LHCb physics – status & prospects

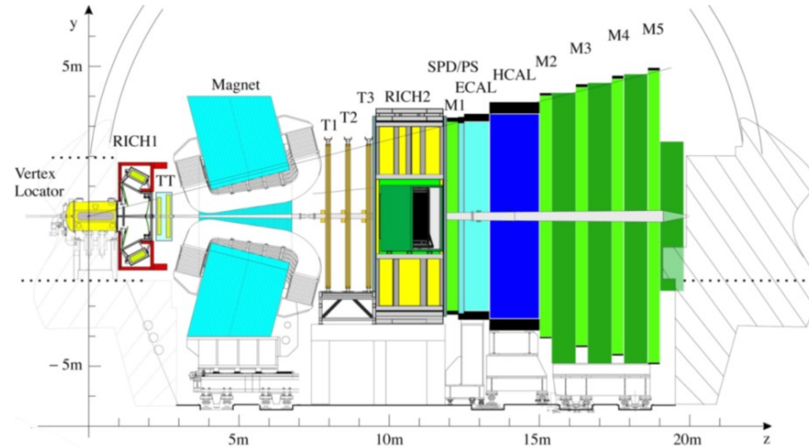
- LHCb overview
- Selected physics topics
  - FCNCs
  - CPV in the *b*-system
  - CPV in the *c*-system
  - Beyond flavour
- Readiness for run 2
- The further future

Guy Wilkinson
University of Oxford and CERN
16/12/14

LHCb – the essentials

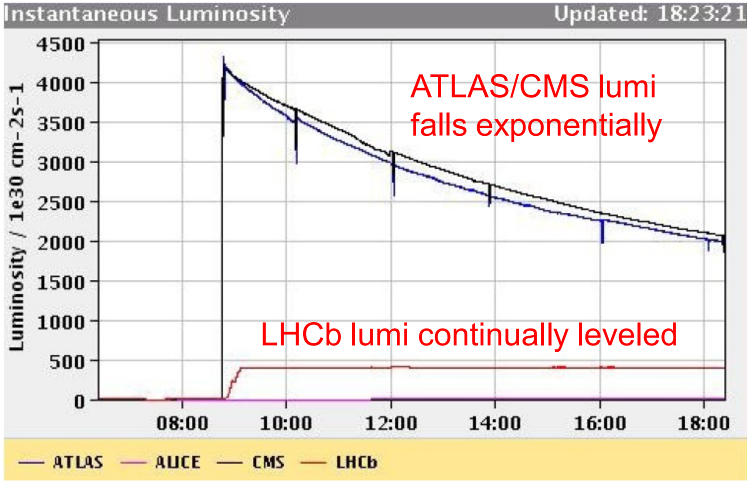
LHCb – a forward spectrometer optimised for heavy-flavour physics at the LHC

- 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.

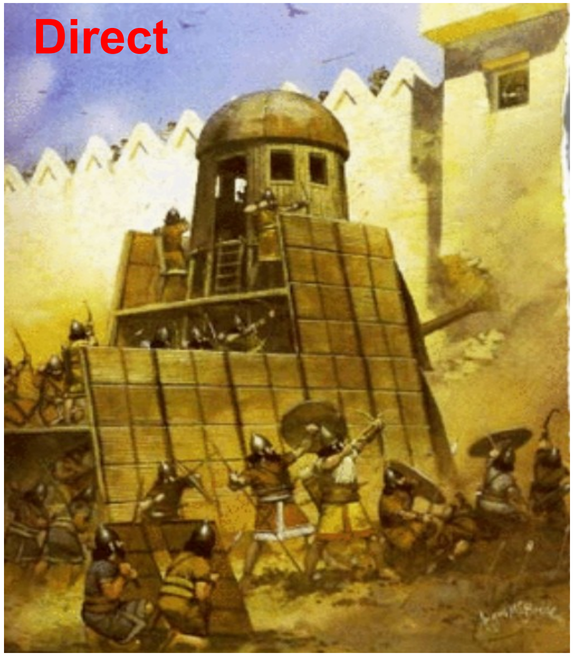
- 37 pb^{-1} collected in 2010
- 1 fb^{-1} in 2011 and 2 fb^{-1} in 2012
- aim for ~8 fb^{-1} before 2018-19 shutdown

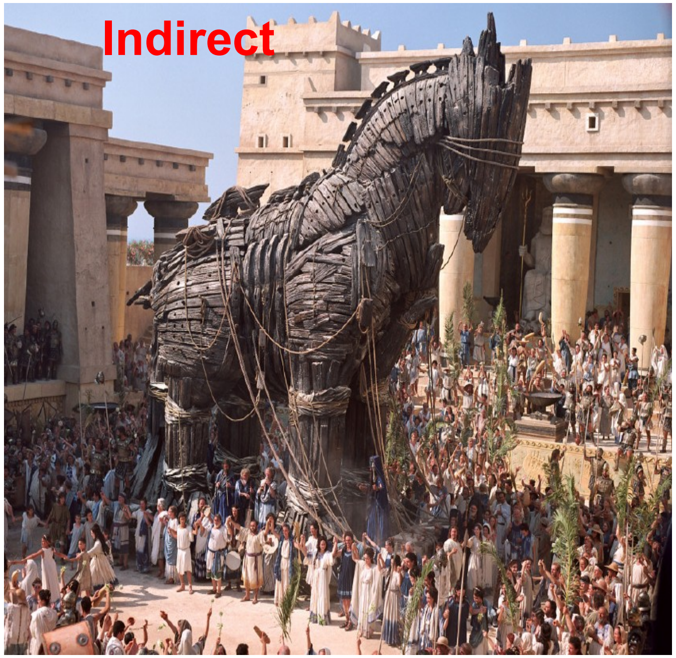


>230 papers & counting on CP violation, rare decays, spectroscopy, & other physics (EW, QCD, exotics…)

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





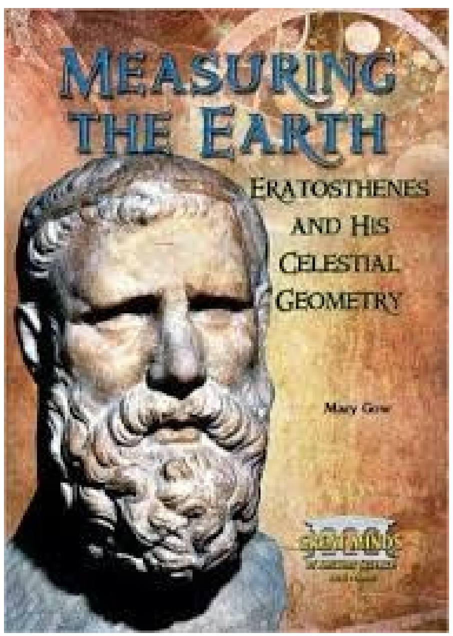
Use the high energy of the LHC to produce the New Physics particles, which we then detect

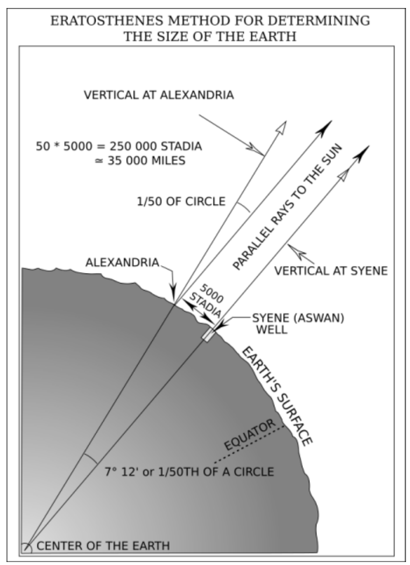
Make precise measurements of processes in which New Physics particles enter through 'virtual loops'

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.

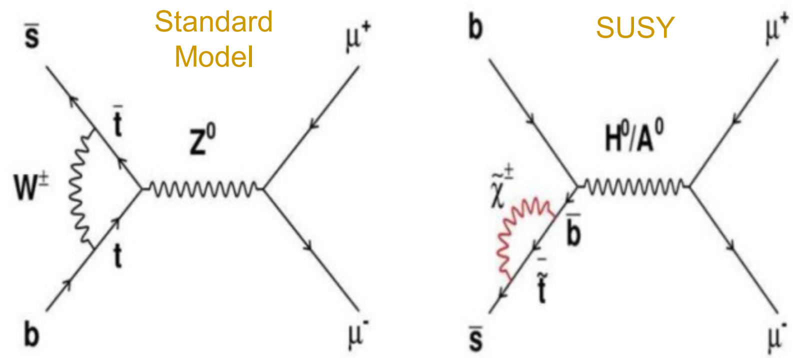
FCNCs / 'Rare decays'

- $B_{s,d} \rightarrow \mu^+\mu^-$
- $B \rightarrow K^{(*)} l^+ l^-$
- Beyond the *b*

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

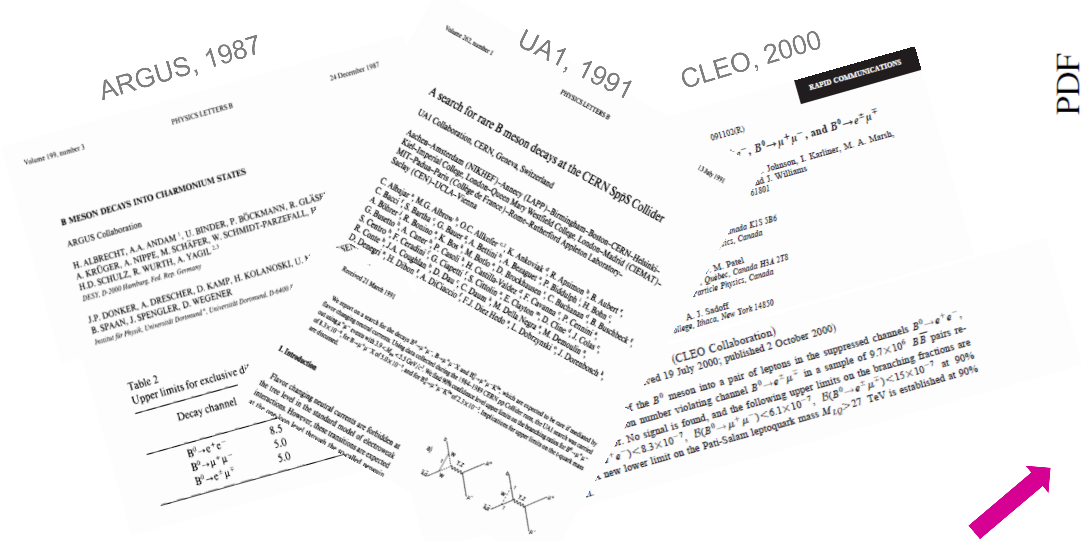
This decay mode can only proceed through suppressed loop diagrams.

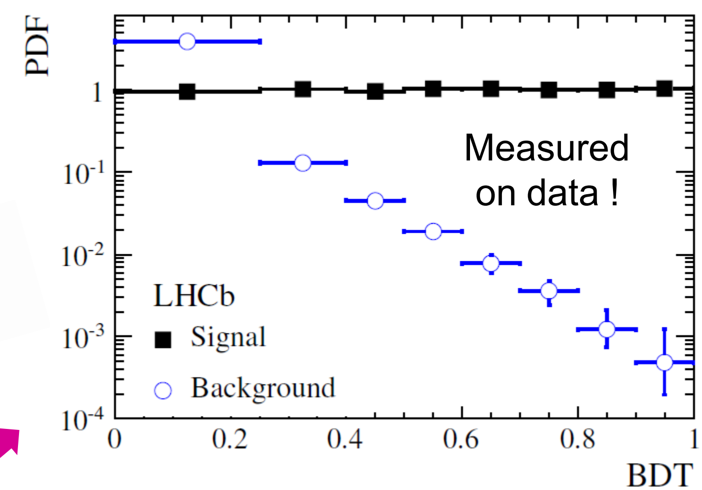
In the Standard Model it happens extremely rarely (~10^{-9}), but the exact rate is very well predicted



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

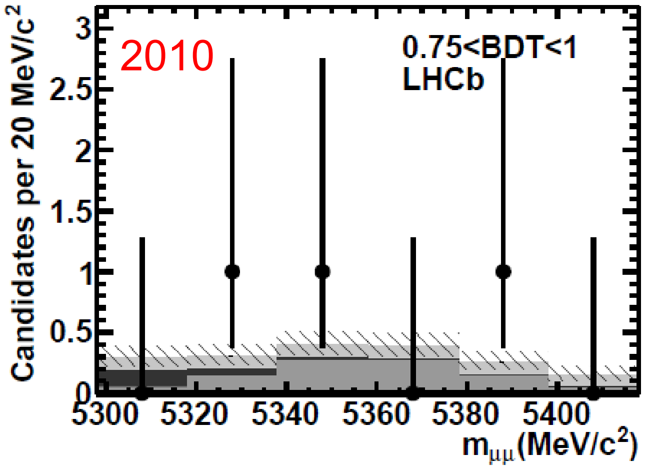




[PRL 111 (2013) 101805]

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

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



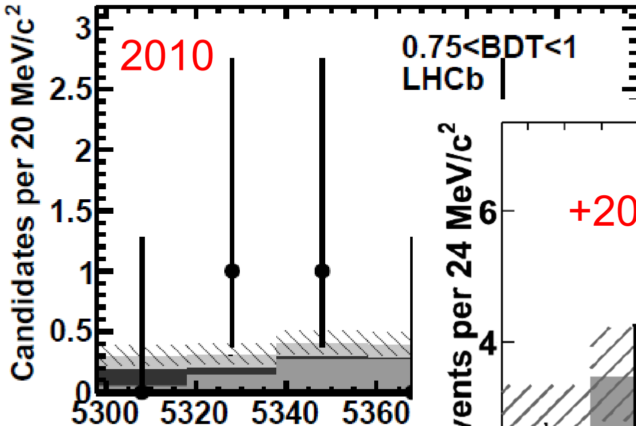
[PLB 708 (2012) 55]

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 !)

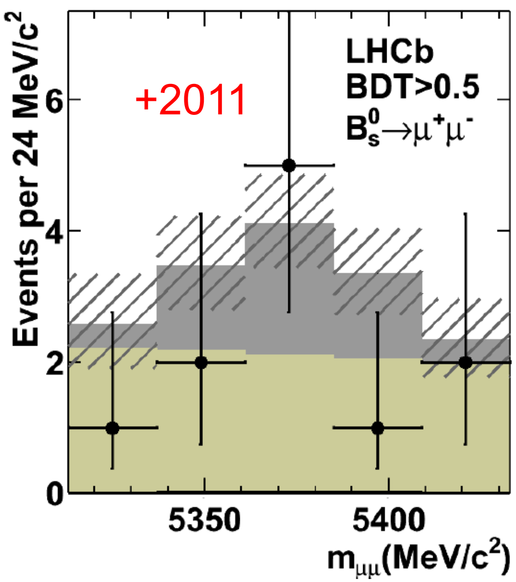
2010

Nothing

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



[PLB 708 (2012) 5



[PRL 108 (2012) 231801]

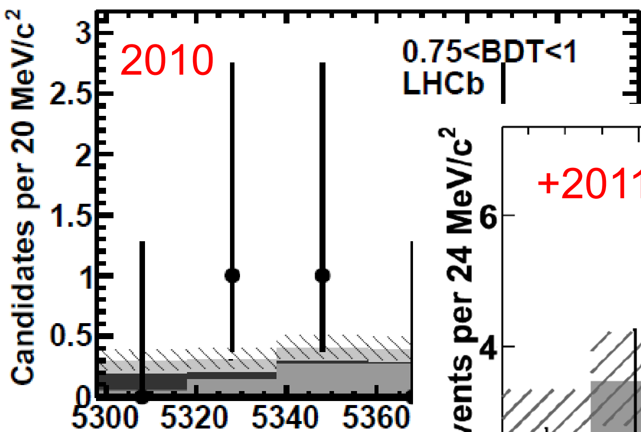
Plot of invariant mass distribution in region of high BDT sensitivity – if there is a signal we should see a peak here (but the BDT uses much more information than the invariant mass alone !)

+ 2011

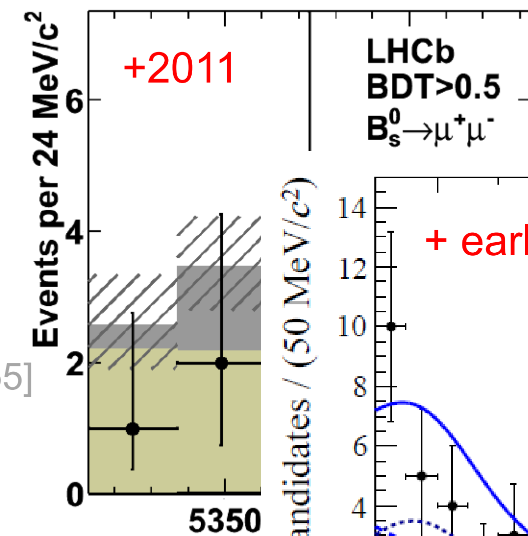
Maybe a hint of a bump, but nothing can be claimed

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

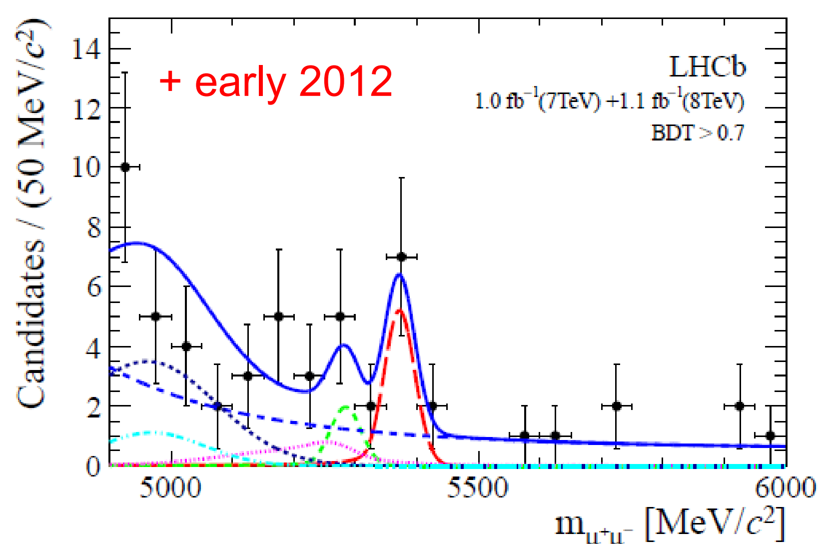
Plot of invariant mass distribution in region of high BDT sensitivity – if there is a signal we should see a peak here (but the BDT uses much more information than the invariant mass alone !)



[PLB 708 (2012) 55]



[PRL 108



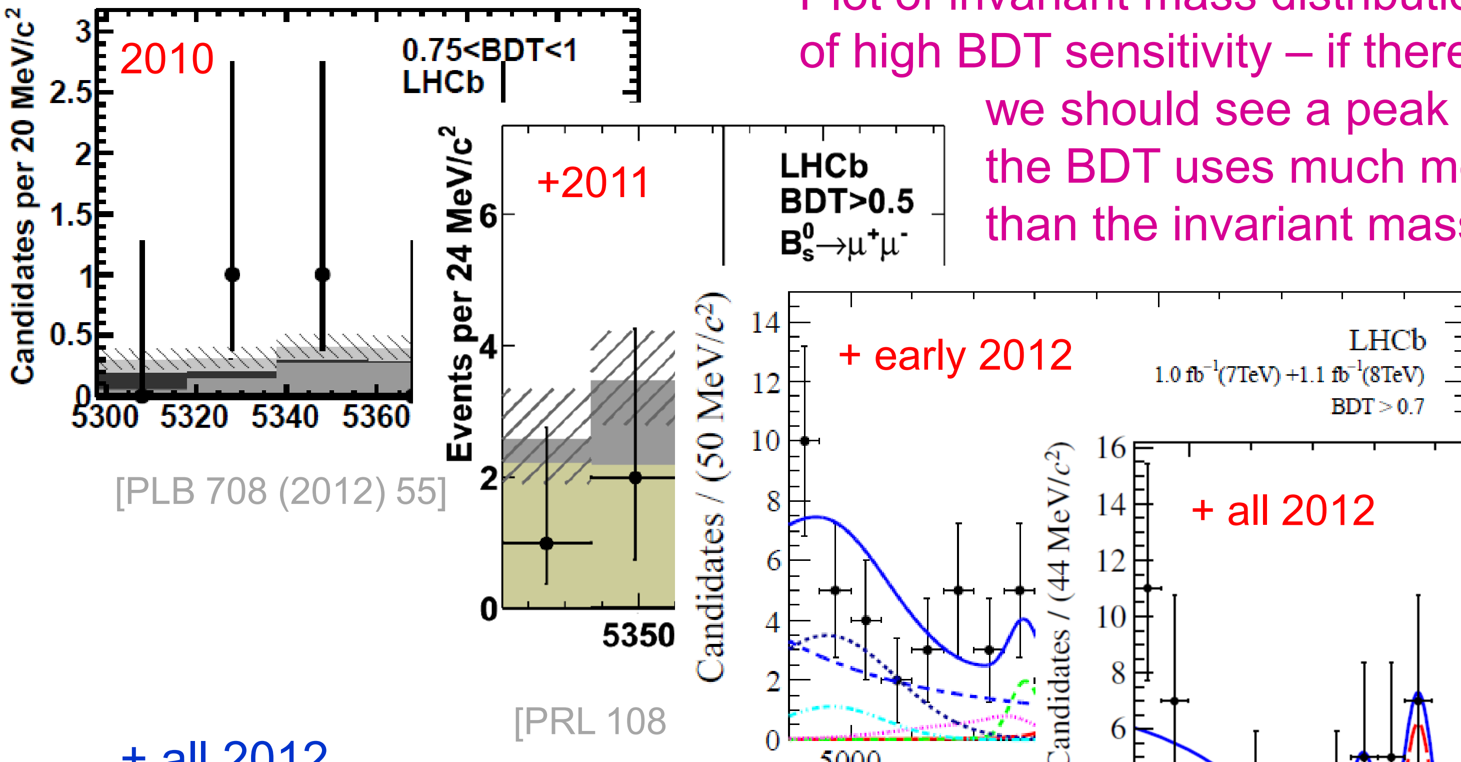
[PRL 110 (2013) 021801]

+ early 2012

First evidence that there is something there !

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

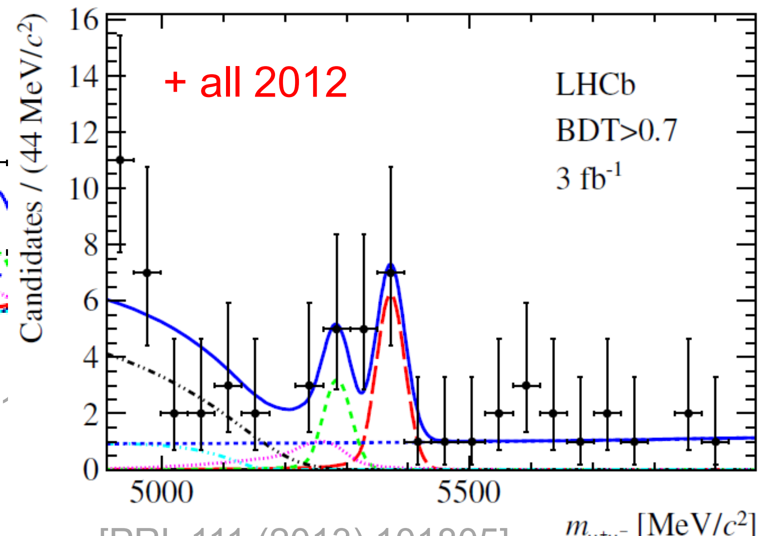
Plot of invariant mass distribution in region of high BDT sensitivity – if there is a signal we should see a peak here (but the BDT uses much more information than the invariant mass alone !)



[PLB 708 (2012) 55]

[PRL 108

[PRL 110 (20



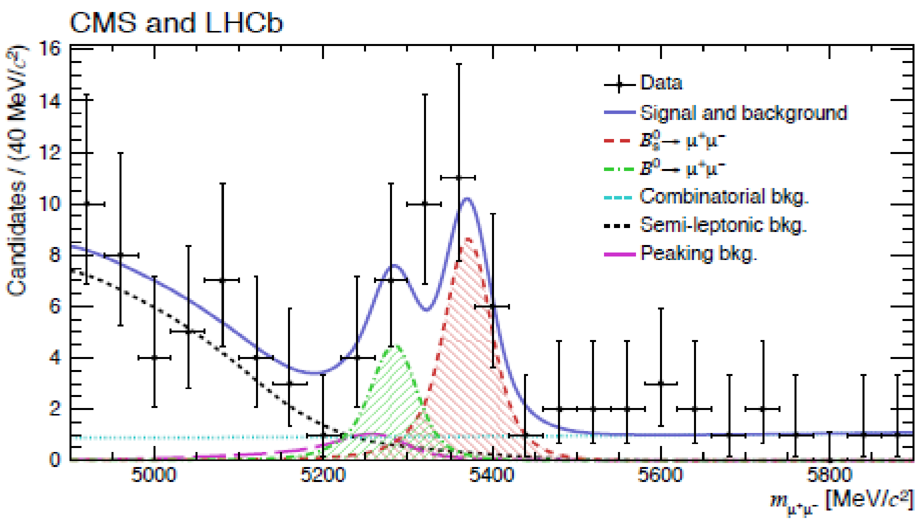
[PRL 111 (2013) 101805]

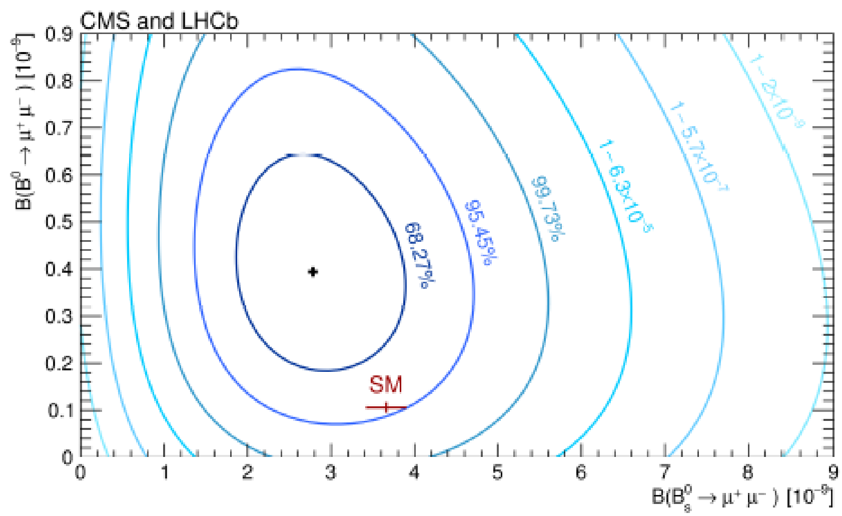
+ all 2012

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 !





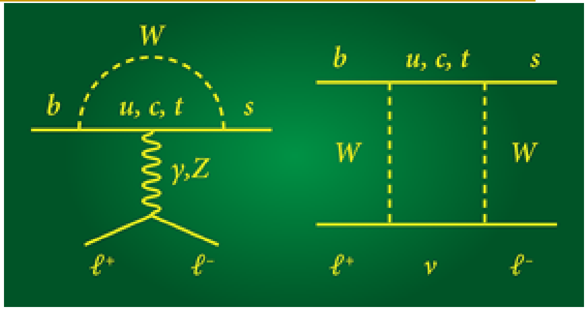
$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = \left(2.8\,^{+0.7}_{-0.6}\right) \times 10^{-9} \quad (6.2\sigma)$$

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

[arXiv:1411.4413, submitted to Nature]

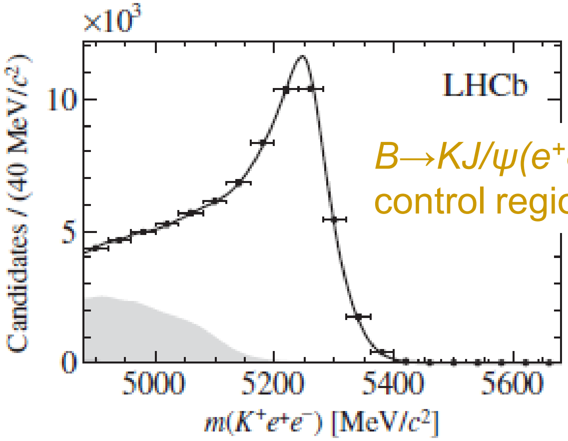
Included also are results for the even rarer $B_d \to \mu\mu$, where a signal may be emerging too. The picture is intriguing and provides encouragement for run 2 !

FCNCs: results to ponder in electroweak Penguins



The decays $B \to K^{(*)} l^+ l^-$ offer many observables that are sensitive to NP in different ways, all through the role of the contributing loop diagrams (*e.g.* EW Penguin)

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

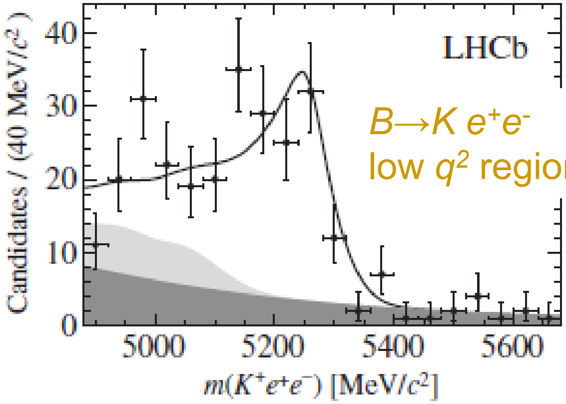


Control region gives R_K consistent with unity. Interesting, low q^2 region gives:

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

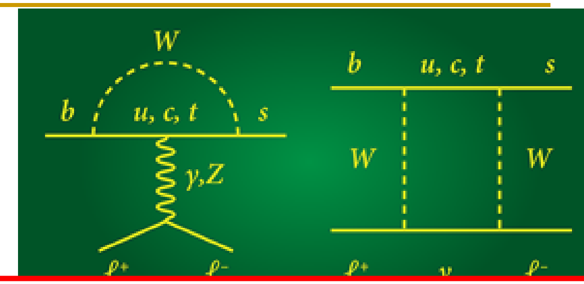
which is 2.6σ from unity, 3σ if BaBar included.

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



Recall there are other puzzles in this sector from LHCb analyses, for example the "P_5' puzzle", where the full 3 fb^{-1} run-1 dataset result is coming soon.

FCNCs: results to ponder in electroweak Penguins



The decays $B \rightarrow K^{(*)} l^+ l^-$ o
ways, all through the ro

Example - test of lepto
the ratio of $B \rightarrow K \mu^+ \mu^-$ to

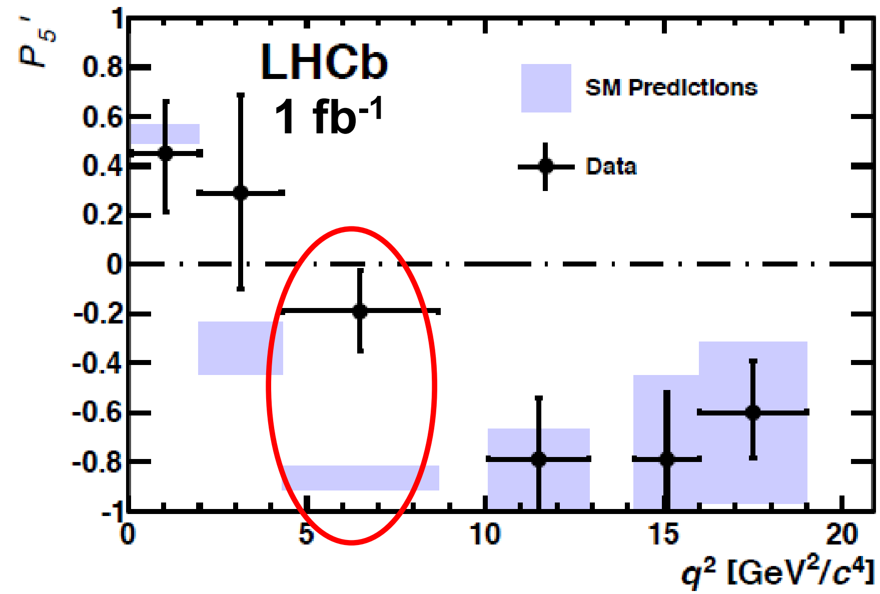
Control region gives RK
Interesting, low q^2 regio

$$R_K = 0.745^{+0.090}_{-0.074}$$

which is 2.6σ from unity

Follow up studies u

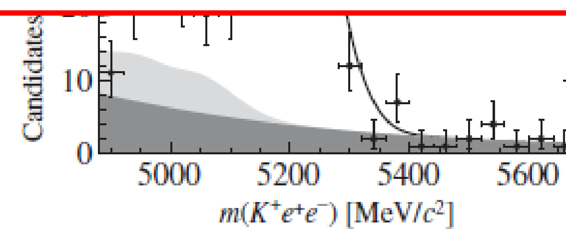
P$_5$' is a theoretically clean(ish) observable measured in the $B^0 \rightarrow K^* \mu^+ \mu^-$ angular analysis



[PRL 111 (2013) 191801]

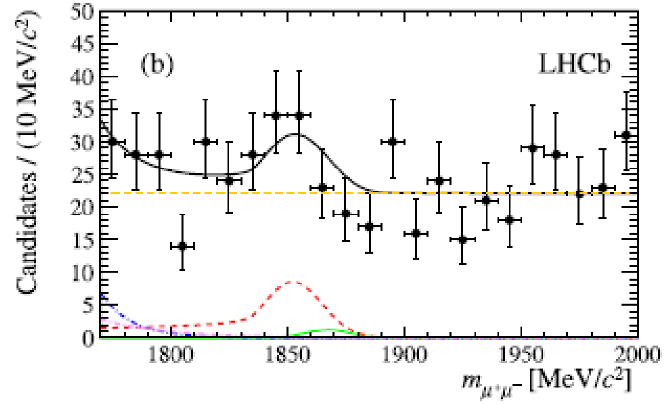
Aim to have update ready for Spring 2015

Recall there are other puzzles in this sector from LHCb analyses, for example the "P$_5$' puzzle", where the full 3 fb^{-1} run-1 dataset result is coming soon.



FCNCs: beyond the *b*

[PLB 725 (2013) 15]



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

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

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.

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

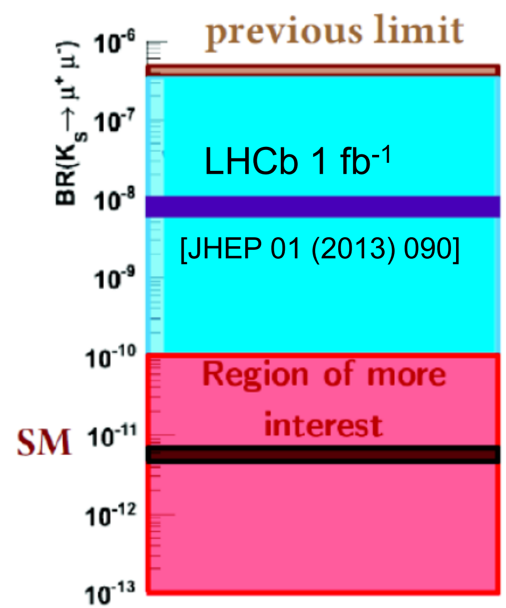
$\sim V_{ts} V_{td} \sim 10^{-4}$

(G. Isidori)

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

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

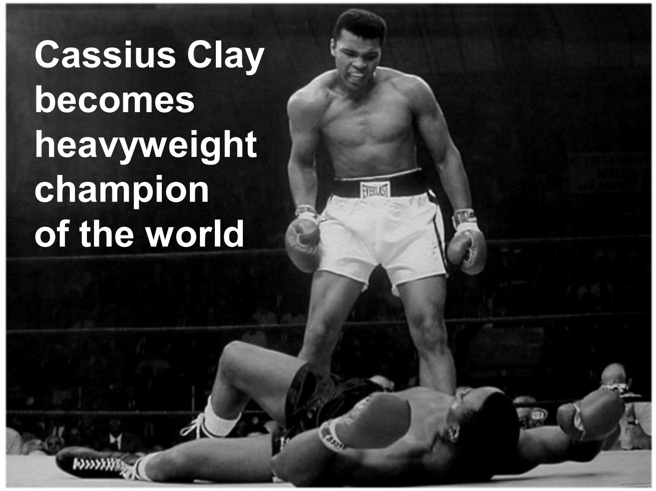
$$\mathcal{B}(K^0_S \to \mu^+\mu^-) < 11(9) \times 10^{-9} \quad \text{at 90\% (95\%) CL}$$

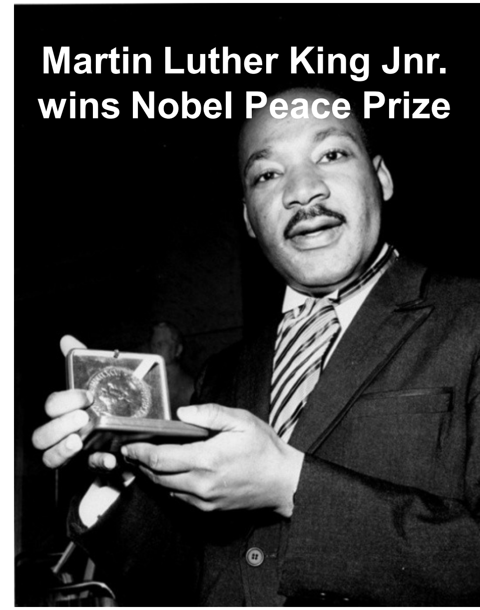


This is a topic where LHCb Upgrade will bring *big* gains.

1964

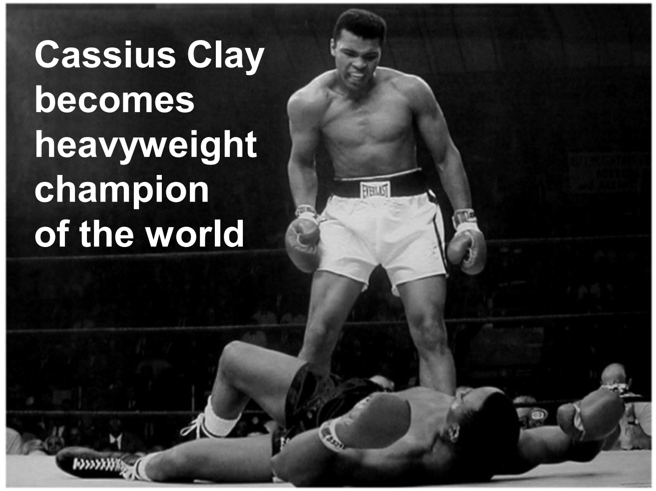
50 years ago – events of 1964

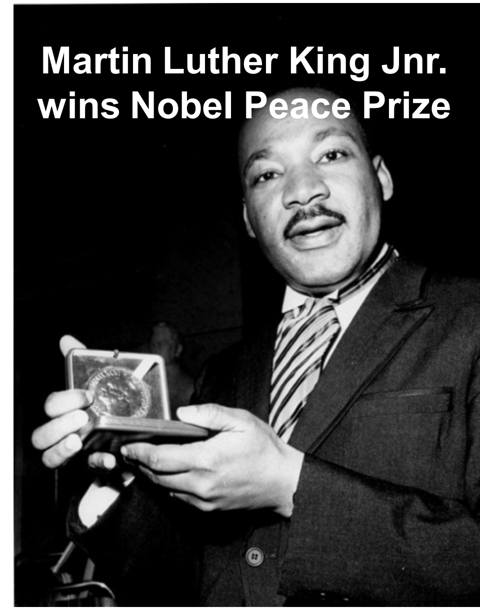


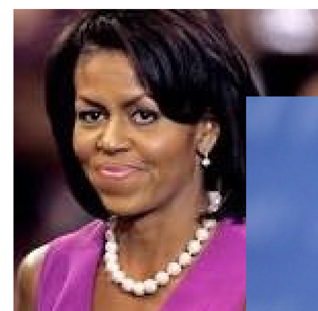


Michele
Obama born

50 years ago – events of 1964

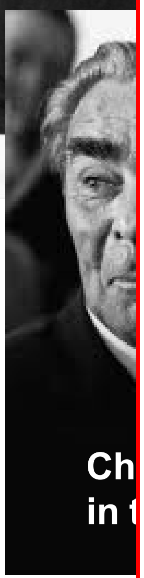


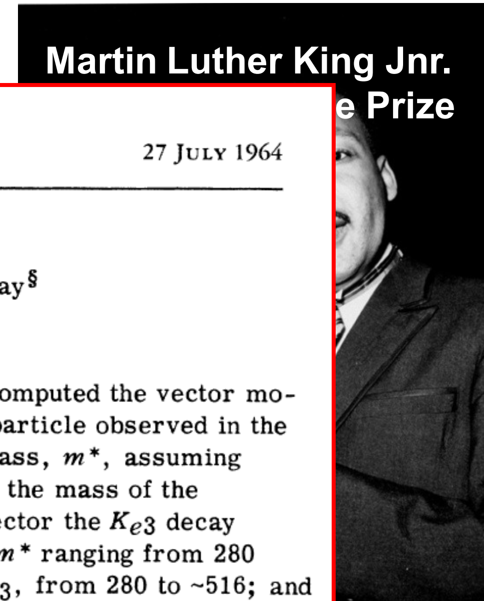




Michele
Obama born… & Sarah Palin

50 years ago – events of 1964





VOLUME 13, NUMBER 4 PHYSICAL REVIEW LETTERS 27 JULY 1964

EVIDENCE FOR THE 2π DECAY OF THE K_2^0 MESON*†

J. H. Christenson, J. W. Cronin,‡ V. L. Fitch,‡ and R. Turlay§
Princeton University, Princeton, New Jersey
(Received 10 July 1964)

This Letter reports the results of experimental studies designed to search for the 2π decay of the K_2^0 meson. Several previous experiments have served[1,2] to set an upper limit of 1/300 for the fraction of K_2^0's which decay into two charged pions. The present experiment, using spark chamber techniques, proposed to extend this limit.

In this measurement, K_2^0 mesons were produced at the Brookhaven AGS in an internal Be target bombarded by 30-BeV protons. A neutral beam was defined at 30 degrees relative to the circulating protons by a $1\frac{1}{2}$-in.$\times 1\frac{1}{2}$-in.$\times$48-in. collimator at an average distance of 14.5 ft. from the internal target. This collimator was followed by a sweeping magnet of 512 kG-in. at ~20 ft. and a 6-in.$\times$6-in.$\times$48-in. collimator at 55 ft. A $1\frac{1}{2}$-in. thickness of Pb was placed in front of the first collimator to attenuate the gamma rays in the beam.

The experimental layout is shown in relation to the beam in Fig. 1. The detector for the decay

The analysis program computed the vector momentum of each charged particle observed in the decay and the invariant mass, m^*, assuming each charged particle had the mass of the charged pion. In this detector the K_{e3} decay leads to a distribution in m^* ranging from 280 MeV to ~536 MeV; the $K_{\mu 3}$, from 280 to ~516; and the $K_{\pi 3}$, from 280 to 363 MeV. We emphasize that m^* equal to the K^0 mass is not a preferred result when the three-body decays are analyzed in this way. In addition, the vector sum of the two momenta and the angle, θ, between it and the direction of the K_2^0 beam were determined. This angle should be zero for two-body decay and is, in general, different from zero for three-body decays.

An important calibration of the apparatus and data reduction system was afforded by observing the decays of K_1^0 mesons produced by coherent regeneration in 43 gm/cm² of tungsten. Since the K_1^0 mesons produced by coherent regeneration

Sarah Palin

CP theorist set for Pentagon top job ?

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Ashton Carter: meet the man rumoured to be Obama's next secretary of defense

The former physicist and Harvard professor who has taken an interest in cybersecurity, lacks a prominent political profile, offending as few people as he inspires

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cording to reports, the former deputy secretary of defense Ashton Carter is pected to be nominated by President Obama for the position of secretary of fense . Photograph: Alex Wong/Getty Images

CP theorist set for Pentagon top job ?

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Ashton Carter: meet the man rumoured to be Obama's next secretary of defense

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Future US defense secretary gives his reaction to LHCb 3 fb^{-1} φ_s result

Seminal papers in *B*-physics

PHYSICAL REVIEW D   VOLUME 23, NUMBER 7   1 APRIL 1981

CP violation in B-meson decays

Ashton B. Carter and A. I. Sanda
The Rockefeller University, New York, New York 10021
(Received 27 June 1980)

The pattern of CP violation in the bottom sector is discussed. We introduce general techniques to expose new CP-violating effects in the cascade decays of B mesons. In the Kobayashi-Maskawa (KM) model, the CP asymmetries so obtained range from 2–20 % for plausible values of the model parameters. This is to be compared with the small effects, of order 10^{-3}–10^{-4}, previously exhibited within this model. Effects of this size should be observable in upcoming experiments. Our approach stresses the on-shell transitions which make up the cascade decays of heavy mesons to ordinary hadrons, as opposed to the off-shell transitions which occur in the analogs of K^0-$\bar{K}^0$ mixing. The CP asymmetries generated by our techniques are of order sinδ, where δ is the KM phase angle, and thus represent the maximum effects obtainable in this model.

Nuclear Physics B193 (1981) 85–108
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NOTES ON THE OBSERVABILITY OF CP VIOLATIONS IN B DECAYS

I.I. BIGI
Institut für Theor. Physik der RWTH Aachen, D-5100 Aachen, FR Germany

A.I. SANDA[1]
Rockefeller University, New York 10021, USA

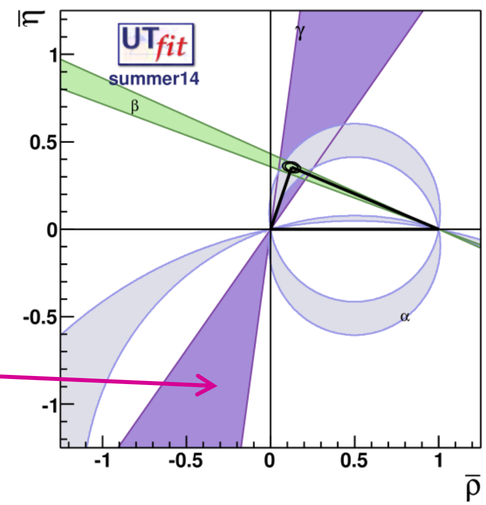
Received 16 June 1981

We describe a general method of exposing CP violations in on-shell transitions of B mesons. Such CP asymmetries can reach values of the order of up to 10% within the Kobayashi–Maskawa model for plausible values of the model parameters. Our discussion focuses on those (mainly non-leptonic) decay modes which carry the promise of exhibiting clean and relatively large CP asymmetries at the expense of a reduction in counting rates. Accordingly we address the complexities encountered when performing CP tests with a high statistics B meson factory like the Z^0 (and a toponium) resonance.

CPV in the beauty sector

- CKM metrology – towards a precise measurement of γ
- Indirect CPV in the B_s system
- Puzzles in charmless B decays

Precision CKM-metrology: the next challenge



B-factories (& others) have done a great job in mapping out unitarity triangle. But further progress needs, in particular, improved knowledge of angle γ

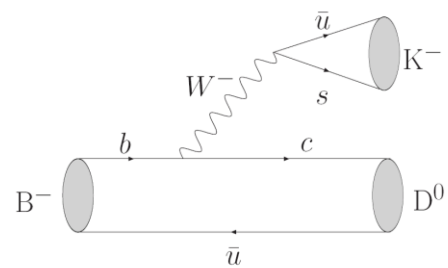
Look in $B^{\pm} \rightarrow DK^{\pm}$ decays using common mode for D^0 & D^0

$\rightarrow \gamma$ sensitive interference

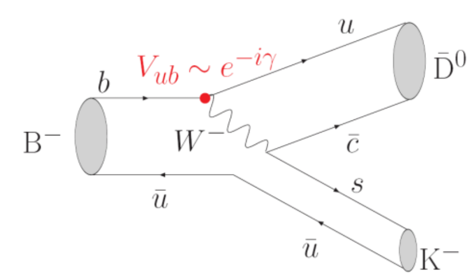
$\rightarrow$ different rates for B^+ & B^- (CPV!)

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

Favoured



Suppressed

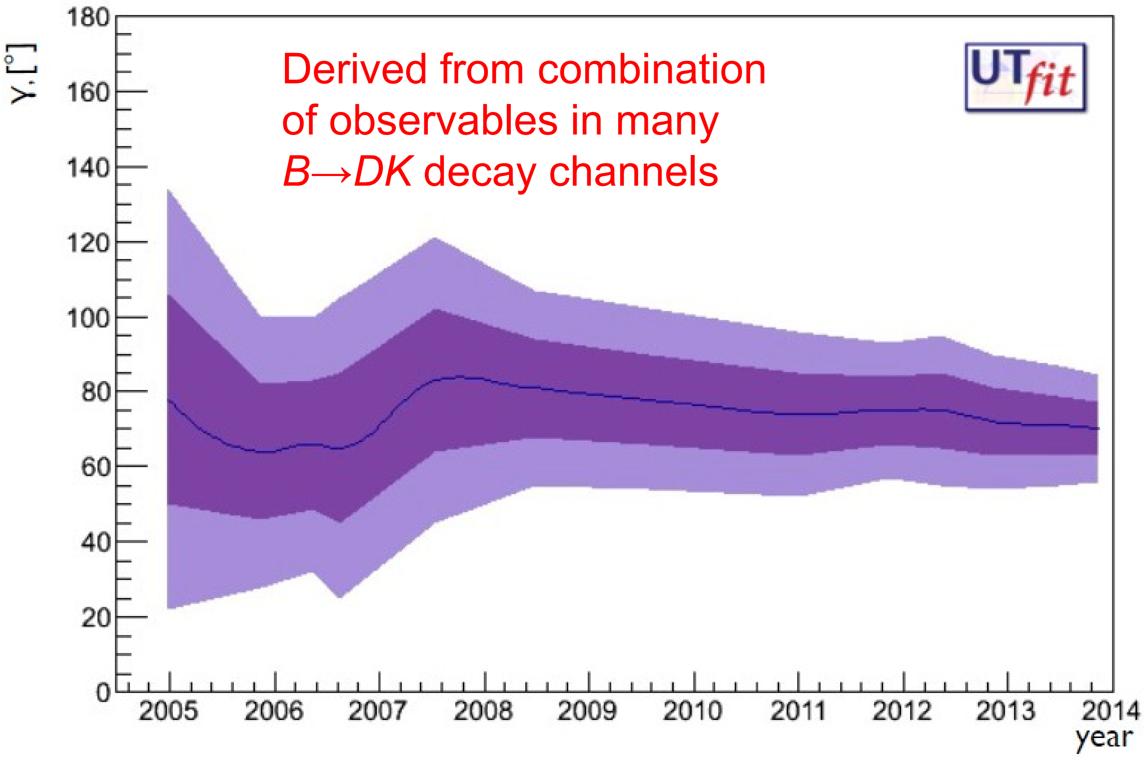


Tree-level decays: strategy very clean & yields result unpolluted by New Physics

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

γ measurement – the last ~10 years

The story so far...



Derived from combination of observables in many $B \to DK$ decay channels

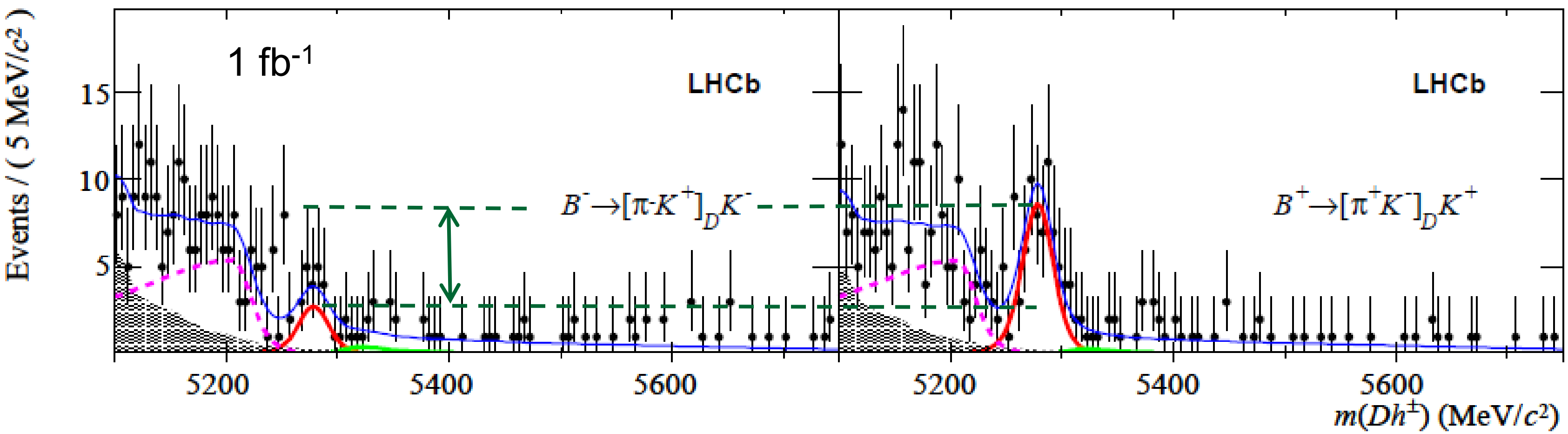
Consistent with the indirect prediction...

...but not nearly as precise

...factor 3 improvement in 10 years.

γ measurement: true precision needs statistical muscle of LHCb

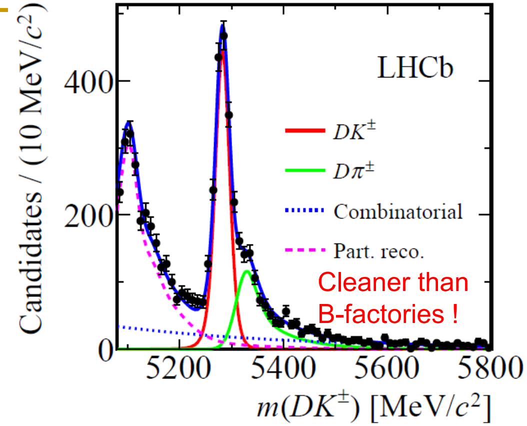
Rare, important decays just beyond the reach of the B-factories (*e.g.* the suppressed 'ADS' $B^{\pm} \rightarrow (K^{\mp}\pi^{\pm})_D K^{\pm}$ mode (BR ~ 10^{-7}) was soon seen at LHCb



[PLB 712 (2012) 203]

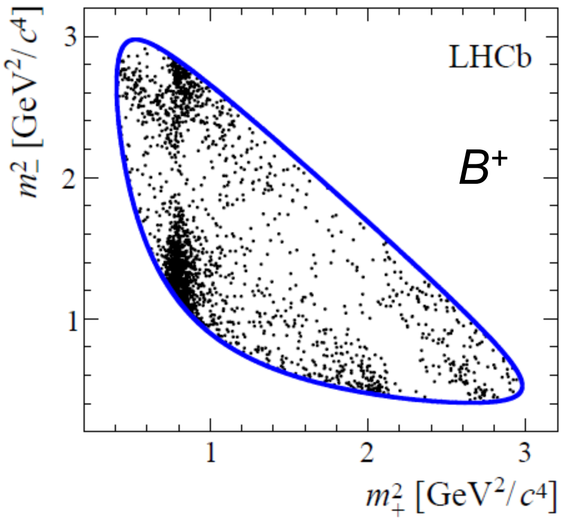
This CP asymmetry carries ultra-clean, easy to interpret, information on γ !

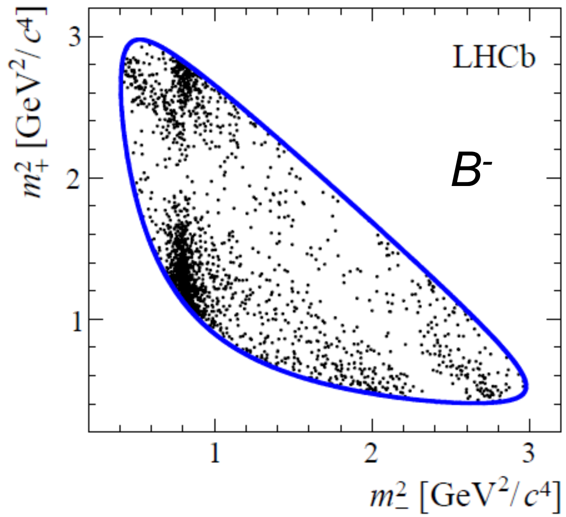
$B \to [K_S hh]_D K$ at LHCb

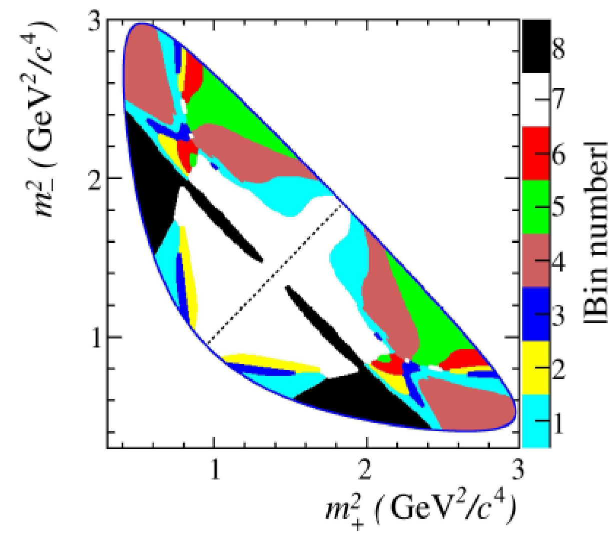


B→DK method has been applied by LHCb to $D \to K_S \pi\pi$ and $K_S KK$. CPV leads to difference in *D* Dalitz plots for B^+ and B^- decays

[JHEP 10 (2014) 097]





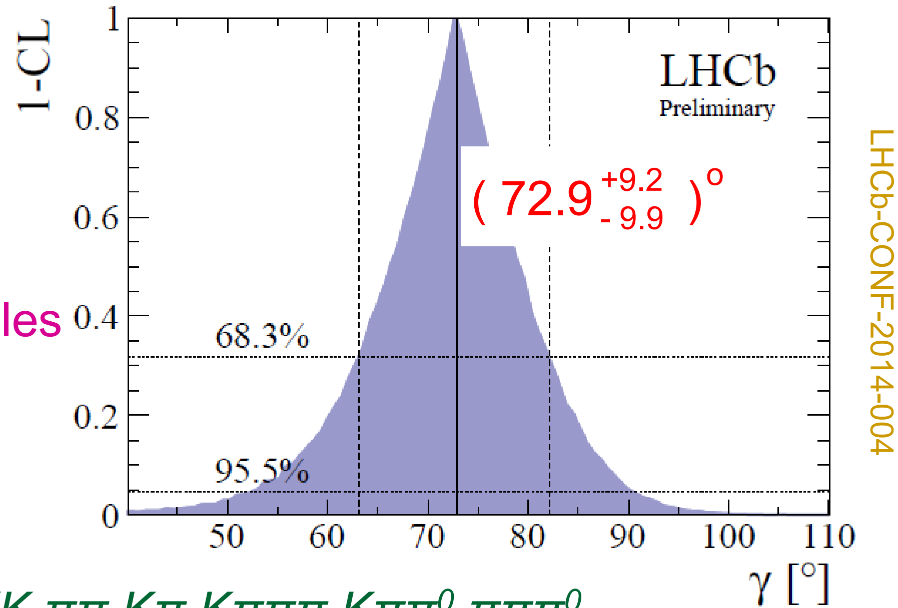


Data analysed in bins which have similar *D* decay strong-phase. To retain model independence these phases are taken from measurements of quantum-correlated *DD*bar pairs at CLEO-c [PRD 82 (2010) 112006] - will be improved by BES-III.

Cleanliness of measurement preserved exploiting synergy of facilities !

LHCb: current precision on γ and future prospects

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



Uncertainty of $<10^{o}$ - 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} $B \to D(KK,\pi\pi,K\pi,K\pi\pi\pi,K\pi\pi^0,\pi\pi\pi^0,KK\pi^0,\pi\pi\pi\pi)K$, $B_s \to D_s K$ still to come)
- Repeat with much larger data set anticipated in Run 2.

Aim to have ready for Spring 2015

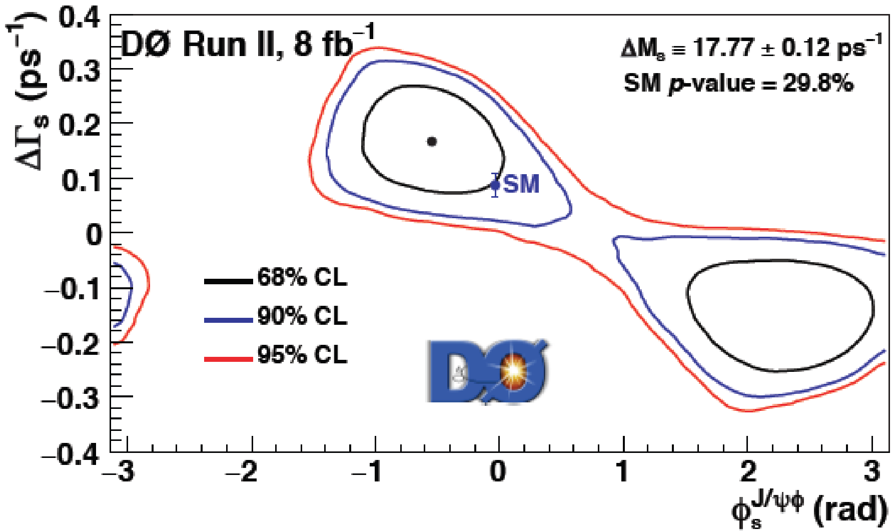
Aim for ~ 3^{o} uncertainty after first stage LHCb (matches current indirect precision)

Mixing induced CPV in B_s system

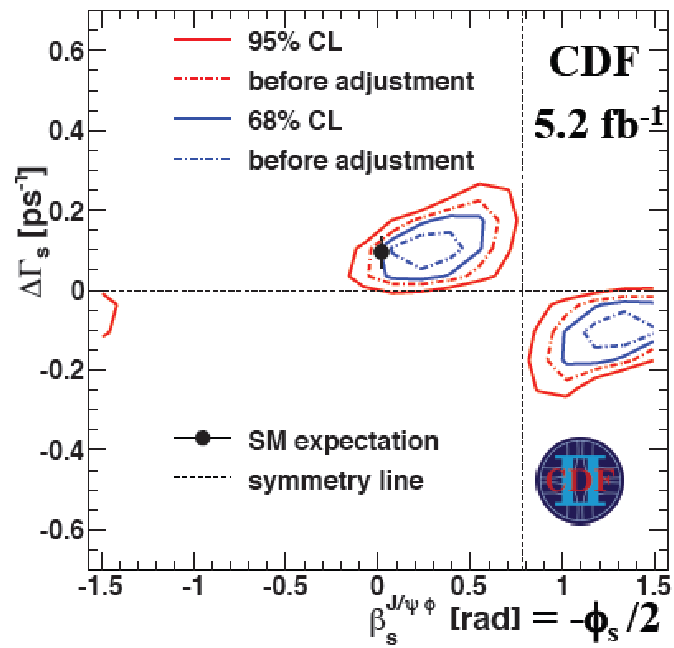
CPV phase, φ_s, in B_s mixing-decay interference, *e.g.* measured in $B_s \rightarrow J/\Psi\Phi$, very small & precisely predicted in SM. Box diagram offers tempting entry point for NP !

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

[PRD 85 (2012) 032006]



[PRD 85 (2012) 072002]



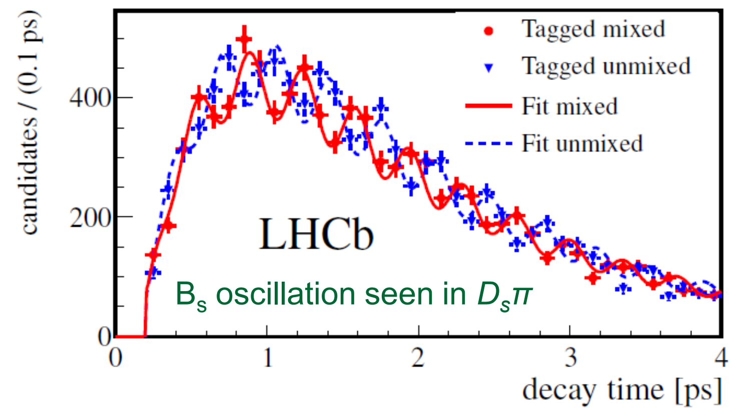
Results are consistent, & both are ~1σ away from SM. What about the LHC?

Precision studies of Φ_s

The LHC (firstly LHCb & now ATLAS/CMS) has brought clarity to the φ_s picture.

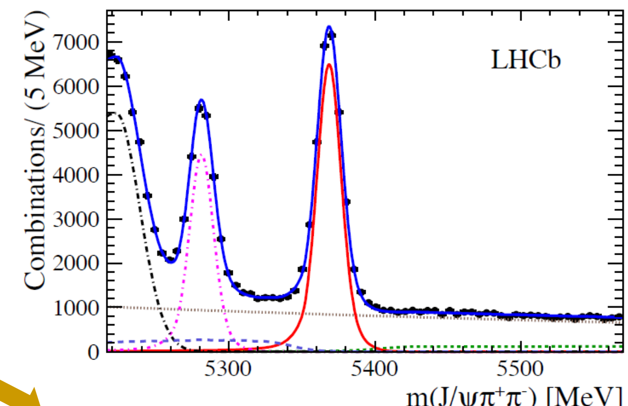
LHCb attributes/contributions:

- Statistics and time resolution!
  $B_s \to J/\Psi\varphi$ analysis with ~20x precision of Tevatron [arXiv:1411.3104]

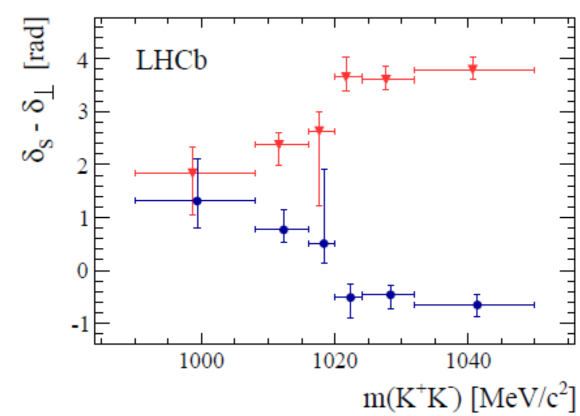


New J. Phys. 15 (2013) 053021

- Augment this with novel analysis in complementary channel $B_s \to J/\Psi\pi\pi$
  [PLB 736 (2014) 186]



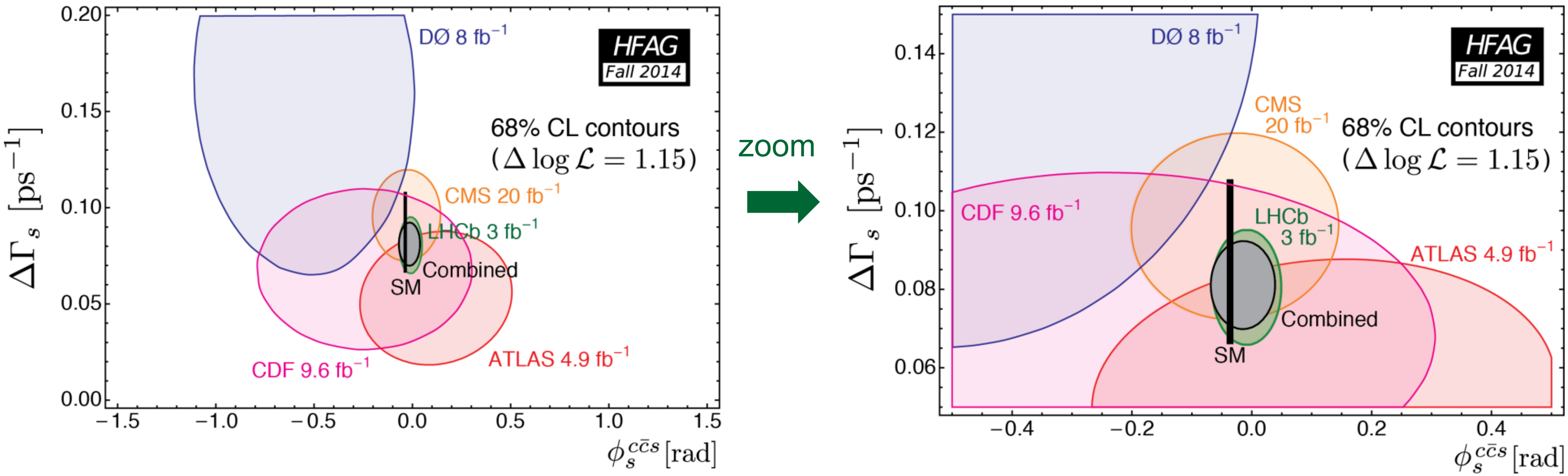
- Finally, perform study looking at strong-phase change w.r.t. *KK* invariant mass in *J/ΨKK* which resolves 2-fold ambiguity [PRL 108 (2012) 241801]



Final LHCb run-1 results [arXiv:1411.3104] now out, together with ATLAS [PRD 90 (2014) 052007] and CMS [CMS-PAS-BPH-13-012] studies - overall picture now clear.

Precision studies of Φ_s

Earlier hints of *large* NP effects emphatically not confirmed...

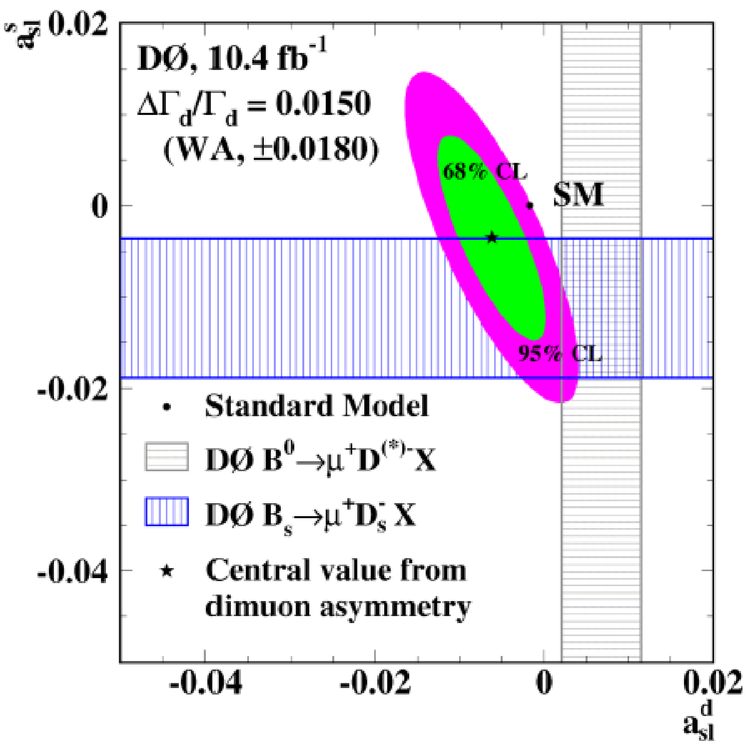


...but observable remains a priori very sensitive to non-SM contributions and essential to improve precision over coming decade.

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}

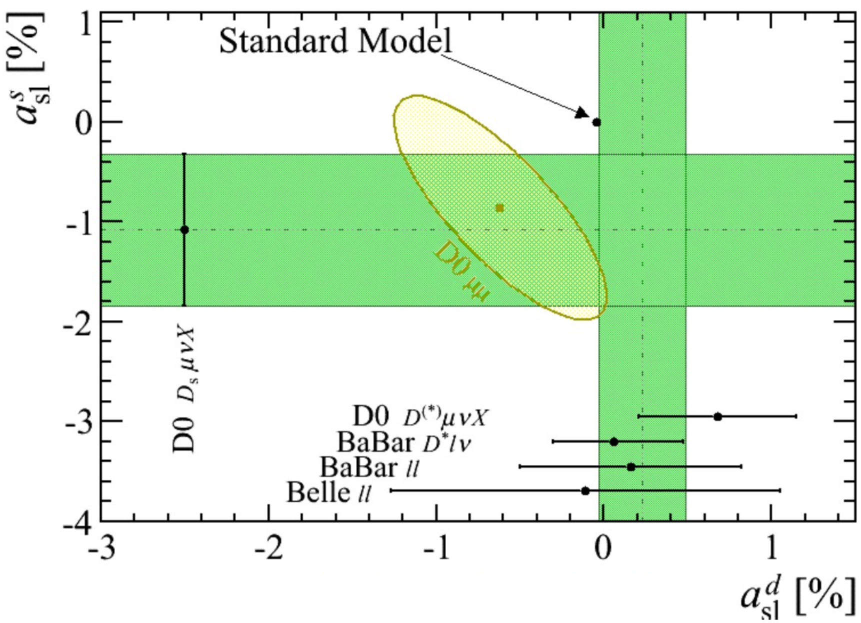
Result lies ~3 σ from SM (exact degree of tension depends on how comparison is made).

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

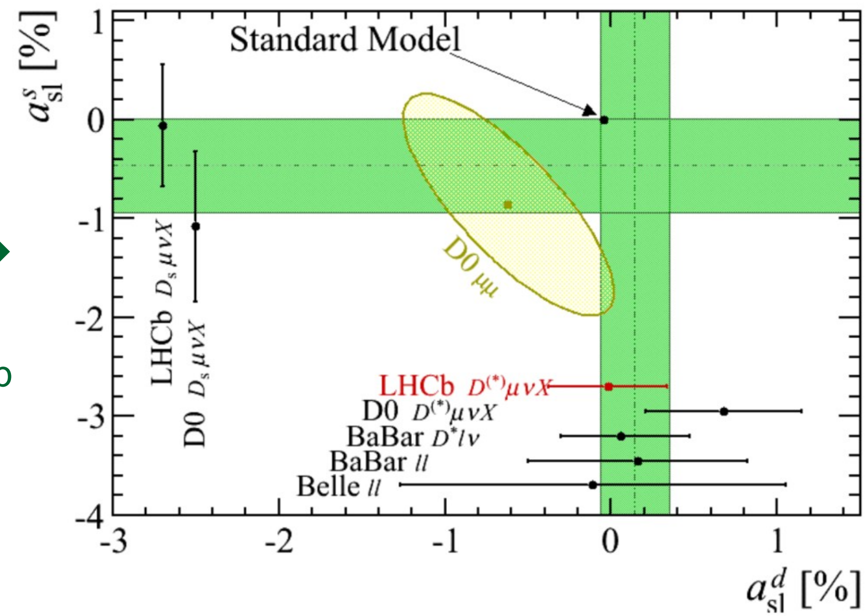
Attempting to resolve the D0 dimuon anomaly

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.



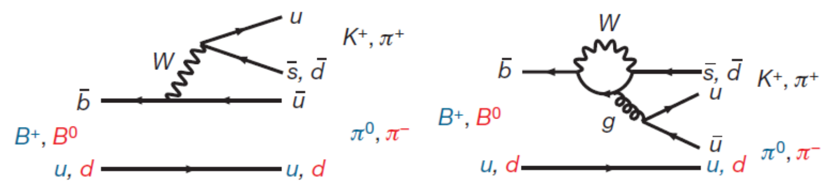
with LHCb input



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



Studies of B decays not involving charm are of great interest, as the CPV is usually generated through interference with a Penguin loop-diagram – what enters the loop?

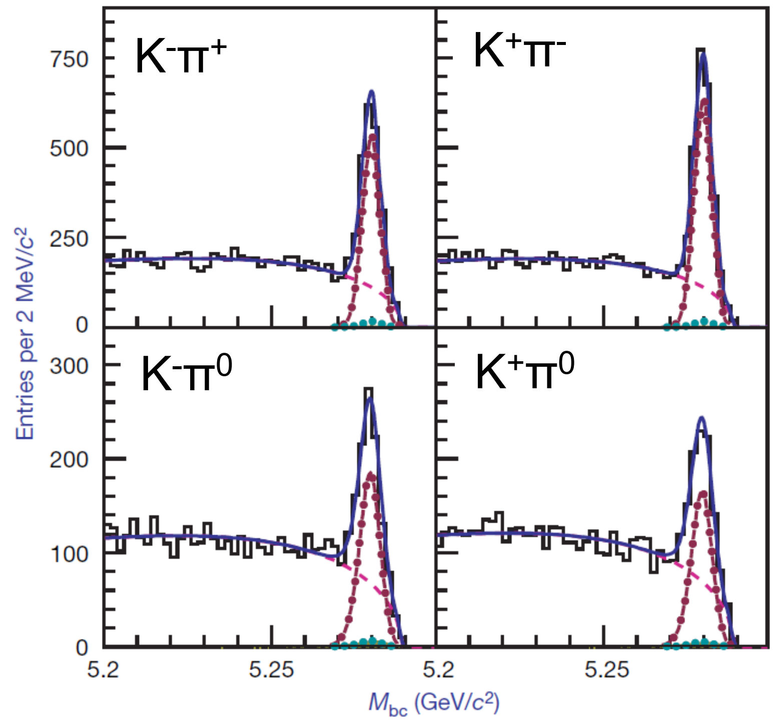
Many studies have been performed, and some have thrown up surprises.

e.g. naively it is expected that the CPV in $B^0 \rightarrow K^+\pi^-$ and $B^- \rightarrow K^-\pi^0$ should be the same, but this is emphatically not so

$$A_{CP}(K^+\pi^-) - A_{CP}(K^+\pi^0) = -0.122 \pm 0.022$$

(5.6σ difference from zero)

[from BaBar, Belle, CDF & LHCb]



Belle, Nature 452 (2008) 332

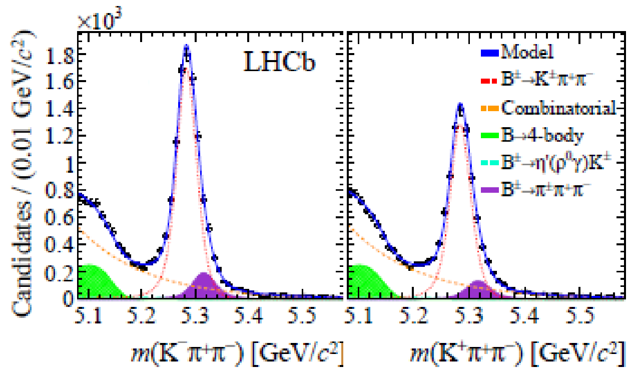
This puzzle has been around for several years, and should be taken seriously. Improved measurements are needed in $B^- \rightarrow K^-\pi^0$ *and* $K^0\pi^-$ *and* $B^0 \rightarrow K^0\pi^0$

Charmless *B* decays

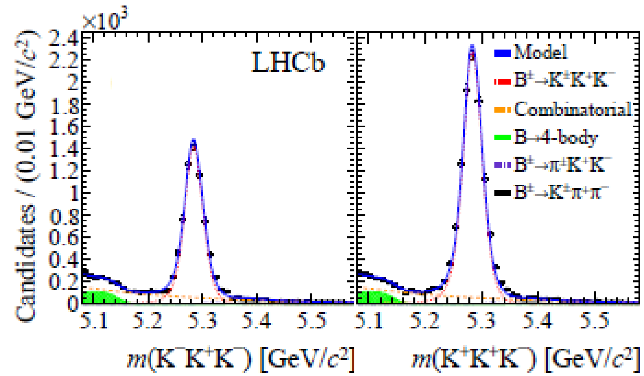
Other surprises are emerging from the large samples now available at the LHC - not all necessarily with New Physics consequences, but still of great interest.

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

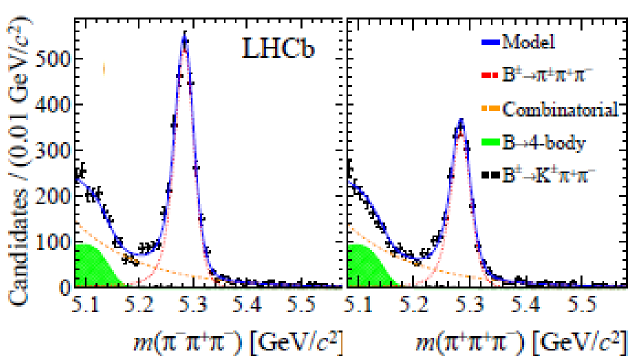
Big asymmetry in $K\pi\pi$…



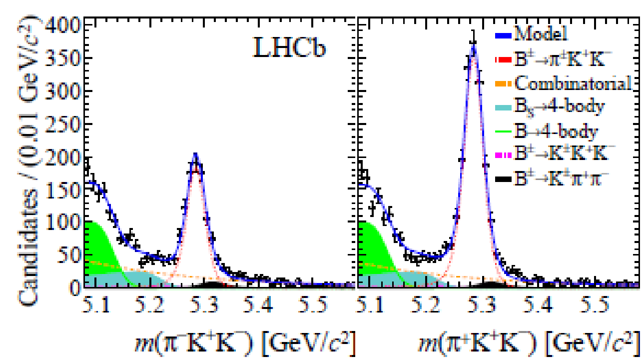
…seemingly mirrored by one of opposite sign in KKK



Same story in $\pi\pi\pi$…



…when compared to πKK



[PRD 90 (2014) 112004]

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

CPV in the charm sector

Setting the scene

Selected topics:

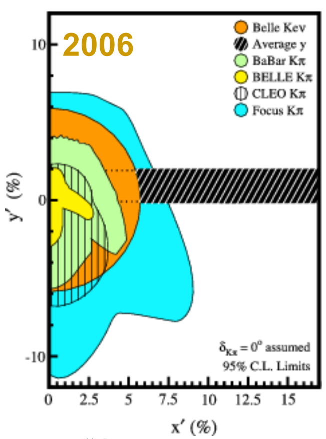
- Direct CPV
- Indirect CPV

The charm renaissance

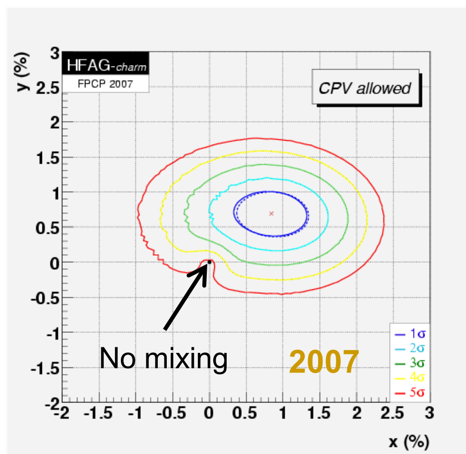
For many years charm was the ‘Cinderella’ of flavour physics studies

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

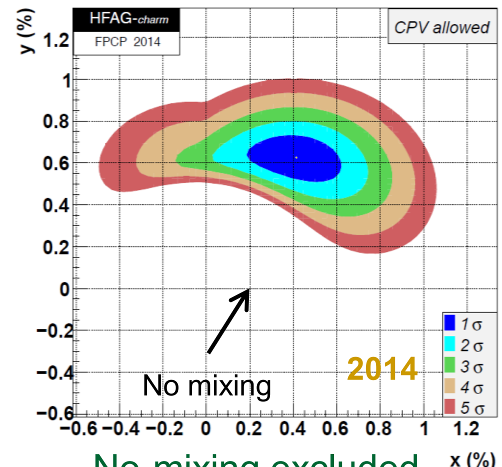
Excluded regions



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



Measurement contours;
no-mixing excluded at 5σ



No-mixing excluded
at lots and lots

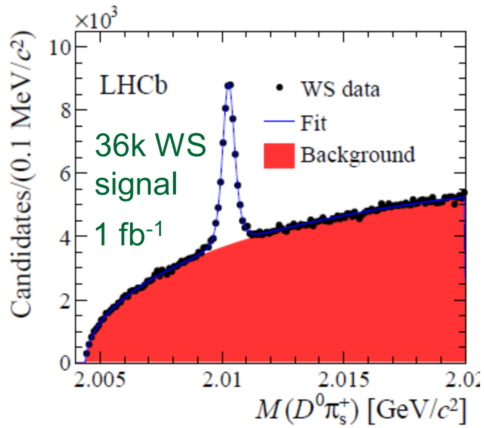
Then combination of B-factory analyses finally saw mixing. New outlook !

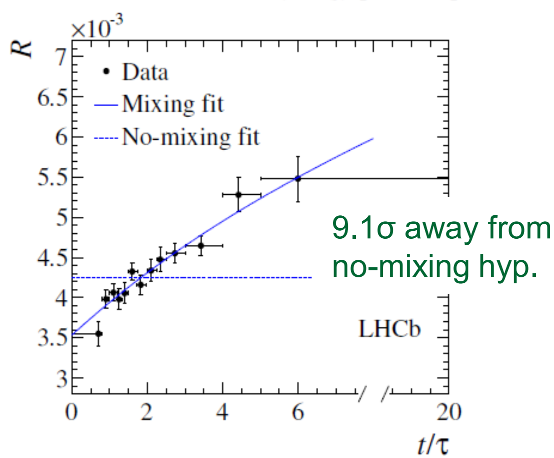
→ mixing parameters not tiny (~1%); good news for (indirect) CPV observables
→ smallness of SM ‘pollution’ not a bad thing in looking for New Physics signal
→ internal down-type quarks in loops – complementary to *b*-physics
→ huge potential of LHC for improving sensitivity

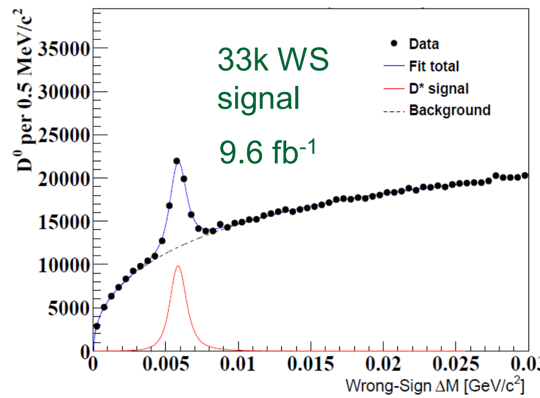
Rise of the hadron machines

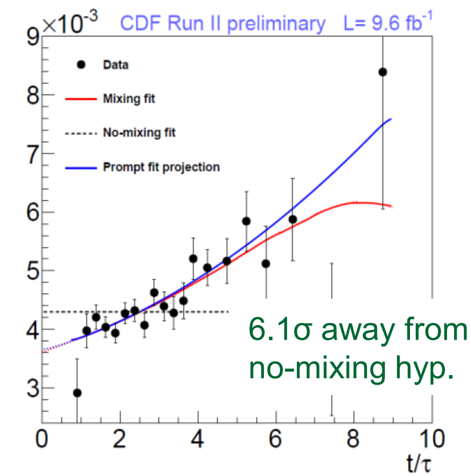
Power of hadron colliders is now clear. Last year LHCb and CDF published first individual (>)>5σ measurements, in WS *Kπ* analyses.

LHCb, PRL 110 (2013) 101802









CDF, PRL 111 (2013) 231802

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

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

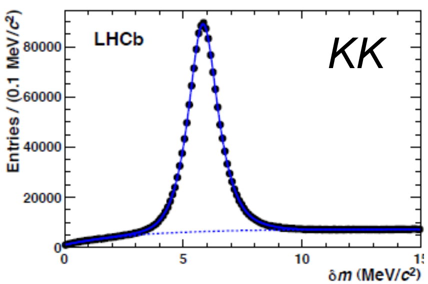
The observable $\Delta A_{CP} \equiv A_{CP}(KK) - A_{CP}(\pi\pi)$ is robust against detector systematics & production asymmetries, and is sensitive to any direct CPV in SCS charm decays

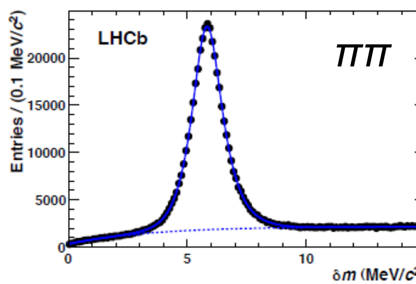
Majority opinion in literature before 2012:

→ 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:

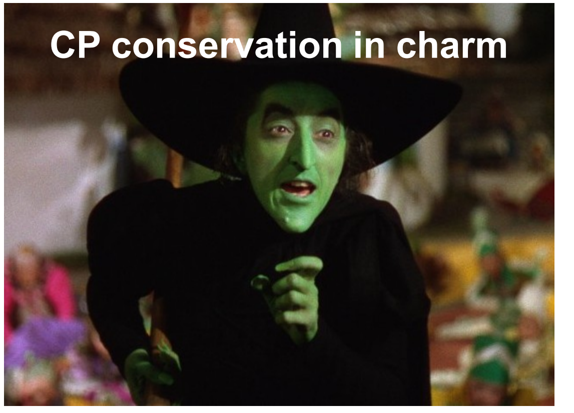
$$\Delta A_{CP} = (-0.62 \pm 0.21\ (\text{stat}) \pm 0.10\ (\text{syst}))\% \quad \text{CDF}$$

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

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}: informing the theory community

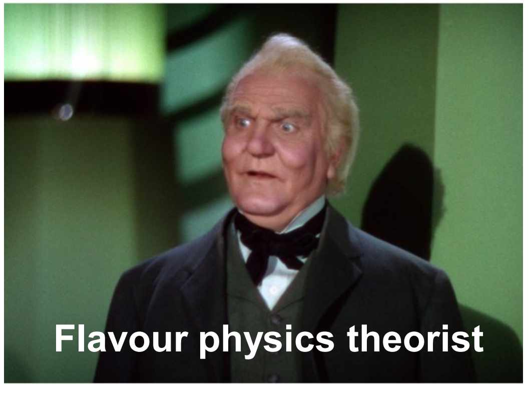


Please, sir. We've done what you told us. We've brought you the broomstick of the Wicked Witch of the West. We melted her.

Oh... You liquidated her, eh? Very resourceful!

Yes, sir. So we'd like you to keep your promise to us, if you please sir.

Not so fast! I'll have to give the matter a little thought. Go away and come back tomorrow.

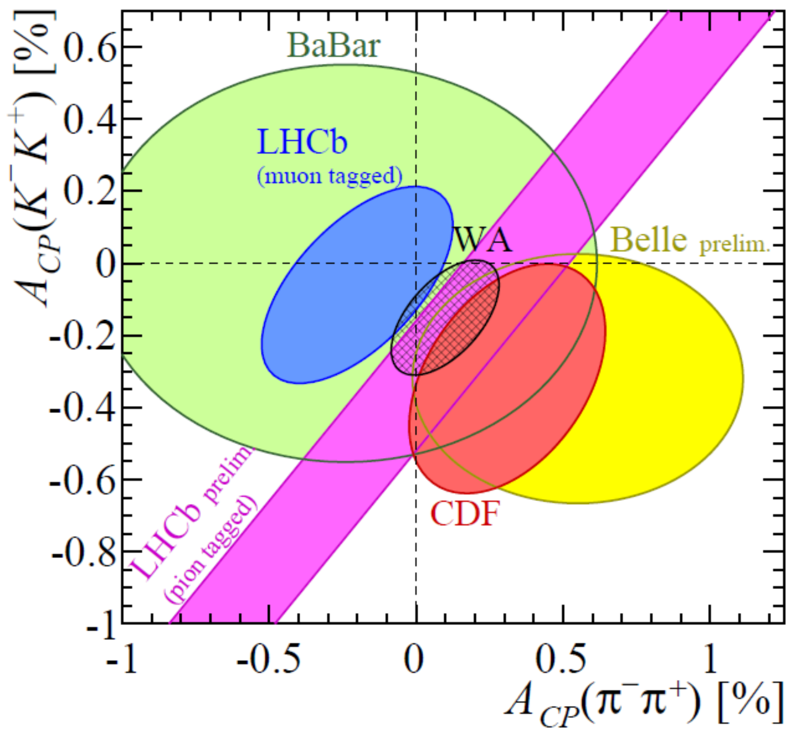


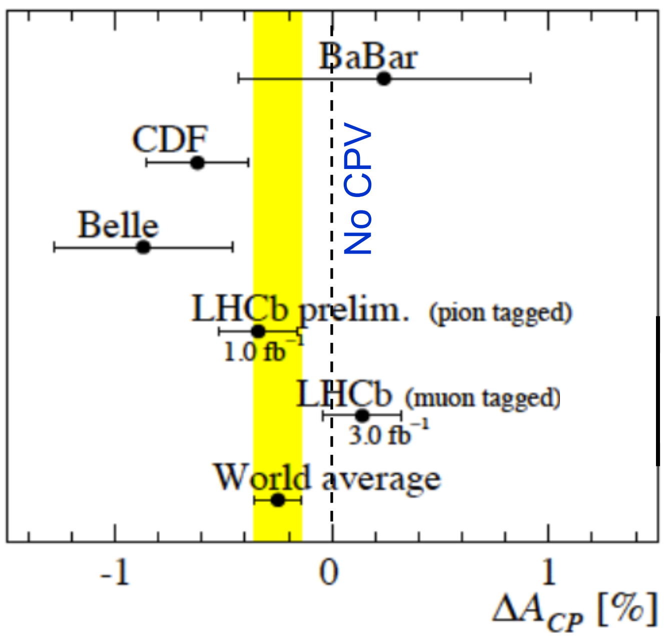
ΔA_{CP}: too early to celebrate

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

Aim to have ready for Spring 2015

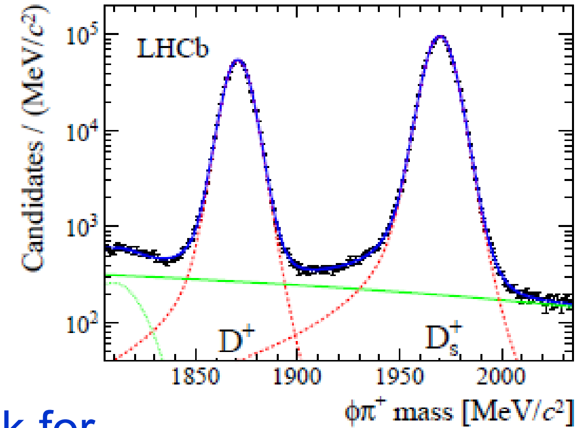
Recent progress in SCS direct CPV searches

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]

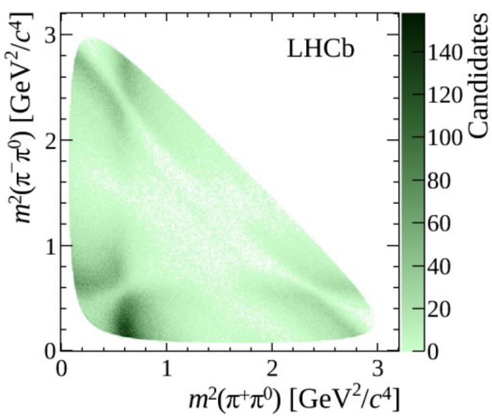
$(+0.51 \pm 0.28 \pm 0.05)\%$ Belle [PRL 108 (2012) 071801]

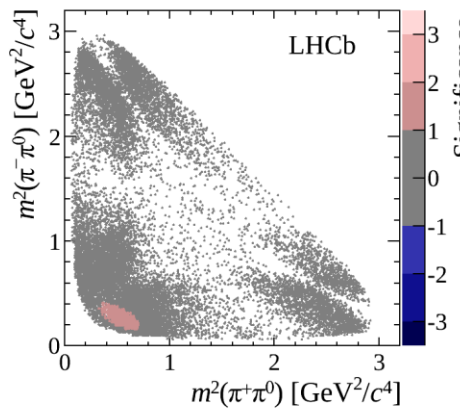
$(-0.3 \pm 0.3 \pm 0.5)\%$ BaBar [PRD 87 (2012) 052010]



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]



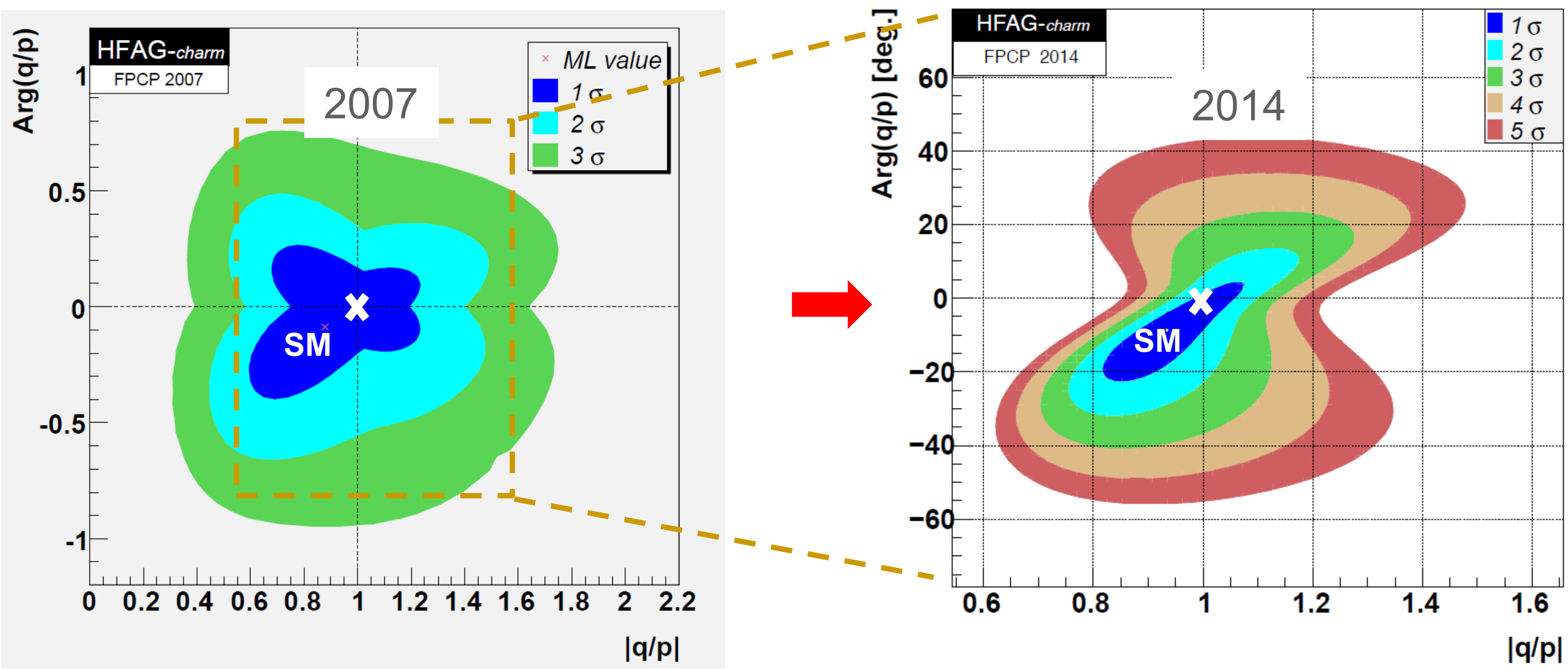


Prospects of direct CPV revealing clear sign of NP appears to be receding.
But still of *great* interest to find a non-0 signal – and LHCb statistics hold promise.

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

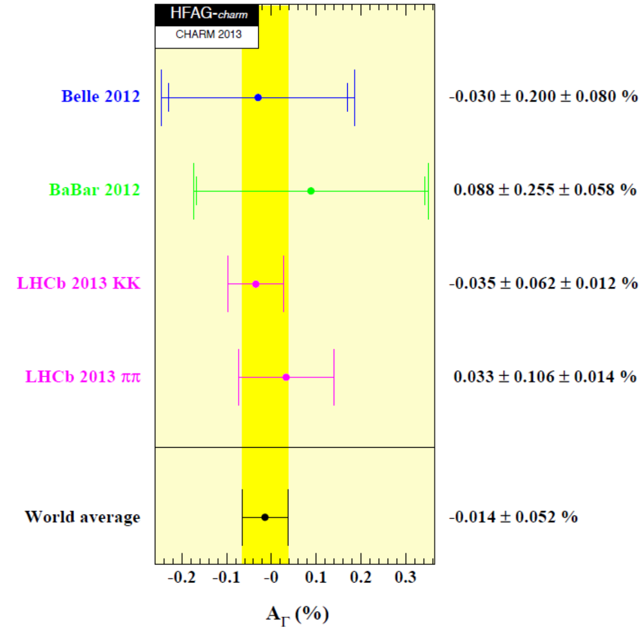
$$A_\Gamma \equiv \frac{\Gamma(D^0 \to KK) - \Gamma(\overline{D}^0 \to KK)}{\Gamma(D^0 \to KK) + \Gamma(\overline{D}^0 \to KK)}$$

(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.

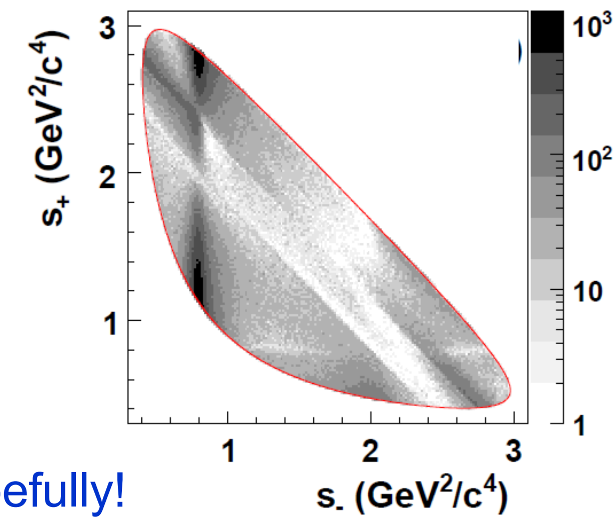


- Generalising WS $K\pi$ fit to D^0 and D^0bar

  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!

Beyond flavour

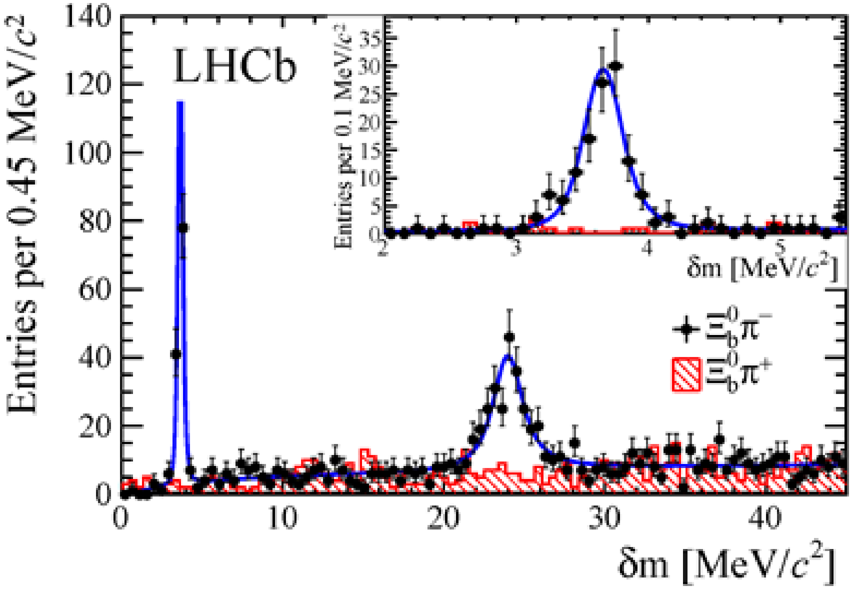
Selected topics in QCD and electroweak

- Spectroscopy
- W and Z production
- Central Exclusive Production

Surprises in spectroscopy

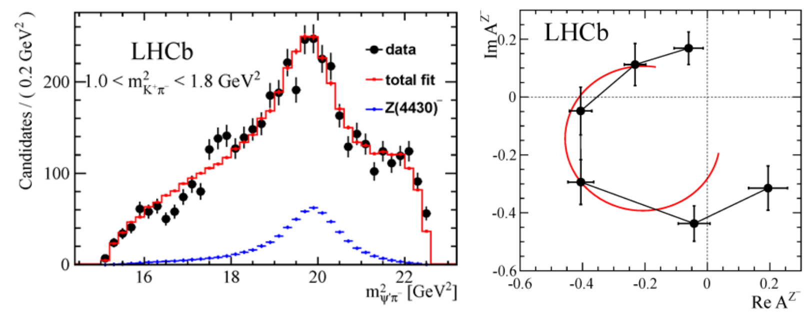
LHCb data continue to tell us more about the family of hadrons and their structure

- Most recently [arXiv:1411.4849] , the discovery of the $\Xi_b^{'-}$ and Ξ_b^{*-}



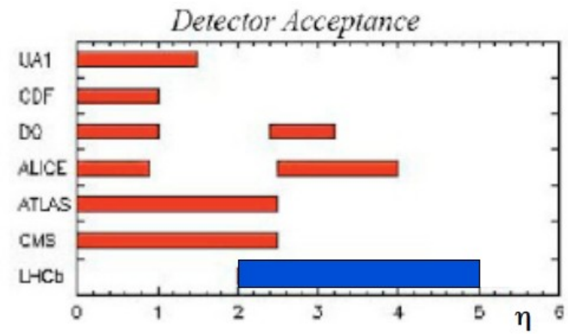
$$m(\Xi_b^{\prime -}) - m(\Xi_b^0) - m(\pi^-) = 3.653 \pm 0.018 \pm 0.006\,\mathrm{MeV}/c^2,$$
$$m(\Xi_b^{*-}) - m(\Xi_b^0) - m(\pi^-) = 23.96 \pm 0.12 \pm 0.06\,\mathrm{MeV}/c^2,$$
$$\Gamma(\Xi_b^{*-}) = 1.65 \pm 0.31 \pm 0.10\,\mathrm{MeV},$$
$$\Gamma(\Xi_b^{\prime -}) < 0.08\,\mathrm{MeV} \text{ at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

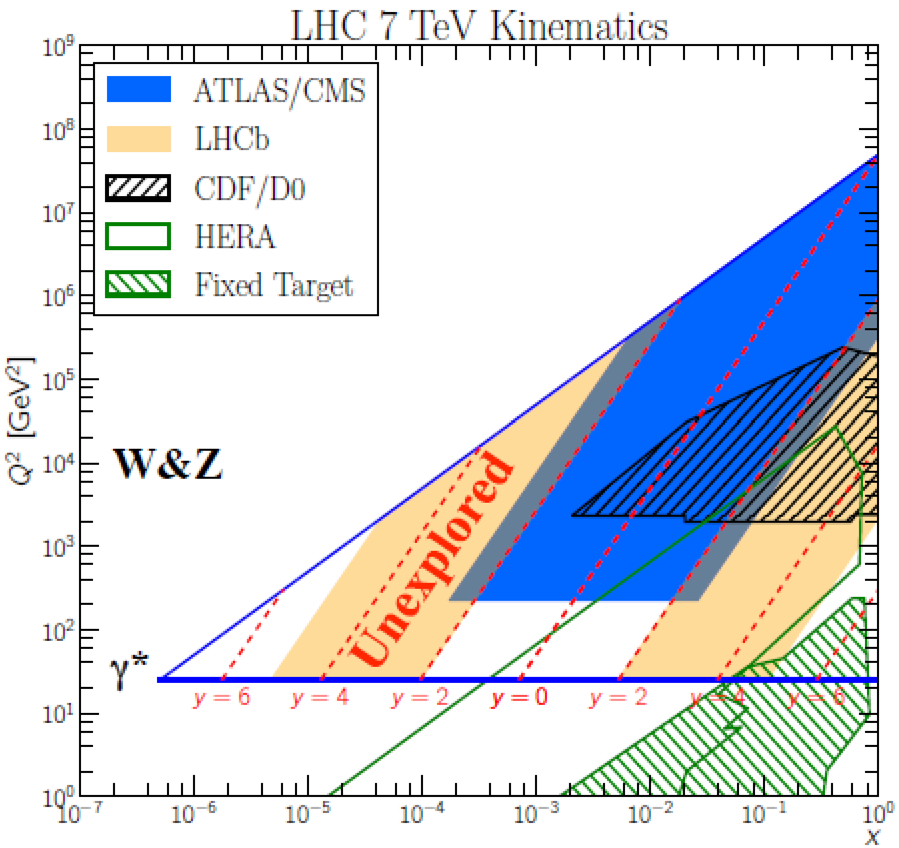
- *Z(4430)*$^-$ observed to be a 4-quark resonant state [PRL 112 (2014) 222002]



- But *f_0(500)* and *f_0(980)* are NOT consistent with tetraquark hypothesis [PRD 90 (2014) 012003]
- First observation of a heavy-flavour spin-3 particle [PRL 113 (2014) 162001; PRD 90 (2014) 072003]
- *X(3872)* NOT pure *DD**bar [NPB 886 (2014) 665]

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.

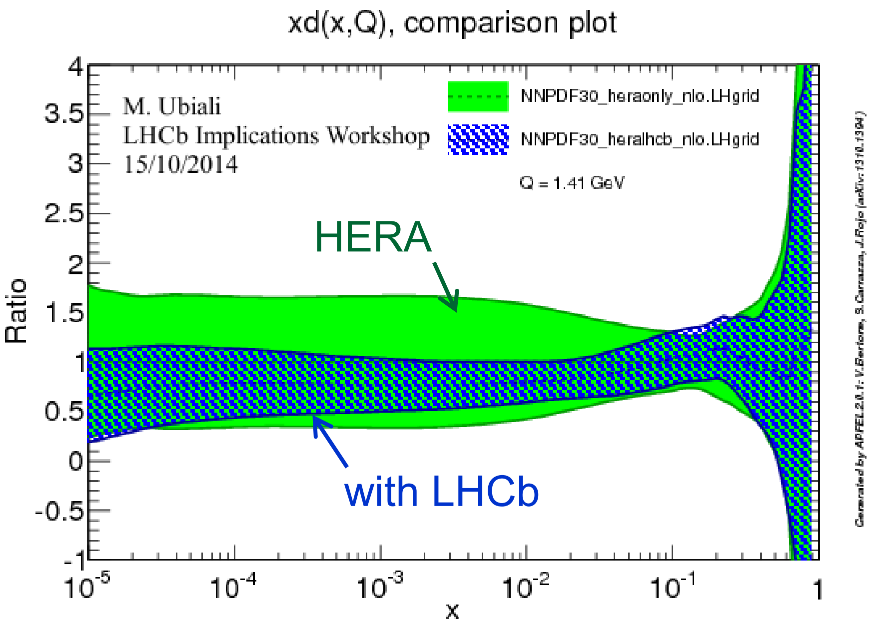
The low-x, high-Q^2 region is of particular interest

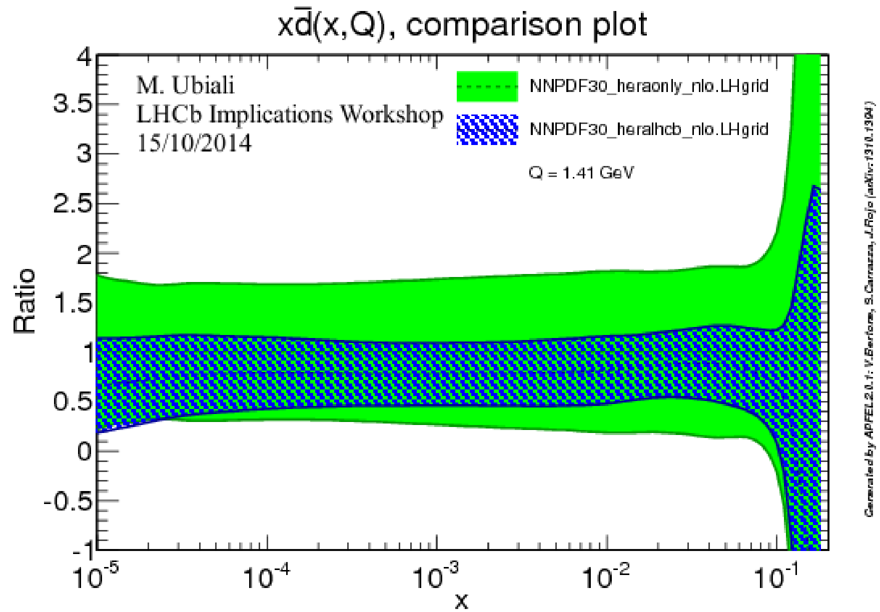
- W & Z: $x \sim 10^{-4}$
- low-mass Drell-Yan: x down to 10^{-6}

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]





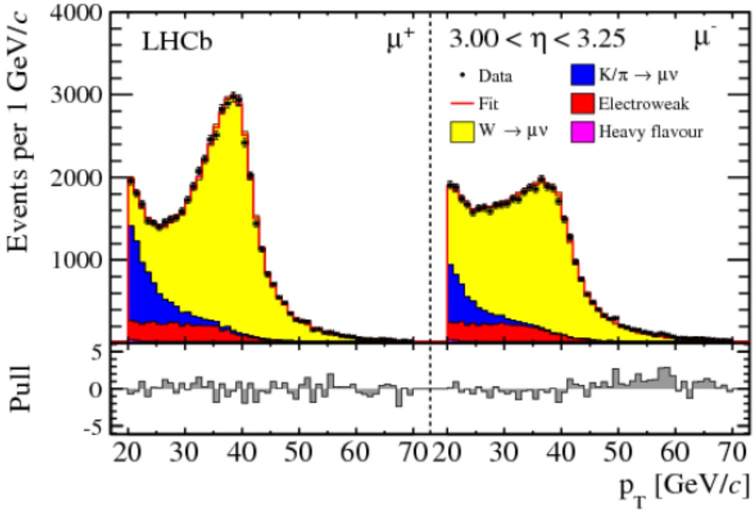
Significant impact! But this is of course not including other LHC measurements…

LHCb W production

[arXiv:1408.4354]

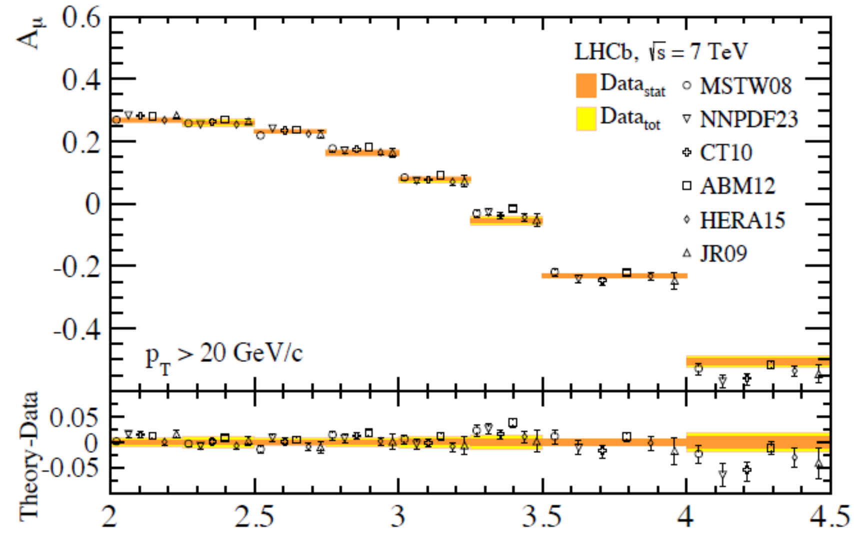
Measurements have been performed of $W \to \mu\nu$ differential cross-section & charge asymmetry for 2011 data with E_{CM}=7 TeV

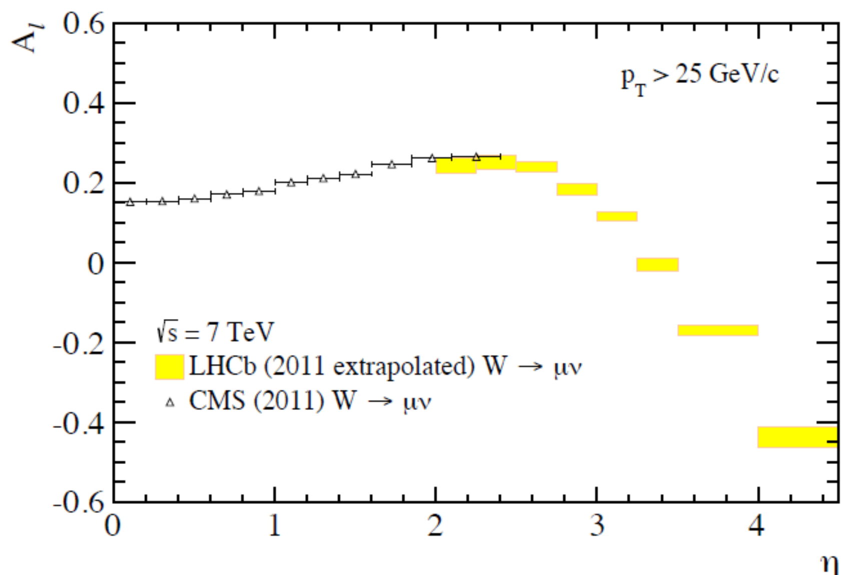
example results in one bin of η



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

Consistency with CMS (ATLAS too)

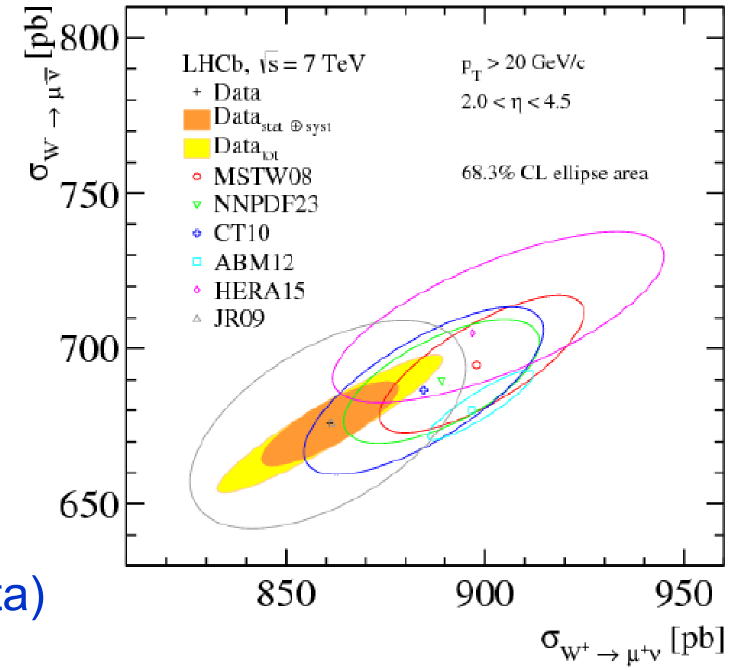


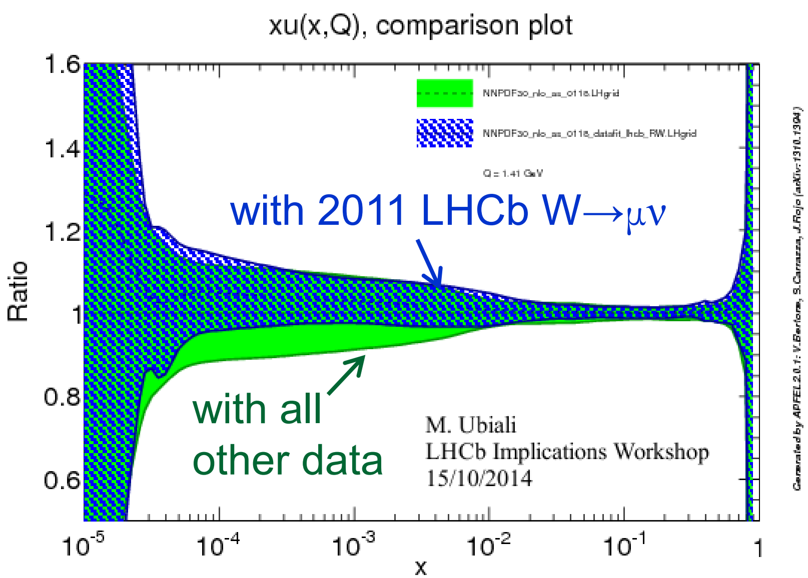


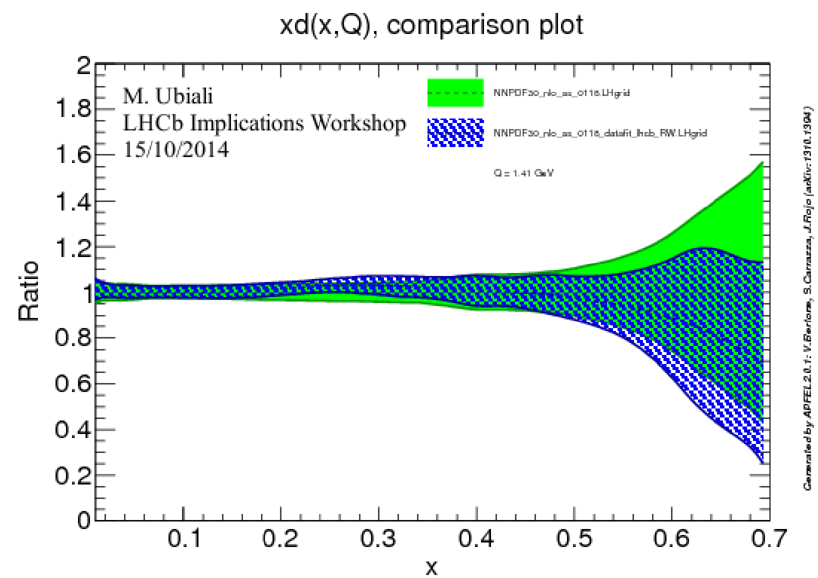
Impact of 2011 W measurement on PDFs

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)

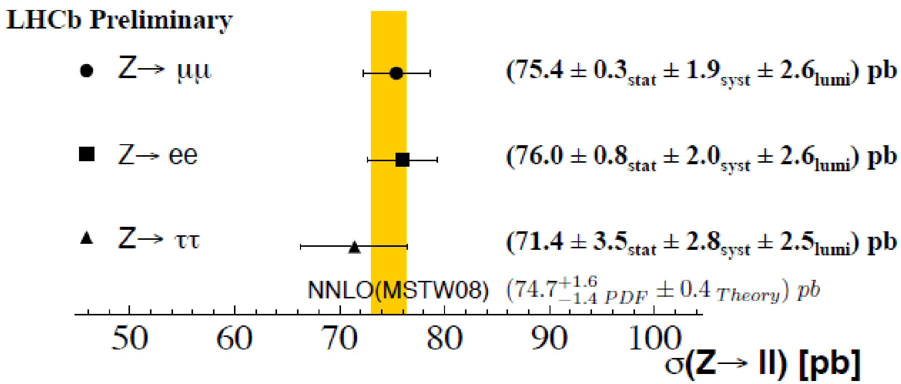


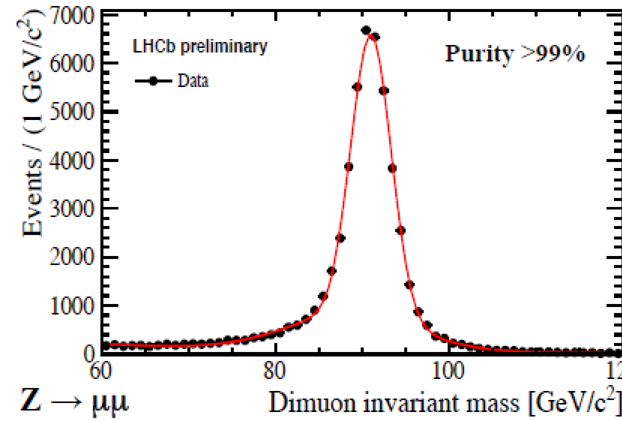




Z production (& luminosity measurement)

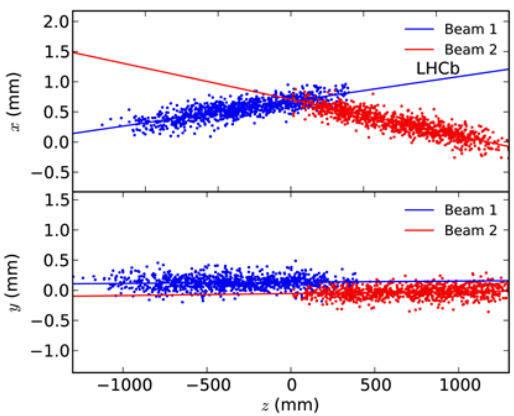
pp→Z+*X* measurements available in all l^+l^- modes





[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)

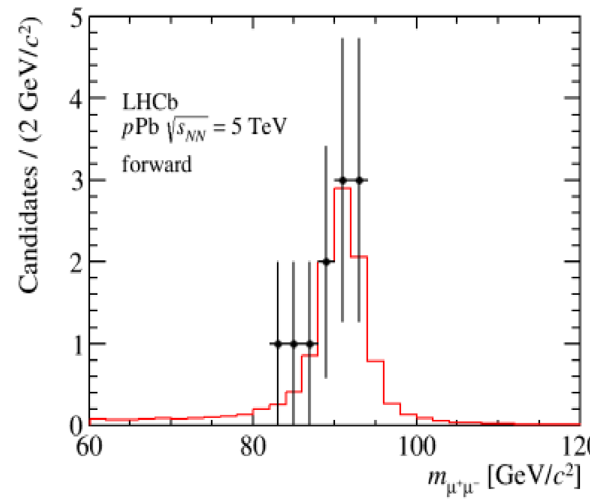


[2014 JINST 9 P12005]

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*

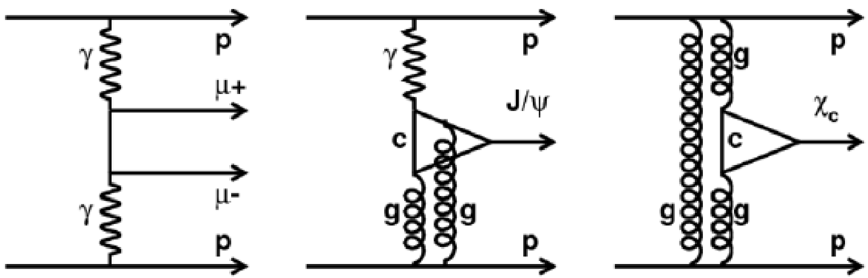


[JHEP 09 (2014) 030]

Central Exclusive Production

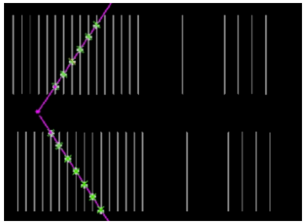
LHCb is an ideal detector for studying $pp \to p\,X\,p$ processes:

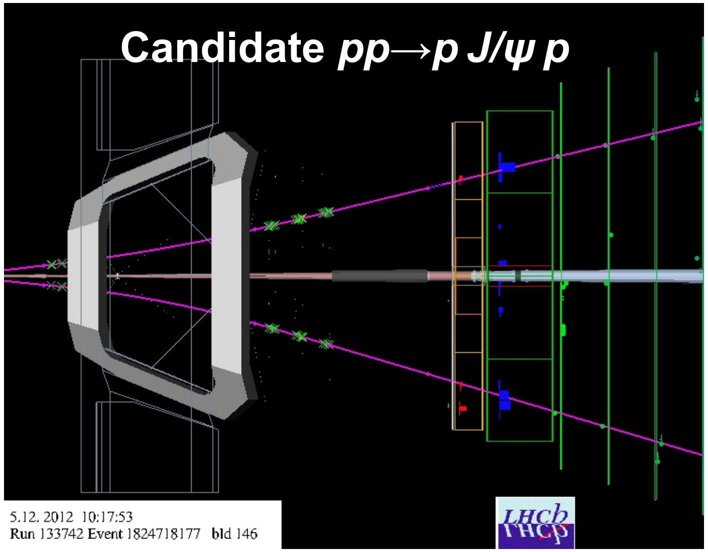
- Luminosity 'just right' (the Goldilocks experiment)
  - high enough to probe pb x-sections
  - not too high: low pileup (especially with 25 ns running of run 2) makes CEP interactions easy to see
- Acceptance down to $p_T \sim 0$
- Particle identification for hadronic final states



QED | Photo production | Double pomeron exchange

VELO zoom

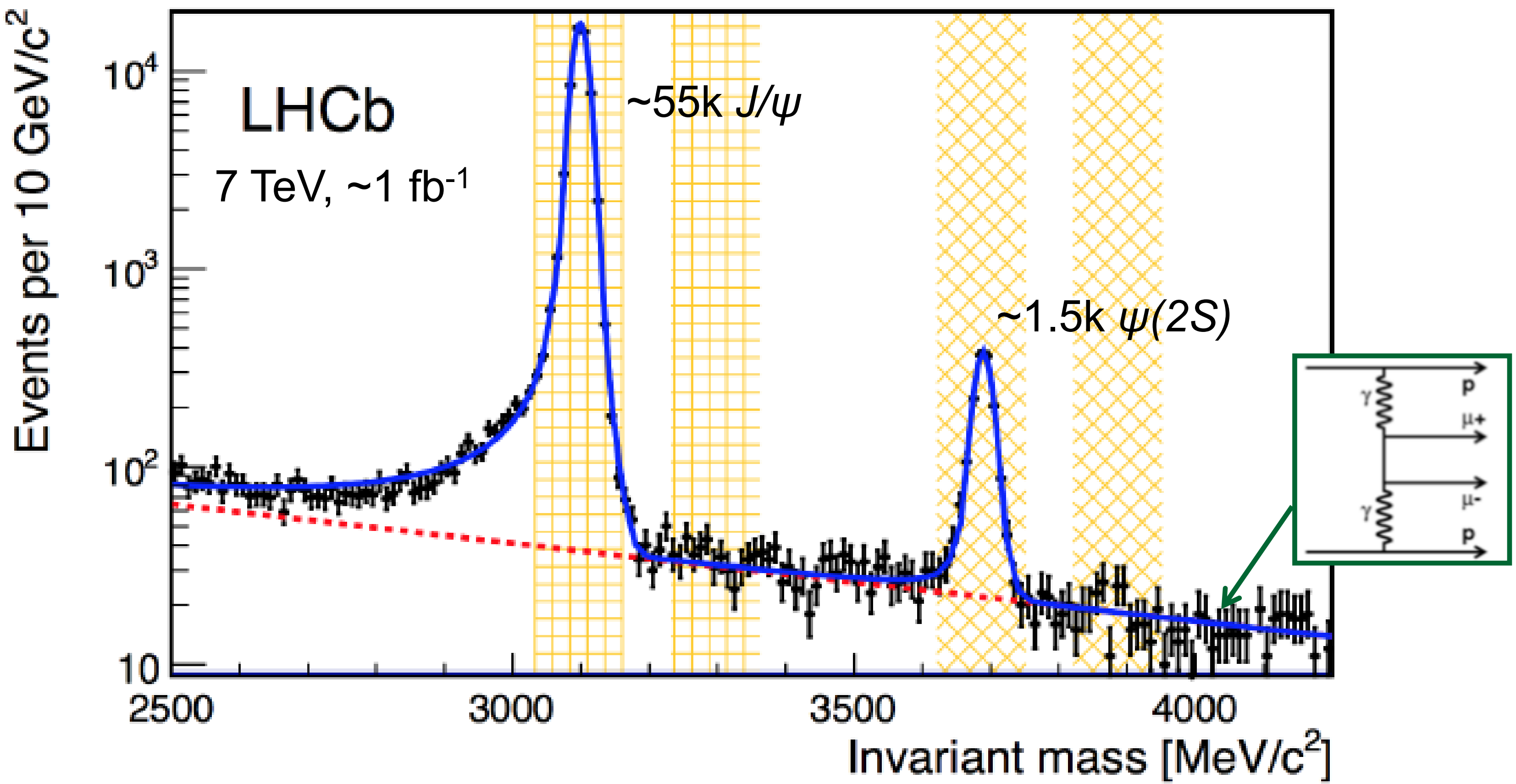




Results aleady available in
7 TeV exclusive J/ψ, $\psi(2S)$ [JPG 41 (2014) 055002]
and full run-1 double J/ψ [JPG 41 (2014) 115002]

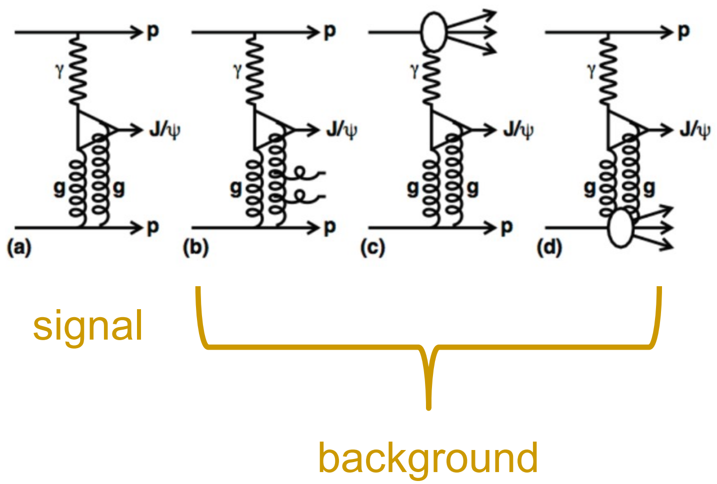
CEP J/ψ, $\psi(2S)\to\mu\mu$

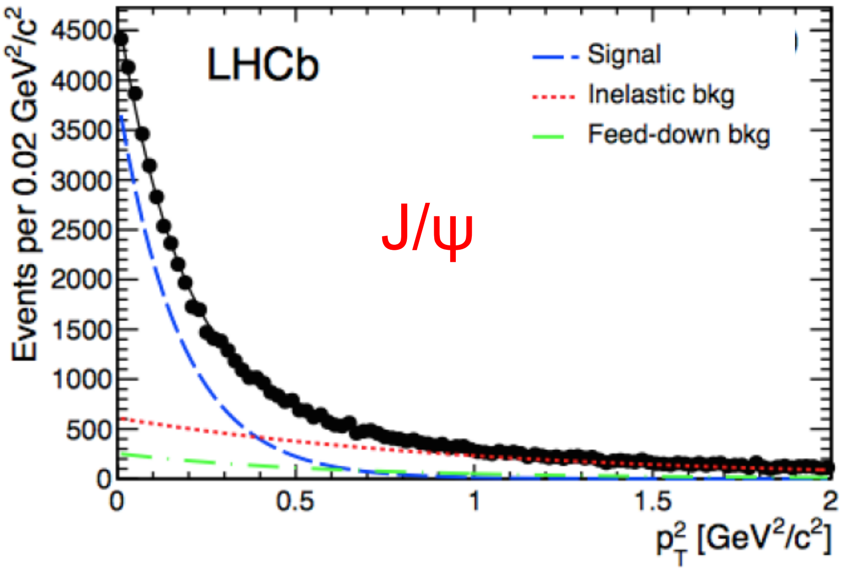
[JPG 41 (2014) 055002]



CEP – dealing with inelastic background

The trickiest part of the analysis is worrying about stuff we don't see.
Proton dissociation or forward gluon radiation may well escape detection.





[JPG 41 (2014) 055002]

Account for this contamination by fitting separate slope parameters in p_T^2 for inelastic & signal components - results compatible with HERA expectations.

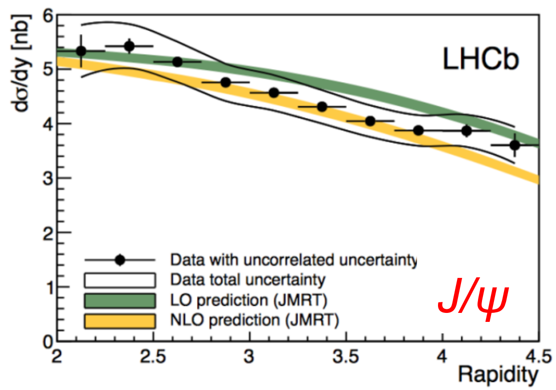
(Ideally though, we would like to suppress this background with improved forward coverage … see later discussion on HeRSCheL system)

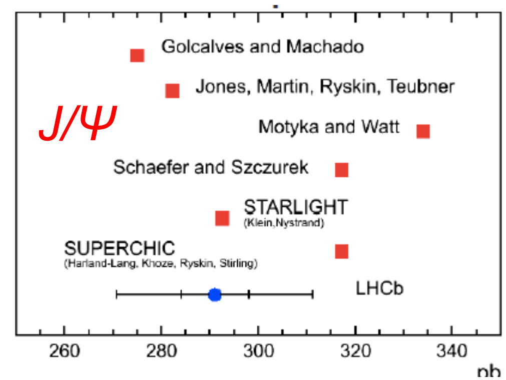
CEP J/ψ, $\psi(2S) \rightarrow \mu\mu$

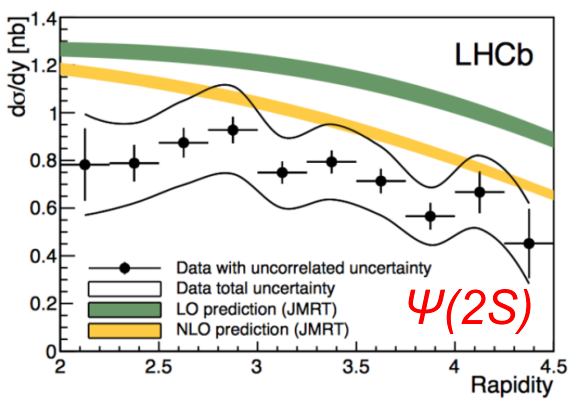
[JPG 41 (2014) 055002]

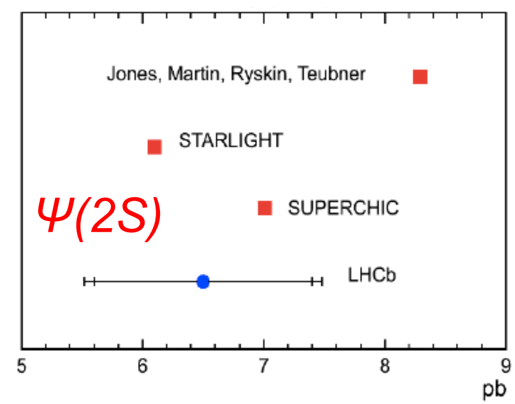
Results show satisfactory agreement for differential and integrated x-sections.

[JMRT = Jones, Martin, Ryskin and Teubner, JHEP 1311 (2013) 085]





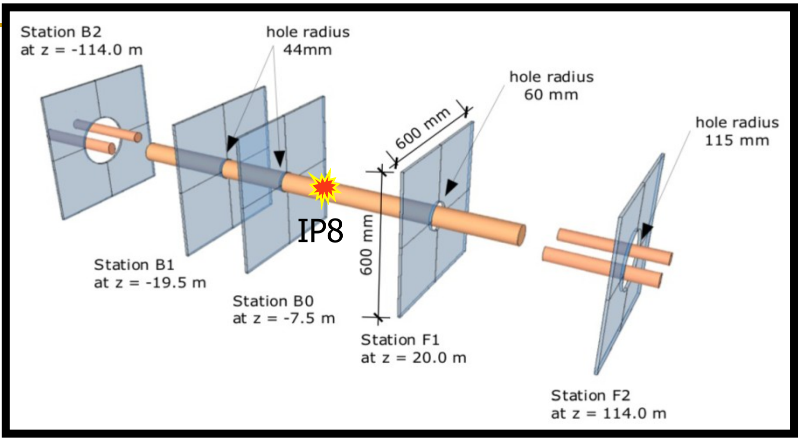




These and new results from 13 TeV running will be valuable in probing gluon PDF down to x~10^{-6}. Many new results to come, some soon. (Υ, DDbar production, pseudoscalar final states, search for exotics…)

Aim to have something new for Spring 2015

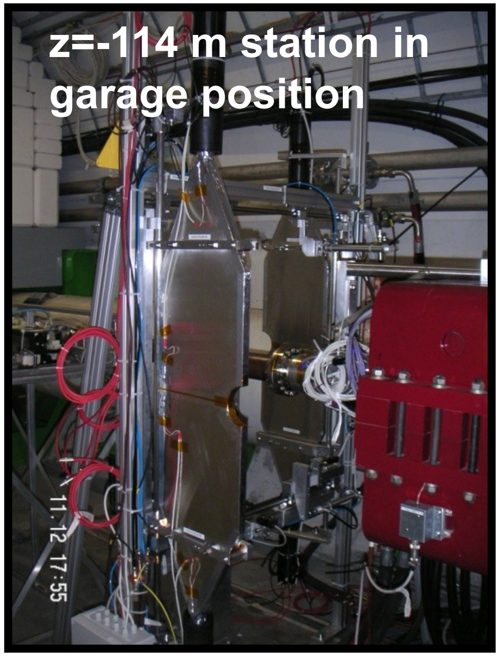
High Rapidity Shower Counters for LHCb – HeRSCheL [new for run 2]



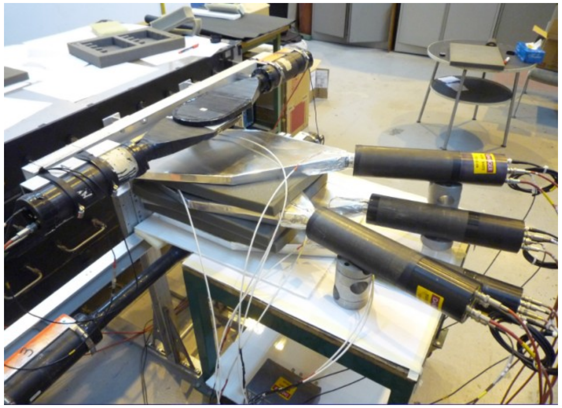
System of forward-shower scintillator planes installed in tunnel up to 114 m away from IP to help in definition of forward rapidity gaps. Main physics motivation is Central Exclusive Production.

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

All stations now installed



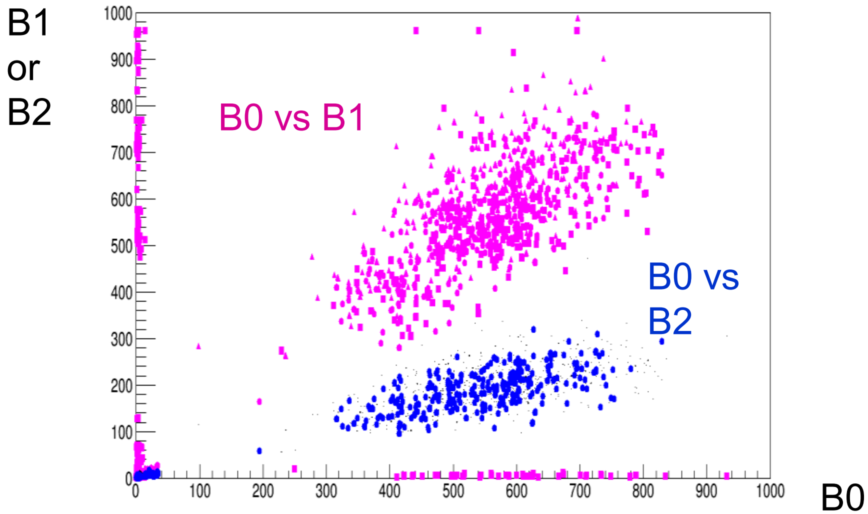
HeRSCheL - early results



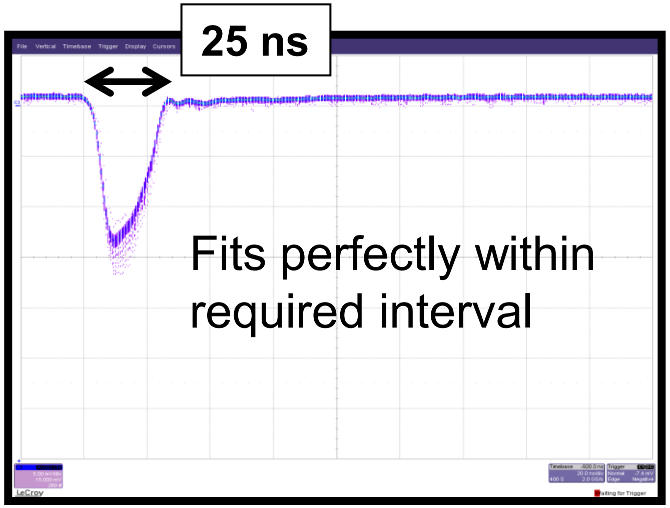
Cosmic calibration campaign shows ~170 p.e.s / MIP

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

Correlation between stations



Beam pulse from furthest station



Preparing for run 2

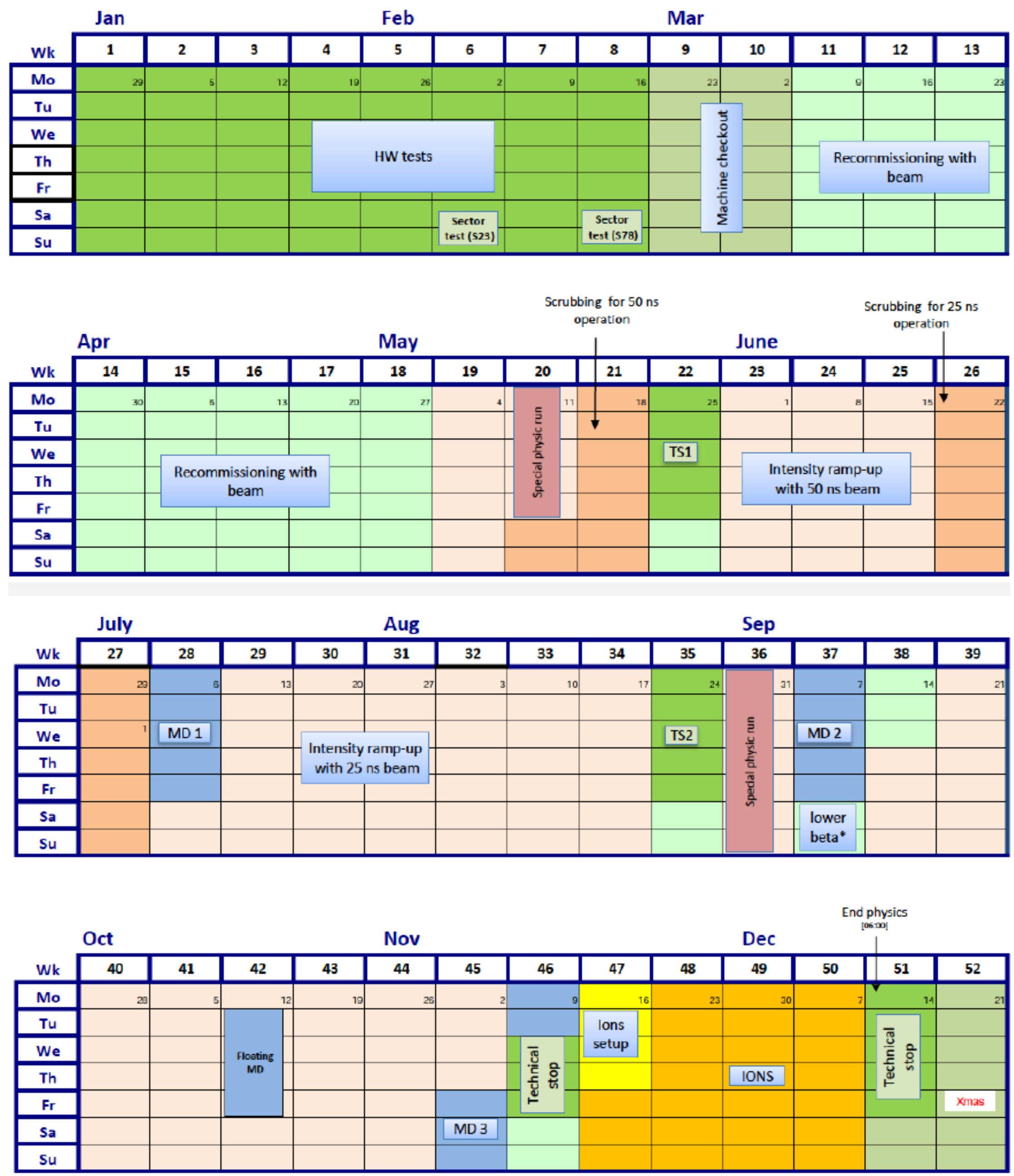
The plan for 2015 & beyond

All currently on track for an on-schedule start

(first sector, 6-7, commissioned to 6.5 TeV last week)

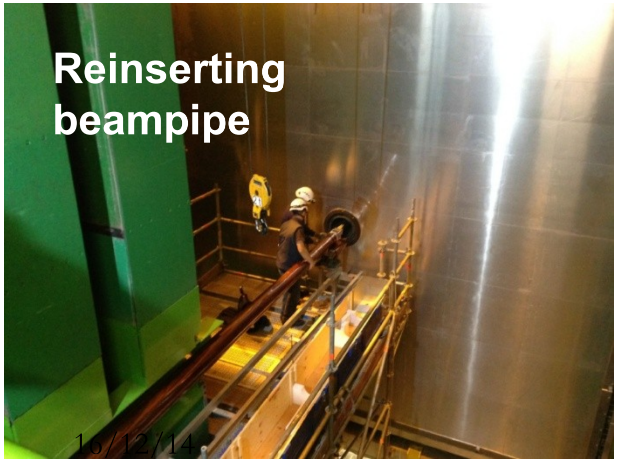
Around 0.5-1.0 fb^{-1} of data expected in 2015, and ~5 fb^{-1} in run 2 as a whole.

This, and higher x-section, will allow for an approximate doubling in precision w.r.t. run-1 results.



LS1 activities – preparing for run 2

A very busy time – all work completed successfully and on schedule. Detector now closed. Only minor tasks remain.



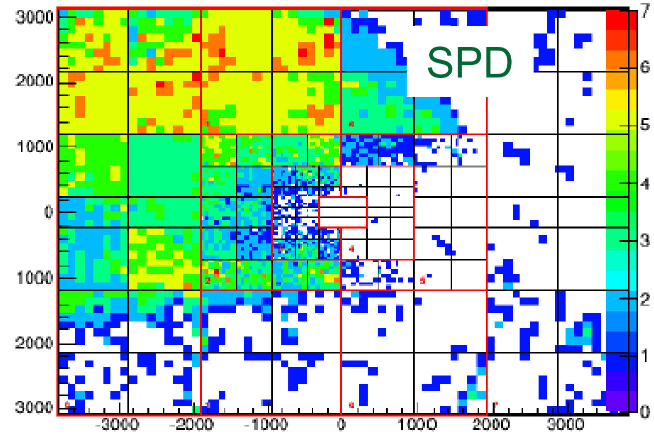
Transfer line test ('TED')

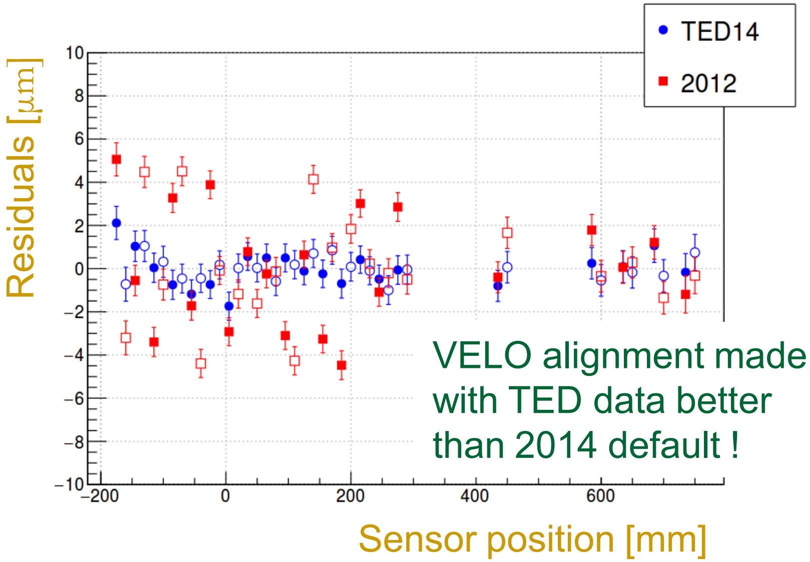
'TED' = stopper at end of transfer line. LHCb profits from resulting muons.

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

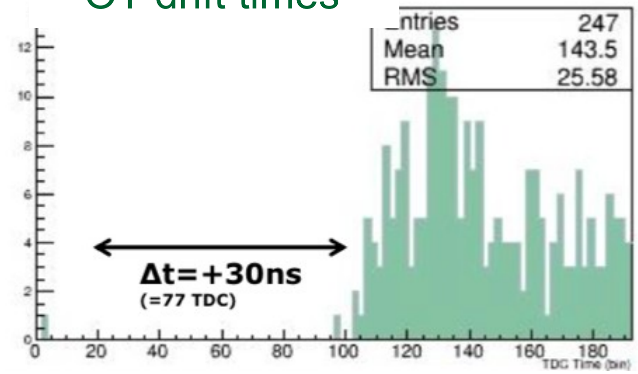
All sub-detectors collected useful data





VELO alignment made with TED data better than 2014 default !

OT drift times



Run-2 operation

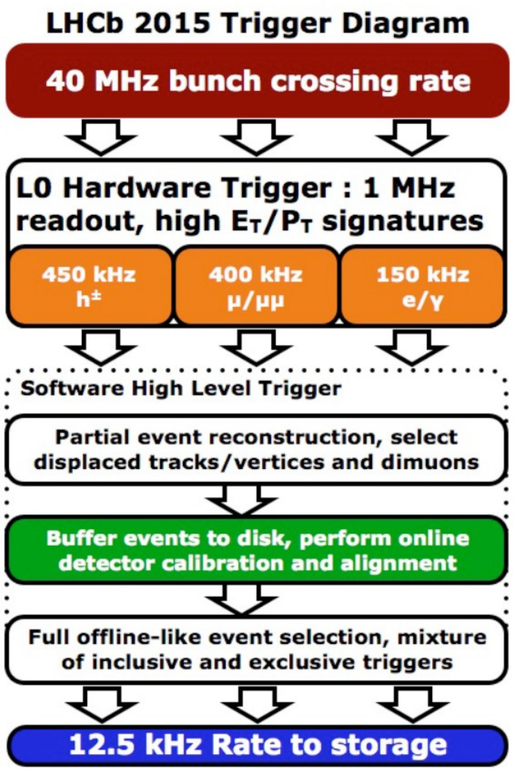
Several ambitious changes planned for operation during run 2 aimed at increasing physics output and making optimal use of resources

Trigger

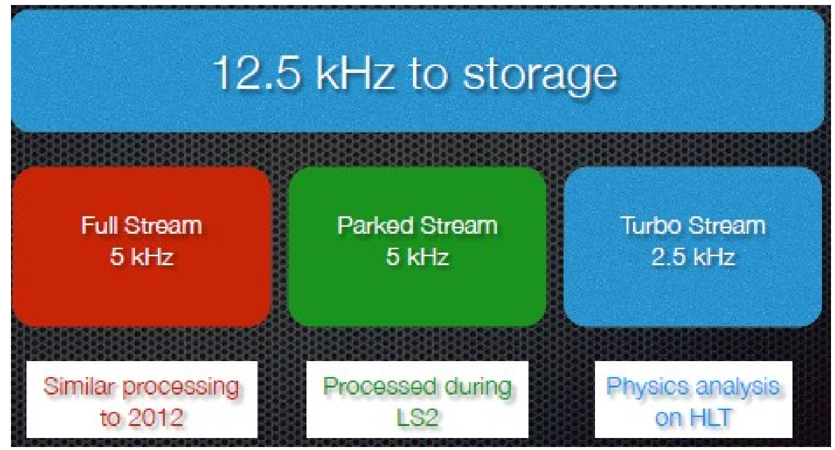
HLT1

New!

HLT2



Output streams



Turbo-stream will need no offline processing. If this works well then it has important implications for Upgrade.

This splitting of HLT into two steps enables more info to be used in HLT2 (*e.g.* RICH) → improved signal-to-background separation (and helps test ideas we wish to use in Upgrade trigger)

The further future

Dreaming about ultra-high statistics

Big improvements foreseen before 2018-19 long shutdown (*e.g.* ~8 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^o.

- 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!

Unwise to assume ~10% (or even 0.1%) is 'good enough'

Courtesy Browder and Soni

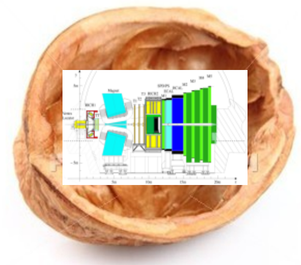
Many of the arguments for increasing the statistical precision are motivated by clear numerical facts, *e.g.* matching theoretical precision or opening up new decay modes. But history tells us that whatever the argument, improved precision is always welcome. We should exploit existing facilities to the utmost.

"A special search at Dubna was carried out by E. Okonov and his group. They did not find a single $K_L \rightarrow \pi^+ \pi^-$ event among 600 decays into charged particles [12] (Anikira et al., JETP 1962). At that stage the search was terminated by the administration of the Lab. The group was unlucky."

-Lev Okun, "The Vacuum as Seen from Moscow"

BR ($K^0_L \rightarrow \pi\pi$) ~ 2 x 10^{-3} Cronin, Fitch *et al.* , 1964

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}

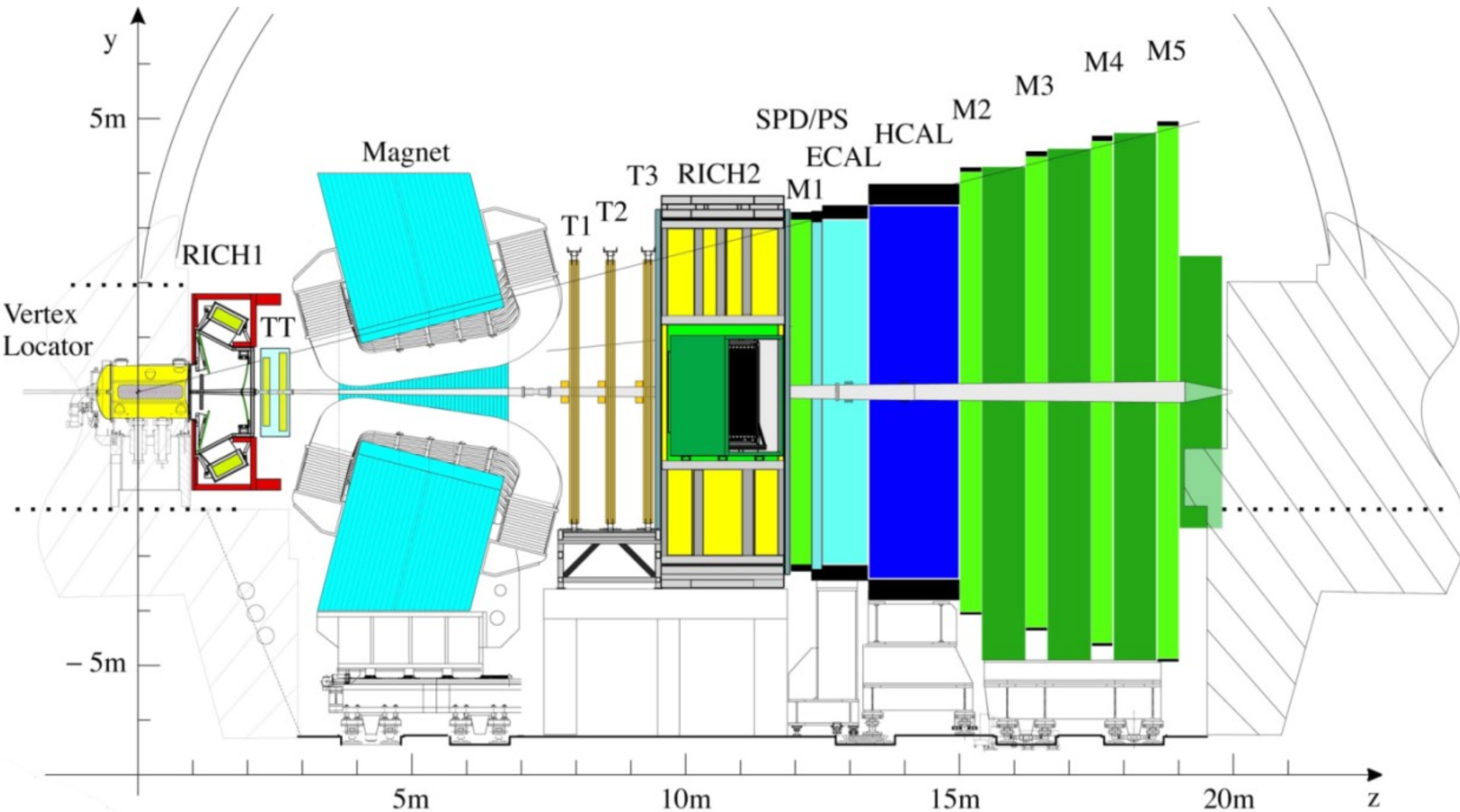
Necessitates redesign of several sub-detectors & overhaul of readout

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

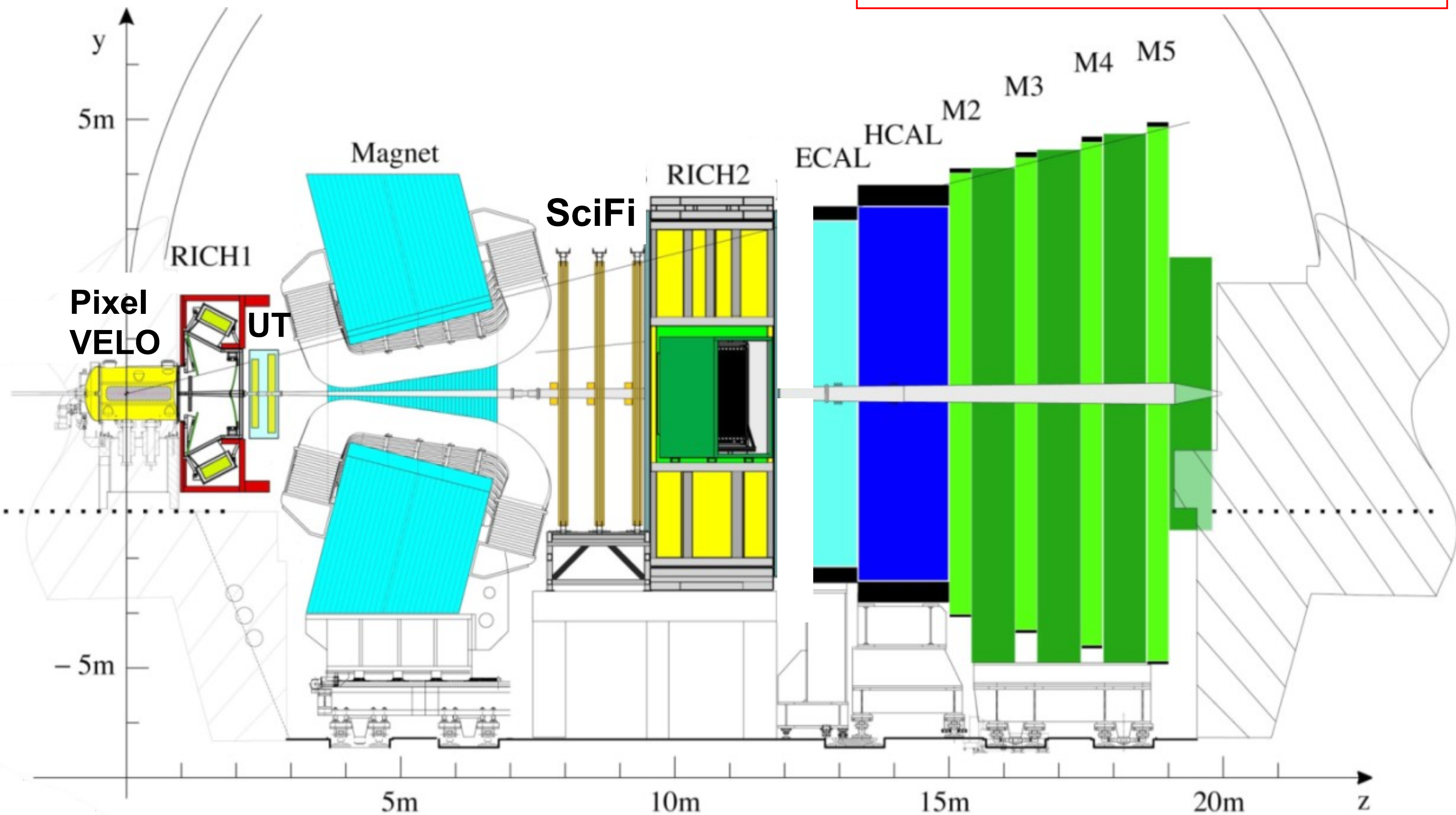
Current detector



Upgrade overview

Current detector → upgraded detector

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



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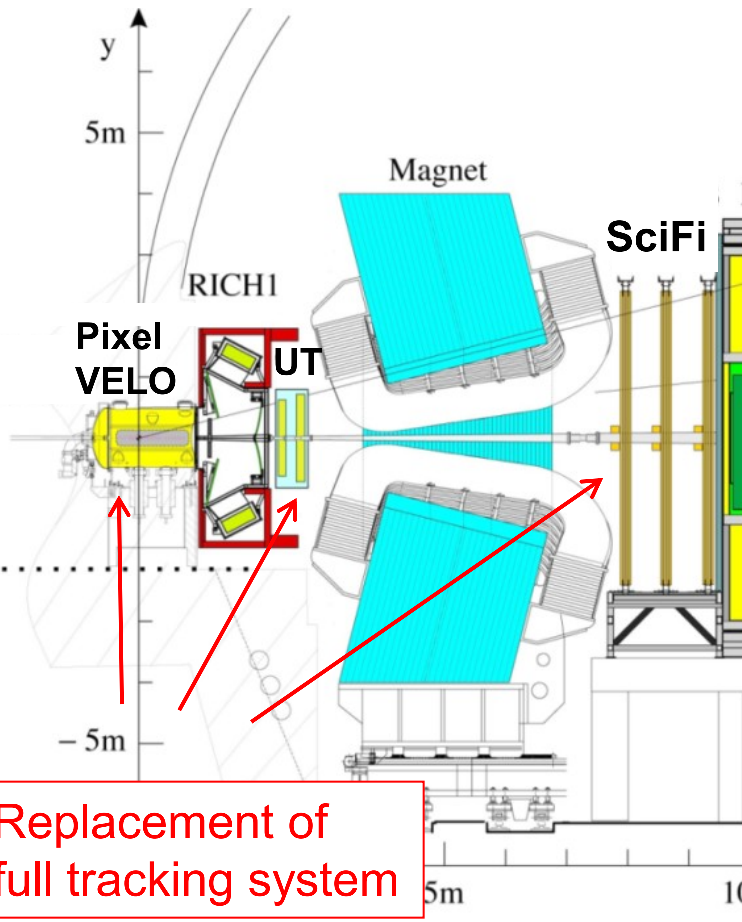
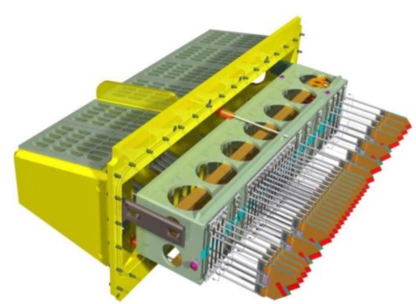


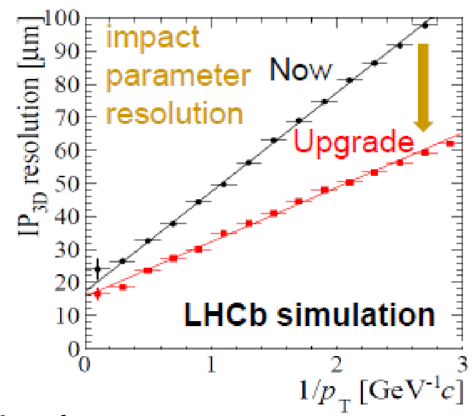
Replacement of full tracking system

Pixel Vertex Locator (VELO)

Half of VELO system



Improved performance

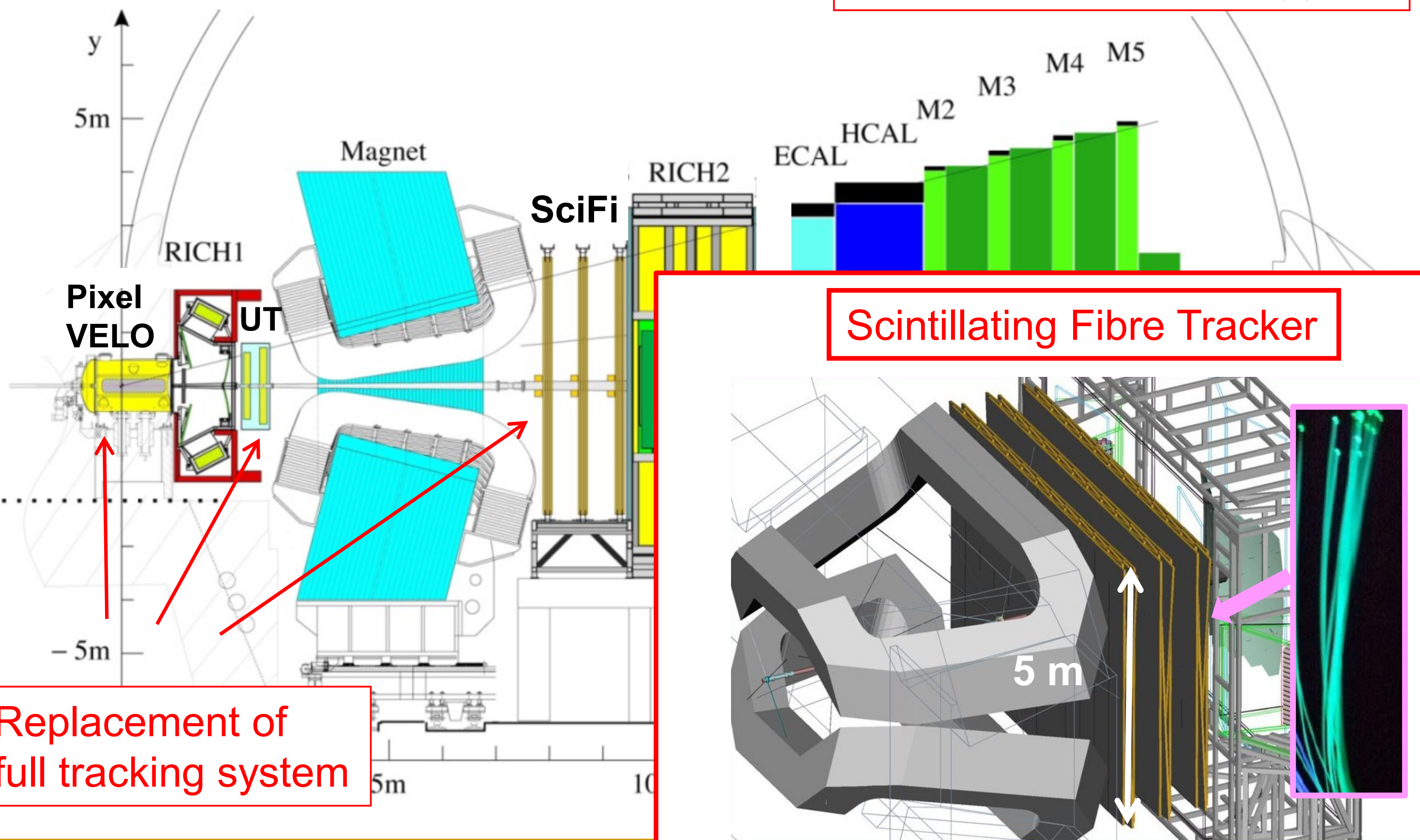


('UT' = 'Upstream tracker', a high performance Si strip detector)

Upgrade overview

Current detector → upgraded detector

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



Replacement of full tracking system

Scintillating Fibre Tracker

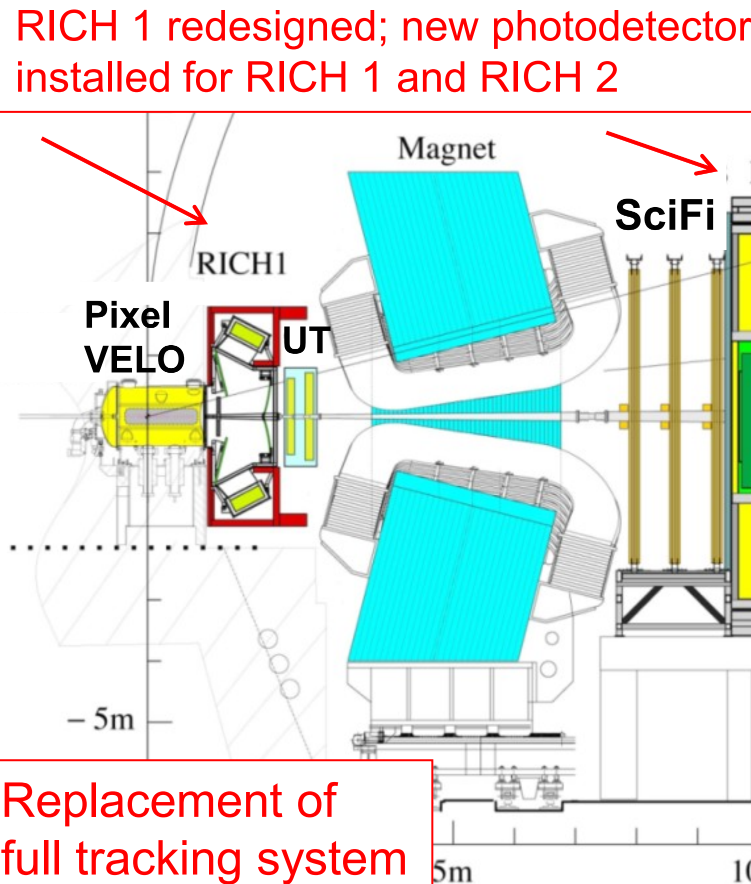
Large scale system (~12,000 km of fibres)

Upgrade overview

Current detector → upgraded detector

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

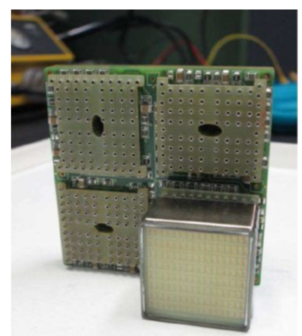
RICH 1 redesigned; new photodetectors installed for RICH 1 and RICH 2



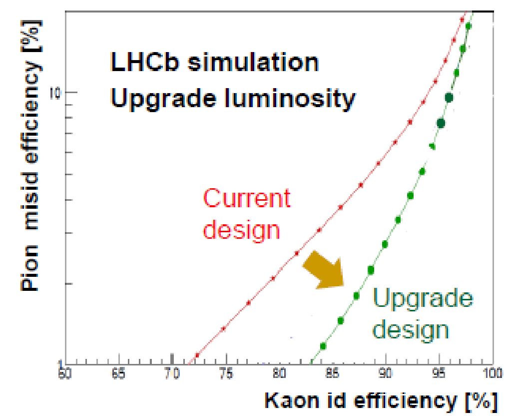
Replacement of full tracking system

RICH system

New photodetector



New optics….



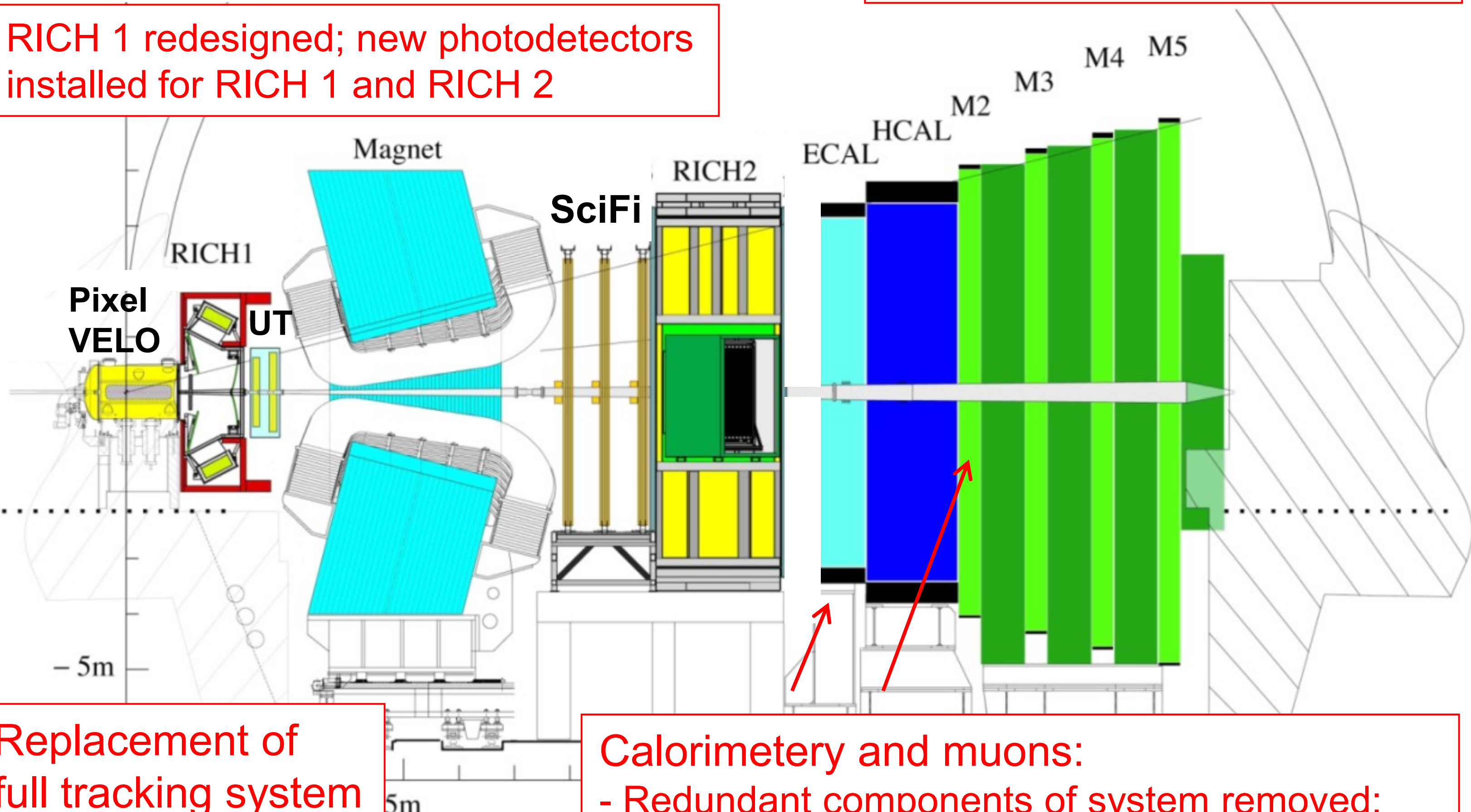
…good performance at high luminosity

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

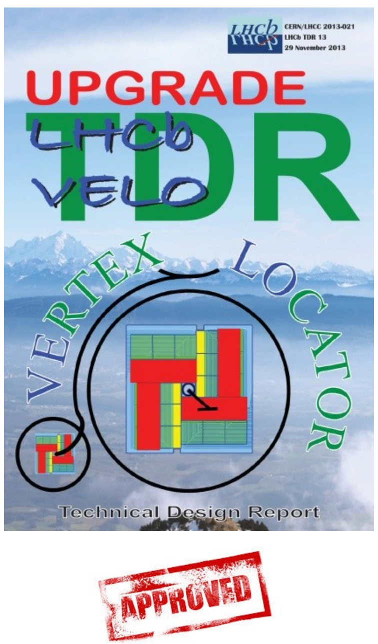


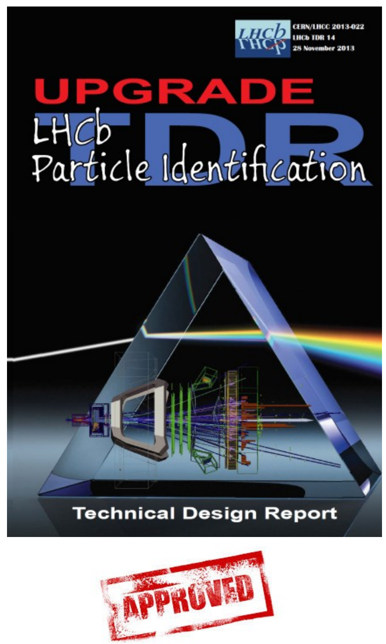
Replacement of full tracking system

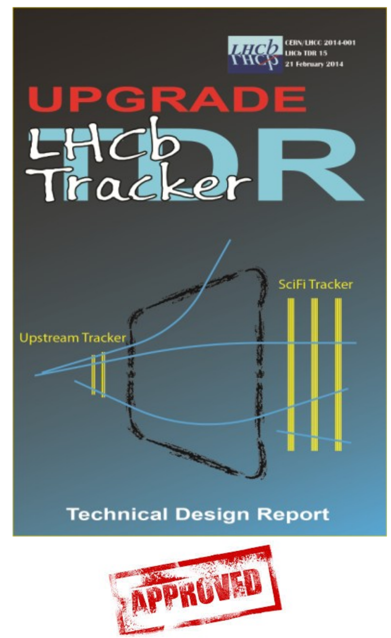
Calorimetery and muons:
- Redundant components of system removed; new electronics added; more shielding included

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 is producing physics results in a wide range of topics
- still harvesting run-1 data at same rate as last year
- important results have appeared in many key measurements (*e.g.* φ_s, $B_s \rightarrow \mu\mu$, γ determination…)…
- …but many are still to come.
- strong and unique programme of non-flavour measurements

LHCb is on schedule for start of run-2 data taking:
- LS1 activities have been performed successfully and on schedule
- we will have a fully functioning detector
- we will enhance our physics output through changes to HLT operation and output strategy

Upgrade preparations are entering a new, exciting phase
- all system TDRs approved: we have all technologies defined
- final R&D, procurement, and construction underway/about to start
- tight, but realisable schedule, in order to be ready for LS2 installation

Backups