Hadronic Physics at CLEO-c

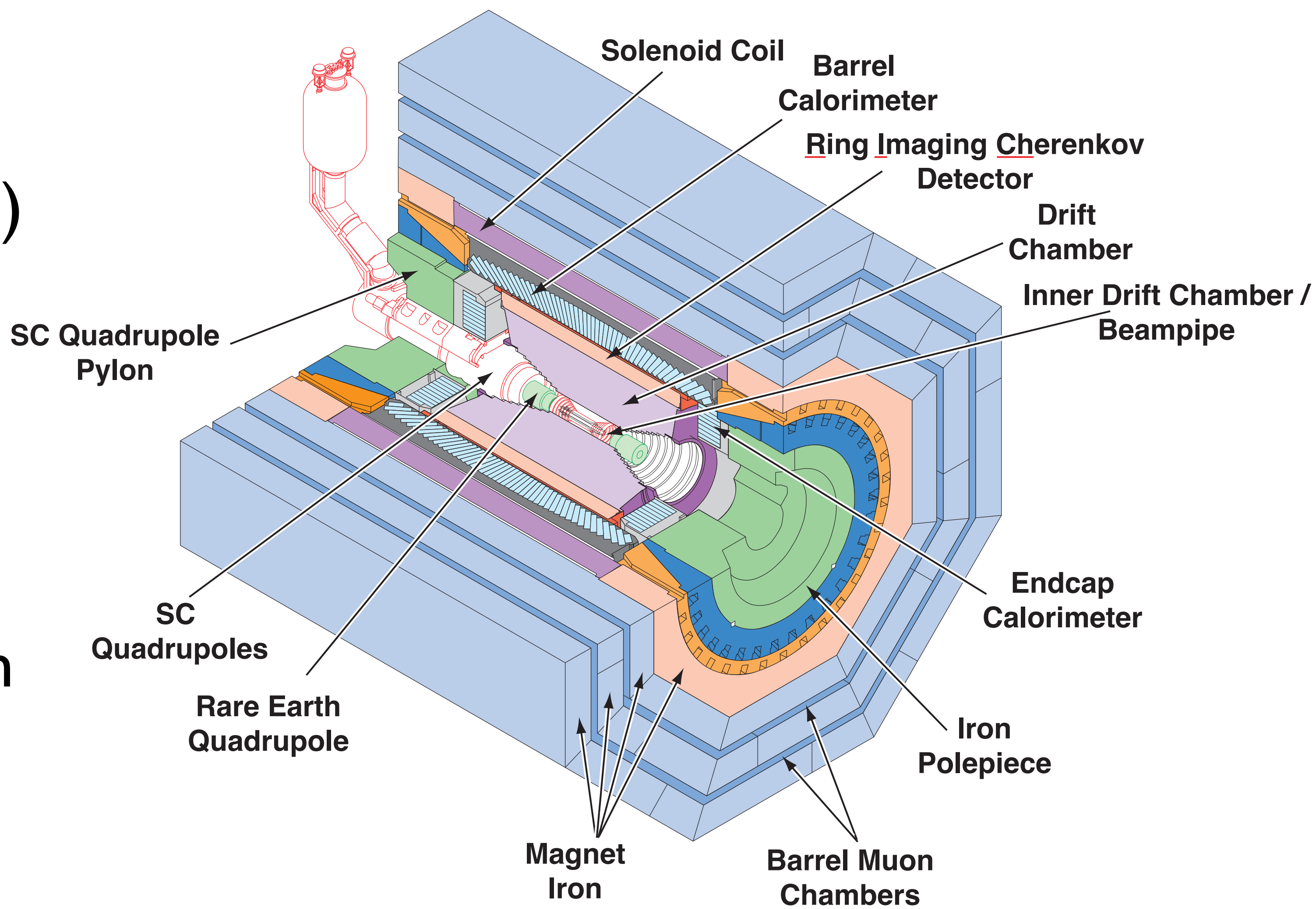
Matthew Shepherd
Indiana University

(on behalf of the CLEO Collaboration)

HADRON 07 / Frascati
October 10, 2007

The CLEO-c Detector

- 6 layer inner stereo and 47 layer stereo+axial drift chambers ($\sigma_p/p \approx 0.6\%$ at 1 GeV/c)
- Ring Imaging Cherenkov (RICH)
- CsI Calorimeter ($\sigma_E/E \approx 2.2\%$ at 1 GeV)
- 1 T solenoidal field
- Located at the Cornell Electron Storage Ring (CESR)
- e^+e^- at E_{CM} = 3.6 - 4.3 GeV

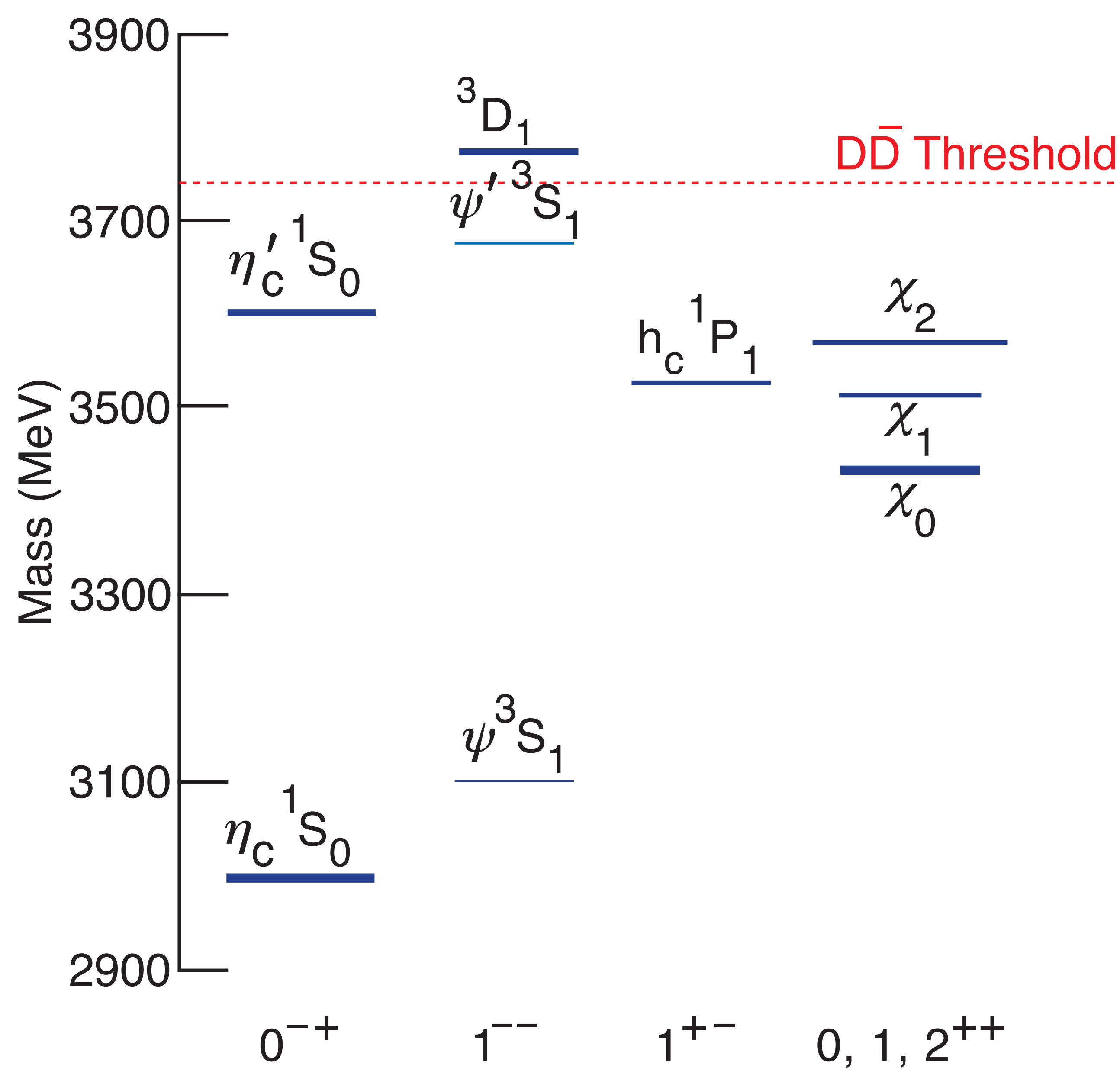


The CLEO-c Physics Program

- Very diverse physics program includes:
  - Scans of open charm cross section from 3.97 GeV to 4.26 GeV
  - Large data samples at E_{CM} = 3770 MeV and E_{CM} = 4170 MeV for D and D_s physics
    - CKM driven: precision tests of LQCD through form factor measurements, precision measurements of hadronic branching fractions
    - D Dalitz Analyses: hadronic physics and CPV (P. Naik - yesterday)
  - Relatively small amount (<5%) of luminosity taken at $E_{CM}=M(\psi')$.
    - The study of our pilot sample of 3M ψ' decays has already produced many interesting hadronic physics results.
    - *This talk focuses on results from our new sample of ~25M ψ' decays.*

The Charmonium System: An Outline

- Hadronic and Electromagnetic Decays of the χ_c
- η meson properties, in $\psi' \to \eta J/\psi$
- $\eta_c(1S)$ production in hindered M1 transitions
- Properties of the h_c



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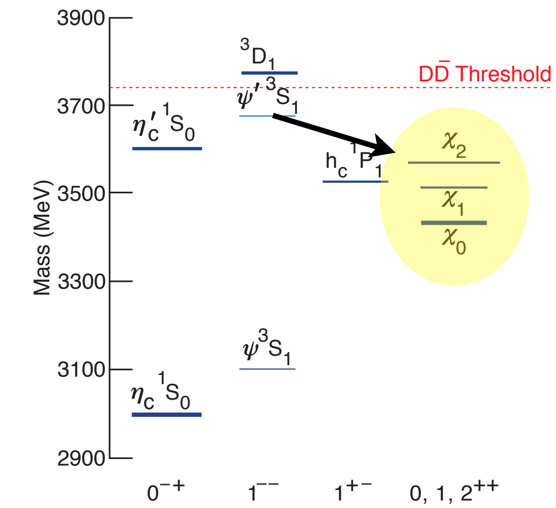
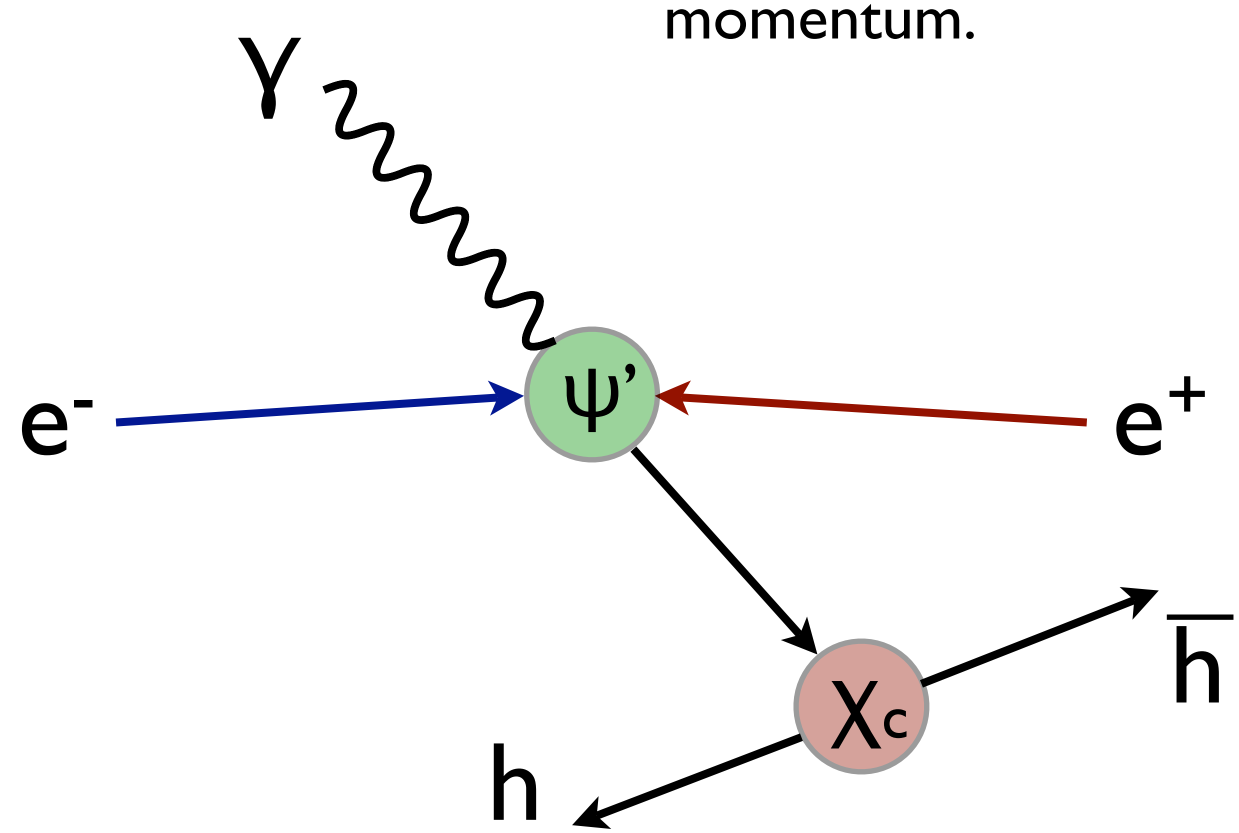
$\chi_{cJ} \rightarrow$ 2 hadrons



- Accurate prediction of 2 hadron decay rates of ^3P_J states rely on understanding of the role of the color octet contribution
- χ_c produced in electromagnetic transitions from the ψ'
- Search for 13 hadronic two-body decay modes of χ_c

Analysis relies on identification of all decay products and kinematic fit to initial ψ' four-momentum.



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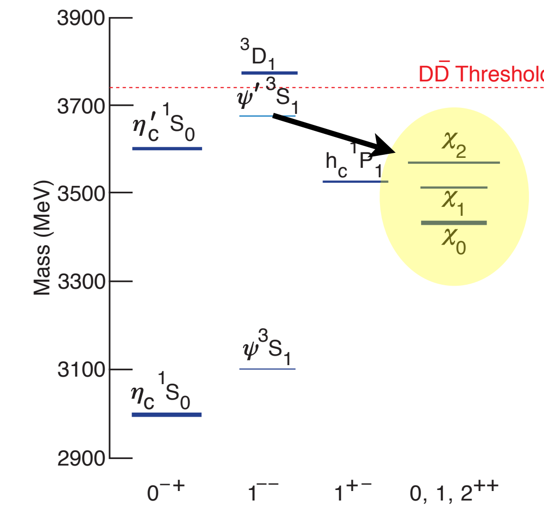
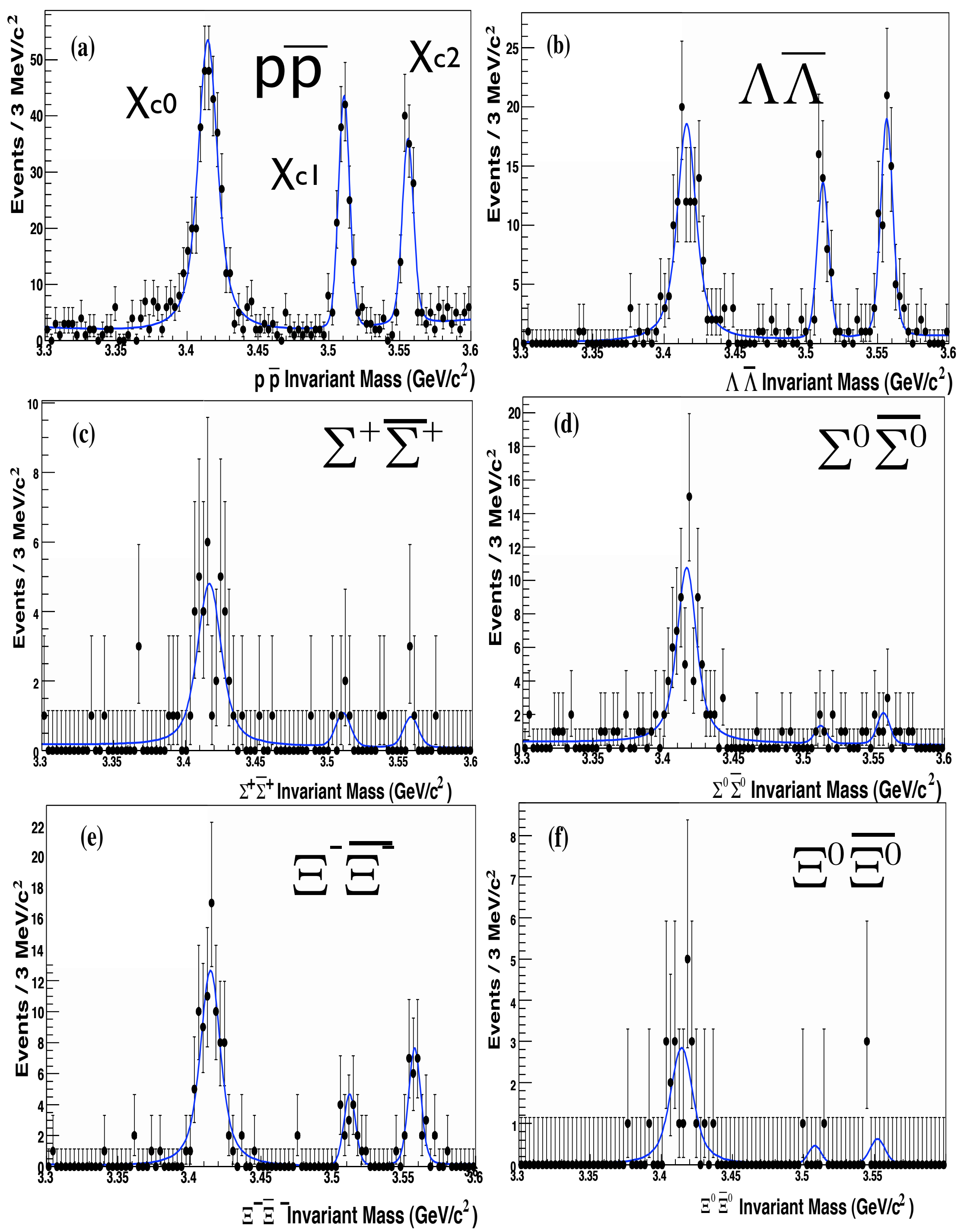
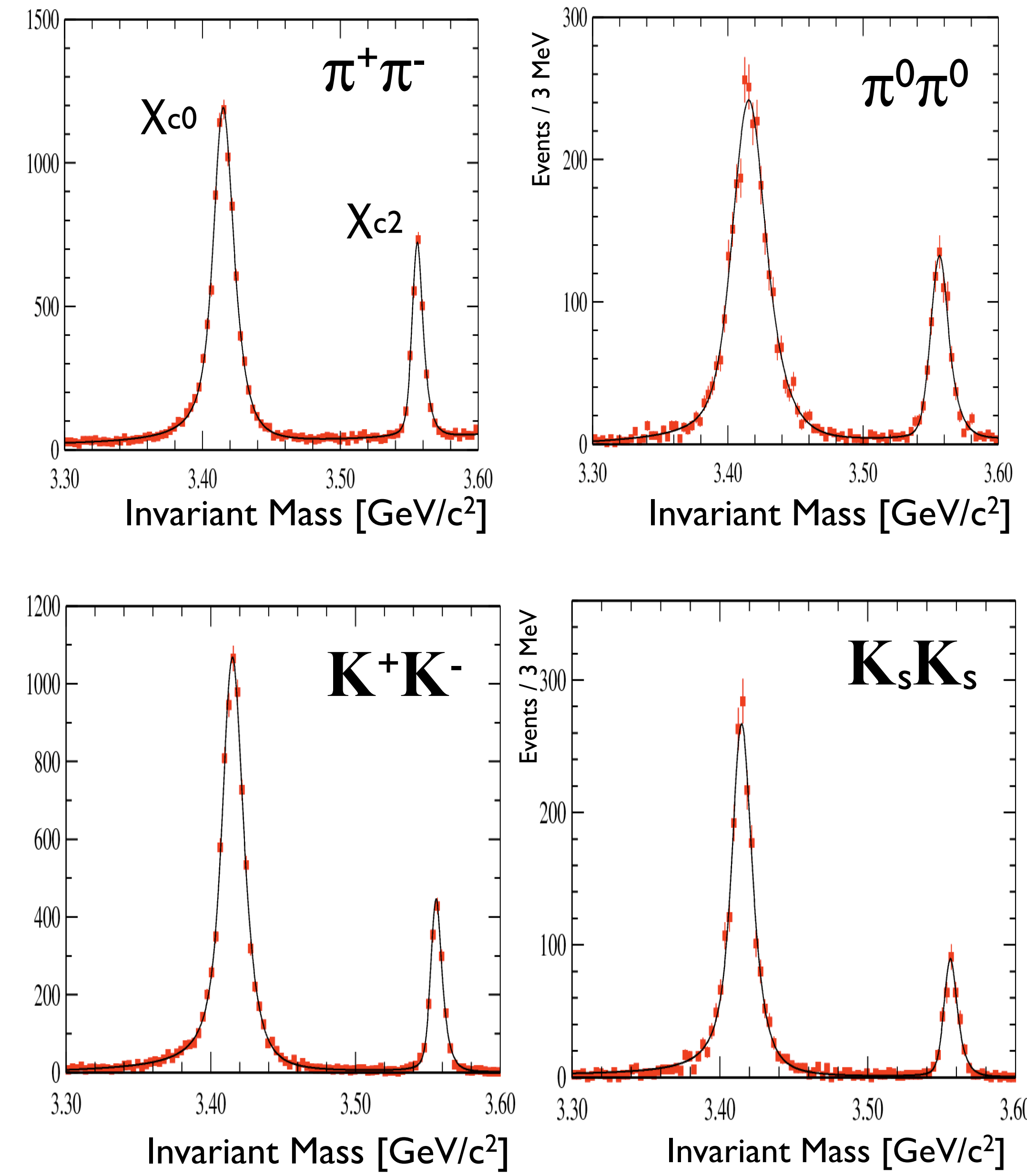


Baryon Modes



($\chi_{c1} \rightarrow$ PP is forbidden)



Meson Modes

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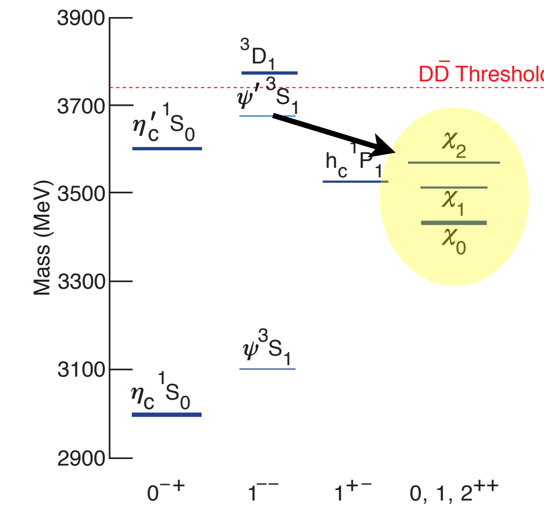
$\chi_{cJ} \rightarrow$ 2 hadrons



Branching Fraction Results:

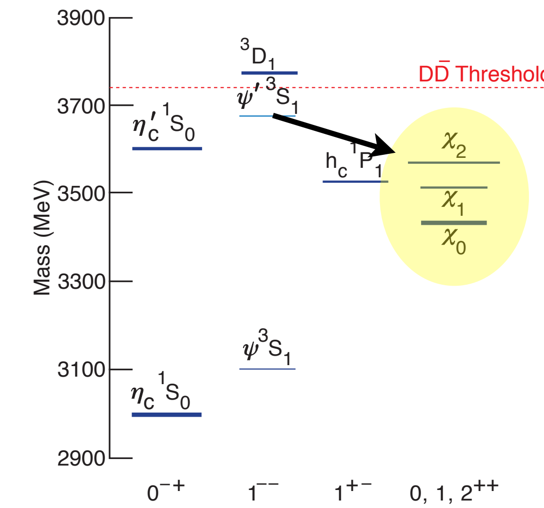
CLEO Preliminary

B.F. ($\times 10^{-3}$)		$\pi^+\pi^-$	$\pi^0\pi^0$	K^+K^-	K_SK_S
χ_{c0}	PDG	4.9±0.6	3.1±0.6	6.0±0.9	2.8±0.7
	Our value	6.37±0.11±0.20±0.32	2.94±0.07±0.16±0.15	6.47±0.11±0.29±0.32	3.49±0.01±0.15±0.17
χ_{c2}	PDG	1.8±0.3	1.1±0.3	0.9±0.2	0.7±0.1
	Our value	1.59±0.04±0.06±0.10	0.68±0.03±0.05±0.04	1.13±0.03±0.05±0.07	0.53±0.03±0.02±0.03

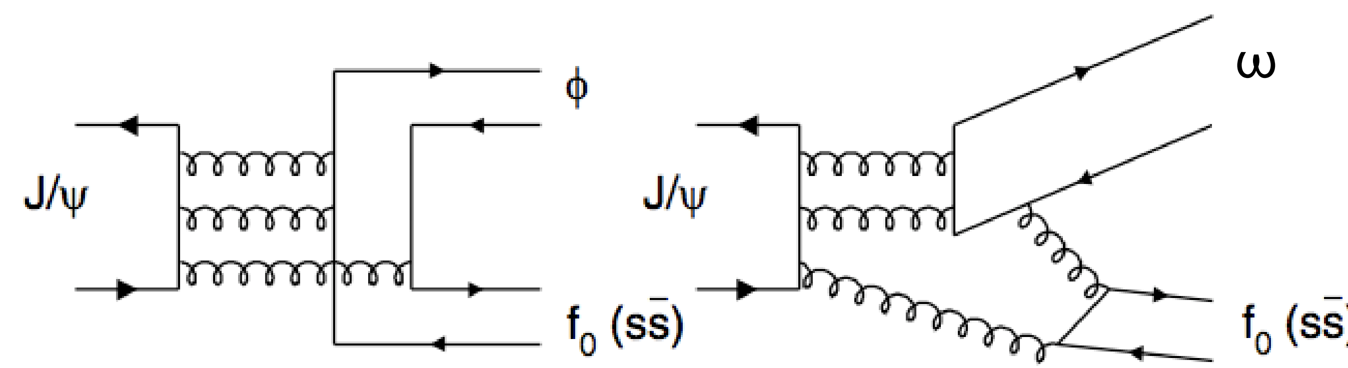
B.F. ($\times 10^{-5}$)		$p\bar{p}$	$\Lambda\bar{\Lambda}$	$\Sigma^0\bar{\Sigma}^0$	$\Sigma^+\bar{\Sigma}^+$	$\Xi^-\bar{\Xi}^-$	$\Xi^0\bar{\Xi}^0$
χ_{c0}	PDG	22.5±2.7	47±16	-	-	<103	-
	Our value	25.7±1.5±1.5±1.3	33.8±3.6±2.3±1.7	44.1±5.6±2.5±2.2	32.5±5.7±4.9±1.7	51.4±6.0±3.8±2.6	33.4±7.0±3.2±1.7
χ_{c1}	PDG	7.2±1.3	26±12	-	-	<34	-
	Our value	9.0±0.8±0.4±0.5	11.6±1.8±0.7±0.7	2.1±1.4±0.2±0.13	3.3±1.8±0.2±0.2	8.6±2.2±0.6±0.5	2.5±2.1±0.2±0.2
χ_{c2}	PDG	6.8±0.7	34±17	-	-	<37	-
	Our value	7.7±0.8±0.4±0.5	17±2.2±1.1±1.1	4.1±1.9±0.3±0.3	3.3±1.9±0.4±0.2	14.5±1.9±1.0±0.9	4.0±2.4±0.4±0.3

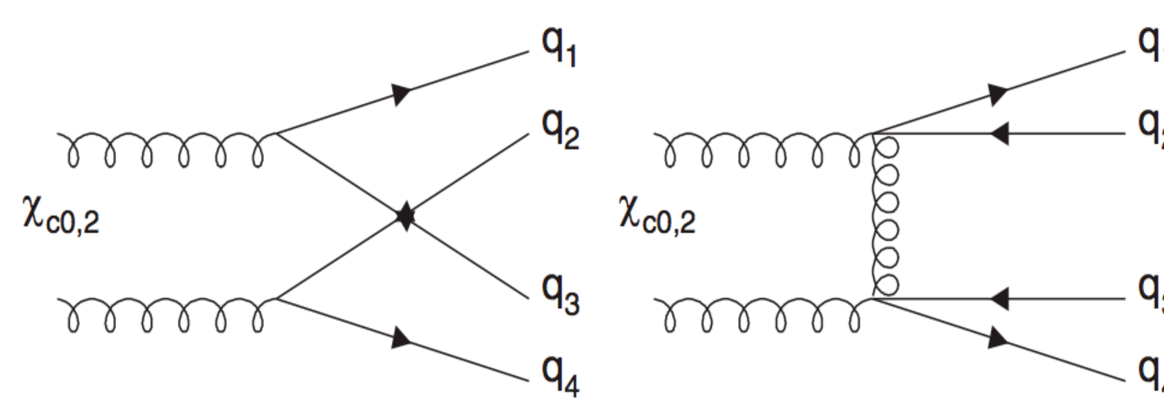
Errors: (stat.) ± (syst.) ± ($B(\psi' \rightarrow \gamma\chi_{cJ})$)

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



- It is interesting that $B(J/\psi \to \omega f_0(1710))$ is larger than $B(J/\psi \to \phi f_0(1710))$ given $f_0(1710)$ is thought to be largely strange.
- Suggestive of large OZI violating effects in J/ψ decay? ....glueball mixing? (F. Close and Q. Zhao, PRD 71, 094002)
- Look for similar effects in χ_c decays to the pseudoscalar the isoscalars
- Use the factorization scheme proposed by Q. Zhao (PRD 72, 074001)

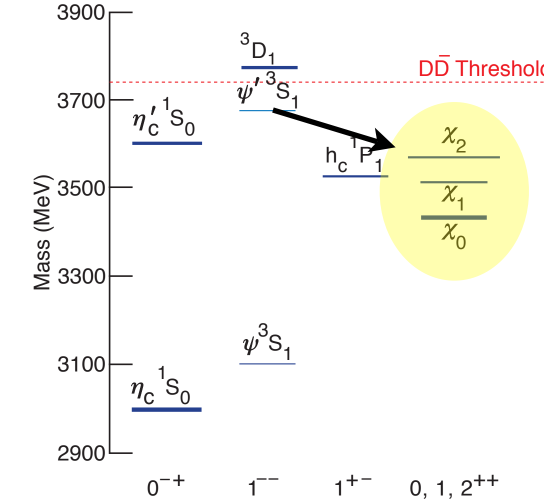


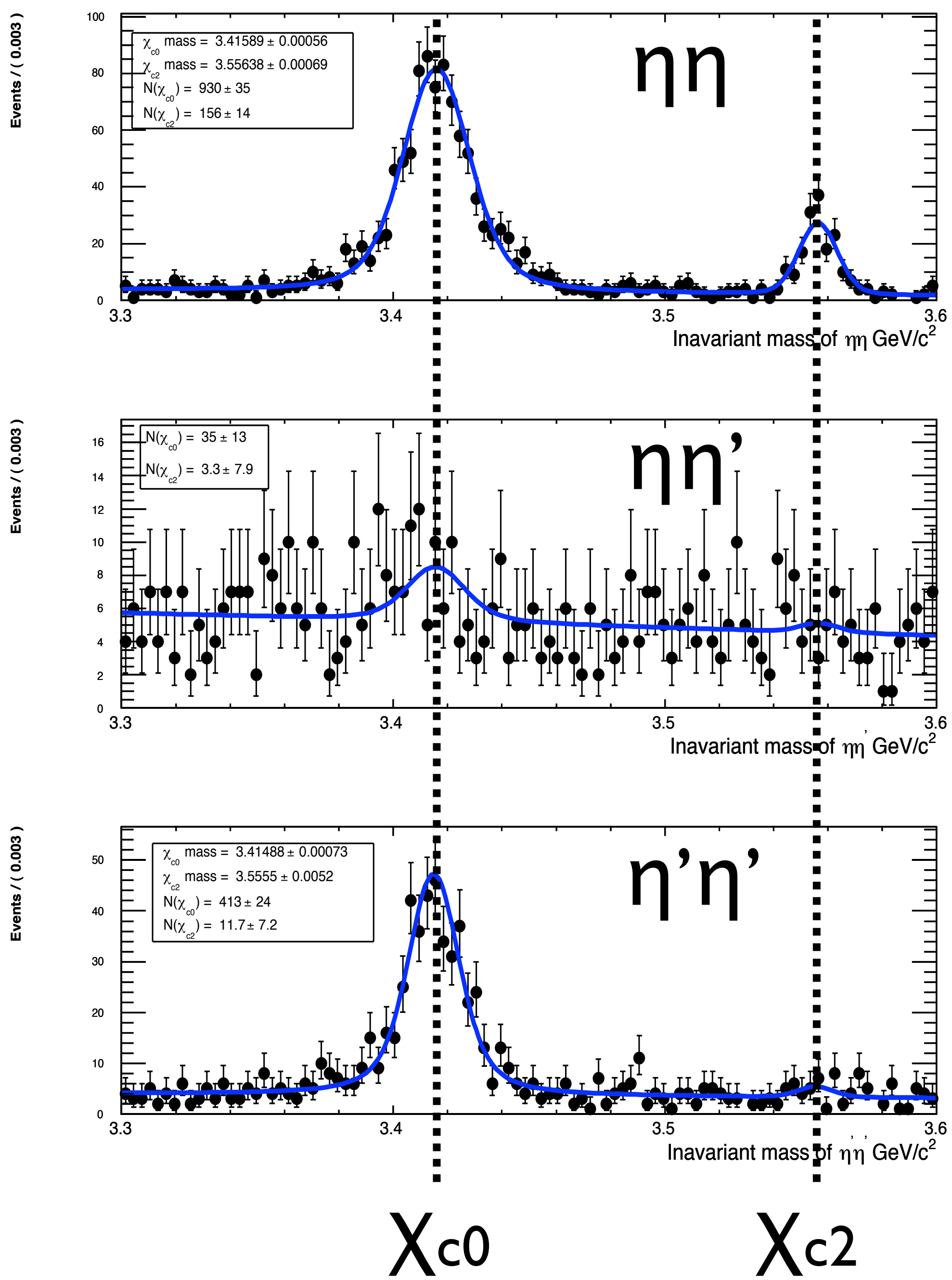


(a) SOZI (b) DOZI

r = relative strength between singly-OZI and doubly-OZI suppressed transition amplitudes

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





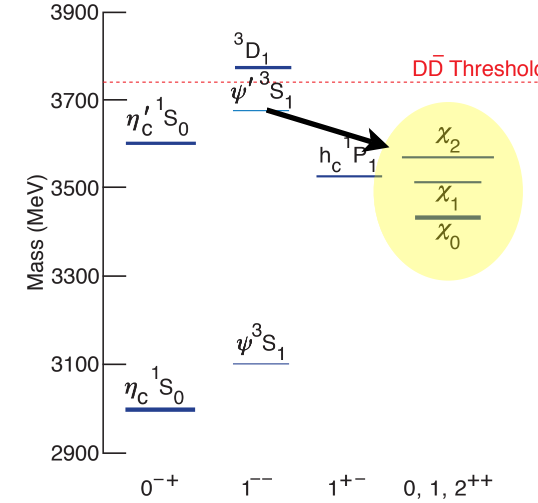
- Use similar analysis technique as used for other two-body modes
- Update of previous CLEO analysis on 3M ψ' (PRD 75, 071101(R)(2007))

CLEO Preliminary

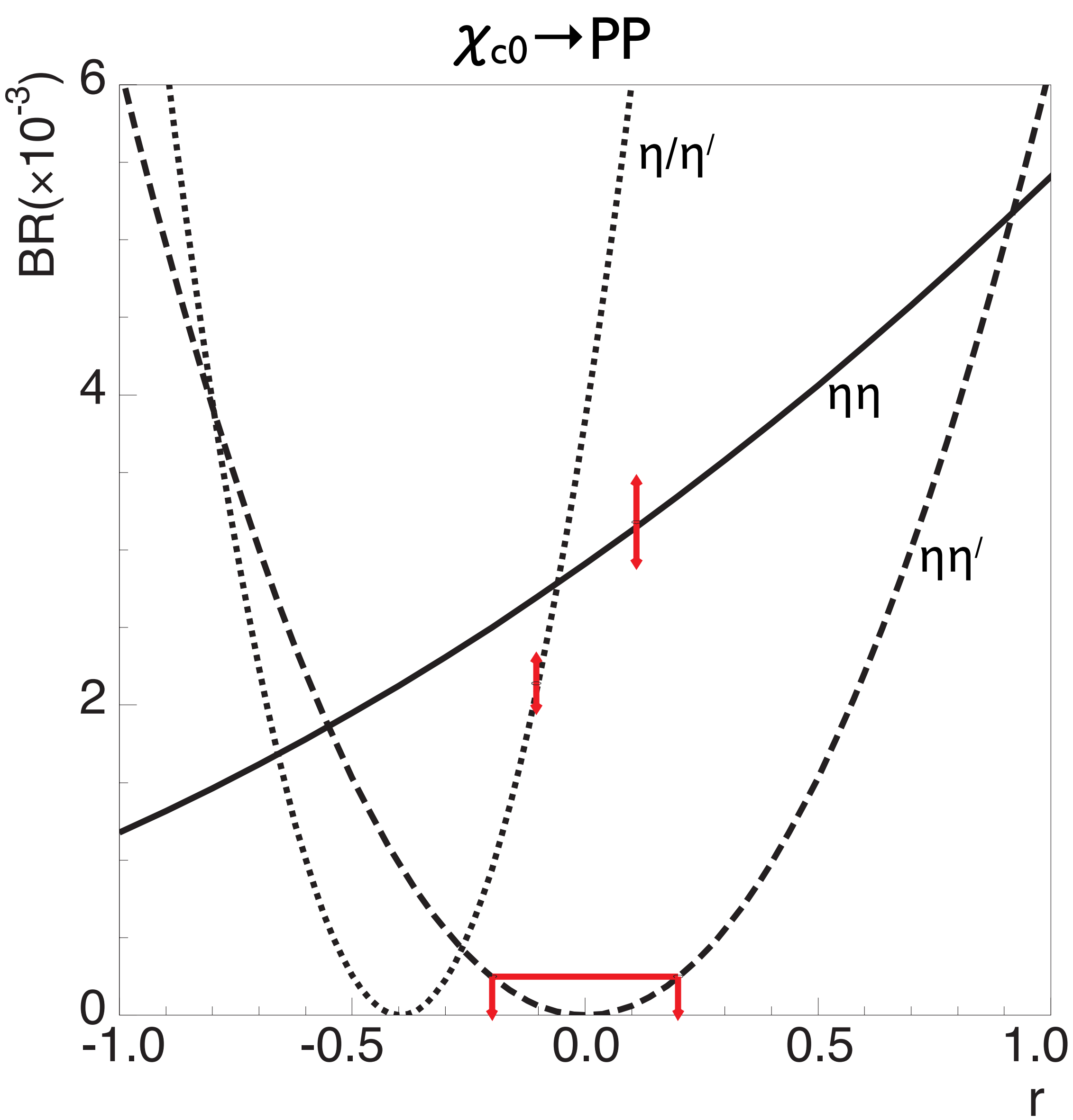
B.F. ($\times 10^{-3}$)	χ_{c0}	χ_{c2}
ηη	3.18±0.13±0.18±0.16	0.51±0.05±0.03±0.03
η'η	<0.25 (90% CL)	<0.05 (90% CL)
η'η'	2.12±0.13±0.11±0.11	0.06±0.03±0.004±0.004 < 0.10 (90%CL)

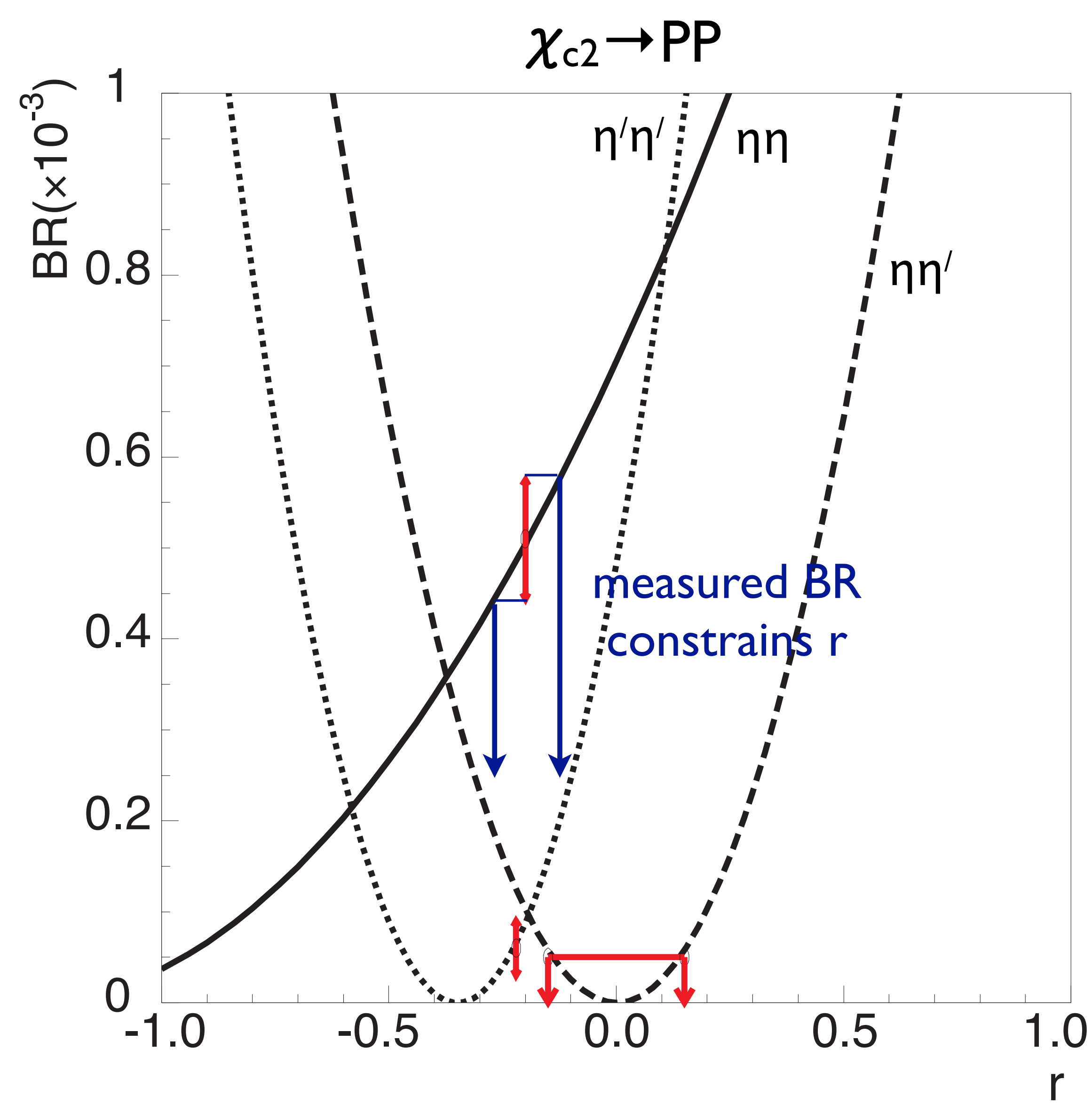
Errors: (stat.) ± (syst.) ± ($B(\psi' \rightarrow \gamma\chi_{cJ})$)

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



Predicted dependence of BR on r (DOZI/SOZI)
(from Q. Zhao (PRD 72, 074001))

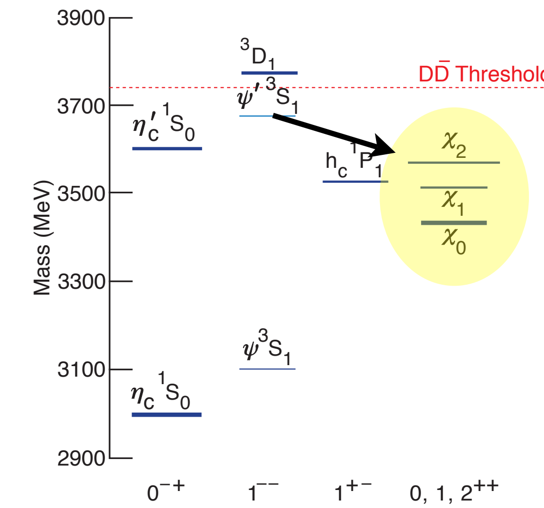




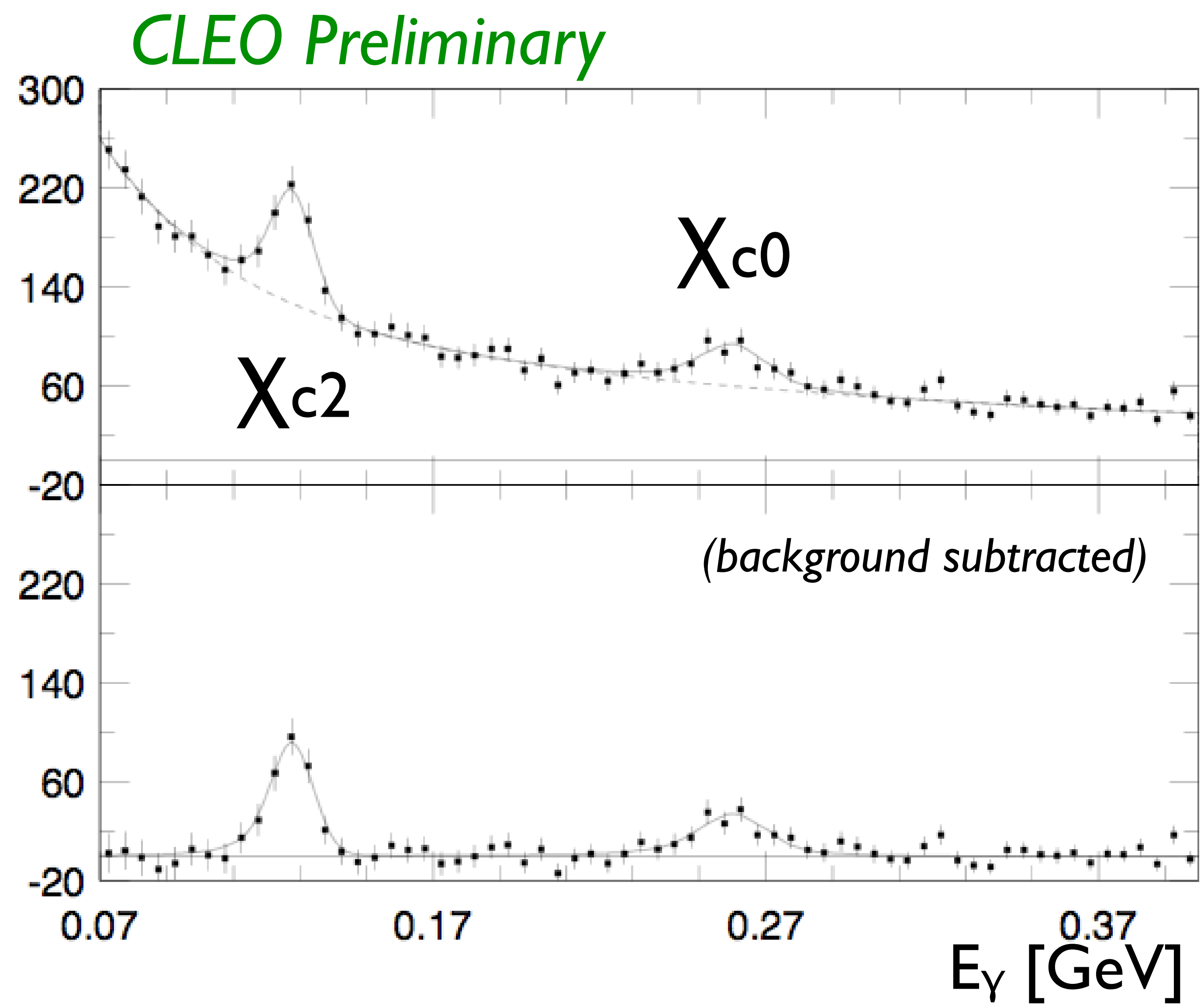
CLEO Preliminary Results

Data suggest small if any contribution for DOZI decays in 0^{-+} channel.

$\chi_{cJ} \to \gamma\gamma$



- Two photon decays of χ_{cJ} are pure QED in first approximation
- A measurement of decay rates allows one to probe relativistic and radiative corrections known to be significant in the charmonium system
- Experimental technique similar to that for χ_{cJ} decays to 2 hadrons
- Fit E1 photon distribution after selecting $\chi_{cJ} \to \gamma\gamma$



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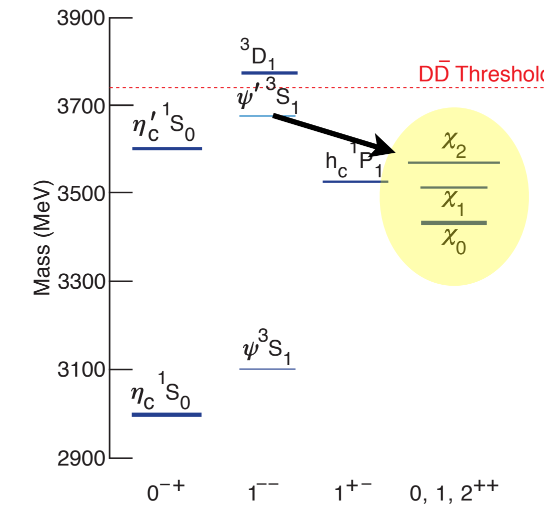
$\chi_{cJ} \to \gamma\gamma$



- *CLEO Preliminary Results*
  - Errors: (stat.) ± (syst.) ± (PDG Input)

Parameter	This measurement	PDG 2007
$B_1(\psi(2S)\to\gamma\chi_0)\times B_2(\chi_0\to\gamma\gamma)\times10^{-5}$	**2.32±0.33±0.15**	
$B_1(\psi(2S)\to\gamma\chi_2)\times B_2(\chi_2\to\gamma\gamma)\times10^{-5}$	**2.82±0.29±0.21**	
$B_2(\chi_0\to\gamma\gamma)\times10^{-4}$	**2.52±0.36±0.16±0.11**	2.76±0.33
$B_2(\chi_2\to\gamma\gamma)\times10^{-4}$	**3.20±0.33±0.24±0.18**	2.58±0.19
$\Gamma(\chi_0\to\gamma\gamma)$ keV	**2.65±0.38±0.17±0.25**	2.87±0.39
$\Gamma(\chi_2\to\gamma\gamma)$ keV	**0.62±0.07±0.05±0.06**	0.53±0.05
$R=\Gamma(\chi_0\to\gamma\gamma)/\Gamma(\chi_2\to\gamma\gamma)$	**0.235±0.042±0.005±0.030**	0.184±0.030

In the non-relativistic limit: R=4/15=0.27

- Also limit the forbidden process:

$$B(\chi_1\to\gamma\gamma) < 3.6\times10^{-5},\ 90\%\ \mathrm{CL.}$$

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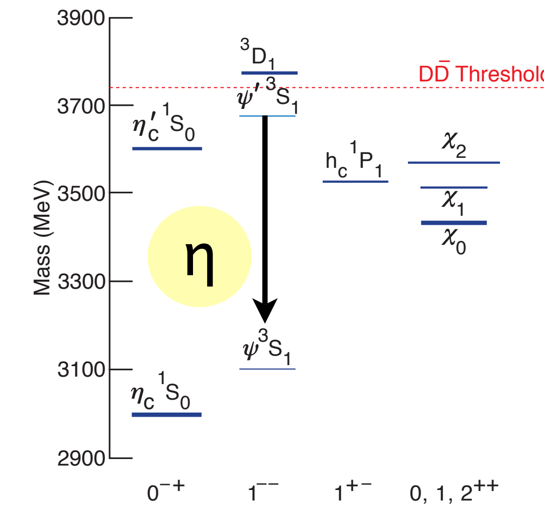
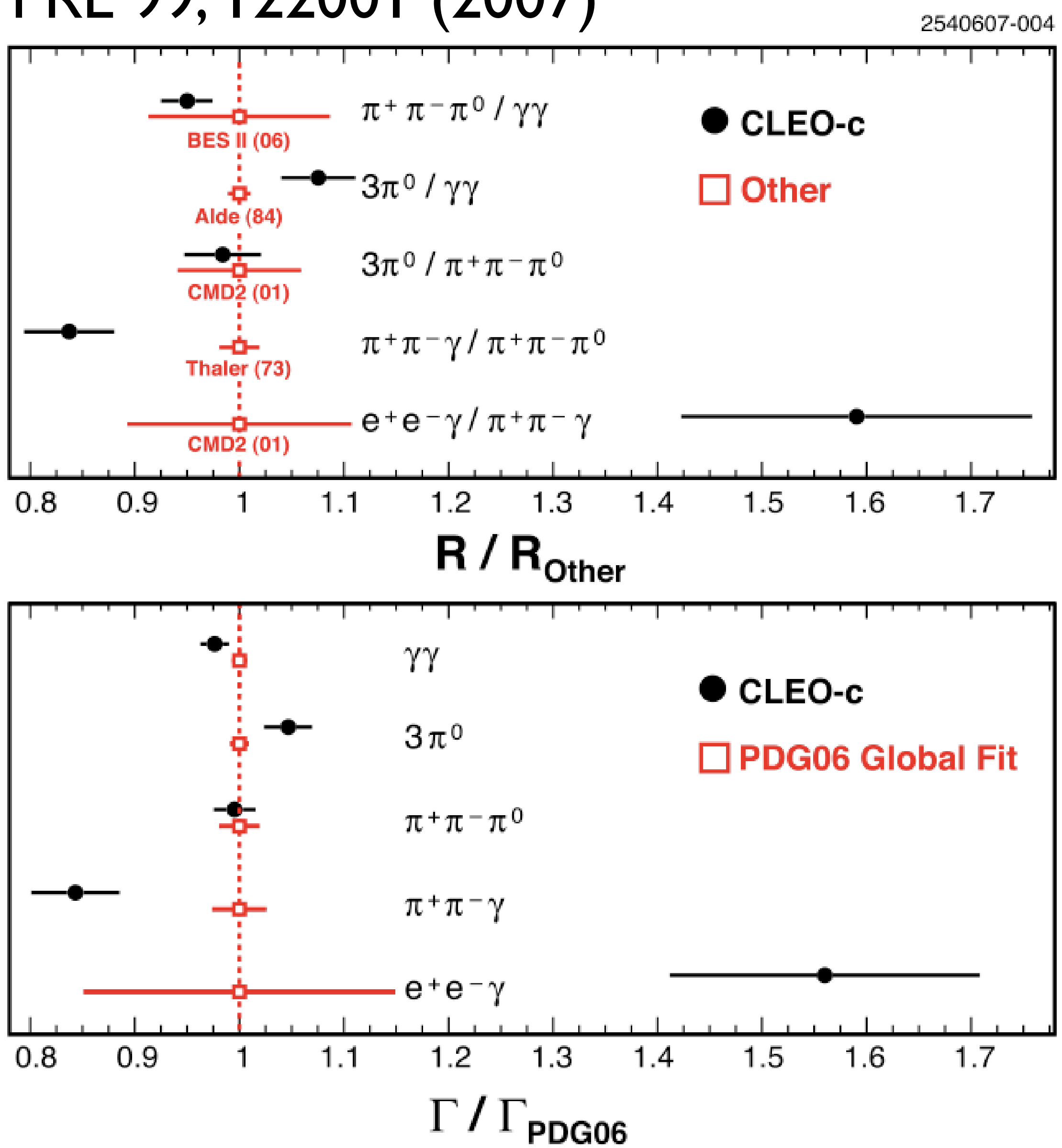
η Mass and B.F.'s

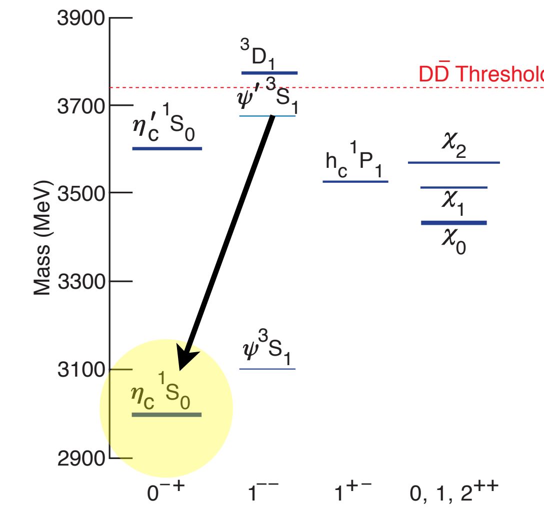


- Use the transition $\psi' \rightarrow \eta\ \psi$, with $\psi \rightarrow l^+l^-$, to study the properties of the η
- Kinematic fitting of both ψ and ψ' to known masses improves η mass resolution:
  $M_\eta = 547.785 \pm 0.017 \pm 0.057$ MeV
  (PRL, 99, 122002 (2007))
- Apply similar technique to simultaneously measure all allowed branching fractions of η
- Systematics are well under control since all measurements are made with the same experiment
- Allows independent determination of absolute η branching fractions

PRL 99, 122001 (2007)



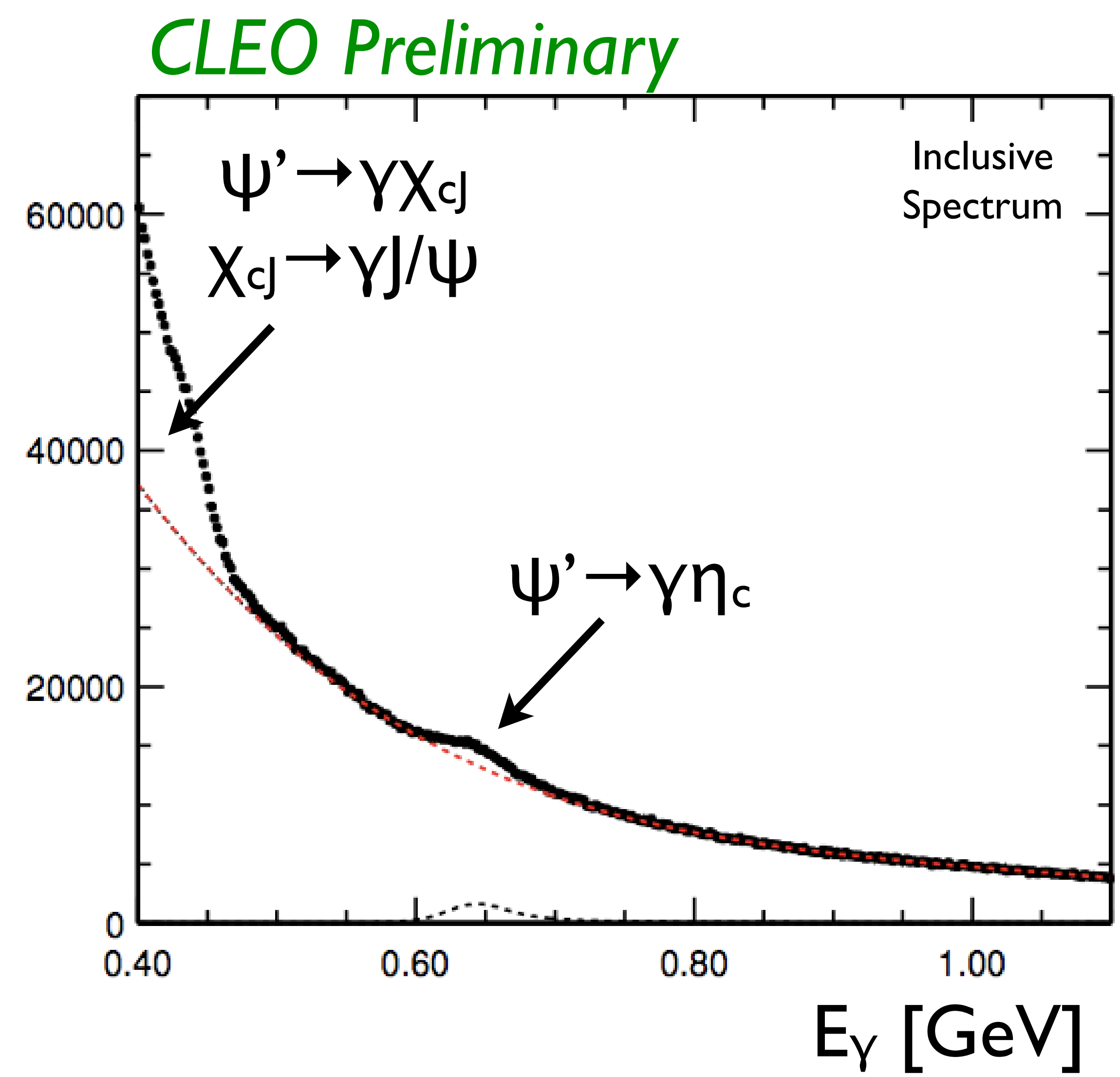
$\psi' \to \gamma \eta_c$



- Precision determination of the hindered M1 ($\psi' \to \gamma \eta_c$) and allowed M1 ($J/\psi \to \gamma \eta_c$) rates are critical for understanding radiative transitions in charmonium and measuring η_c branching fractions

- Measure the rate by a fit to the inclusive photon spectrum in ψ' decay

- Background is smooth and well understood -- <u>*the signal line shape, however, is not!*</u>



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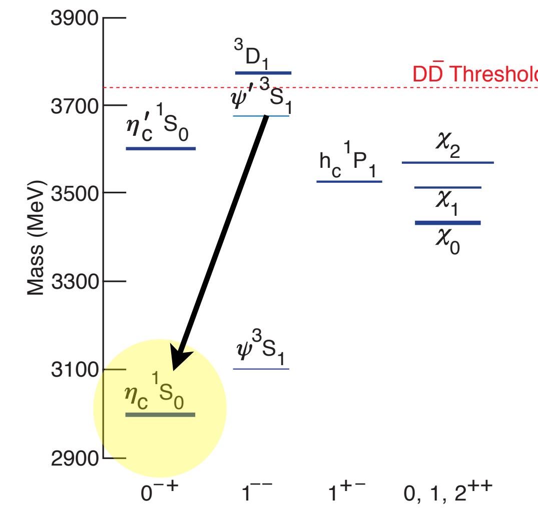
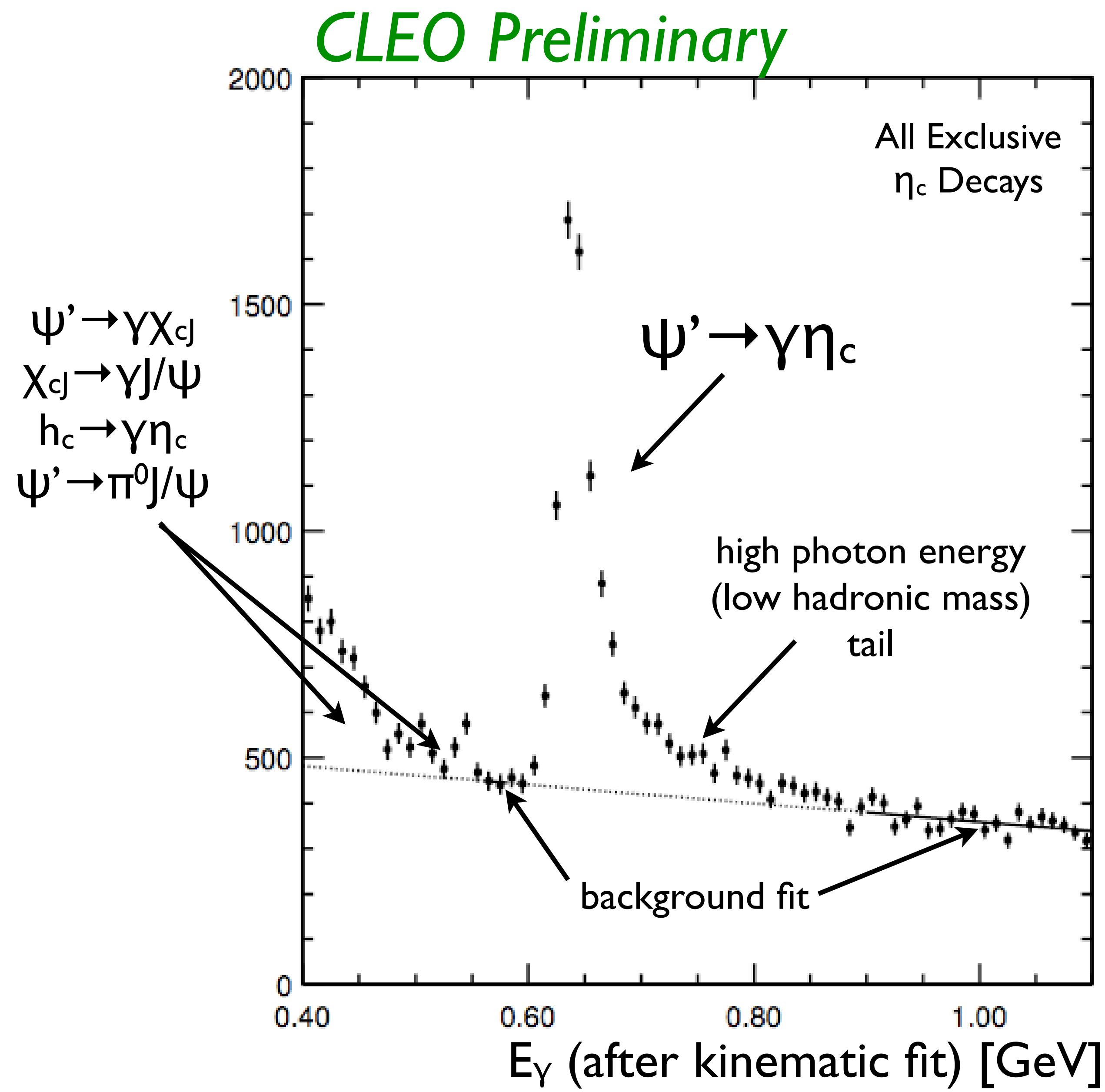
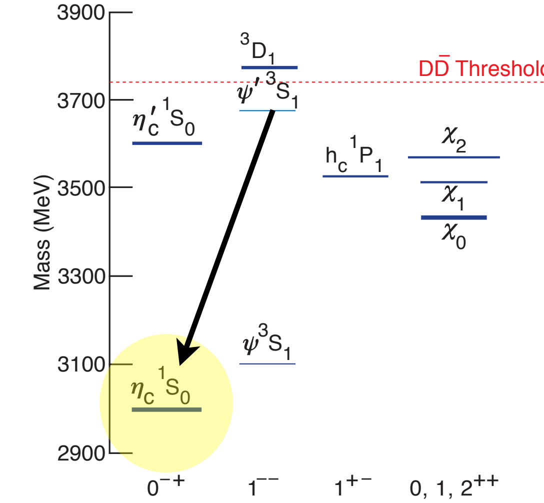
$\psi' \to \gamma \eta_c$

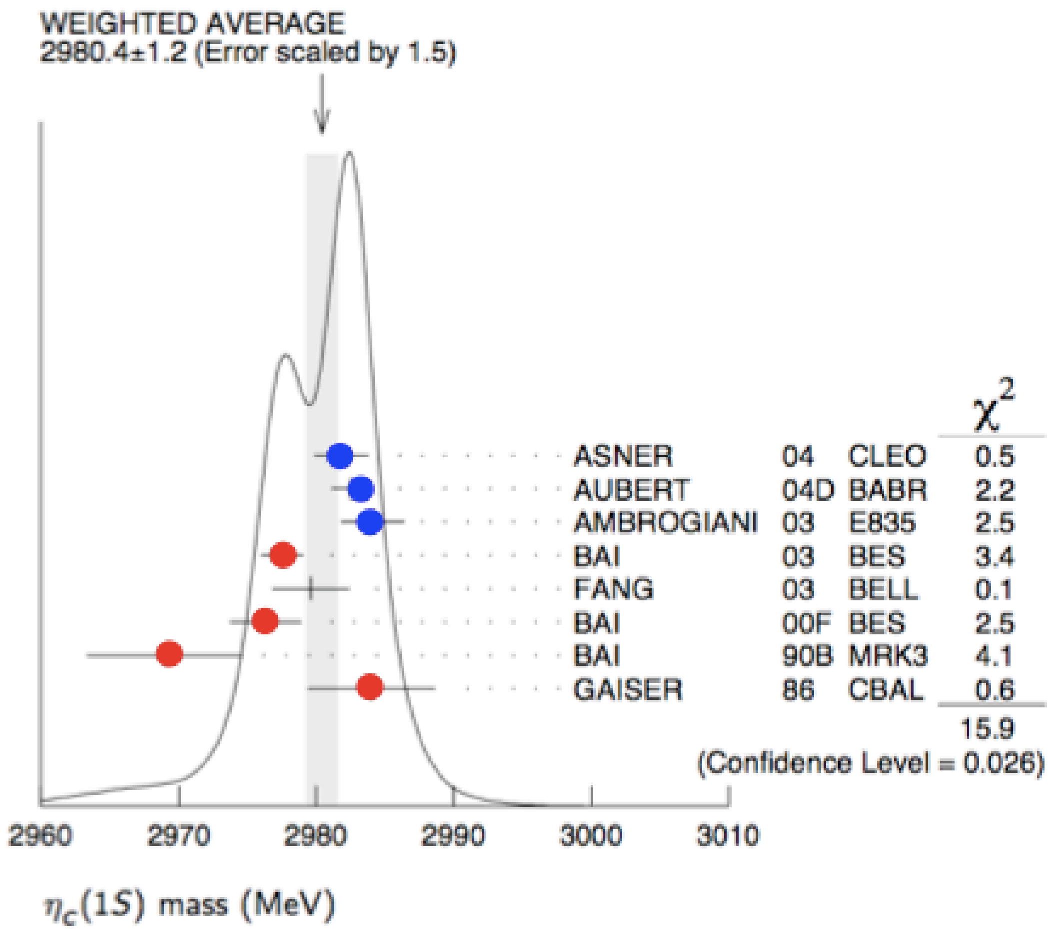


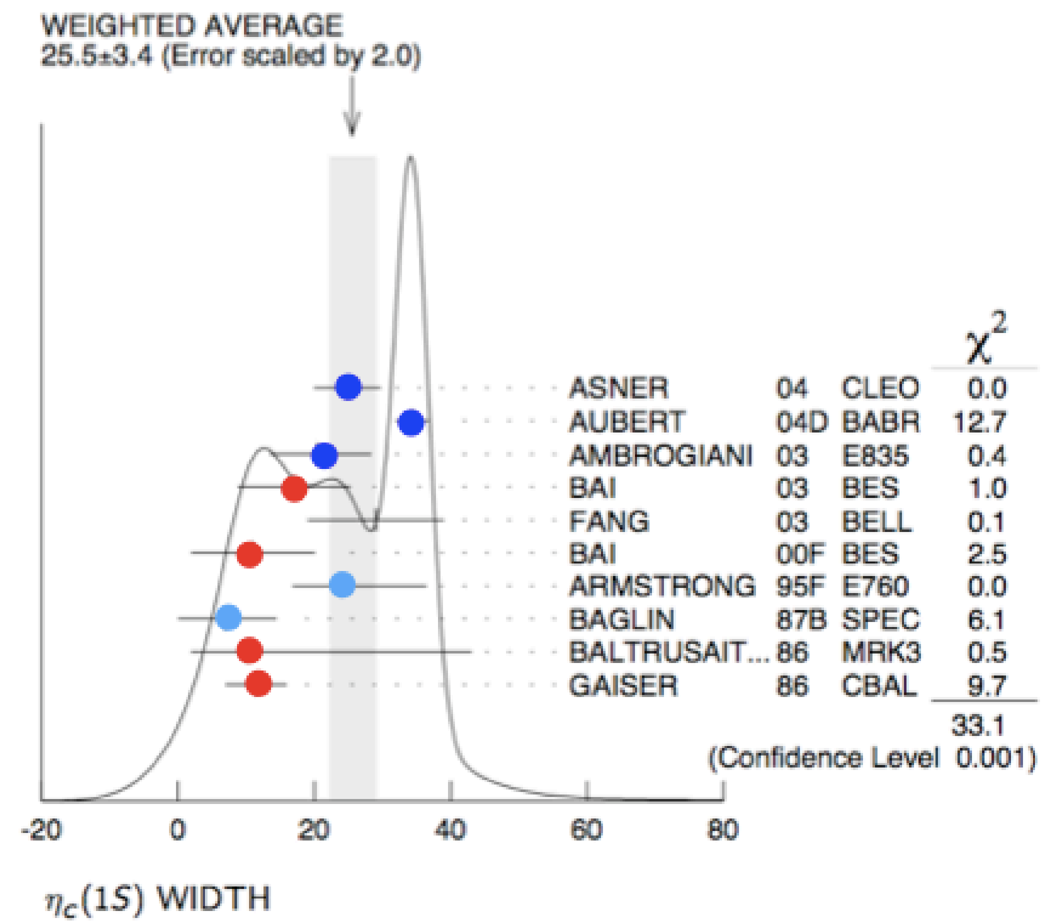
- Tag η_c decay using 13 signal-rich decay modes (some new)
- Perform full event kinematic fit to sharpen photon resolution
- Backgrounds peaking outside of signal region are well understood
- The η_c line shape in hindered M1 transitions is nontrivial and cannot be easily fit by a Breit-Wigner (even when energy-dependent phase space and matrix element terms are included)



η_c Properties (PDG '06)

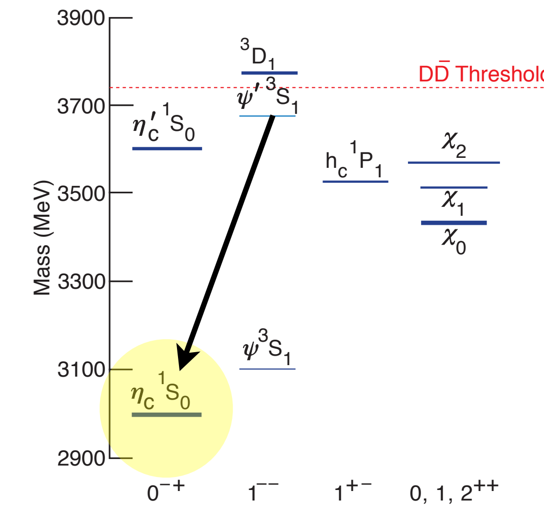






- $\gamma\gamma$ or p^+p^-
- $\gamma\gamma$ or p^+p^- (used for width, but not mass)
- $\psi(1S,2S) \rightarrow \gamma\eta_c$

$\psi' \to \gamma \eta_c$

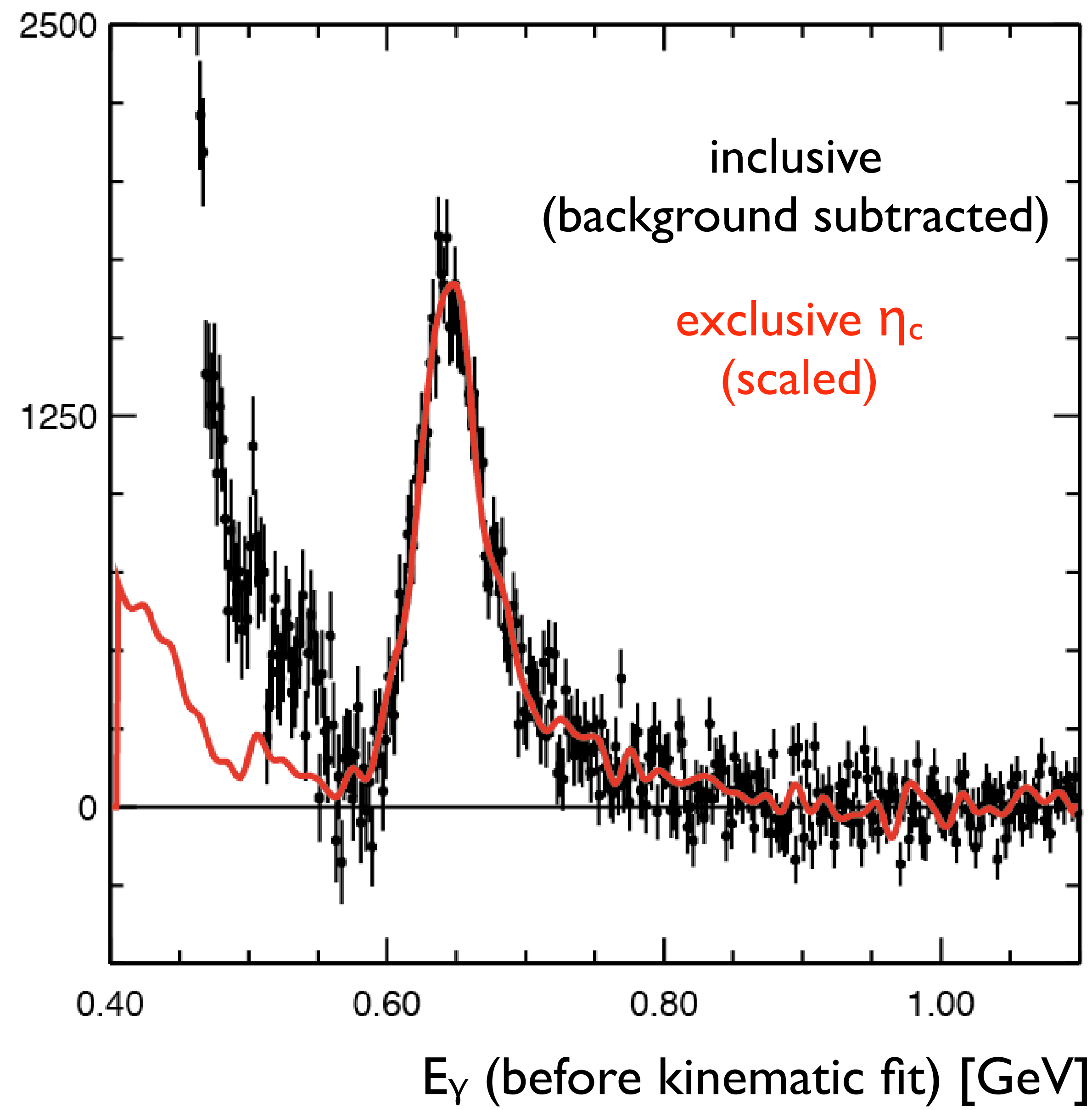


- Inclusive and tagged η_c present a consistent picture of line-shape
- <u>Hindered M1 transitions distort η_c line-shape in a way not apparent in other production mechanisms ($\gamma\gamma$ fusion, pp, B decay)</u>
- A possible explanation for the experimental discrepancy in measurements of the mass and width of η_c?
- Use and empirical function and "cut and count" techniques to extract yield in inclusive spectrum -- line-shape/background uncertainties dominate the systematic error

$$\mathrm{B}(\psi(2S) \to \gamma\eta_c(1S)) = (4.02 \pm 0.11 \pm 0.52) \times 10^{-3}$$

CLEO Preliminary

(PDG Ave.: $3.0 \pm 0.5 \times 10^{-3}$ based on 2 measurements)



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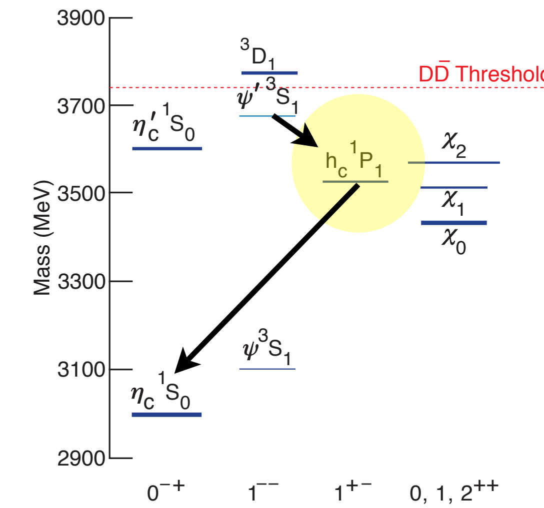
h_c Properties



- E835 (2005): 3σ
  CLEO (2005): 5σ
  consistent but statistically limited h_c properties
- According to simple potential models one expects mass of h_c ($^1P_1$) to be at the spin-averaged mass of the χ_{cJ} (^3P_J) states.
- Mass of h_c yields information on the hyperfine splitting for P-wave states of charmonium
- Study h_c using the decay chain:
  $\psi' \to \pi^0 h_c;\ h_c \to \gamma\eta_c$

Two experimental approaches for reducing background:

<u>Inclusive ηc</u>

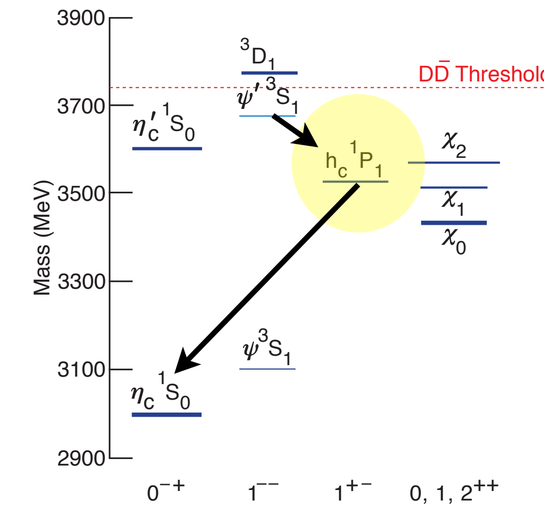
Identify a candidate $h_c \to \gamma\eta_c$ transition photon

<u>Exclusive ηc</u>

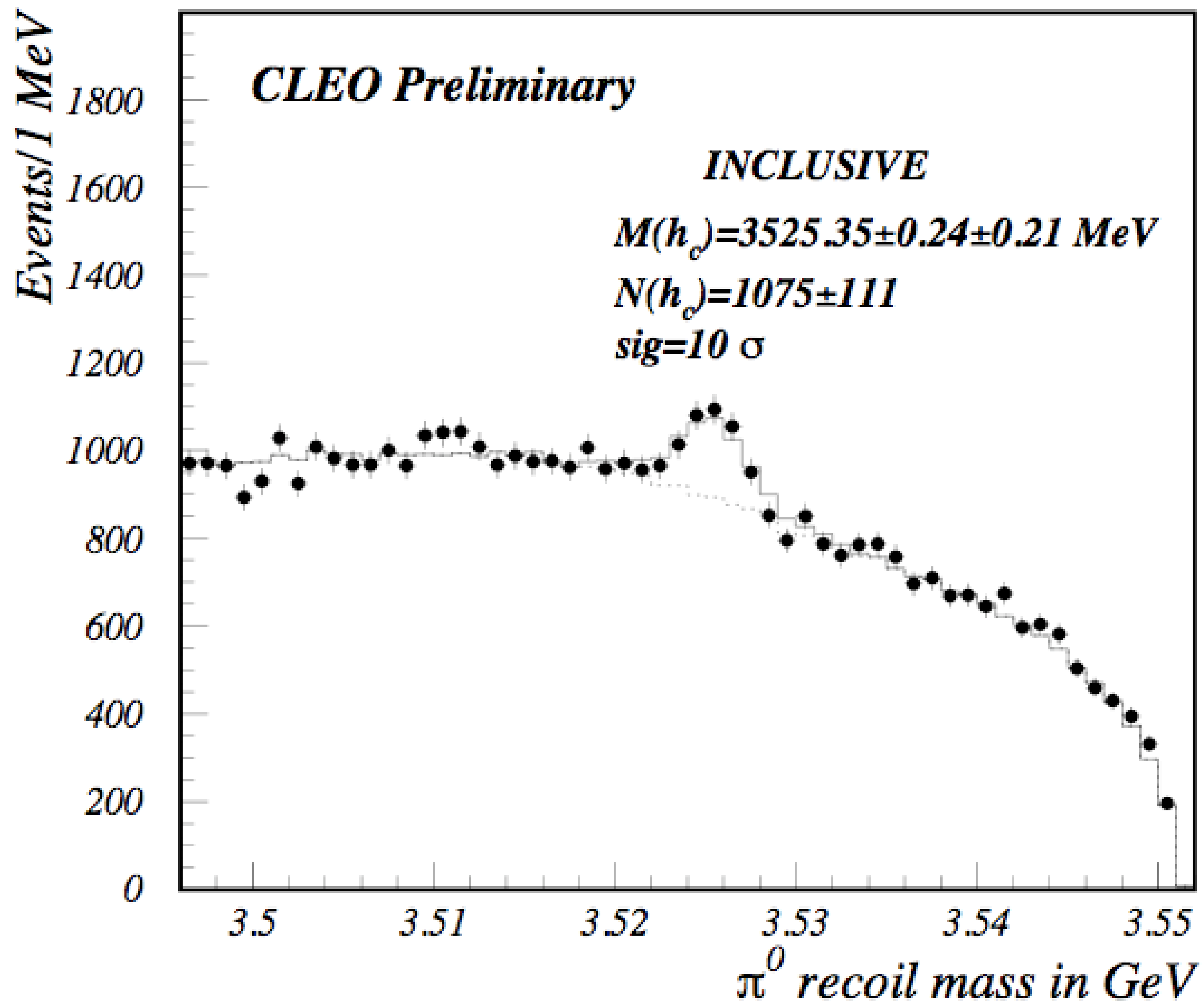
Identify the $h_c \to \gamma\eta_c$ transition photon and use 18 different hadronic decay modes of the η_c

Extract h_c properties from a fit of the recoil mass against the π^0.

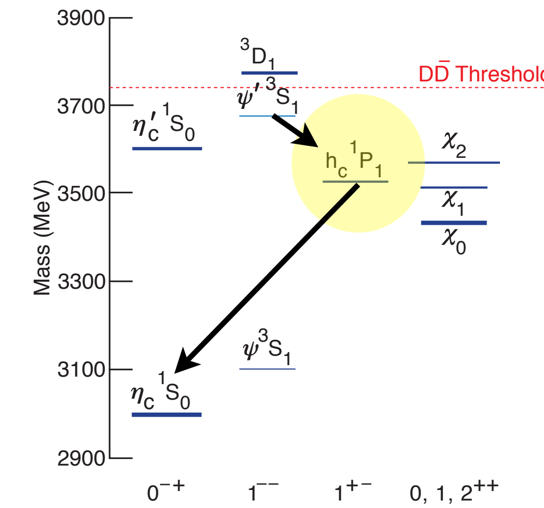
h_c Properties



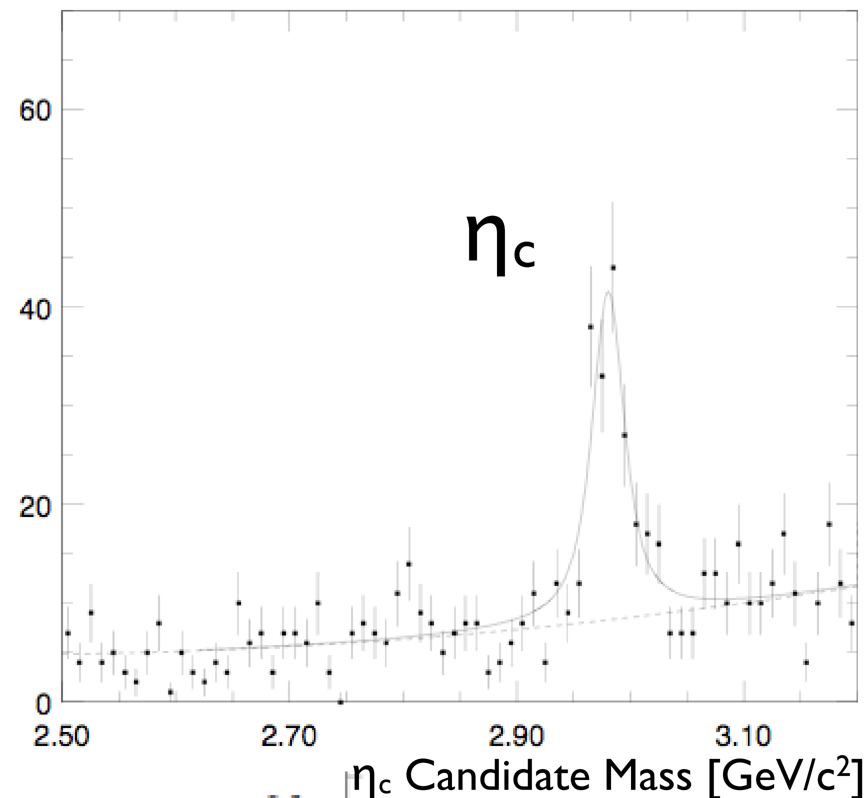
- Inclusive η_c decay
- Tag E1 photon by: 468 MeV < E_γ < 538 MeV
- Background shape derived from data by relaxing the E1 photon requirement
- $M(h_c)$ = 3525.35±0.24±0.21 MeV
- 10σ significance

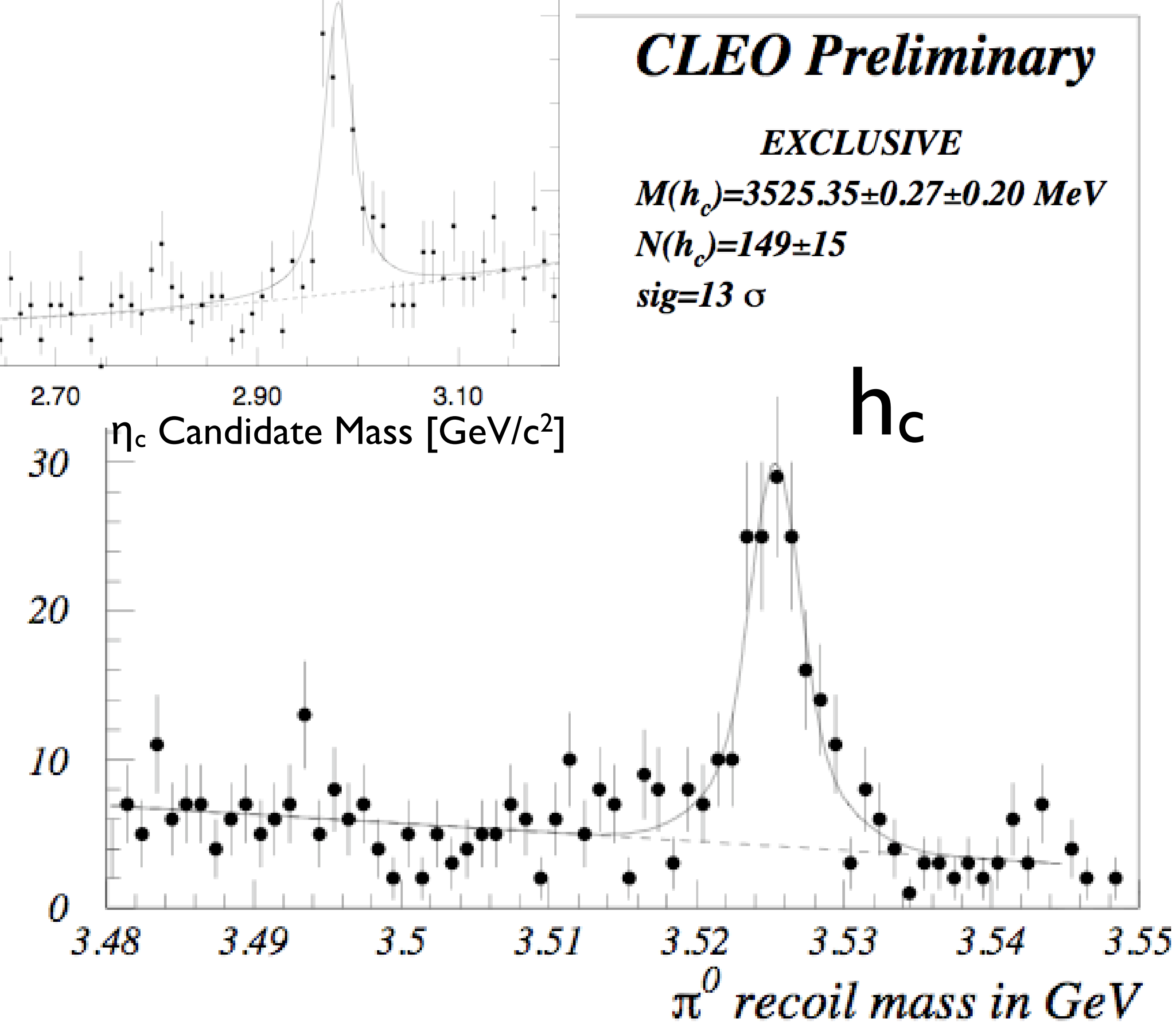


h_c Properties



- Exclusively reconstruct 18 hadronic decay modes of the η_c
- Perform full event kinematic fit
- $M(h_c) = 3525.35 \pm 0.27 \pm 0.20$ MeV
- 13σ significance
- Aside: not statistically sensitive to η_c line-shape





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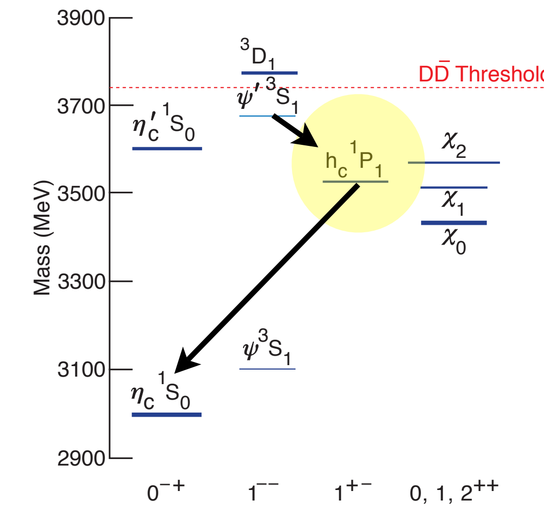
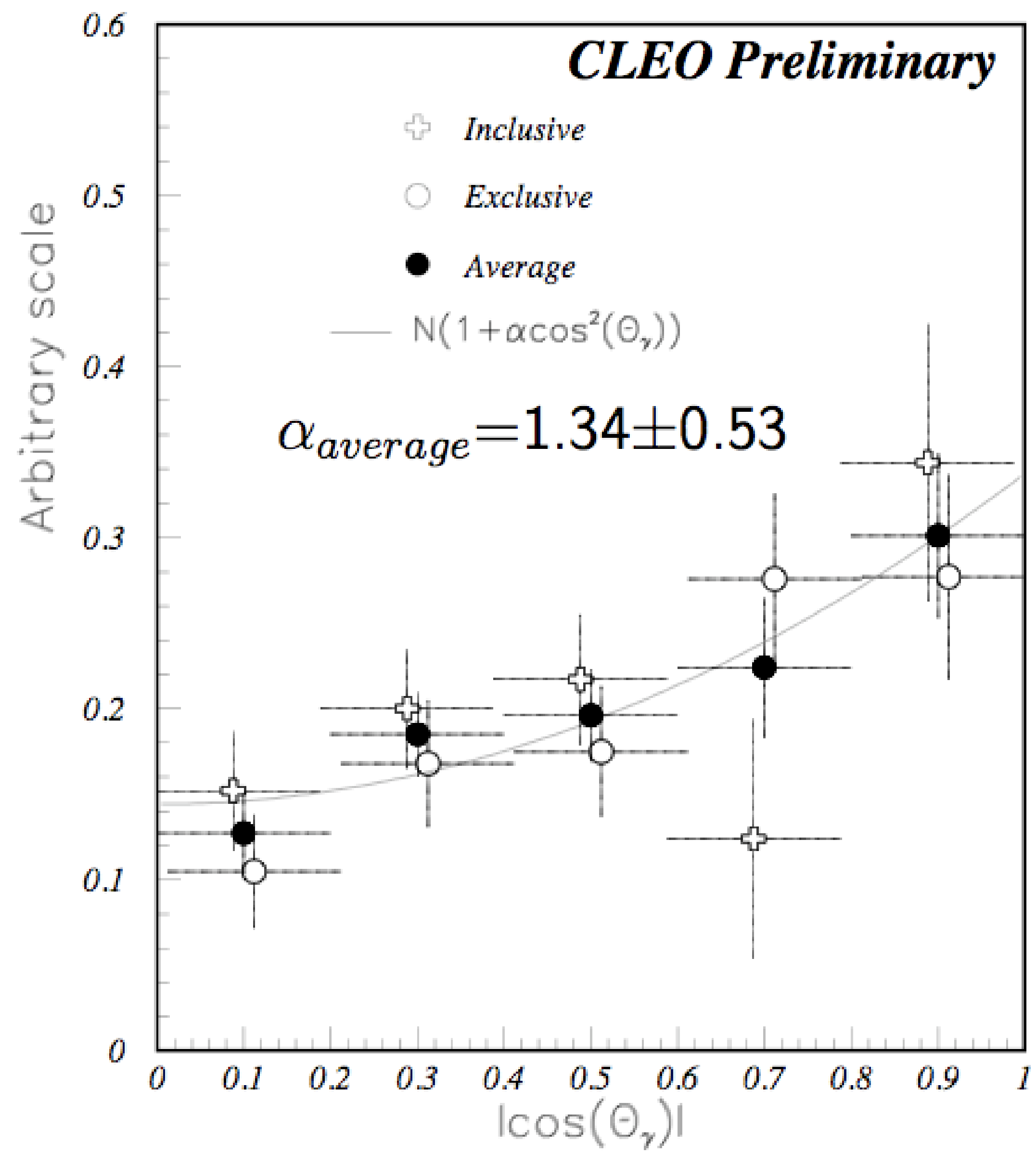
M. R. Shepherd
HADRON 07, INFN Frascati
October 10, 2007

h_c Properties



- Angular distribution is consistent with $^1P_1 \rightarrow {}^1S_0$ transition
- Accounting for statistical correlations in samples one obtains: <u>$M(h_c)$ = 3525.35±0.19±0.15 MeV</u>
- This is consistent at high precision with the spin averaged mass of the ^3P_J states 3525.30±0.11 MeV (PDG).
- Is it surprising that the agreement is this good given the rather large spin orbit interaction in the ^3P_J states?



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Summary

- Many new results with the CLEO-c ~25M ψ' data set including:
  - Probing gluon dynamics through measurements of two-body χ_c decay
  - Precision measurements of η mass and width
  - The η_c line-shape in $\psi'\to\gamma\eta_c$ is non-trivial and needs understanding for extraction of mass and width of η_c

See Ryan Mitchell at QWG next week

CLEO Preliminary

$$B(\psi(2S)\to\gamma\eta_c(1S)) = (4.02 \pm 0.11 \pm 0.52)\times 10^{-3}$$

  - The hyperfine splitting in 1P charmonium appears to be very consistent with naive potential model predictions

See Kam Seth at QWG next week

CLEO Preliminary

$$M(h_c) = 3525.35 \pm 0.19 \pm 0.15 \text{ MeV}$$
$$\Delta M_{\rm hf}(1P) = -0.05 \pm 0.19 \pm 0.16 \text{ MeV}$$

- *The hadronic physics program at CLEO-c is vibrant -- expect many more results in the future!*