Mixing and CP violation in beauty and charm at the LHC

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LES RENCONTRES DE PHYSIQUE DE LA VALLÉE D’AOSTE, MARCH 13, 2019
Why study CP violation?

- The Standard Model (SM) does an excellent job of describing existing data, but it is clearly an incomplete theory.

- Example: SM CP violation is not capable of generating the observed matter-antimatter asymmetry of the universe.

- Most extensions of SM include new sources of CP violation.
  - Likely that the CKM picture of flavour physics is modified, and hopefully at accessible energy scales.

- “Indirect” searches have often provided first glimpse of new particles, e.g. the discovery of the top quark.
Measurements at the LHC

- Each second LHC produces $\mathcal{O}(100k)$ $b$- and $\mathcal{O}(1M)$ $c$-hardrons.
  - ATLAS, CMS, and LHCb take advantage for studying CP violation and mixing.

- LHCb is designed for precision measurements of $b$- and $c$-hadrons.
  - Unsurprisingly the source of most new results.

- And there is a lot that is new!
  - Happy to be able to show some results for the first time.
  - Try to give an overview of the themes studied in context of new results, but not a complete list!
Beauty

○ From unitarity condition \( V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0 \)

○ Goal: precisely measure these triangles to test consistency of CKM description of CPV
Measurements of $\gamma$

- A key part of the CP violation programme at LHCb is measurement of unitarity angle
  \[ \gamma \equiv \arg[-V_{ud}V_{ub}^*/V_{cd}V_{cb}^*] \]

- Accessed through exploiting the interference between $b \to cW$ and $b \to uW$ transitions.
- Combine the knowledge from several $B$ decays and subsequent $D$ decays.
  - Latest LHCb average $\gamma = (74.0^{+5.0}_{-5.8})^\circ$

- As of **summer 2018**, the world average is $\gamma = (72.1^{+5.4}_{-5.7})^\circ$
  - Indirect value is $\gamma = (65.64^{+0.97}_{-3.42})^\circ$
CP violation in interference of mixing and decay

- Excellent probe for physics beyond the SM.

- An important example in the $B_S^0$ system is that of $\phi_S \approx -2\beta_S \equiv \text{arg}[-V_{ts}V_{tb}^*/V_{cs}V_{cb}^*]$
  - Inferred with high precision from other measurements.
  - Can be enhanced by new physics contributions.

- Golden mode for measuring $\phi_S$ is $B_S^0 \to J/\psi K^+K^-$
  - Measurements performed by ATLAS, CMS, and LHCb using Run 1 data

- Also measured by LHCb in $B_S^0 \to J/\psi \pi^+\pi^-$, and similar observables in other $B_S^0$ decay modes.

CMS: PLB 757 (2016) 97
ATLAS: JHEP 08 (2016) 147
"Measurement of the CP-violating phase $\phi_s$ from $B_s^0 \to J/\psi \pi^+ \pi^-$ decays in 13 TeV $pp$ collisions"

- An update has been performed using 1.9fb$^{-1}$ of LHCb data taken in 2015-2016

- Tagged, time-dependent angular analysis needed, making for a complicated analysis:
  - Acceptance modelling in 4 dimensions of the decay phase-space.
  - Decay-time acceptance and resolution.
  - Tagging the flavour of the $B_s$ at production.
  - Description of the $\pi^+ \pi^-$ resonance spectrum.
Detector response and flavour tagging

- Four dimensional efficiency determined from simulation.

- Data-driven determination of decay-time acceptance and resolution (average resolution of 41.5fs)

- Flavour tagging uses information from decays of other $b$ hadron produced in the event (OS) and fragments of jet that produced $B_s$ that contain charged $K$

<table>
<thead>
<tr>
<th>Category</th>
<th>$\varepsilon_{\text{tag}}$ (%)</th>
<th>$\varepsilon_{\text{tag}}D^2$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>OS only</td>
<td>$11.0 \pm 0.6$</td>
<td>$0.86 \pm 0.05$</td>
</tr>
<tr>
<td>SSK only</td>
<td>$42.6 \pm 0.6$</td>
<td>$1.54 \pm 0.33$</td>
</tr>
<tr>
<td>OS and SSK</td>
<td>$24.9 \pm 0.6$</td>
<td>$2.66 \pm 0.19$</td>
</tr>
<tr>
<td>Total</td>
<td>$78.5 \pm 0.7$</td>
<td>$5.06 \pm 0.38$</td>
</tr>
</tbody>
</table>
Resonance model

- Several models considered, with second best used to assign associated systematic uncertainties.
CP-violating parameter results

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Fit result</th>
<th>Correlation</th>
<th>Correlation</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \Gamma_H - \Gamma_{B^0} ) (ps(^{-1}))</td>
<td>(-0.050 \pm 0.004 \pm 0.004)</td>
<td>1.000</td>
<td>0.022</td>
</tr>
<tr>
<td>(</td>
<td>\lambda</td>
<td>)</td>
<td>(1.01^{+0.08}_{-0.06} \pm 0.03)</td>
</tr>
<tr>
<td>(\phi_s) (rad)</td>
<td>(-0.057 \pm 0.060 \pm 0.011)</td>
<td>0.038</td>
<td>0.065</td>
</tr>
</tbody>
</table>

- A combination with the Run 1 measurement gives:
  \[ \Gamma_H - \Gamma_{B^0} = -0.050 \pm 0.004 \pm 0.004 \text{ ps}^{-1}, \]
  \[ |\lambda| = 0.949 \pm 0.036 \pm 0.019, \text{ and} \]
  \[ \phi_s = 0.002 \pm 0.044 \pm 0.012 \text{ rad} \]

Consistent with inferred value of \(-36.5^{+1.3}_{-1.2}\) mrad. \(\textbf{(Phys. Rev. D91 (2015) 073007)}\)
"Measurement of the branching fraction and CP asymmetry in $B^+ \rightarrow J/\psi \rho^+$ decays"

- Analysis of 3fb-1 of data collected by LHCb in 2011/2012
- Gives estimate of imaginary part of penguin-to-tree amplitude ratio in $b \rightarrow cc\bar{d}$ transitions

- Asymmetry measured to be $\mathcal{A}^{CP} = -0.045_{-0.057}^{+0.056} \pm 0.008$
- Following isospin symmetry expectations, consistent with $B^0 \rightarrow J/\psi \rho^0$
Charmless $B$ decays

- Suppressed at tree-level, significant higher order contributions.
- Known to exhibit large asymmetries.
- Several new results in multibody decays, some of which were covered in Cayo Costa Sobral’s talk yesterday evening [link]
  - Amplitude analysis of $B^\pm \rightarrow \pi^\pm K^- K^+$ decays (In preparation)
  - Amplitude analysis of $B^0_S \rightarrow K^0_S K^\pm \pi^{\mp}$ decays [arXiv:1902:07955]
- And even more to show now!
“Study of the $B^0 \rightarrow \rho (770)^0 K^* (892)^0$ decay with an amplitude analysis of $B^0 \rightarrow (\pi^+ \pi^-)(K^+ \pi^-)$ decays”

- Analysed 3 fb$^{-1}$ collected in 2011/2012 in the range of $300 < m(\pi^+ \pi^-) < 1100$ and $750 < m(K^+ \pi^-) < 1200$ MeV/c$^2$

- Tree level $b \rightarrow u\bar{u}s$ is doubly Cabibbo suppressed
  ➢ Higher order diagrams contribute.

- Small longitudinal polarisation fraction and significant direct CP asymmetry found
  
  \[ f_{\rho K^*}^0 = 0.164 \pm 0.015 \pm 0.022 \quad A_{\rho K^*}^0 = -0.62 \pm 0.09 \pm 0.09 \]

- Hints at significant contribution from penguin amplitudes.
Study of the $B^0 \to \rho(770)^0 K^*(892)^0$ decay with an amplitude analysis of $B^0 \to (\pi^+\pi^-)(K^+\pi^-)$ decays

- CP violation in $VV$ component clearly visible in projections.
- First significant observation of CP asymmetry in angular distributions of $B^0 \to VV$ decays.

[arXiv:1812.07008]
“Measurement of CP asymmetries in charmless four-body $\Lambda_b^0$ and $\Xi_b^0$ decays”

CP violation not yet been observed in baryon decays

- LHCb has seen evidence: arXiv:1609.05216

- Measurement of asymmetries in six modes made using 3 fb$^{-1}$ of data collected in 2011/2012.

- Construct difference between CP asymmetries in charmless decays and decays with an intermediate charmed baryon with the same particles in the final state.

- Cancel out production and detection charge-asymmetry effects
Results

- Asymmetries measured in full phase space as well as exploring specific regions of kinematics.
  - In total 18 asymmetries measured.
  - No significant asymmetries found, the search for CP violation in baryons continues.
Mixing and CP violation in charm

- Interesting and unique opportunities:
  - SM signal is very small due to CKM and GIM suppression.
  - Only possibility for studying these phenomenon in up-type quark.
  - Complementary to the strange and beauty systems.

- Challenges:
  - Small signals require millions of candidates and good control of systematic uncertainties.
  - Tricky theoretical uncertainties due to long-distance effects.

Note: Mass and width differences denoted by $\chi = \frac{m_2 - m_1}{\Gamma}$ and $\gamma = \frac{\Gamma_2 - \Gamma_1}{2\Gamma}$, with $\Gamma = \frac{\Gamma_1 + \Gamma_2}{2}$.
Searches for direct CP violation

- We are of course actively pursuing searches for direct CP violation in charm

- Two such recent searches were covered by Tommaso Pajero yesterday: [link]
  - Search for CP violation in $D_s^+ \rightarrow K_S^0\pi^+$, $D^+ \rightarrow K_S^0K^+$, and $D^+ \rightarrow \phi\pi^+$ [arXiv:1903.01150]
  - Search for CP violation through an amplitude analysis of $D^0 \rightarrow K^+K^−\pi^+\pi^−$ decays [arXiv:1811.08304]

- And another will be shown by Julián García Pardiñas this afternoon [link]
  - Measurement of angular and CP asymmetries in $D^0 \rightarrow \pi^+\pi^−\mu^+\mu^−$ [arXiv:1806.10793]
“Current” picture in time-dependent charm analyses

- A few analyses out of date, but conclusion from 2018 HFLAV fit still true.
- Non-mixing hypothesis rejected at overwhelming significance

.... but $x$ is still consistent with zero

.... and there is no indication of indirect CPV
“Measurement of the charm-mixing parameter $\gamma_{CP}$”

- Analysis compares decay width of $D^0$ to CP-even final states ($\Gamma_{CP}$) to the decay width to CP-mixed states ($\Gamma$): $\Delta\Gamma \equiv \Gamma_{CP} - \Gamma$

- Decays to CP eigenstates $D^0 \rightarrow K^+K^-$ and $D^0 \rightarrow \pi^+\pi^-$ are reconstructed along with CP mixed $D^0 \rightarrow K^-\pi^+$.

- 3fb$^{-1}$ of Run 1 data, using $D^0$ mesons coming from semimuonic $B^-$ and $\bar{B}^0$ decays

<table>
<thead>
<tr>
<th>Decay</th>
<th>Signal yield [10$^3$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D^0 \rightarrow K^+K^-$</td>
<td>878.2 ± 1.2</td>
</tr>
<tr>
<td>$D^0 \rightarrow \pi^+\pi^-$</td>
<td>311.6 ± 0.9</td>
</tr>
<tr>
<td>$D^0 \rightarrow K^-\pi^+$</td>
<td>4579.5 ± 3.2</td>
</tr>
</tbody>
</table>
“Measurement of the charm-mixing parameter $\gamma_{CP}$”

- Fit ratio of yields as a function of decay time to determine the best value of $\Delta \tau$.
  - Known $D^0$ lifetime used to extract $\gamma_{CP} = \Delta \tau$.

- Combining the modes gives:

  $\gamma_{CP} = (0.57 \pm 0.13\text{(stat)} \pm 0.099\text{(syst)})\%$.

- As precise as the world average.

- Also consistent with world average value of $y = (0.62 \pm 0.07)\%$.
  - No evidence of CP violation in mixing.

[arXiv:1810.06874]
“Measurement of the mass difference between neutral charm eigenstates”

- Analysis of $D^0 \rightarrow K_S \pi^+ \pi^-$ decays in 1.3M prompt and 1M semileptonic decays, corresponding to 3fb$^{-1}$ of data taken in 2011 and 2012.

- Features a rich resonance spectrum.
  - Pros: Good sensitivity due to varying strong phase differences.
  - Cons: Requires good understanding of decay dynamics and acceptance effects.
The “bin flip” method

- Uses novel approach for minimising the above challenges: 

- Data is binned according to Dalitz coordinates and external measurements of strong-phase variation used as constraints.
  - Avoids modelling dynamics of $D^0$ decay.

- Binned also in decay time, ratio of yields in opposite bins across the symmetry line formed in each decay-time bin.
  - Cancellation of acceptance effects.
  - Particularly sensitive to measuring $x$. 
Fit to ratios

LHCb

Prompt  Semileptonic  Fit

Fit to ratios
Fit results

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>95.5% CL interval</th>
</tr>
</thead>
<tbody>
<tr>
<td>$x \times 10^{-2}$</td>
<td>$0.27 \pm 0.17$</td>
<td>$[-0.05, 0.60]$</td>
</tr>
<tr>
<td>$y \times 10^{-2}$</td>
<td>$0.74 \pm 0.37$</td>
<td>$[0.00, 1.50]$</td>
</tr>
<tr>
<td>$</td>
<td>q/p</td>
<td>$</td>
</tr>
<tr>
<td>$\phi$</td>
<td>$-0.09 \pm 0.11$</td>
<td>$[-0.73, 0.29]$</td>
</tr>
</tbody>
</table>

- Most precise measurement of $x$ by a single experiment
- Consistent with CP symmetry.
Effect on world average

- The measurement helps to significantly improve the limits on the CPV parameters.

- Also note $x$ is $> 3\sigma$ from 0!
- Around 30 times more data was already collected during Run 2.
"Opportunities in Flavour Physics at the HL-LHC and HE-LHC"

- Prepared for the European Strategy for Particle Physics.
  - Physics potential from future upgrades discussed.

- Projections of uncertainties for key measurements are shown.
  - Too many to go through! A beautiful and a charming example:

[arXiv:1812.07638]
Conclusions

- Making precision measurements of CP violation is important for testing Standard Model description of CP violation.
  - Promising area to look for new physics effects.
- There is a very exciting and active program pursuing these studies at the LHC.
- A lot (most) of data taken at LHC remains to be analysed.
  - Higher statistics updates and brand new analyses on the way!
- And of course, we keep our eye on the future and much, much larger statistics.
Backup slides
CP violation in the Standard Model

- Weak interaction known to violate CP symmetry
  - Not invariant under exchange particle with antiparticle and inversion of spatial coordinates

- CP violation described in the SM by the Kobayashi-Maskawa mechanism
  - Due to a single irreducible phase of the Cabibbo-Kobayashi-Maskawa (CKM) matrix

\[
V_{\text{CKM}} = \begin{pmatrix}
V_{ud} & V_{us} & V_{ub} \\
V_{cd} & V_{cs} & V_{cb} \\
V_{td} & V_{ts} & V_{tb}
\end{pmatrix} = \begin{pmatrix}
1 - \lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\
-\lambda & 1 - \lambda^2/2 & A\lambda^2 \\
A\lambda^3(1 - \rho - i\eta) & -A\lambda^2 & 1
\end{pmatrix} + \mathcal{O}(\lambda^4)
\]

Expansion in $\lambda \approx 0.22$ convenient way of viewing hierarchy.
Types of CP violation

- **Direct CPV**
  - Occurs if $|A_f/A_f| \neq 1$, i.e. amplitude for decay and its CP conjugate have different magnitudes

- Only possible in flavoured neutral mesons which “mix” due to non-coincidence of flavour and mass eigenstates
  - $|M_{1,2}⟩ = p|M^0⟩ \pm q|\bar{M}^0⟩$

  - **CPV in mixing**
    - Occurs if $\left|\frac{q}{p}\right| \neq 1$

  - **CPV in interference between mixing and decay**
    - Occurs if $\phi \equiv \arg\left(\frac{qA_f}{pA_f}\right) \neq 0$