Charm Mixing and CP Violation

Weak Interactions and Neutrinos, Natal

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Mixing:

- Mixing in neutral kaons and B mesons is well established.
- Charm mixing discovered through a combination of measurements in 2007. Phys.Rev.Lett., 98:211802 (2007)
- First individual $> 5\sigma$ result for charm mixing released by LHCb in 2012. Phys.Rev.Lett., 110:101802 (2013)

CP Violation:

- CP violation discovered in kaons in 1964. Phys. Rev. Lett. 13, 138140 (1964)
- CP violation observed in B mesons in 2001. Phys.Rev.Lett. 87:091801 (2001)
- CP violation in charm not yet observed.

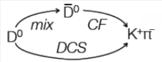
Mass states:

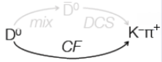
$$|D_1\rangle = p\,|D^0\rangle - q\,|\overline{D}^0\rangle$$
$$|D_2\rangle = p\,|D^0\rangle + q\,|\overline{D}^0\rangle$$

$$CP\,|D^0\rangle = -\,|\overline{D}^0\rangle \;,\; CP\,|\overline{D}^0\rangle = -\,|D^0\rangle$$
$$x = \frac{\Delta m}{\Gamma} \qquad y = \frac{\Delta\Gamma}{2\Gamma}$$
$$\Gamma = \frac{\Gamma_1+\Gamma_2}{2}$$

DCS decays

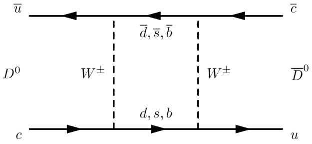
$$R_D = \left|\frac{A(D^0 \to K^+\pi^-)}{A(D^0 \to K^-\pi^+)}\right|$$





$$x' = x\cos\delta + y\sin\delta$$
$$y' = y\cos\delta - x\sin\delta$$

- Mixing is small in charm. arXiv:0907.2950
- Quark loops are second order and GIM suppressed.



- Long distance effects are tricky to calculate. arxiv:0311371

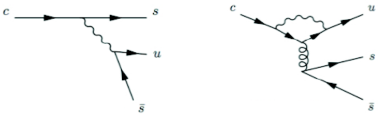
- Current HFAG averages (no CPV):

$$x = (0.4 \pm 0.2)\% \qquad y = (0.5 \pm 0.2)\%$$

CP violating charm

Three possible sources of CP violation:

- Direct through the decays
- Through mixing
- Interference between mixing and decay



CPV in mixing

$$\left|\frac{q}{p}\right| \neq 1 \qquad \phi \neq 0$$

$$\left|\frac{q}{p}\right|^{\pm 2} \approx 1 \pm A_m$$

$$a_{CP}^{ind} = -\frac{A_m}{2} y \cos\phi + x \sin\phi$$

CPV in decay

$$A_{KK} \qquad A_{\pi\pi} \qquad A_D$$

$$\left|\frac{\bar{A}_f}{A_f}\right|^{\pm 2} \approx 1 \pm A_d \qquad a_{CP}^{dir} \approx -\frac{1}{2} A_d$$

CPV in interference

$$\lambda_f = \frac{q}{p} \left|\frac{\bar{A}_f}{A_f}\right| e^{i\phi}$$

- In the Standard Model CP violation is expected to be small.
- Significant enhancements are an indication of New Physics.

Fitted parameters

HFAG fits 10 charm mixing and CPV parameters:

Parameters

- mixing: x, y
- indirect CPV: $|q/p|$, φ
- direct CPV: A_K, A_π, A_D
- R_D
- strong phases: δ, $\delta_{K\pi\pi}$

M. Gersabeck (2012)

Observations

These observations are used in the fit:

Parameters		Observables
mixing	x, y	
indirect CPV	$\lvert q/p \rvert$, φ	y_{CP}, $K_s hh$
direct CPV	A_K, A_π, A_D	A_Γ, ΔA_{CP}
	R_D	$K\pi$
strong phases	δ, $\delta_{K\pi\pi}$	$K\pi\pi^0$

- All of these analyses are under way at LHCb.
- This is not an exhaustive list.

M. Gersabeck (2012)

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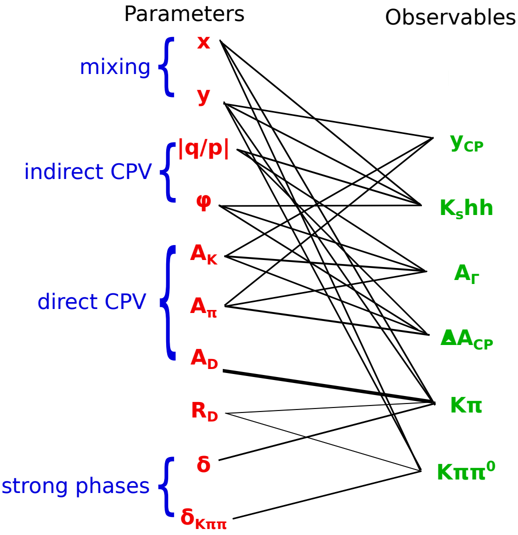

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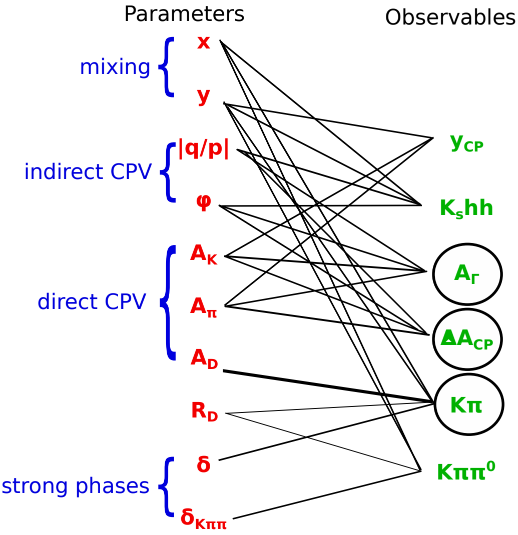

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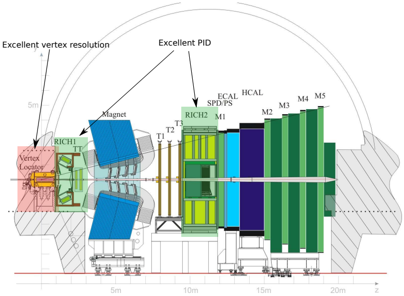
M. Gersabeck (2012)

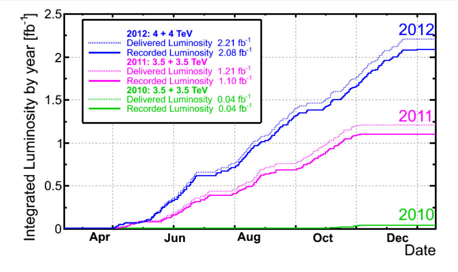
- Forward spectrometer.
- Acceptance $2 < \eta < 5$



- 3 level trigger:
  - L0 hardware selects events with high p_T particles.
  - Two layers of software triggers.
- Output at $\sim$ 5kHz

Data set

- 2011: $1fb^{-1}$ at 7TeV
- 2012: $2fb^{-1}$ at 8TeV



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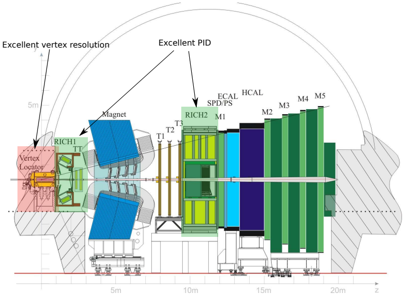

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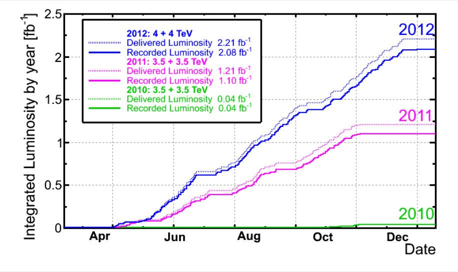


Charm

$$\sigma_{b\bar{b},acc} = 75.3 \pm 14.1\mu\text{b at 7TeV}$$

Phys. Lett. B694 209-216

$$\sigma_{c\bar{c},acc} = 1419 \pm 134\mu\text{b at 7TeV}$$

Nucl. Phys. B871, 1-20

Tagging and backgrounds

Prompt:

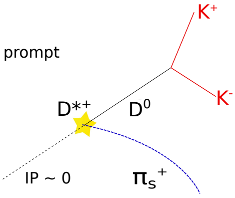
- Look for the decay $D^{*+} \to D^0 \pi_s^+$.

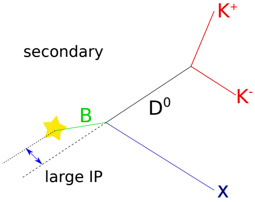
Semi-leptonic:

- Use the μ from semi-leptonic B decays to determine the flavour.

Prompt backgrounds:

- Random π_s^+ - mis-tag:
  - Separated out by fit of difference between D^{*+} and D^0 masses, Δm.
- D^0 from B decays - secondaries:
  - $\ln(\mathrm{IP}\chi^2)$ used as a discriminating variable.



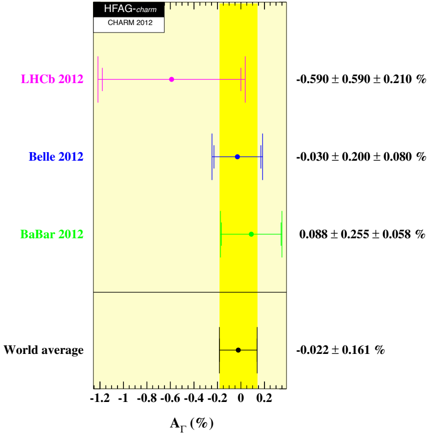


Asymmetry of D^0 and $\overline{D}^0$ decay rates to a CP eigenstate, $K^+ K^-$ or $\pi^+ \pi^-$:

$$A_\Gamma(KK) = \frac{\hat{\Gamma}\left(D^0 \to K^+K^-\right) - \hat{\Gamma}\left(\overline{D}^0 \to K^+K^-\right)}{\hat{\Gamma}\left(D^0 \to K^+K^-\right) + \hat{\Gamma}\left(\overline{D}^0 \to K^+K^-\right)} \approx \frac{A_m + A_d}{2} y \cos\phi - x \sin\phi$$

- Expected to be small in the Standard Model, $\sim 10^{-4}$.
- Approximately final state independent in SM.

$$\Delta A_\Gamma = A_\Gamma(KK) - A_\Gamma(\pi\pi)$$
$$\approx \Delta A_D y \cos\phi + (A_M + A_D) y \Delta \cos\phi$$
$$- x \Delta \sin\phi$$



A_Γ - Analysis method

LHCb-PAPER-2013-054

Extract mean effective lifetimes of D^0 ($\overline{D}^0$) decaying to the *CP* eigenstates by means of a fit to D^0 decay times.

- $1 fb^{-1}$ of 2011 7Tev data.
- Fit 3 final states: $K^+ K^-$, $\pi^+\pi^-$, $K^- \pi^+$.
- Two stage fit process
  - Fit m_{D^0} and Δm simultaneously to separate signal and background.
  - Simultaneous fit to D^0 decay time and $\ln(\mathrm{IP}\chi^2)$ to extract the prompt signal mean lifetime.
- The $\ln(\mathrm{IP}\chi^2)$ variable discriminates between prompt and secondary.
- Acceptance biases due to the selection corrected for using the "swimming" method. J. Phys.: Conf. Ser. 396 022016

Candidates after selection:

Channel	No. of candidates
$D^0 \to K^-\pi^+$	34.1 million
$D^0 \to K^+K^-$	4.8 million
$D^0 \to \pi^+\pi^-$	1.6 million

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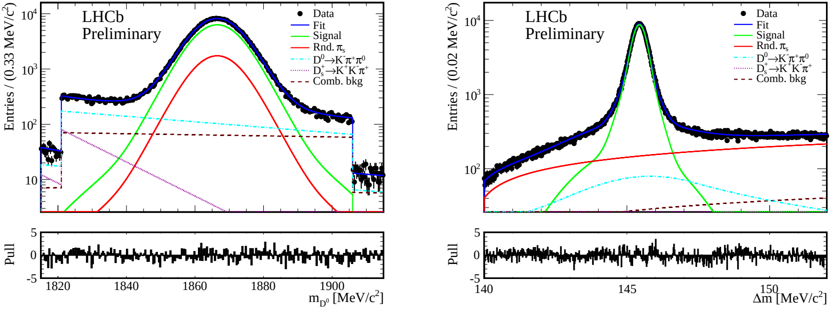
- Unbinned maximum likelihood fit to D^0 mass and Δm to determine signal and backgrounds.
- Separate out:
  - Random π_s^+
  - Combinatoric
  - Mis-reconstructed decays in the $K^+ K^-$ final state

$\overline{D}^0 \to K^+K^-$



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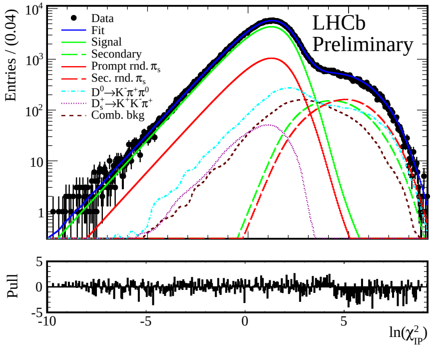
$\overline{D}^0 \to K^+K^-$



The $\ln(\text{IP}\chi^2)$ fit is used to separate prompt and secondary signal and random π_s^+ .

- Prompt and secondary signal and π_s^+ background are described by parametric PDFs.
- Their fit parameters are allowed to evolve in time.
- Secondary components show significant time dependence.
- Background PDFs are constructed by applying kernel density estimators to sPlots.

A_Γ - Time fit

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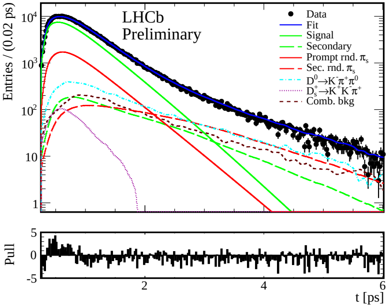
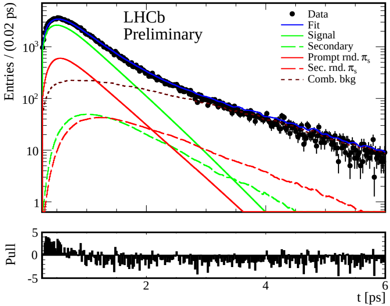
$\overline{D}^0 \to K^+K^-$



$\overline{D}^0 \to \pi^+\pi^-$



$$A_\Gamma(KK) = (-0.35 \pm 0.62_{stat} \pm 0.12_{syst}) \times 10^{-3}$$
$$A_\Gamma(\pi\pi) = (0.33 \pm 1.06_{stat} \pm 0.14_{syst}) \times 10^{-3}$$

Preliminary

- This is the most accurate measurement of A_Γ to date.
- Consistent with no CP violation and no difference in A_Γ between the final states.

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Several cross checks were carried out:

- D^0 lifetime measured using the $K^- \pi^+$ data; $\tau = (412 \pm 0.1) fs$, compared to the PDG value of $\tau = 410.1 \pm 1.5) fs$.
- Null tests.
- Checked dependencies on kinematics, number of PVs in the event, trigger selections etc.
- Simulations with varying configurations.

Studies of systematic uncertainties on the unbinned method are summarised in the table:

Effect	$A_\Gamma\ (K^+ K^-) \times 10^{-3}$	$A_\Gamma\ (\pi^+\pi^-) \times 10^{-3}$
Mis-reconstructed bkg.	± 0.02	± 0.00
Charm from B	± 0.07	± 0.07
Other backgrounds	± 0.02	± 0.04
Acceptance function	± 0.09	± 0.11
Total	± 0.12	± 0.14

Preliminary

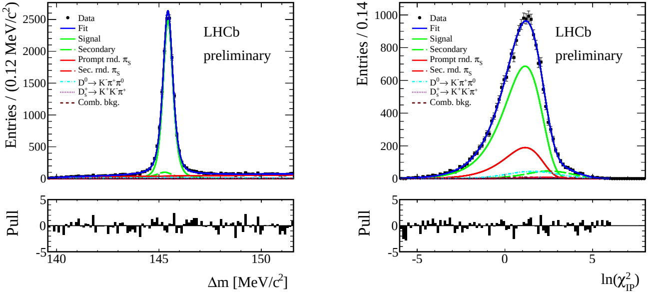
LHCb-PAPER-2013-054

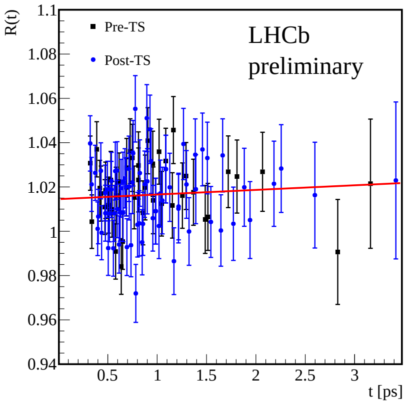
Use an alternative method to measure A_Γ. Measure the ratio of D^0 and $\overline{\text{D}}^0$ yields in bins of decay time.

$$R(t, t+\Delta t) \approx \frac{N_{\overline{\text{D}}0}}{N_{\text{D}^0}}\left(1 + \frac{2A_\Gamma}{\tau_{KK}} t\right) \frac{1 - e^{\frac{-\Delta t}{\tau_{\overline{\text{D}}0}}}}{1 - e^{\frac{-\Delta t}{\tau_{\text{D}0}}}}$$

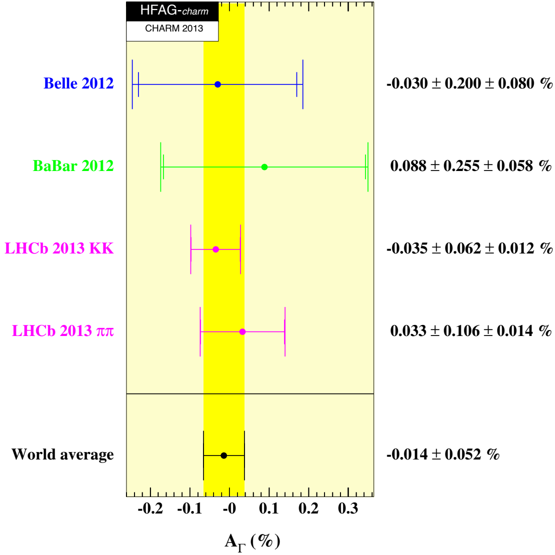
- Fit m_{D^0}, Δm, and $\ln(\text{IP}\chi^2)$ to find yields.
- Plot ratio as function of decay time and fit.

$\overline{\text{D}}^0 \to K^+K^-$, 0.74ps-0.78ps





The binned results are consistent with those from the unbinned fit.


HFAG-charm
CHARM 2013
Belle 2012
-0.030 ± 0.200 ± 0.080 %
BaBar 2012
0.088 ± 0.255 ± 0.058 %
LHCb 2013 KK
-0.035 ± 0.062 ± 0.012 %
LHCb 2013 ππ
0.033 ± 0.106 ± 0.014 %
World average
-0.014 ± 0.052 %
-0.2
-0.1
-0
0.1
0.2
0.3
A_Γ (%)

Time-integrated asymmetries for final states f: $K^+ K^-$ and $\pi^+\pi^-$.

$$A_{CP}(f) = \frac{\Gamma(D^0 \to f) - \Gamma(\overline{D}^0 \to f)}{\Gamma(D^0 \to f) + \Gamma(\overline{D}^0 \to f)}$$

$$A_{CP}^{meas} = A_{CP} + A^{prod} + A^{det}$$

- Taking the difference cancels detection and production asymmetries.
- To a good approximation this is a measure of direct CP violation.

$$\Delta A_{CP} = A_{KK} - A_{\pi\pi} \approx \Delta a_{CP}^{dir}\left(1 + y_{CP}\frac{\langle \bar{t} \rangle}{\tau}\right) + a_{CP}^{ind}\frac{\Delta\langle t \rangle}{\tau}$$

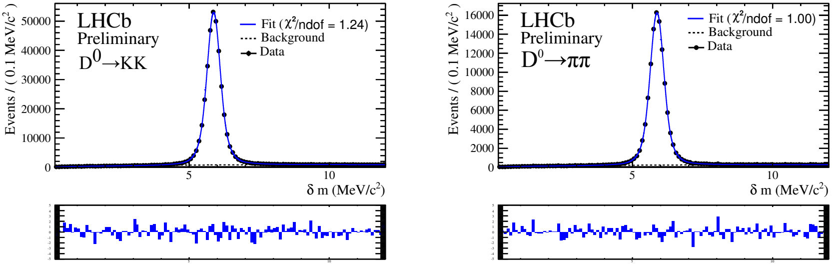
- LHCb result on $0.6 fb^{-1}$ showed evidence of CPV: $(-0.82 \pm 0.21 \pm 0.11)\%$.
- Results on full CDF and Belle datasets looked consistent.

There are two analyses on the 2011 $1 fb^{-1}$ sample: prompt and muon-tagged.

- The analyses were carried out independently.
- The two data sets are statistically independent.
- Changes to prompt analysis - not just adding $0.4 fb^{-1}$.

LHCb-CONF-2013-003

Fit Δm to extract signal yield; $K^+ K^-$ on left, $\pi^+\pi^-$ on right.



$$\frac{\Delta\langle t\rangle}{\tau} = (11.19 \pm 0.13 \pm 0.17)\%$$

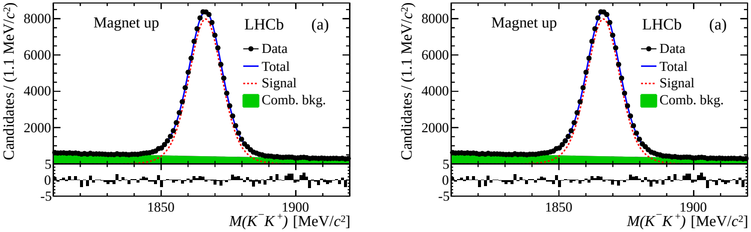
$$\Delta A_{CP} = (-0.34 \pm 0.15_{stat} \pm 0.10_{syst})\%$$

Preliminary

Phys. Lett. B 723 (2013) 33-43

Tag the initial D^0 flavour from the charge of the muon in the decay of B meson.

- Mostly trigger on the muon.
- Extract D^0 and $\overline{D}^0$ yields using a fit to the reconstructed mass.



$$\frac{\Delta\langle t\rangle}{\tau} = (1.8 \pm 0.2 \pm 0.7)\%$$

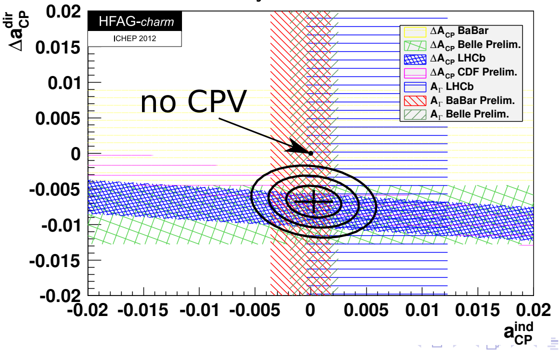
$$\frac{\overline{\langle t\rangle}}{\tau} = 1.062 \pm 0.001 \pm 0.003$$

$$\Delta A_{CP} = (+0.49 \pm 0.30_{stat} \pm 0.14_{syst})\%$$

ΔA_{CP} - Time evolution

Experiment	$\Delta A_{CP}\%$	Paper
LHCb prompt ($0.6fb^{-1}$)	$(-0.82 \pm 0.21 \pm 0.11)$	Phys.Rev.Lett. 108,111602
CDF	$(-0.62 \pm 0.21 \pm 0.10)$	Phys.Rev.Lett. 109,111801
Belle	$(-0.87 \pm 0.41 \pm 0.06)$	arXiv:1212.1975
LHCb prompt (Prelim)	$(-0.34 \pm 0.15 \pm 0.10)$	LHCb-CONF-2013-003
LHCb semi-leptonic	$(0.49 \pm 0.30 \pm 0.14)$	Phys.Lett.B 723
LHCb average	(-0.15 ± 0.16)	LHCb-CONF-2013-003

July 2012



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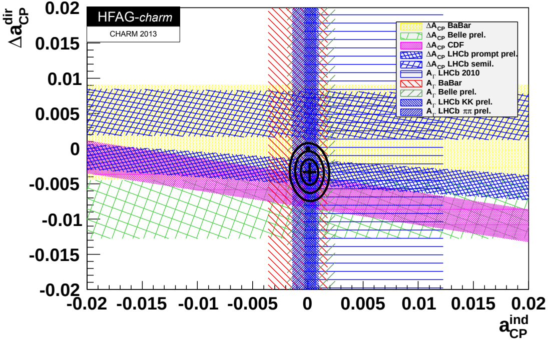
September 2013



Wrong sign - Mixing

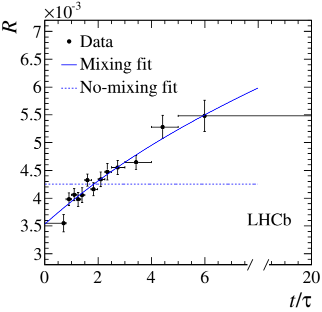
- Study the time dependence of the ratio of CF, $D^0 \to K^-\pi^+$ and DCS, $D^0 \to K^+\pi^-$ decays.
- Assuming no CPV:

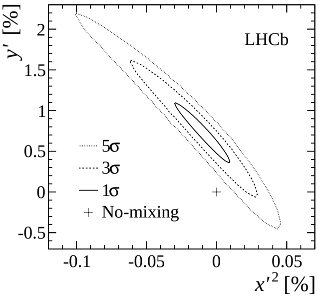
$$R(t) = \frac{N_{WS}(t)}{N_{RS}(t)} = R_D + \sqrt{R_D}\,y' t + \frac{x'^2 + y'^2}{4} t$$

Analysis of 2011 data: PRL 110, 101802 (2013)

$y' = (7.2 \pm 2.4) \times 10^{-3}$ $\quad x'^2 = (-0.09 \pm 0.13) \times 10^{-3}$

No mixing hypothesis excluded at 9.1σ.





If we include CP violation in the mixing and consider D^0 (R^+) and $\overline{D}^0$ (R^-) separately:

$$x'^{\pm} = \left(\frac{1 \pm A_M}{1 \mp A_M}\right)^{\frac{1}{4}} (x' \cos\phi \pm y' \sin\phi)$$

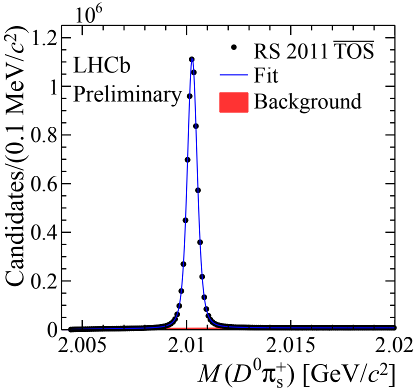
$$y'^{\pm} = \left(\frac{1 \pm A_M}{1 \mp A_M}\right)^{\frac{1}{4}} (y' \cos\phi \mp x' \sin\phi)$$

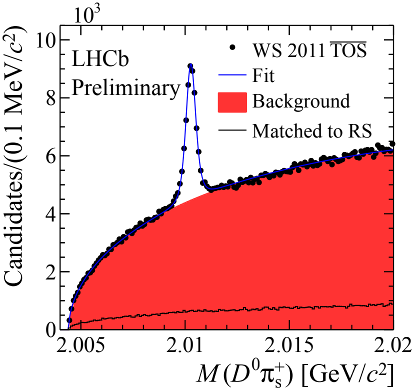
- Perform the mixing measurements for D^0 and $\overline{D}^0$, extract $R_D^{\pm}$, $x'^{2\pm}$ and $y'^{\pm}$ and look for differences to find CP violation in mixing.
- Can extract the direct CP violation in the decay amplitude:

$$A_D = \frac{R_D^+ - R_D^-}{R_D^+ + R_D^-}$$

LHCb-PAPER-2013-053

Fits to the D^{*+} mass to extract RS (left) and WS (right) yields.



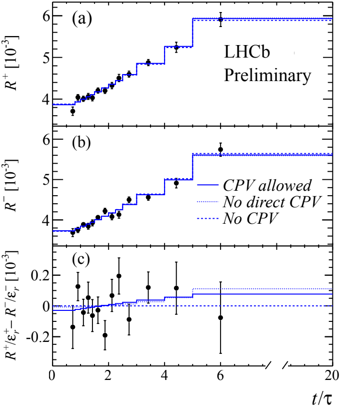


In total 54 millions RS and 0.23 million WS candidates were selected.

Wrong sign - Results

LHCb-PAPER-2013-053

Fit R^+, R^- and plot the difference.



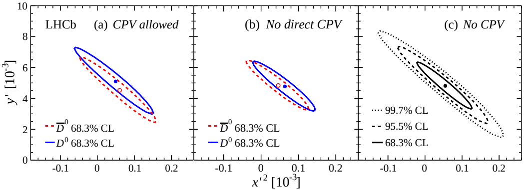
Fit to $3fb^{-1}$ of 2011 + 2012 data.

Consistent with no CP violation.

$A_D = (-1.3 \pm 1.9)\%$

$0.75 < \left|\frac{q}{p}\right| < 1.24$ at 68.3% confidence level.

Preliminary

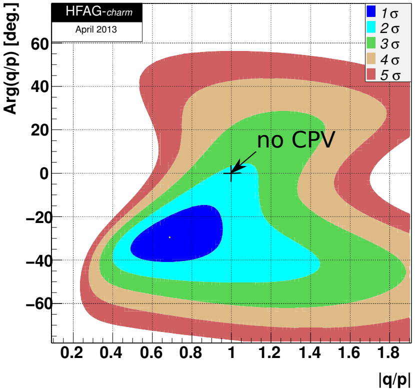


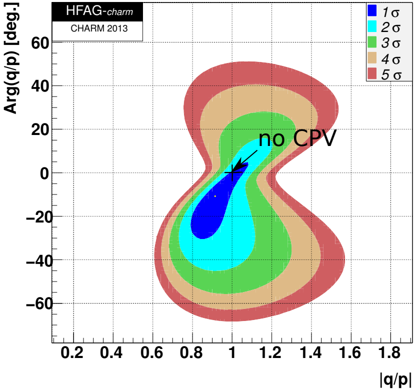
~ factor 2.5 improvement on previous mixing measurement (no CPV).

$y' = (4.81 \pm 0.85 \pm 0.53) \times 10^{-3}$ $\quad x'^2 = (5.5 \pm 4.2 \pm 2.6) \times 10^{-5}$

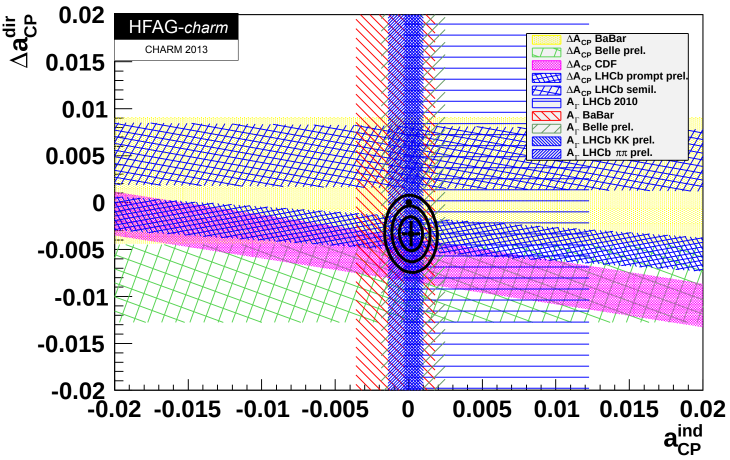
Preliminary

CP violation has yet to be observed in the charm system.





CP violation has yet to be observed in the charm system.



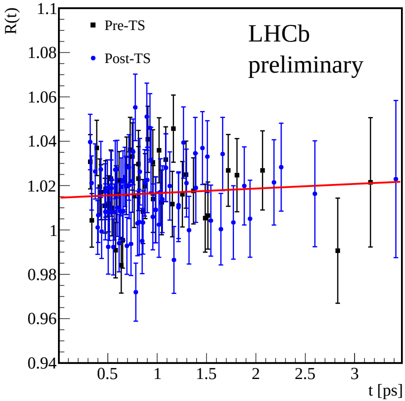
- Mixing is now well established in charm.
- CP violation has yet to be observed in this system.
- The analyses presented show great increases in accuracy over previous results.
- These results will improve when the rest of run 1 data is analysed and run 2 starts.
- Additionally there are many other analyses at LHCb that probe mixing and CP violation.
  - $D^+ \to K^+K^-\pi^+$ Phys. Rev. D 84, 112008 (2011)
  - $D^+ \to \phi\pi^+$ and $D_s^+ \to K_s^0\pi^+$ JHEP 06 (2013) 112
  - $D^0 \to K^+K^-\pi^+\pi^-$ and$D^0 \to \pi^+\pi^-\pi^+\pi^-$ Phys. Lett. B 10,1016 (2013)

Backup

From September 2013:

Parameter	No CPV	CPV-allowed
x (%)	$0.53^{+0.16}_{-0.17}$	$0.39^{+0.16}_{-0.17}$
y (%)	0.67 ± 0.09	$0.67^{+0.07}_{-0.08}$
$\delta_{K\pi}$ (°)	$14.0^{+9.3}_{-10.5}$	$12.5^{+9.4}_{-11.0}$
R_D (%)	0.350 ± 0.004	0.349 ± 0.004
A_D (%)	–	-0.95 ± 1.0
$\lvert q/p \rvert$	–	$0.91^{+0.11}_{-0.09}$
ϕ (°)	–	$-10.8^{+10.5}_{-12.3}$
$\delta_{K\pi\pi}$ (°)	$19.6^{+22.8}_{-23.4}$	$26.8^{+24.2}_{-24.5}$
A_π	–	0.18 ± 0.15
A_K	–	-0.15 ± 0.14

Binned A_Γ results



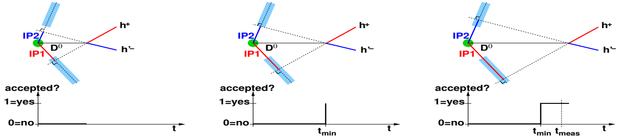
$$A_\Gamma(KK) = (-0.42 \pm 0.58_{stat} \pm 0.73_{syst}) \times 10^{-3}$$
$$A_\Gamma(\pi\pi) = (0.74 \pm 0.96_{stat} \pm 0.80_{syst}) \times 10^{-3}$$

Preliminary

The binned results are consistent with those from the unbinned fit.

Prompt ΔA_{CP} changes

- Data reprocessed with new detector calibration and reconstruction software.
  - $\sim$ 15% of previous signal candidates removed.
  - 17% KK and 34%$\pi\pi$ new candidates.
- Add the rest of 2011 data - $0.4 fb^{-1}$.
- Use kinematic weighting instead of binning.
- Add constraint for π_s^+ to originate at PV - improve Δm resolution and S/B.



- The primary vertex is 'swum' along the D^0 direction and the trigger rerun.
- Trigger decision recorded and a per event acceptance determined.