Truth through beauty: in search of New Physics with b-hadron decays

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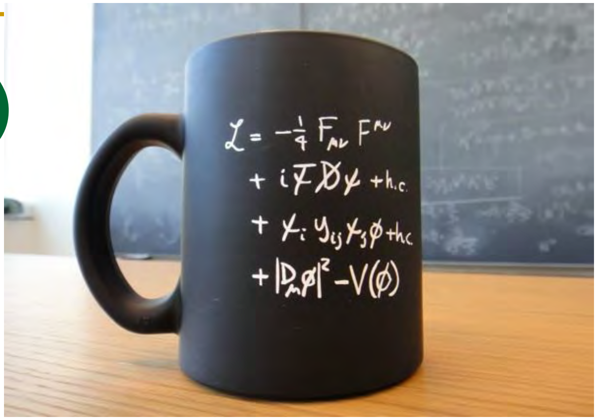
27/6/18

Outline

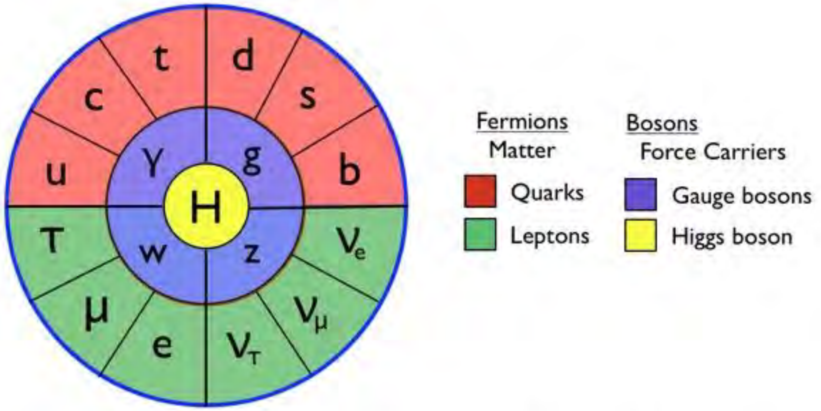
- The Standard Model (SM) and the role of 'flavour'
- Laying siege to the SM: the direct & indirect approaches
- The LHCb experiment
- Current conundrums
- Conclusions & outlook

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

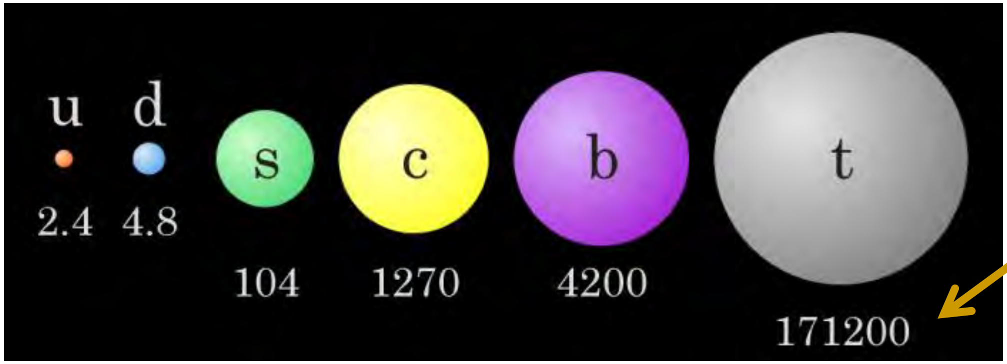
All tests made of the Standard Model in particle colliders have been successful !
The most spectacular recent example was the discovery of the Higgs boson.

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.

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.

Baryons

Mesons

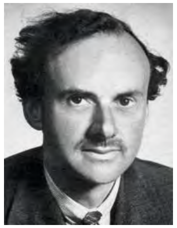
proton

neutron

pion (π^+)

kaon (K^+)

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:



anti-proton

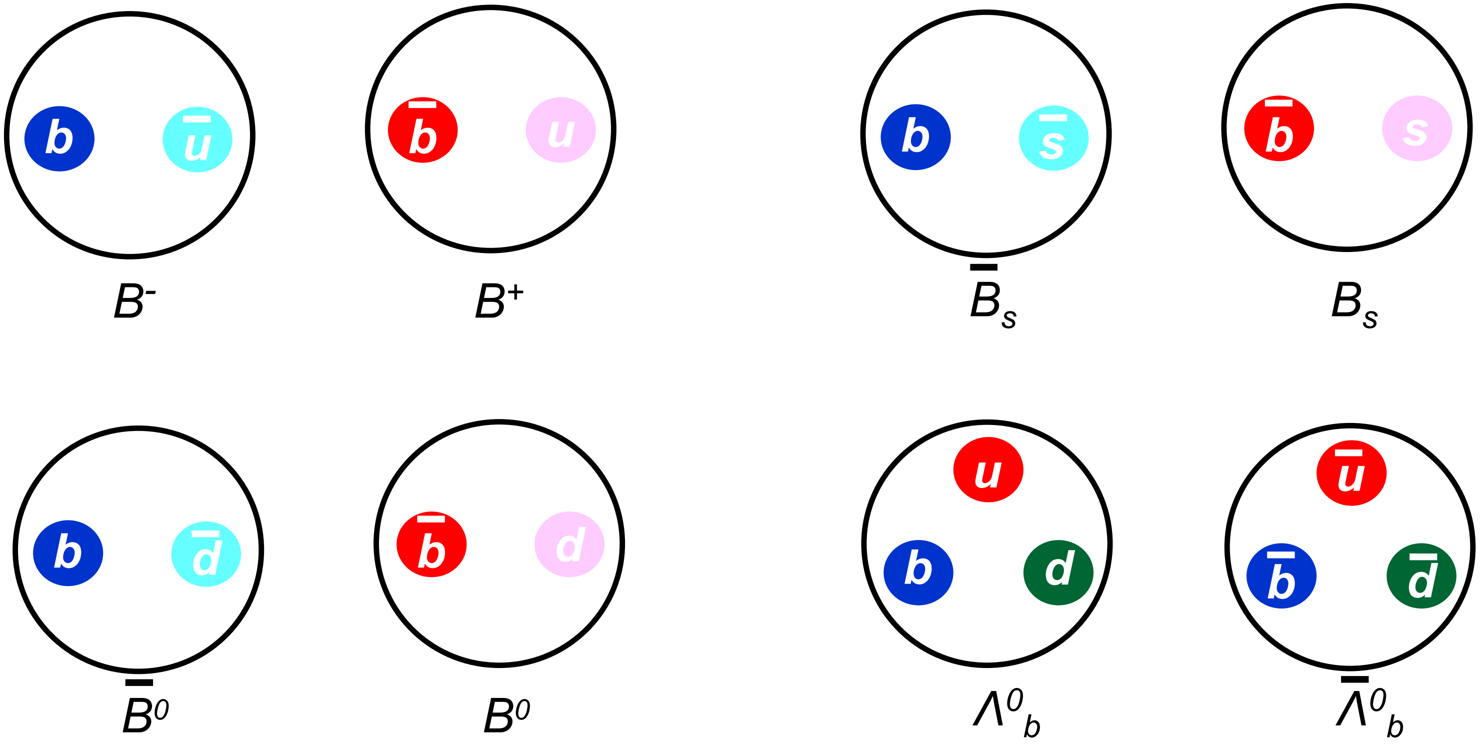
anti-neutron

π^-

K^-

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.



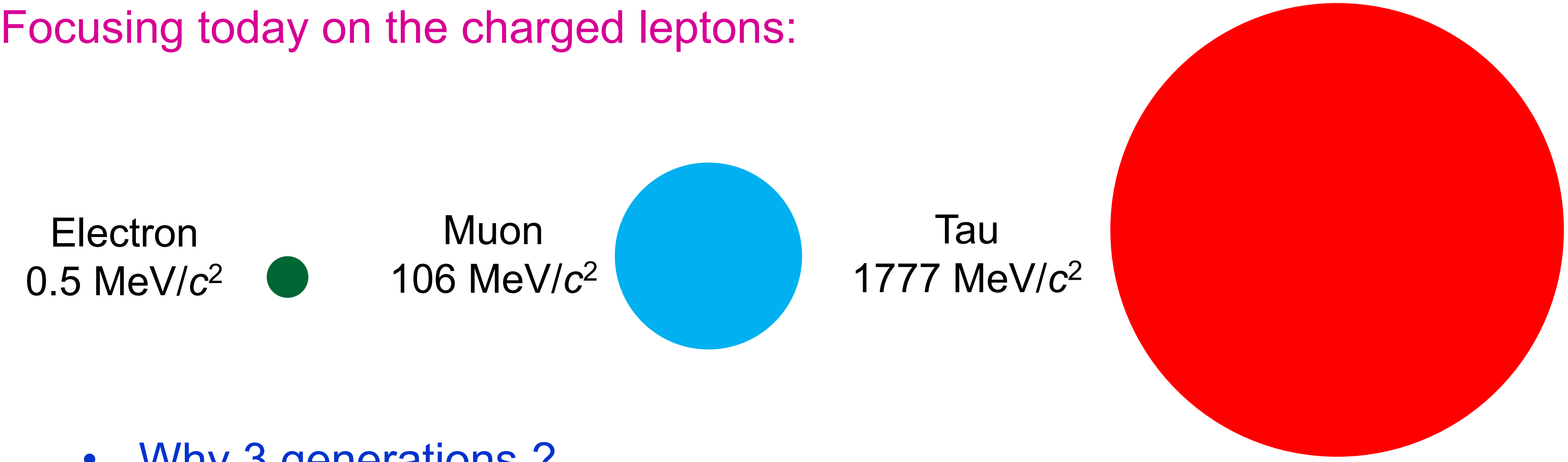
One other thing… all hadrons (apart from protons) are unstable and decay in to lighter particles. From these decays we can learn valuable lessons.

Flavour puzzles in the lepton sector

The mystery of flavour extends into the lepton sector.
Leptons are spin-1/2 particles which do not experience the strong force.

Again, we have three generations, each containing a charged particle & a neutrino.

Focusing today on the charged leptons:



Electron
0.5 MeV/c^2

Muon
106 MeV/c^2

Tau
1777 MeV/c^2

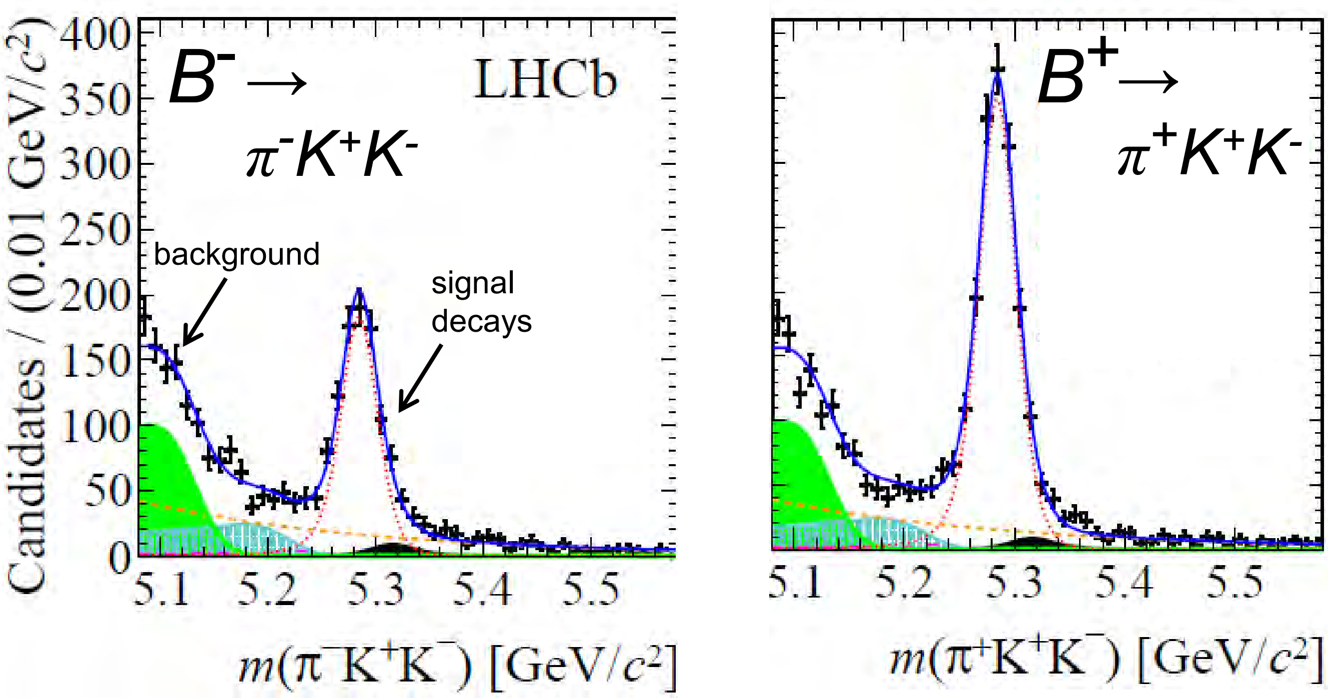
- Why 3 generations ?
- Why the extreme hierarchy in mass ?
- Why do the electroweak bosons (γ, W and Z) treat all generations equally (this is the property of ‘lepton universality’ – remember for later).

CP violation – a broken symmetry

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 *b*-quark hadrons

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



$B^- \rightarrow \pi^- K^+ K^-$

$B^+ \rightarrow \pi^+ K^+ K^-$

background

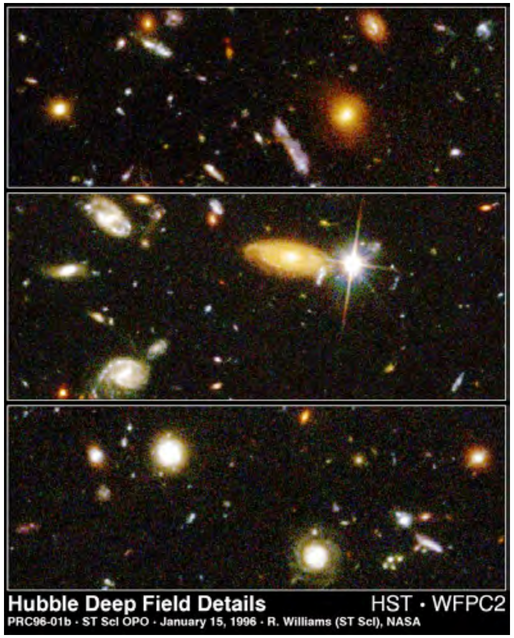
signal decays

[LHCb, PRD 90 (2014) 112004]

…the decay probabilities are manifestly different for B^- & B^+ ! CPV is accommodated in the SM, *but not explained*, by the inclusion of an additional parameter.

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 !



Hubble Deep Field Details HST · WFPC2
PRC96-01b · ST ScI OPO · January 15, 1996 · R. Williams (ST ScI), NASA

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

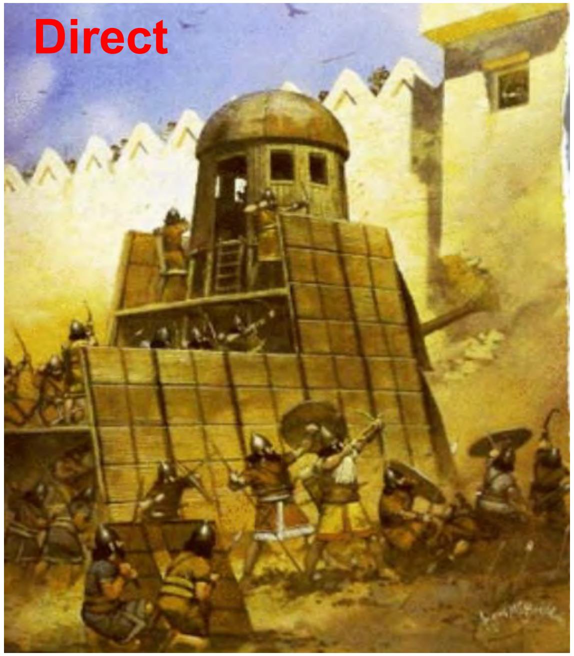
And there are plenty of others, for example:

- 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' !

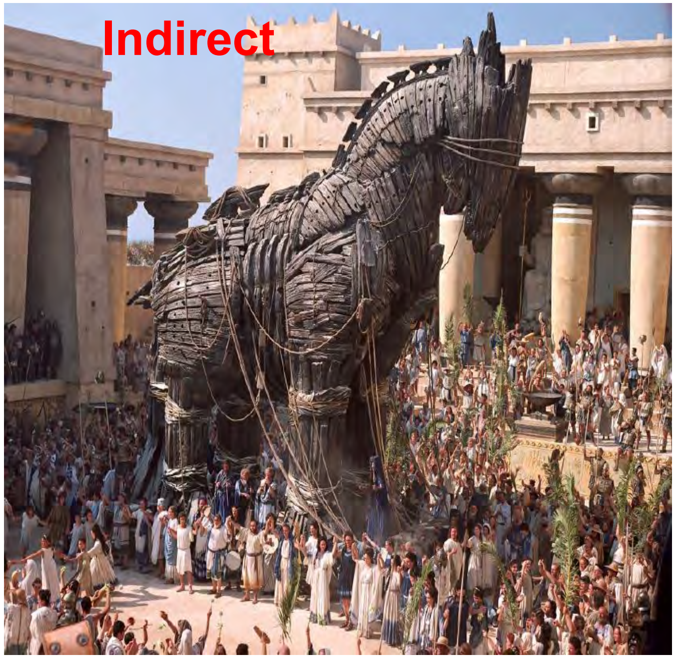
Attacking the fortress of the Standard Model

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



Direct

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



Indirect

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

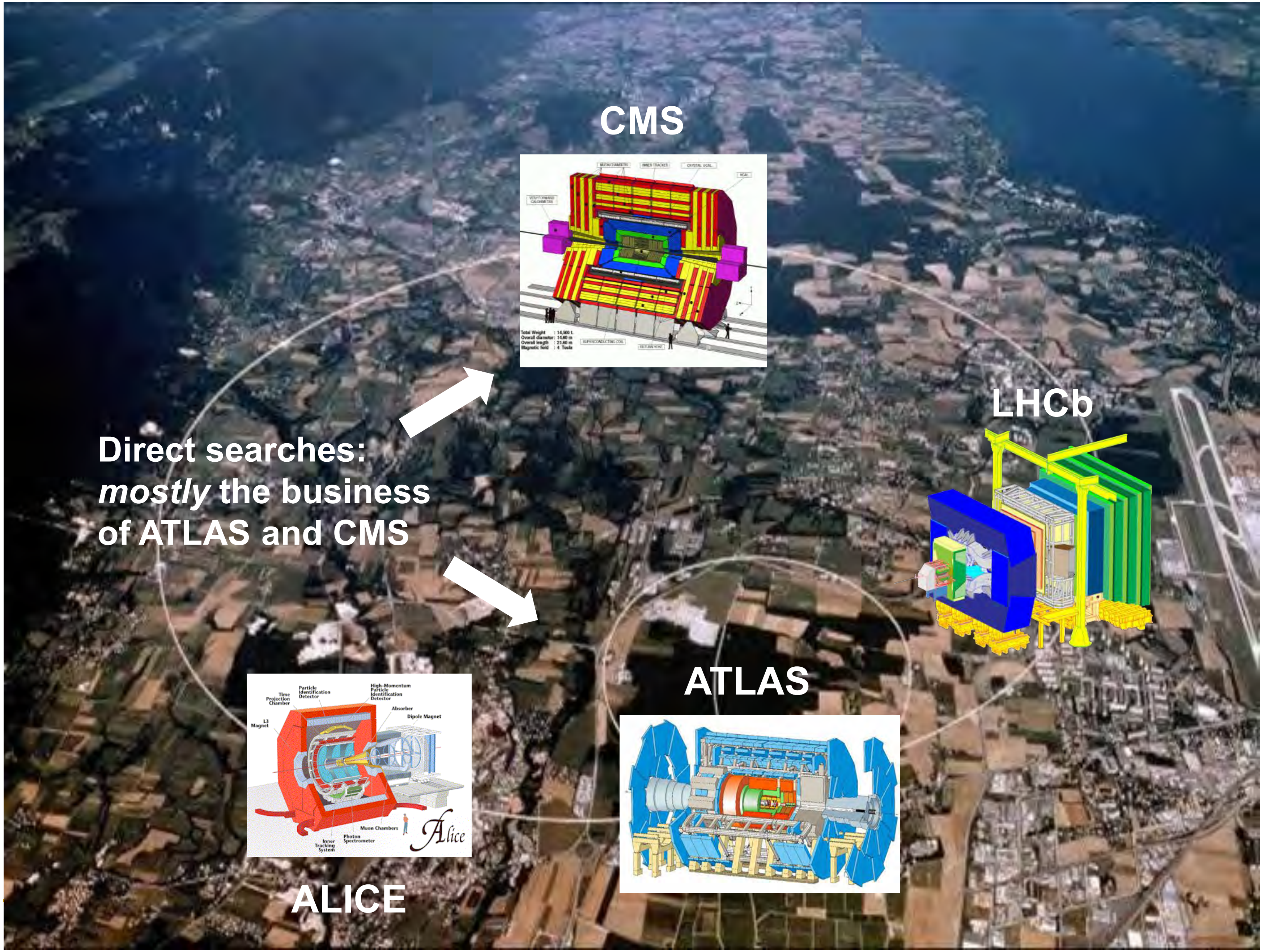
Direct searches at the LHC

- dreams and (so far) disappointments

There were high hopes and good expectations that new particles would be produced and discovered at the LHC in direct searches.

So far this has not happened, although there have been false alarms.

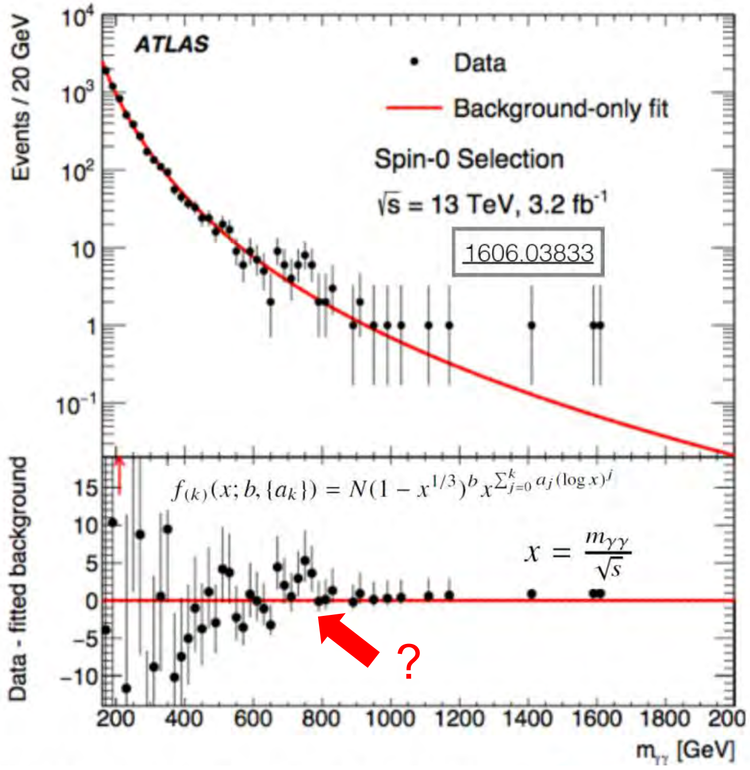
But this is an ongoing story, and the efforts continue. In particular the capabilities of the luminosity upgrade of the accelerator (HL-LHC, foreseen for mid 2020s) will increase the power of the search.

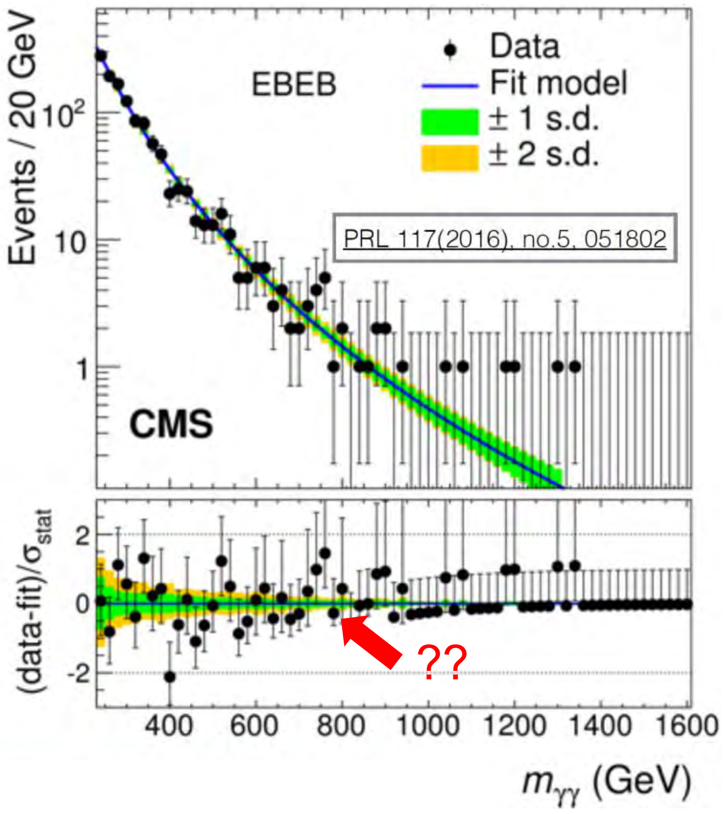


Direct searches:
mostly **the business of ATLAS and CMS**

False dawns: the 750 GeV di-photon excess

There have been several interesting candidate ‘New Physics’ signals that have emerged from direct searches at the LHC. Most notable the di-photon excess which appeared in both ATLAS and CMS in the first year (2015) of 13 TeV running.





Great expectations for the larger data sample that was to be taken in 2016, with an update eagerly awaited at the ICHEP conference in July in Chicago.

Wikipedia: https://en.wikipedia.org/wiki/750_GeV_diphoton_excess

False dawns: the 750 GeV di-photon excess

Eventually, to a hushed audience in Chicago, the updated results were unveiled. (Recall this is a much larger data set, so any genuine signal should have 'grown'.)

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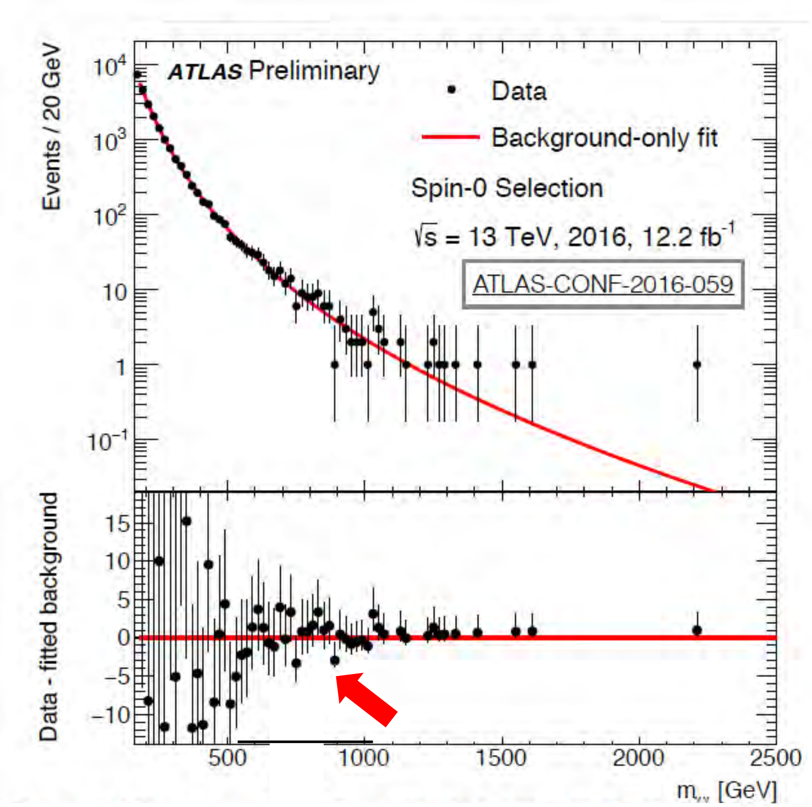
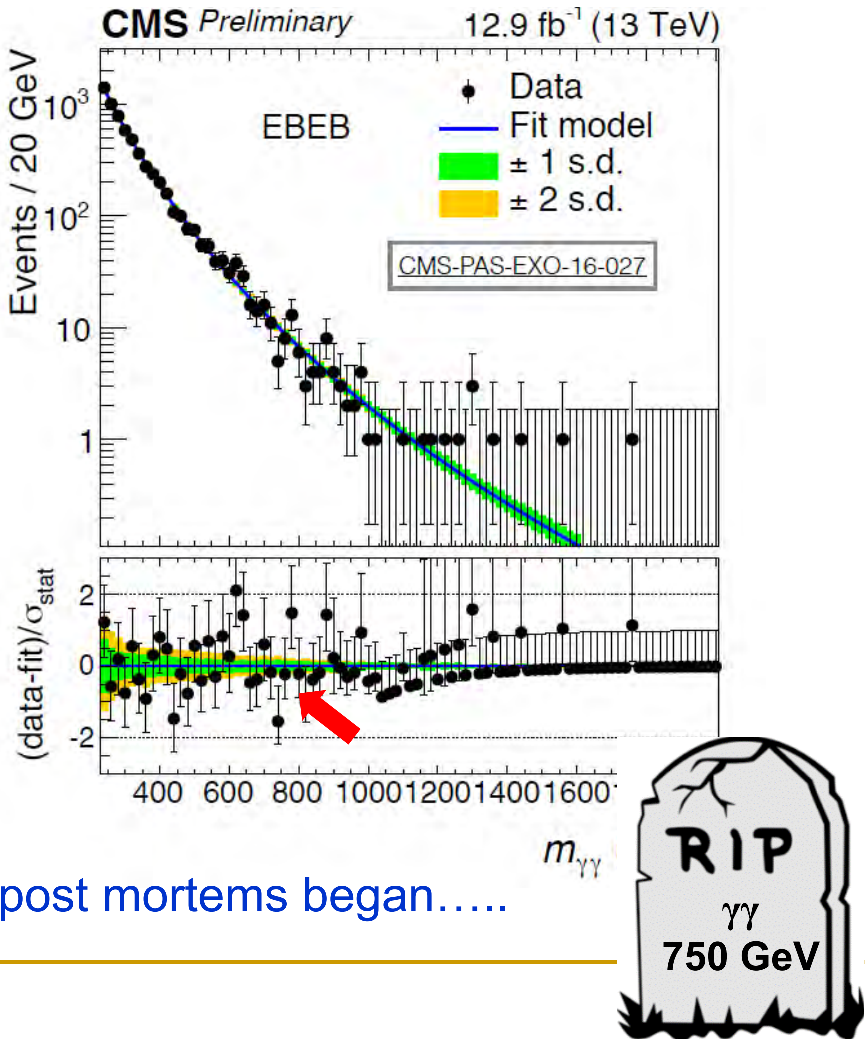
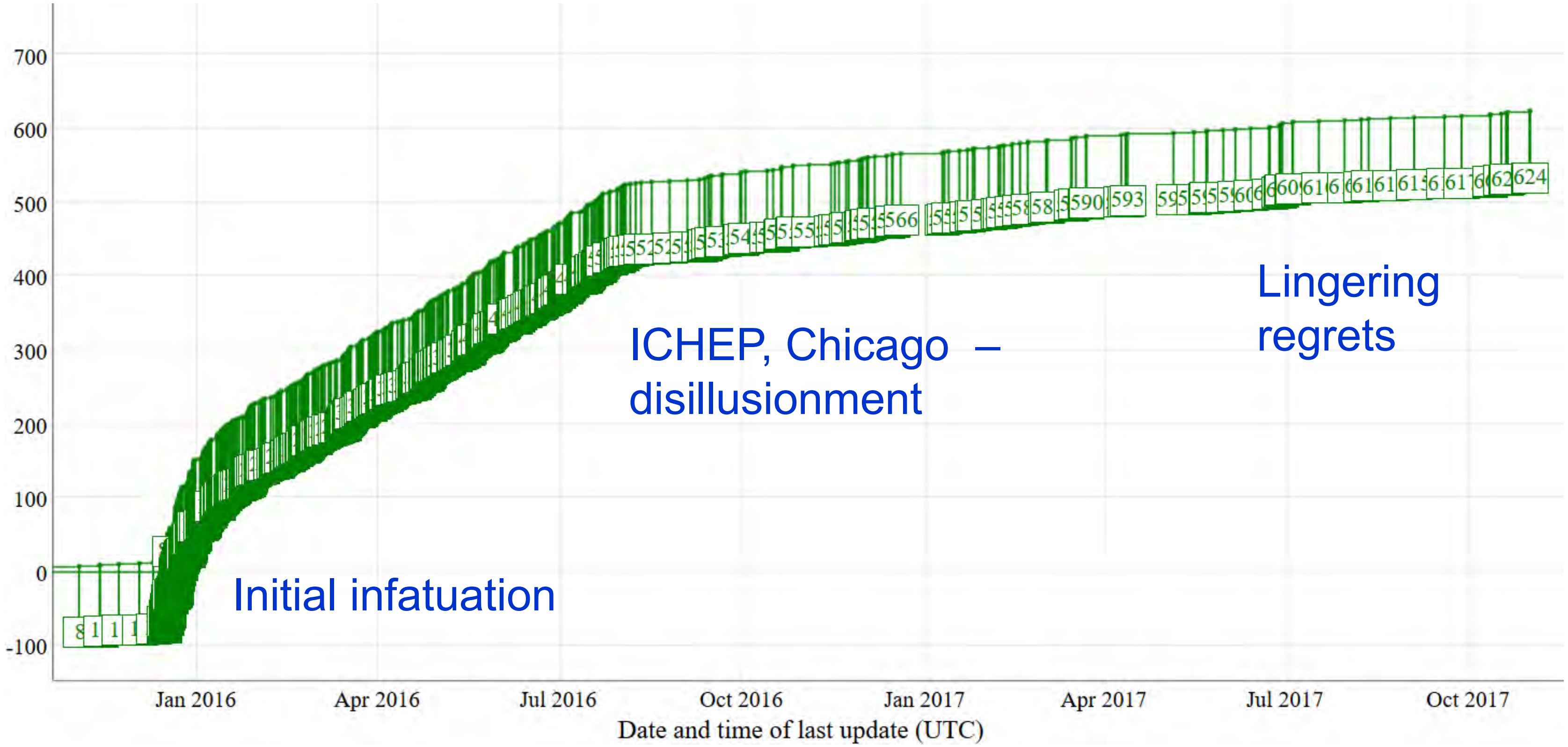




Nothing! Interest cooled rapidly and the post mortems began…..

History of theory community’s love affair with the 750 GeV di-photon ‘excess’

Cumulative number of references vs. time



Initial infatuation

ICHEP, Chicago – disillusionment

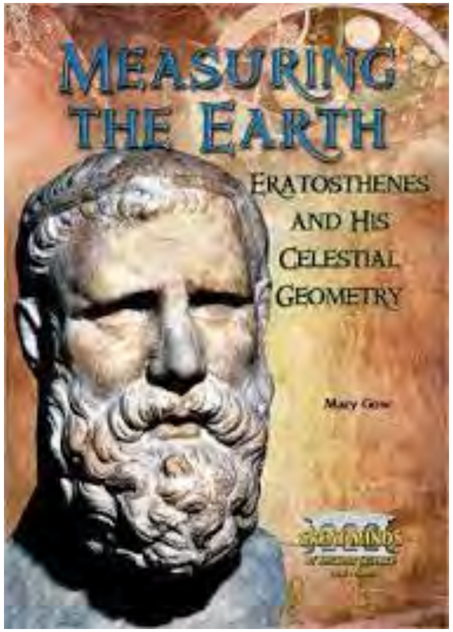
Lingering regrets

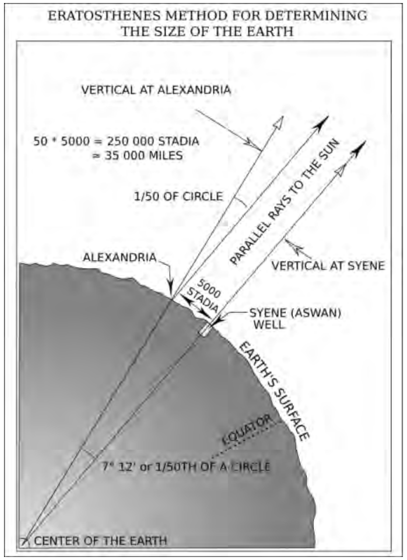
Indirect measurements and searches

- a noble pedigree, an intriguing present, and a bright future

Indirect measurements – an established tradition in science

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





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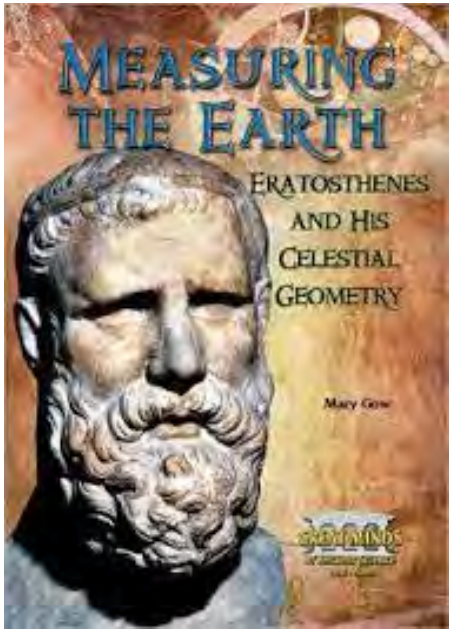
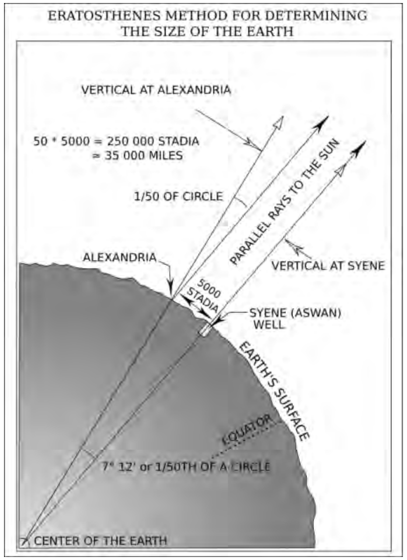


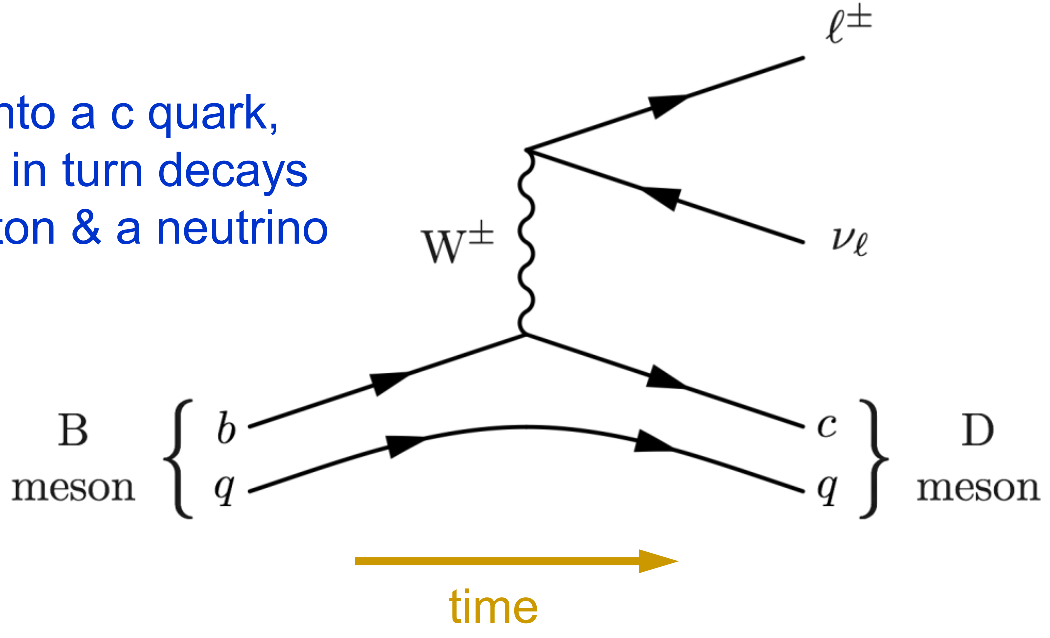


…around 2.2 thousand years
prior to the direct observation.

A hadron weak decay: the most common case

A hadron will usually decay in the weak interaction by the heavier quark emitting a W-boson & turning into something lighter. Often depicted in a ‘Feynman diagram’.

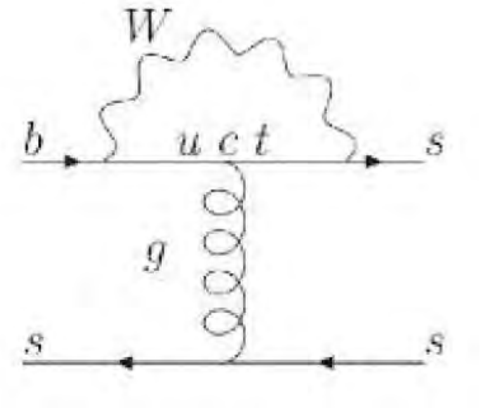
b quark switches into a c quark, and the emitted W in turn decays into a charged lepton & a neutrino

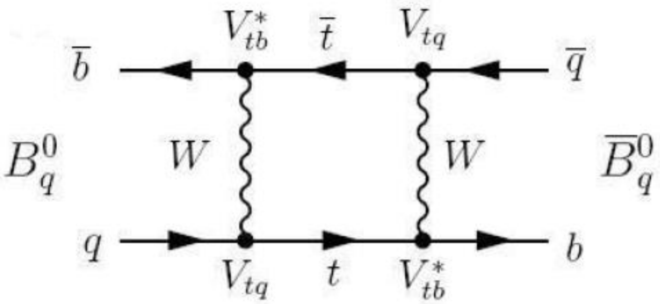


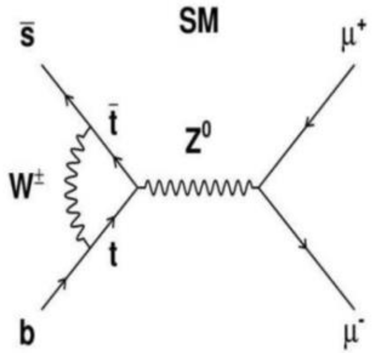
These processes and generally ‘favoured’: the diagram is simple and the decay probability and hence rate of occurrence is high. But there are other possibilities…

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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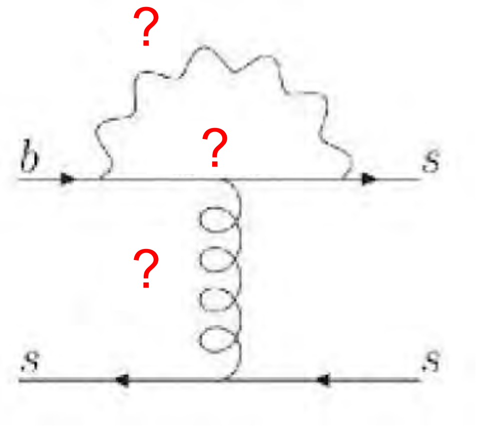
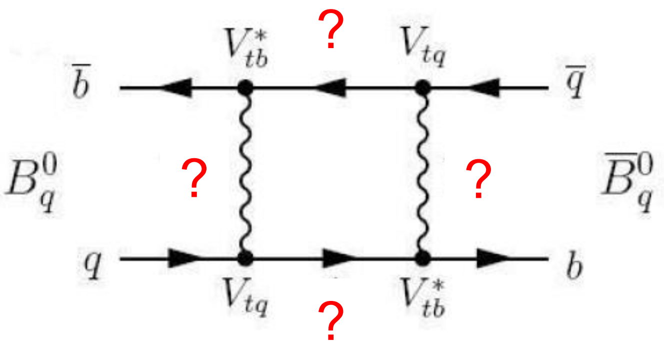
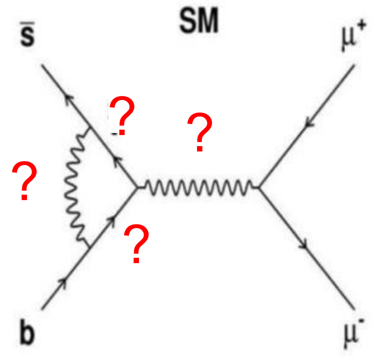






Decays, & other processes, involving *b*-quarks are a good place to study role of these loops. In the loops the contribution of heavy particles, *e.g.* top, is important, even though $m_t >> m_b$. Hence these decays tells us about the particles in the loops.

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

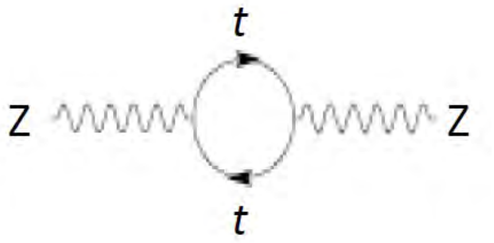
Indirect search principle → Precise measurements of low energy phenomena tells us about unknown physics at higher energies

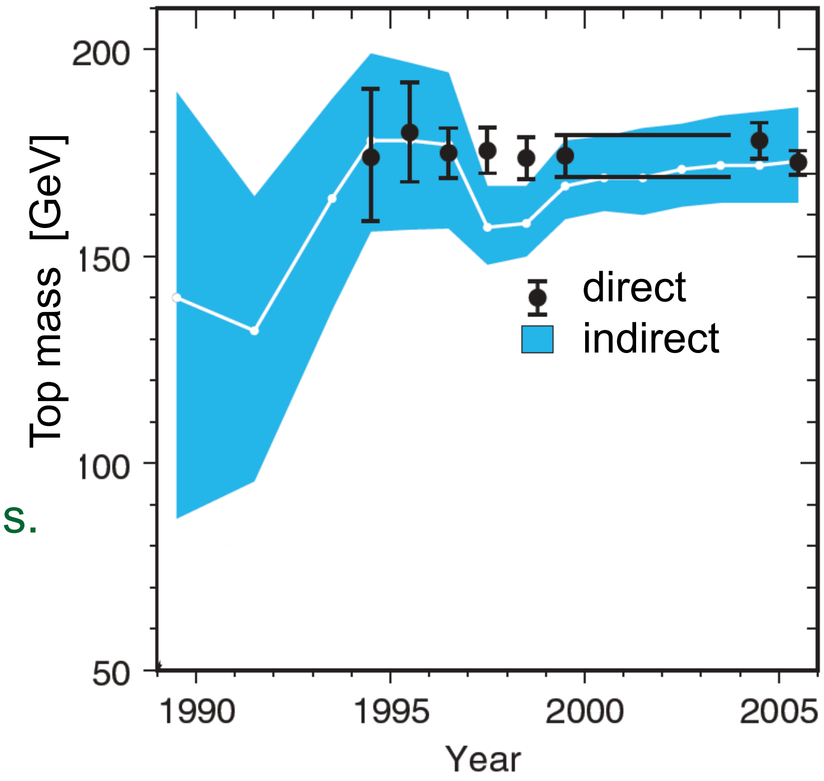
The power of indirect measurements – the top quark mass

LEP, the accelerator operation at CERN in the 1990s, did not have sufficient energy to produce ‘real’ top quarks.

The top quark was instead discovered at the Tevatron, near Chicago in 1995

Nonetheless, the precise measurements of Z boson properties made at LEP carry information on the top through loop diagrams.





LEP was able to measure the top mass indirectly, even before Tevatron discovery !

Flavour physics & the role of beauty

So, to recap, measurements in flavour physics are motivated by:

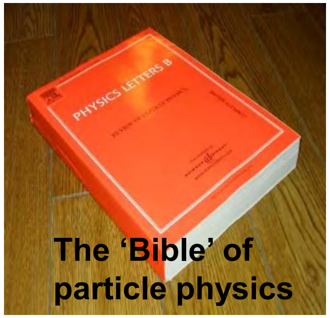
- Probing an area of the SM where there are many unanswered questions and clear deficiencies
- Looking for the contribution of new, massive particles, through virtual loops.

In particular, we wish to study hadron decays where we can:

- Have high sensitivity to the role of the virtual loops. This typically means going to decays that are very rare.
- Observe and learn about CP violation.

The best place to do this is through studies of **beauty hadrons**:

- They can decay in an enormous number of different ways

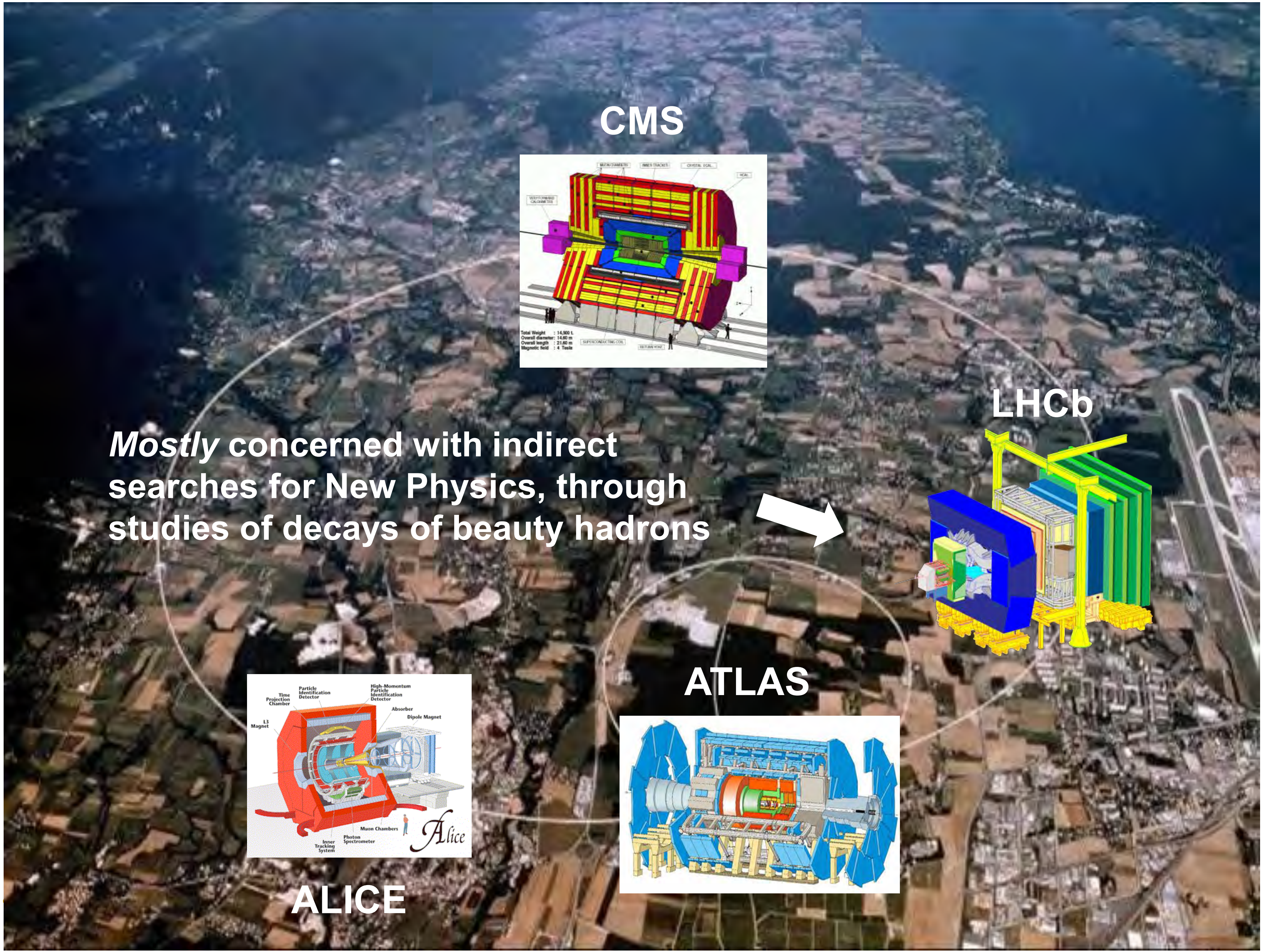


The 'Bible' of particle physics

The 'PDG review of particle properties' has more pages devoted to b-hadrons than any other particle. (>150 in 2014 edition)

- The predictions of the SM are often quite 'clean'. Good for comparing to experiment.
- CP violation is expected to be sizeable in many decays.

The LHCb experiment



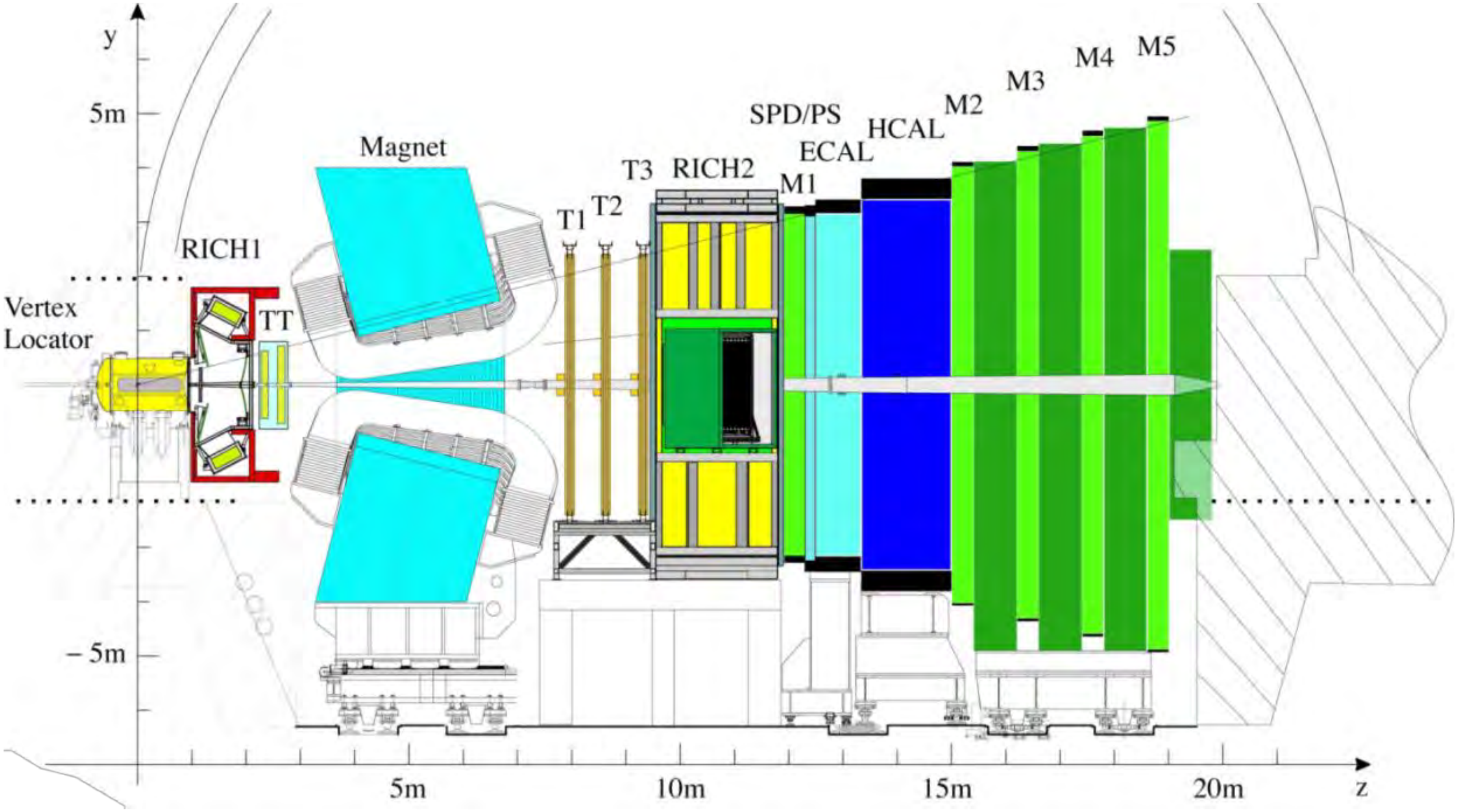
Mostly **concerned with indirect searches for New Physics, through studies of decays of beauty hadrons**

LHCb – a flavour physics experiment at the LHC

A collaboration of ~1300 members from 74 institutes in 16 countries

An experiment to search for physics beyond the **Standard Model**, in an indirect manner through **flavour** studies of particles containing **beauty** (***b***) quarks.

LHCb – a forward spectrometer for flavour physics



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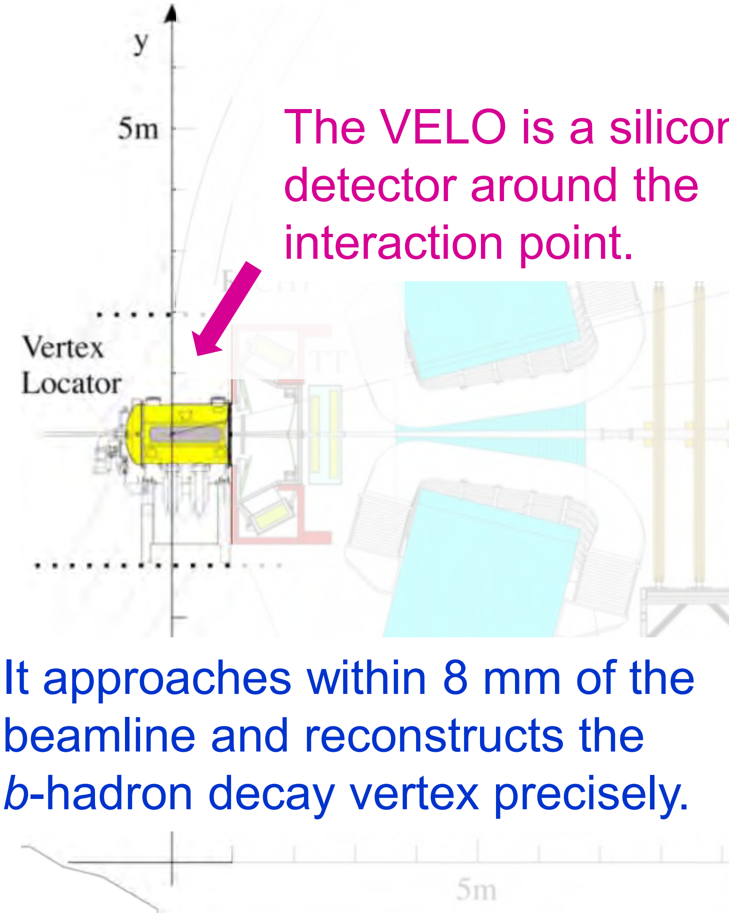
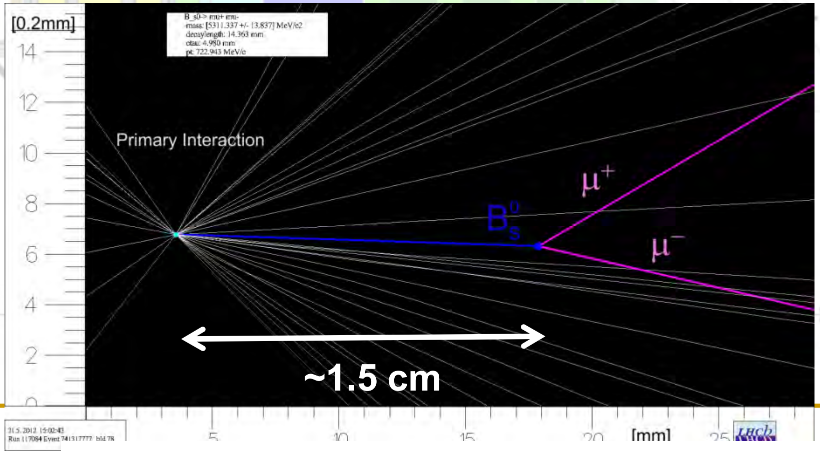


The VELO is a silicon detector around the interaction point.

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

One-half of the VELO under construction



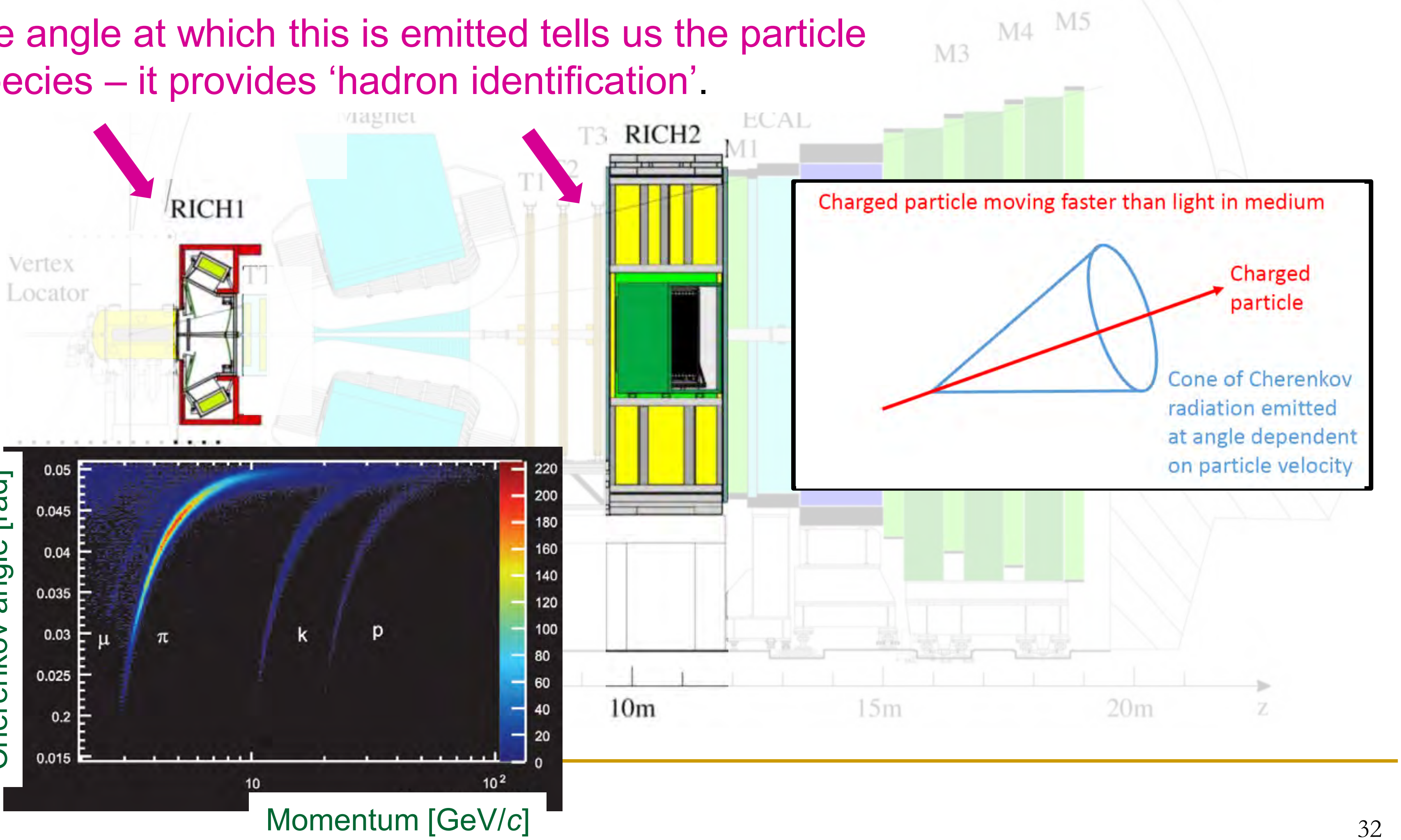
B_s0-> mu+ mu-
mass: [5311.337 +/- 13.837] MeV/c2
decaylength: 14.363 mm
ctau: 4.980 mm
pt: 722.943 MeV/c

31.5.2012 15:02:43
Run 117084 Event 741317777 bld 78

A reconstructed *b*-hadron decay vertex

LHCb – a forward spectrometer for flavour physics

Two ‘RICH’ detectors detect Cherenkov radiation. the angle at which this is emitted tells us the particle species – it provides ‘hadron identification’.



Charged particle moving faster than light in medium

LHCb – a forward spectrometer for flavour physics

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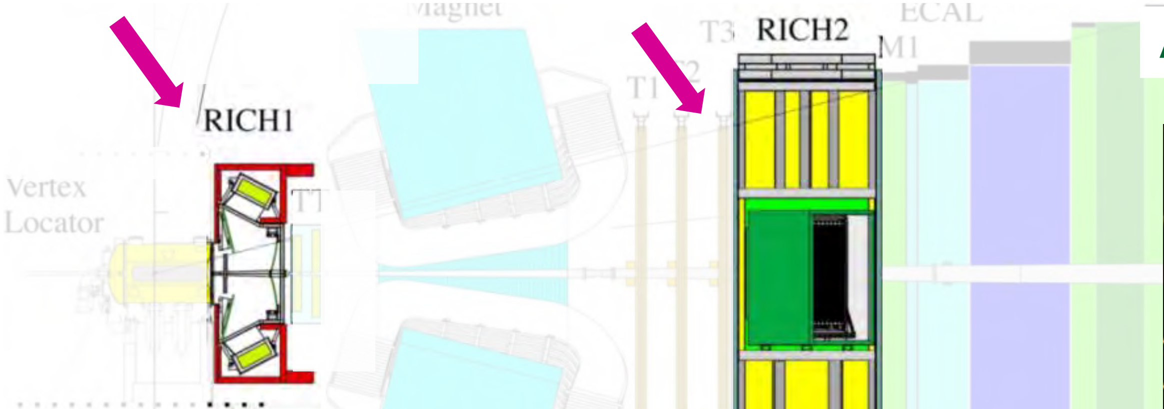
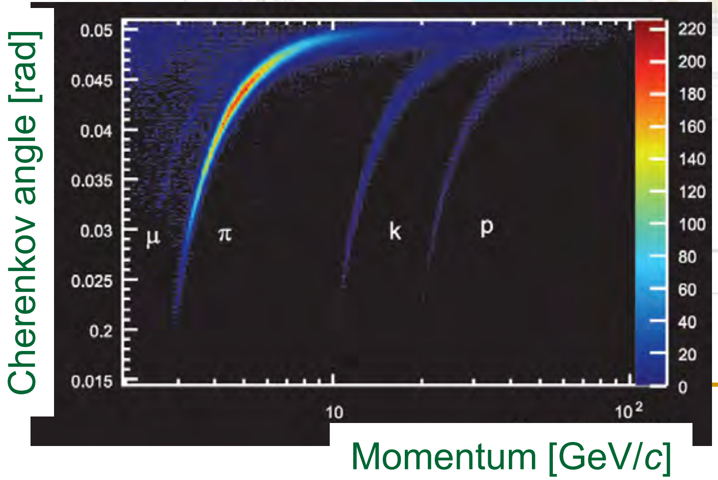
Array of RICH photodetectors

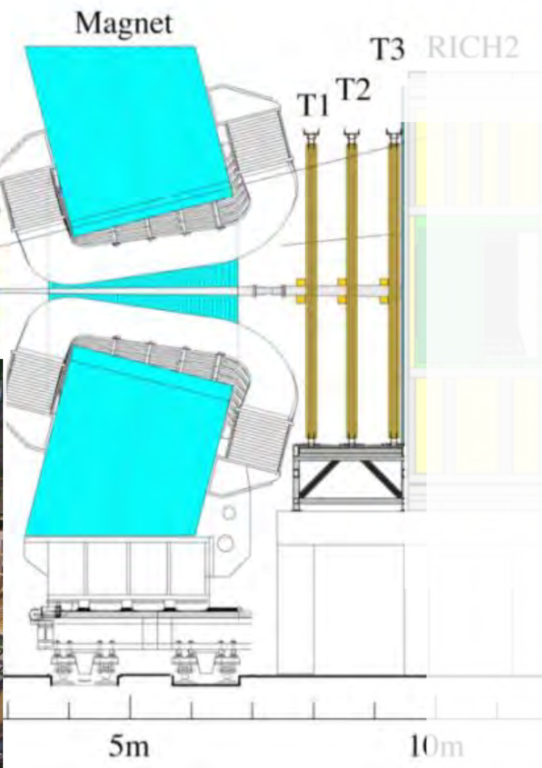


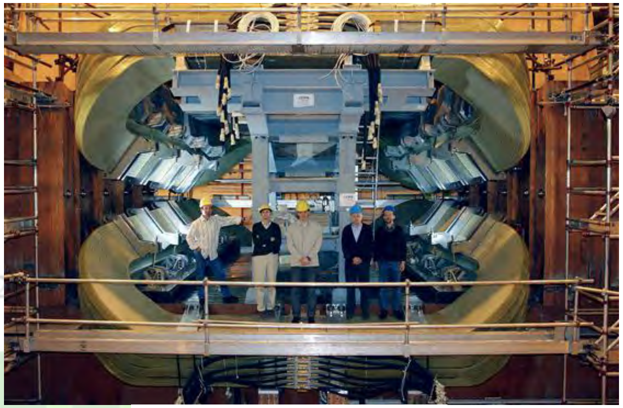


Assembling RICH 2; note the mirrors

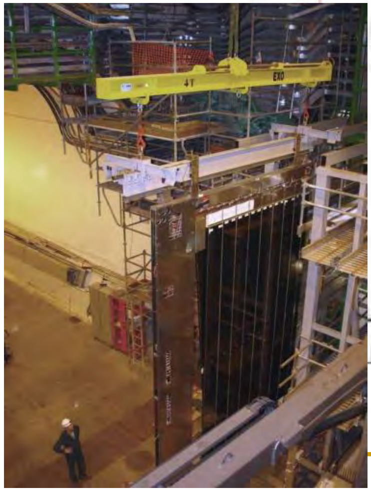
LHCb – a forward spectrometer for flavour physics

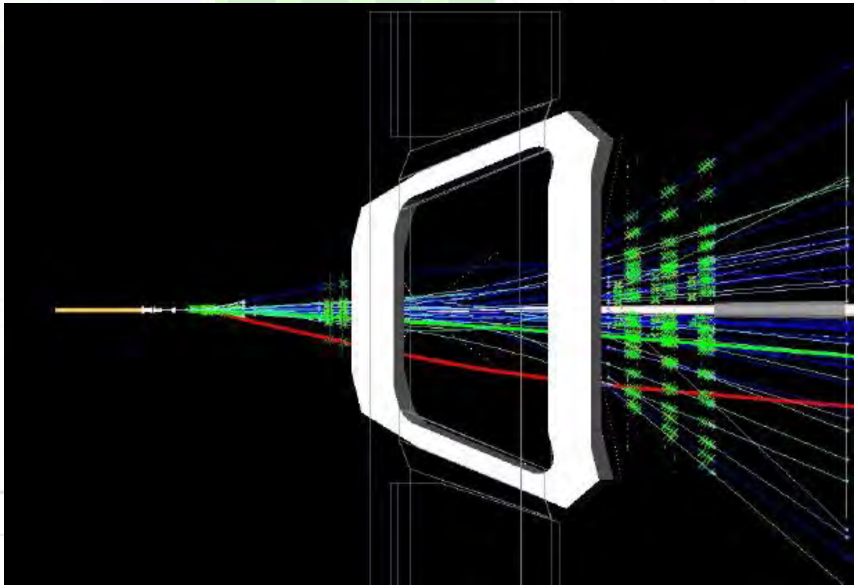
A 4 Tm dipole, and the tracking detectors reconstruct the trajectory of charged particles, and allows their momentum to be determined.





Dipole magnet

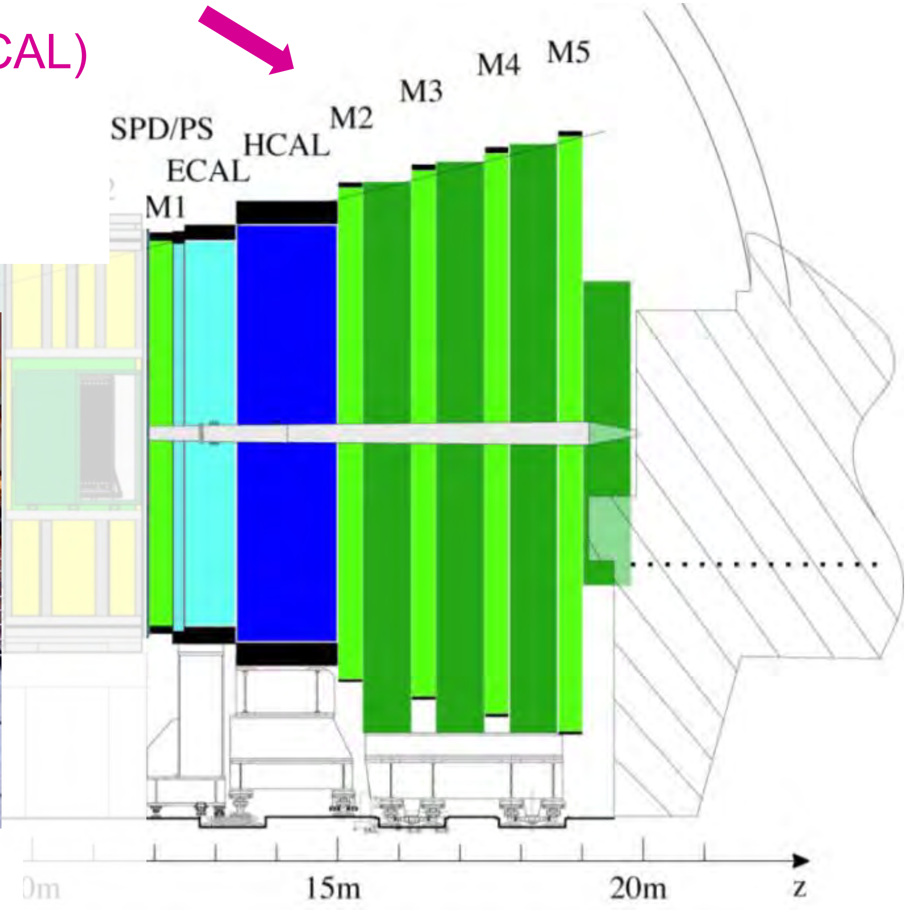


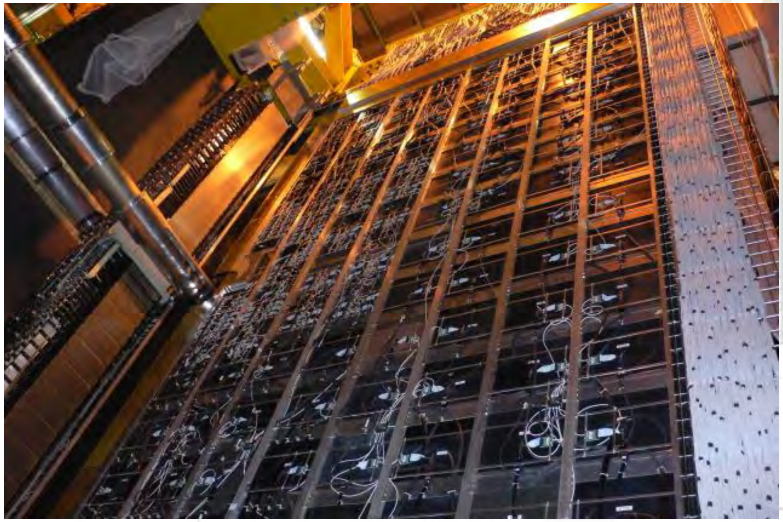


Reconstructed tracks

LHCb – a forward spectrometer for flavour physics

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

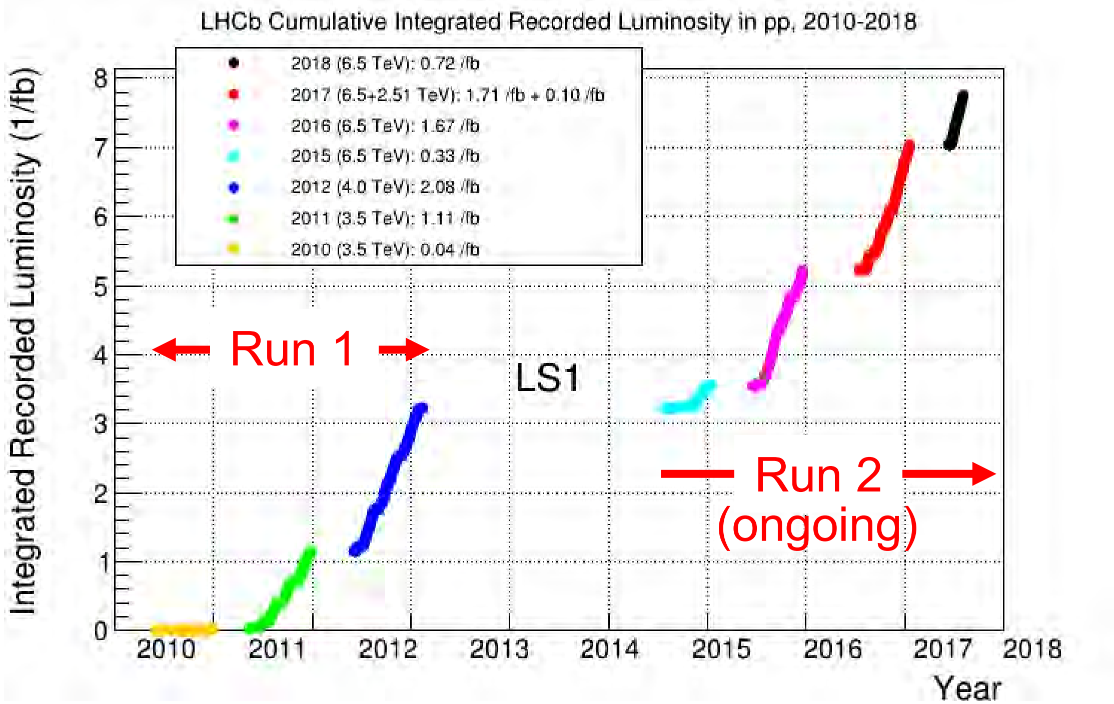




Part of calorimeter system (preshower)

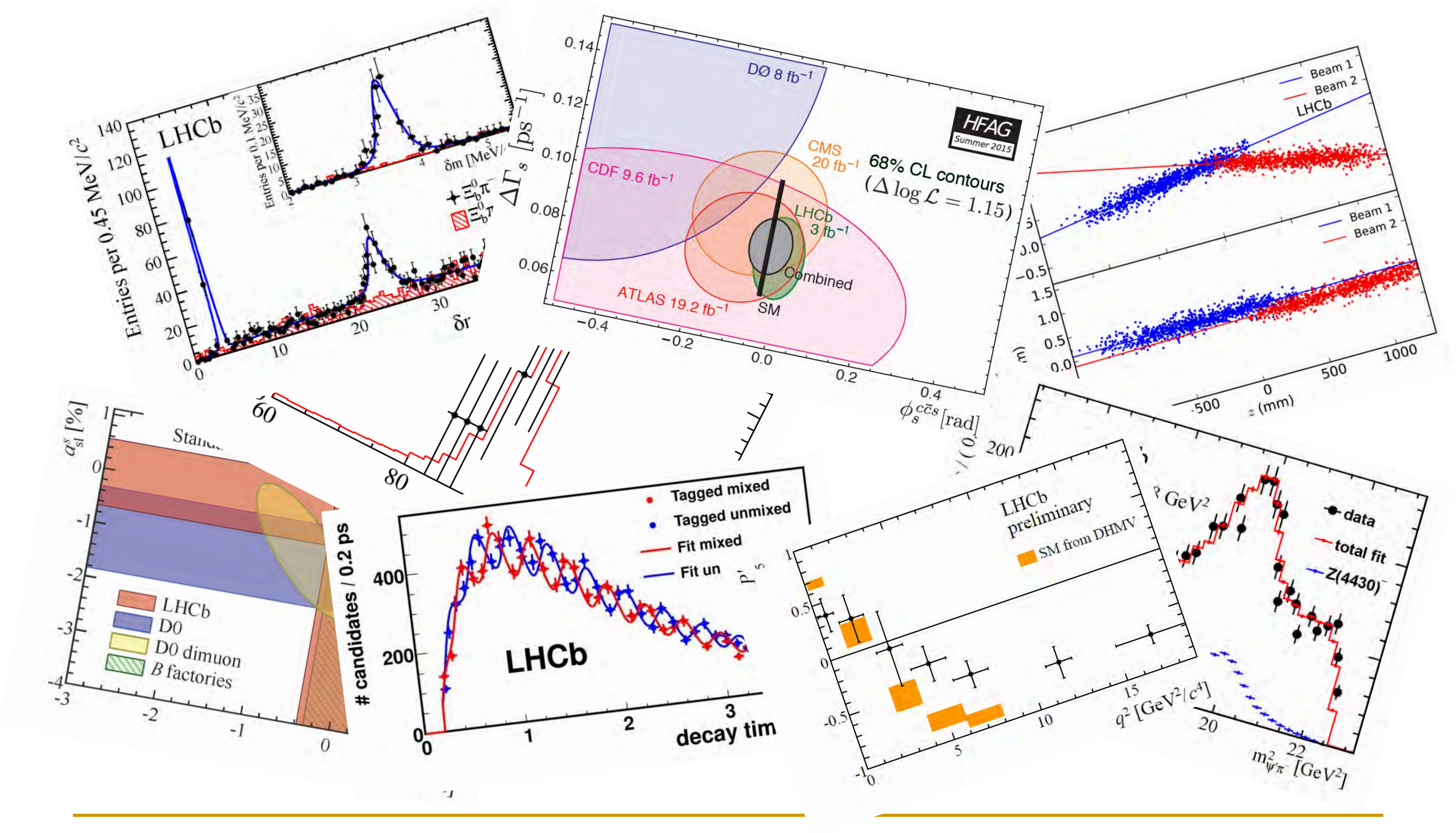
LHCb: the story so far

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

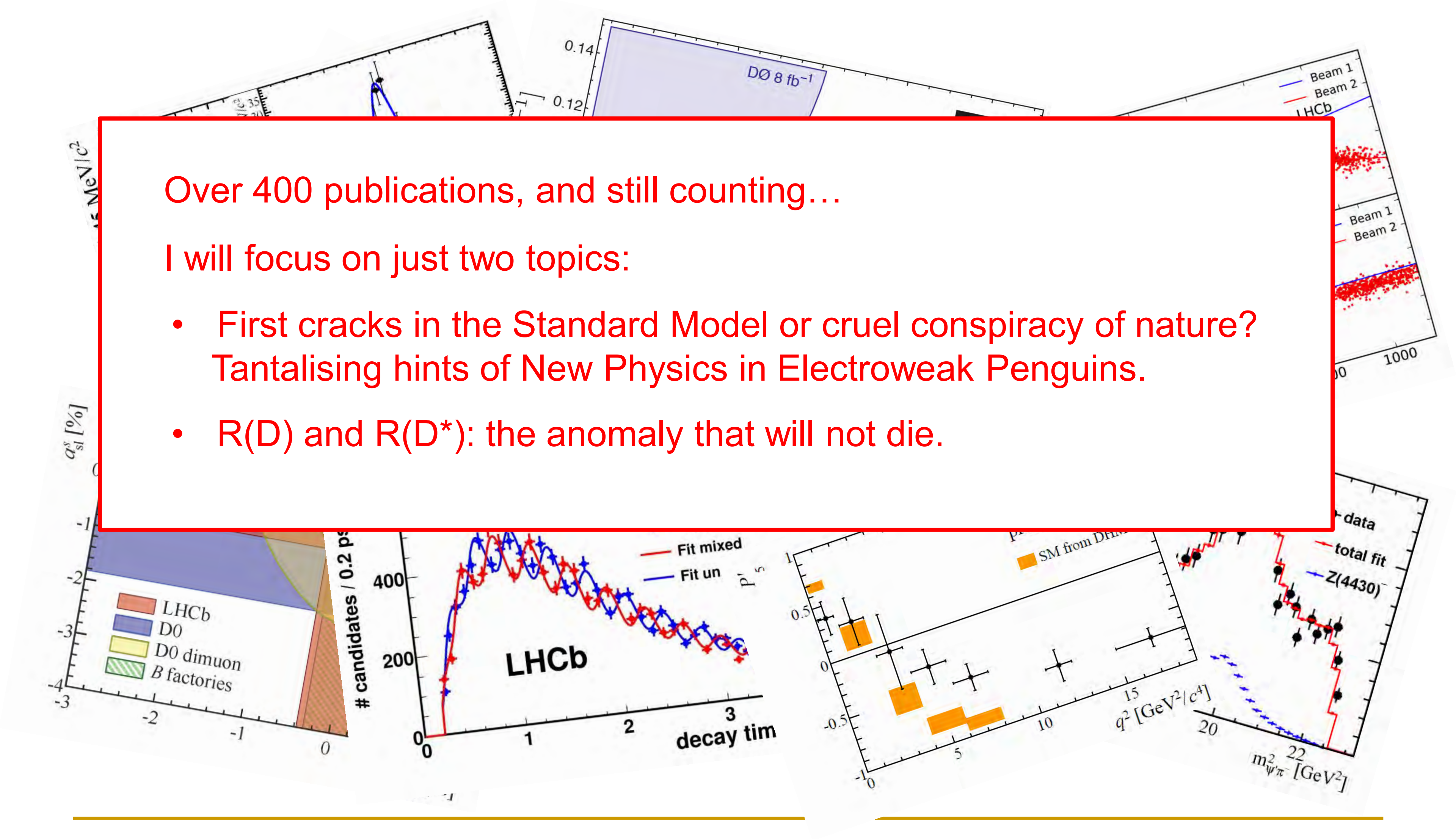


All the results I will show today come from this data set. We now have much more data available (and incoming) from run 2. Analysis of these collisions is in progress, but precise measurements require great care and don't come quickly !

News from the flavour frontier



News from the flavour frontier



Over 400 publications, and still counting…

I will focus on just two topics:

- First cracks in the Standard Model or cruel conspiracy of nature? Tantalising hints of New Physics in Electroweak Penguins.
- R(D) and R(D*): the anomaly that will not die.

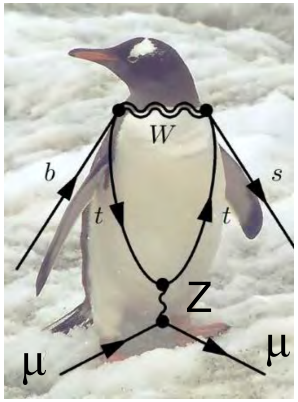
Exploration of ‘electroweak Penguins’ ($b \to s l^+ l^-$): a gateway to New Physics ?

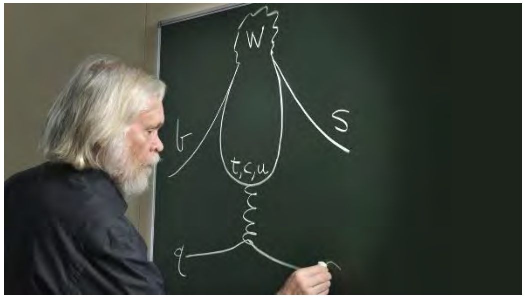
$B \to K^* l^+ l^-$
and friends

$b \to s l^+ l^-$ transitions, where l is a lepton (most conveniently a muon), have long been identified as an excellent place to look for effects of New Physics (NP).

- They are suppressed processes, and occur through loop diagrams, called ‘Electroweak Penguins’:
  - ‘electroweak’, because they involve Z or γ exchange;
  - ‘penguins’ because that is what their creator (John Ellis) termed them in an early b-physics paper.

→ This makes it easier for NP effects to compete against the SM contribution.

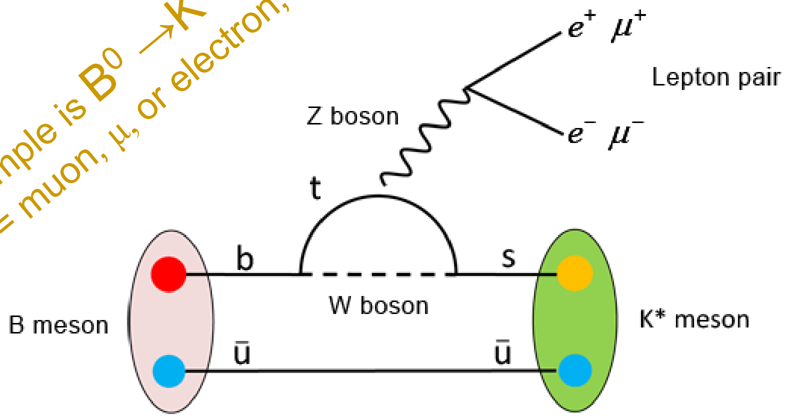




John Ellis drawing a Penguin diagram (though this one is not electroweak…)

- Furthermore, there are an enormous number of observables to measure, each with different NP sensitivity.

→ Possible to build up a coherent picture.



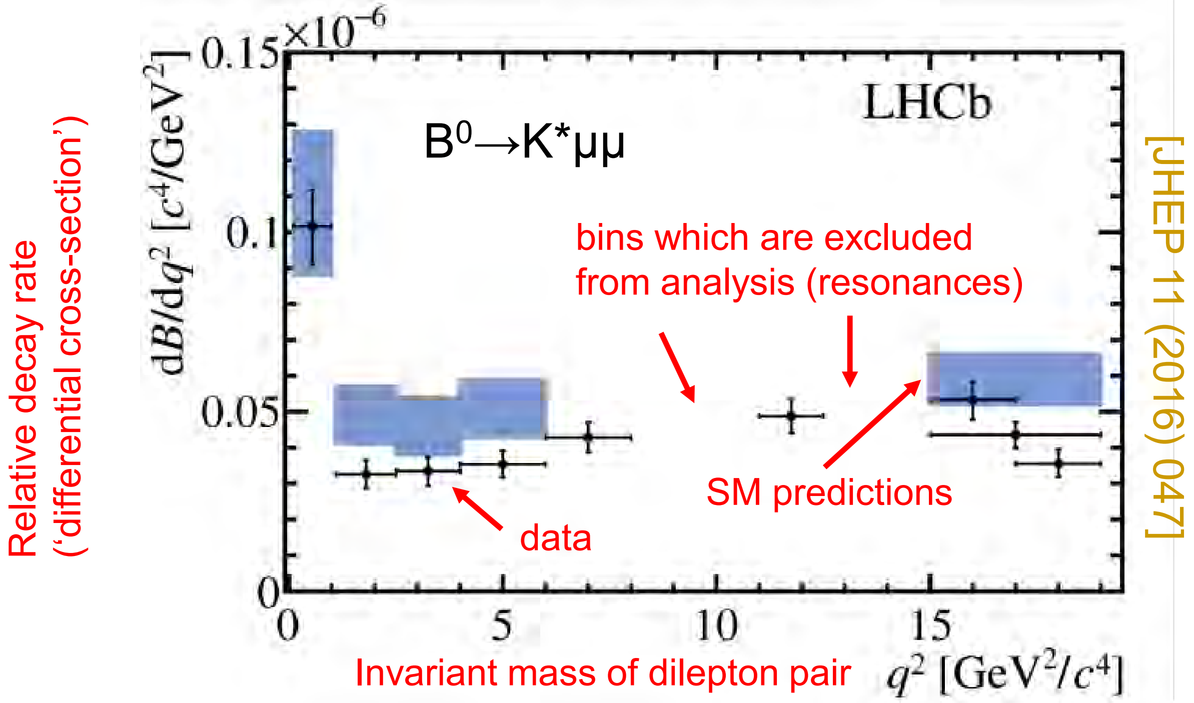
One example is $B^0 \to K^* l^+ l^-$ (here l = muon, μ, or electron, e)

Electroweak Penguins: decay-rate measurements

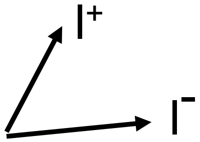
The first thing to measure is the decay rate, and compare to the SM prediction.

We can go one step better, & see how this depends on the 'q^2' of the dilepton pair. (q^2 = the 'invariant mass', & depends on the leptons energies & relative directions.)

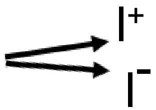
Do this for the case where the leptons are muons, because it's experimentally easier.



[JHEP 11 (2016) 047]



High energy &/or wide angle → high q^2



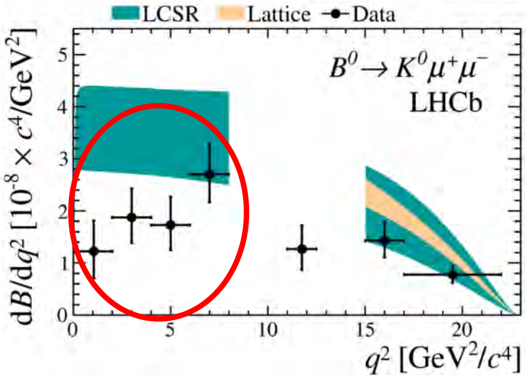
Low energy &/or narrow angle → low q^2

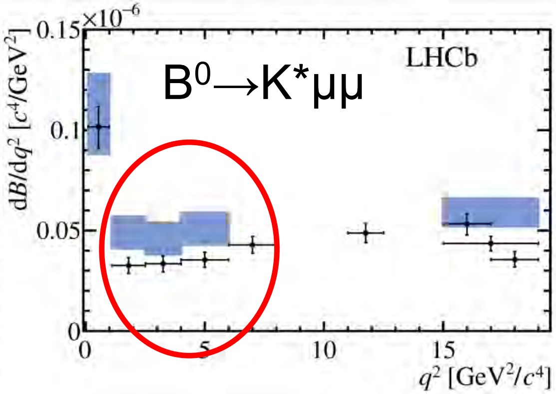
Eye is caught by the tendency for the data to lie lower than the SM predictions.

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

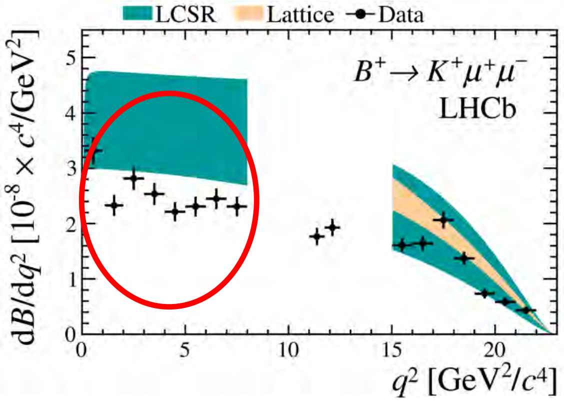
Lets look at the differential cross-sections for other electroweak Penguin decays.

[JHEP 06 (2014) 133]



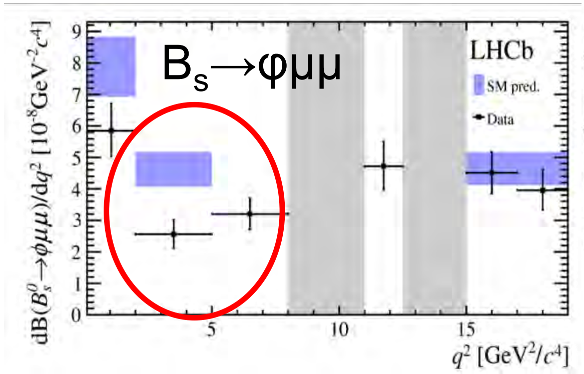


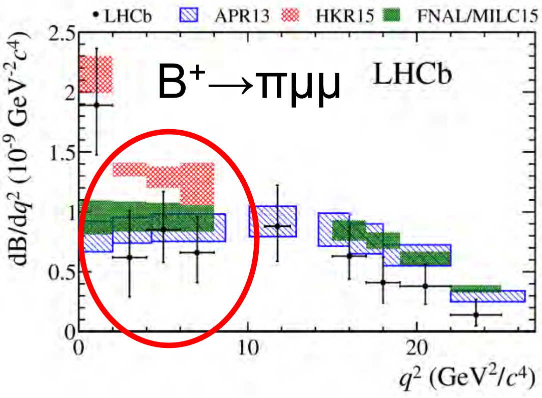
[JHEP 11 (2016) 047]



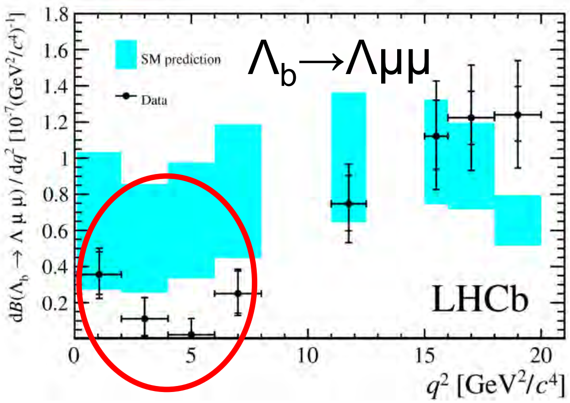
[JHEP 06 (2014) 133]

[JHEP 09 (2015) 179]





[JHEP 10 (2015) 034]



[JHEP 06 (2015) 009]

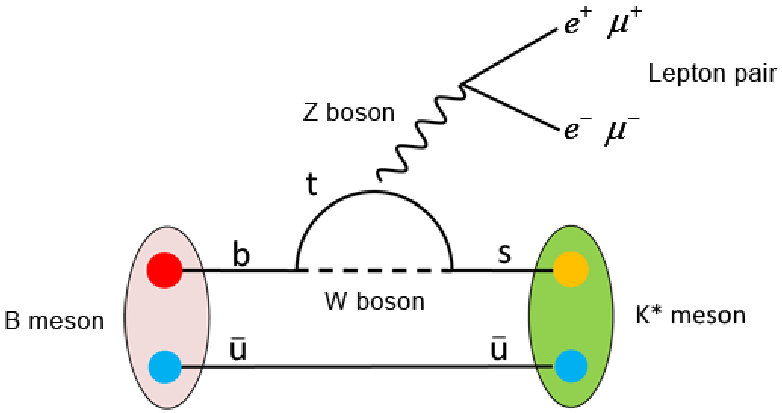
Consistent tendency for differential x-sections to undershoot prediction at low q^2.
Intriguing – but maybe the uncertainties in theory are larger than claimed ?

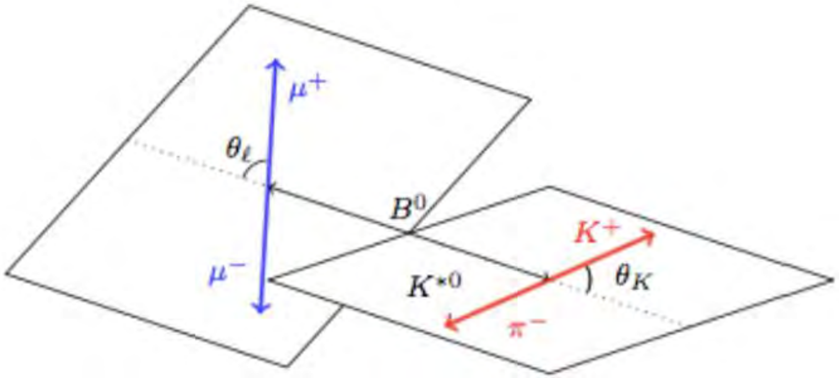
Electroweak Penguins: looking at angular observables

To extract more information go back to our benchmark decay ($B^0 \rightarrow K^*\mu\mu$, with $K^* \rightarrow K\pi$) and measure in detail angular properties of decay products.

From this information many important observables can be built. Key points:

- Each sensitive to New Physics in their own distinctive manner;
- Theoretically more easier to predict in context of SM than the differential cross-sections ('theoretically clean')
- However, what each observable 'means' is very difficult to visualise (even for a physicist). And the nomenclature is very dull (*e.g.* P_5').

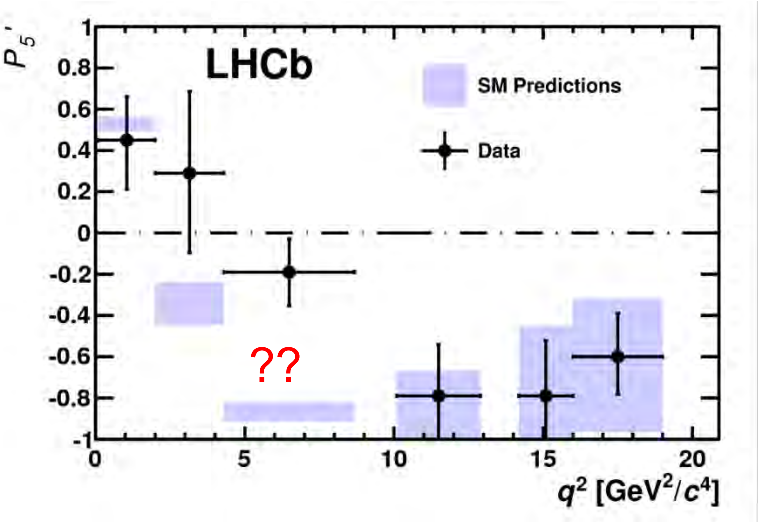




Electroweak Penguins: the P_5’ conundrum

One such observable is *P_5’*. To reiterate, what this describes physically is hard to visualise, but it is constructed in a manner that is robust against strong-interaction uncertainties, but also easily relatable to the physics of interest.

Interesting local deviation found at $q^2 \sim 6$ GeV^2 in 1 fb^{-1} analysis



[PRL 111 (2013) 191801]

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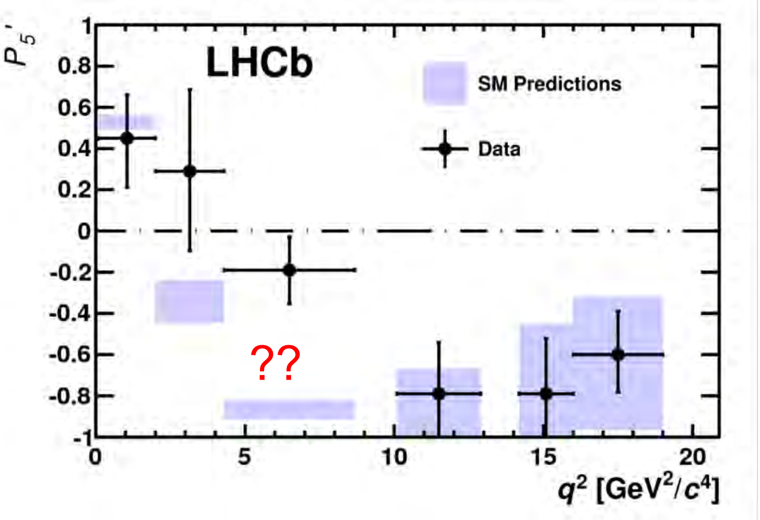
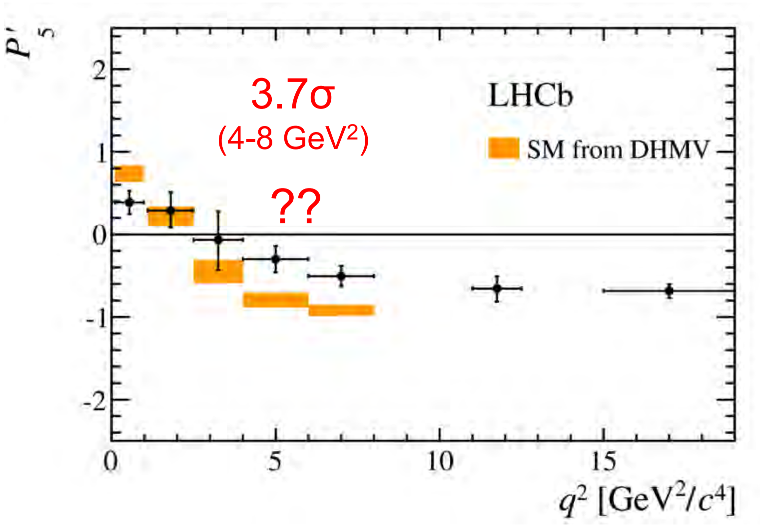


??

[PRL 111 (2013) 191801]

Effect persists with full run-1 3 fb^{-1} update (smaller deviation in absolute terms, but significance undiminished)



3.7σ
(4-8 GeV^2)

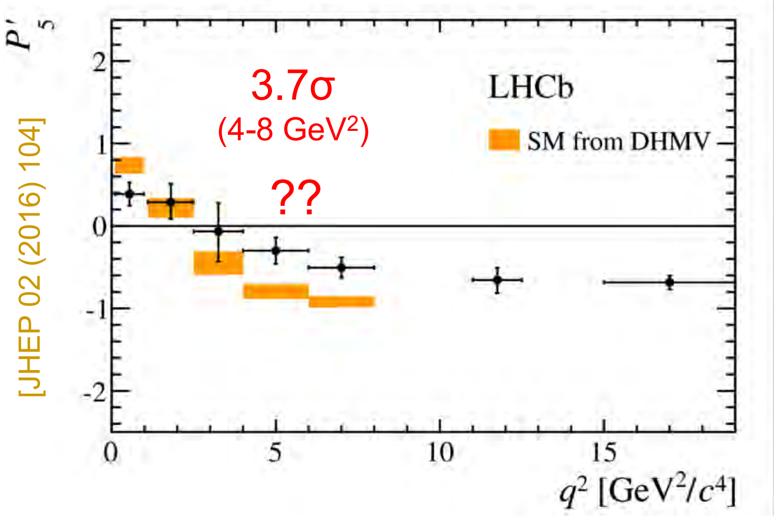
??

[JHEP 02 (2016) 104]

Electroweak Penguins: the P_5’ conundrum

One such observable is *P_5’*. To reiterate, what this describes physically is hard to visualise, but it is constructed in a manner that is robust against strong-interaction uncertainties, but also easily relatable to the physics of interest.

LHCb run-1 result



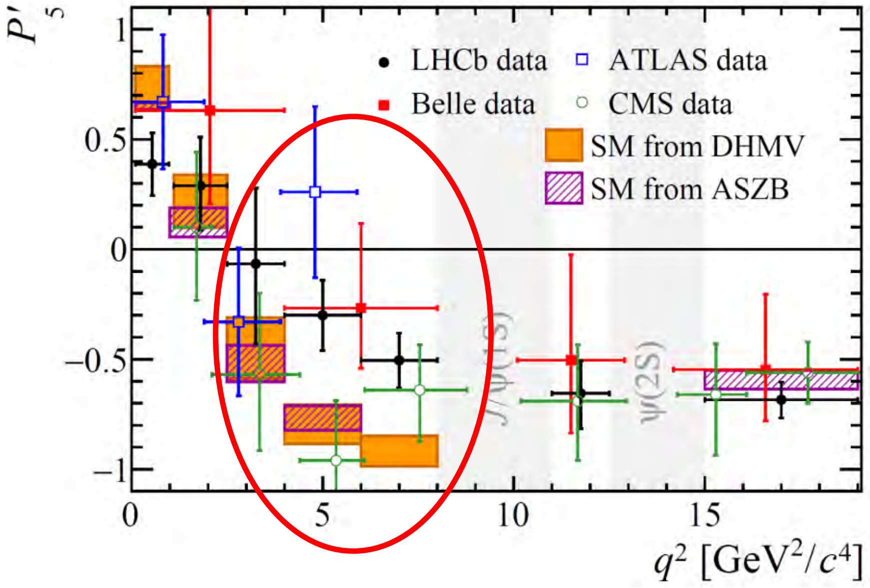
3.7σ

(4-8 GeV^2)

??

[JHEP 02 (2016) 104]

Other experiments have now dug into their data & (largely) agree with LHCb, albeit with lower precision.

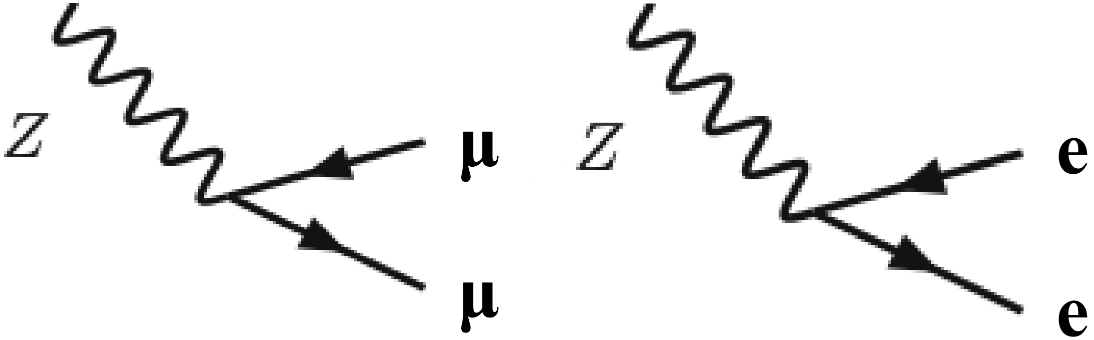


So as with the differential cross-section measurements, there is something odd going on at low q^2. This we must take seriously as P_5’ is a ‘theoretically clean’ observable. But how clean is clean ? Can we *really* trust the theory prediction ?

Electroweak Penguins: lepton universality

We need an observable where there can be *no doubt whatsoever* about the SM prediction. A good choice is to compare the rate of decays involving muons with those with electrons (recall that all studies presented so far involved muons).

Lepton universality (LU) - in the SM these two diagrams have identical strengths:



LU also applies if there are tau pairs produced; also if a photon, rather than a Z Is involved.

LU also applies in diagrams involving the W boson.

LU has been tested to high precision… but NOT in processes with Penguin loops.

Two analyses have now been performed, one with $B \to K l^+ l^-$, one with $B^0 \to K^* l^+ l^-$. in each a ratio R_K (or R_{K^*}) is measured: the ratio of $K^{(*)}\mu^+\mu^- / K^{(*)}e^+e^-$ decays in the most 'interesting' range of dilepton invariant mass $(1 < q^2 < 6 \text{ GeV}^2/c^4)^*$.

Remember, in the SM R_K and R_{K^*} should be unity (or very, very close) !

---

* In the R_{K^*} case the interval is very slightly different, and a second measurement is performed at lower q^2.

Electroweak Penguins: lepton universality

Two analyses have now been performed, one with $B \to K l^+ l^-$, one with $B^0 \to K^* l^+ l^-$.
in each a ratio R_K (or R_{K^*}) is measured: the ratio of $K^{(*)}\mu^+\mu^-/K^{(*)}e^+e^-$ decays
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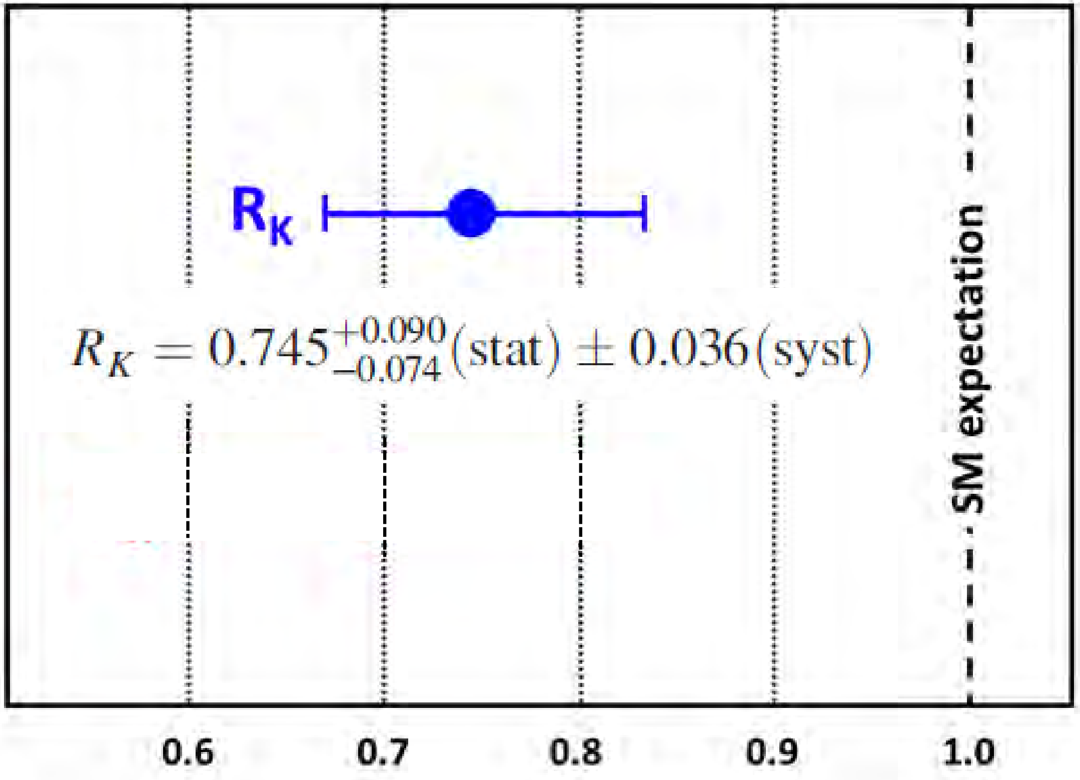
R_K measured first
[PRL 113 (2014) 151601]
and was found to be
2.6σ *below* unity.
Very interesting…



Electroweak Penguins: lepton universality

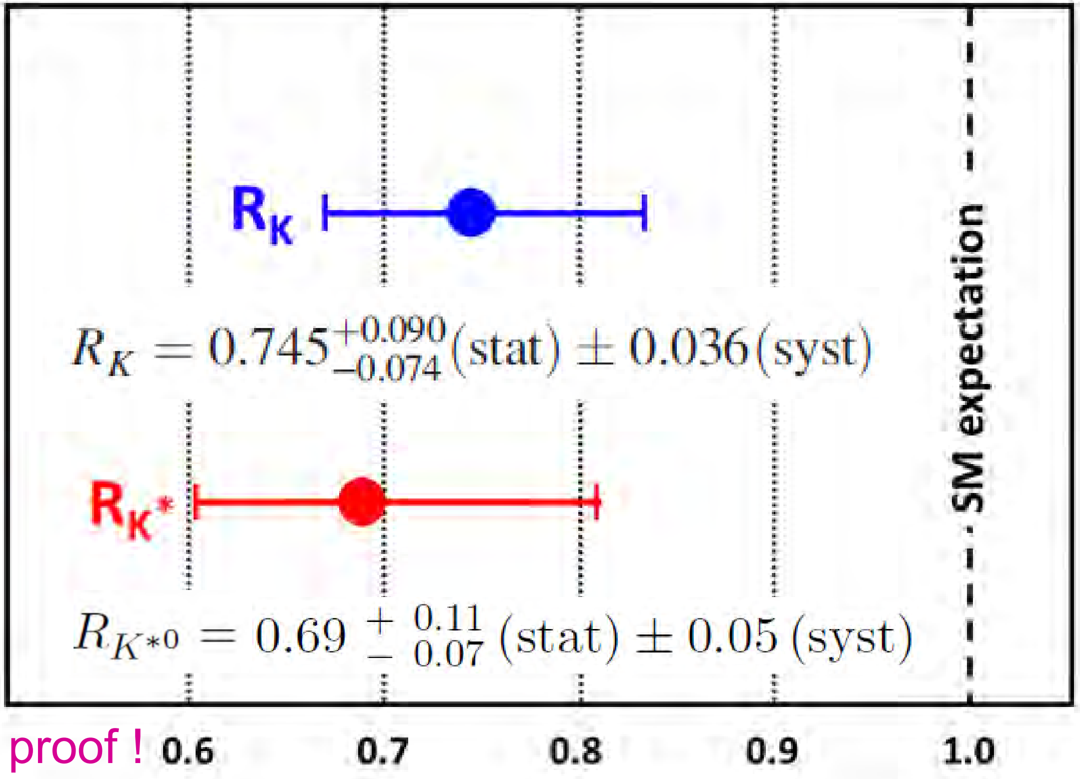
Two analyses have now been performed, one with B→Kl^+l^-, one with B^0→K*l^+l^-. in each a ratio R_K (or R_{K^*}) is measured: the ratio of $K^{(*)}\mu^+\mu^-/K^{(*)}e^+e^-$ decays in the most 'interesting' range of dilepton invariant mass ($1 < q^2 < 6$ GeV^2/c^4)*.

Remember, in the SM R_K and R_{K^*} should be unity (or very, very close) !

R_K measured first
[PRL 113 (2014) 151601]
and was found to be 2.6σ *below* unity.
Very interesting…

…and then R_{K^*}, measured later
[JHEP 08 (2017) 055]
with near identical behaviour.

Two remarkably similar 'fluctuations' (?) where the SM prediction is bullet proof !



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

$$R_{K^{*0}} = 0.69 \begin{matrix} + \\ - \end{matrix} \begin{matrix} 0.11 \\ 0.07 \end{matrix} (\text{stat}) \pm 0.05 (\text{syst})$$

What does it all mean ?

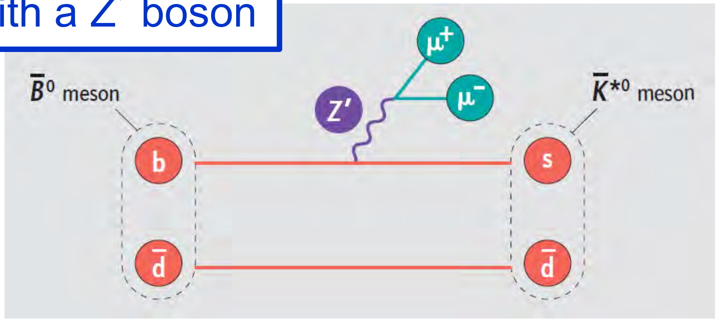
Fact

It is very interesting to see all these anomalies clustering within the same family of decays. Furthermore, the behaviour is very coherent, and can be consistently explained by hypothesising some non-SM effects in the muon system.

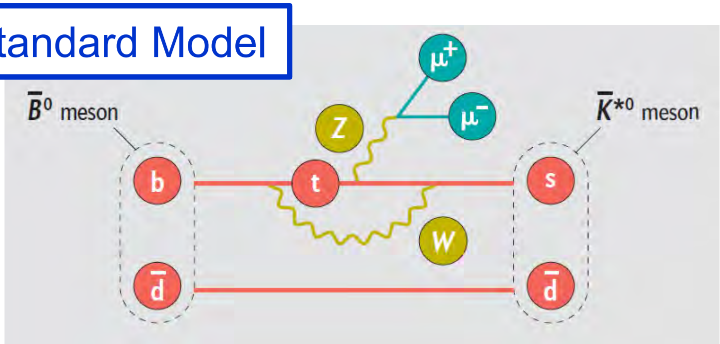
Speculation

Theorists have proposed that these effects could be driven by new particles such as a Z prime boson (Z’), or leptoquark (LQ).

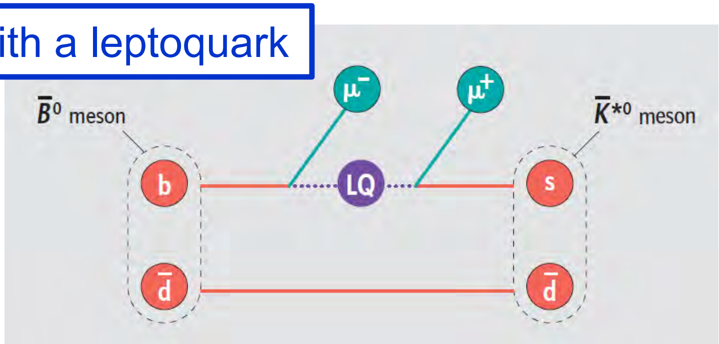
With a Z’ boson



Standard Model



With a leptoquark



If these new particles exist, they may be accessible to direct searches at ATLAS and CMS (who are looking). Conversely, they may turn out to be too heavy…

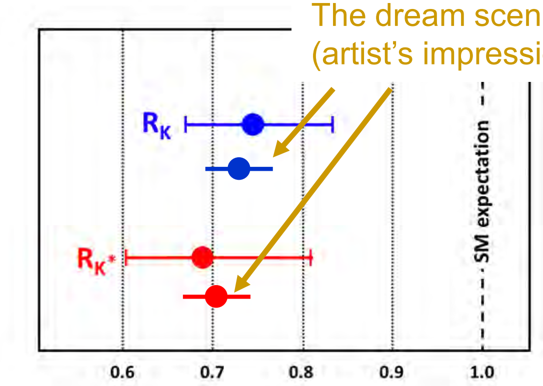
So why have we not declared the defeat of the Standard Model (and what do we do next) ?

Another fact

This could all be an unlucky conspiracy, involving observables (*i.e.* cross-sections & P_5') with wrongly estimated theoretical predictions and statistical fluctuations in the lepton-universality measurements

So what do we do ?

We should make more precise lepton-universality measurements of existing observables (R_K & R_{K^*}) and in related decays.   If these show even more significant effects then there will be little doubt.



The dream scenario (artist's impression!)

But this requires more data

Yes, but these data exist! The measurements you have seen come from Run 1 alone. We have *much more data* on tape, and these are being analysed right now. More news soon !

So, apart from EW Penguins, do all other b-physics results agree well with the SM predictions?

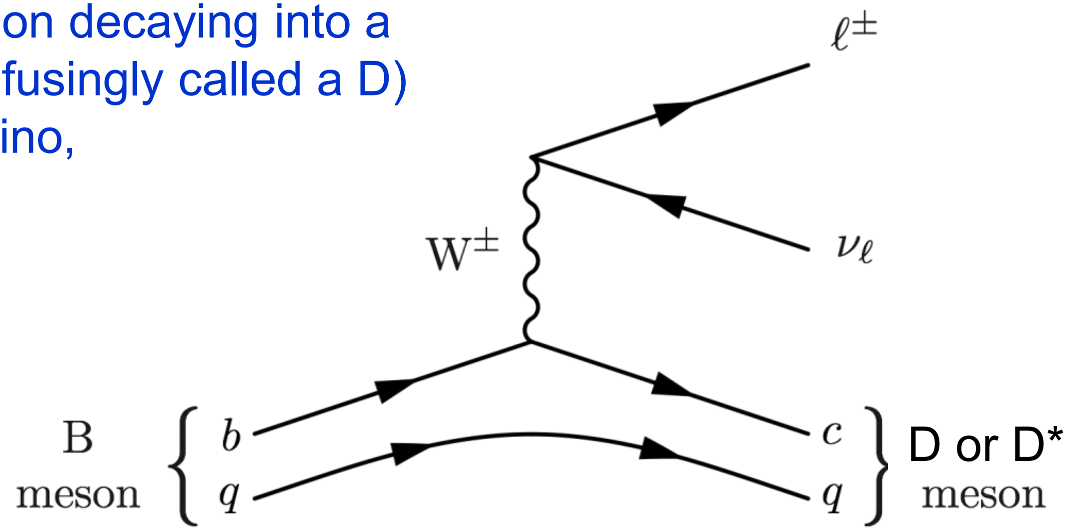
No, curiously there is *another* lepton universality test which is puzzling physicists.

Consider the case of a B meson decaying into a charm meson (somewhat confusingly called a D) a charged lepton, and a neutrino,

$B \rightarrow D\, l^- \nu$

or the sister decay into another charm meson, called the D*.

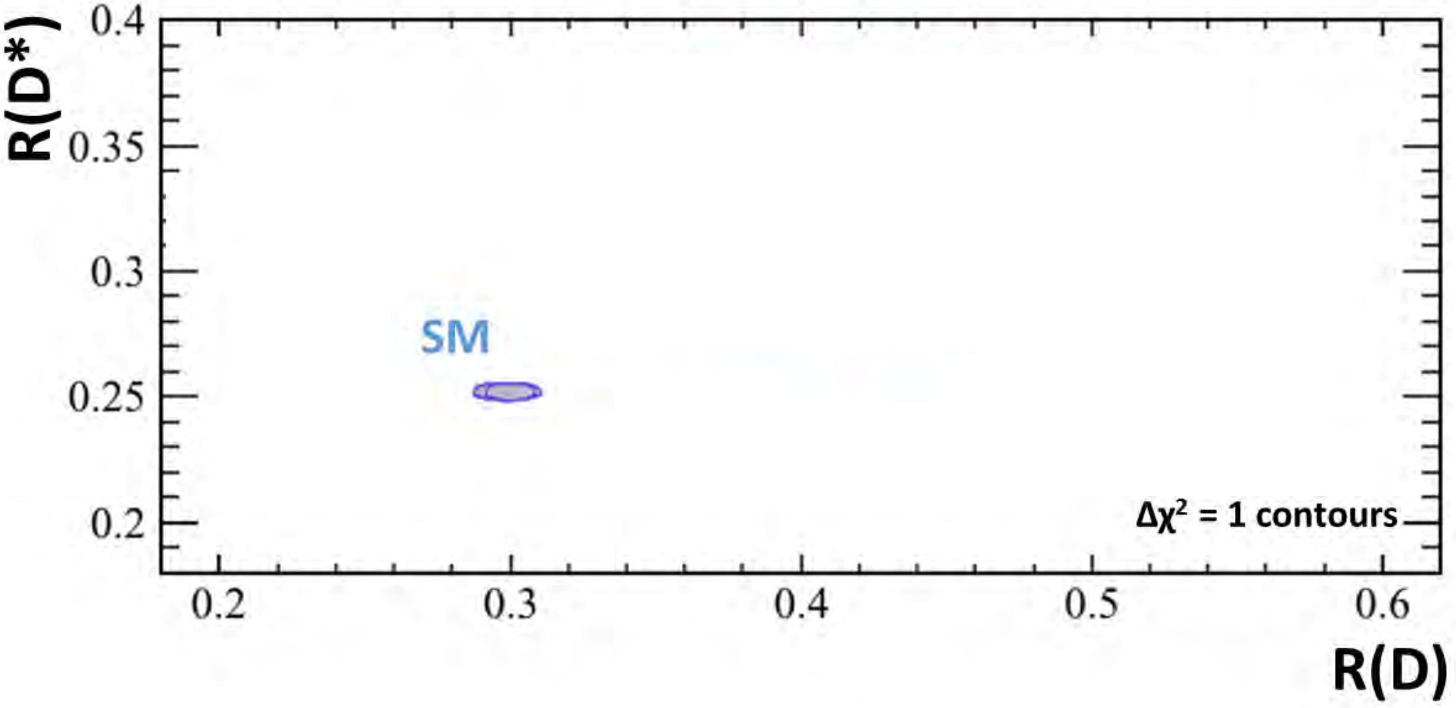
$B \rightarrow D^*\, l^- \nu$



Let's measure this separately for the case where the lepton is a tau (τ), and compare with the muon & electron case. Once more form ratios, R(D) [& R(D*)], which is the ratio of the decay rate with taus to that with muons (or electrons).

The R(D) and R(D*) puzzle

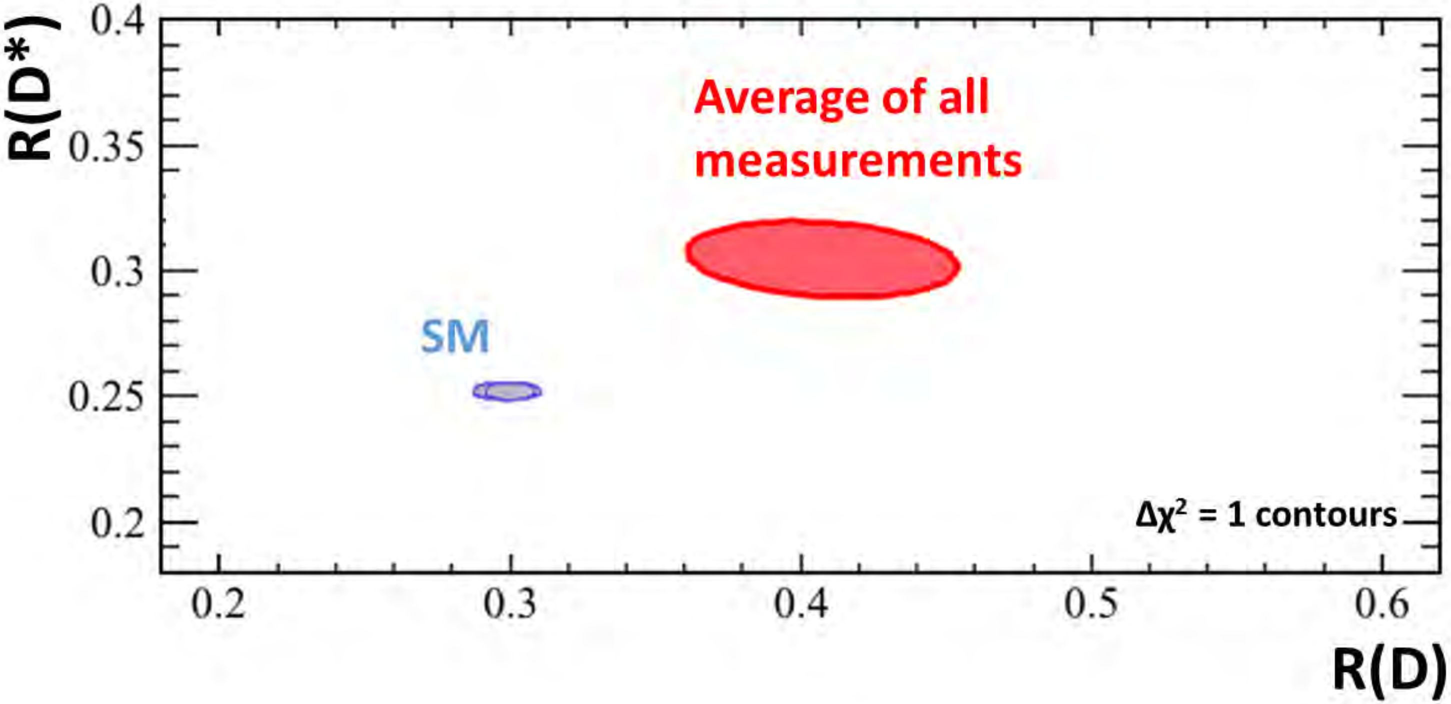
In the SM lepton universality applies, but the predicted value for R(D) (& R(D*)) is not 1 because the tau is very massive, and it 'costs' more for the B to decay this way rather than to the lighter muon or electron. This is very well understood.



The R(D) and R(D*) puzzle

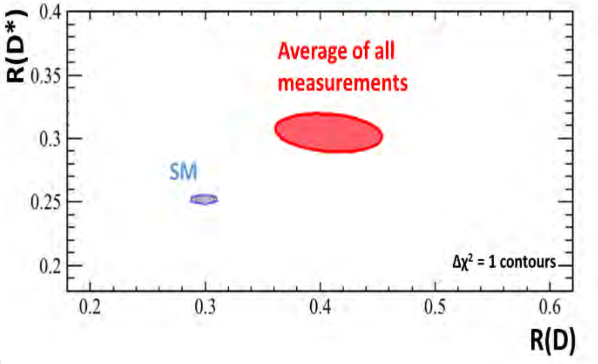
Measurements or R(D) & R(D*) have been made for over 10 years, starting at the B-factory experiments (BaBar in Stanford, Belle in Japan) & continuing with LHCb.

No one measurement is very precise, but all show the same trend. Taken together…



…there's a very significant (~4σ), if not yet overwhelming, discrepancy with the SM.

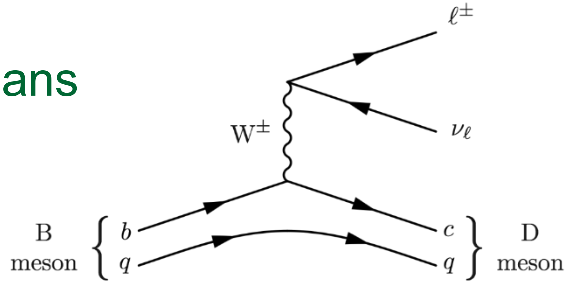
The R(D) and R(D*) puzzle: what does it all mean ?



We have another strong hint of lepton-universality violation, this time involving the third generation tau leptons. Once more ‘leptoquarks’ could do the trick (but not necessarily the same leptoquarks as in the $b \to s l^+ l^-$ case).

However, there are two main differences with the previous set of studies.

- The decay process is NOT a loop & NOT suppressed in the SM. This means any New Physics contribution must be very large to make itself noticed. this makes theorists suspicious…



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- The measurement is very difficult, *e.g.* are all backgrounds under control.

Once more we would like to have a new, single measurement of excellent precision. Again LHCb has the data on tape. Watch this space !

Conclusions and outlook

The Standard Model, though tremendously successful in describing almost all laboratory phenomena for forty years, leaves too many questions unanswered for it to be the ultimate theory.

A higher, more complete theory (‘New Physics’) very likely involves additional particles and/or interactions. These are what we are searching for at the LHC.

The indirect search method, particularly involving precise studies of beauty-hadron decays, provides a powerful method to probe for New Physics effects.

The current set of ‘flavour anomalies’ illustrate the potential of ‘b-physics’ very well indeed:

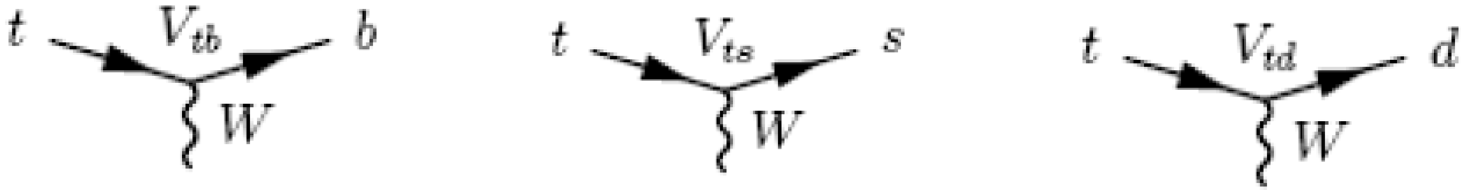
- Even if, with more data, they dissipate, they still provide a text-book example of how cracks may appear and widen in the Standard Model.
- And if they strengthen then a new chapter will begin in fundamental science.

Which is it to be? Stay tuned, we will know soon enough!

Backups

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:



By the way, these are Feynman diagrams, fantastic for visualising what is happening at the quark level.

quark we start with

quark we end with

emitted *W* boson

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-Koboyashi-Maskawa (CKM) matrix, and these factors vary dramatically – here is another hierarchy we don't understand !

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

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.

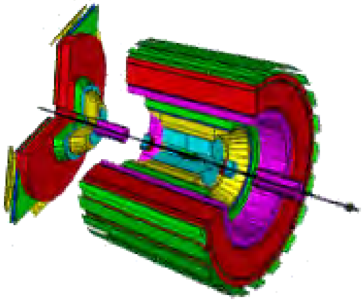
The CKM matrix is also linked to another big puzzle of flavour physics…

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

Making beauty

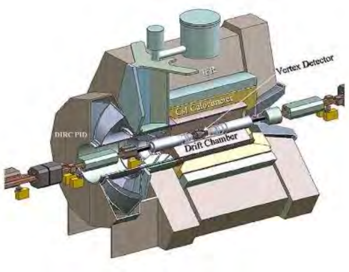
Since the first discovery of hadrons containing *b*-quarks, back in 1977, accelerators have been constructed which have produced beauty hadrons in ever increasing numbers. Good news for the physics, as many of the measurements we wish to perform are of very rare decay processes. Large samples are essential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

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
$pp \to b\bar{b}X$

~400 billion / year *

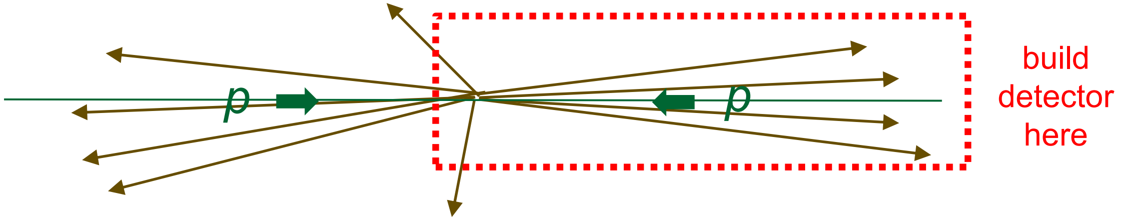
* produced at LHCb interaction point

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.

Three requirements for a beauty experiment

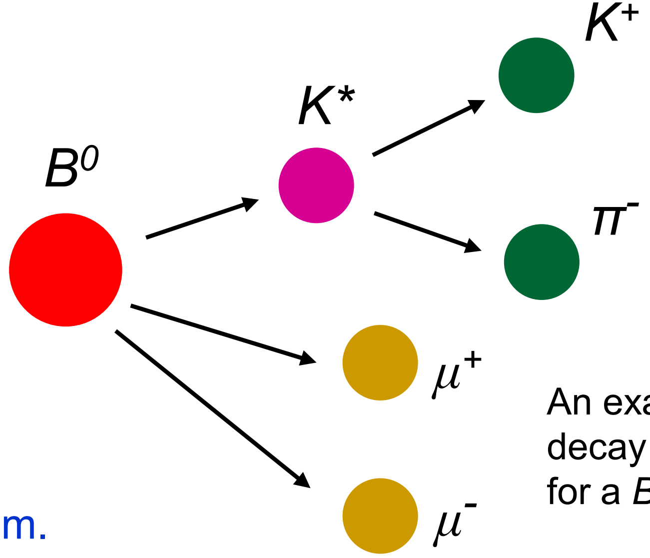
Optimal geometry



At LHC *b*-hadrons are produced predominantly at low angles to beamline.
Hence a ‘forward’, rather than, ‘central’ detector geometry is desirable.

It must be able to reconstruct the ‘decay chain’ of the beauty hadron.

We don’t see the *b*-hadron, which travels for only a few mm before decaying. But we can detect the daughter particles from the decay, and from these ‘re-build’ the parent hadron. We need to know *what* these daughter particles are, and *where* they come from.



An example decay chain for a B^0 meson

Not every collision contains a beauty hadron, & not all *b*-hadron decays are of interest. We need to ‘trigger’ quickly on the collisions we care about & record them. (No more discussion about this today, but it is one of *the* major challenges !)

1995 – an interesting year

Rogue trader ruin's UK's oldest investment bank

ebay

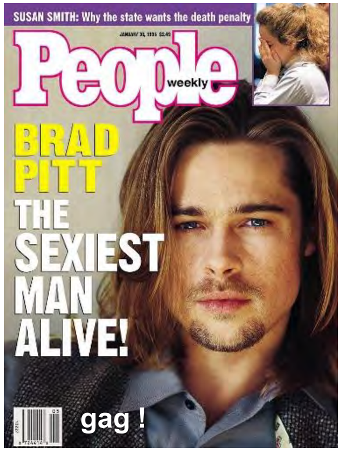
launch (original logo)


Not guilty ?!?


Kung-Fu Frenchman


launch


Mir & shuttle



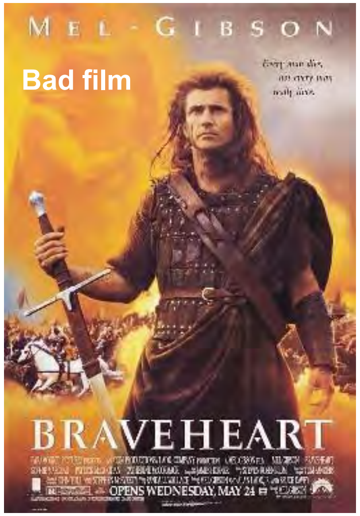
gag !

cringeworthy interviews


Wimbledon winner


Good film


Brixton riots


Bad film

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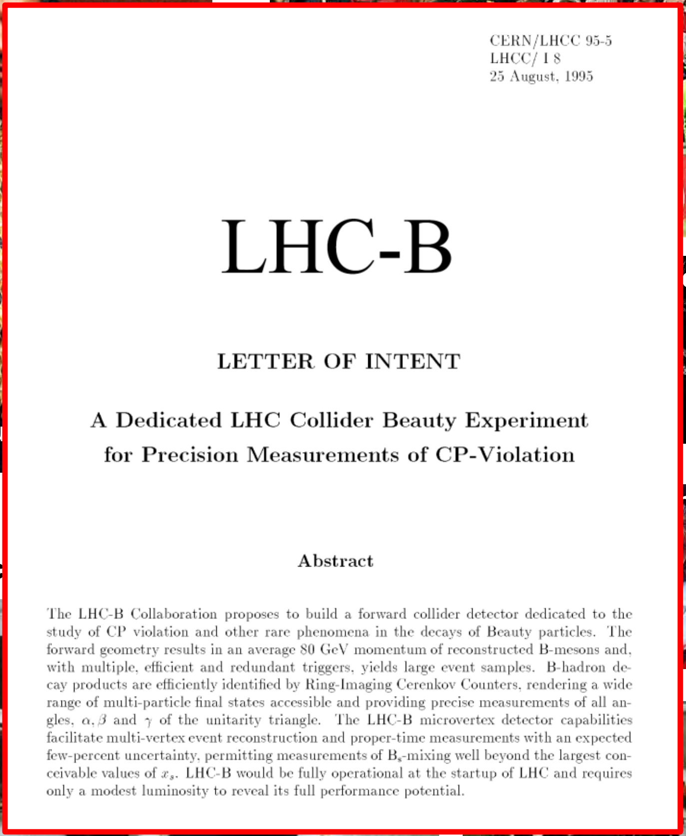
Not gu

Kung-Fu Frenchman



CERN/LHCC 95-5
LHCC/ I 8
25 August, 1995

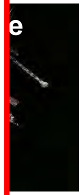
LHC-B

LETTER OF INTENT

A Dedicated LHC Collider Beauty Experiment for Precision Measurements of CP-Violation

Abstract

The LHC-B Collaboration proposes to build a forward collider detector dedicated to the study of CP violation and other rare phenomena in the decays of Beauty particles. The forward geometry results in an average 80 GeV momentum of reconstructed B-mesons and, with multiple, efficient and redundant triggers, yields large event samples. B-hadron decay products are efficiently identified by Ring-Imaging Cerenkov Counters, rendering a wide range of multi-particle final states accessible and providing precise measurements of all angles, α, β and γ of the unitarity triangle. The LHC-B microvertex detector capabilities facilitate multi-vertex event reconstruction and proper-time measurements with an expected few-percent uncertainty, permitting measurements of B_s-mixing well beyond the largest conceivable values of x_s. LHC-B would be fully operational at the startup of LHC and requires only a modest luminosity to reveal its full performance potential.



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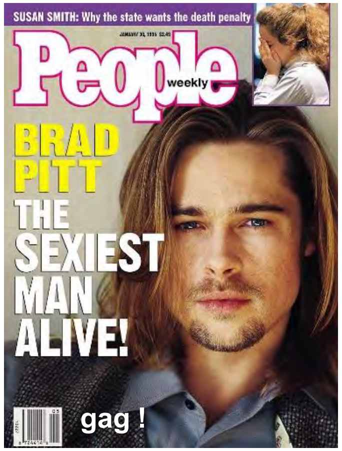
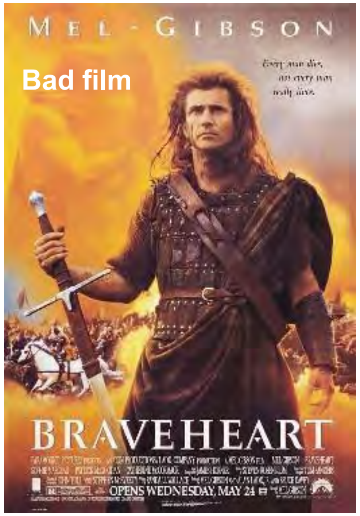


gag !

ebay

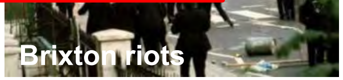
launch (original logo)



Bad film

Good film

c



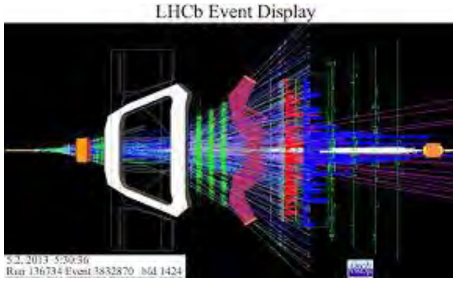
Brixton riots

The data challenge

LHC operates at 40 MHz and does so for ~15% of year

LHCb raw event size ~100 kBytes

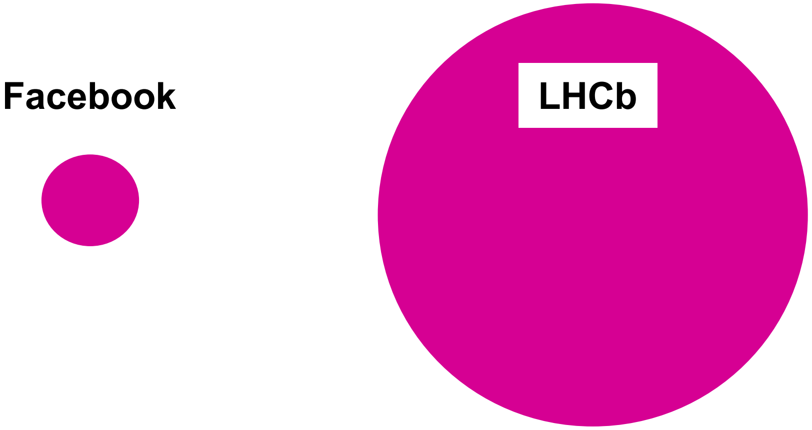
×



→

~ 15000 PetaBytes /yr (raw data alone)

Data rate LHCb ~15000 PB.yr
Facebook ~180 PB / yr



~ 15000 PetaBytes/year is less than dealt with by search engines, but still considerably more than *e.g.* Facebook (~ 180 PB/year).

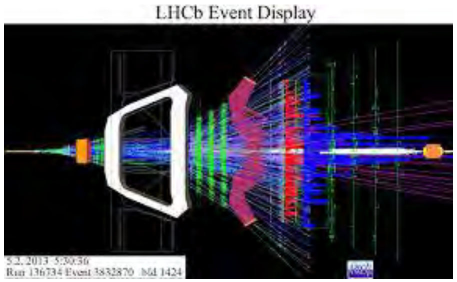
,

The data challenge

LHC operates at 40 MHz and does so for ~15% of year

LHCb raw event size ~100 kBytes

×



→

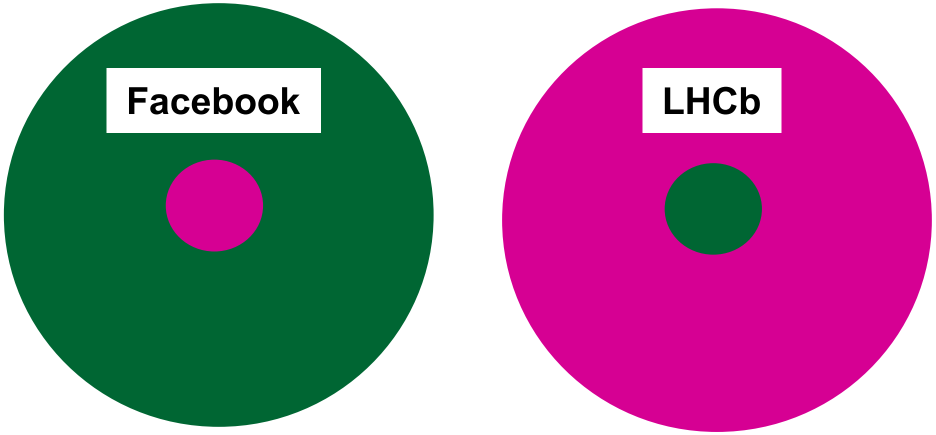
~ 15000
PetaBytes /yr
(raw data alone)

~ 15000 PetaBytes/year is less than dealt with by search engines, but still considerably more than *e.g.* Facebook (~ 180 PB/year).

Public science has less money to spend on computing than Facebook.

Storage costs money. Better to process as much as possible in ‘real time’.

Data rate
LHCb ~15000 PB.yr
Facebook ~180 PB / yr

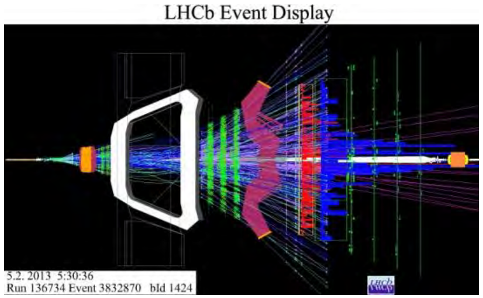


Computing budget
LHCb ~10M$ / yr
Facebook ~600 M$ /yr

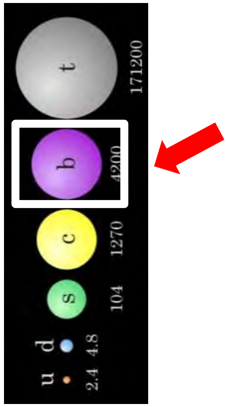
Not all collisions are equally interesting

Core business of LHCb is beauty physics, and here we can be selective

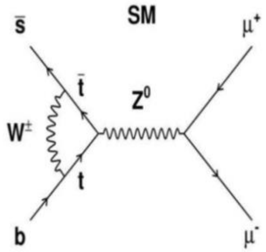
Collision rate 40 MHz
(currently a little less,
but this sets the ballpark)



b-hadrons produced about once every ~150 *pp* collisions



And most *b*-hadrons decays don't interest us.



$B_s \to \mu\mu$
occurs every
4 x 10^{-9}
B_s decays

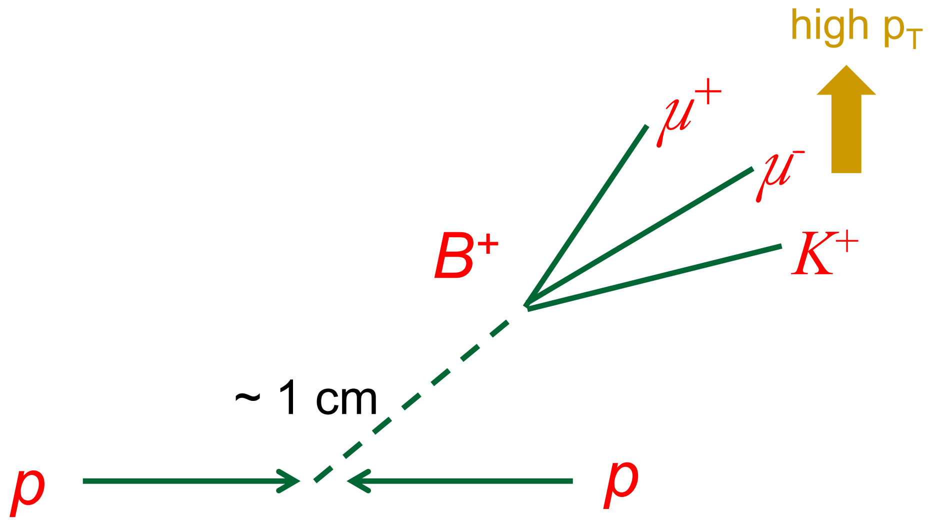
The ones that do, occur every 10^{-3} -10^{-10} of time.

(Situation is complicated by the fact we also want to study charm physics.
Charm is much more abundant, and the decays of interest are more common).

So we only save to disk the potentially interesting collisions – task of the trigger.

Triggering on beauty

There exist characteristics of increasing complexity than can be searched for to determine if the collision is of interest and should be preserved for offline analysis.



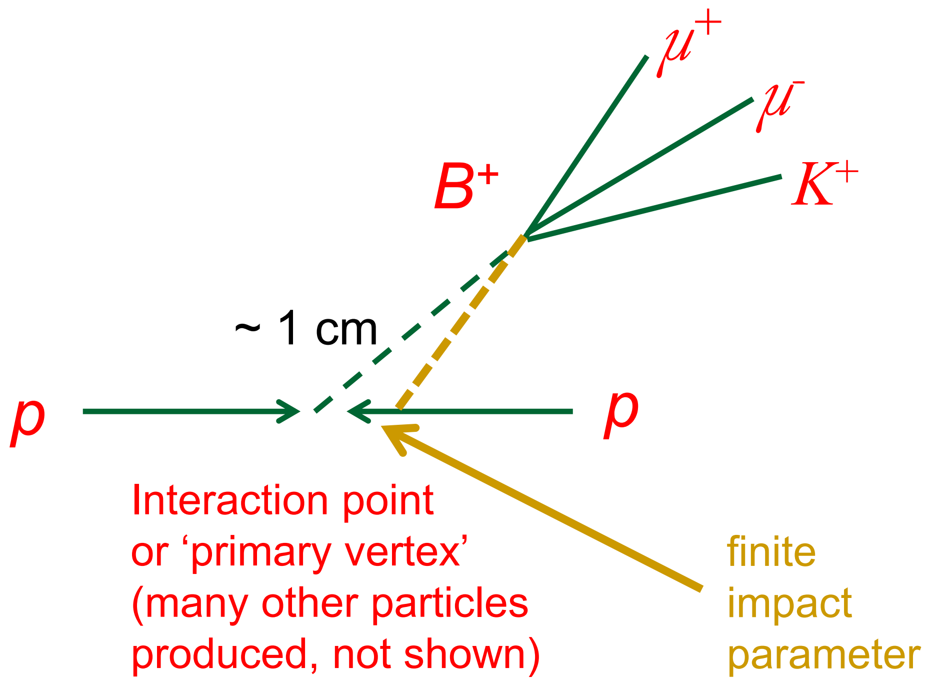
Interaction point
or 'primary vertex'
(many other particles
produced, not shown)

1. Look for high transverse energy (E_T) or momentum (p_T) in calorimeters or muon system from decay products.

   That's because the *b*-hadron is relatively heavy and so gives a significant 'kick' when it decays.

Triggering on beauty

There exist characteristics of increasing complexity than can be searched for to determine if the collision is of interest and should be preserved for offline analysis.

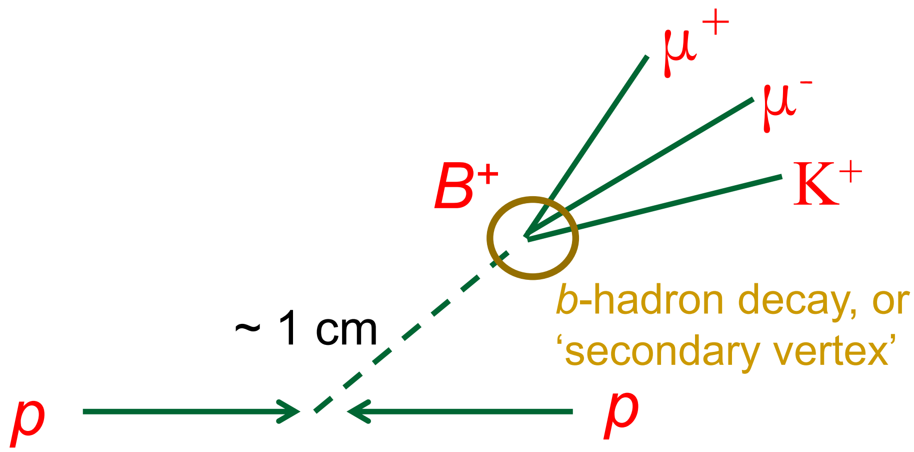


1. Look for high transverse energy (E_T) or momentum (p_T) in calorimeters or muon system from decay products.

2. Look for tracks with significant ‘impact parameter’ with respect to primary vertex.

Triggering on beauty

There exist characteristics of increasing complexity than can be searched for to determine if the collision is of interest and should be preserved for offline analysis.



μ^+

μ^-

K^+

B^+

b-hadron decay, or ‘secondary vertex’

~ 1 cm

p

p

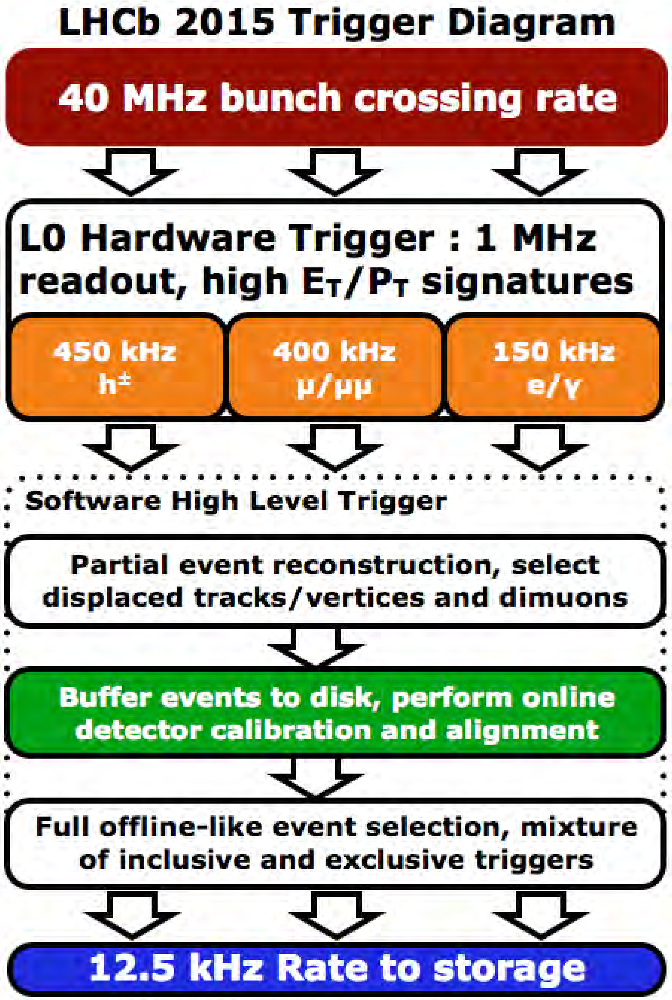
Interaction point
or ‘primary vertex’
(many other particles
produced, not shown)

1. Look for high transverse energy (E_T) or momentum (p_T) in calorimeters or muon system from decay products.
2. Look for tracks with significant ‘impact parameter’ with respect to primary vertex.
3. Reconstruct secondary vertex and full *b*-hadron decay products.

Each successive step provides improved discrimination, but requires more information and time to execute.

Trigger: L0

[LHCb trigger – see JINST 4 (2013) P04022]



LHCb 2015 Trigger Diagram

40 MHz bunch crossing rate

L0 Hardware Trigger : 1 MHz readout, high E_T/P_T signatures

450 kHz
$h^\pm$

400 kHz
$\mu/\mu\mu$

150 kHz
e/γ

Software High Level Trigger

Partial event reconstruction, select displaced tracks/vertices and dimuons

Buffer events to disk, perform online detector calibration and alignment

Full offline-like event selection, mixture of inclusive and exclusive triggers

12.5 kHz Rate to storage

Earliest trigger stage, ‘L0’, makes decisions in hardware based on simple high E_T, high p_T signatures.

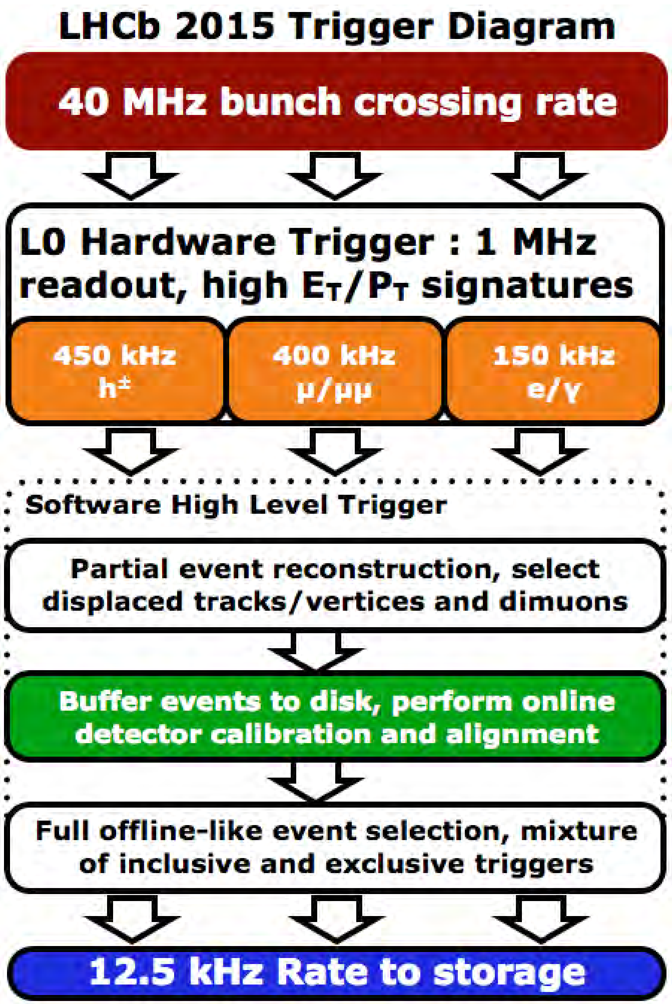
Decision made with partial detector information. No time to build full event.

Trigger decision made within 4 μs synchronous with bunch crossing rate

While decision is being made local detector information is retained in a pipeline within front-end electronics.

Reduces data rate down to 1 MHz
(= rate at which full event is read out)

Trigger: HLT



LHCb 2015 Trigger Diagram

40 MHz bunch crossing rate

L0 Hardware Trigger : 1 MHz readout, high E_T/P_T signatures

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Partial event reconstruction, select displaced tracks/vertices and dimuons

Buffer events to disk, perform online detector calibration and alignment

Full offline-like event selection, mixture of inclusive and exclusive triggers

12.5 kHz Rate to storage

The High Level Trigger (HLT) is a software trigger (C++) that runs on a large number (a ‘farm’) of multiprocessor PCs (~1700 nodes)

L0-accepted event assembled and then digested by this ‘farm’ of PCs.

Two steps:

- HLT1: impact parameter info *etc.* used to reduce rate to ~40 kHz (~35 ms/event)
- HLT2: full event information used to reduce rate to ~12 kHz (~350 ms/event)

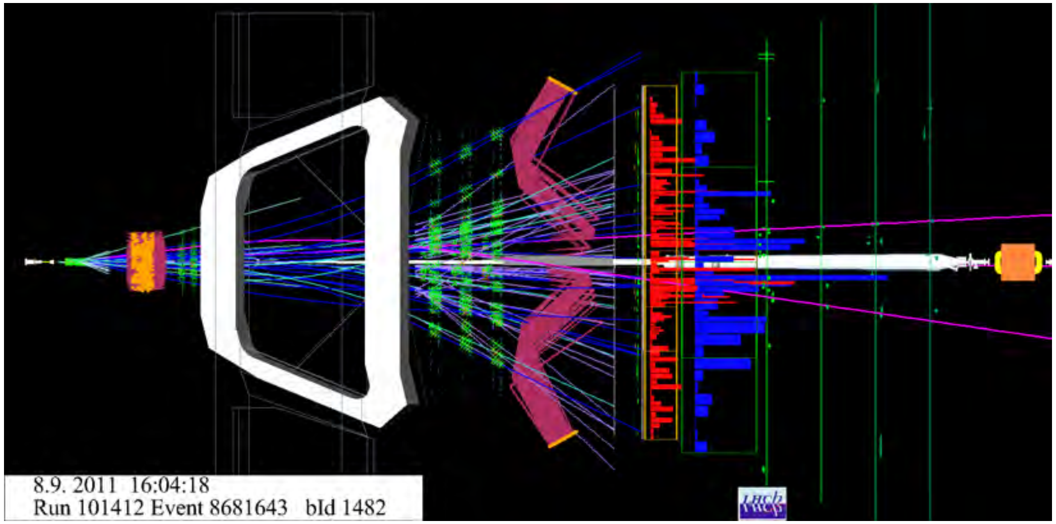
Then written offline.

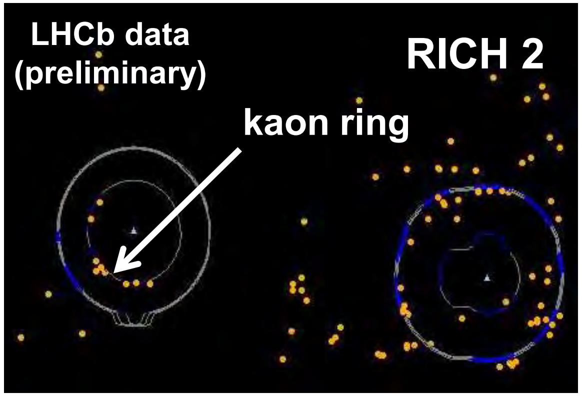
Offline processing - event reconstruction

Event reconstruction:

- reconstruct particles trajectories, providing momentum information and precise knowledge of behaviour close to interaction point

- perform particle identification – *e.g.* finding Cherenkov rings in RICH detectors and providing probability of particle assignment for each track





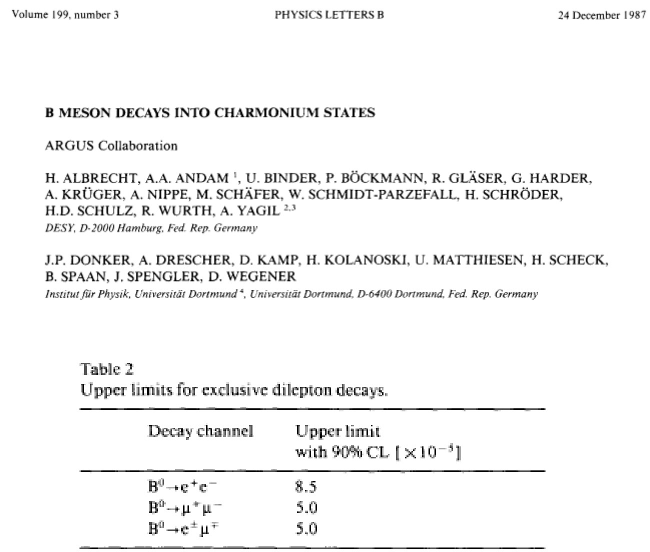
Processing takes ~2 s / event. Occurs in ~5k concurrent jobs run on GRID. Output is DST (data storage tape) – 2012 DST data require 2 PB of disk storage.

After this is done, the analysis can begin !

$B_{s\,(d)} \rightarrow \mu\mu$ – a thirty year old quest

We have been searching for $B_s \rightarrow \mu^+\mu^-$ for a long time...
(and the sister mode B_d [sometimes written B^0], $\rightarrow \mu^+\mu^-$)

(μ = muon, a lepton, just like the electron, only heavier)



Volume 199, number 3 PHYSICS LETTERS B 24 December 1987

B MESON DECAYS INTO CHARMONIUM STATES

ARGUS Collaboration

H. ALBRECHT, A.A. ANDAM [1], U. BINDER, P. BÖCKMANN, R. GLÄSER, G. HARDER,
A. KRÜGER, A. NIPPE, M. SCHÄFER, W. SCHMIDT-PARZEFALL, H. SCHRÖDER,
H.D. SCHULZ, R. WURTH, A. YAGIL [2,3]
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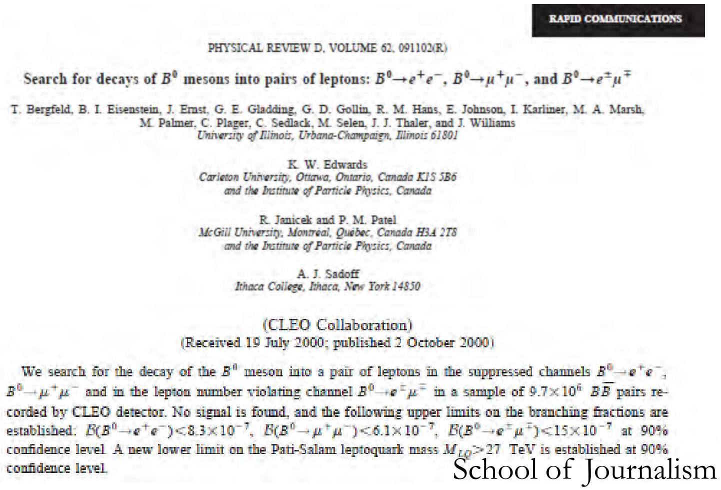
J.P. DONKER, A. DRESCHER, D. KAMP, H. KOLANOSKI, U. MATTHIESEN, H. SCHECK,
B. SPAAN, J. SPENGLER, D. WEGENER
Institut für Physik, Universität Dortmund [4], Universität Dortmund, D-6400 Dortmund, Fed. Rep. Germany

Table 2
Upper limits for exclusive dilepton decays.

Decay channel	Upper limit with 90% CL [$\times 10^{-5}$]
$B^0 \rightarrow e^+e^-$	8.5
$B^0 \rightarrow \mu^+\mu^-$	5.0
$B^0 \rightarrow e^\pm\mu^\mp$	5.0



RAPID COMMUNICATIONS

PHYSICAL REVIEW D, VOLUME 62, 091102(R)

Search for decays of B^0 mesons into pairs of leptons: $B^0 \rightarrow e^+e^-$, $B^0 \rightarrow \mu^+\mu^-$, and $B^0 \rightarrow e^\pm\mu^\mp$

T. Bergfeld, B. I. Eisenstein, J. Ernst, G. E. Gladding, G. D. Gollin, R. M. Hans, E. Johnson, I. Karliner, M. A. Marsh,
M. Palmer, C. Plager, C. Sedlack, M. Selen, J. J. Thaler, and J. Williams
University of Illinois, Urbana-Champaign, Illinois 61801

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and the Institute of Particle Physics, Canada

R. Janicek and P. M. Patel
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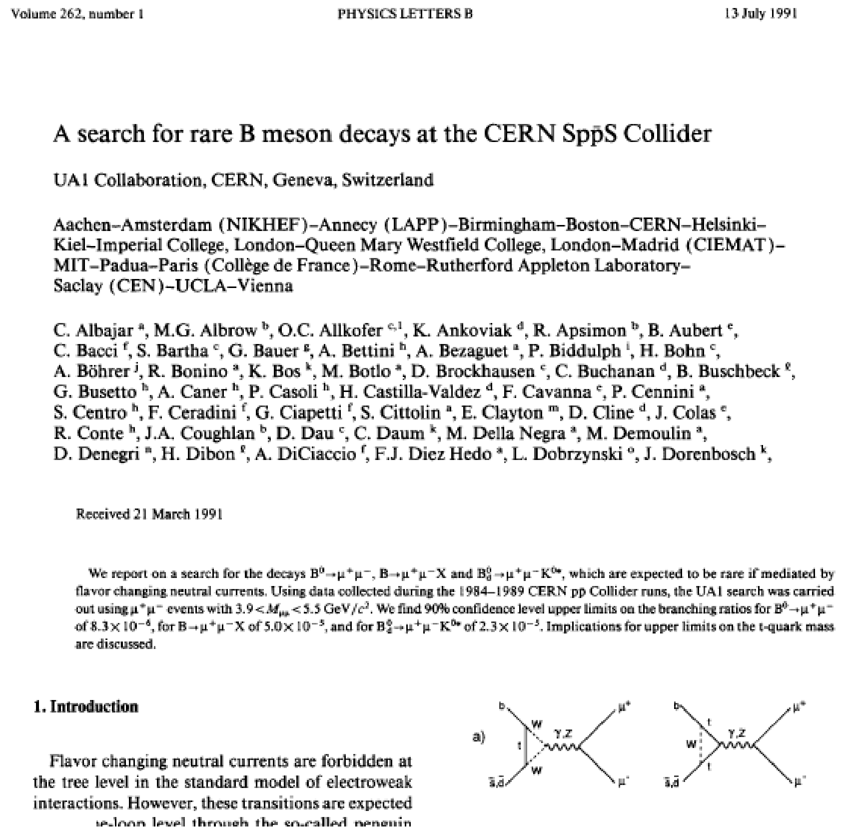
A. J. Sadoff
Ithaca College, Ithaca, New York 14850

(CLEO Collaboration)
(Received 19 July 2000; published 2 October 2000)

We search for the decay of the B^0 meson into a pair of leptons in the suppressed channels $B^0 \rightarrow e^+e^-$, $B^0 \rightarrow \mu^+\mu^-$ and in the lepton number violating channel $B^0 \rightarrow e^\pm\mu^\mp$ in a sample of 9.7×10^6 $B\bar{B}$ pairs recorded by CLEO detector. No signal is found, and the following upper limits on the branching fractions are established: $\mathcal{B}(B^0 \rightarrow e^+e^-) < 8.3\times10^{-7}$, $\mathcal{B}(B^0 \rightarrow \mu^+\mu^-) < 6.1\times10^{-7}$, $\mathcal{B}(B^0 \rightarrow e^\pm\mu^\mp) < 15\times10^{-7}$ at 90% confidence level. A new lower limit on the Pati-Salam leptoquark mass $M_{LQ} > 27$ TeV is established at 90% confidence level.



Volume 262, number 1 PHYSICS LETTERS B 13 July 1991

A search for rare B meson decays at the CERN Sp$\bar{\text{p}}$S Collider

UA1 Collaboration, CERN, Geneva, Switzerland

Aachen–Amsterdam (NIKHEF)–Annecy (LAPP)–Birmingham–Boston–CERN–Helsinki–
Kiel–Imperial College, London–Queen Mary Westfield College, London–Madrid (CIEMAT)–
MIT–Padua–Paris (Collège de France)–Rome–Rutherford Appleton Laboratory–
Saclay (CEN)–UCLA–Vienna

C. Albajar [a], M.G. Albrow [b], O.C. Allkofer [c,1], K. Ankoviak [d], R. Apsimon [b], B. Aubert [e],
C. Bacci [f], S. Bartha [c], G. Bauer [g], A. Bettini [h], A. Bezaguet [a], P. Biddulph [i], H. Bohn [c],
A. Böhrer [j], R. Bonino [a], K. Bos [k], M. Botlo [a], D. Brockhausen [c], C. Buchanan [d], B. Buschbeck [ℓ],
G. Busetto [h], A. Caner [h], P. Casoli [h], H. Castilla-Valdez [d], F. Cavanna [c], P. Cennini [a],
S. Centro [h], F. Ceradini [f], G. Ciapetti [f], S. Cittolin [a], E. Clayton [m], D. Cline [d], J. Colas [e],
R. Conte [h], J.A. Coughlan [b], D. Dau [c], C. Daum [k], M. Della Negra [a], M. Demoulin [a],
D. Denegri [n], H. Dibon [ℓ], A. DiCiaccio [f], F.J. Diez Hedo [a], L. Dobrzynski [o], J. Dorenbosch [k],

Received 21 March 1991

We report on a search for the decays $B^0 \rightarrow \mu^+\mu^-$, $B \rightarrow \mu^+\mu^- X$ and $B^0_d \rightarrow \mu^+\mu^- K^{0*}$, which are expected to be rare if mediated by flavor changing neutral currents. Using data collected during the 1984–1989 CERN p$\bar{\text{p}}$ Collider runs, the UA1 search was carried out using $\mu^+\mu^-$ events with $3.9 < M_{\mu\mu} < 5.5$ GeV/c^2. We find 90% confidence level upper limits on the branching ratios for $B^0 \rightarrow \mu^+\mu^-$ of 8.3×10^{-6}, for $B \rightarrow \mu^+\mu^- X$ of 5.0×10^{-5}, and for $B^0_d \rightarrow \mu^+\mu^- K^{0*}$ of 2.3×10^{-5}. Implications for upper limits on the t-quark mass are discussed.

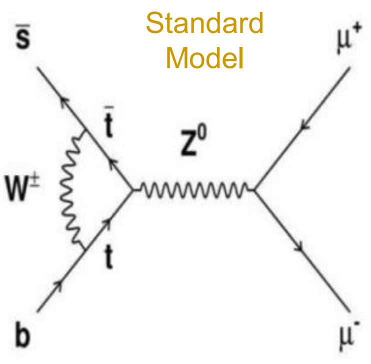
1. Introduction

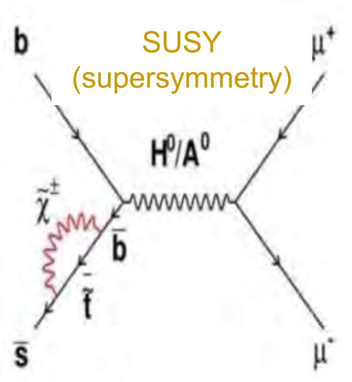
Flavor changing neutral currents are forbidden at the tree level in the standard model of electroweak interactions. However, these transitions are expected
e-loop level through the so-called penguin

$B_s \rightarrow \mu\mu$ – the physics interest

This decay mode can only proceed through suppressed loop diagrams.

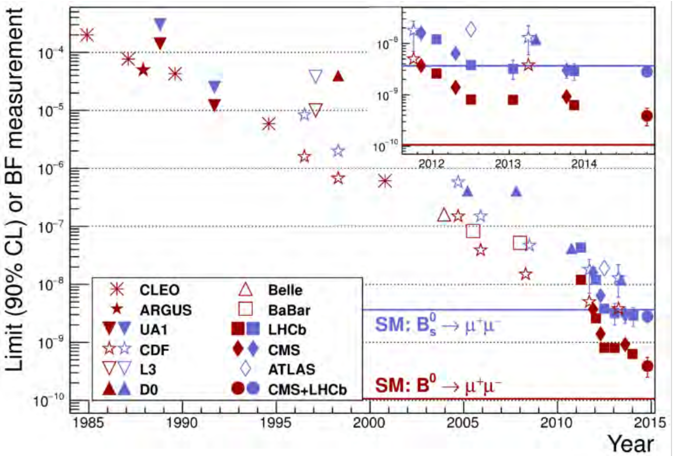
In the SM it happens extremely rarely (***branching fraction*** ~10^{-9}), but the exact rate is very well predicted





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

A 'needle-in-the haystack' search !

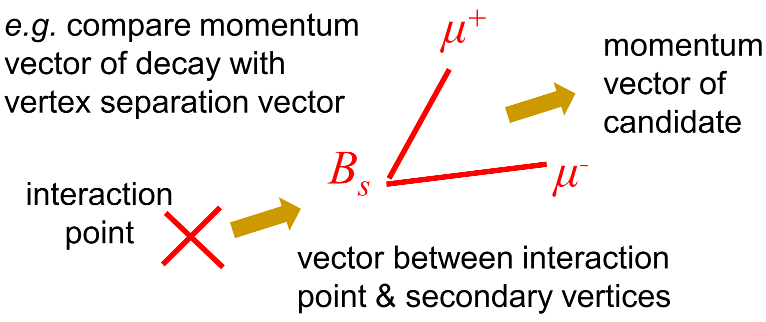


Prior to the LHC, the experiments at Fermilab were pushing the search limits down towards 10^{-8}

Finding the needle

There are lots of *B*-decays that look rather similar to $B_s \to \mu\mu$. And ‘rather similar’ is very dangerous when you are searching for such a rare decay.

One must exploit all signatures that point not just to a *b*-hadron, but to this specific decay. These include good muons; high p_T; good vertex quality (*i.e.* the two muons come from the same point in space); little other activity around the decay point; and quite a few others.



e.g. compare momentum vector of decay with vertex separation vector

μ^+

momentum vector of candidate

B_s

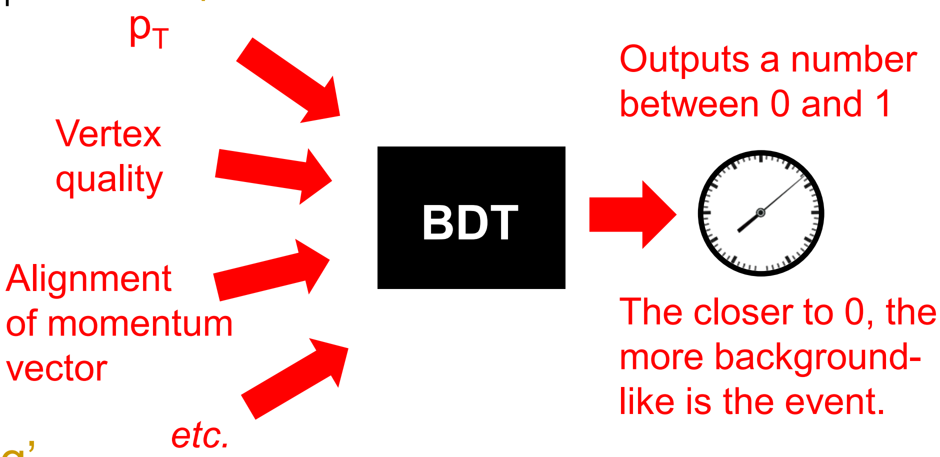
μ^-

interaction point

vector between interaction point & secondary vertices

In order to combine the information concerning these signatures in the optimum way, use a ‘machine learning’ algorithm called a ***boosted decision tree*** (BDT).

BDT learns to separate signal and background using training samples provided from data and simulation.



p_T

Vertex quality

Alignment of momentum vector

etc.

BDT

Outputs a number between 0 and 1

The closer to 0, the more background-like is the event.

Finding the needle

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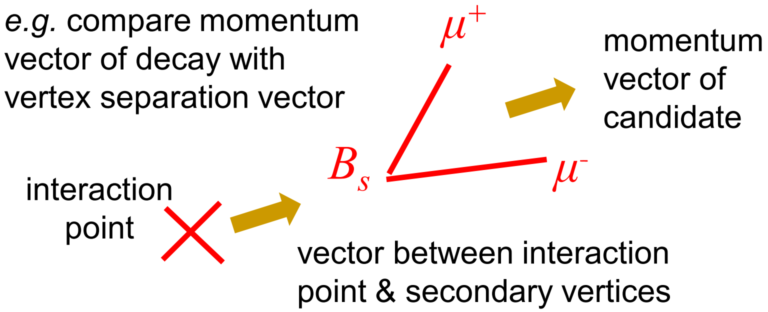
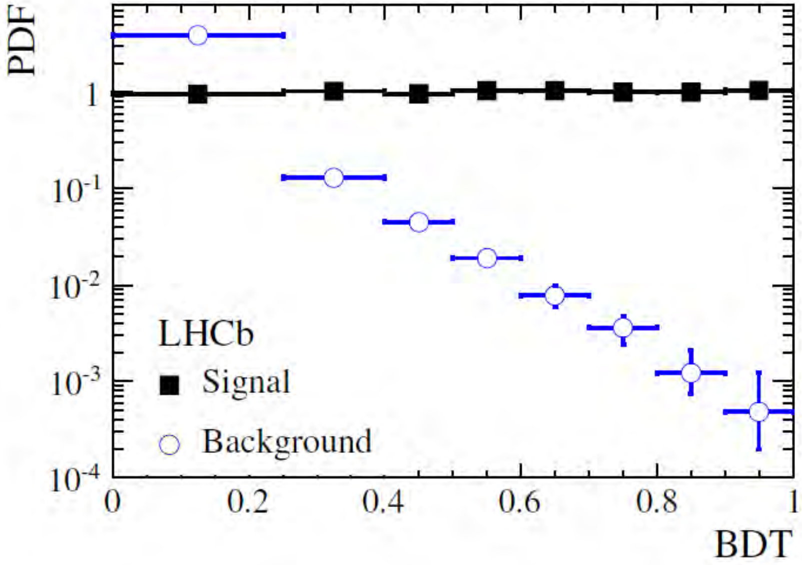


e.g. compare momentum vector of decay with vertex separation vector

momentum vector of candidate

interaction point

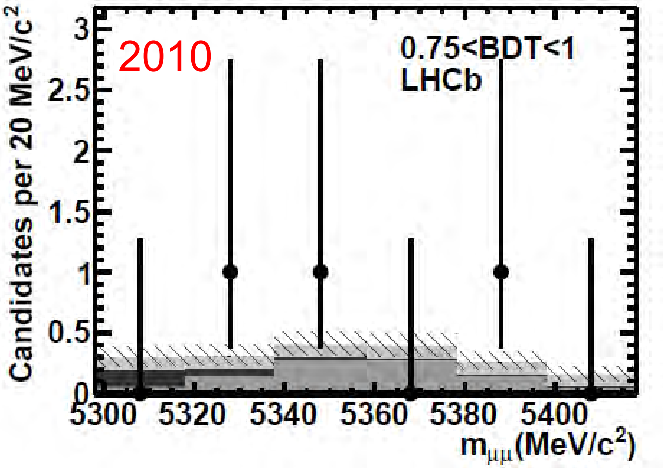
vector between interaction point & secondary vertices



[LHCb, PRL 111 (2013) 101805]

In order to combine the information concerning these signatures in the optimum way, use a ‘machine learning’ algorithm called a ***boosted decision tree*** (BDT).

$B_s \to \mu\mu$ - progress through run 1



[PLB 708 (2012) 55]

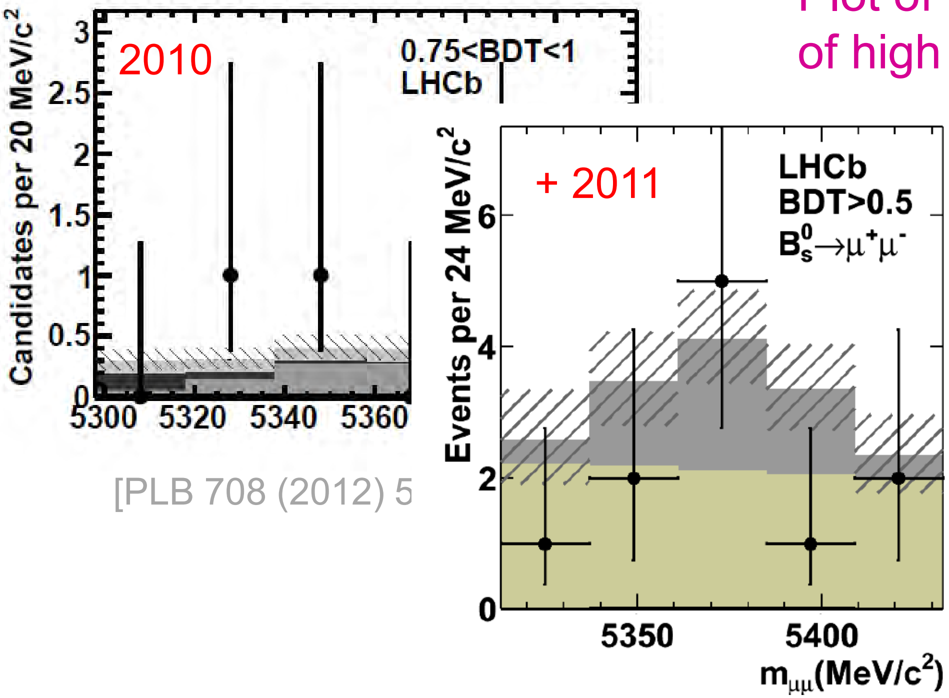
Plot of invariant mass distribution in region of high BDT sensitivity – if there is a signal we should see a peak here (but the analysis considers behaviour across all BDT output).

(In these plots concentrate on the points, *i.e.*

These are the data !)

2010
Nothing

$B_s \to \mu\mu$ - progress through run 1



[PLB 708 (2012) 5

[PRL 108 (2012) 231801]

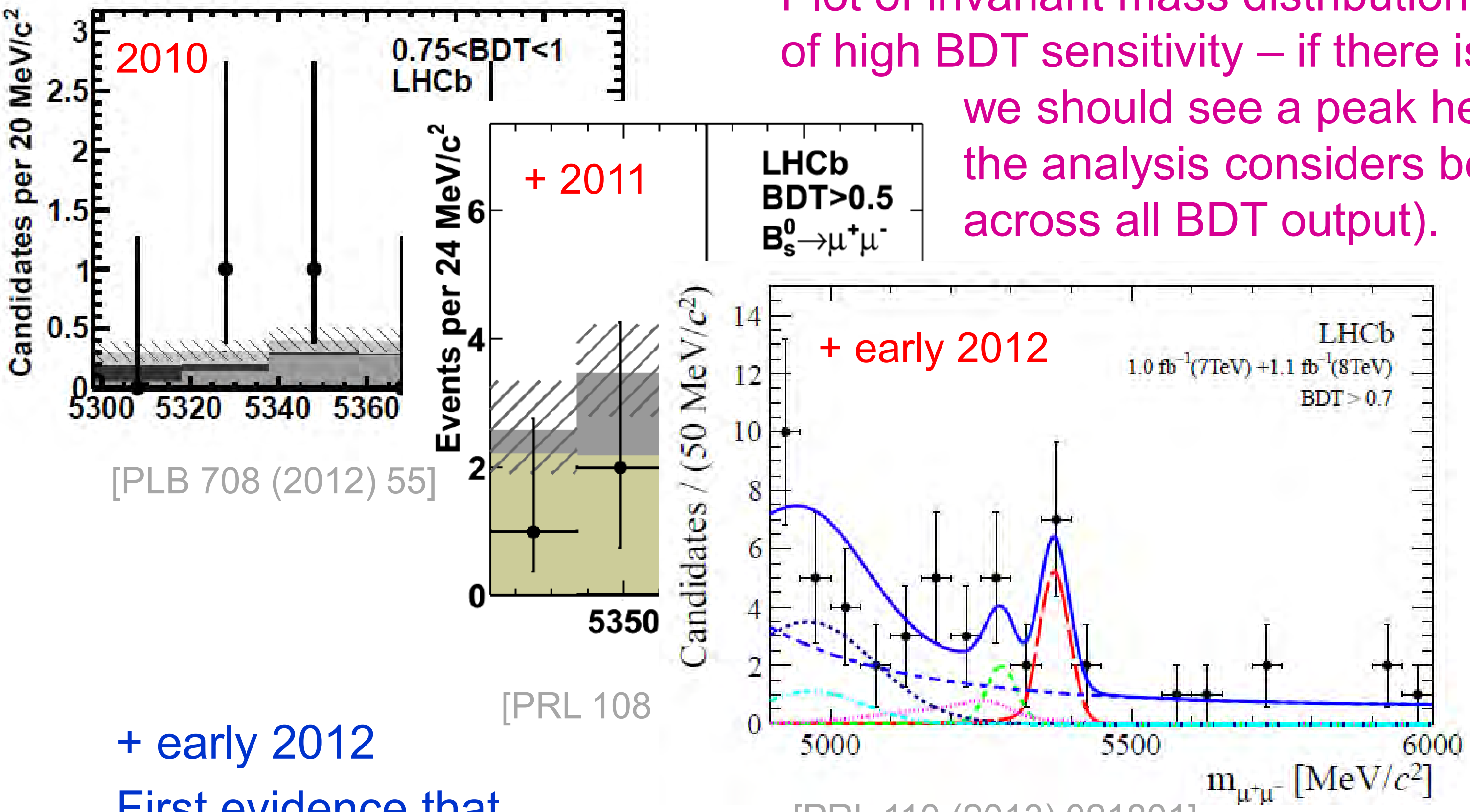
Plot of invariant mass distribution in region of high BDT sensitivity – if there is a signal we should see a peak here (but the analysis considers behaviour across all BDT output).

+ 2011

Maybe a hint of a bump, but nothing can be claimed

$B_s \rightarrow \mu\mu$ - progress through run 1

Plot of invariant mass distribution in region of high BDT sensitivity – if there is a signal we should see a peak here (but the analysis considers behaviour across all BDT output).



[PLB 708 (2012) 55]

[PRL 108

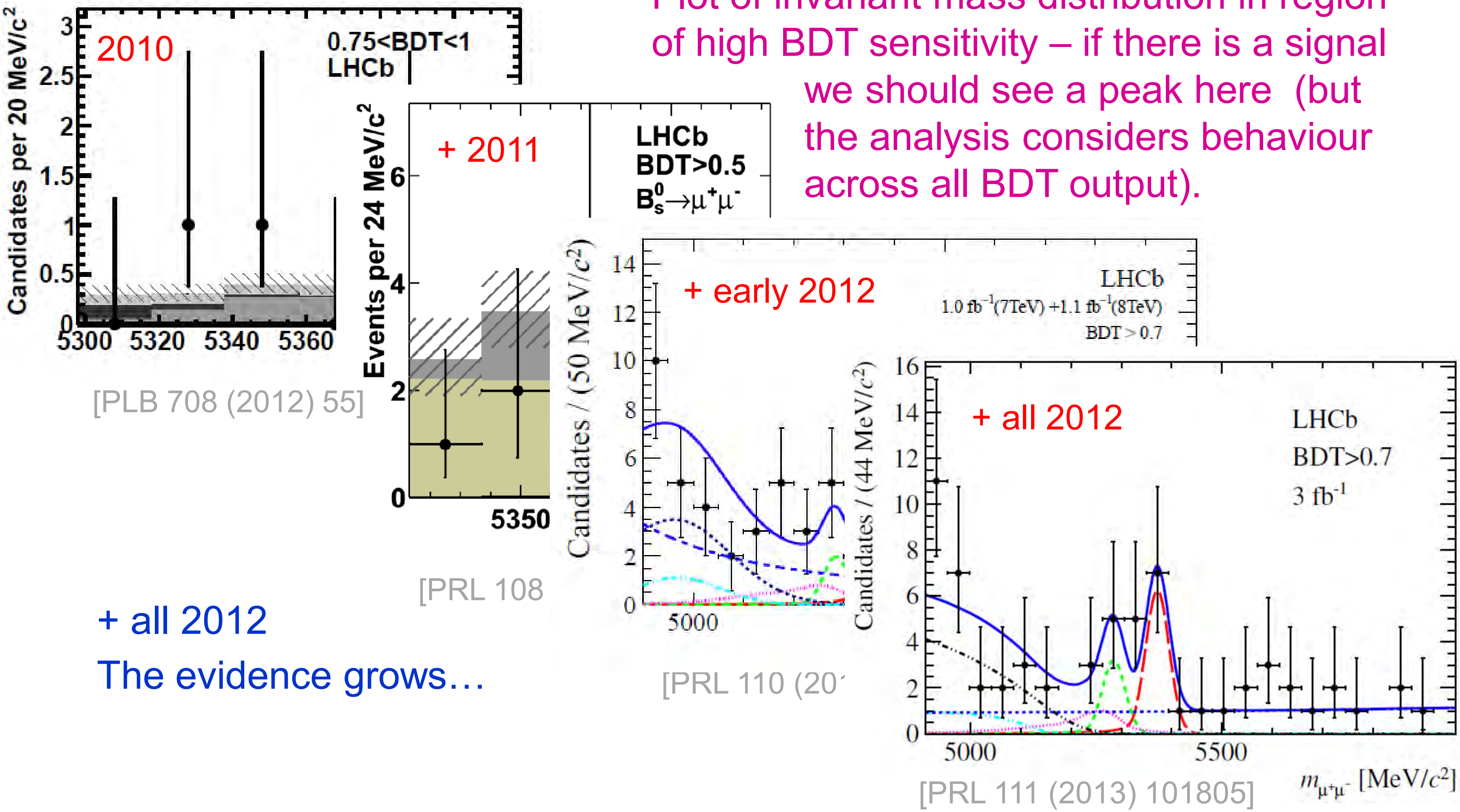
[PRL 110 (2013) 021801]

+ early 2012

First evidence that there is something there !

$B_s \rightarrow \mu\mu$ - progress through run 1

Plot of invariant mass distribution in region of high BDT sensitivity – if there is a signal we should see a peak here (but the analysis considers behaviour across all BDT output).



[PLB 708 (2012) 55]

[PRL 108

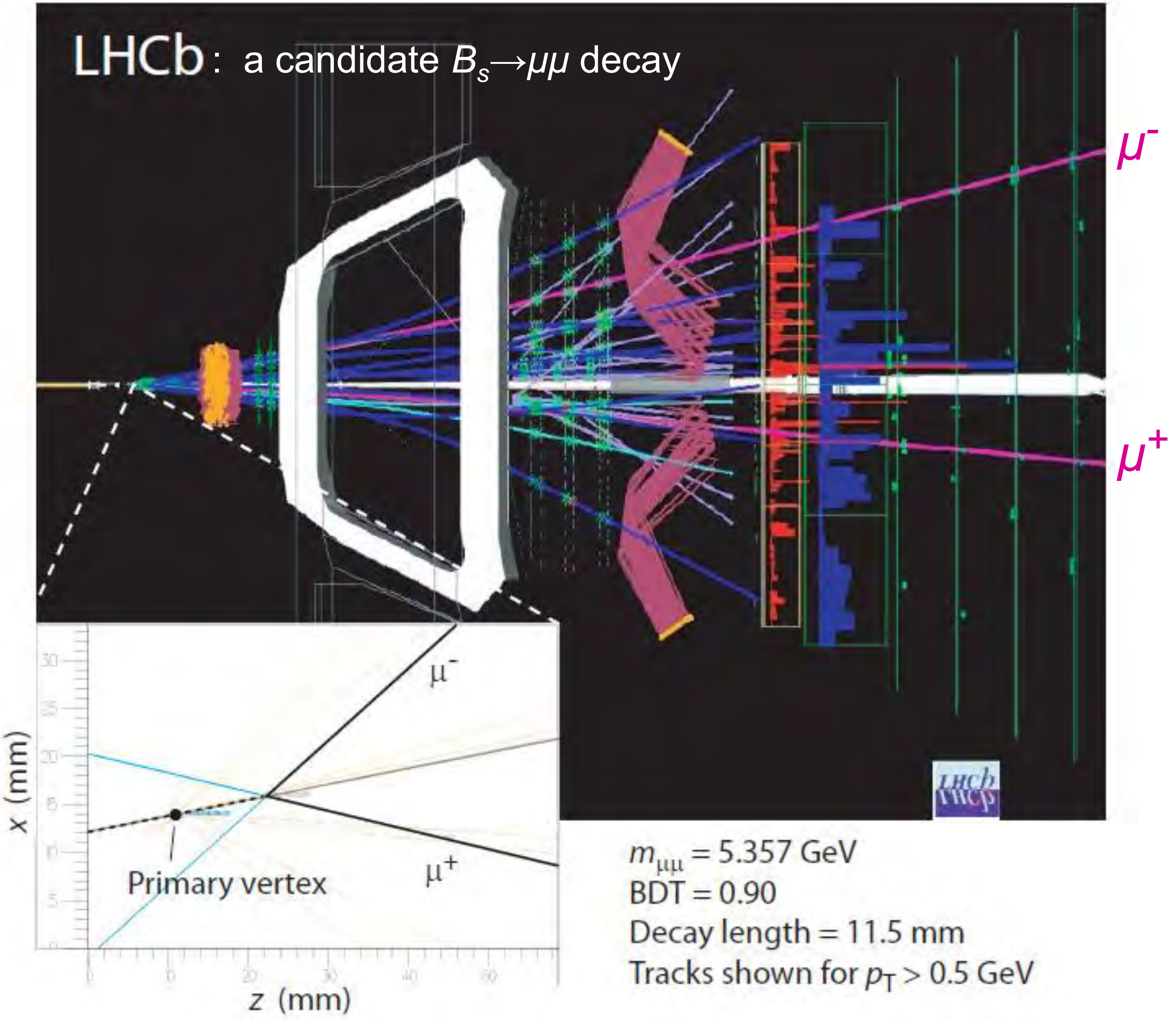
[PRL 110 (201

[PRL 111 (2013) 101805]

+ all 2012

The evidence grows…

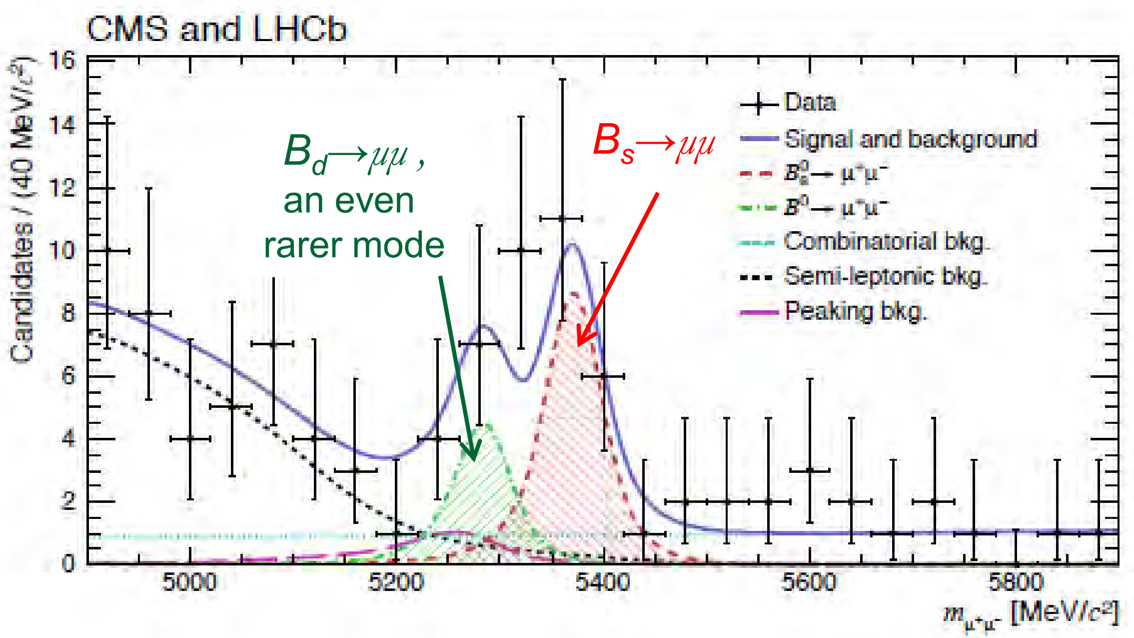
LHCb: a candidate $B_s \to \mu\mu$ decay



$m_{\mu\mu} = 5.357$ GeV
BDT = 0.90
Decay length = 11.5 mm
Tracks shown for $p_T > 0.5$ GeV

$B_s \rightarrow \mu\mu$ – the wait is over

Signal becomes even more compelling, if we look at results of a joint analysis performed on LHCb data and data from the CMS experiment….



$B_d \rightarrow \mu\mu$, an even rarer mode

$B_s \rightarrow \mu\mu$

[Nature 522 (2015) 68]

…the ***branching fraction*** turns out to be consistent with SM prediction. This result is *extremely* important, as it rules out many New Physics models.

$B_s \rightarrow \mu\mu$ – the wait is over

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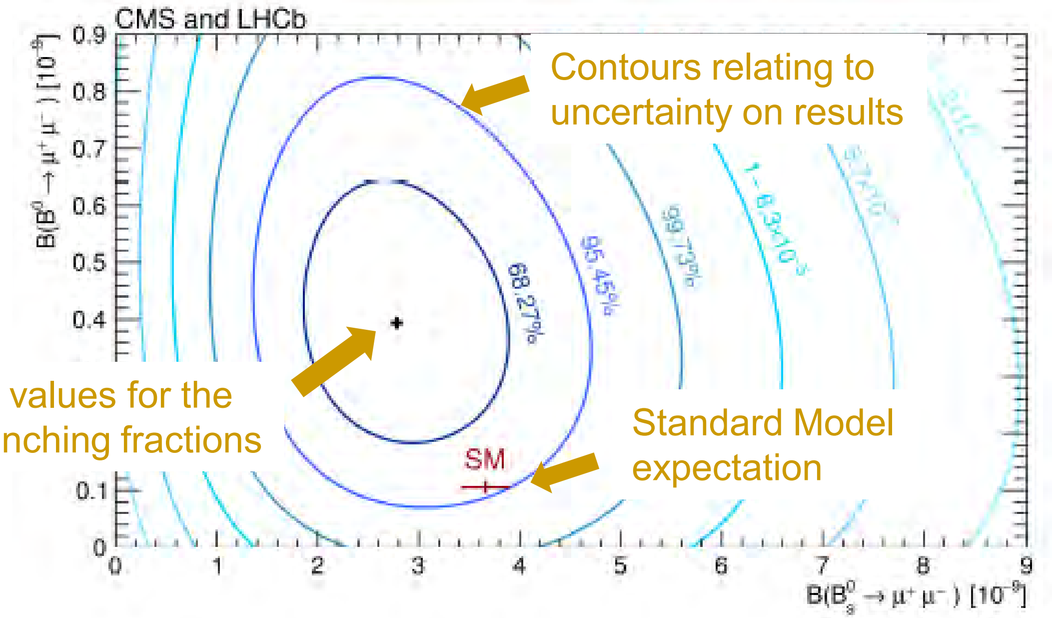

Contours relating to uncertainty on results

Central values for the two branching fractions

Standard Model expectation

[Nature 522 (2015) 68]

…the ***branching fraction*** turns out to be consistent with SM prediction. This result is *extremely* important, as it rules out many New Physics models.

However, the precision of the measurement is limited, and the central values are intriguing ('consistent' does not mean 'spot on'). We need more data !