Experimental results on $B \to D^{(*)}\pi\pi$

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Workshop on *B* decay into *D***
27th November 2012

THE UNIVERSITY OF WARWICK

Overview

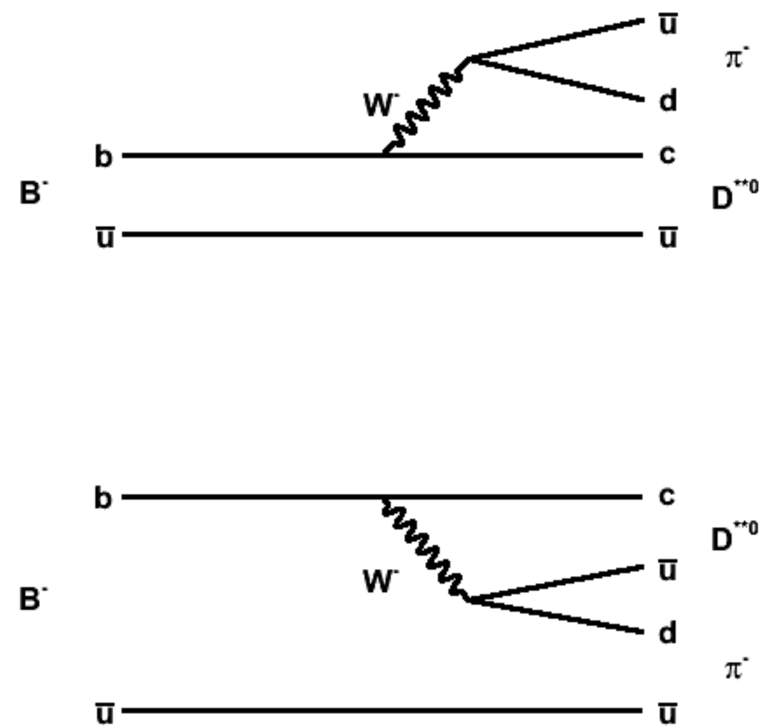
- Quick recap of motivations
- Outline the experimental methods and associated challenges
- Present the experimental results from BaBar on $B \to D\pi\pi$ decays
  - Emphasis on D** intermediate states
  - Include comparisons with Belle results but details of Belle analyses given by D. Matvienko tomorrow
- Show some recent results and future prospects from LHCb

Motivation

- The $B \to D^{(*)}\pi\pi$ Dalitz plots can contain:
  - $D^{**}\pi$ contributions
  - Colour-suppressed D^0h^0 decays
- As we've heard already in this workshop, there is some discrepancy between theory and experiment in $B \to D^{**}l\nu$ decays
- The BFs of $B \to D^{**}\pi$ transitions are of interest to provide more input into this issue (see earlier talk by Alain Le Yaouanc)
- Isospin symmetry relates the BFs of the various $B \to D\rho$ decays
  - Combining such measurements can give insight into strong interaction phases
- In the neutral B decays can perform a time-dependent analysis to measure $\sin(2\beta)$ and $\cos(2\beta)$ if D is reconstructed in decay to a *CP* eigenstate
  - See, for example, TL and T. Gershon, J. Phys. G 36, 025006 (2009)
- Can also measure $\sin(2\beta+\gamma)$ from the time-dependent $B^0 \to D^{**}\pi$ decay rate if the D is reconstructed in a non-*CP* eigenstate

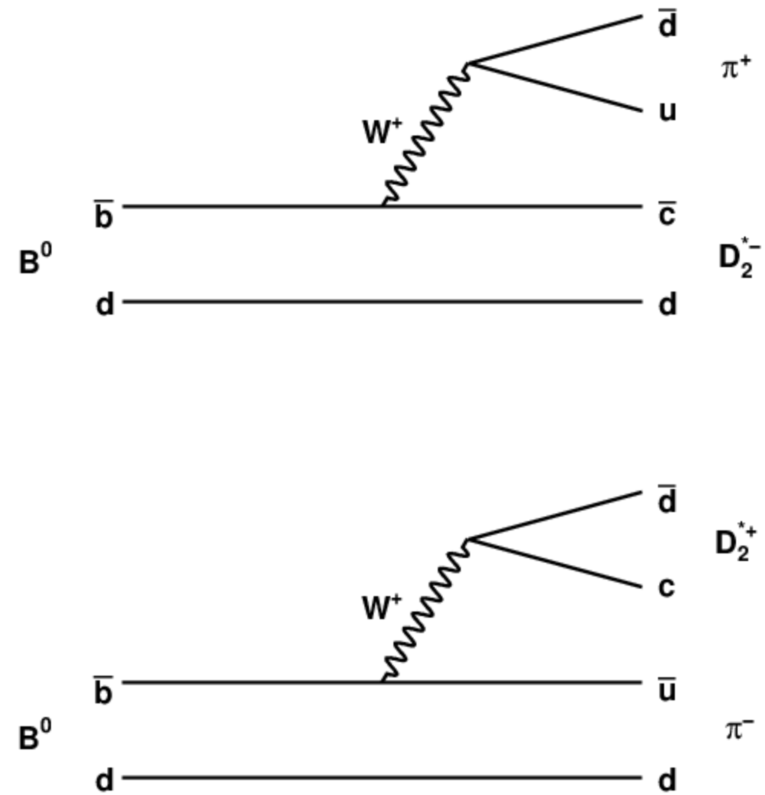
Motivation

- In charged *B* decays there are two tree level diagrams, colour allowed (top) and colour suppressed (bottom)
- Slightly complicates the comparison with the semi-leptonic decays since only the first contributes in that case



Motivation

- In neutral *B* decays there are again two tree level diagrams (both colour allowed)
- But one is heavily CKM suppressed and gives opposite sign *D***
  - (and sensitivity to CKM angle γ)
- Simpler comparison with the semi-leptonic decays

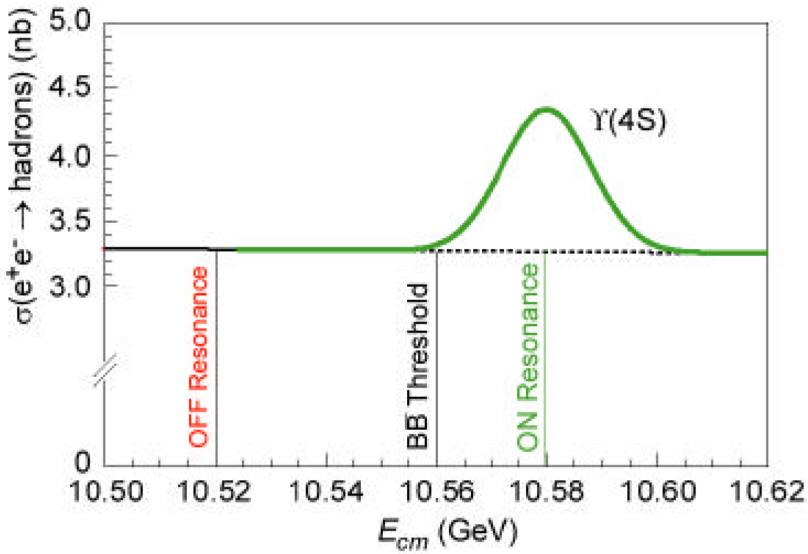


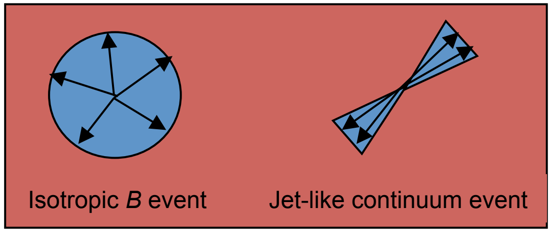
Analysis Overview

- Reconstruct D^0 and D^+ candidates in their decays to $K^-\pi^+(\pi^+\pi^-)$ and $K^-\pi^+\pi^+$
- Optionally reconstruct D^* candidates in decay to $D\pi$
- Form B candidates from D/D^* and two additional pions
- Apply particle ID to pions and D daughters
- Suppress continuum background with event-shape variables
- Fit to kinematic and Dalitz-plot variables determines signal and background yields plus complex amplitude coefficients

Analysis Variables – Topological

- Light quark continuum cross section ~3x $b\bar{b}$
- *B* mesons produced almost at rest since just above threshold
- Use event topology to discriminate
- Combine variables in a Multi-Variate Analyser (MVA) such as a Neural Network (NN)

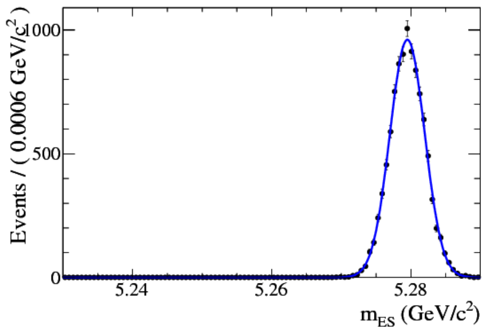


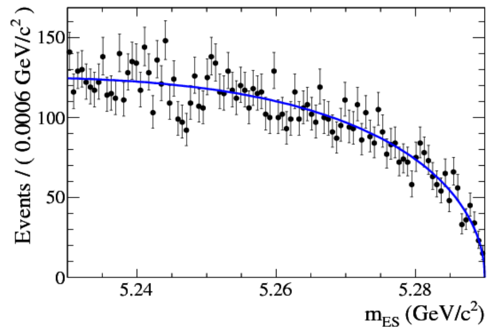


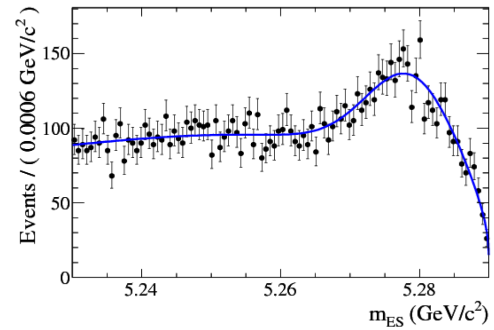
Analysis Variables – Kinematic

Make use of precision kinematic information from the beams.

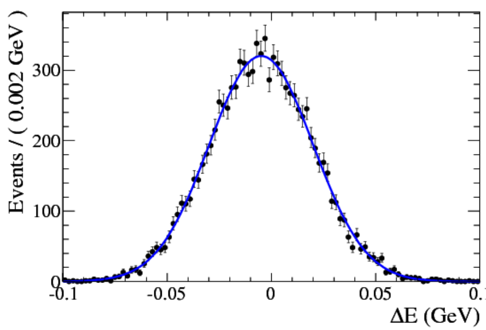
$$m_{ES} = \sqrt{E_{beam}^{*2} - p_B^{*2}}$$

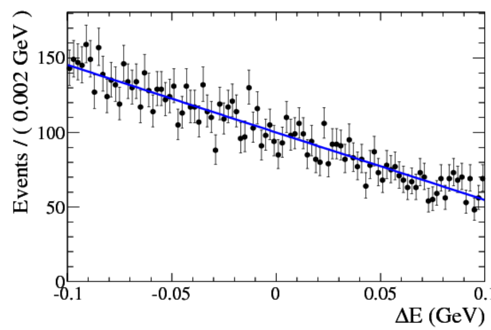


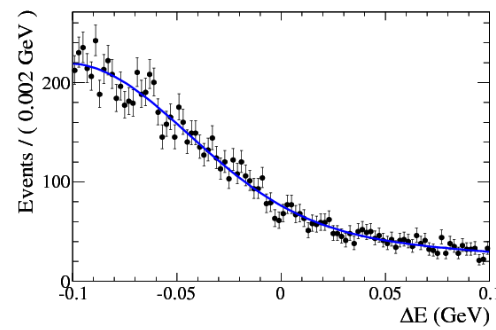




$$\Delta E = E_B^* - E_{beam}^*$$







Plots show MC events

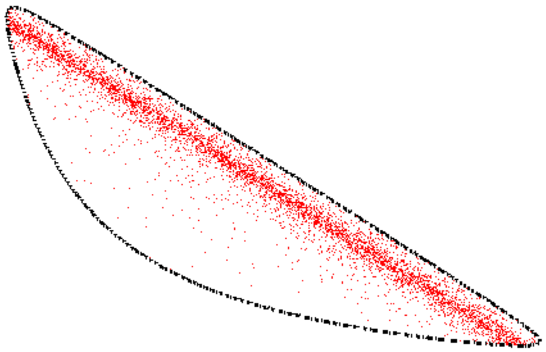
Characteristic Signal Distributions

Characteristic Continuum Distributions

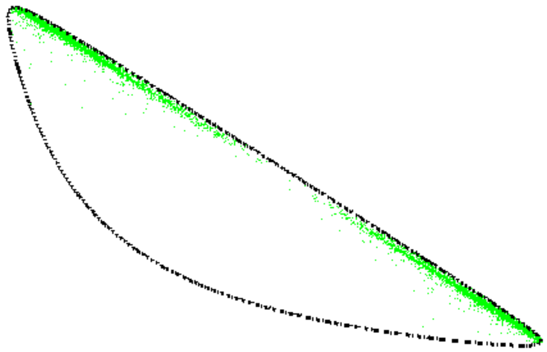
Characteristic B-background Distributions

Dalitz-plot Analysis

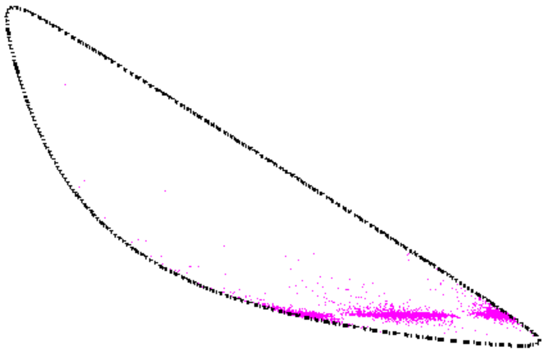
- Dalitz plot is a representation of the $B \to PPP$ phase space
- Structure in the DP gives information on resonance masses, widths and spins, relative phases, interference etc.
- Model each contribution to the DP as a separate amplitude with a complex coefficient (isobar model)
- Amplitude model must be symmetrised if identical particles are present in the final state



Red points show a spin 0 $\pi\pi$ resonance



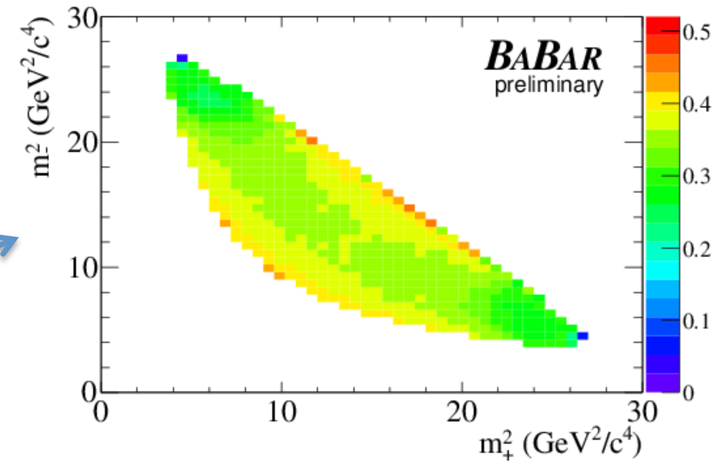
Green points show spin 1 $\pi\pi$ resonance

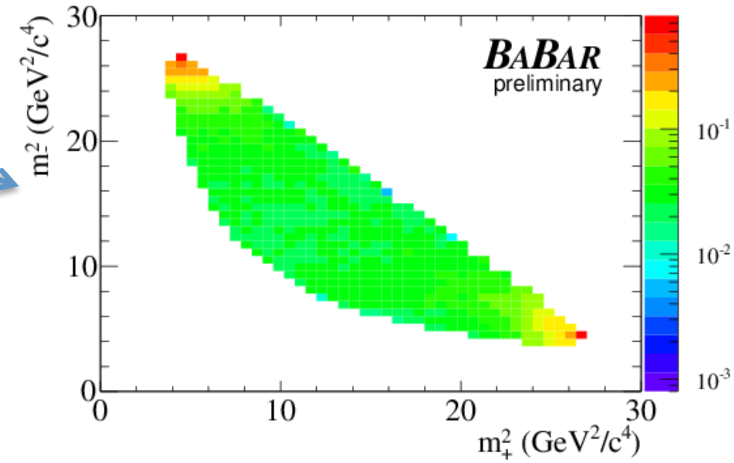


Purple points show spin 2 $D\pi$ resonance

Dalitz-plot Analysis

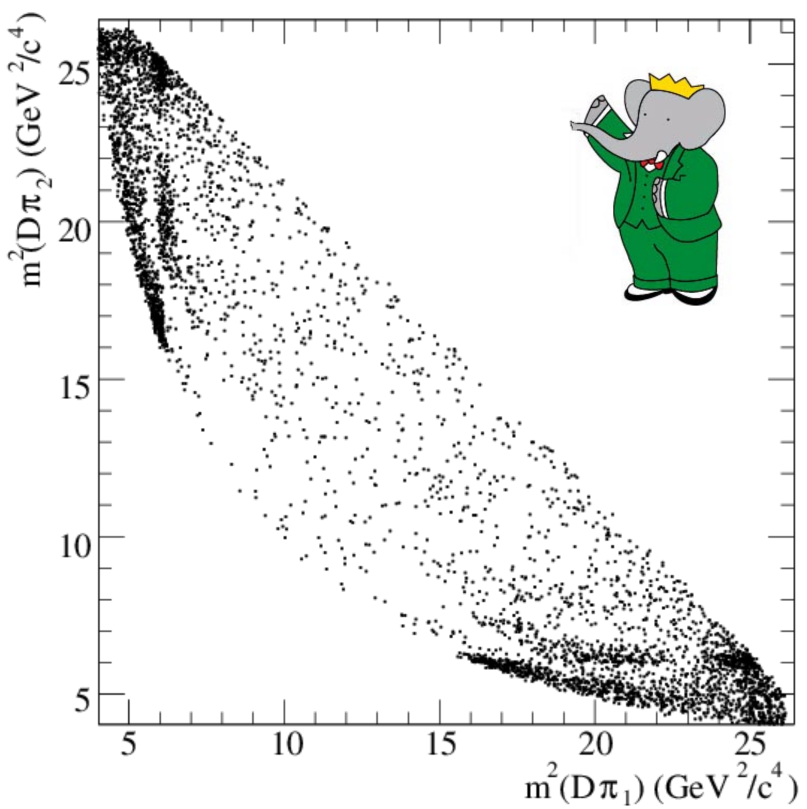
- Also need to account for the following effects and their possible Dalitz-plot dependence:
  - signal reconstruction efficiency
  - fraction of mis-reconstructed signal events
  - experimental resolution on the Dalitz-plot position of each of those categories
  - background event yields



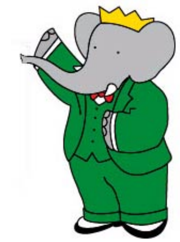


$B^- \to D^+\pi^-\pi^-$

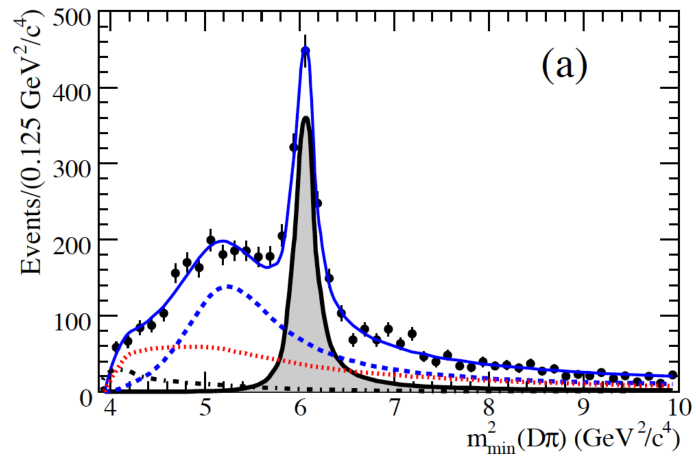
- Both Belle and BaBar have studied this mode
  - Belle: 65M BB pairs, PRD 69, 112002 (2004)
  - BaBar: 383M BB pairs, PRD 79, 112004 (2009)
- Contributions found from
  - two D^{**} states:
    - D_2^{*0} (~30%) and D_0^{*0} (~60%)
  - off-shell $B \to D^*(2007)\pi$ and $B \to B^*\pi$ decays
    - D_v^* (~10%) and B_v^* (~5%)
  - P-wave non-resonant $D\pi\pi$ (BaBar only) (~5%)

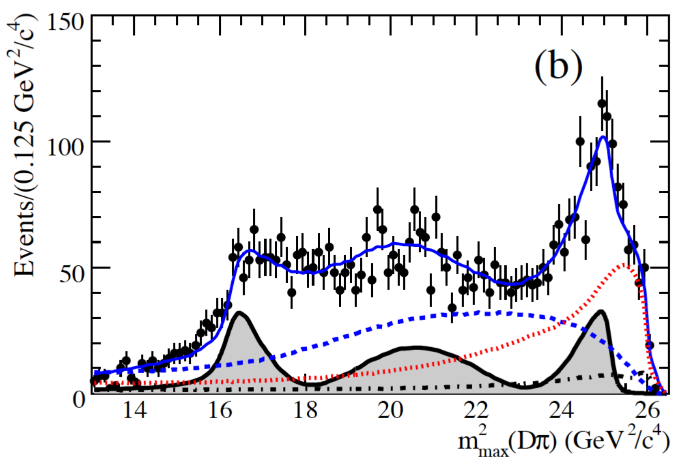


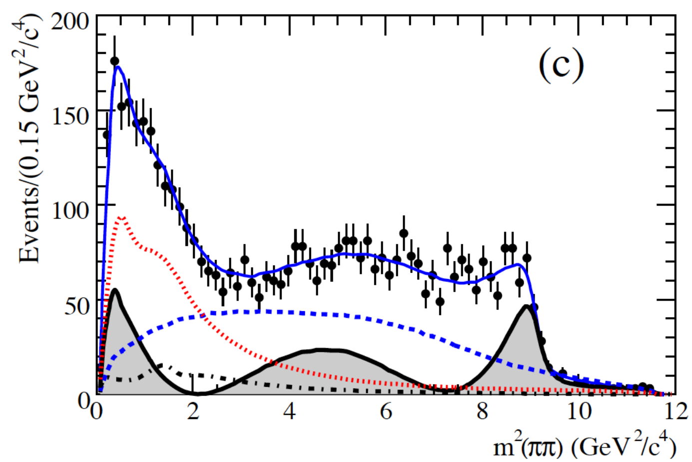
$B^- \to D^+\pi^-\pi^-$



- Projections of the BaBar data with the fit model superimposed
  - ➢ Total fit
  - ➢ D_2*
  - ➢ D_0*
  - ➢ Background
  - ➢ Virtual *D** and *B**







$B^- \to D^+\pi^-\pi^-$

Measured quantity	Belle - PRD 69, 112002 (2004)	BaBar - PRD 79, 112004 (2009)
BF($B^- \to D^+\pi^-\pi^-$)	$(1.02 \pm 0.04 \pm 0.15) \times 10^{-3}$	$(1.08 \pm 0.03 \pm 0.05) \times 10^{-3}$
D_2^* Mass	$(2461.6 \pm 2.1 \pm 0.5 \pm 3.3)$ MeV/c^2	$(2460.4 \pm 1.2 \pm 1.2 \pm 1.9)$ MeV/c^2
D_2^* Width	$(45.6 \pm 4.4 \pm 6.5 \pm 1.6)$ MeV	$(41.8 \pm 2.5 \pm 2.1 \pm 2.0)$ MeV
D_2^* Product BF	$(3.4 \pm 0.3 \pm 0.6 \pm 0.4) \times 10^{-4}$	$(3.5 \pm 0.2 \pm 0.2 \pm 0.4) \times 10^{-4}$
D_0^* Mass	$(2308 \pm 17 \pm 15 \pm 28)$ MeV/c^2	$(2297 \pm 8 \pm 5 \pm 19)$ MeV/c^2
D_0^* Width	$(276 \pm 21 \pm 18 \pm 60)$ MeV	$(273 \pm 12 \pm 17 \pm 45)$ MeV
D_0^* Product BF	$(6.1 \pm 0.6 \pm 0.9 \pm 1.6) \times 10^{-3}$	$(6.8 \pm 0.3 \pm 0.4 \pm 2.0) \times 10^{-3}$
D_2^* and D_0^* $\Delta\phi$	$(-2.37 \pm 0.11 \pm 0.08 \pm 0.10)$ rad	$(-2.07 \pm 0.06 \pm 0.09 \pm 0.18)$ rad

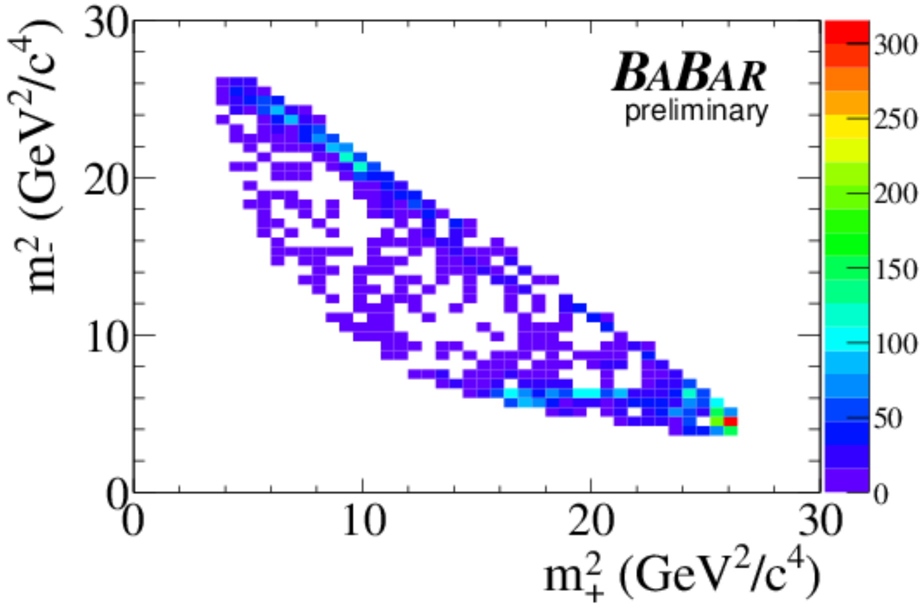
The two experiments give very compatible results for all D^{**} quantities

$B^{-} \rightarrow D^{+}\pi^{-}\pi^{-}$

- Systematic uncertainties mostly dominated by the background parameterisation
- Event selection and fit bias also significant for some parameters, particularly the width of the D_0^*
- Model uncertainties estimated by varying the Blatt-Weisskopf barrier radii and trying alternative models, removing the less significant components and adding other NR components

$B^0 \rightarrow D^0\pi^+\pi^-$

- Both Belle and BaBar have studied this mode
  - Belle: 388M BB pairs, PRD 76, 012006 (2007)
  - BaBar: preliminary results, from 471M BB pairs, arXiv:1007.4464 [hep-ex]
- Analysis is more complicated due to presence of $\pi^+\pi^-$ resonances and physical $D^*(2010)^+$ near threshold
- Contributions found from
  - two D^{**} states: D_2^{*+} and D_0^{*+}
  - virtual D_v^* (~10%)
  - $\rho(770)$ and $f_2(1270)$
  - various S-wave components



- The description of the S-wave is the main difference between the BaBar and Belle analyses

$B^0 \to D^0\pi^+\pi^-$

- BaBar uses a K-matrix approach to model the $\pi^+\pi^-$ S-wave
- Belle uses a sum of Breit-Wigners: $f_0(600)$, $f_0(980)$ and $f_0(1370)$
- BaBar includes a $D\pi$ NR in addition to the D_0* to model enhancement at low invariant mass
  - Find strong destructive interference between these $D\pi$ S-wave contributions

$B^0 \rightarrow D^0\pi^+\pi^-$

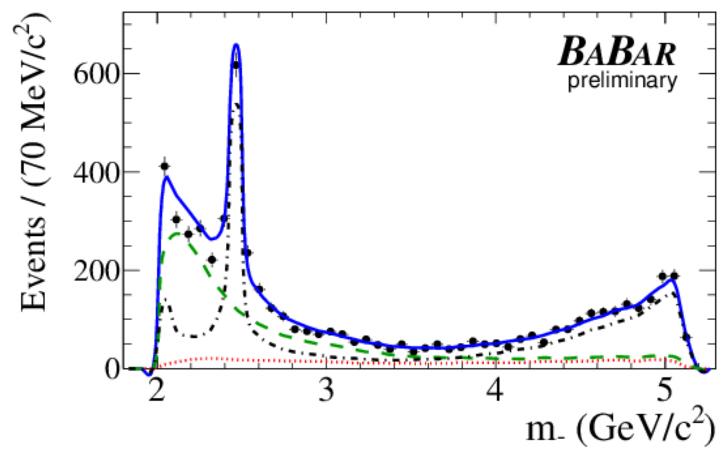
- Projections of the BaBar data with the fit model superimposed

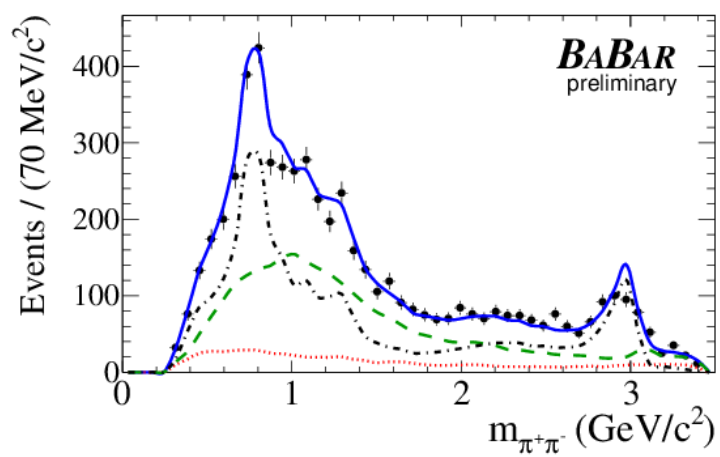
➢ Total fit

➢ Continuum background

➢ Total background (continuum + *B* decays)

➢ Signal component





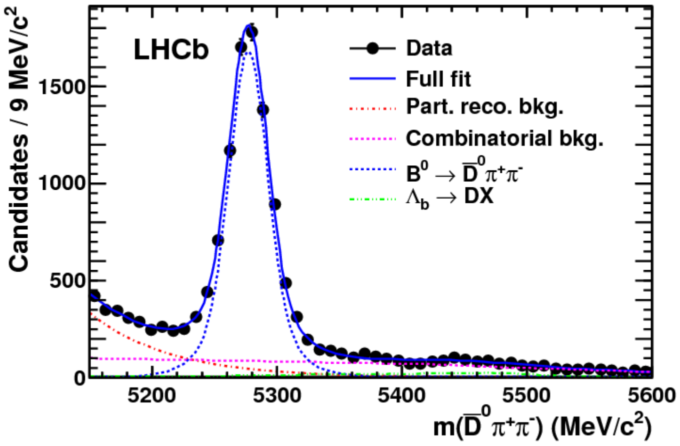
$B^0 \to D^0\pi^+\pi^-$

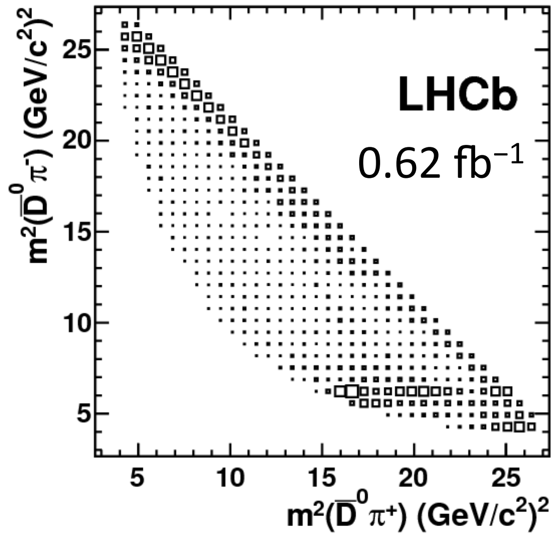
Branching Fraction	*BABAR* Value (10^{-4})	Belle Value (10^{-4})
Inclusive $B^0 \to \overline{D}^0\pi^+\pi^-$	$8.81 \pm 0.18 \pm 0.76 \pm 0.78 \pm 0.11$	$8.4 \pm 0.4 \pm 0.8$
$B^0 \to D_2^*(2460)^-\pi^+ \times D_2^*(2460)^- \to \overline{D}^0\pi^-$	$1.80 \pm 0.09 \pm 0.19 \pm 0.37 \pm 0.02$	$2.15 \pm 0.17 \pm 0.29 \pm 0.12$
$B^0 \to D_0^*(2400)^-\pi^+ \times D_0^*(2400)^- \to \overline{D}^0\pi^-$	$2.18 \pm 0.23 \pm 0.33 \pm 1.15 \pm 0.03$	$0.60 \pm 0.13 \pm 0.15 \pm 0.22$
$B^0 \to \rho(770)^0\overline{D}^0$	$2.98 \pm 0.19 \pm 0.53 \pm 0.93 \pm 0.04$	$3.19 \pm 0.20 \pm 0.24 \pm 0.38$
$B^0 \to f_2(1270)\overline{D}^0$	$1.02 \pm 0.12 \pm 0.18 \pm 0.36 \pm 0.03$	$1.20 \pm 0.18 \pm 0.21 \pm 0.32$
$B^0 \to D_v^*(2010)^-\pi^+ \times D_v^*(2010)^- \to \overline{D}^0\pi^-$	$1.39 \pm 0.08 \pm 0.16 \pm 0.35 \pm 0.02$	0.88 ± 0.13
$D\pi$ nonresonant	$1.62 \pm 0.21 \pm 0.41 \pm 1.21 \pm 0.02$	$\cdots$
K matrix total	$2.26 \pm 0.22 \pm 0.34 \pm 0.58 \pm 0.03$	$\cdots$

- Inclusive and sub-mode BF measurements in good agreement except for $D^*_v(2010)^-\pi^+$ and $D^*_0(2400)^-\pi^+$, where BaBar see larger values than Belle
- Direct comparison complicated due to different S-wave parameterisations

Recent LHCb results

- LHCb recently published observation of $B^0 \rightarrow D^0K^+K^-$ and evidence for the B_s decay to the same final state
  - PRL 109, 131801 (2012)
- Both of these BFs were relative measurements, with the decay $B^0 \rightarrow D^0\pi^+\pi^-$ acting as the normalisation channel
- Approximately 8000 $D^0\pi^+\pi^-$ signal events were found c.f. 5000 in the full BaBar dataset
- The signal is also very clean – see upper right plot





Prospects

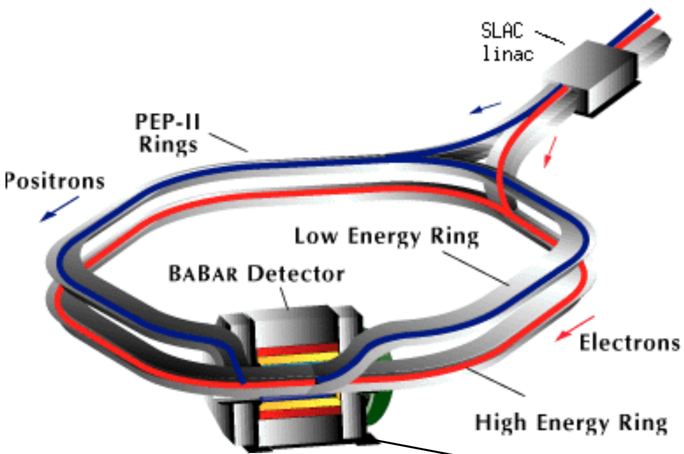
- Programme of $B \rightarrow Dhh$ measurements underway
- Hope for Dalitz-plot analyses of several modes on combined 2011-2012 dataset = 3 fb^{-1}
- Should have, e.g. ~40k $B^0 \rightarrow D^0\pi^+\pi^-$ signal events and similar numbers in the B^+ decays
- With these very large statistics, other modes such as $B^- \rightarrow D^+K^-\pi^-$ (which may be experimentally very clean) could also be studied
- Studies of D_s** resonances also underway, see recent observation of $B_s \rightarrow D_{s1}(2536)^+\pi^-$
  - arXiv:1211.1541 [hep-ex]

Summary

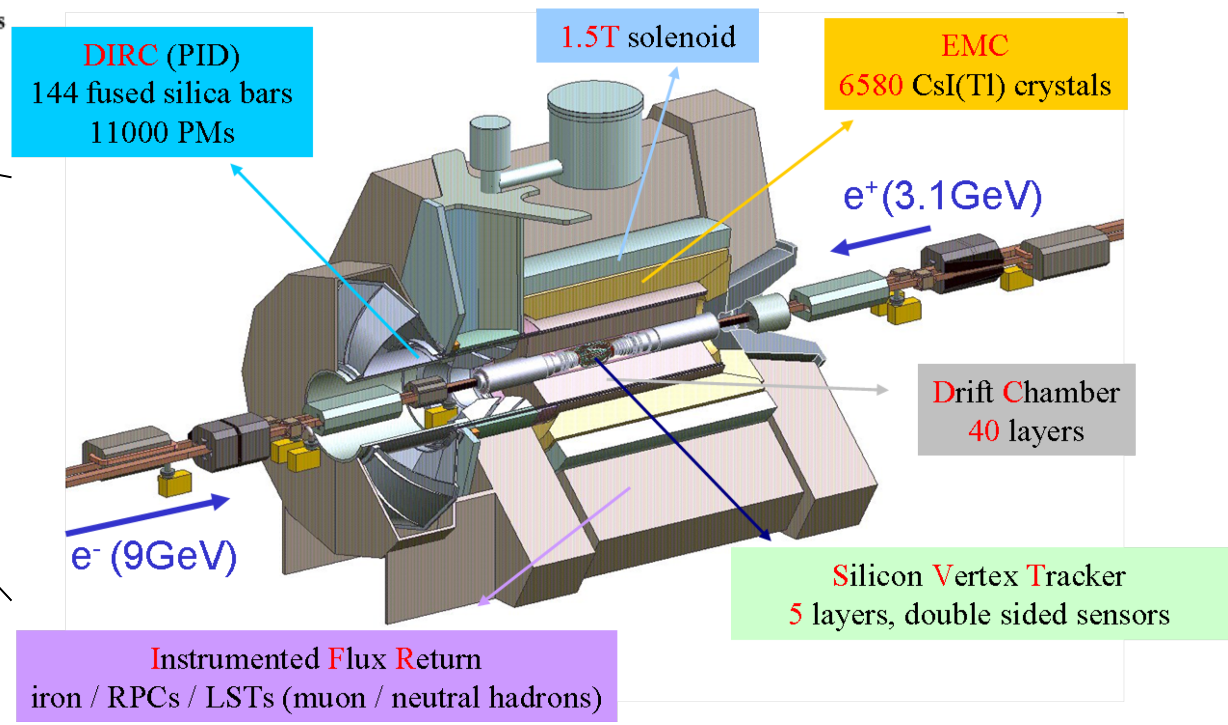
- B factories have established signals for $B \to D^{**}\pi$ decays in both charged and neutral B decays to $D^{(*)}\pi\pi$ final states
- The charged B decays are experimentally cleaner and BaBar and Belle results are in excellent agreement
- The neutral B decays require greater statistics to fully disentangle the numerous contributions to the Dalitz plot
- Future prospects at LHCb look very promising!

BACKUP

PEP-II and BaBar

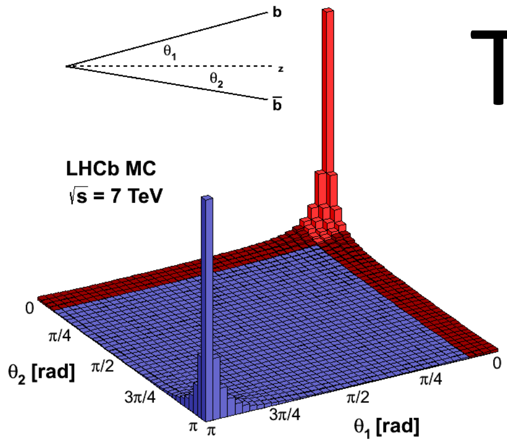


- PEP II/BaBar *B*-Factory located at SLAC National Accelerator Laboratory
- Collided beams of electrons and positrons with asymmetric energies

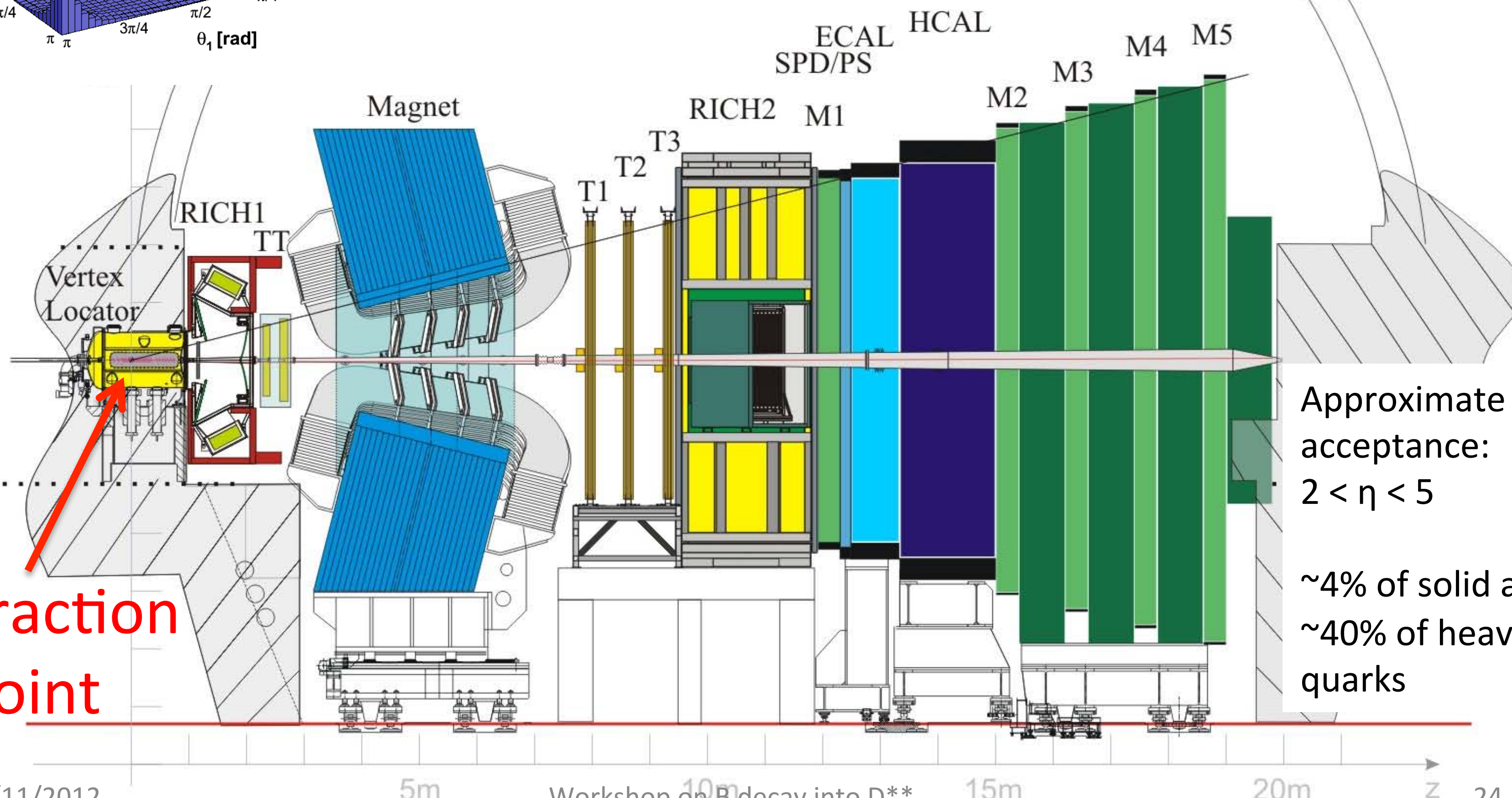


- Analysis presented here uses the full Y(4S) dataset
- Corresponds to 471 x 10^6 BB pairs

The LHCb detector



LHCb $\sigma(pp \to H_b X)$ = (75 ± 5 ± 13) μb
Phys. Lett. B 694, 209-216 (2010)



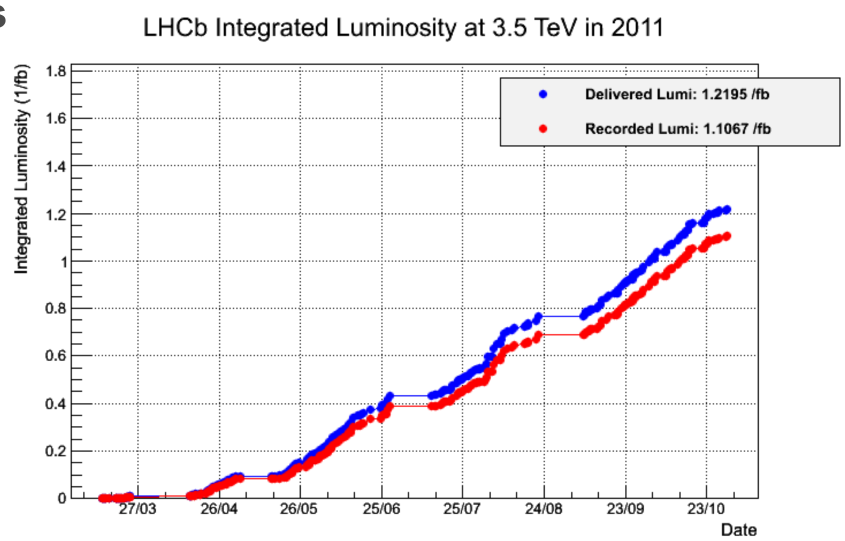
Approximate acceptance:
$2 < \eta < 5$

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

LHCb data acquisition

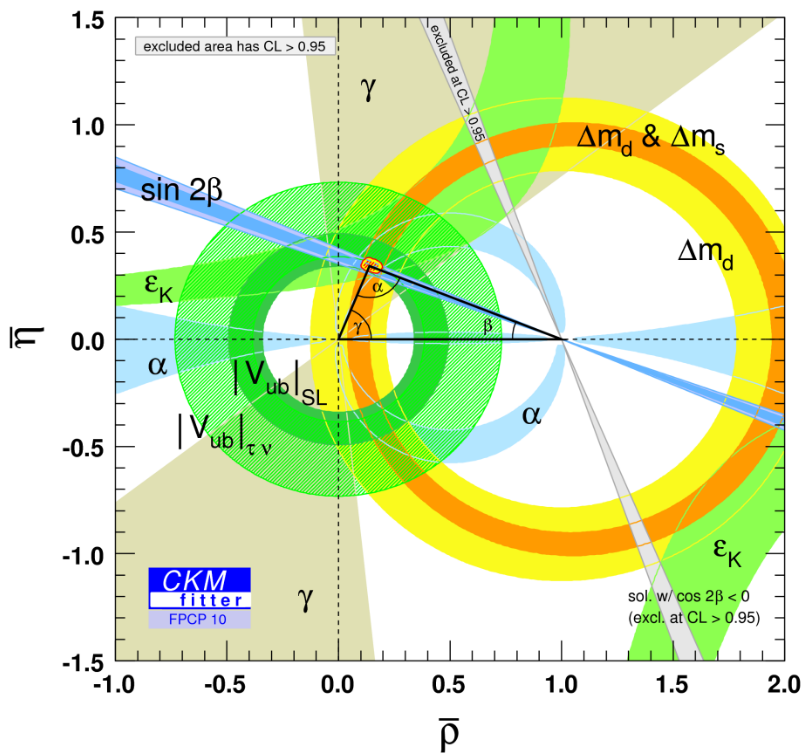
- **Detector**
- **40 MHz**
- **L0 μ** | **L0 Hadron** | **L0 e, γ** — **High P_T candidates**
- **1 MHz (max)**
- **HLT1** — **High P_T displaced tracks (partial reconstruction)**
- **Global Reconstruction** — **30 kHz**
- **HLT2** — **Configurable inclusive + exclusive selections**
- **3-4 kHz**
- **Event Storage** — **~50 kB event^{-1}**

- Trigger Efficiencies:
  - ~30% efficient on multibody hadronic
  - ~90% efficient for dimuons
- Recorded ~1fb^{-1} in 2011
- ~2fb^{-1} in expected in 2012



Motivation

- Need precise measurements of CKM matrix elements using *different quark level transitions* to test the Standard Model
- To maximise precision and remove ambiguities measure cos(2β) as well as sin(2β)



Motivation

- Idea to measure $\sin(2\beta)$ and $\cos(2\beta)$ in time-dependent DP analysis of $B^0 \to D_{CP}\pi^+\pi^-$ discussed in outline in
  - J. Charles et al. Phys. Lett. B 425, 375 (1998) [Erratum-ibid. B 433, 441 (1998)]
- Idea developed and feasibility studies presented in
  - T. Latham and T. Gershon, J. Phys. G 36, 025006 (2009)

Extended DP Analysis

- The $B \rightarrow D^*\pi\pi$ modes have extra degrees of freedom due to the spin of the D^*
- Can consider, for example
  - the angle between the pions from the D^{**} and D^* decays in the D^* rest frame
  - the azimuthal angle of the pion from the D^* wrt the B $\rightarrow D^*\pi\pi$ decay plane
- The different polarisation states of any $\pi^+\pi^-$ resonances must also be accounted for

$B \to D^{*}\pi\pi$

- Only measurements from Belle so far
- Both charged and neutral *B* decays studied:
  - PRD 69, 112002 (2004)
  - BELLE-CONF-0460 (2004)
- Here the 1^{+} states D_1 and D_1' contribute instead of the 0^{+} D_0*
- Will hear more on this tomorrow morning from D. Matvienko

$B^- \to D^+\pi^-\pi^-$ Systematics and Model Errors

TABLE IV: Summary of systematic uncertainties (relative errors in %) in the measurement of the total branching fraction.

Systematic Source	$\frac{\Delta\mathcal{B}(B^-\to D^+\pi^-\pi^-)}{\mathcal{B}(B^-\to D^+\pi^-\pi^-)}$ (%)
Number of B^+B^- events	1.6
Tracking efficiencies	2.5
PID	1.5
ΔE background shape	1.3
D^+ branching fraction	2.3
Fit models	0.7
Fit bias	1.0
Total Systematics	4.4

TABLE V: Summary of systematic uncertainties in the masses, widths and fit fractions of the D_2^{*0} and D_0^{*0} and the phase of D_0^{*0}.

Systematic Source	$\Delta m_{D_2^{*0}}$ (MeV/c^2)	$\Delta\Gamma_{D_2^{*0}}$ (MeV)	$\Delta m_{D_0^{*0}}$ (MeV/c^2)	$\Delta\Gamma_{D_0^{*0}}$ (MeV)	$\Delta f_{D_2^{*0}}$ (%)	$\Delta f_{D_0^{*0}}$ (%)	$\Delta\phi_{D_0^{*0}}$ (rad)
Background parameterization	1.0	1.1	3	5	1.2	0.0	0.04
Background fraction	0.1	0.4	2	1	0.4	0.4	0.00
Event selection	0.6	1.6	1	14	0.3	0.8	0.08
Fit bias	0.3	0.7	4	8	0.7	1.4	0.02
PID efficiency	0.0	0.1	0	0	0.0	0.1	0.01
Total systematic error	1.2	2.1	5	17	1.5	1.7	0.09
Fit models	1.3	0.7	15	40	1.5	17.2	0.07
r constant	1.4	1.9	12	21	3.8	7.8	0.17
Total model-dependent error	1.9	2.0	19	45	4.1	18.9	0.18