Flavour physics at the LHC

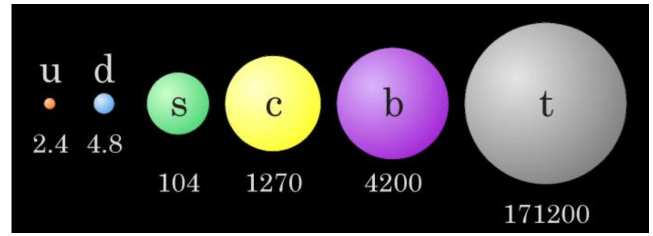
- Flavour physics as a tool of discovery
- LHCb: a flavour experiment at the LHC
- Status of flavour physics at the LHC: selected results
- Flavour physics beyond run 2

Guy Wilkinson
University of Oxford
ICFA seminar, 7 Nov 2017

Why flavour ?

Flavour encompasses many of the open questions of the Standard Model.

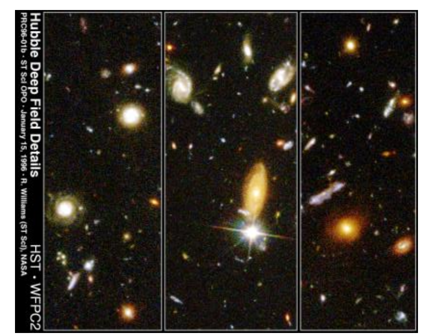
- Why 3 generations of quarks, and why the extreme hierarchy of masses ?



- What determines the hierarchical structure of the CKM matrix ?

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 0.9705-0.9770 & 0.21-0.24 & 0-0.014 \\ 0.21-0.24 & 0.971-0.973 & 0.036-0.070 \\ 0-0.014 & 0.036-0.070 & 0.997-0.999 \end{pmatrix}$$

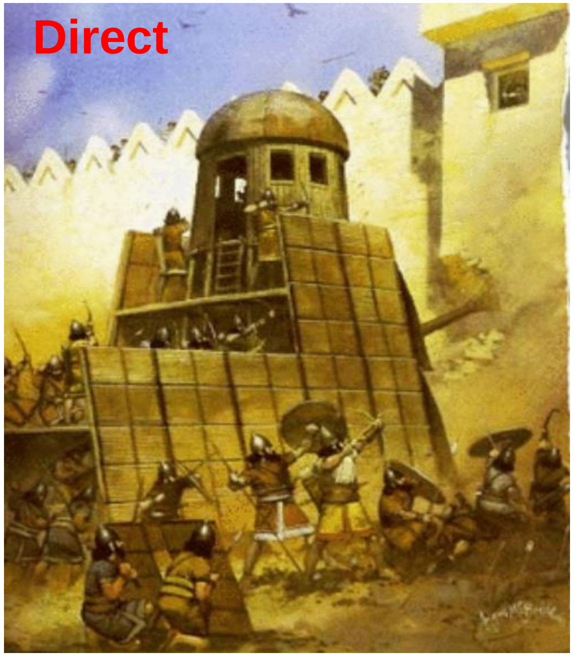
- The CKM paradigm accommodates CP violation, but it does not really explain it. Furthermore, can the study of quark flavour tell us anything about the matter-antimatter asymmetry ?



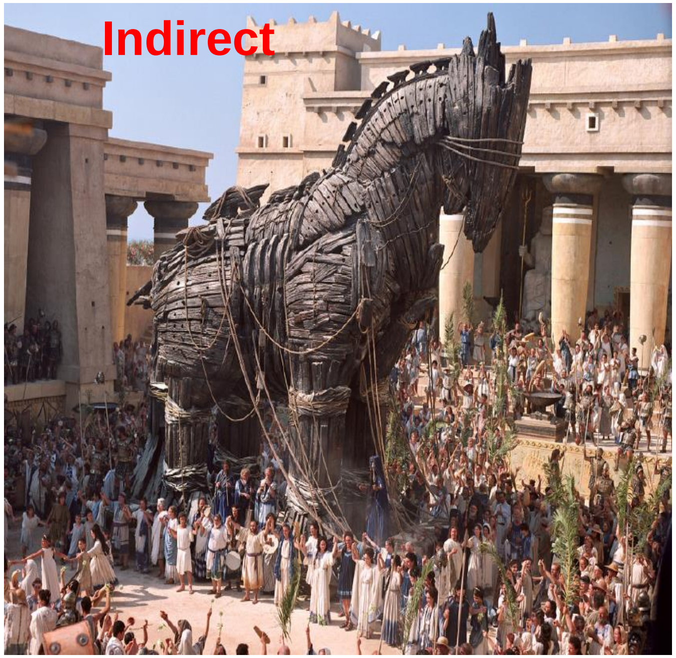
Most importantly, flavour physics is a tool of discovery !

Breaching the walls of the Standard Model

The LHC is searching for New Physics - to find this we need to get behind the walls of the Standard Model fortress. There are two strategies used in this search.



Use the high energy of the LHC to produce the New Physics particles, which we then detect

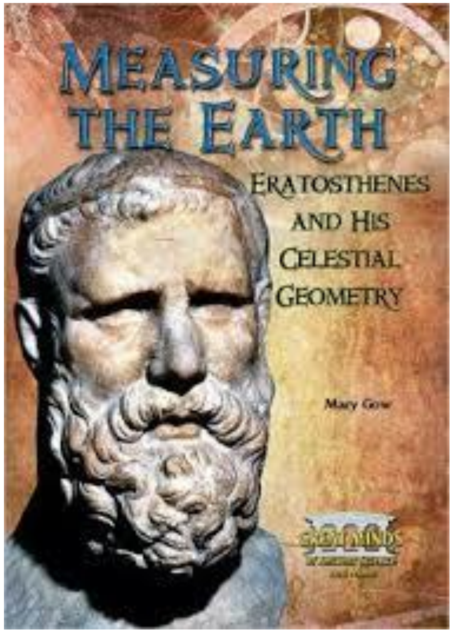


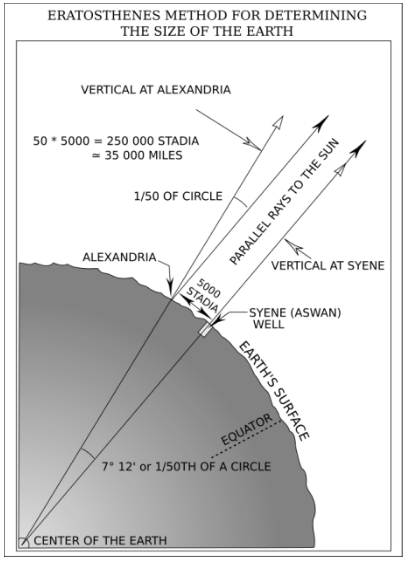
Make precise measurements of processes in which New Physics particles enter through ‘virtual loops’

Both methods are powerful. LHCb specialises (mostly) in the ‘indirect’ approach

Indirect measurements – an established tradition in science

Eratosthenes was able to determine
the circumference of the earth
using indirect means…





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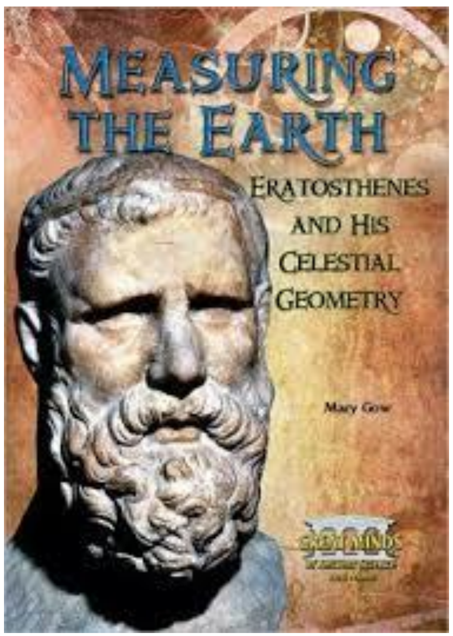
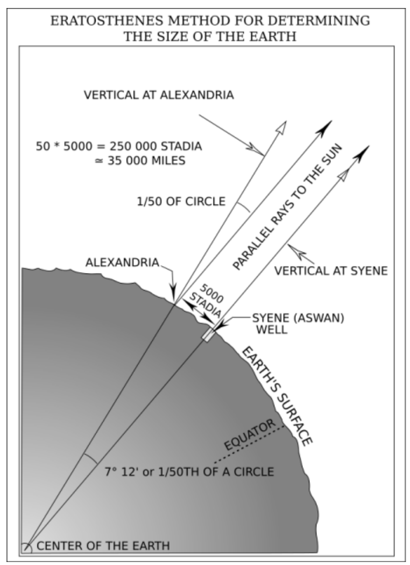
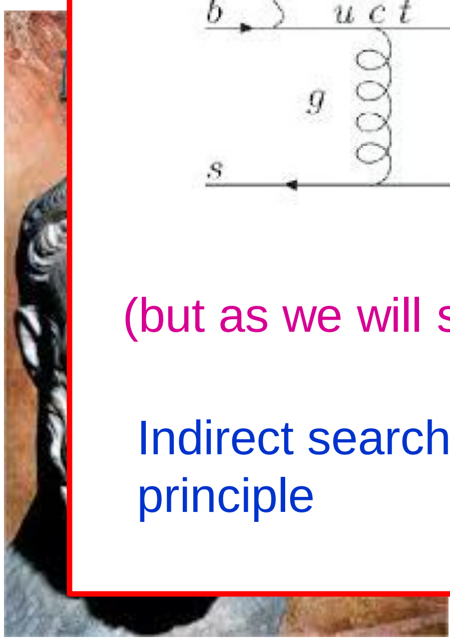


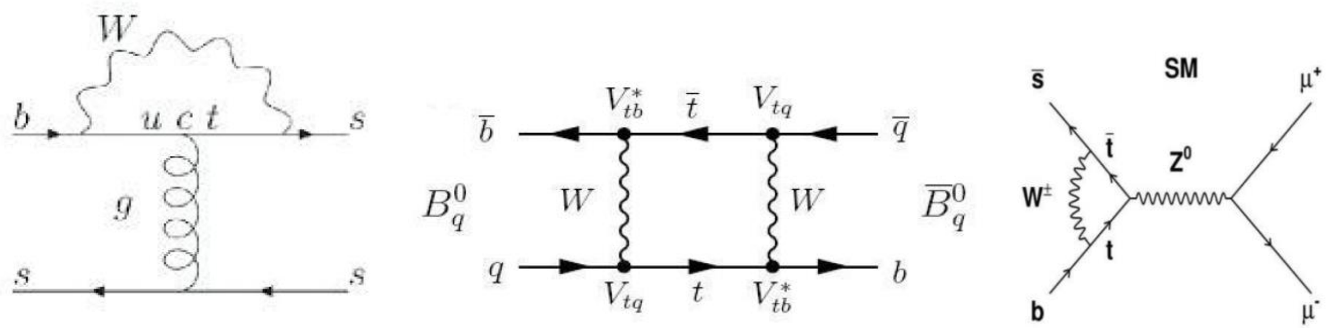


…around 2.2 thousand years prior to the direct observation.

Indirect measurements – an established tradition in science



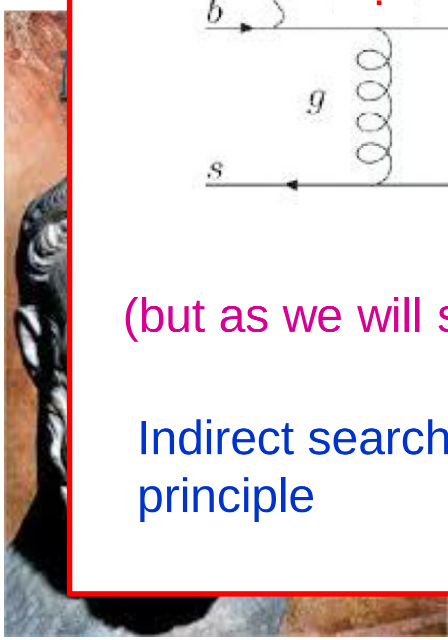
In flavour physics the guiding principle is to probe processes where loop diagrams are important, as here non-SM particles may contribute



(but as we will see, tree-mediated decays also have their role to play)

Indirect search principle ➡ Precise measurements of low energy phenomena tells us about unknown physics at higher energies

Indirect measurements – an established tradition in science



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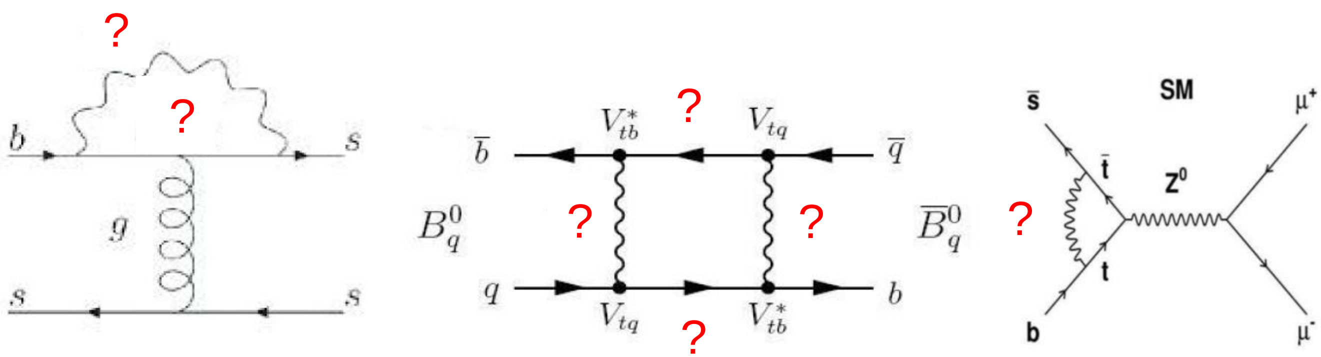
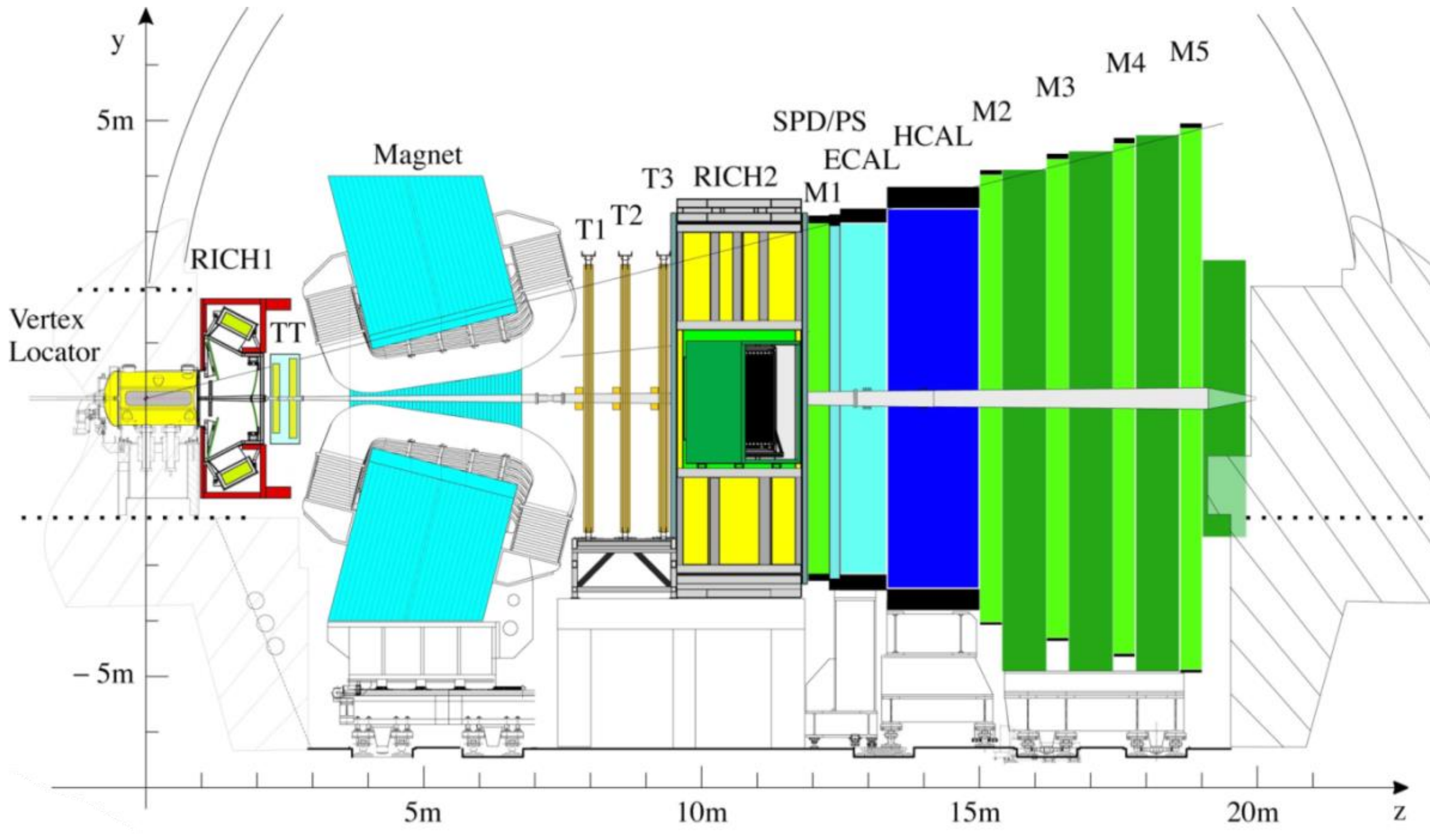


(but as we will see, tree-mediated decays also have their role to play).

Indirect search principle ➡ Precise measurements of low energy phenomena tells us about unknown physics at higher energies

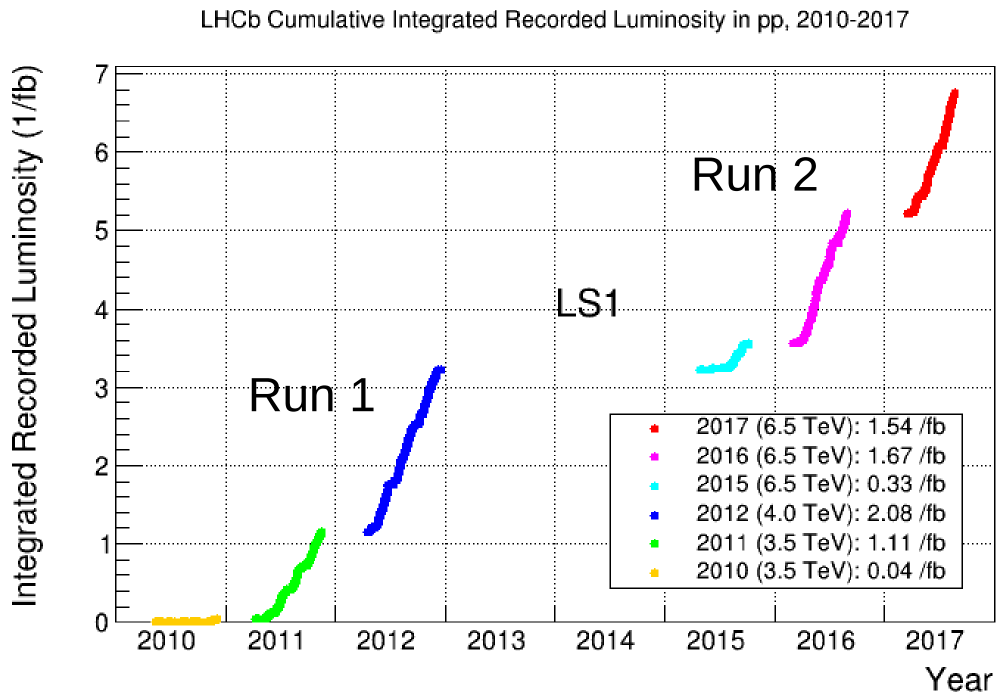
LHCb – a forward spectrometer for flavour physics

Superb capabilities of ATLAS and CMS, and large data sets, mean they also have an important role to play !



LHCb – the story so far

LHC run 1 went from 2010 to 2012, during which LHCb collected 3 fb^{-1} of data (this corresponds to ~3 x 10^{11} b anti-b pairs being produced within LHCb).



Most of results shown today will come from this data set.

Now deep into run-2, which began in 2015. Already > 3.5 fb^{-1} collected. Operating at higher energy and at 25 ns bunch-crossing (+ detector improvements).

Run 2 will go to end of 2018 – aim to increase the beauty sample by x4 w.r.t. run 1.

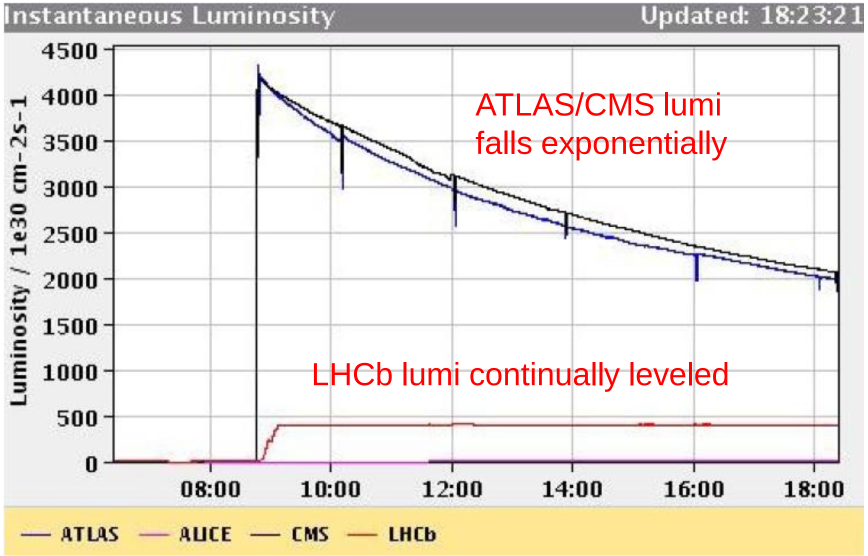
LHCb – the story so far

LHC run 1 went from 2010 to 2012, during which LHCb collected 3 fb^{-1} of data (this corresponds to ~3 x 10^{11} b anti-b pairs being produced within LHCb)

shown

e from

LHCb deliberately operates at lower luminosity than ATLAS/CMS



~4 x 10^{32} $cm^{-2}s^{-1}$

This is (current) best choice for precision b-physics measurements.

Now

Oper … ements).

Run 2 will go to end of 2018 – aim to increase the beauty sample by x4 w.r.t. run 1.

Status of flavour physics at the LHC

- An aside: the unforeseen success story of the LHC flavour programme
- CP violation measurements and the Unitarity Triangle
- 'Rare decays': FCNCs and friends

A whistle-stop tour taking in
only a few selected topics !

Status of flavour physics at the LHC

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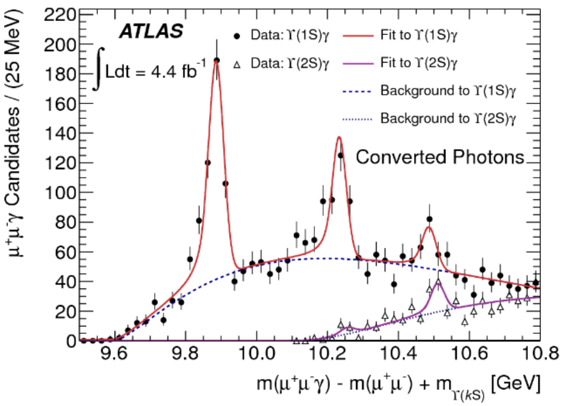
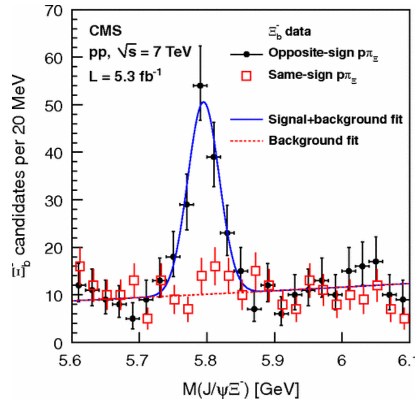
An aside: the Higgs is not (by far) the only new particle discovered at the LHC

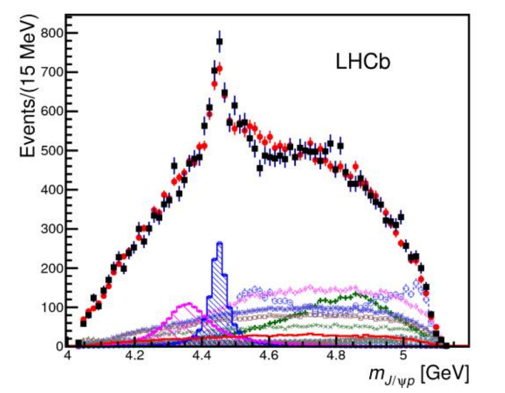
[PRL 108 (2012) 152001]



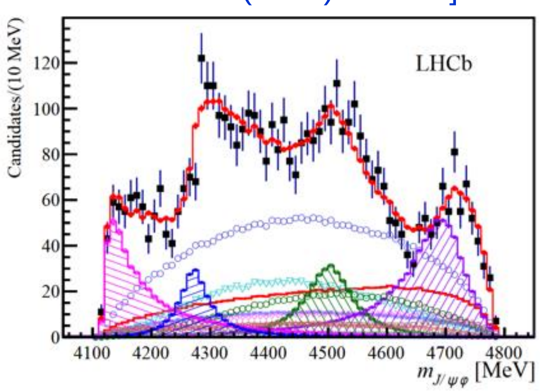
[PRL 108 (2012) 252002]



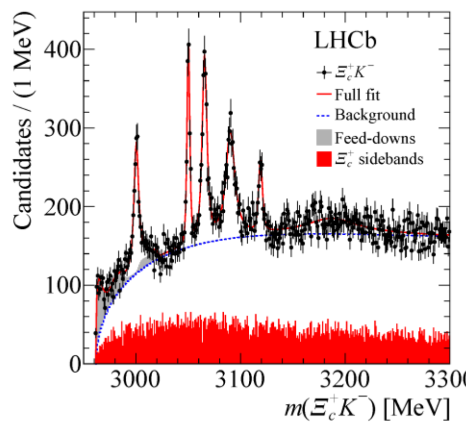
[PRL 115 (2015) 072001]



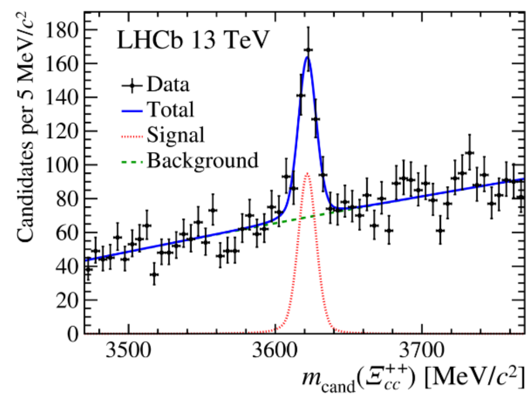
[PRL 118 (2017) 022003; PRD 95 (2017) 012002]



[PRL 118 (2017) 182001]



[PRL 119 (2017) 112001]



Flavour physics experiments are also very well suited to spectroscopy. LHC has proved itself an amazing laboratory for the discovery and characterisation of new hadronic states, & this will continue to be the case: a ***sure thing*** for the years ahead !

These studies attract a surprising amount of attention in the wider world

e.g. coverage of the Z(4430)$^-$ analysis [PRL 112 (2014) 222002] , demonstrated by LHCb to be a four-quark resonance.

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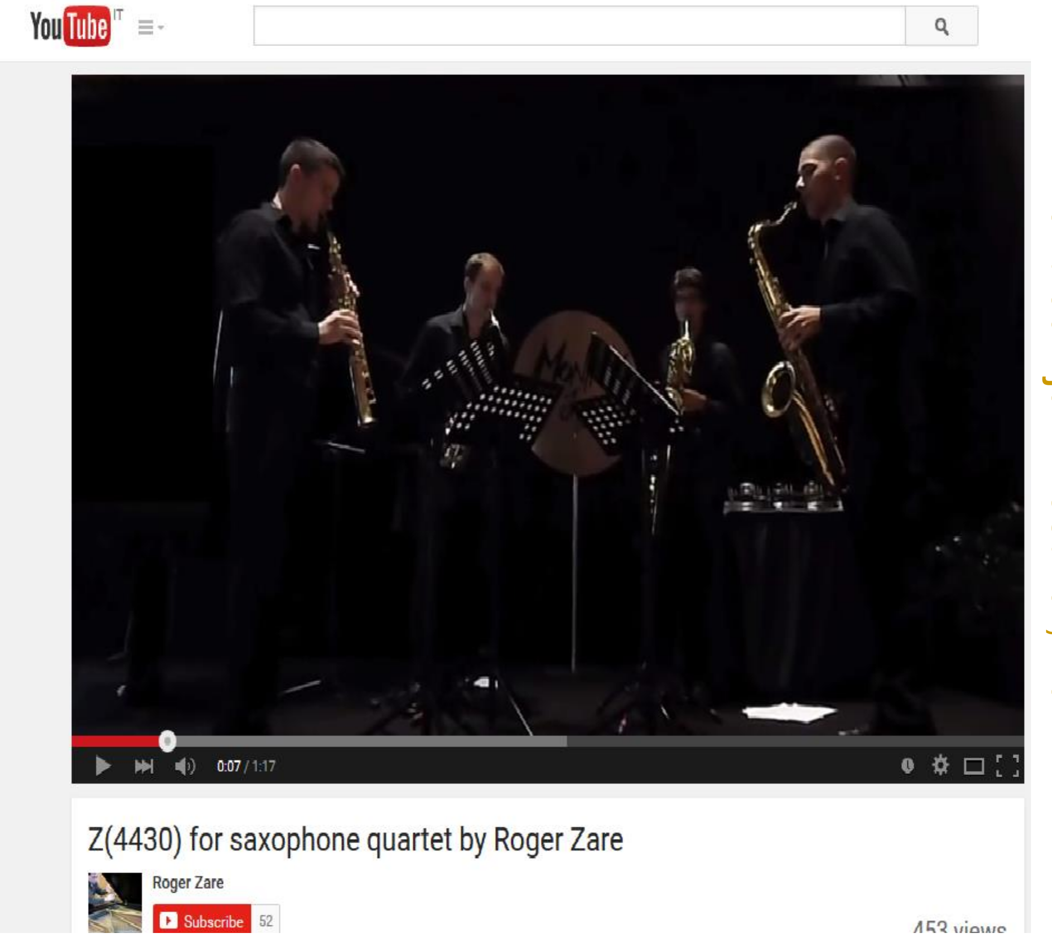

Montreux jazz festival, 2014

Status of flavour physics at the LHC

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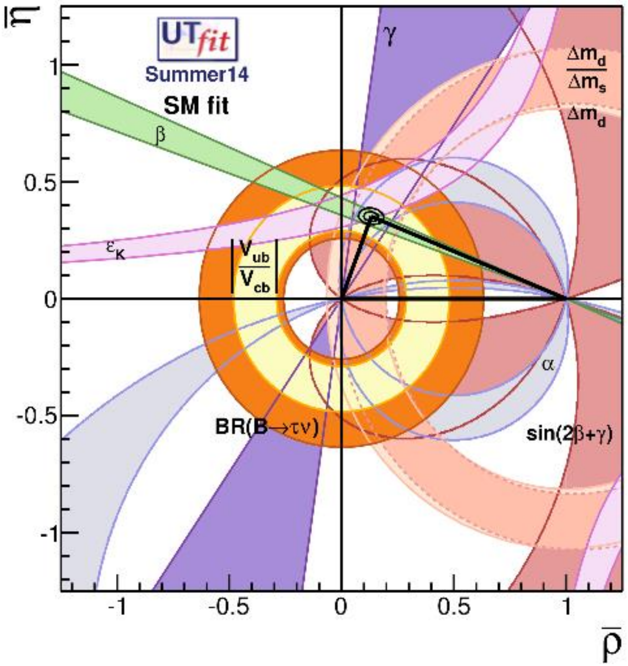
- ‘Rare decays’: FCNCs and friends

The Unitarity Triangle

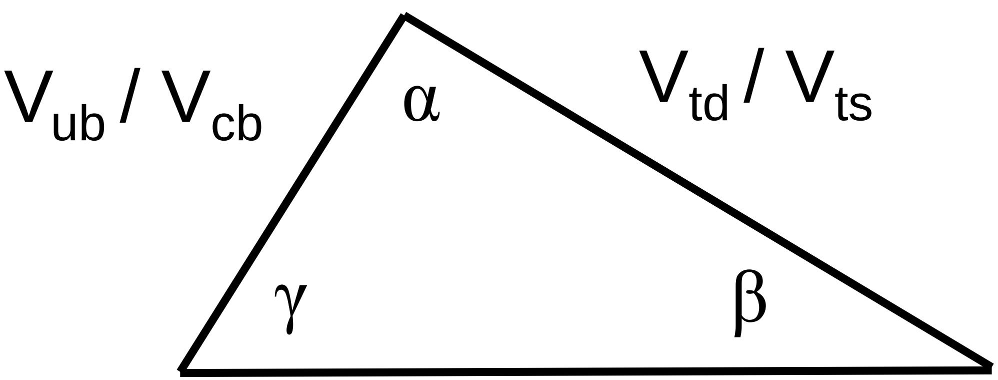
The Unitarity Triangle is a geometrical description of *CP*-violation within the context of the Standard Model, which in the flavour sector is the CKM mechanism.

We must check its consistency through precise measurements.

The B factories did a fantastic job and showed that the CKM paradigm dominates the picture, but New Physics contributions can still be lurking at ~20% level.



Let's see how the LHC is advancing this programme…



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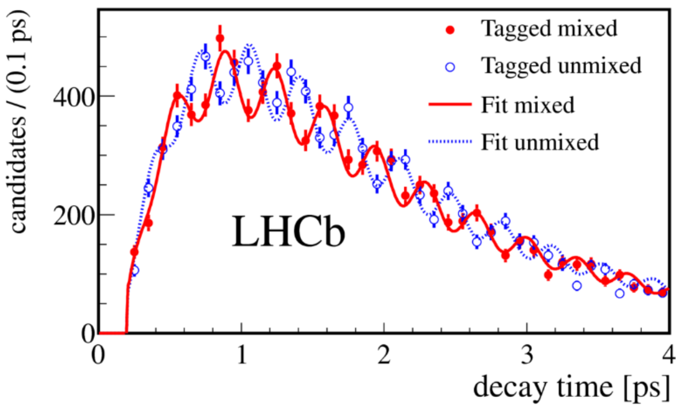
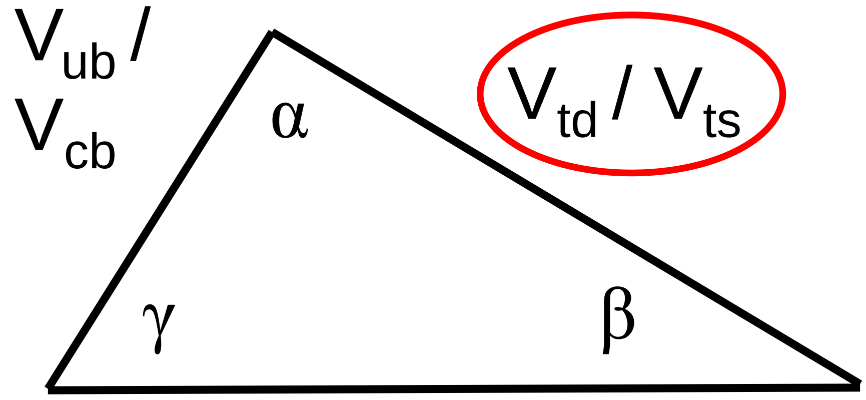
The Unitarity Triangle

LHCb has performed many measurements relevant to the Unitarity Triangle.

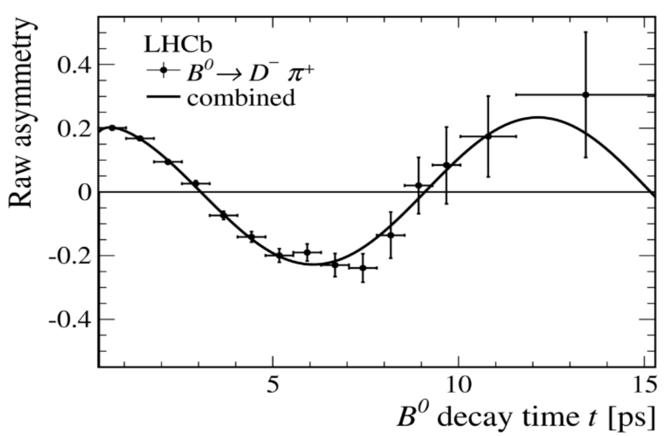
B_s oscillations



[New J. Phys. 15 (2013) 053021]



B^0 oscillations



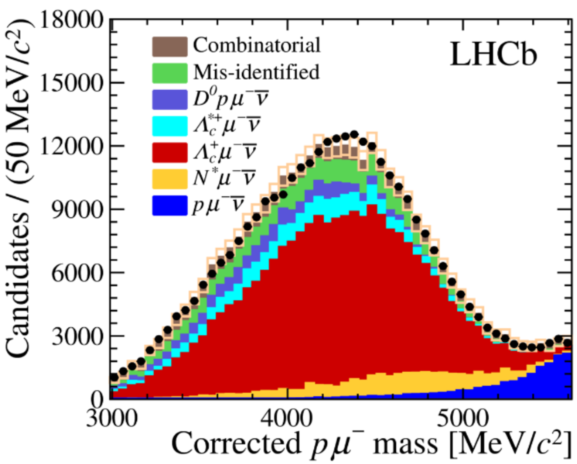
[Phys. Lett. B 719 (2013) 318]

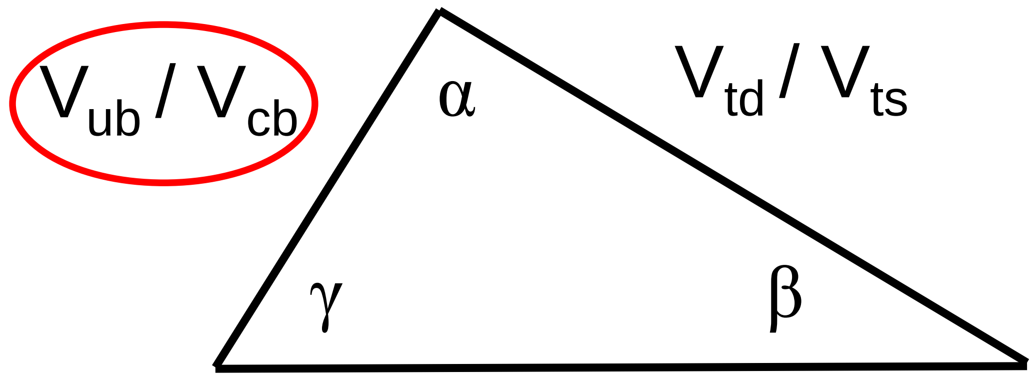
Very precise measurements of the B_s and the B^0 mixing frequency.

Precision 'too good' to be usefully exploited in Unitarity Triangle fits due to lattice QCD uncertainties, but this excellent resolution vital for related CPV measurements.

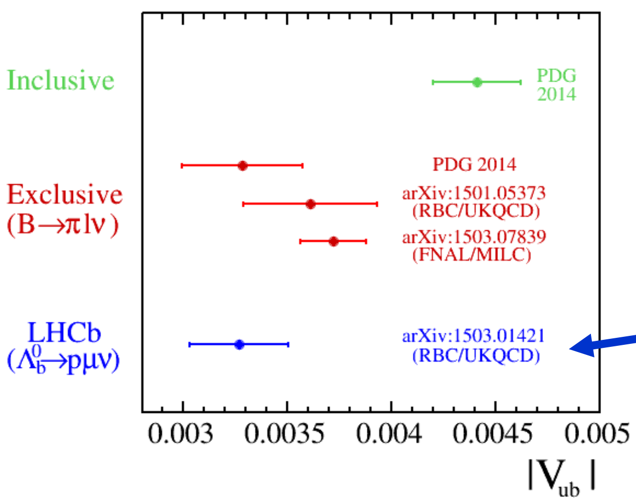
The Unitarity Triangle

LHCb has performed many measurements relevant to the Unitarity Triangle.





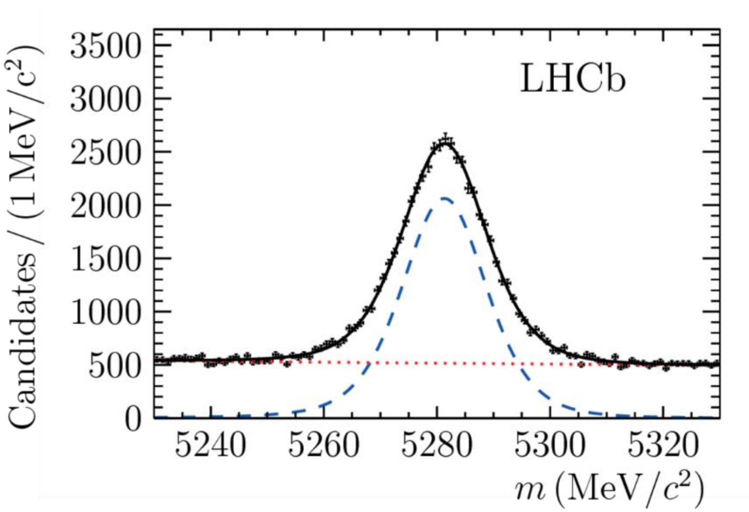
Measurement of V_{ub} through study of $\Lambda_b \to p\mu\nu$ decays [Nature Phys. 10 (2015) 1038]. *Nobody* expected the LHC to contribute to this measurement.

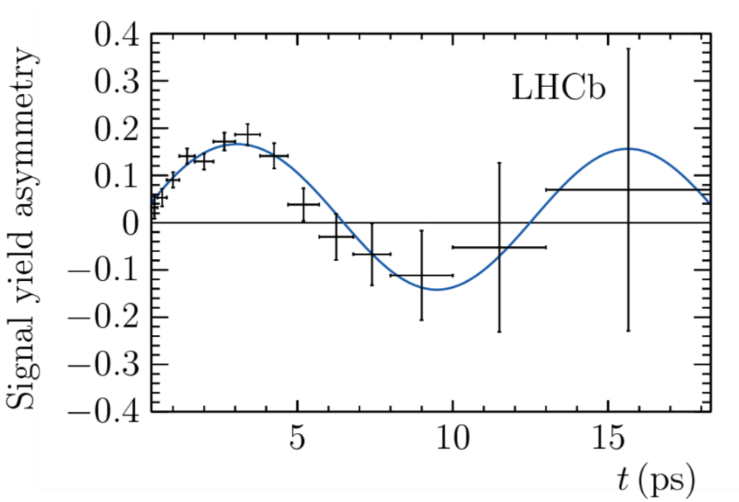


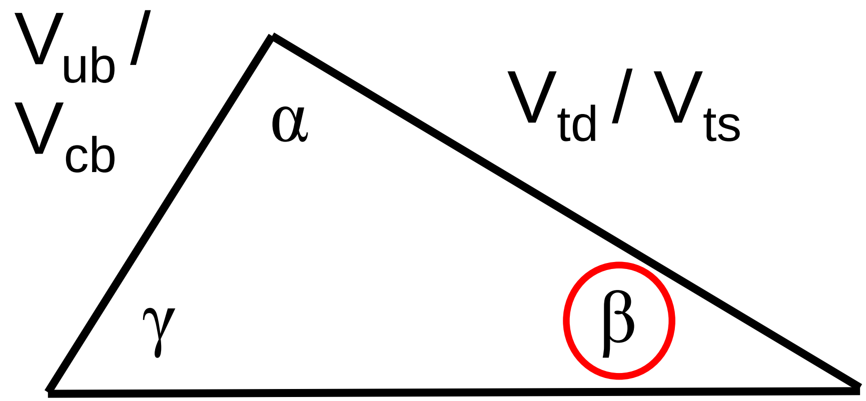
The result is very illuminating for the longstanding 'inclusive vs. exclusive' debate. Much more to come !

The Unitarity Triangle

LHCb has performed many measurements relevant to the Unitarity Triangle.







$B^0 \to J/\psi K_S$, is the golden channel for measuring sin2β, and one very well suited to capabilities of B-factories.

$\sin 2\beta_{eff} = 0.731 \pm 0.035\,(\mathrm{stat}) \pm 0.020\,(\mathrm{syst})$

(BaBar stat error = 0.036, Belle stat error = 0.029)

LHCb run-1 result [PRL 115 (2015) 031601] has very similar precision to B-factory measurements. World-best result expected with run-2 data !

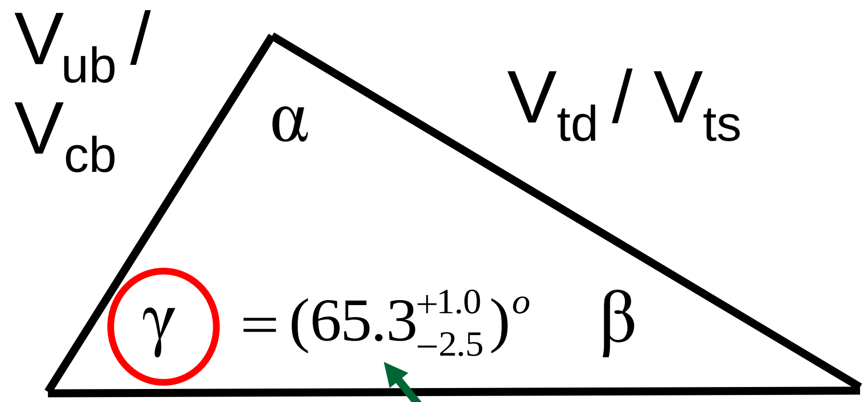
The Unitarity Triangle

LHCb has performed many measurements relevant to the Unitarity Triangle.

Most important task of LHCb in Unitarity Triangle studies has been to pursue programme to improve knowledge of γ.

At LHC turn-on this was very badly known [CKMfitter uncertainty ~ 30°].

Since then much progress, thanks to methods pioneered at B-factories, & LHCb statistical muscle.



Predicted value [CKMfitter 2016] from measurements of other triangle parameters & lattice QCD.

Best way to access γ is to study this decay chain, looking for interference effects when D^0 & $\bar{D}^0$ decay to common final state.

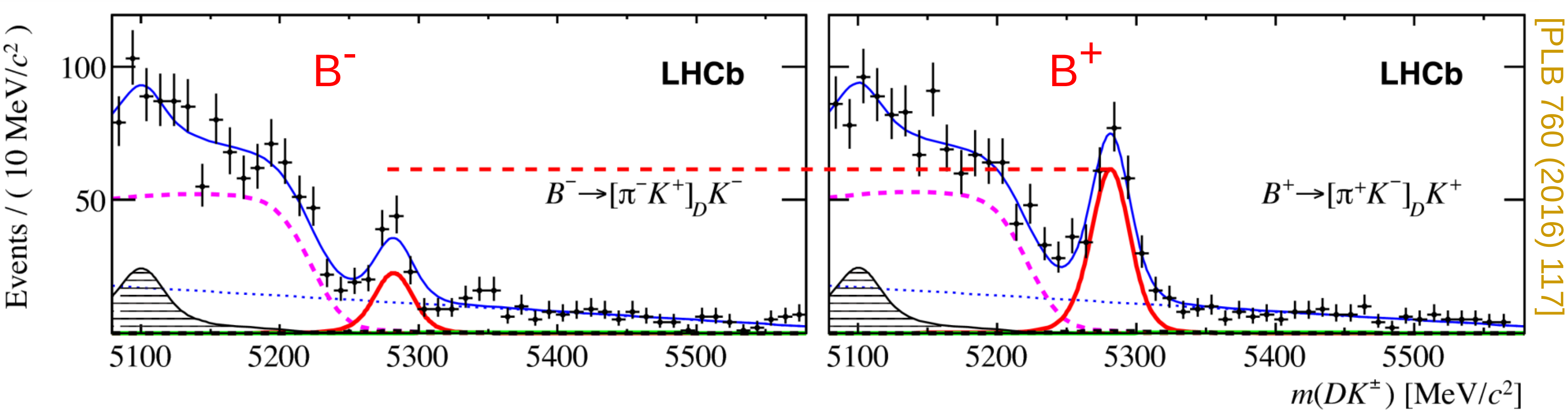
$B^- \to D^0 K^-$

$B^- \to \bar{D}^0 K^-$

phase γ between V_{ub} and V_{cb} amplitudes

The Unitarity Triangle: measuring γ

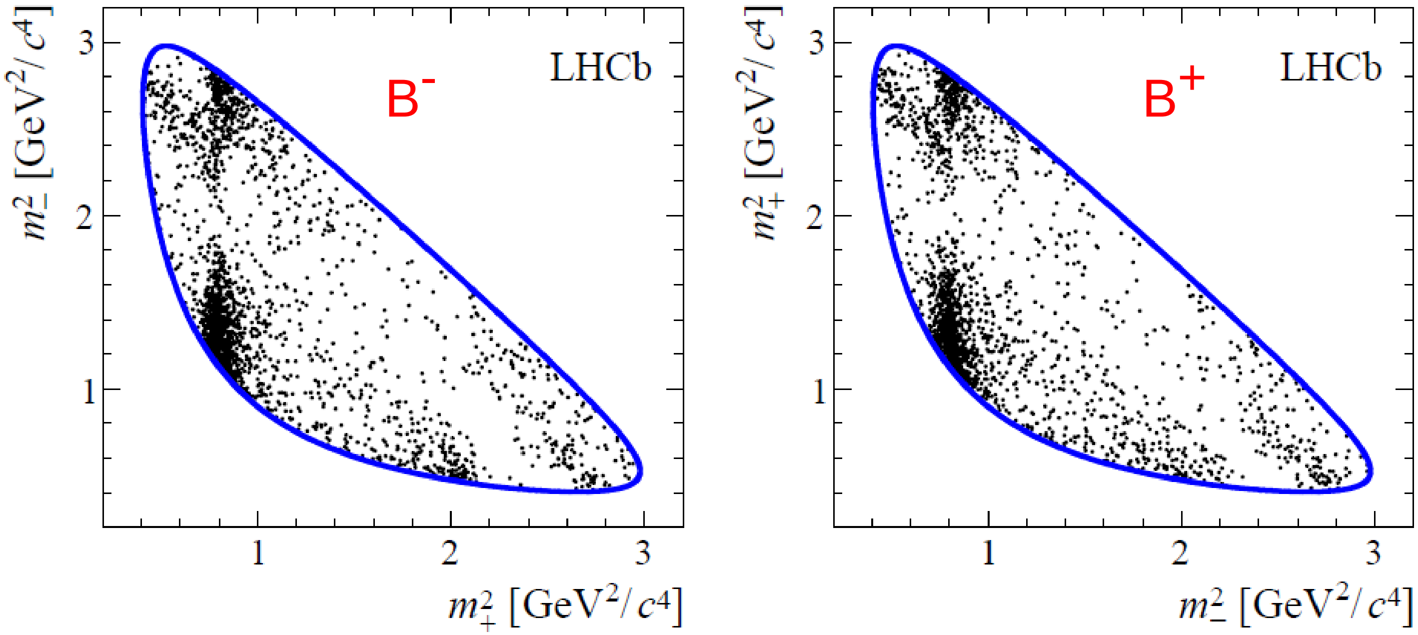
To access these interference effects means looking for rather suppressed decays, *e.g.* this $B^- \to DK^-$ decay, with $D \to K^+\pi^-$ (and B^+ conjugate case): visible BR ~10^{-8}, Hence out of reach to previous generation of flavour physics experiments.



Very significant CP violation observed, that can be cleanly related to the phase γ.

The Unitarity Triangle: measuring γ

Or alternatively take a $B^- \to DK^-$ decay with the D decaying to a three-body final state, *e.g.* $D \to K_S\pi\pi$ and look for differences in D phase-space distributions.



[JHEP 10 (2014) 097]

The Unitarity Triangle: measuring γ

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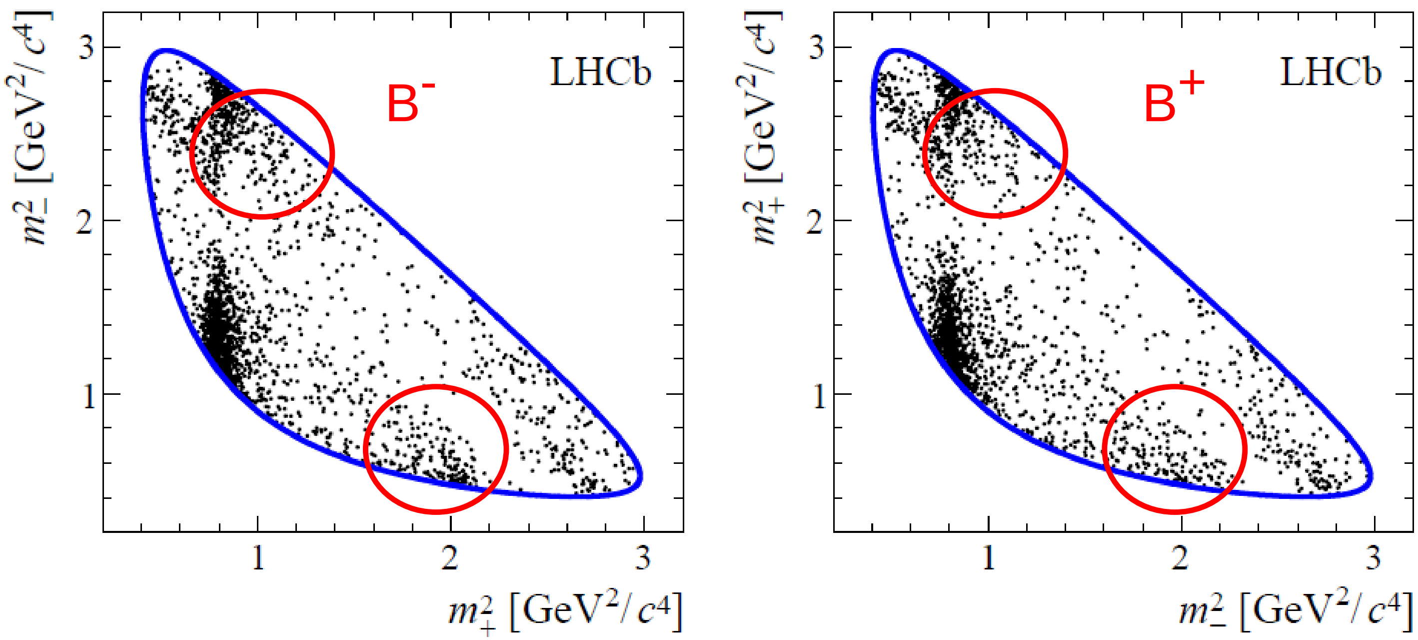


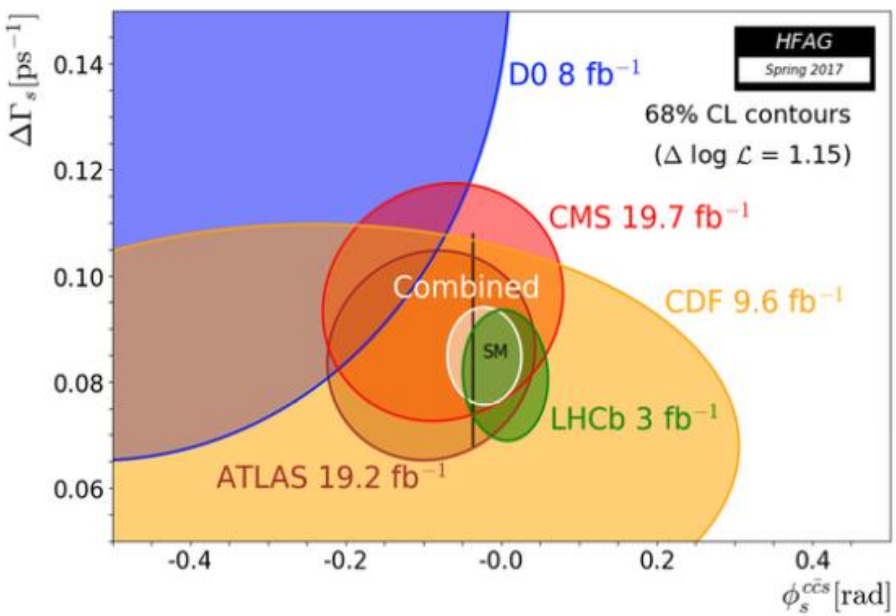
[JHEP 10 (2014) 097]

Putting this all together [LHCb-CONF-2017-04], and making use of >20 separate measurements we determine $\gamma = (76.8\,^{+5.1}_{-5.7})^\circ$, which is compatible (if a touch higher) than 'Standard Model' prediction. Impressive precision, but needs to improve to match prediction. It will do so – this is a long game !

Other CPV studies to keep an eye on

CPV searches in the B_s system

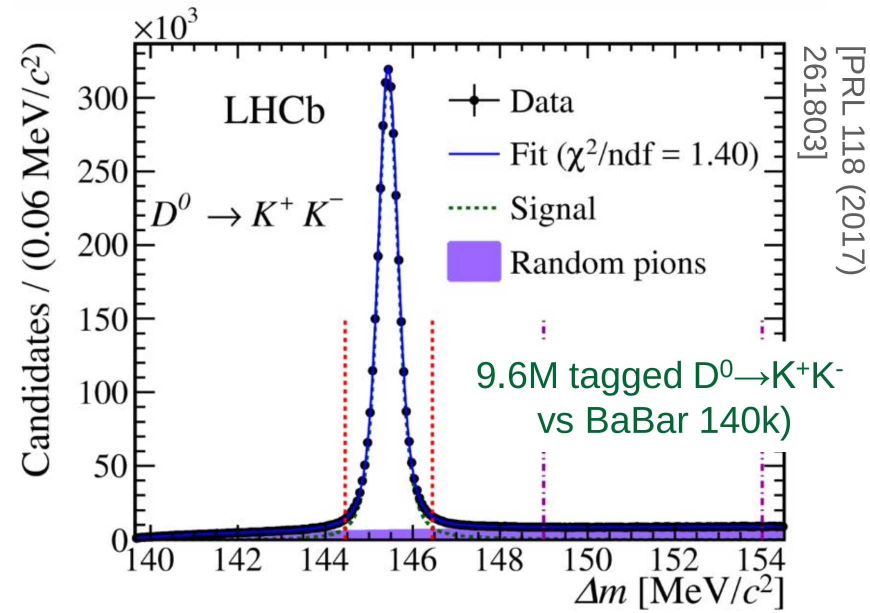
Mixing-decay interference studies (B_s analogue of sin2β measurement), *e.g.* in $B_s \to J/\psi\phi$. In the SM the relevant phase 'ϕ_s' is small but well predicted.



No CPV yet observed, but importance & cleanliness of measurement mean this will be pursued throughout lifetime of LHC.

CPV searches in charm

LHCb has accumulated massive and clean samples of D decays, which can be used to probe for CPV in charm (very small in SM).



Run-1 results have 10^{-4} precision. Big improvements expected with run-2 data &, especially, with Upgrade.

Status of flavour physics at the LHC

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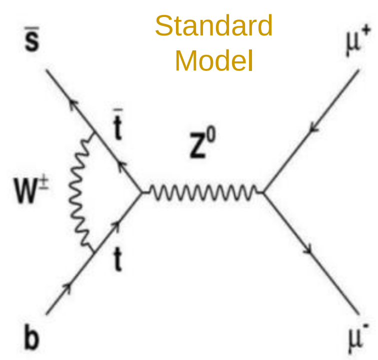
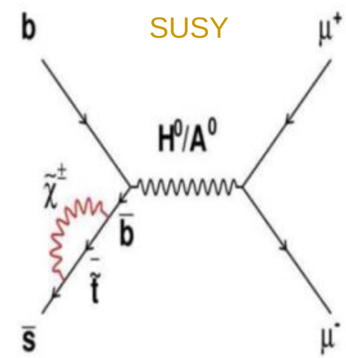
The golden mode: $B_s \to \mu^+\mu^-$

This decay mode can only proceed through suppressed loop diagrams.

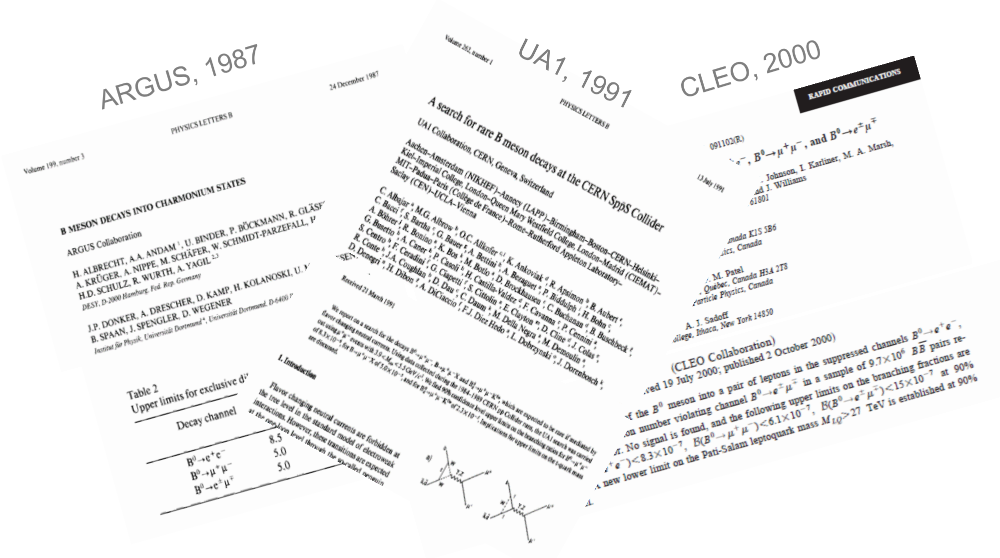
In the Standard Model it happens extremely rarely (~10^{-9}), but the exact rate is very well predicted

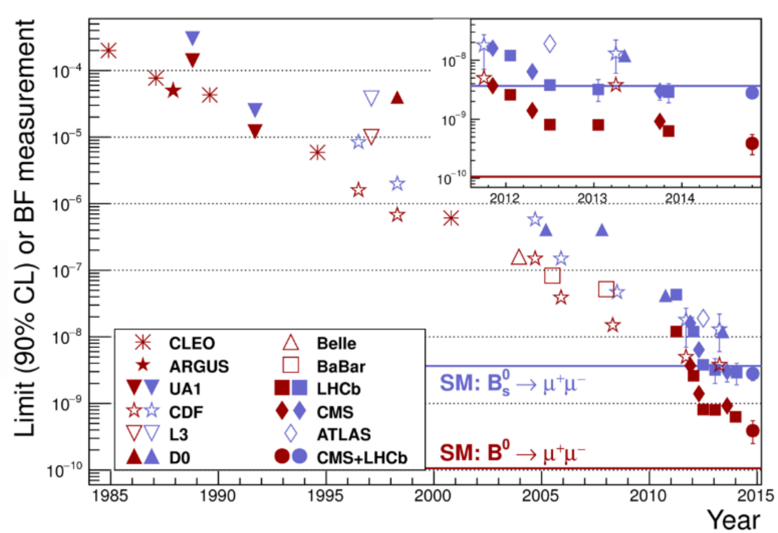




Many models of New Physics (*e.g.* SUSY) can enhance rate significantly !

A 'needle-in-the haystack' search, which has been pursued for over 25 years.

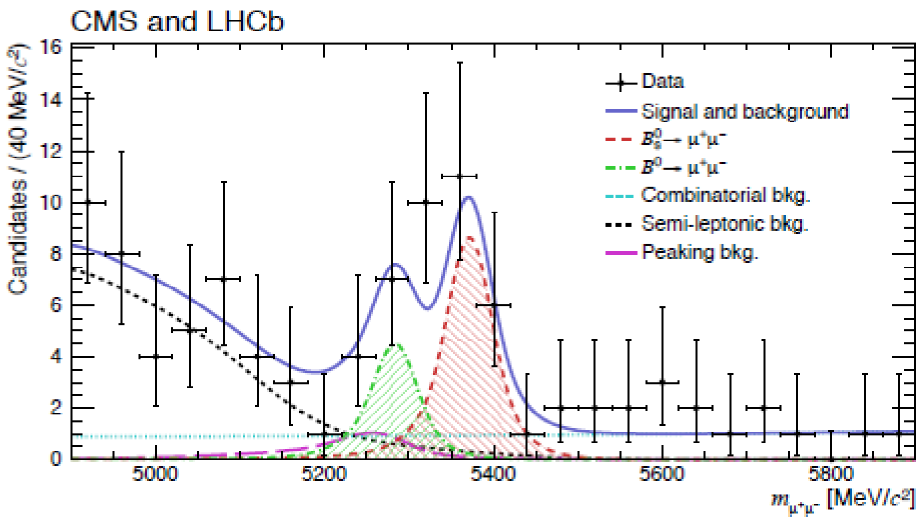


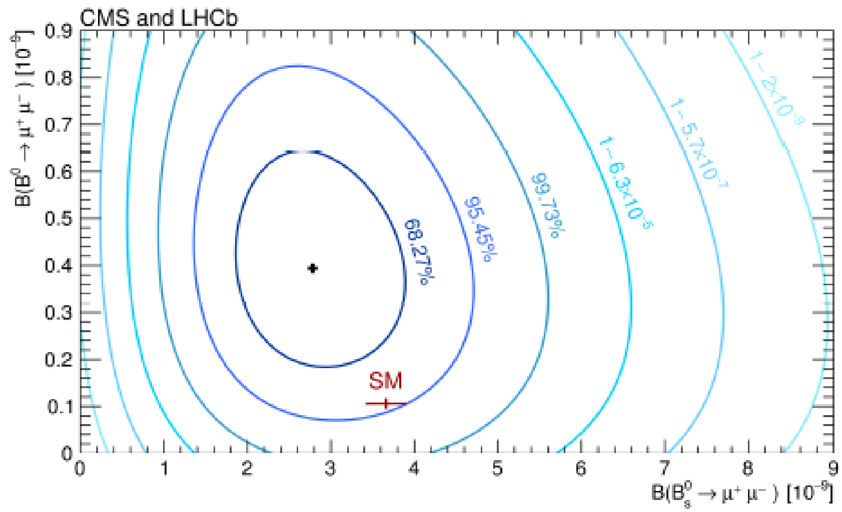


Before the LHC, Fermilab experiments were pushing the limits down towards 10^{-8}.

The golden mode: $B_s \to \mu^+\mu^-$ [PRL 118 (2017) 191801]

The signal finally showed up during Run 1, where LHCb found first evidence [PRL 110 (2013) 021801] , & then a combined LHCb-CMS analysis yielded a 5σ observation [Nature 522 (2015) 68] . The BR, measured to 25%, agrees with the SM…





$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = \left(2.8\,^{+0.7}_{-0.6}\right) \times 10^{-9} \quad (6.2\sigma)$$

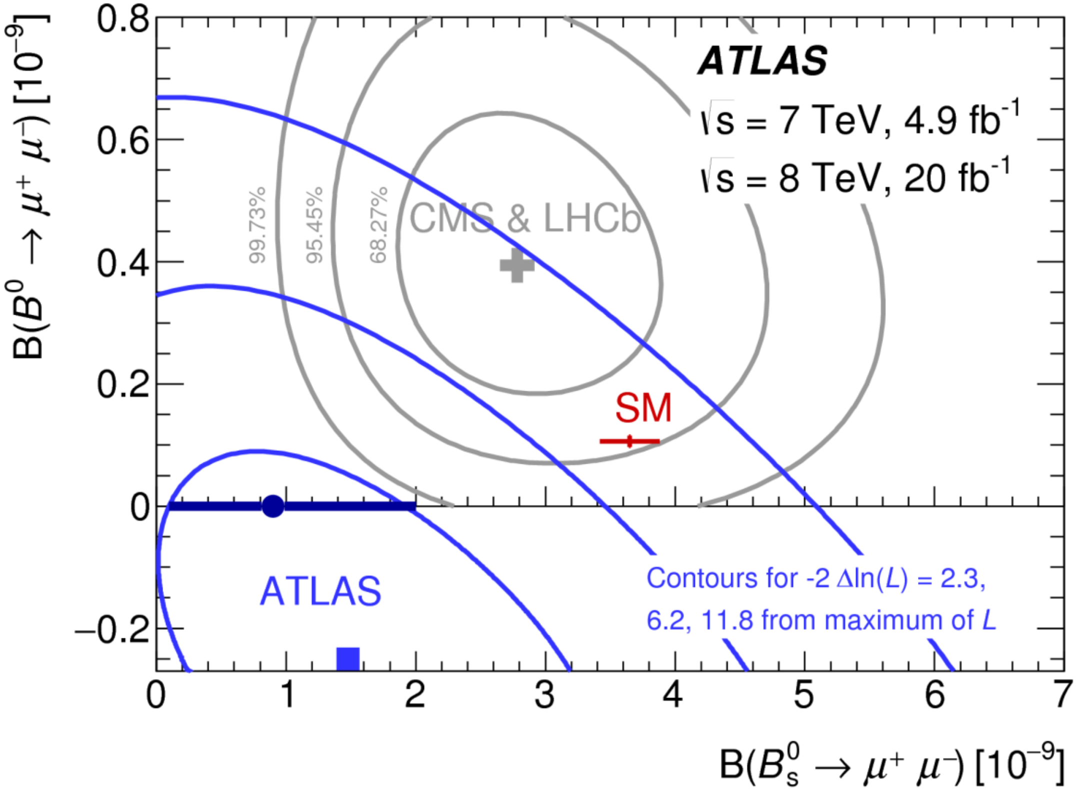
$$\mathcal{B}(B^0 \to \mu^+\mu^-) = \left(3.9\,^{+1.6}_{-1.4}\right) \times 10^{-10} \quad (3.0\sigma)$$

[arXiv:1411.4413, Nature 522 (2015) 68]

…however the analysis also searched for the even rarer $B^0 \to \mu\mu$. Here there is also a hint of a signal. Picture is intriguing & provided encouragement for run 2 !

B→μμ: the complete run-1 LHC picture

And now ATLAS have joined the game [arXiv:1604.04263] !



No signal evidence in either mode… but lower intrinsic sensitivity than LHCb/CMS.

$B \rightarrow \mu^+\mu^-$: first news from run 2

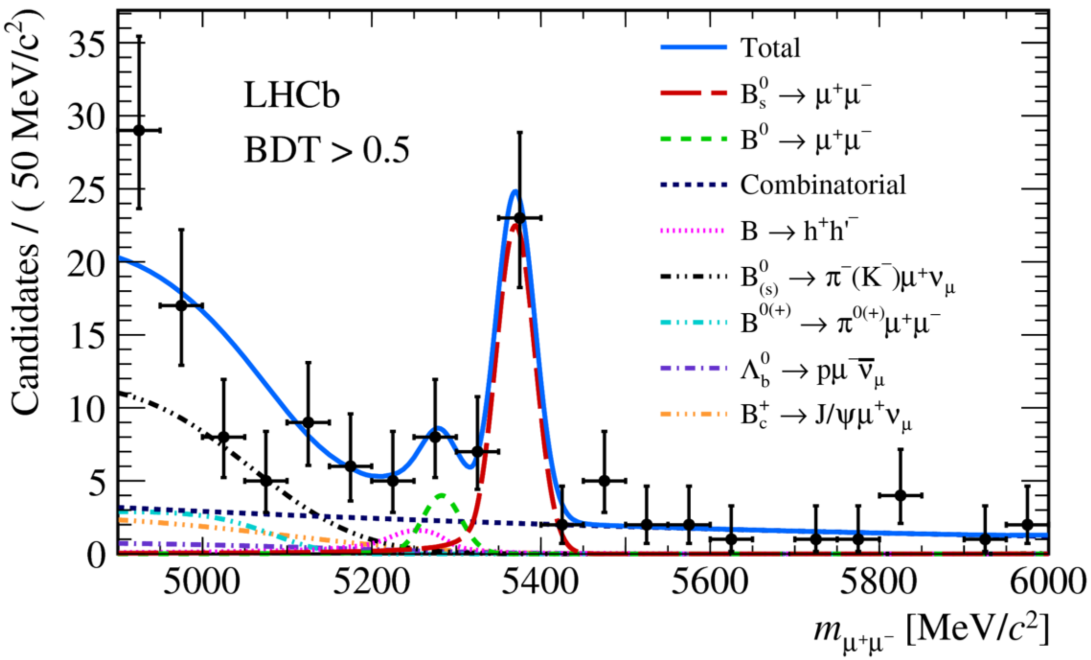
[PRL 118 (2017) 191801]

LHCb has now returned to this critical observable with an improved analysis (~50% combinatoric background than previously). Run 1 + 1.4 fb^{-1} of Run-2 data.

- 7.8 σ signal & first single-experiment observation !
- Precise measurement of branching fraction

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

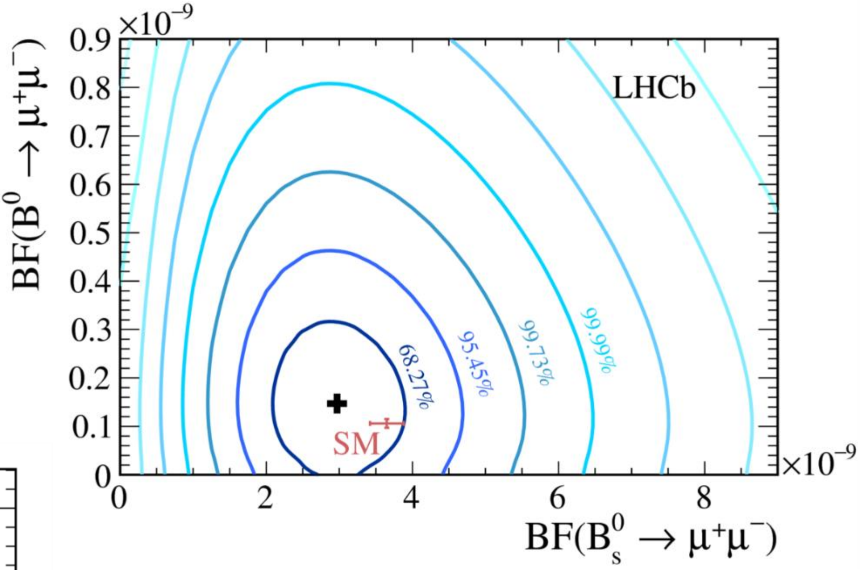
- No evidence yet of the corresponding B^0_d decay.



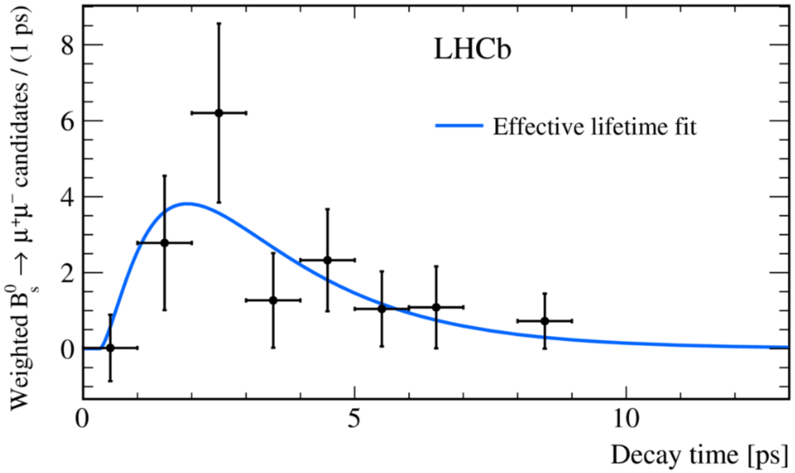
$B \to \mu^+\mu^-$: first news from run 2

[PRL 118 (2017) 191801]

LHCb has now returned to this critical observable with an improved analysis (~50% combinatoric background than previously). Run 1 + 1.4 fb^{-1} of Run-2 data.



Results are very compatible with Standard Model, and will tighten further constraints on New Physics models with an extended scalar sector.

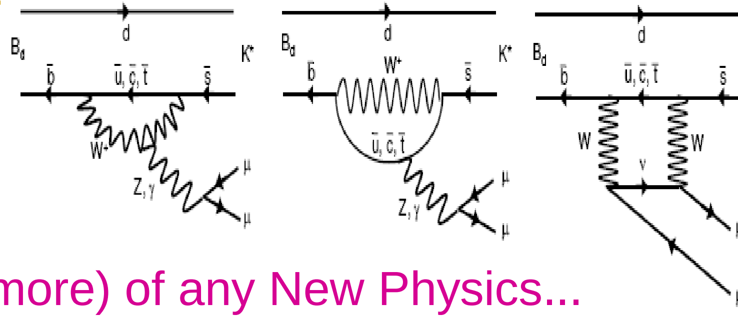


Proof-of-principle measurement.

Vital that these branching ratios are measured ever more precisely - a key goal of the LHCb Upgrade.

In addition, we may start to probe over observables associated with the decay, *e.g.* the effective lifetime.

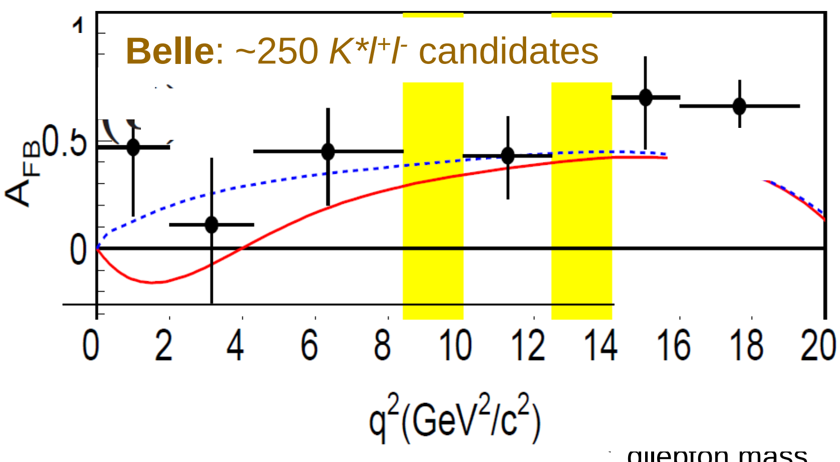
$B^0 \to K^* l^+ l^-$ and friends



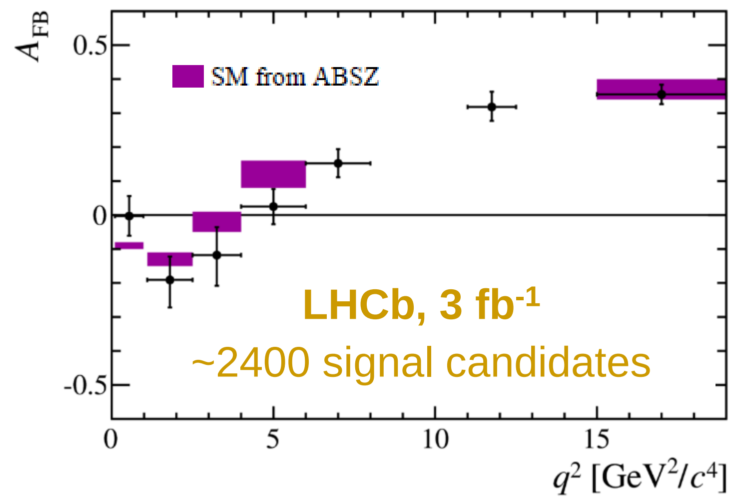
$b \to s l^+ l^-$ decays such as $B^0 \to K^* l^+ l^-$ offer many observables which probe helicity structure (& more) of any New Physics...

The B-factory experiments had inadequate statistics for meaningful tests. This has now all changed, *e.g.* forward-backward asymmetry vs q^2 (dilepton mass).

[PRL 103 (2009) 171801]



[JHEP 02 (2016) 104]



General pattern as predicted; but mild tension at low q^2

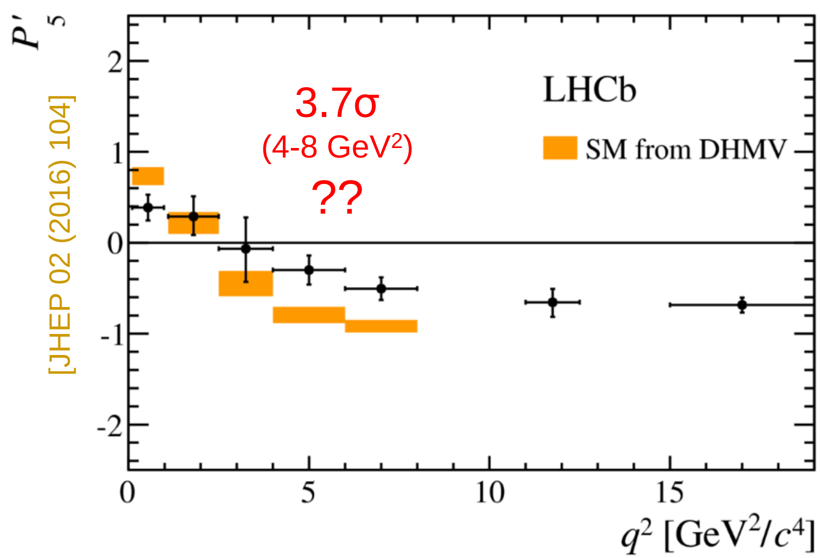
But there are many other observables, which can be built from the measured amplitudes, & are constructed to be intrinsically robust against form factor uncertainties, *e.g.* " P_5' ".

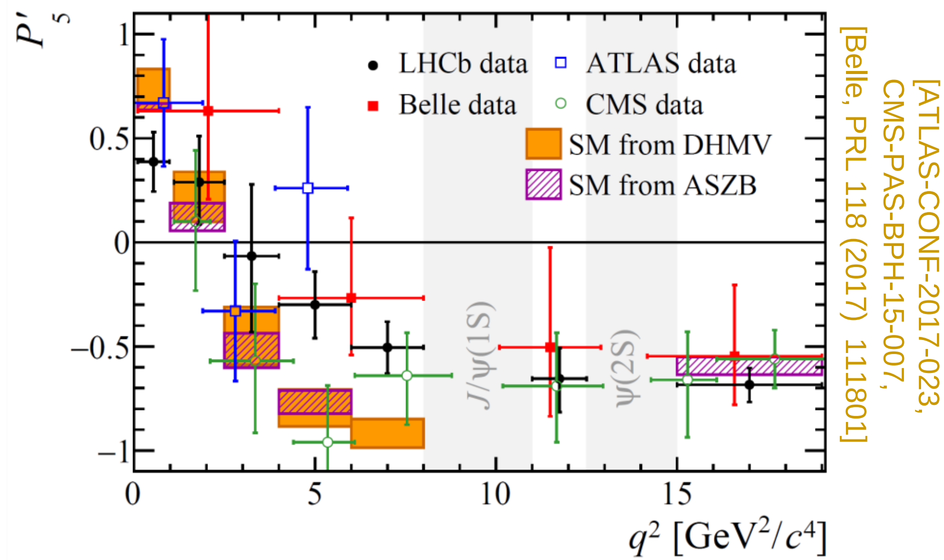
$B^0 \rightarrow K^* l^+ l^-$ and friends: the P_5' conundrum

One such observable is P_5': What this describes physically is hard to visualise, but it is constructed from angular observables in a manner that is robust against form-factor uncertainties, and also easily relatable to the short-distance physics.

Interesting deviation at low q^2.

Same pattern seen by Belle and ATLAS (preliminary), but CMS (preliminary) more SM-like.

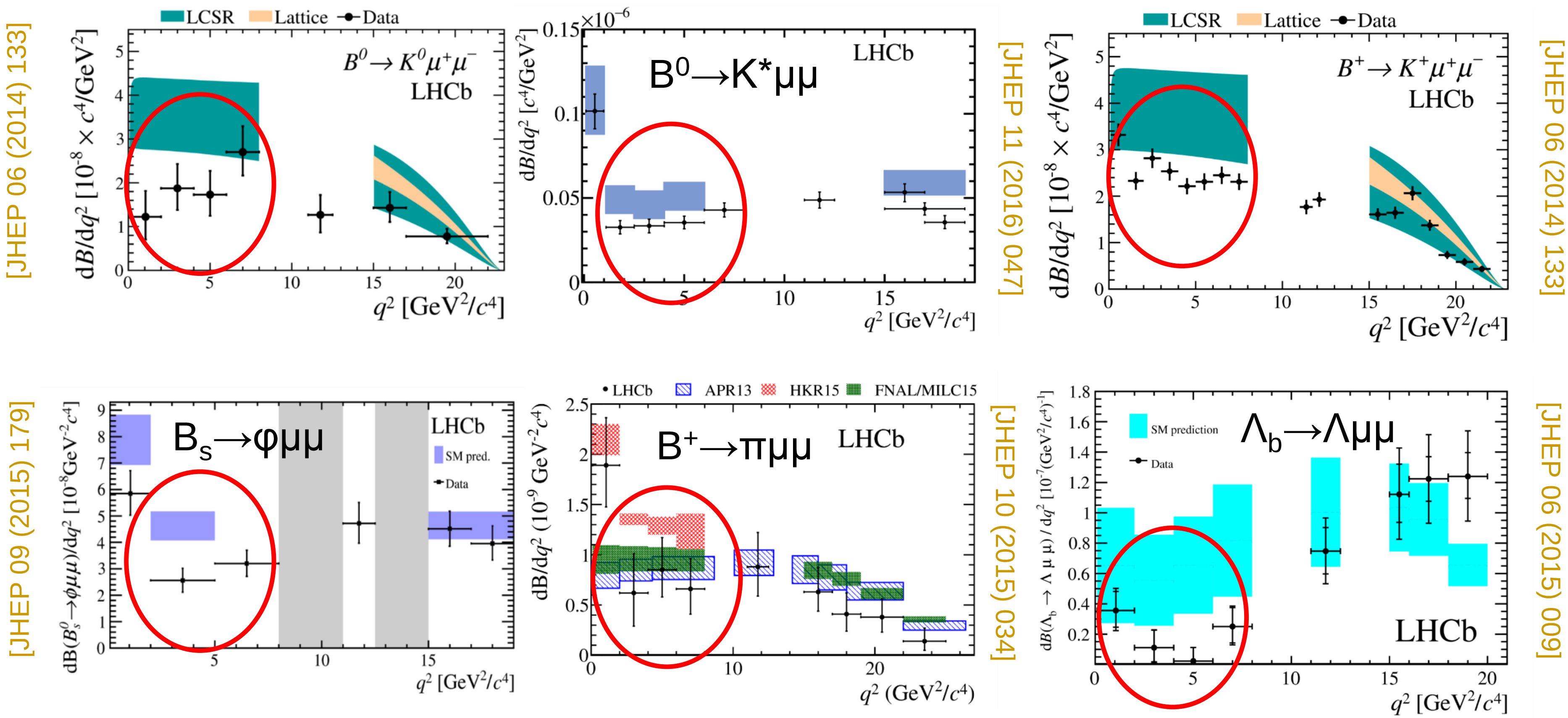




A word of caution. The SM uncertainties shown here are from one group. There are other values on the market, and some are more conservative.

$B^0 \to K^* l^+ l^-$ and friends: differential x-secs

P_5' is not the only funny thing going on in $b \to (s,d) l^+ l^-$ decays.



Consistent tendency for differential x-sections to undershoot prediction at low q^2.
Intriguing – but maybe the uncertainties in theory are larger than claimed ?

$B^0 \to K^* l^+ l^-$ and friends: lepton universality tests

The cleanest way to probe these decays are with lepton universality (LU) tests, *i.e.* comparing decays with di-electrons and di-muons. Negligible theory uncertainty.

- First done [PRL 113 (2014) 151601] by LHCb with $B^+ \to K^+ l^+ l^-$ decays

  R_K = ratio of dimuon to dielecton decay rates, for $1 < q^2 < 6$ GeV^2

$$R_K = 0.745^{+0.090}_{-0.074}(\text{stat}) \pm 0.036(\text{syst})$$

2.6σ low – a statistical fluctuation ?

- An analogous measurement has now been performed with $B^0 \to K^* l^+ l^-$ [JHEP 08 (2017) 055]:

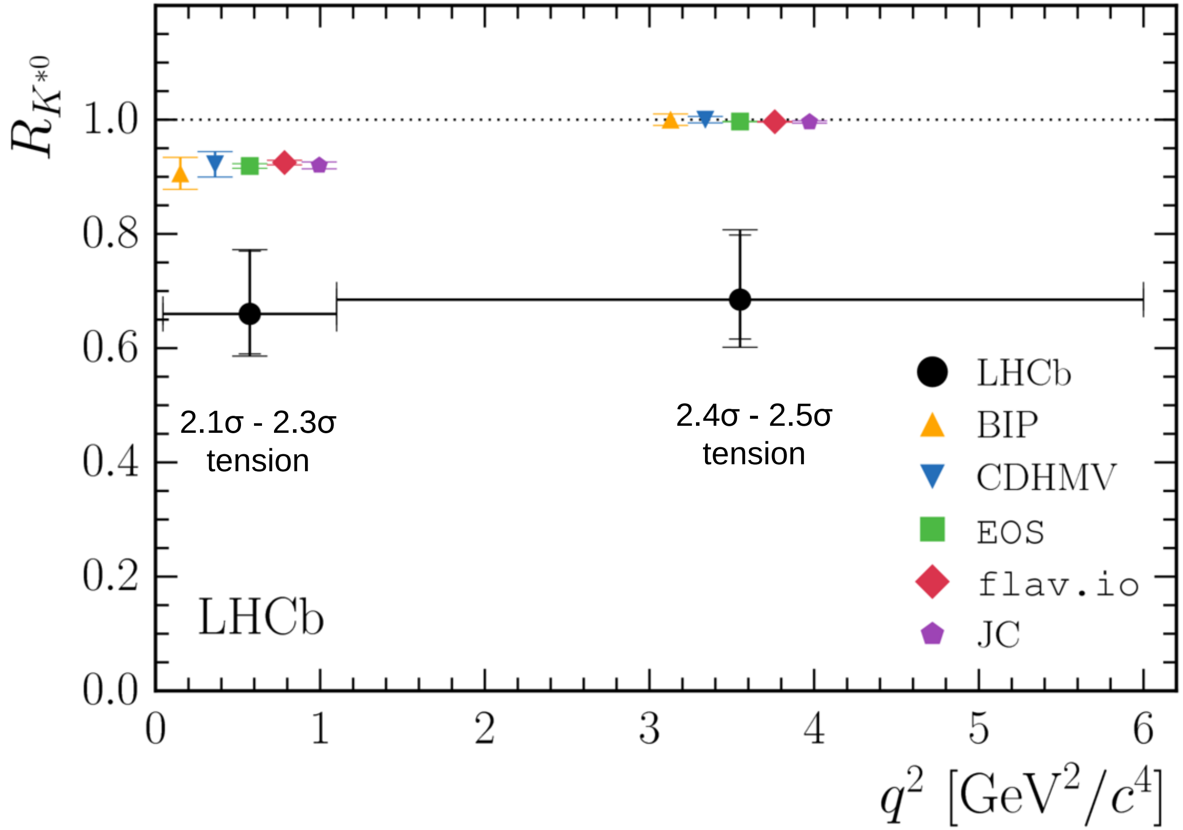
$$\mathcal{R}_{K^{*0}} = \frac{\mathcal{B}(B^0 \to K^{*0}\mu^+\mu^-)}{\mathcal{B}(B^0 \to K^{*0}J/\psi(\to \mu^+\mu^-))} \bigg/ \frac{\mathcal{B}(B^0 \to K^{*0}e^+e^-)}{\mathcal{B}(B^0 \to K^{*0}J/\psi(\to e^+e^-))}$$

  This double ratio (also employed for R_K), involving the control mode $B^0 \to J/\psi K^*$, ensures that all 1st order systematics in efficiency cancel – robust !

  Measure in similar q^2 region as for R_K ('central q^2': 1.1 - 6 GeV^2), but also perform measurement in a low q^2 bin (0.045 - 1.1 GeV^2).

$B^0 \to K^* l^+ l^-$ and friends: lepton universality tests R_{K*}

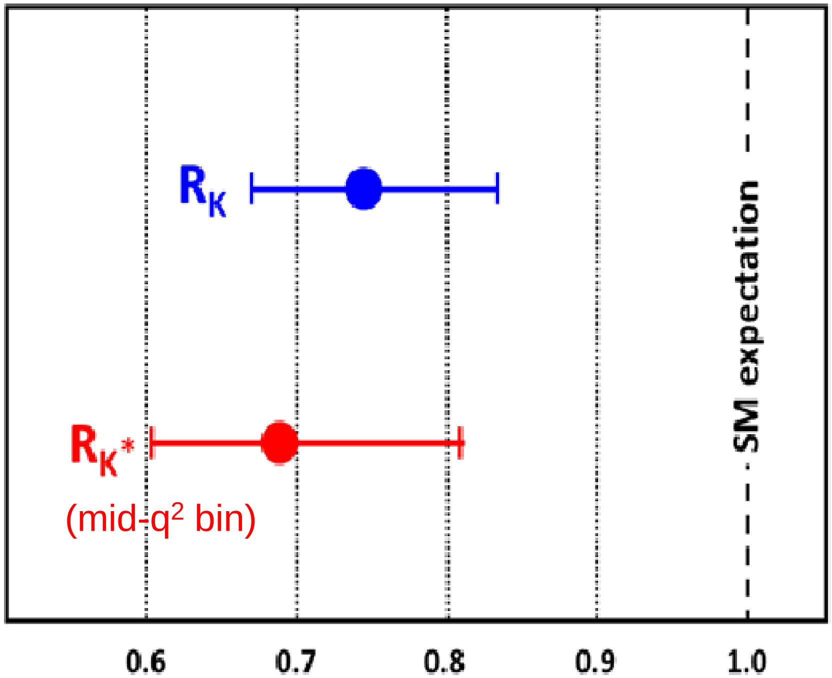
	low- q^2	central- q^2
$R_{K^{*0}}$	$0.66\,^{+\,0.11}_{-\,0.07} \pm 0.03$	$0.69\,^{+\,0.11}_{-\,0.07} \pm 0.05$
95.4% CL	$[0.52, 0.89]$	$[0.53, 0.94]$
99.7% CL	$[0.45, 1.04]$	$[0.46, 1.10]$



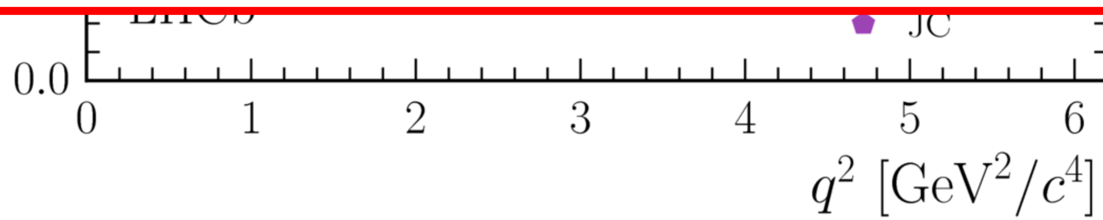
[JHEP 08 (2017) 055]

$B^0 \to K^* l^+ l^-$ and friends: lepton universality tests R_{K^*}

Result uncannily reminiscent of R_K …



….but what could it all mean ?



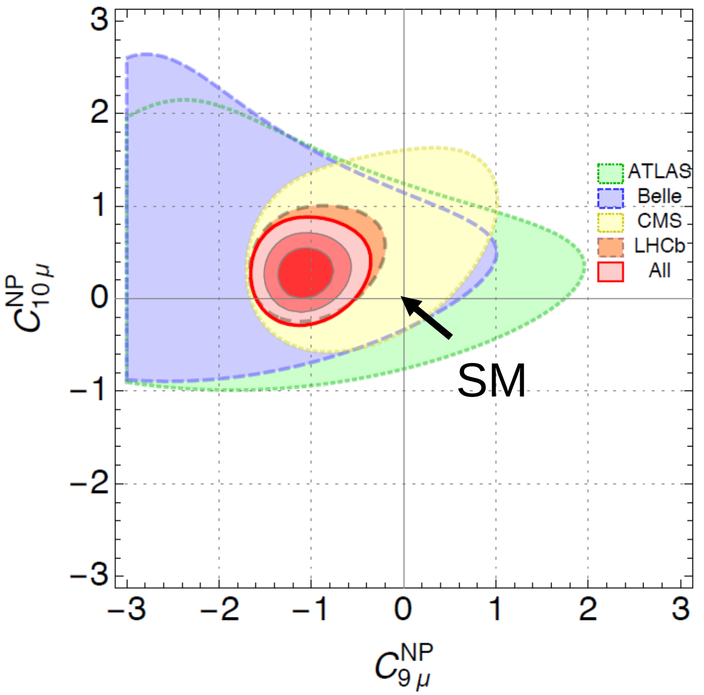
$B^0 \to K^* l^+ l^-$ and friends: what does it all mean ?

Already much theoretical interest in $b \to s l^+ l^-$ sector prior to latest result.

Typical approach – global analysis of all observables and fit to 'Wilson coefficients;.

What is intriguing, and undeniable, is that a *very* coherent picture emerges. The R_{K^*} result fits this picture well (certainly, at central-q^2).

One example [arXiv:1704.05340].
These fits can give >5σ pulls w.r.t. SM, & have led to excited discussion of Z's, leptoquarks *etc*.



The experimentalist's view:

- Hypotheses non fingo !
- Recall, for several of observables there is no consensus on the theory errors.
- Excitement premature: we should wait until we see highly significant deviations in one or more LFU observables. Wait for run-2 updates on R_K, R_{K^*} & indeed R_φ.

$B^0 \rightarrow K^* l^+ l^-$ and friends: what does it all mean ?

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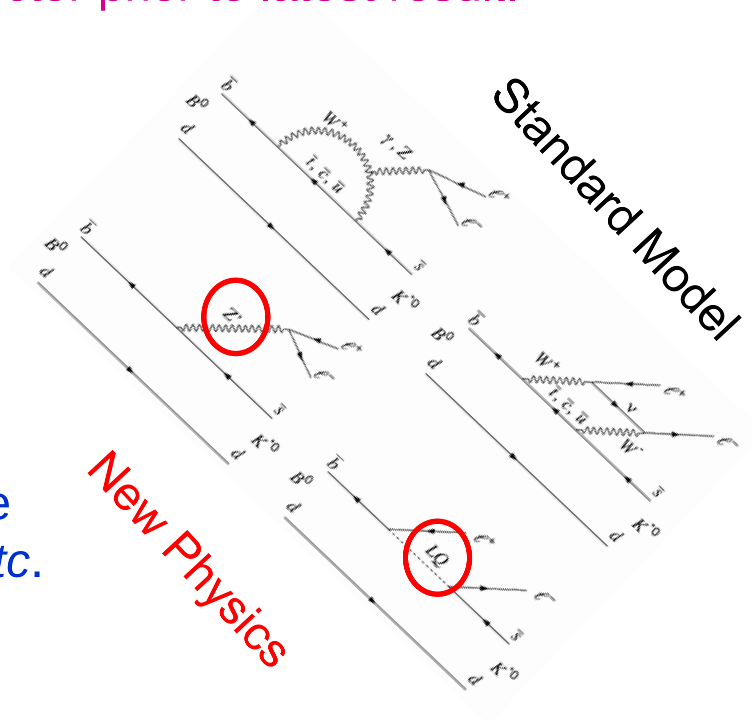

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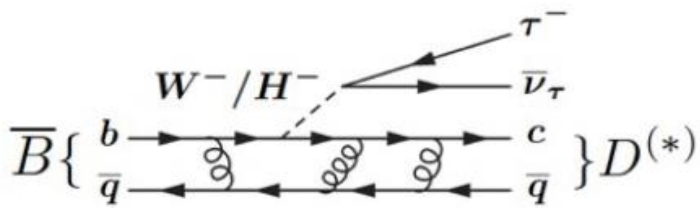
Other hints of Lepton Universality violation: $R(D^{(*)}) \equiv BR(B\to D^{(*)}\tau\nu)/BR(B\to D^{(*)}\mu\nu)$

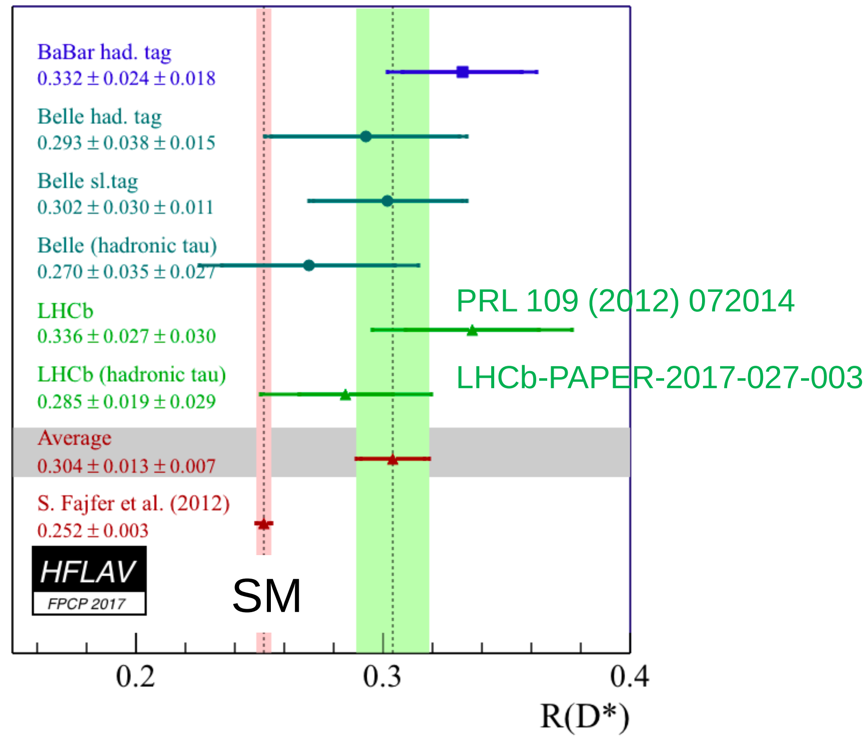
Equal coupling in the SM; but high mass of τ pushes expected ratio down to ~0.25

$B\to D^{(*)}\tau\nu$ is not a 'flavour-changing neutral current', nor even particularly rare, but of great interest, because of its sensitivity to, *e.g.* charged Higgs sector



Moreover, a series of measurements, begun at the B-factories, and continued by LHCb, have begun to show a very interesting pattern, *e.g.* for R(D*)

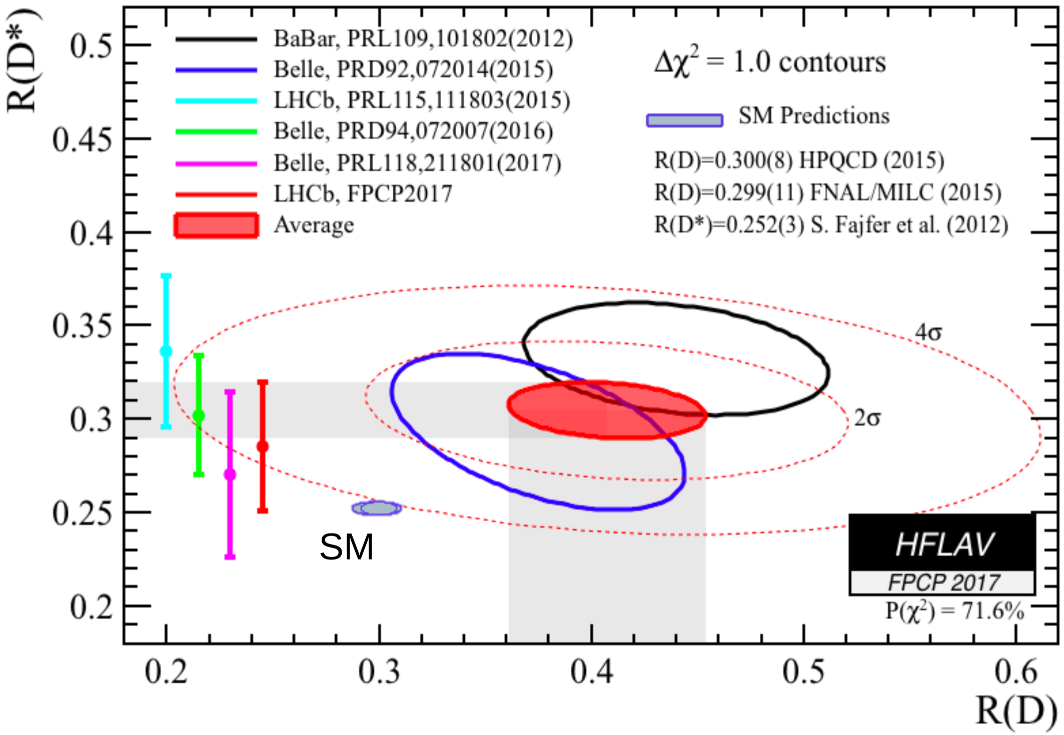
All consistently high !



Very suggestive, but scale of effect can't easily by accommodated in a 'normal' New Physics model, *e.g.* type-II 2HDM. Leptoquark models can work, but a challenge to fit in with the $b\to sl^+l^-$ anomalies.

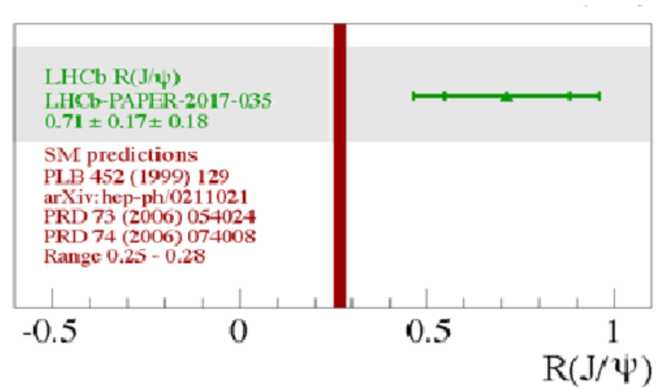
Current global picture for R(D*) and R(D)

Combination of results give a 4.1 σ (!) discrepancy w.r.t. SM.



And something new…

Result of a recent LHCb analysis of $B_c \rightarrow J/\psi \tau \nu$ [LHCb-PAPER-2017-035]. Same physics, different systematics.



Amusingly this is also high, by 2σ ! (but current stat precision is low).

These measurements are difficult ! Is there some unaccounted source of background in the $R(D^{(*)})$ case ??? Upcoming new LHCb results, expected soon, will have precision to push net effect >5σ. We may soon be in a crisis situation…

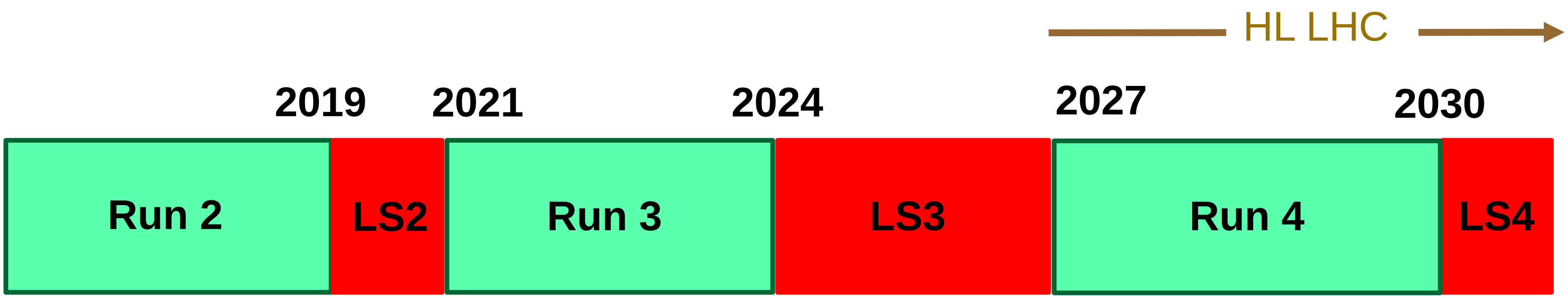
Flavour beyond run 2

Almost all results so far shown are from run-1 data
(precise measurements take time to perform !).

LHC run 2 now in full flow. These data are sure to deliver
a substantial improvement in precision (~halving of uncertainties),
and perhaps many surprises, but let us now look to the further future.

The LHC schedule up to 2030

Aside from LHCb, the coming decade (+) will be an exciting time for flavour physics.



Install HL-LHC and ATLAS & CMS Phase-II Upgrades.

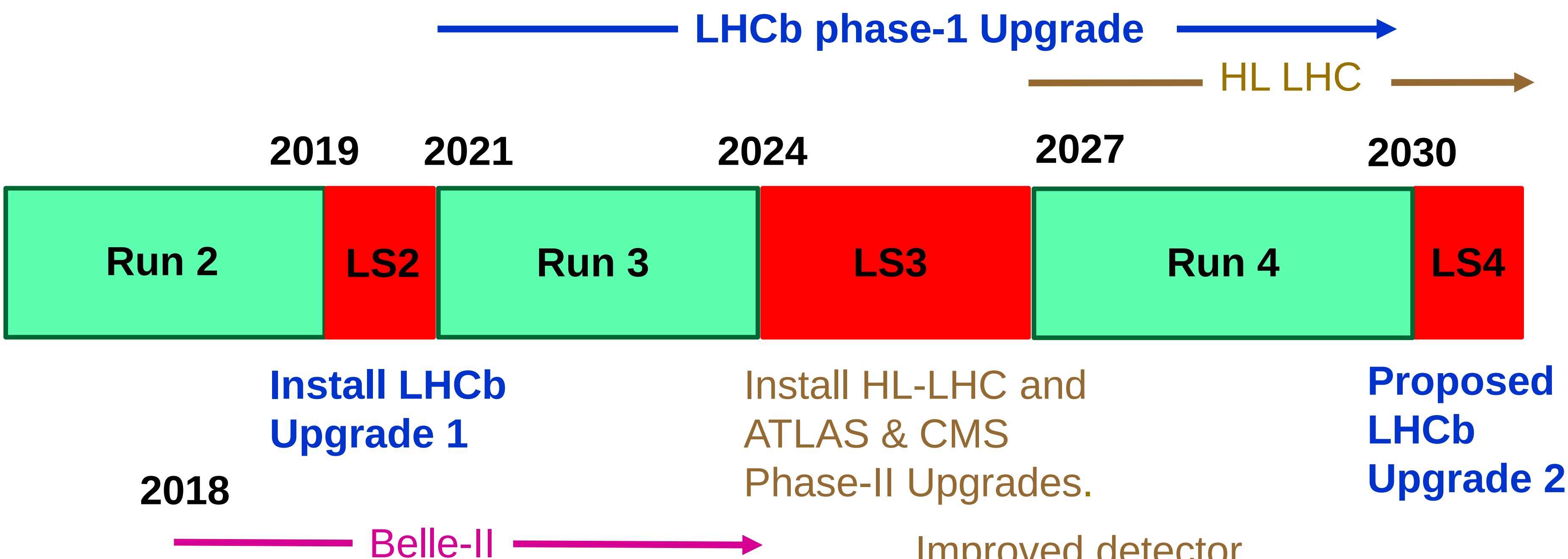
2018

Belle-II →

Very complementary programme to LHCb, with particular strengths in final states with neutrals &/or missing energy.

Improved detector capabilities and very large data sets will open up exciting opportunities in flavour.

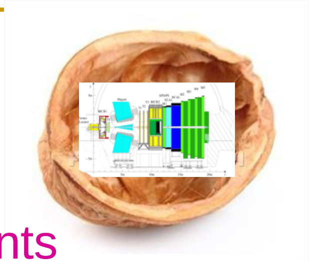
The LHC schedule up to 2030



Very complementary programme to LHCb, with particular strengths in final states with neutrals &/or missing energy.

Improved detector capabilities and very large data sets will open up exciting opportunities in flavour.

LHCb Upgrade 1 (LS2) in a nutshell



Indirect search strategies for New Physics, *e.g.* precise measurements & the study of suppressed processes in the flavour sector become ever-more attractive following the experience of run-1 LHC that direct signals are elusive

Our knowledge of flavour physics has advanced spectacularly thanks to LHCb. Maintaining this rate of progress beyond run 2 requires significant changes.

The LHCb Upgrade

1) Full software trigger
- Allows effective operation at higher luminosity
- Improved efficiency in hadronic modes

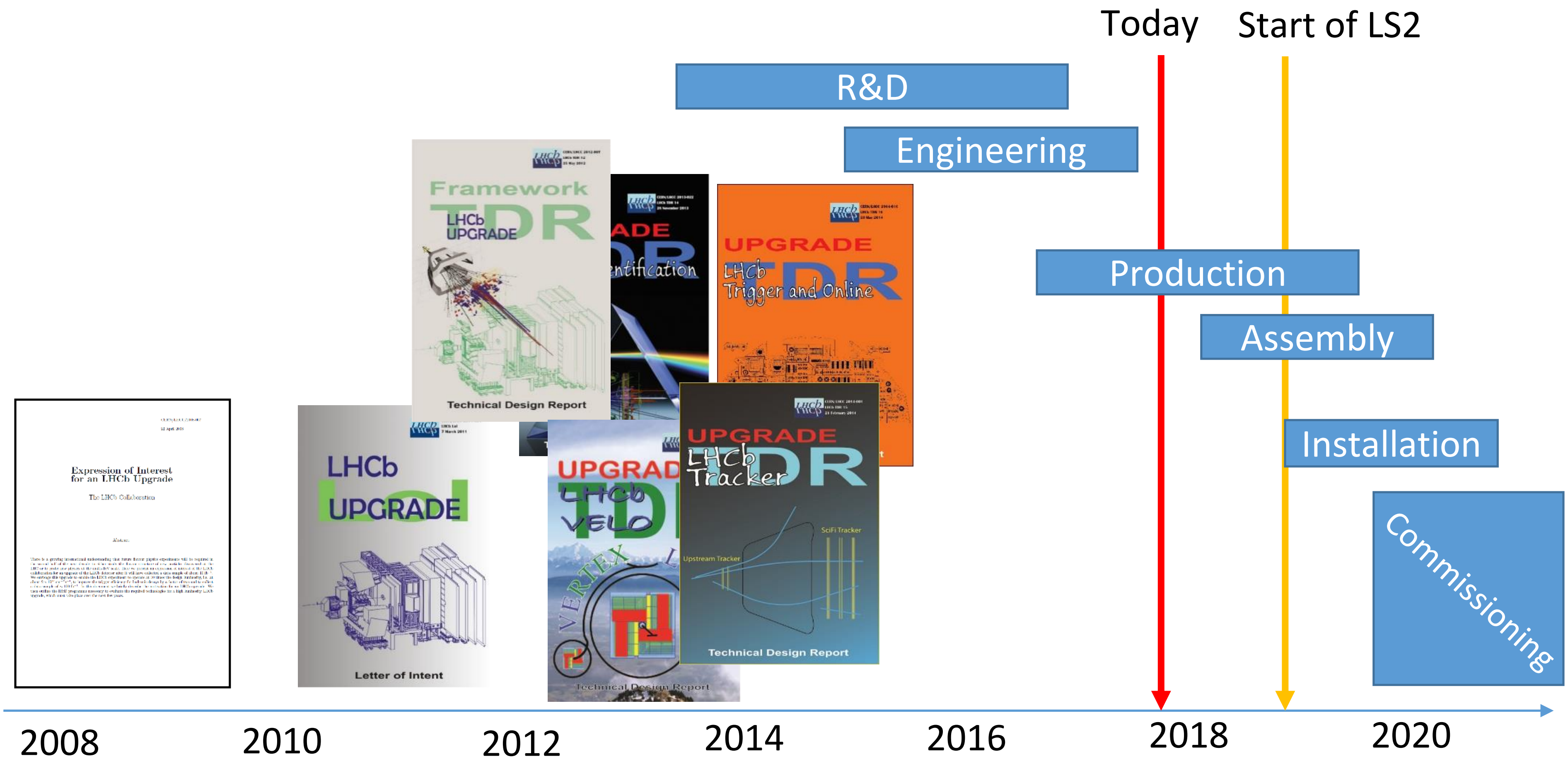
2) Raise operational luminosity to 2 x 10^{33} cm^{-2} s^{-1}

Necessitates redesign of several sub-detectors & overhaul of readout

Huge increase in precision: Upgrade + run 2 yield in hadronic modes ~ 60x that of run 1; also perform studies *beyond the reach of the current detector*.

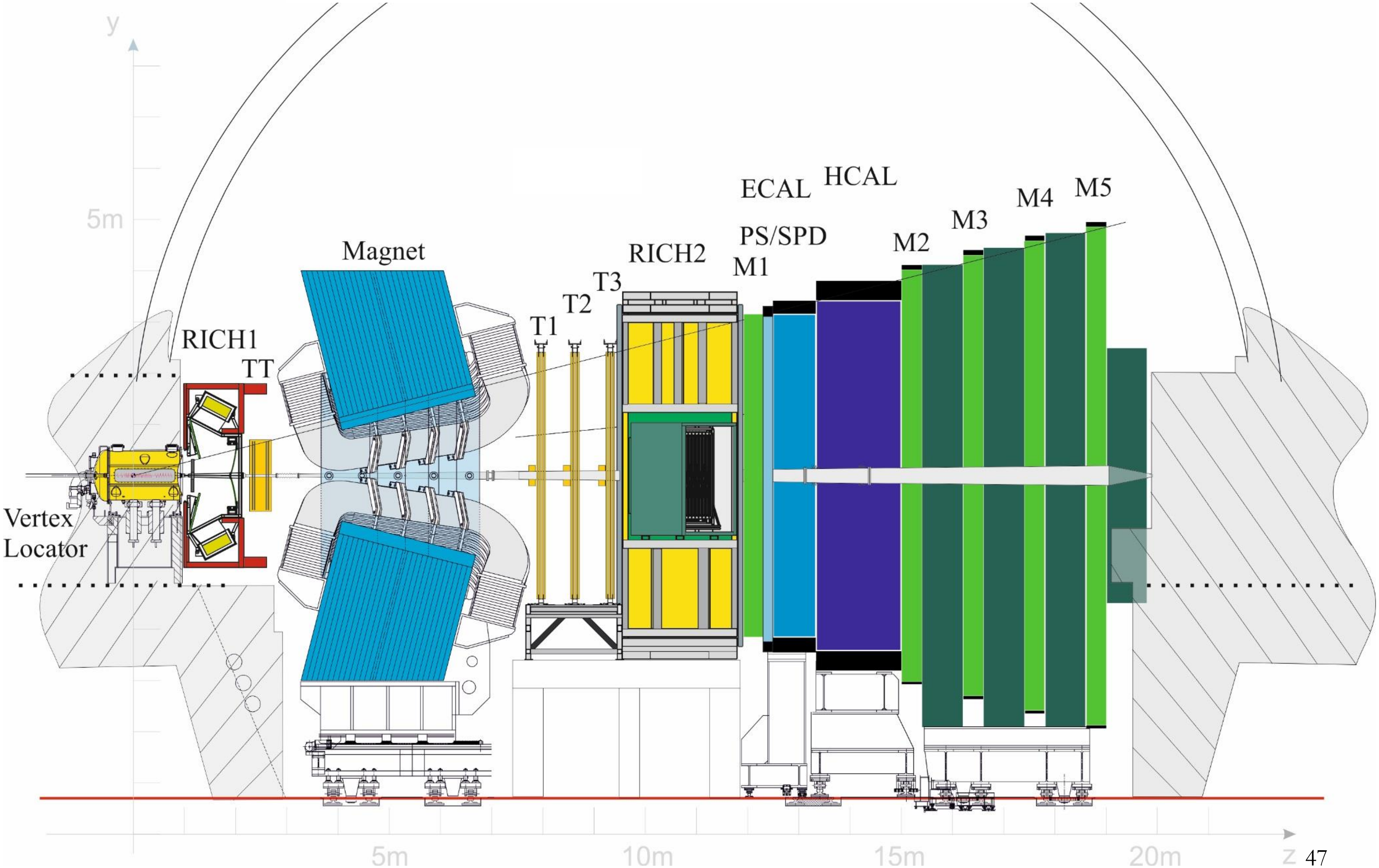
Flexible trigger and unique acceptance also opens up opportunities in other topics apart from flavour ('a general purpose detector in the forward region').

LHCb Upgrade-1 (LS2) timeline



Goal: to operate throughout the 2020s & to have accumulated 50 fb^{-1} by end of run 4.

Current detector



Required modifications

Full s/w trigger →

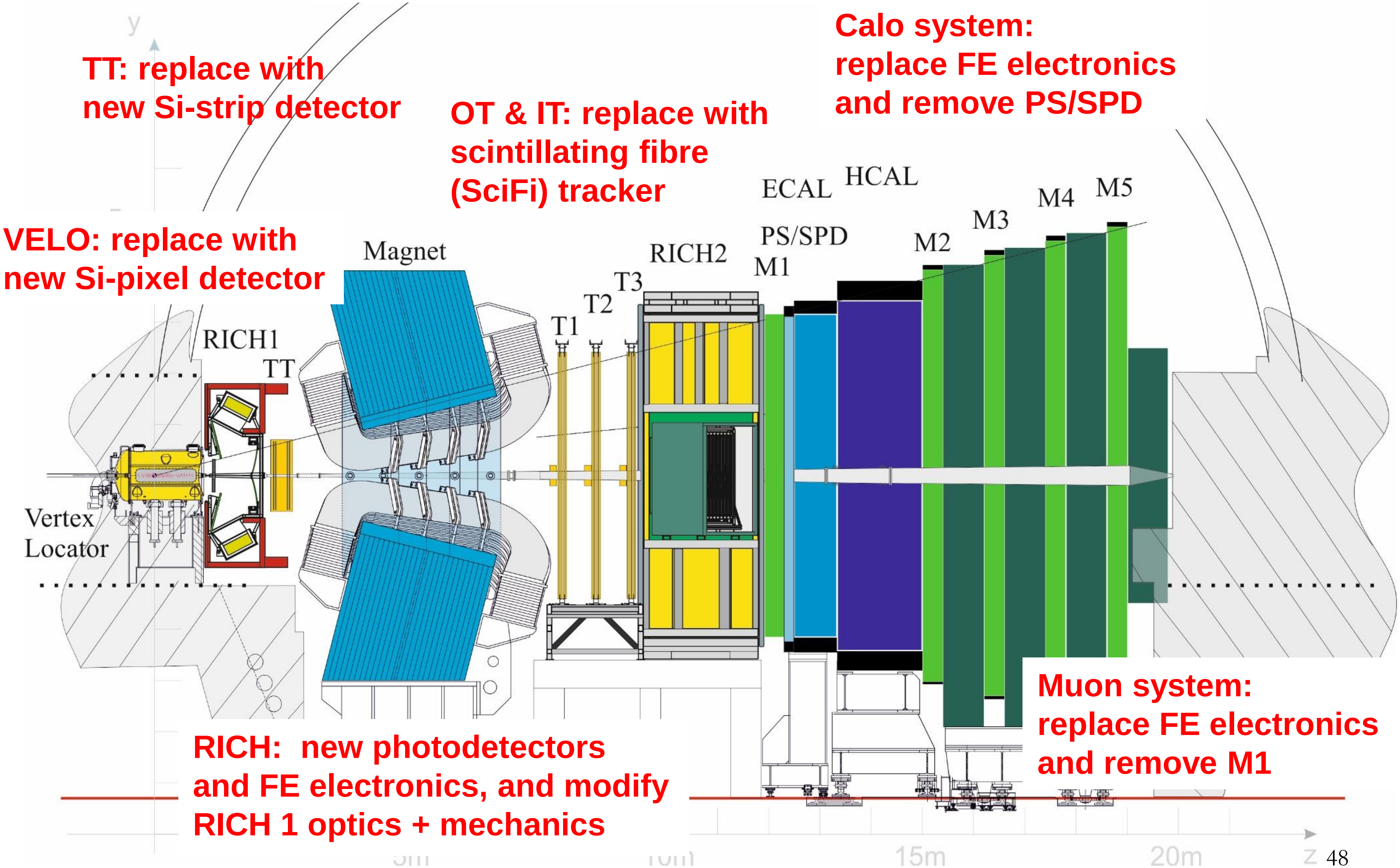
Replace read-out boards and DAQ

TT: replace with new Si-strip detector

OT & IT: replace with scintillating fibre (SciFi) tracker

Calo system: replace FE electronics and remove PS/SPD

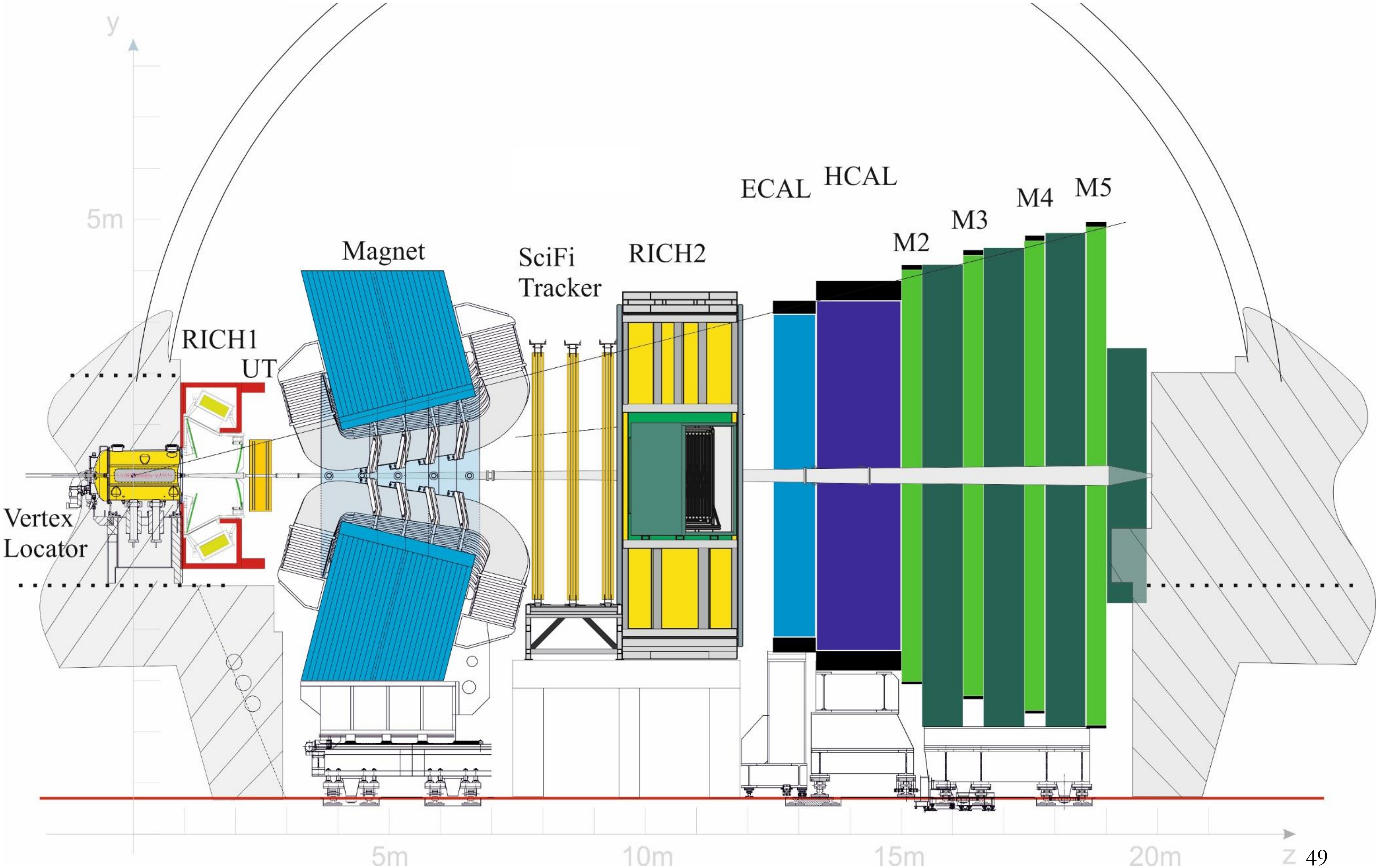
VELO: replace with new Si-pixel detector



RICH: new photodetectors and FE electronics, and modify RICH 1 optics + mechanics

Muon system: replace FE electronics and remove M1

Upgraded detector

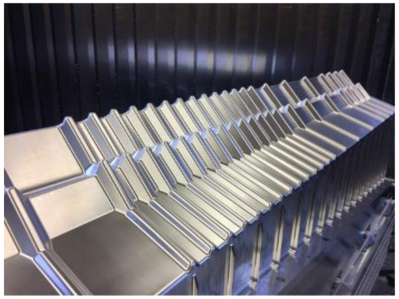


Upgrade progress

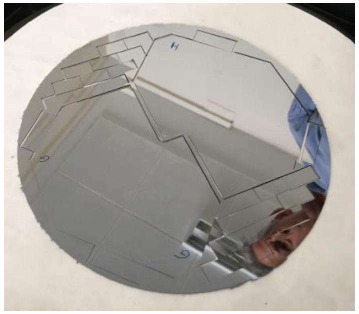
Excellent progress on all aspects of the Upgrade project.

Prototype readout boards

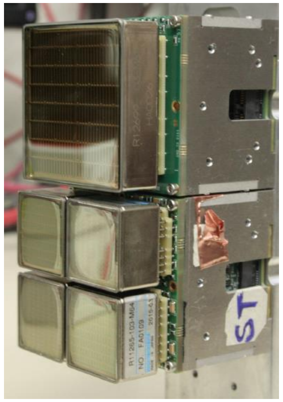
RF box for VELO



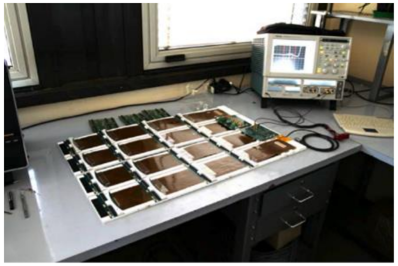
Diced wafer with microchannel cooling substrates for VELO



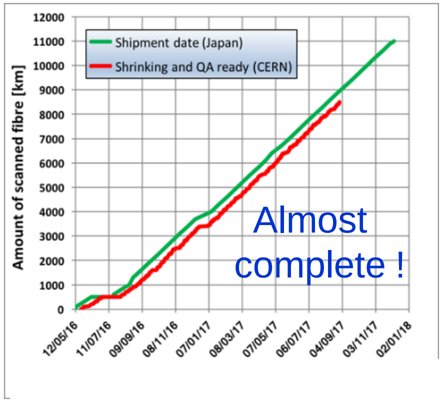
RICH photodetectors



Testing Upstream Tracker ‘flex cables’



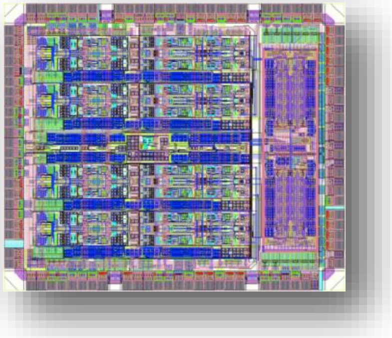
Delivery of tracker scintillating fibres (SciFi)



First batch of SciFi modules arriving at IP8

MWPC for muon system

ECAL front-end ASIC



Timescale tight, but still on-track for installation in LS2 (*i.e.* 2019-20)

How will the LHCb Upgrade 1 perform ?

Projections exist, but the numbers are, IMHO, merely indicative.

['old' table from EPJ C 73 (2013) 2373; arXiv:1208.3355.if re-made with current numbers the argument would remain]

Type	Observable	Current precision	LHCb 2018	Upgrade ($50\,\text{fb}^{-1}$)	Theory uncertainty
B_s^0 mixing	$2\beta_s\ (B_s^0 \to J/\psi\ \phi)$	0.10 [9]	0.025	0.008	~ 0.003
	$2\beta_s\ (B_s^0 \to J/\psi\ f_0(980))$	0.17 [10]	0.045	0.014	~ 0.01
	$A_{\text{fs}}(B_s^0)$	6.4×10^{-3} [18]	0.6×10^{-3}	0.2×10^{-3}	0.03×10^{-3}
Gluonic	$2\beta_s^{\text{eff}}(B_s^0 \to \phi\phi)$	–	0.17	0.03	0.02
penguin	$2\beta_s^{\text{eff}}(B_s^0 \to K^{*0}\bar{K}^{*0})$	–	0.13	0.02	< 0.02
	$2\beta^{\text{eff}}(B^0 \to \phi K_S^0)$	0.17 [18]	0.30	0.05	0.02
Right-handed	$2\beta_s^{\text{eff}}(B_s^0 \to \phi\gamma)$	–	0.09	0.02	< 0.01
currents	$\tau^{\text{eff}}(B_s^0 \to \phi\gamma)/\tau_{B_s^0}$	–	5 %	1 %	0.2 %
Electroweak	$S_3(B^0 \to K^{*0}\mu^+\mu^-; 1 < q^2 < 6\,\text{GeV}^2/c^4)$	0.08 [14]	0.025	0.008	0.02
penguin	$s_0\ A_{\text{FB}}(B^0 \to K^{*0}\mu^+\mu^-)$	25 % [14]	6 %	2 %	7 %
	$A_{\text{I}}(K\mu^+\mu^-; 1 < q^2 < 6\,\text{GeV}^2/c^4)$	0.25 [15]	0.08	0.025	~ 0.02
	$\mathcal{B}(B^+ \to \pi^+\mu^+\mu^-)/\mathcal{B}(B^+ \to K^+\mu^+\mu^-)$	25 % [16]	8 %	2.5 %	~ 10 %
Higgs	$\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	1.5×10^{-9} [2]	0.5×10^{-9}	0.15×10^{-9}	0.3×10^{-9}
penguin	$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	–	~ 100 %	~ 35 %	~ 5 %
Unitarity	$\gamma\ (B \to D^{(*)}K^{(*)})$	~ 10–12° [19, 20]	4°	0.9°	negligible
triangle	$\gamma\ (B_s^0 \to D_sK)$	–	11°	2.0°	negligible
angles	$\beta\ (B^0 \to J/\psi\ K_S^0)$	0.8° [18]	0.6°	0.2°	negligible
Charm	A_Γ	2.3×10^{-3} [18]	0.40×10^{-3}	0.07×10^{-3}	–
CP violation	ΔA_{CP}	2.1×10^{-3} [5]	0.65×10^{-3}	0.12×10^{-3}	–

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					~ 0.01
					$.03 \times 10^{-3}$
					0.02
					< 0.02
					0.02
Ri					< 0.01
					0.2 %
El					0.02
					7 %
					~ 0.02
					$\sim 10\,\%$
					0.3×10^{-9}
					$\sim 5\,\%$
Unitarity	γ ($B \to D^{(*)} K^{(*)}$)	~ 10–12° [19, 20]	4°	0.9°	negligible
triangle	γ ($B_s^0 \to D_s K$)	–	11°	2.0°	negligible
angles	β ($B^0 \to J/\psi\, K_S^0$)	0.8° [18]	0.6°	0.2°	negligible
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CP violation	ΔA_{CP}	2.1×10^{-3} [5]	0.65×10^{-3}	0.12×10^{-3}	–

LHCb Upgrade (+ run 2) aims to collect:

~60 x more than LHCb run 1 in hadronic modes and
~30 x more than LHCb run 1 in muonic modes,

where difference is driven by full software trigger.

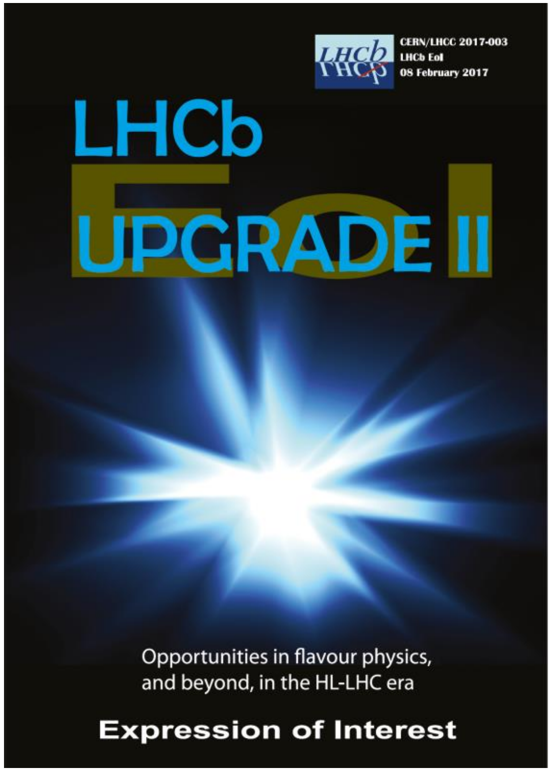
So order of magnitude improvement in precision expected !

['old' table from EPJ C 73 (2013) 2373; arXiv:1208.3355.If re-made with current numbers the argument would remain]

Looking further forward…

Serious thinking now underway about an Upgrade 2 that would occur in LS4 (~2030) & allow full exploitation of flavour potential of the machine in HL-LHC era.

Expression of Interest submitted to February LHCC [CERN-LHCC-2017-003]



- Install in LS4 (~2030), after Phase-I Upgrade.
- Detector to be able to operate at ~2 x 10^{34} $cm^{-2}s^{-1}$;
- Integrate ~300 fb^{-1};
- Comprehensive flavour physics programme and general-purpose forward physics (as now), but targeting clean measurements currently limited by statistics, and new observables;
- Modest activities foreseen for LS3 in consolidation of Upgrade 1 & in preparation for next step.

Significant detector challenges, but many benefits to be gained from R&D for ATLAS & CMS Phase-II Upgrades, *e.g.* fast timing.

Conclusions

- The study of flavour, in particular beauty decays, is a powerful & necessary approach in the search for New Physics beyond the Standard Model.

- The LHC is a flavour factory. LHCb in particular has produced many important results from run 1, with more now emerging from run 2.

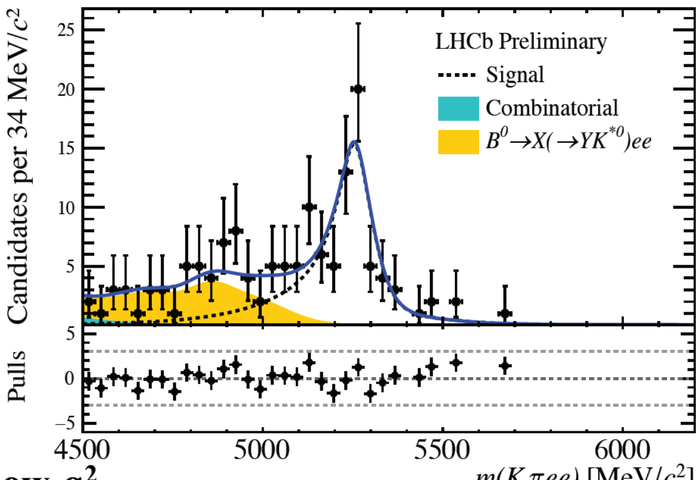
  → In most cases these results are in good agreement with the SM, in others intriguing discrepancies are starting to emerge.
  We should know rather soon whether these anomalies are fluctuations or something more. But even if they dissipate, they illustrate well how a discovery can be made through flavour.

- Further progress beyond run 2 requires an upgraded experiment, to be installed in 2019-20. Plans are already afoot for a second upgrade in ~2030.

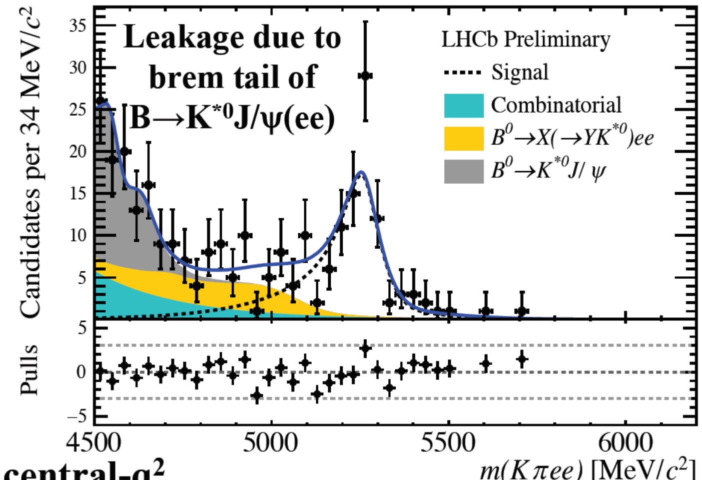
Backups

$B^0 \rightarrow K^{*} l^{+} l^{-}$ and friends: lepton universality tests R_{K^*}

Mass spectra in di-electron final state



low-q^2



central-q^2

[arXiv:1705.05802]

Around 90 and 110 signal candidates in low-q^2 and central q^2, respectively.

58k in control channel.

Muon samples 3-5x larger.