D^0-$\bar{D}^0$ Mixing in the Decay $D^0 \rightarrow K_s \pi^+ \pi^-$ (at $\overline{\text{P}}$ANDA)

Andreas Pitka

II. Physikalisches Institut Gießen

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Outlines

D^0-Mixing in General

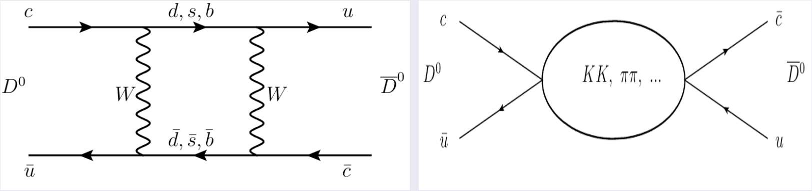


Figure: Short distance (left) and long distance (right) contributions to $D^0 - \bar{D}^0$ mixing in the SM.

- 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:

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

Proper time evolution of eigenstates:

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

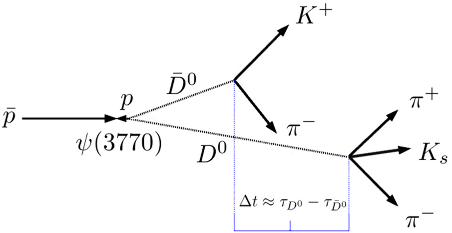
with

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

Strategy of Measurement

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

$$
\begin{aligned}
&\left|\langle K_s\pi^+\pi^- \mid \mathcal{H} \mid D^0(t)\rangle\right|^2 = \frac{1}{2} e^{-\Gamma|t|} \\
&\left[\cos(x\Gamma\Delta t)\left(|\mathcal{A}_f|^2 - \left|\frac{q}{p}\right|^2 |\bar{\mathcal{A}}_f|^2\right)\right. \\
&+ \cosh(y\Gamma\Delta t)\left(|\mathcal{A}_f|^2 + \left|\frac{q}{p}\right|^2 |\bar{\mathcal{A}}_f|^2\right) \\
&+ 2\sin(x\Gamma\Delta t)\cdot \mathrm{Re}(\frac{q}{p}\bar{\mathcal{A}}_f \otimes \mathcal{A}_f^*) \\
&\left. - 2\sinh(y\Gamma\Delta t)\cdot \mathrm{Im}(\frac{q}{p}\bar{\mathcal{A}}_f \otimes \mathcal{A}_f^*)\right]
\end{aligned}
$$



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

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

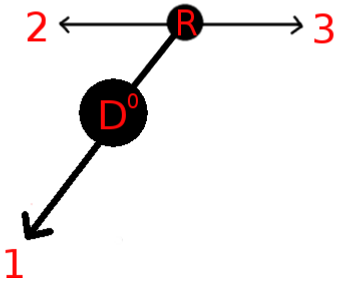
$$x = \frac{m_1 - m_2}{\Gamma}, \quad y = \frac{\Gamma_1 - \Gamma_2}{2\Gamma}$$

- 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
- $D^0 \to K^*(892)^- \pi^+ \to K_s \pi^+ \pi^-$
- $D^0 \to \rho K_s \to K_s \pi^+ \pi^-$
- $D^0 \to K_2(1680)^+ \pi^- \to K_s \pi^+ \pi^-$
- $\cdots$

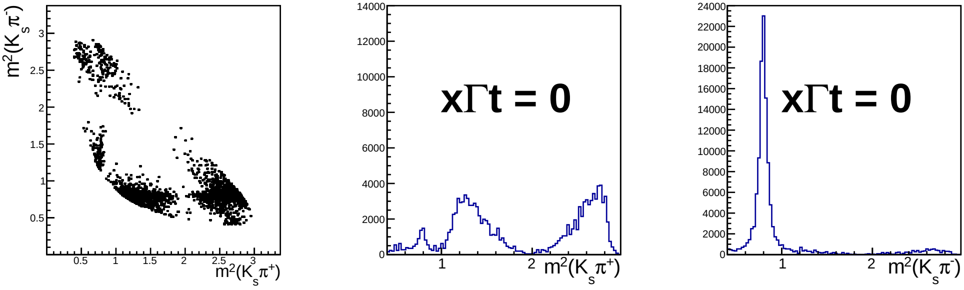


$\mathcal{A}_f = \langle K_s \pi^+ \pi^- \mid \mathcal{H} \mid D^0 \rangle$

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

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

Illustration with a Toy Model



- Simplified world with three inermediate resonances: $K^*(892)^-$ (Cabibbo favored), $K^*(892)^+$ (Cabibbo suppressed) and ρ
- Enhance mixing frequency and neglect lifetime difference
  - $x = 1000 \cdot x_{phys}$
  - $y = 0$
- $x\Gamma\Delta t = 2\pi$ corresponds to a whole oscillation cycle

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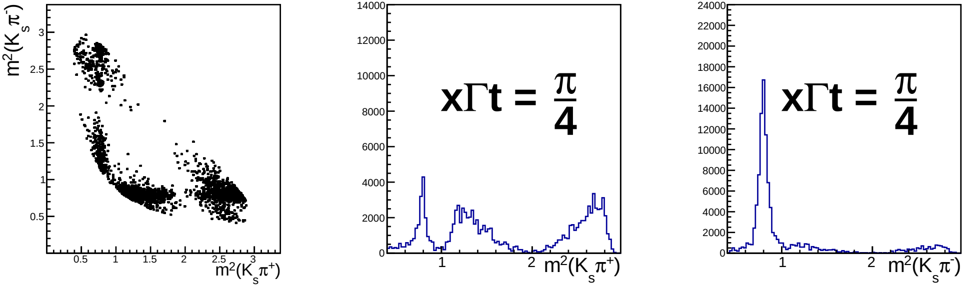

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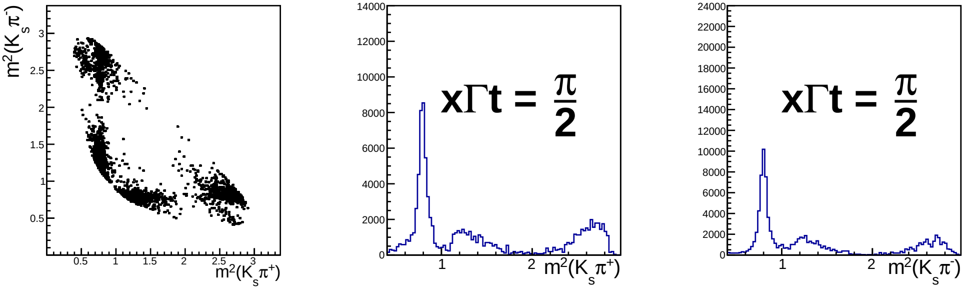

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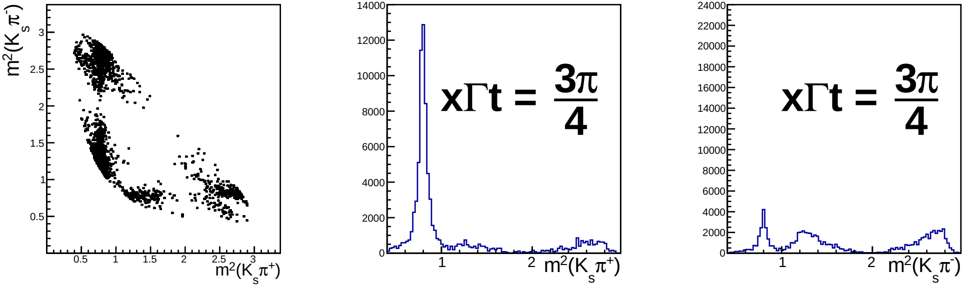

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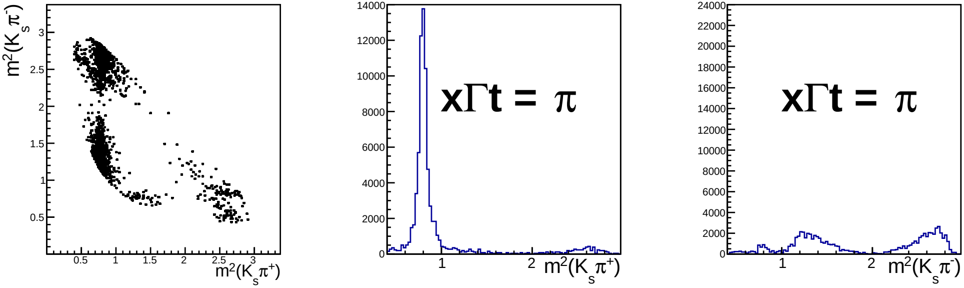

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Used Model

Resonance	J^{PC}	M $[\mathrm{MeV}/c^2]$	Γ $[\mathrm{MeV}/c^2]$	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

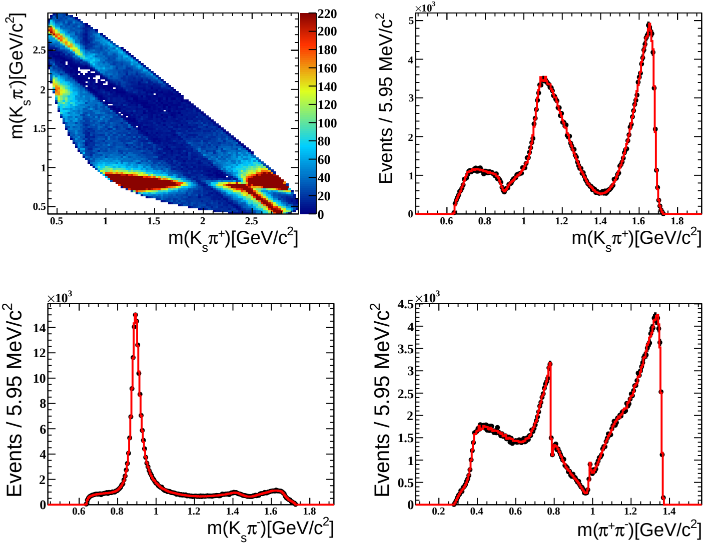
- Adjusted the EvtGen Model EvtD0mixDalitz ($D^{*+} \to D^0\pi^+$ with mixing) to the the case $\psi(3770) \to D^0\bar{D}^0$
- Used Monte Carlo Events: $3 \cdot 10^5$

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

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)

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

	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 inestigated channel
- An unbinned Likelihood fitter was written to extract the D^0 mixing parameters using EvtGen amplitudes

Already in progress

- Detector based simulation with Pandaroot ($\rightarrow$ $\overline{\text{P}}$ANDA Meeting Dec)
  - Acceptance, efficiency, purity...
  - Resolution
  - Background events
- Unbinned goodness of fit tests (already working for toy models)
  - Mixed sample method
  - Energy test
- Examine if CP-Violation can be extracted (so far not successfull)

Thanks for listening!!! :-)

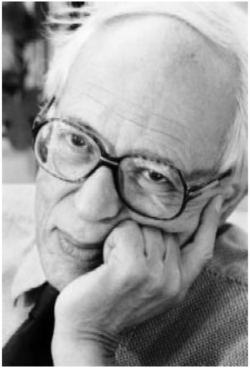


Figure: M. Gell-Mann (left) and A. Pais (right) proposed that the physical neutral Kaons are admixtures of the flavor eigenstates in 1954

Backup

Backup

Simple Example for the evolutionary fitting

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