# Charm Dalitz analyses from CLEO-c

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# Outline

- CLEO-c opportunities in Dalitz plot (DP) analyses
- $D^+ \to \pi^-\pi^+\pi^+$ DP analysis
- $\chi_{cJ}$ 3-body decays BR and DP analysis

# CLEO-c opportunities in Dalitz plot analyses

- $e^+e^- \to \psi(3770) \to D\underline{D}$, 1M $D^0\underline{D}^0$, 0.8M $D^+D^-$, plan ×3
  - D mesons are produced almost at rest; clean events
  - flavor tag
  - CP tag
  - ~20 modes of $D \to P_1P_2P_3$ (where $P_i \equiv \pi$, K, $\eta$) good for DP analysis
    - $D^+ \to \pi^-\pi^+\pi^+$ presented in this talk
- $e^+e^-(\sqrt{s}=4170) \to D_s^*\underline{D}_s$, 0.2M $D_s^*\underline{D}_s$, plan ×4
  - $D_S^+$ : DP analyses are just started, i.e. $D_S^+ \to K^-K^+\pi^+$
- $e^+e^- \to \psi(2S)$, 3M $\psi(2S)$, by the end of the year ×10
  - $\psi(2S) \to \gamma\chi_{cJ}$, $\mathcal{B}\sim 9\%$, tagged $\chi_{cJ}$ "factory"
    - $\chi_{cJ}$ 3-body decays analysis is presented in this talk
  - $\psi(2S) \to \pi\pi\, J/\psi$, $\mathcal{B}\sim 50\%$, $\psi \to h_1h_2h_3$, DP analysis or PWA
- We are working hard on DP analysis of many final states

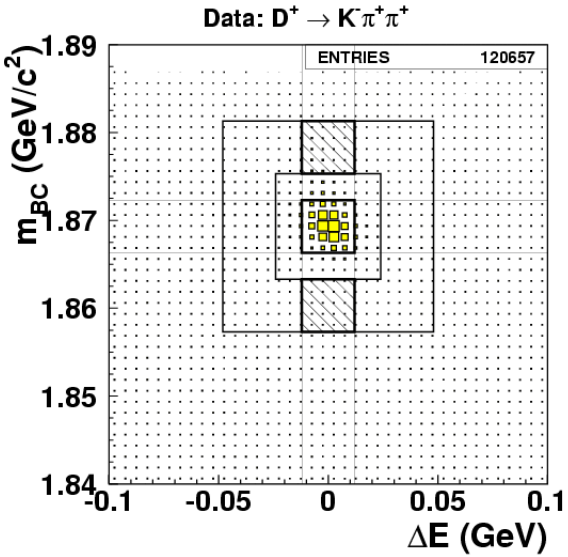
# Example of purity: $D^+ \to K^-\pi^+\pi^+$

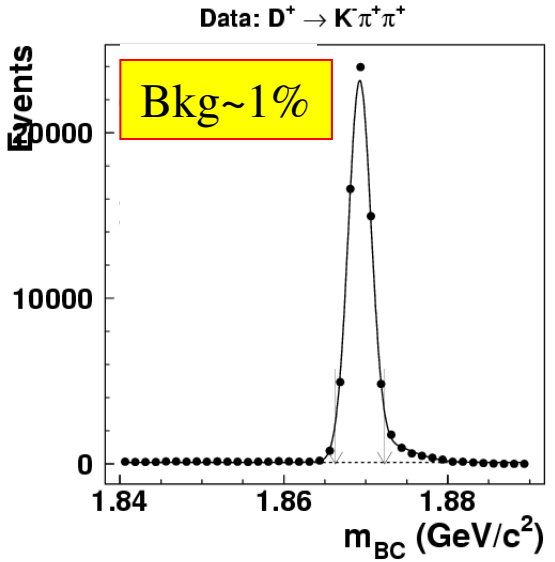
- **281 pb$^{-1}$, 0.8M $D^+D^-$**
- Clean sample in "single tag" mode
- Signal variables:

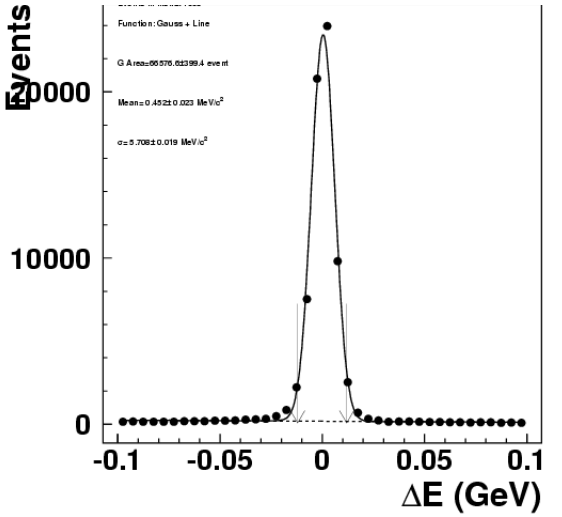
$$m_{BC} = \sqrt{E_{beam}^2 - p_D^2},$$

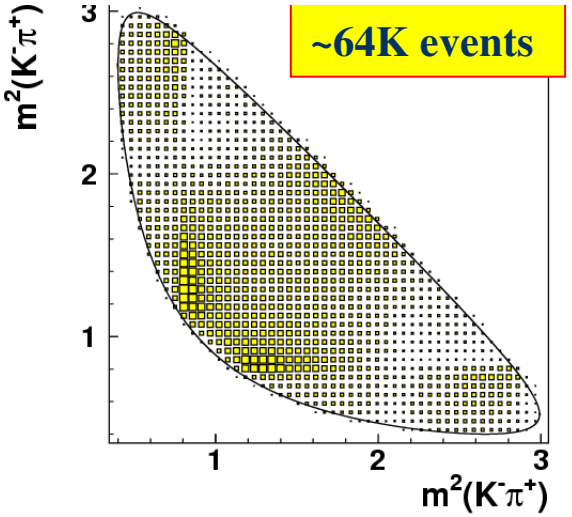
$$\Delta E = E_D - E_{beam},$$

- Not all modes are so clean…



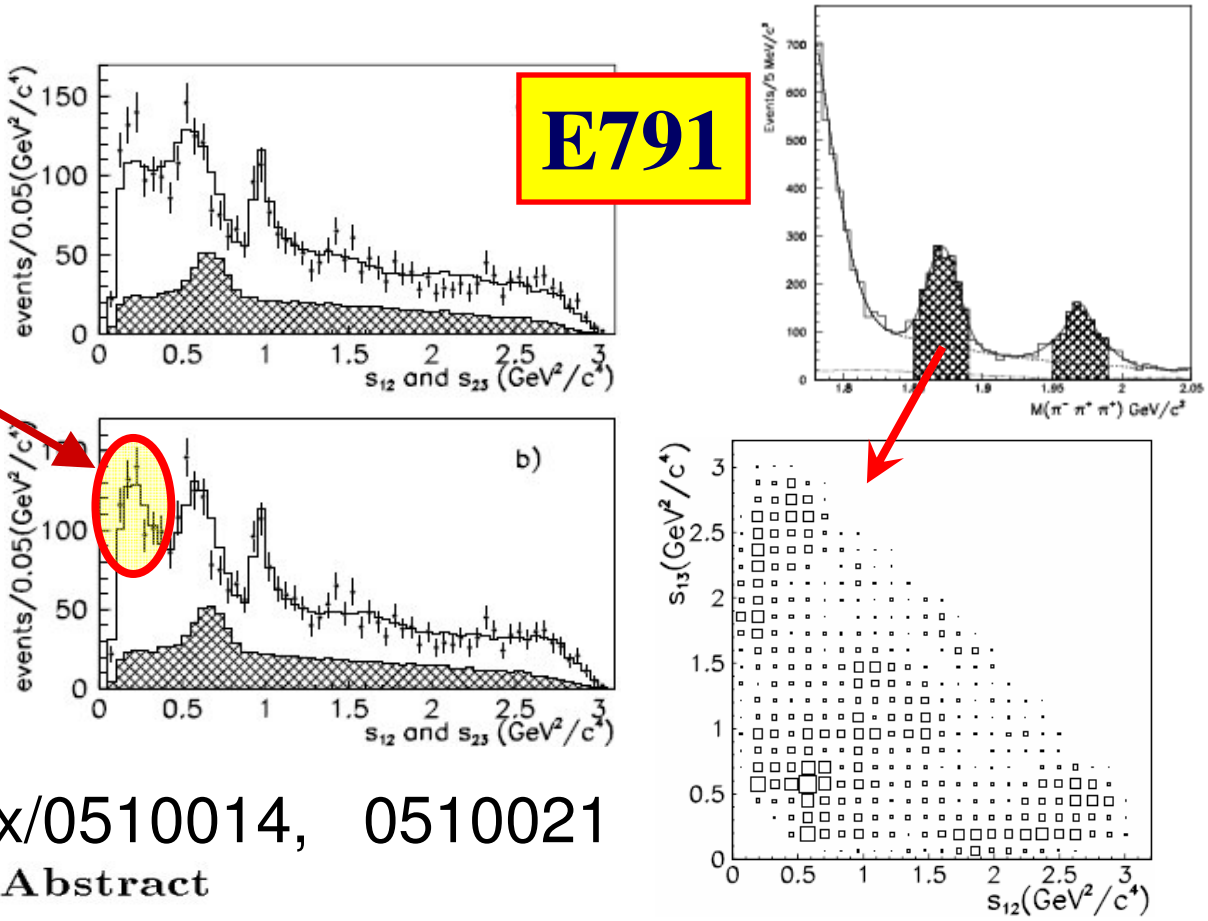



# $D^+ \to \pi^- \pi^+ \pi^+$

- Motivations
- Event selection
- Dalitz plot analysis
- Systematic cross checks
- Results

# σ in $D^+ \to \pi^-\pi^+\pi^+$ from E791 and FOCUS

- FOCUS: K-matrix
- E791: Isobar model
- $\sigma \equiv f_0(600)$ or low mass $\pi^+\pi^-$ S wave is required by their fits




- It looks like σ is recognized.

For example:

- D.V.Bugg, hep-ex/0510014, 0510021

**Abstract**

Both $\sigma$ and $\kappa$ are well established from E791 data on $D \to 3\pi$ and $K\pi\pi$ and BES II data on $J/\Psi \to \omega\pi^+\pi^-$ and $K^+K^-\pi^+\pi^-$.

- CLEO-c have enough stat. **Can we confirm σ(600) ?**

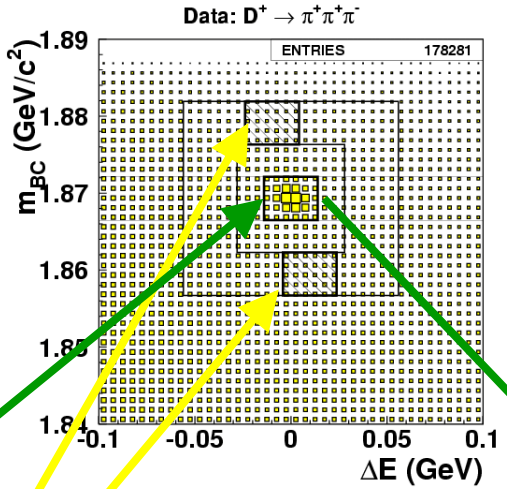
# Event selection

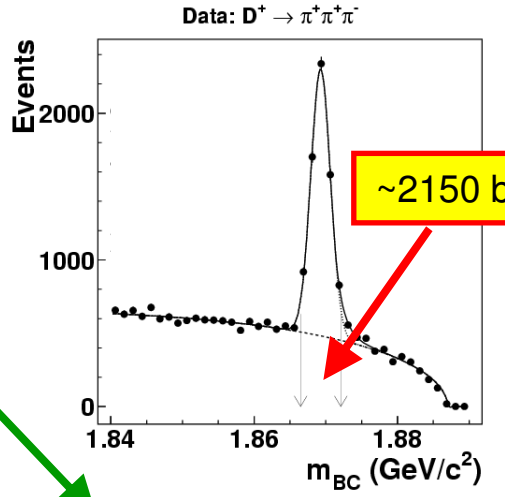
- L=281pb$^{-1}$
- $e^+e^- \to \Psi(3770) \to D\underline{D}$
- Single D reconst.
- Signal variables:

$$m_{BC} = \sqrt{E^2_{beam} - p^2_D},$$

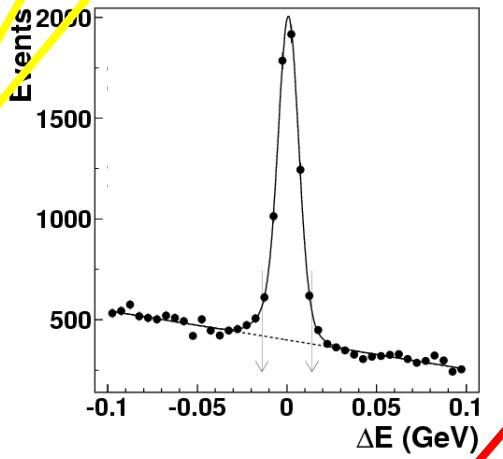
$$\Delta E = E_D - E_{beam},$$

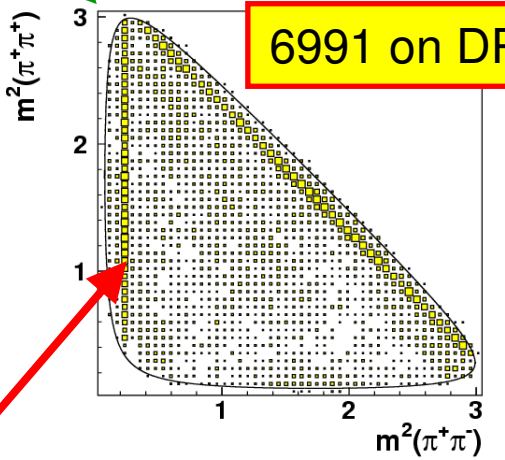
- Signal box for DP
  - $|\Delta E| < 2\sigma$ and
  - $|m_{BC} - m_D| < 2\sigma$
- Bkgd boxes for DP
  - $|\Delta E_{\pm}| < 2\sigma$ and
  - $5\sigma < |m_{BC} - m_D| < 9\sigma$




~2150 bkgd



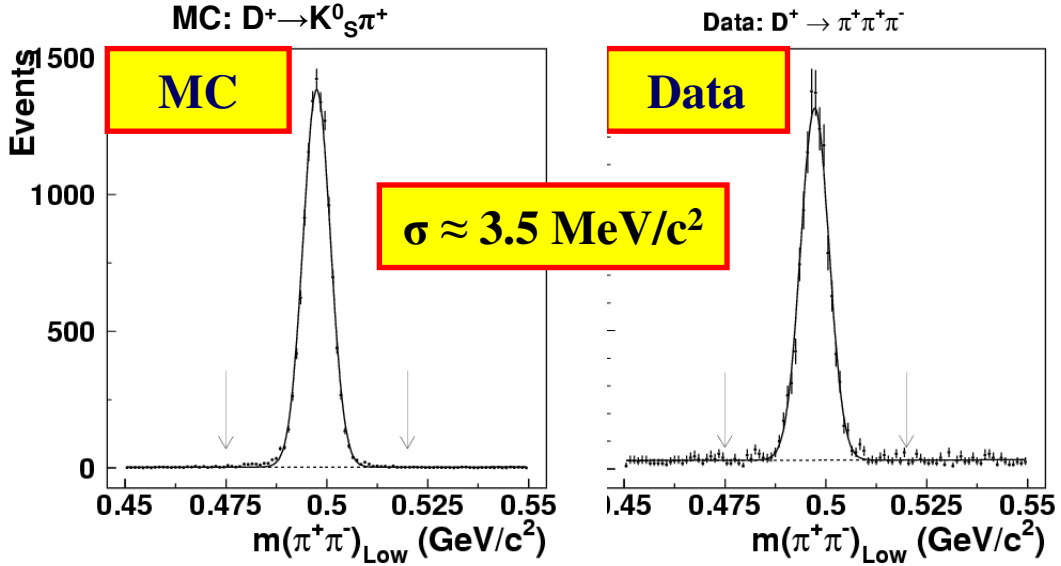

6991 on DP

~2240 $D^+ \to K^0_S \pi^+$

~2600 signal $D^+ \to \pi^-\pi^+\pi^+$

# Cross-check for Branching Ratios

- **Split yield of $D^+ \to \pi^-\pi^+\pi^+$ and $D^+ \to K^0_S\pi^+$ using $m(\pi^+\pi^-)$**




$$\varepsilon_f = \frac{N_f^{MC}}{N_{D^+D^-}[1+\Delta]}$$

$$\mathcal{B}(D^+ \to f^+) \simeq \frac{N_f^{Data}}{2N_{D^+D^-}\varepsilon_f}$$

$\mathcal{B}(D^+ \to \pi^-\pi^+\pi^+) = (0.33 \pm 0.01)\%$

$\mathcal{B}(D^+ \to K^0_S\pi^+) = (1.59 \pm 0.06)\%$

**CLEO-c results:**

$(0.34 \pm 0.02)\%$

P. Rubin et al., PRL **96**, 081802 (2006)

$(1.55 \pm 0.05 \pm 0.06)\%$

Q.He et al., PRL **95**,121801(2005)

# Formalism

- Log likelihood
- PDF
- Matrix element
- Partial waves ($PW_R$):
  - I=2 $\pi^+\pi^+$ S-wave
  - $\pi^+\pi^-$ S-waves:
    - Oller
    - Flatte

$$\mathcal{L} = -2\sum_{n=1}^{N} \log PDF(x_n, y_n)$$

$$PDF(x,y) = \begin{cases} \varepsilon(x,y) \\ B(x,y) \\ fN_S|\mathcal{M}(x,y)|^2\varepsilon(x,y) + (1-f)N_B B(x,y) \end{cases}$$

$$\mathcal{M} = \sum_R c_R PW_R \Omega_R F_R$$

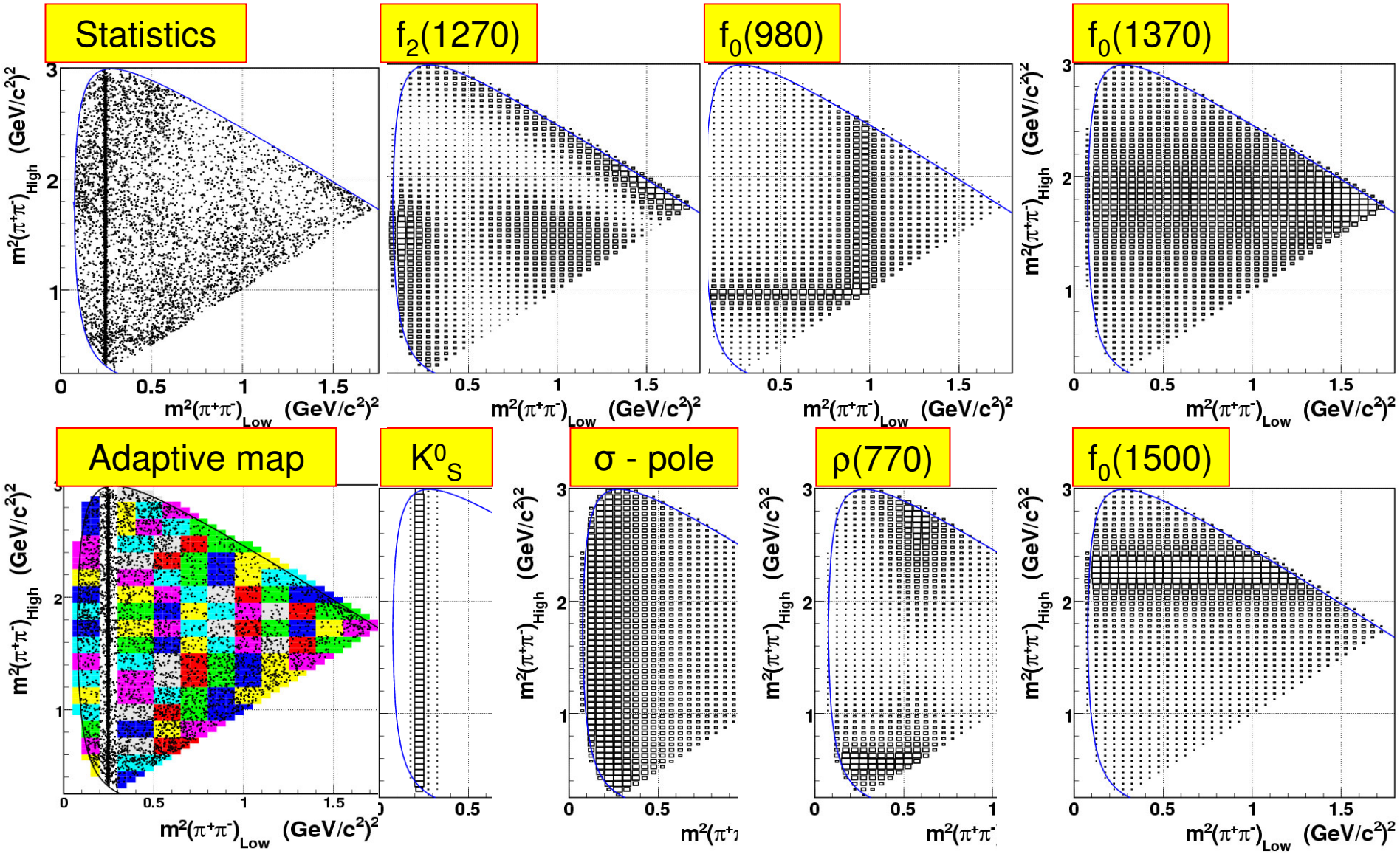
$$a_{J=0}^{I=2}(m) = \frac{\eta_0^2(m)e^{i\delta_0^2(m)} - 1}{2i}$$

$$Pole_A(s) = \frac{1}{s - s_A} \qquad s_\sigma = (0.47 - i0.22)^2 \text{ GeV}^2 \text{ for } \pi\pi \text{ S-wave.}$$

$$Flatte_{f0(980)}(m) = \frac{1}{m_{f_0}^2 - m^2 - i(g_{\pi\pi}^2\rho_{\pi\pi} + g_{K\bar{K}}^2\rho_{K\bar{K}})}$$

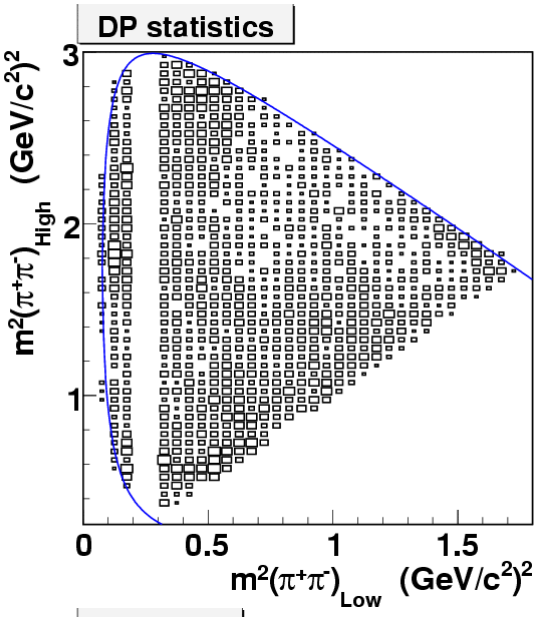
| Experiment | Mass ($MeV/c^2$) | $g_{\pi\pi}^2$ $(MeV/c^2)^2$ | $g_{K\bar{K}}^2/g_{\pi\pi}^2$ |
|---|---|---|---|
| WA102 | 987±6±6 | 190±30±40 | ≃2 |
| E791 | 977±3±2 | 90±10±10 | 4.5±9.0±8.0 |
| BES II | 965±8±6 | 165±10±15 | 4.21±0.25±0.21 |

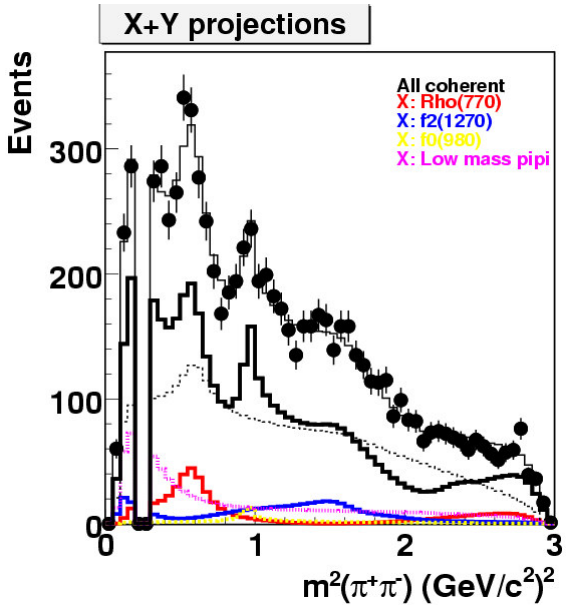
# Statistics & survived intermediate states

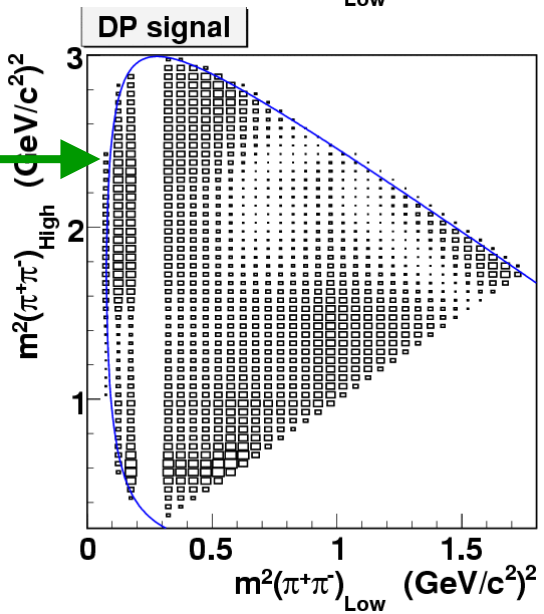


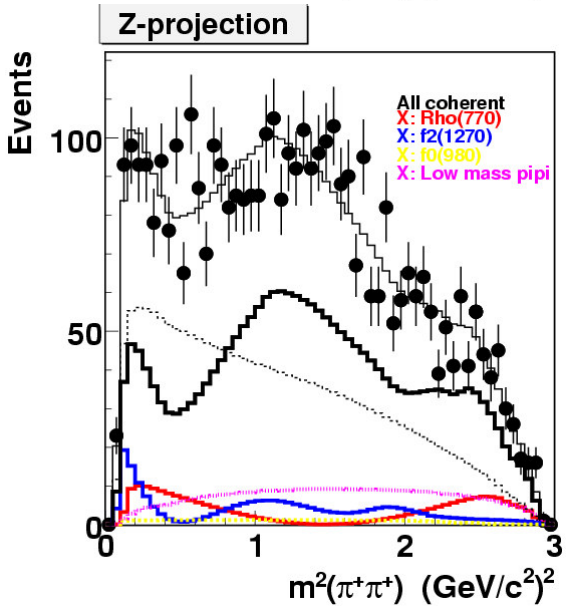
# Nominal fit

- $K^0_S$ removed
- Leading fractions are shown on projections
- Signal p.d.f. (w/o background)



# Sources of systematic uncertainties

- Event selection
  - Variation of the Signal Box size
  - Fit with and w/o cut of $K^0_S$ band
- Efficiency
  - Simultaneous fit to data and MC events with float pars
- Background
  - Variation of the Sideband Boxes
  - Simultaneous fit to data and bkgd events with float pars
- Model dependence
  - Models of E791
  - Other models for $\pi\pi$ S waves, add/remove resonances/waves, free resonance parameters, etc.

Amplitude, a.u.
Phase, degree
Fit fraction, %

# Results for $D^+ \to \pi^-\pi^+\pi^+$

| Mode | Fit#N | Fit#N+1 |
|---|---|---|
| $\rho(770)\pi^+$ | 1(fixed)<br>0(fixed)<br>20.0±2.3±0.9 | 1(fixed)<br>0(fixed) |
| $\rho(1450)\pi^+$ | | 0.9±0.5<br>51±22<br><2.4% |
| $f_0(980)\pi^+$ | 1.4±0.2±0.2<br>12±10±5 | |
| $f_2(1270)\pi^+$ | 4.1±0.9±0.3<br>2.1±0.2±0.1<br>237±6±3 | |
| $f_0(1370)\pi^+$ | 18.2±2.6±0.7<br>1.3±0.4±0.2<br>-21±15±14 | |
| $f_0(1500)\pi^+$ | 2.6±1.8±0.6<br>1.1±0.3±0.2<br>-44±13±16<br>3.4±1.0±0.8 | |
| N.R. | | 1.0±1.5<br>-17±90<br><3.5% |
| I=2 $\pi^+\pi^+$ S wave | | 0.17±0.14<br>±360<br><3.7% |
| $\sigma$ pole | 3.7±0.3±0.2<br>-3±4±2<br>41.8±1.4±2.5 | |
| $f_0(1710)\pi^+$ | | 0.7±0.5<br>26±40<br><1.6% |
| $f_0(1790)\pi^+$ | | 1.0±1.1<br>23±58<br><2% |
| $\sum_i FF_i$, % | 90.2 | |
| Pearson/$N_{d.o.f.}$<br>Probability<br>$-2\sum \log L$ | 97.4/90<br>27.8%<br>395 | |

- Our data agrees with results of models used in E791 analysis
- Have tested other models
- Nominal fit comparing to E791:
  - + $f_0(1500)$ with parameters from BES
  - + $f_0(1710)$, $f_0(1790)$
  - σ (E791) BW is replaced by σ-pole
- Significant fractions:

ρ(770), $f_2(1270)$, $f_0(980)$, σ(600), $f_0(1370)$, $f_0(1500)$

- Upper Limits:
  - ρ(1450), NR and I=2 $\pi^+\pi^+$ are gone,
  - $f_0(1710)$, $f_0(1790)$ do not survive

# $\chi_{cJ} \to h^0 h^+ h^-$

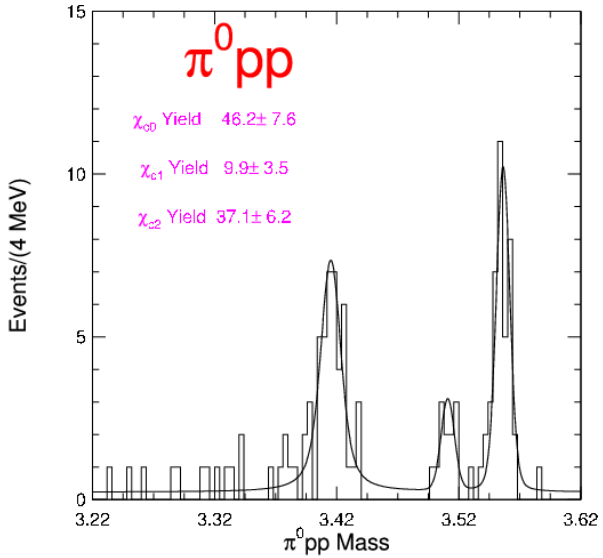
- Study 3-body decays of $\chi_{cJ} \to h^0 h^+ h^-$, produced in $e^+e^- \to \psi(2S) \to \gamma\chi_{cJ}$ , J=0,1,2

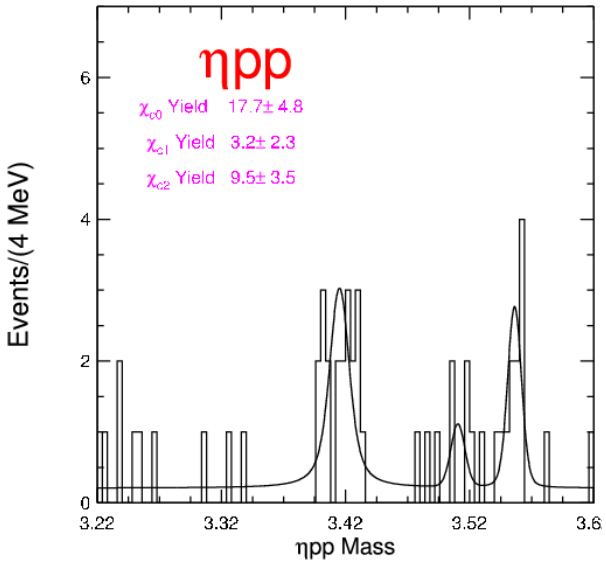
  - Measurement of BR or set UL

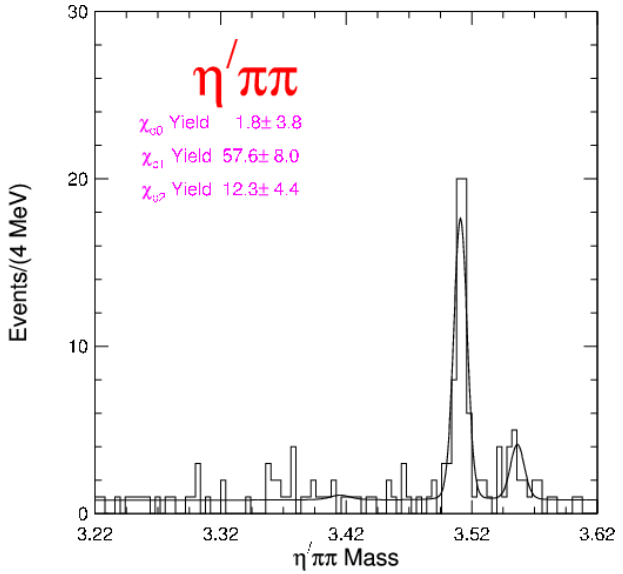
    $\chi_{cJ} \to \eta\pi^+\pi^-$, $K^+K^-\pi^0$, $K^0_S K\pi$, $\eta K^+K^-$, $\eta'\pi^+\pi^-$, $\eta p\bar{p}$, $\pi^0 p\bar{p}$, $\Lambda K\bar{p}$

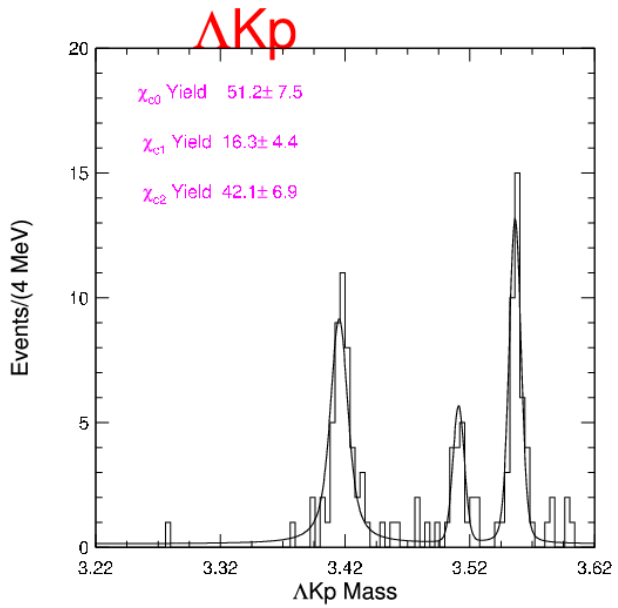
  - Dalitz plot analysis of 3 modes with high statistics: $\chi_{c1} \to \eta\pi^+\pi^-$, $K^+K^-\pi^0$, $K^0_S K\pi$

# Yield $\chi_{cJ} \to \pi^0 p\bar{p}$, $\eta p\bar{p}$, $\Lambda K\bar{p}$, $\eta' \pi^+ \pi^-$



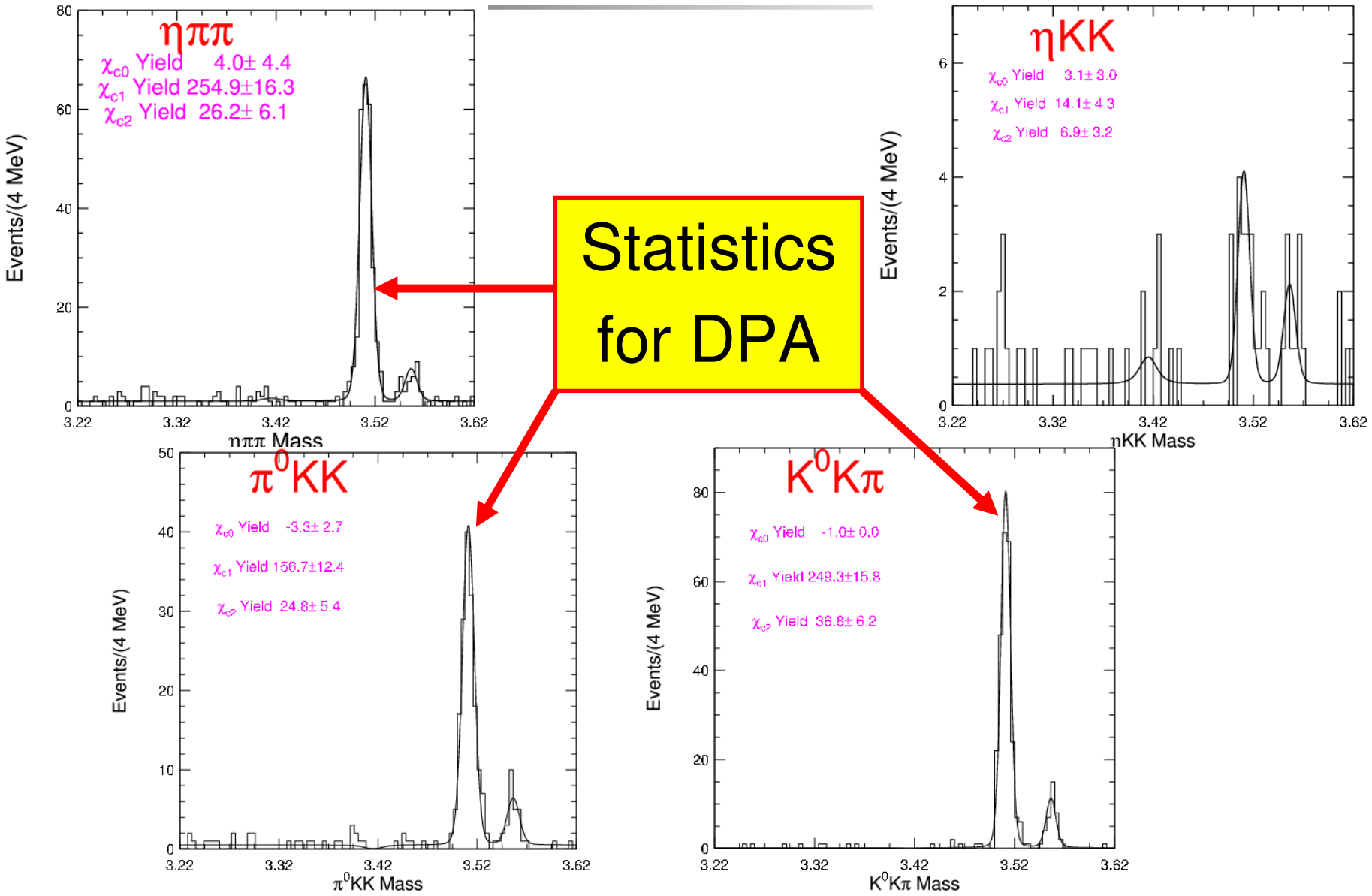



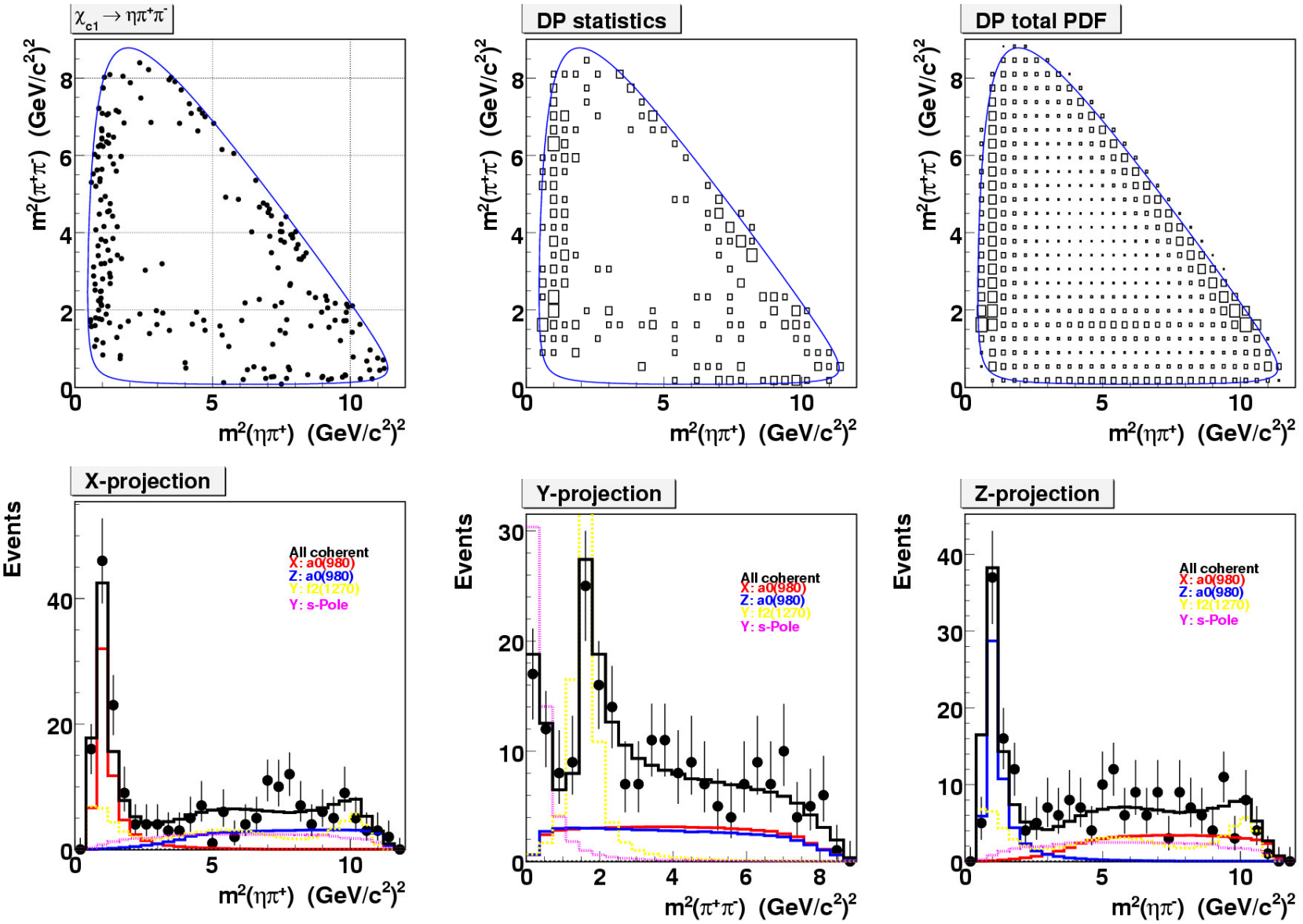




- Signal MC:
  - Resolutions $\sigma$=4-7MeV/$c^2$
  - Efficiencies ~7-30%
- Fit accounts for $\Gamma(\chi_{c0})$=10.1MeV

# Yield $\chi_{cJ} \to \eta\pi^+\pi^-$, $\eta K^+K^-$, $K^0_S K\pi$, $K^+K^-\pi^0$



# DP fit for $\chi_{c1} \to \eta\pi^+\pi^-$



# Results for $\chi_{c1} \to \eta\pi^+\pi^-$

| Mode | Nominal fit |
|---|---|
| $a_0(980)^+$ | 1 |
| | 0 |
| $2\times$ | $28.1\pm1.8\pm0.7$ |
| $f_2(1270)$ | $0.186\pm0.017\pm0.003$ |
| | $-118\pm10\pm4$ |
| | $35.1\pm2.9\pm1.8$ |
| $\sigma$-pole | $0.68\pm0.07\pm0.05$ |
| | $-85\pm18\pm15$ |
| | $21.7\pm3.3\pm0.5$ |
| $\sum_i FF_i$, % | 113.1 |
| $-2\sum \log L$ | $-460.1$ |
| Pearson/$N_{d.o.f.}$ | 22.0/24 |
| P(Pearson,$N_{d.o.f.}$) | 58.1% |

Amplitude, a.u.
Phase, degree
Fit fraction, %

Clebsch-Gordan decomposition for $\chi_{c1} \to \eta\pi^+\pi^-$ gives:

$$a_{a(980)+} = a_{a(980)-}$$
$$\phi_{a(980)+} = \phi_{a(980)-}$$

# Isospin symmetry for $\chi_{c1} \to K\underline{K}\pi$

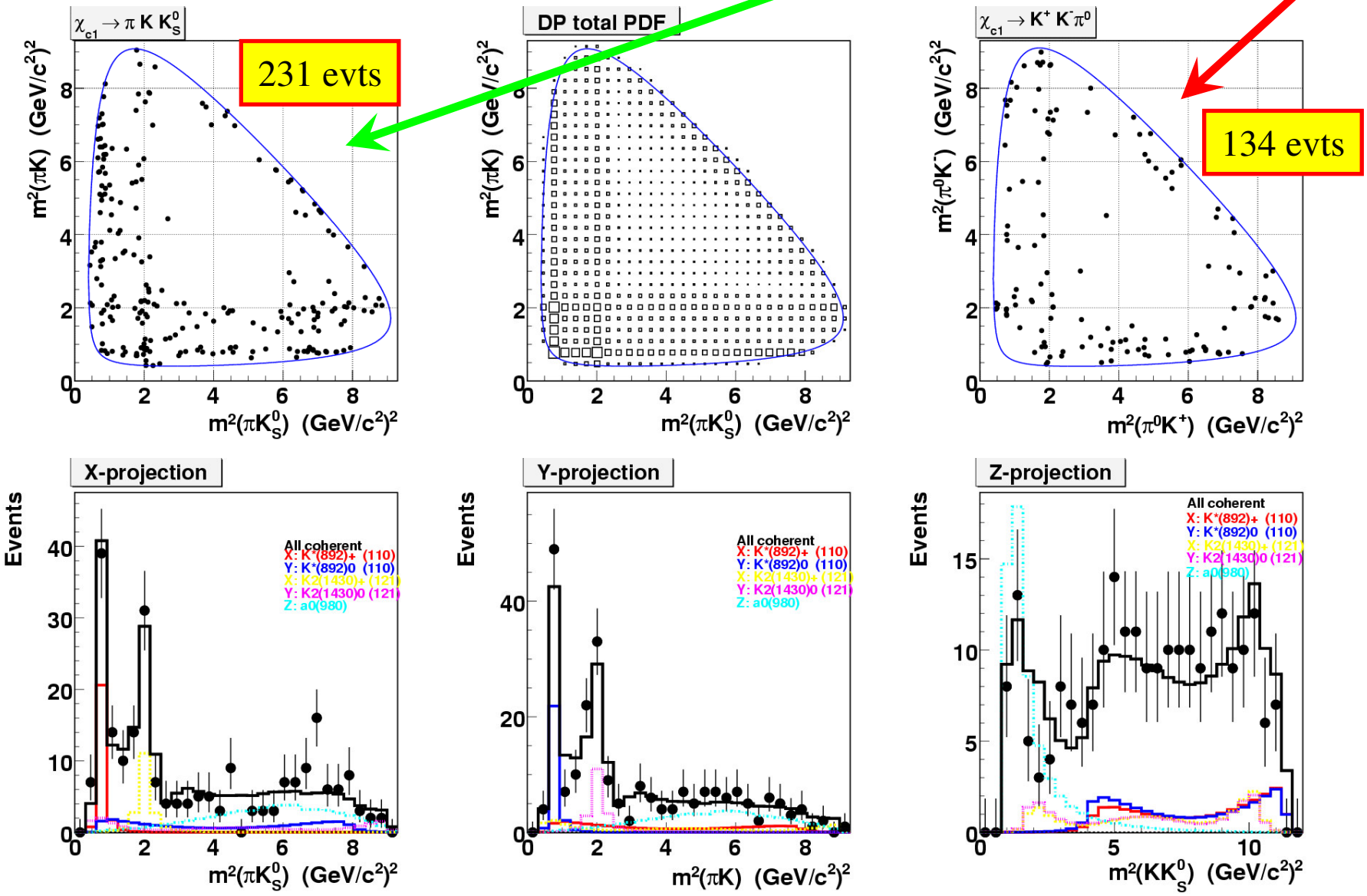
$$\Gamma(\chi_{c1} \to \pi^+ K^- K^0) + \Gamma(\chi_{c1} \to \pi^- K^+ \overline{K^0}) = 4\Gamma(\chi_{c1} \to \pi^0 K^+ K^-)$$

- Relative factor $-\sqrt{2}$ between amplitudes of $K^0_S K\pi$ and $K^+K^-\pi^0$ does not matter due to separate PDF normalization.

- Constrains for the Dalitz plot analysis:

$$\begin{aligned}
a_{K^*+} &= a_{K^*-} = a_{K^{*0}} = a_{\overline{K^{*0}}} \equiv a_{K^*} \ , \\
\phi_{K^*+} &= \phi_{K^*-} = \phi_{K^{*0}} = \phi_{\overline{K^{*0}}} \equiv \phi_{K^*} , \\
a_{a(980)+} &= a_{a(980)-} = a_{a(980)^0} \equiv a_{a(980)} , \\
\phi_{a(980)+} &= \phi_{a(980)-} = \phi_{a(980)^0} \equiv \phi_{a(980)} .
\end{aligned}$$

# Combined fit for $\chi_{c1} \to K^0_S K\pi$, $K^+K^-\pi^0$



# **Combined** fit for $\chi_{c1} \to K^0_S K\pi$, $K^+K^-\pi^0$

| Mode | Nominal fit |
|---|---|
| $K^*(892)$ | 1 |
| | 0 |
| $K^+K^-\pi^0$: 2×, % | 9.8±2.0±1.0 |
| $K^0_SK\pi$: 2×, % | 9.9±2.0±0.9 |
| $K^*_2(1430)$ | 0.50±0.09±0.12 |
| | −2±13±6 |
| $K^+K^-\pi^0$: 2×, % | 9.1±3.4±3.4 |
| $K^0_SK\pi$: FF($K^*_2(1430)^+$), % | 9.3±3.4±1.6 |
| $K^0_SK\pi$: FF($K^*_2(1430)^0$), % | 8.4±3.0±1.5 |
| $K^*_0(1430)$ | 5.3±1.0±0.1 |
| | 77±12±16 |
| $K^+K^-\pi^0$: 2×, % | 17.8±6.3±1.3 |
| $K^0_SK\pi$: 2×, % | 18.2±6.4±1.6 |
| $K^*(1680)$ | 2.3±0.5±0.5 |
| | −38±12±12 |
| $K^+K^-\pi^0$: 2×, % | 5.5±2.7±1.7 |
| $K^0_SK\pi$: 2×, % | 5.6±2.6±1.0 |
| $a_0(980)$ | 10.8±1.2±1.2 |
| | −112±12±3 |
| $K^+K^-\pi^0$, % | 29.5±7.3±2.8 |
| $K^0_SK\pi$, % | 29.4±6.9±2.2 |
| $\sum_i FF_i$, % | ∼115 |
| $-2\sum \log L$ | −545.7 |
| Pearson/$N_{d.o.f.}$ | 57.2/53 |
| P(Pearson,$N_{d.o.f.}$), % | 32.1 |

Amplitude, a.u.
Phase, degree
Fit fraction(s), %

- K*(892), $K_2$*(1430), $a_0$(980) are clearly seen but not sufficient to provide good fit.
- We find several models with good fit quality with additional
  - + $K_0$*(1430), K*(1680) , Prob.~30%
  - + NR, Prob.~17%
  - + κ, Prob.~10%
- With larger statistics we hope to resolve this ambiguity.

# Preliminary BR (%) for $\chi_{cJ} \to h^0 h^+ h^-$

| Mode | $\chi_{c0}$ | $\chi_{c1}$ | $\chi_{c2}$ |
|---|---|---|---|
| $\eta\pi^+\pi^-$ | $< 0.021$ | $0.52 \pm .03 \pm .03 \pm .03$ | $0.051 \pm .011 \pm .004 \pm .003$ |
| $\eta K^+K^-$ | $< 0.024$ | $0.034 \pm .010 \pm .003 \pm .002$ | $< 0.033$ |
| $\eta p\bar{p}$ | $0.038 \pm .010 \pm .003 \pm .02$ | $< 0.015$ | $.019 \pm .007 \pm .002 \pm .002$ |
| $\eta'\pi^+\pi^-$ | $< 0.038$ | $0.24 \pm .03 \pm .02 \pm .02$ | $< 0.053$ |
| $\pi^0 K^+K^-$ | $< 0.006$ | $0.200 \pm .015 \pm .018 \pm .014$ | $0.032 \pm .007 \pm .002 \pm .002$ |
| $\pi^0 p\bar{p}$ | $0.059 \pm .010 \pm .006 \pm .004$ | $0.059 \pm .010 \pm .005 \pm .004$ | $0.045 \pm .007 \pm 0.004 \pm .003$ |
| $\Lambda K^+\bar{p}$ | $0.114 \pm .016 \pm .009 \pm .007$ | $0.034 \pm .009 \pm .003 \pm .002$ | $0.088 \pm .014 \pm .07 \pm .006$ |
| $\overline{K^0}K^+\pi^-$ | $< 0.005$ | $0.84 \pm .05 \pm .06 \pm .05$ | $0.13 \pm .02 \pm .01 \pm .01$ |

PDG 2004, $K^0_S K\pi$ : <0.08 0.25±0.07 <0.13 BES '99

- Uncertainties: *stat., syst.,* $\mathcal{B}(\psi(2S) \to \gamma\chi_{cJ})$
- Dalitz plot analysis gives splitting of BR for sub-modes of $\chi_{c1} \to \eta\pi^+\pi^-$, $K^+K^-\pi^0$, $K^0_S K\pi$

# Summary

- CLEO-c has broad opportunities for DP analyses of **D, $D_s$, $\chi_{cJ}$**, J/ψ...
  - single and double tagging technique
  - flavor and CP tags
- Using ~0.8M $D^+D^-$ we performed the $D^+ \to \pi^-\pi^+\pi^+$ DP analysis.
  - σ(600) or low mass $\pi^+\pi^-$ S wave is required by CLEO-c data.
- Using ~3M ψ(2S) we study $\psi(2S) \to \gamma\chi_{cJ}$, $\chi_{cJ} \to h^0h^+h^-$, J=0,1,2
  - Measurement of BR or set UL for 3 $\chi_{cJ}$ states × 8 modes:
    $\chi_{cJ} \to \eta\pi^+\pi^-$, $K^+K^-\pi^0$, $\eta K^+K^-$, $\eta p\bar{p}$, $\pi^0 p\bar{p}$, $K^0_S K\pi$, $\eta'\pi^+\pi^-$, $\Lambda K\bar{p}$
  - Dalitz plot analysis of 3 modes: $\chi_{c1} \to \eta\pi^+\pi^-$, $K^+K^-\pi^0$, $K^0_S K\pi$
- More CLEO-c results of DP analyses are expected soon.