χ_{cJ} decays to light hadrons at CLEO

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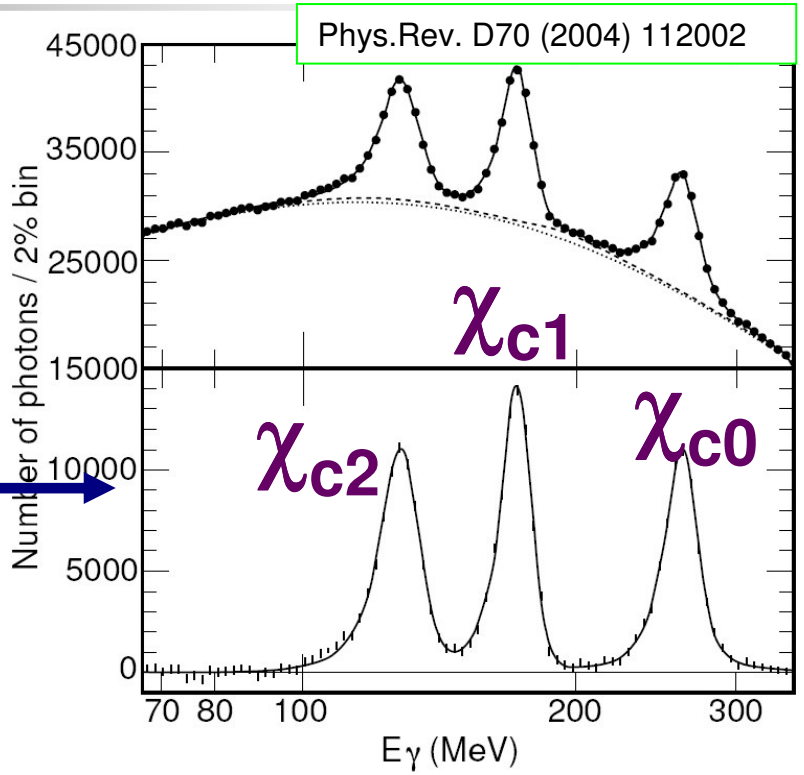
Heavy Quarkonium 2006, BNL

χ_{cJ} production at CLEO-c

- $e^+e^- \to \psi(2S)$
  - $5pb^{-1}$, CLEO III & c, 3M $\psi(2S)$
  - by the end of the year ×10
- $\psi(2S) \to \pi\pi\, J/\psi$
  - $\mathcal{B} \sim 50\%$
- $\psi(2S) \to \gamma\chi_{cJ}$, J=0,1,2
  - $\mathcal{B}_J \sim 9\%$, "χ_{cJ} factory"
  - observed in inclusive analysis
  - $\mathcal{B}(\chi_{cJ} \to \text{hadrons})$ **are not well known**



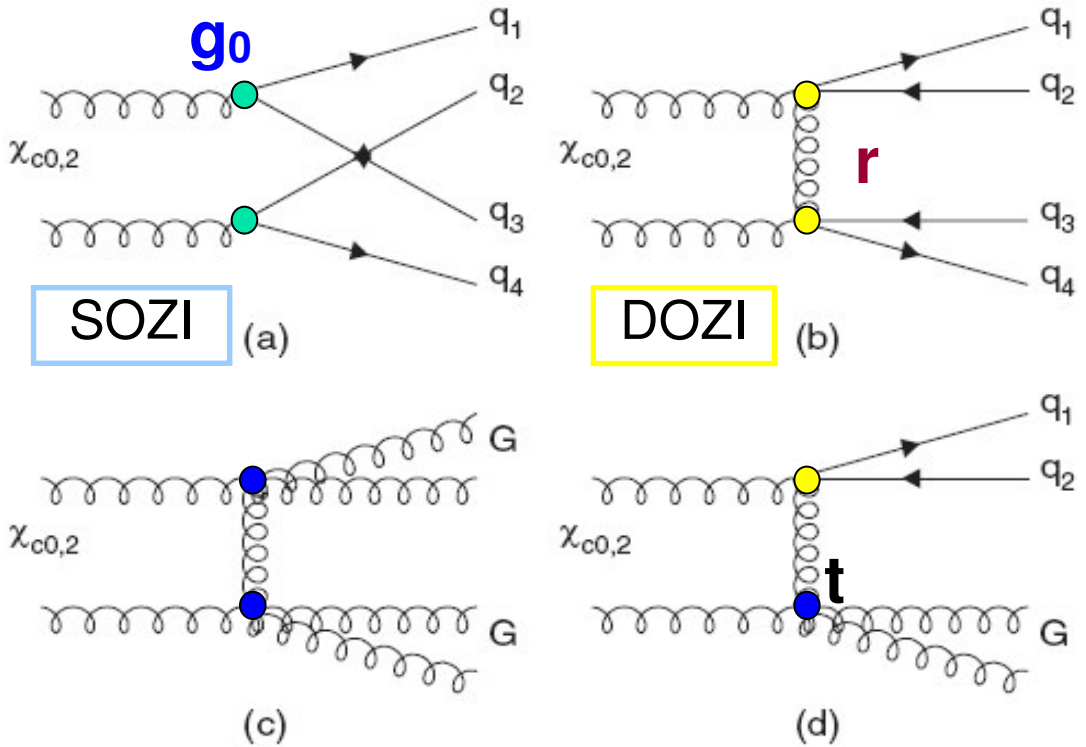
- We find copious χ_{cJ} hadronic decays in exclusive modes
  - $\chi_{cJ} \to$ 2-body
  - $\chi_{cJ} \to$ 3-body, Dalitz analysis
  - $\chi_{cJ} \to$ 4 and multi-body decays

Outline

- Selected analyses of χ_{cJ} hadronic decays:
  - $\chi_{cJ} \to \eta^{(\prime)}\eta^{(\prime)}$
  - $\chi_{cJ} \to VV$ $(V = \varphi, \omega)$
  - $\chi_{cJ} \to h^+h^-h^0h^0$ $(h = \pi, K, \eta, p)$
  - $\chi_{cJ} \to h^+h^-h^0$, 3-body decays, Dalitz plot analysis

Motivation $\chi_{c0,2} \to$ VV, PP, SS

- Qiang Zhao, Phys. Rev., D72:074001, 2005:
  - g_0: basic gqq* coupling
  - r: OZI-rule violation
  - R: SU(3) flavour breaking
  - t: glueball coupling strength



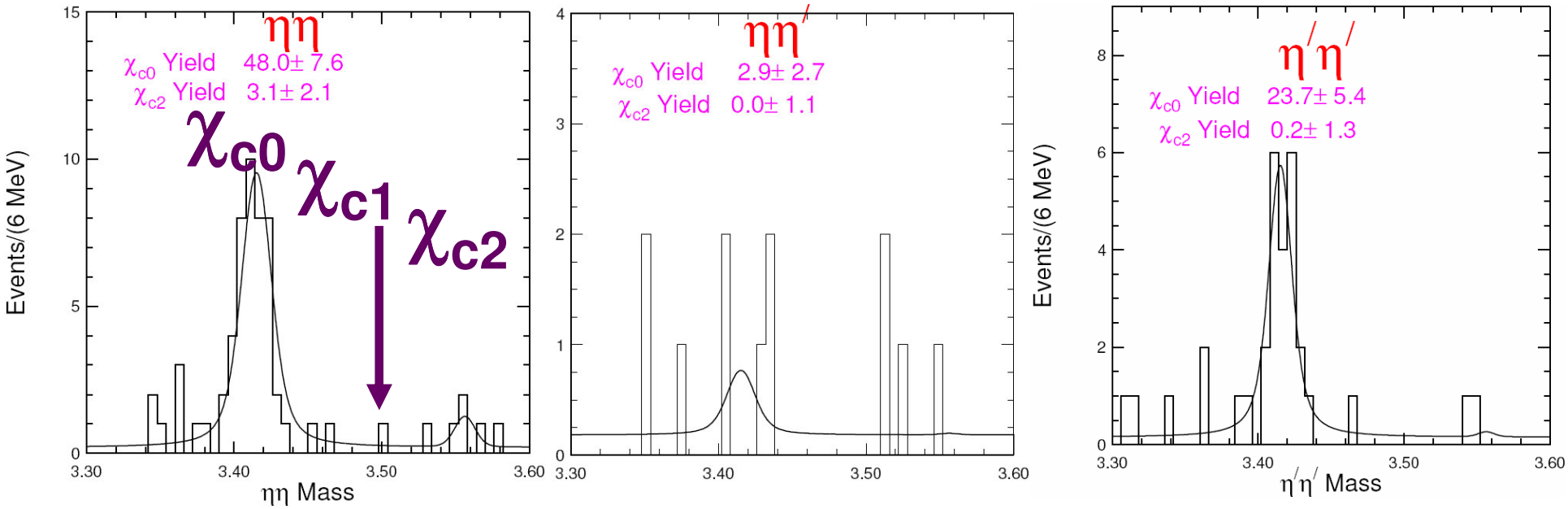
Reconstruction of $\psi(2S) \to \gamma\chi_{cJ}$, $\chi_{cJ} \to h^0h^+h^-$

- Use particle ID (dE/dx & RICH) for π, K, p
- K^0_S / Λ: flight path > 5 / 3mm, $|\Delta m|<10$ / 5 MeV/c^2
- γ : 30MeV in good barrel, 50MeV elsewhere,
  no track match, good shower shape
- $\pi^0 \to \gamma\gamma$, mass constrained fit $\chi^2<10$
- $\eta \to \gamma\gamma$, $\pi^+\pi^-\pi^0$, $\pi^+\pi^-\gamma$, meson mass constrained
- $\eta' \to \eta\pi^+\pi^-$, $\gamma\rho$
- Reconstruct the two charged particles and vertex constrain them. Use this as a starting point for neutral
- Add a radiated photon and constrain total decay $\psi(2S)$ 4-momentum (accounting for crossing angle) and cut at $\chi^2<25$
- Plot the mass spectra of hadron combinations

$\chi_{cJ} \to \eta^{(\prime)}\eta^{(\prime)}$

- Measurement of $\mathcal{BR}$ or set an UL
  - $\chi_{cJ} \to \eta\eta$
  - $\chi_{cJ} \to \eta\eta'$
  - $\chi_{cJ} \to \eta'\eta'$

Invariant mass spectra $\chi_{cJ} \to \eta^{(\prime)}\eta^{(\prime)}$



- $\chi_{c1} \to$ PP spin-parity violated, not seen
- From signal MC:
  - Resolution σ = 4.7-8.3 MeV/c2
  - Efficiency ~4-6% (includes $\mathcal{BR}$)

Preliminary results for $\chi_{cJ} \to \eta^{(')}\eta^{(')}$

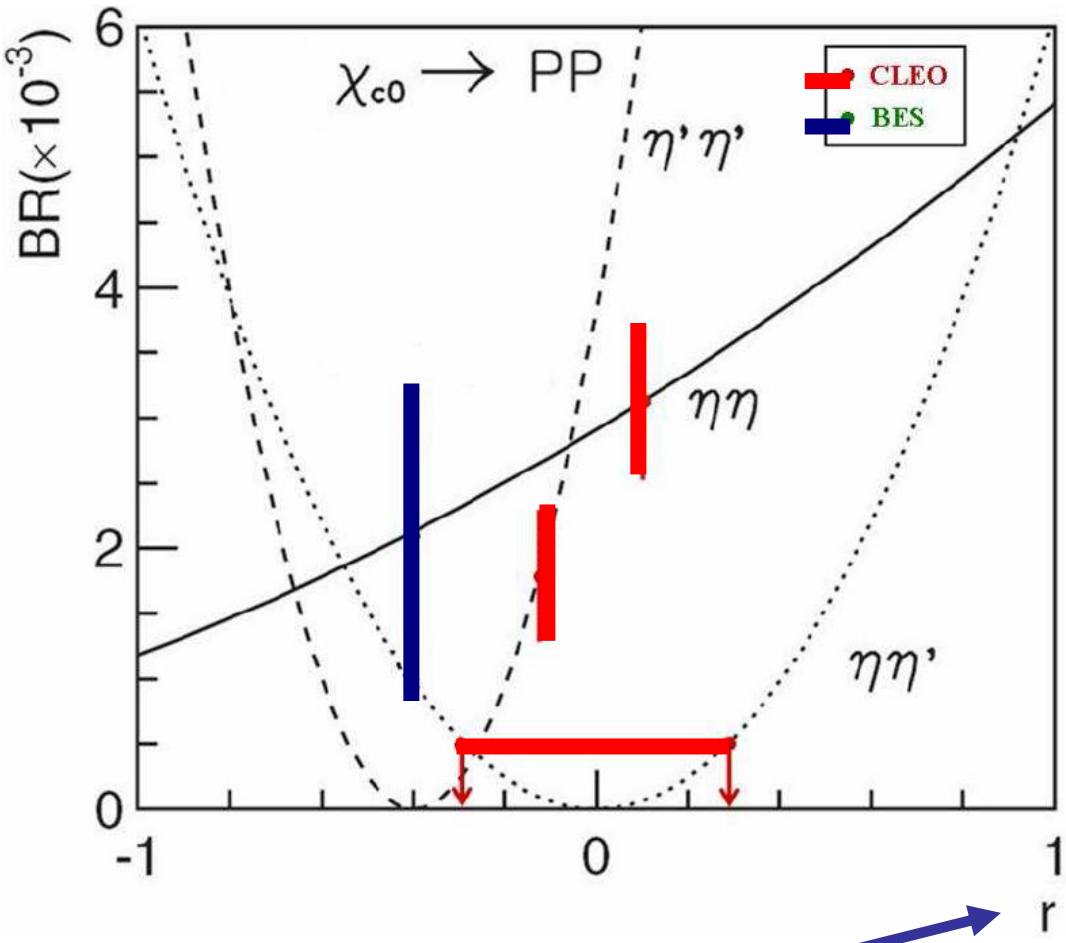
$\chi_{c0} \to \eta\eta$

E835: 0.198 ± 0.068 ± 0.038 %

BES: 0.194 ± 0.084 ± 0.059 %

$\chi_{c0} \to \eta^{(')}\eta^{(')}$

CLEO preliminary



Qiang Zhao, Phys. Rev. D72:074001, 2005 r = A(DOZI) / A(SOZI)

$\chi_{cJ} \to VV$

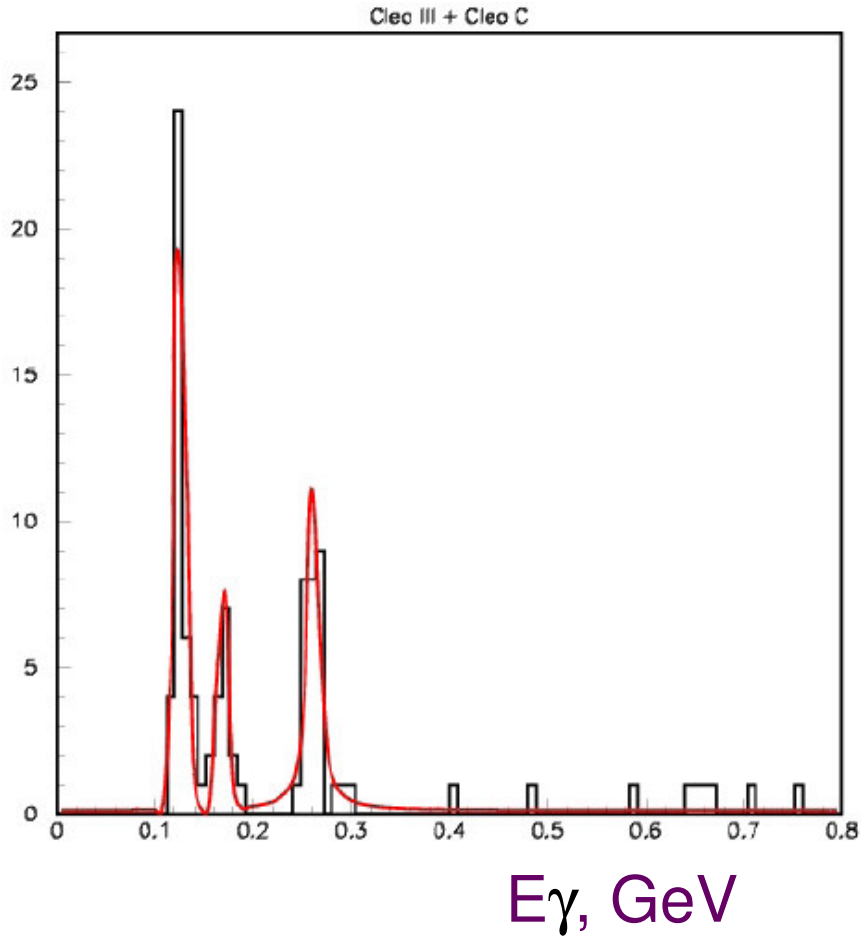
- Measurement of BR or set an UL on
  - $\chi_{cJ} \to \varphi\varphi$
  - $\chi_{cJ} \to \omega\omega$
  - $\chi_{cJ} \to VV$ other modes are not studied yet

Observation of $\chi_{cJ} \to \varphi\varphi$

$\chi_{cJ} \to \varphi\varphi$

- $\varphi \to K^+K^-$

- We observe:
  - Strong correlation in $m(K^+K^-)$ vs $m(K^+K^-)$
  - Signal for J=0,1,2
- Analysis is in progress



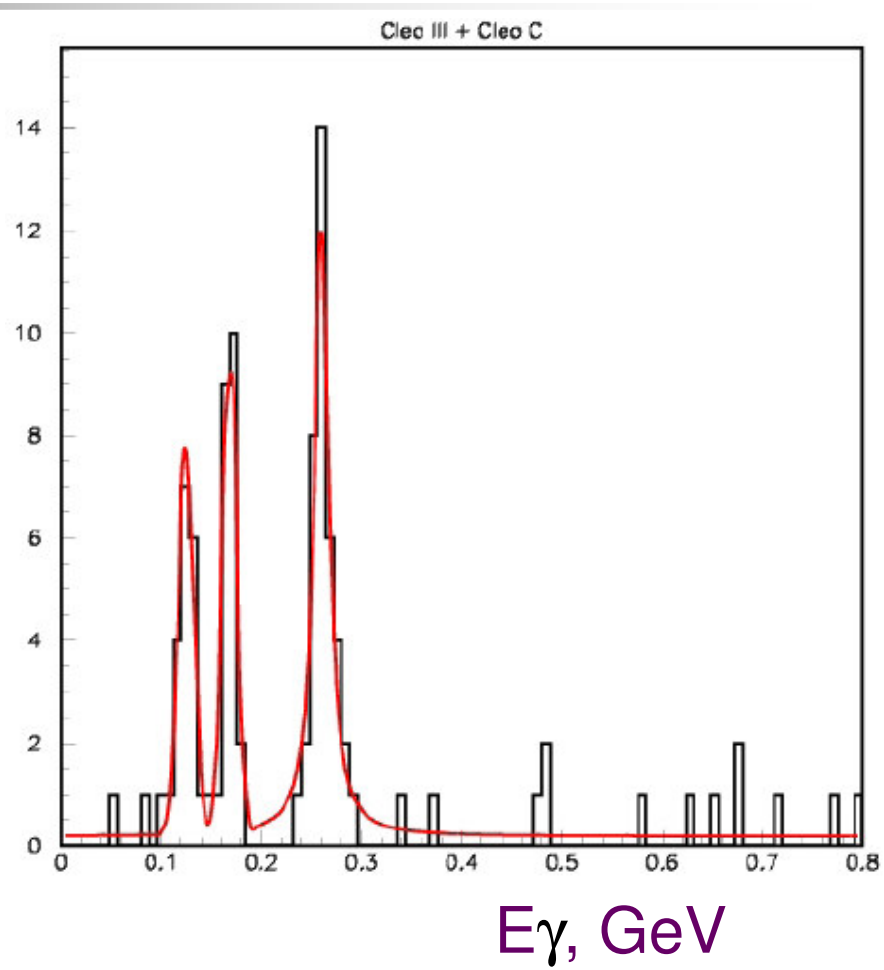
Quantity	$\chi_{c0} \to \phi\phi$	$\chi_{c1} \to \phi\phi$	$\chi_{c2} \to \phi\phi$
BES2: $BR(\chi_c \to \phi\phi)\times 10^{-3}$	$0.94\pm0.21\pm0.14$	—	$1.48\pm0.26\pm0.23$

Observation of $\chi_{cJ} \to \omega\omega$

$\chi_{cJ} \to \omega\omega$

- $\omega \to \pi^+\pi^-\pi^0$

- We observe:
  - Strong correlation in $m(\pi^+\pi^-\pi^0)$ vs $m(\pi^+\pi^-\pi^0)$
  - Signal for J=0,1,2
- Analysis is in progress

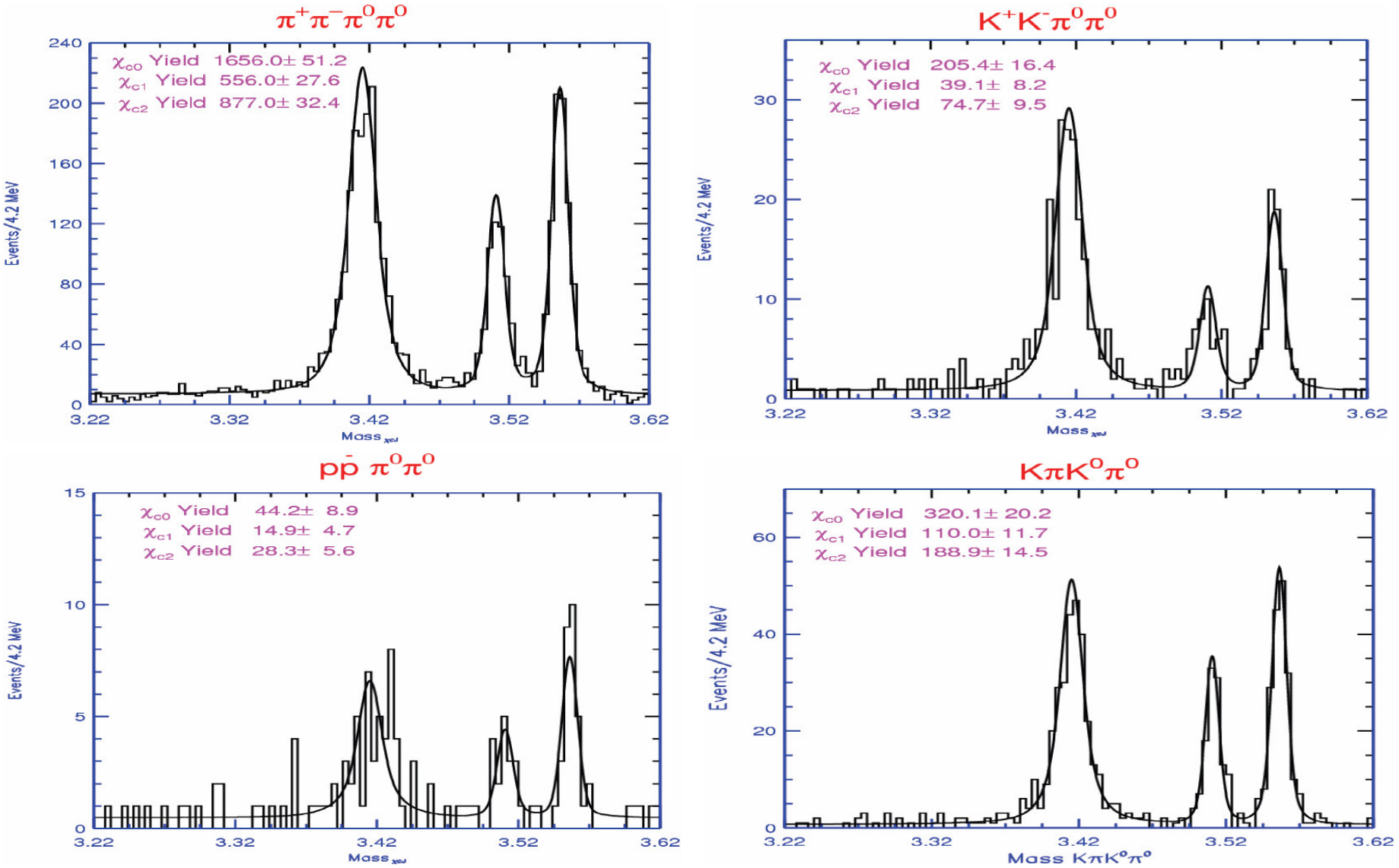


Quantity	$\chi_{c0} \to \phi\phi$	$\chi_{c1} \to \phi\phi$	$\chi_{c2} \to \phi\phi$
BES: $BR(\chi_c \to \omega\omega)\times 10^{-3}$	$2.29\pm0.58\pm0.41$	—	$1.77\pm0.47\pm0.36$

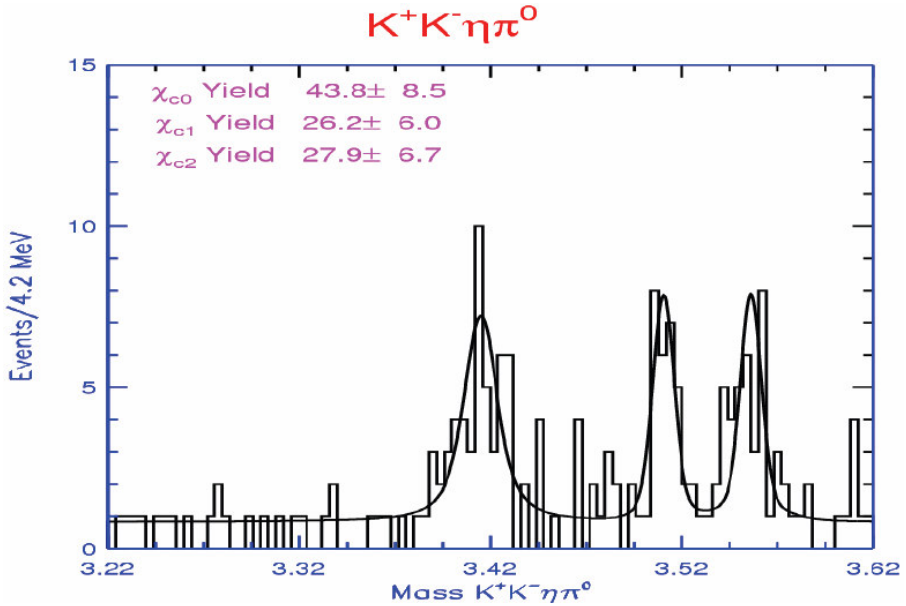
$\chi_{cJ} \to h^+h^-h^0h^0$

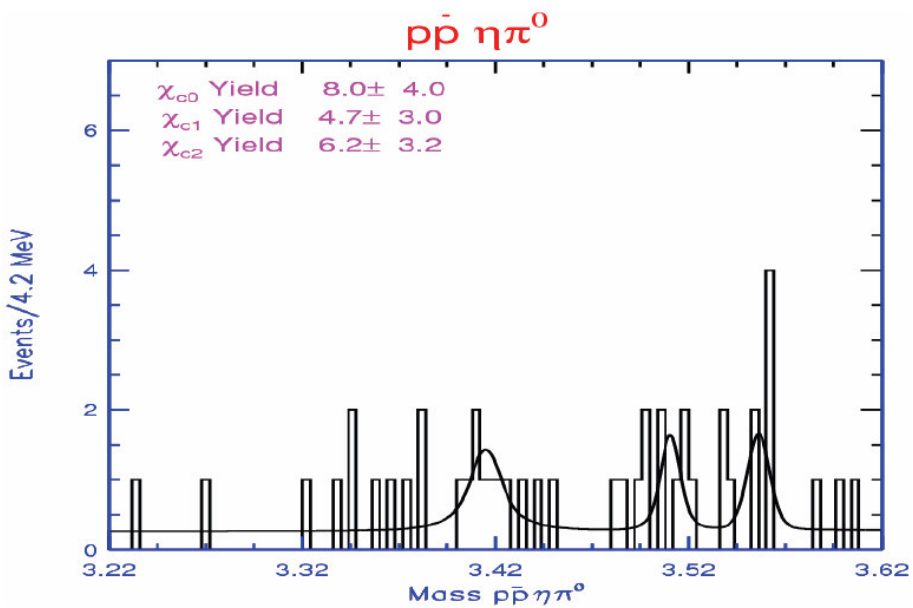
- Measurement of BR or set UL on
  - $\chi_{cJ} \to h^+h^-\pi^0\pi^0$ (h = π, K, p - tracks)
  - $\chi_{cJ} \to h^+h^-\eta\pi^0$
  - $\chi_{cJ} \to K\pi\, K^0\pi^0$
- Motivation
  - modes with two neutral particles π^0 and η have not been seen before

$\chi_{cJ} \to h^+h^-\pi^0\pi^0$, $K\pi\, K^0\pi^0$



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





- Resolution σ=4-9 MeV/c^2, Efficiency ~3-19%
- Work on systematic uncertainties in progress
- Investigate an event substructure (w/o PWA)
- Other 4-body modes need to be studied

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

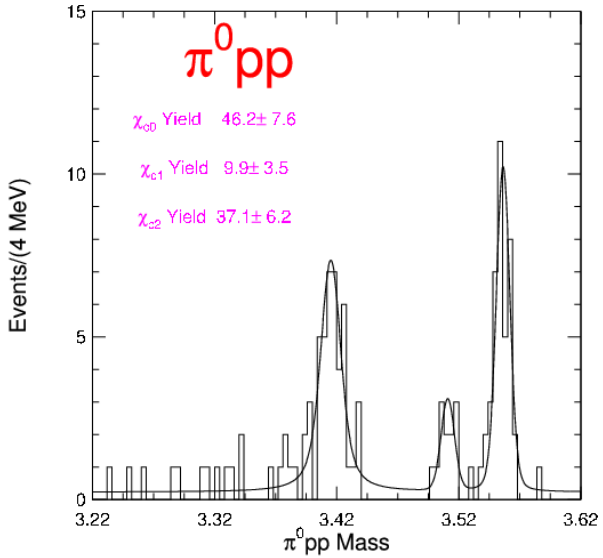
- Study 3-body decays of $\chi_{cJ} \to h^0 h^+ h^-$

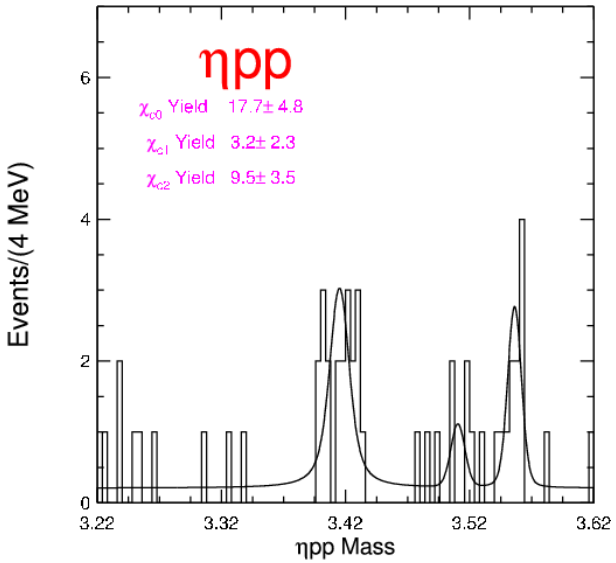
  - Measurement of BR or set UL

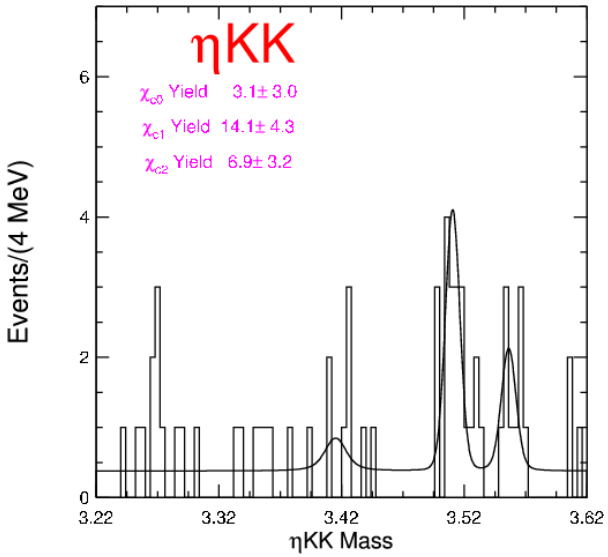
    $\chi_{cJ} \to \eta\pi^+\pi^-$, $K^+K^-\pi^0$, $K^0_S K\pi$, ηK^+K^-, $\eta'\pi^+\pi^-$, $\eta p\bar{p}$, $\pi^0 p\bar{p}$, $\Lambda K\bar{p}$

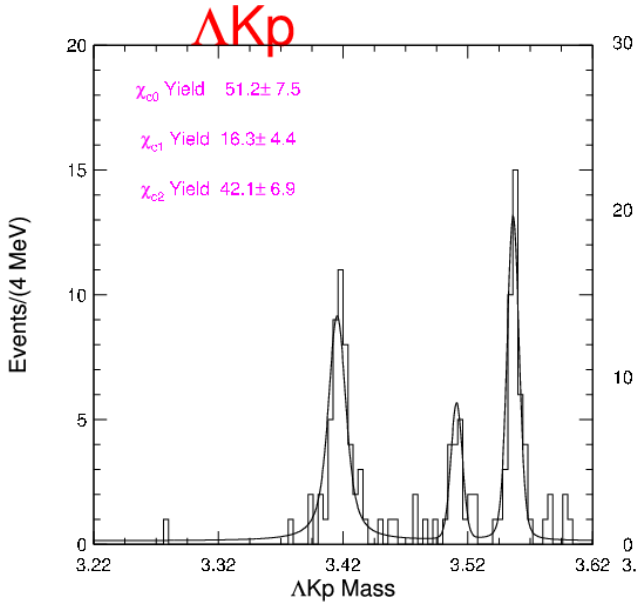
  - Dalitz plot analysis of 3 modes with high statistics: $\chi_{c1} \to \eta\pi^+\pi^-$, $K^+K^-\pi^0$, $K^0_S K\pi$

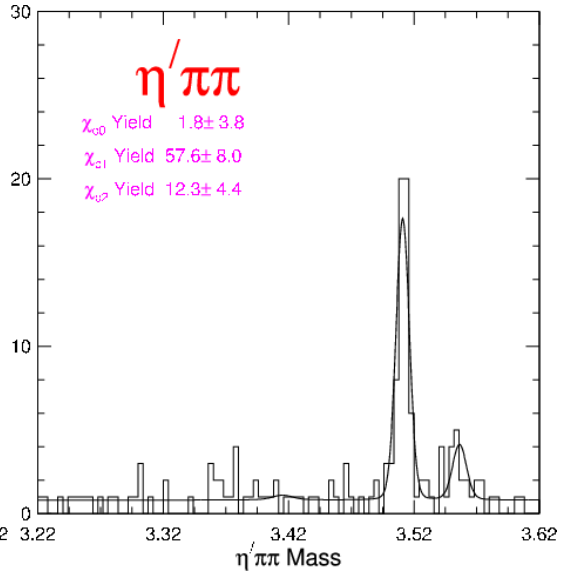
Yield $\chi_{cJ} \to \pi^0 p\bar{p}$, $\eta p\bar{p}$, ηK^+K^-, $\Lambda K\bar{p}$, $\eta'\pi^+\pi^-$





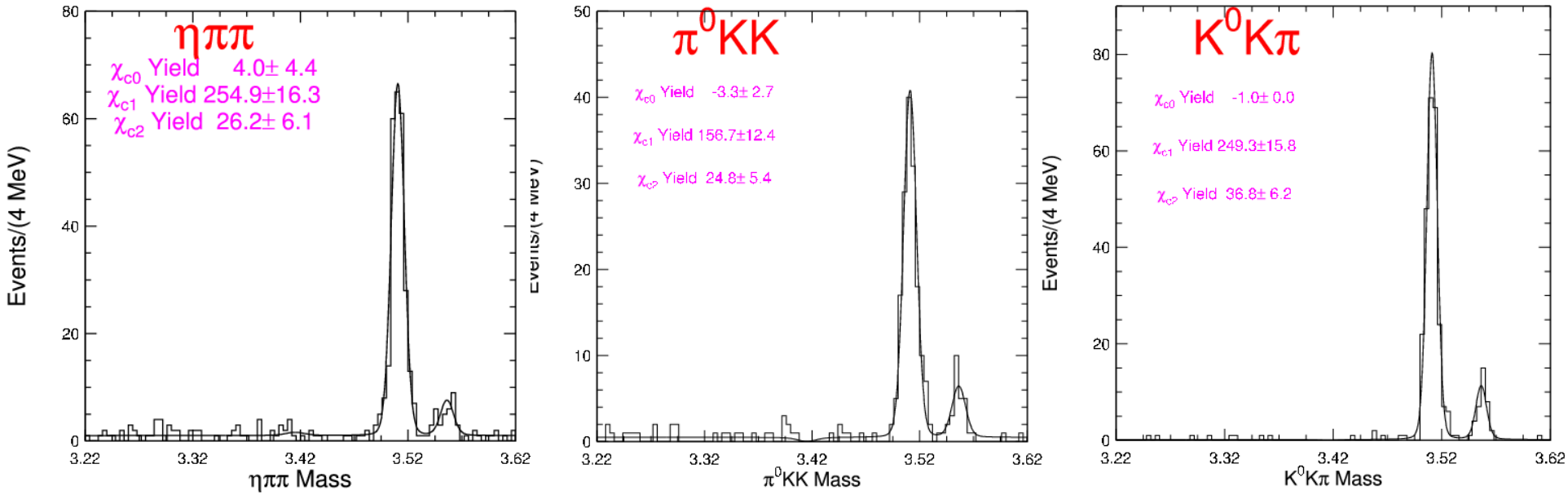






- Signal MC:
  - Resolutions σ=4-7MeV
  - Efficiencies ~7-30%
- Fit accounts for $\Gamma(\chi_{c0})$=10.1MeV

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



Take χ_{c1} statistics for DP analysis

Dalitz plot formalism

- Log likelihood

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

- PDF

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

- Matrix element

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

Fit output

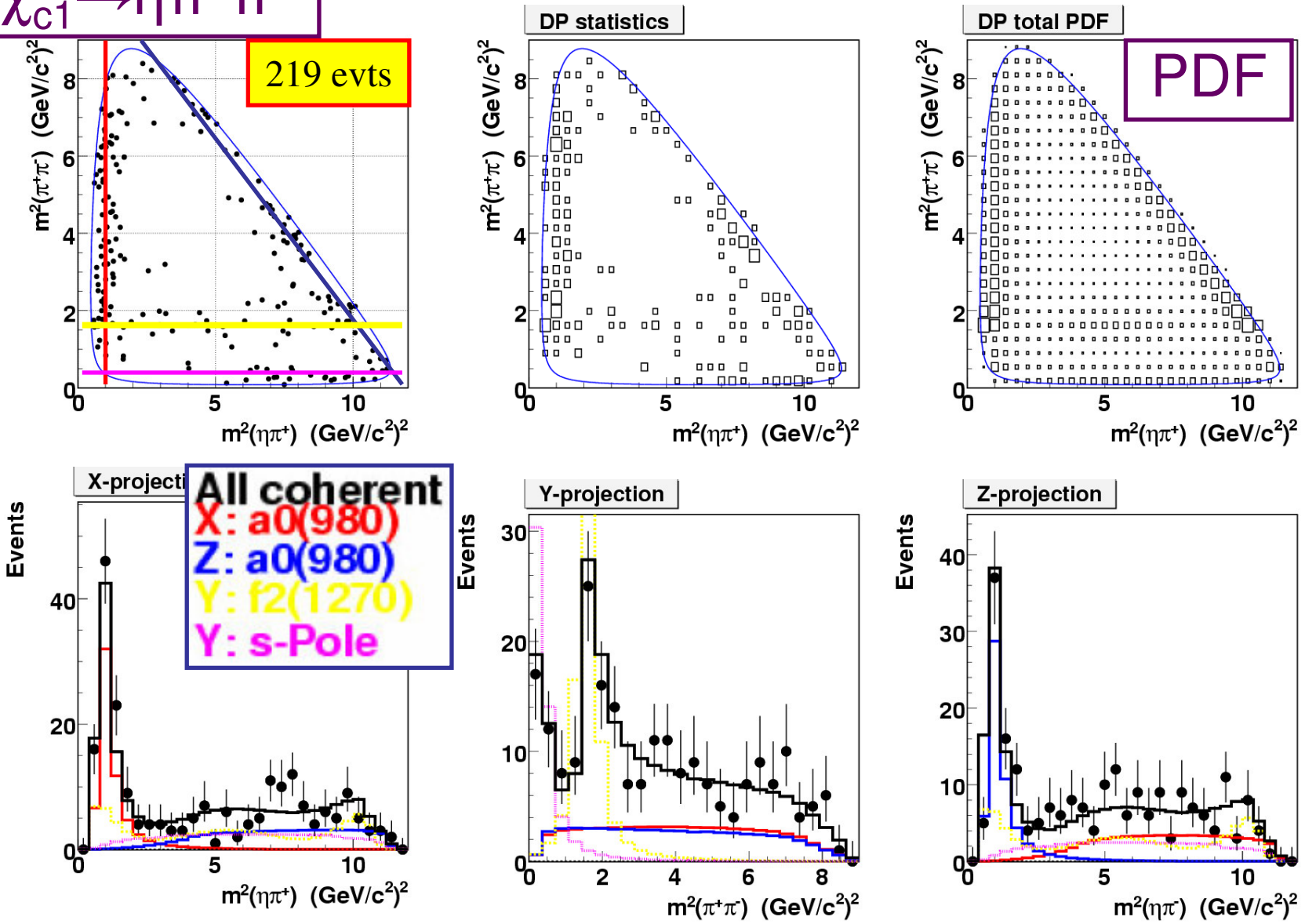
- DP for J=1 ?
  - Angular distributions Ω_R from **V.Filippini, A.Fontany, A.Rotondi, PR D51(1995) 2247**
- Partial waves (PW_R):
  - Breit-Wigner,
  - $\pi^+\pi^-$ S-waves:
    - Oller
    - Flatte

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

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

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

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



Sources of systematic uncertainties

- Event selection
- Efficiency
  - Simultaneous fit to data and MC events with float pars
- Model dependence
  - Angular distributions
  - Other models for $\pi\pi$ S waves, add/remove resonances/waves, free resonance parameters, etc.

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

Mode	Nominal fit
$a_0(980)^+$	1
	0
$2\times$	$28.1\pm1.8\pm0.7$
$f_2(1270)$	$0.186\pm0.017\pm0.003$
	$-118\pm10\pm4$
	$35.1\pm2.9\pm1.8$
σ-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 $\chi_{c1} \to K\underline{K}\pi$

- Rates for $K^0_S K\pi$ and $K^+K^-\pi^0$ modes

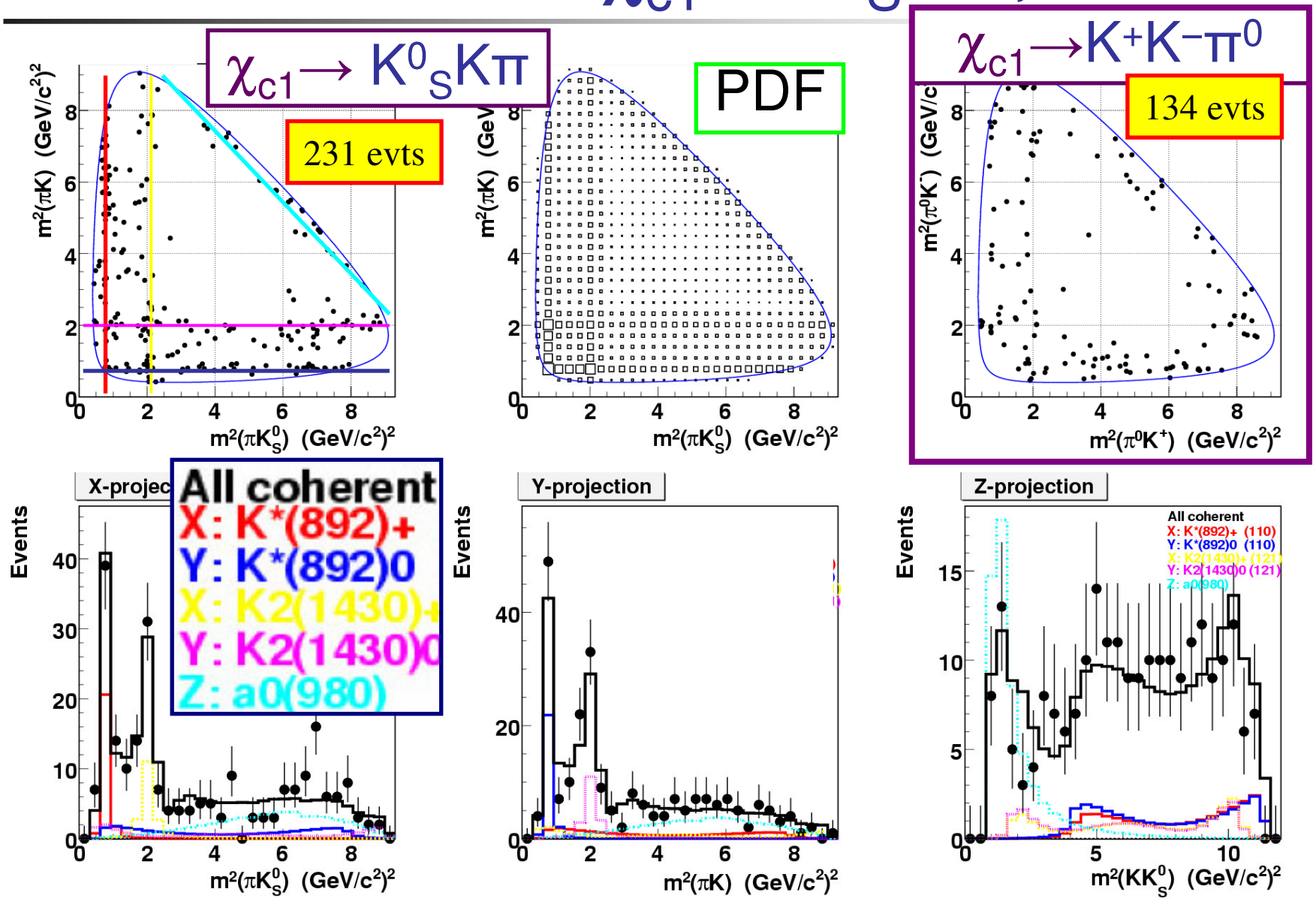
$$\Gamma(\chi_{c1} \to \pi^+ K^- K^0) + \Gamma(\chi_{c1} \to \pi^- K^+ \overline{K^0}) = 4\Gamma(\chi_{c1} \to \pi^0 K^+ K^-)$$

- Constrains for the Dalitz plot parameters

  @ individual PDF normalization:

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

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 $\mathcal{B}$ (%) for $\chi_{cJ} \to h^0 h^+ h^-$

Mode	χ_{c0}	χ_{c1}	χ_{c2}
$\eta\pi^+\pi^-$	< 0.021	$0.52 \pm .03 \pm .03 \pm .03$	$0.051 \pm .011 \pm .004 \pm .003$
ηK^+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	$0.84 \pm .05 \pm .06 \pm .05$	$0.13 \pm .02 \pm .01 \pm .01$

×2

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 $\mathcal{BR}$ for sub-modes of $\chi_{c1} \to \eta\pi^+\pi^-$, $K^+K^-\pi^0$, $K^0_S K\pi$

Summary

- Using ~3M $\psi(2S)$ we study $\psi(2S)\to\gamma\chi_{cJ}$, J=0,1,2
- We search for and find a strong signal in numerous χ_{cJ} hadronic decay modes.

- Today we present a few of them:
  - $\chi_{cJ}\to\eta^{(\prime)}\eta^{(\prime)}$ **3** modes
  - $\chi_{cJ}\to VV$ (V = φ, ω) **2** modes
  - $\chi_{cJ}\to h^+h^-h^0h^0$ (h = π, K, η, p) **7** modes
  - $\chi_{cJ}\to h^+h^-h^0$ **8** modes

  - Measurement of BR or set UL for **20** modes **×** **3** χ_{cJ} states
  - Dalitz plot analysis of 3 modes: $\chi_{c1}\to\eta\pi^+\pi^-$, $K^+K^-\pi^0$, $K^0_SK\pi$

- ×10 ψ(2S) statistics is expected by the end of the year