UNIVERSITY OF CAMBRIDGE

LHCb

Studies of charm mixing and CP violation at LHCb

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on behalf of the LHCb collaboration

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Mixing and CP violation

$|D^0\rangle \; |\bar{D}^0\rangle$

Flavor eigenstates
- Well defined flavor

$|D_1\rangle \; |D_2\rangle$

Hamiltonian eigenstates
- Well defined m and Γ
- Define the mixing parameters

Mixing determines the time evolution of the flavor eigenstates

$$|D_{1,2}\rangle = p|D^0\rangle \pm q|\bar{D}^0\rangle$$

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

$$A_f = \langle f|\mathcal{H}|D^0\rangle$$
$$\bar{A}_{\bar{f}} = \langle \bar{f}|\mathcal{H}|\bar{D}^0\rangle$$
$$\left|\frac{\bar{A}_{\bar{f}}}{A_f}\right| \neq 1$$

CPV in the decay
- Different decay amplitudes for D^0 and $\bar{D}^0$ decays

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

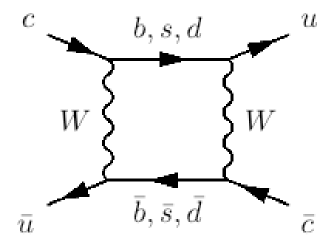
CPV in the mixing
- Hamiltonian eigenstates ≠ CP eigenstates
  - Different mixing rates $D^0 \to \bar{D}^0$ and $\bar{D}^0 \to D^0$.

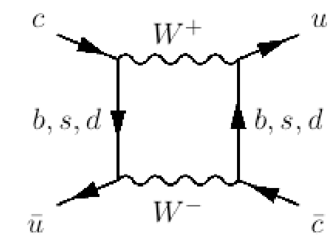
$$\mathrm{Im}\left(\frac{q}{p}\frac{\bar{A}_f}{A_f}\right) \neq 0$$

CPV in the interference
- Hamiltonian eigenstates ≠ CP eigenstates
  - Phase effect

Standard model predictions

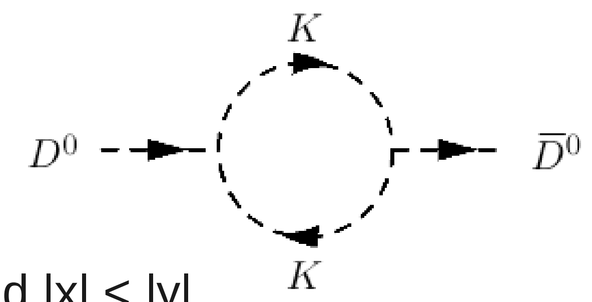
- Short distance contributions





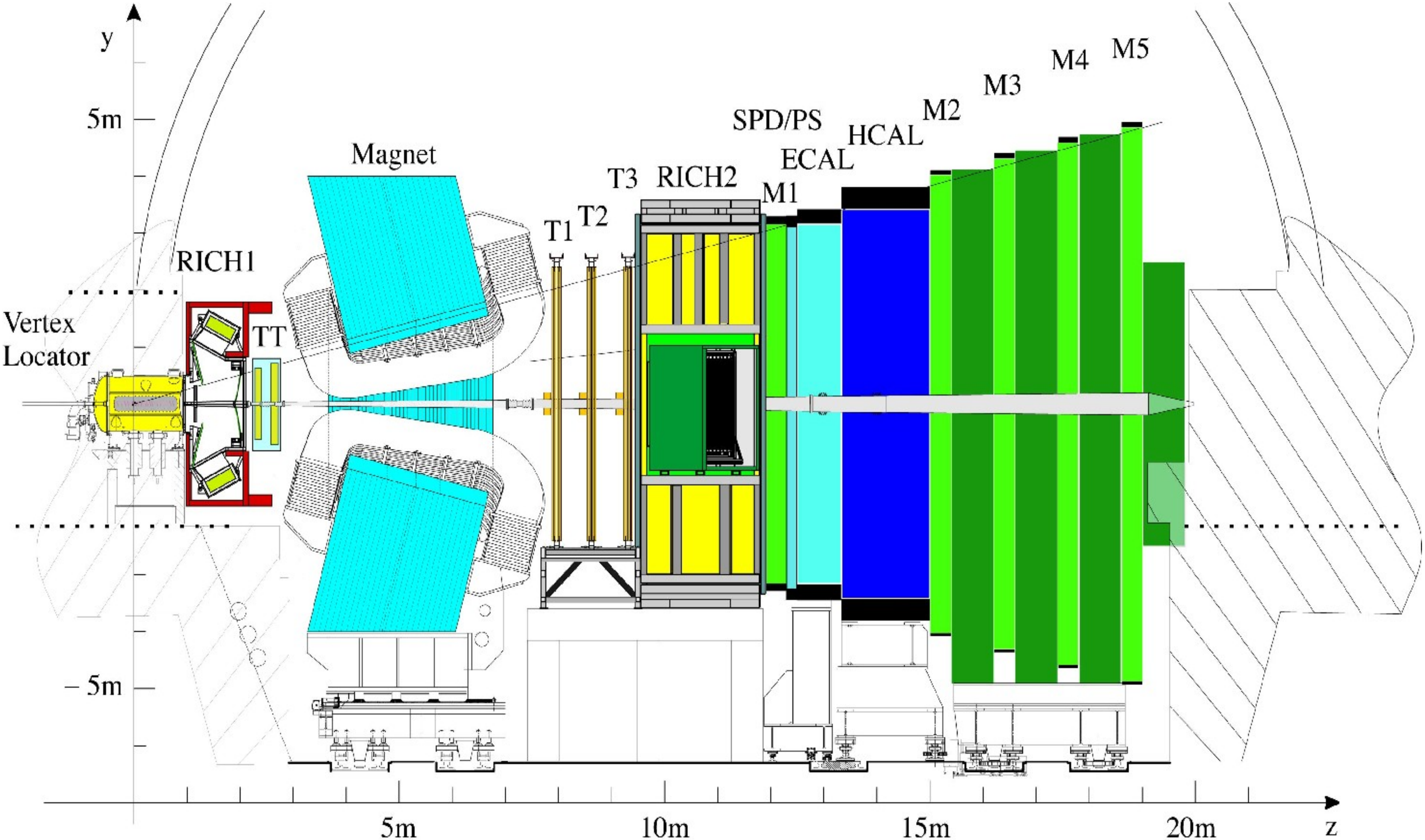
  - Mixing box diagrams.
  - SM predicts small mixing effects.
  - b quarks are CKM suppressed, and s and d quarks are GIM suppressed.
  - They mainly contribute to the x mixing parameter.
- Long distance contributions

A. Falk et al., PRD 69, 114021 (2004)



  - Hadronic intermediate states.
  - Expected to be dominant, but still small.
  - Hard to estimate, since they are not perturbative.
  - Predictions give x and y in the range [0.001, 0.01], and |x| < |y|.
- CPV is predicted to be $O(10^{-5} – 10^{-2})$.

LHCb detector



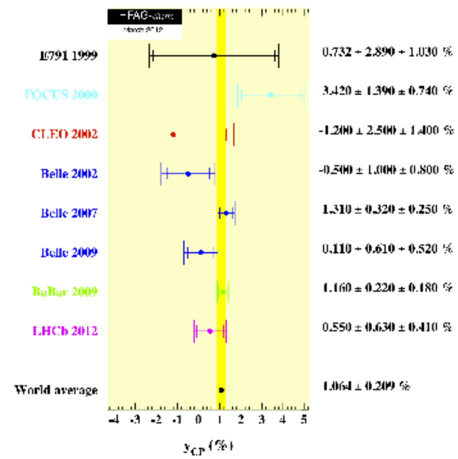
Experimental status

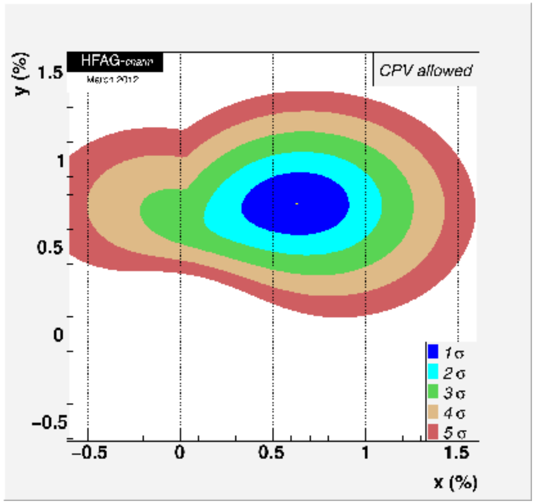
- Charm mixing is well established
- Compatible with the standard model

Only LHCb public result

y_{CP} A_{Γ}

1112.4698 [JHEP04(2012)129]





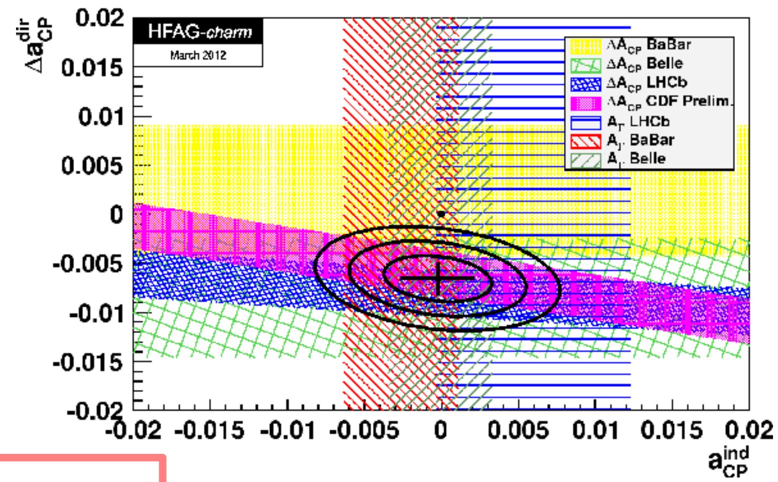
First evidence of charm CPV in $D^0 \to h^+ h^-$ decays

LHCb 1112.0938 [PRL108, 111602 (2012)]

CDF La Thuile 2012 (A. Di Canto) & CDF Note 10784

No evidence in $D^+ \to K^- K^+ \pi^+$ decays at **LHCb**

1110.3970v1 (PRD84, 112008 (2011))



NEW

Search in $D^0 \to \pi^- \pi^+ \pi^+ \pi^-$ decays

In all analyses, D^0 flavor is always tagged using $D^{*+} \to D^0 \pi^+$

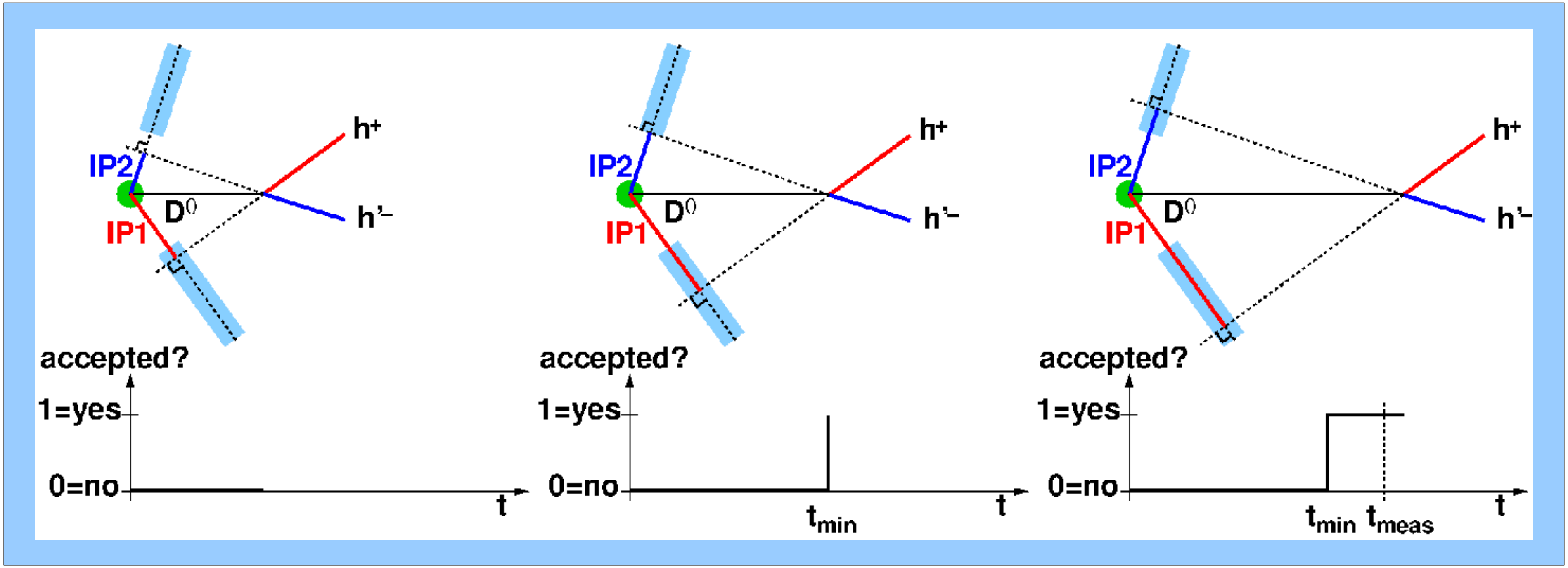
Mixing in two-body decays

$$y_{CP} = \frac{\tau(D^0 \to K^-\pi^+)}{\tau(D^0 \to K^-K^+)} - 1$$

$$A_\Gamma = \frac{\tau(\bar{D}^0 \to K^+K^-) - \tau(D^0 \to K^+K^-)}{\tau(\bar{D}^0 \to K^+K^-) + \tau(D^0 \to K^+K^-)}$$

Uses ***swimming*** technique to obtain D meson **decay time acceptance** from data.

R. Bailey et al, Z. Phys. C 28 (1985) 357
CERN-THESIS-2008-044



29 pb^{-1} (2010), 7 TeV

1112.4698 [JHEP04(2012)129]

y_{CP} = [5.5 ± 6.3 (stat) ± 4.1 (syst)] · 10^{-3}
A_Γ = [-5.9 ± 5.9 (stat) ± 2.1 (syst)] · 10^{-3}

CPV in $D \to h^+ h^-$ decays

Difference of raw asymmetries: $\Delta A_{CP} = A_{CP}(KK) - A_{CP}(\pi\pi) = A_{raw}(KK) - A_{raw}(\pi\pi)$

- Production and soft pion detection asymmetries cancel at 1st order.
- No detection asymmetry for KK or ππ final states.
    - D and π_s detection and D* production systematic uncertainties suppressed at 1st order.

Measurement of ΔA_{CP}:

- Yields obtained from fits to $\delta m = m(D^*) - m(D) - m(\pi^+)$
    - 216 bins of kinematics, magnet polarity and running periods.
- Measured asymmetries consistent in all bins.

First evidence of CPV at **LHCb** [**0.62 fb^{-1} (2011)**]

$$\Delta A_{CP} = [-0.82 + 0.21\ (\text{stat}) + 0.11\ (\text{syst})] \cdot 10^{-2}$$

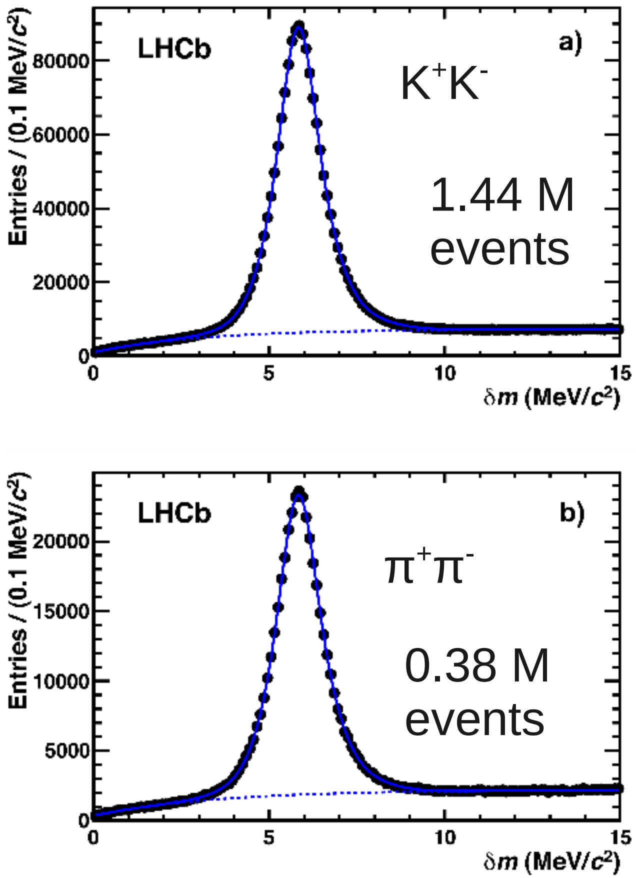
1112.0938 [PRL108, 111602 (2012)]

Also confirmed by **CDF** [**9.7 fb^{-1} (2002-2011)**]

$\Delta A_{CP} = [-0.62 + 0.21\ (\text{stat}) + 0.10\ (\text{syst})] \cdot 10^{-2}$

La Thuile 2012 (A. Di Canto) & CDF Note 10784

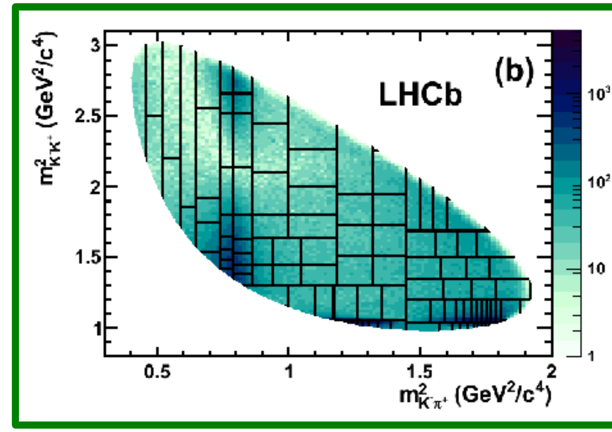
$$\Delta A_{CP} = \left[a_{CP}^{\text{dir}}(K^-K^+) - a_{CP}^{\text{dir}}(\pi^-\pi^+)\right] + \frac{\Delta\langle t\rangle}{\tau_D} a_{CP}^{\text{ind}}$$



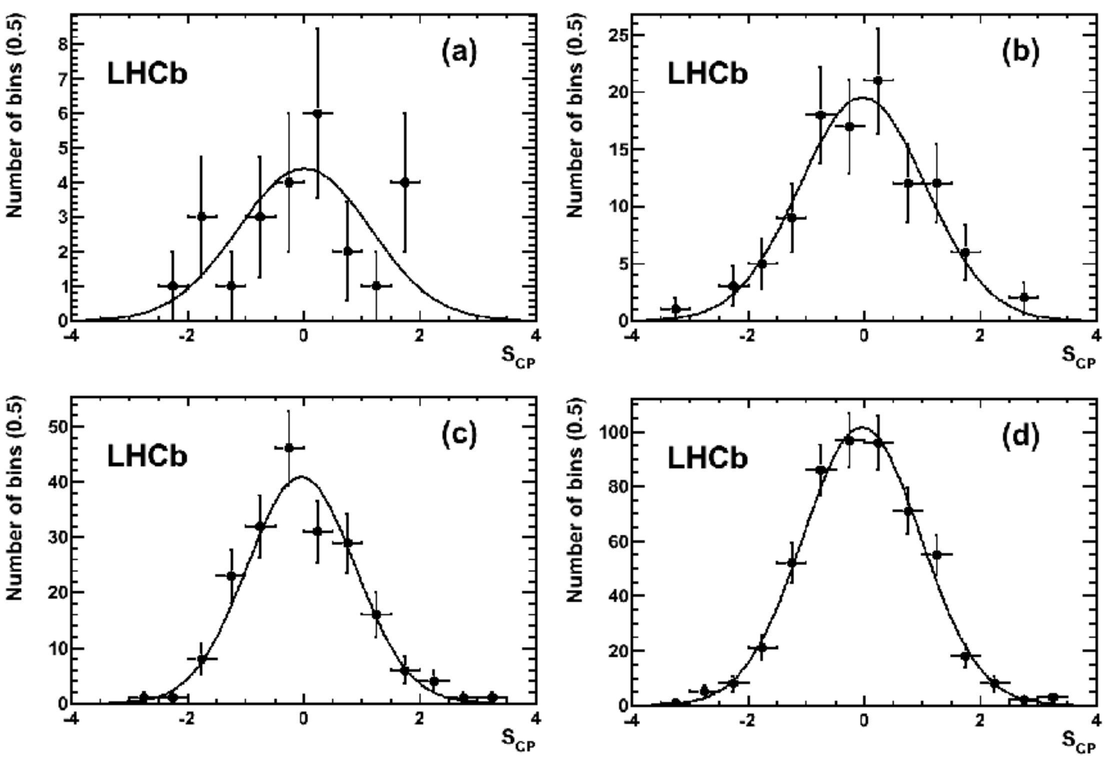
CPV in $D^+ \rightarrow K^-K^+\pi^+$ decays

- Model independent search in distribution across Dalitz plot
- Measurement of **asymmetry significance**
  - Not direct measurement of CPV parameters

$$S_{CP}^{k} = \frac{N_k(D^+) - \alpha N_k(D^-)}{\sqrt{N_k(D^+) + \alpha^2 N_k(D^-)}} \qquad \alpha = \frac{N_{\text{total}}(D^+)}{N_{\text{total}}(D^-)}$$



- If CP is conserved, S_{CP} are normal (μ=0, σ=1).
- Factor α removes any **global**



1110.3970v1 [PRD84, 112008 (2011)]

The method would be sensitive to CP violating

- phase difference of 5º in $\Phi\pi^+$ at 90% CL, and
- magnitude difference of 11% in κ(800)K^+ at 3σ.

But none of these discrepancies have been found

NEW

Search for CPV in $D^0 \rightarrow \pi^- \pi^+ \pi^+ \pi^-$ decays at LHCb

Search for CPV in $D \to \pi\pi\pi\pi$ decays

NEW

- Model independent analysis
- Using CF $D \to K\pi\pi\pi$ as control channel
  - Branching ratio ~10 times larger
  - Useful to study detector and production asymmetries
- Compare bins across phase space

Same method as the 3-body search

$$S_{CP}^{k} = \frac{N_k - \alpha \bar{N}_k}{\sqrt{N_k + \alpha^2 \bar{N}_k}} \qquad \alpha = \frac{N_{\mathrm{total}}}{\bar{N}_{\mathrm{total}}}$$

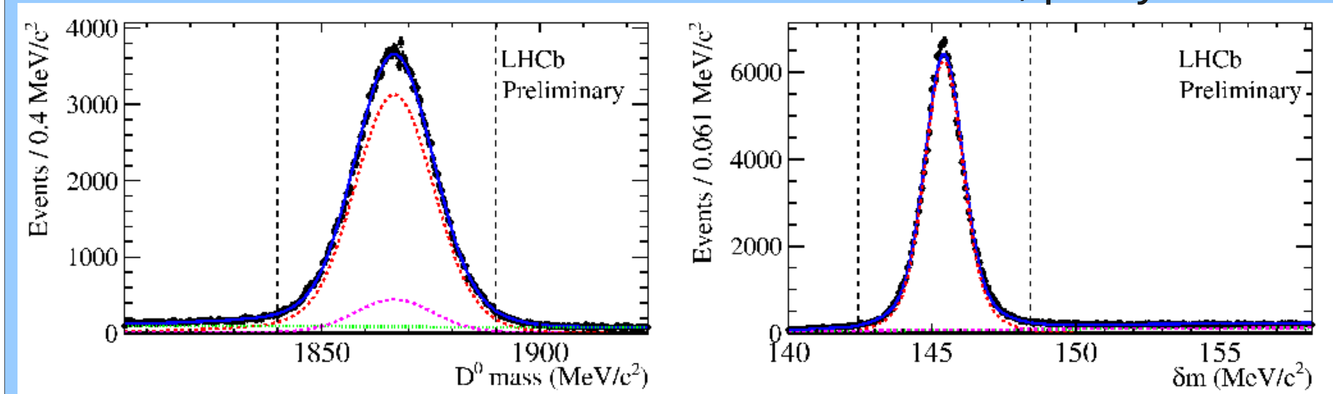
- Factor α removes any **global** asymmetries
- Adaptive binning is chosen such that all bins contain at least 100 entries.
- If CP is conserved, S_{CP} are normal (μ=0, σ=1). Compute p-values using $\chi^2 = \sum (S_{CP}^{k})^2$

Search for CPV in $D \to \pi\pi\pi\pi$ decays

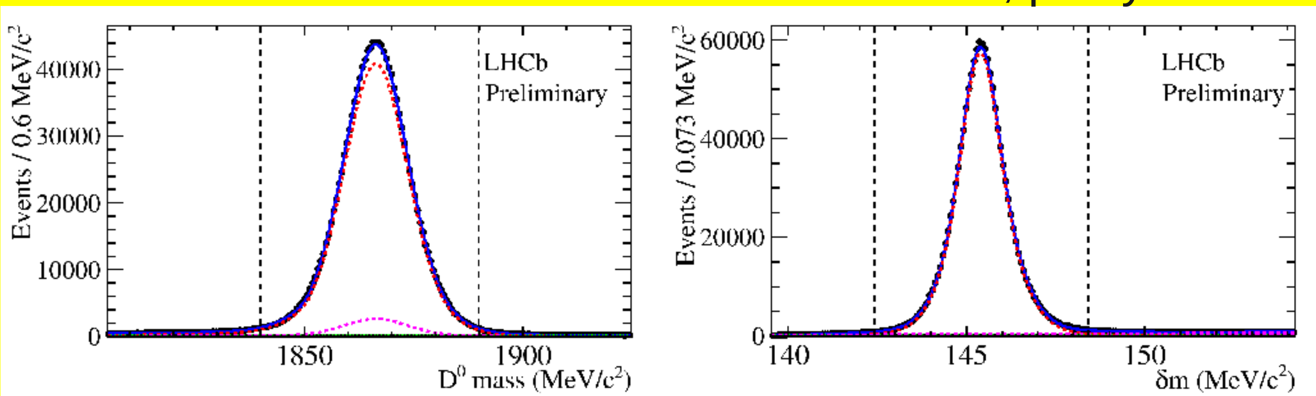
Minimize dectector/production asymmetries:

- Use equal amounts of magnet up and down data
- Apply fiducial cuts to areas with large asymmetry
- Apply 2-dimension re-weighting in D^0 η and p_t to force same amount as in $\bar{D}^0$.

$D \to \pi\pi\pi\pi$ — 180 000 events, purity 95.8 %



$D \to K\pi\pi\pi$ — 1 300 000 events, purity 97.5 %



LHCb *Preliminary*

NEW

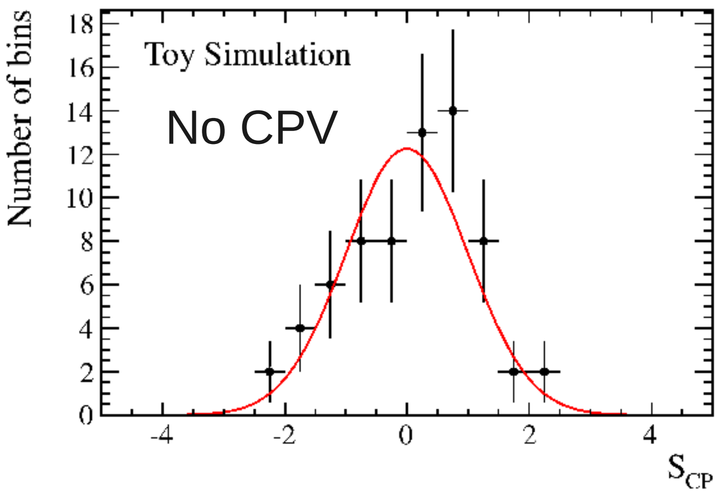
Selection:

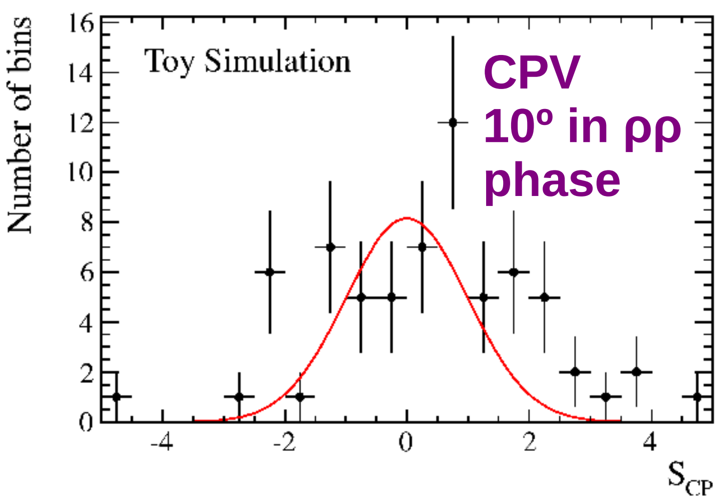
- Rectangular cuts to reconstruct candidates
- Neural network to select signal candidates
  - Same NN used to select control channel

Search for CPV in D → π π π π decays

Sensitivity obtained from toy study

- Events generated with FOCUS model
- Forced relative phase or magnitude difference between D^0 and $\bar{D}^0$.





Preliminary

NEW

CPV		$N_{\rm bins}$	p-values (%)
None		15	49.6
		29	31.8
		66	45.8
$\rho^0\rho^0$ phase	5°	15	30.0
		29	27.8
		66	9.96
	10°	15	$1.2 \cdot 10^{-6}$
		29	$3.05 \cdot 10^{\ 8}$
		66	$1.74 \cdot 10^{\ 16}$
$a_1(1260)^+\pi^-$ phase	5°	15	0.40
		29	0.26
		66	0.24
	10°	15	$5.05 \cdot 10^{\ 6}$
		29	$2.38 \cdot 10^{-8}$
		66	$7.34 \cdot 10^{-13}$
$\rho^0\rho^0$ magnitude	5%	15	0.57
		29	6.9
		66	12.1
	10%	15	$2.9 \cdot 10^{-11}$
		29	$1.1 \cdot 10^{-9}$
		66	$1.2 \cdot 10^{-12}$

Search for CPV in D → π π π π decays

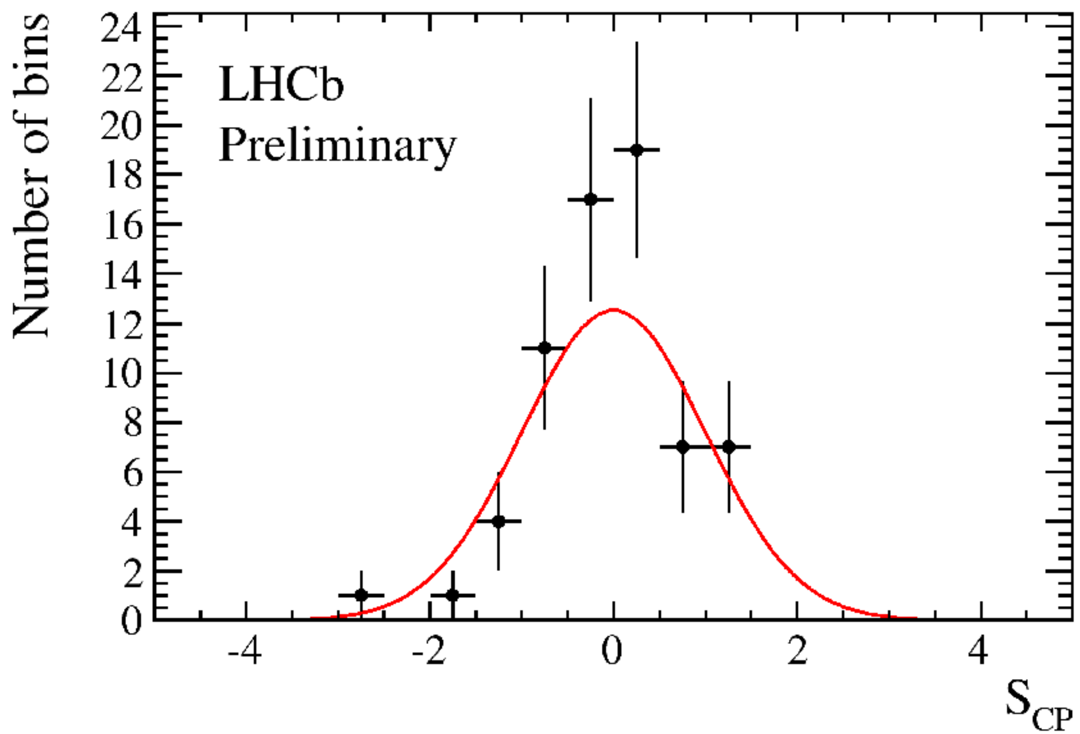
The method is sensitive to CP violating
- phase difference of O(10º) in ρρ, and
- magnitude difference of O(10%) in κ(800)K$^+$ at 3σ.

No discrepancies have been observed

$N_{\rm bins}$	p-valucs (%)
15	97.1
29	95.6
66	99.8

Preliminary

NEW



Conclusions

- LHCb has searched for
  - y_{CP} and A_{Γ} in 2-body charm decays.
  - CPV in
    - $D^0 \rightarrow h^+ h^-$ decays.
    - $D^+ \rightarrow K^- K^+ \pi^+$ decays.
    - **$D^0 \rightarrow \pi^- \pi^+ \pi^+ \pi^-$ decays.**

> - First model-independent search for local CPV in a charm 4-body decay.
> - Used data-driven techniques to keep detection/production asymmetries under control.

- Sensitivity to charm CPV in LHCb is becoming very exciting.
- Measurement of charm mixing in LHCb very promising.