Mixing and indirect CP violation in two-body Charm decays at LHCb

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on behalf of the LHCb collaboration
Overview

1) $A_F$ with Run 1 prompt data (3 fb$^{-1}$)
   
   [PRL 118, 261803 (2017)]

2) Mixing and CP violation in $D^0 \rightarrow K^\pm \pi^\mp$ decays with 2011–2016 prompt data (5 fb$^{-1}$)

   [PRD 97, 031101 (2018)]

3) $\gamma_{CP}$ with Run 1 semileptonic-tagged data (3 fb$^{-1}$)

   [PRL 122, 011802 (2018)]
Mixing and CPV in charm

Mixing is established.

- Mixing parameters: $x = \frac{m_2 - m_1}{\Gamma}$, $y = \frac{\Gamma_2 - \Gamma_1}{2\Gamma}$, $\Gamma = \frac{\Gamma_1 + \Gamma_2}{2}$

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

CPV still not observed.

- Charm is the only up-type quark where CPV can be fully investigated;
- $CPV < \mathcal{O}(10^{-3})$ in the SM, BSM contributions could enhance it.
$A_\Gamma$ with Run 1 data
**$A_\Gamma$ definition**

- Measure of indirect CPV in $D^0$ singly-Cabibbo-suppressed decays to CP eigenstates:

\[
A_{\text{CP}}(t) = \frac{\Gamma(D^0 \to f) - \Gamma(\bar{D}^0 \to f)}{\Gamma(D^0 \to f) + \Gamma(\bar{D}^0 \to f)} \approx A_{\text{CP}}^{\text{dir}} - A_\Gamma \left( \frac{t}{\tau} \right), \quad f = K^+K^-, \pi^+\pi^-
\]

\[
A_\Gamma = \frac{1}{2} \left[ \left( \frac{q}{p} - \frac{p}{q} \right) y \cos \phi + \left( \frac{q}{p} + \frac{p}{q} \right) x \sin \phi \right] \approx y \left( \left| \frac{q}{p} \right| - 1 \right) - x \phi
\]

- If $A_\Gamma \neq 0 \implies$ indirect CPV.

- At LHCb: measurement performed with Run 1 data (3 fb$^{-1}$)
- $D^0$ flavour from strong decay $D^{*+} \to D^0 \pi^+_s$ (prompt).

**[PRL 118, 261803 (2017)]**
\[ \Delta m = m(h^+h^-\pi^\pm_s) - m(h^+h^-) \]

- Cuts on \( m(h^+h^-) \), PID, IP of \( D^0 \) daughters.
Detection charge asymmetries

$$D^{*+} \rightarrow [h^+ h^-]_{D^0} \pi^+_s$$

CP-symmetric, no asymmetries

- Trigger introduces correlations between the measured decay time of the $D^0$ and the momentum of the $\pi^+_s$;
- momentum-dependent detection asymmetries reflect in time-dependent asymmetries mimicking a fake $A_\tau$ value as large as $10^{-3}$ ($3\sigma(A_\tau)$).

- Reweigh the 3D momentum distribution of the $\pi^-_s$ to match that of $\pi^+_s$.
- Validated on $D^0 \rightarrow K \pi^+$ (no CPV expected).

Charge asymmetry of the $\pi_s$

$$k = \frac{1}{\sqrt{p_x^2 + p_z^2}}$$

$\theta_x = \arctan \left( \frac{p_x}{p_z} \right)$
Secondary decays

- Measured decay-time of $D^0$ from $b$-hadrons biased to higher values -> their fraction increases as a function of time;
- $B$ production asymmetry different from $D^{*+}$;
- secondary decays induce time-dependent asymmetries.

- Suppressed requiring the $D^0$ to come from the PV ($\chi^2_{IP} < 9$);
- residual fraction estimated through a model whose normalization is fixed using the yields at high decay times.

$\chi^2_{IP} = $ difference in $pp$ vertex-fit $\chi^2$ reconstructed with and without the particle
Results

\[ A_{\Gamma}^{KK} = (-3.0 \pm 3.2 \pm 1.0) \cdot 10^{-4} \]
\[ A_{\Gamma}^{\pi\pi} = (4.6 \pm 5.8 \pm 1.2) \cdot 10^{-4} \]

- Sys. unc. dominated by secondary decays and multi-body partially and misreconstructed D-meson decays.

- Combination with the smaller, independent muon-tagged sample \( \bar{B} \rightarrow D^0\mu^-X \)

\[ A_{\Gamma} = (-2.9 \pm 2.8) \cdot 10^{-4} \]

- dominates the world average
- compatible with zero within \( 3 \cdot 10^{-4} \)
Mixing and CPV with $D^0 \rightarrow K^{\pm}\pi^{\mp}$ decays
Mixing in $D^0 \rightarrow K^{\pm}\pi^{\mp}$

- **Wrong sign (WS) decays:**

  \[ D_{*+}^0 \rightarrow D^0 \pi_S^+ \quad \text{mix} \quad \bar{D}^0 \quad \text{CF} \quad K^{+}\pi^{-} \]

  A time-dependent WS decay rate implies mixing

- **Right sign (RS) decays:**

  \[ D_{*+}^0 \rightarrow D^0 \pi_S^+ \quad \text{mix} \quad \bar{D}^0 \quad \text{DCS} \quad K^{-}\pi^{+} \]

  Decay rate nearly independent of time

Assuming negligible CPV:

\[
R(t) = \frac{\Gamma_{WS}(t)}{\Gamma_{RS}(t)} = R_D + \sqrt{R_D} y' \left( \frac{t}{\tau} \right) + \frac{(x')^2 + (y')^2}{4} \left( \frac{t}{\tau} \right)^2
\]

DCS decay interference mixing + CF decay

\[
x' = x \cos \delta + y \sin \delta
\]

\[
y' = y \cos \delta - x \sin \delta
\]

\[
A(D^0 \rightarrow K^+\pi^-) = -\sqrt{R_D} e^{-i\delta}
\]

\[
A(\bar{D}^0 \rightarrow K^+\pi^-) = \sqrt{R_D} e^{-i\delta}
\]

\[ x' = x \cos \delta + y \sin \delta \]

\[ y' = y \cos \delta - x \sin \delta \]
CP violation in $D^0 \rightarrow K^{\pm} \pi^{\mp}$

- Measure WS/RS(t) separately for $D^{*+}$ and $D^{-}$ decays:

$$R^\pm(t) = \frac{\Gamma^\pm_{WS}(t)}{\Gamma^\pm_{RS}(t)} = R^\pm_D + \sqrt{R^\pm_D} y^\pm \left(\frac{t - \tau}{\tau}\right) + \frac{(x^\pm)^2 + (y^\pm)^2}{4} \left(\frac{t - \tau}{\tau}\right)^2$$

  - Direct CPV $R^+_D \neq R^-_D$

  - CPV in the mixing or interference

$$x^\pm = \begin{bmatrix} q/p \end{bmatrix}^\pm_1 \left[ x \cos(\delta \pm \phi) + y \sin(\delta \pm \phi) \right]$$

$$y^\pm = \begin{bmatrix} q/p \end{bmatrix}^\pm_1 \left[ y \cos(\delta \pm \phi) - x \sin(\delta \pm \phi) \right]$$

$$\phi = \arg(q/p)$$

- $D^{*+}$ production cross section and $\pi^+_S$ detection asymmetry cancel out in the ratio; need to account only for $K\pi$ detection asymmetry:

$$\frac{N^\pm_{WS}}{N^\pm_{RS}} = \frac{N(D^{*\pm} \rightarrow [K^\pm \pi^{\mp}]_{D^0} \pi^\pm_S)}{N(D^{*\pm} \rightarrow [K^+ \pi^\mp]_{D^0} \pi^\pm_S)} = R^\pm \frac{\epsilon(K^\pm \pi^{\mp})}{\epsilon(K^+ \pi^\mp)}$$
Data sample

- 5 fb⁻¹ (2011–2016);
- prompt decays, sample selection ≈ that of $A_r$.
- $A(K\pi^+)$ accounted for employing measured asymmetries of $D^+ \rightarrow K^-\pi^+\pi^+$ and $D^+ \rightarrow \bar{K}^0\pi^+$ decays, reweighed to make their kinematic distributions coincide with that of $D^0 \rightarrow K^-\pi^+$

estimated at LHCb in [JHEP 07 (2013) 041]

$$A_D(K^-\pi^+) = A_{raw}(K^-\pi^+\pi^+) - A_{raw}(\bar{K}^0\pi^+) + A_D(\bar{K}^0)$$
$$= A_P(D^+) + A_D(K^-\pi^+) + A_D(\pi^+)$$
$$- A_P(D^+) - A_D(\bar{K}^0) - A_D(\pi^+)$$
$$+ A_D(\bar{K}^0)$$
Ghost tagging $\pi^+_s$ 

- It may happen that clusters belonging to the $\pi_s$ track in the tracking stations upstream the magnet are matched to wrong clusters downstream it;
  - measured direction between $D^0$ and $\pi_s$ is correct $\rightarrow$ bkg. peaks in $m(D^{*+})$ even if reconstructed $p(\pi_s)$ is wrong;
  - RS decay is tagged as much rarer WS $\approx$ half of the times.

- Misreconstruction probability must be kept well under $\text{BR}(D^{0}\rightarrow K^+\pi^-)/\text{BR}(D^{0}\rightarrow K^-\pi^+) \approx 3 \times 10^{-3}$
  - neural-network-based algorithm (occupancies & hit multiplicities in each subdetector, momentum of the track) [LHCb-PUB-2017-011]
  - accounts for 30—50% of sys. uncertainty.
Results

- No evidence for CPV

If no CPV is assumed:

\[ x^2 = (0.039 \pm 0.023 \pm 0.014) \cdot 10^{-3} \]

\[ y' = (5.28 \pm 0.45 \pm 0.27) \cdot 10^{-3} \]

- Twice as precise as previous superseded LHCb measurement [PRL 111 251801 (2013)]
$y_{CP}$ with $\bar{B} \rightarrow D^0_{\mu^-}X$ tagging
**$y_{\text{CP}}$ definition**

\[
y_{\text{CP}} = \frac{\hat{\Gamma}(D^0 \rightarrow h^+h^-) + \hat{\Gamma}(\bar{D}^0 \rightarrow h^+h^-)}{2\Gamma} - 1
\]

\[
f = K^+K^-, \pi^+\pi^- \quad \text{(CP-even)}
\]

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

- equal to $y$ in the limit of no CPV;
- differences are
  - linear in mixing parameters
  - quadratic in $\phi$, $|q/p| - 1$
  \[
  \begin{array}{c}
  \text{5\% of } y \text{ or less} \\
  \end{array}
  \]
- current precision ($\approx 20\%$) not as competitive as $A_\tau$ for CPV searches;
- it is a measurement of $y$ independent of $R(t) = WS/RS$.
- First measurement at LHCb [JHEP 04 (2012) 129] with prompt decays but very limited data sample (2010, 29 pb$^{-1}$), not competitive with world average.
New LHCb measurement

- 3 fb⁻¹ (Run 1);
- tagging with $\bar{B} \rightarrow D^0 \mu^- X$
- lower yield w.r.t. prompt decays;
- hardware and first level software trigger on the muon;
  — smaller trigger-induced decay-time biases.

- Extract $\gamma_{CP}$ from the time-dependent ratio between $h^+ h^-$ and $K \pi^+$ yields (same strategy as $B_s$, $D_s$ lifetimes measurements at LHCb [PRL 119, 101801]).
New!

\( \bar{B} \rightarrow D^0 \mu^- X \) selection

- Mainly inherited from muon-tagged \( \Delta A_{CP} \) and \( B_s, D_s \) lifetimes measurements \([JHEP 07 (2014) 041], [PRL 119, 101801]\)
- loose cuts on all tracks \( \chi^2_{IP} \);
- cut in the \( p_T(D^0) - m_{corr}(B) \) plane to reduce contamination from combinatorial bkg., double-charmed \( B \) decays, \( \bar{B} \rightarrow D^0 \tau^- X \)

- Final contamination in \( m(D^0) \) peak:
  - \(< 1.5\% \) from these bkg.
  - \(< 1\% \) from prompt \( D^0 \).

\[
m_{corr}(B) = \sqrt{m^2(D\mu) + p^2_\perp(D\mu) + p^2_\perp(D\mu)}
\]

\( \chi^2_{IP} = \) difference in \( pp \) vertex-fit \( \chi^2 \) reconstructed with and without the particle

\[880k\]
\[310k\]
\[4.6\text{M}\]

[Data: LHCb]

[Fit: LHCb]

[Background: LHCb]
Experimental strategy

- Inspired by [PRL 119, 101801]:
  - determine the yields of $h^+ h^-$ and $K\pi^+$ through a fit to $m(D^0)$, separately for 19 bins of decay time;
  - minimise the $\chi^2$ from the difference of $N_i(h^+ h^-) / N_i(K\pi^+)$ with the expected value:

$$R_i = \frac{\int_{t_i}^{t_{i+1}} e^{-\Gamma t} \, dt}{\int_{t_i}^{t_{i+1}} e^{-\Gamma t} \, dt}$$

$$\Delta \Gamma = \Gamma_{h^+ h^-} - \Gamma$$

$$\gamma_{CP} = \frac{\Delta \Gamma}{\Gamma}$$

normalisation factor common to all time bins

acceptance ratio in time bin $i$ (from MC)

ratio of the PDFs of $h^+ h^-$ and $K\pi^+$ decays (nearly independent of the value of $\Gamma$)
Acceptance ratio

- Acceptances calculated from MC simulation of inclusive $B^0$, $B^-$ semi-muonic decays into $D^0$;
- main MC mismodellings of detector *etc.* expected to cancel in the ratio.

6% variations mainly due to $\chi^2_{IP}$ cuts

[PRl 122, 011802 (2018)]
Null test (1): \( \frac{\Gamma(D^0 \rightarrow K^-\pi^+), \chi^2_{IP} > 60}{\Gamma(D^0 \rightarrow K^-\pi^+), \chi^2_{IP} > 8} \)

- Test the MC description of the time-dependence of the acceptance:
  - split the \( K^-\pi^+ \) sample in two;
  - apply a tighter cut \( \chi^2_{IP} > 60 \) to the \( \mu^-, K^-, \pi^+ \) of the numerator sample (std. is \( \chi^2_{IP} > 8 \));
  - measure \( \Delta \Gamma \) between the two samples (should be 0).

\[ \Delta_{\text{K}^-\pi^+/K^-\pi^+} = (-1.8 \pm 3.3) \cdot 10^{-3} \text{ ps}^{-1} \]

uncertainty corresponds to \( \sigma(y_{CP}) = 0.14\% \)
Null test (2): $\frac{\Gamma(D^+ \rightarrow K^-\pi^+\pi^+)}{\Gamma(D^0 \rightarrow K^-\pi^+)}$

- 3-body vs. 2-body decays $\rightarrow$ different topology, kinematics, acceptance;
- $(B^0: B^-)$ very different for $D^0$ and $D^+$ $\rightarrow$ check impact of B-mixture uncertainty in MC;
- $\tau(D^+) / \tau(D^0) \approx 2.5$ $\rightarrow$ sensitive to biases linear in $\Delta \Gamma$.

\[ \text{[PRL 122, 011802 (2018)]} \]

- Simulation
- Data
- Fit

$\sim$ 10% variations

$\tau(D^+) / \tau(D^0) = 2.5141 \pm 0.0082$ compatible with PDG within 1σ (test limited by PDG precision $2.536 \pm 0.019$).

Biases linear in $\Delta \Gamma$ are $< 0.8\% \Delta \Gamma$. 
Other checks and systematics

- Further checks:
  
  \[
  \frac{\Gamma(D^+ \to K^- \pi^+ \pi^+), \chi^2_{IP} > 60}{\Gamma(D^+ \to K^- \pi^+ \pi^+), \chi^2_{IP} > 8}
  \]

  \[
  \frac{\Gamma(D^+ \to K^- K^+ \pi^+)}{\Gamma(D^+ \to K^- \pi^+ \pi^+)}
  \]

  \(\Delta \Gamma\) consistent with 0 within stat. uncertainty

- Systematic uncertainties:

<table>
<thead>
<tr>
<th>Source</th>
<th>KK (%)</th>
<th>ππ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Finite size of MC sample (acceptance ratio)</td>
<td>0.11</td>
<td>0.15</td>
</tr>
<tr>
<td>Fit bias</td>
<td>0.02</td>
<td>0.02</td>
</tr>
<tr>
<td>(B^0:B^-) ratio and decay model</td>
<td>0.02</td>
<td>0.02</td>
</tr>
<tr>
<td>Decay-time resolution</td>
<td>0.01</td>
<td>0.01</td>
</tr>
<tr>
<td>(B - \bar{B}) production asymm.</td>
<td>&lt; 0.01</td>
<td>&lt; 0.01</td>
</tr>
<tr>
<td>Total sys.</td>
<td>0.11</td>
<td>0.15</td>
</tr>
<tr>
<td>Statistical</td>
<td>0.15</td>
<td>0.28</td>
</tr>
</tbody>
</table>

\([\text{PRL 122, 011802 (2018)}]\)
Fit result

$[PRL\ 122,\ 011802\ (2018)]$

$R_{[KK/K\pi]}$

$R_{[\pi\pi/K\pi]}$

$LHCb$

- $y_{CP}^{KK} = (0.63 \pm 0.15 \pm 0.11)\%$
- $y_{CP}^{\pi\pi} = (0.38 \pm 0.28 \pm 0.15)\%$
- $y_{CP} = (0.57 \pm 0.13 \pm 0.09)\%$

- Compatible and with same precision of world average $(0.835 \pm 0.155)\%$;
- compatible with $y = (0.67^{+0.06}_{-0.13})\%$ within 1σ.
Summary

- LHCb leads the world averages of all indirect CPV parameters thanks to huge c-cbar prompt production at LHC;
  - now eventually entering the region allowed by the SM, $\mathcal{O}(10^{-4})$;
- uncertainty on mixing parameters steadily decreasing, other 4 fb$^{-1}$ of data taken in 2017—2018;
- analyses still limited by the statistical uncertainty.

Thank you for your attention.
Any questions?
Backup
**$A_\Gamma$: systematics**

<table>
<thead>
<tr>
<th>Source</th>
<th>KK (10^{-4})</th>
<th>$\pi\pi$ (10^{-4})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Secondary decays</td>
<td>0.8</td>
<td>1.2</td>
</tr>
<tr>
<td>Discretisation of weighing procedure</td>
<td>0.2</td>
<td>0.2</td>
</tr>
<tr>
<td>Subtraction of $\Delta m$ bkg. from random $\pi^+_s$</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>Bkg. from partially-reconstructed and misidentified D-meson multi-body decays</td>
<td>0.5</td>
<td>-</td>
</tr>
<tr>
<td>Total sys.</td>
<td>1.0</td>
<td>1.2</td>
</tr>
<tr>
<td>Statistical</td>
<td>3.2</td>
<td>5.8</td>
</tr>
</tbody>
</table>

[PRl 118, 261803 (2017)]
A_\Gamma: \text{ contribution from secondary decays}

A_{\text{raw}} = A_{\text{prim}}(t) + f_{\text{sec}}(t) \cdot [A_{\text{sec}}(t) - A_{\text{prim}}(t)]

\approx A_{\text{production}}(B) - A_{\text{production}}(D^{*+})

[PRL 118, 261803 (2017)]

\chi^2_{\text{IP}} < 9

f_{\text{sec}} \text{ extracted from } \ln(\chi^2_{\text{IP}}) \text{ fit in last four time bins and extrapolated with physically-motivated empiric model to lower bins where the distributions of prompt and secondary decays can’t be easily disentangled. Uncertainty on the empiric model is the main source of systematic uncertainty.}
$A_\Gamma$ and $y_{CP}$ world averages

https://hflav.web.cern.ch

-0.032 ± 0.026 %

-0.030 ± 0.200 ± 0.080 %

0.088 ± 0.255 ± 0.058 %

-0.120 ± 0.120 %

-0.125 ± 0.073 %

-0.013 ± 0.028 ± 0.010 %

World average

0.835 ± 0.155 %

0.720 ± 0.180 ± 0.124 %

1.110 ± 0.220 ± 0.110 %

0.550 ± 0.630 ± 0.410 %

0.110 ± 0.610 ± 0.520 %

-1.200 ± 2.500 ± 1.400 %

3.420 ± 1.390 ± 0.740 %

0.732 ± 2.890 ± 1.030 %

-2.000 ± 1.300 ± 0.700 %

0.835 ± 0.155 %

-4 -3 -2 -1 0 1 2 3 4 5

$y_{CP}$ (%)
Indirect CPV: \( D^0 \rightarrow K^{\pm}\pi^{\mp} \) vs \( A_\Gamma \)

\( D^0 \rightarrow K^{\pm}\pi^{\mp} \): determines the 8-like shape of allowed \((\phi, |q/p|)\) region; nearly full degeneracy \( \phi \rightarrow -\phi \)

\[
\phi \approx y \left( \left| \frac{q}{p} \right| - 1 \right) - x\phi
\]

\( A_\Gamma \approx y \left( \left| \frac{q}{p} \right| - 1 \right) - x\phi \)

— it’s a line in the plane
— responsible for the tilt (and significant reduction of CPV-allowed region w.r.t. \( D^0 \rightarrow K^{\pm}\pi^{\mp} \) constraints only)
Tagging strategies at LHCb

To identify the flavour at production of the $D^0$ meson:

- **Prompt tag**: strong decay $D^{*+} \rightarrow D^0\pi^+_S$
  - larger production cross section;
  - tight trigger cut on $D^0$ flight distance and $h^+, h^-$ impact parameters to improve S/B;
  - low trigger efficiency at low decay times;
  - $D^0$ points at the primary vertex (PV).

- **Semileptonic tag**: weak decay $\bar{B} \rightarrow D^0\mu^-\bar{\nu}_\mu X$
  - lower production cross section;
  - no need to cut on $D^0$ flight distance;
  - all $D^0$ decay times collected by the trigger;
  - total yield $\approx 25\%$ of prompt one;
  - $D^0$ does not necessarily point at PV.

- **Double-tag**: $\bar{B} \rightarrow [D^0\pi^+_S]_{D^{*+}\mu^-\bar{\nu}_\mu} X$
  - highest purity;
  - lowest yield.
Indirect CPV prospects at LHCb Upgrade II

| Sample ($\mathcal{L}$) | Yield ($\times 10^6$) | $\sigma(x_{K\pi}^2)$ | $\sigma(y_{K\pi})$ | $\sigma(A_D)$ | $\sigma(|q/p|)$ | $\sigma(\phi)$ |
|------------------------|-----------------------|-----------------------|---------------------|---------------|----------------|----------------|
| Run 1–2 (9 fb$^{-1}$)  | 1.8                   | $1.5 \times 10^{-5}$  | $2.9 \times 10^{-4}$| 0.51%         | 0.12           | 10°            |
| Run 1–3 (23 fb$^{-1}$) | 10                    | $6.4 \times 10^{-6}$  | $1.2 \times 10^{-4}$| 0.22%         | 0.05           | 4°             |
| Run 1–4 (50 fb$^{-1}$) | 25                    | $3.9 \times 10^{-6}$  | $7.6 \times 10^{-5}$| 0.14%         | 0.03           | 3°             |
| Run 1–5 (300 fb$^{-1}$)| 170                   | $1.5 \times 10^{-6}$  | $2.9 \times 10^{-5}$| 0.05%         | 0.01           | 1°             |

<table>
<thead>
<tr>
<th>Sample ($\mathcal{L}$)</th>
<th>Tag</th>
<th>Yield $K^+K^-$</th>
<th>$\sigma(A_\Gamma)$</th>
<th>Yield $\pi^+\pi^-$</th>
<th>$\sigma(A_\Gamma)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Run 1–2 (9 fb$^{-1}$)</td>
<td>Prompt</td>
<td>60M</td>
<td>0.013%</td>
<td>18M</td>
<td>0.024%</td>
</tr>
<tr>
<td>Run 1–3 (23 fb$^{-1}$)</td>
<td>Prompt</td>
<td>310M</td>
<td>0.0056%</td>
<td>92M</td>
<td>0.0104%</td>
</tr>
<tr>
<td>Run 1–4 (50 fb$^{-1}$)</td>
<td>Prompt</td>
<td>793M</td>
<td>0.0035%</td>
<td>236M</td>
<td>0.0065%</td>
</tr>
<tr>
<td>Run 1–5 (300 fb$^{-1}$)</td>
<td>Prompt</td>
<td>5.3G</td>
<td>0.0014%</td>
<td>1.6G</td>
<td>0.0025%</td>
</tr>
</tbody>
</table>

Physics case for an LHCb Upgrade II [arXiv:1808.08865]

Assumptions:
- $x2$ of hadron trigger efficiency (no hardware trigger + new magnet stations);
- current LHCb performance is maintained in Upgrade II conditions;
- statistical uncertainty only (with $1/\sqrt{N}$ scaling).
The LHCb detector at the LHC, JINST 3 S08005 (2008)

CKM, 18/09/2018 Tommaso Pajero on behalf of LHCb | Mixing and CPV in 2-body charm decays