PHYSICS PROSPECTS FOR LHCb UPGRADE II

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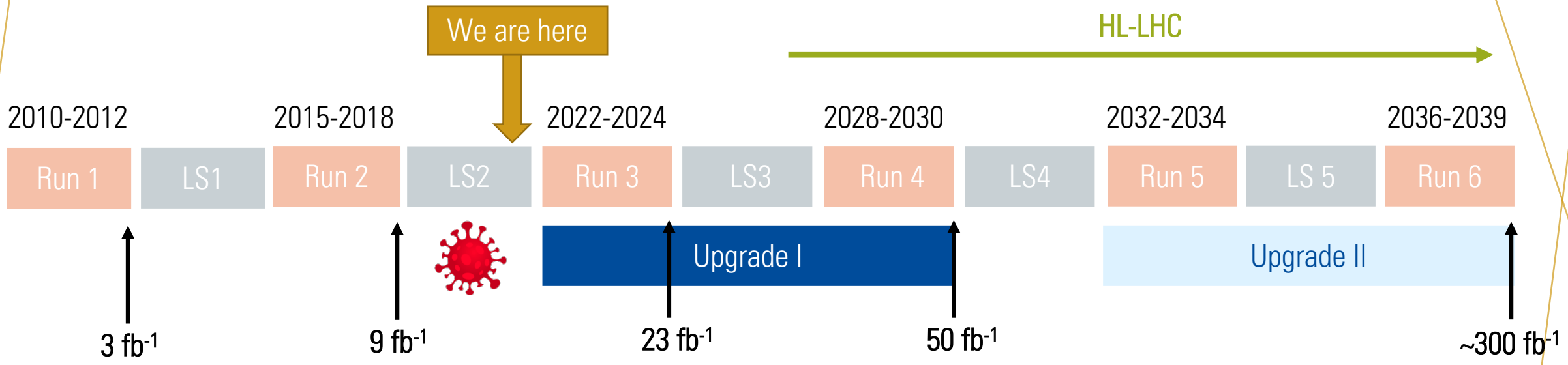
INFN CAGLIARI

ON BEHALF OF LHCb

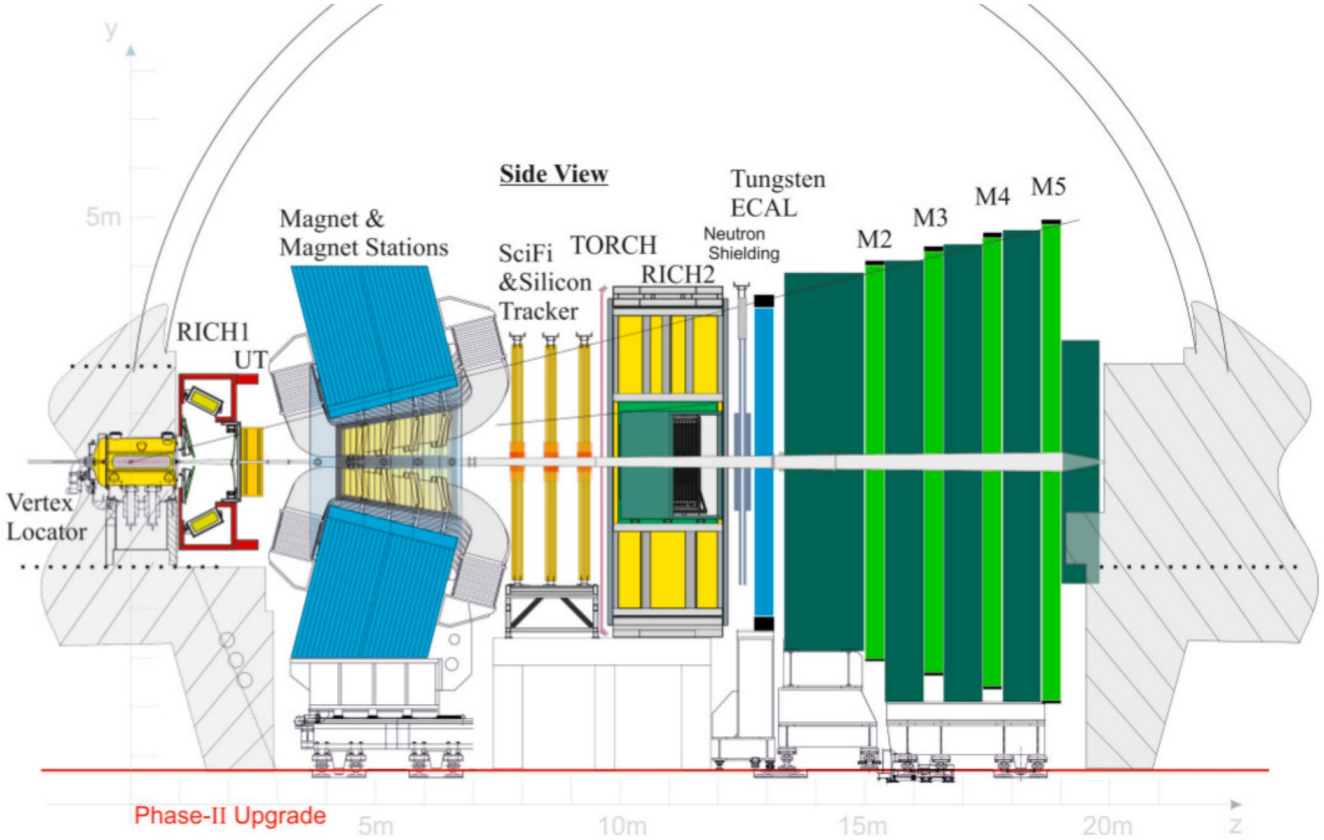
LHCP 2021, 7 JUNE 2021

WHAT IS LHCb UPGRADE II?



- Currently Upgrade I is under installation
- Upgrade II will come online in 2032
- **Goal** > 30 times the current integrated luminosity (inst. Lumi. $\mathcal{L}$~(1-2)x10^{34} $sec^{-1}cm^{-2}$)
- **pile-up** ~40, from ~5 for Run 3/4 (today's challenge)

WHAT IS LHCb UPGRADE II?



arXiv:1808.08865

Upgrade II will involve changes to nearly all parts of experiment

- Vertexing: Pixel detector with timing
- Hadron PID: RICH with timing and improved resolution + TORCH for low-p
- Tracking: Magnet Side stations + (pixel) inner tracker
- Calorimeter: Timing + improved resolution
- Muon system: alternative technologies for high-rate regions

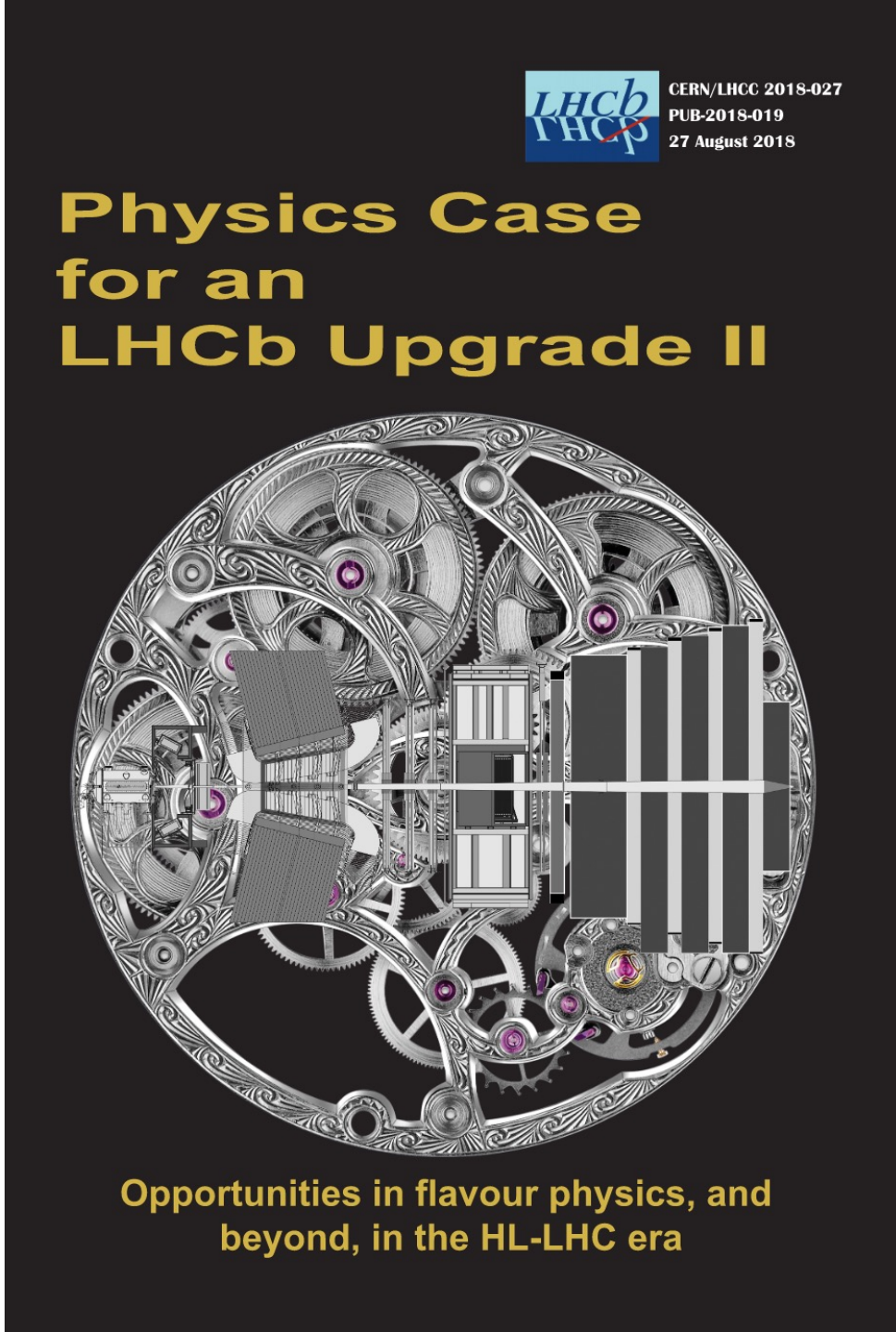
Timing information will be crucial

See the talks of S. Gambetta on Wednesday and T. Szumlak on Friday

WHY UPGRADE?

- Flavour Physics is a powerful tool to access NP beyond the reach of direct production at accelerators.
- Upgrade II aims to make full use of the capabilities of a forward acceptance detector during the High Luminosity LHC (HL-LHC) operational period.
- Some hints of New Physics in LHC Runs 1 & 2.
  - Lepton flavour (non-)universality?
  - No "discovery" but coherent set of discrepancies w.r.t. Standard Model. More data needed.
- More data to further challenge theoretical predictions.
  - Most of the measurements will be still statistically limited after Run 4.
- LHCb will upgrade to continue improving our knowledge of Flavour Physics.

arXiv:1808.08865



RICH PHYSICS PROGRAMME

Charm Physics

CP Violation γ, β, φ_s

Rare decays

Lepton Universality tests

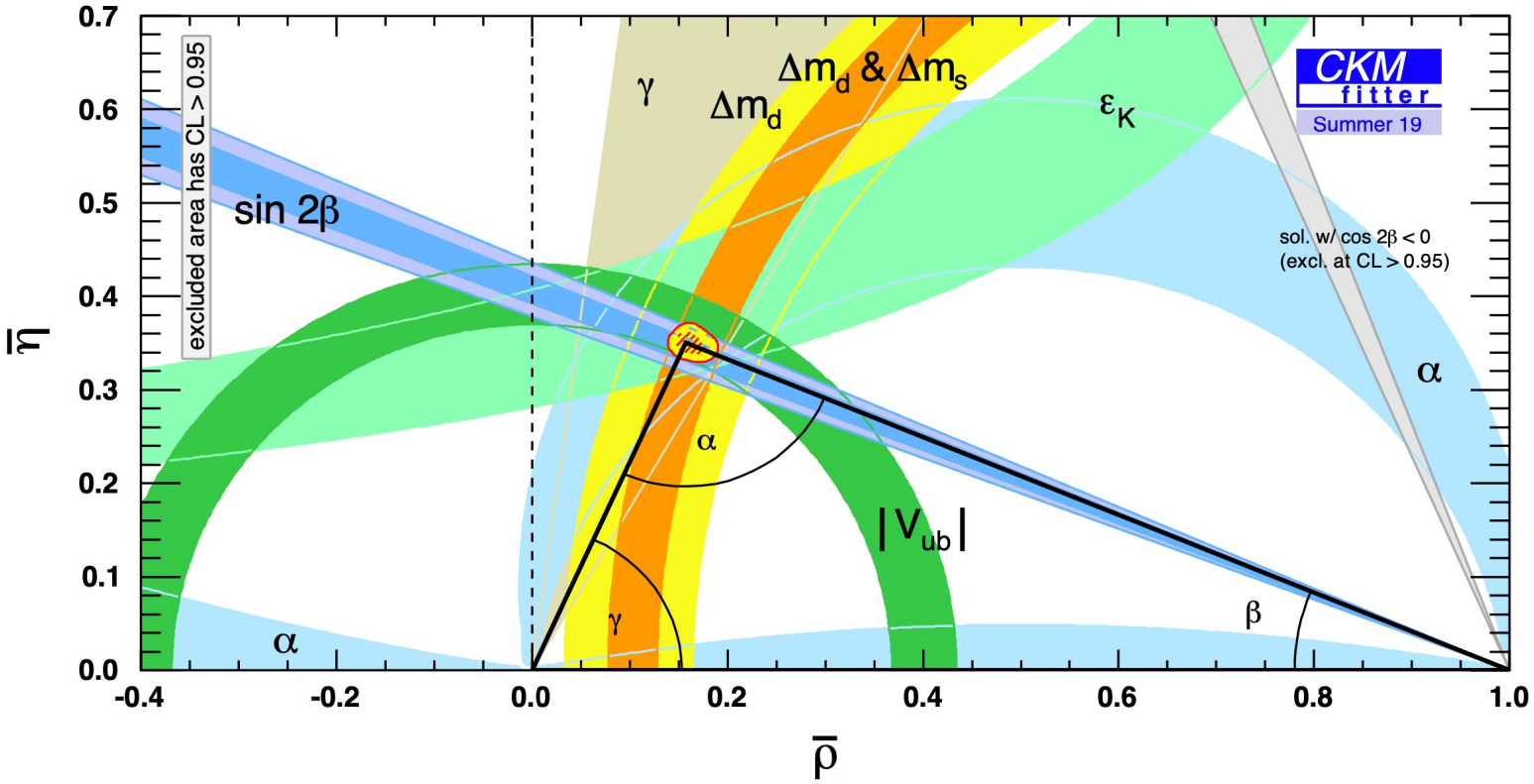
Unitarity triangle sides

Hadron spectroscopy

Forward and high-p_T physics

arXiv:1808.08865

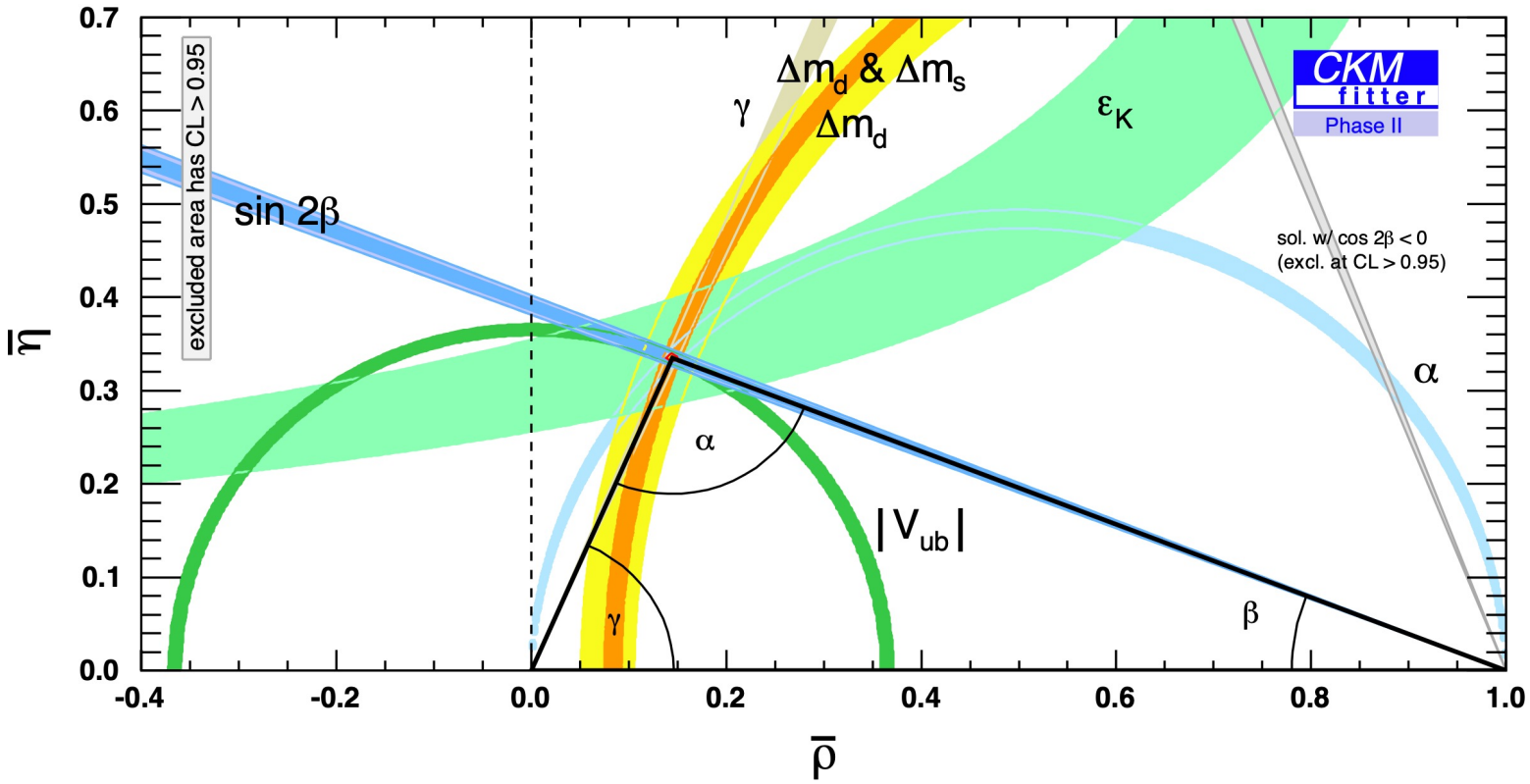
CP VIOLATION



The SM works so remarkably well that we have to make more and more precise measurements.
NP allowed at O(20%) in $b \to d$ and $b \to s$ transitions.

CKM Fitter (EPS 2019 conference)

CP VIOLATION



If we assume NP enters mainly at loop level, it is interesting to compare the determination of the parameters (ρ,η) from processes dominated by tree diagrams (V_{ub},V_{cb}, γ,...) with the ones from loop diagrams (ΔM_d & ΔM_s, Φ_s,ε_K, ...).

CKM Fitter (Phase II)

CKM ANGLE γ

See the talk of A. Bertolin on Wednesday

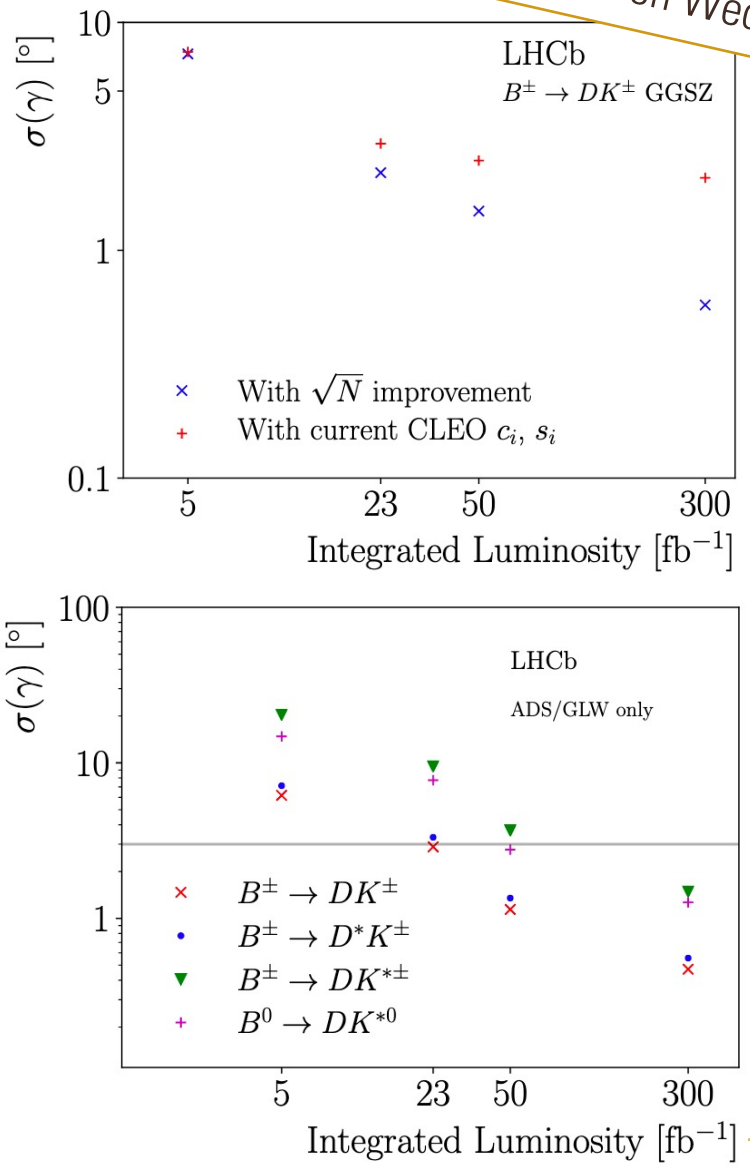
- $\gamma \equiv [-(V_{ub}^{*}V_{ud})/(V_{cb}^{*}V_{cd})]$: it does not depend on a top-quark coupling, measured via interference b⟶u and b⟶c transitions.
- Very well know within SM: $|\delta\gamma/\gamma| \leq 10^{-7}$ JHEP 1401 (2014) 051

LHCb combination

$\gamma = (67 \pm 4)^{\circ}$

LHCb-CONF-2020-003

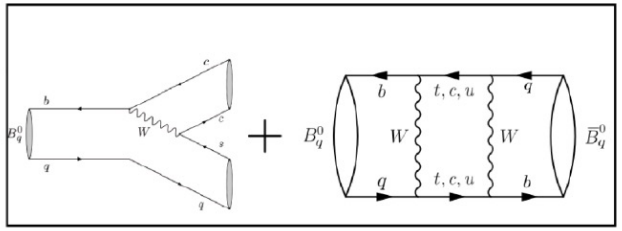
- LHCb is nicely closing the sensitivity gap between direct measurements and global fits $\gamma = (65.7^{+0.9}_{-2.5})^{\circ}$ CKM Fitter
- Expected stat. sensitivity down to the degree level for individual modes. Expect a **0.35° combined sensitivity**.
- Comparison of measurements made in single decay modes interesting after Upgrade II → NP in tree level different for different final states.



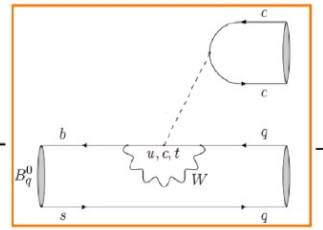
arXiv:1808.08865

B_s^0 MIXING PHASE, Φ_S

See the talk of B. Khanji on Thursday

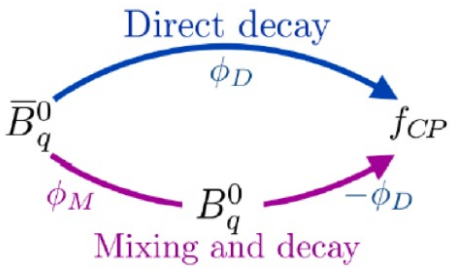


Dominant SM "tree" contribution



Higher order "penguin" contributions from non-perturbative hadronic effects

NP could be difficult to distinguish from penguins...

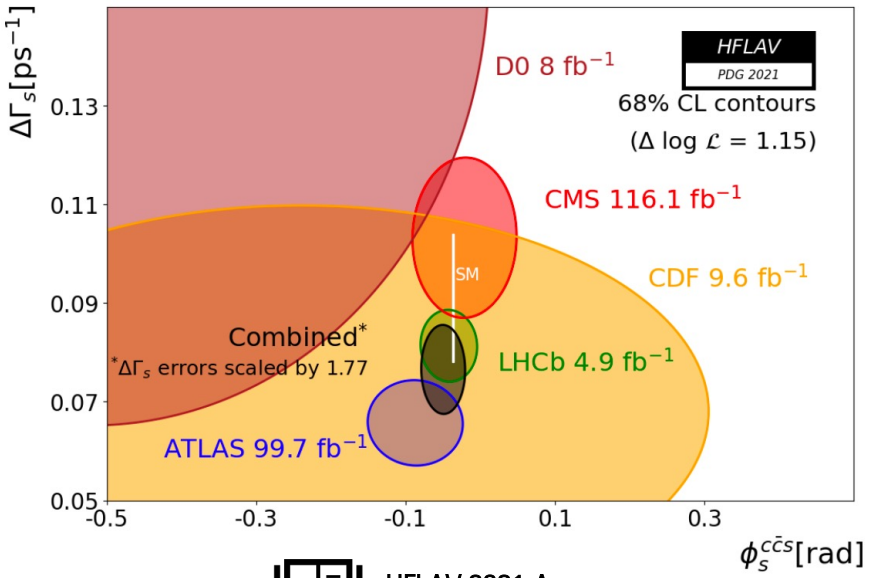


- CP-violating phase arising from interference between mixing and decay, precisely predicted.
- Golden channel exploited by LHCb, ATLAS, CMS: $B_s^0 \to J/\psi\phi$

HFLAV combination

$\phi_s = -0.041 \pm 0.025$ rad

- Statistically limited.



HFLAV 2021 Average

B_s^0 MIXING PHASE, Φ_S

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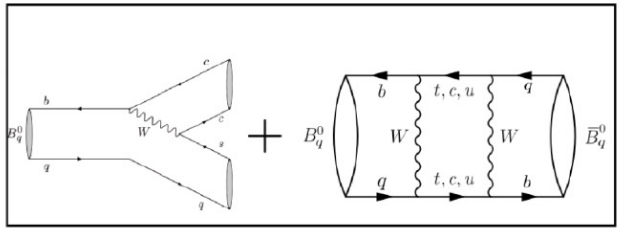

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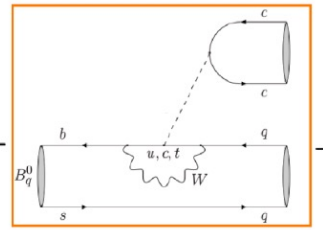

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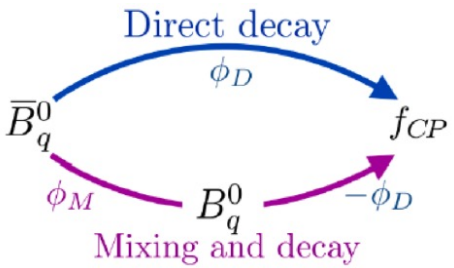

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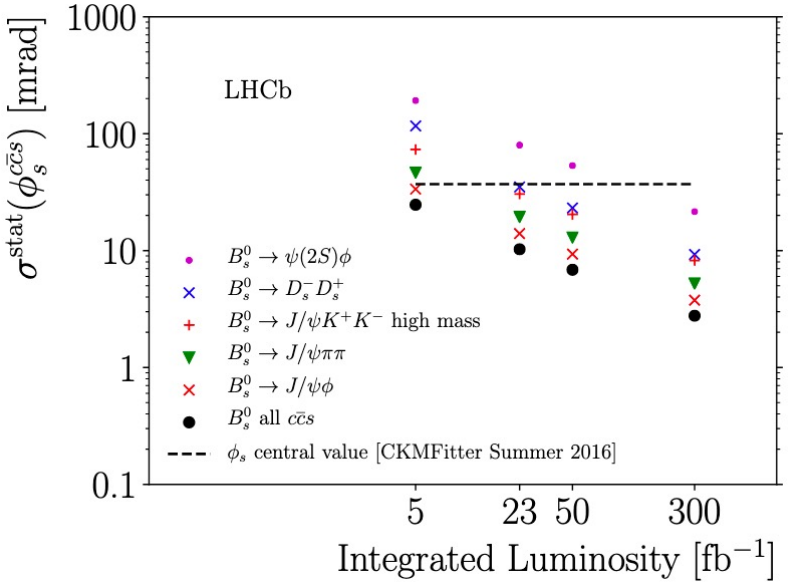
- Golden channel exploited by LHCb, ATLAS, CMS: $B_s^0 \to J/\psi\phi$

HFLAV combination

$\phi_s = -0.041 \pm 0.025$ rad

- Statistically limited also @300 fb^{-1}. LHCb precision <3mrad.
- Same performances as in Run 2 (tagging power, i.e. flavour identification of the B_s^0 at production, ~4%)
- Exp precision of the penguin pollution will scale similarly



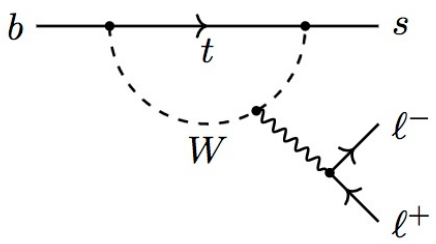
arXiv:1808.08865

RARE DECAYS

RARE DECAYS AS PROBE FOR NP

- Rare FCNC decays are loop-suppressed in the SM ($\mathcal{B}\sim 10^{-6} - 10^{-7}$ but also much smaller)
- New heavy particles can significantly contribute, affecting decay rates and angular distributions
- Model independent description using effective, four-fermion point interactions

Standard Model



Local operator (effective vertex)

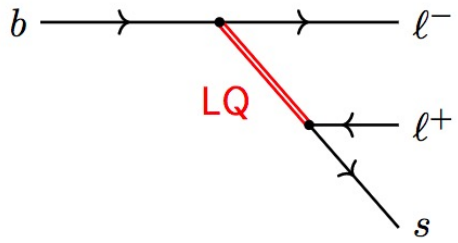
NP coupling

$$\mathcal{H}_{eff} = -\frac{4G_F}{\sqrt{2}} V_{tb}V_{ts}^* \sum_i \mathcal{C}_i \mathcal{O}_i + \frac{k}{\Lambda_{NP}^2} \mathcal{O}_{NP}$$

Wilson Coefficient (effective coupling)

NP scale

New Physics



i=1,2 Tree

i=3-6,8 Gluon Penguin

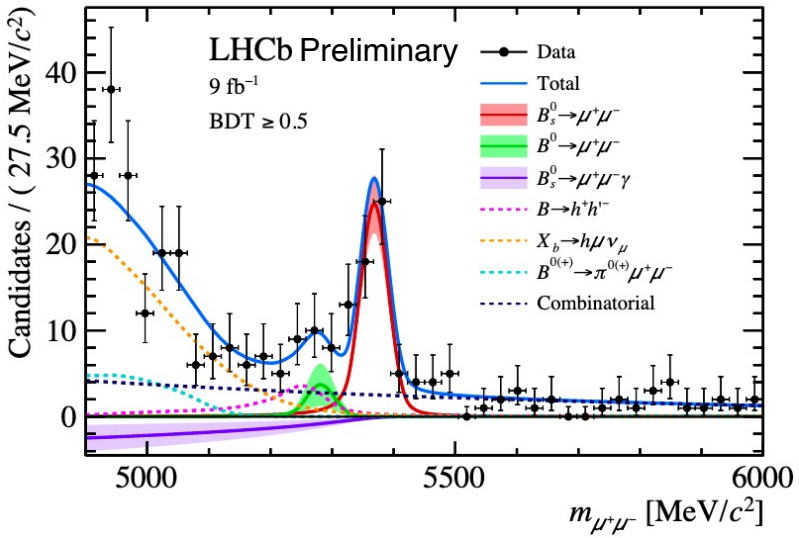
i=7 Photon penguin

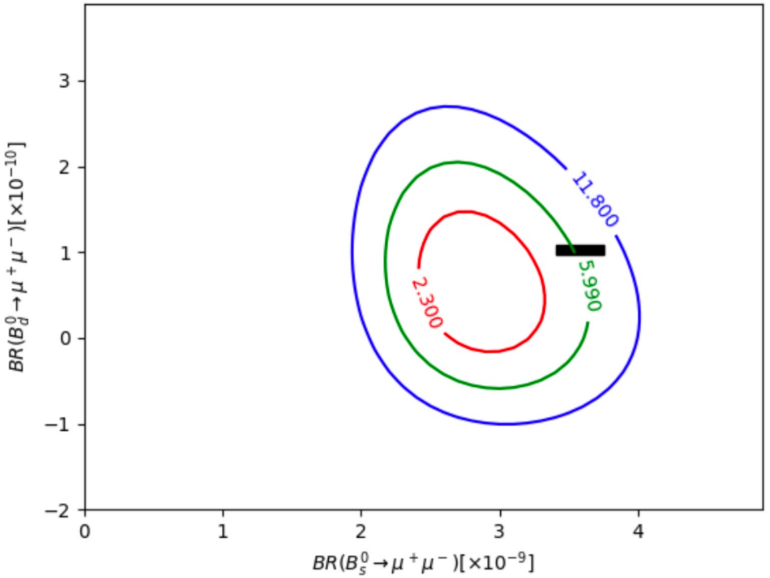
i=9,10 EW penguin

i=S,P (Pseudo)scalar penguin

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

LHCb-PAPER-2021-007, in preparation
ATLAS [JHEP 04 (2019) 098]
CMS [JHEP 04 (2020) 188]





Hurth et al., arXiv:2104.10058

Golden modes in NP searches: precisely predicted in the SM.

With 2011–2018 LHCb data (9 fb^{-1}):

- $\mathcal{B}(B_s^0 \to \mu^+\mu^-) = 3.09^{+0.46+0.15}_{-0.43-0.11} \times 10^{-9}$
- $\mathcal{B}(B^0 \to \mu^+\mu^-) = 1.2^{+0.8}_{-0.7} \pm 0.1 \times 10^{-10}$

The SM point is near the 2σ band.

See the talk of Jacco de Vries on Tuesday

- $\mathcal{B}(B_s^0 \to \mu^+\mu^-)$ has now 15% precision. Stat will be 1.8% with 300 fb^{-1}.
- The systematics are now 4-5%, dominated by f_s/f_d. Hard to predict how this will evolve. → New f_s/f_d 2021 measurement

arXiv:2103.06810, submitted to PRD

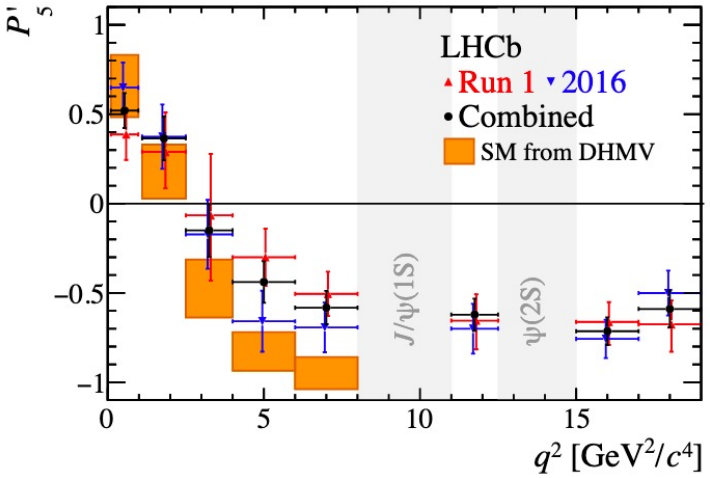
- $\mathcal{B}(B^0 \to \mu^+\mu^-)$ The statistical precision will be 10% with 300 fb^{-1}.
- $\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$ suffers from the same f_s/f_d limitation but will be still statistics-dominated (10% uncertainty).
- Yields will allow effective lifetime (2%) and TD CP asymmetries (10-20%)

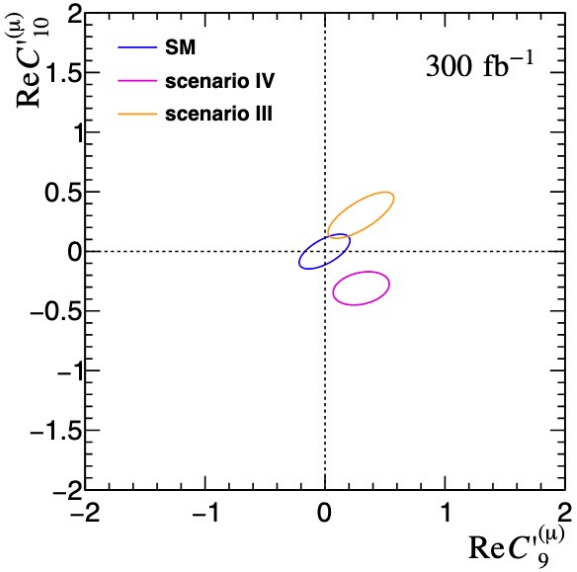
$B^0 \to K^{*0}\,\mu\mu$

See the talk of Yanting Fan on Tuesday

PRL 125 (2020) 011802

- $B^0 \to K^{*0}(\to K^+\pi^-)\mu^+\mu^-$ exhibits rich angular structure
- Measure optimised angular observables with reduced hadronic uncertainty, like P_5'
- Most precise measurement from LHCb is above the SM
- However, non trivial charm-loop contribution close to the resonant regions





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

I. $b \to sll$ data

II. $b \to sll$ & $b \to cl\nu$ data

III. and IV. small right-handed currents

- Expect ~440 000 $B^0 \to K^{*0}\mu^+\mu^-$ candidates in Upgrade II
- Allows for determination of angular observables with unprecedented precision
- Different NP scenarios can be cleanly separated

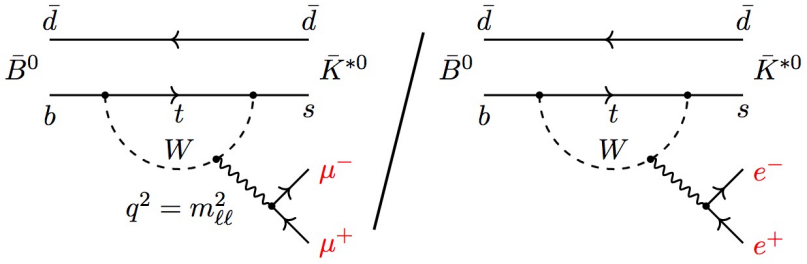
arXiv:1808.08865

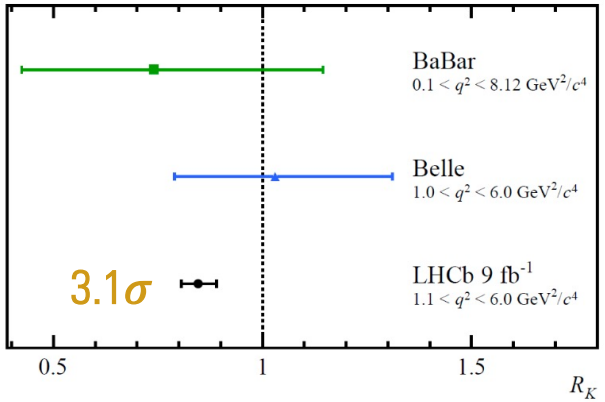
LEPTON UNIVERSALITY: $R(K^{(*)})$

See the talk of Yanting Fan on Tuesday

$$R_{K^{(*)}} = \frac{\Gamma(\bar{B}\to\bar{K}^{(*)}\mu^+\mu^-)}{\Gamma(\bar{B}\to\bar{K}^{(*)}J/\psi\to\mu^+\mu^-)} \Big/ \frac{\Gamma(\bar{B}\to\bar{K}^{(*)}e^+e^-)}{\Gamma(\bar{B}\to\bar{K}^{(*)}J/\psi\to e^+e^-)}$$

- LHCb results are consistently lower than 1
- Results from B-factories are compatible (with less precision)



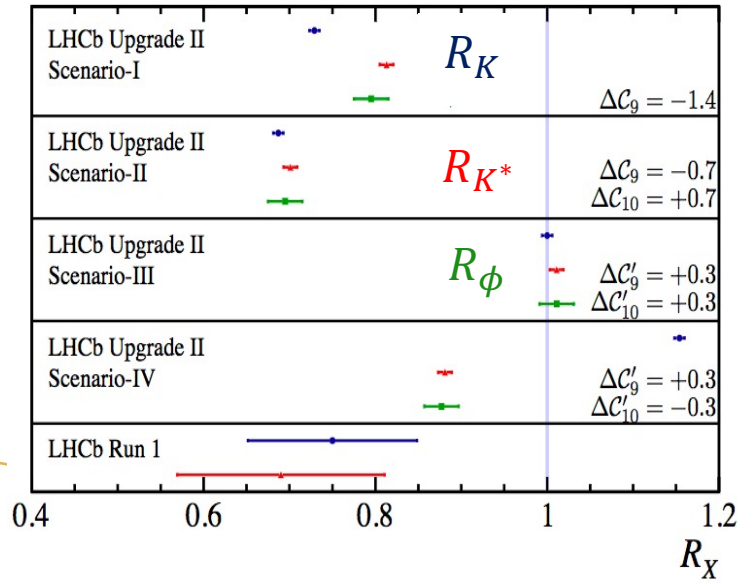


arXiv:2103.11769

Upgrade 2: All 4 NP scenarios could be distinguished at >5σ:

Nominal NP scenario

Right-handed components



Yield	Run 1 result	9 fb^{-1}	23 fb^{-1}	50 fb^{-1}	300 fb^{-1}
$B^+\to K^+e^+e^-$	254 ± 29 $\boxed{272}$	1 120	3 300	7 500	46 000
$B^0\to K^{*0}e^+e^-$	111 ± 14 $\boxed{273}$	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 fb^{-1}	23 fb^{-1}	50 fb^{-1}	300 fb^{-1}
R_K	$0.745\pm0.090\pm0.036$ $\boxed{272}$	0.043	0.025	0.017	0.007
$R_{K^{*0}}$	$0.69\pm0.11\pm0.05$ $\boxed{273}$	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 yields

Expected R_X uncertainties

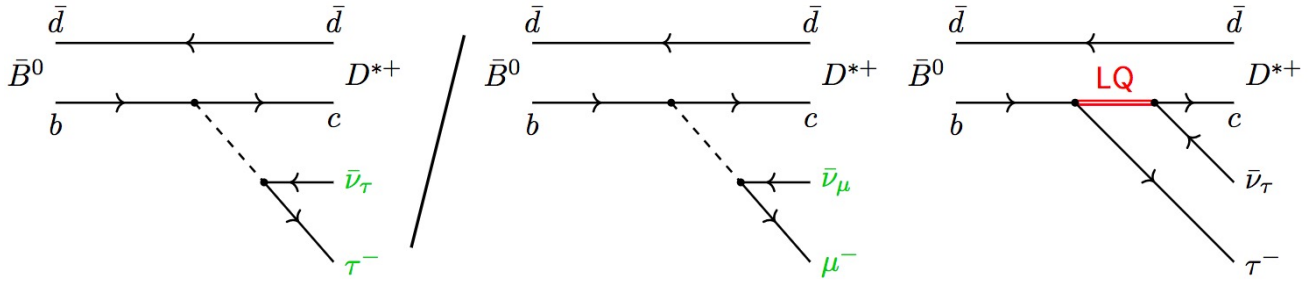
arXiv:1808.08865

LEPTON FLAVOUR UNIVERSALITY AT TREE LEVEL

"I suppose I'll be the one to mention the elephant in the room."

LEPTON UNIVERSALITY TEST IN TREE-LEVEL DECAYS

See the talk of Alessandra Gioventu on Tuesday

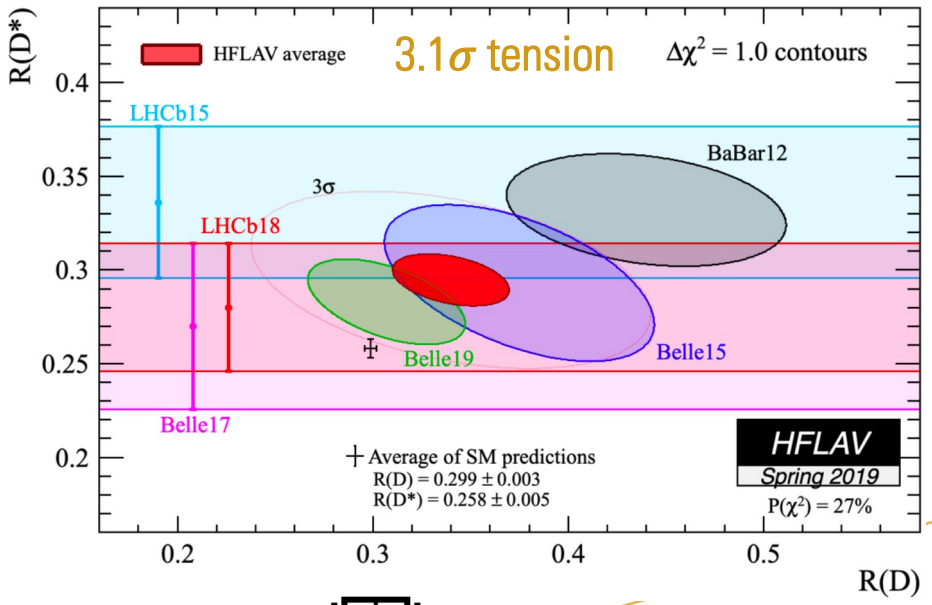


Tests of LFU in semitauonic decays are obtained measuring the following ratios

$$R_X = \frac{\Gamma(B \to X_c\, \tau^+ \nu_\tau)}{\Gamma(B \to X_c\, \mu^+ \nu_\mu)} \quad \text{with } X_c = D^* \text{ or } J/\psi$$

LHCb has performed analysis of

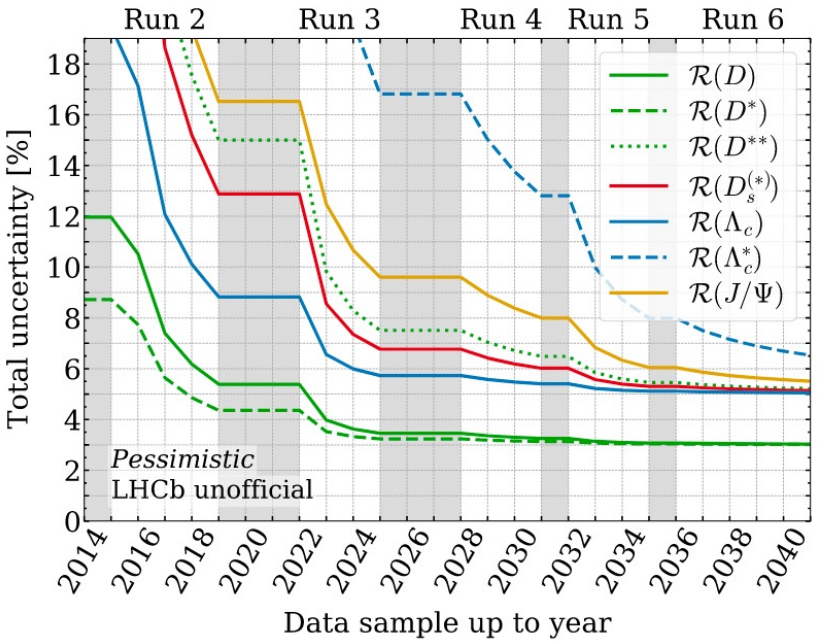
- $R_{D^*} = 0.336 \pm 0.027 \pm 0.030$ with $\tau^- \to \mu^- \nu_\tau \bar{\nu}_\mu$ compatible with the SM at $2.1\,\sigma$ [PRL 115 (2015) 111803]
- $R_{D^*} = 0.291 \pm 0.019 \pm 0.026 \pm 0.013$ with $\tau^- \to \pi^- \pi^+ \pi^- (\pi^0) \nu_\tau$ compatible with the SM at $1\,\sigma$ [PRL 120 (2018) 171802]
- $R_{J/\psi} = 0.71 \pm 0.17 \pm 0.18$ using B_c^+ decays compatible with the SM at $\sim 2\,\sigma$ [PRL 120 (2018) 121801]



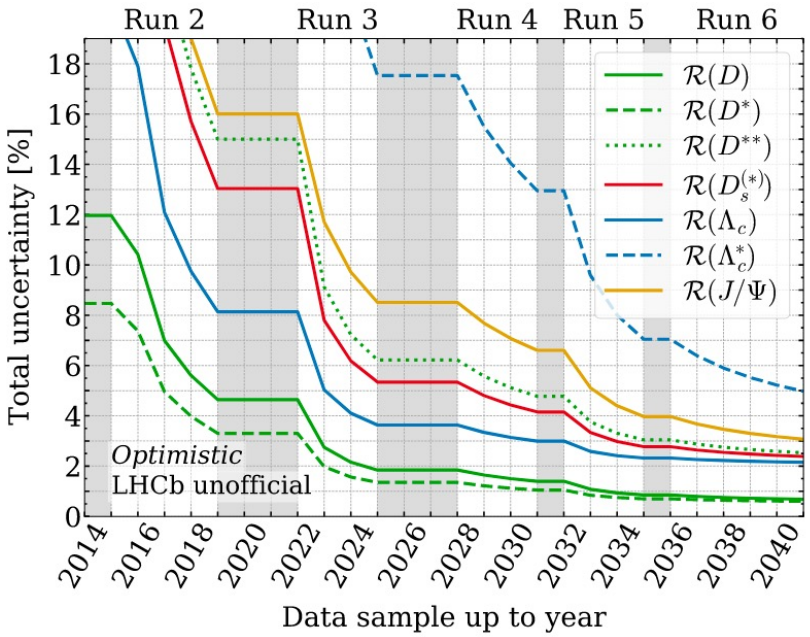
HFLAV 2019

FUTURE PROSPECTS

See the talk of Alessandra Gioventu on Tuesday



For an irreducible systematic uncertainty of 3% on R(D(*)) and 5% on the other ratios.



For an irreducible systematic uncertainty of 0.5% on R(D(*)) and 2% on the other ratios.

arXiv:2101.08326

- Expect O(10 M) $\bar{B} \to D^{(*)}\tau\bar{\nu}$ candidates
- Sensitivity Upgrade II: $\sigma(R_{D^*})/R_{D^*} \sim 1\%$

Upgrade II: exploit other b-hadron species

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

CONCLUSIONS

- 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;
- LHCb Upgrade has a far-reaching Flavour Physics program – see more in LHCB-PUB-2018-009
- We must push forward to use as efficiently the unique opportunity of a High-Luminosity Hadronic Collider
  - FTDR in preparation: coming by the end of summer!
- The Phase-II upgrade would collect a thirty times bigger data sample than LHCb currently has
- Improvements in detector will open up many little-explored modes

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LHCb LETTER OF INTENT

What we think is the main physics right now might not be what we use the detector for.
Important that the detector is versatile.

- Was written in 1995
- Observation of CP violation in B mesons and B_s^0 oscillations the main selling points
- CP angle γ would mainly be from time dependent analysis of $B_s^0 \to D_s^+K^-$
- Charm physics only from $B \to D\ell\nu$ decays
- $B_s^0 \to \mu^+\mu^-$ only rare decay
- Λ_b never mentioned

See Ulrik Egede, ICHEP 2020

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- Charm physics only fro[illegible] decays
- $B_s^0 \to \mu^+\mu^-$ [illegible]e decay [illegible]mentioned

Done before start-up

Different method

Prompt production

Vastly expanded

See Ulrik Egede, ICHEP 2020

LUMINOSITY IN UPGRADE II

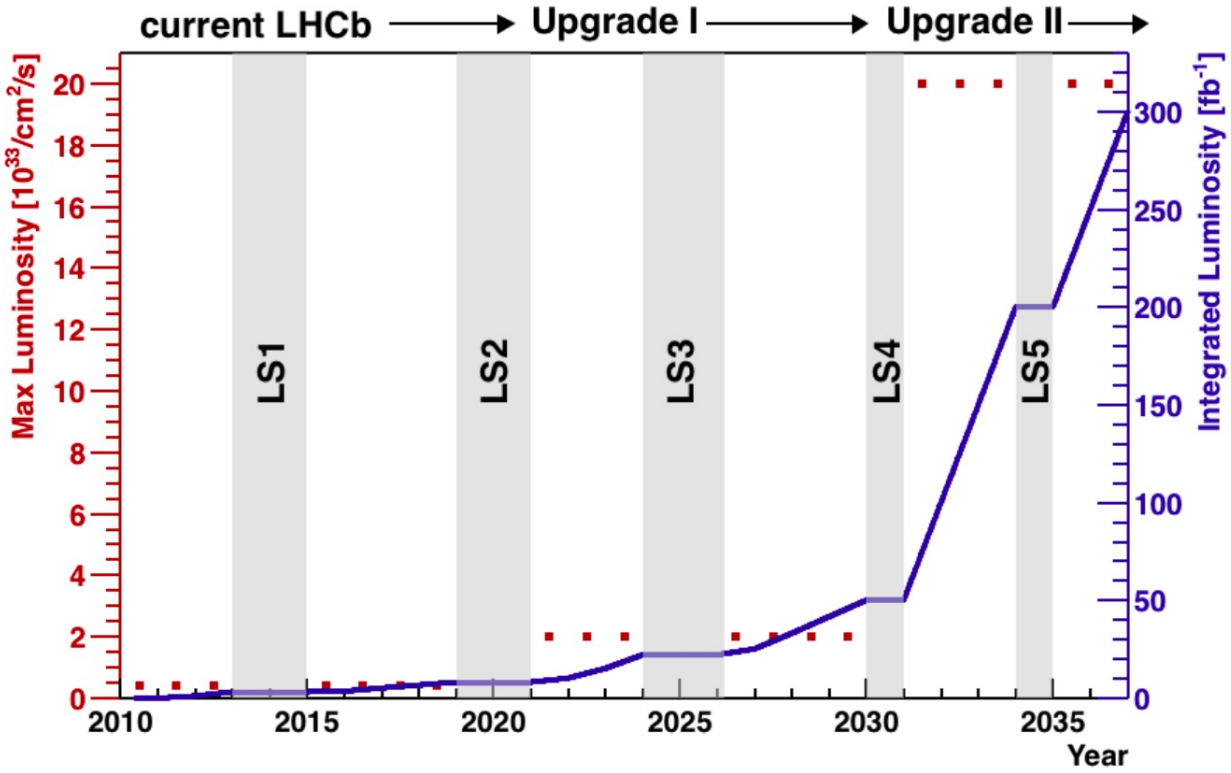


Figure 2.1: Luminosity projections for the original LHCb, Upgrade I, and Upgrade II experiments as a function of time. The red points and the left scale indicate the anticipated instantaneous luminosity during each period, with the blue line and right scale indicating the integrated luminosity accumulated.

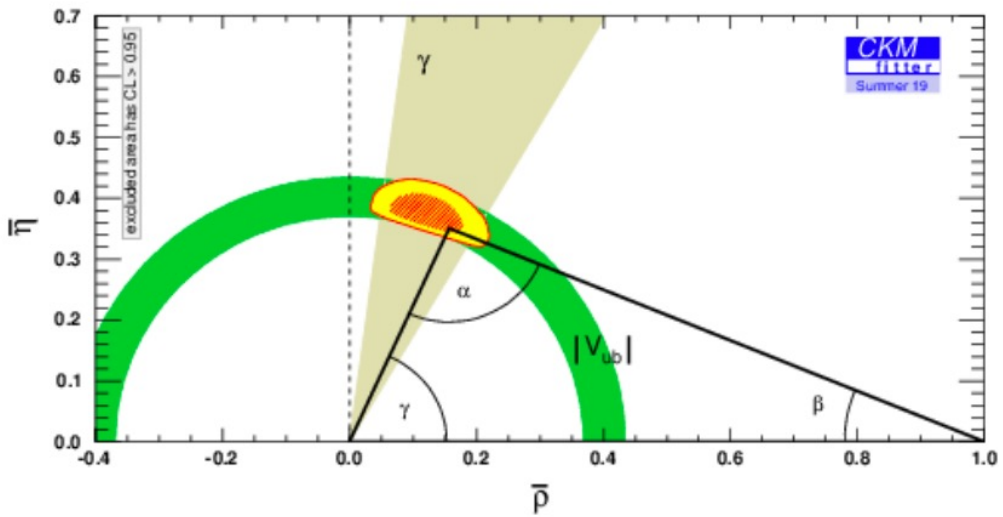
	Current	Phase I	Phase II	Ref.
$\lvert V_{ud}\rvert$	± 0.00021	± 0.00021	± 0.00021	[4]
$\lvert V_{us}\rvert f_+^{K\to\pi}(0)$	± 0.0004	± 0.0004	± 0.0004	[4]
$\lvert\epsilon_K\rvert \times 10^3$	± 0.011	± 0.011	± 0.011	[4]
$\lvert V_{cd}\rvert$	± 0.005	± 0.003	± 0.003	[2]
$\lvert V_{cs}\rvert$	± 0.016	± 0.014	± 0.014	[2]
Δm_d [ps^{-1}]	± 0.0019	± 0.0019	± 0.0019	[5]
Δm_s [ps^{-1}]	± 0.021	± 0.021	± 0.021	[5]
$\lvert V_{ub}\rvert \times 10^3$ $(b \to u\ell\bar{\nu})$	± 0.23	± 0.04	± 0.04	[3]
$\lvert V_{cb}\rvert \times 10^3$ $(b \to c\ell\bar{\nu})$	± 0.7	± 0.5	± 0.5	[3]
$\lvert V_{ub}/V_{cb}\rvert$ (Λ_b)	± 0.0050	± 0.0025	± 0.0008	[1]
$\sin 2\beta$	± 0.017	± 0.005	± 0.003	[1] and [3]
α [°]	± 4.4	± 0.6	± 0.6	[3]
γ [°]	± 5.6	± 1	± 0.35	[1] and [3]
β_s [rad]	± 0.031	± 0.014	± 0.004	[1]
$\mathcal{B}(B \to \tau\nu) \times 10^4$	± 0.21	± 0.04	± 0.04	[3]
$\mathcal{B}(B \to \mu\nu) \times 10^6$	–	± 0.03	± 0.03	[3]
$\mathcal{B}(B_s \to \mu\mu) \times 10^9$	± 0.66	± 0.34	± 0.17	[1]
$\mathcal{B}(B_d \to \mu\mu) \times 10^{11}$	–	± 3.5	± 1.0	[1]
$\frac{\mathcal{B}(B_d\to\mu\mu)}{\mathcal{B}(B_s\to\mu\mu)}$	–	± 0.010	± 0.003	[1]
$\bar{m}_c$ [GeV]	± 0.012 (0.9 %)	± 0.005 (0.4 %)	± 0.005 (0.4 %)	[1]
$\bar{m}_t$ [GeV]	± 0.73 (0.4 %)	± 0.35 (0.2 %)	± 0.35 (0.2 %)	[4]
$\alpha_s(m_Z)$	± 0.0011 (0.9 %)	± 0.0011 (0.9 %)	± 0.0011 (0.9 %)	[4]
$f_+^{K\to\pi}(0)$	± 0.0026 (0.3 %)	± 0.0012 (0.12 %)	± 0.0012 (0.12 %)	[1]
f_K	± 0.0006 (0.5 %)	± 0.0005 (0.4 %)	± 0.0005 (0.4 %)	[1]
B_K	± 0.012 (1.6 %)	± 0.005 (0.7 %)	± 0.004 (0.5 %)	[1]
f_{B_s} [GeV]	± 0.0025 (1.1 %)	± 0.0011 (0.5 %)	± 0.0011 (0.5 %)	[1]
B_{B_s}	± 0.034 (2.8 %)	± 0.010 (0.8 %)	± 0.007 (0.5 %)	[1]
f_{B_s}/f_{B_d}	± 0.007 (0.6 %)	± 0.005 (0.4 %)	± 0.005 (0.4 %)	[1]
B_{B_s}/B_{B_d}	± 0.020 (1.9 %)	± 0.005 (0.5 %)	± 0.003 (0.3 %)	[1]

Table 1: Uncertainties for the CKMfitter projections.

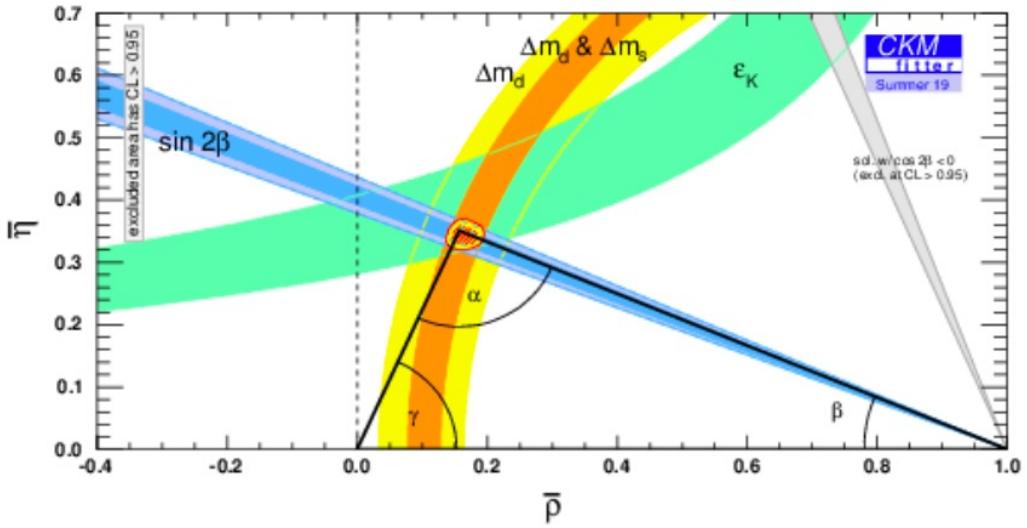
INPUTS FOR PROSPECTIVE STUDIES IN THE HL-LHC/BELLE II ERA

DIRECT VS INDIRECT CKM

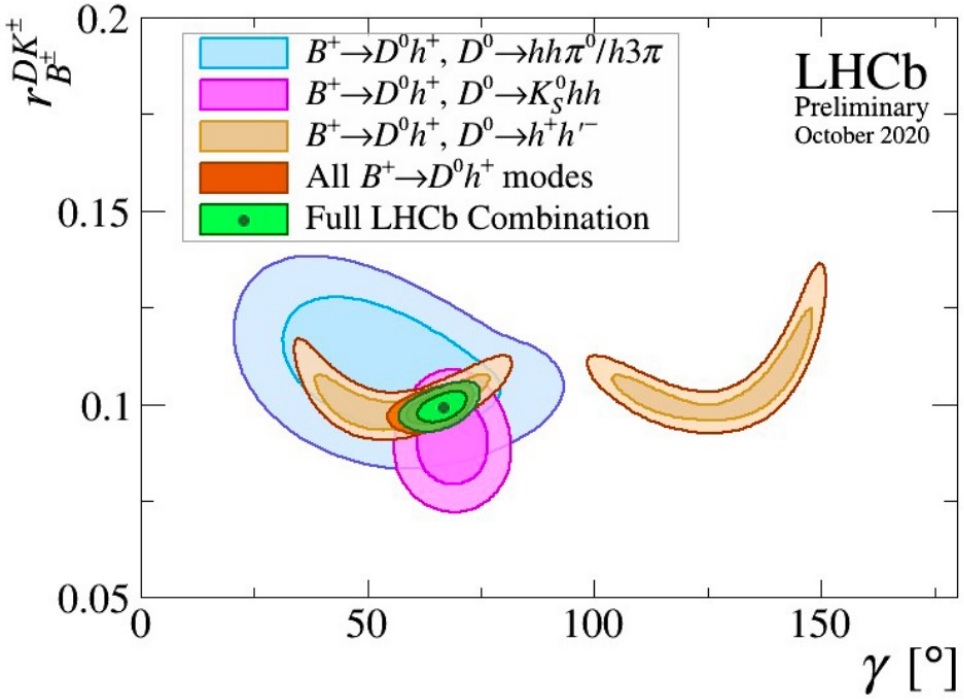
Direct

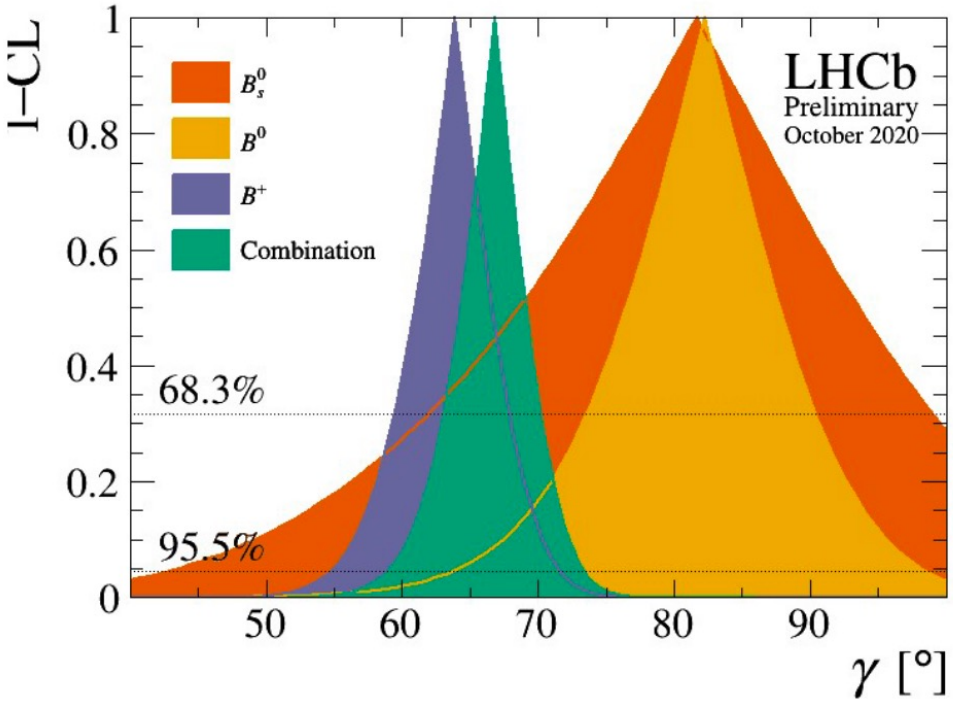


"Indirect"



ANGLE γ


$r_{B^\pm}^{DK^\pm}$
0.2
0.15
0.1
0.05
0
50
100
150
γ [°]
$B^+ \to D^0 h^+$, $D^0 \to hh\pi^0/h3\pi$
$B^+ \to D^0 h^+$, $D^0 \to K_S^0 hh$
$B^+ \to D^0 h^+$, $D^0 \to h^+ h'^-$
All $B^+ \to D^0 h^+$ modes
Full LHCb Combination
LHCb
Preliminary
October 2020


1−CL
1
0.8
0.6
0.4
0.2
0
50
60
70
80
90
γ [°]
B_s^0
B^0
B^+
Combination
68.3%
95.5%
LHCb
Preliminary
October 2020

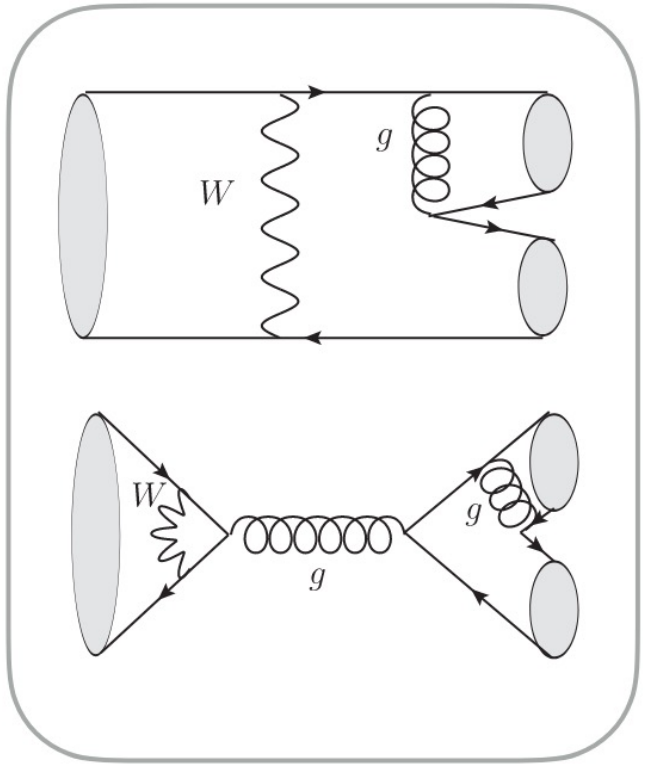
DIRECT CPV CHARM

- The observation of CPV in charm decays is a milestone that marks the start of a next era for charm physics.
- Significant theory interest in ACP(D^0 -> K_sK_s)
- Estimates vary from ~ 1% to O(3/2 ΔA_{CP}) (depending on SU(3) breaking)

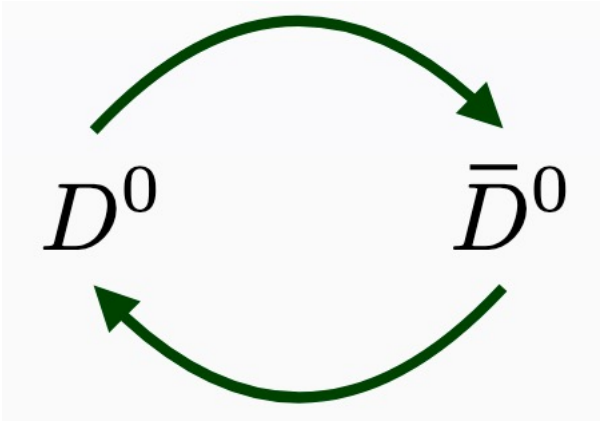
	Uncertainty [%]
Belle I	± 1.53 ± 0.17
LHCb '12-'16	± 2.8 ± 0.9
LHCb Run 2	± 1.5
Belle II	± 0.23
LHCb Upgrade-II	± 0.12 - 0.23*

Upgrade-II essential, event trigger main challenge

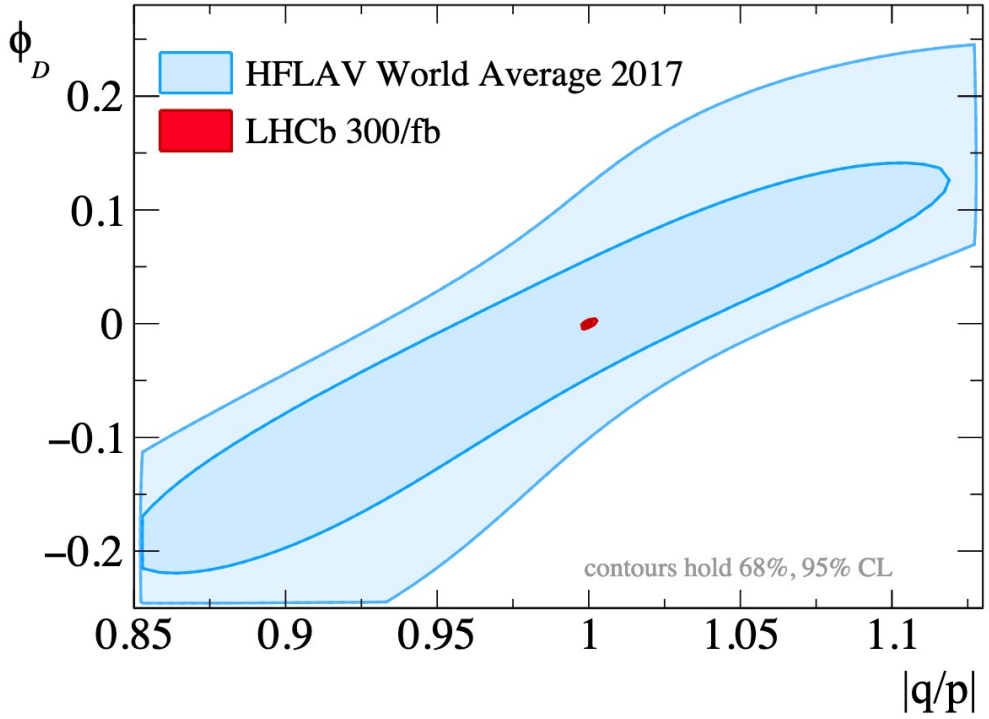
[1]: Nierste, Schacht '15
[2]: Hiller, Jung, Schacht '13
[2]: Cheng, Chaing '12



CPV IN MIXING



Mixing phase



CPV in mixing (similar to a_{sl})

LEPTON FLAVOUR 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

	$\mathcal{B}(B^0_{(s)} \to e\mu)$	$\mathcal{B}(B \to \tau\mu)$	$\mathcal{B}(\tau \to \mu\mu\mu)$
Run I @ 90 C.L.	< 1.0 (5.4) x10^{-9}	Soon	< 4.6x10^{-8}
Upgrade II @ 90 C.L.	< 3 (9) x$10^{-10(11)}$	<3x10^{-6}	<$\mathcal{O}(10^{-9})$

Similar to what is expected from Belle II

Searches for $B \to Ke\mu, B \to K^{*0}\tau(\to \pi\pi\pi\nu)\mu, \mathrm{B} \to K\tau(\to \pi\pi\pi\nu)\mu$ 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

BEYOND THE PLANNED PHYSICS

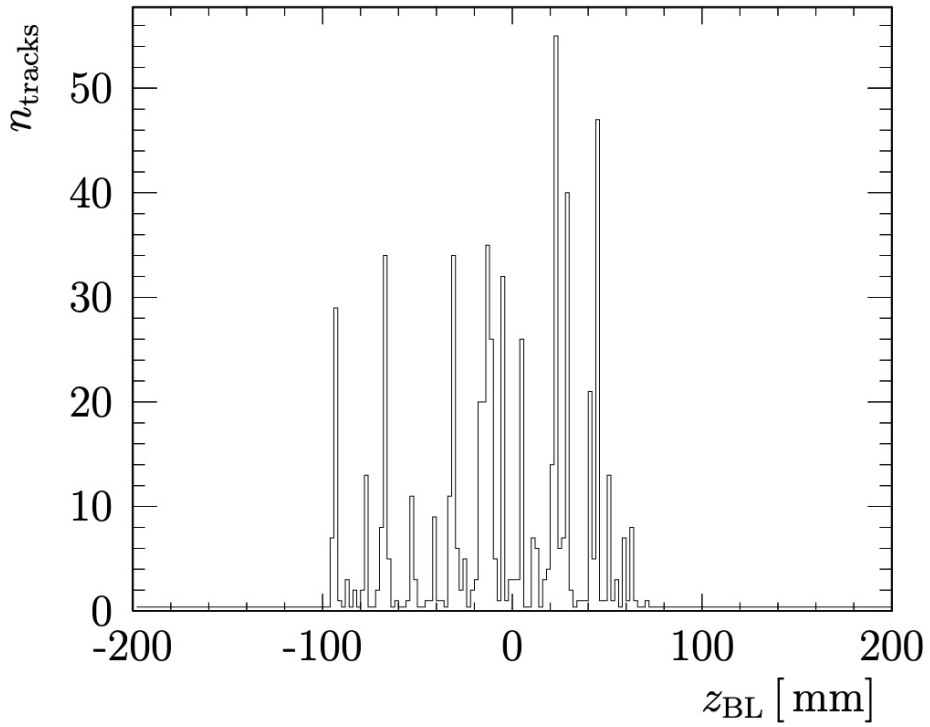
Part of the success of the LHCb experiment was the unplanned:

- Λb physics and baryon CPV;
- spectroscopy;
- top and electroweak physics;
- searches for dark photons;
- heavy ion physics;
- …

With its flexible trigger, LHCb has proven itself as a general purpose detector in the forward region. Head room for innovative techniques was key for these developments. The phase-2 upgrade detector should preserve this

WHY TIMING?

Upgrade 2: ~40 visible interactions



Primary vertices are also spread in time