Charm: Mixing, CP Violation and Rare Decays at LHCb

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On behalf of the LHCb Collaboration

PhiPsi 13, $11^{\rm th}$ September, 2013

Outline

Introduction

Mixing

- Mixing & Indirect CPV from $\mathrm{D}^0 \to \mathrm{K}^+\pi^-$

CP Violation

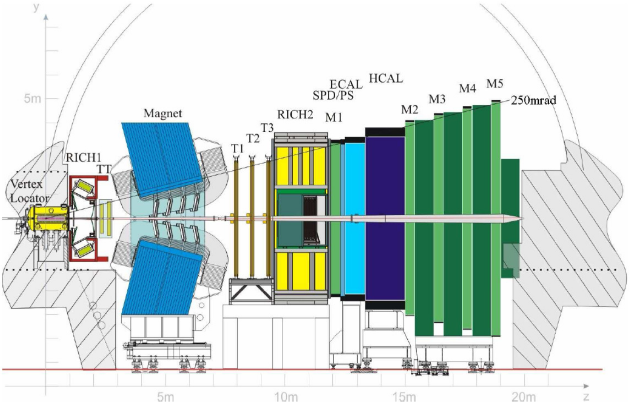
- Indirect CPV from A_Γ with $\mathrm{D}^0 \to \mathrm{h}^+\mathrm{h}^-$
- Direct CPV from $\Delta\mathcal{A}^{\mathrm{CP}}$ with $\mathrm{D}^0 \to \mathrm{h}^+\mathrm{h}^-$

Rare Decays

- ${\mathrm{D}^+}_{(s)} \to \pi^+\mu^+\mu^-$ and ${\mathrm{D}^+}_{(s)} \to \pi^-\mu^+\mu^+$
- $\mathrm{D}^0 \to \mu^+\mu^-$

Conclusions

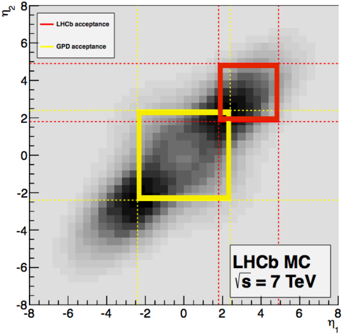
The LHCb Detector



- VErtex LOcator (VELO) provides excellent decay-time resolution ~ 50 fs - essential for time dependent analyses.
- Downstream tracking gives precise p measurements, $\sigma(p)/p \sim 0.5\%$, resulting in excellent mass resolutions.
- Two Ring Imaging CHerenkov (RICH) detectors provide very clean π/K separation.

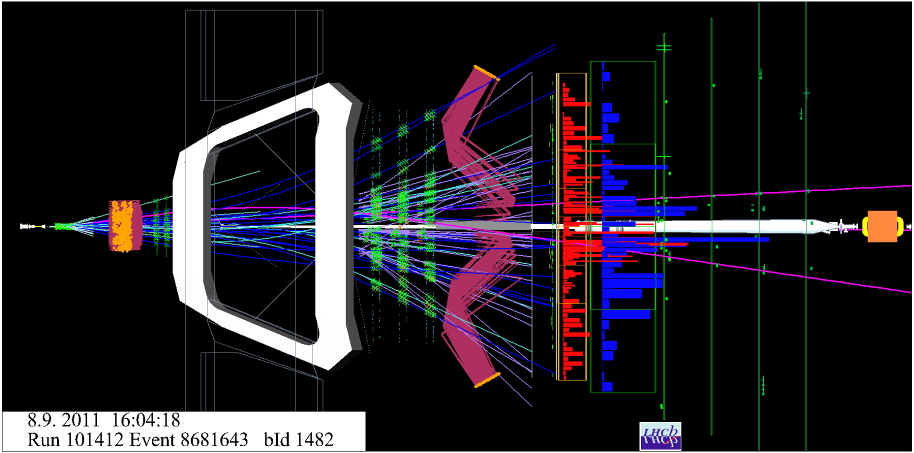
Charm Triggering

- Huge $c\bar{c}$ cross-section: $\sim 1.4\,\mathrm{mb}$ within LHCb acceptance.
- L0 hardware trigger fires on high p_T hadrons or charged leptons - not very efficient for charm.
- In first stage software trigger most hadronic modes trigger on single high p_T track with large displacement from primary interaction.



- Second stage uses full event reconstruction & predominantly "exclusive" selections on full decays using PID, mass, vertexing, etc, criteria.
- Full trigger serves to reduce 40 MHz bunch crossing rate to tape rates for charm of 1 kHz in 2011 & 2 kHz in 2012.
- 1.1 fb^{-1} recorded in 2011 at $\sqrt{s} = 7\ \mathrm{TeV}$ & 2.1 fb^{-1} in 2012 at $\sqrt{s} = 8\ \mathrm{TeV}$, yielding worlds largest charm samples.

Event Display



- Example $\mu^+\mu^-$ event.

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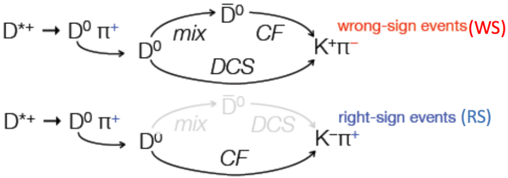
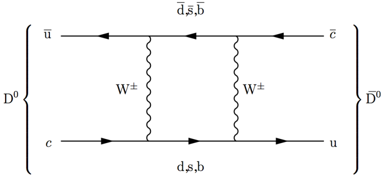
- $D^0 \to \mu^+\mu^-$

Conclusions

Formalism





- "Box diagram" mixing in D^0 system can be enhanced by NP.
- Ratio of WS to RS decay rates vs decay time give access to mixing parameters (assuming no CPV):

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

where:

$$R_D = \left|\frac{A_{DCS}}{A_{CF}}\right|^2, \; x' = x\cos(\delta) + y\sin(\delta), \; y' = -x\sin(\delta) + y\cos(\delta),$$

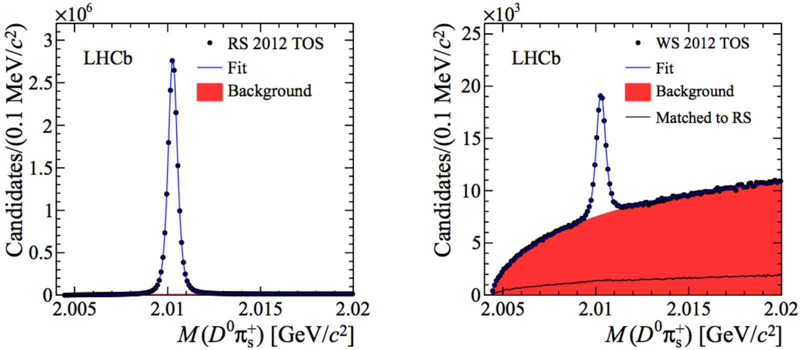
$$\delta = \arg\left(\frac{A_{DCS}}{A_{CF}}\right), \; x = \frac{\Delta m_{\mathrm{D}^0}}{m_{\mathrm{D}^0}}, \; y = \frac{\Delta\Gamma_{\mathrm{D}^0}}{2\Gamma_{\mathrm{D}^0}}.$$

- Analysing D^0 and $\bar{\mathrm{D}}^0$ separately gives sensitivity to CPV.

Strategy

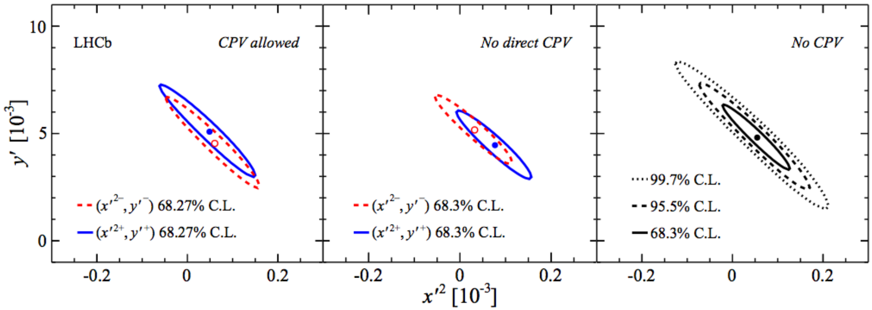
[PRL 110, 101802 (2013)]

- Flavour tag using $D^{*+} \to D^0\pi_s^+$.
- Suppress contribution from D^0 produced in $B \to D^0 X$ with tight cut on D^0 χ^2_{IP} - estimate systematic for remaining bias.
- Divide WS and RS candidates in bins of decay time.
- Fit $m_{D^{*+}}$ in each bin to obtain ratio of yields.
- Fit yield ratio vs decay time with $R(t)$ to obtain R_D, x'^2 and y'.



Results

[PRL 110, 101802 (2013)]



- Using 3.0 fb^{-1} find:

$$x'^2 = (5.5 \pm 4.9) \times 10^{-5}, \quad y' = (4.8 \pm 1.0) \times 10^{-3},$$

$$R_D = (3.568 \pm 0.066) \times 10^{-3}.$$

- No mixing hypothesis excluded at $> 10\sigma$.
- x'^2 and y' consistent for D^0 and $\overline{D}^0$- no evidence for CPV.

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- $D^0 \to \mu^+\mu^-$

Conclusions

Formalism

- CPV in charm difficult to predict precisely in SM, but is "small" and can be enhanced by NP.
- CP asymmetry of effective D^0 lifetime decaying to CP eigenstate sensitive to indirect CPV:

$$A_\Gamma = \frac{\tau_{\text{eff}}(\bar{D}^0 \to h^+h^-) - \tau_{\text{eff}}(D^0 \to h^+h^-)}{\tau_{\text{eff}}(\bar{D}^0 \to h^+h^-) + \tau_{\text{eff}}(D^0 \to h^+h^-)} \simeq \left[\frac{1}{2}(A_m + A_d) y \cos\phi - x \sin\phi\right],$$

where:

$$A_m = \frac{|q/p|^2 - |p/q|^2}{|q/p|^2 + |p/q|^2},\ A_d = \frac{\left|A_f/\bar{A}_f\right|^2 - \left|\bar{A}_f/A_f\right|^2}{\left|A_f/\bar{A}_f\right|^2 + \left|\bar{A}_f/A_f\right|^2},\ \phi = \arg\left(\frac{q}{p}\frac{\bar{A}_f}{A_f}\right).$$

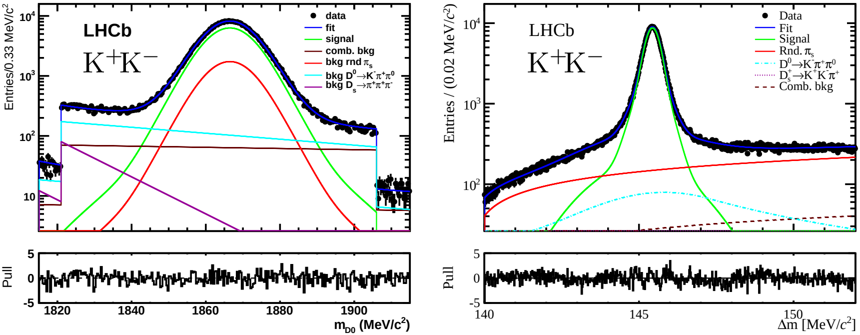
Strategy

- Two possible methods to extract A_Γ:
  - Fit decay-time distributions of D^0 and $\bar{\mathrm{D}}^0$ to extract lifetimes - requires correction of candidate selection bias.
  - Extract $N(\mathrm{D}^0)/N(\bar{\mathrm{D}}^0)$ in bins of decay time & obtain A_Γ from time dependence of ratio.
- Both techniques employed at LHCb & found to give consistent results - lifetimes method taken as baseline result.

- Flavour tag using $\mathrm{D}^{*+} \to \mathrm{D}^0\pi_s^+$.
- Fits to m_{D^0} and $\Delta m = m_{\mathrm{D}^{*+}} - m_{\mathrm{D}^0}$ distributions used to determine signal yields & distinguish backgrounds.
- Data-driven, candidate-by-candidate method used to correct for selection bias in decay-time fit for lifetimes.
- D^0 produced by $\mathrm{B} \to \mathrm{D}^0 X$ distinguished by also fitting χ^2_{IP} of D^0.
- Both $\mathrm{K}^+\mathrm{K}^-$ and $\pi^+\pi^-$ final states used.

Mass Fits

[LHCb-PAPER-2013-054 in preparation]

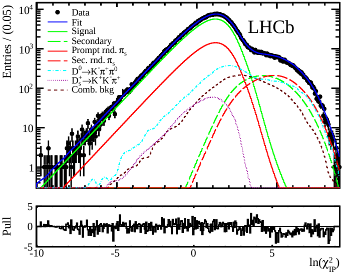


- Data divided by flavour tag, magnet polarity, & two running periods (before and after July 2011 technical stop).
- Fits performed independently on all 8 subsets.
- 4.8M K^+K^- and 1.5M $\pi^+\pi^-$ candidates in total (1.1 fb^{-1}).
- Part-rec. 3-body D decays also distinguished for K^+K^-.

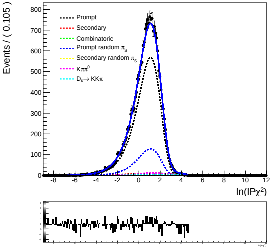
Secondaries Discrimination

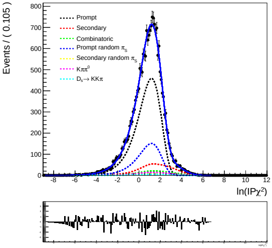
[LHCb-PAPER-2013-054 in preparation]

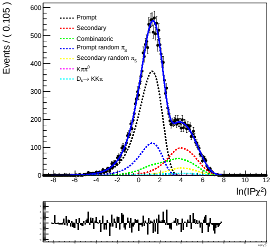
K^+K^-



- Secondary D^0 well discriminated by fit to χ^2_{IP}.
- Time evolution clear from fits in bins of decay time (alternative fit method).
- Determine ~ 3.11M K^+K^- and ~ 1.03M $\pi^+\pi^-$ prompt signal candidates.

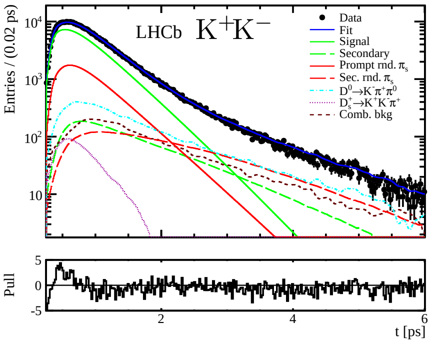


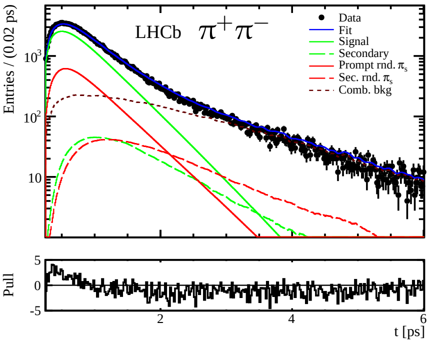




Decay Time Fits

[LHCb-PAPER-2013-054 in preparation]





- Acceptance vs decay time reproduced well by data-driven technique.
- Small inaccuracies in fit models studied in detail on simulation & systematic uncertainty applied.

Results

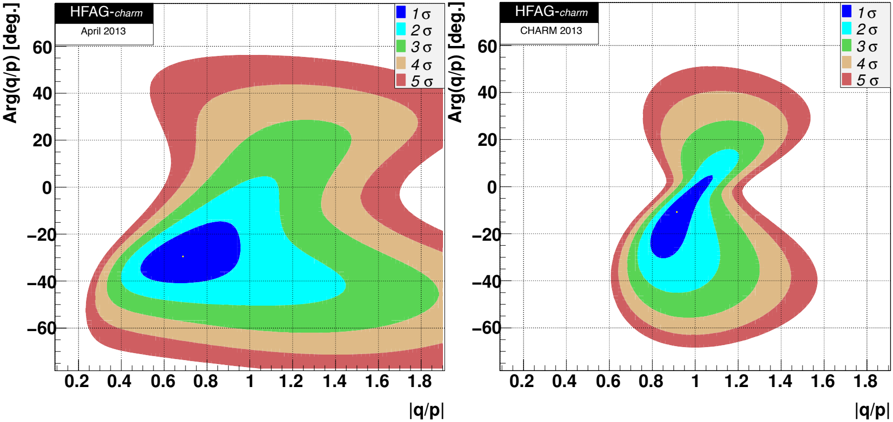
[LHCb-PAPER-2013-054
in preparation]

$$A_\Gamma^{KK} = (-0.35 \pm 0.62 \pm 0.12) \times 10^{-3},$$
$$A_\Gamma^{\pi\pi} = (0.33 \pm 1.03 \pm 0.14) \times 10^{-3}.$$

- Consistent with zero - no evidence for CPV.
- Dominate systematics from accuracy of acceptance correction & modelling of backgrounds.
- Paper in preparation.

Indirect CPV HFAG Averages

[Charm 2013]
[HFAG]



- Big improvement in precision on averages of CPV parameters $|q/p|$ and $\arg(q/p)$ from latest LHCb results.
- Latest averages more consistent with no CPV, $(|q/p|, \arg(q/p)) = (1, 0)$.

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Conclusions

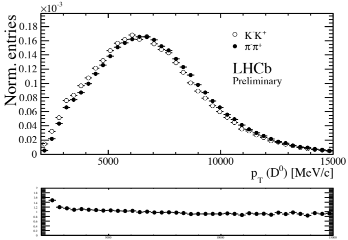
Formalism

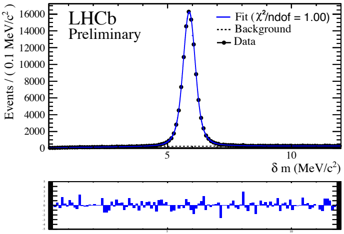
[LHCb-CONF-2013-003]

- Measure difference of time integrated asymmetries in K^+K^- and $\pi^+\pi^-$ final states to quantify direct CPV:

$$\Delta\mathcal{A}^{CP} = \mathcal{A}^{CP}(K^+K^-) - \mathcal{A}^{CP}(\pi^+\pi^-).$$

- Detection & production asymmetries largely cancel in difference - very robust against systematics.
- Re-weight K^+K^- candidates to match kinematic distributions of $\pi^+\pi^-$ to further improve cancellation of nuisance asymmetries.
- Fit Δm distribution to obtain yields.





Results

[LHCb-CONF-2013-003]
[Phys. Lett. B 723 (2013) 33-43]
[More info: Charm 2013]

- 2012 measurement on 0.6 fb^{-1} ($\rm D^{*+} \to D^0\pi_s^+$ tagged):

$$\Delta\mathcal{A}^{\rm CP} = -0.82 \pm 0.21 \pm 0.11\%.$$

  - Reinforced by measurements with same sign from CDF and BELLE, causing tension with CP conservation in world average.

- 2013 update on 1 fb^{-1}:

$$\Delta\mathcal{A}^{\rm CP} = -0.34 \pm 0.15 \pm 0.10\%.$$

- Semi-leptonic tagged ($\rm B^+ \to D^0\mu^+ X$) result on 1 fb^{-1}:

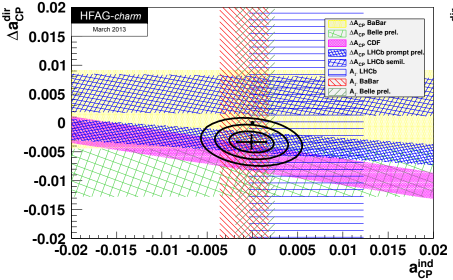
$$\Delta\mathcal{A}^{\rm CP} = +0.49 \pm 0.30 \pm 0.14\%.$$

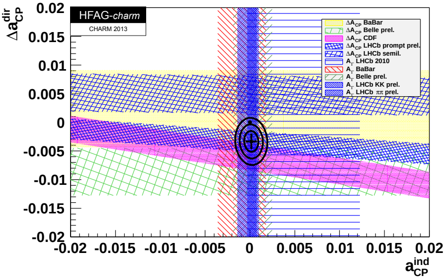
- LHCb average:

$$\Delta\mathcal{A}^{\rm CP} = -0.15 \pm 0.16\%.$$

Average Direct & Indirect CPV

[Charm 2013]
[HFAG]





- Both direct & indirect CPV averages dominated by LHCb.

$$a_{CP}^{ind} = 0.015 \pm 0.052\%, \quad \Delta a_{CP}^{dir} = -0.330 \pm 0.120\%.$$

- Consistent with CP conservation at 2.0 % level - tension driven by $\Delta\mathcal{A}^{\rm CP}$.

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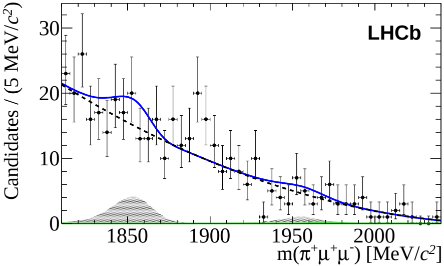
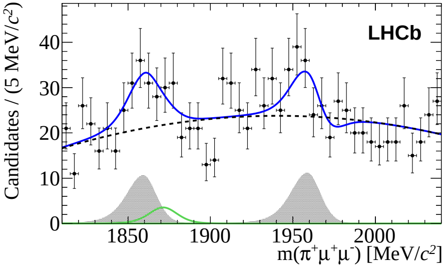
Strategy

[PLB 724 (2013) 203-212]

- NP can significantly enhance $\mathcal{B}$ of very rare decays in SM.
- LFV processes forbidden in SM - could occur with existence of, *e.g.* Majorana neutrino.

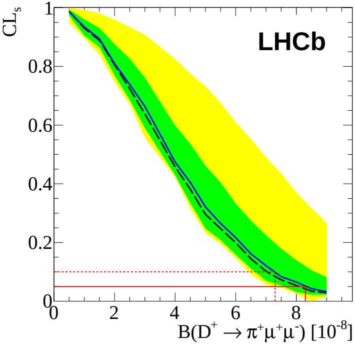
- Fit $\pi\mu\mu$ invariant mass to determine yields in bins of $\mu^+\mu^-/\pi^-\mu^+$ invariant mass.
- Use well measured $\mathcal{B}(D^+_{(s)} \to \pi^+(\phi \to \mu^+\mu^-))$ to normalise yields in bins not including resonances to extract $\mathcal{B}$ of non-resonant decays.
- Main background from $D^+_{(s)} \to \pi^+\pi^+\pi^-$.





Results

[PLB 724 (2013) 203-212]



- 90 % CLs from 1 fb^{-1}:
- $\mathcal{B}(D^+ \to \pi^+\mu^+\mu^-) < 7.3 \times 10^{-8}$,
- $\mathcal{B}(D_s^+ \to \pi^+\mu^+\mu^-) < 4.1 \times 10^{-7}$,
- $\mathcal{B}(D^+ \to \pi^-\mu^+\mu^+) < 2.2 \times 10^{-8}$,
- $\mathcal{B}(D_s^+ \to \pi^-\mu^+\mu^+) < 1.2 \times 10^{-7}$.

- No evidence for FCNC or LFV decays.
- Best limits to date by two orders of magnitude.

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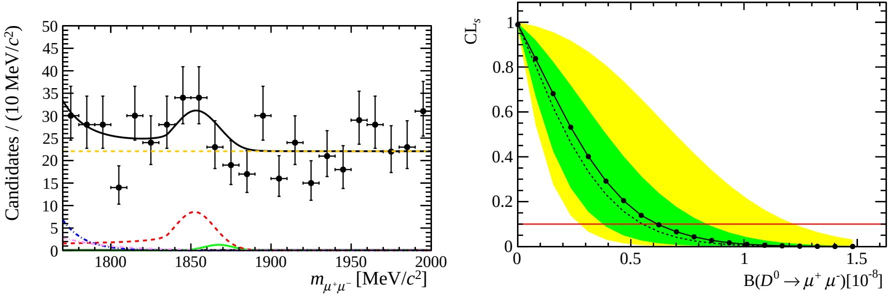
$D^0 \to \mu^+\mu^-$ Results

[Phys. Lett. B 725 (2013) 15-24]



$$\mathcal{B}(D^0 \to \mu^+\mu^-) < 6.2 \times 10^{-9} \text{ (90 \% CL)}$$

- Similar methodology to $D^+_{(s)} \to \pi\mu\mu$.
- Main background from $D^0 \to \pi^+\pi^-$.
- No evidence found on 0.9 fb^{-1}.
- Order of magnitude tighter constraint than previous best.

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$D^+{}_{(s)} \to \pi^+\mu^+\mu^-$ and $D^+{}_{(s)} \to \pi^-\mu^+\mu^+$

$D^0 \to \mu^+\mu^-$

Conclusions

Conclusions

- LHCb is establishing itself as a world leader in high precision charm physics measurements.

- WS/RS $\mathrm{D}^0 \rightarrow \mathrm{K}\pi$ confirms charm mixing to high precision with a single measurement.
- World best measurements of indirect & direct CP violation from A_Γ and $\Delta\mathcal{A}^{\mathrm{CP}}$ with $\mathrm{D}^0 \rightarrow \mathrm{h}^+\mathrm{h}^-$ - now dominating world averages.
- No evidence for CP violation or new physics in the charm system yet.
- No evidence for rare decays $\mathrm{D}^+_{(s)} \rightarrow \pi\mu\mu$ and $\mathrm{D}^0 \rightarrow \mu^+\mu^-$.
- Stringent limits set on NP in FCNC and LFV.

- Prospect for significant increase in precision for many measurements by adding 2.1 fb^{-1} from 2012.
- Longer term, LHCb upgrade, with $\sim 10\times$ instantaneous luminosity, will leave NP little room to hide in the charm sector.

- Many excellent measurements made to date - many more to come!

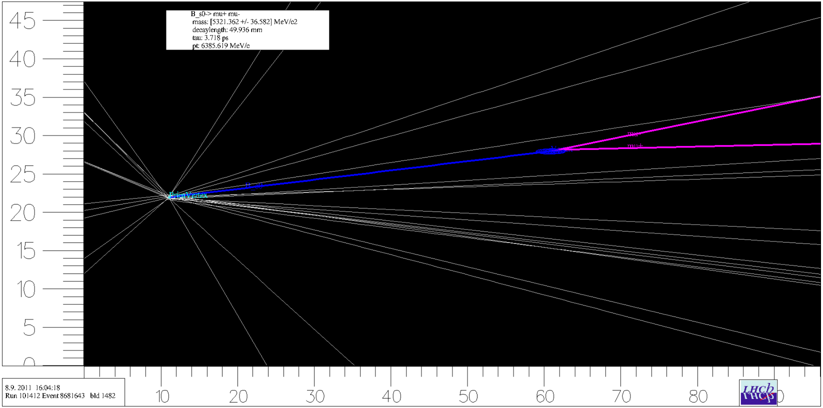
Backup

Other LHCb CPV & Rare Decay Results

[JHEP06(2013)112]
[arXiv:1308.3189 [hep-ex]]
[LHCb-PAPER-2013-50]

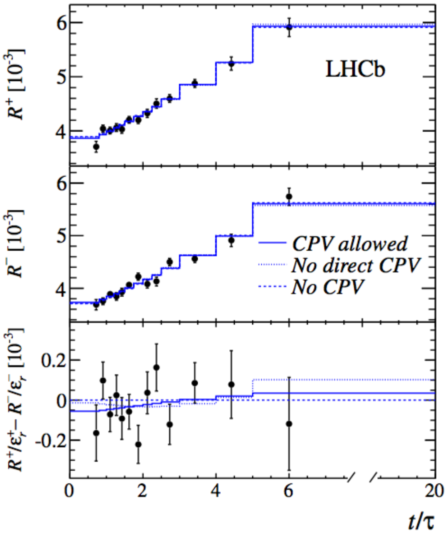
- All 1 fb^{-1} from 2011.
- $\mathcal{A}^{\text{CP}}(\text{D}^+ \to \phi\pi^+) = -0.04 \pm 0.14 \pm 0.14\%$ &
  $\mathcal{A}^{\text{CP}}(\text{D}_s^+ \to \text{K}_\text{S}^0\pi^+) = +0.61 \pm 0.83 \pm 0.14\%$.
- Search for anisotropy in Dalitz plot of $\text{D}^0 \to 4\pi$ & $\text{D}^0 \to \text{K}^+\text{K}^-\pi^+\pi^-$ consistent with CP conservation.
- $\mathcal{B}(\text{D}^0 \to \pi^+\pi^-\mu^+\mu^-) < 5.5 \times 10^{-7}$ (90 % CL).
- No evidence for CPV or FCNC decays in charm.

$\mu^+\mu^-$ Decay Vertex



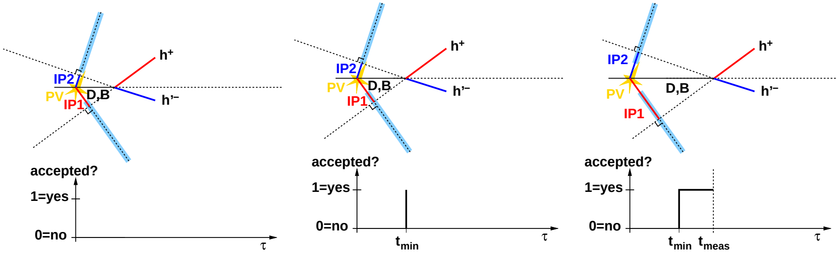
WS/RS vs time

[PRL 110, 101802 (2013)]



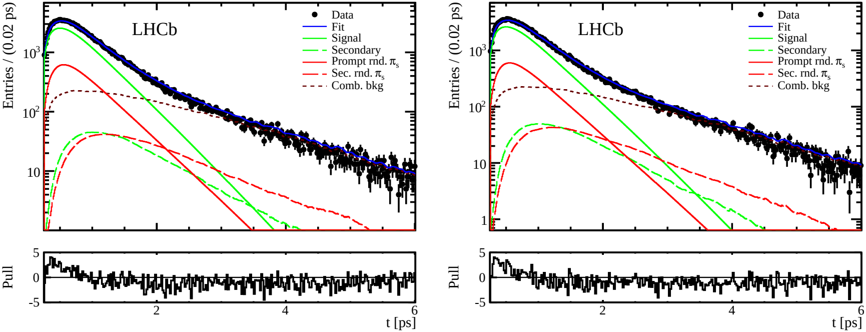
- $N(\mathrm{WS})/N(\mathrm{RS})$ vs decay-time for D^0 (top) and $\bar{\mathrm{D}}^0$ (middle).
- Lower plot shows efficiency corrected difference between D^0 and $\bar{\mathrm{D}}^0$ in each bin of decay-time.
- Any constant or time-dependent difference would indicate CPV.
- No significant evidence for CPV.

Swimming Method



- Candidate selection favours longer lived particles & distorts the decay-time distribution.
- "Swimming" is a data-driven method of determining selection efficiency vs decay time *per candidate*.
- Change decay time of given candidate by moving primary vertex (PV) in direction of p vector of candidate.
- Re-evaluate selection decision at each decay time to build acceptance function.
  - Like asking: "Had this candidate lived *this* long instead, would it have passed the selection?"
  - Software trigger at LHCb essential: allows trigger to be re-run in identical configuration to that during data-taking.

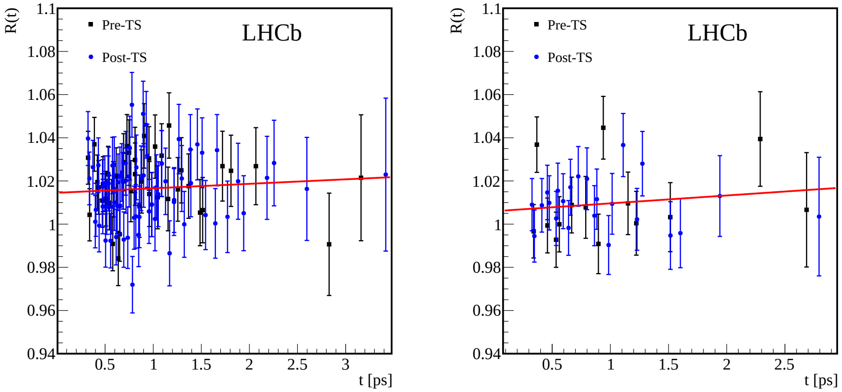
More A_Γ Fits, $\pi^+\pi^-$



- D^0 (left) and $\overline{\mathrm{D}}^0$ (right) have same poor pulls.
- Raw lifetimes are slightly biased but biases to $\tau(\mathrm{D}^0)$ and $\tau(\overline{\mathrm{D}}^0)$ are 100 % correlated & cancel in A_Γ.
- Simulation studies also verified cancellation of bias for non-zero A_Γ.

More A_Γ Fits, Alternative Fit

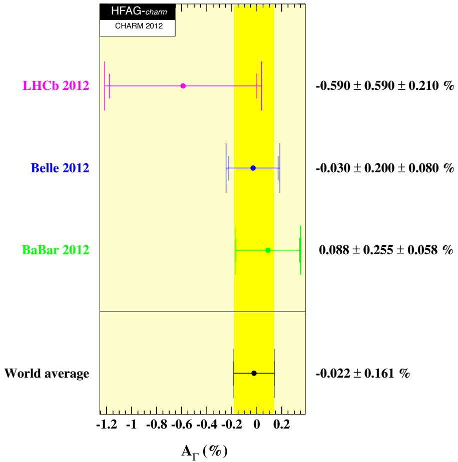
[LHCb-PAPER-2013-054 in preparation]

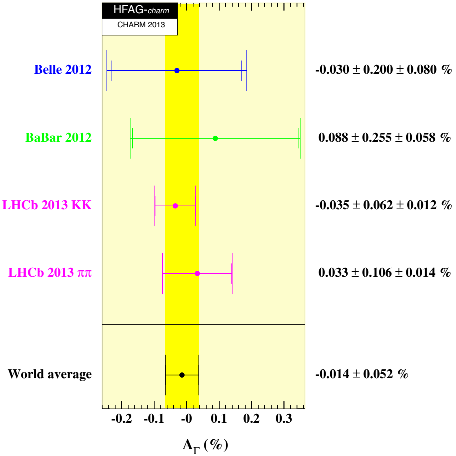


- $N(\mathrm{D}^0)/N(\bar{\mathrm{D}}^0)$ vs decay-time for $\mathrm{K}^+\mathrm{K}^-$ (left) and $\pi^+\pi^-$ (right).
- Results consistent with A_Γ from lifetimes technique - also consistent with zero.

A_Γ Averages

[Charm 2013]
[HFAG]

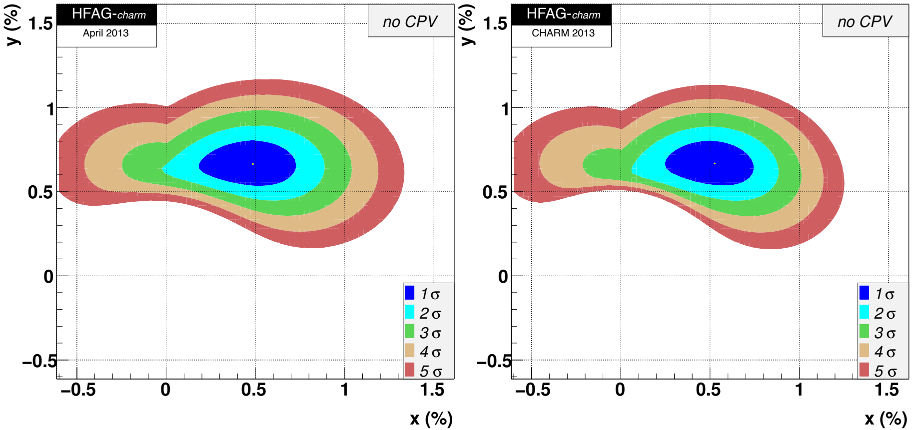




- New world average still very much consistent with zero.

x & y HFAG Averages, no CPV

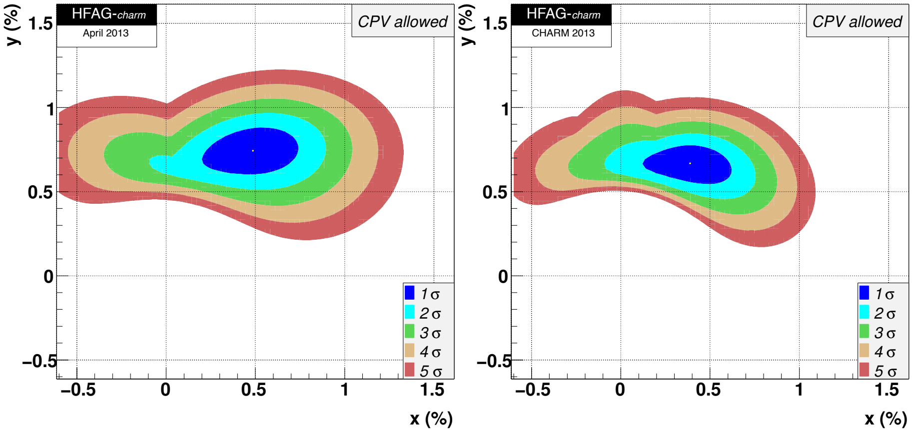
[Charm 2013]
[HFAG]



- WS $D^0 \to K^+\pi^-$ measurements give significant improvement in x & y averages.

x & y HFAG Averages, CPV allowed

[Charm 2013]
[HFAG]



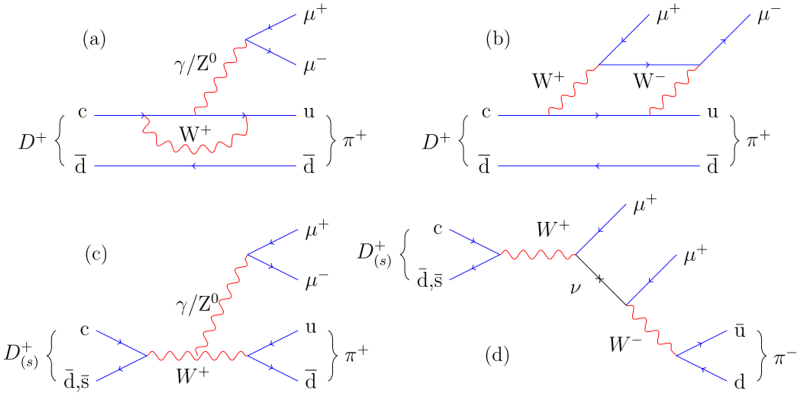
- WS $D^0 \to K^+\pi^-$ measurements give significant improvement in x & y averages.

Summary of Averages of CPV & Mixing Parameters

[Charm 2013]
[HFAG]

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

$D^+_{(s)} \to \pi^+\mu^+\mu^-$ and $D^+_{(s)} \to \pi^-\mu^+\mu^+$ Diagrams [PLB 724 (2013) 203-212]



$D^0 \to \mu^+\mu^-$ Strategy [Phys. Lett. B 725 (2013) 15-24]

- $D^0 \to \mu^+\mu^-$ suppressed by CKM & GIM - extremely rare process in SM.
- Fit both m_{D^0} and Δm to determine yields.
- Normalise w.r.t. $D^0 \to \pi^+\pi^-$ to determine $\mathcal{B}$.
- Backgrounds from mis-ID h^+h^- decays.