LHCb highlights

- Flavour physics
  - a topic of intrinsic interest
  - a tool for indirect discovery
- LHCb overview
- *Selected* recent results
  - Rare decays & FCNCs
  - CPV & unitarity triangle tests
  - Spectroscopy & exotics
- Run 2 and the voyage beyond

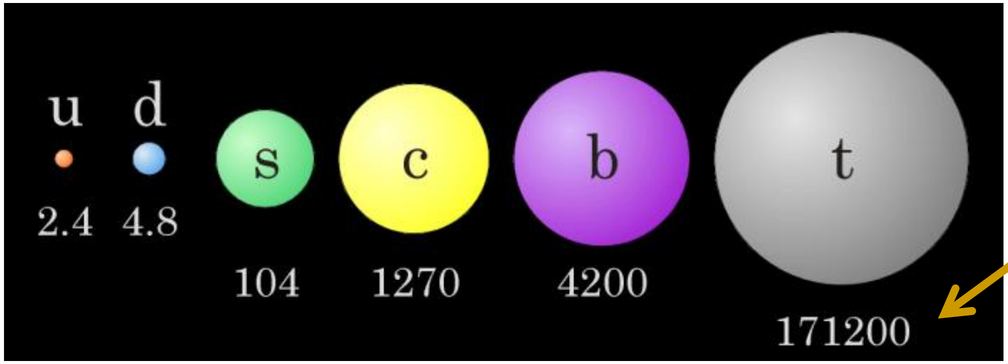
The cyclops pursuing Acis on Mt Etna

Guy Wilkinson, University of Oxford and CERN, June 2015

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 ?

see Thursday talk by Harald Fritsch

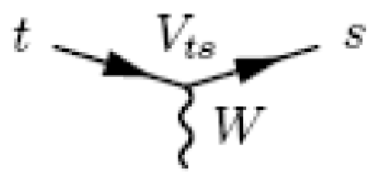
No answer yet !
These values (i.e. ‘3’ & the masses) are free parameters of the SM

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.

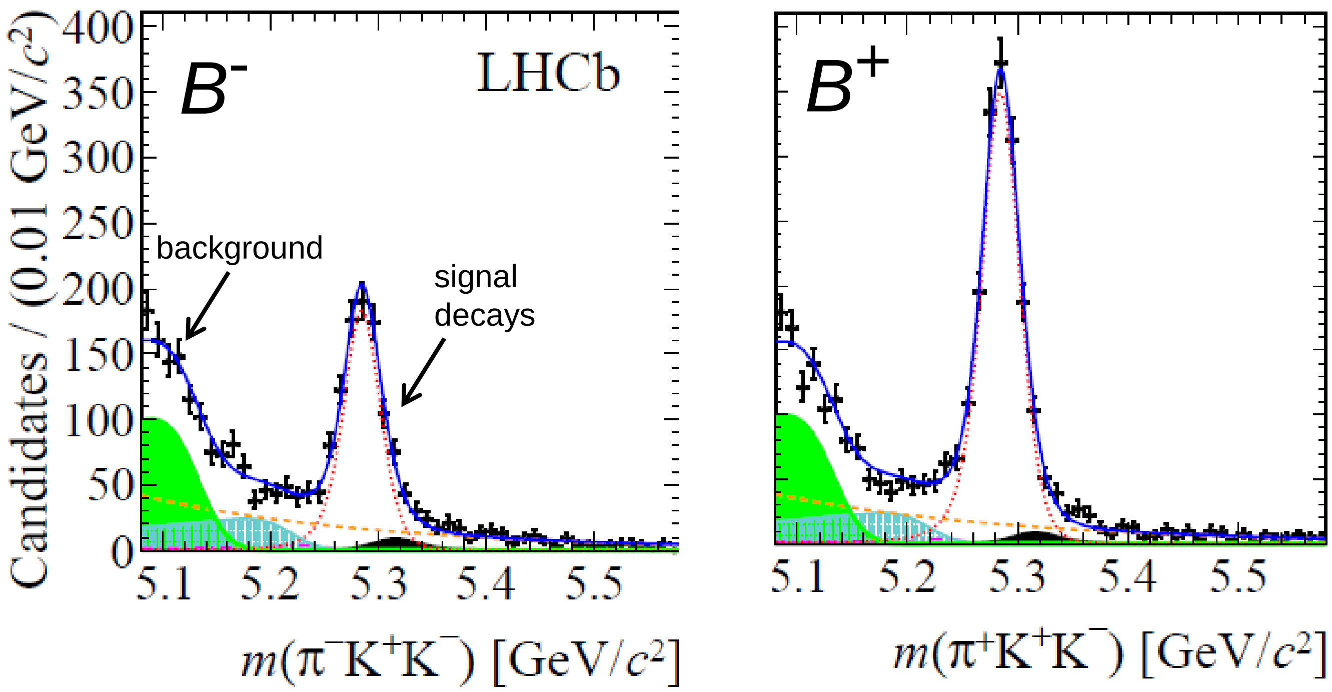
The CKM matrix is also linked to another big puzzle of flavour physics…

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…

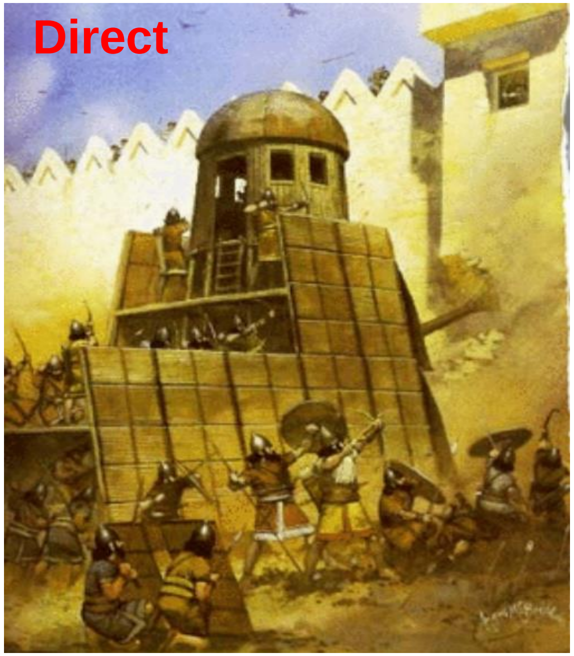


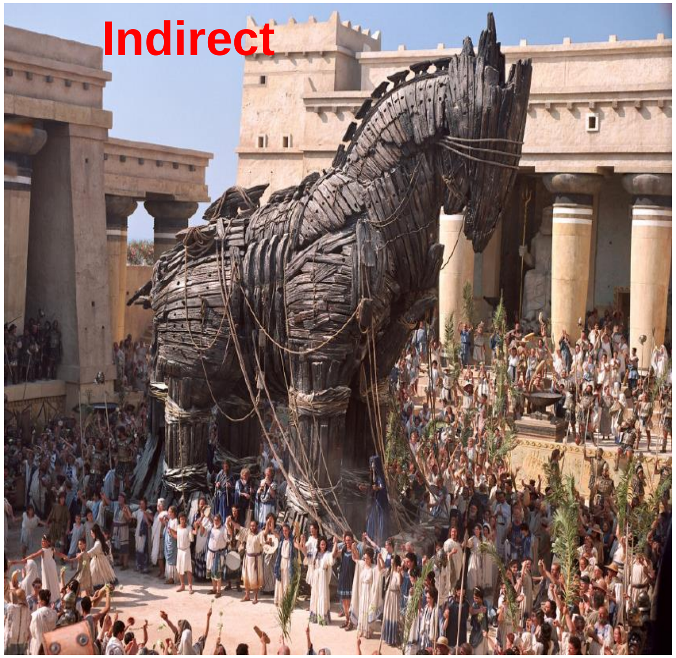
[LHCb, PRD 90 (2014) 112004]

…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

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.





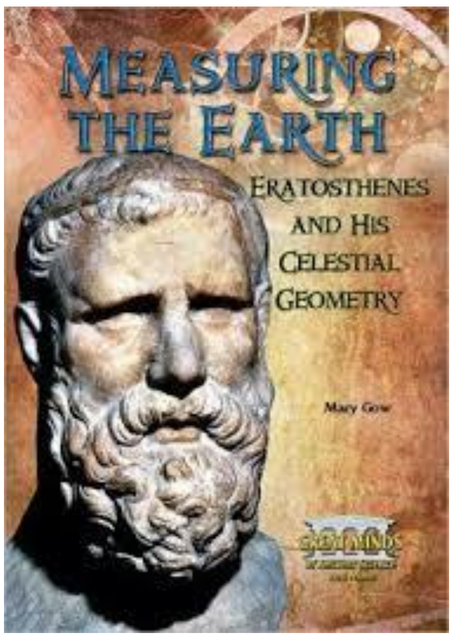
Use the high energy of the LHC to produce the New Physics particles, which we then detect

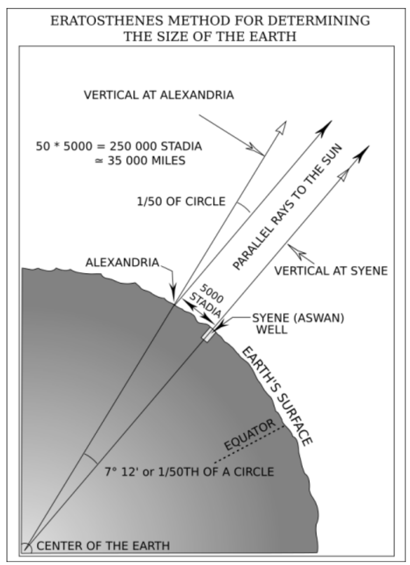
Make precise measurements of processes in which New Physics particles enter through 'virtual loops'

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…

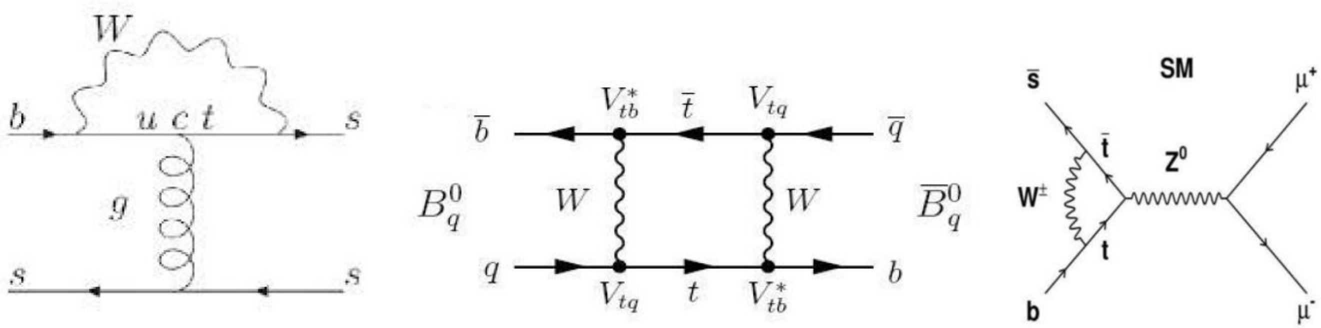




…around 2.2 thousand years prior to the direct observation.

Indirect measurements – an established tradition in science

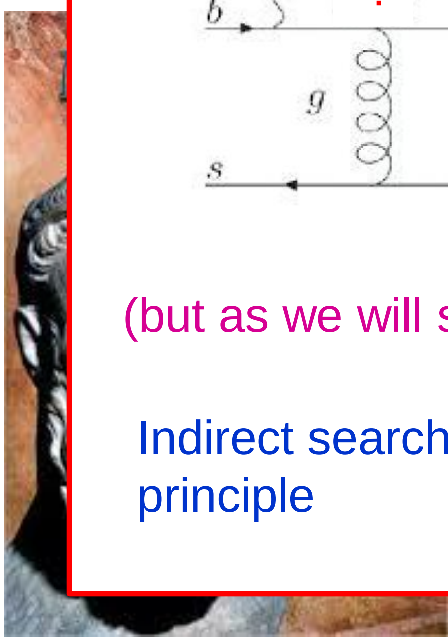
In flavour physics the guiding principle is to probe processes where loop diagrams are important, as here non-SM particles may contribute



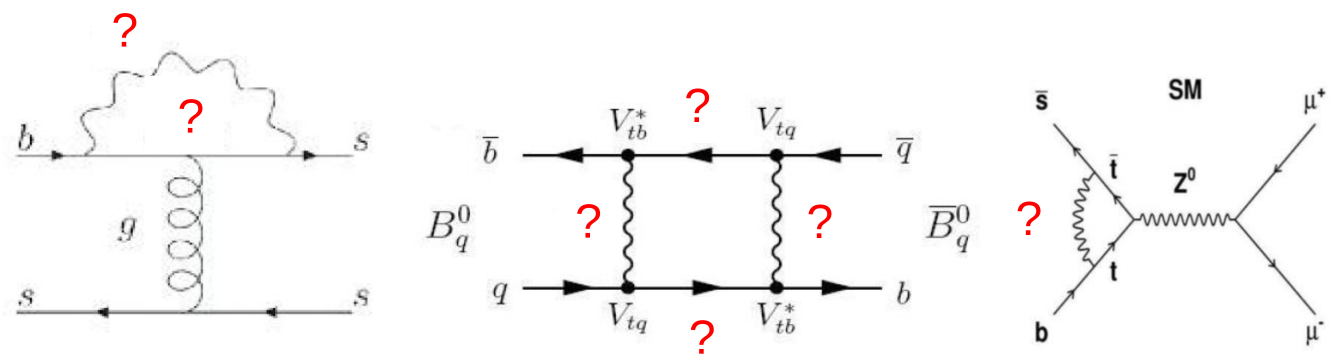
(but as we will see, tree-mediated decays also have their role to play)

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).

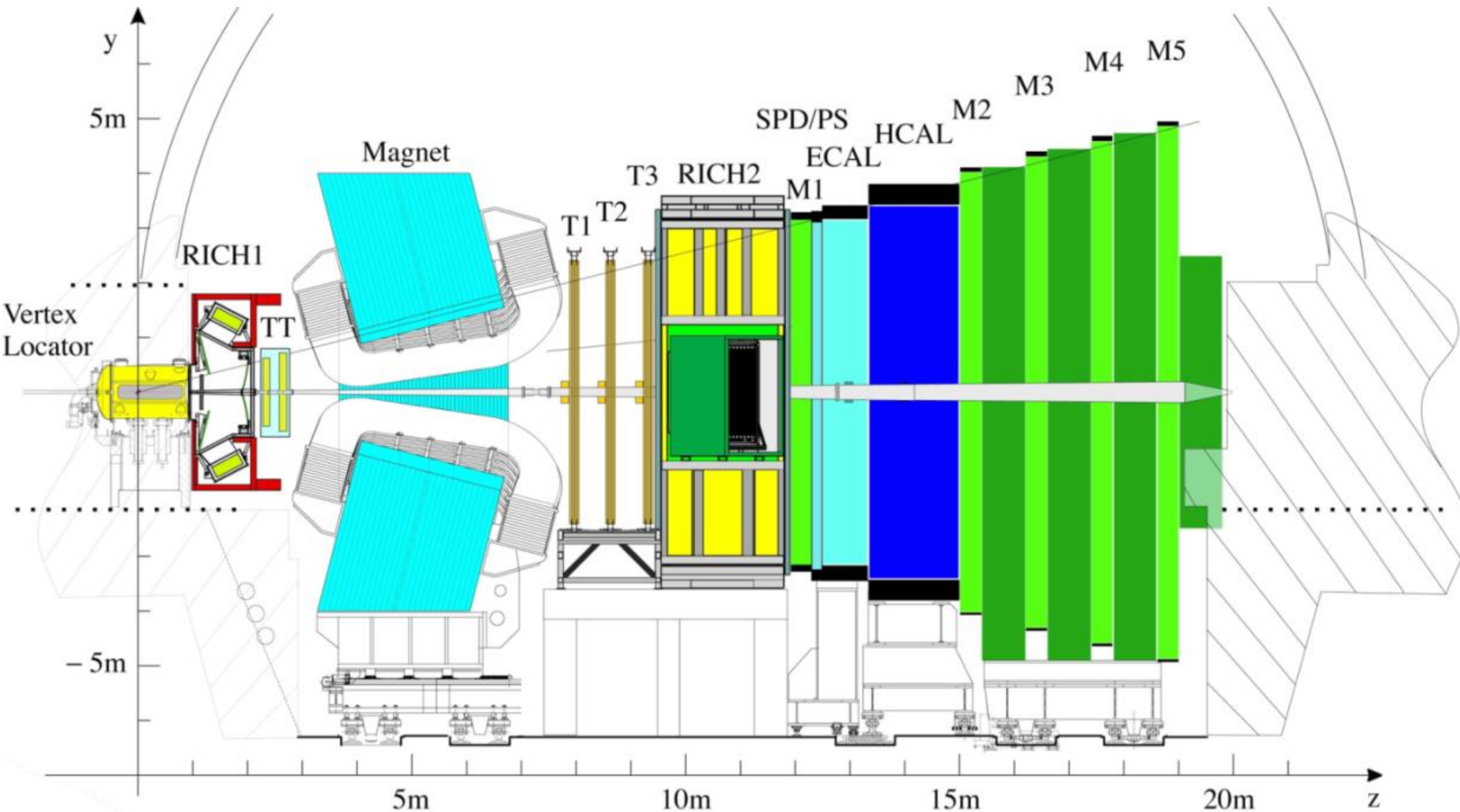
Indirect search principle ➡ Precise measurements of low energy phenomena tells us about unknown physics at higher energies

LHCb – a flavour physics experiment at the LHC

A collaboration of ~1100 members from 68 institutes in 16 countries

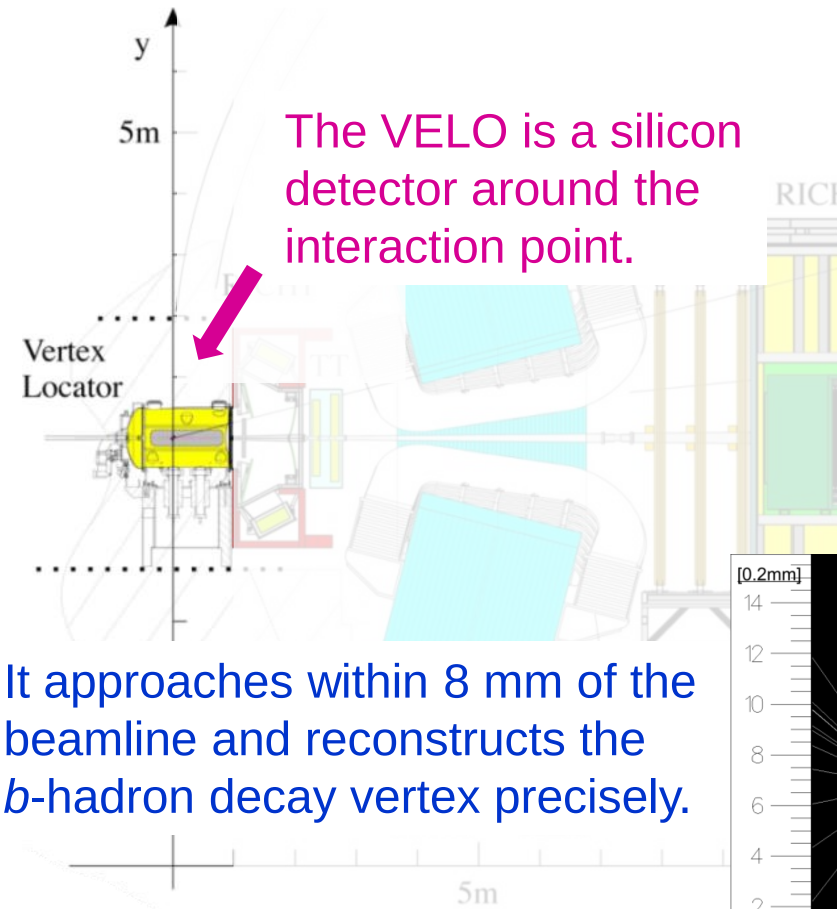
An experiment to search for physics beyond the Standard Model, through flavour studies of beauty- and charm-hadrons (and general forward physics)

LHCb – a forward spectrometer for flavour physics



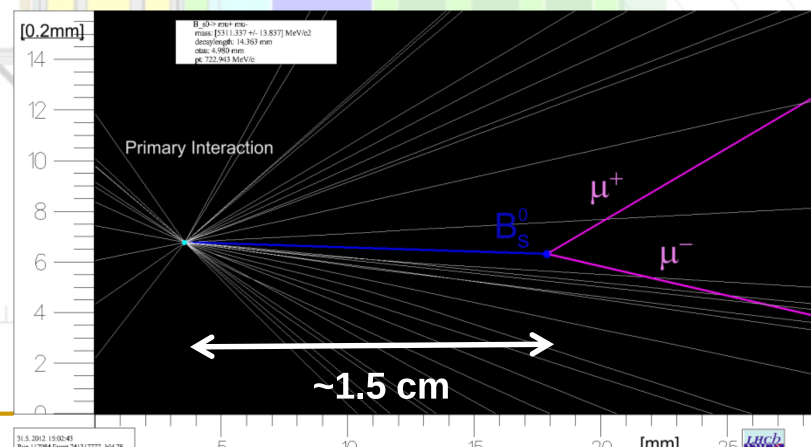
LHCb – a forward spectrometer for flavour physics

The VELO is a silicon detector around the interaction point.



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

One-half of the VELO under construction

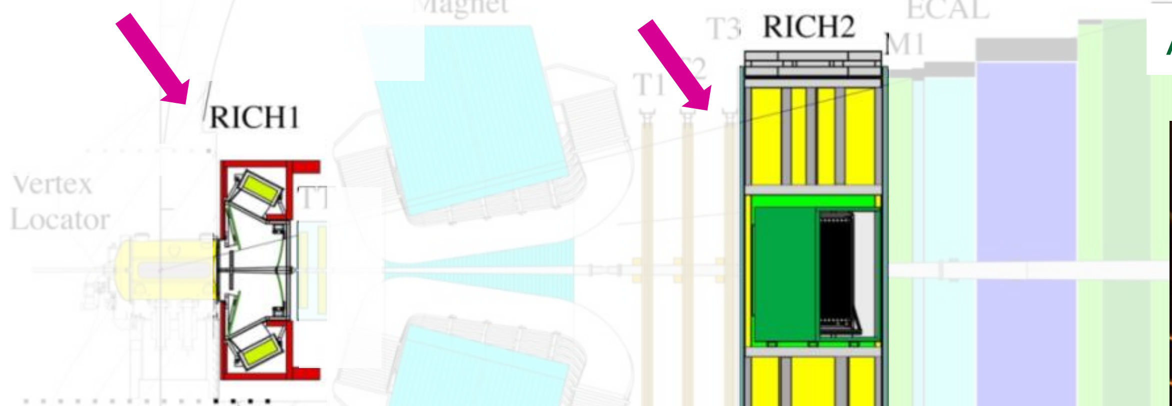


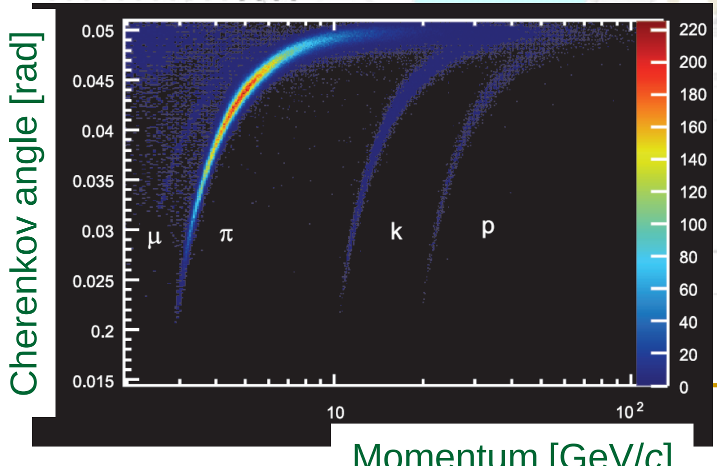
A reconstructed *b*-hadron decay vertex

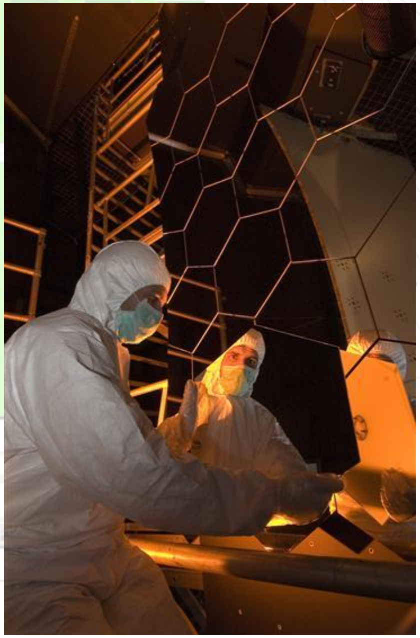
LHCb – a forward spectrometer for flavour physics

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

Array of RICH photodetectors



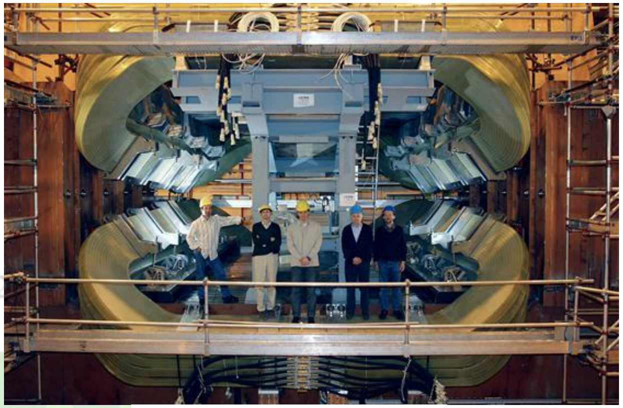




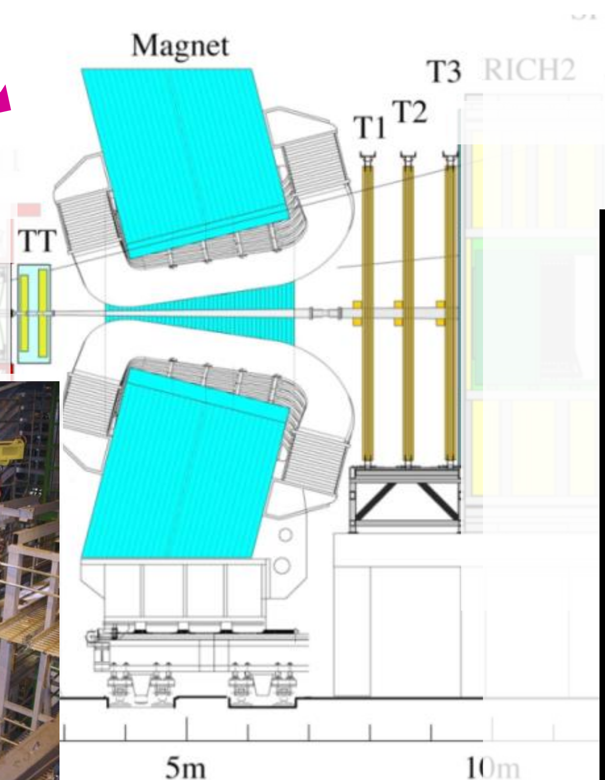
Assembling RICH 2; note the mirrors

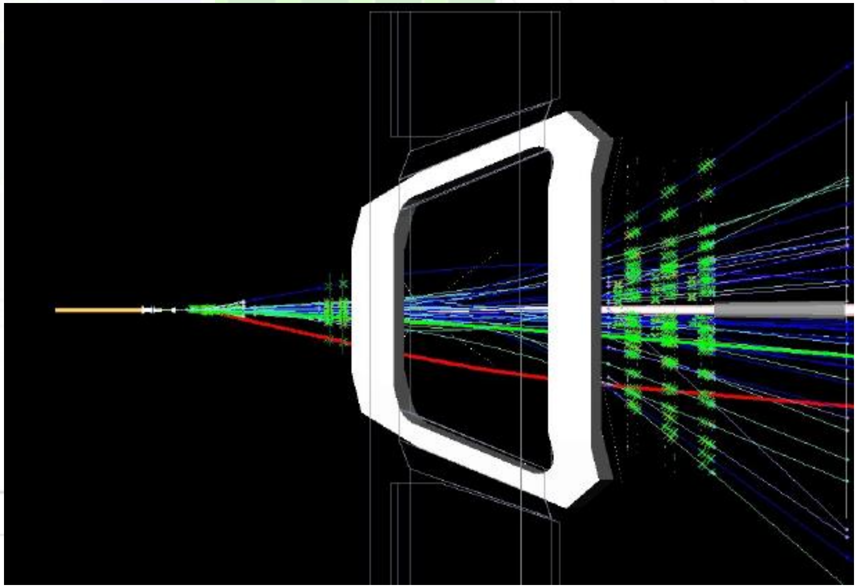
LHCb – a forward spectrometer for flavour physics

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

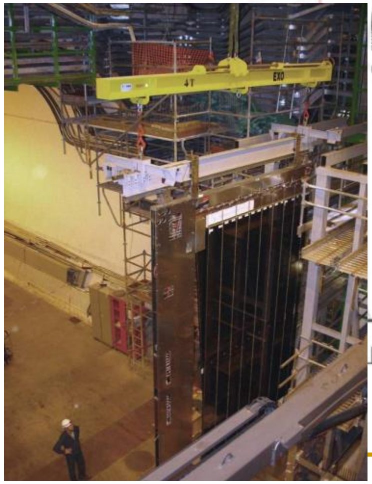


Dipole magnet





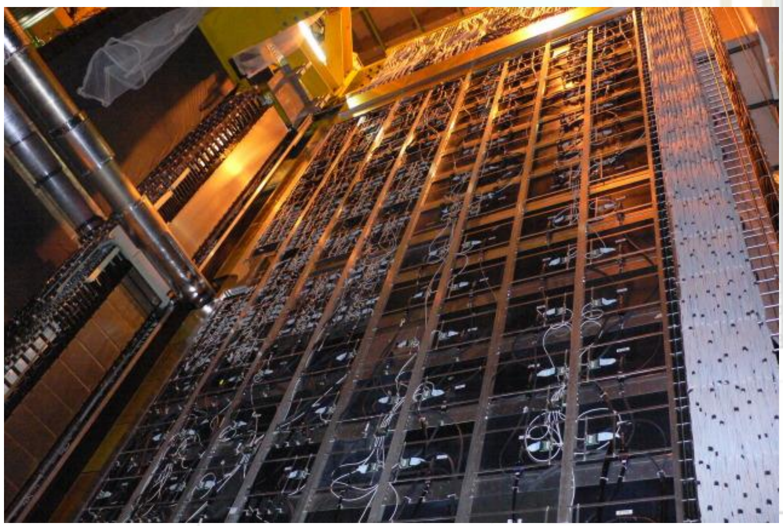
Reconstructed tracks



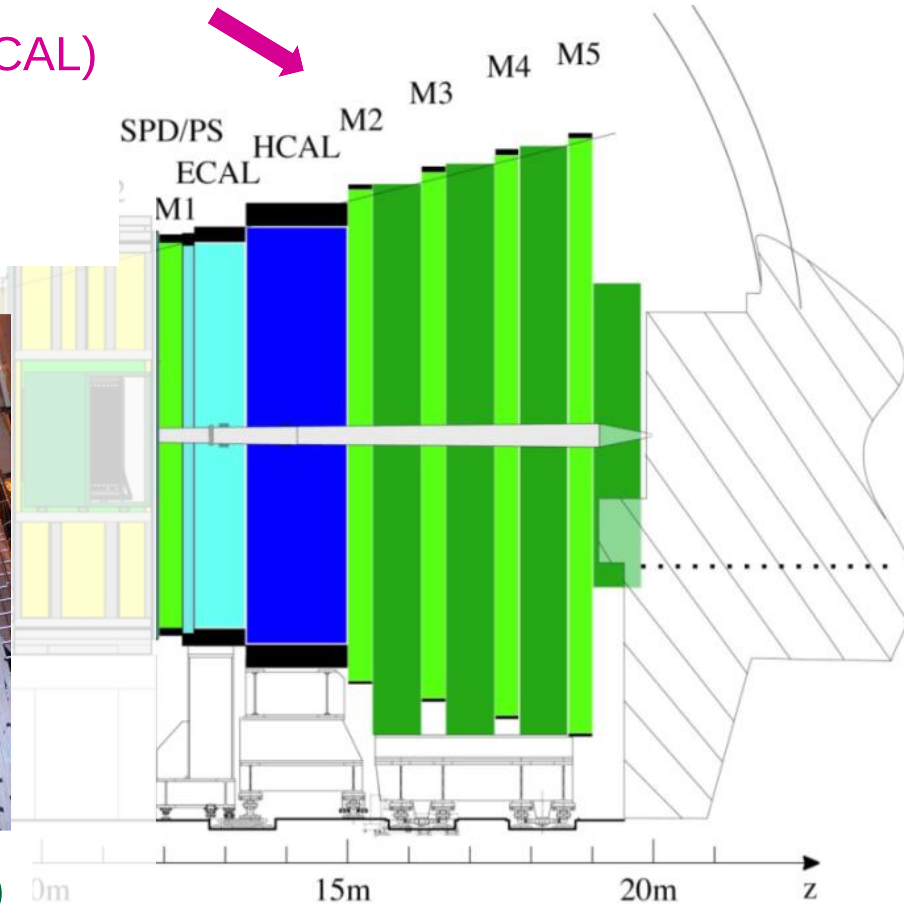
Part of outer tracker

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.



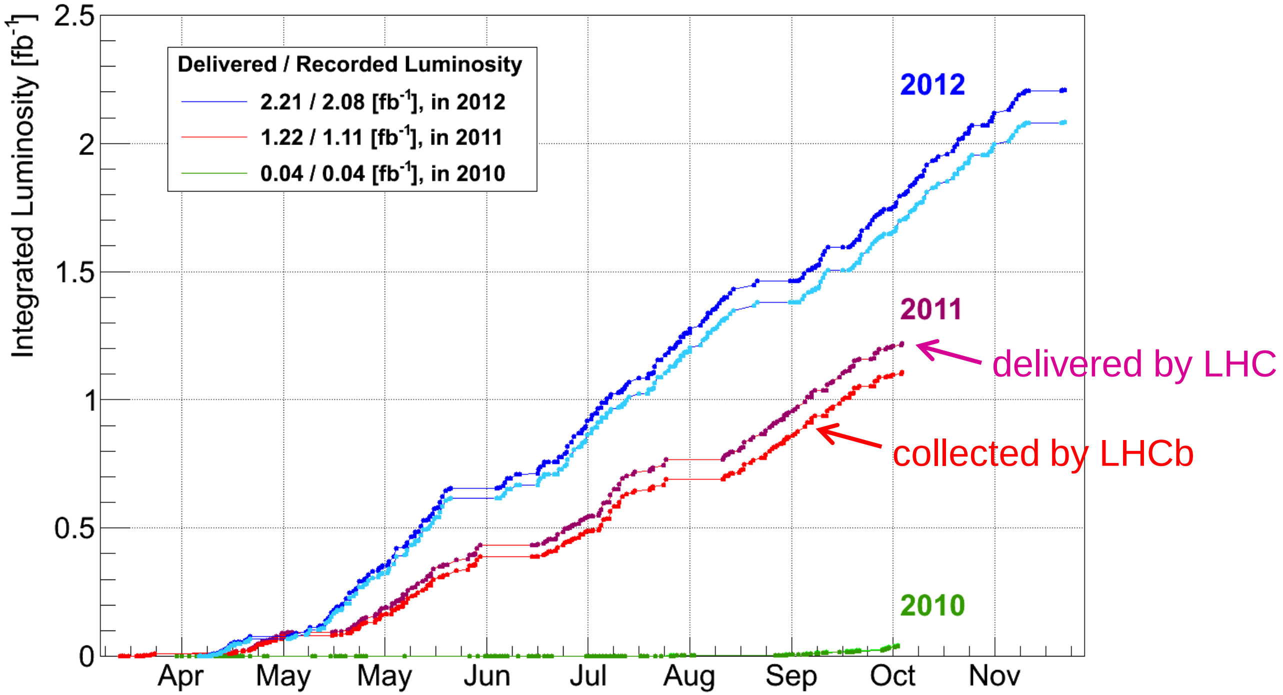
Part of calorimeter system (preshower)



These detectors are particularly important for the role they play in the LHCb trigger

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).



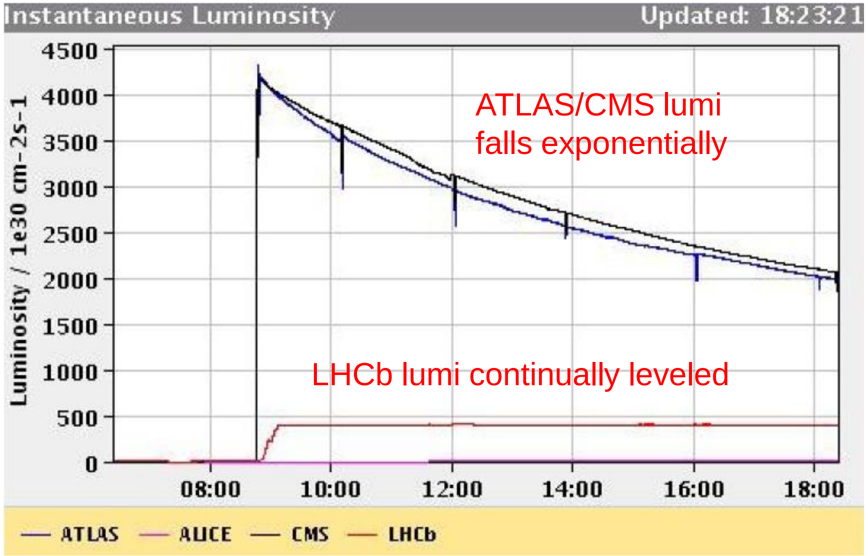
We have just emerged from a 2 year shutdown, necessary to upgrade LHC energy.

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

LHCb – the story so far

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

LHCb deliberately operates at lower luminosity than ATLAS/CMS

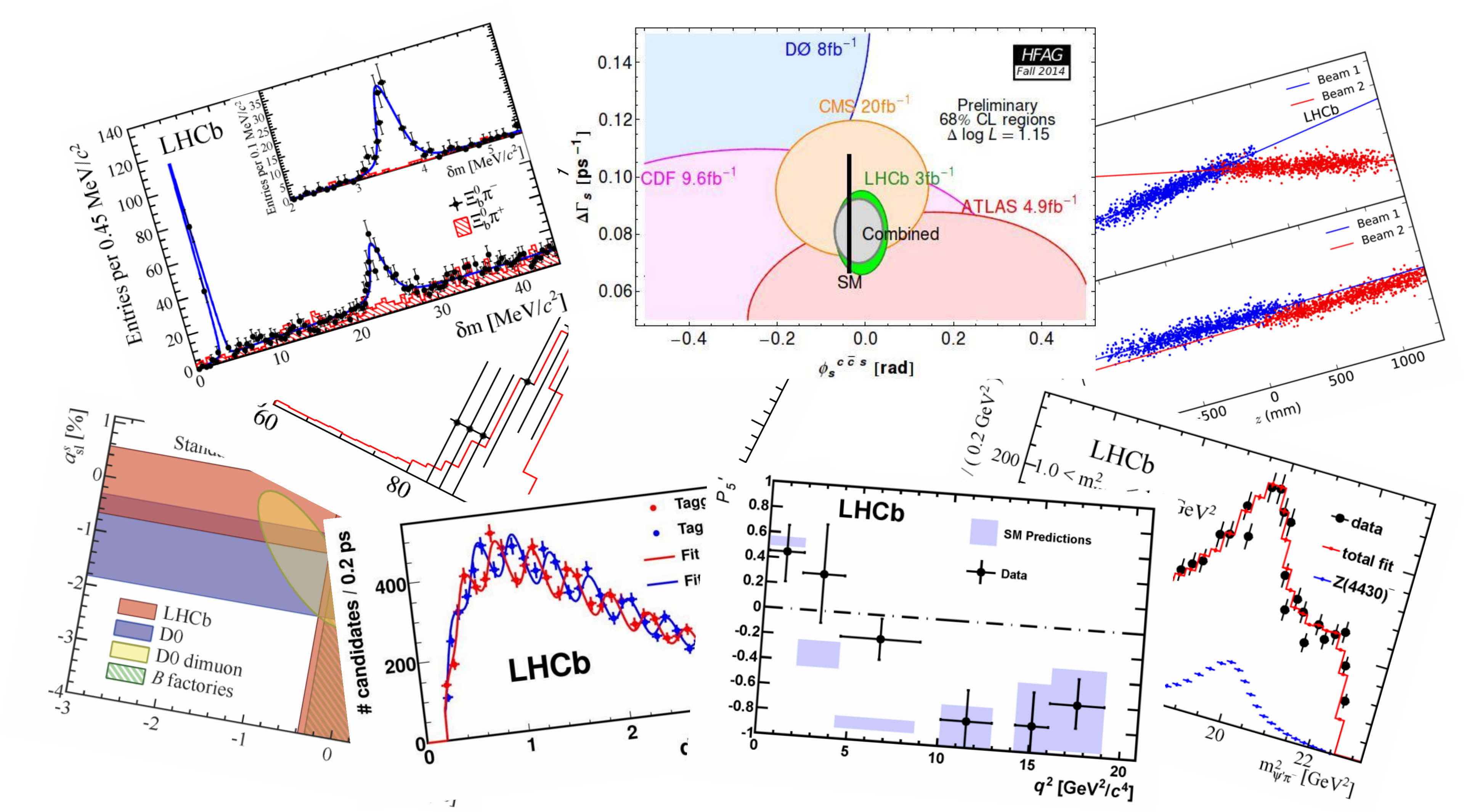


This is (current) best choice for precision *b*-physics measurements.

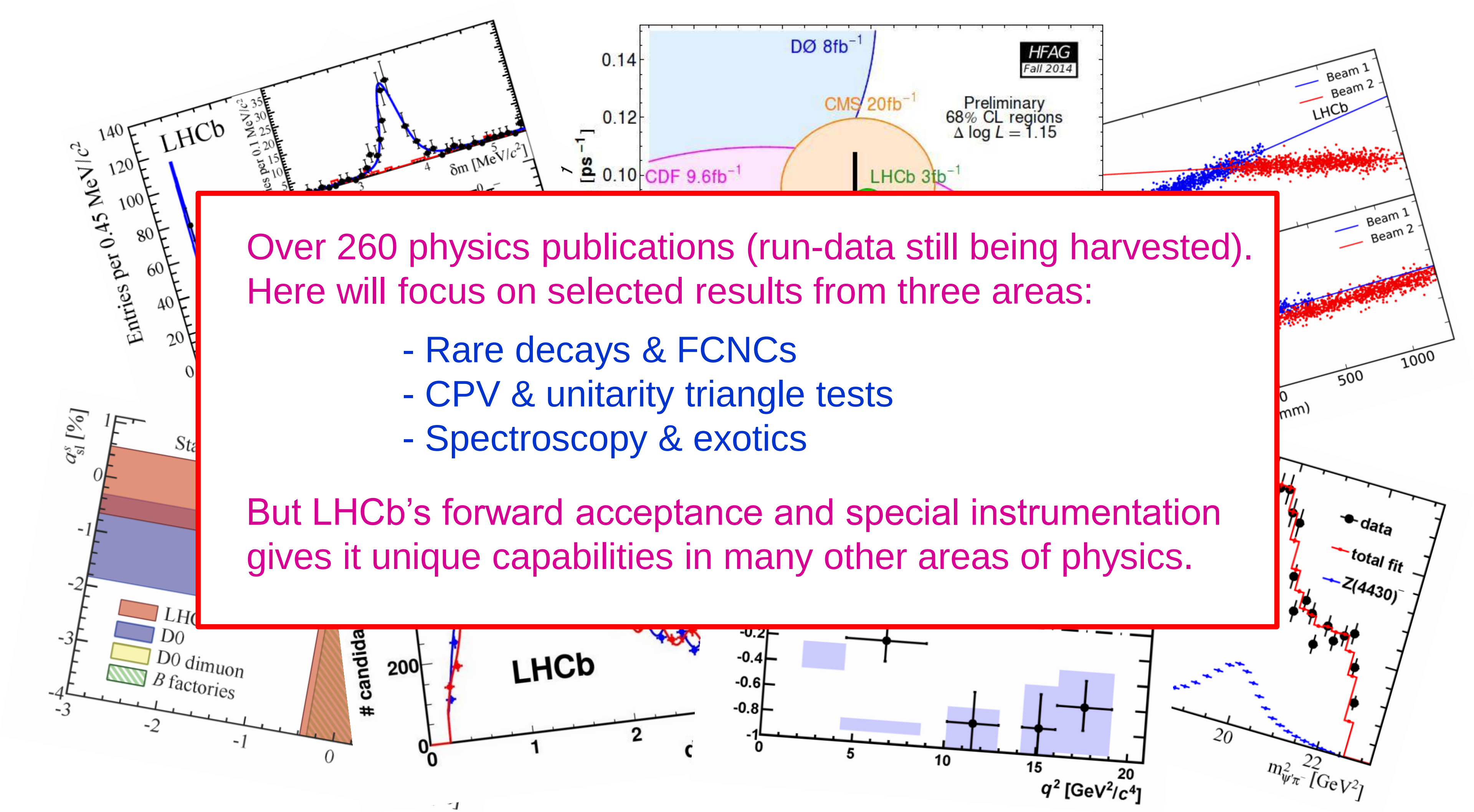
We have just emerged from a 2 year shutdown, necessary to upgrade LHC energy.

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

Selected physics results



Selected physics results



Over 260 physics publications (run-data still being harvested). Here will focus on selected results from three areas:

- Rare decays & FCNCs
- CPV & unitarity triangle tests
- Spectroscopy & exotics

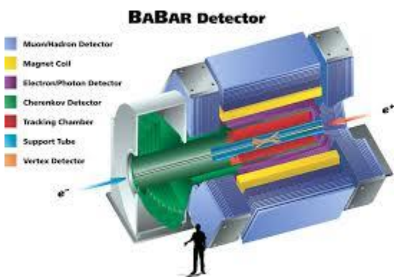
But LHCb's forward acceptance and special instrumentation gives it unique capabilities in many other areas of physics.

Experimental glossary

To understand LHCb's role
it is useful to know the context
of previous & current experiments

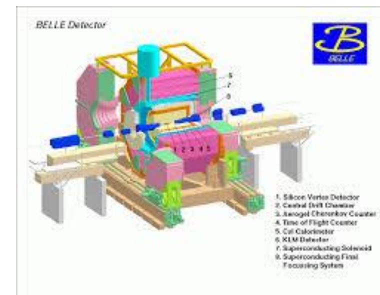
b-factories

also LEP, ARGUS, CLEO, BES-III



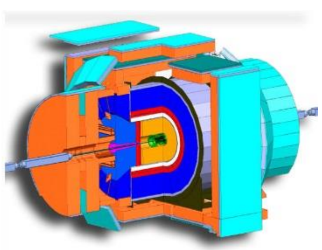
BaBar (SLAC) & Belle (KEK)

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.



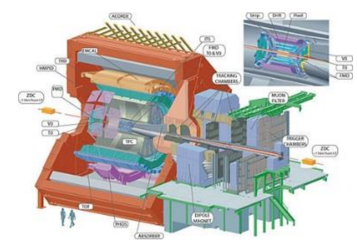
Tevatron experiments

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.

‘Rare decays’ and FCNCs

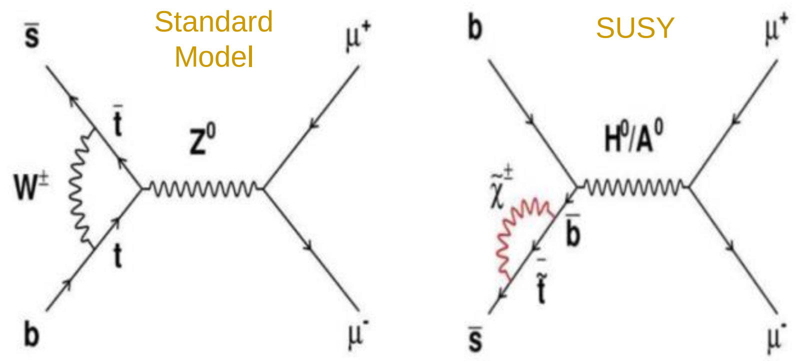
- In search of the super-rare: $B_{s,d} \to \mu^+\mu^-$
- Electroweak penguins: $B \to K^{(*)} l^+ l^-$
- Trouble at tree-level: $B \to D^* \tau \nu$

Searching for a rare object

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

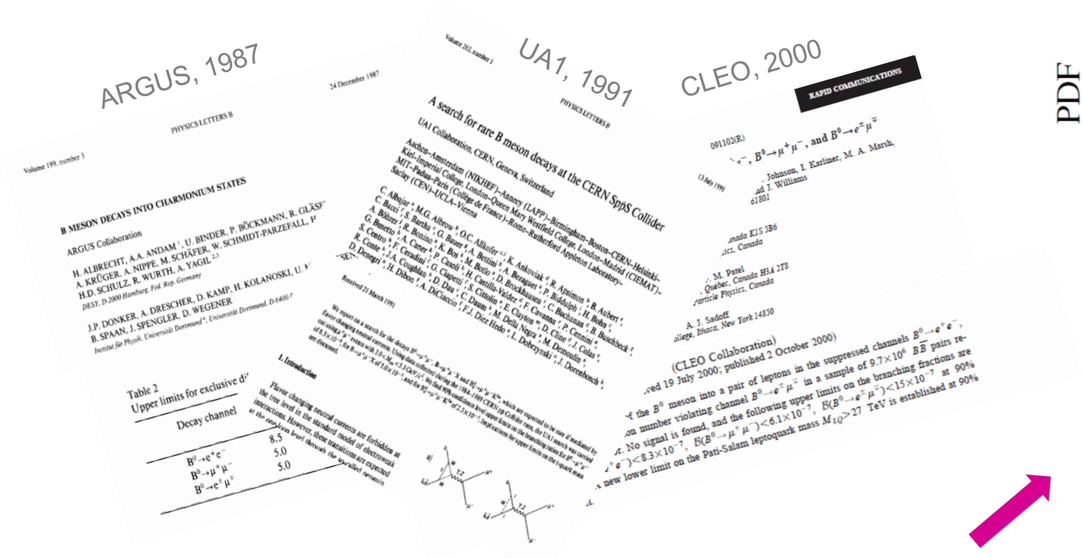
This decay mode can only proceed through suppressed loop diagrams.

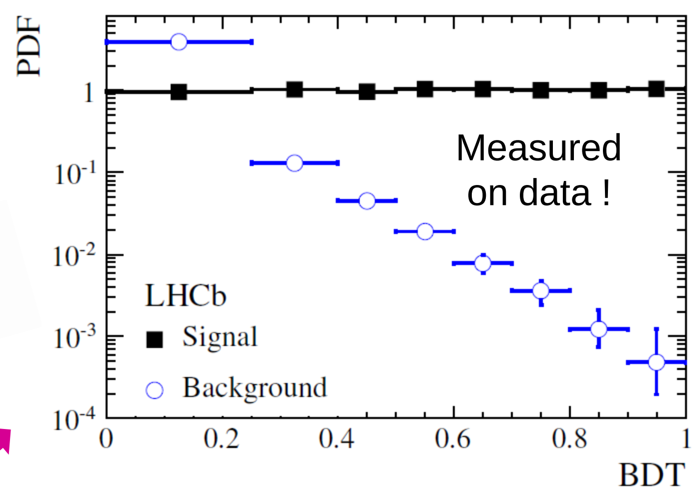
In the Standard Model it happens extremely rarely (~10^{-9}), but the exact rate is very well predicted



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

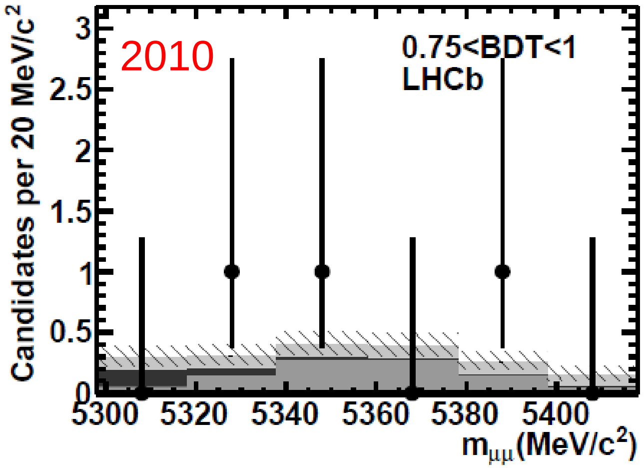




[PRL 111 (2013) 101805]

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

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



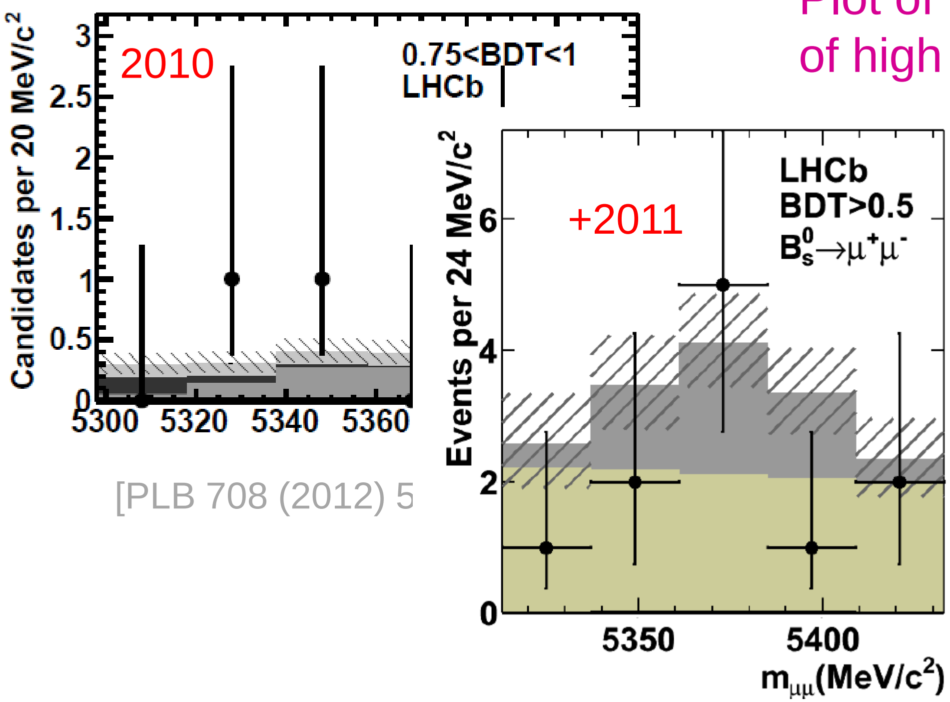
[PLB 708 (2012) 55]

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

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



[PLB 708 (2012) 5

[PRL 108 (2012) 231801]

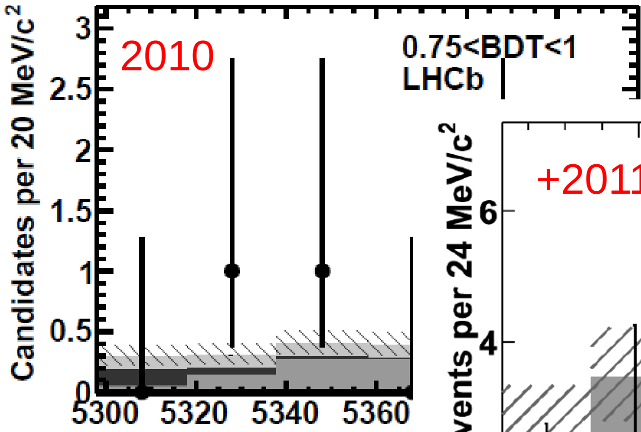
Plot of invariant mass distribution in region of high BDT sensitivity – if there is a signal we should see a peak here (but the BDT uses much more information than the invariant mass alone !)

+ 2011

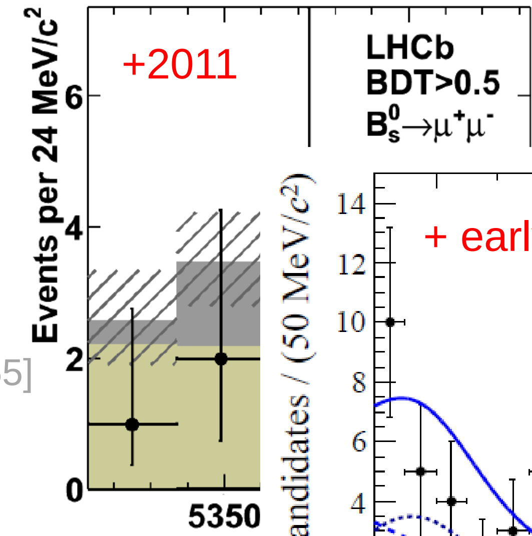
Maybe a hint of a bump, but nothing can be claimed

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

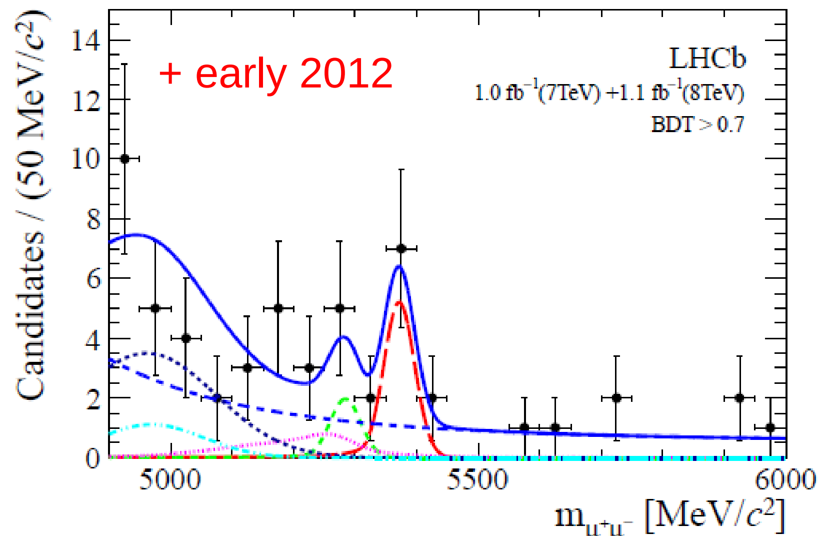
Plot of invariant mass distribution in region of high BDT sensitivity – if there is a signal we should see a peak here (but the BDT uses much more information than the invariant mass alone !)



[PLB 708 (2012) 55]



[PRL 108



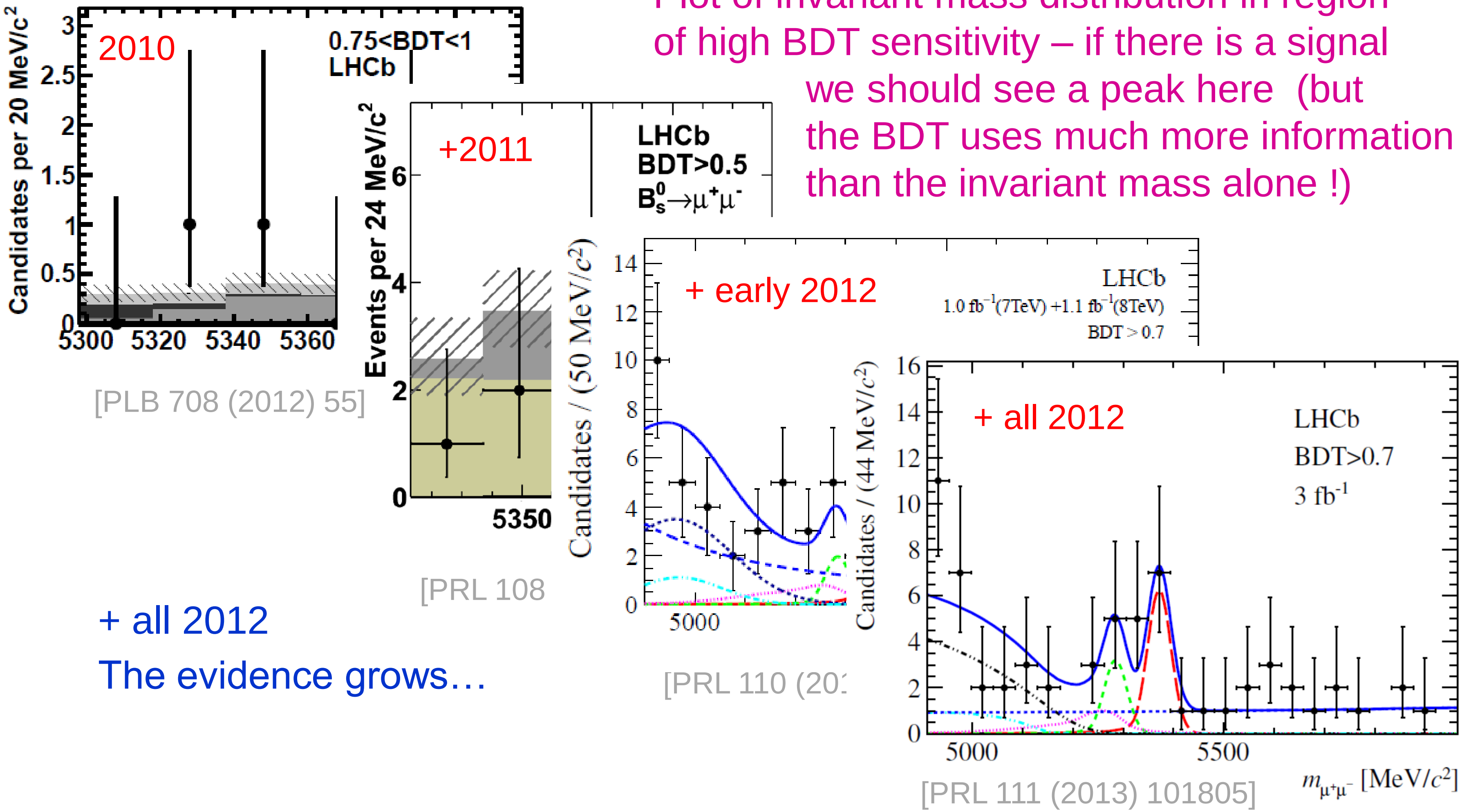
[PRL 110 (2013) 021801]

+ early 2012

First evidence that there is something there !

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

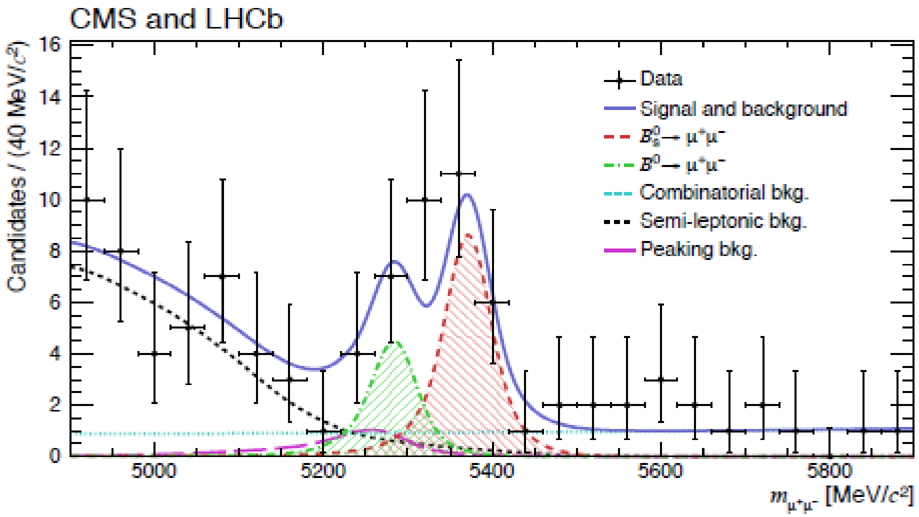


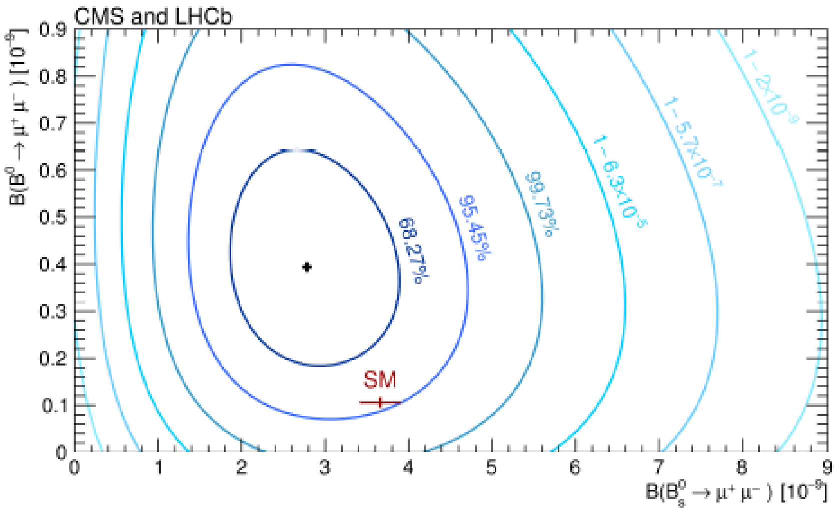
+ all 2012

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 !





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

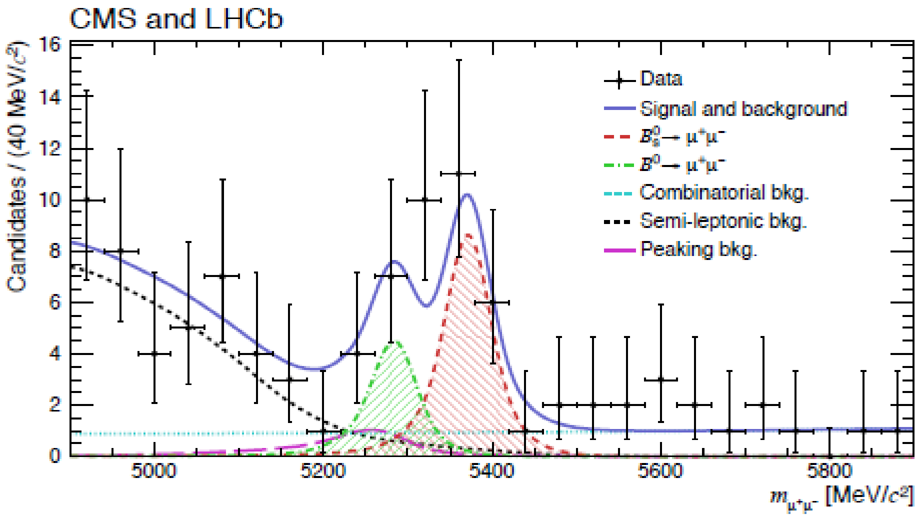
$$\mathcal{B}(B^0 \to \mu^+\mu^-) = \left(3.9\,^{+1.6}_{-1.4}\right) \times 10^{-10} \quad (3.0\sigma)$$

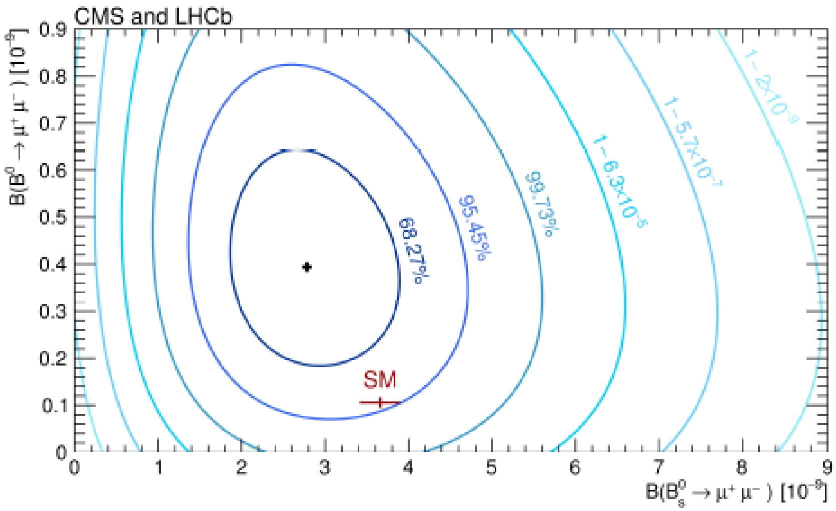
[arXiv:1411.4413, Nature 522 (2015) 68]

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 !

$B_{d,s} \to \mu\mu$: 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 !





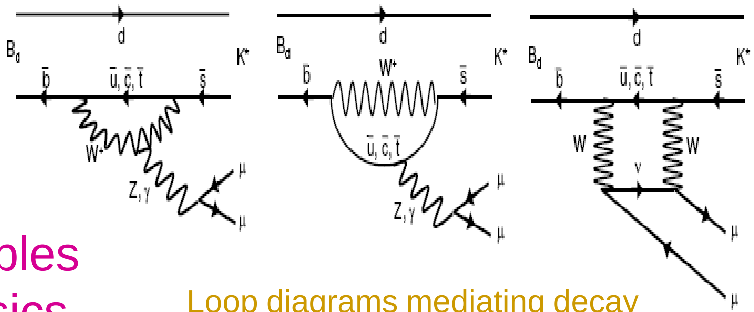
$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = \left(2.8\,^{+0.7}_{-0.6}\right) \times 10^{-9}$$ (6.2σ)

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

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

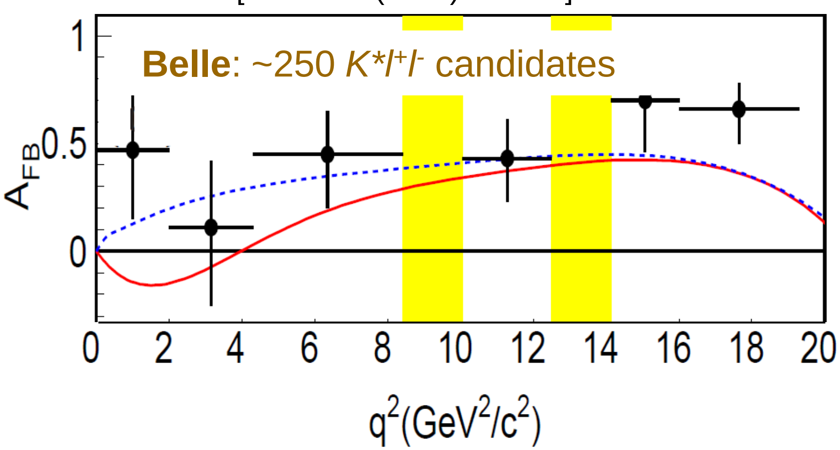


Loop diagrams mediating decay

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

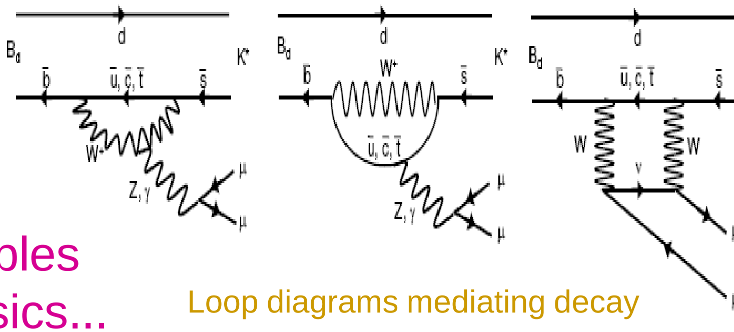
The B-factory experiments had inadequate statistics for meaningful tests. This has now all changed, *e.g.* forward-backward asymmetry vs dilepton q^2.

[PRL 103 (2009) 171801]



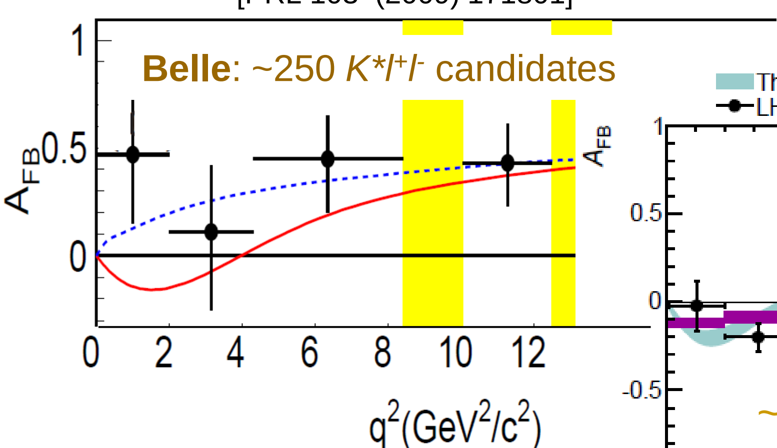
Hint of lying above prediction

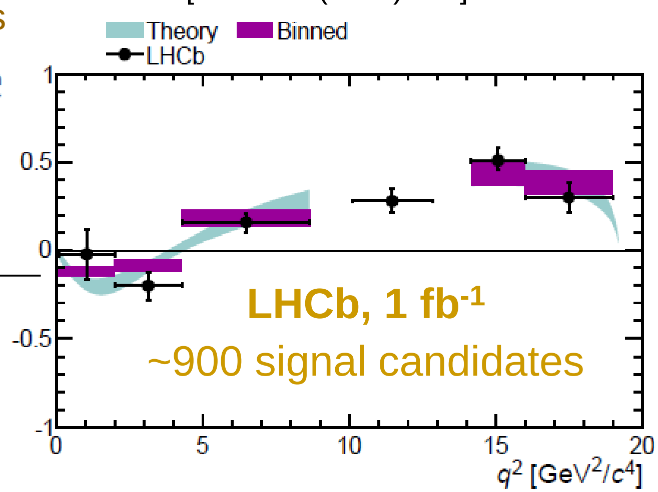
$B^0 \rightarrow K^* \mu^+ \mu^-$ and friends



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

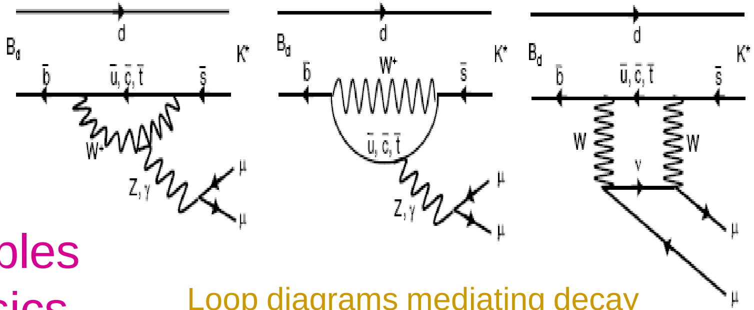
The *B*-factory experiments had inadequate statistics for meaningful tests.
This has now all changed, *e.g.* forward-backward asymmetry vs dilepton q^2.





'Textbook' behaviour within uncertainties

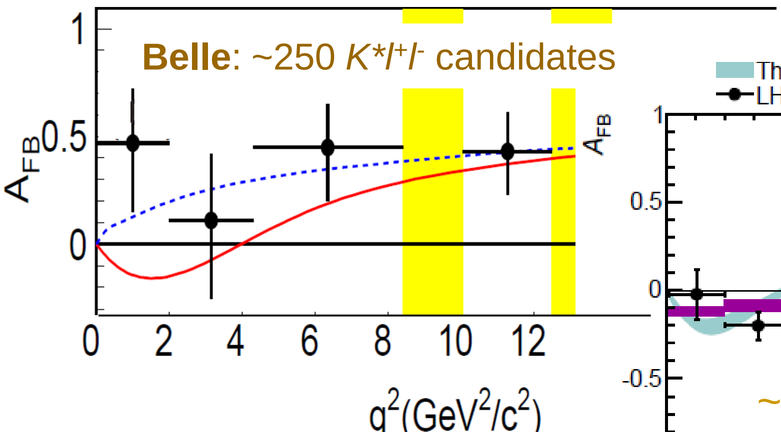
$B^0 \to K^* \mu^+ \mu^-$ and friends



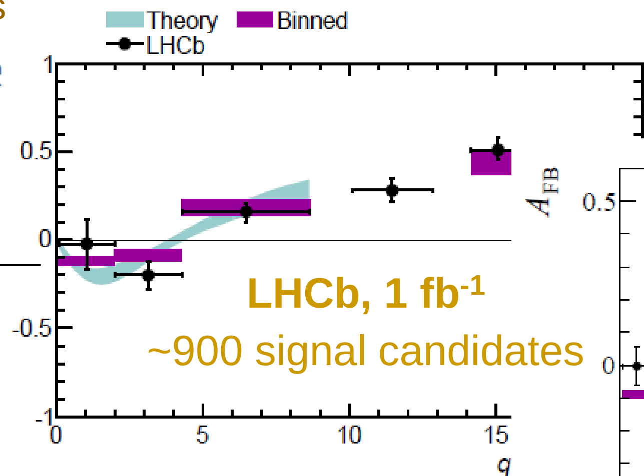
Decays such as $B^0 \to K^* l^+ l^-$ offer many observables which probe helicity structure of any New Physics...

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]

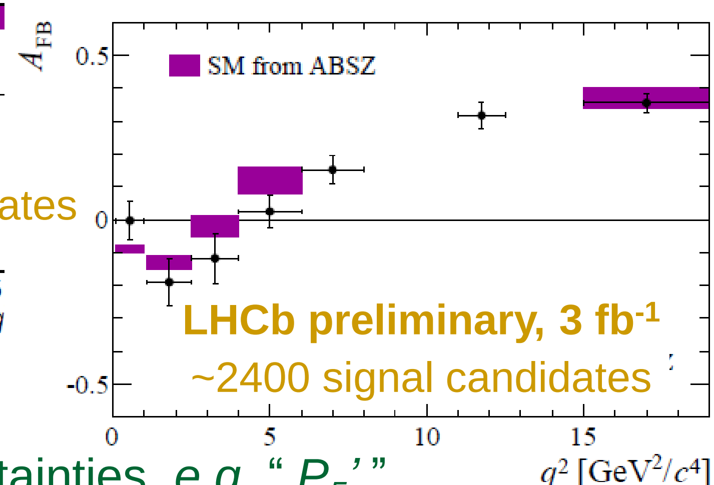


[JHEP 08 (2013) 131]



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

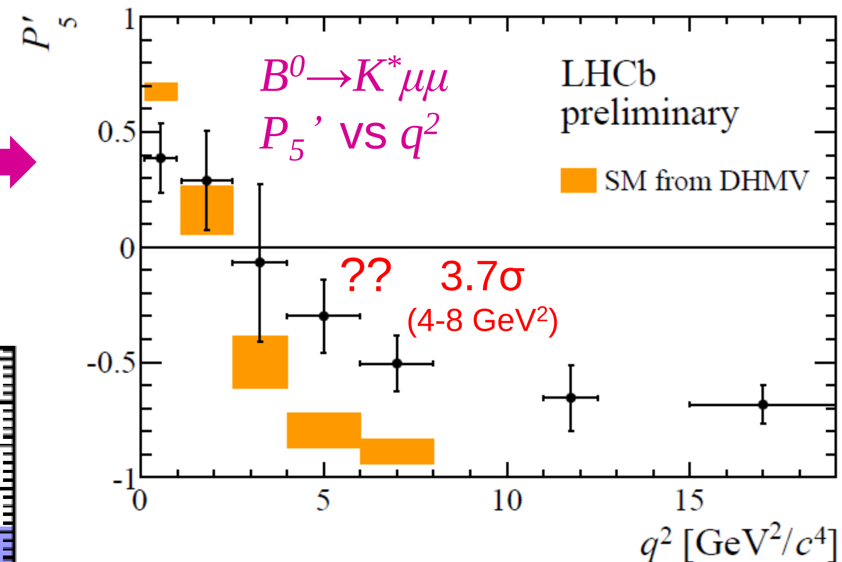
[LHCb-CONF-2015-002]



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' "

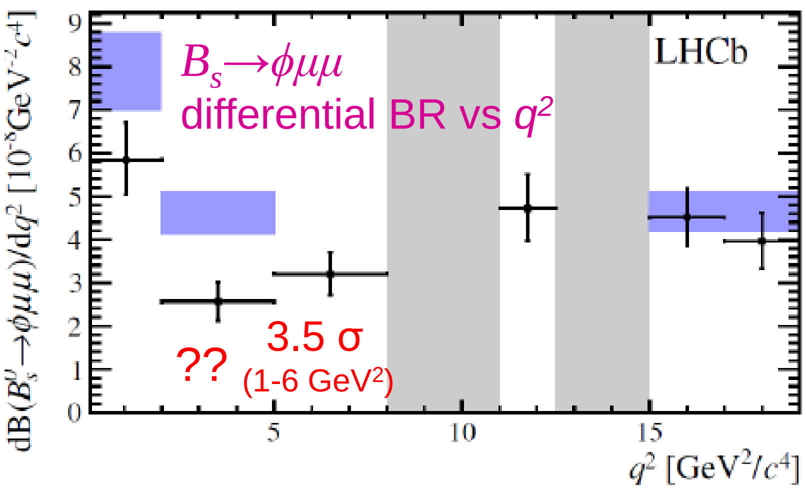
$B^0 \to K^* \mu^+ \mu^-$, $B_s \to \phi \mu^+ \mu^-$ and friends

One such observable is P_5': this showed a local discrepancy in the 1 fb^{-1} analysis which has persisted in the 3 fb^{-1} update.



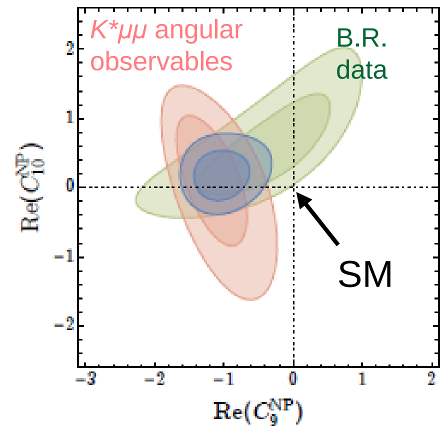
[LHCb-CONF-2015-002]

[LHCb-PAPER-2015-013]



There are other several slightly odd results in $b \to s l^+ l^-$ decays…

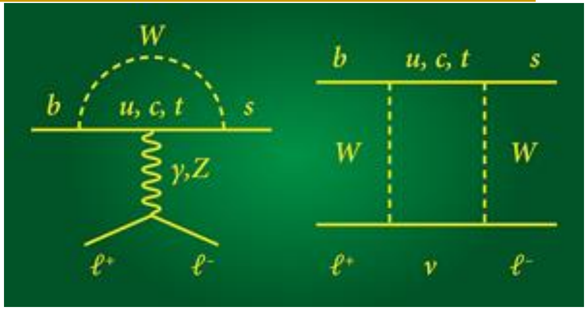
…which some (non-LHCb) people have sought to explain in a coherent way, *e.g.* through Wilson coefficient analysis



[Altmannshofer & Straub, arXiv:1503.06199]

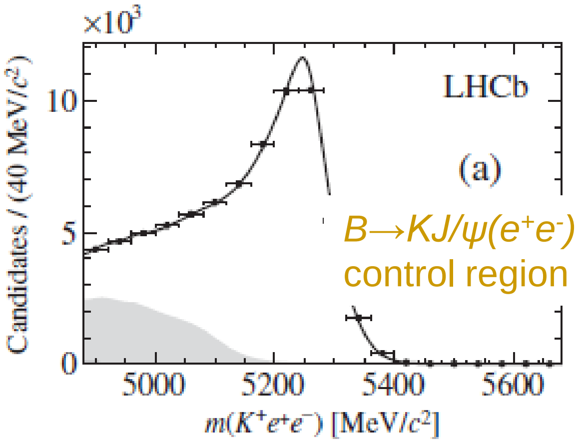
Does this point to New Physics or underestimated theory errors? Time and run 2 will tell us more !

Hints of lepton-flavour violation in $B \to K l^+ l^-$?



FCNC processes are also an excellent place to look for evidence of New Physics effects in contraction to the SM paradigm of lepton universality.

$\mu^+\mu^-$ vs e^+e^- ?



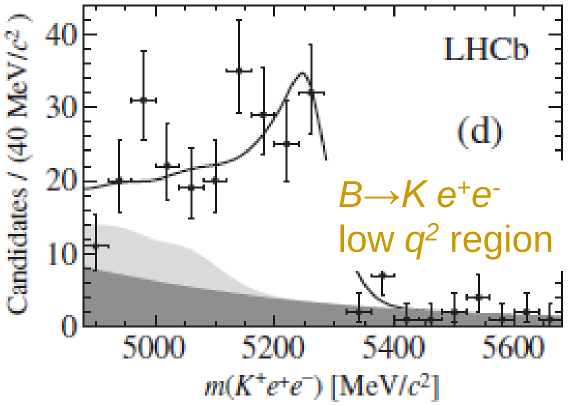
$B \to KJ/\psi(e^+e^-)$ control region

Example - test of lepton universality through R_K, the ratio of $B \to K\mu^+\mu^-$ to $B \to Ke^+e^-$ [PRL 113 (2014) 151601]

Control region gives R_K consistent with unity. Interesting, low q^2 region gives:

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

which is 2.6σ from unity (3σ if BaBar included).



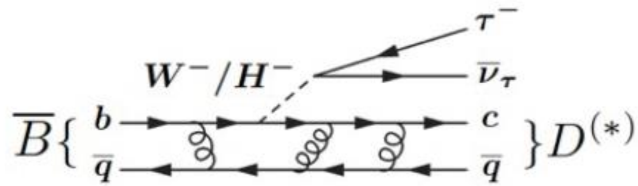
$B \to K e^+e^-$ low q^2 region

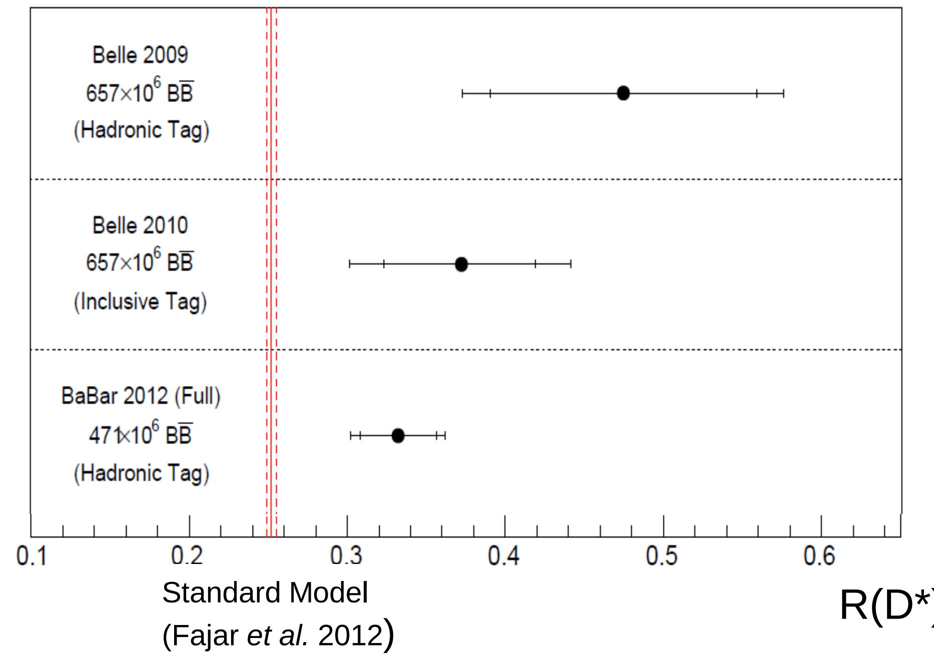
Follow up studies underway, *e.g.* $B \to K^* l^+ l^-$

This is not the first hint of LFV effects in B decays…

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

$B \to D^*\tau\nu$ is not a FCNC, nor even particularly rare, but of great interest, because of its sensitivity to the charged Higgs sector & the *B*-factory legacy.





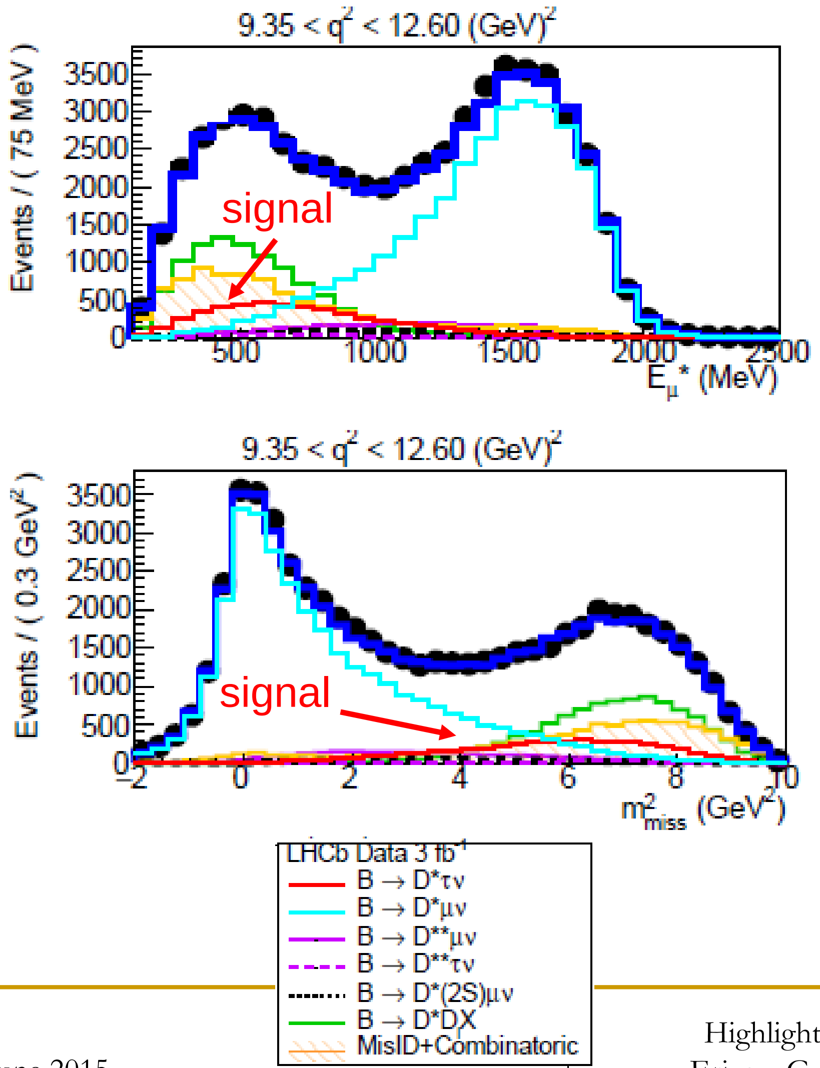
A very suggestive pattern of measurements !

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:



[LHCb-PAPER-2015-025]

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

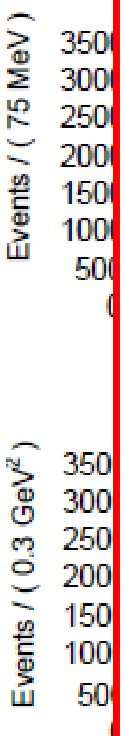
$$R(D^*) = 0.336 \pm 0.027 \pm 0.030$$

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

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

One q^2

[LHCb-PAPER-2015-025]



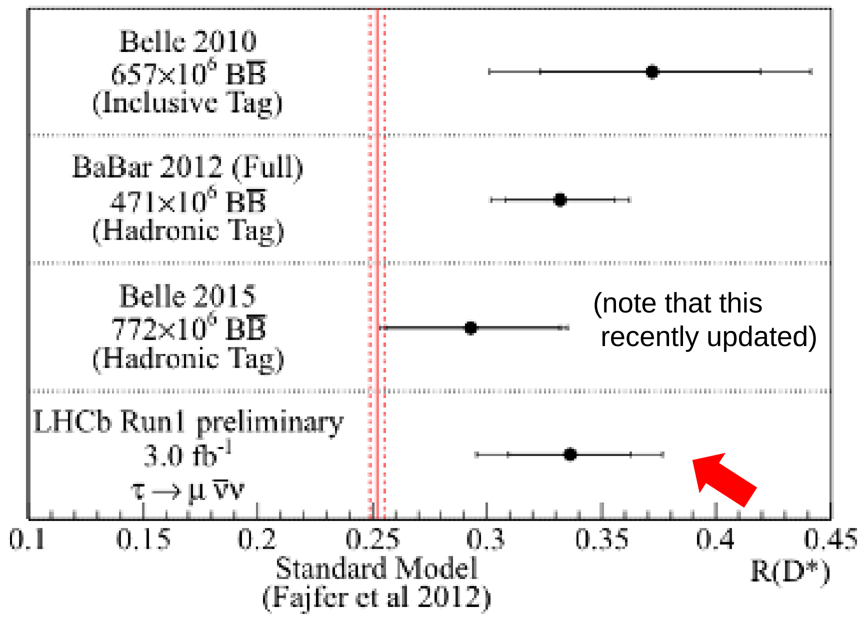
$\to\mu\nu\nu$,

tion
MVA
om
l.
and
against

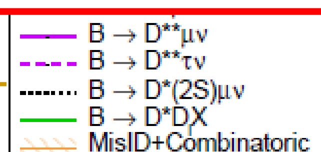
0.030

e

Current global picture:



Wait for global average of these and *R(D)* results.
Hope for more out of run-1 data with other decay modes, and run-2 data. At the LHC the impossible is possible!



CPV and unitarity triangle tests

- Matter-antimatter trigonometry
  - the angle γ
  - sin 2β
  - V_{ub}
- Search for CPV in the B_s sector

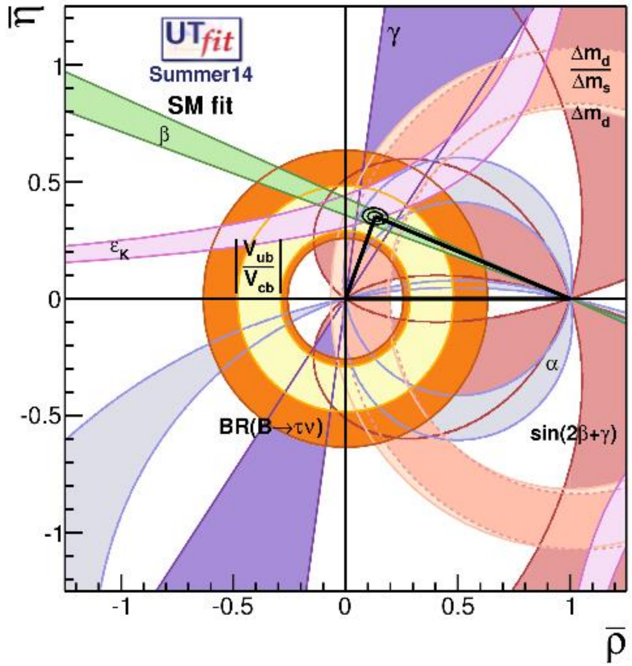
Medusa in the mirror

Matter-antimatter trigonometry

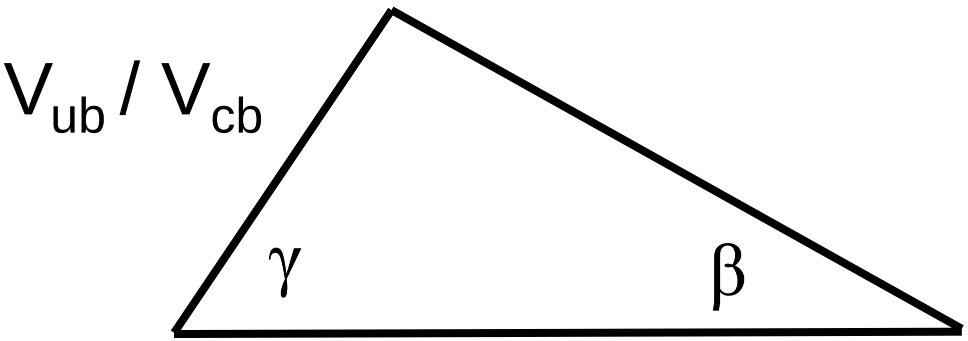
The Unitarity Triangle is a geometrical description of *CP*-violation within the context of the Standard Model, which in the flavour sector is the CKM mechanism.

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.

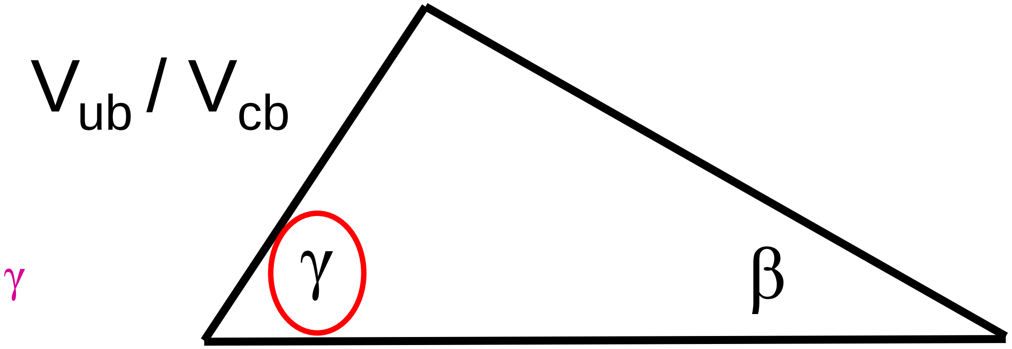


Let's see how LHCb is advancing this programme…



…through three key measurements.

Matter-antimatter trigonometry: γ



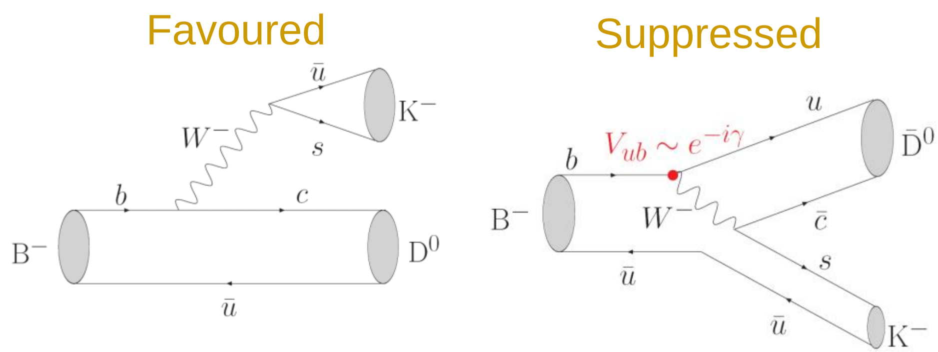
A precise measurement of the angle γ is a raison d'être of LHCb.

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

→ γ sensitive interference

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

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

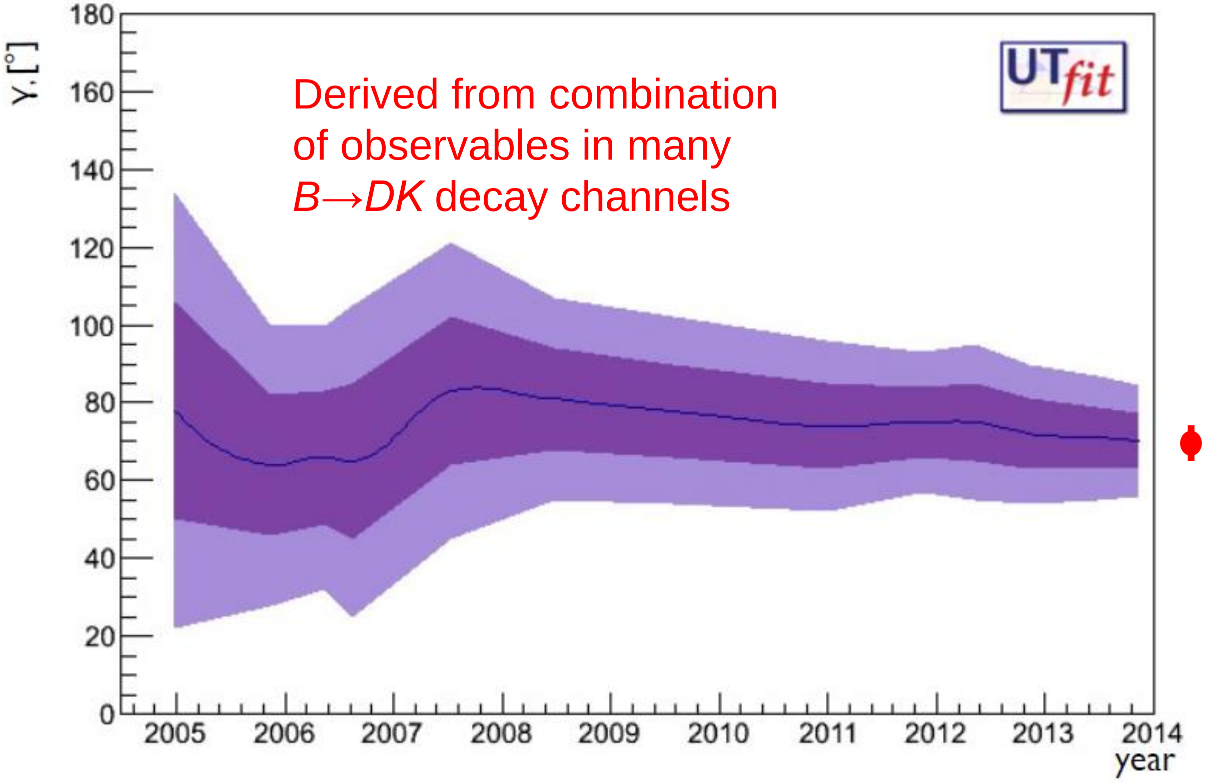


Tree-level decays: strategy very clean & yields result unpolluted by New Physics

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 $B \rightarrow hh$)

γ measurement – the last ~10 years

The story so far...



Consistent with the indirect prediction...

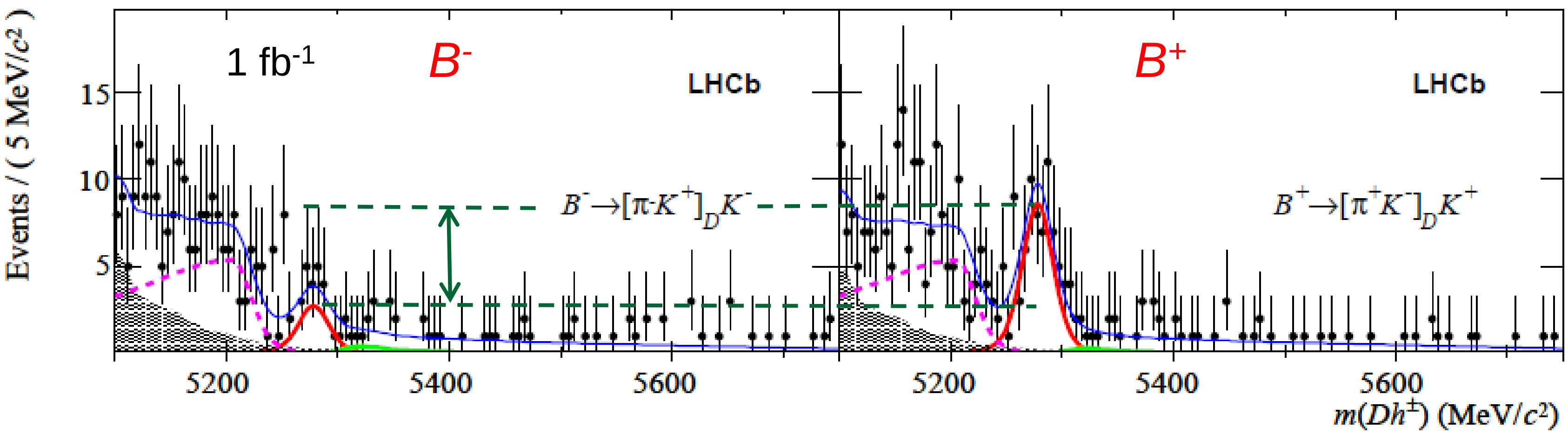
...but not nearly as precise

Indirect prediction from rest of triangle

...factor 3 improvement in 10 years.

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



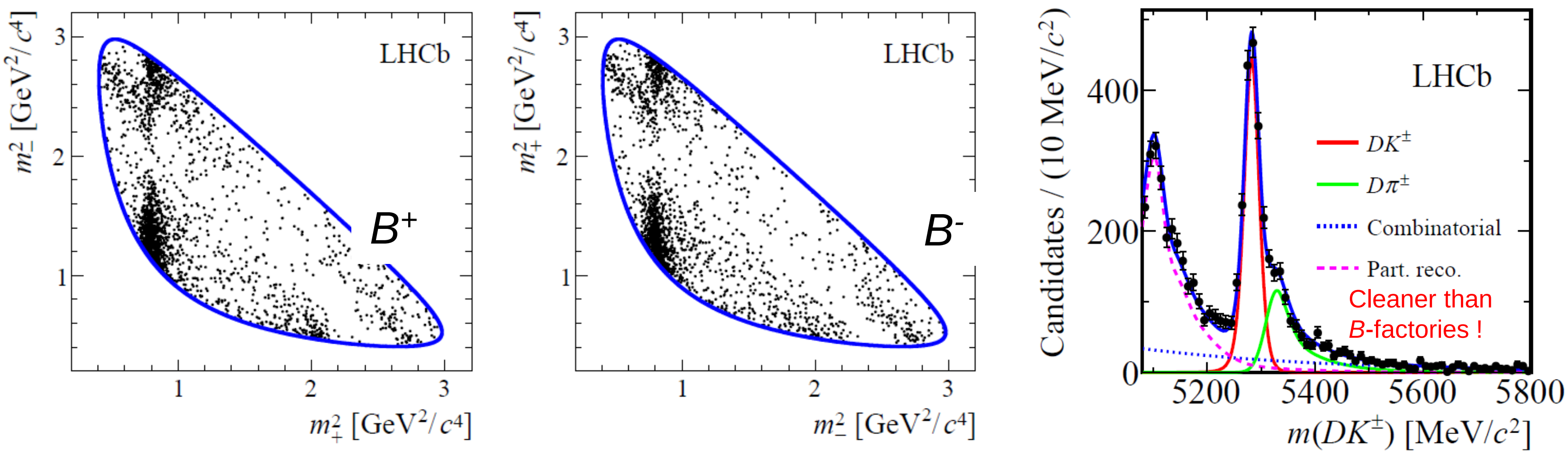
[PLB 712 (2012) 203]

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_SKK. In all cases benefit from the surprising (?) purity of signal.

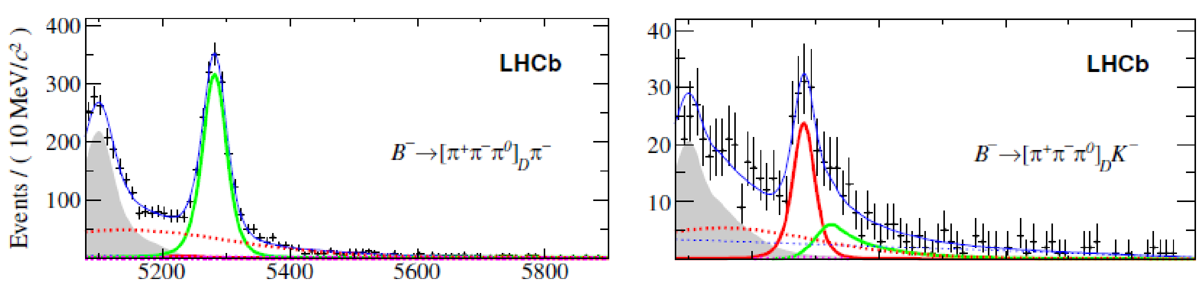
[JHEP 10 (2014) 097]



This cleanliness thanks to:

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

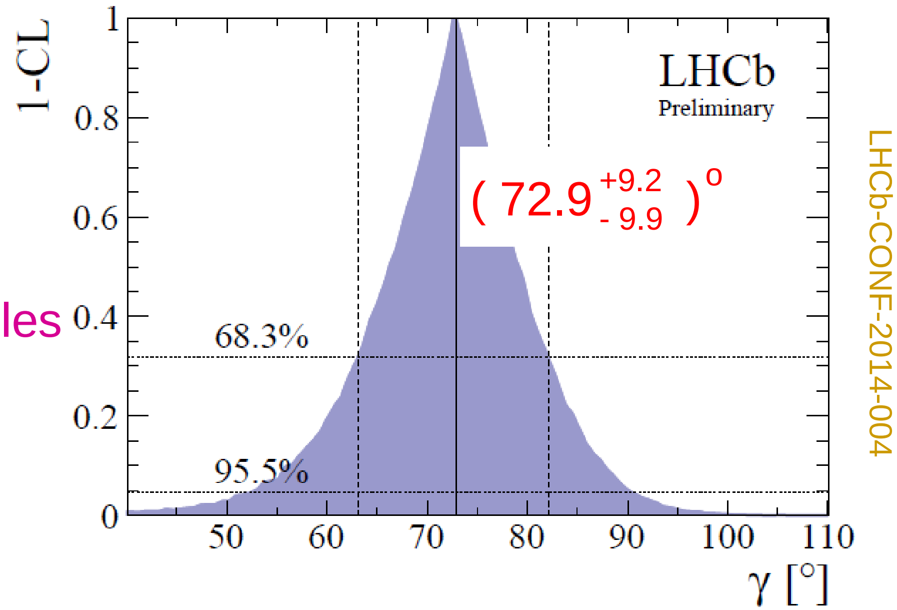
Seen in all modes that enter the γ analysis, even those with π^0's (once thought 'impossible' at the LHC).



[arXiv:1504.05442]

LHCb: current precision on γ and future prospects

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



Uncertainty of <10° - better than that obtained with combined B-factory samples

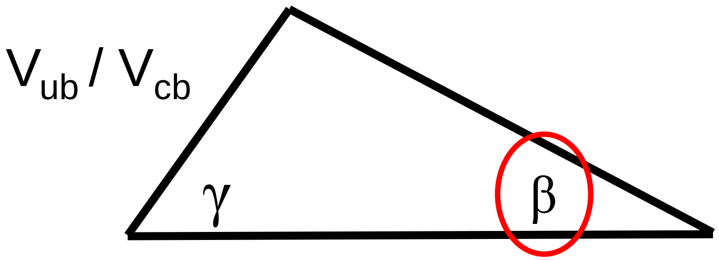
Will improve steadily:

- still many important run 1 modes to be published (*e.g.* 3 fb^{-1} $B \rightarrow D(KK,\pi\pi,K\pi,K\pi\pi\pi,\pi\pi\pi\pi)K$, $B_s \rightarrow D_s K$)
- Repeat with much larger data set anticipated in run 2.

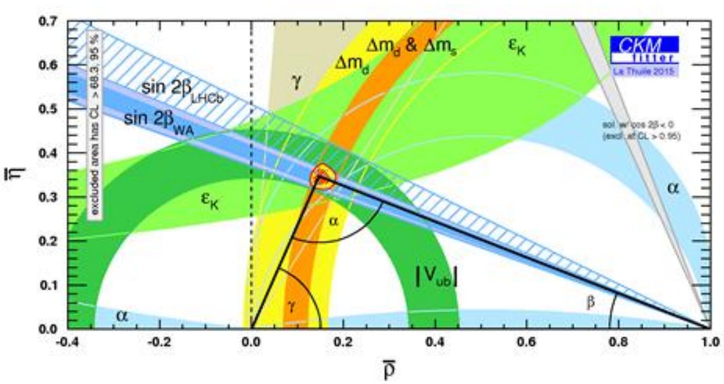
Aim for ~ 3° uncertainty after run 2 (matches current indirect precision)

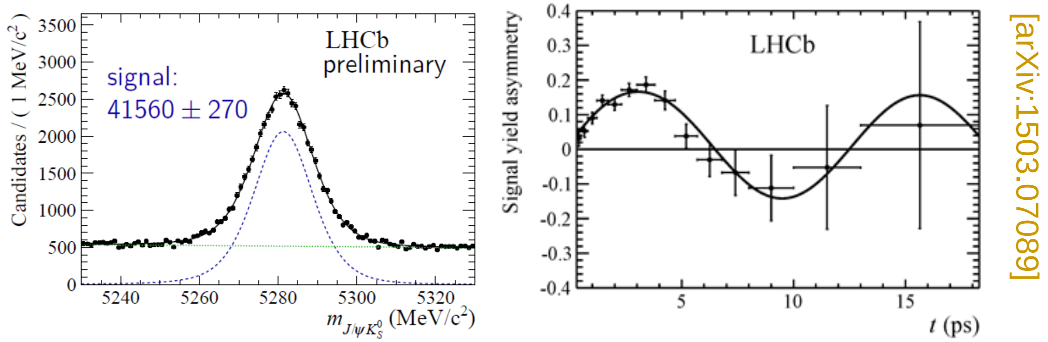
Matter-antimatter trigonometry: sin2β

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.



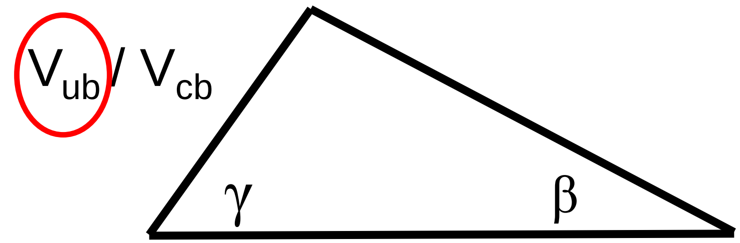


$$\sin 2\beta_{\text{eff}} = 0.731 \pm 0.035\,(\text{stat}) \pm 0.020\,(\text{syst})$$

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

Precision obtained by LHCb with $B^0 \rightarrow J/\Psi K_S$ is very similar to that of the *B*-factories. LHCb will dominate measurement with run-2 data. Upgrade prospects exciting !

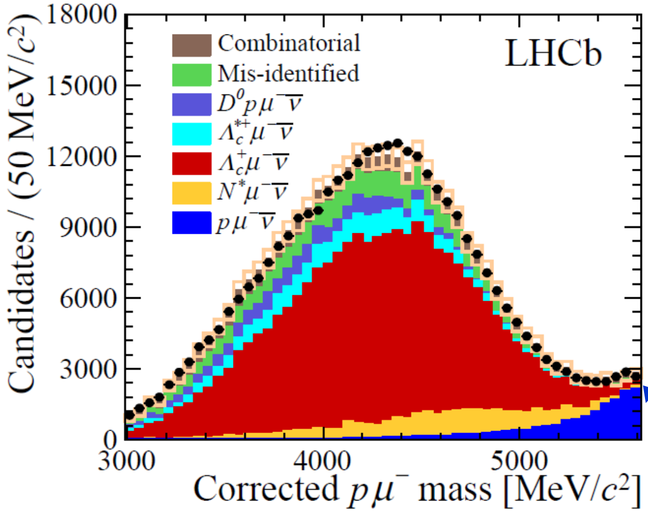
Matter-antimatter trigonometry: V_{ub}



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

We have now shown it can be done! Use baryon decay $\Lambda_b \to p\mu\nu$ and benefit from RICH & vertexing capabilities.

[arXiv:1504.01568]



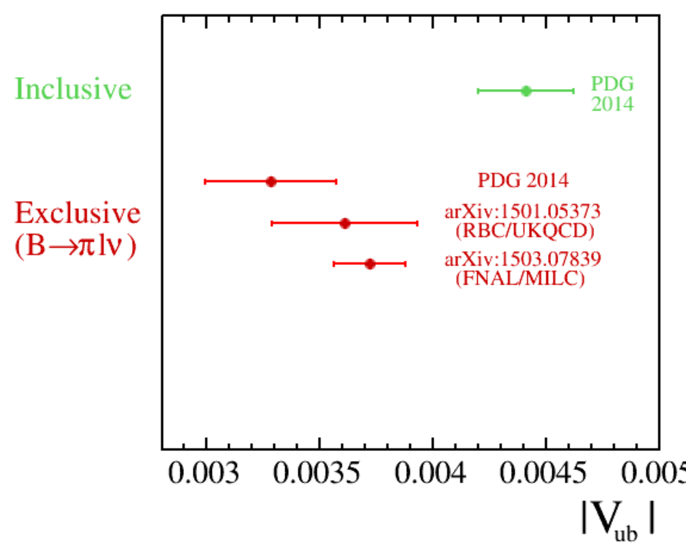
signal

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

Very precise result:

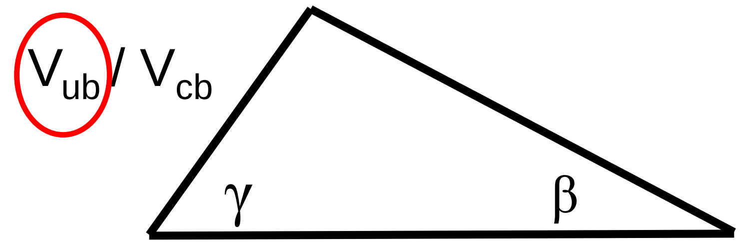
$$|V_{ub}| = (3.27 \pm 0.15 \pm 0.16 \pm 0.06) \times 10^{-3}$$

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



tension !

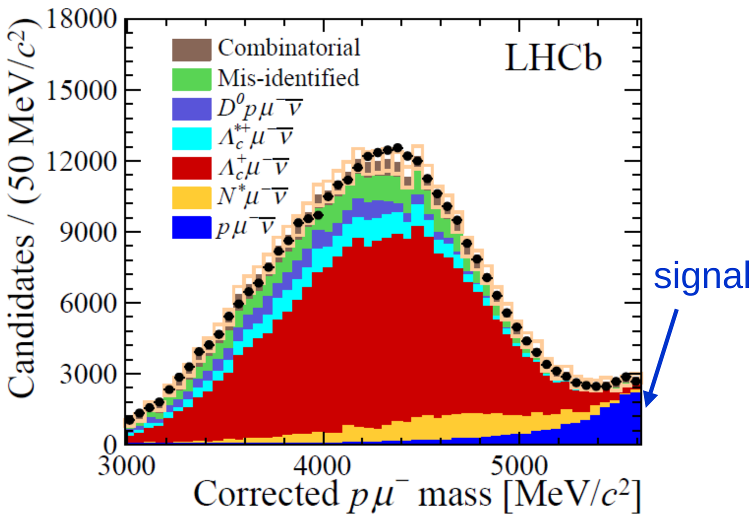
Matter-antimatter trigonometry: V_{ub}



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

We have now shown it can be done!
Use baryon decay $\Lambda_b \to p\mu\nu$ and benefit from RICH & vertexing capabilities.

[arXiv:1504.01568]

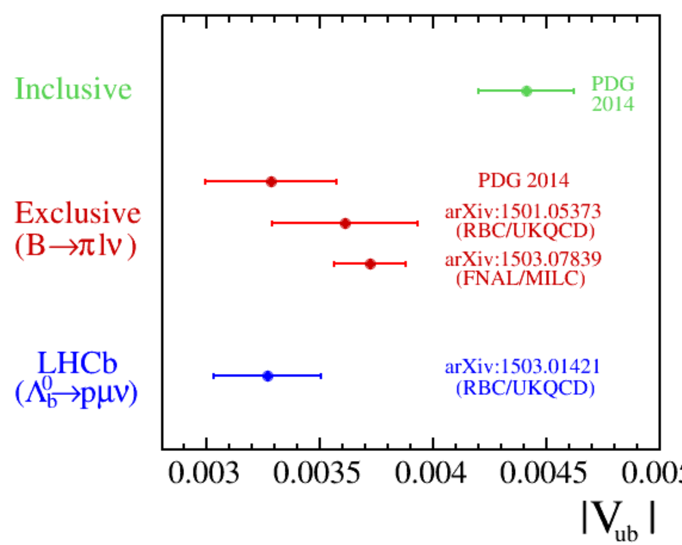


Normalise to $\Lambda_b \to \Lambda_c \mu\nu$ and use lattice QCD to interpret result.

Very precise result:

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

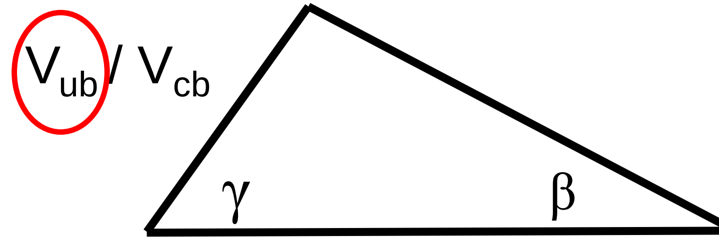
Brings new insight to long-standing 'inclusive vs exclusive' V_{ub} puzzle.



tension !

LHCb result agrees with exclusive results

Matter-antimatter trigonometry: V_{ub}

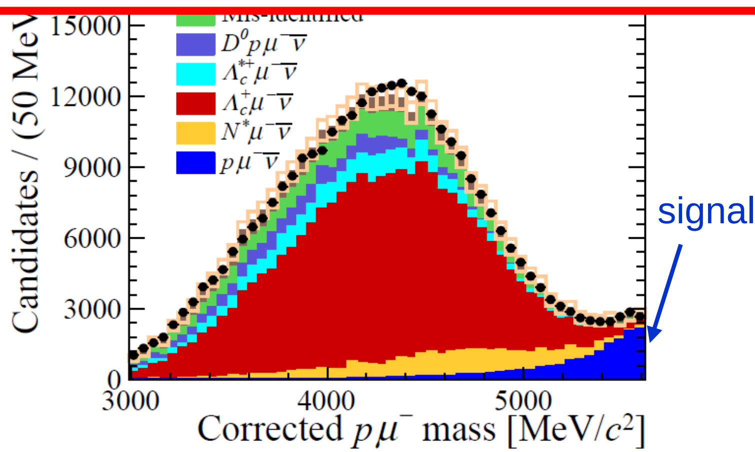


Measurement of V_{ub} long thought essentially impossible at LHC. Challenging to separate $b \rightarrow u\mu\nu$ and $b \rightarrow c\mu\nu$ processes without any beam energy constraint.

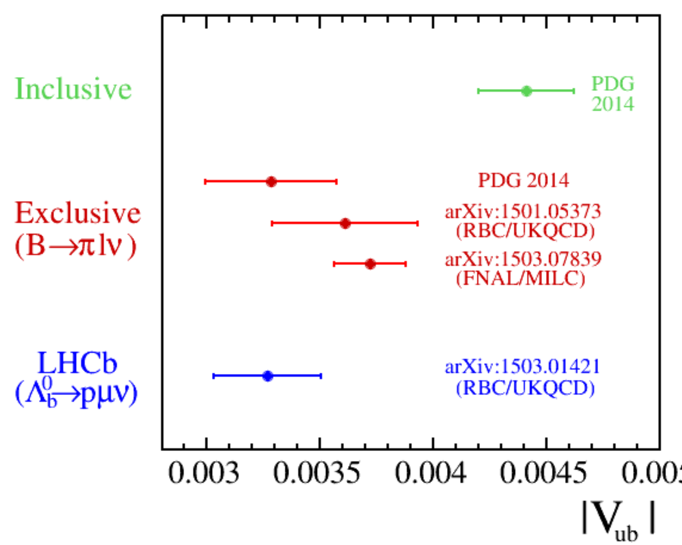
Still much to understand, but new LHCb result, as with $B \rightarrow D^{*}\tau\nu$, has redefined the 'art of the possible' for *B*-physics at hadron machines!

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

[arXiv:1504.01568]



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



tension !

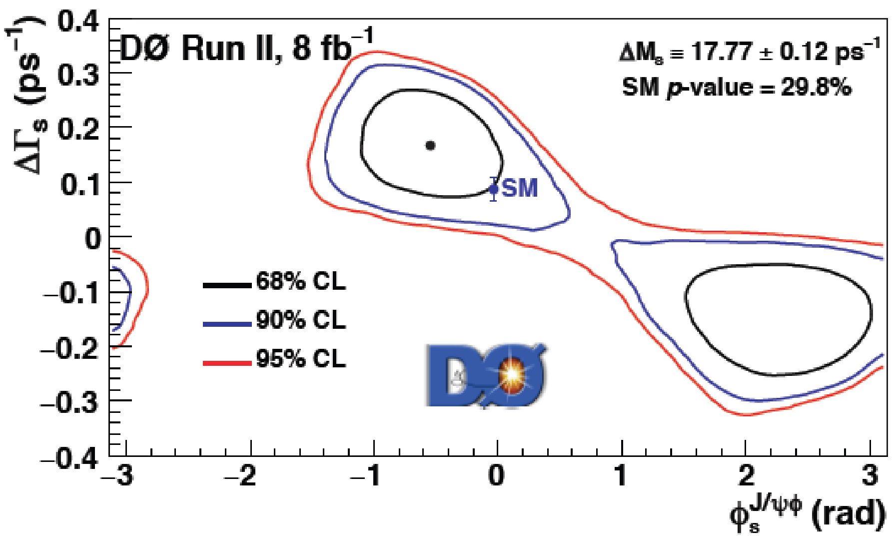
LHCb result agrees with exclusive results

Mixing induced CPV in B_s system

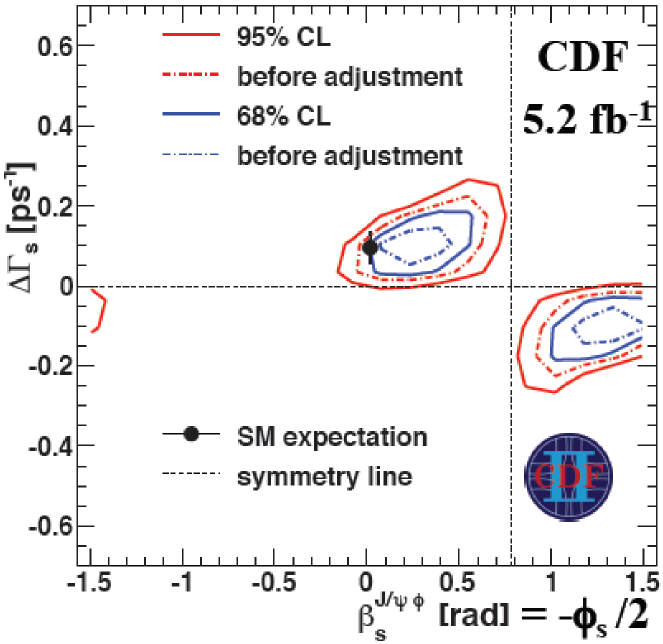
CPV phase, φ_s, in B_s mixing-decay interference, *e.g.* measured in $B_s \to J/\Psi\Phi$, very small & precisely predicted in SM. Box diagram offers tempting entry point for NP !

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

[PRD 85 (2012) 032006]



[PRD 85 (2012) 072002]



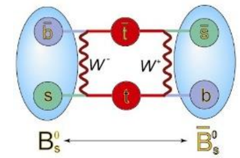
Results are consistent, & both are ~1σ away from SM. What about the LHC?

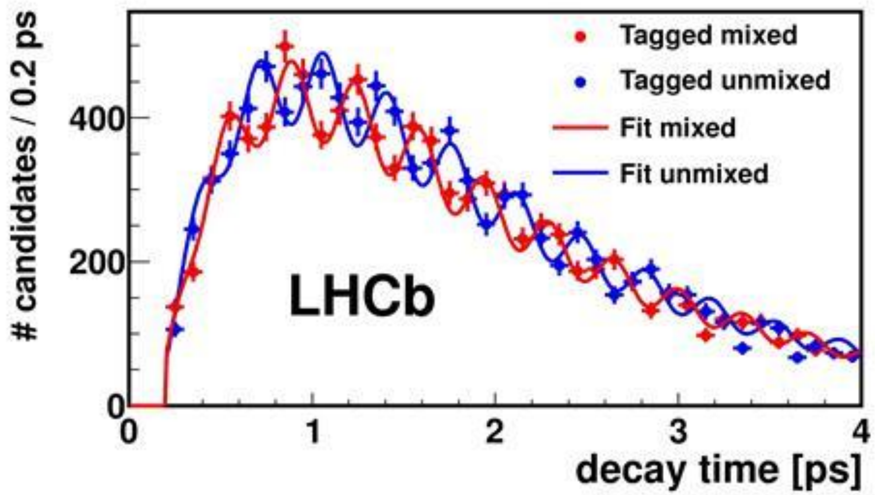
Mixing induced CPV in B_s system

CPV phase φ_s in B_s mixing-decay interference, e.g. measured in $B_s \rightarrow J/\Psi\Phi$, very small & … t for NP !

Tevatr… data a…

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





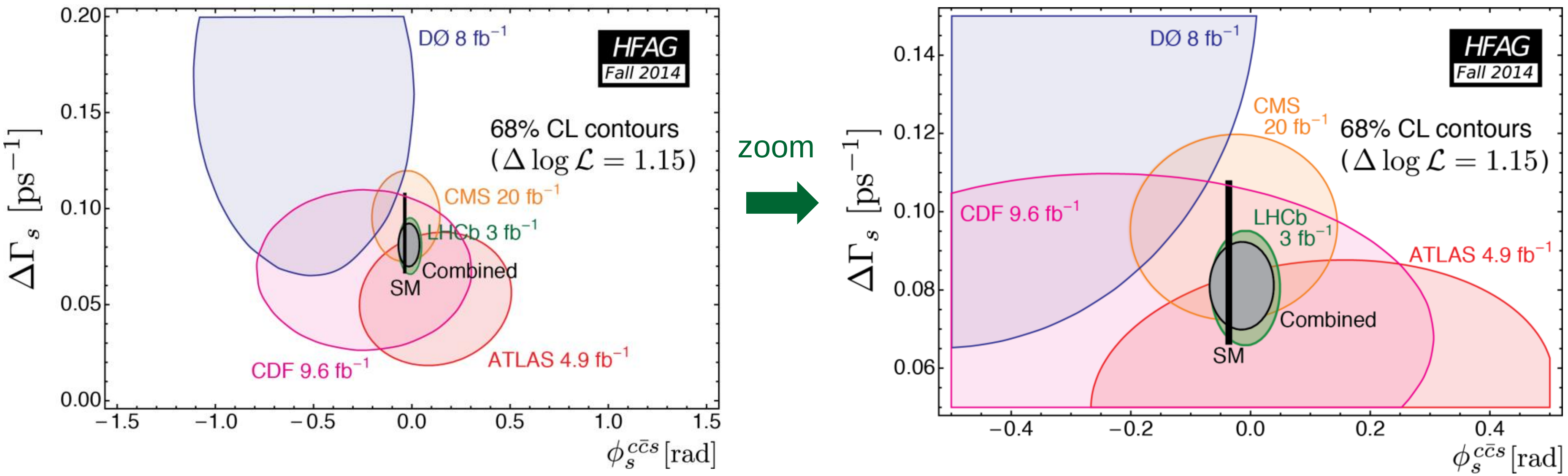
[New J. Phys. 15 (2013) 053021]

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

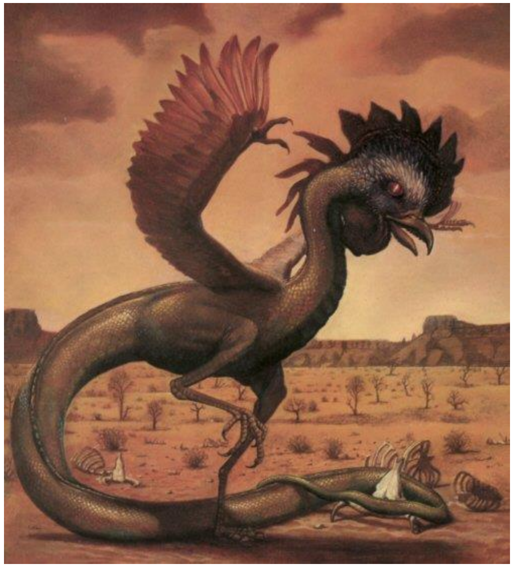
LHCb has now completed its run-1 measurement of φ_s, attaining a precision ~20x better than Tevatron in $B_s \to J/\psi\varphi(KK)$ [PRL 114 (2015) 041801] & adding important new modes *e.g.* $B_s \to J/\psi\pi\pi$ [PLB 736 (2014) 186]. Earlier hints of *large* NP effects have gone…



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

Spectroscopy & the search for exotics

- New baryons
- Unambiguous observation of a four-quark hadron

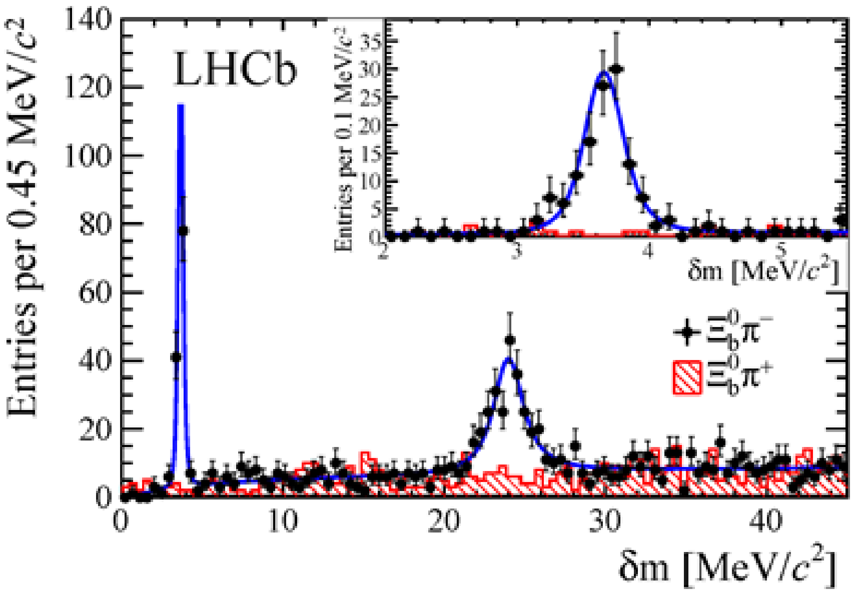


The fabled basilisk

Spectroscopy

Many new states found by LHCb, 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]



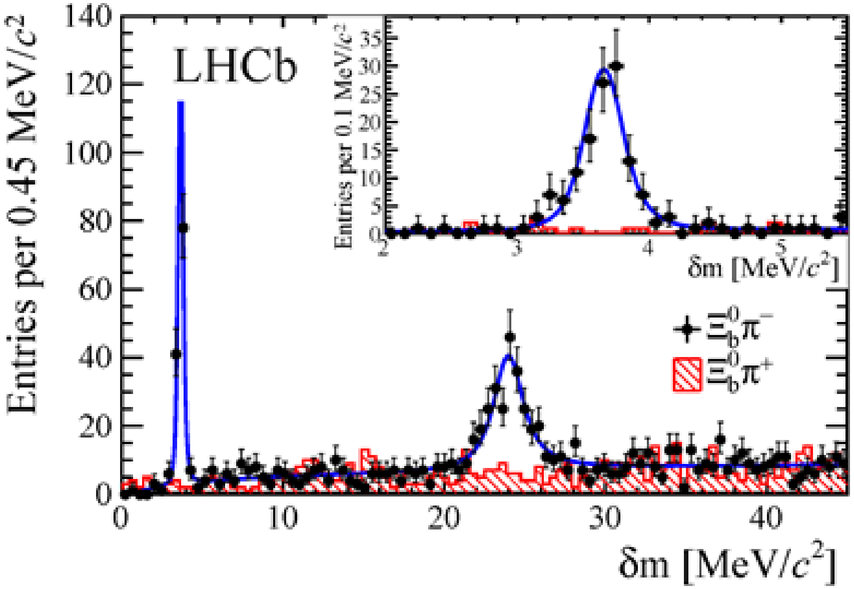
$$
\begin{aligned}
m(\Xi_b^{\prime -}) - m(\Xi_b^0) - m(\pi^-) &= 3.653 \pm 0.018 \pm 0.006\,\mathrm{MeV}/c^2,\\
m(\Xi_b^{*-}) - m(\Xi_b^0) - m(\pi^-) &= 23.96 \pm 0.12 \pm 0.06\,\mathrm{MeV}/c^2,\\
\Gamma(\Xi_b^{*-}) &= 1.65 \pm 0.31 \pm 0.10\,\mathrm{MeV},\\
\Gamma(\Xi_b^{\prime -}) &< 0.08\,\mathrm{MeV}\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

New particles always provoke interest

Spectroscopy

Many new states found by LHCb, 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]



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

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

Murray Gell-Mann

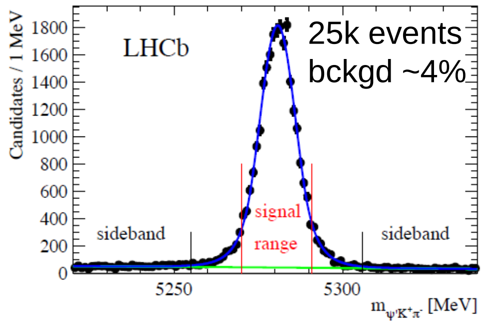
Spectroscopy - exotics

[PRL 112 (2014) 222002]

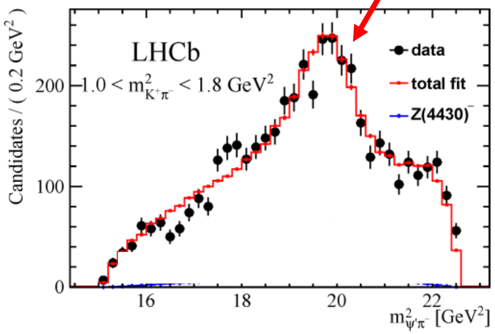
$Z(4430)^-$ seen by Belle in $B \to \Psi' K \pi$ but not confirmed by BaBar.

?

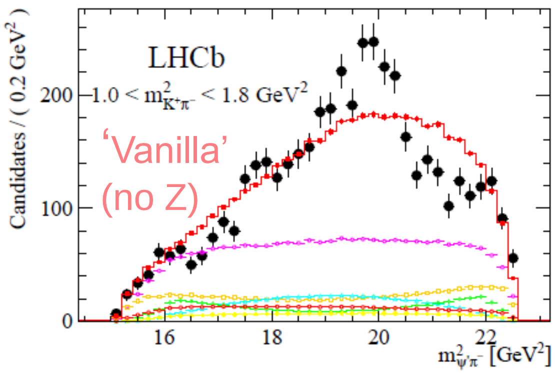
LHCb has a very large and clean sample…

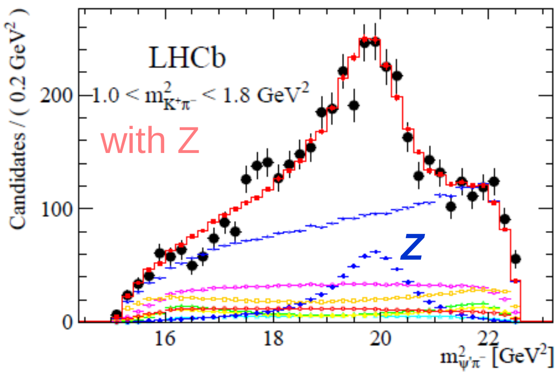


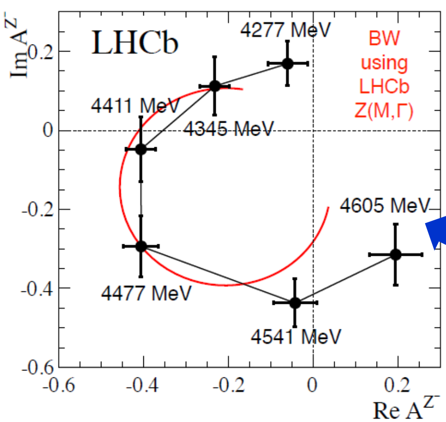
…which leaves little doubt that something is there.



But can this structure be produced by a combination of known resonances?







No! *p*-value of complete fit goes from 10^{-6} with only standard mesons included to 12% with 'exotic' component present.

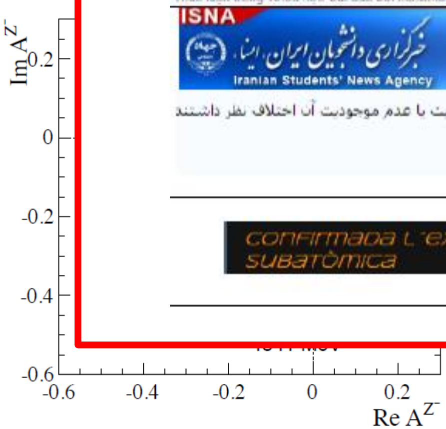
Furthermore, 'bump' shows textbook resonance behaviour.

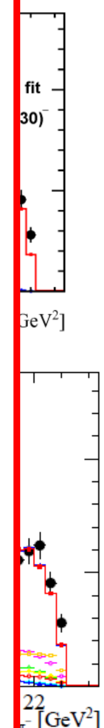
Unambiguous observation of a *four-quark* state (*not* 'vanilla'!)

Spectroscopy - exotics

[PRL 112 (2014) 222002]

Again, plenty of interest in the press (and beyond):





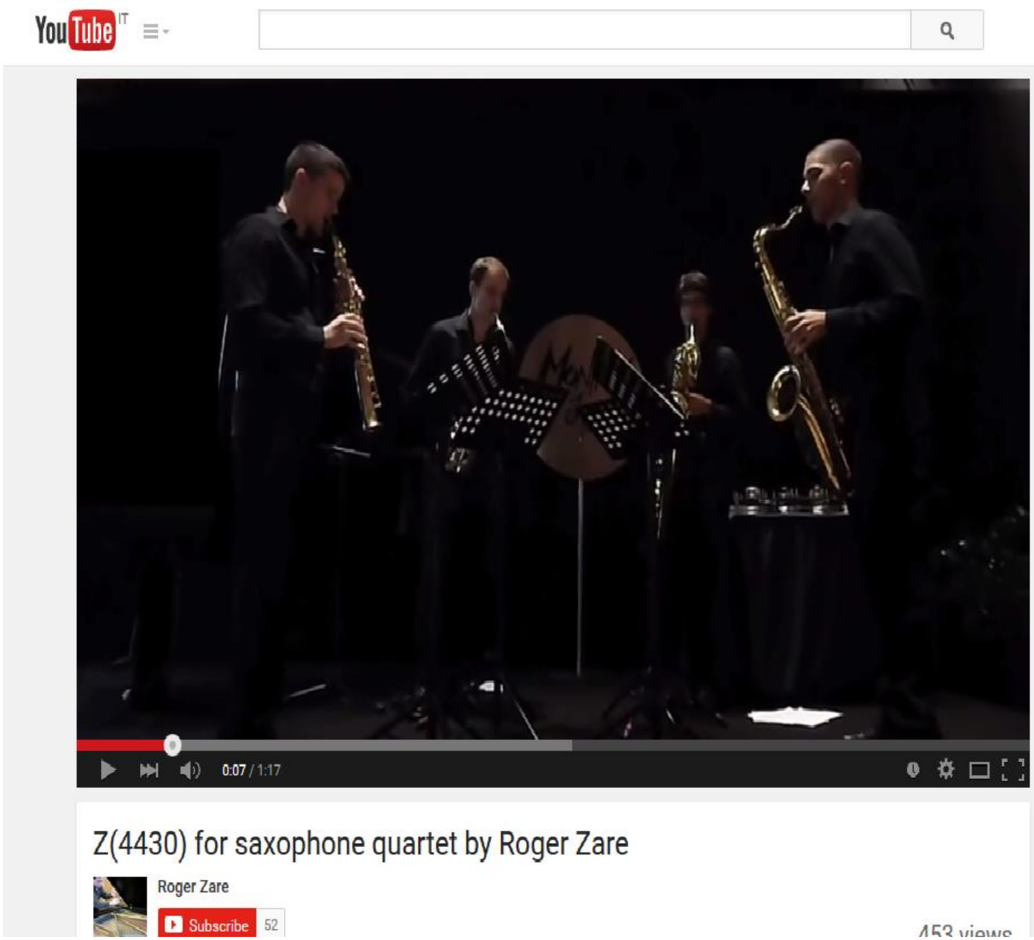
Unambiguous observation of a *four-quark* state (*not* 'vanilla'!)

Spectroscopy - exotics

[PRL 112 (2014) 222002]

Z(

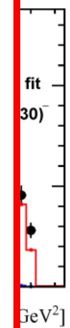
Again, plenty of interest in the press (and beyond):

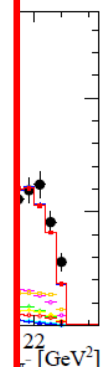


Montreux jazz festival, 2014

LH
ve
ar
sa

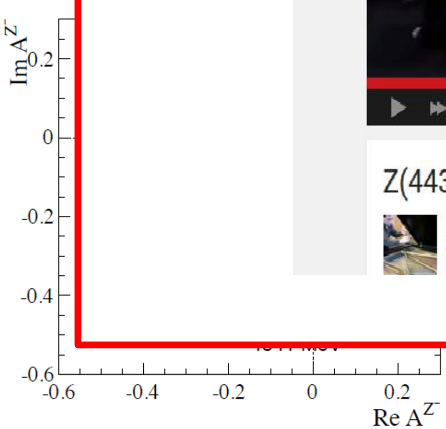
Bu
be
co
kn





andard
ent.

iour.



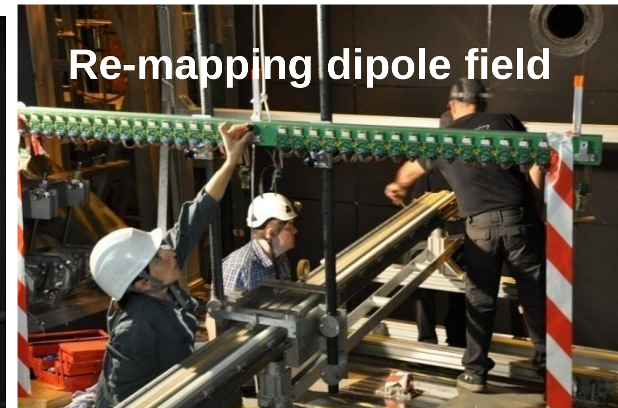
Unambiguous observation of a *four-quark* state (*not* 'vanilla'!)

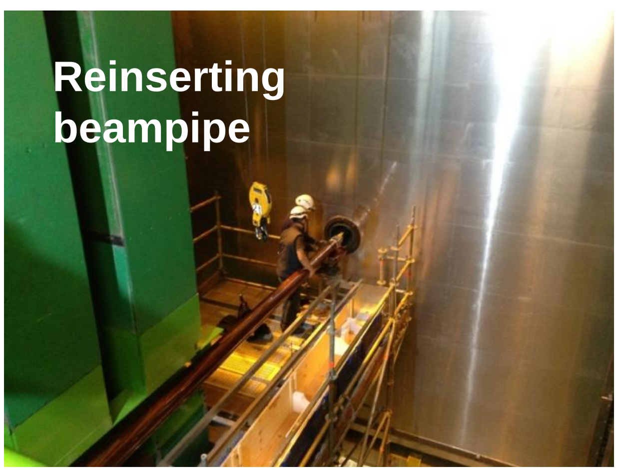
Run 2 and the voyage beyond

The straits of Messina:
sailing between Charybdis and Scylla

LS1 activities – preparing for run 2

A very busy time – all work completed successfully and on schedule. Many improvements & small repairs.

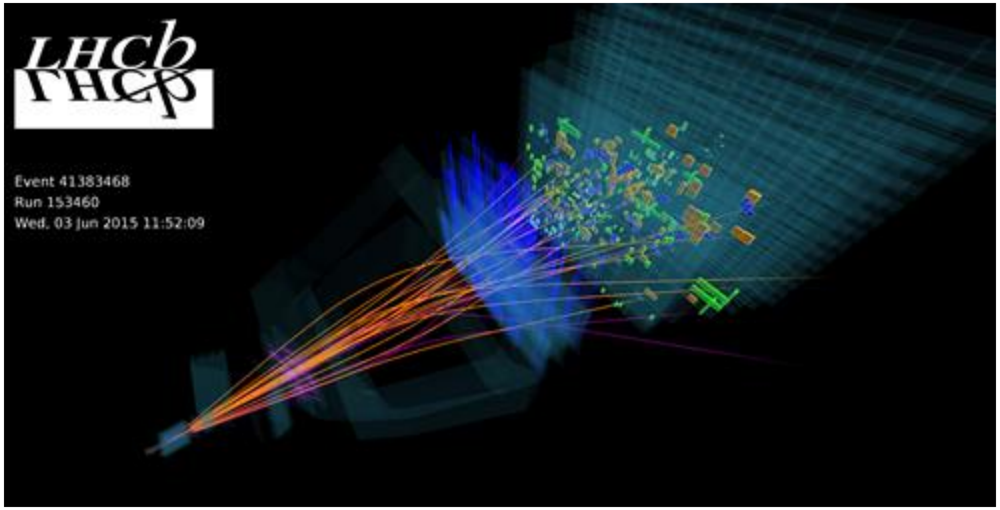




Run-2 restart

We successfully closed the VELO & participated in first stable beam fill at 13 TeV.

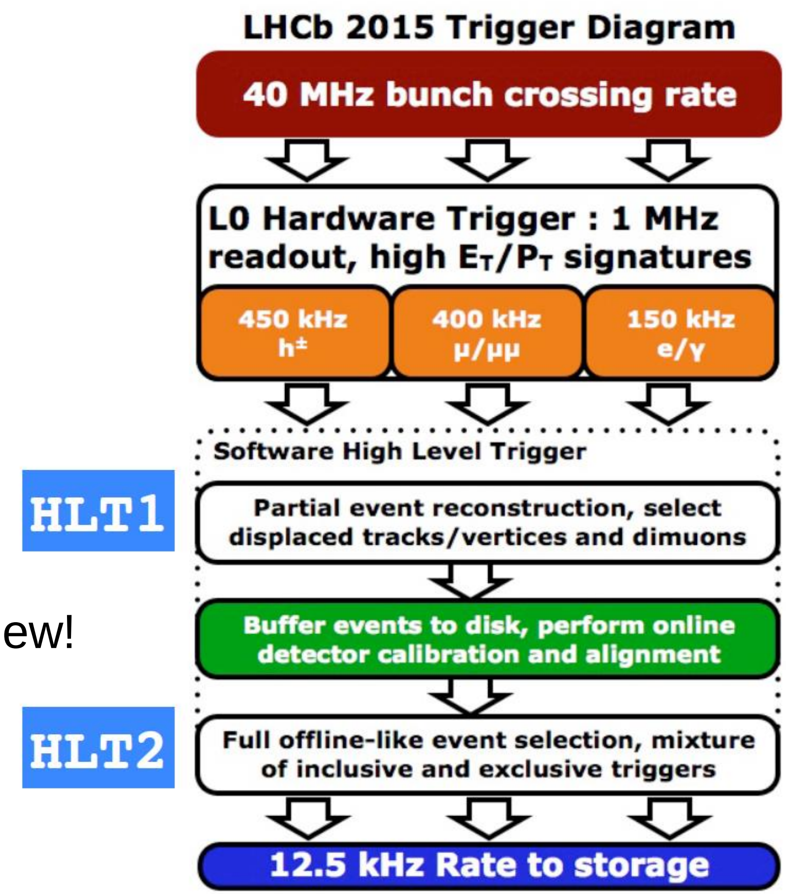
We have run without problem in fills since then, data taking for detector calibration, trigger tuning , calibrating & aligning, & preparing for physics production.



We are all ready to go ! Note that our run 2 operation is far from identical to run 1…

Run-2 operation

Several ambitious changes planned for operation during run 2 aimed at increasing physics output and making optimal use of resources.



New!

New!

Including several kHz of ‘TURBO’

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

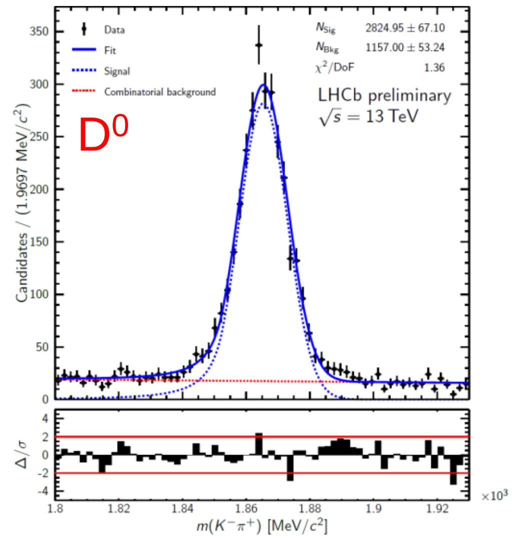
This means the trigger runs with offline-like performance
→ better background rejection.

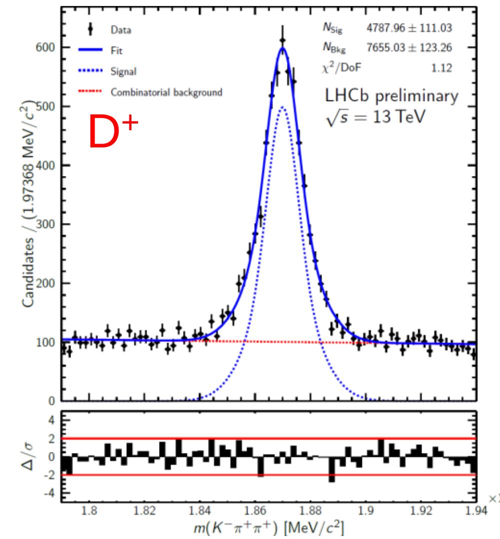
Furthermore, we can dare to use some of the trigger output directly for physics analysis without any offline processing! This we call the ‘TURBO stream’.

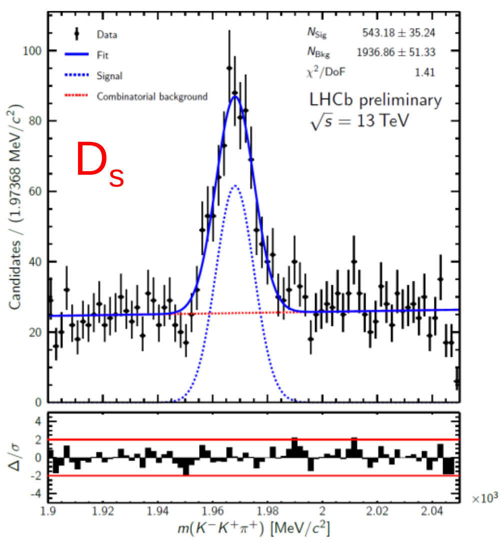
Run 2 – first data from ‘Turbo’ stream

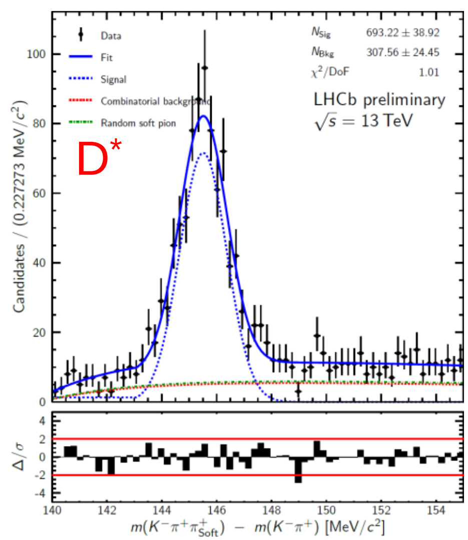
Charm signals from Turbo stream as reconstructed in one of first fills of run 2.

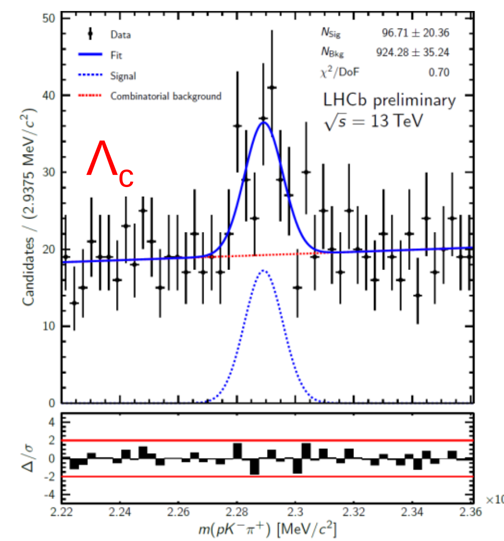
Recall: full reconstruction run in trigger – physics quality with no further offline processing needed!



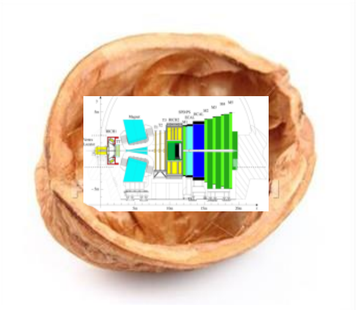








LHCb Upgrade in a nutshell



An LHCb Upgrade is scheduled, with installation in LS2 and first data-taking in run 3. The motivation is to take increased advantage of the huge rate of heavy-flavour production at the LHC.

The LHCb Upgrade

1) *Full* software trigger
- Allows effective operation at higher luminosity
- Improved efficiency in hadronic modes

2) Raise operational luminosity by factor five to 2×10^{33} cm^{-2} s^{-1}

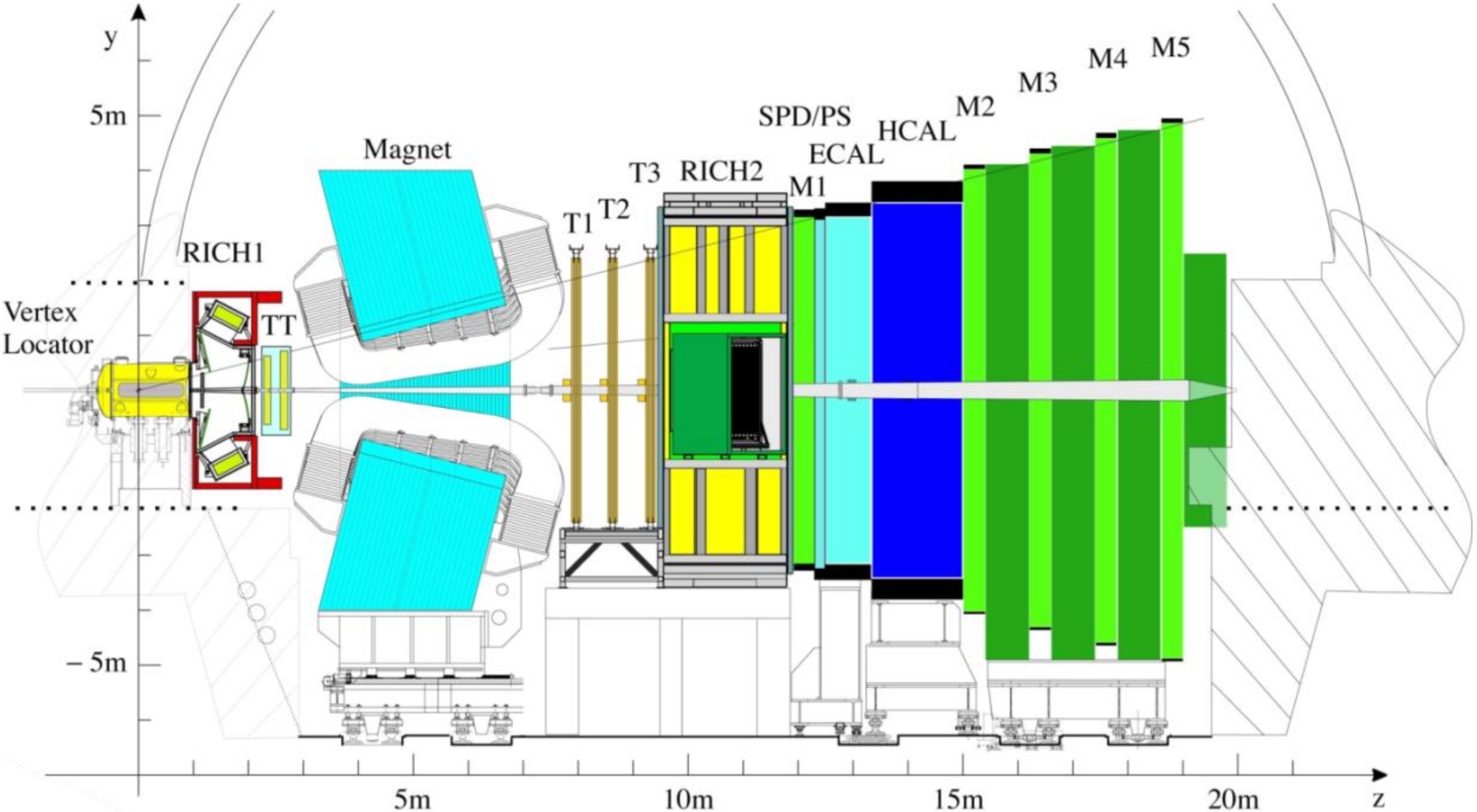
Necessitates redesign of several sub-detectors & overhaul of readout

Huge increase in precision, in many cases to the theoretical limit, and the ability to perform studies beyond the reach of the current detector.

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

Upgrade overview

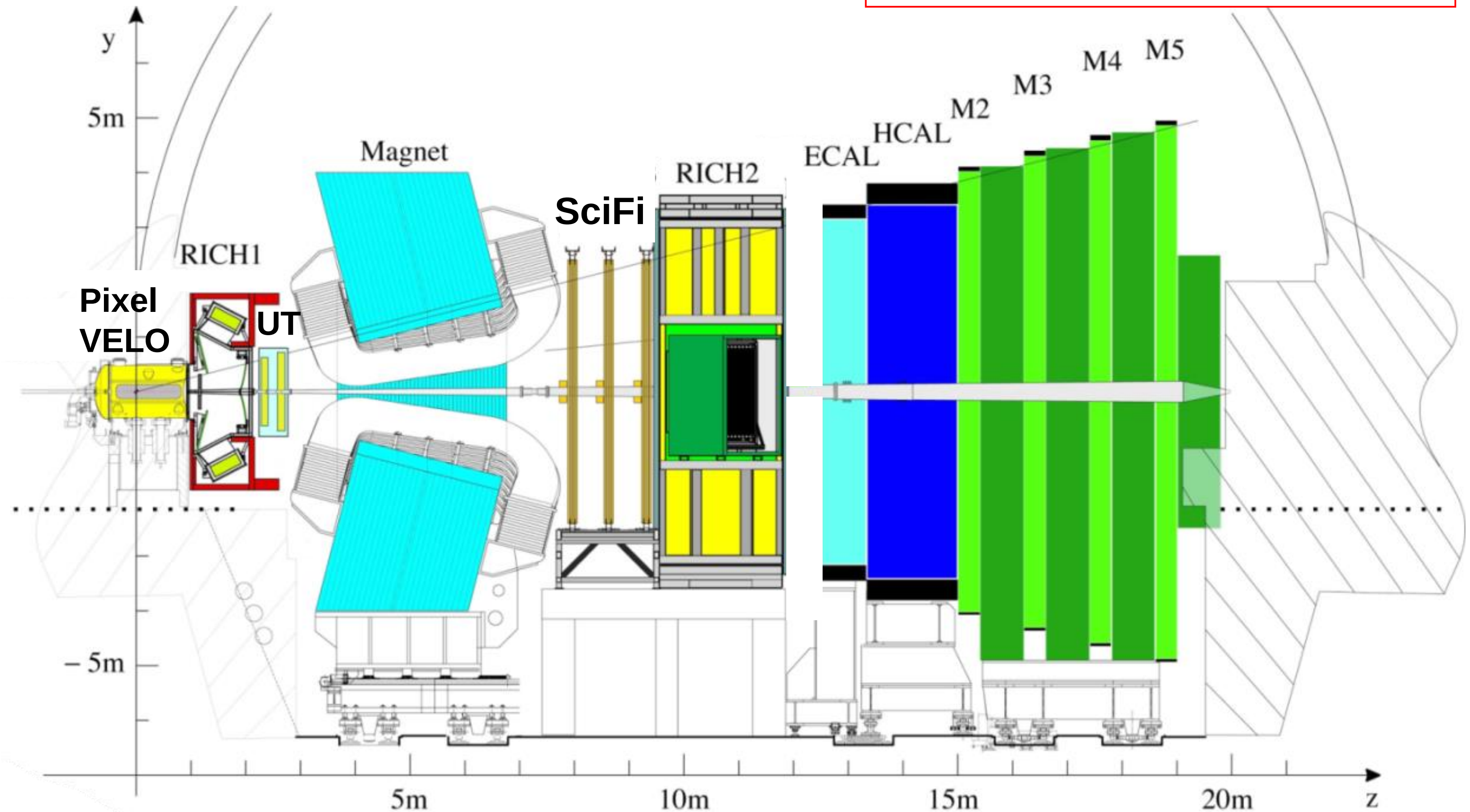
Current detector



Upgrade overview

Current detector → upgraded detector

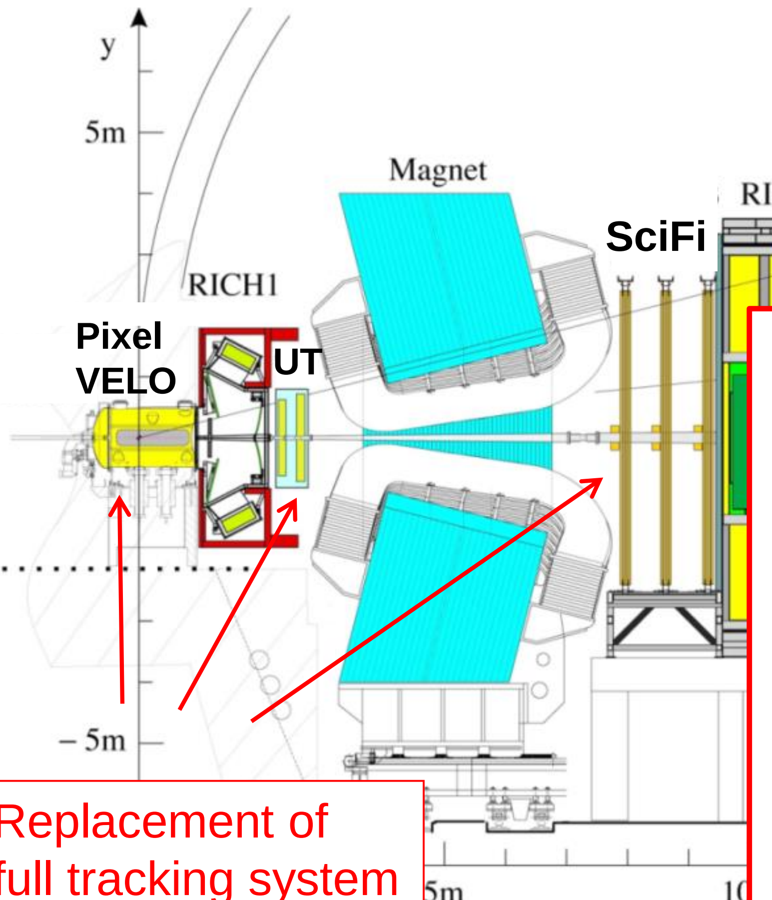
All sub-detectors read out at 40 MHz for software trigger



Upgrade overview

Current detector → upgraded detector

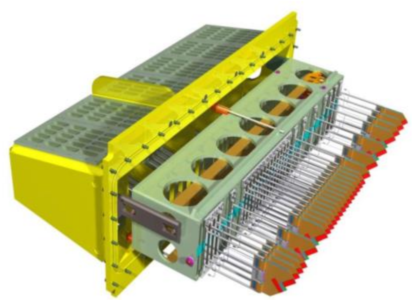
All sub-detectors read out at 40 MHz for software trigger



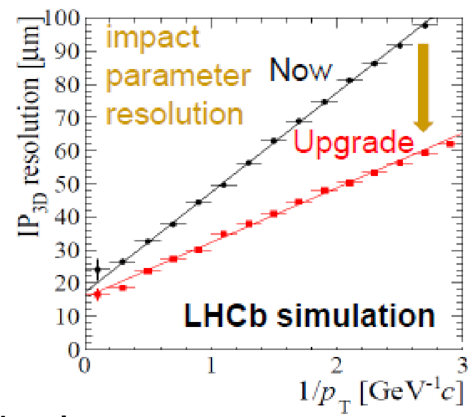
Replacement of full tracking system

Pixel Vertex Locator (VELO)

Half of VELO system



Improved performance

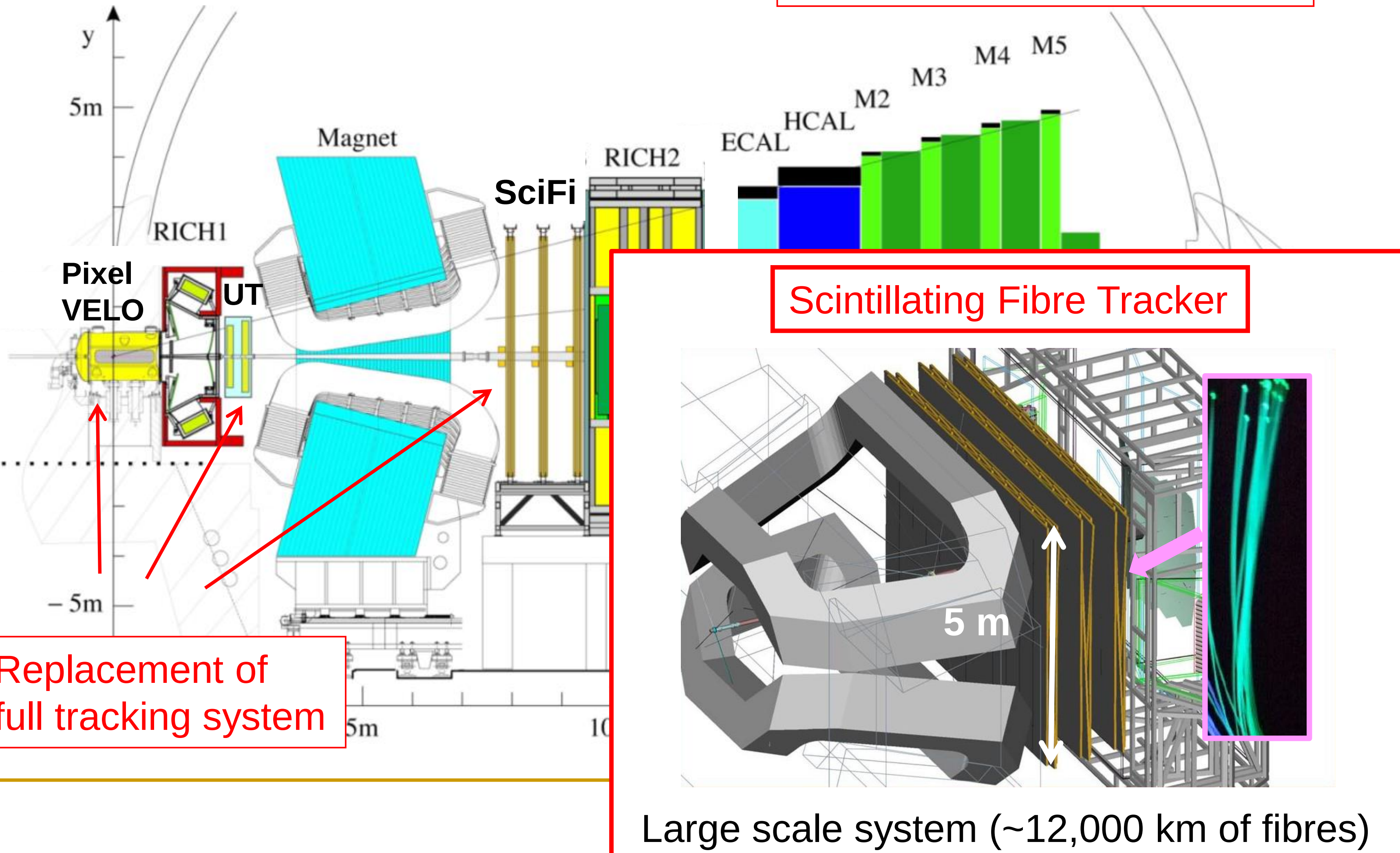


(‘UT’ = ‘Upstream tracker’, a high performance Si strip detector)

Upgrade overview

Current detector → upgraded detector

All sub-detectors read out at 40 MHz for software trigger



Replacement of full tracking system

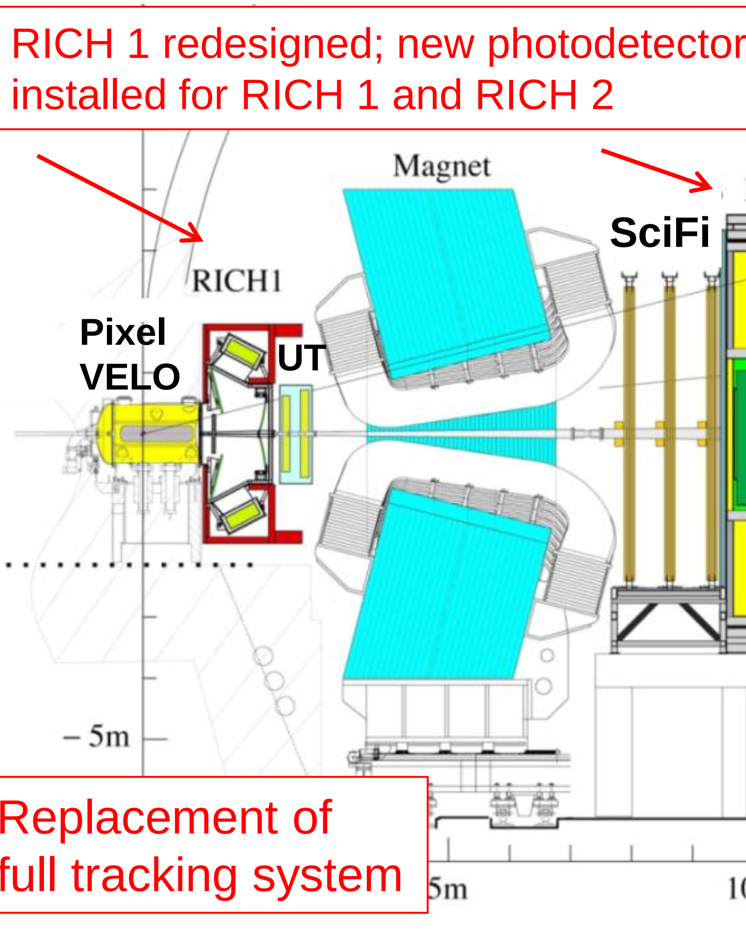
Large scale system (~12,000 km of fibres)

Upgrade overview

Current detector → upgraded detector

All sub-detectors read out at 40 MHz for software trigger

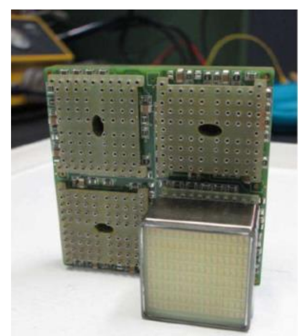
RICH 1 redesigned; new photodetectors installed for RICH 1 and RICH 2



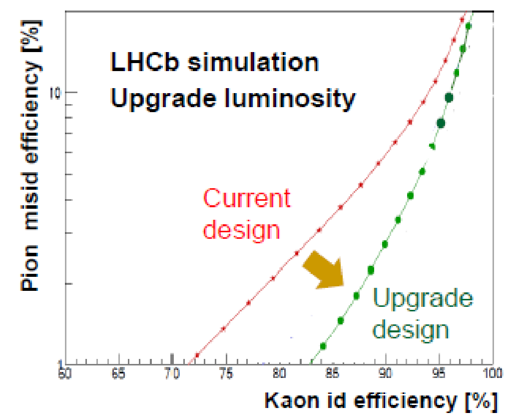
Replacement of full tracking system

RICH system

New photodetector



New optics....



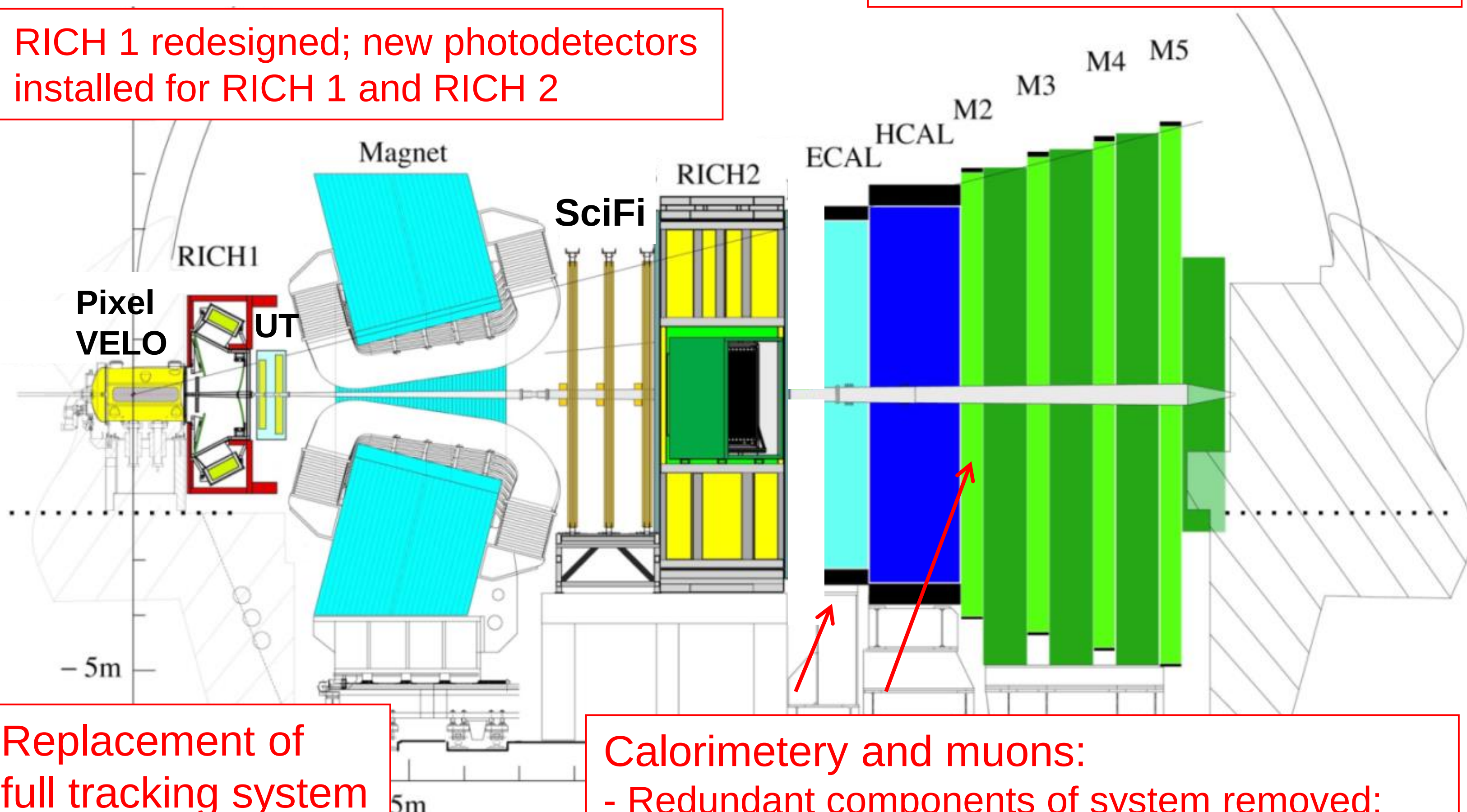
...good performance at high luminosity

Upgrade overview

Current detector → upgraded detector

All sub-detectors read out at 40 MHz for software trigger

RICH 1 redesigned; new photodetectors installed for RICH 1 and RICH 2

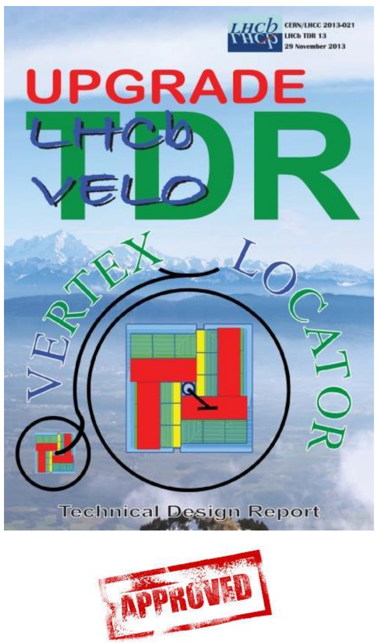


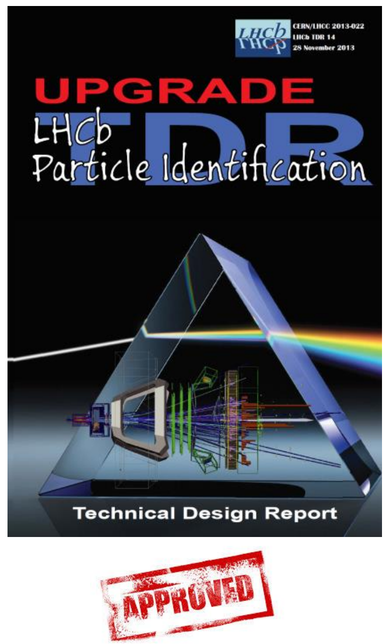
Replacement of full tracking system

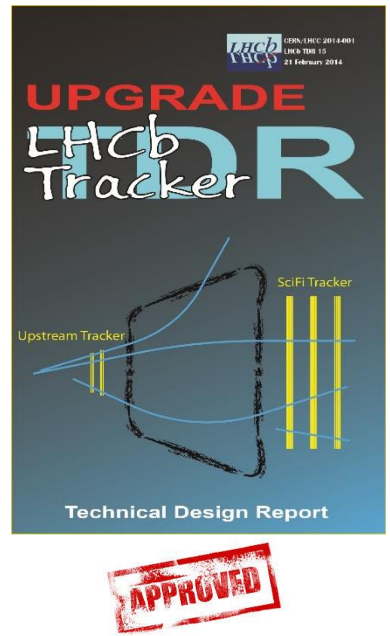
Calorimetery and muons:
- Redundant components of system removed; new electronics added; more shielding included

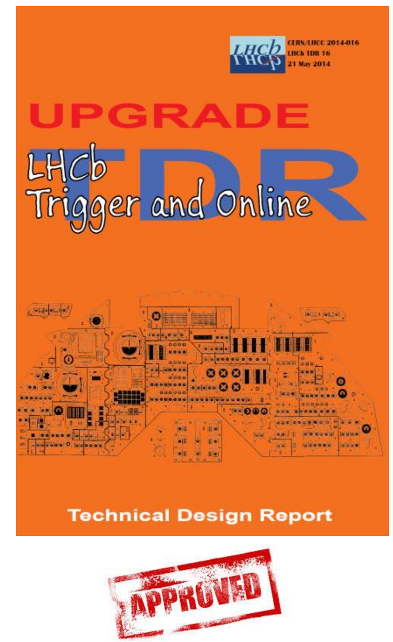
Completion of upgrade TDRs

All* upgrade TDRs have now been approved by the Research Board.
We have final & achievable technology choices for all systems.









We have now organised ourselves for the next phase of the programme, *i.e.* final stages of R&D, engineering and production readiness reviews, and production.

* Caveat: a computing TDR is foreseen for Q1 2017

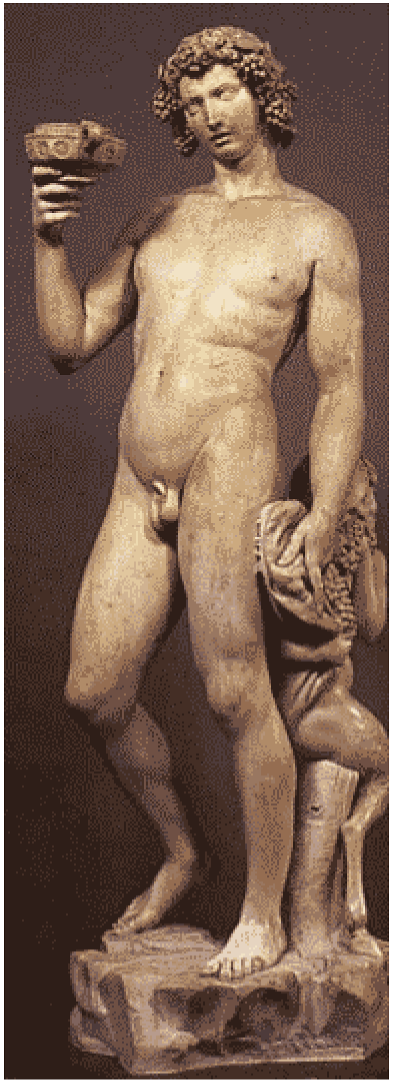
Conclusions

LHCb continues to produce world-leading results in flavour-physics (and beyond)

- some of these are in topics previously thought inaccessible to the LHC
- some of these are intriguing…

Much to look forward to in the coming years

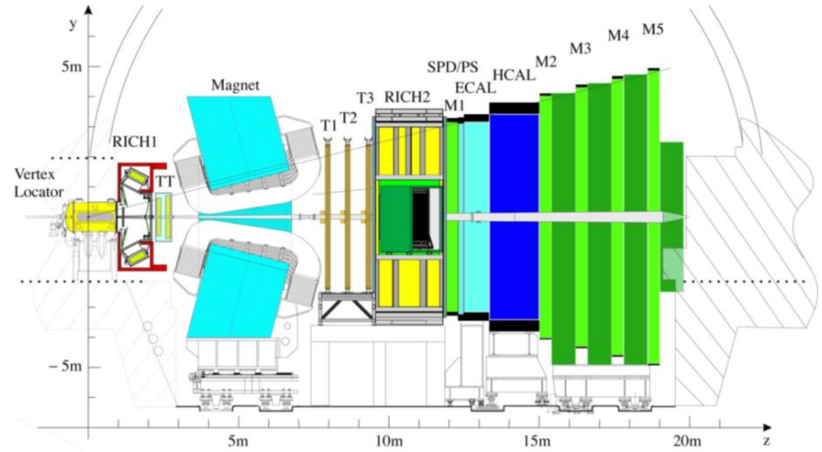
- LHCb in excellent shape for run-2 data-taking
- Exciting Upgrade on schedule for run 3



Dionysus making use of the vine he discovered on Sicily

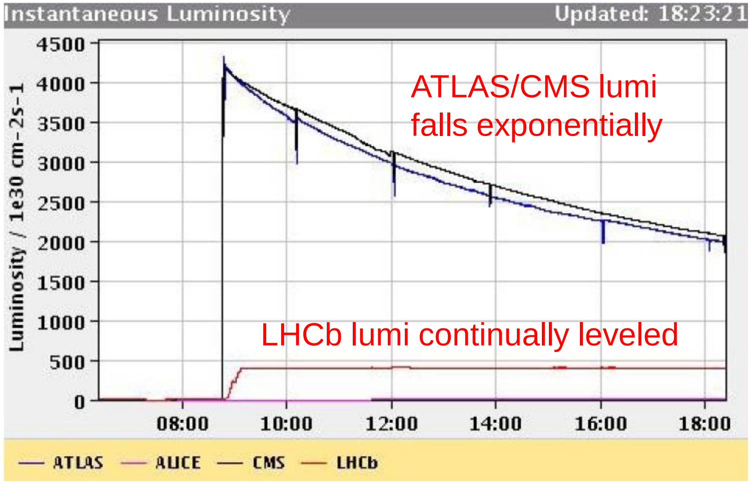
Backups

LHCb – the essentials



LHCb – a forward spectrometer optimised for heavy-flavour physics at the LHC

- forward acceptance ($2 < \eta < 5$)
- high bandwidth trigger
- acceptance down to low p_T
- precise vertexing (VELO)
- hadron identification (RICHes)



LHCb operation proceeds in harmony with higher luminosity operation of ATLAS/CMS thanks to luminosity leveling.

- 37 pb^{-1} collected in 2010
- 1 fb^{-1} in 2011 and 2 fb^{-1} in 2012
- aim for ~6-7 fb^{-1} during run 2

>260 papers & counting on CP violation, rare decays & spectroscopy (+ EW, QCD, ion physics… no time to cover here)

$B^0 \rightarrow K^*\mu\mu$ fit

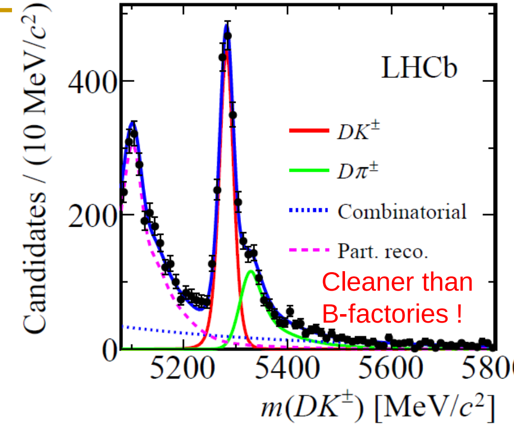
[LHCb-CONF-2015-002]

The angle θ_K is defined as the angle between the direction of the K^+ (K^-) and the B^0 ($\overline{B}^0$) in the rest frame of the K^{*0} ($\overline{K}^{*0}$) system. The angle ϕ describes the angle between the plane defined by the μ^+ and μ^- and the plane defined by the kaon and pion in the B^0 ($\overline{B}^0$) rest frame.

$$
\begin{aligned}
\frac{1}{\mathrm{d}(\Gamma+\bar{\Gamma})/\mathrm{d}q^2} \frac{\mathrm{d}^3(\Gamma+\bar{\Gamma})}{\mathrm{d}\vec{\Omega}}\Bigg|_{\mathrm{P}} = \frac{9}{32\pi} \Big[& \tfrac{3}{4}(1-F_{\mathrm{L}})\sin^2\theta_K + F_{\mathrm{L}}\cos^2\theta_K \\
& + \tfrac{1}{4}(1-F_{\mathrm{L}})\sin^2\theta_K \cos 2\theta_l \\
& - F_{\mathrm{L}}\cos^2\theta_K \cos 2\theta_l + S_3 \sin^2\theta_K \sin^2\theta_l \cos 2\phi \\
& + S_4 \sin 2\theta_K \sin 2\theta_l \cos\phi + S_5 \sin 2\theta_K \sin\theta_l \cos\phi \\
& + \tfrac{4}{3} A_{\mathrm{FB}} \sin^2\theta_K \cos\theta_l + S_7 \sin 2\theta_K \sin\theta_l \sin\phi \\
& + S_8 \sin 2\theta_K \sin 2\theta_l \sin\phi + S_9 \sin^2\theta_K \sin^2\theta_l \sin 2\phi \Big]
\end{aligned}
$$

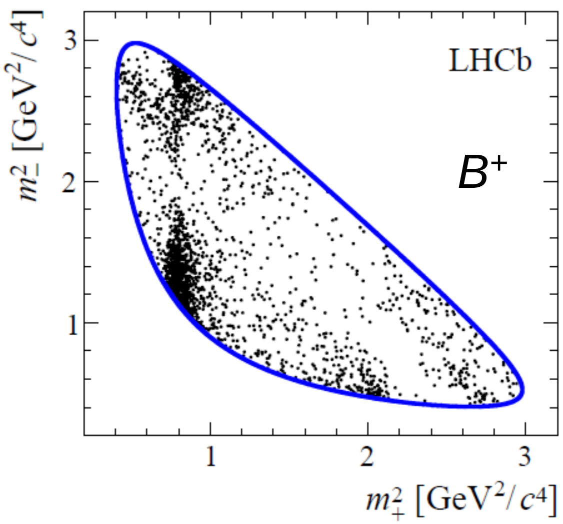
$$P'_{4,5} = S_{4,5}/\sqrt{F_{\mathrm{L}}(1-F_{\mathrm{L}})}$$

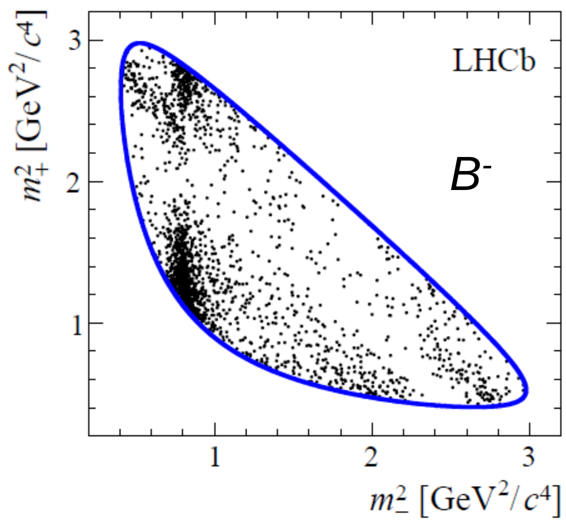
$B\to[K_S hh]_D K$ at LHCb

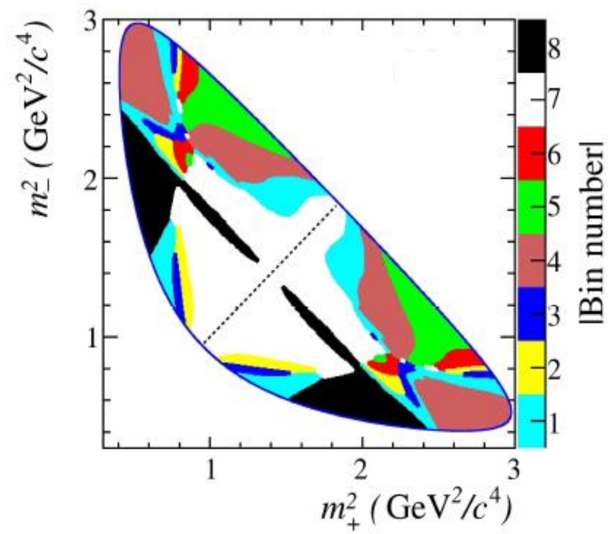


$B\to DK$ method has been applied by LHCb to $D\to K_S\pi\pi$ and K_SKK. CPV leads to difference in D Dalitz plots for B^+ and B^- decays

[JHEP 10 (2014) 097]







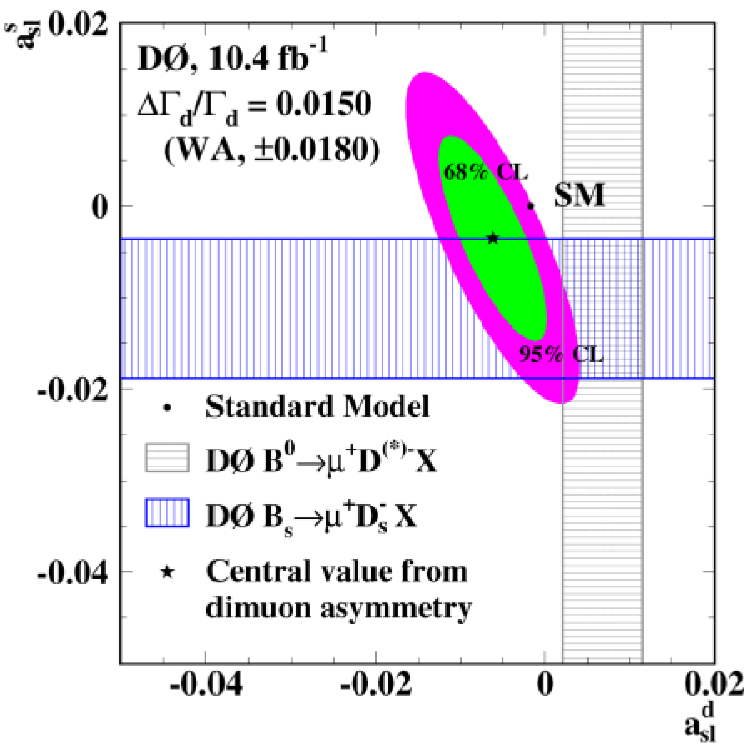
Data analysed in bins which have similar D decay strong-phase. To retain model independence these phases are taken from measurements of quantum-correlated DDbar pairs at CLEO-c [PRD 82 (2010) 112006] - will be improved by BES-III.

Cleanliness of measurement preserved exploiting synergy of facilities !

The elephant in the room: a_{sl}

Flavour-specific CP asymmetry in *B* decays, most easily measured in semileptonics (hence a_{sl}) accesses CP-violation in mixing. Extremely small in SM, especially in B_s system.

[D0, PRD 89 (2014) 012002]



D0 measurement, made with dileptons, measures a superposition of a^s_{sl} and a^d_{sl}

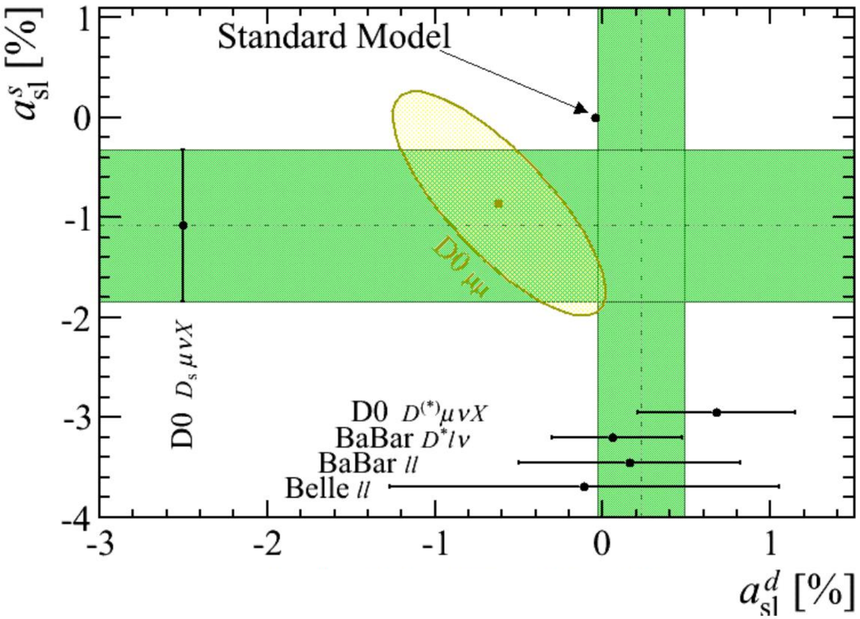
Result lies ~3 σ from SM (exact degree of tension depends on how comparison is made).

Most usually interpreted as a B_s driven effect. Challenging, however, to reconcile with other measurements, *e.g.* $B_s \to J/\Psi\varphi$, $J/\Psi\pi\pi$

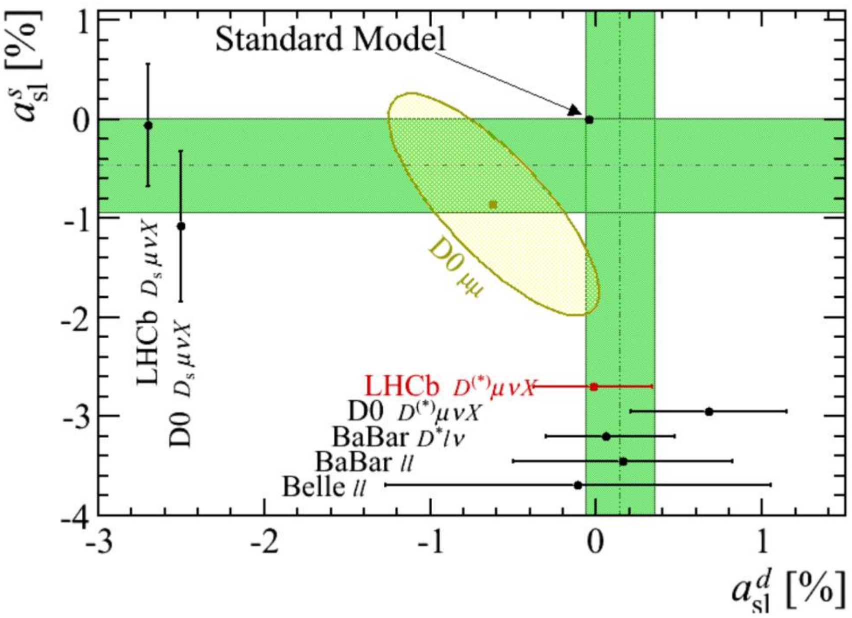
Attempting to resolve the D0 dimuon anomaly

Systematics associated with being a *pp* collider makes it very difficult to repeat D0 measurement at LHC. However it is possible to measure a_{sl}^{s} and a_{sl}^{d}.

LHCb has performed 1 fb^{-1} a_{sl}^{s} [PLB (728) (2014) 607] and 3 fb^{-1} a_{sl}^{s} [arXiv:1409.8586] studies.



with LHCb input



These recent measurements agree with SM, but do not exclude dimuon result.

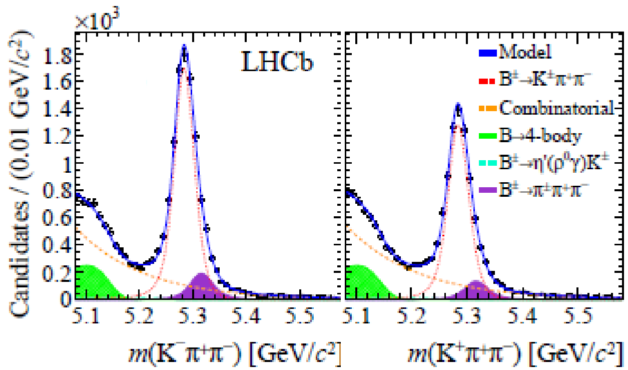
New, much more precise a_{sl}^{s} result on way. Improved $\Delta\Gamma_d/\Gamma_d$ would also be welcome.

Charmless B decays

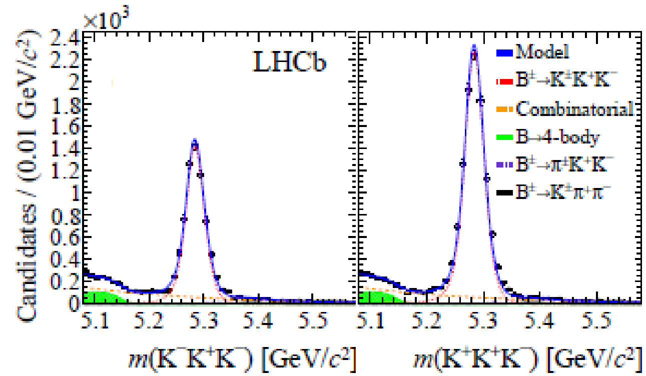
Other surprises are emerging from the large samples now available at the LHC - not all necessarily with New Physics consequences, but still of great interest.

e.g. large CPV seen in low mass non-resonance region of 3-body decays

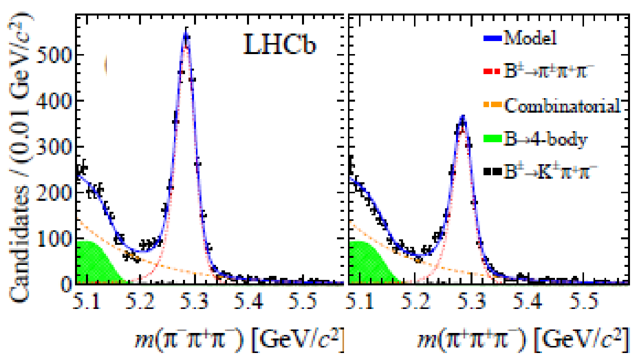
Big asymmetry in $K\pi\pi$…



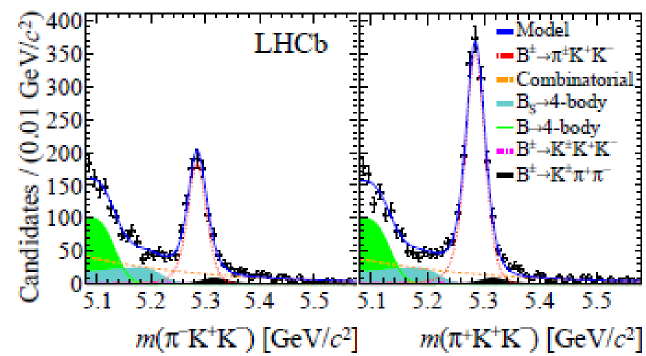
…seemingly mirrored by one of opposite sign in KKK



Same story in $\pi\pi\pi$…



…when compared to πKK



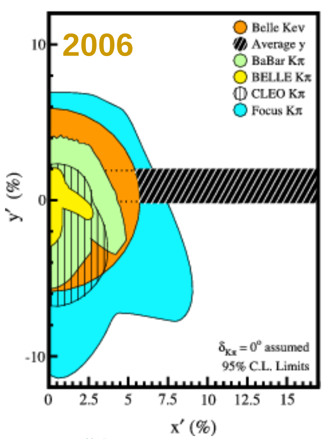
[PRD 90 (2014) 112004]

Perhaps due to long-distance $\pi\pi\leftrightarrow KK$ rescattering?

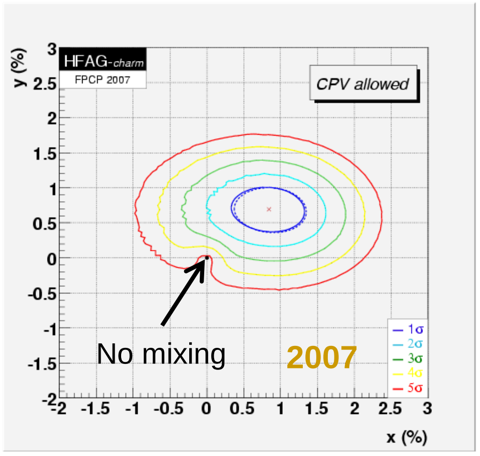
The charm renaissance

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

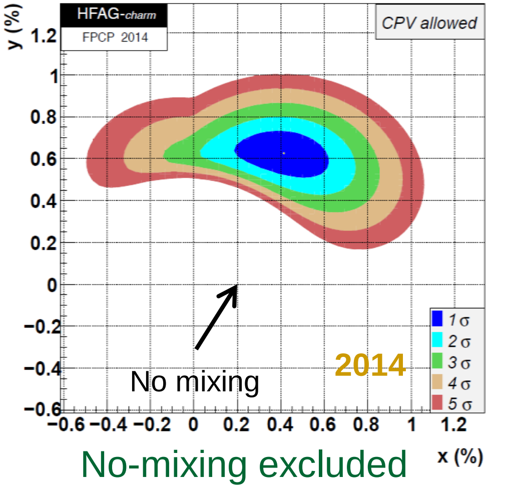
Excluded regions



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



Measurement contours;
no-mixing excluded at 5σ



No-mixing excluded
at lots and lots

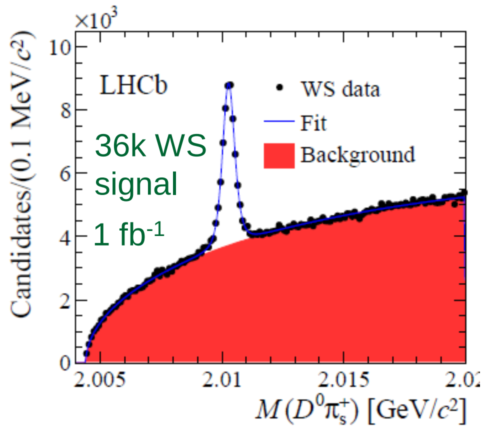
Then combination of B-factory analyses finally saw mixing. New outlook !

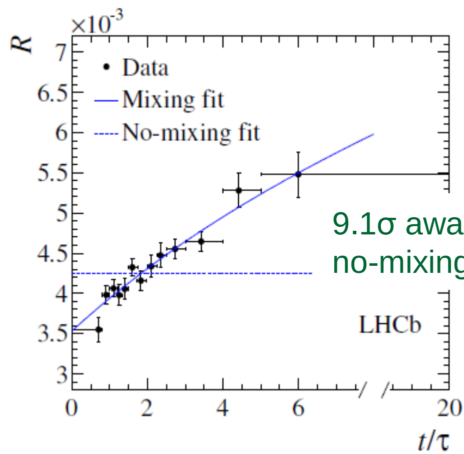
→ mixing parameters not tiny (~1%); good news for (indirect) CPV observables
→ smallness of SM ‘pollution’ not a bad thing in looking for New Physics signal
→ internal down-type quarks in loops – complementary to *b*-physics
→ huge potential of LHC for improving sensitivity

Rise of the hadron machines

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

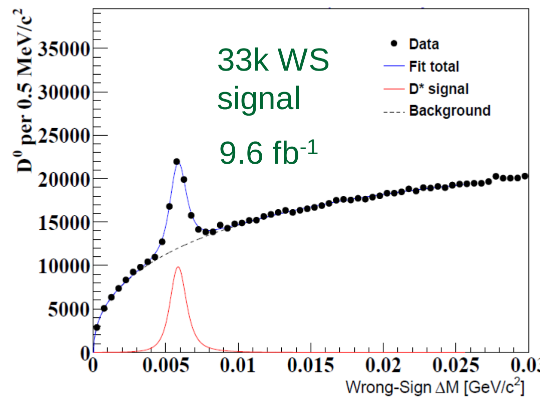
LHCb, PRL 110 (2013) 101802

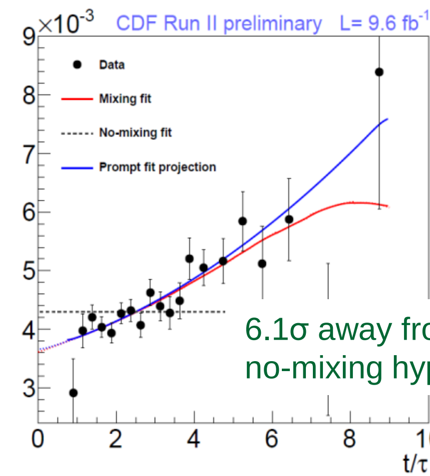




9.1σ away from no-mixing hyp.

CDF, PRL 111 (2013) 231802





6.1σ away from no-mixing hyp.

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.

ΔA_{CP}: first sighting of direct CPV in charm?

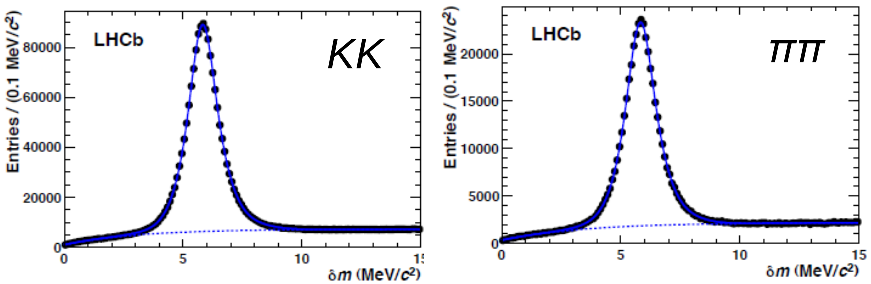
The observable $\Delta A_{CP} \equiv A_{CP}(KK) - A_{CP}(\pi\pi)$ is robust against detector systematics & production asymmetries, and is sensitive to any direct CPV in SCS charm decays

Majority opinion in literature before 2012:

→ direct CPV at or above a few per-mille in SCS decays is very unlikely in SM

Hence LHCb result [PRL 108 (2012) 111602] with 0.6 fb^{-1} of D^* decays of great interest:

$$\Delta A_{CP} = [-0.82 \pm 0.21(\text{stat.}) \pm 0.11(\text{syst.})]\,\%$$



Soon after, measurements from CDF 9.7 fb^{-1} [PRL 109 (2012) 111801] and Belle 976 fb^{-1} [arXiv:1212.1975] increased the excitement:

$$\Delta A_{CP} = (-0.62 \pm 0.21\ (\text{stat}) \pm 0.10\ (\text{syst}))\%$$ CDF

$$\Delta A_{CP}^{hh} = (-0.87 \pm 0.41 \pm 0.06)\%$$ Belle

These (together with other measurements) only consistent with no-CPV at ~2%.

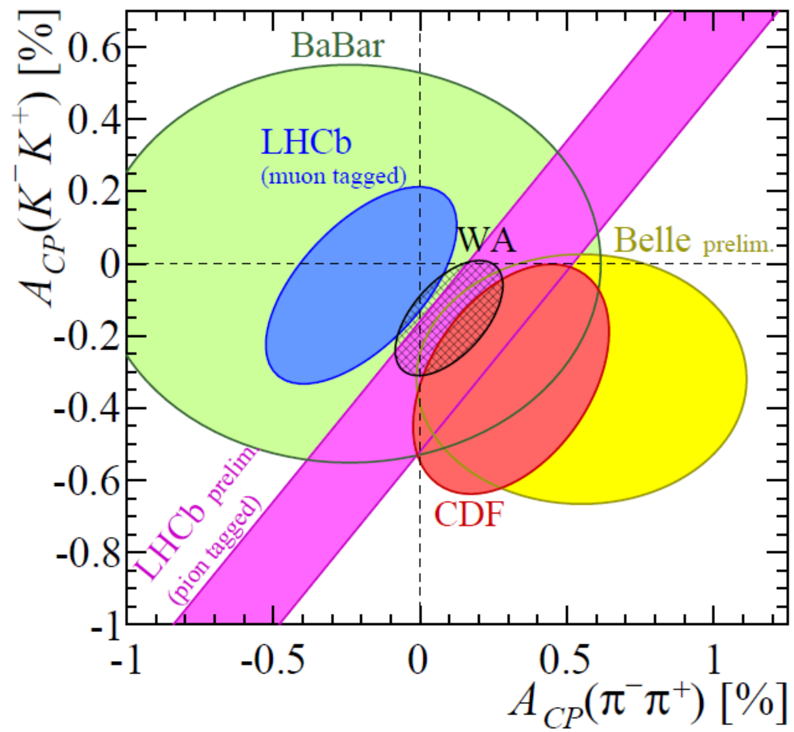
A story to get the theorists interested? Yes! And surely *very* unlikely to be SM ???

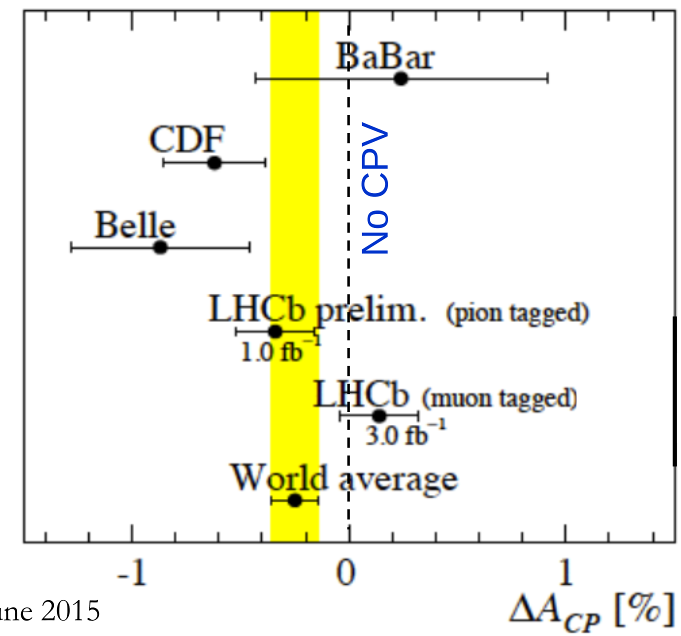
ΔA_{CP}: too early to celebrate

So it seemed a consistent picture had emerged of ~0.5% direct CPV in SCS charm decays (thanks to LHCb, CDF, Belle)

This caused the theory community to re-evaluate their position...

…but later LHCb results (1 fb^{-1} D^* update [LHCb-CONF-2013-003] and 3 fb^{-1} $B \to D^0 \mu X$ [JHEP 07 (2014) 041]) indicate reduced / ~null effect



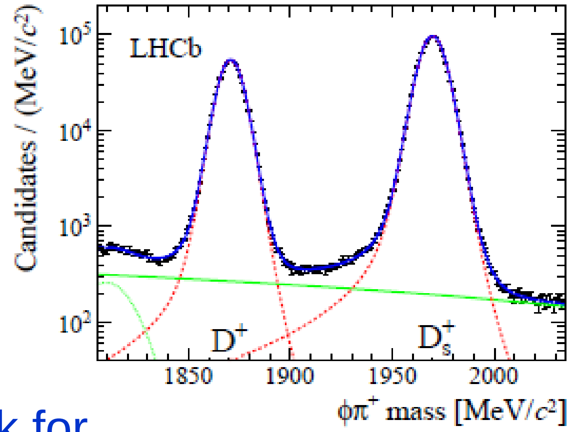


Next steps required for progress:

- Final LHCb D^* results from 2012 data set (& beyond)
- More precise results in other SCS modes

Recent progress in SCS direct CPV searches

Other two-body (& pseudo-body) SCS searches now have 0.1% precision, *e.g.* $D^+ \to \Phi\pi^+$



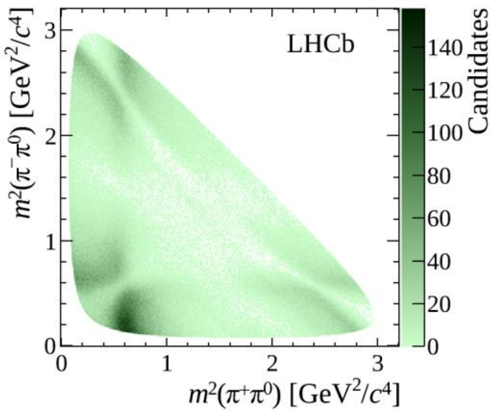
$(-0.04 \pm 0.14 \pm 0.14)\%$ LHCb [JHEP 06 (2013) 112]

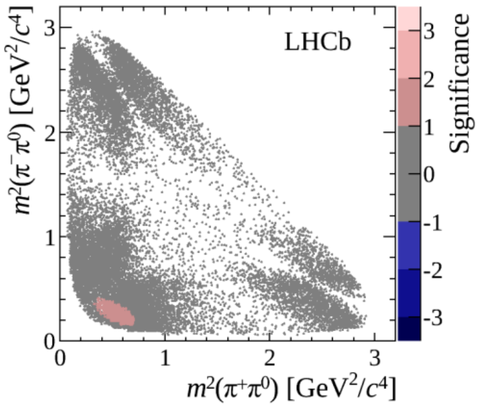
$(+0.51 \pm 0.28 \pm 0.05)\%$ Belle [PRL 108 (2012) 071801]

$(-0.3 \pm 0.3 \pm 0.5)\%$ BaBar [PRD 87 (2012) 052010]

Moreover a developing area, of great promise, is to look for regions of local CPV in multi-body modes, where interference between neighbouring resonances may allow effects to be seen.

e.g. LHCb analysis of 0.7 M $D^0 \to \pi^+\pi^-\pi^0$ decays with model independent 'energy' test [PLB 740 (2015) 158]



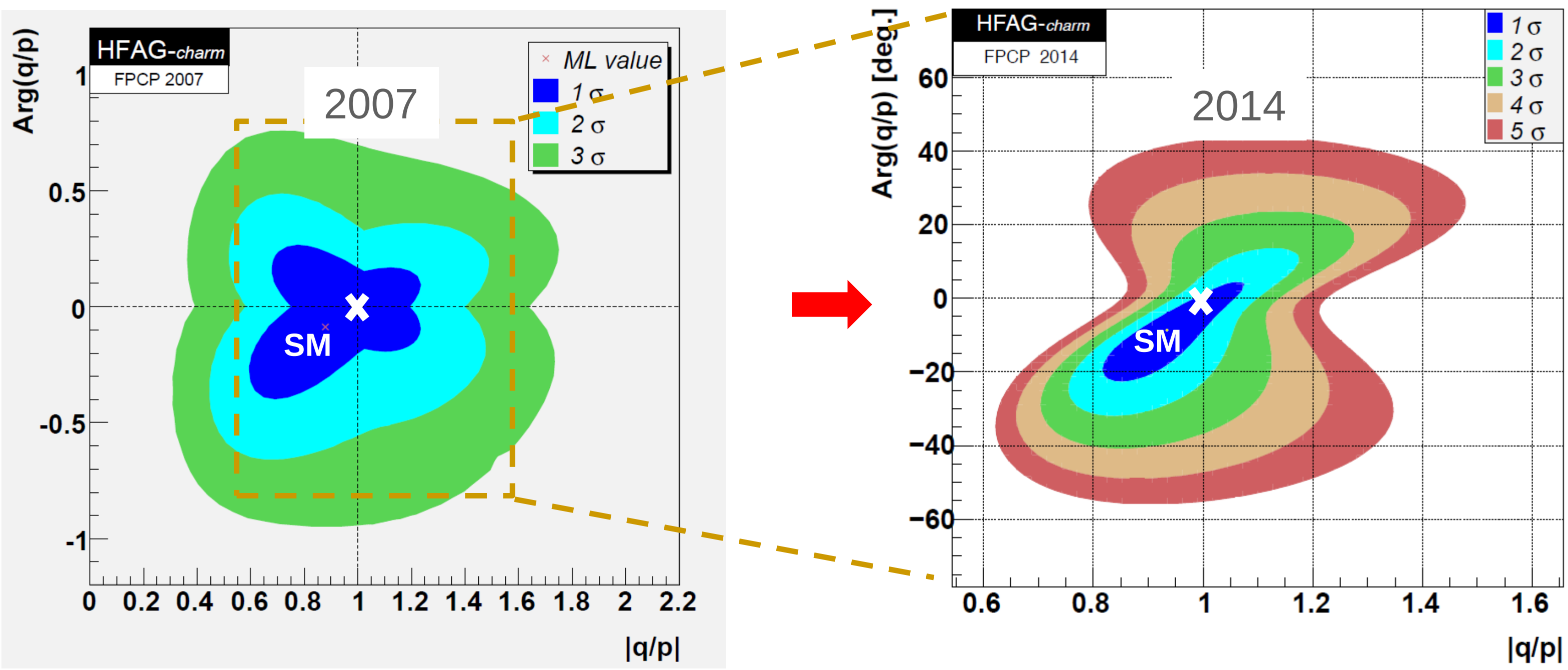


Prospects of direct CPV revealing clear sign of NP appears to be receding.
But still of *great* interest to find a non-0 signal – and LHCb statistics hold promise.

CPV searches in mixing

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.

Searching for indirect CPV

Hunt for indirect CPV can be performed with:

- Dedicated observables, such as A_Γ

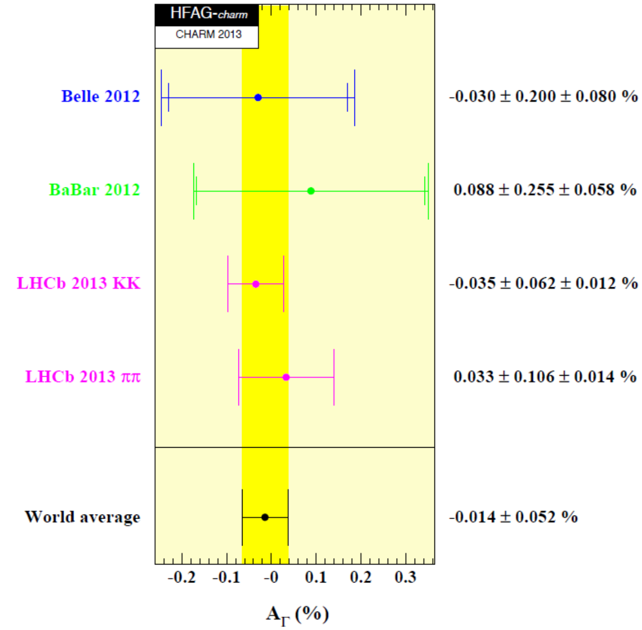
$$A_\Gamma \equiv \frac{\Gamma(D^0 \to KK) - \Gamma(\overline{D}^0 \to KK)}{\Gamma(D^0 \to KK) + \Gamma(\overline{D}^0 \to KK)}$$

(similarly for any other CP eigenstate)

$$A_\Gamma = \frac{1}{2}\left[\left(|q/p| - |p/q|\right) y\cos\phi - \left(|q/p| + |p/q|\right) x\sin\phi\right]$$

(neglecting direct CPV)

Current precision 0.05% and is LHCb driven. Significant improvements already expected with full run 1 data set.

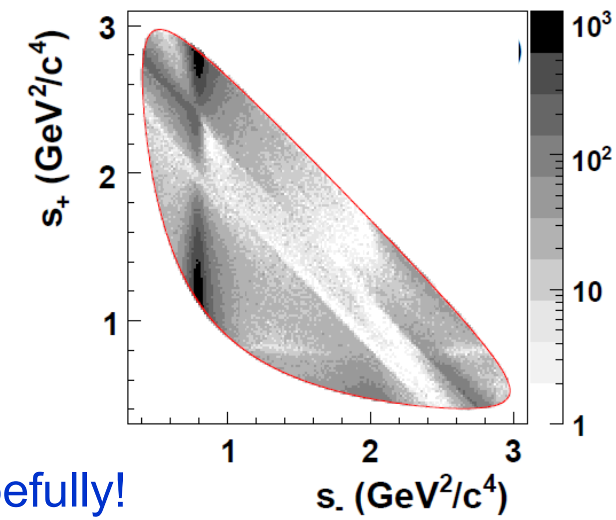


- Generalising WS $K\pi$ fit to D^0 and D^0bar

  e.g. LHCb PRL 111 (2013) 251801

- Time-dependent Dalitz studies of multi-body decays, *e.g.* $K_S\pi\pi$

  First LHCb run-1 results coming very soon



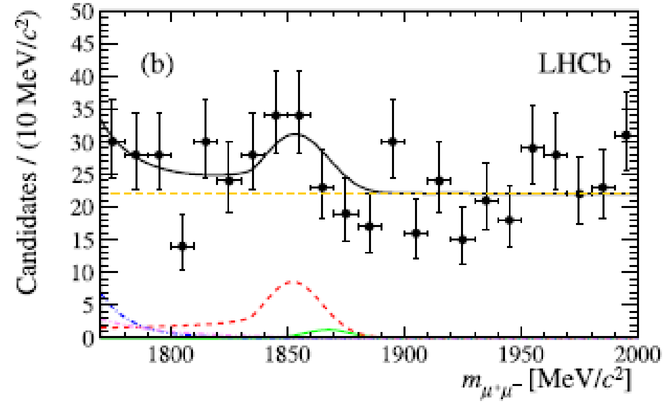
e.g. BaBar PRL 105 (2010) 081803

We're at the start of a long journey – let's travel hopefully!

FCNCs: beyond the *b*

LHCb performs strongly in the study of FCNC searches in rare charm decays, attaining world leading sensitivities, *e.g.* 1 fb^{-1} $D^0\to\mu\mu$ result

[PLB 725 (2013) 15]



$$\mathcal{B}(D^0 \to \mu^+\mu^-) < 6.2\ (7.6) \times 10^{-9} \quad \text{at 90\% (95\%) CL}$$

This will improve with full run-1 data set and beyond – interesting region is ~10^{-10} .

Also of growing interest is the experiment's potential in kaon and hyperon decays. $s\to d$ transitions of interest because SM 'background' is highly suppressed.

$$A = A_0 \left[c_{SM} \frac{1}{M_W^2} + c_{NP} \frac{1}{\Lambda^2} \right]$$

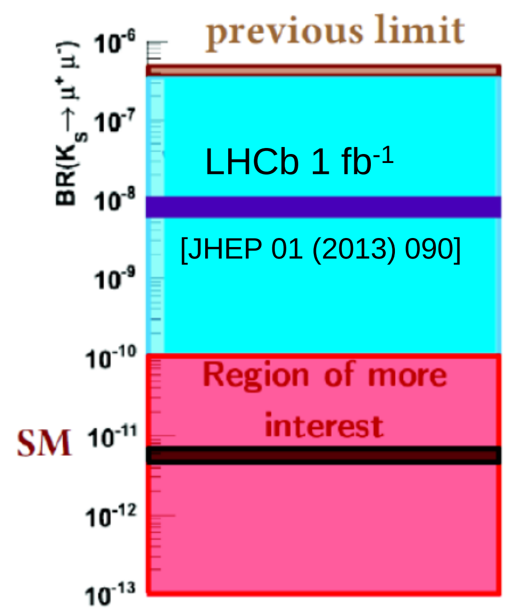
c_{SM} ~ $V_{ts}V_{td}$ ~ 10^{-4}

(G. Isidori)

~10^{13} K_S / yr at LHCb !

The problem is the trigger - with current detector efficiency is very low. Nonetheless…

$$\mathcal{B}(K^0_S \to \mu^+\mu^-) < 11(9) \times 10^{-9} \quad \text{at 90\% (95\%) CL}$$

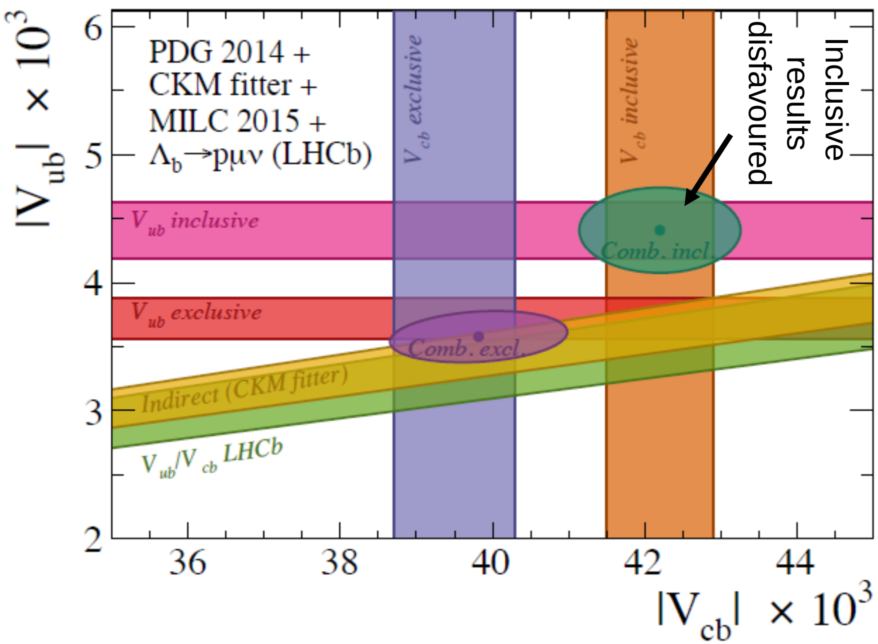


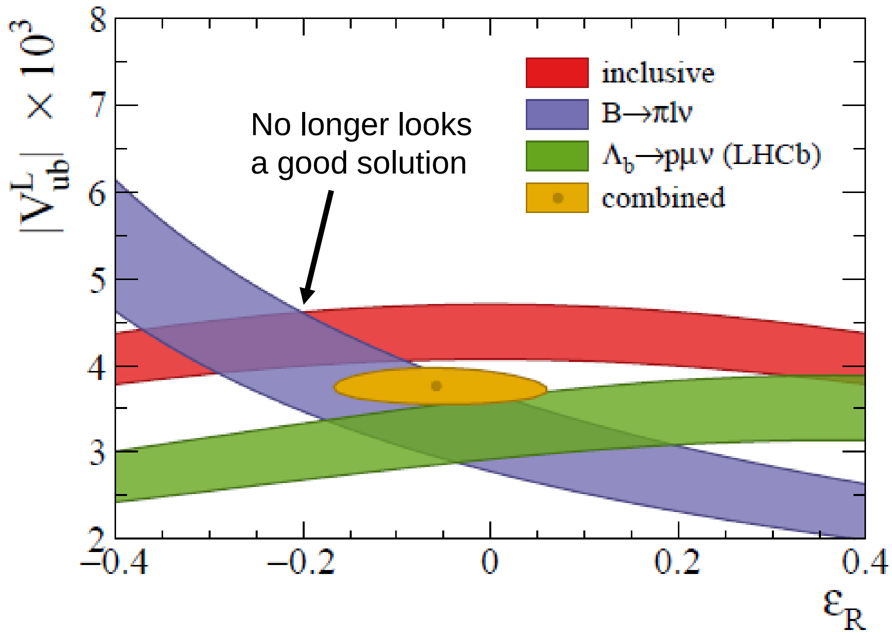
This is a topic where LHCb Upgrade will bring *big* gains.

LHCb V_{ub}: possible interpretations

Not only has there has there been a long-standing inclusive vs exclusive puzzle in V_{ub}, but also in V_{cb} .

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





The LHCb result (which is really a V_{ub}/V_{cb} measurement) is suggestive, and also agrees well with the indirect prediction.

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

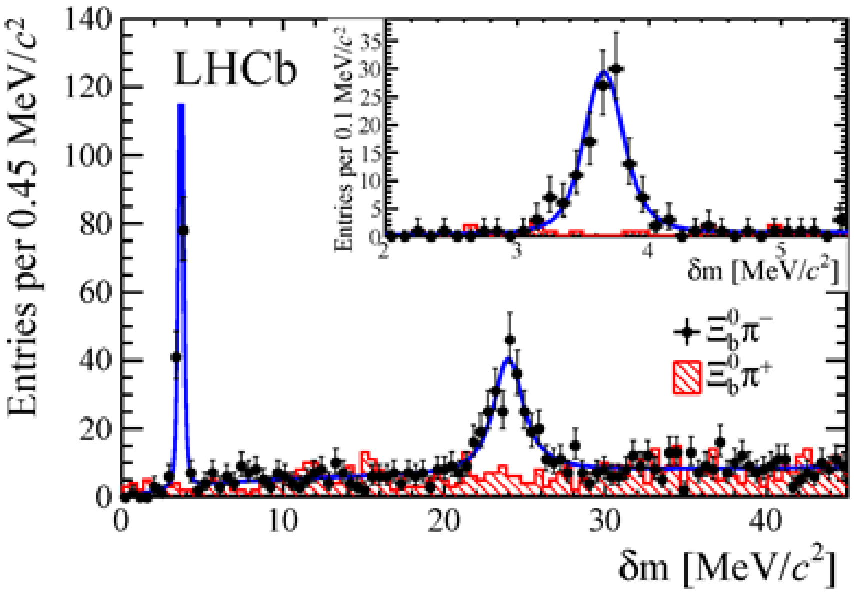
* Chen & Nam, PLB 666 (2008) 462;
Crivellin, PRD 81 (2010) 031301;
Buras, Gemmler & Isidori, NPB 843 (2011) 107

Spectroscopy

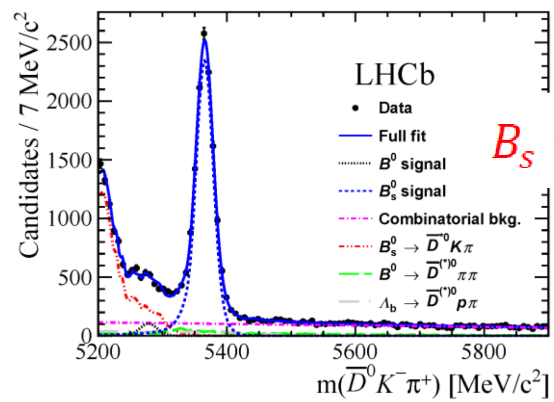
Many new states found by LHCb, most of which fit within the ‘vanilla’ quark model

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

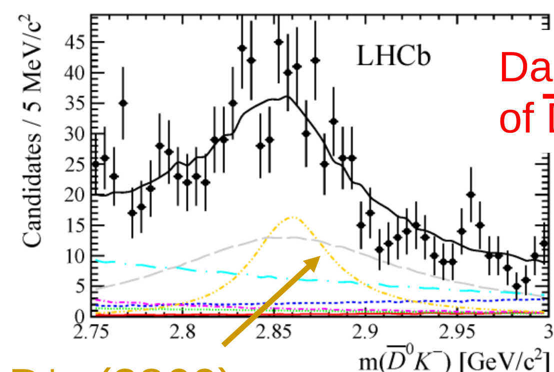
e.g. mesons: first observation of a heavy flavour spin-3 particle
[PRL 113 (2014) 162001;PRD 90 (2014) 072003]



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



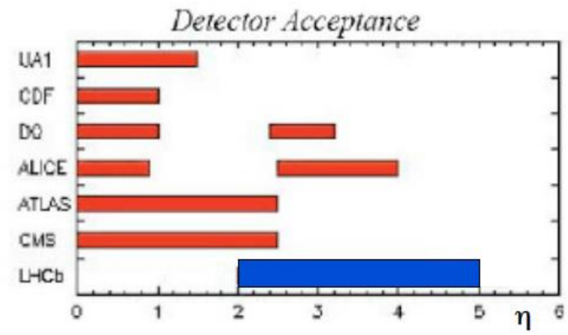
$B_s \to \overline{D}^0 K^- \pi^+$

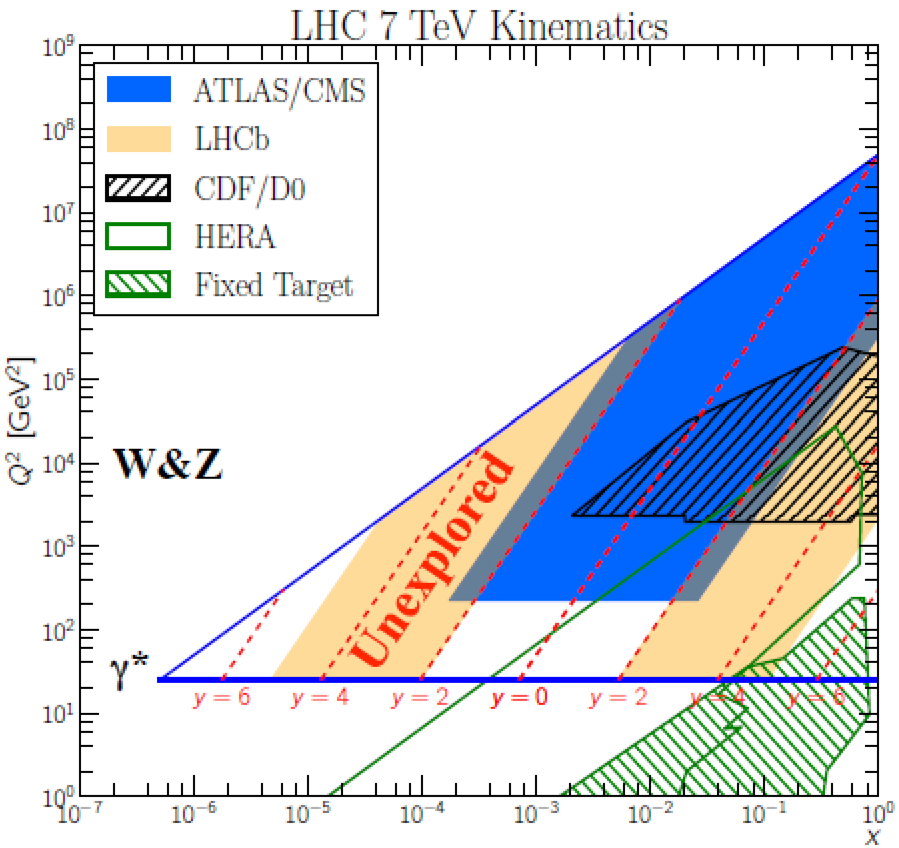


Dalitz analysis of $\overline{\mathrm{D}}^0$ K^- system

$D^*_{s3}(2860)^-$

EW boson production in forward region





LHCb's unique forward acceptance means that W and Z (+ low-mass Drell-Yan) production probes two distinct regions of (x, Q^2) space.

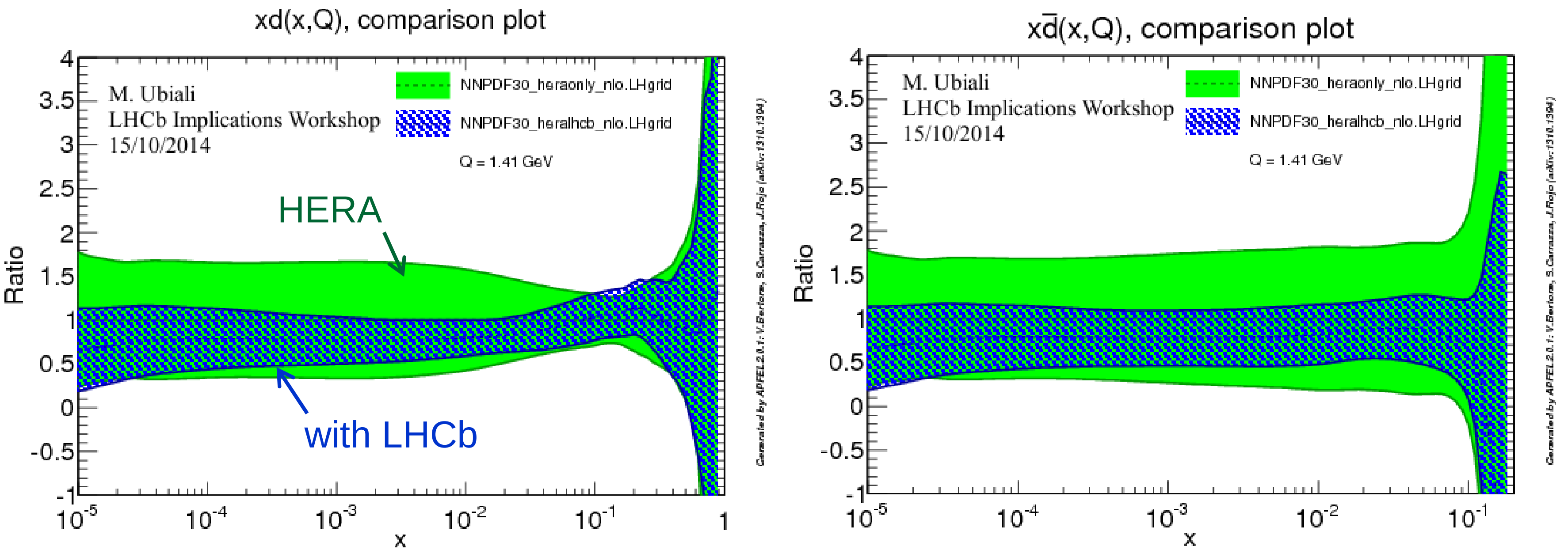
The low-x, high-Q^2 region is of particular interest

- W & Z: $x \sim 10^{-4}$
- low-mass Drell-Yan: x down to 10^{-6}

Impact of LHCb data on PDFs

Look at impact of 2010 LHCb $W \rightarrow \mu\nu$ & $Z \rightarrow e^+e^-$ measurements on HERA-only PDFs

[NNPDF3.0, Maria Ubiali]



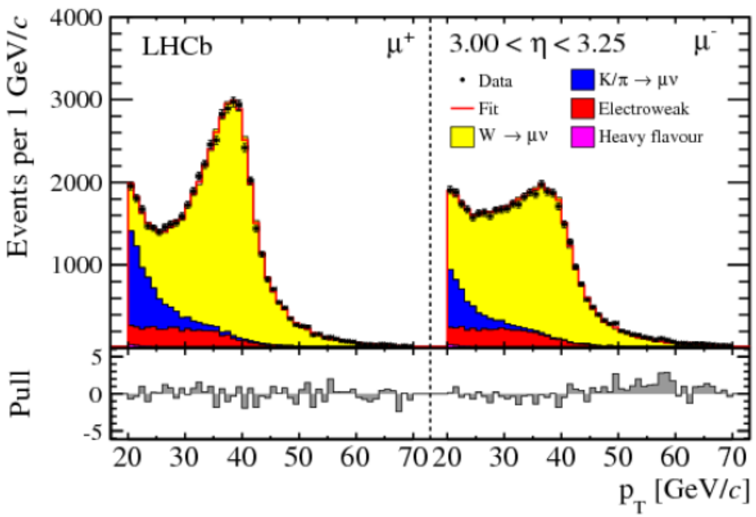
Significant impact! But this is of course not including other LHC measurements…

LHCb W production

[arXiv:1408.4354]

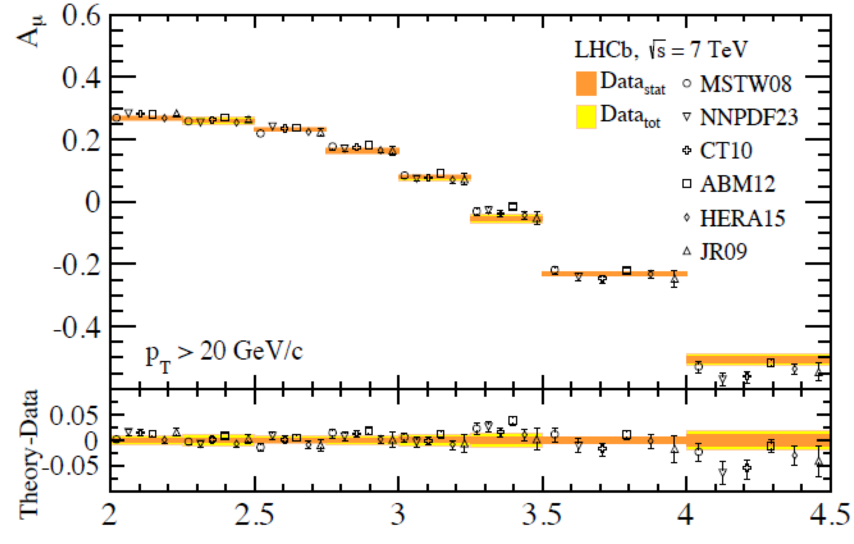
Measurements have been performed of $W \rightarrow \mu\nu$ differential cross-section & charge asymmetry for 2011 data with E_{CM}=7 TeV

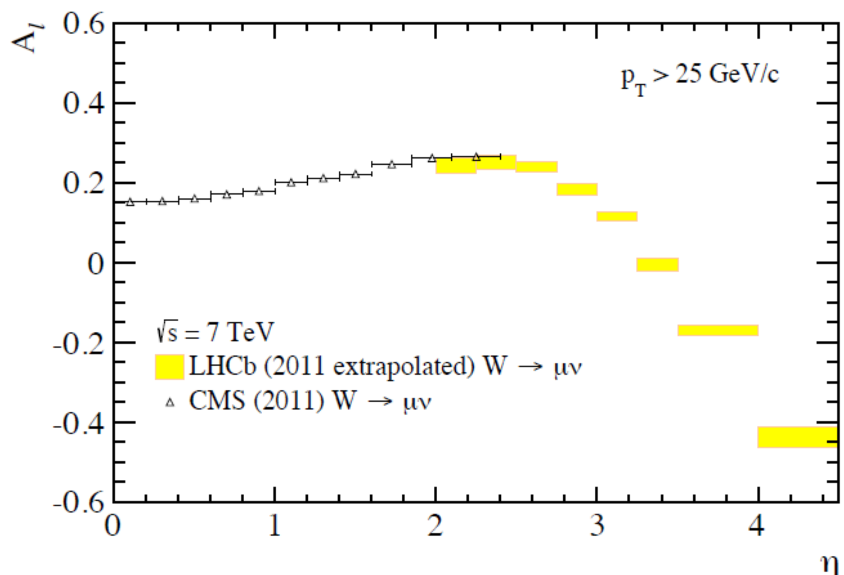
example results in one bin of η



Good agreement with NNLO predictions (using FEWZ) , and a variety of PDF sets.

Consistency with CMS (ATLAS too)

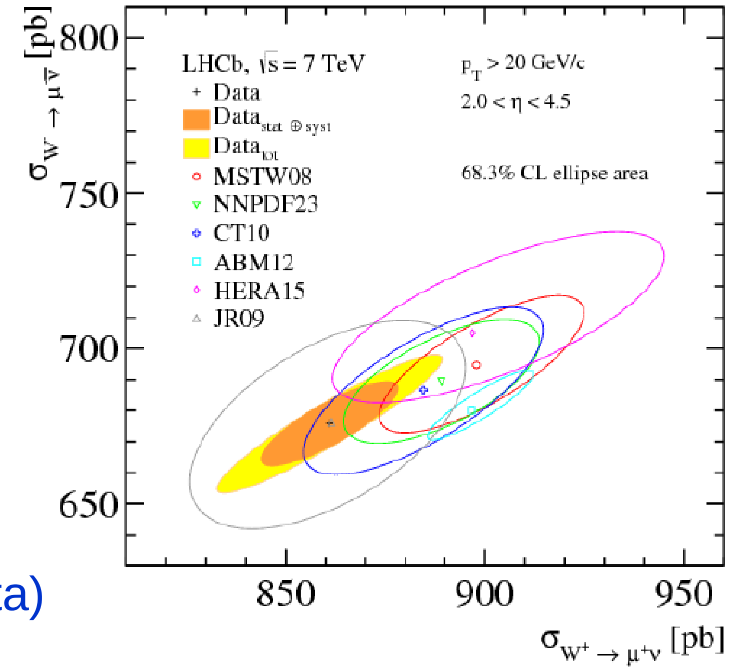


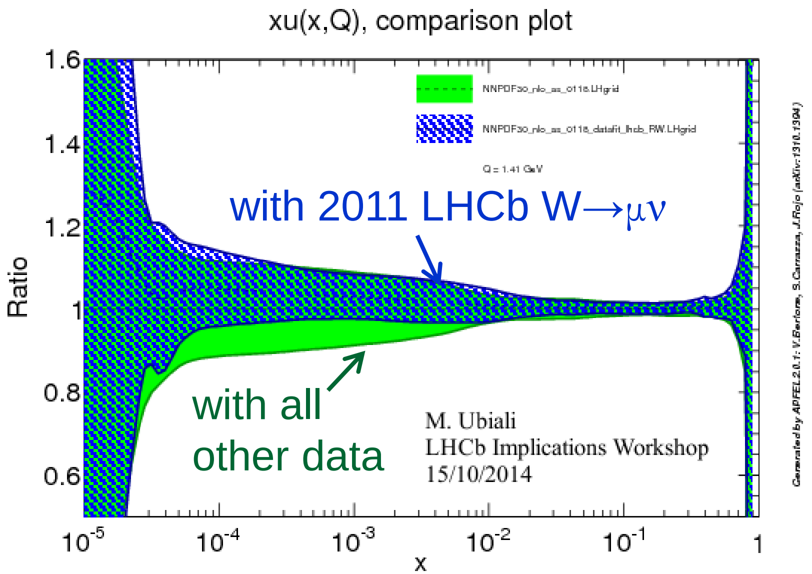


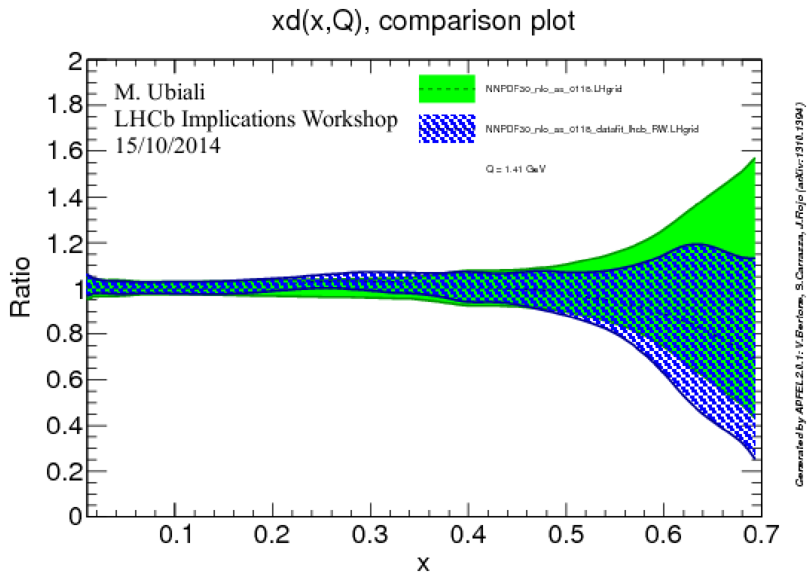
Impact of 2011 W measurement on PDFs

This measurement [arXiv:1408.4354] provides useful discrimination between PDFs sets…

…and when added into the fits provides significant improvement (now comparing to fit made with HERA and ensemble of *all* other data)

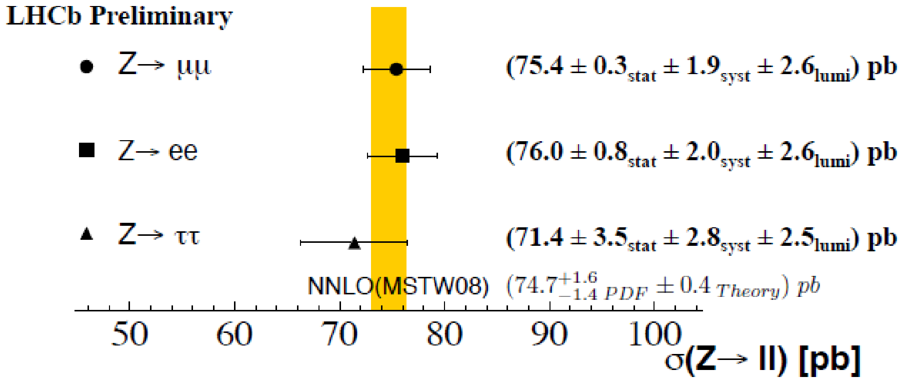


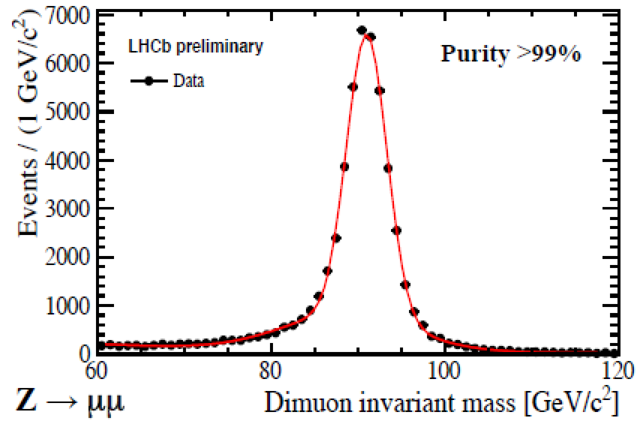




Z production (& luminosity measurement)

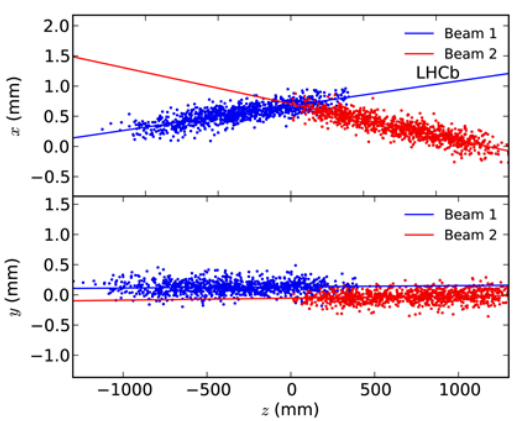
pp→Z+*X* measurements available in all l^+l^- modes





[LHCb-CONF-2013-007]

Aside – note that LHCb now has most precise luminosity measurement at LHC (indeed, best precision achieved at a bunched hadron collider)

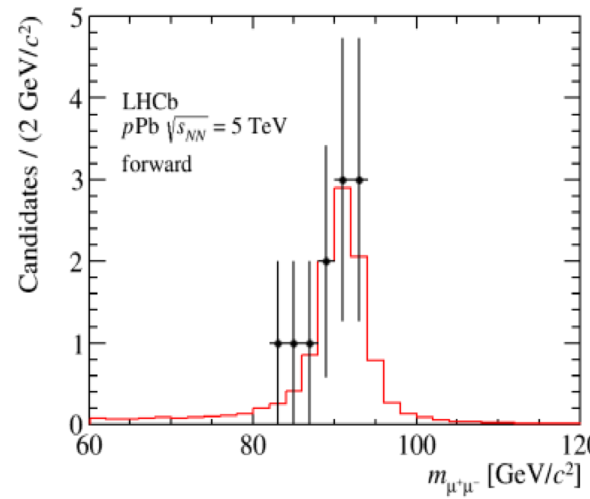


[2014 JINST 9 P12005]

This thanks to beam-gas 'SMOG' technique, which complements van der Meer scan measurement

Lumi error = 1.12%

LHCb has also been first to observe Z production in *Pb-p*

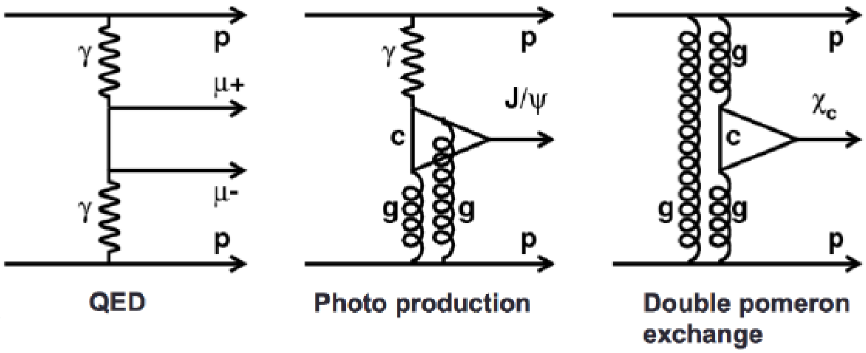


[JHEP 09 (2014) 030]

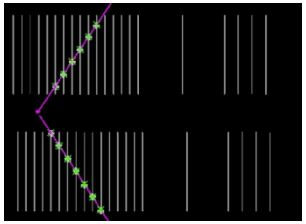
Central Exclusive Production

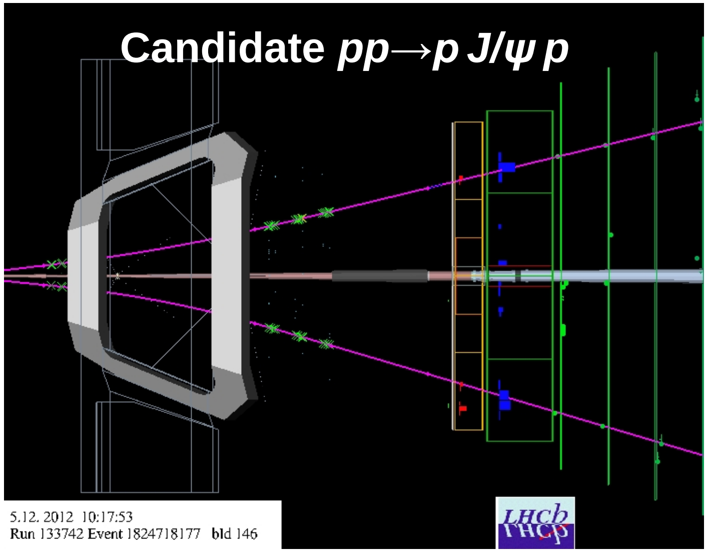
LHCb is an ideal detector for studying $pp \rightarrow p\,X\,p$ processes:

- Luminosity 'just right' (the Goldilocks experiment)
  - high enough to probe pb x-sections
  - not too high: low pileup (especially with 25 ns running of run 2) makes CEP interactions easy to see
- Acceptance down to p_T~0
- Particle identification for hadronic final states



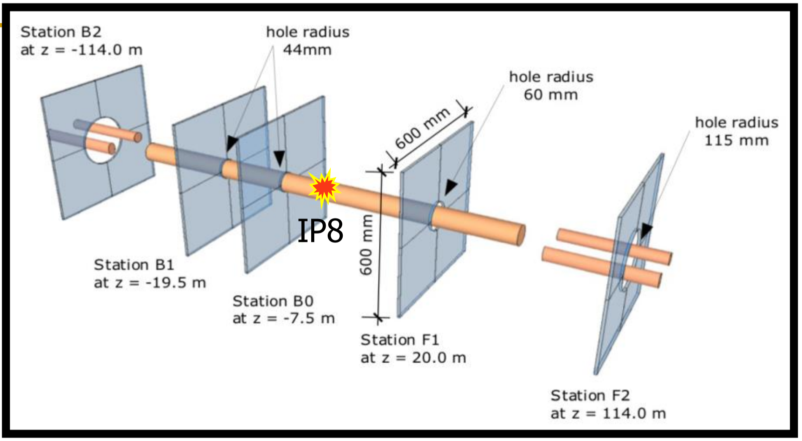
VELO zoom





Results aleady available in
7 TeV exclusive J/ψ, $\psi(2S)$ [JPG 41 (2014) 055002]
and full run-1 double J/ψ [JPG 41 (2014) 115002]

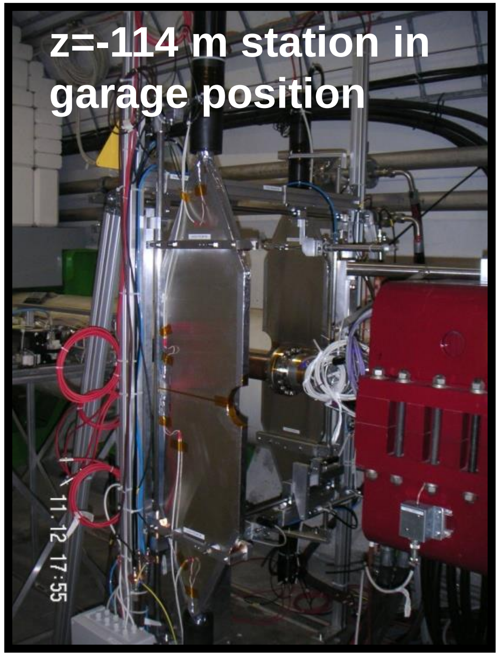
High Rapidity Shower Counters for LHCb – HeRSCheL [new for run 2]



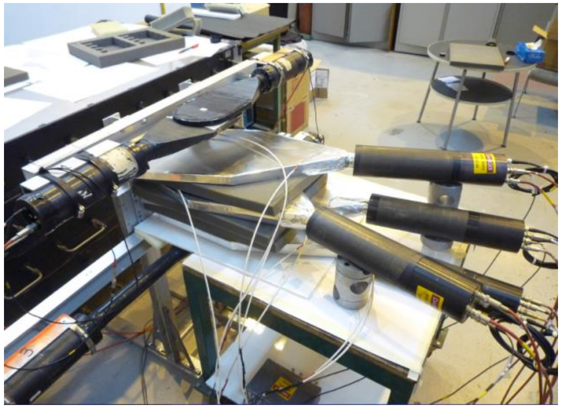
System of forward-shower scintillator planes installed in tunnel up to 114 m away from IP to help in definition of forward rapidity gaps. Main physics motivation is Central Exclusive Production.

Five planes, with phototubes and readout optimised for high rate 25 ns operation.

All stations now installed



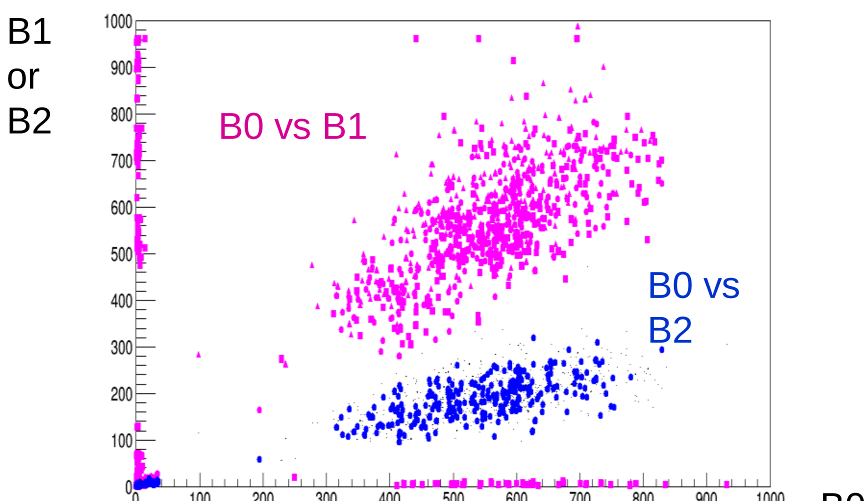
HeRSCheL - early results



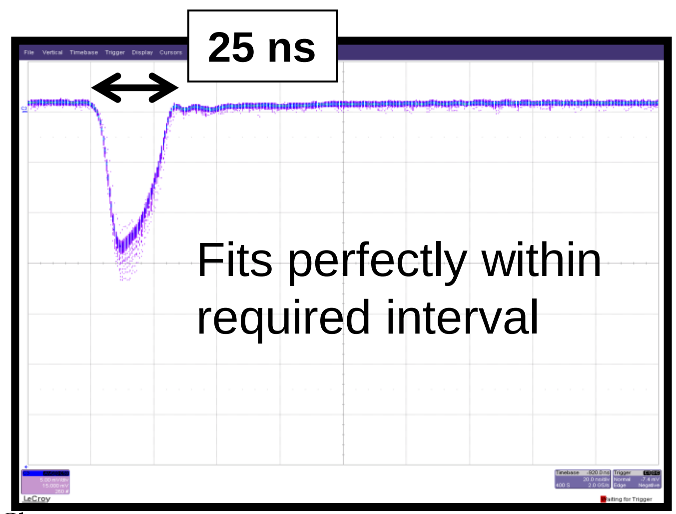
Cosmic calibration campaign shows ~170 p.e.s / MIP

Results from beam muons in tunnel (November ‘TED’ tests)

Correlation between stations



Beam pulse from furthest station



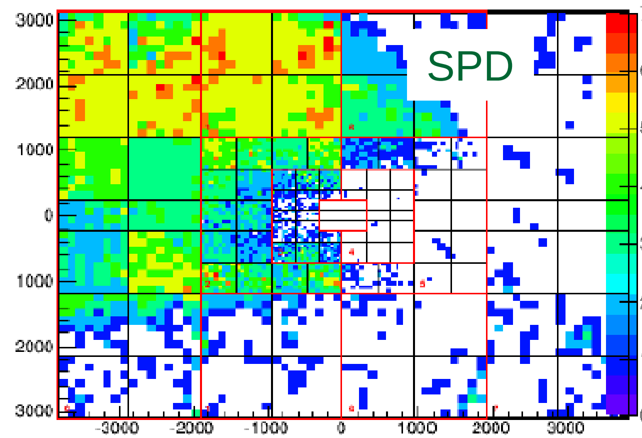
Transfer line test ('TED')

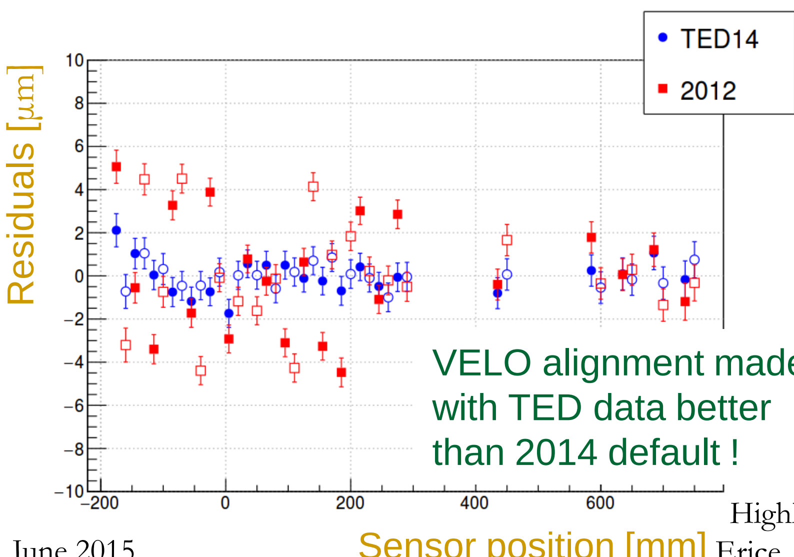
'TED' = stopper at end of transfer line. LHCb profits from resulting muons.

Sequence of 'commissioning weeks', increasing in intensity and focus, intended to wake up detector from hibernation, culminated in transfer line tests of 22-23 Nov.

Vibrant atmosphere in control room

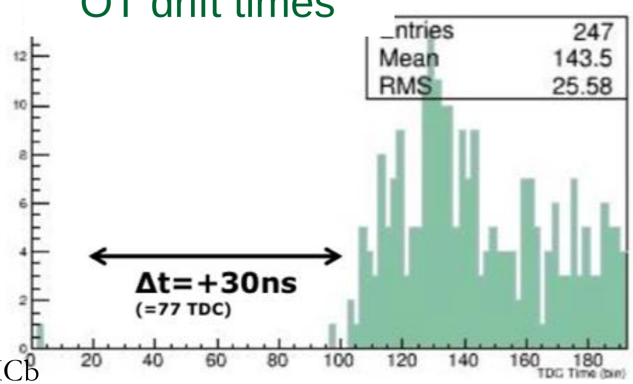
All sub-detectors collected useful data





VELO alignment made with TED data better than 2014 default !

OT drift times



Dreaming about ultra-high statistics

Big improvements foreseen before 2018-19 long shutdown (*e.g.* ~7 fb^{-1} at LHCb, ~ doubling in x-sec from E_{CM} w.r.t. 2012, improved analysis methods) but we can dream of what could be achieved with a very large increase in sample sizes *e.g.*

- CKM metrology

  Determine γ with sub-degree precision to match anticipated improvements in indirect precision coming from lattice QCD. Improve β down to ~0.02°.

- CPV in B_s mixing

  Measurement of φ_s with precision much better than SM central value, to probe for sub-leading contributions from NP.

- $B^0_{(s)} \to \mu\mu$

  True precision measurement of BR down to theory uncertainty and first measurement of ultra-suppressed $B^0 \to \mu\mu$ BR.

- $B^0 \to K^*\mu\mu$

  Precision studies of all observables of interest through full angular analysis

- Charm

  Extensive study of direct CPV across wide range of modes.
  Sensitivity to indirect CPV down to SM expectation.

Plus great improvements in precision, & *new* measurements, in many other topics!