Mixing and CPV in charm hadrons at LHCb

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On behalf of the LHCb collaboration

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Outline

- Introduction
- Mixing and CP studies in $D^0 \rightarrow K^+\pi^-$ decays
- Search for direct CPV with $D^+_1(s) \rightarrow \eta'\pi^+$ decay
- $A_\Gamma$ measurements with $D^0 \rightarrow h^+h^-$
- Summary & Outlook
Neutral flavour mesons mixing

Weak interactions do not conserve the flavour
Neutral flavour mesons mixing

Weak interactions do not conserve the flavour

Flavour states are not eigenvectors of the full Hamiltonian

\[
\frac{\partial}{\partial t} |\Phi> = H |\Phi>
\]
Neutral flavour mesons mixing

Weak interactions do not conserve the flavour

\[ D^0 \quad d,s,b \quad W^+ \quad u \quad \bar{D}^0 \quad \bar{d},\bar{s},\bar{b} \]
\[ \bar{u} \quad W^- \quad \bar{c} \]
\[ d^0 \quad W^+ \quad W^- \quad \bar{d},\bar{s},\bar{b} \quad \bar{c} \]

Flavour states are not eigenvectors of the full Hamiltonian

\[ \frac{\partial}{\partial t} |\Phi\rangle = H |\Phi\rangle \]

Mass eigenstates expressed as a superposition of flavour eigenstates:

\[ |D_{1,2}\rangle = p|D^0\rangle \pm q|\bar{D}^0\rangle \quad |p|^2 + |q|^2 = 1 \quad p, q \text{ are complex} \]
Neutral flavour mesons mixing

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Neutral flavour mesons mixing II

Probabilities of mixing:

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

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

Mixing parameters:

$$x = \frac{\Delta m}{\Gamma}$$

$$\Delta \Gamma = \Gamma_1 - \Gamma_2$$

$$y = \frac{\Delta \Gamma}{2\Gamma}$$

$$\Delta m = m_1 - m_2$$
Neutral flavour mesons mixing II

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\]

Mixing parameters:

\[
x = \frac{\Delta m}{\Gamma} \\
\Delta \Gamma = \Gamma_1 - \Gamma_2 \\
y = \frac{\Delta \Gamma}{2\Gamma} \\
\Delta m = m_1 - m_2
\]

**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_s^0** 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:

\[\lambda_f \equiv \frac{q}{p} \quad \frac{\overline{A_f}}{A_f} \neq 1\]

CP violation in decay

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

\[|\frac{\overline{A_f}}{A_f}| \neq 1\]

- Depends on decay mode
- At least one amplitude with different strong and weak phases
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CP violation in decay
\[ \Gamma(P^0 \rightarrow f) \neq \Gamma(\bar{P}^0 \rightarrow \bar{f}) \]
\[ \frac{|\bar{A}_f|}{|A_f|} \neq 1 \]

CP violation in mixing
\[ \Gamma(P^0 \rightarrow \bar{P}^0) \neq \Gamma(\bar{P}^0 \rightarrow P^0) \]
\[ |\frac{q}{p}| \neq 1 \]

- Depends on decay mode
- At least one amplitude with different strong and weak phases
CP violation and its types

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The CP discrete symmetry is broken if:

\[ \lambda_f \equiv \frac{q}{p} \quad \frac{A_{f^-}}{A_f} \neq 1 \]

<table>
<thead>
<tr>
<th>CP violation in decay</th>
<th>CP violation in mixing</th>
<th>CP violation in interference between mixing and decay</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \Gamma(P^0 \rightarrow f) \neq \Gamma(\bar{P}^0 \rightarrow \bar{f}) )</td>
<td>( \Gamma(P^0 \rightarrow \bar{P}^0) \neq \Gamma(\bar{P}^0 \rightarrow P^0) )</td>
<td>( \Gamma(P^0 \rightarrow \bar{P}^0 \rightarrow f_{CP}) \neq \Gamma(\bar{P}^0 \rightarrow P^0 \rightarrow f_{CP}) )</td>
</tr>
<tr>
<td>(</td>
<td>A_{f^-}</td>
<td>/A_f</td>
</tr>
</tbody>
</table>

- Depends on decay mode
- At least one amplitude with different strong and weak phases
- Not depends on decay mode
- only for neutral mesons

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Mixing and CPV in charm

Standard Model predictions (PDG2016):

- Predictions for mixing very imprecise
  
  \( x, y: \mathcal{O}(10^{-2}) - \mathcal{O}(10^{-7}) \)

- Almost no CPV effects expected \( \sim \mathcal{O}(10^{-3}) \)

**Diagram:**

- Long-range contributions dominates – hard to calculate

\( D^0 \) \( \rightarrow \) \( d, s, b \) \( W^\pm \) \( W^\pm \) \( \bar{D}^0 \)

\( \bar{u} \) \( \rightarrow \) \( d, s, b \) \( \bar{c} \)
Mixing and CPV in charm

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Experimental status:

- Mixing established (\(~ 11 \sigma \) effect)
  - Recent LHCb measurement: PRL 113 (2013) 231802

- No CPV observed so far
Mixing and CPV in charm

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Charm as a unique place to look for New Physics effects
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 $\mu m$ from high $p_T$ tracks, decay lifetime $\sim$45 fs
Charm in LHCb

- Charm produced copiously in the pp collisions:
  \[ \sigma(pp \rightarrow c\bar{c}) \sim 1419 \, \mu b \, @ \, 7 \, \text{TeV} \]
  \text{Nucl.Phys.B871(2016)1}
  \[ \sigma(pp \rightarrow c\bar{c}) \sim 2940 \, \mu b \, @ \, 13 \, \text{TeV} \]
  \text{JHEP03(2016)159}

- In Run I 2011-2012 ( L = 3 \, \text{fb}^{-1} ) produced:
  \sim 5 \times 10^{12} \, D^0,
  \sim 2 \times 10^{12} \, D^{*+}
  \sim 30 \times \text{larger collected statistics than previous experiments}

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

W. Krzemień, PA
Mixing and CP studies in $D^0 \rightarrow K^+\pi^-$ decays

$D^0 \rightarrow K^-\pi^+$  
$D^0 \rightarrow K^+\pi^-$

Right Sign  
Wrong Sign
Mixing and CP studies in $D^0 \rightarrow K^+\pi^-$ decays

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

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

$$R_D^+ = |A_f^-/A_f|^2 \quad R_D^- = |A_f^-/A_f|^2$$

- $x' = x \cos(\delta) + y \sin(\delta)$
- $y' = y \cos(\delta) + x \sin(\delta)$
Mixing and CP studies in $D^0 \rightarrow K^+\pi^-$ decays

$D^0 \rightarrow K^-\pi^+$ \hspace{3cm} $D^0 \rightarrow K^+\pi^-$

**Right Sign**

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$$R_D^+ = |A^-_f/A_f|^2 \quad R_D^- = |A_f/A^-_f|^2$$

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 $\sim O(10^{-3})$

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Mixing and CP studies in $D^0 \rightarrow K^+\pi^-$ 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: $\bar{B} \rightarrow D^{*+}\mu^-X$, $D^{*+} \rightarrow D^0\pi^+$
- Fit $D^*$ mass to extract $D^0$ in five time bins
- Correct for time-dependent detector effects

**Prompt charm:**

$$D^0 \quad \pi^+$$

**Double-tagged secondary charm**

$$pp \rightarrow \bar{B} \rightarrow D^{*+}\mu^-X$$

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

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- Double-tagged data: $\bar{B} \to D^{*+}\mu^-X$, $D^{*+} \to D^0\pi^+$
- 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
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)

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

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

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

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- 63 x $10^3$ $D^\pm$, 152 x $10^3$ $D^\pm_{(s)}$
- Never measured before at hadron colliders
- Measured with respect to the control channels to eliminate the detector and production asymmetries

\[
A_{CP}(D^\pm \to \eta' \pi^\pm) \approx \Delta A_{CP}(D^\pm \to \eta' \pi^\pm) + A_{CP}(D^\pm \to K_0^\pm \pi^\pm)
\]

\[
A_{CP}(D^\pm_{(s)} \to \eta' \pi^\pm) \approx \Delta A_{CP}(D^\pm_{(s)} \to \eta' \pi^\pm) + A_{CP}(D^\pm_{(s)} \to \phi \pi^\pm)
\]

$A_{CP}$ known from previous measurements at level $O(10^{-3})$:
D0: PRL 112 (2014) 111804
Search for direct CPV with $D^+_{(s)} \rightarrow \eta' \pi^+$ decay

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\]

\[
A_{CP}(D \rightarrow \eta'\pi^+) = (-0.61 \pm 0.72 \pm 0.53 \pm 0.12)\%
A_{CP}(D_S \rightarrow \eta'\pi^+) = (-0.82 \pm 0.36 \pm 0.22 \pm 0.27)\%
\]

- The most precise measurement
- Consistent with CP symmetry invariance

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$A_\Gamma$ 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:

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

$f = \pi^+\pi^- \text{ or } K^+K^-$
A_{\Gamma} measurements with D^0 \rightarrow h^+h^-

Measurement of indirect asymmetry of effective lifetimes

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\[ f = \pi^+\pi^- \text{ or } K^+K^- \]

Neglecting sub-leading amplitudes: \[ A_{CP}^{dir} = 0 \]

A_{\Gamma} becomes universal

(not depended on decay mode)
**A_{\Gamma} measurements with D^0 \rightarrow h^+h^-**

Measurement of indirect asymmetry of effective lifetimes

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\]

\[ f = \pi^+\pi^- \text{ or } K^+K^- \]

Neglecting sub-leading amplitudes: \[ A_{CP}^{dir} = 0 \]

If no CPV asymmetry in mixing:

\[ A_{\Gamma} = -x \sin \phi \rightarrow |A_{\Gamma}| < |x| \lesssim 5 \times 10^{-3} \]

\[ \phi = \arg \left( \frac{qA_f}{pA_f} \right) \]
A₂ 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)
$A_F$ measurements with $D^0 \rightarrow h^+h^-$

$$A_F(K^+K^-) = (-0.30 \pm 0.32 \pm 0.10) \times 10^{-3}$$

$$A_F(\pi^+\pi^-) = (+0.46 \pm 0.58 \pm 0.12) \times 10^{-3}$$
$A_{\Gamma}$ measurements with $D^0 \rightarrow h^+h^-$

Assuming no direct CPV and combining two channels:

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

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

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

$\Delta A_{\Gamma} = (-0.76 \pm 0.66 \pm 0.04) \times 10^{-3}$
Assuming no direct CPV and combining two channels:

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Combining with muon-tagged statistically independent sample \( B \rightarrow D^0\mu^-X \) (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
$A_T$ measurements with $D^0 \rightarrow h^+ h^-$

Earlier LHCb results:

$\Delta A_{CP}$
- PRL116(2016)191601
- JHEP07(2014)041

$\gamma_{CP}$
- JHEP04(2012)129

$A_T$
- PRL112(2014)041801
- JHEP04(2015)043

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

<table>
<thead>
<tr>
<th></th>
<th>LHC era</th>
<th>HL-LHC era</th>
</tr>
</thead>
<tbody>
<tr>
<td>ATLAS, CMS</td>
<td>25 fb⁻¹</td>
<td>100 fb⁻¹</td>
</tr>
<tr>
<td>LHCb</td>
<td>3 fb⁻¹</td>
<td>8 fb⁻¹</td>
</tr>
</tbody>
</table>

* assumes a future LHCb upgrade to raise the instantaneous luminosity to $2 \times 10^{34}$ cm⁻²
Thank you for your attention
Mixing and CPV in charm
The high-statistics control sample of $D^0 K \rightarrow \pi$ (assumption: CPV effect below the sensitivity).

$D^0$ reconstruction asymmetries corrected using $D^0 - \bar{D}^0$ 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

Month of year: Mar, May, Jul, Sep, Nov

Integrated Recorded Luminosity (1/fb)
Asymmetries relations

Observables:

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

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

Theoretical params:

\[ a_{CP}^{\text{dir}} \equiv \frac{|A_{D^0 \to f}|^2 - |A_{\bar{D}^0 \to f}|^2}{|A_{D^0 \to f}|^2 + |A_{\bar{D}^0 \to f}|^2} \]

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

Relations:

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

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

\[ \approx \Delta a_{CP}^{\text{dir}} \left( 1 + y_{CP} \frac{\langle t \rangle}{\tau} \right) + a_{CP}^{\text{ind}} \frac{\Delta \langle t \rangle}{\tau} . \]
Search for direct CPV with $D^+_{(s)} \rightarrow \eta'\pi^+$ decay

$$A_{\text{raw}}(D^+_{(s)} \rightarrow f^\pm) = \frac{N(D^+_{(s)} \rightarrow f^+) - N(D^-_{(s)} \rightarrow f^-)}{N(D^+_{(s)} \rightarrow f^+) + N(D^-_{(s)} \rightarrow f^-)}.$$  

$$A_{\text{raw}} \approx A_{CP} + A_P + A_D.$$

$$\Delta A_{CP}(D^\pm \rightarrow \eta'\pi^\pm) \equiv A_{CP}(D^\pm \rightarrow \eta'\pi^\pm) - A_{CP}(D^\pm \rightarrow K^0_S\pi^\pm)$$

$$= A_{\text{raw}}(D^\pm \rightarrow \eta'\pi^\pm) - A_{\text{raw}}(D^\pm \rightarrow K^0_S\pi^\pm) + A(K^0 - K^0),$$

$$\Delta A_{CP}(D^+_s \rightarrow \eta'\pi^\pm) \equiv A_{CP}(D^+_s \rightarrow \eta'\pi^\pm) - A_{CP}(D^+_s \rightarrow \phi\pi^\pm)$$

$$= A_{\text{raw}}(D^+_s \rightarrow \eta'\pi^\pm) - A_{\text{raw}}(D^+_s \rightarrow \phi\pi^\pm).$$

- Estimated by simulation, taking into account mixing, regeneration and CP violation $\sim (-0.08 \pm 0.01)\%$
Search for direct CPV with $D^{+(s)} \rightarrow \eta' \pi^+$ decay

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

Table 1
Systematic uncertainties (absolute values in %) on $\Delta A_{CP}$. The total systematic uncertainty is the sum in quadrature of the individual contributions.

<table>
<thead>
<tr>
<th>Source</th>
<th>$\delta[\Delta A_{CP}(D^{\pm})]$</th>
<th>$\delta[\Delta A_{CP}(D^{\pm}_c)]$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Non-prompt charm</td>
<td>0.03</td>
<td>0.03</td>
</tr>
<tr>
<td>Trigger</td>
<td>0.09</td>
<td>0.09</td>
</tr>
<tr>
<td>Background model</td>
<td>0.50</td>
<td>0.19</td>
</tr>
<tr>
<td>Fit procedure</td>
<td>0.08</td>
<td>0.04</td>
</tr>
<tr>
<td>Sideband subtraction</td>
<td>0.03</td>
<td>0.02</td>
</tr>
<tr>
<td>$K^0$ asymmetry</td>
<td>0.08</td>
<td>–</td>
</tr>
<tr>
<td>$\pi^\pm$ detection asymmetry</td>
<td>0.06</td>
<td>0.01</td>
</tr>
<tr>
<td>$D^{\pm}_{(s)}$ production asymmetry</td>
<td>0.07</td>
<td>0.02</td>
</tr>
<tr>
<td>Total</td>
<td>0.53</td>
<td>0.22</td>
</tr>
</tbody>
</table>
Search for direct CPV with $D^+_{{(s)}} \rightarrow \eta'\pi^+$ decay

- 12 exclusive subsamples for each final state:
  - Collision energies
  - Magnet polarity
  - 3 Trigger selections

- In each subsample: 3x3 kinematic bins based on $p_T$ and eta of bachelor pion

Fig. 4. $\Delta A_{CP}$ results for (a) $D^\pm \rightarrow \eta'\pi^\pm$ and (b) $D^+_s \rightarrow \eta'\pi^+$ 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

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

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

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

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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: $1 \text{ fb}^{-1}$ (2011), $2 \text{ fb}^{-1}$ (2012)
- Acceptance: $2 \mid \eta \mid 5$
- Data taking efficiency $\geq 90\%$
- Trigger efficiency: 90% for dimuon channels, 30% for multi-body hadronic final states
- Track reco. efficiency: $\geq 96\%$ for long tracks
- Momentum resolution: $\frac{\Delta p}{p} = 0.5\%$ for low momentum till 1% at 200 GeV/c
- ECAL resolution: $1\% + 10\% \frac{E[GeV]}{E}$
- Impact parameter resolution: 20 $\mu m$ 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 $B$ to phi photon
- Decay time resolution: 45 fs for $B_s$ to $J/$Psi and $B_s$ to $D_s$ pi
- Electron ID efficiency: 90% (5% miss probability)
- Kaon ID efficiency: 95% (5% miss probability)
- Muon ID efficiency: 97% (1-3% miss probability)
LHCb parameters

- LHC beam energy in pp collisions ($\sqrt{s}$): 7 and 8 TeV (2010-2012), 13 to 14 TeV (ongoing Run II)
- Acceptance: 2 $\mu m$ 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
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- 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 B to phi photon
- Decay time resolution: 45 fs for Bs to J/Psi and Bs to Ds pi
- Electron ID efficiency: 90% (5% miss probability)
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