# Charm mixing and CP violation at LHCb

Evelina Gersabeck

Ruprecht-Karls-Universität Heidelberg
on behalf of the LHCb collaboration

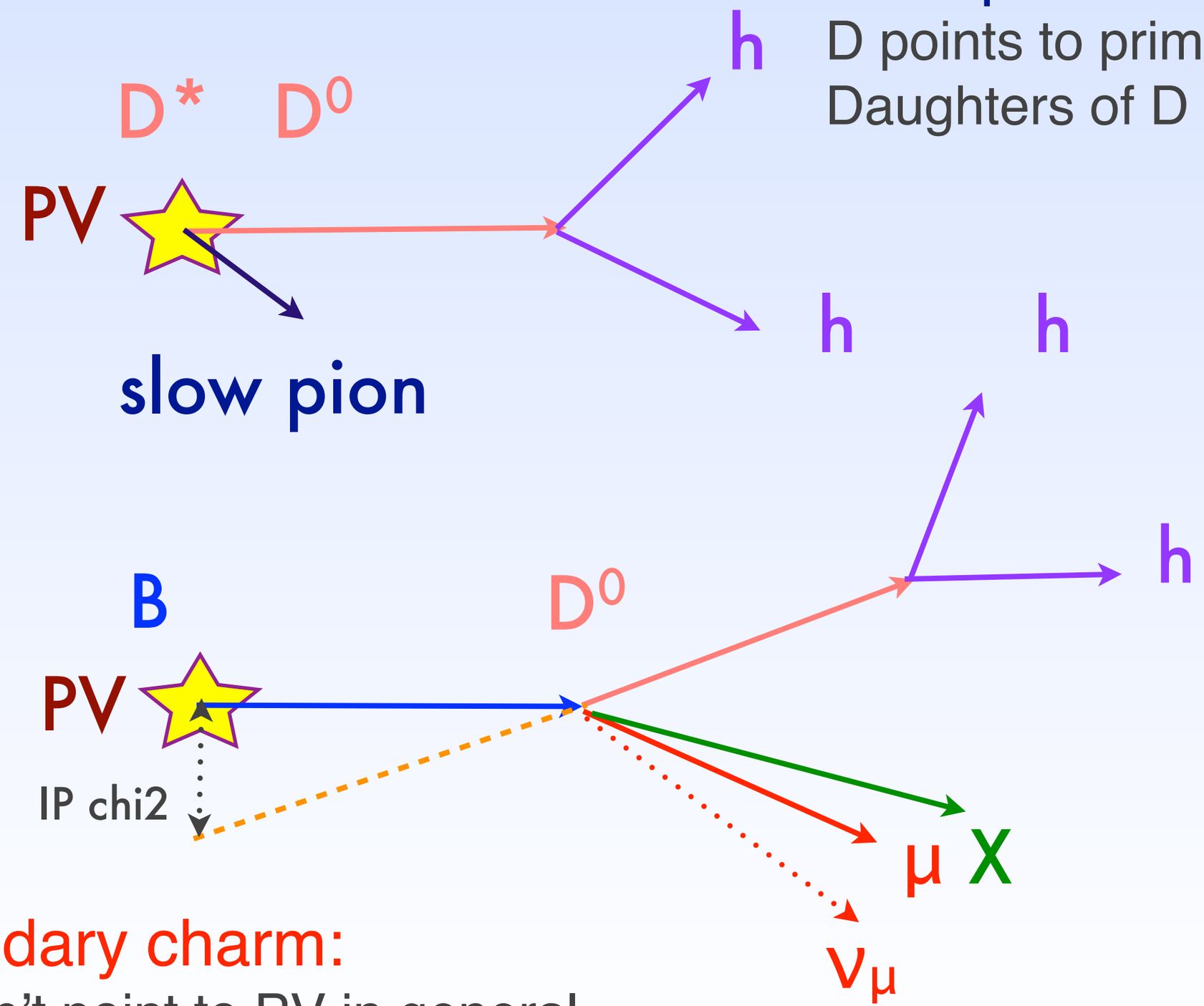
UNIVERSITÄT
HEIDELBERG
ZUKUNFT
SEIT 1386


Rencontres de Blois, Blois, France, 20 May 2014

# CP violation in Charm

- No unambiguous evidence for CP violation in the charm sector
- In SM, the CP-violating effects in charm are small but hard to predict
- Huge amount of prompt and secondary charm decays collected and reconstructed at LHCb
- Sensitivity to measure small CP violating effects

# Prompt and secondary charm




**Prompt charm:**

D points to primary vertex

Daughters of D don't in general

**Secondary charm:**

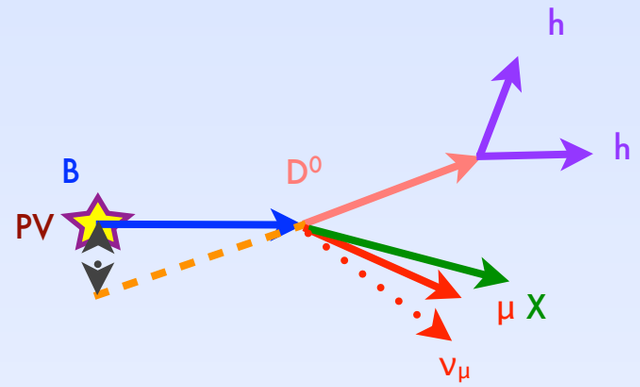
D doesn't point to PV in general

# Direct CPV

CPV in the decay amplitude;
time independent

# Time-integrated CP asymmetry in $D^0 \to h^+h^-$ with semileptonic decays

The flavour of the initial state $\left(D^0, \bar{D}^0\right)$ is tagged by the semileptonic decay $B \to D^0 \mu^- \nu_\mu X$




the charge of the muon identifies the $D^0$ flavour

We are looking for CP asymmetry

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

$$f = \bar{f} = K^+K^-$$

$$or$$

$$f = \bar{f} = \pi^+\pi^-$$

$D^0$ decays to CP eigenstates

# Time-integrated CP asymmetry

The raw asymmetry for tagged $D^0$ decays to a final state f is given by:

$$A_{raw}(f) = \frac{N\left(B \to D^0 \mu^- X\right) - N\left(B \to \bar{D}^0 \mu^+ X\right)}{N\left(B \to D^0 \mu^- X\right) + N\left(B \to \bar{D}^0 \mu^+ X\right)}$$

where N(X) refers to the number of reconstructed events of decay X after background subtraction

We measure the physical CP asymmetry plus asymmetries due to detection effects and production

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

Physics CP asymmetry

Detection asymmetry of muons

Production asymmetry

Main experimental challenge: separate the asymmetries

# Time-integrated CP asymmetry

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

if we take the raw asymmetry difference:
experimentally more robust

$$\Delta A_{CP} \equiv A_{raw}(KK) - A_{raw}(\pi\pi) = A_{CP}(KK) - A_{CP}(\pi\pi)$$

the production and the muon detection asymmetries will cancel

# Challenge: Individual CP asymmetries

$$A_{CP}(KK) = A_{raw}(KK) - \underbrace{A_D(\mu) - A_P(B)}$$

want measure

Assume no CPV in CF final states

$$B \to D^0(\to K\pi)\mu^- \nu_\mu X$$

$A_D(K\pi)$

$$\begin{cases} D^+ \to K^-\pi^+\pi^+ \\ D^+ \to \bar{K}^0_S\pi^+ \end{cases} \longrightarrow A_{CP/i}(K^0)$$

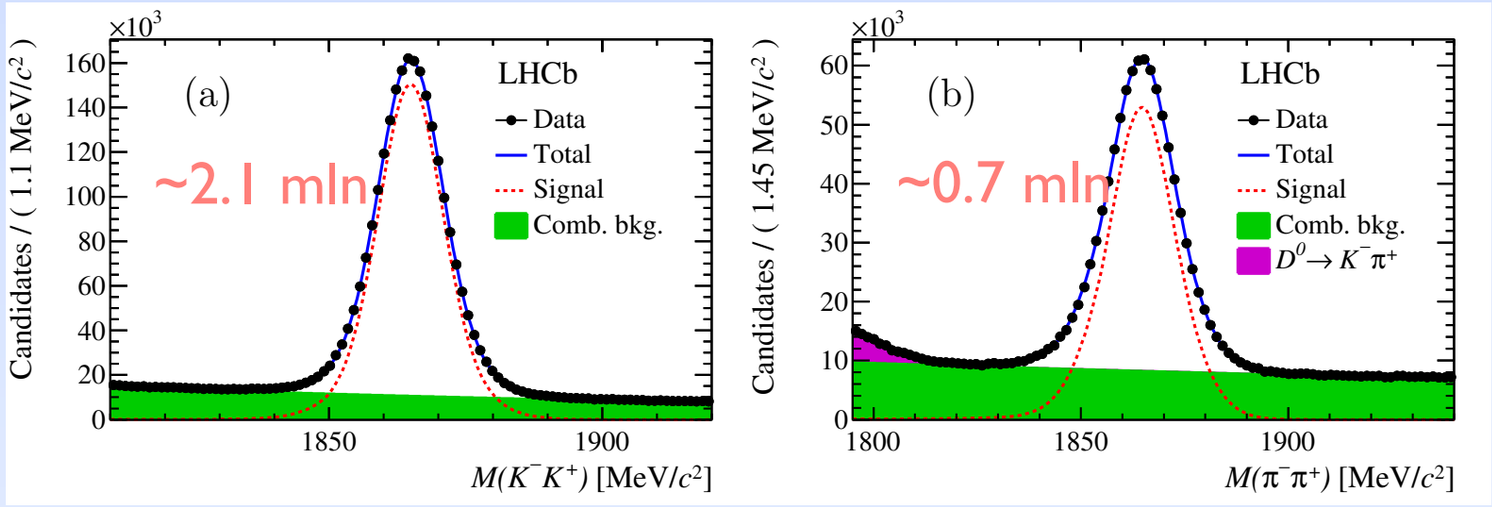
$A_D(\pi^+), A_P(D^+)$

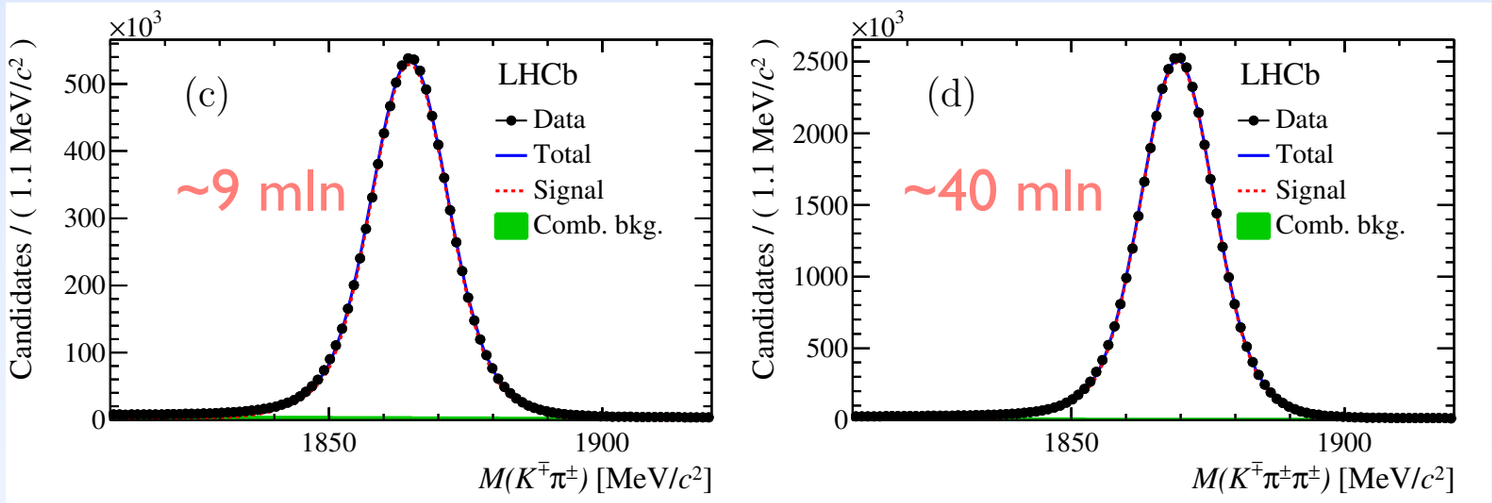
$$A_{CP}(\pi\pi) = A_{CP}(KK) - \Delta A_{CP}$$

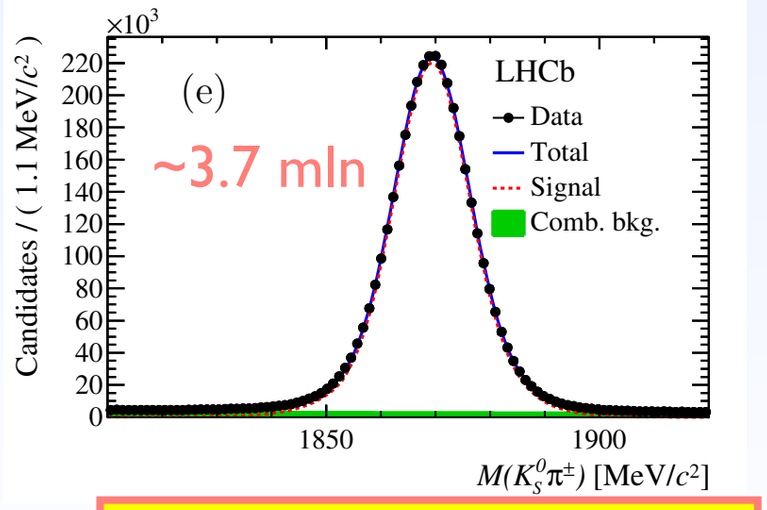
First measurement by LHCb of an individual CP asymmetry

# Yields

- Using 3 $fb^{-1}$ data (2011 and 2012 data)
- Regular magnet polarity swap
- 2011 and 2012 data and the up-down magnet polarities independently analysed
- Kinematical re-weighting
- Mistag probability obtained from $D^0 \to K^{\pm}\pi^{\mp}$
- Careful treatment of kaon interactions with matter




Signal: sum of 2 Gaussian functions with a power-law tail
Bckg: combinatorial: exponential function
Mis-ID: gaussian function

arXiv:1405.2797 [hep-ex]
submitted to JHEP

# Results

arXiv:1405.2797 [hep-ex]
submitted to JHEP

Systematic uncertainties:

| Source of uncertainty | $\Delta A_{CP}$ | $A_{CP}(K^-K^+)$ |
|---|---|---|
| Production asymmetry: | | |
| Difference in $b$-hadron mixture | 0.02% | 0.02% |
| Difference in $B$ decay time acceptance | 0.02% | 0.02% |
| Production and detection asymmetry: | | |
| Different weighting | 0.02% | 0.05% |
| Non-cancellation | - | 0.03% |
| Neutral kaon asymmetry | - | 0.01% |
| Background from real $D^0$ mesons: | | |
| Mistag asymmetry | 0.03% | 0.03% |
| Background from fake $D^0$ mesons: | | |
| $D^0$ mass fit model | 0.06% | 0.06% |
| Wrong background modelling | 0.03% | 0.03% |
| **Quadratic sum** | 0.08% | 0.10% |

NEW

$$\Delta A_{CP} = (+0.14 \pm 0.16\,(\text{stat}) \pm 0.08\,(\text{syst}))\% \ ,$$
$$A_{CP}(K^-K^+) = (-0.06 \pm 0.15\,(\text{stat}) \pm 0.10\,(\text{syst}))\% \ .$$

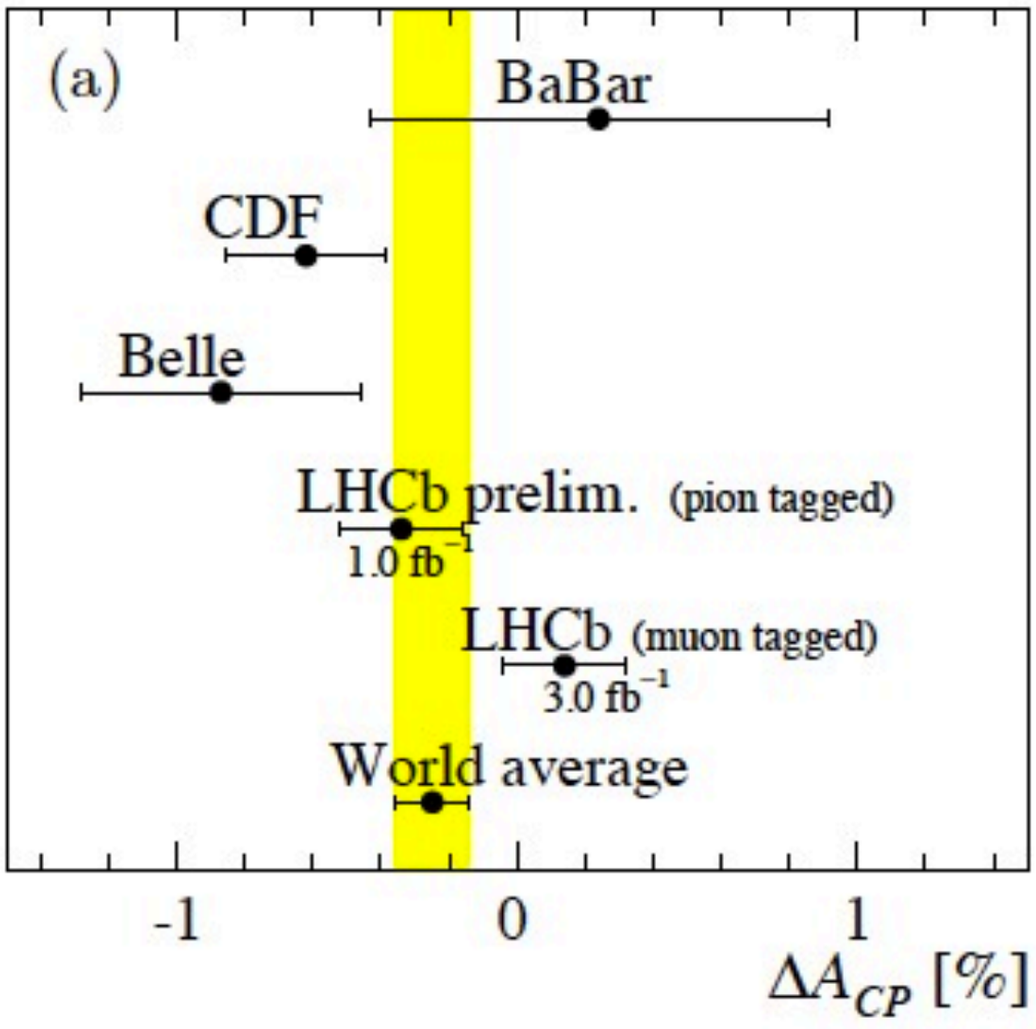
Correlation ρ = 0.28

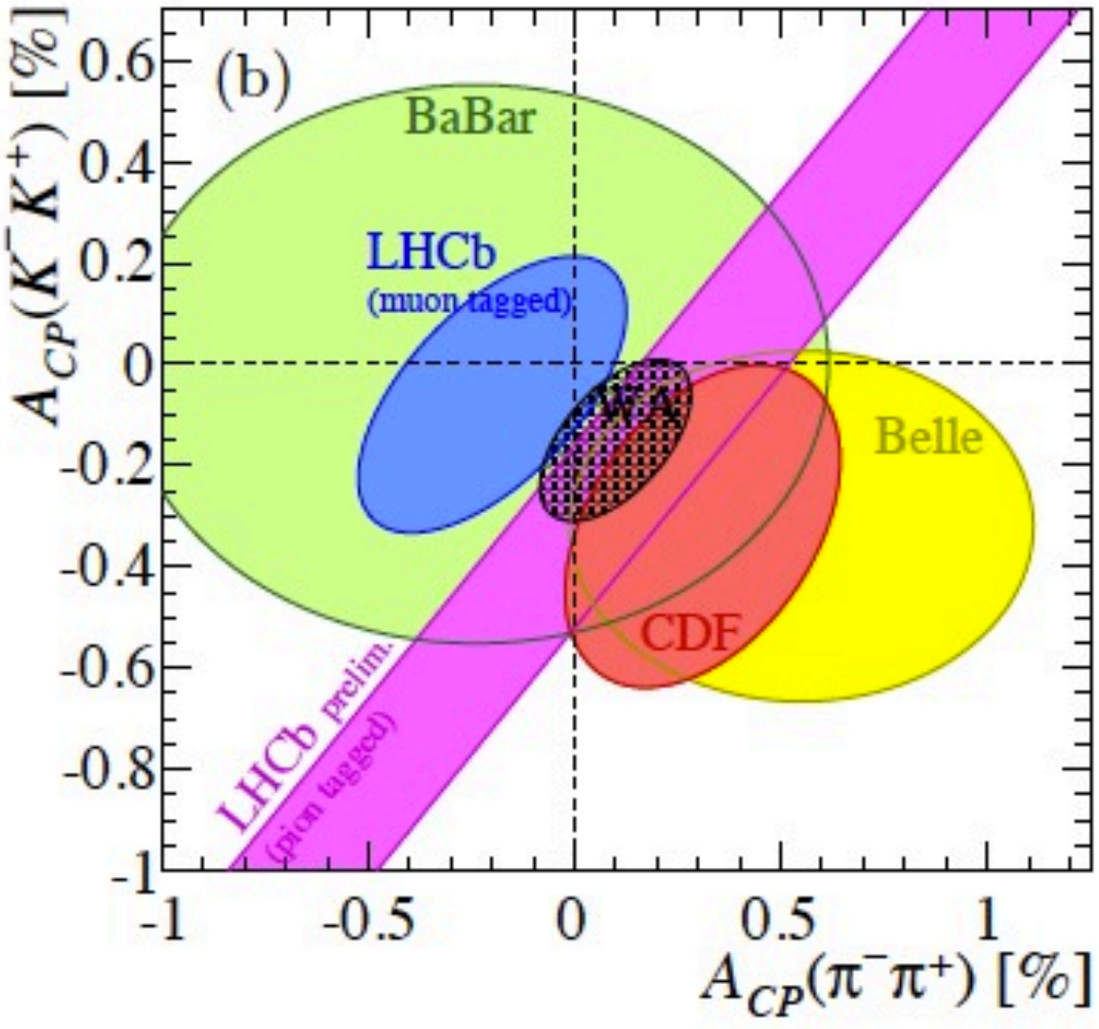
$$A_{CP}(\pi^-\pi^+) = (-0.20 \pm 0.19(\text{stat}) \pm 0.10(\text{syst}))\%$$

no CPV

Most precise measurement of individual asymmetries

# World averages



# CP violation in SCS $D^+_{(s)} \to K^0_S h^+$ decays

$$A_{raw}(f) = A_{CP}(f) + A_{CP/\text{int}}\left(K^0 / \bar{K}^0\right) + A_D\left(h^+\right) + A_P\left(D^+_{(s)}\right)$$

$h^+ = K^+$ or $\pi^+$

Similarly for the control channel $D^+_{(s)} \to \Phi h^+$

**Measure:**

$$A_{CP}^{DD} = \left(A_{raw}\left(D_s^\pm \to K_s^0\pi^\pm\right) - A_{raw}\left(D_s^\pm \to K_s^0 K^\pm\right)\right) - \left(A_{raw}\left(D^\pm \to K_s^0\pi^\pm\right) - A_{raw}\left(D^\pm \to K_s^0 K^\pm\right)\right)$$

$$A_{CP}^{DD} \approx A_{CP}\left(D_s^\pm \to K_s^0\pi^\pm\right) + A_{CP}\left(D^\pm \to K_s^0 K^\pm\right)$$

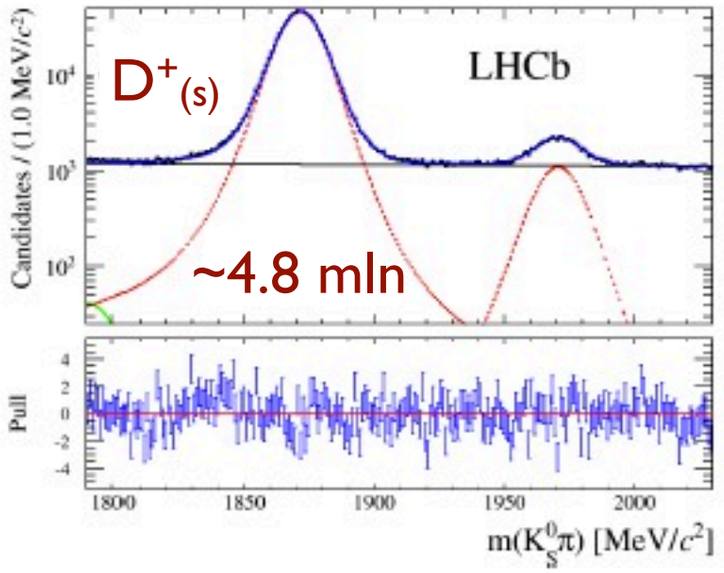
$$A_{CP}\left(D_s^\pm \to K_s^0\pi^\pm\right) \approx A_{raw}\left(D_s^\pm \to K_s^0\pi^\pm\right) - A_{raw}\left(D_s^\pm \to \Phi\pi^\pm\right)$$

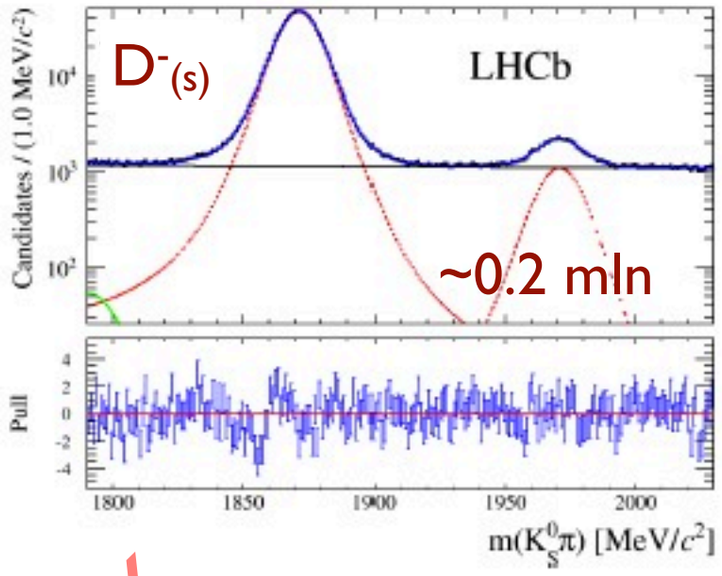
$$A_{CP}\left(D^\pm \to K_s^0 K^\pm\right) \approx \left(A_{raw}\left(D^\pm \to K_s^0 K^\pm\right) - A_{raw}\left(D_s^\pm \to K_s^0 K^\pm\right)\right) - \left(A_{raw}\left(D^\pm \to K_s^0\pi^\pm\right) - A_{raw}\left(D_s^\pm \to \Phi\pi^\pm\right)\right)$$

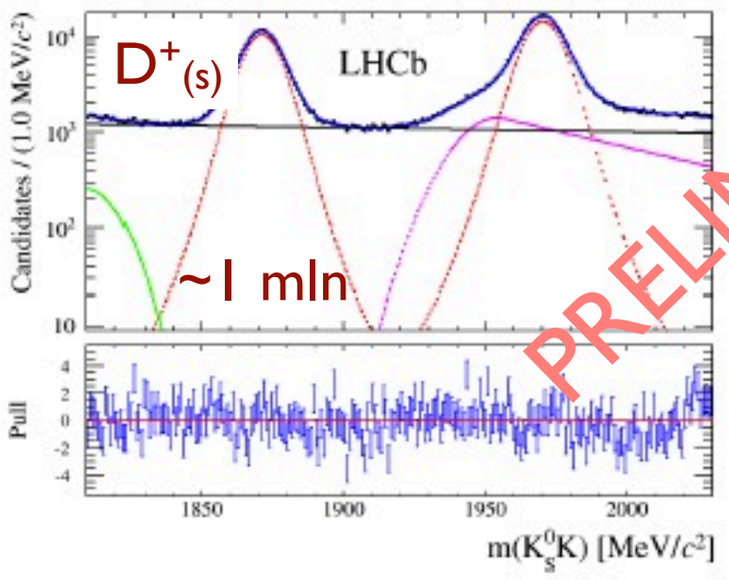
Cancel production and detection asymmetries

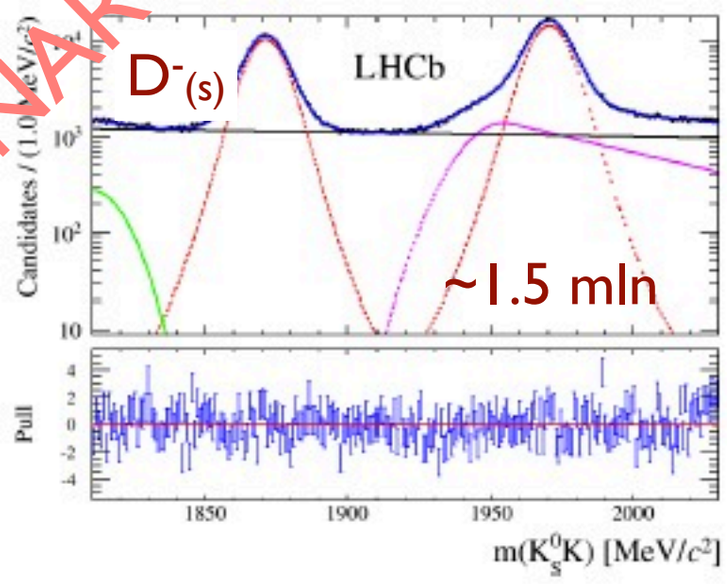
$A_{CP/\text{int}}(K^0)$: small effect from mixing , only $K^0$ decays with short times used

# Yields

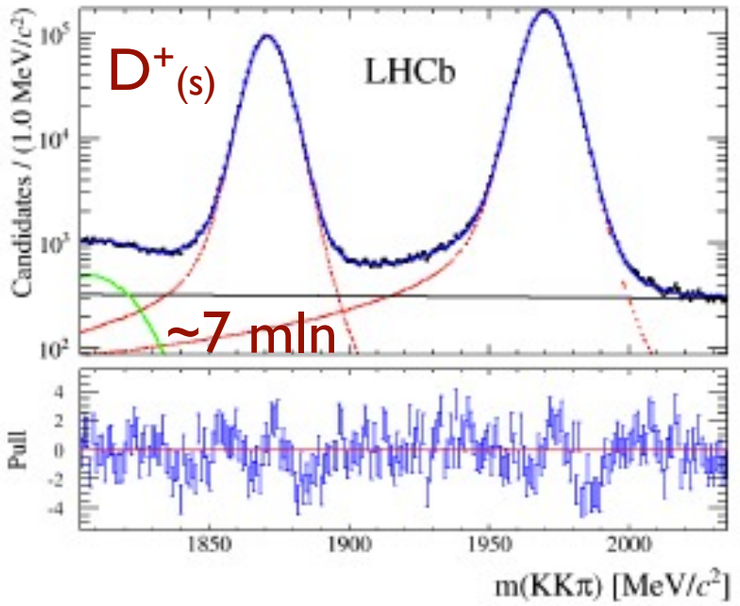


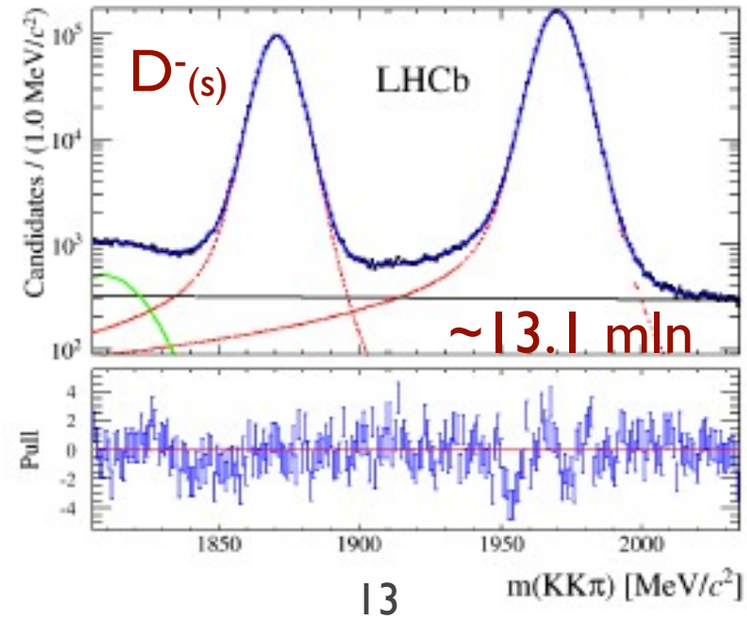






- Using 3 $fb^{-1}$ data (2011 and 2012 data)
- Regular magnet polarity swap
- 2011 and 2012 data independently analysed
- Simultaneous fit for up-down magnet polarities and $D^+/D^-$
- Kinematical re-weighting

LHCb-PAPER-2014-018

Signal: Cruijff function
Bkgd: comb: 1st order Chebychev polynomial; cross-feed: gaussian with power-law tail; partially reconstructed: gaussian

# PRELIMINARY Results

Systematic uncertainties:

LHCb-PAPER-2014-018

| | $\sqrt{s} = 7$ TeV | | | $\sqrt{s} = 8$ TeV | | |
|---|---|---|---|---|---|---|
| Source | $\mathcal{A}_{CP}^{DD}$ | $\mathcal{A}_{CP}^{D^\pm \to K_S^0 K^\pm}$ | $\mathcal{A}_{CP}^{D_s^\pm \to K_S^0 \pi^\pm}$ | $\mathcal{A}_{CP}^{DD}$ | $\mathcal{A}_{CP}^{D^\pm \to K_S^0 K^\pm}$ | $\mathcal{A}_{CP}^{D_s^\pm \to K_S^0 \pi^\pm}$ |
| Fit procedure | 0.14 | 0.09 | 0.11 | 0.07 | 0.05 | 0.01 |
| Cross-feed bkgd. | 0.03 | 0.01 | 0.02 | 0.01 | – | 0.01 |
| Non-prompt charm | 0.01 | – | – | 0.01 | – | – |
| Kinematics | 0.08 | 0.06 | 0.13 | 0.05 | 0.07 | 0.12 |
| Fiducial region | 0.10 | 0.06 | 0.04 | 0.19 | 0.02 | 0.17 |
| Trigger | 0.13 | 0.13 | 0.07 | 0.17 | 0.17 | 0.09 |
| $K^0$ $CP$ violation and regeneration | 0.03 | 0.02 | 0.02 | 0.04 | 0.02 | 0.02 |
| Total | 0.23 | 0.18 | 0.19 | 0.27 | 0.19 | 0.22 |

NEW

$$\mathcal{A}_{CP}^{D^\pm \to K_S^0 K^\pm} = (+0.03 \pm 0.17 \pm 0.14)\%$$

$$\mathcal{A}_{CP}^{D_s^\pm \to K_S^0 \pi^\pm} = (+0.38 \pm 0.46 \pm 0.17)\%.$$

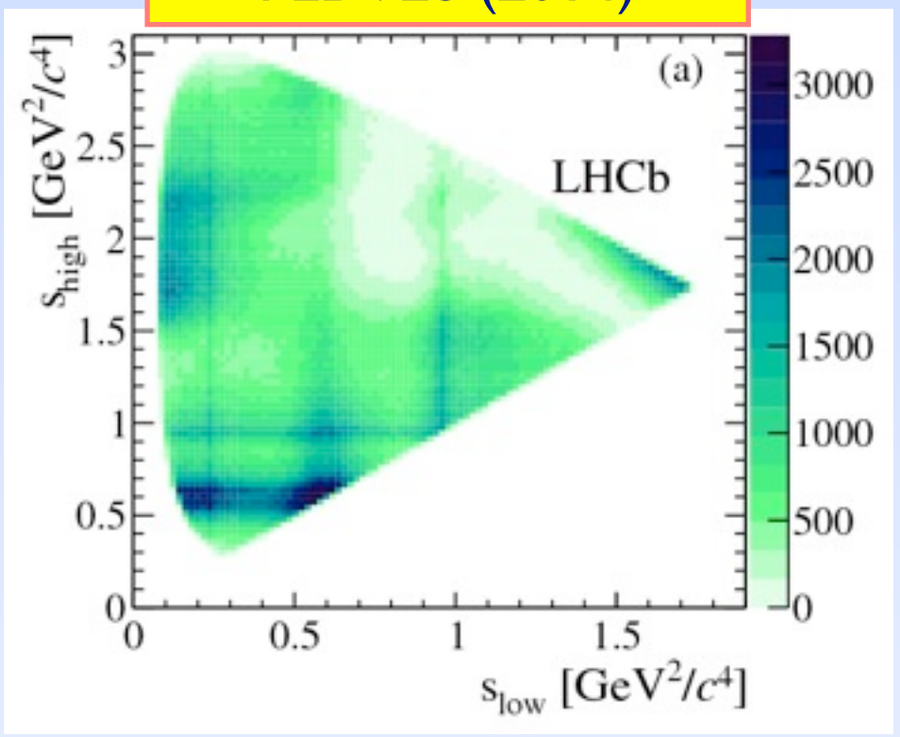
$$\mathcal{A}_{CP}^{D^\pm \to K_S^0 K^\pm|} + \mathcal{A}_{CP}^{D_s^\pm \to K_S^0 \pi^\pm} = (+0.41 \pm 0.49 \pm 0.26)\%.$$

Most precise measurement of these quantities

No indication for CPV

# CPV in $D^+ \to \pi^- \pi^+ \pi^+$

PLB 728 (2014)




Model-independent
searches for CP violation:

Local asymmetries might manifest:

- larger than the phase space integrated ones
- may change sign across the Dalitz plot
- additional information about the dynamics

Over 3M $D^+$ & $D^-$ decays in 1 $fb^{-1}$ (2011 data)

2 complementary methods:

✓ Search for asymmetry significances in bins of phase space

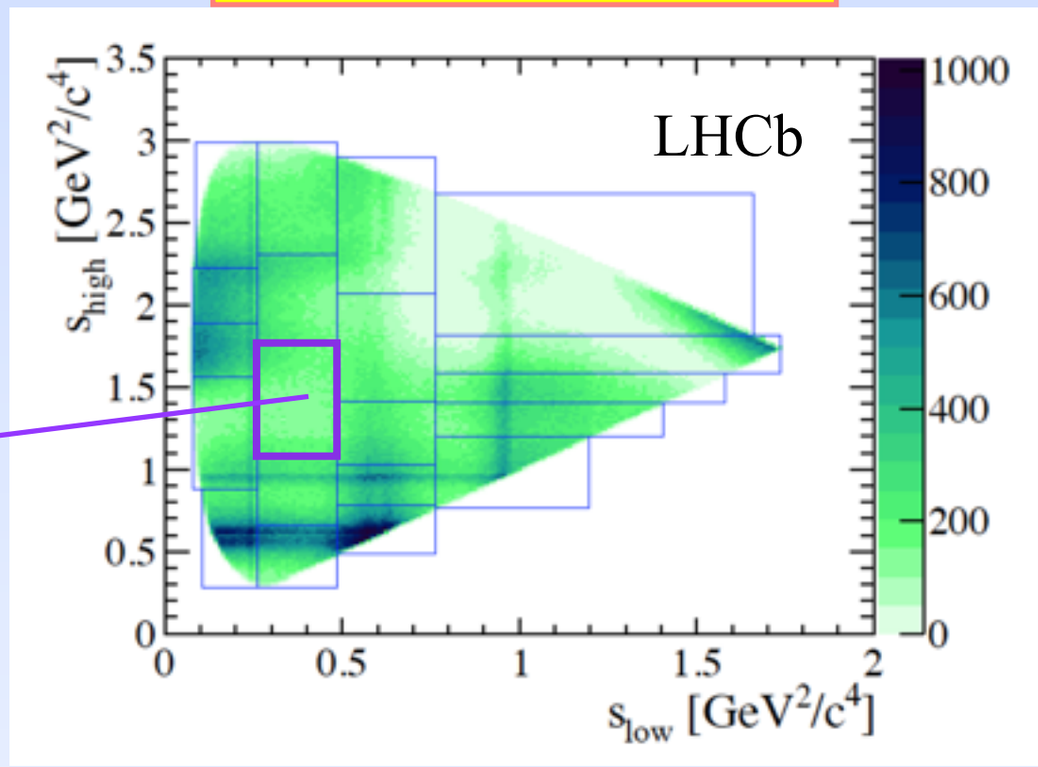
✓ Search for local asymmetries through un-binned comparison with nearest neighbours

PLB 728 (2014) 585-595

# Binned method

asymmetry significance

$$\mathcal{S}^i_{CP} = \frac{N^i(D^+) - \alpha N^i(D^-)}{\sqrt{N^i(D^+) + \alpha^2 N^i(D^-)}}$$




$$\alpha = \frac{N_{\rm tot}(D^+)}{N_{\rm tot}(D^-)}$$

removes sensitivity to global asymmetries

$$\chi^2 = \sum (\mathcal{S}^i_{CP})^2$$

p-values for no-CPV hypothesis
> 50% for different binnings

No CPV

With 2011 data sensitive to 1°-10° differences in phase and 1-10% in magnitude

# Mixing in charm

$$D^0 \rightarrow \overline{D}^0 \rightarrow D^0 \rightarrow \overline{D}^0$$

$$|M_{1,2}\rangle = p|M^0\rangle \pm q|\overline{M}^0\rangle$$

Mass eigenstates

Flavour eigenstates

$$y \equiv \Delta\Gamma/(2\Gamma)$$

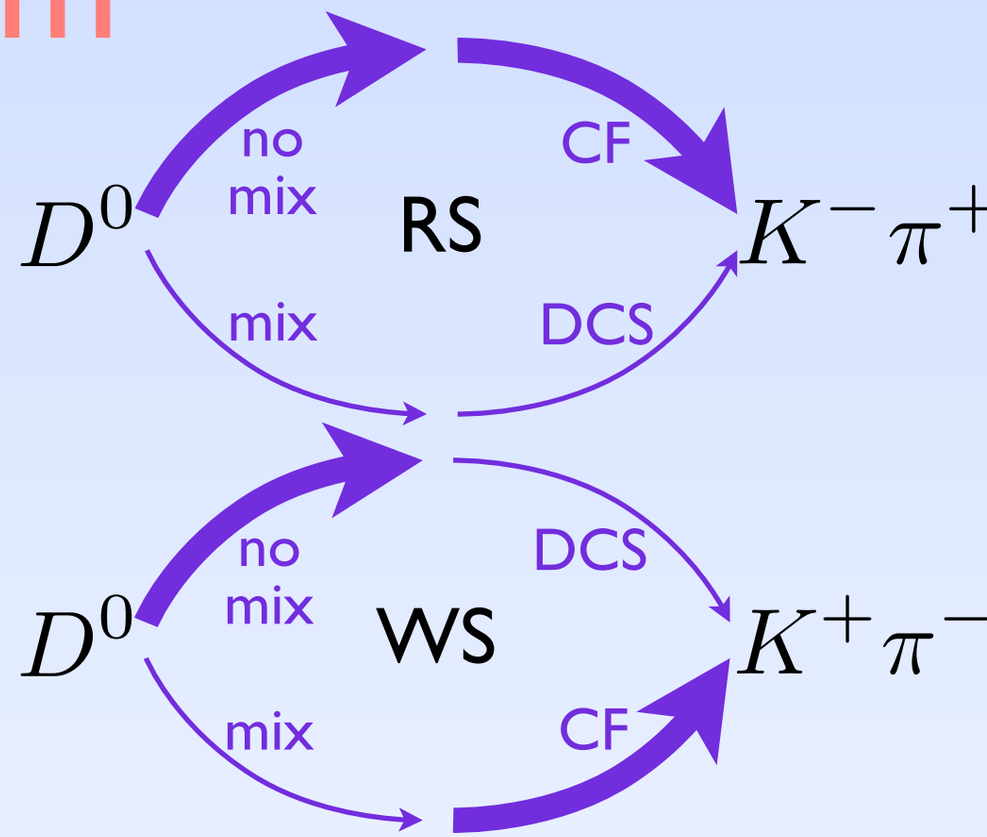
$$x \equiv \Delta m/\Gamma$$

# CPV and mixing in charm

- Measure the ratio of WS to RS events

$$R(t) \equiv \frac{N_{WS}(t)}{N_{RS}(t)} \approx R_d + \sqrt{R_D} y' \frac{t}{\tau} + \frac{x'^2 + y'^2}{4} (\frac{t}{\tau})^2$$

  - $x'^{\pm} = |q/p|^{\pm 1}(x' \cos\Phi \pm y' \sin\Phi)$
  - $y'^{\pm} = |q/p|^{\pm 1}(y' \cos\Phi \mp x' \sin\Phi)$



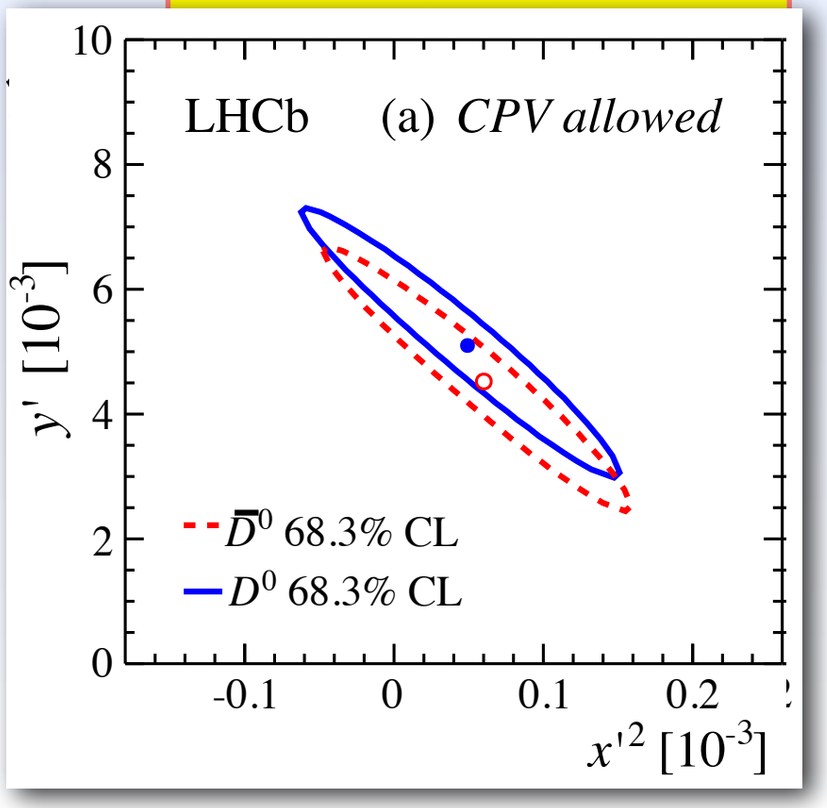

- Measurements use prompt $D^0 \to K\pi$ decays (3 fb$^{-1}$): split by flavour

| | | |
|---|---|---|
| $R_D^+$ | $[10^{-3}]$ | $3.545 \pm 0.082 \pm 0.048$ |
| $y'^+$ | $[10^{-3}]$ | $5.1 \pm 1.2 \pm 0.7$ |
| $x'^{2+}$ | $[10^{-5}]$ | $4.9 \pm 6.0 \pm 3.6$ |
| $R_D^-$ | $[10^{-3}]$ | $3.591 \pm 0.081 \pm 0.048$ |
| $y'^-$ | $[10^{-3}]$ | $4.5 \pm 1.2 \pm 0.7$ |
| $x'^{2-}$ | $[10^{-5}]$ | $6.0 \pm 5.8 \pm 3.6$ |

No direct or indirect CPV

Most stringent constraint on the magnitude of q/p

PRL 111 (2013) 251801



# Indirect CPV

CPV in mixing and/or the interference
of direct CPV and mixing;
time dependent

# Indirect CP violation in $D^0 \to h^+h^-$

- Measure asymmetries of effective lifetimes of decays to CP eigenstates:

$A_\Gamma \approx A_M\, y \cos\phi + x \sin\phi \equiv -a_{CP}^{ind}$

(Neglecting $A_d\, y \cos\phi$)

$$A_M = \frac{|q/p|^2 - |p/q|^2}{|q/p|^2 + |p/q|^2}$$

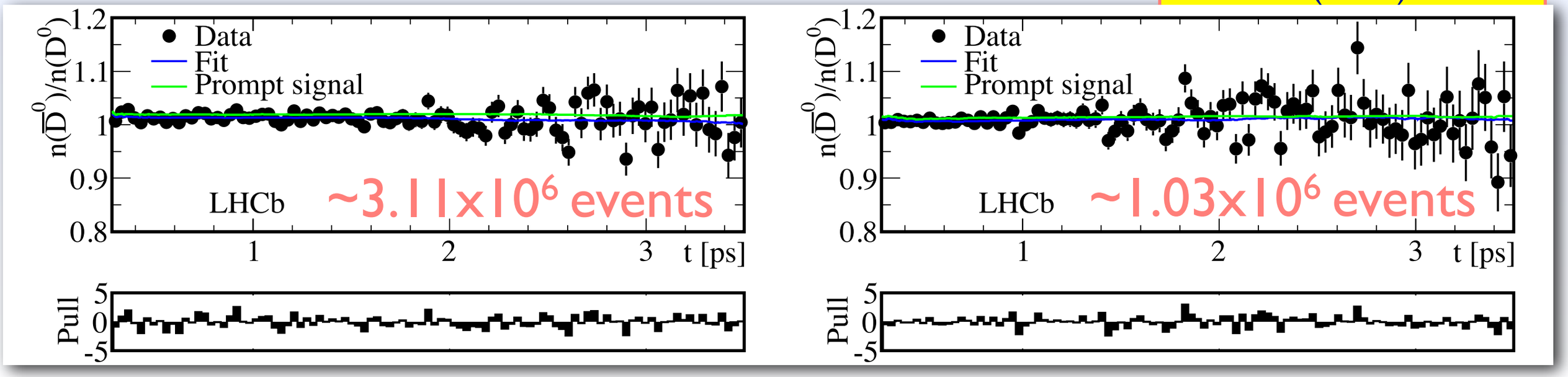
- Measurements use prompt $D^0 \to K^-K^+$ and $D^0 \to \pi^-\pi^+$ decays (1 $fb^{-1}$)

$A_\Gamma(KK) = (-0.35 \pm 0.62 \pm 0.12) \times 10^{-3}$

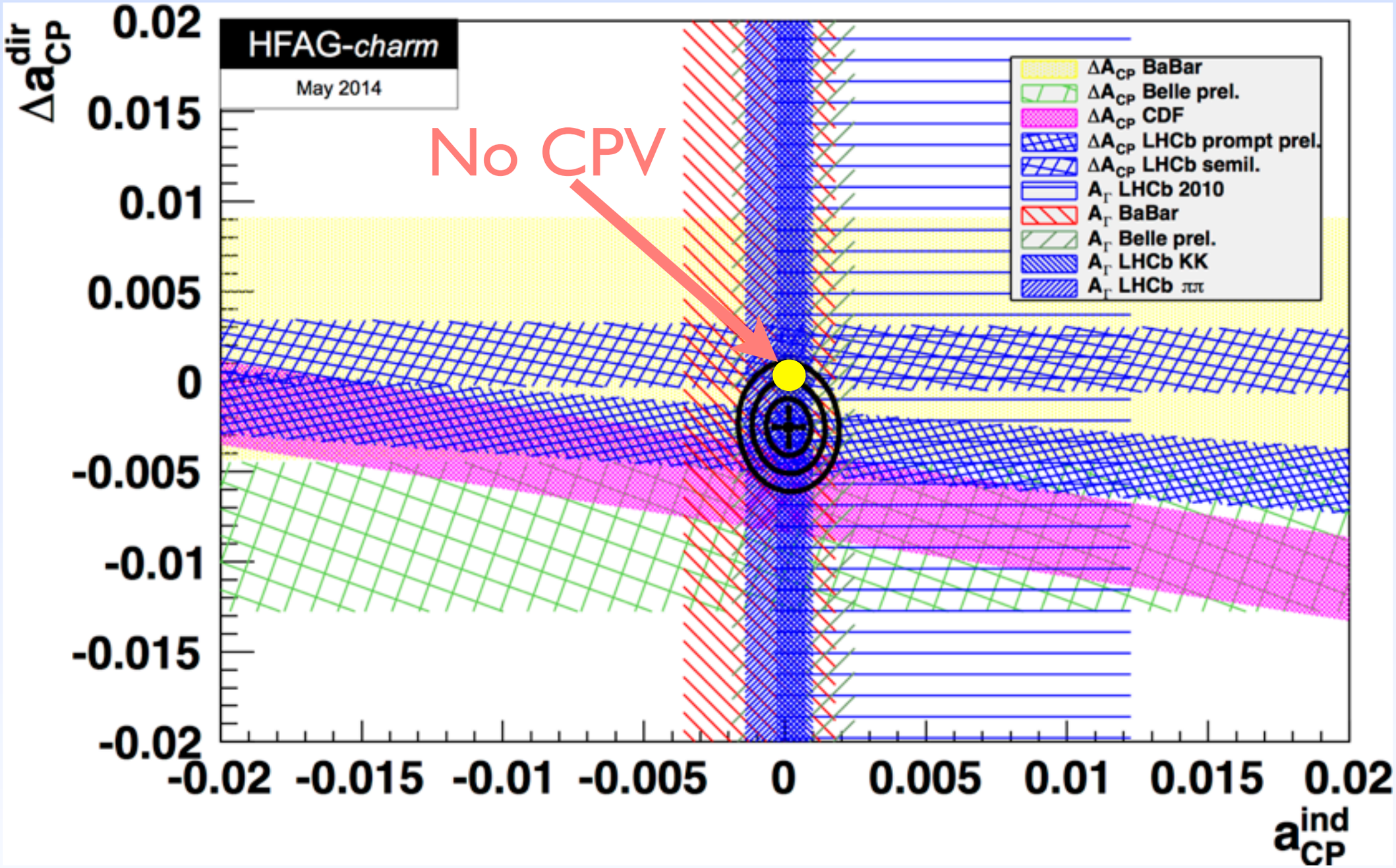
$A_\Gamma(\pi\pi) = (0.33 \pm 1.06 \pm 0.14) \times 10^{-3}$

Most precise measurement of CP asymmetries

PRL 112 (2014) 041801



# HFAG averages




$a_{CP}^{ind} = 0.00013 \pm 0.00052$

$\Delta a_{CP}^{dir} = -0.00253 \pm 0.00104$

# Conclusions

- Precision CPV measurements in the charm sector at LHCb
- Reached sub-$10^{-3}$ precision
- No evidence for direct and indirect CPV