Charm IX

Novosibirsk

Review of recent results on Amplitude Analyses

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On behalf of the LHCb collaboration

Why study amplitudes?

- Window into CP violation, charm mixing ..
- Measurements of CP violating phase of the CKM matrix, γ.
- Learn about hadron physics along the way.
- Presenting results from the LHCb collaboration.

Studies of the resonance structure in $D^0 \to K^{\mp}\pi^{\pm}\pi^{\pm}\pi^{\mp}$ decays [3]

$D^0 \to K^-\pi^+\pi^+\pi^-$, largest contribution from:

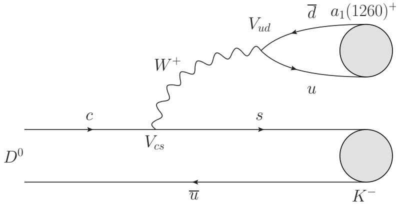


Diagram is $\mathcal{O}(1)$ in terms of CKM matrix element → Cabibbo favoured (CF).
BR. $\sim 8\%$
Studied by Mark III [1] and BES III [2].

$D^0 \to K^+\pi^-\pi^-\pi^+$, largest contribution from:

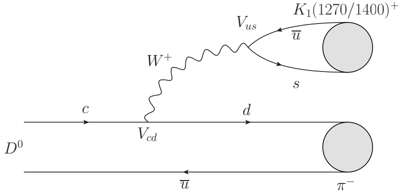
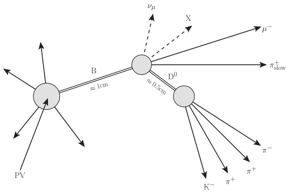


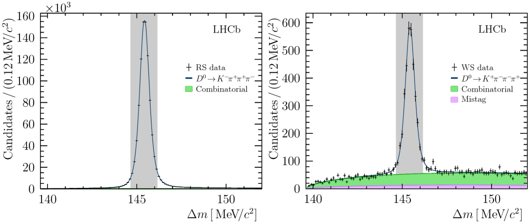
Diagram has two off-diagonal CKM elements → doubly-Cabibbo suppressed (DCS).
BR. $\sim 2 \times 10^{-4}$

"Golden modes" for studies of γ and charm mixing.

Data samples

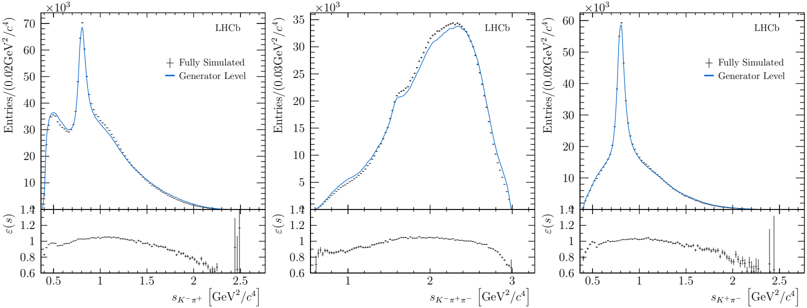


Reconstruct $B \to D^{*+}\left[D^0\pi^+\right]\mu^- X$ as a clean source of D^0 decays. Charge of 'slow' pion and muon relative to kaon is used to infer D^0 flavour at production.



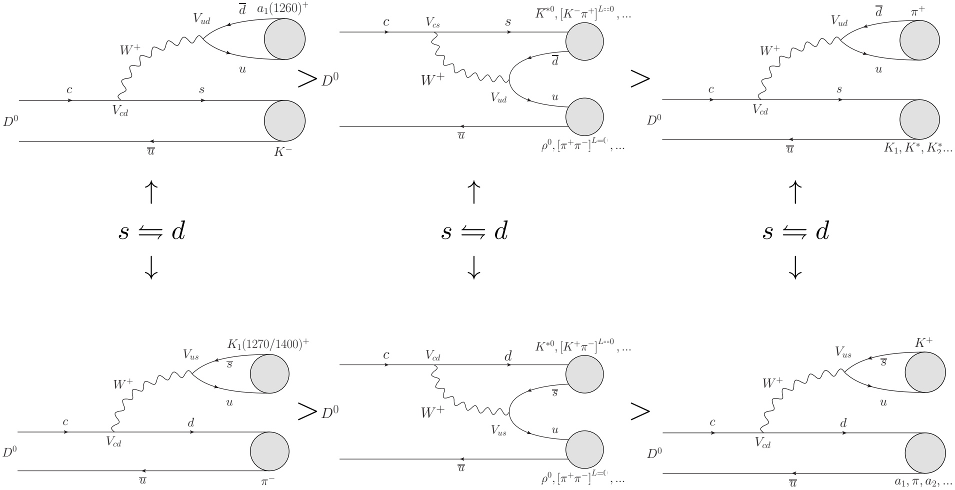
- Uses 2011 + 2012 sample ($3\,\text{fb}^{-1}$ @ 7 and 8 TeV).
- $m_{D*} - m_{D^0}$ peaks for 'Right Sign' (RS) and 'Wrong Sign' (WS).
- RS sample has $\sim 900,000$ candidates @ $> 99.9\%$ purity, WS has ~ 3000@80% purity.

Phase space acceptance

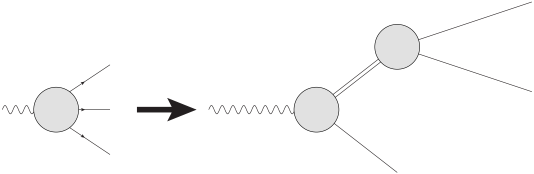


- Acceptance corrected using simulated events.
- Corrections are very small due to use of B sample / muonic trigger.

Quark level diagrams



The Isobar model



$$\mathcal{A}(\mathbf{x}) \propto \mathcal{F}(q^2)\mathcal{S}(\mathbf{x})\mathcal{T}_R(s_R)$$

where: $\mathcal{F}(q^2)$ is a form-factor (Blatt-Weisskopf, exponential ...)
$\mathcal{S}(\mathbf{x})$ accounts for the spin/angular momentum configuration
$\mathcal{T}_R(s_R)$ is a dynamical function that parametrises the isobar (Breit-Wigner, K Matrix ...)

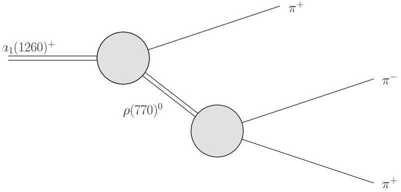
Extending to more bodies

Quasi two-body topology Cascade topology

Turn one of the final state particles into a second isobar → leads to two different decay topologies. Very broadly:

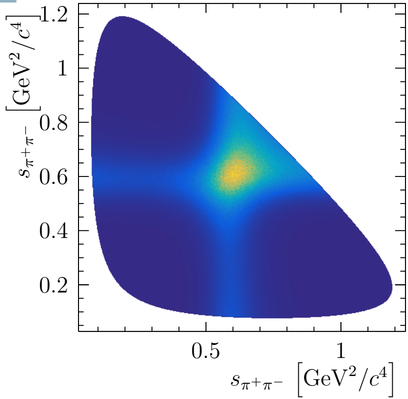
$$\mathcal{A}(\mathbf{x}) \propto \mathcal{F}(q^2)\mathcal{S}(\mathbf{x})\mathcal{T}_R(s_R)\mathcal{T}_{R'}(s_{R'})$$

More about the cascade topology



Three-body decays proceed a pair of quasi two-body decays in isobar model, for example:
$a_1(1260)^+ \to \rho(770)^0\pi^+$.
Decay amplitude would be:

$$\mathcal{A}_{\text{decay}} = \lambda_\mu(a_1)^* q^\mu \mathcal{T}_{RBW}(s_{\pi^+\pi^-})$$



Spin-averaged decay rate for $a_1(1260) \to \rho\pi$

But what about the dynamical function for the a_1?

Dynamics of cascade resonances

Form of dynamical functions largely constrained by two-body unitarity:

$$\mathcal{T}_{RBW}(s) \propto \left(m^2 - s - im\Gamma(s)\right)^{-1}$$

where $\Gamma(s) \propto q(s)^{2L} \times$ phase-space density. Can generalise to the case of unstable decay products by:

$$\Gamma(s) \propto \sum_{\mathrm{pol}} \int D\mathbf{x} \left|\mathcal{A}_{\mathrm{decay}}(\mathbf{x})\right|^2$$

where the integral is over the phase space of the three body decay.

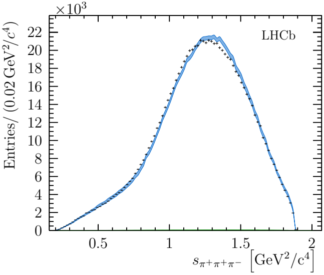
- Integrates out the second isobar in the width.
- Converges to two-body phase-space in limit of narrow resonances.

Significantly simplifed model of complicated system → see talk of Mikhail for more advanced treatment.

Model building

- Model(s) have $\mathcal{O}(100)$ possible contributing components (different resonances, different orbital configurations...)
- If model of "reasonable" complexity include $\mathcal{O}(20)$ contributions, number of possible models = ${}^{100}C_{20} \approx 10^{20}$.
- Select plausible contributions to the amplitude using an additive algorithm, results in "forest" of models of comparable fit quality.
- Models presented include components preferred by a simple majority in the ensemble.

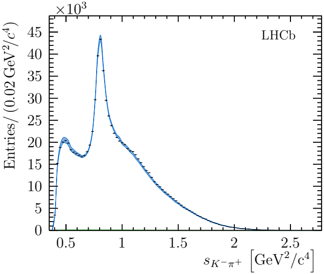
$D^0 \to K^-\pi^+\pi^+\pi^-$

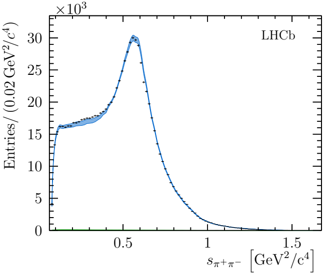


Largest contributions from:

- $D^0 \to a_1(1260)^+ K^- \sim 40\%$
- $D^0 \to \overline{K}^*(892)^0 \rho(770)^0 \sim 20\%$
- $D^0 \to [K^-\pi^+]^{L=0} [\pi^+\pi^-]^{L=0} \sim 20\%$

Width of bands indicate total systematic uncertainty on model.



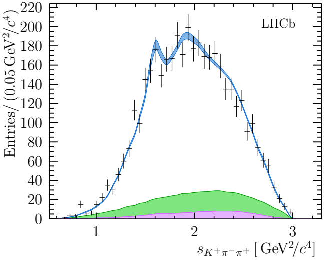


$D^0 \to K^-\pi^+\pi^+\pi^-$ (II)

	Fit Fraction [%]
$\left[\overline{K}^*(892)^0\rho(770)^0\right]^{L=0}$	$7.34 \pm 0.08 \pm 0.47$
$\left[\overline{K}^*(892)^0\rho(770)^0\right]^{L=1}$	$6.03 \pm 0.05 \pm 0.25$
$\left[\overline{K}^*(892)^0\rho(770)^0\right]^{L=2}$	$8.47 \pm 0.09 \pm 0.67$
$\left[\rho(1450)^0\overline{K}^*(892)^0\right]^{L=0}$	$0.61 \pm 0.04 \pm 0.17$
$\left[\rho(1450)^0\overline{K}^*(892)^0\right]^{L=1}$	$1.98 \pm 0.03 \pm 0.33$
$\left[\rho(1450)^0\overline{K}^*(892)^0\right]^{L=2}$	$0.46 \pm 0.03 \pm 0.15$
$\rho(770)^0\left[K^-\pi^+\right]^{L=0}$	$0.93 \pm 0.03 \pm 0.05$
$\overline{K}^*(892)^0\left[\pi^+\pi^-\right]^{L=0}$	$2.35 \pm 0.09 \pm 0.33$
$a_1(1260)^+K^-$	$38.07 \pm 0.24 \pm 1.38$
$K_1(1270)^-\pi^+$	$4.66 \pm 0.05 \pm 0.39$
$K_1(1400)^-\pi^+$	$1.15 \pm 0.04 \pm 0.20$
$K_2^*(1430)^-\pi^+$	$0.46 \pm 0.01 \pm 0.03$
$K(1460)^-\pi^+$	$3.75 \pm 0.10 \pm 0.37$
$\left[K^-\pi^+\right]^{L=0}\left[\pi^+\pi^-\right]^{L=0}$	$22.04 \pm 0.28 \pm 2.09$
Sum of Fit Fractions	$98.29 \pm 0.37 \pm 0.84$
χ^2/ν	$40483/32701 = 1.238$

- All two-body scalar contributions ($[hh']^{L=0}$) parametrised using K matrices $\to$ no ad-hoc nonresonant terms.
- Uncertainties dominated by systematics.

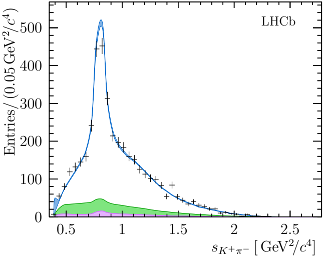
$D^0 \to K^+\pi^-\pi^-\pi^+$

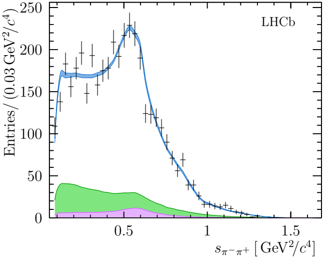


Largest contributions from:

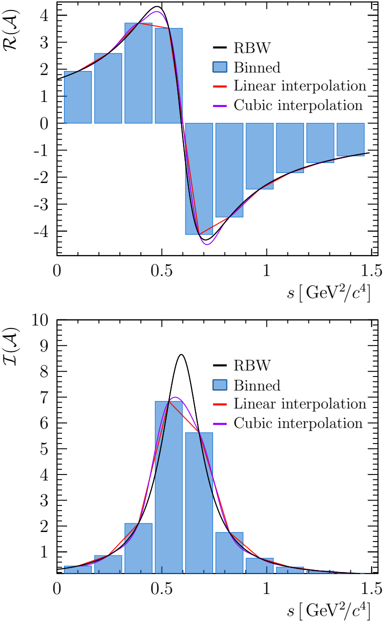
- $D^0 \to K_1(1270/1400)^+\pi^- \sim 40\%$
- $D^0 \to K^*(892)^0\rho(770)^0 \sim 20\%$
- $D^0 \to [K^+\pi^-]^{L=0}[\pi^+\pi^-]^{L=0} \sim 20\%$

Backgrounds indicated by filled area (combinatorial + mistagged RS decays)





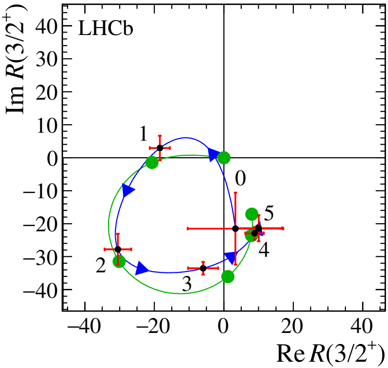
(quasi) Model Independent Partial Waves



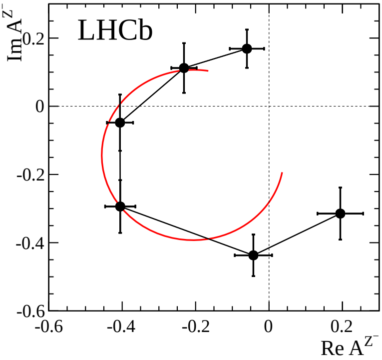
How much do we really know about dynamics?
↳ (quasi) Model independent methods (QMIPWA).

- Real and imaginary parts of amplitude r_n, i_n on a discrete set of points are free parameters.
- Different interpolation schemes (binned, linear, cubic) evaluate the amplitude everywhere else.

Example usage in other final states



$\Lambda_c(2860)^+$ argand diagram [4].

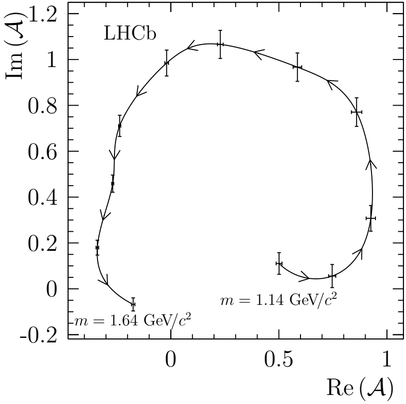


$Z(4430)$ argand diagram [5].

See presentations of Anton and Tomasz.

$D^0 \to K(1460)^- \pi^+$

- First radial excitation the kaon, $K(1460)^-$, is found to contribute significantly to RS decay mode ($m \approx 1.48\,\mathrm{GeV}/c^2, \Gamma_0 \approx 0.35\,\mathrm{GeV}$).
- Decays exclusively to three body final states, via $K^*(892)$ and isoscalar amplitudes.
- Confirm using QMIPWA as $K(1460)^-$ is very broad in $m_{K^-\pi^+\pi^-}$.



Argand diagram for the $K(1460)^-$ from QMIPWA → phase motion expected from a resonant state.

Parity violation

Generic amplitude for decays to a pair of vector mesons (for example, $D^0 \to \overline{K}^*(892)^0 \rho(770)^0$) is:

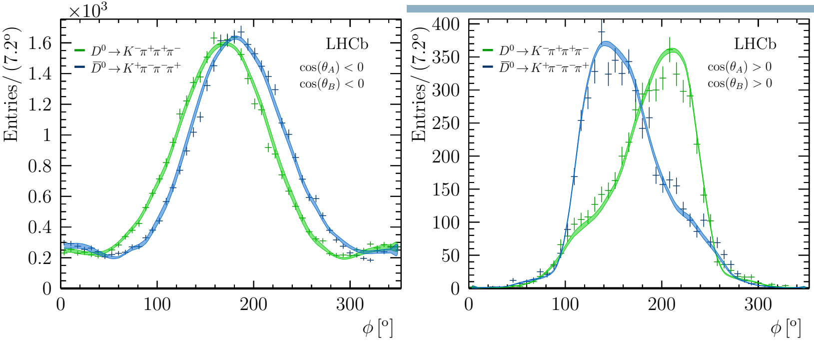
$$\mathcal{A}_{V_1 V_2} = \lambda_\mu(V_1)\lambda_\nu(V_2)\left(g_0 \eta_{\mu\nu} + g_1 \varepsilon_{\mu\nu\alpha\beta} p^\alpha_{V_1} p^\beta_{V_2} + g_2 p^\mu_{V_2} p^\nu_{V_1}\right)$$

where:

- λ_μ, λ_ν are polarisation vectors
- $g_{0,1,2}$ are (energy-dependent) couplings.
- Terms with $g_{0,2}$ are even under parity transformations,
- Term with g_1 is odd under parity transformations.

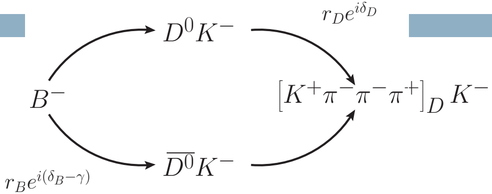
All three terms will generally be present in weak decays → observable parity (and charge conjugation) violations.

Parity violation (II)



- Measure angle ϕ between the decay planes of the two particle systems, in the region of the K^*/ρ resonances.
- Divide into quadrants of helicity angle(s).
- Clear asymmetries about 180° → parity violation. Also clear asymmetries between D^0 and $\overline{D}^0$ decays.
- But, P asymmetries equal and opposite to C asymmetries →CP is still good.

Coherence factor and ADS method



- Both DCS and CF amplitudes contribute to $B^\mp \to [K^\pm\pi^\mp\pi^\mp\pi^\pm]_D K^\mp$ with differing weak phases.
- Phase-space integrated rate is

$$\Gamma \propto r_{K3\pi}^2 + r_B^2 + 2r_B R_{K3\pi} r_{K3\pi} \cos(\delta_B \mp \gamma - \delta_{K3\pi})$$

- Where the coherence factor $R_{K3\pi}$ and $\delta_{K3\pi}$, the average strong-phase difference are defined by:

$$R_{K3\pi} e^{-i\delta_{K3\pi}} = \frac{\int \mathrm{d}\mathbf{x} \mathcal{A}_{D^0\to K^+\pi^-\pi^-\pi^+}(\mathbf{x}) \mathcal{A}^*_{\overline{D}^0\to K^+\pi^-\pi^-\pi^+}(\mathbf{x})}{A_{D^0\to K^+\pi^-\pi^-\pi^+} A_{\overline{D}^0\to K^+\pi^-\pi^-\pi^+}}$$

- So $0 \leqslant R_{K3\pi} \leqslant 1$

Coherence factor and ADS method (II)

- Use models to calculate coherence factor:

$$R_{K3\pi}^{\text{mod}} = 0.458 \pm 0.010 \pm 0.012 \pm 0.020,$$

  where the first uncertainty is statistical, the second systematic, the third from choosing a different model from the ensemble.
- Compare with direct determination[6] from CLEO-c + LHCb:

$$R_{K3\pi} = 0.43^{+0.17}_{-0.13}$$

Conclusions and Outlook

- LHCb has developed models of WS/RS $D \to K3\pi \to$ these models are valuable inputs for charm mixing and CP violating phase γ.
- Amplitude studies of many other charm decays ongoing @ LHCb.

References

- Mark III collaboration, D. Coffman *et al.*, Phys. Rev. **D45** (1992) 2196.
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- LHCb, R. Aaij *et al.*, Phys. Rev. Lett. **112** (2014), no. 22 222002, `arXiv:1404.1903`.
- T. Evans *et al.*, Phys. Lett. **B757** (2016) 520, `arXiv:1602.07430`, [Erratum: Phys. Lett. **B765** (2017) 402].