D-mixing as input for model-independent determinations of the CKM phase γ

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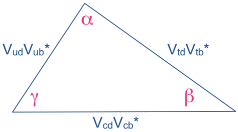
Outline

- CKM Phase γ
- D-Mixing Formalism
  - How does this relate to γ
- D-Mixing at LHCb in $D \to K^+\pi^-\pi^+\pi^-$ Decays

CP Violating Phase γ

- Angle γ is a CP violating phase in the CKM matrix.
  - Least constrained angle of the 'unitary triangle'.



- A sensitive decay is $B^+ \to DK^+$ where $D \to K^-\pi^+\pi^-\pi^+$.

$$\mathrm{R}\left(B^- \to DK^-,\ D \to K^+\pi^-\pi^+\pi^-\right) \propto r_B^2 + r_D^2 + 2r_B r_D R_D^{K3\pi}\cos(\delta_D^{K3\pi} + \delta_B - \gamma)$$

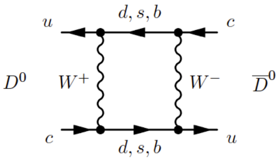
$$\mathrm{R}\left(B^+ \to DK^+,\ D \to K^-\pi^+\pi^-\pi^+\right) \propto r_B^2 + r_D^2 + 2r_B r_D R_D^{K3\pi}\cos(\delta_D^{K3\pi} + \delta_B + \gamma)$$

- **But** need input from several parameters related to D decay amplitudes and phase space integration.
  - Use D-mixing to constrain the D related parameters.

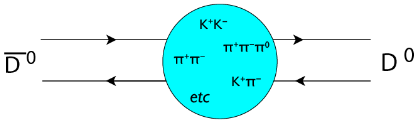
D-Mixing

- Mixing is when a neutral meson oscillates to its anti-particle.
  - Well established in K and B mesons.
  - Recently been observed in D mesons.
- D-Mixing is thought to be dominated by long range processes.

Short Range



Long Range



D-Mixing

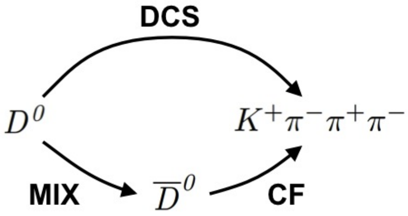
- Define the mass eigenstates as a superposition of flavour eigenstates.
  - CP conservation assumed here.

$$|D_1\rangle = |D^0\rangle + |\overline{D^0}\rangle$$
$$|D_2\rangle = |D^0\rangle - |\overline{D^0}\rangle$$

- At production and decay the D meson is in a flavour eigenstate.
  - But propagates as a superposition of mass eigenstates $\rightarrow$ mixing!
- Mixing is parameterised by two dimensionless parameters:

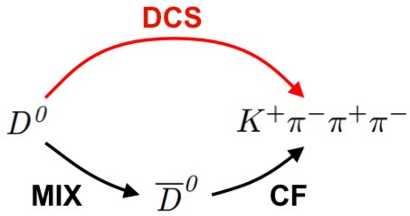
$$x \equiv \frac{m_1 - m_2}{\Gamma} \qquad y \equiv \frac{\Gamma_1 - \Gamma_2}{2\Gamma}.$$

Wrong Sign $D^0 \to K^+\pi^-\pi^+\pi^-$ Decays

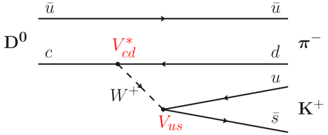


- Now look at the specific case of mixing in Wrong Sign $D^0 \to K^+\pi^-\pi^+\pi^-$ decays.
- There are two routes from the initial to the final state...

Wrong Sign $D^0 \to K^+\pi^-\pi^+\pi^-$ Decays



Doubly Cabibbo Suppressed (DCS) Amplitude



$$\mathrm{R}\left[D^0 \to K^+\pi^-\pi^+\pi^-\right](t) = e^{-\Gamma t}\left[\mathcal{A}^2_{\mathrm{DCS}} + \mathcal{A}_{\mathrm{DCS}}\mathcal{A}_{\mathrm{CF}} R_D^{K3\pi} y'\Gamma t + \mathcal{A}^2_{\mathrm{CF}}\frac{x^2+y^2}{4}(\Gamma t)^2\right]$$

$$\mathcal{A}^2_{\mathrm{DCS}} = \int |\mathcal{A}(\mathbf{p})_{\mathrm{DCS}}|^2 \mathrm{d}\mathbf{p}$$

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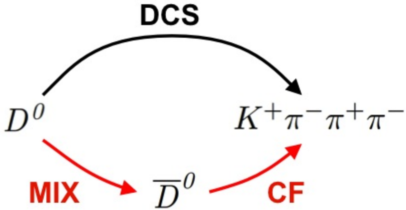
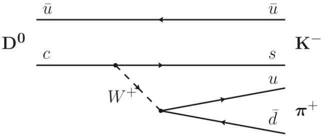
Wrong Sign $D^0 \to K^+\pi^-\pi^+\pi^-$ Decays



Cabibbo Favoured (CF) Amplitude



$$\mathrm{R}\left[D^0 \to K^+\pi^-\pi^+\pi^-\right](t) = e^{-\Gamma t}\left[\mathcal{A}^2_{\mathrm{DCS}} + \mathcal{A}_{\mathrm{DCS}}\mathcal{A}_{\mathrm{CF}} R_D^{K3\pi} y' \Gamma t + \mathcal{A}^2_{\mathrm{CF}} \frac{x^2+y^2}{4} (\Gamma t)^2\right]$$

$\mathcal{A}^2_{\mathrm{CF}} = \int |\mathcal{A}(\mathbf{p})_{\mathrm{CF}}|^2 \mathrm{d}\mathbf{p}$

x, y are dimensionless mixing parameters

Time Dependent!

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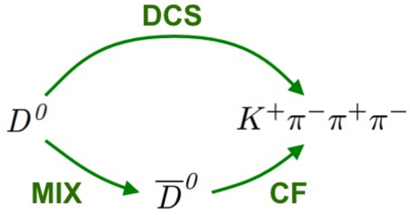
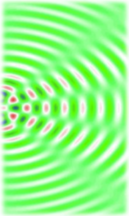
Wrong Sign $D^0 \to K^+\pi^-\pi^{+-}\pi^-$ Decays





$$\mathrm{R}\left[D^0 \to K^+\pi^-\pi^+\pi^-\right](t) = e^{-\Gamma t}\left[\mathcal{A}^2_{\mathrm{DCS}} + \mathcal{A}_{\mathrm{DCS}}\mathcal{A}_{\mathrm{CF}} R_D^{K3\pi} y'\Gamma t + \mathcal{A}^2_{\mathrm{CF}} \frac{x^2+y^2}{4}(\Gamma t)^2\right]$$

$$y' = y\cos\delta_D^{K3\pi} - x\sin\delta_D^{K3\pi}$$

$R_D^{K3\pi}$ - Coherence Factor

$\delta_D^{K3\pi}$ - Average Strong Phase Difference

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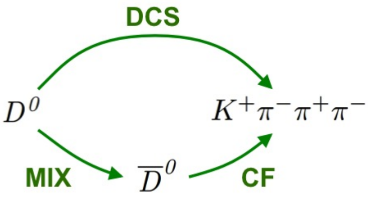
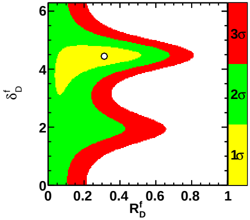
Multibody Decays and the Coherence Factor

- $D \to K^+\pi^-\pi^+\pi^-$ has a 5 dimensional phase space.
- Strong phase varies over this space.
  - Interference between CF and DCS amplitudes varies.
- Integrating over this variation dilutes the interference term.
  - 'Dilution' is parameterised by the coherence factor R_D^f.
  - Average phase difference amplitudes given by δ_D^f.

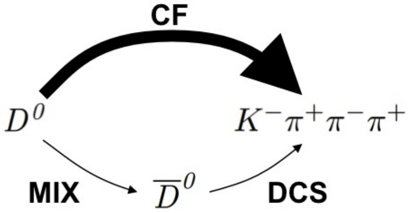


Cleo-c [1]



[1] Phys.Lett. B731, 197203, 2014

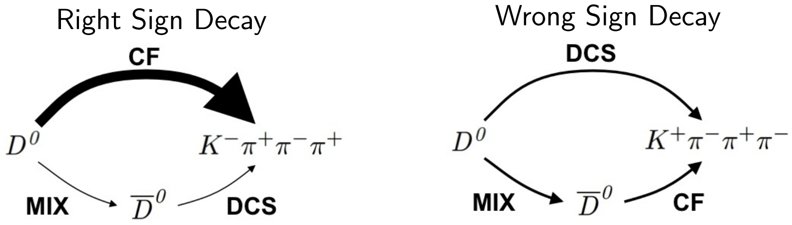
Right Sign $D^0 \to K^-\pi^+\pi^-\pi^+$ Decays



$$\mathrm{R}\left[D^0 \to K^-\pi^+\pi^-\pi^+\right](t) = \mathcal{A}_{\mathrm{CF}}^2 e^{-\Gamma t}$$

- Use Right Sign decays as a normalisation channel
- These are completely dominated by the Cabibbo Favoured Amplitude (no Mixing).

WS to RS ratio



$$r(t) = \frac{\mathrm{R}\left[D^0 \to K^+\pi^-\pi^+\pi^-\right](t)}{\mathrm{R}\left[D^0 \to K^-\pi^+\pi^-\pi^+\right](t)} = r_D^2 + r_D R_D^{K3\pi} y' \Gamma t + \frac{x^2+y^2}{4} (\Gamma t)^2$$

- By taking the ratio of WS to RS decays it is possible to cancel many detection and selection efficiencies
- r_D is the ratio $\mathcal{A}_{\mathrm{DCS}}/\mathcal{A}_{\mathrm{CF}}$

CP Violating Phase γ

- Rate for $B^+ \to DK^+$ where $D \to K^-\pi^+\pi^-\pi^+$:

$$\mathrm{R}\left(B^- \to DK^-,\ D \to K^+\pi^-\pi^+\pi^-\right) \propto r_B^2 + r_D^2 + 2 r_B r_D R_D^{K3\pi} \cos(\delta_D^{K3\pi} + \delta_B - \gamma)$$

$$\mathrm{R}\left(B^+ \to DK^+,\ D \to K^-\pi^+\pi^-\pi^+\right) \propto r_B^2 + r_D^2 + 2 r_B r_D R_D^{K3\pi} \cos(\delta_D^{K3\pi} + \delta_B + \gamma)$$

- Expression for WS/RS ratio:

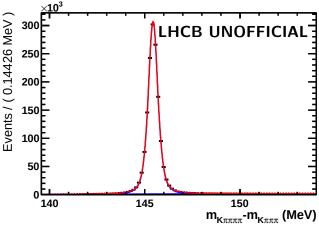
$$r(t) = r_D^2 + r_D R_D^{K3\pi} \left(y \cos \delta_D^{K3\pi} - x \sin \delta_D^{K3\pi}\right) \Gamma t + \frac{x^2+y^2}{4} (\Gamma t)^2$$

- Highlighted parameters show up in both expressions.

LHCb Dataset

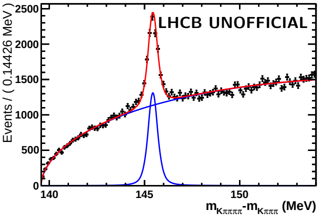
- Use 1.0fb^{-1} of data collected by the LHCb detector.
- Approximately 3.5 million tagged $D \to K^+\pi^-\pi^+\pi^-$ candidates after all selection requirements.
  - $D^{+*} \to D^0\pi^+$ decays tag the flavour of the D.
- Fit $\Delta m = m(K\pi\pi\pi\pi) - m(K\pi\pi\pi)$ to distinguish signal from background.

Right Sign



$\sim$ **3.3 million**

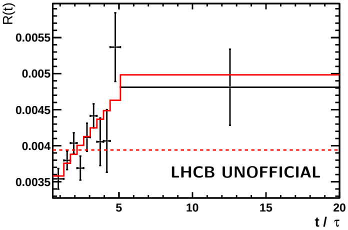
Wrong Sign



$\sim \mathbf{14,000}$

Mixing Significance

- Fit Δm in bins of lifetime to get WS/RS ratio.
- Look at the $\Delta\chi^2$ to evaluate the significance between mixing and no-mixing hypotheses.



Significance $= 4.3\sigma$

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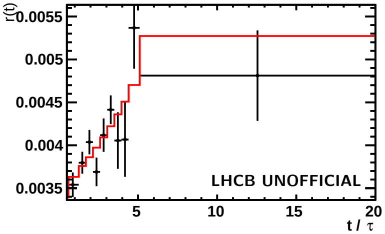
STATISTICAL ONLY

$$r_{\mathcal{H}_1}(t) = r_D^2 + r_D R_D^{K3\pi} y' \Gamma t + \frac{x^2 + y^2}{4} (\Gamma t)^2$$

$$r_{\mathcal{H}_0}(t) = r_D^2$$

WS to RS ratio

- Interested in parameters related to D decay amplitudes.
  - Constrain mixing parameters x and y to their PDG averages.



$$r_D = 0.0591 \pm 0.0012$$
$$R_D^{K3\pi} y' = 0.0026 \pm 0.0012$$
$$x = 0.0060 \pm 0.0018$$
$$y = 0.0073 \pm 0.0011$$

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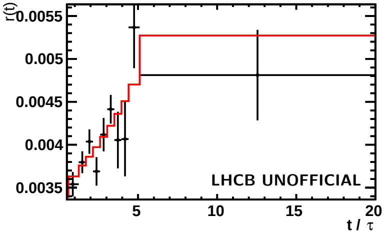
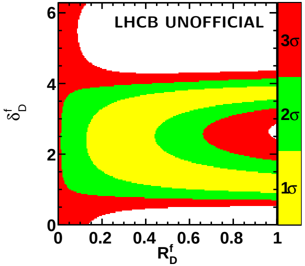
STATISTICAL ONLY

$$r(t) = r_D^2 + r_D R_D^{K3\pi} y' \Gamma t + \frac{x^2+y^2}{4} (\Gamma t)^2$$

Coherence Factor

- Likelihood scan in the physical region of $R_D^{K3\pi}$ and $\delta_D^{K3\pi}$.
- χ^2_{MIN} follows a curve in the 2D plane.

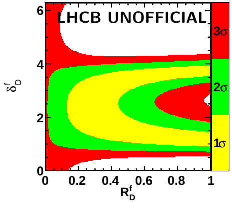




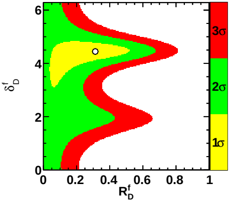
Cleo-c Combination

- Cleo-c measurement using quantum correlated $\psi(3770)$ decays.
- Different shaped confidence regions give nice LHCb and Cleo-c combination.

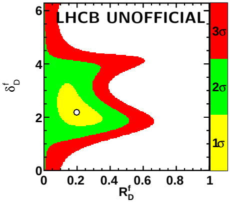
LHCb



Cleo-c [1]



Combination



$R_D^{K3\pi} = 0.31^{+0.20}_{-0.28}$ $\delta_D^{K3\pi} = 4.45^{+0.37}_{-1.36}$ **[CLEO]**

$R_D^{K3\pi} = 0.20^{+0.16}_{-0.12}$ $\delta_D^{K3\pi} = 2.18^{+1.08}_{-0.52}$ **[CLEO + LHCb UNOFFICIAL]**

[1] Phys.Lett. B731, 197203, 2014

Conclusions

- Further constraining $R_D^{K3\pi}$ can improve sensitivity to the CKM phase γ.
- Substantial improvements can be made by studying the time dependence of WS $D^0 \to K^+\pi^-\pi^+\pi^-$ decays at LHCb.
- Another $2\mathrm{fb}^{-1}$ of data to add to the $1.0\mathrm{fb}^{-1}$ already presented.