Mixing and CPV in charm hadrons at LHCb

Wojciech Krzemień

On behalf of the LHCb collaboration

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LHCb

NCBJ

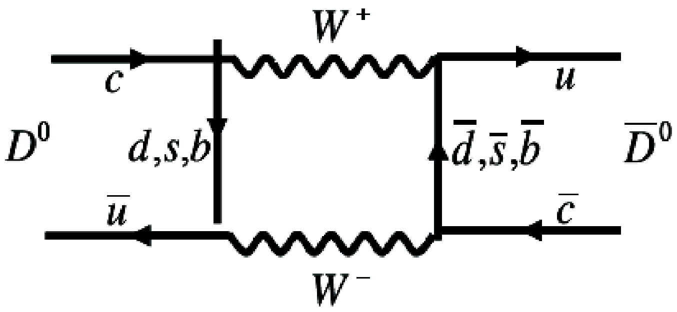
NATIONAL SCIENCE CENTRE POLAND

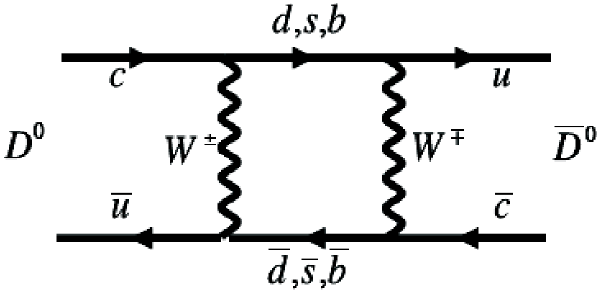
Outline

- Introduction
- Mixing and CP studies in $D^0 \to K^+\pi^-$ decays
- Search for direct CPV with $D^+_{(s)} \to \eta'\pi^+$ decay
- A_Γ measurements with $D^0 \to h^+h^-$
- Summary& Outlook

Neutral flavour mesons mixing

Weak interactions do not conserve the flavour





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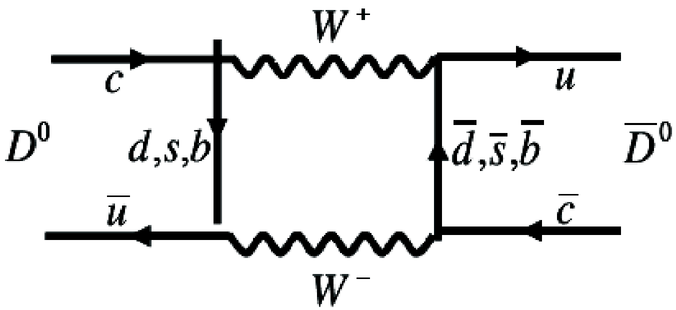

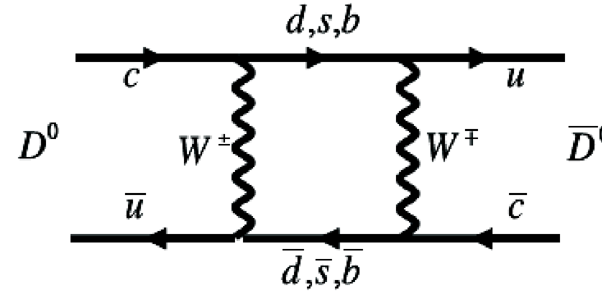

Flavour states are not eigenvectors of the full Hamiltonian

$$\frac{\partial}{\partial t}|\Phi> = H|\Phi>$$

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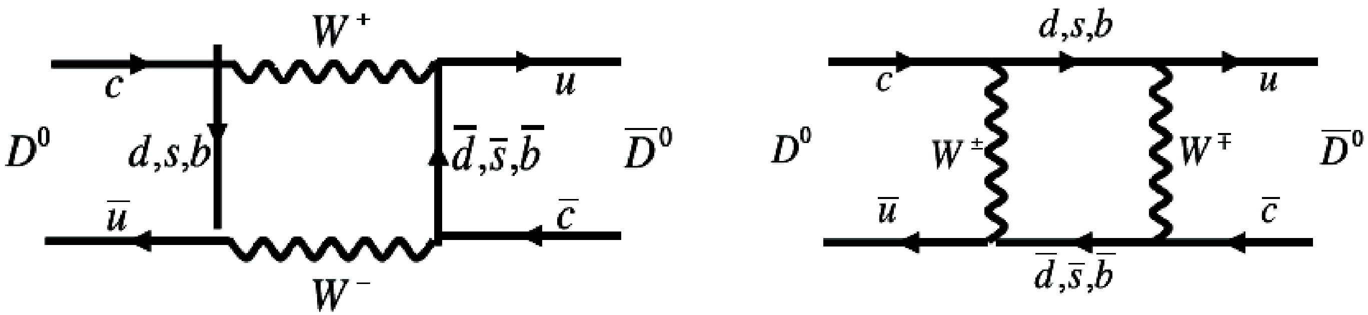

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Mass eigenstates expressed as a superposition of flavour eigenstates :

$|D_{1,2}\rangle = p|\mathrm{D}^0\rangle \pm q|\overline{\mathrm{D}}^0\rangle$ $|p|^2 + |q|^2 = 1$ *p, q* are complex

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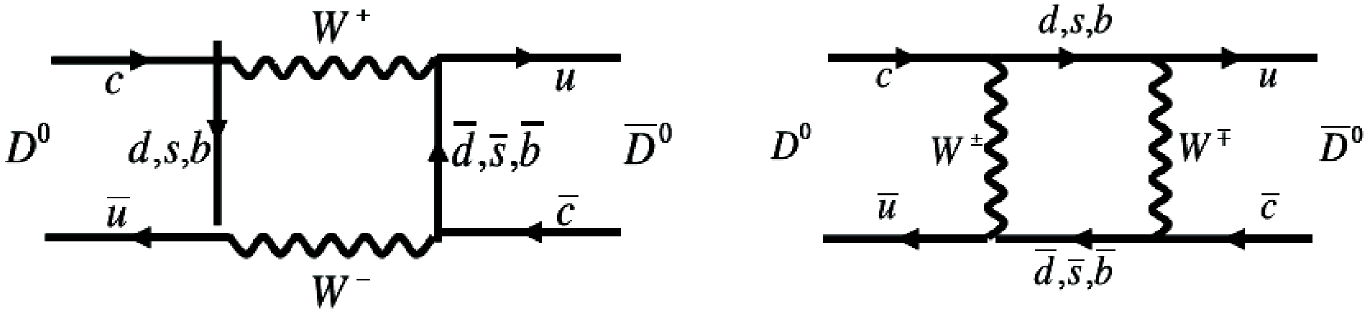

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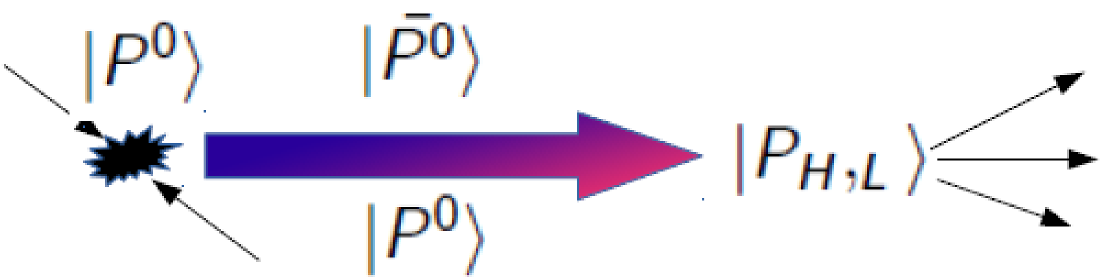

Neutral flavour mesons mixing II

Probabilities of mixing:

$Pr[P^0 \rightarrow P^0] \sim e^{-\Gamma t} (\cosh(y\Gamma t) + \cos(x\Gamma t))$

$Pr[P^0 \rightarrow \overline{P}^0] \sim e^{-\Gamma t} |q/p|^2 (\cosh(y\Gamma t) - \cos(x\Gamma t))$

Mixing parameters:

$$x = \frac{\Delta m}{\Gamma} \qquad \Delta\Gamma = \Gamma_1 - \Gamma_2$$

$$y = \frac{\Delta\Gamma}{2\Gamma} \qquad \Delta m = m_1 - m_2$$

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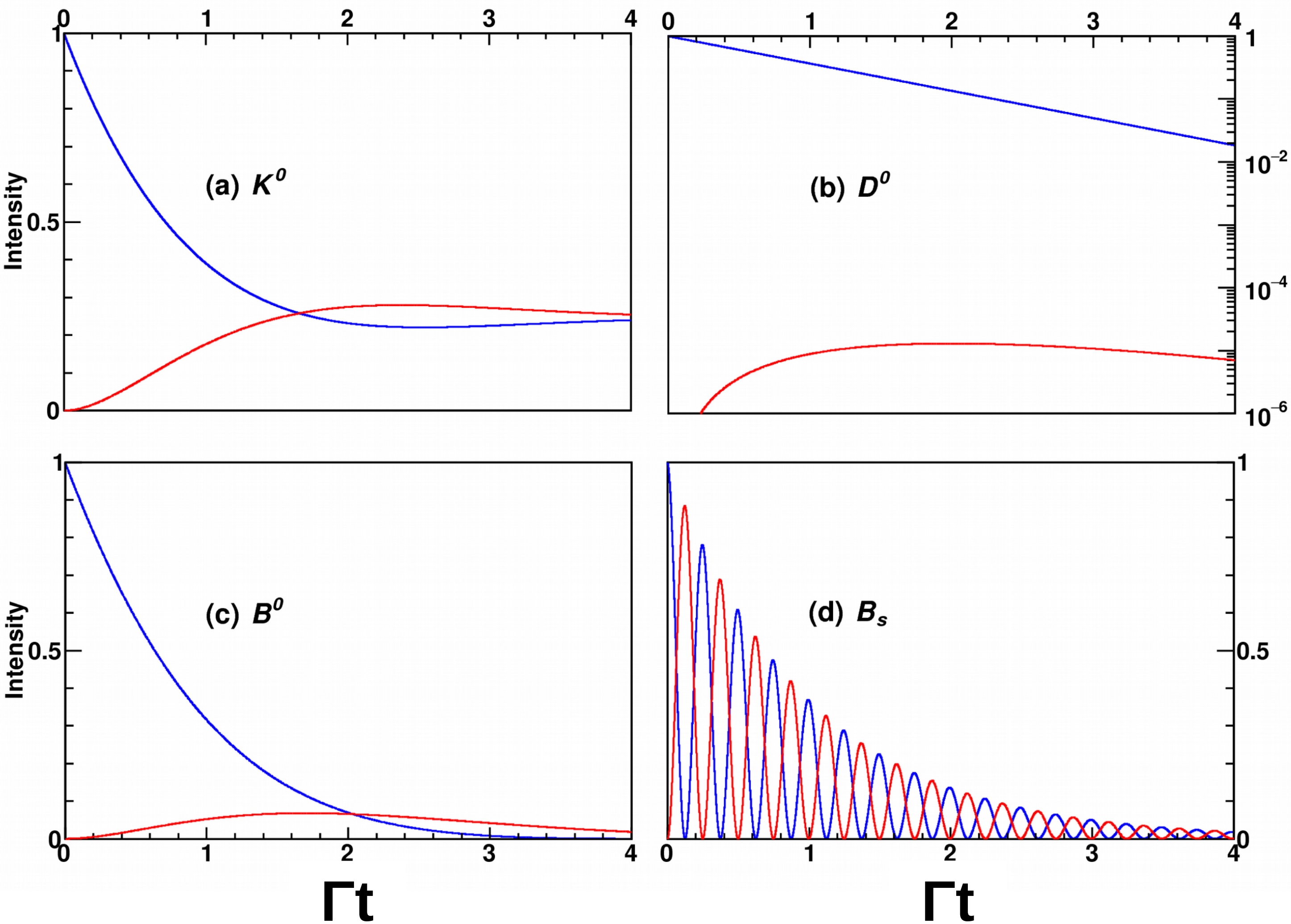

D^0 very slow:
$x \approx 0.001$, $y \approx 0.001$

K^0 slow:
$X \approx -0.95$, $y = 0.99$

B^0 fast:
$x \approx 0.78$, $y < 0.01$

B^0_s the fastest:
$x \approx 26.1$, $y \approx 0.15$

CP violation and its types

C – charge conjugation (particle → antiparticle) $\hat{C}|\vec{r},t,q>=e^{i\alpha_1}|\vec{r},t,-q>$

P – partity (spatial reflection) $\hat{P}|\vec{r},t,q>=e^{i\alpha_2}|-\vec{r},t,q>$

The CP discrete symmetry is broken if: $\lambda_f \equiv q/p\ \overline{A}_{\bar{f}}/A_f \neq 1$

CP violation in decay

$$\Gamma(P^0 \rightarrow f) \neq \Gamma(\bar{P}^0 \rightarrow \bar{f})$$

$$|\overline{A}_{\bar{f}}/A_f| \neq 1$$

- Depends on decay mode
- At least one amplitude with different strong and weak phases

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CP violation in mixing

$$\Gamma(P^0 \to \bar{P}^0) \neq \Gamma(\bar{P}^0 \to P^0)$$

$$|q/p| \neq 1$$

- Not depends on decay mode
- only for neutral mesons

CP violation in interference between mixing and decay

$$\Gamma(P^0 \to \bar{P}^0 \to f_{CP}) \neq \Gamma(\bar{P}^0 \to P^0 \to f_{CP})$$

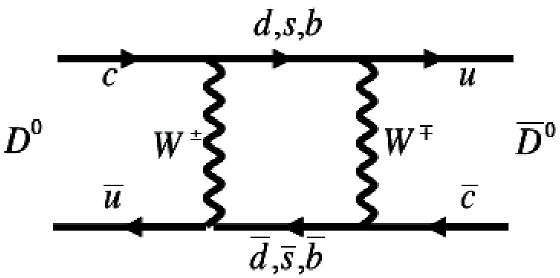
Relative phase between q/p and $\bar{A}_{\bar{f}}/A_f$ non-zero

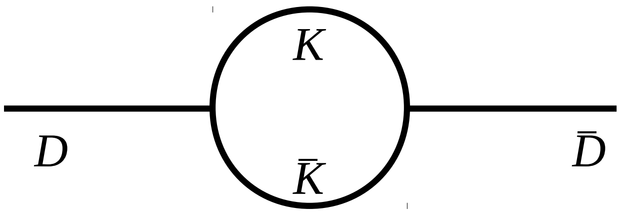
Mixing and CPV in charm

Standard Model predictions (PDG2016):

- **Predictions for mixing very imprecise**

  x, y: **O(10^{-2})- O(10^{-7})**





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- **Almost no CPV effects expected ~ O(10^{-3})**

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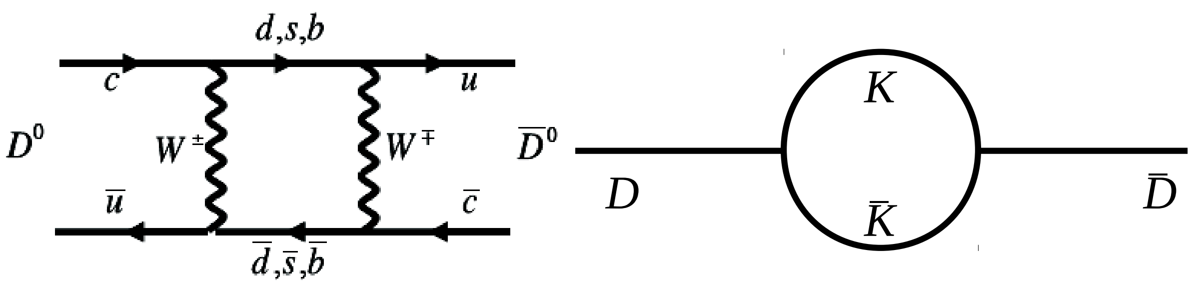

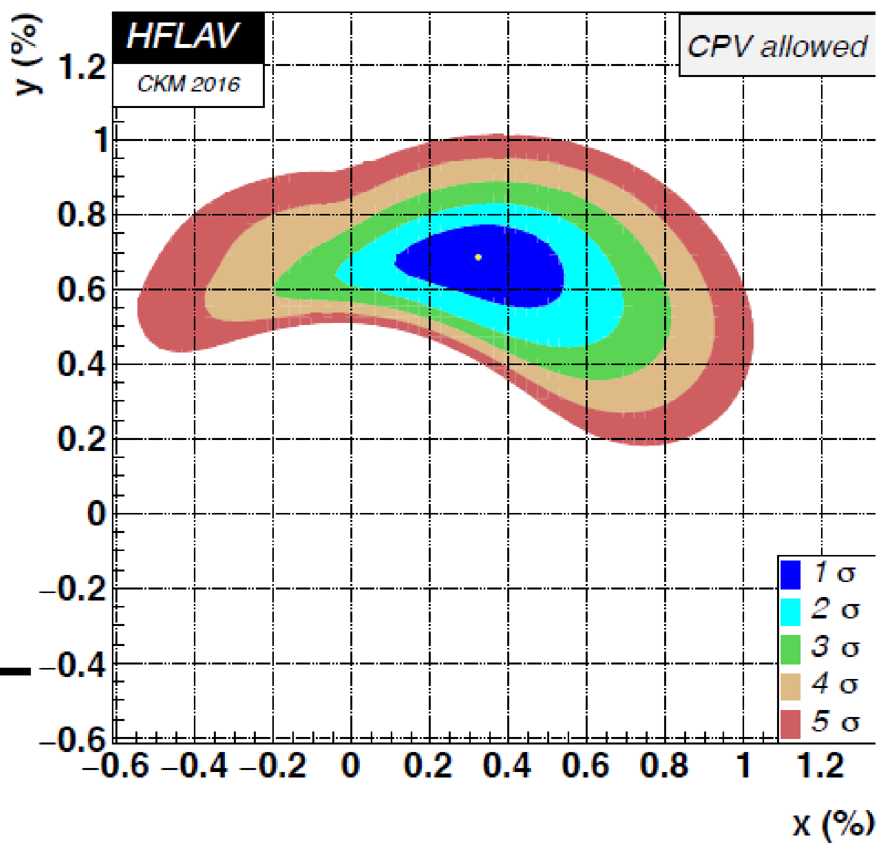

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Experimental status:

- **Mixing established (~ 11 σ effect)**
  - First evidence Babar, Belle, CDF: PRL 98 (2007) 211802, PRL 98 (2007) 211803, PRL 100 (2008) 121802
  - Recent LHCb measurement: PRL 113 (2013) 231802
- **No CPV observed so far**

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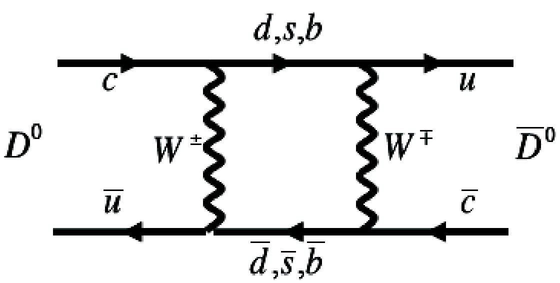

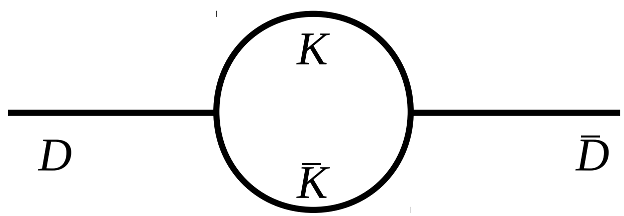

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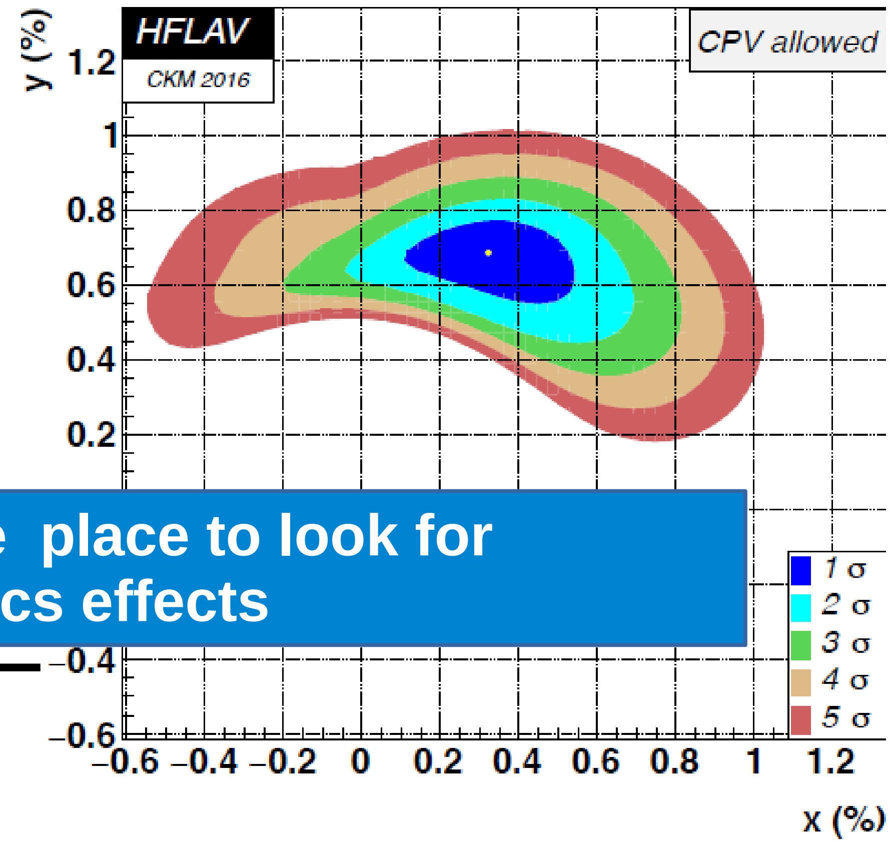
Charm as a unique place to look for New Physics effects



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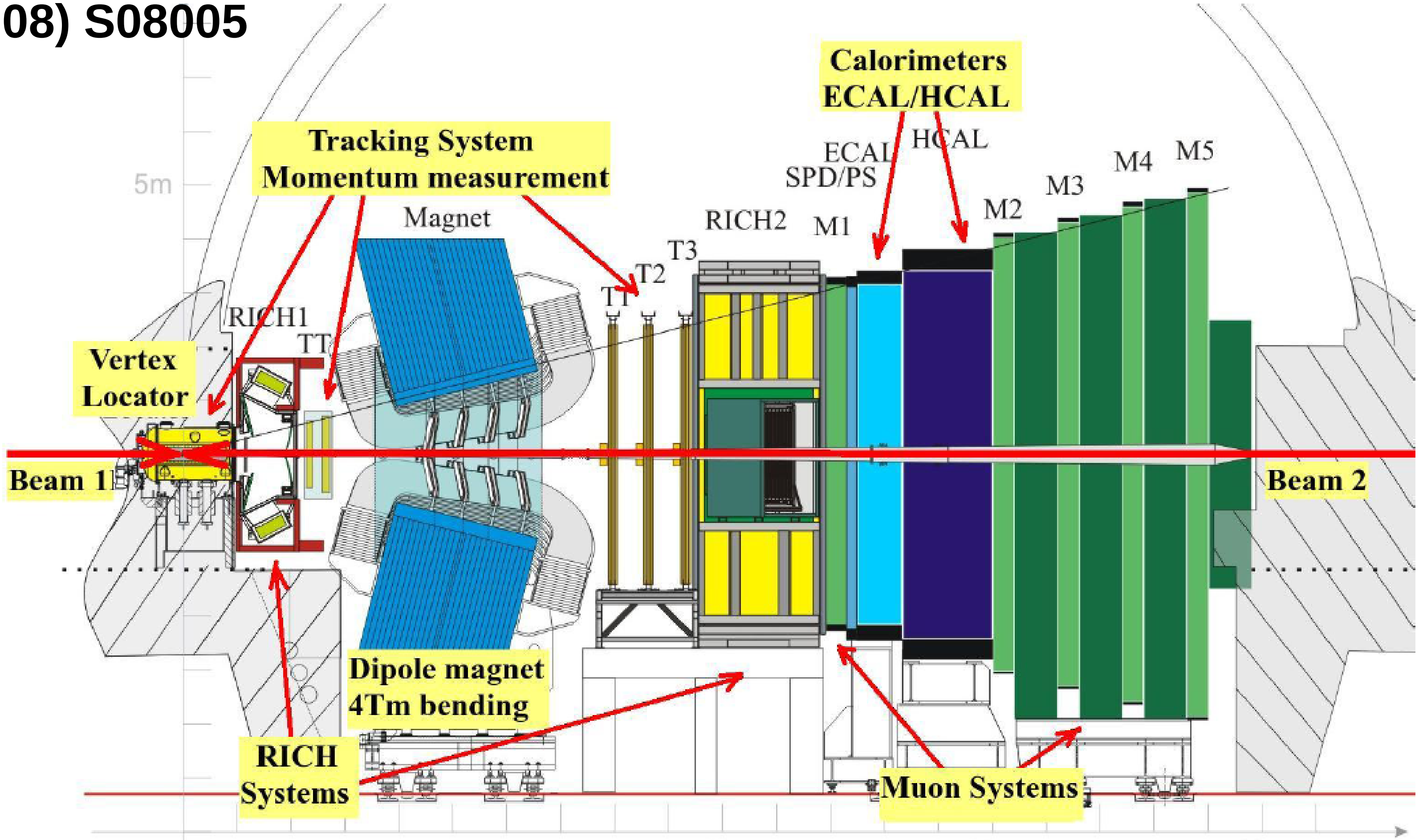
Large Hadron Collider Beauty detector

JINST 3 (2008) S08005



- Single-arm forward spectrometer covering range $2 < \eta < 5$ ($10 < \theta < 300$ mrad)
- Momentum resolution $\Delta p/p$ = 0.5 % @ 5 GeV/c to 1% @ 200 GeV/c
- Impact parameter resolution: 20 μm from high p_T tracks, decay lifetime ~45 fs

Charm in LHCb

LHCb-CONF-2016-005

- Charm produced copiously in the pp collisions:

  $\sigma(pp \rightarrow c\bar{c})$ ~ 1419 μb @ 7 TeV

  Nucl.Phys.B871(2016)1

  $\sigma(pp \rightarrow c\bar{c})$ ~ 2940 μb @ 13 TeV

  JHEP03(2016) 159

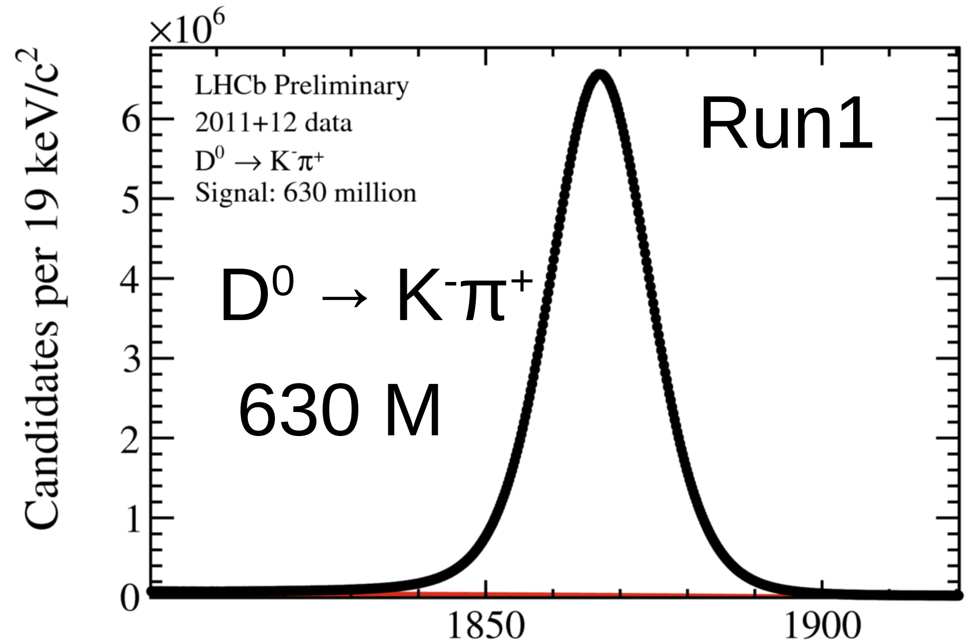
- In Run I 2011-2012 (L = 3 fb^{-1}) produced:

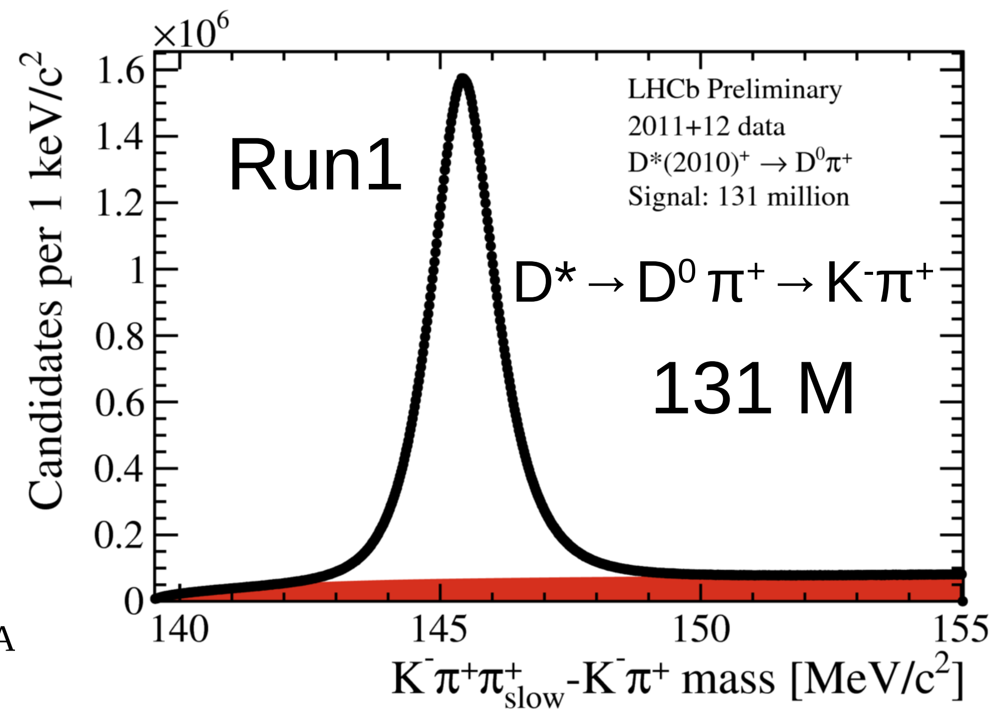
  ~5 x 10^{12} D^0,

  ~2 x 10^{12} D^{*+}

  ~**30 x larger collected statistics than previous experiments**

- In Run II: higher cross-sections due to higher energy and improved trigger





Mixing and CP studies in $D^0 \to K^+\pi^-$ decays

Right Sign

Wrong Sign

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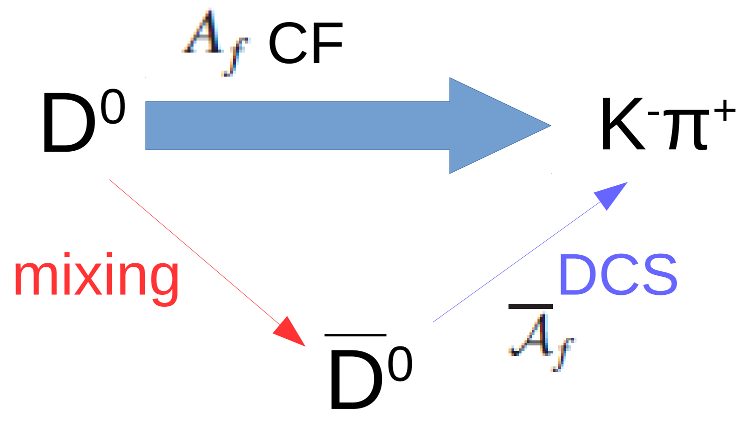

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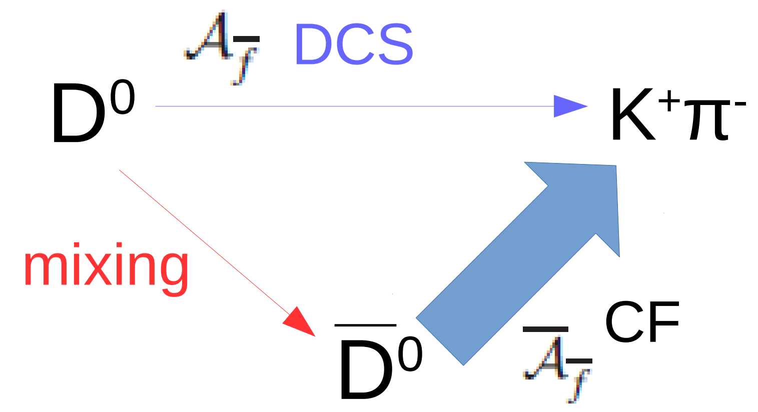


Wrong Sign

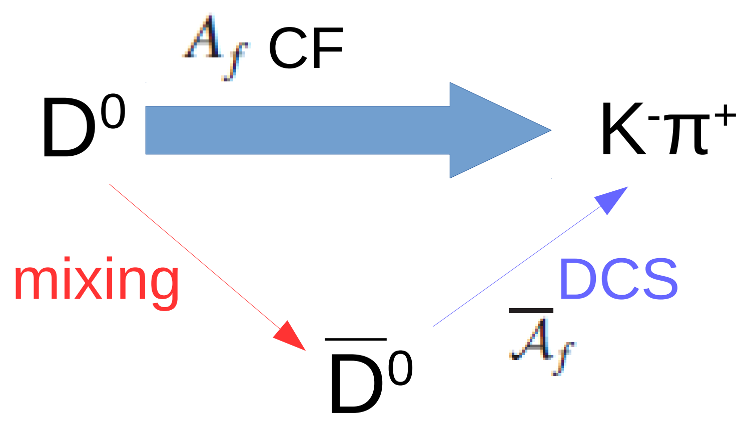
Assuming small values of x and y parameters the ratio R(t) = WS/RS (t):

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

$$R_D^{+} = |\mathcal{A}_{\bar{f}}/\mathcal{A}_f|^2 \qquad R_D^{-} = |\overline{\mathcal{A}}_f/\overline{\mathcal{A}}_{\bar{f}}|^2$$

- $x' = x\cos(\delta) + y\sin(\delta)$
- $y' = y\cos(\delta) + x\sin(\delta)$

Mixing and CP studies in $D^0 \to K^+\pi^-$ decays



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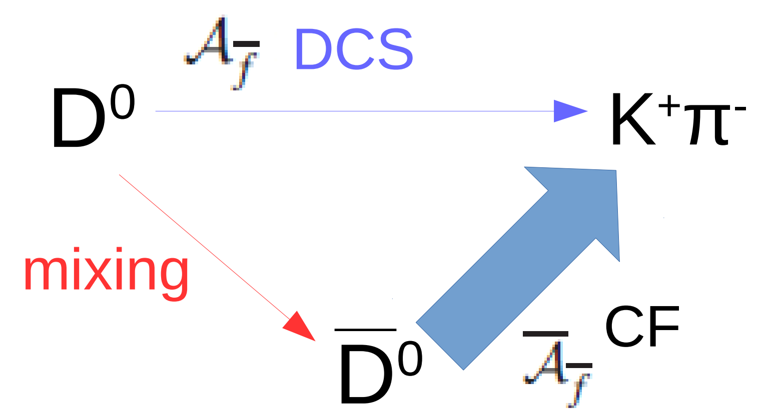

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- $x' = x\cos(\delta) + y\sin(\delta)$
- $y' = y\cos(\delta) + x\sin(\delta)$

If $R^+(t) \neq R^-(t)$ then CP is violated:

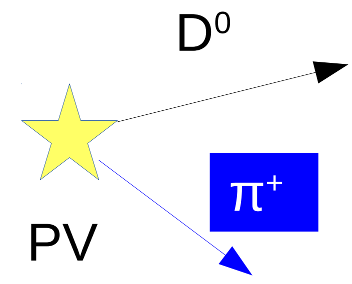
- $R^+_D \neq R^-_D$ direct CPV
- $x'^+ \neq x'^-$ or $y'^+ \neq y'^-$ indirect CPV

SM expectation for CPV in mixing ~O(10^{-3})

Mixing and CP studies in $D^0 \to K^+\pi^-$ decays

- Run I data sample 2011 and 2012 (3 fb^{-1} pp @7 TeV and @8 TeV)
- Time-dependent asymmetry R(t)
- Double-tagged data : $\overline{B} \to D^{*+}\mu^- X$, $D^{*+} \to D^0\pi^+$
- Fit D^* mass to extract D^0 in five time bins
- Correct for time-dependent detector effects

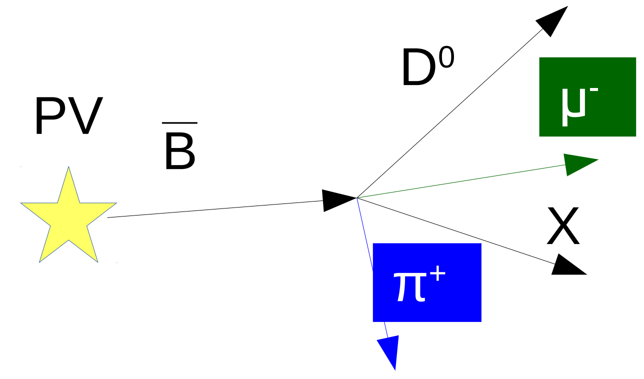
Prompt charm:



pp → D^{*+}

D^{*+} → $D^0\pi^+$

Double-tagged secondary charm



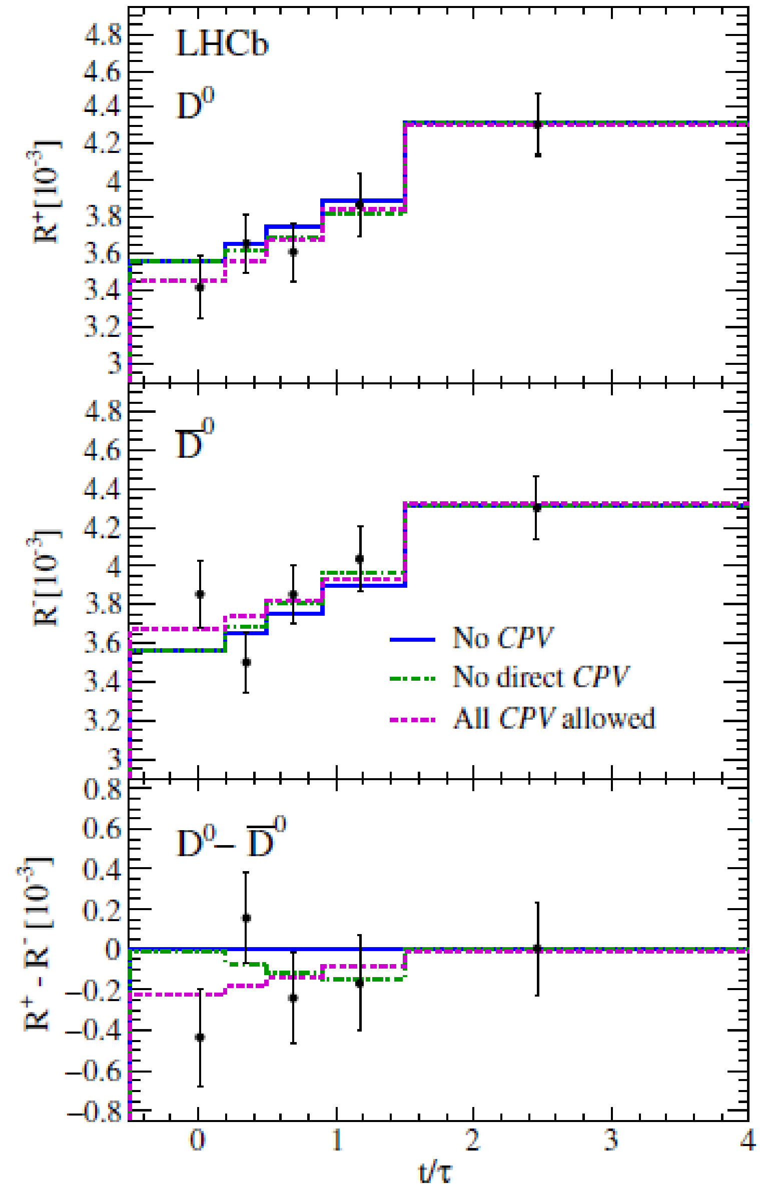
pp → $\overline{B} \to D^{*+}\mu^- X$

D^{*+} → $D^0\pi^+$

Phys. Rev. D 95 (2017) 052004

Mixing and CP studies in $D^0 \to K^+\pi^-$ decays

- Run I data sample 2011 and 2012 (3 fb^{-1} pp @7 TeV and @8 TeV)
- Time-dependent asymmetry R(t)
- Double-tagged data : $\overline{B} \to D^{*+}\mu^- X$, $D^{*+} \to D^0\pi^+$
- Fit D^* mass to extract D^0 in five time bins
- Correct for time-dependent detector effects
- Three fit scenario considered:
  - **No CPV allowed**
  - No direct CPV allowed
  - All CPV allowed



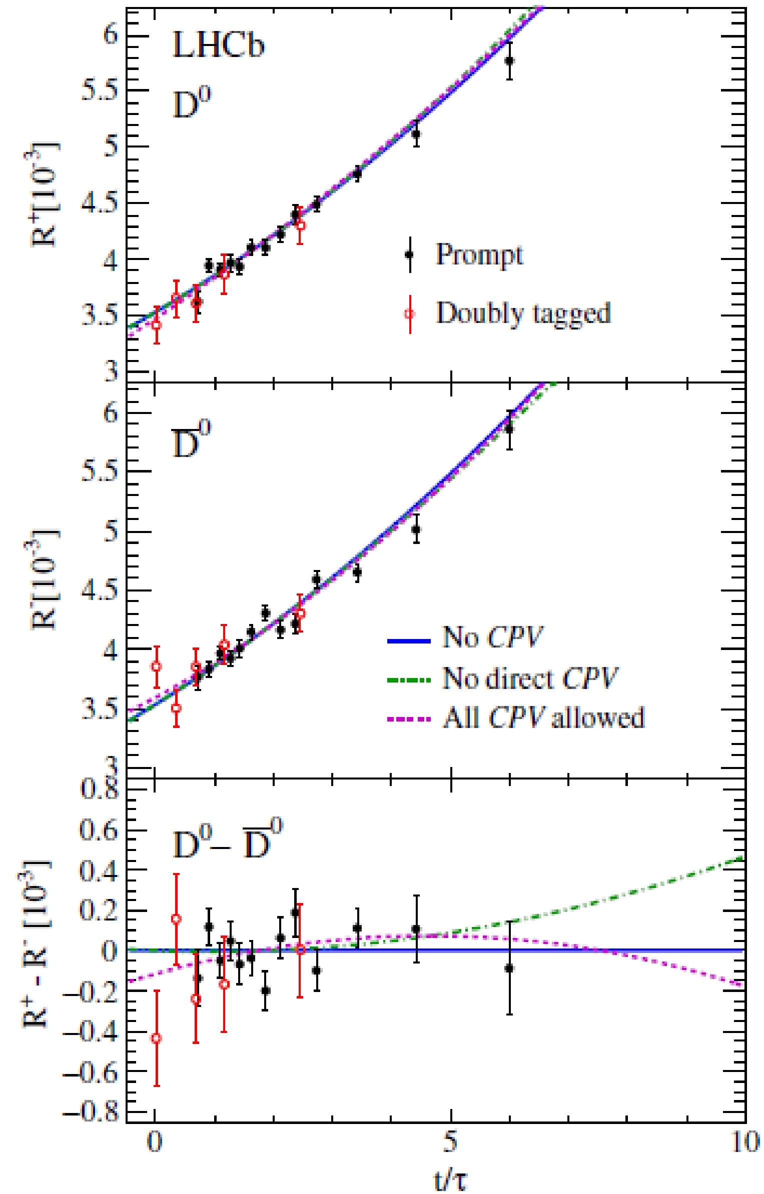
Consistent with non-CPV hypothesis

Phys. Rev. D 95 (2017) 052004

Mixing and CP studies in $D^0 \to K^+\pi^-$ decays

- Combined fit using to independent data samples:
  - Double-tagged (DT) sample
  - Prompt sample (**PRL 111 (2013) 251801**)
- Complementary decay-time coverage and higher purity for DT
- Precision improved by 10-20 % (DT sample 2.5% of signal)

	All CPV allowed	
$R_D^+[10^{-3}]$	3.474 ± 0.081	3.545 ± 0.095
$(x'^+)^2[10^{-4}]$	0.11 ± 0.65	0.49 ± 0.70
$y'^+[10^{-3}]$	5.97 ± 1.25	5.1 ± 1.4
$R_D^-[10^{-3}]$	3.591 ± 0.081	3.591 ± 0.090
$(x'^-)^2[10^{-4}]$	0.61 ± 0.61	0.60 ± 0.68
$y'^-[10^{-3}]$	4.50 ± 1.21	4.5 ± 1.4
χ^2/ndf	95.0/108	85.9/98

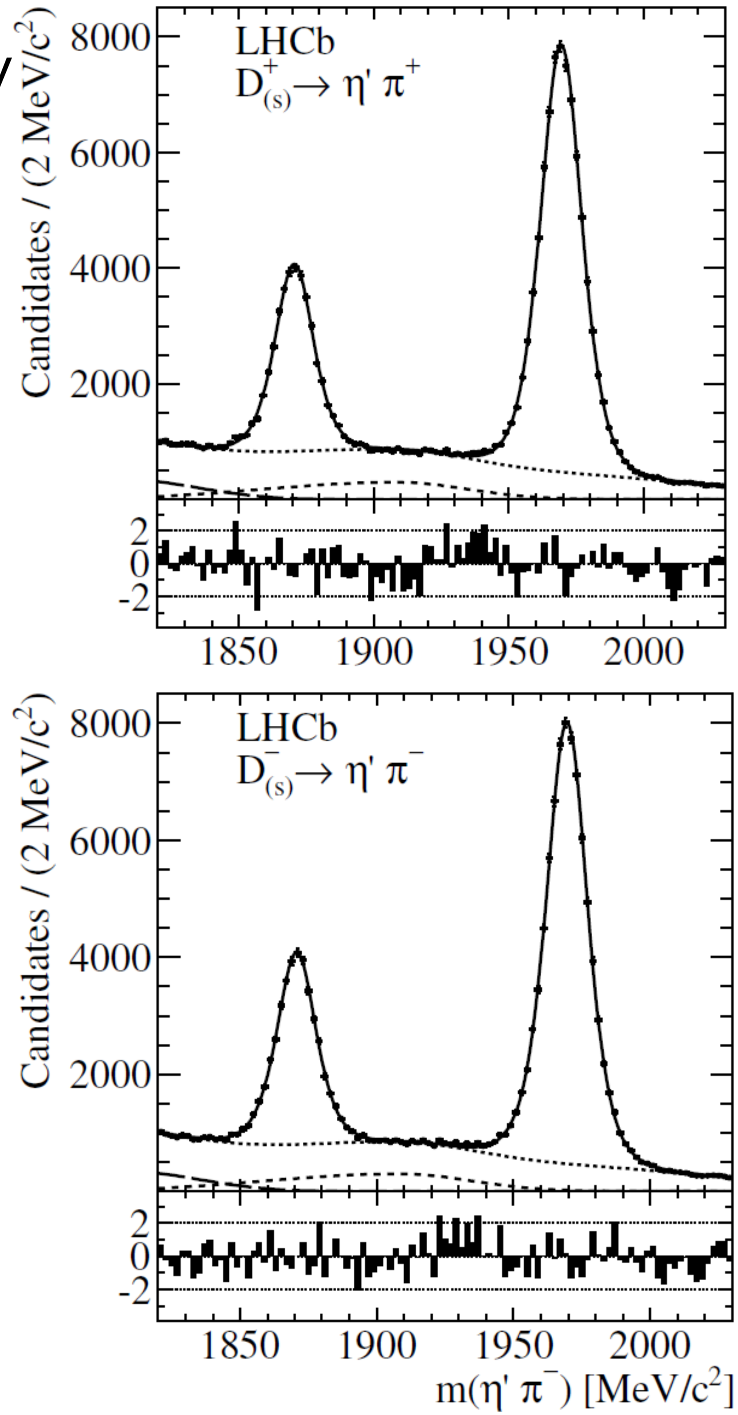


Consistent with non-CPV hypothesis

Phys. Lett. B 771 (2017) 21

Search for direct CPV with $D^+_{(s)} \to \eta'\pi^+$ decay

- Run I data sample 2011 and 2012 (3 fb^{-1} pp @7 TeV and @8 TeV)
- Reconstruction of $\eta' \to \pi^-\pi^+\gamma$
- 63 x 10^3 $D^\pm$, 152 x 10^3 $D^\pm_{(s)}$
- Never measured before at hadron colliders



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- Measured with respect to the control channels to eliminate the detector and production asymmetries

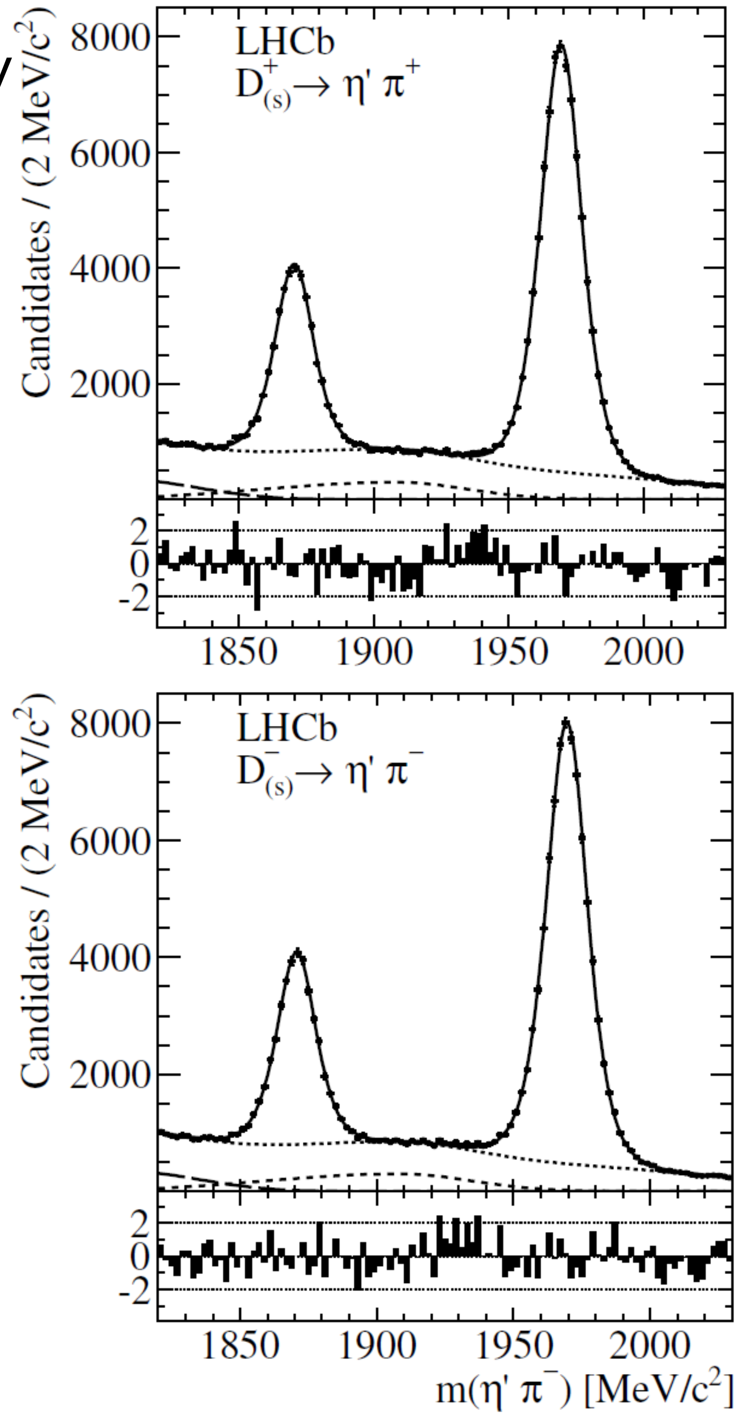
$$\mathcal{A}_{CP}(D^\pm \to \eta'\pi^\pm) \approx \Delta\mathcal{A}_{CP}(D^\pm \to \eta'\pi^\pm) + \mathcal{A}_{CP}(D^\pm \to K^0_S\pi^\pm)$$

$$\mathcal{A}_{CP}(D^\pm_s \to \eta'\pi^\pm) \approx \Delta\mathcal{A}_{CP}(D^\pm_s \to \eta'\pi^\pm) + \mathcal{A}_{CP}(D^\pm_s \to \phi\pi^\pm)$$

A_{CP} known from previous measurements at level $O(10^{-3})$:

Belle: PRL 102 (2012) 021601, erratum:PRL 102 (2012)119903

D0: PRL 112 (2014) 111804



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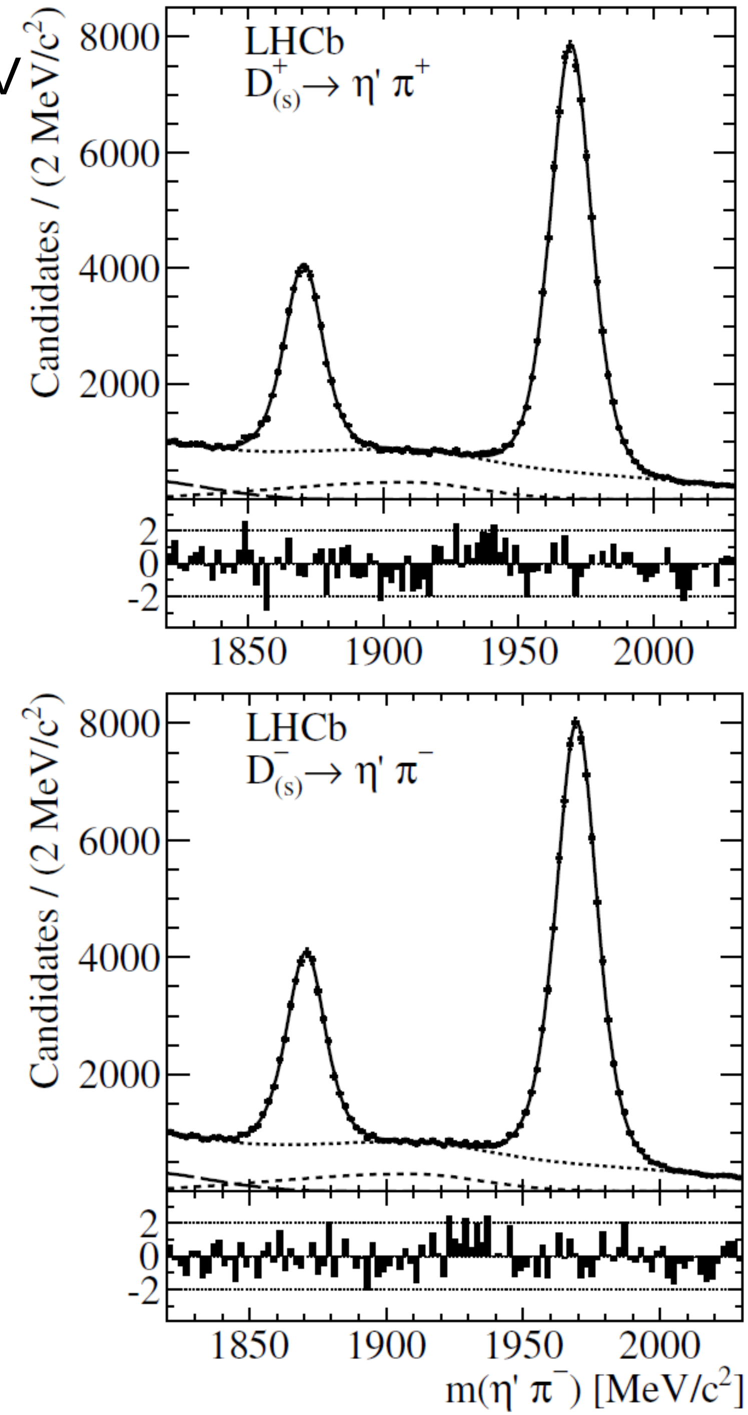
$$\mathcal{A}_{CP}(D \to \eta'\pi^+) = (-0.61 \pm 0.72 \pm 0.53 \pm 0.12)\%$$
$$\mathcal{A}_{CP}(D_s \to \eta'\pi^+) = (-0.82 \pm 0.36 \pm 0.22 \pm 0.27)\%$$

- **The most precise measurement**
- **Consistent with CP symmetry invariance**



W. Krzemień, PANIC 2017

Phys. Rev. Lett. 118 (2017) 261803

A_Γ measurements with $D^0 \to h^+h^-$

Measurement of indirect asymmetry of effective lifetimes $A_\Gamma \simeq -A_{CP}^{indir}$

Assuming mixing parameters *x,y* are small time-dependent asymmetry to CP eigenstates:

average D^0 lifetime

$$A(t) \equiv \frac{\Gamma(D^0(t) \to f) - \Gamma(\bar{D}^0(t) \to f)}{\Gamma(D^0(t) \to f) + \Gamma(\bar{D}^0(t) \to f)} \simeq A_{CP}^{dir} - A_\Gamma \frac{t}{\tau_D}$$

$f = \pi^+\pi^-$ or K^+K^-

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If no CPV asymmetry in mixing:

$$A_\Gamma = -x \sin\phi \to |A_\Gamma| < |x| \lesssim 5 \times 10^{-3} \qquad \phi = \arg\left((q\bar{A}_f)/(pA_f)\right)$$

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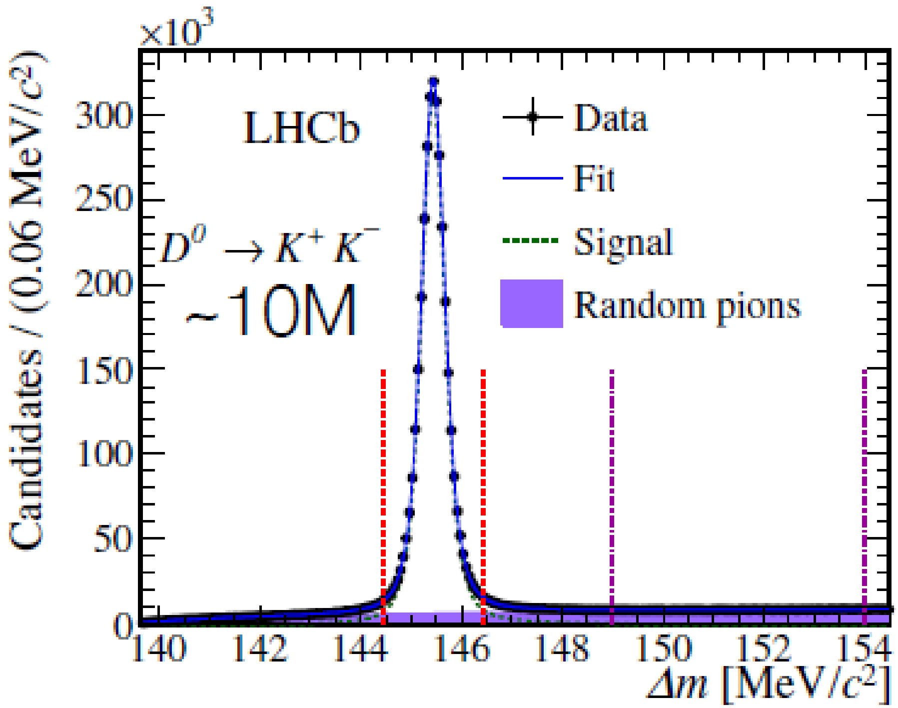
A_Γ measurements with $D^0 \rightarrow h^+h^-$



- Run I data sample 2011 and 2012 (3 fb^{-1} pp @7 TeV and @8 TeV)
- Prompt D^0
- Initial flavour based on the “soft” pion charge: $D^{*+} \rightarrow D^0\pi^+$
- High statistics control sample $D^0 \rightarrow K^-\pi^+$
- Two independent analyses (different approaches)

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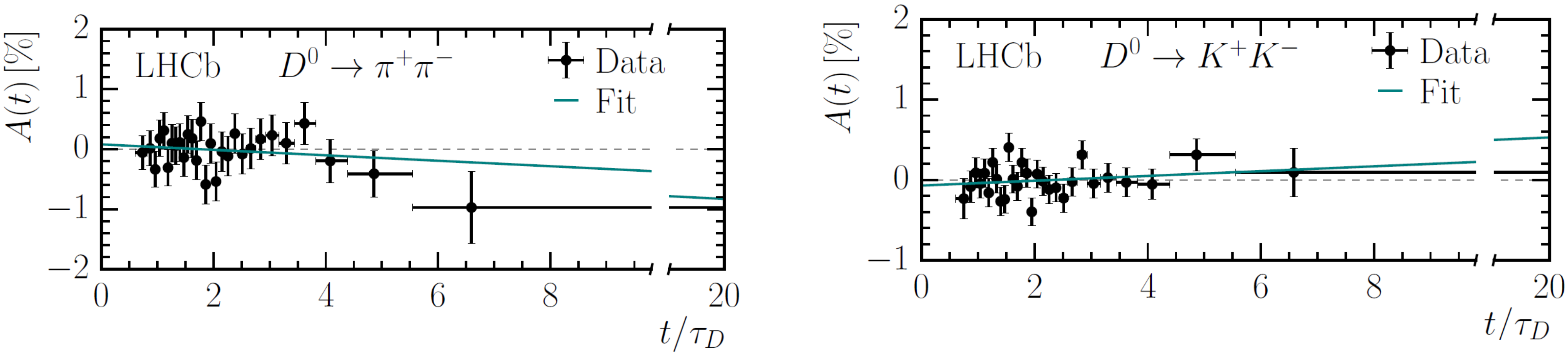

$$A_\Gamma(K^+K^-) = (-0.30 \pm 0.32 \pm 0.10)\times 10^{-3}$$
$$A_\Gamma(\pi^+\pi^-) = (+0.46 \pm 0.58 \pm 0.12)\times 10^{-3}$$

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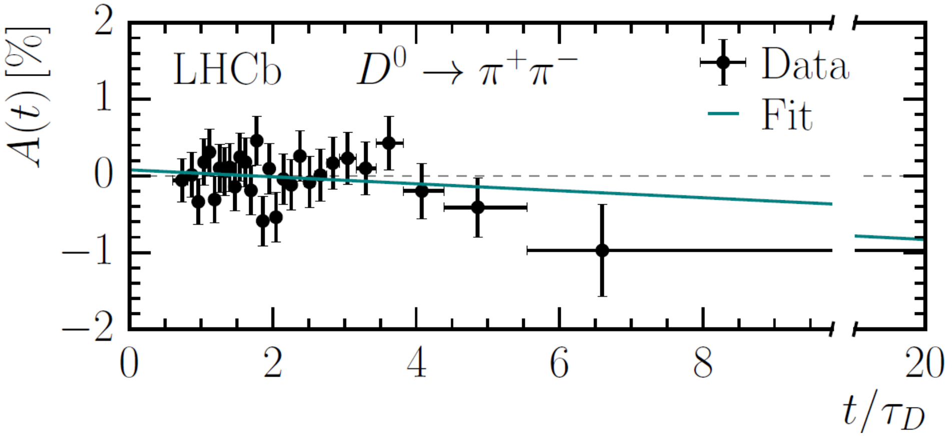
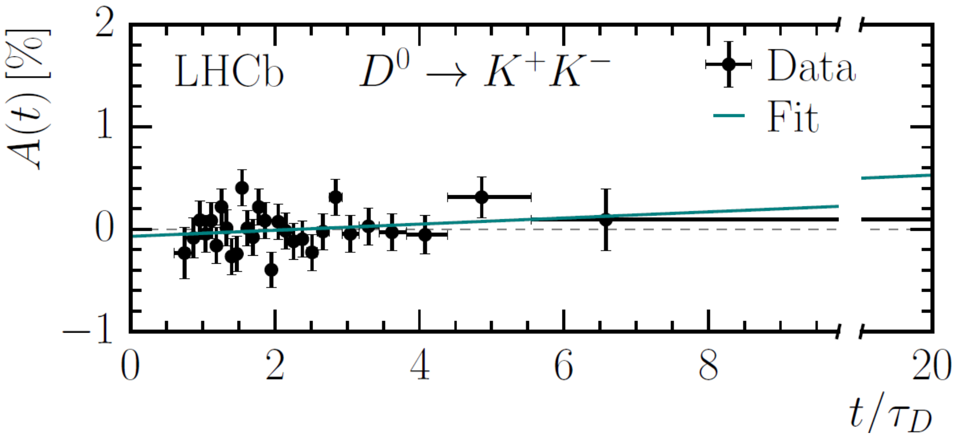
A_Γ measurements with $D^0 \to h^+h^-$





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Assuming no direct CPV and combining two channels:

$$A_\Gamma = (-0.13 \pm 0.28 \pm 0.10) \times 10^{-3}$$
$$\Delta A_\Gamma = (-0.76 \pm 0.66 \pm 0.04) \times 10^{-3}$$

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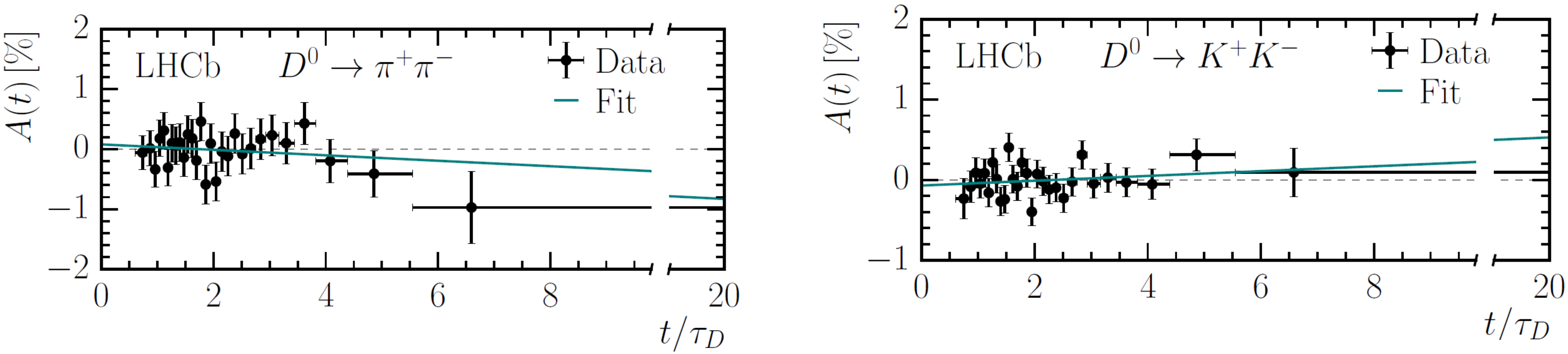
A_Γ measurements with $D^0 \to h^+h^-$



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Combining with muon-tagged statistically

independent sample $B \to D^0\mu^- X$ (JHEP 04 (2015) 043)

$$A_\Gamma = (-0.29 \pm 0.28) \times 10^{-3}$$

Consistent with CP symmetry conservation. The most precise result to date

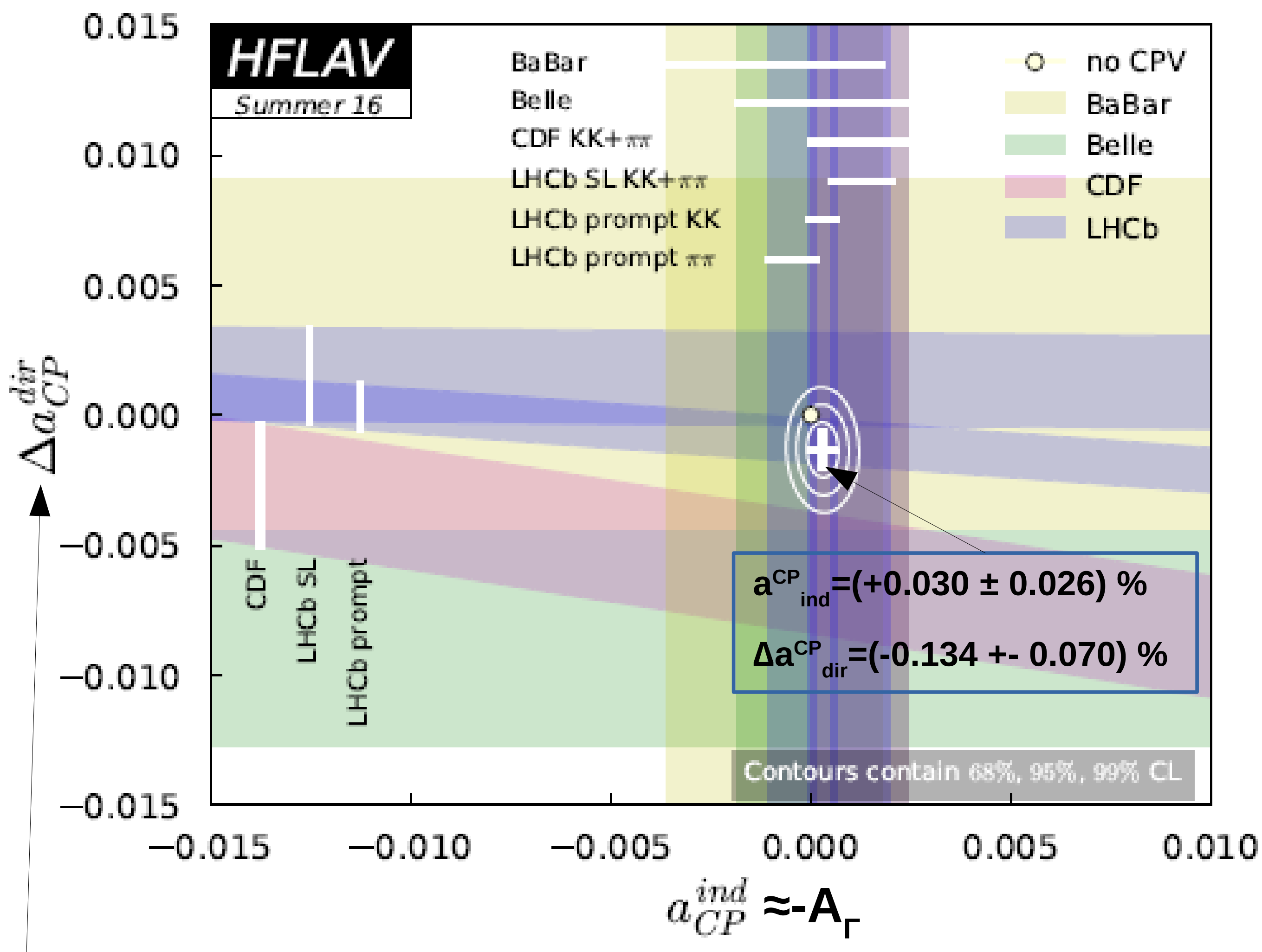
A_Γ measurements with $D^0 \to h^+h^-$

Earlier LHCb results:

ΔA_{CP} PRL116(2016)191601
JHEP07(2014)041

y_{CP} JHEP04(2012)129

A_Γ PRL112(2014)041801
JHEP04(2015)043



$$\Delta A_{CP} = \Delta a_{CP}^{dir}\left(1 + \frac{\langle \bar{t} \rangle}{\tau} y_{CP}\right) + \frac{\Delta \langle t \rangle}{\tau} a_{CP}^{ind}$$

Summary and Outlook

- Mixing and CP violation studies as precise tests of SM and probes of New Physics effects,
- LHCb provided many results confirming SM predictions based on Run I 2011/2012 data (3 fb^{-1}),
- Charm mixing confirmed, no CP violation discovered so far,
- Results mostly limited by statistics,

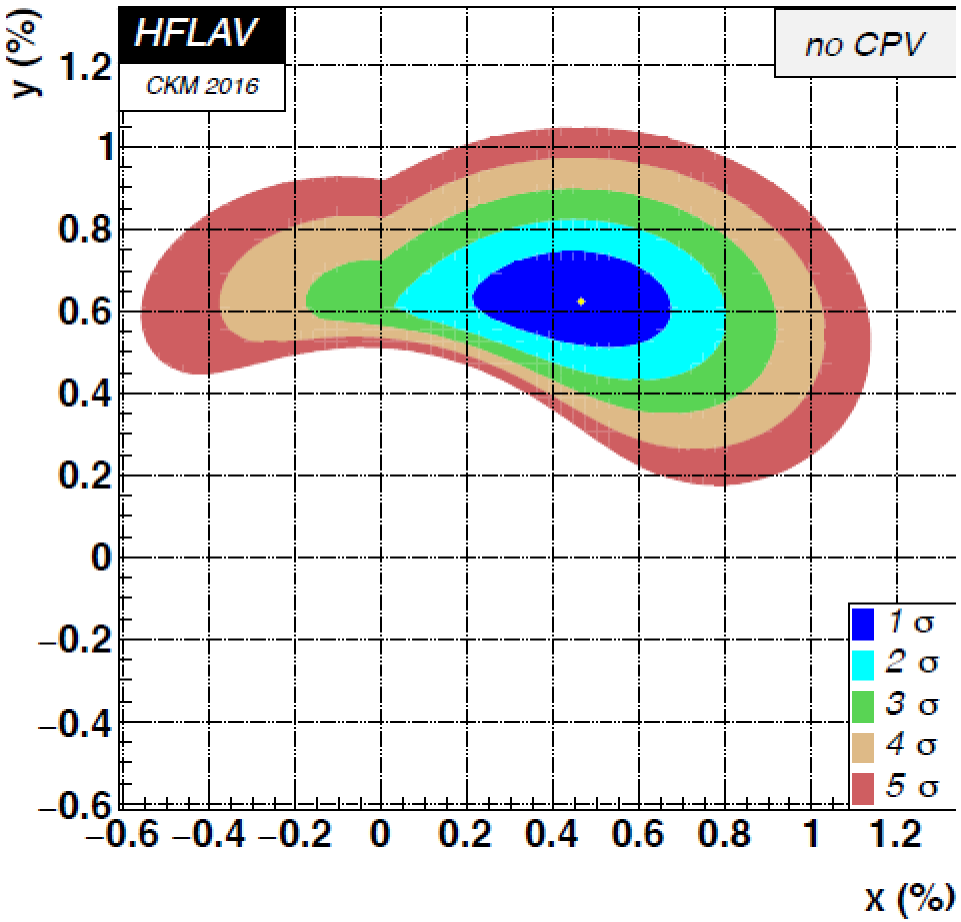
- Run II in progress

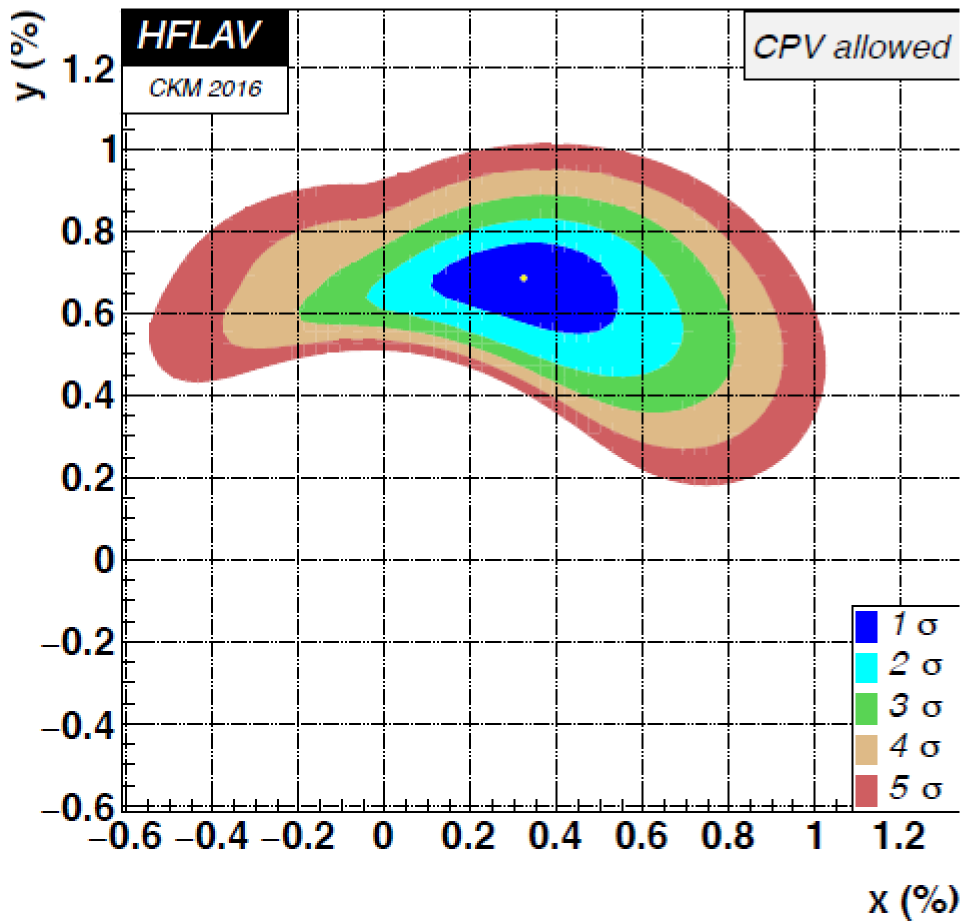
	LHC era			HL-LHC era	
	Run 1 (2010-12)	Run 2 (2015-18)	Run 3 (2021-24)	Run 4 (2027-30)	Run 5+ (2031+)
ATLAS, CMS	25 fb^{-1}	100 fb^{-1}	300 fb^{-1}	⟶	3000 fb^{-1}
LHCb	3 fb^{-1}	8 fb^{-1}	25 fb^{-1}	50 fb^{-1}	*300 fb^{-1}

* assumes a future LHCb upgrade to raise the instantaneous luminosity to 2×10^{34} cm^{-2}

Thank you for your attention

Mixing and CPV in charm





$D^0 \to h^+h^-$ decays - more details

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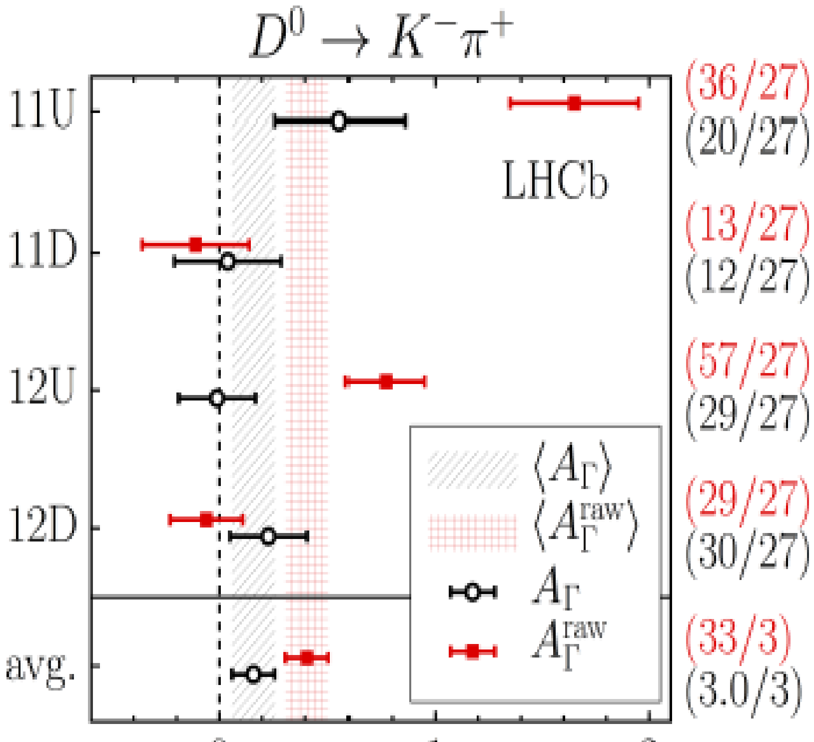
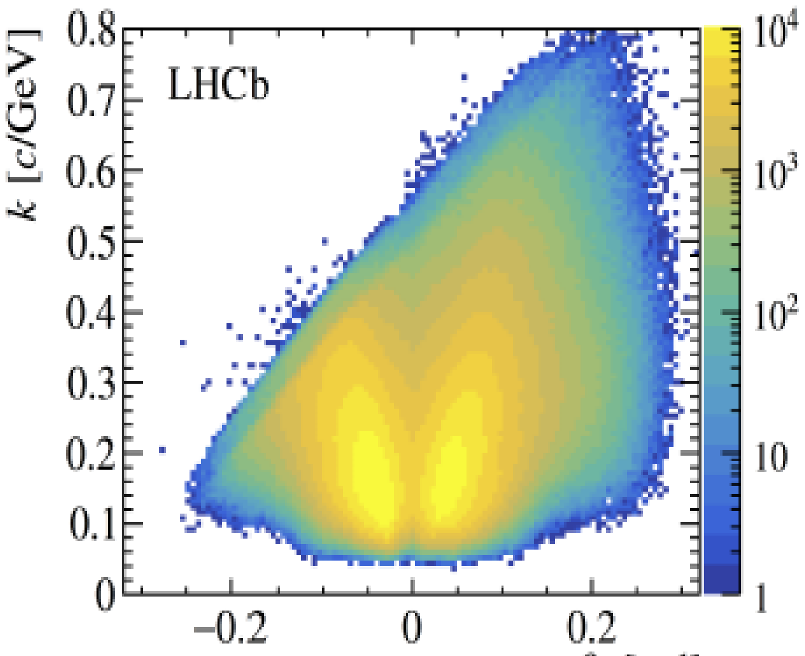
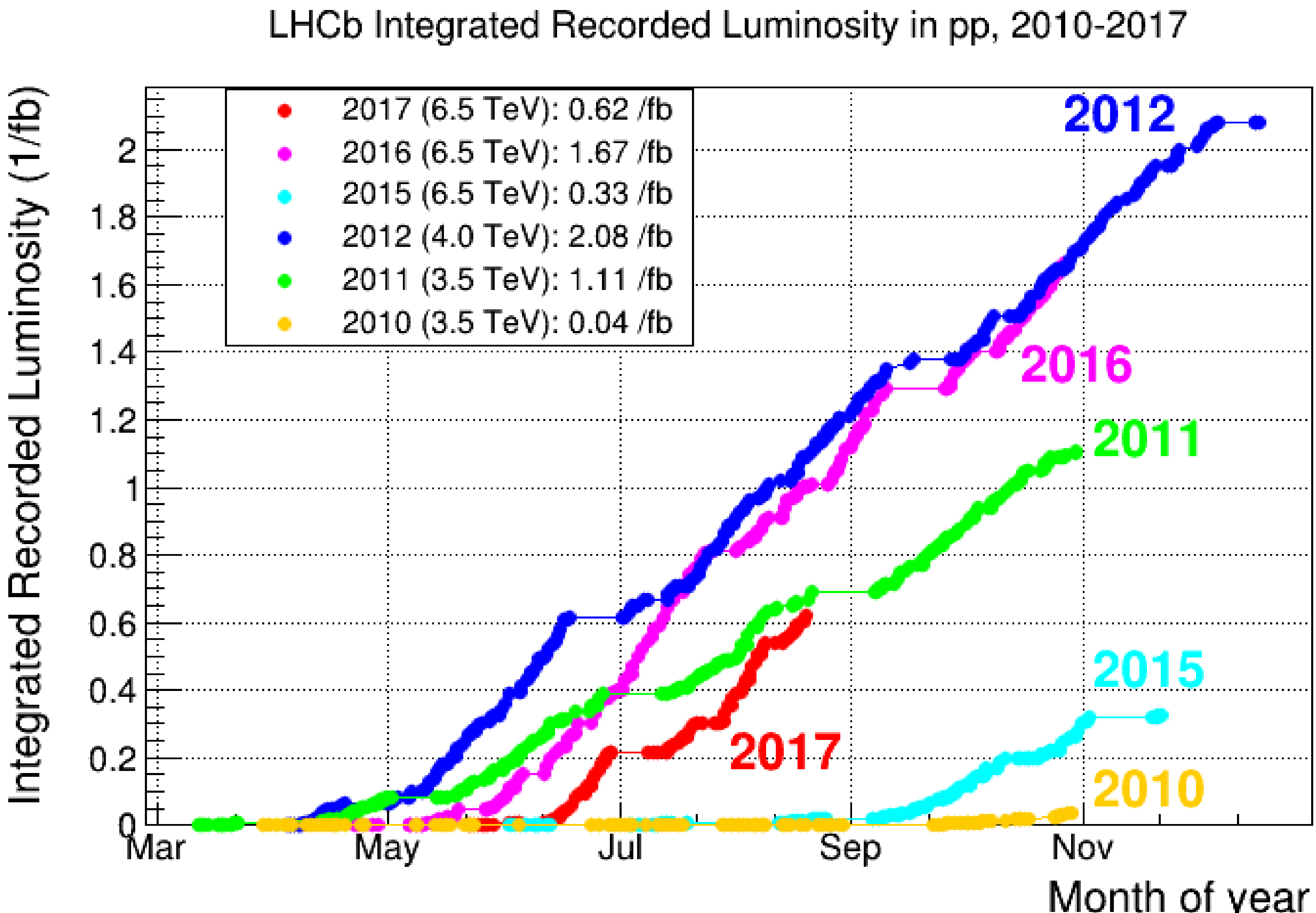
- The high-statistics control sample of $D^0 K \to \pi$ (assumption: CPV effect below the sensitivity)
- D^0 reconstruction asymmetries corrected using $D^0 - \overline{D}^0$ yields in equally populated times bin.
- main source of systematic errors: peaking background from D^0 coming from B decays.
- soft-pion detection asymmetries corrected by reweighting using 3-D distributions






LHCb Integrated Recorded Luminosity in pp, 2010-2017
2017 (6.5 TeV): 0.62 /fb
2016 (6.5 TeV): 1.67 /fb
2015 (6.5 TeV): 0.33 /fb
2012 (4.0 TeV): 2.08 /fb
2011 (3.5 TeV): 1.11 /fb
2010 (3.5 TeV): 0.04 /fb
2012
2016
2011
2015
2017
2010
Integrated Recorded Luminosity (1/fb)
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
Mar
May
Jul
Sep
Nov
Month of year

Asymmetries relations

Observables:

$$A_\Gamma \equiv \frac{\tau(\overline{D}^0 \to h^+h^-) - \tau(D^0 \to h^+h^-)}{\tau(\overline{D}^0 \to h^+h^-) + \tau(D^0 \to h^+h^-)}$$

$$\Delta A_{CP} \equiv A_{CP}(K^+K^-) - A_{CP}(\pi^+\pi^-)$$

Theoretical params:

$$a_{CP}^{\text{dir}} \equiv \frac{|\mathcal{A}_{D^0\to f}|^2 - |\mathcal{A}_{\overline{D}^0\to f}|^2}{|\mathcal{A}_{D^0\to f}|^2 + |\mathcal{A}_{\overline{D}^0\to f}|^2}$$

$$a_{CP}^{\text{ind}} \equiv \frac{1}{2}\left[\left(\left|\frac{q}{p}\right| + \left|\frac{p}{q}\right|\right) x\sin\phi - \left(\left|\frac{q}{p}\right| - \left|\frac{p}{q}\right|\right) y\cos\phi\right]$$

Relations:

$$A_\Gamma = -a_{CP}^{\text{ind}} - a_{CP}^{\text{dir}} y_{CP}$$

$$\Delta A_{CP} = \Delta a_{CP}^{\text{dir}}\left(1 + y_{CP}\frac{\overline{\langle t\rangle}}{\tau}\right) + a_{CP}^{\text{ind}}\frac{\Delta\langle t\rangle}{\tau} + \overline{a_{CP}^{\text{dir}}} y_{CP}\frac{\Delta\langle t\rangle}{\tau}$$

$$\approx \Delta a_{CP}^{\text{dir}}\left(1 + y_{CP}\frac{\overline{\langle t\rangle}}{\tau}\right) + a_{CP}^{\text{ind}}\frac{\Delta\langle t\rangle}{\tau}.$$

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Search for direct CPV with $D^+_{(s)} \rightarrow \eta'\pi^+$ decay

$$\mathcal{A}_{\text{raw}}(D^\pm_{(s)} \to f^\pm) = \frac{N(D^+_{(s)} \to f^+) - N(D^-_{(s)} \to f^-)}{N(D^+_{(s)} \to f^+) + N(D^-_{(s)} \to f^-)},$$

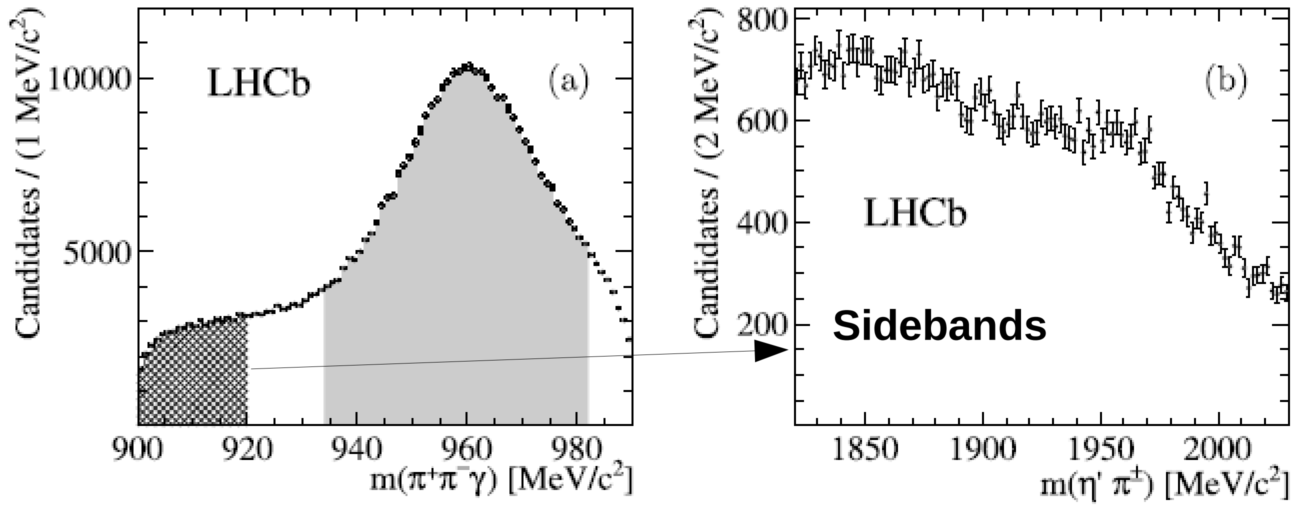
$$\mathcal{A}_{\text{raw}} \approx \mathcal{A}_{CP} + \mathcal{A}_{\text{P}} + \mathcal{A}_{\text{D}},$$

$$\begin{aligned}
\Delta\mathcal{A}_{CP}(D^\pm \to \eta'\pi^\pm) &\equiv \mathcal{A}_{CP}(D^\pm \to \eta'\pi^\pm) - \mathcal{A}_{CP}(D^\pm \to K^0_S\pi^\pm) \\
&= \mathcal{A}_{\text{raw}}(D^\pm \to \eta'\pi^\pm) - \mathcal{A}_{\text{raw}}(D^\pm \to K^0_S\pi^\pm) \\
&\quad + \mathcal{A}(\overline{K}^0 - K^0), \\
\Delta\mathcal{A}_{CP}(D^\pm_s \to \eta'\pi^\pm) &\equiv \mathcal{A}_{CP}(D^\pm_s \to \eta'\pi^\pm) - \mathcal{A}_{CP}(D^\pm_s \to \phi\pi^\pm) \\
&= \mathcal{A}_{\text{raw}}(D^\pm_s \to \eta'\pi^\pm) - \mathcal{A}_{\text{raw}}(D^\pm_s \to \phi\pi^\pm).
\end{aligned}$$

→ Estimated by simulation, taking into account mixing,regeneration and CP violation ~ $(-0.08 \pm 0.01)\%$

Phys. Lett. B 771 (2017) 21

Search for direct CPV with $D^+_{(s)} \to \eta' \pi^+$ decay



Main peaking background: $D^{\pm}_{(s)} \to \phi_{3\pi} \pi^{\pm}$

Table 1

Systematic uncertainties (absolute values in %) on $\Delta\mathcal{A}_{CP}$. The total systematic uncertainty is the sum in quadrature of the individual contributions.

Source	$\delta[\Delta\mathcal{A}_{CP}(D^{\pm})]$	$\delta[\Delta\mathcal{A}_{CP}(D_s^{\pm})]$
Non-prompt charm	0.03	0.03
Trigger	0.09	0.09
Background model	0.50	0.19
Fit procedure	0.08	0.04
Sideband subtraction	0.03	0.02
K^0 asymmetry	0.08	–
$\pi^{\pm}$ detection asymmetry	0.06	0.01
$D^{\pm}_{(s)}$ production asymmetry	0.07	0.02
Total	0.53	0.22

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Search for direct CPV with $D^+_{(s)} \to \eta'\pi^+$ decay

- 12 exclusive subsamples for each final state:
  - Collision energies
  - Magnet polarity
  - 3 Trigger selections
- In each subsample: 3x3 kinematic bins base on p_T and eta of bachelor pion

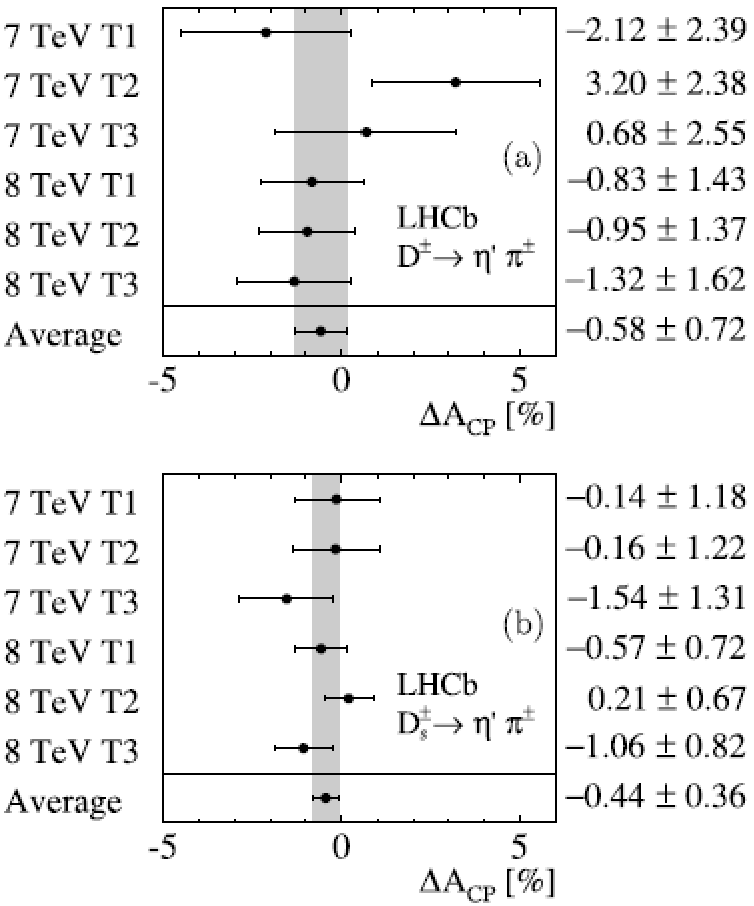
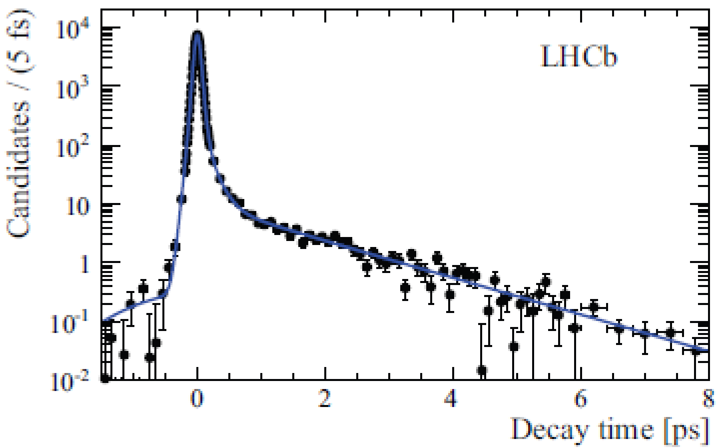


Fig. 4. $\Delta\mathcal{A}_{CP}$ results for (a) $D^\pm \to \eta'\pi^\pm$ and (b) $D_s^\pm \to \eta'\pi^\pm$ decays, as a function of pp centre-of-mass energy and trigger selection. Uncertainties are statistical only. A shaded band representing the 68.3% confidence intervals obtained from the weighted average over all the samples is shown to guide the eye.

Decay time resolution

- B_s^0 have fast oscillations: period $2\pi/\Delta m_s \approx 350\,\text{fs}$
- Decay time resolution σ_t will dilute the measured oscillation amplitude
- The dilution factor: $D(\sigma_t) = e^{-\frac{(\sigma_t \Delta m_s)^2}{2}}$



[Phys. Rev. D 87, 112010]

- Resolution measured from data
- Combinations of $\mu^+\mu^-K^+K^-$ events
- Same selection as for B_s^0 apart for decay time cuts
- Mostly prompt events with true decay time of zero
- Effective decay time resolution $\sigma_t = 45\,\text{fs}$

$D(\sigma_t = 45\,\text{fs}) \approx 0.73$

LHCb parameters

- LHC beam energy in pp collisions ($\sqrt{s}$): 7 and 8 TeV (2010-2012), 13 to 14 TeV (ongoing Run II)
- Collected integrated luminosity: 1 fb $^{-1}$ (2011), 2 fb $^{-1}$ (2012)
- Acceptance: 2 ¡ η ¡ 5
- data taking efficency ¿ 90 %
- trigger efficiency: 90 % for dimuon channels, 30% for multi-body hadronic final states
- track reco. efficiency: ¿96 % for long tracks
- Momentum resolution: $\frac{\Delta p}{p}$ =0.5 % for low momentum till 1% at 200 GeV/c
- ECAL resolution: $1\% + 10\% \overline{E[GeV]}$
- impact parameter resolution: 20 μm for high-pT tracks
- invariant mass resolution: 8 MeV/c^2 for B to J/Psi decays, 22 Mev/C for two-body B decays, 100 MeV/c^2 for Bsto phi photon
- decay time resolution: 45 fs for Bs tp J/Psi and Bs to Ds pi
- electron ID efficiecny: 90 % (5 % miss probabilty)
- kaon ID efficiecny: 95 % (5 % miss probabilty)
- muon ID efficiecny: 97 % (1-3 % miss probabilty)

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