# Four Body Amplitude Analysis of $D \rightarrow K^+K^-\pi^+\pi^-$ at CLEO

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# $D \to K^+K^-\pi^+\pi^-$ Decays at CLEO

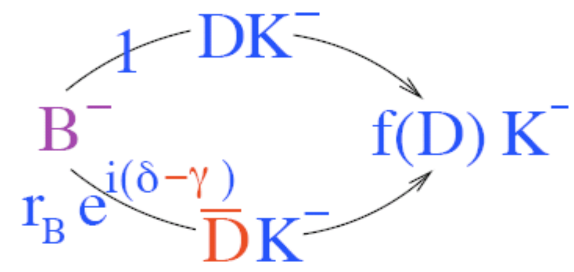
## Motivation:

- Possible Decay to look for Direct CP violation in Singly Cabibbo suppressed decays
- Will be used for γ measurement in $B^\pm \to D_0 K^\pm$ decays

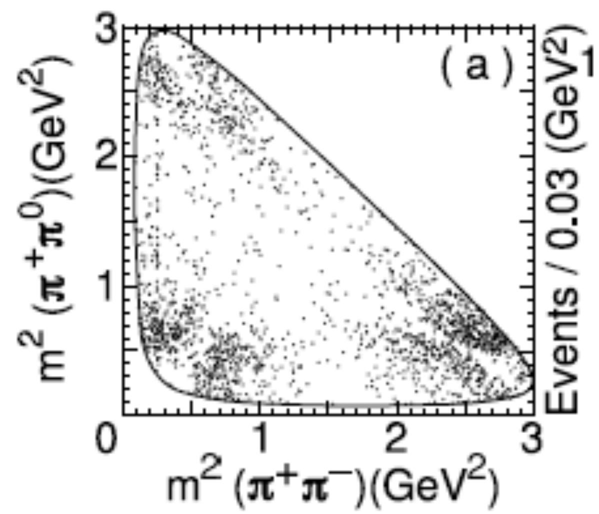
## Previous Studies:

- Only recent amplitude analysis of this decay was by FOCUS in 2005, with ~1000 events PLB 610 (2005) 225

# Dalitz Analysis Methods




- For D decays to 3 or 4 particles the decay can proceed via a number of intermediate resonances
- Each point in the Dalitz plane effectively corresponds to a unique final state with it's own strong phase



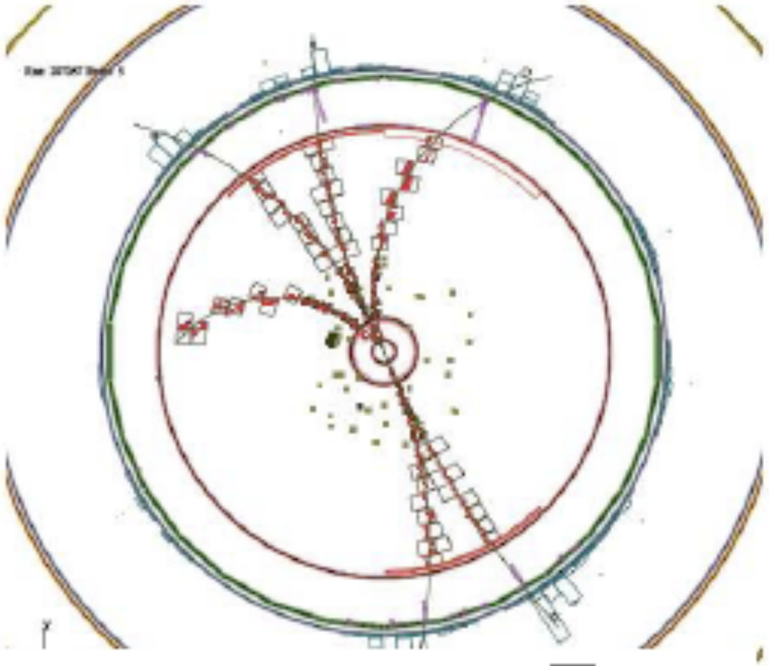

  - => From such final states it is possible to extract γ from a single decay mode
- In order to extract γ a detailed Knowledge of the $D^0$ decay structure is required
- This has already been carried out at B-factories for $K_s\pi\pi$
- This has not yet been carried out for four body decays e.g. $D_0 \rightarrow K^+K^-\pi^+\pi^-$
- One of the best environments to investigate decay parameters is in datasets available at CLEO-c
- A LHCb specific sensitivity study has been carried out : [Phys. Lett. B 647 (2007) 400]
  - Found the possible sensitivity to $\sigma(\gamma) = 18^\circ$ with 2fb-1
- $D \rightarrow K^+K^-\pi^+\pi^-$ decays advantageous for LHCb - contains final state with only charged particles

# Introduction to CLEO

- CLEO was a symmetrical $e^+e^-$experiment which was located at the Cornell Electron Storage Ring
- Collected data between 1979 and 2008
- Operated at energies at and above the charm threshold
- CLEO 2.5, CLEO III $e^+e^- \to \gamma(4S)$
- CLEO-c $E_{CM} = 4170MeV, 3770MeV$

$$e^+e^- \to \psi(3770) \to D_0\overline{D}_0$$

  - By reconstructing one D meson in one flavor => other D is of opposite flavor
  - Additional advantage of threshold running provides clean environment with no fragmentation particles



$\psi(3770) \to D^0(K\pi\pi\pi)\overline{D}^0(\pi\pi)$

# CLEO $D \to K^+K^-\pi^+\pi^-$ Data

$e^+e^- \to \gamma(4S)$ $\quad D^{*+} \to D_0\pi^+$ $\quad \overline{D}^{*-} \to \overline{D}_0\pi^-$

- CLEO 2.5: 279 events
- CLEO III: 1225 events

    - CLEO-c:

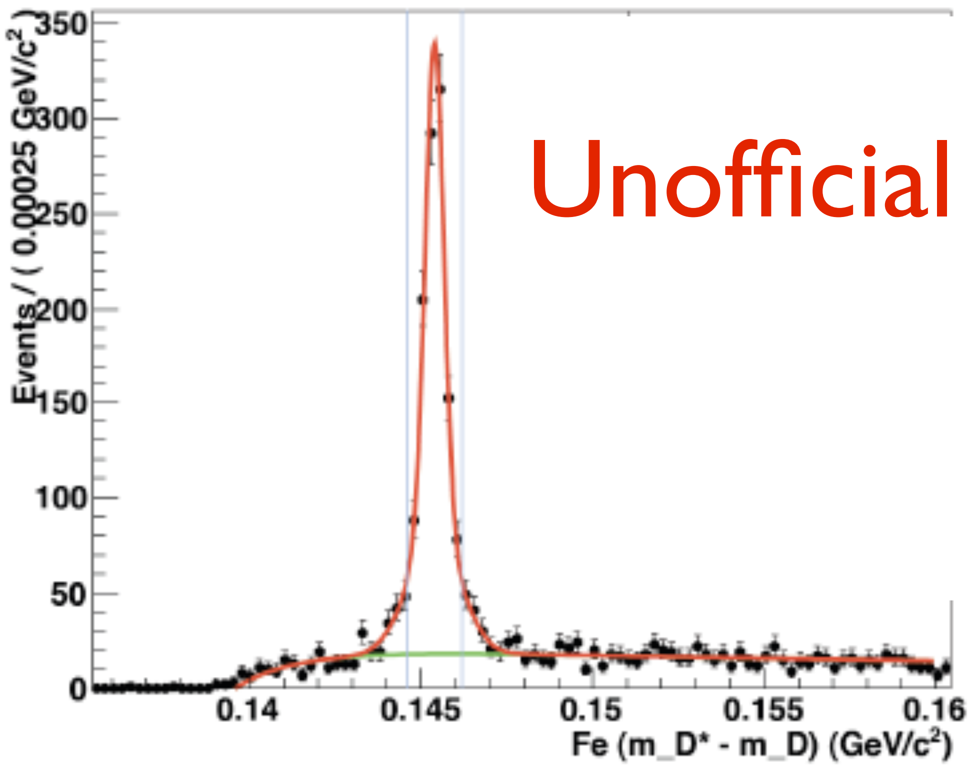
- Ecm = 4170 MeV:

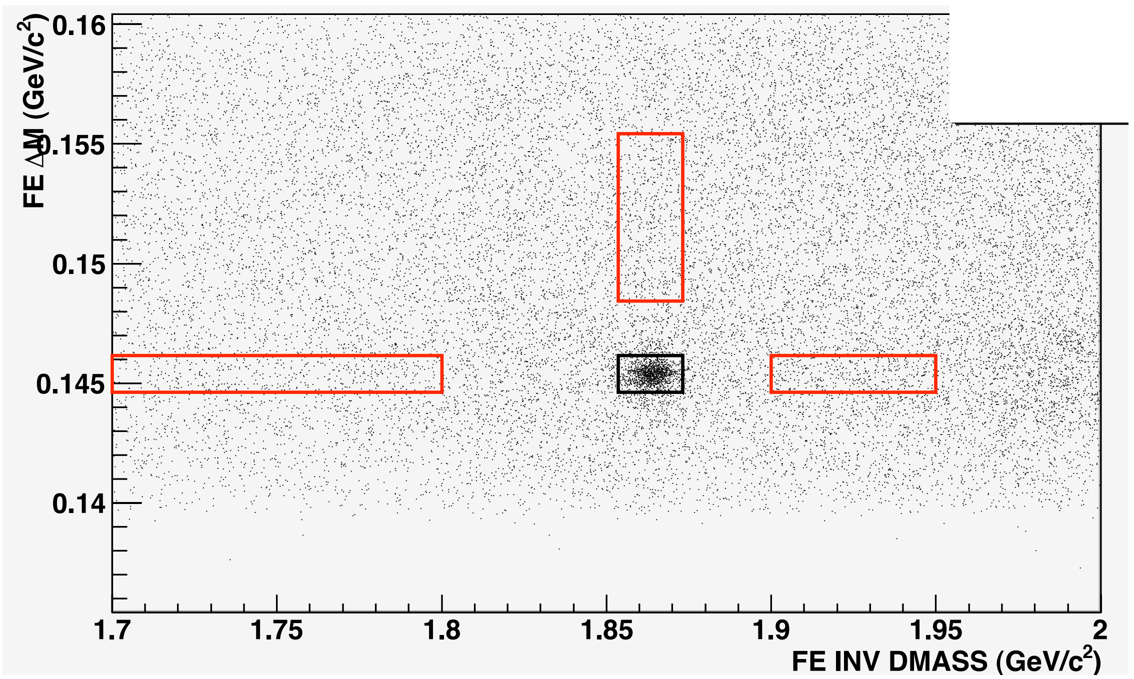
$\psi(4170) \to D_0^*\overline{D_0^*}$ $\quad \psi(4170) \to D^{*+}D^{*-}$

    - 744 events

- Ecm = 3770 MeV: $\psi(3770) \to D_0\overline{D_0}$

    - 1410 flavor tagged events



# 4 Body Decay Model

- A $4$ Body final state requires $5$ parameters to fully describe the decay kinematics
  - Can choose these from invariant masses of combinations of final state particles e.g. $S_{K^-\pi^+\pi^-} S_{K^+K^-} S_{K^-\pi^+} S_{\pi^+\pi^-} S_{K^+\pi^+\pi^-}$
- Unlike $3$ body decays the $4$ body phase space is not flat in these dimensions
- In order to model the decay consider the isobar formalism – the decay can proceed through a variety of $2$ or $3$ body intermediate states, or entirely non resonantly.
- e.g. $D_0 \to K^*(\to K\pi)K\pi \quad D_0 \to \phi(\to KK)\rho(\pi\pi) \quad D_0 \to K_1(1270)^*(\to K^*(892)(\to K\pi)\pi)K$
- The amplitude for a single resonance is given by: $A = S(l)BW$
- For two resonances by: $A = S(l)BW_a BW_b$
  - S(l) gives the spin factor which depends on the spins of the resonances and the orbital angular momentum of the decay
  - BW gives the lineshape of the resonance
- The full amplitude is then given by a coherent sum of individual resonances

# $D \to K^+K^-\pi^+\pi^-$ Decay Model

- Many possible resonances can be included
- Resonances highlighted in red are those used by FOCUS
- For most resonances BW lineshape is used
- for f(0)(980) a "flatte" lineshape is used
- For D->VV and D->VPP decays higher orbital angular momentum decays were considered
- (P and D waves in addition to S waves)

$\phi(1020)\rho(770)$
$\phi(1020)\rho(770)$ P wave
$\phi(1020)\rho(770)$ D wave
$\phi(1020), \pi^+, \pi^-$
$\rho(770)K^+, K^-$
( FocusFlatte) $f(0)(980), \pi^+, \pi^-$
Flatte $f(0)(980), K^+, K^-$
$f(0)(980), K^+, K^-$
$K^+, K^-, \pi^+, \pi^-$
$\rho(770)K^+, K^-$ D wave
$\rho(770)K^+, K^-$ P wave
$\phi(1020), \pi^+, \pi^-$ D wave
$\phi(1020), \pi^+, \pi^-$ P wave
$K^+, K^-, \pi^+, \pi^-$ D wave
$K^+, K^-, \pi^+, \pi^-$ P wave
$\rho(770)K^+, K^-$ P wave
$K^+, \pi^-, K^+, \pi^+$ D wave
$K^+, \pi^-, K^+, \pi^+$ P wave
$\overline{K^*}(892), K^+, \pi^-$ D wave
$\overline{K^*}(892), K^+, \pi^-$ P wave
$K^*(892), K^-, \pi^+$ P wave
$K^*(892), K^-, \pi^+$ D wave

$K_1(1270)^+(\to K_0^*(1430), \pi^+), K^-$
$\overline{K_1}(1270)^-(\to \overline{K_0}^*(1430), \pi^-), K^+$
$K_1(1270)^+(\to K^*(892), \pi^+), K^-$
$\overline{K_1}(1270)^-(\to \overline{K_0}^*(892), \pi^-), K^+$
$K_1(1270)^+(\to \omega(782), K^+), K^-$
$\overline{K_1}(1270)^-(\to \omega(782), K^-), K^+$
$K_1(1270)^+(\to \rho(770), K^+), K^-$
$\overline{K_1}(1270)^-(\to \rho(770), K^-), K^+$
$K_1(1400)^+(\to K_0^*(892), \pi^+), K^-$
$\overline{K_1}(1400)^-(\to \overline{K_0^*}(892), \pi^-), K^+$
$K^+(1680)(\to \rho(770), K^+), K^-$
$\overline{K^-}(1680)(\to \rho(770), K^-), K^+$
$K^+(1680)(\to K^*(892), \pi^+), K^-$
$\overline{K^-}(1680)(\to \overline{K^*}(892), \pi^-), K^+$
$K_2^+(1430)(\to \rho(770), K^+), K^-$
$\overline{K_2^-}(1430)(\to \rho(770), K^-), K^+$
$K_2^+(1430)(\to K^*(892), \pi^+), K^-$
$\overline{K_2^-}(1430)(\to \overline{K^*}(892), \pi^-), K^+$
$K^+(1410)(\to K^*(892), \pi^+), K^-$
$\overline{K^-}(1410)(\to \overline{K^*}(892), \pi^-), K^+$
$K^*(892), K^-, \pi^+$
$\overline{K^*}(892), K^+, \pi^-$
$K^*(892)\overline{K^*}(892)$
$K^*(892)\overline{K^*}(892)$ P wave
$K^*(892)\overline{K^*}(892)$ D wave

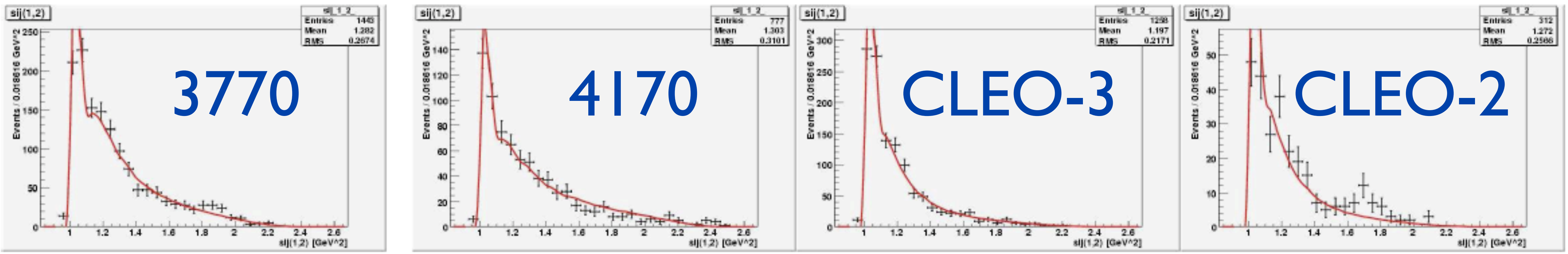
# Fitting to Data

- For all flavor tagged data sets both $D_0$ and $\overline{D}_0$ decays are combined
- The background level was:
  **CLEO-2.5** : ~$30\%$, **CLEO-3**: ~ $10\%$, **4170**: ~$30\%$, **3770**: ~$14\%$
- For each data set the background is fit with an incoherent model to data from side bands
  - For CLEO-c datasets there is also a KsKK background which is fit separately to a simple model
- The efficiency effects for each dataset are included implicitly in the fit:
  - Events which have been passed through the detector simulation and had selection cuts applied to them are used in order to integrate the PDFs which are fitted
- New resonances were introduced one by one, and removed if they didn't contribute significantly (fit fraction < $5\%$)
- $\chi^2$ per degree of freedom (calculated in binned multidimensional phase space) was used as a figure of merit in order to determine the best configuration
- Parameters fit with MINT framework developed by collaborators in Bristol

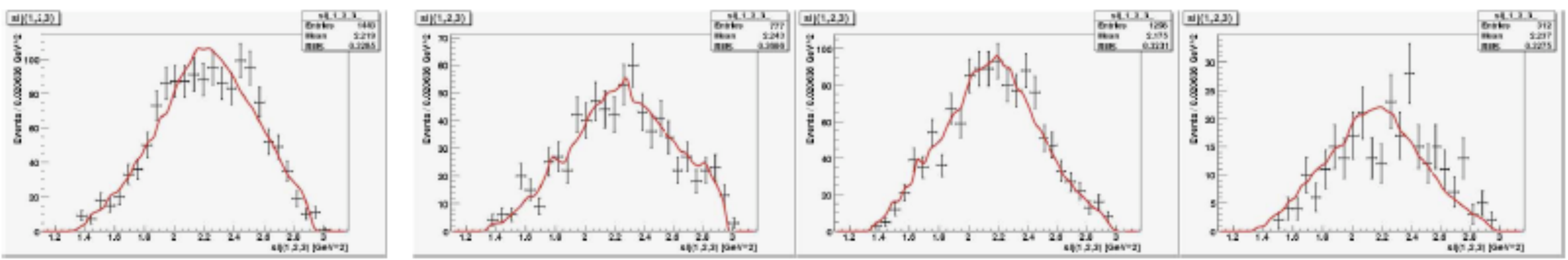
# Preliminary Fit

- Invariant mass projections for the best configuration for a combined fit to all datasets

(KK) Unofficial

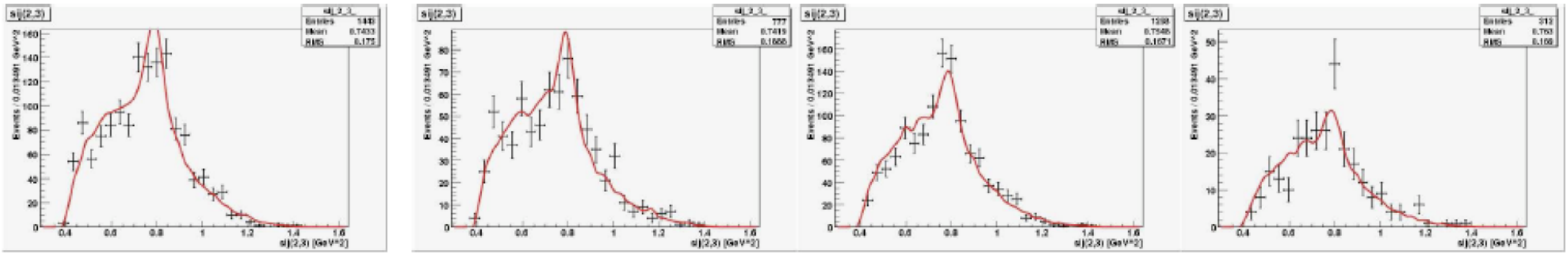



($KK\pi$)

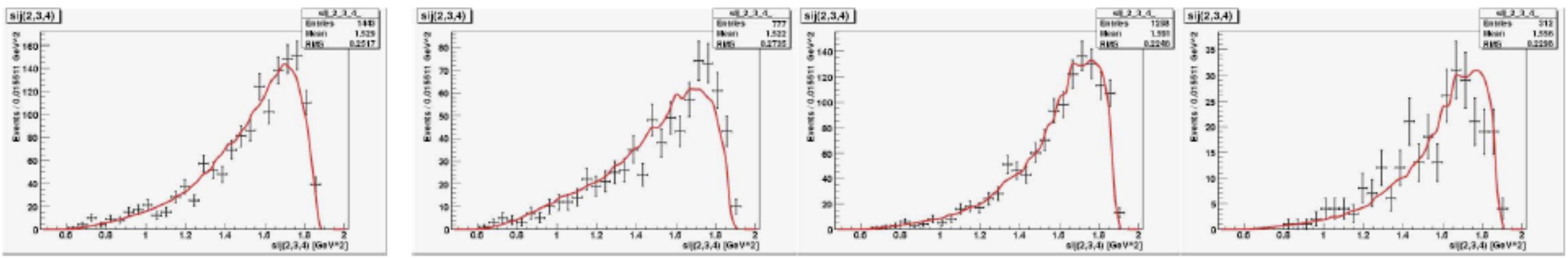


Unofficial

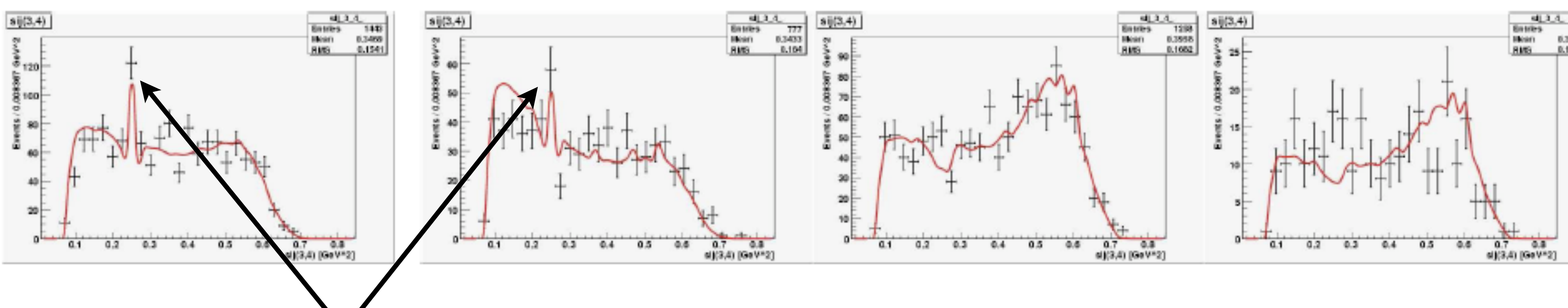
# (Kπ)




# (Kππ)




# (ππ)




Residual KsKK background

# Unofficial Fit Fractions & χ^2

| | |
|---|---|
| $K_1(1270)^+(\to K^*(892),\pi^+),K^-$ | 0.084±0.011 |
| $K_1(1270)^+(\to \rho(770),K^+),K^-$ | 0.043±0.008 |
| $\overline{K_1}(1270)^-(\to \rho(770),K^-),K^+$ | 0.056±0.009 |
| $K^+(1410)(\to K^*(892),\pi^+),K^-$ | 0.058±0.008 |
| $\overline{K^-}(1410)(\to \overline{K^*}(892),\pi^-),K^+$ | 0.057±0.008 |
| $K^*(892)\overline{K^*}(892)$ | 0.056±0.009 |
| $\phi(1020)\rho(770)$ | 0.394±0.024 |
| $\phi(1020)\rho(770)$ D wave | 0.039±0.009 |
| $\phi(1020),\pi^+,\pi^-$ | 0.097±0.011 |
| $\pi K,\pi K$ VS S wave | 0.09±0.012 |
| **Sum** | **0.974±0.028** |
| $\chi^2$ **per DOF** | **1.55** |

## Focus Model

PLB 610 (2005) 225

| Mode | Magnitude | Phase | Fraction (%) |
|---|---|---|---|
| $K_1(1270)^+K^-$, $K_1 \to \rho(770)^0K^+$ | 1 (fixed) | 0 (fixed) | $18 \pm 6 \pm 3$ |
| $K_1(1270)^+K^-$, $K_1 \to K_0^*(1430)\pi^+$ | $0.27 \pm 0.08 \pm 0.06$ | $354 \pm 19 \pm 19$ | $2 \pm 1 \pm 0$ |
| $K_1(1270)^+K^-$, $K_1 \to K^*(892)^0\pi^+$ | $0.94 \pm 0.16 \pm 0.13$ | $12 \pm 12 \pm 15$ | $16 \pm 4 \pm 5$ |
| $K_1(1270)^+K^-$, (all modes) | — | — | $33 \pm 6 \pm 4$ |
| $K_1(1400)^+K^-$ | $1.18 \pm 0.19 \pm 0.09$ | $259 \pm 11 \pm 13$ | $22 \pm 3 \pm 4$ |
| $K^*(892)0\bar{K}^*(892)^0$ | $0.39 \pm 0.09 \pm 0.11$ | $28 \pm 13 \pm 10$ | $3 \pm 2 \pm 1$ |
| $\phi(1020)\rho(770)^0$ | $1.30 \pm 0.11 \pm 0.07$ | $49 \pm 11 \pm 12$ | $29 \pm 2 \pm 1$ |
| $\rho(770)^0K^+K^-$ | $0.33 \pm 0.12 \pm 0.16$ | $278 \pm 26 \pm 20$ | $2 \pm 2 \pm 2$ |
| $\phi(1020)\pi^+\pi^-$ | $0.30 \pm 0.06 \pm 0.06$ | $163 \pm 16 \pm 15$ | $1 \pm 1 \pm 0$ |
| $K^*(892)^0K^+\pi^-$ | $0.83 \pm 0.09 \pm 0.10$ | $234 \pm 10 \pm 11$ | $11 \pm 2 \pm 1$ |
| $f_0(980)\pi^+\pi^-$ | $0.91 \pm 0.13 \pm 0.05$ | $240 \pm 11 \pm 17$ | $15 \pm 3 \pm 2$ |

- 10 resonances => 20 Fit parameters (9 complex amplitudes + KsKK fraction for 3770 and 4170 datasets) for the 3737 total events
- Qualitatively similar to the model produced by the FOCUS analysis
  - Included higher orbital angular momentum states
  - The K1(1400) resonance included by FOCUS did not improve the fit to the CLEO data
  - FOCUS made no attempt to distinguish between D->X, D->Xbar so it is difficult to make quantitative comparisons between results

# Next Steps

## CP Tagged Data

CP eigenstate (C=−1) $e^+e^- \rightarrow \psi(3770) \rightarrow D_0\overline{D_0}$

- By reconstructing one D meson in a CP eigenstate => opposite side D is in opposite CP state
  - 79 CP-tagged events (49 even 30 odd) available at 3770 CM energy

## Test Direct CP Violation

- By comparing a separate amplitude analysis to the $D_0$ and $\overline{D}_0$ it is possible to look for direct CP violation in this decay

# Conclusions

- $D \to K^+K^-\pi^+\pi^-$ decays provide potential for $\gamma$ measurement
- CLEO provides ideal environment for studying these parameters
- Encouraging preliminary results from fits to CLEO data
- Further data to be analyzed