Search for CP Violation in $D^0 \to K_S^0 \pi^+ \pi^-$

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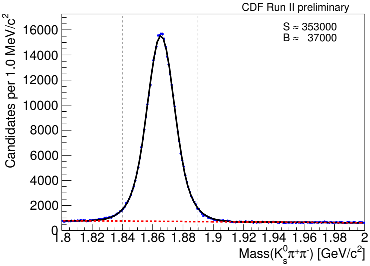
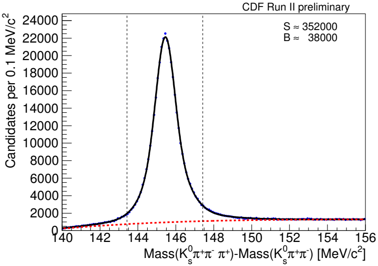
Overview and Motivation

- considered decay: $D^0 \to K_S^0\,\pi^+\,\pi^-$
- study of resonant substructure (Dalitz plot)
- production flavor tagged:
  $D^*(2010)^+ \to D^0\,\pi^+$ respective $D^*(2010)^- \to \bar{D}^0\,\pi^-$
- search for time-integrated CPV (very small in SM)
- no hints for CPV in charm sector up to now
- further applications of $D^0 \to K_S^0\,\pi^+\,\pi^-$:
  - D^0-$\bar{D}^0$ mixing (time-dependent Dalitz analysis)
  - CKM angle γ from $B^\mp \to D\,K^\mp$ (problem: K-π separation)

Signal Selection

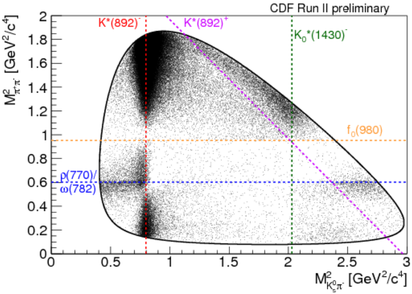
- hadronic trigger requires two displaced tracks with $p_T > 2\,\mathrm{GeV}/c$ (selection of secondary vertex decays)
- use integrated luminosity of $\approx 6.0\,\mathrm{fb}^{-1}$
- NeuroBayes
  training based on real data only by means of ${}_s\mathcal{P}lot$ weights (improved sideband subtraction) $\Rightarrow$ no need for simulated events



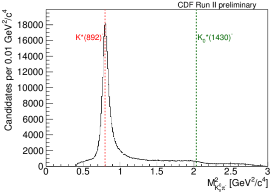


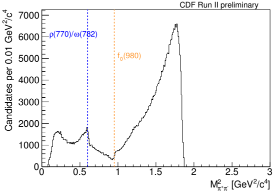
Resonant Substructure (Dalitz Plot)

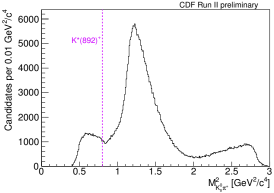
$$m_{D^0}^2 + m_{K_S^0}^2 + m_{\pi^+}^2 + m_{\pi^+}^2 = M_{K_S^0\pi^+}^2 + M_{K_S^0\pi^-}^2 + M_{\pi^+\pi^-}^2$$



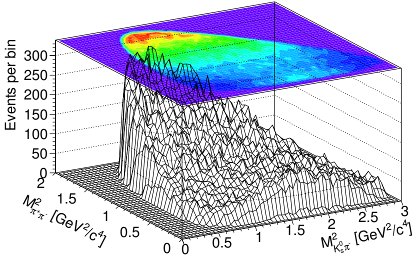
- $K_S^0\pi^-$: $K^*(892)^-$, $K_0^*(1430)^-$ $K_2^*(1430)^-$, $K^*(1410)^-$
- $\pi^+\pi^-$: $\rho(770)$, ω, $f_0(980)$ $f_2(1270)$, $f_0(1370)$, $\rho(1450)$, $f_0(600)$, σ_2
- $K_S^0\pi^+$ (DCS): $K^*(892)^+$ $K_0^*(1430)^+$, $K_2^*(1430)^+$
- nonresonant



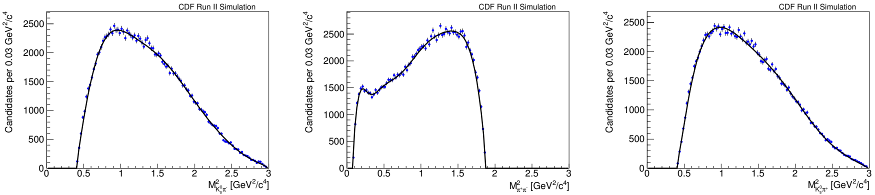




Relative Reconstruction Efficiency



- phase space flat over Dalitz plot
- efficiency varies strongly (hadronic trigger)
- determined with simulated events (generated nonresonantly)



Applied Dalitz Model

- decay rate of $D \to A\,B\,C$ depends on complex matrix element $\mathcal{M}$

$$d\Gamma = \frac{|\mathcal{M}|^2}{256\pi^3 M_D^3} dM_{AB}^2 dM_{BC}^2$$

- Isobar model

$$\mathcal{M} = a_0 \cdot e^{i\delta_0} + \sum_j a_j \cdot e^{i\delta_j} \cdot \mathcal{A}_j$$

  - a_j, δ_j: relative amplitudes and phases (fit parameters)
  - fixed reference resonance $a_{\rho(770)} = 1$, $\delta_{\rho(770)} = 0$
  - $a_0 \cdot e^{i\delta_0}$: nonresonant contribution
  - $\mathcal{A}_j$: individual complex matrix elements (Breit-Wigner with spin-dependent angular factor)

Likelihood Function

- binned maximum likelihood method

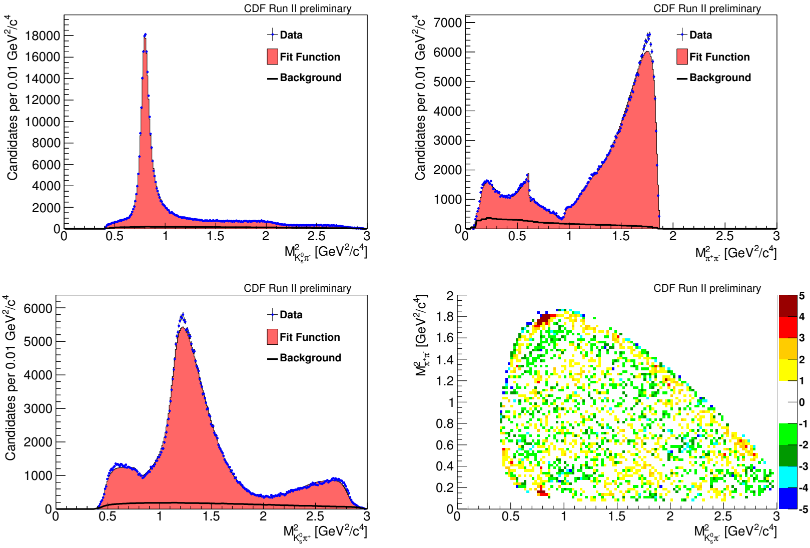
$$-\ln\mathcal{L}(\vec{a}) = -\sum_{j=1}^{J} n_j \ln\mu_j + \sum_{j=1}^{J}\mu_j + \sum_{j=1}^{J}\ln(n_j!)$$

  - $\vec{a}$: free parameters
  - n_j: number of entries in bin j
  - μ_i: expected number of entries in bin i
- fit function

$$\begin{aligned}\mu(M^2_{K^0_S\pi^-}, M^2_{\pi^+\pi^-}) &= T\cdot\epsilon(M^2_{K^0_S\pi^-}, M^2_{\pi^+\pi^-})\cdot|\mathcal{M}(M^2_{K^0_S\pi^-}, M^2_{\pi^+\pi^-})|^2 \\ &+ (1-T)\cdot\epsilon(M^2_{K^0_S\pi^-}, M^2_{\pi^+\pi^-})\cdot|\mathcal{M}(M^2_{K^0_S\pi^+}, M^2_{\pi^+\pi^-})|^2 \\ &+ B(M^2_{K^0_S\pi^-}, M^2_{\pi^+\pi^-})\end{aligned}$$

  - $(1-T)$: mistag fraction (free fit parameter)
  - $\epsilon(M^2_{K^0_S\pi^-}, M^2_{\pi^+\pi^-})$: relative efficiency over Dalitz plot
  - $B(M^2_{K^0_S\pi^-}, M^2_{\pi^+\pi^-})$: background distribution

Fit Results



CDF Run II preliminary
Candidates per 0.01 GeV²/c⁴
Data
Fit Function
Background
M²(K⁰s π⁻) [GeV²/c⁴]
CDF Run II preliminary
Candidates per 0.01 GeV²/c⁴
Data
Fit Function
Background
M²(π⁺π⁻) [GeV²/c⁴]
CDF Run II preliminary
Candidates per 0.01 GeV²/c⁴
Data
Fit Function
Background
M²(K⁰s π⁺) [GeV²/c⁴]
CDF Run II preliminary
M²(π⁺π⁻) [GeV²/c⁴]
M²(K⁰s π⁻) [GeV²/c⁴]

Fit Fractions

- correspond to individual resonance contributions to total decay rate
- calculated from fitted amplitudes and phases

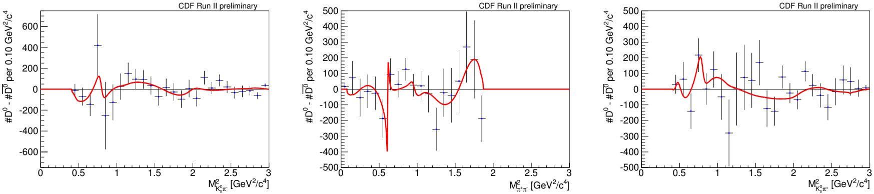
$$\mathrm{FF_r} = \frac{\int |a_r e^{i\delta_r} \mathcal{A}_r|^2 dM^2_{K^0_S\pi^-} dM^2_{\pi^+\pi^-}}{\int |\sum_j a_j e^{i\delta_j} \mathcal{A}_j|^2 dM^2_{K^0_S\pi^-} dM^2_{\pi^+\pi^-}}$$

$$\begin{aligned} FF_{K^*(892)^-} &= (59.44 \pm 0.29)\% \\ FF_{\rho(770)} &= (21.08 \pm 0.20)\% \\ FF_{f_0(980)} &= (5.20 \pm 0.23)\% \\ &\ldots \end{aligned}$$

Search for CPV in Dalitz Fit

- separate D^0 and $\bar{D}^0$ samples (from D^{*+} and D^{*-})

D^0-$\bar{D}^0$ differences and fit projections:



- calculate fit fraction asymmetries:

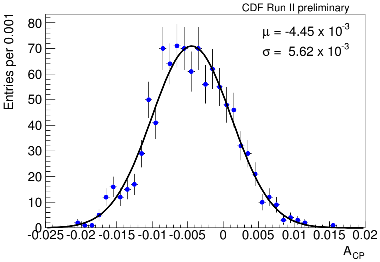
$$\mathcal{A}_{\rm FF} = \frac{{\rm FF}_{D^0} - {\rm FF}_{\bar{D}^0}}{{\rm FF}_{D^0} + {\rm FF}_{\bar{D}^0}}$$

Results for $\mathcal{A}_{\rm FF}$

Resonance	$\mathcal{A}_{\rm FF}$ [%]
$K^*(892)^-$	$-0.05 \pm 0.39 \pm 0.41$
$K_0^*(1430)^-$	$0.48 \pm 2.89 \pm 3.54$
$K_2^*(1430)^-$	$4.80 \pm 2.93 \pm 4.05$
$K^*(1410)^-$	$-13.66 \pm 5.95 \pm 7.83$
$\rho(770)$	$0.09 \pm 0.17 \pm 0.13$
ω	$-11.76 \pm 5.77 \pm 1.58$
$f_0(980)$	$-0.20 \pm 1.84 \pm 1.60$
$f_2(1270)$	$-4.10 \pm 4.00 \pm 2.35$
$f_0(1370)$	$5.63 \pm 15.47 \pm 21.77$
$\rho(1450)$	$1.96 \pm 9.87 \pm 5.21$
$f_0(600)$	$-0.70 \pm 2.31 \pm 3.46$
σ_2	$2.65 \pm 7.67 \pm 4.66$
$K^*(892)^+$	$-1.00 \pm 4.05 \pm 2.75$
$K_0^*(1430)^+$	$4.30 \pm 8.33 \pm 10.59$
$K_2^*(1430)^+$	$-13.56 \pm 13.59 \pm 15.88$

Overall integrated CP Asymmetry

- $$\mathcal{A}_{CP} = \frac{\int \frac{|\mathcal{M}|^2 - |\overline{\mathcal{M}}|^2}{|\mathcal{M}|^2 + |\overline{\mathcal{M}}|^2} dM^2_{K^0_S\pi^-} dM^2_{\pi^+\pi^-}}{\int dM^2_{K^0_S\pi^-} dM^2_{\pi^+\pi^-}}$$
- statistical uncertainty determined by random parameter sets generated according to full covariance matrix of Dalitz fit

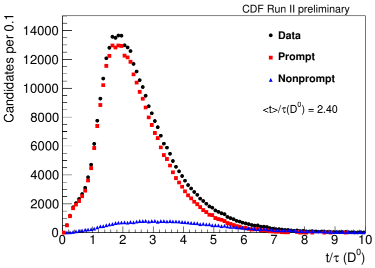


- $\mathcal{A}_{CP} = -0.004 \pm 0.006 \pm 0.005$
- value from CLEO for comparison: $\mathcal{A}_{CP} = 0.009 \pm 0.021\,^{+0.010}_{-0.043}\,^{+0.013}_{-0.037}$

Direct vs. Indirect CPV

- slow D^0 mixing allows approximation:

$$\mathcal{A}_{CP} = a_{CP}^{\text{dir}} + \frac{\langle t \rangle}{\tau} \cdot a_{CP}^{\text{ind}}$$

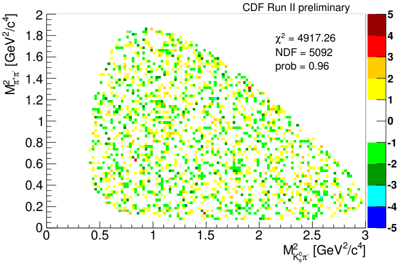


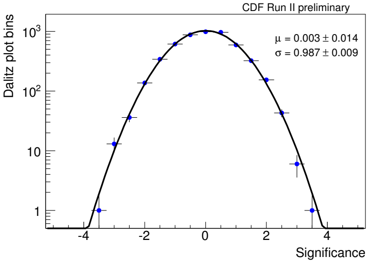
- $\mathcal{A}_{CP}$ measured
- assuming $a_{CP}^{\text{dir}} = 0$

$$\rightarrow a_{CP}^{\text{ind}} = -0.0018 \pm 0.0026 \pm 0.0022$$

Model-independent Approach

- binning of D^0 and $\bar{D}^0$ Dalitz plots
- consider significance asymmetry per bin $\frac{N_{D^0}-N_{\bar{D}^0}}{\sqrt{N_{D^0}+N_{\bar{D}^0}}}$
- sum of squares of significance asymmetries per bin corresponds to χ^2, NDF $\widehat{=}$ Dalitz plot bins minus 1 (normalization), $\rightarrow$ p-value





Conclusion

- $D^0 \to K_S^0 \pi^+ \pi^-$, first full Dalitz fit at hadron collider
- results compatible and comparable in precision to B-factories
- production flavor tagged by $D^*(2010)^+ \to D^0 \pi^+$
- search for time-integrated CPV in Dalitz fit
- most precise determinations of CP violating quantities
- no hints for CPV
- complementary verification by model-independent approach

Backup

Individual Matrix Elements $\mathcal{A}_j$

- $\mathcal{A}_j$ consist of Breit-Wigner part and spin-dependent angular factor
- for spin-0 resonances

$$\mathcal{A}_r(ABC|0) = F_D \cdot F_r \cdot \frac{1}{M_r^2 - M_{AB}^2 - iM_r\Gamma_{AB}}$$

- for spin-1 resonances

$$\mathcal{A}_r(ABC|1) = F_D \cdot F_r \cdot \frac{M_{AC}^2 - M_{BC}^2 + \frac{(M_D^2 - M_C^2)(M_B^2 - M_A^2)}{M_r^2}}{M_r^2 - M_{AB}^2 - iM_r\Gamma_{AB}}$$

- spin-2 ...
- mass-dependent width Γ_{AB}

$$\Gamma_{AB} = \Gamma_r \cdot \left(\frac{p_{AB}}{p_r}\right)^{2J+1} \cdot \left(\frac{M_r}{M_{AB}}\right) \cdot F_r^2$$

- F_D, F_r: spin-dependent Blatt-Weisskopf penetration factors for D^0 respective the different intermediate resonances

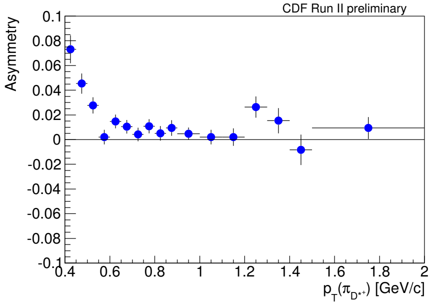
Dalitz Fit Results

Resonance	a	δ [°]	FF [%]
$K^*(892)^-$	1.774 ± 0.010	130.0 ± 0.7	59.44 ± 0.29
$K_0^*(1430)^-$	1.677 ± 0.038	17.0 ± 1.4	4.01 ± 0.17
$K_2^*(1430)^-$	1.219 ± 0.027	305.9 ± 1.5	2.17 ± 0.09
$K^*(1410)^-$	0.877 ± 0.042	131.0 ± 2.6	0.72 ± 0.07
$\rho(770)$	1	0	21.08 ± 0.20
$\omega(782)$	0.038 ± 0.002	110.9 ± 1.7	0.52 ± 0.05
$f_0(980)$	0.453 ± 0.010	205.5 ± 2.1	5.20 ± 0.23
$f_2(1270)$	1.048 ± 0.033	340.1 ± 2.5	0.80 ± 0.05
$f_0(1370)$	0.727 ± 0.067	28.5 ± 6.6	0.34 ± 0.06
$\rho(1450)$	2.298 ± 0.151	346.9 ± 3.8	0.45 ± 0.06
$f_0(600)$	1.450 ± 0.051	193.8 ± 1.8	10.38 ± 0.41
σ_2	0.210 ± 0.022	165.7 ± 8.4	0.56 ± 0.04
$K^*(892)^+$	0.182 ± 0.008	318.5 ± 1.8	0.63 ± 0.05
$K_0^*(1430)^+$	0.621 ± 0.036	121.7 ± 3.5	0.55 ± 0.06
$K_2^*(1430)^+$	0.282 ± 0.030	232.0 ± 5.7	0.12 ± 0.02
Nonresonant	3.437 ± 0.123	112.7 ± 2.3	6.71 ± 0.47
Sum	$\cdots$	$\cdots$	113.7

Efficiency Discrepancies between D^0 and $\bar{D}^0$

- differences between D^0 and $\bar{D}^0$ efficiencies over the Dalitz plot can fake CPV
- can originate from $p_T(\pi_{D^{*+}})$-dependent $\pi_{D^{*+}}$ charge asymmetry

$$\mathcal{A} = \frac{N_{\pi^-} - N_{\pi^+}}{N_{\pi^-} + N_{\pi^+}}$$



- $\rightarrow$ reweighting of $\bar{D}^0$ Dalitz plot according to deviations between $p_T(\pi_{D^{*+}})$ and $p_T(\pi_{D^{*-}})$ distributions

Systematic Uncertainties

- experimental sources
  - efficiency asymmetries varying over Dalitz plot
    $\rightarrow$ repeat fits without reweighting $\bar{D}^0$ Dalitz plot
  - asymmetries of D^0 and $\bar{D}^0$ background
    $\rightarrow$ repeat fits with separate D^0 and $\bar{D}^0$ background samples
- modeling uncertainties
  - included resonances
    $\rightarrow$ repeat fits when excluding $K^*(1410)^-$, $f_0(1370)$, σ_2, $K_2^*(1430)^+$, or nonresonant contribution
  - discrepancies between fit and data
    $\rightarrow$ repeat fits when excluding Dalitz plot regions with largest discrepancies

Fit Discrepancies

- exclude regions with largest discrepancies