Searches for CP violation in two-body charm decays at LHCb

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on behalf of the LHCb collaboration

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EPS, 2015/07/24

Outline

Introduction

Direct *CP* violation in $\mathrm{D}^0 \to \mathrm{K}^0_\mathrm{S}\mathrm{K}^0_\mathrm{S}$ - NEW!
(LHCb-PAPER-2015-030 (in preparation))

Indirect *CP* violation in semi-leptonic-tagged $\mathrm{D}^0 \to \mathrm{h}^+\mathrm{h}^-$
(JHEP 04 (2015) 043)

Conclusions

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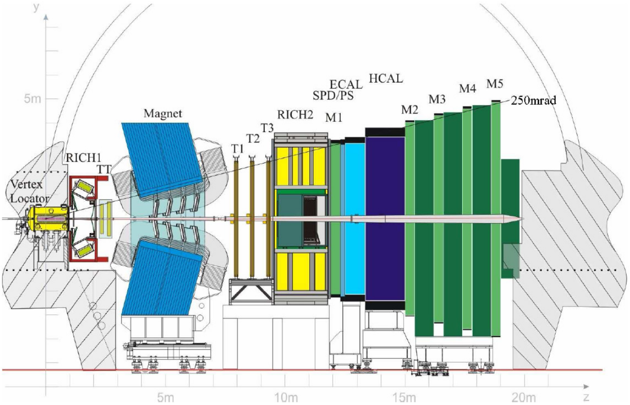
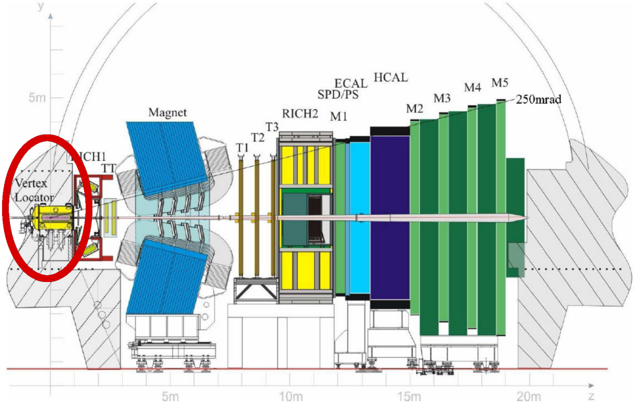
The LHCb detector



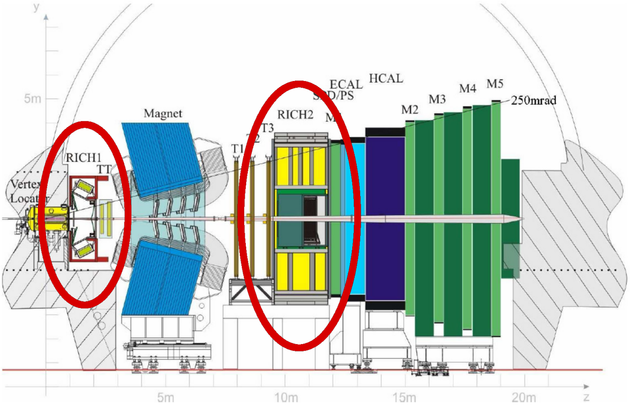
Single-arm forward spectrometer with acceptance $2 < \eta < 5$, designed for high precision measurements of decays involving b and c quarks[1].

The Vertex Locator



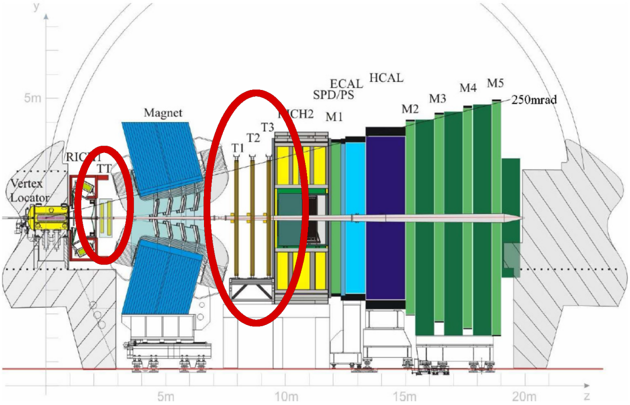
Provides fine tracking about the interaction point, achieving impact parameter resolutions of $\sim$20 μm for tracks with $p_T > 1\,\mathrm{GeV}$[2].

The Ring Imaging Cherenkov detectors



Two RICH detectors provide particle identification, with excellent separation of π and K over a wide momentum range[3].

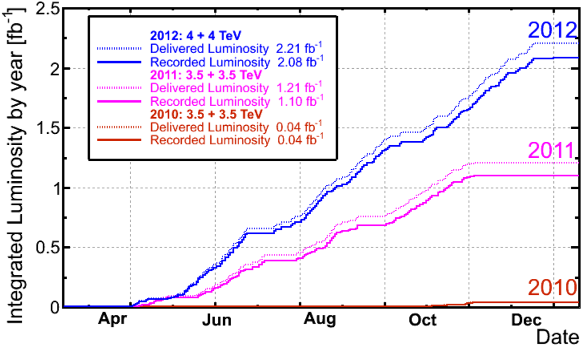
The tracking stations



Tracking stations before & after the dipole magnet achieve momentum resolution of ∼0.5-0.8 % [4].

 [5] Nucl. Phys. B 871(2013), 1

Data sample



- Integrated luminosity of 1.0 fb^{-1} recorded at $\sqrt{s} = 7\,\text{TeV}$ in 2011 and 2.0 fb^{-1} at $\sqrt{s} = 8\,\text{TeV}$ in 2012.
- Huge $c\bar{c}$ production cross-section ($1419 \pm 133\,\mu\text{b}$ at $\sqrt{s} = 7$ TeV [4]) yields largest data sets of charm meson decays in the world.

The D^0 system

The only heavy, neutral meson comprised from up-type quarks - unique system in which to study CP violation.

Due to the form of the CKM matrix, CP violation in charm is strongly suppressed:

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

$$= \begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4),$$

$$\lambda \simeq 0.23, \quad A \simeq 0.81, \quad \rho - i\eta \simeq 0.14 - 0.35i.$$

Direct *CP* violation

Defining

$$A_f = \langle f|\mathcal{H}|\mathrm{D}^0\rangle, \qquad A_{\bar{f}} = \langle \bar{f}|\mathcal{H}|\mathrm{D}^0\rangle,$$
$$\bar{A}_f = \langle f|\mathcal{H}|\overline{\mathrm{D}}^0\rangle, \qquad \bar{A}_{\bar{f}} = \langle \bar{f}|\mathcal{H}|\overline{\mathrm{D}}^0\rangle,$$

direct *CP* violation is quantified by

$$A_{CP}^{dir} \equiv \frac{|A_f|^2 - |\bar{A}_{\bar{f}}|^2}{|A_f|^2 + |\bar{A}_{\bar{f}}|^2}.$$

The Standard Model (SM) predicts direct *CP* violation in D^0 decays to be $\mathcal{O}(10^{-3})$ in $\mathrm{D}^0 \to \mathrm{K}^+\mathrm{K}^-$ and $\mathrm{D}^0 \to \pi^+\pi^-$ [6].

Mixing

The mass eigenstates of the D^0 meson are superpositions of the flavour eigenstates

$$|\mathrm{D}_{L,H}\rangle = p|\mathrm{D}^0\rangle \pm q|\overline{\mathrm{D}}^0\rangle,$$

with masses $m_{H,L}$ and widths $\Gamma_{H,L}$. Here p and q are complex, satisfying $|p|^2 + |q|^2 = 1$.

The rate of mixing is quantified by

$$x = \frac{2(m_H - m_L)}{\Gamma_H + \Gamma_L}, \quad y = \frac{\Gamma_H - \Gamma_L}{\Gamma_H + \Gamma_L}.$$

D^0 mixing now firmly established experimentally, though uncertainties are still relatively large [7].

Indirect CP violation

CP violation in mixing is quantified by

$$A_{CP}^{mix} = \left|\frac{q}{p}\right|^2 - 1.$$

For a final state accessible to both D^0 and $\bar{\mathrm{D}}^0$ CP violation can arise from interference between mixing and decay, which is quantified by

$$\lambda_f \equiv \frac{qA_f}{p\bar{A}_f}$$
$$= \left|\frac{qA_f}{p\bar{A}_f}\right| e^{i\phi}.$$

Such indirect CP violation is predicted to be $\mathcal{O}(10^{-4})$ in the SM[8]. Observation of larger CP violation would be a strong indication of new physics.

Current LHCb measurements of $D \to hh^{(\prime)}$ decays

- "A search for time-integrated *CP* violation in $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$ decays" - $D^{*\pm}$-tagged ΔA_{CP} with 1 fb^{-1} (LHCB-CONF-2013-003-001).
- "Measurement of D^0-$\overline{D}^0$ mixing parameters and search for *CP* violation using $D^0 \to K^+\pi^-$ decays" - $D^{*\pm}$-tagged, 3 fb^{-1} (Phys. Rev. Lett. 111 (2013) 251801).
- "Measurements of indirect *CP* asymmetries in $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$ decays" - $D^{*\pm}$-tagged A_Γ with 1 fb^{-1} (Phys. Rev. Lett. 112 (2014) 041801).
- "Measurement of *CP* asymmetry in $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$ decays" - $\mu^\pm$-tagged ΔA_{CP} with 3 fb^{-1} (J. High Energy Phys. 07 (2014) 014).
- "Search for *CP* violation in $D^\pm \to K^0_S K^\pm$ and $D_s^\pm \to K^0_S \pi^\pm$ decays" - A_{CP} with 3 fb^{-1} (J. High Energy Phys. 10 (2014) 025).

➔ "Measurement of indirect *CP* asymmetries in $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$ decays using semileptonic B decays" - $\mu^\pm$-tagged A_Γ with 3 fb^{-1} (JHEP 04 (2015) 043).

➔ "Measurement of *CP* asymmetry in $D^0 \to K^0_S K^0_S$ decays" - $D^{*\pm}$-tagged A_{CP} with 3 fb^{-1} (LHCb-PAPER-2015-030 (in preparation)).

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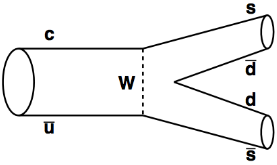
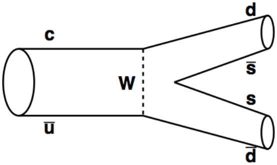
Conclusions

Background





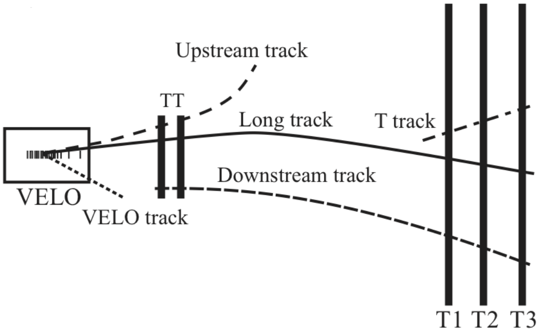
- Dominant diagrams for $D^0 \to K^0\overline{K}^0$ largely cancel ($V_{cd}V_{ud} \simeq -V_{cs}V_{us}$), so final state is predominantly reached through final state scattering $\pi^+\pi^- \to K^0\overline{K}^0$ and $K^+K^- \to K^0\overline{K}^0$.
- Interference can enhance the direct *CP* asymmetry to $\mathcal{O}(10^{-2})$.
- Only previous measurement from CLEO found[9]

$$A_{CP}(D^0 \to K^0_S K^0_S) = (23 \pm 19)\%.$$

Methodology

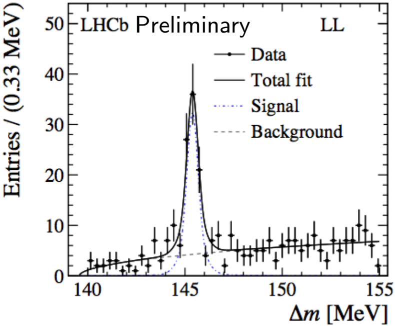
- Reconstruct $D^0 \to K^0_S K^0_S$ with $K^0_S \to \pi^+\pi^-$ - no final state detection asymmetry.
- Use $D^{*+} \to D^0\pi_s^+$ to flavour tag the D^0 using the charge of the soft pion, π_s^+.
- Control channel $D^0 \to K^-\pi^+$ used to assess D^{*+} production and π_s^+ detection asymmetries.
- Exclude background from $D^0 \to K^0_S\pi^+\pi^-$ by applying decay-time cut to K^0_S candidates.
- Combinatorial background reduced with MVA selection using candidate kinematics, decay times, geometry and decay-tree fit quality.

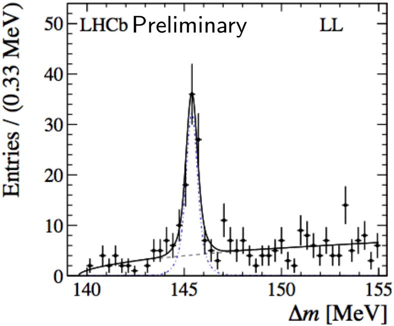
Candidate classification



K^0_S candidates are separated according to where in the detector they decay, within the VELO (Long) or downstream from the VELO (Downstream), due to different detection efficiencies and detector resolutions.

Data fits





- To improve mass resolutions, K^0_S candidates constrained to world average K^0_S mass, and D^0 constrained to originate from the position of the p-p collision.
- Fits to distribution of $\Delta m \equiv m(D^{*+}) - m(D^0)$ finds ∼630 signal decays.
- Shape parameters shared between data subsamples with yields determined independently.

Results & systematics

- Using full 3 fb^{-1} run I dataset, weighted average of asymmetries on subsamples gives (preliminary)

$$A_{CP}(\mathrm{D}^0 \to \mathrm{K}^0_\mathrm{S}\mathrm{K}^0_\mathrm{S}) = (-2.9 \pm 5.2 \pm 2.2)\,\%.$$

- Systematics arise from accuracy of fit model and D^0 production and π_s^+ detection asymmetries.
- Significant improvement over previous measurement, though with no indication of *CP* violation.
- New dedicated trigger lines for run II will greatly improve efficiency & sensitivity.

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Background

- CP asymmetry of the average decay time of an initial state of D^0 ($\bar{\mathrm{D}}^0$) ("effective lifetime") decaying to a CP eigenstate f defined as[11]

$$A_\Gamma \equiv \frac{\hat{\Gamma}(\mathrm{D}^0 \to f) - \hat{\Gamma}(\bar{\mathrm{D}}^0 \to f)}{\hat{\Gamma}(\mathrm{D}^0 \to f) + \hat{\Gamma}(\bar{\mathrm{D}}^0 \to f)}$$
$$\approx \eta_{CP}\left[\left(A_{CP}^{mix}/2 - A_{CP}^{dir}\right) y\cos\phi - x\sin\phi\right],$$

  with $\hat{\Gamma}$ the inverse of the effective lifetime and η_{CP} the CP eigenvalue of f ($= 1$ for $\mathrm{K}^+\mathrm{K}^-$ and $\pi^+\pi^-$).
- Sensitive to CP violation even in the case $A_{CP}^{mix} = A_{CP}^{dir} = 0$ through the interference phase ϕ.

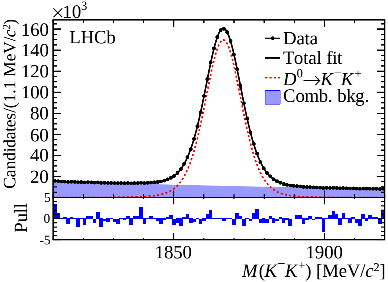
Methodology

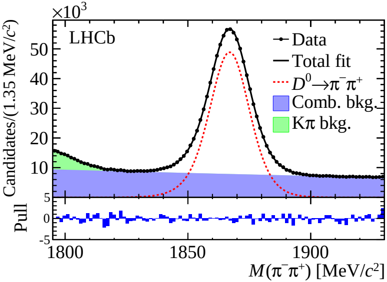
- Reconstruct $\mathrm{D}^0 \to \mathrm{K}^+\mathrm{K}^-$ and $\mathrm{D}^0 \to \pi^+\pi^-$.
- Flavour tag using $\mathrm{B} \to \mathrm{D}^0\mu^- X$, with charge of μ^- giving flavour of D^0.
- Minimise combinatorial backgrounds with cut based selection using kinematic and decay-tree fit quality variables.
- Fit D^0 mass spectrum in bins of D^0 decay time to determine yields and calculate

$$A_{CP}(t) \simeq A_{CP}^{dir} - A_\Gamma \frac{t}{\tau},$$

  with τ the world average D^0 lifetime.
- Measured value of A_{CP}^{dir} here includes production & detection asymmetries.
- Selection efficiency vs decay time cancels in $A_{CP}(t)$, assuming no decay time dependent detection asymmetry.
- Mistag rate cancels similarly and only reduces sensitivity slightly.

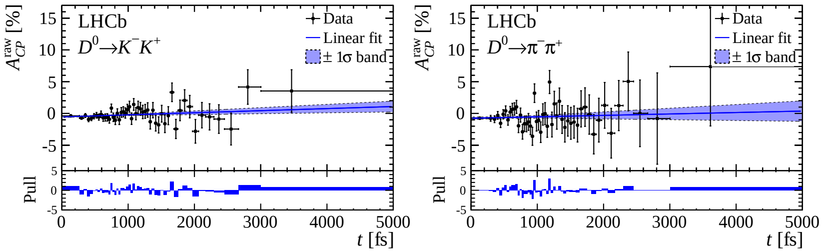
Data fits





- Time integrated fit determines shape parameters, which are then fixed for fits in decay time bins.
- D^0 and $\bar{D}^0$ candidates are fitted simultaneously to determine the asymmetry directly.
- Fits find 2.34M $D^0 \to K^+K^-$ and 0.79M $D^0 \to \pi^+\pi^-$ signal decays.

Results & systematics

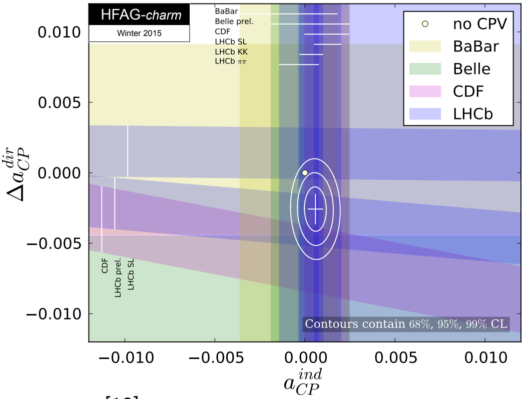


- Using full 3 fb^{-1} run I dataset, yields

$$A_\Gamma(\mathrm{K}^+\mathrm{K}^-) = (-0.134 \pm 0.077^{+0.026}_{-0.034})\,\%,$$
$$A_\Gamma(\pi^+\pi^-) = (-0.092 \pm 0.145^{+0.025}_{-0.033})\,\%.$$

- Cross check on $\mathrm{D}^0 \to \mathrm{K}^-\pi^+$ yields $A_\Gamma(\mathrm{K}^-\pi^+)$ consistent with zero.
- Systematics well understood, should scale with statistics for run II.

Averages



HFAG averages find[13]

$$-A_\Gamma \simeq a_{CP}^{ind} = (0.058 \pm 0.040)\,\%, \quad \Delta a_{CP}^{dir} = (-0.257 \pm 0.104)\,\%,$$

where $\Delta a_{CP}^{dir} \simeq A_{CP}(K^+K^-) - A_{CP}(\pi^+\pi^-)$, with a p-value for CP conservation of 1.8 %.

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- New world best measurement (preliminary)[10]:

$$A_{CP}(\mathrm{D}^0 \to \mathrm{K}^0_\mathrm{S}\mathrm{K}^0_\mathrm{S}) = (-2.9 \pm 5.2 \pm 2.2)\,\%.$$

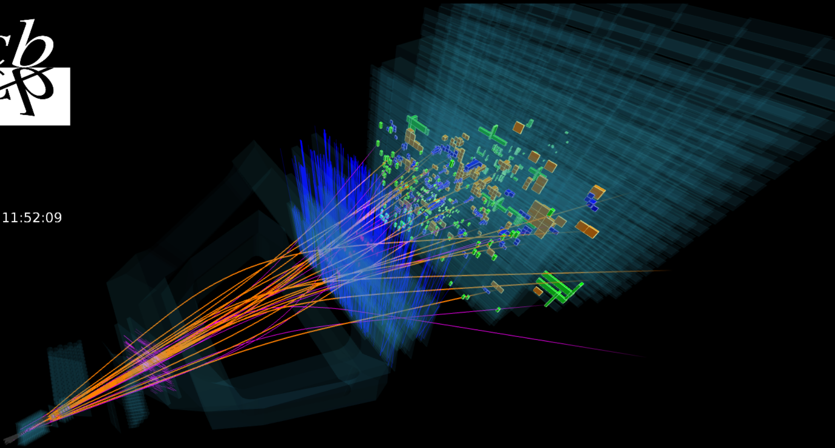
- Further constraints on indirect *CP* violation[12] :

$$A_\Gamma(\mathrm{K}^+\mathrm{K}^-) = (-0.134 \pm 0.077^{+0.026}_{-0.034})\,\%,$$
$$A_\Gamma(\pi^+\pi^-) = (-0.092 \pm 0.145^{+0.025}_{-0.033})\,\%.$$

- LHCb measurements constrain *CP* violation in $\mathrm{D}^0 \to \mathrm{h}^+\mathrm{h}^-$ decays at 1×10^{-3} precision, no evidence for *CP* violation yet.
- Complementary D^{*+} and semi-leptonic tagged samples exploited for maximum sensitivity.
- Run II data, with many improvements in triggering, will yield sensitivities of $\mathcal{O}(10^{-4})$.
- Upgrade will give a further order of magnitude in statistics.
- Huge potential for discovering *CP* violation in the D^0 system, and perhaps new physics.

Thank you

Event 41383468
Run 153460
Wed, 03 Jun 2015 11:52:09



Backup

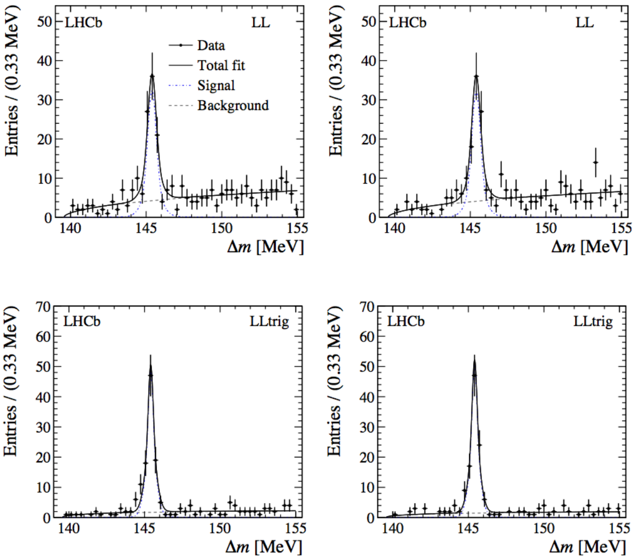
$D^0 \to K^0_S K^0_S$ subsamples

category	description
LL	both K^0_S are of category long, candidate *did not* pass the dedicated trigger
LLtrig	both K^0_S are of category long, candidate *did* pass the dedicated trigger
LD	one K^0_S is long, the other one is downstream
DD	both K^0_S are downstream

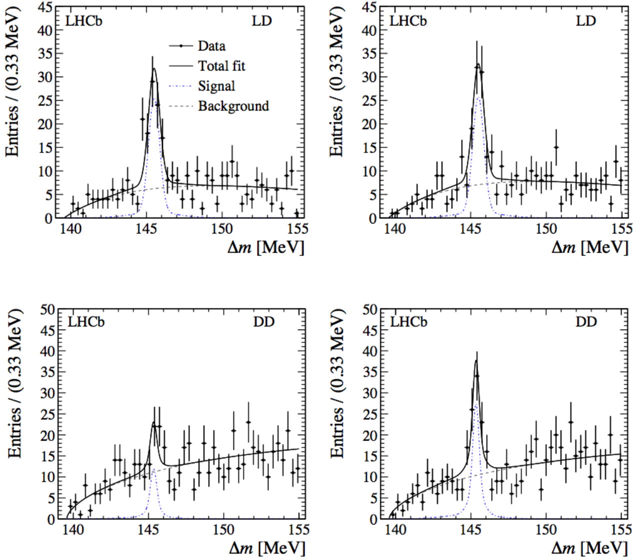
Category	N^+	N^-	A_{CP}
LL	86 ± 11	86 ± 12	0.00 ± 0.09
LLtrig	96 ± 11	99 ± 11	-0.02 ± 0.08
LD	82 ± 14	83 ± 13	-0.00 ± 0.11
DD	29 ± 14	66 ± 14	-0.39 ± 0.23

Dedicated trigger existed only for LL combinations in 2012 but not 2011.
Run II adds trigger lines for LD and DD.

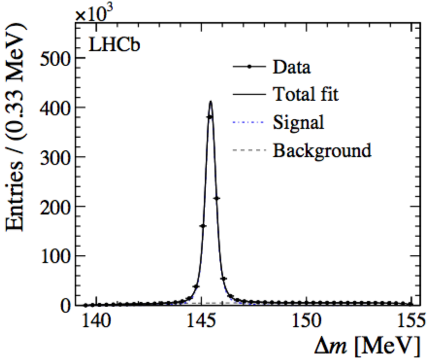
$D^0 \to K^0_S K^0_S$ LL and LLtrig Δm fits



$D^0 \to K^0_S K^0_S$ LD and DD Δm fits



$D^0 \to K^0_S K^0_S$ normalisation channel



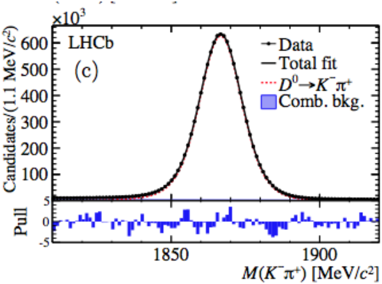
Only 1 % random subsample of $D^0 \to K^- \pi^+$ used due to high statistics.

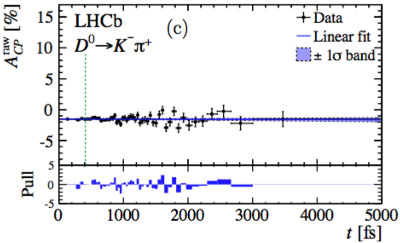
$A_{CP}(D^0 \rightarrow K^0_S K^0_S)$ systematics

Systematic source	value
Background determination	0.019
Detection charge asymmetry and production asymmetry	0.011
Total	0.022

- Background modelling systematic obtained by performing fit only to Δm sidebands, extrapolating under the signal peak, and subtracting from the total n. candidates to obtain n. signal.
- Detection & production asymmetries obtained from $D^0 \rightarrow K^- \pi^+$ after correcting for the $K^\pm$ detection asymmetry.

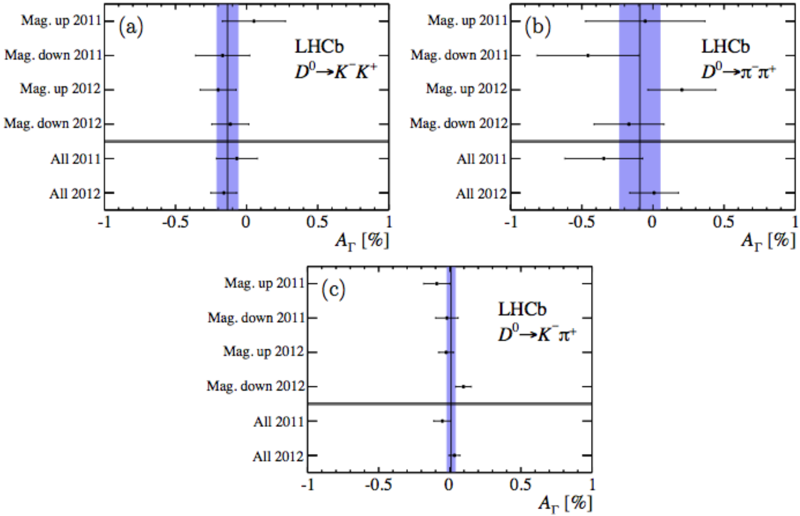
A_Γ with control $\mathrm{D}^0 \to \mathrm{K}^-\pi^+$





$$A_\Gamma(\mathrm{K}\pi) = (0.009 \pm 0.032)\,\%.$$

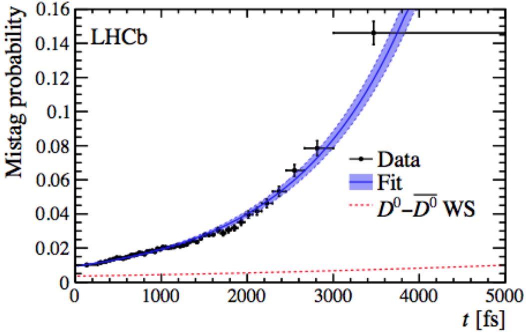
A_Γ data subsets



A_Γ systematics

Source of uncertainty	$D^0 \to K^-K^+$		$D^0 \to \pi^-\pi^+$	
	constant	scale	constant	scale
Mistag probability	0.006%	0.05	0.008%	0.05
Mistag asymmetry	0.016%		0.016%	
Time-dependent efficiency	0.010%		0.010%	
Detection and production asymmetries	0.010%		0.010%	
D^0 mass fit model	0.011%		0.007%	
D^0 decay-time resolution		0.09		0.07
B^0–$\overline{B}^0$ mixing	0.007%		0.007%	
Quadratic sum	0.026%	0.10	0.025%	0.09

A_Γ mistag rate from $\mathrm{D}^0 \to \mathrm{K}^-\pi^+$



Determined from fraction of $\mathrm{D}^0 \to \mathrm{K}^-\pi^+$ candidates associated with wrong charge μ, after subtracting contribution from D^0 mixing and DCS decays.