Model dependent approach to mixing and indirect CP violation in prompt $D^0 \to K_S^0\pi^+\pi^-$ decays at LHCb

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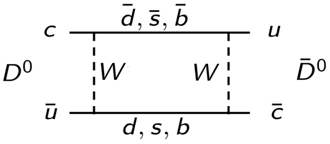
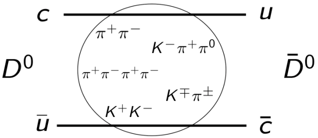
Mixing and CP violation in charm

Mixing:

- Neutral meson produced with definite flavour flips between matter and anti-matter over time



Mixing via W boson exchange.



Mixing via long range hadronic exchange.

- Flavour eigenstates $(D^0, \bar{D}^0)$ have definite quark content, differ from physical mass eigenstates (D_1, D_2) which have definite mass and width
- Mas eigenstates can be written in the flavour basis as

$$|D_{1,2} >= p|D^0 > \pm q|\bar{D}^0 > \tag{1}$$

where p and q are complex coefficients that satisfy $p^2 + q^2 = 1$

- Parameterise mixing using dimensionless variables x and y:

$$x = \frac{M_1 - M_2}{\Gamma} \qquad y = \frac{\Gamma_1 - \Gamma_2}{2\Gamma} \tag{2}$$

where $\Gamma = \frac{\Gamma_1 + \Gamma_2}{2}$ is the average decay width

Mixing and CP violation in charm

- Standard Model (SM) $\rightarrow K^0$, B^0 and B_S^0
- In the charm sector mixing is small in the SM ($\mathcal{O}(1\%)$)
- Long range contribution is hard to calculate
- LHCb recently published the first observation of mixing in charm (Link to paper)

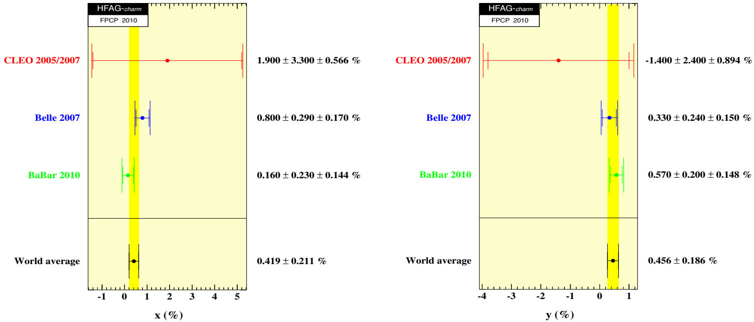
CP Violation:

- C = Charge conjugation (matter $\rightarrow$ anti-matter)
- P = Parity (swap left and right i.e. $\underline{\mathbf{x}} \rightarrow -\underline{\mathbf{x}}$)
- Violation of the combined CP symmetry is well known in the SM
- CP violation (CPV) manifests in different ways:
    - Direct: difference in decay amplitude under CP transformation
    - Indirect: CP eigenstates differ from Hamiltonian eigenstates
    - Interference between direct and indirect CP violation
- CP violation in charm is predicted to be small in the SM
- Indirect CP conserved if $p = q$ (see equation (1))
- LHCb has searched extensively for direct CPV in charm (Link to paper)
- Updated results with D^0 from semi-leptonic B decays
  (Link to paper, also see Alex Pearce's talk this afternoon)

Analysis outline

Question: Why do we need to look elsewhere for charm mixing and CPV?
... or rather: Why is the $D^0 \to K^0_S\pi^+\pi^-$ channel so interesting?

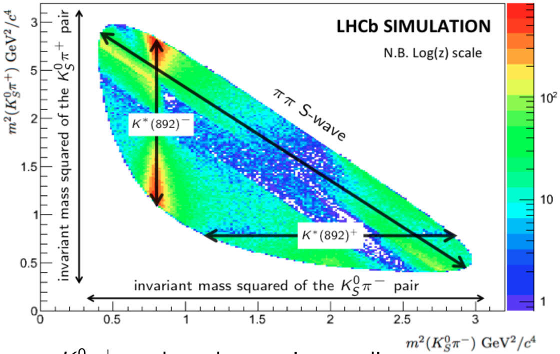
- Sensitivity to the relative sign between x and y
- 2 complimentary analysis techniques (see Tomas Pilar's slides from other parallel session)
- Self-conjugate final state with mixed CP content, access indirect CPV
- Compliments other mixing measurements (y_{CP}, x', y')
- Can learn a lot from this channel in the future (Link to paper)



World average of (left) x and (right) y from $D^0 \to K^0_S\pi^+\pi^-$ decays. Source http://www.slac.stanford.edu/xorg/hfag/charm/

Analysis outline

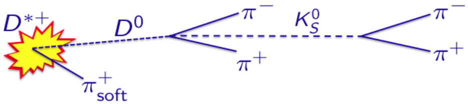
- This is a time dependent Dalitz plot analysis ... example of a Dalitz plot



- D^0 decays to $K_S^0\pi^+\pi^-$ through many intermediate resonances
- Access full dynamics of decay, local population $\propto$ amplitude squared
- Resonant structure invariant of decay kinematics
- Use BaBar 2010 amplitude model for initial decay structure (Link to paper)
- Sensitivity to $D^0 - \bar{D}^0$ mixing arises from modification of decay amplitude as a function of position in Dalitz space and time
- Sensitivity to indirect CPV from ratio of q/p

Dataset and selection

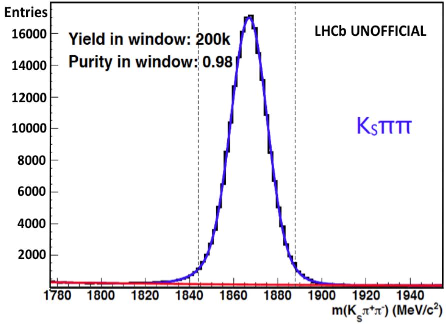
- This analysis uses $\approx 1\text{fb}^{-1}$ of data collected by LHCb during 2011
- Reconstruct signal chain as: $D^{*+} \to (D^0 \to (K^0_S \to \pi^+\pi^-)\pi^+\pi^-)\pi^+_{\text{soft}}$



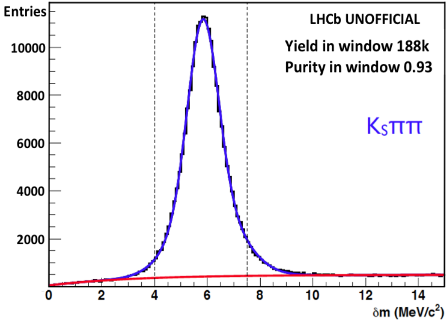
- Charge of π^+_{soft} tags flavour of D^0 at production
- LHCb uses a 3-stage trigger: 1 hardware (L0), 2 software (Hlt1/2)
  - L0: look for high p_T deposit in hadronic calorimeter
  - Hlt1: single track with high p_T and large impact parameter (IP)
  - Hlt2: exclusive $K^0_S h^+ h^-$ trigger, look for displaced 2-body vertex, combine with K^0_S within nominal D^0 mass window
- Very clean out of the detector but still some background from:
  - (1) Real D^0 combined with a random slow pion (mistag initial D^0)
  - (2) Real D^0 coming from mis-reconstructed B decays, secondary charm
  - (3) $D^0 \to \pi^+\pi^+\pi^-\pi^-$
  - (4) Mis-reconstructed D^0 and combinatoric background
- Use a cut based offline selection to remove most of (1), (3) and (4)

D^0 mass and Δm plots

- Δm is defined as: $\Delta m = m(D^{*+}) - m(D^0) - m(\pi^+_{soft})$
- Useful variable in suppressing combinatorics and real D^0 with random π^+_{soft}



Reconstructed D^0 mass fit to real data

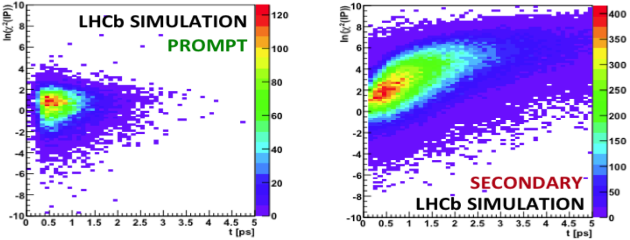


Δm fit to real data

- D^0 mass: signal = double gaussian, bg = 2^{nd} order polynomial
- Δm: signal = triple gaussian, bg = RooDstD0BG custom PDF
- Signal has very high purity due to excellent performance of the LHCb detector and reconstruction software

Secondary charm

- One of the most dangerous backgrounds is real D^0 coming from B decays
- Looks like signal but has the wrong decay time distribution!
- Expect prompt D^0 to point back to the PV
- Fit to Impact Parameter χ^2 to estimate secondary component
- Taking $\log(\chi^2_{\text{IP}})$ of the reconstructed D^0 candidate one can clearly distinguish between prompt and secondary decays

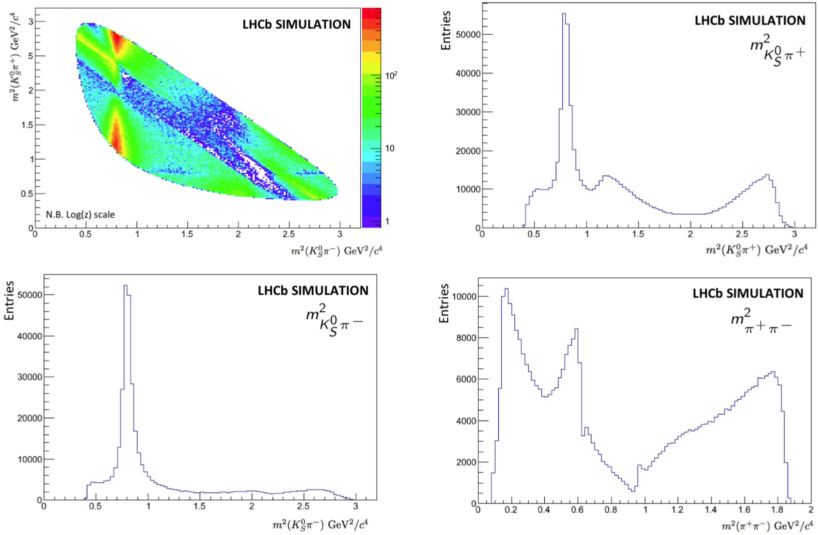


Time evolution of $\log(\chi^2_{\text{IP}})$ for simulated prompt and secondary charm decays

- Solution: Fit $\log(\chi^2_{\text{IP}})$ in bins of D^0 decay time
- Assign each event a weight according to how "prompt like" it is

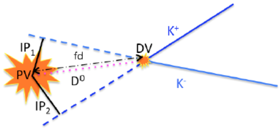
Amplitude model: resonant structure

- Example Dalitz plot and projections from signal Monte Carlo generated using the BaBar 2010 model including K-Matrix and LASS parameterisations

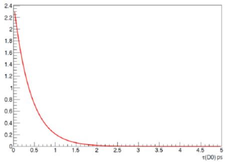


Detection efficiency

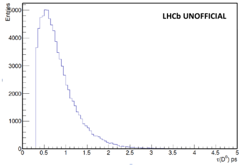
- Phase space dependent efficiency:
  - Driven by opening angle of $D^0(\pi^\pm)$ daughters at high K^0_S invariant mass
  - Efficiency drops off at the edges of Dalitz space, one track has very low p
  - Don't need to worry about this as we take a fixed amplitude model
  - See Tomas Pilar's talk for more detail
- Decay time dependent efficiency:
  - Hostile environment of LHC requires hard cuts to select displaced vertices
  - Correlated with decay time, induces a bias in measured distribution
  - Use a novel data driven technique, "swimming", to correct for decay time acceptance on an event by event basis (see CHEP 2012 proceedings, link)



Schematic of 2-body D decay with displaced vertex



Example true decay time distribution from toy MC



Decay time distribution from data after displacement cuts applied

- This analysis is not sensitive to the correlation between these efficiencies

Plans for the future

Current analysis:

- Analysis on 2011 data is well underway ($\approx$ 200k signal events)
- Aiming for a paper in the summer
- First time comparison of model dependent/independent approach

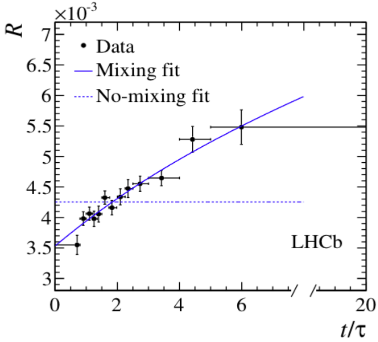
Future work:

- Finished taking *pp* data in December 2012, LHCb has $\approx$ 3 fb^{-1} on tape
- Corresponds to roughly 3.5 M $D^0 \to K^0_S \pi^+ \pi^-$ signal events
- Challenges:
  - Need to account for phase space dependent efficiency
  - Data coming from multiple sources
  - Inclusion of $D^0 \to K^0_S \pi^+ \pi^-$ decays from semi-leptonic B decays
  - Unbinned amplitude fits take time, use of GPU code?
- Flagship analysis of the LHCb upgrade program

Watch this space!

Backup

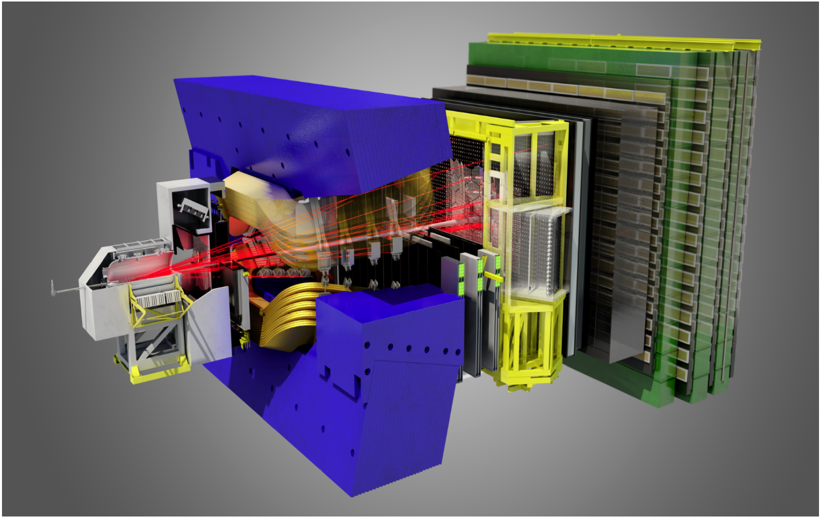
Mixing from prompt $D^0 \to K^{\mp}\pi^{\pm}$ decays at LHCb



- Measured the decay time evolution of ratio, R
- R is the ratio of WS (DCS) to RS (CF) decays in $D^0 \to K^{\mp}\pi^{\pm}$
- The blue horizontal line shows the no mixing hypothesis
- Ruled out no mixing to 9.1 σ significance
- $x'^2 = (-0.9 \pm 1.3) \times 10^{-4}$
  $y'^2 = (7.2 \pm 2.4) \times 10^{-3}$
- Phys. Rev. Lett. **110**, 101802 (2013)

Links to experimental summaries on charm mixing: Belle, BaBar, LHCb

The LHCb detector



Dataset and selection

- This analysis uses $\approx 1\text{fb}^{-1}$ of data collected during 2011
- Look for prompt $D^0 \to K_S^0\pi^+\pi^-$ i.e. tag the D^0 flavour using $D^{*+} \to D^0\pi^+_{\text{soft}}$
- Require the K_S^0 decays to $\pi^+\pi^-$
- LHCb uses a 3-stage trigger: 1 hardware (L0), 2 software (Hlt1/2)
  - L0: look for high p_T deposit in hadronic calorimeter
  - Hlt1: single track with high p_T and large impact parameter (IP)
  - Hlt2: exclusive $K_S^0 h^+ h^-$ trigger, looks for displaced 2-body vertex, combines with common K_S^0 selector within nominal D^0 mass window
  - Require all events to have passed Hlt1 && Hlt2
- Stripping: prompt reconstruction/selection
  - Generally looser cuts than the trigger but better quality tracks
  - Combine D^0 candidates with π^+_{soft} to make D^{*+}
  - Hard cut on D^0 decay time to reduce combinatorics
- DecayTreeFitter []: powerful re-fitting algorithm
  - Constrain π^+_{soft} to originate from PV, $\approx$ 3x better Δm resolution
  - Constrain reconstructed D^0 mass, prevents events from lying outside of the physically allowed region of Dalitz space

Dataset and selection

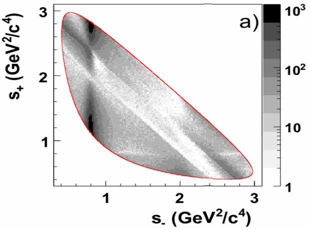
- Main sources of background:
  - (1) Real D^0 combined with a random slow pion (mistag initial D^0)
  - (2) Real D^0 coming from mis-reconstructed B decays, secondary charm
  - (3) $D^0 \to \pi^+\pi^+\pi^-\pi^-$
  - (4) Mis-reconstructed D^0 and combinatoric background
- Offline selection:
  - Use a simple cut-based selection to suppress (1), (3) and (4)

Variable	Cut value
Log($IP_{D^0}\chi^2$) w.r.t PV	< 3.0
D^0 flight distance w.r.t PV	> 2.0 mm
π_{soft} ghost probability	< 0.7
π_{soft} PID Delta Log Likelihood (e - π)	< 2.0
D^0 decay time w.r.t PV	< 10.0 ps
K_S^0 flight distance w.r.t D^0 decay vertex	> 10.0 mm

- Quality of fit cuts on D^0 decay time and re-fitting with DecayTreeFitter

Amplitude model

- Leading measurement from BaBar had 500k signal events
- 2011 LHCb dataset has roughly half that amount
- We can take a fixed amplitude model from the BaBar 2010 analysis Phys. Rev. Lett. **105**, 081803 (2010)



Dalitz distribution of real data from the BaBar 2010 analysis from which we take our amplitude model

- Decay model: (apologies for the jargon!)
  - Breit Wigner line shapes for narrow, isolated resonances
  - F-Vector/K-Matrix parameterisation for $\pi\pi$ S-wave component
  - Generalised LASS parameterisation for $K\pi$ S-wave component
- S-wave refers to spin-0 component of amplitude, notoriously difficult to describe
- P-wave and D-wave generally well described using Breit Wigner terms