Overview of LHCb results

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On behalf of the LHCb Collaboration

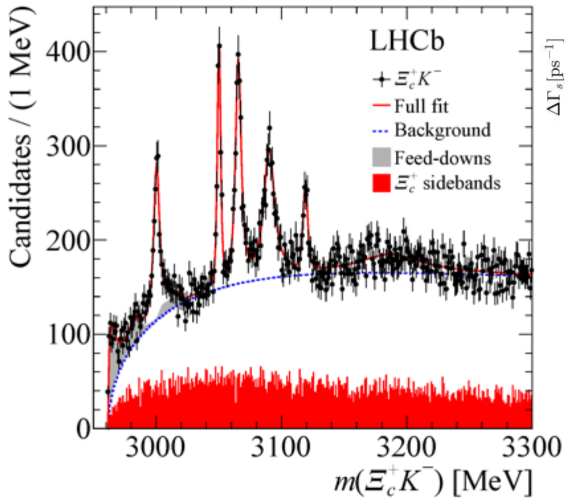
UK Research and Innovation

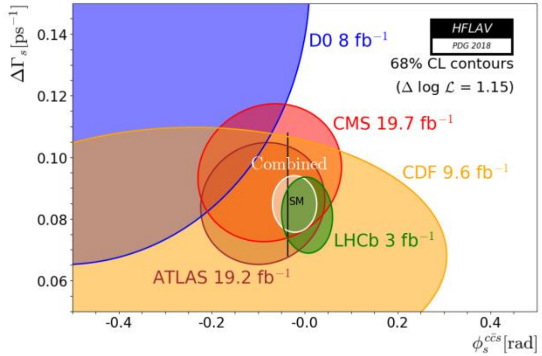
Science & Technology Facilities Council
Rutherford Appleton Laboratory

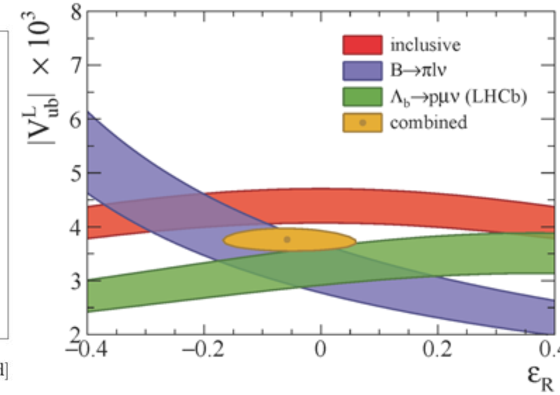
LHCb

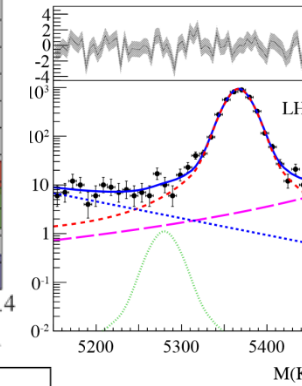
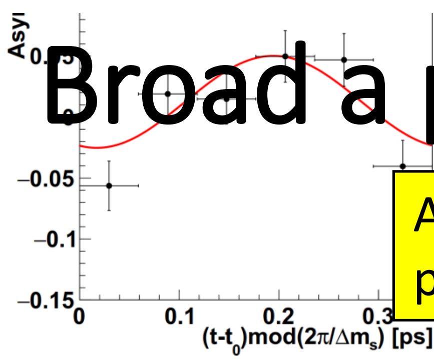
Broad a physics programme @ LHCb

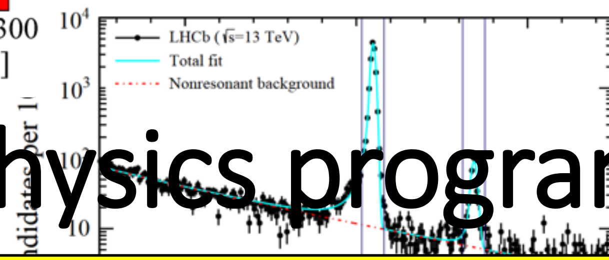
About 450 papers encompassing heavy flavour physics, EWK, QCD, exotica searches, heavy-ions, …

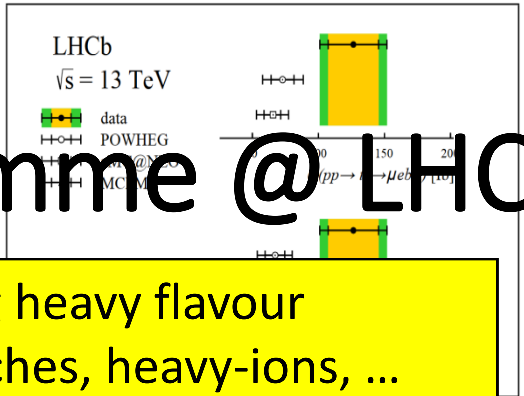


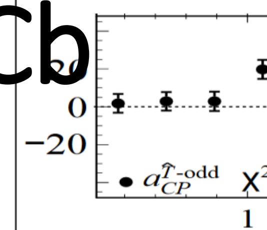
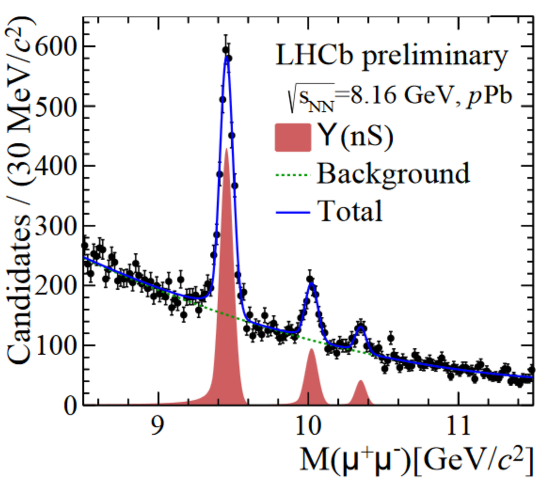


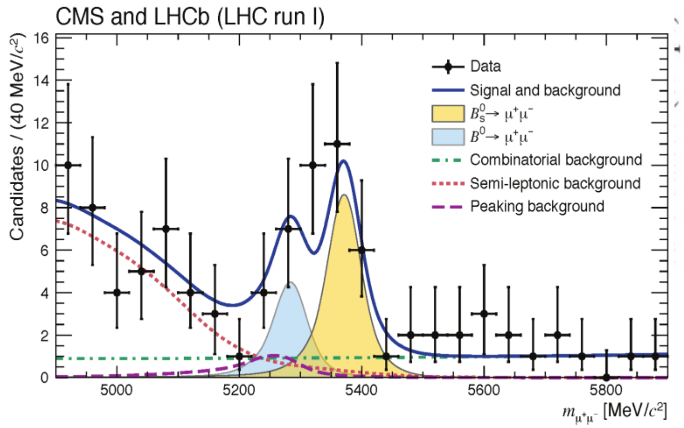


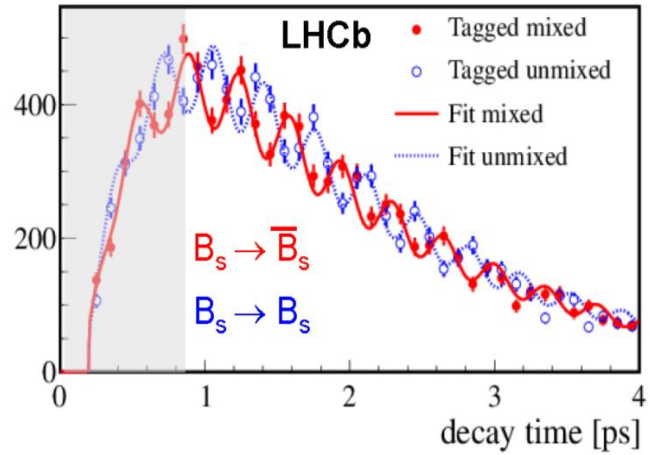











Overview

Several LHCb results shown in this conference:

- Lepton flavour universality – Lorenzo Capriotti [Tuesday]
- EWK – Vuko Brigljevic [Today]
- B spectroscopy – Niladribihari Sahoo [Today]
- Multi-quark states – Antimo Palano [Today]
- Dark matter searches - Pablo Martinez Ruiz del Arbol [Tomorrow]

Here a personal selection of recent results from areas not covered by other speakers

- CP violation
- Rare Decays
- Charm spectroscopy
- Fixed-target physics

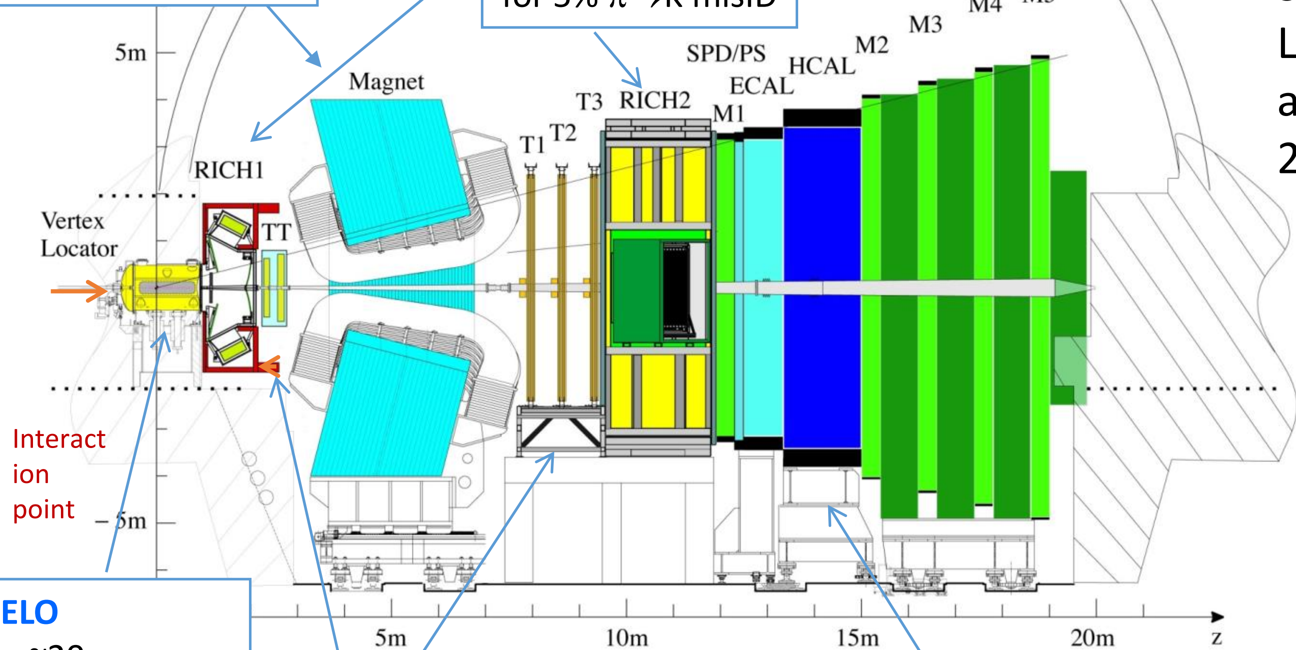
LHCb detector

JINST 3(2008) S08005
IJMPA 30 (2015) 1530022

Dipole magnet
4Tm bending power
Polarity +/-

RICh detectors
$\varepsilon(K) \sim 95\%$
for 5% $\pi \to K$ misID

MUON system
$\varepsilon(\mu) \sim 97\%$
for 1-3% $\pi \to \mu$ misID

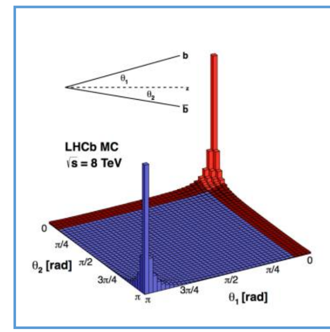


VELO
$\sigma_{IP} \sim 20\mu m$
(high p^T tracks)

TRACKING Systems
$\Delta p/p = 0.5 - 0.8\%$
(20-100 GeV)

CALORIMETERS
ECAL: $\sigma_E/E \sim 1\% \oplus 10\%/\sqrt{E}$

Single arm spectrometer:
Large acceptance for $b\bar{b}$ and $c\bar{c}$ in forward region
$2<\eta<5$



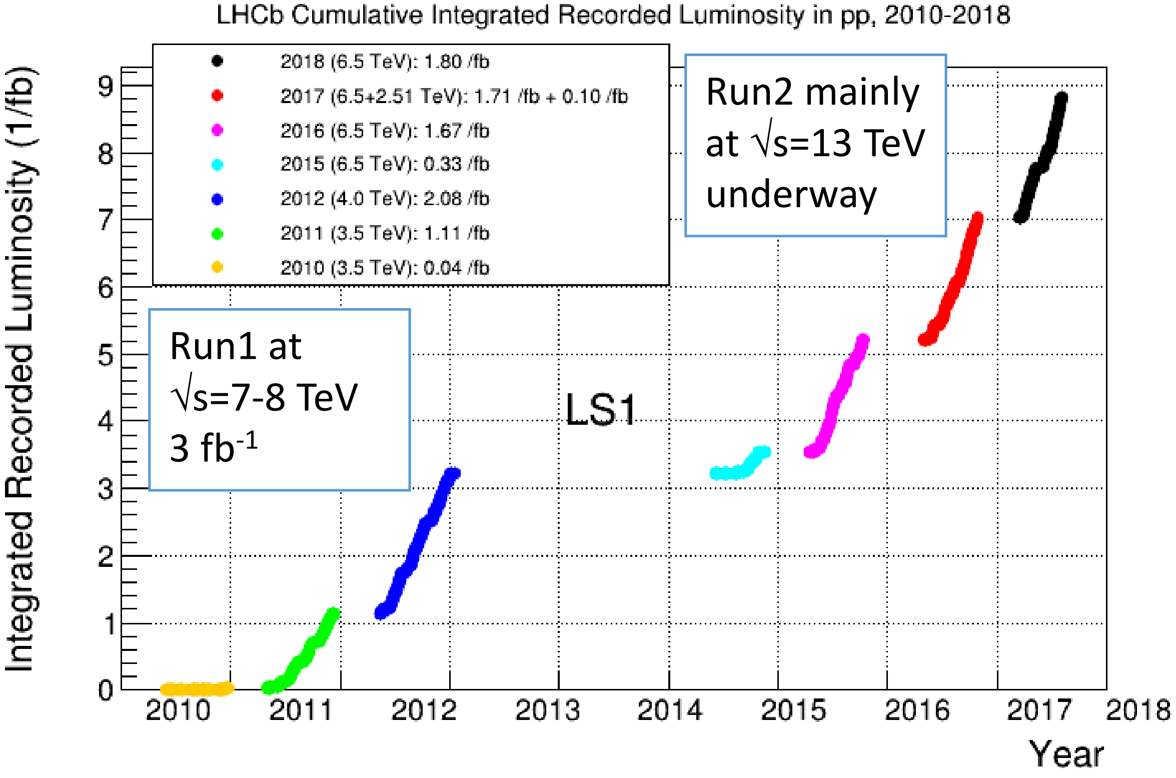
Precision tracking and vertexing
Excellent PID systems
Efficient leptonic and hadronic trigger

Recorded Luminosity

Total integrated recorded luminosity approaching 9 fb^{-1}

Above target (8 fb^{-1}) thanks to excellent LHC performance

Large beauty and charm cross-sections in pp collisions at LHC energies:
O(10^{11}) $b\bar{b}$ pairs/fb^{-1}
O(10^{12}) $c\bar{c}$ pairs/fb^{-1}
in LHCb acceptance



New sources of CPV, predicted in many BSM scenarios, may be revealed through effects in the KM mechanism

Indirect search of new physics through CKM metrology

CP violation in B decays

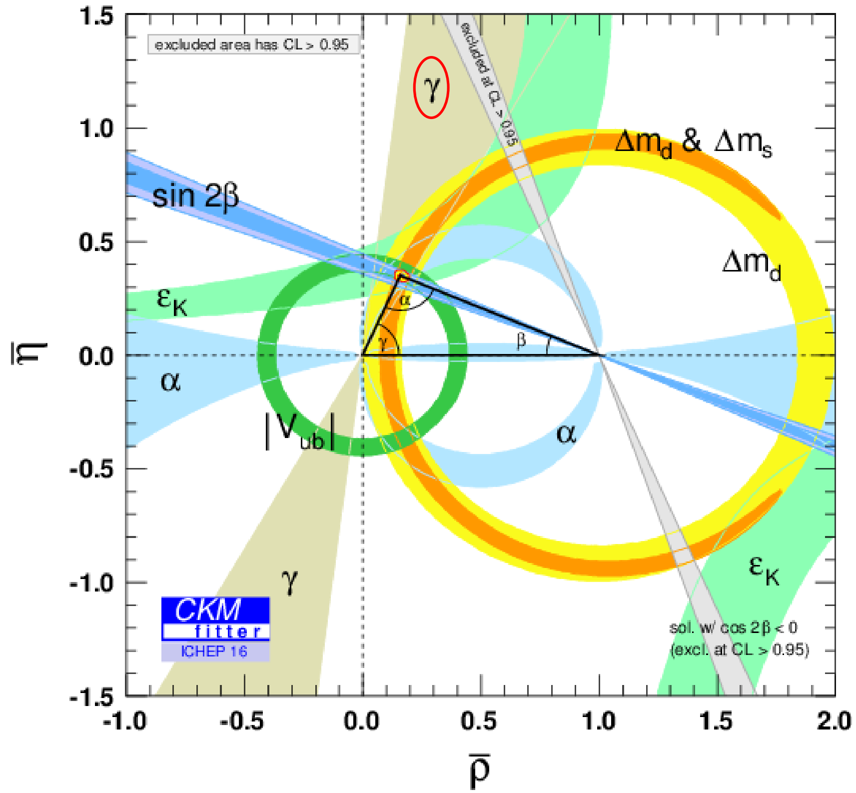
- Measurement of γ with $B \rightarrow DK$
- Combination of measurements of γ

Status of CKM

All constraints on the apex of Unitarity Triangle are consistent

The irreducible phase of the CKM matrix explains all CPV effects observed so far

Great success for the SM! Many experiments contributing



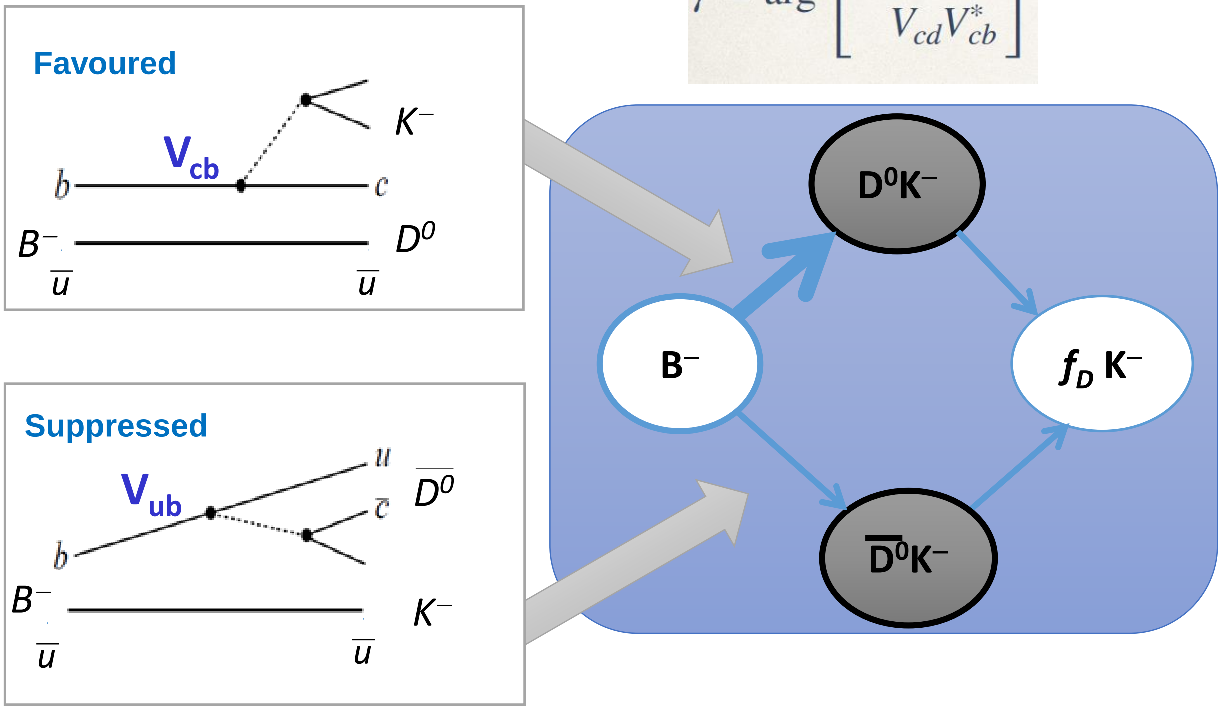
Still room for NP at 10-20% level

More precision necessary to reveal potential discrepancies

Crucial role played by theoretically “clean” measurements, particularly γ

$B^- \to DK^-$: the golden mode for γ

$$\gamma = \arg\left[-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right]$$



Essentially no theoretical uncertainties:

- Tree-level only
- All hadronic unknowns determined from data

Experimental challenges

- V_{ub} mediated transitions involved $\Rightarrow$ Small BF
- Fully hadronic decays

Different methods to determine γ depending on f_D (final state common to D^0 and D^0bar)

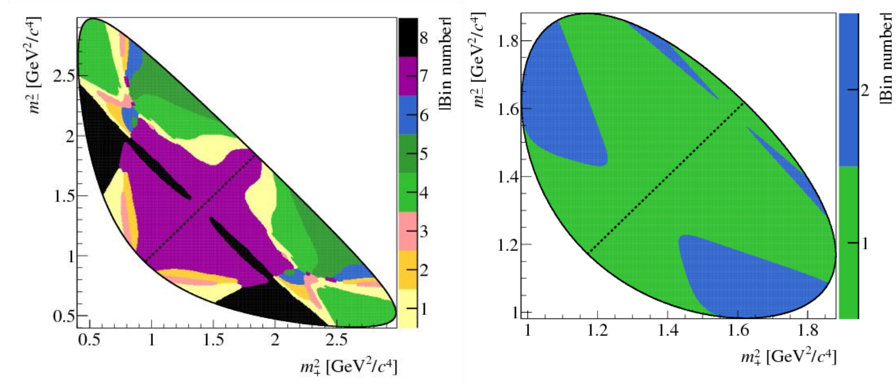
GLW	: f_D = KK, ππ	[Gronau-London-Wyler] PLB 253,483(1991), PLB 265,172 1991)
ADS	: f_D = Kπ, Kπππ	[Atwood-Dunietz-Soni] PRL 78,257(1997), PRD 63,036005(2001)
GGSZ	: f_D = K_Sππ, K_SKK	[Giri-Grossman-Soffer-Zupan] PRD 68,054018(2003)
GLS	: f_D= K_SKπ	[Grossman-Ligeti-Soffer] PRD 67,071301(2003)

γ from $B^- \to DK^-$, $D \to K_S h^+ h^-$

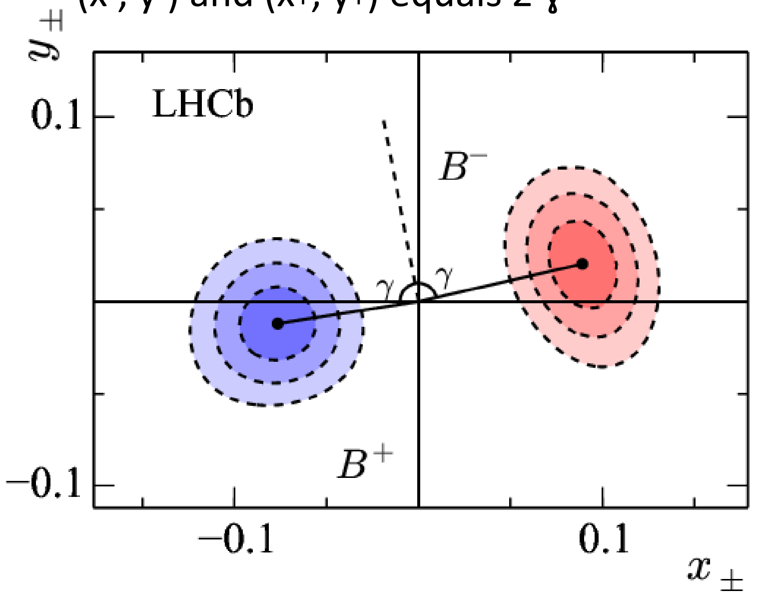
JHEP08(2018)176
LHCb, Run2, 2 fb^{-1}

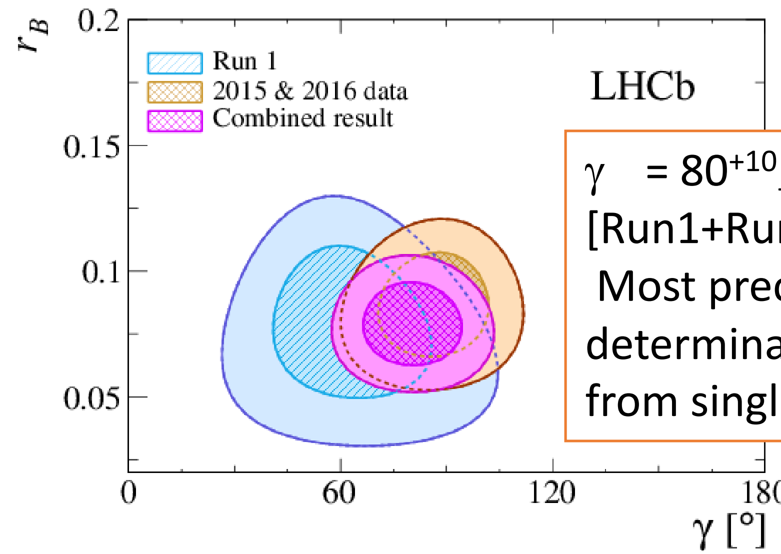
Measure $B^\pm$ rates in bins of $K_S\pi\pi$ and K_sKK Dalitz Plots (DP) - Bins chosen to maximise sensitivity to γ

Fit for cartesian coordinates
$x_\pm = r_B \cos(\delta_B \pm \gamma)$
$y_\pm = r_B \sin(\delta_B \pm \gamma)$
using external input from CLEO-c
No assumptions on D decay amplitude



Non-zero opening angle between
(x-, y-) and (x+, y+) equals 2 γ



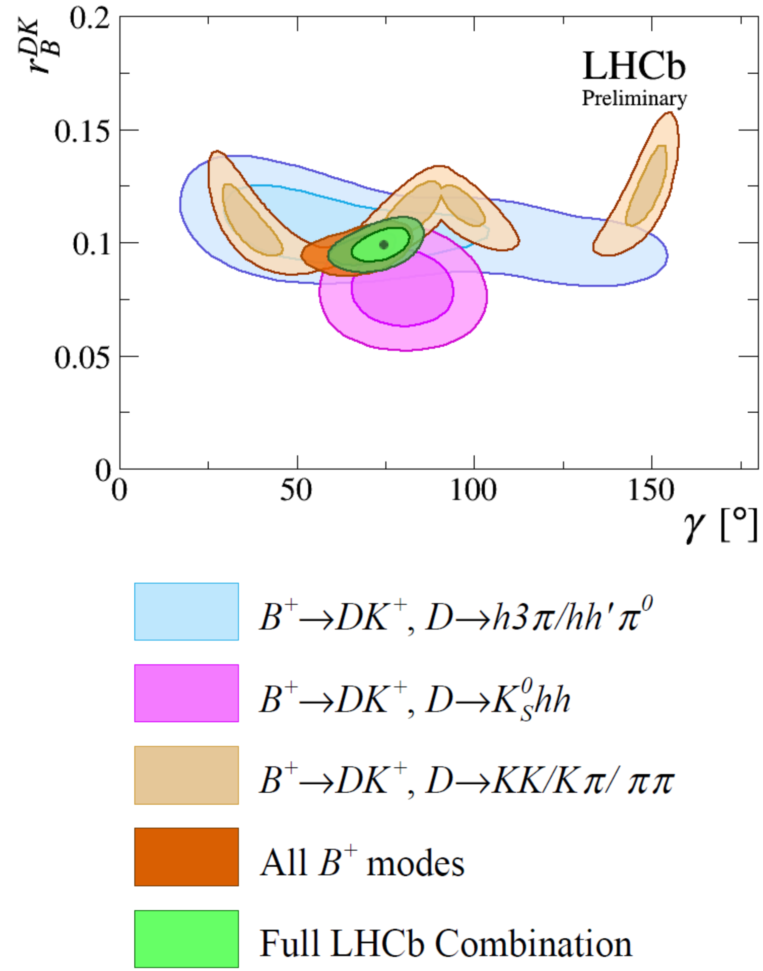


$\gamma = 80^{+10}_{-9}$ ^{o}
[Run1+Run2, 5 fb^{-1}]
Most precise determination of γ from single channel

Combination of tree-level measurements of γ

LHCb-CONF-2018-002

B decay	D decay	Method	Ref.	Dataset†
				***New additions**
$B^+ \to DK^+$	$D \to h^+h^-$	GLW	[14]	Run 1 & 2
$B^+ \to DK^+$	$D \to h^+h^-$	ADS	[15]	Run 1
$B^+ \to DK^+$	$D \to h^+\pi^-\pi^+\pi^-$	GLW/ADS	[15]	Run 1
$B^+ \to DK^+$	$D \to h^+h^-\pi^0$	GLW/ADS	[16]	Run 1
$B^+ \to DK^+$	$D \to K^0_S h^+h^-$	GGSZ	[17]	Run 1
$B^+ \to DK^+$	$D \to K^0_S h^+h^-$	GGSZ	[18]	Run 2
$B^+ \to DK^+$	$D \to K^0_S K^+\pi^-$	GLS	[19]	Run 1 *
$B^+ \to D^*K^+$	$D \to h^+h^-$	GLW	[14]	Run 1 & 2
$B^+ \to DK^{*+}$	$D \to h^+h^-$	GLW/ADS	[20]	Run 1 & 2
$B^+ \to DK^{*+}$	$D \to h^+\pi^-\pi^+\pi^-$	GLW/ADS	[20]	Run 1 & 2 *
$B^+ \to DK^+\pi^+\pi^-$	$D \to h^+h^-$	GLW/ADS	[21]	Run 1
$B^0 \to DK^{*0}$	$D \to K^+\pi^-$	ADS	[22]	Run 1
$B^0 \to DK^+\pi^-$	$D \to h^+h^-$	GLW-Dalitz	[23]	Run 1
$B^0 \to DK^{*0}$	$D \to K^0_S\pi^+\pi^-$	GGSZ	[24]	Run 1
$B^0_s \to D_s^{\mp}K^{\pm}$	$D_s^+ \to h^+h^-\pi^+$	TD	[25]	Run 1
$B^0 \to D^{\mp}\pi^{\pm}$	$D^+ \to K^+\pi^-\pi^+$	TD	[26]	Run 1 *

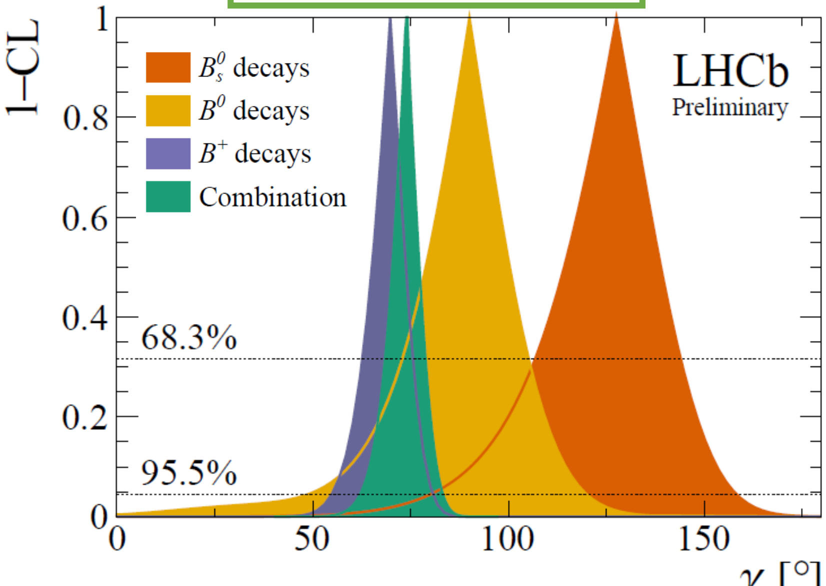


Updated combination of LHCb measurements of γ

LHCb-CONF-2018-002

Most precise measurement from single experiment

$\gamma = (74.0^{+5.0}_{-5.8})^{\circ}$



The absolute highlight for CKM physics
P. Sphicas, this conference

B^+, B^0, B_s combination is an LHCb triumph
P.Urquijo, ICHEP18

WA of direct measurements
$\gamma = (73.5^{+4.2}_{-5.1})^{\circ}$ HFLAV , winter 2018

Indirect measurement consistent within ~2σ
$\gamma = (65.8 \pm 2.2)^{\circ}$ UTFIT, summer 2018, preliminary

Small internal tensions [B_s vs B^+ :~2σ] will be monitored as more data are analysed

Charm = only up-type quark that forms weakly decaying hadrons. Unique physics access

CPV in the SM very small O(10^{-3} – 10^{-4}): not observed yet. Requires very large data samples.

Excellent prospects for observing new physics that could enhance it above SM level

LHCb has the largest data-sample of charmed hadrons on tape, and is ideally positioned to do these measurements

A holy grail

CP violation in charm

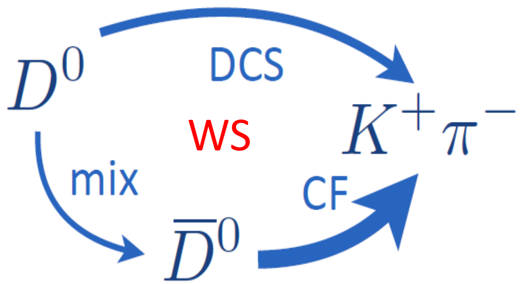
- CPV search with $D \to K\pi$

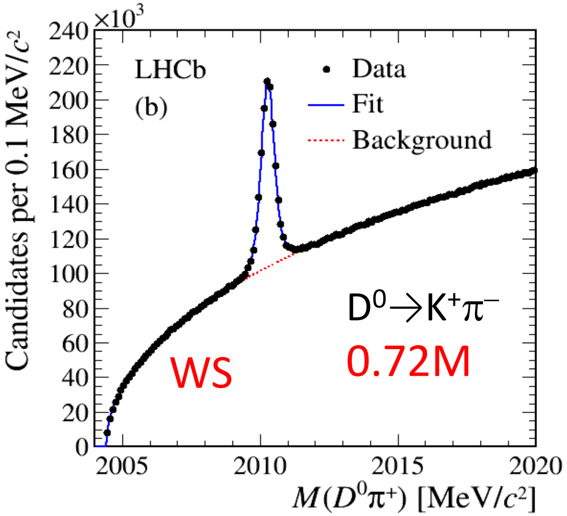
Phys Rev D97 (2018)031101

CPV and mixing with D→Kπ

5 fb^{-1}, Run1+Run2

Very large data samples of both RS($D^0 \to K^-\pi^+$) and, crucially, WS ($D^0 \to K^+\pi^-$)



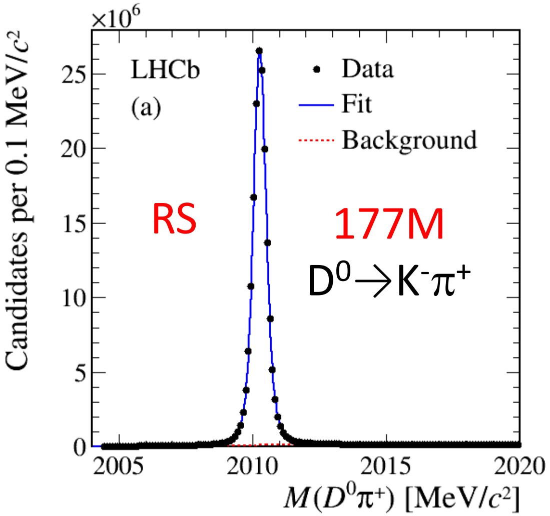


CP-averaged time-dependant ratio of WS over RS

$$R(t) \approx R_D + \sqrt{R_D}\, y' \,\frac{t}{\tau} + \frac{x'^2 + y'^2}{4}\left(\frac{t}{\tau}\right)^2$$

$x' = x \cos\delta + y \sin\delta$ $\qquad$ $x = \Delta m/\Gamma$

$y' = y \cos\delta - x \sin\delta$ $\qquad$ $y = \Delta\Gamma/2\Gamma$



Variations of R with decay-time imply D^0-D^0bar mixing

Differing patterns between D^0 and D^0bar imply CPV

Phys Rev D97 (2018)031101

$R^+(t)$ and $R^-(t)$

WS/RS yields measured separately for D^0 [R^+] and D^0bar [R^-] tagged events as a function of decay time

Soft-pion from $D^{*\pm}$ decays tags flavour at production, e.g. $D^{*+} \to D^0\pi^+$

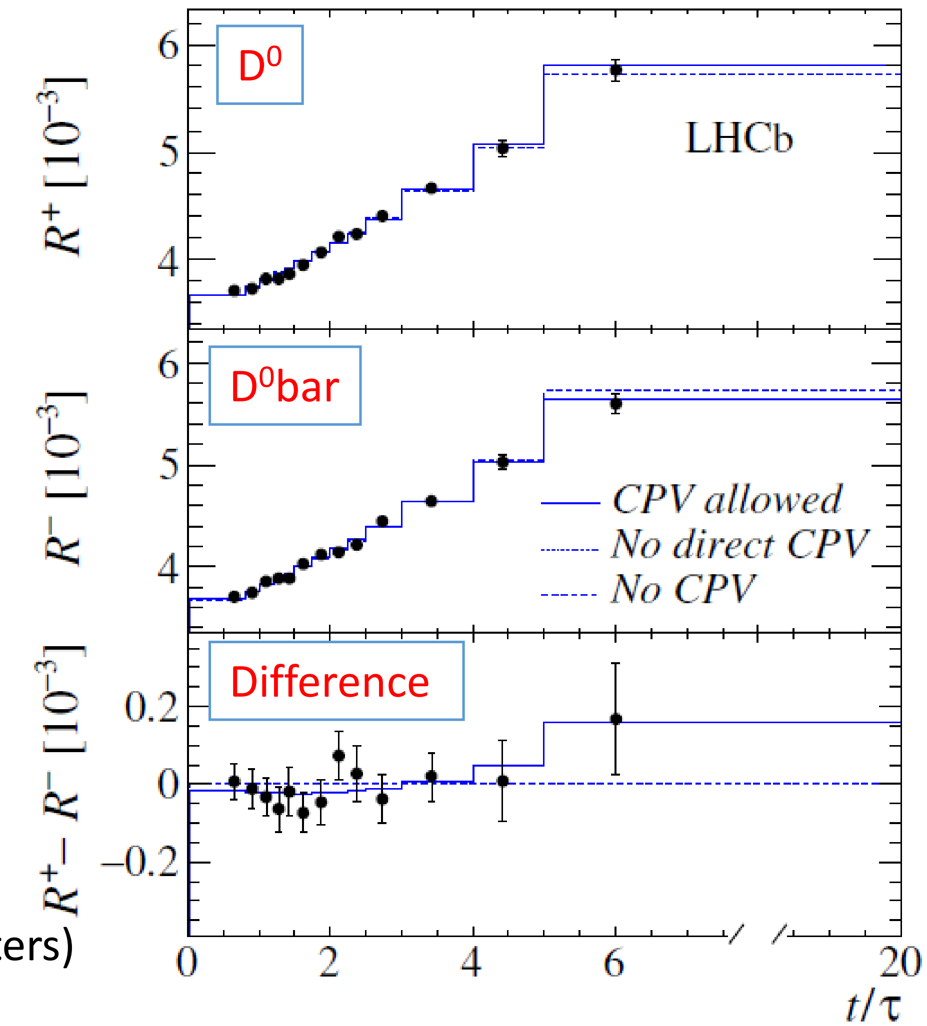
$R^+(t) \neq R^-(t) \Rightarrow$ CPV (direct +indirect)

$R_D^+ \neq R_D^- \Rightarrow$ direct CPV

No differences observed

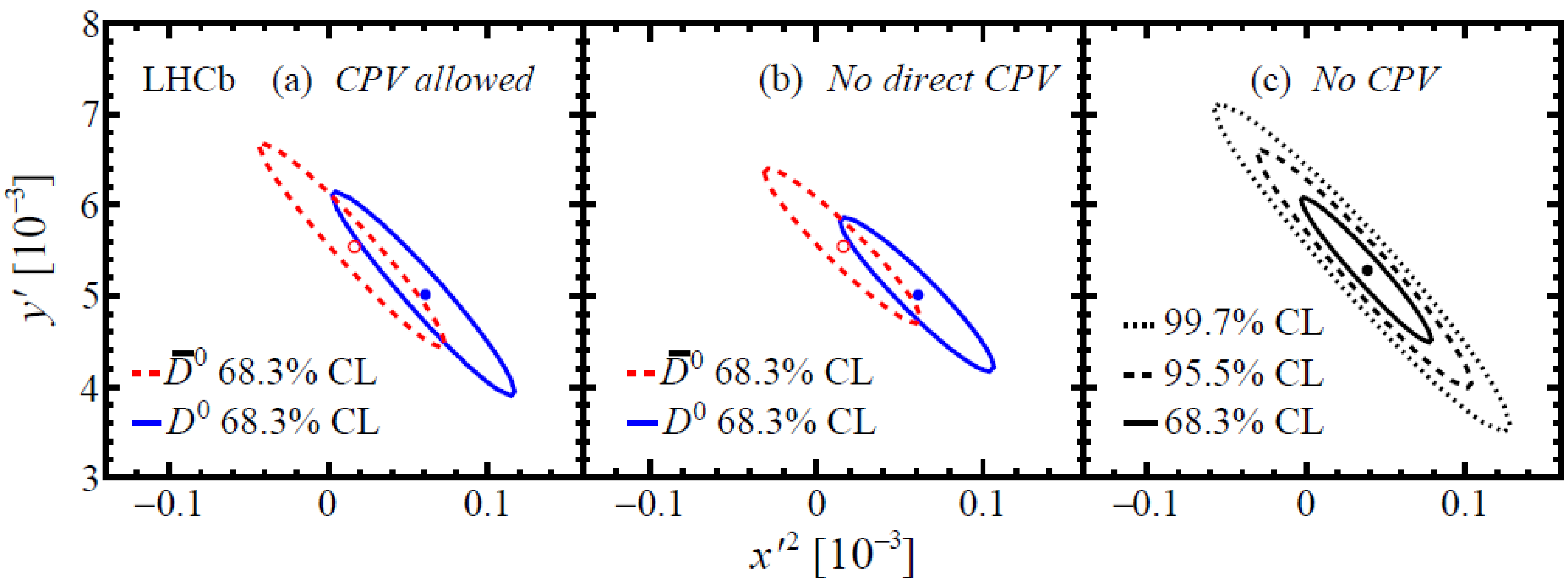
Fit ratios of yields in decay-time bins using three different hypotheses :

- CPV allowed (two sets of mixing parameters)
- No direct CPV
- No CPV (only one set of mixing parameters)



Phys Rev D97 (2018)031101

No CPV in charm! yet..



Assuming CP conservation

$$x'^2 = (3.9 \pm 2.7) \cdot 10^{-5}$$

$$y' = (5.28 \pm 0.52) \cdot 10^{-3}$$

$$R_D = (3.454 \pm 0.031) \cdot 10^{-3}$$

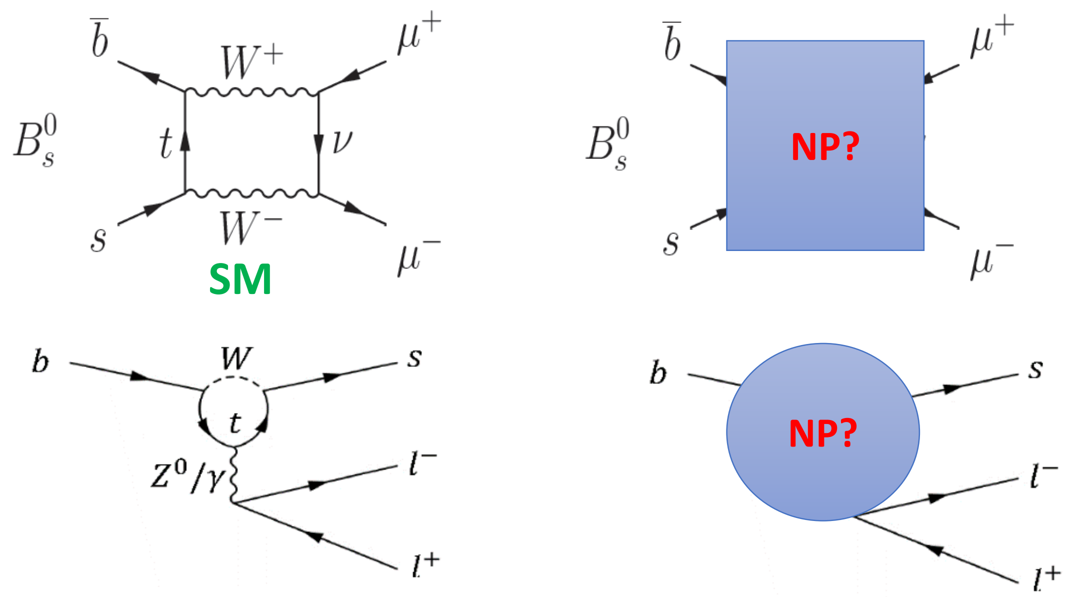
$$A_D \equiv (R_D^+ - R_D^-)/(R_D^+ + R_D^-)$$

Allowing for CPV

$$A_D = (-0.1 \pm 9.1) \cdot 10^{-3}$$

$$1.00 < |q/p| < 1.35$$

Most stringent bounds from single experiment



FCNC suppressed in SM hence NP effects can compete

New particles may significantly alter decay rates or phases.
Many observables, depending on final state

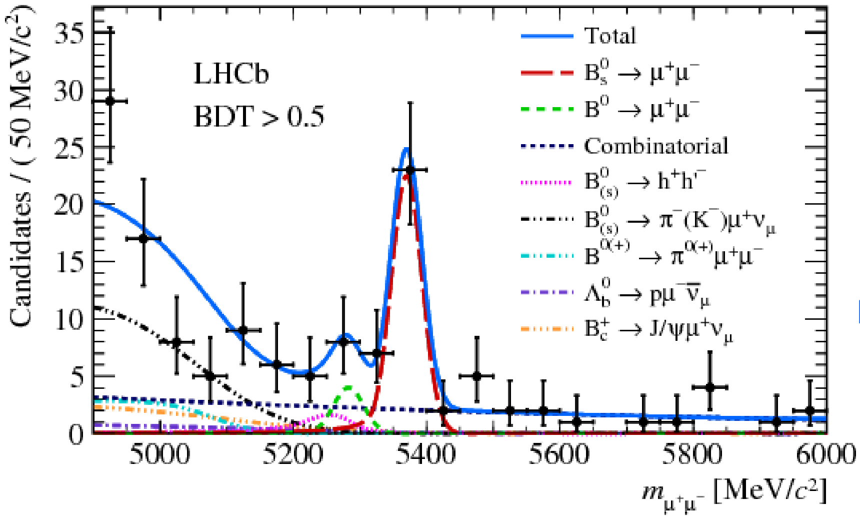
Another indirect way to probe NP

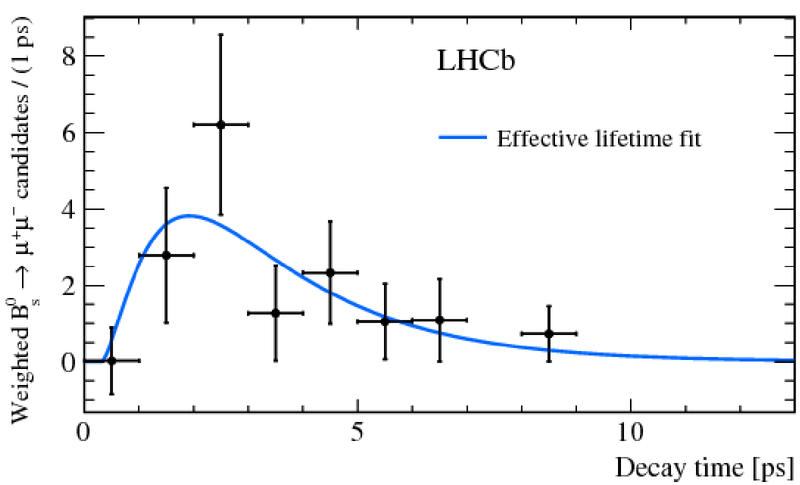
Rare decays

- Fully leptonic $B_{(s)} \to \mu\mu$
- Semileptonic b→sll and b→dll
- Rare charm D→hhμμ

$B^{(0)}_S \to \mu^+\mu^-$ "a golden mode for SUSY"

PRL 118, 191801 (2017)





CKM and helicity suppressed, tiny BF in SM:

$$\mathcal{B}(B^0_s \to \mu^+\mu^-) = (3.66 \pm 0.23) \times 10^{-9}$$
$$\mathcal{B}(B^0 \to \mu^+\mu^-) = (1.06 \pm 0.09) \times 10^{-10}$$

Bobeth et al, PRL 112 (2014) 101801

Precisely predicted

$\Rightarrow$ very sensitive to NP

Bs→μμ first observed with CMS+LHCb Run1 data
Nature 522(2015)68

LHCb 2017 update uses Run1(3fb^{-1}) + Run2(1.4 fb^{-1})

Bs→μμ finally observed by a single experiment! (7.8σ)

$$\mathcal{B}(B^0_s \to \mu^+\mu^-) = (3.0 \pm 0.6^{+0.3}_{-0.2}) \times 10^{-9}$$ (~20%)

$$\mathcal{B}(B^0 \to \mu^+\mu^-) < 3.4 \times 10^{-10} \text{ at } 95\% \text{ CL}$$

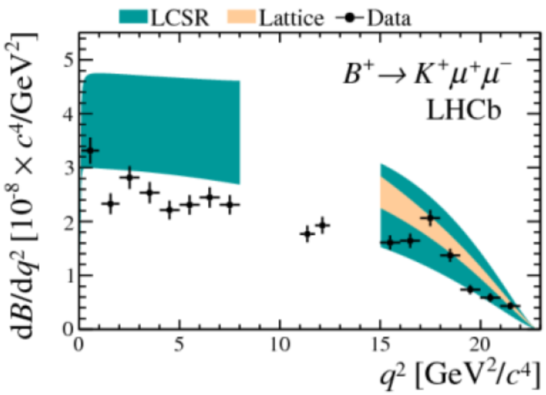
Also first lifetime measurement

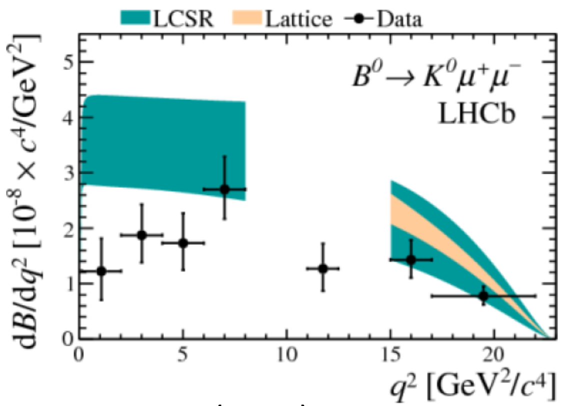
$$\tau_{\rm eff}(B_s(t) \to \mu^+\mu^-) = (2.04 \pm 0.44 \pm 0.05)\, ps$$

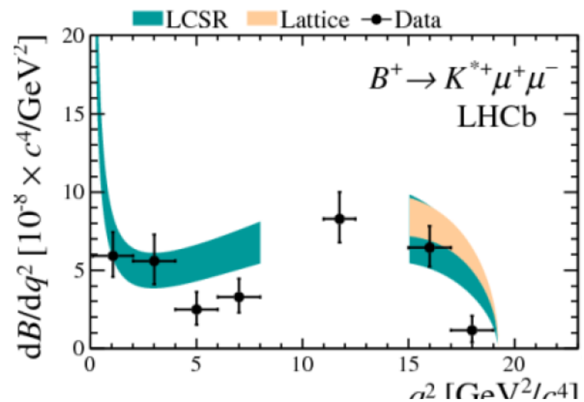
It could be affected by NP via large $\Delta\Gamma_s$
More data needed to be sensitive

b→sμμ decay rates

Differential branching fractions measured with Run1 data

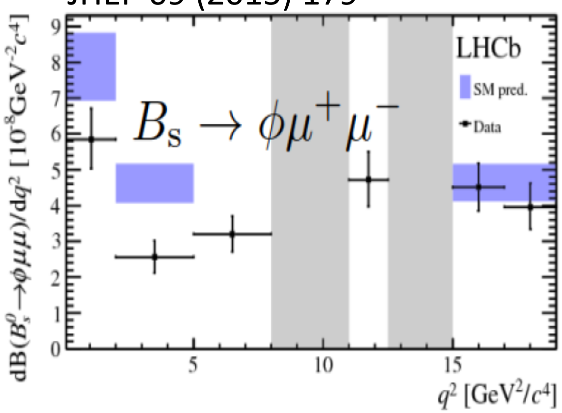




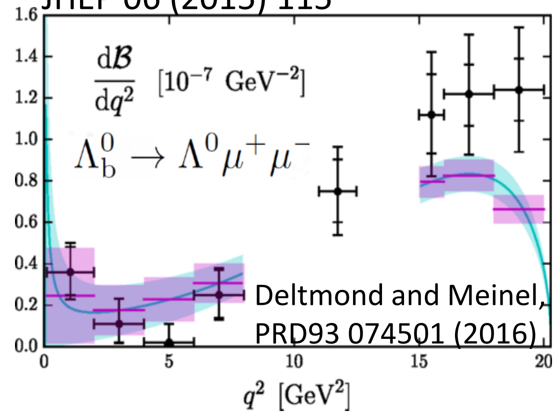


JHEP 06(2014)133

JHEP 09 (2015) 179

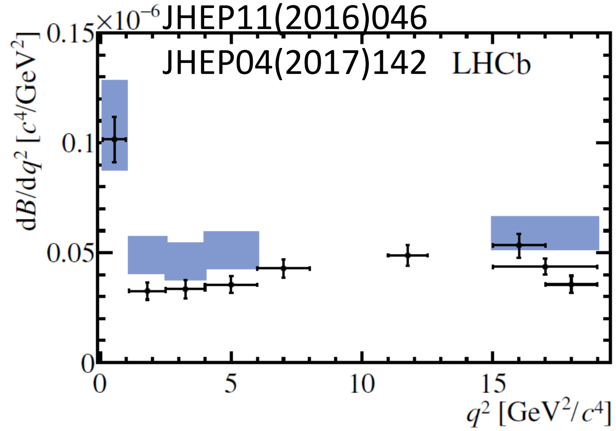


JHEP 06 (2015) 115



JHEP11(2016)046

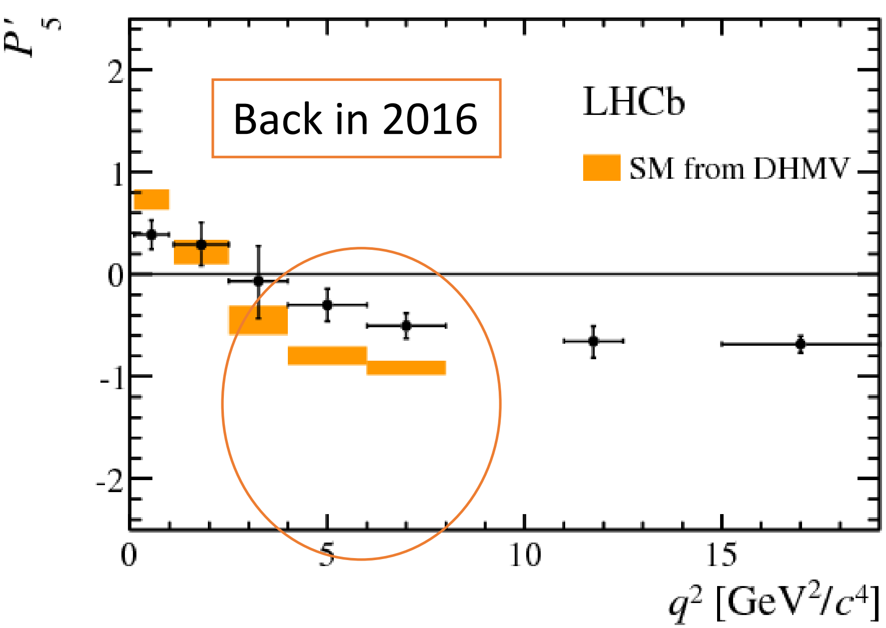
JHEP04(2017)142



In general, data tend to be lower than SM prediction at low q^2 (~1-3 σ)
Comparison limited by theoretical uncertainties [form factors]

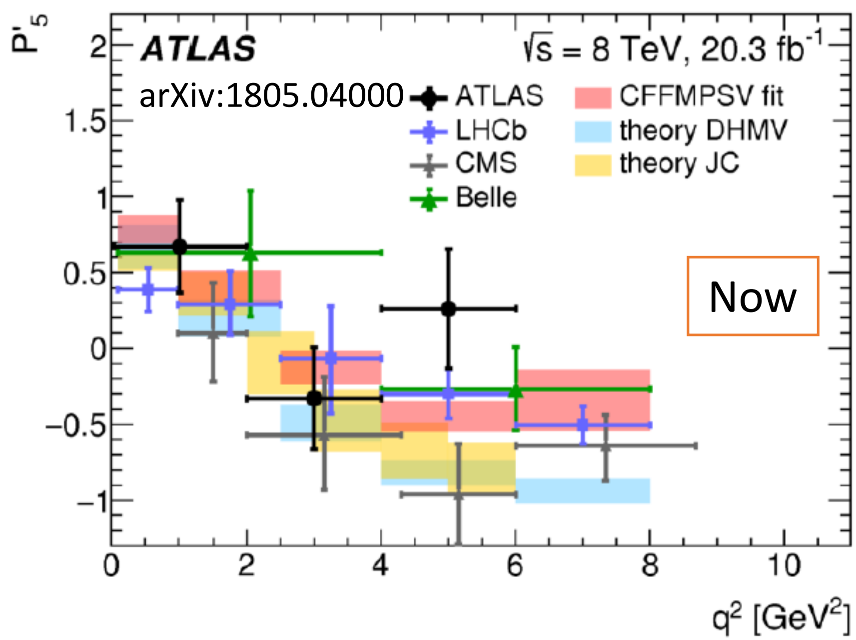
$B^0 \to K^{*0}\mu\mu$ angular analysis

LHCb, JHEP 02(2016) 104



LHCb, JHEP 02(2016) 104

Belle, PRL 118(2017)111801
CMS, PLB 781(2018)517



3.4 σ global significance

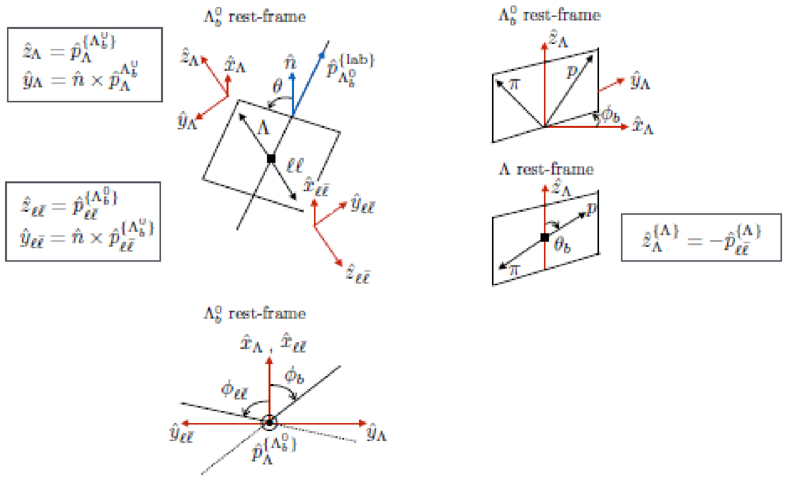
Tempting anomaly.: the angular distribution parameter P_5' was built to be robust against FF uncertainties. Even more tempting when considered together with the other b->sll anomalies , particularly the hints of LFUV (see talk by Lorenzo Capriotti and J. Kamenik on Tuesday).

Need to improve experimental precision and theoretical understanding of hadronic corrections. Run2 data will shed more light.

$\Lambda_b \to \Lambda\mu\mu$ angular analysis

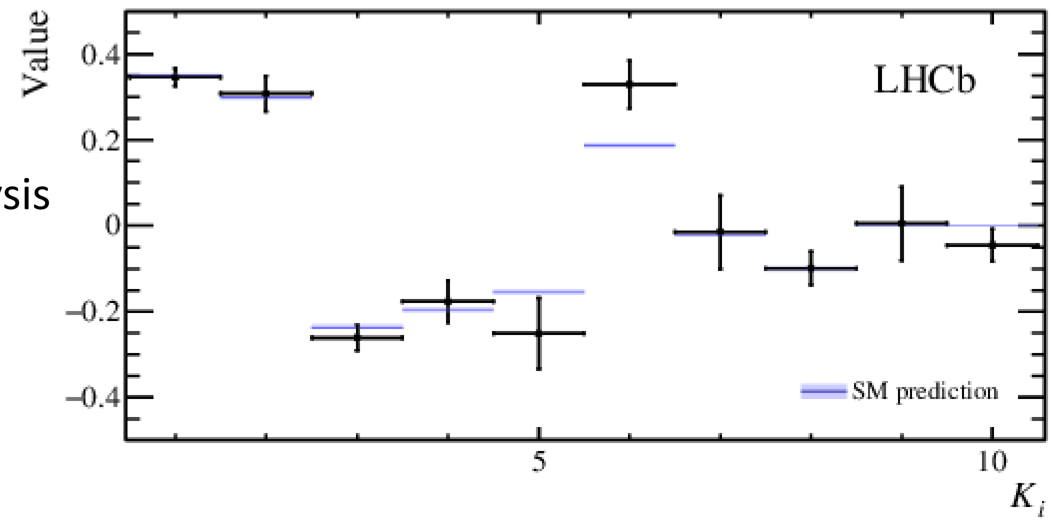
arXiv:1808.00264

- Another b->sμμ transition in baryon sector
  - Spin ½ fermions ⇒ system described by 5 angles
  - Fit angular distribution, 34 observables
    (some vanish if lambda is unpolarised)



$$\frac{d^5\Gamma}{d\vec{\Omega}} = \frac{3}{32\pi^2}\sum_{i}^{34} K_i f_i(\vec{\Omega})$$

- Analysis use 3fb^{-1} Run1 + 2fb^{-1} Run2 data
- Fit performed in high q^2 region
  15<q^2 <20 GeV^2
  where yields allows full angular analysis
  (~600 signal events)
- First analysis of this kind
  Consistent with SM expectation



b→dll transitions

JHEP 07 (2018) 020

4.6 fb^{-1}, Run1 + Run2

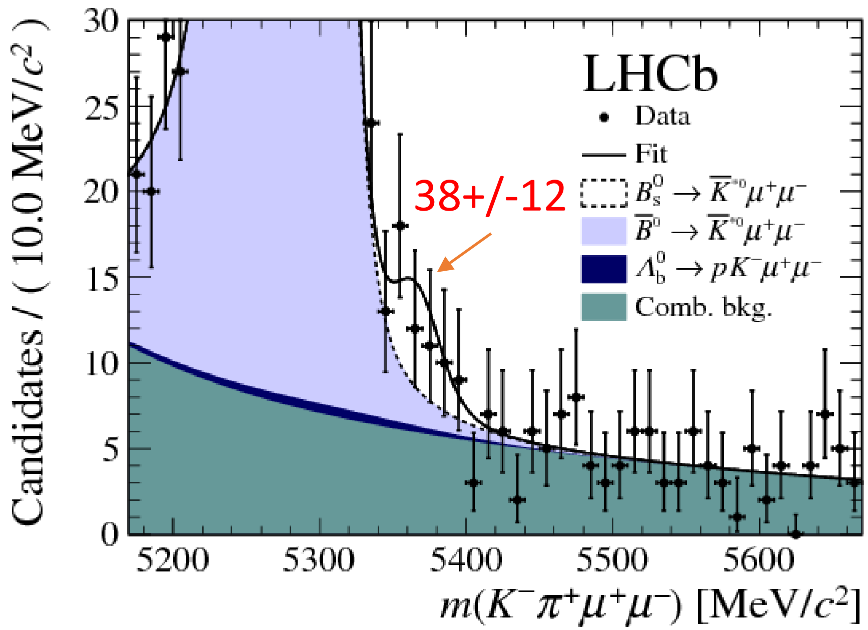
Increased interest in the suppressed b→dll transition due to the b→sll anomalies

Already observed: $B^+ \to \pi^+\mu\mu$, $B^0 \to \pi^-\pi^+\mu\mu$, $\Lambda_b \to p\pi^-\mu\mu$

LHCb, JHEP 10(2015)034
LHCb, PLB 743(2015) 46
LHCb, JHEP 04(2016)029

LHCb 2018: first evidence for $B_s \to K^{*0}\mu\mu$ [3.4 σ]

$$\mathcal{B}(B_s^0 \to \overline{K}^{*0}\mu^+\mu^-) = [2.9 \pm 1.0\,(\text{stat}) \pm 0.2\,(\text{syst}) \pm 0.3\,(\text{norm})] \times 10^{-8}$$



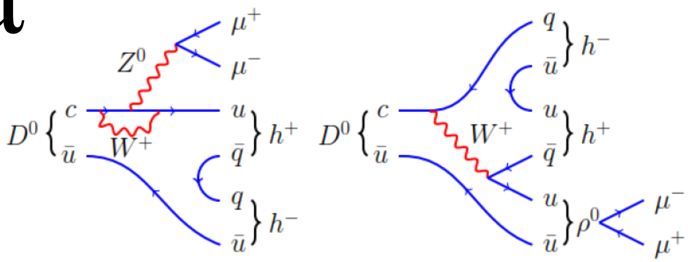
Measured BF consistent with SM prediction $O(10^{-8})$ and naïve scaling by $|V_{td}/V_{ts}|^2$ of $B^0 \to K^{*0}\mu\mu$ branching fraction

Angular distributions and LFU studies with future LHCb upgrade data-sample

Rare charm: $D^0 \to h^+h^-\mu^+\mu^-$

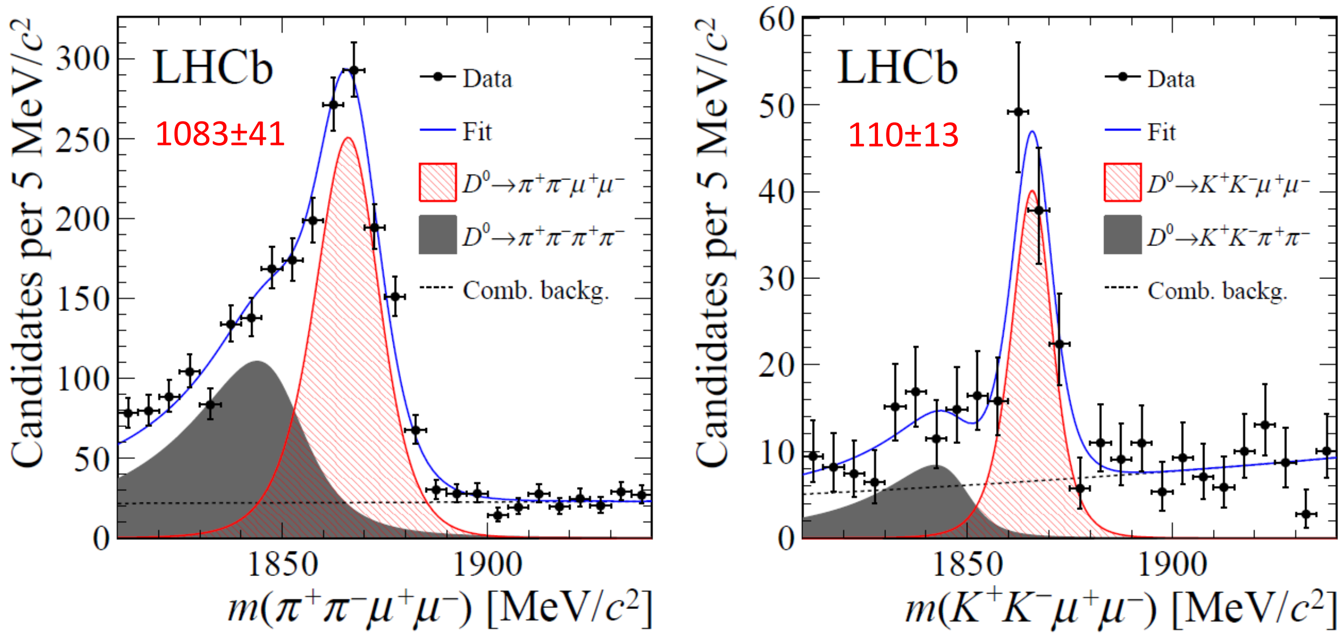
$D^0 \to \pi^+\pi^-\mu^+\mu^-$ and $D^0 \to K^+K^-\mu^+\mu^-$ are the rarest charm decays observed [BF $O(10^{-7})$] LHCb, PRL119(2017)181805

Sensitive to NP but need to mitigate effects from long-distance contributions



“short-distance” “long-distance”

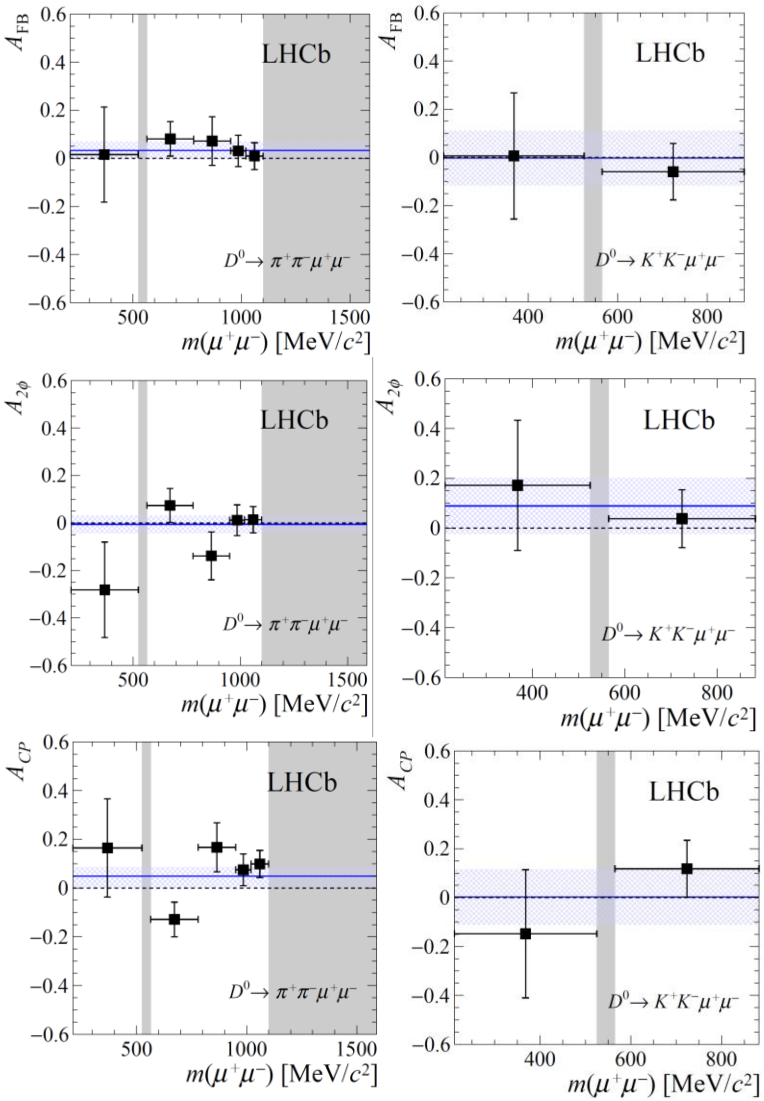
5 fb^{-1}, Run1+Run2 Phys.Rev. Lett. 121 (2018) 091801

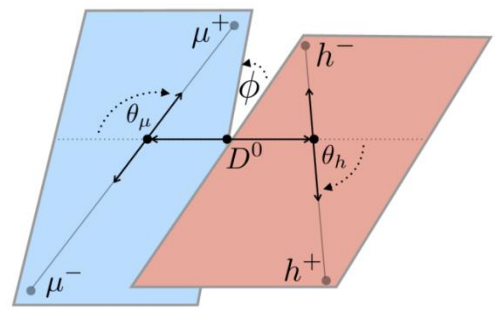


We can now look at kinematic correlations between final states particles, which provide discrimination between short and long-distance contributions

Phys.Rev. Lett. 121 (2018) 091801

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





A_{FB} = Forward-backward asymmetry

$A_{2\phi}$ = Triple product asymmetry

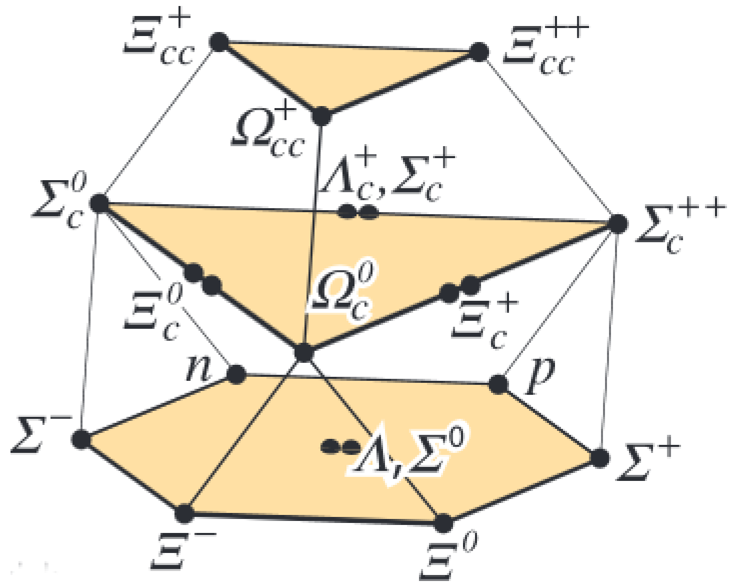
A_{CP} = CP asymmetry

All asymmetries predicted to be tiny in the SM

$$A_{FB}(D^0 \to \pi^+\pi^-\mu^+\mu^-) = (3.3 \pm 3.7 \pm 0.6)\%,$$
$$A_{2\phi}(D^0 \to \pi^+\pi^-\mu^+\mu^-) = (-0.6 \pm 3.7 \pm 0.6)\%,$$
$$A_{CP}(D^0 \to \pi^+\pi^-\mu^+\mu^-) = (4.9 \pm 3.8 \pm 0.7)\%,$$
$$A_{FB}(D^0 \to K^+K^-\mu^+\mu^-) = (0 \pm 11 \pm 2)\%,$$
$$A_{2\phi}(D^0 \to K^+K^-\mu^+\mu^-) = (9 \pm 11 \pm 1)\%,$$
$$A_{CP}(D^0 \to K^+K^-\mu^+\mu^-) = (0 \pm 11 \pm 2)\%,$$

All consistent with zero

First measurement of this kind with rare charm!



Hadron spectroscopy

Recent results on charmed baryons

For results on beauty spectroscopy, see contribution by N.Sahoo

For results on multiquark states, see contribution by A.Palano

Ξ_{cc}^{++}

- First observation of this doubly-charmed baryon in the decay $\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+$

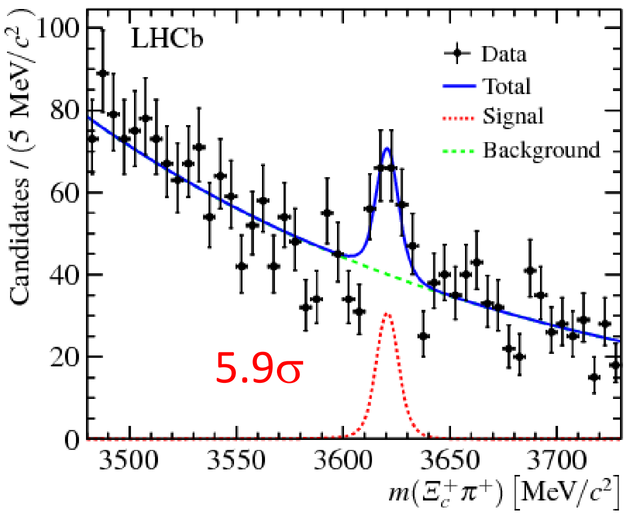
  Phys.Rev.Lett. 119 (2017)112001

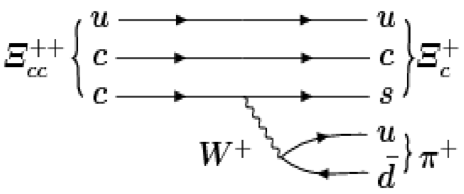
- Measurement of the lifetime critical to confirm its nature. Result consistent with expectations from weak decays

  PhysRevLett 121 (2018) 052002

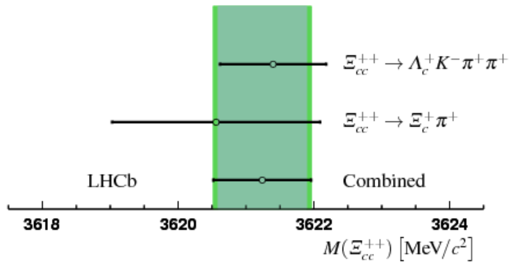
$$\tau(\Xi_{cc}^{++}) = 0.256^{+0.024}_{-0.022} \pm 0.014\,\text{ps}$$

- Recently observed also in $\Xi_{cc}^{++} \to \Xi_c^+ \pi^+$





arXiv:1807.01919



Combined mass:

$$m(\Xi_{cc}^{++}) = 3621.24 \pm 0.65\,(\text{stat}) \pm 0.31\,(\text{syst})\,\text{MeV}/c^2$$

$\Omega^0{}_c$ lifetime

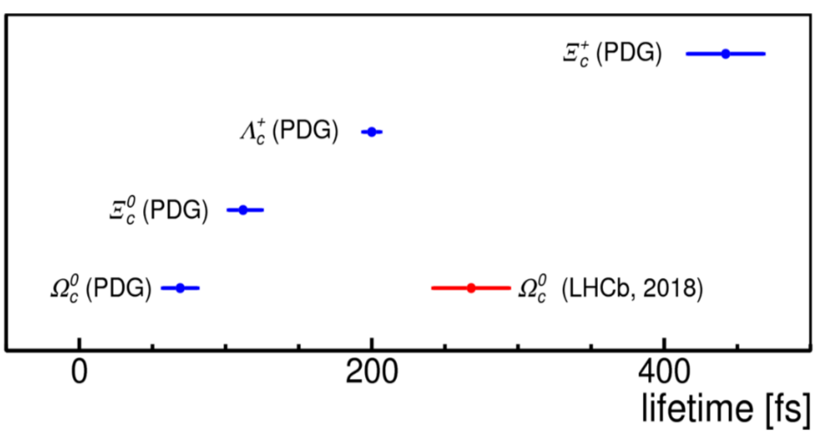
PhysRevLett.121(2018)092003

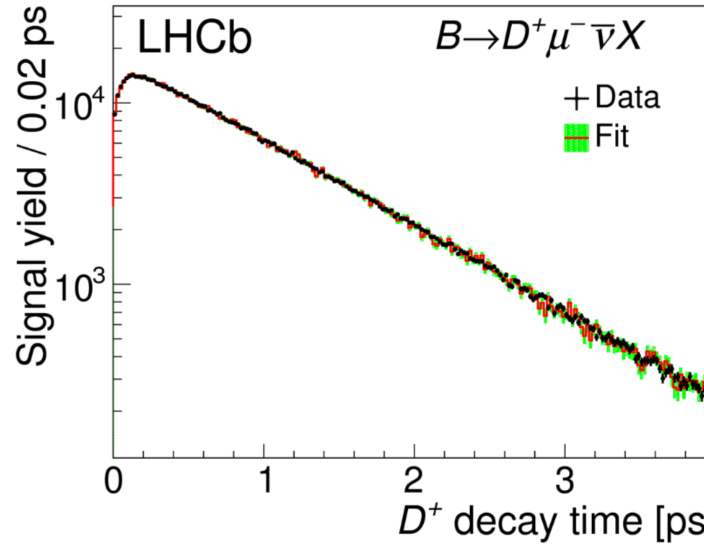
Run 1, 3 fb^{-1}

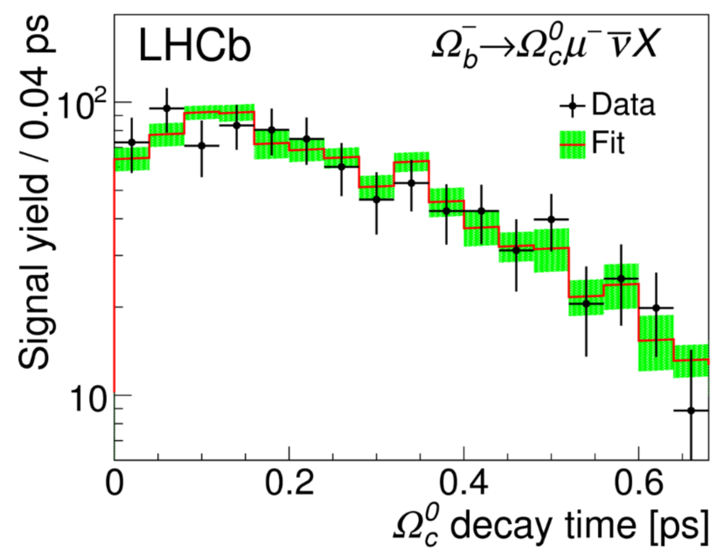
- About 1000 $\Omega^0{}_c \rightarrow pK^- K^- \pi^+$ from $\Omega^-{}_b \rightarrow \Omega^0{}_c\, \mu^- \nu_\mu X$
- Measured wrt $D^+ \rightarrow K^-\pi^+\pi^+$ from $B \rightarrow D^+\mu\nu_\mu X$ to reduce systematic uncertainties

$$\tau(\Omega_c^0) = 268 \pm 24\,(\mathrm{stat}) \pm 10\,(\mathrm{syst}) \pm 2(\mathrm{D}^+)\ \mathrm{fs}$$

4 times larger than and not consistent with current PDG average (69 ± 12 fs)





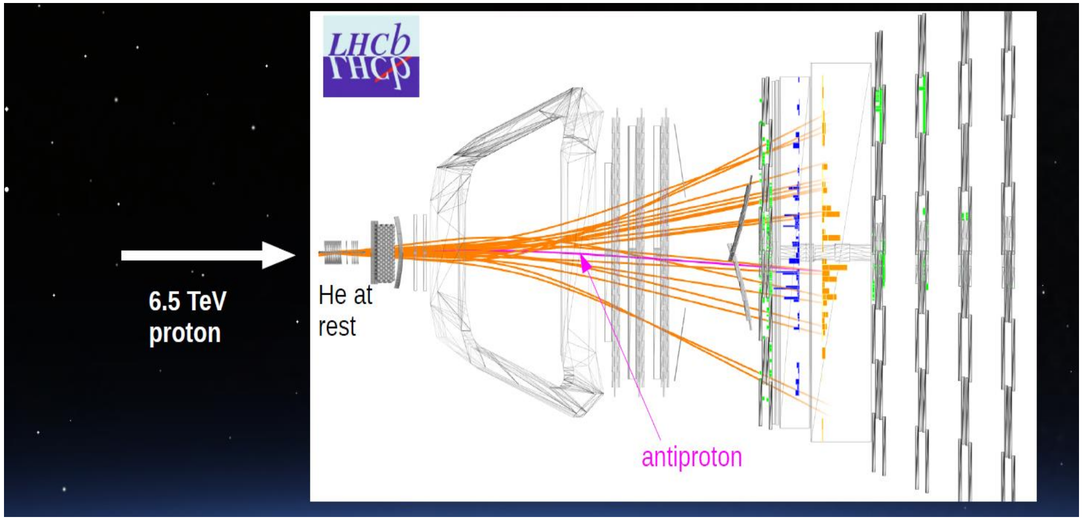


Fixed target physics

Something beyond flavour

LHCb fixed target-like geometry well suited for fixed-target physics

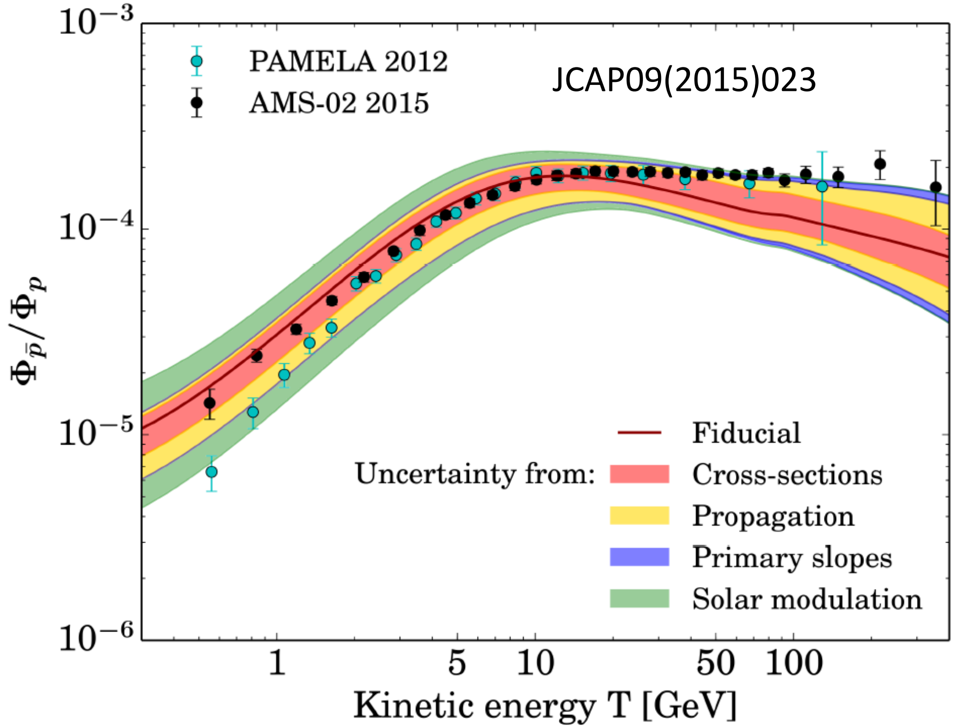
A small amount of noble gas (He, Ne, Ar,..) can be injected in the beam pipe around the LHCb interaction region (~±20m) using **SMOG** (System for Measuring Overlap with Gas)



Rich and varied programme
Important synergies with astro-particle physics

Antiproton production in pHe

- Ratio of antiproton to proton flux in cosmic rays measured precisely by AMS-02 and PAMELA



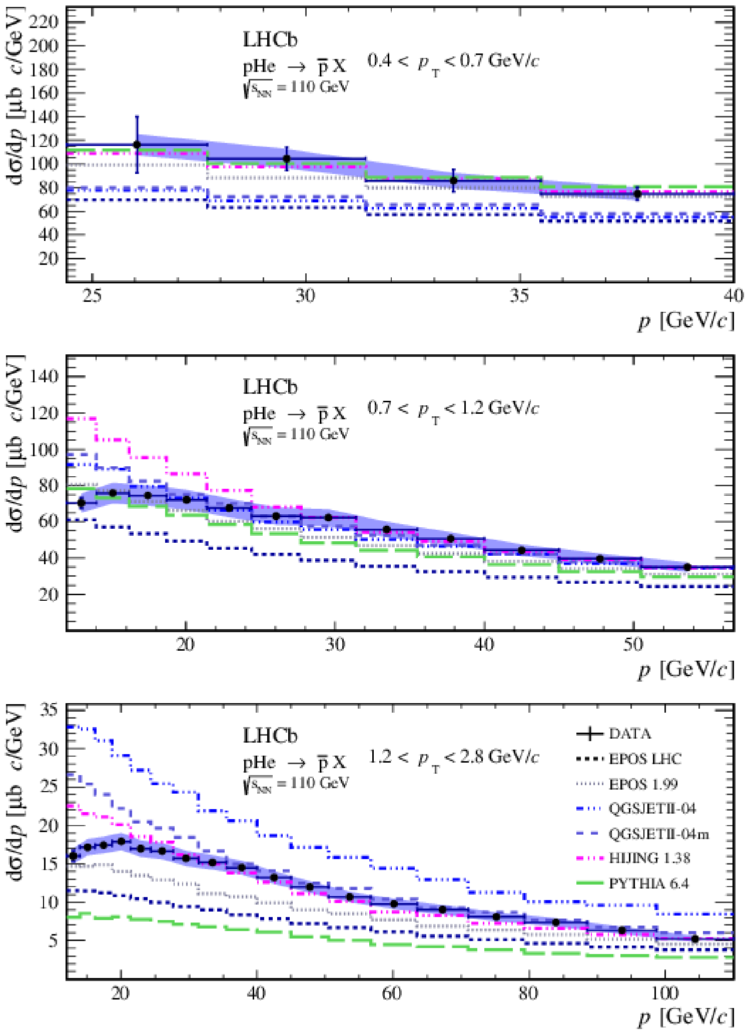
Main anti-p production mechanism: interaction of cosmic-ray protons with interstellar medium (H, He)

Excess observed at high T, though can be accommodated within current uncertainties

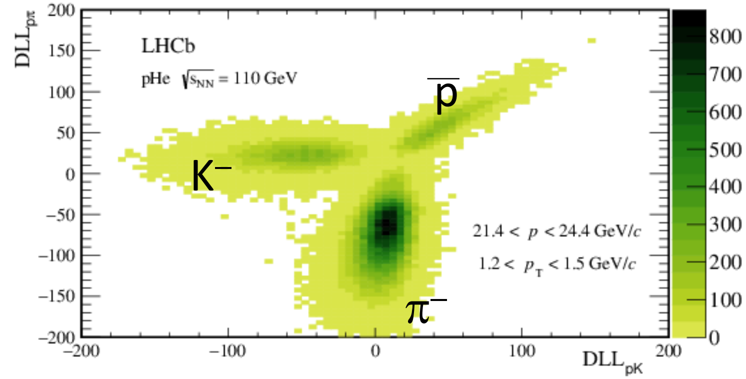
Predictions limited by knowledge of anti-p production cross-sections.

Large uncertainties on cross-section from models of hadronic interactions [predictions vary by a factor ~2] arXiv:1808.06127

Anti-proton production in pHe



- Proton energy 6.5 TeV, $\sqrt{s_{NN}}$ = 110 GeV
- 0.5 nb^{-1}, most data from a single LHC fill (5h)
- Exploit excellent PID capabilities to count antiprotons in (p, PT) bins

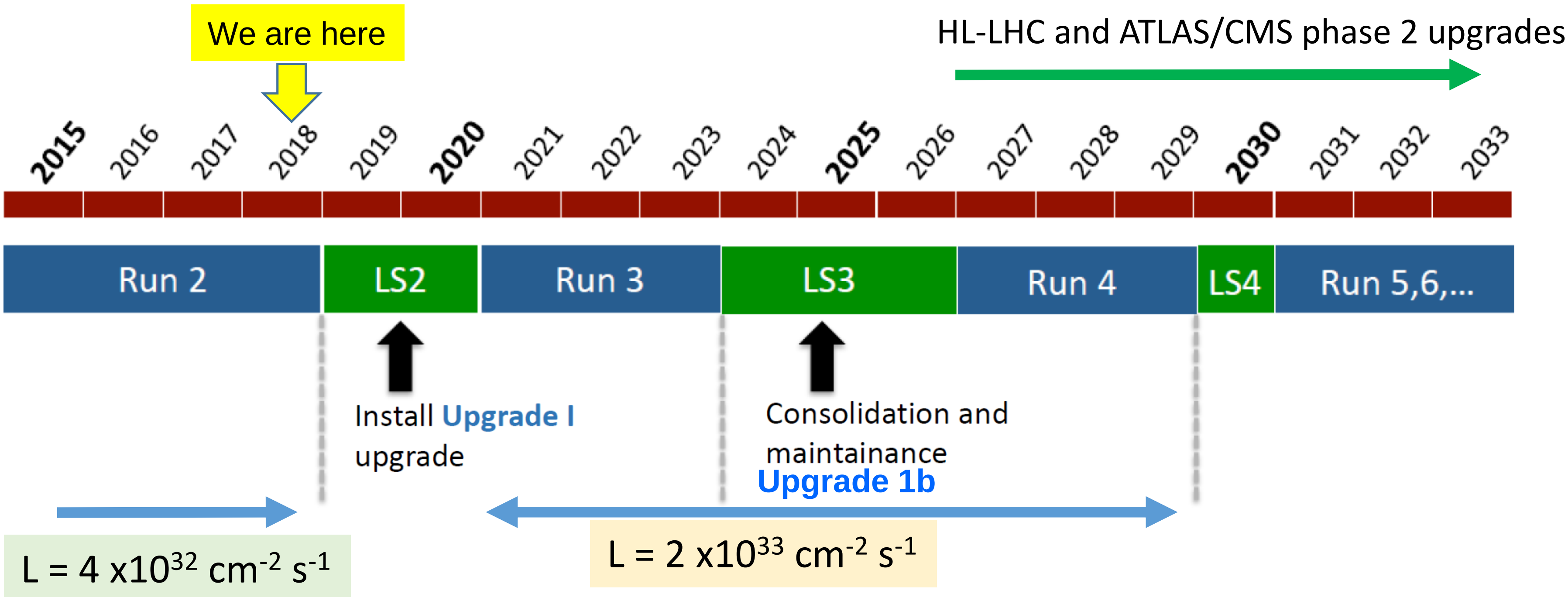


- First measurement of antiproton production in pHe collision
- Precision well below the spread among models (uncertainty <10% for most bins)
- Crucial input for interpreting the results from space-born experiments in the 10-100 GeV region

LHCb upgrades

What’s ahead of us?

LHCb Upgrade I



Upgrade I in construction

- will allow to run at 5 x current instant luminosity
- aim to collect 50 fb^{-1} by LS4
- detector consolidation and modest enhancement foreseen in LS3 (start of HL-LHC)

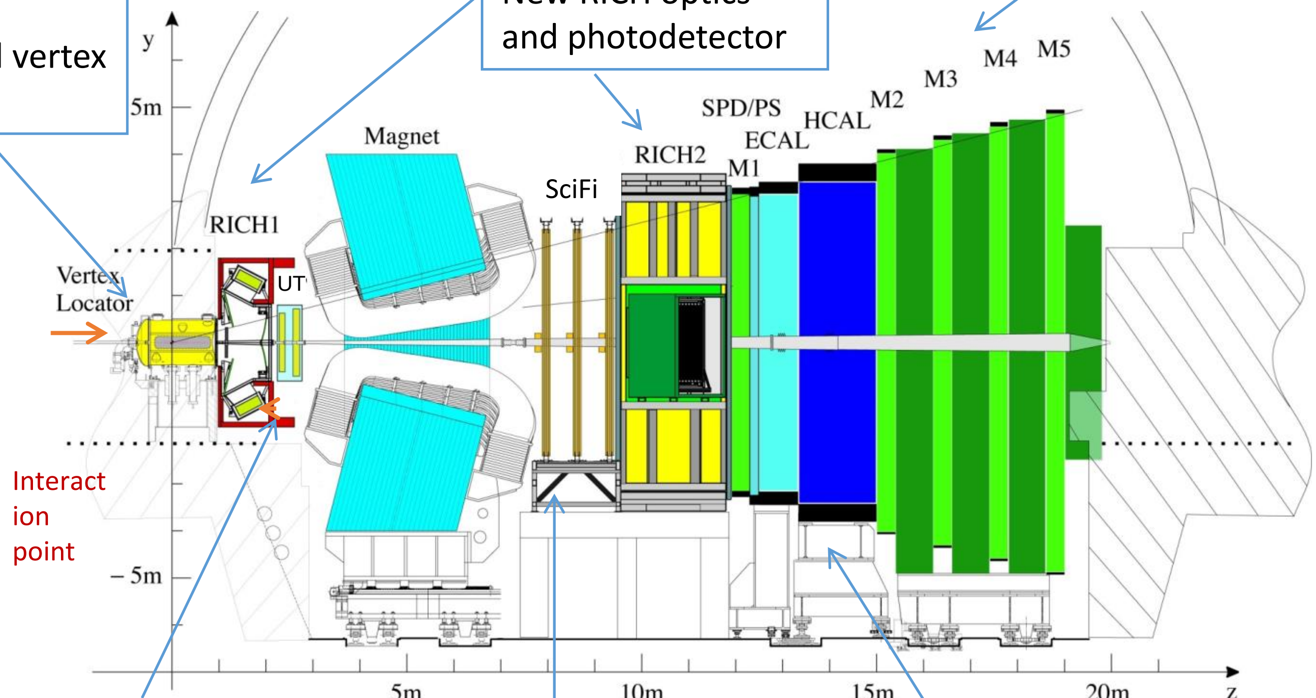
LHCb Upgrade I detector

All sub-detectors read-out at 40 MHz for a fully software trigger

VELO
New pixel vertex detector

RICh detectors
New RICH optics and photodetector

MUON system
New electronics

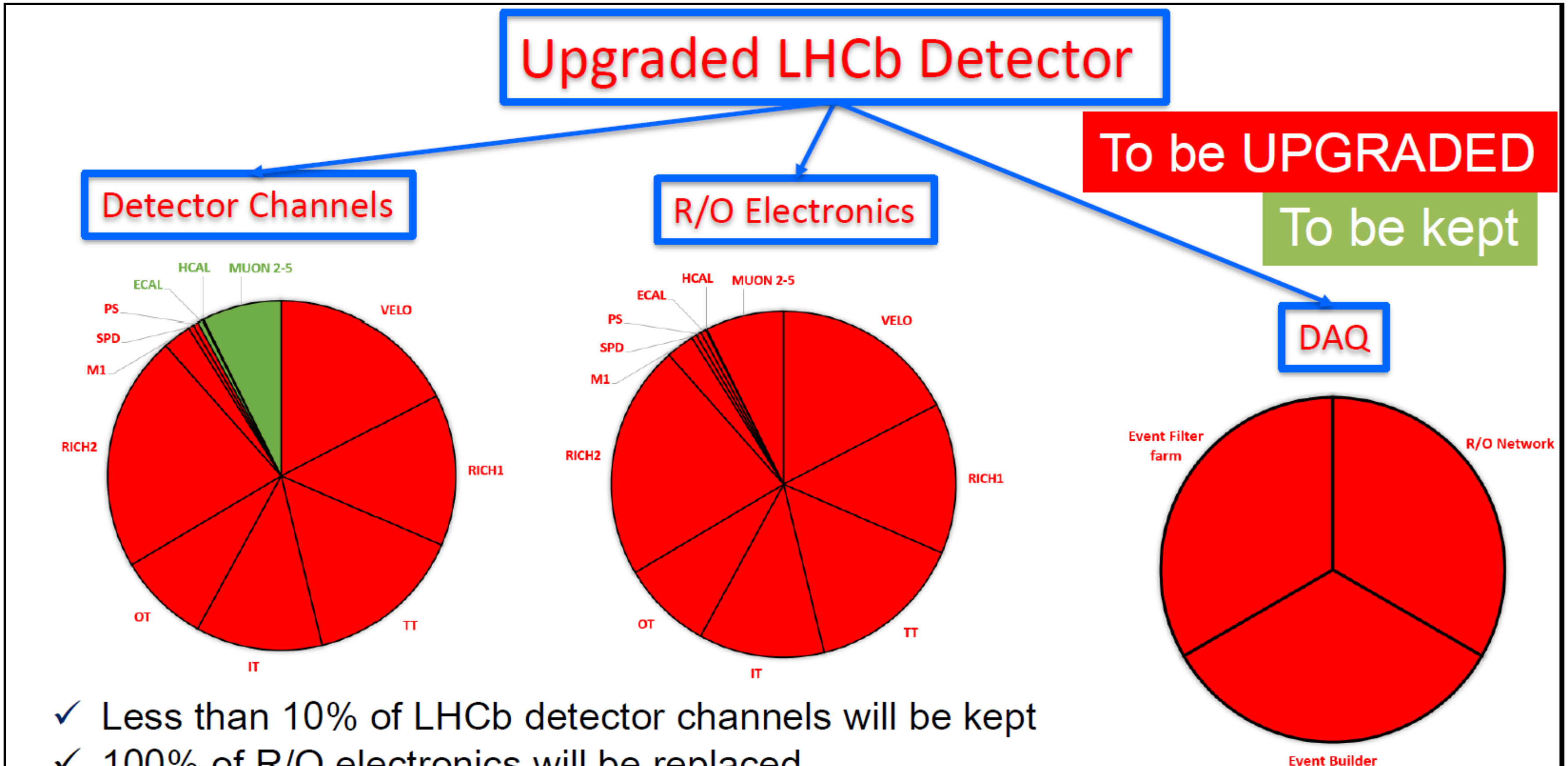


UT
New silicon Upstream Tracker

SciFi
New SCIntillator Fiber tracker

CALORIMETERS
New electronics

LHCb Upgrade I: essentially a new detector at LHC!



- ✓ Less than 10% of LHCb detector channels will be kept
- ✓ 100% of R/O electronics will be replaced
- ✓ NEW DAQ system and DATA CENTER

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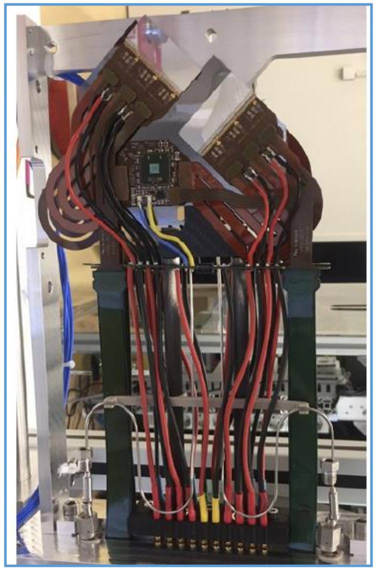
LHCb Upgrade I:
sub-detector construction underway

Velo module

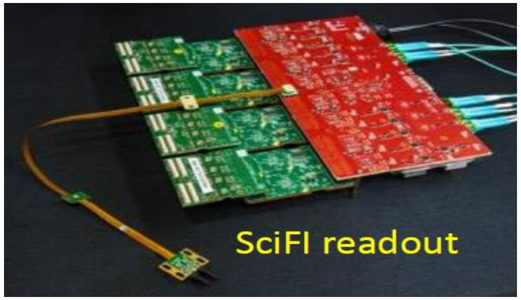


UT sensor

RICH MAMPT under test

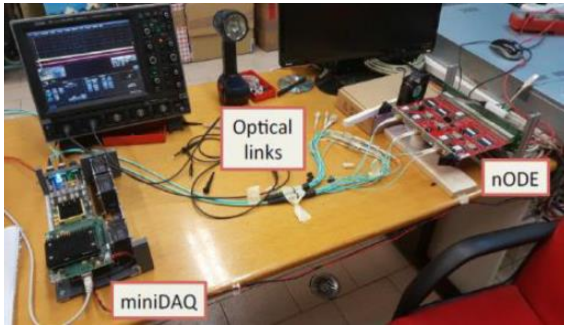
SciFi Module

UT staves constructions

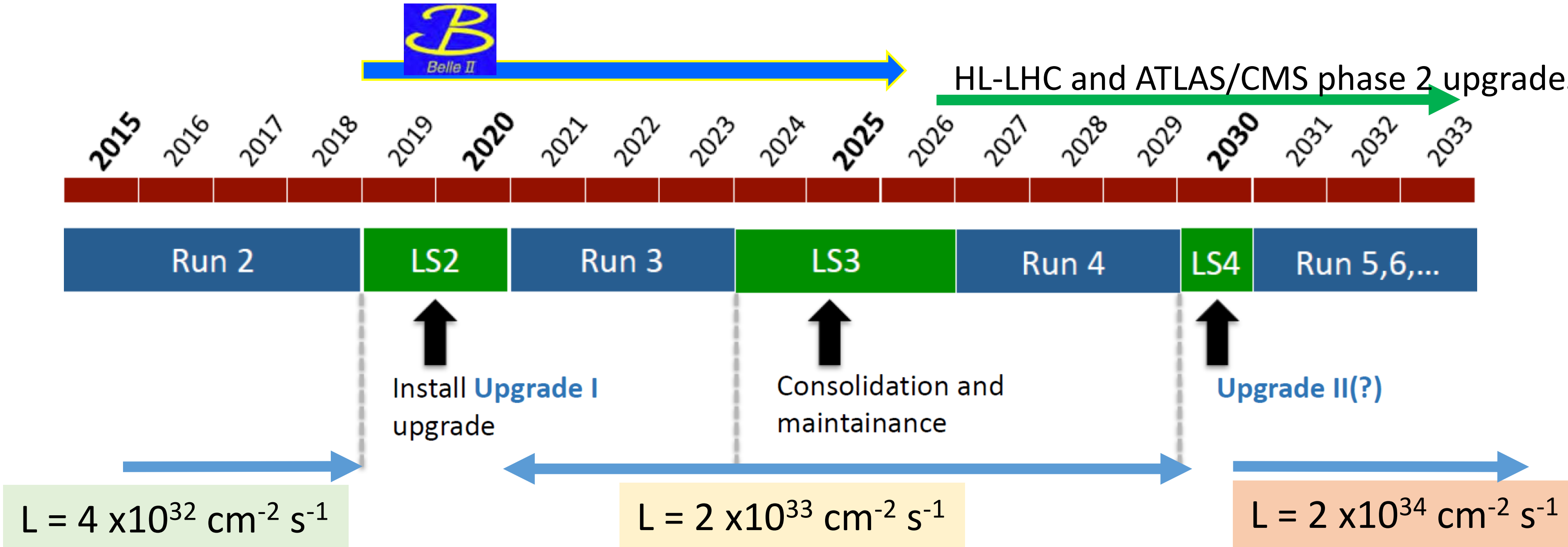


Calorimter electornics

Test of muon electronics



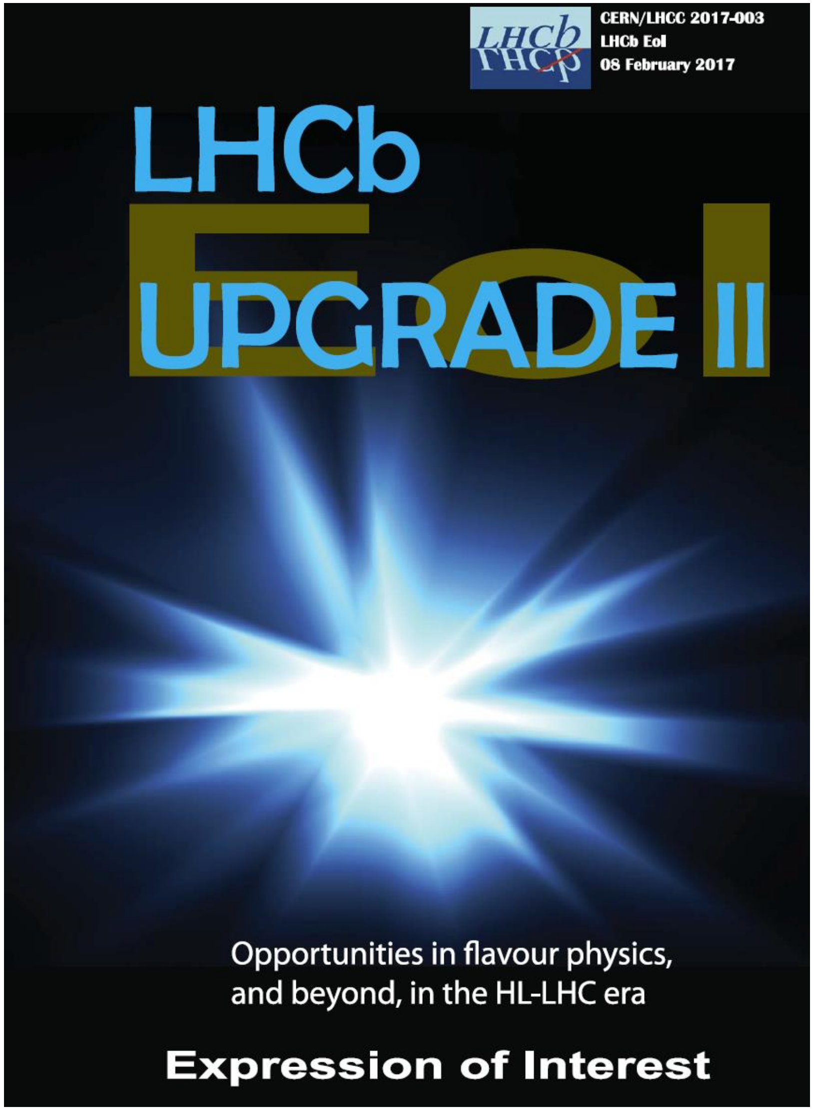
LHCb Upgrade II



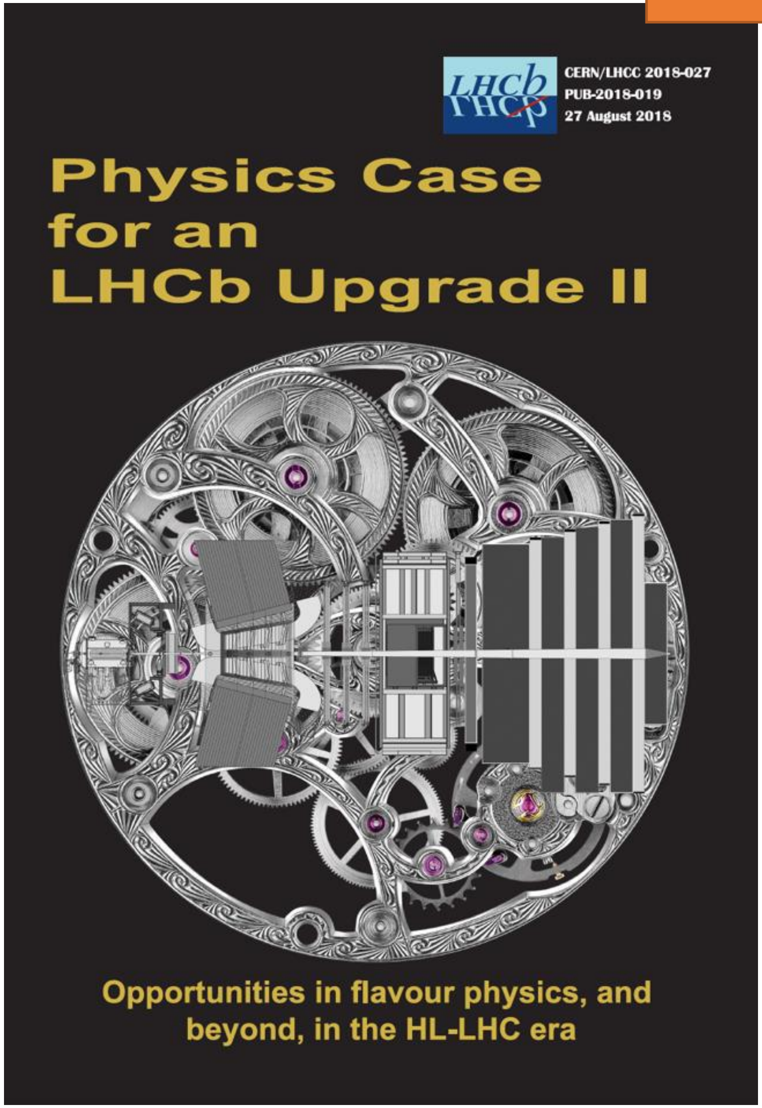
Upgrade II

- Major detector upgrade in LS4 (2030)
    - Expression of Interest [CERN-LHCC-2017-003]
- Aim to run at 10 x Upgrade I luminosity and collect 300 fb^{-1}
    - Challenging conditions for flavour physics (number of visible interactions/bunch crossing ~50)
- Physics case document released last month [CERN-LHCC-2018-027]
- LHCb may be the only large-scale flavour physics experiment to run in HL-LHC era

More information here



NEW



Conclusion

- Flavour physics is a powerful probe for physics beyond the SM. Indirect searches of new physics with flavour are complementary to direct searches. Flavour extends the new physics reach of LHC to scales beyond the collision energy
- Flavour physics is the LHCb main purpose but a broad programme even beyond flavour has been developed
- ~100 papers since last “LHC days” in Split by LHCb. Only a few presented here
  - CKM metrology: improving precision. Uncertainty on angle γ now ~5°
  - No CPV violation in charm observed yet, but precision has reached interesting region $O(10^{-2}\text{-}10^{-3})$ [SM predictions in the range 10^{-3}- 10^{-4}]
  - Rare decays: good consistency of data with SM in most cases, setting strong constraints on BSM scenarios, but some alluring tensions have emerged
  - Hadron spectroscopy also providing exciting/puzzling results
  - Fixed target programme: unique among LHC experiments. Important inputs to cosmic rays studies
- Many key measurements will still be limited by statistics after upcoming LHCb upgrade (Upgrade I, installation in 2019-20). Strong physics case for a second major upgrade in the HL-LHC era (Upgrade II, ~2030?).

HVALA

Thank You

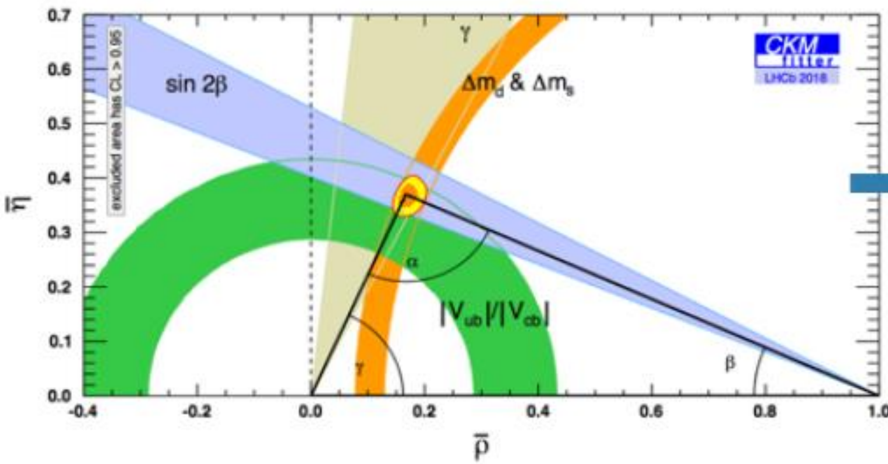

ZNANSTVENA
KNJIŽARA

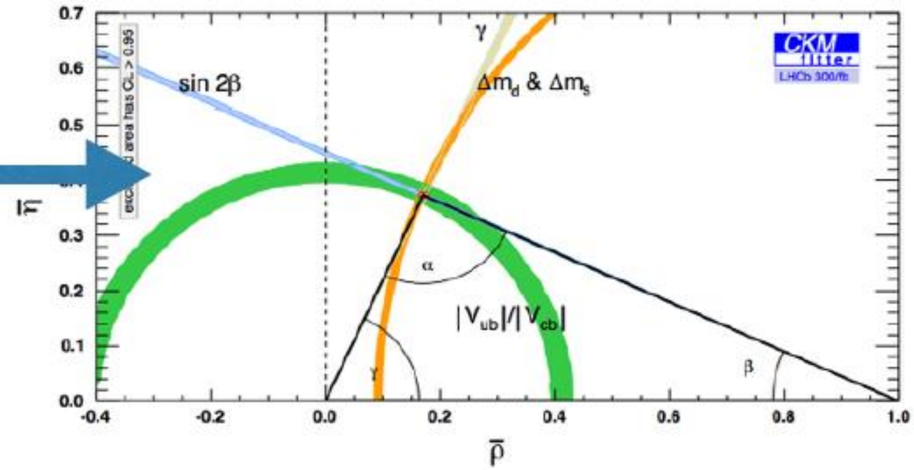
Projected sensitivity

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	0.025	0.036	0.007	–
R_{K^*} $(1 < q^2 < 6\,\mathrm{GeV}^2c^4)$	0.1	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 $B_s^0 \to D_s^+ K^-$	$(^{+17}_{-22})^\circ$	4°	–	1°	–
γ, all modes	$(^{+5.0}_{-5.8})^\circ$	1.5°	1.5°	0.35°	–
$\sin 2\beta$, with $B^0 \to J/\psi K_S^0$	0.04	0.011	0.005	0.003	–
ϕ_s, with $B_s^0 \to J/\psi\phi$	49 mrad	14 mrad	–	4 mrad	22 mrad
ϕ_s, with $B_s^0 \to D_s^+ D_s^-$	170 mrad	35 mrad	–	9 mrad	–
$\phi_s^{s\bar{s}s}$, with $B_s^0 \to \phi\phi$	154 mrad	39 mrad	–	11 mrad	Under study
a_{sl}^s	33×10^{-4}	10×10^{-4}	–	3×10^{-4}	–
$\|V_{ub}\|/\|V_{cb}\|$	6%	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%	34%	–	10%	21%
$\tau_{B_s^0 \to \mu^+\mu^-}$	22%	8%	–	2%	–
$S_{\mu\mu}$	–	–	–	0.2	–
$b \to c\ell^-\bar{\nu}_l$ **LUV studies**					
$R(D^*)$	0.026	0.0072	0.005	0.002	–
$R(J/\psi)$	0.24	0.071	–	0.02	–
Charm					
$\Delta A_{CP}(KK - \pi\pi)$	8.5×10^{-4}	1.7×10^{-4}	5.4×10^{-4}	3.0×10^{-5}	–
A_Γ $(\approx x \sin\phi)$	2.8×10^{-4}	4.3×10^{-5}	3.5×10^{-4}	1.0×10^{-5}	–
$x \sin\phi$ from $D^0 \to K^+\pi^-$	13×10^{-4}	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}	–

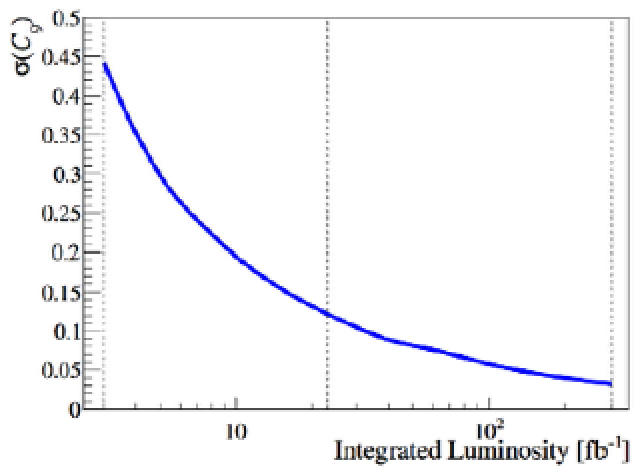
25

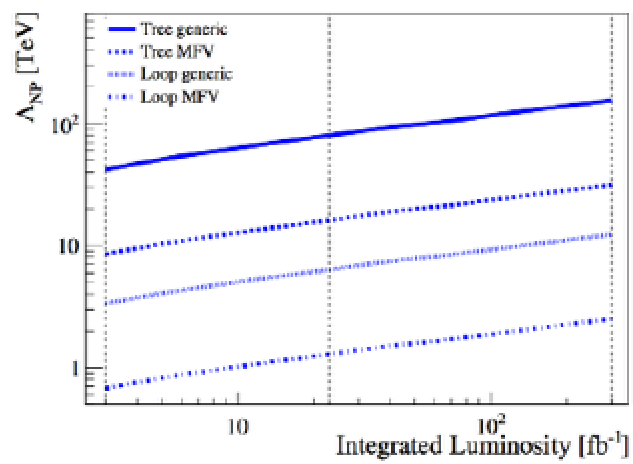
LHCb Upgrade II





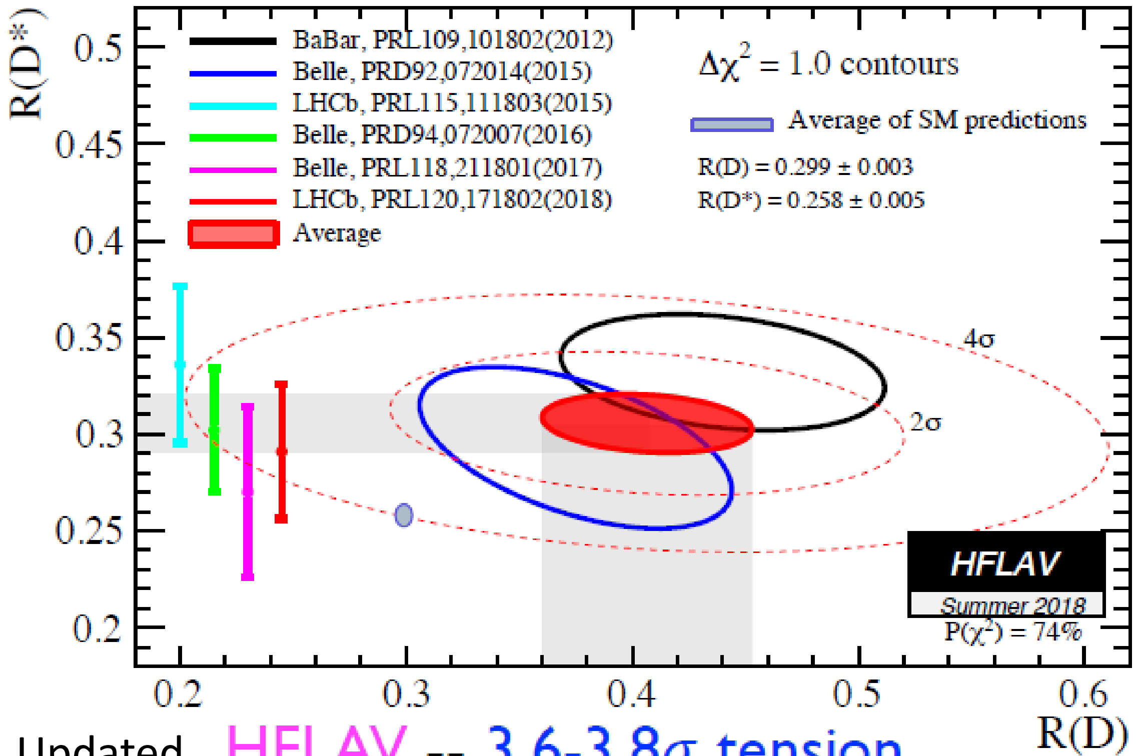
EWK penguins





LFUV in b→clν?

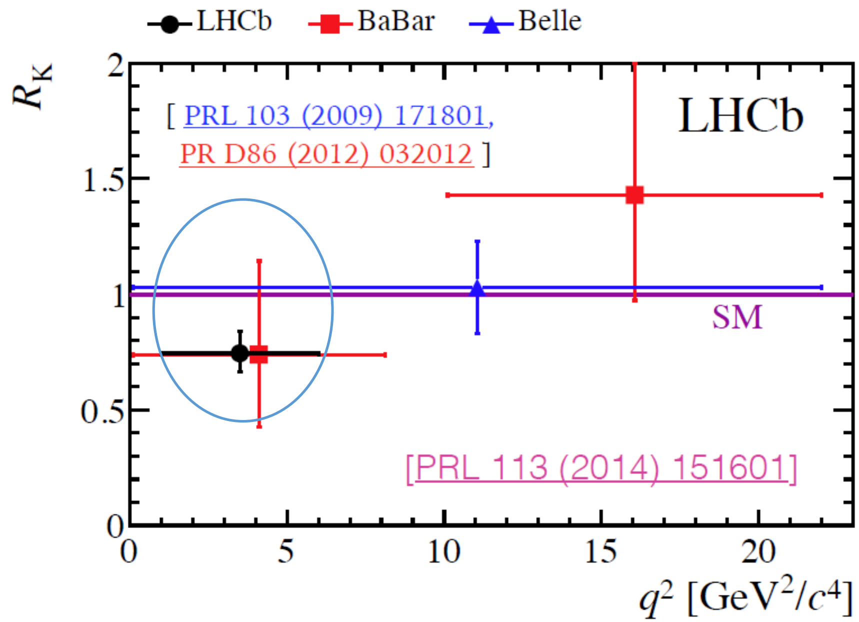
$$R(D^*) \equiv \frac{\overline{B}^0 \to D^{*+}\tau^-\bar{\nu}_\tau}{\overline{B}^0 \to D^{*+}\mu^-\bar{\nu}_\mu}$$



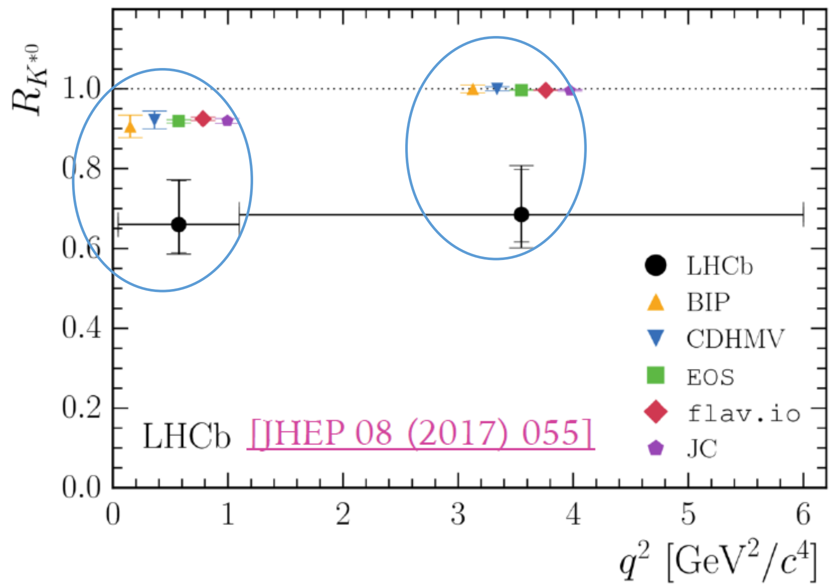
Updated HFLAV -- 3.6-3.8σ tension

LFUV in b→sll?

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



2.6σ low

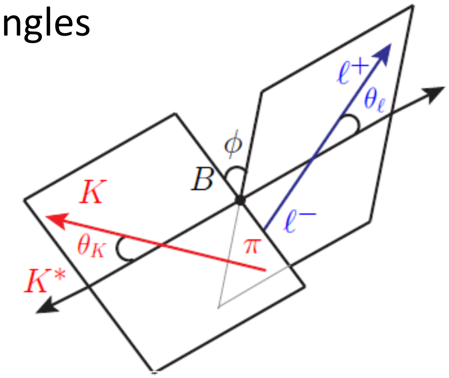


2-2.5σ low

$B^0 \to K^{*0}(K\pi)\mu\mu$: angular analysis

Study decay rate as a function of muon invariant mass and three angles

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



LHCb, Run1, JHEP 02(2016) 104

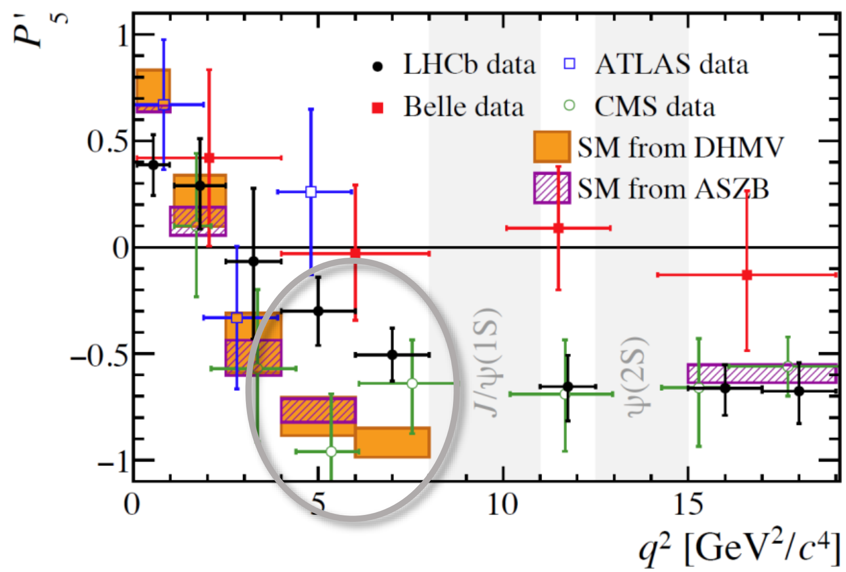
F_L , fraction of longitudinal polarisation of K^{*0}

Set of observables with reduced hadronic uncertainties defined using ratios

$$P'_{4,5,8} = \frac{S_{4,5,8}}{\sqrt{F_{\mathrm{L}}(1-F_{\mathrm{L}})}}$$

Independent of form-factors at leading order

S.Descotes-Genon et al., JHEP01(2013)048



PRL 118(2017)11180

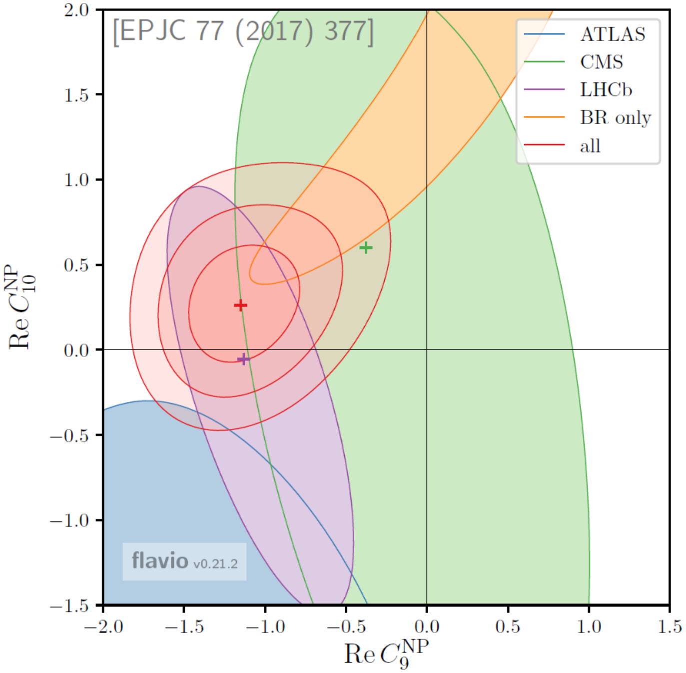
PLB 781(2018)517

arXiv:1805.04000

Compatibility of LHCb result with SM: 3.4σ

b->sμμ anomalies interpretations

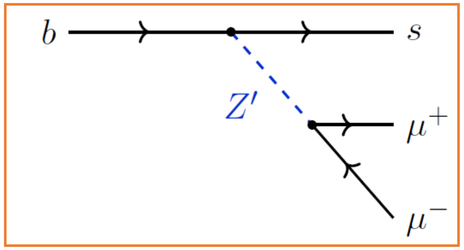
Global fits to b->sμμ measurements including branching fractions and angular observables

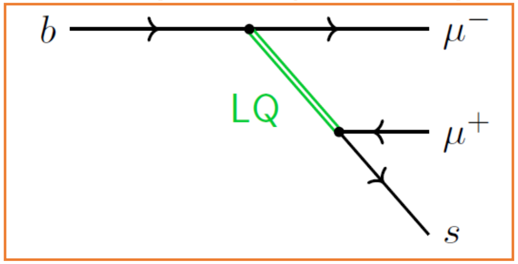


Good consistency among measurements

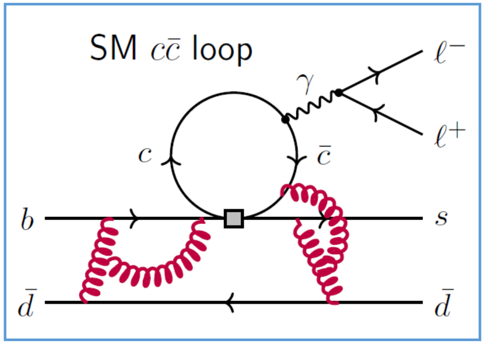
~4-5 σ deviation wrt SM for Wilson coefficient C_9

Possible NP scenarios (among others)



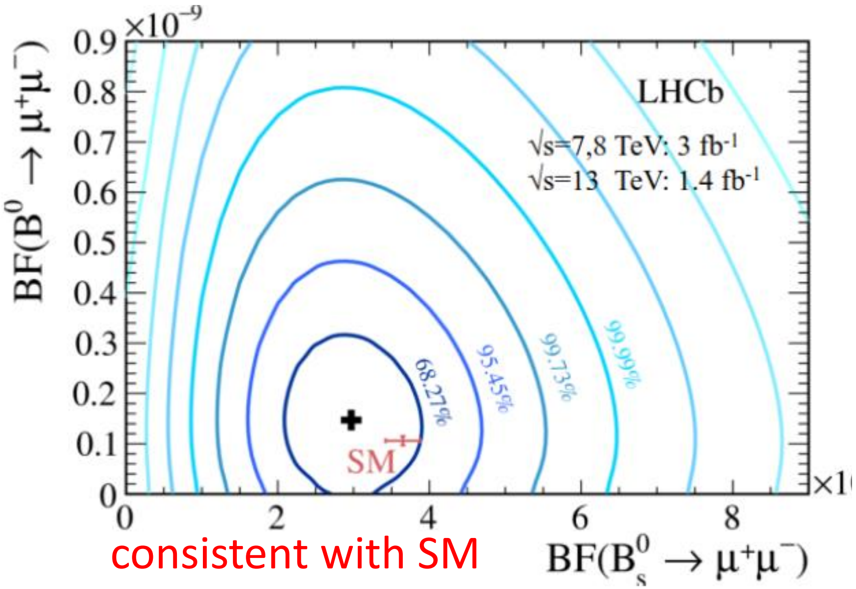


SM explanations not ruled out:
uncertainties from poorly understood charm loop contributions



Note: charm-loop contributions are lepton-flavour universal.

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

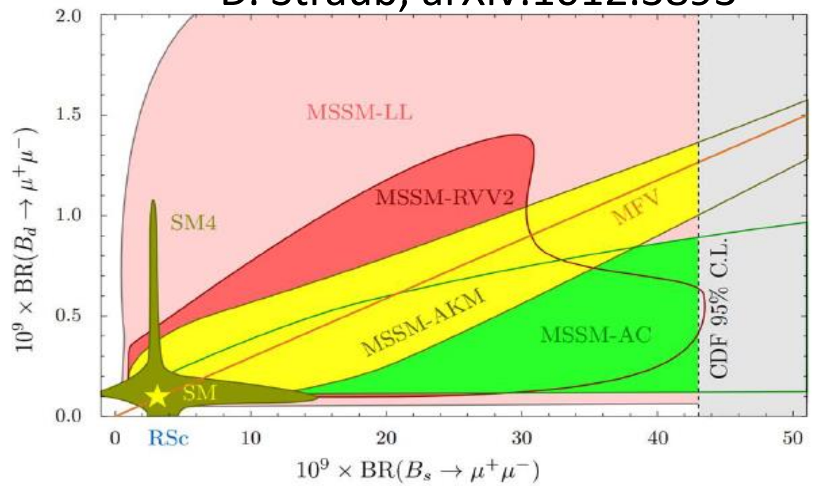


consistent with SM

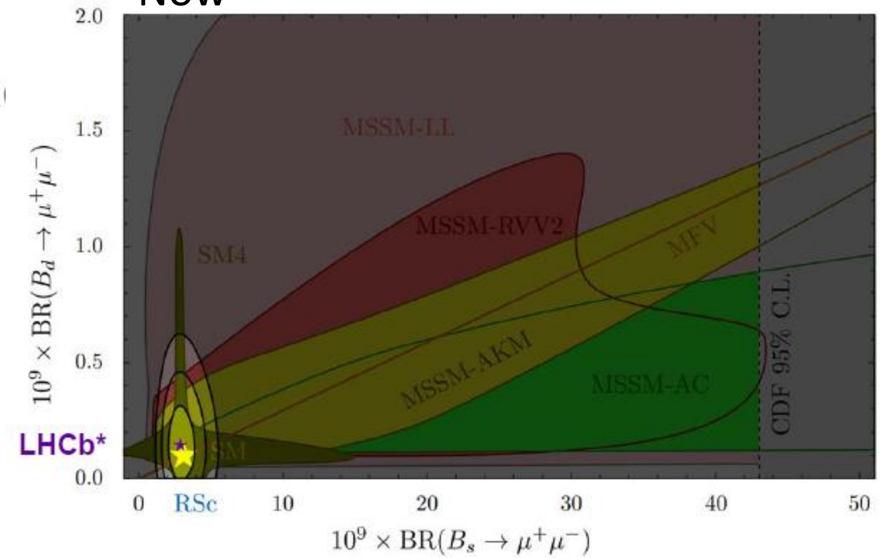
PRL 118, 191801 (2017)

Setting strong constraints on NP models, e.g., SUSY

D. Straub, arXiv:1012.3893



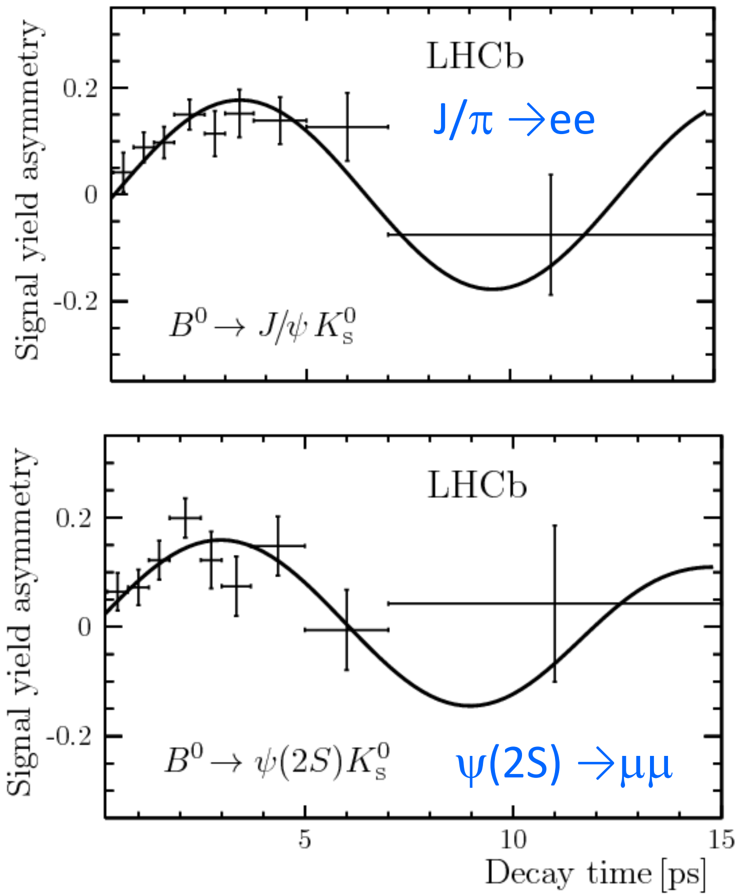
Now

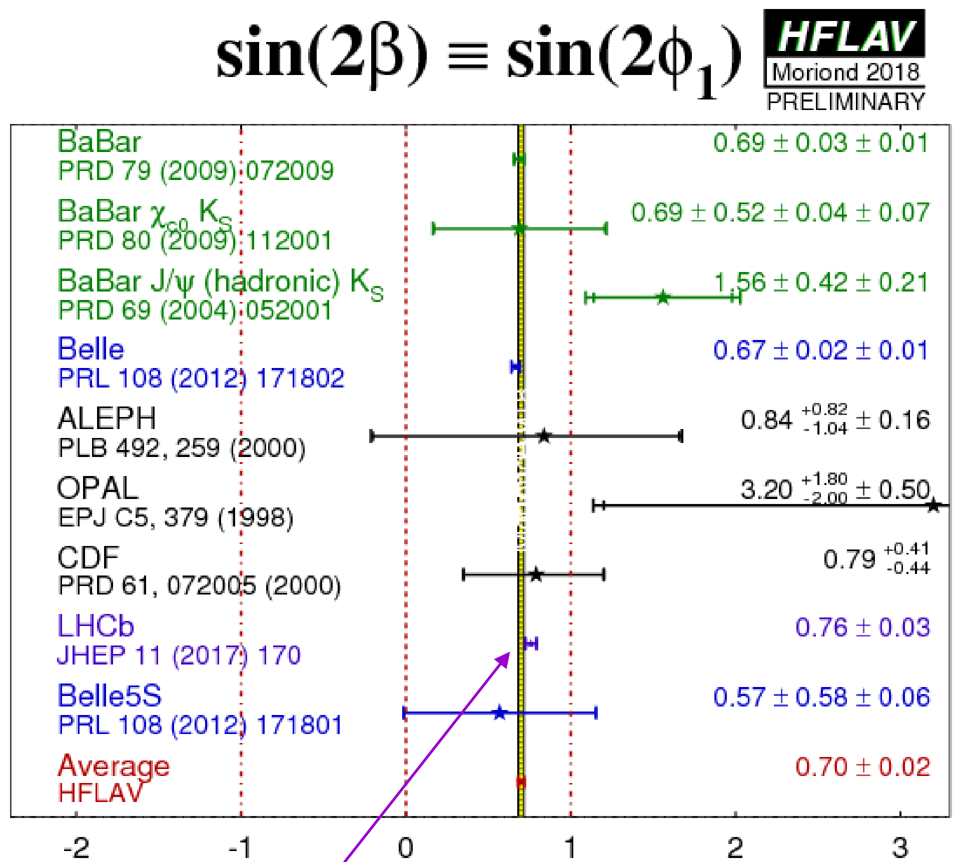


* Courtesy J.Coelho

sin2β from $B^0 \to J/\psi K^0_S$ and $B^0 \to \psi(2S)\ K^0_S$

JHEP11(2017)170





LHCb Run1 result dominated by statistical uncertainties

Precision competitive with BaBar and Belle

Indirect constraint: 0.740 $[^{+0.020}_{-0.025}]$ CKMFITTER

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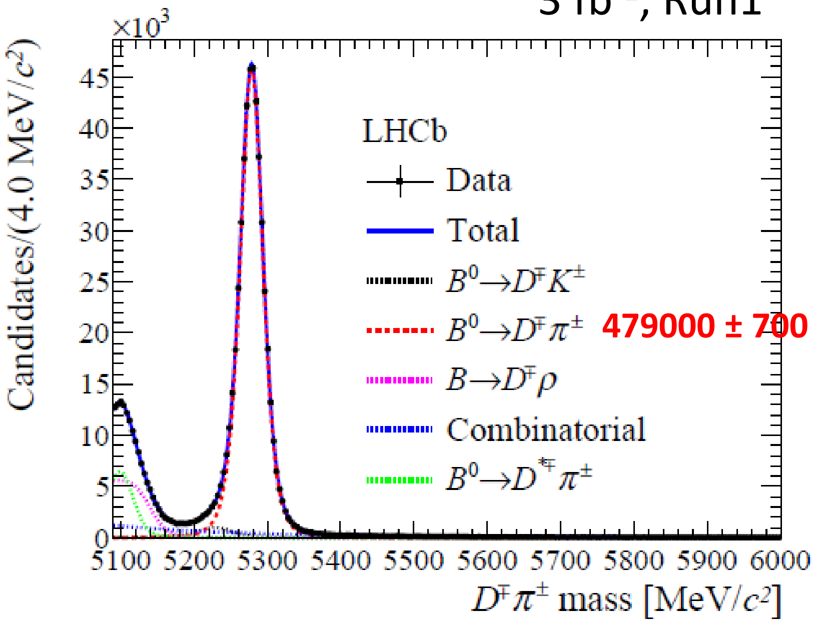
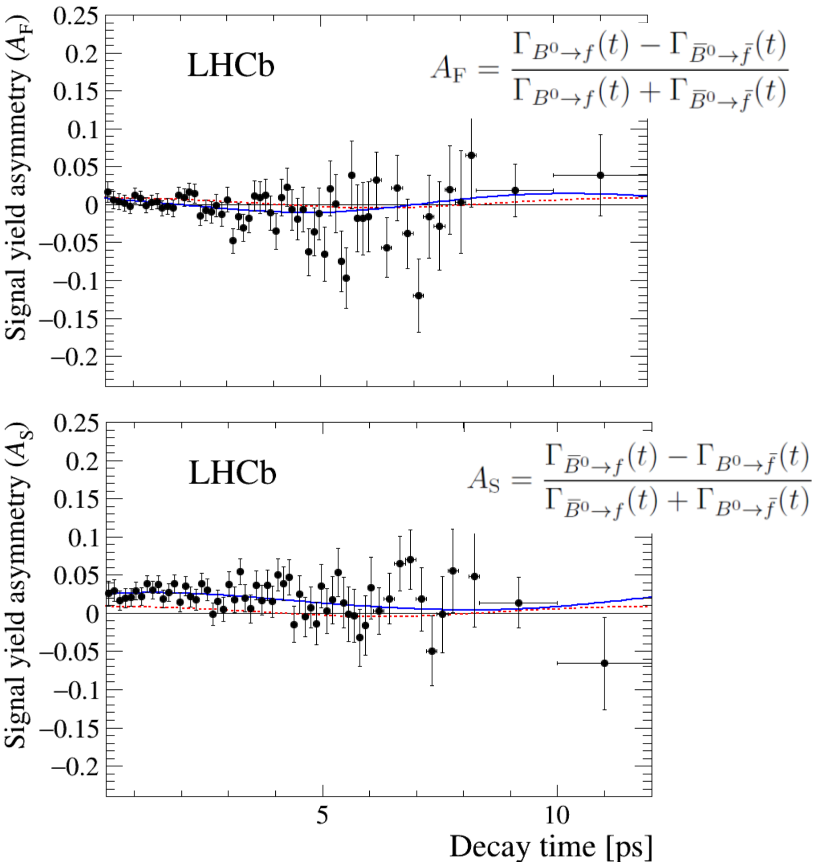
$2\beta+\gamma$ from $B^0 \to D^{\pm}\pi^{\mp}$ decays

CP violating phase from time-dependent asymmetries of B^0 and B^0bar rates vs decay

3 fb^{-1}, Run1

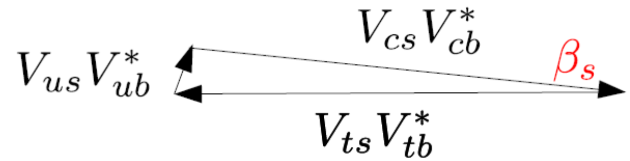




Large yields but small CP asymmetries (suppressed by ratio of suppressed over favoured decay amplitudes)

Used to constrain γ, using β from external measurements

ϕ_s from $B_s \to J/\pi\phi$



Ignoring small penguin contributions $\phi_s = -2\beta_s$

Most recent LHCb result (Run1) include $B_s \to J/\pi\ \phi$, $B_s \to J/\pi\ \pi\pi$, $B_s \to J/\pi$ KK above $\phi(1020)$

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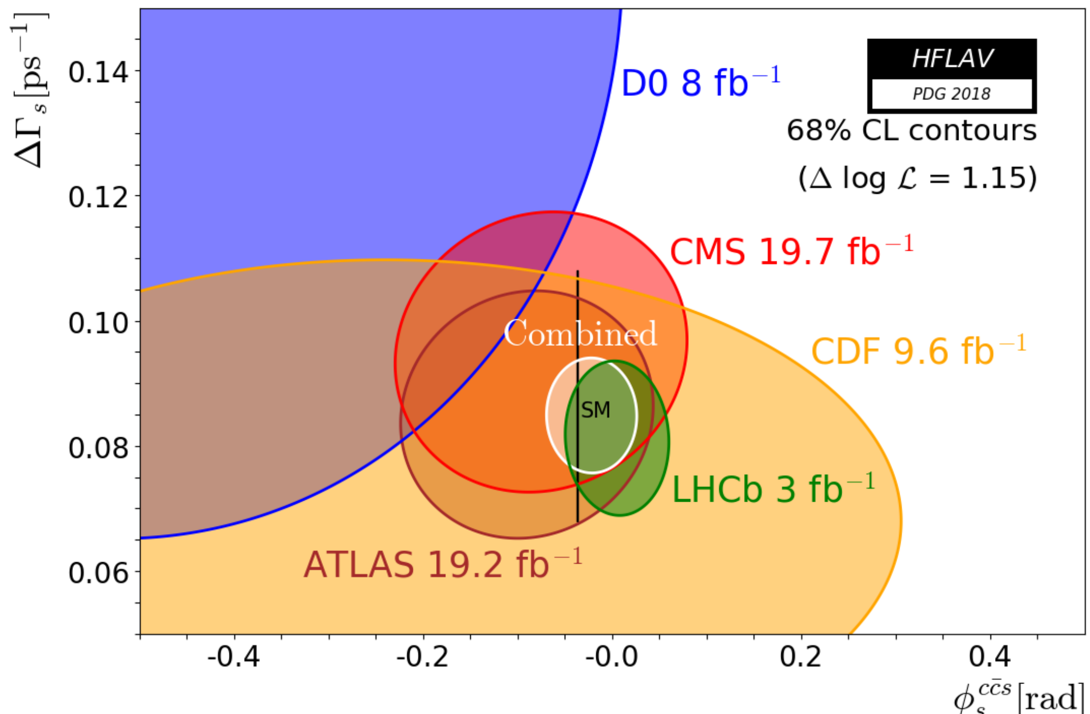
$$\phi_s = 1 \pm 37\,\mathrm{mrad}$$
$$|\lambda| = 0.973 \pm 0.013$$
$$\Gamma_s = 0.6588 \pm 0.0022 \pm 0.0015\,\mathrm{ps}^{-1}$$
$$\Delta\Gamma_s = 0.0813 \pm 0.0073 \pm 0.0036\,\mathrm{ps}^{-1}$$



Good agreement with SM: $-2\beta_s = -37 \pm 0.6$ mrad

[CKMfitter, Phys. Rev. D84, 033005 (2011), updated with Summer 2016 results],

HFLAV 2018 combined precision on $\phi_{s:}$ 33mrad