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

LHCb – the essentials

The famous five – selected flavour observables sensitive to New Physics

- what did we hope for ?
- where are we after 1 fb^{-1} ?
- where do we hope to be in a few years time?

The final frontier – the LHCb upgrade

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IMFP, Benasque, 31/5/12

on behalf of the LHCb collaboration

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:

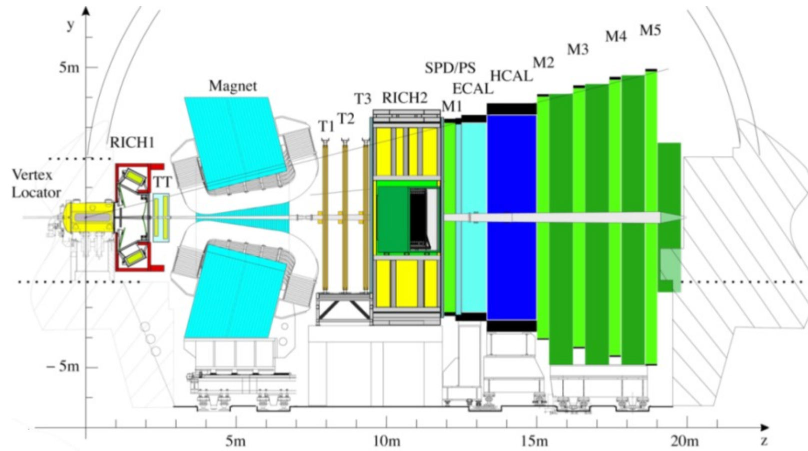
- Kaon mixing, BR($K^0_L \to \mu\mu$) & GIM → prediction of charm
- CP violation → need for a third generation
- B mixing → mass of top is very heavy
- SUSY parameter space already severely constrained by e.g. $b \to s\gamma$

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

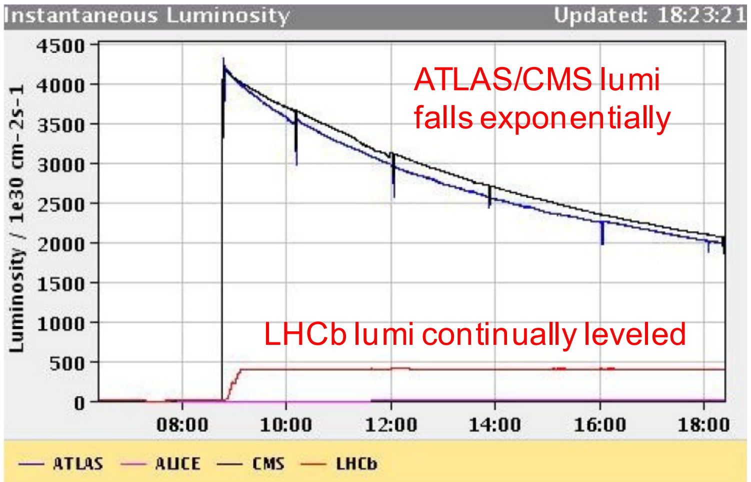
LHCb – the essentials

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

Five potential game-changers – possible roads to NP in the LHC era

- CP violation in B_s mixing
- BR($B_s \to \mu^+\mu^-$)
- Observables in $B \to K^{(*)}\mu^+\mu^-$
- CP violation in charm
- Precise CKM metrology

These are *selected* topics!
Many other examples exist.

What did we hope for? Where are we after 1 fb^{-1}? Where will we be in 2018?

Five potential game-changers – possible roads to NP in the LHC era

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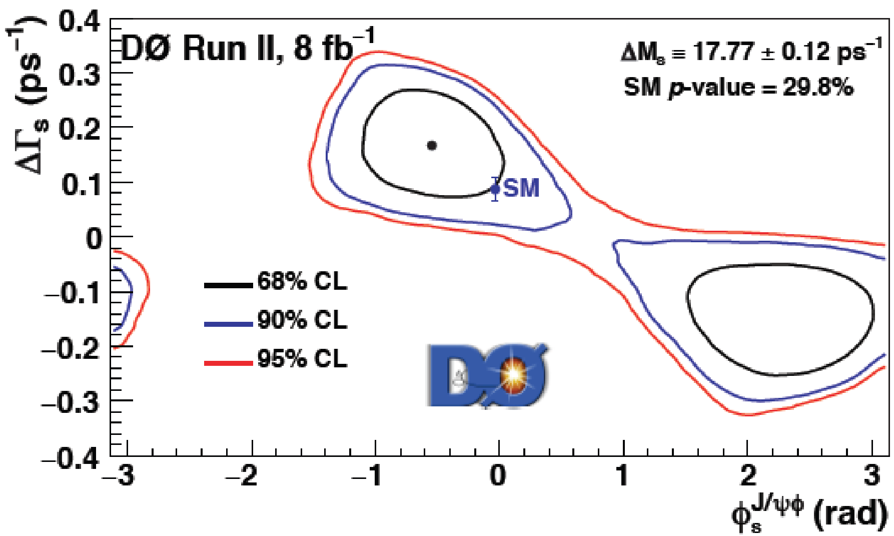
Mixing induced CPV in B_s system

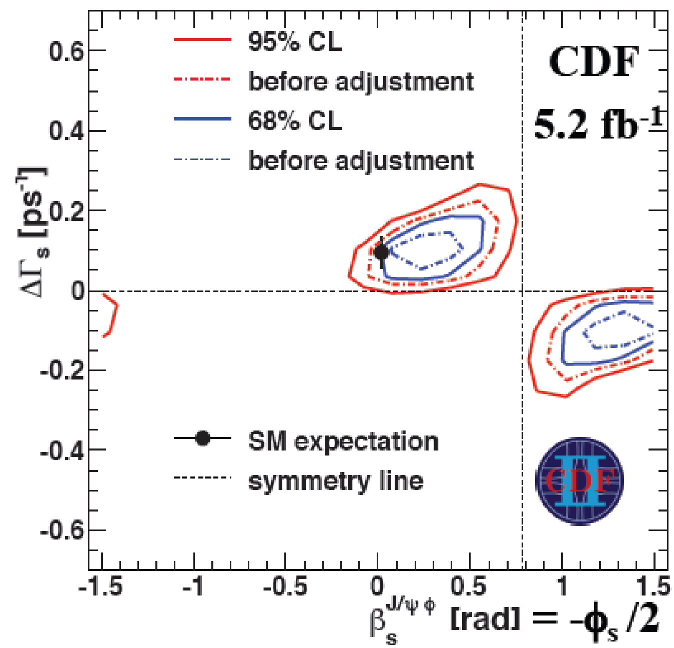
CPV phase, φ_s, in B_s mixing-decay interference, e.g. measured in $B_s \rightarrow J/\Psi\Phi$, very small & precisely predicted in SM. Box diagram offers tempting entry point for NP!

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

[PRD 85 (2012) 032006]



[PRD 85 (2012) 072002]

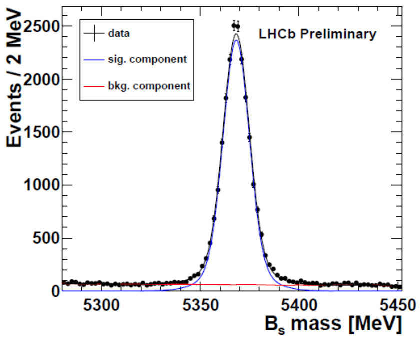


Results are consistent, & both are ~1σ away from SM. What about LHCb?

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

LHCb-CONF-2012-002

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

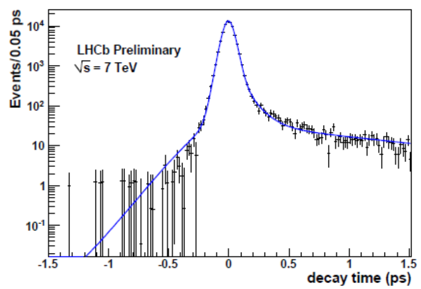


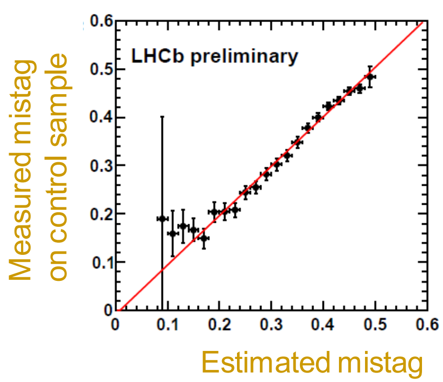
Large, clean, sample

~21k events

Excellent proper time resolution

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

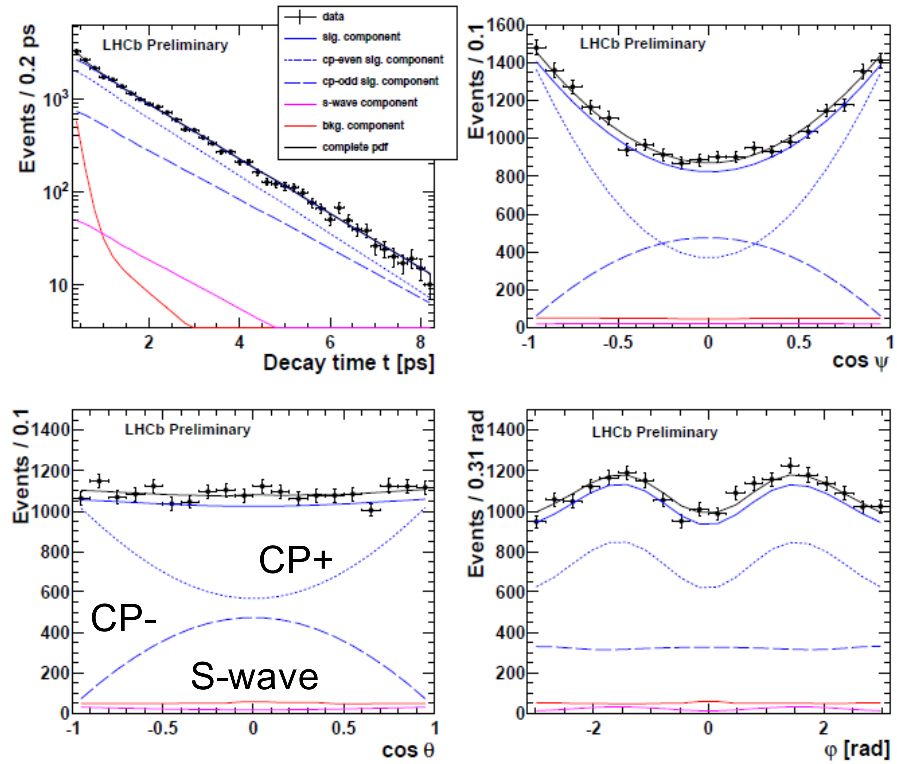




Good, well understood flavour-tagging of initial state

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

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

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

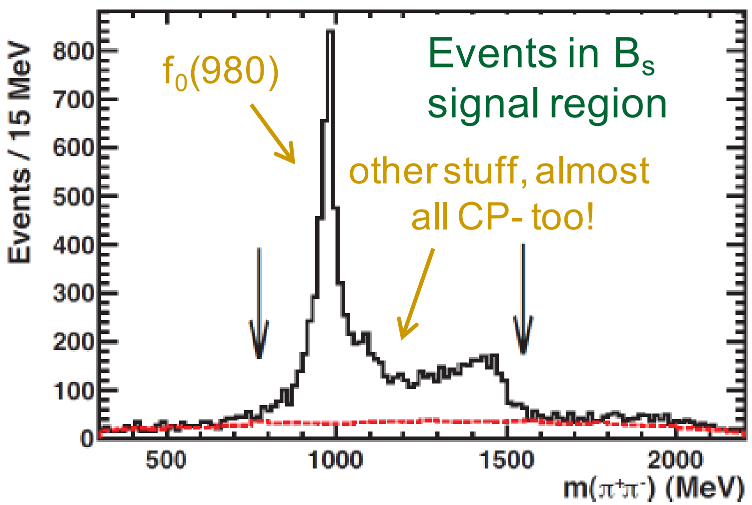
arXiv: 1204.5675

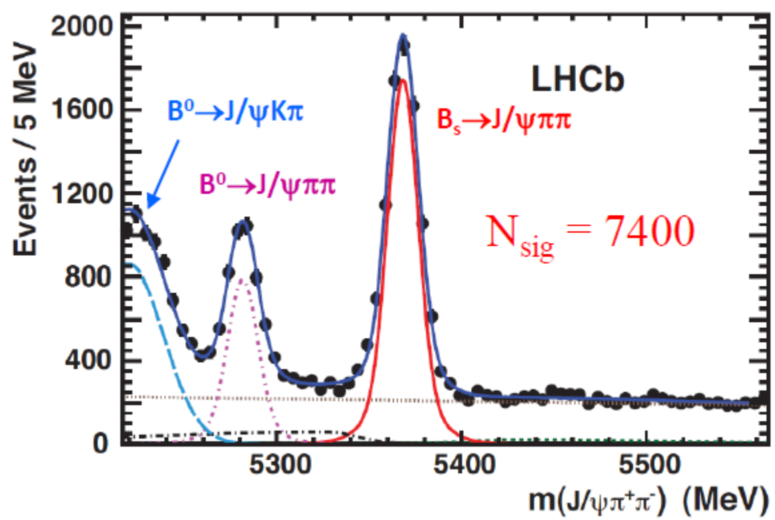
Other modes can be used to measure φ_s, in particular $B_s \to J\Psi\pi\pi$. Already early measurement with $B_s \to J/\Psi f_0(980)[\pi\pi]$ [PLB 707 (2012) 497]. Key point: this is a CP-eigenstate so no need of angular analysis. Also true for *extended* $\pi\pi$ region !

Resonance	Normalized fraction (%)	
$f_0(980)$	69.7 ± 2.3	CP odd
$f_0(1370)$	21.2 ± 2.7	CP odd
non-resonant $\pi^+\pi^-$	8.4 ± 1.5	CP odd
$f_2(1270)$, $\Lambda = 0$	0.49 ± 0.16	CP odd
$f_2(1270)$, $\|\Lambda\| = 1$	0.21 ± 0.65	← Mixed CP

arXiv:1204.5643

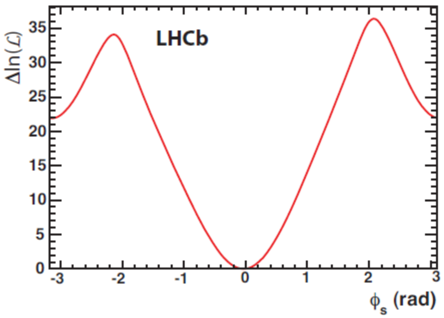
Conclusion: fraction of CP-even states <2.3% at 95% CL





LHCb 1 fb^{-1} results for φ_s

Results for $B_s \to J/\Psi\pi\pi$...



$$\phi_s = -0.019^{+0.173+0.004}_{-0.174-0.003}\,\mathrm{rad}$$

...and for $B_s \to J/\Psi\varphi$:

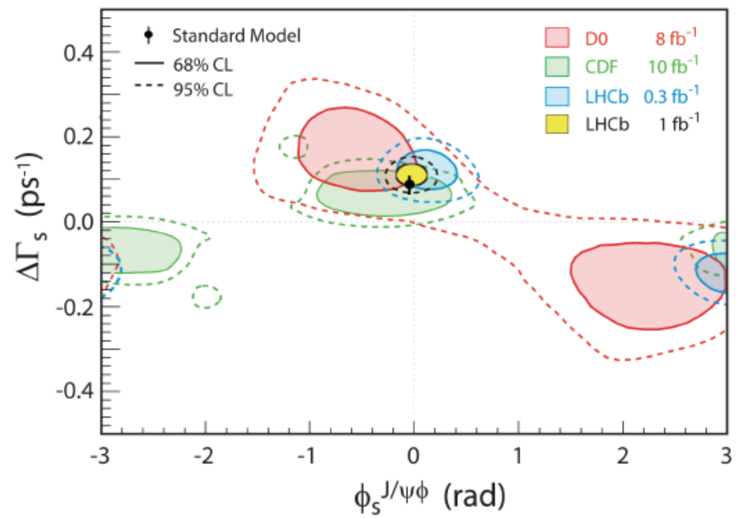
$$\phi_s = -0.001 \pm 0.101 \ (\mathrm{stat}) \pm 0.027 \ (\mathrm{syst}) \ \mathrm{rad}$$
$$\Delta\Gamma_s = 0.116 \pm 0.018 \ (\mathrm{stat}) \pm 0.006 \ (\mathrm{syst}) \ \mathrm{ps}^{-1}$$

A big improvement on previous results, and also first direct observation of a non-zero value for $\Delta\Gamma_s$!

Preliminary combination [LHCb-CONF-2012-004]:

$$\boxed{\phi_s^{\mathrm{combined}} = -0.002 \pm 0.083(\mathrm{stat}) \pm 0.027(\mathrm{syst})\ \mathrm{rad}}$$

SM: φ_s= -0.036 +- 0.002 rad [PRL 84 (2011) 03305]



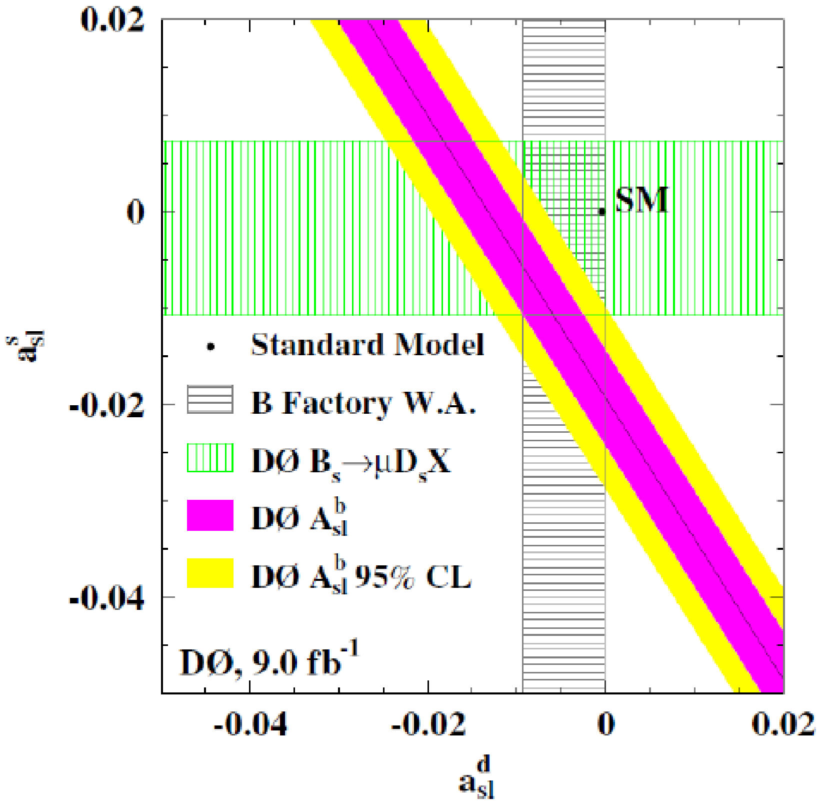
Clear message: no big non-SM effects in φ_s. However a priori worth of observable for NP search remains. Must improve precision! By 2018 it should be similar to SM central value.

(Ambiguous solution eliminated by LHCb study [arXiv:1202.4717])

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 84 (2011) 052007]



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

Result lies 3.9σ from SM.

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

More measurements urgently needed !

LHCb finalising a time integrated study of $B_s \to D_s(\varphi\pi)\mu\nu$ decays to measure a^s_{sl}

Stay tuned !

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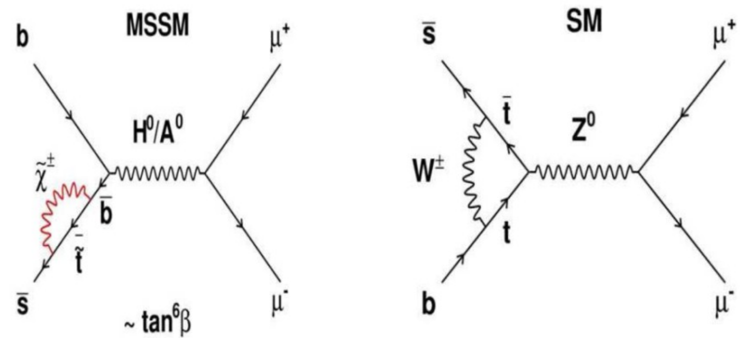
The golden mode: $B_s \rightarrow \mu\mu$

B physics rare decay par excellence:

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

[A.J.Buras, arXiv:1012.1447]

Precise prediction (which will improve) !

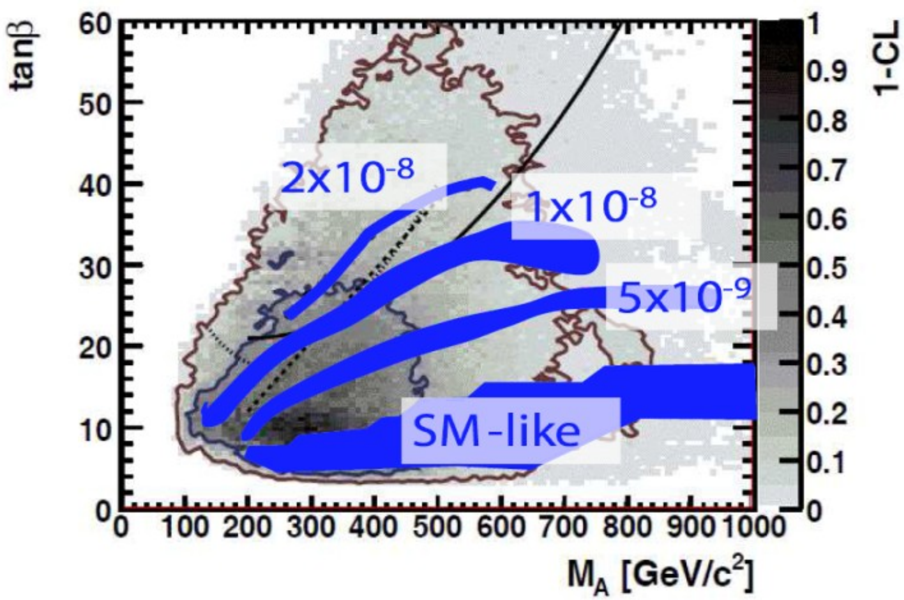


Very high sensitivity to NP, eg. MSSM:

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

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

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



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

CDF (3.7 fb^{-1}): < 4.3×10^{-8}

D0 (6.1 fb^{-1}): < 5.1×10^{-8}

LHCb (37 pb^{-1}): < 5.6×10^{-8}

Plenty of space left for NP to hide!

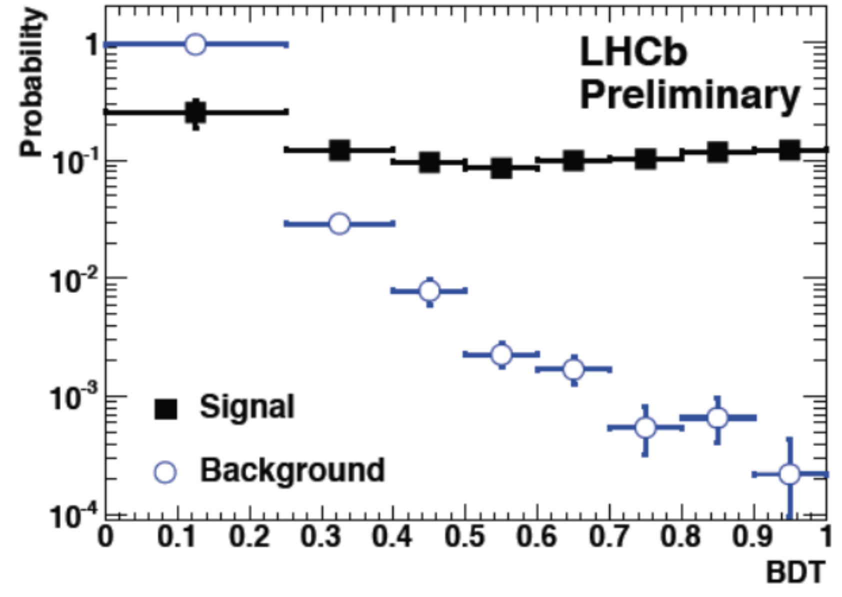
2011 $B_s \to \mu^+\mu^-$ search at LHCb with 1 fb^{-1}

Strategy very similar to earlier analyses
[PLB 699 (2011) 330, PLB 708(2012) 55]
After preselection:

- Build Boosted Decision Tree out of 9 kinematical and topological variables

  Train BDT on MC, but calibrate on data:

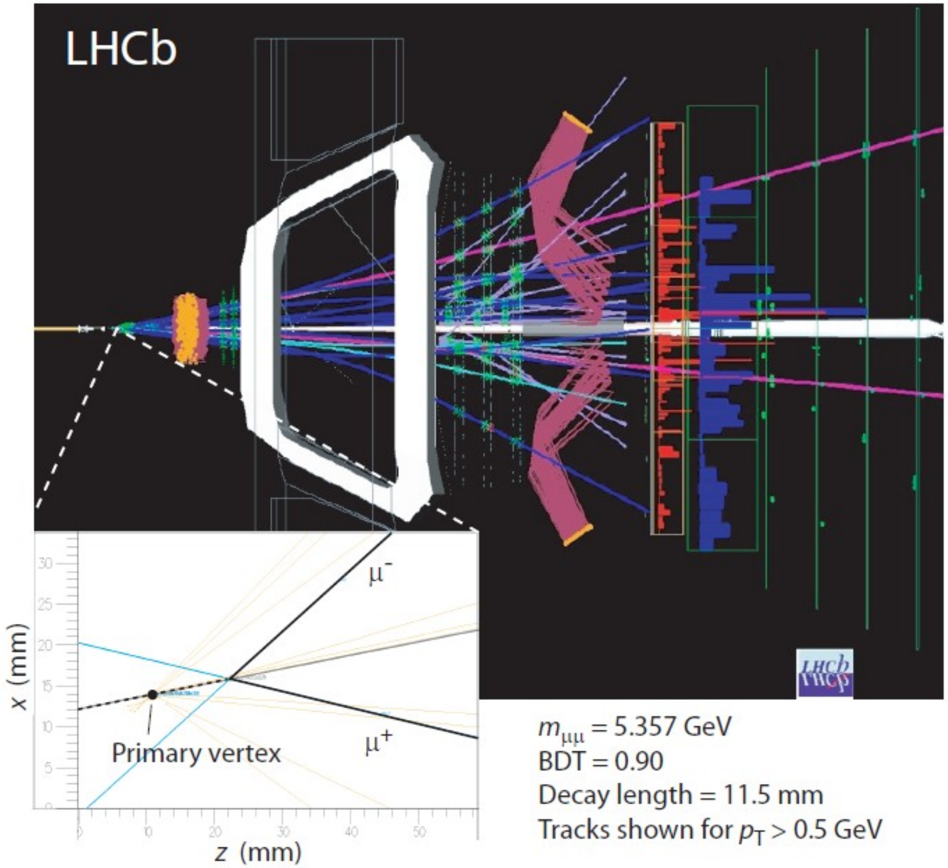
  - signal response: use $B \to hh$ decays triggered on 'other B' (avoid biases!)
  - background response: use sidebands



- Invariant mass of expected signal parameterised as crystal ball, with scale & resolution (~25 MeV) calibrated from data (dimuon resonances & $B \to hh$)
- Now look in a 9 x 8 grid of $\mu^+\mu^-$ invariant mass vs BDT output
- To obtain relative BR for signal use three normalisation channels: $B^+ \to J/\Psi K^+$, $B_s \to J/\Psi \varphi$ and $B^0 \to K\pi$ – all give consistent results

Entering the signal regime

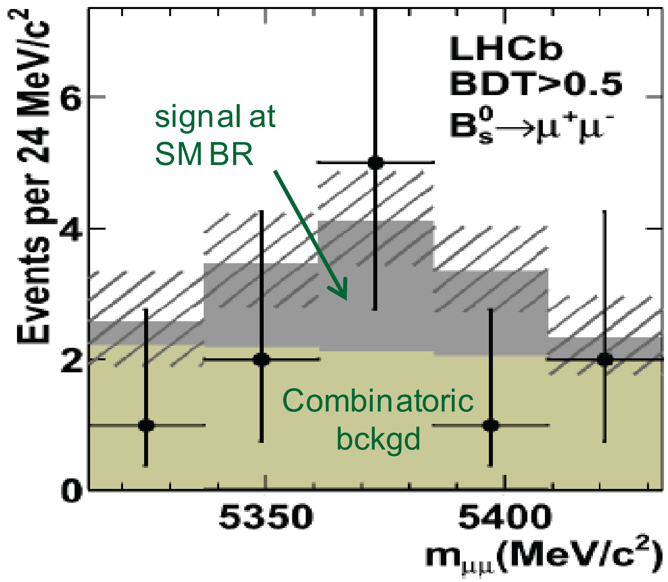
Even at the SM branching ratio LHCb expects to accumulate $B_s \rightarrow \mu\mu$ decays in 2011 data (~12 after pre-selection). And indeed plausible candidates are seen!



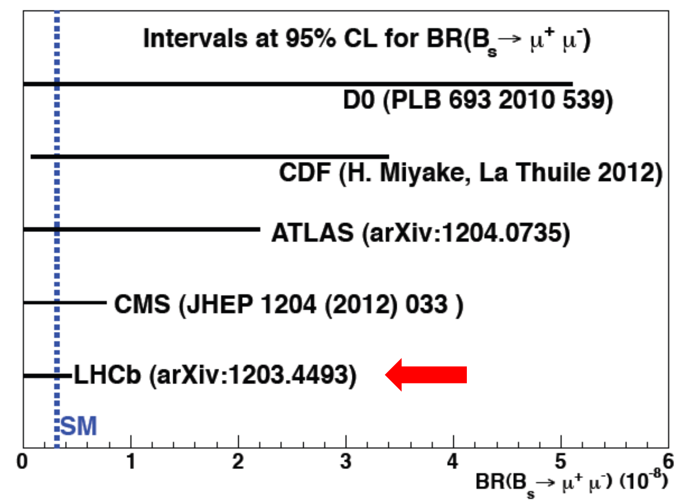
LHCb $B_s \to \mu\mu$ results with 1 fb^{-1}

arXiv:1203.4493

No excess seen – e.g for BDT>0.5... 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	$\boxed{4.5 \times 10^{-9}}$



Limit now very close to SM – no large NP enhancements. Big consequences for NP parameter space (→Nazilla)

Now the game changes – LHCb must prepare for performing a precision measurement to test if BR is *really* SM. Potential for ~15% stat error by 2018. Data driven analysis well equipped for keeping systematics under control

Common message from φ_s and $B_s \rightarrow \mu\mu$ studies after 1 fb^{-1}

There seems to be no ‘low hanging fruit’ so we’ll have to climb higher.

That’s OK, as the view will be better !

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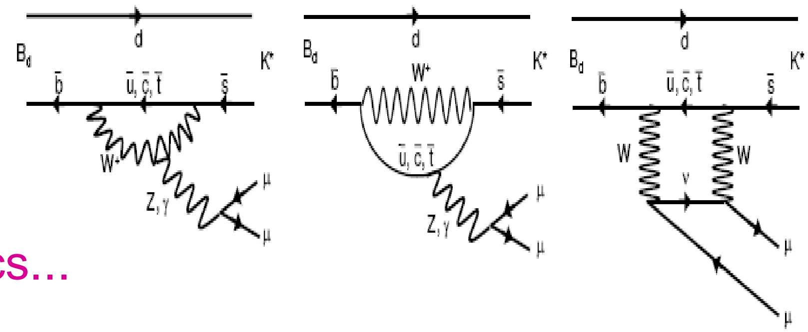
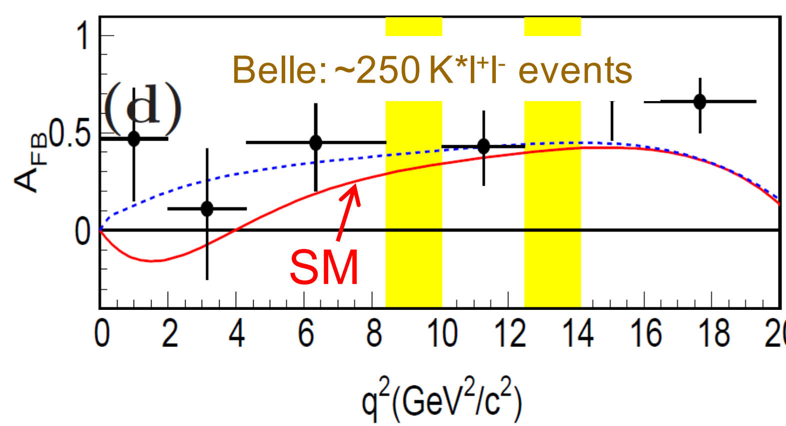
$B^0 \to K^* l^+ l^-$



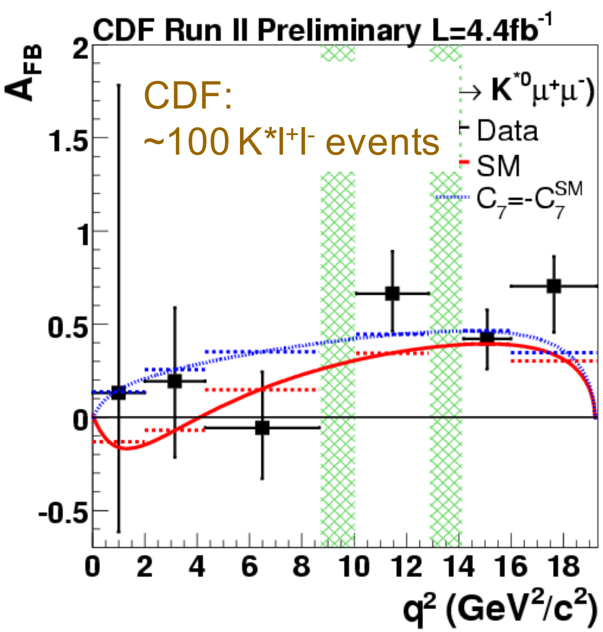
Many observables exist in $B^0 \to K^* l^+ l^-$ to probe helicity structure of any New Physics...

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

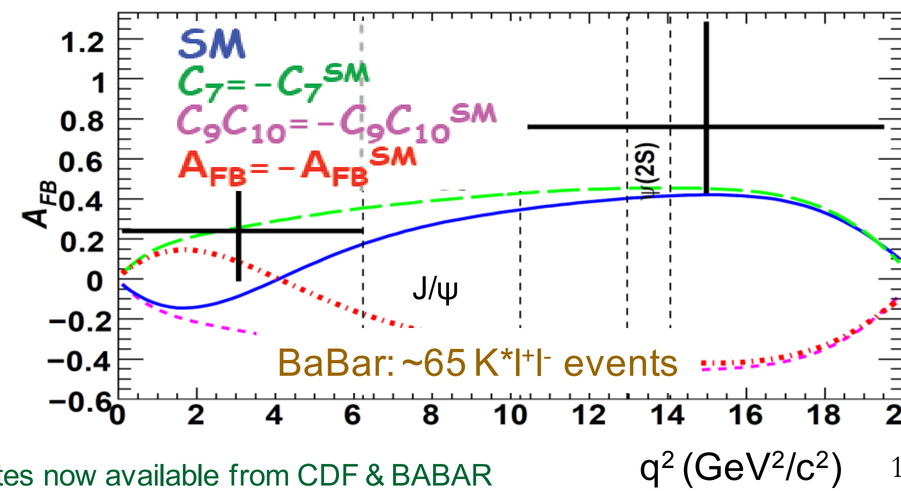
Early results from CDF & B-factories* show intriguing behaviour at low q^2, But precision too low yet to speak of an ‘anomaly’



PRL 103 (2009) 171801



CDF note 10047



PRD 79 (2009) 031102

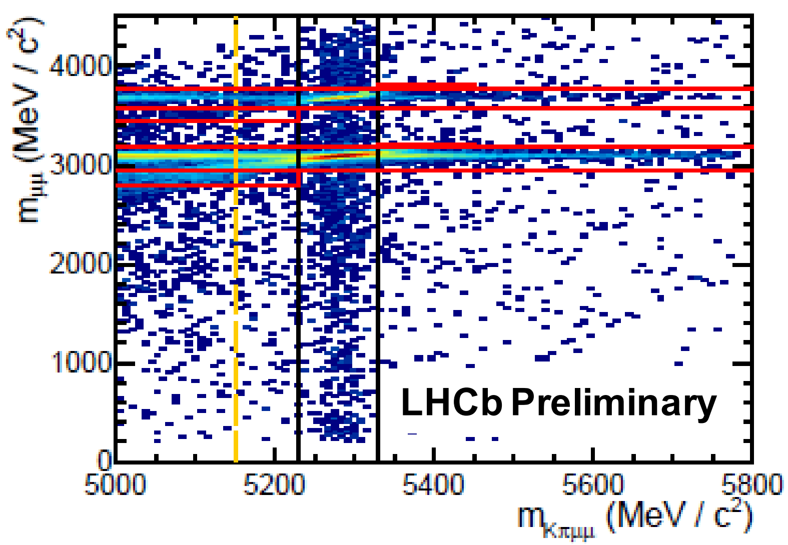
* updates now available from CDF & BABAR

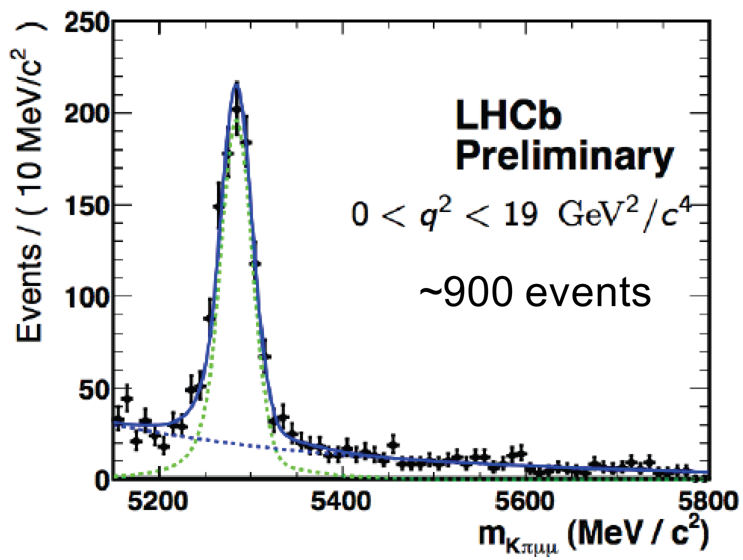
$B^0 \to K^* \mu^+ \mu^-$ at LHCb

LHCb-CONF-2012-008

Selection uses Boosted Decision Tree trained on $J/\Psi K^*$ (signal proxy) & sidebands

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

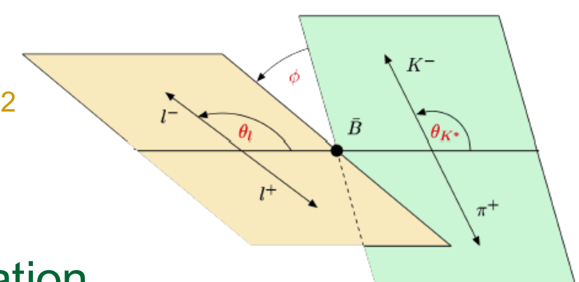




Measure in 6 q^2 bins:

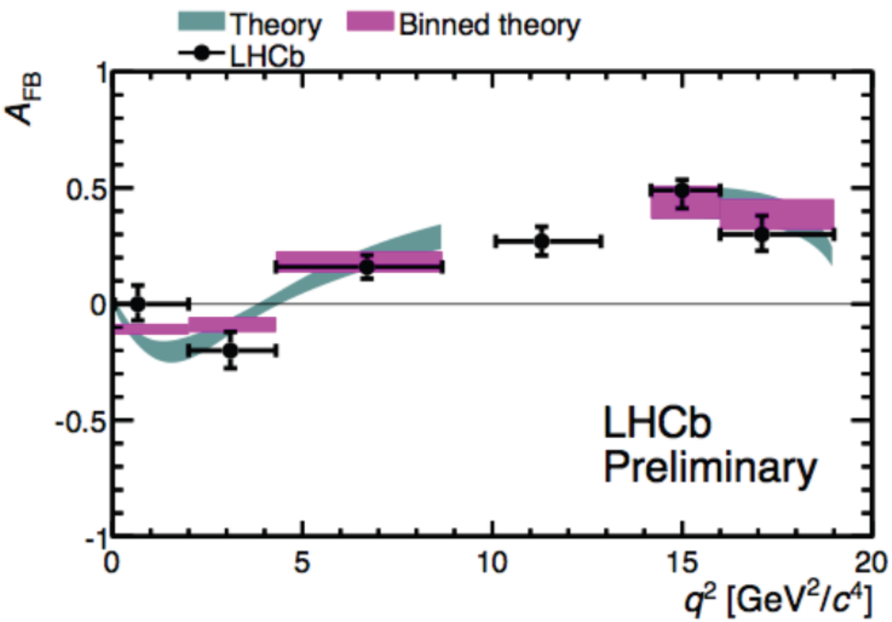
- differential branching fraction, $d\Gamma/dq^2$
- A_{FB}
- A_{IM}: T-odd CP asymmetry
- longitudinal polarisation, F_L
- S_3: asymmetry in K^* transverse polarisation

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

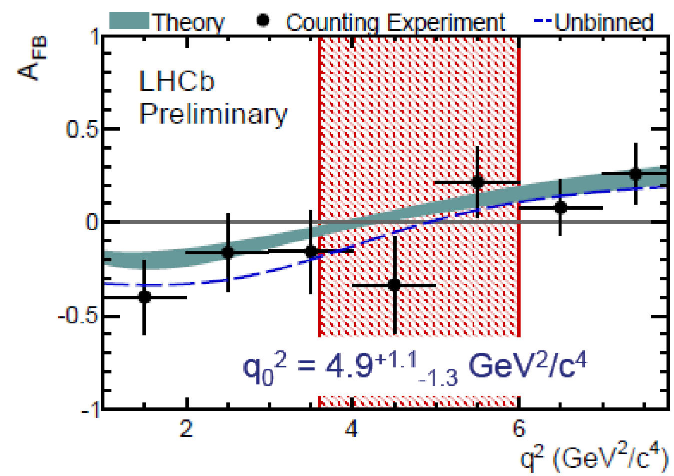


A_{FB} in $B^0 \to K^*\mu^+\mu^-$ in LHCb with 1 fb^{-1}

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

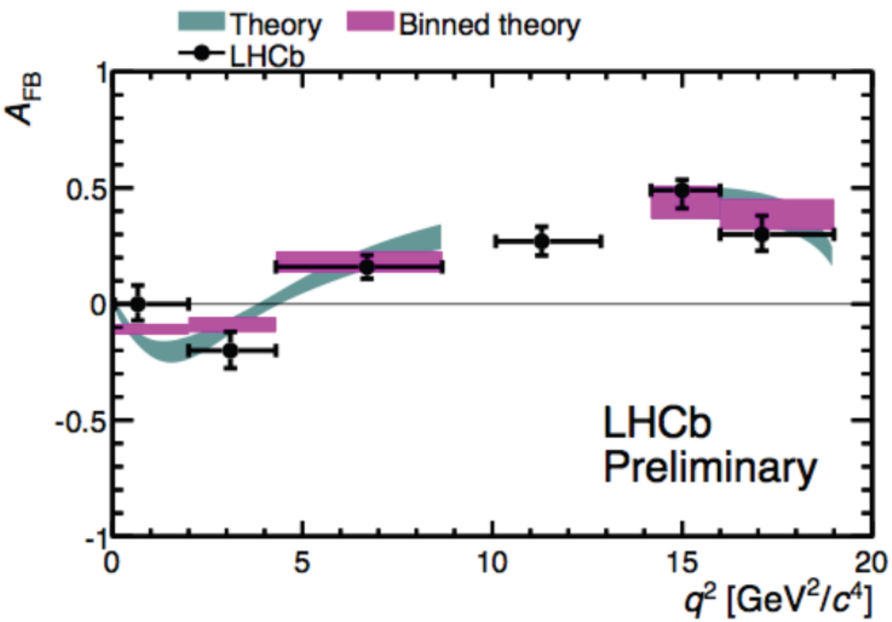


Data consistent ('textbook'!) with SM predictions at present sensitivity. Next tasks:

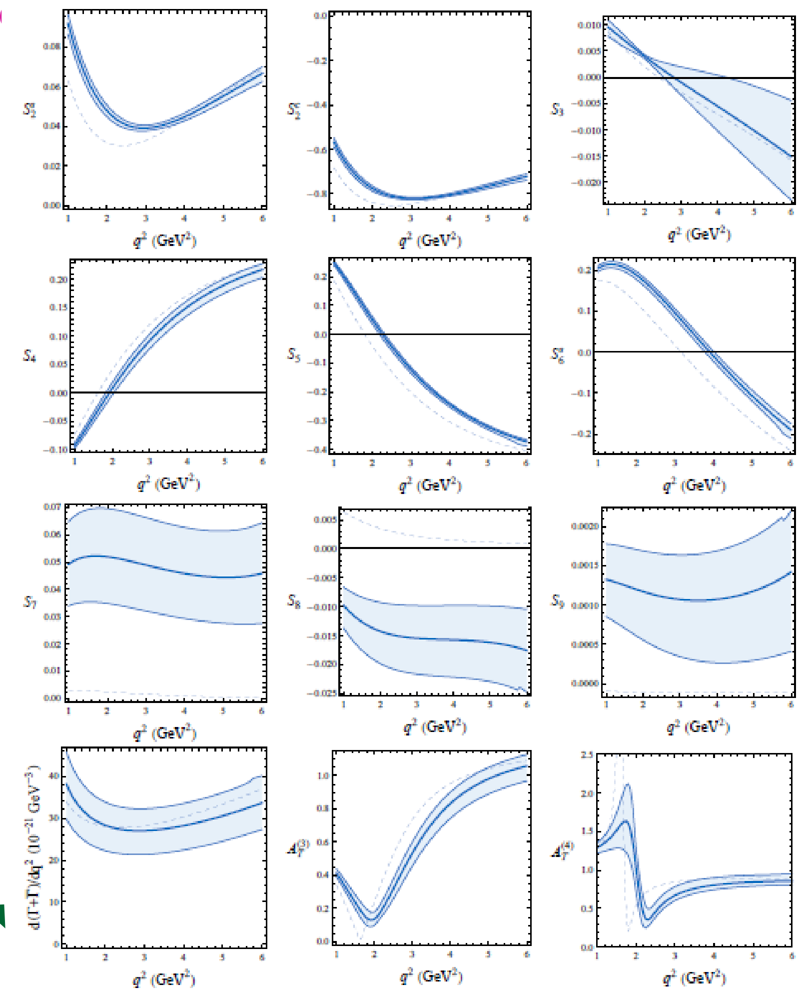
- improve precision...
- measure CP asymmetry
- full angular fit to extract complete set of observables – there are *many*, sensitive to different classes of New Physics

A_{FB} in $B^0 \to K^* \mu^+ \mu^-$ 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

Isospin asymmetries in B→K$^{(*)}$μμ

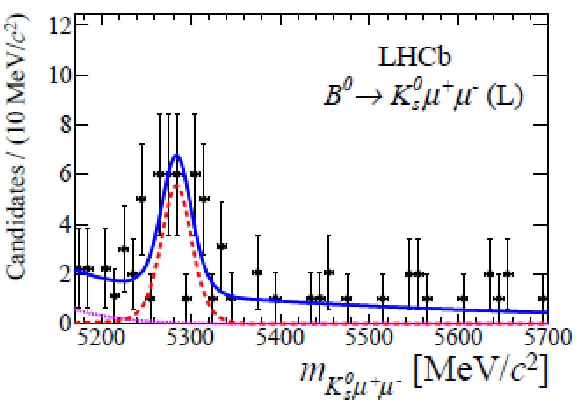
The isospin asymmetry $$A_I = \frac{\mathcal{B}(B^0 \to K^{(*)0}\mu^+\mu^-) - \frac{\tau_0}{\tau_+}\mathcal{B}(B^+ \to K^{(*)+}\mu^+\mu^-)}{\mathcal{B}(B^0 \to K^{(*)0}\mu^+\mu^-) + \frac{\tau_0}{\tau_+}\mathcal{B}(B^+ \to K^{(*)+}\mu^+\mu^-)}$$

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

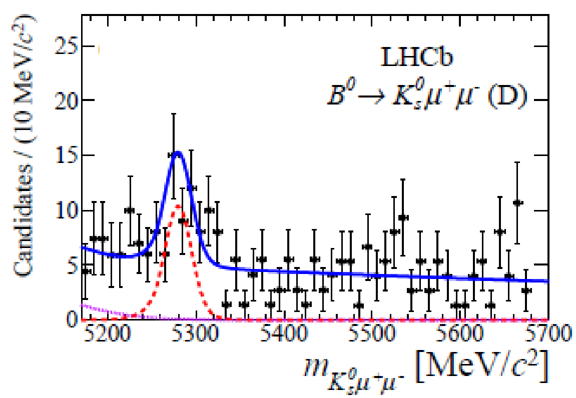
Very recently measured by LHCb [arXiv:1205.3422] making use of K_S final states

e.g. for B→Kμμ

$B^0 \to K_S \mu\mu$

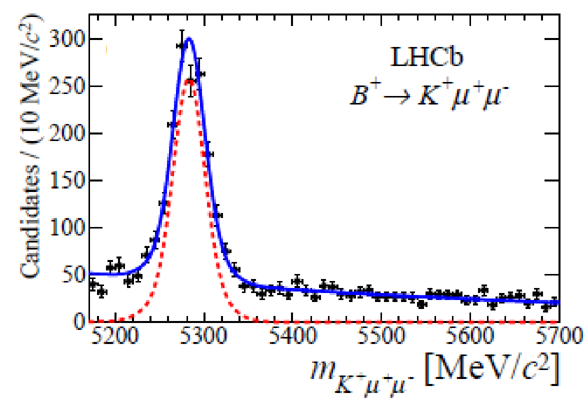


K_S decaying in VELO detector



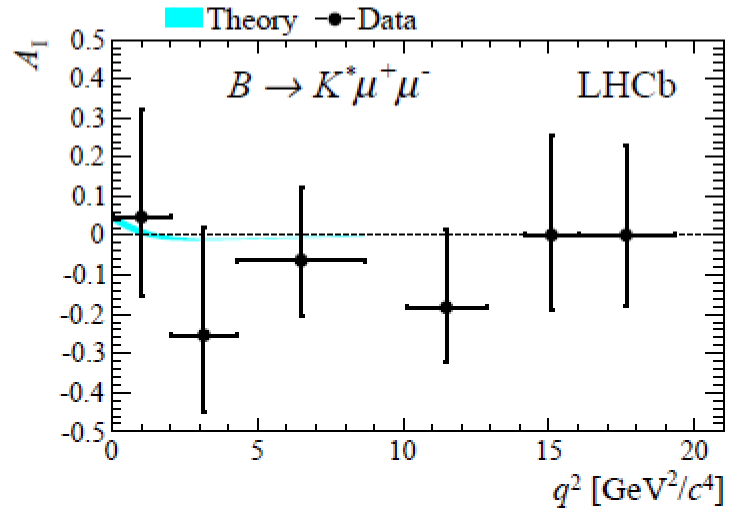
K_S decaying after VELO detector

$B^+ \to K^+\mu\mu$

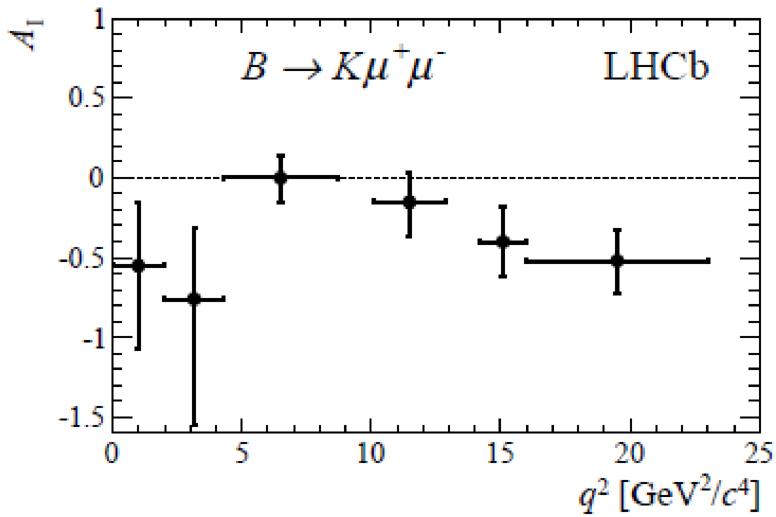


Isospin asymmetries in B→K$^{(*)}$μμ

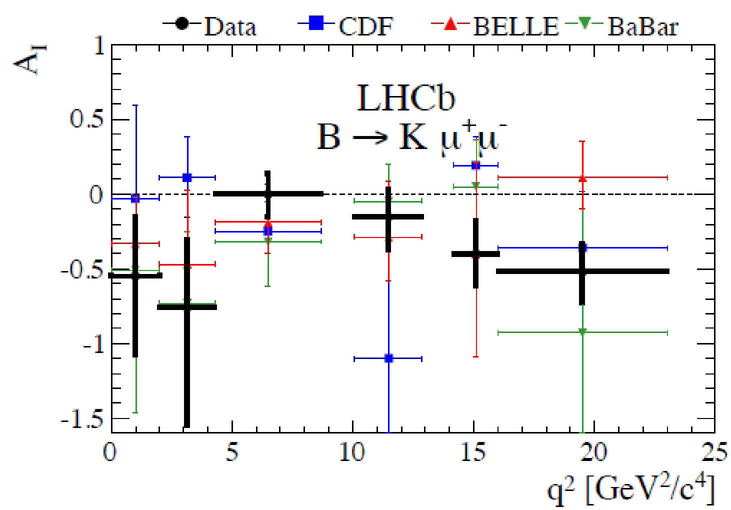
Results for B→K*μμ vs q2 of di-muons consistent with 0, as expected



But that for B→Kμμ is systematically low !
Naive average over q^2 gives 4.4σ effect,...



...one hinted at by previous experiments



This doesnt smell like New Physics (e.g. why is effect seen only in B→Kμμ?) but certainly unexpected. What is going on here ?

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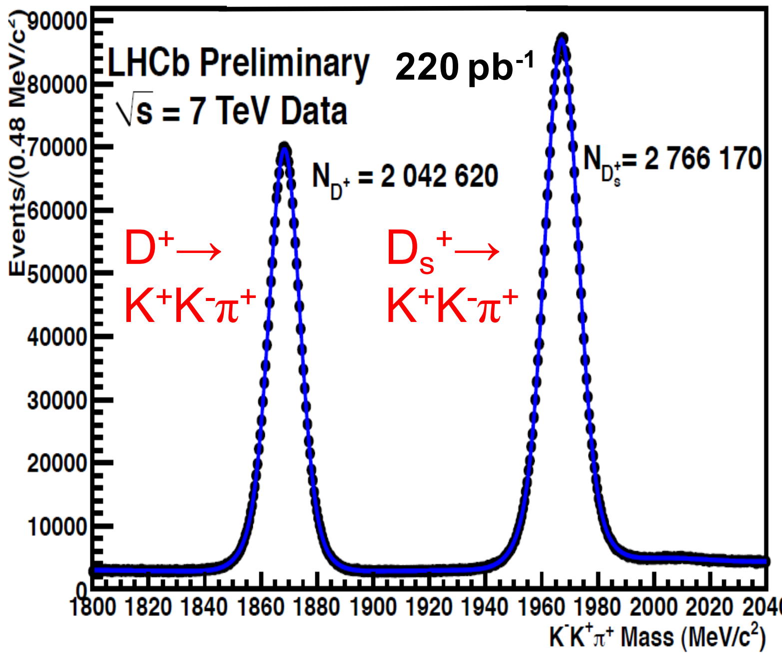
Search for New Physics with charm

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!

But what to do with these events ?

- direct CPV searches, especially in singly Cabibbo suppressed modes (SCS)
- searches for CPV in mixing
- searches for very rare decays
- spectroscopy

Search for direct CPV in SCS decays

Direct CPV in charm very small in the SM

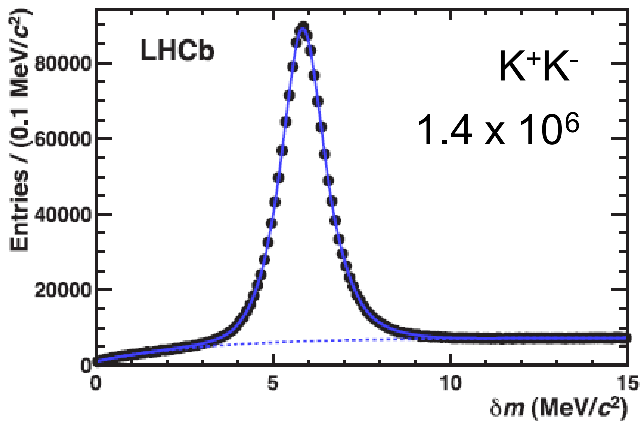
If one looks in Singly Cabibbo Suppressed (SCS) decays, the interplay between tree and Penguin diagrams gives possibility for New Physics to manifest itself.

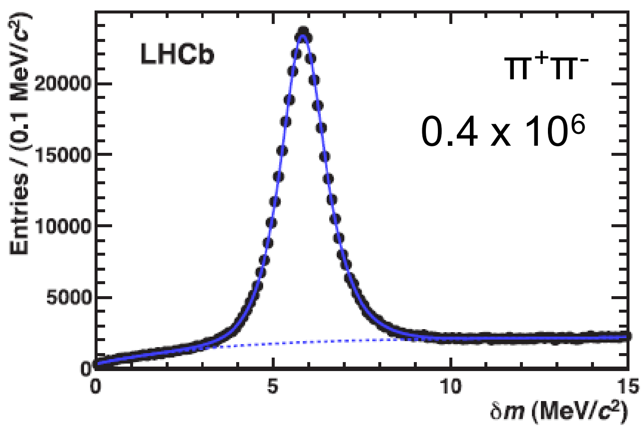
Clear steer from theory community:

> "We conclude that CPV in SCS D decays at the percent level signals new physics"
> [Grossman, Kagan, Nir, PRD 75 (2007) 036008]

LHCb has very large samples (e.g. statistics in $D^0 \to hh$ for 2011 data alone are order of magnitude higher than total B-factory yields)

LHCb D^*-D^0-m_π [0.6 fb^{-1}]





[PRL 108 (2012) 111602]

Clear opportunity for NP search! But challenging to control systematics to ~0.1%

ΔA_{CP} – the essentials

Measure the raw CP asymmetry of $D^0 \to f$ (f=K^+K^- or $\pi^+\pi^-$) using $D^{*+} \to D^0 \pi_s^+$ tag.
Does not equal the 'physics' asymmetry due to detector & production effects !

Physics asymmetry

Detection asymmetry for slow π

$$A_{\rm raw}(f) = A_{CP}(f) + \cancel{A_{\rm D}}(f) + A_{\rm D}(\pi_{\rm s}) + A_{\rm P}(D^{*+})$$

Detection asymmetry for D-decay – zero in this case

Production asymmetry – can be non-zero in *pp* collision

$A_D(\pi_s)$ and $A_P(D^{*+})$ will be the same for both D final states – so cancel in difference

$$\Delta A_{CP} \equiv A_{raw}(KK) - A_{raw}(\pi\pi) = A_{CP}(KK) - A_{CP}(\pi\pi)$$

Added insurance:
- perform analysis in kinematic bins to protect vs 2nd order effects
- average between two polarities of dipole

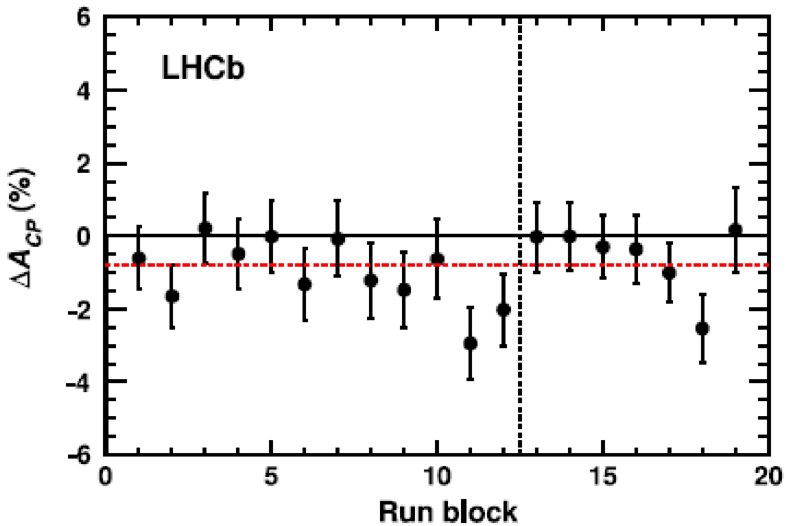
Nice bonus: in U-spin limit $A_{CP}(KK)= - A_{CP}(\pi\pi)$ for any direct CPV, so we may hope that any real physics asymmetry will be amplified by taking difference

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).

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

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])

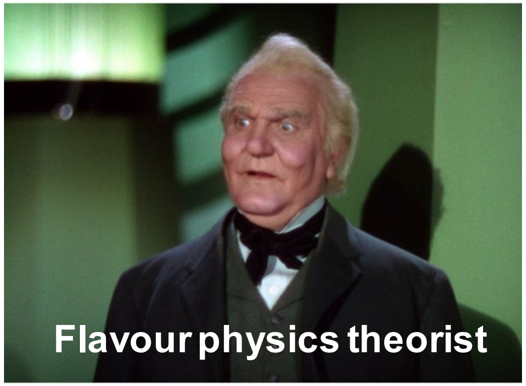
Informing the theory community

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.



Informing the theory community

A posteriori analysis has led to 'softening' of original viewpoint

"We conclude that CPV in SCS D decays at the percent level signals new physics"

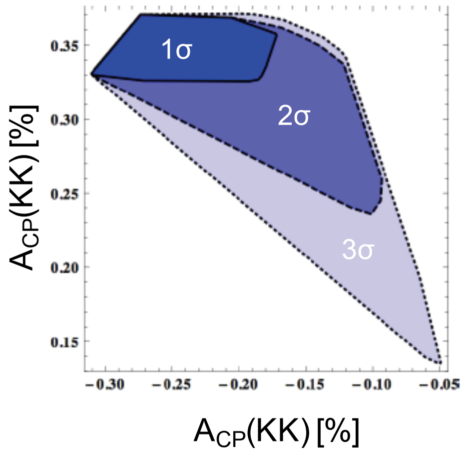
[Grossman, Kagan, Nir, PRD 75 (2007) 036008]

"We have shown that it is plausible that the SM accounts for the measured value of ΔA_{CP}"

[Brod, Kagan, Zupan, Nov 2011, arXiv:1111.5000]

SM explanation requires larger than expected contributions from Penguin contractions. Feasible as m_c is light(ish).

e.g. fitting SCS D A_{CP} & BR data allowing for big Penguins → consistent picture



Brod, Grossman, Kagan, Zupan, arXiv:1203.6659

Central value can't be excluded in SM from first principles, but accommodating it is a stretch. If NP is contributing it is likely through chromomagnetic operators.

Progress Requires:

- establishing ΔA_{CP} signal
- precision studies of other SCS modes
- other observables e.g. CPV in radiative D decays [Isidori, Kamenik, arXiv:1205.3164]

coming soon from LHCb!

Five potential game-changers – possible roads to NP in the LHC era

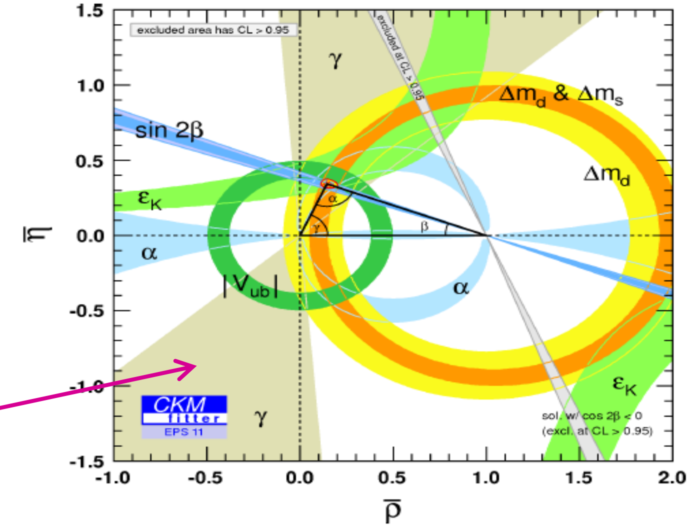
- CP violation in B_s mixing
- $BR(B_s \rightarrow \mu^+\mu^-)$
- Observables in $B \rightarrow K^{(*)}\mu^+\mu^-$
- CP violation in charm
- Precise CKM metrology

These are *selected* topics!

Many other examples exist.

What did we hope for? Where are we after 1 fb^{-1}? Where will we be in 2018?

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)

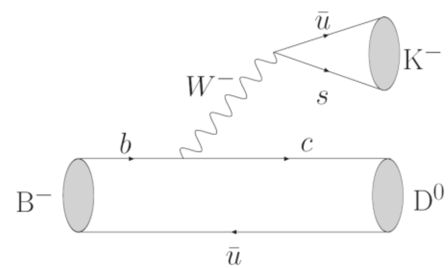
Look in $B^\pm \rightarrow DK^\pm$ decays using common mode for D^0 & D^0

$\rightarrow \gamma$ sensitive interference

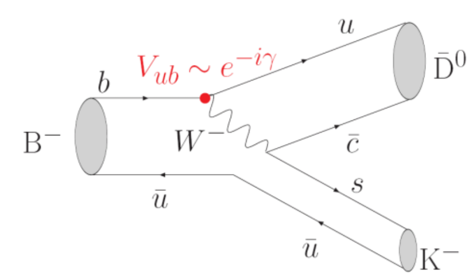
$\rightarrow$ different rates for B^+ & B^- (CPV!)

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

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 $B\rightarrow hh$)

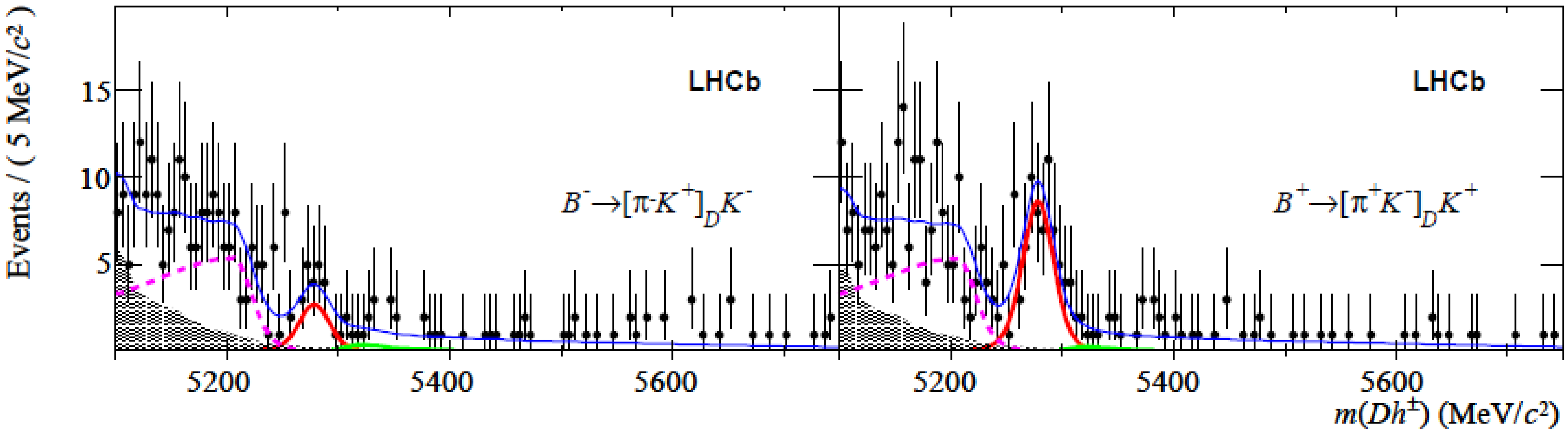
Current measurement error ~ 12° ; indirect (e.g. loops) precision ~4° (& improving...)

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 soon, together with complementary measurements from B_s system ($B_s \to D_sK$)

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

Dreaming about ultra-high statistics

Big improvements foreseen before 2018-19 long shutdown (~6.5 fb^{-1}, doubling in x-section from E_{CM} w.r.t. 2011, improved analysis methods) but we can dream of what could be achieved with a very large increase in sample sizes, e.g.

- $B_s \rightarrow \mu\mu$

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

- 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.

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

  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.

- 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.

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

Realising the dream – the LHCb upgrade

LHCb collaboration plans an upgrade, to be installed in 2018-19 shutdown

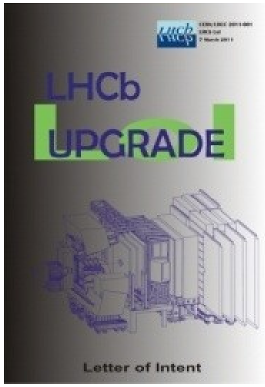
Essential features:

- Full software trigger: will readout into DAQ all subdetectors at 40 MHz (c.f. 1 MHz at present). This will improve efficiency compared with current hardware trigger, giving factor of two improvement for hadronic final states
- Increase operational luminosity to 10^{33} cm^{-2}s^{-1} (and a possibility to raise still further to 2×10^{33} cm^{-2}s^{-1})

Annual yields in muonic final states will increase 10x w.r.t. 2011, and 20x for hadronic decays. Aim to collect 50 fb^{-1}.

LoI submitted to LHCC March 2011. Physics case endorsed.

'Framework TDR' submitted May 2012. Under review.



Conclusions

LHCb is performing excellently, delivering world-best results over a wide range of flavour physics measurements

Alas, no sign of large New Physics effects. We have to work harder! Thus in certain key topics (e.g. $B_s \to \mu\mu$) the game is now switching from exploration to precision measurement

Nonetheless, not everything is following the SM script, e.g.:

- direct CPV in charm
- isospin asymmetry in $B \to K\mu\mu$

What do these mean? More measurements required!

Plenty of scope for the picture to change over the next ~5 years

LHCb upgrade will bring an added order of magnitude in precision

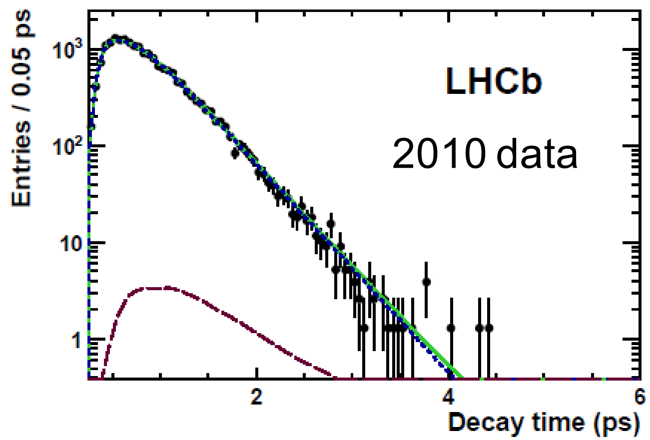
Backups

Other paths to New Physics with charm

Current thinking is still that any CPV in mixing close to current experimental limit would be an unambiguous sign of NP – so time-dependent CPV studies are an key goal of LHCb. Similarly, exciting prospects in searches for FCNC decays.

Proper time of triggered and reconstructed $D^0 \to KK$ decays

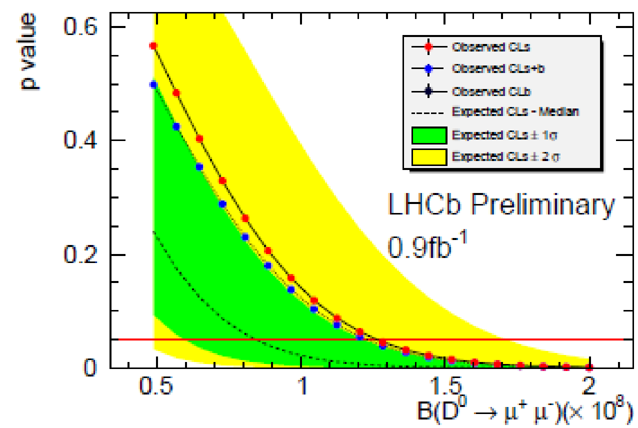
JHEP 1204 (2012) 129



Acceptance well understood with data driven techniques

2011 data alone will allow for very significant improvement in many mixing and indirect CPV studies

$D^0 \to \mu\mu$ highly suppressed in SM ($\sim 10^{-13}$?), but not in e.g. $\not{R}_P$ SUSY



LHCb-CONF-2012-005

LHCb 2011 preliminary:

$$\mathcal{B}(D^0 \to \mu^+\mu^-) < 1.3 \cdot 10^{-8}$$

@ 95% CL

~10x better than previous limit.

Coming soon: search for $D^+ \to \pi^+\mu\mu$!

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 [9]	0.025	0.008	~ 0.003
	$2\beta_s\ (B_s^0 \to J/\psi\ f_0(980))$	0.17 [10]	0.045	0.014	~ 0.01
	$A_{\mathrm{fs}}(B_s^0)$	6.4×10^{-3} [18]	0.6×10^{-3}	0.2×10^{-3}	0.03×10^{-3}
Gluonic penguin	$2\beta_s^{\mathrm{eff}}(B_s^0 \to \phi\phi)$	–	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 [18]	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 penguin	$S_3(B^0 \to K^{*0}\mu^+\mu^-; 1 < q^2 < 6\,\mathrm{GeV}^2/c^4)$	0.08 [14]	0.025	0.008	0.02
	$s_0\ A_{\mathrm{FB}}(B^0 \to K^{*0}\mu^+\mu^-)$	25 % [14]	6 %	2 %	7 %
	$A_{\mathrm{I}}(K\mu^+\mu^-; 1 < q^2 < 6\,\mathrm{GeV}^2/c^4)$	0.25 [15]	0.08	0.025	~ 0.02
	$\mathcal{B}(B^+ \to \pi^+\mu^+\mu^-)/\mathcal{B}(B^+ \to K^+\mu^+\mu^-)$	25 % [16]	8 %	2.5 %	~ 10 %
Higgs penguin	$\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	1.5×10^{-9} [2]	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–$12°$ [19, 20]	$4°$	$0.9°$	negligible
	$\gamma\ (B_s^0 \to D_s K)$	–	$11°$	$2.0°$	negligible
	$\beta\ (B^0 \to J/\psi\ K_S^0)$	$0.8°$ [18]	$0.6°$	$0.2°$	negligible
Charm CP violation	A_Γ	2.3×10^{-3} [18]	0.40×10^{-3}	0.07×10^{-3}	–
	ΔA_{CP}	2.1×10^{-3} [5]	0.65×10^{-3}	0.12×10^{-3}	–

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