OZLEM OZCELIK

(ON BEHALF OF LHCB, ATLAS AND CMS COLLABORATIONS)

CP VIOLATION AND MIXING IN B AND CHARM DECAYS

LHCP, 2022
Outline

• $\gamma$ angle measurement
  • LHCb combination [JHEP 12 (2021) 141]
  • $B^{\pm} \to D[K^\pm \pi^\pm \pi^\mp]h^\pm$ decays  ****NEW**** [LHCb-PAPER-2022-017, preliminary]
• Effective lifetime measurement.  ****NEW****  [PAPER-2022-010, preliminary]
  • $B_s^0 \to J/\psi \eta$
• CPV in B decays
  • CPV in B->3h across the Dalitz plane.  [LHCb-PAPER-2021-049, LHCb-PAPER-2021-050, Preliminary]
  • $B^0 \to p\bar{p}K^+\pi^-$  [LHCb-PAPER-2022-003, Preliminary]
• CPV and mixing in charm decays:
  • CP asymmetry in Ds decays.  [arXiv:2204.12228]
  • $y_{cp}$ from 2-body decays.  [LHCb-PAPER-2021-041] [arXiv:2202.09106]
Introduction

Cabibbo-Kobayashi-Maskawa unitary triangle
LHCb combination of $\gamma$ angle

- LHCb measurements sensitive to $\gamma$ and charm mixing are combined
  - $\gamma = (65.4^{+3.8}_{-4.2})^\circ$
- Most precise by single experiment!
- Around $2\sigma$ tension between charged and neutral B mesons
- Excellent agreement with indirect results
  
  \[
  \gamma = (65.8 \pm 2.2)^\circ, \quad \gamma = (65.55^{+0.90}_{-2.65})^\circ
  \]

- $x \equiv \Delta M/\Gamma = (0.400^{+0.052}_{-0.053})%$
- $y \equiv \Delta \Gamma/2\Gamma = (0.630^{+0.033}_{-0.030})%$ (factor of 2 improved!)
- $|q/p| = 0.997 \pm 0.016$ and $\phi = (-2.4 \pm 1.2)^\circ$
CKM angle $\gamma$ in $B^\pm \rightarrow Dh^\pm$ decays

***New*** [LHCb-PAPER-2022-017, preliminary]

- Decay $B^\pm \rightarrow DK^\pm$, $D \rightarrow K^+\pi^-\pi^-\pi^+$
- Large CP asymmetry measured in bins of D phase space
  D hadronic parameters from BESII, CLEO-c
- Run1/2: 9 fb$^{-1}$

$\gamma = (54.8^{+6.0+0.6+6.7}_{-5.8-0.6+4.3})^\circ$

the second most precise result in single D decay mode!

- Compatible results with LHCb combination
Effective lifetime in $B_S^0 \rightarrow J/\psi \eta$  

- The decay is CP-even in the limit of CP conservation effective lifetime $\tau_L = 1/\Gamma_L$
- Improving the precision is important for direct $\Delta \Gamma_S$ measurements, e.g. $B_S^0 \rightarrow J/\psi \phi$
- 2D ML fit to mass and decay time to obtain the effective lifetime.
Run2 result is factor of 2 more precise than Run 1!

\[ \tau_L = 1.445 \pm 0.016 \pm 0.008 \text{ ps} \]

Combination of Run 1 and Run 2 result:

\[ \tau_L = 1.452 \pm 0.014 \pm 0.007 \pm 0.002 \text{ ps} \]
$\phi_s$ measurement in CMS and ATLAS
A Golden channel..

• $B_s^0 \rightarrow J/\psi(\rightarrow \mu^+\mu^-)\phi(\rightarrow K^+K^-)$ decay is studied at 13 TeV.

• It’s a golden channel to measure $\phi_s$

$$\phi_s = -2\beta_s = \text{arg}( -V_{ts}V_{tb}^*/V_{cs}V_{cb}^*)$$

• SM prediction: $\phi_s \approx -2\beta_s = -36.96_{-0.84}^{+0.72}$ mrad [CKM fitter]

• New physics can modify the phase via the contribution of BSM particles to $B_s$ mixing!

• Not a single CP state - an angular analysis needed to separate CP-odd and CP-even components in the final state

• A novel OS trigger to estimate the initial flavour of the $B_s^0$ meson in the production.

• Many additional observables measured : $\Gamma_s , \Delta\Gamma_s , |\lambda| = (q/p)(\bar{A}_f/A_f)$,
Fit Projections (CMS)

- Multi-dimensional fit
Results (CMS)

- Run 1 + Run 2 (116.1 fb$^{-1}$)
  - $\phi_s = -21 \pm 44$ (stat) $\pm 10$ (syst) mrad
  - $\Delta \Gamma_s = 0.114 \pm 0.014$ (stat) $\pm 0.007$ (syst) ps$^{-1}$

- Greatly improved $\phi_s$ due to statistics and the new tagging strategy in Run 2.

- Run 2 only (96.4 fb$^{-1}$)
  - $\phi_s = -11 \pm 50$ (stat) $\pm 10$ (syst) mrad
  - $\Delta \Gamma_s = 0.1032 \pm 0.0095$ (stat) $\pm 0.0048$ (syst) ps$^{-1}$

- Results are consistent with SM predictions.
  - The first measurement by CMS of $\Delta m_s$ and $|\lambda|$
Fit Projections (ATLAS)

Results (ATLAS)

- Run 2 only (80.5 fb\(^{-1}\))
  - \(\phi_S = -0.081 \pm 0.041\) (stat) \(\pm 0.022\) (syst) rad
  - \(\Delta \Gamma_S = 0.0607 \pm 0.047\) (stat) \(\pm 0.0043\) (syst) ps\(^{-1}\)

- Run 1 + Run 2 (99.7 fb\(^{-1}\))
  - \(\phi_S = -0.087 \pm 0.036\) (stat) \(\pm 0.021\) (syst) mrad
  - \(\Delta \Gamma_S = 0.0657 \pm 0.0043\) (stat) \(\pm 0.0037\) (syst) ps\(^{-1}\)

Combination of 7, 8 TeV and 13 TeV

Overview of the results

\[ \Delta \Gamma_s [\text{ps}^{-1}] \]

**ATLAS**
\[ \sqrt{s} = 7, 8, \text{ and } 13 \text{ TeV} \]
68% CL contours

- CMS, \(J/\psi K^+ K^-\), 116.1 fb\(^{-1}\)
- LHCb, \(J/\psi K^+ K^-\), 4.9 fb\(^{-1}\)
- LHCb, all channels, 4.9 fb\(^{-1}\)
- ATLAS, \(J/\psi K^+ K^-\), 99.7 fb\(^{-1}\)
Direct CP violation 3-body B+ decays

The raw asymmetry is obtained from simultaneous UML fit to \(B^\pm\) invariant mass distributions.

The acceptance-corrected raw asymmetry is defined:

\[
A_{\text{raw}}^{\text{acc}} = \frac{N_{B^-} - N_{B^+}^{\text{acc}}}{N_{B^-} + N_{B^+}^{\text{acc}}}, \quad R = \frac{e^{\text{det}}(B^-)}{e^{\text{det}}(B^+)}, \quad A_{C\text{P}} = \frac{A_{\text{raw}}^{\text{acc}} - A_P}{1 - A_{\text{raw}}^{\text{acc}}A_P}
\]

(physical) CP asymmetry

AP is the production asymmetry and obtained from \(B^\pm \to J/\psi K^\pm\) as a control channel.

\[
A_P = A_{\text{raw}}^{\text{acc}}(B^\pm \to J/\psi K^\pm) - A_{C\text{P}}(B^\pm \to J/\psi K^\pm)
\]

\[
A_{C\text{P}}(B^\pm \to K^\pm \pi^+ \pi^-) = +0.011 \pm 0.002 \pm 0.003 \pm 0.003, \\
A_{C\text{P}}(B^\pm \to K^\pm K^+ K^-) = -0.037 \pm 0.002 \pm 0.002 \pm 0.003, \\
A_{C\text{P}}(B^\pm \to \pi^\pm \pi^+ \pi^-) = +0.080 \pm 0.004 \pm 0.003 \pm 0.003, \\
A_{C\text{P}}(B^\pm \to \pi^\pm K^+ K^-) = -0.114 \pm 0.007 \pm 0.003 \pm 0.003,
\]
Direct CP violation 3-body $B^+$ decays

- $A_{CP}$ in bins of the Dalitz plots.
- Adaptive binning to have similar number of events in each bin.
- A rich pattern of large and localised asymmetries observed in $\pi \pi \rightarrow KK$ scattering region ($1 \text{ GeV}^2/c^4 < m^2 < 2.25 \text{ GeV}^2/c^4$)

$B^\pm \rightarrow \pi^\pm \pi^- \pi^-$

$B^\pm \rightarrow K^\pm \pi^- \pi^-$

$B^\pm \rightarrow \pi^\pm K^-K^-$

$B^\pm \rightarrow K^\pm K^-K^-$

[Reference: LHCb-PAPER-2021-049]
Direct CP violation in charged $B \to PV$ decays

- The $B \to PV$ quasi-two-body decays of $B \to R(\to h_1^- h_2^+) h_3^+$ where $R$ is the resonance
  - $s_\parallel = m^2(h_1^- h_2^+) \text{ vs } s_\perp = m^2(h_1^- h_3^+)$
- For the low mass and narrow resonances:
  \[ |M_\pm|^2 = p_0^\pm + p_1^\pm \cos\theta(m_V, s_\perp) + p_2^\pm \cos^2\theta(m_V, s_\perp) \]
  \[ (p_{0,1,2}^\pm \text{ polynomial coefficients, } \theta \text{ helicity angle}) \]
- CP asymmetry given in the $B \to PV$ decay is a function of $p_2^\pm$:
  \[ A_{CP}^V = \frac{p_2^- - p_2^+}{p_2^- + p_2^+} \]

A large CP asymmetry is found in $B^\pm \to \rho(770)^0 (\to \pi^+ \pi^-) K^\pm$ decays

$A_{CP} = +0.150 \pm 0.019 \pm 0.011$
CPV in $B^0 \rightarrow p\bar{p}K^+\pi^-$-decays

- CPV in triple product asymmetries
- in the region of $M(p\bar{p}) < 2.85$ GeV/c$^2$ (Charmonium resonances excluded)
- The triple products are defined:
  - $C_T = \bar{p}_K^+ \cdot (\bar{p}_\pi^- \times \bar{p}_\rho^-)$ and $\bar{C}_T = \bar{p}_K^- \cdot (\bar{p}_\pi^+ \times \bar{p}_\rho^+)$
- Under the CP transformation:
  - $\hat{A}_T = \frac{N(C_T > 0) - N(C_T < 0)}{N(C_T > 0) + N(C_T < 0)}$
  - $\hat{\bar{A}}_T = \frac{\bar{N}(\bar{C}_T > 0) - \bar{N}(\bar{C}_T < 0)}{\bar{N}(\bar{C}_T > 0) + \bar{N}(\bar{C}_T < 0)}$
- CP-violating observables are:
  - $a_{CP}^{\hat{T}-odd} = \frac{1}{2}(A_T - \bar{A}_T)$  $a_{CP}^{\hat{T}+odd} = \frac{1}{2}(A_T + \bar{A}_T)$

$a_{CP}^{\hat{T}-odd} = (1.49 \pm 0.85 \pm 0.08)\%$, 
$a_{CP}^{\hat{T}+odd} = (0.51 \pm 0.85 \pm 0.08)\%$

Significant P-asymmetries found in the low $M(p\bar{p})$ (5.8$\sigma$), no CP violation observed!
CPV and mixing in charm decays
Charm Mixing

• Neutral charm meson oscillates through its antiparticle known as $D^0 - \bar{D}^0$ mixing.

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

$$[|p|^2 + |q|^2 = 1]$$

• Oscillations can be defined by two dimensionless parameters:

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

• Final state particles $D^0 \to f$ is measured via effective decay widths:

$$y_{CP}^f = \frac{\hat{\Gamma}(D^0 \to f) + \hat{\Gamma}(\bar{D}^0 \to f)}{2\Gamma} - 1.$$  

$$y_{CP}^f \approx y \quad \text{in absence of CP violation}$$
\( \mathcal{y}_{CP} = \mathcal{y}_{CP}^{K\pi} \) in 2-body \( D^0 \) decays

- Uses \( D^0 \rightarrow K^-\pi^+ \) and \( \bar{D}^0 \rightarrow K^+\pi^- \) as a proxy in decay widths.

\[
\frac{\hat{\Gamma}(D^0 \rightarrow f) + \hat{\Gamma}(\bar{D}^0 \rightarrow f)}{\hat{\Gamma}(D^0 \rightarrow K^-\pi^+) + \hat{\Gamma}(\bar{D}^0 \rightarrow K^+\pi^-)} - 1 \approx \mathcal{y}_f - \mathcal{y}_{CP}^{K\pi}.
\]

- Run2: (6 fb\(^{-1}\))

- \( D^0 \) candidates selected from \( D^{*+} \rightarrow D^0\pi_{tag} \)

\[
R^f(t) = \frac{N(D^0 \rightarrow f, t)}{N(D^0 \rightarrow K^-\pi^+, t)} \propto e^{-\mathcal{y}_f - \mathcal{y}_{CP}^{K\pi} t/\tau_{D^0}} \frac{\varepsilon(f, t)}{\varepsilon(K^-\pi^+, t)}
\]

Time dependent efficiencies:

\[\varepsilon(f, t) = \varepsilon_{sel} \times \varepsilon_{det}\]
$y_{CP} - y_{CP}^{K\pi}$ in 2-body $D^0$ decays

- Uses $D^0 \rightarrow K^-\pi^+$ and $\bar{D}^0 \rightarrow K^+\pi^-$ as a proxy in decay widths.

\[
\frac{\hat{\Gamma}(D^0 \rightarrow f) + \hat{\Gamma}(\bar{D}^0 \rightarrow f)}{\hat{\Gamma}(D^0 \rightarrow K^-\pi^+) + \hat{\Gamma}(\bar{D}^0 \rightarrow K^+\pi^-)} - 1 \approx y_{CP}^f - y_{CP}^{K\pi}.
\]

- Run2 : (6 fb$^{-1}$)

- $D^0$ candidates selected from $D^{\pm} \rightarrow D^0\pi^{\pm}$

\[
R^f(t) = \frac{N(D^0 \rightarrow f, t)}{N(D^0 \rightarrow K^-\pi^+, t)} \propto e^{-(y_{CP}^f - y_{CP}^{K\pi}) t / \tau_{D^0}} \frac{\epsilon(f, t)}{\epsilon(K^-\pi^+, t)}
\]

time dependent efficiencies : $\epsilon(f, t) = \epsilon_{sel} \times \epsilon_{det}$

Fit to $\Delta M = m(h^-h^+\pi_{tag}^+) - m(h^-h^+)$
Results

\[ y^{\pi\pi}_{CP} - y^{K\pi}_{CP} = (6.57 \pm 0.53 \pm 0.16) \times 10^{-3} \]
\[ y^{KK}_{CP} - y^{K\pi}_{CP} = (7.08 \pm 0.30 \pm 0.14) \times 10^{-3} \]

Assuming that all systematic uncertainties are fully correlated, the combination of the results:

\[ y_{CP} - y^{K\pi}_{CP} = (6.96 \pm 0.26 \pm 0.13) \times 10^{-3} \]

- 4 times more precise than World Average!
CP asymmetry in $D_{(s)}^+ \rightarrow \eta^{(')}\pi^+$ decays

- CP asymmetry obtained from simultaneous, binned, extended ML fit to $m(\eta^{(')}\pi^+)$, in bins of $m(\gamma\pi^+\pi^-)$
- Detection and production asymmetries subtracted using control channel: $D_{(s)}^+ \rightarrow \phi\pi^+$
- Run2: 5.6 fb$^{-1}$

$\mathcal{A}^\text{CP}(D^+ \rightarrow \eta\pi^+) = (0.34 \pm 0.66 \pm 0.16 \pm 0.05)\%$,
$\mathcal{A}^\text{CP}(D_s^+ \rightarrow \eta\pi^+) = (0.32 \pm 0.51 \pm 0.12)\%$,
$\mathcal{A}^\text{CP}(D^+ \rightarrow \eta'\pi^+) = (0.49 \pm 0.18 \pm 0.06 \pm 0.05)\%$,
$\mathcal{A}^\text{CP}(D_s^+ \rightarrow \eta'\pi^+) = (0.01 \pm 0.12 \pm 0.08)\%$,

- most precise measurements up to date!
- No CP violation effect is observed!
Summary

- LHC delivers many interesting results on the CPV in B and charm decays!
- With the new data that will be collected from this year, many more is on the way with more precision!
- Stay tuned!
BACKUP
# CMS Run 2 results

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Fit value</th>
<th>Stat. uncer.</th>
<th>Syst. uncer.</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\phi_s$ [mrad]</td>
<td>$-11$</td>
<td>$\pm 50$</td>
<td>$\pm 10$</td>
</tr>
<tr>
<td>$\Delta \Gamma_s$ [ps$^{-1}$]</td>
<td>$0.114$</td>
<td>$\pm 0.014$</td>
<td>$\pm 0.007$</td>
</tr>
<tr>
<td>$\Delta m_s$ [$\hbar$ ps$^{-1}$]</td>
<td>$17.51$</td>
<td>$^{+0.10}_{-0.09}$</td>
<td>$\pm 0.03$</td>
</tr>
<tr>
<td>$</td>
<td>\lambda</td>
<td>$</td>
<td>$0.972$</td>
</tr>
<tr>
<td>$\Gamma_s$ [ps$^{-1}$]</td>
<td>$0.6531$</td>
<td>$\pm 0.0042$</td>
<td>$\pm 0.0026$</td>
</tr>
<tr>
<td>$</td>
<td>A_0</td>
<td>^2$</td>
<td>$0.5350$</td>
</tr>
<tr>
<td>$</td>
<td>A_\perp</td>
<td>^2$</td>
<td>$0.2337$</td>
</tr>
<tr>
<td>$</td>
<td>A_S</td>
<td>^2$</td>
<td>$0.022$</td>
</tr>
<tr>
<td>$\delta_{\parallel}$ [rad]</td>
<td>$3.18$</td>
<td>$\pm 0.12$</td>
<td>$\pm 0.03$</td>
</tr>
<tr>
<td>$\delta_{\perp}$ [rad]</td>
<td>$2.77$</td>
<td>$\pm 0.16$</td>
<td>$\pm 0.05$</td>
</tr>
<tr>
<td>$\delta_{S\perp}$ [rad]</td>
<td>$0.221$</td>
<td>$^{+0.083}_{-0.070}$</td>
<td>$\pm 0.048$</td>
</tr>
</tbody>
</table>
## ATLAS Run 2 results

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Statistical uncertainty</th>
<th>Systematic uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \phi_s [\text{rad}] )</td>
<td>(-0.081)</td>
<td>0.041</td>
<td>0.022</td>
</tr>
<tr>
<td>( \Delta \Gamma_s [\text{ps}^{-1}] )</td>
<td>0.0607</td>
<td>0.0047</td>
<td>0.0043</td>
</tr>
<tr>
<td>( \Gamma_s [\text{ps}^{-1}] )</td>
<td>0.6687</td>
<td>0.0015</td>
<td>0.0022</td>
</tr>
<tr>
<td>(</td>
<td>A_{</td>
<td></td>
<td>}(0)</td>
</tr>
<tr>
<td>(</td>
<td>A_0(0)</td>
<td>^2 )</td>
<td>0.5131</td>
</tr>
<tr>
<td>(</td>
<td>A_S(0)</td>
<td>^2 )</td>
<td>0.0321</td>
</tr>
<tr>
<td>( \delta_{\perp} - \delta_S [\text{rad}] )</td>
<td>(-0.25)</td>
<td>0.05</td>
<td>0.04</td>
</tr>
</tbody>
</table>

**Solution (a)**

| \( \delta_{\perp} [\text{rad}] \) | 3.12 | 0.11 | 0.06 |
| \( \delta_{\parallel} [\text{rad}] \) | 3.35 | 0.05 | 0.09 |

**Solution (b)**

| \( \delta_{\perp} [\text{rad}] \) | 2.91 | 0.11 | 0.06 |
| \( \delta_{\parallel} [\text{rad}] \) | 2.94 | 0.05 | 0.09 |
CP asymmetry in $D_{(s)}^+ \rightarrow \eta(1^{\prime})\pi^+$ decays

CP asymmetry is defined as:

$$A_{CP}^{D_{(s)}^+ \rightarrow f^+} \equiv \frac{\Gamma(D_{(s)}^+ \rightarrow f^+) - \Gamma(D_{(s)}^- \rightarrow f^-)}{\Gamma(D_{(s)}^+ \rightarrow f^+) + \Gamma(D_{(s)}^- \rightarrow f^-)}, \quad A_{raw}^{D_{(s)}^+ \rightarrow f^+} \equiv \frac{N(D_{(s)}^+ \rightarrow f^+) - N(D_{(s)}^- \rightarrow f^-)}{N(D_{(s)}^+ \rightarrow f^+) + N(D_{(s)}^- \rightarrow f^-)}.$$  

approximately

$$A_{raw}^{D_{(s)}^+ \rightarrow f^+} \approx A_{CP}^{D_{(s)}^+ \rightarrow f^+} + A_{prod}^{D_{(s)}^+} + A_{det}^{f^+},$$

production asym detection asym

Same $A_{prod}$ and $A_{det}$ with control samples $D_s^+ \rightarrow \phi\pi^+$ and $D^+ \rightarrow \phi\pi^+$

$$A_{raw}^{D^+ \rightarrow \eta(1^{\prime})\pi^+} - A_{raw}^{D^+ \rightarrow \phi\pi^+} = A_{CP}^{D^+ \rightarrow \eta(1^{\prime})\pi^+} - A_{CP}^{D^+ \rightarrow \phi\pi^+},$$

external input as = (0.005 ± 0.051)%

$$A_{raw}^{D_s^+ \rightarrow \eta(1^{\prime})\pi^+} - A_{raw}^{D_s^+ \rightarrow \phi\pi^+} = A_{CP}^{D_s^+ \rightarrow \eta(1^{\prime})\pi^+}.$$
Simultaneous determination of $\gamma$ angle

- Results from the charm and beauty sectors are combined
- Many inputs from LHCb charm analyses are included in the combination for the first time!
- Additional external constraints used on the hadronic parameters and coherence factors in B and D decays.
- Frequentist approach with 151 observables to determine 52 parameters

<table>
<thead>
<tr>
<th>$B$ decay</th>
<th>$D$ decay</th>
<th>Ref.</th>
<th>Dataset</th>
<th>Status since Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^{\pm} \to D h^{\pm}$</td>
<td>$D \to h^+ h^-$</td>
<td>[20]</td>
<td>Run 1&amp;2</td>
<td>Updated</td>
</tr>
<tr>
<td>$B^{\pm} \to D h^{\pm}$</td>
<td>$D \to h^+ \pi^- \pi^+$</td>
<td>[21]</td>
<td>Run 1</td>
<td>As before</td>
</tr>
<tr>
<td>$B^{\pm} \to D h^{\pm}$</td>
<td>$D \to h^+ h^- \pi^0$</td>
<td>[22]</td>
<td>Run 1</td>
<td>As before</td>
</tr>
<tr>
<td>$B^{\pm} \to D h^{\pm}$</td>
<td>$D \to K^0_S h^+ h^-$</td>
<td>[19]</td>
<td>Run 1&amp;2</td>
<td>Updated</td>
</tr>
<tr>
<td>$B^{\pm} \to D h^{\pm}$</td>
<td>$D \to K^0_S K^\pm \pi^\mp$</td>
<td>[23]</td>
<td>Run 1&amp;2</td>
<td>Updated</td>
</tr>
<tr>
<td>$B^{\pm} \to D^0 h^{\pm}$</td>
<td>$D \to h^+ h^-$</td>
<td>[20]</td>
<td>Run 1&amp;2</td>
<td>Updated</td>
</tr>
<tr>
<td>$B^{\pm} \to D K^{\pm*}$</td>
<td>$D \to h^+ h^-$</td>
<td>[24]</td>
<td>Run 1&amp;2(*)</td>
<td>As before</td>
</tr>
<tr>
<td>$B^{\pm} \to D K^{\pm*}$</td>
<td>$D \to h^+ \pi^- \pi^+$</td>
<td>[24]</td>
<td>Run 1&amp;2(*)</td>
<td>As before</td>
</tr>
<tr>
<td>$B^{\pm} \to D h^\pm \pi^+ \pi^-$</td>
<td>$D \to h^+ h^-$</td>
<td>[25]</td>
<td>Run 1</td>
<td>As before</td>
</tr>
<tr>
<td>$B^{\pm} \to D K^{\pm}$</td>
<td>$D \to h^+ h^-$</td>
<td>[26]</td>
<td>Run 1&amp;2(*)</td>
<td>Updated</td>
</tr>
<tr>
<td>$B^{\pm} \to D K^{\pm}$</td>
<td>$D \to h^+ h^- \pi^+$</td>
<td>[27]</td>
<td>Run 1</td>
<td>As before</td>
</tr>
<tr>
<td>$B^{\pm} \to D K^{\pm}$</td>
<td>$D \to K^0_S h^+ h^-$</td>
<td>[28]</td>
<td>Run 1</td>
<td>As before</td>
</tr>
<tr>
<td>$B^{\pm} \to D^0 K^{\pm}$</td>
<td>$D^+_s \to h^+ h^- \pi^+$</td>
<td>[29]</td>
<td>Run 1</td>
<td>As before</td>
</tr>
<tr>
<td>$B^{\pm} \to D^0 K^{\pm}$</td>
<td>$D^+_s \to h^+ h^- \pi^+$</td>
<td>[30]</td>
<td>Run 1&amp;2</td>
<td>New</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$D$ decay</th>
<th>Observable(s)</th>
<th>Ref.</th>
<th>Dataset</th>
<th>Status since Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D^0 \to h^+ h^-$</td>
<td>$\Delta A_{CP}$</td>
<td>[31–33]</td>
<td>Run 1&amp;2</td>
<td>New</td>
</tr>
<tr>
<td>$D^0 \to h^+ h^-$</td>
<td>$y_{CP}$</td>
<td>[34]</td>
<td>Run 1</td>
<td>New</td>
</tr>
<tr>
<td>$D^0 \to h^+ h^-$</td>
<td>$\Delta Y$</td>
<td>[35–38]</td>
<td>Run 1&amp;2</td>
<td>New</td>
</tr>
<tr>
<td>$D^0 \to K^+ \pi^-$ (Single Tag)</td>
<td>$R^{\pm}_C, (x^{\pm}_C)^2, y^{\pm}_C$</td>
<td>[39]</td>
<td>Run 1</td>
<td>New</td>
</tr>
<tr>
<td>$D^0 \to K^+ \pi^-$ (Double Tag)</td>
<td>$R^{\pm}_C, (x^{\pm}_C)^2, y^{\pm}_C$</td>
<td>[40]</td>
<td>Run 1&amp;2(*)</td>
<td>New</td>
</tr>
<tr>
<td>$D^0 \to K^+ \pi^- \pi^+$</td>
<td>$(x^2 + y^2)/4$</td>
<td>[41]</td>
<td>Run 1</td>
<td>New</td>
</tr>
<tr>
<td>$D^0 \to K^0_S \pi^+ \pi^-$</td>
<td>$x, y$</td>
<td>[42]</td>
<td>Run 1</td>
<td>New</td>
</tr>
<tr>
<td>$D^0 \to K^0_S \pi^+ \pi^-$</td>
<td>$x_{CP}, y_{CP}, \Delta x, \Delta y$</td>
<td>[43]</td>
<td>Run 1</td>
<td>New</td>
</tr>
<tr>
<td>$D^0 \to K^0_S \pi^+ \pi^-$</td>
<td>$x_{CP}, y_{CP}, \Delta x, \Delta y$</td>
<td>[44]</td>
<td>Run 2</td>
<td>New</td>
</tr>
</tbody>
</table>
Event pdf: \( P = N_{\text{sig}} P_{\text{sig}} + N_{\text{bkg}} P_{\text{bkg}} + N_{\text{peak}} P_{\text{peak}} \)

\[
P_{\text{sig}} = \epsilon (ct) \epsilon (\Theta) \left[ \mathcal{F} (\Theta, ct, \alpha) \otimes G (ct, \sigma_{ct}) \right] P_{\text{sig}} (m_{B^0_s}) P_{\text{sig}} (\sigma_{ct}) P_{\text{sig}} (\xi)
\]

- \( \epsilon (ct) \epsilon (\Theta) \): efficiency functions
- \( \mathcal{F} (\Theta, ct, \alpha) \): differential decay rate
- \( G (ct, \sigma_{ct}) \): gaussian resolution model
- \( P_{\text{sig}} (m_{B^0_s}) \): signal mass pdf
- \( P_{\text{sig}} (\sigma_{ct}) \): signal \( \sigma_{ct} \) pdf
- \( P_{\text{sig}} (\xi) \): tag distribution