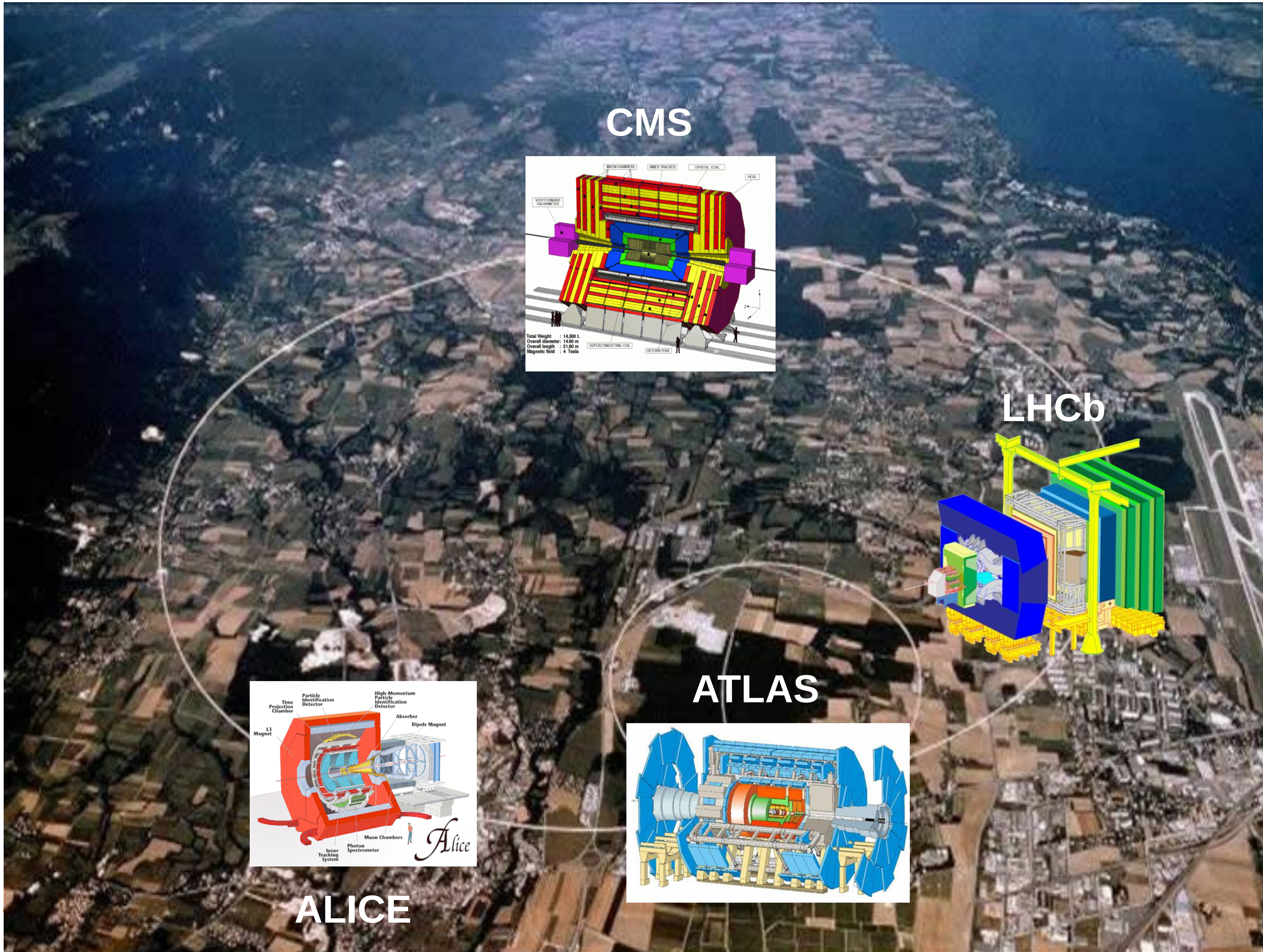
LHCb and the flavour frontier

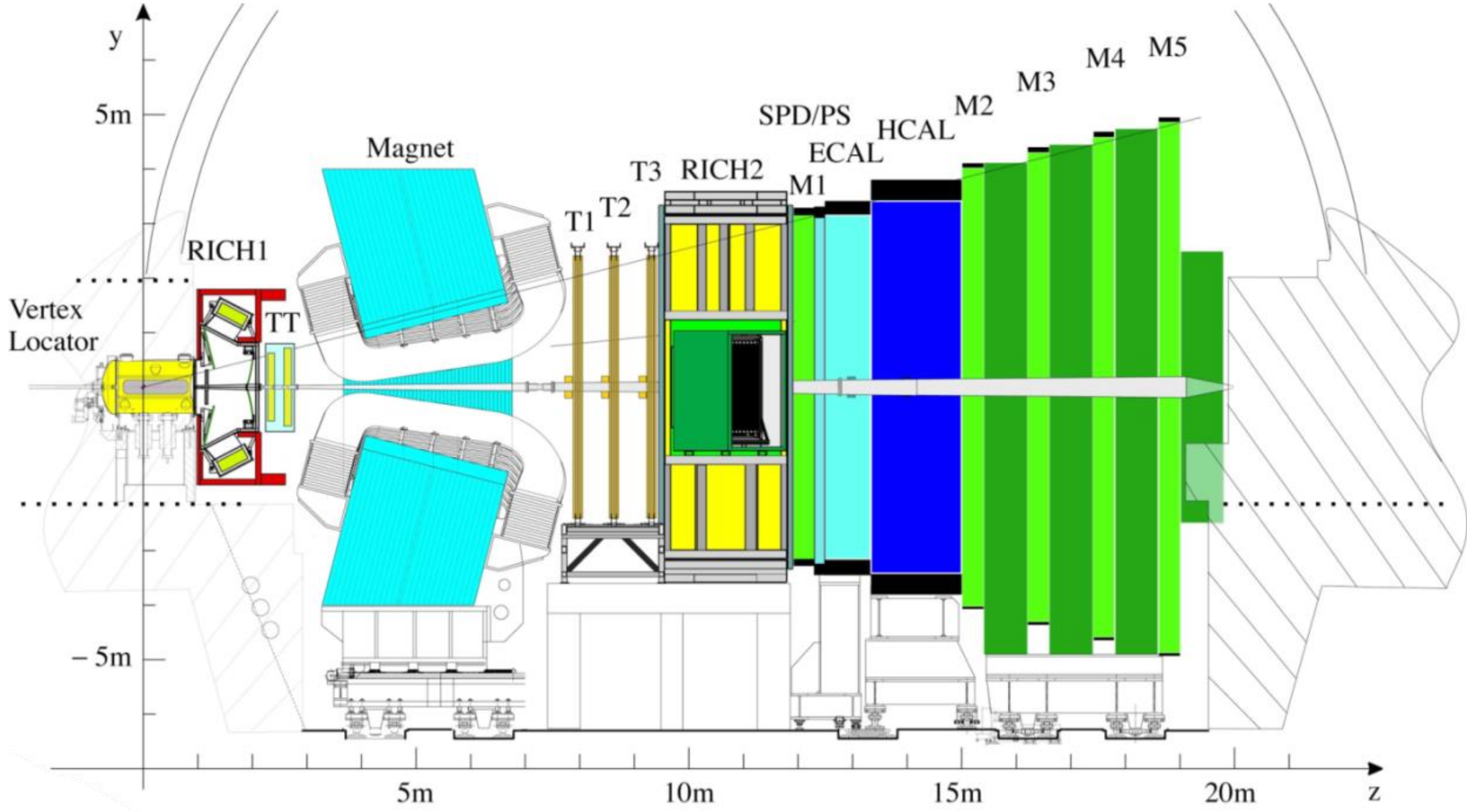
- Beginnings
- LHCb – an overview
- Selected physics results, and their historical context
- Run 2 and the road ahead

Guy Wilkinson
University of Oxford and CERN
30/6/15


CMS
LHCb
ATLAS
ALICE
Particle Identification Detector
Time Projection Chamber
High-Momentum Particle Identification Detector
Absorber
Dipole Magnet
L3 Magnet
Muon Chambers
Photon Spectrometer
Inner Tracking System
Alice

LHCb – a forward spectrometer for flavour physics

i.e. the study of beauty and charm hadrons, in particular suppressed decays and CP violation



b-physics options in the mid-1990s

Thrusting young lecturer looking to assume leading role in new initiative in post-LEP/HERA era. At that time, there were several promising options in *b*-physics.

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e^+e^- *b*-factory, KEK, Japan

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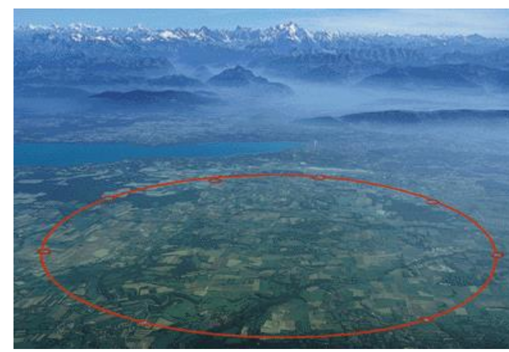
e^+e^- *b*-factory, SLAC, USA



pp *b*-factory, LHC, Switzerland

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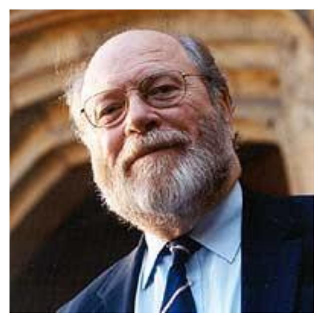
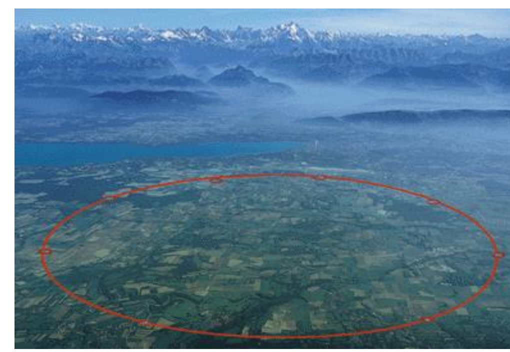




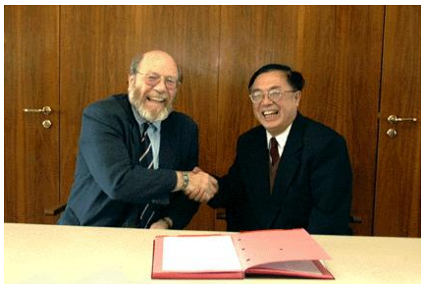
pp *b*-factory, LHC, Switzerland

Wise guidance from Head of Sub-Dept. encouraged him to choose the longer-term, most exciting project, where Oxford & the UK could have the biggest impact.

Wise guidance from the CERN Research Director

Roger’s term as research director at CERN was a critical period for the LHCb collaboration, which was making final decisions on the detector technologies.

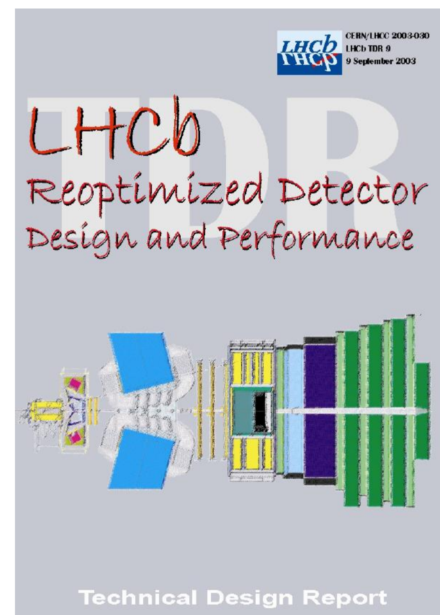
Despite being very busy, much wise advice was given…



Key decision (albeit one taken rather late in the day).

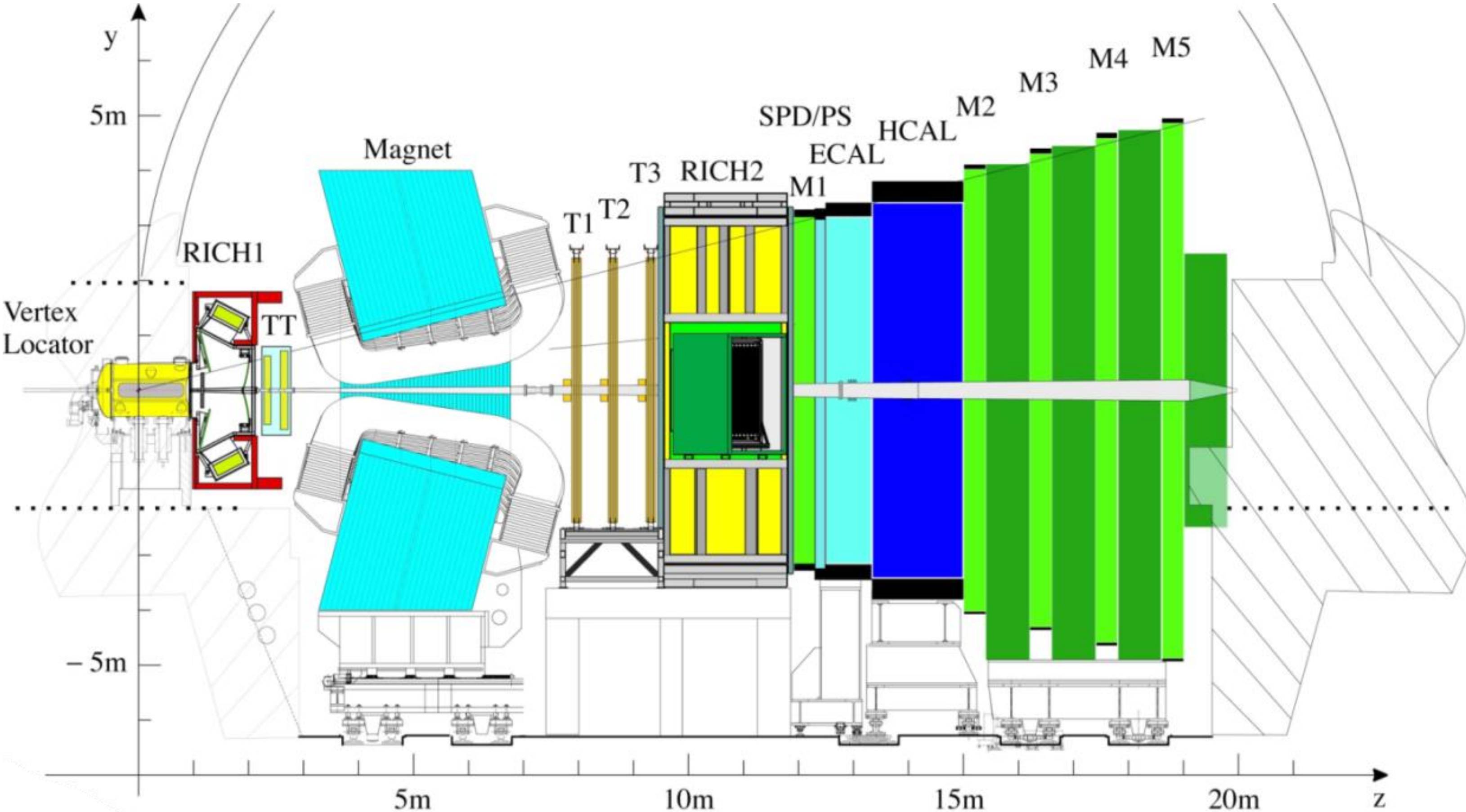
Dramatic ‘weight-loss’ campaign to eliminate excess material, including removal of tracking planes within magnet

(we learned from tough experience of HERA-B).



LHCb – a forward spectrometer for flavour physics

i.e. the study of beauty and charm hadrons,
in particular suppressed decays and CP violation



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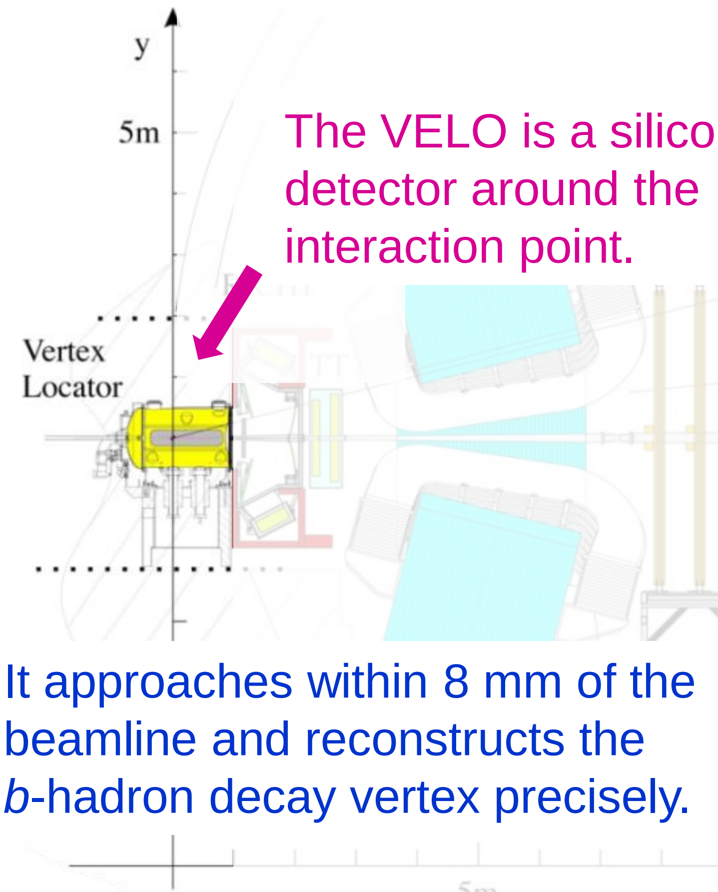
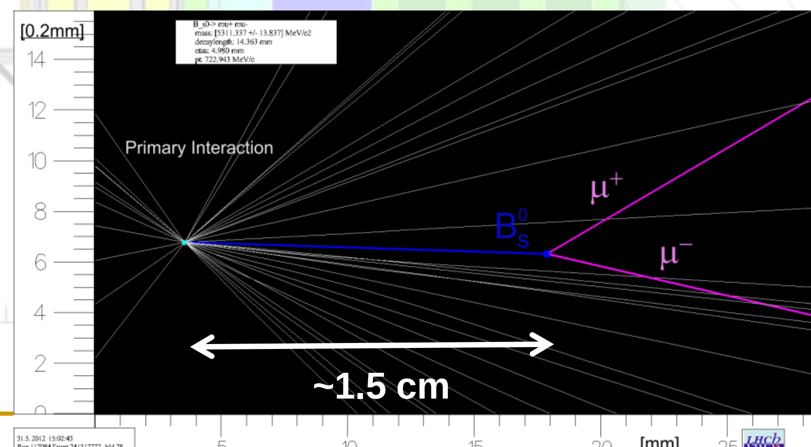


The VELO is a silicon detector around the interaction point.

One-half of the VELO under construction

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

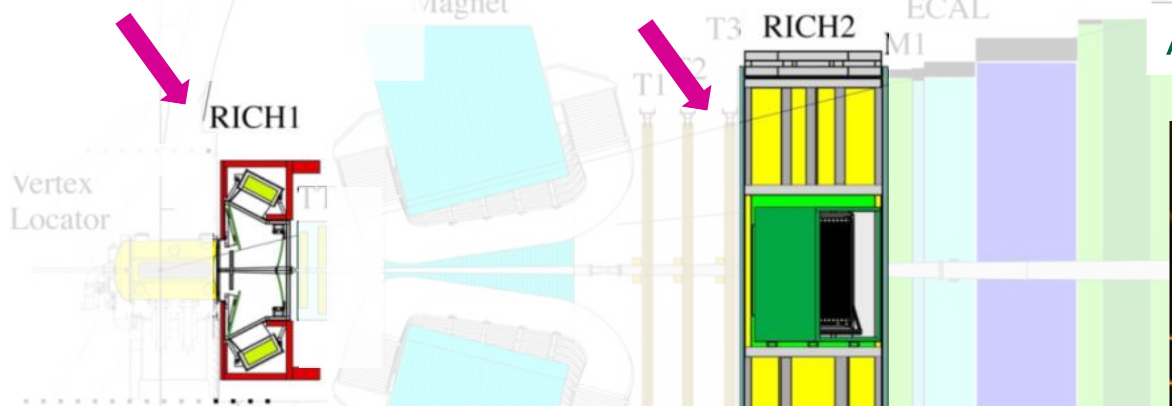


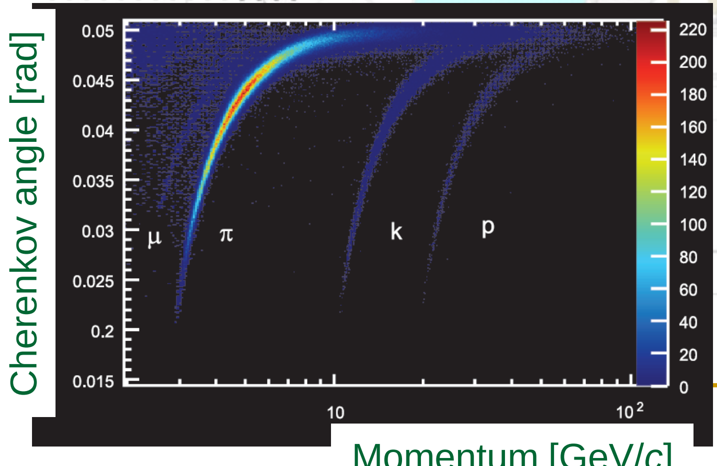
A reconstructed *b*-hadron decay vertex

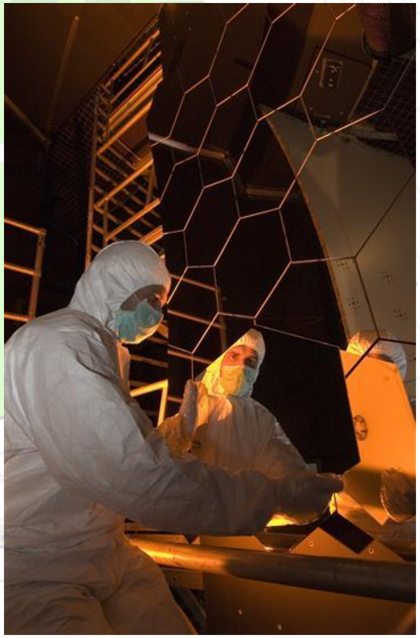
LHCb – a forward spectrometer for flavour physics

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

Array of RICH photodetectors



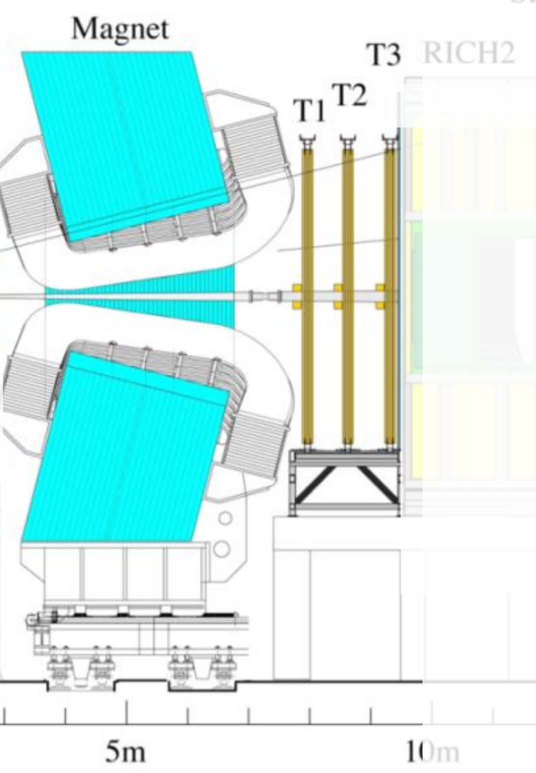


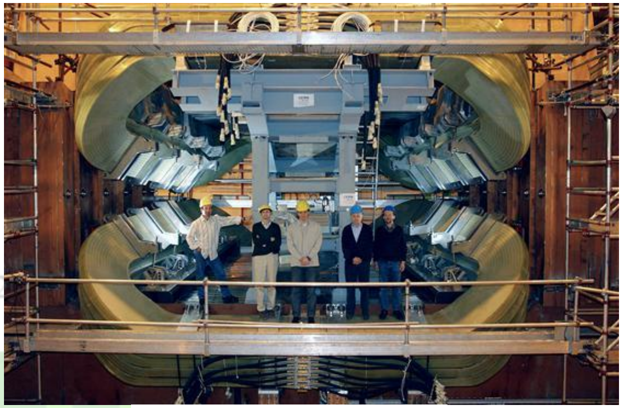


Assembling RICH 2; note the mirrors

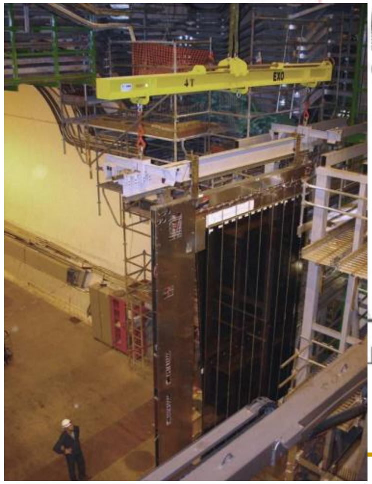
LHCb – a forward spectrometer for flavour physics

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

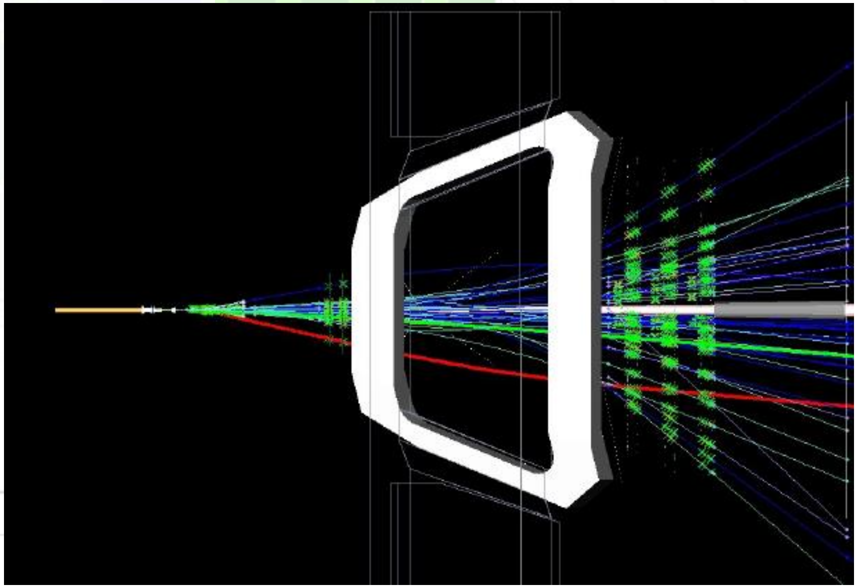




Dipole magnet



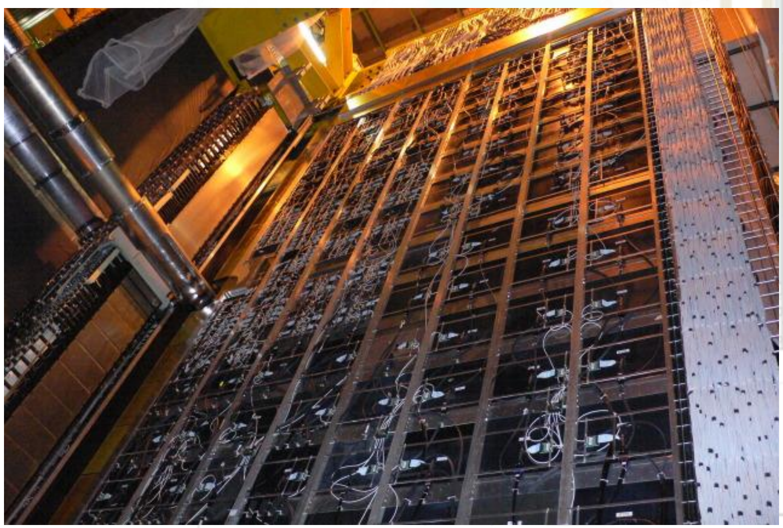
Part of outer tracker

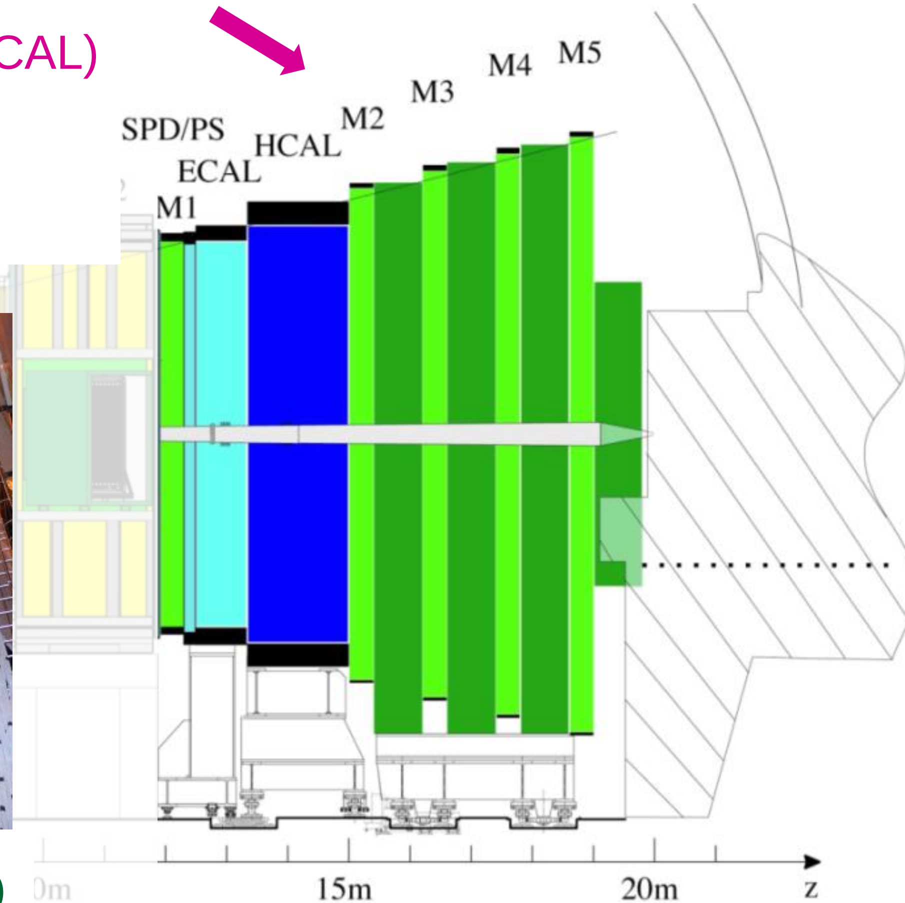


Reconstructed tracks

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.

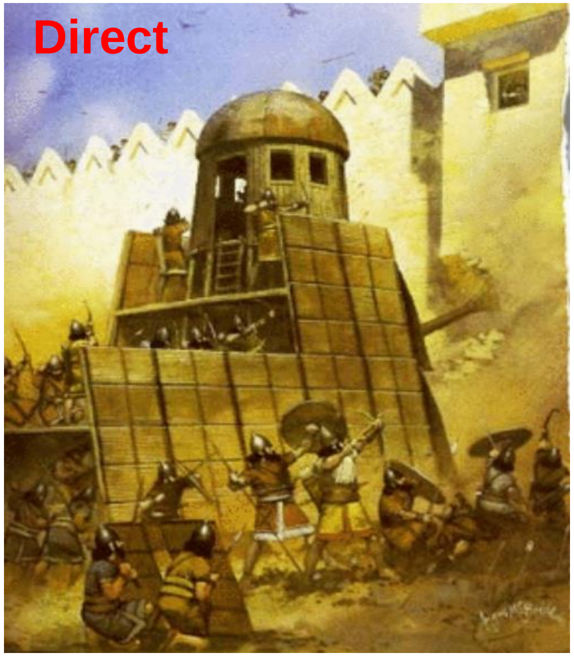

Part of calorimeter system (preshower)

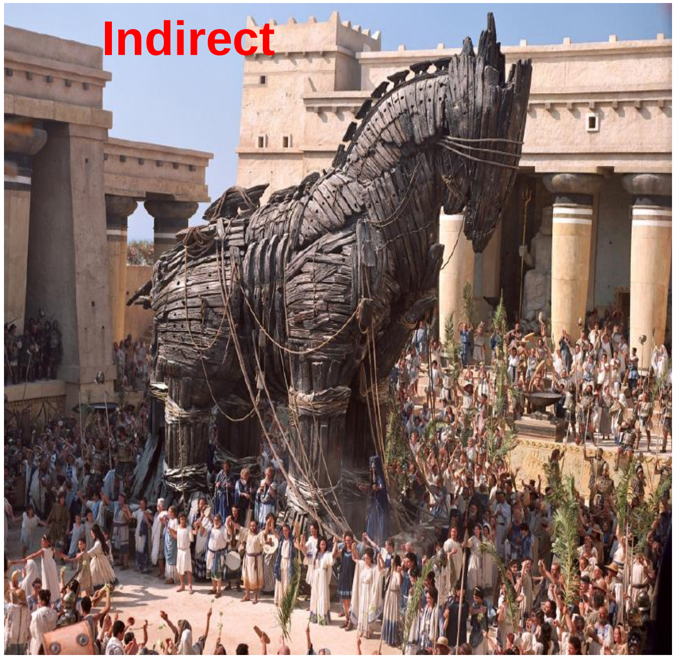


These detectors are particularly important for the role they play in the LHCb trigger

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.





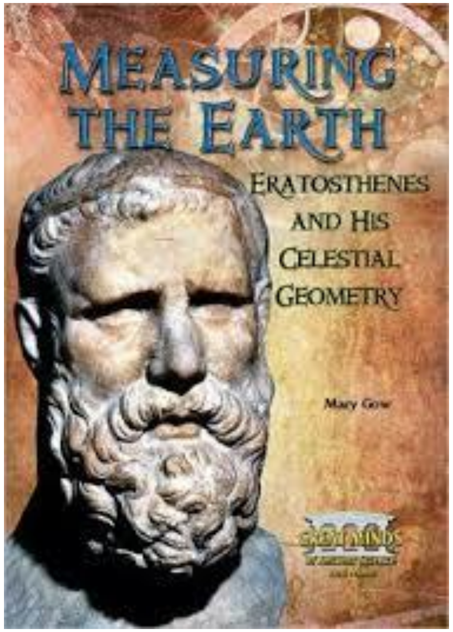
Use the high energy of the LHC to produce the New Physics particles, which we then detect

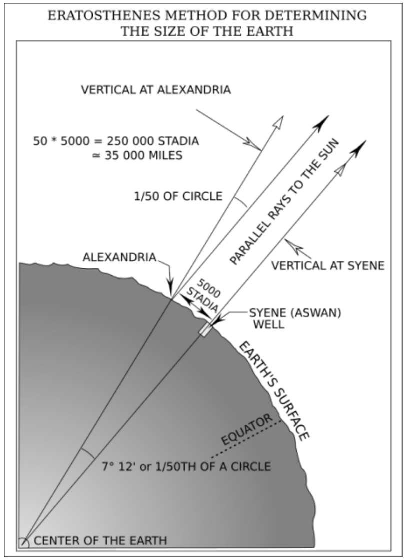
Make precise measurements of processes in which New Physics particles enter through 'virtual loops'

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…

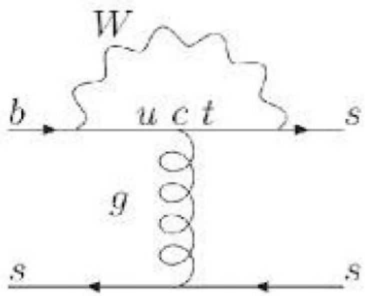


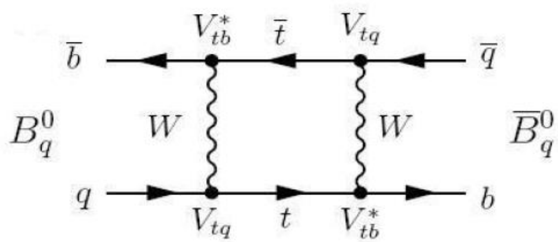


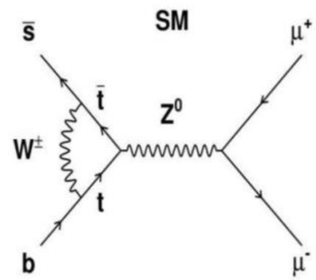
…around 2.2 thousand years prior to the direct observation.

Indirect measurements – an established tradition in science

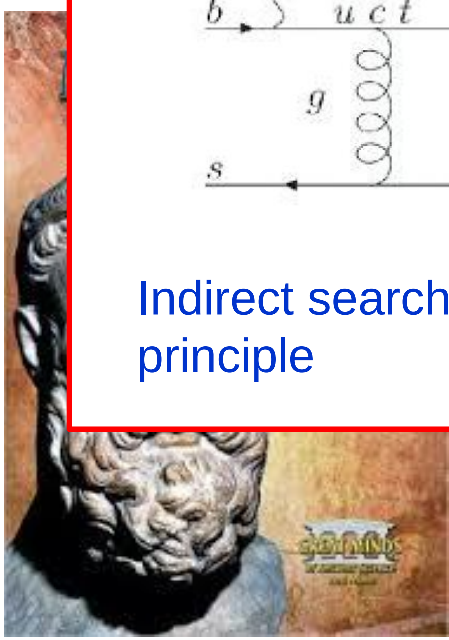
In flavour physics the guiding principle is to probe processes where loop diagrams are important, as here non-SM particles may contribute

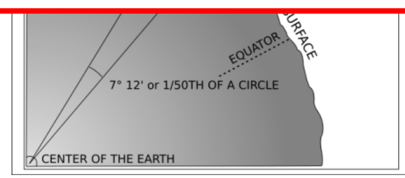






Indirect search principle ➡ Precise measurements of low energy phenomena tells us about unknown physics at higher energies





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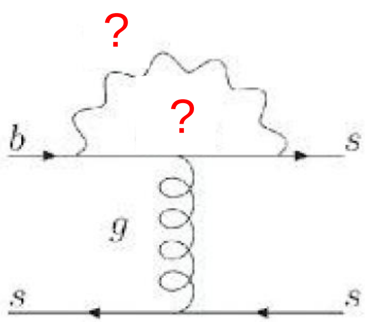

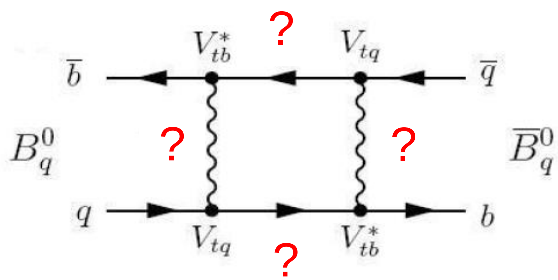

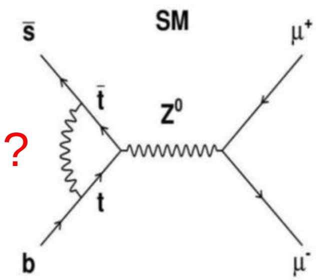

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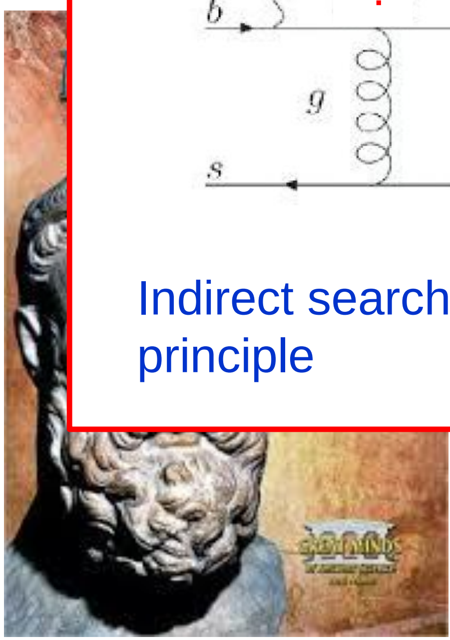

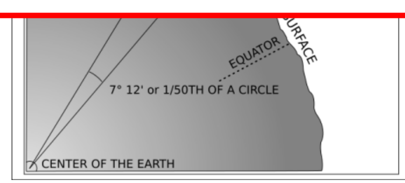

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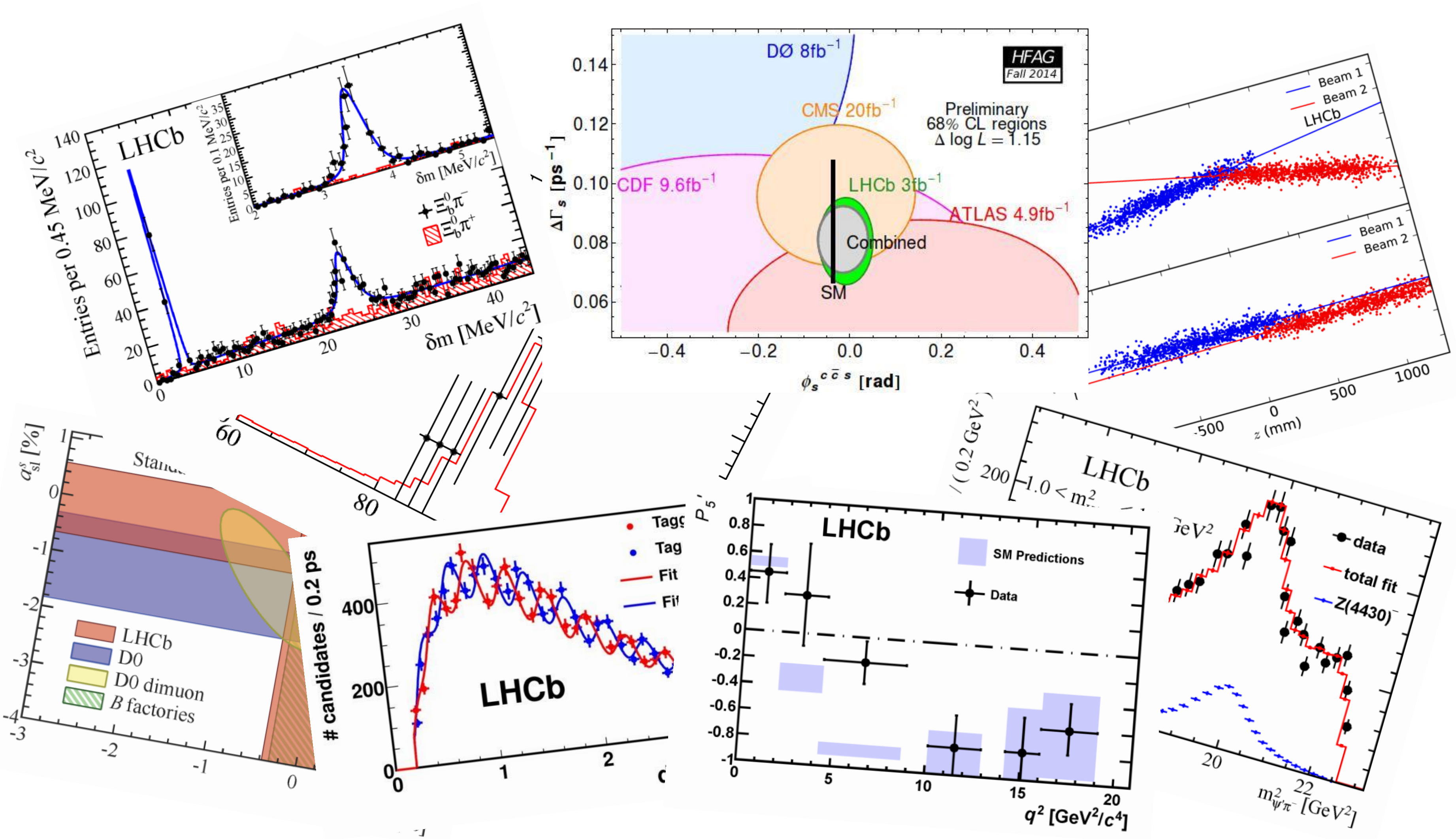
Selected physics results



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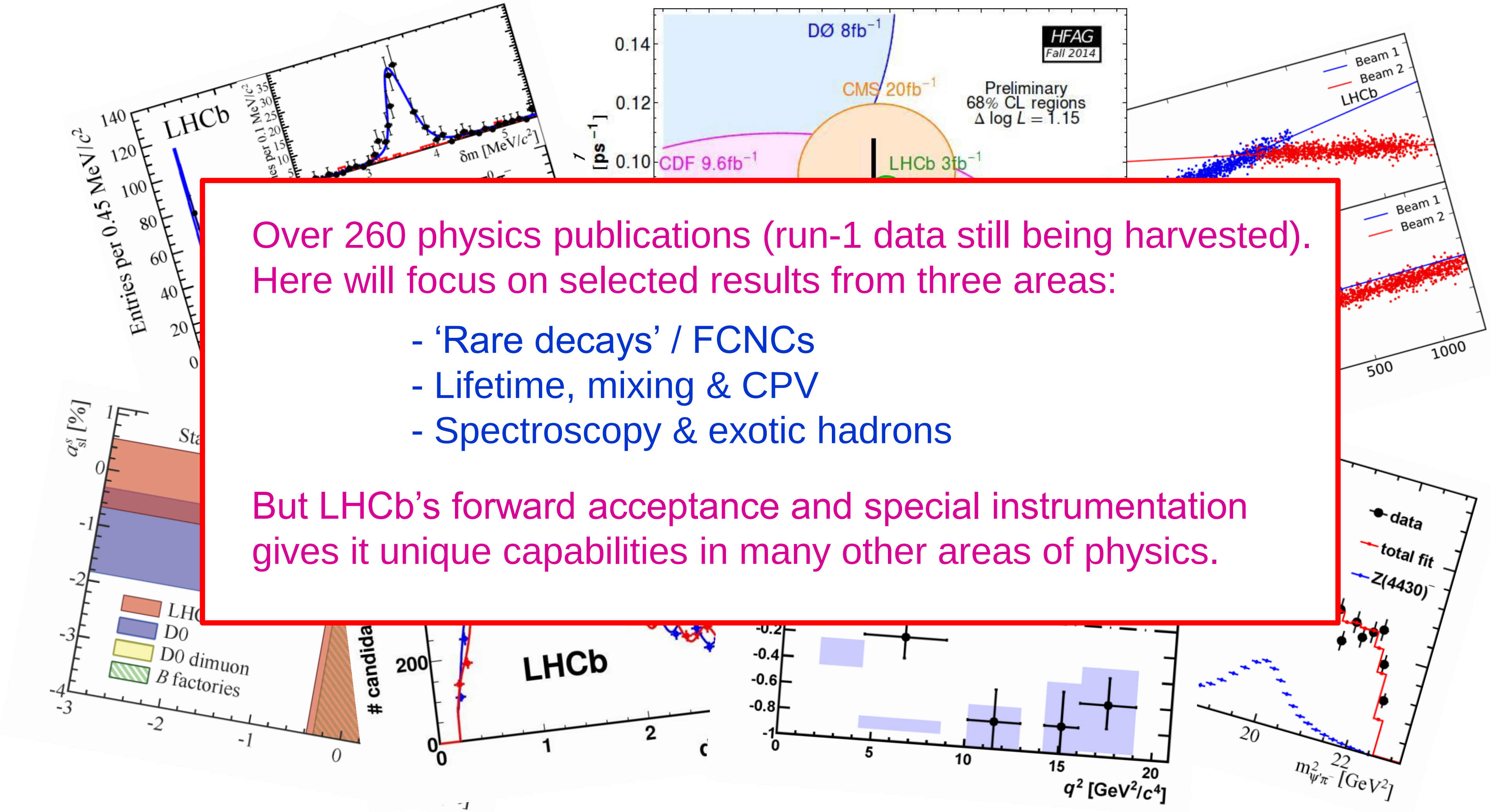


Over 260 physics publications (run-1 data still being harvested). Here will focus on selected results from three areas:

- 'Rare decays' / FCNCs
- Lifetime, mixing & CPV
- Spectroscopy & exotic hadrons

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

Rare decays / Flavour Changing Neutral Currents

Knowledge of *b*-decays: the 1994 PDG

Only 3 pages in total on *b*-decays (compare 152 in 2014 PDG).

Negligible information about B^0_s decays.

No *b*-decay seen with BR < 10^{-3}.

BOTTOM, STRANGE MESONS
$(B = \pm 1, S = \mp 1)$

$B^0_s = s\bar{b}$, $\overline{B}^0_s = \bar{s}b$, similarly for B^*_s's

B^0_s

$I(J^P) = \frac{1}{2}(0^-)$

I, J, P need confirmation. Quantum numbers shown are quark-model predictions.

Mass $m_{B^0_s} = 5375 \pm 6$ MeV (S = 1.3)

Mean life $\tau = (1.34^{+0.32}_{-0.27}) \times 10^{-12}$ s (S = 1.4)

B^0_s-$\overline{B}^0_s$ mixing parameters

$\chi_s = 0.62 \pm 0.13$

$\Delta m_{B^0_s} = m_{B^0_{sH}} - m_{B^0_{sL}} > 1.8 \times 10^{12}\ \hbar\ s^{-1}$, CL = 95%

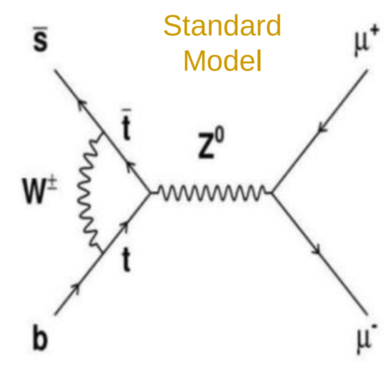
$x_s = \Delta m_{B^0_s}/\Gamma_{B^0_s} > 2.0$, CL = 95%

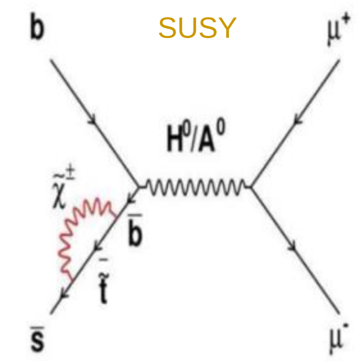
B^0_s DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
D^-_s anything	seen	–
$D^-_s \ell^+ \nu_\ell$ anything (ℓ means sum of e and μ)	seen	–
$D^-_s \pi^+$	seen	2325
$J/\psi(1S)\phi$	seen	1594
$\psi(2S)\phi$	seen	1128

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

This decay mode can only proceed through suppressed loop diagrams.

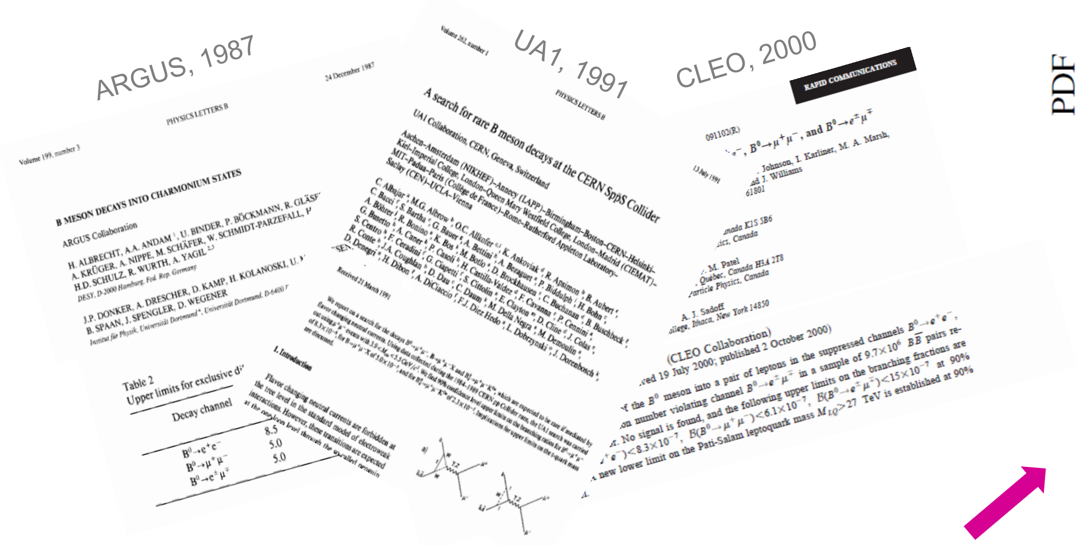
In the Standard Model it happens extremely rarely (~10^{-9}), but the exact rate is very well predicted

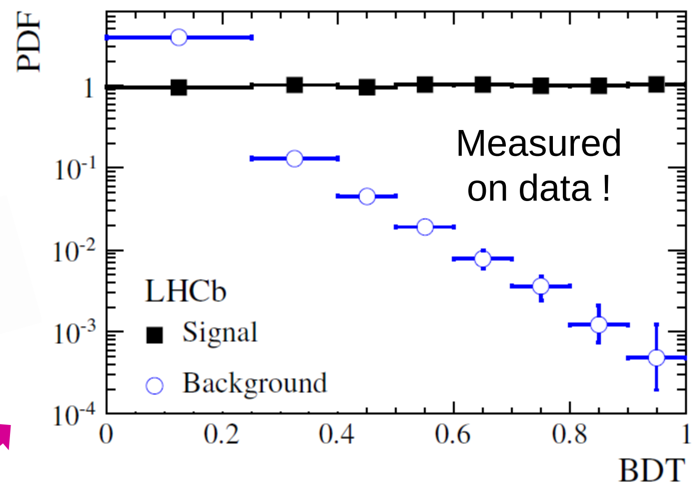




Many models of New Physics (*e.g.* SUSY) can enhance rate significantly !

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

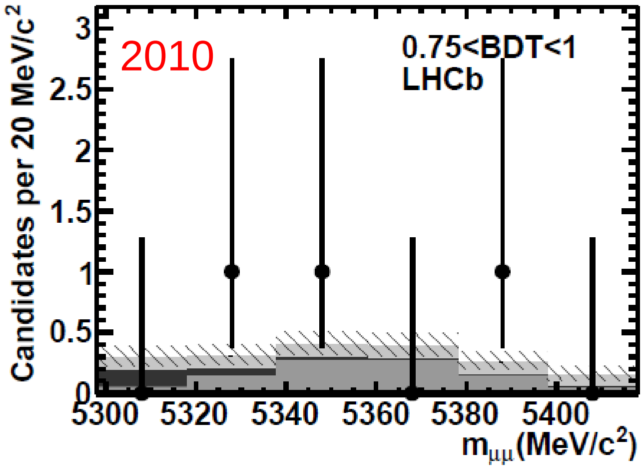




[PRL 111 (2013) 101805]

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

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



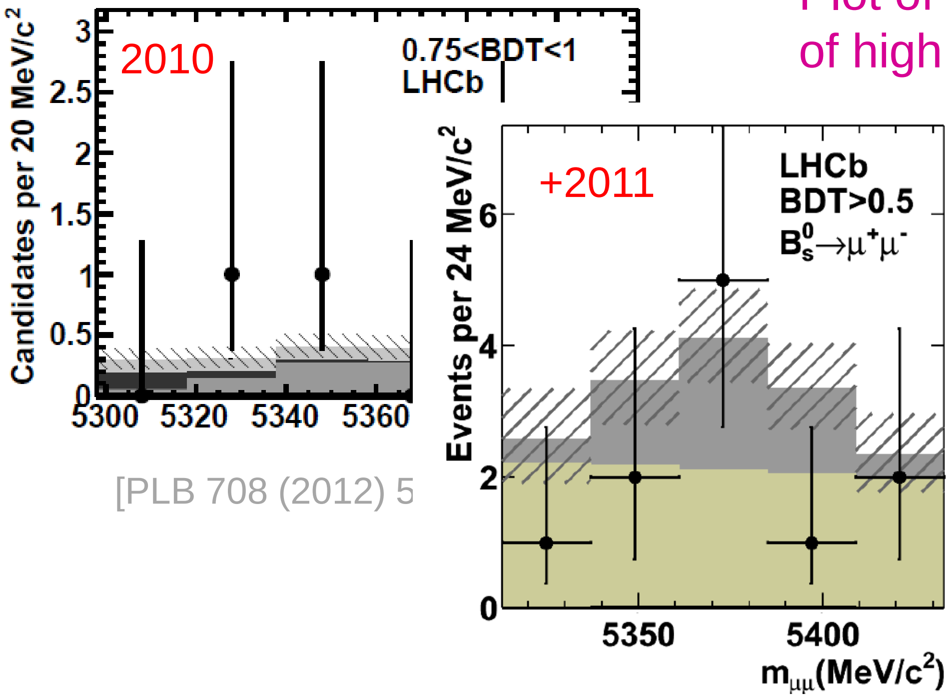
[PLB 708 (2012) 55]

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

2010

Nothing

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



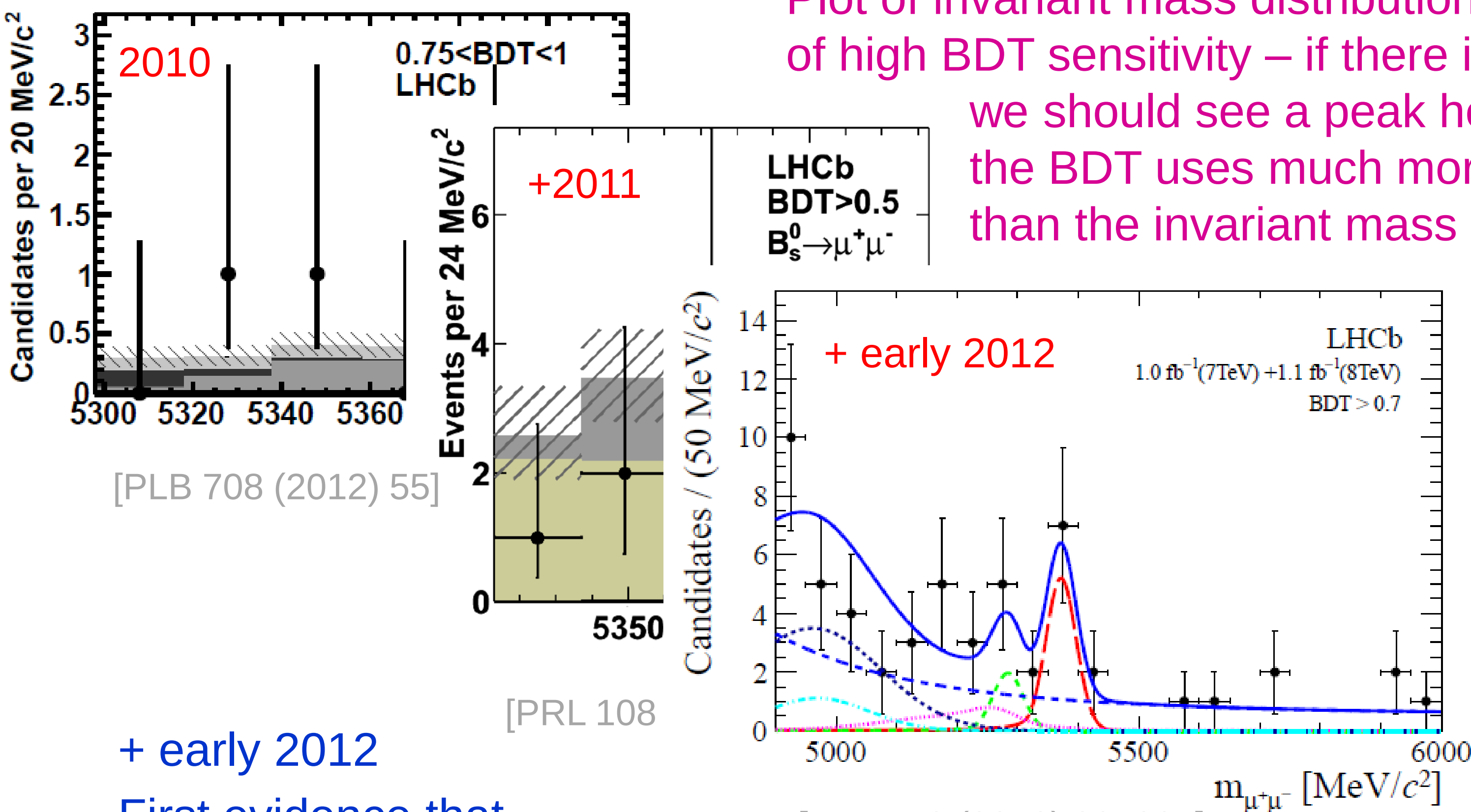
[PRL 108 (2012) 231801]

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

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



[PLB 708 (2012) 55]

[PRL 108

[PRL 110 (2013) 021801]

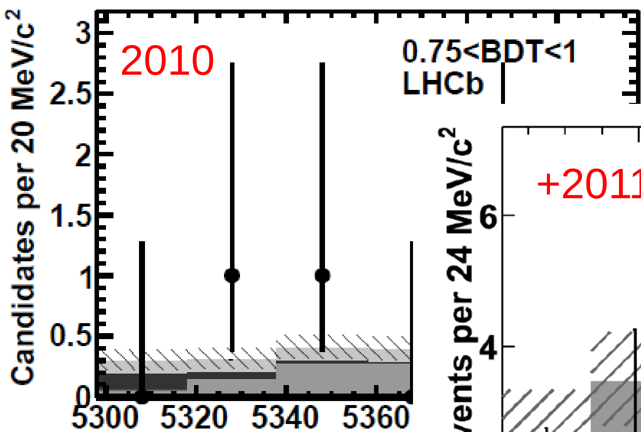
Plot of invariant mass distribution in region of high BDT sensitivity – if there is a signal we should see a peak here (but the BDT uses much more information than the invariant mass alone !)

+ 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 !)



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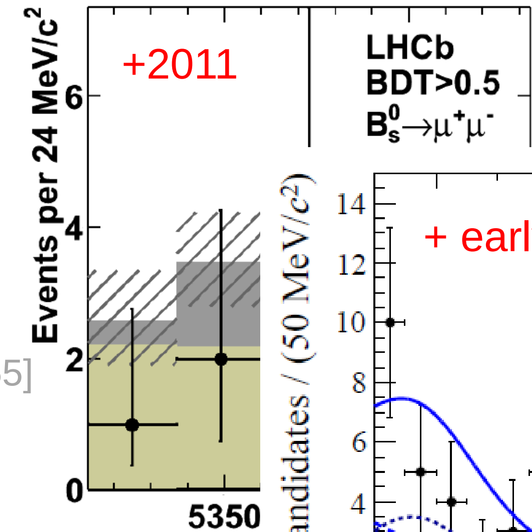
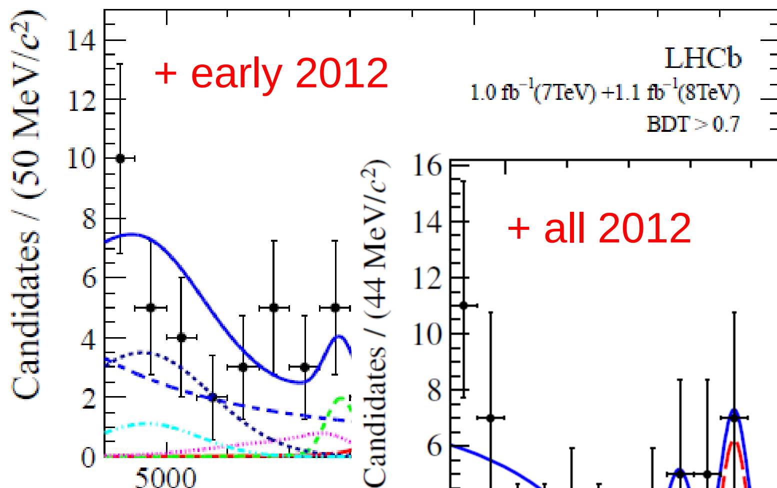
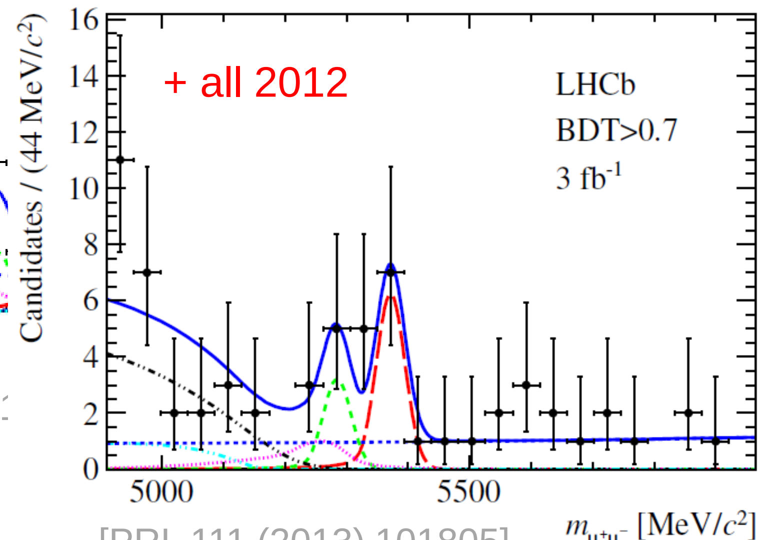


[PRL 108



[PRL 110 (20



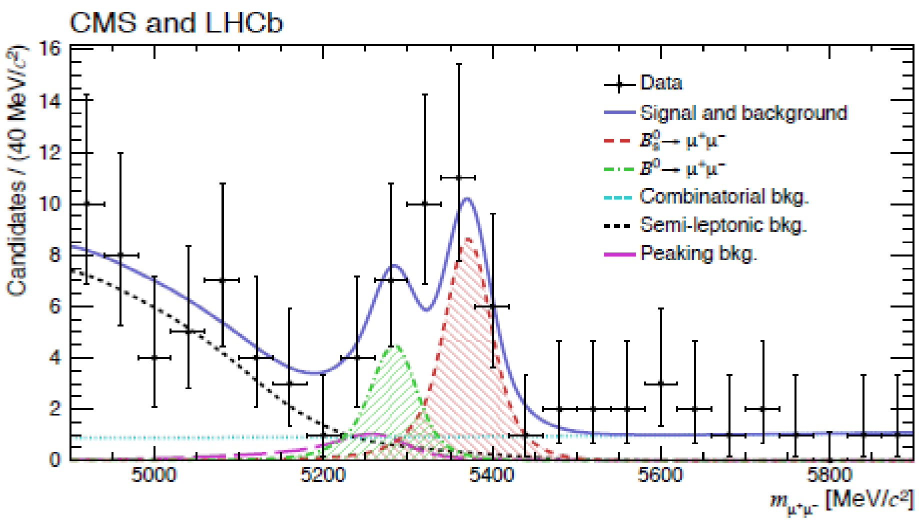
[PRL 111 (2013) 101805]

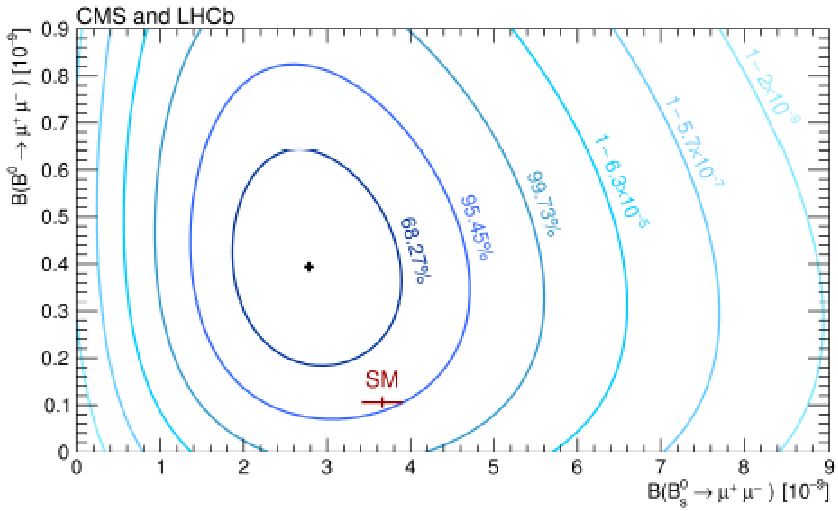
+ all 2012

The evidence grows…

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





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

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

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

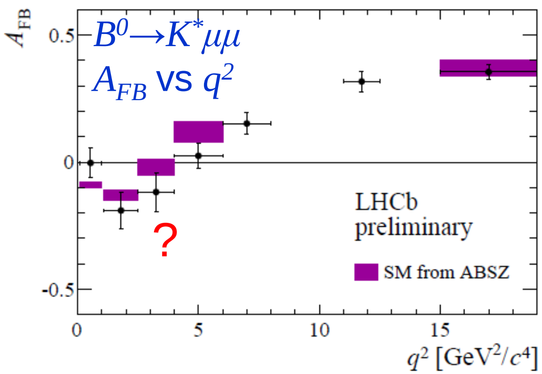
Included also are results for the even rarer $B_d \rightarrow \mu\mu$, where a signal may be emerging too. The picture is intriguing and provides encouragement for run 2 !

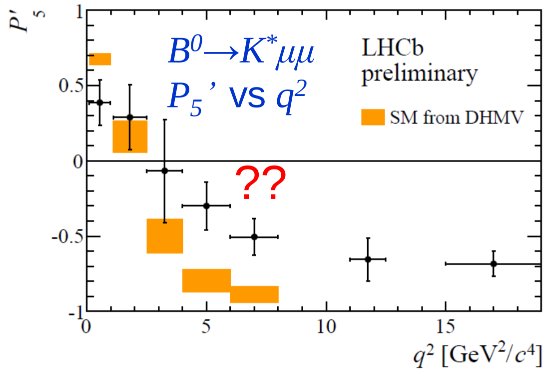
Other puzzles in ‘rare decays’ / FCNCs

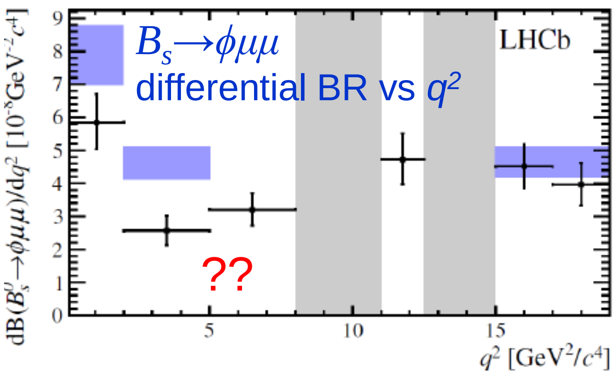
Pattern of measurements gives picture that is far from ‘text-book’ Standard Model

e.g. local discrepancies in differential observables in $b \to s l^+ l^-$ decays

[LHCb-CONF-2015-002]







[LHCb-PAPER-2015-013]

e.g. hints of lepton flavour violation: value too low by 2.6σ for BR($B \to K\mu^+\mu^-$)/ BR($B \to Ke^+e^-$). Also..

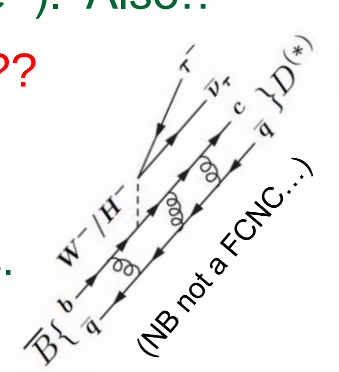
[PRL 113 (2014) 151601]

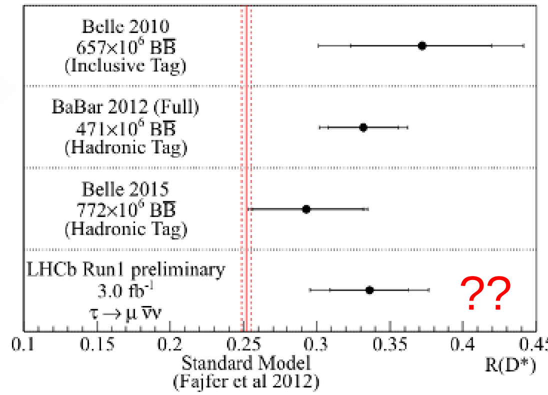
Very recent LHCb measurement of

R(D*)=BR($B \to D^*\tau\nu$) /BR($B \to D^*\mu\nu$),

(previously thought impossible at hadron machine), confirms *b*-factory High values. Implications for charged Higgs?

??





[LHCb-PAPER-2015-025]

More measurements (and more theory) is needed to assess what all this means.

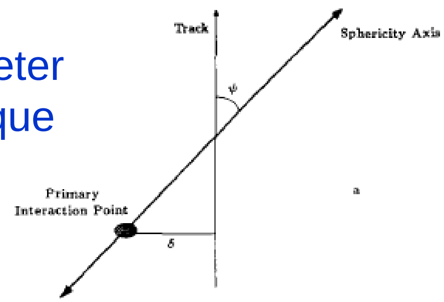
Lifetimes, mixing & CP-violation

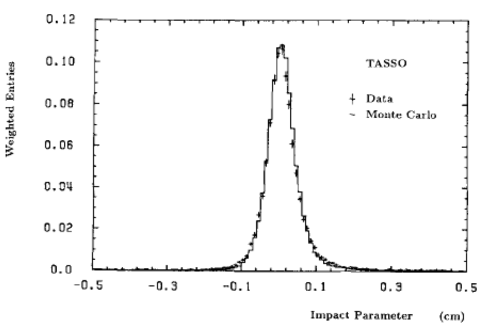
b-lifetimes at PETRA

[TASSO, Z Phys. C 44 (1989) 1]

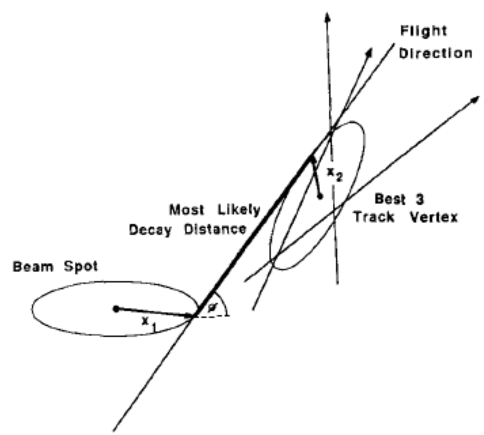
TASSO & the PETRA experiments were able to measure the lifetime of the *b*-hadron (averaged over species) → gives info about the CKM element V_{cb}

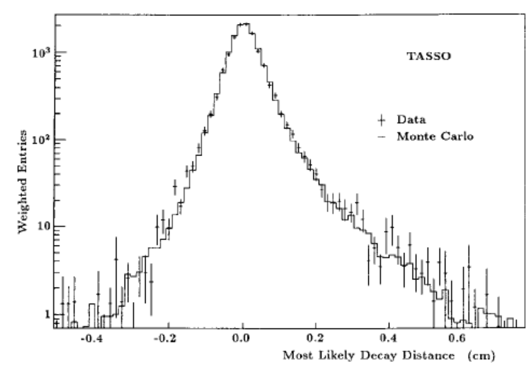
Impact parameter technique





Vertex separation technique





$$\boxed{\tau_B = 1.35 \pm 0.10\,(\text{statistical}) \pm 0.24\,(\text{systematic})\ \text{ps.}}$$

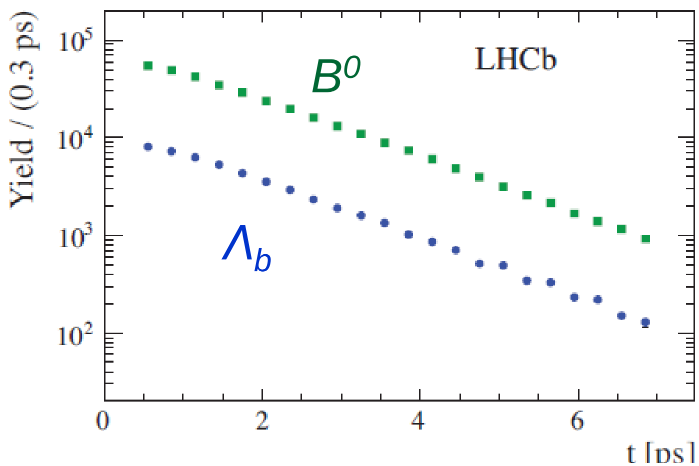
Methods developed then are still used now, although we now have Si detectors.

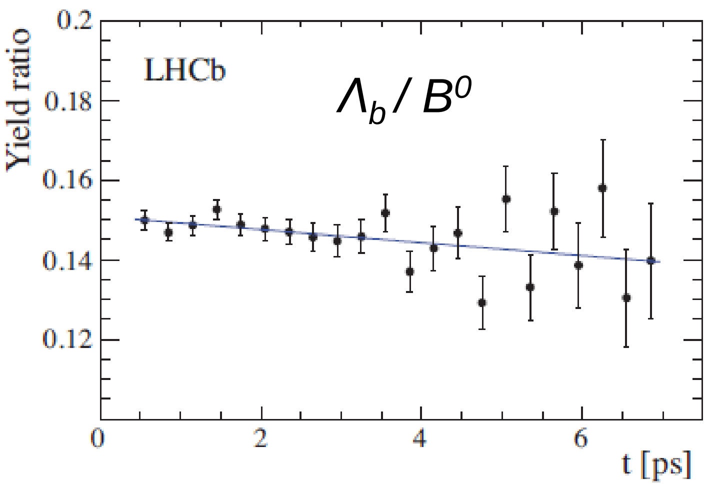
b-lifetimes at LHCb

Game has now progressed beyond ‘average’ *b*-lifetimes, to measuring lifetimes of different *b*-hadron species, and comparing relative pattern against theory.

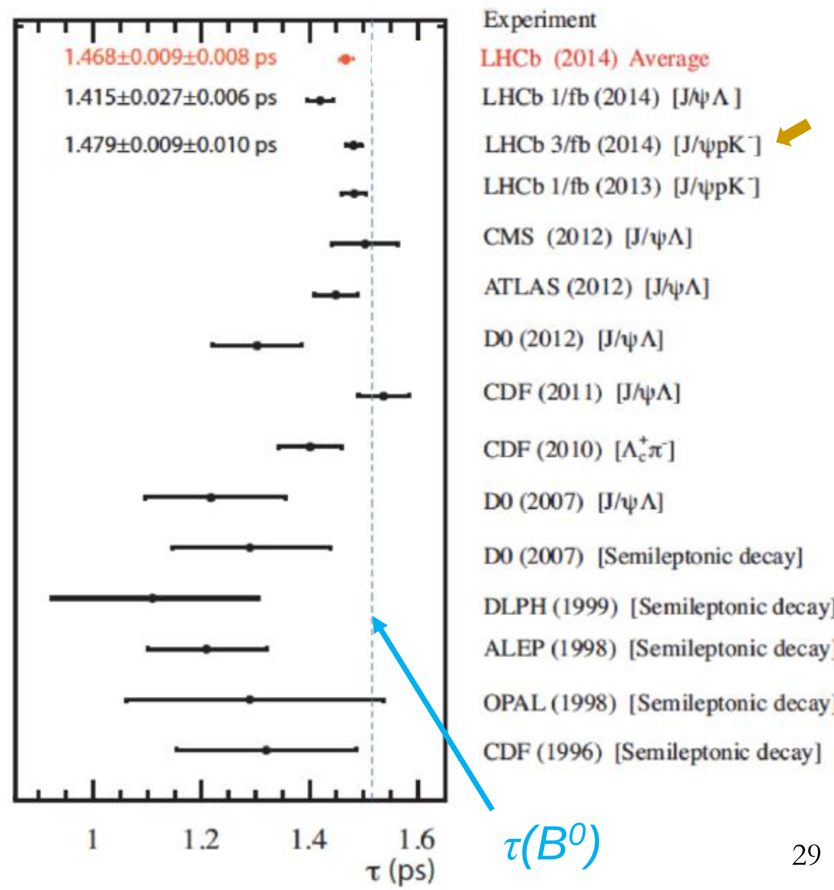
e.g. Λ_b lifetime measured in $J/\Psi pK$, compared to B^0 lifetime measured in $J/\Psi K\pi$

[PLB 734 (2014) 122]





Evolution of Λ_b lifetime measurements

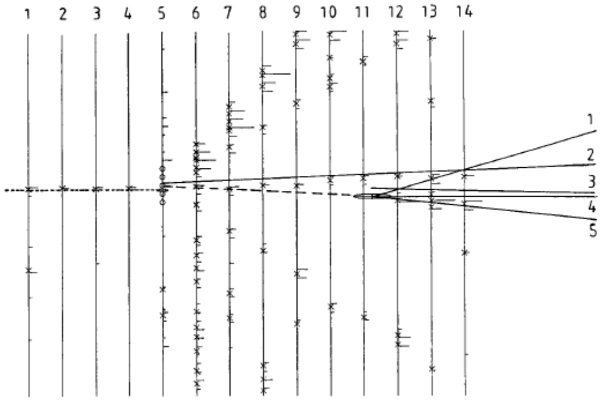


c-physics & Si vertex detectors at ACCMOR

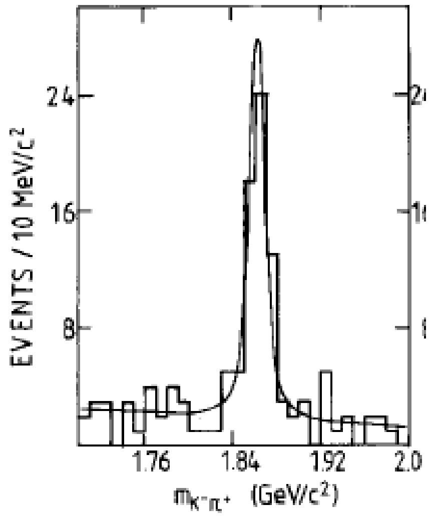
Almost all measurements in flavour-physics over the last two decades have benefitted from the use of precise semi-conductor based vertex detectors.

Early example: ACCMOR - fixed target with array of Si strips (+ later CCD pixels)

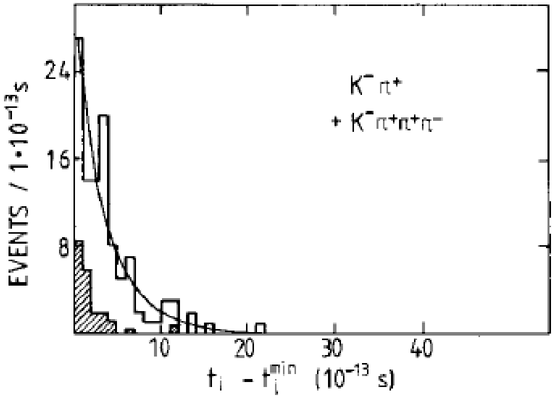
D⁰ decay reconstructed
In vertex detector planes



58 $D^0 \rightarrow K\pi$ decays



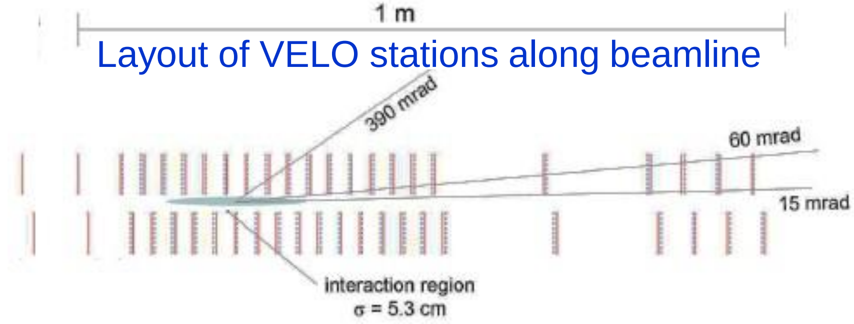
D^0 lifetime distribution
(measured to ~12%)



Invaluable for pioneering measurements of charm-meson lifetimes [Z Phys. C 37 (1987) 37]

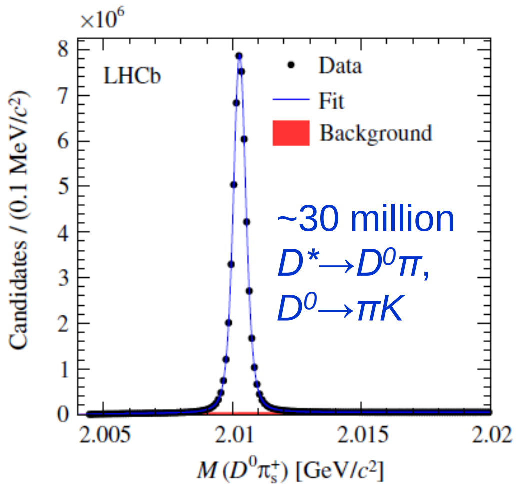
c-physics & Si-vertex detectors at LHCb

LHCb *c*/*b*-physics benefits from a vertex detector geometry reminiscent of ACCMOR.

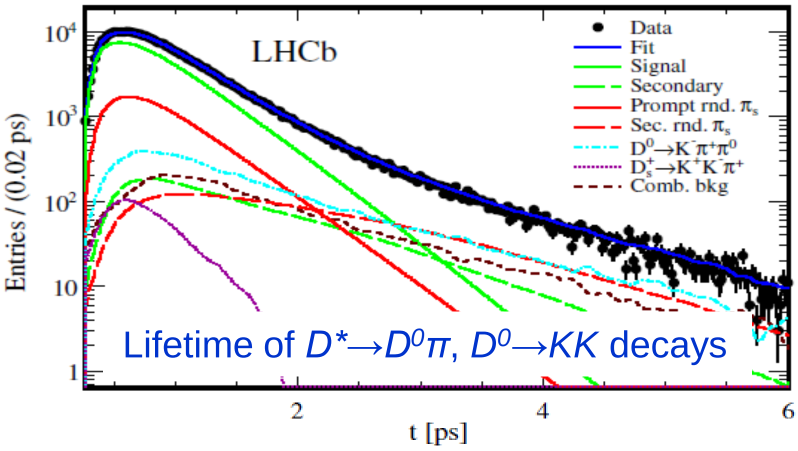


One half of the VELO

[PRL 111 (2013) 251801]



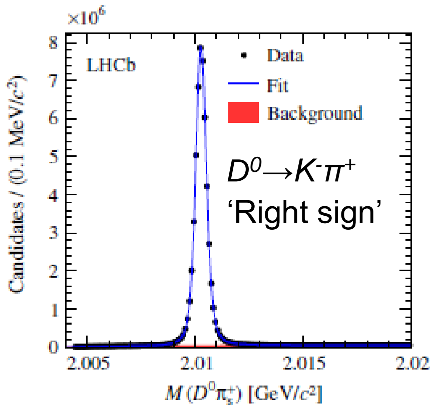
[PRL 112 (2014) 041801]

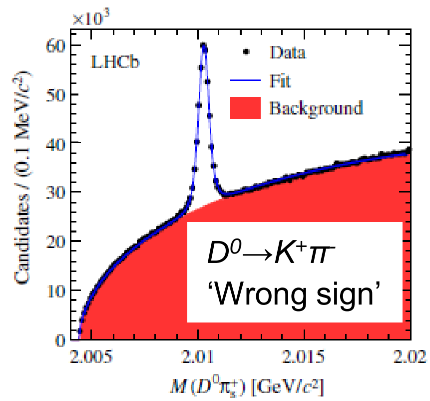


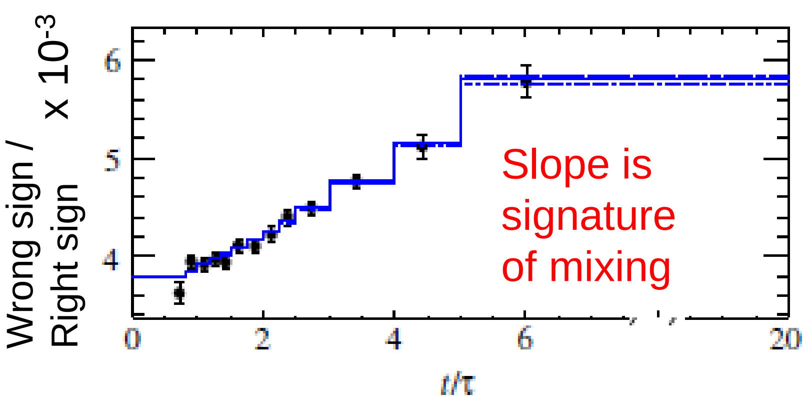
But most interesting physics accessed by this instrument is no longer lifetimes….

Beyond lifetimes – D^0 and B_s mixing

D^0 mixing very slow – no 5σ observation by a single experiment. With huge LHCb data samples there is no doubt whatsoever.

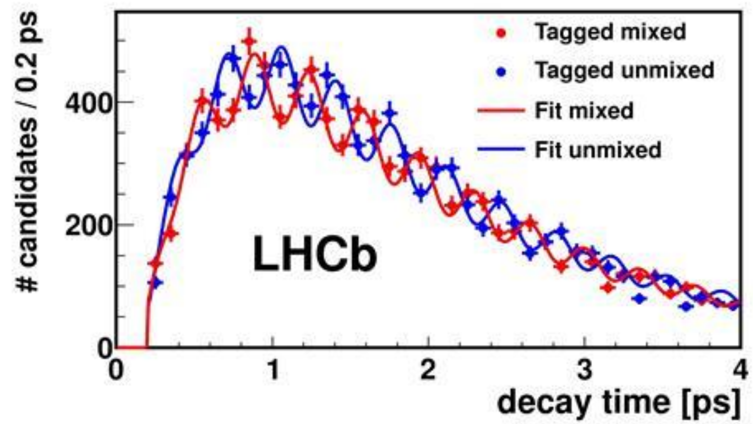




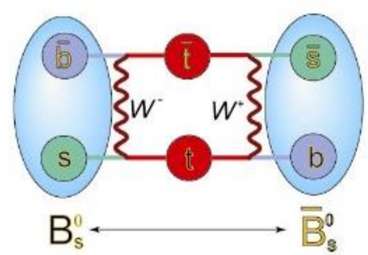


[PRL 111 (2013) 251801; PRL 110 (2013) 101802]

B_s mixing is very rapid. LHCb proper time resolution allows oscillations to be clearly seen and gives world's best measurement of mixing frequency.

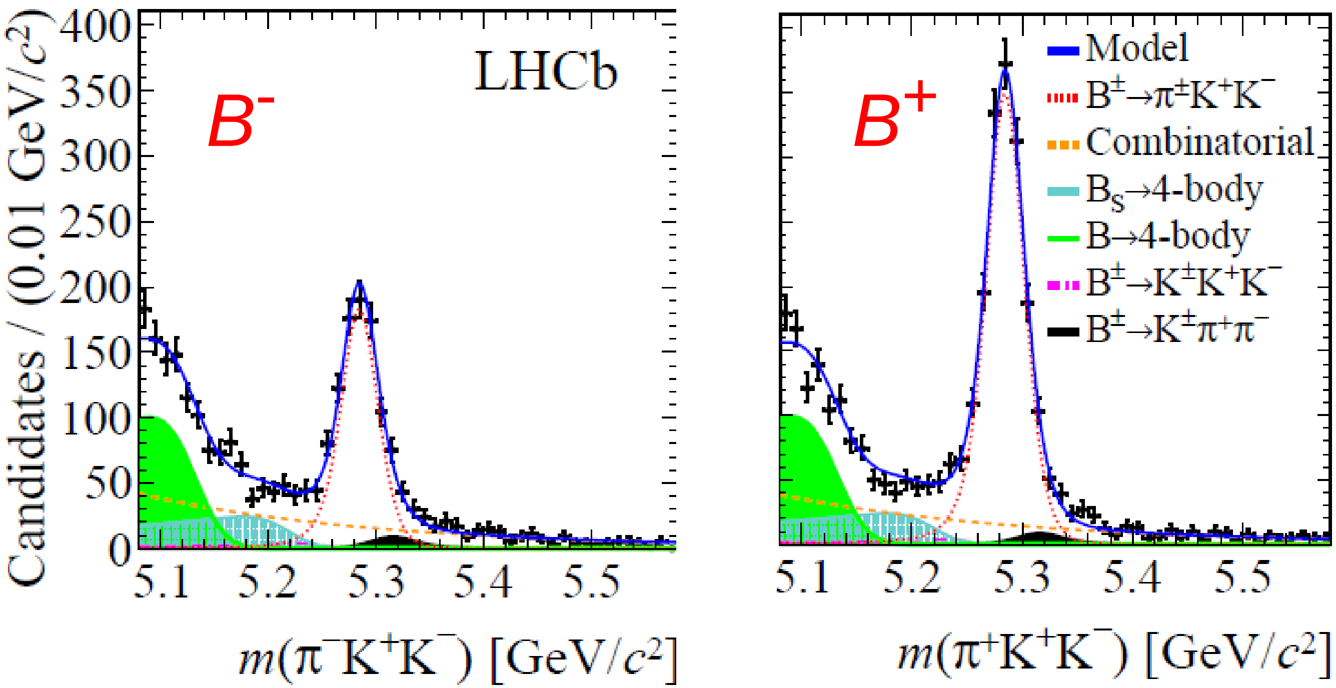


[New J. Phys. 15 (2013) 053021]



CP violation

When we can see the mixing, we can perform time-dependent (*i.e.* indirect) CP violation studies, which complement the many direct CPV measurements:

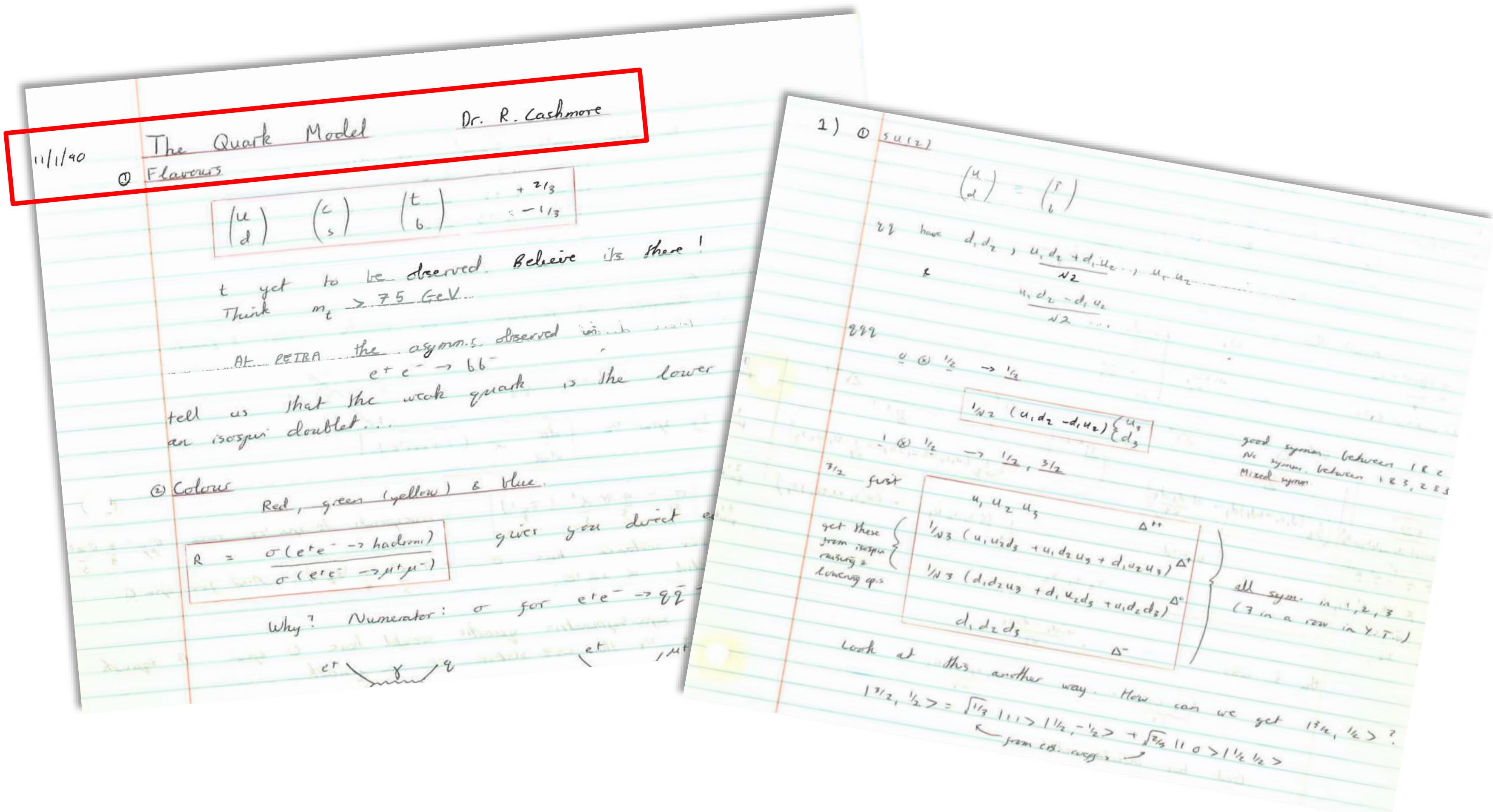


[LHCb, PRD 90 (2014) 112004]

LHCb now has a precision on the unitarity triangle angle $\gamma < 10^o$, which is better than the *b*-factory experiments combined, and will reach ~3^o during run 2.

Spectroscopy & the search for exotic hadrons

My training in hadron spectroscopy



My training in hadron spectroscopy

A promising start…

Problems Sheet 1

1. Demonstrate that the GIM mechanism ensures the absence of flavour changing neutral currents

~~2. By explicitly demonstrate~~

2. ~~Pk~~ Show that the doublet $\begin{pmatrix} \bar d \\ -\bar u \end{pmatrix}$ transforms in a similar manner to $\begin{pmatrix} u \\ d \end{pmatrix}$

3. By explicitly writing out the quark wave functions of the $p, n, \Lambda, \Sigma^{\pm}$ and Ξ evaluate the magnetic moments and compare

α

DR. CASHMORE

(from G. WILKINSON)

we would expect the matrix element to contain non-zero terms in $d\bar s$, $\bar s d$ in addition to $u\bar u$, $d\bar d$, $c\bar c$, $s\bar s$.

The total neutral-current coupling will come from the four diagrams

So the matter part of the matrix element (the γ matrices only operate on the space and spin parts – for neutral currents the operator for the matter component is the identity op.) is

$$\bar u u + \bar d_c d_c + \bar c c + \bar s_c s$$

$$= \bar u u + (\bar d \cos\theta_c + \bar s \sin\theta_c)(d \cos\theta_c + s \sin\theta_c) + \bar c c + (\bar s \cos\theta_c - \bar d \sin\theta_c)(s \cos\theta - d \sin\theta_c)$$

$$= \bar u u + \bar d d \cos^2\theta_c + \bar d s \cos\theta_c \sin\theta_c + \bar s d \sin\theta_c \cos\theta_c + \bar s s \sin^2\theta_c + \bar c c + \bar s s \cos^2\theta_c + \bar d d \sin^2\theta_c - \bar d s \cos\theta_c \sin\theta_c - \bar d s \sin\theta_c \cos\theta_c$$

diligent marking

My training in hadron spectroscopy

And then downhill…

Problem Sheet 2

1. Calculate the rate for the decay

$\omega^0 \to \pi^0\gamma$ and $\rho^0 \to \pi^0\gamma$

Estimate the rates for similar decays $K^* \to K\gamma$, $D^* \to D\gamma$, $\psi \to \eta_c\gamma$, $\Upsilon \to \eta_b\gamma$.

Why might the last decay be difficult to observe

2. Calculate ~~Compare~~ the EM transitions between ψ' and χ and χ and ψ states. Why is the branching fraction for $\chi_{J=0} \to \gamma\psi$ so small.

What results are obtained for the Υ system.

3. Compare the e^+e^- widths of different vector mesons.

Why might the toponium system be different?

$\boxed{\beta}$

GUY WILKINSON

for DR. CASHMORE

1) $V \to P\gamma$

Calculate the matrix element for the transition:

$$\langle P | \sum_{i=1}^{2} e_i \mu_i \underline{\sigma} \cdot \underline{B} | V \rangle$$

Now $\underline{\sigma} \cdot \underline{B} = \sigma_x B_x + \sigma_y B_y + \sigma_z B_z$
$= \sqrt{2}(\sigma_+ B_- + \sigma_- B_+) + \sigma_z B_z$

where $\sigma_\pm = \frac{1}{2}(\sigma_x \pm i\sigma_y)$, $B_\pm = \frac{1}{\sqrt{2}}(B_x \pm iB_y)$ the helicity states

Define the z-axis to be that along which the γ is emitted $\to \sigma_z B_z = 0$ as $B_z = 0$ for all real photons

$\overleftarrow{P}\ \overset{V}{\bullet}\ \underset{\gamma}{\rightsquigarrow}$ $\to z$

$$M = \sqrt{2}\langle P | (e_1\mu_1\sigma_1^+ + e_2\mu_2\sigma_2^+) B_- | V \rangle + \sqrt{2}\langle P | (e_1\mu_1\sigma_1^- + e_2\mu_2\sigma_2^-) B_+ | V \rangle$$

① ②

Will need to evaluate $|M|^2$ for each of the spin states $J_z = \pm 1$ ($J_z = 0$ doesn't contribute as photon is real).

$\omega^0 \to \pi^0\gamma$

$|\omega^0\rangle = |(u\bar{u} + d\bar{d})\uparrow\uparrow\rangle / \sqrt{2}$

$|\pi^0\rangle = |(d\bar{d} - u\bar{u})(\uparrow\downarrow - \downarrow\uparrow)\rangle / 2$

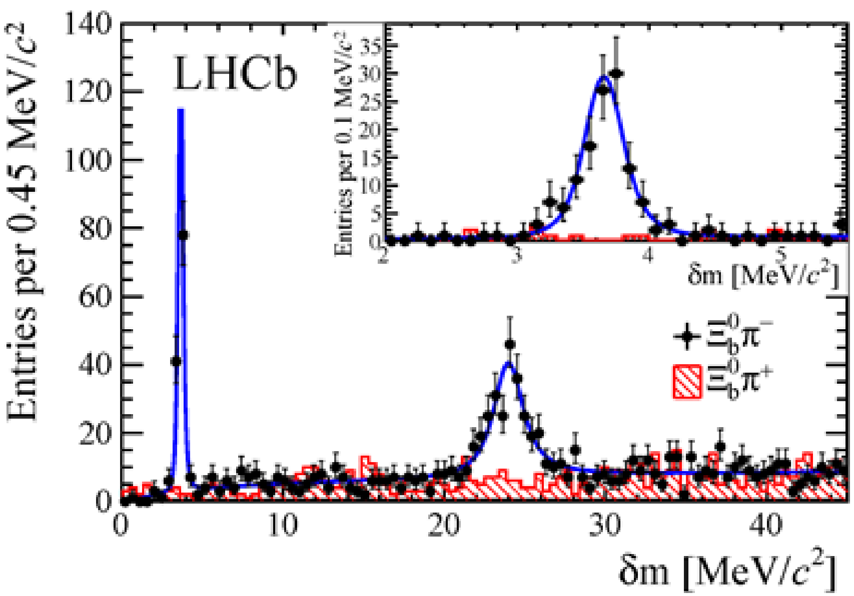
$\mu_1 = \mu_2 = \mu_{u,d} = \mu_q = \mu_p$

$J_z = +1$:

Spectroscopy at LHCb

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]



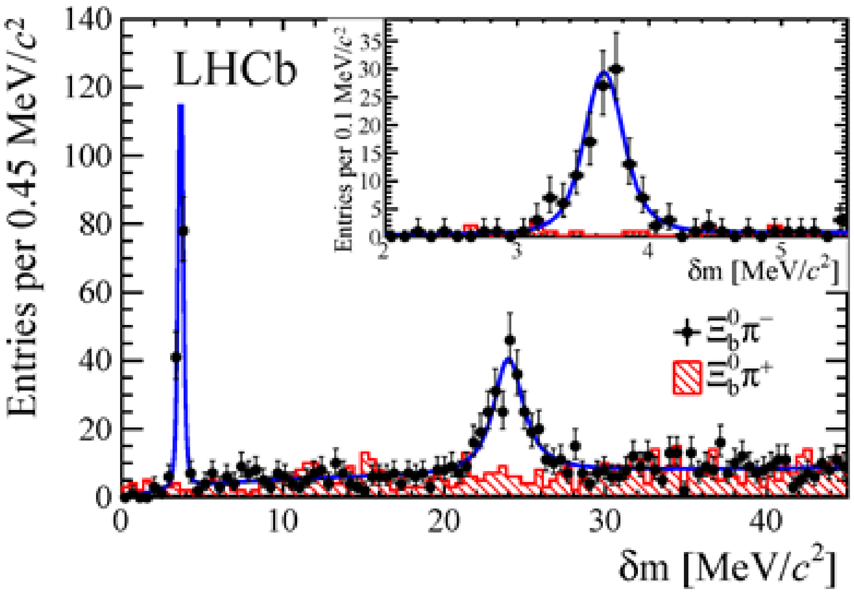
$$
\begin{aligned}
m(\Xi_b^{\prime -}) - m(\Xi_b^0) - m(\pi^-) &= 3.653 \pm 0.018 \pm 0.006\,\mathrm{MeV}/c^2, \\
m(\Xi_b^{*-}) - m(\Xi_b^0) - m(\pi^-) &= 23.96 \pm 0.12 \pm 0.06\,\mathrm{MeV}/c^2, \\
\Gamma(\Xi_b^{*-}) &= 1.65 \pm 0.31 \pm 0.10\,\mathrm{MeV}, \\
\Gamma(\Xi_b^{\prime -}) &< 0.08\,\mathrm{MeV}\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

New particles always provoke interest

Spectroscopy at LHCb

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]



> *Baryons can now be constructed from quarks by using the combinations qqq, $qqqq\bar{q}$, etc, while mesons are made out of $q\bar{q}$, $q\bar{q}q\bar{q}$, etc.*
>
> **Murray Gell-Mann**

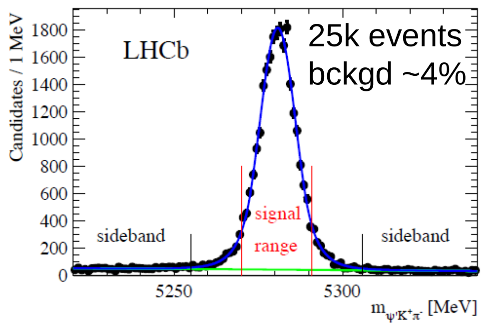
$$m(\Xi_b^{\prime -}) - m(\Xi_b^0) - m(\pi^-) = 3.653 \pm 0.018 \pm 0.006\,\text{MeV}/c^2,$$
$$m(\Xi_b^{*-}) - m(\Xi_b^0) - m(\pi^-) = 23.96 \pm 0.12 \pm 0.06\,\text{MeV}/c^2,$$
$$\Gamma(\Xi_b^{*-}) = 1.65 \pm 0.31 \pm 0.10\,\text{MeV},$$
$$\Gamma(\Xi_b^{\prime -}) < 0.08\,\text{MeV at } 95\% \text{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

Spectroscopy - exotics

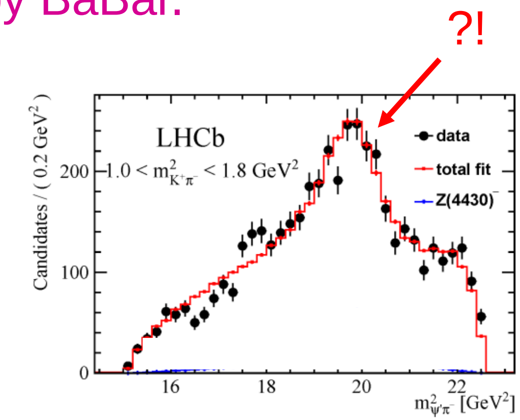
[PRL 112 (2014) 222002]

Z(4430)⁻ seen by Belle in *B*→*Ψ'Kπ* but not confirmed by BaBar.

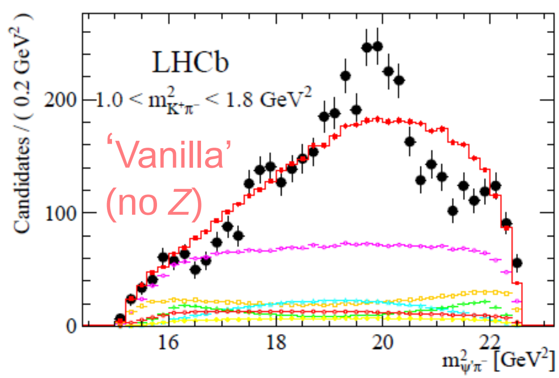
LHCb has a very large and clean sample…

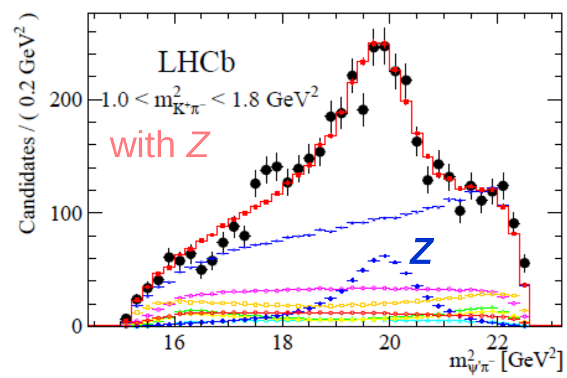


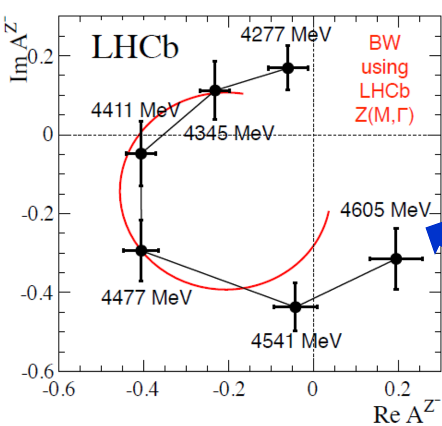
…which leaves little doubt that something is there.



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.

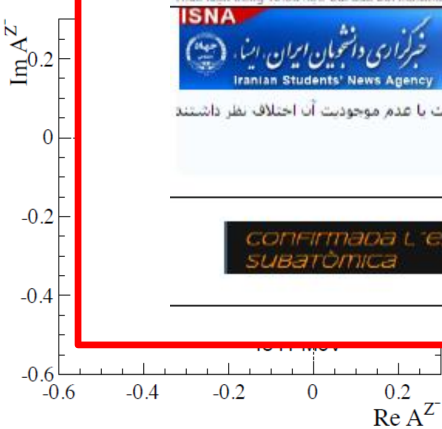
Furthermore, 'bump' shows textbook resonance behaviour.

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

Spectroscopy - exotics

[PRL 112 (2014) 222002]

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



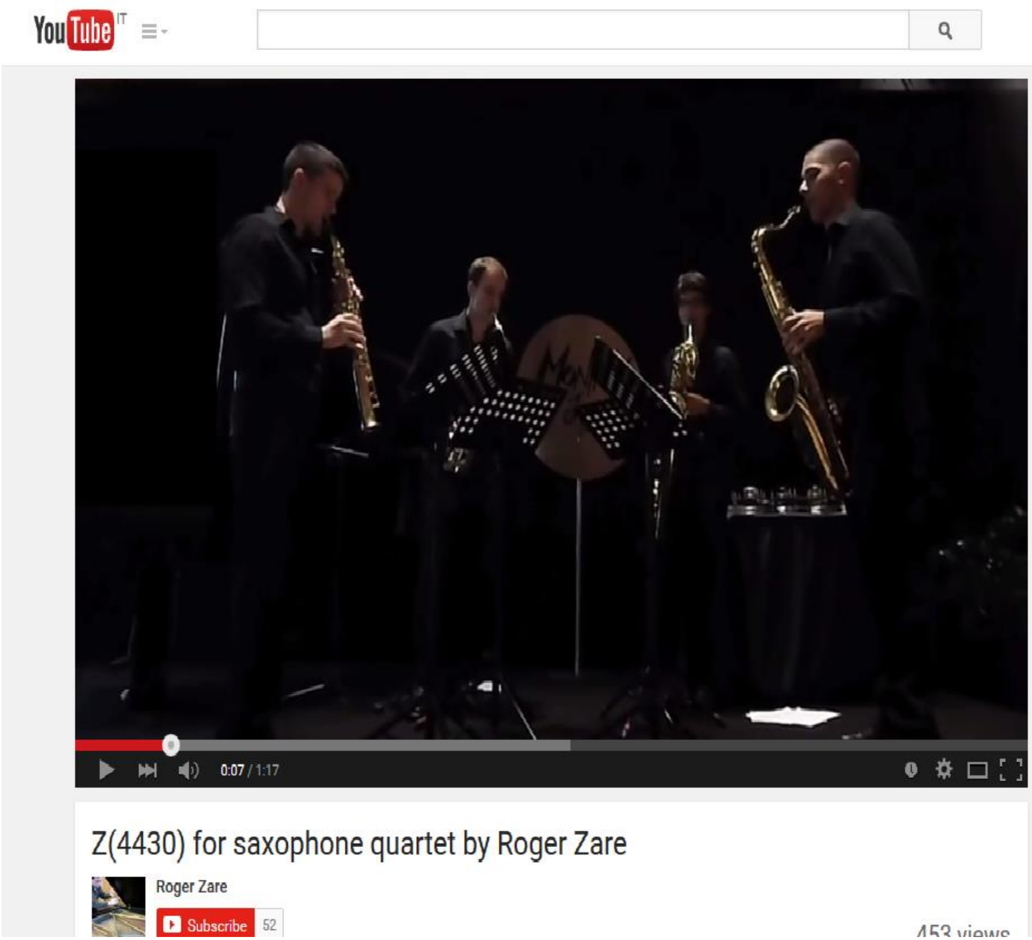
Unambiguous observation of a *four-quark* state (*not* 'vanilla'!)

Spectroscopy - exotics

[PRL 112 (2014) 222002]

Z(

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



Montreux jazz festival, 2014

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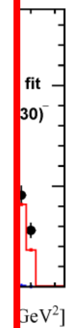

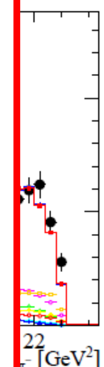

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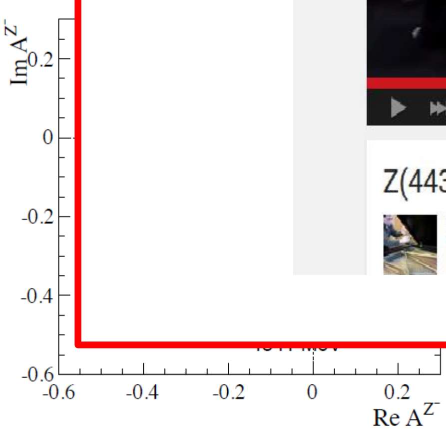
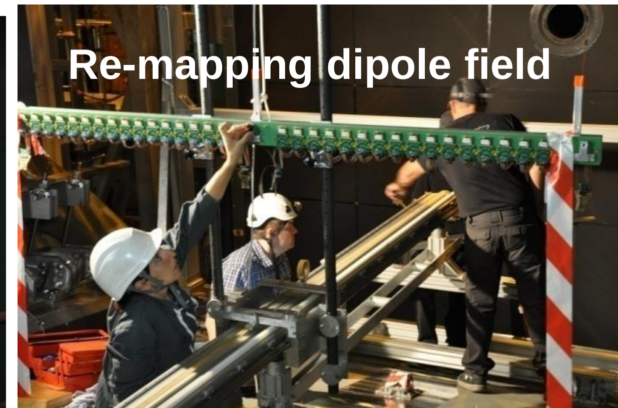


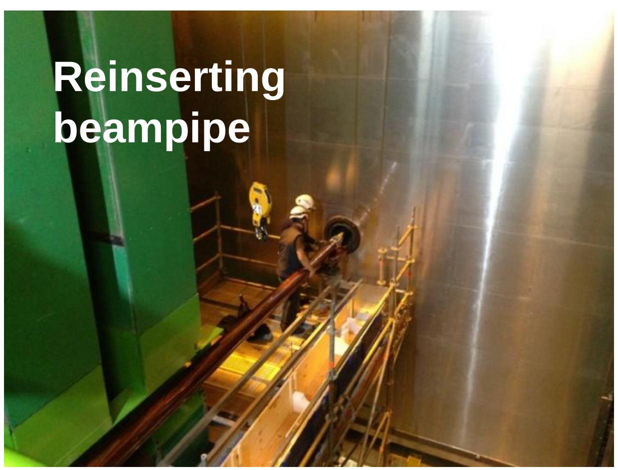
Unambiguous observation of a *four-quark* state (*not* 'vanilla'!)

Where to now? The road ahead - run 2 & beyond

LS1 activities – preparing for run 2

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

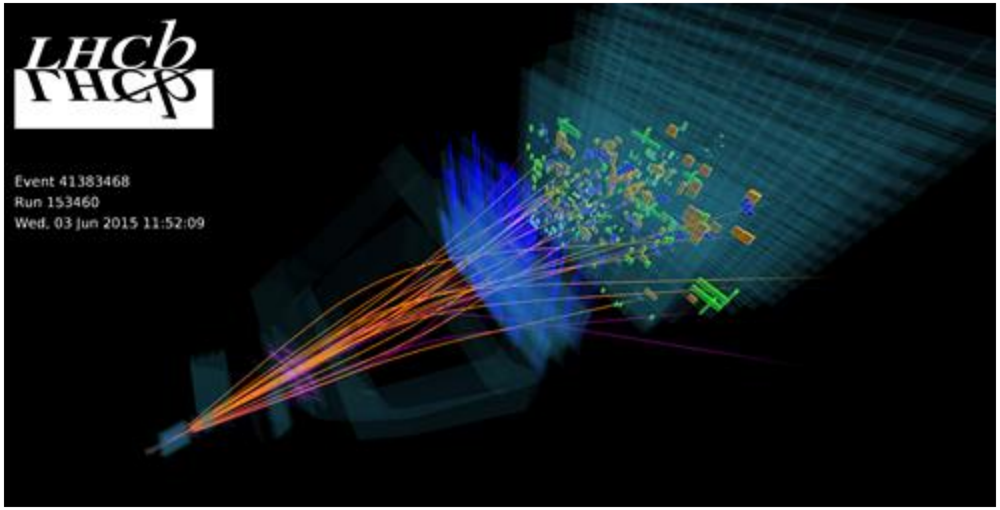




Run-2 restart

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.

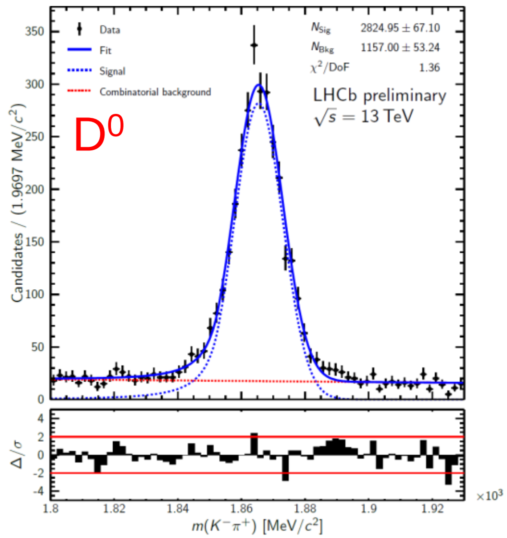


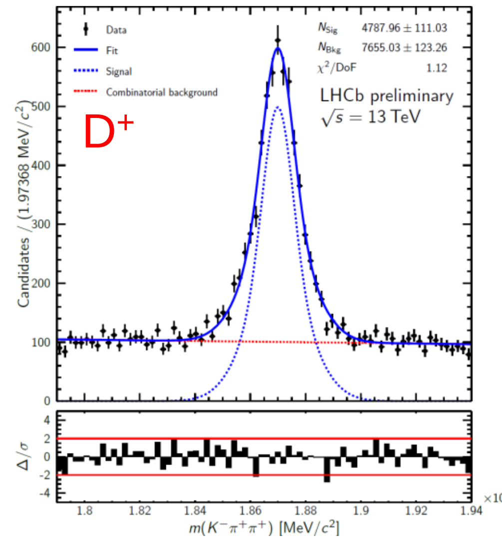
We are all ready to go ! Note that our run 2 operation is far from identical to run 1…

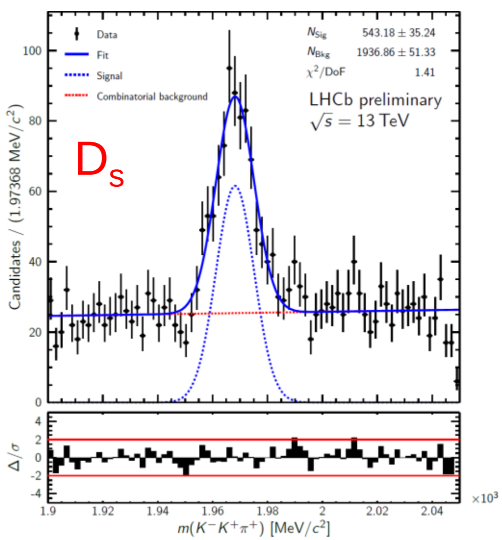
Run 2 – first data from High Level Trigger

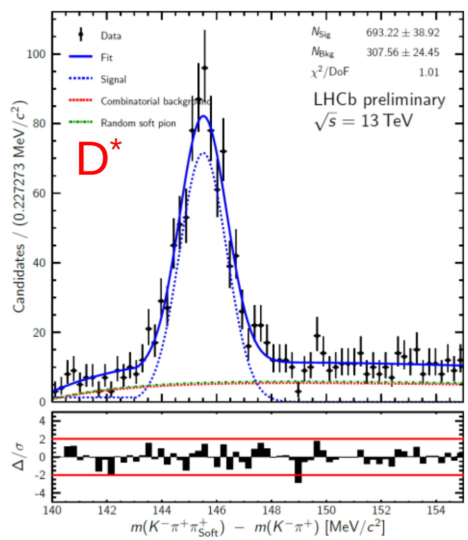
Charm signals directly
from High Level Trigger
in one of first fills of run 2.

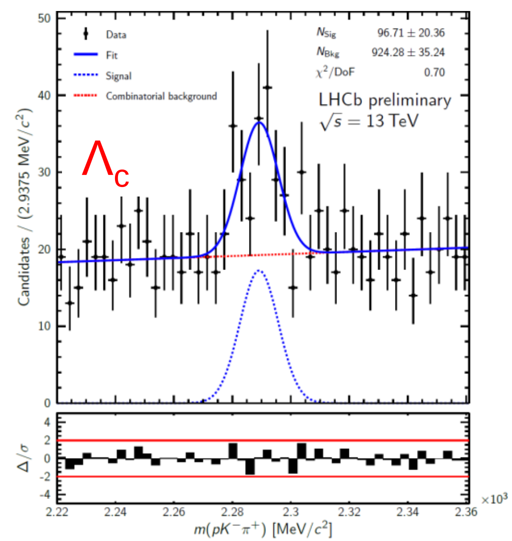
Full reconstruction now
run in trigger, with RICH,
full alignment & calibration.
Some of this output can go
straight for analysis without
further offline processing !



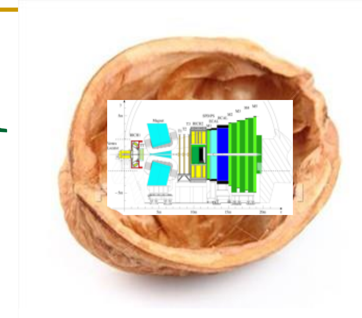








LHCb Upgrade in a nutshell



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 x 10^{33} cm^{-2} s^{-1}

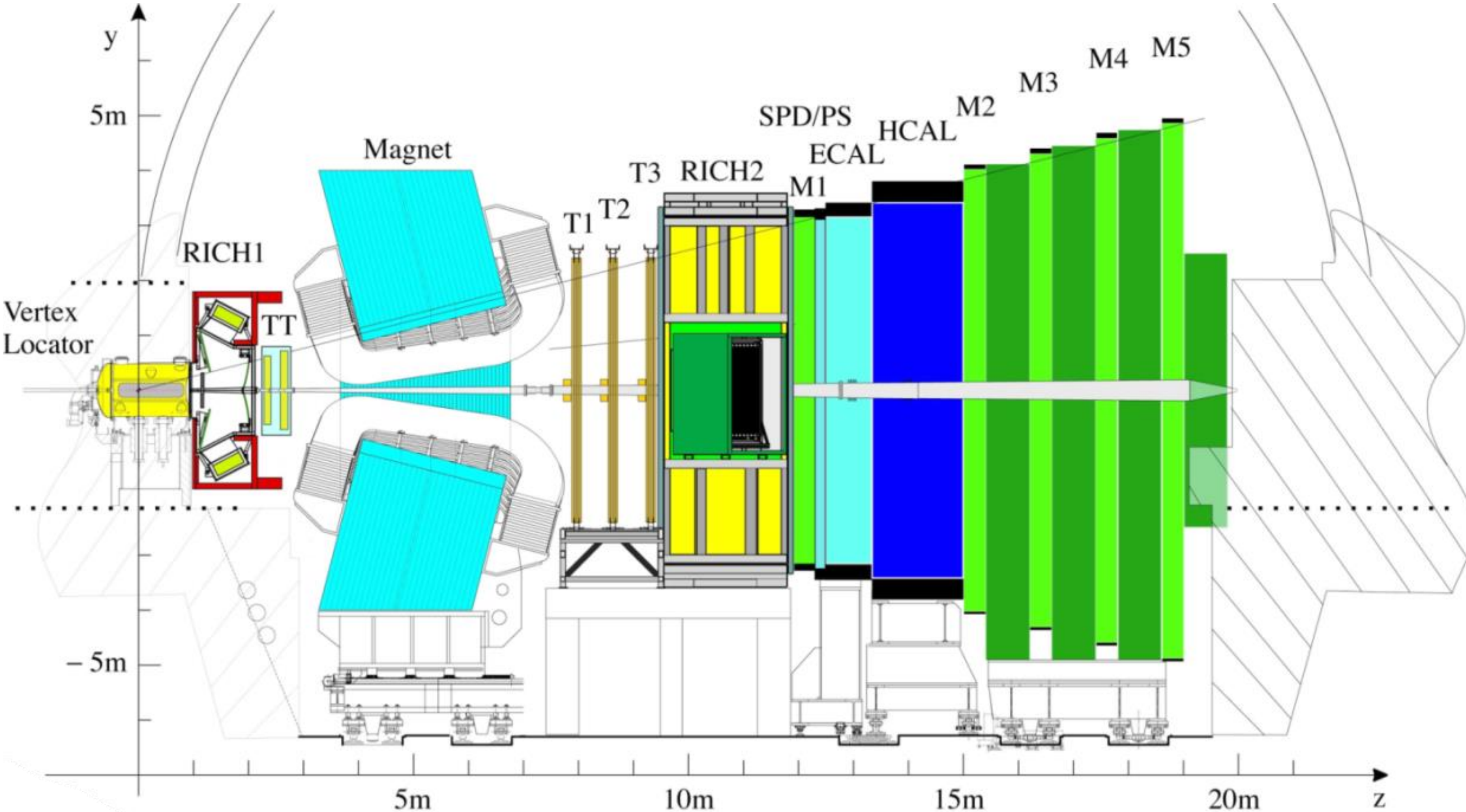
Necessitates redesign of several sub-detectors & overhaul of readout

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

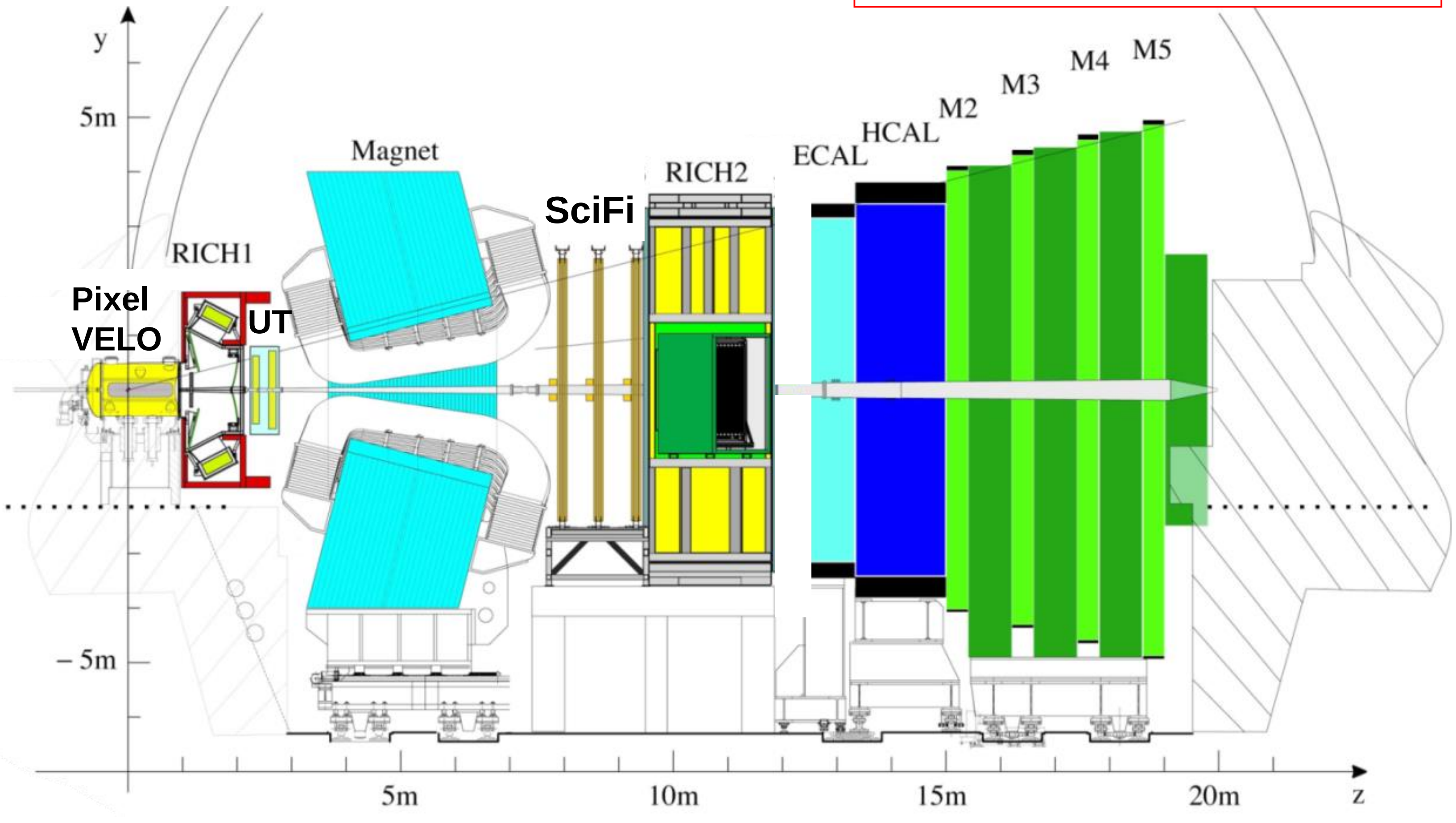
Current detector



Upgrade overview

Current detector → upgraded detector

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



Upgrade overview

Current detector → upgraded detector

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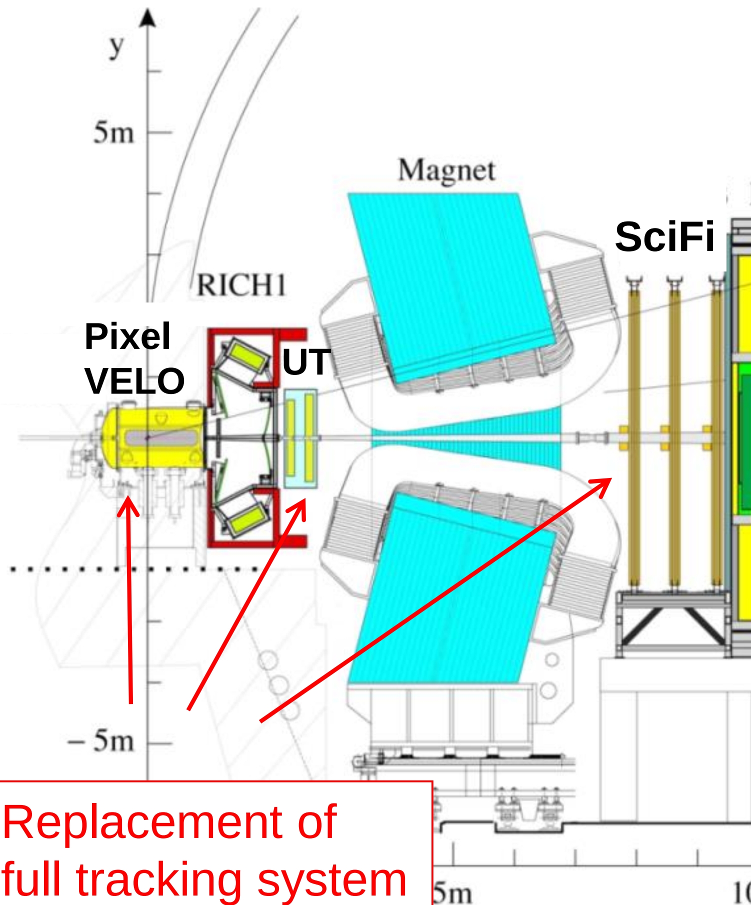
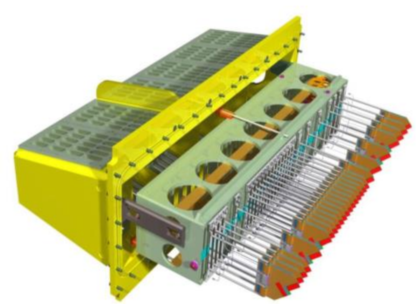


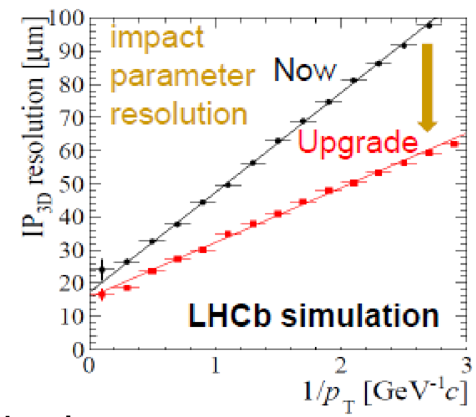
Replacement of full tracking system

Pixel Vertex Locator (VELO)

Half of VELO system



Improved performance

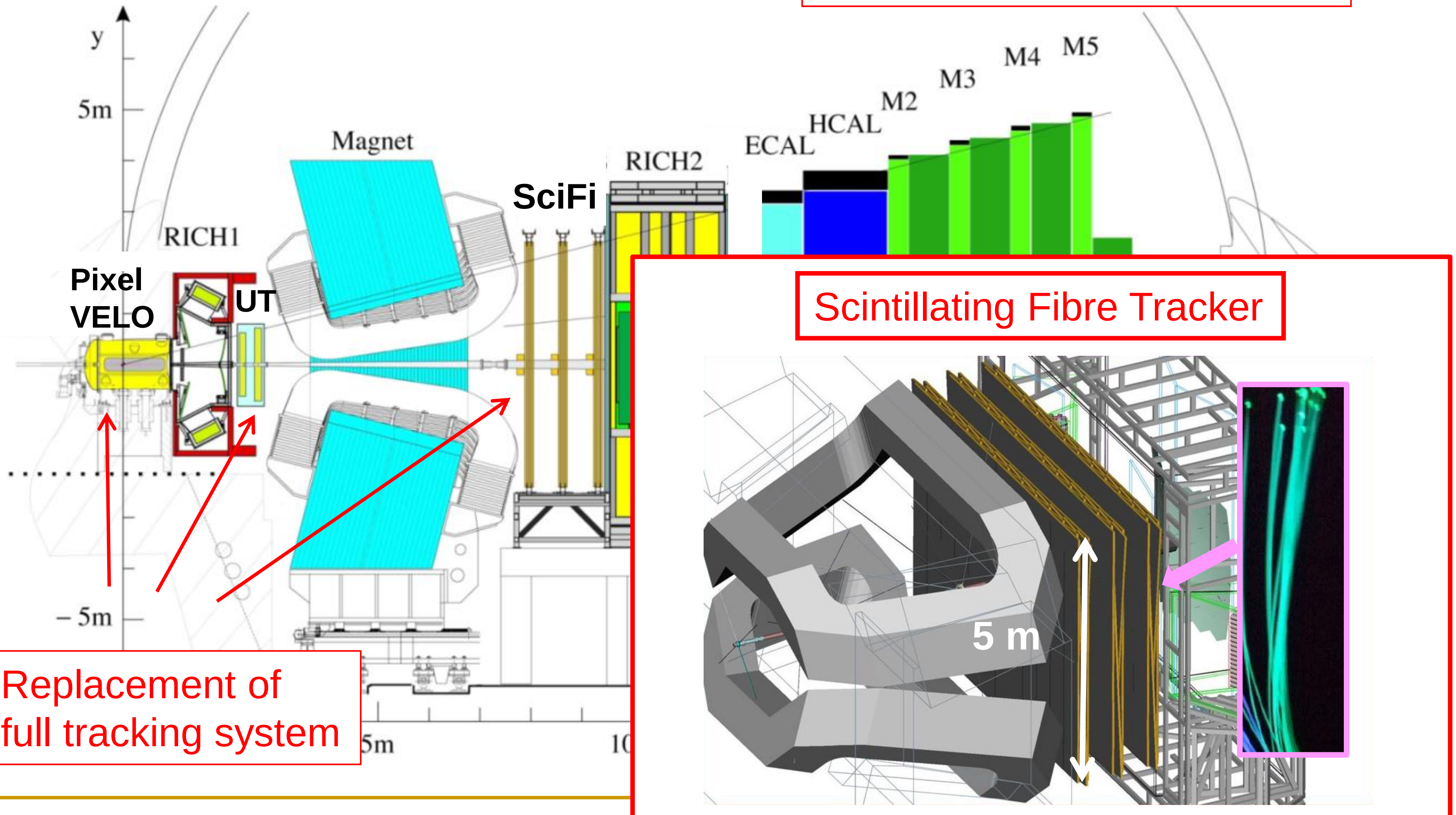


(‘UT’ = ‘Upstream tracker’, a high performance Si strip detector)

Upgrade overview

Current detector → upgraded detector

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



Replacement of full tracking system

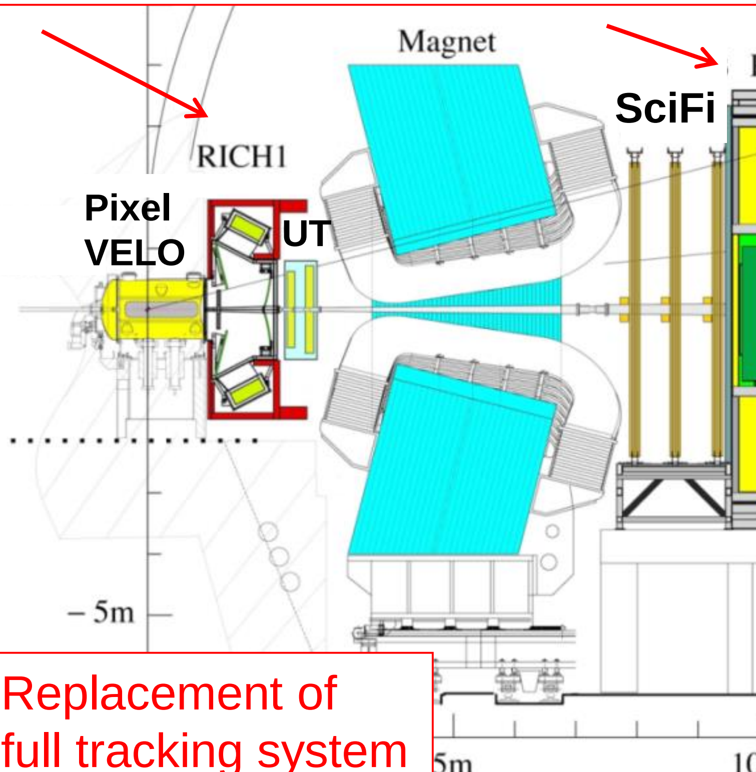
Large scale system (~12,000 km of fibres)

Upgrade overview

Current detector → upgraded detector

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

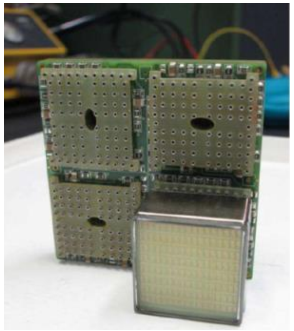
RICH 1 redesigned; new photodetectors installed for RICH 1 and RICH 2



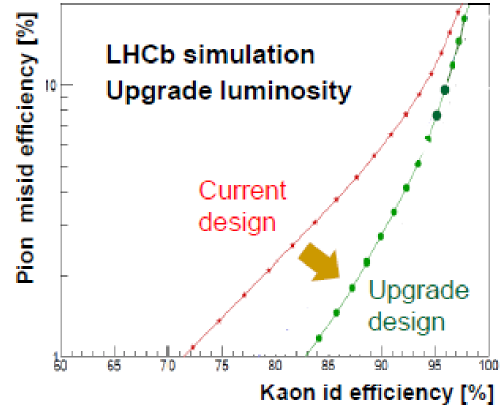
Replacement of full tracking system

RICH system

New photodetector



New optics….



…good performance at high luminosity

Upgrade overview

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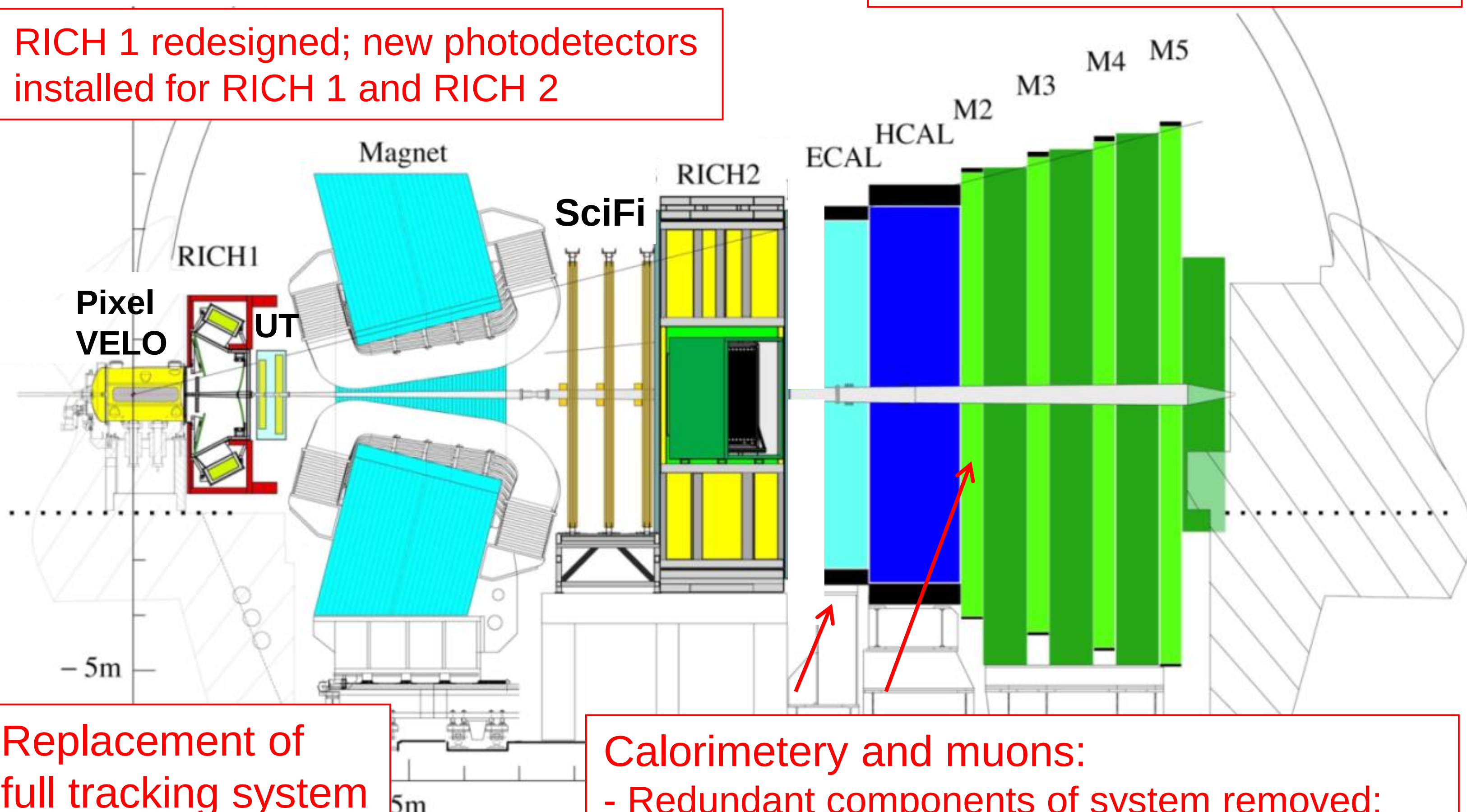
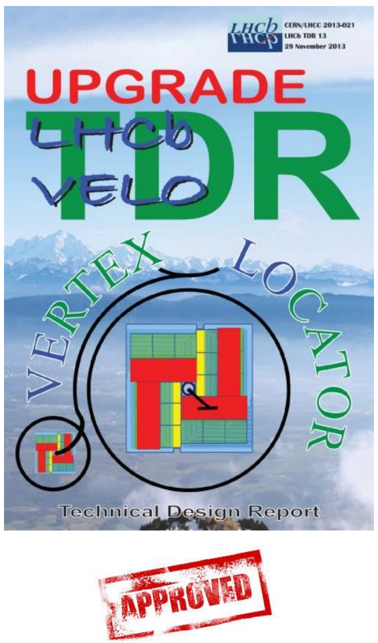


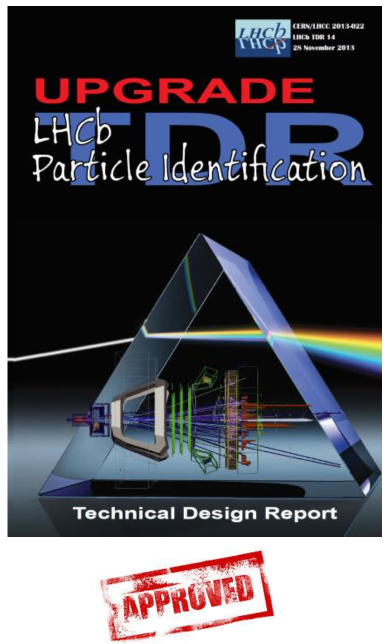
Replacement of full tracking system

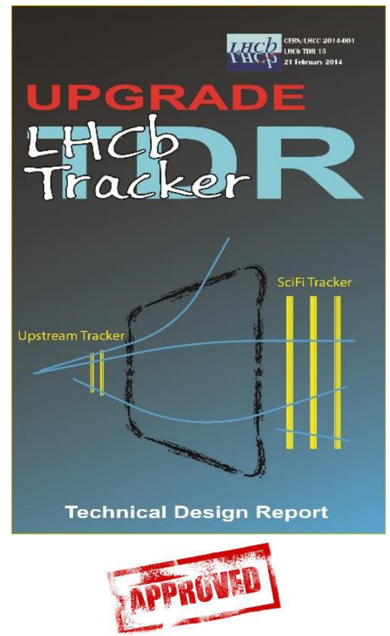
Calorimetery and muons:
- Redundant components of system removed; new electronics added; more shielding included

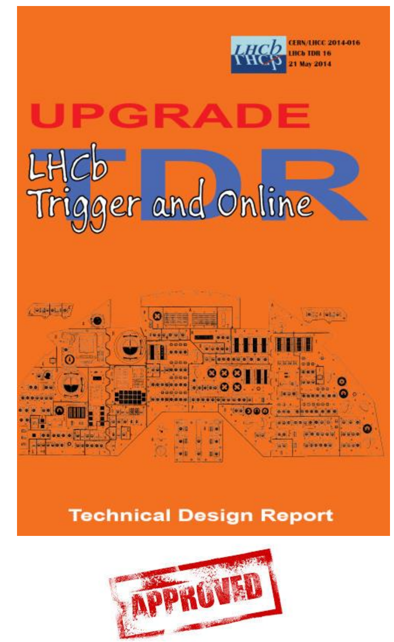
Completion of upgrade TDRs

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)

- Rare decays, CPV and spectroscopy
- 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

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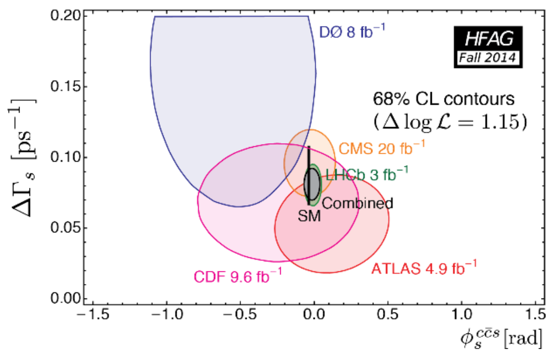
- Thanks Roger !

Backup

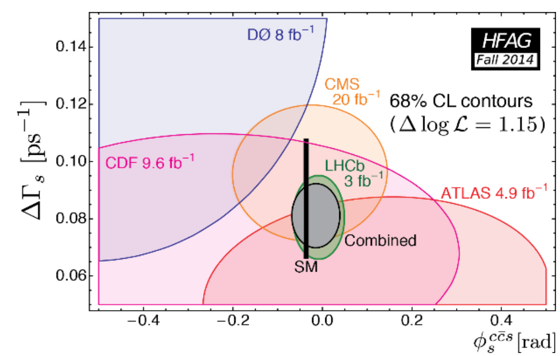
Beyond lifetimes – indirect CP violation

Mixing is however a tool – it enables us to measure/probe for time-dependent (indirect) CP-violation. LHCb has made impressive contributions here in 3 systems.

B_s CPV, parametrised by 'ϕ_s', known to be very small in SM.
LHCb has achieved a precision 20x better than Tevatron experiments.

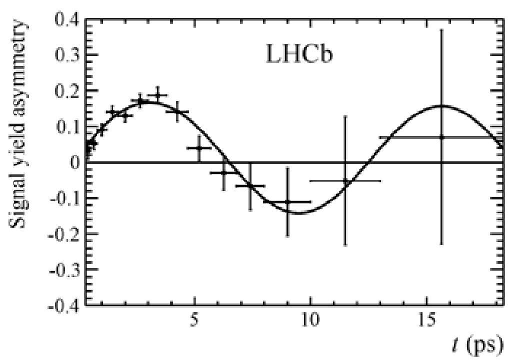


zoom



[PRL 114 (2015) 041801; PLB 736 (2014) 186]

B^0 CPV, parametrised by sin2β, sizable but must be measured well – a key parameter in unitarity triangle! LHCb has already matched *b*-factory performance in $B^0 \rightarrow J/\Psi K_S$ and will go beyond.



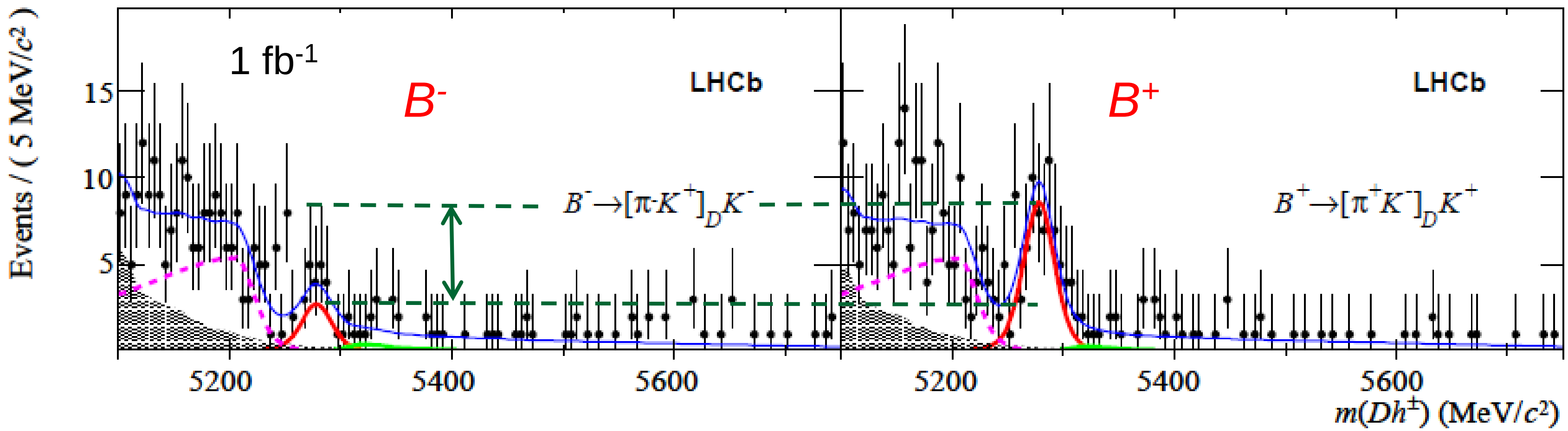
[arXiv:1503.07089]

D^0 CPV negligible in SM, but can be enhanced by New Physics. LHCb is leading the search!

Direct CPV and the unitarity triangle

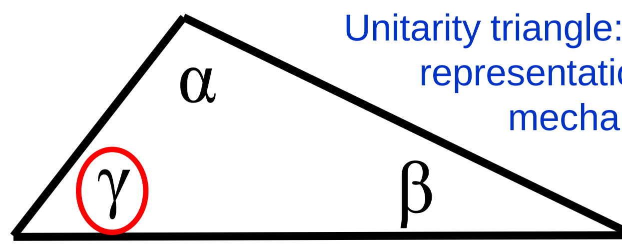
In parallel, LHCb is making the world's most precise measurements in direct CPV, in particular of '*B*→*DK*' processes that are sensitive to the unitarity triangle angle γ.

e.g. the suppressed 'ADS' $B^{\pm} \to (K^{\mp}\pi^{\pm})_D K^{\pm}$ mode (BR ~ 10^{-7}) first seen at LHCb



[PLB 712 (2012) 203]

With these the precision on γ from LHCb alone is now <10° (better than the *b*-factory experiments combined), & will improve to ~3° by end of run 2.



Unitarity triangle: geometrical representation of the SM mechanism of CPV