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Charm mixing and CP violation at LHCb

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on behalf of the LHCb collaboration

Mixing and CP violation

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

Flavor eigenstates

- Well defined flavor

$$|D_1\rangle \quad |D_2\rangle$$

Hamiltonian eigenstates

- Well defined m and Γ
- Define the mixing parameters

Mixing determines the time evolution of the flavor eigenstates

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

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

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

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 \neq CP eigenstates
 - Different mixing rates $D^0 \rightarrow \bar{D}^0$ and $\bar{D}^0 \rightarrow D^0$.

$$\text{Im} \left(\frac{q}{p} \frac{\bar{A}_{\bar{f}}}{A_f} \right) \neq 0$$

CPV in the interference

- Hamiltonian eigenstates \neq CP eigenstates
 - Phase effect

Standard model predictions

- Short distance contributions

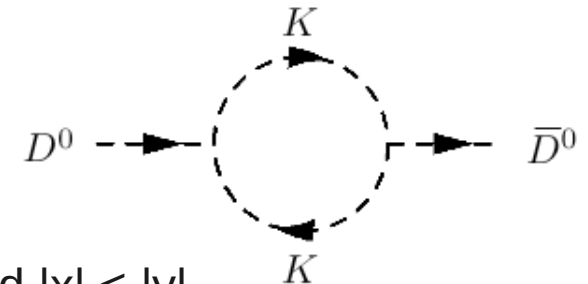
- Mixing box diagrams.
- SM predicts small mixing effects.
- b quarks are CKM suppressed, and s and d quarks are GIM suppressed.
- They mainly contribute to the x mixing parameter.



- Long distance contributions

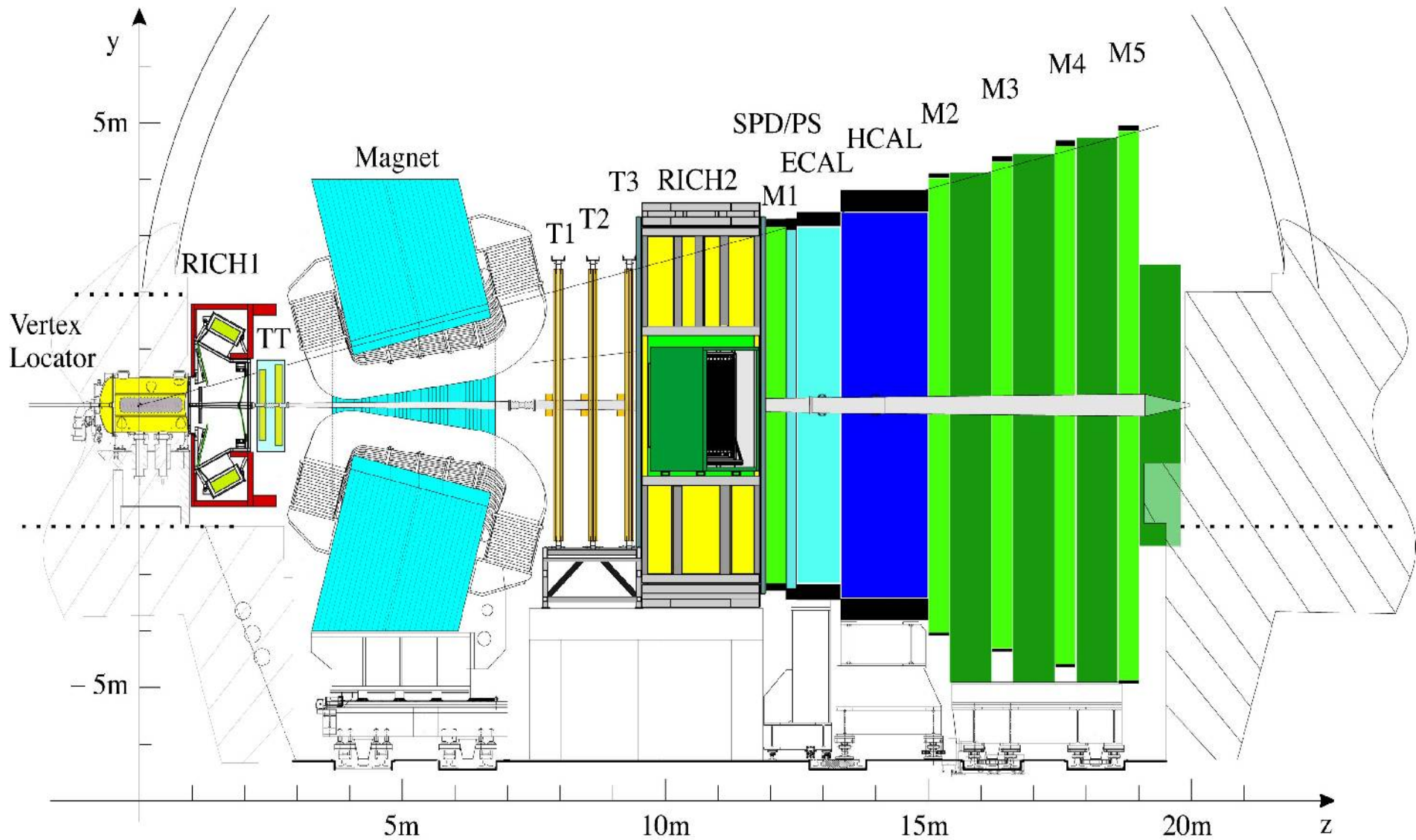
A. Falk et al., PRD 69, 114021 (2004)

- 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



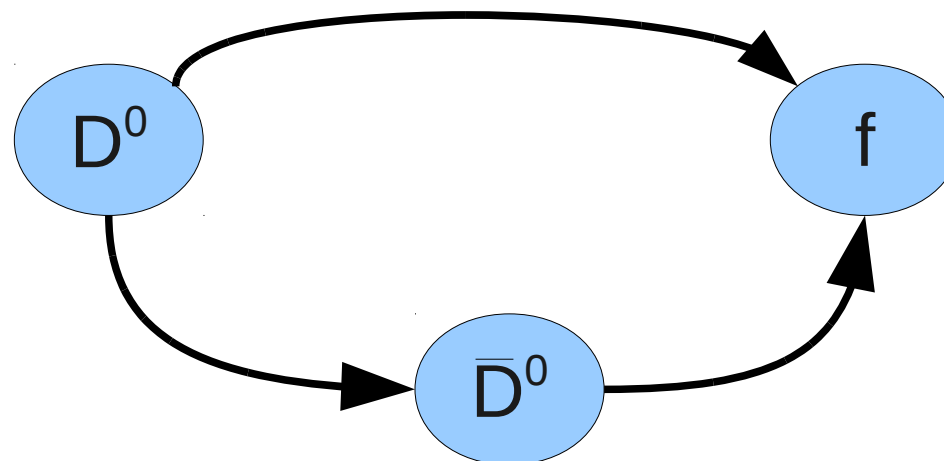
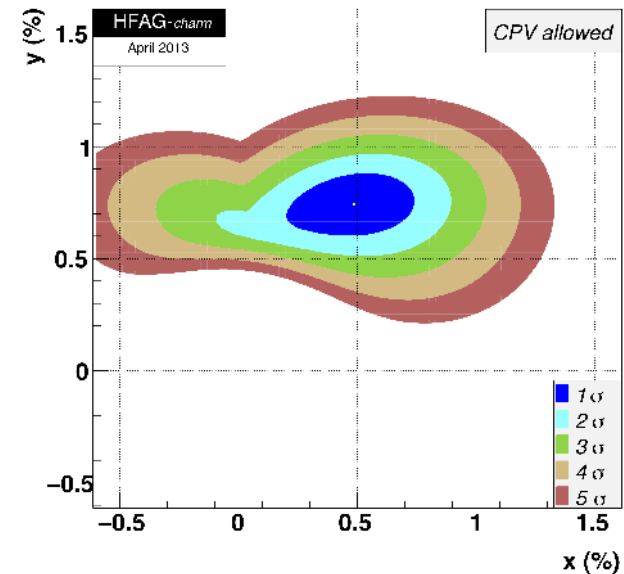


Experimental status

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

y_{CP}, A_{Γ} arXiv: 1112.4698 (JHEP04, 2012)

Observation of D mixing in $D \rightarrow K\pi$
arXiv: 1211.1230 (PRL, 2013)



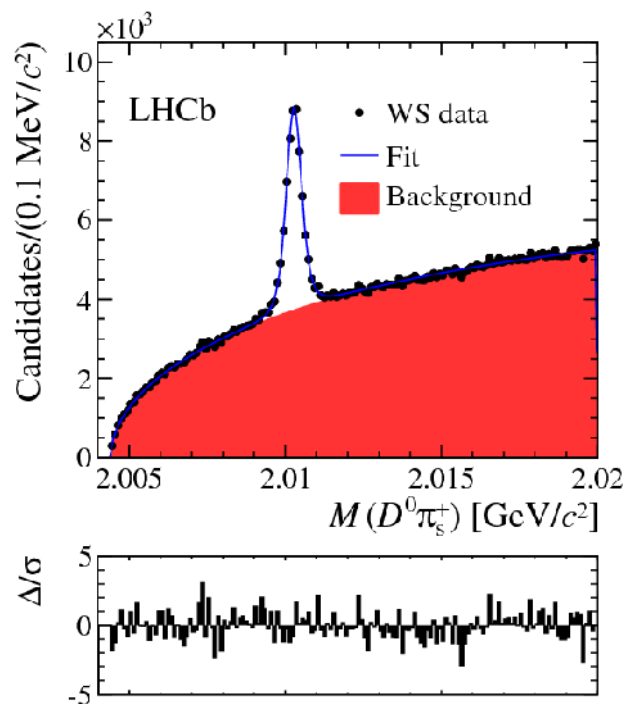
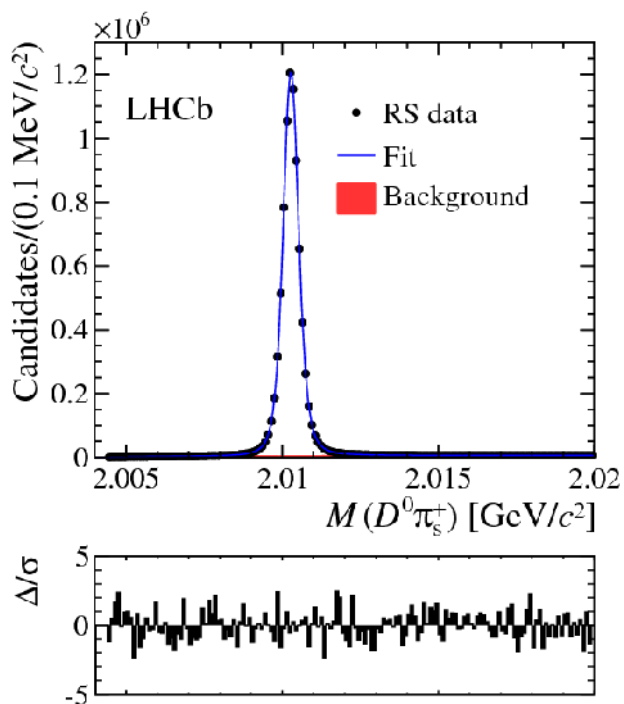
Mixing in $D \rightarrow K \pi$

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

Based on ratio of wrong-sign ($D^0 \rightarrow K^+ \pi^-$) to right-sign ($D^0 \rightarrow K^- \pi^+$) decay rates:

$$R(t) \approx R_D + \sqrt{R_D} y' \frac{t}{\tau} + \frac{x'^2 + y'^2}{4} \left(\frac{t}{\tau} \right)^2$$

$D^{*\pm} \rightarrow D^0 \pi^\pm$, where pion charge tags D flavor.

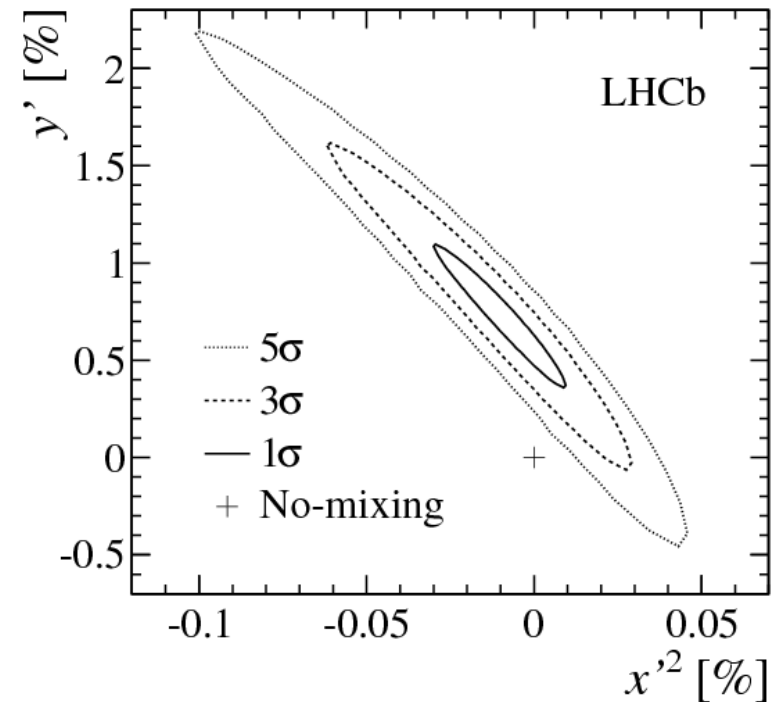
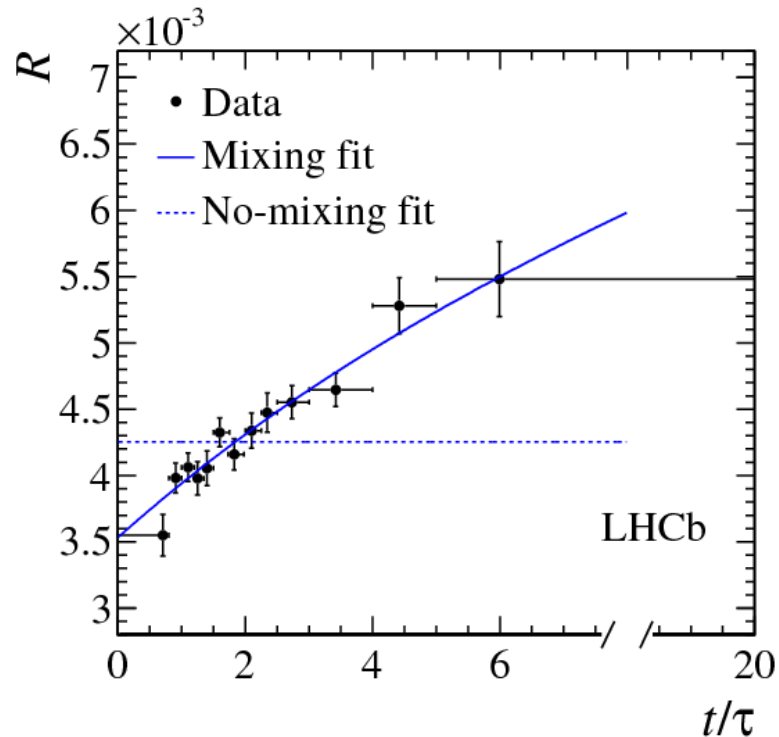


Mixing in $D \rightarrow K \pi$

LHCb [1.0 fb^{-1} (2011)] arXiv: 1211.1230 (PRL, 2013)

$$x'^2 = [-0.9 \pm 1.3] \cdot 10^{-4}$$

$$y' = [7.2 \pm 2.4] \cdot 10^{-3}$$



Result excludes the no-mixing hypothesis at 9.1σ





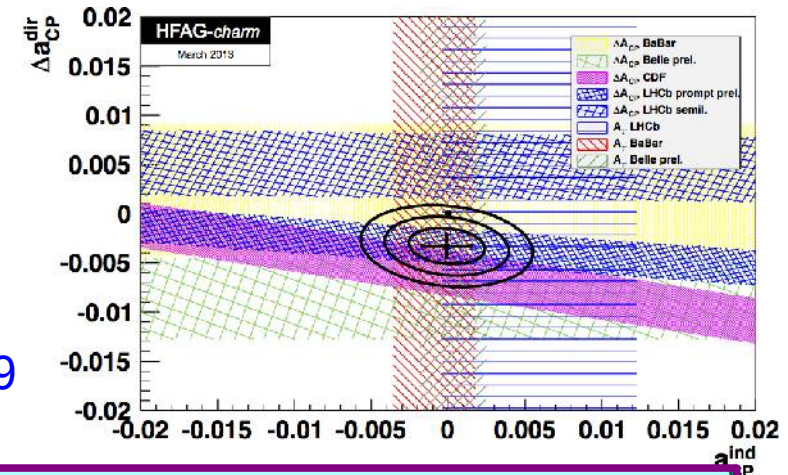
Experimental status

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

LHCb [arXiv: 1112.0938](https://arxiv.org/abs/1112.0938) (PRL, 2012) **updated**

Search in $D^+ \rightarrow K^- K^+ \pi^+$ [arXiv: 1110.3970v1](https://arxiv.org/abs/1110.3970v1) (PRD, 2011)

Search in $D^0 \rightarrow \pi^- \pi^+ \pi^+ \pi^-$ decays [LHCb-CONF-2012-019](https://arxiv.org/abs/LHCb-CONF-2012-019)



$$\Delta A_{CP} = [a_{CP}^{\text{dir}}(K^- K^+) - a_{CP}^{\text{dir}}(\pi^- \pi^+)] \left(1 + y \frac{\overline{\langle t \rangle}}{\tau} \cos \phi \right) + \left(a_{CP}^{\text{ind}} + \overline{a_{CP}^{\text{dir}}} y \cos \phi \right) \frac{\Delta \langle t \rangle}{\tau_D}$$

Search for direct CPV in $D \rightarrow h^- h^+$ from semileptonic B decays [arXiv: 1303.2614](https://arxiv.org/abs/1303.2614)

Search for CPV in $D \rightarrow KK$ and $D \rightarrow \pi\pi$ from D^* [LHCb-CONF-2013-003](https://arxiv.org/abs/LHCb-CONF-2013-003)

Search for CPV in $D^+ \rightarrow \phi \pi^+$ and $D^+ \rightarrow K_s \pi^+$ [arXiv: 1303.4906](https://arxiv.org/abs/1303.4906)

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

$D^{*\pm} \rightarrow D^0 \pi^\pm$, where pion charge tags D flavor.

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 $\pi\pi$ 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 $\delta m = m(D^*) - m(D) - m(\pi^+)$

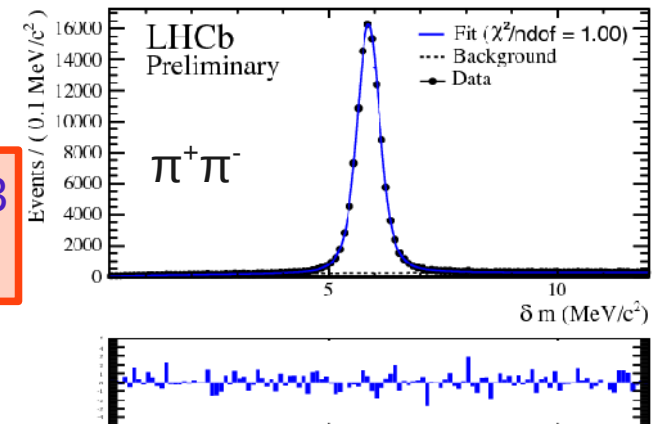
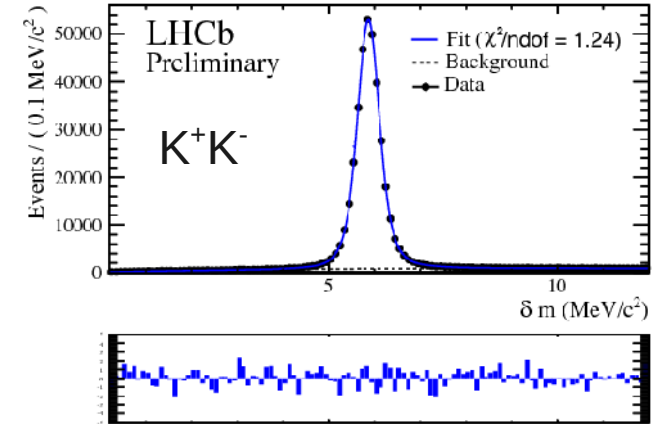
First evidence of CPV at LHCb [0.62 fb⁻¹ (2011)]

$$\Delta A_{CP} = [-0.82 \pm 0.21 \text{ (stat)} + 0.11 \text{ (syst)}] \cdot 10^{-2} \text{ arXiv: 1112.0938}$$

Update of CPV at LHCb [1.0 fb⁻¹ (2011)] LHCb-CONF-2013-003

$$\Delta A_{CP} = [-0.34 \pm 0.15 \text{ (stat)} \pm 0.10 \text{ (syst)}] \cdot 10^{-2}$$

update

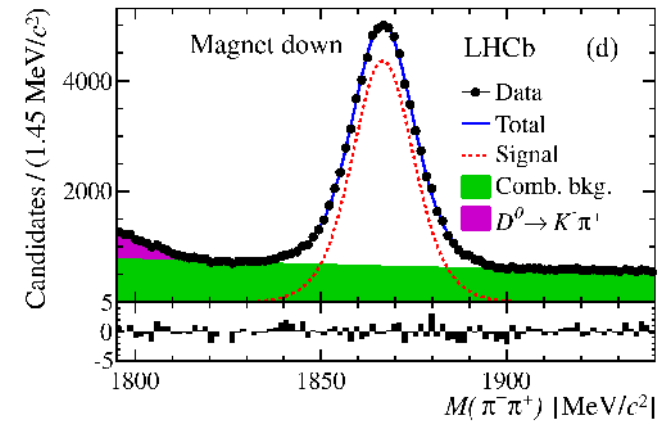
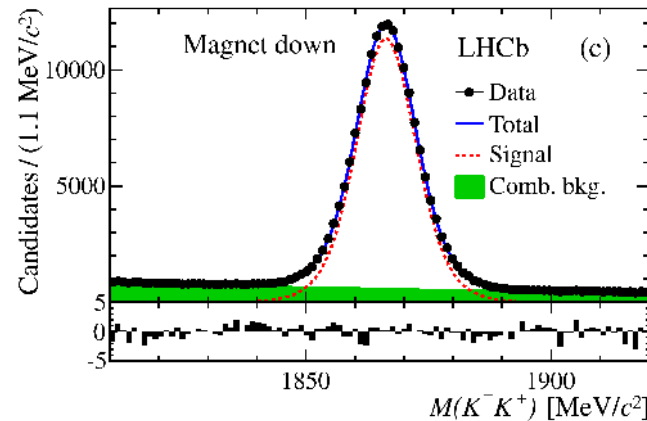
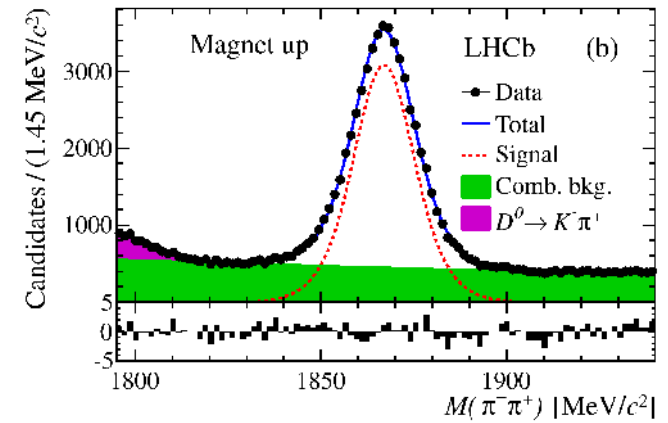
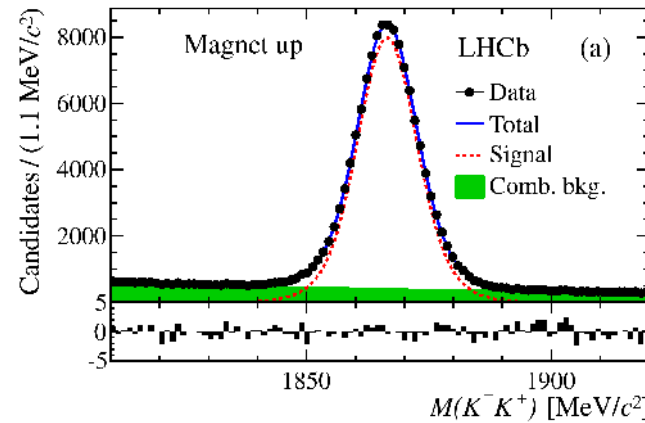


Differences wrt previous result

- New reconstruction
 - Better particle ID for D daughters
- Additional constraint in vertex fit
 - Improved mass resolution
- Events weighted to match kinematics of KK and $\pi\pi$.
 - Ensure the same production and detection asymmetries
- Larger dataset (0.6 fb^{-1} to 1 fb^{-1})
- **The difference is understood and compatible with statistical fluctuations.**

CPV in secondary $D \rightarrow h^+ h^-$ decays

- Use differences of raw asymmetries.
- Tag D flavor from μ charge in $B \rightarrow D \mu X$.



LHCb [**1.0 fb⁻¹ (2011)**]

$$\Delta A_{CP} = [-0.49 + 0.30 \text{ (stat)} + 0.14 \text{ (syst)}] \cdot 10^{-2}$$

[arXiv: 1303.2614](https://arxiv.org/abs/1303.2614)

It does not confirm the direct CPV observed in other analyses

CPV in $D^+ \rightarrow \phi\pi^+$

$$A_{\text{CP}}(D^+ \rightarrow \phi\pi^+) = A_{\text{raw}}(D^+ \rightarrow \phi\pi^+) - A_{\text{raw}}(D^+ \rightarrow K_s\pi^+) + A_{\text{CP}}(K^0/\bar{K}^0)$$

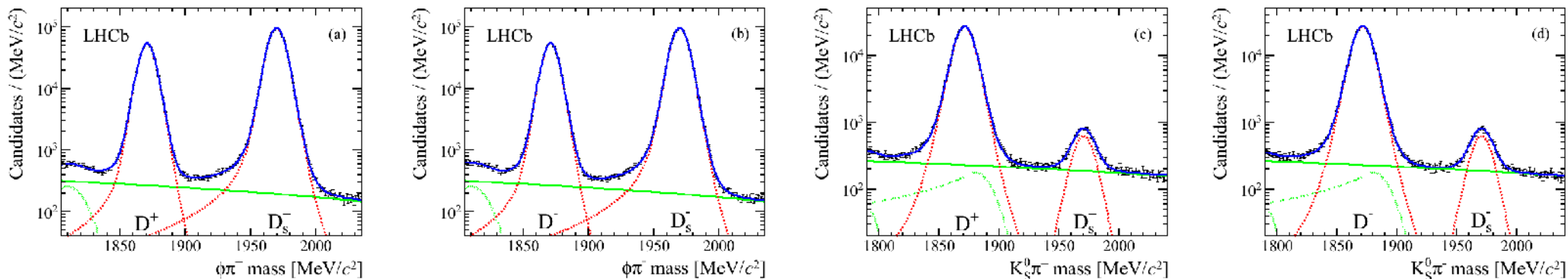
$$A_{\text{CP}}(D_s^+ \rightarrow K_s\pi^+) = A_{\text{raw}}(D_s^+ \rightarrow K_s\pi^+) - A_{\text{raw}}(D_s^+ \rightarrow \phi\pi^+) + A_{\text{CP}}(K^0/\bar{K}^0)$$

Difference of raw asymmetries for robustness

Account for CPV in the K system

Assume $A_{\text{CP}}(D^+ \rightarrow K_s\pi^+) \approx A_{\text{CP}}(D_s^+ \rightarrow \phi\pi^+) \approx 0$

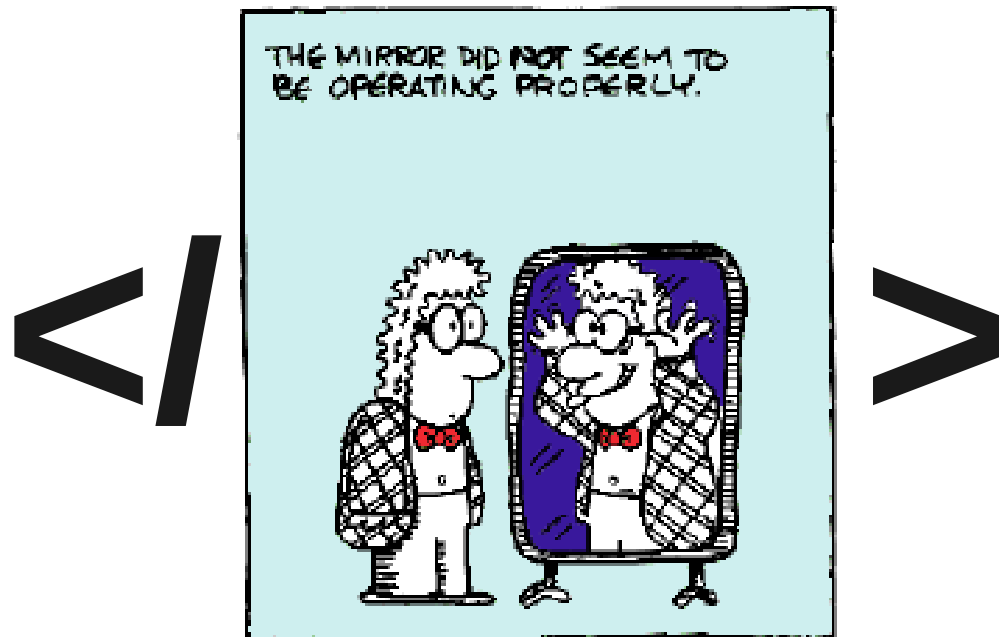
Assume no CPV in the mixing or interference



LHCb [1.0 fb⁻¹ (2011)] [arXiv: 1303.4906](https://arxiv.org/abs/1303.4906)

$$A_{\text{CP}}(D^+ \rightarrow \phi\pi^+) = [-0.04 \pm 0.14 (\text{stat}) \pm 0.13 (\text{syst})] \cdot 10^{-2}$$

$$A_{\text{CP}}(D^+ \rightarrow K_s\pi^+) = [0.61 \pm 0.83 (\text{stat}) \pm 0.13 (\text{syst})] \cdot 10^{-2}$$



Conclusions

- LHCb has confirmed D mixing at 9.1σ .
- CPV in charm not confirmed.
- The presented analyses use 1 fb^{-1} (2011), but 2 fb^{-1} (2012) yet to give promising results.
 - Sensitivity to charm CPV in LHCb is becoming very exciting.

BACKUP

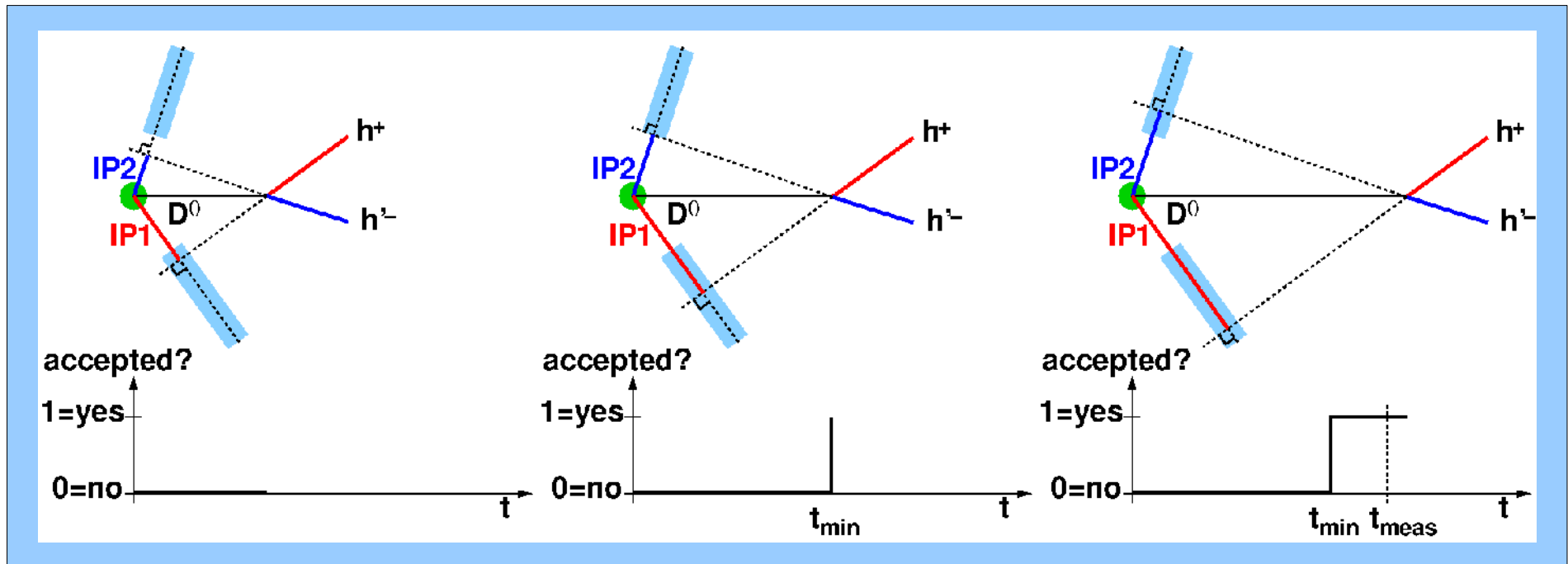
Mixing in two-body decays

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

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

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]

$$y_{CP} = [5.5 \pm 6.3 \text{ (stat)} \pm 4.1 \text{ (syst)}] \cdot 10^{-3}$$

$$A_\Gamma = [-5.9 \pm 5.9 \text{ (stat)} \pm 2.1 \text{ (syst)}] \cdot 10^{-3}$$



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

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

- Model independent analysis
- Using CF $D \rightarrow K \pi \pi \pi$ 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

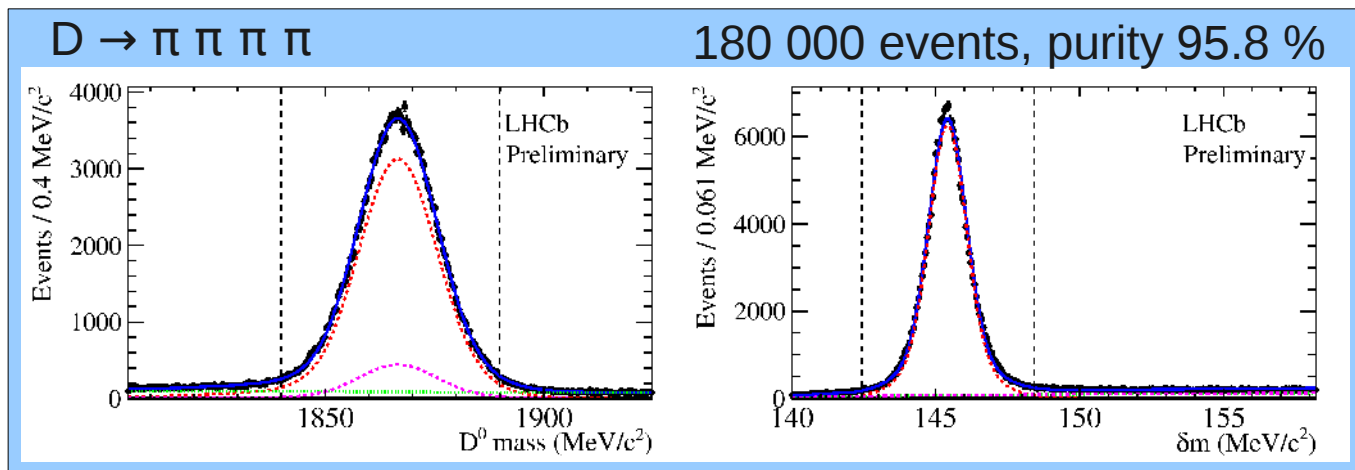
$$S_{CP}^k = \frac{N_k - \alpha \bar{N}_k}{\sqrt{N_k + \alpha^2 \bar{N}_k}} \quad \alpha = \frac{N_{\text{total}}}{\bar{N}_{\text{total}}}$$

- 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 ($\mu=0, \sigma=1$). Compute p-values using $\chi^2 = \sum (S_{CP}^k)^2$

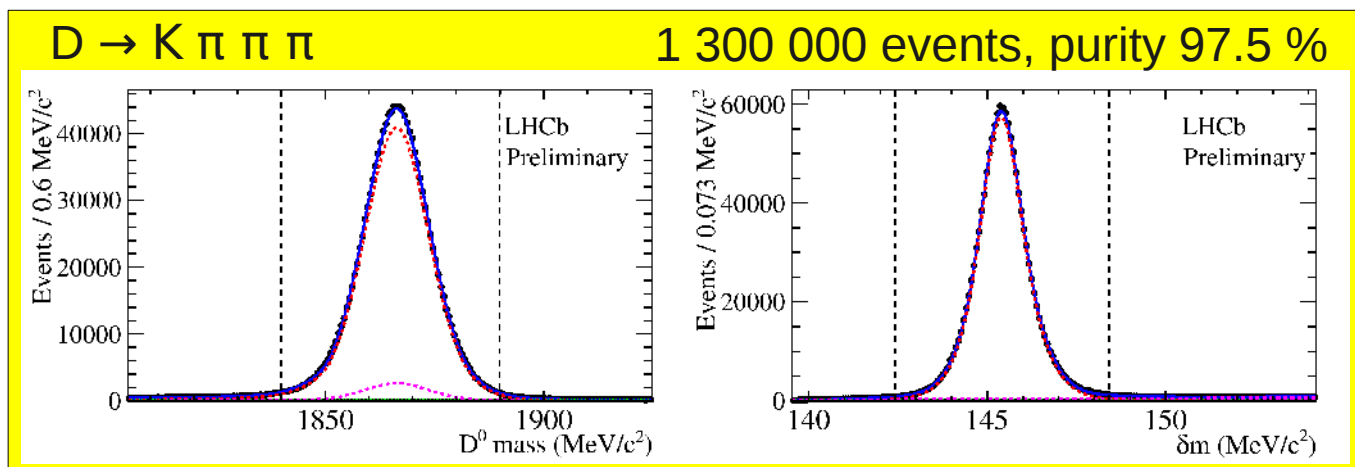
Search for CPV in $D \rightarrow \pi \pi \pi \pi$ decays

Minimize detector/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 $D^0 \eta$ and p_t to force same amount as in D^0 .



Preliminary



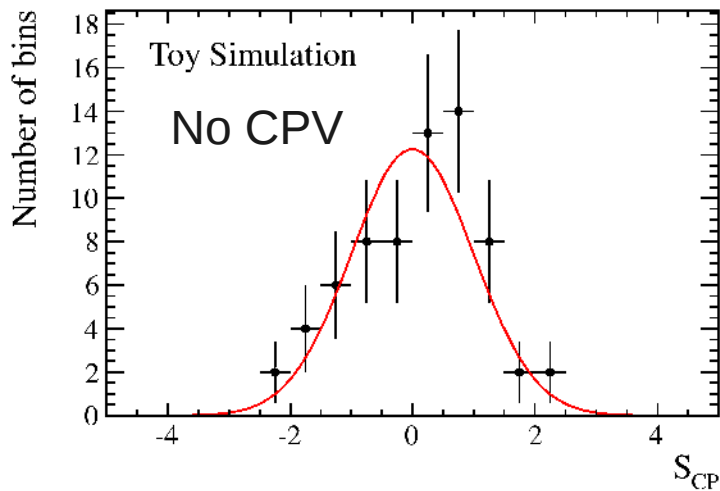
Selection:

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

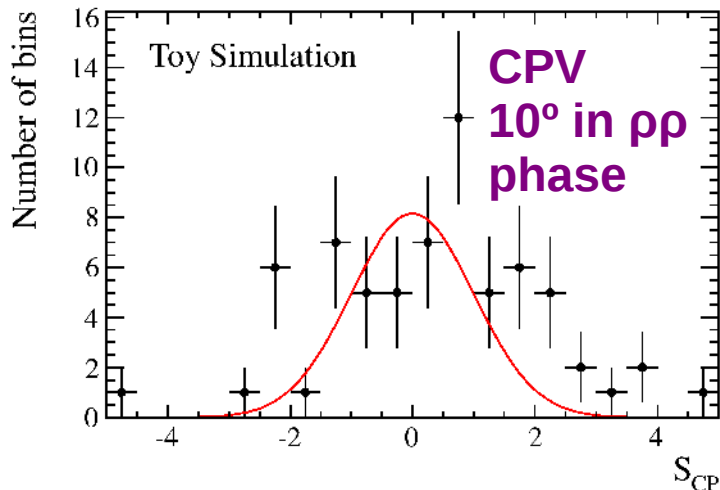
Search for CPV in $D \rightarrow \pi \pi \pi \pi$ decays

Sensitivity obtained from toy study

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



Preliminary



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

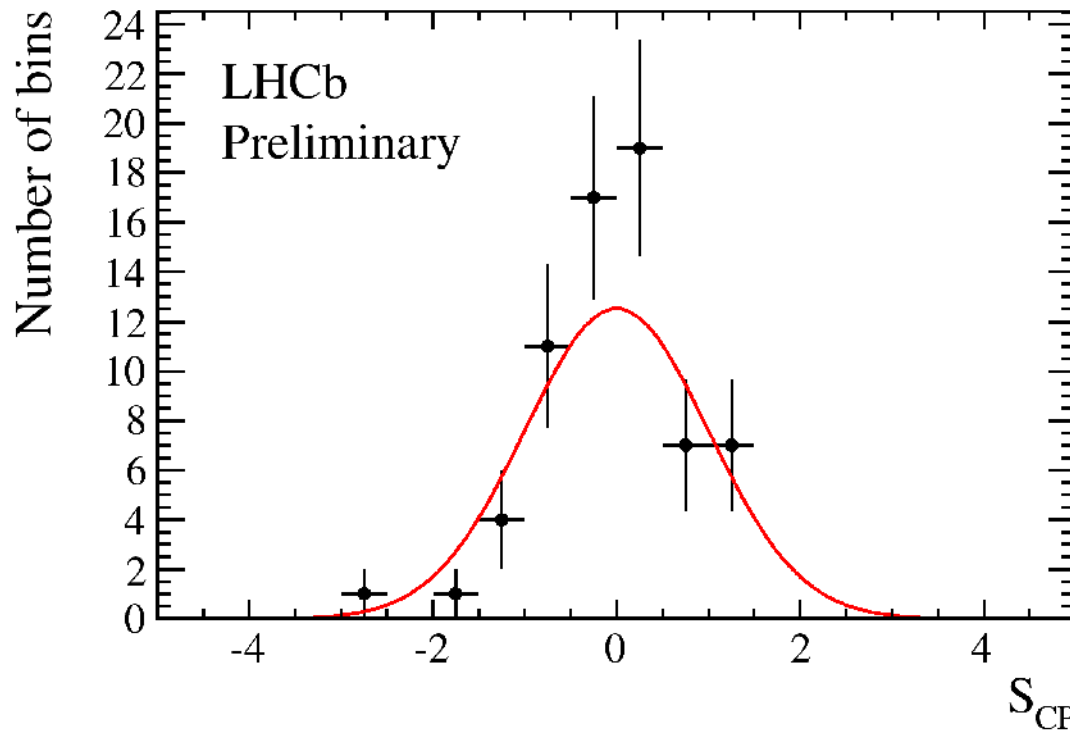
Search for CPV in $D \rightarrow \pi \pi \pi \pi$ decays

The method is sensitive to CP violating

- phase difference of $O(10^\circ)$ in $\rho\rho$, and
- magnitude difference of $O(10\%)$ in $\kappa(800)K^+$ at 3σ .

**No discrepancies
have been observed**

N_{bins}	p-values (%)
15	97.1
29	95.6
66	99.8



LHCb
LHCb
Preliminary

NEW