Dispatch from the flavour frontier - an experimental perspective

- Flavour physics
  - A topic of intrinsic interest
  - A tool for indirect discovery
- LHCb overview
- *Selected* topics
  - Spectroscopy and hadron exotics
  - CPV in beauty and charm
  - Rare decays, FCNCs and R_{K^*}
- Beyond Run II
  - Belle II
  - The LHCb Upgrade(s)

Guy Wilkinson
University of Oxford and CERN
5 June 2017

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Some excuses are in order:

- This talk will not touch on kaon physics – but this topic is a vital and important piece of the jigsaw;
- Similarly, no discussion of neutrinos, $(g\text{-}2)_\mu$ *etc*;
- It will be LHCb-centric. Apply your own bias correction.

Also note that I have defined spectroscopy to lie within the tent of flavour physics. Flavour-expt.s are good at spectroscopy !

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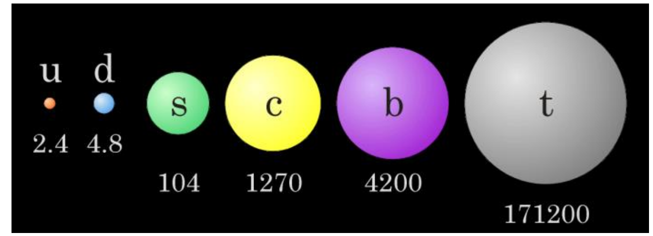
Why flavour ?

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

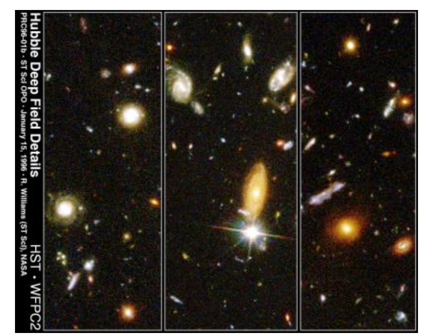
- Why 3 generations of quarks, and
  why the extreme hierarchy of masses ?



- 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 ?

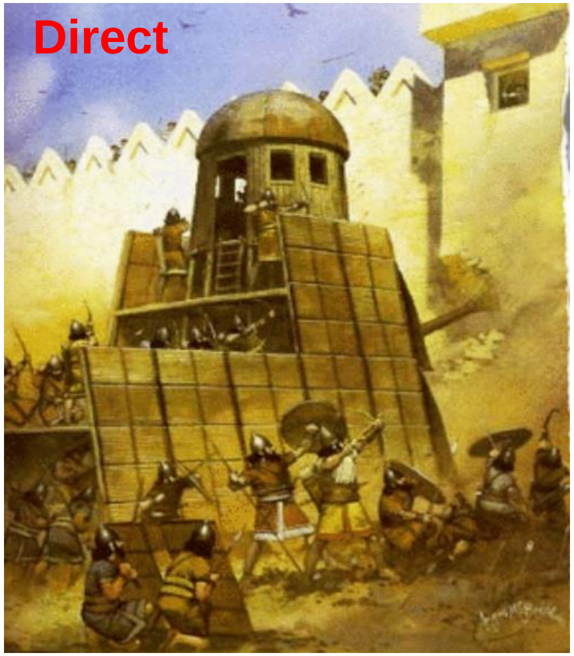


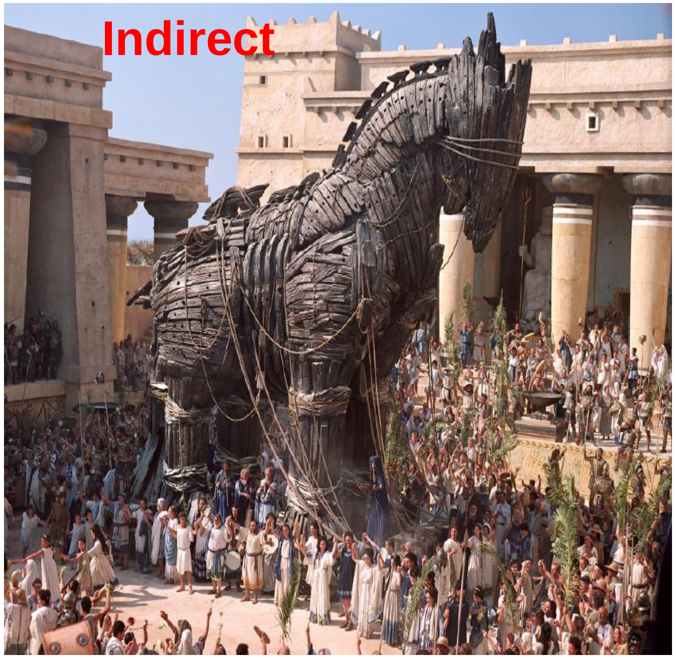
(Moreover, the tools of the flavour physicist are well suited to probing hadron spectroscopy, where the behaviour of QCD can be studied in the non-perturbative regime.)

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.





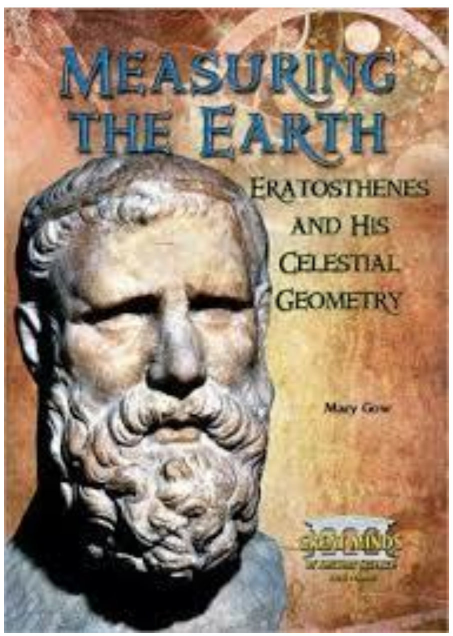
Use the high energy of the LHC to produce the New Physics particles, which we then detect

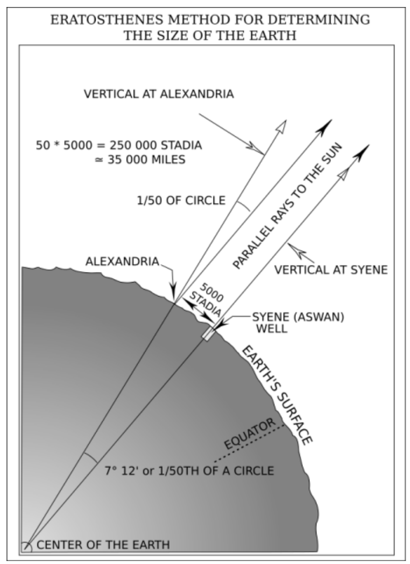
Make precise measurements of processes in which New Physics particles enter through ‘virtual loops’

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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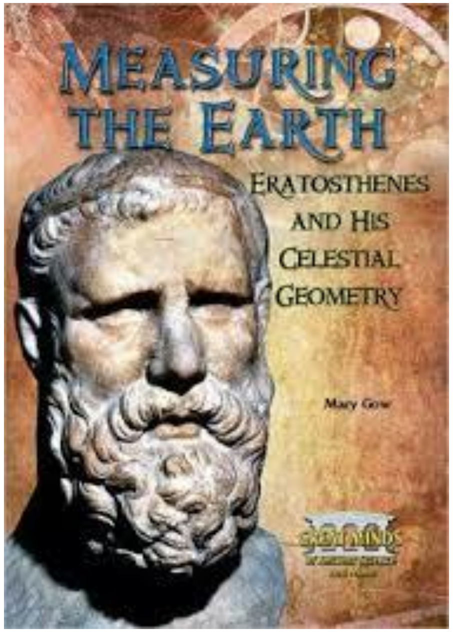
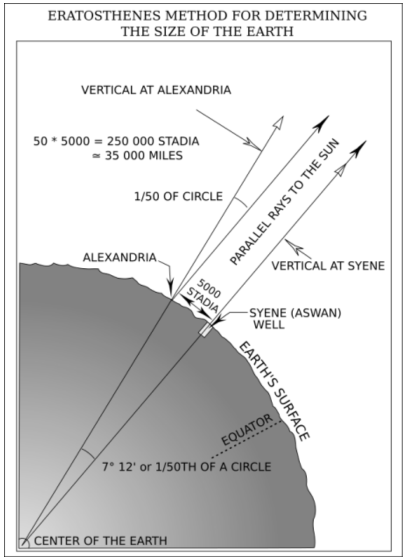
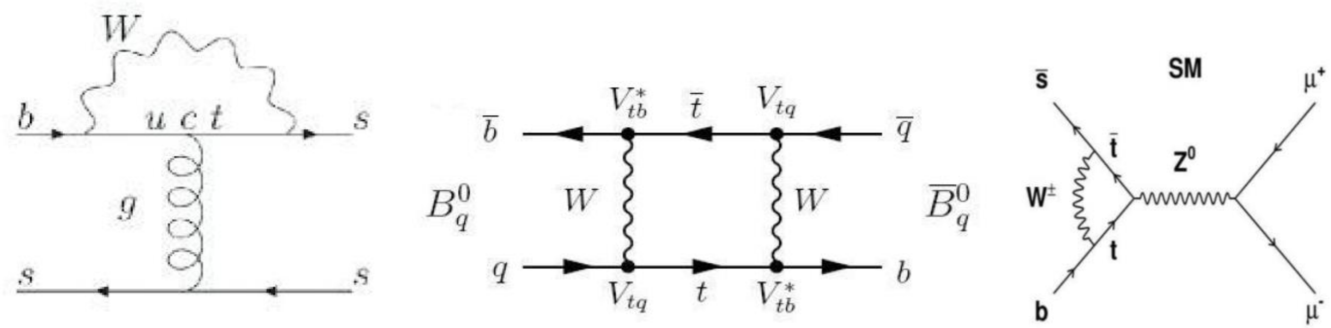




…around 2.2 thousand years
prior to the direct observation.

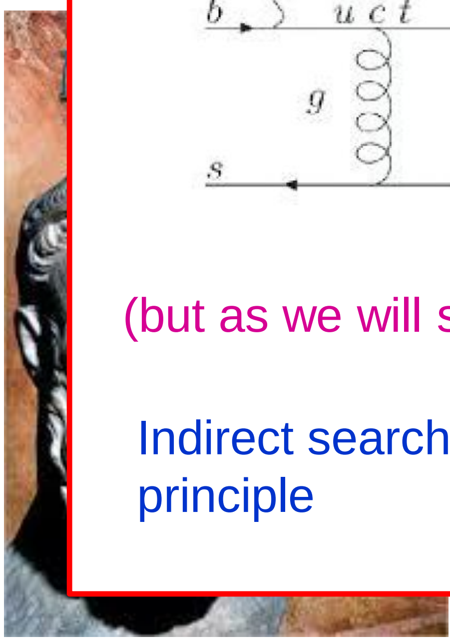
Indirect measurements – an established tradition in science

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



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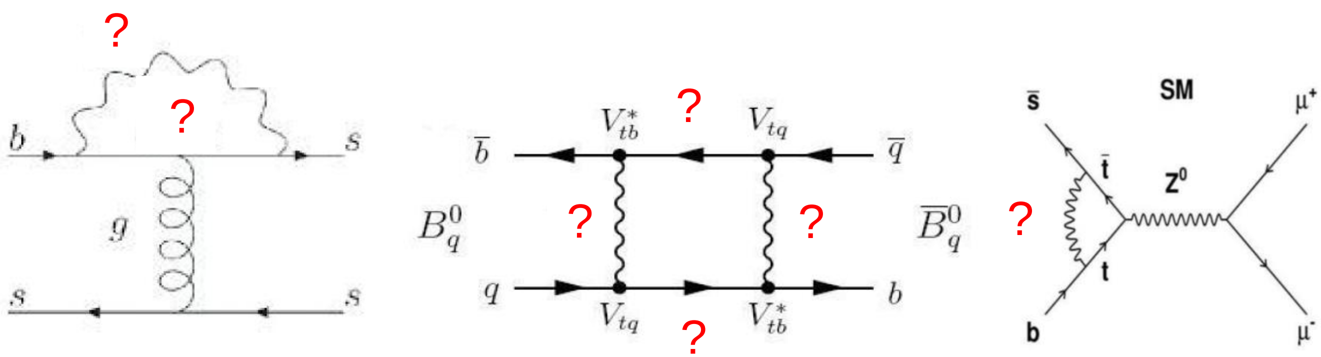

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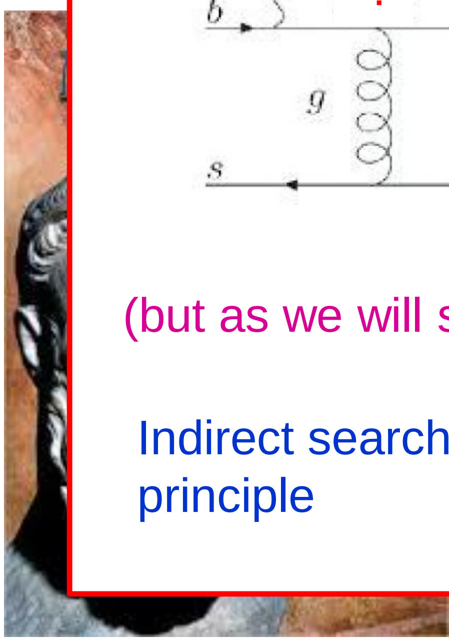
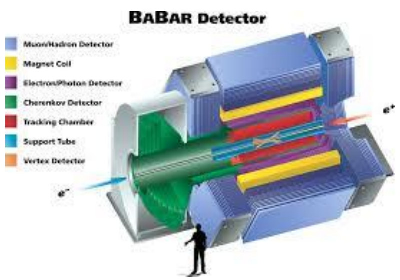


The main players in b (and c) physics

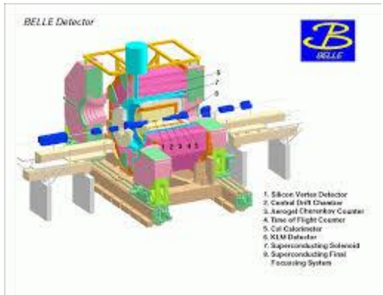
b-factories

also LEP, ARGUS, CLEO, BES-III



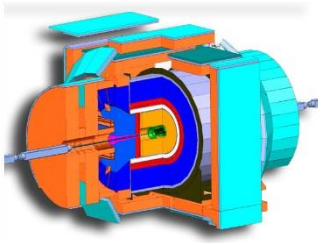
BaBar (SLAC) & Belle (KEK)

Operated in the 2000's
e^+e^- machines with asymmetric beams for time-dep studies, mainly at $Y(4S)$, hence B^0 and B^+ samples. Considered 'clean' environments.



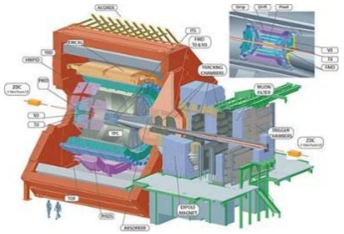
Tevatron experiments

also UA1, UA2



CDF & D0

Tevatrons 'general purpose detectors'.
Pioneered *b*-physics in hadronic collisions.
Important early B_s and *b*-baryon studies.



ATLAS & CMS

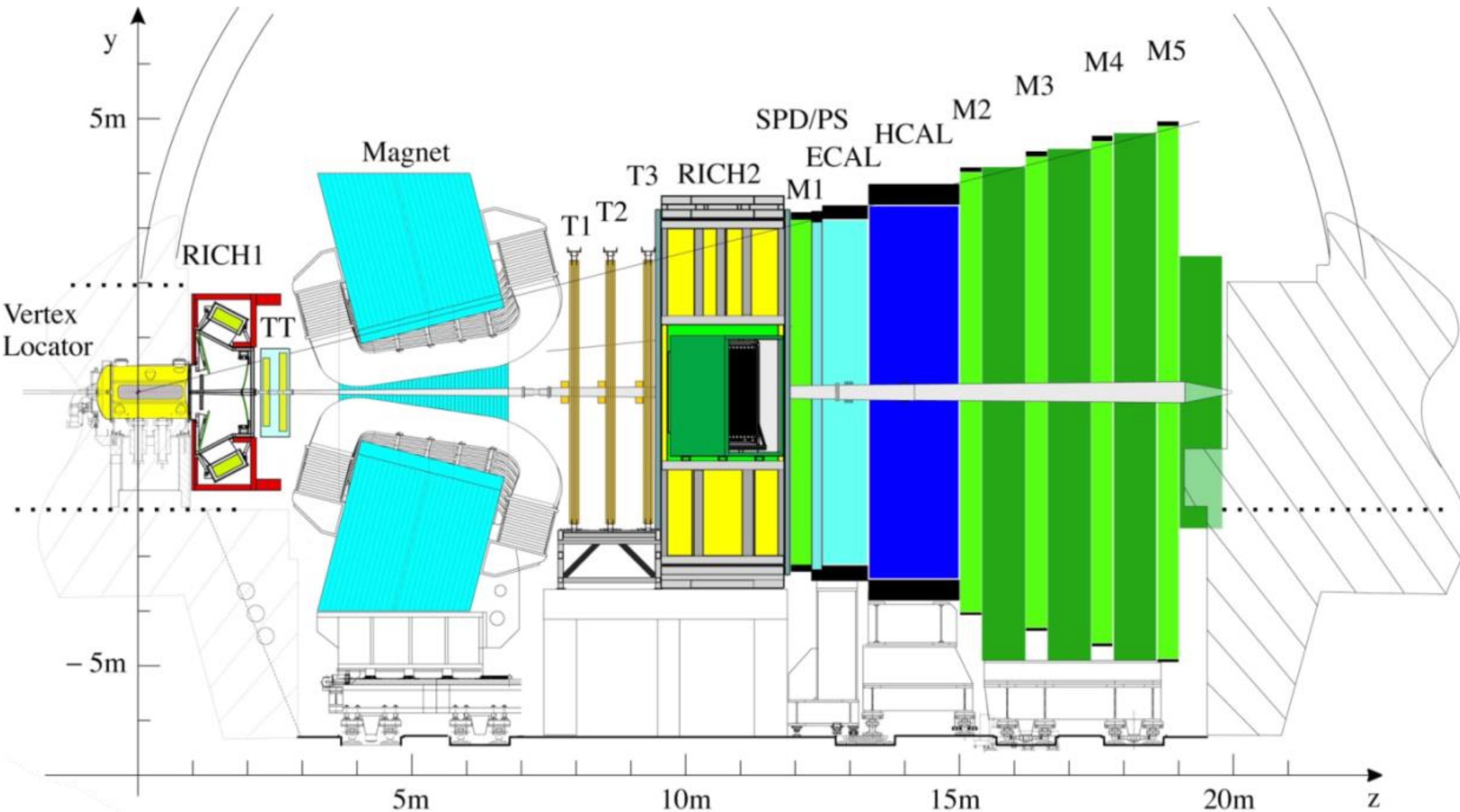
Their excellent instrumentation gives them great capabilities in certain *b*-physics channels, especially those with dilepton final states.

LHCb – a flavour physics experiment at the LHC

A collaboration of ~1200 members from 72 institutes in 16 countries

An experiment to search for physics beyond the Standard Model, through flavour studies of beauty- and charm-hadrons (but also general 'forward physics')

LHCb – a forward spectrometer for flavour physics



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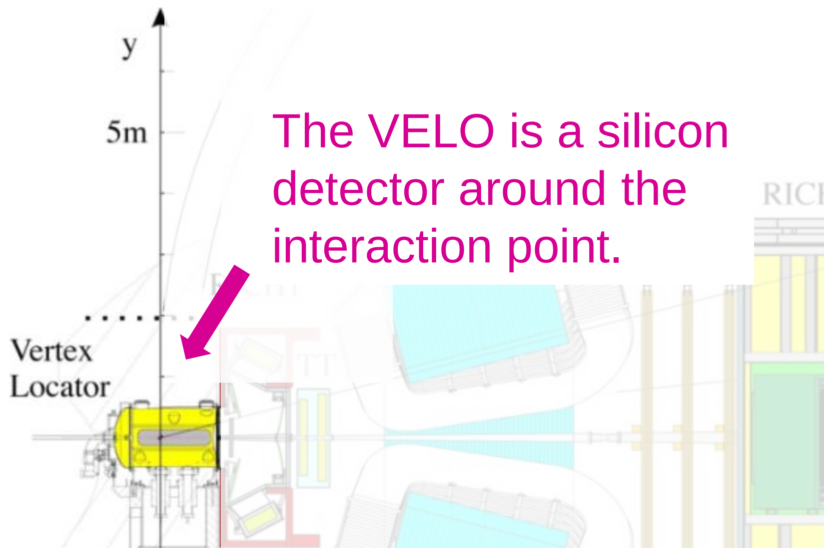
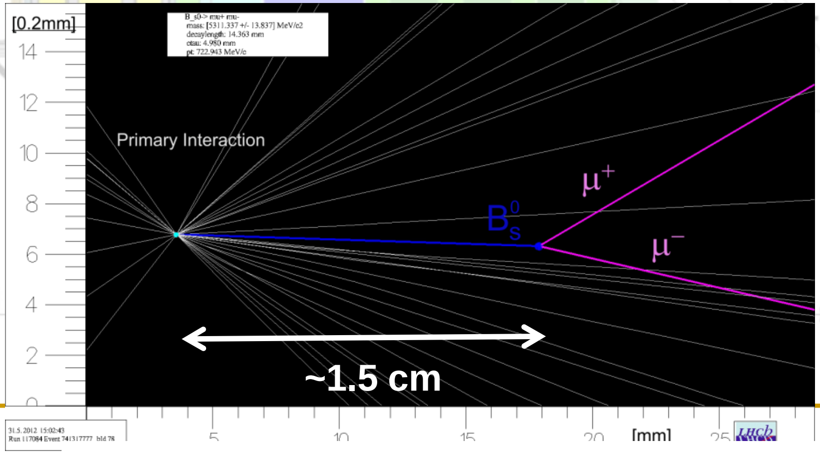


The VELO is a silicon detector around the interaction point.

One-half of the VELO under construction

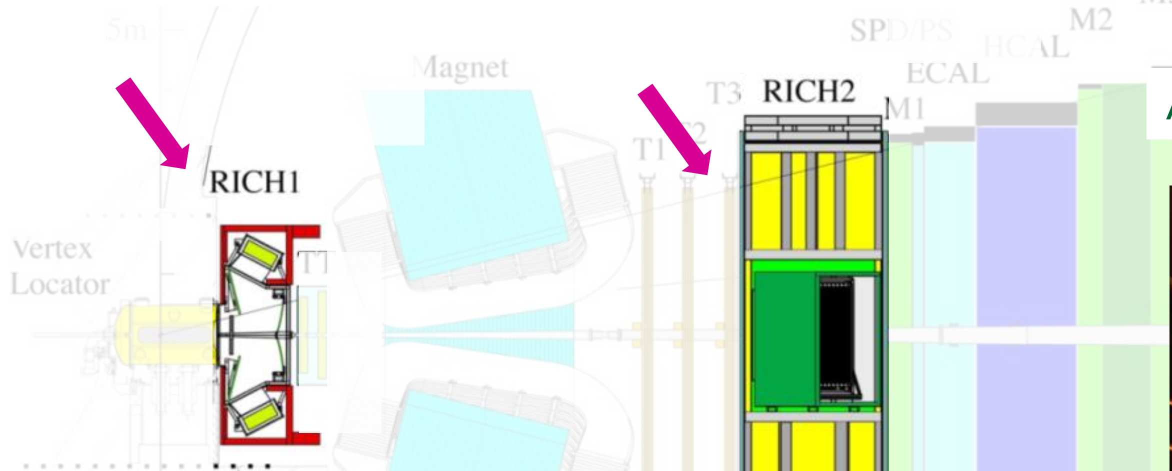
It approaches within 8 mm of the beamline and reconstructs the *b*-hadron decay vertex precisely.

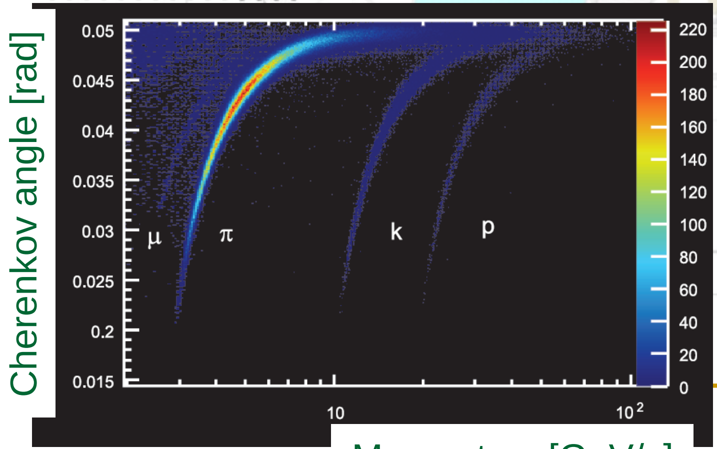


A reconstructed *b*-hadron decay vertex

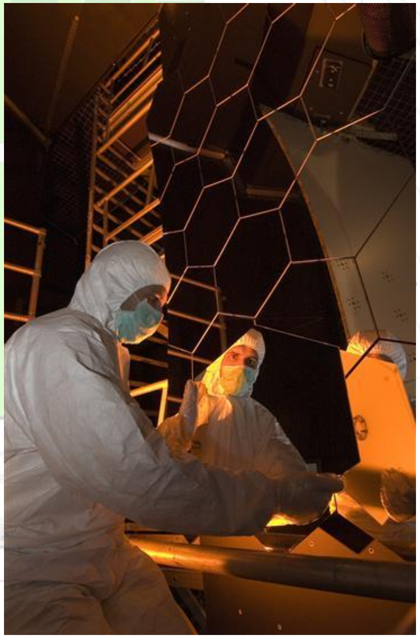
LHCb – a forward spectrometer for flavour physics

Two ‘RICH’ detectors provide
hadron identification from ~2-100 GeV.





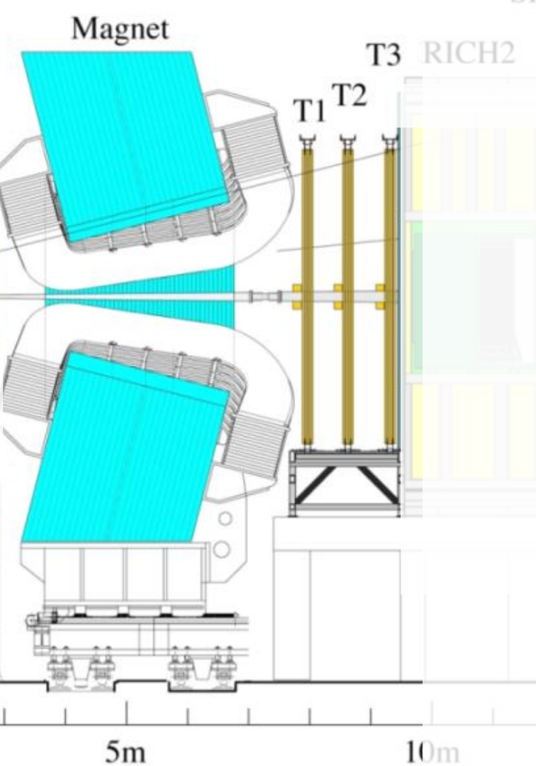
Array of RICH photodetectors

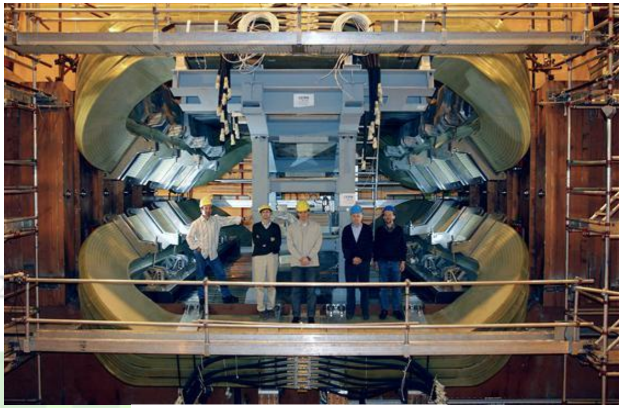


Assembling RICH 2;
note the mirrors

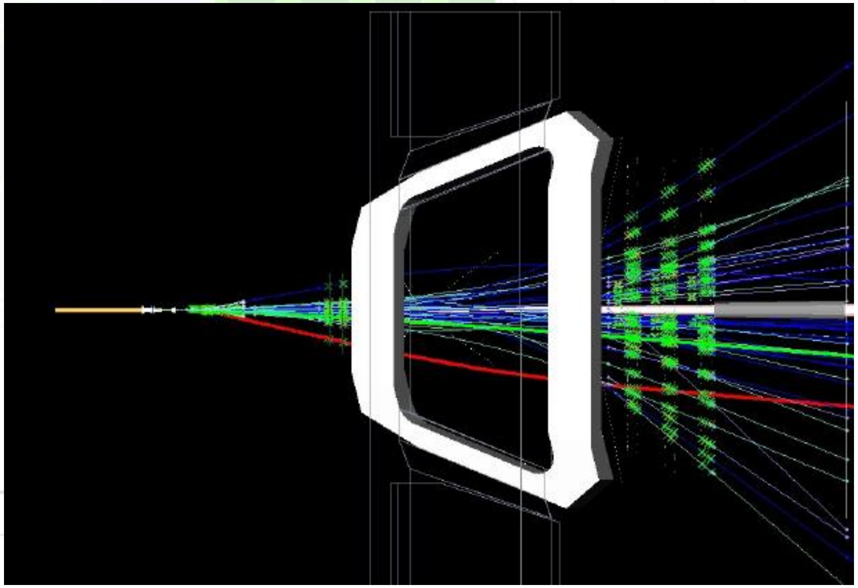
LHCb – a forward spectrometer for flavour physics

A 4 Tm dipole, and the tracking detectors provide momentum resolution with precision 0.4-0.6 % (for 5 < p < 100 GeV)





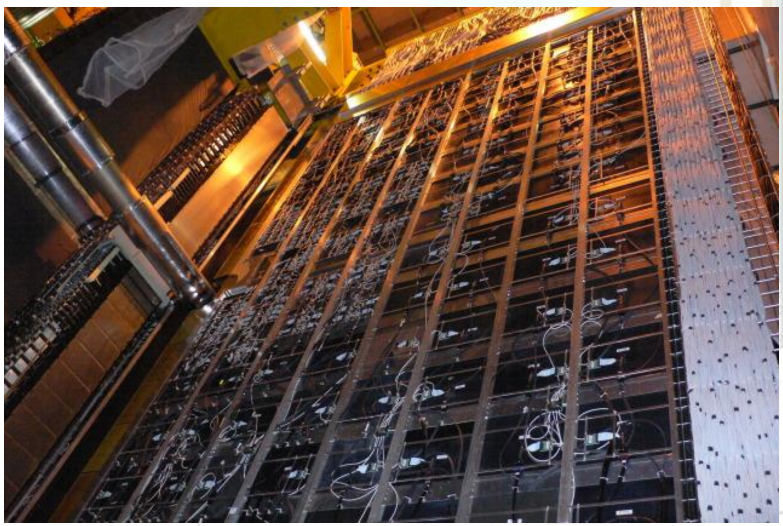
Dipole magnet



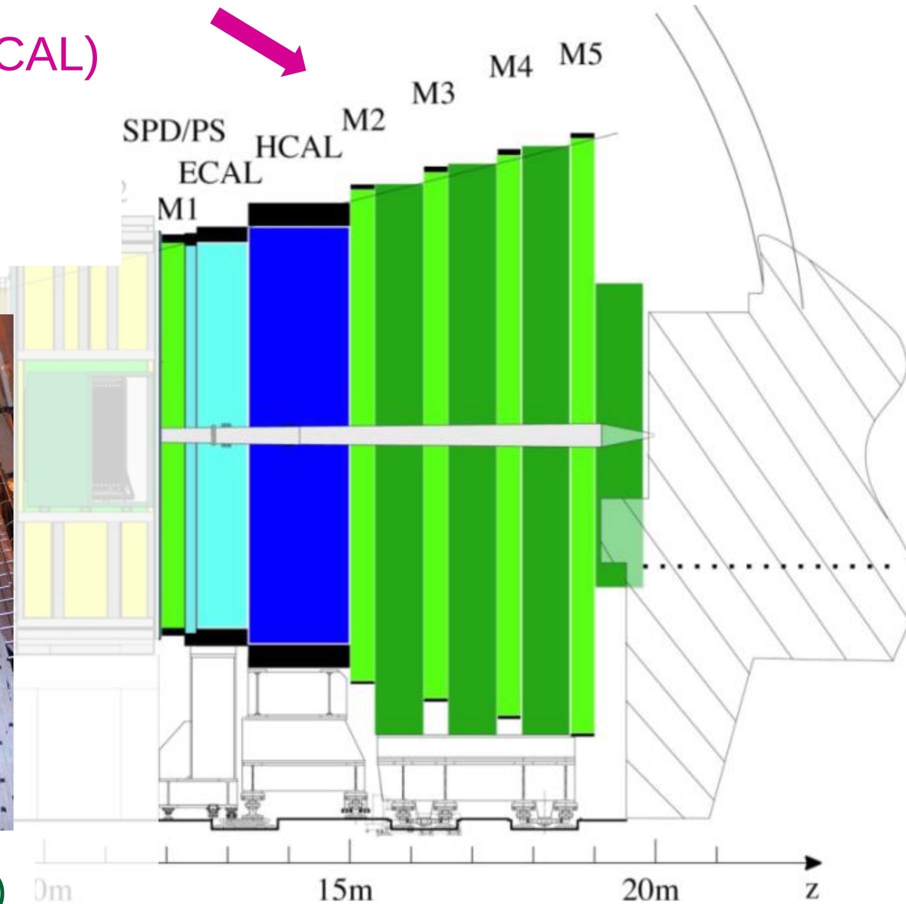
Reconstructed tracks

LHCb – a forward spectrometer for flavour physics

The calorimeter system (ECAL & HCAL) reconstructs the energy of photons, electrons and hadrons. The muon system (M1-M5) identifies muons.

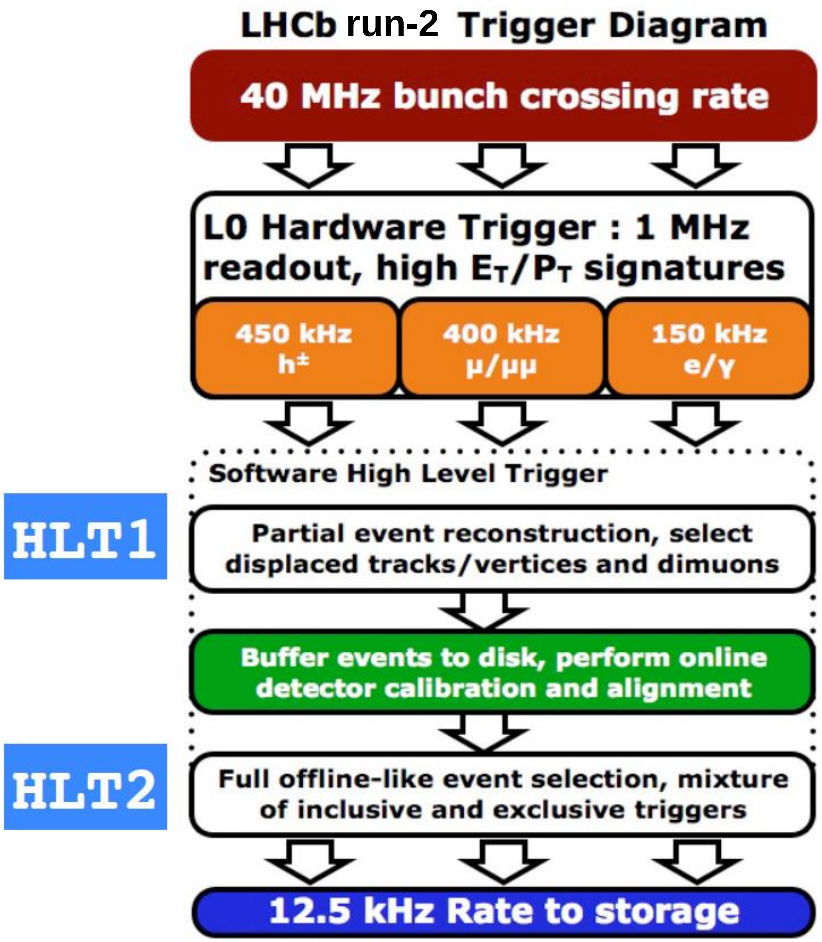


Part of calorimeter system (preshower)



These detectors play a major role in the LHCb trigger

The LHCb trigger



LHCb trigger is unique in being fully optimised for flavour-physics.

At earliest stage (L0) a hardware trigger fires on single hadrons, leptons, photons from heavy-flavour decays.

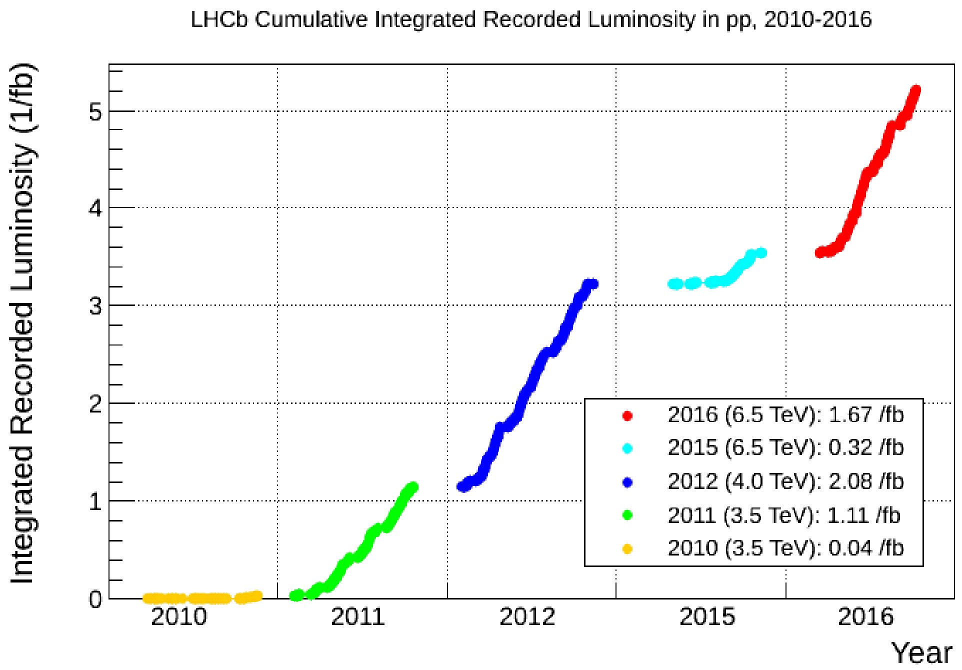
→ gives access to all topologies of heavy-flavour decay (not just dimuons).

Software trigger (HLT) split into two steps, with HLT2 not run until calibration and alignment validated.

→ this 'split HLT' ensures final trigger decision has offline-like quality.

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).



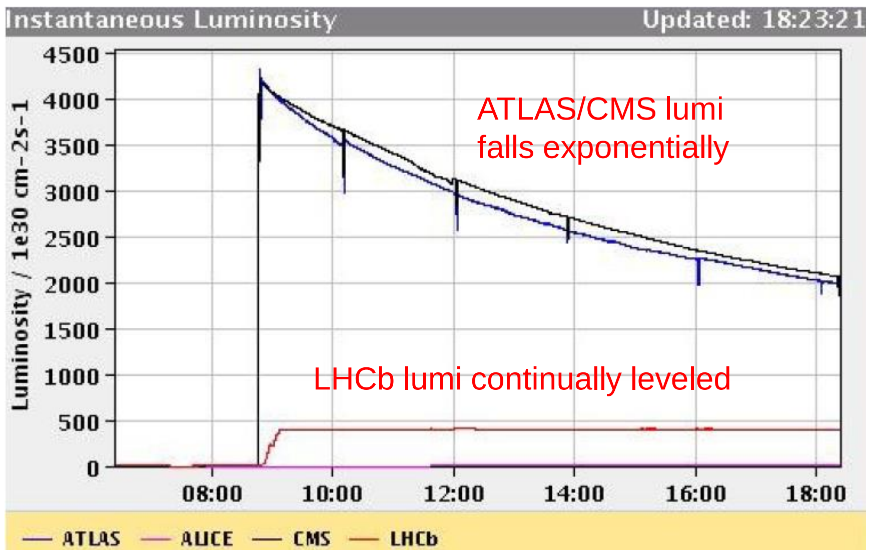
Now embarking on second 'production year' of run-2 (after a 'start-up' year in 2015). Operating at higher energy and at 25 ns bunch-crossing (+ detector improvements).

Run 2 will go to end of 2018 – expect to increase the beauty sample by x3 or more.

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)

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 ... in 2015).
Oper... ements).

Run 2 will go to end of 2018 – expect to increase our beauty sample by x3 or more.

Selected physics topics

- Spectroscopy and hadron exotics
- CP violation measurements in beauty and charrn
- Rare decays, FCNCs and R_{K^*}

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- A case study: the pentaquark
- Strange happenings: the X(5568)
- The famous five: excited Ω_c states

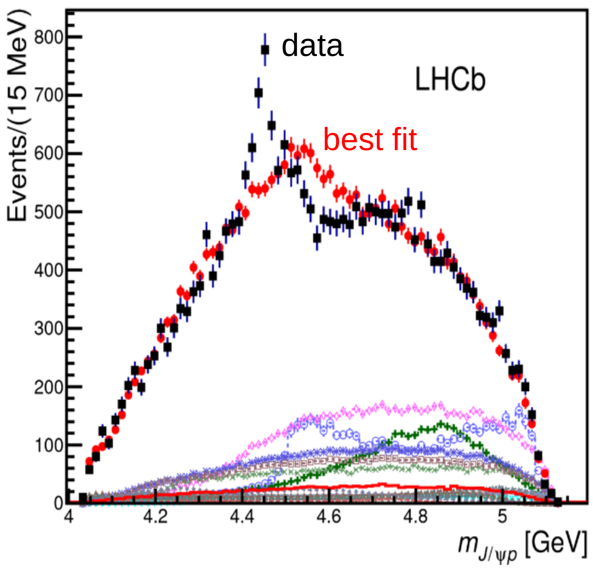
Hadron spectroscopy at the LHC

The LHC has turned out to be a first-rate facility for hadron spectroscopy, a topic that was virtually never discussed prior to first collisions.

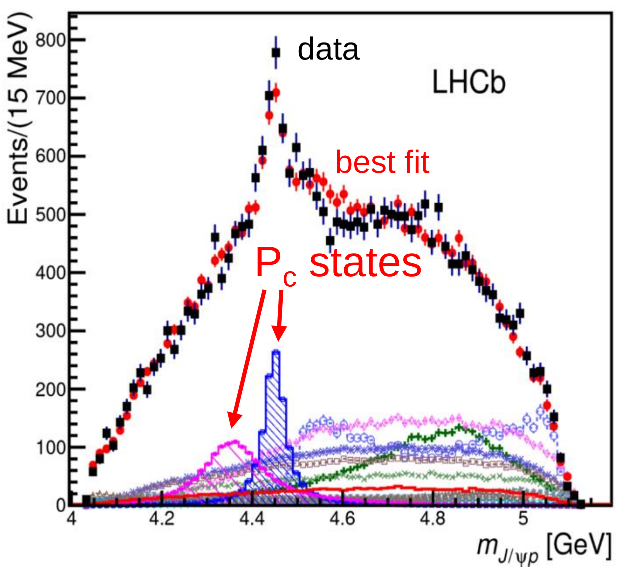
Many examples, most notably the pentaquark discovery in $\Lambda_b \to J/\psi pK$ decays.

One important message is the that this game is more than bump-hunting. In certain cases it is necessary to deploy the full armoury of amplitude analysis.

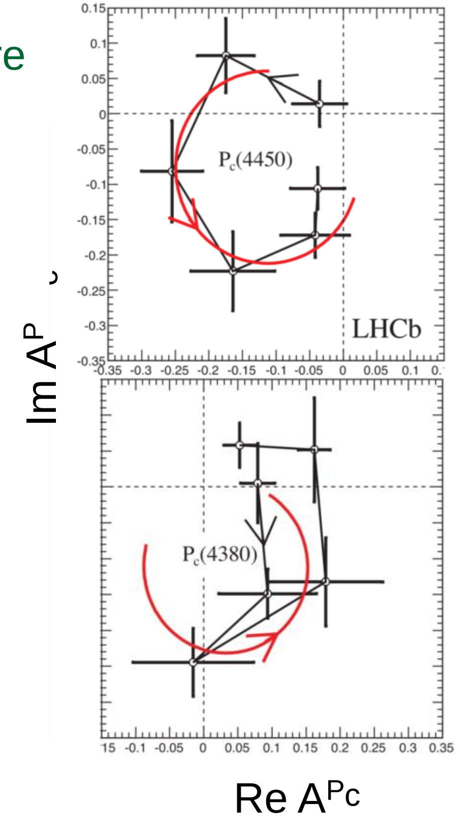
Try to fit J/ψpK kinematics with conventional hadrons – failure !



Now allow for exotics. Require two new (5-quark) P_c states.



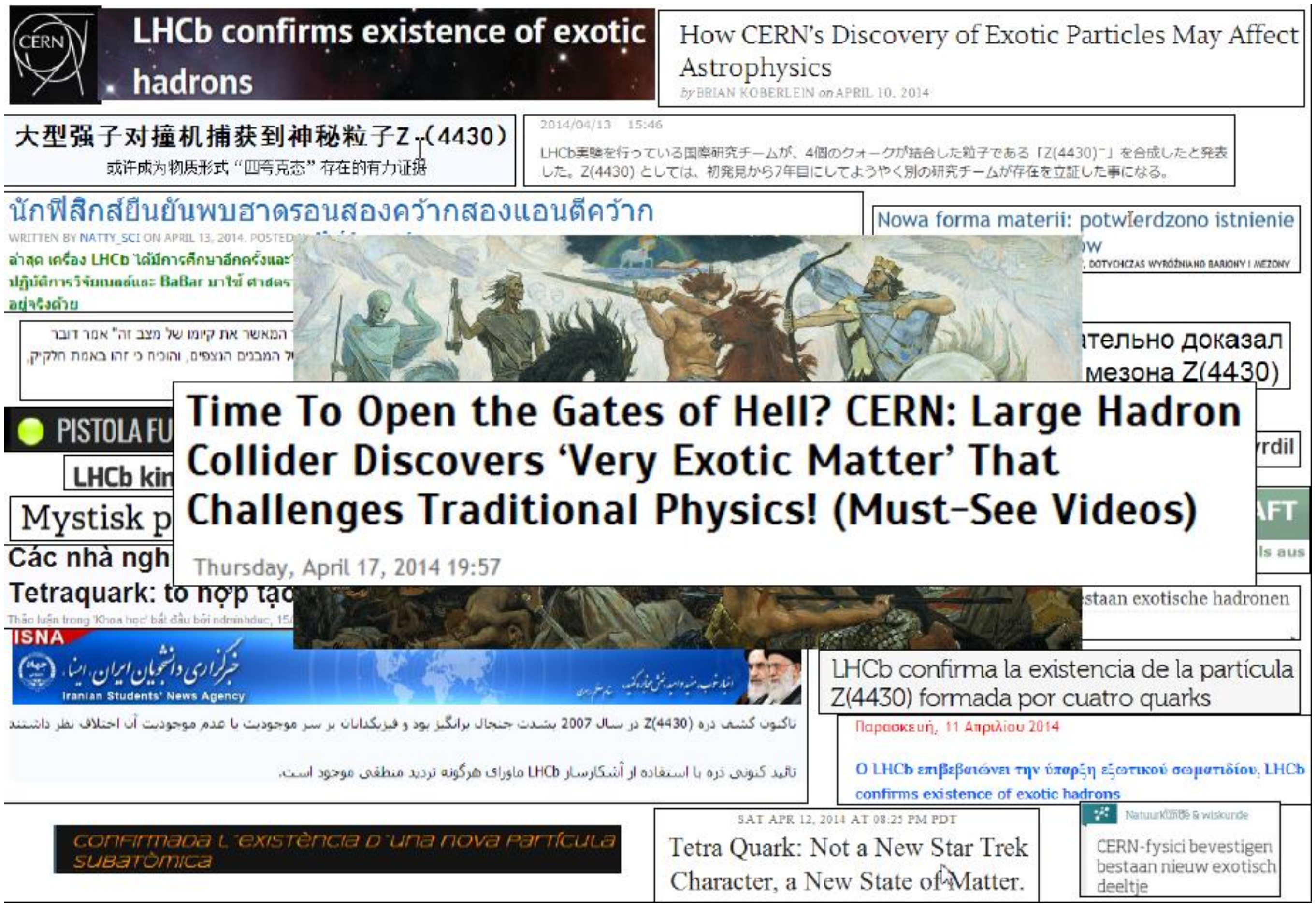
[PRL 115 (2015) 072001]



Demonstrate resonant nature of states in Argand plane.

Aside: these studies attract a surprising amount of attention in the wider world

e.g. overage of the Z(4430)$^-$ analysis [LHCb, PRL 112 (2014) 222002] , demonstrated to be a four-quark resonance in same way as was used for the five-quark case.



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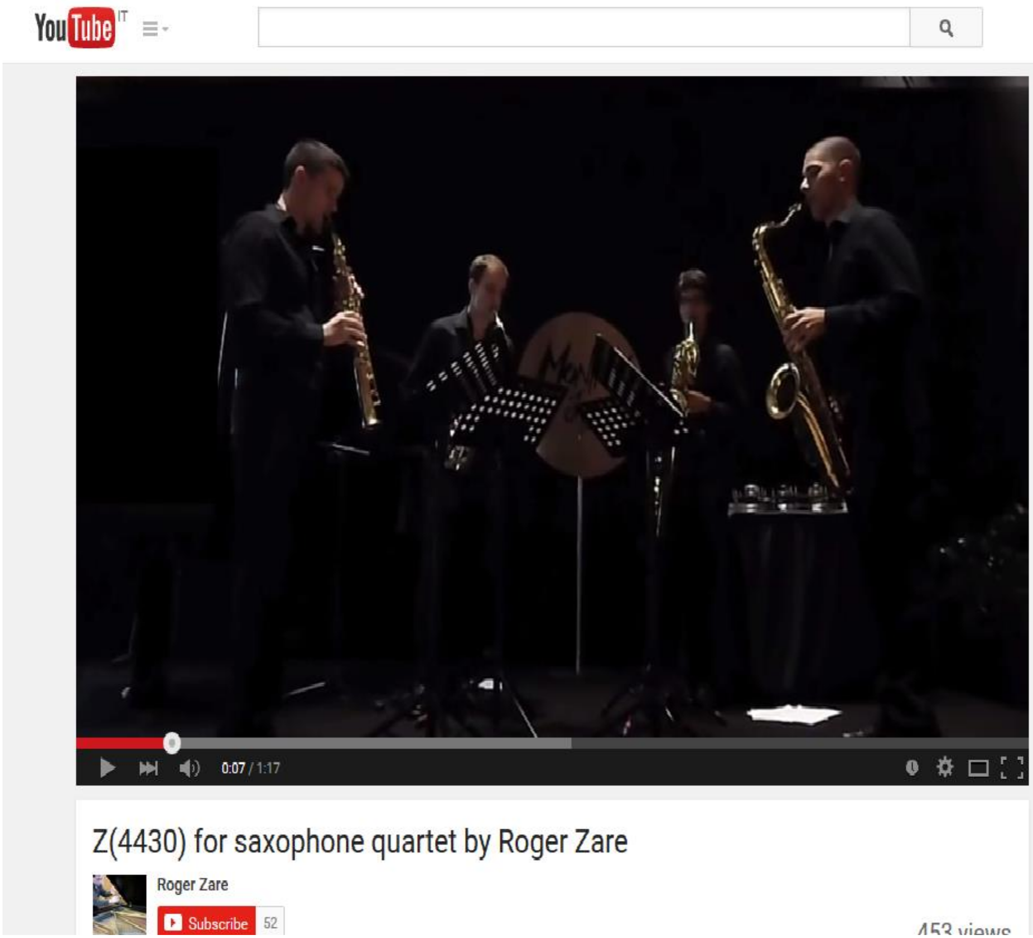


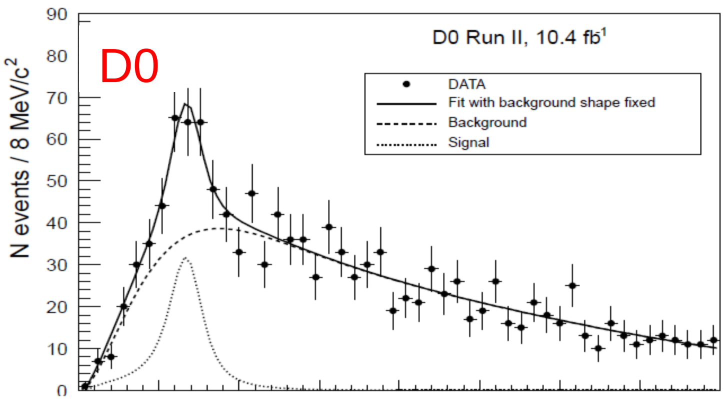
Montreux jazz festival, 2014

New puzzles

Spectroscopy is not all about bump-hunting, but it helps if all agree that the bump exists. Recently a real puzzle has emerged with the X(5568) signal in $B_s\pi$.

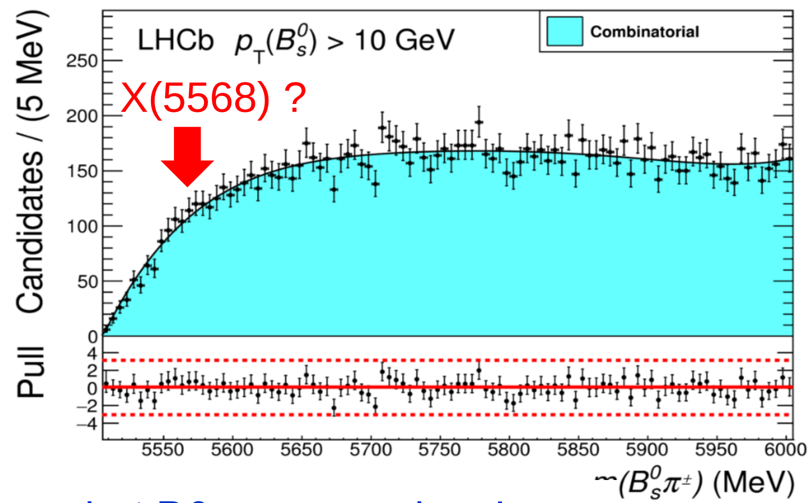
Signal found by D0 with $B_s\pi$ with $B_s \to J/\psi\varphi$.

[PRL 117 (2016) 022003]

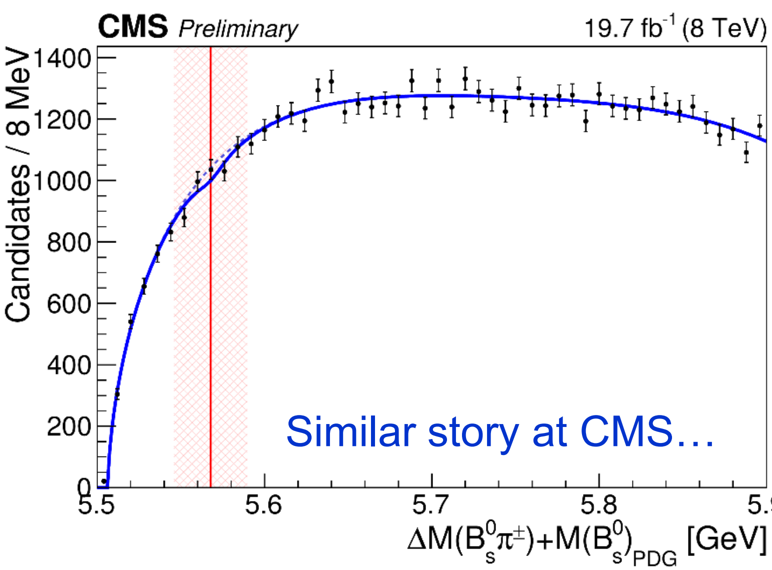


Nothing found by LHCb in 20x larger sample.

[PRL 117 (2016) 152003]

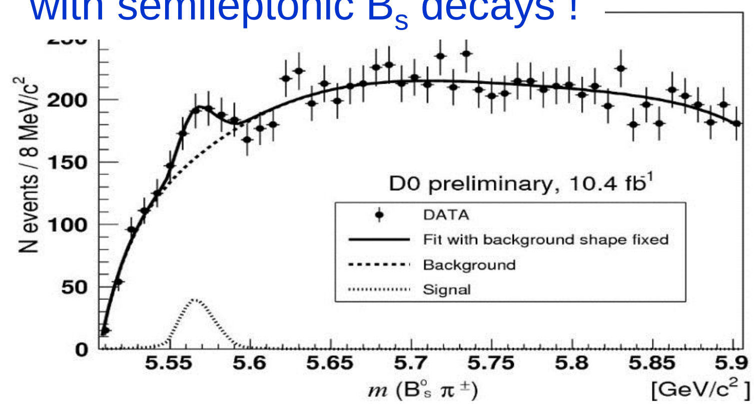


[CMS, BPH-PAS-16-002]



…but D0 now see signal with semileptonic B_s decays !

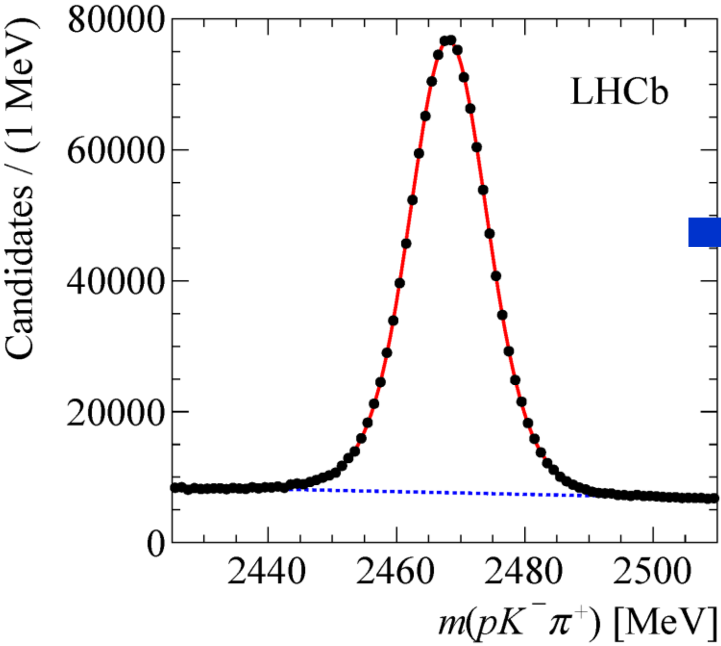
[D0 conference note 6496]

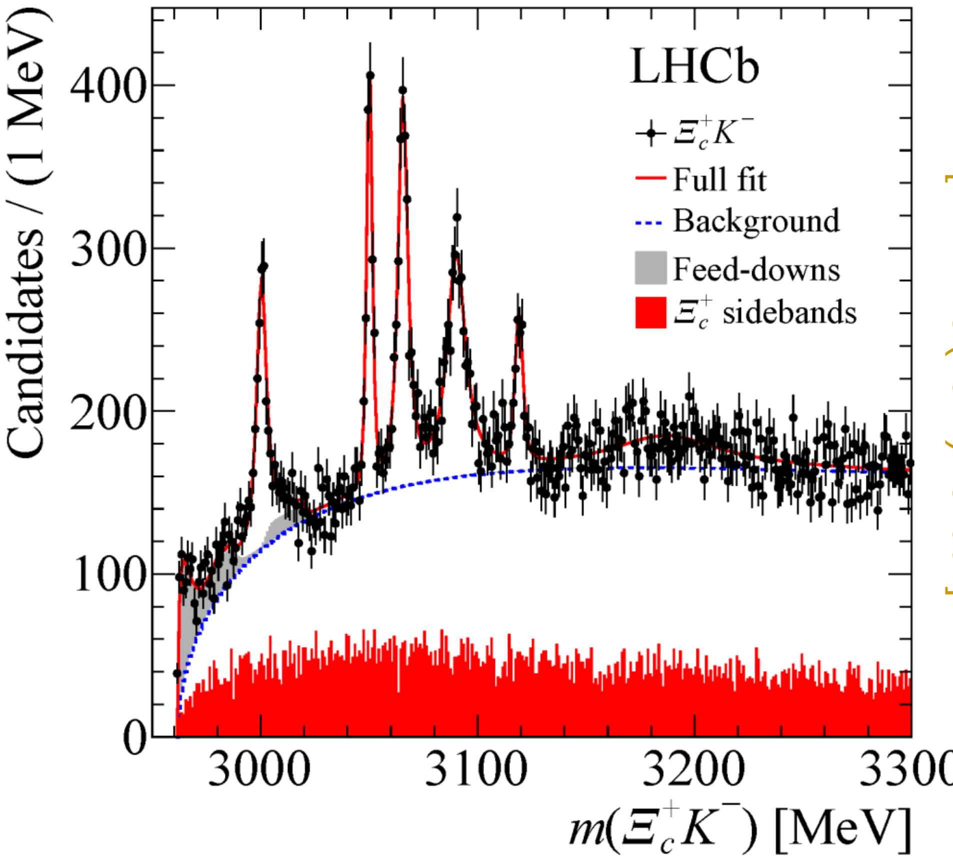


New treasures

Surprises continue to emerge in spectroscopy of conventional hadrons also.

Take these and add a kaon…





[PRL 118 (2017) 182001]

Five (!) new narrow states found in the $\Xi_c^+K^-$ spectrum → excited Ω_c^0 baryons.

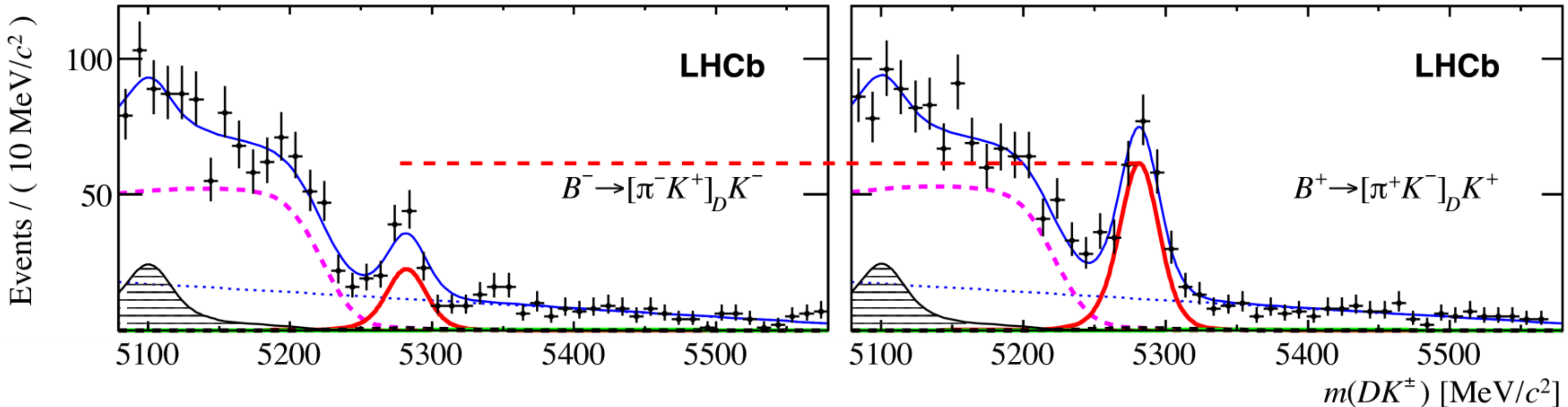
Selected physics topics

- Spectroscopy and hadron exotics
- $\boxed{\text{CP violation measurements in beauty and charrn}}$
- Rare decays, FCNCs and R_{K^*}

- the angle γ
- CPV in the B_s system (φ_s)
- CPV in charm

CPV and the Unitarity Triangle: γ

Almost all the best channels for the determination of the CKM angle γ have now been analysed for run 1. For example, suppressed 'ADS' mode, $B^- \to (\pi^- K^+)_D K^-$ (+CC):



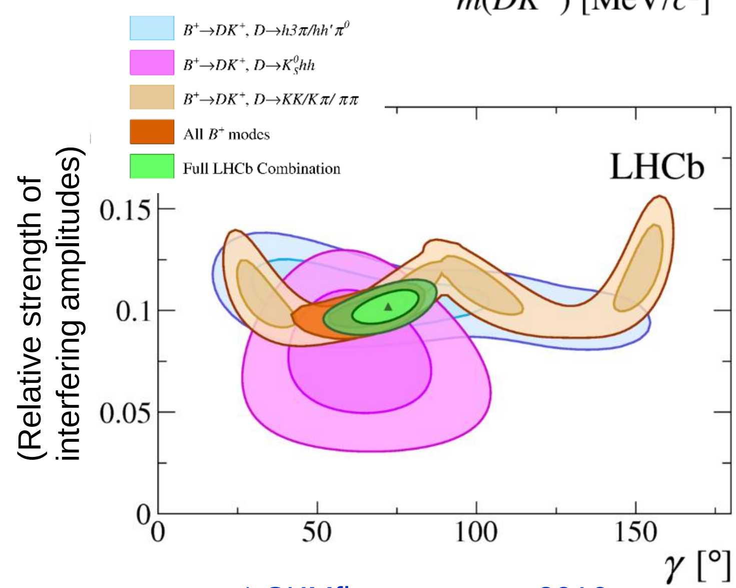
[PLB 760 (2016) 117]

Combination of LHCb B→DK results obtained so far

$$\gamma = (72.2^{+6.8}_{-7.3})^\circ$$

Uncertainty significantly better than that obtained with combined B-factory results.

Agrees with prediction * from rest of triangle $\gamma^{\,\text{indirect}} = (65.3^{+1.0}_{-2.5})^\circ$



[JHEP 12 (2016) 087]

No theory or experimental showstopper. Aim for factor ~2 improvement from run 2.

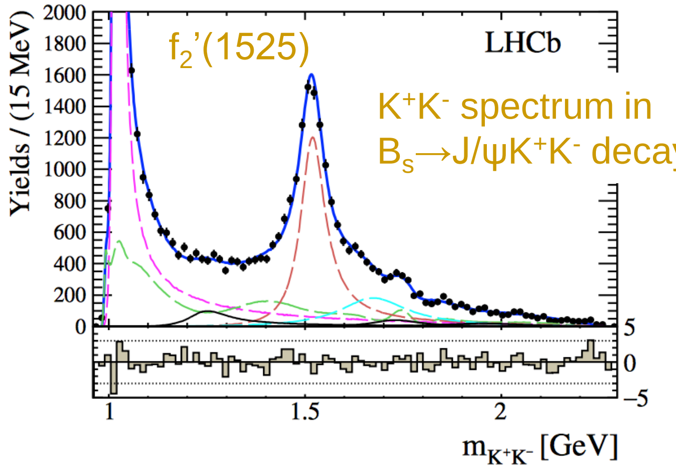
* CKMfitter, summer 2016

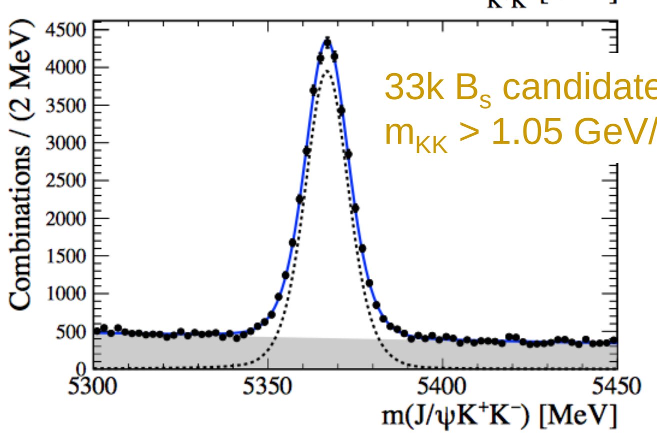
CPV in the B_s system: φ_s

Measurement of φ_s, the CP-violating phase from interference between B_s mixing and decay in channels such as $B_s \to J/\psi\varphi(K^+K^-)$ a flagship measurement of LHCb.

Existing LHCb measurements had used $B_s \to J/\psi K^+K^-$ data around the φ, as well as $B_s \to J/\psi\pi\pi$. Now augment this with $m_{KK} > 1.05$ GeV/c^2 data [arXiv:1704.08217].

Challenging, as requires time-dependent amplitude analysis.





High mass region:

$$\begin{aligned} \phi_s &= 119 \pm 107 \pm 34\,\text{mrad}, \\ |\lambda| &= 0.994 \pm 0.018 \pm 0.006, \\ \Gamma_s &= 0.650 \pm 0.006 \pm 0.004\,\text{ps}^{-1}, \\ \Delta\Gamma_s &= 0.066 \pm 0.018 \pm 0.010\,\text{ps}^{-1}. \end{aligned}$$

($|\lambda|$ different from unity would indicate direct CPV)

Averaging with existing low mass result [PRL 114 (2015) 041801] :

$$\begin{aligned} \phi_s &= -25 \pm 45 \pm 8\,\text{mrad}, \\ |\lambda| &= 0.978 \pm 0.013 \pm 0.003, \\ \Gamma_s &= 0.6588 \pm 0.0022 \pm 0.0015\,\text{ps}^{-1}, \\ \Delta\Gamma_s &= 0.0813 \pm 0.0073 \pm 0.0036\,\text{ps}^{-1}. \end{aligned}$$

Including $B_s \to J/\psi\pi^+\pi^-$ [PLB 736 (2014) 186] :

$$\boxed{\phi_s = 1 \pm 37\,\text{mrad and } |\lambda| = 0.973 \pm 0.013}$$

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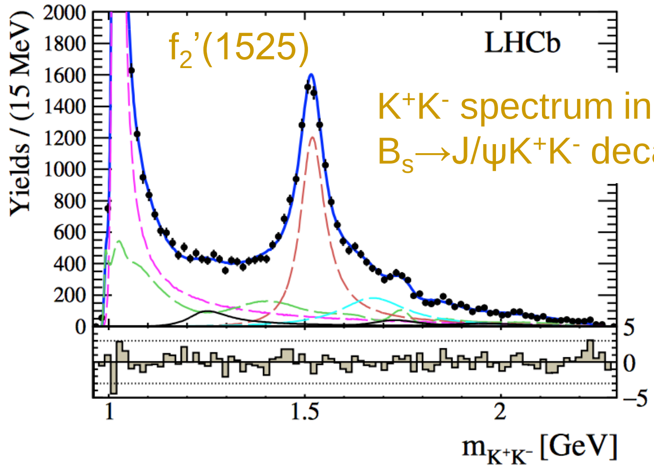
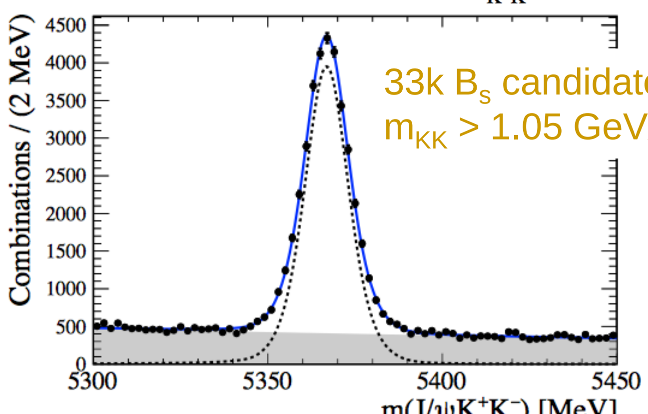
Existing LHCb measurements had used $B_s \rightarrow J/\psi K^+K^-$ data around the φ, as well as $B_s \rightarrow J/\psi\pi\pi$. Now augment this with m_{KK}>1.05 GeV/c^2 data [arXiv:1704.08217].

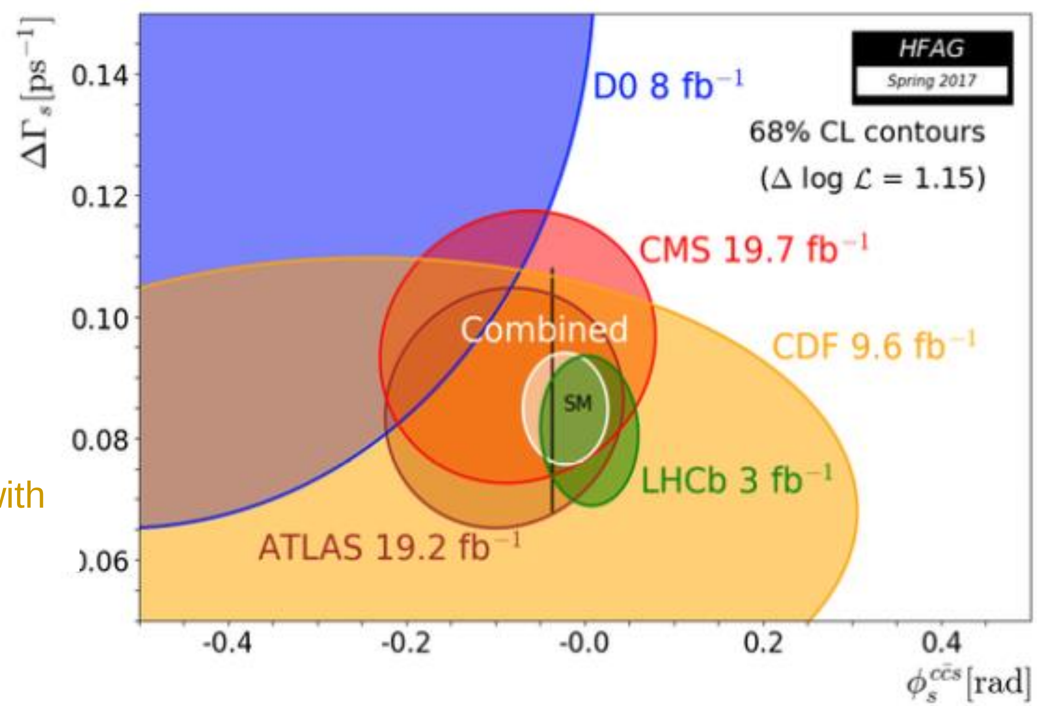
Challenging, as requires time-dependent amplitude analysis.



K^+K^- spectrum in $B_s \rightarrow J/\psi K^+K^-$ decays



33k B_s candidates with m_{KK} > 1.05 GeV/c^2.

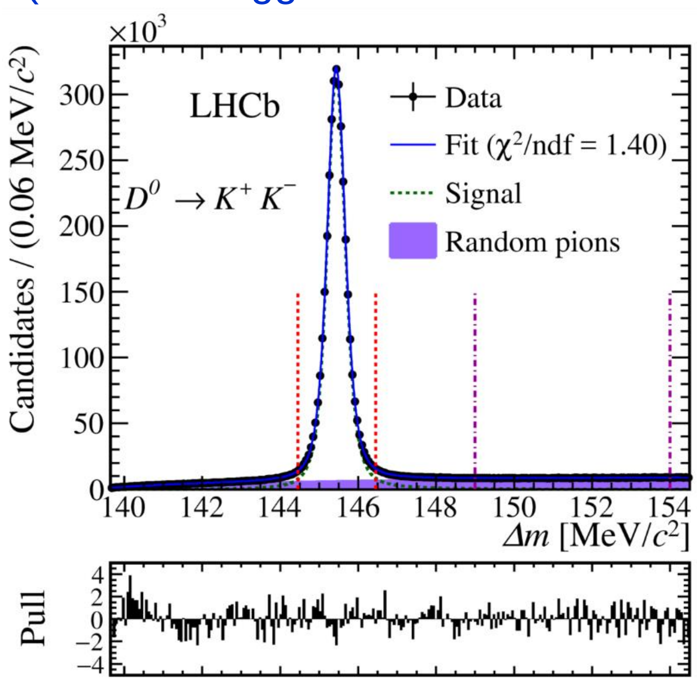


Run-1 legacy result – now focus is on run-2 data.

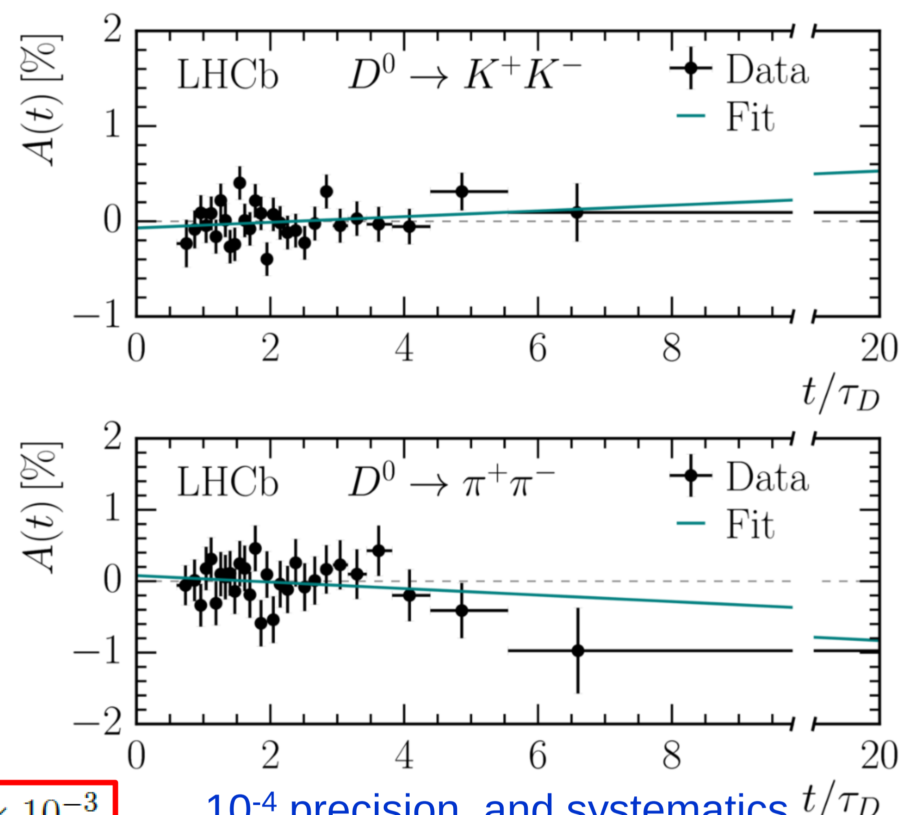
CPV searches in charm

A very important task is to probe for CP violation in charm, both direct & indirect, which is very small in the SM. For example, look for time-dependent CP asymmetry, expressed in A_Γ parameter, in decay to *CP* eigenstate, *e.g.* $D^0 \to KK$ or $\pi\pi$.

Massive, clean & well-understood samples.
(*i.e.* 9.6M tagged K^+K^- vs BaBar 140k)



No slope, so no CP violation (yet)



[arXiv:1702.06490]

$$A_\Gamma(D^0 \to K^+K^-) = (-0.30 \pm 0.32 \pm 0.14) \times 10^{-3}$$
$$A_\Gamma(D^0 \to \pi^+\pi^-) = (\ \ 0.46 \pm 0.58 \pm 0.16) \times 10^{-3}$$

10^{-4} precision, and systematics under good control. Excellent prospects for run 2 and beyond !

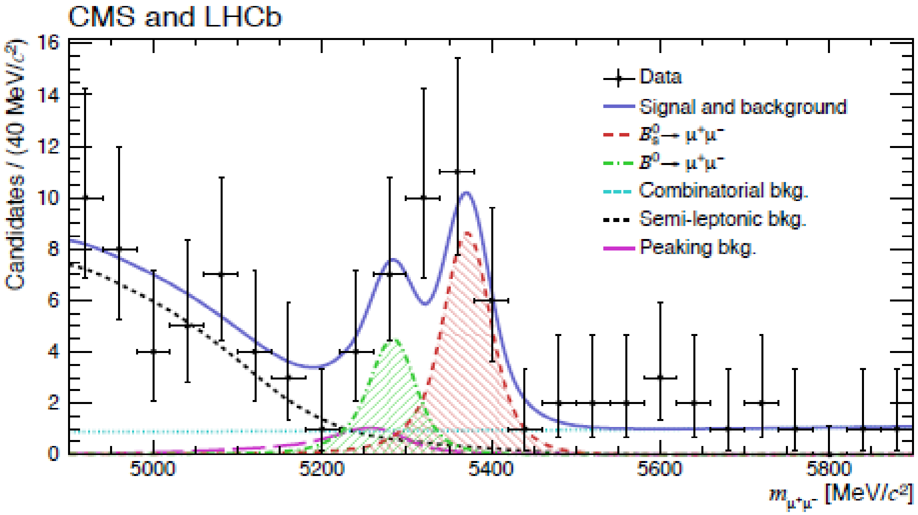
Selected physics topics

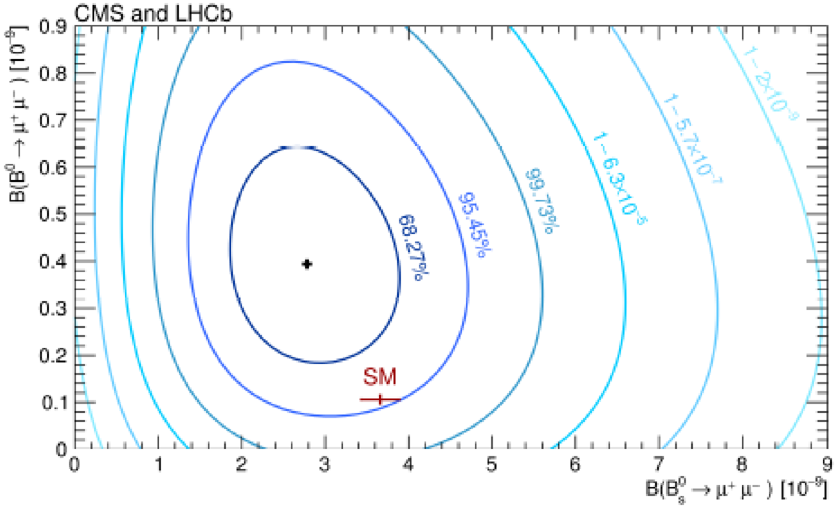
- Spectroscopy and hadron exotics
- CP violation measurements in beauty and charrn
- Rare decays, FCNCs and R_{K^*}

- In search of the super-rare: $B_{s,d} \to \mu^+\mu^-$
- $B \to K^{(*)}l^+l^-$ & friends, including R_{K^*}
- Trouble at tree-level: $B \to D^*\tau\nu$

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

Recall: $B_s \to \mu\mu$ is ultra-rare in the Standard Model (~3 x 10^{-9}) & very sensitive to New Physics contributions. LHCb found first evidence in Run 1 [PRL 110 (2013) 021801] , & then a combined LHCb-CMS analysis yielded a 5σ observation [Nature 522 (2015) 68] .





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

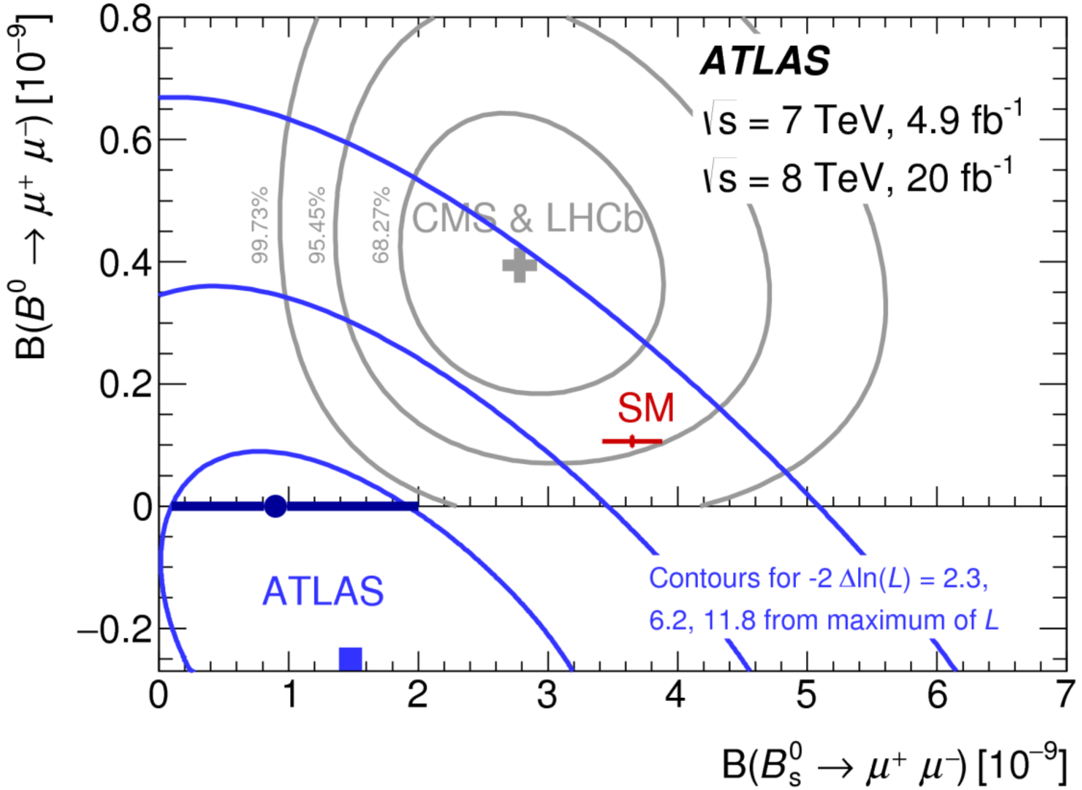
$$\mathcal{B}(B^0 \to \mu^+\mu^-) = \left(3.9\,^{+1.6}_{-1.4}\right) \times 10^{-10} \quad (3.0\sigma)$$

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

Analysis also searched for the even rarer $B_d \to \mu\mu$. Here there is also a hint of a signal. The picture is intriguing and has provided encouragement for run 2 !

$B_{d,s}\rightarrow\mu\mu$: 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

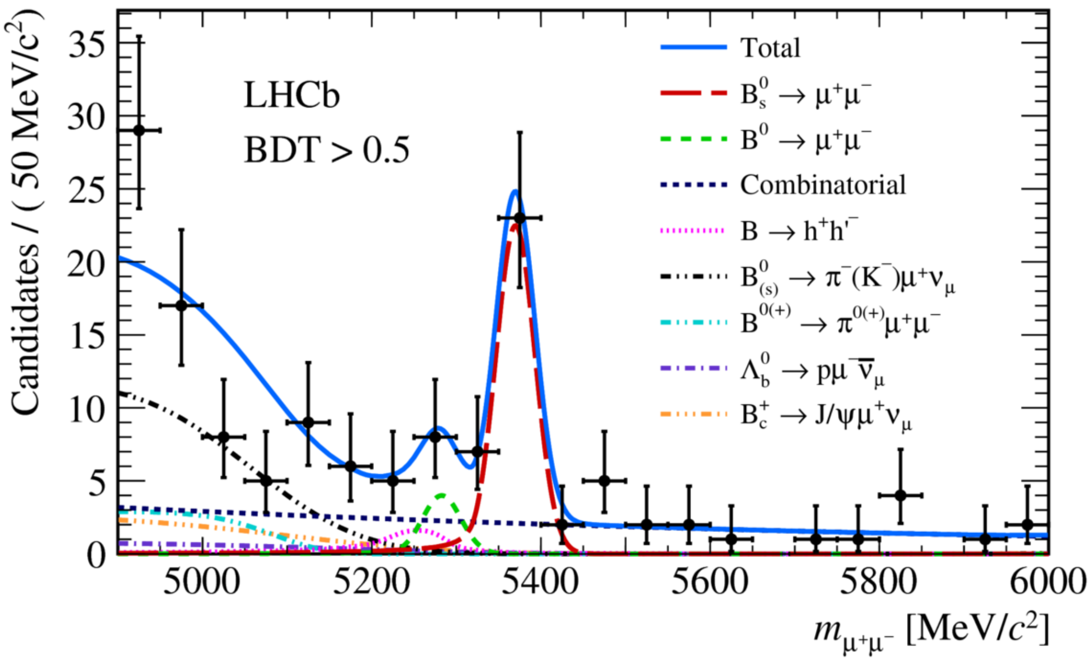
$B_s \to \mu^+\mu^-$: first news from run 2 [PRL 118 (2017) 191801]

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.

- 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



$B_s \to \mu^+\mu^-$: first news from run 2 [PRL 118 (2017) 191801]

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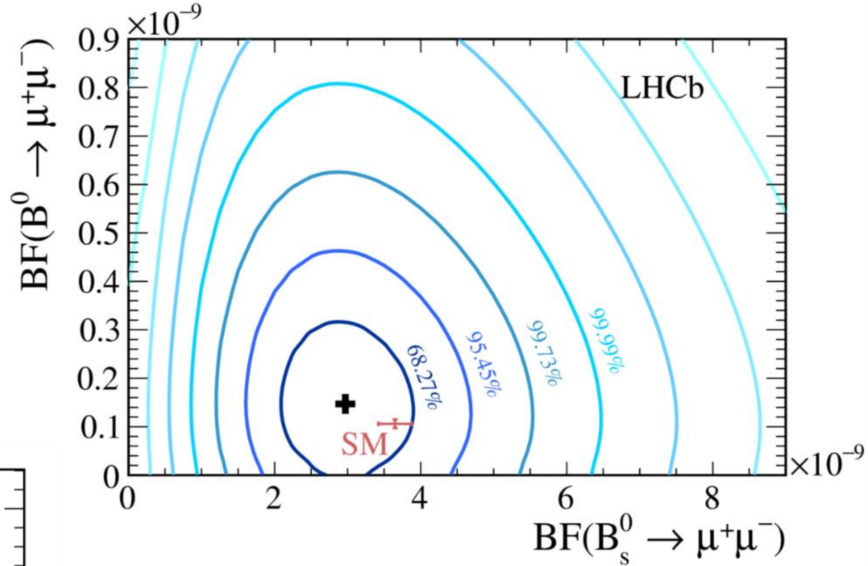
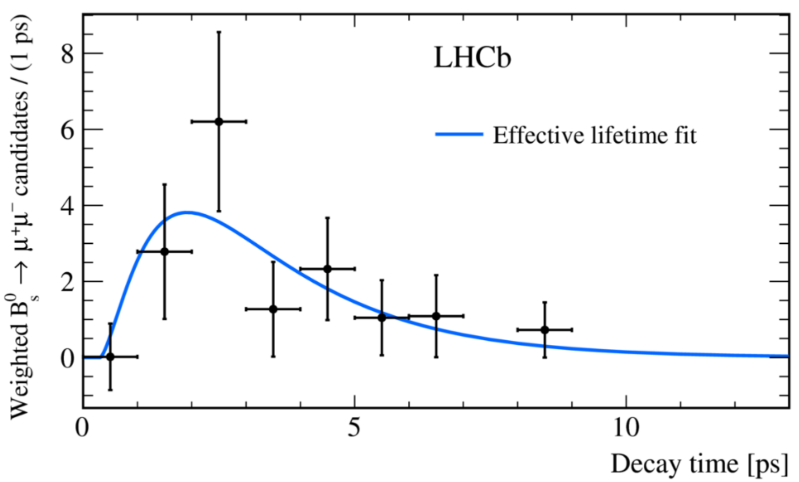


Results are very compatible with Standard Model, and will tighten further constraints on New Physics models with an extended scalar sector.

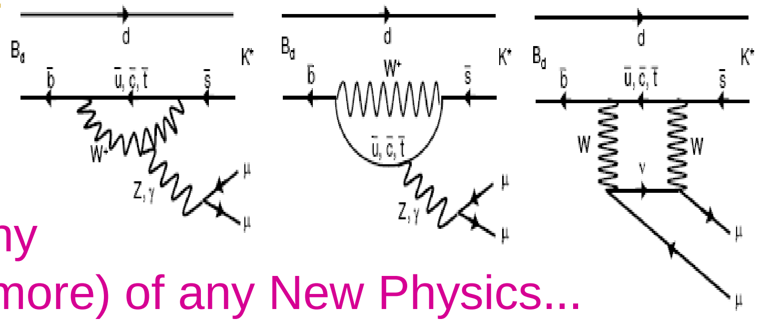


Proof-of-principle measurement

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.

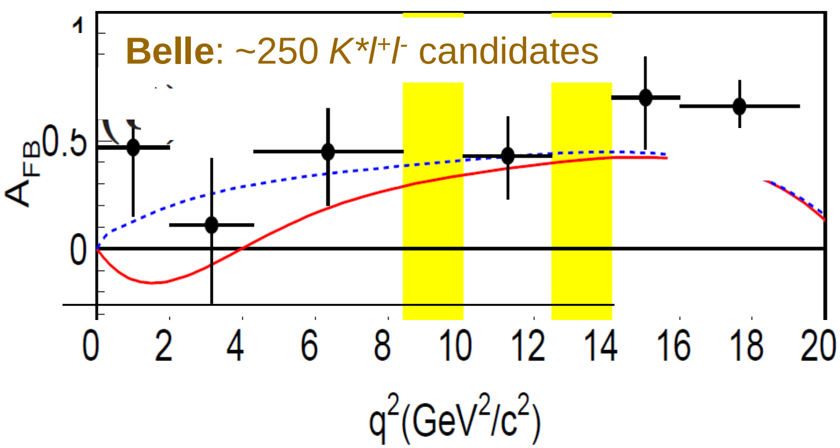
$B^0 \rightarrow K^* l^+ l^-$ and friends



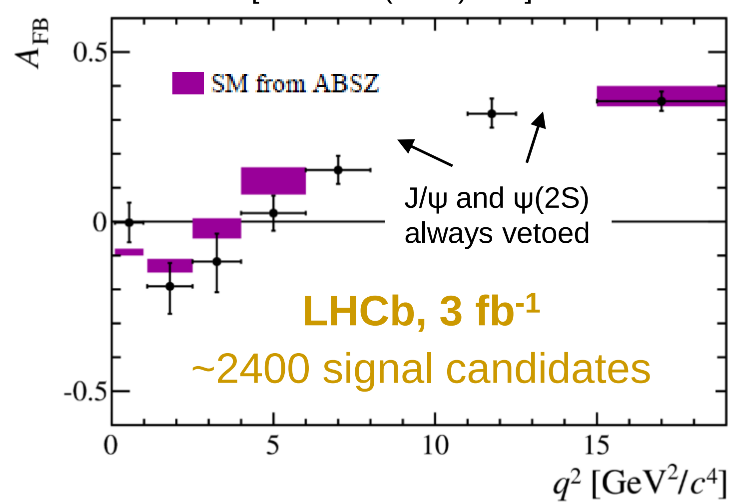
$b \rightarrow (s,d) l^+ l^-$ decays such as $B^0 \rightarrow K^* l^+ l^-$ offer many observables which probe helicity structure (& more) of any New Physics...

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]



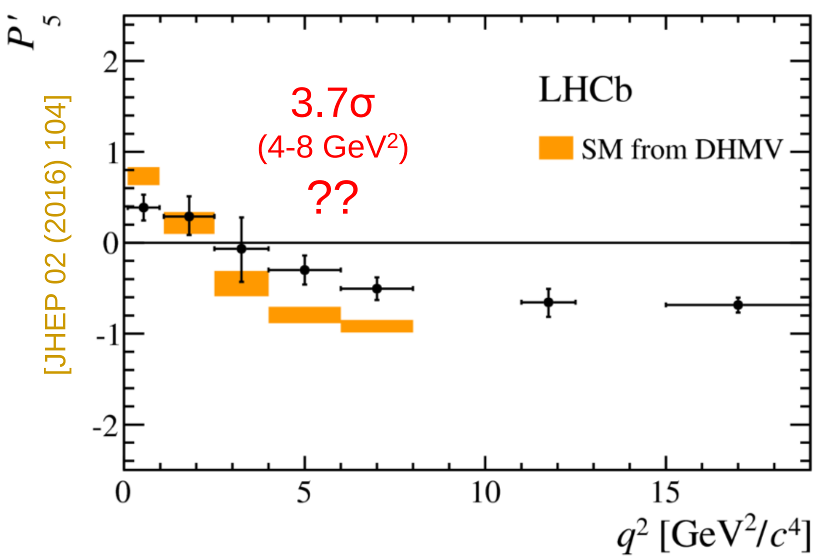
General pattern as predicted; mild tension at low q^2

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' "

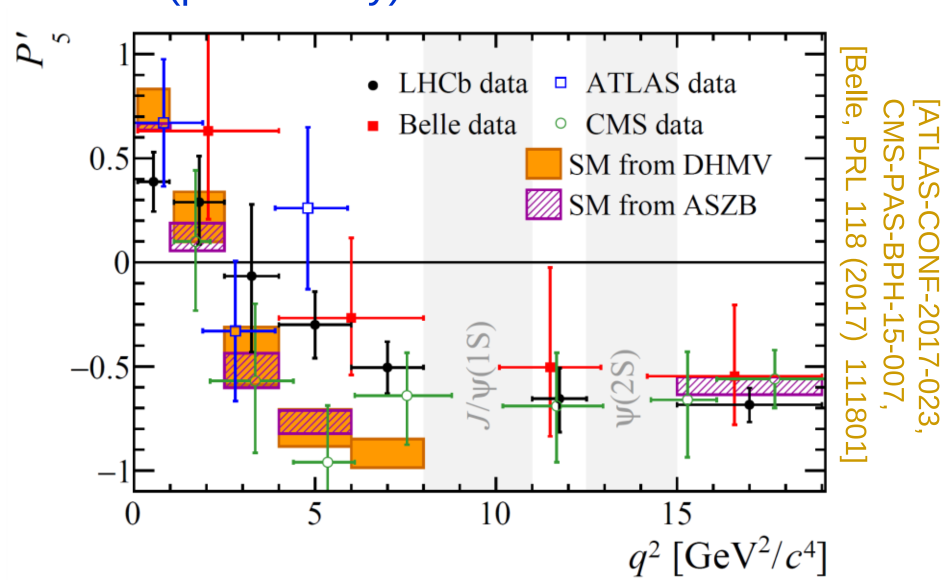
$B^0 \to K^* l^+ l^-$ and friends: the P_5' conundrum

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.

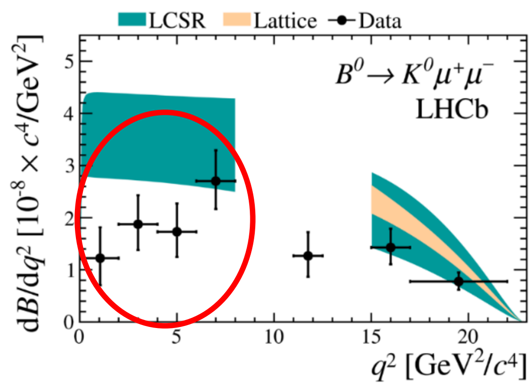


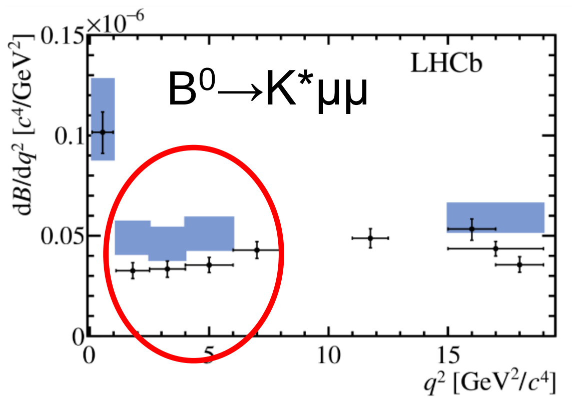
A word of caution. The SM uncertainties shown here are from one group. There are other values on the market, and some are more conservative.

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

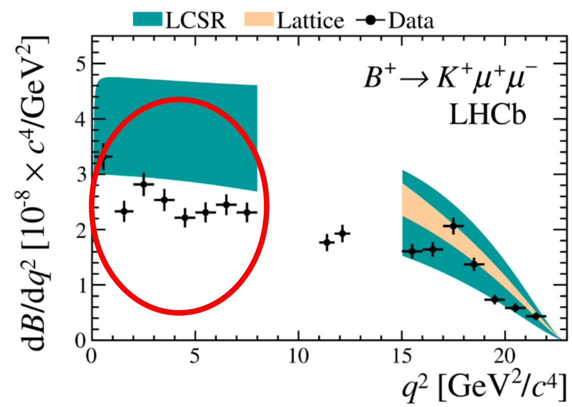
P_5' is not the only funny thing going on in $b \to (s,d) l^+ l^-$ decays.

[JHEP 06 (2014) 133]



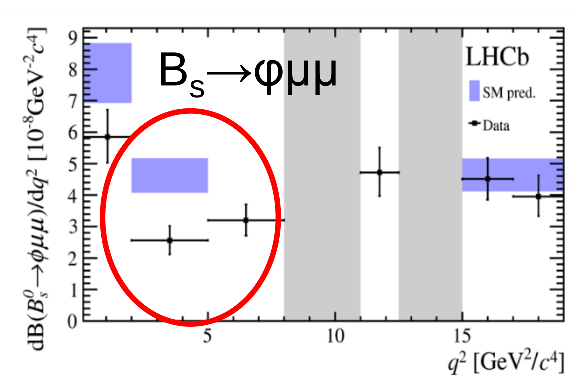


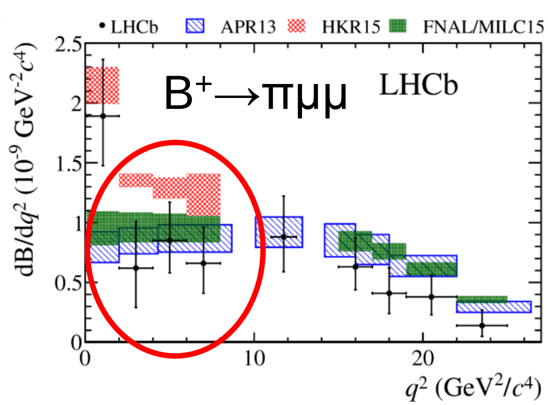
[JHEP 11 (2016) 047]



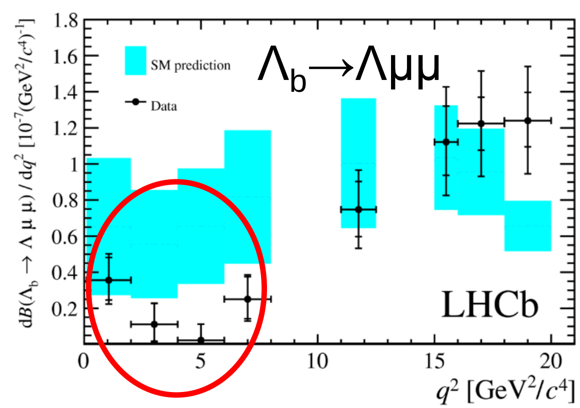
[JHEP 06 (2014) 133]

[JHEP 09 (2015) 179]





[JHEP 10 (2015) 034]



[JHEP 06 (2015) 009]

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

$B^0 \rightarrow K^* l^+ l^-$ 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 $B^+ \rightarrow K^+ l^+ l^-$ 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 $B^0 \rightarrow K^* l^+ l^-$ [arXiv:1705.05802] :

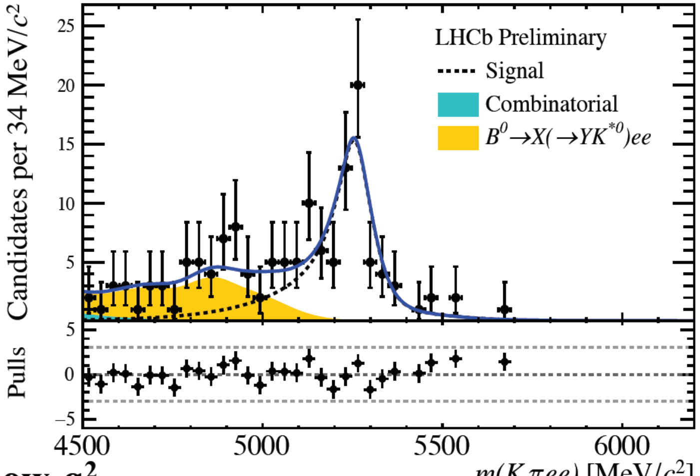
$$\mathcal{R}_{K^{*0}} = \frac{\mathcal{B}(B^0 \rightarrow K^{*0}\mu^+\mu^-)}{\mathcal{B}(B^0 \rightarrow K^{*0}J/\psi(\rightarrow \mu^+\mu^-))} \Bigg/ \frac{\mathcal{B}(B^0 \rightarrow K^{*0}e^+e^-)}{\mathcal{B}(B^0 \rightarrow K^{*0}J/\psi(\rightarrow e^+e^-))}$$

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

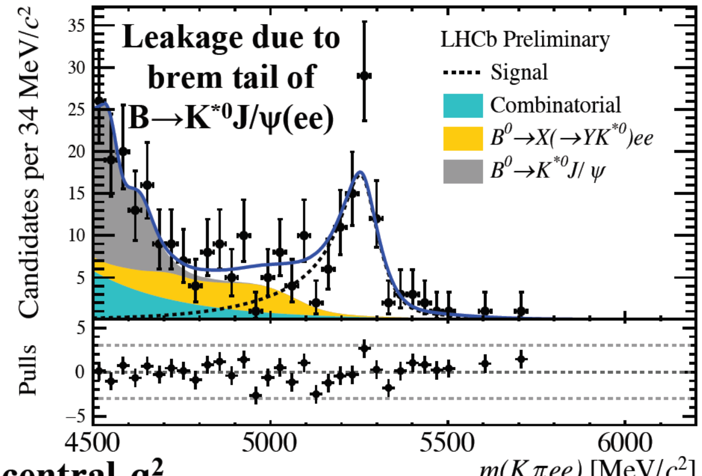
Measure in similar q^2 region as for R_K ('central q^2': 1.1 - 6 GeV^2), but also perform measurement in a low q^2 bin (0.045 - 1.1 GeV^2).

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

Mass spectra in di-electron final state



low-q^2



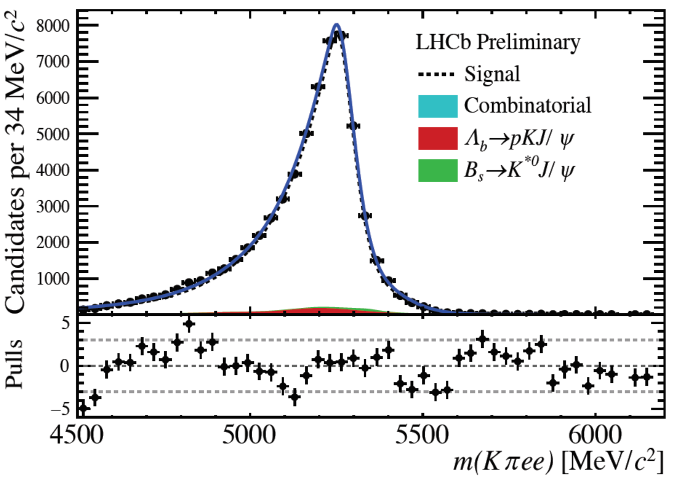
central-q^2

[arXiv:1705.05802]

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

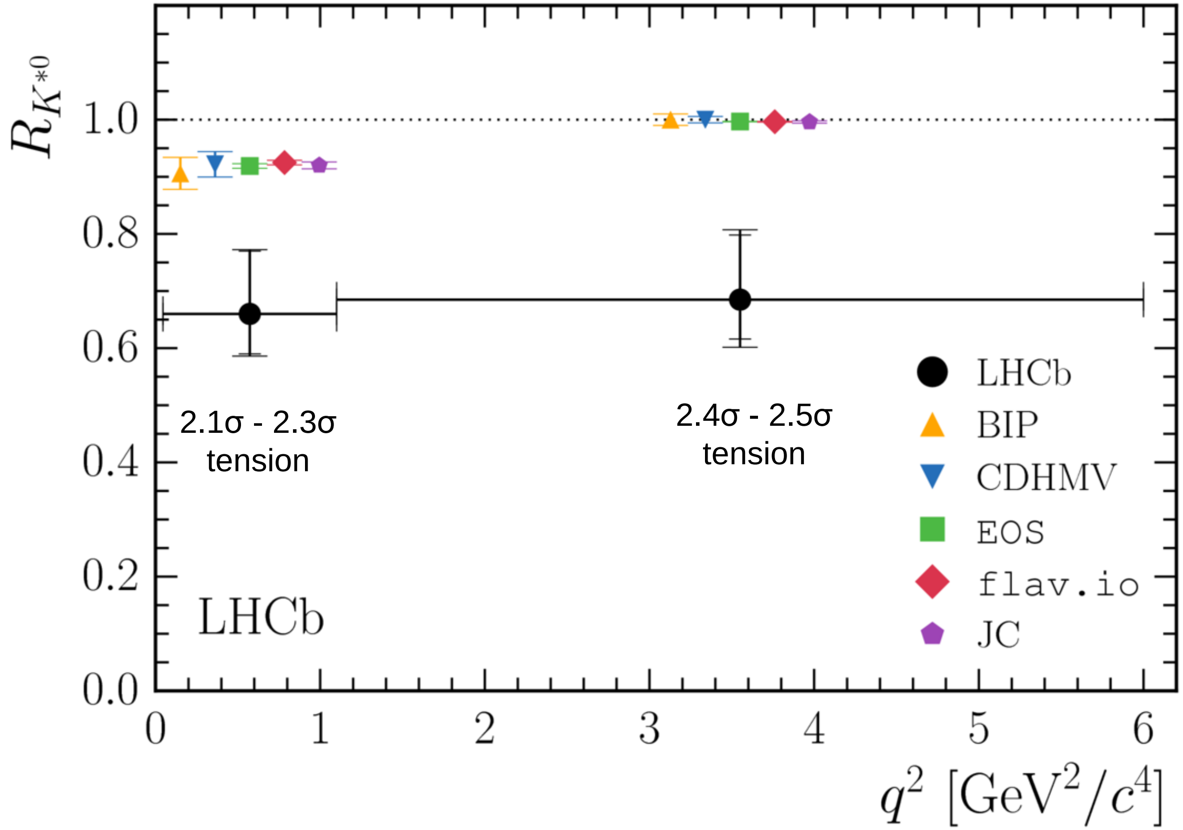
58k in control channel

Muon samples 3-5x larger



$B^0 \to K^* l^+ l^-$ 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	$[0.45, 1.04]$	$[0.46, 1.10]$



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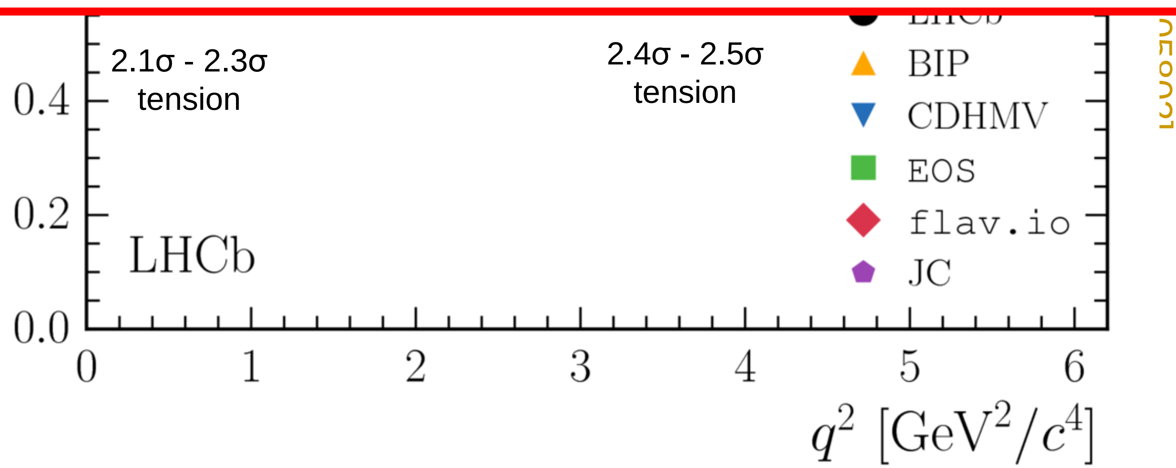
95.4% CL	[0.52, 0.89]	[0.53, 0.94]

Intriguing! What happens next?

- New R_K measurement, including run-2 data.
- Measure R_φ, analogous observable with B_s decays, including run-2 data.
- Run-2 update of R_{K^*}.
- Seek to include high-q^2 region above $\psi(2S)$.

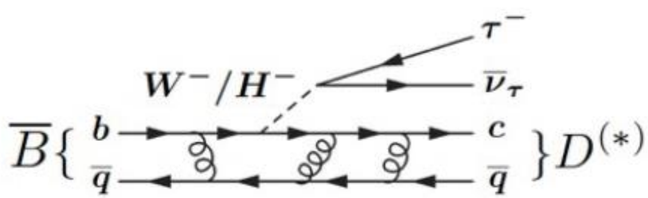
Available data should be sufficient to clarify picture.

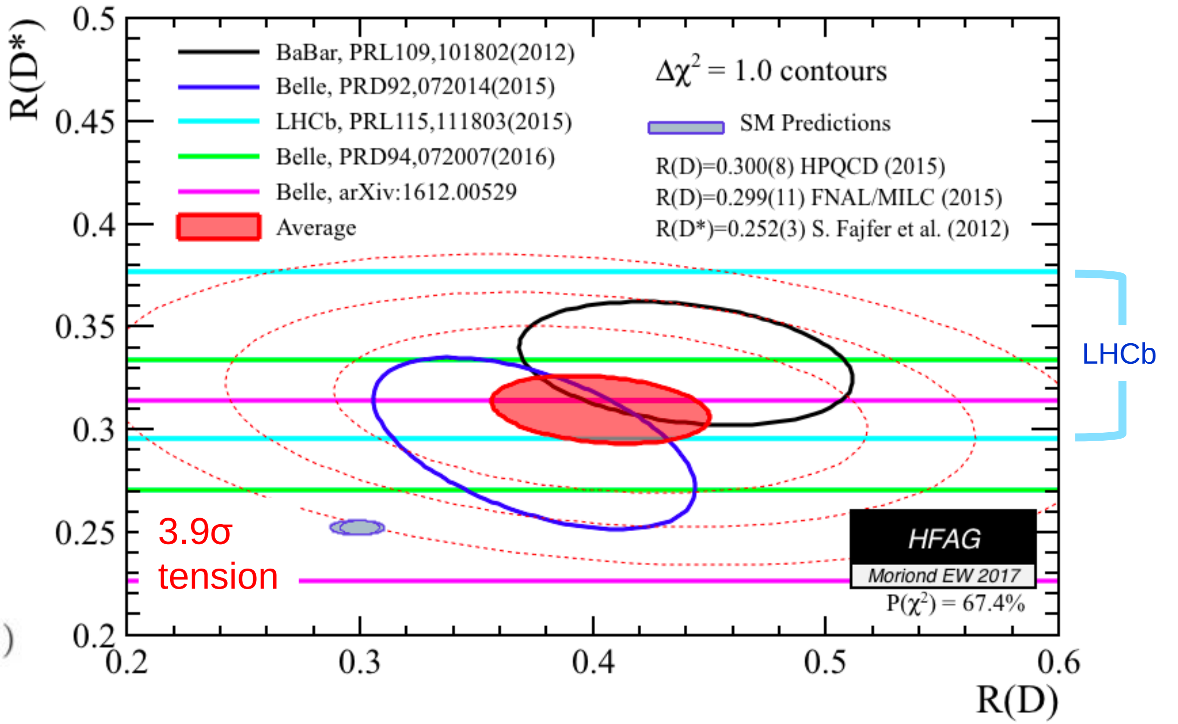


Other hints of lepton universality violation

Remember, there is another class of decays, b→clν, (tree level – not a FCNC!) where there is a stubborn longstanding tension between data and the SM expectation.

$$R(D^{(*)}) \equiv BR(B \to D^{(*)}\tau\nu)/BR(B \to D^{(*)}\mu\nu)$$





Most measurements are from B-factories, but LHCb result with B→D*τν, τ→μνν [PRL 115 (2015) 111803] is a very important (if unexpected) piece of the picture.

LHCb will have more to say on this *very* soon (measurements underway with hadronic τ decays, simultaneous fits of B→Dτν, D*τν and B_c→J/ψτν).

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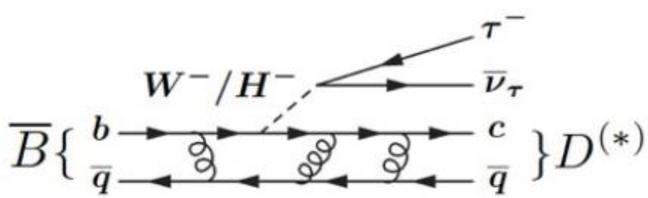
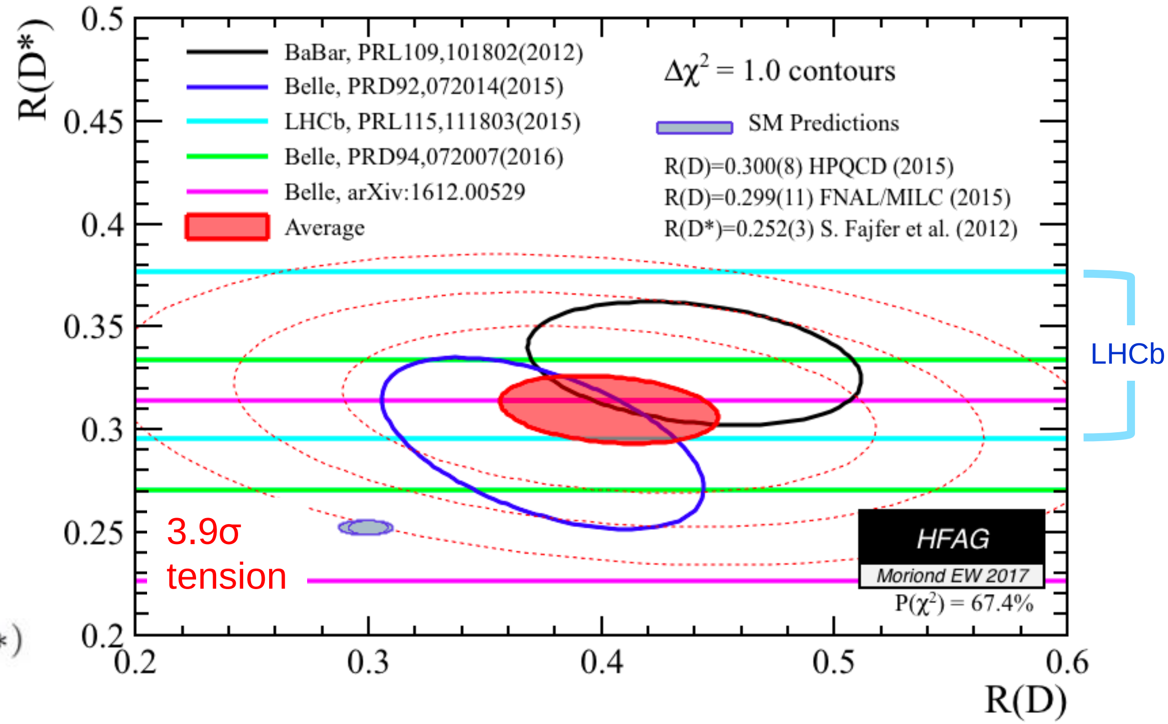




New LHCb R(D*) result to be presented later *today* at FPCP conference !

First ever to exploit $\tau \to \pi^+\pi^-\pi^-(\pi^0)\nu$ decays.

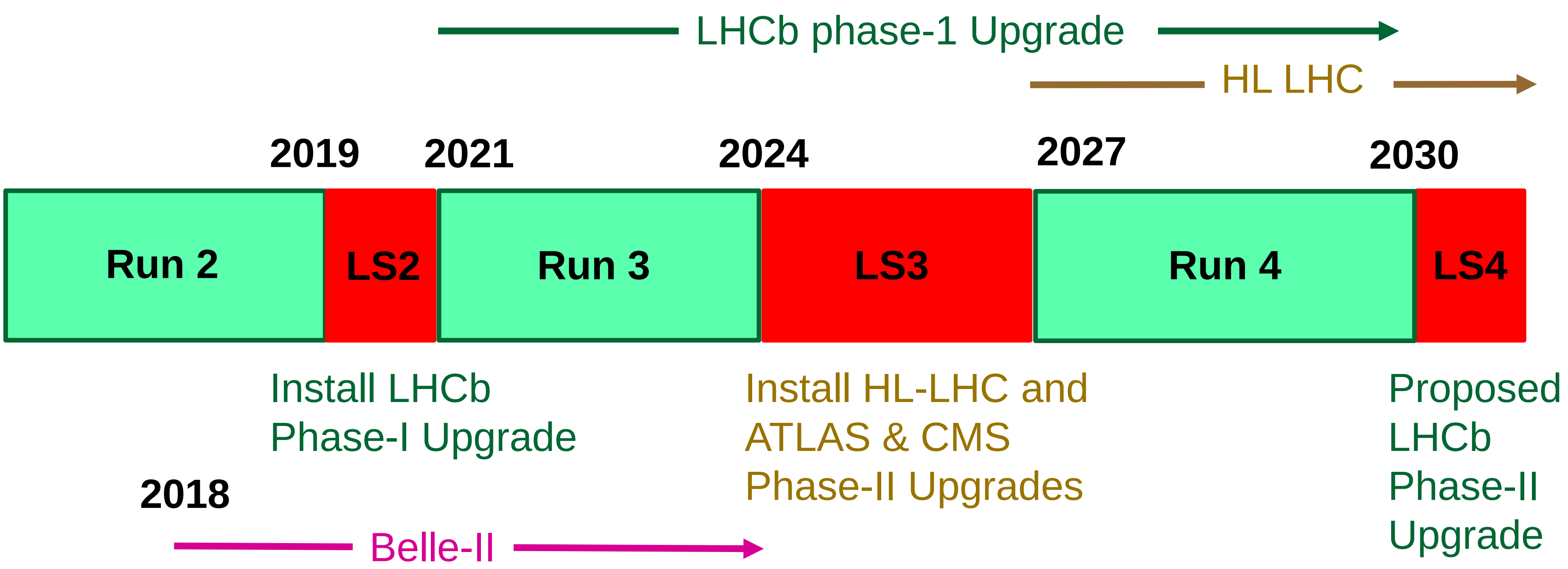
Competitive sensitivity !

Flavour beyond run 2

LHC run 2 now in full flow. This is sure to deliver a substantial Improvement in precision, and perhaps many surprises, but let us look both to the further future, and to other initiatives in flavour:

- Timeline
- Belle II
- The LHCb Phase-I Upgrade
- GPD Phase-II Upgrades
- LHCb Phase II: the ultimate flavour experiment

The LHC schedule up to 2030

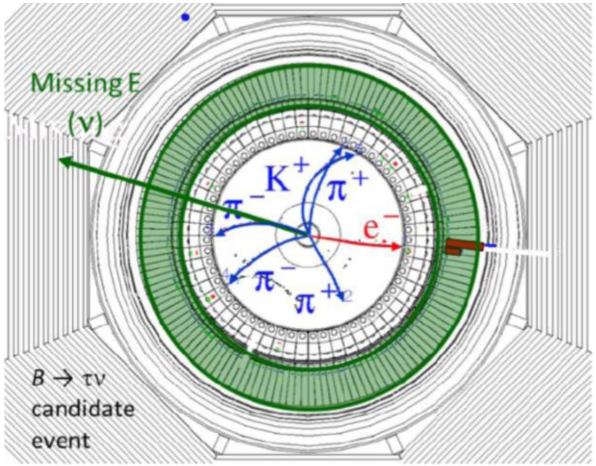


Why Belle II ?

B production at the Y(4S) presents several advantages over hadron environment.

- Can reconstruct full event, which is beneficial for missing energy modes and also inclusive measurements (lower theory uncertainties).

e.g. B→τν



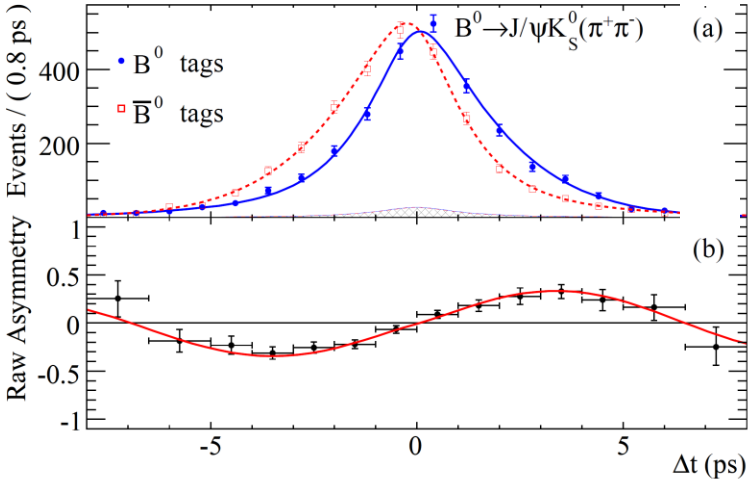
- Low multiplicity environment permits excellent performance for final states with π^0s, η's, photons. Also, good efficiency for long-lived particles K_S and K_L.

- Coherent B^0B^0bar production at Y(4S) makes flavour tagging easier and compensates for lower sample sizes in time-dependent CP measurements

e.g. in sin2β measurement with $B^0 \rightarrow J/\psi K_S$

ε (tag effective) BaBar ~ 31 %
[PRD 79 (2009) 072009]

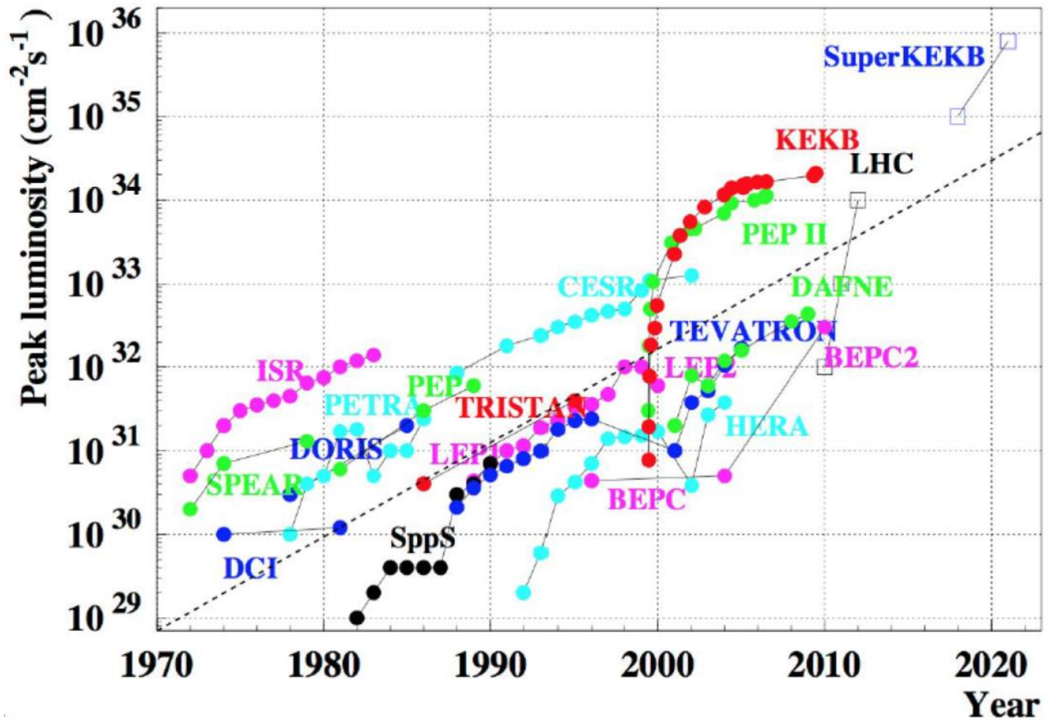
ε (tag effective) LHCb ~ 3 %
[PRL 115 (2015) 031601]

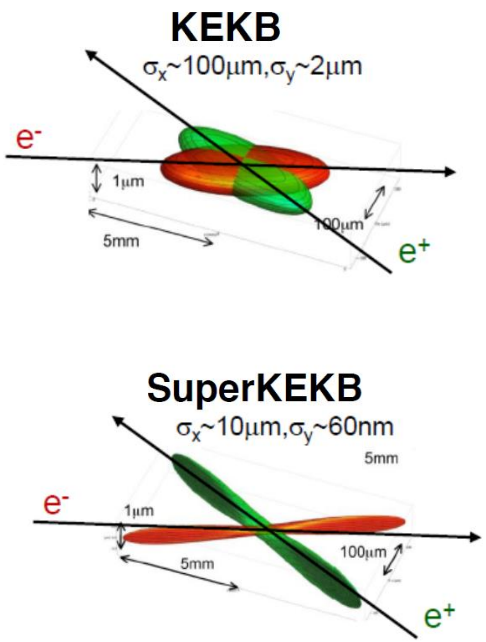


SuperKEKB

- Beams circulating already;
- Collisions planned for this year;
- First collisions with full detector late next year.

SuperKEKB goals: luminosity of 8 x 10^{35} $cm^{-2}s^{-1}$ and 50 ab^{-1} by 2024



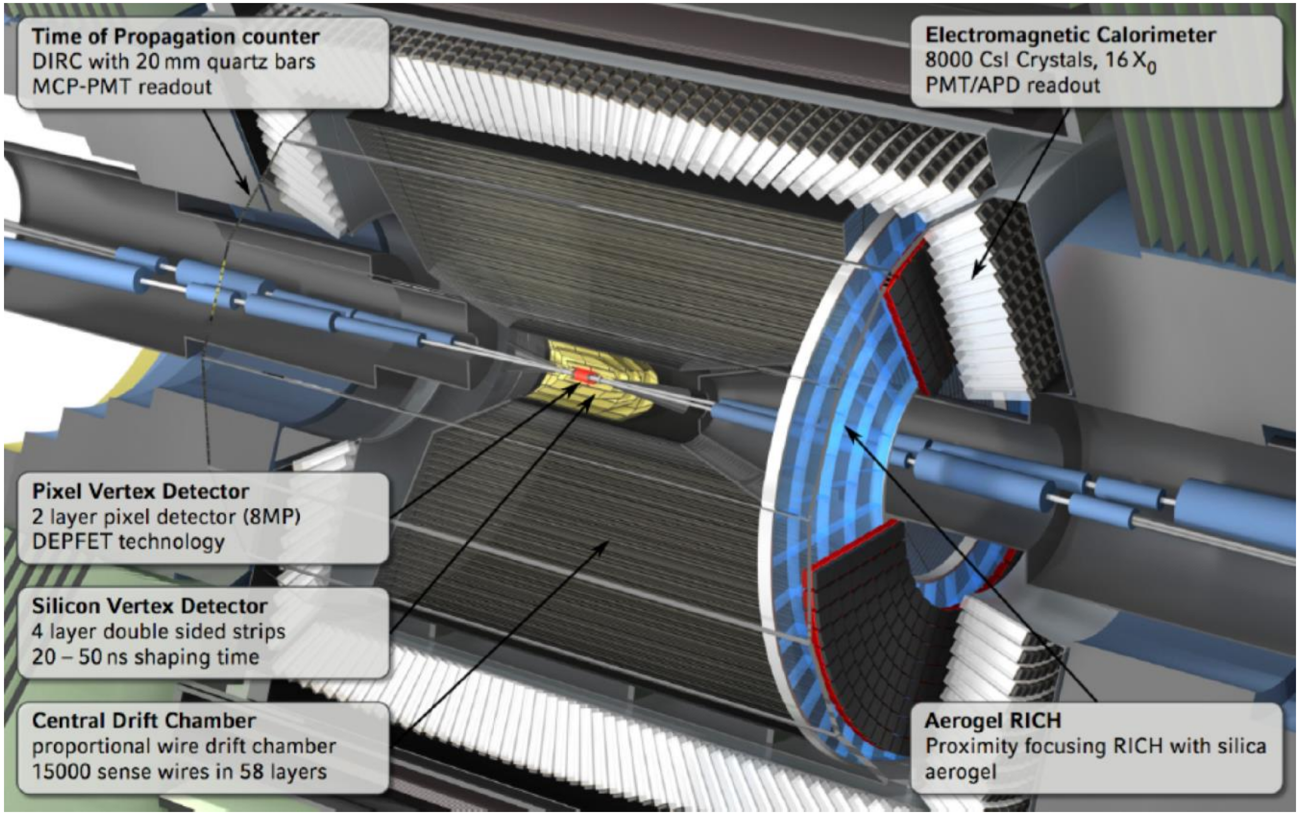


An ambitious 40-fold increase in luminosity on KEKB, to be achieved by squeezing the beams by ~1/20 and doubling the currents.

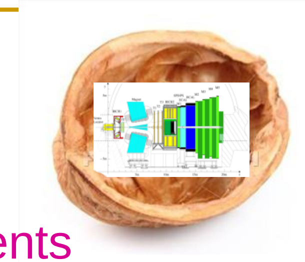
Belle II detector

Targeted improvements w.r.t. Belle

- Improved K_S efficiency
- Improved IP and vertex efficiency
- Improved K/π separation
- Improved π^0 efficiency
- Hadron & muon ID in endcaps



The LHCb Upgrade 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

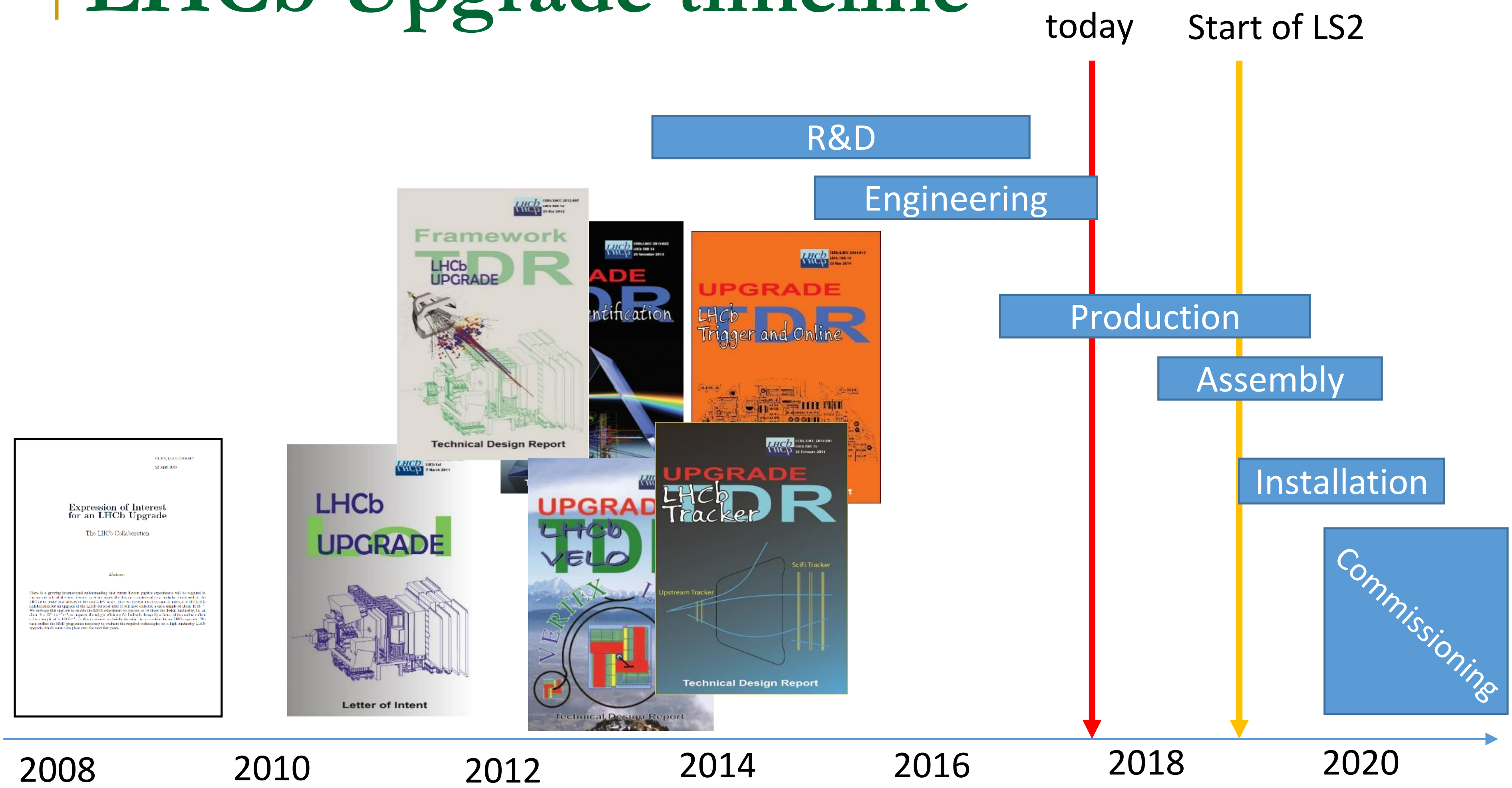
2) Raise operational luminosity to 2 x 10^{33} cm^{-2} s^{-1}

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*.

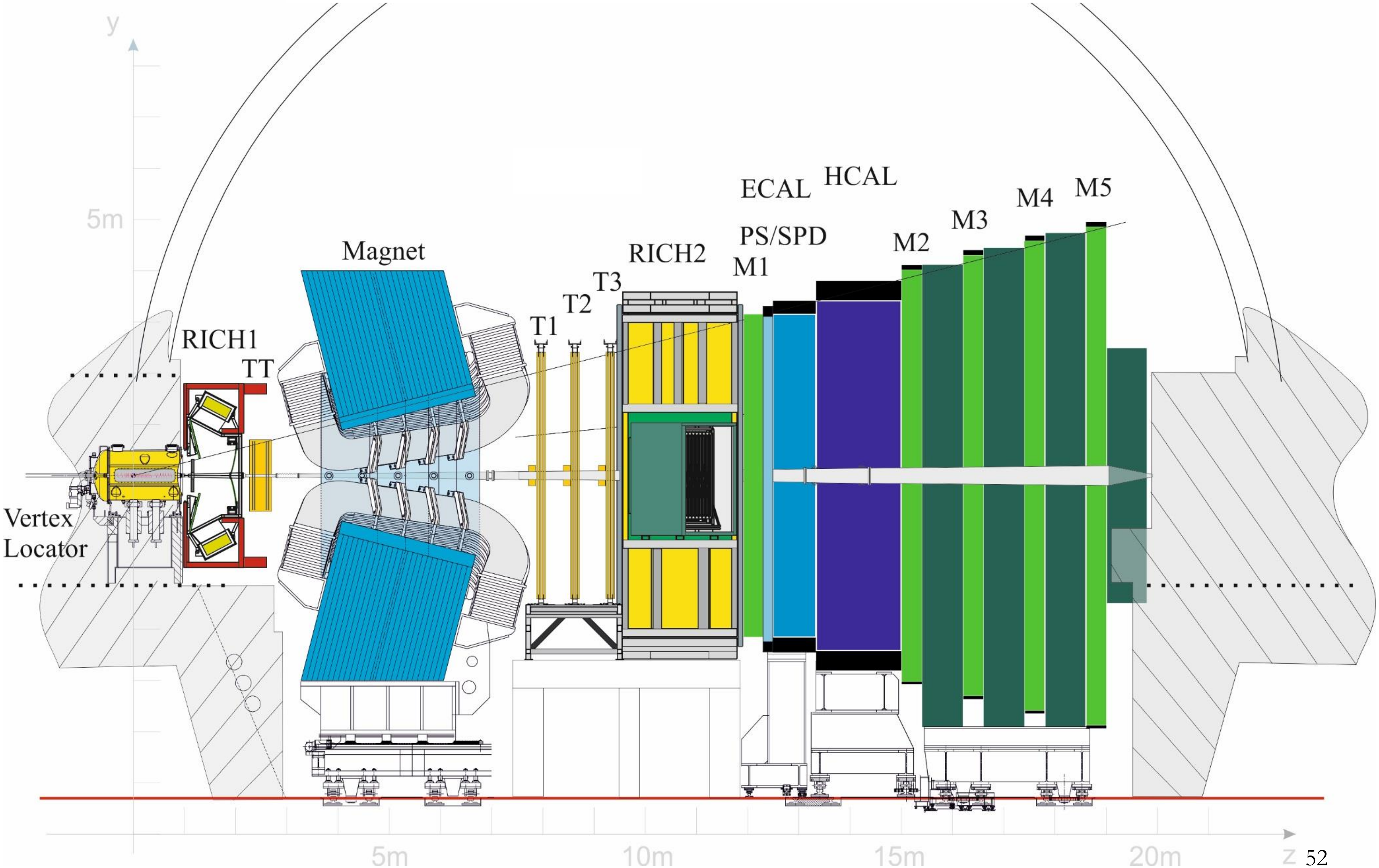
Flexible trigger and unique acceptance also opens up opportunities in other topics apart from flavour (‘a general purpose detector in the forward region’)

LHCb Upgrade 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 →

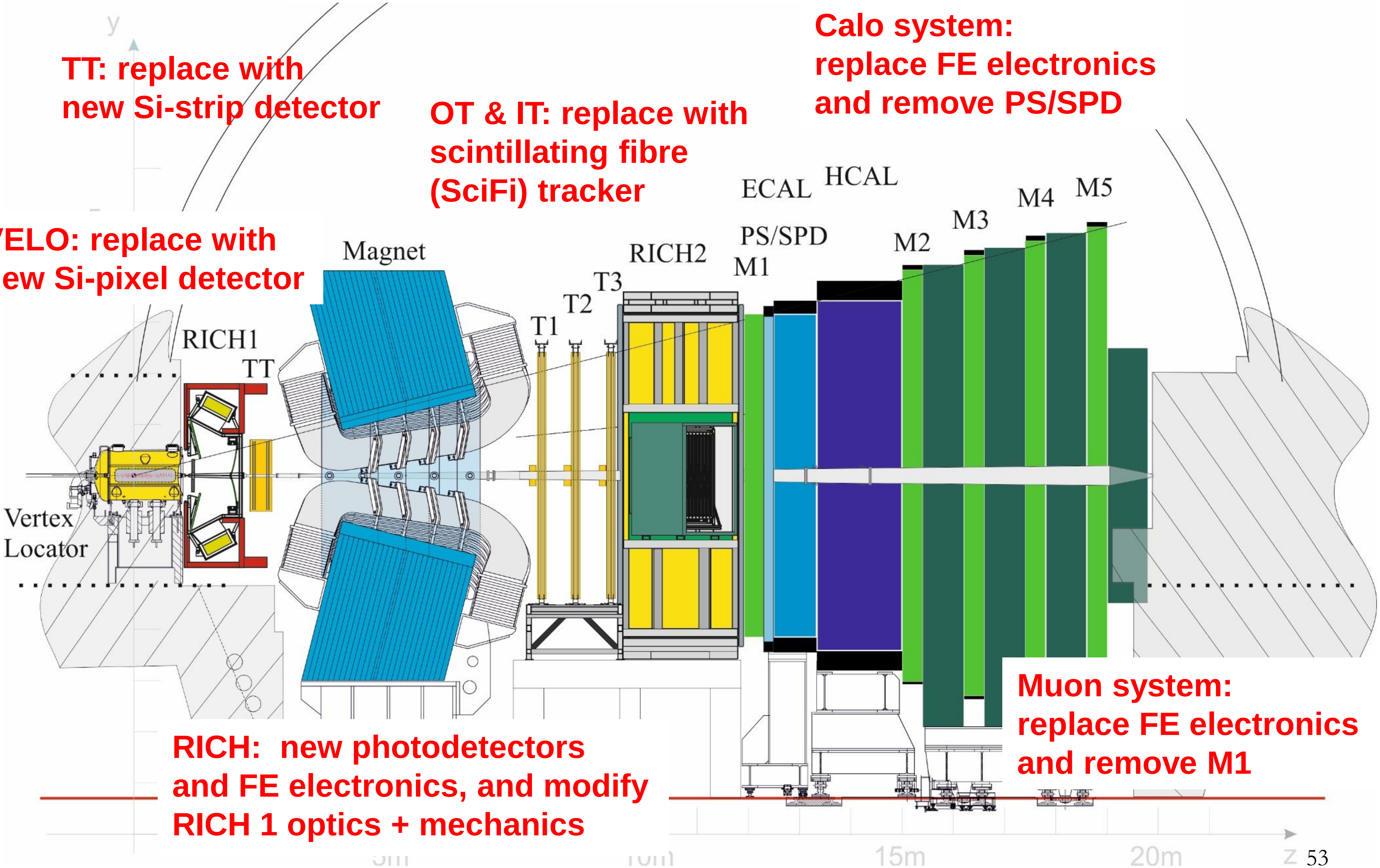
Replace read-out boards and DAQ

TT: replace with new Si-strip detector

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

Calo system: replace FE electronics and remove PS/SPD

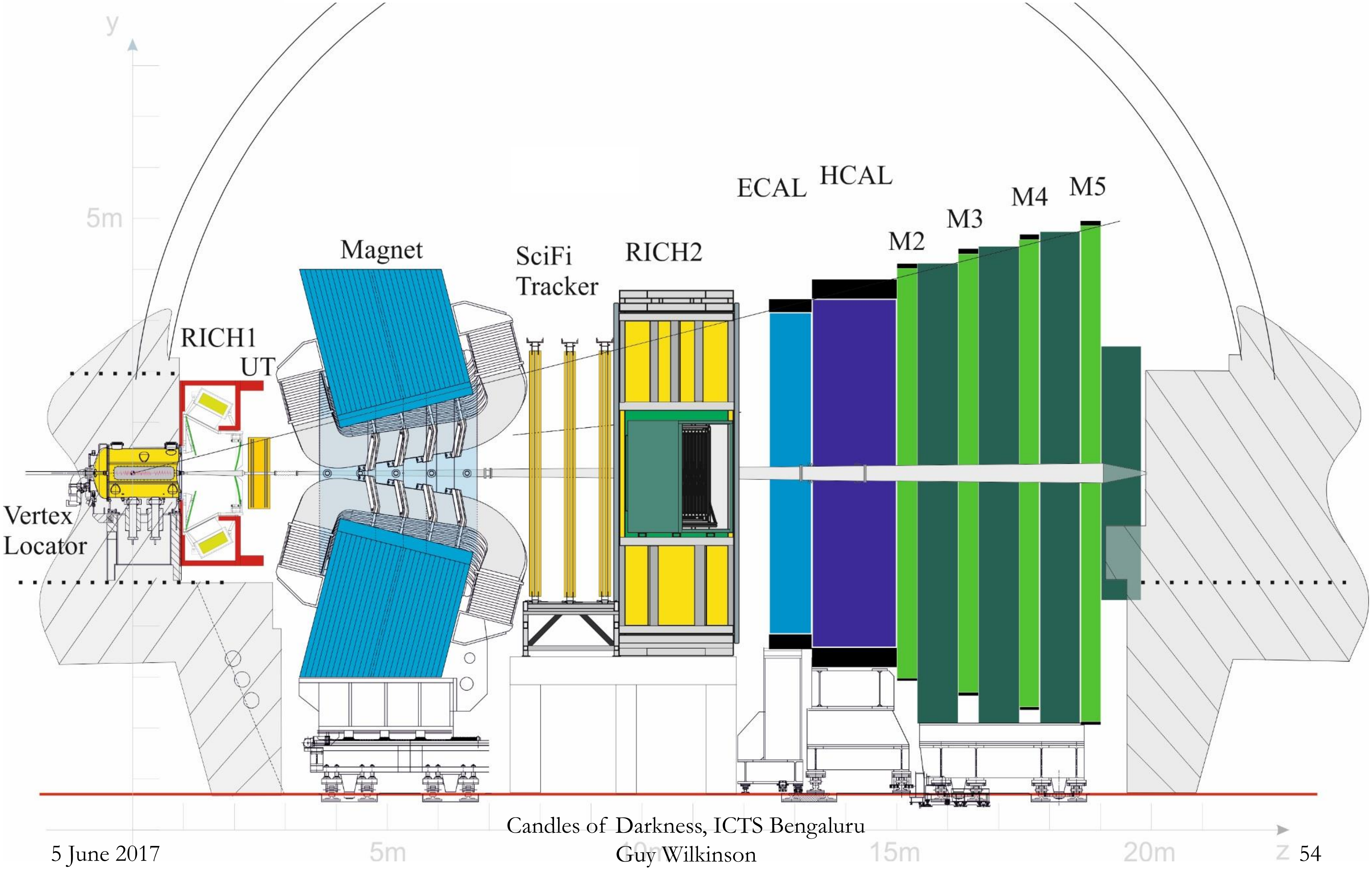
VELO: replace with new Si-pixel detector



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

Muon system: replace FE electronics and remove M1

Upgraded detector

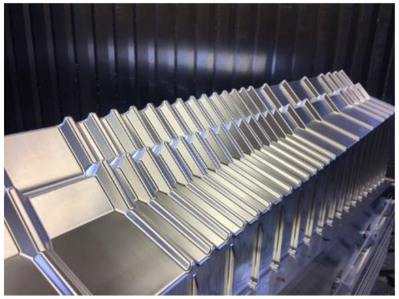


Upgrade progress

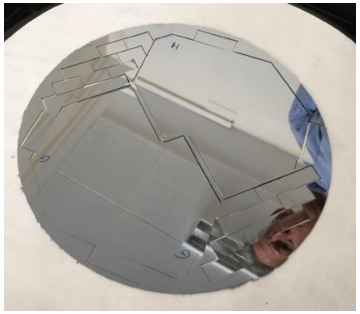
Excellent progress on all aspects of the Upgrade project.

Prototype readout boards

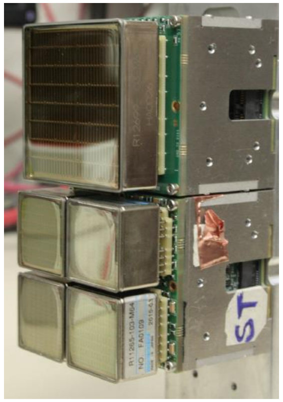
RF box for VELO



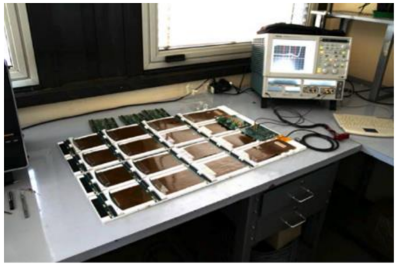
Diced wafer with microchannel cooling substrates for VELO



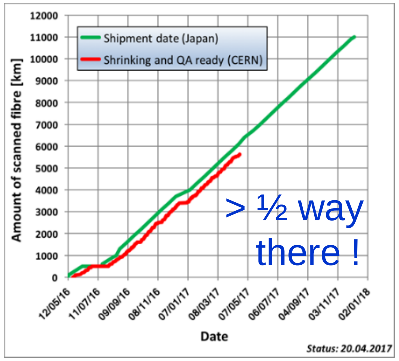
RICH photodetectors



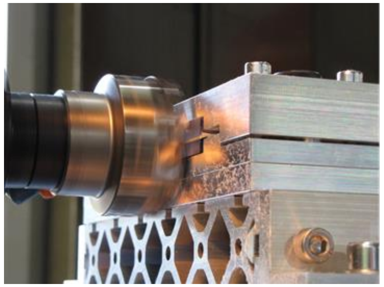
Testing Upstream Tracker ‘flex cables’

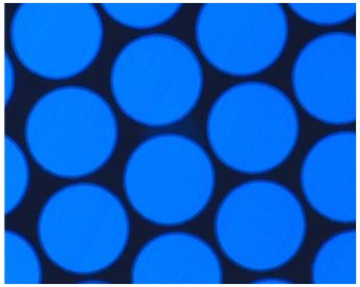


Delivery of tracker scintillating fibres (SciFi)



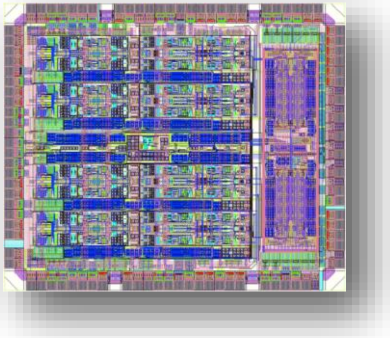
Machining of SciFi mat and scan of fibres





MWPC for muon system

ECAL front-end ASIC



Timescale tight, but still on-track for installation in LS2.

How will the next generation of flavour experiments perform ?

Projections exist, but the numbers are, IMHO, merely indicative, *e.g.* LHCb Upgrade

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

How will the next generation of flavour experiments perform ?

Projections exist, but the numbers are, IMHO, merely indicative, *e.g.* Belle II

B2TiP Report (in progress)

Observables	Expected th. accuracy	Expected exp. uncertainty	Facility (2025)
UT angles & sides			
ϕ_1 [°]	***	0.4	Belle II
ϕ_2 [°]	**	1.0	Belle II
ϕ_3 [°]	***	1.0	Belle II/LHCb
$S(B_s \to J/\psi\phi)$	***	0.01	LHCb
$\|V_{cb}\|$ incl.	***	1%	Belle II
$\|V_{cb}\|$ excl.	***	1.5%	Belle II
$\|V_{ub}\|$ incl.	**	3%	Belle II
$\|V_{ub}\|$ excl.	**	2%	Belle II/LHCb
CPV			
$S(B \to \phi K^0)$	***	0.02	Belle II
$S(B \to \eta' K^0)$	***	0.01	Belle II
$\beta_s^{\rm eff}(B_s \to \phi\phi)$ [rad]	**	0.1	LHCb
$\beta_s^{\rm eff}(B_s \to K^{*0}\bar{K}^{*0})$ [rad]	**	0.1	LHCb
$\mathcal{A}(B \to K^0\pi^0)[10^{-2}]$	***	4	Belle II
$\mathcal{A}(B \to K^+\pi^-)$ $[10^{-2}]$	***	0.20	LHCb/Belle II
(Semi-)leptonic			
$\mathcal{B}(B \to \tau\nu)$ $[10^{-6}]$	**	3%	Belle II
$\mathcal{B}(B \to \mu\nu)$ $[10^{-6}]$	**	7%	Belle II
$R(B \to D\tau\nu)$	***	3%	Belle II
$R(B \to D^*\tau\nu)$	***	2%	Belle II/LHCb

P. Goldenzweig,
La Thuile,11/3/2017

CPV			
$S(B \to \phi K^0)$	***	0.02	Belle II
$S(B \to \eta' K^0)$	***	0.01	Belle II
$\beta_s^{\rm eff}(B_s \to \phi\phi)$ [rad]	**	0.1	LHCb
$\beta_s^{\rm eff}(B_s \to K^{*0}\bar{K}^{*0})$ [rad]	**	0.1	LHCb
$\mathcal{A}(B \to K^0\pi^0)[10^{-2}]$	***	4	Belle II
$\mathcal{A}(B \to K^+\pi^-)$ $[10^{-2}]$	***	0.20	LHCb/Belle II
(Semi-)leptonic			
$\mathcal{B}(B \to \tau\nu)$ $[10^{-6}]$	**	3%	Belle II
$\mathcal{B}(B \to \mu\nu)$ $[10^{-6}]$	**	7%	Belle II
$R(B \to D\tau\nu)$	***	3%	Belle II
$R(B \to D^*\tau\nu)$	***	2%	Belle II/LHCb

Radiative & EW Penguins			
$\mathcal{B}(B \to X_s\gamma)$	**	4%	Belle II
$A_{CP}(B \to X_{s,d}\gamma)$ $[10^{-2}]$	***	0.005	Belle II
$S(B \to K_S^0\pi^0\gamma)$	***	0.03	Belle II
$2\beta_s^{\rm eff}(B_s \to \phi\gamma)$	***	0.05	LHCb
$S(B \to \rho\gamma)$	**	0.07	Belle II
$\mathcal{B}(B_s \to \gamma\gamma)$ $[10^{-6}]$	**	0.3	Belle II
$\mathcal{B}(B \to K^*\nu\bar{\nu})$ $[10^{-6}]$	***	15%	Belle II
$\mathcal{B}(B \to K\nu\bar{\nu})$ $[10^{-6}]$	***	20%	Belle II
$q_0^2 A_{\rm FB}(B \to K^*\mu\mu)$	**	0.05	LHCb/Belle II
$\mathcal{B}(B_s \to \tau\tau)$ $[10^{-3}]$	***	< 2	Belle II
$\mathcal{B}(B_s \to \mu\mu)$	***	10%	LHCb/Belle II
Charm			
$\mathcal{B}(D_s \to \mu\nu)$	***	0.9%	Belle II
$\mathcal{B}(D_s \to \tau\nu)$	***	2%	Belle II
$\Delta A_{CP}(D^0 \to K^+K^-)$ $[10^{-4}]$	**	0.1	LHCb
$A_{CP}(D^0 \to K_S^0\pi^0)$ $[10^{-2}]$	**	0.03	Belle II
$\|q/p\|(D^0 \to K_S^0\pi^+\pi^-)$	***	0.03	Belle Ii
$\phi(D^0 \to K_S^0\pi^+\pi^-)$ [°]	***	4	Belle II
Tau			
$\tau \to \mu\gamma$ $[10^{-9}]$	***	< 5	Belle II
$\tau \to e\gamma$ $[10^{-9}]$	***	< 10	Belle II
$\tau \to \mu\mu\mu$ $[10^{-9}]$	***	< 0.3	Belle II/LHCb

How will the next generation of flavour experiments perform ?

Projections exist, but the numbers are, IMHO, merely indicative, *e.g.* Belle II

Key facts.

Belle II's aim is to collect ~50 x more than BaBar + Belle, plus benefit from several detector improvements.

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 !

Observables
UT angles & sid
ϕ_1 [°]
ϕ_2 [°]
ϕ_3 [°]
$S(B_s \to J/\psi\phi)$
$\lvert V_{cb}\rvert$ incl.
$\lvert V_{cb}\rvert$ excl.
$\lvert V_{ub}\rvert$ incl.
$\lvert V_{ub}\rvert$ excl.
CPV
$S(B \to \phi K^0)$
$S(B \to \eta' K^0)$
$\beta_s^{\rm eff}(B_s \to \phi\phi)$ [r
$\beta_s^{\rm eff}(B_s \to K^{*0}\bar{K}$
$\mathcal{A}(B \to K^0\pi^0)$[1
$\mathcal{A}(B \to K^+\pi^-)$
(Semi-)leptonic
$\mathcal{B}(B \to \tau\nu)$ [10^-
$\mathcal{B}(B \to \mu\nu)$ [10^-
$R(B \to D\tau\nu)$
$R(B \to D^*\tau\nu)$

			Belle II
			Belle II
			LHCb
			LHCb
			Belle II
			LHCb/Belle II
			Belle II
			Belle II
			Belle II
			Belle II/LHCb
			Belle II
			Belle II
			Belle II
			LHCb
			Belle II
			Belle II
			Belle II
			Belle II
			LHCb/Belle II
			Belle II
			LHCb/Belle II
			Belle II
			Belle II
			LHCb
			Belle II
			Belle Ii
			Belle II
			Belle II
			Belle II
$\tau \to \mu\mu\mu$ [10^{-9}]	***	< 0.3	Belle II/LHCb

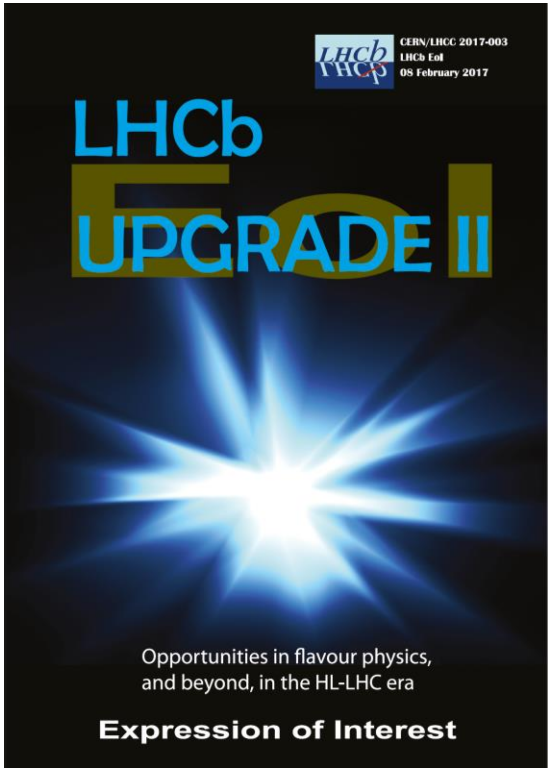
P. Golden
La Thuile,11/3/2017

Looking further forward…

Serious thinking now underway about a phase-II Upgrade 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 Phase I & 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

Precise measurements of flavour observables provide a powerful way to probe for New Physics effects beyond the Standard Model.

Flavour-physics measurements at the LHC, in particular by LHCb, but also by the GPDs, are dramatically adding to the already impressive knowledge accumulated by the B-factories and Tevatron.

The results obtained in run 1 have matched, & in many cases exceeded the sensitivities expected prior to data taking. Many of these results show good compatibility with the SM (for now), but some signs of tension are emerging.

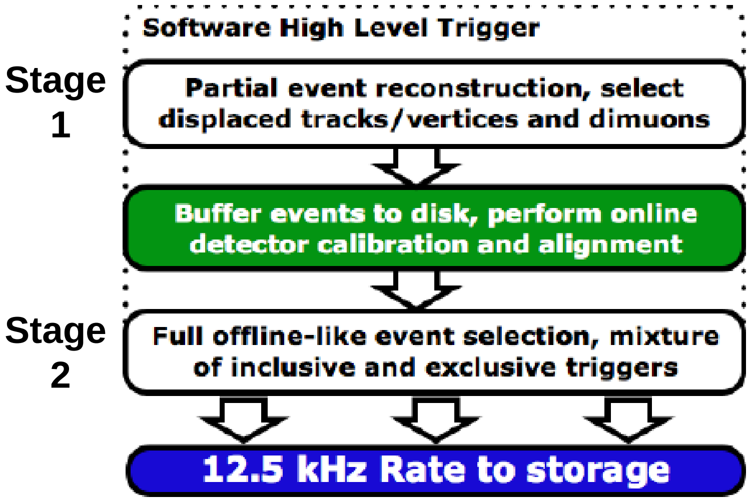
Need more data to test these hints. These data are arriving during run 2.

$\rightarrow$ stay tuned !

Belle II and the LHCb Upgrade(s) will open up a new frontier in precision.

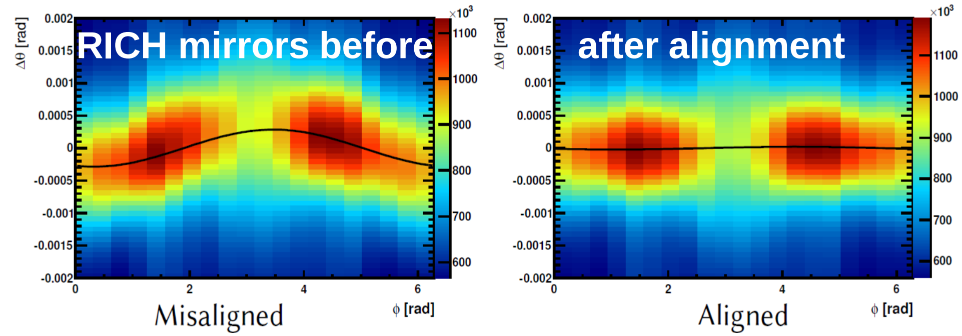
Backups

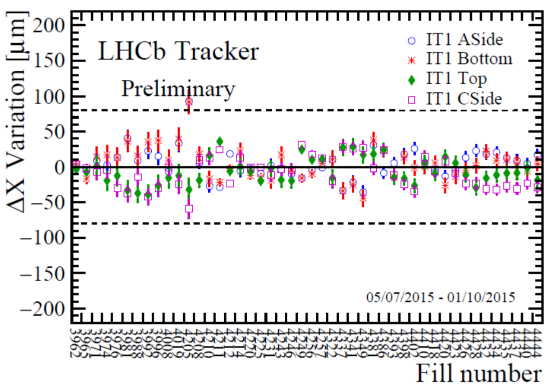
Focus on the software trigger

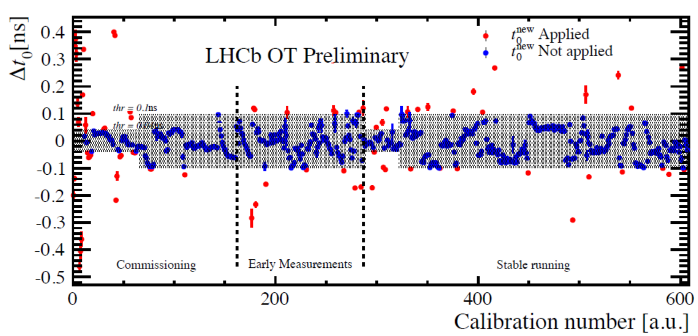


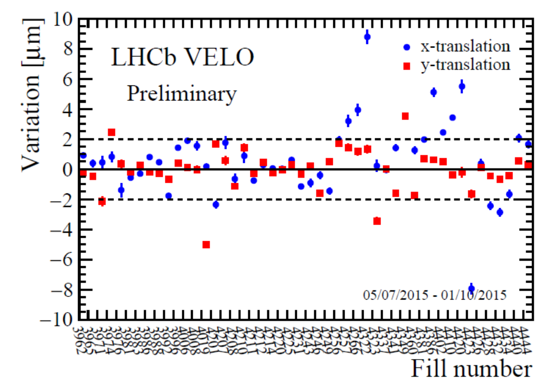
The Big Idea of run-2 data taking:

- Calibrate and align detector (if needed) as soon as data are collected;

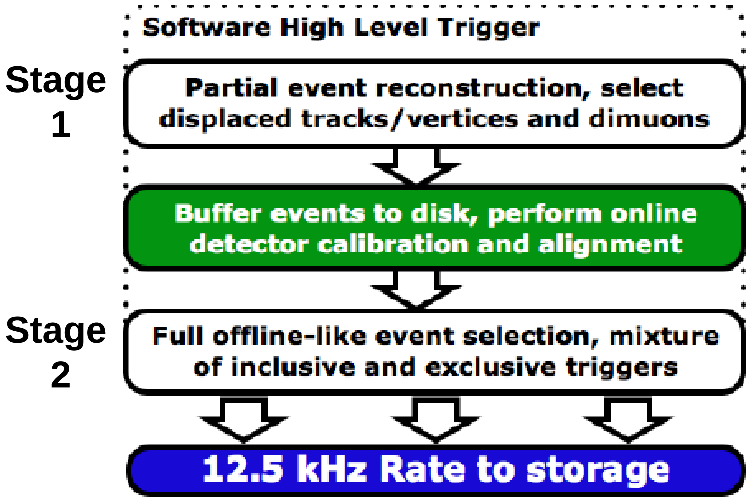








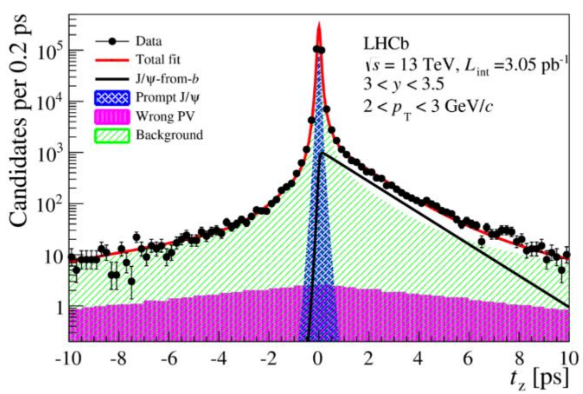
Focus on the software trigger



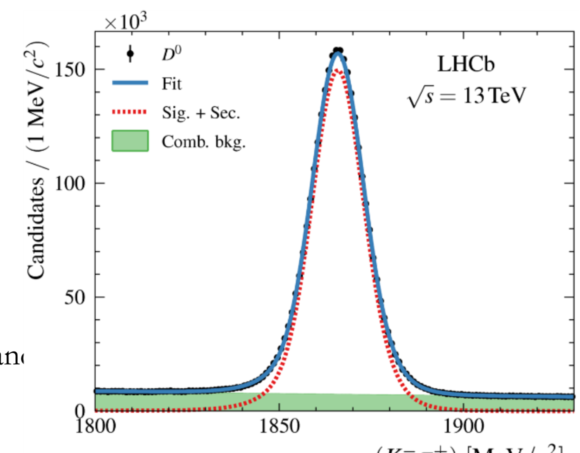
The Big Idea of run-2 data taking:

- Calibrate and align detector (if needed) as soon as data are collected;
- Only run 2nd stage of software trigger when calibration / alignment OK;
- Consequences: most critical trigger step has access to offline-like data quality.
  - → more discriminant trigger;
  - → no time-consuming offline reprocessing;
  - → immediate analysis with trigger information ('the TURBO' stream) !

e.g. forward J/ψ production at 13 TeV [JHEP 10 (2015) 172]

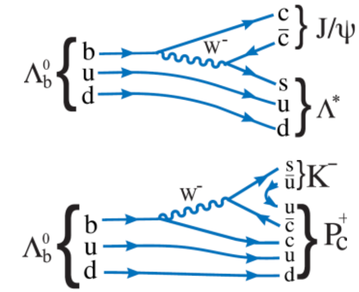


First results shown within 2 weeks of data collection !



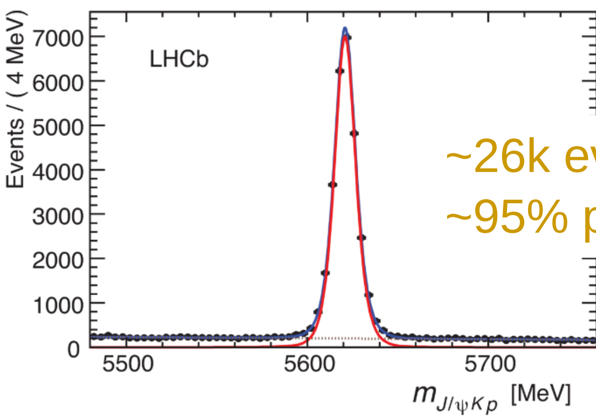
e.g. open charm production at 13 TeV [JHEP 03 (2016) 159]

J/Ψp resonances consistent with pentaquark states



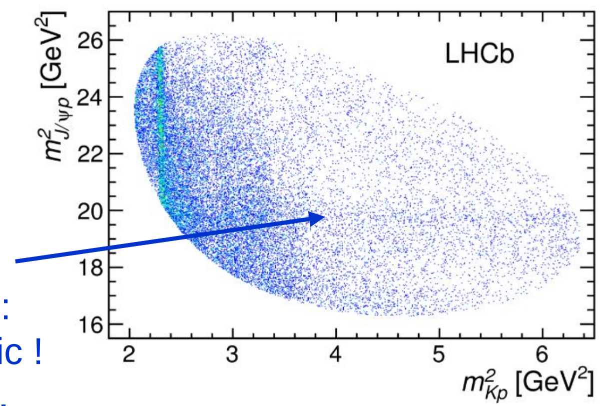
[PRL 115 (2015) 072001]

Large & pure sample of $\Lambda_b \rightarrow J/\Psi pK$ decays



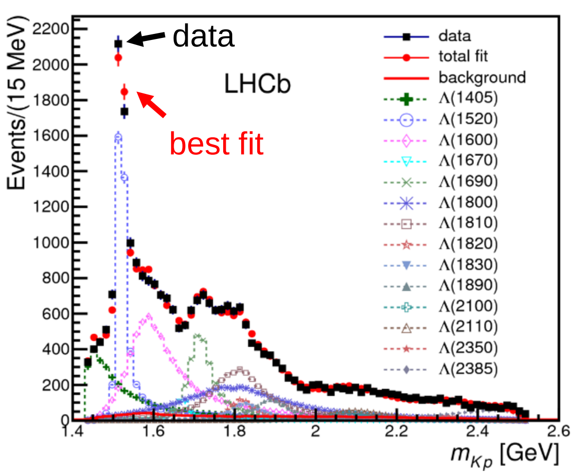
~26k events
~95% purity

Distinctive structure in J/Ψp spectrum

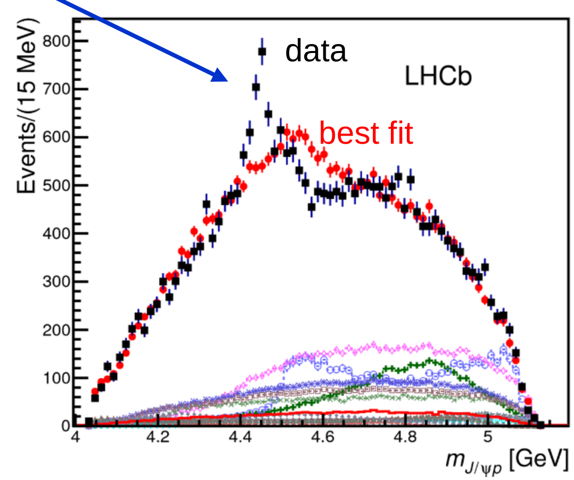


Naïve first impression: this is exotic ! (uudccbar).

Amplitude model of conventional states can reproduce Kp spectrum well enough…



…but cannot describe the J/Ψ projection at all.



J/Ψp resonances consistent with pentaquark states

[PRL 115 (2015) 072001]

$P_c(4380)$:

$M = 4380 \pm 8 \pm 29\,\mathrm{MeV}$,

$\Gamma = 205 \pm 18 \pm 86\,\mathrm{MeV}$

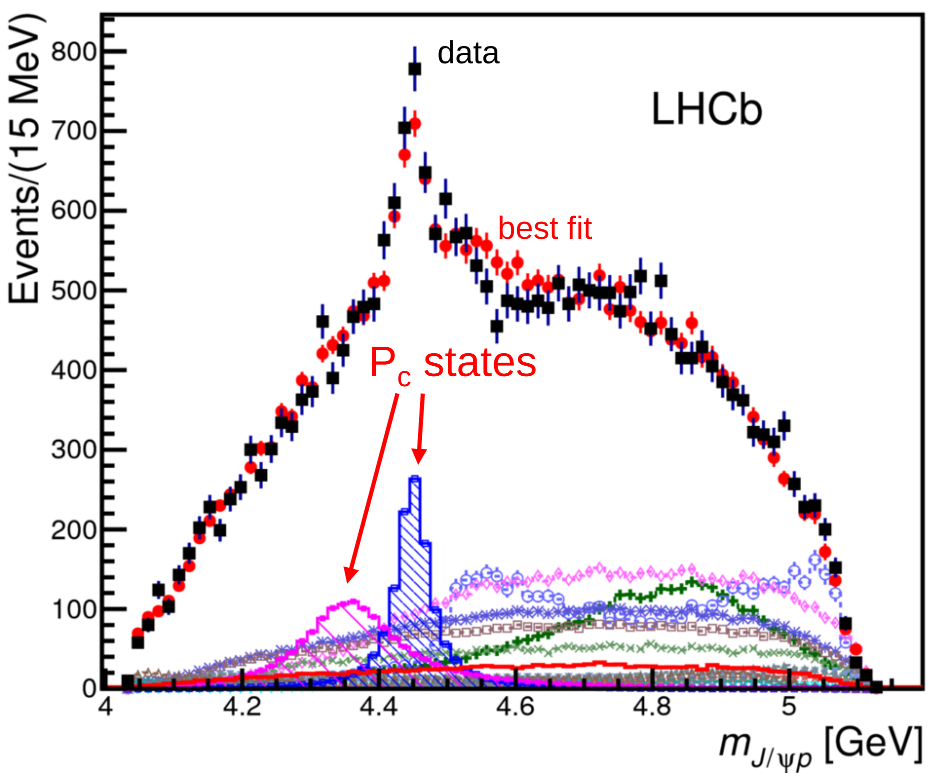
$P_c(4450)$:

$M = 4449.8 \pm 1.7 \pm 2.5\,\mathrm{MeV}$

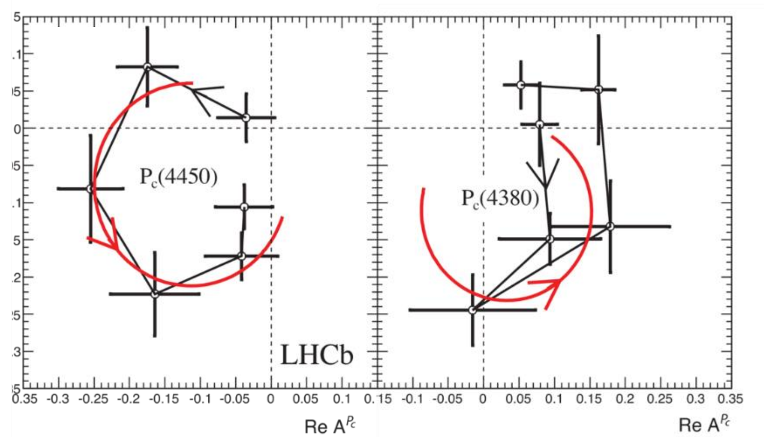
$\Gamma = 39 \pm 5 \pm 19\,\mathrm{MeV}$

Need to add two states with content uudccbar.

Best fit has J=3/2 and 5/2 with opposite parities.



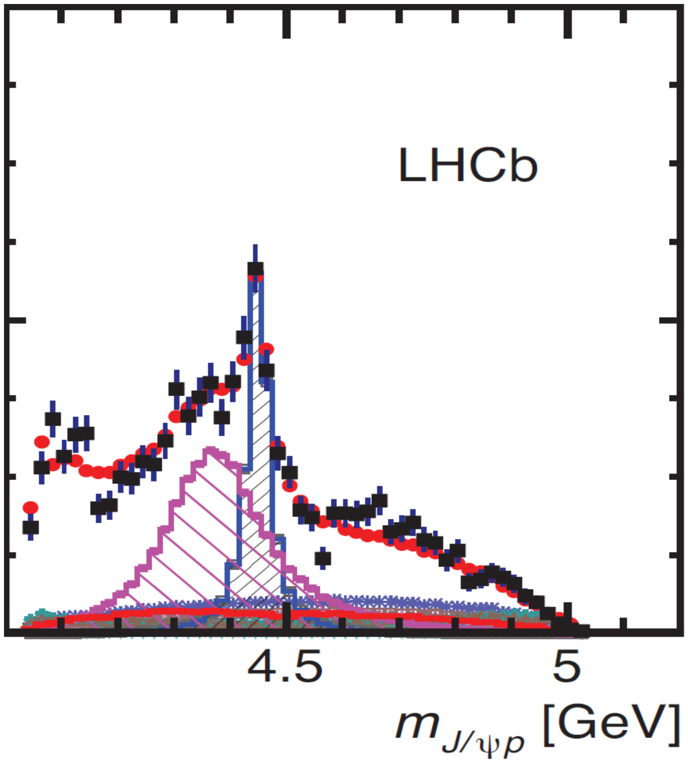
ear resonant behaviour for narrow state,
eed more statistics to elucidate wider one.



J/Ψp resonances consistent with pentaquark states

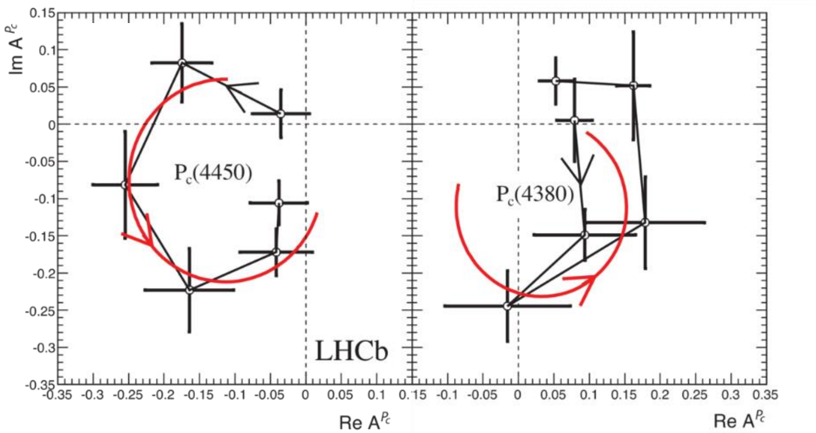
[PRL 115 (2015) 072001]

Contribution of wider state clearer if one focuses on m_{Kp} > 2 GeV region.



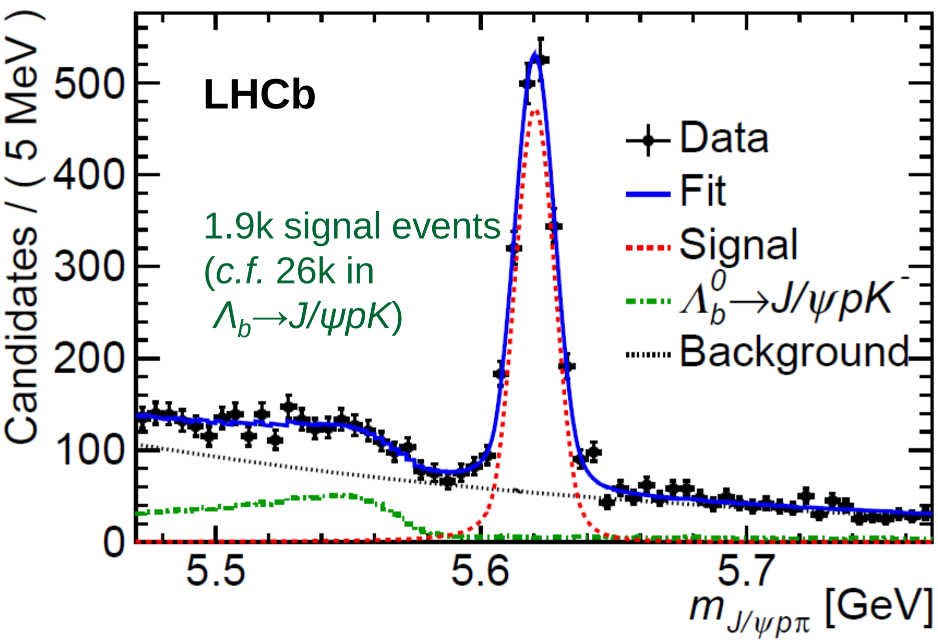
$P_c(4380)$:
$M = 4380 \pm 8 \pm 29\,\mathrm{MeV}$,
$\Gamma = 205 \pm 18 \pm 86\,\mathrm{MeV}$
$P_c(4450)$:
$M = 4449.8 \pm 1.7 \pm 2.5\,\mathrm{MeV}$
$\Gamma = 39 \pm 5 \pm 19\,\mathrm{MeV}$

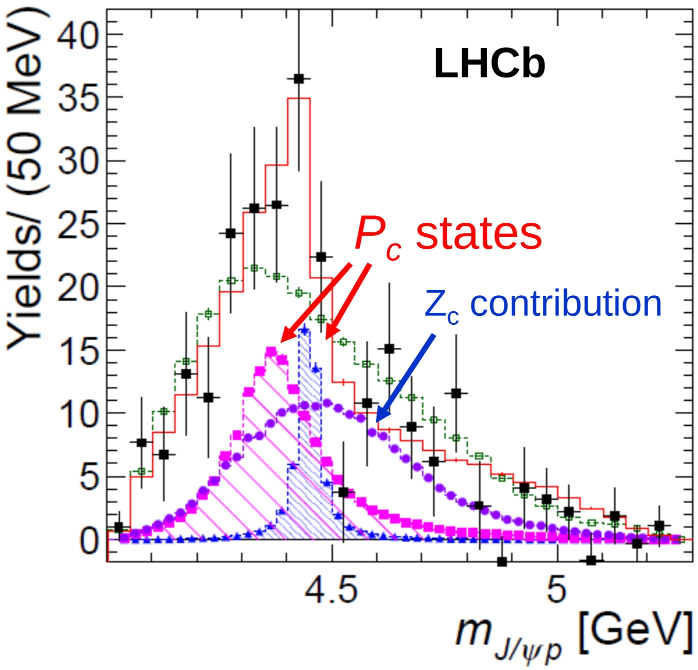
Clear resonant behaviour for narrow state,
Need more statistics to elucidate wider one.



Where else to look ?

If the P_c shows up in $\Lambda_b \rightarrow J/\psi p K$ it should also be visible in $\Lambda_b \rightarrow J/\psi p\ \pi$, albeit harder to see, as this is Cabibbo suppressed, and there is a potential 'background' from another candidate 4-quark exotic, the Z_c^- ($\Lambda_b \rightarrow Z_c^- p$, $Z_c^- \rightarrow J/\psi \pi^-$).





[PRL 117 (2016) 082002]

Including the exotic contributions fits the data better (3.1 σ) than N^* states alone. Entirely compatible with earlier analysis. More data will allow for more precise measurements of P_c properties and for searches for other pentaquark states.

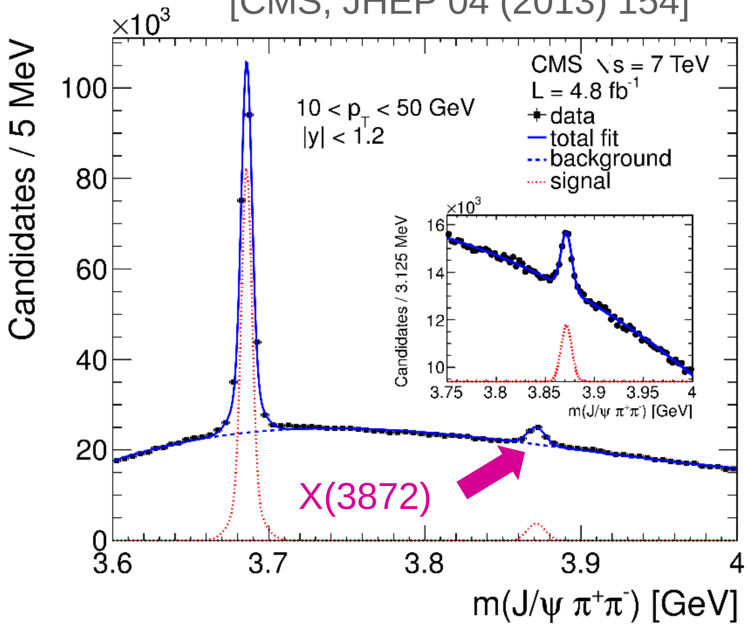
Four-quark states

Many more candidates for four-quark exotics, with studies still ongoing in B factory and Tevatron data, and at BESIII experiment.

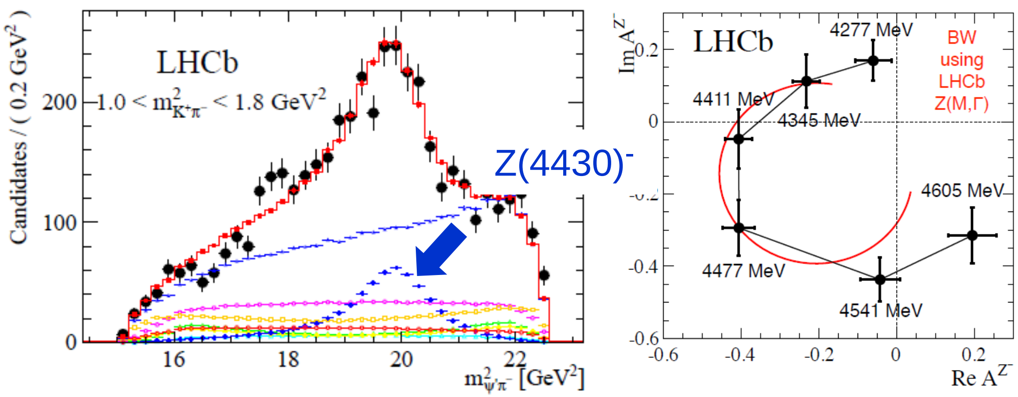
The most famous of these states, already studied extensively at the LHC, is the X(3872).

Many other examples. The first demonstration that such a state is a genuine four-quark resonance came with the Z(4430)$^-$ and LHCb.

[CMS, JHEP 04 (2013) 154]



[PRL 112 (2014) 222002]



Invariant mass

amplitude variation across signal

The argument goes like this:

1. The ‘bump’ is certainly there;
2. It can NOT be built from standard states;
3. It has textbook resonance behaviour.

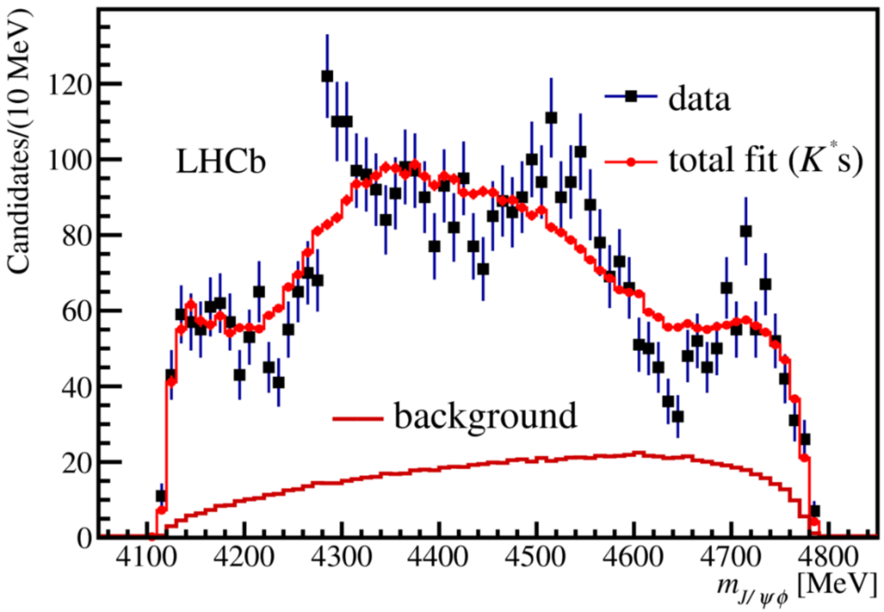
i.e. the same as was used in the pentaquark analysis.

More four-quark candidates

[PRL 118 (2018) 022003; PRD 95 (2017) 012002]

The J/ψΦ spectrum in $B^+ \rightarrow J/\psi \Phi K^+$ decays has attracted attention for some time. Here CDF saw a narrow structure [PRL 102 (2009) 242002], dubbed the X(4140). Confirmed by D0 [PRD 89 (2014) 012004] & CMS [PRL B 734 (2014) 261], all in 'bump-hunting' analyses.

Study spectrum with full LHCb run-1 sample, & complete amplitude model machinery.



Spectrum in undeniably lumpy, most obviously *above* the *X*(4140) region (CMS & D0 had also seen evidence of structure ~4300 MeV)

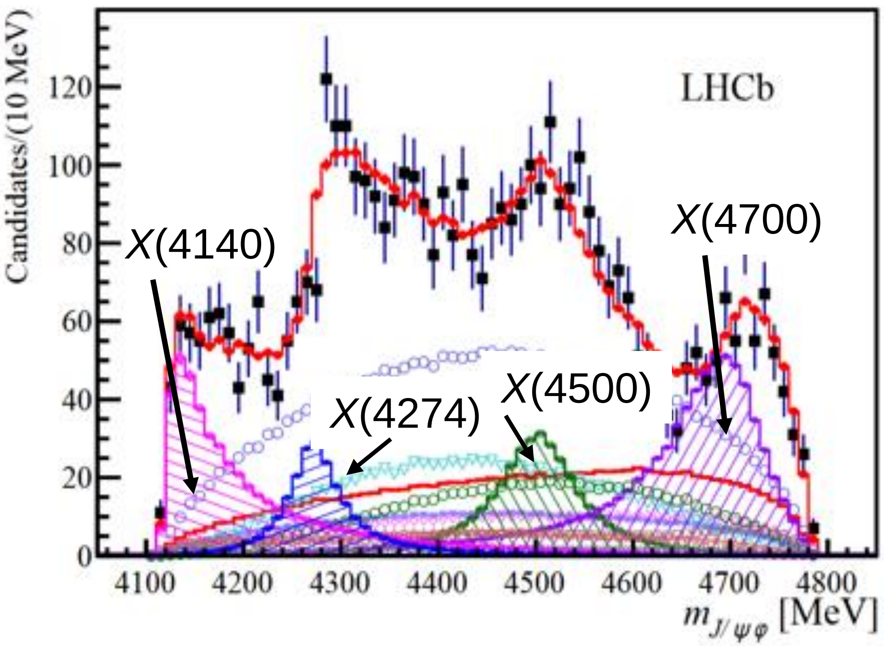
Very importantly, a model based on conventional PDG states *cannot* describe data. So must inject exotics….

More four-quark candidates

[PRL 118 (2018) 022003; PRD 95 (2017) 012002]

The J/ψΦ spectrum in $B^+ \rightarrow J/\psi \Phi K^+$ decays has attracted attention for some time. Here CDF saw a narrow structure [PRL 102 (2009) 242002], dubbed the X(4140). Confirmed by D0 [PRD 89 (2014) 012004] & CMS [PRL B 734 (2014) 261], all in 'bump-hunting' analyses.

Study spectrum with full LHCb run-1 sample, & complete amplitude model machinery.



A good description of spectrum requires four (!) non-standard contributions, all of which are present at >5σ level.

X(4140) found to have larger width than previous analyses, and its quantum numbers are found to be 1^{++}.

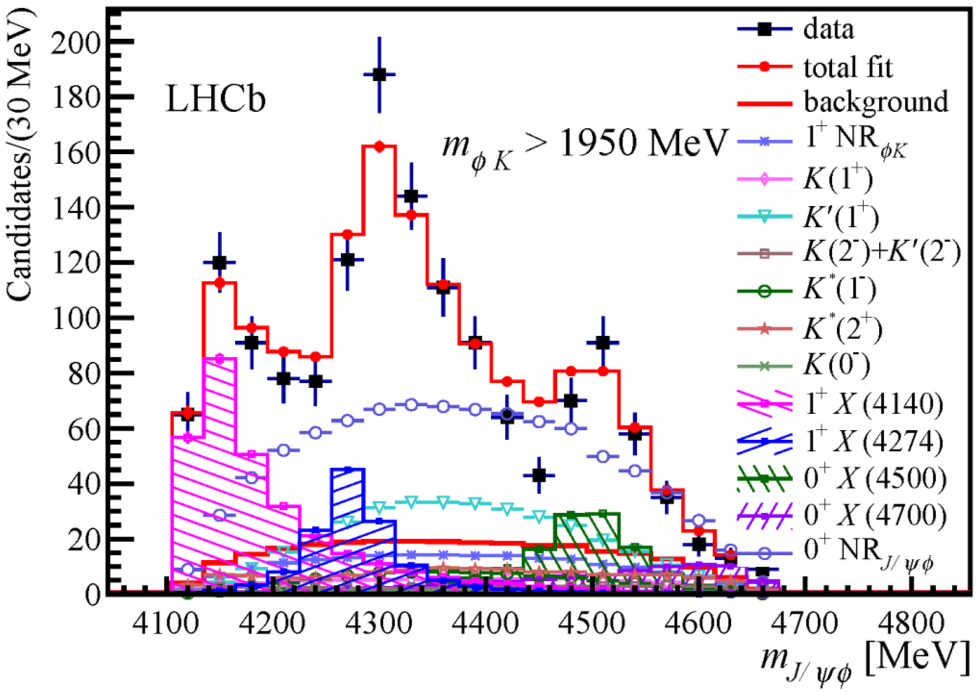
This structure can also be described by a below threshold $D_sD_s{}^*$ cusp.

X(4274) is found to be 1^{++}. Other two structures best described by 0^{++} resonances.

Four-quark exotics: study of $J/\psi\Phi$ structure in $B^+ \rightarrow J/\psi\Phi K^+$

[PRL 118 (2018) 022003; PRD 95 (2017) 012002]

Looking in a specific *ΦK* mass window



A good description of spectrum requires four (!) non-standard contributions, all of which are present at >5σ level.

X(4140) found to have larger width than previous analyses, and its quantum numbers are found to be 1^{++}.

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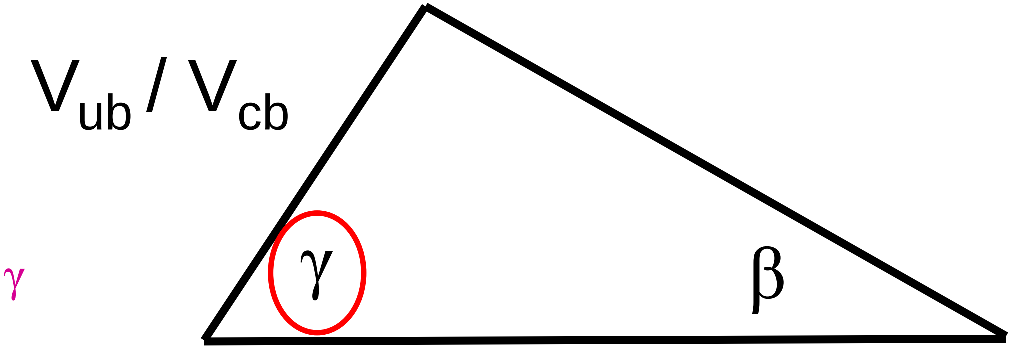
Quantum numbers of *X*(4274) are also determined to be 1^{++}.
The other two structures are best described by 0^{++} resonances.

The Unitarity Triangle: γ



A precise measurement of the angle γ is a raison d'être of LHCb.

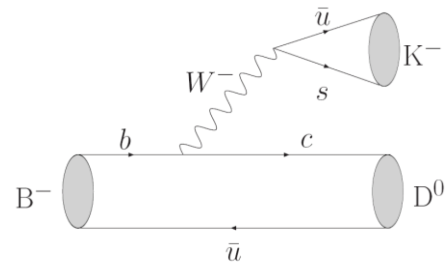
Look in $B^{\pm} \to DK^{\pm}$ decays using common mode for D^0 & $\bar{D}^0$

→ γ sensitive interference

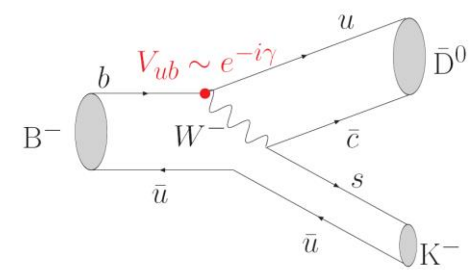
→ different rates for B^+ & B^- (CPV!)

Many possibilities: $K\pi$, KK, $K\pi\pi\pi$...

Favoured



Suppressed



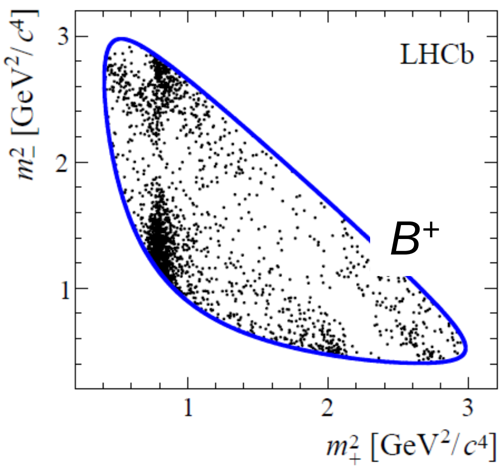
Tree-level decays: strategy very clean & yields result unpolluted by New Physics

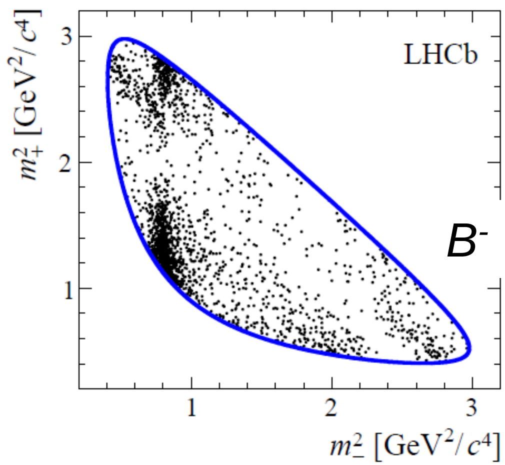
This is a good thing! Provides SM benchmark against which other loop-driven NP sensitive observables can be compared (*e.g.* $\Delta m_d/\Delta m_s$, sin2β, γ measured in $B \to hh$)

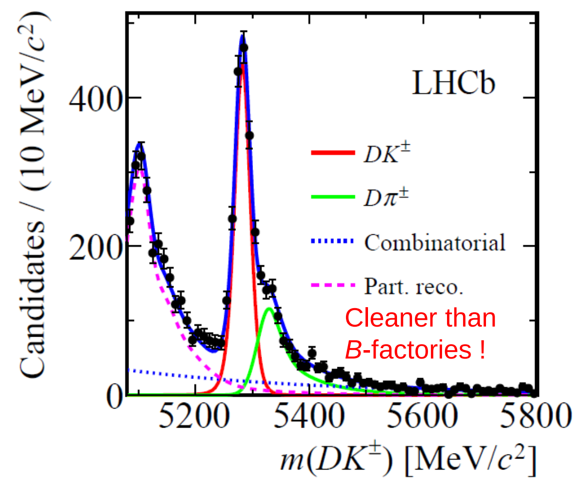
Measurement of γ: $B \to DK$ at LHCb

Sometimes CPV involves looking for B^- / B^+ differences in multibody phase space, *e.g.* $D \to K_S \pi\pi$ or $K_S KK$. In all cases benefit from the surprising (?) purity of signal.

[JHEP 10 (2014) 097]



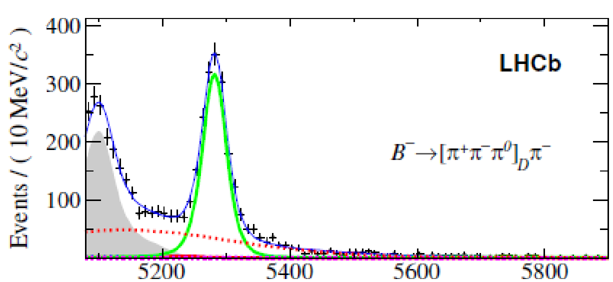


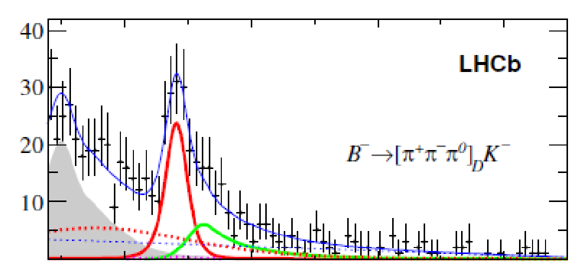


This cleanliness thanks to:

- excellent particle ID and vertexing
- separation of *D* and *B* vertices

Seen in all modes that enter the γ analysis, even those with π^0's (once thought 'impossible' at the LHC).





[PRD 91 (2015) 112014]

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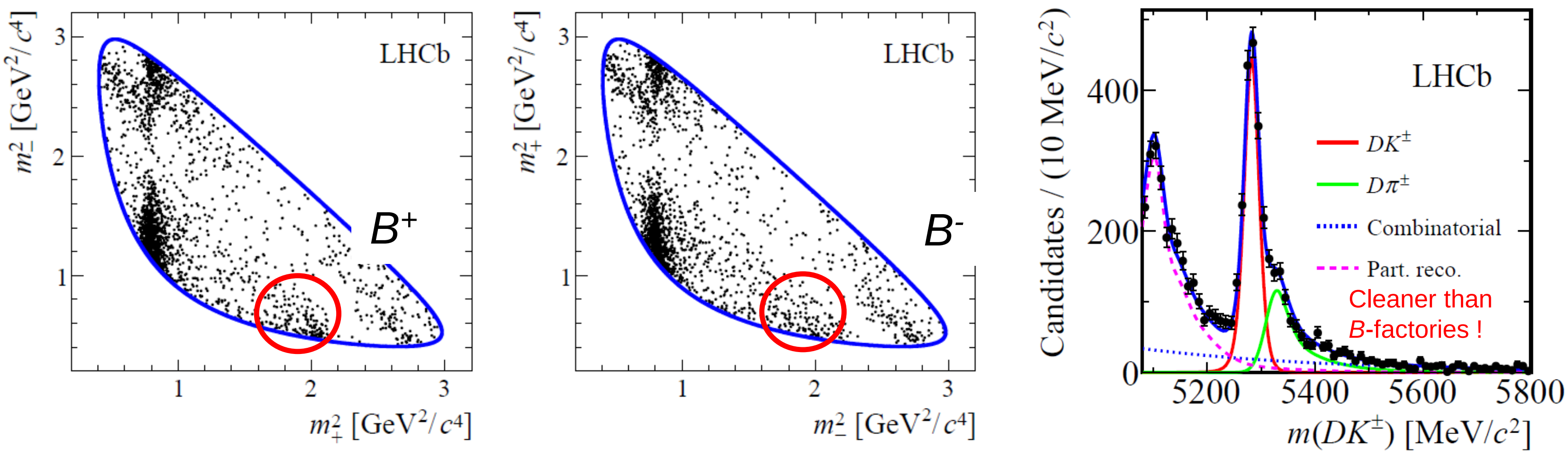

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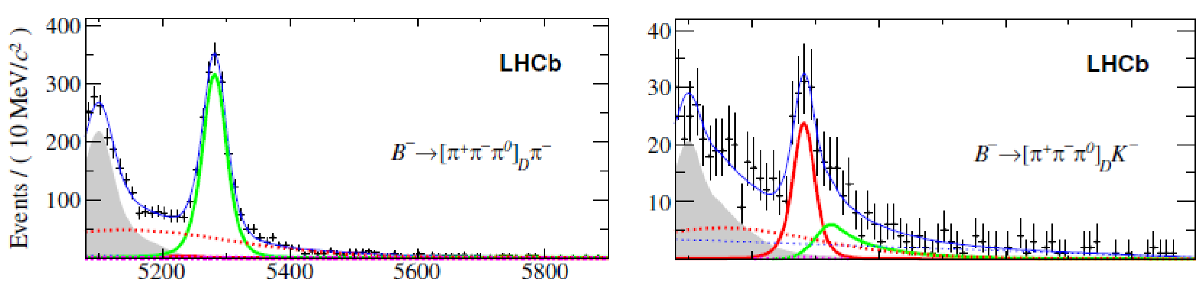


[PRD 91 (2015) 112014]

LHCb: current precision on γ and future prospects

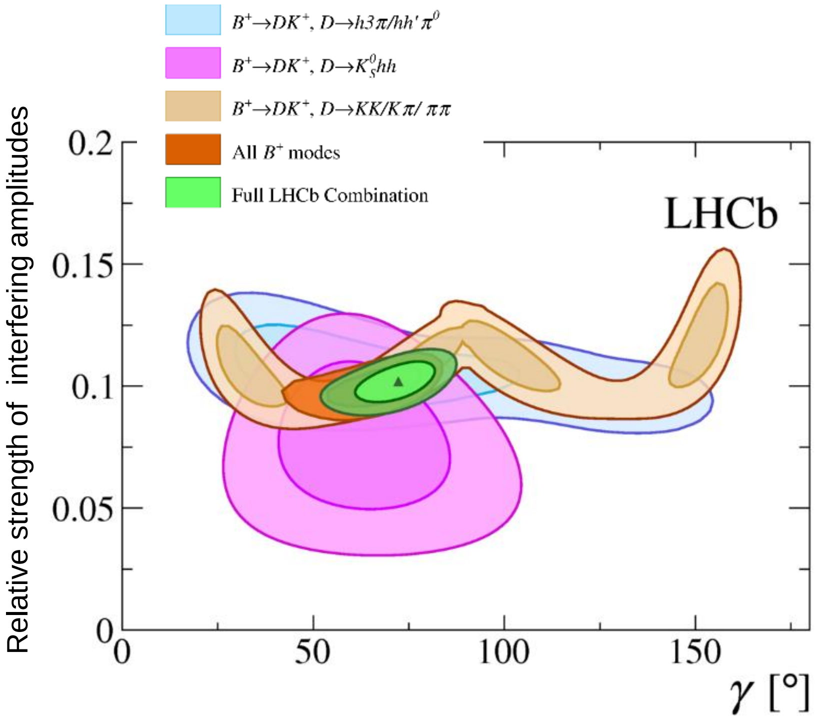
Combination of LHCb *B→DK* results obtained so far

$$\gamma = (72.2\,^{+6.8}_{-7.3})^\circ$$

Uncertainty significantly better than that obtained with combined B-factory results.

Agrees with prediction * from rest of triangle

$$\gamma^{\text{indirect}} = (65.3^{+1.0}_{-2.5})^\circ$$

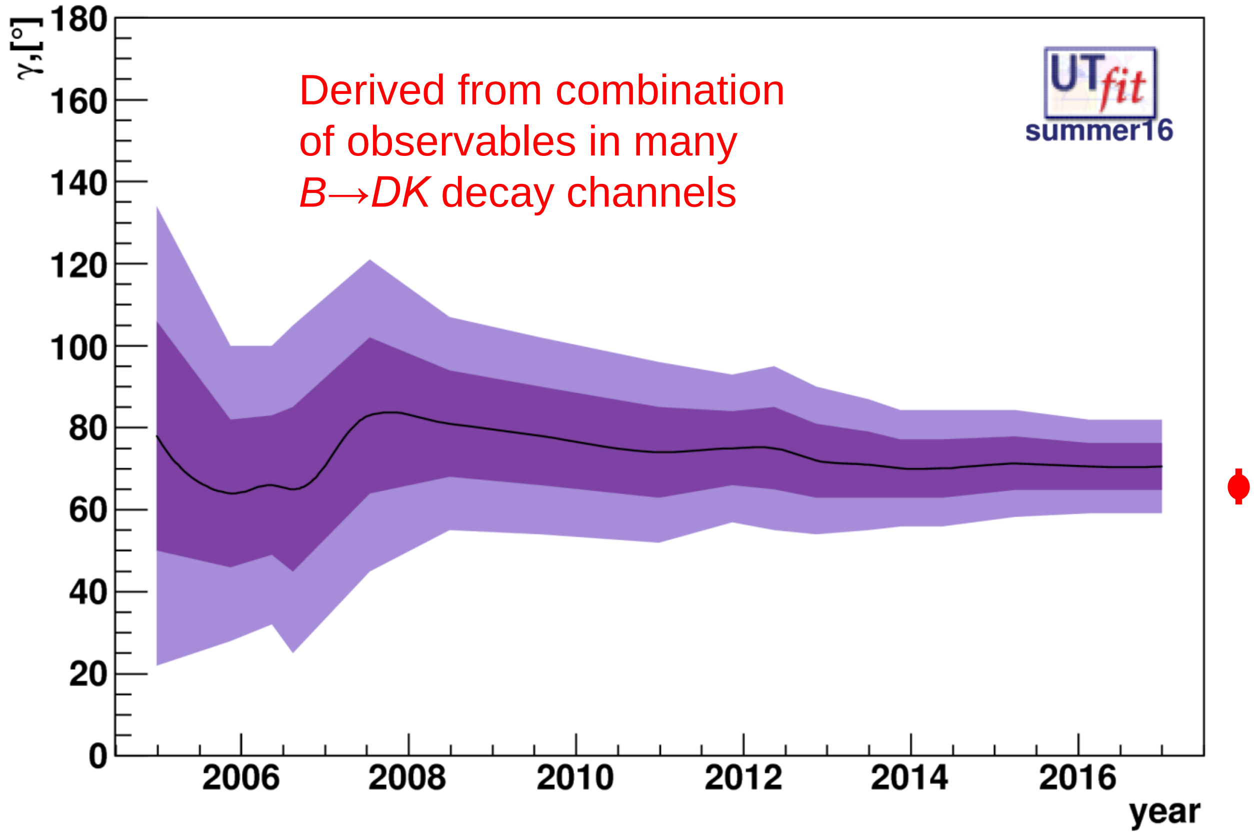


[JHEP 12 (2016) 087]

* CKMfitter, summer 2016

γ measurement – the last ~10 years

The story so far...



Consistent with the indirect prediction...

...but not nearly as precise

Indirect prediction from rest of triangle

...factor 3 improvement in 10 years.

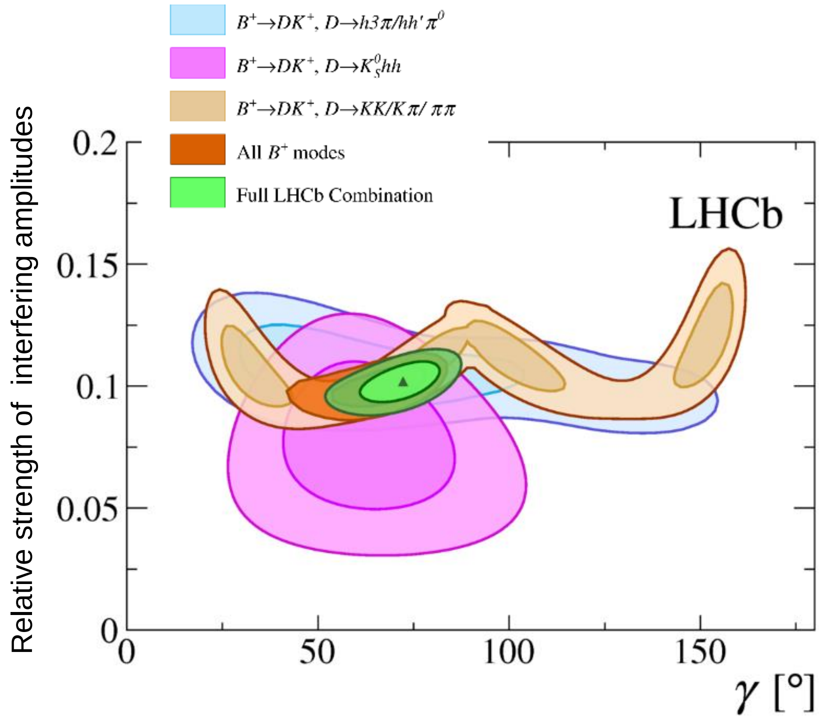
LHCb: current precision on γ and future prospects

Combination of LHCb $B \to DK$ results obtained so far

$$\gamma = (72.2\,^{+6.8}_{-7.3})^\circ$$

Uncertainty significantly better than that obtained with combined B-factory results.

Agrees with prediction * from rest of triangle $\gamma^{\text{indirect}} = (65.3^{+1.0}_{-2.5})^\circ$



[JHEP 12 (2016) 087]

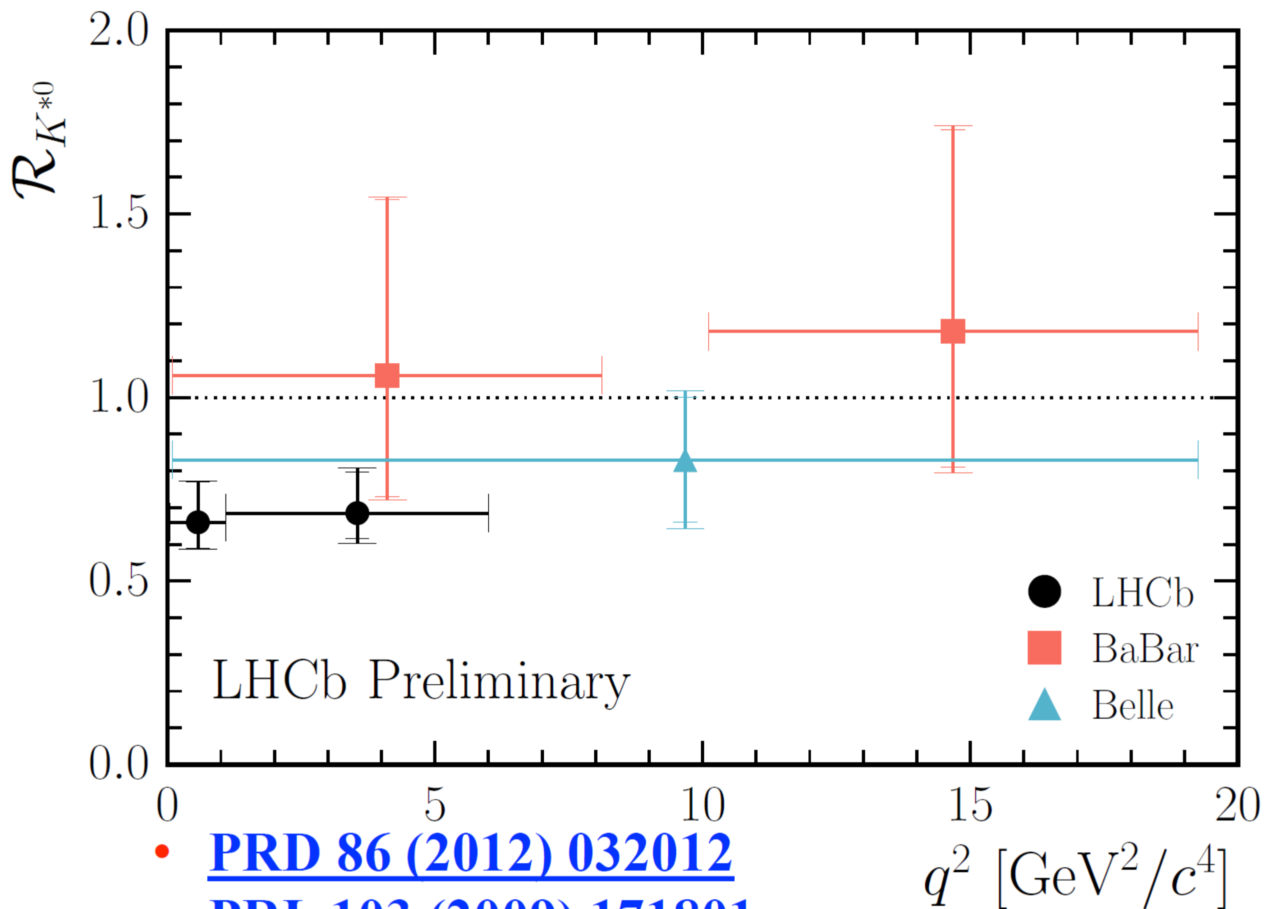
Will improve steadily:

- still several important run 1 modes to be published (*e.g.* 3 fb^{-1} $B_s \to D_s K$)
- repeat with much larger data set being collected in run 2.

Aim for ~ 3-4° uncertainty after run 2 to match current indirect precision. The LHCb Upgrade (see later) will allow for even higher sensitivity (~1°). Ditto Belle II.

* CKMfitter, summer 2016

All measurements: R_{K*}



- [PRD 86 (2012) 032012](#)
- [PRL 103 (2009) 171801](#)

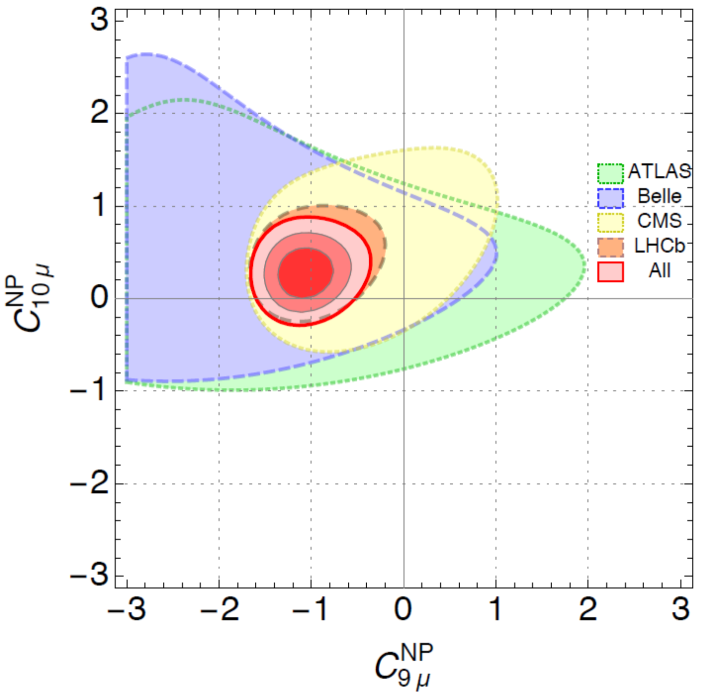
$B^0 \to K^* l^+ l^-$ and friends: what does it all mean ?

Already much theoretical interest in $b \to (s,d) l^+ l^-$ 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 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*.

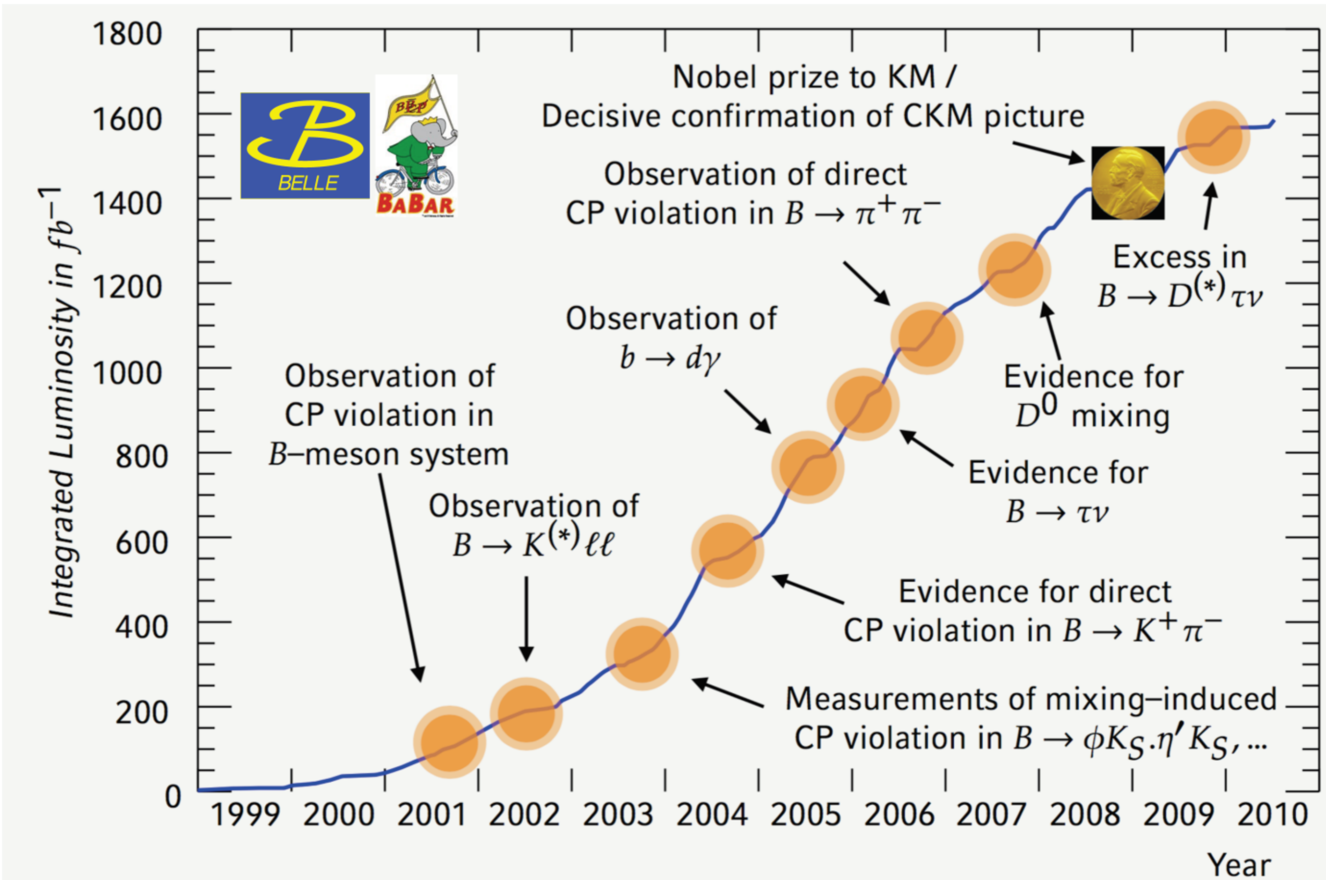


The experimentalist's view:

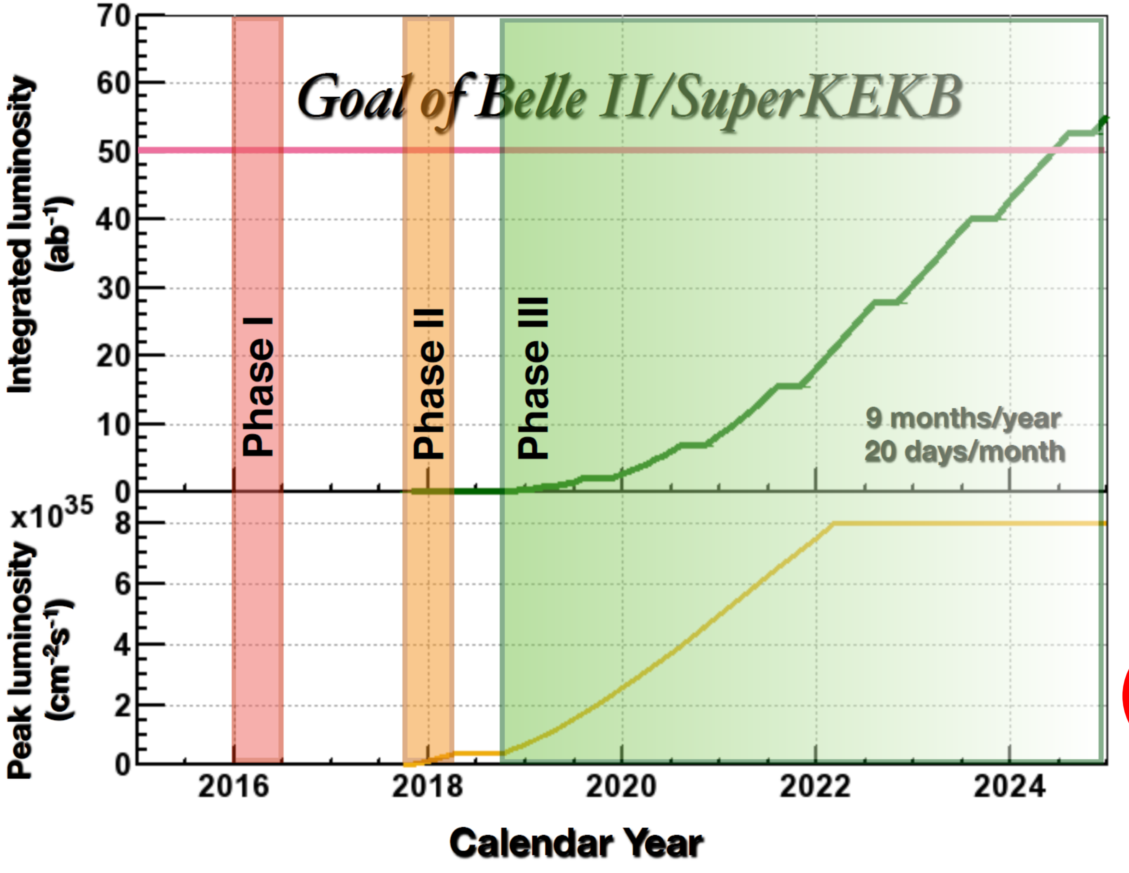
- Hypotheses non fingo !
- Recall, for several of observables there is no consensus on the theory errors.
- Excitement premature: we should wait until we see highly significant deviations in one or more LFU observables. Wait for run-2 updates on R_K, R_{K^*} & indeed R_φ.

Why Belle II ?

BaBar & Belle were astonishingly successful experiments. Most importantly, they demonstrated that CKM mechanism drives CP violation (at least at 1st order).



SuperKEKB and Belle II roadmap



Phase 1 (completed)

- Circulate beams (no collisions)
- Tune optics *etc.*

Phase 2 (2017-2018)

- First collisions
- Physics run, without vertex detector

Phase 3 (2018-)

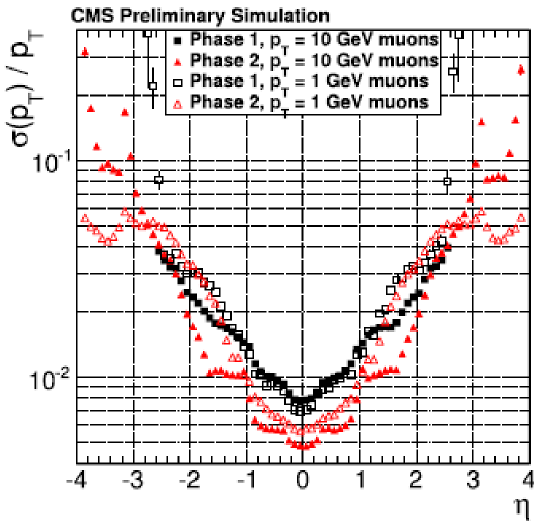
- Physics run with full Belle II

GPD phase-II Upgrades (LS3)

In run 1 ATLAS and CMS have already made high quality B-physics measurements in modes with di-muon final states.

New capabilities of GPDs after Phase-II Upgrade (CMS in particular) will strengthen their capabilities in flavour physics

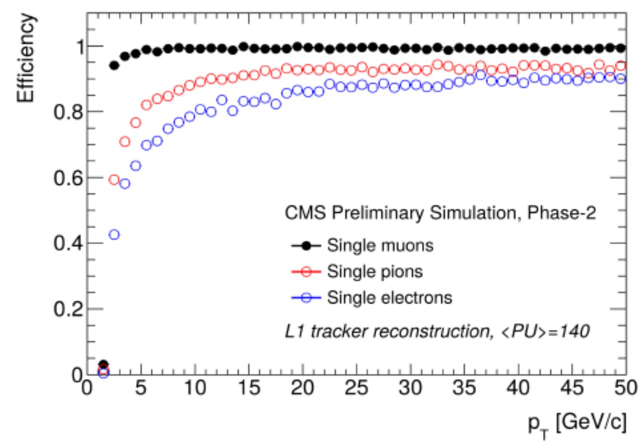
e.g. new CMS tracker



Jeremiah Mans, ECFA HL LHC, Aix-les-Bains, Oct 2014

Significantly improved p resolution

e.g. CMS new L1 track trigger



Anders Ryd, ECFA HL LHC, Aix-les-Bains, Oct 2014

Could allow CMS to accumulate large samples even in hadronic modes!