

D^0 - \bar{D}^0 Mixing in the Decay $D^0 \rightarrow K_s \pi^+ \pi^-$

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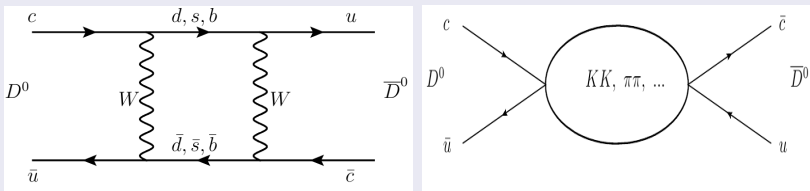
D⁰-Mixing in General

Figure: Short distance (left) and long distance (right) contributions to $D^0 - \bar{D}^0$ mixing in the SM.

- There are four known mesons which mix with their anti-particles (K^0, D^0, B^0, B_s^0).
- The $D^0 - \bar{D}^0$ -System is the only one with d-type quarks in the intermediate loops.
- Particles not included in the SM can enlarge the short range contribution

Formalism

Free Schrödinger equation:

$$i \frac{d}{dt} \begin{pmatrix} D^0(t) \\ \bar{D}^0(t) \end{pmatrix} = \left(\hat{M} - \frac{i}{2} \hat{\Gamma} \right) \begin{pmatrix} D^0(t) \\ \bar{D}^0(t) \end{pmatrix}$$

Eigenstates are flavor superpositions:

$$|D_{1,2}\rangle = p |D^0\rangle \mp q |\bar{D}^0\rangle, \quad p^2 + q^2 = 1.$$

Proper time evolution of eigenstates:

$$|D^0(t)\rangle = \frac{1}{2p} [p(e_1(t) + e_2(t)) |D^0\rangle + q(e_2(t) - e_1(t)) |\bar{D}^0\rangle]$$

with

$$|D_{1,2}(t)\rangle = e_{1,2}(t) |D_{1,2}\rangle = e^{-i(m_{1,2} - \frac{i}{2}\Gamma_{1,2})t} |D_{1,2}\rangle$$

Strategy of Measurement

Decay rate to final state $K_s\pi^+\pi^-$

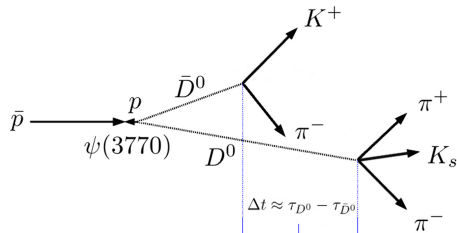
$$|\langle K_s\pi^+\pi^- | \mathcal{H} | D^0(t) \rangle|^2 = \frac{1}{2} e^{-\Gamma|t|}$$

$$\left[\cos(x\Gamma\Delta t) \left(|\mathcal{A}_f|^2 - \left| \frac{q}{p} \right|^2 |\bar{\mathcal{A}}_f|^2 \right) \right.$$

$$+ \cosh(y\Gamma\Delta t) \left(|\mathcal{A}_f|^2 + \left| \frac{q}{p} \right|^2 |\bar{\mathcal{A}}_f|^2 \right)$$

$$+ 2 \sin(x\Gamma\Delta t) \cdot \text{Re} \left(\frac{q}{p} \bar{\mathcal{A}}_f \otimes \mathcal{A}_f^* \right)$$

$$\left. - 2 \sinh(y\Gamma\Delta t) \cdot \text{Im} \left(\frac{q}{p} \bar{\mathcal{A}}_f \otimes \mathcal{A}_f^* \right) \right]$$



$$\mathcal{A}_f = \langle K_s\pi^+\pi^- | \mathcal{H} | D^0 \rangle$$

$$\bar{\mathcal{A}}_f = \langle K_s\pi^+\pi^- | \mathcal{H} | \bar{D}^0 \rangle$$

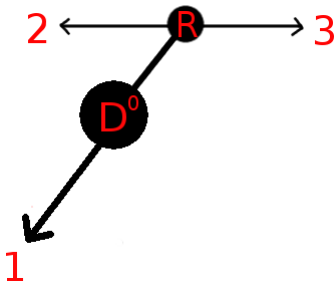
$$x = \frac{m_1 - m_2}{\Gamma}, \quad y = \frac{\Gamma_1 - \Gamma_2}{2\Gamma}$$

- Normalized mass difference x arises from short range part
- Normalized lifetime difference y arises from long range part

Three body Amplitude \mathcal{A}_f

Isobar approach

- coherent sum of quasi-two-body amplitudes
- $D^0 \rightarrow K^*(892)^- \pi^+ \rightarrow K_S \pi^+ \pi^-$
- $D^0 \rightarrow \rho K_S \rightarrow K_S \pi^+ \pi^-$
- $D^0 \rightarrow K_2(1680)^+ \pi^- \rightarrow K_S \pi^+ \pi^-$
- ...



$$\mathcal{A}_f = \langle K_S \pi^+ \pi^- | \mathcal{H} | D^0 \rangle$$

$$\mathcal{A}_f = \sum_r c_r \exp(i\theta_r) \mathcal{A}_r(m^2), \quad r = K^*(892)^-, \rho, K_2(1680)^+, \dots$$

\mathcal{A}_r : Breit-Wigner function in a simple case

Used Model

Resonance	J^{PC}	M [MeV/c ²]	Γ [MeV/c ²]	Type
$K^*(892)^-$	1^-	893.6	46.7	RBW
$K^*(892)^+$	1^-	893.6	46.7	RBW
ρ	1^{--}	775.8	146.4	GS
ω	1^{--}	782.59	8.49	RBW
$f_2(1270)$	2^{++}	1275.4	185.1	RBW
$K_0^*(1430)^-$	0^+	1463.1	232.3	LASS
$K_0^*(1430)^+$	0^+	1463.1	232.3	LASS
$K_2^*(1430)^-$	2^+	1425.6	98.5	RBW
$K_2^*(1430)^+$	2^+	1425.6	98.5	RBW
$K^*(1680)^-$	1^-	1677.0	205.0	RBW
$\pi^+\pi^-$ S-Wave	0^{++}	—	—	K-Matrix

RBW: Relativistic Breit-Wigner
 GS: Gounaris-Sakurai
 LASS: RBW + non resonant effective range potential

Fitting Pseudodata

- Adjusted the EvtGen Model EvtD0mixDalitz ($D^{*+} \rightarrow D^0 \pi^+$ with mixing) to the the case $\psi(3770) \rightarrow D^0 \bar{D}^0$
- Used Monte Carlo Events: $3 \cdot 10^5$

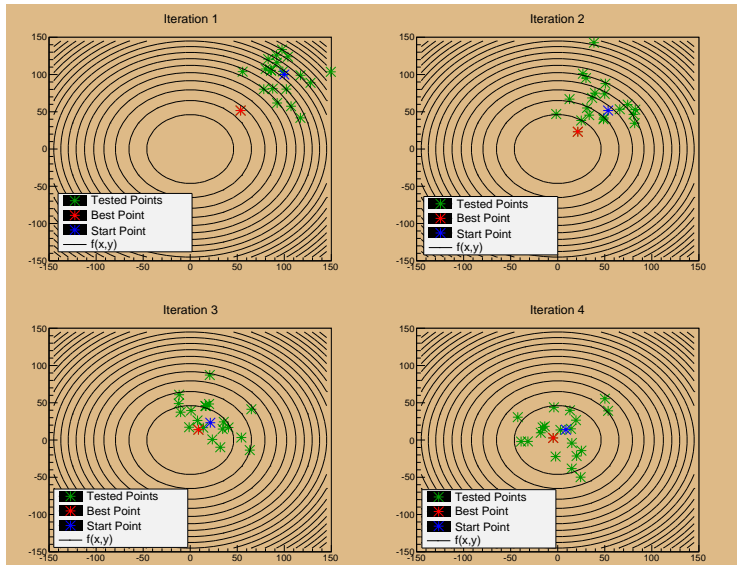
Minimize negative Logarithm of Likelihood (unbinned)

$$-\ln \mathcal{L} = N_{\text{Data}} \sum_{j=1}^{N_{\text{PHSP}}} f(x_j, \mathbf{a}) - \sum_{i=1}^{N_{\text{Data}}} f(x_i, \mathbf{a})$$

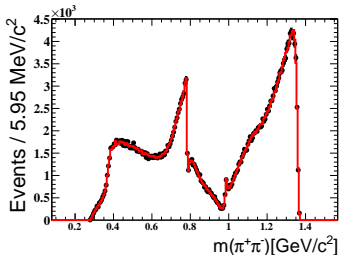
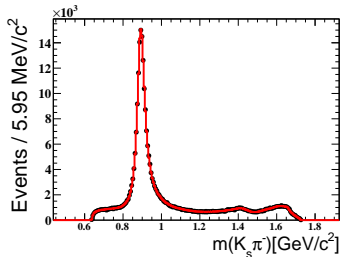
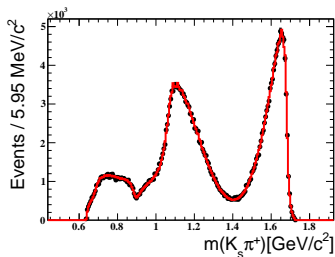
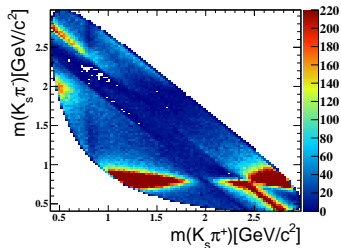
- In first steps Evolutionary fit algorithm to avoid local minima
- In the end Minuit2 with Migrad (Gradient based algorithm with variable metric)
- Use Message Passing Interface (MPI) to split the calculation on different machines

Simple Example for the evolutionary fitting

$$f(x, y) = x^2 + y^2 - 10 \cos(2\pi x) - 10 \cos(2\pi y) + 20$$



Result of the Fit (qualitative)



Result of the Fit (quantitative)

Fit Fractions [%]		
Resonance	Truth	Fit
$K^*(892)^-$	48.02	33.39
$K^*(892)^+$	0.40	0.28
ρ	17.43	11.75
ω	0.79	0.50
$f_2(1270)$	0.46	0.30
$K_0^*(1430)^-$	20.32	40.60
$K_0^*(1430)^+$	0.03	4.26
$K_2^*(1430)^-$	1.84	1.28
$K_2^*(1430)^+$	0.008	0.006
$K^*(1680)^-$	0.61	0.55
$\pi^+\pi^-$ S-Wave	10.10	7.08

Fit Fractions

$$FF_r = \frac{\int |\mathcal{A}_r|^2 dm_{AB}^2 dm_{AC}^2}{\int |\sum_i \mathcal{A}_i|^2 dm_{AB}^2 dm_{AC}^2}$$

Binned χ^2 (integrating time)

$$\chi^2/\text{dof} = 4429.72/4211 = 1.05$$

	Truth [%]	Fit [%]
x	0.63	0.685 ± 0.204
y	0.75	0.888 ± 0.166

Summary

- A EvtGen decay model was adjusted for the investigated channel
- An unbinned Likelihood fitter was written to extract the D^0 mixing parameters

Already in progress

- Detector based simulation with Pandaroot
 - Acceptance
 - Resolution
 - Background events
- Unbinned goodness of fit evaluation
 - Mixed sample method
 - Point-to-point dissimilarity method
- Examine if CP-Violation can be fitted

Thanks for listening!!! :-)



Figure: M. Gell-Mann (left) and A. Pais (right) proposed that the physical neutral Kaons are admixtures of the flavor eigenstates in 1954