Flavour physics: experimental status

- Flavour physics
  - a topic of intrinsic interest
  - a tool for indirect discovery
- LHCb overview
- *Selected* topics
  - Spectroscopy and hadron exotics
  - CPV & unitarity triangle tests
  - Charm physics
  - Rare decays, FCNCs and R_{K^*}

Guy Wilkinson
University of Oxford and CERN
24 April 2017

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Apologies are in order:

- This talk will not touch on kaon physics – but this topic is a vital and important piece of the jigsaw;
- Unsurprisingly it will be LHCb-centric. Please apply your own bias correction.

b

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

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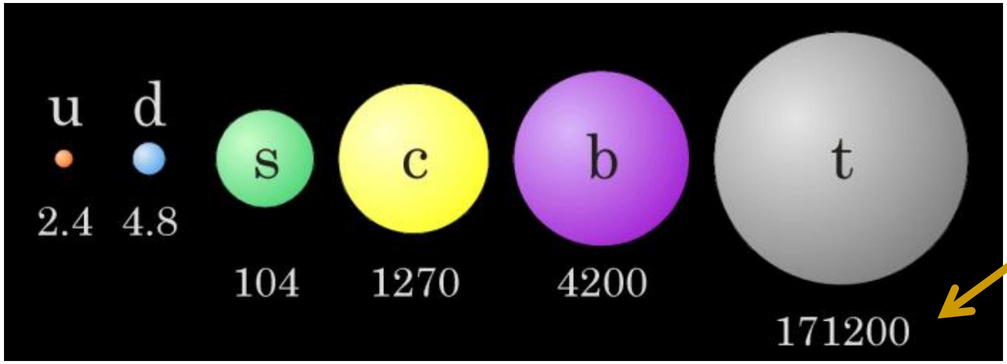
What is flavour physics?

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

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



Not to linear scale !

mass in MeV/c^2

Open questions:

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

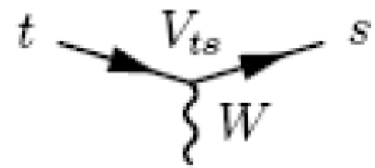
No answer yet !
These values (i.e. '3' & the masses) are free parameters of the SM

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

* the concept of flavour extends to the lepton sector too

Flavour and the CKM matrix

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



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

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

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

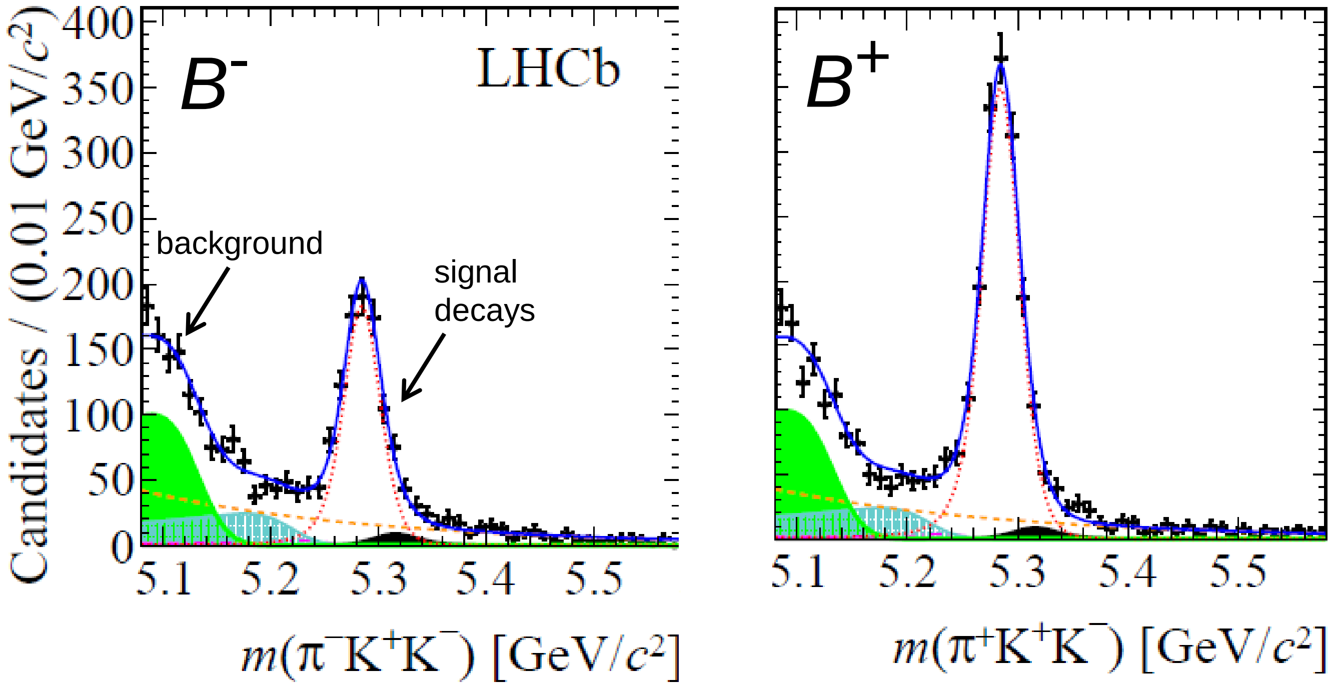
The CKM matrix is also linked to another big puzzle of flavour physics…

CP violation

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

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

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

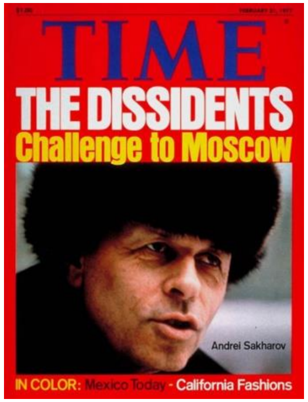


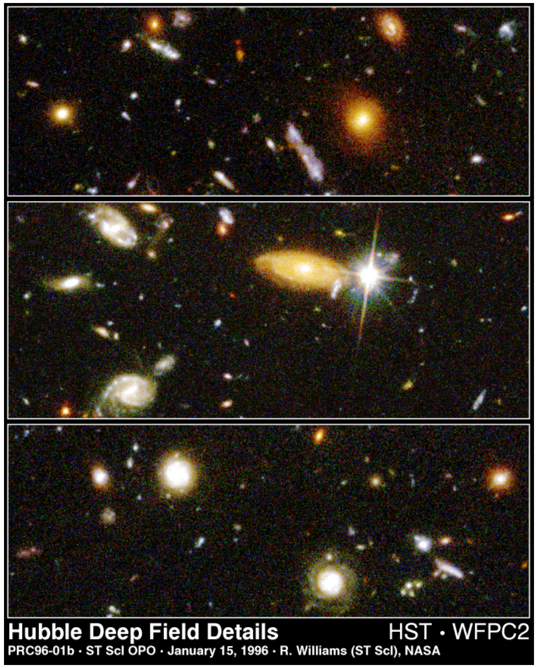
[LHCb, PRD 90 (2014) 112004]

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

Cosmological connections ?

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





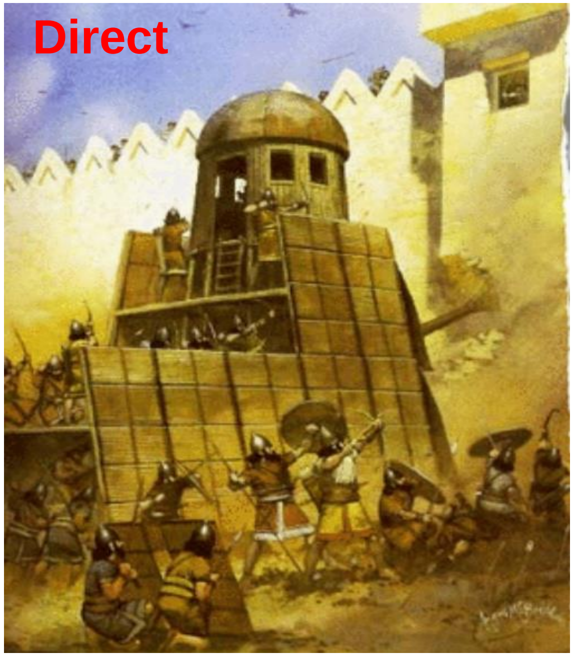
The problem is that the CP-violation that appears in the Standard Model, is woefully inadequate to explain the matter-antimatter asymmetry we have today.

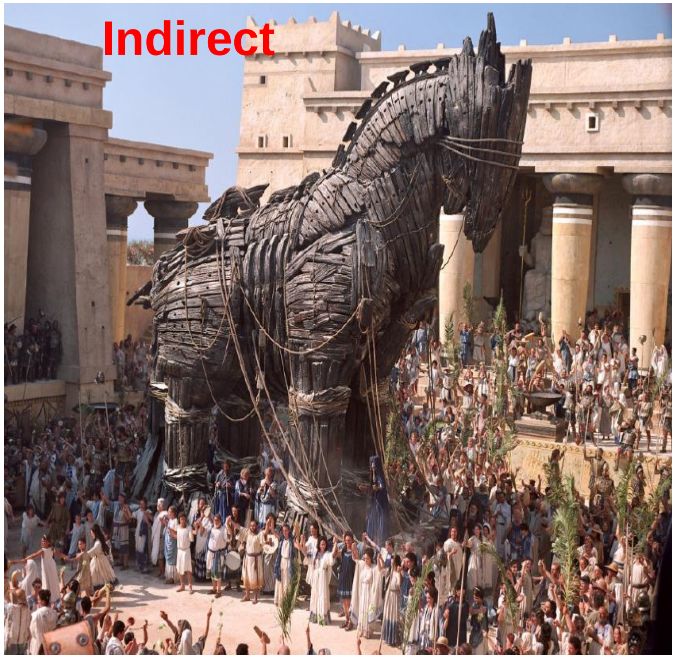
This is a big problem with the Standard Model !

More & better measurements may point a way forward.

Breaching the walls of the Standard Model

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





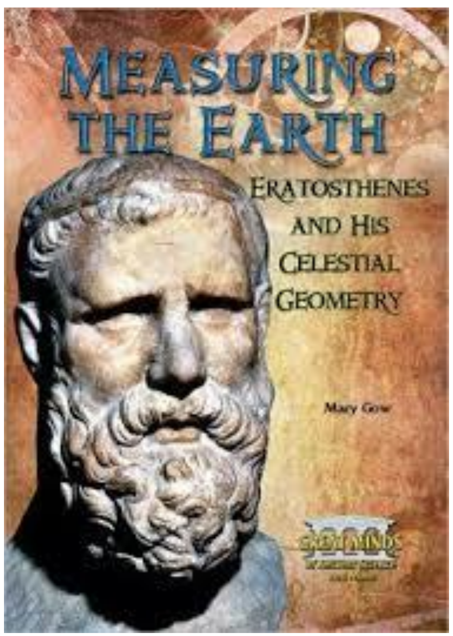
Use the high energy of the LHC to produce the New Physics particles, which we then detect

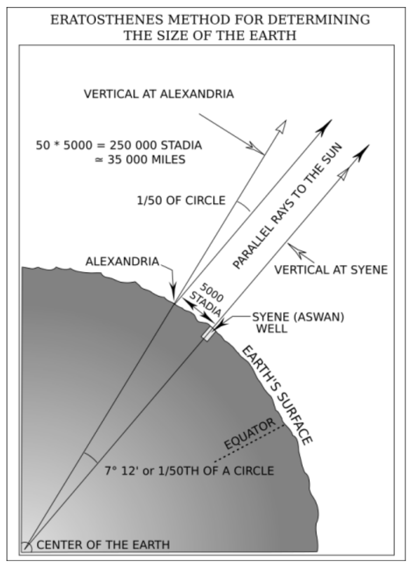
Make precise measurements of processes in which New Physics particles enter through ‘virtual loops’

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

Indirect measurements – an established tradition in science

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

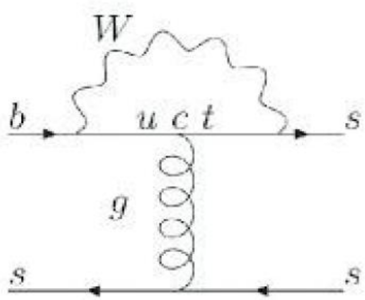


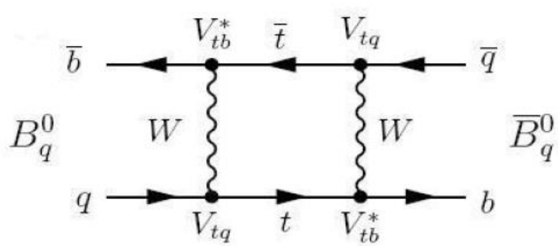


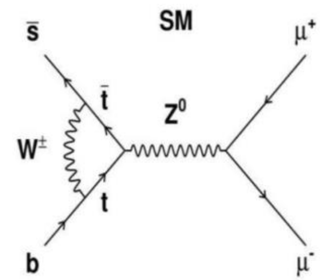
…around 2.2 thousand years prior to the direct observation.

Indirect measurements – an established tradition in science

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





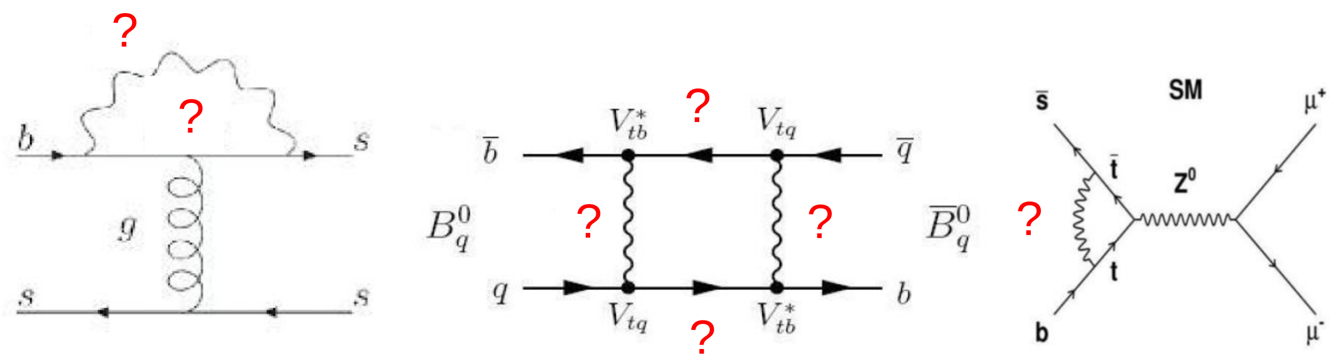


(but as we will see, tree-mediated decays also have their role to play)

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

Indirect measurements – an established tradition in science

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



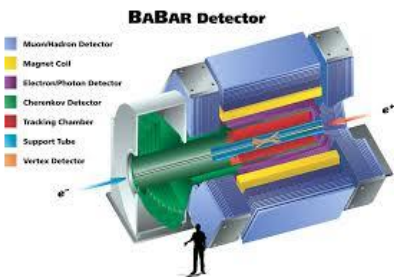
(but as we will see, tree-mediated decays also have their role to play).

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

The main players in b (and c) physics

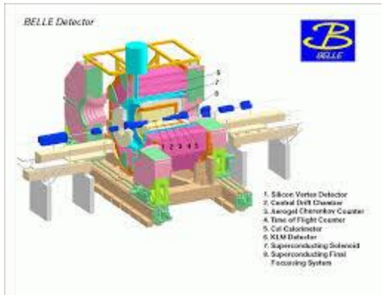
b-factories

also LEP, ARGUS, CLEO, BES-III



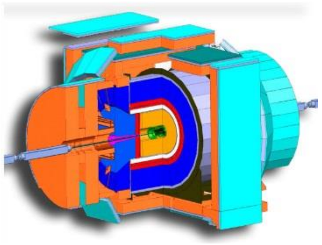
BaBar (SLAC) & Belle (KEK)

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



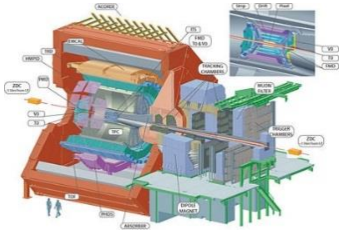
Tevatron experiments

also UA1, UA2



CDF & D0

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



ATLAS & CMS

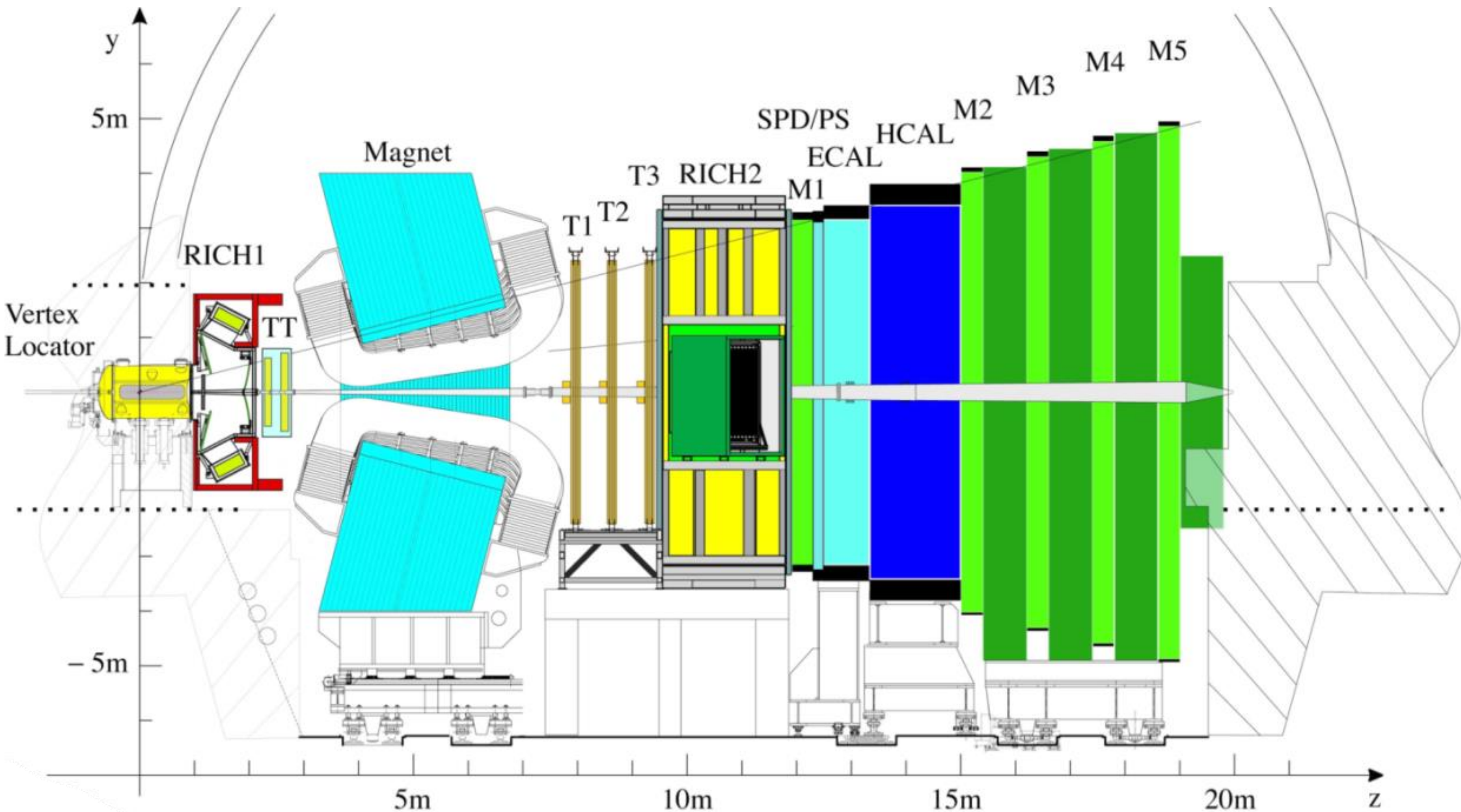
Their excellent instrumentation gives them great capabilities in certain *b*-physics channels, especially those with dilepton final states.

LHCb – a flavour physics experiment at the LHC

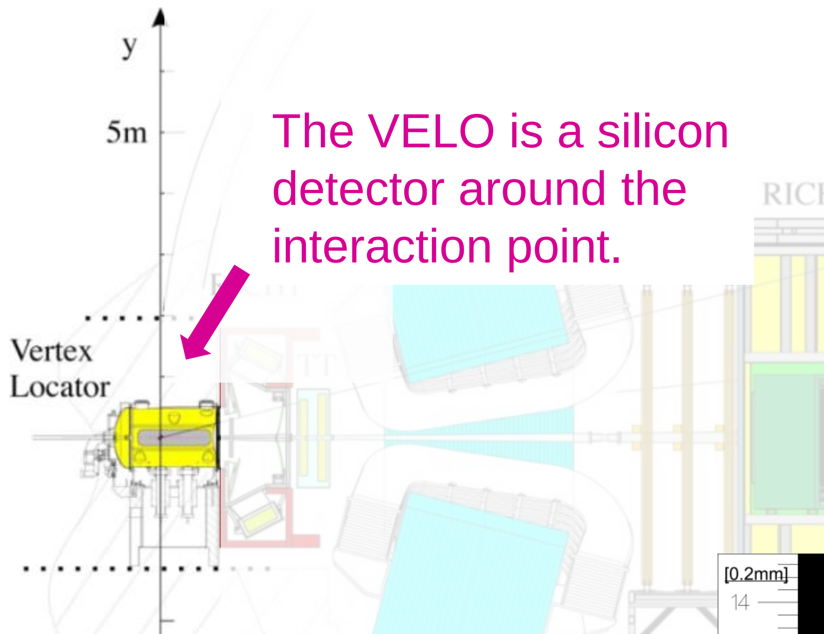
A collaboration of ~1200 members from 72 institutes in 16 countries

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

LHCb – a forward spectrometer for flavour physics



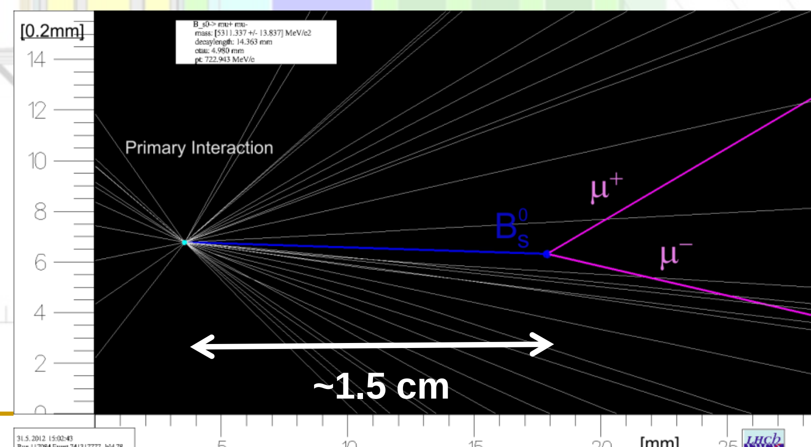
LHCb – a forward spectrometer for flavour physics



The VELO is a silicon detector around the interaction point.

One-half of the VELO under construction

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

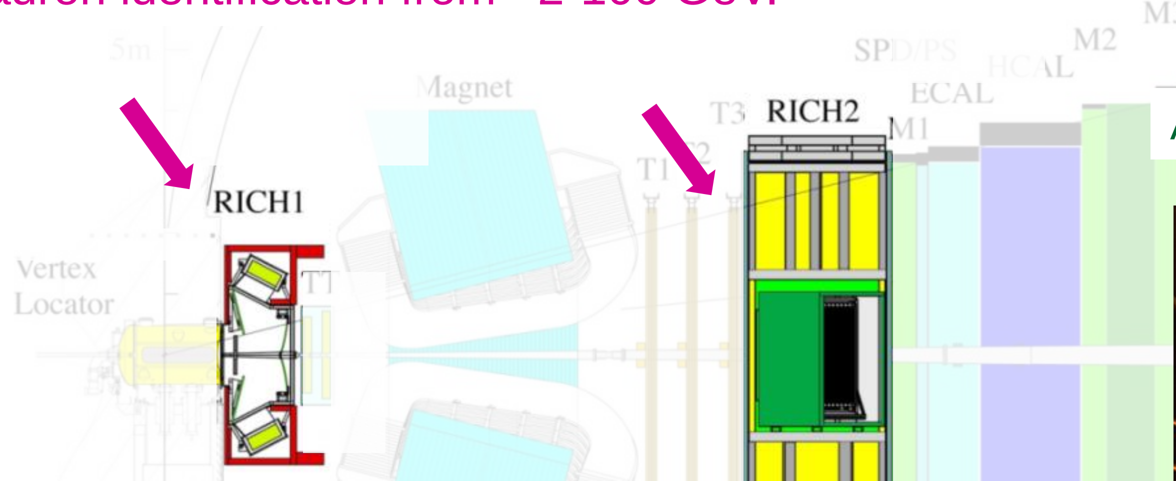


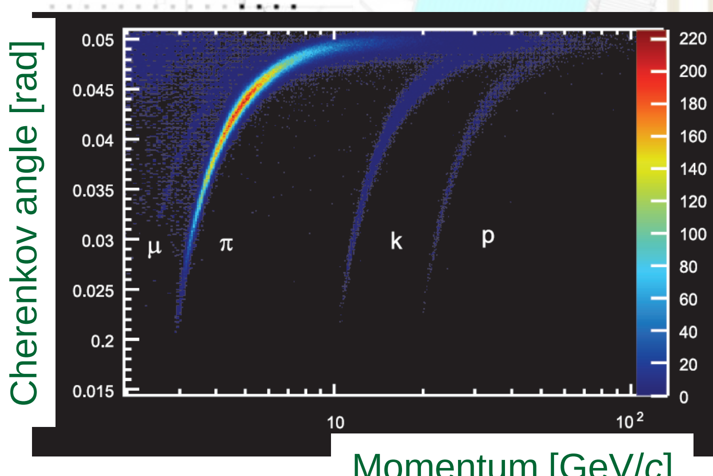
A reconstructed *b*-hadron decay vertex

LHCb – a forward spectrometer for flavour physics

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


Array of RICH photodetectors

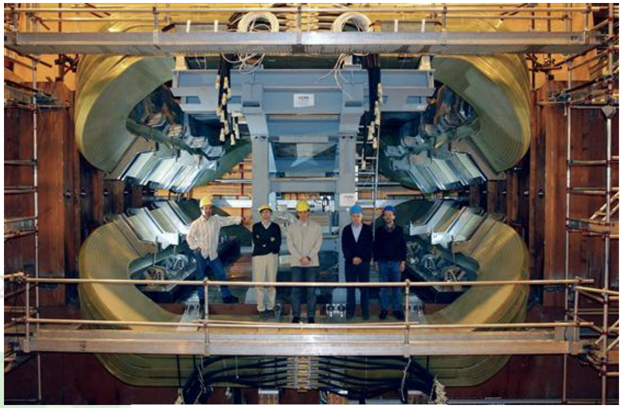




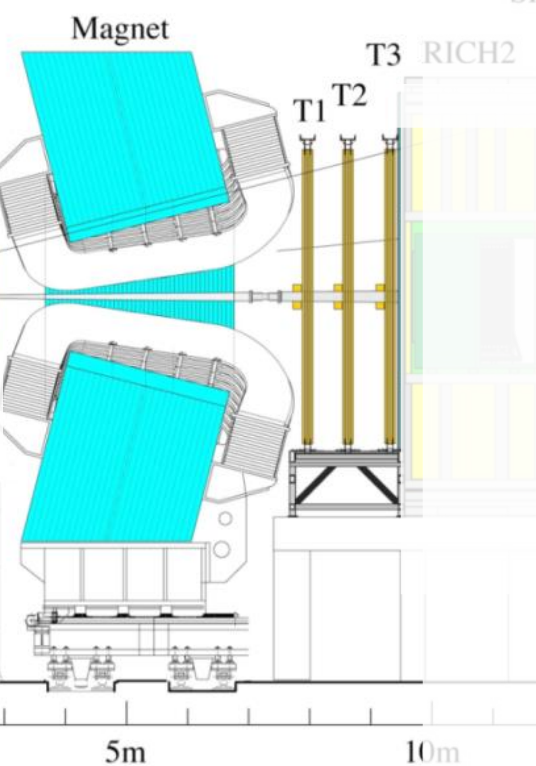

Assembling RICH 2;
note the mirrors

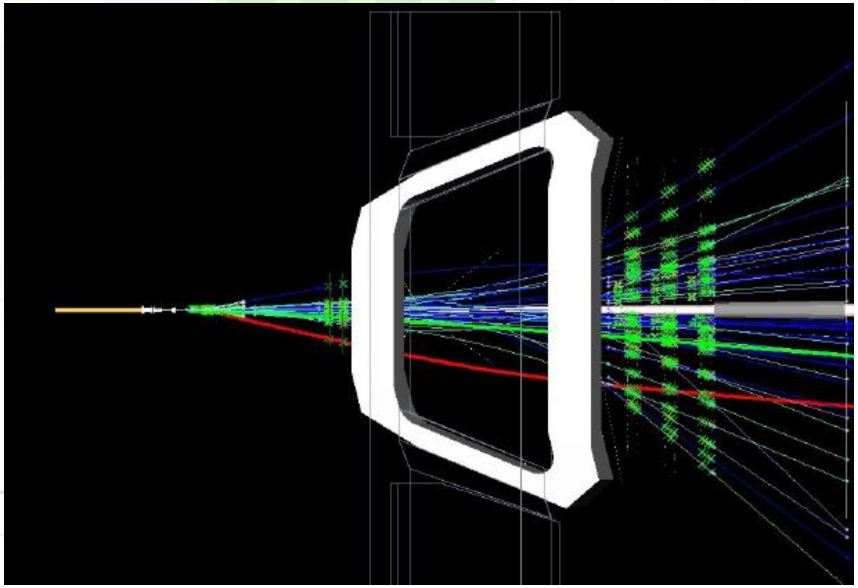
LHCb – a forward spectrometer for flavour physics

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



Dipole magnet

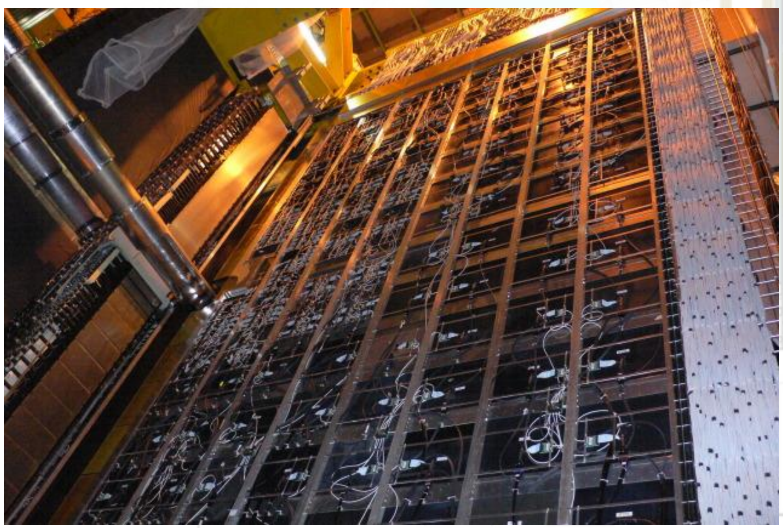




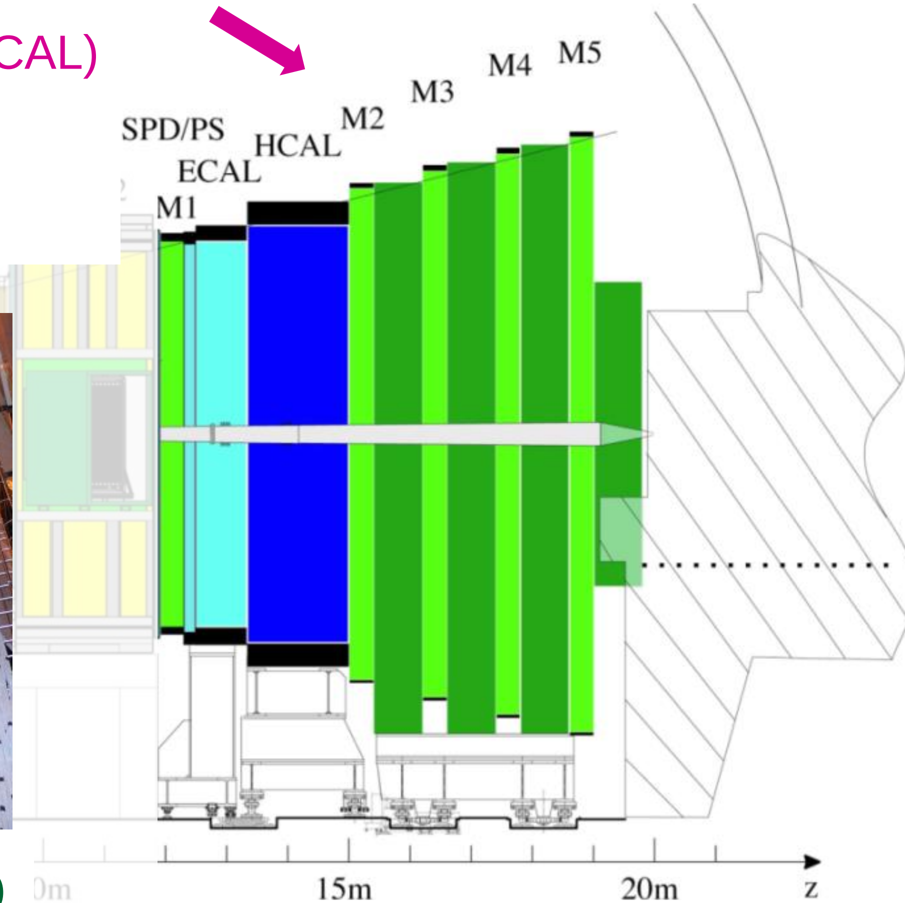
Reconstructed tracks

LHCb – a forward spectrometer for flavour physics

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

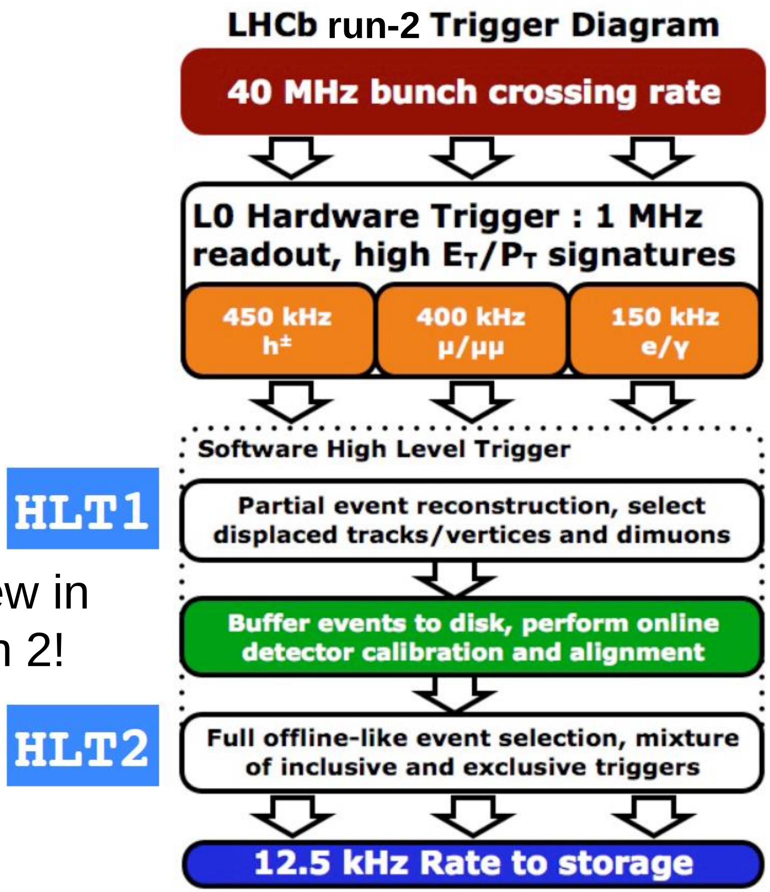


Part of calorimeter system (preshower)



These detectors play a major role in the LHCb trigger

The LHCb trigger & data flow



New in run 2!

Also new!

Including several kHz of 'TURBO'

LHCb has a dedicated flavour-physics trigger. At earliest stage (L0) it can trigger on single hadrons, leptons, photons from heavy-flavour decays.

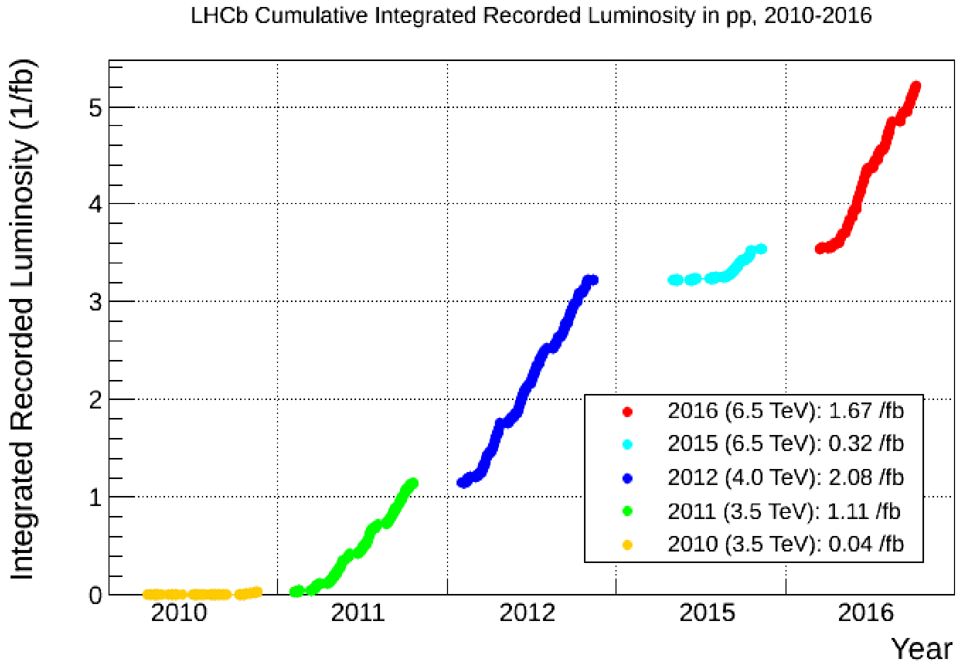
Software trigger (HLT) split into two steps, with HLT2 not run until calibration and alignment validated.

This means the trigger runs with offline-like performance
→ better background rejection.

Furthermore, can dare to use some of the trigger output directly for physics analysis without any offline processing! This is called the 'TURBO stream'.

LHCb – the story so far

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



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

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

LHCb – the story so far

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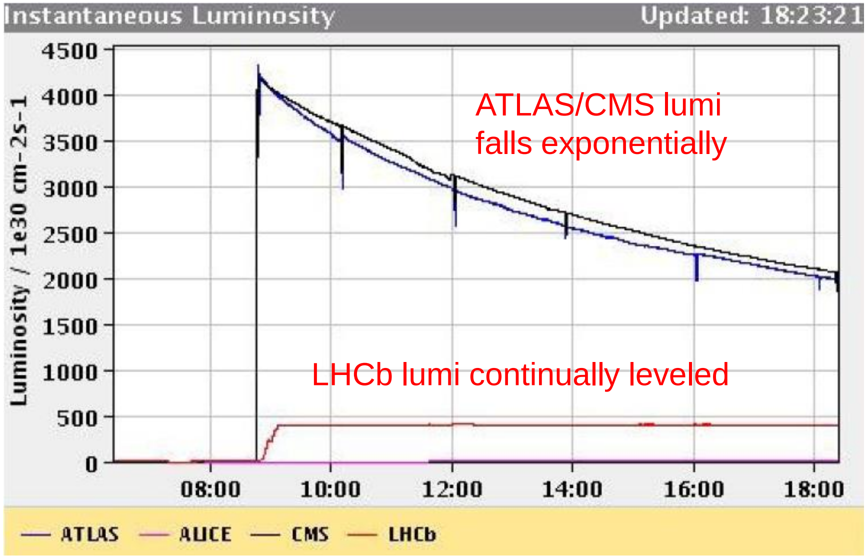
LHCb deliberately operates at lower luminosity than ATLAS/CMS



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

Now … in 2015).
Oper… ements).

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

Selected physics topics

- Spectroscopy and hadron exotics
- CPV & unitarity triangle tests
- Charm physics
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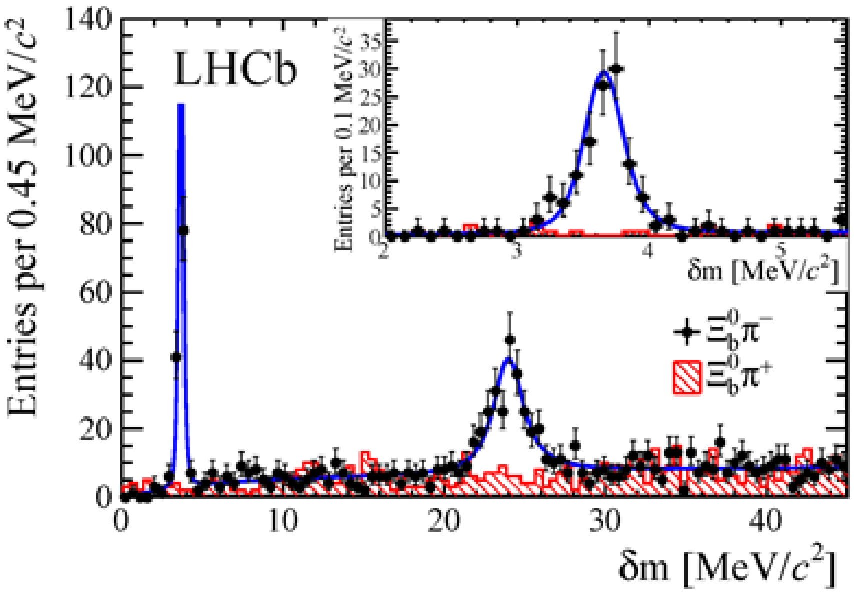
- Spectroscopy at the LHC
- A case study: the pentaquark
- Four-quark states and the X(4140) revisited
- Strange happenings

Spectroscopy - the conventional

Many new states found at the LHC, most of which fit within the ‘vanilla’ quark model

e.g. baryons: the discovery of the
$\Xi_b^{\prime -}$ and Ξ_b^{*-} [PRL 114 (2015) 062004]



$$
\begin{aligned}
m(\Xi_b^{\prime -}) - m(\Xi_b^0) - m(\pi^-) &= 3.653 \pm 0.018 \pm 0.006\,\mathrm{MeV}/c^2, \\
m(\Xi_b^{*-}) - m(\Xi_b^0) - m(\pi^-) &= 23.96 \pm 0.12 \pm 0.06\,\mathrm{MeV}/c^2, \\
\Gamma(\Xi_b^{*-}) &= 1.65 \pm 0.31 \pm 0.10\,\mathrm{MeV}, \\
\Gamma(\Xi_b^{\prime -}) &< 0.08\,\mathrm{MeV} \text{ at } 95\% \text{ C.L.}
\end{aligned}
$$

New particles always provoke interest

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Many new states found at the LHC, most of which fit within the $\boxed{\text{‘vanilla’}}$ quark model

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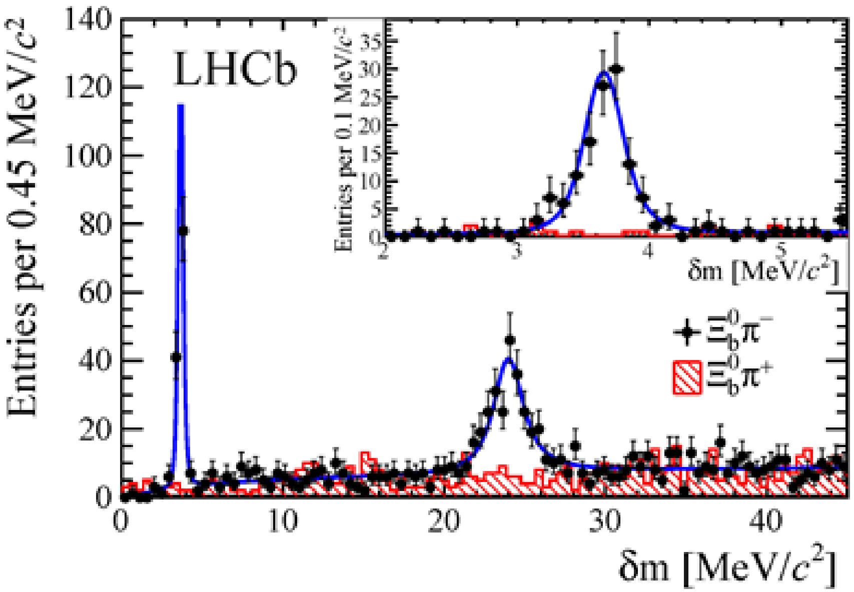

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Baryons can now be constructed from quarks by using the combinations $\boxed{qqq,}$ $qqq\bar{q}q$, etc, while mesons are made out of $\boxed{q\bar{q},}$ $q\bar{q}q\bar{q}$, etc.

Murray Gell-Mann

Spectroscopy - the conventional

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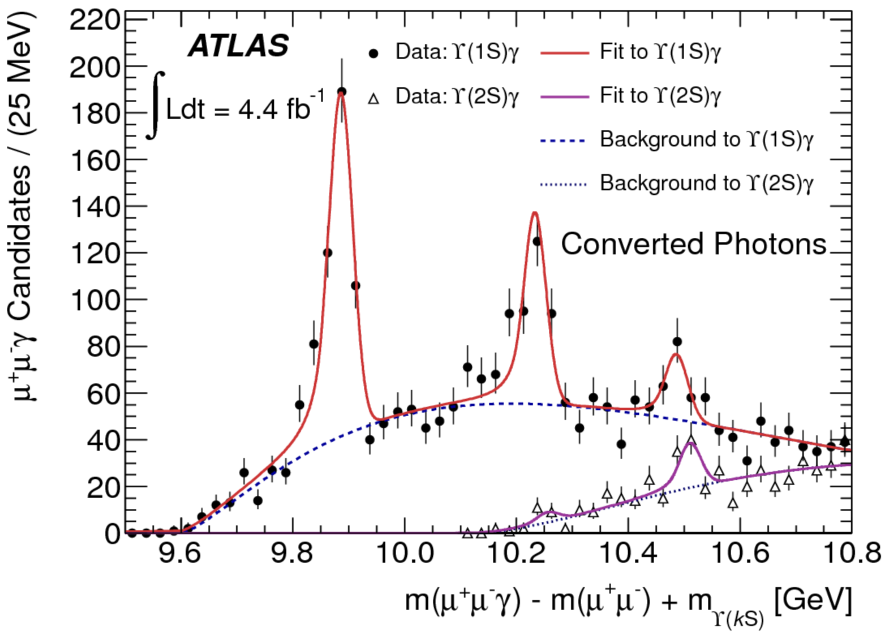
e.g. mesons: the discovery of the $\Upsilon_b(3P)$ system [ATLAS, PRL 108 (2012) 152001]



$$\overline{m}_3 = 10.530 \pm 0.005\ (\text{stat.}) \pm 0.009\ (\text{syst.})\ \text{GeV}$$

"*Baryons can now be constructed from quarks by using the combinations qqq, $qqq\bar{q}$, etc, while mesons are made out of $q\bar{q}$, $qq\bar{q}\bar{q}$, etc.*"

Murray Gell-Mann

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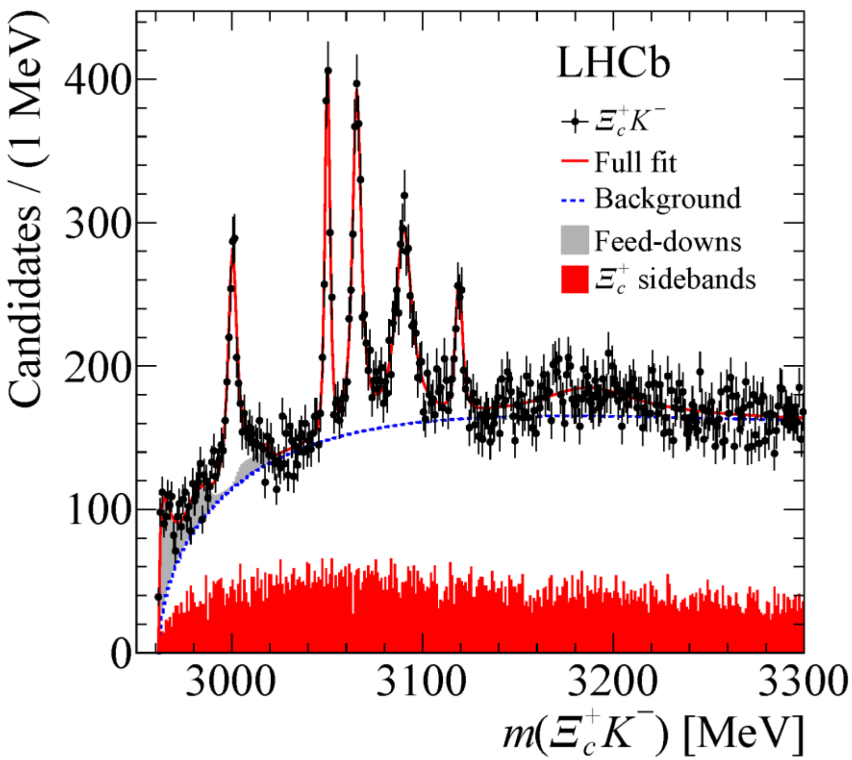
e.g. baryons: five (!) narrow excited Ω^0_c resonances [LHCb, arXiv:1703.04649]



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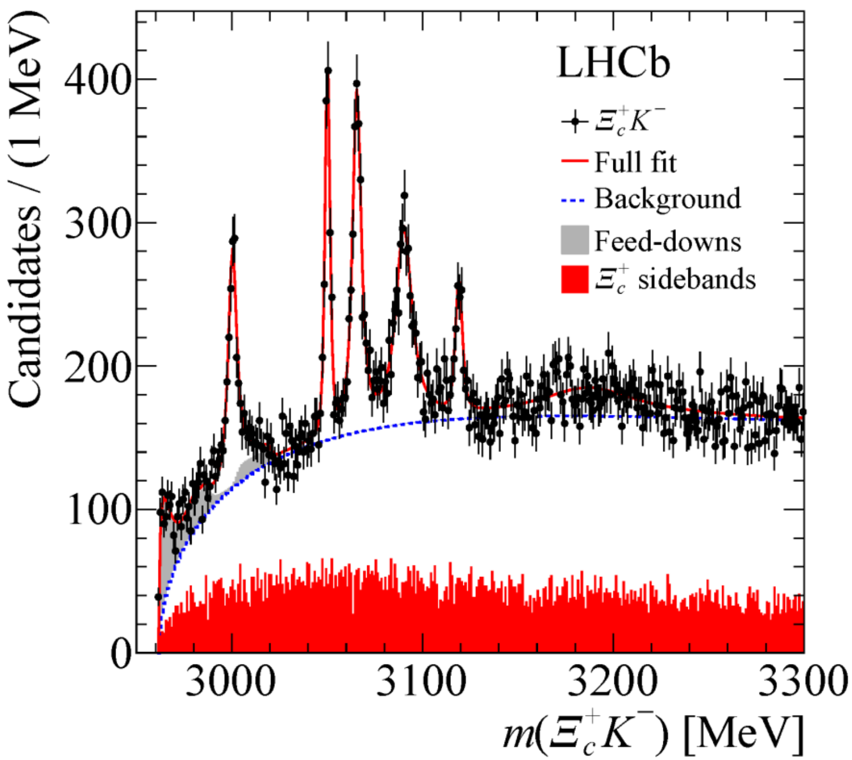

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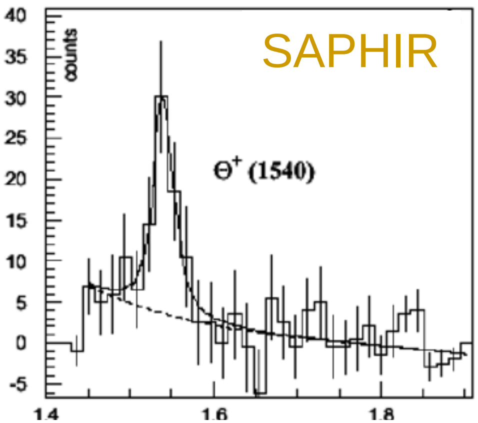
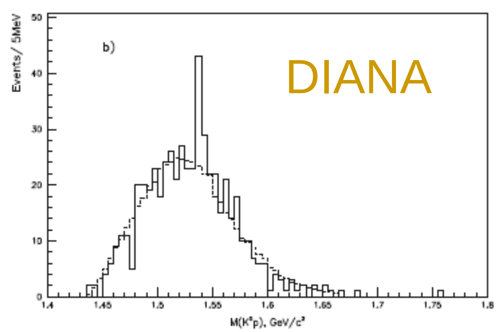
>
> **Murray Gell-Mann**

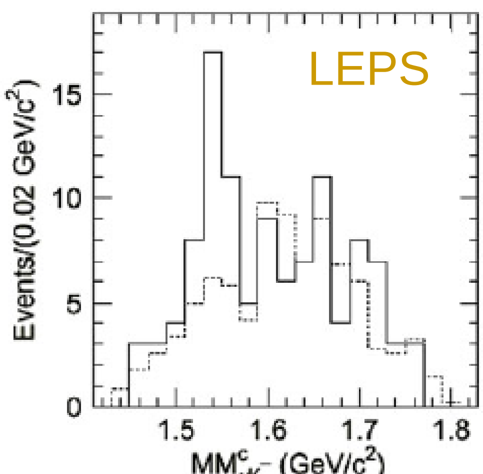
But what of the more exotic possibilities ?

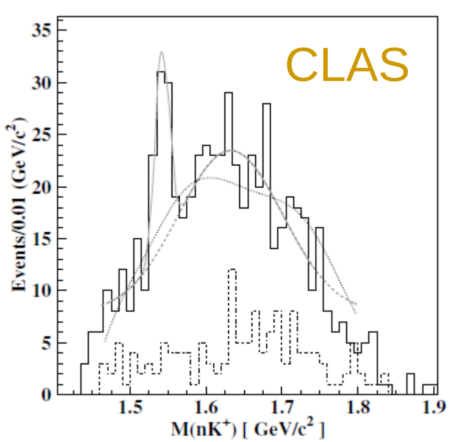
The hunt for pentaquarks – a long journey with several cul-de-sacs

Pentaquark signals have been claimed before, for example the θ⁺ (sbar uudd) ‘seen’ by several experiments in the early 2000s.







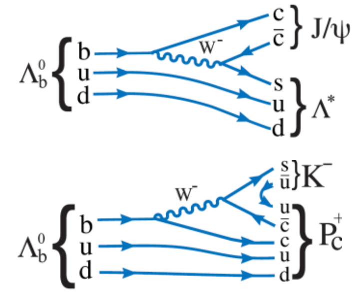


After an initial rush of confirmations, null results from more sensitive experiments appeared, & eventually it was accepted to be non-existent.

“ The whole story – the discoveries themselves, the tidal wave of papers by theorists and phenomenologists that followed, and the eventual ‘undiscovery’ - is a curious episode in the history of science.” PDG 2008

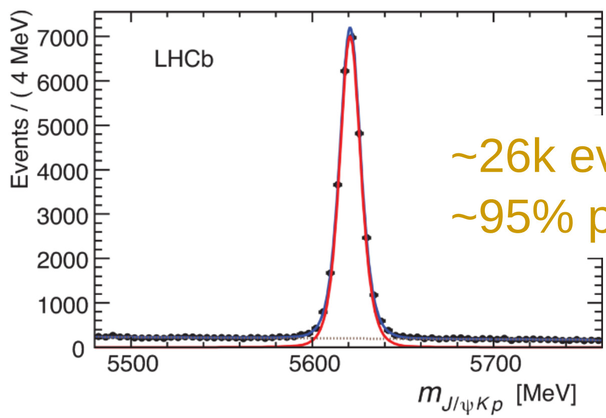
[for more information, see Hicks, Eur. Phys. J. H 37 (2012) 1]

$J/\Psi p$ resonances consistent with pentaquark states



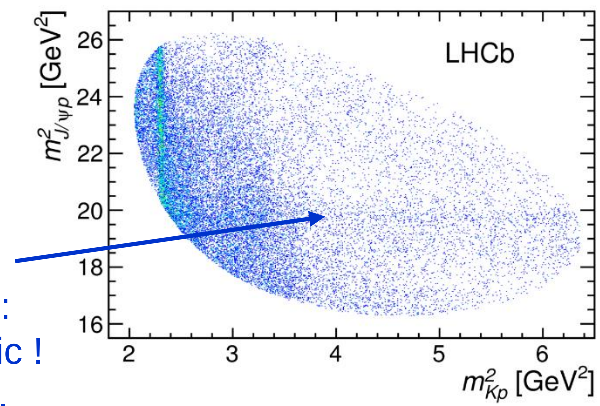
[PRL 115 (2015) 072001]

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



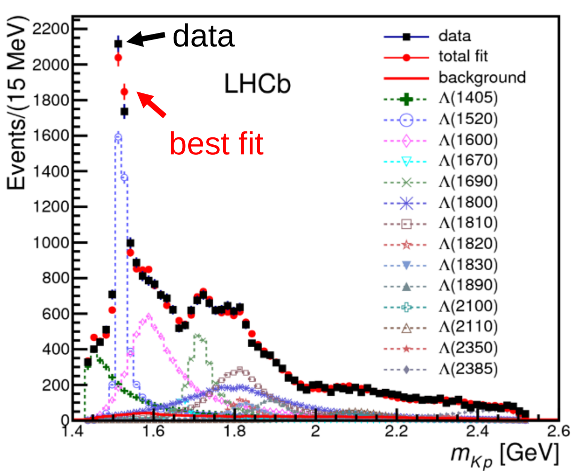
~26k events
~95% purity

Distinctive structure in $J/\Psi p$ spectrum

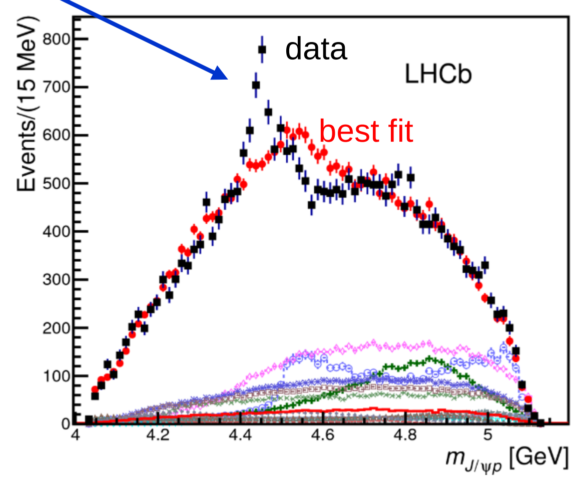


Naïve first impression: this is exotic ! (uudccbar).

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



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



Eliminating the impossible

" How often have I said to you that when you have eliminated the impossible, whatever remains, however improbable, must be the truth? "

Sherlock Holmes
(Sir. Arthur Conan-Doyle)

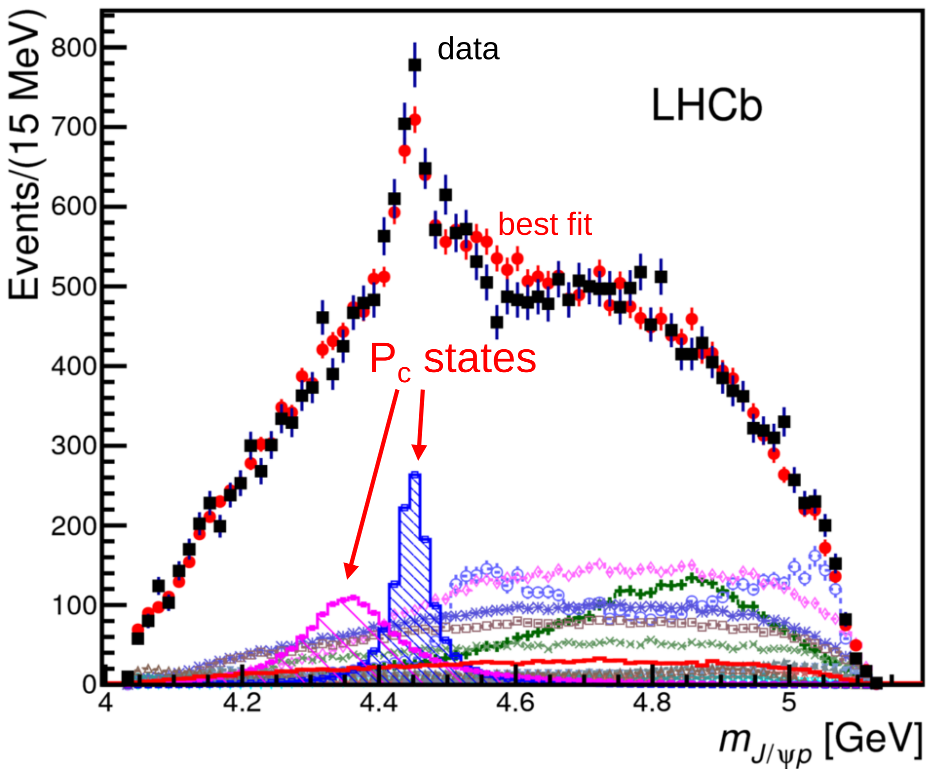
So let us now try by allowing for 'exotic' contributions (*i.e.* pentaquarks) feeding directly in the $J/\psi p$ final state, and find out if this gives a more acceptable description.

$J/\Psi p$ resonances consistent with pentaquark states

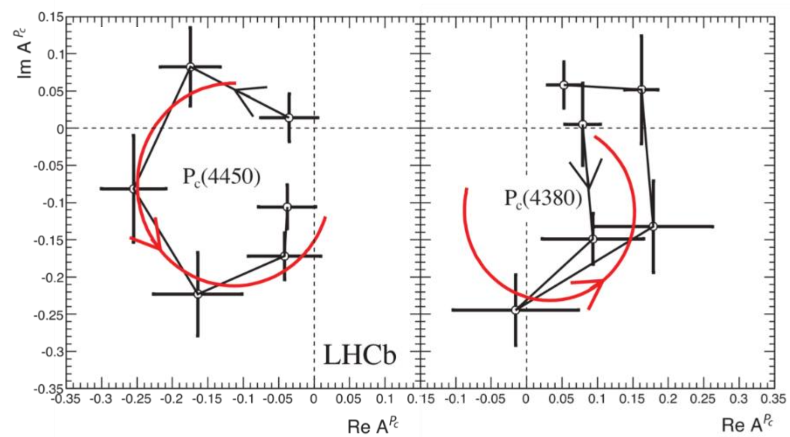
[PRL 115 (2015) 072001]

Need to add two states with content uudccbar.
Best fit has J=3/2 and 5/2 with opposite parities.

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



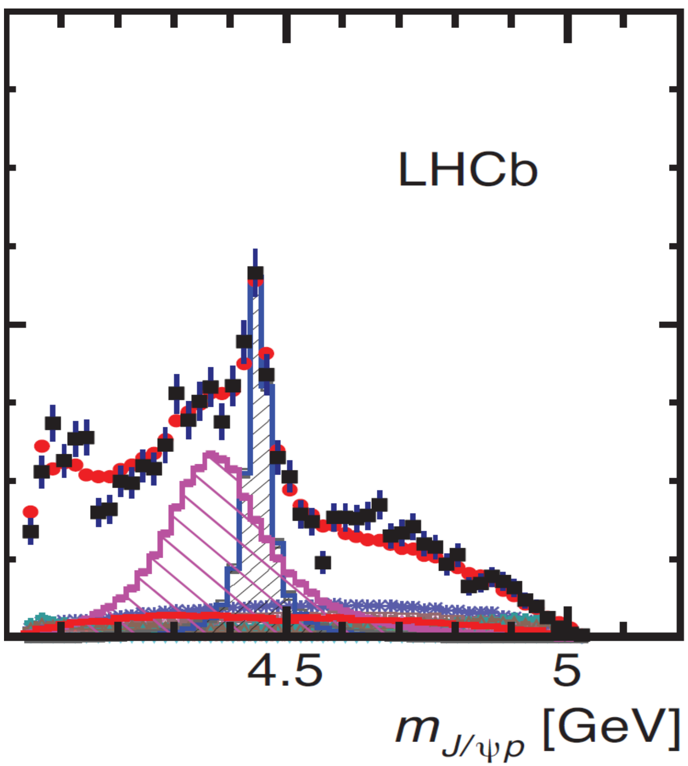
Clear resonant behaviour for narrow state,
Need more statistics to elucidate wider one.



$J/\Psi p$ resonances consistent with pentaquark states

[PRL 115 (2015) 072001]

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



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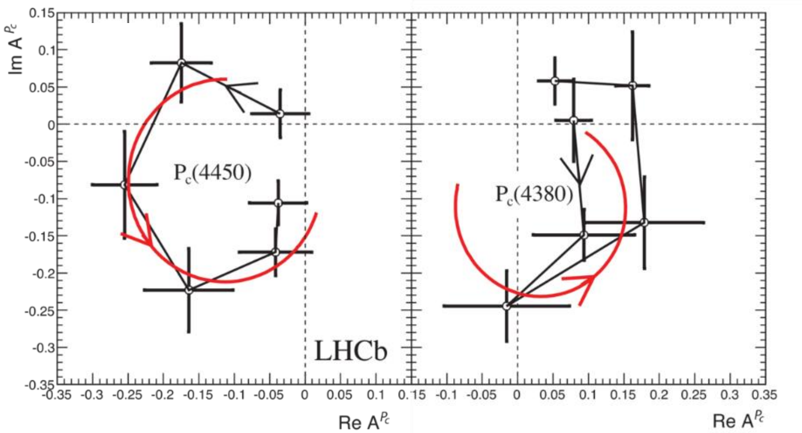
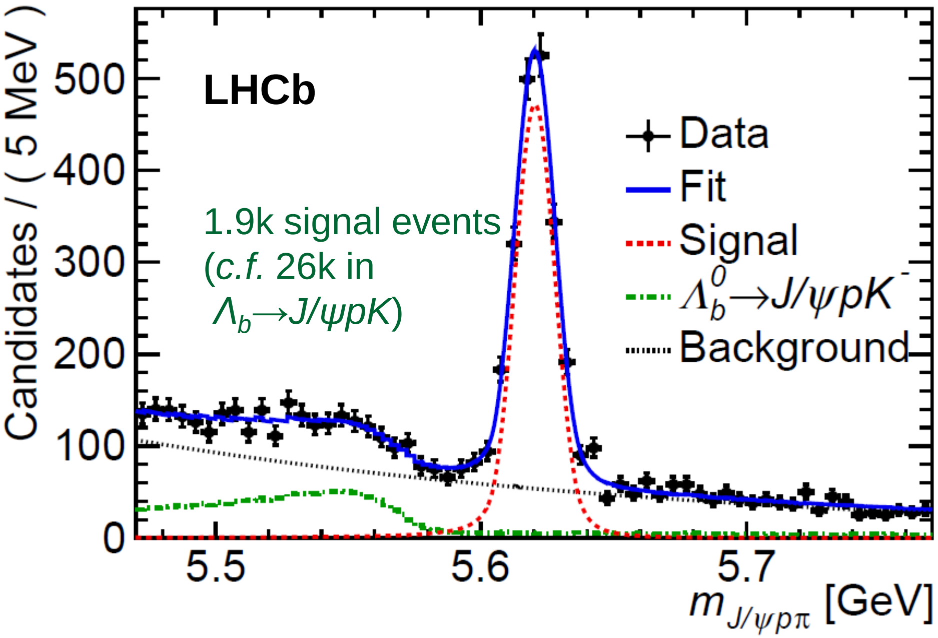
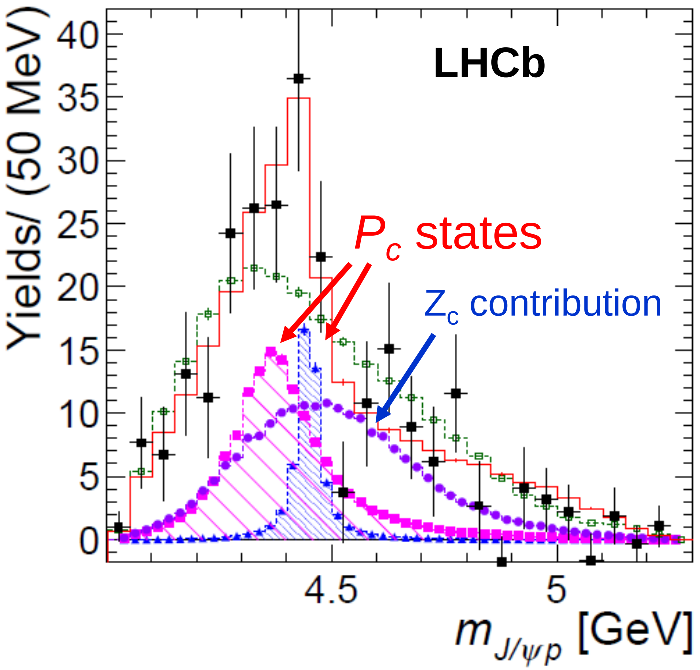


Where else to look ?

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





[PRL 117 (2016) 082002]

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

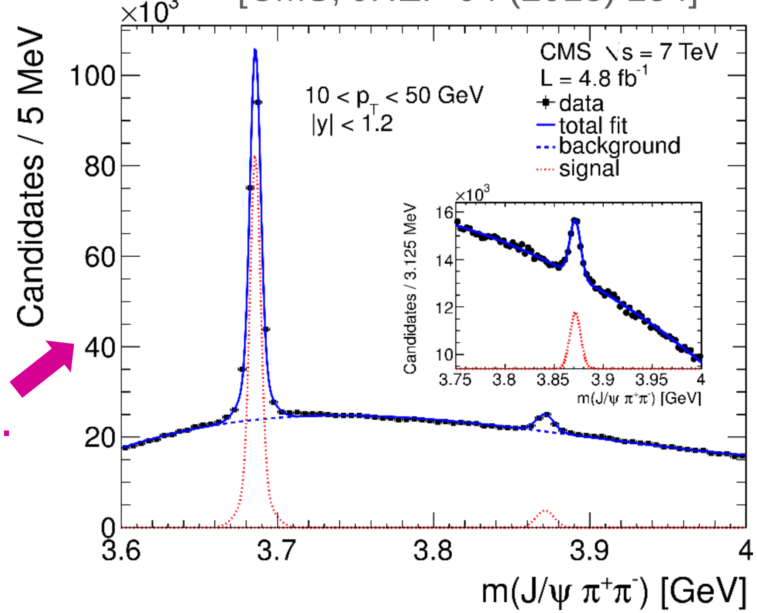
Four-quark states

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

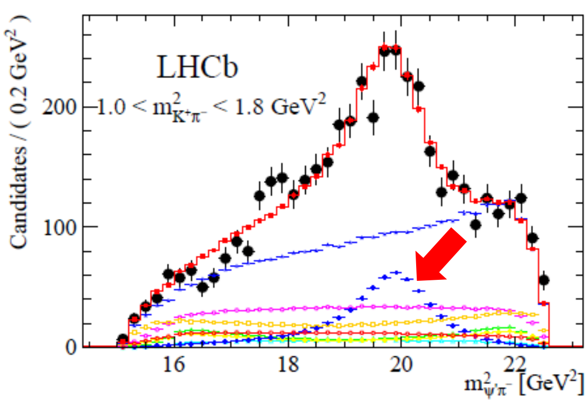
The most famous of these States, already studied extensively at the LHC, is the X(3872).

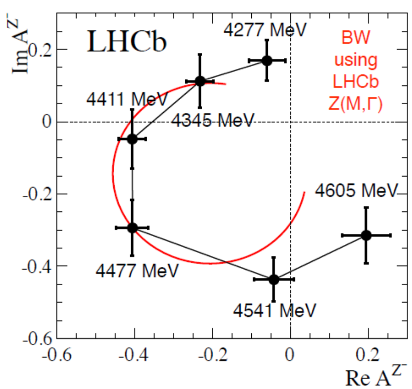
Many other examples. The first demonstration that such a state is a genuine four-quark resonance came with the $Z(4430)^-$ and LHCb.

[CMS, JHEP 04 (2013) 154]



[PRL 112 (2014) 222002]





Invariant mass

amplitude variation across signal

The argument goes like this:

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

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

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

Some coverage of the Z(4430) analysis

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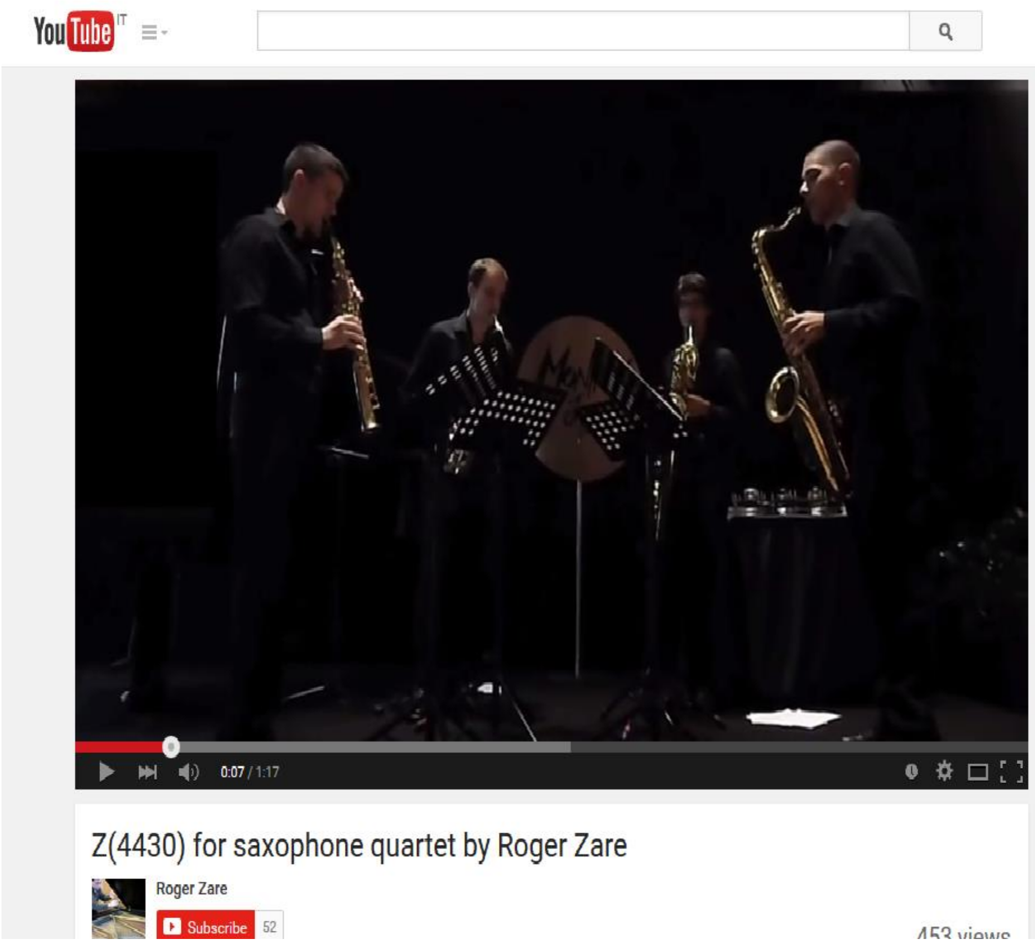
Some coverage of the Z(4430) analysis



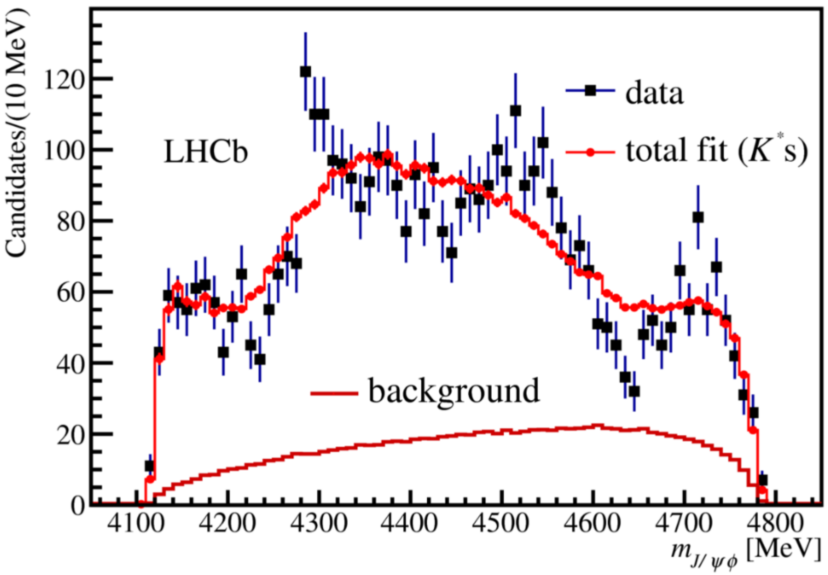
Montreux jazz festival, 2014

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

[arXiv:1606.07895; arXiv:1606.07898]

Long standing interest in $J/\psi\Phi$ spectrum in $B^+ \to J/\psi\Phi K^+$, where CDF saw a narrow structure [PRL 102 (2009) 242002] dubbed the $X(4140)$. Confirmed by D0 [PRD 89 (2014) 012004] & CMS [PRL B 734 (2014) 261] , but not by LHCb in early 0.37 fb^{-1} analysis [PRD 85 (2012) 091103(R)].

Time to revisit with full LHCb run-1 data set, & complete amplitude model machinery.

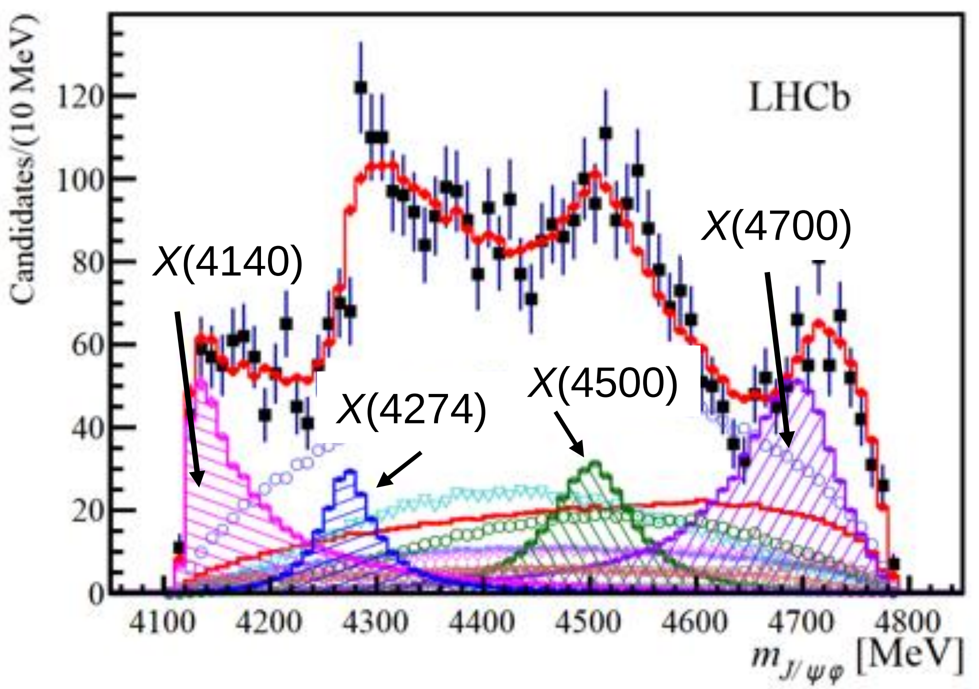


Spectrum in undeniably lumpy, most obviously *above* the $X(4140)$ region (CMS & D0 had also seen evidence of structure ~4300 MeV)

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

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

[arXiv:1606.07895; arXiv:1606.07898]



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

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

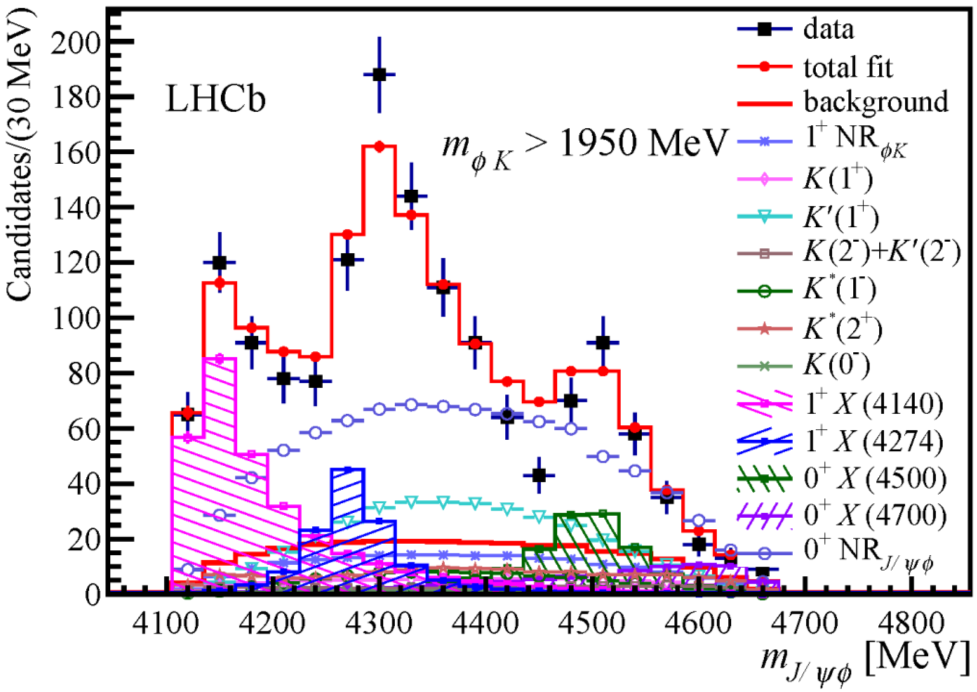
This structure can also be described by a below threshold $D_sD_s^*$ cusp.

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

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

[arXiv:1606.07895; arXiv:1606.07898]

Looking in a specific ΦK mass window



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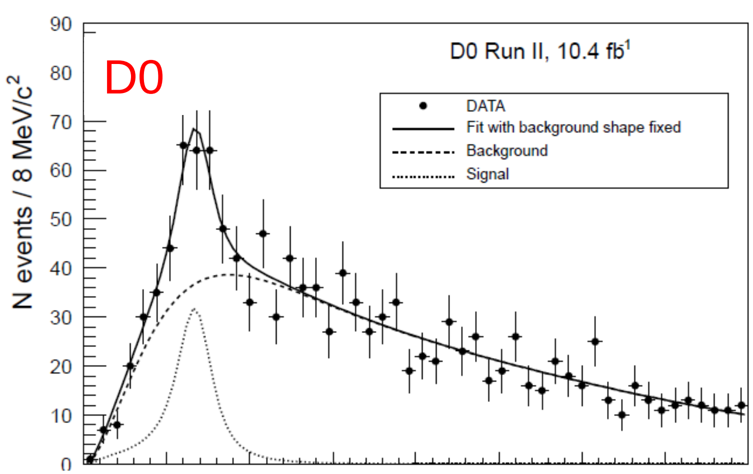
The other two structures are best described by 0^{++} resonances.

New puzzles

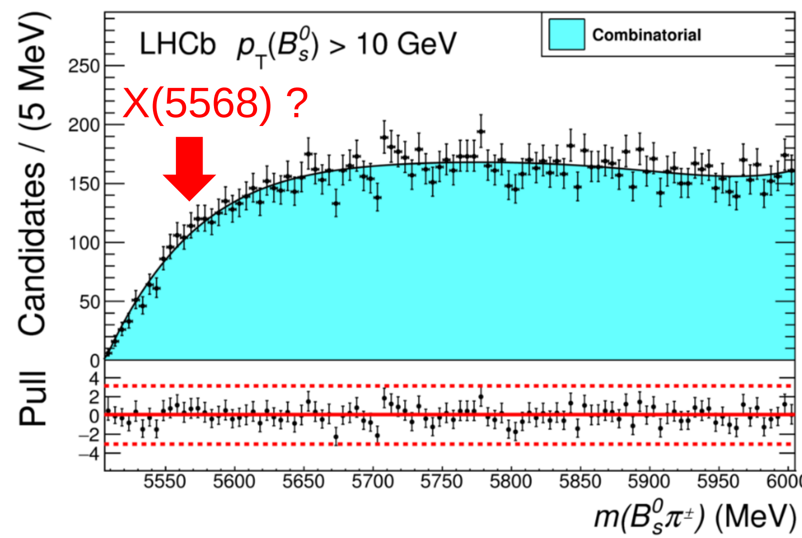
One year ago the D0 collaboration announced the sighting of a $B_s\pi$ resonance which would be interpreted as a tetraquark.

LHCb responded quickly, exploiting fast analysis chain, >20x larger data set, PID, more precise vertexing *etc*.

[PRL 117 (2016) 022003]



B_s reconstructed in J/ψφ



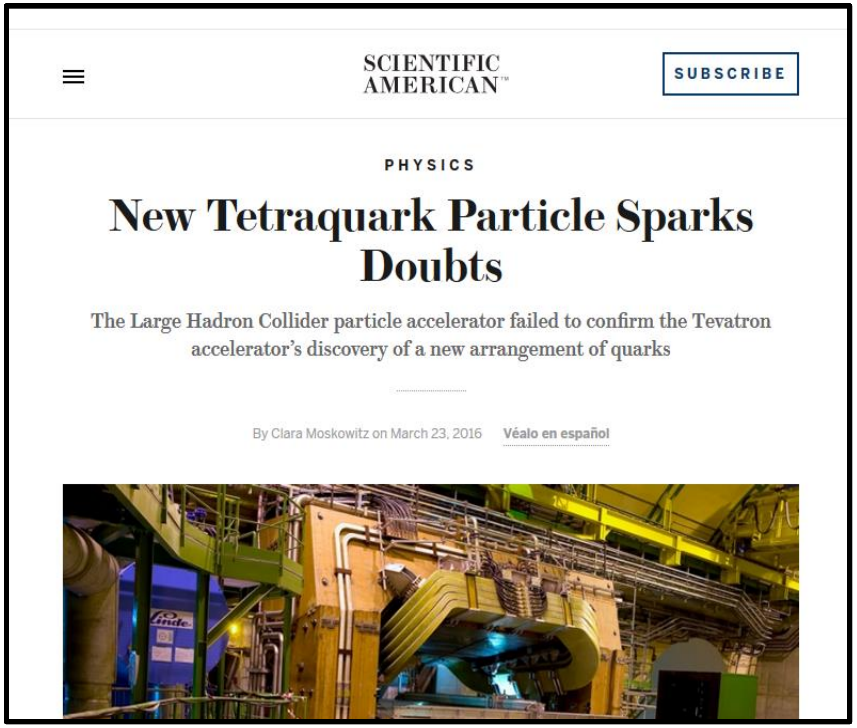
[PRL 117 (2016) 152003]

Production rate w.r.t. B_s mesons $\rho_X^{\mathrm{D0}} = (8.6 \pm 1.9 \pm 1.4)\,\%$

$$\rho_X^{\mathrm{LHCb}}(p_{\mathrm{T}}(B_s^0) > 5\,\mathrm{GeV}) < 0.011\ (0.012)\,,$$
$$\rho_X^{\mathrm{LHCb}}(p_{\mathrm{T}}(B_s^0) > 10\,\mathrm{GeV}) < 0.021\ (0.024)\,,$$
$$\rho_X^{\mathrm{LHCb}}(p_{\mathrm{T}}(B_s^0) > 15\,\mathrm{GeV}) < 0.018\ (0.020)\,.$$

90 % (95 %) C.L.

New puzzles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New Tetraquark Particle Sparks Doubts

The Large Hadron Collider particle accelerator failed to confirm the Tevatron accelerator's discovery of a new arrangement of quarks

By Clara Moskowitz on March 23, 2016 Véalo en español

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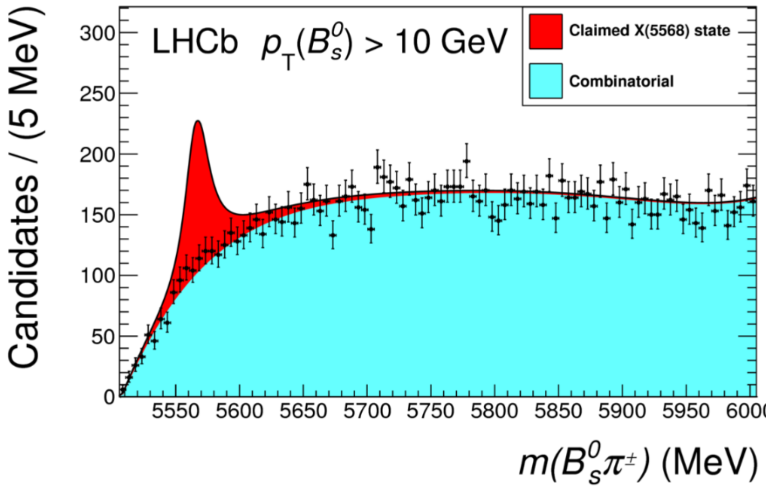
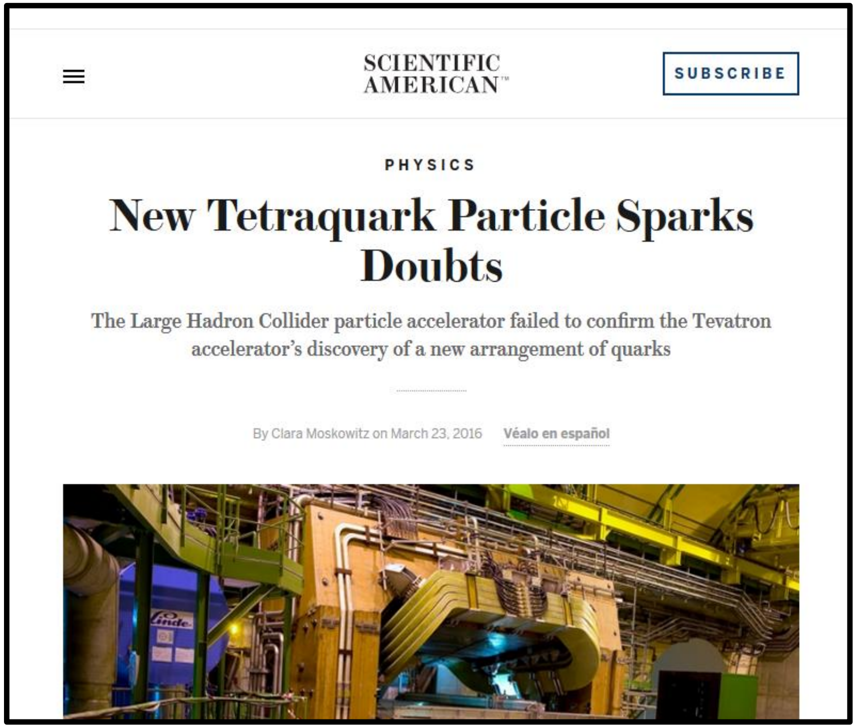


[PRL 117 (2016) 152003]

What should have been seen.

New puzzles



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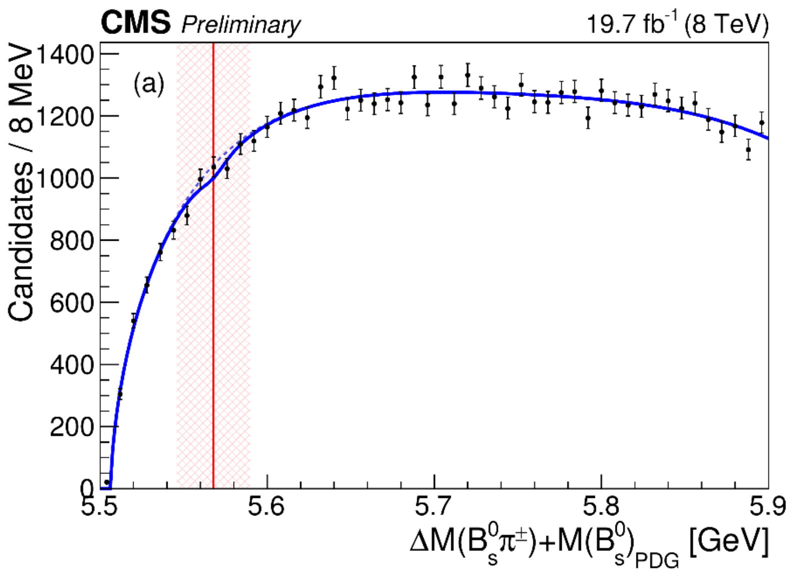
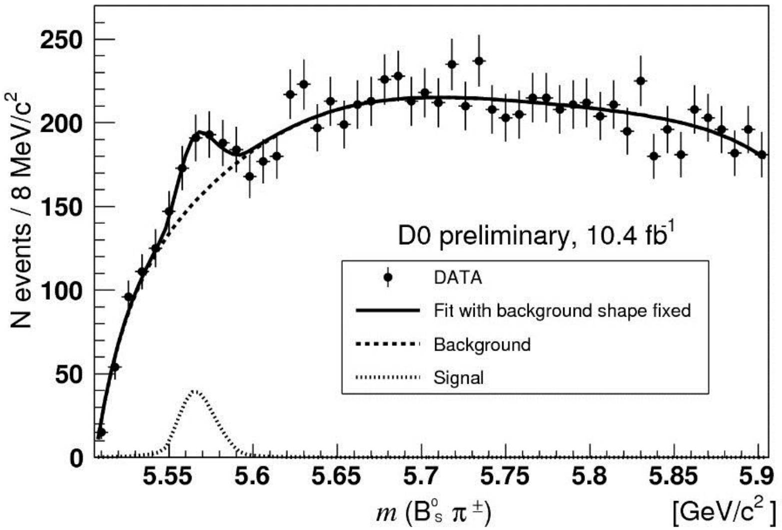


[CMS, BPH-PAS-16-002]

$\rho_X < 3.9\%$ @ 95% C.L.

New puzzles

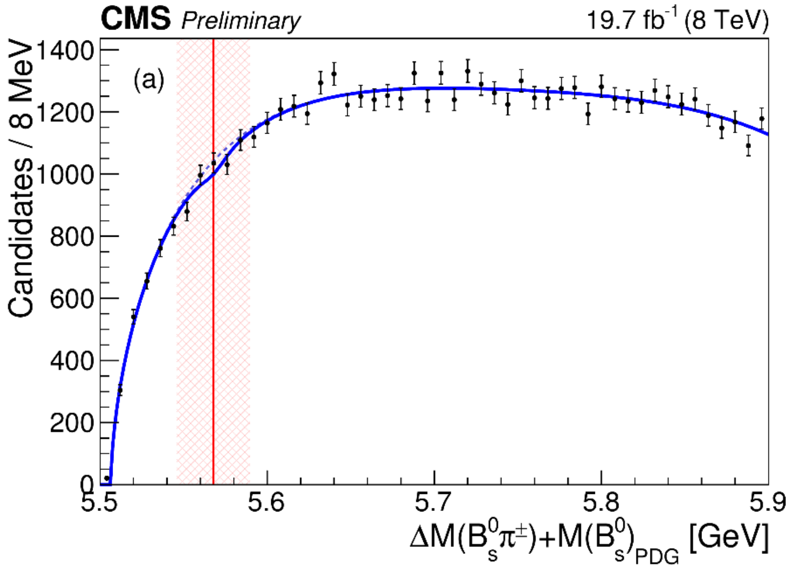
Just last month D0 updated their analysis to include Bs candidates from semileptonic decays…



[D0 conference note 6496]

…they see something there also. Curiouser and curiouser !

CMS have now joined the hunt, and have also found no signal…



[CMS, BPH-PAS-16-002]

$\rho_X < 3.9\%$ @ 95% C.L.

Selected physics topics

- Spectroscopy and hadron exotics
- CPV & unitarity triangle tests
- Charm physics
- Rare decays, FCNCs and R_{K^*}

Constraining the unitarity triangle

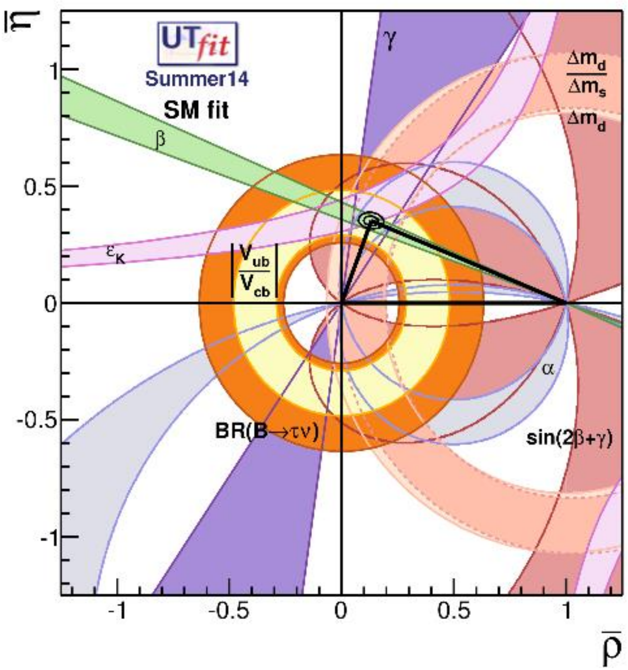
- the angle γ
- sin 2β
- V_{ub}

The Unitarity Triangle

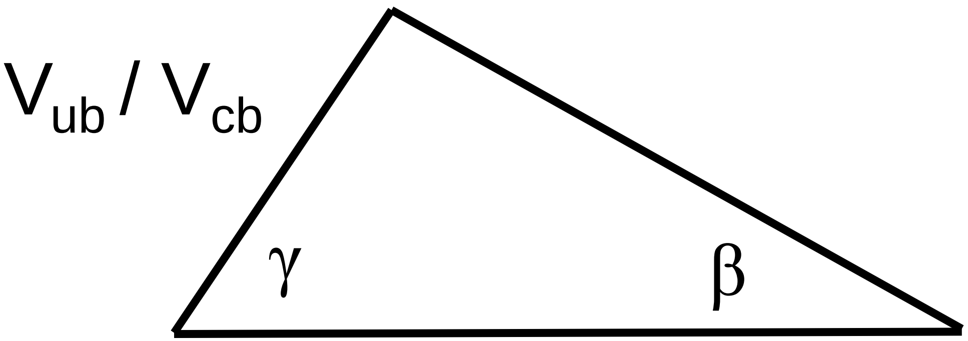
The Unitarity Triangle is a geometrical description of *CP*-violation within the context of the Standard Model, which in the flavour sector is the CKM mechanism.

We must check its consistency through precise measurements.

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

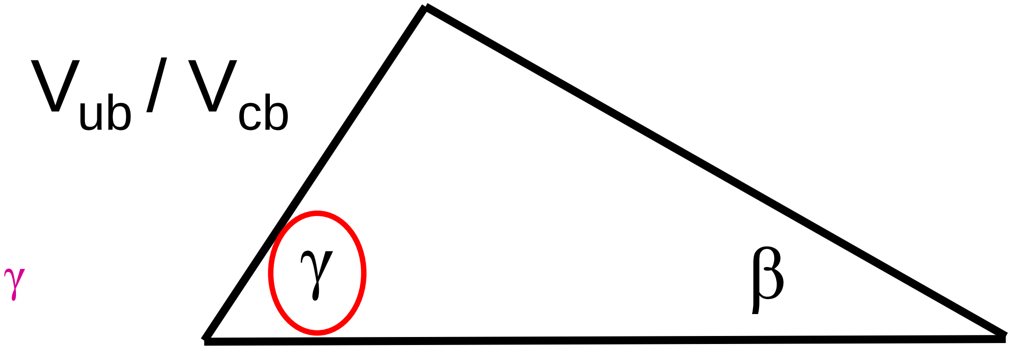


Let's see how the LHC is advancing this programme…



…through three key measurements.

The Unitarity Triangle: γ



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

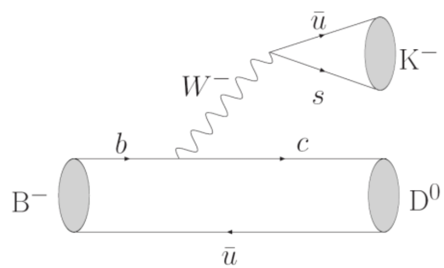
Look in $B^{\pm} \to DK^{\pm}$ decay<u>s</u> using common mode for D^0 & $\bar{D}^0$

$\to \gamma$ sensitive interference

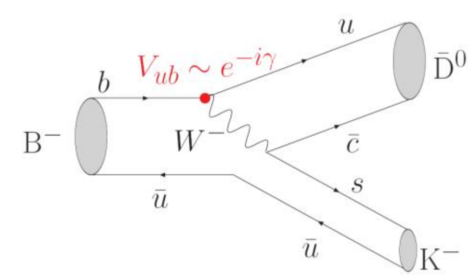
$\to$ different rates for B^+ & B^- (CPV!)

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

Favoured



Suppressed

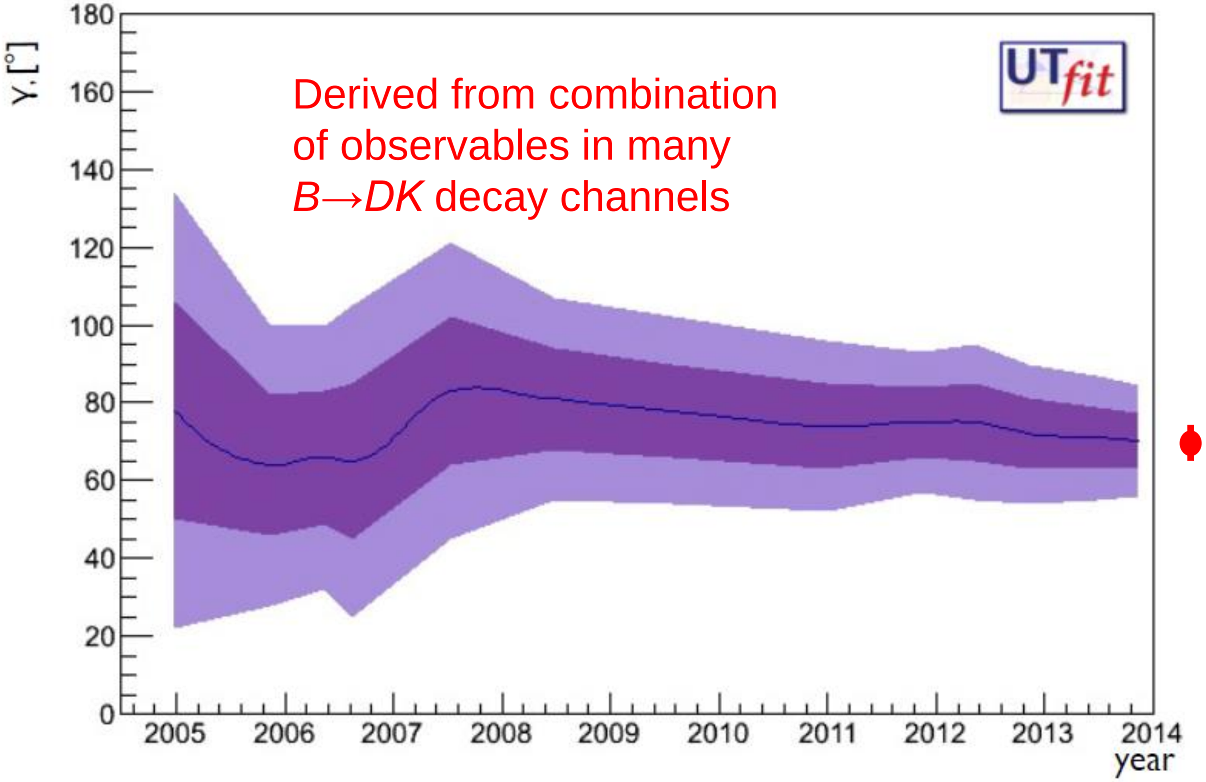


Tree-level decays: strategy very clean & yields result unpolluted by New Physics

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

γ measurement – the last ~10 years

The story so far...



Derived from combination of observables in many *B→DK* decay channels

Consistent with the indirect prediction...

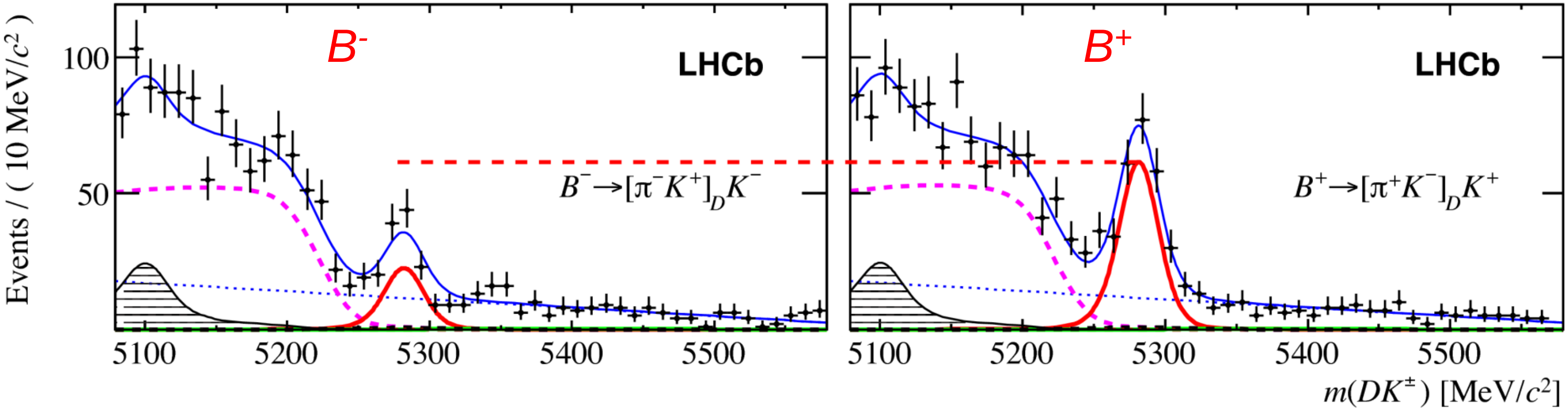
...but not nearly as precise

Indirect prediction from rest of triangle

...factor 3 improvement in 10 years.

γ measurement: true precision needs statistical muscle of LHCb

Rare, important decays just beyond the reach of the B-factories (*e.g.* the suppressed 'ADS' $B^{\pm} \rightarrow (K^{\mp}\pi^{\pm})_D K^{\pm}$ mode (BR ~ 10^{-7}) was soon seen at LHCb and is now being exploited for high-precision CP-violation measurements.



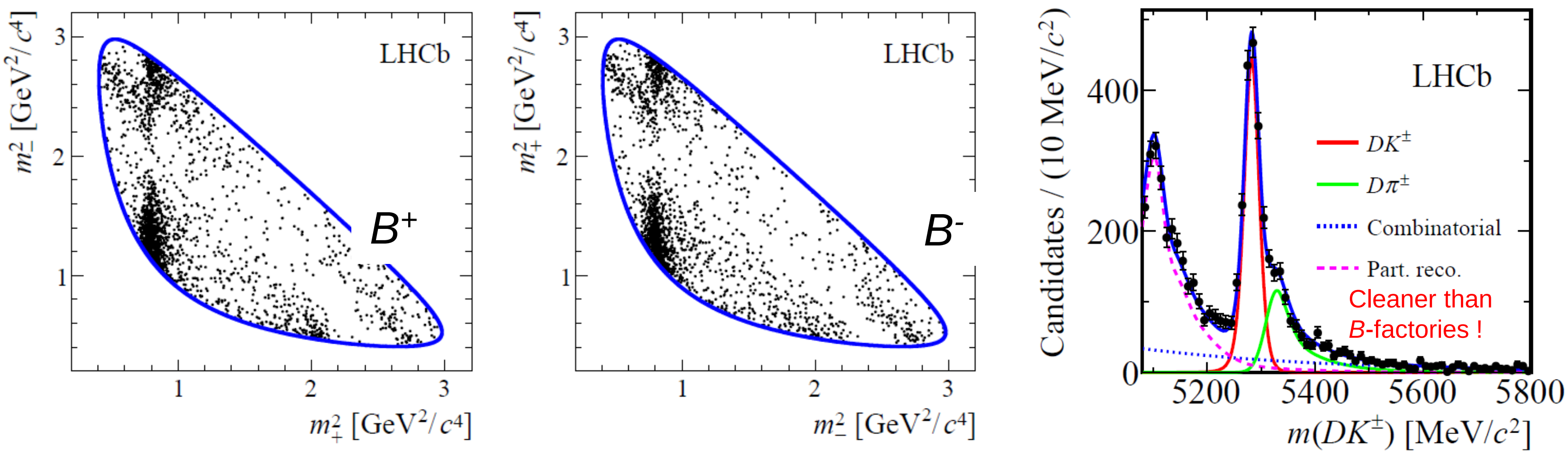
[PLB 760 (2016) 117]

This CP asymmetry carries ultra-clean, easy to interpret, information on γ !

Measurement of γ: $B \to DK$ at LHCb

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

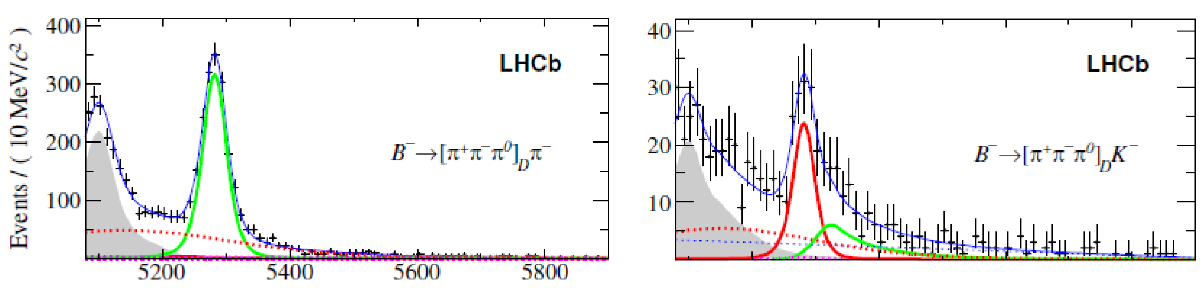
[JHEP 10 (2014) 097]



This cleanliness thanks to:

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

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



[PRD 91 (2015) 112014]

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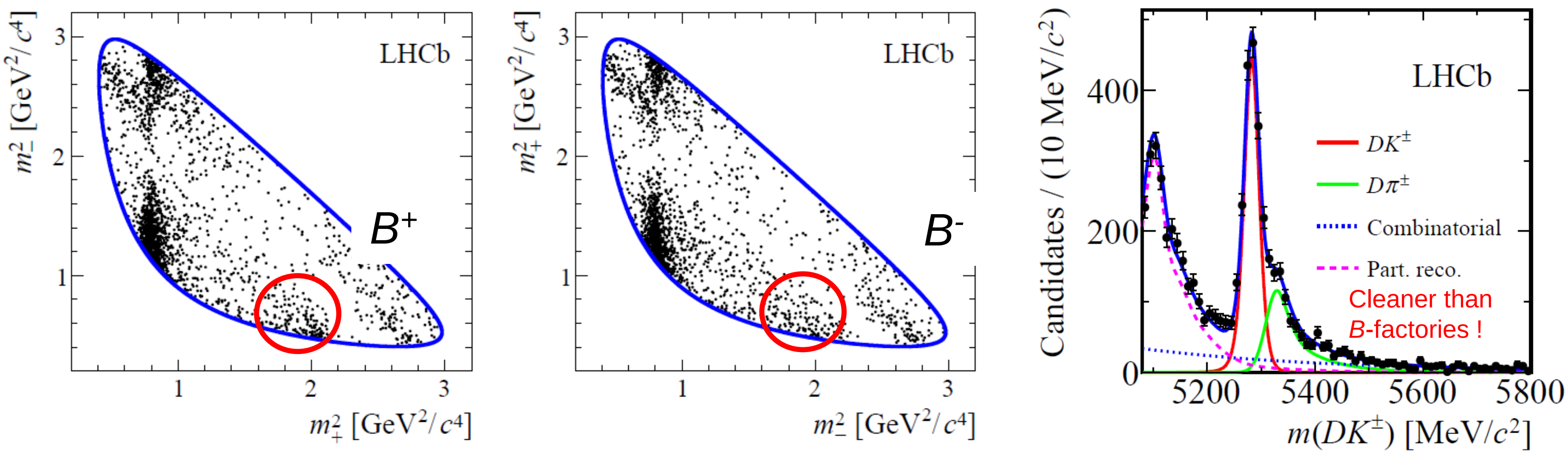

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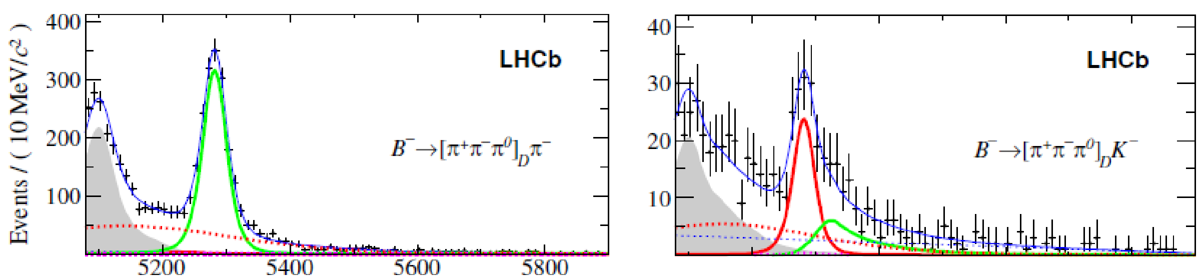
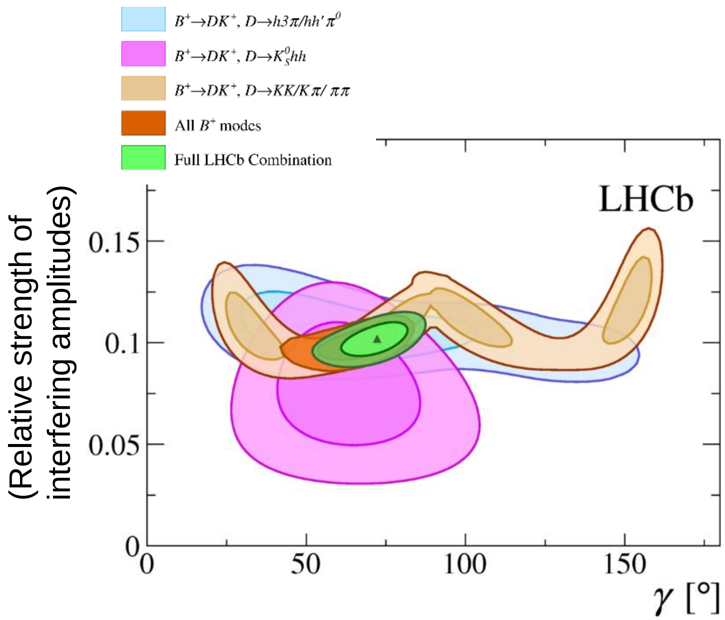


[PRD 91 (2015) 112014]

LHCb: current precision on γ and future prospects

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

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



[JHEP 12 (2016) 087]

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

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

Will improve steadily:

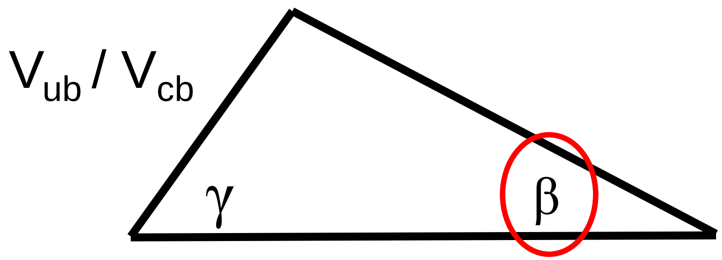
- still several important run 1 modes to be published (*e.g.* 3 fb^{-1} $B_s \to D_s K$)
- repeat with much larger data set anticipated in run 2.

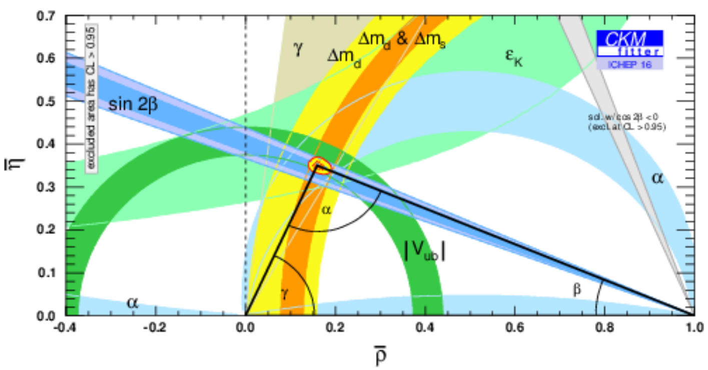
Aim for ~ 3-4° uncertainty after run 2 to match current indirect precision.
The LHCb Upgrade (see later) will allow for even higher sensitivity (~1°).

* CKMfitter, summer 2016

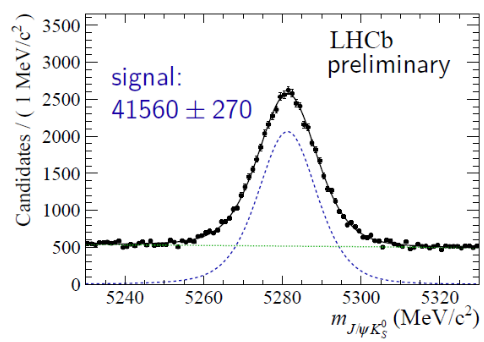
The Unitarity Triangle: sin2β

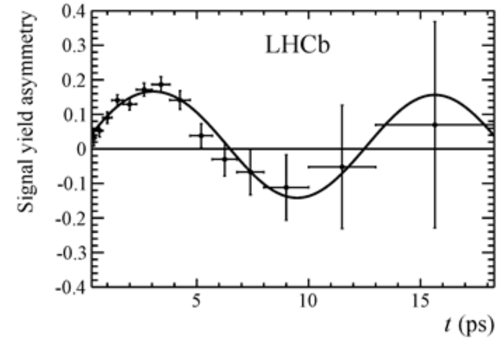
Measurement on β was the legacy of the *B*-factories, and helped pave way for 2008 Nobel Prize for Kobyashi and Maskawa. Now LHCb has entered the game !





This measurement requires time-dependent measurement & flavour tagging, which is trickier at a hadron collider than at an e^+e^- machine.





[PRL 115 (2015) 031601]

sin2β_{eff} = $0.731 \pm 0.035\,(\text{stat}) \pm 0.020\,(\text{syst})$

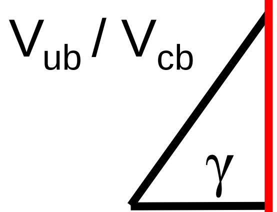
(BaBar stat error = 0.036, Belle stat error = 0.029)

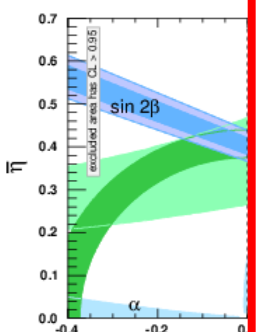
Precision obtained by LHCb with $B^0 \rightarrow J/\Psi K_S$ is very similar to that of the *B*-factories.

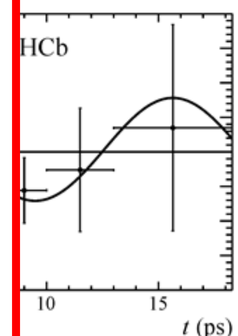
The Unitarity Triangle: sin2β

Measurem… way for
2008 Nobe… the game !

…ependent
…hich is trickier
…machine.







[PRL 115 (2015) 031601]

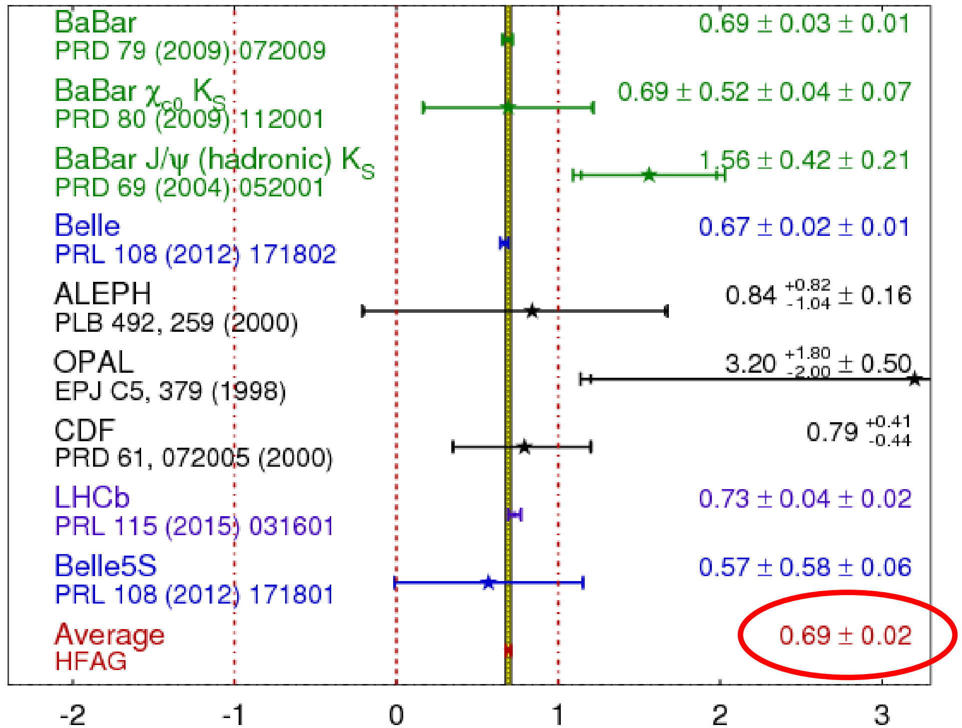
…0.020 (syst)

…error = 0.029)

Precision o… …e *B*-factories.

$\sin(2\beta) \equiv \sin(2\phi_1)$

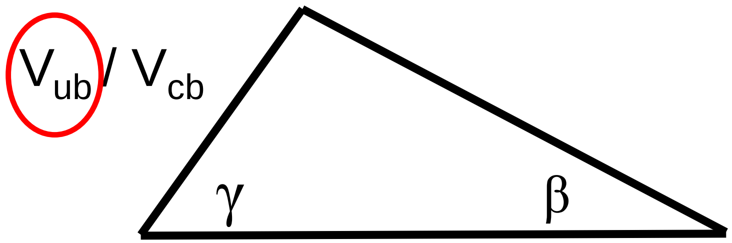
HFAG Moriond 2015 PRELIMINARY



To be compared to prediction of 0.740 $^{+0.020}_{-0.025}$ CKMfitter summer'16

Some tension. Vital to keep improving the precision of this very important parameter. A long-term goal !

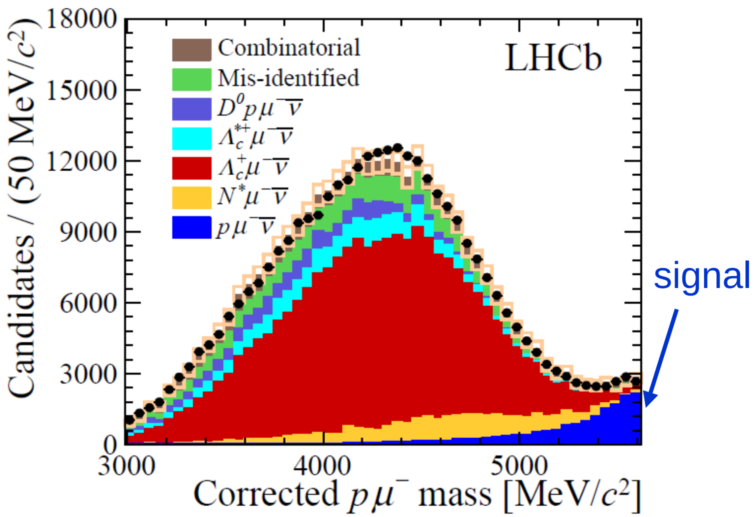
The Unitarity Triangle: V_{ub}



Measurement of V_{ub} long thought essentially impossible at LHC. Challenging to separate $b \rightarrow u\mu\nu$ and $b \rightarrow c\mu\nu$ processes without any beam energy constraint.

But it can be done!
Use baryon decay $\Lambda_b \rightarrow p\mu\nu$ and benefit from RICH & vertexing capabilities.

[Nature Phys 10 (2015) 1038]

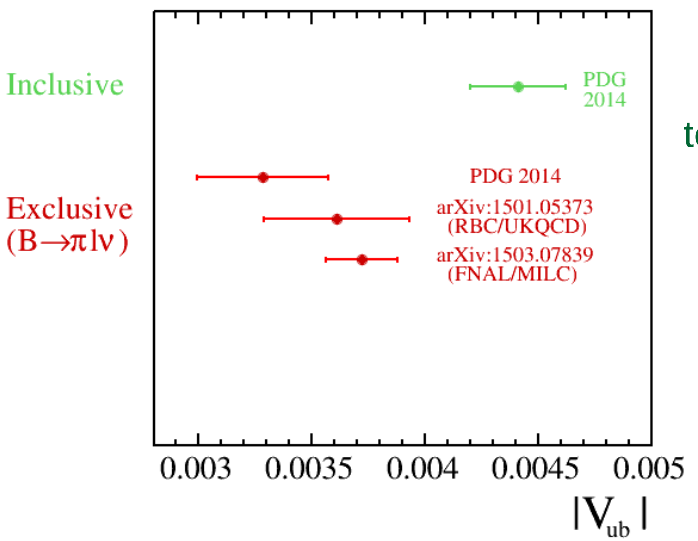


Normalise to $\Lambda_b \rightarrow \Lambda_c \mu\nu$ and use lattice QCD to interpret result.

Very precise result:

$$|V_{ub}| = (3.27 \pm 0.15 \pm 0.16 \pm 0.06) \times 10^{-3}$$

Brings new insight to long-standing 'inclusive vs exclusive' V_{ub} puzzle.



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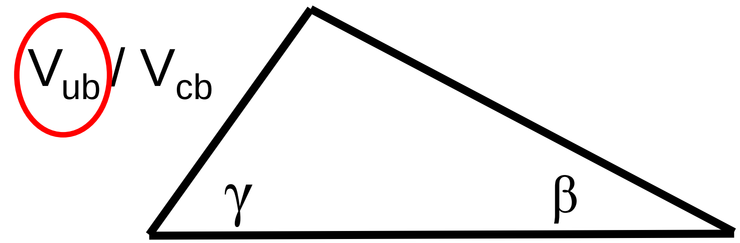

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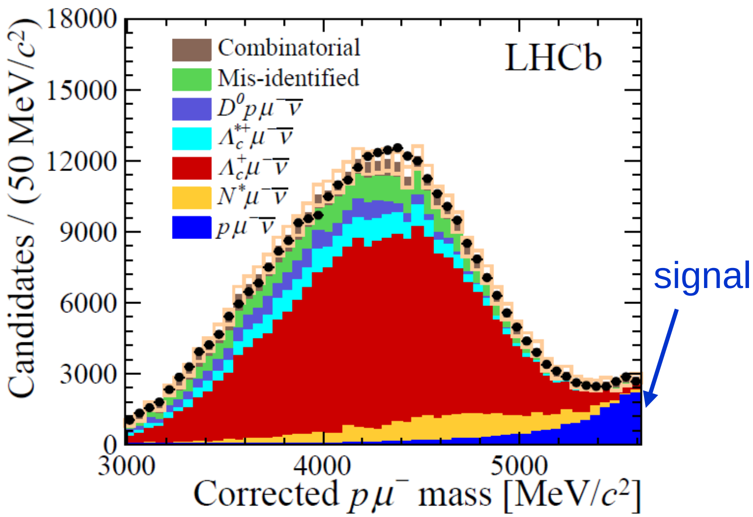

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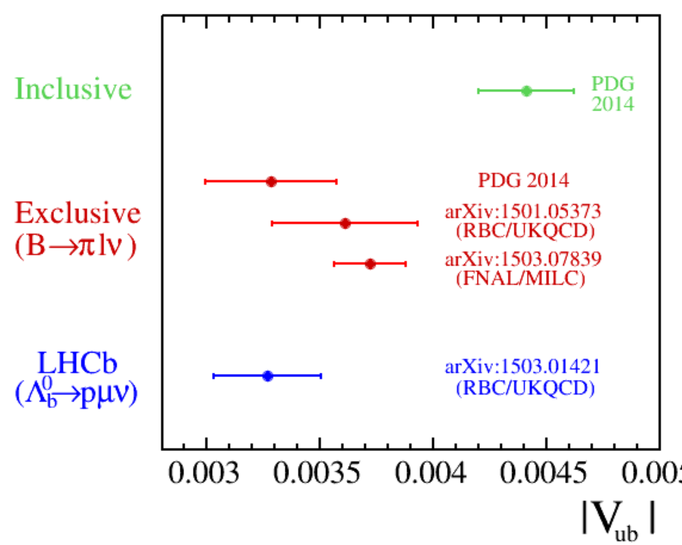
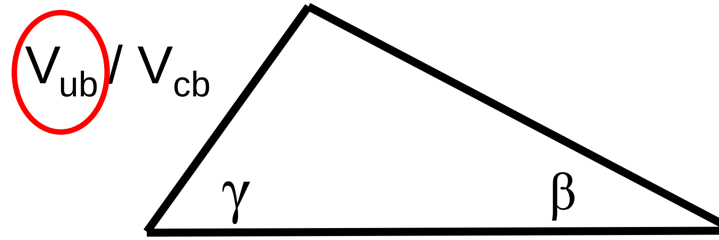


tension !

LHCb result agrees with exclusive results

The Unitarity Triangle: V_{ub}



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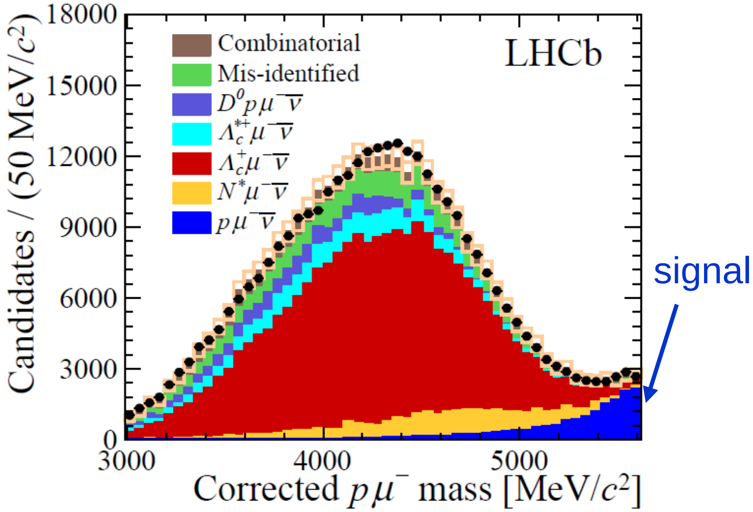

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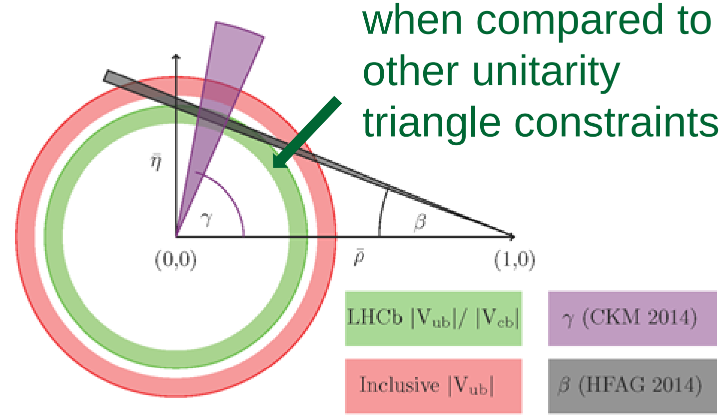
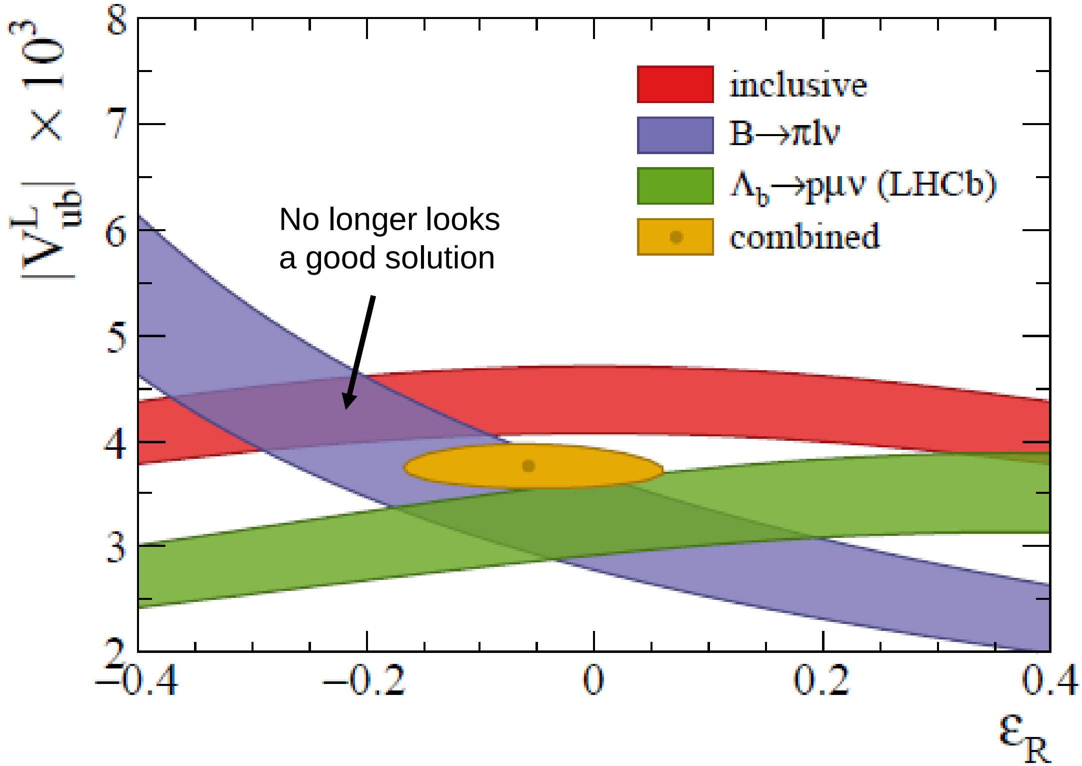
Result is suggestive when compared to other unitarity triangle constraints



LHCb V_{ub}: possible interpretations

Some commentators* have tried to explain the V_{ub} inclusive vs exclusive puzzle with help of right-handed currents,



but the different sensitivity that the baryon result affords disfavours this.

* Chen & Nam, PLB 666 (2008) 462;
Crivellin, PRD 81 (2010) 031301;
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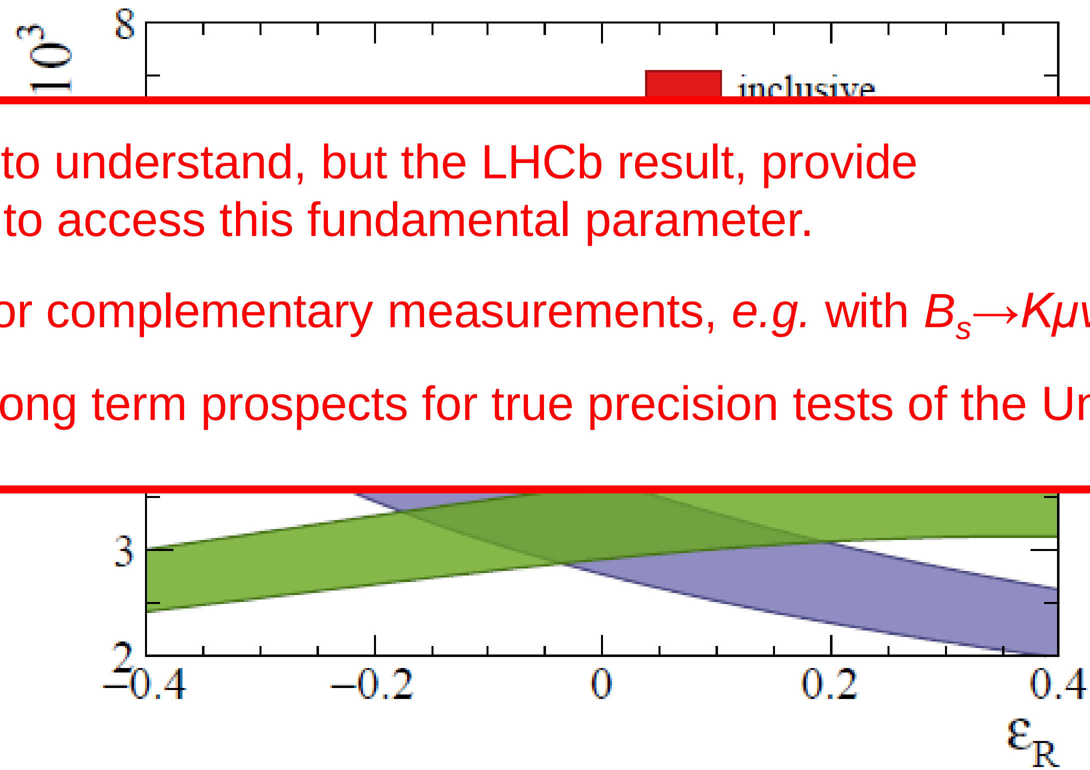

Still much to understand, but the LHCb result, provide new ways to access this fundamental parameter.

Look out for complementary measurements, *e.g.* with $B_s \to K\mu\nu$.

Excellent long term prospects for true precision tests of the Unitarity Triangle.

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Selected physics topics

- Spectroscopy and hadron exotics
- CPV & unitarity triangle tests
- Charm physics
- Rare decays, FCNCs and R_{K^*}

Setting the scene

Selected topics:

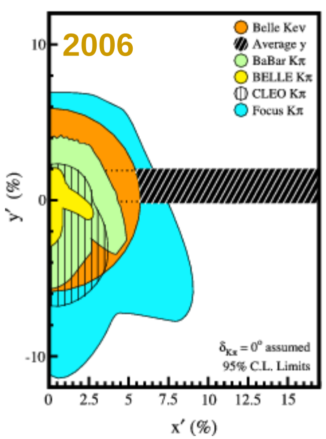
- Direct CPV
- Indirect CPV

The charm renaissance

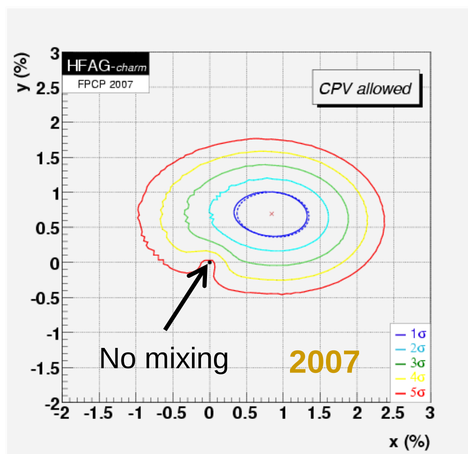
For many years charm was the ‘Cinderella’ of flavour physics studies

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

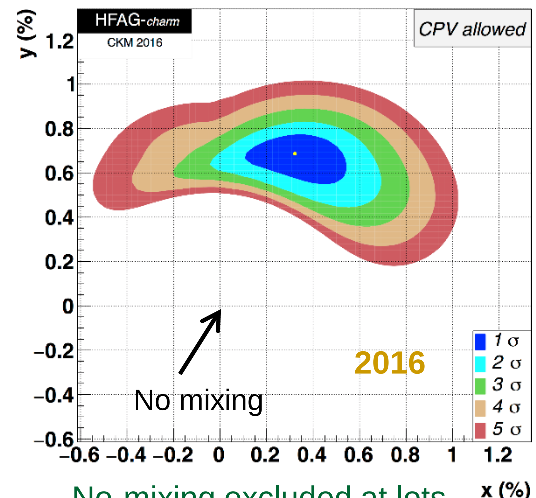
Excluded regions



“All results are null.”
Ian Shipsey, Charm 2006.



Measurement contours;
no-mixing excluded at 5σ



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

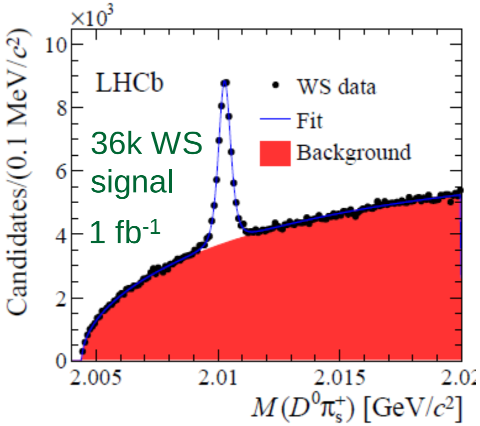
Then combination of B-factory analyses finally saw mixing. New outlook !

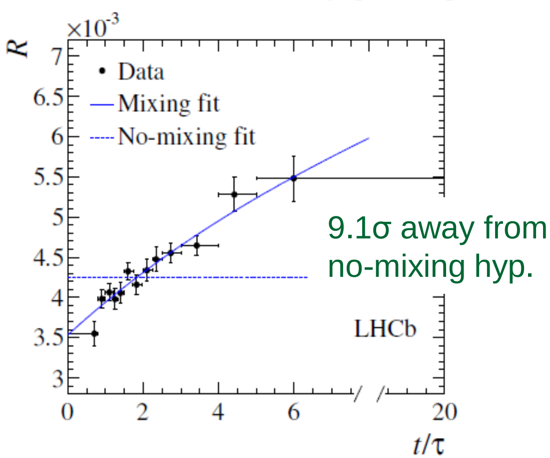
→ mixing parameters not tiny (~1%); good news for (indirect) CPV observables
→ smallness of SM ‘pollution’ not a bad thing in looking for New Physics signal
→ internal down-type quarks in loops – complementary to *b*-physics
→ huge potential of LHC for improving sensitivity

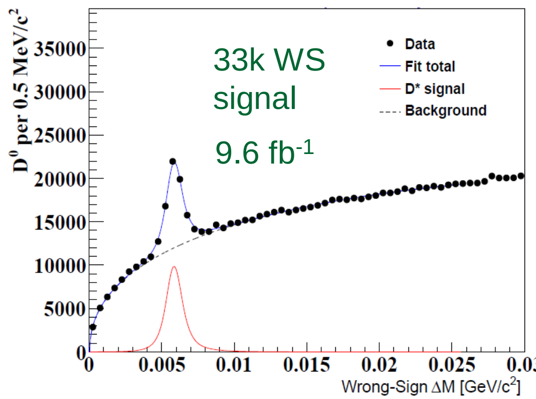
Rise of the hadron machines

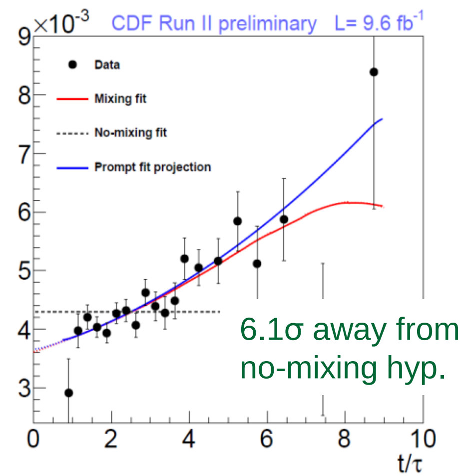
Power of hadron colliders is now clear. In 2013 LHCb and CDF published first individual (>)>5σ measurements, in WS *Kπ* analyses.

LHCb, PRL 110 (2013) 101802









CDF, PRL 111 (2013) 231802

Although e^+e^- machines retain advantages for many modes with neutrals, LHC has huge advantages for charged modes (*e.g.* # WS *Kπ* in Run 1 at LHCb = 230 x 10^3 ; at Belle in 0.9 ab^{-1} = 12 x 10^3) and also time resolution.

Searching for direct CPV in SCS charm decays

CPV not yet observed in the charm system. Two categories of searches:

- Direct CPV – with charged hadrons or time-integrated D^0 studies
- Indirect CPV – requires time-dependent D^0 studies

Best hope of seeing direct CPV is with singly Cabibbo suppressed decays, as here there is hope of interference between diagrams.

Precision that is being attained at LHCb with run-1 data is now at 10^{-3} level:

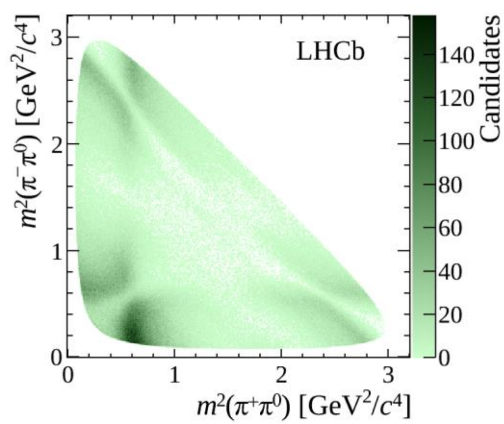
$$\Delta A_{CP} = A_{CP}(K^-K^+) - A_{CP}(\pi^-\pi^+) = (+0.14 \pm 0.16\,(\mathrm{stat}) \pm 0.08\,(\mathrm{syst}))\%$$

[JHEP 07 (2014) 041]

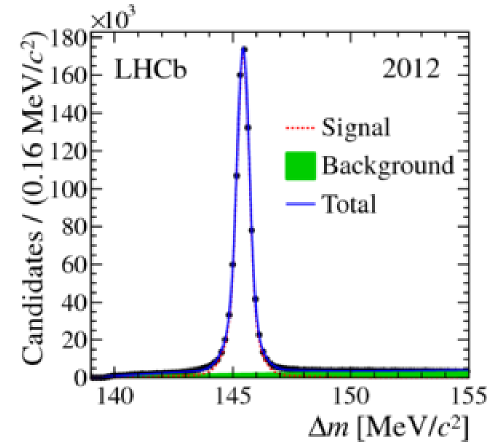
We are entering the regime where there is a real hope to see effect !

Even more interesting is to probe
The phase space of multibody modes
e.g. $D^0 \to \pi\pi\pi^0$ with 'energy test' technique [PLB 740 (2015) 158].

In some such studies interesting hints are emerging *e.g.* 2.7σ tension with SM in $D^0 \to \pi\pi\pi\pi$ [PLB 769 (2017) 345].



$D^0 \to \pi\pi\pi^0$
Dalitz space

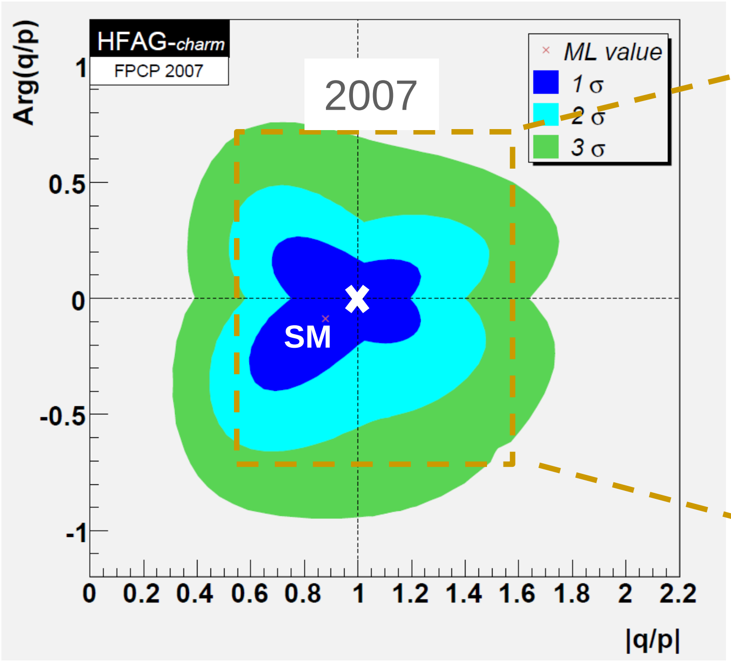


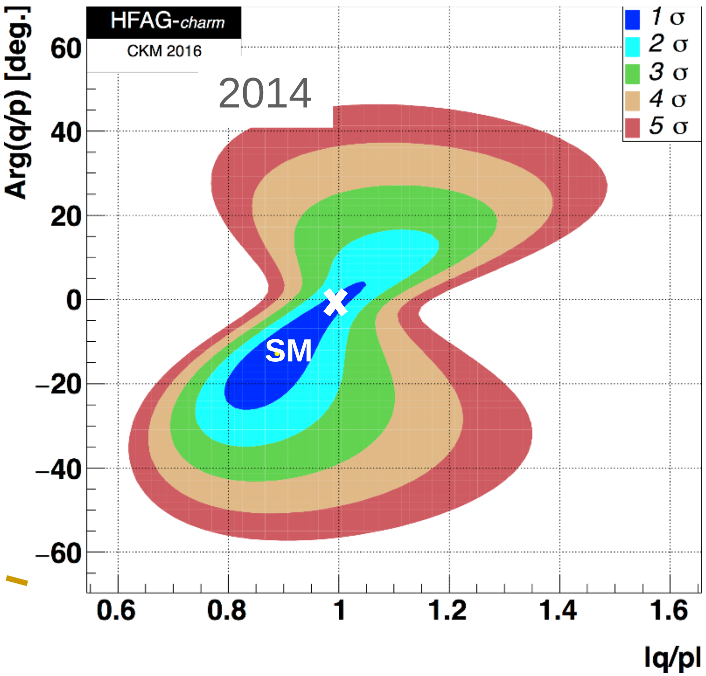
$D^0 \to \pi\pi\pi\pi$
signal

CPV searches in mixing (*i.e.* indirect CPV)

More important is to search for CPV in mixing related phenomena. Observables are pre-multiplied by x,y, so 'large' (~1%) value of mixing is encouraging in this quest.

Already plenty of progress in last few years…



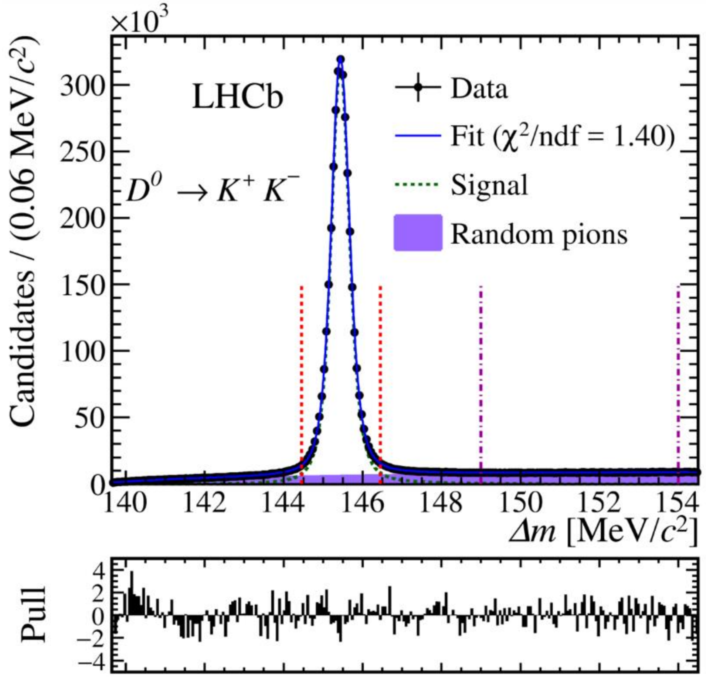


…any non-zero signal with current and near-future precision would indicate NP.

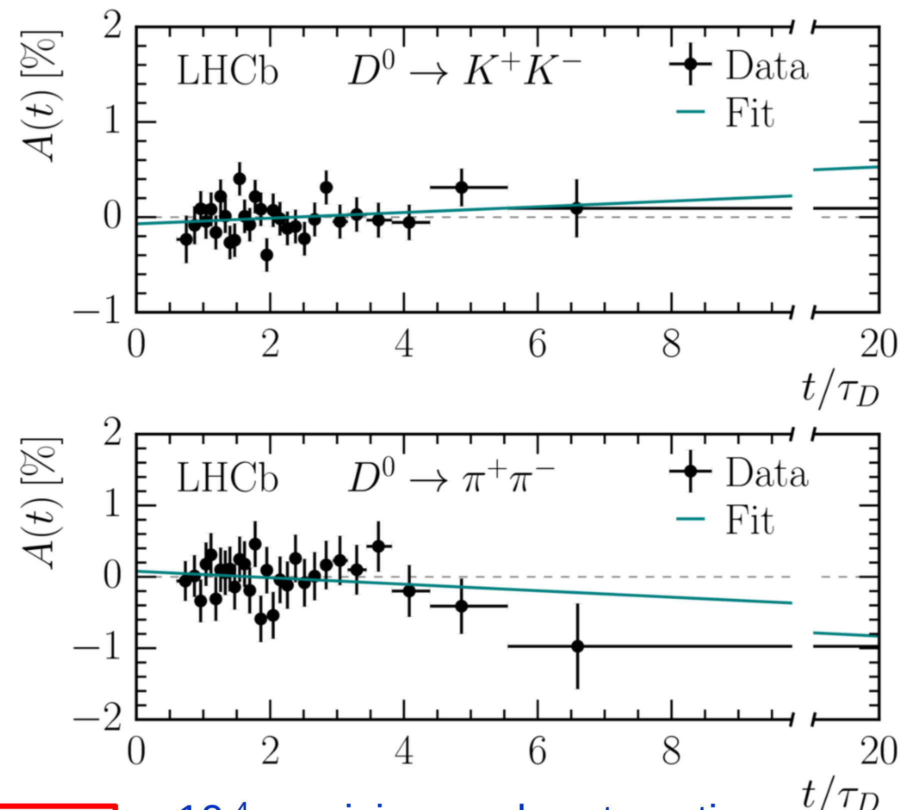
CPV searches in mixing (*i.e.* indirect CPV)

Many observables to probe. For example, look for time-dependent CP asymmetry, expressed in A_Γ parameter, in decay to *CP* eigenstate, such as $D^0 \to KK$ or $\pi\pi$.

Massive, clean & well-understood data sets.



No slope, so no CP violation (yet)



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

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

Selected physics topics

- Spectroscopy and hadron exotics

- CPV & unitarity triangle tests

- Charm physics

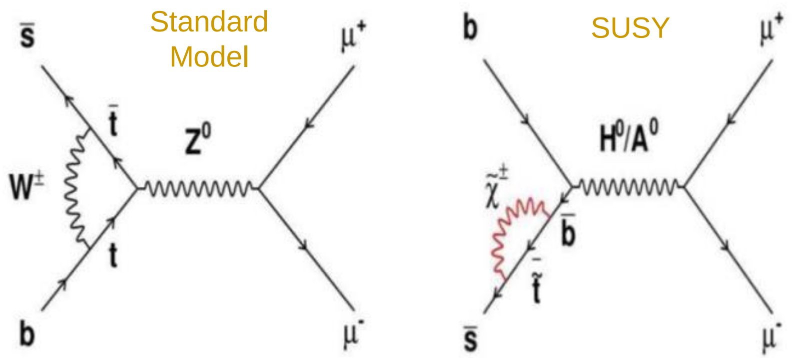
- Rare decays, FCNCs and R_{K^*}

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

FCNCs: the search for $B_s \to \mu\mu$

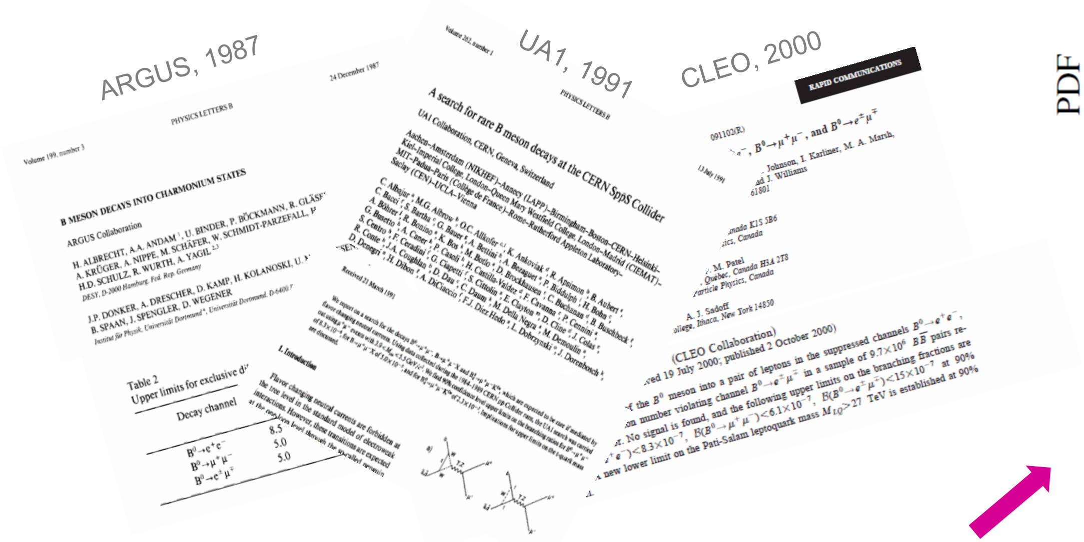
This decay mode can only proceed through suppressed loop diagrams.

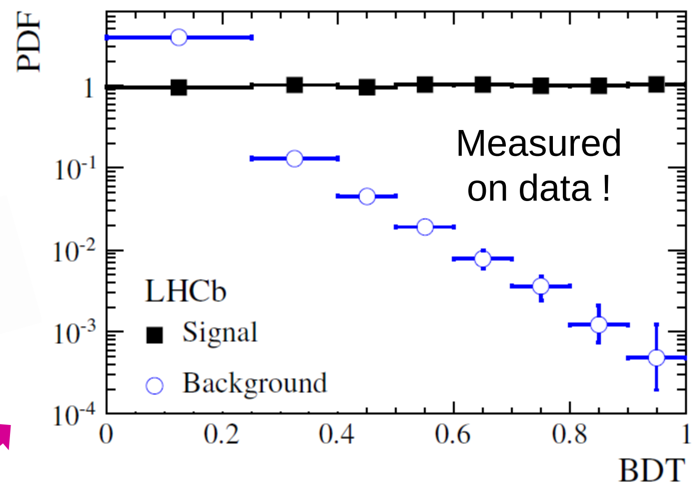
In the Standard Model it happens extremely rarely (~10^{-9}), but the exact rate is very well predicted



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

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

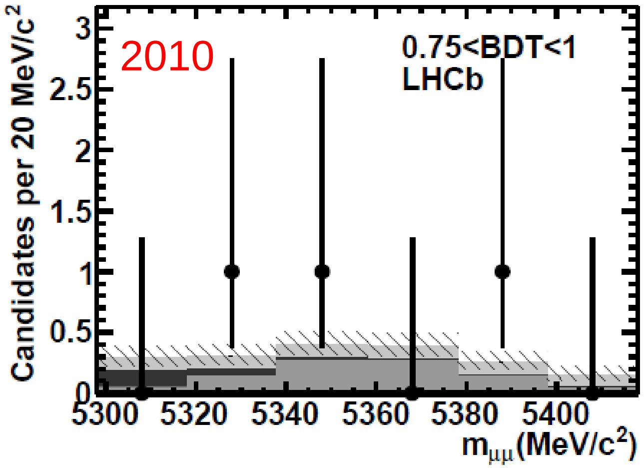




[PRL 111 (2013) 101805]

Since 2010 LHCb has been using, and refining, a multivariate (BDT) approach.

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

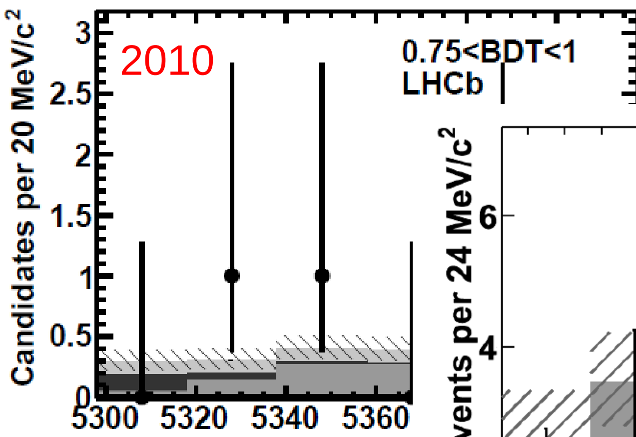


[PLB 708 (2012) 55]

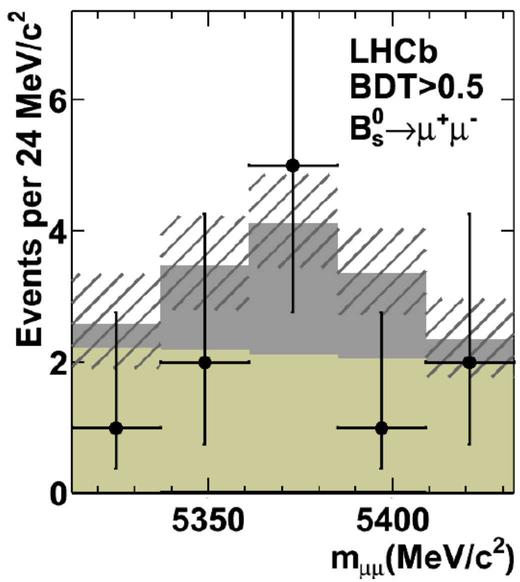
Plot of invariant mass distribution in region of high BDT sensitivity – if there is a signal we should see a peak here (but the BDT uses much more information than the invariant mass alone !)

2010
Nothing

$B_s \rightarrow \mu\mu$ - 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 BDT uses much more information than the invariant mass alone !)

+ 2011

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

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

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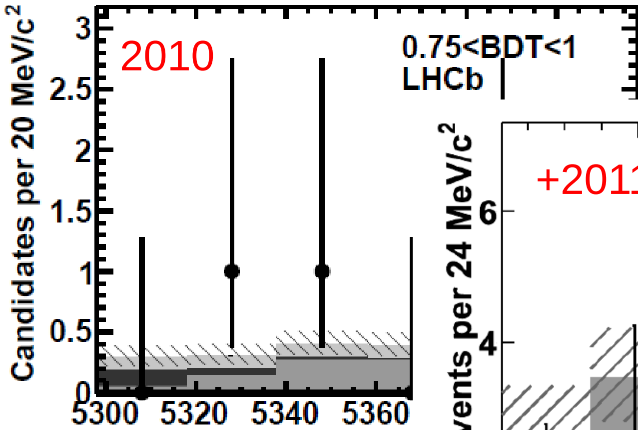

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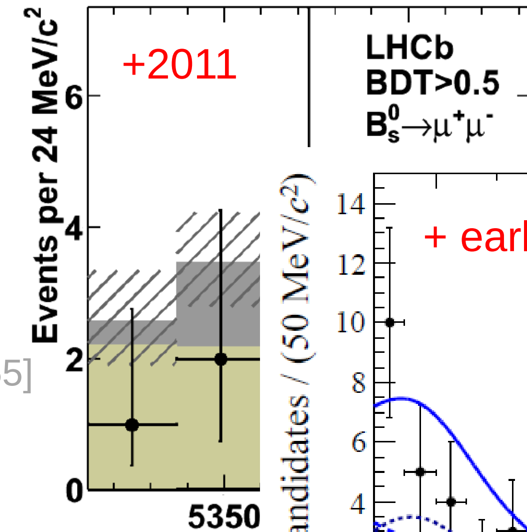
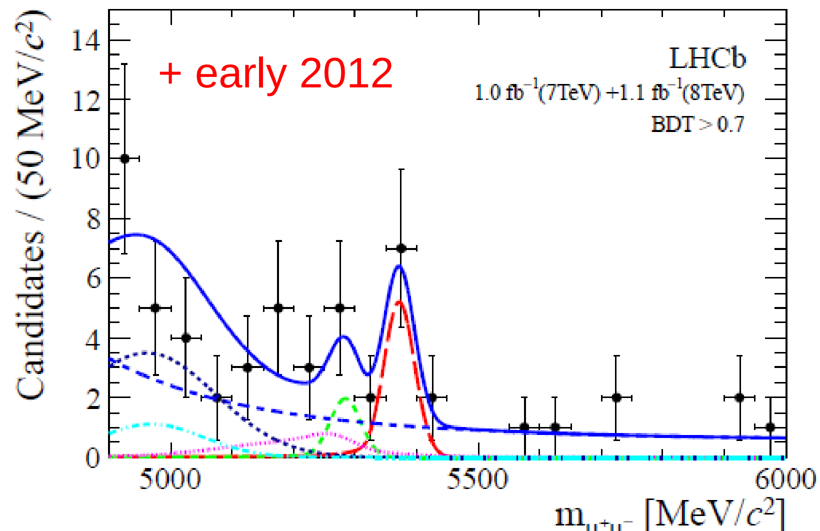


[PRL 108



[PRL 110 (2013) 021801]

+ early 2012

First evidence that there is something there !

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

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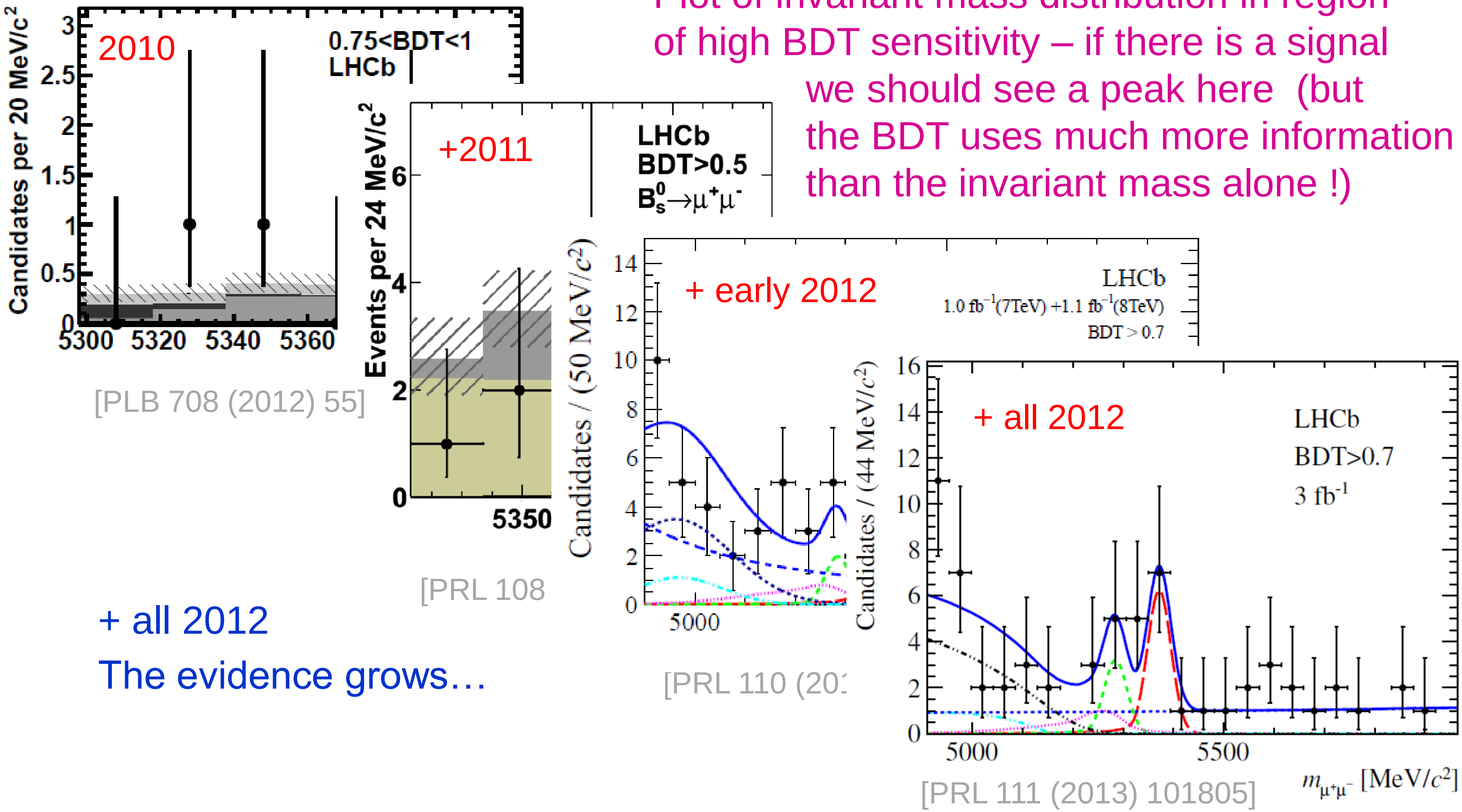
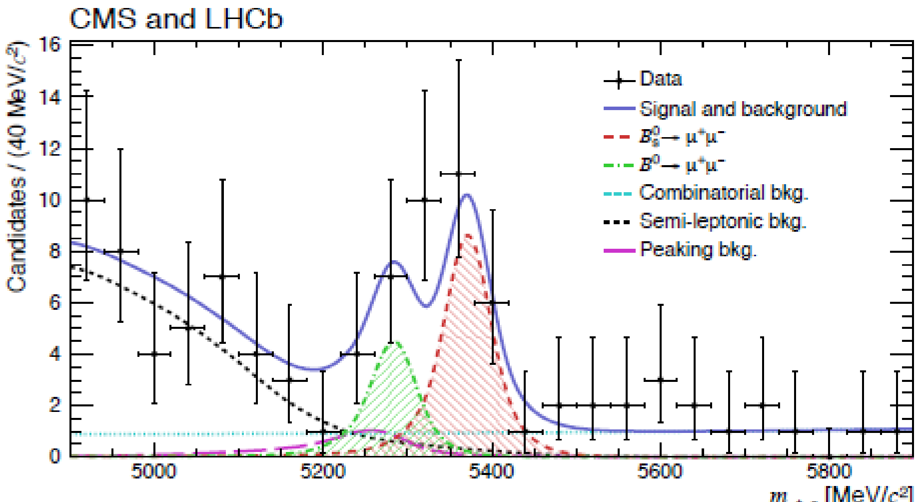


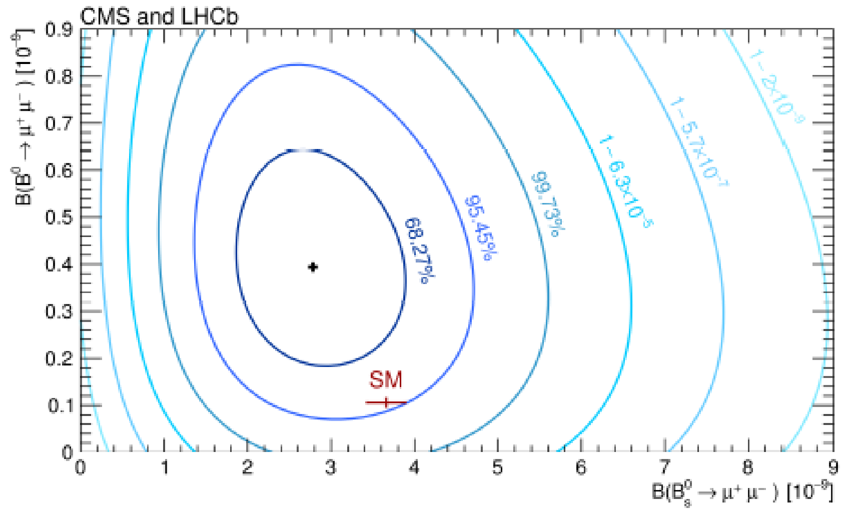
+ all 2012

The evidence grows…

$B_{d,s} \to \mu\mu$: run-1 legacy paper and CMS-LHCb combination

LHCb and CMS physicists have now performed a combined fit to their datasets, making use of common assumptions. The first combination of results from the LHC !





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

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

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

Included also are results for the even rarer $B_d \to \mu\mu$, where a signal may be emerging too. The picture is intriguing and provides encouragement for run 2 !

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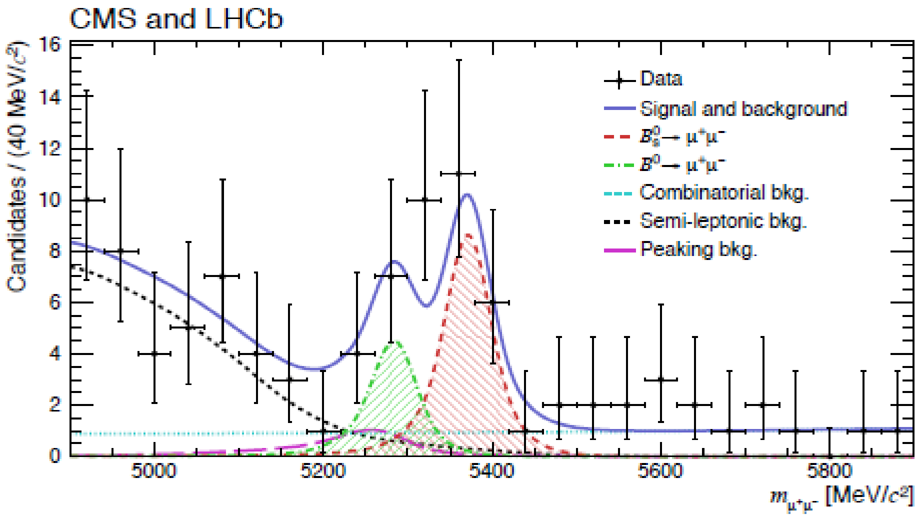

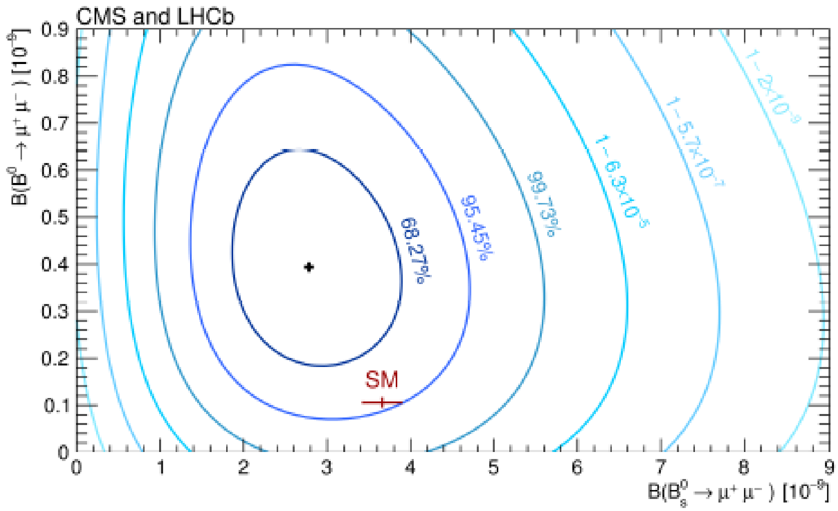

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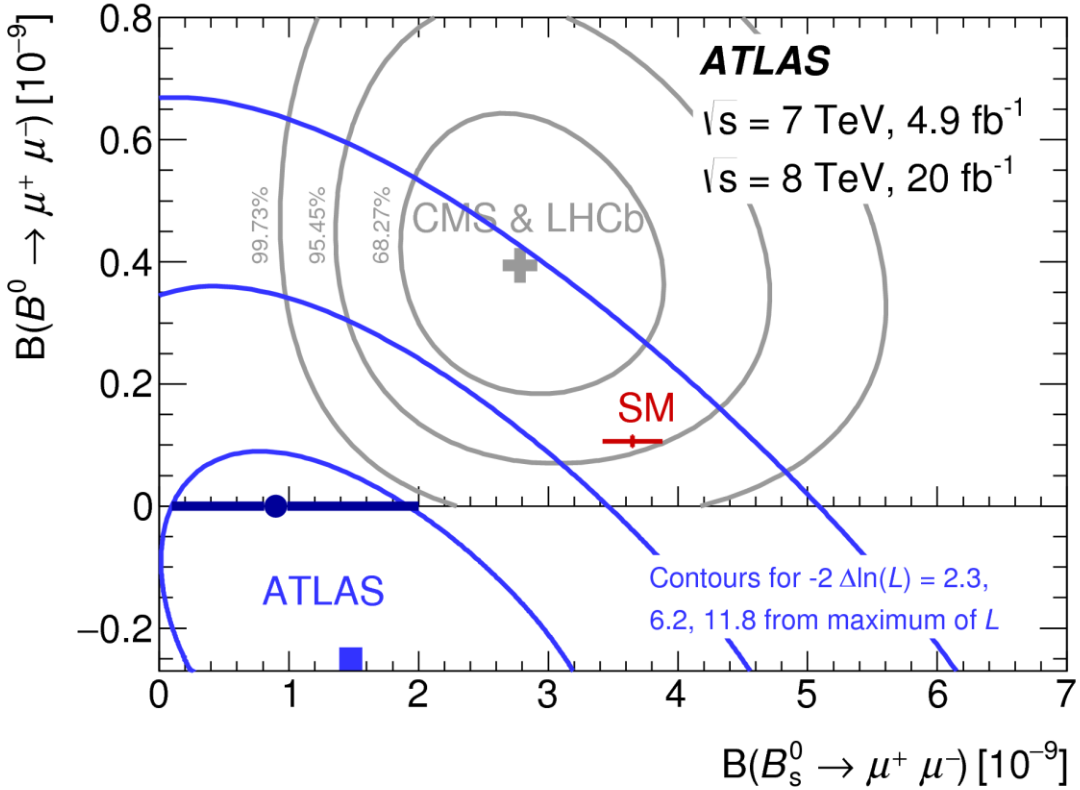
$B_{d,s} \to \mu\mu$: the complete run-1 LHC picture

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



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

$B_{d,s} \rightarrow \mu\mu$: first news from run 2

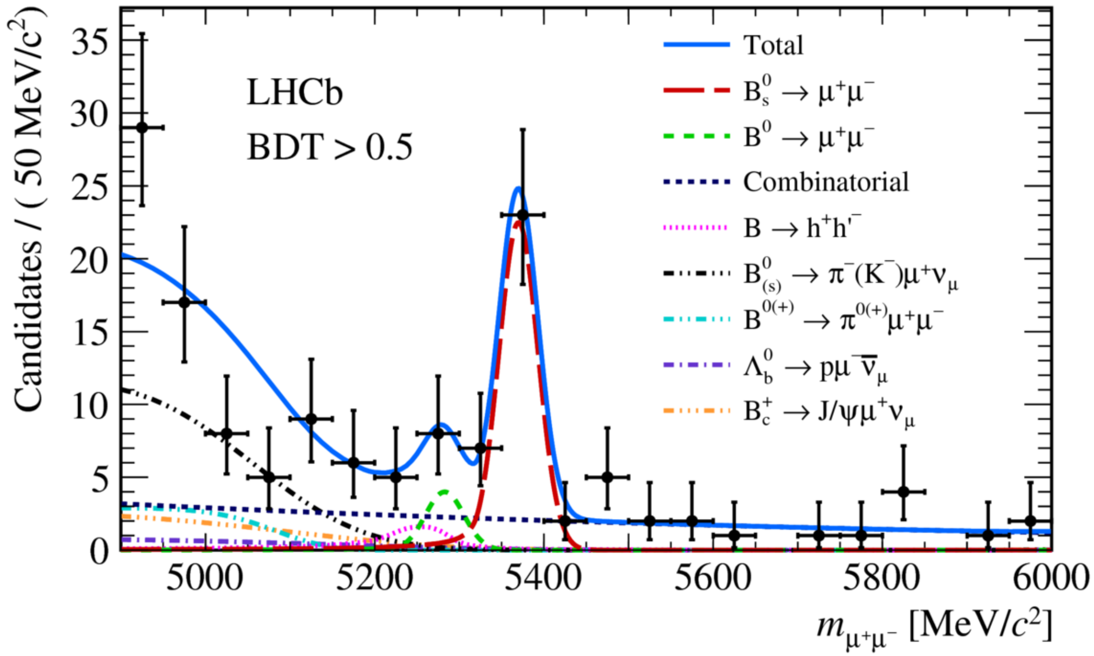
[arXiv:1703.05747]

Such is the importance of these modes, they warrant a measurement with early run-2 data. This has been done by LHCb, also benefitting from an updated analysis with improved background suppression: run 1 + 1.4 fb^{-1}.

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

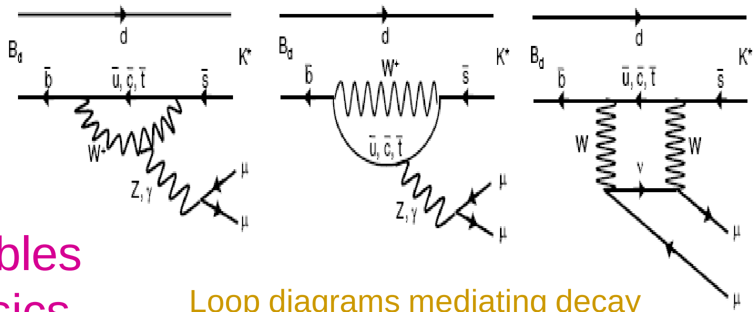
$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (3.0 \pm 0.6\,^{+0.3}_{-0.2}) \times 10^{-9}$$

- No evidence yet of the corresponding B^0_d decay ($< 3.4 \times 10^{-10}$ at 95% C.L.)



So no sign of 1st order New Physics effects, but continued study of these golden modes remains essential, throughout run 2 and beyond.

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

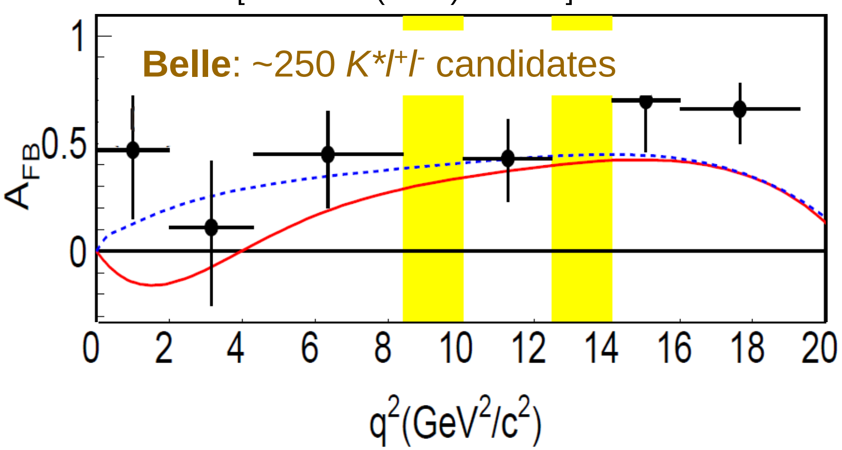


Decays such as $B^0 \to K^* l^+ l^-$ offer many observables which probe helicity structure of any New Physics...

Loop diagrams mediating decay

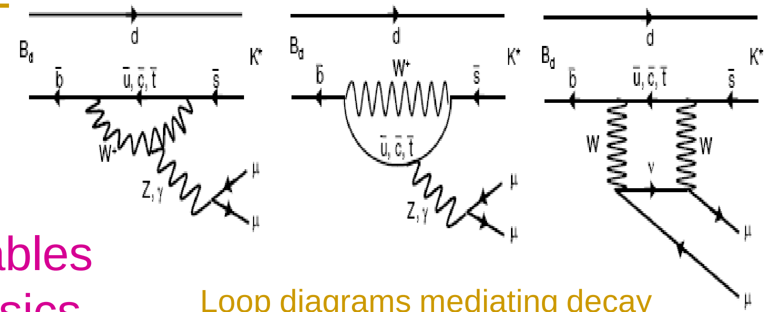
The *B*-factory experiments had inadequate statistics for meaningful tests. This has now all changed, *e.g.* forward-backward asymmetry vs dilepton q^2.

[PRL 103 (2009) 171801]



Hint of lying above prediction

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



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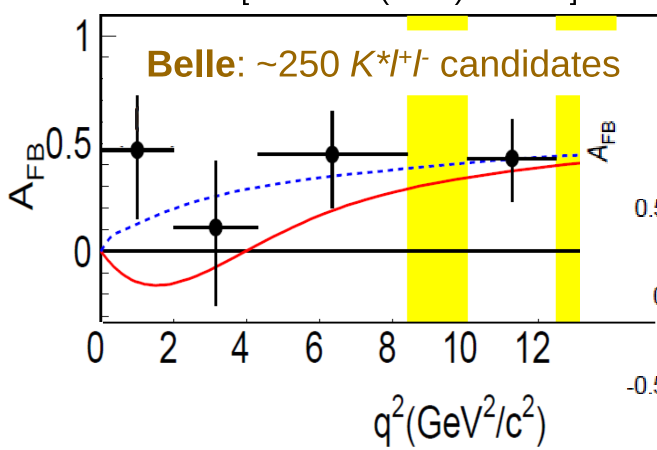
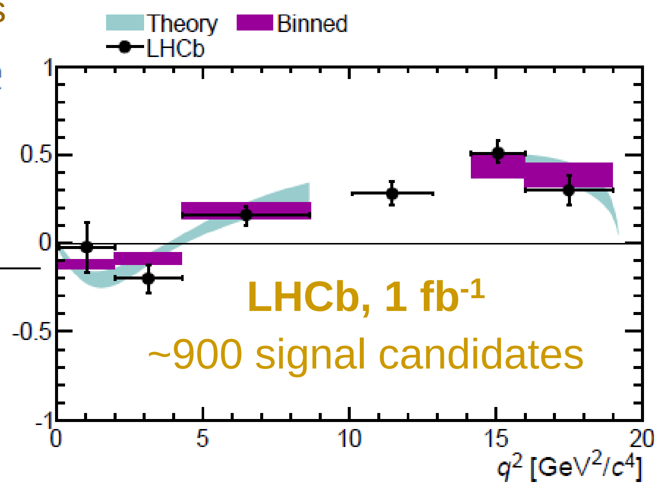
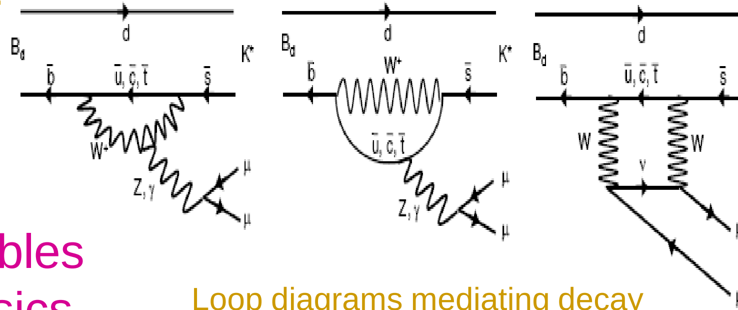


[JHEP 08 (2013) 131]



'Textbook' behaviour within uncertainties

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

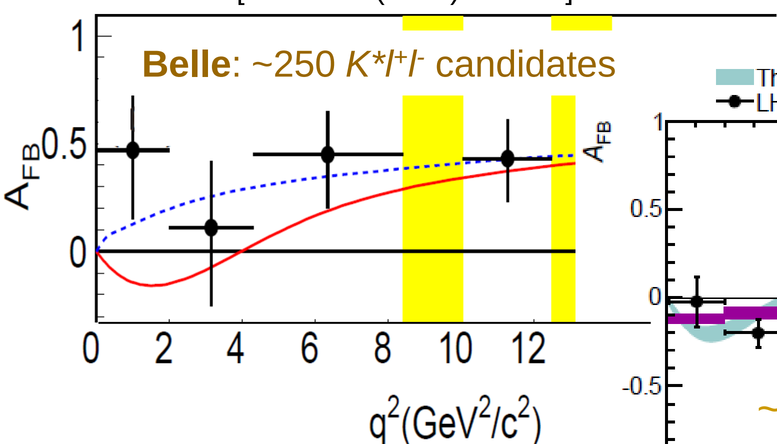


Loop diagrams mediating decay

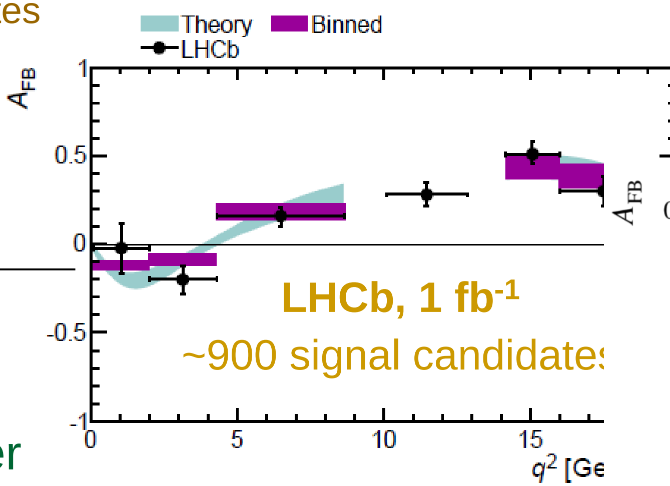
Decays such as $B^0 \to K^* l^+ l^-$ offer many observables which probe helicity structure of any New Physics...

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

[PRL 103 (2009) 171801]

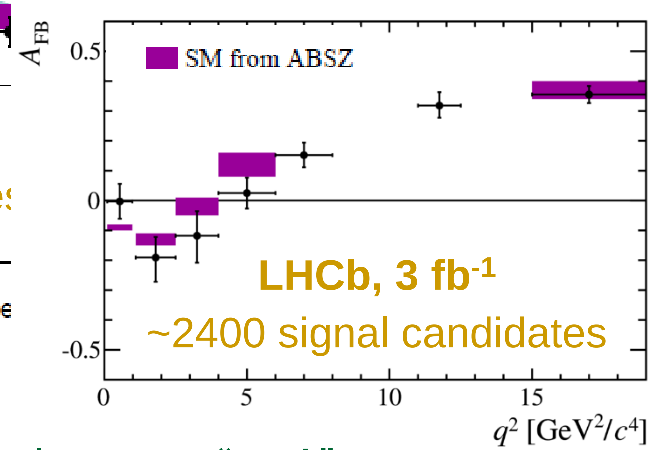


[JHEP 08 (2013) 131]



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

[JHEP 02 (2016) 104]

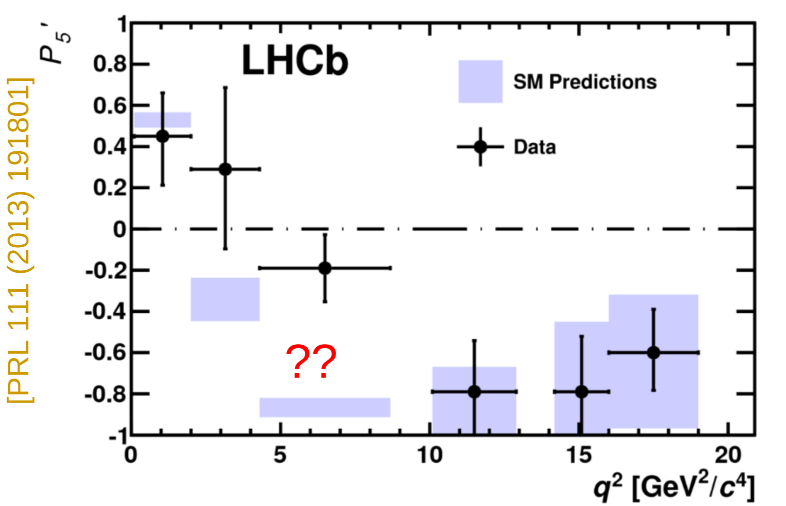


But there are many other observables, which can be built from the measured amplitudes, & are constructed to be intrinsically robust against form factor uncertainties, *e.g.* " P_5' "

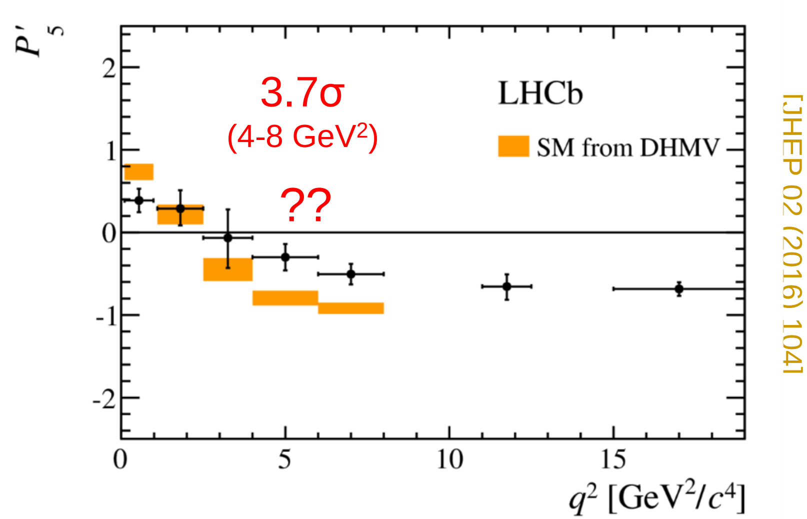
$B^0 \to K^* l^+ l^-$ and friends: the P_5' conundrum

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

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



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



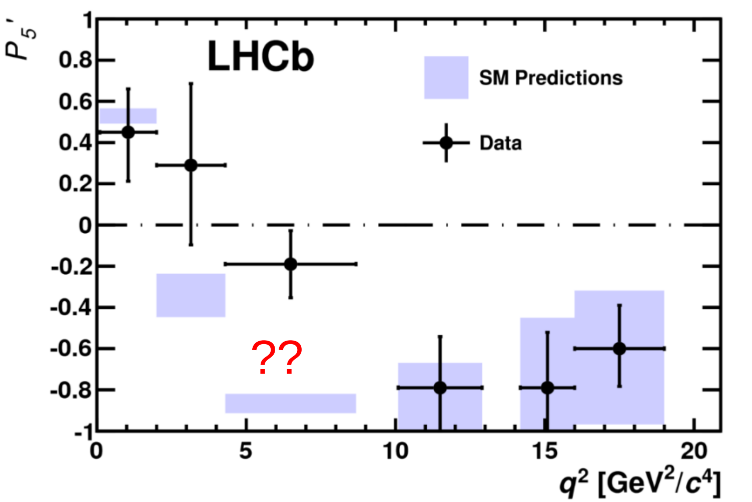
A word of caution. The uncertainties associated with the SM are from one group. There are other values on the market, and some are more conservative.

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

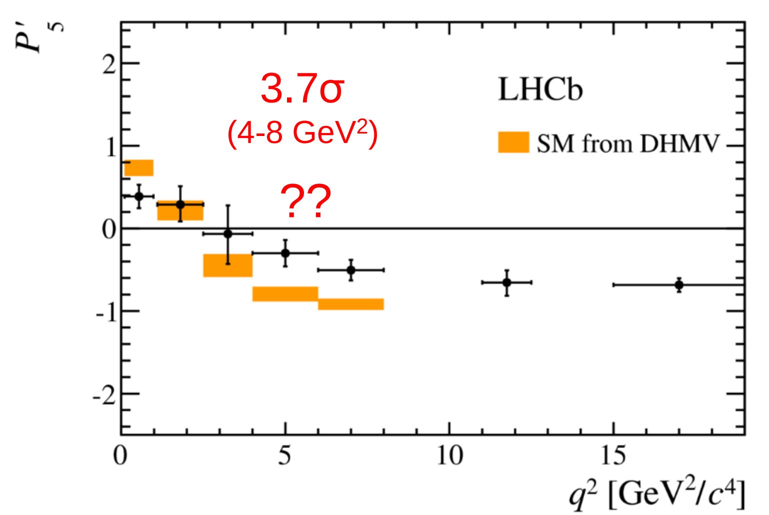
One such observable is P_5': What this describes physically is hard to visualise, but it is constructed from angular observables in a manner that is robust against form-factor uncertainties, and also easily relatable to the short-distance physics.

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

[PRL 111 (2013) 191801]



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



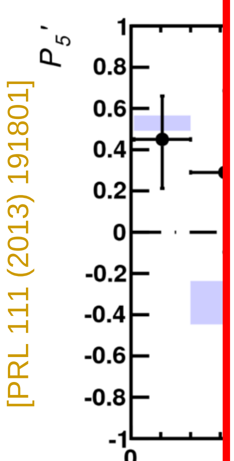
[JHEP 02 (2016) 104]

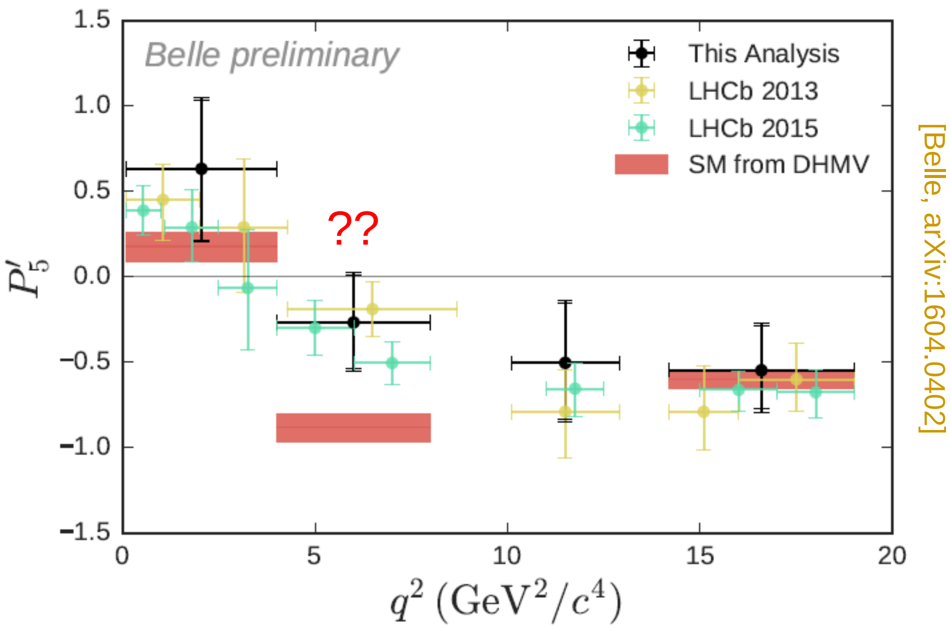
These results have encouraged the B-factories to dig deep into their data….

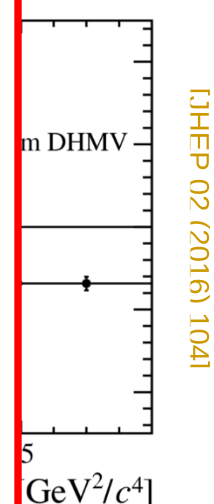
$B^0 \to K^* l^+ l^-$ and friends: the P_5' conundrum

One such observable is P_5': What this describes physically is hard to visualise, but it is constructed from angular observables in a manner that is robust against form-fact … ce physics.

Intere … at q^2 … 3 fb^{-1} … absolute … minished)







Lower statistical power, but very consistent

These results have encouraged the B-factories to dig deep into their data….

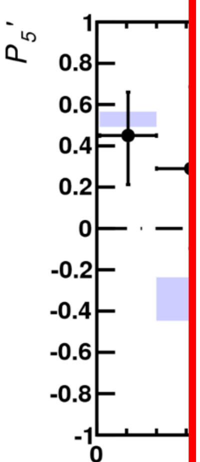
$B^0 \to K^* l^+ l^-$ and friends: the P_5' conundrum

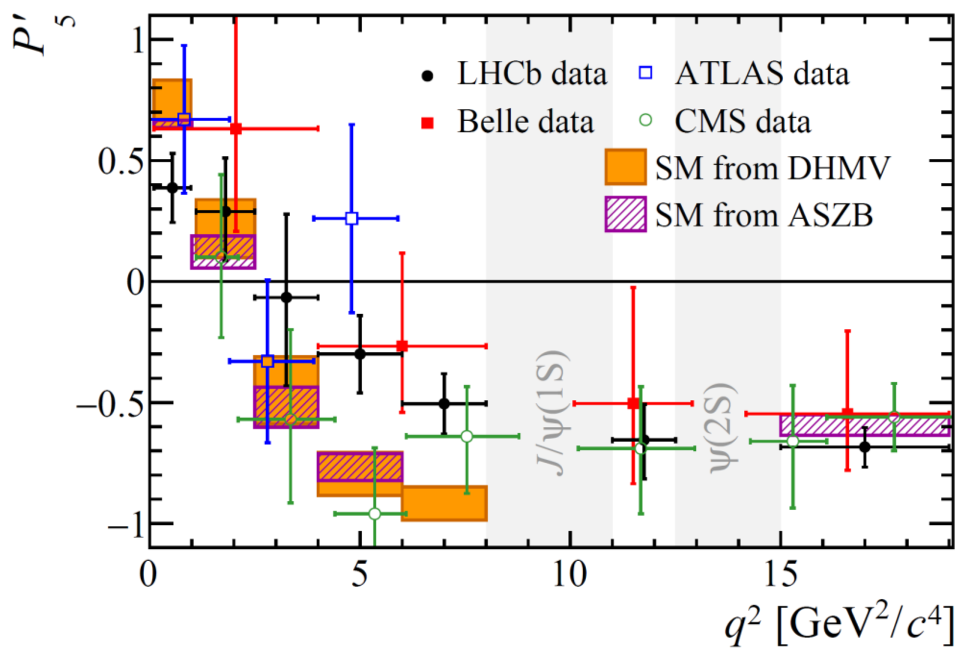
One such observable is P_5': What this describes physically is hard to visualise, but it is constructed from angular observables in a manner that is robust against form-fact … ce physics.

Intere … at q^2

… 3 fb^{-1} … absolute … minished)

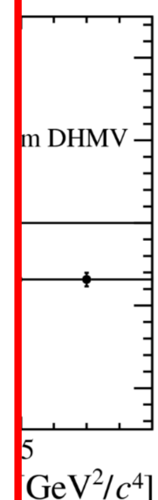
[PRL 111 (2013) 191801]





And last month ATLAS and CMS joined the party

[ATLAS-CONF-2017-023, CMS-PAS-BPH-15-007]



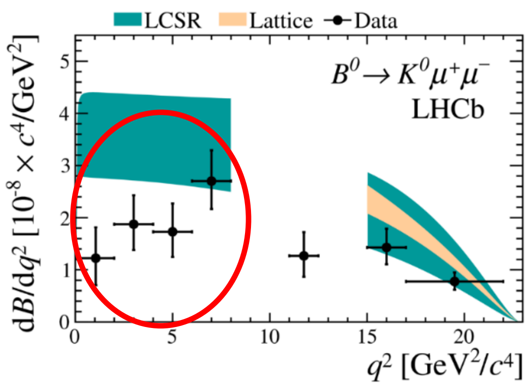
[JHEP 02 (2016) 104]

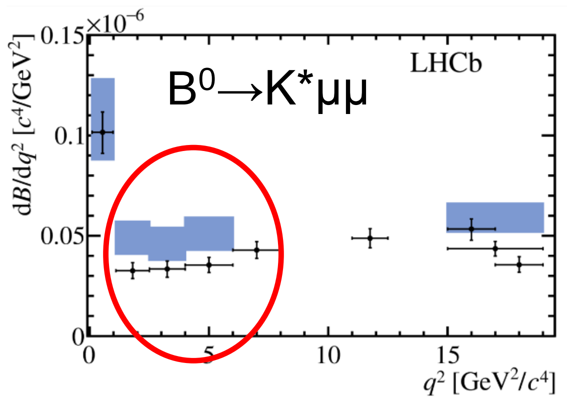
These results have encouraged the B-factories to dig deep into their data….

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

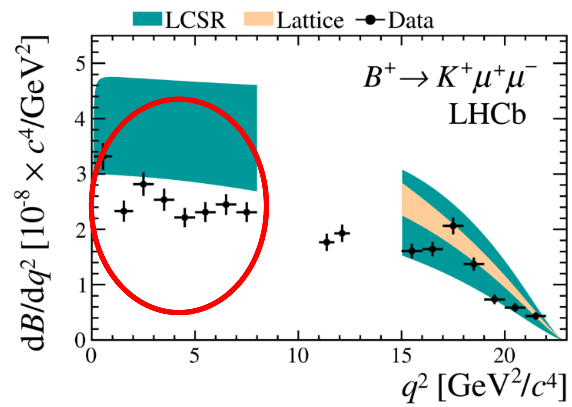
P_5' is not the only funny thing going on in $b \to (s,d) l^+ l^-$ decays.

[JHEP 06 (2014) 133]



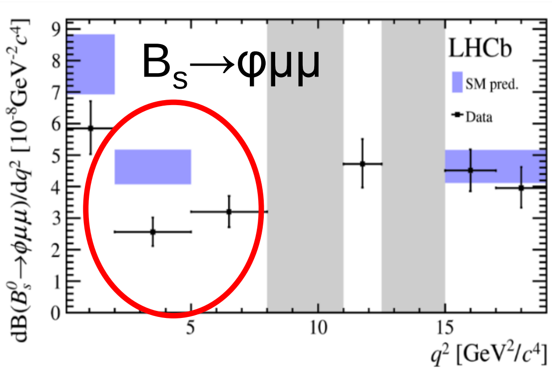


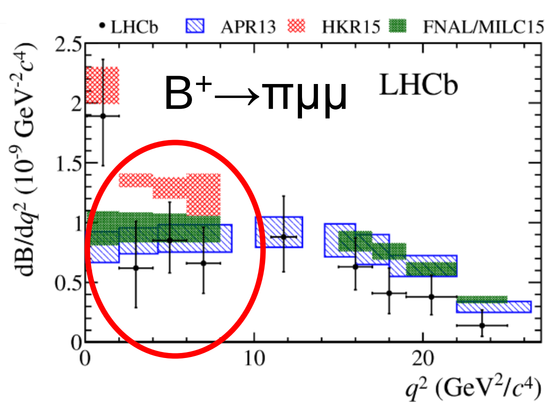
[JHEP 11 (2016) 047]



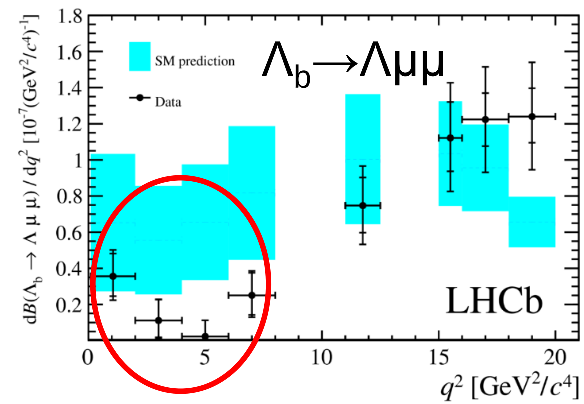
[JHEP 06 (2014) 133]

[JHEP 09 (2015) 179]





[JHEP 10 (2015) 034]



[JHEP 06 (2015) 009]

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

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

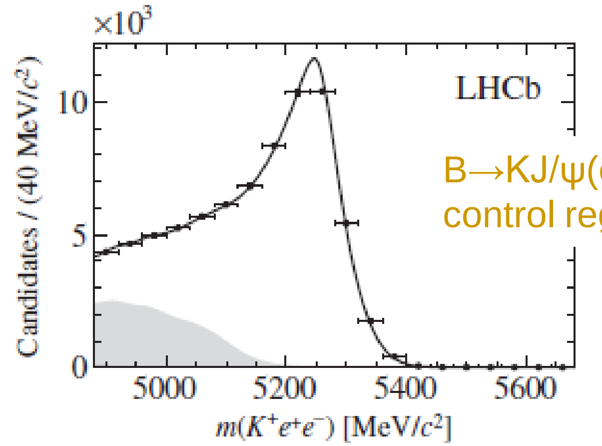
What we need is an observable that is theoretically really clean…

Pretty much everything shown so far has come from decays with muons.
A question: do electrons behave in the same way?
First interesting measurement of this is R_K, the ratio of $B \to K\mu^+\mu^-$ to $B \to Ke^+e^-$

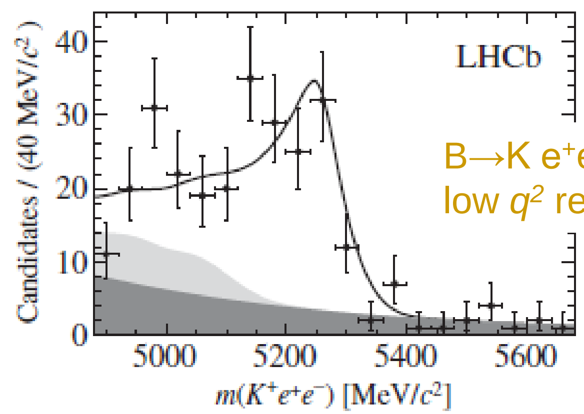
Should be exactly 1 in the SM.
In fact LHCb measures, for $1<q^2<6$ GeV^2,
[PRL 113 (2014) 151601] :

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

which is 2.6σ low…
A statistical fluctuation ?



$B \to KJ/\psi(e^+e^-)$ control region



$B \to K e^+e^-$ low q^2 region

Hot news from last week !

Science stories from Tues 18th

Hot news from last week !

Science stories from Tues 18th

Discovery of first living, ~1m long, giant shipworm

Hot news from last week: R_{K*} !

Science stories from Tues 18th

An analogous measurement has now been performed with $B^0 \to K^* l^+ l^-$
[LHCb-PAPER-2017-013]

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

This double ratio, involving the control mode $B^0 \to J/\psi K^*$, ensures that all 1st order systematics in efficiency cancel – robust ! Nonetheless, great efforts are made to understand these efficiencies from data, and also to check that $\mathcal{B}(B^0 \to J/\psi K^*)$ is measured to be the same in both muon and electron channel – a stringent test !

$$r_{J/\psi} = \frac{\mathcal{B}(B^0 \to K^{*0}J/\psi(\to \mu^+\mu^-))}{\mathcal{B}(B^0 \to K^{*0}J/\psi(\to e^+e^-))} = 1.043 \pm 0.006\,(\text{stat}) \pm 0.045\,(\text{syst})$$

Similar cross-checks performed with *e.g.* $\psi(2S)$.

Attention paid to partially reconstructed region & potential leakage from J/ψ region.

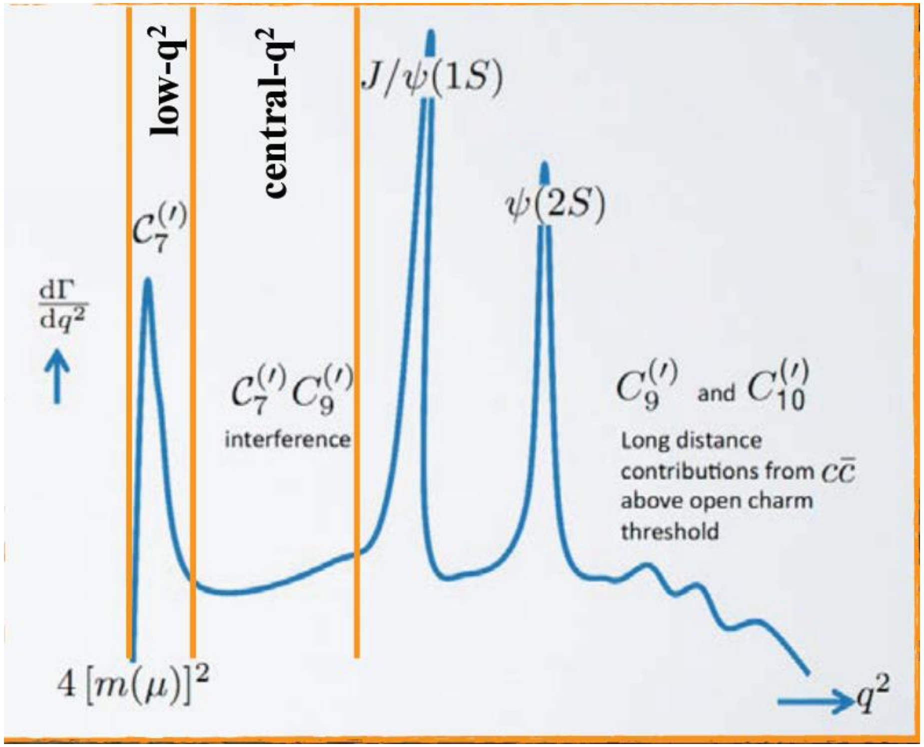
$B^0 \rightarrow K^* l^+ l^-$ and friends: lepton universality tests R_{K^*}

Measurement performed in two q^2 regions:

Low: $0.045 < q^2 < 1.1$ GeV^2

Central: $1.1 < q^2 < 6.0$ GeV^2

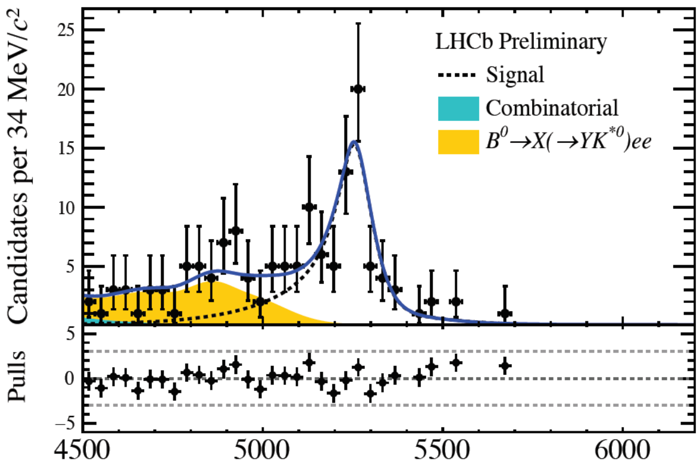
(high q^2 region, above resonances, is certainly of interest, but this presents different experimental challenges, and requires a separate analysis)



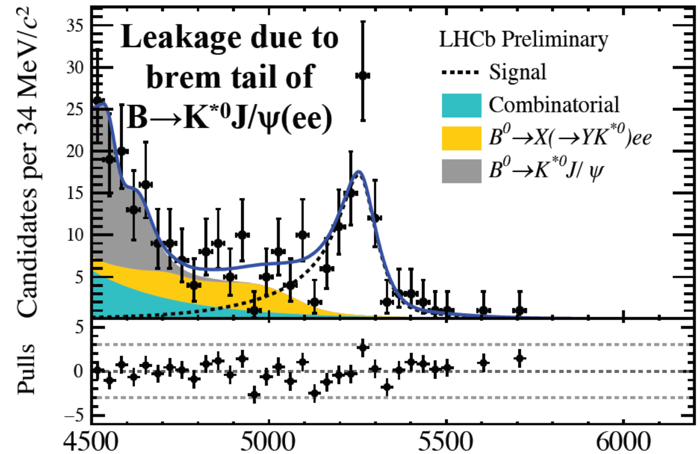
For $K^*e^+e^-$, three exclusive trigger categories are used, depending on whether triggered on electron(s) (L0E), K* candidate(s) (L0H), or not on signal (TIS)

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

Mass spectra in di-electron final state



low-q^2

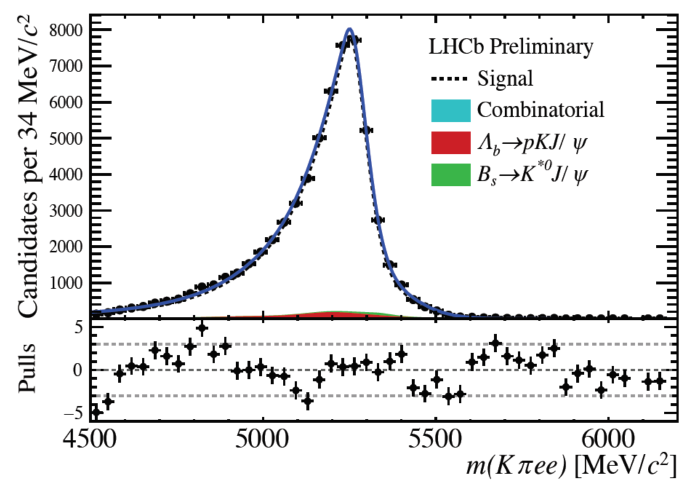


central-q^2

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

58k in control channel

Muon samples 3-5x larger



Systematics on R_{K*} (%)

	low-q^2			central-q^2		
Trigger category	L0E	L0H	L0I	L0E	L0H	L0I
Corrections to simulation	2.5	4.8	3.9	2.2	4.2	3.4
Trigger	0.1	1.2	0.1	0.2	0.8	0.2
PID	0.2	0.4	0.3	0.2	1.0	0.5
Kinematic selection	2.1	2.1	2.1	2.1	2.1	2.1
Residual background	–	–	–	5.0	5.0	5.0
Mass fits	1.4	2.1	2.5	2.0	0.9	1.0
Bin migration	1.0	1.0	1.0	1.6	1.6	1.6
$r_{J/\psi}$ **flatness**	1.6	1.4	1.7	0.7	2.1	0.7
Total	4.0	6.1	5.5	6.4	7.5	6.7

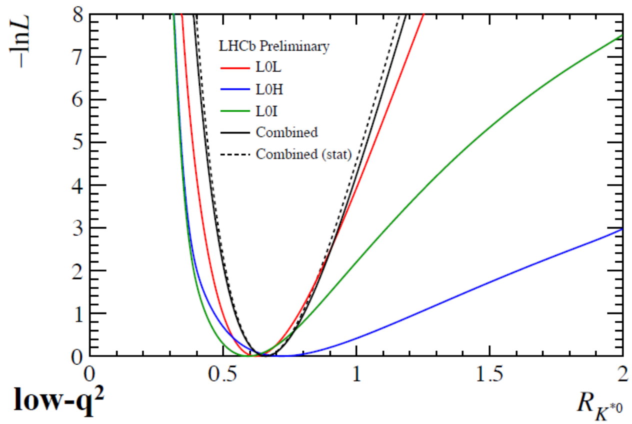
Statistical uncertainty around 4x larger at low-q^2, and 2x larger at central-q^2.

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

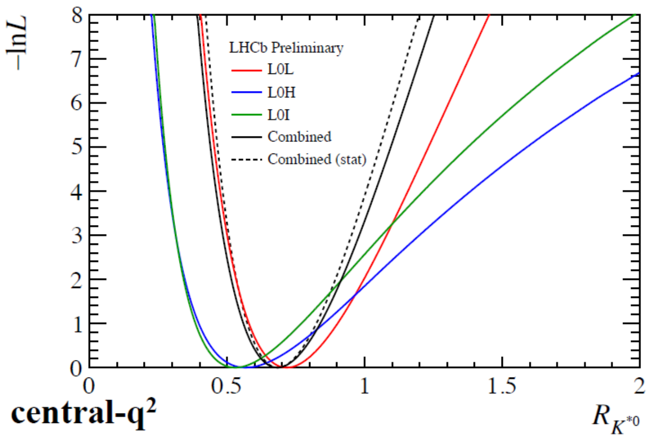
Preliminary results:

LHCb Preliminary	low-q^2	central-q^2
$\mathcal{R}_{K^{*0}}$	$0.660\,^{+\,0.110}_{-\,0.070} \pm 0.024$	$0.685\,^{+\,0.113}_{-\,0.069} \pm 0.047$
95% CL	[0.517–0.891]	[0.530–0.935]
99.7% CL	[0.454–1.042]	[0.462–1.100]

Good compatibility between trigger classes:

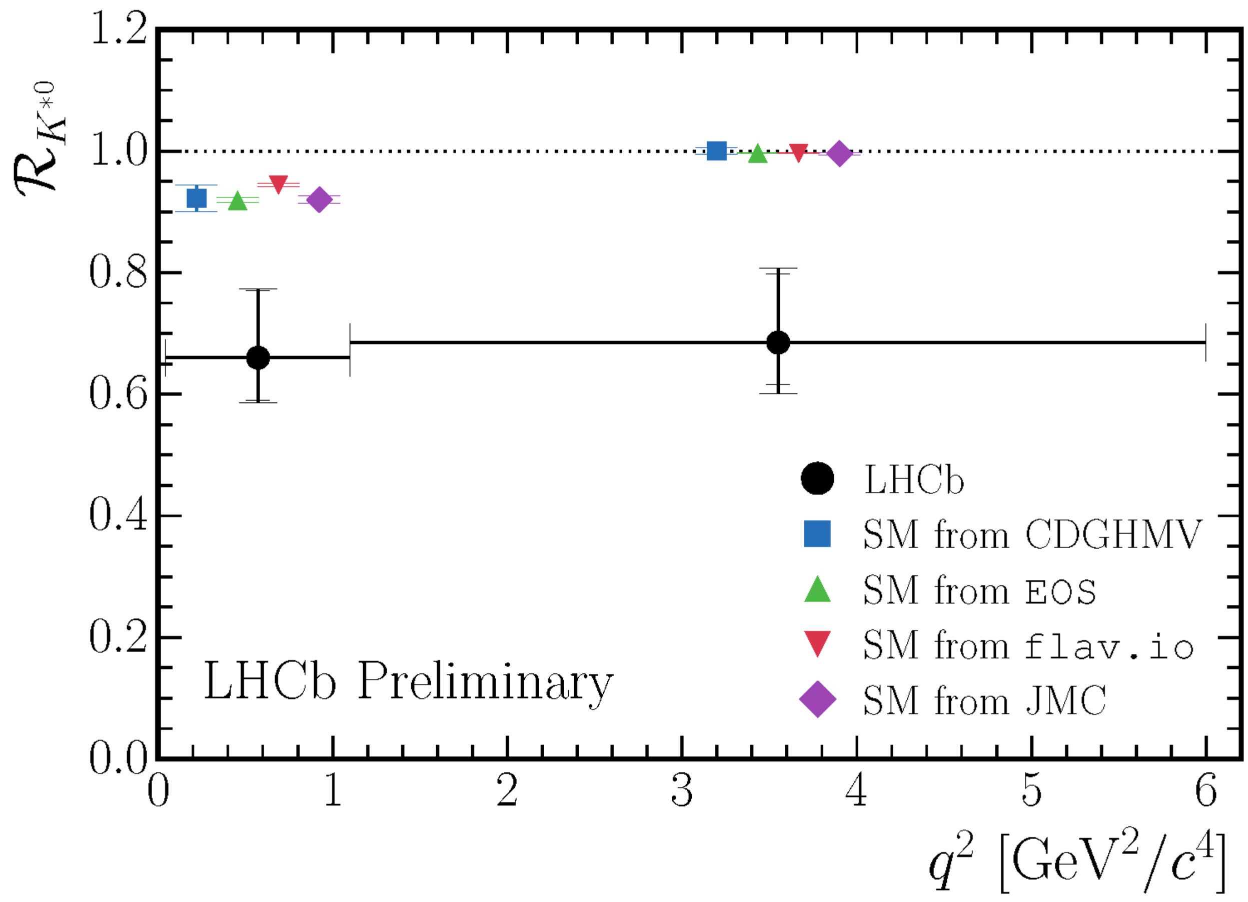


low-q^2



central-q^2

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



2.2-2.4 σ and 2.4-2.5 σ away from SM at low and central-q^2, respectively.

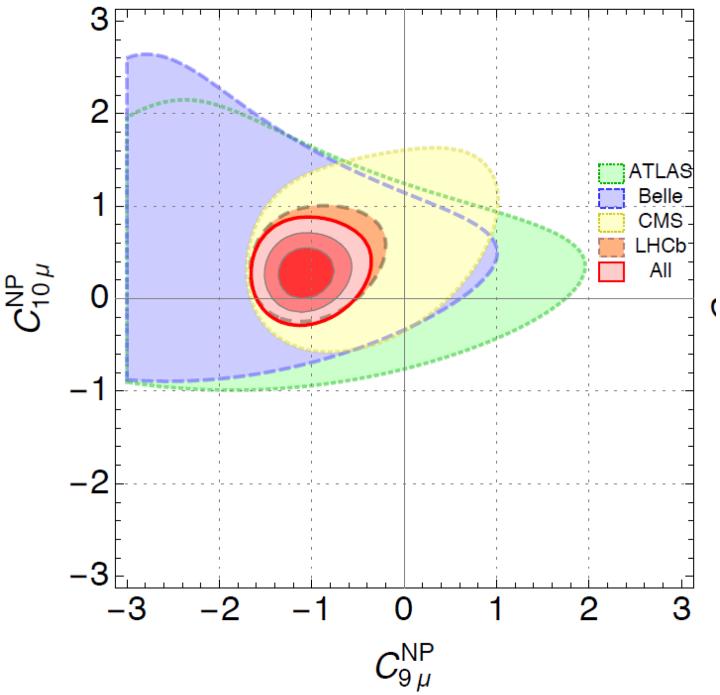
$B^0 \to K^* l^+ l^-$ and friends: what does it all mean ?

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

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

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

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

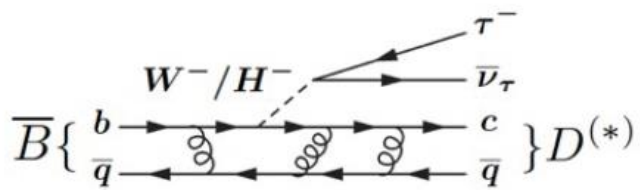


The experimentalist's view:

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

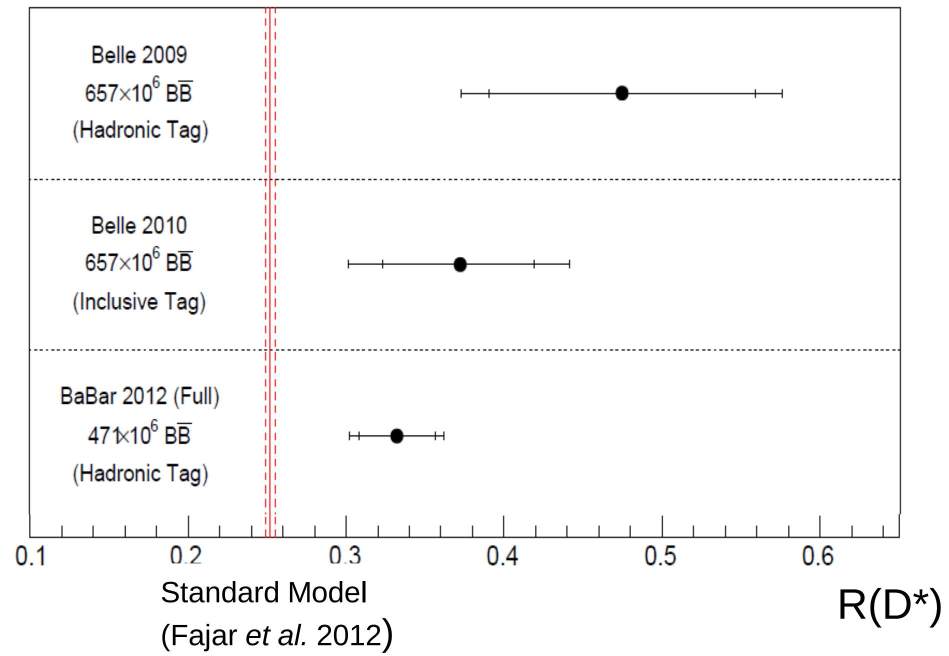
Other hints of LU violation: $R(D^*) \equiv \mathrm{BR}(B \to D^{(*)}\tau\nu)/\mathrm{BR}(B \to D^{(*)}\mu\nu)$

*B→D*τν* is not a FCNC, nor even particularly rare, but of great interest, because of its sensitivity to, *e.g.* charged Higgs sector, & the *B*-factory legacy.



A very suggestive pattern of measurements !

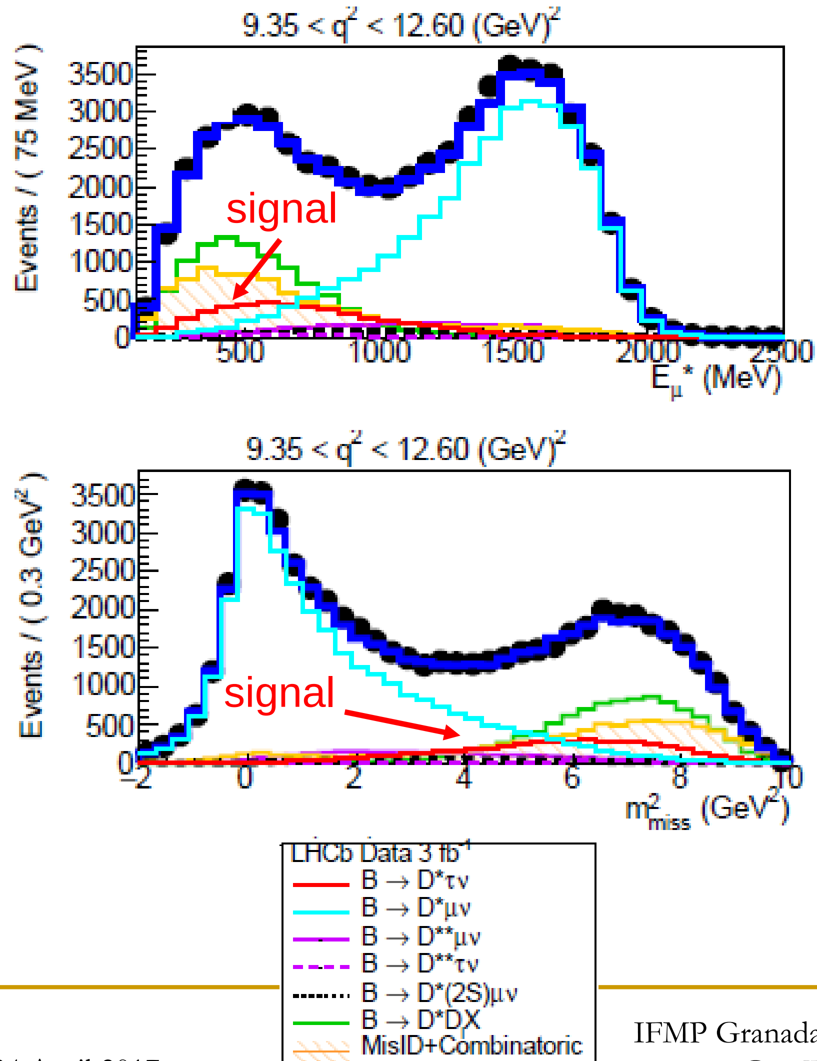
Interesting tension in *R(D)* too, but taken together they are not compatible with *e.g.* type-II 2HDM.



Something that LHCb cannot do due to impossibility of reconstructing full event?

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

One q^2 bin:



[PRL 115 (2015) 111803]

Reconstruct $B^0\to D^*\tau\nu$ with $\tau\to\mu\nu\nu$,

Demand good vertex separation and isolation with dedicated MVA

Approximate B momentum from boost of reconstructed signal.

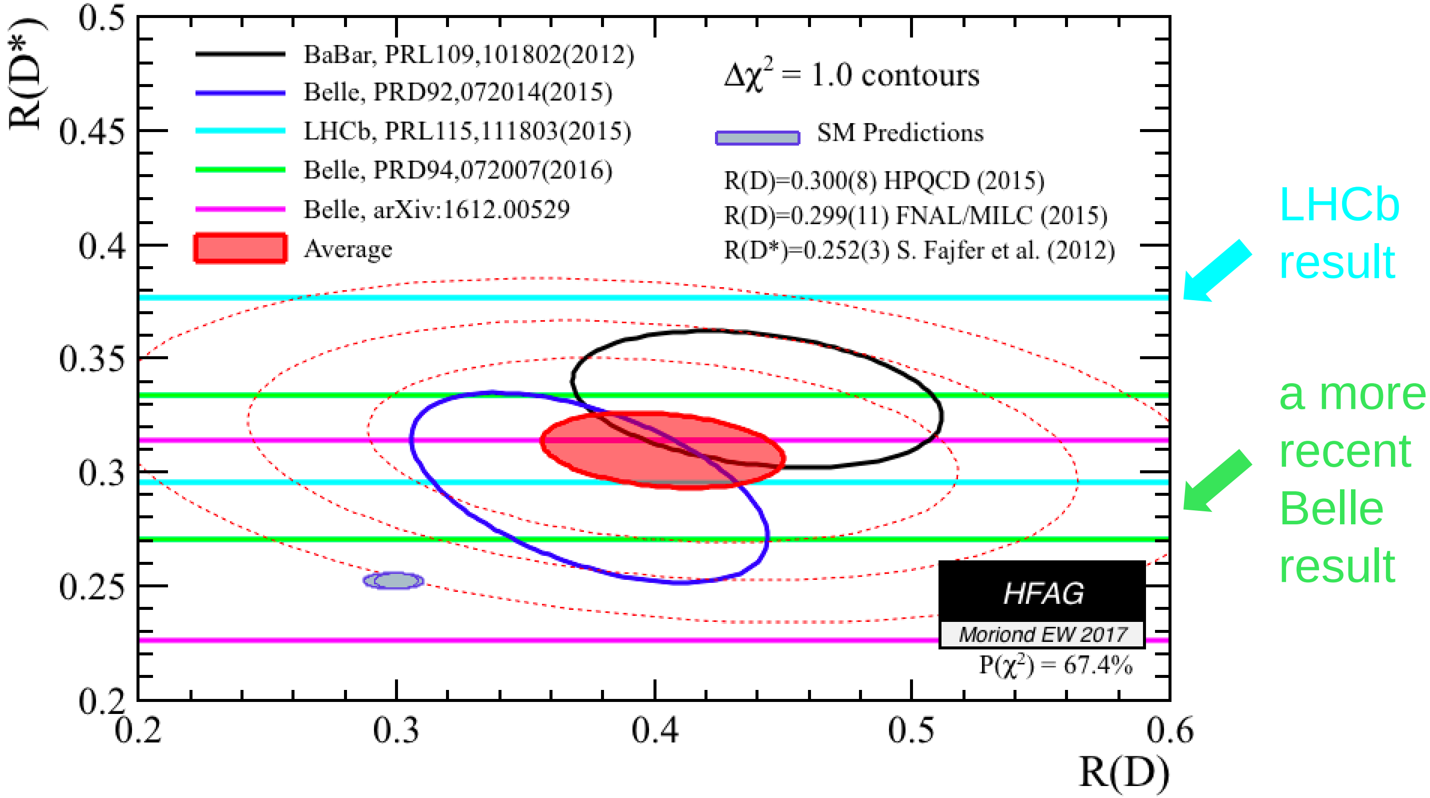
Disentangle from $B^0\to D^*\mu\nu$ and other backgrounds by fitting against E^*_μ and m^2_{miss} in bins of q^2

$$R(D^*) = 0.336 \pm 0.027 \pm 0.030$$

Similar to BaBar central value and 2.1 σ above the SM !

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

Combination of measurements paint an intriguing picture…



…3.9σ away from SM predictions. New measurements will come from LHCb, including (very soon) a determination of *R(D*)* using *τ→πππν*, which will be rather precise. If the central value remains stable, we may well have a 'crisis' !

Conclusions

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

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

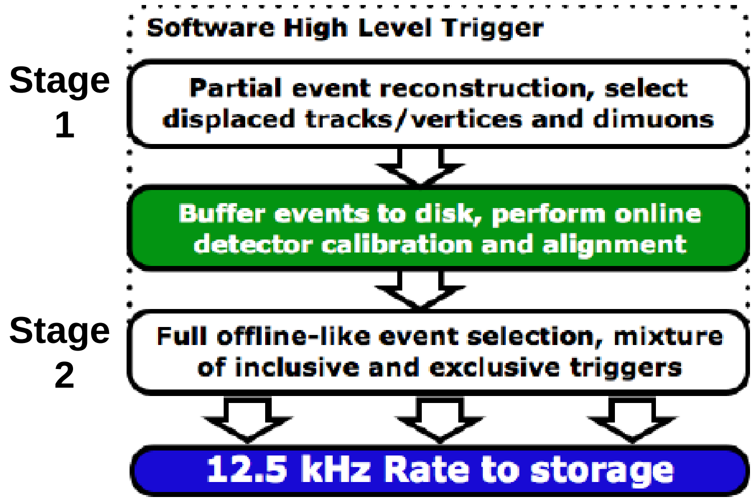
The results obtained in run 1 have matched, & in many cases exceeded The sensitivities expected prior to data taking. Many of these results show good compatibility with the SM (for now), but some signs of tension are emerging.

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

$\rightarrow$ stay tuned !

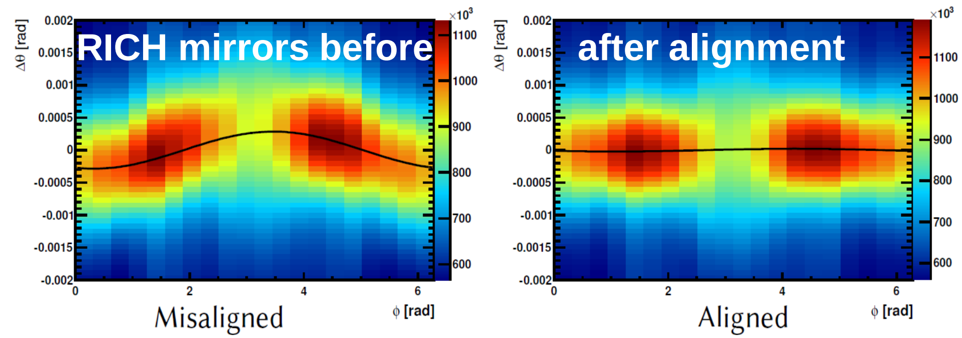
Backups

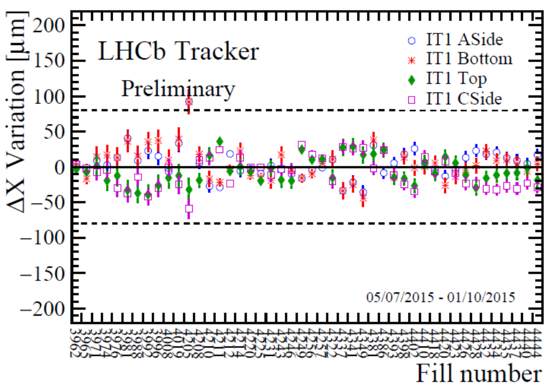
Focus on the software trigger

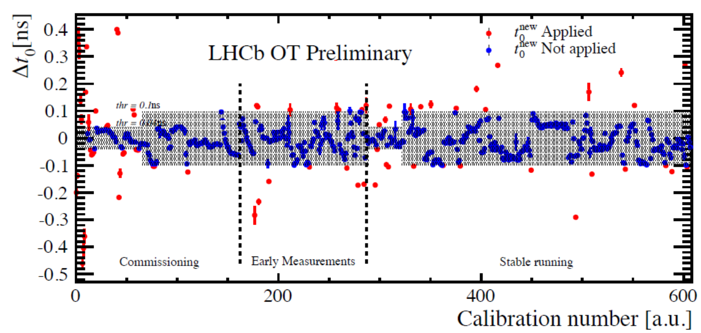


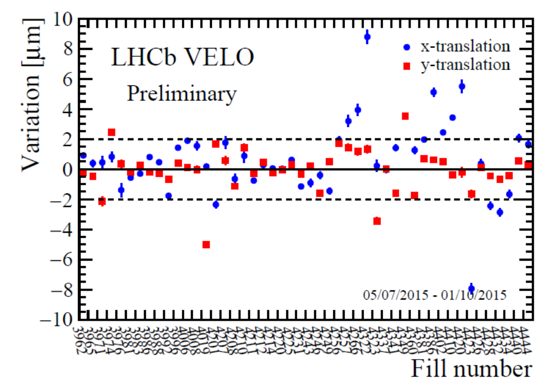
The Big Idea of run-2 data taking:

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

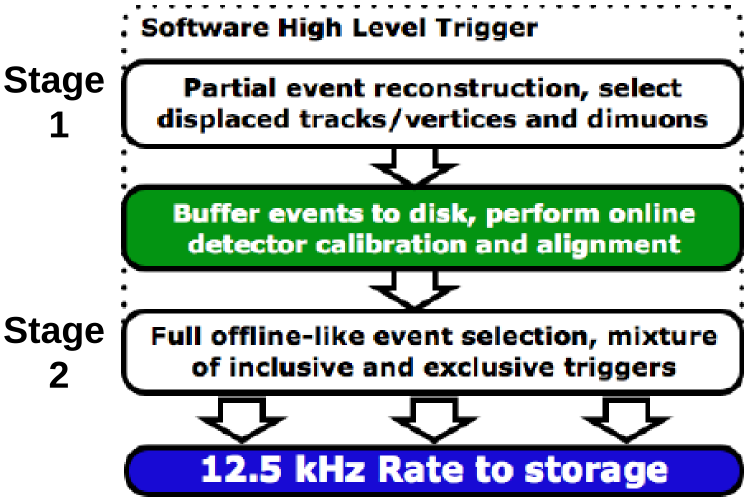








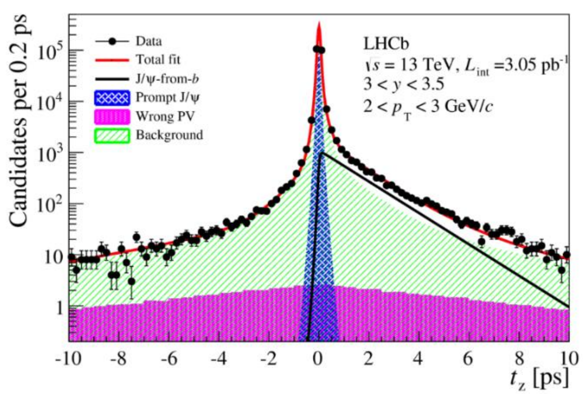
Focus on the software trigger



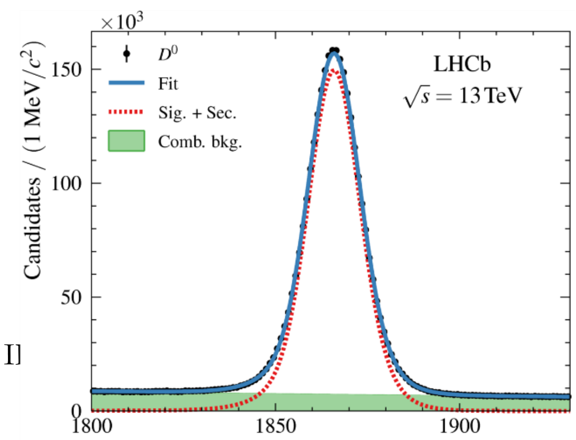
The Big Idea of run-2 data taking:

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

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



First results shown within 2 weeks of data collection !

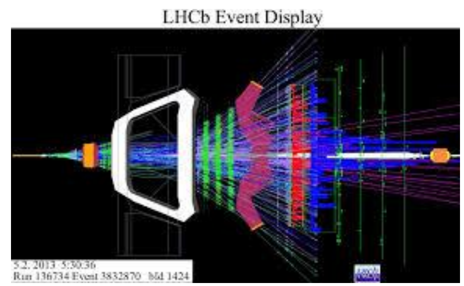


e.g. open charm production at 13 TeV [JHEP 03 (2016) 159]

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).

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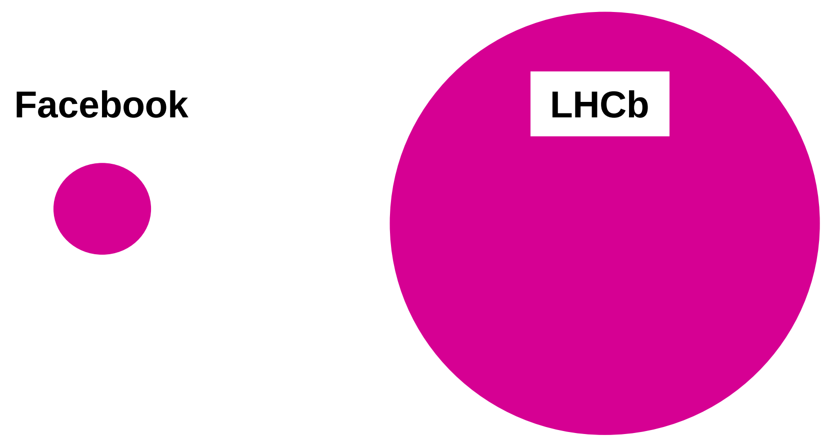
Data rate

LHCb ~15000 PB.yr

Facebook ~180 PB / yr



The data challenge

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

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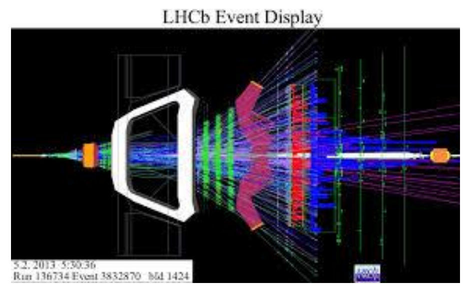

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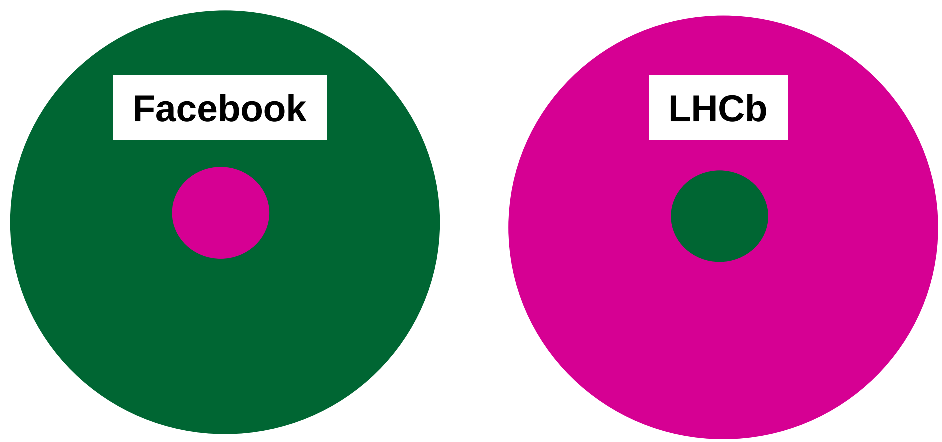


Public science has less money to spend on computing than Facebook.

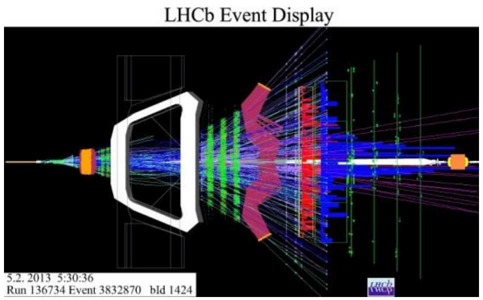
Storage costs money. Better to process as much as possible in 'real time'.

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

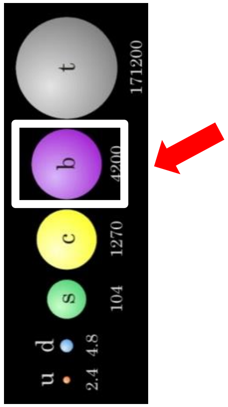
Not all collisions are equally interesting

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

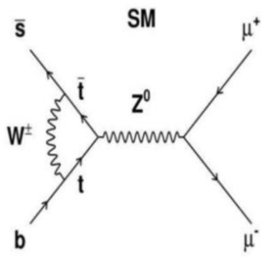
Collision rate 40 MHz
(currently a little less,
but this sets the ballpark)



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



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



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

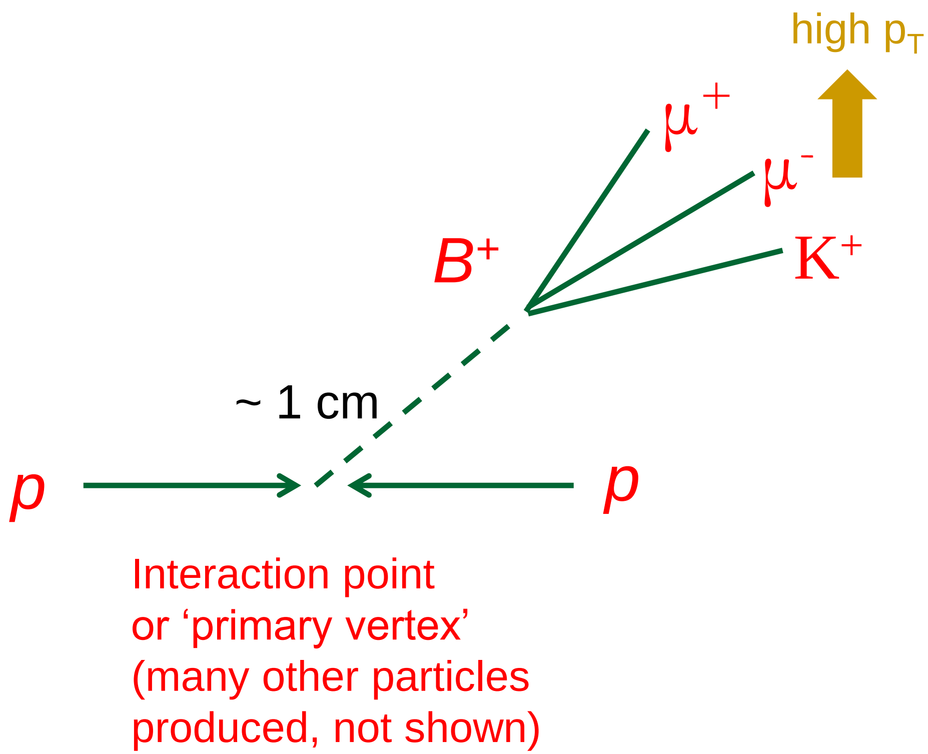
The ones that do, occur every 10^{-3} -10^{-10} of time.

(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.



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

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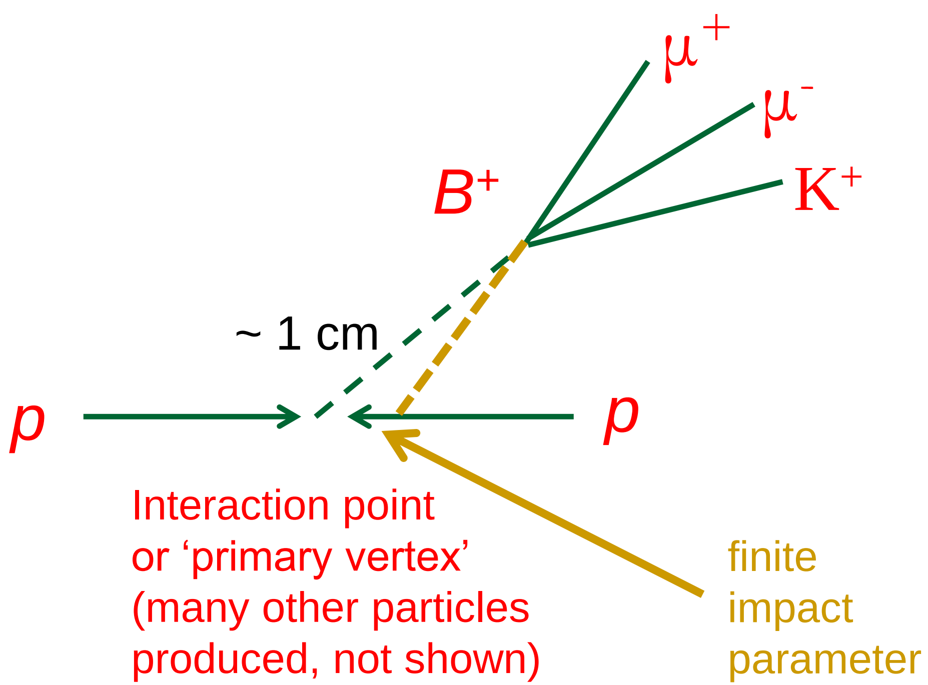

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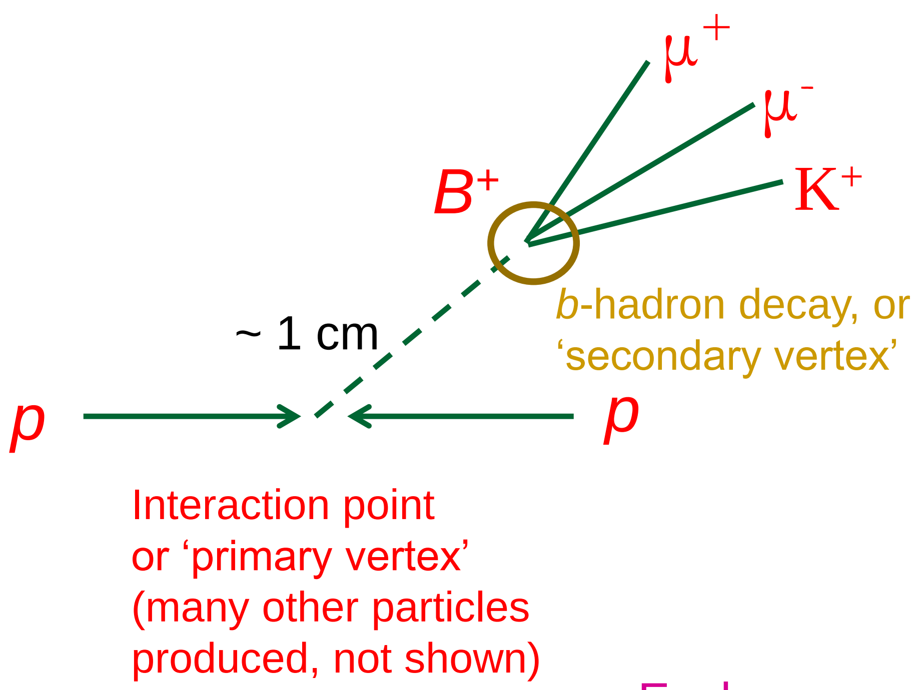
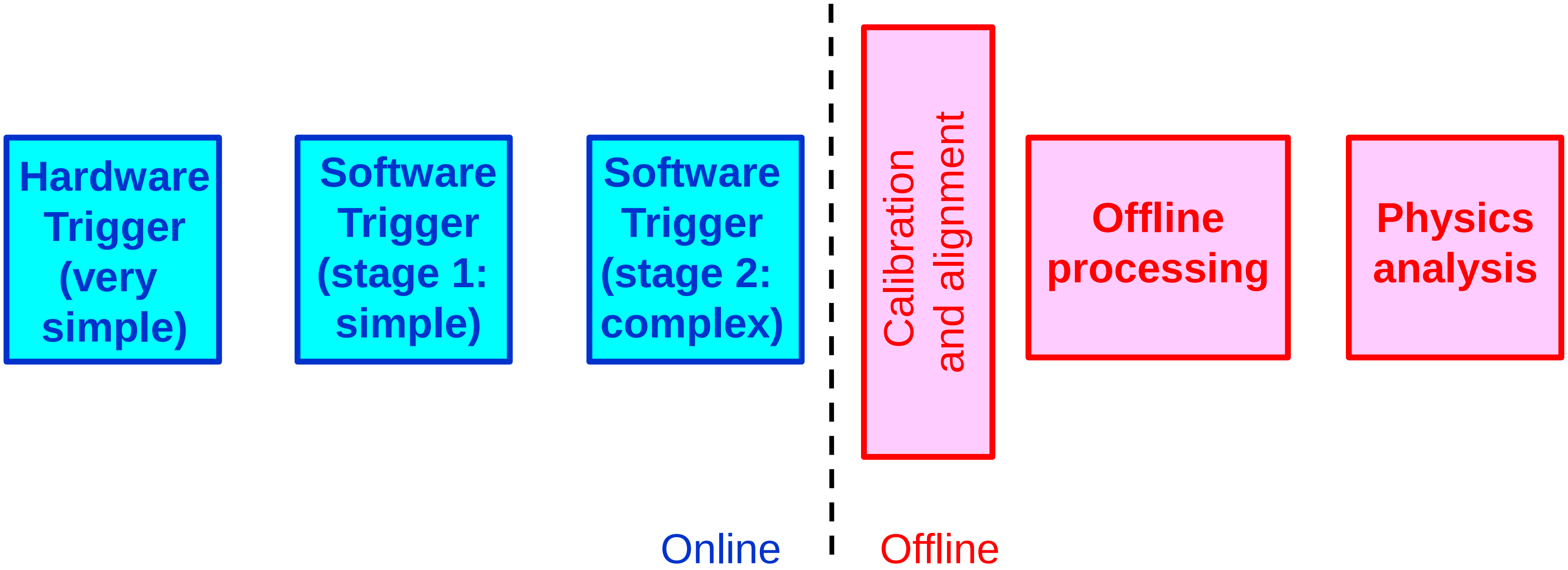


1. Look for high transverse energy (E_T) or momentum (p_T) in calorimeters or muon system from decay products.
2. Look for tracks with significant 'impact parameter' with respect to primary vertex.
3. Reconstruct secondary vertex and full *b*-hadron decay products.

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

Revolutionising the trigger & data analysis chain

The classical data flow for a collider experiment, *e.g.* LHCb in run 1, is as follows:



Revolutionising the trigger & data analysis chain

The classical data flow for a collider experiment, *e.g.* LHCb in run 1, is as follows:

Imperfect calibration & alignment limits signal vs. background discrimination

Time consuming; often re-iterations necessary → very heavy on computing resources

Hardware Trigger (very simple)

Software Trigger (stage 1: simple)

Software Trigger (stage 2: complex)

Calibration and alignment

Offline processing

Physics analysis

Poor-to-moderate efficiency; inflexible

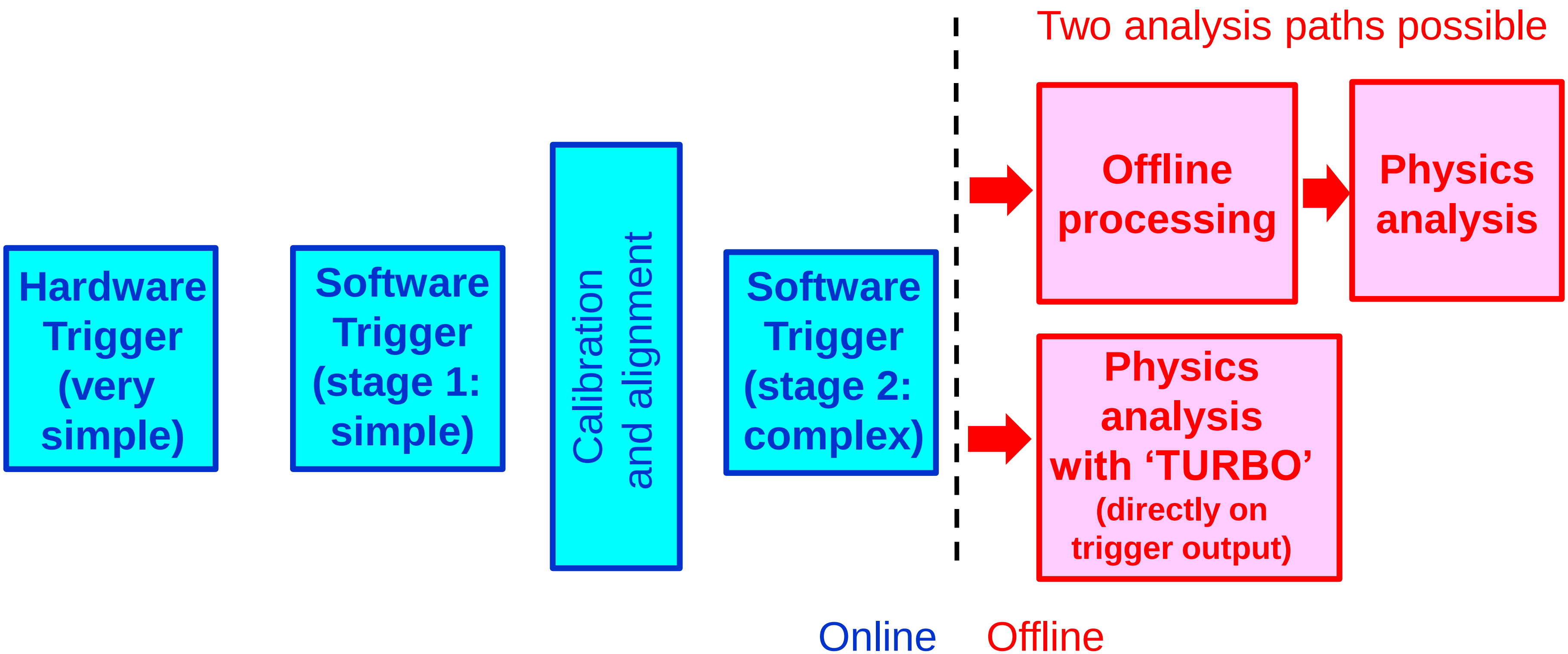
Online

Offline

It has some disadvantages…

Revolutionising the trigger & data analysis chain

Now consider the scheme that LHCb is operating in run 2:

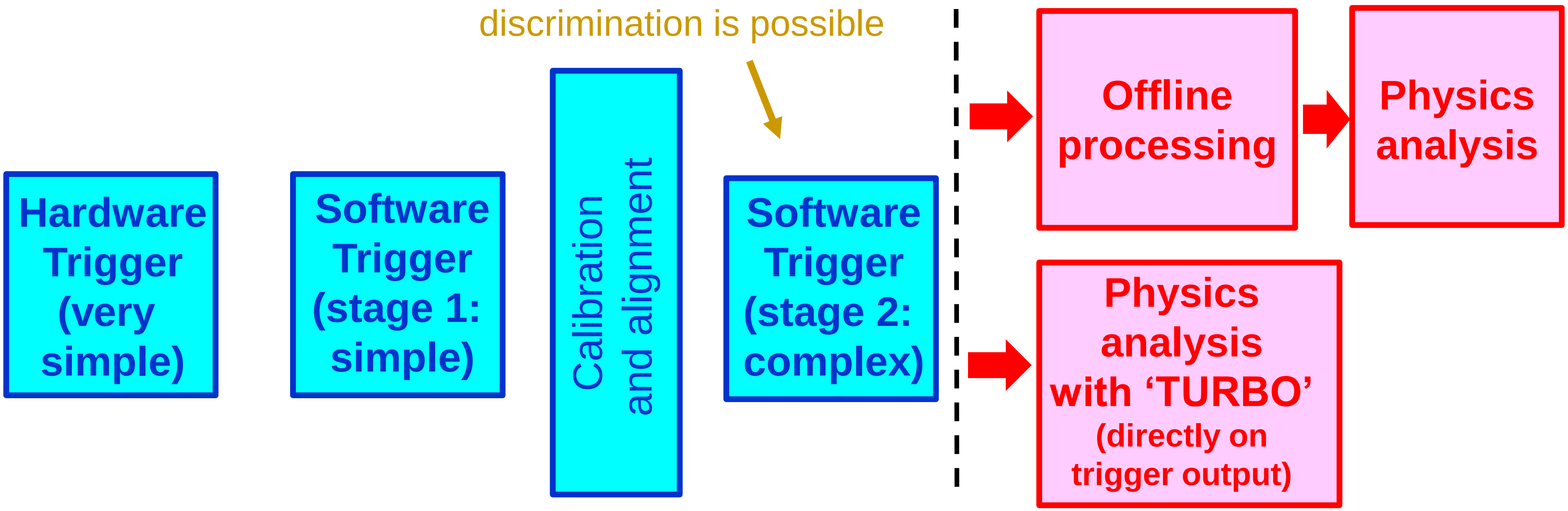


Revolutionising the trigger & data analysis chain

Now consider the scheme that LHCb is operating in run 2:

Offline-quality information available → much improved discrimination is possible

Two analysis paths possible



Online Offline

This brings many advantages !

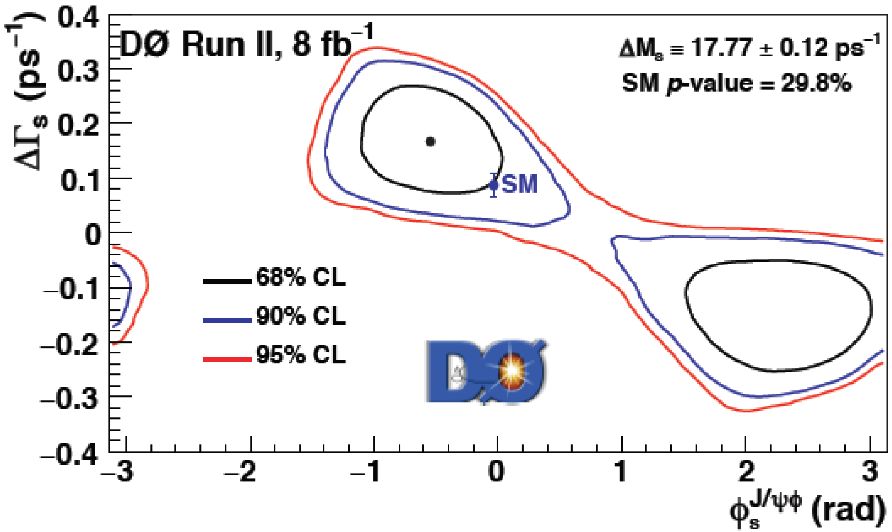
Much quicker and more lightweight offline procedure required; TURBO route allows instant analysis !

Mixing induced CPV in B_s system

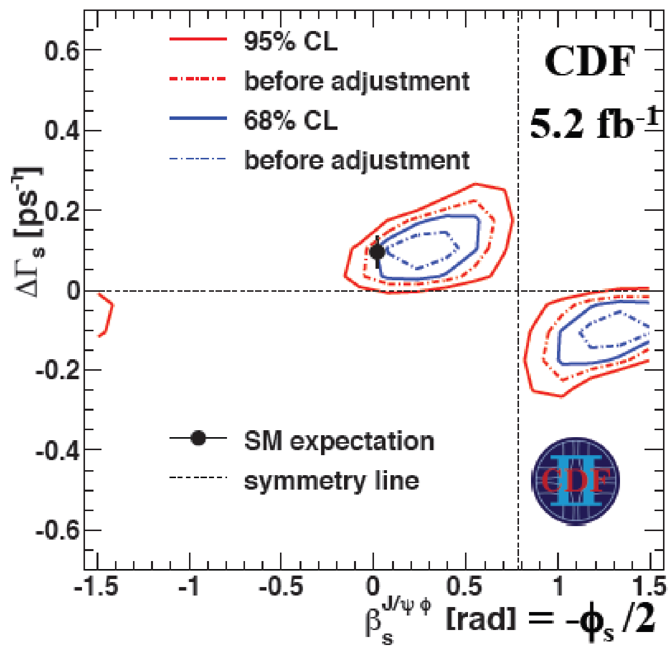
CPV phase, φ_s, in B_s mixing-decay interference, *e.g.* measured in $B_s \rightarrow J/\Psi\Phi$, very small & precisely predicted in SM. Box diagram offers tempting entry point for NP !

Tevatron results were tantalising with early data and remain intriguing with final sample:

[PRD 85 (2012) 032006]



[PRD 85 (2012) 072002]



Results are consistent, & both are ~1σ away from SM. What about the LHC?

Mixing induced CPV in B_s system

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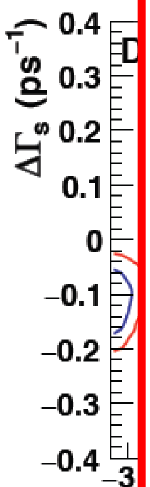
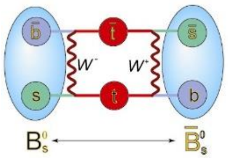
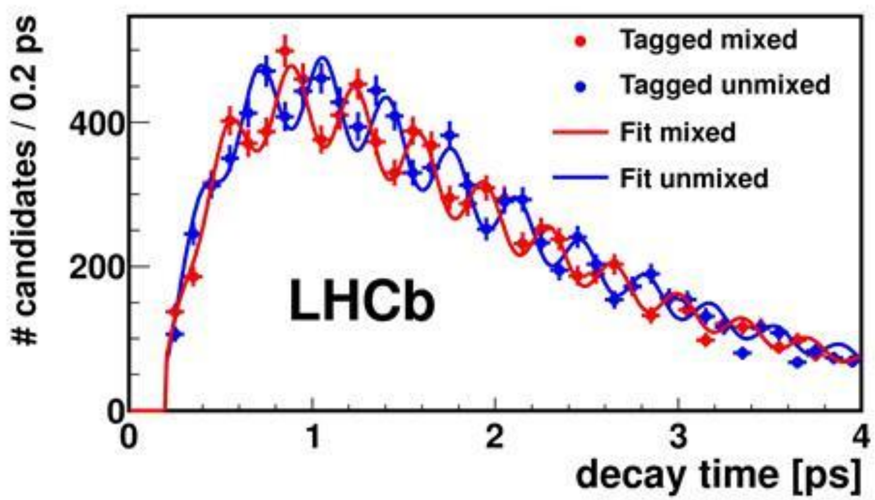
Tevatr... data ar...

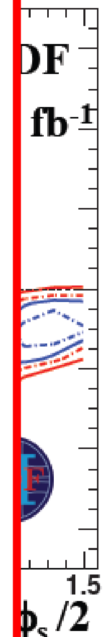


LHCb designed with excellent time resolution, necessary to resolve the rapid B_s-$\bar{B}_s$ oscillations:





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

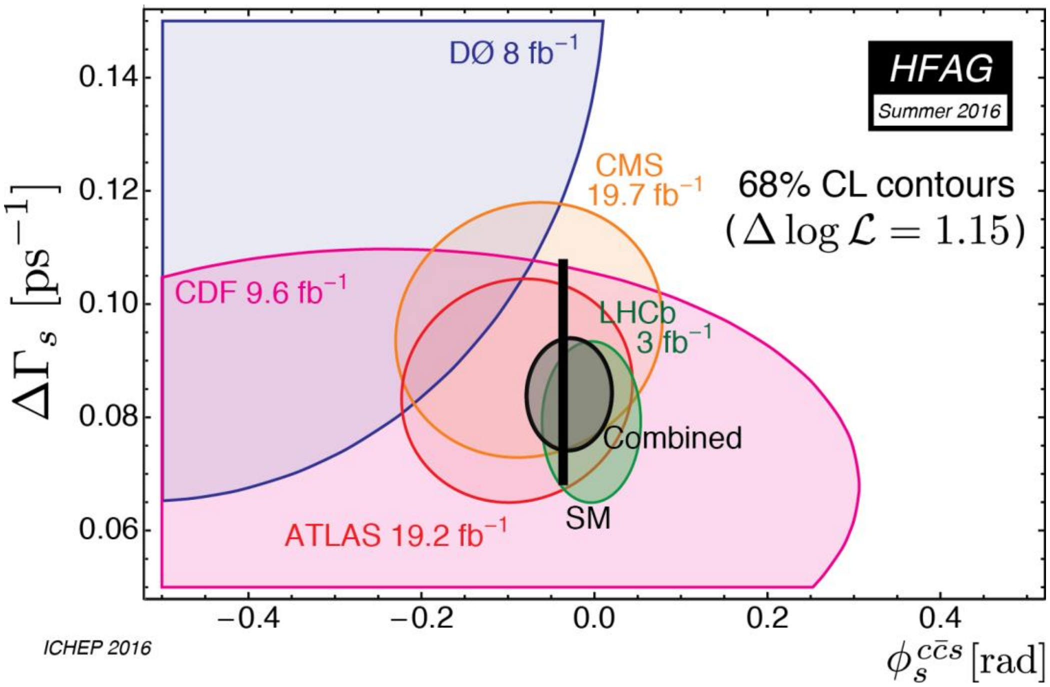


In addition: additional channels and very large data samples.

Results are consistent, & both are ~1σ away from SM. What about the LHC?

Precision studies of Φ_s

LHCb has now completed its run-1 measurement of φ_s, attaining a precision ~20x better than Tevatron in $B_s \to J/\psi\varphi(KK)$ [PRL 114 (2015) 041801] & adding important new modes *e.g.* $B_s \to J/\psi\pi\pi$ [PLB 736 (2014) 186]. Earlier hints of *large* NP effects have gone…



Precise measurements also coming from ATLAS & CMS !

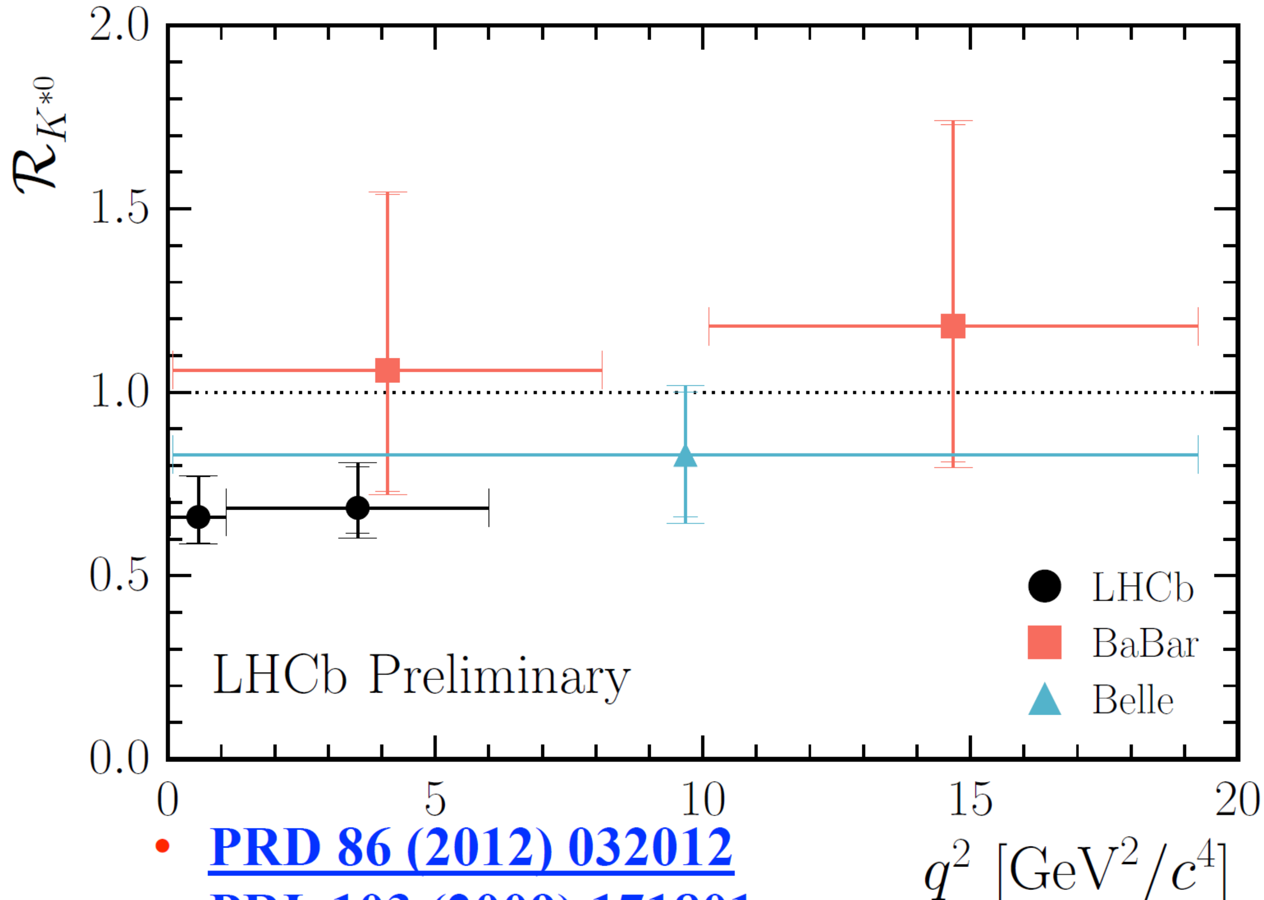
[ATLAS JHEP 08 (2016) 147; CMS, PLB 757 (2016) 97]

New updates from LHCb, exploiting high mass KK region in $B_s \to J/\psi KK$ not included

[LHCb-PAPER-2017-008]

...but observable remains a priori very sensitive to non-SM contributions and essential to improve precision in run 2, and in particular at Upgrade.

All measurements: R_{K*}



- PRD 86 (2012) 032012
- PRL 103 (2009) 171801