Charm mixing and CP violation in LHCb

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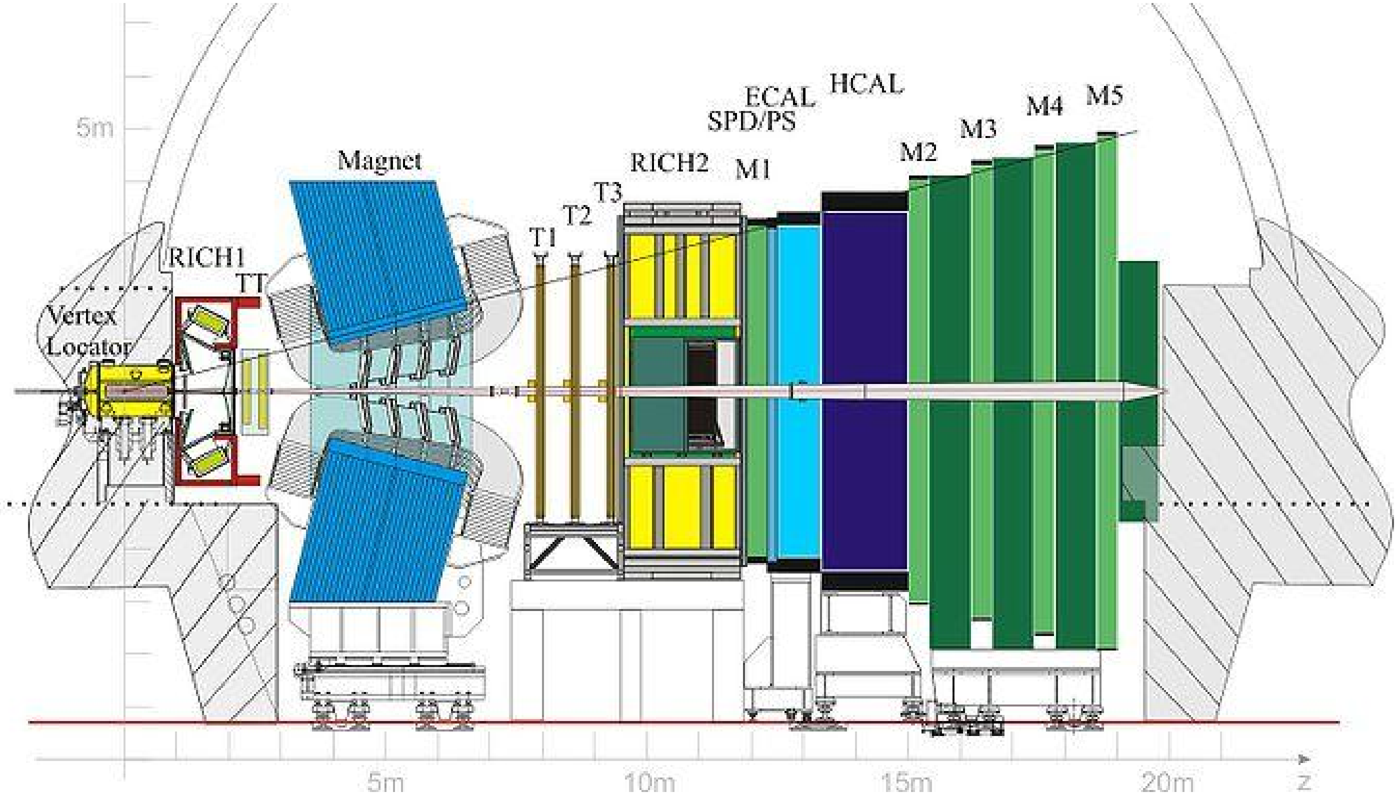
on behalf of the LHCb Collaboration

The LHCb Detector

Forward arm spectrometer on the LHC ring:
Pseudorapidity region: $2 < \eta < 5$
Charm cross section: $\sigma(c\bar{c}) = 1419 \pm 12(stat) \pm 116(syst) \pm 65(frag)\ \mu b.$

$\sigma(c\bar{c}) \approx 20 \times \sigma(b\bar{b})$

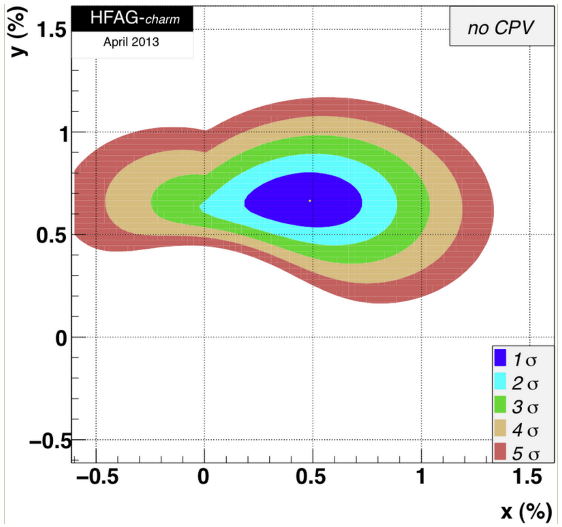
[Nucl. Phys. B 871, (2013), pp. 1 - 20] $p_T < 8GeV/c$, $2.0 < \eta < 4.5$, $\sqrt{s} = 7TeV$



Charm mixing

- Well established in the SM [K, B and D sectors]
- Mixing expected to be small x~y~O(1%)
- Previous evidence from many results

[HFAG arXiv:1207.1158 [hep-ex]]

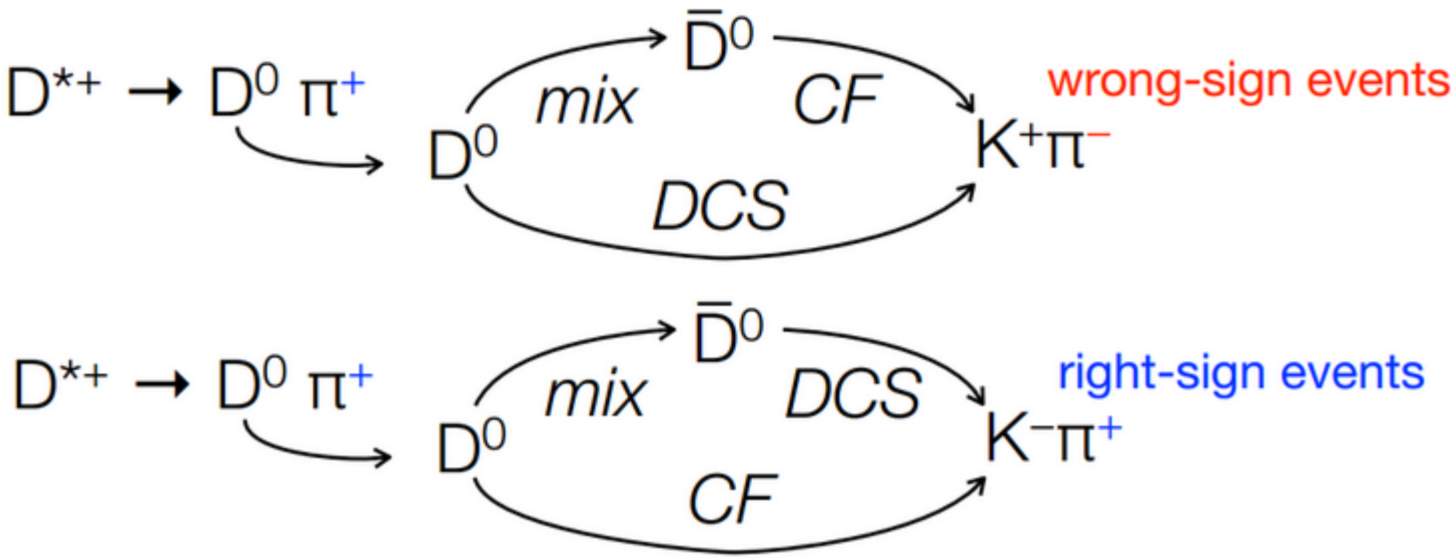


- Parametrized dimensionlessly:

$$x = \frac{m_2 - m_1}{\Gamma}, \; y = \frac{\Gamma_2 - \Gamma_1}{2\Gamma}, \; \Gamma = \frac{\Gamma_1 + \Gamma_2}{2}$$

- First evidence of mixing in D sector from BaBar, Belle and CDF
[Phys.Rev.Lett. 98 (2007) 211802, Phys.Rev.Lett. 98 (2007) 211803, Phys. Rev. Lett. 100 (2008) 121802]
- Use CF and DCS decays to same final state:
  - Right-sign(RS) : CF decays only
  - Wrong-sign(WS) : DCS decays and mixing + CF decays

Charm mixing



If we assume no CPV and mixing to be small, we can take a ratio of RS to WS

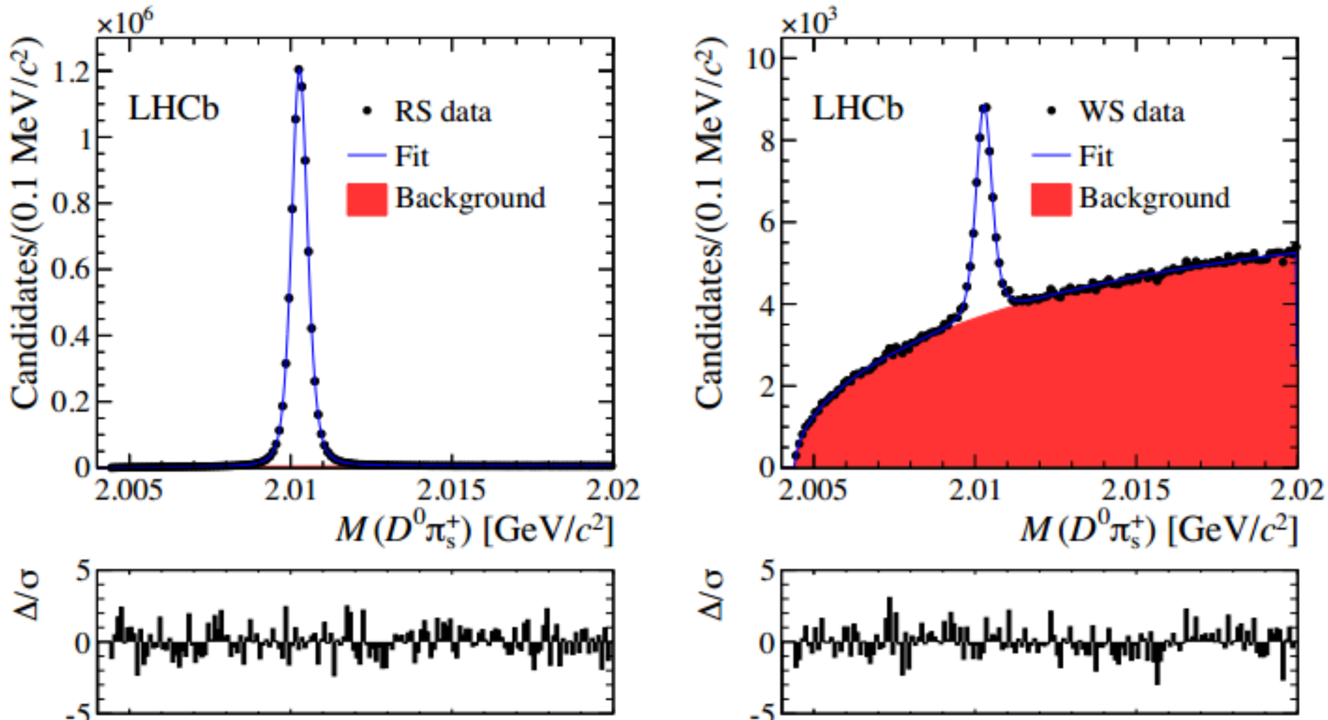
$$R(t) = \frac{N_{WS}(t)}{N_{RS}(t)} = R_D + \sqrt{R_D}\,y't + \frac{x'^2 + y'^2}{4}t^2$$

$$\begin{aligned} x' &= x\cos\delta + y\sin\delta \\ y' &= y\cos\delta - x\sin\delta \end{aligned}$$

N.B. The mixing parameters are transformed with the strong phase between the CF and DCS amplitudes

Charm mixing in $D^0 \to K\pi$ decays

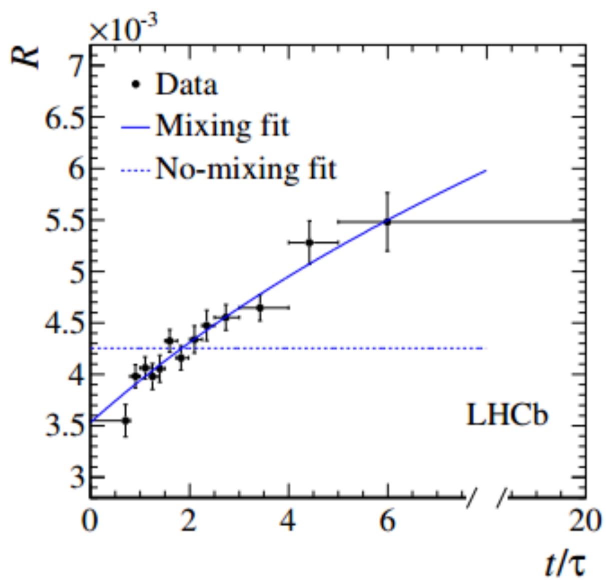
- Dataset consists of 1 fb^{-1} of data collected by LHCb in 2011
- Prompts charm events: $D^{*+} \to (D^0 \to K^{\mp}\pi^{\pm})\,\pi^+_{soft}$
- Soft pion acting as a tag on the flavour of D^0

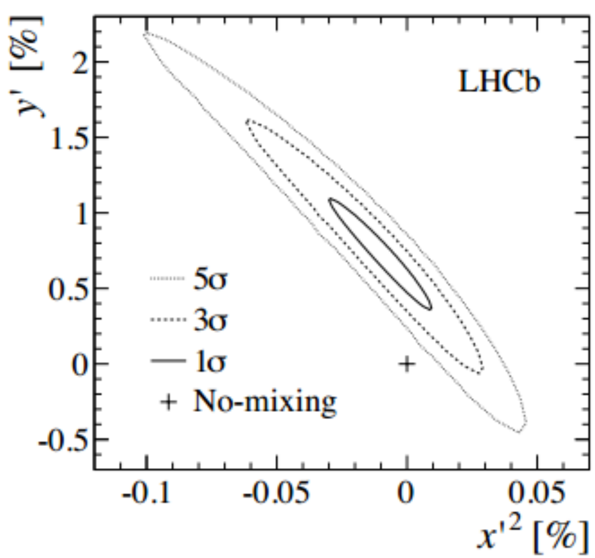


[Phys. Rev. Lett. 110, 101802 (2013)]

Charm mixing in $D^0 \rightarrow K\pi$ decays

- Two non-trivial backgrounds that could bias the measurement:
  - Secondary component misidentified as prompt (2.7%)
  - Peaking mis-reconstructed D^0 candidates (0.4%)
- Measurement resolution is found to be dominated by statistical error





[Phys. Rev. Lett. 110, 101802 (2013)]

Charm mixing

$$x' = (0.9 \pm 1.3) \times 10^{-4} \,, y' = (7.2 \pm 2.4) \times 10^{-3}$$
$$R_D = (3.52 \pm 0.15) \times 10^{-3}$$

- Observation of neutral charm mixing [Phys. Rev. Lett. 110, 101802 (2013)]
- Excludes no-mixing hypothesis with a significance of 9.1σ
- Recent result from CDF with a 6.1σ observation [Paolo Maestro's slides from Beauty 2013]
- Both are one-experiment observations of charm mixing!

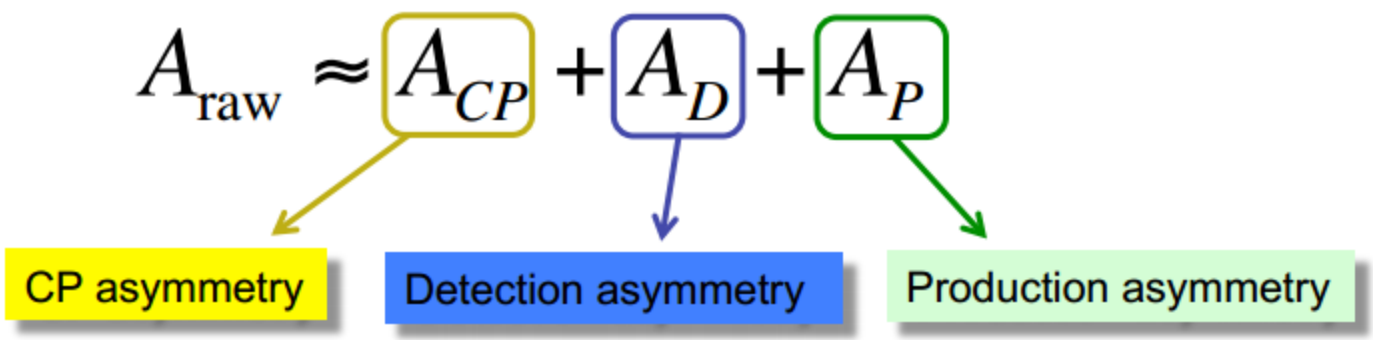
NB. Remember R_D is the ratio of wrong-sign to right-sign events.

CP Violation in SCS decays

- Single-Cabbibo-Suppressed decays allows for interference between tree and penguin diagrams >>> sensitive to CP violation
- CP violation is expected to be small (only up to ~O(10^{-3}) in SM)
  [Phys. Rev. D75:036008, 2007]
- Direct CP violation can be measured by CP asymmetry:

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

- Detected 'raw' asymmetry however includes production and detection asymmetries



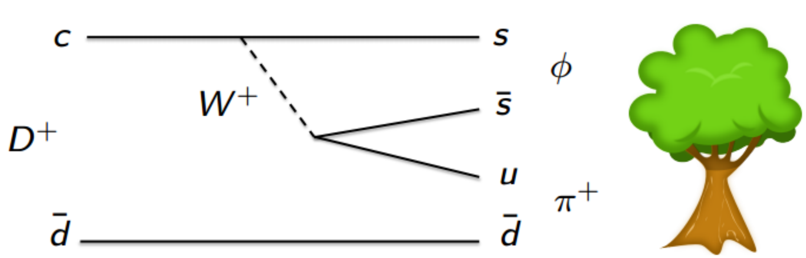
[Jeroen's slides at LHCP 2013]

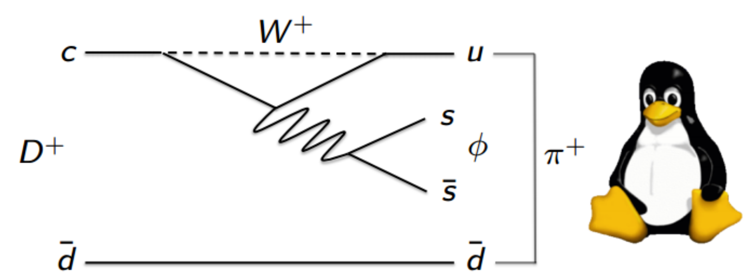
CP Violation in $D^{\pm} \rightarrow \phi\pi^{+}$ and $D^{\pm} \rightarrow K_{S}\pi^{+}$

- To solve this, one can compare two similar channels and extract a difference in CP asymmetries

$$\Delta A_{CP} = A_{CP}(D \rightarrow f_1) - A_{CP}(D \rightarrow f_2) \approx A_{raw}(D \rightarrow f_1) - A_{raw}(D \rightarrow f_2)$$

- Detection and production asymmetries cancel to first order
- Channel advantages:
  - High BF (2.65×10^{-3})
  - Quasi-two body (ϕ dominates narrow region of Dalitz space)
- Theoretical predictions challenging (V -> PS)





CP Violation in $D^{\pm}\to \phi\pi^{+}$ and $D^{\pm}\to K_S\pi^{+}$

- Define the A_{CP} as the difference in asymmetries of K_S and ϕ channels

$$A_{CP} = A_{raw}(D^+ \to \phi\pi^+) - A_{raw}(D^+ \to K_s^0\pi^+) + A_{CP}\left(\frac{K^0}{\bar{K}^0}\right)$$

- Similarly can extract A_{CP} from D_s candidates

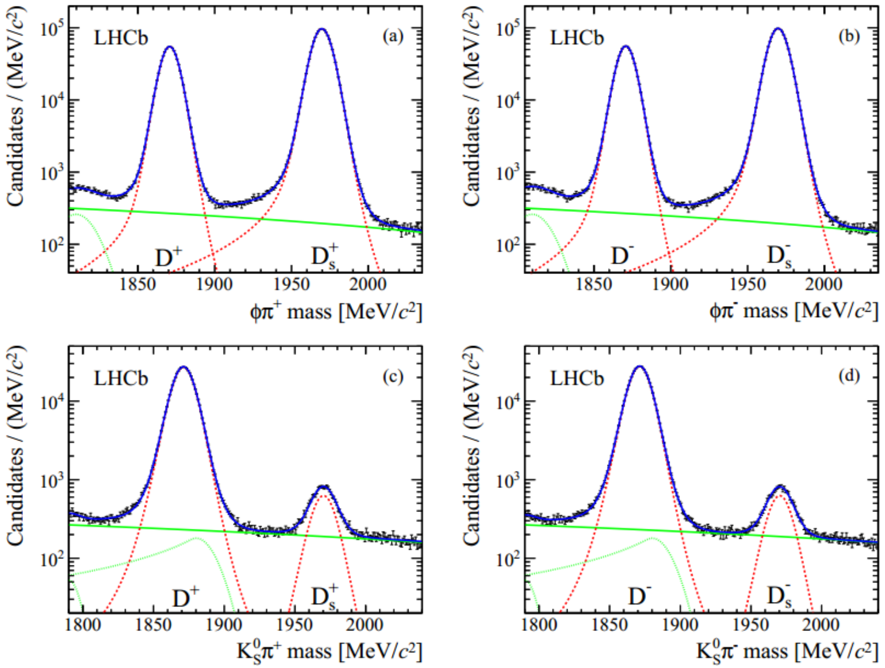
$$A_{CP} = A_{raw}(D_s^+ \to K_s^0\pi^+) - A_{raw}(D_s^+ \to \phi\pi^+) - A_{CP}\left(\frac{K^0}{\bar{K}^0}\right)$$

- The CP violation coming from K system is accounted for in the last term
- We can safely assume that there is no mixing or interference CP violation

NB. $A_{CP}(D^+ \to K_s^0\pi^+) \approx A_{CP}(D_s^+ \to \phi\pi^+) \approx 0$

CP Violation in $D^{\pm} \rightarrow \phi\pi^{+}$ and $D^{\pm} \rightarrow K_s\pi^{+}$

- Analysis uses 1 fb^{-1} of data collected by LHCb in 2011



[arXiv:1303.4906v1]

$$A_{CP}(D^+ \rightarrow \phi\pi^+) = (-0.04 \pm 0.14(stat) \pm 0.13(sys))\%$$

$$A_{CP}(D_s^+ \rightarrow K_s^0\pi^+) = (-0.61 \pm 0.83(stat) \pm 0.13(sys))\%$$

$$A_{CP|S}(D^+ \rightarrow \phi\pi^+) = (-0.18 \pm 0.17(stat) \pm 0.18(sys))\%$$

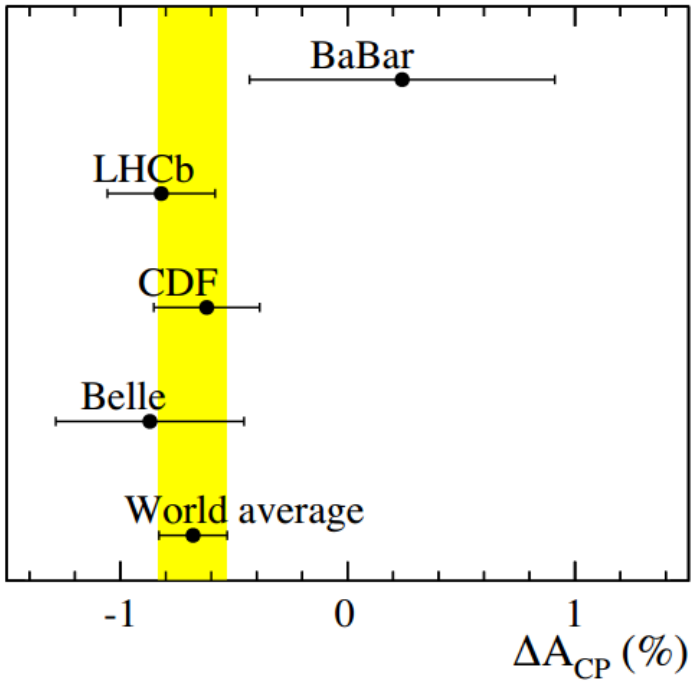
ΔA_{CP} discombobulation in $D^0 \to h^+h^-$

Previous results in the $D^0 \to \pi^+\pi^-, K^+K^-$ channels sparked controversy - CP violation from beyond SM?

Previous results for ΔA_{CP} (March 2012)

HFAG average
$$\Delta A_{CP} = (-0.68 \pm 0.15)\%$$
4.6σ effect

Experiment	ΔA_{CP}	
LHCb	$(-0.82 \pm 0.21 \pm 0.11)\%$	[PRL108.111602]
CDF	$(-0.62 \pm 0.21 \pm 0.10)\%$	[PRL109.111801]
Belle	$(-0.87 \pm 0.41 \pm 0.06)\%$	[arXiv:1212.1975]
BaBar	$(+0.24 \pm 0.62 \pm 0.26)\%$	[PRL100.061803]



[Jeroen's slides at LHCP 2013]

ΔA_{CP} in $D^0 \to \pi^+\pi^-, K^+K^-$

- Decay time dependent asymmetry: $A_{CP}(t) = a_{CP}^{dir} + \frac{t}{\tau} a_{CP}^{mix}$
- Assuming common decay time acceptance for K and π [Phys. Rev. D75 (2007) 036008]

$$\Delta A_{CP}(t) = a_{CP}^{dir}(K^+K^-) - a_{CP}^{dir}(\pi^+\pi^-) + \frac{\Delta\langle t\rangle}{\tau} a_{CP}^{mix}$$

- Not sensitive to CP violation in mixing
- Past results motivated the use of more data:
  - Prompt: $D^{*+} \to (D^0 \to h^+h^-)\pi^+_{soft}$
  - Secondary: $B \to (D^0 \to h^+h^-)\mu X$
- Both cases define ΔA_{CP}

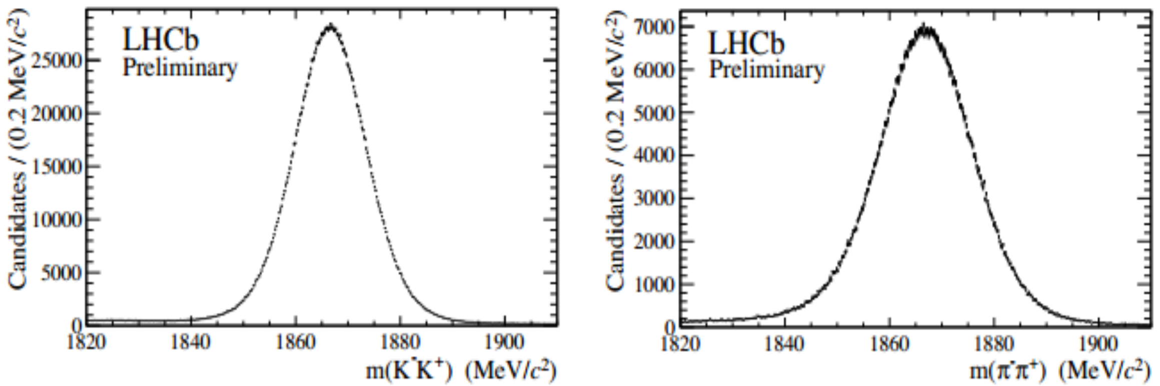
$$\Delta A_{CP} = A_{CP}(K^+K^-) - A_{CP}(\pi^+\pi^-) \approx A_{raw}(K^+K^-) - A_{raw}(\pi^+\pi^-)$$

- Treatment different for production and detection asymmetries between prompt and secondary, uncorrelated systematic and statistical uncertainties

ΔA_{CP} in prompt $D^0 \rightarrow \pi^+\pi^-, K^+K^-$

Uses 1 fb^{-1} of data from LHCb in 2011

[CERN-LHCb-CONF-2013-003]



- Raw asymmetry can be defined using

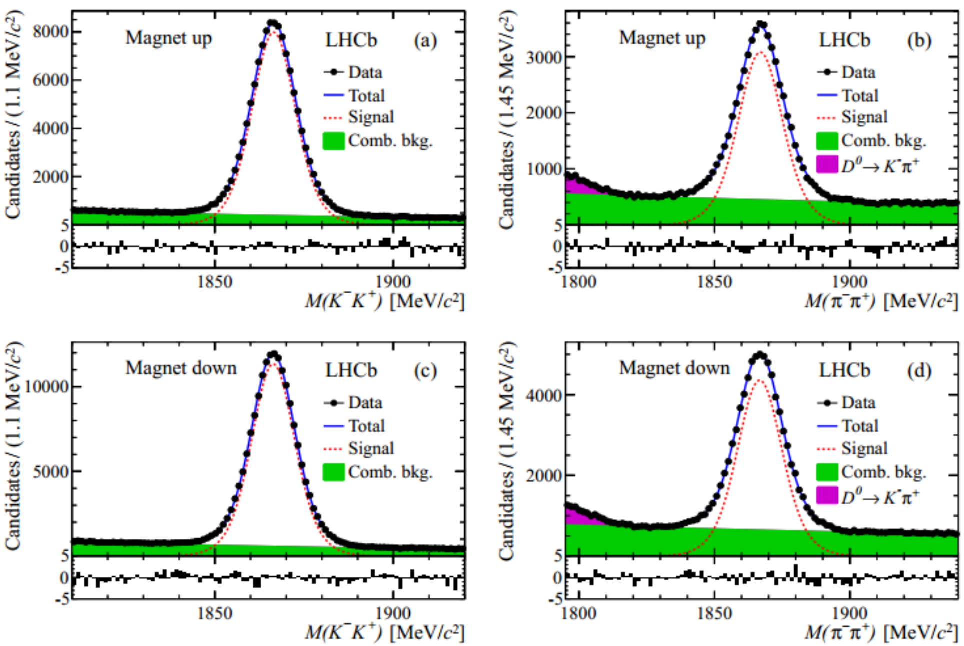
$$A_{raw} = A_{CP}(f) + A_D(f) + A_D(\pi^+_{soft}) + A_P(D^{*+})$$

- Self-conjugate spin-0 final states mean no detection asymmetry due to final state
- $A_D(\pi_{soft})$ and $A_P(D^*)$ depend on D^* kinematics (p, p_T and ϕ)
- Can reweigh variable distributions account for differences in kinematics and selection criteria between the final states

ΔA_{CP} in secondary $D^0 \to \pi^+\pi^-, K^+K^-$

- All previous measurements from prompt charm - motivation to include a result from secondary as an independent measurement

[arXiv:1303.2614 [hep-ex]]



- Define raw asymmetry

$$A_{raw} = A_{CP}(f) + A_D(\mu) + A_P(B)$$

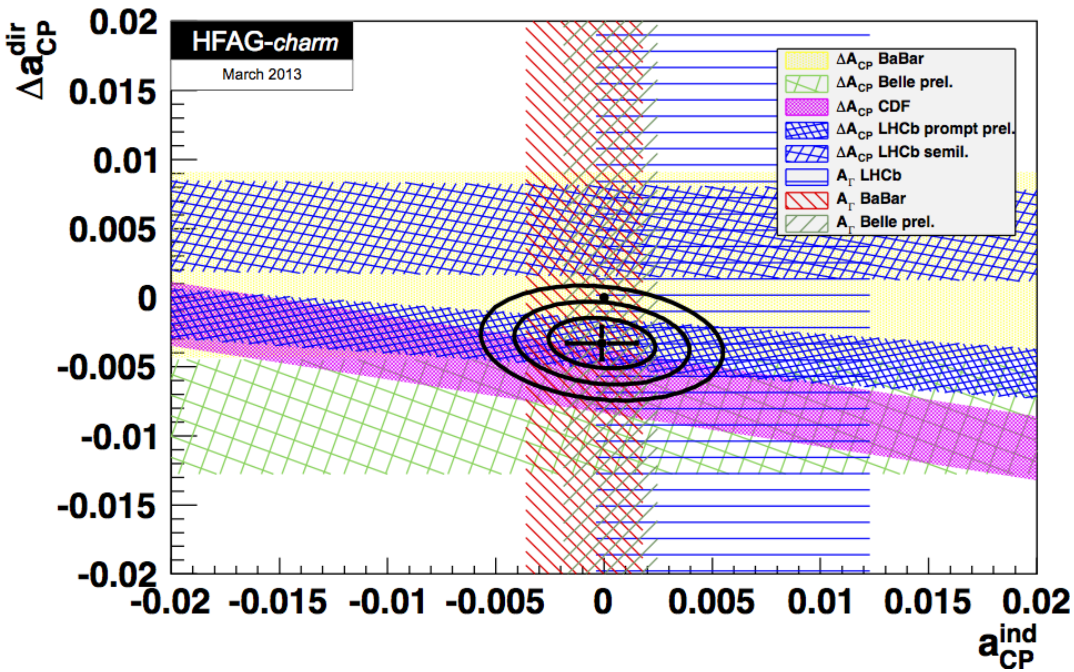
- $A_P(B)$ is independent of final state
- Can reweight D^0 variable distributions to account for $A_D(\mu)$ difference between the final states

ΔA_{CP} in $D^0 \to \pi^+\pi^-, K^+K^-$ (new) results

- Fit results:
  - Prompt $\Delta A_{CP} = (-0.34 \pm 0.15(stat) \pm 0.10(sys))\%$

    [CERN-LHCb-CONF-2013-003]
  - Secondary $\Delta A_{CP} = (+0.49 \pm 0.30(stat) \pm 0.14(sys))\%$

    [arXiv:1303.2614 [hep-ex]]



Combined HFAG value

$$\Delta a_{CP}^{dir} = (-0.329 \pm 0.121)\%$$

LHCb average value

$$\Delta a_{CP}^{dir} = (-0.15 \pm 0.16)\%$$

[arXiv:1207.1158 [hep-ex]]

Summary

- Beautiful charm mixing result confirming at 9.1σ
- CP violation in some channels constrained with precision ~O(10^{-3})
- We have 2 fb^{-1} more data on tape and more in 2015
- Stay Tuned

Backup slides

Here be dragons....

Summary of results

- Charm mixing measurement confirming mixing at 9.1σ

$$x' = (0.9 \pm 1.3) \times 10^{-4}\ , y' = (7.2 \pm 2.4) \times 10^{-3}$$

$$R_D = (3.52 \pm 0.15) \times 10^{-3}$$

- Results from time-integrated charm CP violation searches

$$A_{CP}(D^+ \to \phi\pi^+) = (-0.04 \pm 0.14(stat) \pm 0.13(sys))\%$$

$$A_{CP}(D_s^+ \to K_s^0\pi^+) = (-0.61 \pm 0.83(stat) \pm 0.13(sys))\%$$

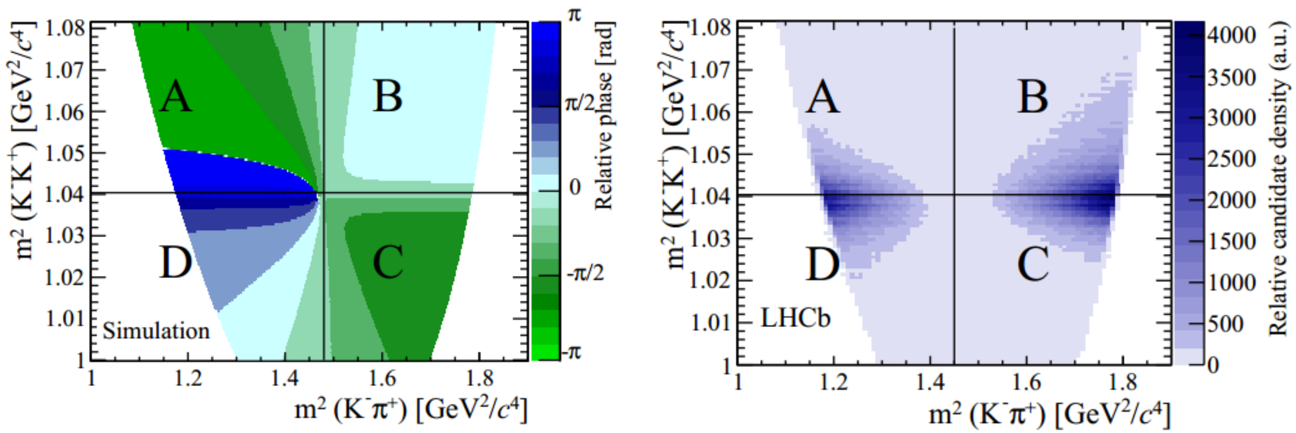
$$A_{CP|S}(D^+ \to \phi\pi^+) = (-0.18 \pm 0.17(stat) \pm 0.18(sys))\%$$

$$\Delta A_{CP}^{prompt}(D^0 \to h^+h^-) = (-0.34 \pm -0.15(stat) \pm 0.10(sys))\%$$

$$\Delta A_{CP}^{secondary}(D^0 \to h^+h^-) = (0.49 \pm -0.30(stat) \pm 0.14(sys))\%$$

CP Violation in $D^{\pm} \to \phi\pi^{+}$ and $D^{\pm} \to K_S\pi^{+}$

- Strong phase variations throughout ϕ region could mean that a constant A_{CP} could cancel out
- Split the Dalitz plot around the ϕ resonance into four regions, minimising strong phase variations (using CLEO data)



- Introduce a new variable more robust to this effect

$$A_{CP|S} = \left(A^{A}_{raw} + A^{C}_{raw} - A^{B}_{raw} - A^{D}_{raw}\right)$$

$$A_{CP|S}(D^{+} \to \phi\pi^{+}) = (-0.18 \pm 0.17(stat) \pm 0.18(sys))\%$$