New Physics through flavour:
LHCb - first steps, next steps & future strides

Importance of flavour physics

Selected highlights from the first 1 fb^{-1} and next steps

The flavour frontier – LHCb upgrade

Guy Wilkinson
University of Oxford
on behalf of UK LHCb

PPAP community meeting
Birmingham
18/9/12

Flavour Physics is Important

Many of open questions in Standard Model (SM) found in flavour sector:

- Why are there 3 generations ? (and is it only 3 ?)
- What determines the extreme hierarchy of fermion masses?
- What determines the elements of the CKM matrix?
- What is the origin of CP violation (CPV)?

Progress in flavour physics may help understand open questions in cosmology - SM CPV insufficient to explain matter/antimatter asymmetry

Flavour physics is a proven tool of discovery:

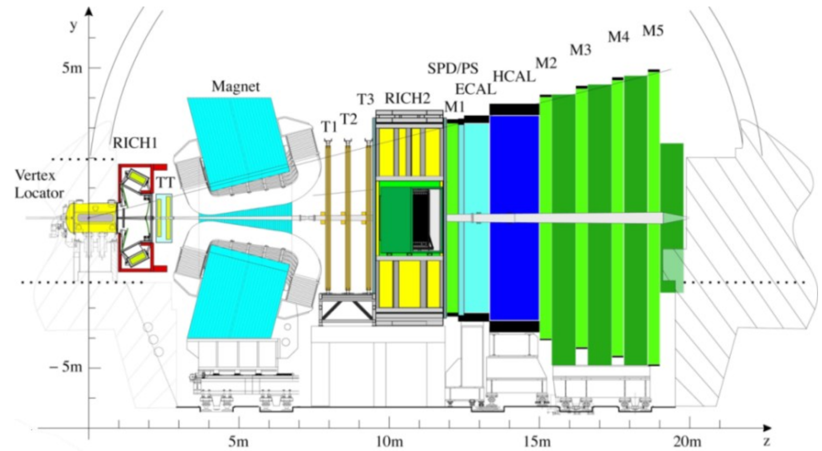
- Kaon mixing, BR($K^0_L \to \mu\mu$) & GIM → prediction of charm
- CP violation → need for a third generation
- B mixing → mass of top is very heavy
- SUSY parameter space already severely constrained by e.g. $b \to s\gamma$

Precise studies of flavour observables are an excellent way to look for New Physics!

LHCb – a reminder

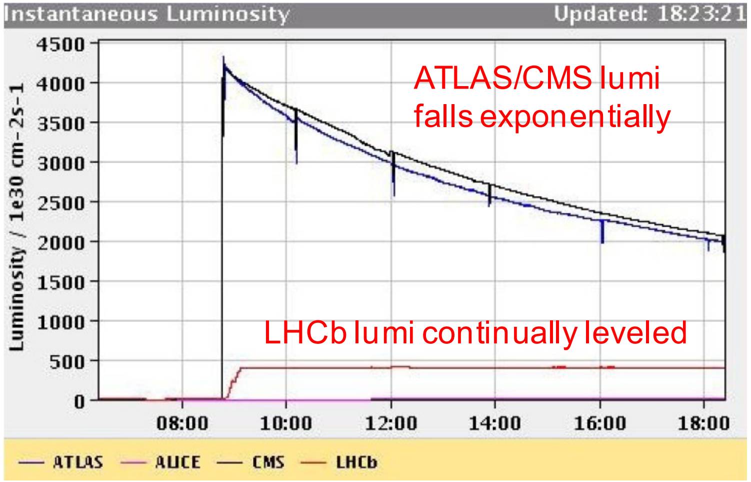
LHCb – a forward spectrometer optimised for heavy-flavour physics at the LHC

- 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
- so far 1.4 fb^{-1} in 2012 – hope for 2.5 fb^{-1}
- aim for 7-8 fb^{-1} before 2018-19 shutdown



How Team GB has got LHCb ahead of the competition

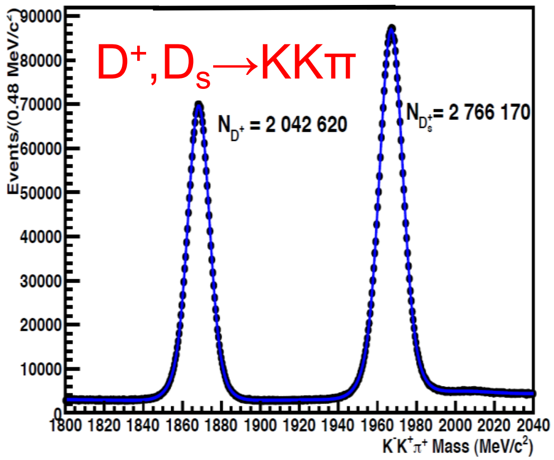
UK has had enormous impact on LHCb

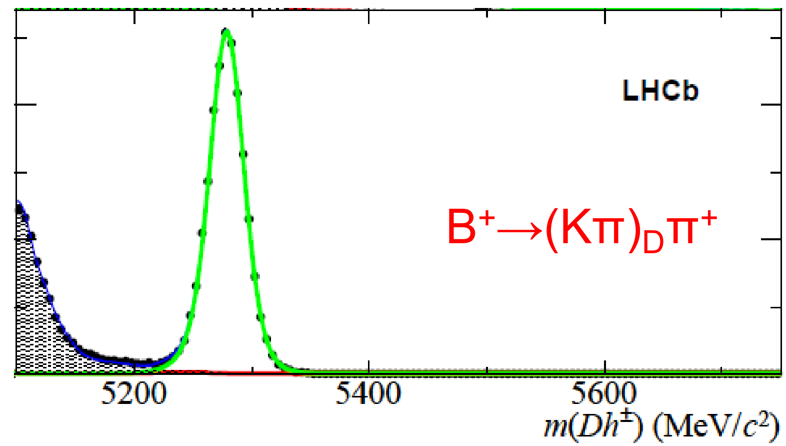
- Founding members of collaboration
- Now 11 UK LHCb institutes, constituting 23% of full collaboration
- So far have provided 1 spokesperson, 2 physics coordinators, 1 CB chair, several project leaders, and many working group convenors
- Leadership of the two flagship subdetectors: RICH and VELO
- Driving the physics output: lead authors on 1/3 of the papers to date

Worries before start-up, or what the doomsayers said

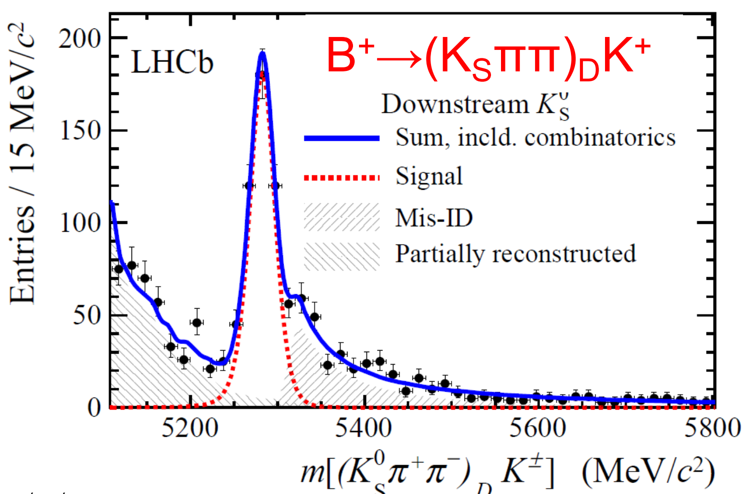
- "Hadron colliders are too dirty an environment for flavour-physics"
- "Impossible to trigger efficiently on non-leptonic final states"
- "Collider experiments are inflexible. If conditions or operation is different from anticipated, the experiment's performance will suffer"
- "It will take a long time to understand detector performance, and so significant physics output will take several years to emerge"

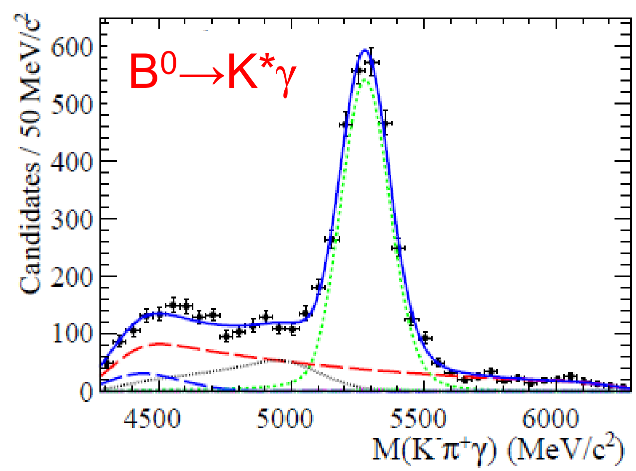
Clean reconstruction of B and D decays *is* possible at a hadron collider…





…even with photons

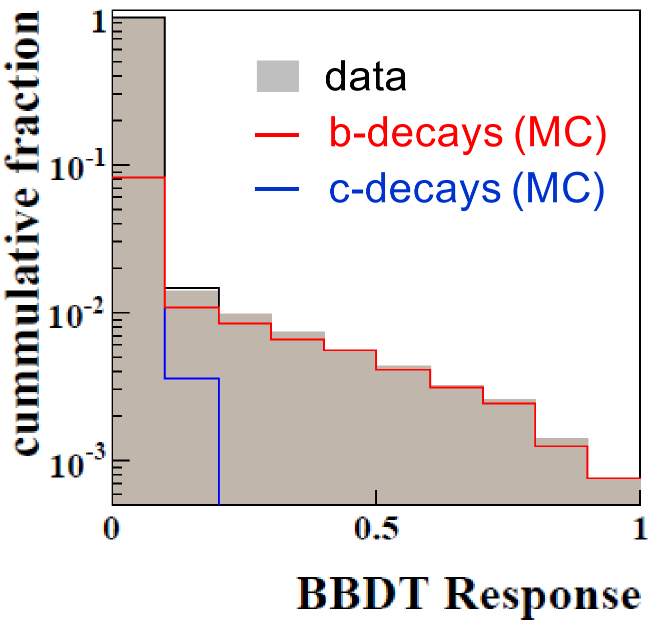




Good trigger performance across wide spectrum of final states

Majority of LHCb's physics goals involve hadronic final states, so trigger must be sensitive to more than dimuons! Events are pre-filtered with inclusive & robust 'L0' decision based on 'high' p_T calorimeter clusters (+ muons), then into HLT...

Response of HLT b-decay BBDT

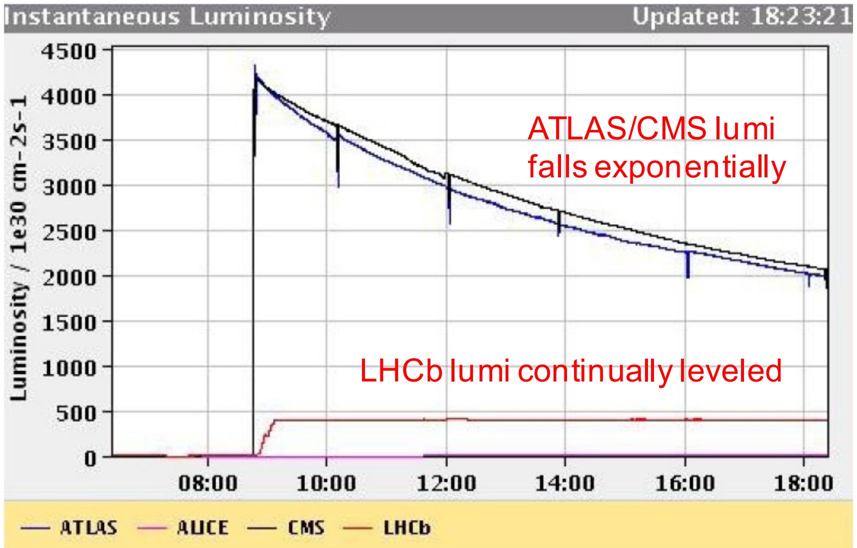


- ~100% pure in b-decays
- very efficient: >75% for most decays
- very inclusive ('inclusive' in sense that anything we can reconstruct, we can also trigger on!)
- last but not least – proof-of-principle for upgrade trigger scheme (see later)

LHCb has reactive positively to the challenges and opportunities

In many aspects, experiment has modified operational strategy w.r.t. original plans, and always in a direction to increase the physics output.

- Running luminosity factor 2x higher than design
- Pileup 2x higher than design (and even higher in early running)
- Output rate ~4 kHz, twice higher than design (indeed, 20x higher than TDR...)
- Novel features introduced:
  - luminosity leveling
  - 'HLT deferral' – some events written to temporary storage and only considered by HLT *after* the end of the fill



Selected highlights from early running

- Flavour changing neutral current: searches & studies
- Studies of CPV in the B_s system
- Studies with B and D decays to hadronic final states
- Beyond flavour

These are *all* searches for New Physics!

A very selective list – LHCb has now submitted/published ~65 papers - highest paper/author ratio at the LHC...

Most examples based on 1 fb^{-1} of 2011 data – already made a great impact ! In years up to 2017 we expect 7-8 fb^{-1} in total, and much of this at ~double the current heavy-flavour production cross-section (since $\sqrt{s}$: 8→14 TeV)

UK extremely prominent throughout LHCb physics – driving force behind almost all of the examples shown here

Selected highlights from early running

- Flavour changing neutral current: searches & studies
- Studies of CPV in the B_s system
- Studies with B and D decays to hadronic final states
- Beyond flavour

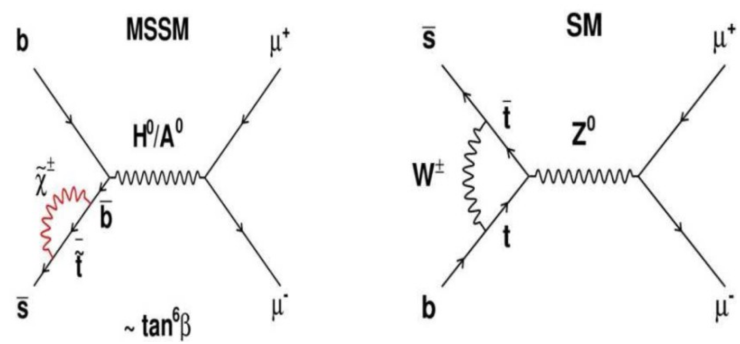
The golden mode: $B_s \to \mu\mu$

B physics rare decay par excellence:

$BR(B_s \to \mu\mu)_{SM} = (3.2 \pm 0.2) \times 10^{-9}$

[A.J.Buras, arXiv:1012.1447]

Precise prediction (which will improve) !

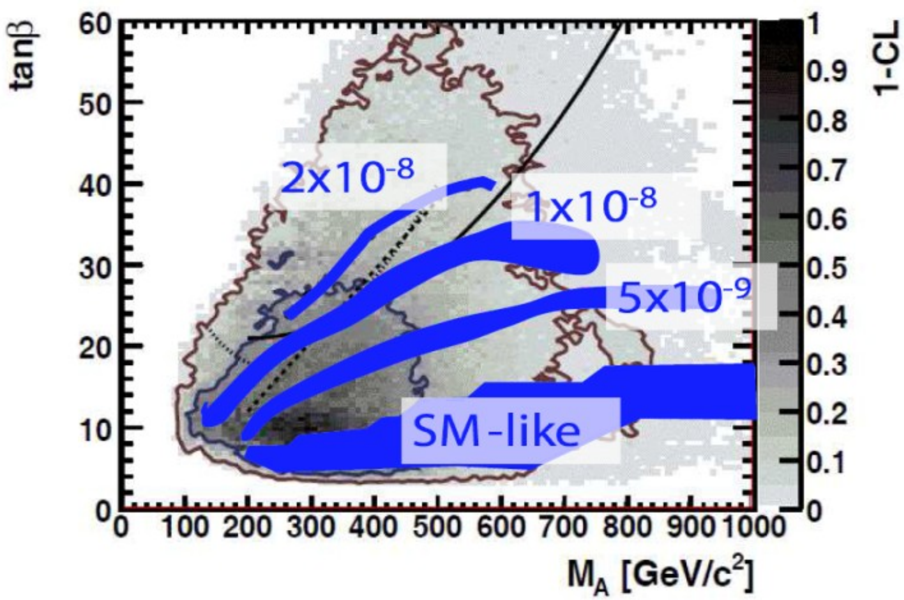


Very high sensitivity to NP, eg. MSSM:

$$Br^{MSSM}(Bq \to l^+l^-) \propto \frac{m_b^2 m_l^2 \tan^6\beta}{M_{A0}^4}$$

One example [O. Buchmuller et al, arXiv:0907.5568] : NUHM (= generalised version of CMSSM)

$BR(B_s \to \mu\mu)$ - highly discriminatory



BR UL 95% CL as of Spring 2011, i.e. before any results from LHC 2011 run:

CDF (3.7 fb^{-1}): < 4.3 x 10^{-8}

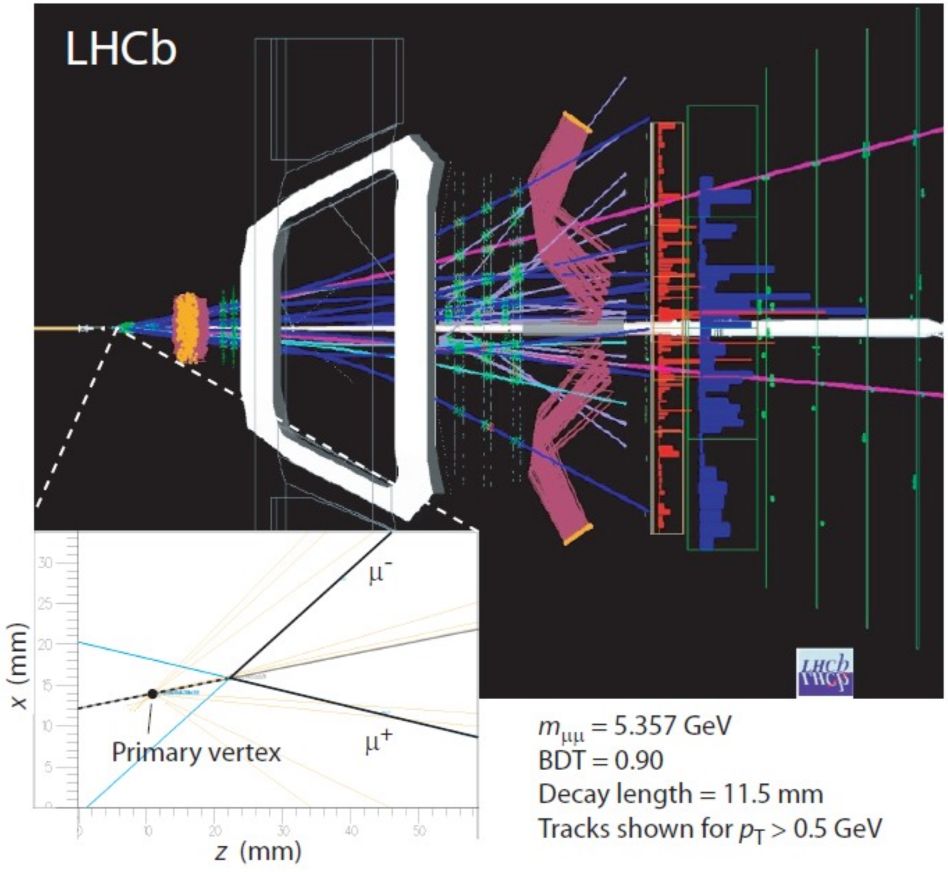
D0 (6.1 fb^{-1}): < 5.1 x 10^{-8}

LHCb (37 pb^{-1}): < 5.6 x 10^{-8}

Plenty of space left for NP to hide!

Entering the signal regime

Even at the SM branching ratio LHCb expects to accumulate $B_s \to \mu\mu$ decays in 2011 data (~12 after pre-selection). And indeed plausible candidates are seen!

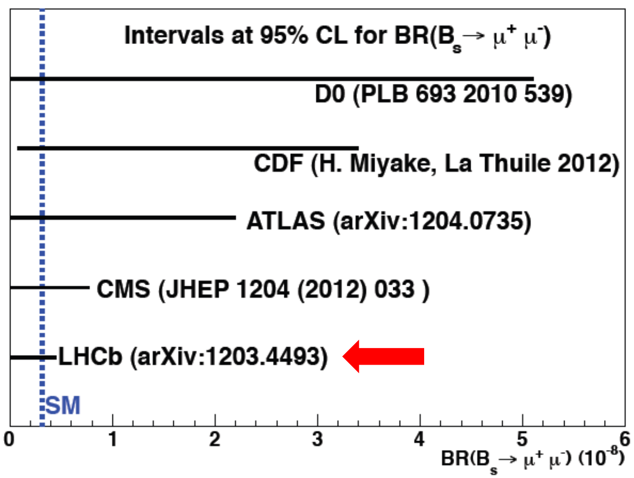


LHCb $B_s \to \mu\mu$ results with 1 fb^{-1}

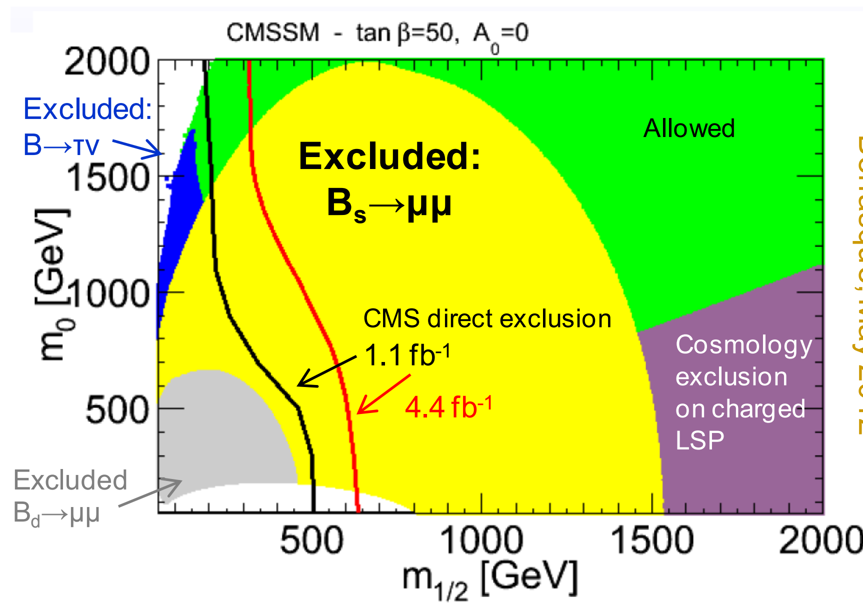
PRL 108 (2012) 231801

But with full analysis no excess seen… indeed limit is even better than expected!

Mode	Limit	at 95 % CL
$B_s^0 \to \mu^+\mu^-$	Exp. bkg+SM	7.2×10^{-9}
	Exp. bkg	3.4×10^{-9}
	Observed	4.5×10^{-9}



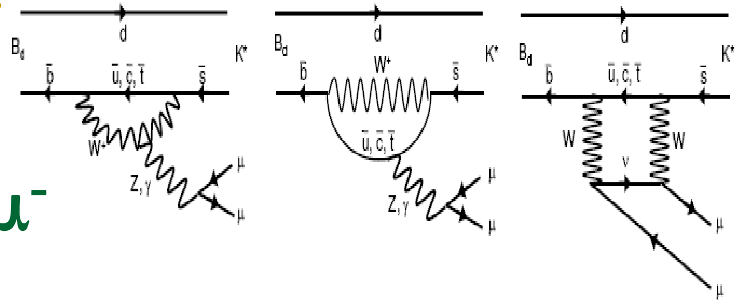
Limit now very close to SM – no large NP enhancements. Big consequences for NP parameter space, e.g. high tanβ SUSY



Nazilla Mahmoudi, Benasque, May 2012

Now the game changes! LHCb must prepare for performing a precision measurement to test if BR is *really* SM. Potential for <20% stat error by 2018. ***Data driven analysis*** well equipped for keeping systematics under control

Probing electroweak penguins with $B \rightarrow K^{(*)}\mu^+\mu^-$

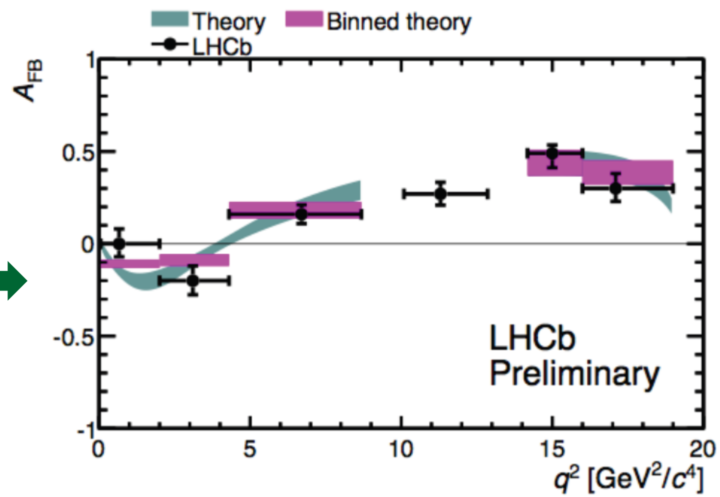


Many observables exist in $B^0 \rightarrow K^* l^+ l^-$ to probe helicity structure of any New Physics

LHCb 2011 yields surpass sum of those of previous experiments and allow for first meaningful tests with these decays

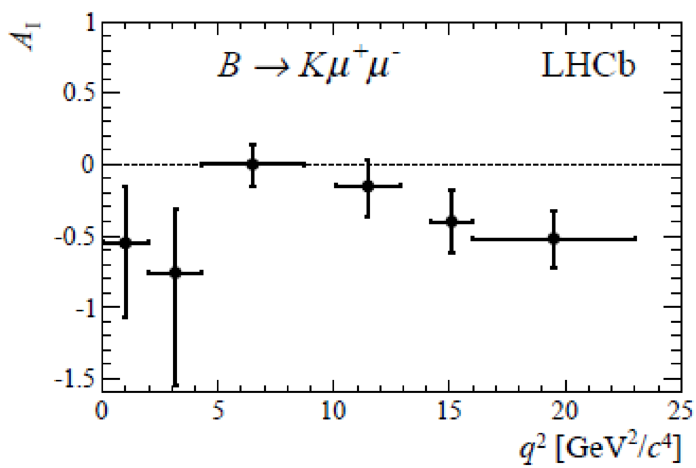
e.g. forward-backward asymmetry of dimuon system as a function of invariant mass (q^2).

This is beautiful – but textbook SM with current precision. Must improve precision!



LHCb-CONF-2012-008

But not everything is as expected....



JHEP 07 (2012) 133

Isospin asymmetry in $B \rightarrow K\mu\mu$

Expected to be zero in SM – significant deviation emerging. Requires further studies and more theoretical understanding

Selected highlights from early running

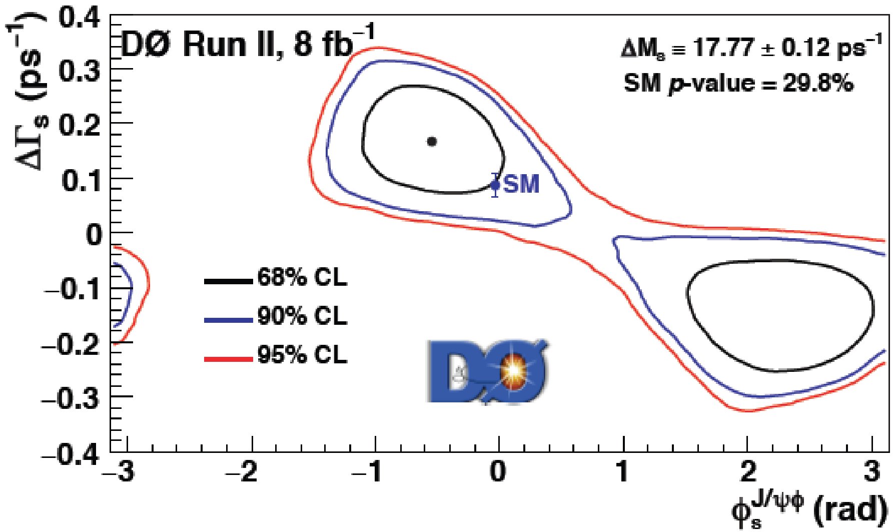
- Flavour changing neutral current: searches & studies
- Studies of CPV in the B_s system
- Studies with B and D decays to hadronic final states
- Beyond flavour

Mixing induced CPV in B_s system

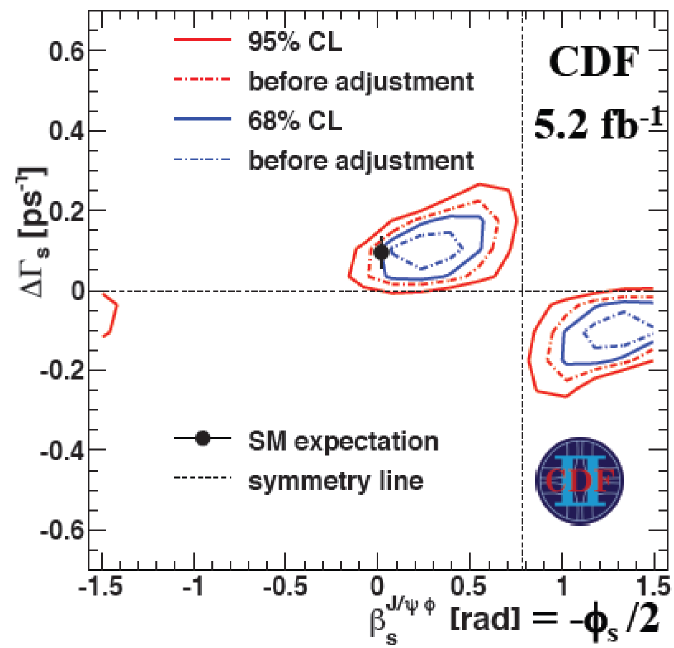
CPV phase, φ_s, in B_s mixing-decay interference, e.g. measured in $B_s \to J/\Psi\Phi$, very small & precisely predicted in SM. Box diagram offers tempting entry point for NP!

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

[PRD 85 (2012) 032006]



[PRD 85 (2012) 072002]



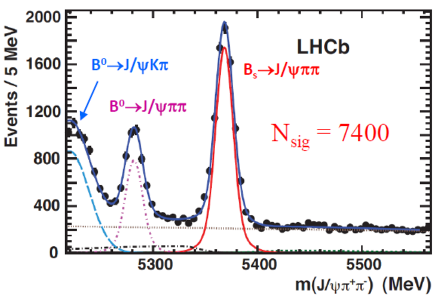
Results are consistent, & both are ~1σ away from SM. What about LHCb?

Precision studies of B_s CPV

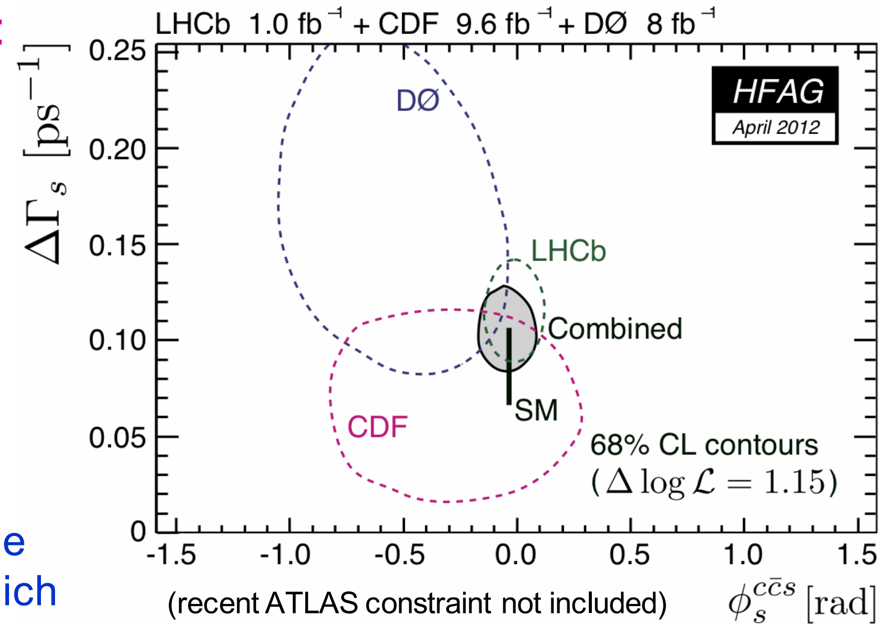
LHCb has brought clarity to the φ_s picture:

- $B_s \to J/\Psi\varphi$ analysis with ~4x precision of Tevatron studies [LHCb-CONF-2012-002]

- Augment this with novel analysis in complementary channel $B_s \to J/\Psi\pi\pi$ [PLB 713 (2012) 378]



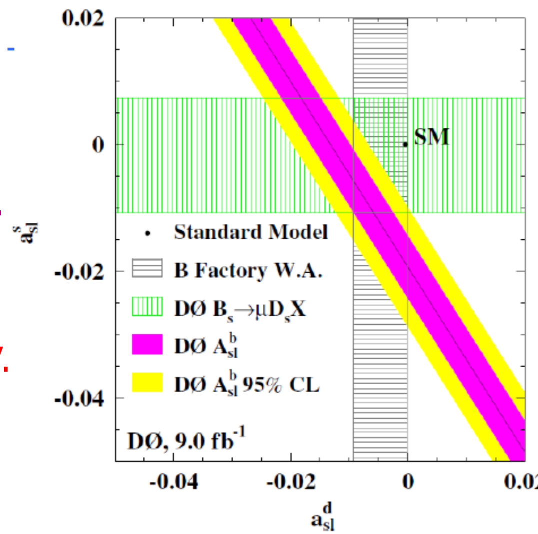
- Finally, perform study looking at strong-phase change w.r.t. KK invariant mass in J/ΨKK which resolves 2-fold ambiguity [PRL 108 (2012) 241801]



(recent ATLAS constraint not included)

No big NP effect in B_s mixing-decay interference, but essential to improve precision as φ_s remains a priori highly sensitive to non-SM contributions. Will take time…

…what should come quicker is a resolution to the related issue (CPV in mixing) of the D0 di-μ asymmetry anomaly.

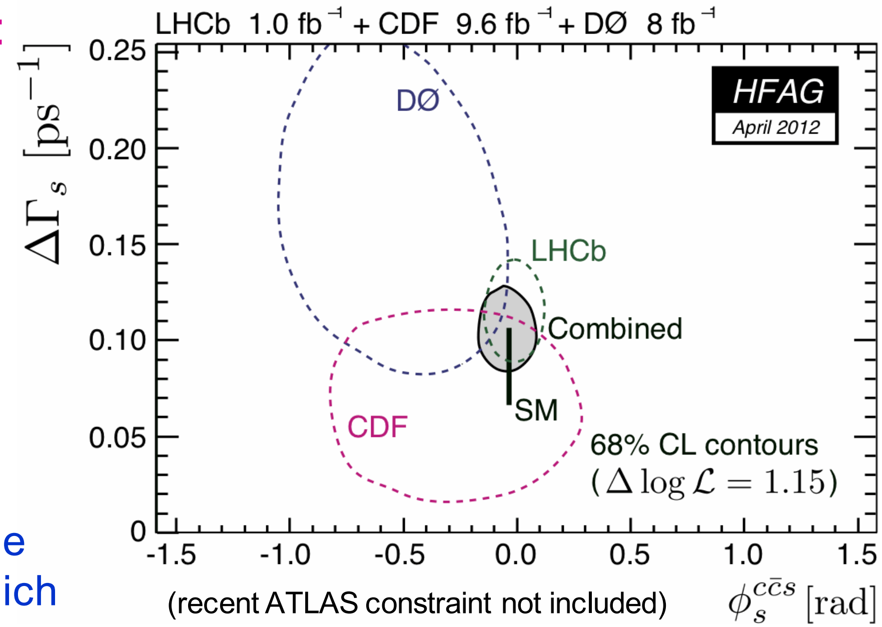


[D0, PRD 84 (2011) 052007]

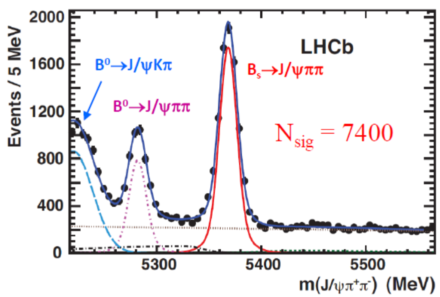
Precision studies of B_s CPV

LHCb has brought clarity to the φ_s picture:

- $B_s \to J/\Psi\varphi$ analysis with ~4x precision of Tevatron studies [LHCb-CONF-2012-002]



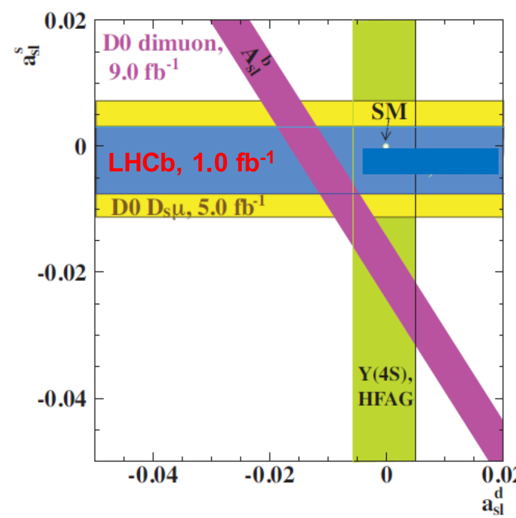
- Augment this with novel analysis in complementary channel $B_s \to J/\Psi\pi\pi$ [PLB 713 (2012) 378]



- 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]

No big NP effect in B_s mixing-decay interference, but essential to improve precision as φ_s remains a priori highly sensitive to non-SM contributions. Will take time…

…what should come quicker is a resolution to the related issue (CPV in mixing) of the D0 di-μ asymmetry anomaly. First LHCb input appeared recently, more will come soon

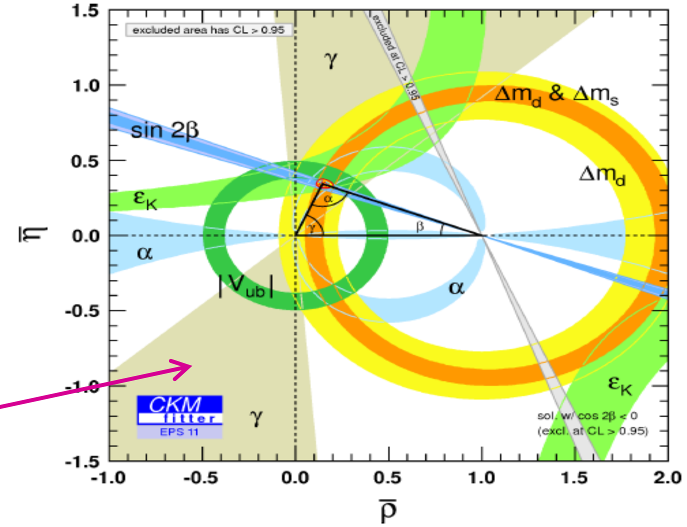


[LHCb-CONF-2012-022]

Selected highlights from early running

- Flavour changing neutral current: searches & studies
- Studies of CPV in the B_s system
- Studies with B and D decays to hadronic final states
- Beyond flavour

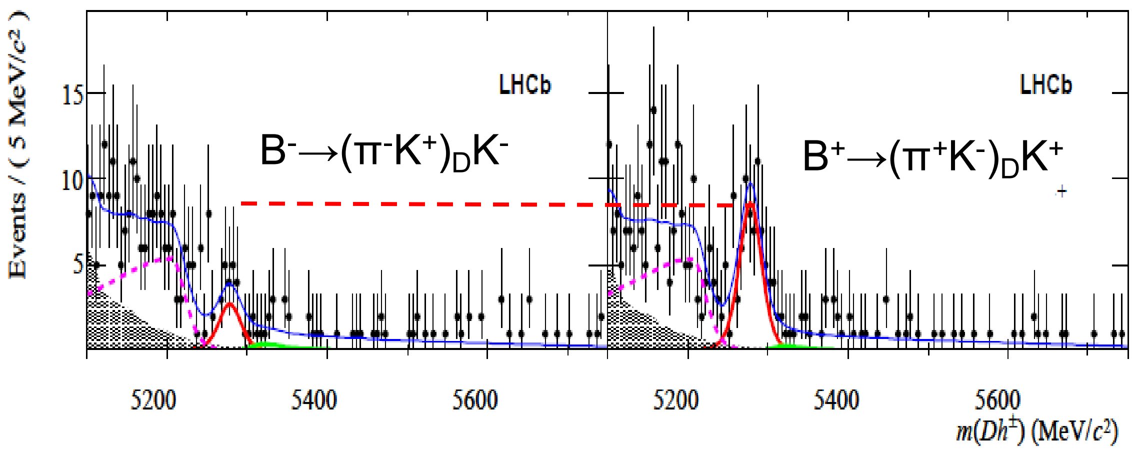
Precision CKM-metrology: the unitarity triangle angle γ



B-factories (& others) have done a great job in mapping out unitarity triangle. But progress needs improved knowledge of angle γ (a.k.a. φ_3)

Current measurement error ~ 12° ; indirect (e.g. NP sensitive loops) precision ~4°

LHCb has entered game with discovery of long-sought 'suppressed ADS' mode. Visible BR ~ 10^{-7} Large CP asymmetry gives *clean* information on γ



[PLB 712 (2012) 203]

New results coming *very* soon exploiting other modes ➡ LHCb well on target to (at least) matching (current) indirect precision before upgrade

Search for New Physics with charm

Same qualities which make LHCb a great B-physics detector also hold for charm

- ability to trigger on hadronic final states
- acceptance down to low p_T
- hadron PID from RICH system
- excellent vertex resolution
- high output rate (~1 kHz given to charm)

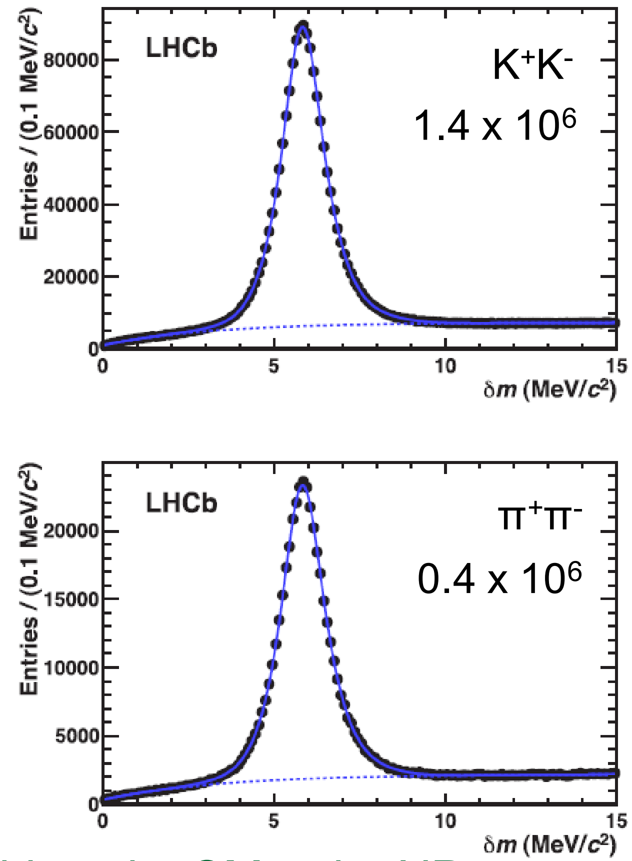
These features & the enormous production x-section (~6.5 mb @$\sqrt{s}$ = 7 TeV) allow for *very large* & very *clean* event samples!

Already, very interesting results have emerged

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

first evidence of CPV in charm [PRL 108 (2012) 111602]

LHCb D^*-D^0-m_π [0.6 fb^{-1}]



[PRL 108 (2012) 111602]

Hunt is on to establish observation, see effects in other modes, and understanding if this is being driven by SM or by NP

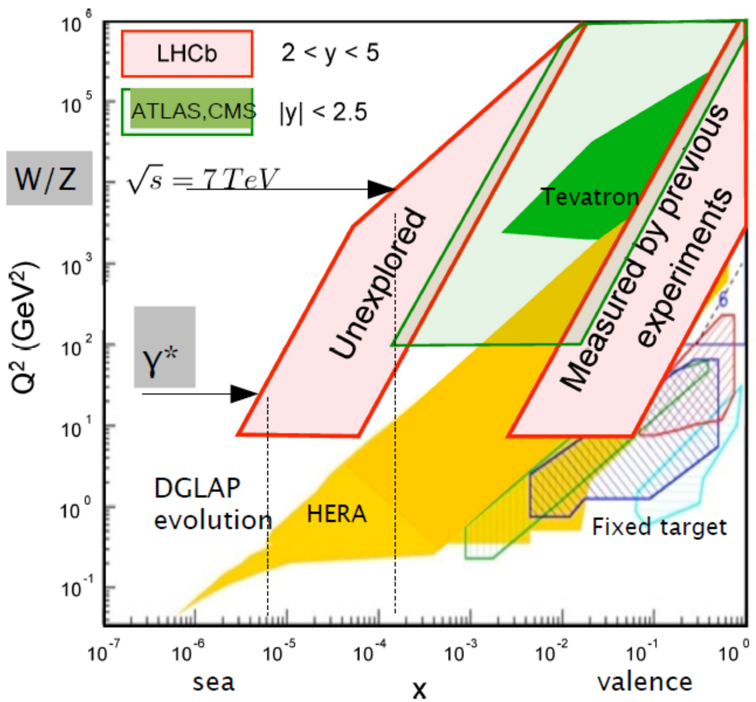
Selected highlights from early running

- Flavour changing neutral current: searches & studies
- Studies of CPV in the B_s system
- Studies with B and D decays to hadronic final states
- Beyond flavour

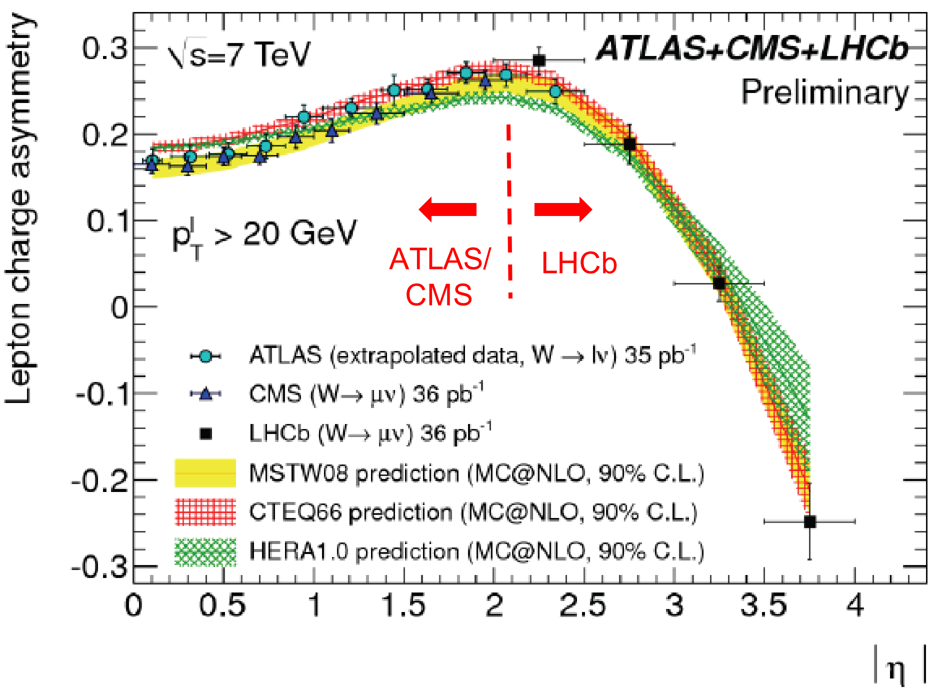
Away from flavour

LHCb's unique forward and low p_T acceptance equips it to perform EW / QCD measurements which are highly complementary to those of mid-rapididty GPDs

Unique kinematical acceptance

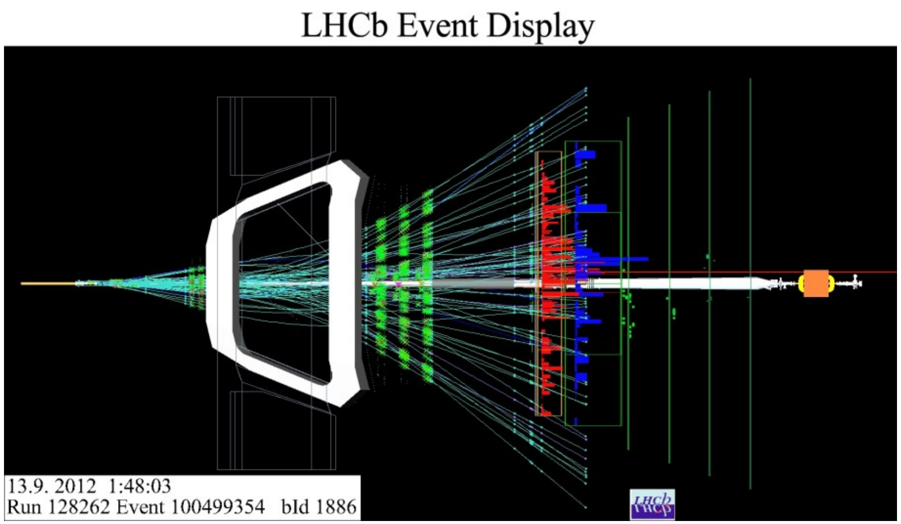


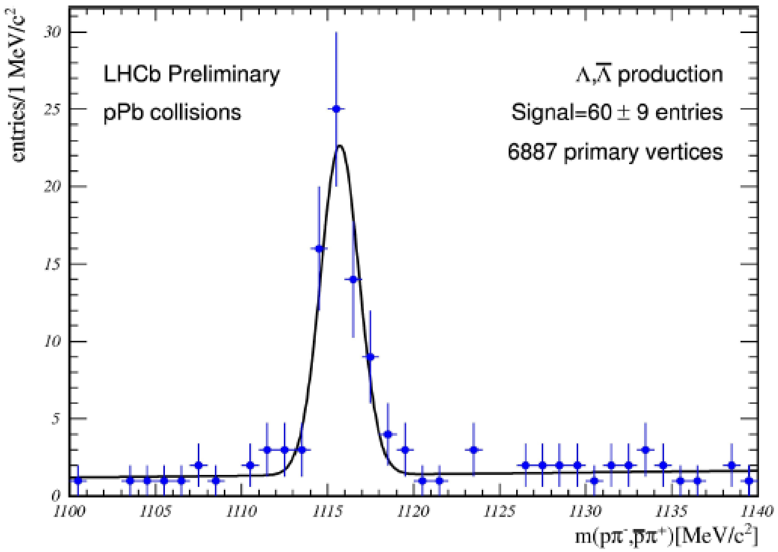
Studies of W/Z production [JHEP 6 (2012) 58], alongside ATLAS/CMS, give complete picture



And not just p-p

LHCb will participate in 2013 p-Pb run, & collected first data in last week's pilot fill





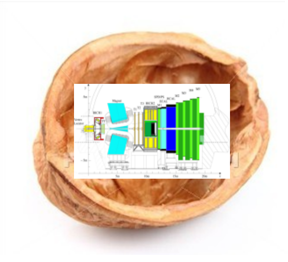
Emerging message from flavour & high p_T searches after first period of LHC running

As regards New Physics there seems to be no 'low hanging fruit'...

That's OK, as we know how to do it...

...so we'll have to climb higher

Upgrade in a nutshell



When:

Upgrade will be installed in 2018/19, during LS2 shutdown

Key attributes:

Raise luminosity to 1-2 $\times 10^{33}$ $cm^{-2}s^{-1}$:
Easy - LHC has already reached this performance!

Upgrade readout of all subdetectors + DAQ architecture to 40 MHz (driven by full-software trigger – the key element – see next slide)

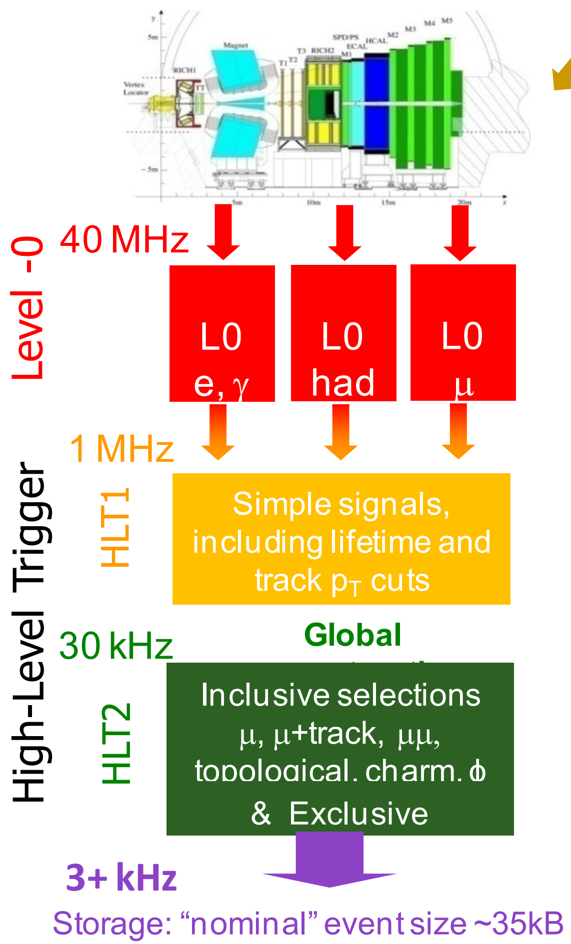
New readout necessitates changes for some subdetectors (VELO, RICH photodetectors, TT/IT) – good opportunity to benefit from new technologies

Goals:

Collect ~5 fb^{-1} / year, with more efficient and flexible trigger

Flavour physics programme of greatly enhanced precision (particularly in hadronic final states) & scope, plus exciting opportunities in other topics

LHCb trigger – upgrade solution



Present strategy:

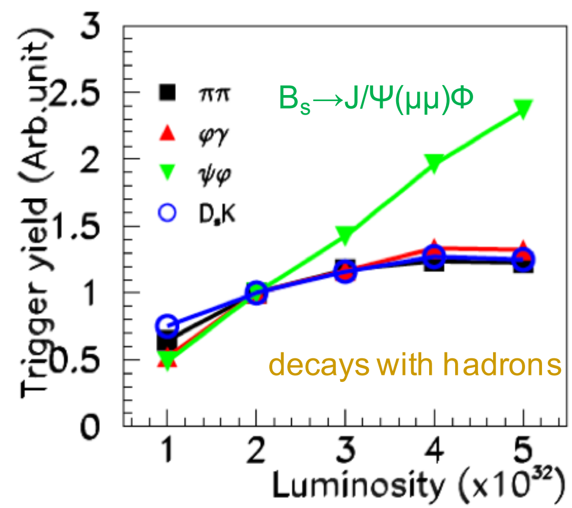
Hardware high p_T signal at earliest level – robust

Performs well at L ~ few x10^{32} cm^{-2}s^{-1}, but yield in hadronic channels does not scale with luminosity

Must raise p_T cuts to stay within 1 MHz readout limit

Decays to leptons - linear gain

Hadronic final states – yield flatlines...



Upgrade solution:

Readout at 40 MHz & use s/w trigger *throughout*

A win-win-win solution!

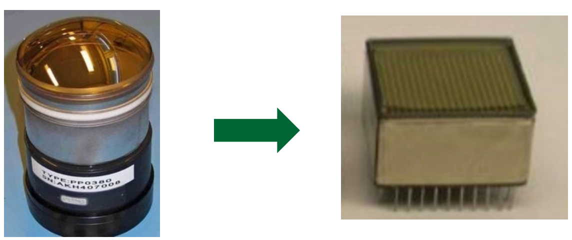
1) higher trigger efficiency (x ~2) at given lumi for hadronic modes
2) freedom to raise operational luminosity
3) very high degree of trigger flexibility – good for all physics!

UK leadership in detector upgrades

UK physicists are leading players in upgrade activities in RICH and VELO.

RICH

Photodetectors must be changed from HPD, as readout chips encapsulated inside tubes. Commercial MaPMTs a strong candidate.

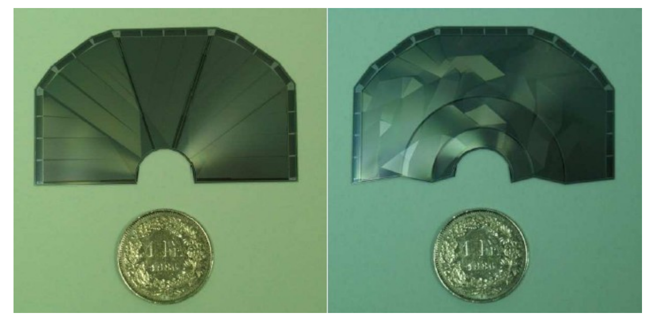


Plenty of engineering and electronics work required, but no ‘impossible problems’

High occupancy in inner region *may* necessitate optics redesign of RICHes

VELO

Choice to be made between pixels & strips



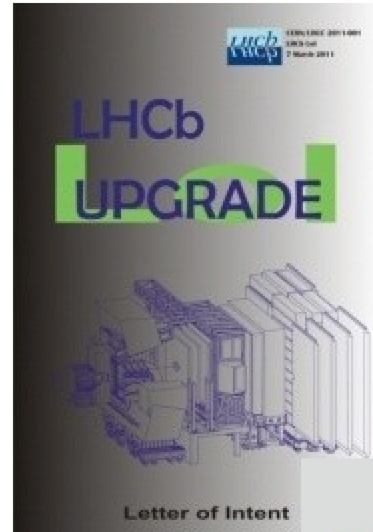
Prototype strip sensors
(30 μm min pitch, 200μm thick, n-in-p)

Pixel readout: Timepix3 → Velopix

Strip readout: LHCb dedicated strip ASIC (also needed for IT & TT)

Interesting common challenges on cooling etc

Path to the upgrade



EoI submitted to LHCC in 2008.

LoI submitted to LHCC March 2011.
Enthusiastically received:

> '..arguments for flavour physics with 50 fb^{-1} very compelling.'

'Framework TDR' submitted May 2012. Now under review. Document signed by all LHC institutes. In recent months new, strong groups, have joined or are joining collaboration.

Technological choices will be made before mid-2013, and sub-system TDRs submitted at end of 2013.

UK physicists have championed upgrade from beginning. Occupy (& have occupied) leadership positions in overall upgrade coordination, upgrade physics planning and RICH and VELO upgrade activities.

Upgrade era physics

- Exactitude in golden observables
- Diving deeper, e.g. charm
- New horizons
- A general purpose detector in the forward region

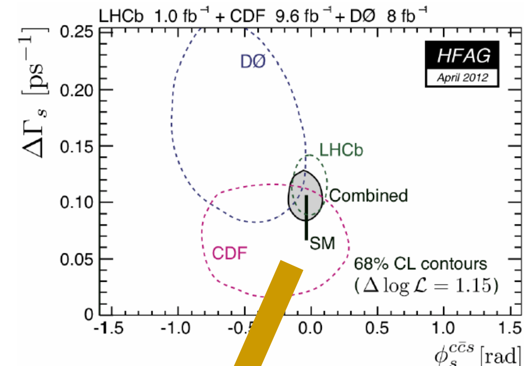
only a few examples
mentioned for each !

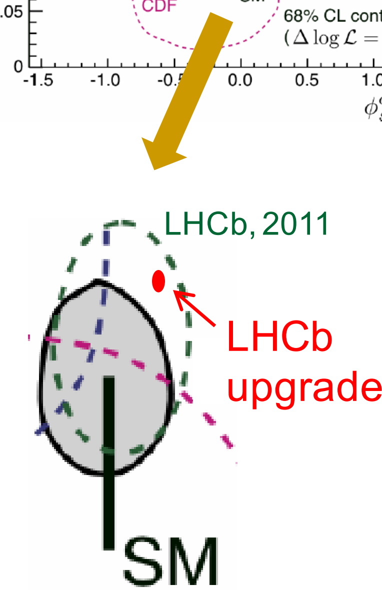
Exactitude in golden observables

Flavour physics contains several golden observables – both very sensitive in the search for NP, and precisely predicted in SM.

- φ_s (i.e. CPV phase in $B_s \rightarrow J/\Psi\varphi$, $J/\Psi\pi\pi$…)

  Upgrade precision < 0.01 rad, which starts to reach regime where theoretical difficulties bite (e.g. Penguin pollution). Super-precise search for NP through CPV





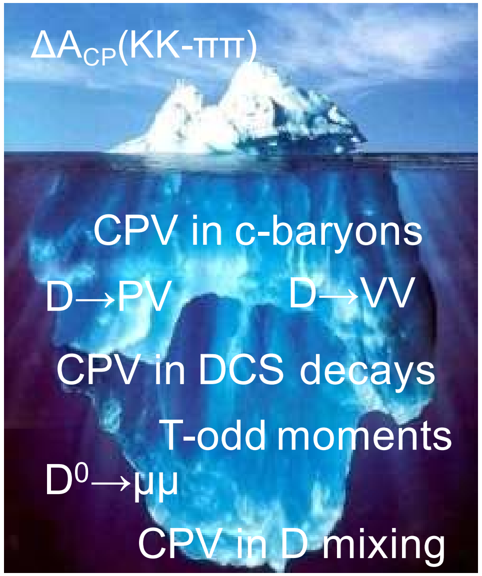
- BR($B_s \rightarrow \mu\mu$)

  Upgrade can achieve σ_{stat} <10%, which is ~σ_{theory}
  Data driven analysis methods and other capabilities of LHCb bode well for σ_{syst}, e.g. fragmentation ratios needed for normalisation can only measured at LHCb

- CKM angle γ

  Unitarity triangle studies a powerful test of SM in flavour physics. Precision on indirect γ prediction will improve to ~1^o thanks to lattice QCD. Upgrade can match this in direct measurement.

Diving deeper, e.g. charm



Certain topics already show exciting promise in 2011 but will require much larger samples to yield full potential.

Existing trigger less efficient for charm than beauty because of p_T thresholds at earliest trigger stage. full s/w trigger of upgrade will be *highly* beneficial.

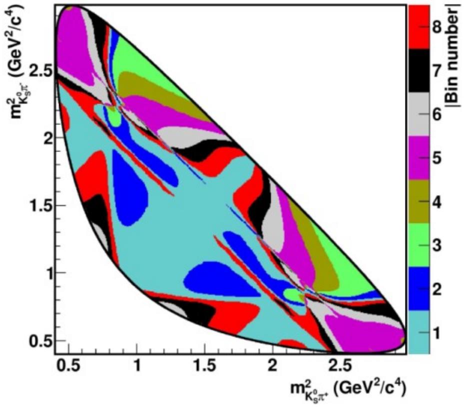
→ samples of ~10^8 in most interesting decays

Upgrade will allow:

- opportunity to observe direct CPV in a range of decays, essential for unpicking role of NP vs SM
- opportunity to look for indirect CPV down to the SM/theory limit. A very clean probe of NP.

Key analyses have data driven systematics or can be tackled in model-ind. manner → fully exploit statistics!

e.g. binned time-dependent study of $D^0\to K_S\pi\pi$ Dalitz plot



PRD 82 (2010) 034003; arXiv:1209.0172

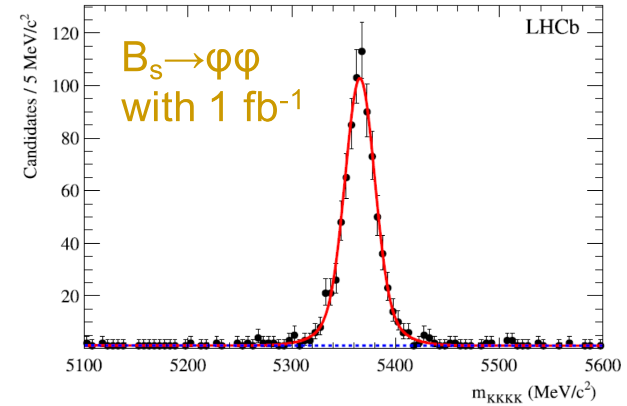
Model-independent!

New horizons

Many observables, sensitive to NP often in a complementary manner to those currently under study, are beyond reach of existing experiment, or cannot be probed with sufficient precision to make interesting tests. Ideal for upgrade!

- CPV in pure gluonic Penguins

  Asymmetries in modes such as $B^0 \to K_S \varphi$ probed to ~0.20 at B-factories. Work continuing at LHCb, augmented with other decays, e.g. $B_s \to \varphi\varphi$. But interesting sensitivity (<0.05) needs upgrade.

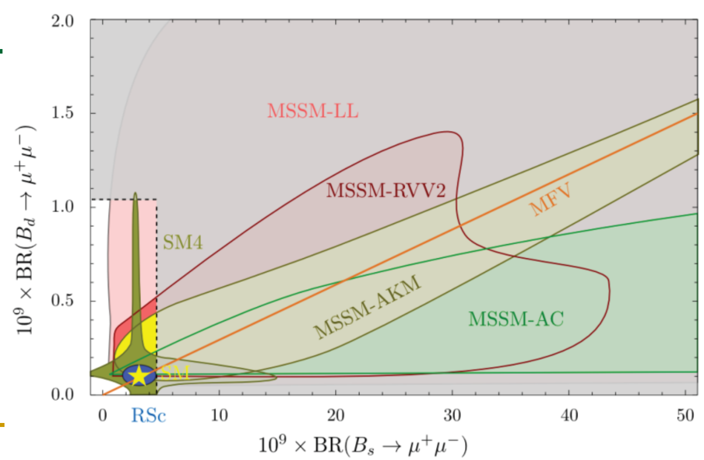


- Full span of $B^0 \to K^*\mu\mu$ observables

  $B^0 \to K^*\mu\mu$ contains many asymmetries besides A_{FB}, all accessible with angular analysis and upgrade statistics. e.g. $A_T^{(2)}$ – sensitive to presence of RH currents.

- Super-rare FCNC decays

  e.g. $B^0 \to \mu\mu$. $BR(B_s \to \mu\mu)/BR(B^0 \to \mu\mu)$ ~ 30 in SM. This ratio a powerful discriminator of NP models.



A GPD in the forward region

Now

- forward geometry
- low p_T acceptance
- superb instrumentation (esp. RICH + vertexing)

+

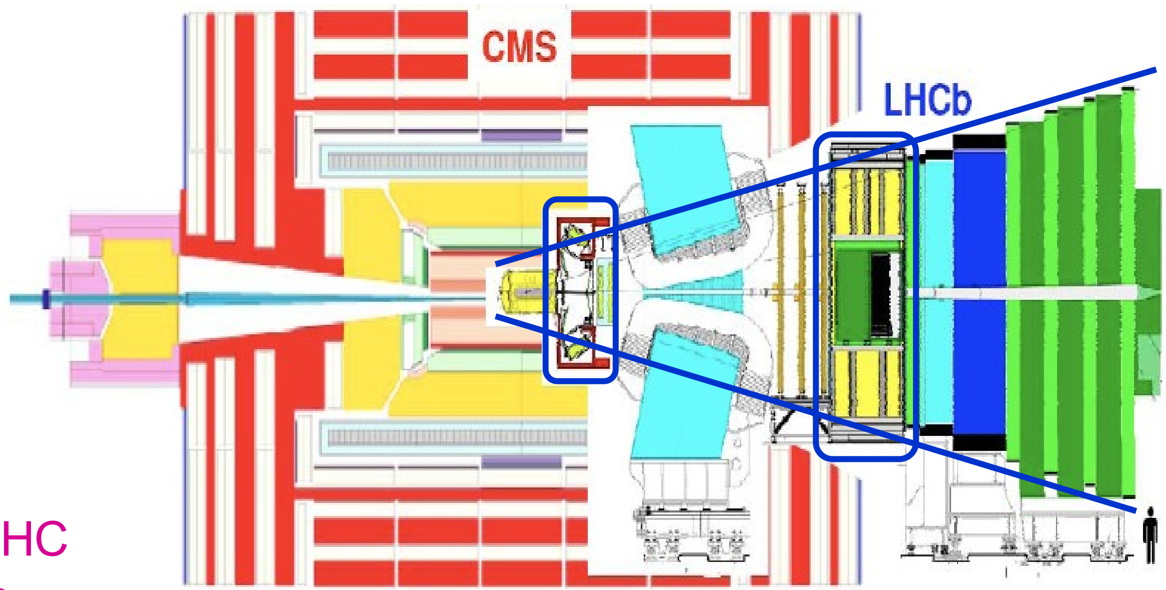
Upgrade

- most flexible trigger @ LHC
- high luminosity operation

⬇

Unique possibilities over wide range of physics topics

e.g.



- Electroweak physics: acceptance gives unique advantages for measuring $\sin^2\vartheta_W$ in $Z^0 \rightarrow \mu\mu$ A_{FB}
- Trigger will allow efficient searches for long-lived particles predicted in many NP models
- Indeed, trigger can be deployed on any signature (within acceptance) that might be seen as important!

Summary

Flavour observables have a central role to play in the search for New Physics during the LHC era.

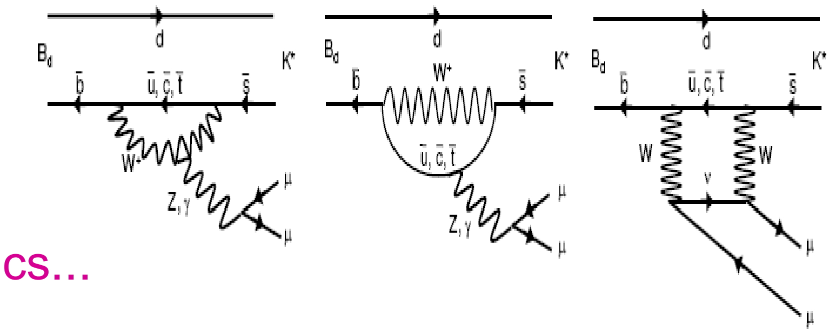
In a very short time LHCb has already told us a great deal that is new about the flavour sector, but there is much more to come!

UK groups can take much credit for this success

A clear path now lies before us leading to the upgrade - a realisable project that is essential for fully realising the potential of the LHC as a flavour factory, and extending the physics reach of the facility in many other topics

Backups

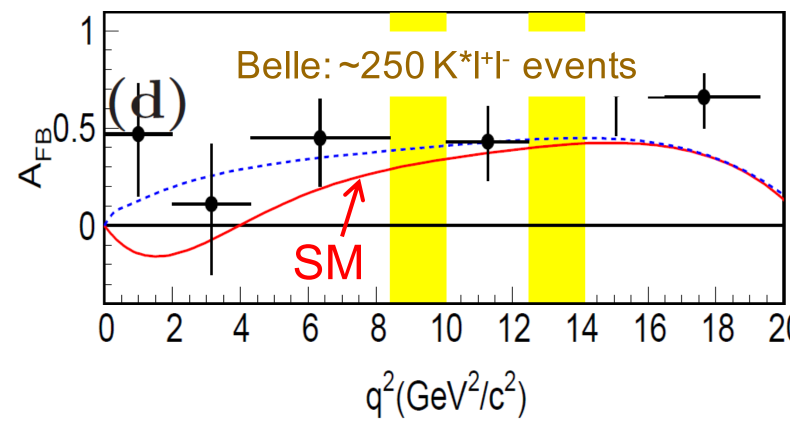
$B^0 \rightarrow K^* l^+ l^-$



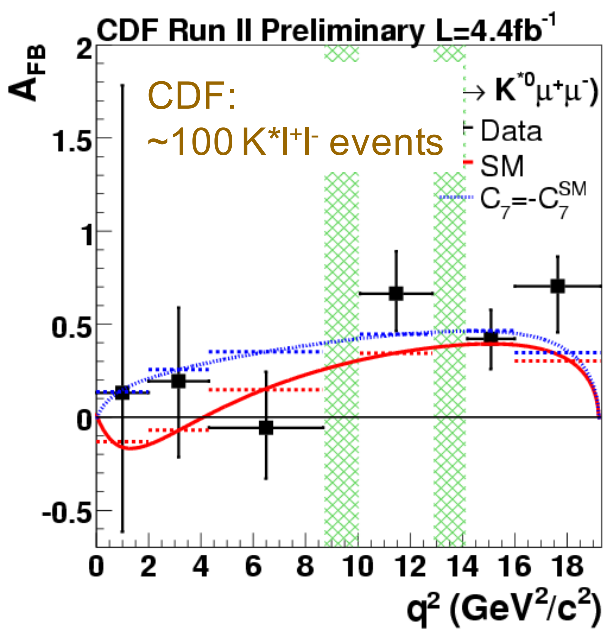
Many observables exist in $B^0 \rightarrow K^* l^+ l^-$ to probe helicity structure of any New Physics...

...in particular, forward-backward asymmetry (A_{FB}) of lepton system as a function of lepton invariant mass (q^2).

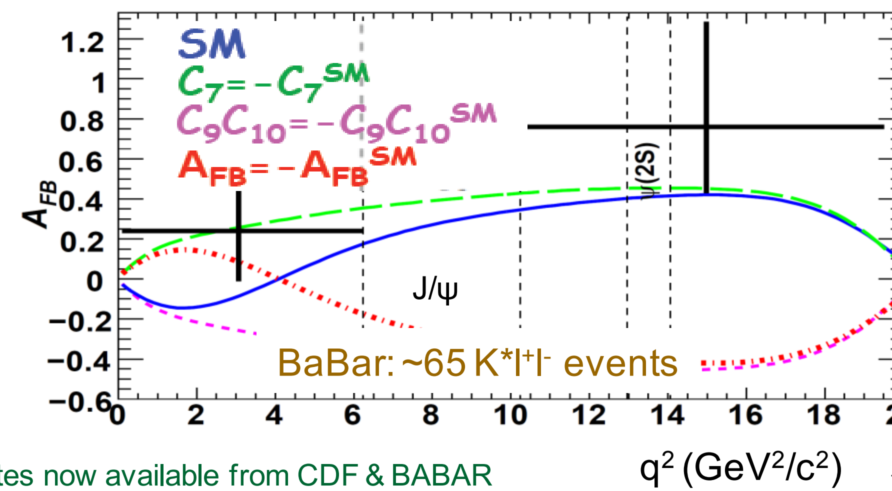
Early results from CDF & B-factories* show intriguing behaviour at low q^2, But precision too low yet to speak of an 'anomaly'



PRL 103 (2009) 171801



CDF note 10047



PRD 79 (2009) 031102

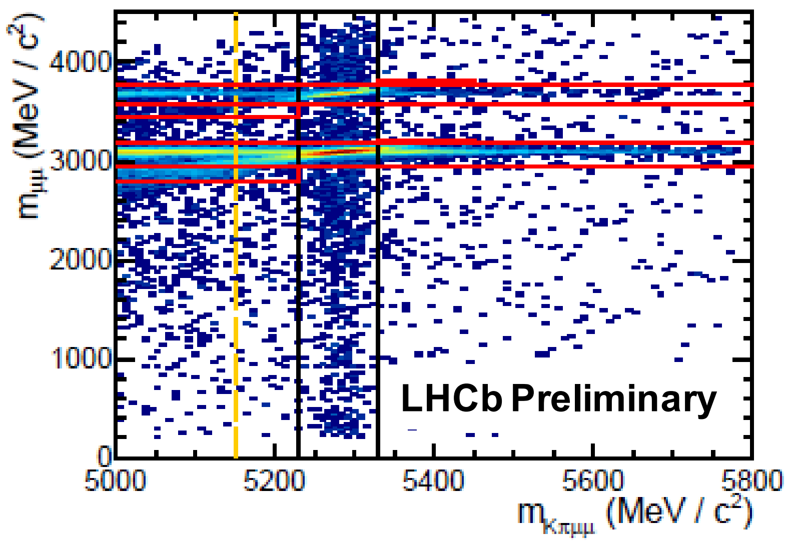
* updates now available from CDF & BABAR

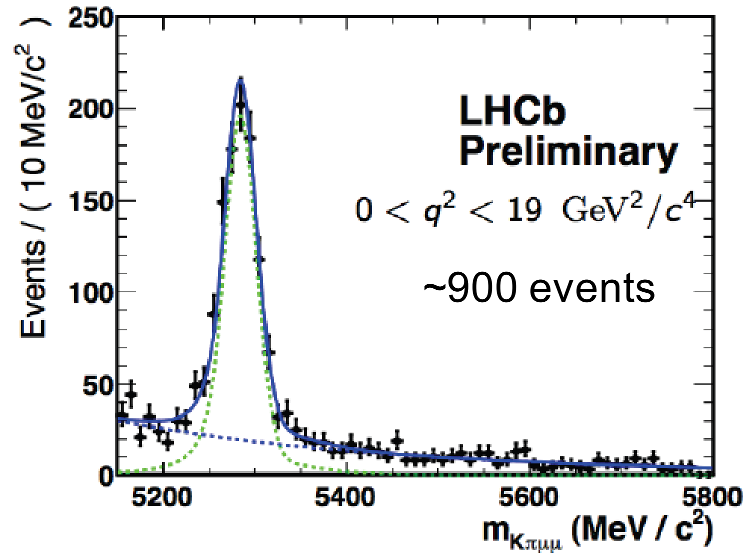
$B^0 \to K^*\mu^+\mu^-$ at LHCb

LHCb-CONF-2012-008

Selection uses Boosted Decision Tree trained on J/ΨK* (signal proxy) & sidebands

Veto decays in J/Ψ and Ψ(2S) resonance regions



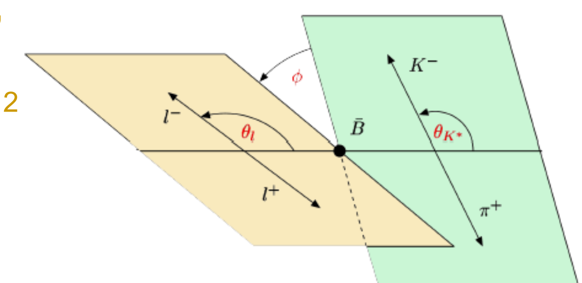


Sample as large as sum of those of all previous experiments

Measure in 6 q^2 bins:

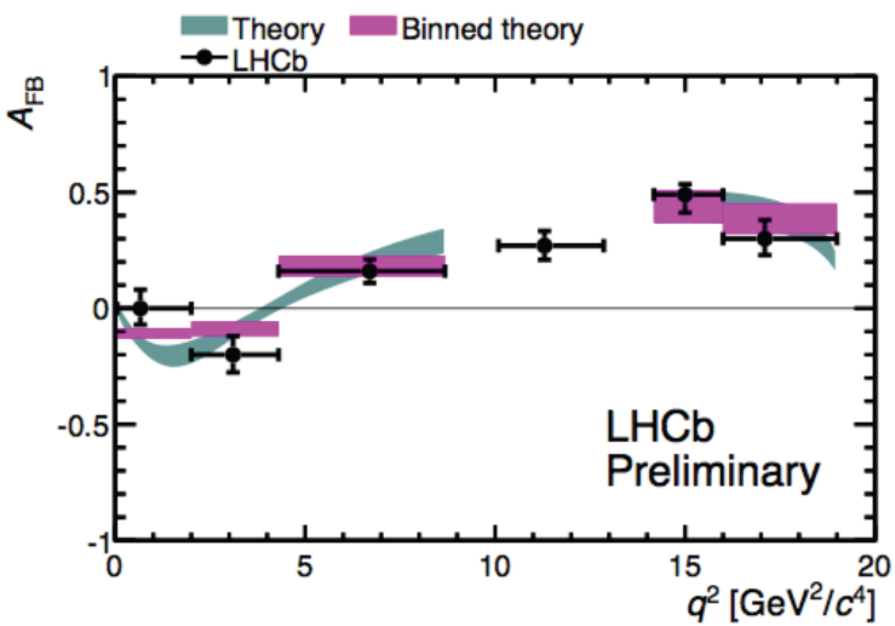
- differential branching fraction, $d\Gamma/dq^2$
- A_{FB}
- & several other observables...

Unbinned LL fit to mass, Θ_l, θ_K & φ in bins of q^2

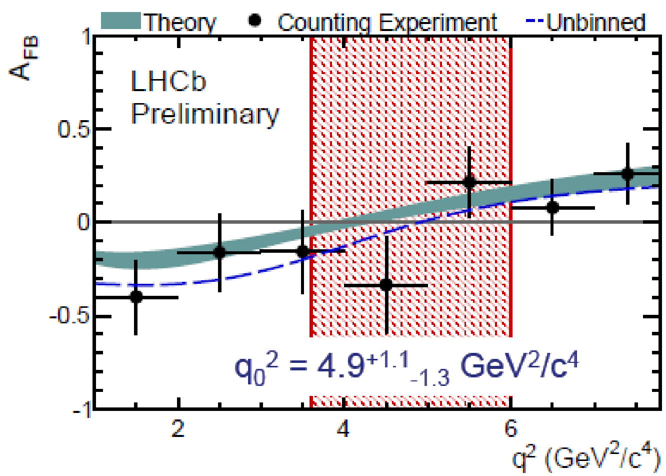


A_{FB} in $B^0 \rightarrow K^*\mu^+\mu^-$ in LHCb with 1 fb^{-1}

Systematic uncertainties are small, and generally themselves statistics limited.



0-crossing point, q_0^2, theoretically clean. Extracted from 2-D fit to forward & backward going mass & q^2 distributions



Data consistent ('textbook'!) with SM predictions at present sensitivity. Next tasks:

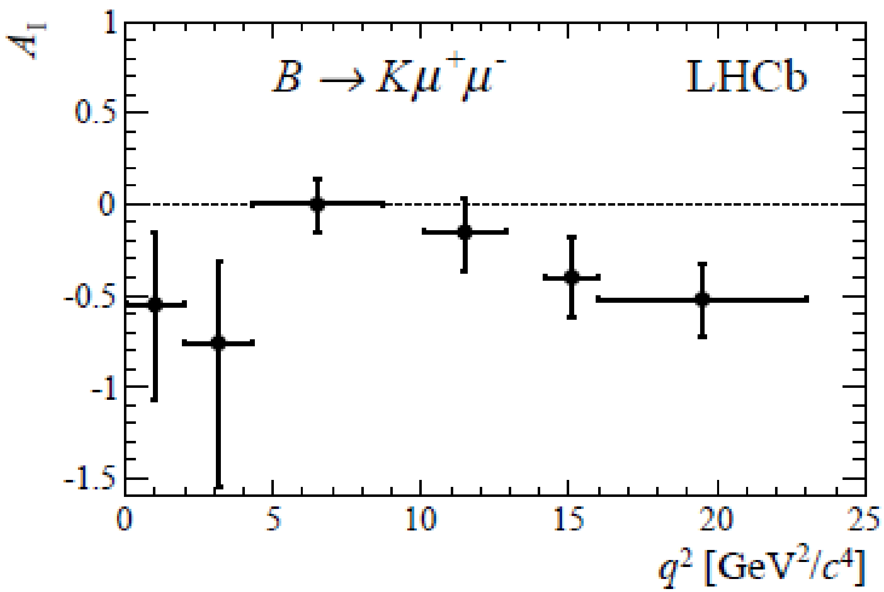
- improve precision...
- measure CP asymmetry
- full angular fit to extract complete set of observables – there are *many*, sensitive to different classes of New Physics

But not all is as expected in B→Kμμ...

The isospin asymmetry $$A_{\rm I} = \frac{\mathcal{B}(B^0 \to K^{(*)0}\mu^+\mu^-) - \frac{\tau_0}{\tau_+}\mathcal{B}(B^+ \to K^{(*)+}\mu^+\mu^-)}{\mathcal{B}(B^0 \to K^{(*)0}\mu^+\mu^-) + \frac{\tau_0}{\tau_+}\mathcal{B}(B^+ \to K^{(*)+}\mu^+\mu^-)}$$

is expected to be very close to zero in SM (but rises for $q^2 < 1$ GeV^2 in B→K*μμ)

But LHCb result for B→Kμμ does not exhibit this behaviour! [JHEP 07 (2012) 133]



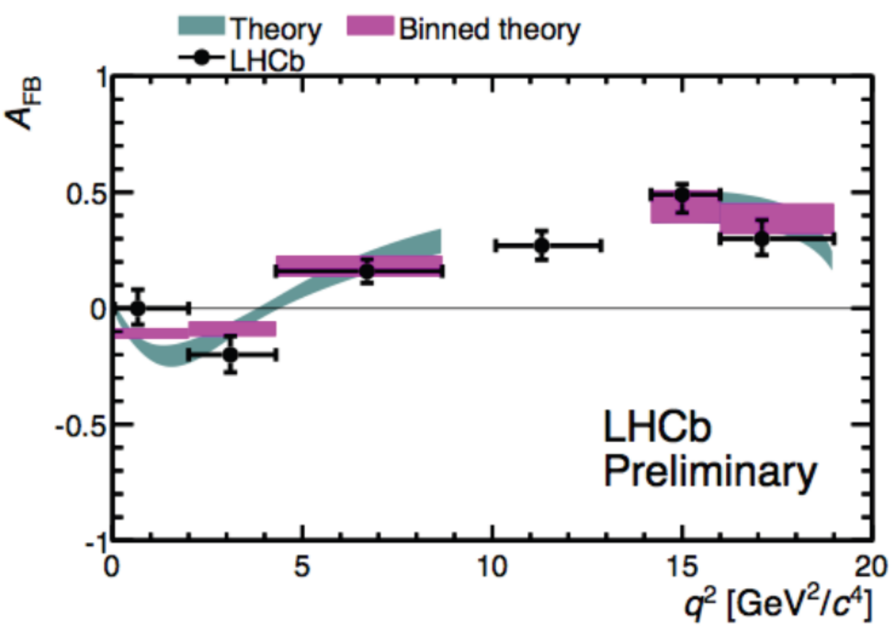
This tendency hinted at by previous, more imprecise measurements, which - on this occasion – LHCb confirms

Intriguing, particularly since asymmetry *is* consistent with 0 in B →K*μμ

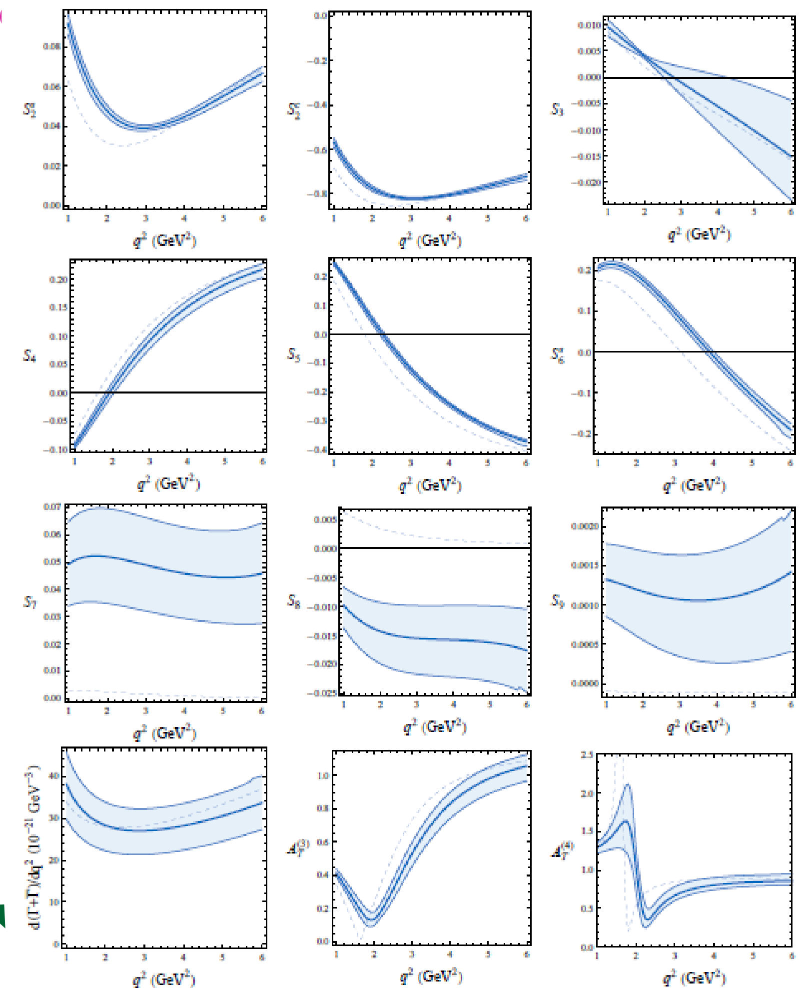
Needs improved measurements, & further reflection, to make sense of

A_{FB} in $B^0 \rightarrow K^* \mu^+ \mu^-$ in LHCb with 1 fb^{-1}

Systematic uncertainties are small, and gen



[Altmannshofer et al., JHEP 0901 (2009) 019]



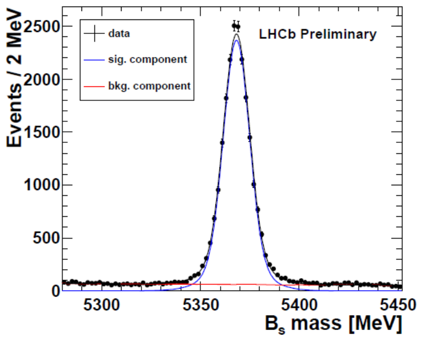
Data consistent ('textbook'!) with predictions

- improve precision...
- measure CP asymmetry
- full angular fit to extract complete set of observables – there are *many*, sensitive to different classes of New Physics

$B_s \to J/\Psi\varphi$ with 1 fb^{-1} at LHCb

LHCb-CONF-2012-002

To measure φ_s in $B_s \to J/\Psi\varphi$ require:

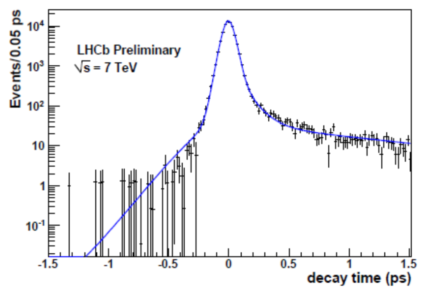


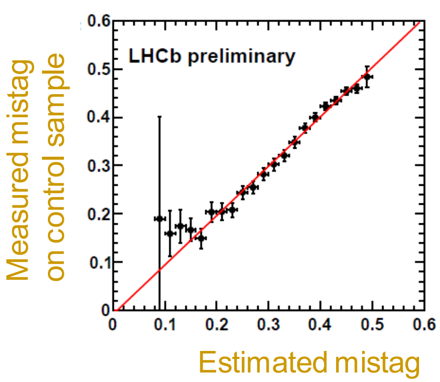
Large, clean, sample

~21k events

Excellent proper time resolution

$\sigma_T \sim 45\ ps^{-1}$

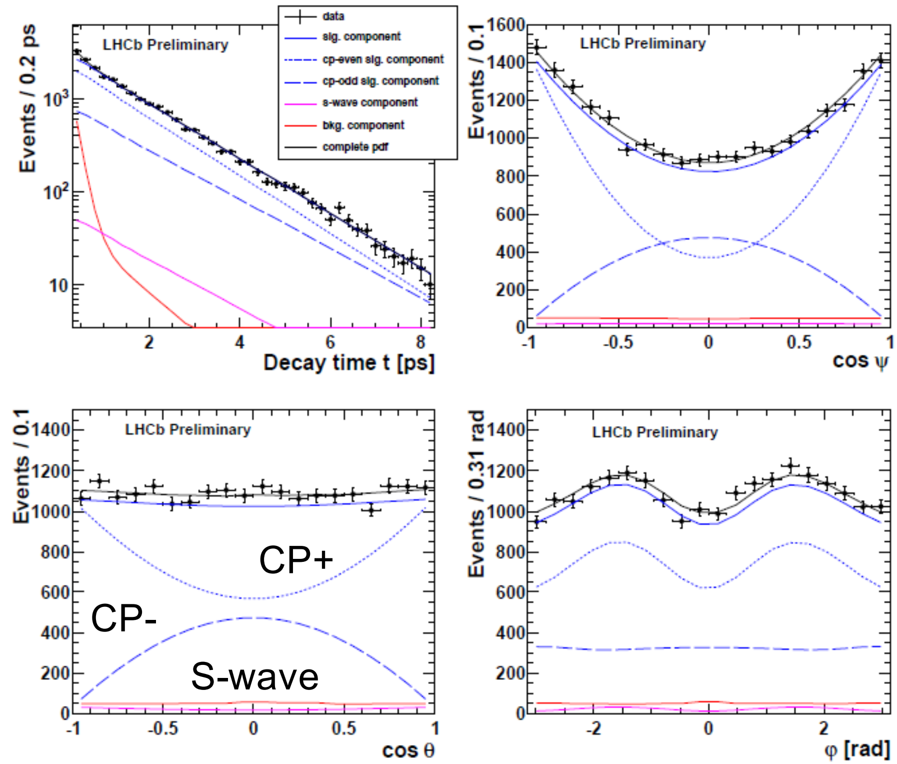




Good, well understood flavour-tagging of initial state

$\varepsilon_{tag} \sim 2.3\%$

Then perform time-dependent angular fit



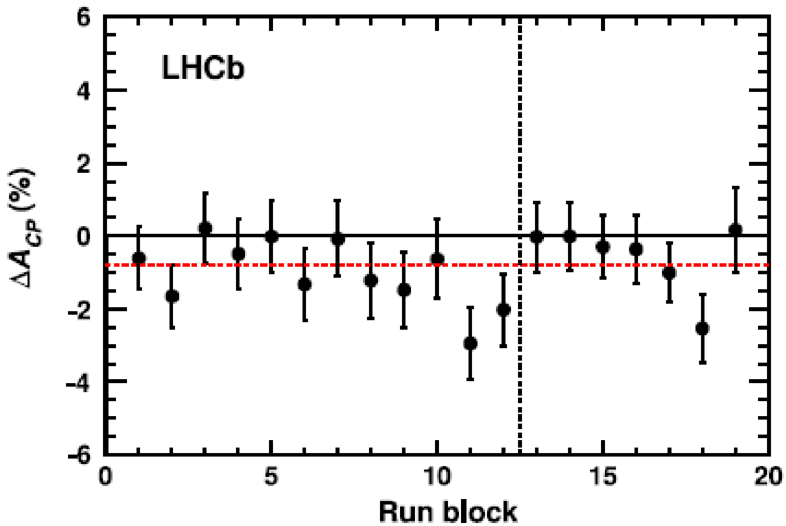
Why angular fit? Need to use decay kinematics to isolate different angular momentum contributions (CP eigenstates) since $B_s \to J/\Psi\varphi$ is a $P \to VV$ decay

ΔA_{CP} – the result

[PRL 108 (2012) 111602]

Numerous cross-checks performed

- dividing between polarities
- checking there is no dependence on kinematics of D meson, or proper time
- checking there is no dependence on data taking period



Systematics small, as largely statistical in nature (e.g. can decrease in future).

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

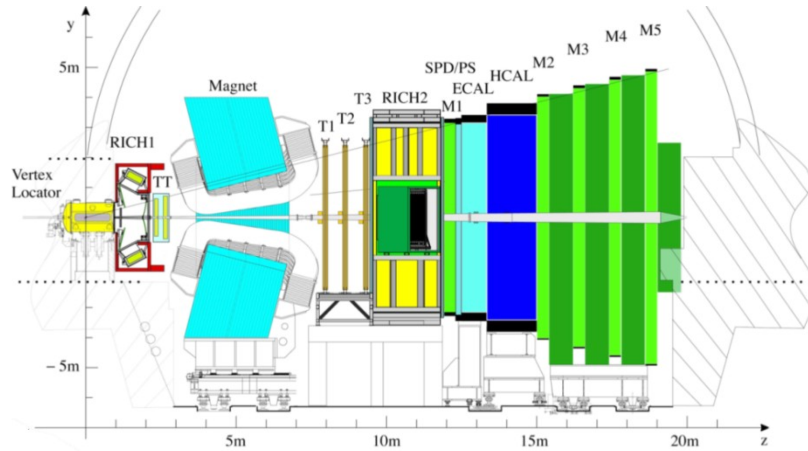
A 3.5σ effect – constitutes first evidence of CP-violation in charm decays. If real, it is (almost certainly) direct CPV, as indirect CPV (almost) cancels in difference

(Note also recent preliminary CDF result: -0.62 +- 0.21 +- .10% [CDF note 10784])

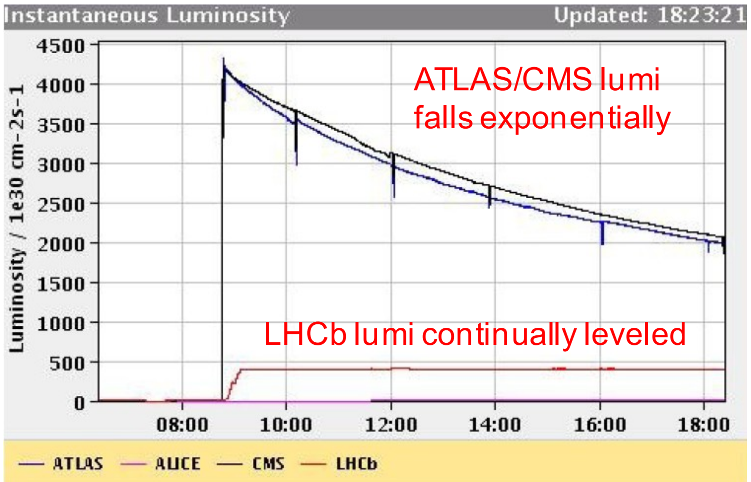
LHCb – the essentials

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)



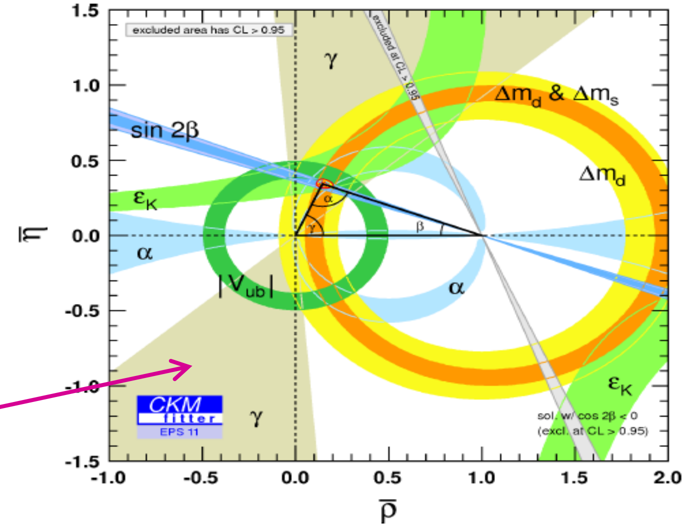
LHCb operation proceeds in harmony with higher luminosity operation of ATLAS/CMS thanks to luminosity leveling



- 37 pb^{-1} collected in 2010
- 1 fb^{-1} in 2011
- so far >0.35 fb^{-1} in 2012 – hope for 1.5 fb^{-1}
- aim for ~6.5 fb^{-1} before 2018-19 shutdown

56 journal papers submitted or accepted; 81 conference papers

Precision CKM-metrology: the next challenge



B-factories (& others) have done a great job in mapping out unitarity triangle. But progress needs improved knowledge of angle γ (a.k.a. φ_3)

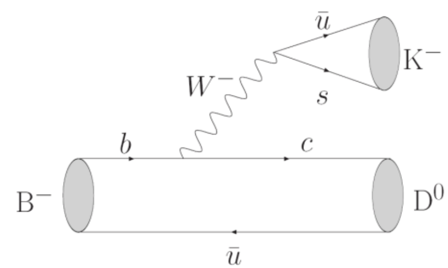
Look in $B^\pm \to DK^\pm$ decays using common mode for D^0 & $\bar{D}^0$

→ γ sensitive interference

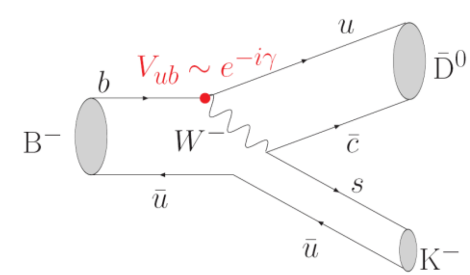
→ different rates for B^+ & B^- (CPV!)

Many possibilities: Kπ, KK, $K_S\pi\pi$...

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→hh)

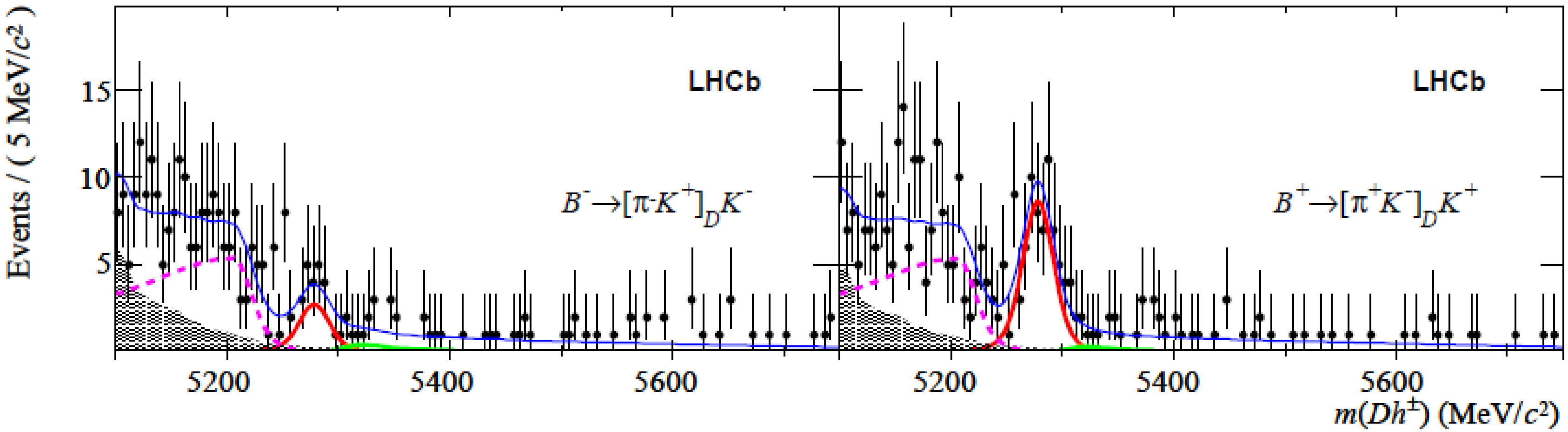
Current measurement error ~ 12° ; indirect (e.g. loops) precision ~4° (& improving...)

CKM metrology at LHCb: playing the long game

Precise CKM metrology at LHCb, most importantly measurement of γ, but also improved β precision, will be in the long-term a critical factor in the search for NP

Important first step – first observation of the suppressed 'ADS' mode $B^\pm \to (K^\mp\pi^\pm)K^\pm$

Highly suppressed (visible BR ~10^{-7}) & not seen at 5σ with full B-factory dataset



[PLB 712 (2012) 203]

LHCb sees mode with ~10σ stat significance. As expected, it has a very large CP asymmetry $-0.52 \pm 0.15 \pm 0.02$ which will be critical input in LHCb γ measurement.

New B→DK results with other modes ($K_S\pi\pi$, K_SKK, $K\pi\pi\pi$...) coming *very* soon, together with complementary measurements from B_s system ($B_s \to D_sK$)

→Anticipated sensitivity by 2018 ~ 3-4° (i.e. matching current indirect precision)

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

Courtesy Browder and Soni

"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"

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

Upgrade expectations

Type	Observable	Current precision	LHCb 2018	**Upgrade** ($50\,\mathrm{fb}^{-1}$)	Theory uncertainty
B_s^0 mixing	$2\beta_s\ (B_s^0 \to J/\psi\ \phi)$	0.10 [30]	0.025	0.008	~ 0.003
	$2\beta_s\ (B_s^0 \to J/\psi\ f_0(980))$	0.17 [32]	0.045	0.014	~ 0.01
	a_{sl}^s	6.4×10^{-3} [63]	0.6×10^{-3}	0.2×10^{-3}	0.03×10^{-3}
Gluonic penguins	$2\beta_s^{\mathrm{eff}}(B_s^0 \to \phi\phi)$	–	0.17	0.03	0.02
	$2\beta_s^{\mathrm{eff}}(B_s^0 \to K^{*0}\bar{K}^{*0})$	–	0.13	0.02	< 0.02
	$2\beta^{\mathrm{eff}}(B^0 \to \phi K_S^0)$	0.17 [63]	0.30	0.05	0.02
Right-handed currents	$2\beta_s^{\mathrm{eff}}(B_s^0 \to \phi\gamma)$	–	0.09	0.02	< 0.01
	$\tau^{\mathrm{eff}}(B_s^0 \to \phi\gamma)/\tau_{B_s^0}$	–	5 %	1 %	0.2 %
Electroweak penguins	$S_3(B^0 \to K^{*0}\mu^+\mu^-; 1 < q^2 < 6\,\mathrm{GeV}^2/c^4)$	0.08 [64]	0.025	0.008	0.02
	$s_0\, A_{\mathrm{FB}}(B^0 \to K^{*0}\mu^+\mu^-)$	25 % [64]	6 %	2 %	7 %
	$A_{\mathrm{I}}(K\mu^+\mu^-; 1 < q^2 < 6\,\mathrm{GeV}^2/c^4)$	0.25 [9]	0.08	0.025	~ 0.02
	$\mathcal{B}(B^+ \to \pi^+\mu^+\mu^-)/\mathcal{B}(B^+ \to K^+\mu^+\mu^-)$	25 % [29]	8 %	2.5 %	~ 10 %
Higgs penguins	$\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	1.5×10^{-9} [4]	0.5×10^{-9}	0.15×10^{-9}	0.3×10^{-9}
	$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	–	~ 100 %	~ 35 %	~ 5 %
Unitarity triangle angles	$\gamma\ (B \to D^{(*)}K^{(*)})$	~ 10–$12°$ [40, 41]	4°	0.9°	negligible
	$\gamma\ (B_s^0 \to D_s K)$	–	11°	2.0°	negligible
	$\beta\ (B^0 \to J/\psi\, K_S^0)$	0.8° [63]	0.6°	0.2°	negligible
Charm CP violation	A_Γ	2.3×10^{-3} [63]	0.40×10^{-3}	0.07×10^{-3}	–
	ΔA_{CP}	2.1×10^{-3} [8]	0.65×10^{-3}	0.12×10^{-3}	–