BSM through flavour physics at the LHC

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Flavour physics is important

Many open questions in the Standard Model are found in the flavour sector :

- Why 3 generations?
- What determines the extreme hierarchy of fermion masses?
- What determines the CKM elements?
- What is the origin of CPV?

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

Proven tool of discovery

Kaon mixing & GIM ➔prediction of charm

CP violation ➔ need for a third generation

B mixing ➔ mass of the top is heavy

Br(B_s➔$\mu\mu$) ➔ already constrained SUSY parameter space

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

Possible roads to BSM in the LHC era

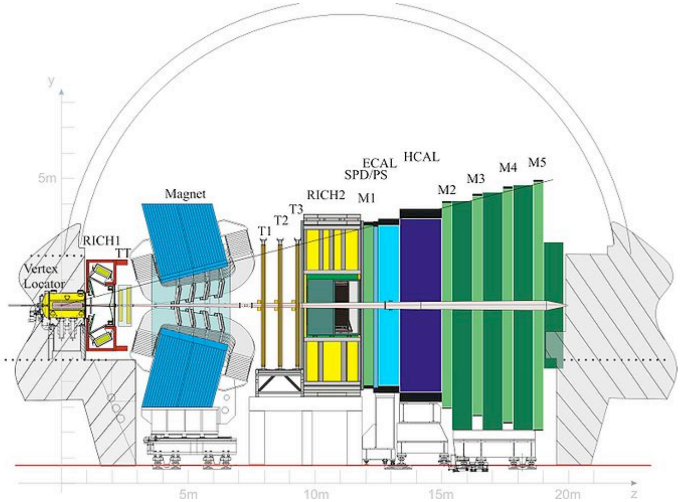
- Br ($B_s \rightarrow \mu\mu$)
- CP violation in B_s mixing
- Observables in $B \rightarrow K^{(*)} \mu\mu$
- CP violation in charm
- Precision CKM metrology

Caveat : Selected topics, focus on recent results. Many other examples exist.

Flavour physics at LHC experiments : LHCb

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

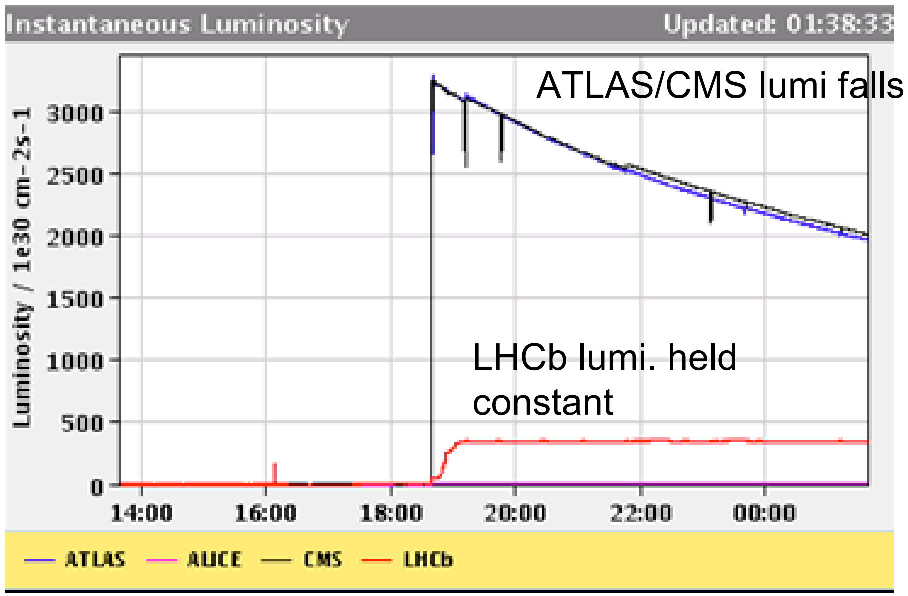
- forward acceptance ($2<\eta<5$)
- acceptance down to low p_t
- precise vertexing (VELO)
- hadron identification (RICHes)



LHCb operation proceeds alongside ATLAS/CMS thanks to luminosity leveling.

1 fb^{-1} collected in 2011

Expect ~ 2.2 fb^{-1} in 2012



Flavour physics at LHC : ATLAS & CMS

Both GPD's can take advantage of the higher luminosities.

P_t trigger thresholds are higher

Central region acceptance :

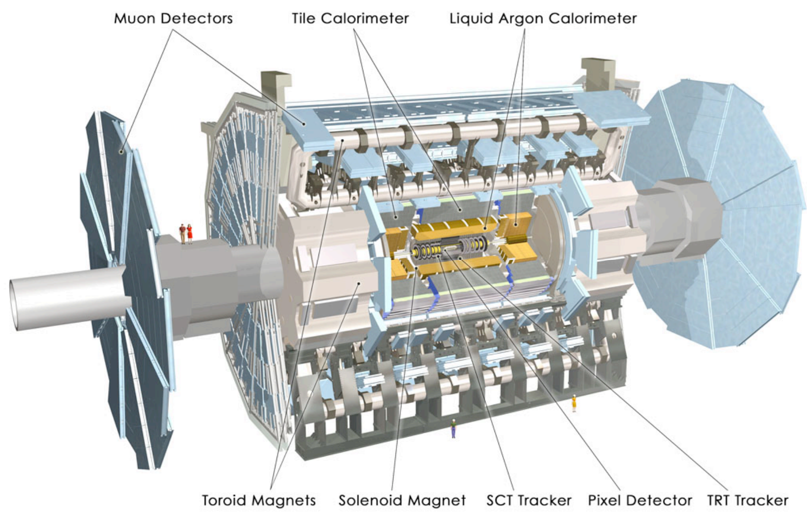
ATLAS fiducial volume covered by 2011 B physics triggers $\sigma(bb \rightarrow J/\psi X)$ is 3 times smaller than in LHCb

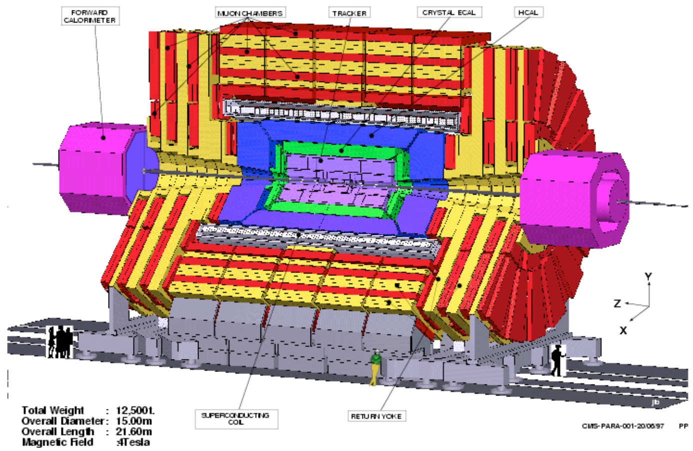
Concentrate on channels with muons

ATLAS di-muon mass resolution ~ 60MeV in barrel, ~ 110 MeV in end cap

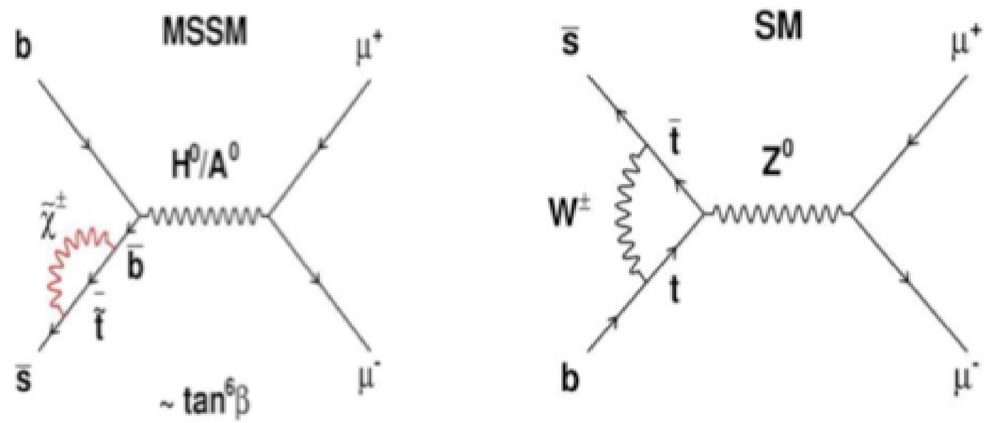
CMS di-muon mass resolution ~35 MeV in barrel and ~77 Mev in the endcap

(c.f LHCb, ~ 25 MeV)





$Br(B_{s(d)} \rightarrow \mu\mu)$



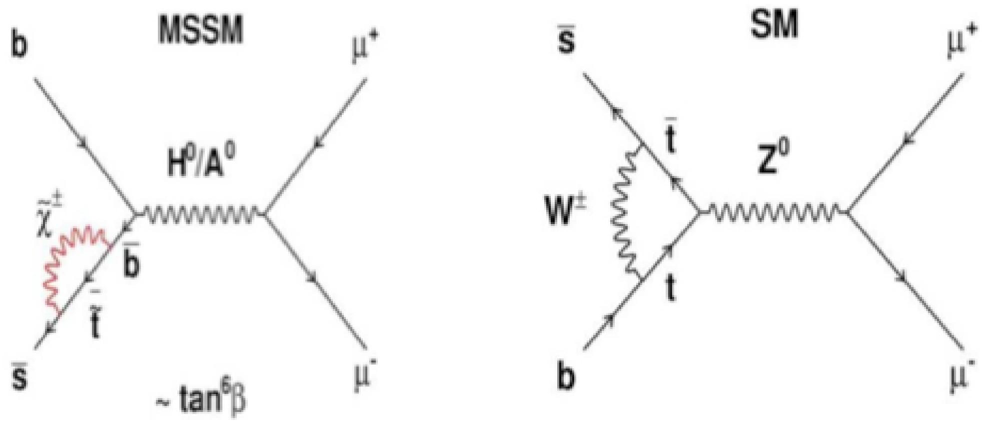
The golden mode : $B_s \rightarrow \mu\mu$

Forbidden at tree level, and lowest order CKM suppressed.

Br $B_s \rightarrow \mu\mu$ $(3.23 \pm 0.27)\times10^{-9}$

Br $B_d \rightarrow \mu\mu$ $(1.07 \pm 0.10)\times10^{-10}$

AJ Buras et al, CERN-PH-TH-2012-210



Very high sensitivity to NP with expectations of enhanced branching fractions.

Ratio of Branching fractions of B_s and B_d excellent test of MFV models

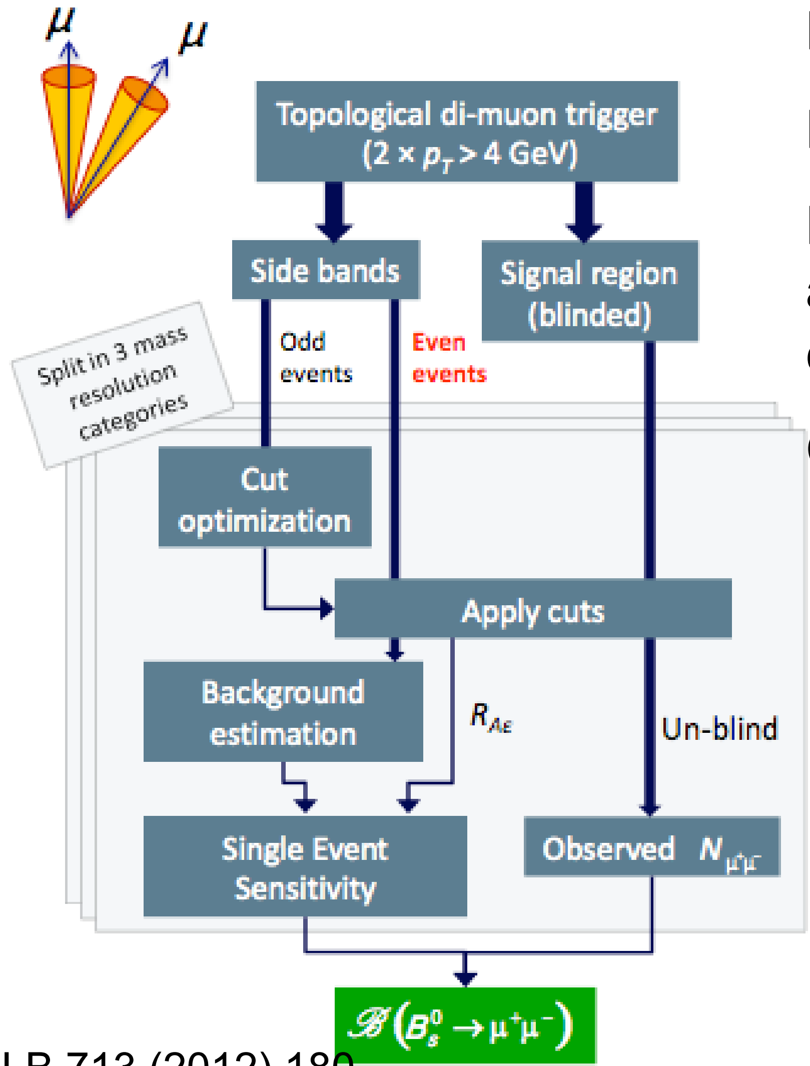
Spring 2011 results :

CDF (3.7 fb^{-1}) : $< 4.3 \times 10^{-8}$

D0 (6.1 fb^{-1}) : $< 5.1 \times 10^{-8}$

LHCb(37 pb^{-1}): $< 5.6 \times 10^{-8}$

ATLAS analysis: 2.4 fb^{-1}



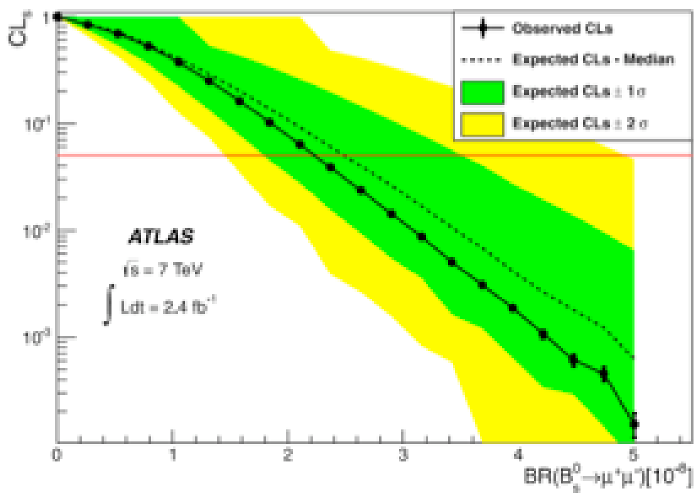
PLB 713 (2012) 180

Br(Bs➔μμ) measured relative to B$^+$➔J/ψ K$^+$

Multivariate selection

MC used for estimating efficiency and acceptance differences between signal and control mode.

CL$_s$ method used to set limits

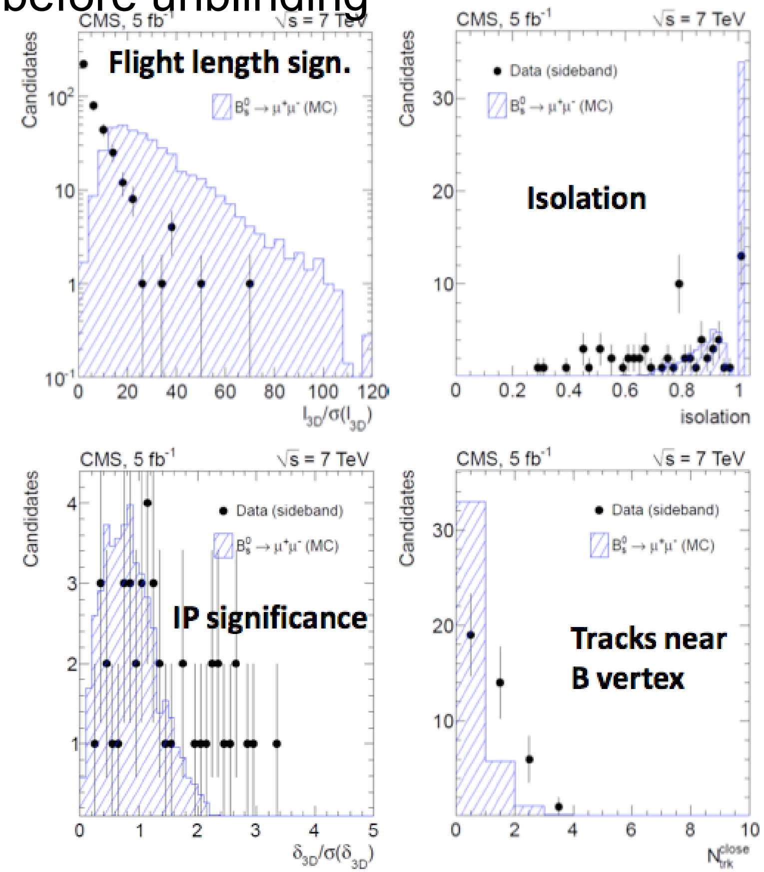


- **Upper limit: 2.2 × 10^{-8} @ 95% CL**
- **Expected: 2.3 × 10^{-8} @ 95% CL**

CMS analysis : $5fb^{-1}$

B_d decay also searched for

Cut based selection optimized before unblinding



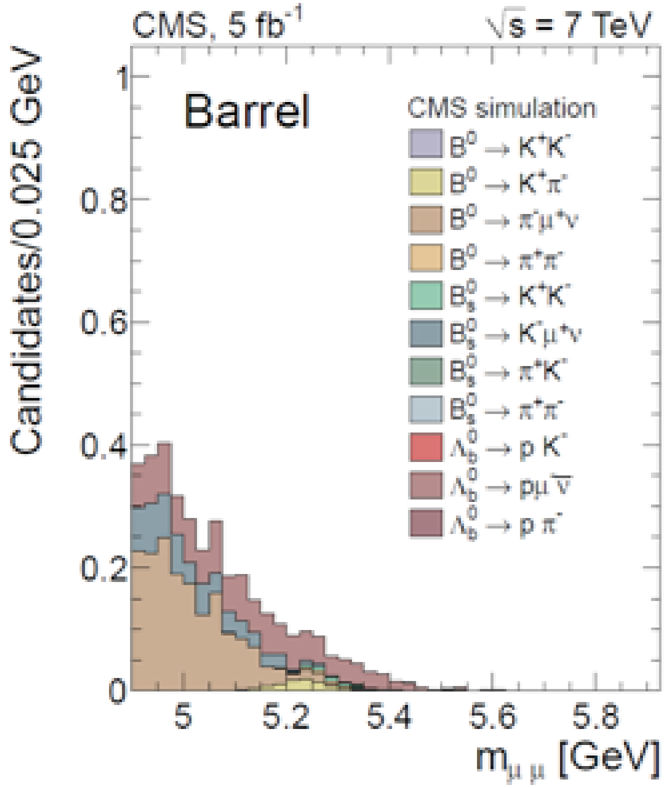
Backgrounds in signal channel:

peaking backgrounds

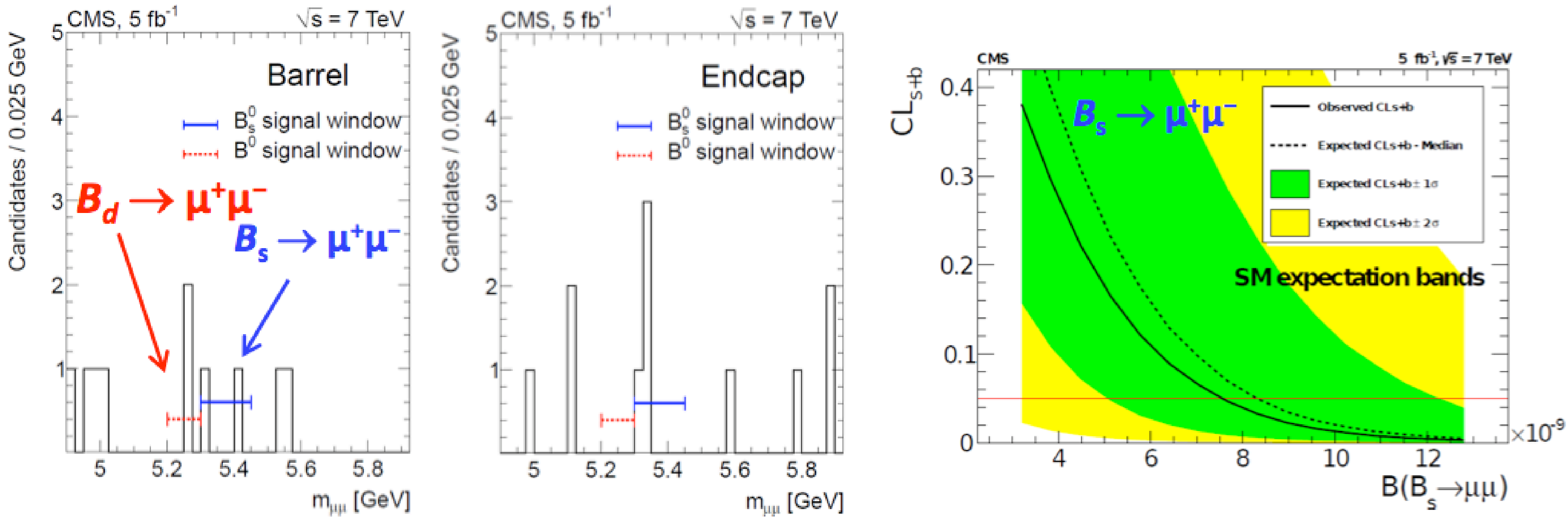
semi-leptonic decays

combinatorial background

(normalized to the measured B^+ yield)



CMS analysis : $5fb^{-1}$



$Br(B_s \rightarrow \mu\mu) < 7.7 \times 10^{-9}$ @ 95% CL

$Br(B_d \rightarrow \mu\mu) < 1.8 \times 10^{-9}$ @ 95% CL

JHEP 04 (2012) 033

LHCb analysis: 1.0 fb^{-1} (7TeV) + 1.1 fb^{-1} (8TeV)

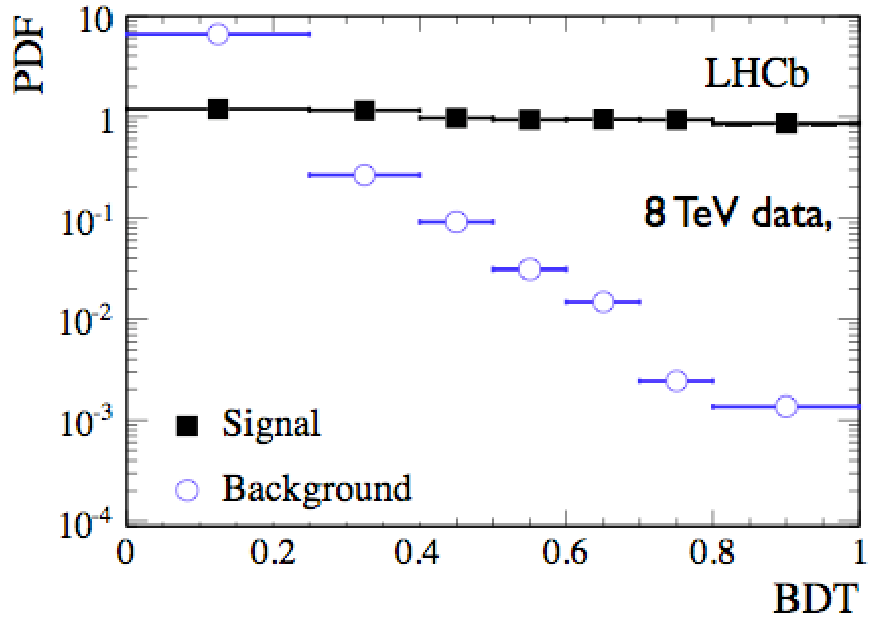
Strategy similar to earlier analyses

BDT on 9 kinematical and topological variables

Train BDT on MC but calibrate on data:

-signal response: use B→hh decays triggered on ‘other B’

-background response: use sidebands

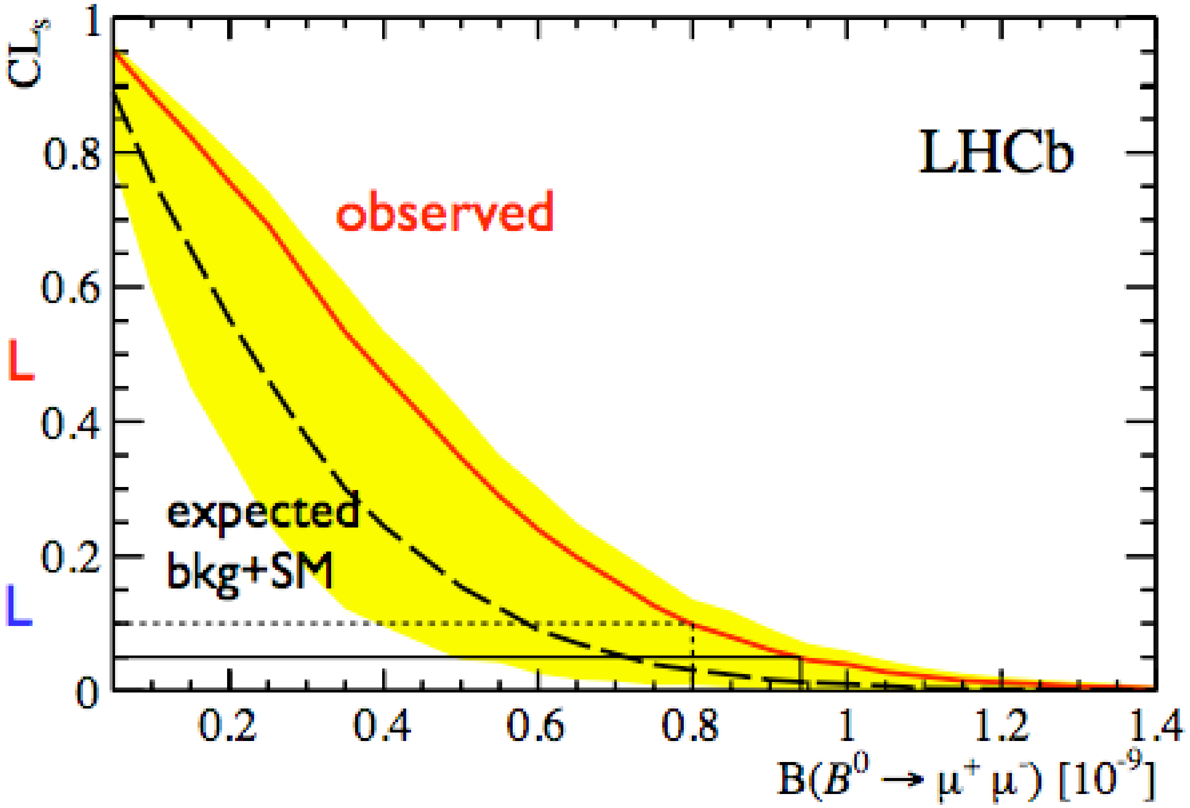


Invariant mass resolution calibrated from data (dimuon resonances & B→hh)

Results looked at in bins of $\mu\mu$ invariant mass vs BDT output.

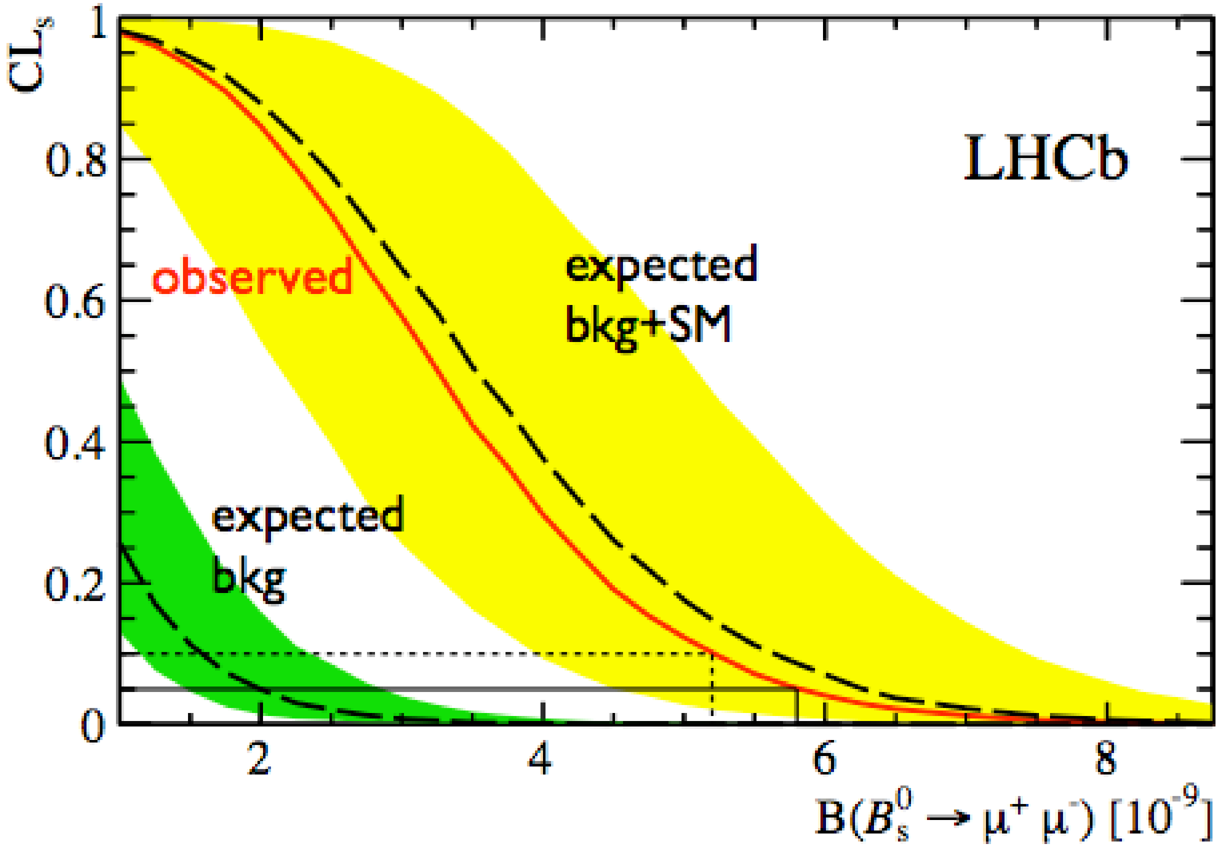
$B^+ \rightarrow J/\psi K^+$ and $B^0 \rightarrow K\pi$ are normalisation channels both give consistent results.

$B_d \rightarrow \mu\mu$



Observed upper limit < 9.4 x 10^{-10} @ 95% CL

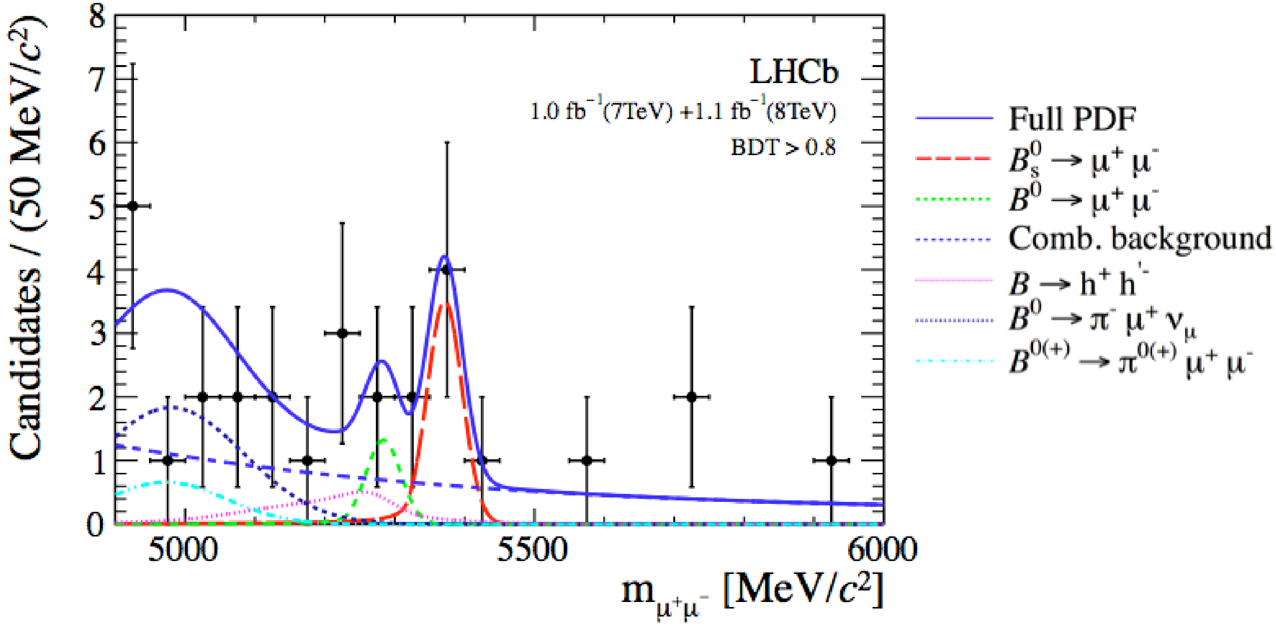
$B_s \rightarrow \mu\mu$



7 TeV + 8 TeV data

bkg only p value 5.3x 10^{-4} → 3.5σ excess

First evidence for $B_s \rightarrow \mu\mu$



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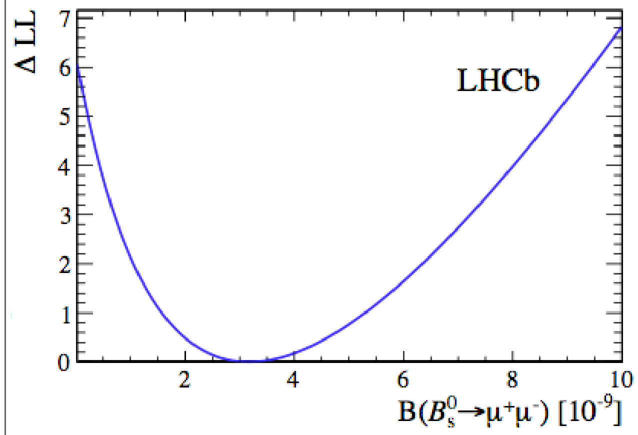


$Br(B_s \rightarrow \mu\mu)=$

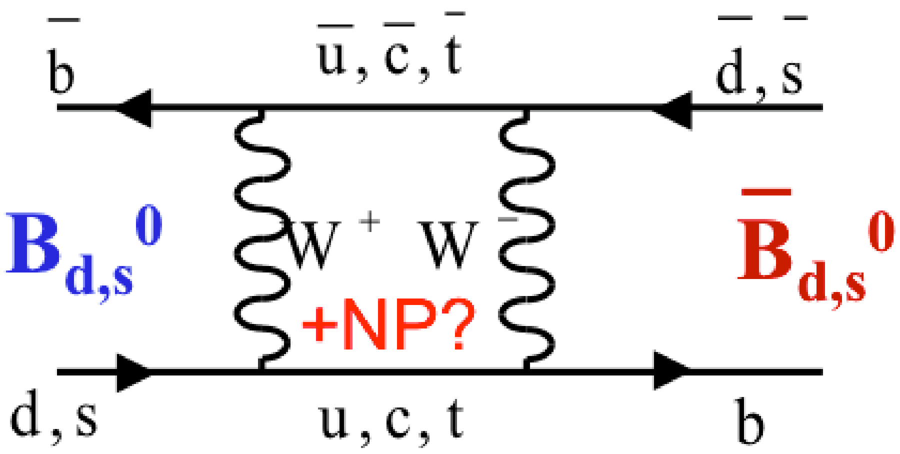
$(3.2^{+1.4}_{-1.2}(stat)\ ^{+0.5}_{-0.3}(syst)) \times 10^{-9}$

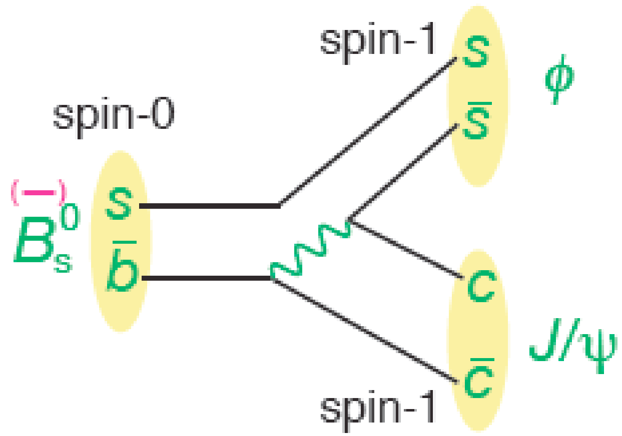
Consistent with the SM

Br $B_s \rightarrow \mu\mu$ $(3.23 \pm 0.27)\times 10^{-9}$

Contribution from the GPDs will remain important

CP violation in B_s mixing

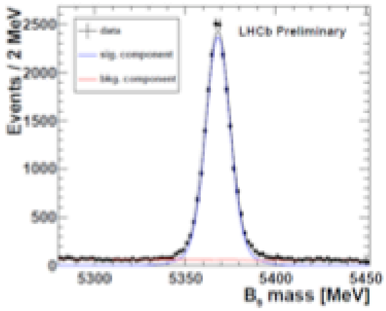




Golden mode: $B_s \rightarrow J/\psi\phi$

CPV phase φ_s in B_s mixing-decay interference. Very small and precisely predicted in SM. Box diagram is a tempting entry point for NP.

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

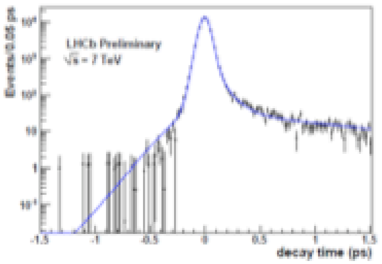


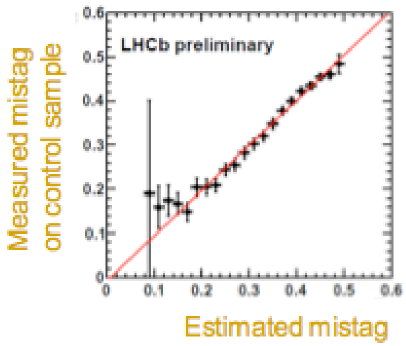
Large, clean, sample

~21k events

Excellent proper time resolution

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

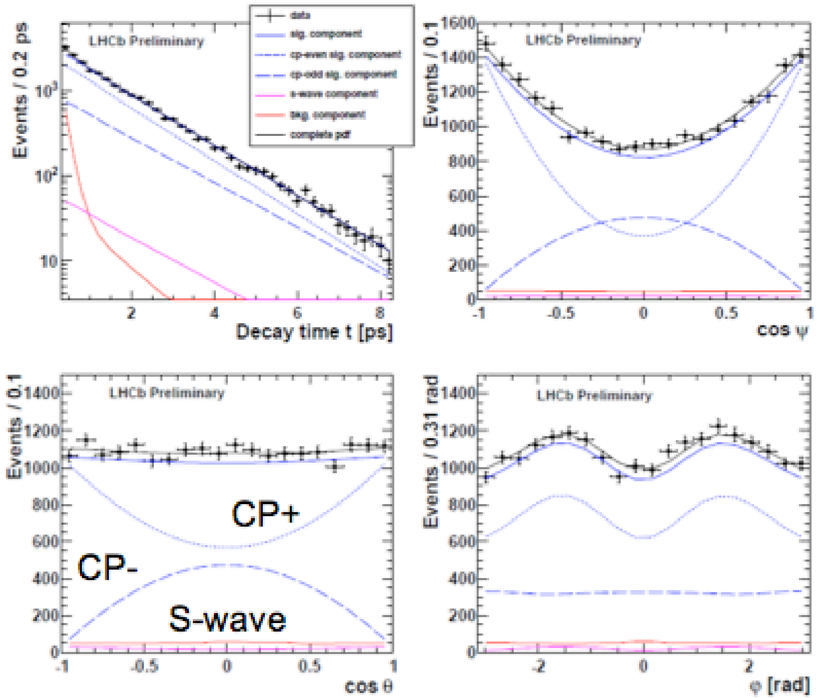




Good, well understood flavour-tagging of initial state

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

Then perform time-dependent angular fit



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

Results from $B_s \rightarrow J/\psi\phi$

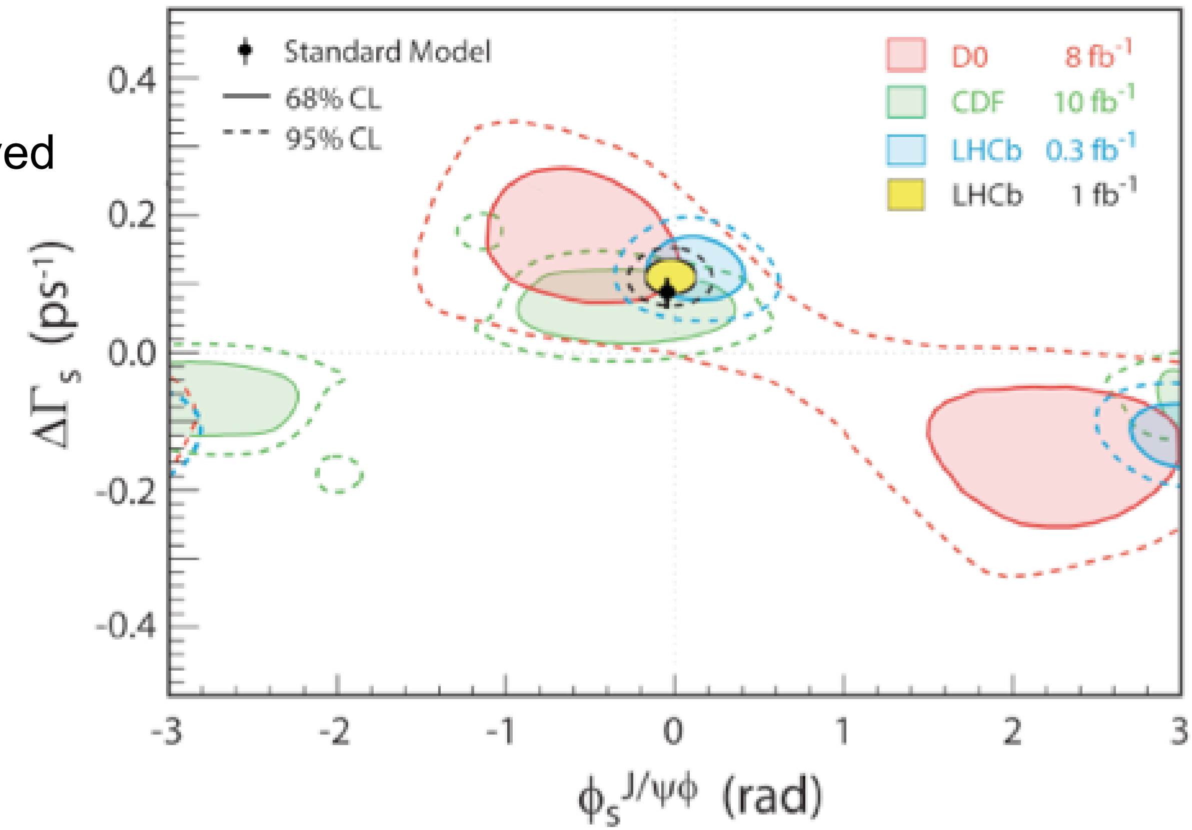
$$\phi_s = -0.001 \pm 0.101 \quad (\text{stat}) \pm 0.027 \quad (\text{syst}) \ \text{rad}$$

$$\Delta\Gamma_s = 0.116 \quad \pm 0.018 \quad (\text{stat}) \pm 0.006 \quad (\text{syst}) \ \text{ps}^{-1}$$

Two-fold ambiguity resolved by using $B_s \rightarrow J/\psi KK$

[LHCb-paper-2011-028

LHCb-CONF-2012-002]



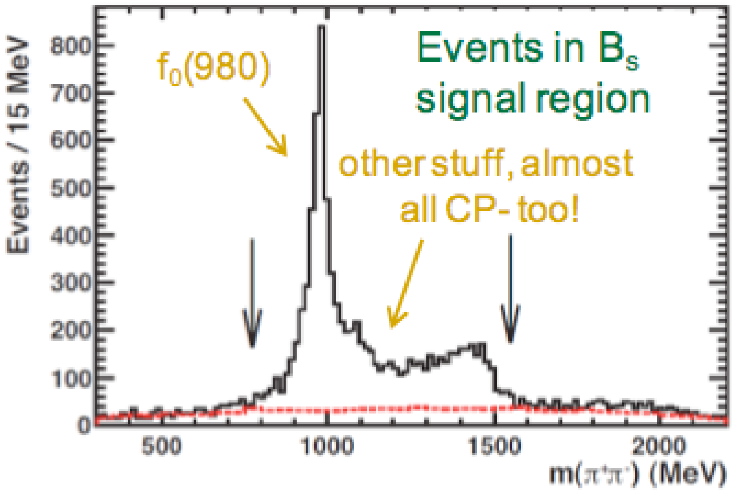
ATLAS also studies this channel but as analysis is still untagged sensitivity to ϕ_s is low arXiv:1208.0572

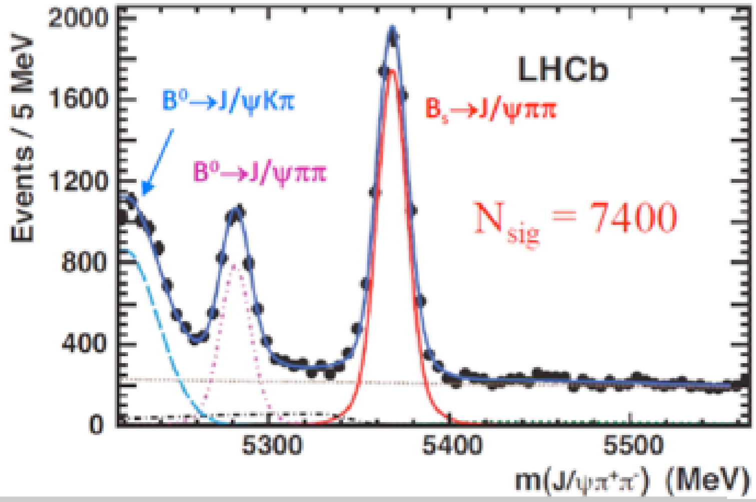
ϕ_s with $B_s \rightarrow J/\psi\pi\pi$ 1.0fb^{-1}

Other modes can be used. $B_s \rightarrow J/\psi\pi\pi$ is CP-odd eigenstate so no need of angular analysis. Also true for extended region.

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

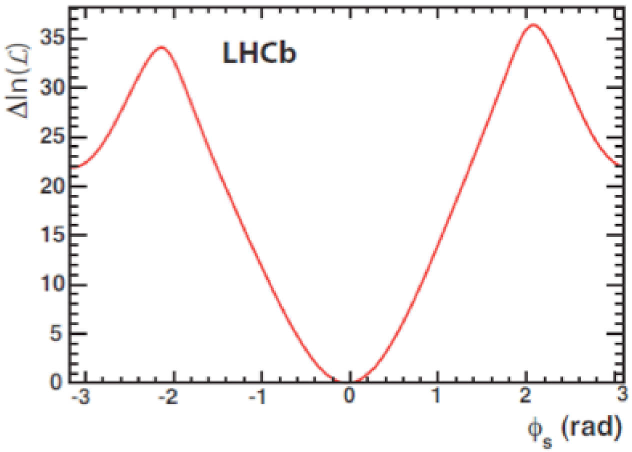
Fraction of CP-even is <2.3% and 95% CL





ϕ_s

From $B_s \rightarrow J/\psi\pi\pi$



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

LHCb-PAPER-2012-006

& combining with $B_s \rightarrow J/\psi\phi$

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]

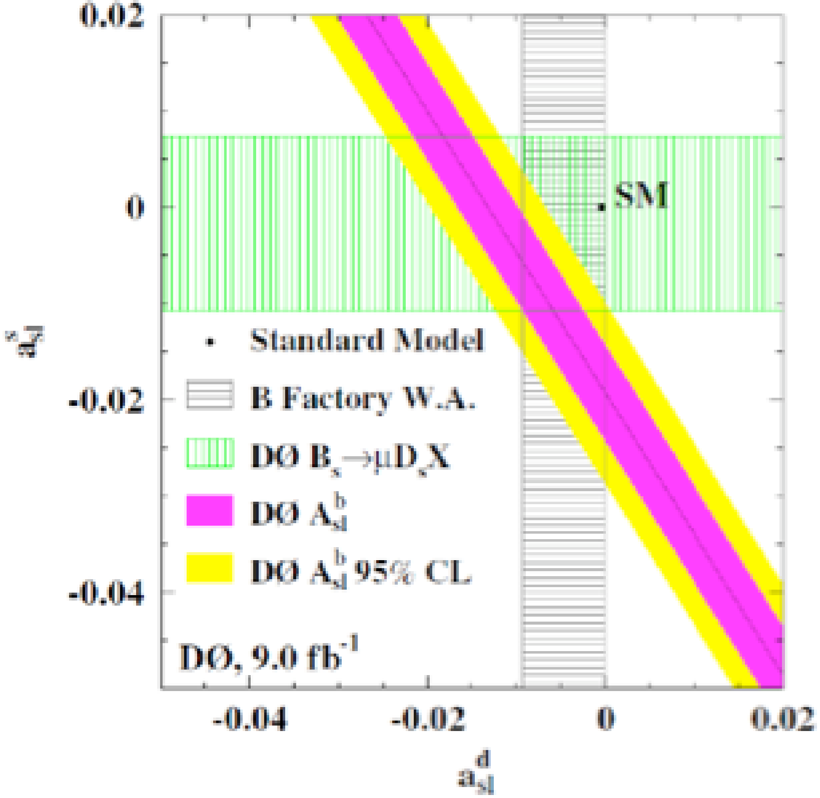
Early tantalizing results from the Tevatron did not point the way to NP

Nonetheless must still improve precision to draw understanding from theory.

Semileptonic Asymmetry

Flavour-specific CP asymmetry in B decays accesses CPV in mixing. Extremely small in SM esp. for B_s system

[D0, PRD 84 (2011) 052007]



D0 measurement is made with dileptons. Mixture of a^s_{sl} and a^d_{sl}.

Result lies 3.9σ from SM

Generated considerable interest

Difficult to reconcile these results with others from e.g. $B_s \rightarrow J/\psi\phi$

LHCb a^s_{sl} measurement

$$A_{\rm meas} = \frac{\Gamma[D_s^-\mu^+] - \Gamma[D_s^+\mu^-]}{\Gamma[D_s^-\mu^+] + \Gamma[D_s^+\mu^-]} = \frac{a^s_{\rm sl}}{2} + \left[a_{\rm p} - \frac{a^s_{\rm sl}}{2}\right] \frac{\int_{t=0}^{\infty} e^{-\Gamma_s t}\cos(\Delta M_s t)\epsilon(t)dt}{\int_{t=0}^{\infty} e^{-\Gamma_s t}\cosh\frac{\Delta\Gamma_s t}{2}\epsilon(t)dt}$$

B_s/B_s production asymmetry ~ 1%

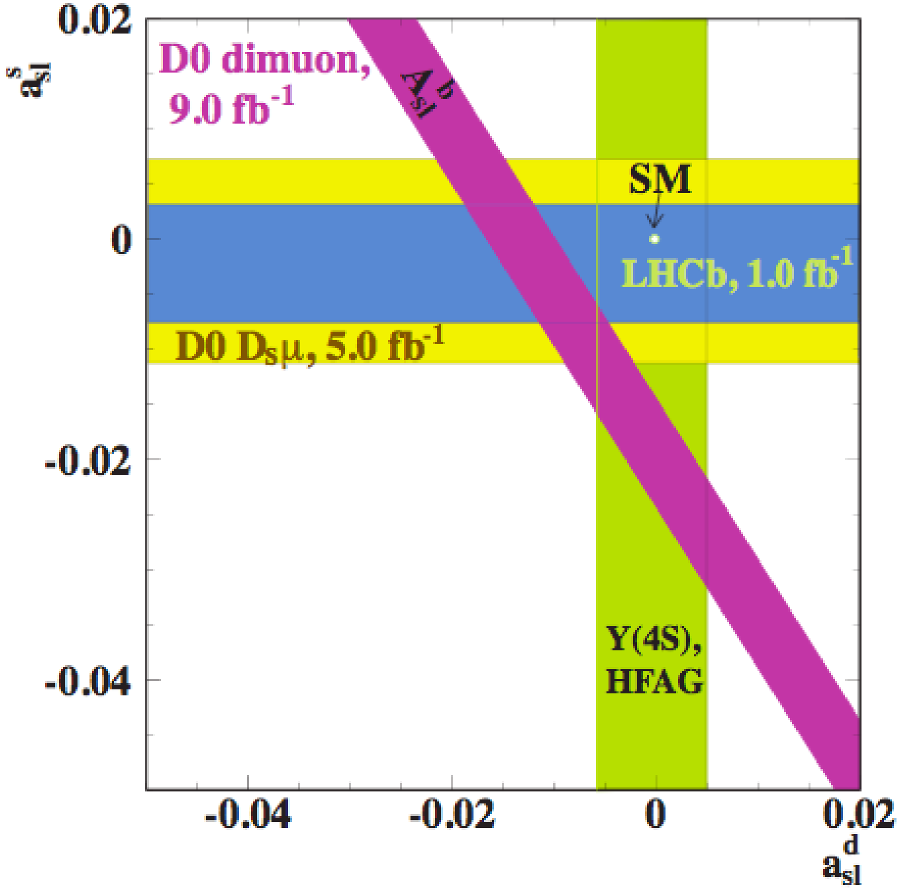
Time-integrated analysis. Term takes into account decay time acceptance. ~ 0.2%

$$A_{\rm meas} = \frac{N(D_s^-\mu^+) - N(D_s^+\mu^-) \times \frac{\epsilon(D_s^-\mu^+)}{\epsilon(D_s^+\mu^-)}}{N(D_s^-\mu^+) + N(D_s^+\mu^-) \times \frac{\epsilon(D_s^-\mu^+)}{\epsilon(D_s^+\mu^-)}}$$

Efficiency corrections cover trigger, tracking and muon identification effects.

$D_s \rightarrow \phi\pi$ only channel considered so far

LHCb a^s_{sl} result



$$a^s_{sl} = (-0.24 \pm 0.54 \pm 0.33)\%.$$

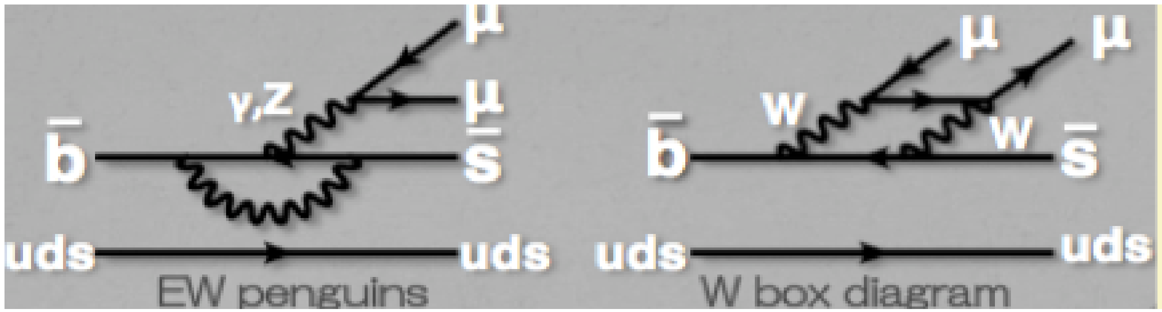
LHCb measurement consistent with the

SM= $a^s_{sl} = (1.9 \pm 0.3) \times 10^{-5}$

Not the end of the story. Additional D_s decays will be added soon.

LHCb-CONF-2012-022

Physics with EW penguins at LHCb



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

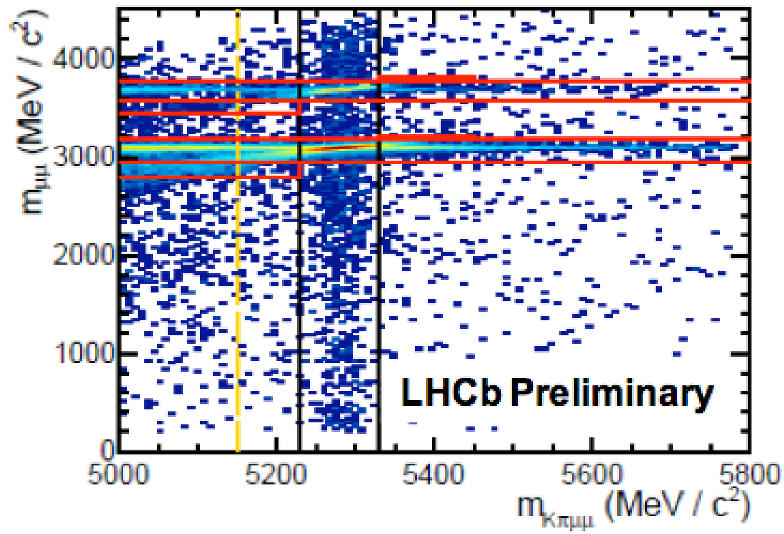
Many observables exist in $B^0 \rightarrow K^*\mu\mu$ that could probe the helicity structure of any NP

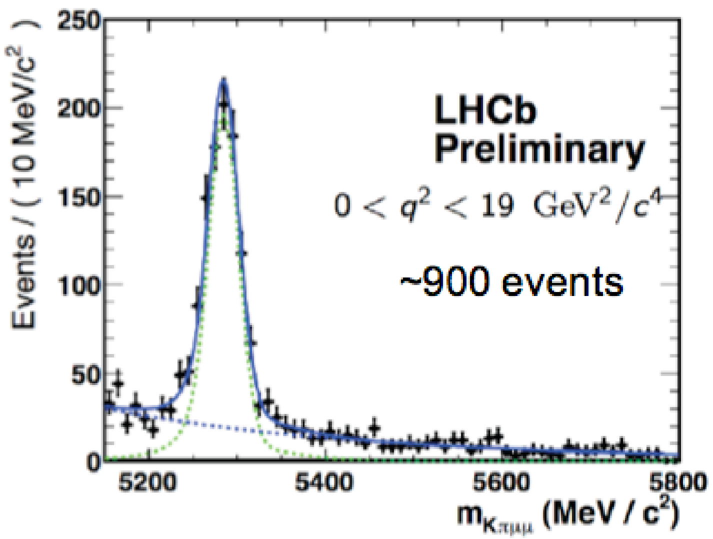
Cut out $B^0 \rightarrow J/\psi K^*$ and $B^0 \rightarrow \psi(2S)K^*$.

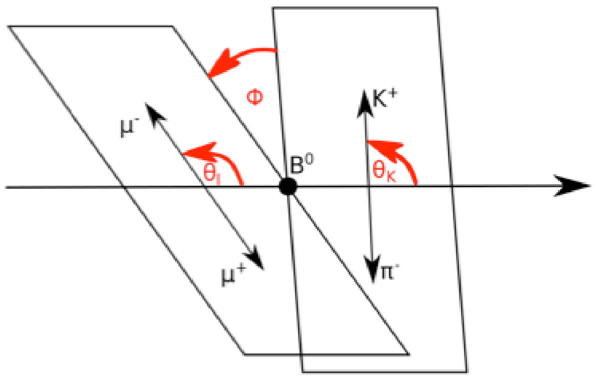
Select signal events with BDT

Correct for acceptance effects with event-by-events correction using MC

Measurements in $q^2(\mu\mu)$ bins. Decay fully described by q^2 and three angles

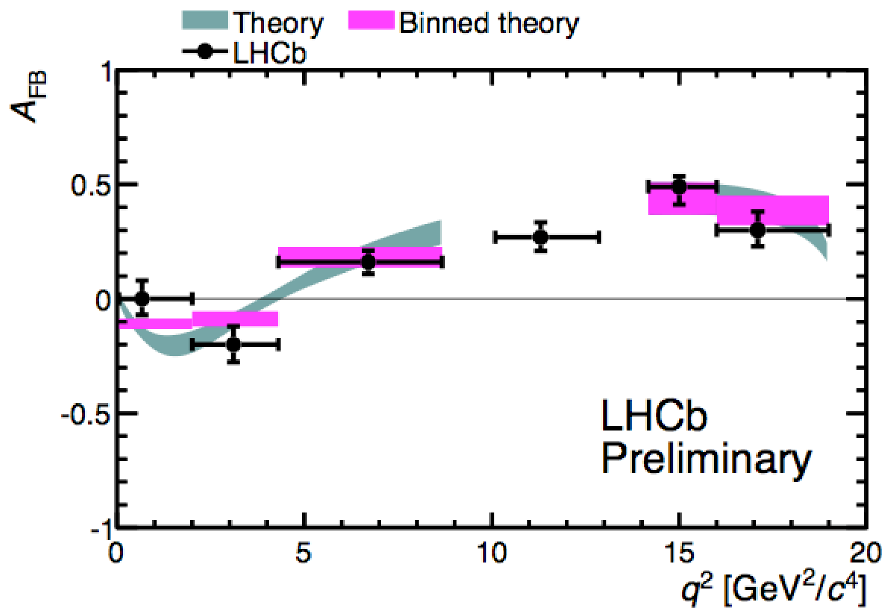


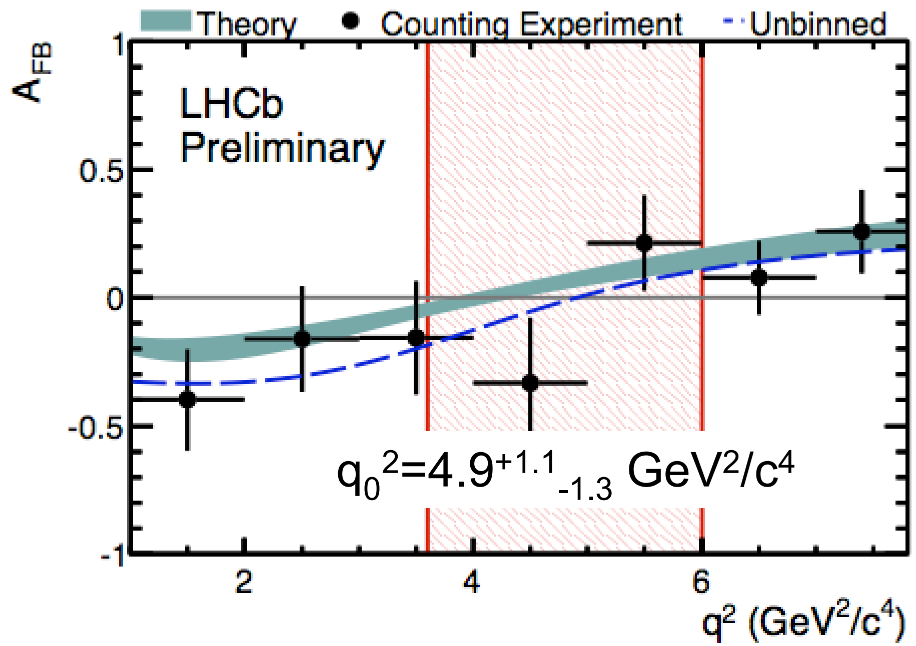




A_{FB} in $B^0 \rightarrow K^*\mu\mu$

Forward backward asymmetry of lepton system





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

With present sensitivity all data consistent with SM

LHCb-CONF-2012-008

CP-asymmetry in $B^0 \rightarrow K^*\mu\mu$

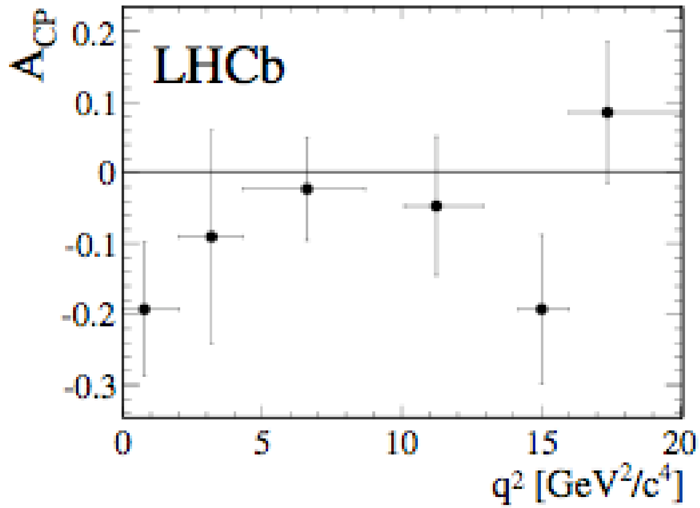
$$\mathcal{A}_{CP} = \frac{\Gamma(\overline{B}^0 \to \overline{K}^{*0}\mu^+\mu^-) - \Gamma(B^0 \to K^{*0}\mu^+\mu^-)}{\Gamma(\overline{B}^0 \to \overline{K}^{*0}\mu^+\mu^-) + \Gamma(B^0 \to K^{*0}\mu^+\mu^-)}$$

Predicted to be ~10^{-3} in SM

Very clean due to form factor suppression

Asymmetry up to 15% in certain models

Detector and production asymmetries controlled through $B^0 \rightarrow J/\psi K^*$ decay

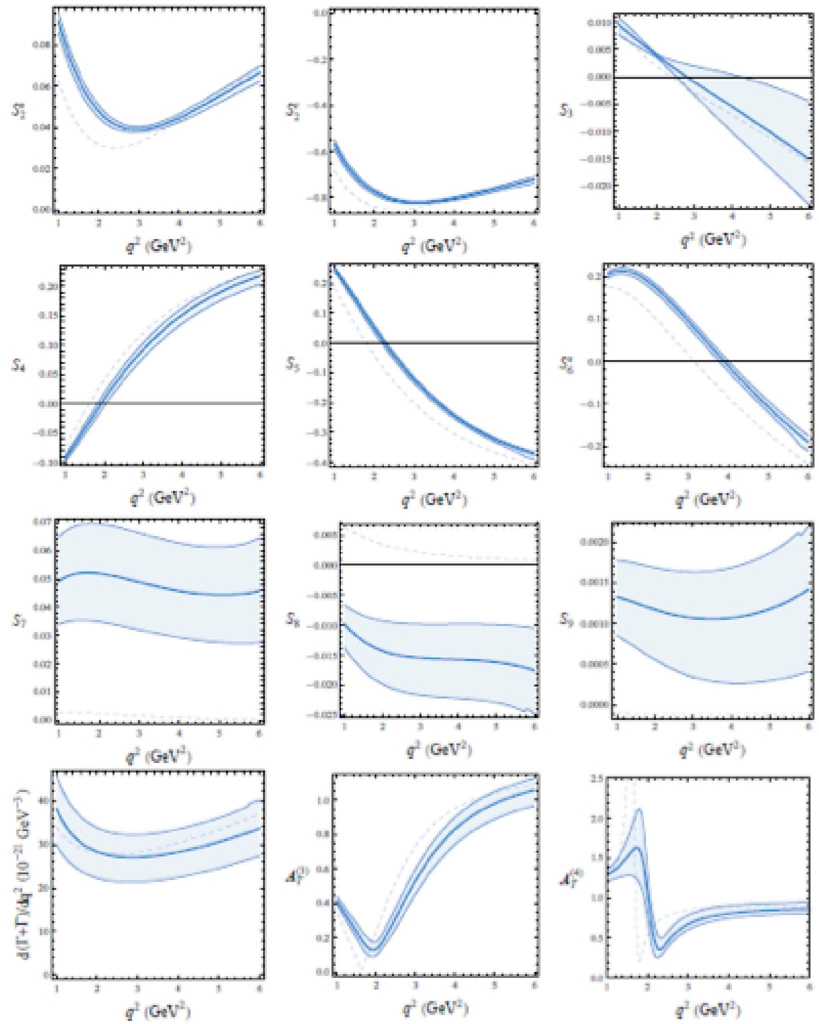


$$\mathcal{A}_{CP} = -0.072 \pm 0.040 \text{ (stat)} \pm 0.005 \text{ (sys)}$$

LHCB-PAPER-2012-021

Further studies in EW penguin decays

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



Despite agreement with SM, there remains a need to improve precision

Full angular fit to extract complete set of observables.

There are many, sensitive to different classes of New Physics

CPV in charm

Direct CPV in SCS decays

Direct CPV in charm v small in the SM

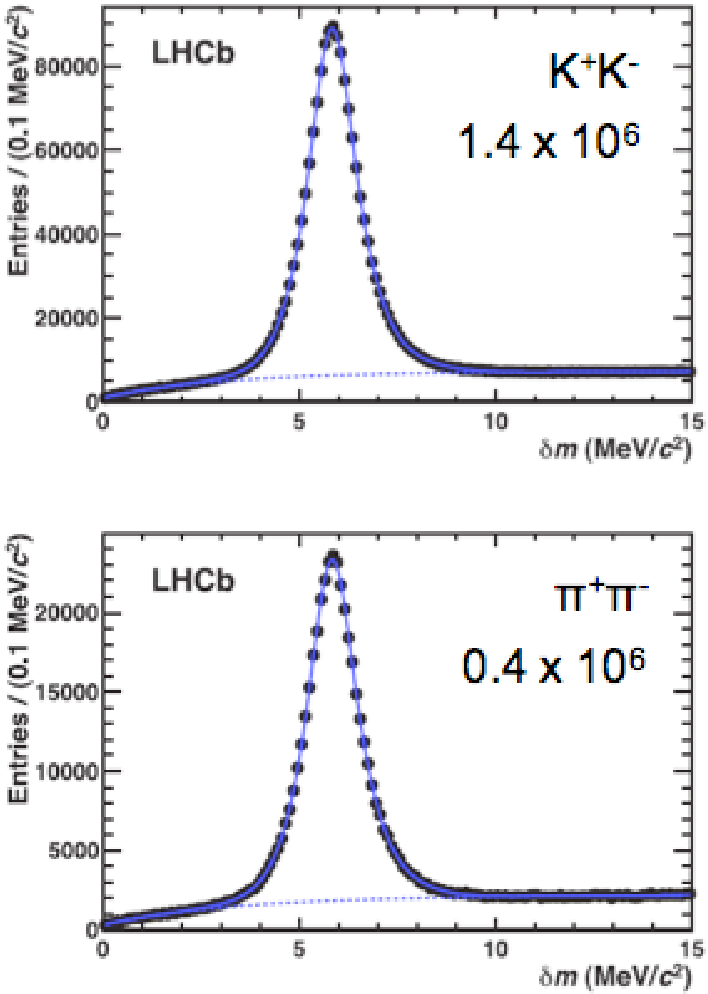
In Singly Cabibbo Suppressed decays interplay between tree and penguin diagrams gives possibility to observe effects of NP.

Same qualities that make LHCb a great B physics detector also hold for charm.

LHCb has very large samples (order of mag. larger than B factories)

Controlling systematic uncertainties to ~0.1% level is challenging

LHCb D^*-D^0-m_π [0.6 fb^{-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

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

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

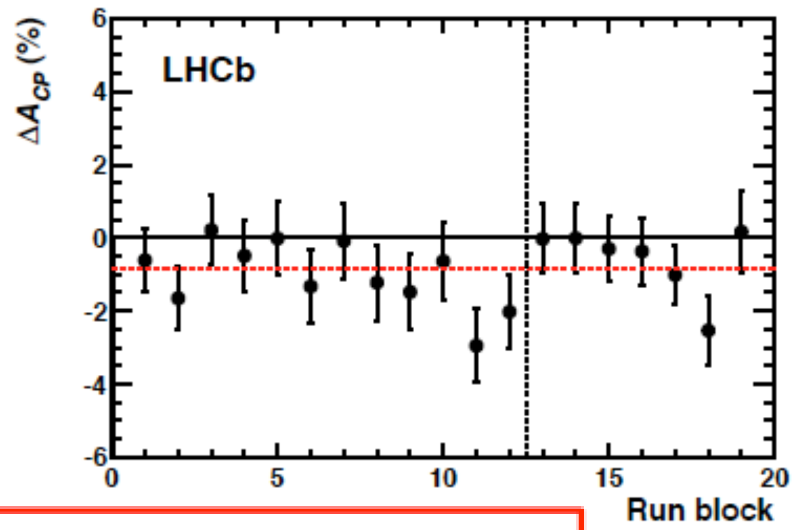
ΔA_{CP} - the result

Numerous cross checks

-dividing between magnet polarities

-data taking dependence

-no D meson kinematic dependence



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

A 3.5σ effect - constitutes first evidence of CPV in charm

Central value can't be excluded in SM though on the large side

Further updates expected + precision studies of other SCS modes

PRL 108 (2012) 111602

Precision CKM metrology

Precision measurement of γ

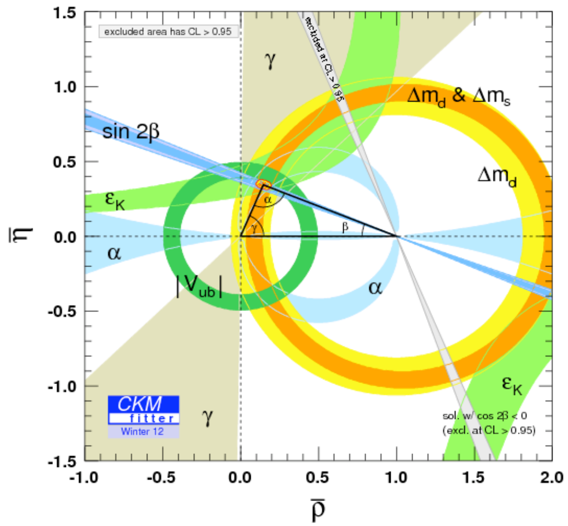
Progress required to improve knowledge of γ

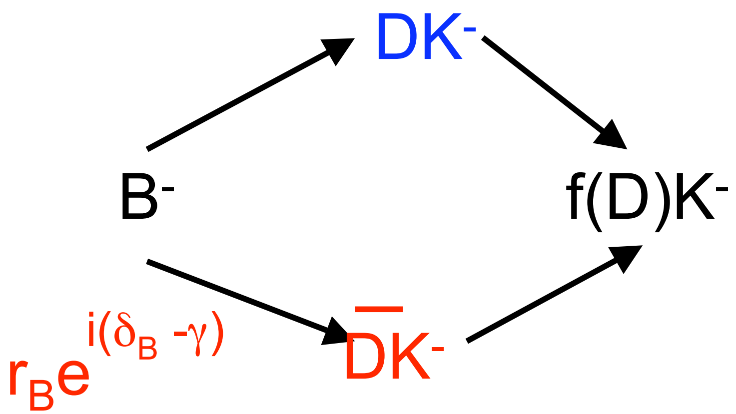
Tree level decays $B^+ \rightarrow DK^+$ great LHCb opportunity. Unpolluted by NP

Provides a SM benchmark against which other loop driven observables can be compared.

pre-summer direct precision ~ 12°

Indirect precision (loops) ~ 4°



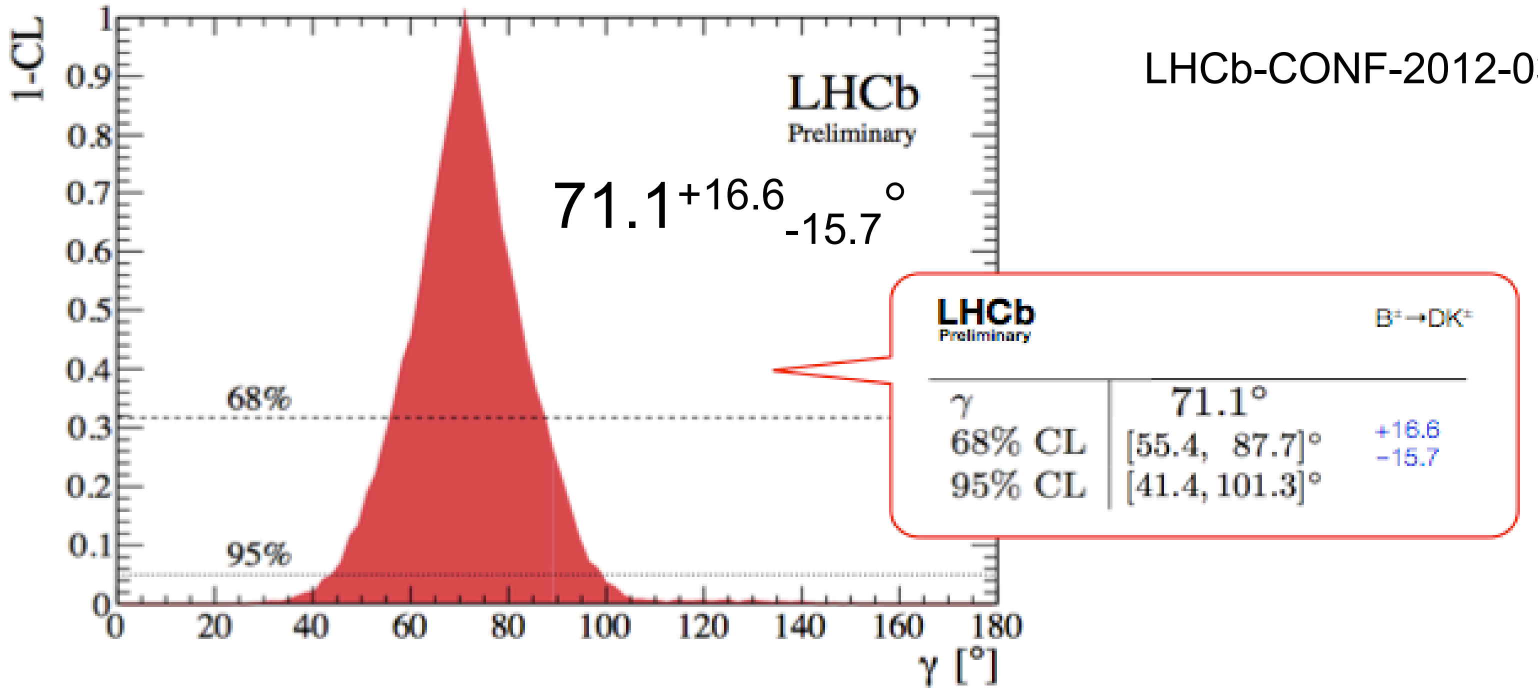


Sensitivity to γ from $b \rightarrow c$ and $b \rightarrow u$ interference

Number of D final states considered:

KK, $\pi\pi$, $K\pi$, $K\pi\pi\pi$, $Ks\pi\pi$, KsKK

LHCb γ combination



LHCb-CONF-2012-032

Current precision of similar size to that from Babar or Belle

More data and more channels currently being analysed

Long term goal, but expect to match current indirect γ precision by 2018

Possible roads to BSM in the LHC era

- Br ($B_s \rightarrow \mu\mu$)
- CP violation in B_s mixing
- EW penguin decays
- CP violation in charm
- Precision CKM metrology

Caveat : Selected topics, focus on recent results. Many other examples exist.

No hints of BSM in the “obvious first-look” observables

Good progress on longer-term observables

Many measurements still statistically limited

LHC experiments continue to take data. Increase in precision & expansion of accessible flavour observables

Flavour physics remains of significant importance in the search for BSM

Backup