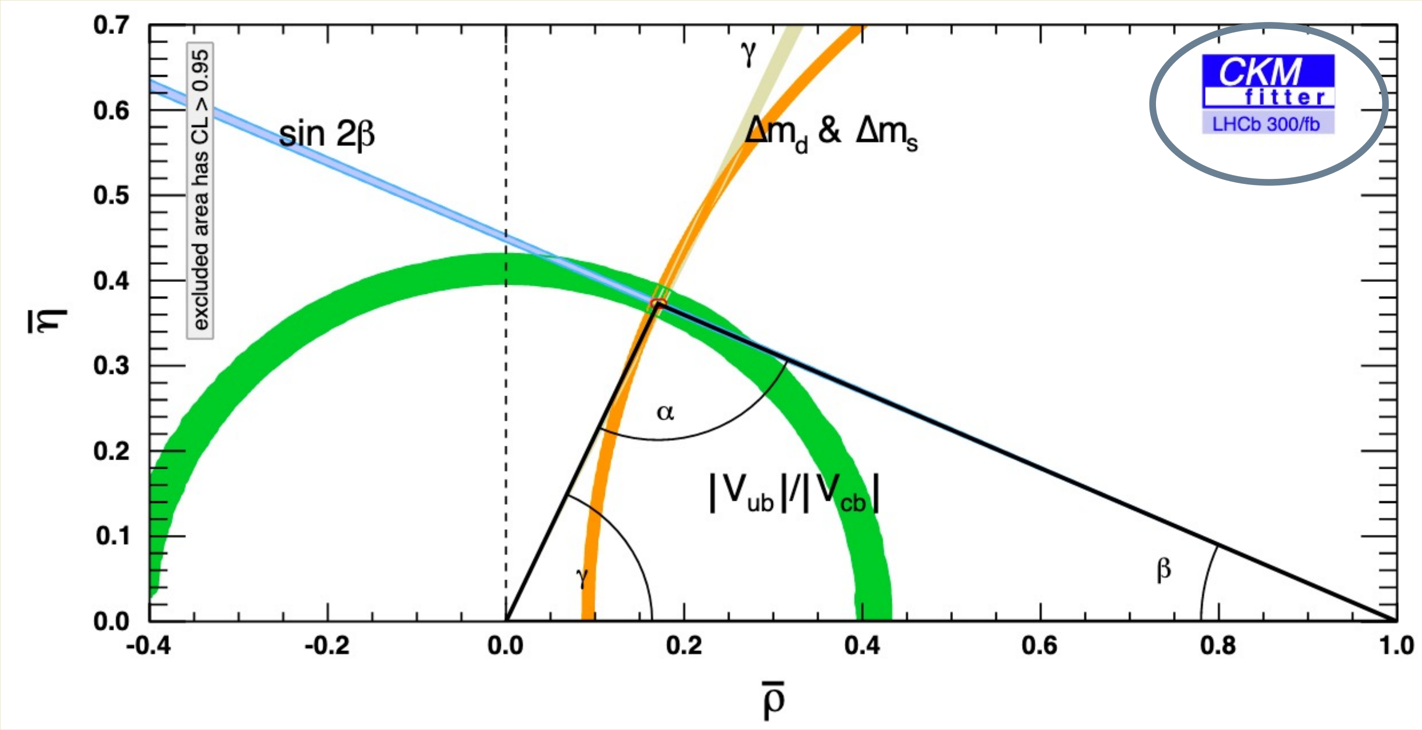
- Pile-up: ~40
- 200 Tb/second data produced
- To keep the same performance in more difficult conditions, timing will be required in some sub-detectors
- A lot of R&D on new technologies
- Sub-detector TDRs expected after Run 3

The HL-LHC provides an opportunity for the ultimate heavy-flavour experiment at the LHC!



What could be achieved in Upgrade II?





[arXiv:1808.08865]

Conclusions and remarks

- Interest in precision flavour measurements is stronger than ever

  → If no direct evidence of NP pops out of the LHC, flavour physics can play a key role.

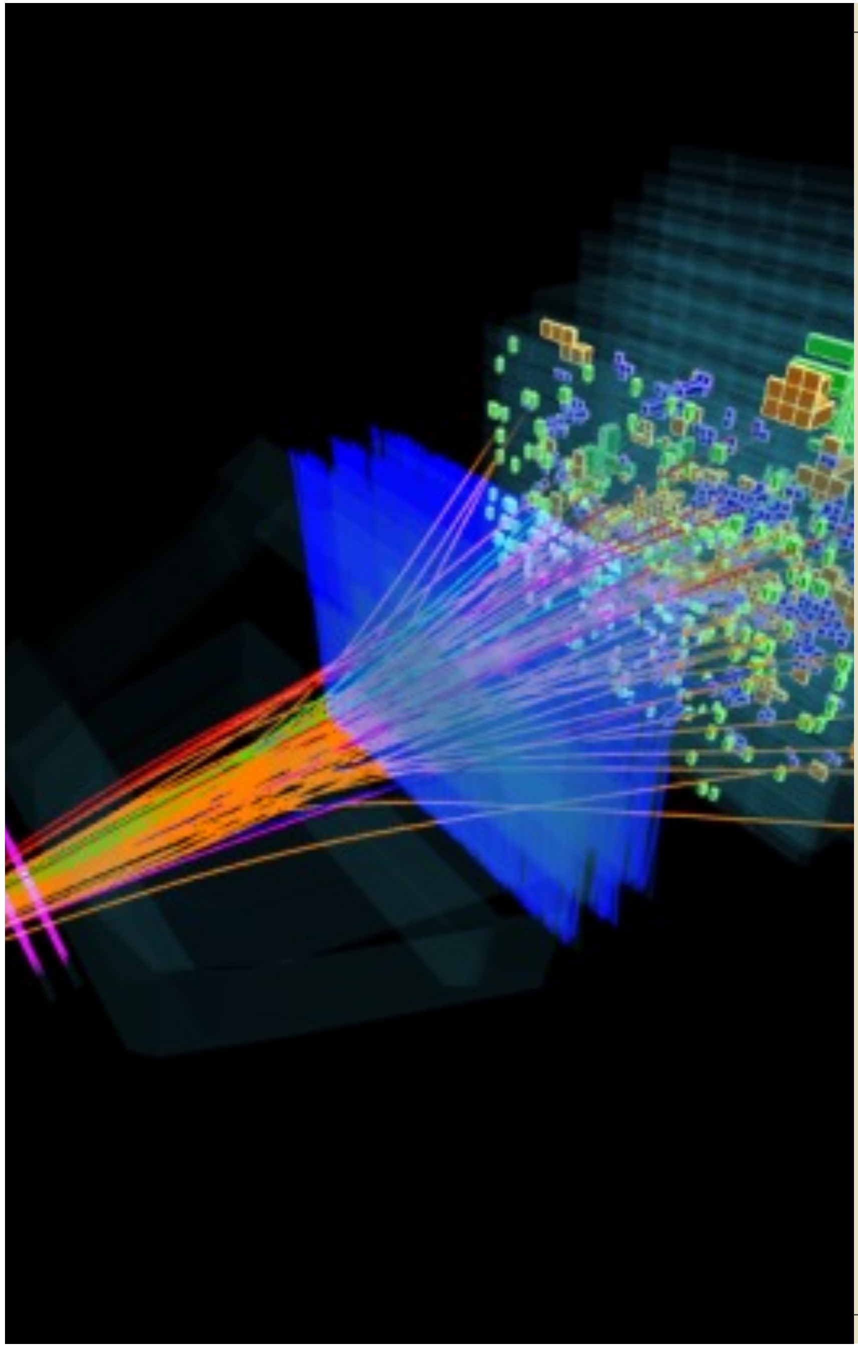
- Most of the results in the CKM sector in **good agreement with SM**, need to go to even **higher precision**: now focused on Run3 to get the new detector in shape to acquire an even larger dataset!

- Still some anomalies remain that need to be clarified.

- **Excellent prospects for precision measurements in the Upgrade II** phase of LHCb.

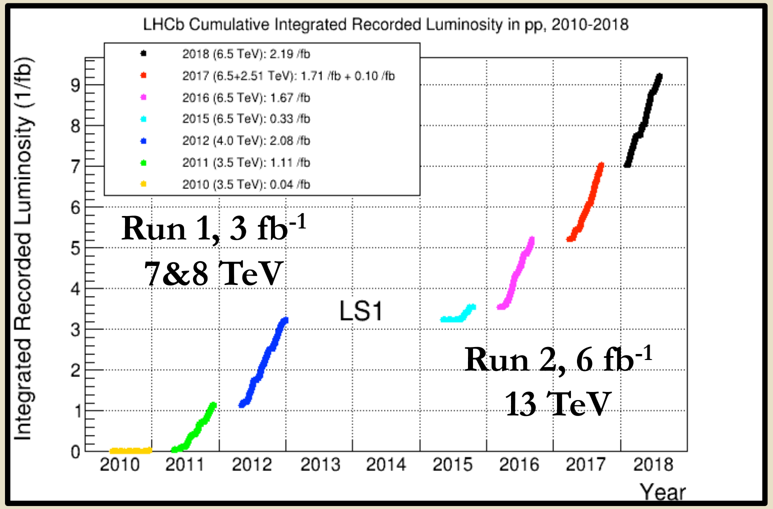
"And if someone dares to yawn during your presentation, this pointer easily transforms from a laser to a taser!"

BACKUP



Flavour physics @LHCb Run 1-2

- # of Primary Vertices ~ 2
- Decay time resolution: ~45 fs
- IP res: ~20 μm for high p_T
- Highly eff. Particle IDentification
- Excellent primary and secondary vertex reconstruction
  [INT.J.MOD.PHYS A30 (2015) 1530022]



Large number of beauty and charm hadrons within LHCb acceptance:

$\sigma_{b\bar{b}}$(7 TeV) = 72.0 ± 0.3 ± 6.8 μb

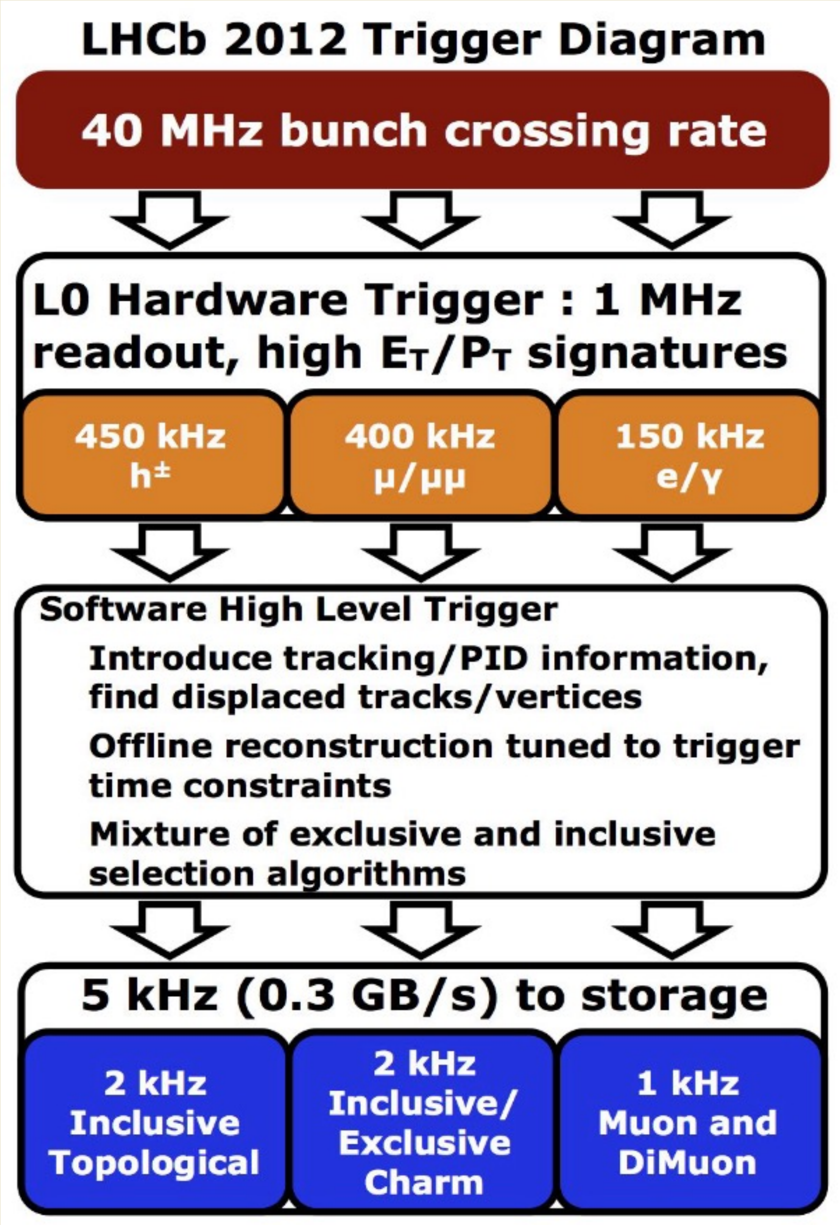
$\sigma_{b\bar{b}}$(13 TeV) = 144 ± 1 ± 21 μb

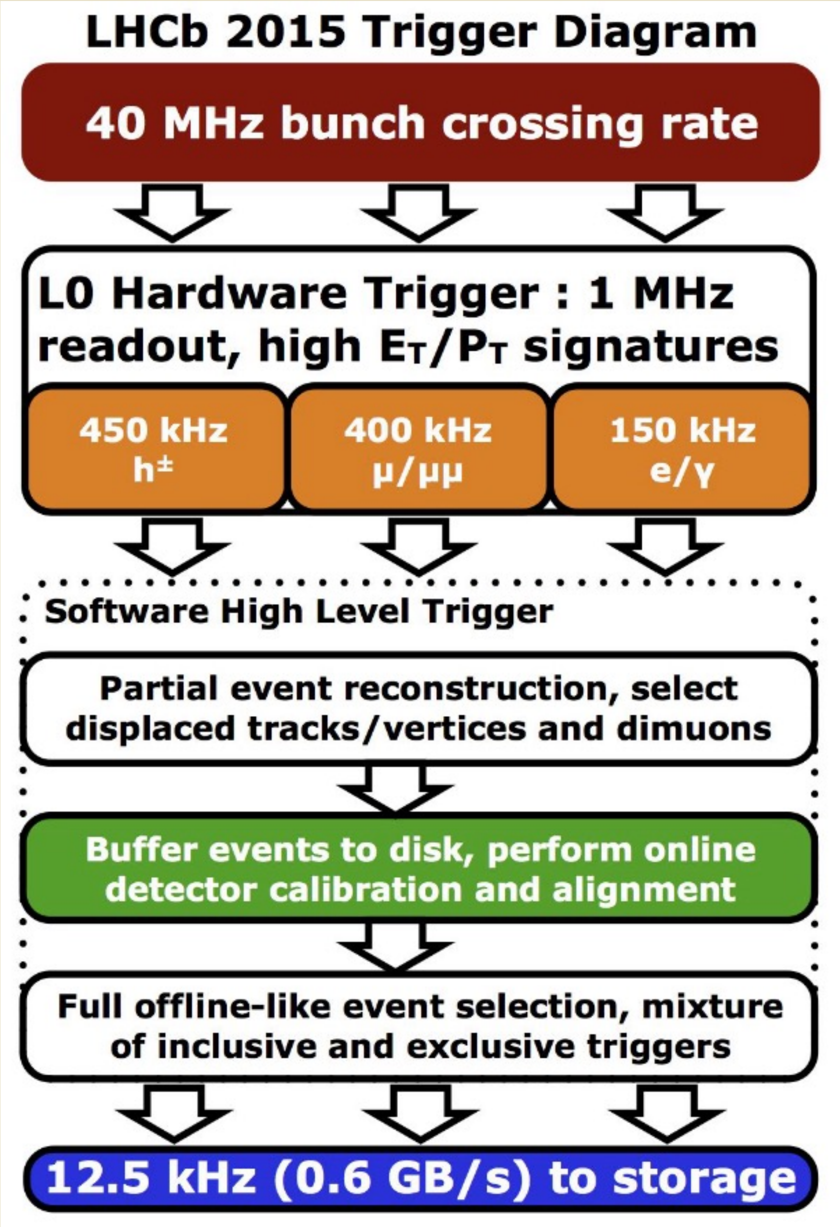
[PRL 119 (2017) 169901]

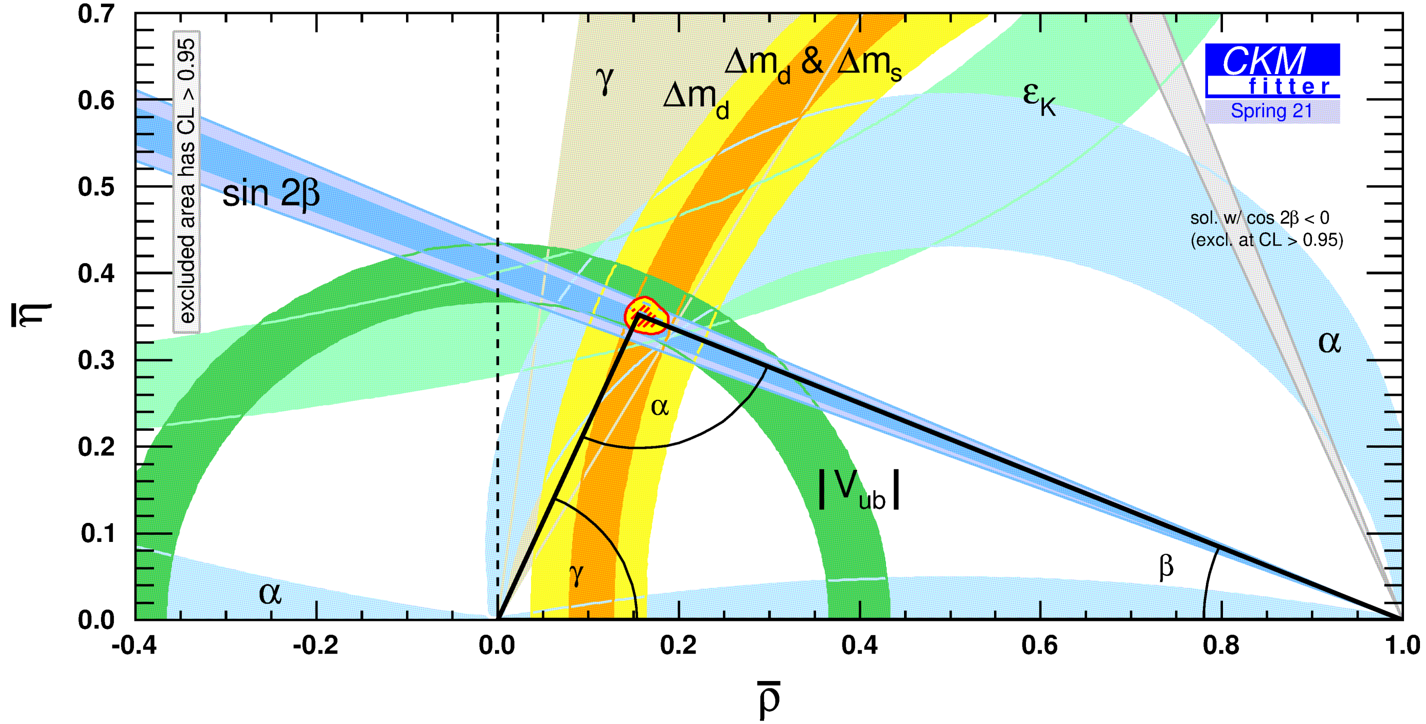
$\sigma_{c\bar{c}}$(7 TeV) = 2369 ± 3 ± 152 ± 118 μb

[JHEP 05 (2017) 074]

LHCb Trigger System



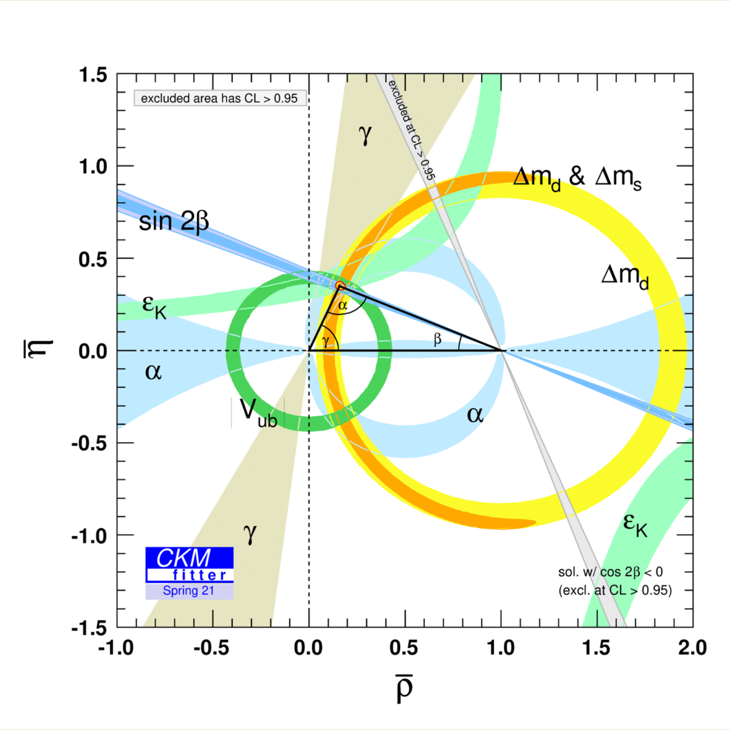


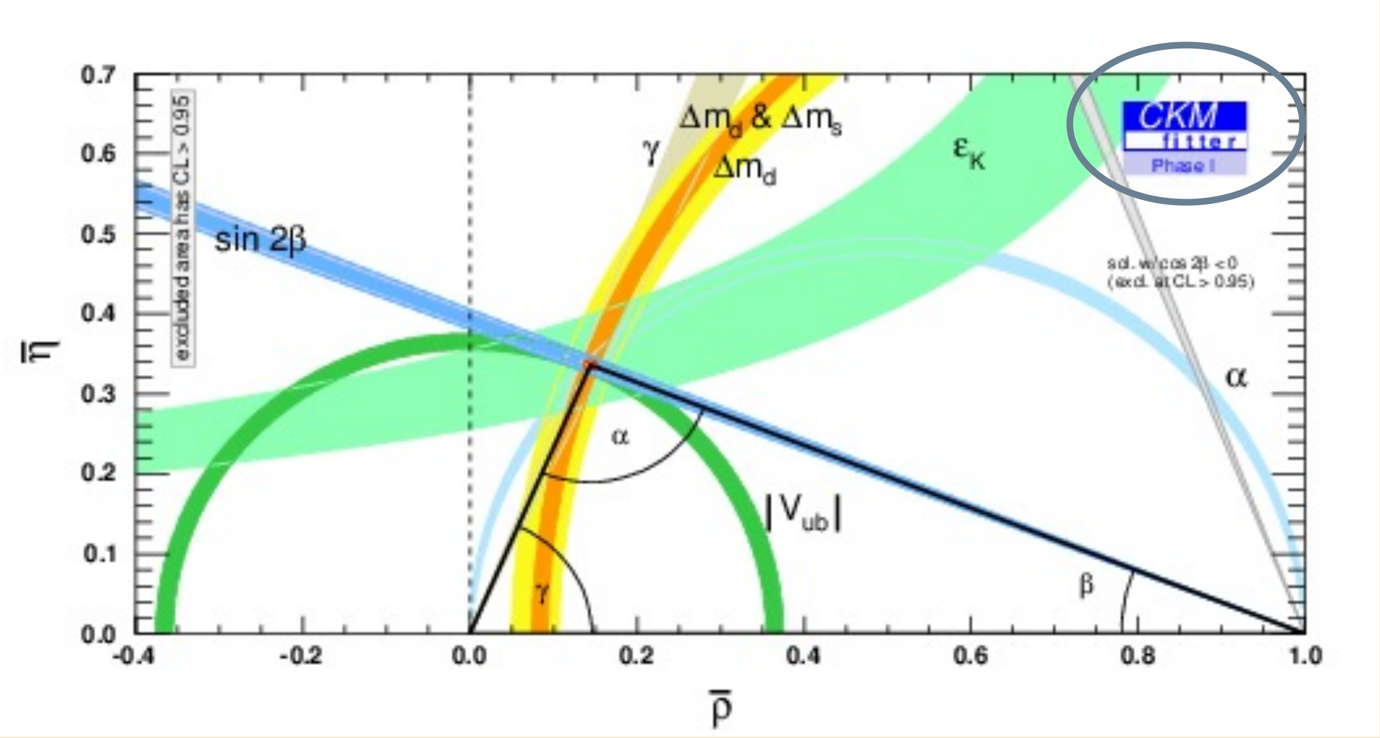


$$V_{CKM} \cong \begin{pmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & |V_{ub}|e^{-i\gamma} \\ V_{cd} & V_{cs} & V_{cb} \\ |V_{td}|e^{-i\beta} & -|V_{ts}|e^{i\beta_s} & V_{tb} \end{pmatrix}$$

CKM METROLOGY

What could be achieved with Run3+4?

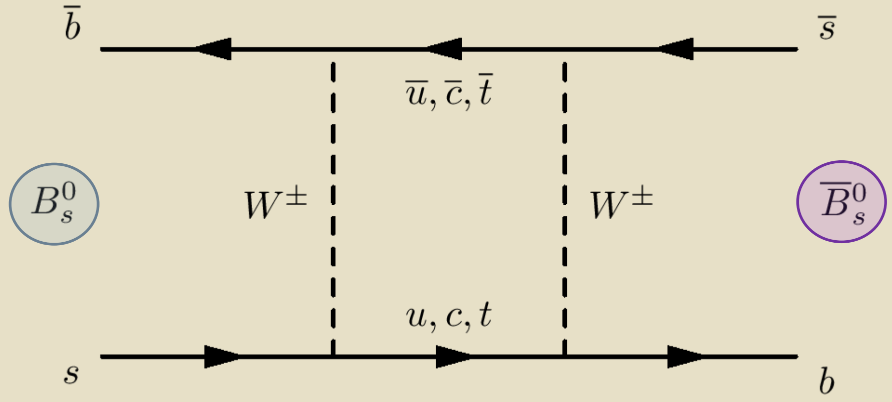


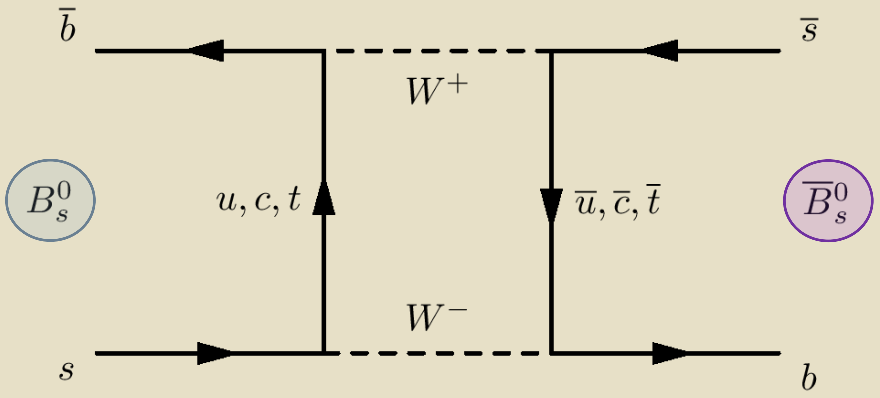


[arXiv:1808.08865]

B flavour mixing

- Neutral B_s^0 mesons can **oscillate** between their particle and anti-particle states





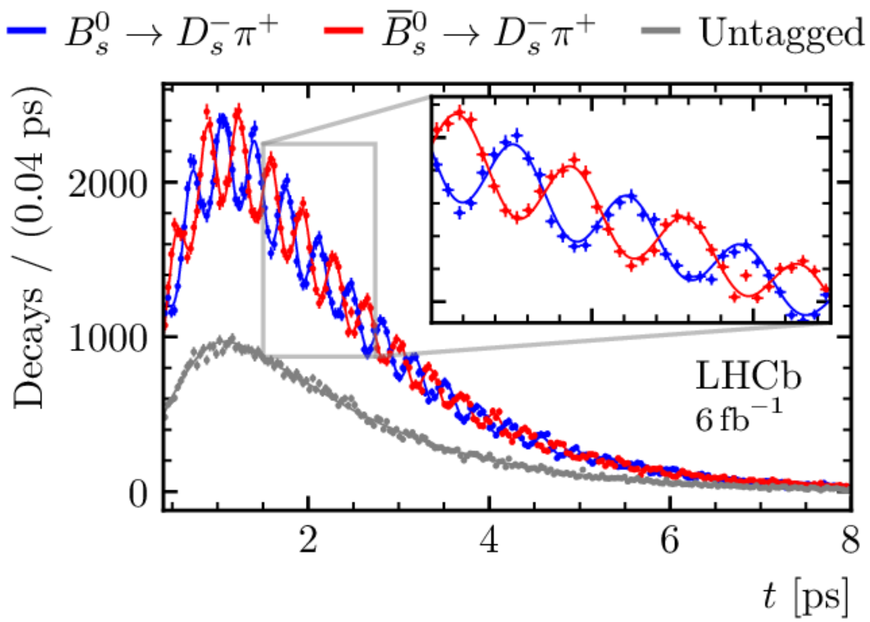
The physical mass eigenstates (L,H) are admixtures of the weak eigenstates:

$$|B_L> = p\,|B_s^0> + q\,|\bar{B}_s^0>$$
$$|B_H> = p\,|B_s^0> - q\,|\bar{B}_s^0>$$

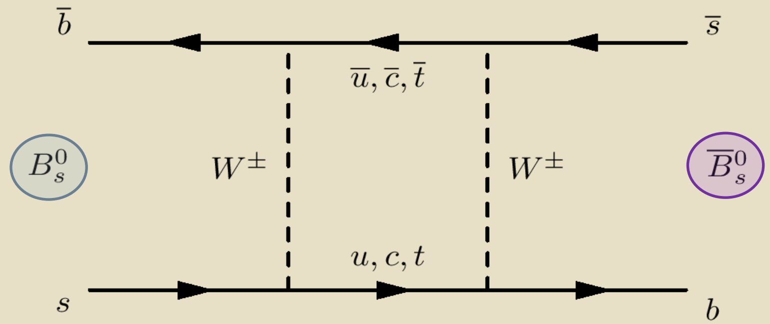
- with **mass difference** $\Delta m = m_H - m_L$ and **decay-width difference** $\Delta\Gamma = \Gamma_L - \Gamma_H$
- flavor at production (t=0) could be different from flavour at decay time t

B_s^0 mixing

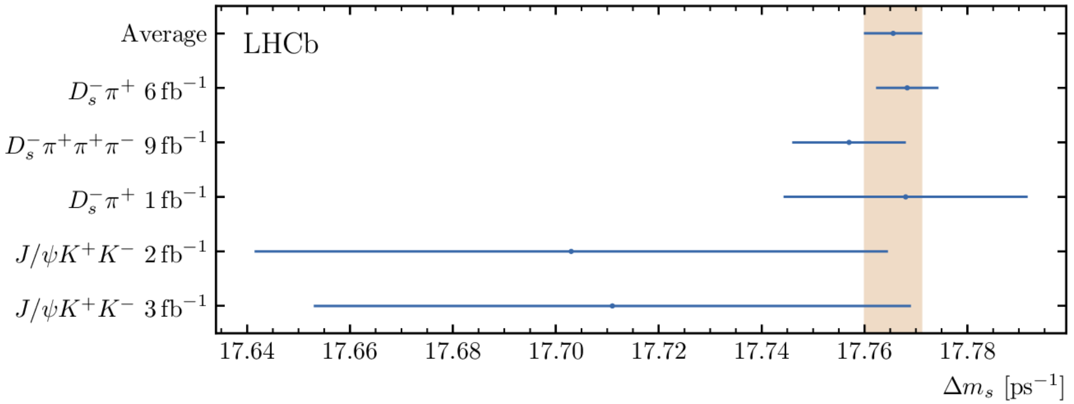
$|B_L> = p\,|B_s^0> + q\,|\bar{B}_s^0>$
$|B_H> = p\,|B_s^0> - q\,|\bar{B}_s^0>$



- Neutral B_s^0 mass(~CP) eigenstates characterised by **sizeable difference in decay width and mass**!
  $\Delta\Gamma_s/\Gamma_s = 0.124 \pm 0.008$, $\Delta m_s/\Gamma_s \approx 30$



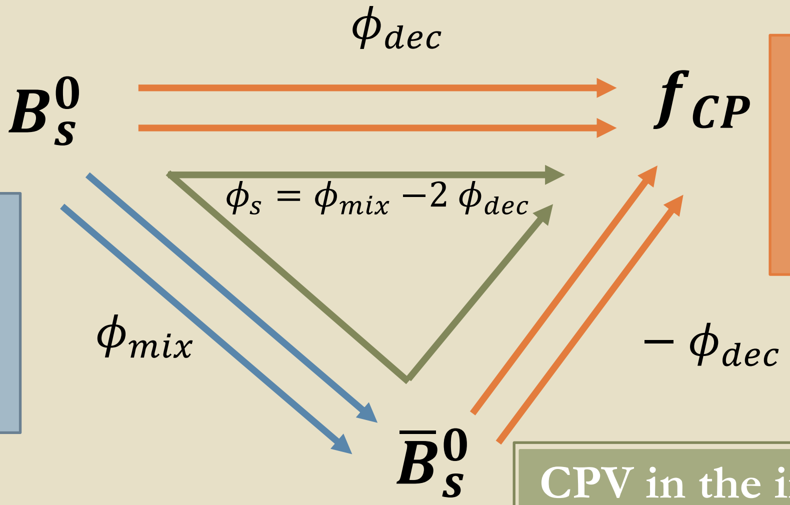
- To measure oscillation, need to know B_s^0 state at production (flavour tagging) and B_s^0 state at decay!
- Recent LHCb measurement of Δm_s uses $B_s^0 \to D_s^- \pi^+ / \bar{B}_s^0 \to D_s^+ \pi^-$
- B_s^0 state at decay fixed by final state
- **Most precise measurement of Δm_s**
  $\Delta m_s = 17.7683 \pm 0.0051 \pm 0.0032\ \text{ps}^{-1}$



[Nature Physics 18 (2022) 1]

Different kinds of CP violation

- Must have **two interfering amplitudes** with different strong (δ) and weak (φ) phases
- For a B_s^0 decay to a **CP eigenstate *f***, CP-violating effects depend on $\lambda_f = \frac{q}{p}\frac{\bar{A}_f}{A_f}$



CPV in mixing

- $P(B_s^0 \to \bar{B}_s^0) \neq P(\bar{B}_s^0 \to B_s^0)$
- $|q/p| \neq 1$

CPV in decay

- $P(B_s^0 \to f) \neq P(\bar{B}_s^0 \to f)$
- $|\bar{A}_f / A_f| \neq 1$

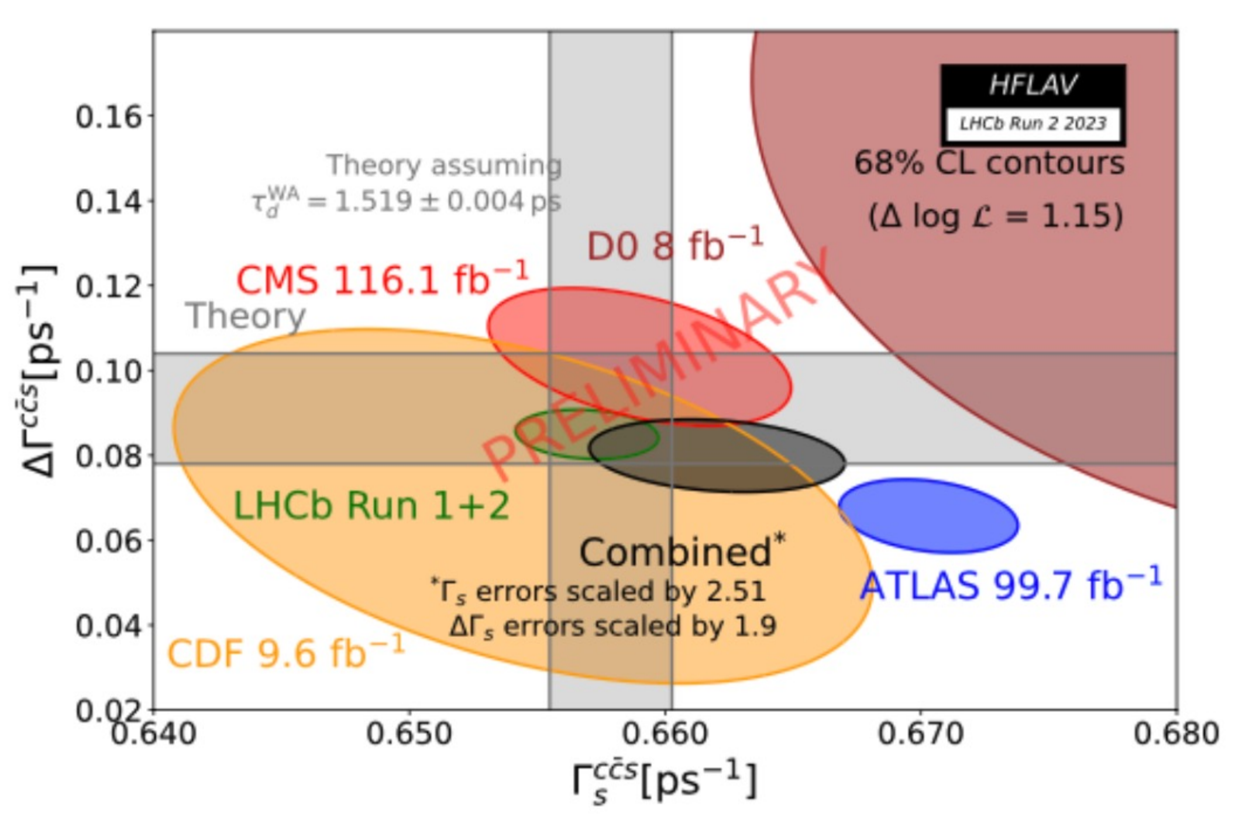
CPV in the interference between decay and mixing

- $P(B_s^0 \to f) \neq P(B_s^0 \to \bar{B}_s^0 \to f)$
- $\arg(\lambda_f) \neq 0$

HFLAV PRELIMINARY AVERAGE

- $\phi_s^{c\bar{c}c}$ = -0.039 ± 0.016 [rad]
- $\Delta\Gamma_s$ = 0.080 ± 0.006 [ps^{-1}]
- Γ_s = 0.6627 ± 0.0036 [ps^{-1}]

Tension between LHCb, CMS and ATLAS results



Interest triggered by a measurement from D0 yielding an anomalous like-sign dimuon asymmetry [Phys. Rev. D 89, 012002 (2014)]

- Consider a **flavour-specific** final state f:

$$B^0_{(s)} \to f \quad \text{or} \quad \overline{B}^0_{(s)} \to B^0_{(s)} \to f$$

$$\overline{B}^0_{(s)} \to \bar{f} \quad \text{or} \quad B^0_{(s)} \to \overline{B}^0_{(s)} \to \bar{f}$$

- $a_{sl} \equiv \frac{\Gamma(\overline{B}^0_{(s)}(t)\to f) - \Gamma(B^0_{(s)}(t)\to \bar{f})}{\Gamma(\overline{B}^0_{(s)}(t)\to f) + \Gamma(B^0_{(s)}(t)\to \bar{f})} \cong \frac{\Delta\Gamma}{\Delta M} \tan \phi_M$

LHCb measured both $a_{sl}^{d,s}$ using Run I

- $a_{sl}^s = (0.39 \pm 0.26(\text{stat}) \pm 0.20(\text{syst}))\%$
[Phys. Rev. Lett. 117, 061803 (2016)]

- $a_{sl}^d = (-0.02 \pm 0.19(\text{stat}) \pm 0.30(\text{syst}))\%$
[Phys. Rev. Lett. 114, 041601 (2015)]

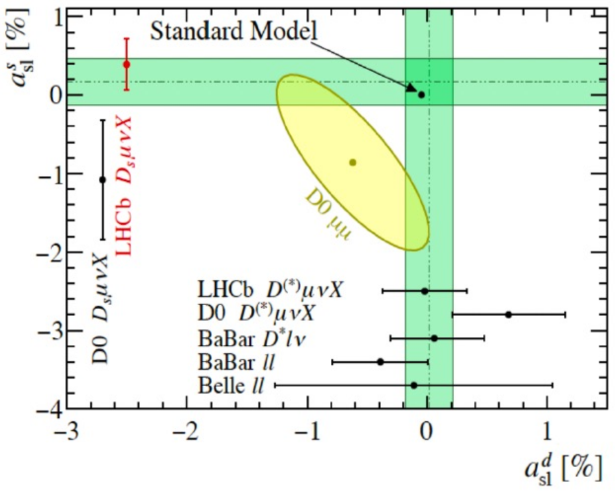
ATLAS measured same- and opposite-sign charge asymmetries based on the μ charge from a top and the charge of the soft μ from a b-hadron in $t\bar{t}$ events [JHEP 02 (2017) 071]

- Four *CP* asymmetries (one mixing and three direct) compatible with SM (uncertainty $\sim$ 1%).

$\not{CP}$ in mixing is very small in the SM

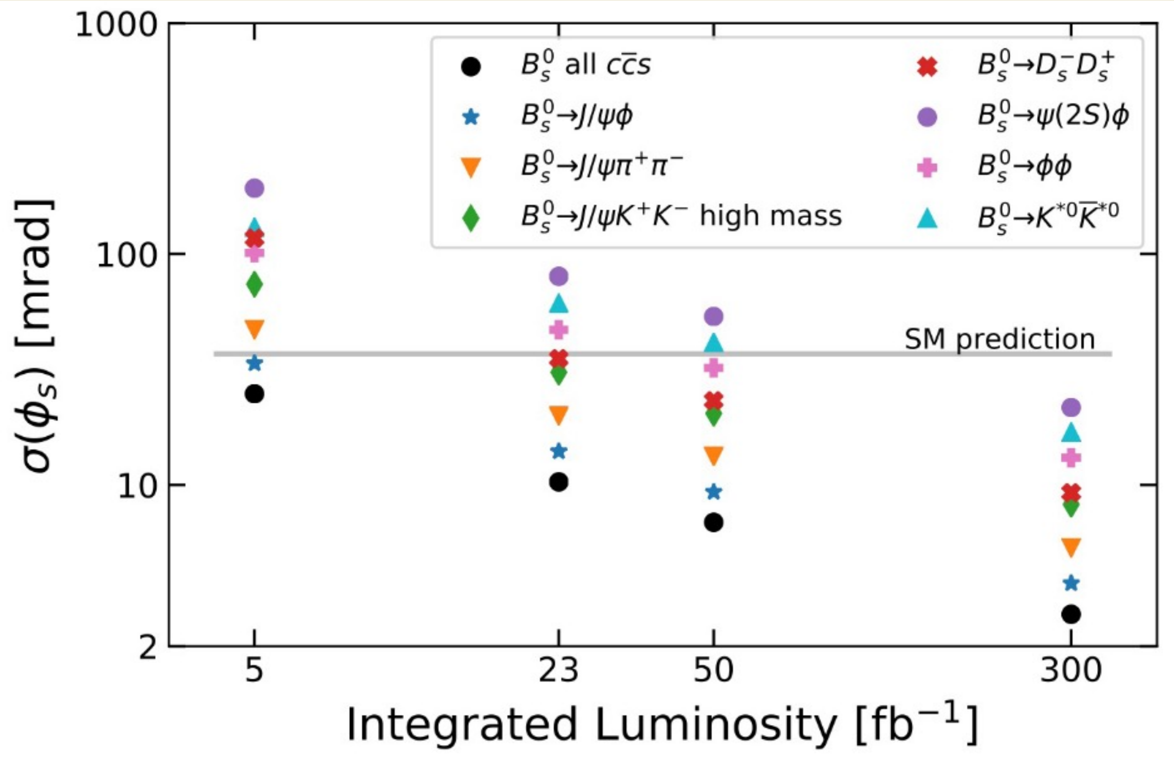
$a_{sl}^d(B^0)^{SM} = (-4.1 \pm 0.6) \cdot 10^{-4}$
$a_{sl}^s(B_s^0)^{SM} = (+1.9 \pm 0.3) \cdot 10^{-5}$

[Lenz & Nierste, arXiv:1102.4274 [hep-ph]]



CP violation in B mixing

Prospects for the future



[LHCB-PUB-2018-009]

- Include gain in trigger for $B_s^0 \to D_s^- D_s^+$ after Upgrade 1
- Same performances as in Run I
  - Assumed tagging power 4%
- Additional modes planned: $J/\psi \to ee, \eta' \to \rho^0\gamma$ or , $\eta' \to \eta\pi\pi$ or $\gamma\gamma$ as cross cheks

300/fb: $\sigma^{STAT}(\varphi_s) \sim$ 4 mrad from $B_s^0 \to J/\psi KK$ only

- **φ_s expected to be statistically limited**
- **Upgrade II sensitivity below SM prediction in multiple channels**

Impact of Upgrade I and II very important for φ_s!

Flavour tagging in the future

Almost everything will be new in Run3 (similar situation as in 2010)

- **Upgrade challenge**: increase in track multiplicity and pile-up (~6 for Upgrade-I and ~55 for Upgrade-II) that have negative effect on ω and ε_{tag}.
- FT performance directly linked to the ability to associate PV ⟺ track. To improve/maintain tagging performance need:
  - **Hardware**: timing information (upgrade-II workshops)
  - **Software**: deep neural networks to learn correlations between all tracks and the signal B meson (inclusive taggers), need to reduce significantly persisted info.

Control of penguin pollution

- U-spin or SU(3) flavour symmetry to constrain size of penguin with b→c$\bar{c}$d (related by s-d spectator exchange)
- Penguin pollution and/or CP violation **could be different for each polarisation state**, f ∈ (0, ⊥, ∥, S)

→ no sign yet of dependence in $B_s^0 \to J/\psi$ KK (also in Run 2) so penguins are small

- **SU(3)$_F$: $B_s^0 \to J/\psi K^{*0}$ and $B^0 \to J/\psi \rho^0$ are b→c$\bar{c}$d transitions**.

$$\Delta\phi_{s,0}^{J/\psi\phi} = 0.000^{+0.009}_{-0.011}\,(\text{stat})\;{}^{+0.004}_{-0.009}\,(\text{syst})\ \text{rad}$$
$$\Delta\phi_{s,\parallel}^{J/\psi\phi} = 0.001^{+0.010}_{-0.014}\,(\text{stat}) \pm 0.008\,(\text{syst})\ \text{rad}$$
$$\Delta\phi_{s,\perp}^{J/\psi\phi} = 0.003^{+0.010}_{-0.014}\,(\text{stat}) \pm 0.008\,(\text{syst})\ \text{rad}$$

[JHEP 11 (2015) 082]

Precision of ~10 mrad
To be compared with the current precision of HFLAV of **21 mrad**

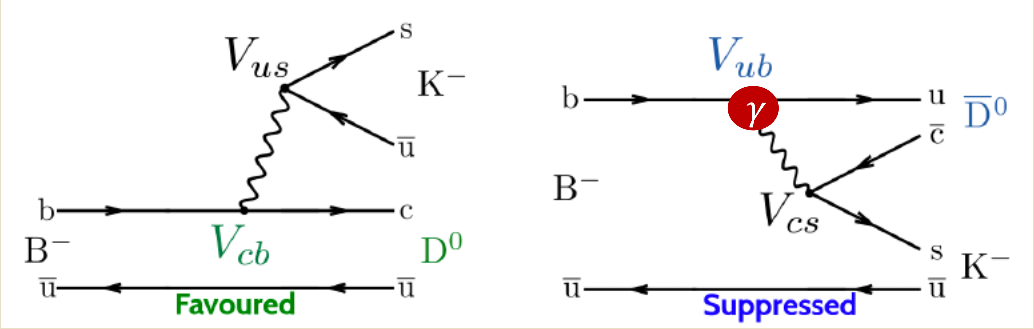
Fundamental to update these analyses, expected sensitivity **at 300/fb is 1.5 mrad** (statistically limited)
+ adding $B_s^0 \to J/\psi\omega$ and $B^0 \to J/\psi\varphi$ (E + PA diagrams only)

Status of γ

- $\gamma = -\arg(V_{ud}V_{ub}^*/V_{cd}V_{cb}^*)$
- TI measurements of γ from B decays mediated only by tree-level transitions provide a **standard candle for the SM** (assuming no new physics in tree-level decays [Phys. Rev. D 92, 033002 (2015)] $\Longrightarrow$ **Theoretically clean** $[\delta\gamma/\gamma] \lesssim \mathcal{O}(10^{-7})$ [JHEP 1401 (2014) 051]
- This can be compared with γ values from B decays involving loop-level transitions, such as $B^0_{d,s} \to hh'$ decays ($h = K, \pi$), to **get signs of NP**

→If the assumption is dropped, Upgrade 2 will allow to search for NP.

◦ Can be measured in the interference between $b \to c$ (favoured) and $b \to u$ (suppressed) transitions, e.g.:



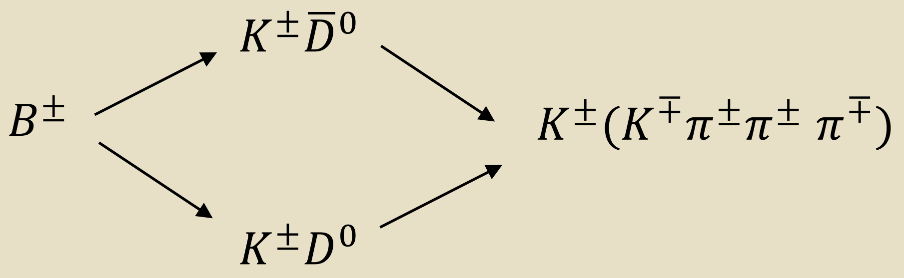
Ratio of magnitudes

$$\frac{A_{sup}}{A_{fav}} = r_B^{Dh} e^{i(\delta_B^{Dh} \pm \gamma)}$$

Strong phase difference, **ext. input from CLEO and BES III**

Small signal yields (BR 10⁻⁷), small interference effects (10%). Combining a plethora of independent decay modes is the key to achieve the ultimate precision.

Direct measurement of γ



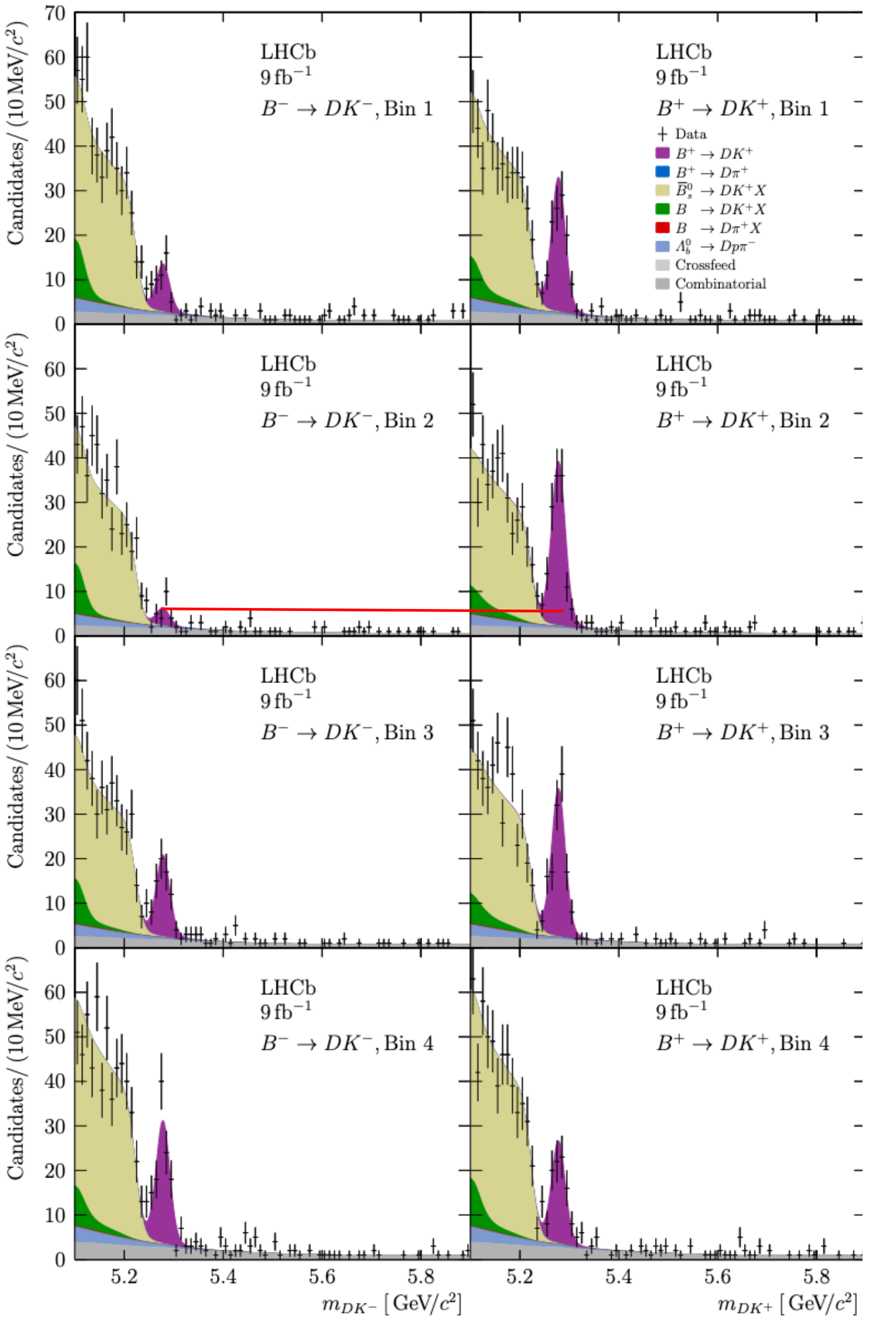
Largest CPV ever measured (~85%)!

- Recent LHCb measurement with the full dataset
- Model-independent determination **in 4 bins of the D decay phase space** with different strong phases
- **Second most precise measurement from a single D mode**

$$\gamma = (54.8^{+6.0}_{-5.8}(\text{stat.})^{+0.6}_{-0.6}(\text{syst.})^{+6.7}_{-4.3}(\text{ext.}))^\circ$$

- Using inputs from BESIII/CLEO

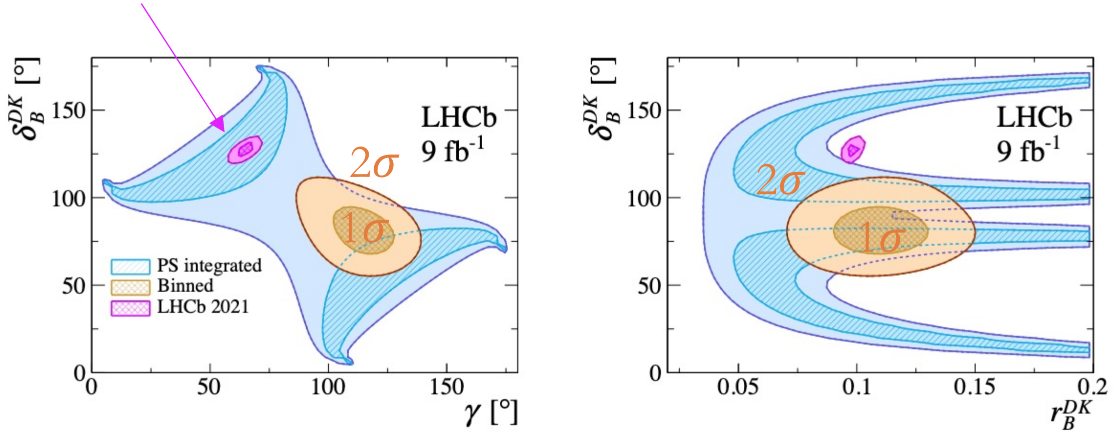
[LHCb-PAPER-2022-017, arXiv:2209.03692]



Using the binned analysis alone:

$$\gamma = (116^{+12}_{-14})^\circ,$$
$$\delta_B^{DK} = (81^{+14}_{-13})^\circ,$$
$$r_B^{DK} = 0.110^{+0.020}_{-0.020},$$
$$\delta_B^{D\pi} = (298^{+62}_{-118})^\circ,$$
$$r_B^{D\pi} = 0.0041^{+0.0054}_{-0.0041},$$

Analysis of other decay modes at LHCb



Latest measurement of γ

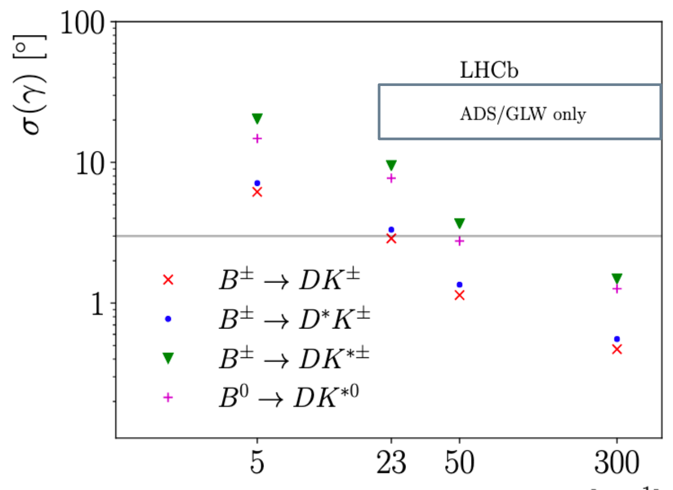
- First study of CP violation in the decay mode $B^\pm \to [K^+K^-\pi^+\pi^-]_D\, h^\pm$, with $h = K, \pi$
- Self conjugated D decay mode, analysis performed **in bins of phase space**
- External charm-decay parameters taken from LHCb amplitude analysis
- Phase space integrated measurement also performed for $B^\pm \to [\pi^+\pi^-\pi^+\pi^-]_D h^\pm$
- Full Run 2 exploited, precision of the four-body D-decay studies is limited by the sample size.

[arXiv:2301.10328]

Prospects for γ

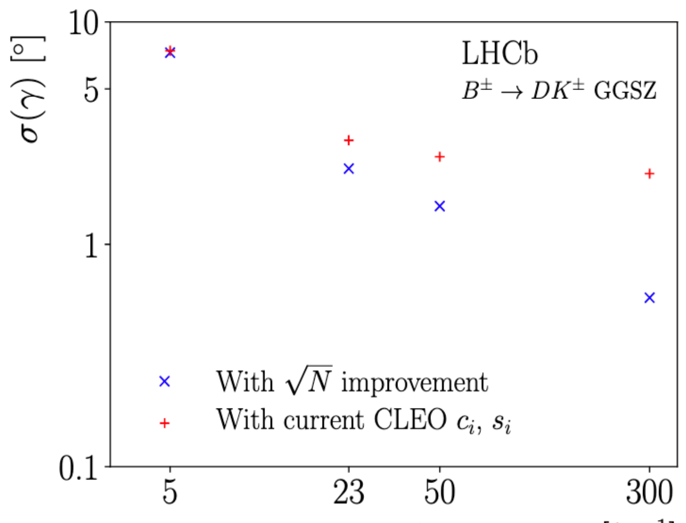
- 4° with Run 2 data (~ 9 fb^{-1})
- 1.5° by the end of Run 3 (~ 22 fb^{-1})
- < 1° by the end of Run 4 (~ 50 fb^{-1})
- ~0.4° in Phase 2 upgrade (~ 300 fb^{-1})

[arXiv:1709.10308v5][CERN-LHCC-2017-003]



[arXiv:1808.08865]

- D reconstructed in a 2 charged-track final state
- All ADS/GLW asymm. currently statistically limited
- Dominant syst., due to knowledge of background contributions, expected to scale with statistics



[arXiv:1808.08865]

- D is reco in a 3-body self-conjugated final state
- Powerful input to the overall determination of γ
- Need good description of strong phase difference δ_D
  - Current inputs taken from CLEO-c (current syst ~ 2°)
  - Future BESIII and LHCb charm inputs are vital

Some thoughts on γ in Upgrade 2

- Since the bulk of the sensitivity to γ comes from the difference in rates of the $B - \bar{B}$ processes, a **precise control of asymmetries in charged-particle identification and detection is crucial**
  → these systematic uncertainties are considered to scale with integrated luminosity

- Upgrade of the calorimeter will greatly expand LHCb's capabilities for modes with neutrals in the final state.

- Upgrade 2 will also make it interesting to measure γ using baryonic decays
  → **TORCH** system particularly helpful in allowing for low-momentum separation of protons and kaons

- Addition of **magnet-side stations** may lead to important signal-yield improvements, particularly for high-multiplicity final states.

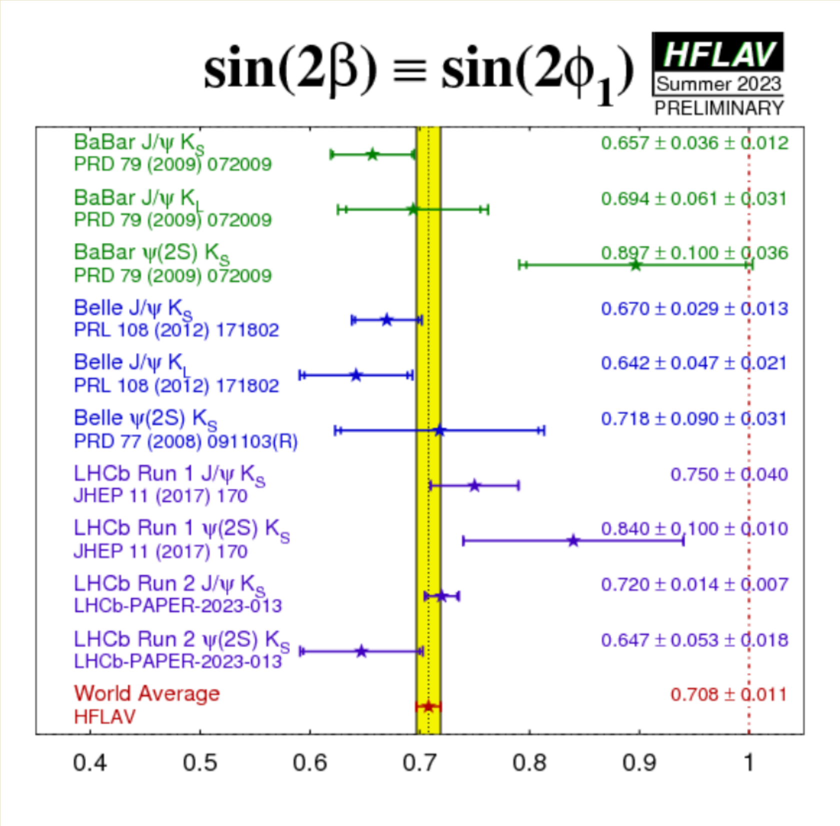
- Constrain $\beta_{(s)}$ without penguin contaminations → $\sim 2°$ sensitivity on $\gamma - 2\beta_s$ from $B_s^0 \to D_s K$

$\sin(2\beta)$ determinations

LHCb determination is:

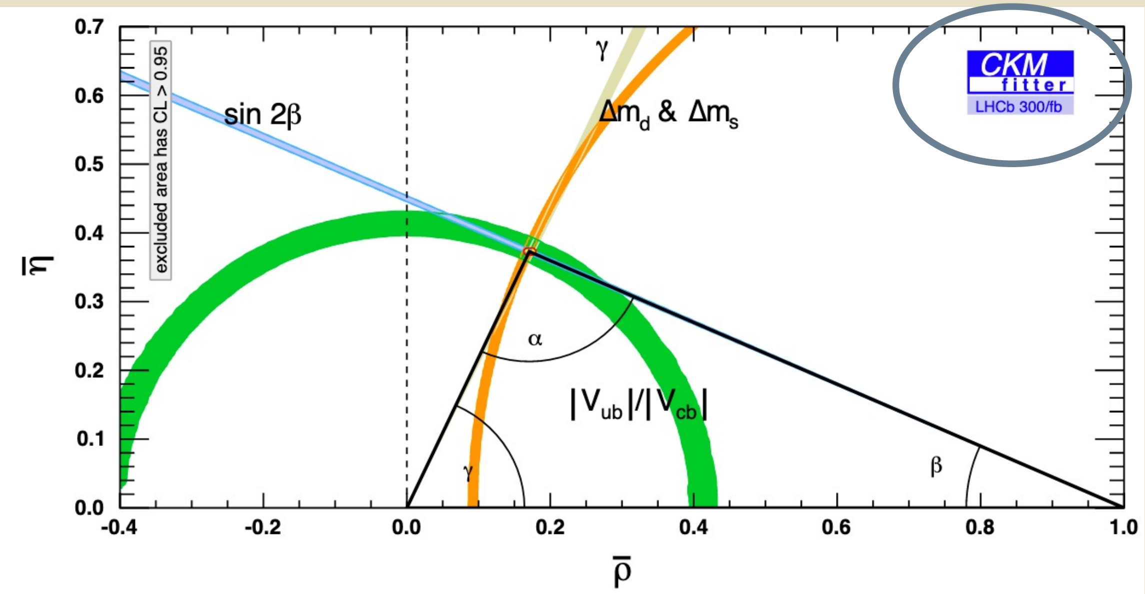
- Consistent with other measurements, still statistical uncertainty limited

- Dominant contribution to the World Average



Prospects for $\sin(2\beta)$

- @50/fb: $\sigma_{stat} = 0.006$ with $B^0 \to J/\psi K_s^0$
- @300/fb: $\sigma_{stat} = 0.003$ with $B^0 \to J/\psi K_s^0$



[arXiv:1808.08865]

Systematics:

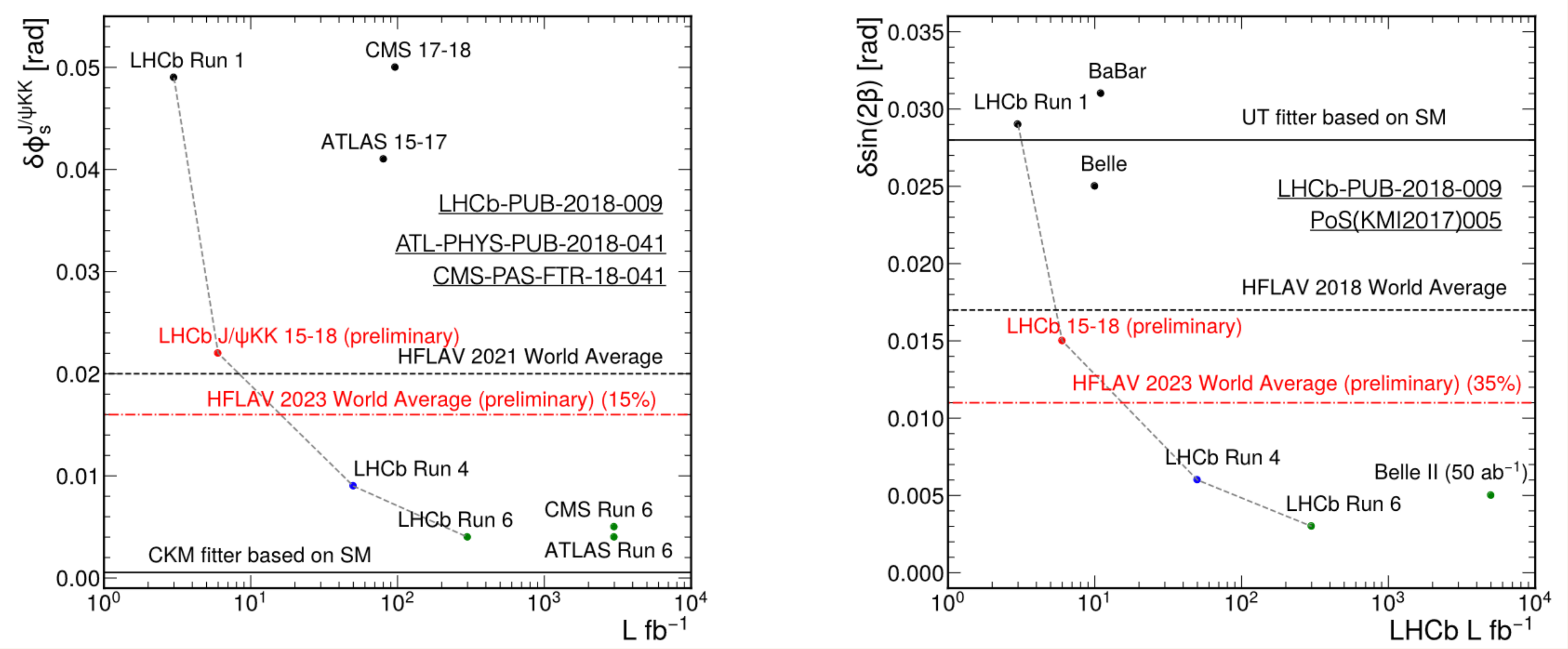
- Mostly depends on size of control samples → scale with statistics
- Important to understand how to take into account $K^0 - \overline{K}^0$ CP violation and nuclear cross-section asymmetry.

Leading sources of systematic uncertainty are different between Belle II and LHCb

Penguins controlled using $B^0 \to J/\psi \pi^0$ and $B_s^0 \to J/\psi K_s^0$

- $B_s^0 \to J/\psi K_s^0$ studied by LHCb [Phys. Rev. Lett. 115 (2015) 031601]
- Belle II expects a good precision for $B^0 \to J/\psi \pi^0$
- Improving ECAL will allow also LHCb to contribute
- Upgrade II will also allow to study other SU(3) related modes

Prospects for $\sin(2\beta)$ and φ_s



CP violation in charm

- Searching for CP violation (CPV) in charm decays is a **stress test to the Standard Model**:
  - **Up-type quark**: complementary to studies in K and B systems
- **Small CP asymmetries expected** $\lesssim 0.1\%$ [Phys.Lett. B222 (1989) 501]
- CPV searched for since decades, **finally observed in 2019 with the ΔA_{CP} measurement** [Phys. Rev. Lett. 122, 211803]!

The raw asymmetry (A) in Cabibbo Suppressed $D^0 \to h^-h^+$ decays ($h = K$ or π) includes both physics and detector effects:

Detection asym. from π^+soft or μ^+

$$A = A(D \to f) = \frac{N(D\to f) - N(\bar{D}\to\bar{f})}{N(D\to f) + N(\bar{D}\to\bar{f})} = \mathbf{A_{CP}} + A_D + A_P$$

Production asym. from D^{*+} or B decays

To eliminate these contributions:

$$\boldsymbol{\Delta A_{CP}} = A(K^+K^-) - A(\pi^+\pi^-) = A_{CP}(K^+K^-) - A_{CP}(\pi^+\pi^-)$$

- Experimentally robust as production and detection asymmetries cancel to first order

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

CP Violation observed @ 5.3σ!

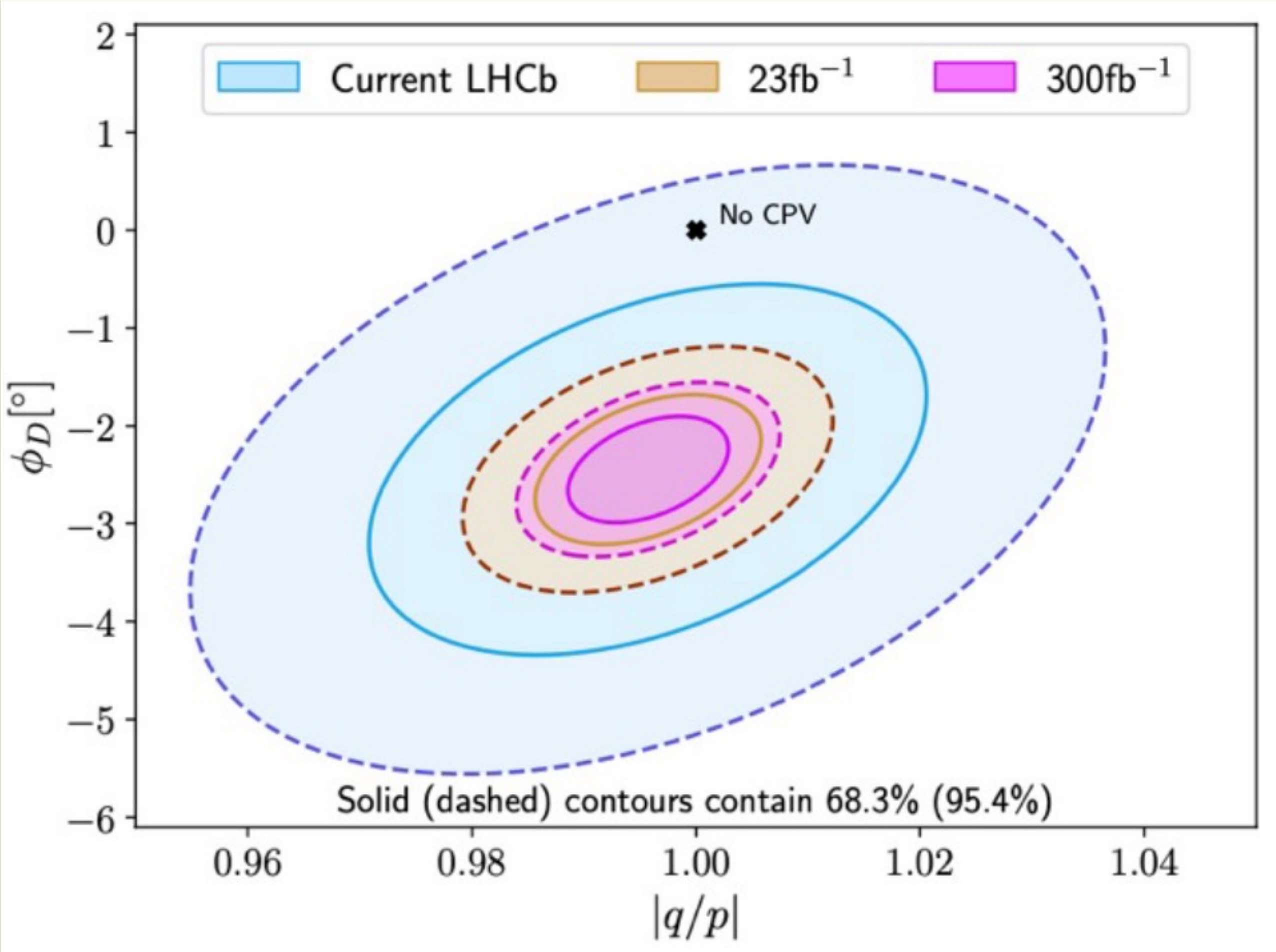
- Additional measurements are needed to have a better understanding!

Prospects for the future III

CP violation in charm

With more data, LHCb has the potential to map the structure of CP violation in the charm system.
Merely scratching the surface now!

LHCb Upgrade II is the only planned facility with a realistic possibility to observe particle anti-particle difference in charm mixing
(at >5σ if present central values are assumed)



[LHCB-PUB-2018-009]

Time integrated CP asymmetry in $D^0 \to K^+K^-$

- Measuring time integrated asymmetries of single channels is much harder, the raw asymmetry must be corrected for using calibration samples to extract the physical asymmetry

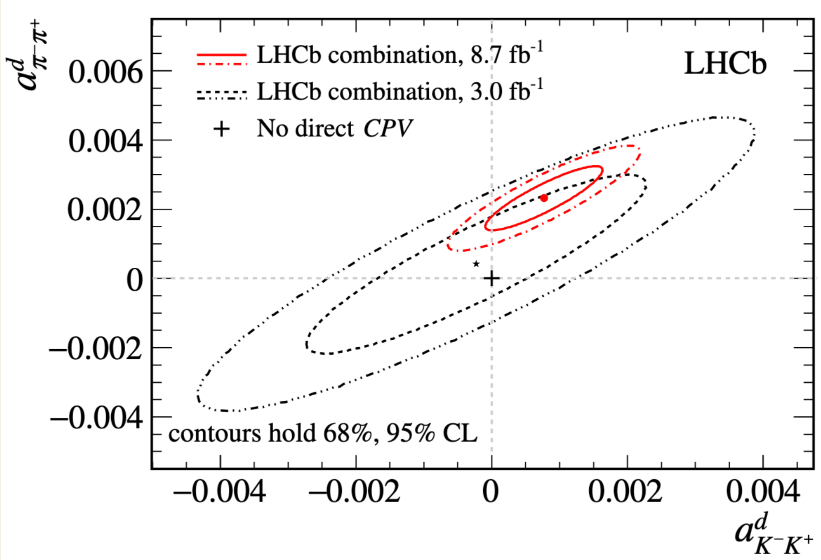
$$A = A\,(D \to f) = \frac{N(D\to f) - N(\bar{D}\to \bar{f})}{N(D\to f) + N(\bar{D}\to \bar{f})} = \mathbf{A_{CP}} + A_D + A_P$$

Detection asymmetry due to the detector

Production asymmetry in pp collisions

- Measurement from LHCb using the full Run2 dataset

$$A_{CP}(K^+K^-) = [6.8 \pm 5.4\ (\text{stat}) \pm 1.6\ (\text{syst})\ ] \times 10^{-4}$$

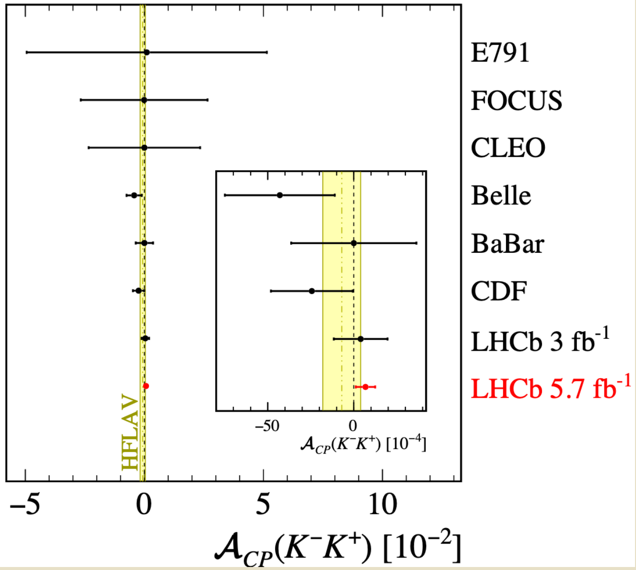


In **combination with ΔA_{CP}**:

$$a^d_{K^+K^-} = (7.7 \pm 5.7)\times 10^{-4} \quad 1.4\sigma$$

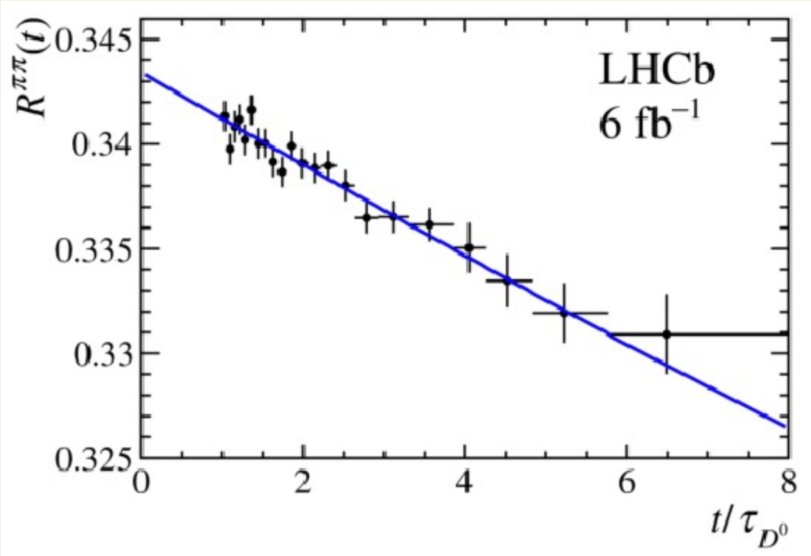
$$a^d_{\pi^+\pi^-} = (23.2 \pm 6.1)\times 10^{-4} \quad 3.8\sigma!$$

CP violation in the decay amplitude

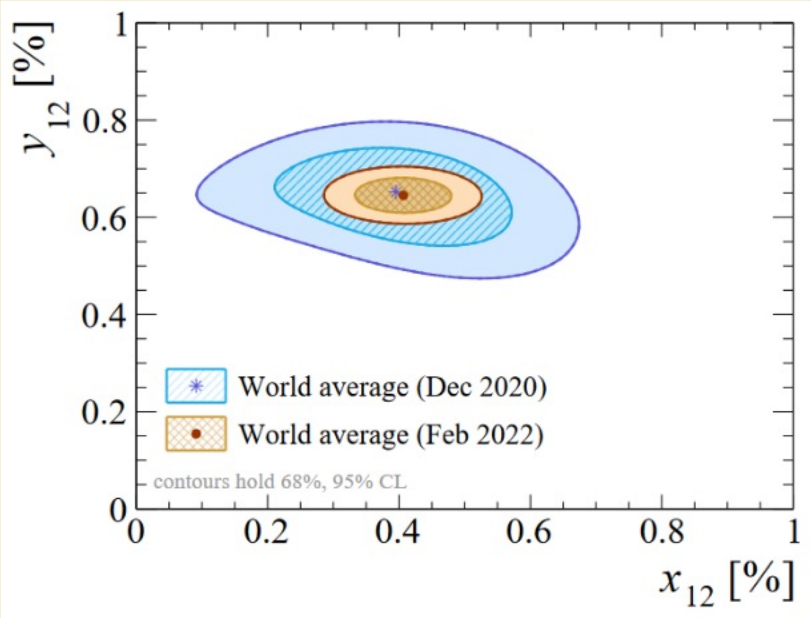


Charm mixing

- Until very recently (2020), no observation yet of charm mixing (extremely difficult).
- New measurement: **precise determination of lifetime difference**
- Study two-body D^0-meson decays
- Decay $D^0 \rightarrow K^-\pi^+$ is a **CP-mixed state**:
  $\tau(D^0 \rightarrow K^-\pi^+) \approx 1/\Gamma$
- Decay $D^0 \rightarrow h^-h^+ (h \in \pi, K)$ is a **CP-even state**:
  $\tau(D^0 \rightarrow h^-h^+) < \tau(D^0 \rightarrow K^-\pi^+)$
- From difference in lifetimes determine
  $\boldsymbol{y} = (\mathbf{6.96} \pm \mathbf{0.26} \pm \mathbf{0.13}) \times \mathbf{10^{-3}}$
- The new world average becomes: $\boldsymbol{y} = (6.46^{+0.24}_{-0.25}) \times \mathbf{10^{-3}}$, improving the previous result by more than a factor of two.



[PRD 105 (2022) 092013]



[PRD 105 (2022) 092013]

The Bd width difference

\ deviation in the value of $\Delta\Gamma_d$ from the SM prediction has recently been proposed as a pc
:xplanation for the anomalous like-sign dimuon charge asymmetry measured by the D0 col
ırXiv:1409.6963 (2014)] [Phys. Rev. D 89, 012002 (2014)].

$$\left|\frac{\Delta\Gamma_d}{\Gamma_d}\right|^{\mathrm{SM}} = (0.42 \pm 0.08)\%$$

[arXiv:1409.6963 (2014)]

DELPHI	$\lvert\Delta\Gamma_d\rvert/\Gamma_d < 18\%$ at 95% CL	[Z. Phys. C76, 579 (1997)]
BaBar	$-6.8\% < \mathrm{sign}(Re_{\lambda_{CP}})\Delta\Gamma_d/\Gamma_d < 8.4\%$	[Phys.Rev.D 70:012007 (2004)]
Belle	$\mathrm{sign}(Re_{\lambda_{CP}})\Delta\Gamma_d/\Gamma_d = (1.7 \pm 1.8 \pm 1.1)\%$	[Phys. Rev. D 85, 071105(R) (2
LHCb	$\Delta\Gamma_d/\Gamma_d = (-4.4 \pm 2.5 \pm 1.1)\%$	[JHEP04 (2014) 114]
ATLAS	$\Delta\Gamma_d/\Gamma_d = (-0.1 \pm 1.1 \pm 0.9)\%$	[JHEP06 (2016) 081]

3oth LHCb and ATLAS measure it comparing the decay time distributions of $B^0 \to J/\psi K_S^0$
$B^0 \to J/\psi K^{*0}$ decays [J. Phys. G 42 (2015) 119501]:

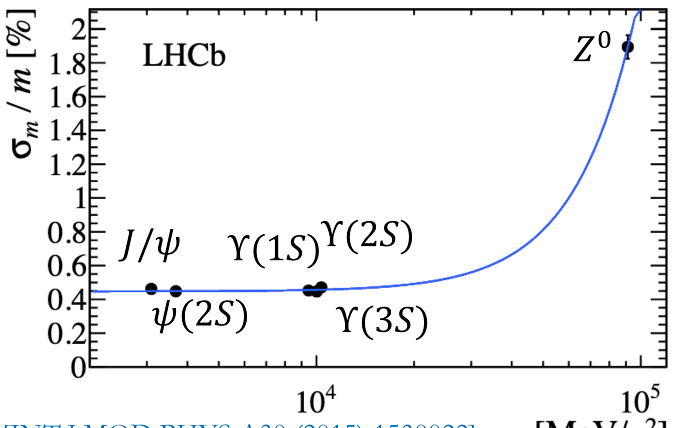
- ATLAS measurement (full Run I) is the most precise measurement from a single exp date;
- LHCb measurement still on a limited data sample (2011 only) $\Rightarrow$ factor 7 in statistics available from 2012 and Run II;

LEPTON FLAVOUR UNIVER SALITY

LEPTONS RECONSTRUCTION @LHCb

MUONS

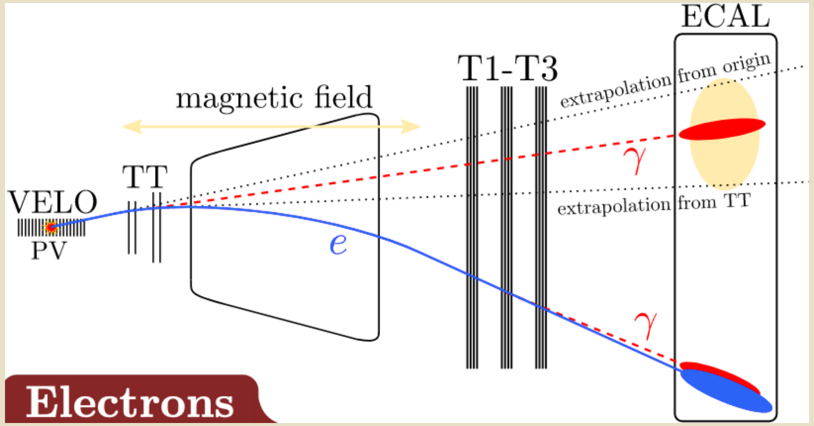
- Dedicated muon chambers
  - Clear trigger and PID
- Very efficient tracking system
- Very good di-muon resolution



[INT.J.MOD.PHYS A30 (2015) 1530022]

ELECTRONS

- Higher occupancy in calorimeter
  - Higher trigger thresholds than for μ
- Bremsstrahlung emission:
  - Degradation of B mass resolution
  - Large partially reconstructed bkg
  - Recovery not 100% efficient



[JINST 14 (2019) P11023]

TAUS

- Missing energy from ν degrading the resolution
- τ vertex not easy to identify in prompt decays
- More background polluting the mass distr.

τ decay	BR(%)
$\tau^+ \to \mu^+(e^+)\nu\nu$	17.39(.82) ± 0.04
$\tau^+ \to \pi^+\nu$	10.82 ± 0.05
$\tau^+ \to \pi^+\pi^0\nu$	25.49 ± 0.09
$\tau^+ \to \pi^+\pi^0\pi^0\nu$	9.26 ± 0.10
$\tau^+ \to \pi^+\pi^+\pi^-\nu$	9.31 ± 0.05
$\tau^+ \to \pi^+\pi^+\pi^-\pi^0\nu$	4.62 ± 0.05

Measurement of $R_{K_S^0}$

- Decay used: $B^0 \to K_S^0 \ell^+ \ell^-$
- Measured in $q^2 \in [1.1, 6.0\ \mathrm{GeV}^2/c^4]$
- Using Run1 + Run 2, but still statistically limited
- Biggest systematic: simulation size ~2-3%

Validation

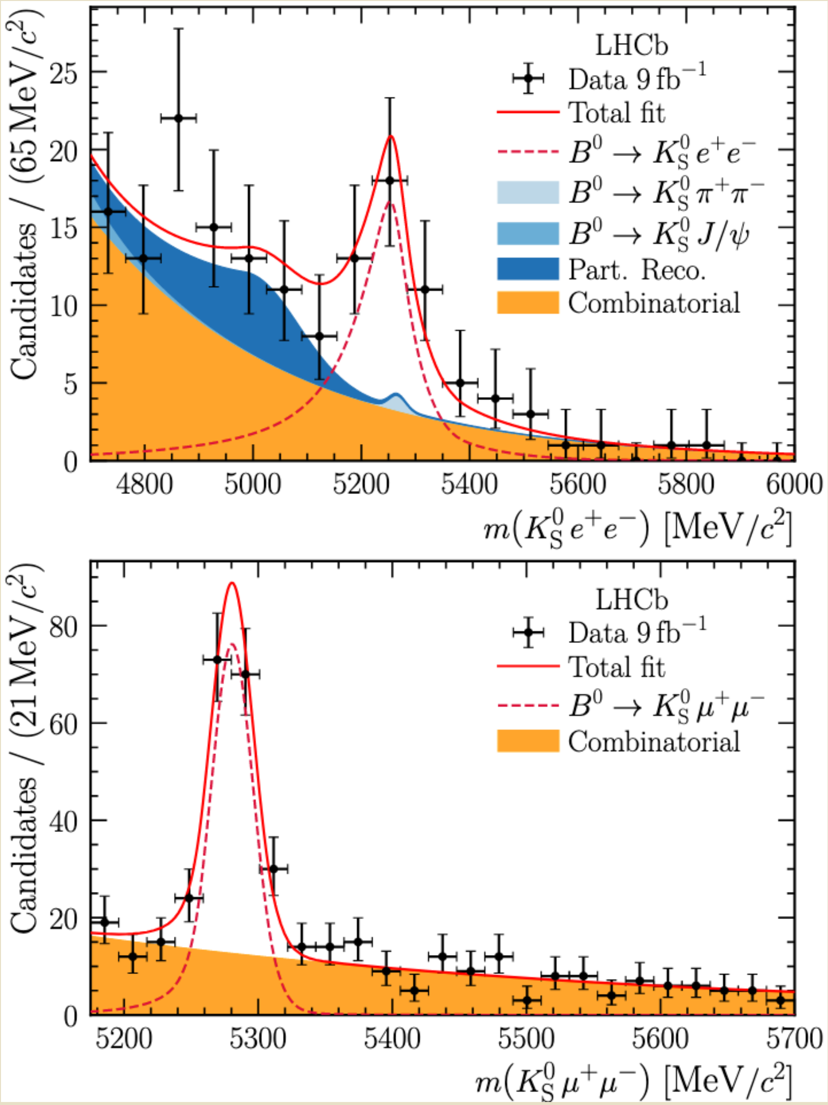
- $r_{J/\psi}^{-1} = 0.977 \pm 0.008\ (\mathrm{stat}) \pm 0.027\ (\mathrm{syst})$
- $R_{\psi(2S)}^{-1} = 1.014 \pm 0.030\ (\mathrm{stat}) \pm 0.020\ (\mathrm{syst})$

Result

- $\boldsymbol{R_{K_S^0} = 0.66^{+0.20}_{-0.14}(\mathrm{stat})^{+0.02}_{-0.04}\ (\mathrm{syst})}$
- Agreement with SM at **1.5σ** level

[PRL 128, 19 (2022)]

First observation of rare electron mode



Measurement of R_{pK}

- Decay used: $\Lambda_b \to pK^- \ell^+ \ell^-$
- Measured in $q^2 \in [0.1, 6.0\ \text{GeV}^2/c^4]$ and $m(pK^-) < 2600\ \text{MeV}/c^2$
- Using Run 1+2016, still statistically limited
- Biggest systematic: fit model ~5%

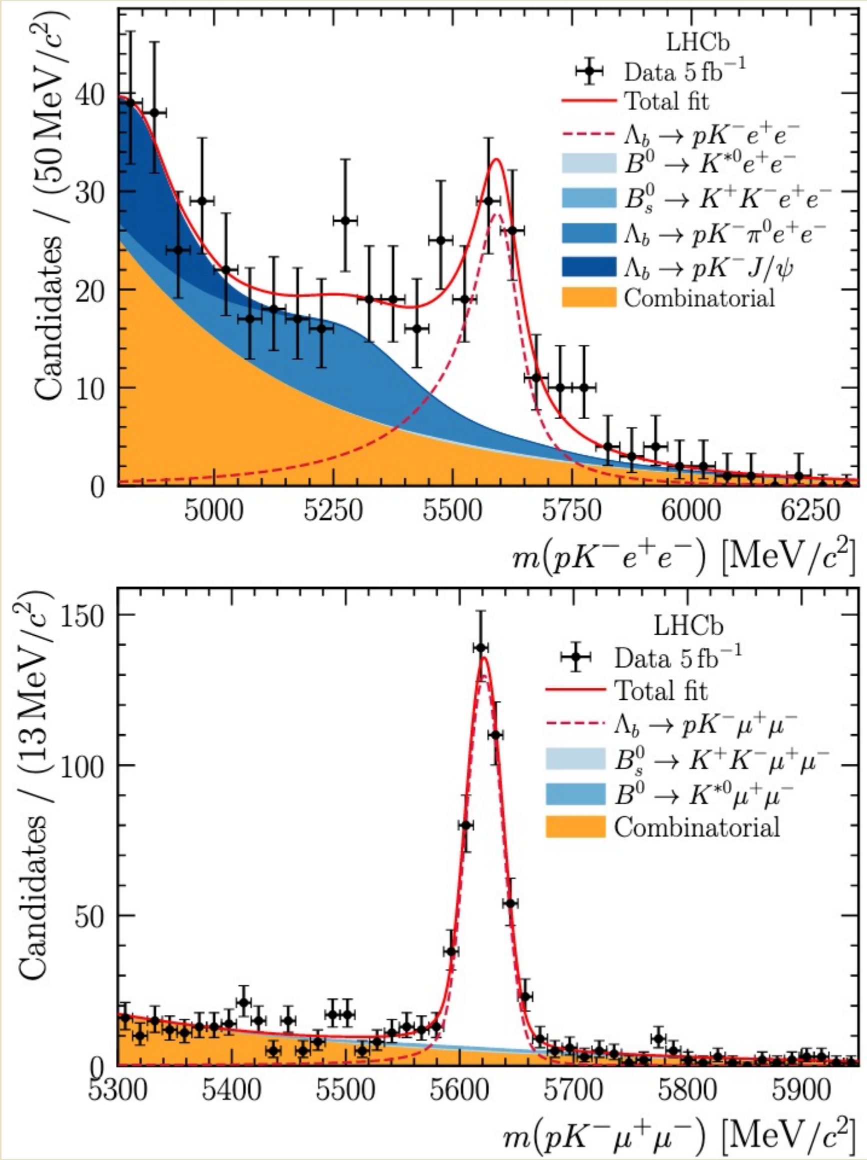
Validation

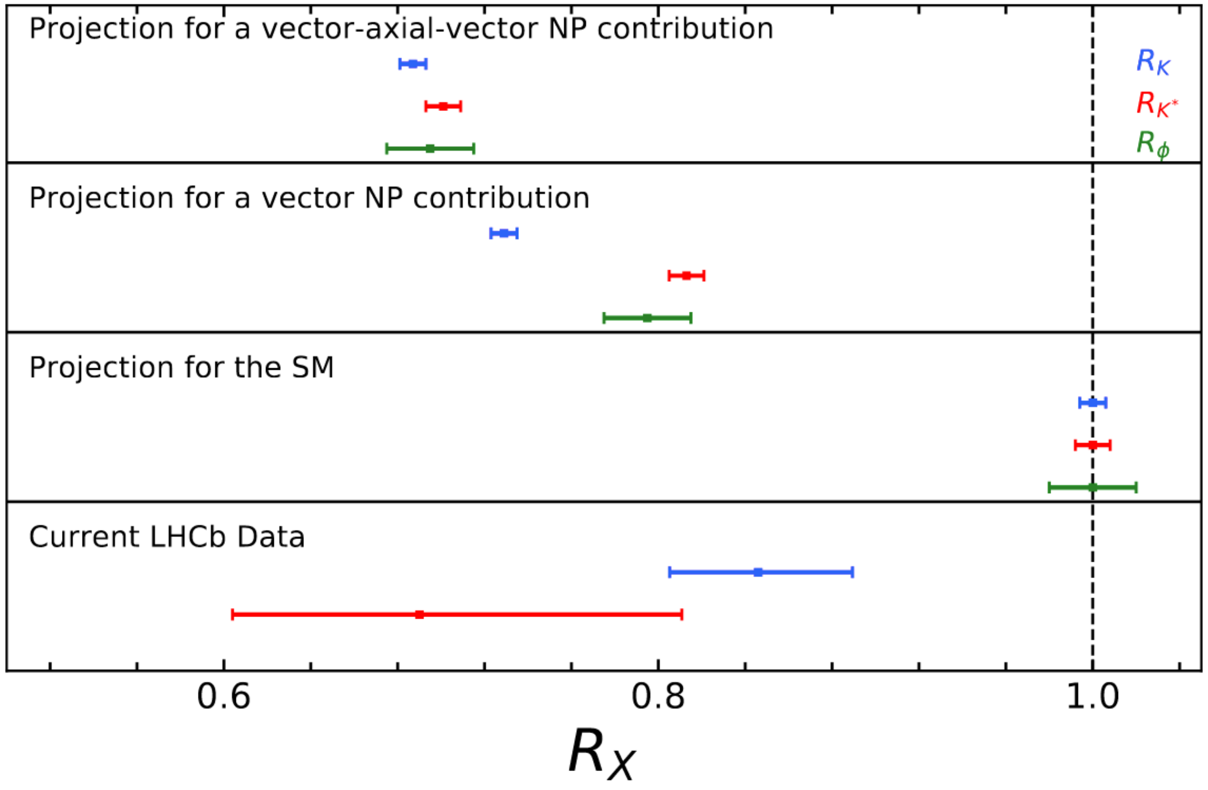
- $r_{J/\psi}^{-1} = 0.96 \pm 0.05$ (stat $\oplus$ syst)
- $R_{\psi(2S)}$ compatible with unity whitin 1σ

Result

- $\boldsymbol{R_{pK} = 0.86^{+0.14}_{-0.11}(\text{stat}) \pm 0.05(\text{syst})}$
- Agreement with SM at **<1σ** level

[JHEP 05, 040 (2020)]





[LHCb Upgrade II TDR]

Future prospects

- Precision on $\boldsymbol{R_K}$ **and** $\boldsymbol{R_{K^{*0}}}$ will be **~2.5% and 2% with ~23 fb^{-1} and ~50 fb^{-1}**
- Projected sensitivity with the LHCb **Upgrade II** detector, with ~300 fb^{-1}
- Huge samples of rare electron modes available in Upgrade II $N_{K^+e^+e^-}$~46 000, $N_{K^{*0}e^+e^-}$~20 000
- Ultimate precision on $\boldsymbol{R_K}$ **and** $\boldsymbol{R_{K^{*0}}}$ **will be better than 1%**

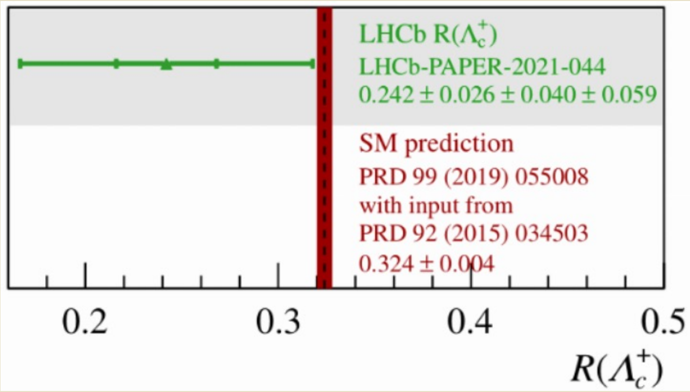
[LHCb Upgrade Physics Document]
PUB-2018-009

Current experimental status $R(\Lambda_c^+)$

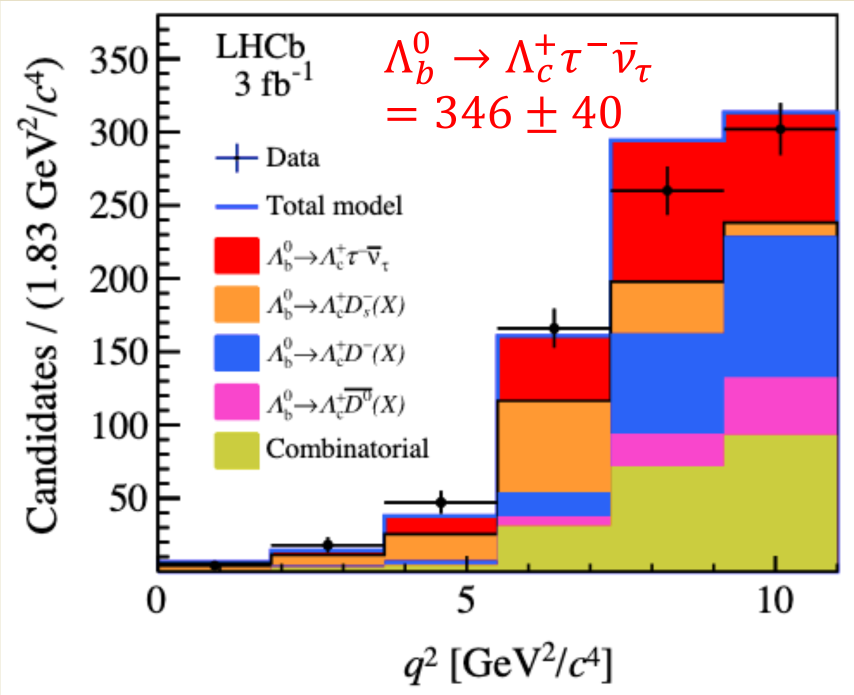
LHCb has performed analysis of

$$R(\Lambda_c^+) = \frac{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ \tau^- \bar{\nu}_\tau)}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ \mu^- \bar{\nu}_\mu)}$$

- First **LFU test** in a **baryonic** $b \to c\ell\nu$ decay
  - Initial state spin ½ → could couple to different physics beyond the SM
- With **3-prong hadronic** $\tau^- \to \pi^+\pi^-\pi^-(\pi^0)\nu_\tau$ using Run 1: $\boldsymbol{R(\Lambda_c^+) = 0.242 \pm 0.026(\text{stat}) \pm 0.040(\text{syst}) \pm 0.059(\text{ext})}$*
  [PRL 128, 191803 (2022)]
- To be compared with the SM prediction: $R(\Lambda_c^+) = 0.324 \pm 0.004$
  [PRD 99, 055008 (2019)]



Agreement with SM within 1σ



First observation of $\Lambda_b^0 \to \Lambda_c^+ \tau^- \bar{\nu}_\tau$ with 6σ significance

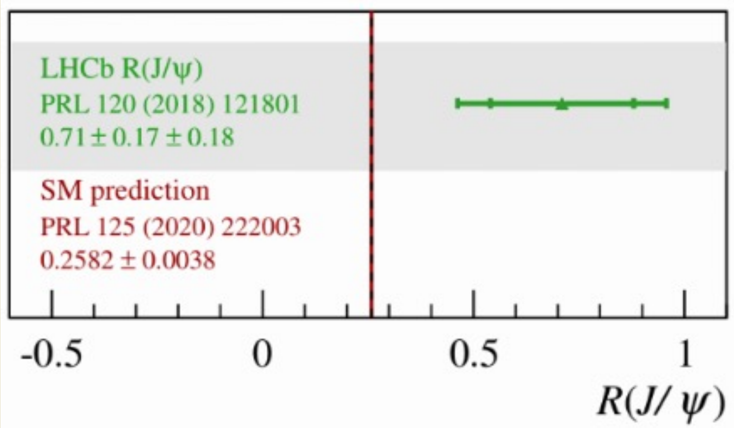
* Measured relative to $\Lambda_b^0 \to \Lambda_c^+ 3\pi$

Current experimental status $R(J/\psi)$

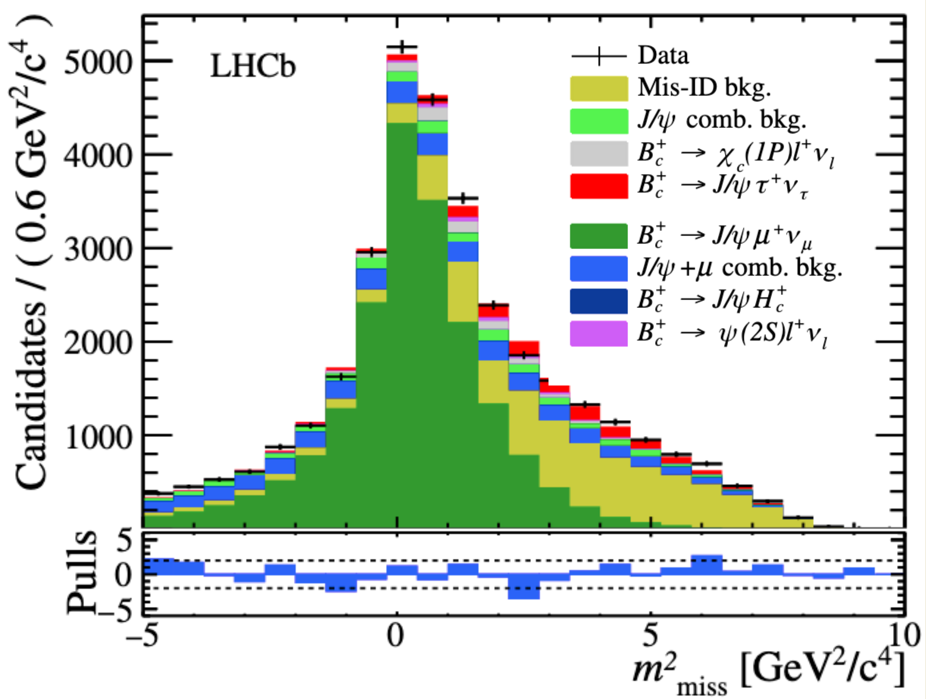
LHCb has performed analysis of

$$R(J/\psi) = \frac{\mathcal{B}(B_c^+ \to J/\psi\tau^+\nu_\tau)}{\mathcal{B}(B_c^+ \to J/\psi\mu^+\nu_\mu)}$$

- With **muonic** $\tau^+ \to \mu^+\nu_\mu\bar{\nu}_\tau$ using Run 1:
  $\boldsymbol{R(J/\psi) = 0.71 \pm 0.17(\text{stat}) \pm 0.18(\text{syst})}$
  [PRL 120, 121801 (2018)]
- To be compared with the SM prediction: $R(J/\psi) = 0.2582 \pm 0.0038$
  [PRL 125, 222003 (2020)]



2σ above the SM



$\boldsymbol{B_c^+ \to J/\psi\tau^+\nu_\tau = 1400 \pm 300}$

Observation of $B_c^+ \to J/\psi\tau^+\nu_\tau$ with 3σ significance accounting also for systematics

LFU TESTS

To **0.28%** in Z decays

$$\frac{\Gamma_{Z\to\mu\mu}}{\Gamma_{Z\to ee}} = 1.0009 \pm 0.0028$$

LEP, Phys. Rept. 427 (2006) 257

$$\frac{\Gamma_{Z\to\tau\tau}}{\Gamma_{Z\to ee}} = 1.0019 \pm 0.0032$$

LEP, Phys. Rept. 427 (2006) 257

To **0.8%** in W decays

$$\frac{\mathcal{B}(W\to e\nu)}{\mathcal{B}(W\to \mu\nu)} = 1.004 \pm 0.008$$

CDF + LHC, JPG: NPP, 46, 2 (2019)

$$\frac{\Gamma_{W\to\tau\nu}}{\Gamma_{W\to\mu\nu}} = 0.992 \pm 0.013$$

ATLAS, Nature 17, 813 (2021)

To **0.2%** in meson decays

$$\frac{\Gamma_{J/\psi\to\mu\mu}}{\Gamma_{J/\psi\to ee}} = 1.0016 \pm 0.0031$$

PDG (BESIII), RPP, Chin. Phys. C40 (2016) 100001

$$\frac{\Gamma_{\pi\to e\nu}}{\Gamma_{\pi\to\mu\nu}} = (1.234 \pm 0.003) \times 10^{-4}$$

PiENu, Phys. Rev. Lett. 115, 071801 (2015)

$$\frac{\Gamma_{D_s\to\tau\nu}}{\Gamma_{D_s\to\mu\nu}} = 9.95 \pm 0.61$$

HFLAV, Eur. Phys. J. C77 (2017) 895

$$\frac{\Gamma^{1.1-6}_{B\to K^+\mu\mu}}{\Gamma^{1.1-6}_{B\to K^+ee}} = R_K = 0.95 \pm 0.05$$

LHCb, PRL 131, 051803 (2023)

To **0.14%** in $\tau \to \ell\nu\nu$

$$g_\mu/g_e = 1.0018 \pm 0.0014$$

PDG, A. Pich, Prog. Part. Nucl. Phys. 75 (2014) 41

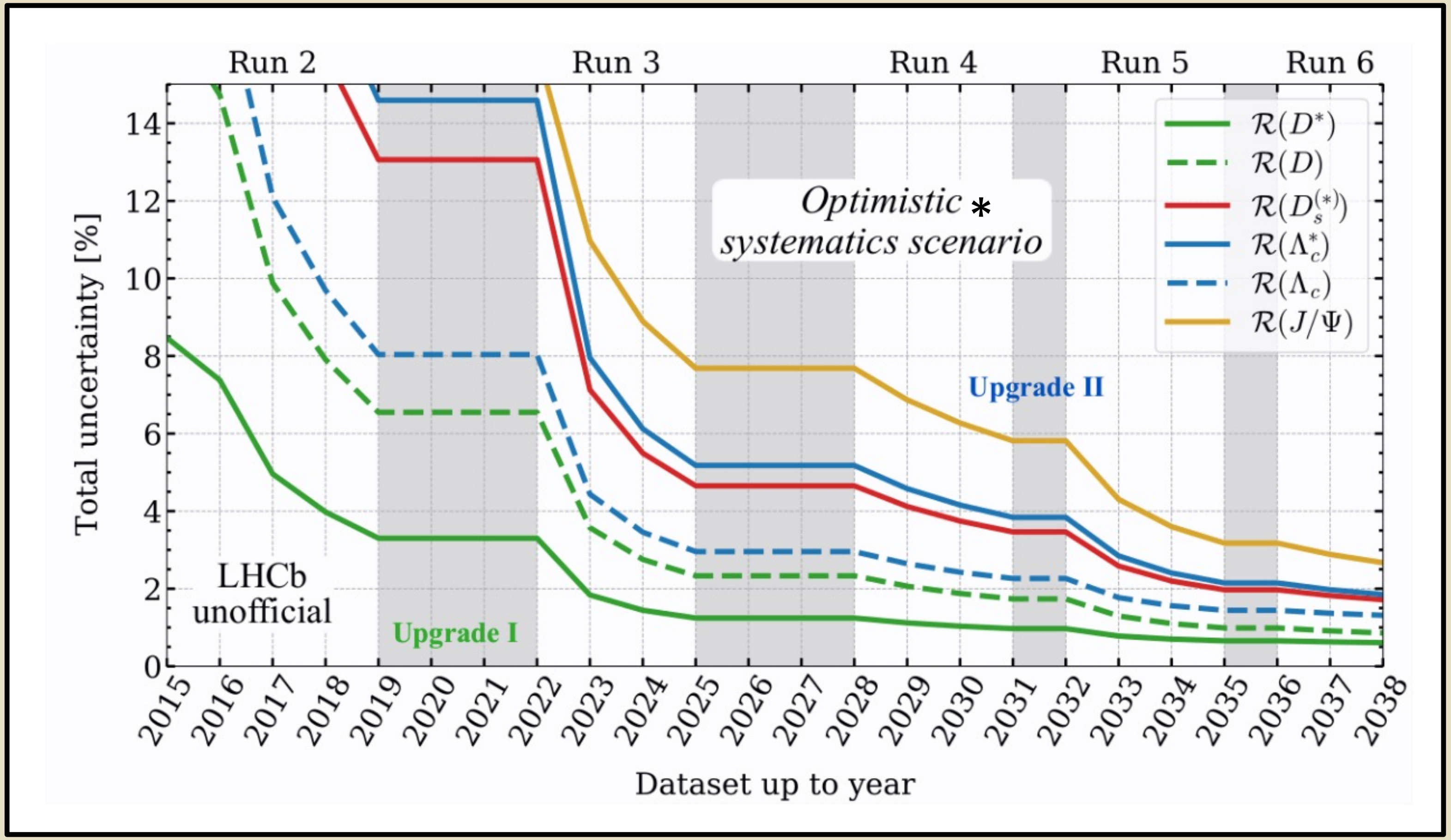
$$g_\tau/g_\mu = 1.0030 \pm 0.0015$$

PDG, S. Pich, Prog. Part. Nucl. Phys. 75 (2014) 41

Prospects

LHCb plans to include also:

- $R(D^+)$
- $R(D^*) - (e - \mu)$
- Combined $R(D^*) - R(D^0)$
- $R(D^{**})$
- $R(D_s^*)$
- $R(\Lambda_c^{**})$



[Rev. Mod. Phys. 94, 015003][arXiv:1808.08865]

- Exploring new observables beyond the branching fraction ratios, e.g. **angular observables** to determine spin structure of potential new physics

* Irreducible systematic uncertainty of 0.5% on $R(D^{(*)})$ and 2% on the other ratios

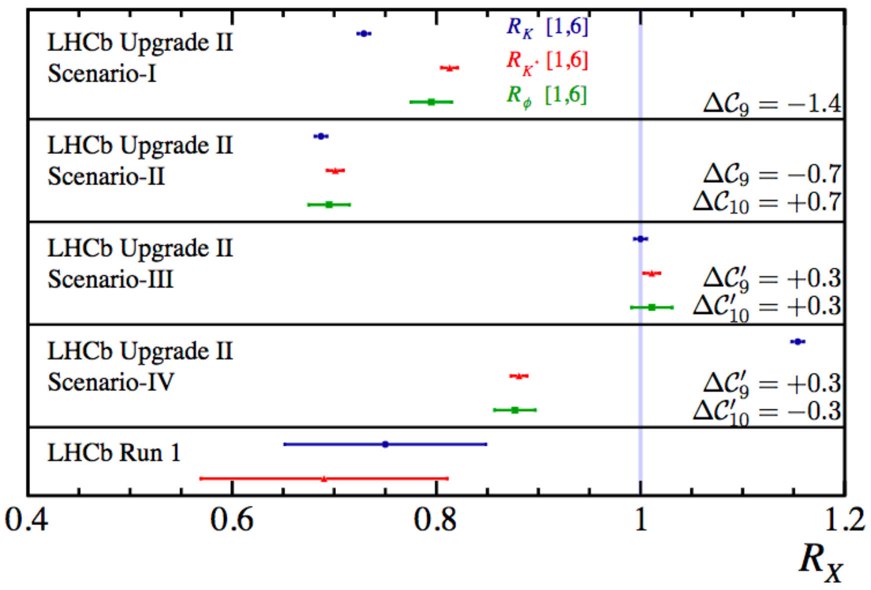
B-anomalies and neutrino interplay

- **Impact of lepton flavour universality violation on CP violation sensitivity of long baseline neutrino oscillation experiments** [https://arxiv.org/abs/1701.00327]
- **Combined explanations of B-physics anomalies: the sterile neutrino solution** [https://arxiv.org/abs/1807.10745]
- **Anomalies in (semi)-leptonic *B* decays and possible resolution with sterile neutrino** [https://arxiv.org/abs/1702.04335]
- **Leptoquarks in Flavour Physics and the anomalous magnetic moment of the muon** [https://arxiv.org/abs/1801.03380]
- **Synergy and complementarity between neutrino physics and low-energy intensity frontiers** [https://arxiv.org/abs/1712.05947]
- **B-physics anomalies: a guide to combined explanations** [https://arxiv.org/abs/1706.07808]
- **And many more!**

Upgrade II expectations for $R(K^{(*)})$

Nominal NP scenario

Right-handed components



Expected yields

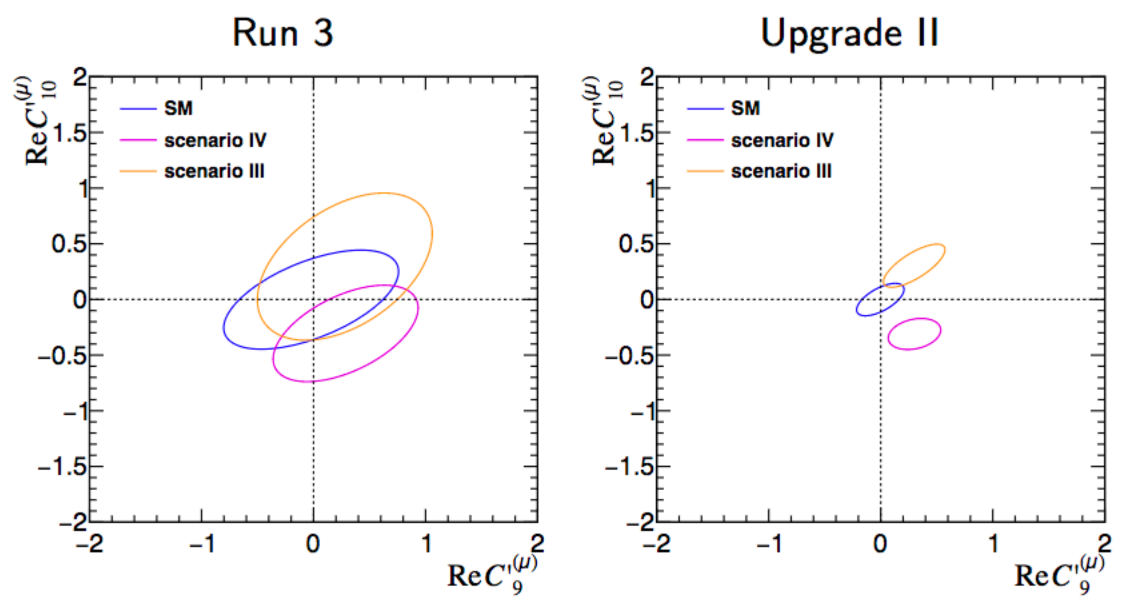
Yield	Run 1 result	$9\,\text{fb}^{-1}$	$23\,\text{fb}^{-1}$	$50\,\text{fb}^{-1}$	$300\,\text{fb}^{-1}$
$B^+ \to K^+e^+e^-$	254 ± 29 [272]	1 120	3 300	7 500	46 000
$B^0 \to K^{*0}e^+e^-$	111 ± 14 [273]	490	1 400	3 300	20 000
$B^0_s \to \phi e^+e^-$	–	80	230	530	3 300
$\Lambda^0_b \to pKe^+e^-$	–	120	360	820	5 000
$B^+ \to \pi^+e^+e^-$	–	20	70	150	900
R_X precision	Run 1 result	$9\,\text{fb}^{-1}$	$23\,\text{fb}^{-1}$	$50\,\text{fb}^{-1}$	$300\,\text{fb}^{-1}$
R_K	$0.745 \pm 0.090 \pm 0.036$ [272]	0.043	0.025	0.017	0.007
$R_{K^{*0}}$	$0.69 \pm 0.11 \pm 0.05$ [273]	0.052	0.031	0.020	0.008
R_ϕ	–	0.130	0.076	0.050	0.020
R_{pK}	–	0.105	0.061	0.041	0.016
R_π	–	0.302	0.176	0.117	0.047

Expected R_X uncertainties

[LHCb Upgrade Physics Document]
PUB-2018-009 (in preparation)

- Huge samples of rare electron modes available in Upgrade II $N_{K^+e^+e^-}\sim$46 000, $N_{K^{*0}e^+e^-}\sim$20 000
- Ultimate precision on R_{K,K^*} will be better than 1%
- Different R_X allow to probe different combinations of Wilson coefficients, separation of NP scenarios possible!
- Projections don't include improved ECAL for Upgrade II

Upgrade II sensitivity with $B^0 \to K^{*0}\mu^+\mu^-$



Scenario	C'_9	C'_{10}
SM	0	0
III	+0.3	+0.3
IV	+0.3	-0.3

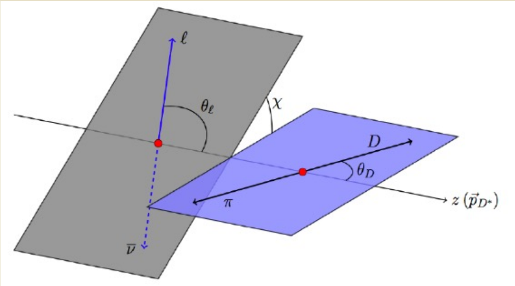
[LHCb Upgrade Physics Document]
PUB-2018-009 (in preparation)

- Expect ~440 000 $B^0 \to K^{*0}\mu^+\mu^-$ candidates in Upgrade II (roughly Run 1 statistics for tree-level charmonia modes)
- Allows for determination of angular observables with unprecedented precision
- Different NP scenarios can be cleanly separated
- q^2-unbinned approaches allow to better exploit the data [JHEP 11 (2017) 176]

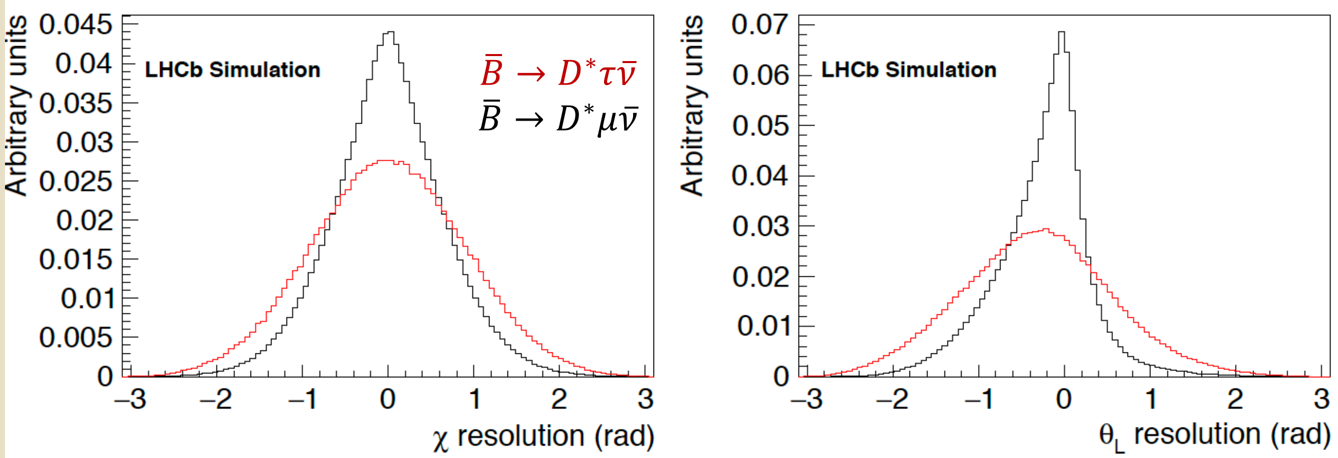
Upgrade II prospects

Upgrade II: new observables beyond the BF ratio

- Expect O(10 M) $\bar{B} \to D^{(*)}\tau\bar{\nu}$ candidates
- Sensitivity Upgr. II: $\sigma(R_{D^*})/\ R_{D^*} \sim 1\%$
- Angular analysis would allow to determine spin structure of potential NP contribution



- Kinematics of $\bar{B} \to D^{(*)}\tau\bar{\nu}$ fully described by dilepton mass, and three angles, χ, θ_L and θ_d (better resolution)



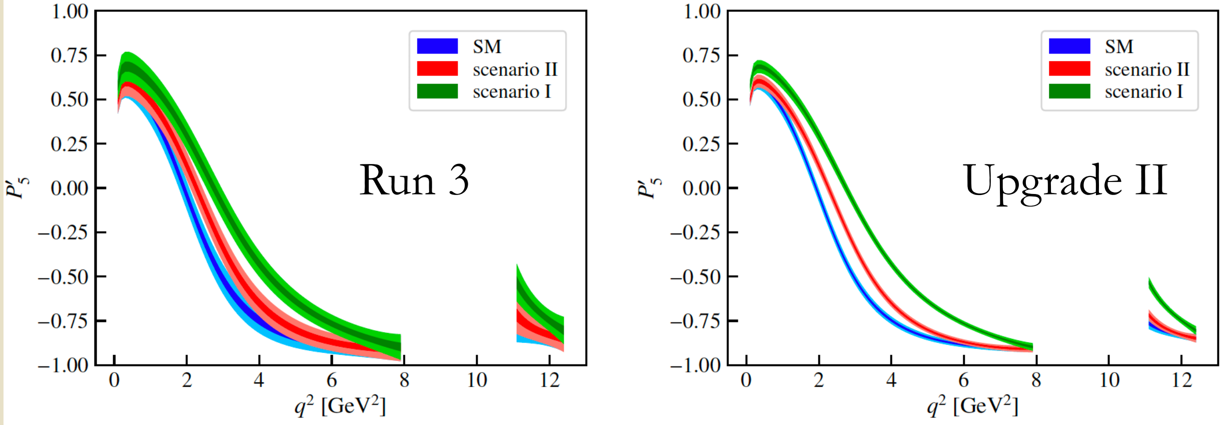
Upgrade II: exploit other b-hadron species

- $\overline{B_s^0} \to D_s^{(*)+}\tau^-\bar{\nu}$: 6% (2.5%) relat. unc. after Run 3 (Upgrade II)
- Semitauonic decays of b-baryons and of B_c^+ mesons
  - $R(\Lambda_c^+)$ 4% (2.5%) relat. unc. after Run 3 (Upgrade II)

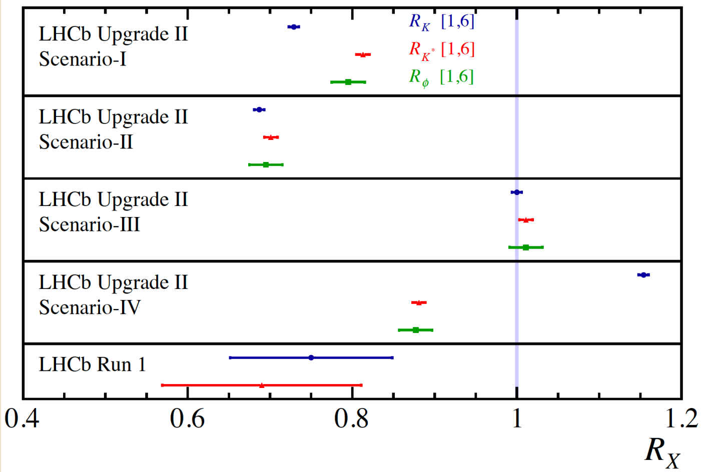
FCNC transitions

scenario	C_9^{NP}	C_{10}^{NP}	C'_9	C'_{10}
I	-1.4	0	0	0
II	-0.7	0.7	0	0
III	0	0	0.3	0.3
IV	0	0	0.3	-0.3

- LFU will play a large role in Upgrade II physics case
- Improvements: Reduce the material (e.g. RF-foil), improve ECAL granularity, better Brem recovery algorithms
- Upgrade II: 440k fully reconstructed $B^0 \to K^{*0}\mu^+\mu^-$ will allow a q^2-unbinned approach ⇒ probe the SM contributions, NP expected to have no q^2 dependence
- Compare angular distr. $B^0 \to K^{*0}e^+e^- / B^0 \to K^{*0}\mu^+\mu^-$



- Upgrade will provide thousands of $b \to d\ell^+\ell^-$ decays (e.g. 4300 $B_s^0 \to K^{*0}\mu^+\mu^-$), angular analysis possible
- 45k $B^+ \to K^+e^+e^-$ and 20k $B^0 \to K^{*0}e^+e^-$ in the Upgrade II → **Ultimate precision on $R_{K^{(*)}}$<1%**
- $R_\varphi, R_{pK}, R_\pi, \ldots$ will be possible un Upgrade II



All four NP scenarios could be distinguished at more than 5σ in Upgrade II!

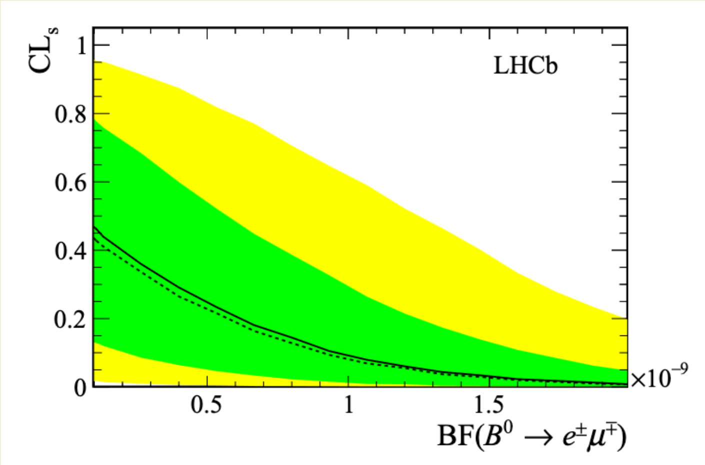
LEPTON FLAVOUR NUMBER VIOLATION

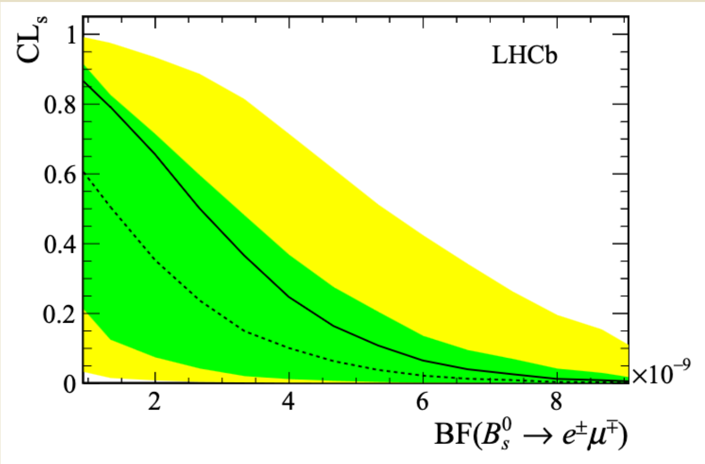
$B_s^0 \to e^\pm\mu^\pm$ and $B^0 \to e^\pm\mu^\pm$ decay

- Run 1 analysis, the observed yields are consistent with the background-only hypothesis.
- Upper limits on the branching fractions are determined at 95% C.L.

$$\mathcal{B}(B_s^0 \to e^\pm\mu^\mp) < 6.3\,(5.4) \times 10^{-9}$$
$$\mathcal{B}(B^0 \to e^\pm\mu^\mp) < 1.3\,(1.0) \times 10^{-9}$$

- The upper limit on the B0s decay is evaluated in two extreme hypotheses: where the amplitude is completely dominated by the heavy eigenstate or by the light eigenstate.
- At the end of the Upgrade I data taking period the LHCb experiment will be able to probe branching fractions of B0s → e±μ∓ and B0 → e±μ∓ decays down to 8×10^{-10} and 2×10^{-10}, respectively.
- The additional samples accumulated during the Upgrade II data taking period will push down these limits to 3×10^{-10} and 9×10^{-11}





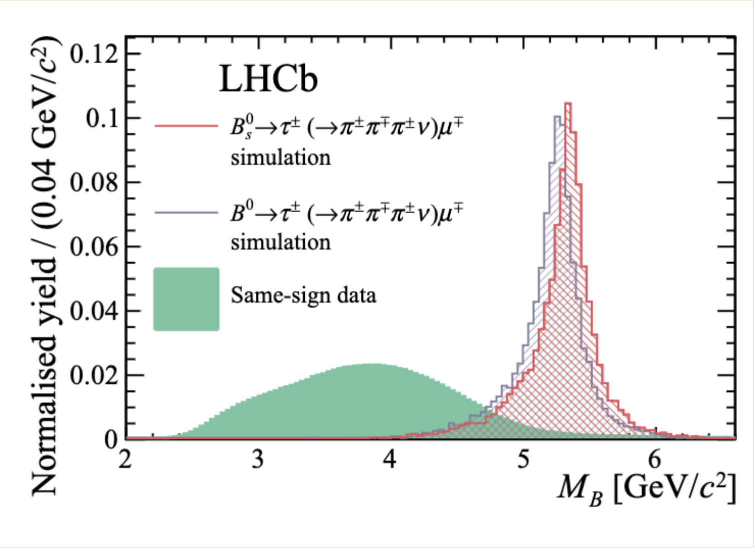
[JHEP 1803 (2018) 078]

$B_s^0 \to \tau^\pm\mu^\pm$ and $B^0 \to \tau^\pm\mu^\pm$ decay

- Run 1 analysis, the observed yields are consistent with the background-only hypothesis. Tau lepton reconstructed in $\tau^- \to \pi^-\pi^+\pi^-\nu_\tau$
- Upper limits on the branching fractions are determined at 95% C.L.

$$\mathcal{B}\left(B_s^0 \to \tau^\pm\mu^\mp\right) < 4.2 \times 10^{-5}$$
$$\mathcal{B}\left(B^0 \to \tau^\pm\mu^\mp\right) < 1.4 \times 10^{-5}$$

- A wide variety of Beyond Standard Model (BSM) scenarios predict the occurrence of lepton-flavour violating B decays, **with the highest rates where third generation leptons are involved**, such as $B_{(s)}^0 \to \tau^\pm\mu^\pm$. For different models, not excluded by the current experimental constraints, the expected branching fraction is in the range $10^{-9} - 10^{-4}$
- The Upgrade II LHCb could read $B^0 \to \tau^\pm\mu^\pm < 3 \times 10^{-7}$ at 90% CL



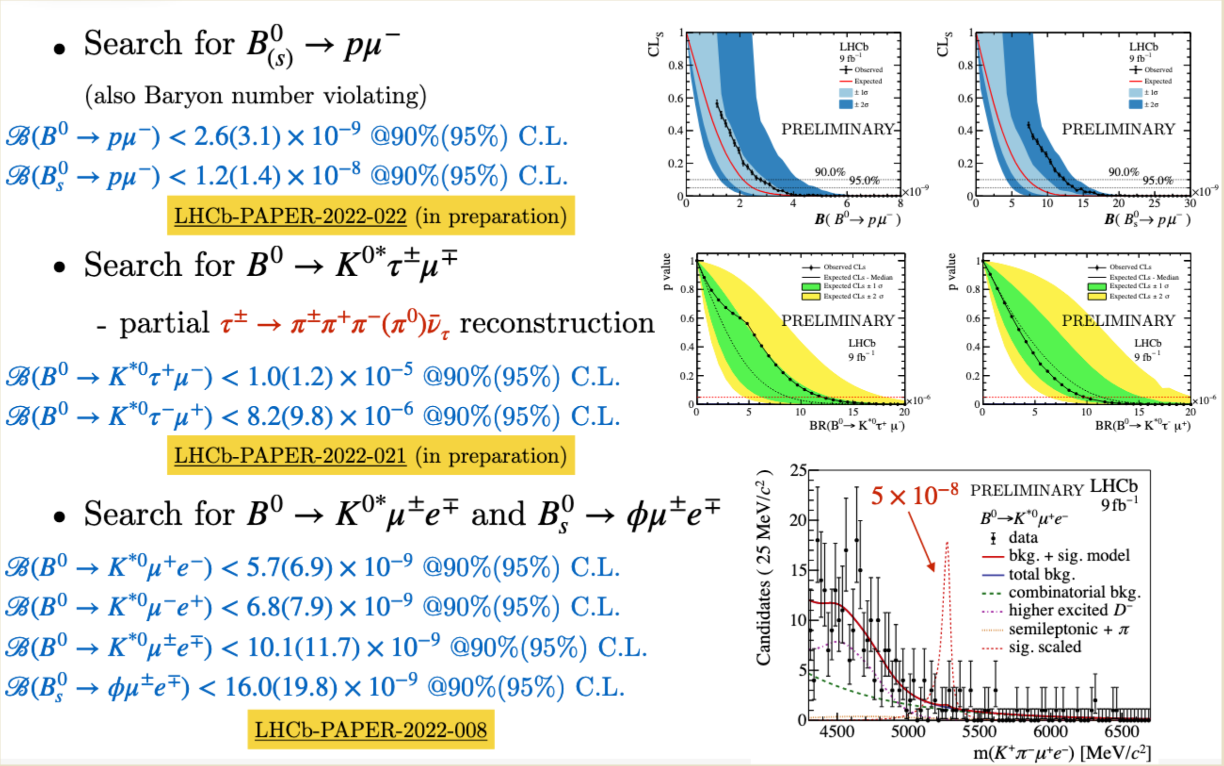
Phys. Rev. Lett. 123 (2019) 211801

Lepton flavour (number) violation

- LFV branching fractions enhanced to 10^{-11} in certain models of leptoquarks, Z' [Medeiros Varzielas, Hiller, JHEP 06 (2015) 072]
- LHCb was the first experiment to search for LFV τ decays in a hadron collider

Searches for $B \to Ke\mu, B \to K^{*0}\tau(\to \pi\pi\pi\nu)\mu$, $B \to K\tau(\to \pi\pi\pi\nu)\mu$ and $\Lambda_b^0 \to \Lambda^0 e\mu$ are ongoing

- Using Run1 + Run2 data expects limits $\mathcal{O}(10^{-9})$ and $\mathcal{O}(10^{-6})$ for $B \to Ke\mu$ and $B \to K^{*0}\tau\mu$, respectively
- Complementary as charged lepton FV couplings among different families are expected to be different
- Multi-body final states: allow the measurement of more observables



Lepton flavour (number) violation

7.2.4 Search for $\tau^+ \to \mu^+\mu^-\mu^+$ decays

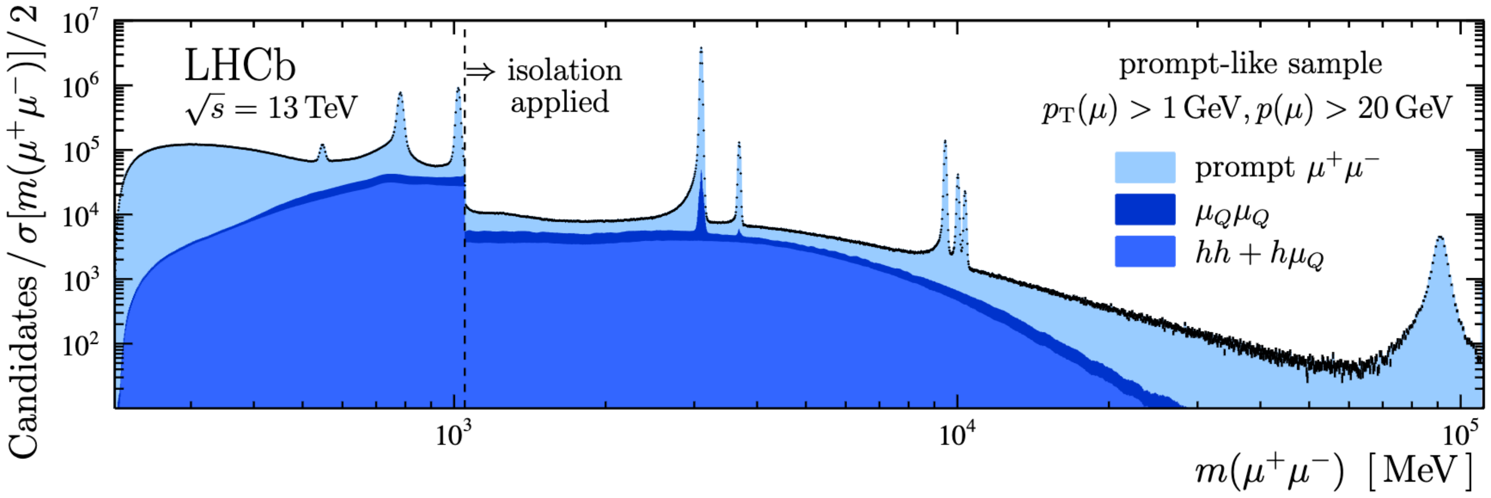
An important test of the SM is the search for the lepton-flavour-violating process $\tau^\pm \to \mu^\pm\mu^+\mu^-$. Within the SM with zero neutrino masses this process is strictly forbidden. Depending on the mechanism of neutrino mass generation, many theories [293–296] beyond the SM predict this branching ratio to be in the region $(10^{-9} - 10^{-8})$. The current experimental limit [297–299], $\mathcal{B}(\tau^\pm \to \mu^\pm\mu^+\mu^-) < 1.2 \times 10^{-8}$, is a combination of the results from LHCb and the B Factories and reaches the starting point of this range. Belle II will probe this interesting region of sensitivity when accumulating up to 50 ab^{-1}. The LHC proton collisions at 13 TeV produces τ leptons, primarily in the decay of heavy flavour hadrons, with a cross-section five orders of magnitude larger than at Belle II. This compensates for the higher background levels and lower integrated luminosity, and means that during the Upgrade II LHCb would also be able to probe down to $\mathcal{O}(10^{-9})$, and independently confirm any Belle II discovery or significantly improve the combined limit. In addition, the proposed improvements to the LHCb calorimeter during the Upgrade II will be helpful in suppressing backgrounds such as $D_s^+ \to \eta(\to \mu^+\mu^-\gamma)\mu^+\nu_\mu$, enabling LHCb to make best use of its statistical power.

DARK PHOTONS AND LONG LIVED OBJECTS

Visible dark photon in $\ell\ell$

Phys. Rev. Lett. 120, 061801 (2018)

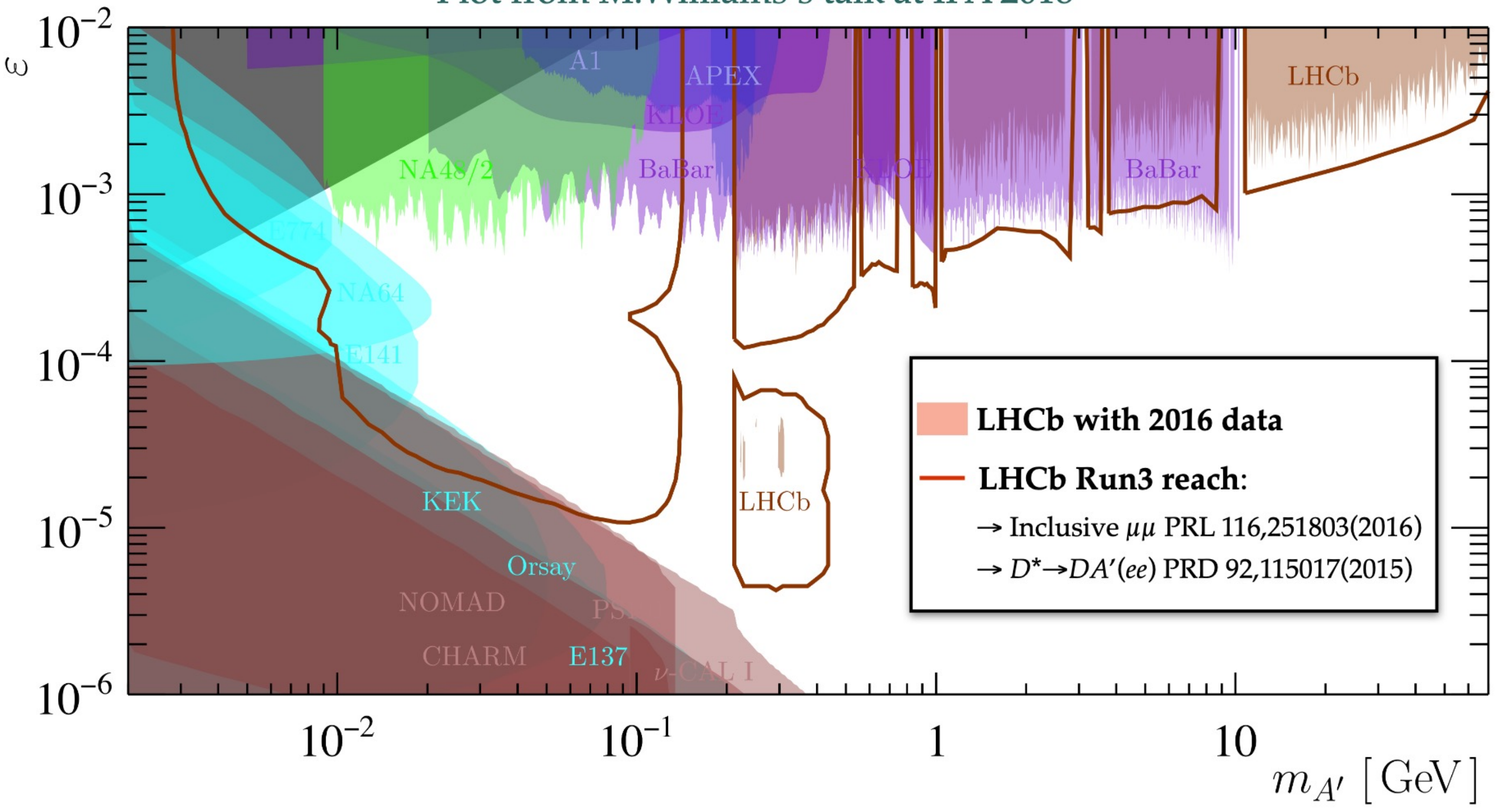
- Signature:
  - Inclusive $\mu\mu$ (prompt or displaced)
  - Sensitive down to $2\,m_\mu$
- Trigger:
  - Hardware $p_T(\mu)$ cut ~1.8 GeV
  - Real-time analysis including μ-ID allows to avoid prescale
- Analysis:
  - Template fit to separate prompt dimuons from heavy-flavour
  - Bump search on top of γ^* background (auto-normalising)
  - Displaced analysis at low mass is almost free of background



Visible dark photon in $\ell\ell$

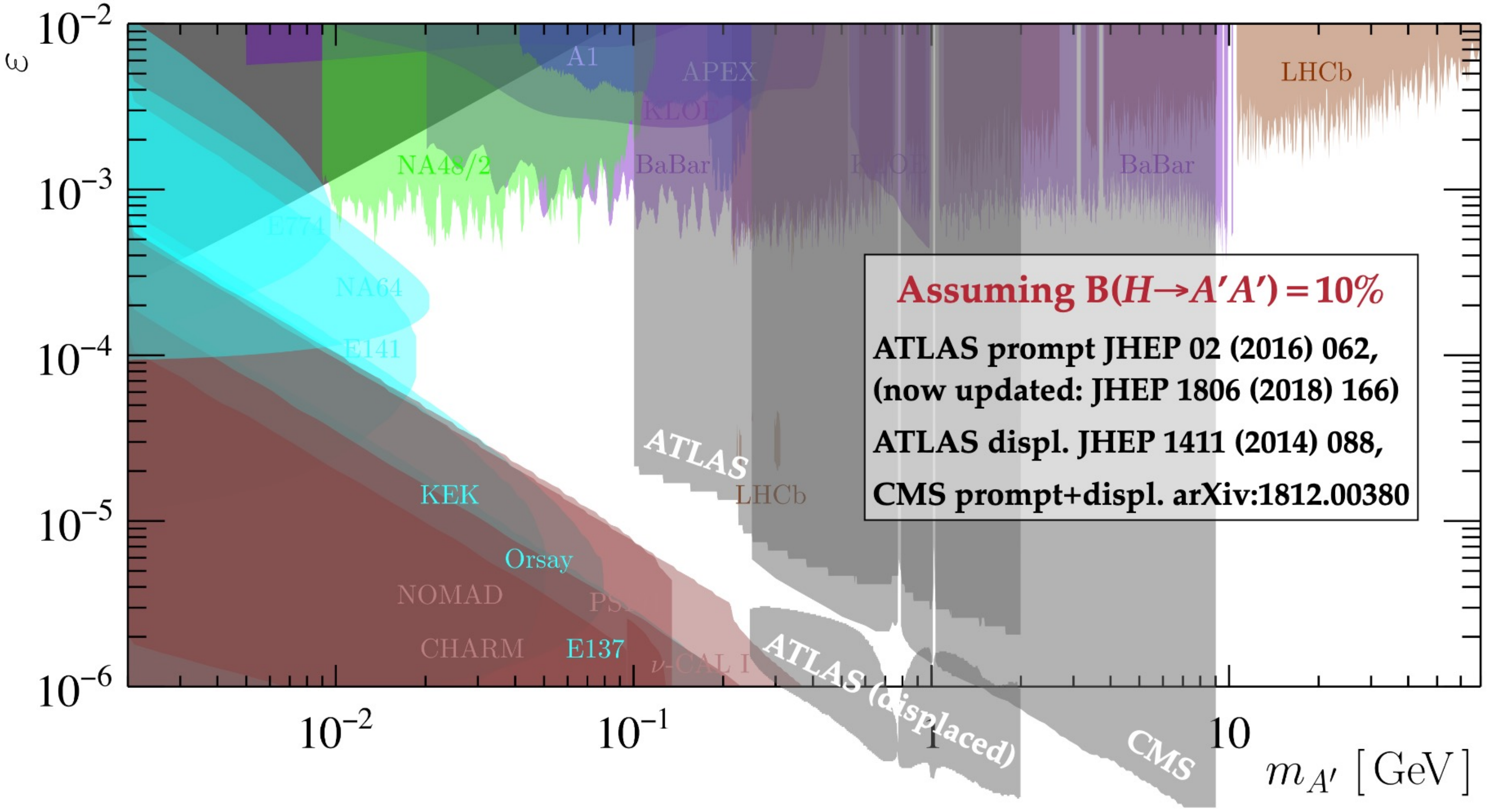
Phys. Rev. Lett. 120, 061801 (2018

Plot from M.Williams's talk at IPA 2018



$H \to A'(\ell\ell)A'(\ell\ell)$

Plot from M.Williams's talk at IPA 2018



Searches in heavy flavour

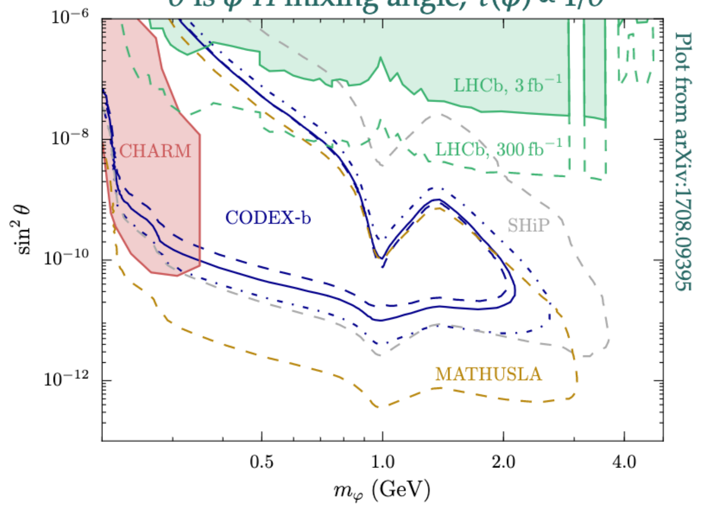
- *B* meson decays to search for light (long-lived) objects
  - Dark Bosons φ
    - In prompt/displaced dimuons
    - Using $b \to s$ channel $B \to \varphi(\mu\mu)K^{+/*}$

Phys Rev Lett 115 161802 (2015)
Phys. Rev. D 95, 071101(R) (2017)

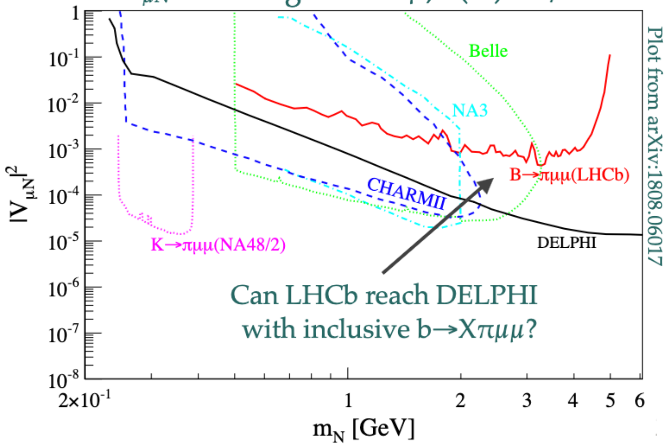
  - Heavy Neutral Leptons
    - In displaced $\pi^-\mu^+$ resonances
    - Eventually accompanied by same-sign μ^+ from *B*
    - So far searched only in $B \to N(\pi^-\mu^+)\mu^+$

Phys Rev Lett 112 131802 (2014)

θ is φ-H mixing angle, $\tau(\varphi) \propto 1/\theta^2$



$V_{\mu N}$ is mixing N with μ, $\tau(N) \propto 1/V^2$



Prospects for selected flavour observables

Observable	Current LHCb	LHCb 2025	Belle II	Upgrade II	GPDs Phase II
EW Penguins					
R_K $(1 < q^2 < 6\,\mathrm{GeV}^2c^4)$	0.1 [255]	0.022	0.036	0.006	–
R_{K^*} $(1 < q^2 < 6\,\mathrm{GeV}^2c^4)$	0.1 [254]	0.029	0.032	0.008	–
R_ϕ, R_{pK}, R_π	–	0.07, 0.04, 0.11	–	0.02, 0.01, 0.03	–
CKM tests					
γ, with $B_s^0 \to D_s^+ K^-$	$(^{+17}_{-22})^\circ$ [123]	4°	–	1°	–
γ, all modes	$(^{+5.0}_{-5.8})^\circ$ [152]	1.5°	1.5°	0.35°	–
$\sin 2\beta$, with $B^0 \to J/\psi K_S^0$	0.04 [569]	0.011	0.005	0.003	–
ϕ_s, with $B_s^0 \to J/\psi\phi$	49 mrad [32]	14 mrad	–	4 mrad	22 mrad [570]
ϕ_s, with $B_s^0 \to D_s^+ D_s^-$	170 mrad [37]	35 mrad	–	9 mrad	–
$\phi_s^{s\bar{s}s}$, with $B_s^0 \to \phi\phi$	150 mrad [571]	60 mrad	–	17 mrad	Under study [572]
a_{sl}^s	33×10^{-4} [193]	10×10^{-4}	–	3×10^{-4}	–
$\lvert V_{ub}\rvert/\lvert V_{cb}\rvert$	6% [186]	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% [244]	34%	–	10%	21% [573]
$\tau_{B_s^0 \to \mu^+\mu^-}$	22% [244]	8%	–	2%	–
$S_{\mu\mu}$	–	–	–	0.2	–
$b \to c l^- \bar{\nu}_l$ LUV studies					
$R(D^*)$	9% [199, 202]	3%	2%	1%	–
$R(J/\psi)$	25% [202]	8%	–	2%	–
Charm					
$\Delta A_{CP}(KK - \pi\pi)$	8.5×10^{-4} [574]	1.7×10^{-4}	5.4×10^{-4}	3.0×10^{-5}	–
A_Γ $(\approx x \sin\phi)$	2.8×10^{-4} [222]	4.3×10^{-5}	3.5×10^{-5}	1.0×10^{-5}	–
$x \sin\phi$ from $D^0 \to K^+\pi^-$	13×10^{-4} [210]	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}	–

Based on extrapolations from current measurements, and take no account of detector improvements apart from an approximate **factor two increase in efficiency for hadronic modes**, coming from the full software trigger that will be deployed from Run 3 onwards.