SEARCH FOR CP VIOLATION IN ANGULAR DISTRIBUTIONS OF $D^0 \rightarrow 4h$ DECAYS AT LHCB

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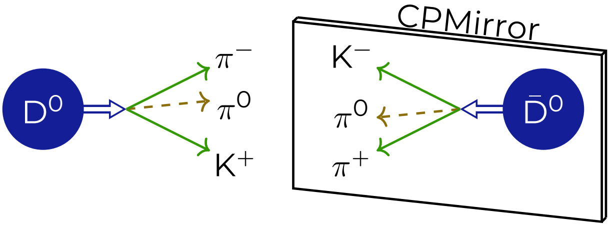
CP violation: matter - antimatter asymmetry



In the Standard Model (SM): Wolfenstein parametrisation of V_{CKM}:

$$\begin{pmatrix} 1-\lambda^2/2-\lambda^4/8 & \lambda & A\lambda^3(\rho-i\eta) \\ \lambda+A^2\lambda^5(1-2(\rho+i\eta))/2 & 1-\lambda^2/2-\lambda^4(1+4A^2)/8 & A\lambda^2 \\ A\lambda^3(1-(1-\lambda^2/2)(\rho+i\eta)) & -A\lambda^2+A\lambda^4(1-2(\rho+i\eta))/2 & 1-A^2\lambda^4/2 \end{pmatrix} + \mathcal{O}(\lambda^6)$$

All SM CPV in the complex part.
CPV in charm is small: $\mathcal{O}(10^{-3})$.
New Physics case: other sources of CPV must exist

Still a top priority topic

Types of CP violation (CPV)

- The usual break down: in decay and/or mixing
- Decay amplitudes:

$$
\begin{aligned}
A_f &= |a_1|e^{i(\delta_1+\phi_1)} + |a_2|e^{i(\delta_2+\phi_2)} \\
\overline{A}_{\bar{f}} &= |a_1|e^{i(\delta_1-\phi_1)} + |a_2|e^{i(\delta_2-\phi_2)} \\
A_{CP} &= \frac{\Gamma(X \to f) - \Gamma(\overline{X} \to \bar{f})}{\Gamma(X \to f) + \Gamma(\overline{X} \to \bar{f})} \sim \sin\Delta\phi \sin\Delta\delta
\end{aligned}
$$

- The common asymmetries may not be the most sensitive ones!

- Can acess CPV also through other observables (EDMs...)
- Through CPT conservation → T violation = CP violation:
  - Triple product observables

Triple product (TP) asymmetries

Game plan:

- Construct an asymmetry that is odd under time-reversal
  - Example in multi-body decays $M \to h_1 h_2 h_3 h_4$:

$$c_T = p_1 \cdot (p_2 \times p_3)$$

- Through CPT conservation → T violation = CP violation
- Construct asymmetries:

$$A_T = \frac{\Gamma(X, C_T > 0) - \Gamma(X, C_T < 0)}{\Gamma(X, C_T > 0) + \Gamma(X, C_T < 0)}$$

$$\overline{A}_T = \frac{\Gamma(\overline{X}, -C_T > 0) - \Gamma(\overline{X}, -C_T < 0)}{\Gamma(\overline{X}, -C_T > 0) + \Gamma(\overline{X}, -C_T < 0)}$$

$$a_{CP}^{T-odd} = \frac{1}{2}(A_T - \overline{A}_T)$$

Benefits of TPs

- Remember:

$$A_{CP} \sim \sin\Delta\phi \sin\Delta\delta$$

- But in TP case:

$$a_{CP}^{T-odd} \sim \sin\Delta\phi \cos\Delta\delta$$

does not depend on non-zero $\Delta\delta$; maximised for small $\Delta\delta$

- Model-independent approach
- Typical multi-body decays amplitude analyses will use a model-dependant approach

Complementary approach to search for CPV

TP in charm

- Current TP measurements:
  - FOCUS, $D^0 \to K^+K^-\pi^+\pi^-$, $D^+ \to K^0_S K^-\pi^+\pi^-$ and $D^+_s \to K^0_S K^-\pi^+\pi^-$, PLB **622**, 239 (2005)
  - BaBar, $D^0 \to K^+K^-\pi^+\pi^-$, PRD **81**, 111103 (2010)
  - LHCb, $D^0 \to K^+K^-\pi^+\pi^-$, JHEP **1410**, 005 (2014)
  - Belle, $D^0 \to K^0_S\pi^+\pi^-\pi^0$, PRD **95**, 091101 (2017)
  - Belle, $D^0 \to K^+K^-\pi^+\pi^-$, PRD **99**, 011104 (2019)

This analysis:

- Proposal to study TP asymmetries in $D^0 \to K^+K^-\pi^+\pi^-$ and $\pi^+\pi^-\pi^+\pi^-$
  - TP not studied yet in 4π
- Unprecedended statistics now available at LHCb
  - dataset 2015, 2016, (2017, 2018)
- Novel observables as proposed by Durieux, Grossman PRD **92**, 076013 (2015)

Proposed approach

- No clear indication on how CPV will manifest itself...
- Exploit different regions in multi-body phase space to probe for localised CPV
  - LHCb observation of large CPV in certain phase space regions of $B^+ \to hhh$ from resonance interference, PRD **90**, 112004
- Sensitivity depends on strong phase difference $\to a_{CP}^{T-odd} \sim \sin\Delta\phi \cos\Delta\delta$
- Method that does not rely on process dynamics assumptions
- Methods:

  Durieux, Grossman: observables constructed on differential distributions that arise from the various intermediate states

  Binned approach: study in more detailes regions in which the method is most sensitive

  Binning in decay time : expose CPV effects in mixing

Angular observables

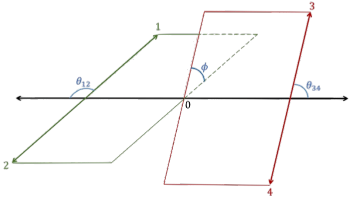
$$\Phi_{lmn} = P_l(\cos\theta_{12})P_m(\cos\theta_{34})\sin(n\phi_{12-34})$$

$l, m = 0, 1, 2$

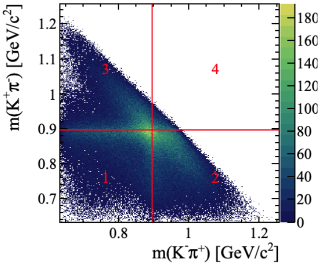
$n = 1, 2$

P_i: Legendre polynomials

Each asymmetry different than the other!

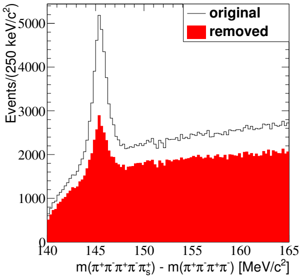


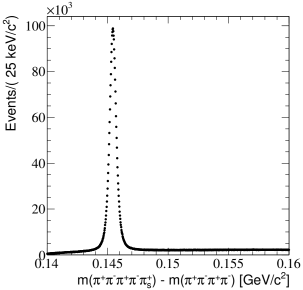
- Binned approach:
  - Dominant amplitudes: $K^{*0}\overline{K}^{*0}, \phi\rho^0, \rho^0\rho^0$
  - $l, m = 0; n = 1, 2$



- Binning in decay time: standard momentum C_T observable

Selection and fit





- $D^{*+} \to D^0(\to 4h)\pi^+$
- specifically remove K^0_S
- 9M events

Fit $\Delta m = m(D^{*+}) - m(D^0)$

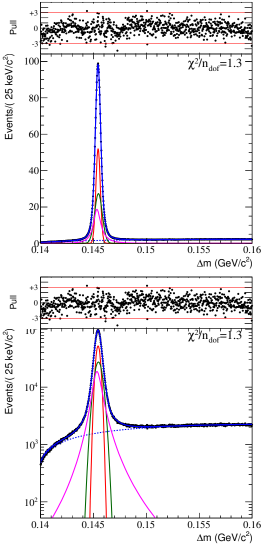
Simultaneus fit:

$$N_1 = N(D^0, \Phi > 0) = 0.5 \cdot N_{D^0} \cdot (1 + A_T)$$
$$N_2 = N(D^0, \Phi < 0) = 0.5 \cdot N_{D^0} \cdot (1 - A_T)$$
$$N_3 = N(\overline{D}^0, \bar{\Phi} > 0) = 0.5 \cdot N_{\overline{D}^0} \cdot (1 - \overline{A}_T)$$
$$N_4 = N(\overline{D}^0, \bar{\Phi} < 0) = 0.5 \cdot N_{\overline{D}^0} \cdot (1 + \overline{A}_T)$$

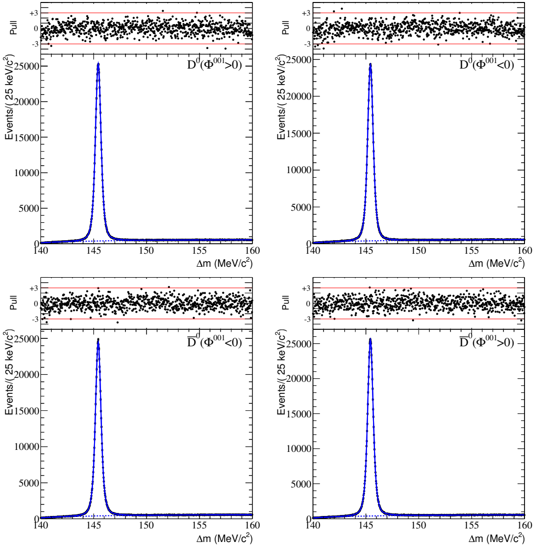
Blinded analysis.

Fit results

Global fit



Simultaneous fit for lmn = 001 (unbinned)



Conclusions

- Can be the most sensitive search of CPV in these decays so far.
- Novel approach to explore possible localised effects.
- Individual Φ_{lmn} asymmteries + combined
- Model-independent.
- Analysis of 2015,2016 data in good shape - finalising systematics
- Statistical uncertainty (blinded) of 2015-2016 data: $\mathcal{O}^{-3}$
- Systematics: under control,
  from TP analysis of $D^0 \rightarrow KK\pi\pi$ (LHCb, 2014): $\mathcal{O}^{-4}$
- Working to include 2017, 2018 data