The flavour frontier: searching for New Physics through studies of quark transitions

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Alternative title: The quest for truth through beauty

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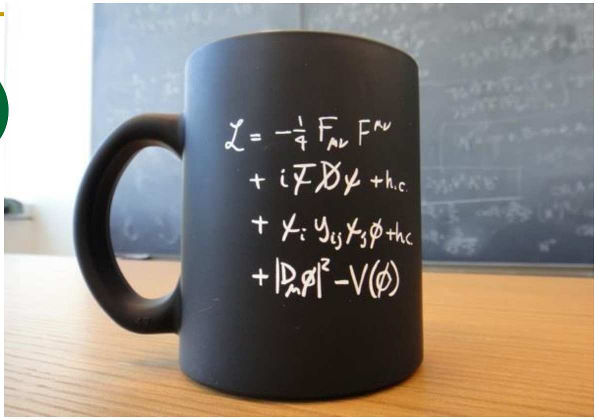
Outline

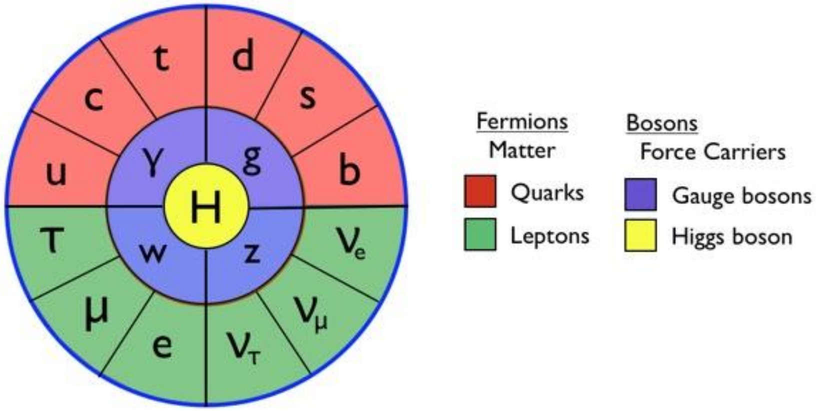
- The Standard Model and the role of 'flavour'
- The LHCb experiment
- Selected results: snapshot on three topics of interest
- The future of flavour

The Standard Model and the role of 'flavour'

The Standard Model (SM)



The Standard Model of particle physics is a quantum-field theory that describes the fundamental particles, plus the electromagnetic, weak & strong interactions



Particles of the Standard Model

CERN, July 2012

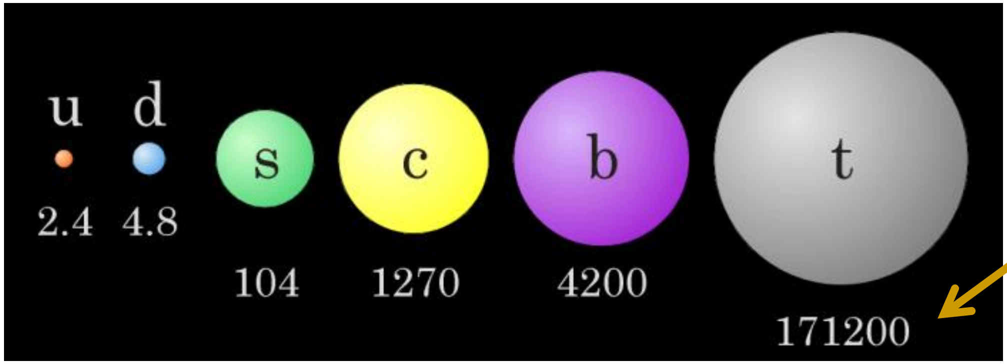
All tests made of the Standard Model in particle colliders have been successful !
The most spectacular recent example was the discovery of the Higgs boson.

One very important part of the theory is the ‘flavour sector’ & its associated physics.

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

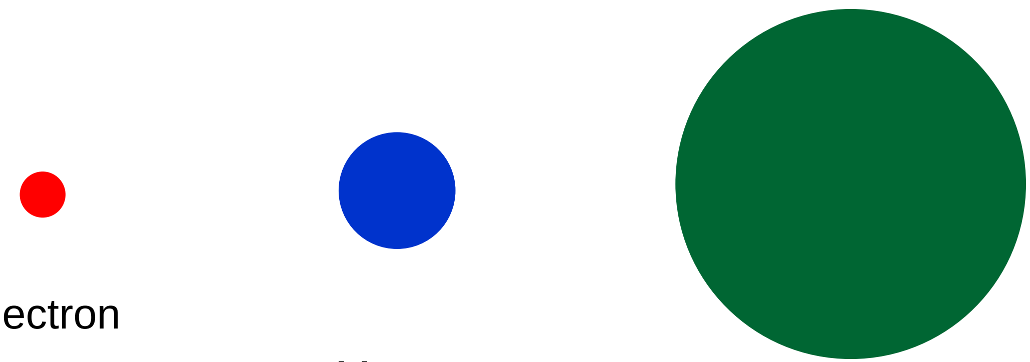
Open questions:
- why 3 generations ?
- why do the quarks exhibit this striking hierarchy in mass ?

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

No answer yet ! These values (i.e. '3' & the masses) are free parameters of the SM. We presume they are explained by some, as yet unknown, deep-lying symmetry.

What is flavour physics?

Leptons are fundamental particles that do not experience strong force.
Again, there are three generations of charged leptons:



Not to linear scale !

Electron

mass 0.5 MeV/c^2

Muon

mass 106 MeV/c^2

Tau

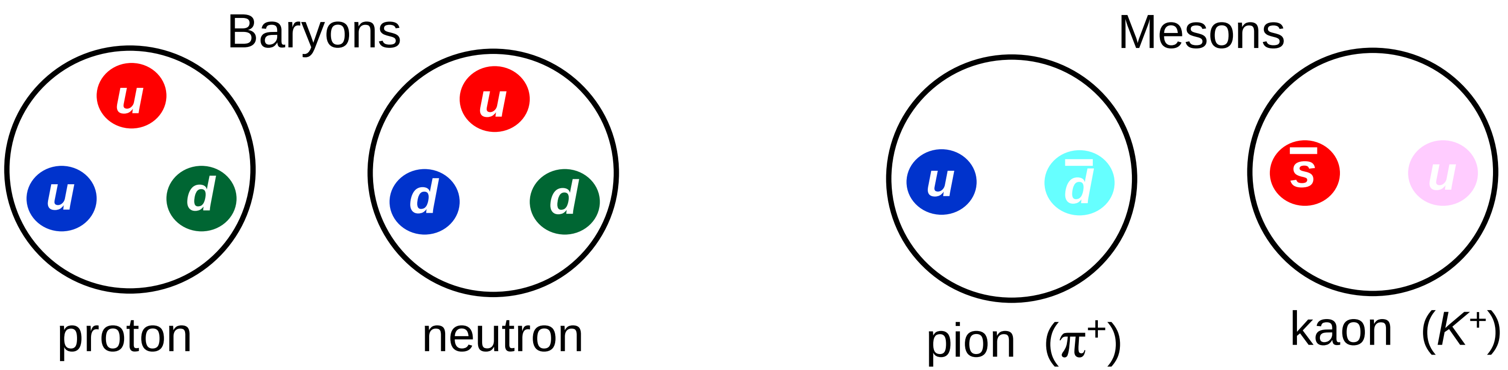
mass 1777 MeV/c^2

Once more: why three generations, and why the hierarchy in masses ?

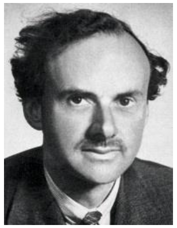
(Note we are not even discussing the neutral leptons, which are the neutrinos. These bring many many puzzling questions of their own.)

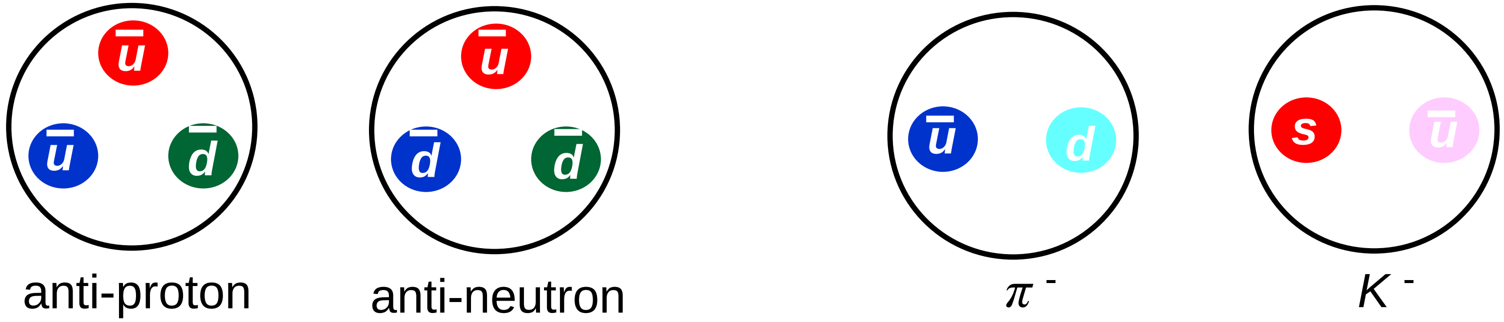
By the way, we can't study quarks in isolation…

The nature of the strong force does not allow the quarks to exist in isolation.
Rather we find them bound together in hadrons, in either baryons or mesons.



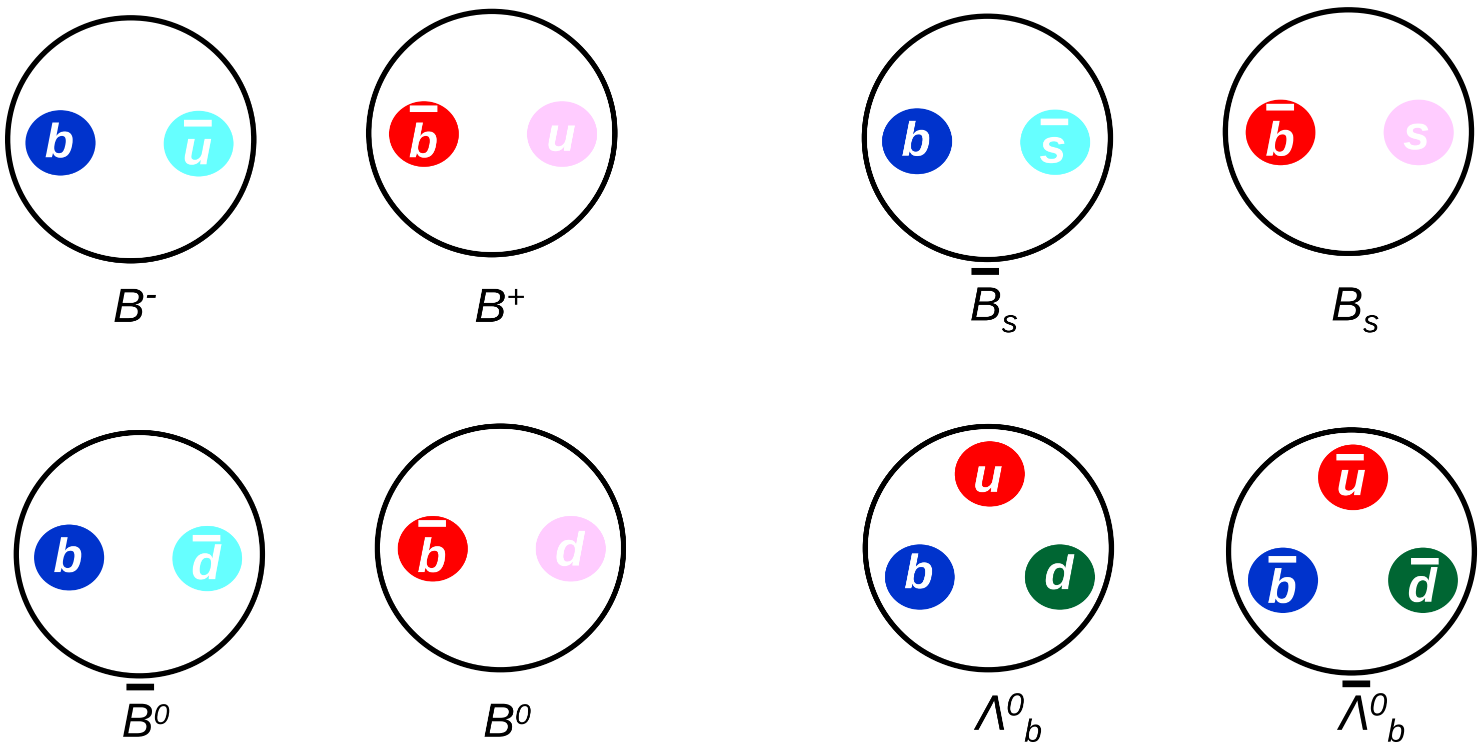
Note the 'anti-quarks' in the mesons. Anti-particles were predicted by Paul Dirac back in 1928 (although we didn't know about quarks then). Indeed, we can have 'anti-hadrons' too:





By the way, we can't study quarks in isolation…

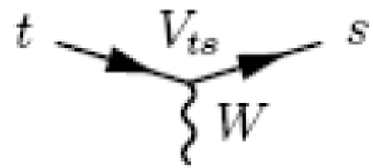
Much of our discussion will be focused on *b*-hadrons, so lets look at a few.



One other thing… all hadrons (apart from protons) are unstable and decay in to lighter particles. From these decays we can learn valuable lessons.

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:



(These are Feynman diagrams, excellent for visualising what is happening at the quark level.)

quark we start with

quark we end with

emitted *W* boson

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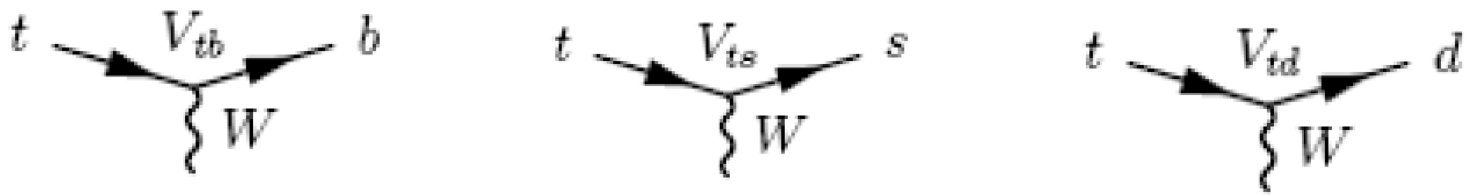


But these decays are not equally likely. At the amplitude level they are weighted by factors that are elements of the Cabibbo-Koboyashi-Maskawa (CKM) matrix, and these factors vary dramatically – here is another hierarchy we don't understand !

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ \boxed{V_{td} \quad V_{ts} \quad V_{tb}} \end{pmatrix} = \begin{pmatrix} 0.974 & 0.225 & 0.004 \\ 0.225 & 0.973 & 0.041 \\ \boxed{0.009 \quad 0.041 \quad 0.999} \end{pmatrix}$$

Decay probabilities depend on *square* of these values.

These elements of the CKM matrix are also fundamental parameters of the SM. Why they have these values is another great mystery we have not solved.

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

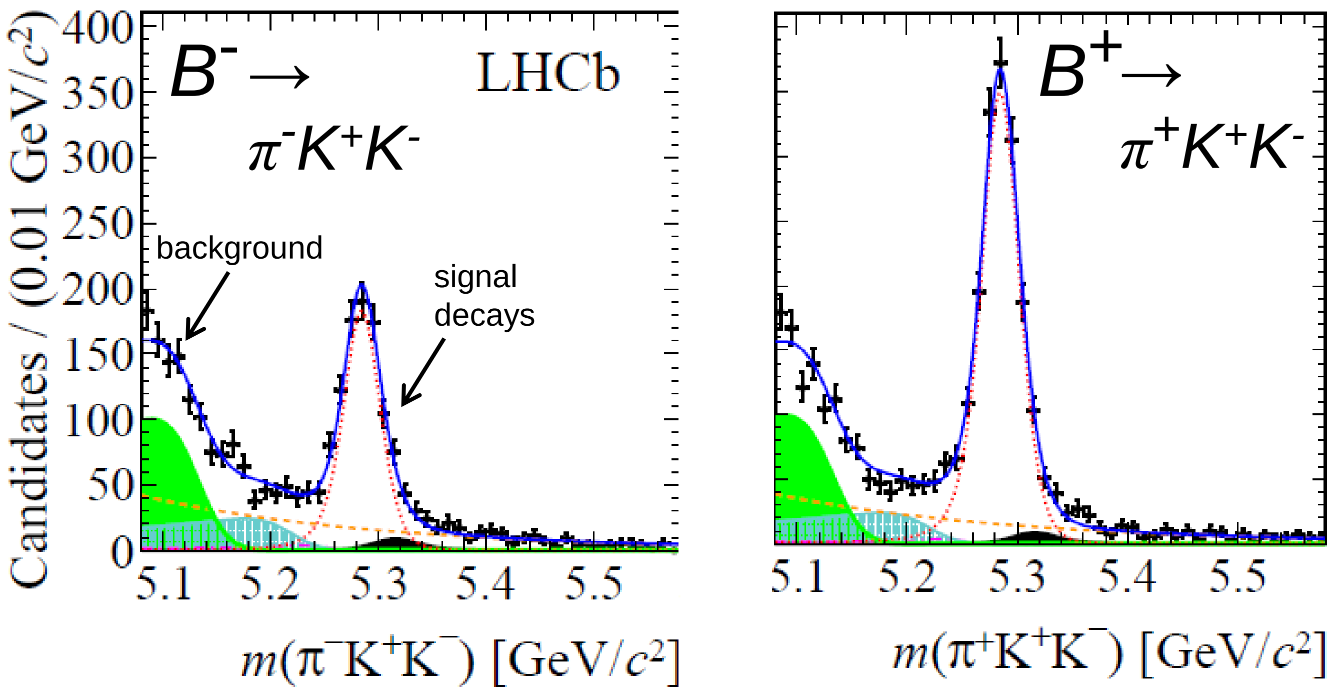
(NB values of CKM matrix not perfectly known, but here range of uncertainties are omitted for clarity)

CP violation… and the beauty of b-hadrons

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

First discovered in decays of kaon mesons in 1964, opportunities of study were limited until colliders arrived that could make lots & lots of beauty (*b*-quark) hadrons

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

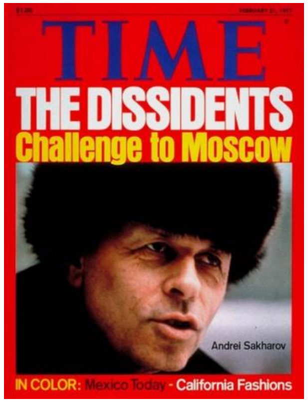


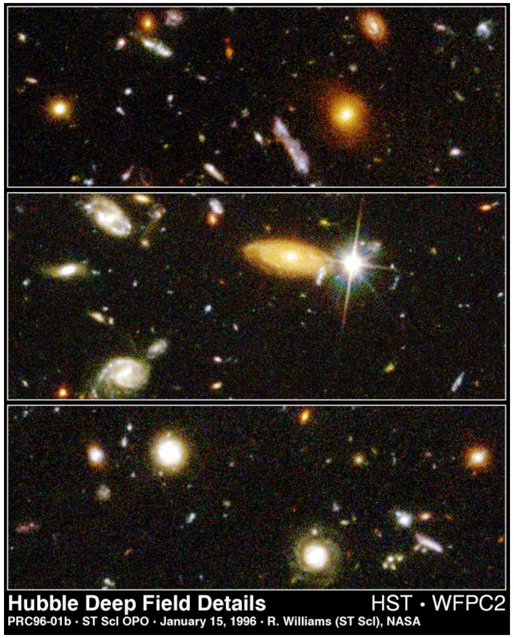
[LHCb, PRD 90 (2014) 112004]

…the decay probabilities are manifestly different for B^- & B^+ ! CPV is accommodated in the SM, *but not explained*, by an attribute of the CKM matrix ('imaginary phase').

Cosmological connections ?

As far as we can tell, the universe is almost entirely made of matter. In the Big Bang matter and antimatter would have been created equally. A process called ***baryogenesis*** occurred, which took as from this initial state to the matter dominated universe of today. As first pointed out by Andrei Sakharov, one requirement for this to happen is CP violation !





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 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.

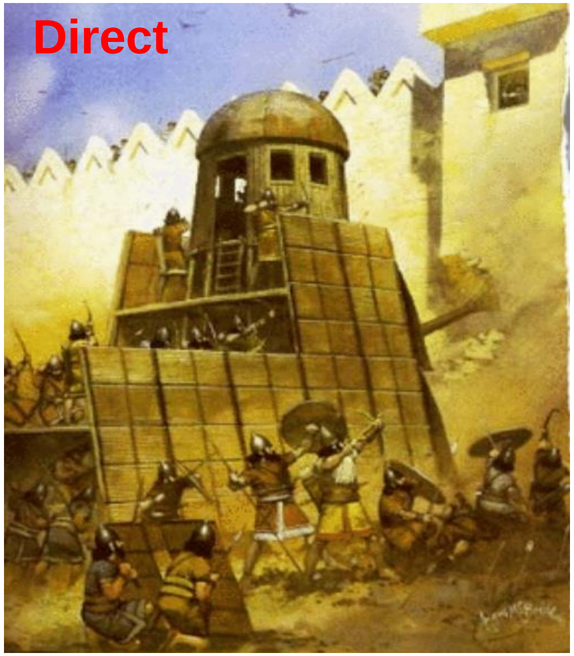
And there are plenty of others, for example:

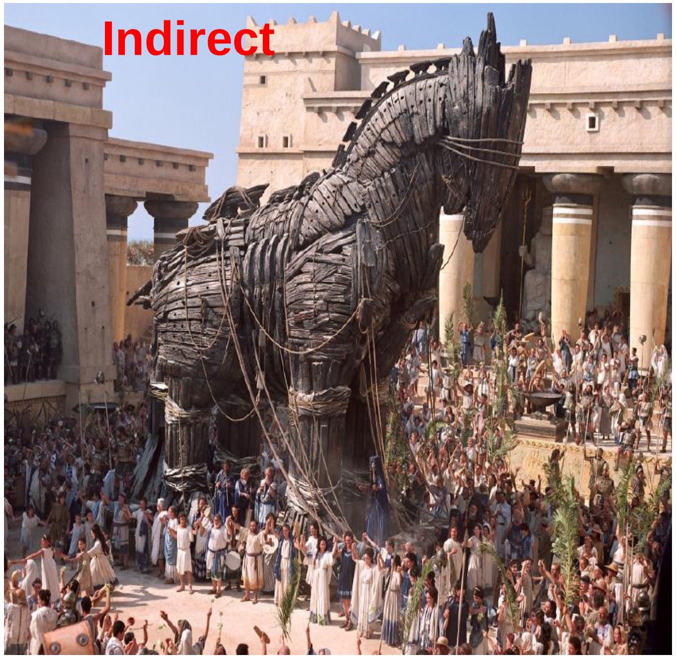
- No explanation for dark matter or dark energy
- No explanation for neutrino masses
- Gravity not included
- No explanation for why the Higgs boson has the mass it does (left to itself the theory would make it much, much heavier)

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. The goal of the LHC is to search for evidence of this 'New Physics' !

Attacking the fortress 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





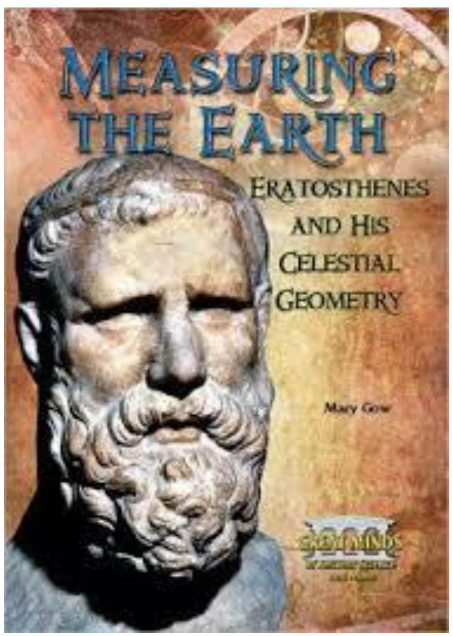
Use the high energy of the LHC to produce the New Physics particles, which we then detect

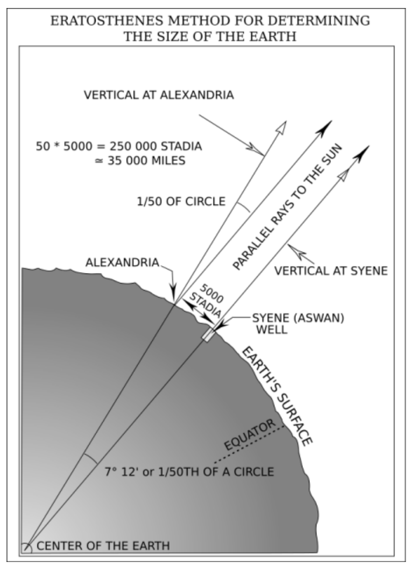
Make precise measurements of processes in which New Physics particles enter through 'virtual loops'

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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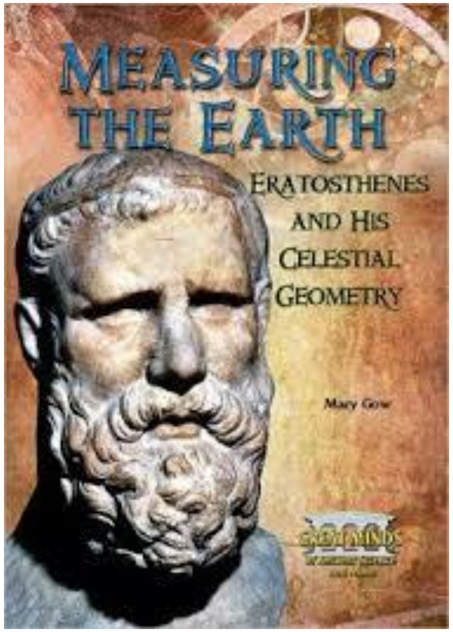
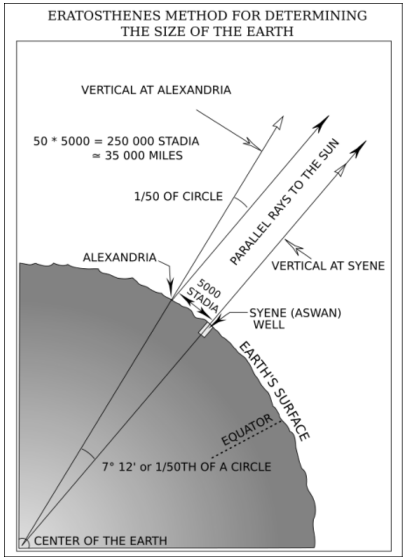
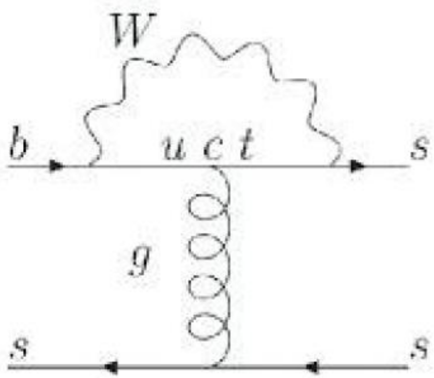


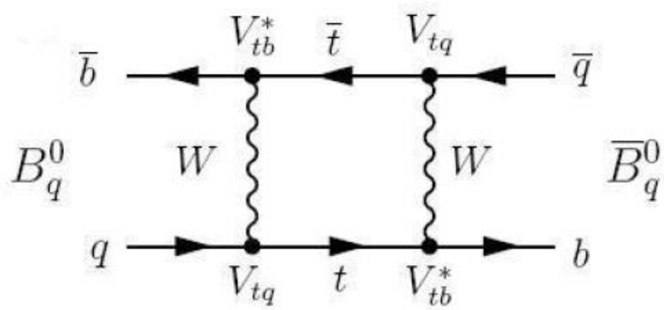


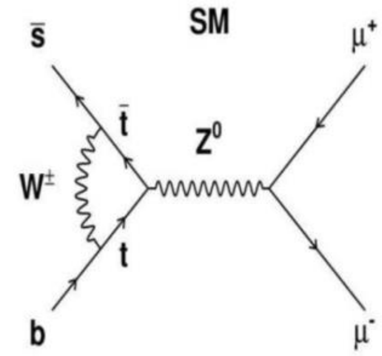
…around 2.2 thousand years
prior to the direct observation.

Loop diagrams & ‘indirect searches’

For some processes, especially suppressed decays, more complicated Feynman diagrams are important. These contain ‘loops’ in which *virtual particles* participate







Decays, & other processes, involving *b*-quarks are a good place to study role of these loops. In the loops the contribution of heavy particles, *e.g.* top, is important, even though $m_t >> m_b$. Hence these decays tells us about the particles in the loops.

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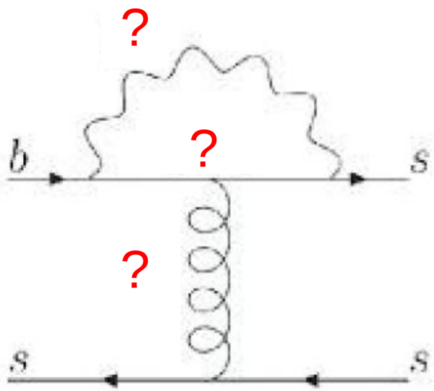

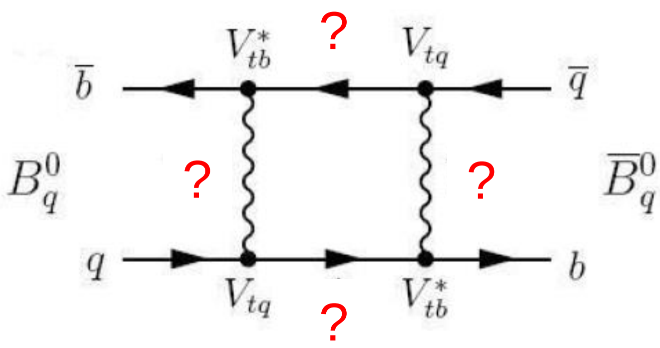

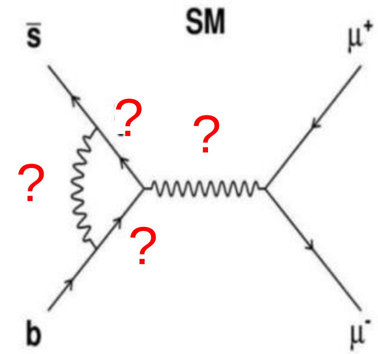

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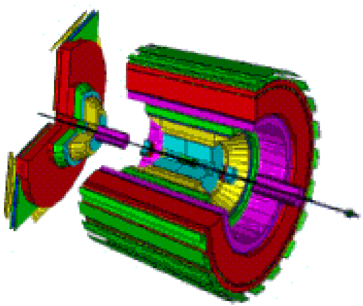
As drawn above, the loop contains Standard Model particles***, but New Physics particles could also contribute***, affecting decay rates, CP violation *etc* !

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

Making beauty

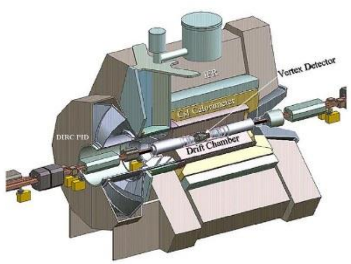
Since the first discovery of hadrons containing *b*-quarks, back in 1977, accelerators have been constructed which have produced beauty hadrons in ever increasing numbers. Good news for the physics, as many of the measurements we wish to perform are of very rare decay processes. Large samples are essential !

LEP experiments,
CERN, 1990s
$e^+e^- \to Z^0 \to b\bar{b}$



\# of $b\bar{b}$ produced
~ 1 million / year

BaBar experiment,
SLAC, California, 2000s
$e^+e^- \to Y(4S) \to b\bar{b}$



~ 100 million / year

LHC,
CERN, 2010s→
$pp \to b\bar{b}X$

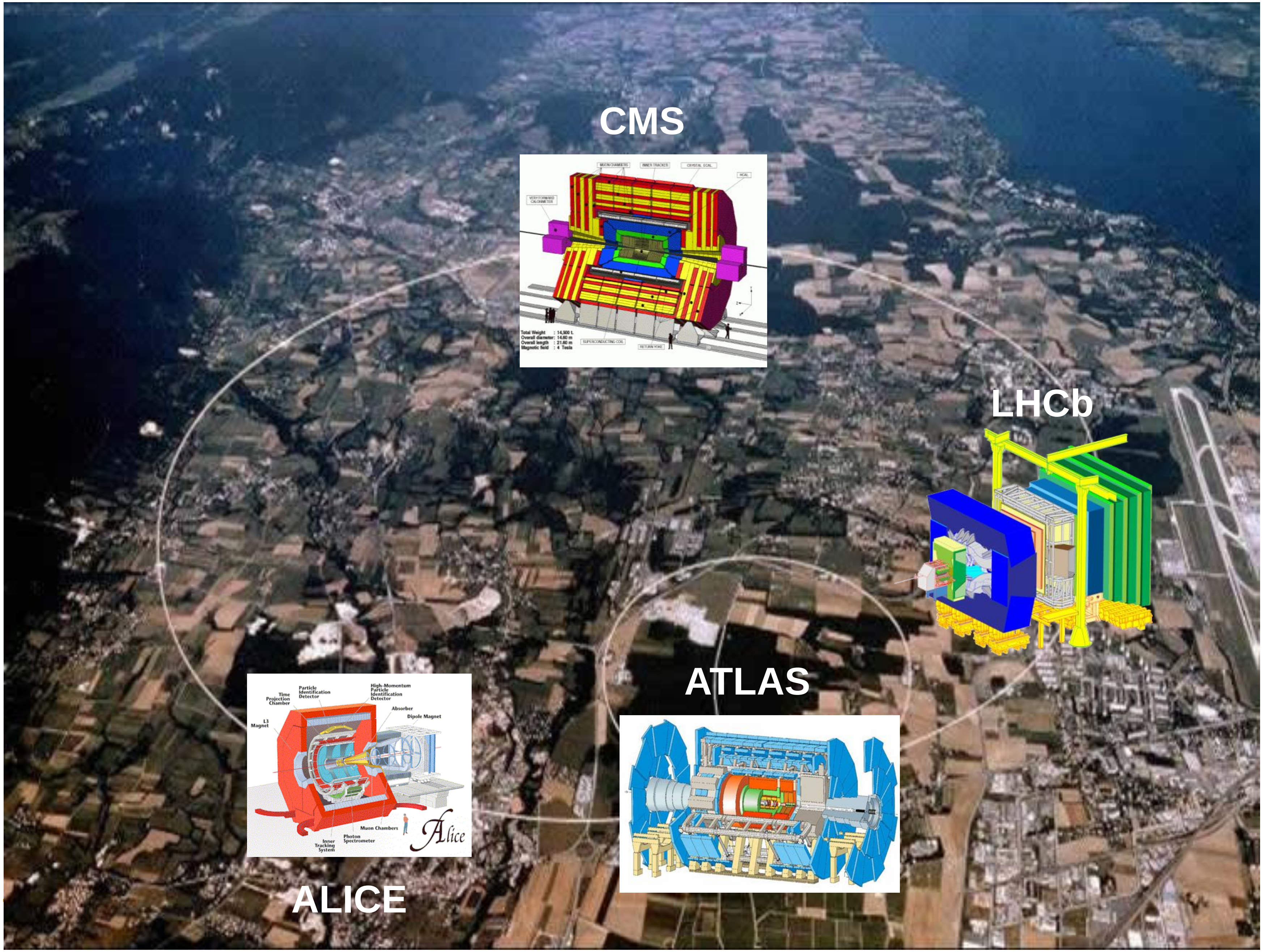
~1000 billion / year *

* produced at LHCb interaction point

So on top of all its attributes as a machine for producing Higgs bosons and (maybe) new, exotic, particles, the LHC also happens to be a beauty factory !

LHCb is a dedicated experiment designed to exploit fully this rich resource.

The LHCb experiment

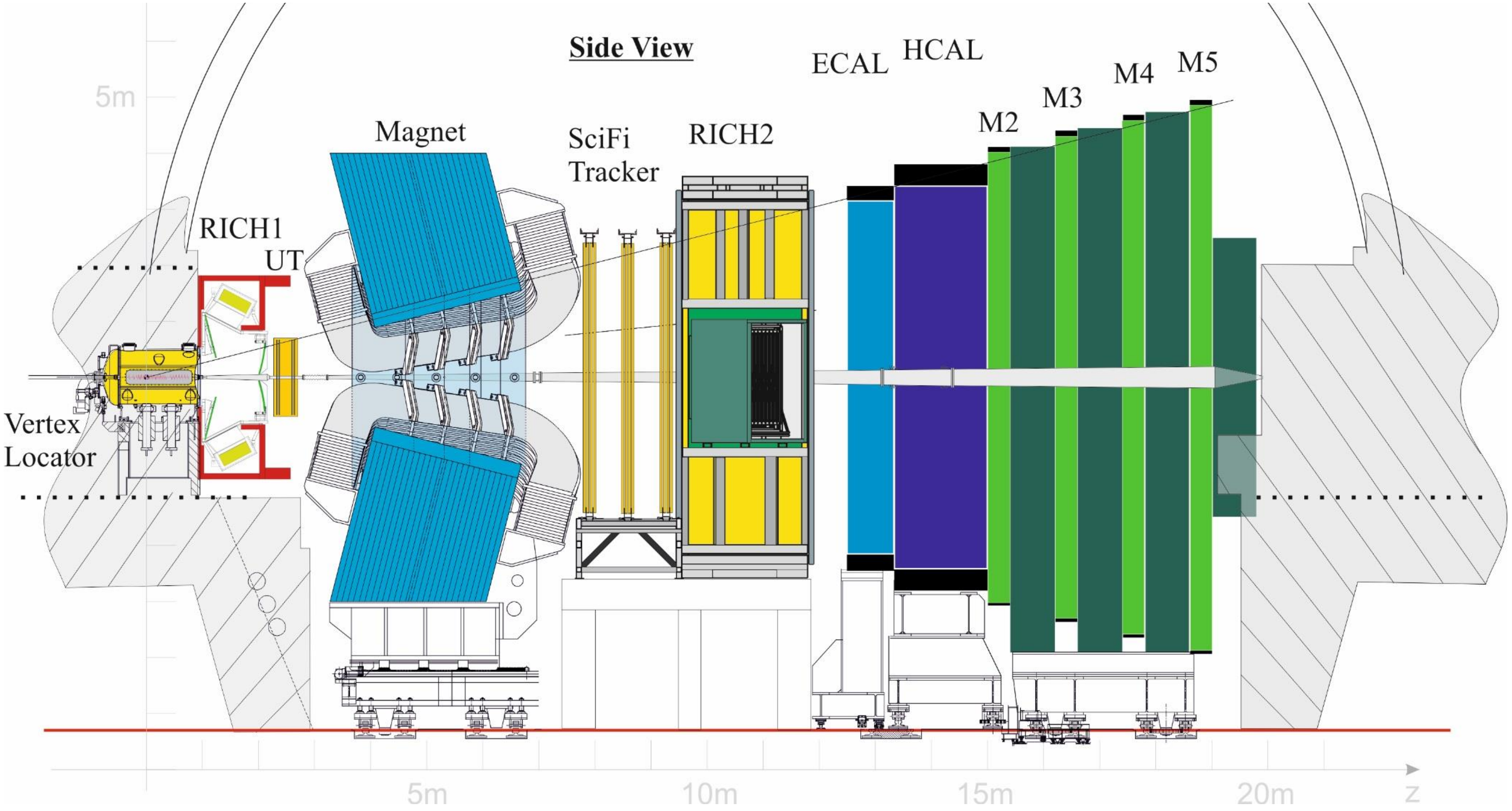

CMS
LHCb
ATLAS
ALICE
Alice

LHCb – a flavour physics experiment at the LHC

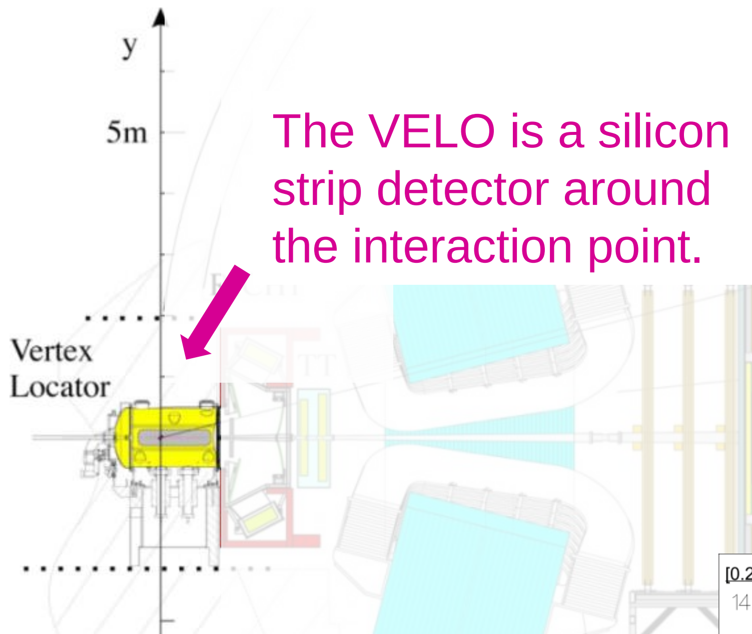
A collaboration of ~1800 members from 105 institutes in 25 countries, of which 10 institutes are from China.

An experiment to search for physics beyond the **Standard Model**, through **flavour** studies of particles containing **beauty** (**b**) and **charm** (**c**) quarks.

LHCb – a forward spectrometer for flavour physics: Runs 3 and 4 (Upgrade 1)



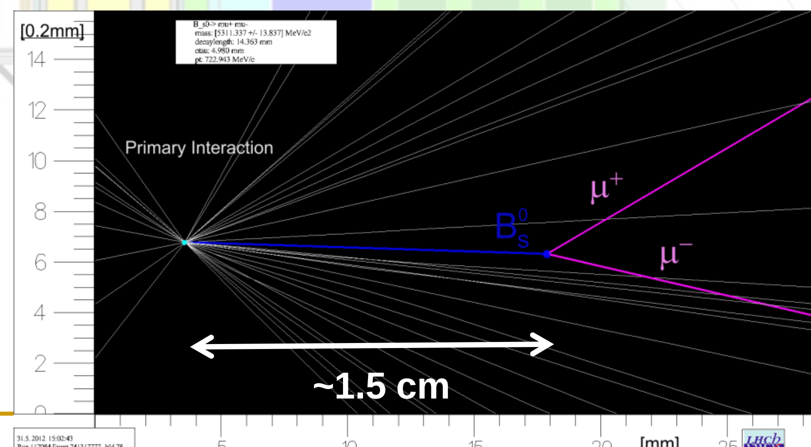
LHCb – vertex locator (VELO)



The VELO is a silicon strip detector around the interaction point.

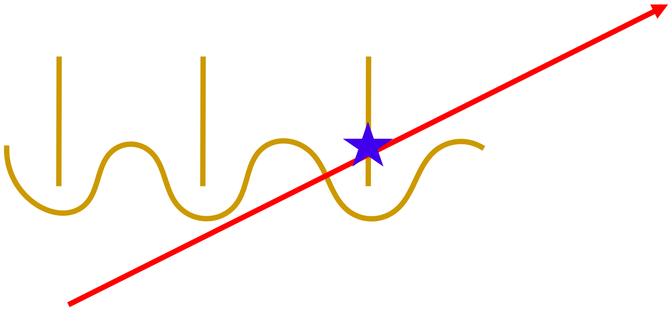
One-half of the Run 1 & 2 VELO under construction

It approaches within 5 mm of the beamline, sits in a secondary vacuum, and reconstructs the *b*-hadron decay vertex precisely.



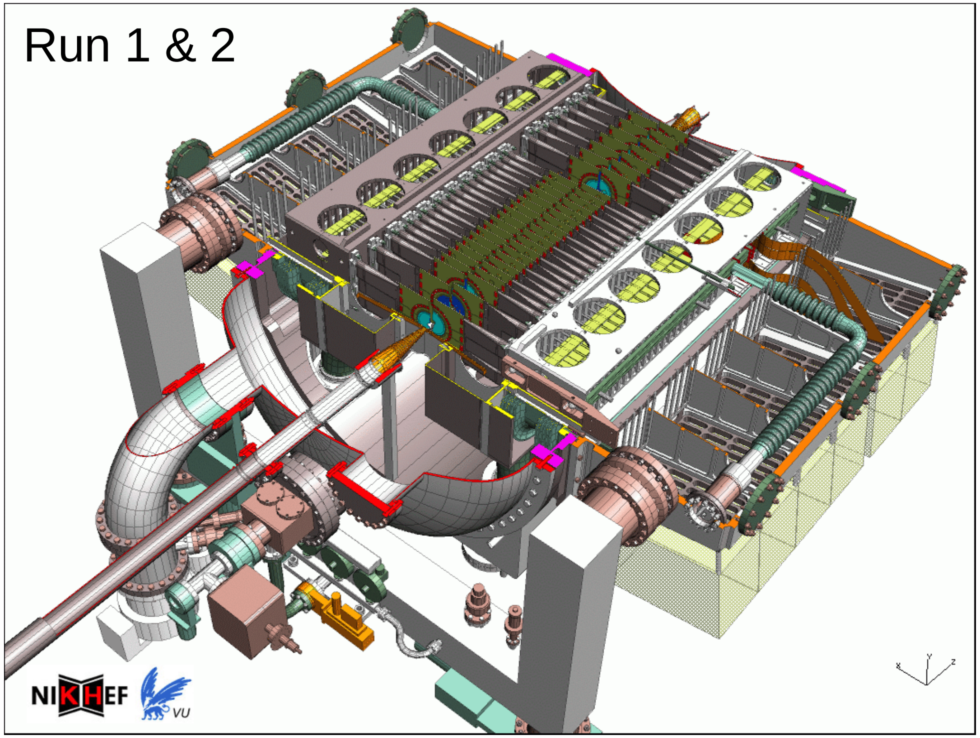
A reconstructed *b*-hadron decay vertex

VELO – close to beam

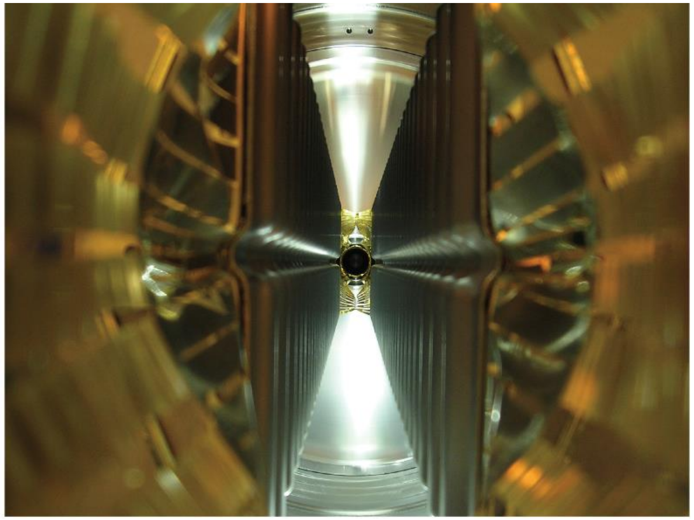


VELO is moveable and operates in vacuum.
The RF foil "beampipe" surrounding it
is ultra-thin, and corrugated.

Track passes through RF foil perpendicularly – good for multiple coulomb scattering.



What the protons see in injection



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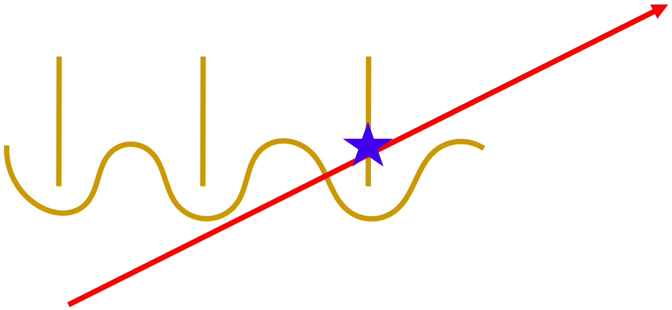

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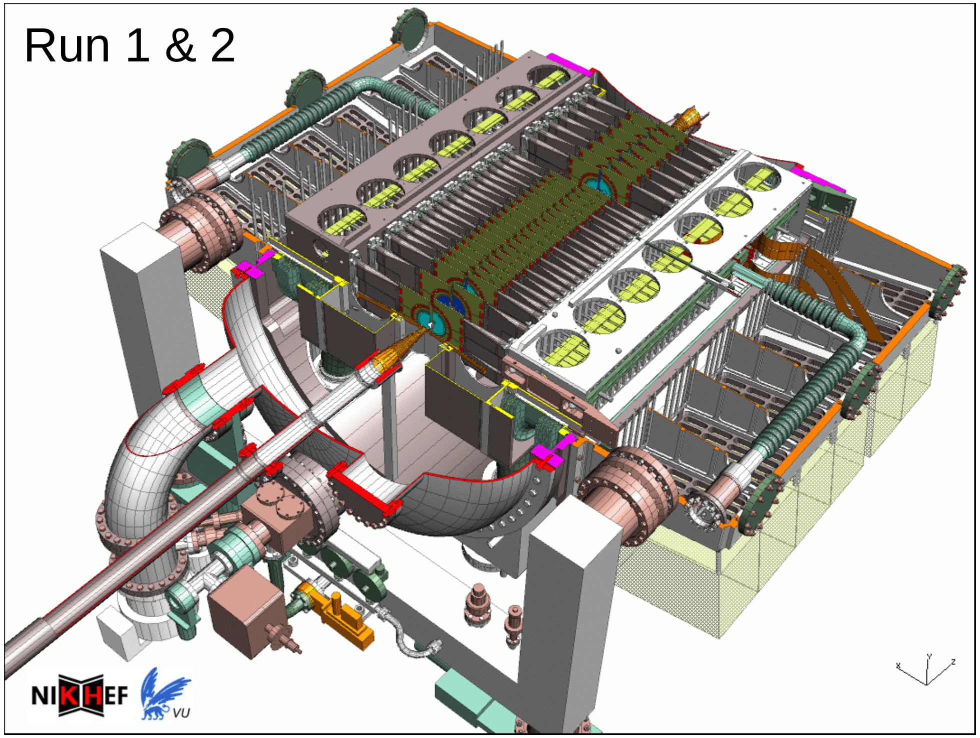
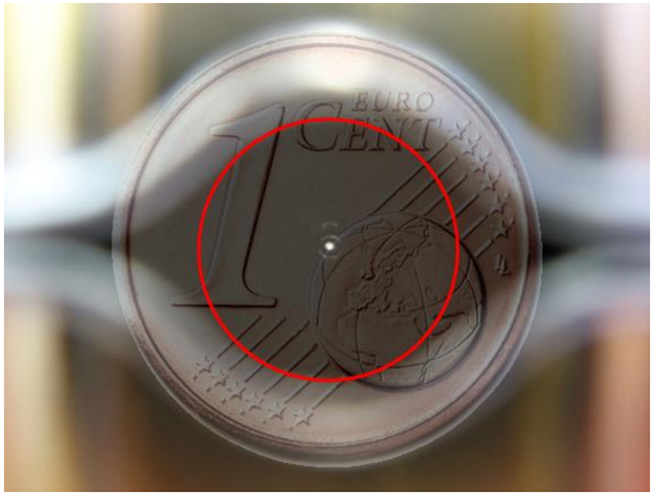


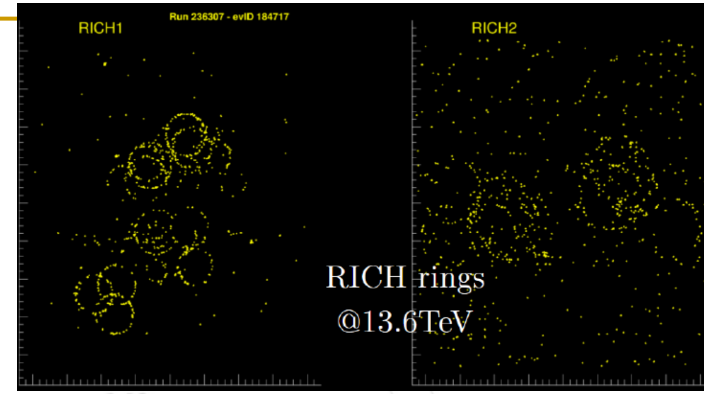
What the protons see in collisions

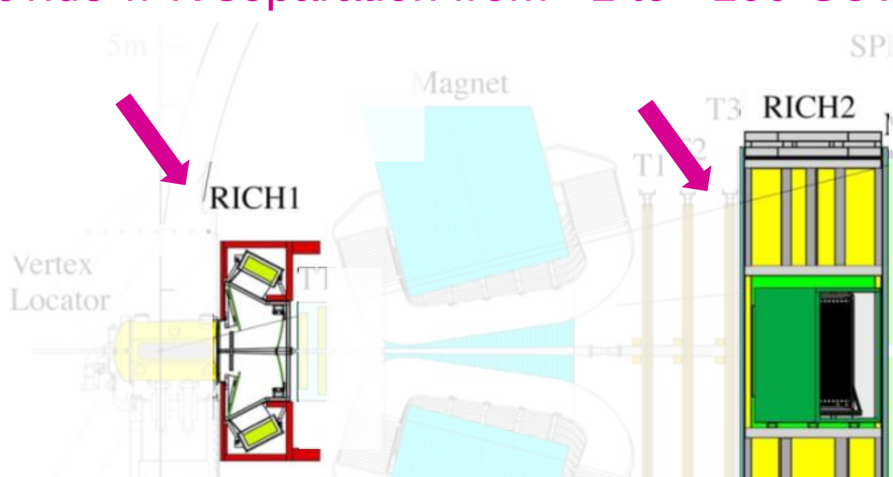


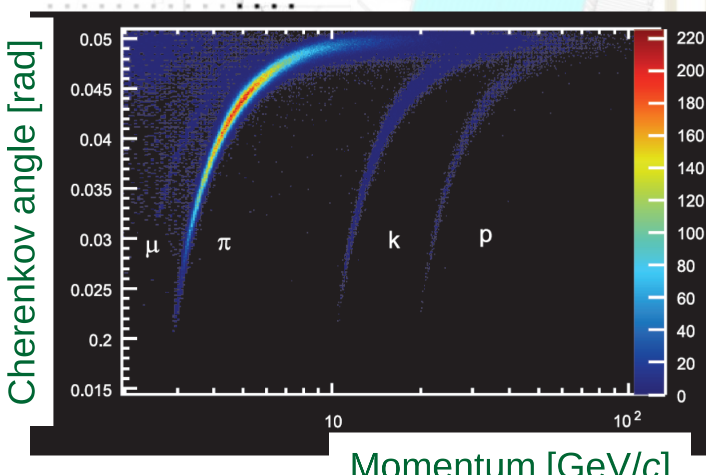
Size of beam aperture (Run 1 & 2) compared with one Euro.

LHCb – RICH system

Two Ring Imaging Cherenkov (RICH) detectors provide π-K separation from ~1 to ~100 GeV/c.





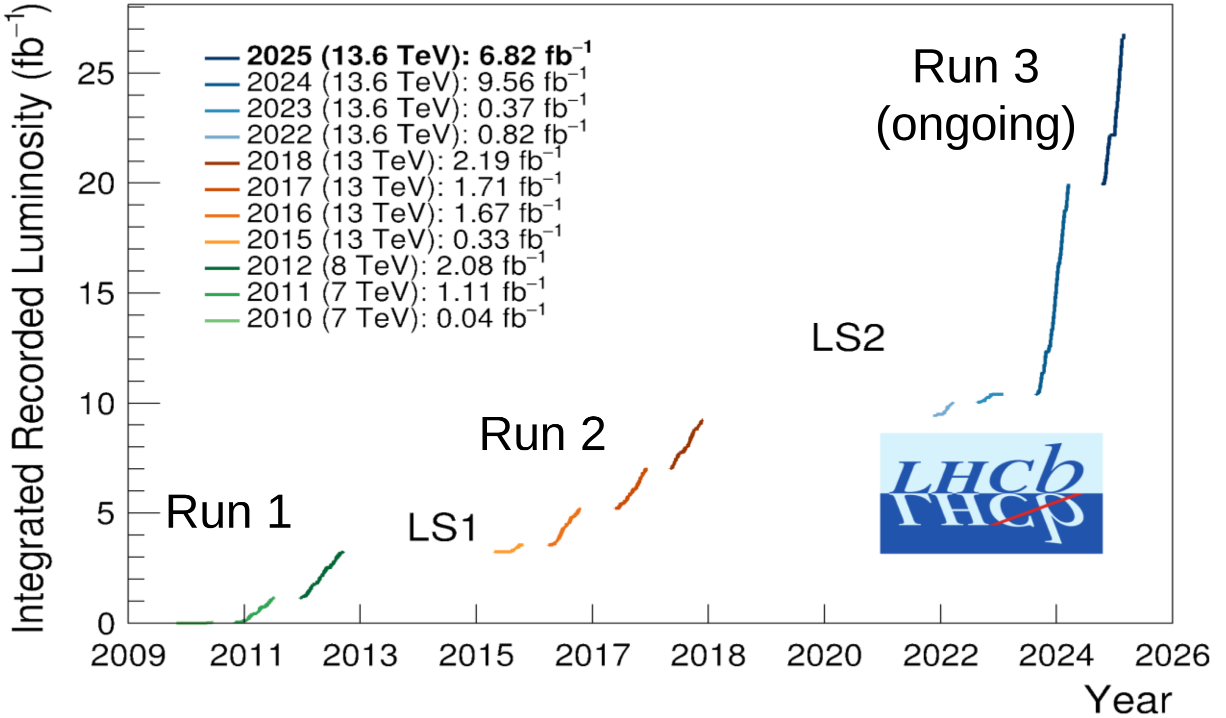


Assembling RICH 2; note the mirrors

Array of RICH 2 photodetectors (for Run 3)

LHCb – the story so far

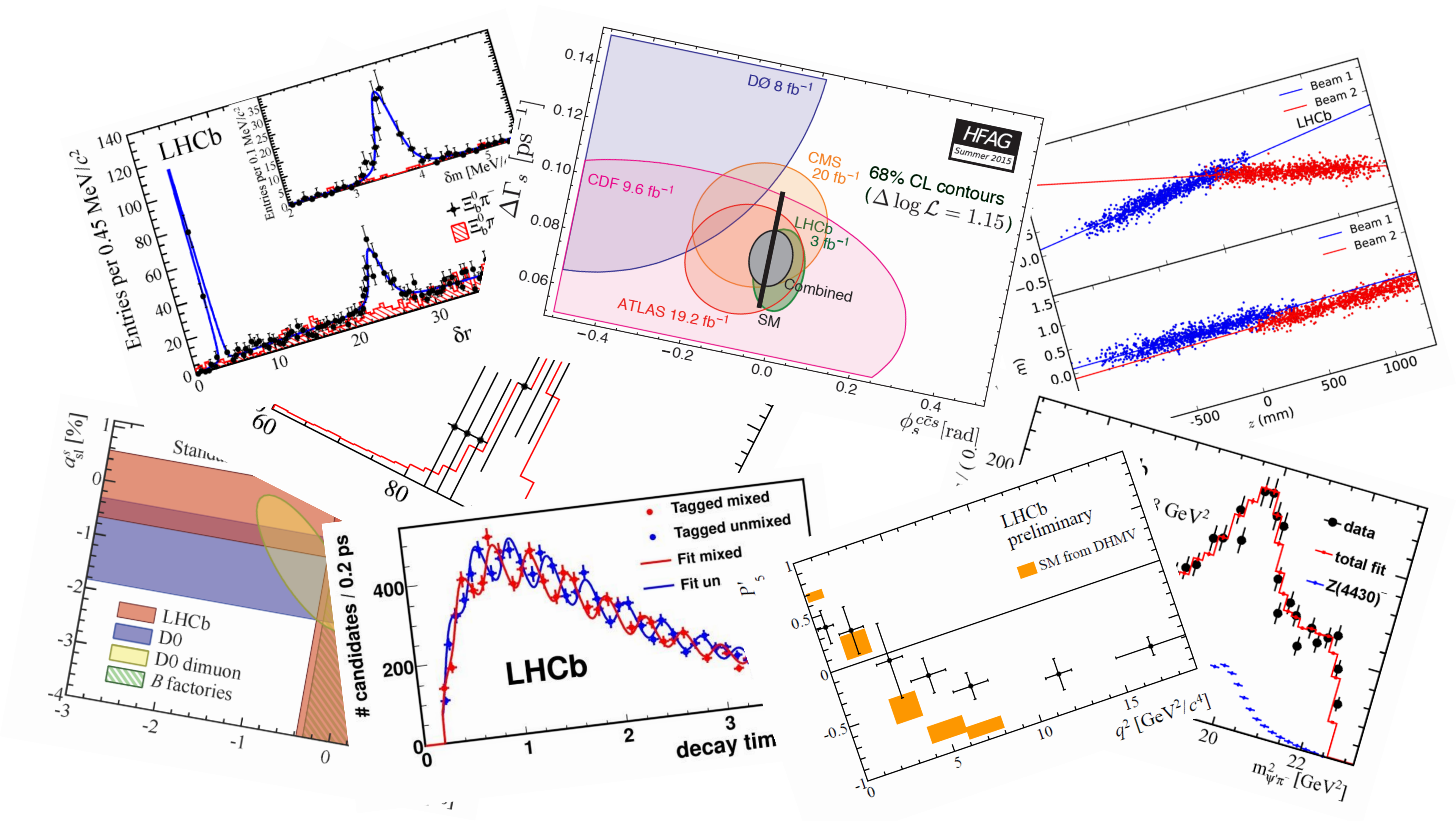
LHCb collected ~9 fb^{-1} of data throughout Runs 1 and 2 of the LHC.
(This corresponds to ~10^{12} b anti-b pairs being produced within LHCb.)



All results I will show come from Runs 1 and 2. Now collecting data in Run 3 at much higher rate – exciting results to come.

Selected results: snapshot on three topics of interest

Selected physics highlights



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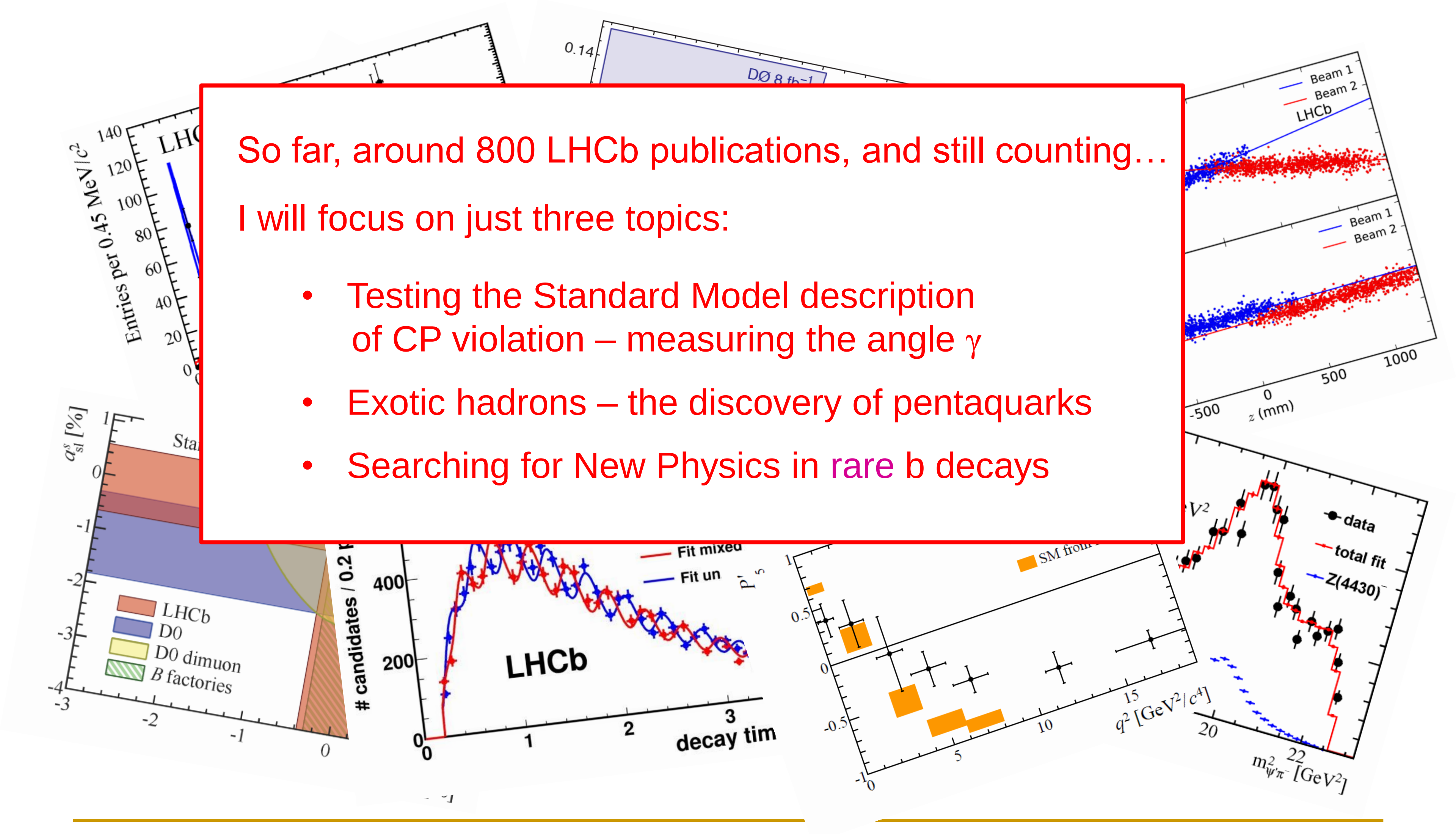
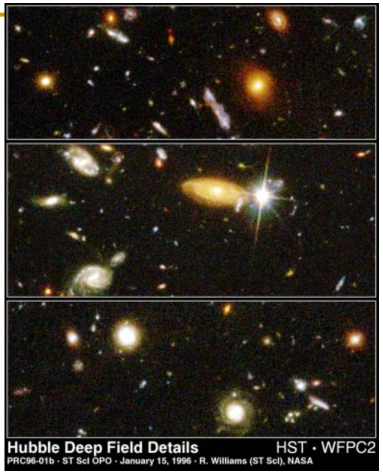


So far, around 800 LHCb publications, and still counting…

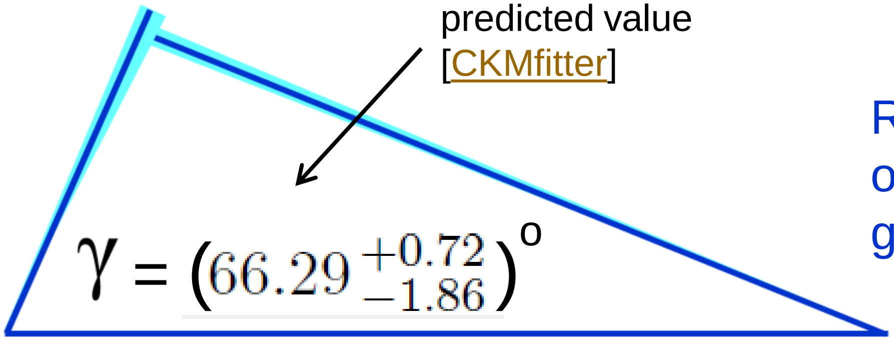
I will focus on just three topics:

- Testing the Standard Model description of CP violation – measuring the angle γ
- Exotic hadrons – the discovery of pentaquarks
- Searching for New Physics in rare b decays

Measuring the angle γ - testing CP violation in the Standard Model



CP violation, the difference in behaviour between matter and antimatter, is accommodated in the Standard Model by a single complex phase in the CKM matrix.



$$\gamma = (66.29^{+0.72}_{-1.86})^{o}$$

Relations exist between the elements of the matrix which can be displayed geometrically – as triangles.

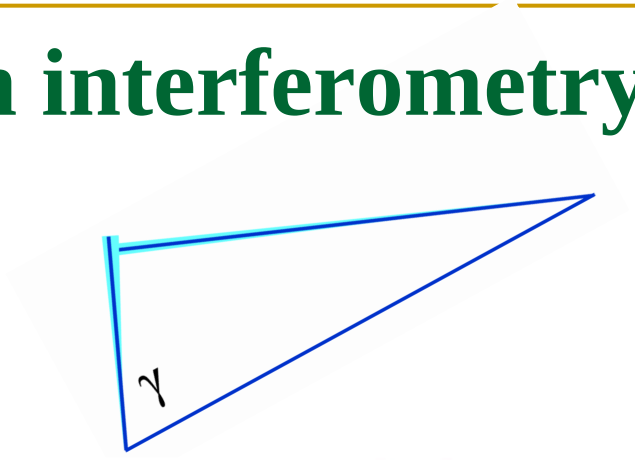
One of the angles of this triangle, γ, is related very directly to the CKM phase.

Our knowledge of the other elements of the matrix allow us to *predict* the angle with high precision. Now LHCb must *measure* CP-violating processes to obtain a direct measurement of γ to compare with this prediction.

➡ Any discrepancy would point to New Physics effects in flavour physics observables (*e.g.* supersymmetric particles, 4th generation of quarks *etc*)

Measuring γ – quantum interferometry

How to measure γ ?

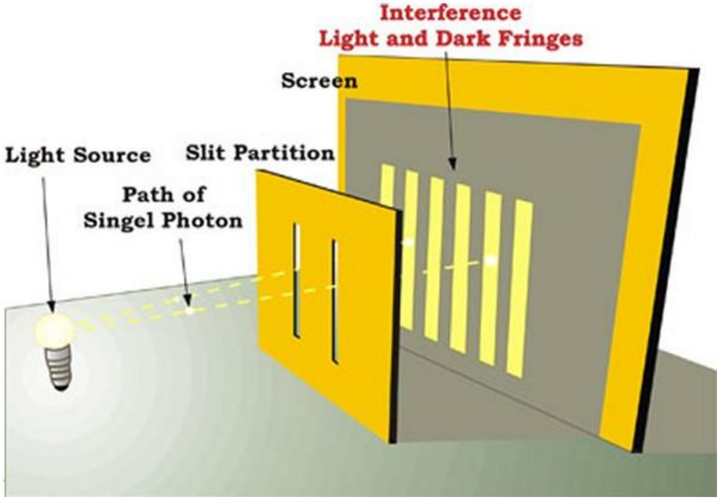


- It is a hidden phase, which exist between different *b*-quark decays

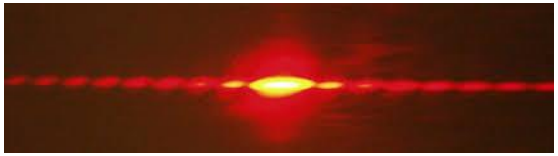
$B^- \rightarrow D^0 K^-$

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

phase γ between amplitudes



- The only way to access this phase is to look for a decay mode that is *common* to both D^0 and anti-D^0. Then we don't know by which path the decay has taken, and we get quantum interference, as in the famous double-slit experiment



- The phase is CP-violating, which means it should generate different effects for B^+ & B^-.

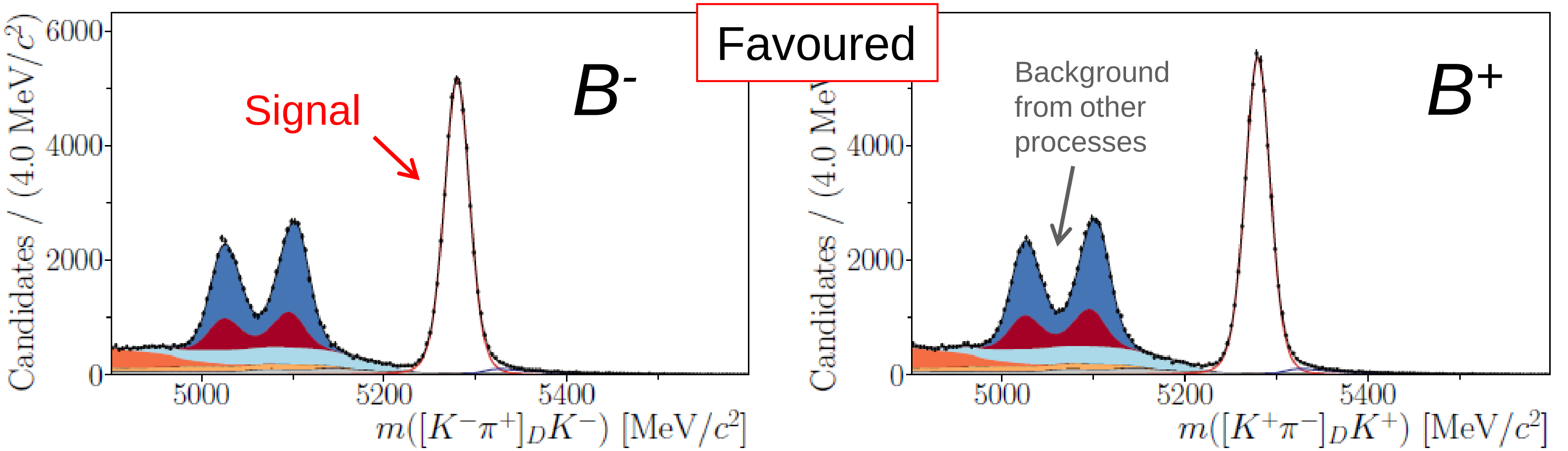
Measuring γ – quantum interferometry

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

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

First look at the case where the (anti-)D^0 is reconstructed in the 'favoured' mode $K^-\pi^+$ for the B^- decay (or $K^+\pi^-$ for B^+).

This is (almost) completely dominated by a single decay path, and so no quantum interference is expected…



[LHCb, JHEP 04 (2021) 081]

..and none is seen, since the decay rates are essentially the same.

Note also that the statistics are high – the 'favoured' decay happens often.

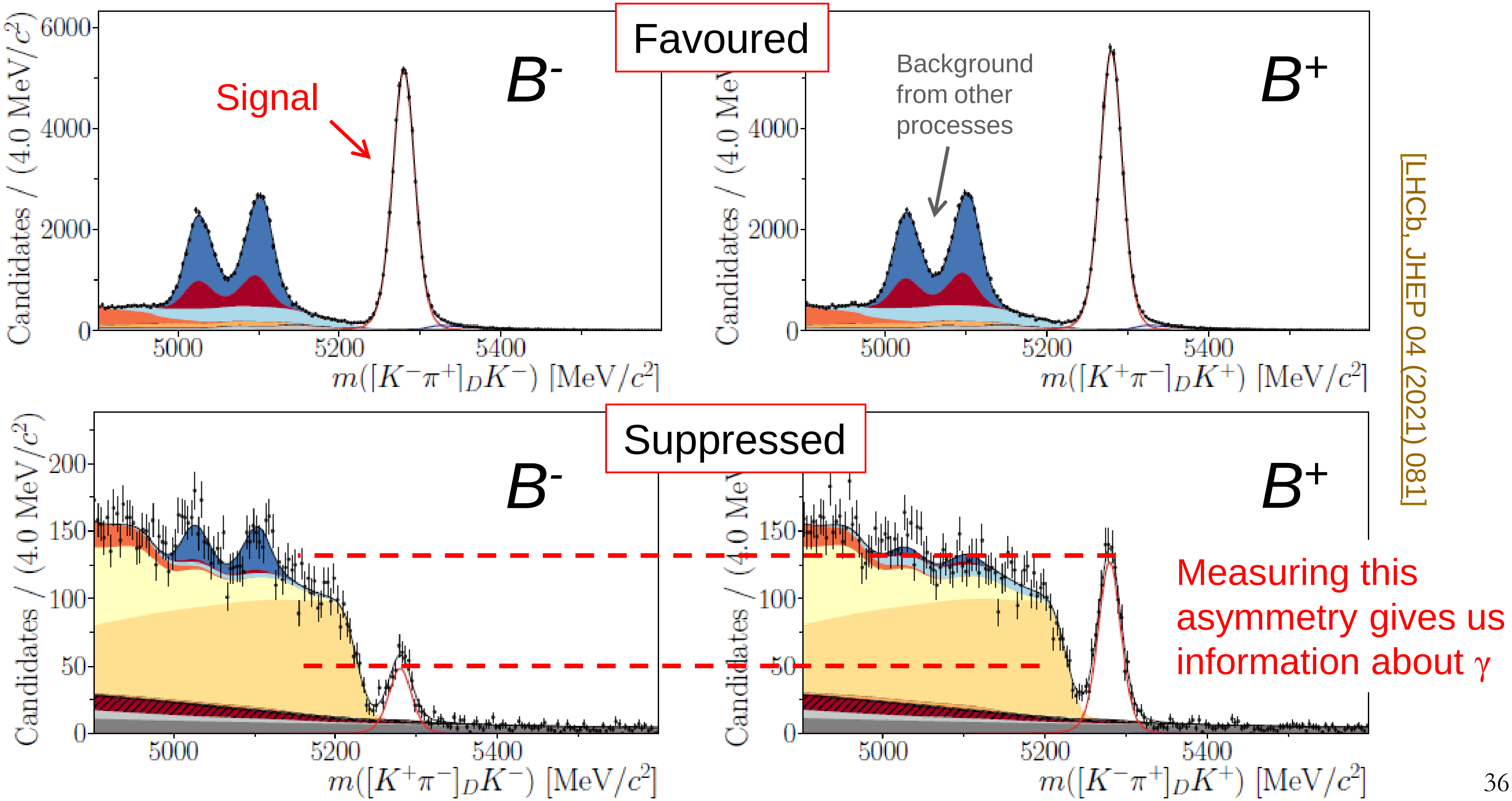
Measuring γ – quantum interferometry

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

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

Now look at the case where the (anti-)D^0 is reconstructed in the 'suppressed' mode $K^+\pi^-$ for the B^- decay (or $K^-\pi^+$ for B^+).

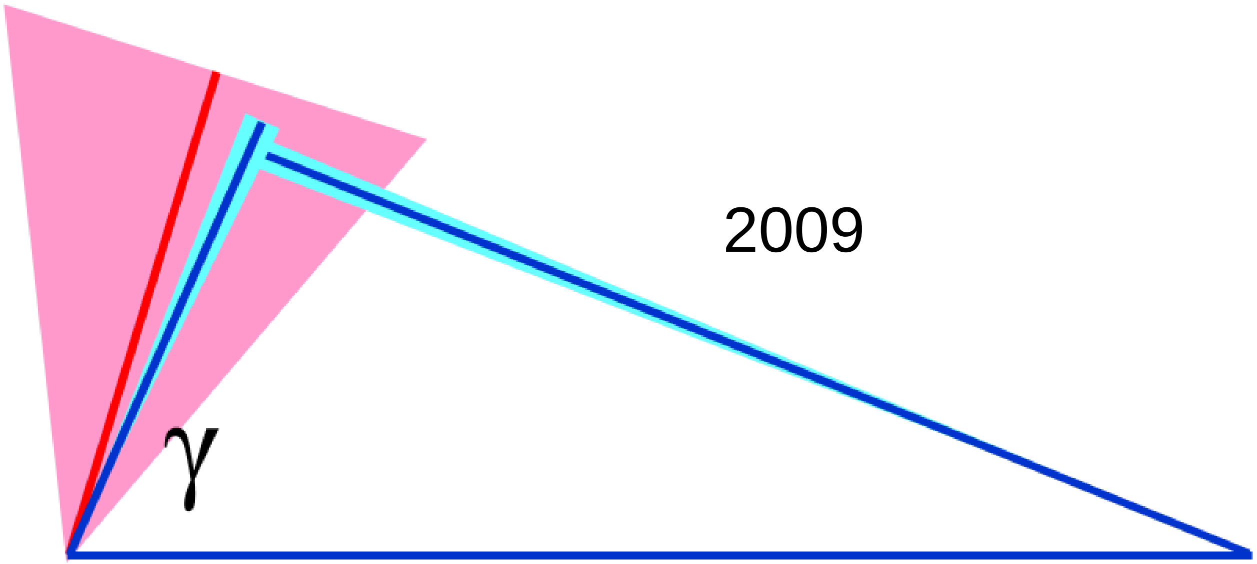
Here we expect significant interference, and indeed a large CP-violating difference in rates is seen between B^- and B^+!



[LHCb, JHEP 04 (2021) 081]

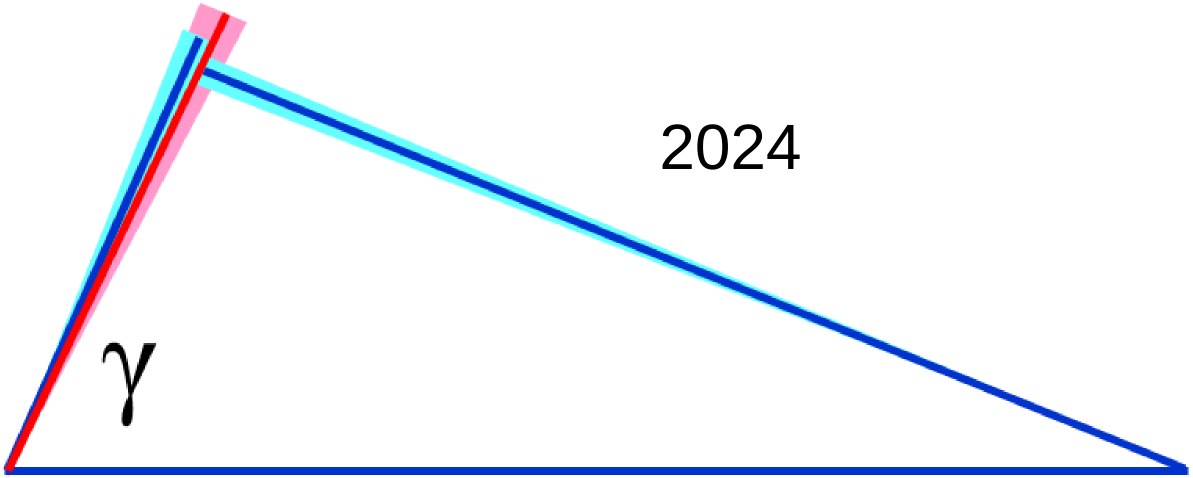
Measuring γ – current status & prospects

Prior to LHCb turn on, γ was known with a precision of around 24° [CKMfitter 2009].



Measuring γ – current status & prospects

Prior to LHCb turn on, γ was known with a precision of around 24º [CKMfitter 2009].
Now known to precision of around 3º [LHCb-CONF-2024-004], a factor 8 improvement.



Measurement agrees with indirect prediction, but is not yet as precise.

This is a continuing journey – measurements must improve (so will prediction).
The final phase of LHCb, and future experiments, aim for sub-degree precision !

How many new particles have been discovered at the LHC ?

Answer - Only one, the Higgs boson ?

How many new particles have been discovered at the LHC ?

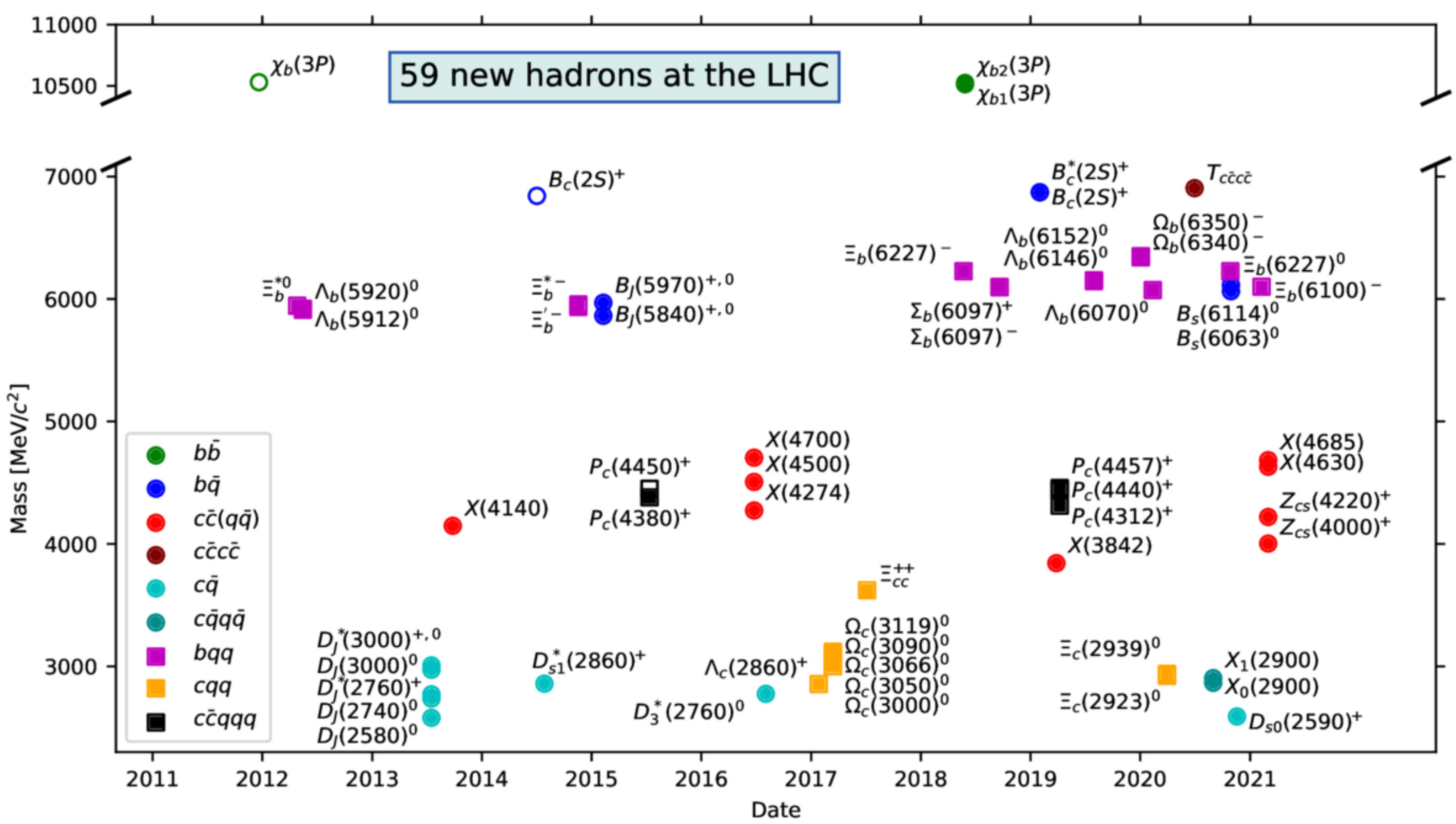
Answer - Only one, the Higgs boson ?

Wrong

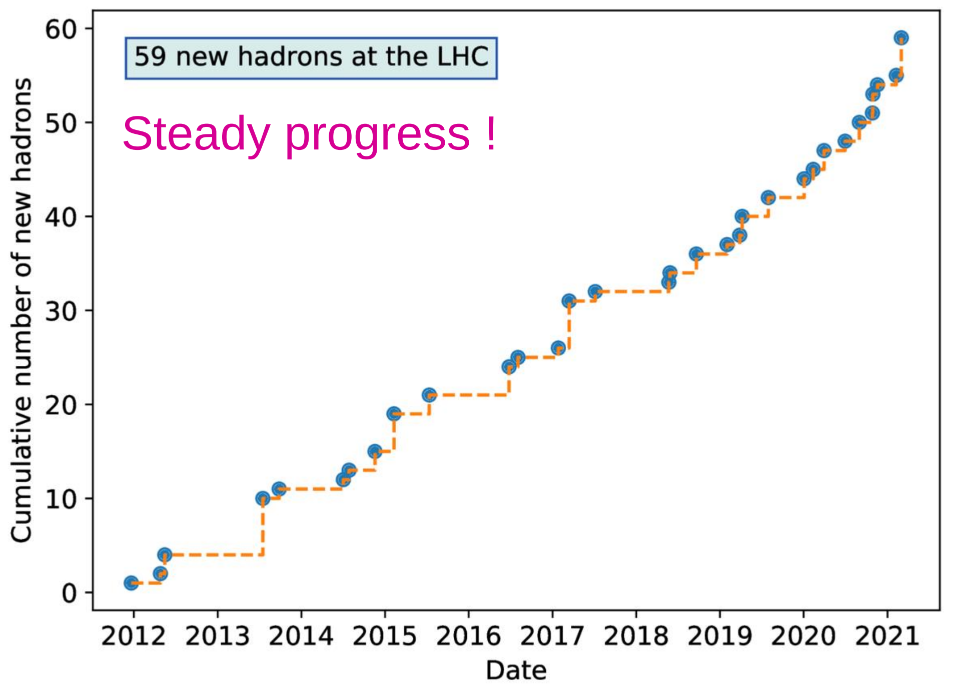
Correct answer -

60: the Higgs boson and 59 new hadrons

How many new particles have been discovered at the LHC ?



How many new particles have been discovered at the LHC ?

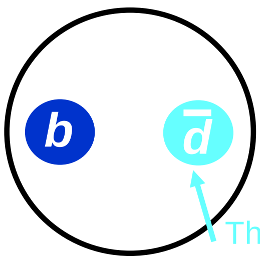


Finding and studying these hadrons is unlikely to tell as anything about 'New Physics', but it does tell us more about how the Standard Model works, in particular how quarks are bound together within the hadrons.

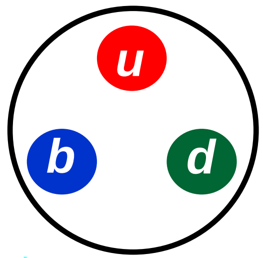
The search for exotic hadrons

In 1964 The fathers of the quark model, Murray Gell-Mann and George Zweig, explained how hadrons are made. Recall:

meson



baryon

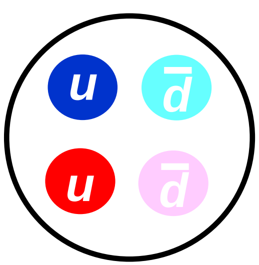


This colour is meant to represent 'anti-blue', but I don't know what that looks like…

> *Baryons can now be constructed from quarks by using the combinations qqq, qqqq̄q, etc, while mesons are made out of qq̄, qq̄qq̄, etc.*
>
> **Murray Gell-Mann**

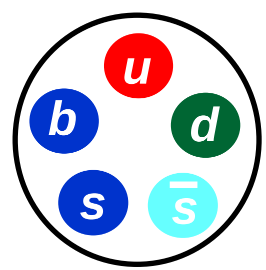
These two arrangements are necessitated by the fact that the quarks come in 3 'colours' & that the hadron itself must be an overall colourless object. These are the standard hadrons we know & love. But there are more exotic possibilities:

tetraquark



meson

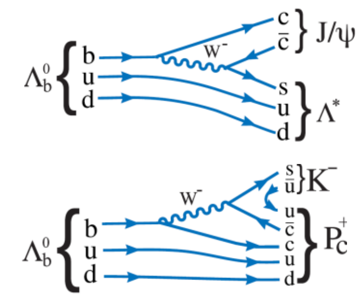
pentaquark



baryon

If these are allowed then examples *should* exist. Where are they?

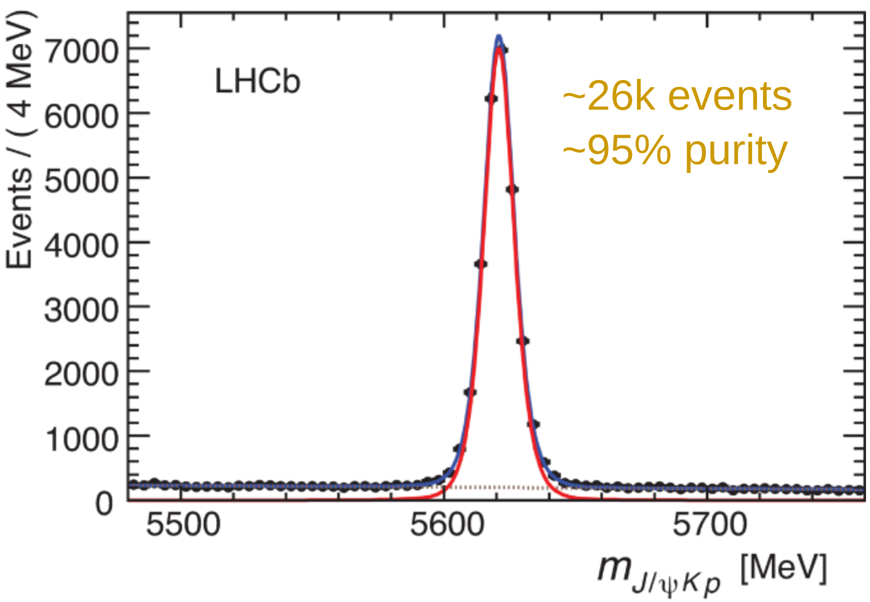
J/Ψp resonances consistent with pentaquark states



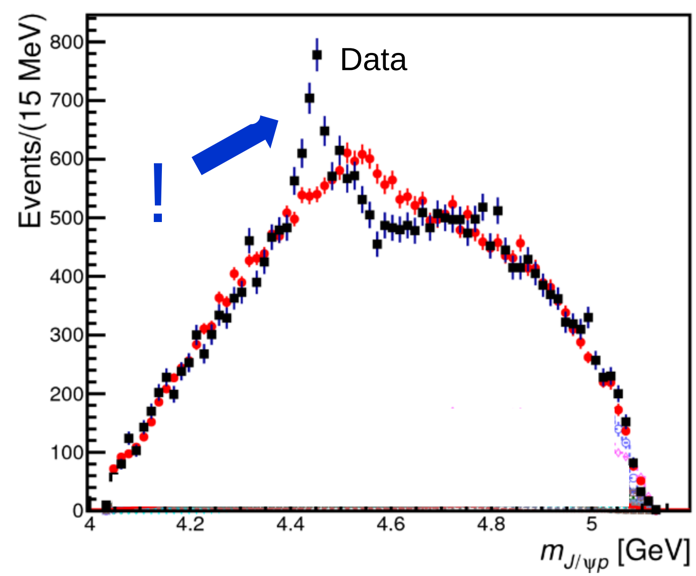
[PRL 115 (2015) 072001]

With its Run 1 data set, LHCb isolated a large & pure sample of $\Lambda_b \to J/\Psi pK$ decays.

Here is the signal from the Λ_b decay.

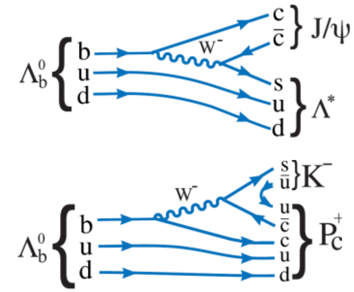


And this is what we get is we plot the invariant mass of the J/ψ p pair.



There appears to be a signal, which indicates that the Λ_b is decaying into some intermediate state before again decaying into the final-state particles. Because the J/ψ contains c cbar, and the proton uud, this intermediate state has five quarks !

J/Ψp resonances consistent with pentaquark states



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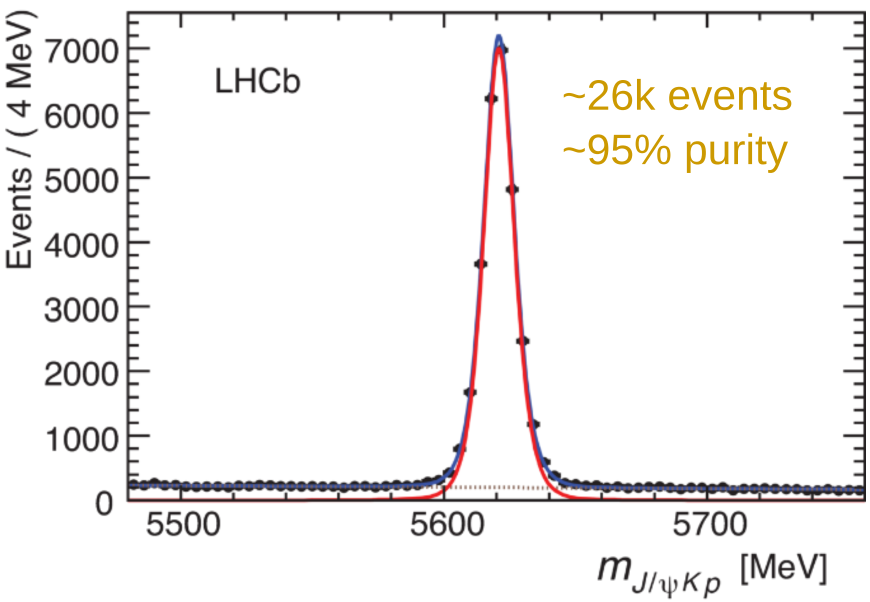

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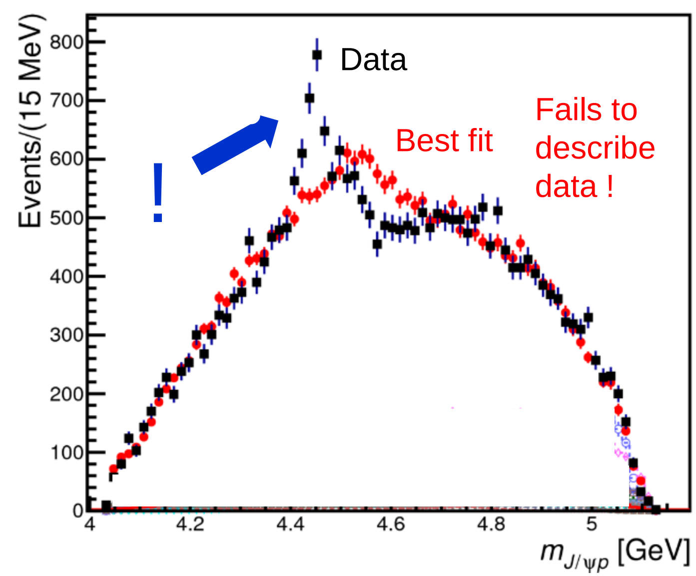


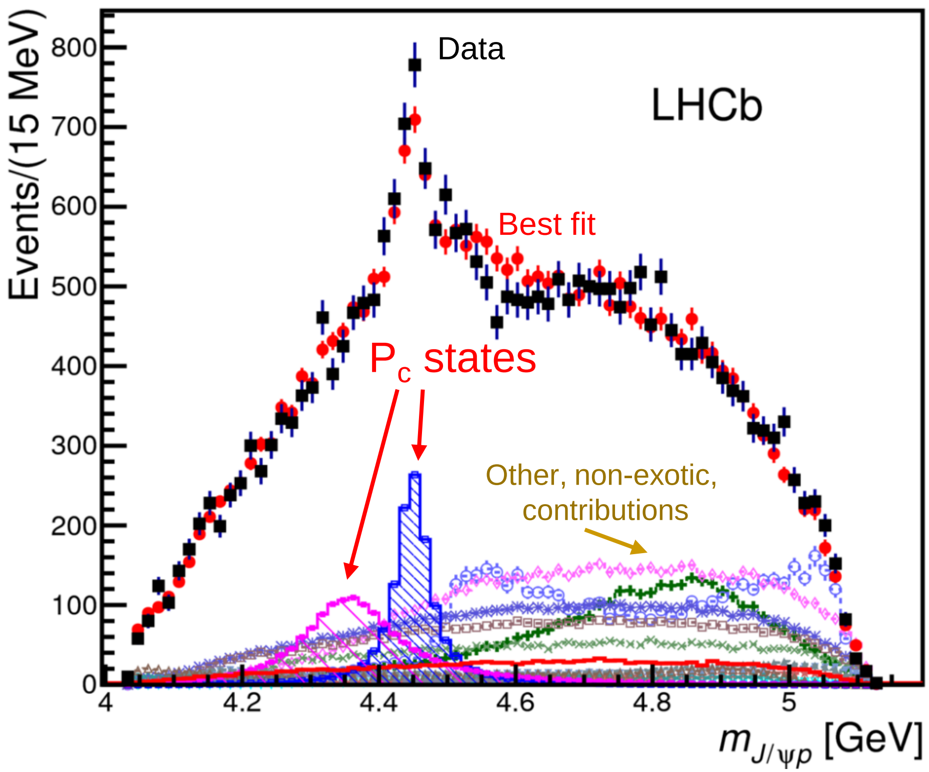
To check our conclusion is good, we can try to fit data in full decay chain using conventional states, with no inclusion of pentaquark hypothesis. This fails !

J/Ψp resonances consistent with pentaquark states

[PRL 115 (2015) 072001]

2,005 citations (as of 10/9/25)

Can only describe data satisfactorily by adding two exotic pentaquark states with content uudccbar. Best fit has J=3/2 and 5/2 with opposite parities.

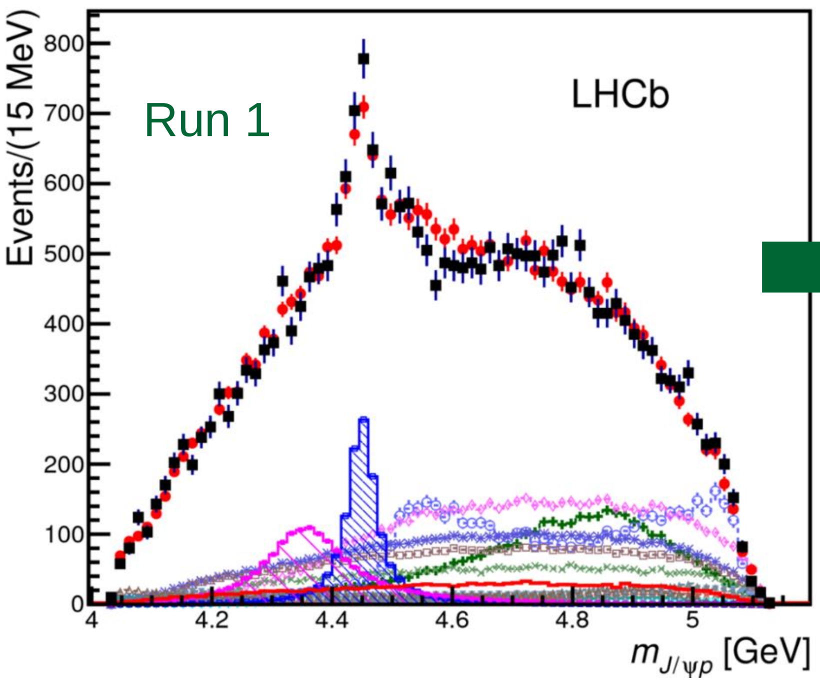


$P_c(4380)$:
$M = 4380 \pm 8 \pm 29\,\mathrm{MeV}$,
$\Gamma = 205 \pm 18 \pm 86\,\mathrm{MeV}$
$P_c(4450)$:
$M = 4449.8 \pm 1.7 \pm 2.5\,\mathrm{MeV}$
$\Gamma = 39 \pm 5 \pm 19\,\mathrm{MeV}$

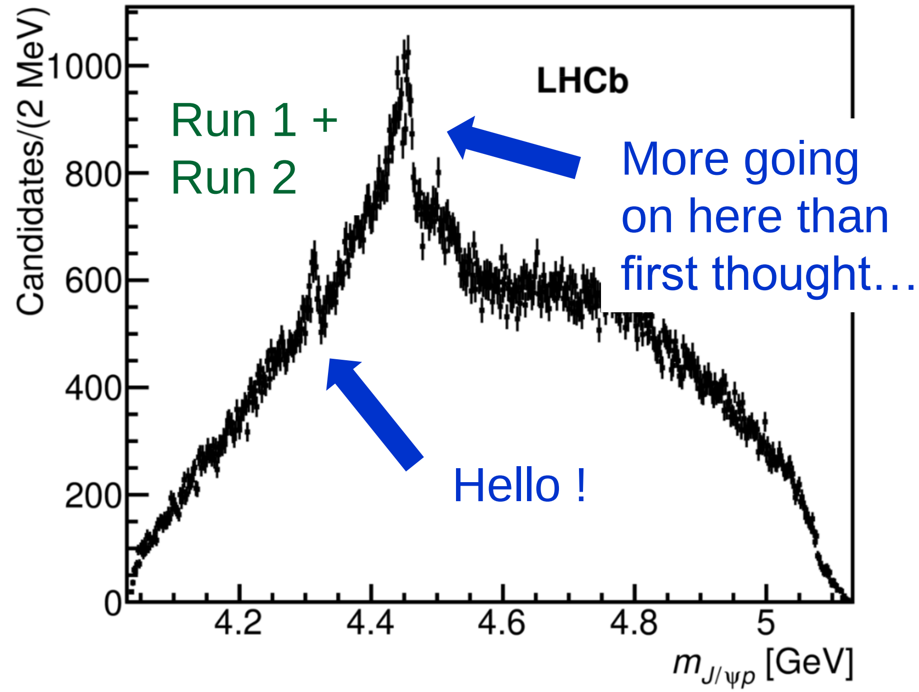
A very exciting & much discussed discovery (with significant Chinese involvement), but this was not the end of the story…

Pentaquarks – why more data matters

Run 2 data and improved selection provide x9 increase in signal



[PRL 115 (2015) 072001]

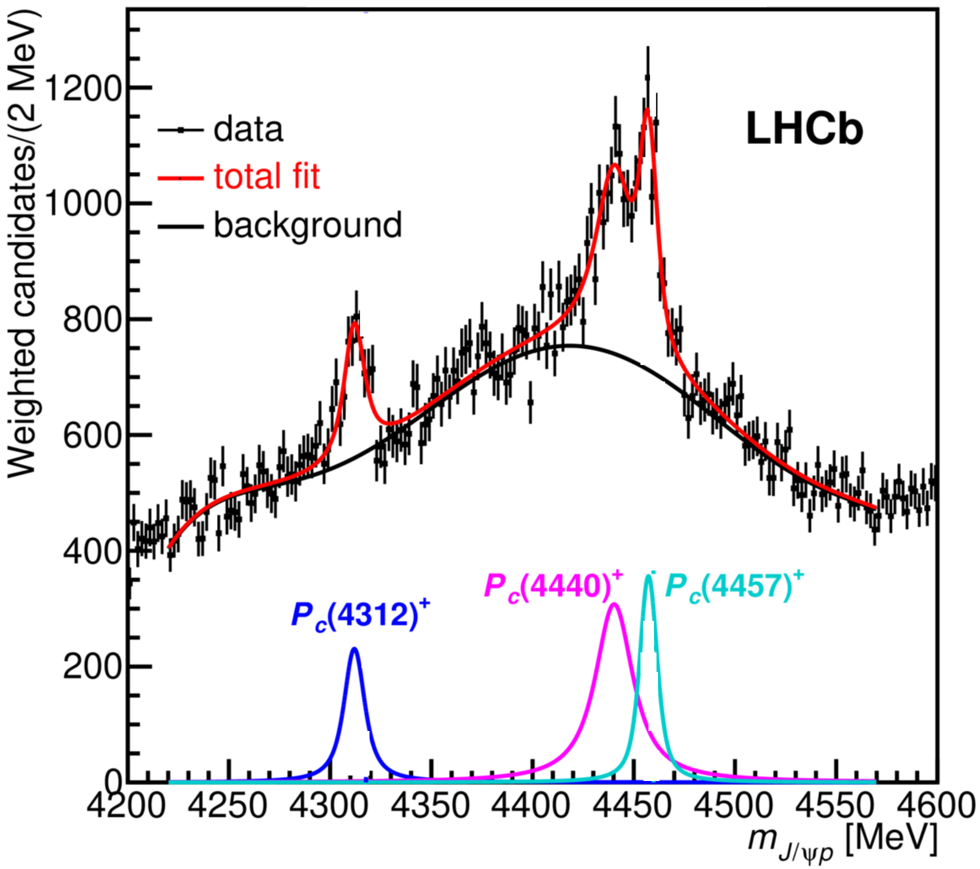


[PRL 122 (2019) 222001]

Not one narrow state, but three

A closer look at Run 2 data, after weighting to suppress effect of Λ* background.

[PRL 122 (2019) 222001]



A new narrow state is observed at 4312 MeV, and the previous narrowish state is resolved into two close-lying narrower states.

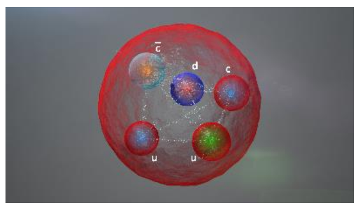
This demonstrates well the importance of increased precision !

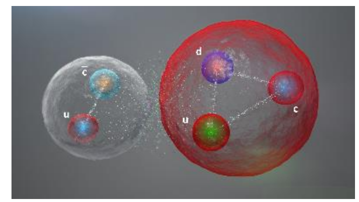
Not one narrow state, but three

A closer look at Run 2 data, after weighting to suppress effect of Λ* background.

Next question - are these states

tightly bound or molecular ?





Some clues come from their masses, which favour the molecular interpretation, but more measurements required:

- Measuring quantum numbers of these states;
- Looking for their occurrence in other decay modes;
- Finding other species of pentaquark.

Greater clarity, and no doubt more surprises, guaranteed with data from future LHCb running & Upgrade programme.

narrowish state is resolved into two close-lying narrower states.

This demonstrates well the importance of increased precision !

Spectroscopy results – provoke great interest among public

e.g. reactions to LHCb study of resonant nature of $Z(4430)^-$ [PRL 112 (2013) 222002]

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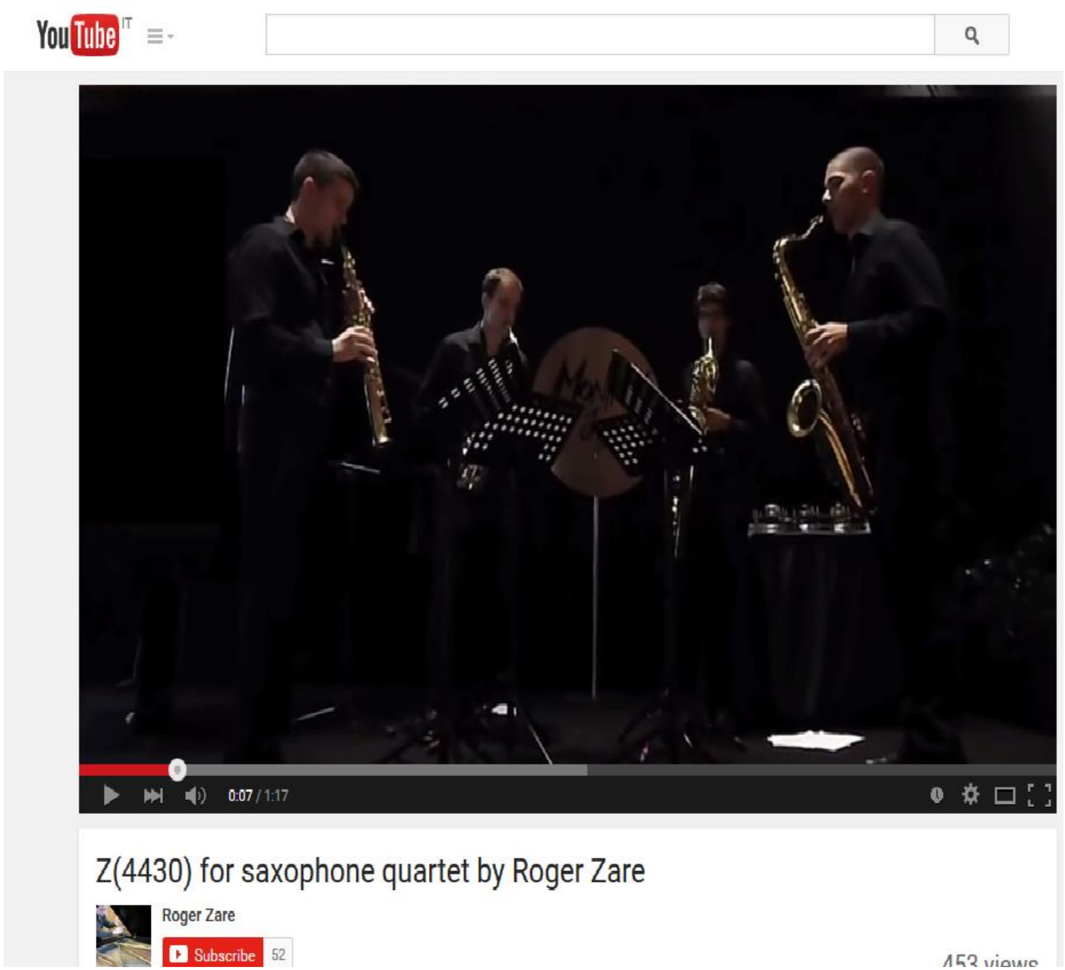


Montreux jazz festival, 2014

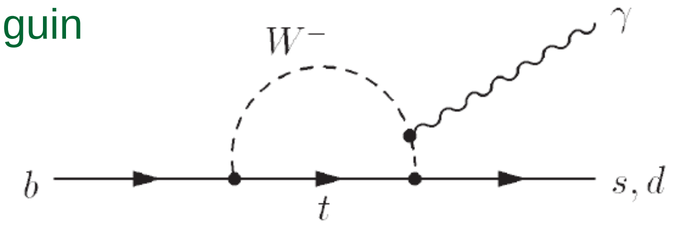
Rare decays involving loop-level (or Penguin) processes as a probe of New Physics

Rare decays proceed through higher-order diagrams →
suppressed in Standard Model and susceptible to New Physics contributions.

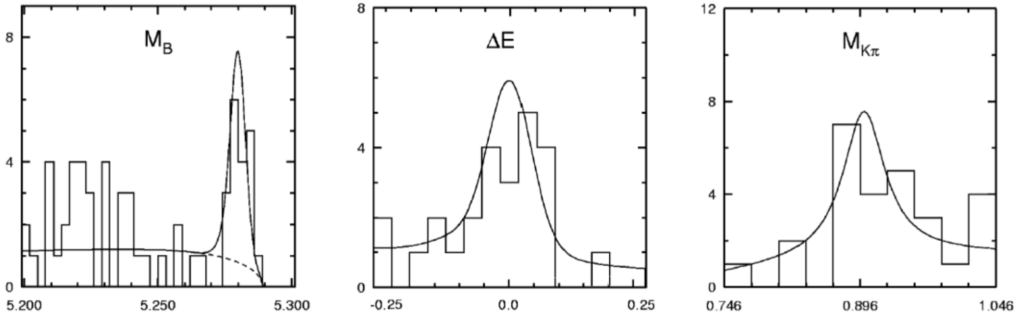
e.g. Penguin diagram (nomenclature introduced by John Ellis in 1977 after lost bet [Ellis *et al.*, NPB 131 (1977) 285].)

Most interesting measurements involve EM & weak penguins, with photon or dileptons – precise predictions.

(EM) Radiative penguin



EM penguin first discovered by CLEO in B→K*(892)γ (BR~10^{-5}) [CLEO, PRL 71 (1993) 674].



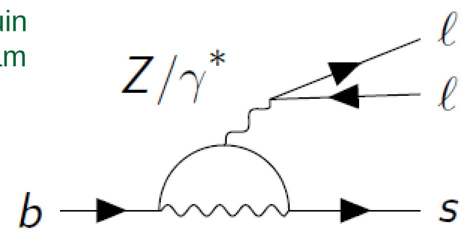
Studies of radiative penguins still very important, but we will not discuss them further.

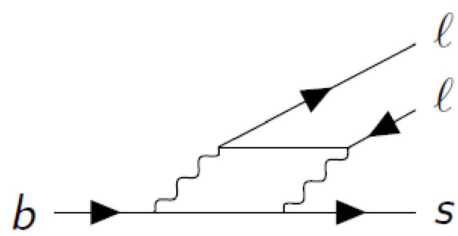
$B^0 \to K^* l^+ l^-$ and friends – the gift that keeps on giving

A particular interesting set of loop-level mediated rare decays are those involving the process $b \to s l^+ l^-$ (and indeed $b \to d l^+ l^-$), where 'l' indicates a lepton, *e.g*. muon. These provide a very rich set of observables to probe for New Physics effects.

In the Standard Model these processes occur by diagrams such as

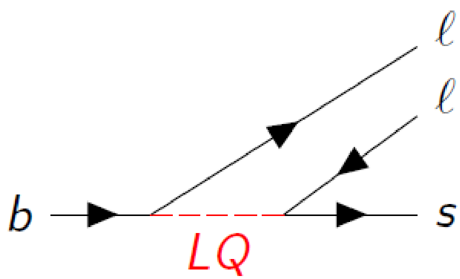
Penguin diagram

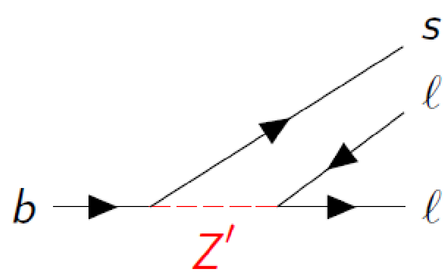




Box diagram

But if there are heavy New Physics particles out there, such as 'leptoquarks' (LQ), or new heavy gauge bosons *e.g.* `Z primes' (Z'), they may play a role.





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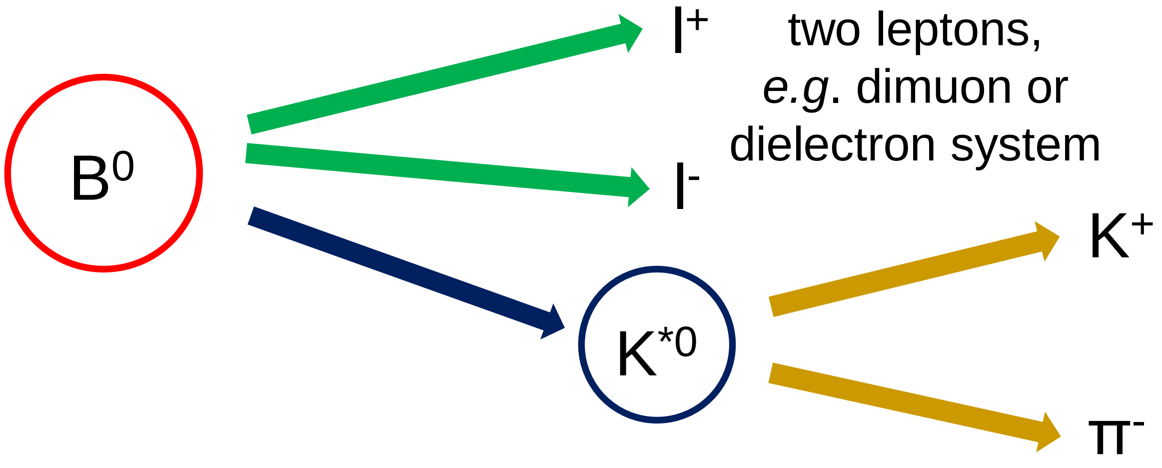
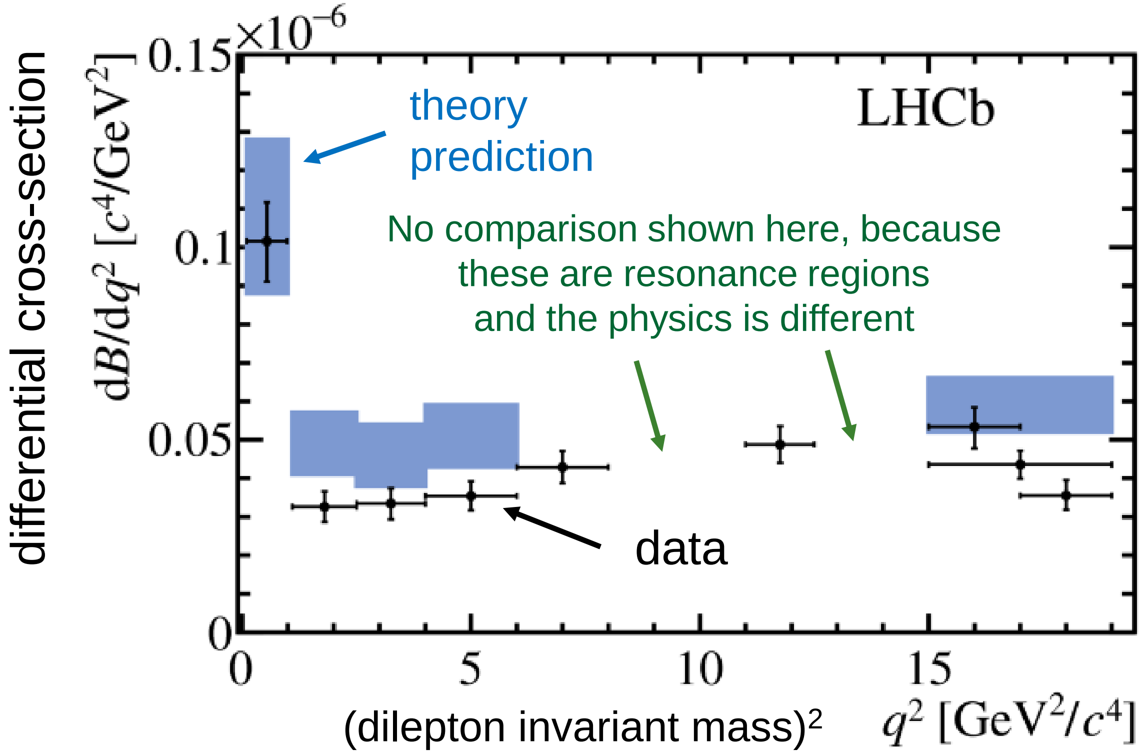
Many realisations, but the poster-child decay is $B^0 \to K^{*0} l^+ l^-$, with $K^{*0} \to K^+ \pi^-$.



Four-body final state can be characterised in terms of three angles, Θ_l, θ_K and φ, & q^2, & the invariant-mass of the dilepton pair (see *e.g.* [LHCb, PRL 111 (2013) 191801]).

$B^0 \to K^* l^+ l^-$: differential cross-section

The first thing to measure is the differential cross-section vs. q^2, which is essentially the rate of the decay measured in bins of dilepton invariant mass.



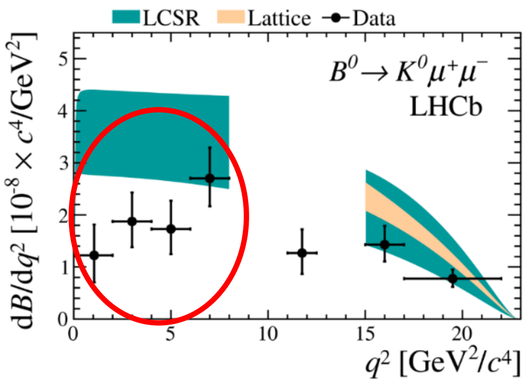
[JHEP 04 (2017) 142]

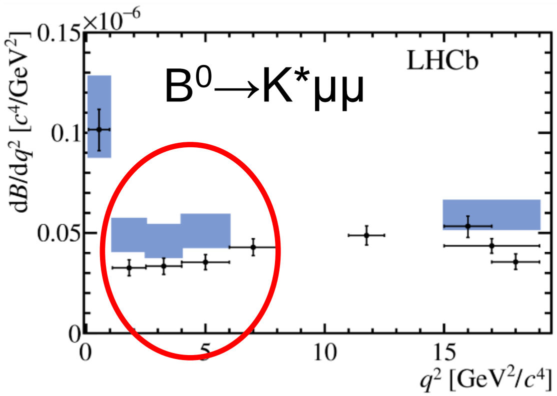
We observe that there is a tendency for the data to be lower than the prediction. This is most interesting at low invariant mass, where the prediction is most reliable.

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

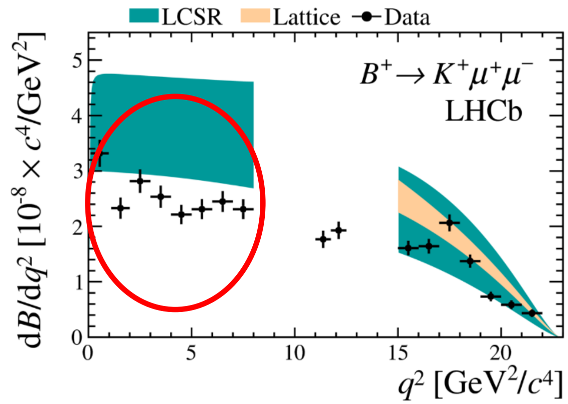
$P_5^/$ is not the only funny thing going on in $b \to (s,d) l^+ l^-$ decays.

[JHEP 06 (2014) 133]



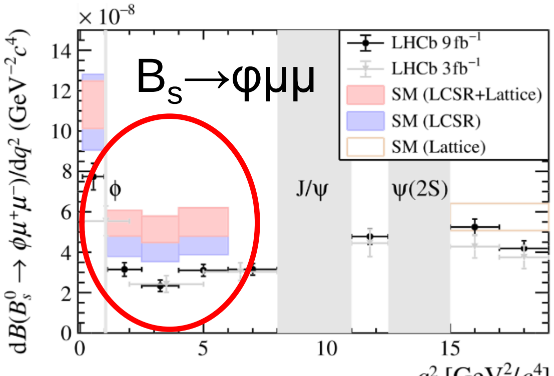


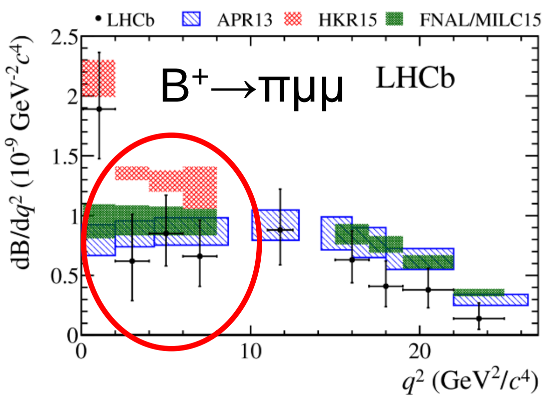
[JHEP 04 (2017) 142]



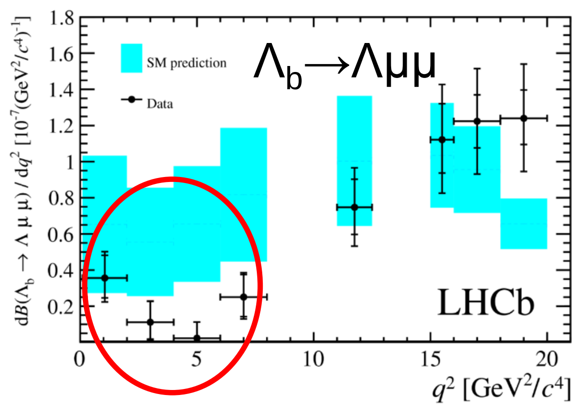
[JHEP 06 (2014) 133]

[PRL 127 (2021) 151801]





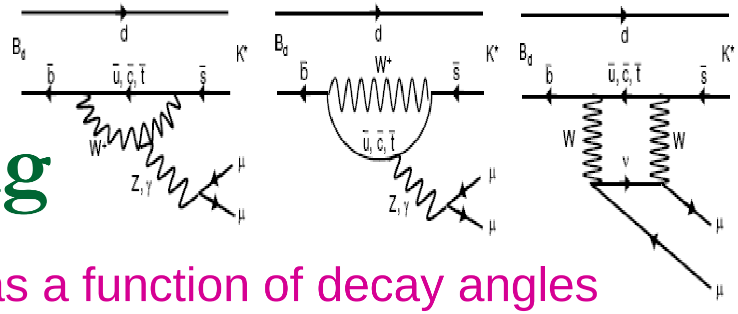
[JHEP 10 (2015) 034]



[JHEP 06 (2015) 009]

All measurements undershoot prediction at low q^2. Intriguing – but maybe the uncertainties in theory are larger than claimed, or is there a common systematic ?

$B^0 \rightarrow K^* l^+ l^-$ and friends – the gift that keeps on giving



The differential cross-section can be measured as a function of decay angles of four-body final state. This brings a lot of additional information…

$$\frac{1}{\mathrm{d}(\Gamma+\bar{\Gamma})/\mathrm{d}q^2}\frac{\mathrm{d}^4(\Gamma+\bar{\Gamma})}{\mathrm{d}q^2\,\mathrm{d}\vec{\Omega}} = \frac{9}{32\pi}\Big[\tfrac{3}{4}(1-F_{\mathrm{L}})\sin^2\theta_K + F_{\mathrm{L}}\cos^2\theta_K$$

$$+\tfrac{1}{4}(1-F_{\mathrm{L}})\sin^2\theta_K\cos 2\theta_l$$

$$-F_{\mathrm{L}}\cos^2\theta_K\cos 2\theta_l + S_3\sin^2\theta_K\sin^2\theta_l\cos 2\phi$$

$$+S_4\sin 2\theta_K\sin 2\theta_l\cos\phi + S_5\sin 2\theta_K\sin\theta_l\cos\phi$$

$$+\tfrac{4}{3}A_{\mathrm{FB}}\sin^2\theta_K\cos\theta_l + S_7\sin 2\theta_K\sin\theta_l\sin\phi$$

$$+S_8\sin 2\theta_K\sin 2\theta_l\sin\phi + S_9\sin^2\theta_K\sin^2\theta_l\sin 2\phi\Big]$$

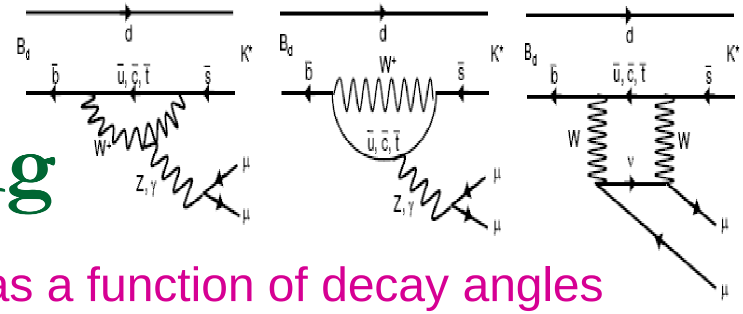
Note, this is the CP-averaged expression (*i.e.* assuming no CPV).

F_L – fraction of longitudinal polarisation of K*

A_{FB} – forward-backward asymmetry of dilepton pair in B-meson frame

…moreover, suitably chosen combinations of the coefficients are theoretically very robust.

$B^0 \to K^* l^+ l^-$ and friends – the gift that keeps on giving



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$$+S_4\sin 2\theta_K\sin 2\theta_l\cos\phi + S_5\sin 2\theta_K\sin\theta_l\cos\phi$$
$$+\tfrac{4}{3}A_\mathrm{FB}\sin^2\theta_K\cos\theta_l + S_7\sin 2\theta_K\sin\theta_l\sin\phi$$
$$+S_8\sin 2\theta_K\sin 2\theta_l\sin\phi + S_9\sin^2\theta_K\sin^2\theta_l\sin 2\phi\Big]$$

One such robust, so-called 'optimal observable' is

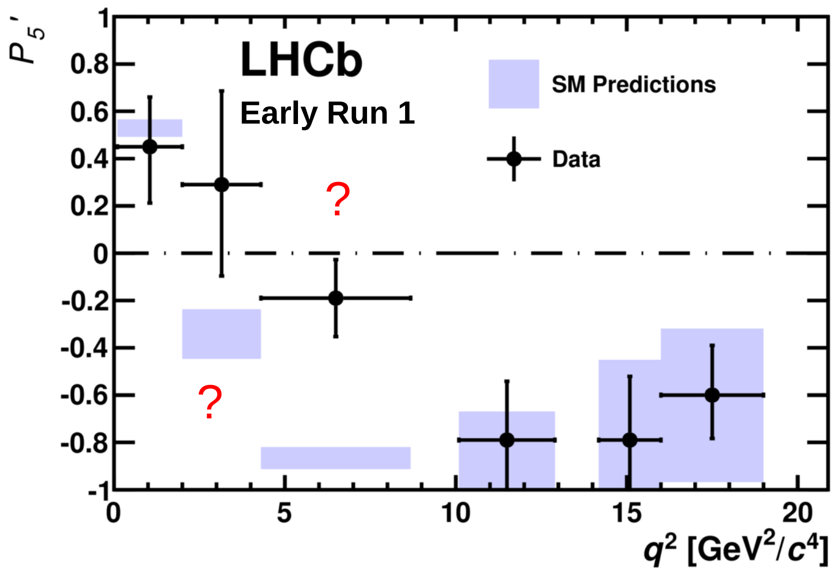
$$P_5' = \frac{S_5}{\sqrt{F_l(1-F_L)}}$$

which, despite its dull name, has attracted much attention.

…moreover, suitably chosen combinations of the coefficients are theoretically very robust.

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

The ‘optimum observable’ that has attracted most attention is $P_5^{/}$. A deviation at low q^2, was first seen in an early LHCb Run-1 analysis [PRL 111 (2013) 191801]



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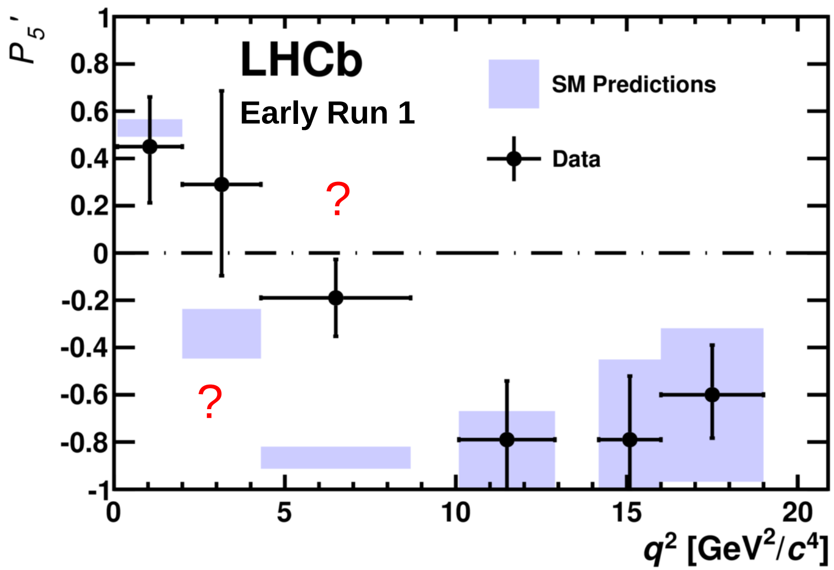
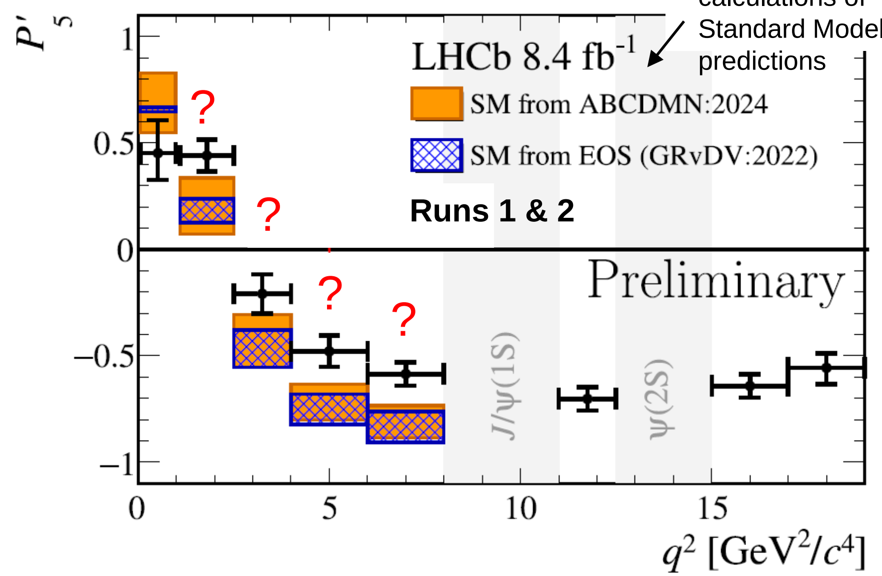
The ‘optimum observable’ that has attracted most attention is $P_5^{/}$. A deviation at low q^2, was first seen in an early LHCb Run-1 analysis [PRL 111 (2013) 191801], and has been confirmed with very recent (last week!) results from the full Run-1 & -2 data sets.

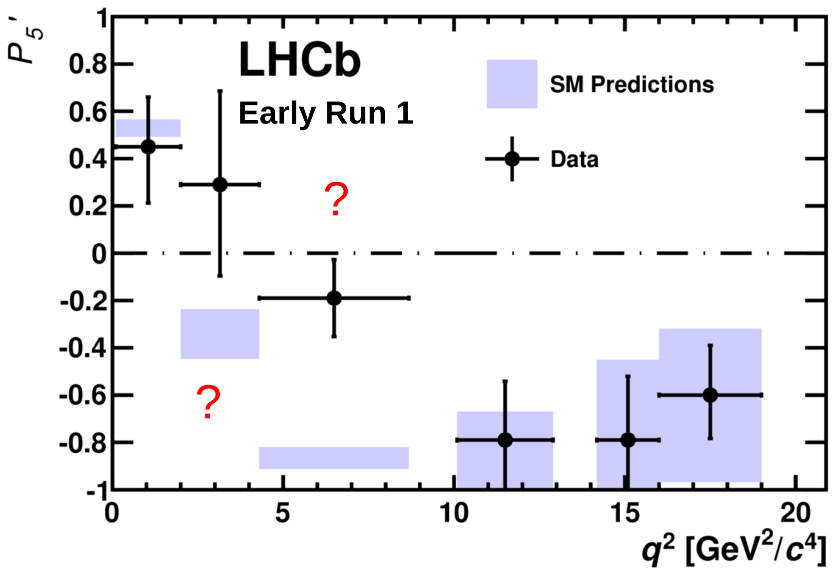




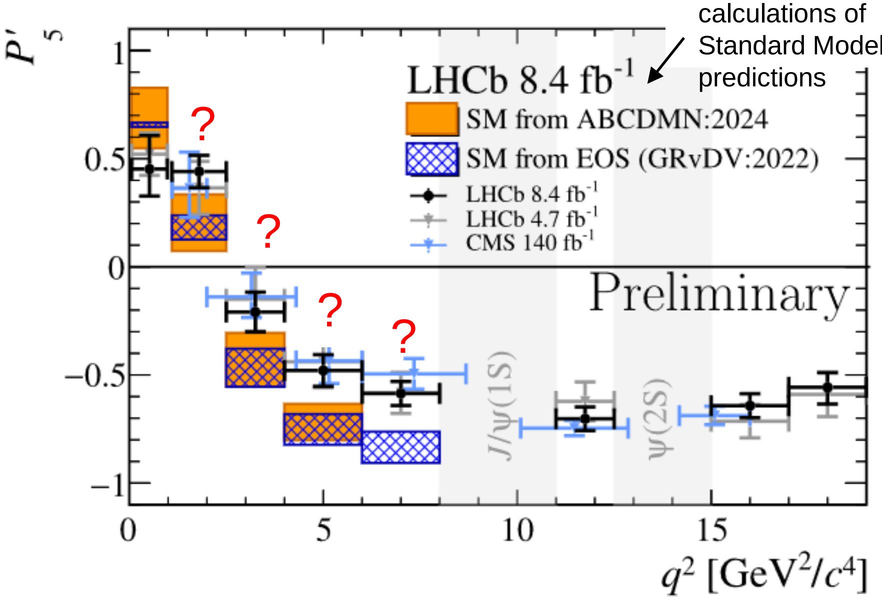
Although magnitude of deviation is smaller than in Run 1 alone, significance remains just as high, if not higher.

$B^0 \rightarrow K^* l^+ l^-$ and friends: the $P_5^{\prime}$ puzzle

The 'optimum observable' that has attracted most attention is $P_5^{\prime}$. A deviation at low q^2, was first seen in an early LHCb Run-1 analysis [PRL 111 (2013) 191801], and has been confirmed with very recent (last week!) results from the full Run-1 & -2 data sets.



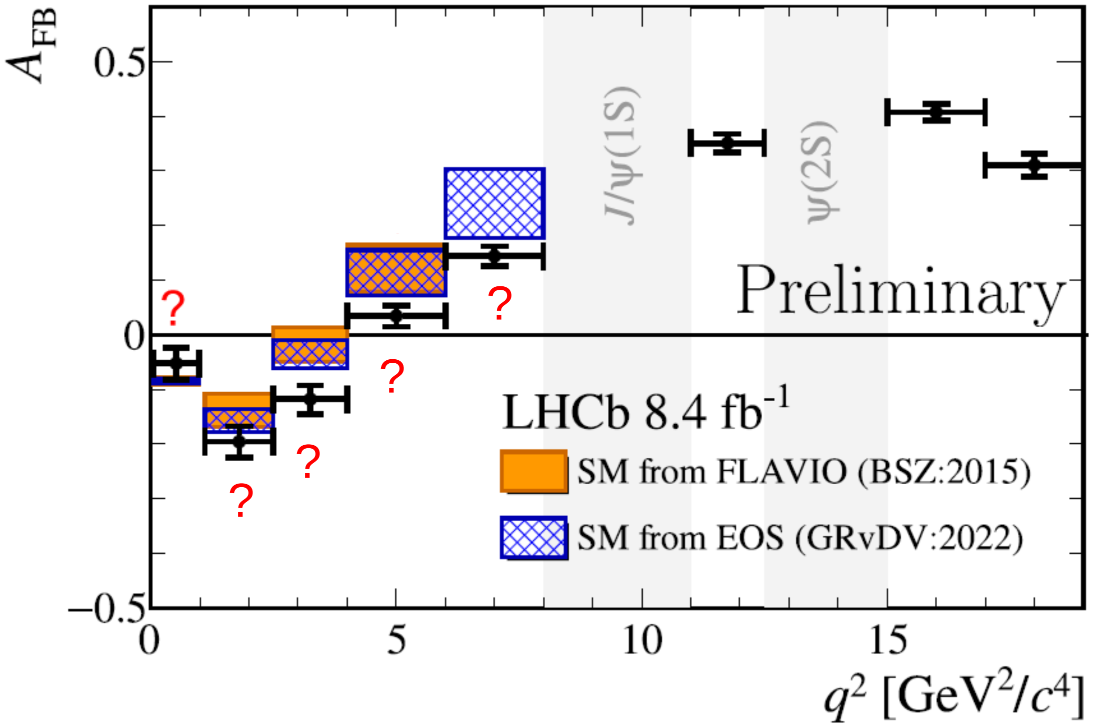
Two alternative calculations of Standard Model predictions



Although magnitude of deviation is smaller than in Run 1 alone, significance remains just as high, if not higher. Moreover, other LHC experiments see a similar effect *e.g.* CMS [PLB 864 (2025) 139406]. Odd behaviour also seen in other observables.

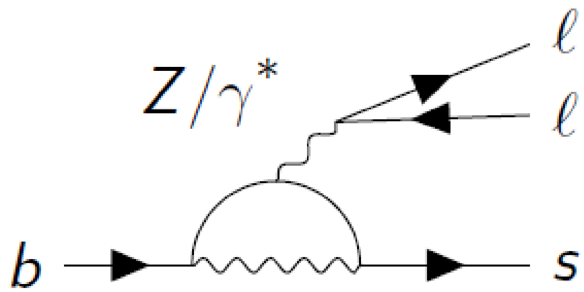
More trouble in $B^0 \to K^* l^+ l^-$: A_{FB}

The forward-backward asymmetry, also, does not match the SM in same region.



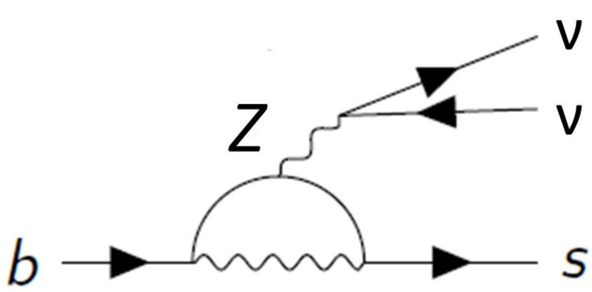
Taken together these differences w.r.t. the SM are significant (4 standard deviations), and are unlikely to be a statistical fluctuation. But some commentators question the reliability of the SM predictions. So, is there anywhere else we can look ?

Looking for clues in related decays



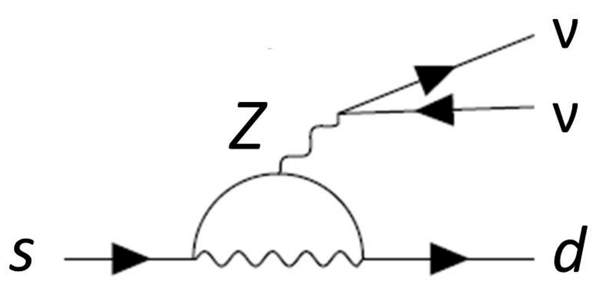
This is the process we have been discussing, studied by LHCb in decays such as $B^0 \to K^{*0} \mu\mu$.

There are related processes, not suited for LHCb, but can be studied at sister experiments elsewhere.



b→sννbar, exemplified in the decay $B^+ \to K^+ \nu\nu$bar.

Here the theory prediction is cleaner. Very difficult experimentally, but Belle II experiment in Japan has seen evidence [PRD 109 (2024) 112006] … & rate is 2.8 standard deviations (sigma) discrepant with SM.



s→dννbar, exemplified in the decay $K^+ \to \pi^+ \nu\nu$bar.

Ultra rare (~10^{-11}) but theoretically very clean. Observed by the NA62 experiment at CERN [JHEP 02 (2025) 191]…. & rate is 1.7 sigma above SM.

Deviations not yet large enough to be a problem, but intriguing ! Motivates improved measurements at existing and future generation of experiment.

The future of flavour

Particle physics and flavour - the road ahead

(approved experiments) (proposed experiments)

2020s	2030s	2040s	2070s
LHCb (Upgrade I) ATLAS & CMS	LHCb Upgrade II ATLAS & CMS Phase-II Upgrades		
Belle II	Belle II+ ?	FCC-ee ….	FCC-hh
BESIII	STCF	CEPC ….	SPPC

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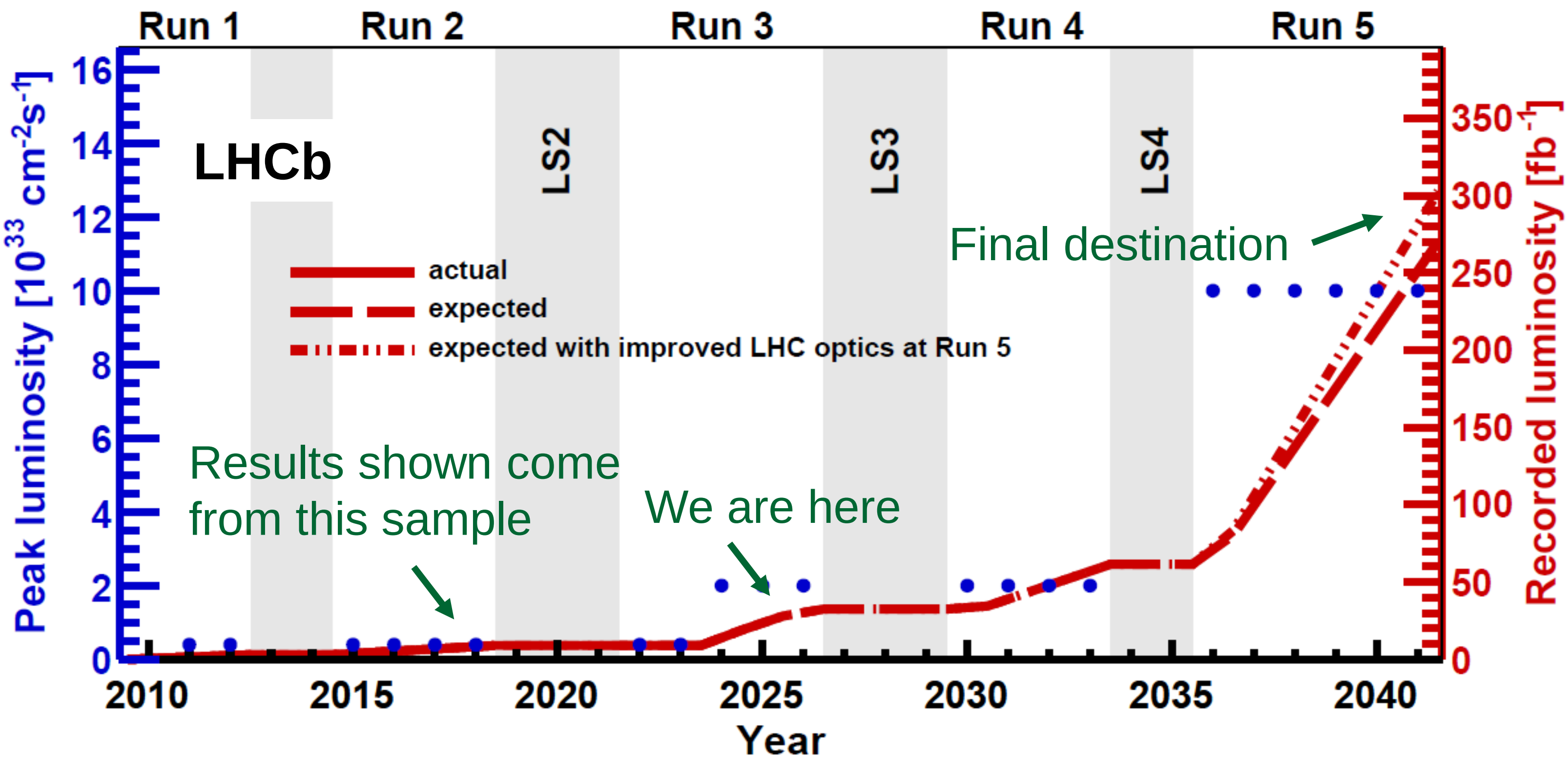
High-Luminosity LHC

LHC will soon undergo a major upgrade in luminosity (High-Luminosity LHC), as will the experiments, including LHCb at the end of decade. These are all challenging and exciting projects that will give very large increases in data !



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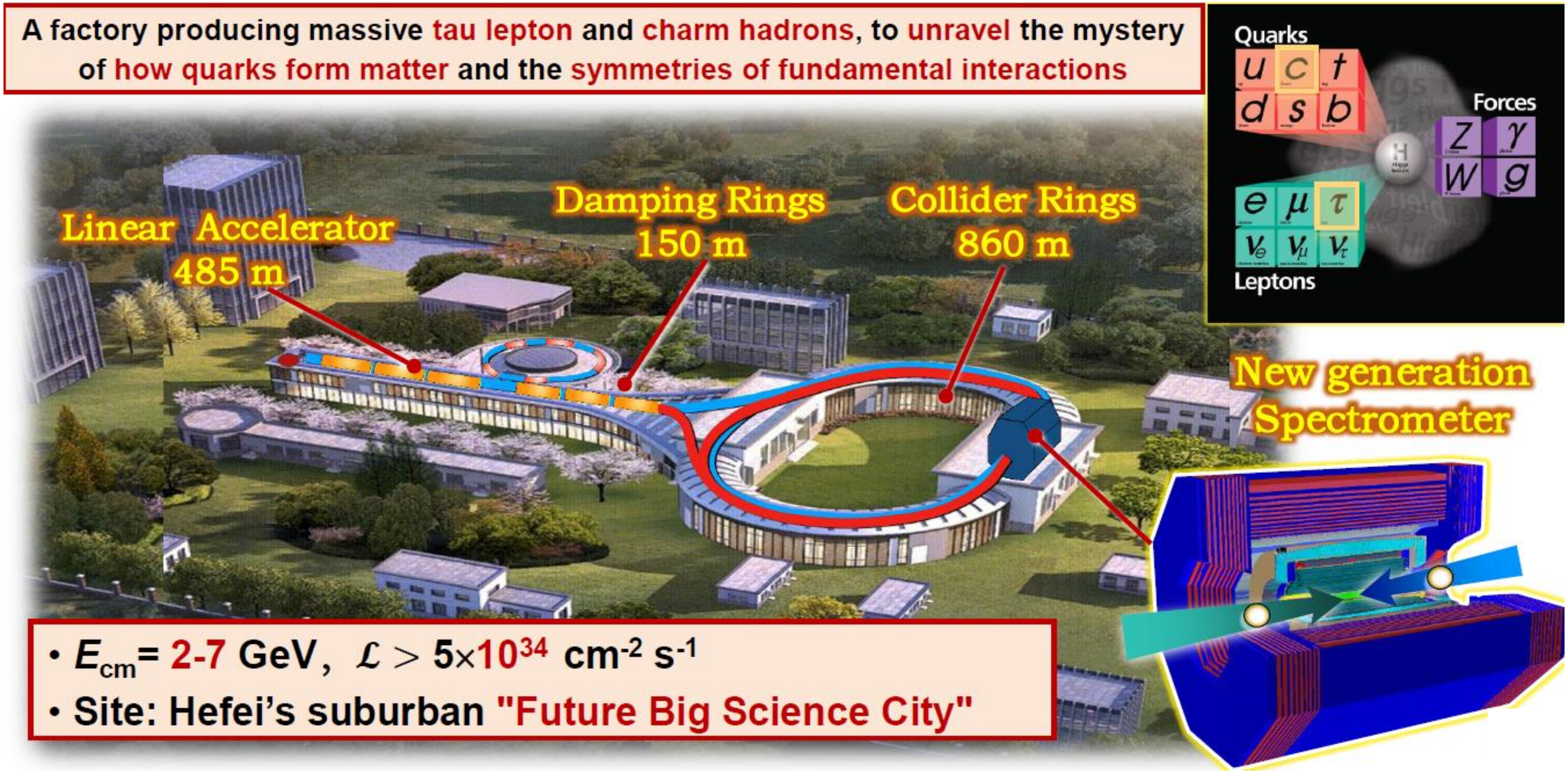
Super tau charm facility

A project proposed to begin construction in next five-year plan in Hefei.



Builds on success on BESIII experiment in Beijing, but 100x larger data samples.
Detailed studies of charm mesons, tau lepton, and other physics at these energies.

Particle physics and flavour - the road ahead

(approved experiments)

LHCb (Upgrade I)
ATLAS & CMS

Belle II

BESIII

2020s

LHCb Upgrade II
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2030s

(proposed experiments)

FCC-ee …. FCC-hh

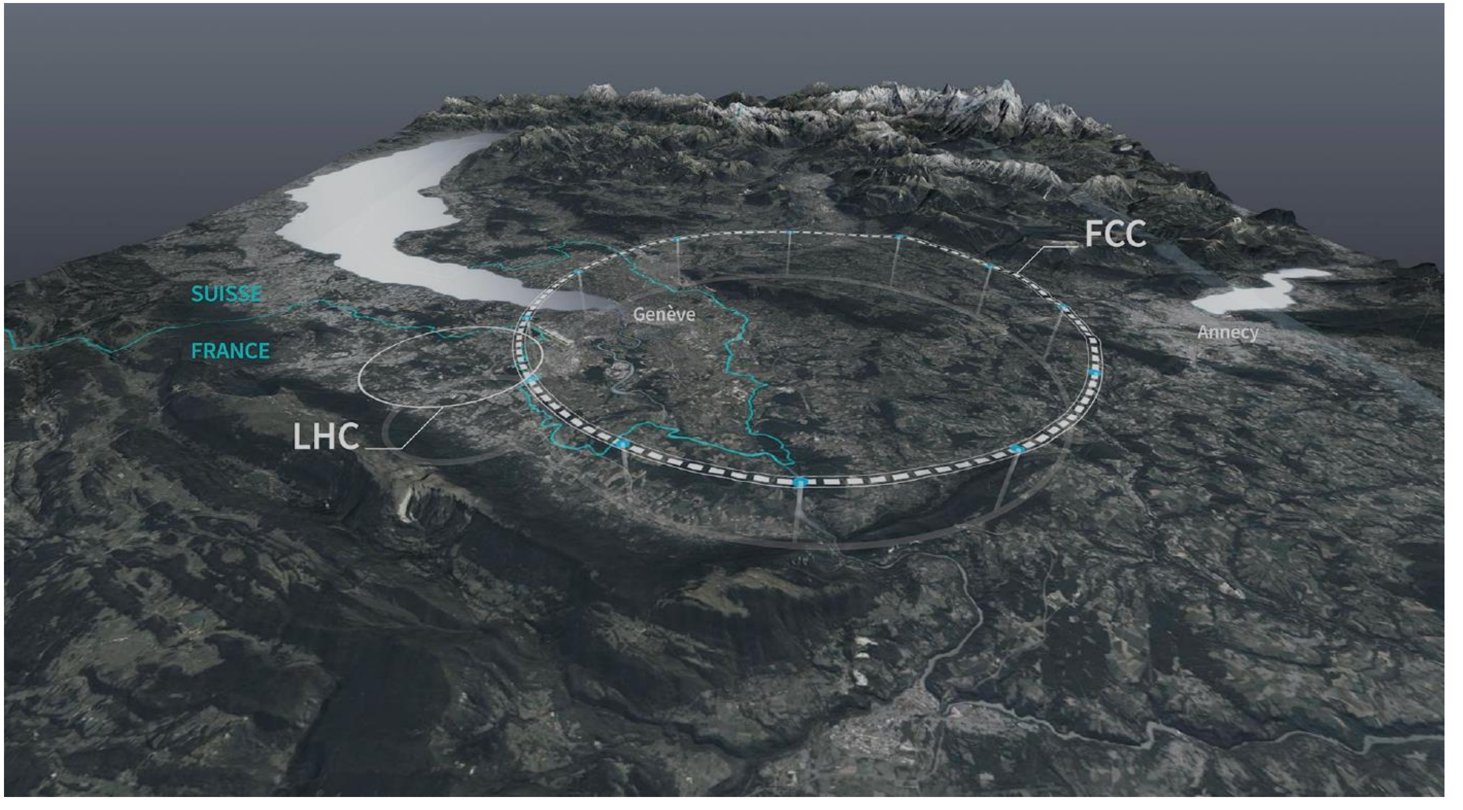
CEPC …. SPPC

2040s

2070s

The Future Circular Collider (FCC)

A 91 km e^+e^- collider proposed for CERN in the 2040s. It will study the Higgs boson in great detail, but can do much, much more, including flavour physics.



CEPC is a very similar project proposed in China.

Conclusions

Flavour physics is important because it addresses many of the open questions of the Standard Model, and is intrinsically very sensitive to any New Physics that lies beyond.

Great progress is being made, especially at LHCb, in making precise studies of CP violation, in discovering new exotic hadronic states, and in probing for discrepancies with the Standard Model in rare b decays.

The story is ongoing. Existing experiments aim for >10x more data, and a new generation of experiments is set to carry the programme forward.

We are truly living through a golden age of flavour, one in which beauty hadrons play a central role:

‘ “Truth is beauty, beauty truth” – that is all
Ye know on earth, and all ye need to know.’

John Keats, 1795-1821

Backups

Parameters of the Standard Model

- 3 gauge couplings
- 2 Higgs parameters
- strong CP parameter θ
- 6 quark masses
- 3 quark mixing angles + 1 phase [*i.e.* CKM matrix]
- 3 (+3) lepton masses
- (3 lepton mixing angles + 1 phase [*i.e.* PMNS matrix])

() = with Dirac neutrino masses

Parameters of the Standard Model

- 3 gauge couplings
- 2 Higgs parameters
- strong CP parameter θ

These are all flavour parameters !

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This is of particular relevance…

() = with Dirac neutrino masses