Hadronic B Decays at LHCb

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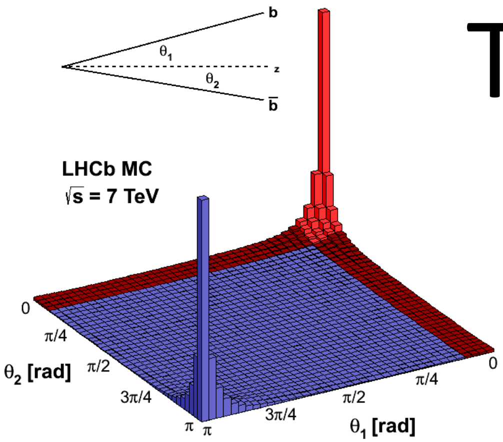
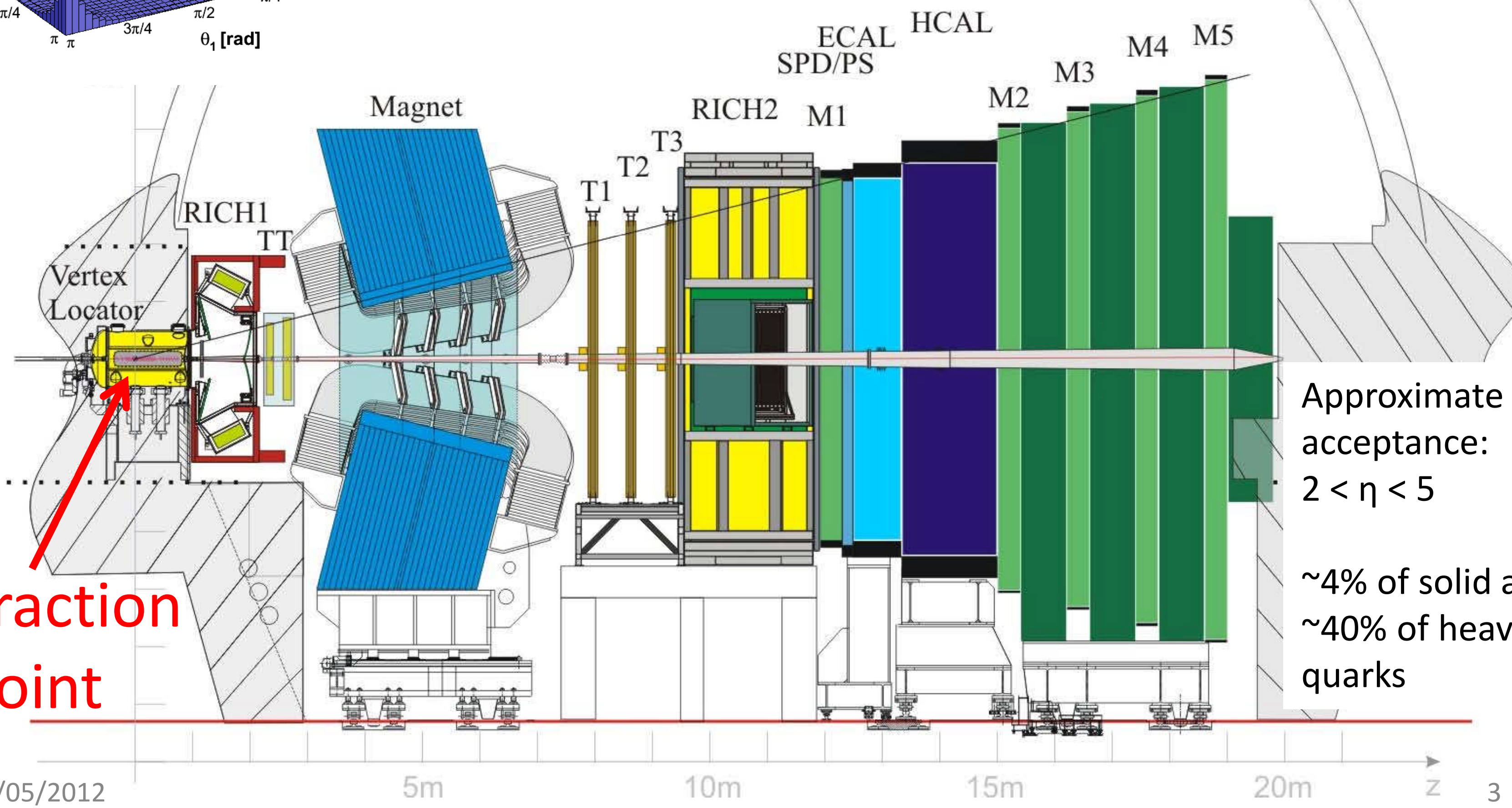
Overview

- Introduction
- Branching fraction measurements of B_s^0 decays to double-charm final states
- Polarisation amplitudes and triple product asymmetries in $B_s^0 \to \phi\phi$
- Resonant components of $B_s^0 \to J/\psi\pi^+\pi^-$
- Conclusion

The LHCb detector



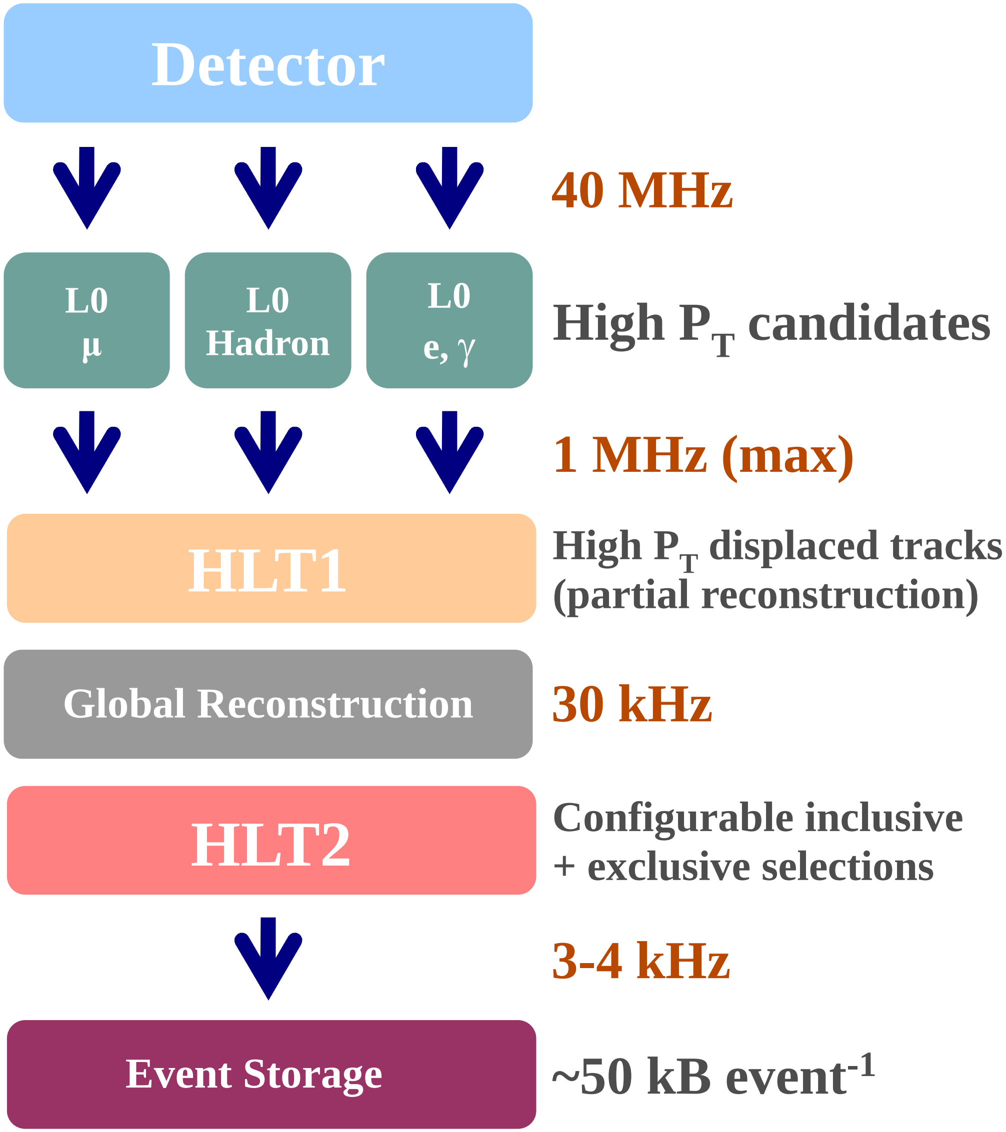
LHCb σ(pp → H_b X) = (75 ± 5 ± 13) μb
Phys. Lett. B 694, 209-216 (2010)



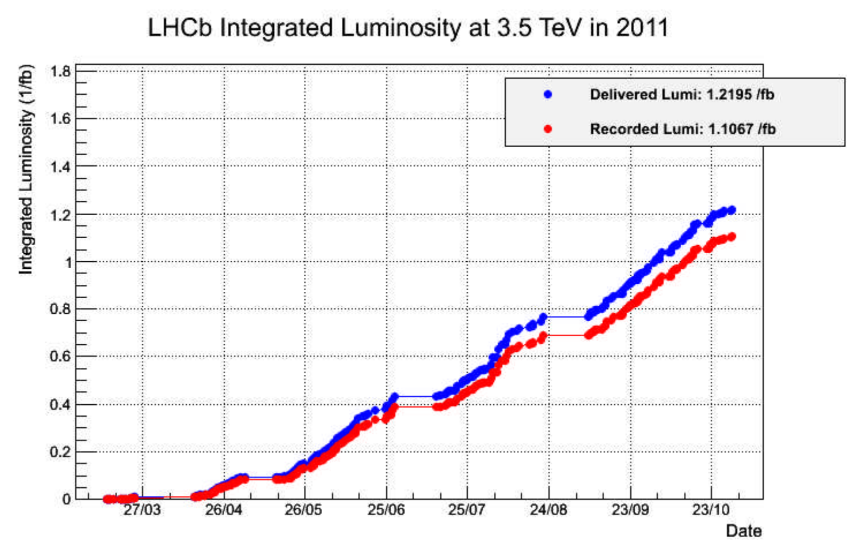
Approximate acceptance:
2 < η < 5

~4% of solid angle
~40% of heavy quarks

Data acquisition



- Trigger Efficiencies:
  - ~30% efficient on multibody hadronic
  - ~90% efficient for dimuons
- Recorded ~1fb^{-1} in 2011



$B_s^0 \rightarrow$ double-charm final states

- Such decays are an excellent laboratory to search for New Physics effects and study final state interactions
- Assuming U-spin symmetry can measure CKM angle γ in $B^0 \rightarrow D^+D^-$ and $B_s^0 \rightarrow D_s^+D_s^-$
- $B^0 \rightarrow D^+D^-$ provides an alternative way to measure $\sin 2\beta$ for comparison with results from $B^0 \rightarrow (c\bar{c})K_S^0$
- Slight discrepancy between BaBar and Belle results for direct CP violation in $B^0 \rightarrow D^+D^-$:
  - $A_{\mathrm{dir}} = -0.07 \pm 0.23 \pm 0.03$: BaBar – PRD 79, 032002 (2009)
  - $A_{\mathrm{dir}} = -0.43 \pm 0.16 \pm 0.05$: Belle – PRD 85, 091106 (2012)
- A large, O(10%), value of this parameter would be a sign of new physics in EW penguins

$B_s^0 \to$ double-charm final states

- Analysis measures 4 relative branching ratios
- Branching fraction ratios calculated from yields, ratios of efficiencies and some external inputs:

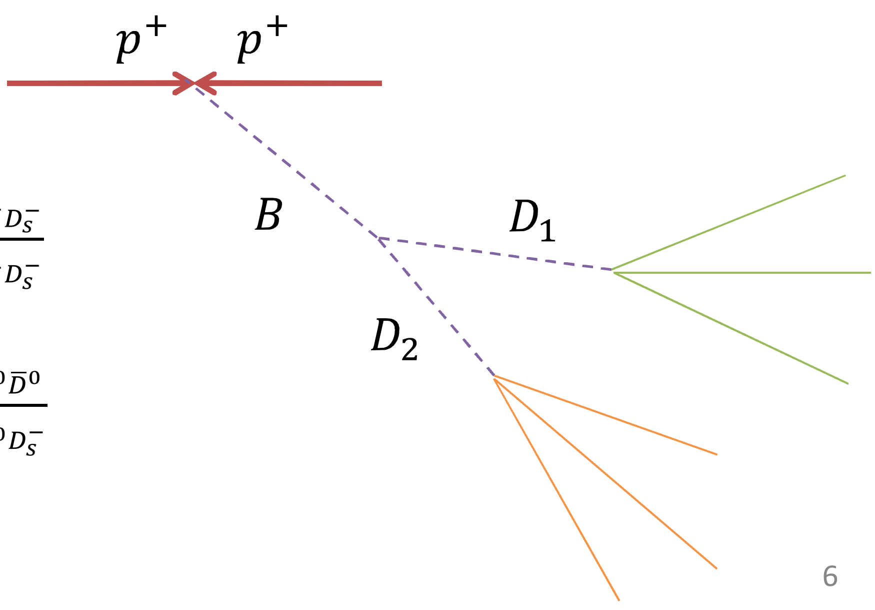
$$\frac{\mathcal{B}(\bar{B}_s^0 \to D^+D^-)}{\mathcal{B}(\bar{B}^0 \to D^+D^-)} = \frac{f_d}{f_s} \cdot \frac{N_{\bar{B}_s^0 \to D^+D^-}}{N_{\bar{B}^0 \to D^+D^-}}$$

$$\frac{\mathcal{B}(\bar{B}_s^0 \to D^+D^-)}{\mathcal{B}(B^0 \to D^+D^-)} = \frac{f_d}{f_s} \cdot \frac{N_{\bar{B}_s^0 \to D_s^+D^-}}{N_{B^0 \to D_s^+D^-}}$$

$$\frac{\mathcal{B}(\bar{B}_s^0 \to D_s^+D_s^-)}{\mathcal{B}(\bar{B}^0 \to D^+D_s^-)} = \frac{f_d}{f_s} \cdot \frac{\varepsilon(\bar{B}^0)}{\varepsilon(\bar{B}_s^0)} \cdot \frac{\mathcal{B}(D^+ \to K^-\pi^+\pi^+)}{\mathcal{B}(D_s^+ \to K^+K^-\pi^+)} \frac{N_{\bar{B}_s^0 \to D_s^+D_s^-}}{N_{\bar{B}^0 \to D^+D_s^-}}$$

$$\frac{\mathcal{B}(\bar{B}_s^0 \to D^0\bar{D}^0)}{\mathcal{B}(B^- \to D^0D_s^-)} = \frac{f_d}{f_s} \cdot \frac{\varepsilon(B^-)}{\varepsilon(\bar{B}_s^0)} \cdot \frac{\mathcal{B}(D_s^+ \to K^+K^-\pi^+)}{\mathcal{B}(D^0 \to K^-\pi^+)} \frac{N_{\bar{B}_s^0 \to D^0\bar{D}^0}}{N_{B^- \to D^0D_s^-}}$$

- Selection of D meson candidates trained on data using $B \to D\pi$ control samples
- Further requirements made on e.g. vertex separation & pointing quantities, to ensure D candidates originate from B decay
- Yields obtained from fit to B candidate invariant mass



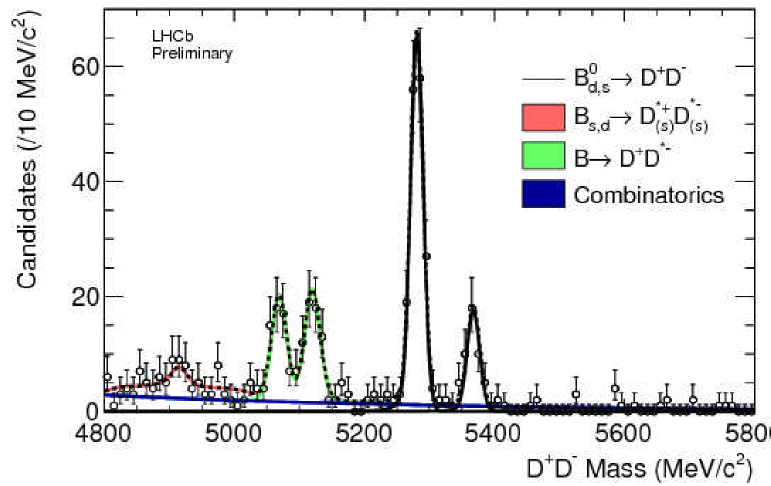
$B_s^0 \to$ double-charm final states

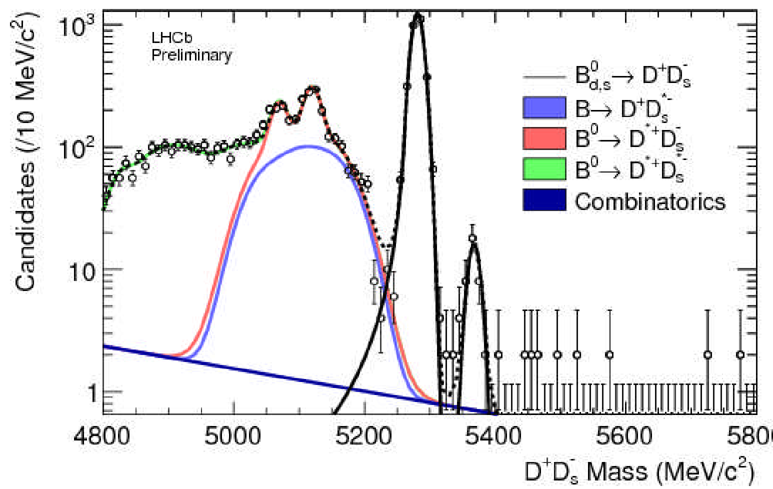
- Preliminary results:

$$\frac{\mathcal{B}(\bar{B}_s^0 \to D^+D^-)}{\mathcal{B}(\bar{B}^0 \to D^+D^-)} = 1.00 \pm 0.18 \pm 0.09$$

$$\frac{\mathcal{B}(\bar{B}_s^0 \to D_s^+D^-)}{\mathcal{B}(B^0 \to D_s^+D^-)} = 0.048 \pm 0.008 \pm 0.004$$

- Both are first observations
- Largest contributions to systematic uncertainties:
  - $\frac{f_d}{f_s}$ (~8%)
  - Lifetime acceptance (1-4%)
  - Secondary branching fractions (where applicable ~5%)





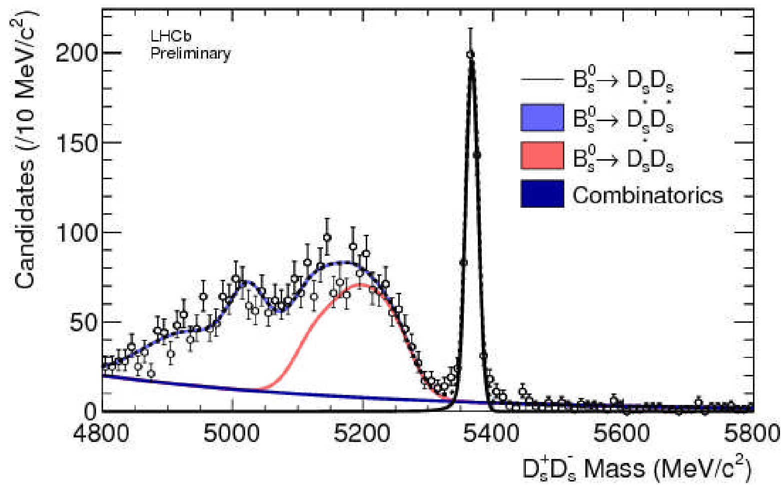
$B_s^0 \to$ double-charm final states

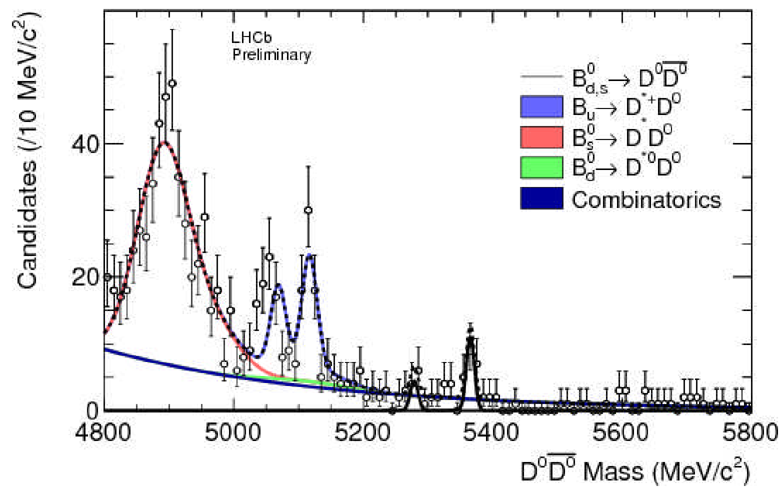
- Preliminary results:

$$\frac{\mathcal{B}(\bar{B}_s^0 \to D_s^+ D_s^-)}{\mathcal{B}(\bar{B}^0 \to D^+ D_s^-)} = 0.508 \pm 0.026 \pm 0.043$$

$$\frac{\mathcal{B}(\bar{B}_s^0 \to D^0 \bar{D}^0)}{\mathcal{B}(B^- \to D^0 D_s^-)} = 0.015 \pm 0.004 \pm 0.002$$

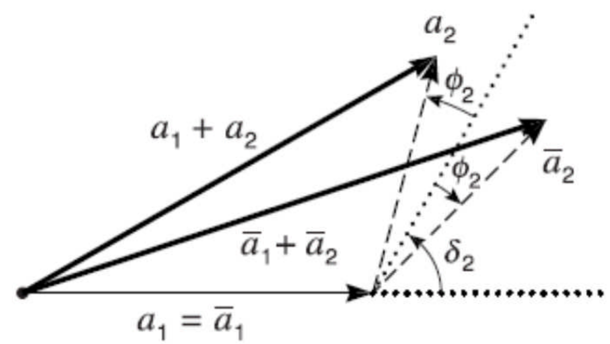
- First observation of $\bar{B}_s^0 \to D^0 \bar{D}^0$
- New relative BF result for $B_s^0 \to D_s^+ D_s^-$ with greatly improved precision c.f. current world average: $1.44^{+0.43}_{-0.40}$
- And is consistent with recently updated value from CDF:
  - $0.680 \pm 0.078 \pm 0.063 \pm 0.083$
  - Phys. Rev. Lett. 108, 201801 (2012)

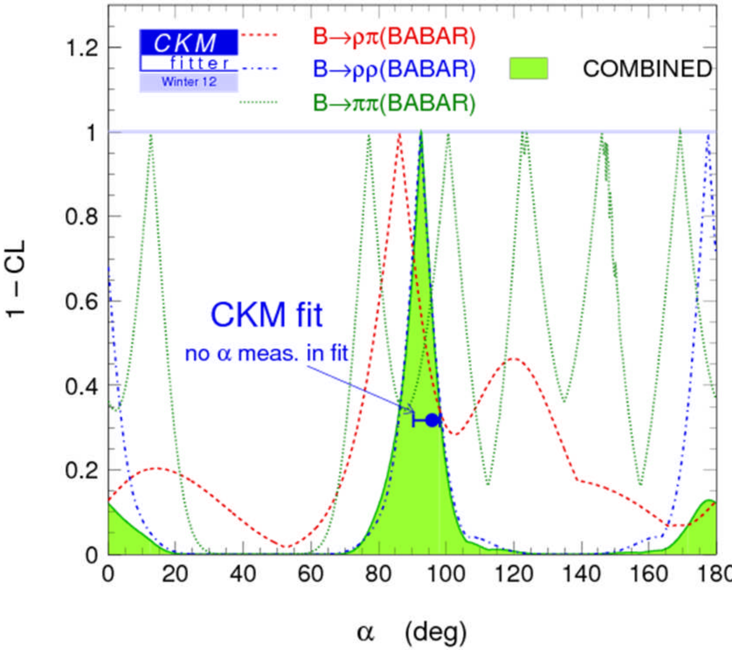




Amplitude Analysis

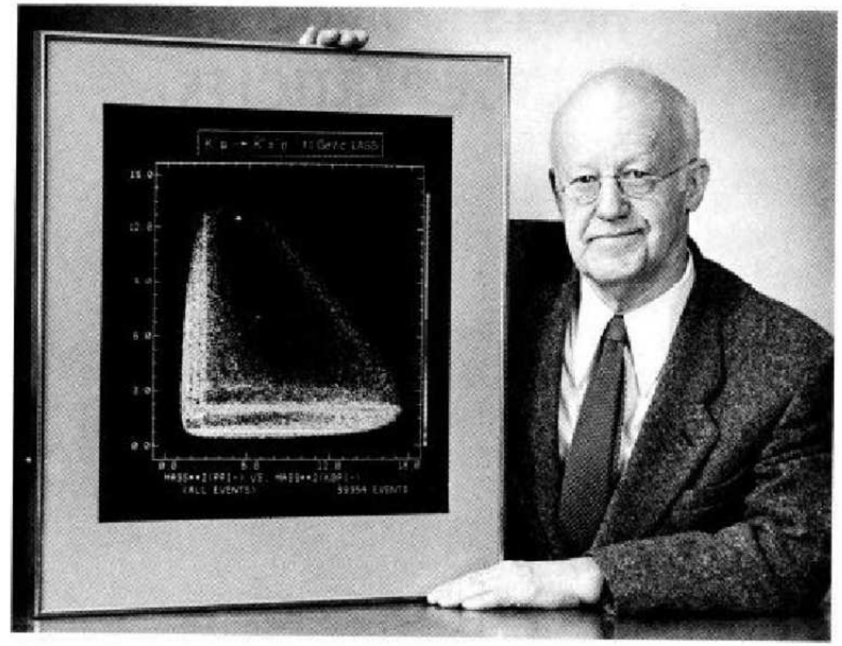
- Interference between intermediate states is a feature of decays to multi-body final states
- Permits measurements of relative phases
- Gives greater sensitivity to CP violating observables and can resolve ambiguities
- Generally requires formulating a model of the decay at the amplitude level

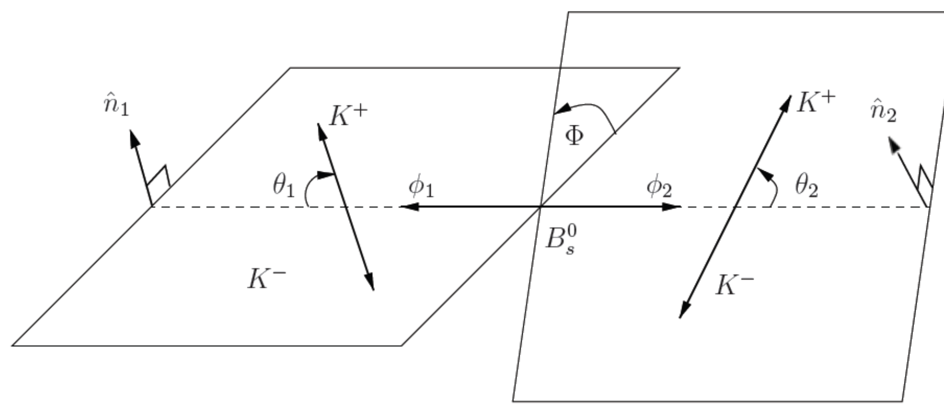




Amplitude Analysis

- Common forms in B-decay analyses:
  - Dalitz-plot (DP) analysis – 3-body final state of spin-0 particles
  - "Extended" DP analysis – one final-state particle is not spin-0
  - Angular analysis, e.g. Vector-Vector intermediate state with 4-body final state





“Polarisation puzzle”

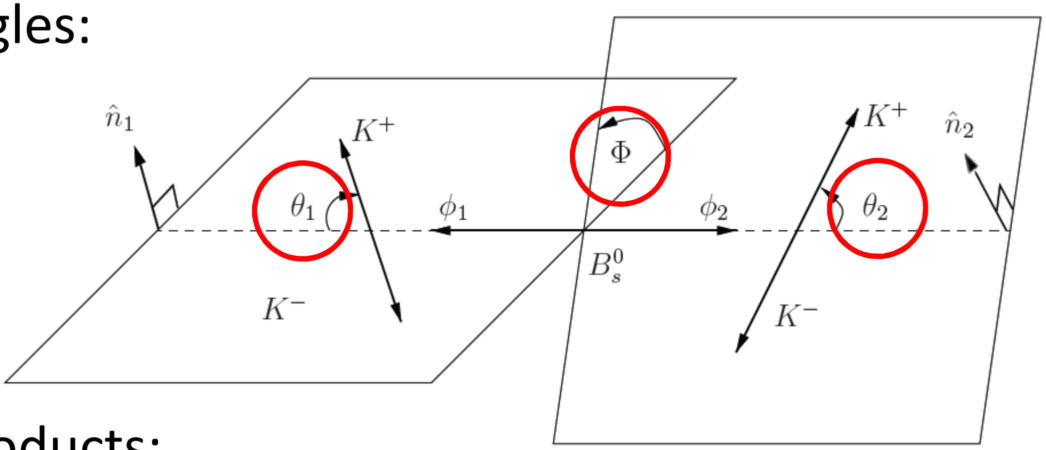
- In B → Vector Vector decays there are 3 possible spin configurations
- These are often described by the longitudinal (A_0), parallel ($A_\parallel$) and perpendicular ($A_\perp$) components
- The first two are CP-even and the last CP-odd
- From the V-A structure of weak interaction longitudinal component is expected to dominate ($f_L \sim 1$)
- However, a number of measurements find roughly equal longitudinal and transverse components, e.g.
  - $B^+ \to \phi K^{*+}$, $B^0 \to \phi K^{*0}$, $B^+ \to \rho^0 K^{*+}$, $B^0 \to \rho^0 K^{*0}$
  - And recently LHCb found $f_L = 0.31 \pm 0.12 \pm 0.04$ in $B_s \to K^{*0}\overline{K}^{*0}$

LHCb-PAPER-2011-012, arXiv:1111.4183 [hep-ex], Phys. Lett. B709 (2012) 50

- To explain these measurements, large contributions from penguin annihilation or final state interactions have been proposed
- Recent calculations allow f_L in the range 0.4 – 0.7
  - Beneke, Rohrer & Yang, Nucl. Phys. B774, 64 (2007)
  - Cheng & Chua, Phys. Rev. D80, 114026 (2009)

Angular analysis of $B_s^0 \to \phi\phi$

- In B decays to 4-body final state, phase space is 5-dimensional!
- Choosing a particular quasi-two-body intermediate state, e.g. $\phi\phi$, reduces this to 3 angles:



- Define two triple-products:

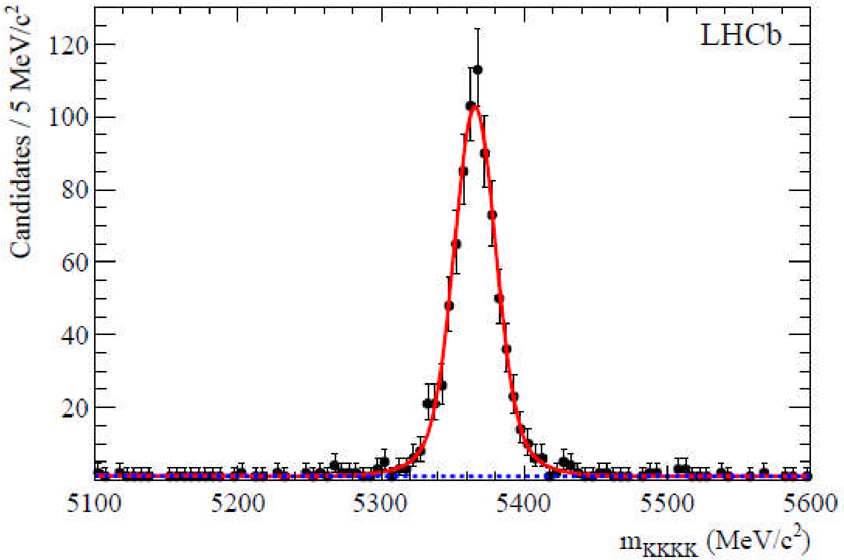
$$U = \frac{\sin 2\Phi}{2} \qquad V = \begin{cases} +\sin\Phi : & \cos\theta_1 \cos\theta_2 \geq 0 \\ -\sin\Phi : & \cos\theta_1 \cos\theta_2 < 0 \end{cases}$$

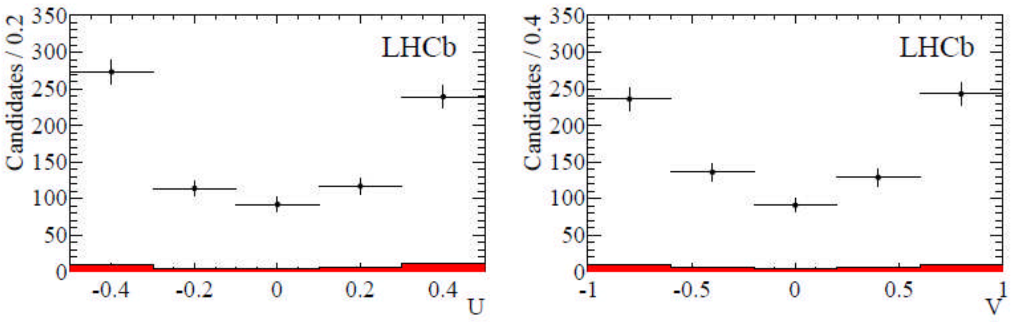
- Asymmetries of these should be zero in SM
- Some New Physics models can give non-zero values

LHCb-PAPER-2012-004, arXiv:1204.2813 [hep-ex], Submitted to Phys. Lett. B

Angular analysis of $B_s^0 \to \phi\phi$

- Signal yield = 801 ± 29 (stat. error)
- Polarisation amplitudes:
  $|A_0|^2 = 0.365 \pm 0.022 \pm 0.012$
  $|A_\perp|^2 = 0.291 \pm 0.024 \pm 0.010$
  $|A_\parallel|^2 = 0.344 \pm 0.024 \pm 0.014$
- Longitudinal fraction very similar to $B_s \to K^{*0}\overline{K}^{*0}$
- Strong phase difference:
  $\cos\delta_\parallel = -0.844 \pm 0.068 \pm 0.029$
- Triple product asymmetries:
  $A_U = -0.055 \pm 0.036 \pm 0.018$
  $A_V = \;\; 0.010 \pm 0.036 \pm 0.018$
- Consistent with no CPV and hence Standard Model prediction
- Largest systematic uncertainties from S-wave component, decay time acceptance and angular acceptance

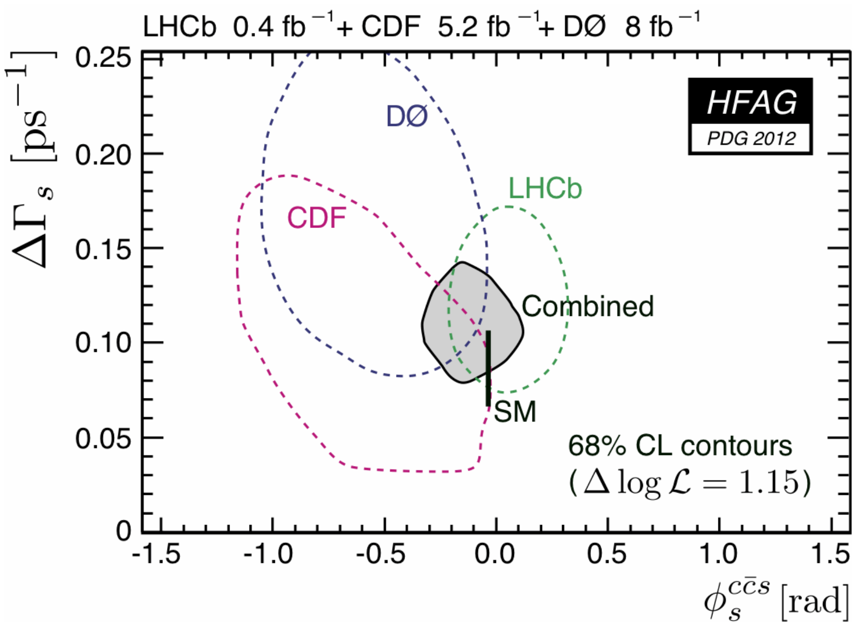


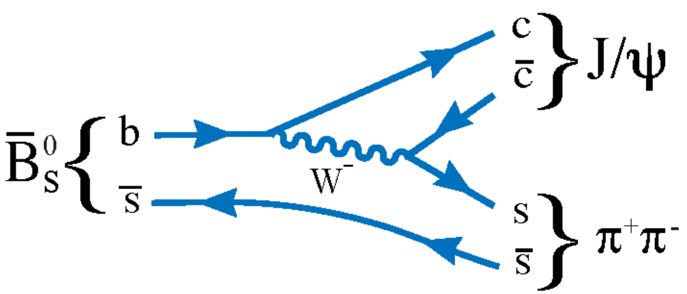


Red histogram = background

Resonant components of $B_s^0 \rightarrow J/\psi\pi^+\pi^-$

- The decay $B_s \rightarrow J/\psi f_0(980)$, first observed by LHCb, has been used to measure the CP-violating phase ϕ_s, in complement to measurements from $B_s \rightarrow J/\psi\phi$
- Such measurements are crucial in probing physics beyond the Standard Model
- Greater precision could potentially be achieved from utilising the whole 3-body decay
- However, the resonant and CP content must first be determined

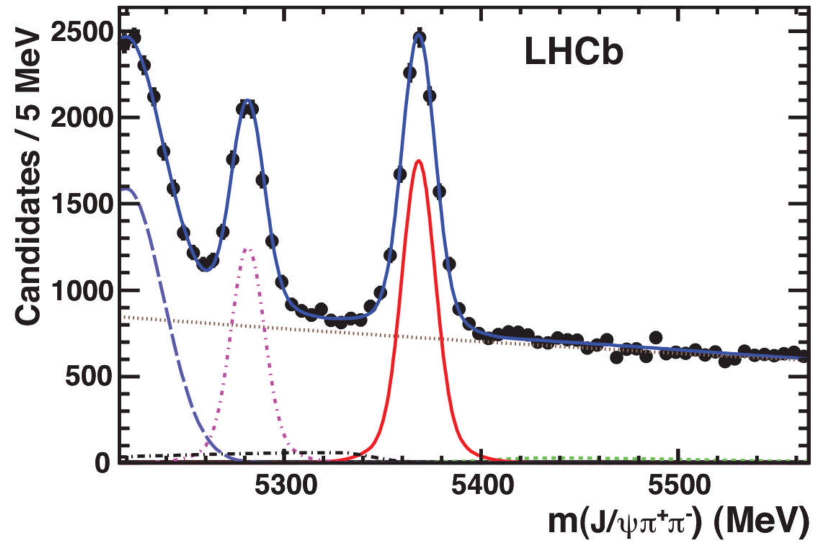


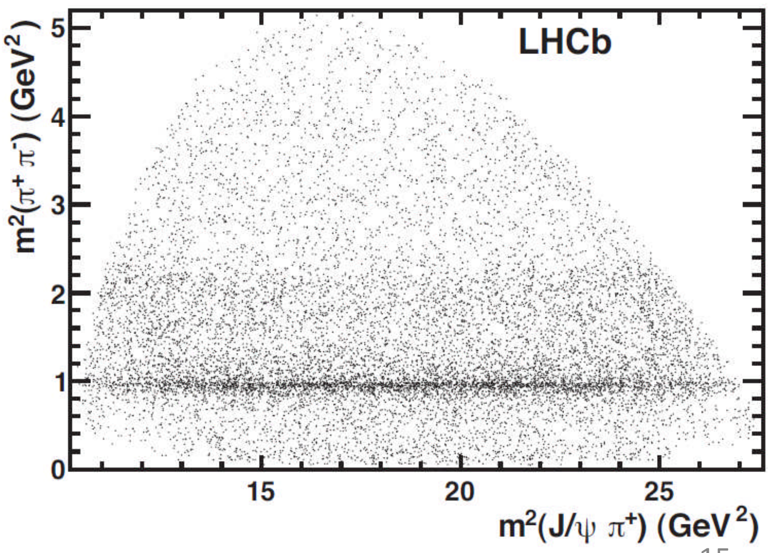


LHCb-PAPER-2012-005, arXiv:1204.5643 [hep-ex], Submitted to Phys. Rev. D

$B_s^0 \rightarrow J/\psi\pi^+\pi^-$

- Signal yield of 7598 ± 120 (statistical error only)
- Analysis integrates over angle between J/ψ and $\pi^+\pi^-$ decay plane, which shows little structure
- Leaves 3 variables:
  - $m^2(J/\psi\,\pi^+)$
  - $m^2(\pi^+\pi^-)$
  - J/ψ helicity angle ($\theta_{J/\psi}$)
- No resonant structure visible in $m^2(J/\psi\,\pi^+)$
- Very clear structure in $m^2(\pi^+\pi^-)$

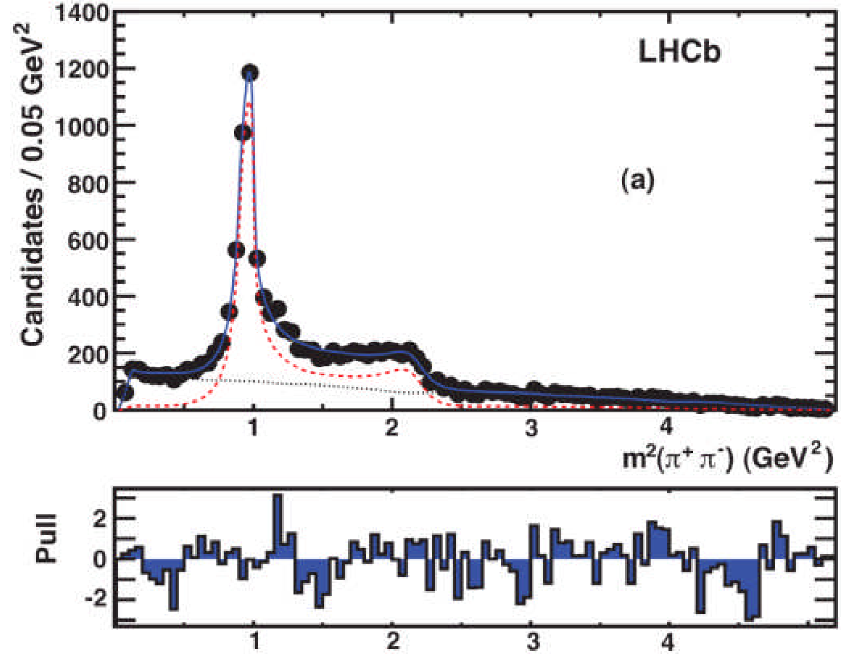




LHCb-PAPER-2012-005, arXiv:1204.5643 [hep-ex], Submitted to Phys. Rev. D

$B_s^0 \to J/\psi\pi^+\pi^-$

- Largest component (~70%) is the $f_0(980)$ resonance
- Some D-wave from $f_2(1270)$, about 0.5% of the helicity 0 rate
- Mixed CP $A_{2\pm1}$ amplitude is $(0.2 \pm 0.7)\%$ of total rate
- Addition of $\rho^0(770)$ resonance does not improve fit likelihood
- Decay is dominantly CP-odd, > 0.977 at 95% CL
- Indicates that whole mass range can be used for CP violation studies



Relative branching fraction also measured:

$$\frac{\mathcal{B}(B_s^0 \to J/\psi\pi^+\pi^-)}{\mathcal{B}(B_s^0 \to J/\psi\phi)} = (21.28 \pm 0.51 \pm 0.56)\%$$

See talk of G. Lanfranchi from this morning

Conclusion

- Have shown a selection of recent results of hadronic B decays from LHCb
- A wealth of different decay modes being studied in order to probe for signs of physics beyond the Standard Model
- The statistics available from the 2011 data sample ($1\mathrm{fb}^{-1}$) already allow to employ sophisticated analysis techniques
- Hope to have another $1.5\mathrm{fb}^{-1}$ of data by the end of the year – exciting times ahead!

BACKUP

Angular analysis of $B_s^0 \to \phi\phi$

- A time-integrated, untagged analysis is performed
- Allows measurements of:
  - polarisation amplitudes
  - relative phase of the two CP-even components
  - two triple-product asymmetries A_U and A_V

$$\frac{d^3\Gamma}{d\cos\theta_1\, d\cos\theta_2\, d\Phi} \propto \sum_{i=1}^{4} K_i f_i(\theta_1, \theta_2, \Phi)$$

$$K_1 = \frac{|A_0|^2}{\Gamma_L}, \qquad K_2 = \frac{|A_\parallel|^2}{\Gamma_L},$$
$$K_3 = \frac{|A_\perp|^2}{\Gamma_H}, \qquad K_4 = \frac{|A_0||A_\parallel|\cos\delta_\parallel}{\Gamma_L}$$

$$f_1(\theta_1, \theta_2, \Phi) = 4\cos^2\theta_1 \cos^2\theta_2\,,$$
$$f_2(\theta_1, \theta_2, \Phi) = \sin^2\theta_1 \sin^2\theta_2 (1 + \cos 2\Phi)\,,$$
$$f_3(\theta_1, \theta_2, \Phi) = \sin^2\theta_1 \sin^2\theta_2 (1 - \cos 2\Phi)\,,$$
$$f_4(\theta_1, \theta_2, \Phi) = \sqrt{2}\sin 2\theta_1 \sin 2\theta_2 \cos\Phi$$

$$U = \frac{\sin 2\Phi}{2} \qquad V = \begin{cases} +\sin\Phi: & \cos\theta_1\cos\theta_2 \geq 0 \\ -\sin\Phi: & \cos\theta_1\cos\theta_2 < 0 \end{cases}$$

$B_s^0 \to J/\psi\pi^+\pi^-$

- The signal amplitude model consists of a sum over the 3 helicity states:

$$S(s_{12}, s_{23}, \theta_{J/\psi}) = \sum_{\lambda=0,\pm1} \left| \sum_i a_\lambda{}^{R_i} e^{i\phi_\lambda^{R_i}} \mathcal{A}_\lambda^{R_i}(s_{12}, s_{23}, \theta_{J/\psi}) \right|^2$$

- For each of these there is a model of the "extended Dalitz plot", including for each component the mass shape, angular term and form factors, plus the J/ψ decay angle term
- The nominal resonance model consists of the $f_0(980)$, $f_2(1270)$, $f_0(1370)$ resonances and a non-resonant component
- Variation of the detection efficiency over the Dalitz plot is modelled by a 4th order polynomial function
- The acceptance in the J/ψ decay angle is uniform