The age of flavour

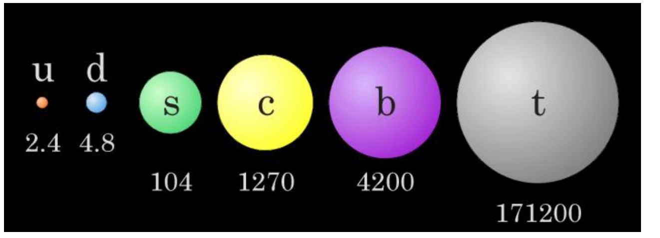
- Why study flavour physics ?
- 2001: dawn of the age of flavour
- Four (ongoing) achievements of the age of flavour
- The future of flavour physics

Guy Wilkinson
University of Oxford
Beijing seminar, July 2019

Why flavour ?

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

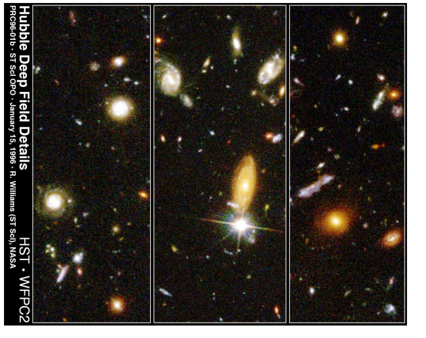
- Why 3 generations of quarks, and
  why the extreme hierarchy of masses ?



- What determines the hierarchical structure of the CKM matrix ?

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

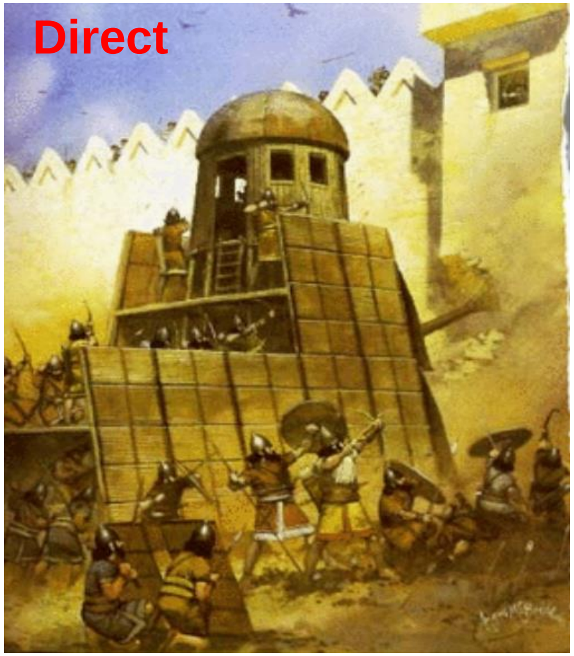
- The CKM paradigm accommodates CP violation,
  but it does not really explain it. Furthermore, can
  the study of quark flavour tell us anything about
  the matter-antimatter asymmetry of the universe ?



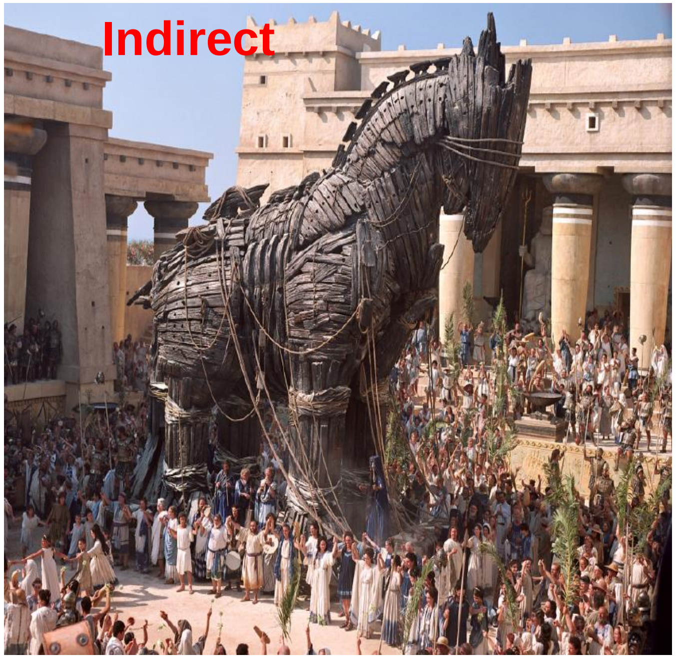
Most importantly, flavour physics is a tool of discovery !

Breaching the walls of the Standard Model

The HEP community is searching for 'New Physics' - to find this we need to penetrate the walls of the Standard Model fortress. There are two strategies used in this search.



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

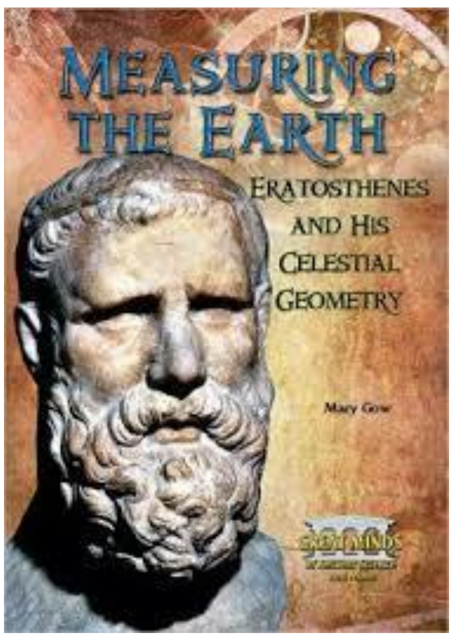


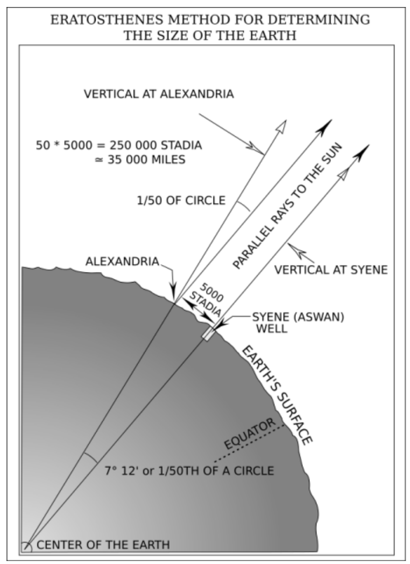
Make precise measurements of processes in which New Physics particles enter through 'virtual loops'

Both methods are powerful. Flavour physics follows 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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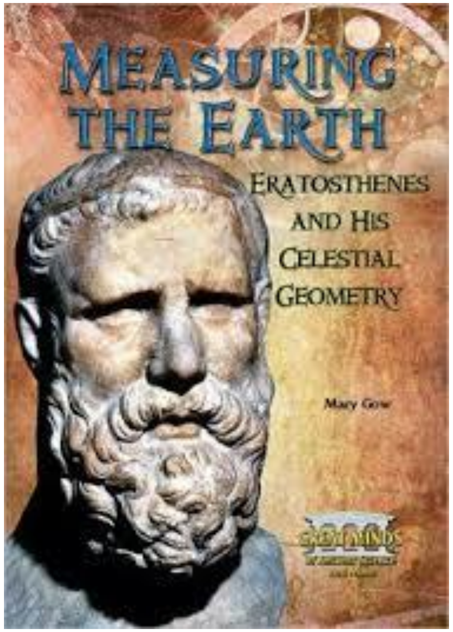
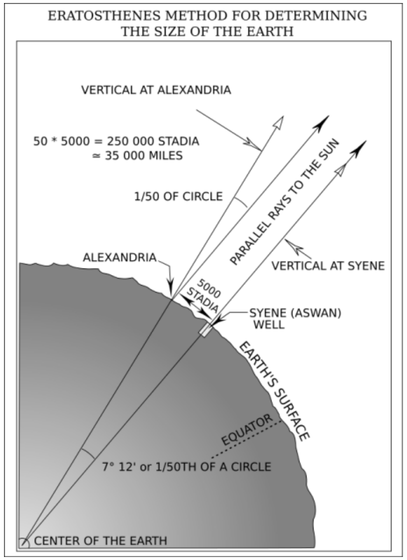
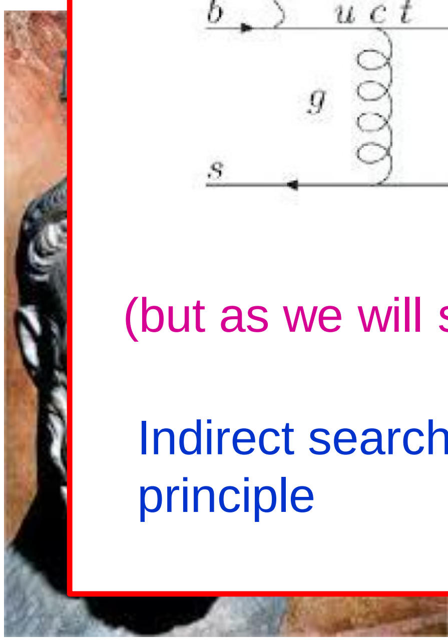


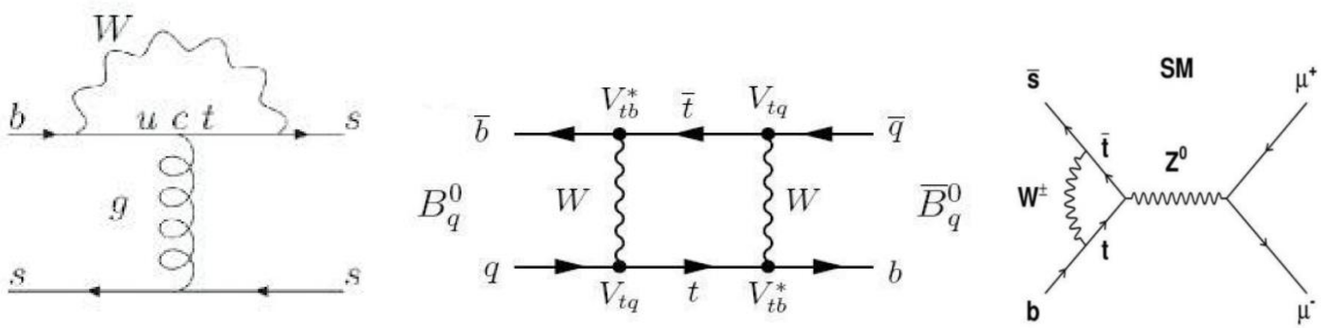


…around 2.2 thousand years prior to the direct observation.

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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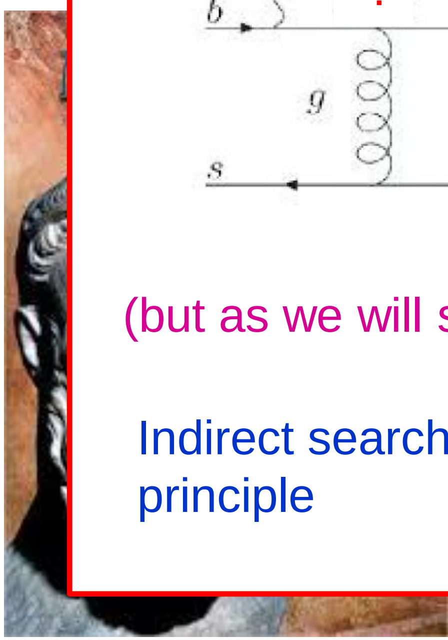

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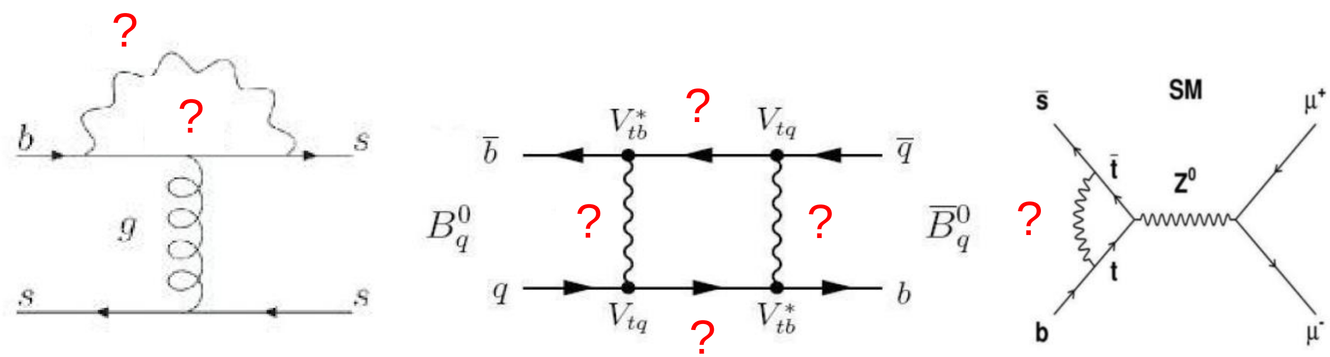

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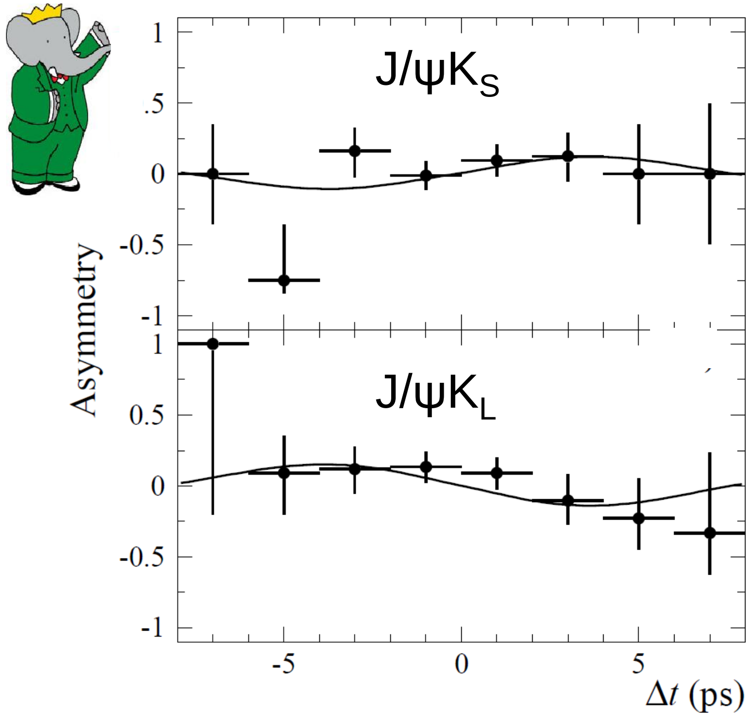
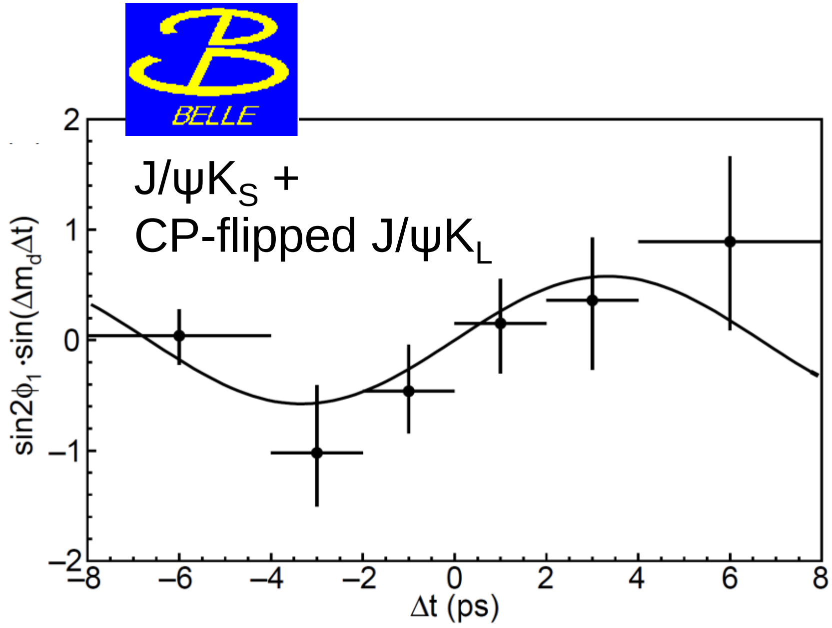
2001 - dawn of age of flavour

2008 Nobel Prize

We can date the dawn of the ‘age of flavour’ to the 2001 measurements of the CP-violating asymmetry in $B^0 \to J/\psi K^0$ decays that give unitarity triangle angle β (or φ_1).



[BaBar, PRL 86 (2001) 2515]



[Belle, PRL 86 (2001) 2509]

These studies, when improved with larger samples, confirmed the CKM paradigm as the dominant mechanism of CP violation in nature (→2008 Nobel Prize), and also opened up a rich and wide spectrum of complementary measurements.

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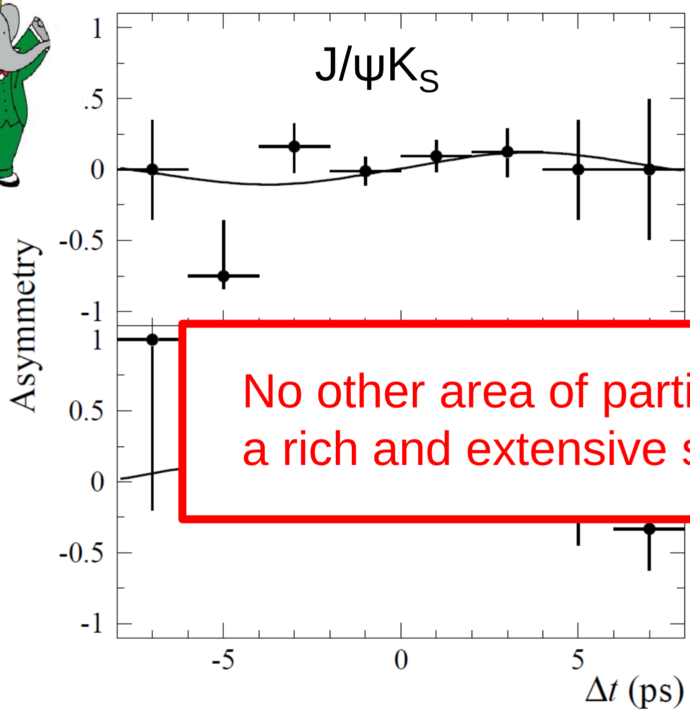

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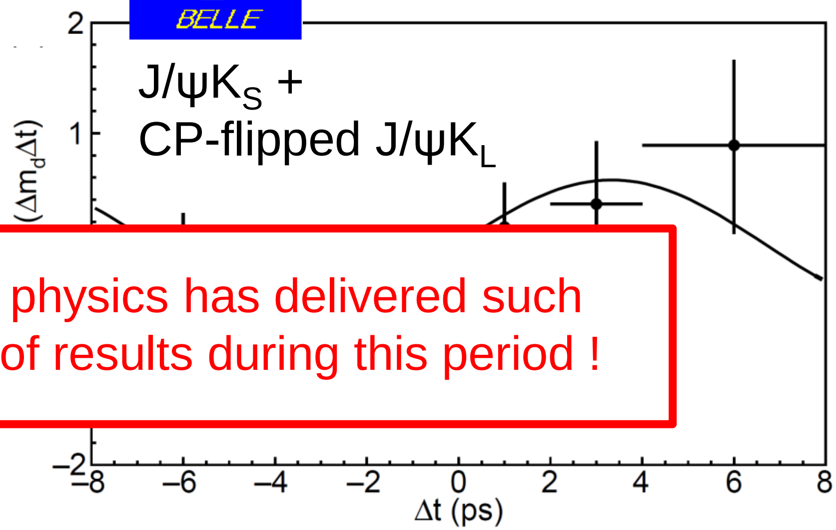

[Belle, PRL 86 (2001) 2509]

No other area of particle physics has delivered such a rich and extensive set of results during this period !

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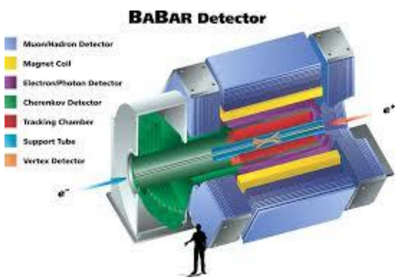
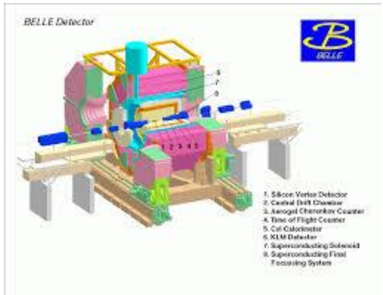
Heroes of the age of flavour

b-factories

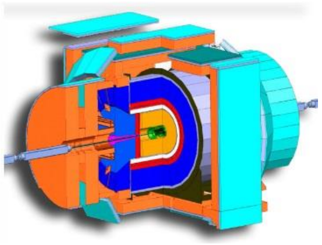


BaBar (SLAC) & Belle (KEK)

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.

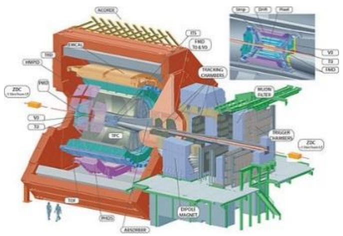


Tevatron experiments



CDF & D0

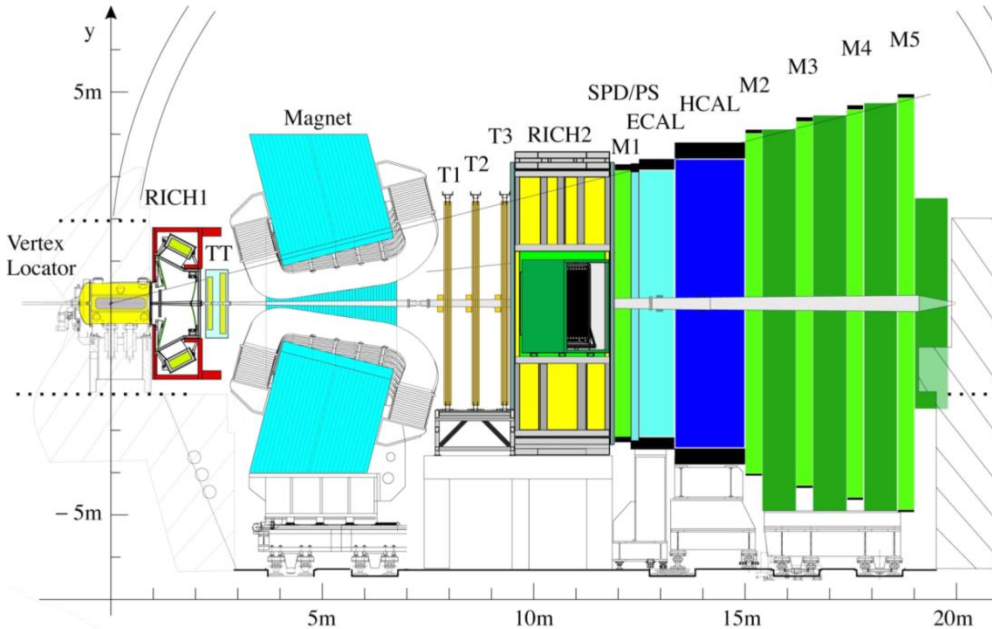
Tevatrons 'general purpose detectors'.
Pioneered *b*-physics in hadronic collisions.
Important early B_s and b-baryon studies.

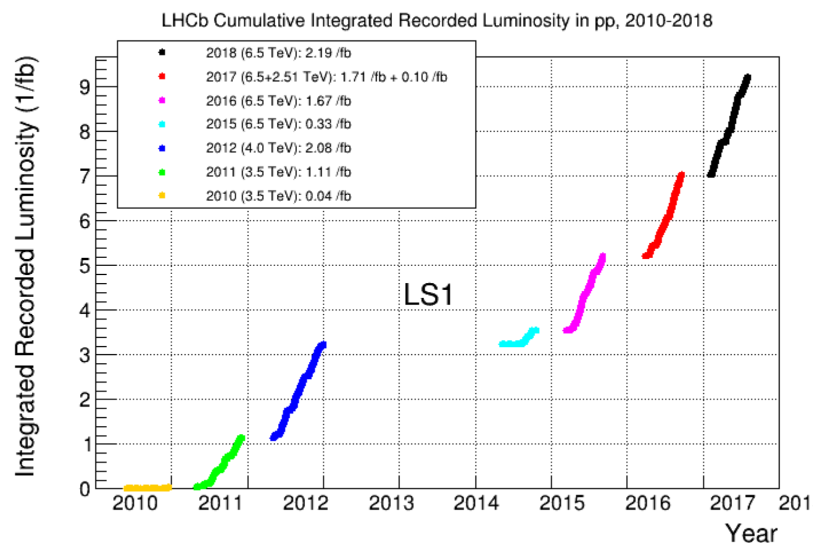


ATLAS & CMS

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

Heroes of the age of flavour - LHCb





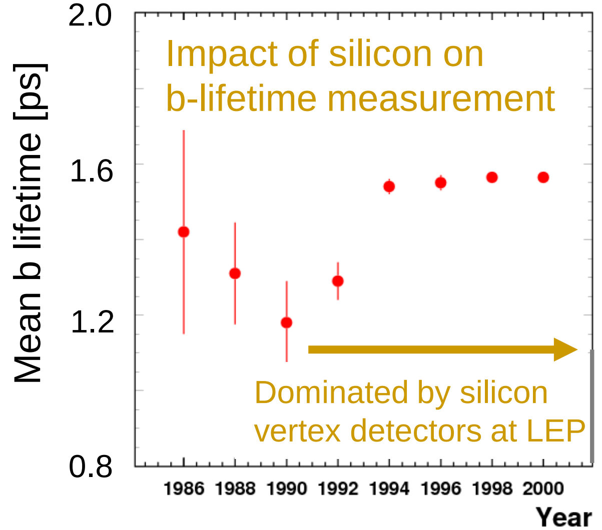
80 institutes from 18 countries, including 7 from China

Note, that majority of Run 2 data are still to be analysed for most measurements

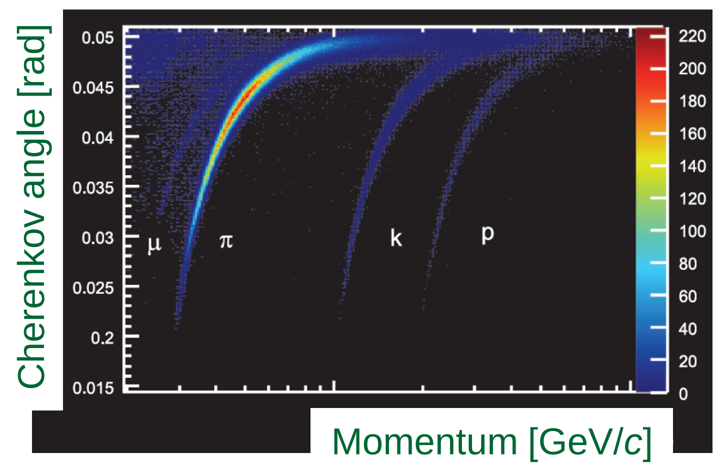
Why have we made progress?

Important flavour-physics measurements were performed prior to 2001 (*e.g.* at ARGUS, CLEO, the SPS and LEP), but since then there has been an avalanche of results. What has enabled this explosion of progress?

- High-luminosity accelerators with large bbbar production cross-sections;
  - Number of b-hadrons produced at LEP ~ 10^7
  - Number of b-hadrons produced (so far) at LHCb ~ 10^{12}
- Improved and dedicated instrumentation, *e.g.* vertex detectors and RICHes;



Cherenkov angle vs momentum in LHCb RICH



- Improved triggering, essential for hadron collider experiments;
- And not forgetting progress in theory, in particular lattice QCD.

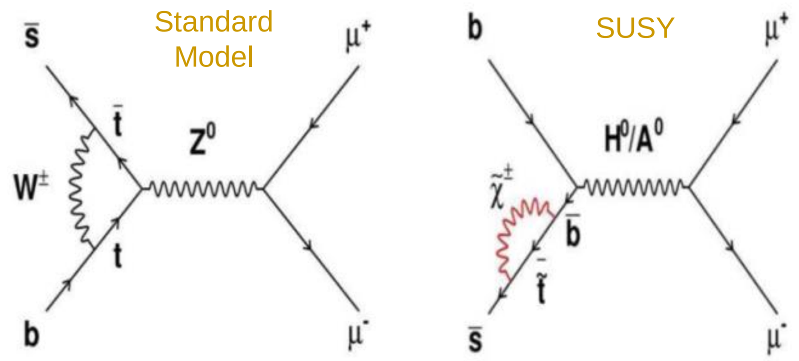
Four (selected) ongoing achievements from the age of flavour

- In search of the ultra-rare: $B_s \to \mu^+\mu^-$
- Electroweak penguins: $B^0 \to K^{(*)} l^+ l^-$ and friends
- The unitarity triangle: towards a precise measurement of the angle γ
- The charm renaissance

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

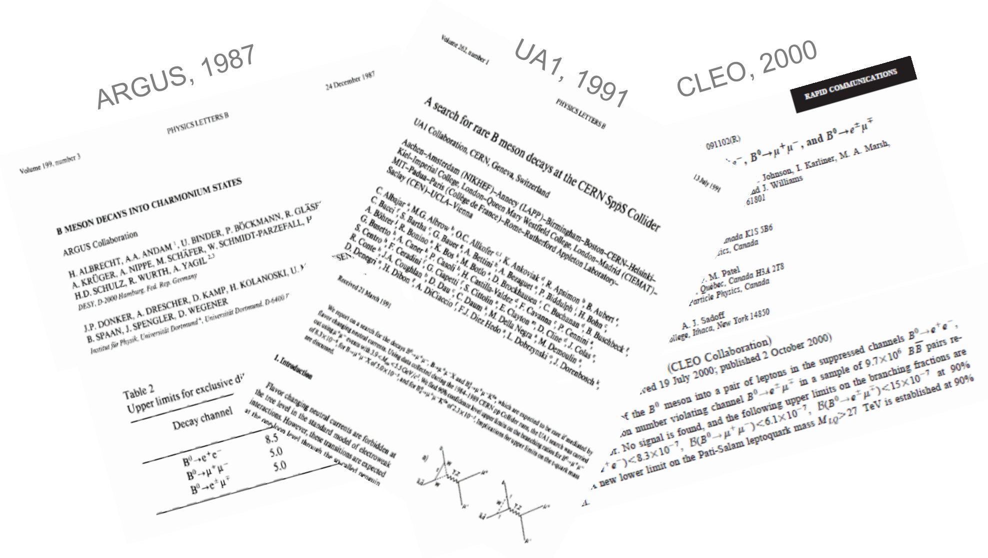
This decay mode can only proceed through suppressed loop diagrams.

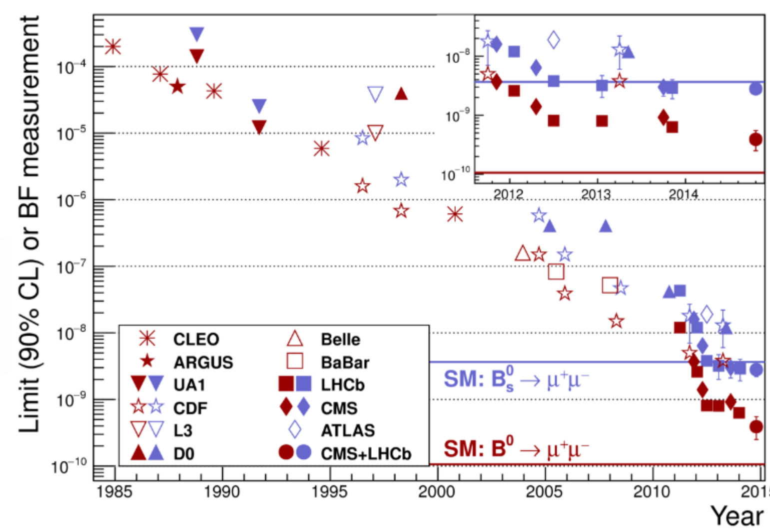
In the Standard Model it happens extremely rarely ($\sim 10^{-9}$), but the exact rate is very well predicted



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

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

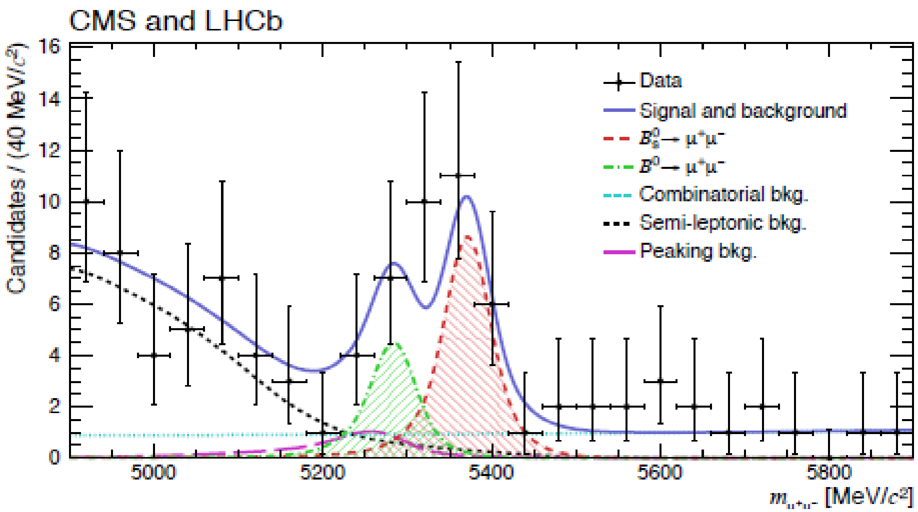


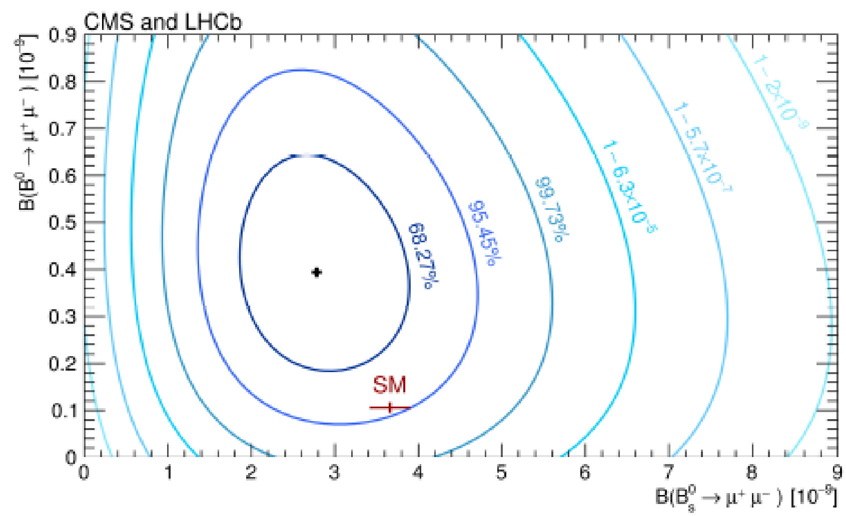


Before the LHC, Fermilab experiments were pushing the limits down towards 10^{-8}.

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…





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

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

[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 !

LHCb $B \rightarrow \mu^+\mu^-$ run 2 update

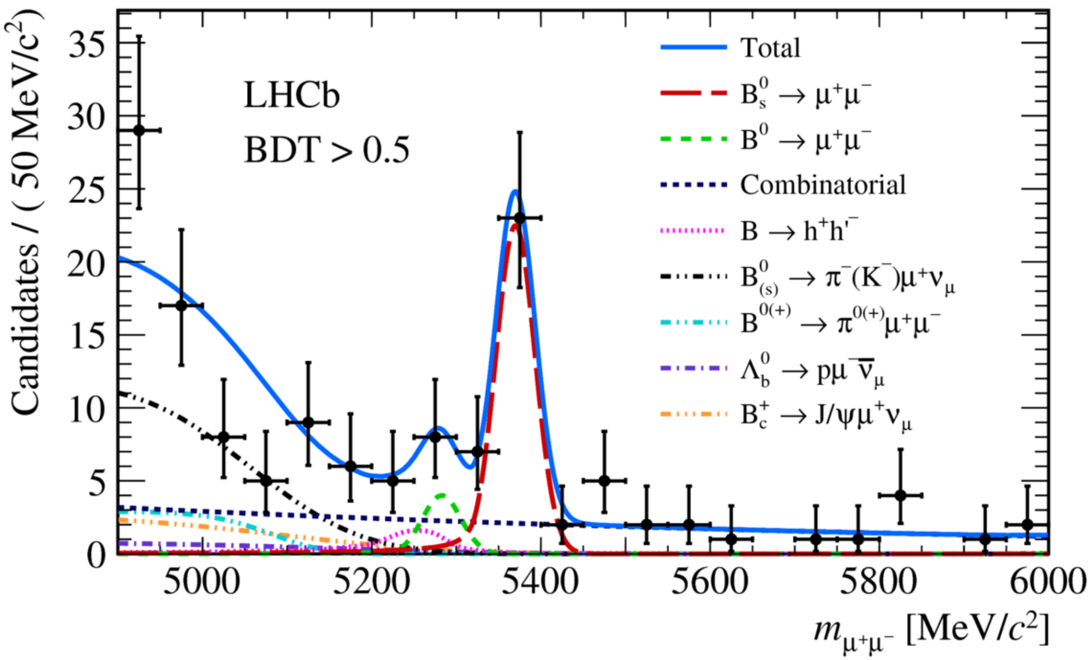
[PRL 118 (2017) 191801]

Early in Run 2 LHCb 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.



Uses only 1/4 of Run 2 data, so ‘legacy’ Run 1+2 result will be much more precise.

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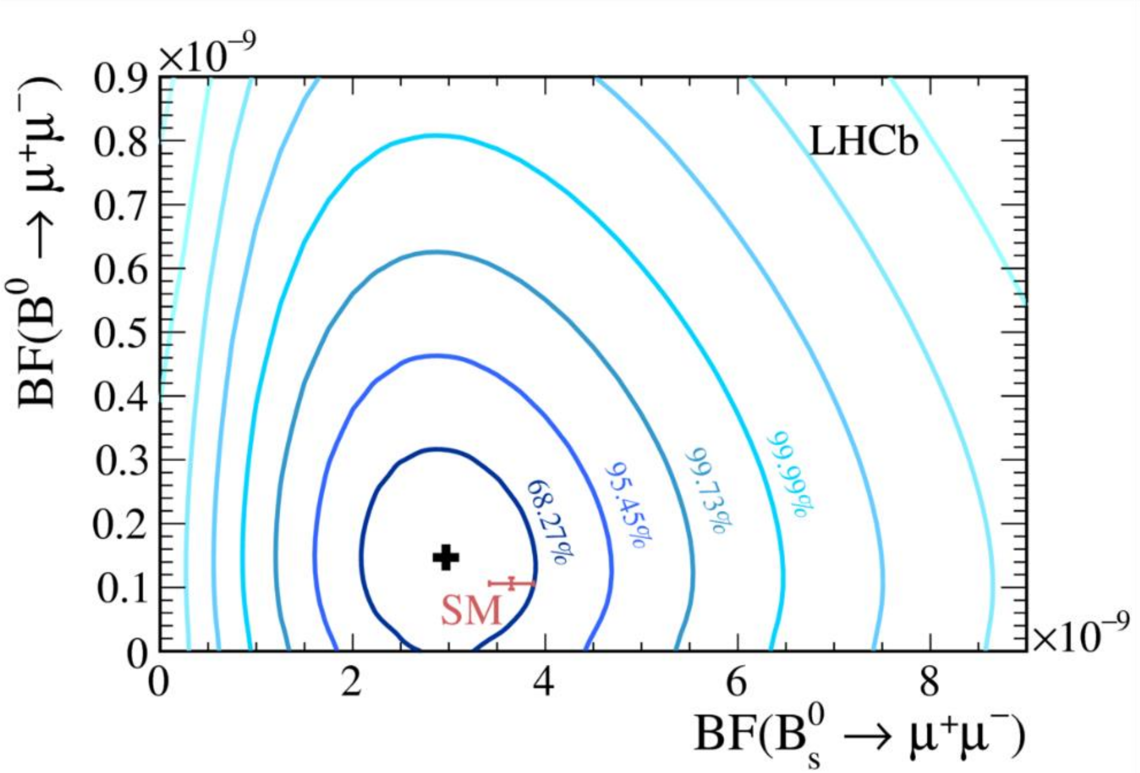

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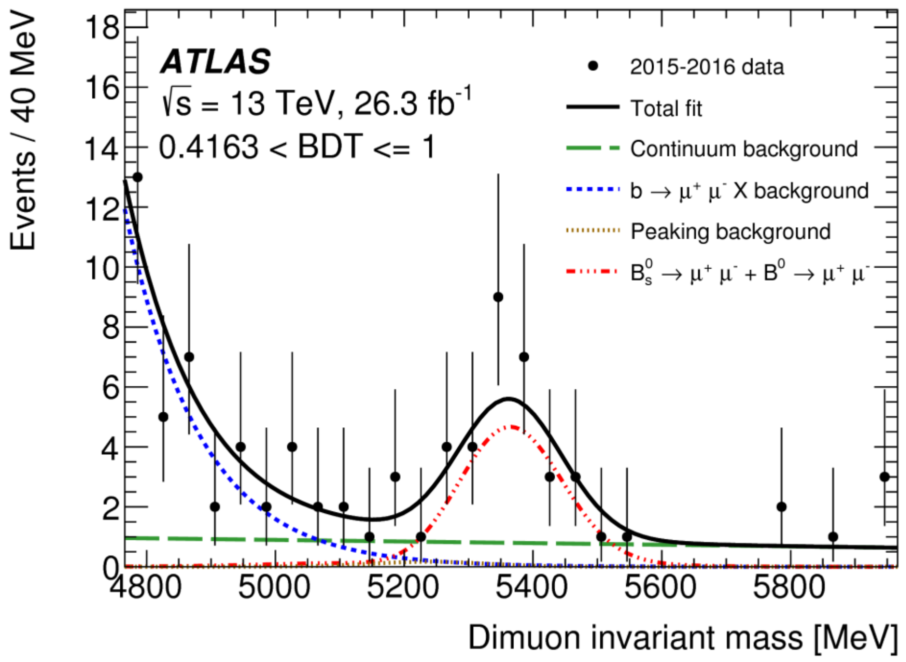
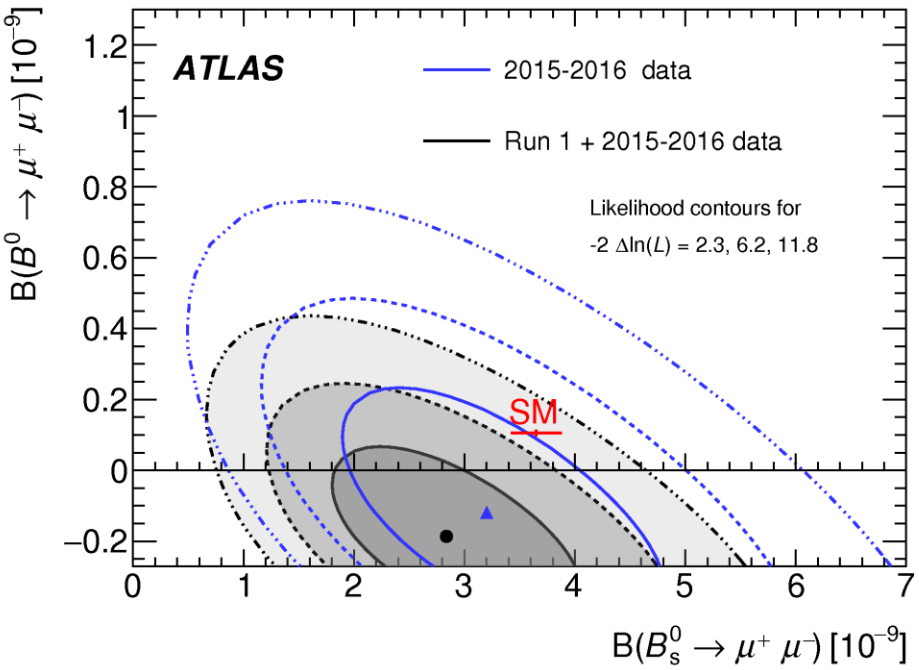
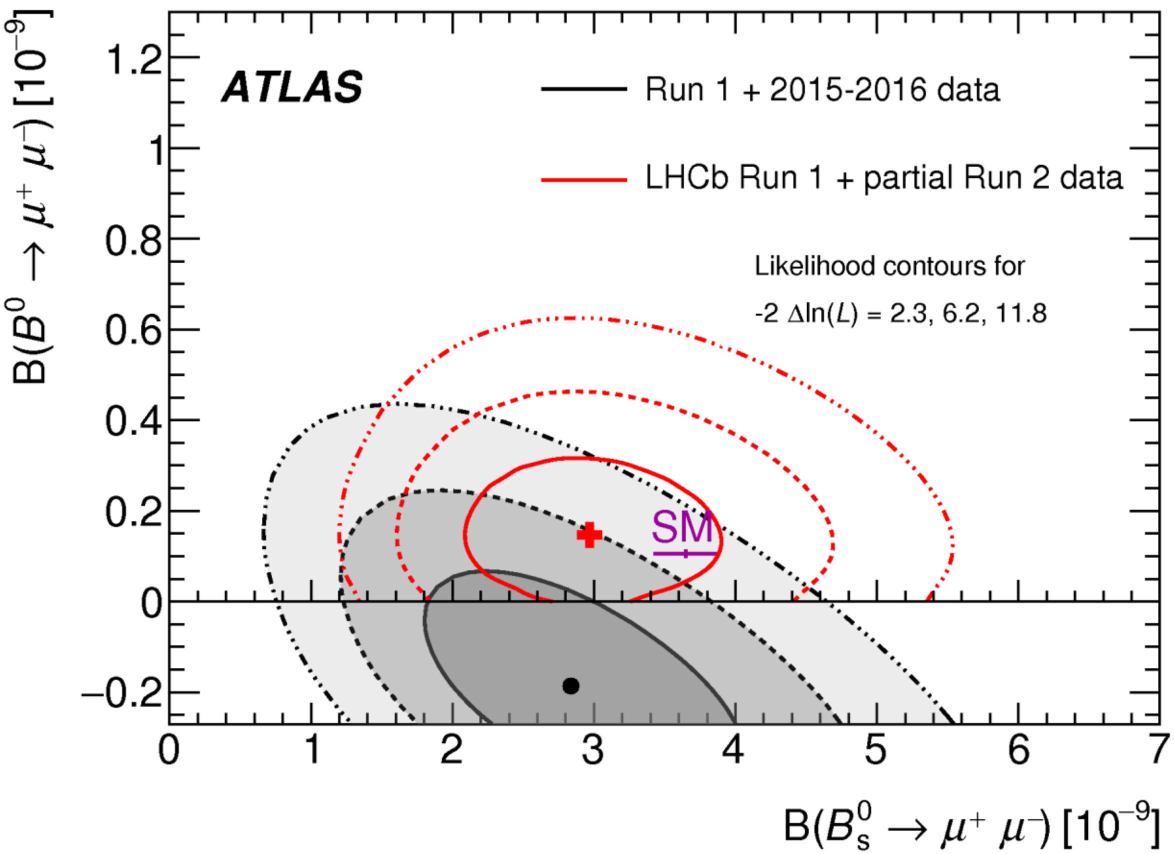
ATLAS joins the party !

With recent analysis of 2015-16 Run 2 data [JHEP 04 (2019) 098] ATLAS has joined club, & also sees a signal (although mass resolution does not permit a clean B_d, B_s separation). Can be combined with result of ATLAS Run 1 analysis [EPJC 76 (2016) 513].





Comparison of LHCb & ATLAS results



- Good consistency between data sets.
- We will have to wait a while for B_d signal.
- Compatibility with the SM predictions…

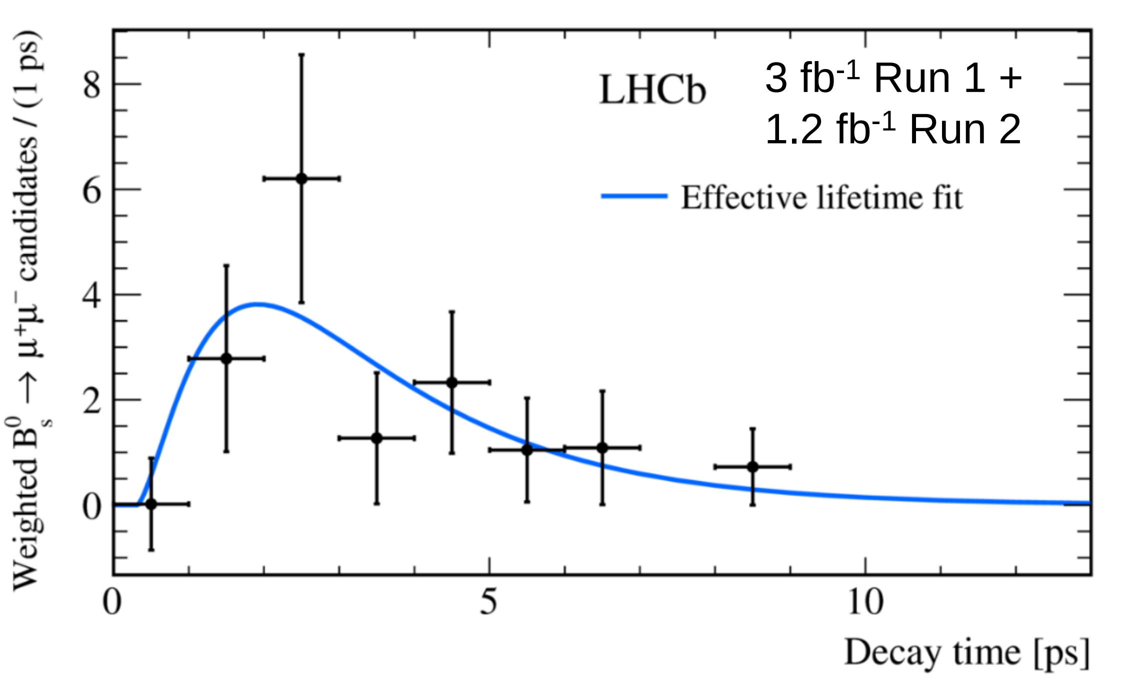
  …although optimists will say that the B_s result looks low.
- Eagerly wait for full Run 2 LHCb results, & new CMS results.
- Is it too much to ask that the 3 collaborations make a global average ?

Remember – the SM prediction is rather clean, and so improved measurements throughout the lifetime of the LHC are *very* valuable, particularly of the theoretically pristine ratio $BR(B_s \to \mu\mu)/BR(B_d \to \mu\mu)$, which can be measured to better than 10%...

Unlocking new observables with $B_s \rightarrow \mu^+\mu^-$

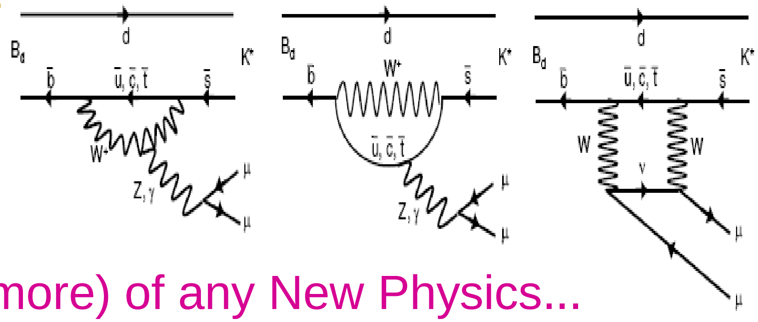
With very large data sets, we can plan on measuring new observables that bring complementary info. on any New Physics (particularly an extended scalar sector), *e.g.* CP-violating asymmetries or the *effective lifetime* [PRL 109 (2012) 041801] .

Proof-of-principle measurement of effective lifetime by LHCb [PRL 118 (2017) 191801] :



With LHCb Upgrade II it will be possible to measure effective lifetime to ~2%.

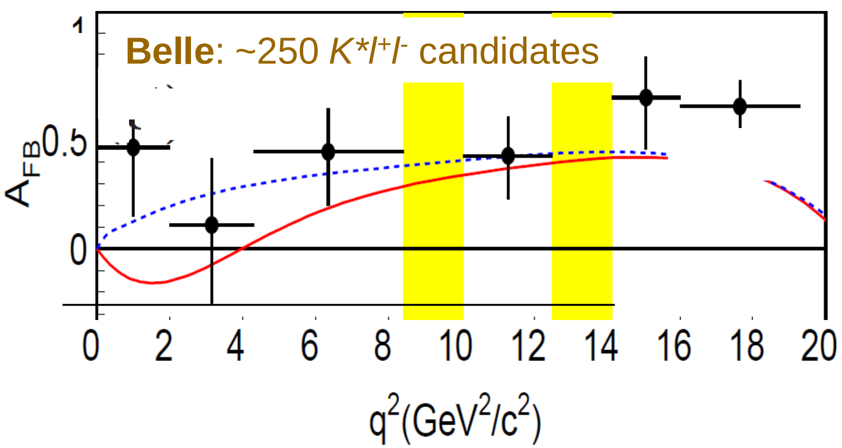
$B^0 \to K^* l^+ l^-$ and friends



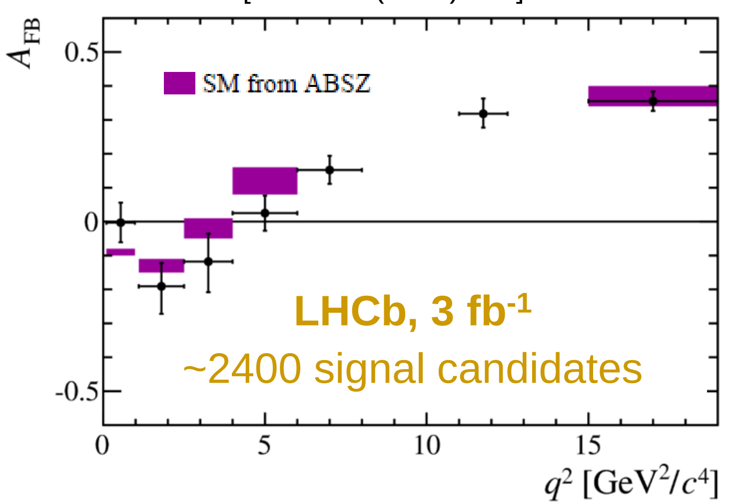
$b \to s l^+ l^-$ decays such as $B^0 \to K^* l^+ l^-$ offer many observables which probe helicity structure (& more) of any New Physics...

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)^2.

[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' ".

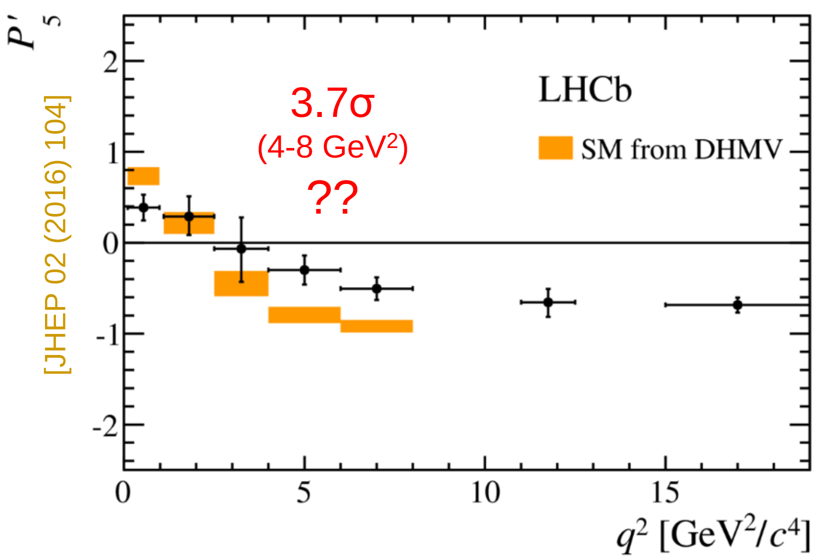
$B^0 \to K^* l^+ l^-$ and friends: the $P_5^{/}$ conundrum

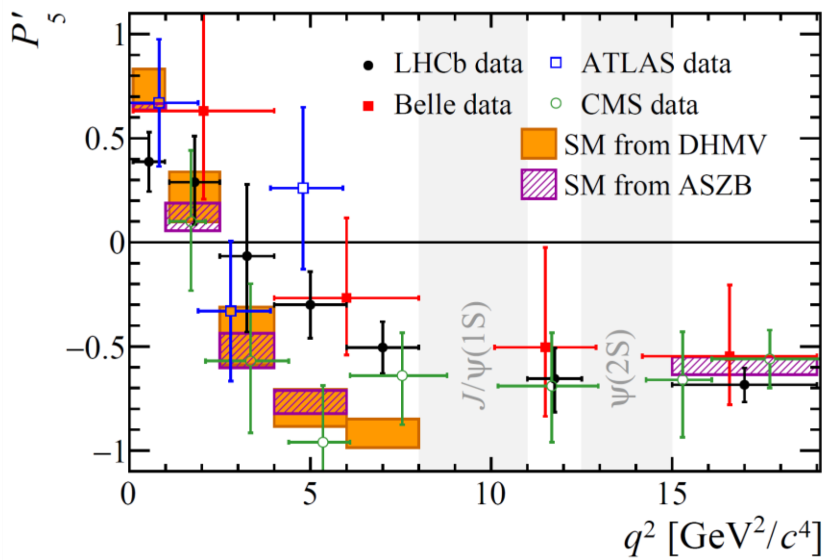
One such observable is $P_5^{/}$: What this describes physically is hard to visualise, but it is constructed from angular observables in a manner that is robust against form-factor uncertainties, and also easily relatable to the short-distance physics.

Interesting deviation at low q^2.

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

[JHEP 02 (2016) 104]





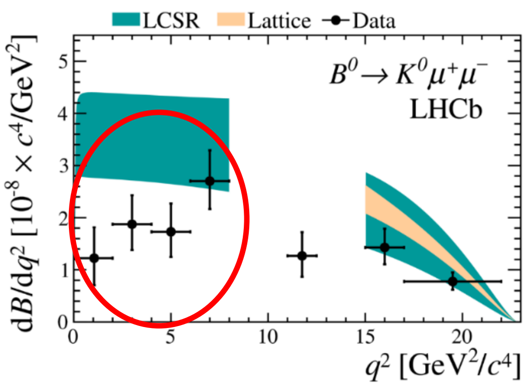
[ATLAS, JHEP 10 (2018) 047]
[CMS, PLB 781 (2018) 517]
[Belle, PRL 118 (2017) 111801]

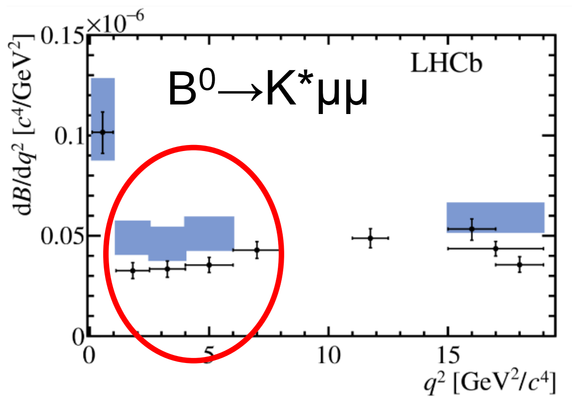
A word of caution. The SM uncertainties shown here are from one group. There are other values on the market, and some are more conservative.

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

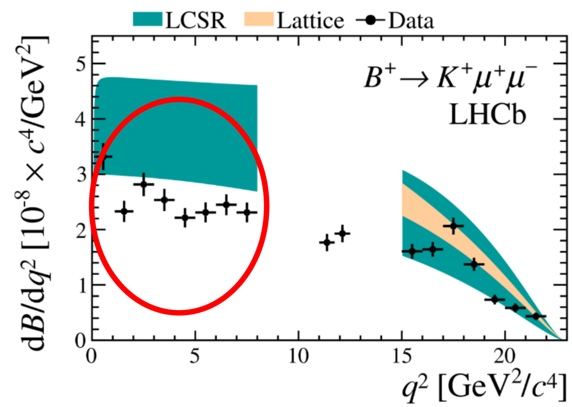
$P_5^{/}$ is not the only funny thing going on in $b \to (s,d) l^+ l^-$ decays.

[JHEP 06 (2014) 133]



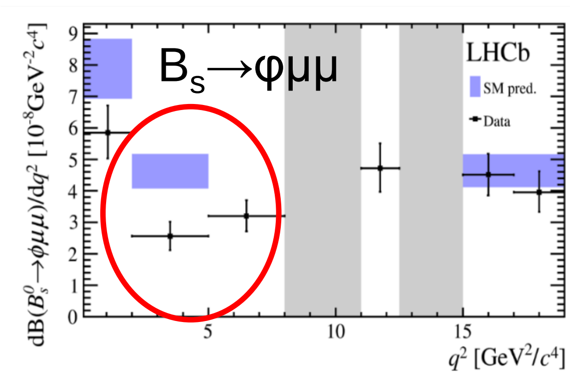


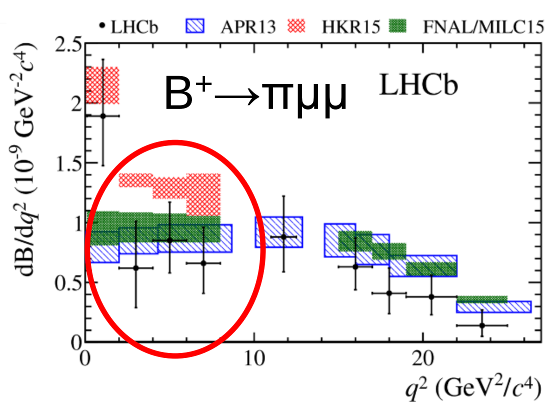
[JHEP 11 (2016) 047]



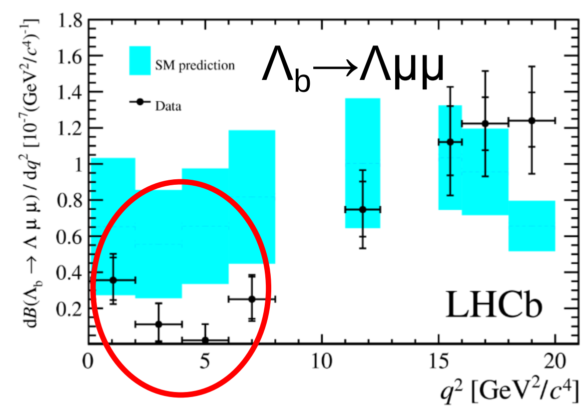
[JHEP 06 (2014) 133]

[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 ?

$B^0 \to K^* l^+ l^-$ 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.

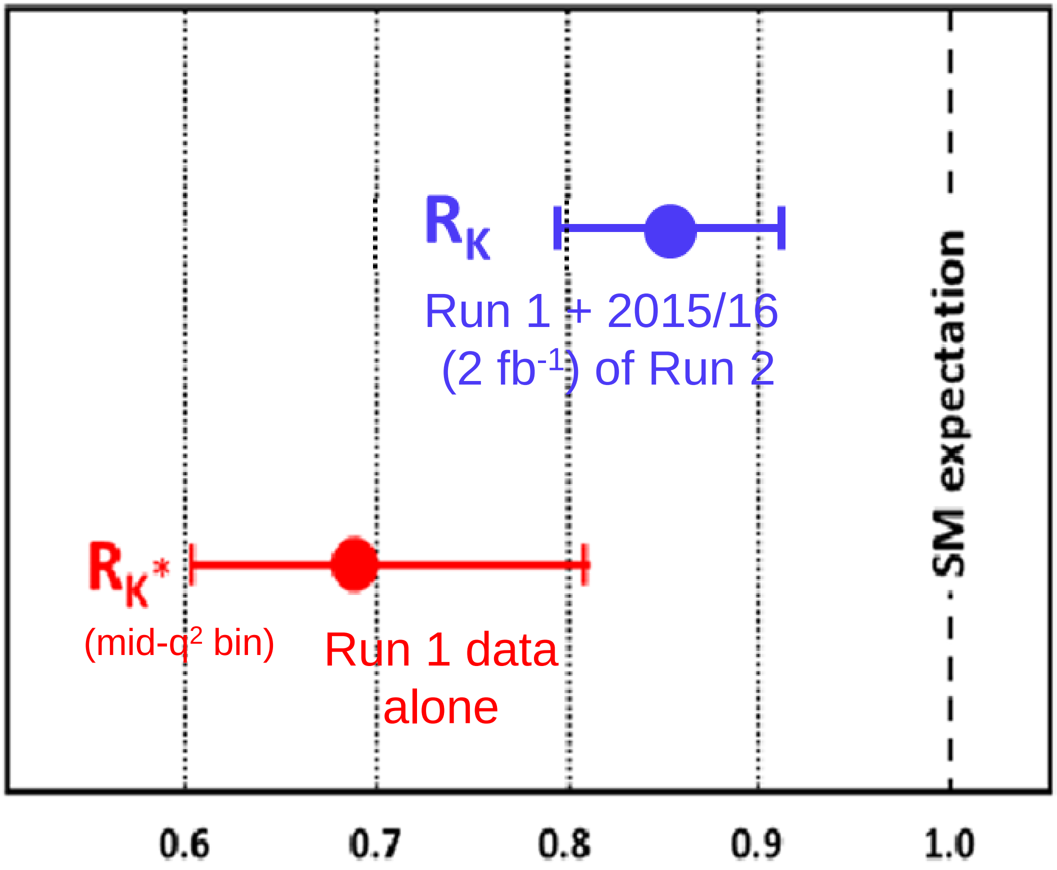
Ratios of decay rates have been measured for $b \to s\mu^+\mu^- / b \to se^+e^-$ for ~$1 < q^2 < 6$ GeV^2 for both $B \to Kl^+l^-$ (R_K) and $B^0 \to K^*l^+l^-$ (R_{K^*}). In SM we expect 1 for both.

$B^0 \to K^* l^+ l^-$ 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.

Ratios of decay rates have been measured for $b \to s\mu^+\mu^-/b \to se^+e^-$ for ~$1 < q^2 < 6$ GeV^2 for both $B \to Kl^+l^-$ (R_K) and $B^0 \to K^*l^+l^-$ (R_{K^*}). In SM we expect 1 for both.

In both cases measurements are ~2.5 σ below SM !



[PRL 122 (2019) 191801] [JHEP 08 (2017) 055]:

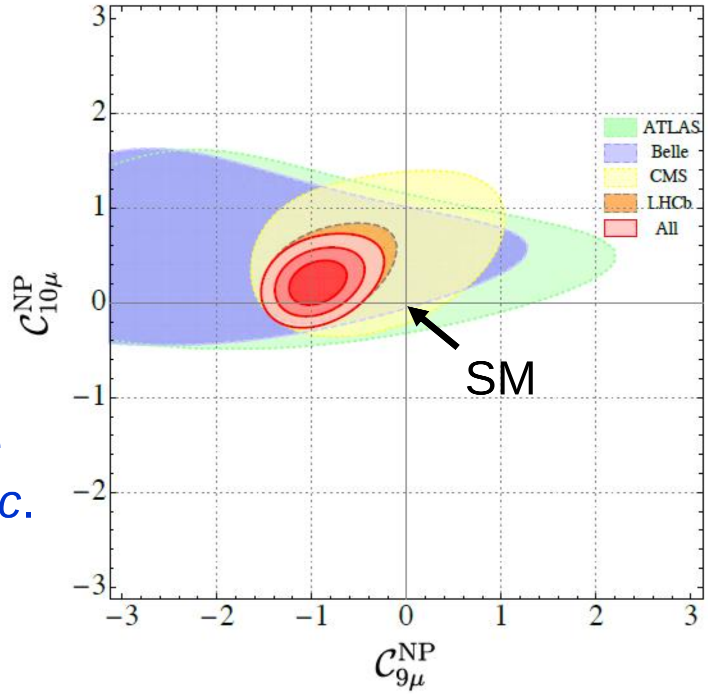
$B^0 \to K^* l^+ l^-$ and friends: what does it all mean ?

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:1903.09578].
These fits can give >5σ pulls w.r.t. SM, & have led to excited discussion of Z's, leptoquarks *etc*.



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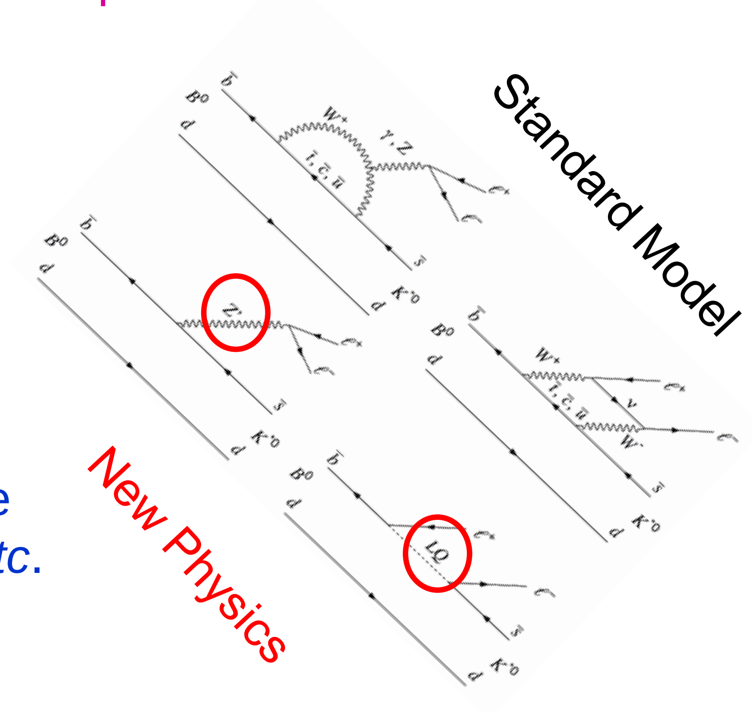


The experimentalist's view:

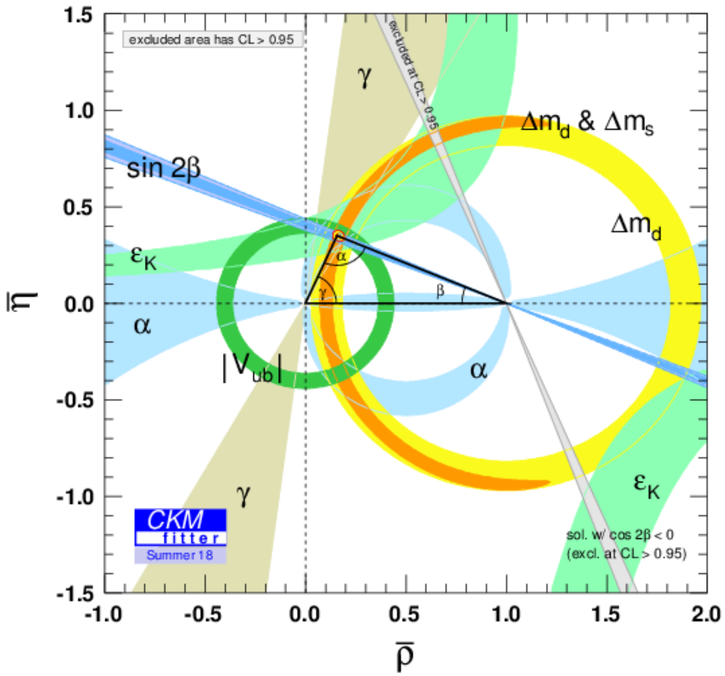
- Hypotheses non fingo !
- Recall, for several of observables there is no consensus on the theory errors.
- Excitement premature: we should wait until we see highly significant deviations in one or more LFU observables. Need more Run 2 updates on R_K, R_{K^*} & indeed R_φ.

The Unitarity Triangle

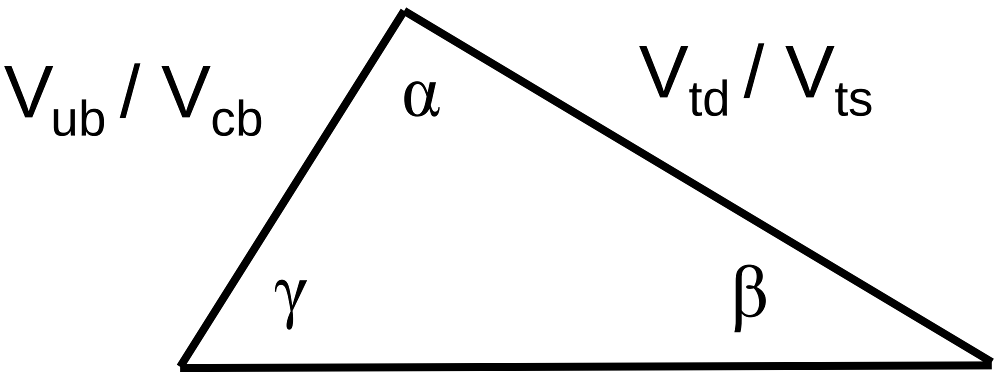
The Unitarity Triangle is a geometrical description of CP-violation within the context of the Standard Model, which in the flavour sector is the CKM mechanism.

We must check its consistency through precise measurements.

The B factories showed that the CKM paradigm dominates the picture (the first triumph of the 'age of flavour' !), but New Physics can still be lurking at ~20% level.



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



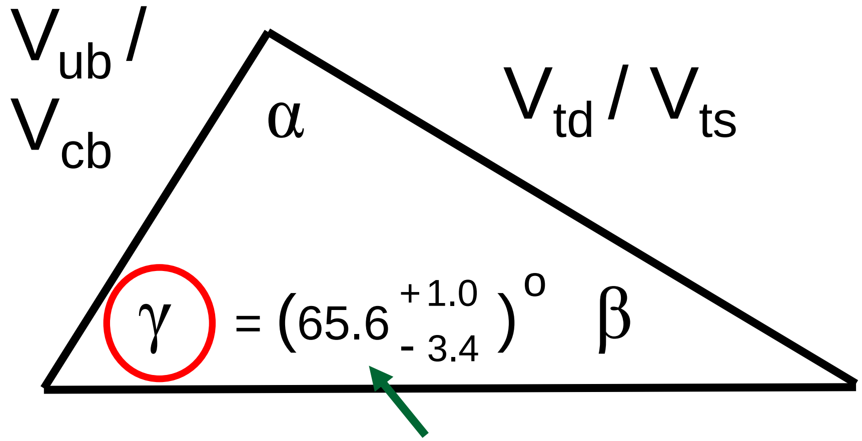
The Unitarity Triangle

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 2018] 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.

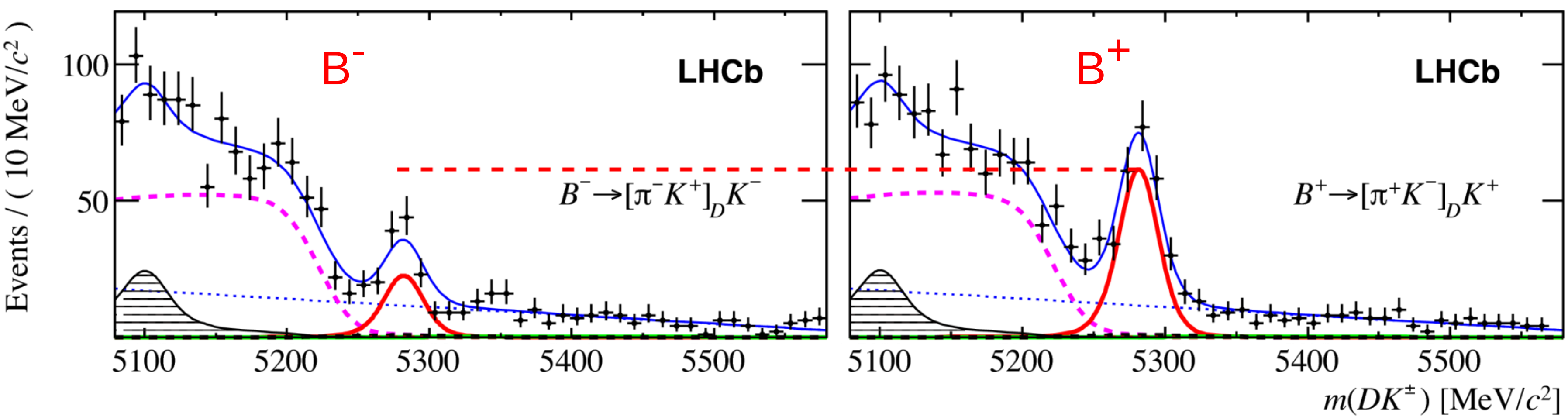
$B^- \rightarrow D^0 K^-$

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

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.



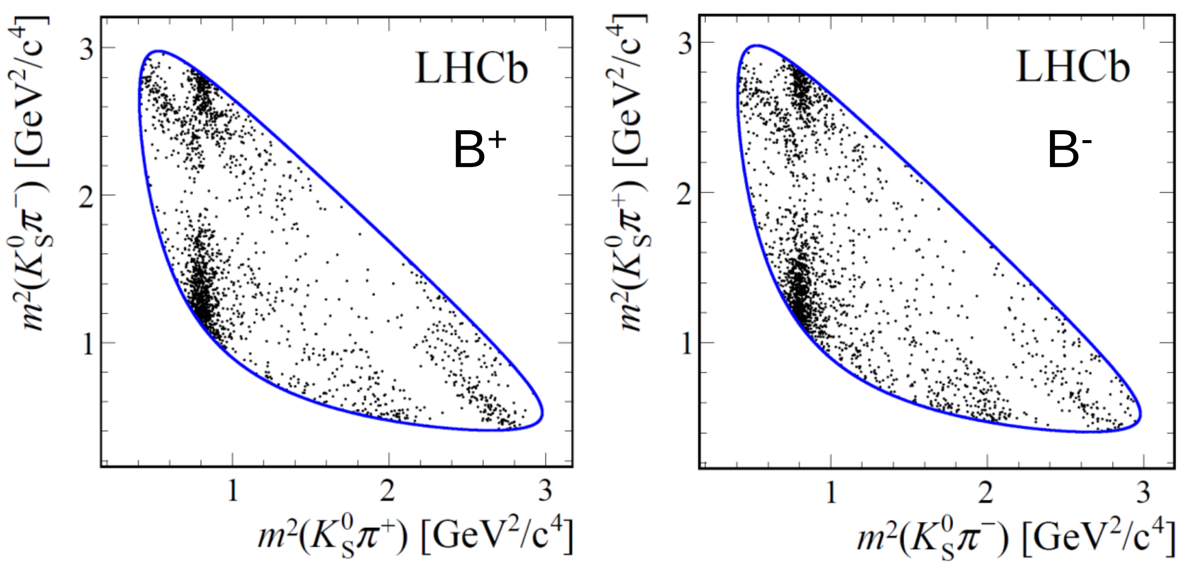
[PLB 760 (2016) 117]

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

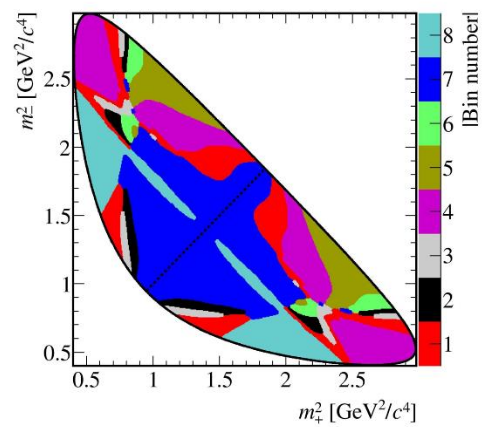
γ measurement at LHCb with B→DK decays: D→$K_S\pi\pi$ (and K_SKK) with Run 2 data [JHEP 08 (2018) 176]

A powerful sub-set of B→DK analyses is when the D decays into a multibody final state, of which $K_S\pi\pi$ is the most prominent example. Variation of D strong phase over Dalitz space leads to corresponding variation in interference and CP violation.

Analysis of ~3000 decays from 2 fb^{-1} of early Run 2 data



Study yields in bins of Dalitz space, chosen for optimal sensitivity.



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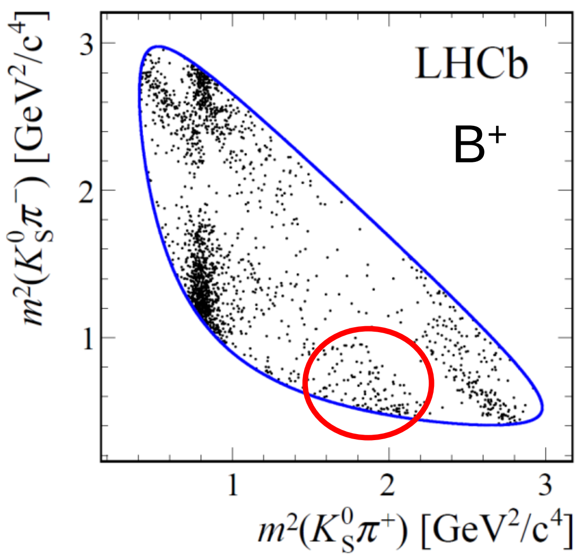

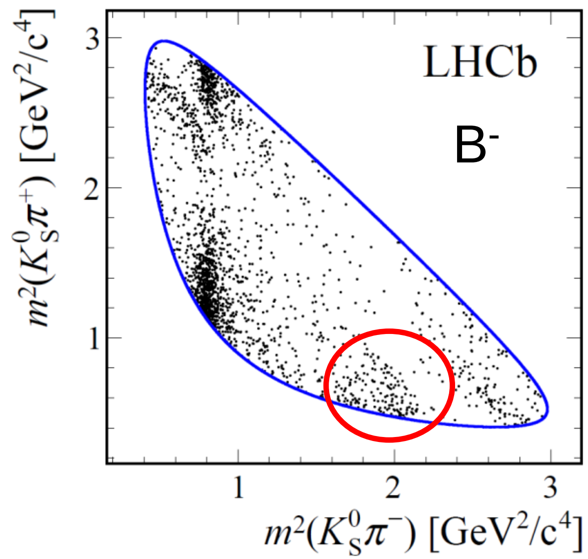

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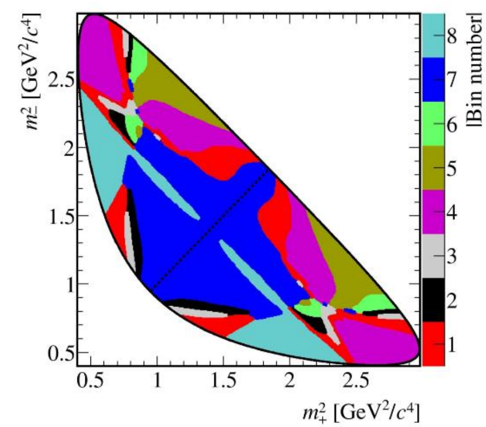
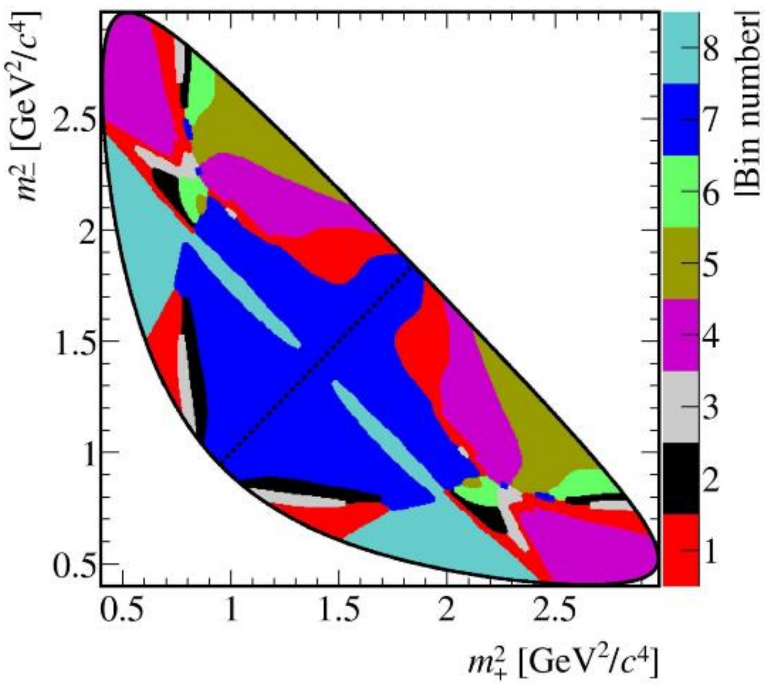


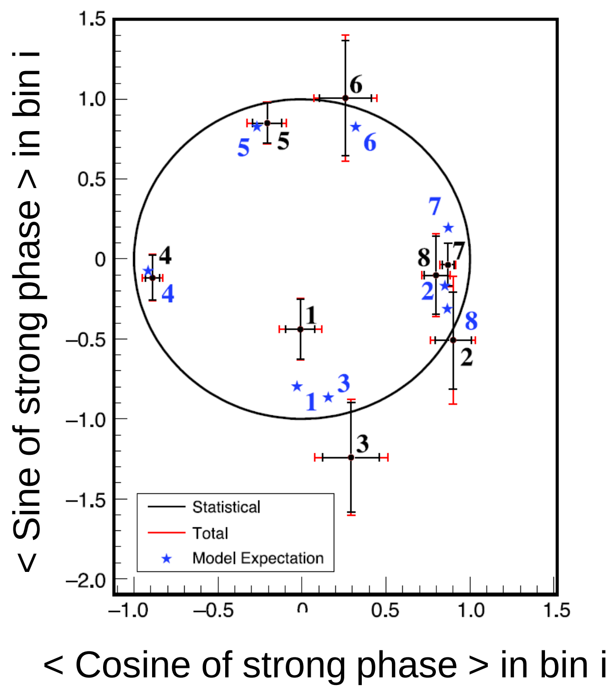
CP asymmetries visible by eye, but quantitative analysis requires external input...

Measuring γ – a synergy of experiments

In order to make sense of these *CP* asymmetries, we need to know how the CP-conserving strong phase between D & Dbar varies over the Dalitz plot.

This information can be measured in bins on the Dalitz plot from quantum-correlated ψ(3770)→DDbar events, available at CLEO-c [PRD 82 (2010) 112006].





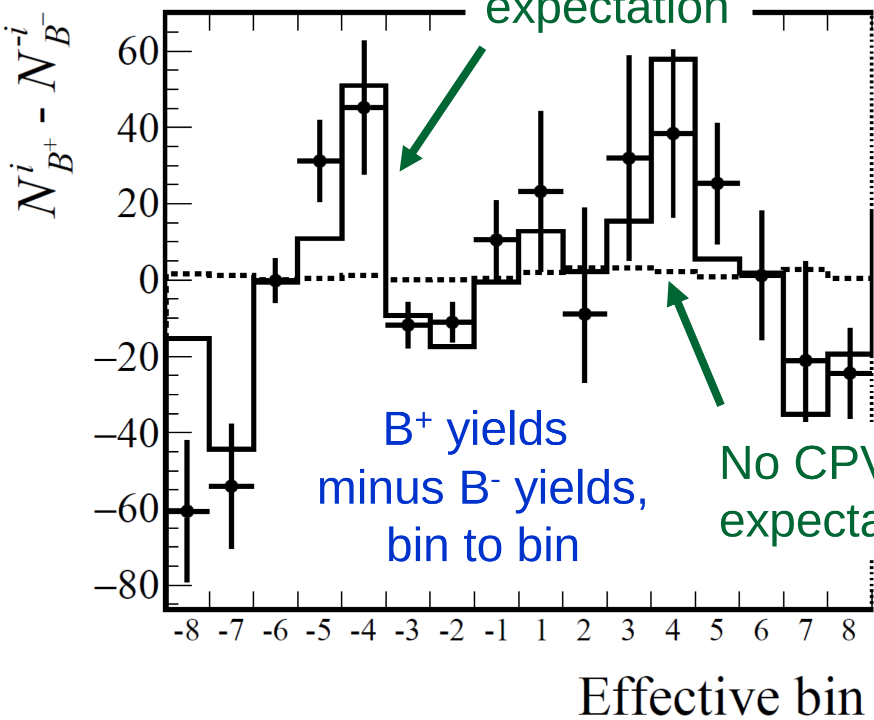
CLEO-c data adequate for current LHCb sample sizes.

LHCb Upgrade data & Belle II will require improved measurements from BES III !

γ measurement at LHCb with B→DK decays: D→$K_S\pi\pi$ (and K_SKK) with Run 2 data [JHEP 08 (2018) 176]

A powerful sub-set of B→DK analyses is when the D decays into a multibody final state, of which $K_S\pi\pi$ is the most prominent example. Variation of D strong phase over Dalitz space leads to corresponding variation in interference and CP violation.

CPV expectation

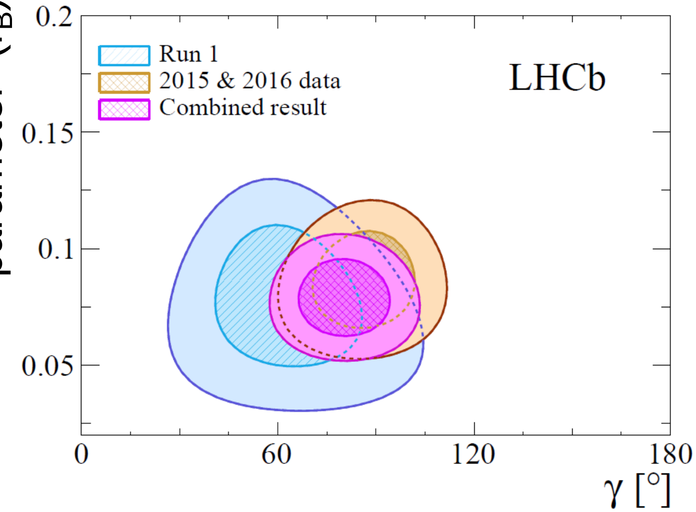


B⁺ yields minus B⁻ yields, bin to bin

No CPV expectation

Compatible with Run 1 analysis of same channel

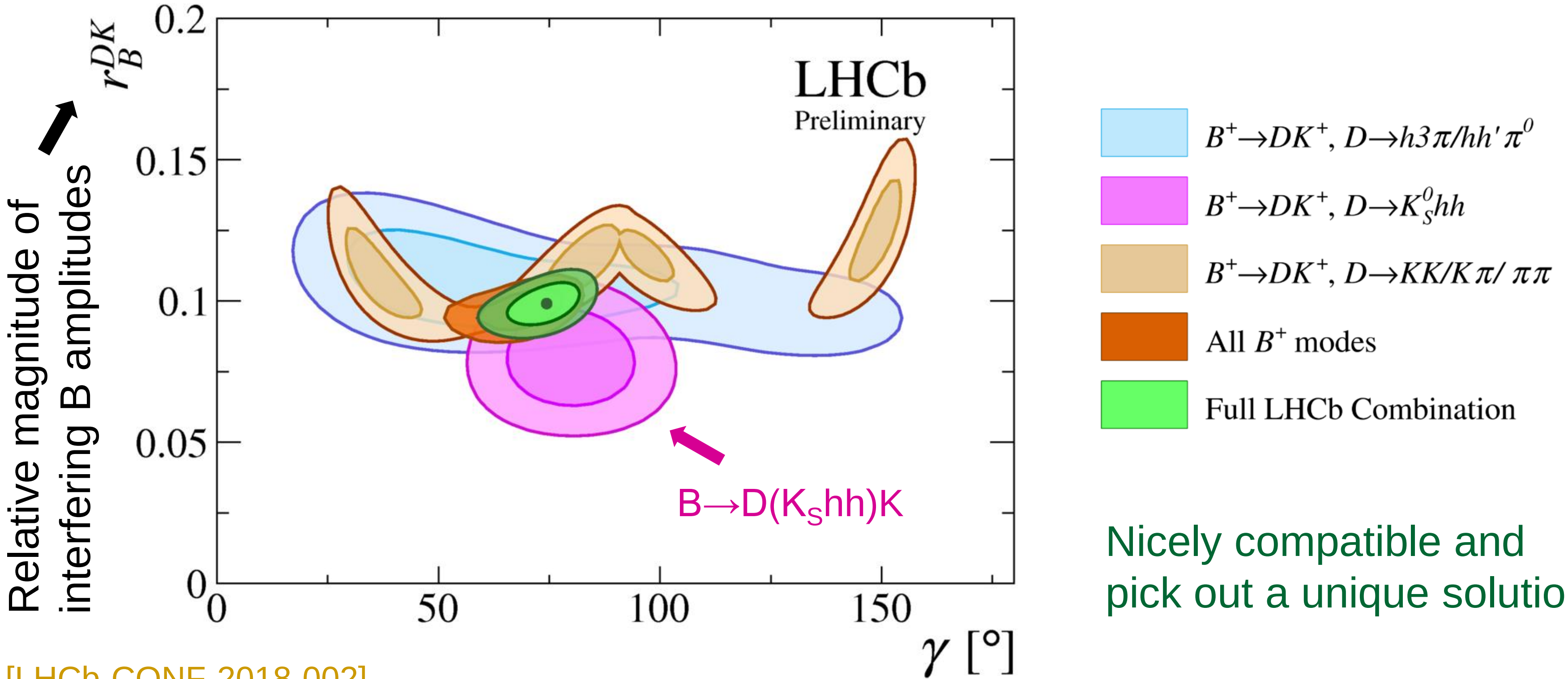
A nuisance parameter (r_B)



Together gives: $\gamma = 80^\circ\ {}^{+10^\circ}_{-9^\circ}$

LHCb: combining B→DK modes for γ

The B→D($K_S\pi\pi$,K_SKK)K result may be combined together with those of other B→DK analyses. They depend on common nuisance parameters, but have difference degeneracies → whole is greater than the sum of the parts !



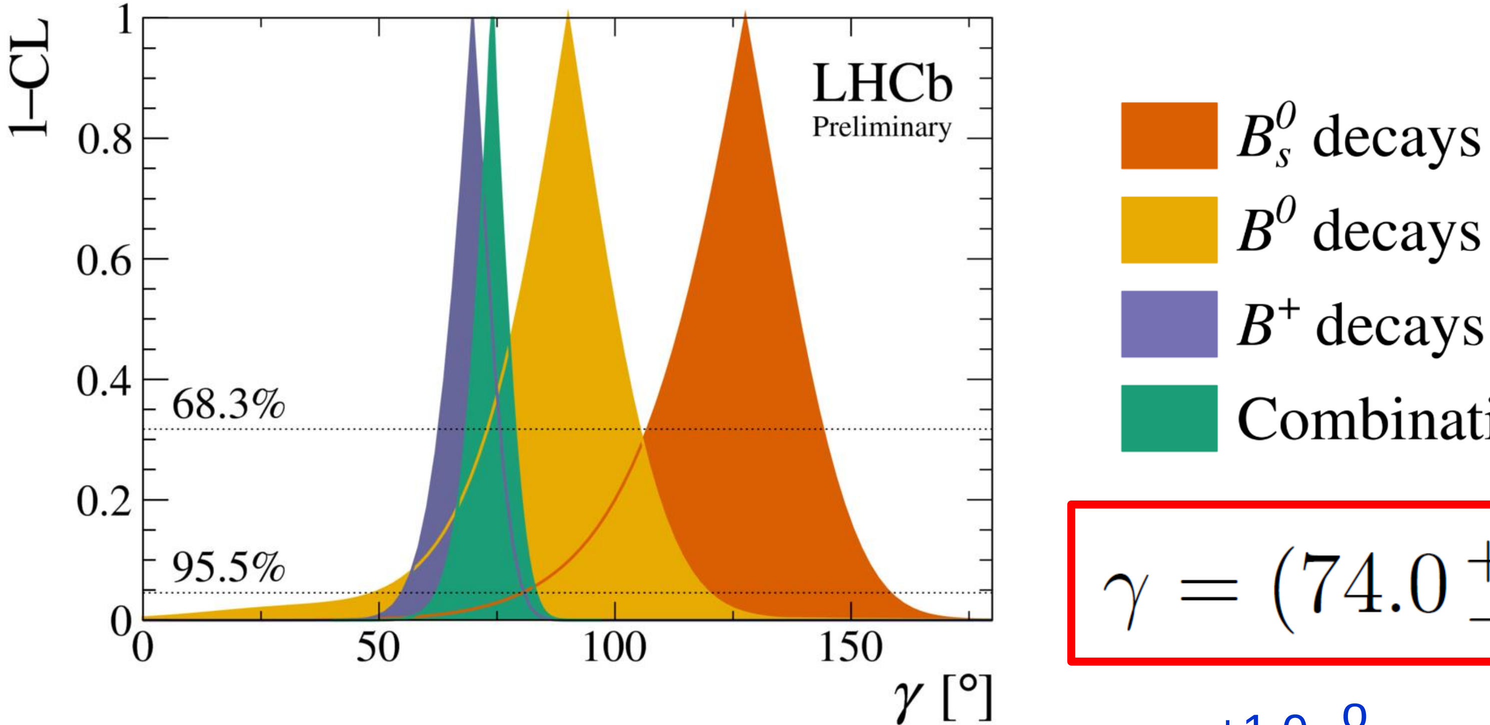
Nicely compatible and pick out a unique solution.

[LHCb-CONF-2018-002]

LHCb: current precision on γ

Global LHCb average, now including information from time-dependent analyses of Run 1 data with B_s [JHEP 03 (2018) 059] and B^0 decays [JHEP 06 (2018) 084].

[LHCb-CONF-2018-002]



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

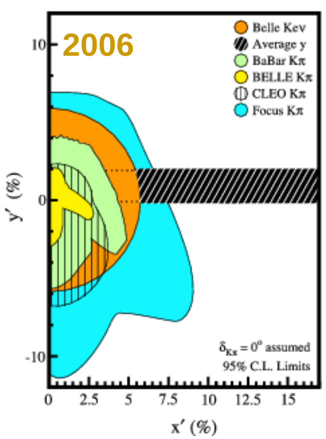
Result is to be compared with indirect prediction of $(65.6\,^{+1.0}_{-3.4})^{\mathrm{o}}$ [CKMfitter, 2018].
Compatible, albeit with a little tension (~2σ).
Big improvements expected in near future, as still little Run 2 data in average.

The charm renaissance

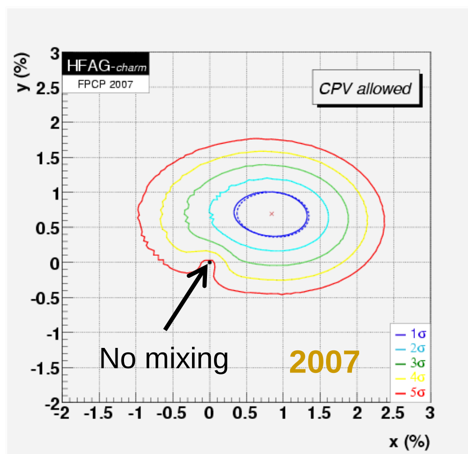
For many years charm was the 'Cinderella' of flavour physics studies

- tiny CPV and mixing effects expected in the SM…
- …and no evidence of either despite intensive searches
- long-distance effects complicate predictions

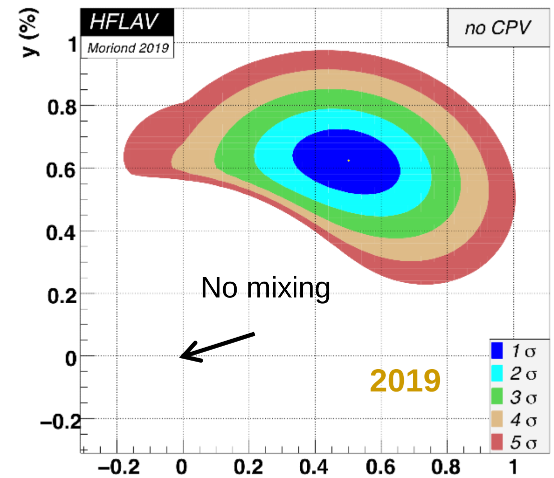
Excluded regions



"All results are null."
Ian Shipsey, Charm 2006.



Measurement contours;
no-mixing excluded at 5σ



No-mixing excluded at lots
and lots (but x=0 still possible…)

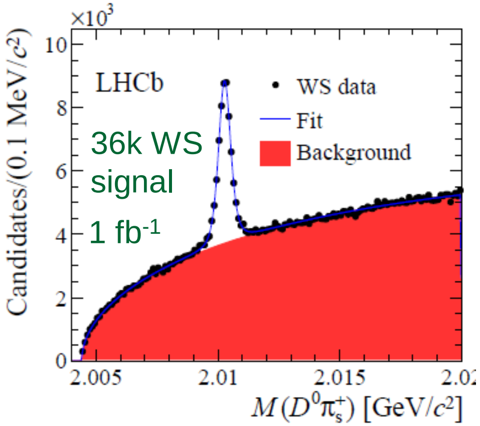
Then combination of B-factory analyses finally saw mixing. New outlook !

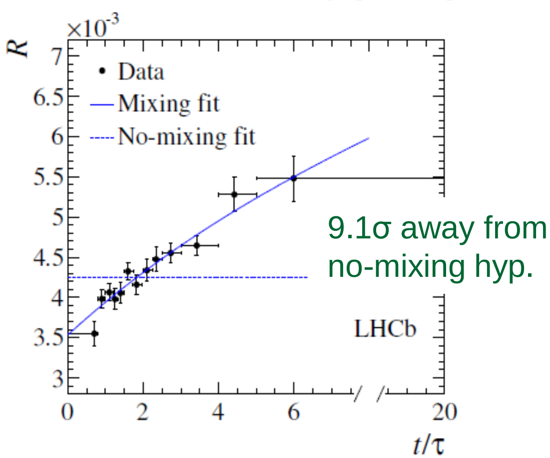
→ mixing parameters not tiny (~1%); good news for (indirect) CPV observables
→ smallness of SM 'pollution' not a bad thing in looking for New Physics signal
→ internal down-type quarks in loops – complementary to *b*-physics
→ huge potential of LHC for improving sensitivity

Rise of the hadron machines

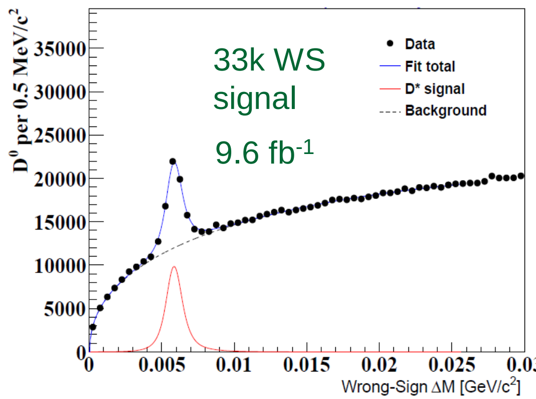
Power of hadron colliders is now clear. In 2013 LHCb and CDF published first individual (>)>5σ measurements, in `wrong sign' (WS) Kπ analyses.

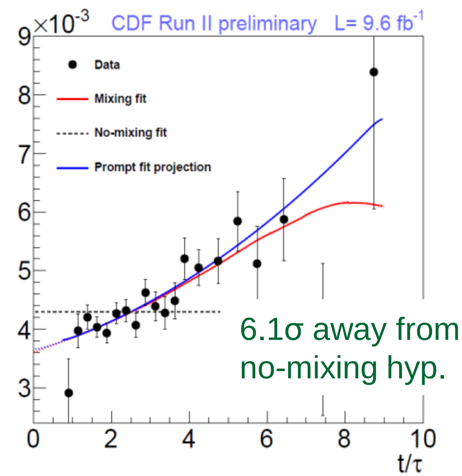
LHCb, PRL 110 (2013) 101802





CDF, PRL 111 (2013) 231802



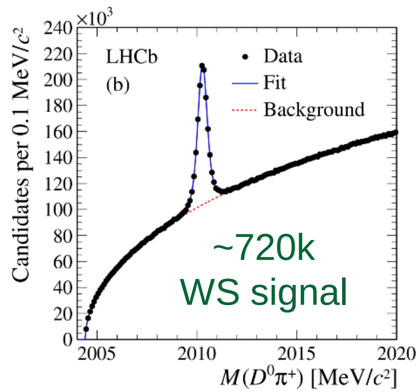


Although e^+e^- machines retain advantages for modes with neutrals, LHC has huge advantages for charged modes (*e.g.* # WS Kπ in above plot, which is a small fraction of Run 1, is 3x whole Belle sample) and also time resolution.

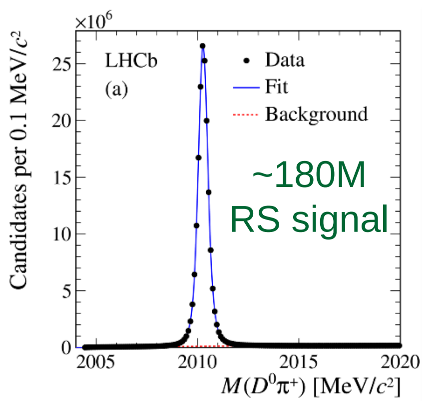
Search for indirect CPV in charm with Run 2 data

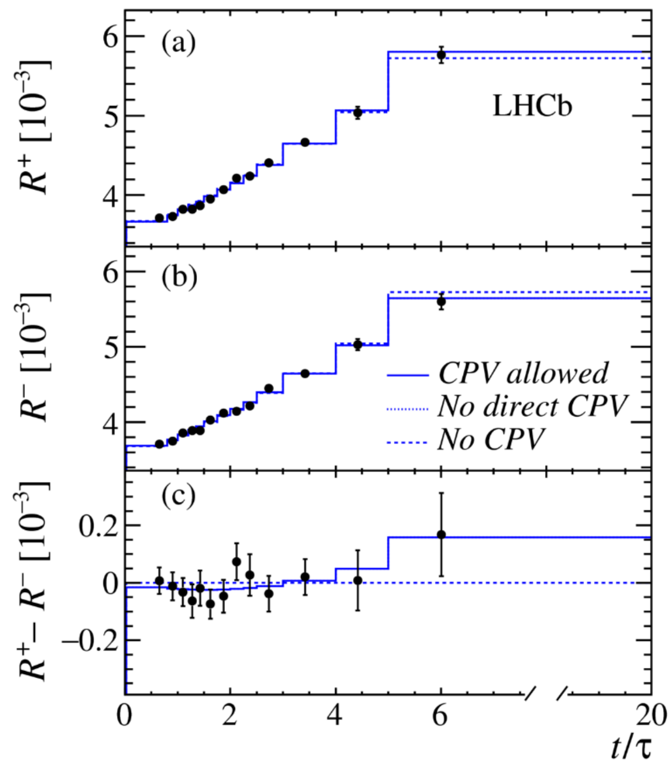
LHCb samples have grown rapidly, and now allow for high sensitivity searches for mixing-induced CPV, *e.g.* take WS Kπ analysis used for mixing discovery, now updated with full Run 1 data & 2 fb^{-1} from Run 2, and study D^0 & D^0bar separately.

Study ratio of WS (*i.e.* $D^0 \to K^+\pi^-$)…



…to RS (*i.e.* $D^0 \to K^-\pi^+$), vs. proper decay time





For D^0…

…and D^0bar…

…and difference of both.

[PRD 97 (2018) 031101]

Difference flat → no evidence of CPV (yet).

Dawn of a new era: observation of (direct) CPV in charm

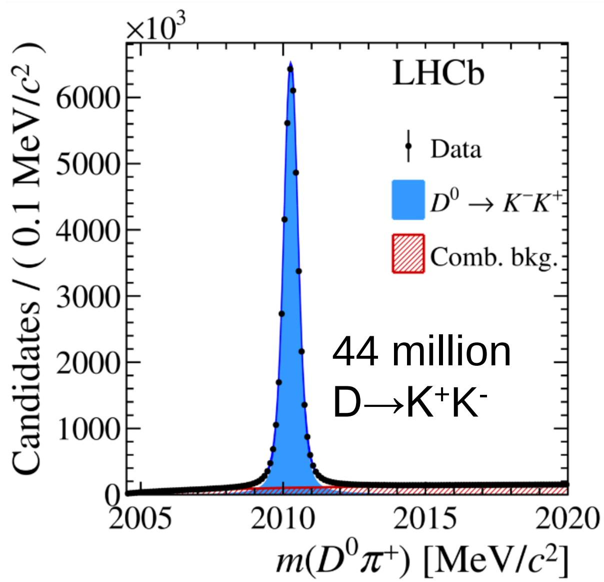
[PRL 122 (2019) 211803]

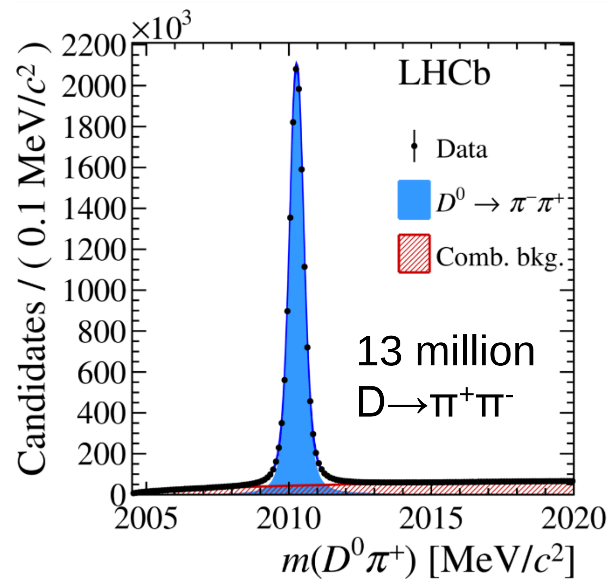
As for indirect CPV, searches for *direct* CPV in charm have yielded null results throughout many decades of searches – this year the story changed !

Measurement is of *difference* in CPV asymmetry between $D \rightarrow K^+K^-$ and $D^0 \rightarrow \pi^+\pi^-$. This is done to cancel out systematic asymmetries common to both modes.

Harnesses full statistical might of experiment – first to use full Run 2 data set.

Dull plots, because effect is tiny, and almost impossible to visualise





Run 1 + Run 2 ➡

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

5.3σ from 0 !

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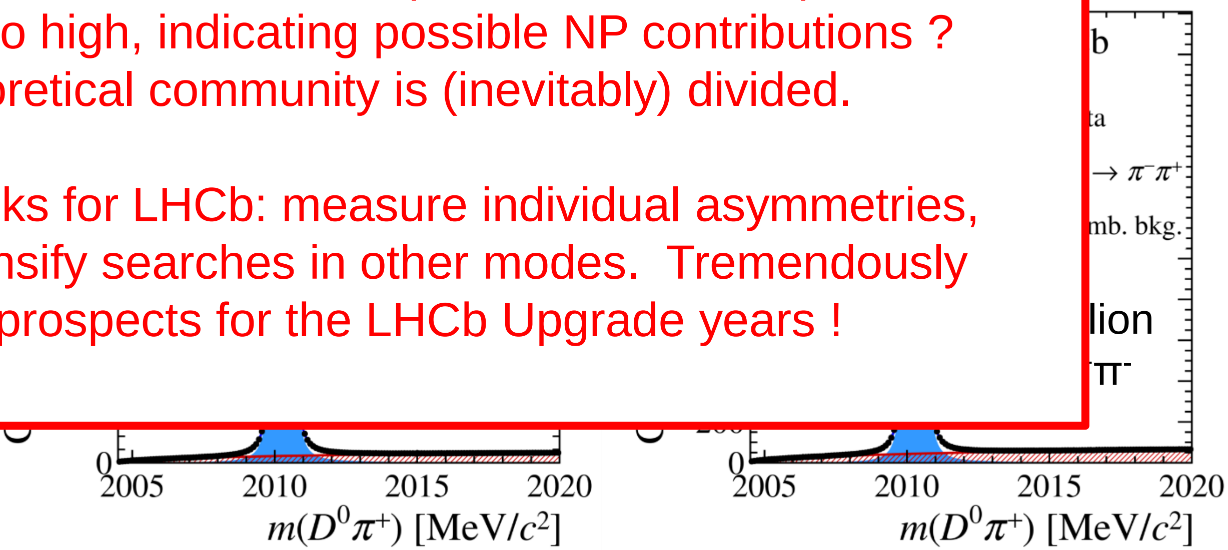
As for indirect CPV, searches for *direct* CPV in charm have yielded null results throughout many decades of searches – this year the story changed !

Measu… $^0 \to \pi^+\pi^-$.
This is … es.

Harnes… set.

Dull plo…
effect is…
almost …
to visua… lion … π^-

- The effect is almost wholly driven by direct CPV
- Is the size of the effect compatible with SM expectations, or is it too high, indicating possible NP contributions ? The theoretical community is (inevitably) divided.
- Next tasks for LHCb: measure individual asymmetries, and intensify searches in other modes. Tremendously exciting prospects for the LHCb Upgrade years !



Run 1 + Run 2 ➡ $$\Delta A_{CP} = (-15.4 \pm 2.9) \times 10^{-4}$$ 5.3σ from 0 !

The future of flavour

The full LHCb Run 1 & 2 data sets are still being analysed & will yield significantly improved precision in all measurements & (no doubt) some surprises !

But this is not the end of the story – almost all important measurements will remain statistics limited, and there will be other studies that are possible with current sample sizes. More data are required !

We will briefly survey some future opportunities, some reasonably well known

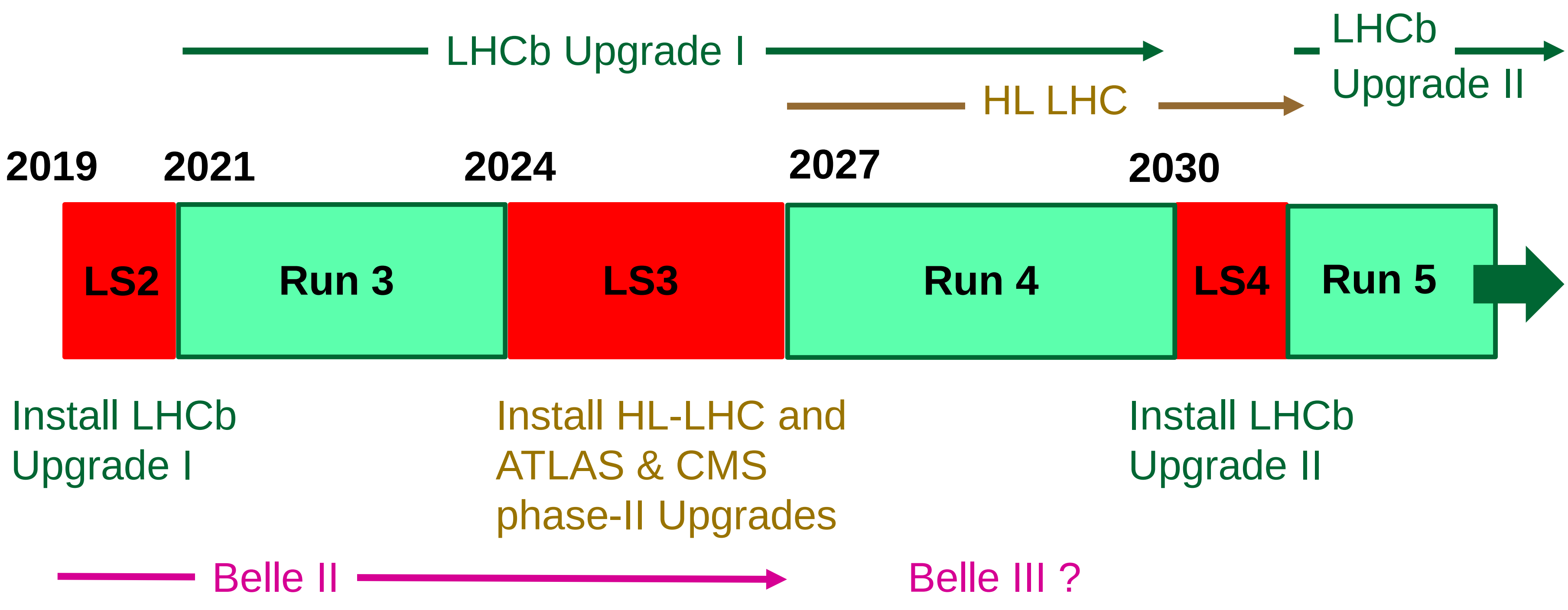
- Belle II
- LHCb Upgrade I
- LHCb Upgrade II,

and others, somewhat less well known as flavour facilities:

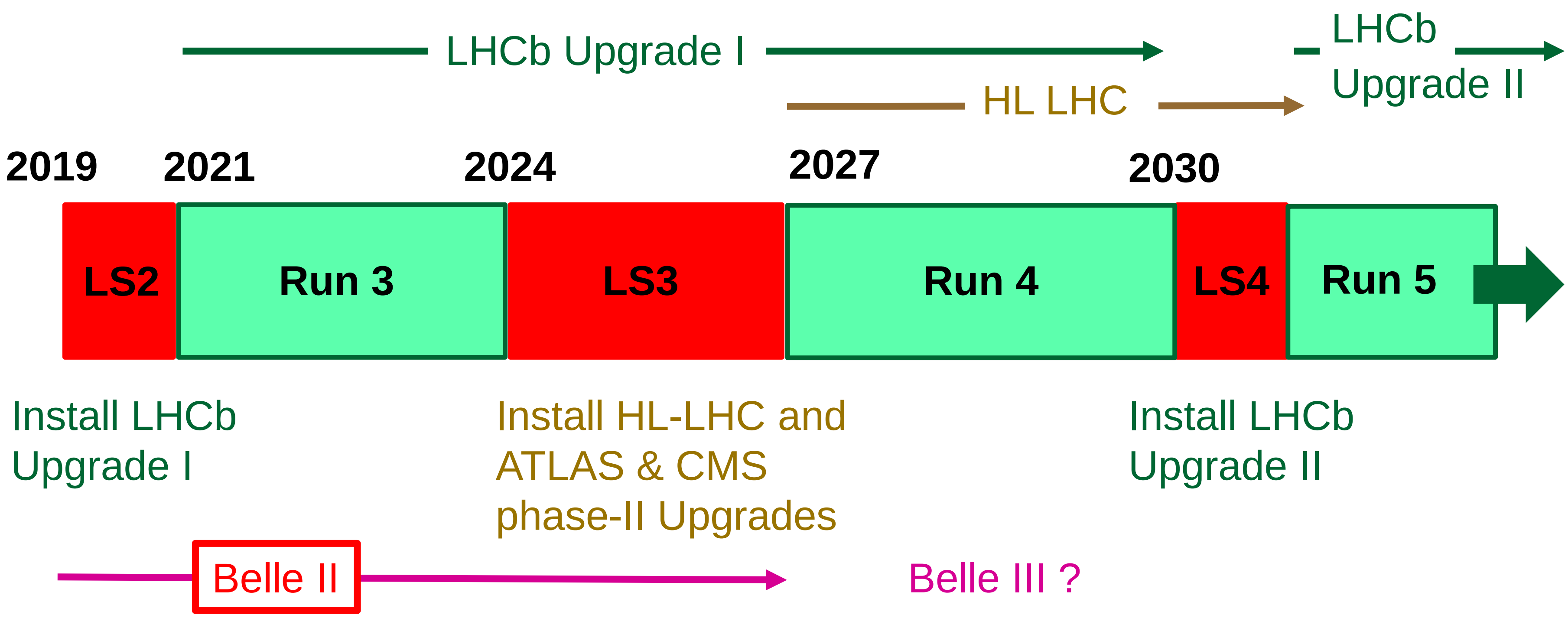
- TauFV at the SPS Beam Dump Facility
- FCC-ee (& CEPC).

Several others (*e.g*. Super Tau Charm Factory) not covered through lack of time.

The LHC schedule – current planning



The LHC schedule – current planning

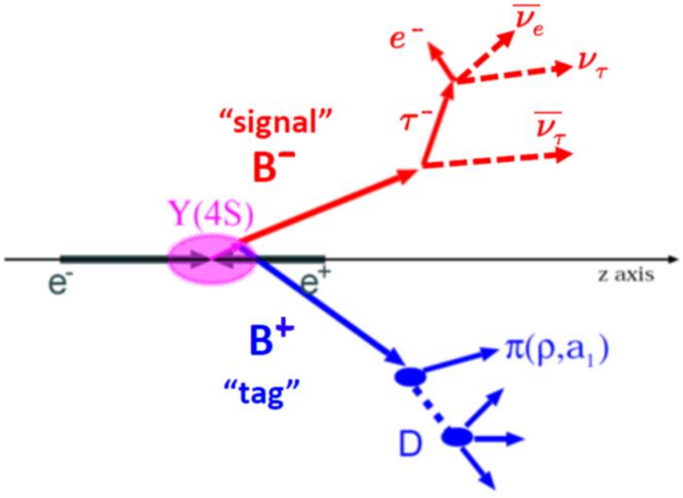


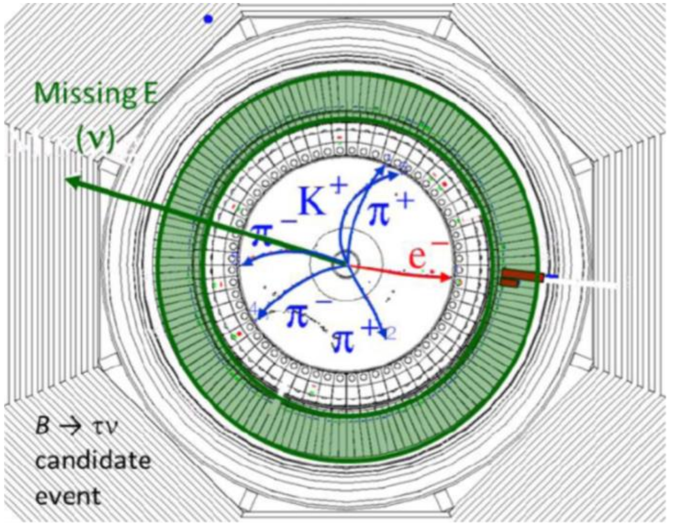
Why Belle II ?

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

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

e.g. B→τν





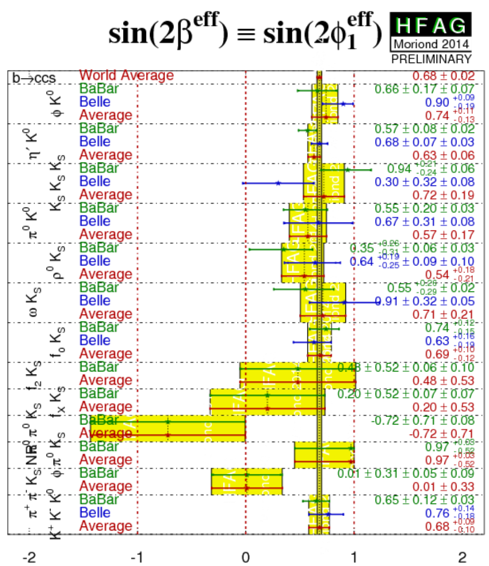
Why Belle II ?

B production at the $\Upsilon(4S)$ presents several advantages over hadron environment

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

- 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.

e.g. most modes suitable for sin2β measurements involving Penguin loops (b→ccbar s) are rather tough at LHCb…



…and other important decays *e.g.* $D^0 \to \gamma\gamma$, $B^0 \to \pi^0\pi^0$… are essentially inaccessible.

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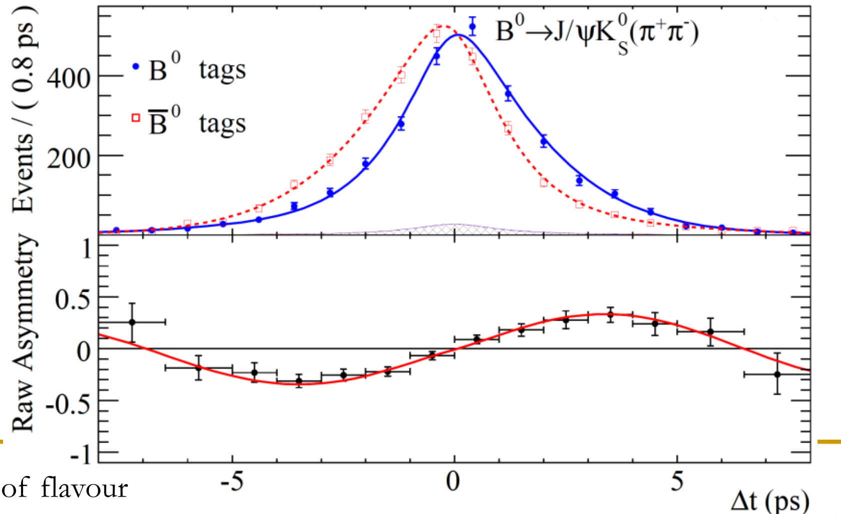
- Low multiplicity environment permits excellent performance for final states with π^0s, η's, photons. Also, good efficiency for long-lived particles K_S and K_L.

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

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

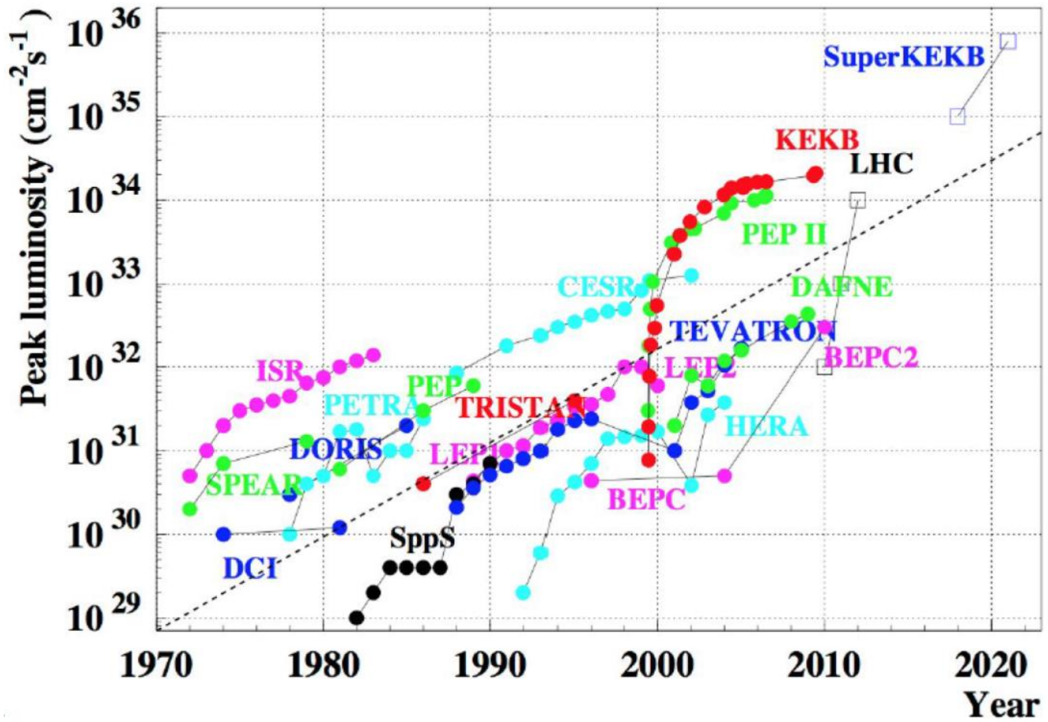
ε (tag effective) BaBar ~ 31 %
[PRD 79 (2009) 072009]

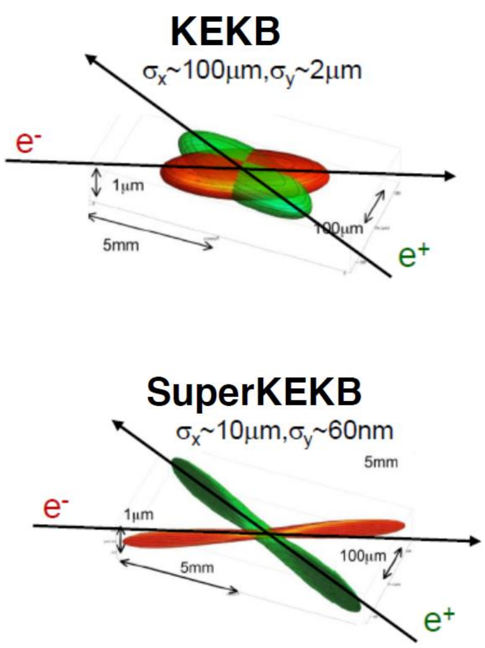
ε (tag effective) LHCb ~ 3 %
[PRL 115 (2015) 031601]



SuperKEKB

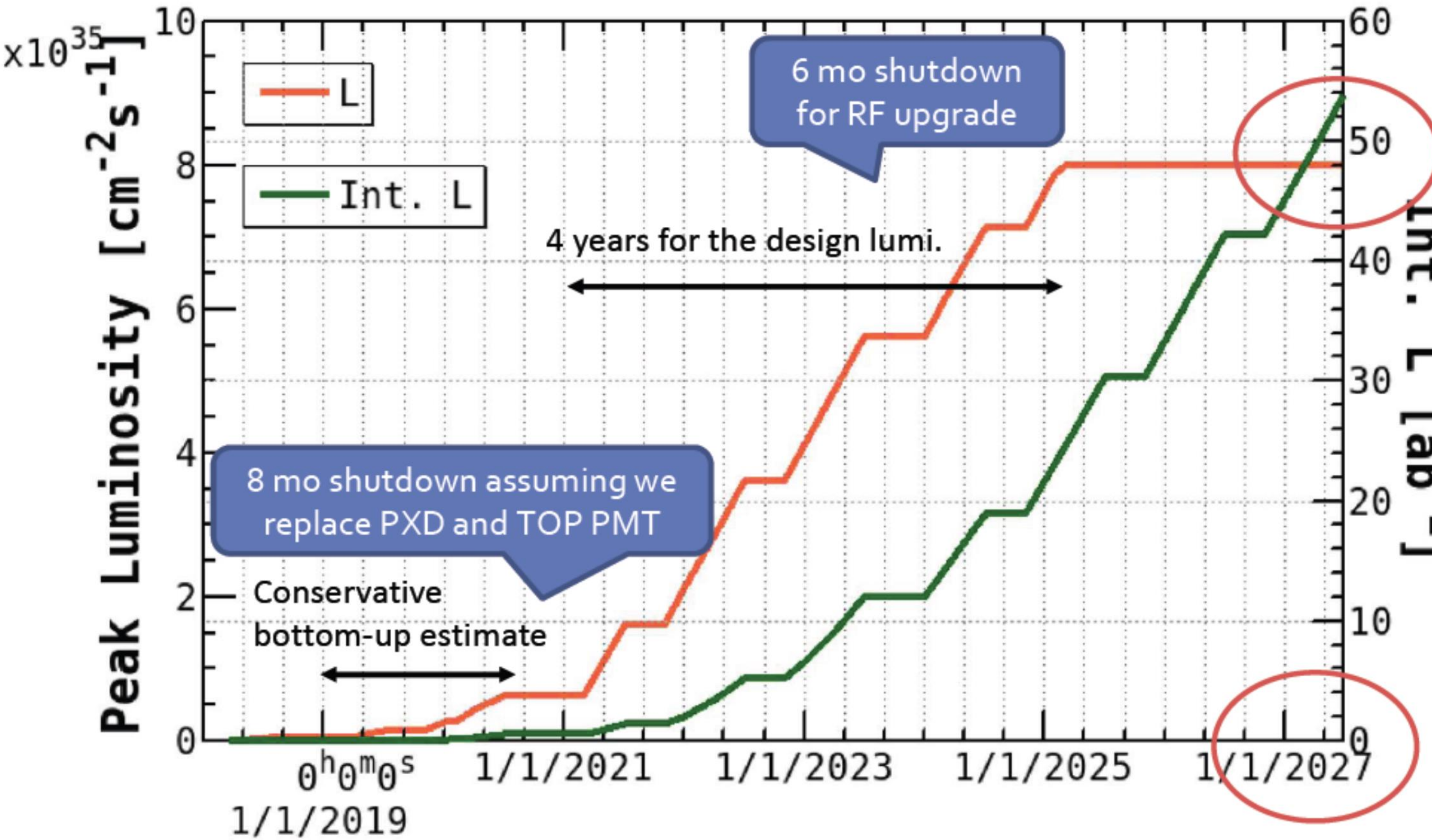
SuperKEKB goals: luminosity of 8 x 10^{35} $cm^{-2}s^{-1}$ and 50 ab^{-1} by 2024





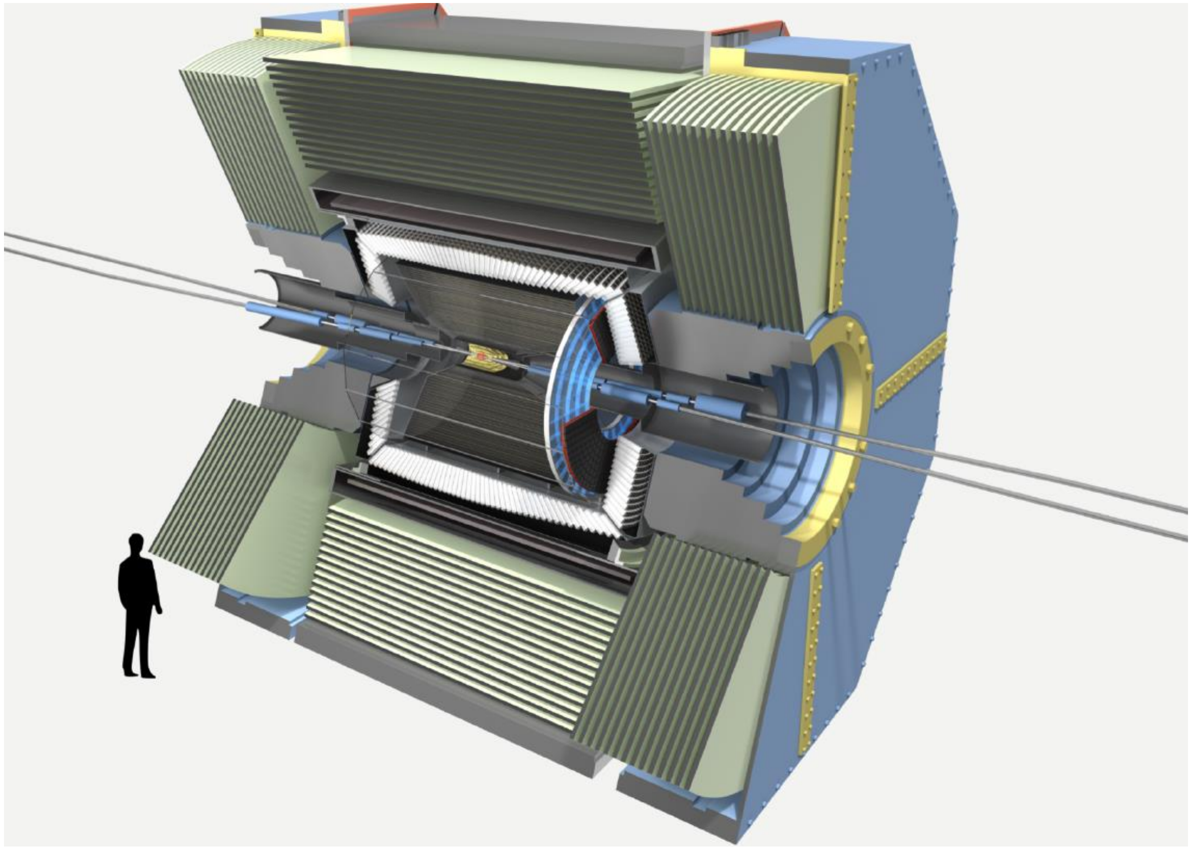
An ambitious 40-fold increase in luminosity on KEKB, to be achieved by squeezing the beams by ~1/20 and doubling the currents.

SuperKEKB and Belle II roadmap

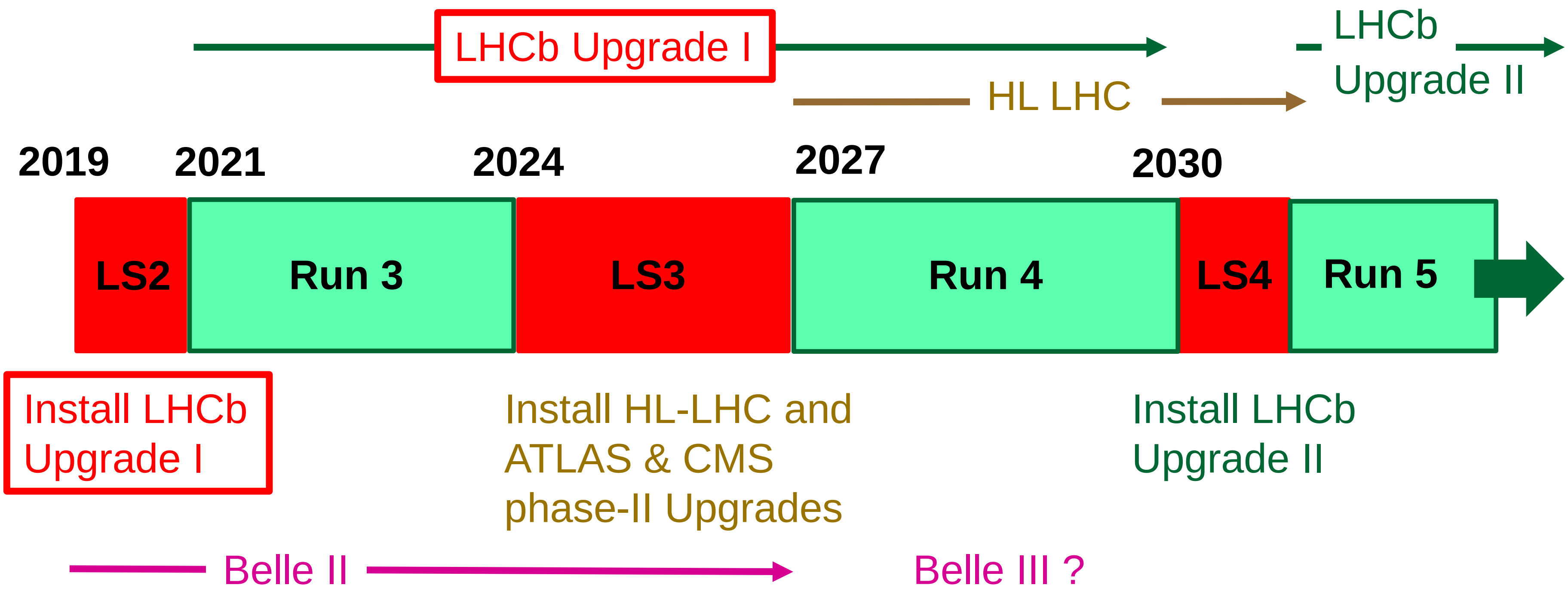


Belle II detector

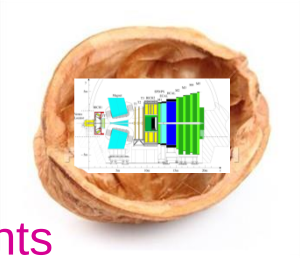
All sub-detectors upgraded from Belle, except for ECL crystals and part of the barrel KLM



The LHC schedule – current planning



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 Runs1 & 2 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

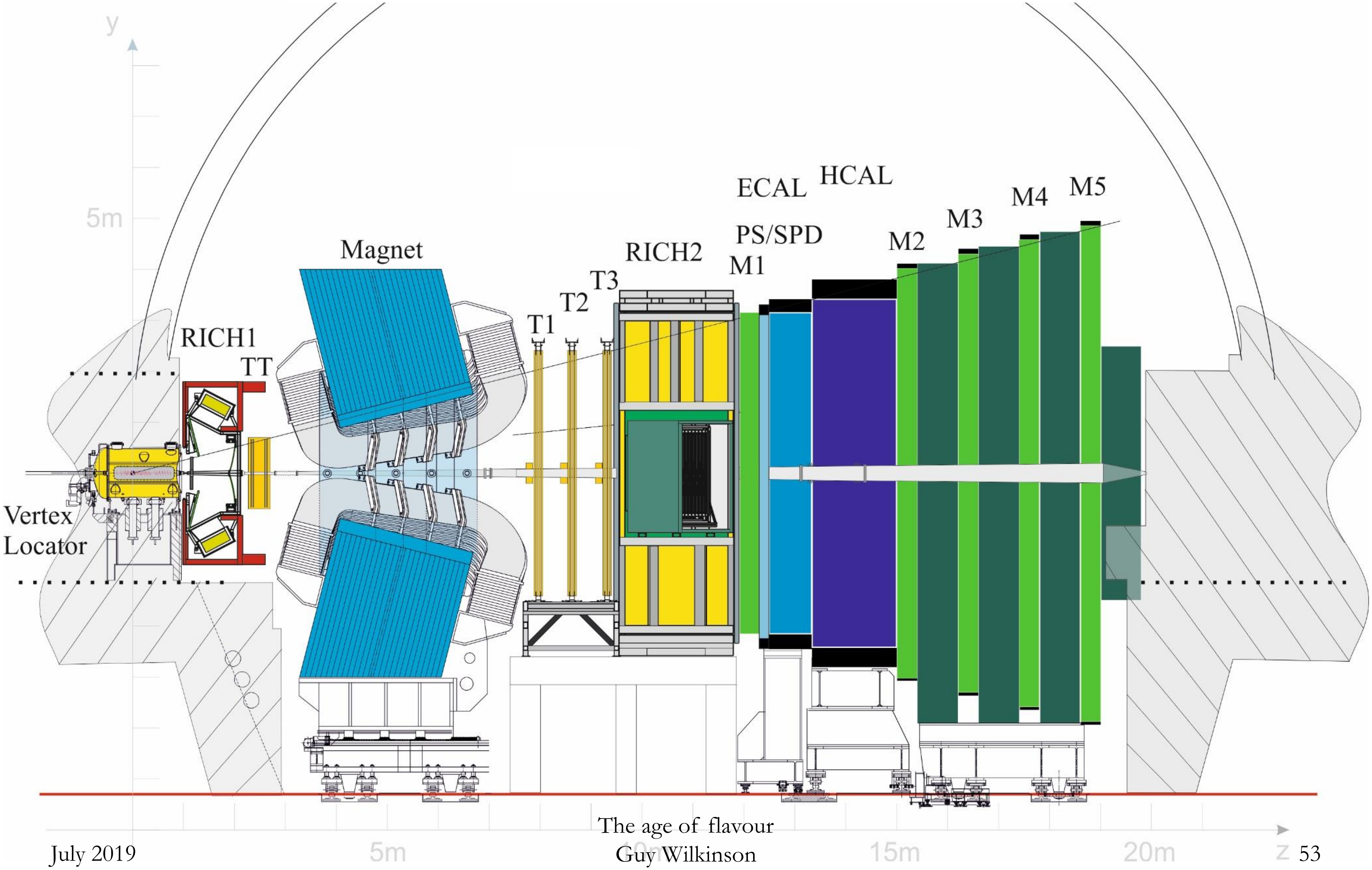
2) Raise operational luminosity to 2 x 10^{33} cm^{-2} s^{-1}

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').

Run 1 & 2 detector



Required modifications

Full s/w trigger →

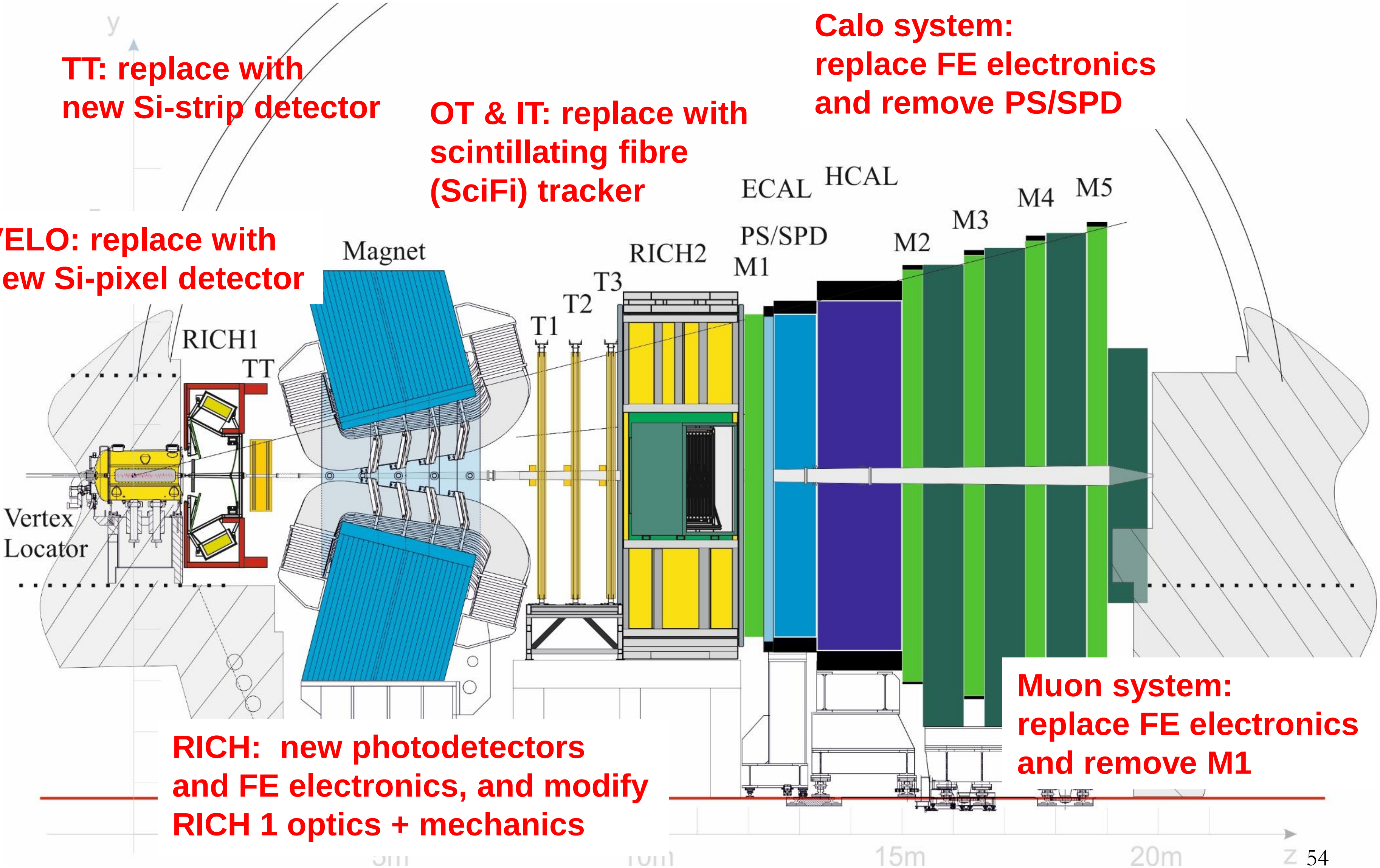
Replace read-out boards and DAQ

TT: replace with new Si-strip detector

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

Calo system: replace FE electronics and remove PS/SPD

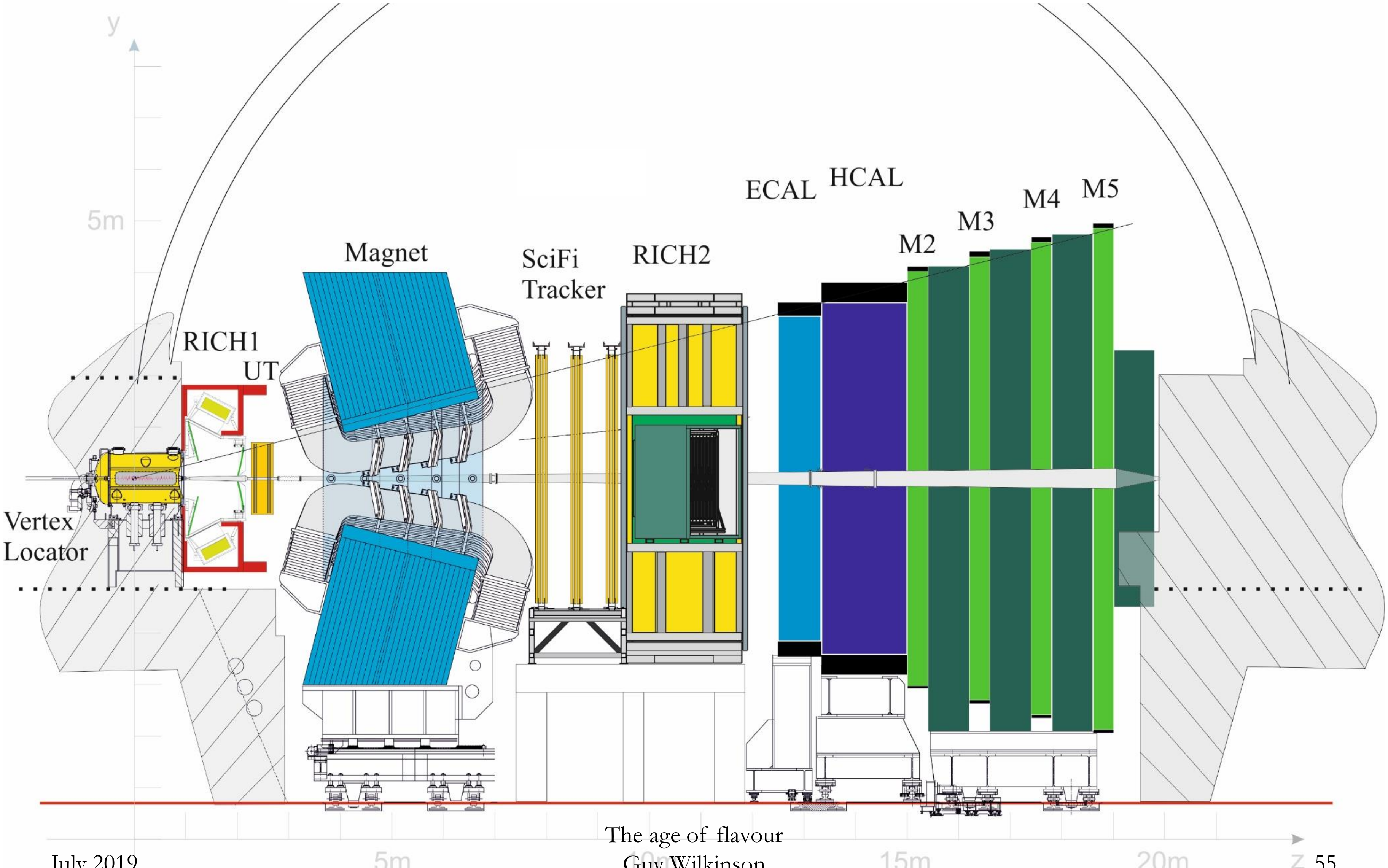
VELO: replace with new Si-pixel detector



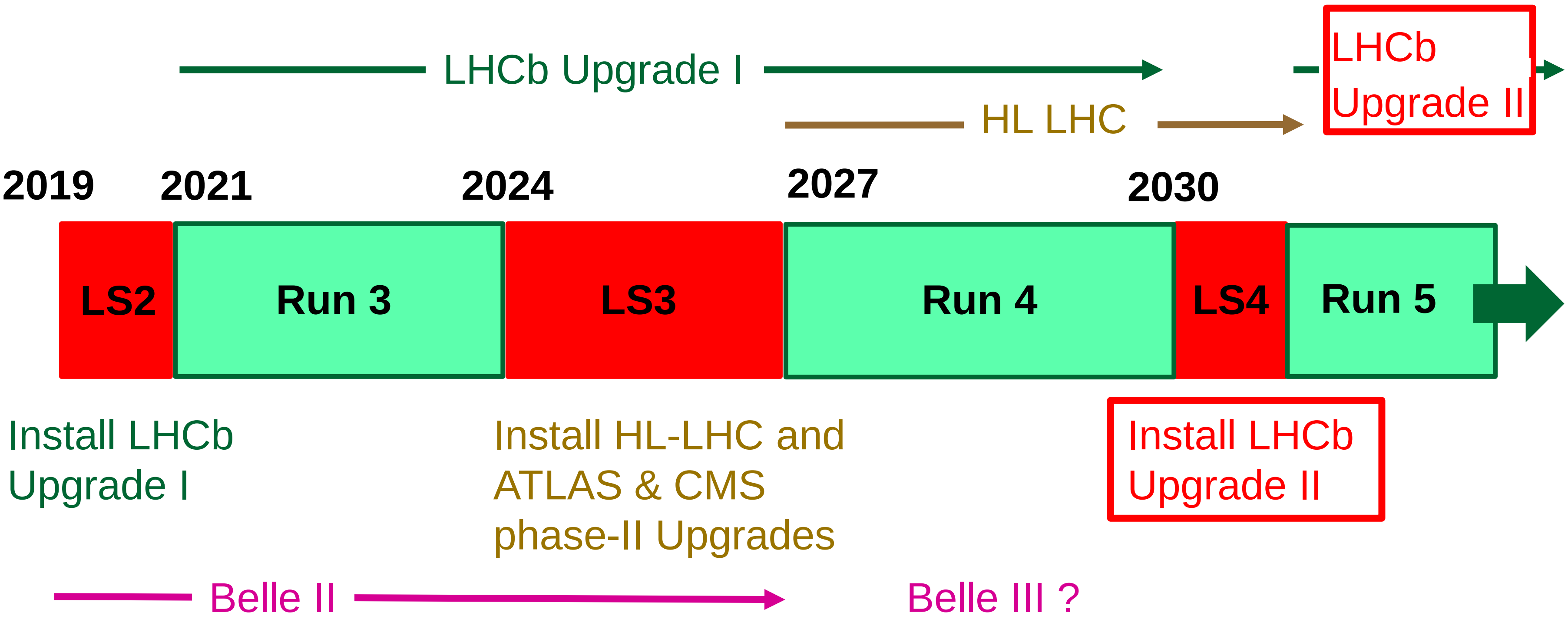
Muon system: replace FE electronics and remove M1

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

Upgrade I detector



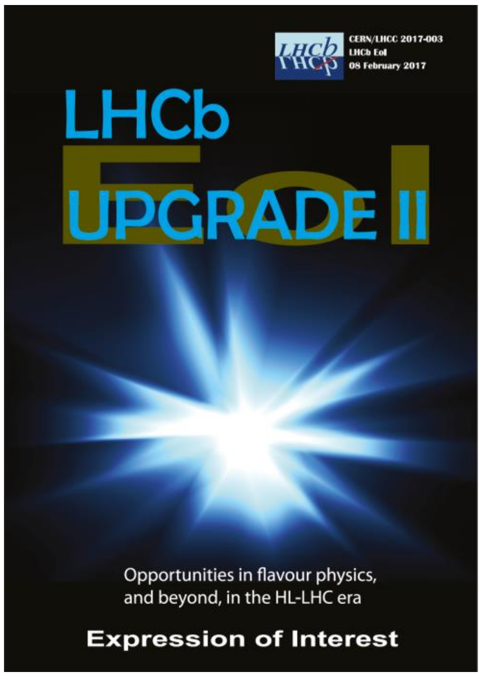
The LHC schedule – current planning



LHCb Upgrade II – the ultimate LHC flavour experiment

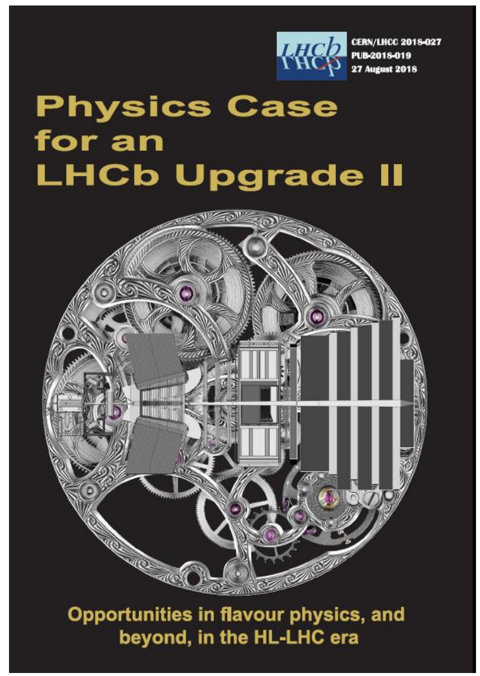
Begin after LS4 (2030). Operate at up to 2 x 10^{34} $cm^{-2}s^{-1}$ & collect (at least) 300 fb^{-1}.

Expression of interest



[CERN-LHCC-2017-003]

Full physics case



[CERN-LHCC-2018-027, also arXiv:1808.08865]

In parallel, many studies from the machine side, summarised in a report which identifies

"a range of potential solutions for operating LHCb Upgrade II at a luminosity of up to 2 x 10^{34} $cm^{-2}s^{-1}$ and permitting the collection of 300 fb^{-1} or more at IP8 during the envisaged lifetime of the LHC"

[CERN-ACC-NOTE-2018-038]

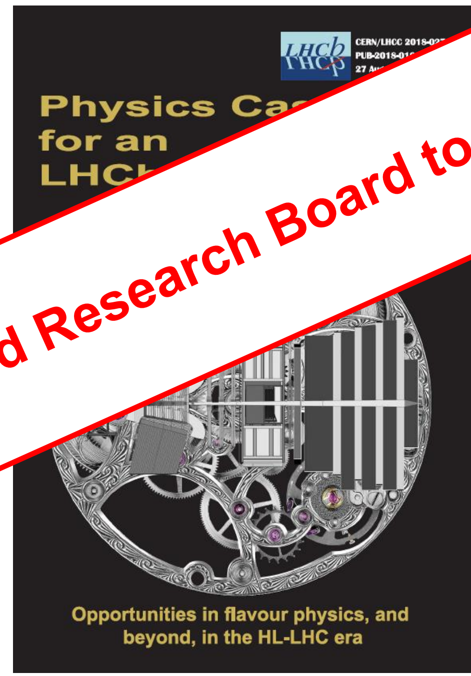
LHCb Upgrade II – the ultimate LHC flavour experiment

Begin after LS4 (2030). Operate at up to 2 x 10^{34} $cm^{-2}s^{-1}$ & collect (at least) 300 fb^{-1}.

Expression of interest

[CERN-LHCC-2017-003]

Full physics case



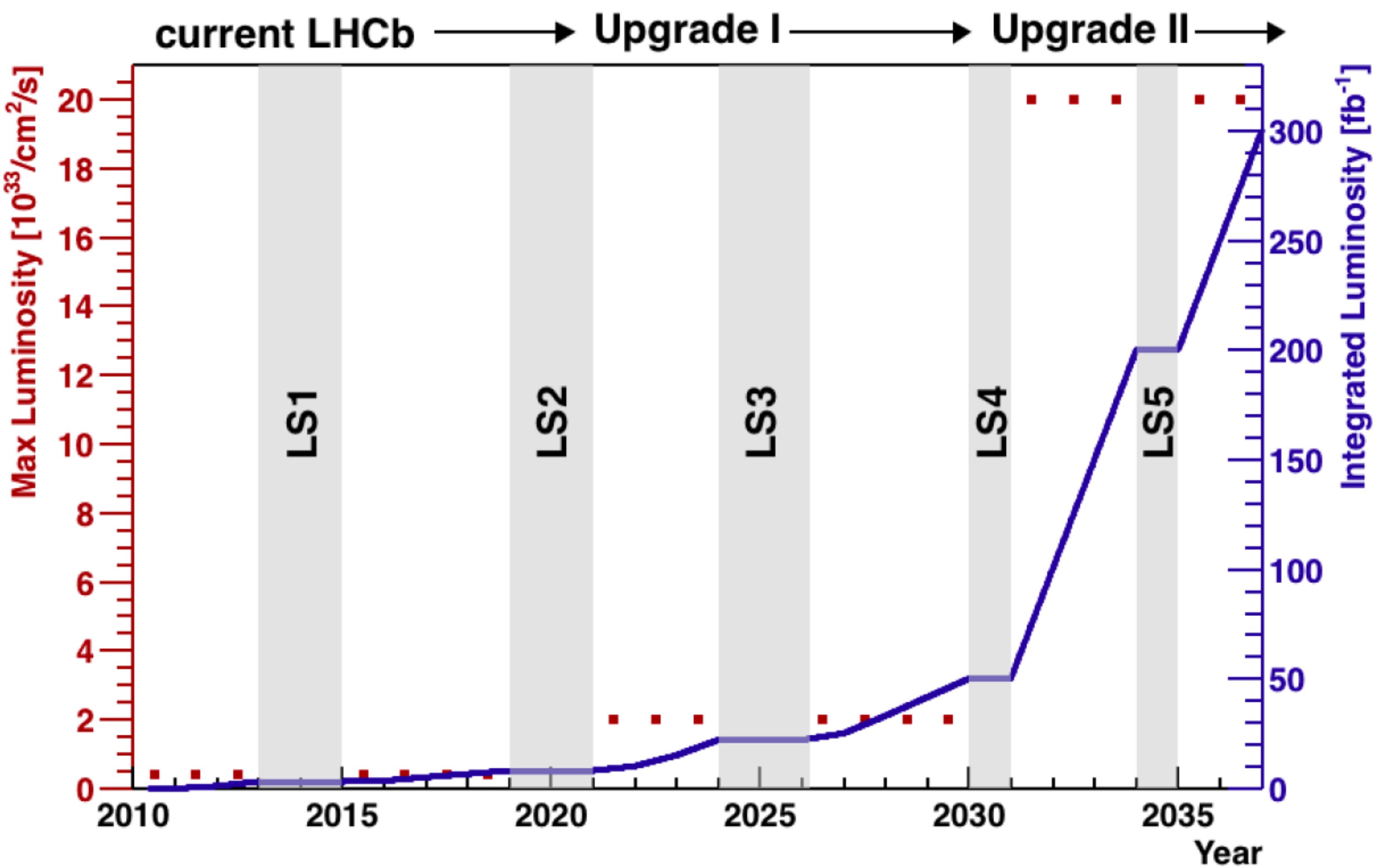
[CERN-LHCC-2018-027, also arXiv:1808.08865]

In parall… …dies fro… …le, …port …ntifies …range of potential solutions for operating LHCb Upgrade II at a luminosity of up to 2 x 10^{34} $cm^{-2}s^{-1}$ and permitting the collection of 300 fb^{-1} or more at IP8 during the envisaged lifetime of the LHC"

[CERN-ACC-NOTE-2018-038]

Approved by LHCC and Research Board to proceed to TDRs

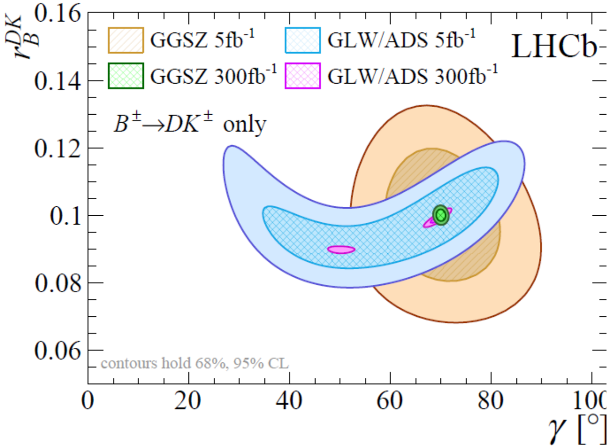
LHCb Upgrade II – the ultimate LHC flavour experiment



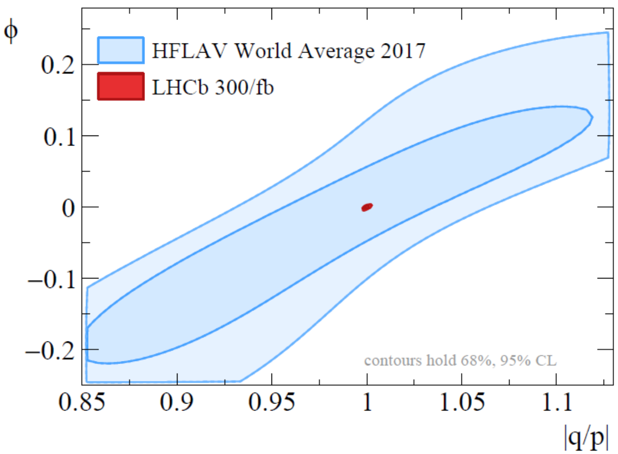
Upgrade-II physics highlights

Too much to cover – here are a few examples:

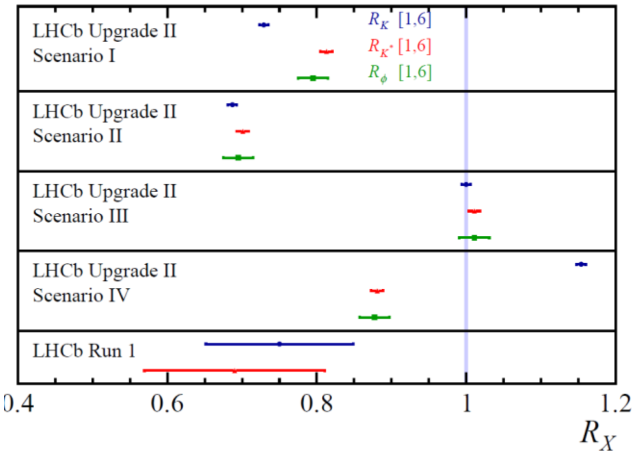
γ determination: sub-degree precision



CPV in charm down to 10^{-5}



Resolving New Physics models with R_K and friends



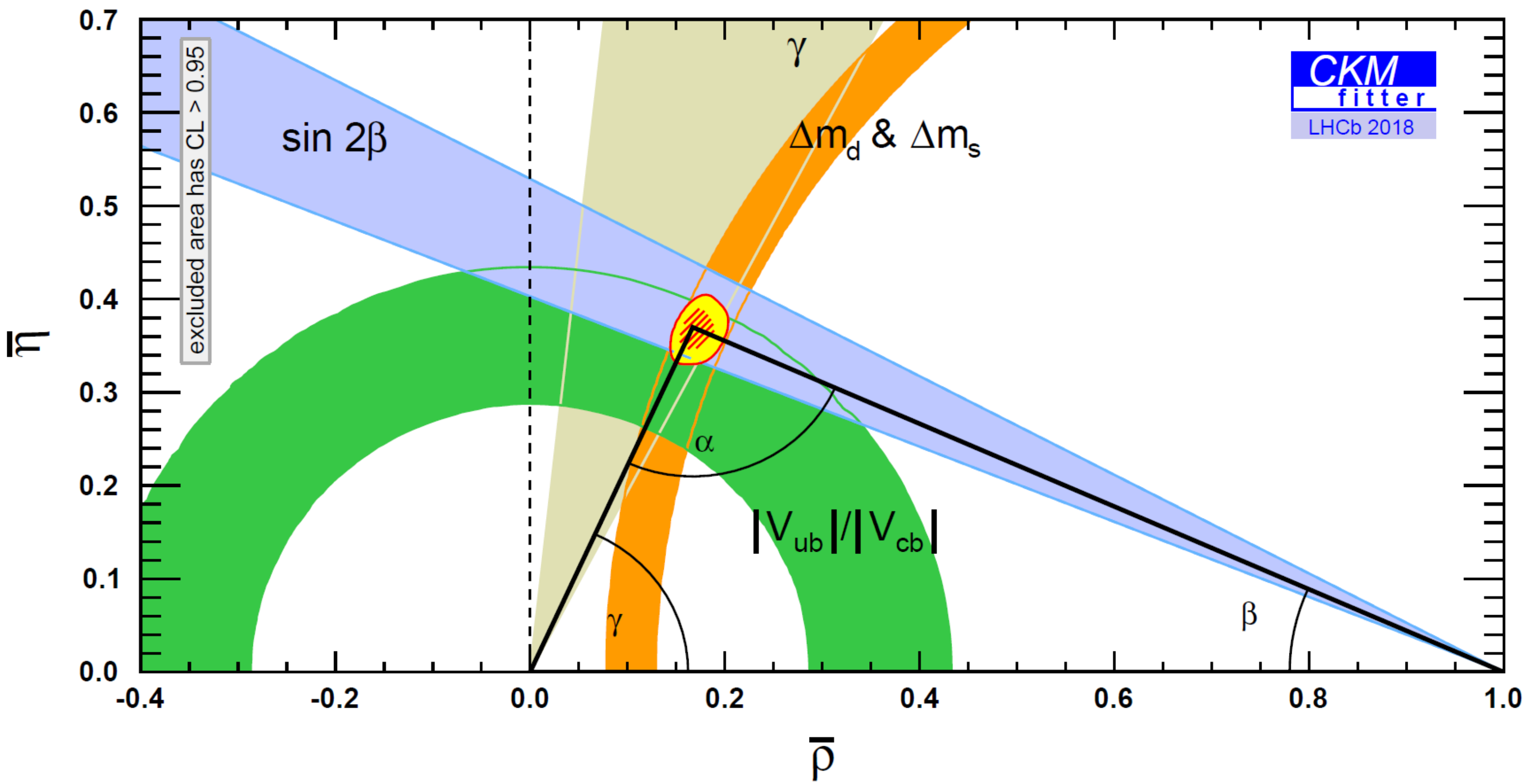
Two key points:

- Many key theoretically clean observables will remain statistics limited even after Upgrade I (*e.g.* γ, φ_s, sin2β, R_K and friends, $B(B^0\to\mu\mu)/B(B_s\to\mu\mu)$…
- Also, will be able to access new observables *e.g.* angular studies of $b\to de^+e^-$.

This will enable great advances in CPV tests, and will give an almost doubling of the New Physics mass scale (w.r.t. start of HL-LHC era) to which we are sensitive.

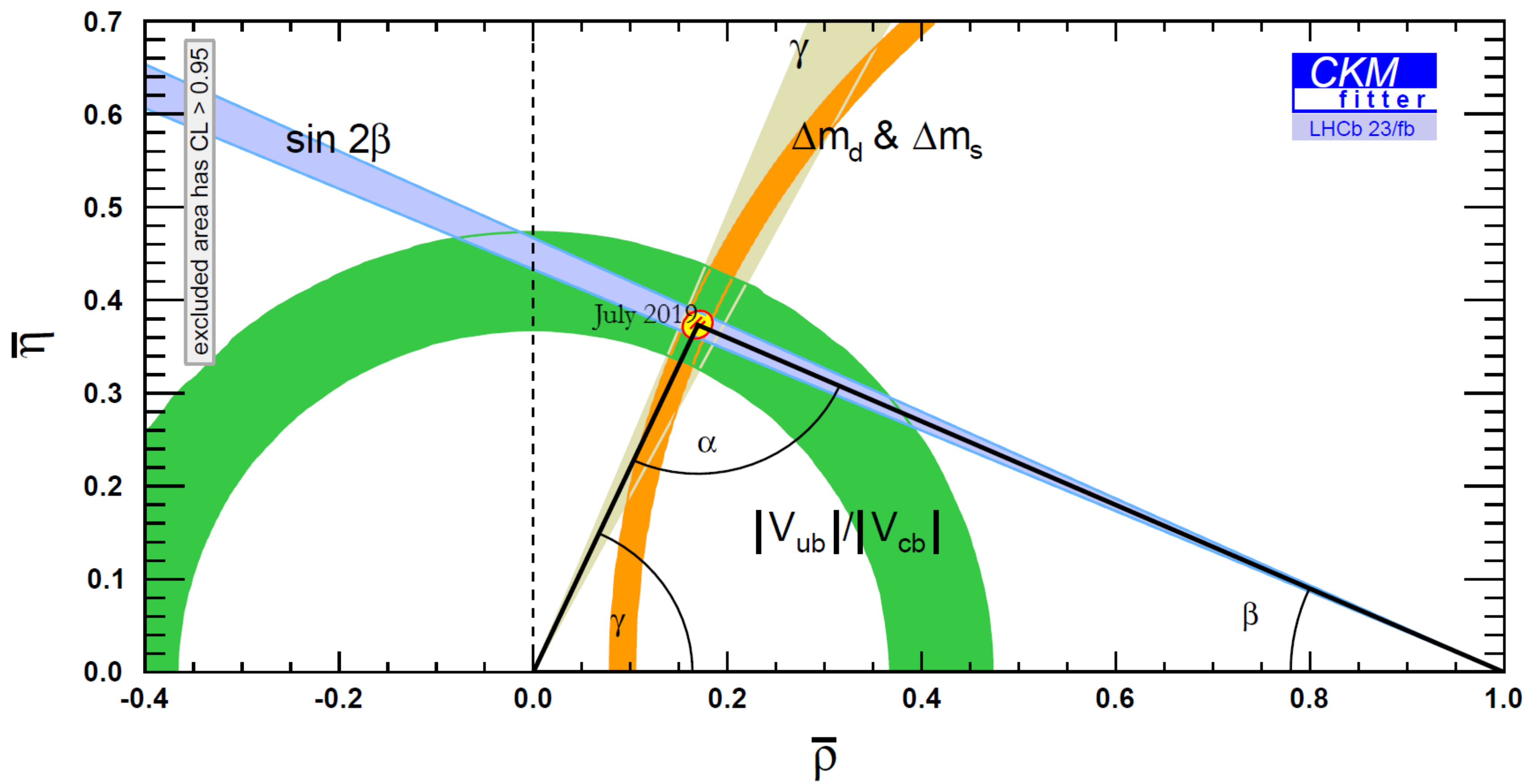
Evolution of constraints on Unitarity Triangle

UT plotted using constraints from LHCb alone (+ lattice QCD): current status



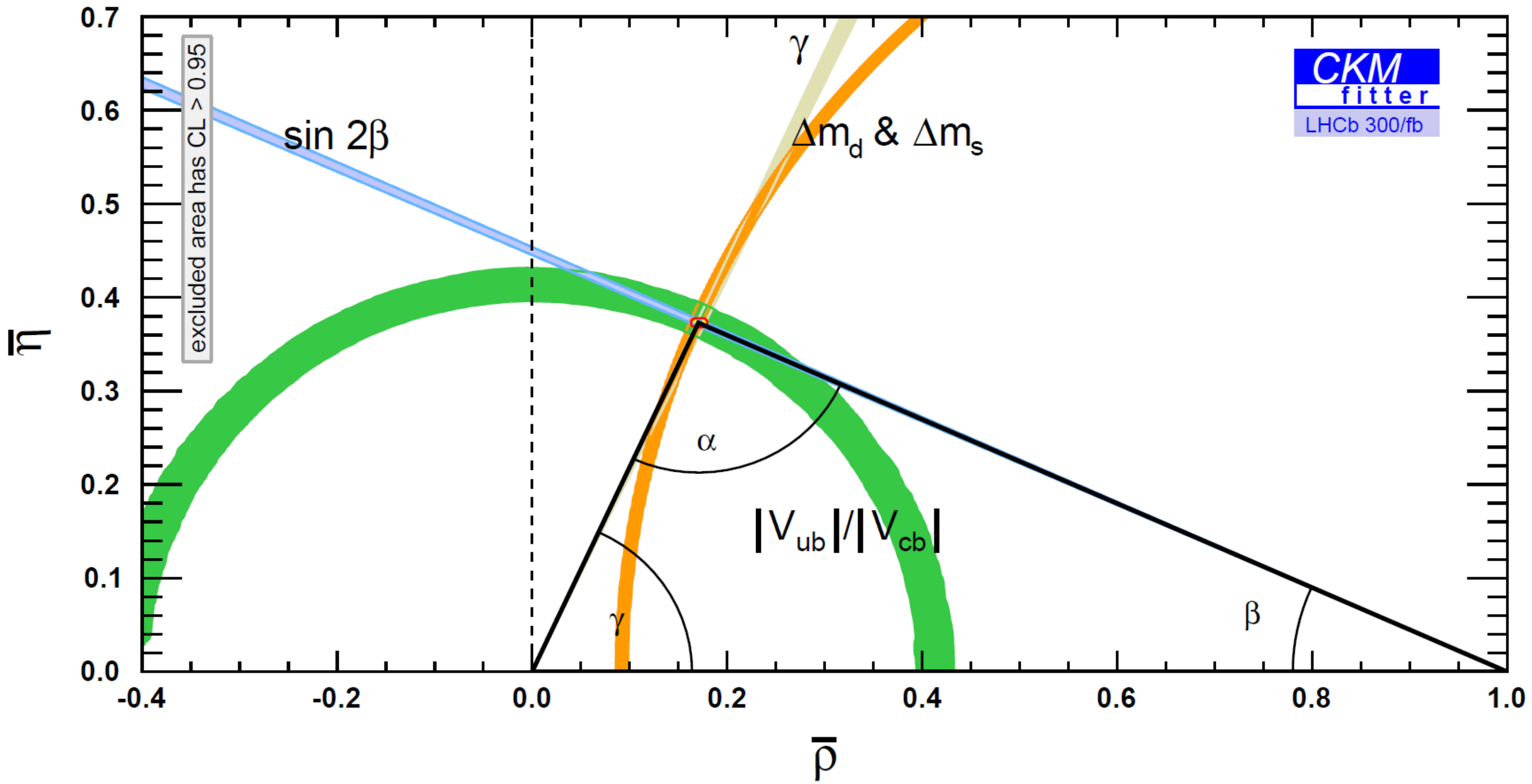
Evolution of constraints on Unitarity Triangle

UT plotted using constraints from LHCb alone (+ lattice QCD): start of HL-LHC



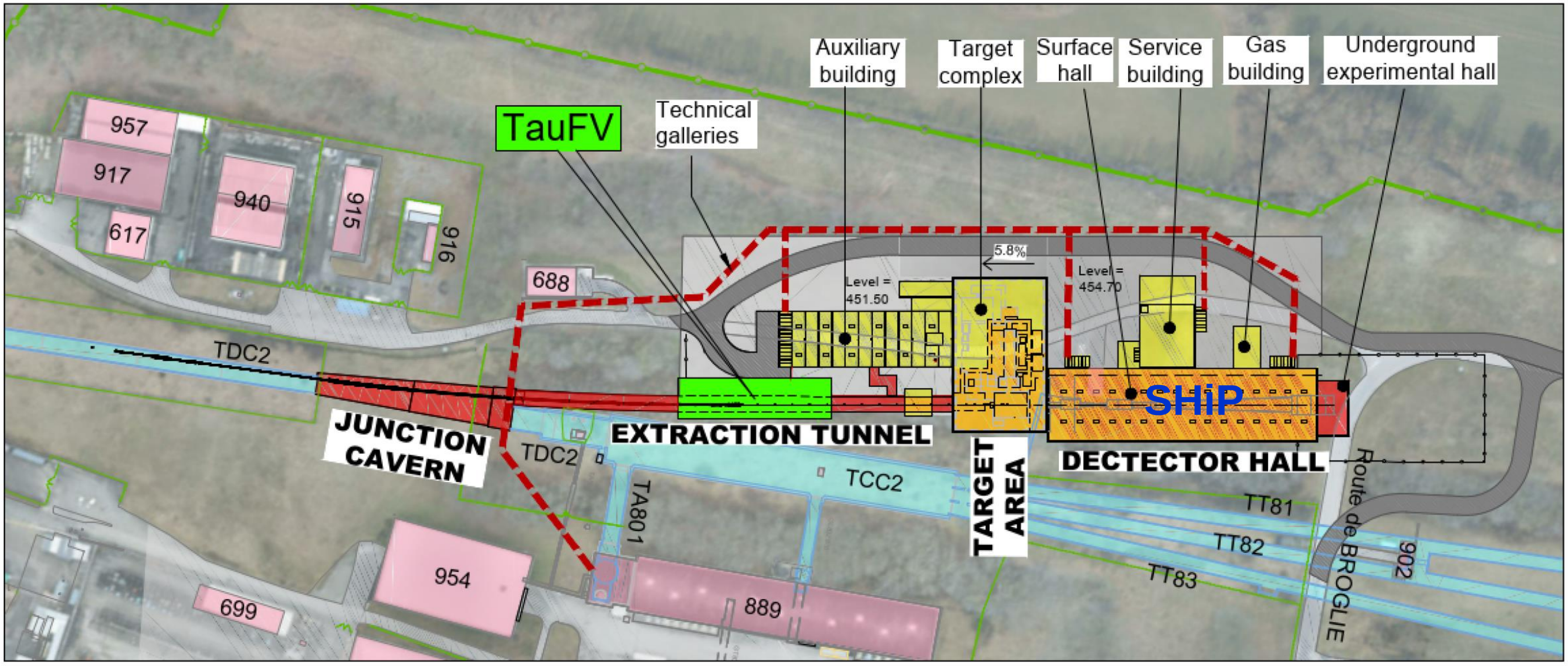
Evolution of constraints on Unitarity Triangle

UT plotted using constraints from LHCb alone (+ lattice QCD): after Upgrade II



TauFV: fixed-target flavour opportunities

Beam-Dump Facility (BDF) is a new beam line required from SPS required for proposed SHiP experiment. If approved, it will be constructed in LS3 (~2026). This facility provides parallel opportunities for a fixed-target experiment: TauFV.

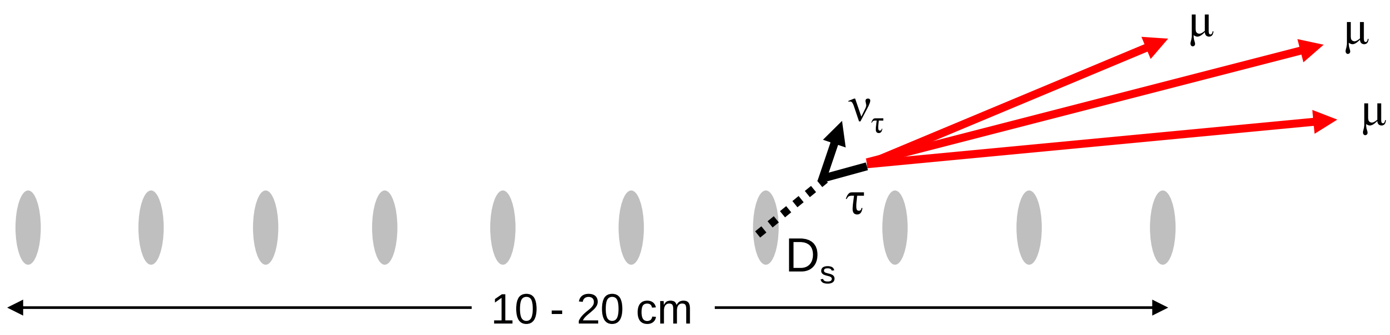


Flavour-physics opportunities at TauFV

Inserting 2 mm of tungsten in beam, distributed over several targets, will bleed off 2% of beam and provide 4 x 10^{18} protons-on-target in 5 years of operation.

Charm is produced in 0.17% of interactions → potentially the highest yield charm ever (or at least before the FCC-hh / CppC) ! Outstanding opportunities.

One possibility: 8 x 10^{13} $D_s \to \tau \bar{\nu}$ decays – high sensitivity for $\tau \to \mu\mu\mu$ searches.

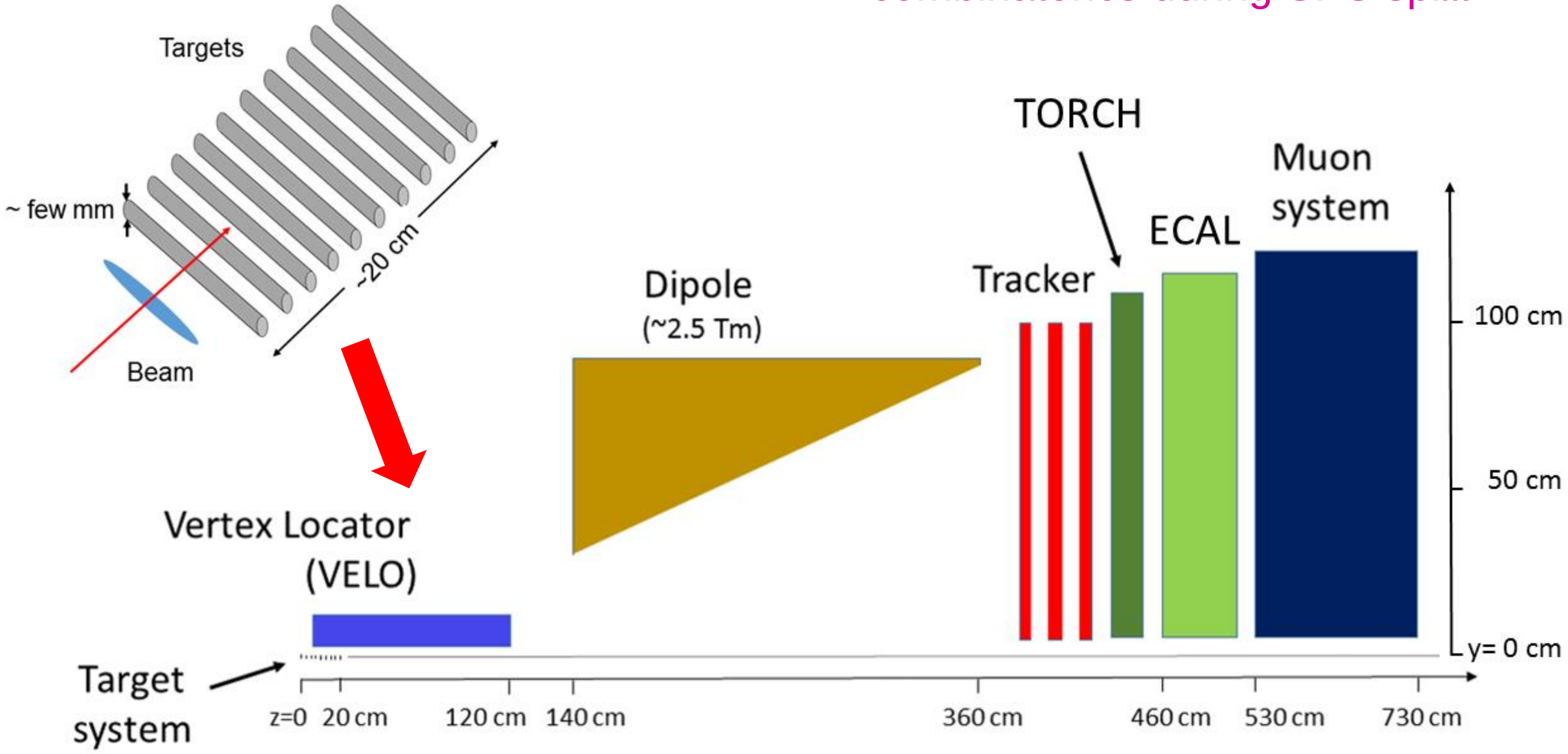


Extensive of target region and infrastructure. Physics studies ongoing.
For more information see submission made to EPPSU.

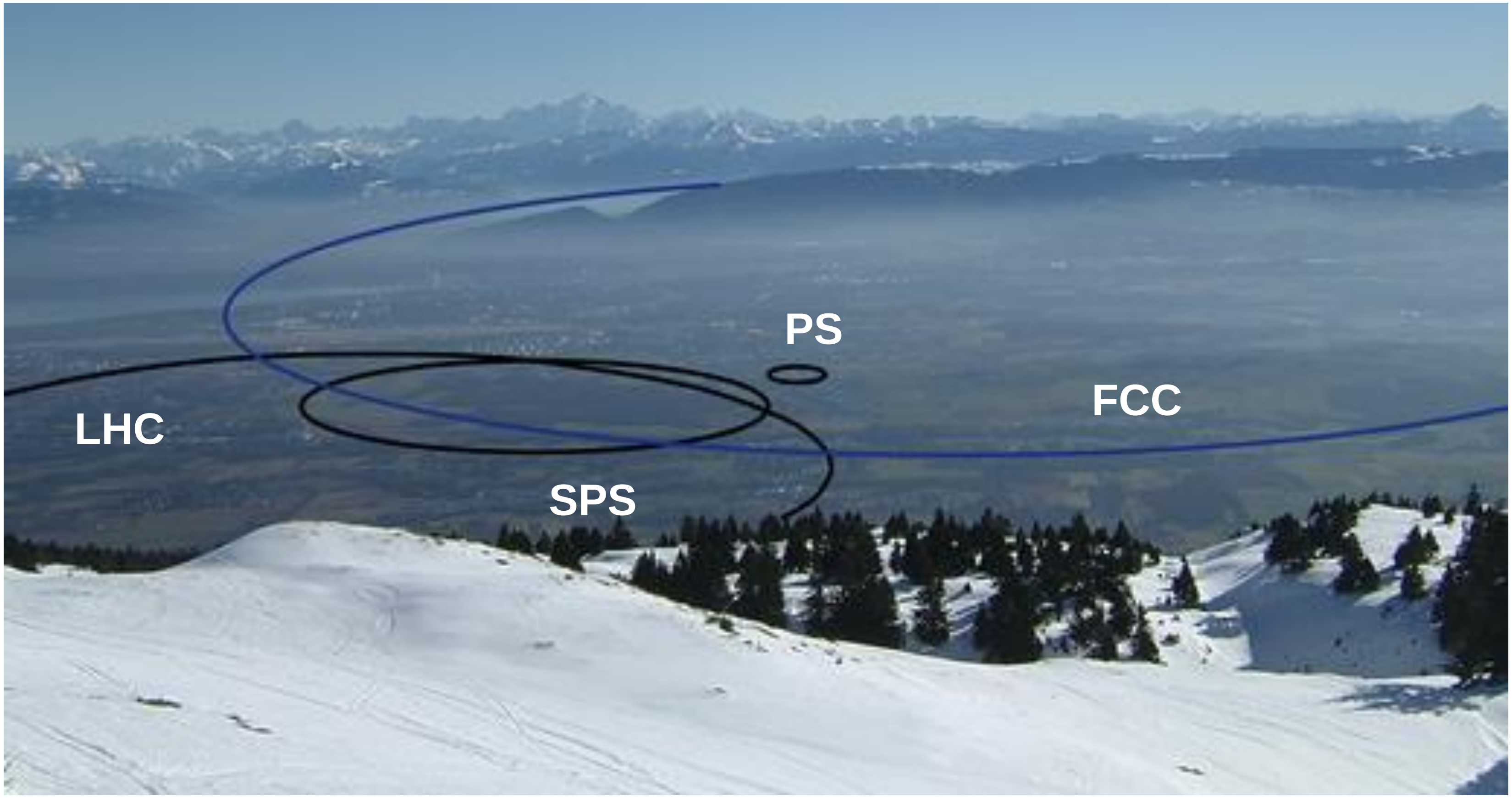
Layout of TauFV

Tungsten blades integrating to 2 mm thickness.

All detector components require excellent Radiation hardness & also ~20 ps timing resolution to suppress combinatorics during SPS spill.



Opportunities at the Z pole: FCC-ee

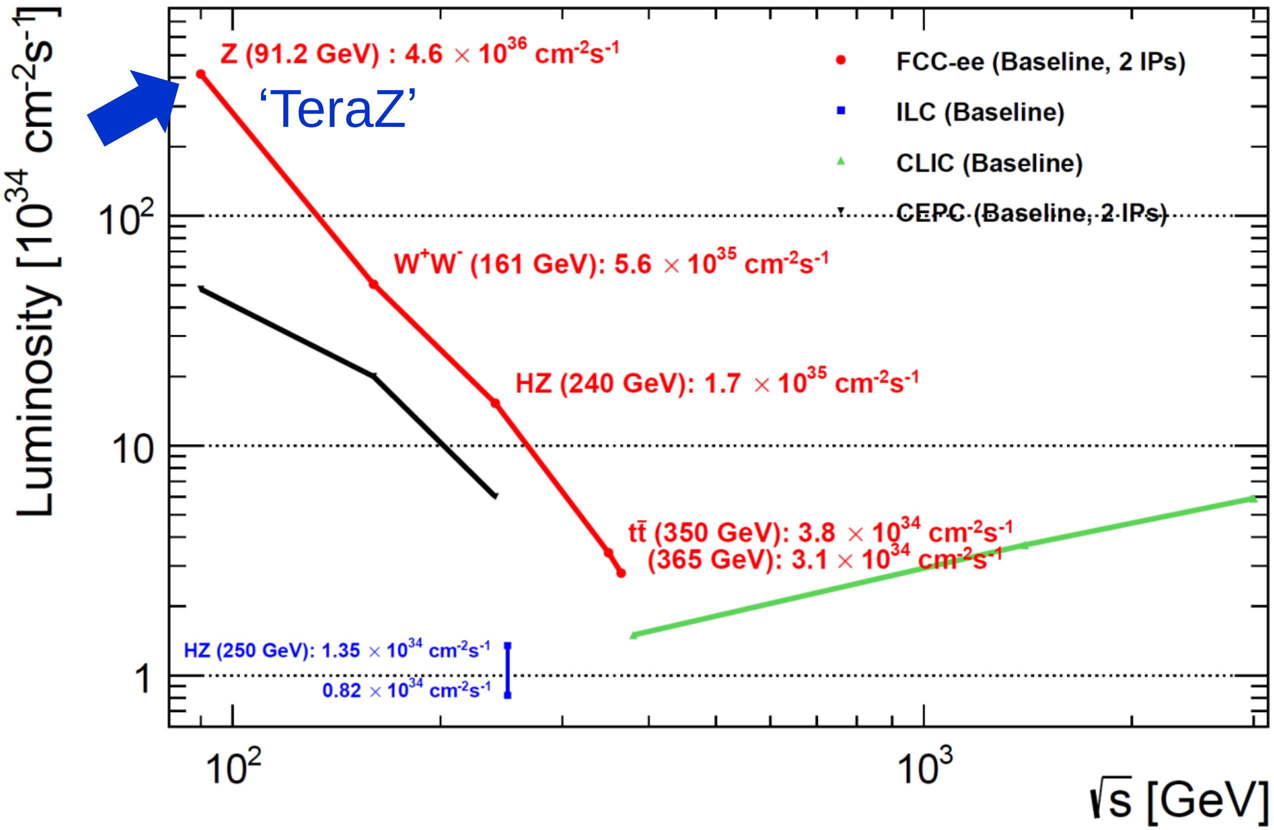


FCC-ee is a proposed e^+e^- collider for 2039→ that would run at the Z pole (91 GeV), WW threshold (161 GeV), HZ energies (240 GeV), ttbar energies (350 & 365 GeV).

(CEPC is a parallel Chinese project, with shorter timescale & ~lower design lumi.).

Opportunities at the Z pole: FCC-ee

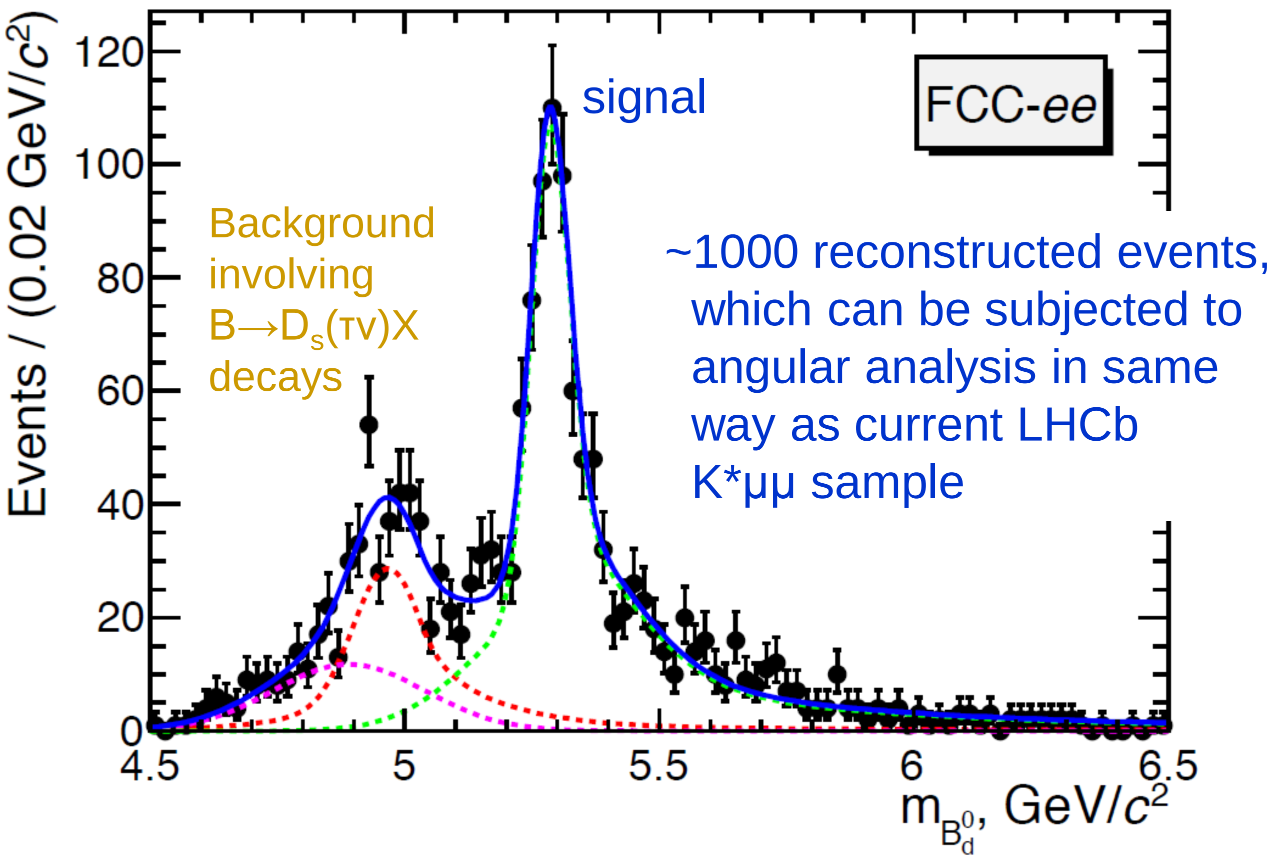
FCC-ee was initially conceived as a facility for precision-Higgs physics, but it could also operate at Z^0 with ultra-high luminosity (10^5 [!] above LEP). Extremely interesting possibilities for electroweak physics, and also b-physics.



arXiv:1906.02693

Opportunities at the Z pole: FCC-ee

100 ab^{-1} at Z pole → $>10^{12}$ bbar pairs. Exciting b-physics programme, particularly promising for channels including neutrals & missing energy, *e.g.* $B_s \to \tau^+\tau^-$, $B^0 \to K^* \tau^+\tau^-$.



Conclusions

The last ~20 years has delivered a rich and extensive set of results in the field of quark-flavour physics

The measurements are important because they both address many of the open questions of the Standard Model, and they are intrinsically sensitive to very high mass scales.

The programme is ongoing. Belle II and the LHCb Upgrades will bring great leap forwards in precision, and will make new observables accessible. New experiments in very different facilities will bring complementary information.

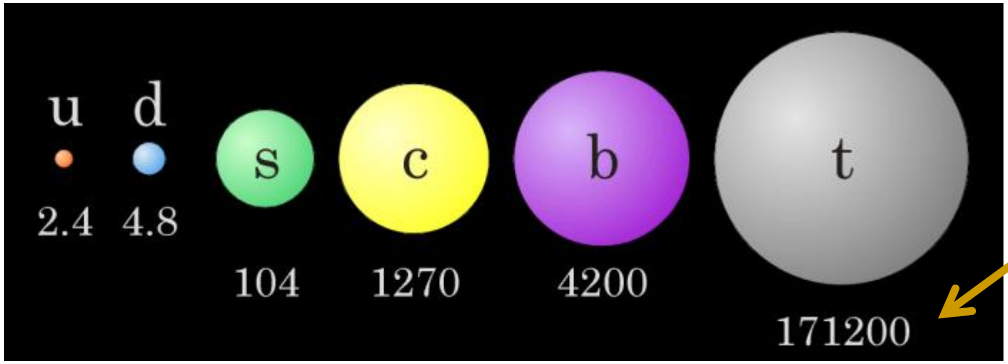
We are truly living through a golden age of flavour !

Backups

What is flavour physics?

The concept of 'flavour' in particle physics relates to the existence of different families of quarks*, and how they couple to each other

i.e. 6 known flavours of quark, grouped into 3 generations



Not to linear scale !

mass in MeV/c^2

Open questions:

- why 3 generations ?
- why do the quarks exhibit this striking hierarchy in mass ?

No answer yet !
These values (i.e. '3' & the masses) are free parameters of the SM

These mysteries make the 'flavour sector' of the Standard Model of great interest.

* the concept of flavour extends to the lepton sector too

Flavour and the CKM matrix

In the Standard Model quarks can only change flavour through emission of a W boson (*i.e.* weak force). For example a t quark can decay into a b, s or d quark:

But these decays are not equally likely. At the amplitude level they are weighted by factors that are elements of the Cabibbo-Kobyashi-Maskawa (CKM) matrix, and these factors vary dramatically – here is another hierarchy we don't understand !

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

These elements of the CKM matrix are also fundamental parameters of the Standard Model. Why they have these values is another great mystery.

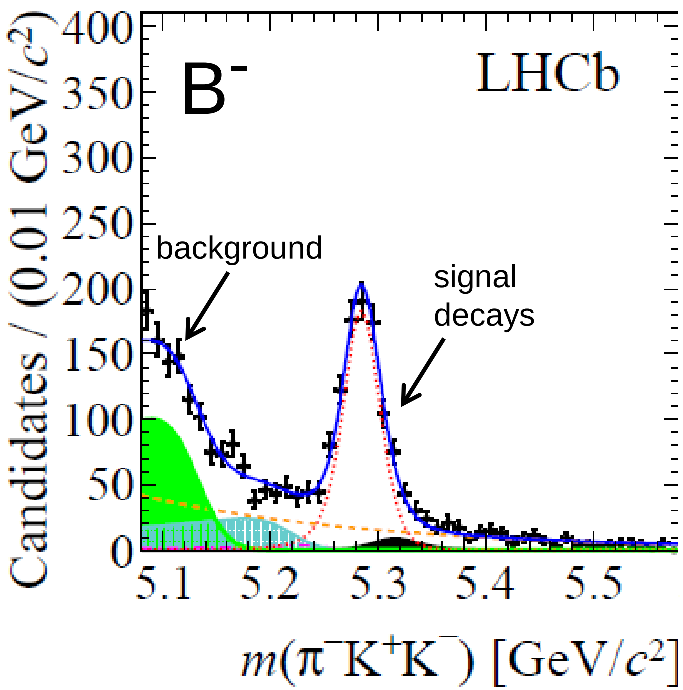
The CKM matrix is also linked to another big puzzle of flavour physics…

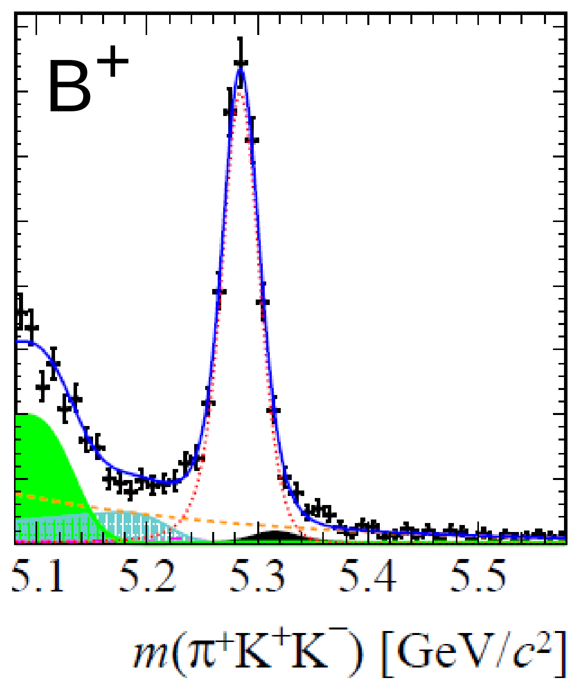
CP violation

CP violation (CPV) → difference in behaviour between matter and anti-matter.

First discovered in the kaon system in 1964, opportunities of study were limited until colliders arrived that could make lots & lots of *b*-quark hadrons, *e.g.* the LHC

A recent example from LHCb - look at *B* meson decaying into a pion & two kaons…



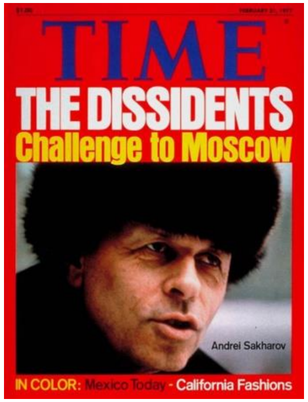


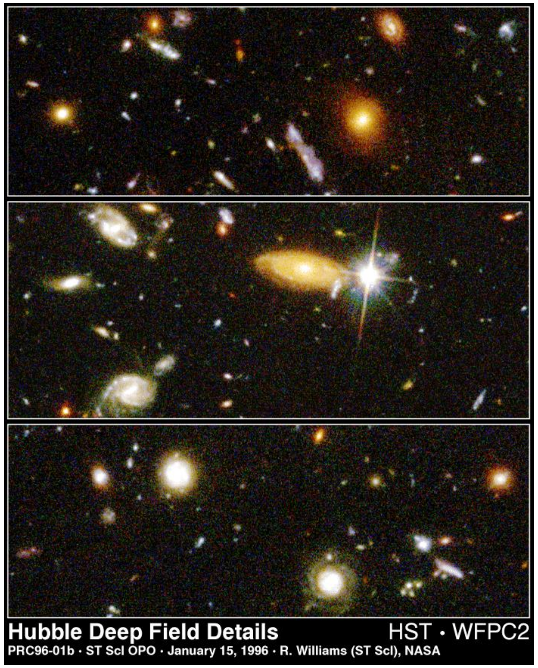
[LHCb, PRD 90 (2014) 112004]

…the decay probabilities are manifestly different for B^- & B^+ ! In the Standard Model CPV is accommodated, *but not explained*, by an imaginary phase in the CKM matrix

Cosmological connections ?

As first pointed out by Andrei Sakharov, CP-violation is one requirement for explaining *baryogenesis* – the process that took us from the equal amounts of matter and anti-matter produced in the Big Bang, to the matter dominated universe of today





The problem is that the CP-violation that appears in the Standard Model, is woefully inadequate to explain the matter-antimatter asymmetry we have today.

This is a big problem with the Standard Model !

More & better measurements
may point a way forward.

Problems with the Standard Model

The Standard Model (SM) cannot be a final theory

We have already encountered the following shortcomings:

- No explanation for baryogenesis
- No explanation for the quark or CKM hierarchy
- No real explanation for CP violation, and why it is only found in the weak interaction.

And there are plenty of others, for example:

- No explanation for dark matter or dark energy
- No explanation for neutrino masses
- Gravity not included
- No explanation for why the Higgs boson has the mass it does (left to itself the theory would make it much, much heavier)

More ambitious theories (*e.g.* supersymmetry or SUSY) can solve at least some of these problems. They generally predict new particles or effects outside the SM. Finding these effects is the goal of the LHC & many other present/planned facilities !

$B^0 \to K^* l^+ l^-$ 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 ?

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

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- Recently updated with improved analysis and adding 2 fb^{-1} of Run 2 data [PRL 122 (2019) 191801]

$$R_K = 0.846\,^{+0.060}_{-0.054}\,^{+0.016}_{-0.014}$$

Higher central value, but still 2.5σ low !

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Higher central value, but still 2.5σ low !

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

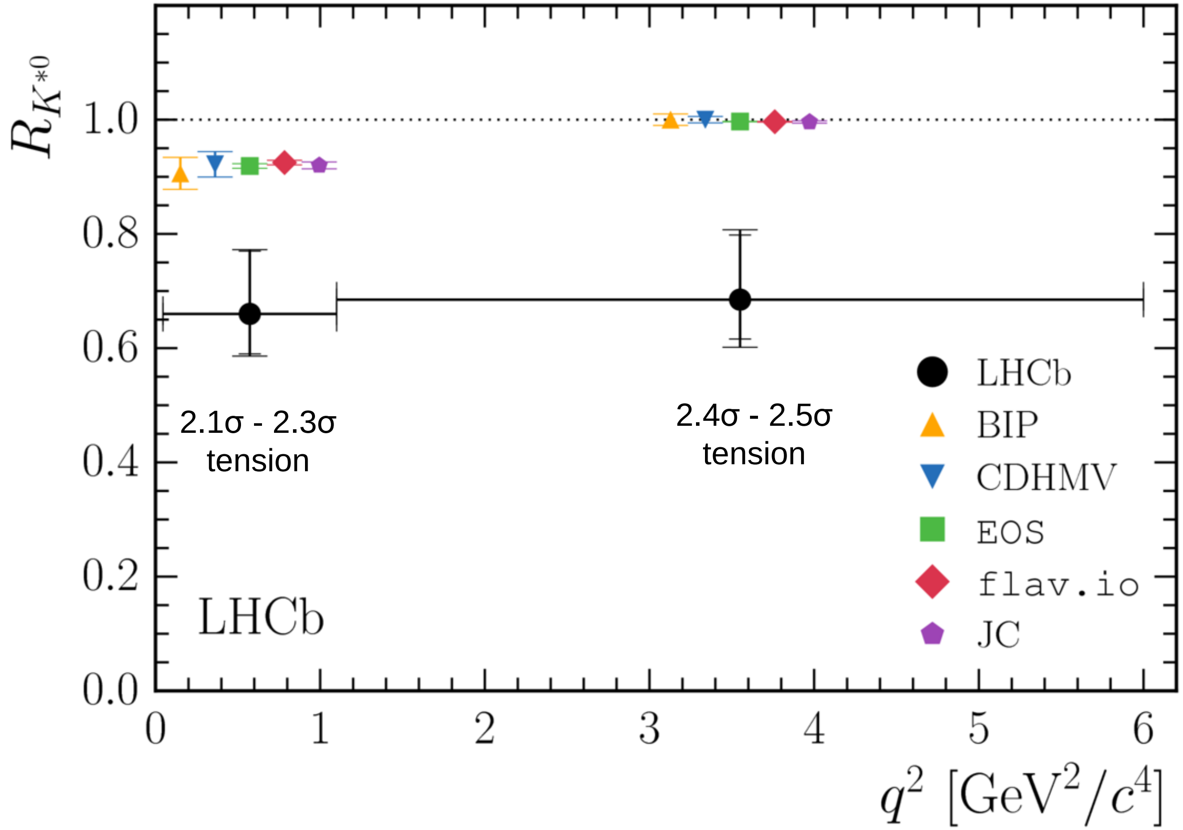
$$\mathcal{R}_{K^{*0}} = \frac{\mathcal{B}(B^0 \to K^{*0}\mu^+\mu^-)}{\mathcal{B}(B^0 \to K^{*0}J/\psi(\to \mu^+\mu^-))} \Bigg/ \frac{\mathcal{B}(B^0 \to K^{*0}e^+e^-)}{\mathcal{B}(B^0 \to K^{*0}J/\psi(\to e^+e^-))}$$

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).

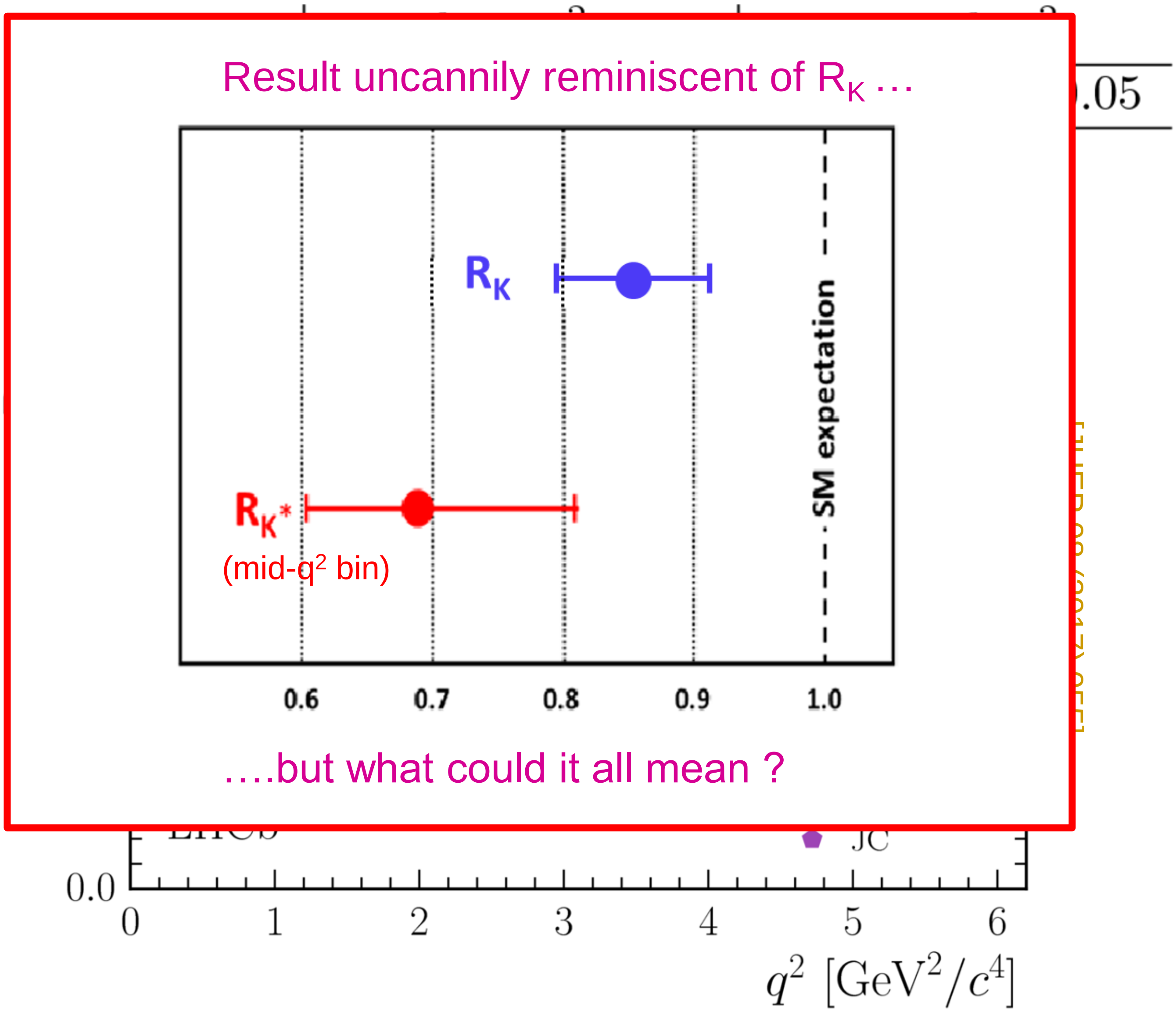
$B^0 \to K^* l^+ l^-$ and friends: lepton universality tests R_{K*}

	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]

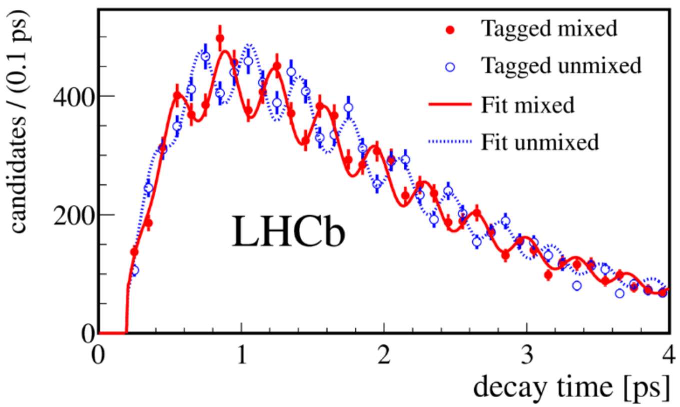
$B^0 \rightarrow K^* l^+ l^-$ and friends: lepton universality tests R_{K*}



The Unitarity Triangle

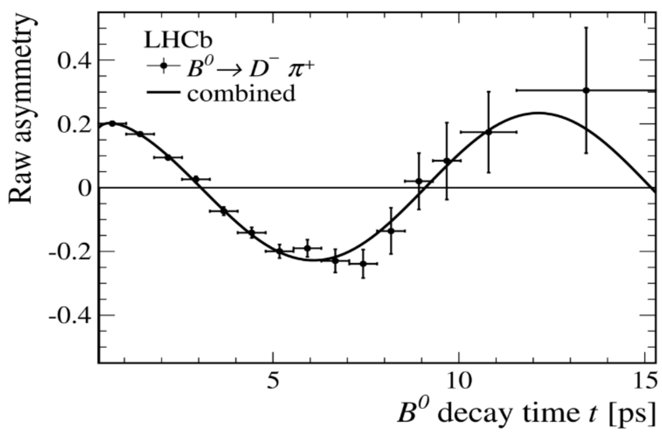
LHCb has performed many measurements relevant to the Unitarity Triangle.

B_s oscillations

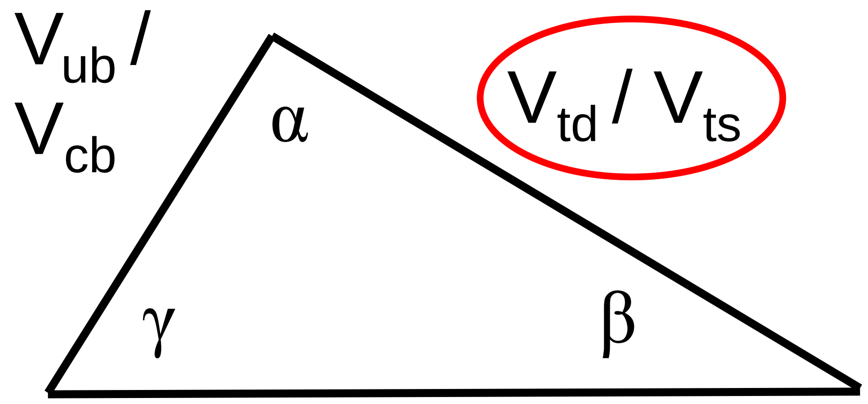


[New J. Phys. 15 (2013) 053021]

B^0 oscillations



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

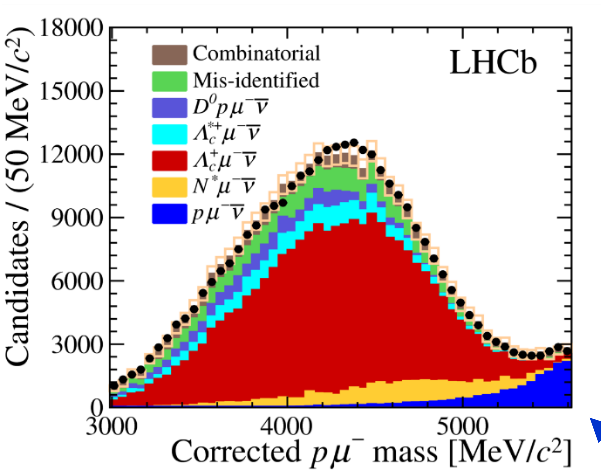


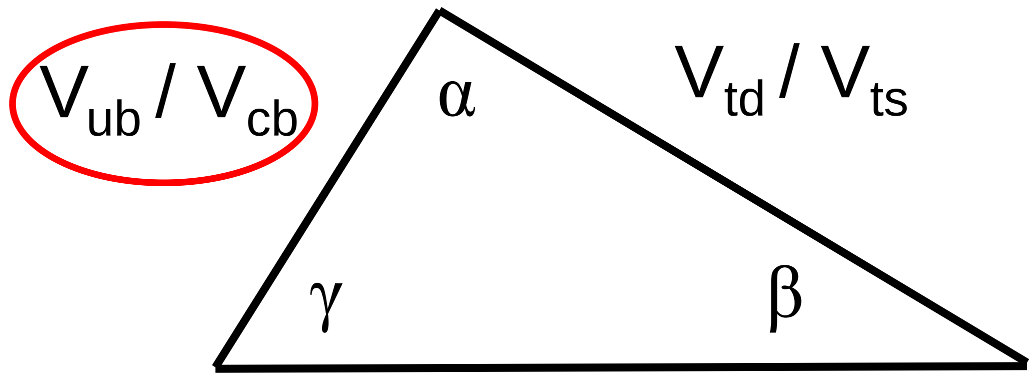
Very precise measurements of the B_s and the B^0 mixing frequency.

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.

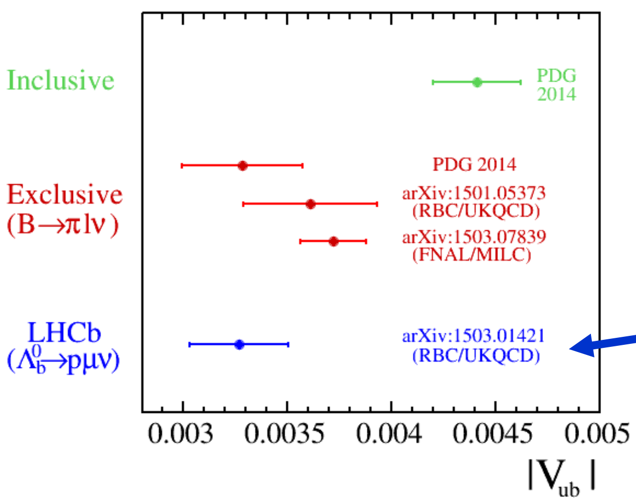
The Unitarity Triangle

LHCb has performed many measurements relevant to the Unitarity Triangle.





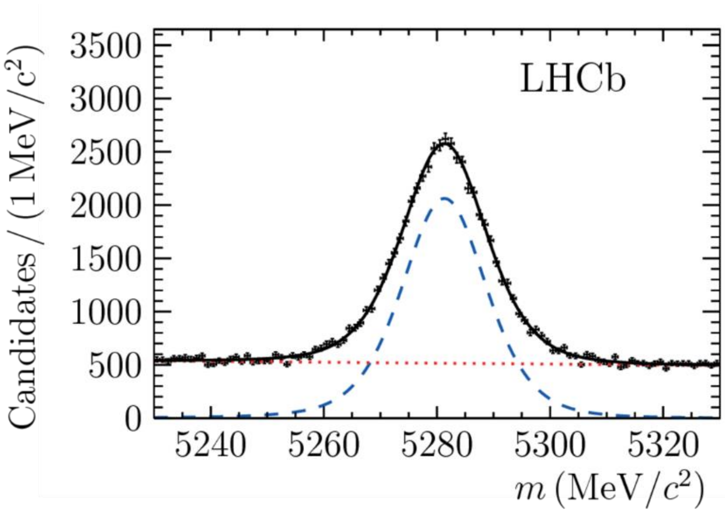
Measurement of V_{ub} through study of $\Lambda_b \rightarrow p\mu\nu$ decays [Nature Phys. 10 (2015) 1038]. *Nobody* expected the LHC to contribute to this measurement.

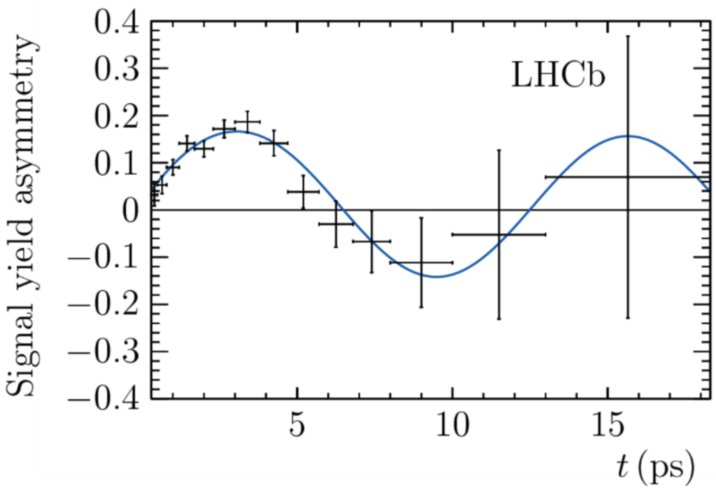


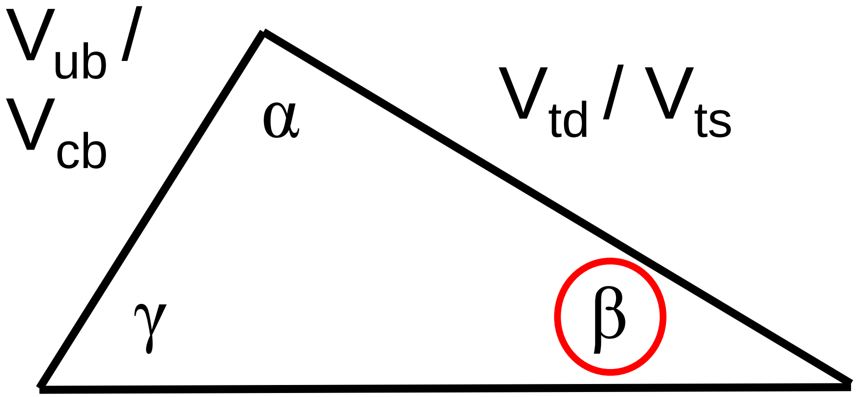
The result is very illuminating for the longstanding 'inclusive vs. exclusive' debate. Much more to come !

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.

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

(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 !

Physics reach – the obligatory table

Observable	Current LHCb	LHCb 2025	Belle II	Upgrade II	ATLAS & CMS
EW Penguins					
R_K $(1 < q^2 < 6\,\mathrm{GeV}^2c^4)$	0.1 [274]	0.025	0.036	0.007	–
R_{K^*} $(1 < q^2 < 6\,\mathrm{GeV}^2c^4)$	0.1 [275]	0.031	0.032	0.008	–
R_ϕ, R_{pK}, R_π	–	0.08, 0.06, 0.18	–	0.02, 0.02, 0.05	–
CKM tests					
γ, with $B_s^0 \to D_s^+ K^-$	$(^{+17}_{-22})^\circ$ [136]	4°	–	1°	–
γ, all modes	$(^{+5.0}_{-5.8})^\circ$ [167]	1.5°	1.5°	0.35°	–
$\sin 2\beta$, with $B^0 \to J/\psi K_S^0$	0.04 [609]	0.011	0.005	0.003	–
ϕ_s, with $B_s^0 \to J/\psi\phi$	49 mrad [44]	14 mrad	–	4 mrad	22 mrad [610]
ϕ_s, with $B_s^0 \to D_s^+ D_s^-$	170 mrad [49]	35 mrad	–	9 mrad	–
$\phi_s^{s\bar{s}s}$, with $B_s^0 \to \phi\phi$	154 mrad [94]	39 mrad	–	11 mrad	Under study [611]
a_{sl}^s	33×10^{-4} [211]	10×10^{-4}	–	3×10^{-4}	–
$\lvert V_{ub}\rvert/\lvert V_{cb}\rvert$	6% [201]	3%	1%	1%	–
$\boldsymbol{B_s^0, B^0 \to \mu^+\mu^-}$					
$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	90% [264]	34%	–	10%	21% [612]
$\tau_{B_s^0 \to \mu^+\mu^-}$	22% [264]	8%	–	2%	–
$S_{\mu\mu}$	–	–	–	0.2	–
$\boldsymbol{b \to c\ell^-\bar{\nu}_l}$ **LUV studies**					
$R(D^*)$	0.026 [215, 217]	0.0072	0.005	0.002	–
$R(J/\psi)$	0.24 [220]	0.071	–	0.02	–
Charm					
$\Delta A_{CP}(KK - \pi\pi)$	8.5×10^{-4} [613]	1.7×10^{-4}	5.4×10^{-4}	3.0×10^{-5}	–
A_Γ $(\approx x \sin\phi)$	2.8×10^{-4} [240]	4.3×10^{-5}	3.5×10^{-4}	1.0×10^{-5}	–
$x \sin\phi$ from $D^0 \to K^+\pi^-$	13×10^{-4} [228]	3.2×10^{-4}	4.6×10^{-4}	8.0×10^{-5}	–
$x \sin\phi$ from multibody decays	–	$(K3\pi)$ 4.0×10^{-5}	$(K_S^0\pi\pi)$ 1.2×10^{-4}	$(K3\pi)$ 8.0×10^{-6}	–

New Physics sensitivity through FCNCs

Improving sensitivity to the Wilson coefficient C_9 and the corresponding limits on New Physics mass scales, under different assumptions, from R_K and R_{K^*} .