Mixing and CP Violation in Charm at LHCb

Michael Alexander
University of Glasgow
on behalf of the LHCb collaboration

SUSY, Barcelona, 2018/07/24

Introduction

Mixing with $D^0 \to K^{\mp}\pi^{\pm}$

$A_{CP}(D^0 \to K^0_{\mathrm{S}} K^0_{\mathrm{S}})$

Angular asymmetries in $D^0 \to h^+ h^- \mu^+ \mu^-$

$\Delta\mathcal{A}_{\mathrm{CP}}$ in $\Lambda_c^+ \to p h^+ h^-$

Conclusions

Outline

Introduction

Mixing with $D^0 \to K^{\mp}\pi^{\pm}$

$A_{CP}(D^0 \to K^0_{\rm S} K^0_{\rm S})$

Angular asymmetries in $D^0 \to h^+h^-\mu^+\mu^-$

$\Delta\mathcal{A}_{\rm CP}$ in $\Lambda_c^+ \to ph^+h^-$

Conclusions

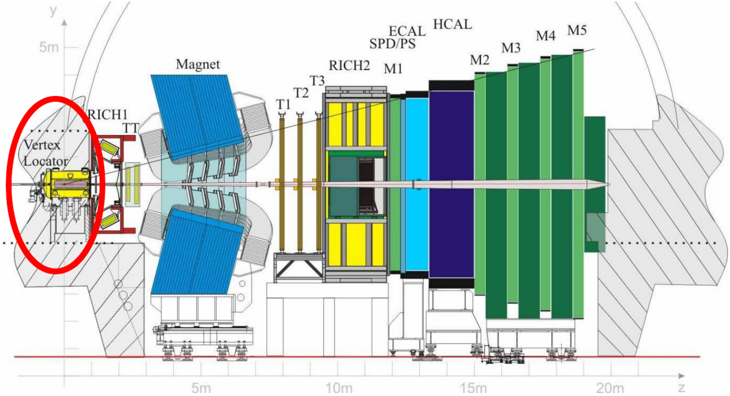
[1] JHEP 05 (2017) 74

Charm at LHCb - the quest for non-zero CPV

- CP violation in charm is predicted to be very small in the standard model since $\arg(V_{cd})$ is $\mathcal{O}(10^{-4})$.
- Non-SM particles can enhance mixing & CPV through loop amplitudes.
- Large $c\overline{c}$ production cross section of $\sim$2400 $\mu\mathrm{b}$ [1] in the LHCb detector acceptance allows for high precision measurements, potentially revealing new physics.

[2] Int. J. Mod. Phys. A 30 (2015) 1530022

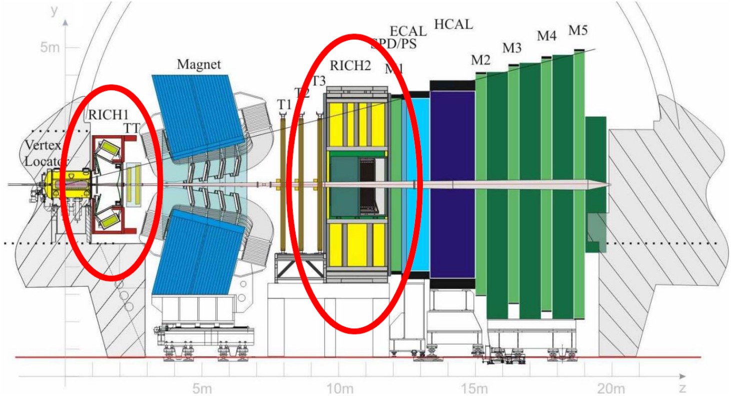
LHCb - high precision detector



- Silicon strip Vertex Locator provides fine tracking for primary & secondary vertex reconstruction.
- Achieves impact parameter (IP) resolutions of $(15 + 29/p_{\mathrm{T}}\ [\mathrm{GeV}/c\ ])\ \mu\mathrm{m}$ [2].

[2] Int. J. Mod. Phys. A 30 (2015) 1530022

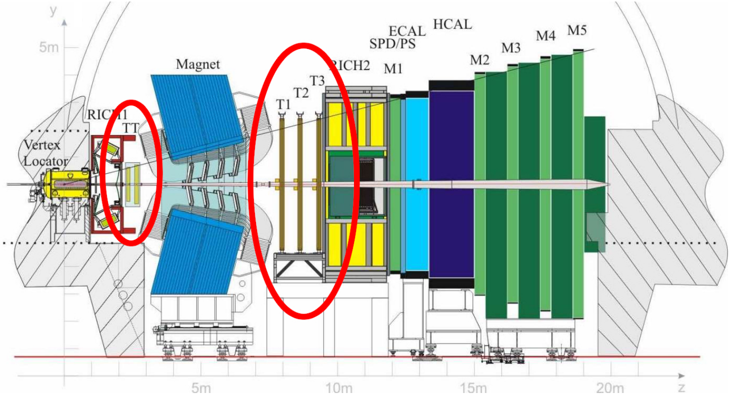
LHCb - high precision detector



- Two Ring Imaging Cherenkov detectors provide particle ID over a large momentum range.
- Excellent K/π separation & suppression of mis-ID backgrounds [2].

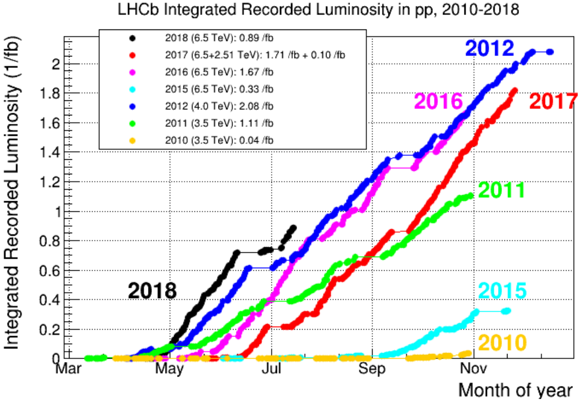
[2] Int. J. Mod. Phys. A 30 (2015) 1530022

LHCb - high precision detector



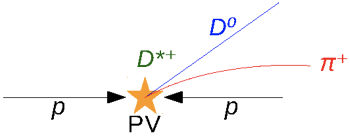
- Tracking stations before and after dipole magnet provide momentum measurements.
- Resolution ranges from 0.5% at low momentum to 1.0% at 200 GeV/c [2].

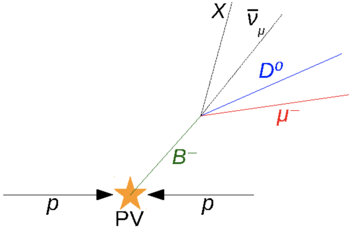
LHCb data set



- Run 1: 1 fb^{-1} at $\sqrt{s} = 7\,\mathrm{TeV}$ & 2 fb^{-1} at 8 TeV.
- Run 2: 4.6 fb^{-1} so far at 13 TeV.
- Analyses presented cover Run 1 (3 fb^{-1}) or Run 1 plus 2015 & 2016 (5 fb^{-1}).

Flavour tagging - prompt or secondary





- Use either $D^{*\pm} \to \overset{(-)}{D}{}^0\pi^\pm$ (prompt) or $B \to \overset{(-)}{D}{}^0\mu^\mp X$ (secondary).
- Secondary samples are cleaner as the $\mu^\mp$ is used for triggering, but lower stats due to smaller $b\bar{b}$ production cross section.
- Prompt & secondary are affected by different production & detection asymmetries.
- Both are backgrounds for each other.

Outline

Introduction

Mixing with $D^0 \to K^\mp\pi^\pm$

$A_{CP}(D^0 \to K^0_\mathrm{S} K^0_\mathrm{S})$

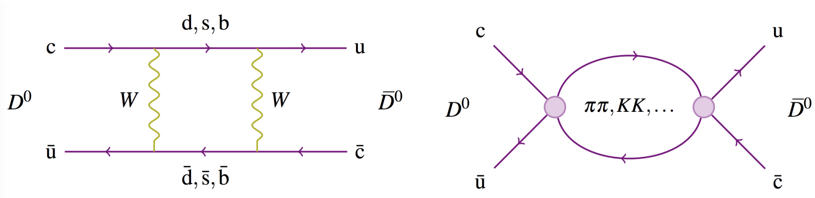
Angular asymmetries in $D^0 \to h^+h^-\mu^+\mu^-$

$\Delta\mathcal{A}_\mathrm{CP}$ in $\Lambda_c^+ \to ph^+h^-$

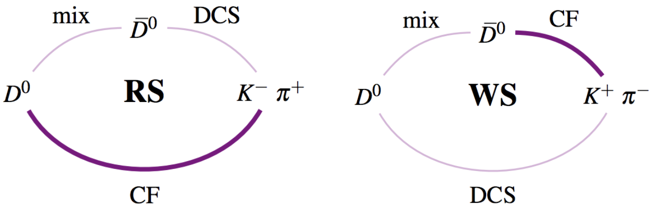
Conclusions

D^0 mixing

- Mass eigenstates of D^0 system are combinations of flavour eigenstates: $|D_{1,2}\rangle = p|D^0\rangle \pm q|\overline{D}^0\rangle$.
- Rate of mixing parametrised by $x = (m_2 - m_1)/\Gamma$ and $y = (\Gamma_2 - \Gamma_1)/2\Gamma$, with $m_{1,2}$ ($\Gamma_{1,2}$) the mass (width) of the mass eigenstates and Γ their average width.



Wrong sign/right sign formalism



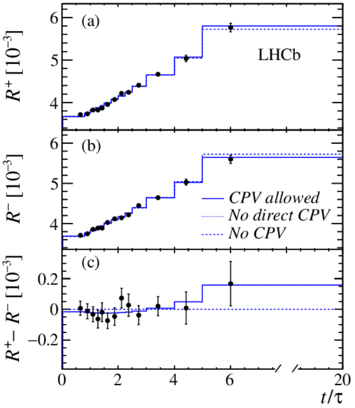
- "Wrong sign" (WS) $D^0 \to K^+\pi^-$ decays proceed via DCS amplitudes or mixing followed by CF "right sign" (RS) decay $D^0 \to \bar{D}^0 \to K^+\pi^-$.
- Consequently, the ratio of WS to RS decays as a function of proper decay time t is given by

$$R(t) \simeq R_D + \sqrt{R_D} y' \frac{t}{\tau} + \frac{x'^2 + y'^2}{4} \left(\frac{t}{\tau}\right)^2 ,$$

with τ the average D^0 lifetime, $x' \equiv x \cos\delta + y \sin\delta$,
$y' = y \cos\delta - x \sin\delta$, and
$\mathcal{A}(D^0 \to K^+\pi^-)/\mathcal{A}(D^0 \to K^-\pi^+) = -\sqrt{R_D} e^{-i\delta}$.

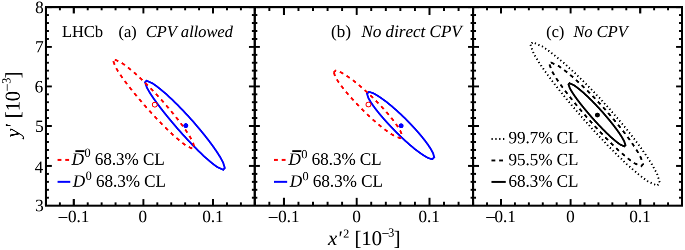
Ratio fits

- Using 2011-2016 prompt-tagged data with a cuts based & artificial neural network selection, mass fits find 1.77×10^8 RS & 7.22×10^5 WS signal candidates.



- Ratio of WS/RS yields in bins of decay time determined independently for D^0 (R^+) and $\bar{D}^0$ (R^-) candidates.
- Detection asymmetry of $K^\mp\pi^\pm$ corrected for using ratio of $D^- \to K^+\pi^-\pi^-$ and $D^- \to K^0_S(\to \pi^+\pi^-)\pi^-$.
- Remaining secondaries contamination estimated from fits to χ^2 distribution of hypothesis that D^0 is prompt.
- Incorrectly reconstructed tagging pions suppressed using MVA trained on track quality variables.

Results



- Assuming no CPV:

$$x'^2 = (3.9 \pm 2.7) \times 10^{-5},\ y' = (5.28 \pm 0.52) \times 10^{-3},$$
$$R_D = (3.454 \pm 0.031) \times 10^{-3}.$$

- Allowing CPV:

$$A_D \equiv \frac{R_D^+ - R_D^-}{R_D^+ + R_D^-} = (-0.1 \pm 9.1) \times 10^{-3}, \text{ and } 1.00 < |q/p| < 1.35 \text{ (68.3\% CL)}.$$

- Uncertainties include systematics, the dominant of which are from residual secondaries & misreconstructed tagging pions.

Outline

Introduction

Mixing with $D^0 \to K^\mp\pi^\pm$

$A_{CP}(D^0 \to K^0_S K^0_S)$

Angular asymmetries in $D^0 \to h^+h^-\mu^+\mu^-$

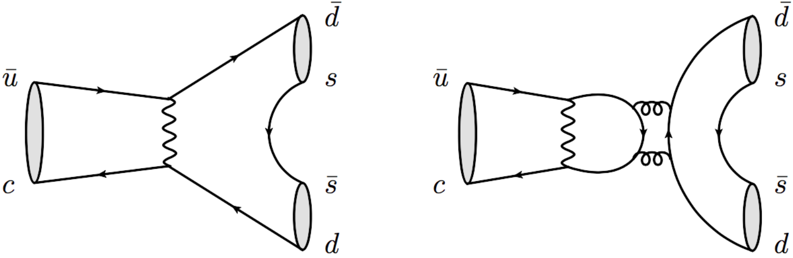
$\Delta\mathcal{A}_{\rm CP}$ in $\Lambda_c^+ \to ph^+h^-$

Conclusions

[4] PRD92 (2015) 054036
[5] PRL 119 (2017) 171801

Direct CPV can be relatively large

- $D^0 \to K^0_S K^0_S$ decays proceed via exchange & loop amplitudes that are suppressed by SU(3) flavour symmetry.
- Amplitudes have similar size but different strong & weak phases, so CPV can be up to 1.1% [4].
- Current best measurement from Belle of $\mathcal{A}_{CP}(K^0_S K^0_S) = (-0.02 \pm 1.53 \pm 0.17)\%$ [5].



[6] arXiv:1806.01642 [hep-ex]
[7] PLB767 (2017) 177

$D^0 \to K^+K^-$ used to cancel nuisance asymmetries

- Using prompt-tagged D^0 candidates decaying to a CP eigenstate, the measured asymmetry

$$\mathcal{A}_{\mathrm{Raw}}(f) = \frac{N(D^0 \to f) - N(\overline{D}^0 \to f)}{N(D^0 \to f) + N(\overline{D}^0 \to f)} \simeq \mathcal{A}_{CP}(f) + \mathcal{A}^{D^{*\pm}}_{\mathrm{Prod.}} + \mathcal{A}^{\pi^\pm}_{\mathrm{Det.}}$$

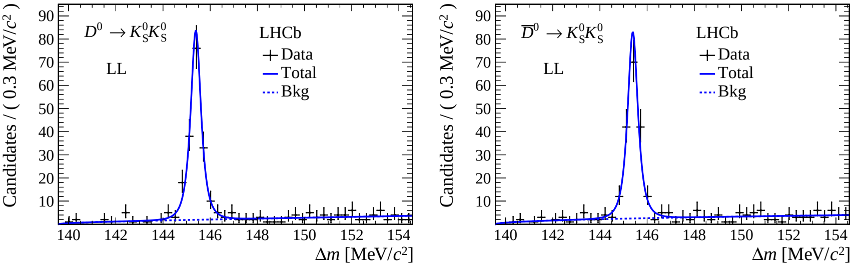
  with $\mathcal{A}^{D^{*\pm}}_{\mathrm{Prod.}}$ the $D^{*\pm}$ production asymmetry and $\mathcal{A}^{\pi^\pm}_{\mathrm{Det.}}$ the detection asymmetry of the tagging $\pi^\pm$.

- Assuming similar kinematics between $D^0 \to K^0_S K^0_S$ and $D^0 \to K^+K^-$, one can measure [6]

$$\mathcal{A}_{CP}(K^0_S K^0_S) = \mathcal{A}_{\mathrm{Raw}}(K^0_S K^0_S) - \mathcal{A}_{\mathrm{Raw}}(K^+K^-) + \mathcal{A}_{CP}(K^+K^-)$$

  using the previous measurement of $\mathcal{A}_{CP}(K^+K^-) = (0.04 \pm 0.12 \pm 0.10)\%$ [7].

Mass fits extract raw asymmetry



- From 2015-2016 data, reconstructing $K^0_S \to \pi^+\pi^-$, select candidates using kinematic cuts and an MVA classifier.
- Main background from $D^0 \to K^0_S\pi^+\pi^-$ suppressed with flight distance cuts on K^0_S candidates.
- Separate according to whether both K^0_S decay within the VELO (LL) or one decays downstream of the VELO (LD).
- Perform fits to $\Delta m \equiv m(D^{*\pm}) - m(D^0)$ to extract $\mathcal{A}_{\mathrm{Raw}}$, finding $\sim$1000 signal $K^0_S K^0_S$ candidates.

Results - consistent with Standard Model

- Combining with $\mathcal{A}_{\mathrm{Raw}}(K^+K^-)$ and $\mathcal{A}_{CP}(K^+K^-)$ gives

$$\begin{aligned}\mathcal{A}_{CP}(LL) &= (\;\;6.7 \pm 3.8 \pm 0.9)\%,\\ \mathcal{A}_{CP}(LD) &= (-5.3 \pm 7.4 \pm 1.3)\%.\end{aligned}$$

- Averaging with the previous LHCb measurement using Run 1 data gives

$$\mathcal{A}_{CP}(K^0_{\mathrm{S}} K^0_{\mathrm{S}}) = (2.0 \pm 2.9 \pm 1.0)\%.$$

- Dominant systematic from Δm modelling - expected to scale with statistics.

Outline

Introduction

Mixing with $D^0 \to K^{\mp}\pi^{\pm}$

$A_{CP}(D^0 \to K^0_S K^0_S)$

Angular asymmetries in $D^0 \to h^+ h^- \mu^+ \mu^-$

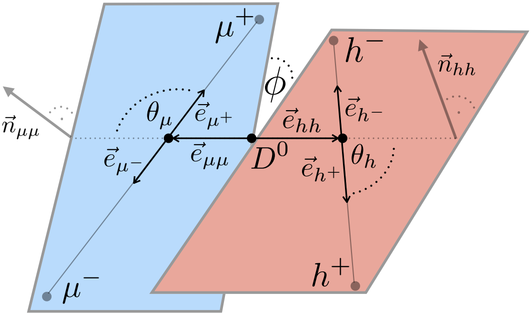
$\Delta\mathcal{A}_{\rm CP}$ in $\Lambda_c^+ \to p h^+ h^-$

Conclusions

New physics sensitivity in angular distributions

- "Short distance" $c \to u\mu^+\mu^-$ FCNC processes very rare in SM but potentially greatly enhanced by new physics.
- In addition, CP & angular asymmetries can be enhanced to $\mathcal{O}(1\%)$.
- "Long distance" tree level SM processes dominate around $\mu^+\mu^-$ resonances, so greatest sensitivity is in off-resonance regions of m($\mu^+\mu^-$).
- Good modes for studying such effects at LHCb are $D^0 \to h^+h^-\mu^+\mu^-$, with h a π or K, which have recently been observed [5].

5D phase space parametrisation



- $m(h^+h^-)$ & $m(\mu^+\mu^-)$.
- Angle ϕ between h^+h^- and $\mu^+\mu^-$ planes in D^0 rest frame.
- Angle θ_μ between μ^+ (μ^-) and opposite of D^0 ($\bar{D}^0$) in the $\mu^+\mu^-$ rest frame.
- Angle θ_h between h^+ (h^-) and opposite of D^0 ($\bar{D}^0$) in the h^+h^- rest frame.

Asymmetry definitions

- The most sensitive observables are

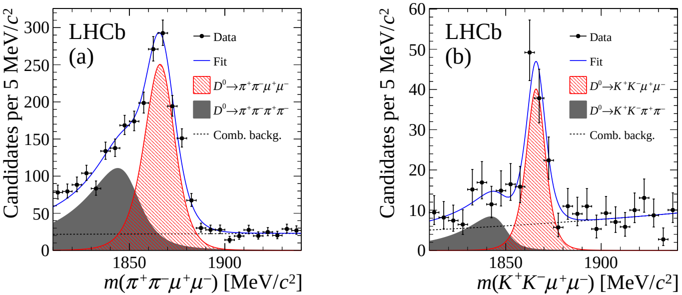
$$\mathcal{A}_{\rm FB} = \frac{\Gamma(\cos\theta_\mu > 0) - \Gamma(\cos\theta_\mu < 0)}{\Gamma(\cos\theta_\mu > 0) + \Gamma(\cos\theta_\mu < 0)},$$

$$\mathcal{A}_{2\phi} = \frac{\Gamma(\sin 2\phi > 0) - \Gamma(\sin 2\phi < 0)}{\Gamma(\sin 2\phi > 0) + \Gamma(\sin 2\phi < 0)},$$

$$\mathcal{A}_{\rm CP} = \frac{\Gamma(D^0 \to h^+h^-\mu^+\mu^-) - \Gamma(\bar{D}^0 \to h^+h^-\mu^+\mu^-)}{\Gamma(D^0 \to h^+h^-\mu^+\mu^-) + \Gamma(\bar{D}^0 \to h^+h^-\mu^+\mu^-)}.$$

- These are measured in $m(\mu^+\mu^-)$ regions around the η, ρ^0/ω, and ϕ resonances, as well as low and high mass regions.

Mass fits for yields



- Using prompt-tagged data from 2011-2016, after a Boosted-Decision-Tree (BDT) selection, fits yield 1326 ± 45 $D^0 \to \pi^+\pi^-\mu^+\mu^-$ & 137 ± 14 $D^0 \to K^+K^-\mu^+\mu^-$.
- Main background from double mis-ID $D^0 \to h^+h^-\pi^+\pi^-$ reduced with MVA using PID info.
- Efficiency across phase space is corrected for using a BDT to determine weights, trained on simulated data.

Asymmetry measurements - consistent with zero

- For $\mathcal{A}_{\mathrm{CP}}$, nuisance asymmetries are removed using $\mathcal{A}_{\mathrm{CP}}(D^0 \to K^+K^-)$ as for $\mathcal{A}_{\mathrm{CP}}(D^0 \to K^0_{\mathrm{S}}K^0_{\mathrm{S}})$.
- Integrating over $m(\mu^+\mu^-)$, asymmetries are found to be

$$
\begin{aligned}
\mathcal{A}_{\mathrm{FB}}(D^0 \to \pi^+\pi^-\mu^+\mu^-) &= (3.3 \pm 3.7 \pm 0.6)\%,\\
\mathcal{A}_{2\phi}(D^0 \to \pi^+\pi^-\mu^+\mu^-) &= (-0.6 \pm 3.7 \pm 0.6)\%,\\
\mathcal{A}_{\mathrm{CP}}(D^0 \to \pi^+\pi^-\mu^+\mu^-) &= (4.9 \pm 3.8 \pm 0.7)\%,\\
\mathcal{A}_{\mathrm{FB}}(D^0 \to K^+K^-\mu^+\mu^-) &= (0 \pm 11 \pm 2)\%,\\
\mathcal{A}_{2\phi}(D^0 \to K^+K^-\mu^+\mu^-) &= (9 \pm 11 \pm 1)\%,\\
\mathcal{A}_{\mathrm{CP}}(D^0 \to K^+K^-\mu^+\mu^-) &= (0 \pm 11 \pm 2)\%.
\end{aligned}
$$

- Asymmetries in bins of $m(\mu^+\mu^-)$ also consistent with zero.
- Dominant systematics arise from efficiency corrections, & nuisance asymmetries for $\mathcal{A}_{\mathrm{CP}}$.

Outline

Introduction

Mixing with $D^0 \to K^\mp \pi^\pm$

$A_{CP}(D^0 \to K^0_S K^0_S)$

Angular asymmetries in $D^0 \to h^+ h^- \mu^+ \mu^-$

$\Delta\mathcal{A}_{\mathrm{CP}}$ in $\Lambda_c^+ \to p h^+ h^-$

Conclusions

Formalism

- SCS $\Lambda_c^+ \to ph^+h^-$ decays can exhibit CPV as in $D^0 \to h^+h^-$ decays.
- Using $\Lambda_b^0 \to \Lambda_c^\pm \mu^\mp X$ decays gives a clean sample.
- Measured asymmetry

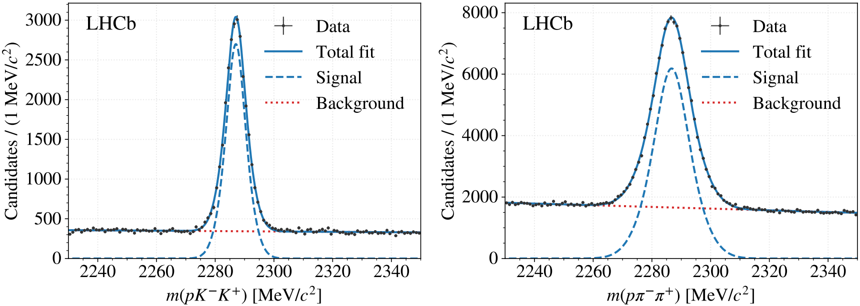
$$\mathcal{A}_{\mathrm{Raw}}(ph^+h^-) = \mathcal{A}_{\mathrm{CP}}(ph^+h^-) + \mathcal{A}_{\mathrm{Prod}}^{\Lambda_b^0}(ph^+h^-\mu) + \mathcal{A}_{\mathrm{Det}}^{\mu}(\mu) + \mathcal{A}_{\mathrm{Det}}^{ph^+h^-}(ph^+h^-)$$

- Weighting $p\pi^+\pi^-\mu$ to match $pK^+K^-\mu$ phase space ensures cancellation of nuisance asymmetries in

$$\begin{aligned}\Delta\mathcal{A}_{\mathrm{CP}}^{\mathrm{wgt}} &\equiv \mathcal{A}_{\mathrm{Raw}}(pK^+K^-) - \mathcal{A}_{\mathrm{Raw}}^{\mathrm{wgt}}(p\pi^+\pi^-) \\ &\simeq \mathcal{A}_{\mathrm{CP}}(\Lambda_c^+ \to pK^+K^-) - \mathcal{A}_{\mathrm{CP}}^{\mathrm{wgt}}(\Lambda_c^+ \to p\pi^+\pi^-).\end{aligned}$$

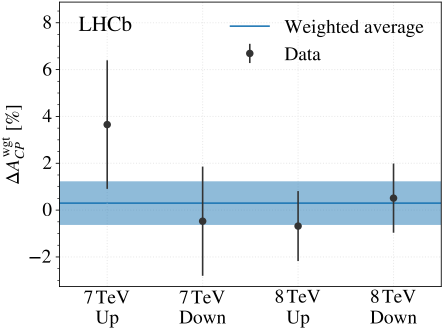
- However, weighting can distort $p\pi^+\pi^-$ phase space and any local CP asymmetries.

Mass fits



- Using 2011-2012 data, mass fits find ~25k $\Lambda_c^+ \to pK^+K^-$ and ~161k $\Lambda_c^+ \to p\pi^+\pi^-$ signal candidates.
- BDTs used for both efficiency correction and weighting of $p\pi^+\pi^-$ as a function of phase space.

Results - consistent with zero



- Averaging across data-taking periods & magnet polarities gives

$$\mathcal{A}_{\mathrm{Raw}}(pK^+K^-) = (3.72 \pm 0.78)\%,\ \mathcal{A}_{\mathrm{Raw}}^{\mathrm{wgt}}(p\pi^+\pi^-) = (3.42 \pm 0.47)\%,$$

$$\Delta\mathcal{A}_{\mathrm{CP}}^{\mathrm{wgt}} = (0.30 \pm 0.91 \pm 0.61)\%.$$

- Dominant systematics are efficiency correction & mass modelling.
- Future studies of local CPV may increase sensitivity.

Outline

Introduction

Mixing with $D^0 \to K^\mp\pi^\pm$

$A_{CP}(D^0 \to K^0_S K^0_S)$

Angular asymmetries in $D^0 \to h^+h^-\mu^+\mu^-$

$\Delta\mathcal{A}_{\mathrm{CP}}$ in $\Lambda_c^+ \to ph^+h^-$

Conclusions

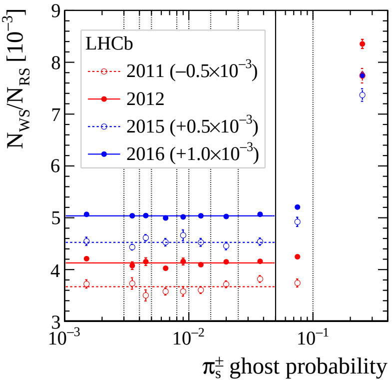
Conclusions

- LHCb has an extensive charm physics programme examining a wide range of decay modes.
- Precision on mixing measurements continues to be pushed.
- First searches for CPV in $D^0 \to h^+h^-\mu^+\mu^-$ angular distributions and charm baryon decays.
- No evidence for CPV yet.
- Plenty more opportunities to be made of Run 1+2 dataset.
- Great prospects for discoveries after the LHCb upgrade, due to start data taking in 2020.

Cheers!

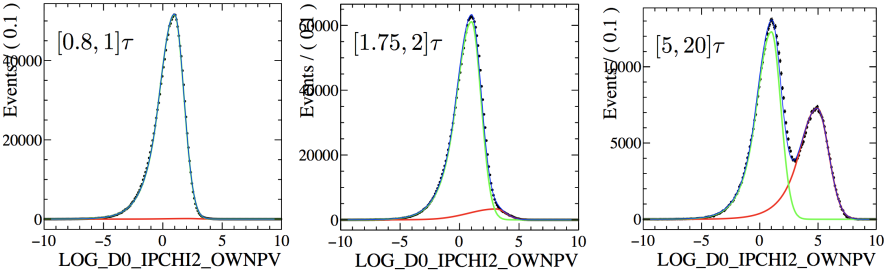
Backup

Misreconstructed tagging pions in $D^0 \to K^\pm\pi^\mp$



- Below the nominal cut of < 0.05, the χ^2 for being flat are (2011) 12.8, (2012) 9.3, (2015) 7.7 and (2016) 3.7 for 7 degrees of freedom.
- Uncertainties on WS/RS yield in each decay time bin are scaled by $\sqrt{\chi^2/\mathrm{NDF}}$ for all samples with $\chi^2 > 7$.

Secondaries contamination in $D^0 \to K^\pm\pi^\mp$



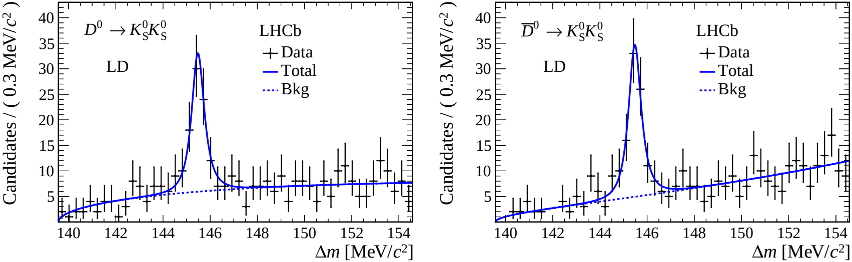
- Sideband subtracted $\ln(IP\chi^2)$ fits for RS decays in 2011 dataset.
- Fits used to extract secondaries fraction in region IP $\chi^2 < 9$.
- First decay time bin, $t < 0.8\tau$, used to fix tail parameters of signal PDF.
- Secondaries shape constrained from sub-sample of $B \to D^{*-}\mu^+X$.

$K^-\pi^+$ detection asymmetry

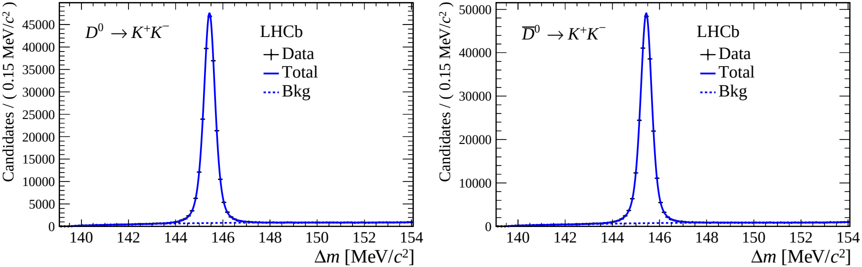
$$\begin{aligned}
\mathcal{A}_{\text{Raw}}(K^-\pi^+\pi^+) &= \mathcal{A}_{\text{Prod}}(D^+) + \mathcal{A}_{\text{Det}}(K^-\pi^+) + \mathcal{A}_{\text{Det}}({\pi^+}_{\text{trig}}) \\
\mathcal{A}_{\text{Raw}}(\overline{K}^0\pi^+) &= \mathcal{A}_{\text{Prod}}(D^+) + \mathcal{A}_{\text{Det}}(\overline{K}^0) + \mathcal{A}_{\text{Det}}({\pi^+}_{\text{trig}}) \\
\mathcal{A}_{\text{Det}}(K^-\pi^+) &= -\mathcal{A}_{\text{Det}}(K^+\pi^-) = \frac{\epsilon(K^-\pi^+) - \epsilon(K^+\pi^-)}{\epsilon(K^-\pi^+) + \epsilon(K^+\pi^-)} \\
&= \mathcal{A}_{\text{Raw}}(K^-\pi^+\pi^+) - \mathcal{A}_{\text{Raw}}(\overline{K}^0\pi^+) + \mathcal{A}_{\text{Det}}(\overline{K}^0)
\end{aligned}$$

- ${\pi^+}_{\text{trig}}$ is the pion which passed the first level software trigger.
- Use $\mathcal{A}_{\text{Det}}(\overline{K}^0) = (0.054 \pm 0.014)\%$ from JHEP 07 (2014) 041.
- Calculate $\mathcal{A}_{\text{Det}}(K^-\pi^+)$ in bins of K^- momentum.

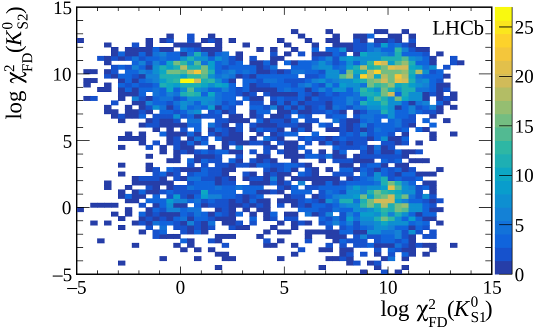
LD $D^0 \to K^0_S K^0_S$ mass fits



$D^0 \to K^+K^-$ mass fits for $\mathcal{A}_{CP}(K_S^0 K_S^0)$

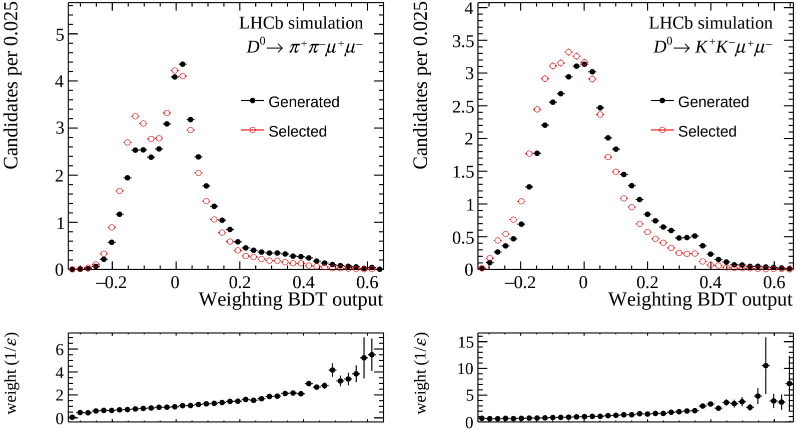


K^0_S flight distance



- Top right: signal.
- Top left & bottom right: $D^0 \rightarrow K^0_S \pi^+ \pi^-$.
- Bottom left: combinatorial background.

$D^0 \to h^+h^-\mu^+\mu^-$ efficiency calculation



- Weight $1/\epsilon$ is calculated as (n. generated)/(n. selected) in each bin of classifier output.

$D^0 \rightarrow h^+ h^- \mu^+ \mu^-$ asymmetries in bins of $m(\mu^+ \mathrm{\mu m})$