Heavy Meson Spectroscopy at CLEO-c

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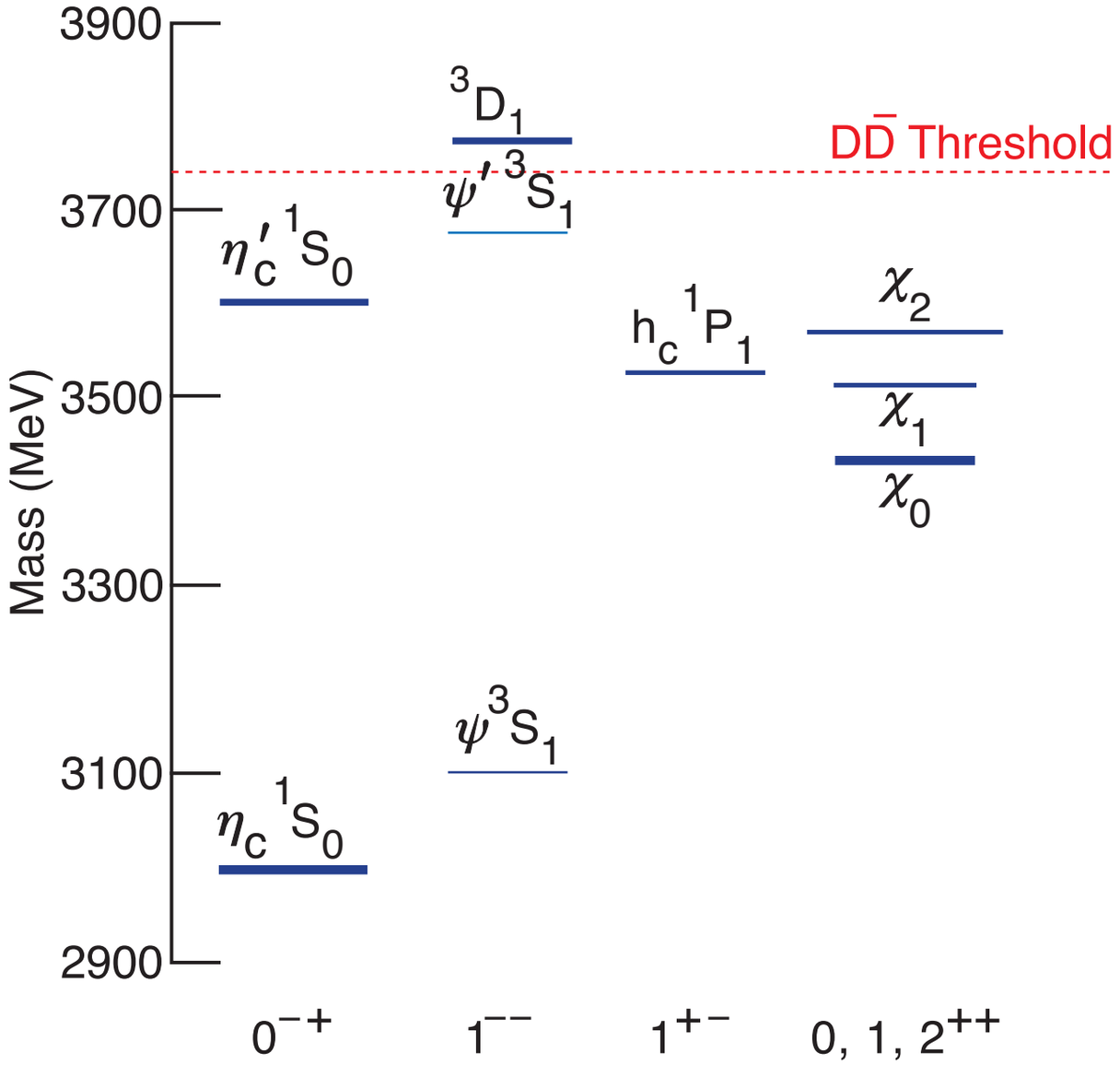
(for the CLEO Collaboration)

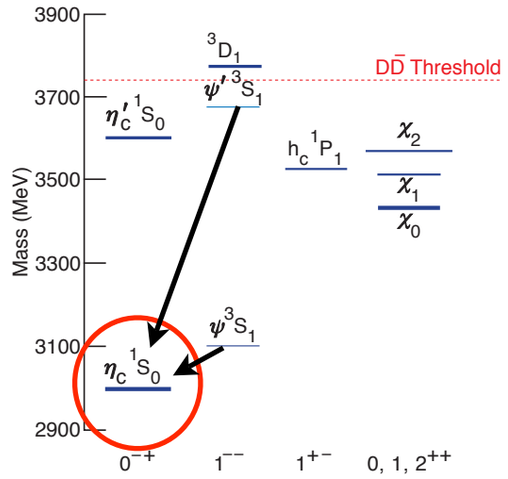
April 10, 2008
International Workshop on e^+e^- Collisions from Φ to ψ

The Charmonium System: An Outline

- Utilize the ~25 M ψ' sample collected at CLEO-c to study QCD in heavy quark systems
- New results on:
  - $\eta_c(1S)$ production in hindered and allowed M1 transitions
  - properties of the h_c
  - purely electromagnetic decays of the χ_c and J/ψ



$J/\psi, \psi' \rightarrow \gamma\eta_c$

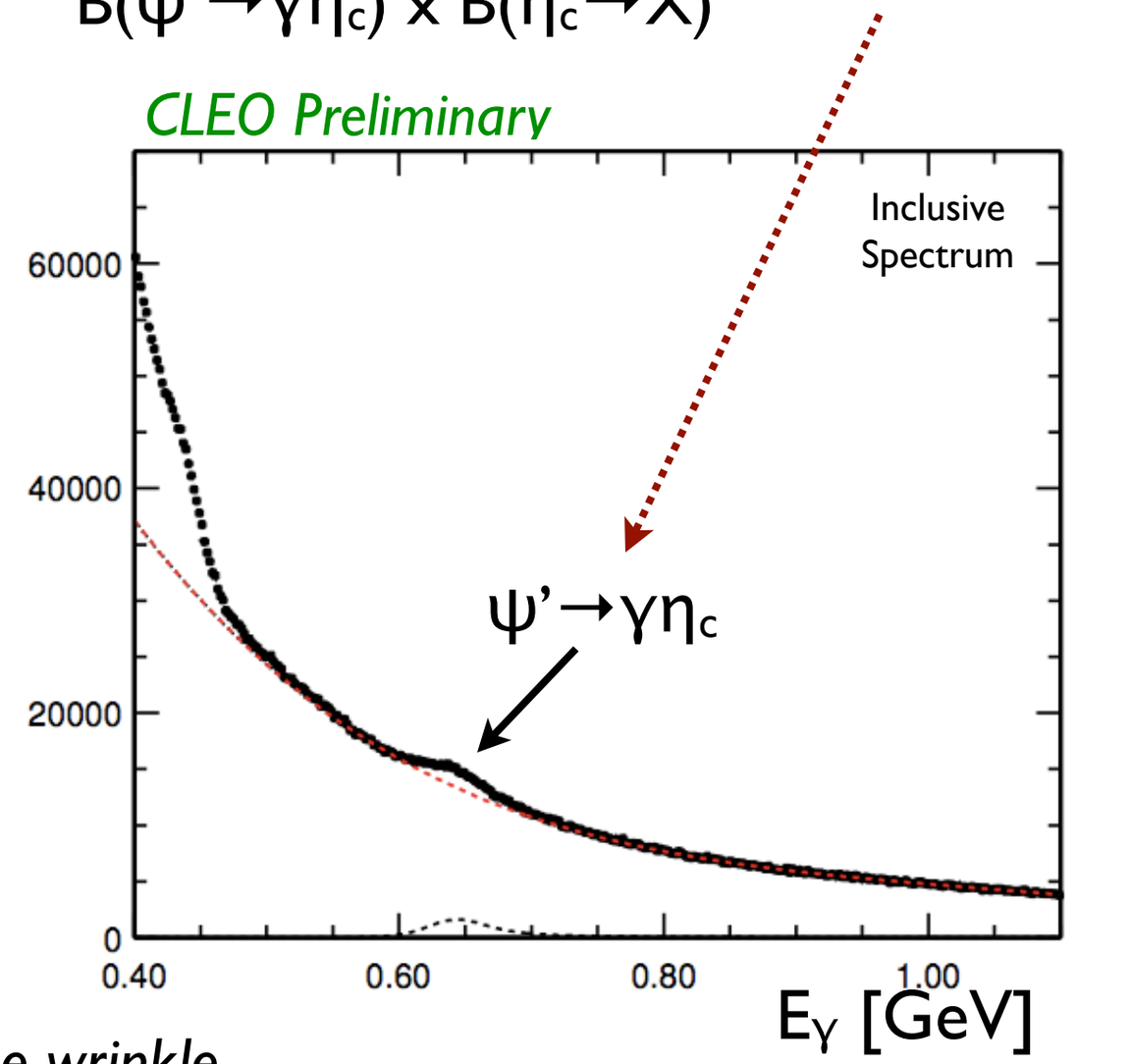


- Precision determination of the hindered M1 ($\psi' \rightarrow \gamma\eta_c$) and allowed M1 ($J/\psi \rightarrow \gamma\eta_c$) rates are critical for understanding radiative transitions in charmonium and measuring η_c branching fractions

- Measure the $\psi' \rightarrow \gamma\eta_c$ rate by a fit to the inclusive photon spectrum in ψ' decay

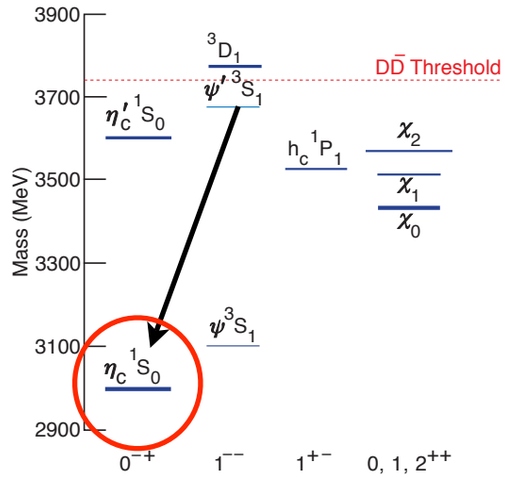
- 114 MeV photon line in $J/\psi \rightarrow \gamma\eta_c$ is dominated by background -- extract $J/\psi \rightarrow \gamma\eta_c$ rate by measuring ratio of allowed to hindered M1 using exclusive η_c decays, then multiply by inclusive $\psi' \rightarrow \gamma\eta_c$ rate.

$$B(J/\psi \rightarrow \gamma\eta_c) = \frac{B(J/\psi \rightarrow \gamma\eta_c) \times B(\eta_c \rightarrow X)}{B(\psi' \rightarrow \gamma\eta_c) \times B(\eta_c \rightarrow X)} \times B(\psi' \rightarrow \gamma\eta_c)$$



...but there is one wrinkle

$\psi' \rightarrow \gamma\eta_c$



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

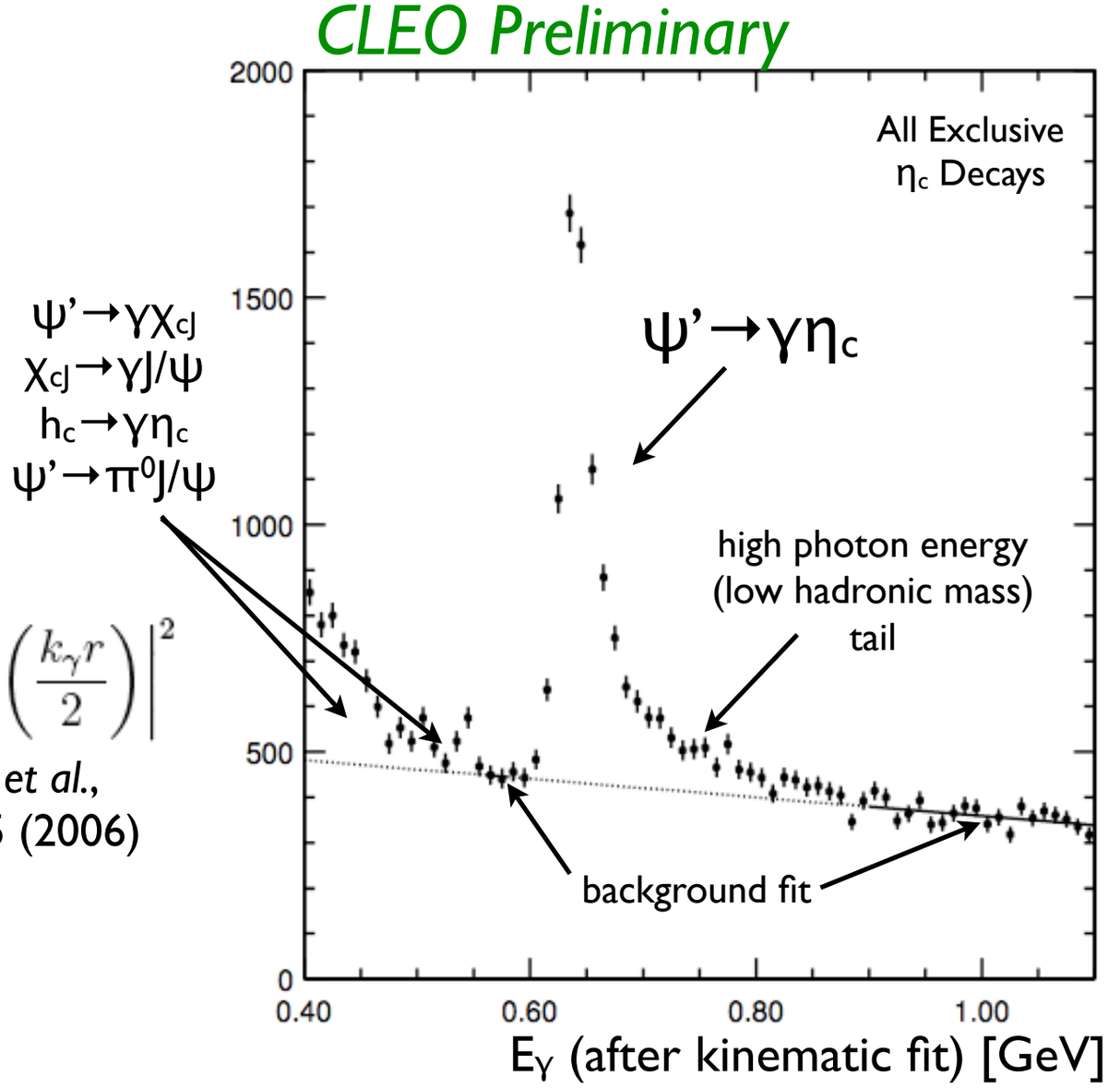
$$\Gamma_{n^3S_1 \to n'^1S_0\gamma} = \frac{4}{3}\alpha\, e_Q^2\, \frac{k_\gamma^3}{m^2} \left| \int_0^\infty dr\, r^2\, R_{n'0}(r)\, R_{n0}(r)\, j_0\left(\frac{k_\gamma r}{2}\right) \right|^2$$

$$j_0(k_\gamma r/2) = 1 - (k_\gamma r)^2/24 + \ldots .$$

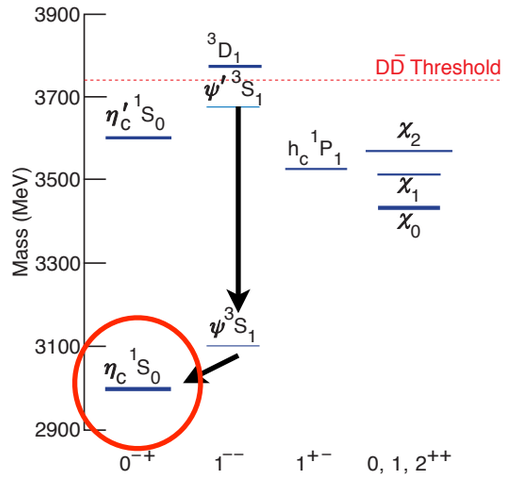
c.f.: Brambilla *et al.*, PRD 73, 054005 (2006)

$\Gamma(\psi' \rightarrow \gamma\eta_c)\ [n \neq n'] \propto E_\gamma^7$

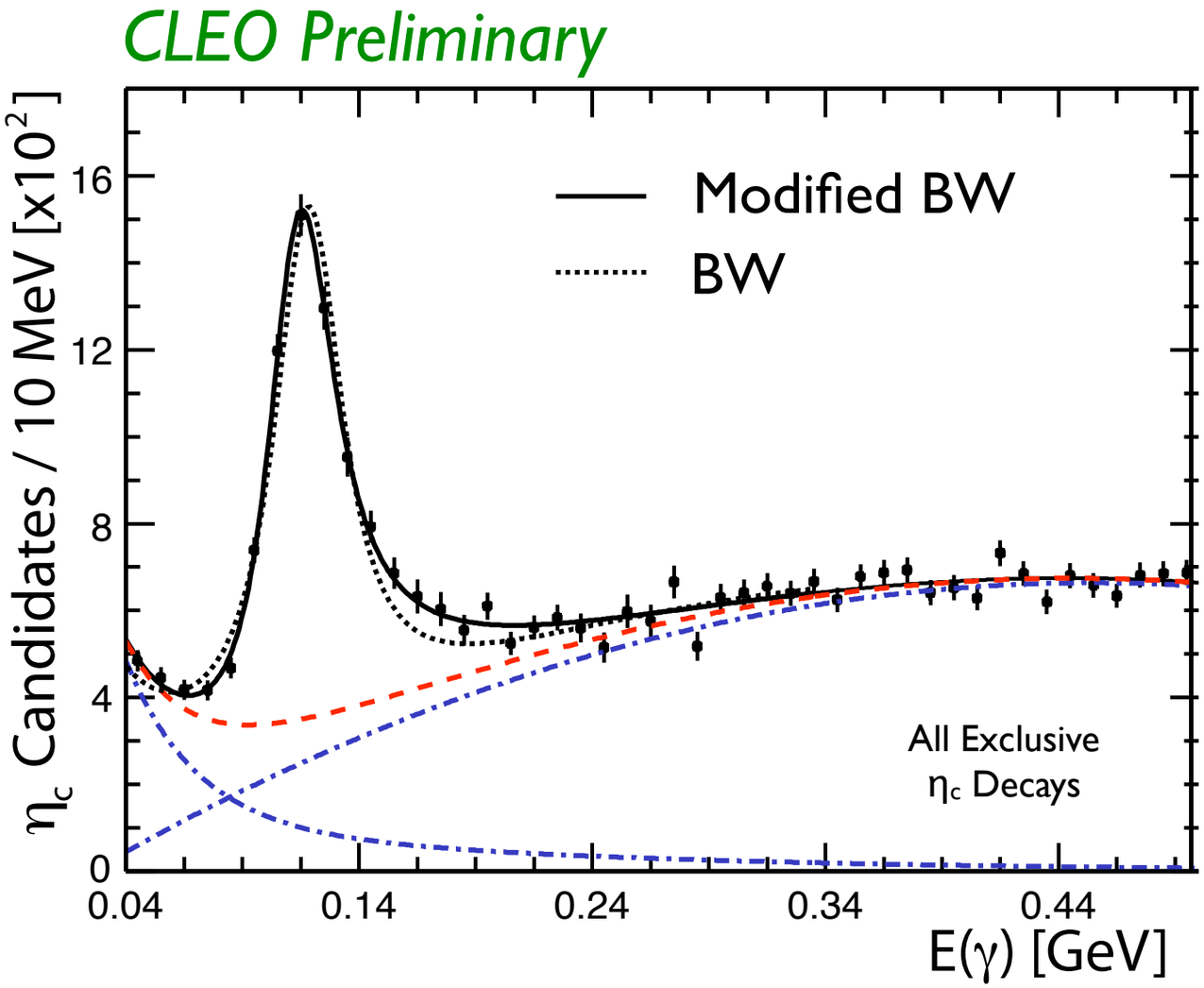
$\Gamma(J/\psi \rightarrow \gamma\eta_c)\ [n = n'] \propto E_\gamma^3$



$J/\psi \rightarrow \gamma \eta_c$

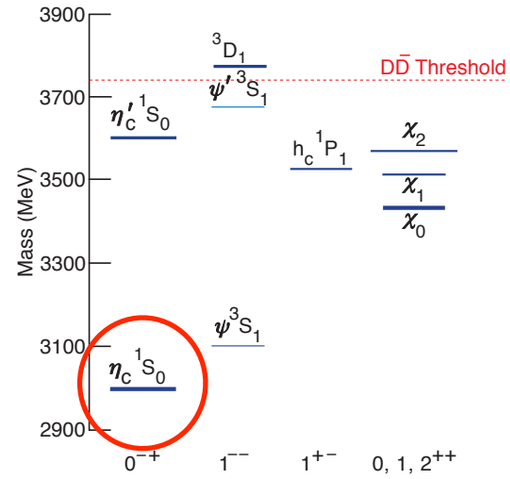


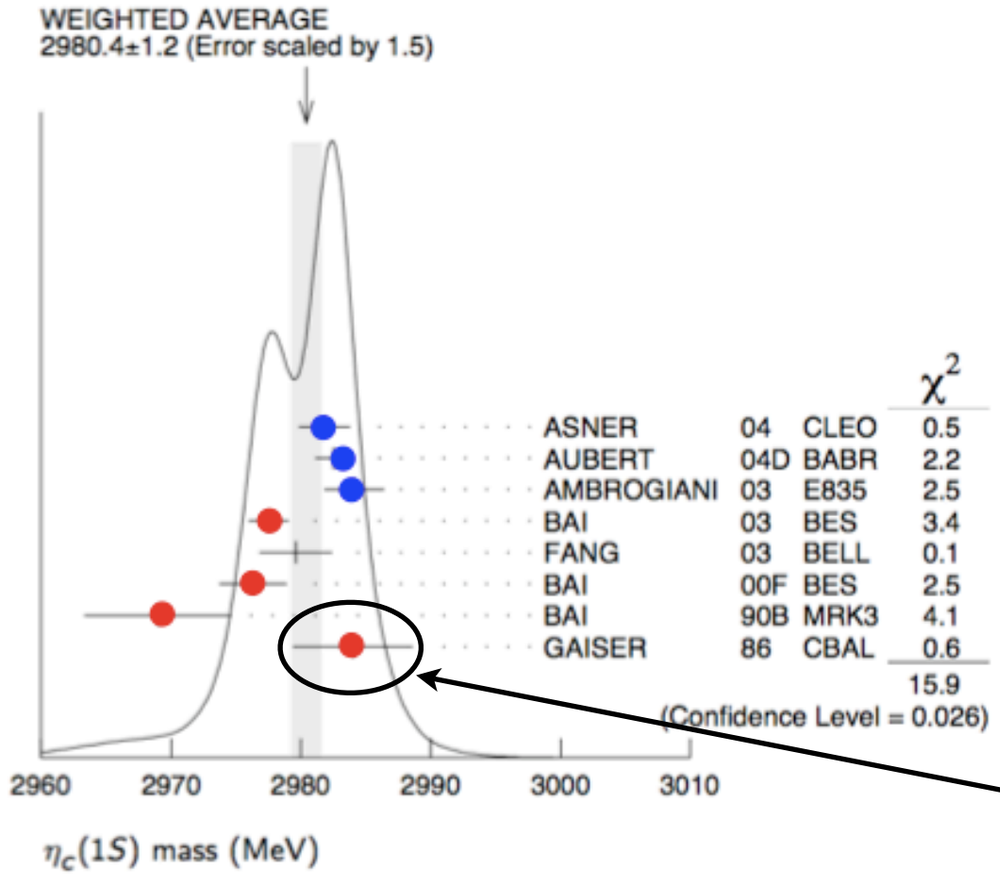
- $J/\psi \rightarrow \gamma \eta_c$ photon line shape spectrum also shows distortion
- Constrain background shapes using MC
  - falling hadronic shower background (floating scale factor)
  - free rising polynomial background
- Breit-Wigner alone provides poor fit to data
- Nominal fit is a Breit-Wigner modified by E_γ^3 and damped by $\exp(E_\gamma^2/\beta)$



~5.5 MeV shift in ηc mass between BW and Modified BW fits

η_c Properties (PDG '06)



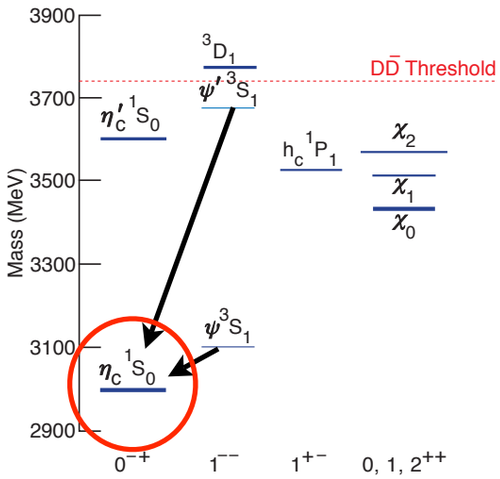


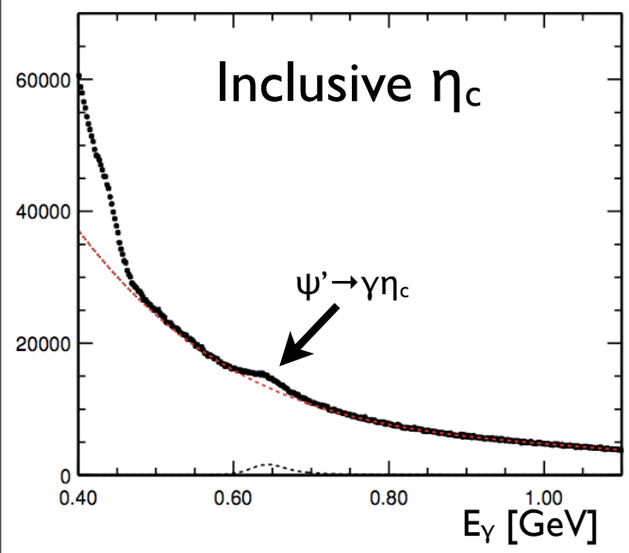
- $\gamma\gamma$ or p+p−
- $\gamma\gamma$ or p+p− (used for width, but not mass)
- $\psi(1S,2S) \rightarrow \gamma\eta_c$

Line shape understanding is needed for precision mass and width measurement in M1 transitions.

included E_γ^7 distortion in fit to $\psi' \rightarrow \gamma\eta_c$ decays

J/ψ,ψ'→γη$_c$





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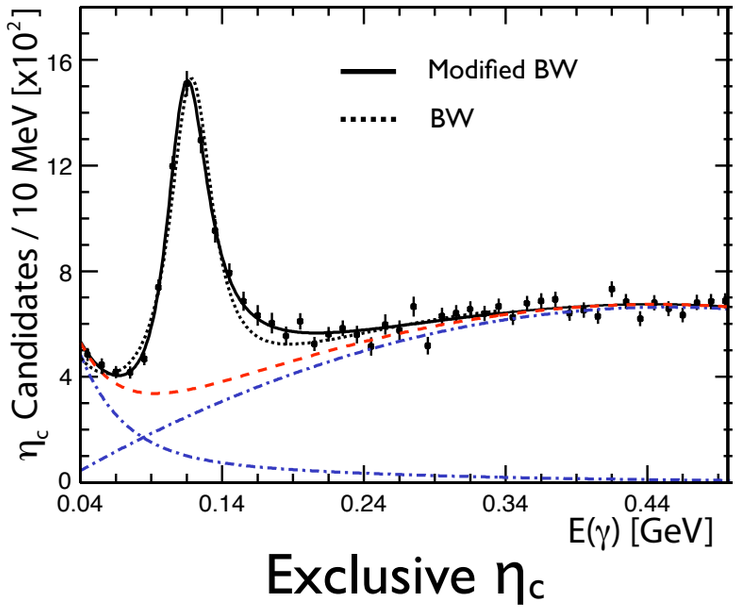

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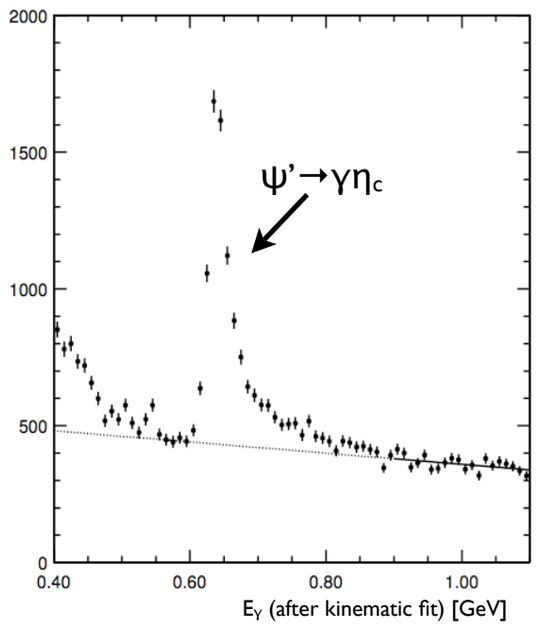


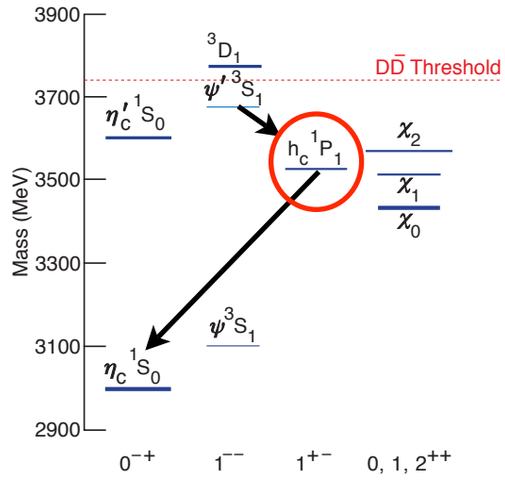
=B(J/ψ→γη$_c$)

- Systematically limited by understanding of line shape and background

Branching Fraction	CLEO-c (Preliminary)	PDG2006
$\mathcal{B}(\psi' \to \gamma\eta_c)$	$(4.02 \pm 0.11 \pm 0.52) \times 10^{-3}$	$2.6 \pm 0.4 \times 10^{-3}$
$\mathcal{B}(J/\psi \to \gamma\eta_c)$	$(2.07 \pm 0.09 \pm 0.35)\%$	$1.3 \pm 0.4\%$

only one previous direct measurement:
Gaiser *et al.* (CBAL), PRD 34, 711 (1986)

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 -- detailed info on qq interaction
- Study h_c using the decay chain:
  $\psi' \rightarrow \pi^0 h_c$; $h_c \rightarrow \gamma\eta_c$

Two experimental approaches for reducing background:

Inclusive η_c

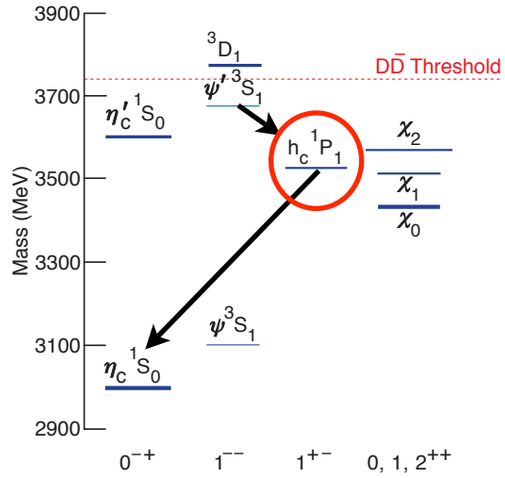
Identify a candidate $h_c \rightarrow \gamma\eta_c$ E1 transition photon

Exclusive η_c

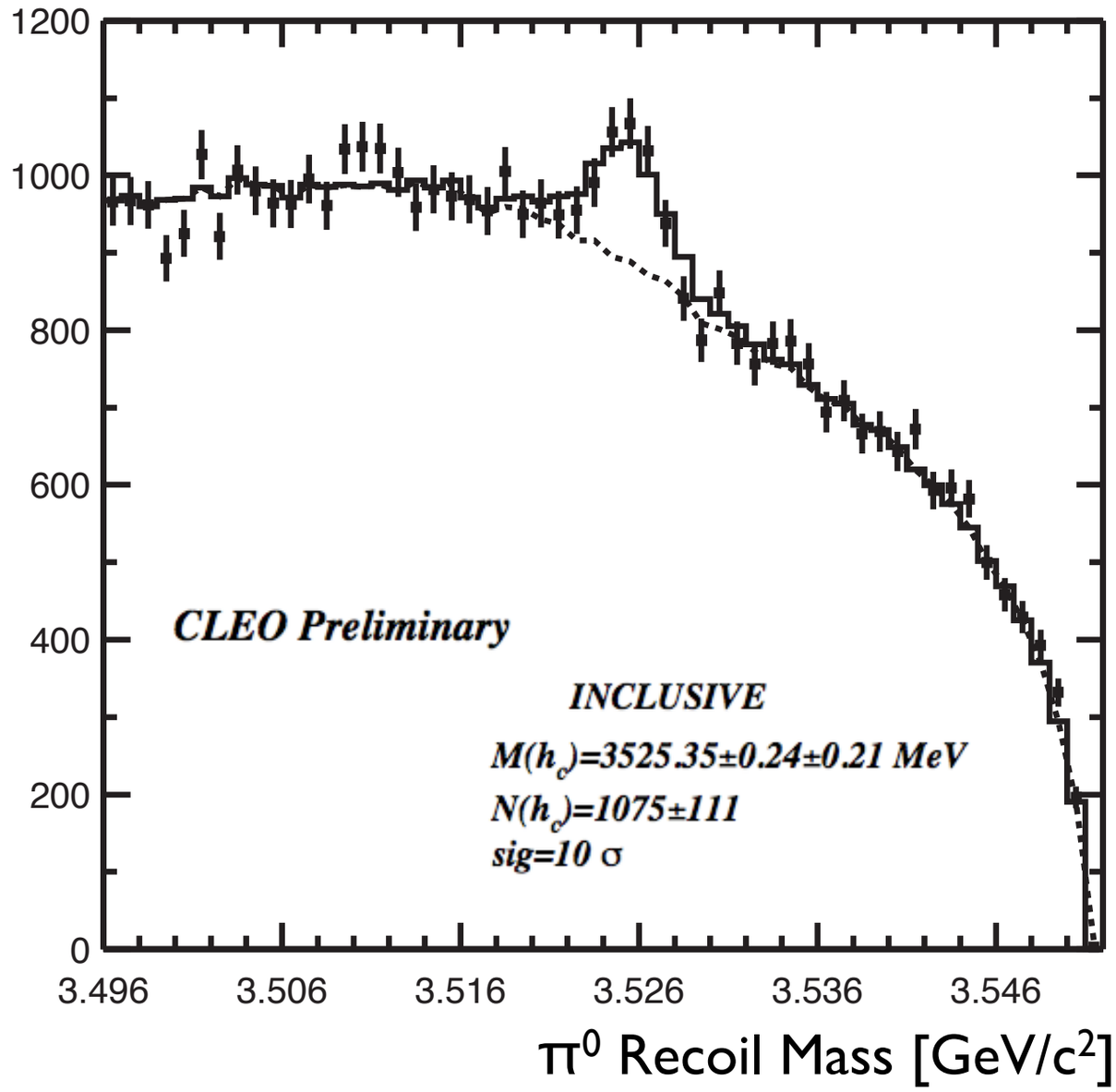
Identify the $h_c \rightarrow \gamma\eta_c$ transition photon and use 18 different hadronic decay modes of the η_c

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

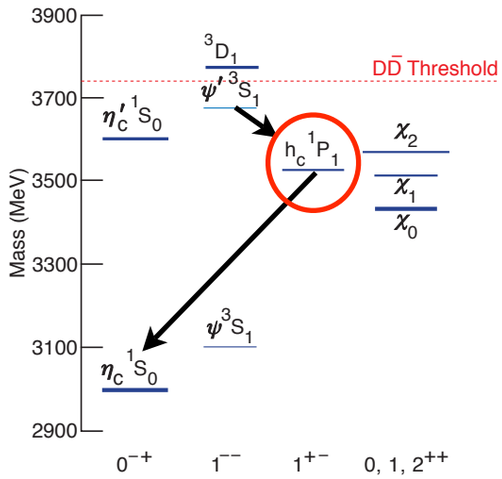
h_c Properties



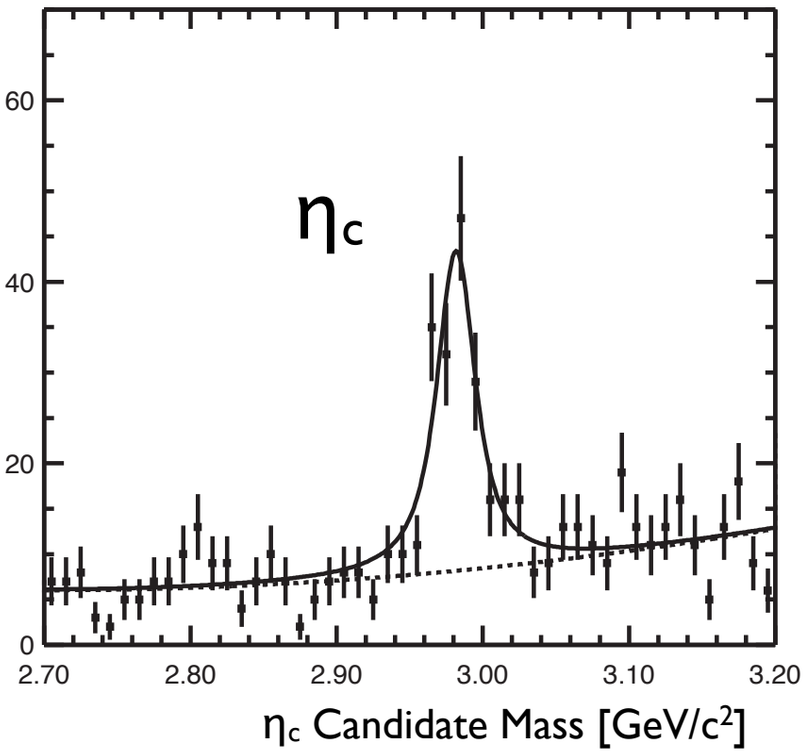
- Inclusive η_c decay
- Tag E1 photon by:
  468 MeV < E_γ < 538 MeV
- Background shape derived from data by relaxing the E1 photon requirement
- $M(h_c)$ = 3525.35±0.24±0.21 MeV
- 10σ significance

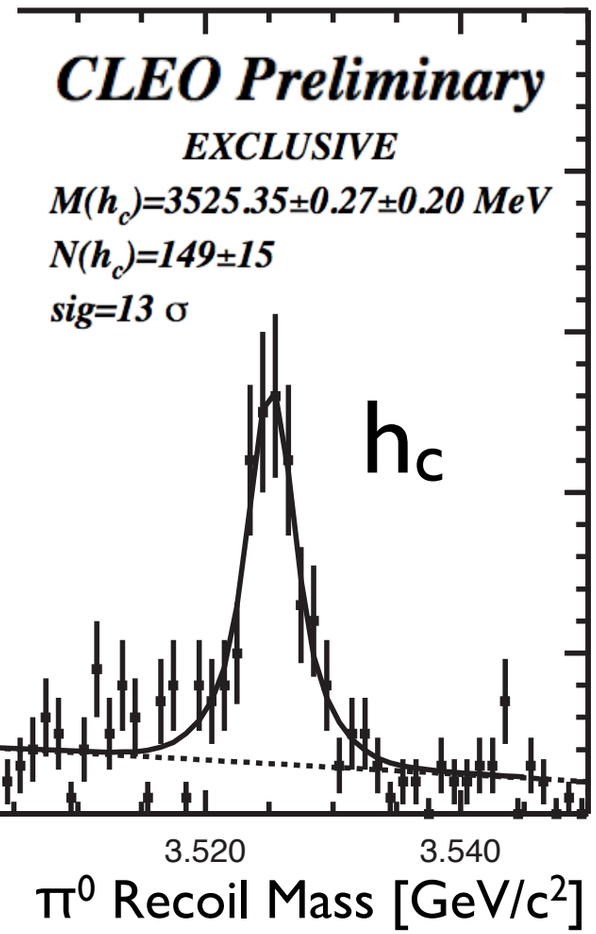


h_c Properties

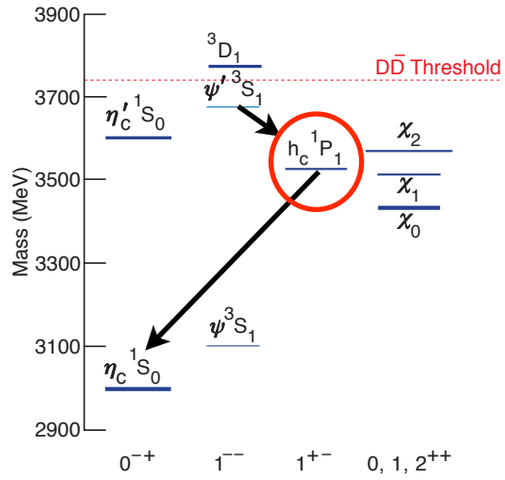


- Exclusively reconstruct many hadronic decay modes of the η_c
- Perform full event kinematic fit
- $M(h_c)$ = 3525.35±0.27±0.20 MeV
- 13σ significance
- Aside: not statistically sensitive to η_c line-shape





h_c Properties

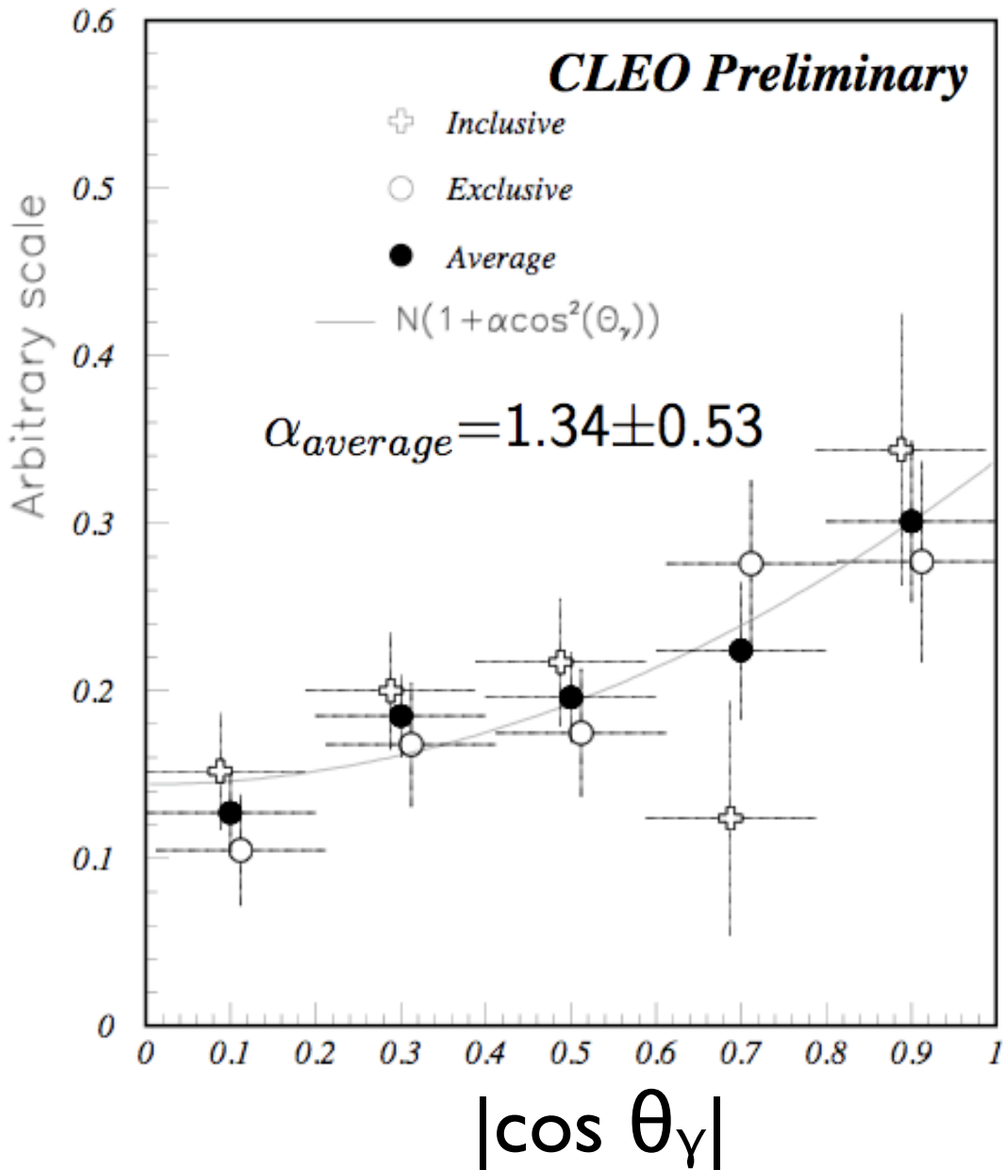


- Angular distribution is consistent with $^1P_1 \rightarrow {}^1S_0$ transition

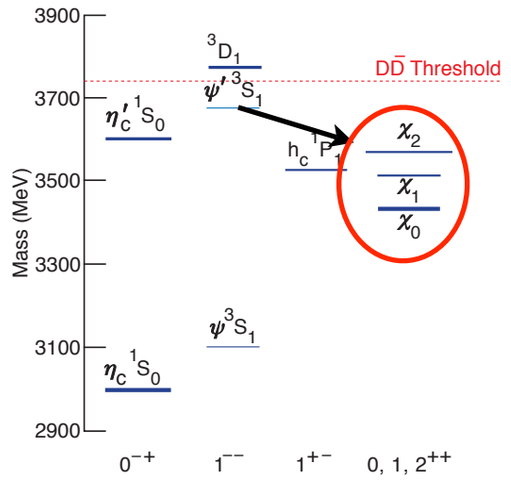
- Accounting for statistical correlations in samples one obtains: $M(h_c) = 3525.35 \pm 0.19 \pm 0.15$ MeV

- 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?



$\chi_{cJ} \rightarrow \gamma\gamma$

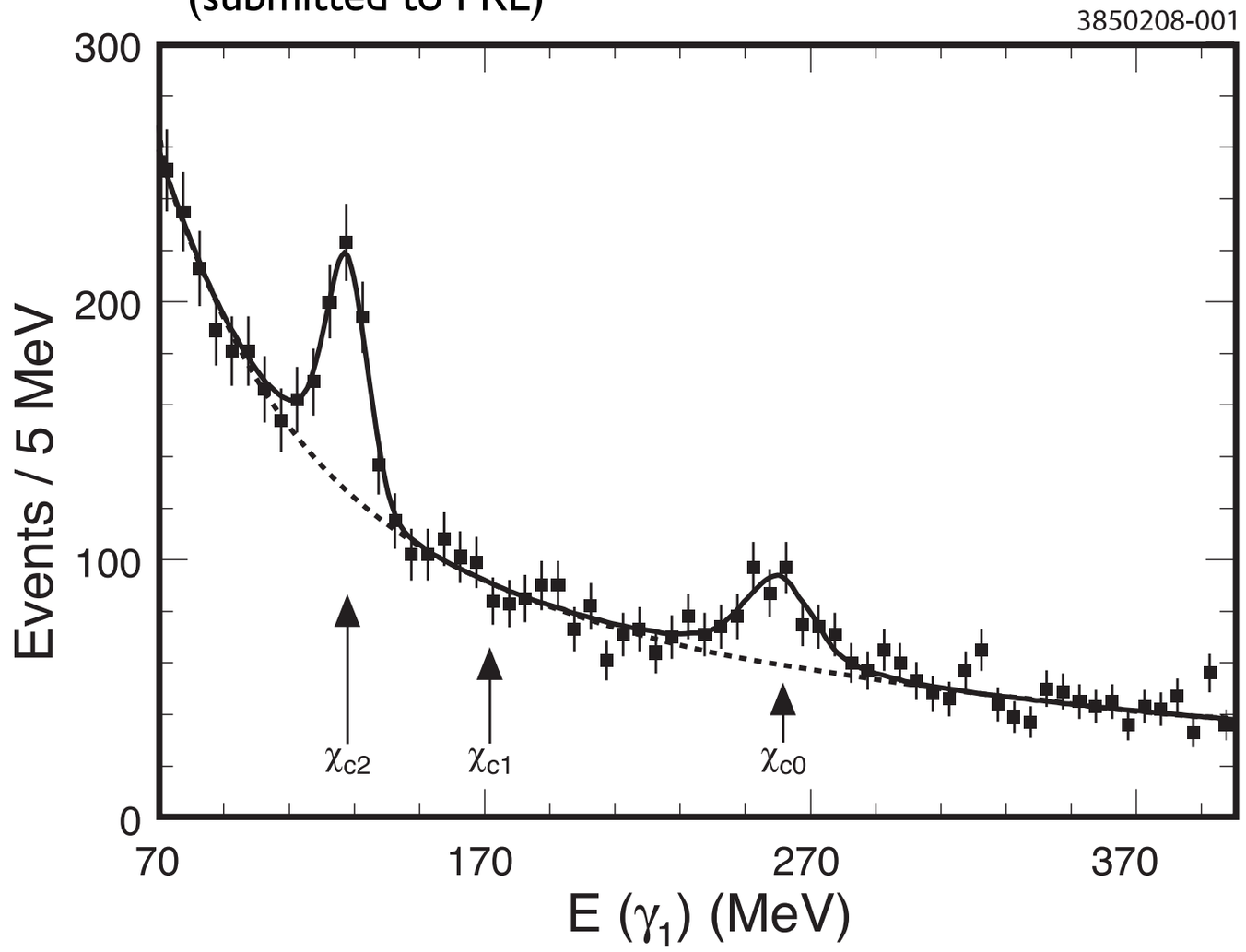


- Two photon decays of χ_{cJ} probe relativistic and radiative corrections known to be significant in the charmonium system

- Kinematically constrain three photons to the initial ψ' four momentum

- Fit E1 photon distribution after selecting $\chi_{cJ} \rightarrow \gamma\gamma$

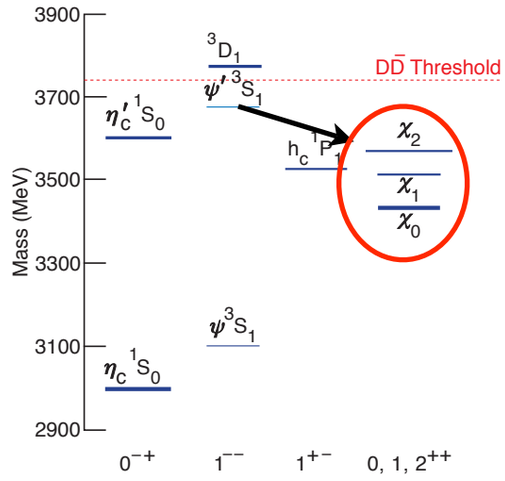
arXiv:0803.2869
(submitted to PRL)



$$\mathcal{R}_{th} = \frac{\Gamma_{\gamma\gamma}(\chi_{c2}) = 4(|\Psi'(0)|^2\alpha_{em}^2/m_c^4) \times [1 - 1.70\alpha_s]}{\Gamma_{\gamma\gamma}(\chi_{c0}) = 15(|\Psi'(0)|^2\alpha_{em}^2/m_c^4) \times [1 + 0.06\alpha_s]} = (4/15)\,[1 - 1.76\alpha_s]$$

Barbieri *et al.*
(PLB 95, 93 (1980))

$\chi_{cJ} \rightarrow \gamma\gamma$



$$\mathcal{B}_1 \equiv \mathcal{B}(\psi(2S) \rightarrow \gamma\chi_{c0,c2})$$
$$\mathcal{B}_2 \equiv \mathcal{B}(\chi_{c0,c2} \rightarrow \gamma\gamma)$$
$$\Gamma_{\gamma\gamma} \equiv \Gamma_{\gamma\gamma}(\chi_{c0,c2} \rightarrow \gamma\gamma)$$

(PDG used for B_1 and $\Gamma_{tot}(\chi_{c0,2})$)

Quantity	χ_{c0}	χ_{c2}
$\mathcal{B}_1 \times \mathcal{B}_2 \times 10^5$	$2.22 \pm 0.32 \pm 0.10$	$2.70 \pm 0.28 \pm 0.15$
$\mathcal{B}_2 \times 10^4$	$2.41 \pm 0.35 \pm 0.11 \pm 0.10$	$3.06 \pm 0.32 \pm 0.17 \pm 0.17$
$\Gamma_{\gamma\gamma}$ (keV)	$2.53 \pm 0.37 \pm 0.11 \pm 0.24$	$0.60 \pm 0.06 \pm 0.03 \pm 0.05$
$\mathcal{R}$	$0.237 \pm 0.043(\text{stat}) \pm 0.015(\text{syst}) \pm 0.031(\text{PDG})$	

arXiv:0803.2869
(submitted to PRL)

In pQCD quark mass and wave function uncertainties cancel, making *R* a key quantity -- at first order in α_s

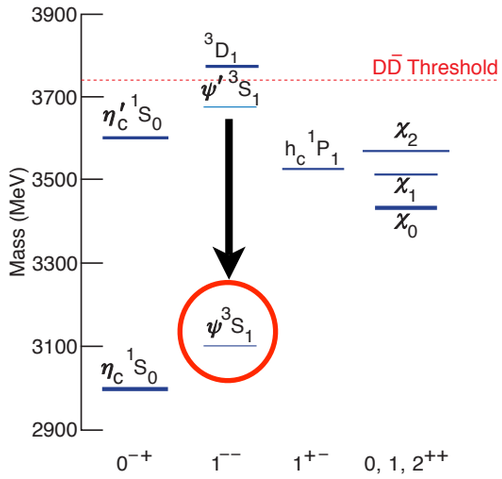
$$\mathcal{R}_{th} = \frac{\Gamma_{\gamma\gamma}(\chi_{c2}) = 4(|\Psi'(0)|^2\alpha_{em}^2/m_c^4) \times [1 - 1.70\alpha_s]}{\Gamma_{\gamma\gamma}(\chi_{c0}) = 15(|\Psi'(0)|^2\alpha_{em}^2/m_c^4) \times [1 + 0.06\alpha_s]} = (4/15)\,[1 - 1.76\alpha_s]$$

$\alpha_s = 0.32 \rightarrow R = 0.12$

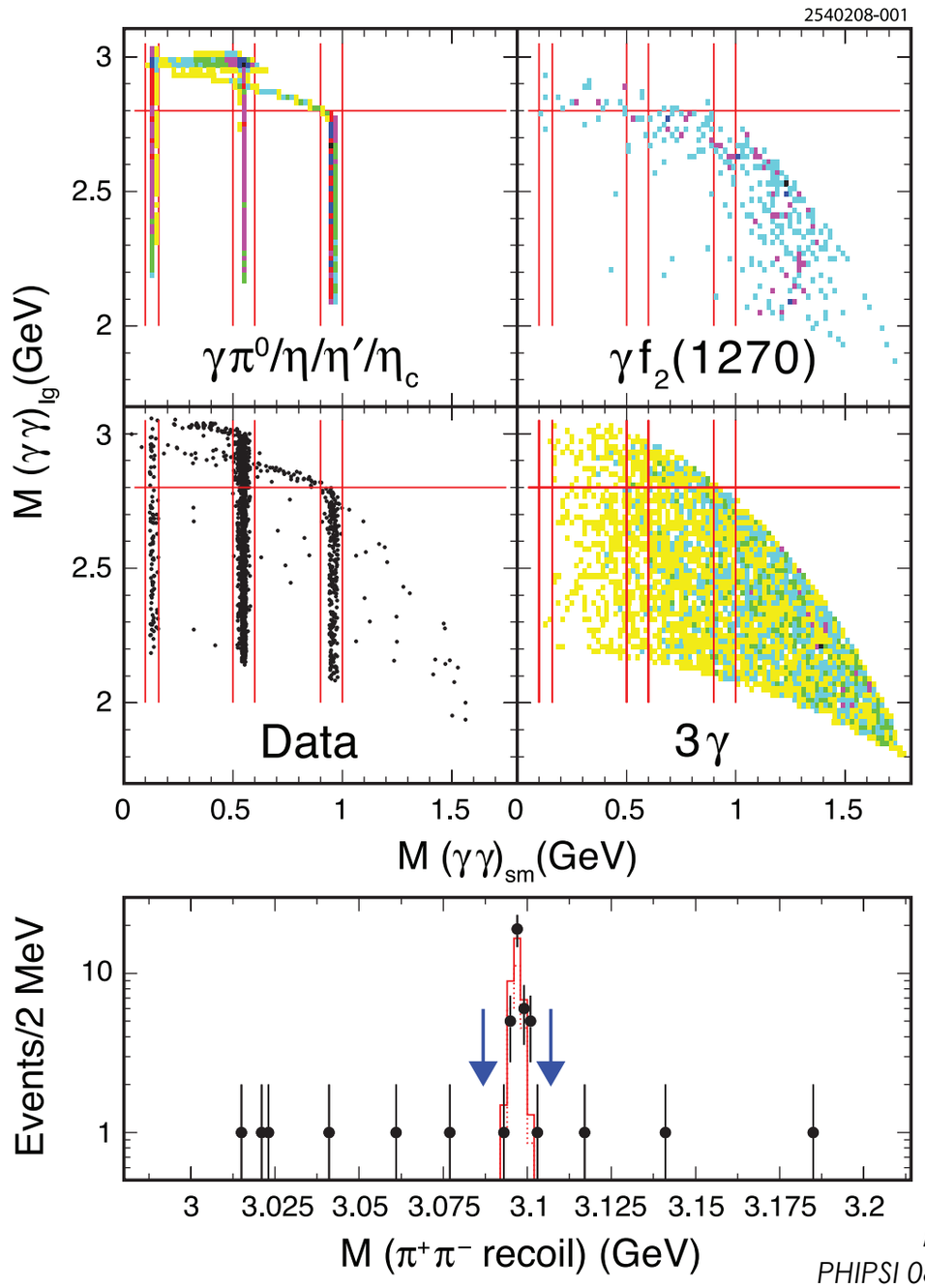
new world avg.: R = 0.20 ± 0.02

higher order corrections significant

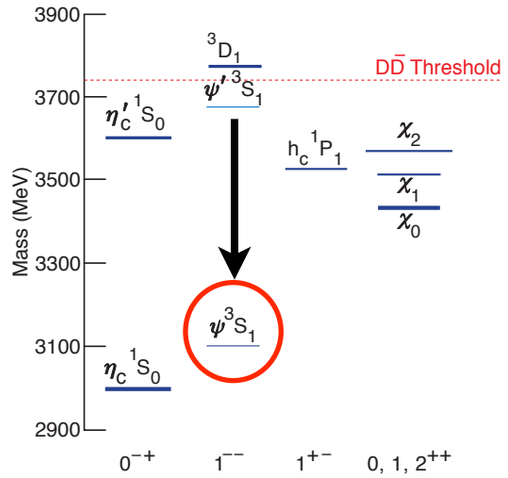
J/ψ→γγγ



- The only direct 3 photon decay ever observed in nature is in the ortho-positronium ($^3S_1$) system
- Kwong *et al.* (PRD 37, 3210 (1988)) predict a rate of order 10^{-5}
- Tag J/ψ in ππ transition from ψ' and reconstruct 3γ decay
- Explicitly cut background from γ + pseudoscalar decays
- Missing photons in 4γ tensor/scalar decays is dominant remaining background



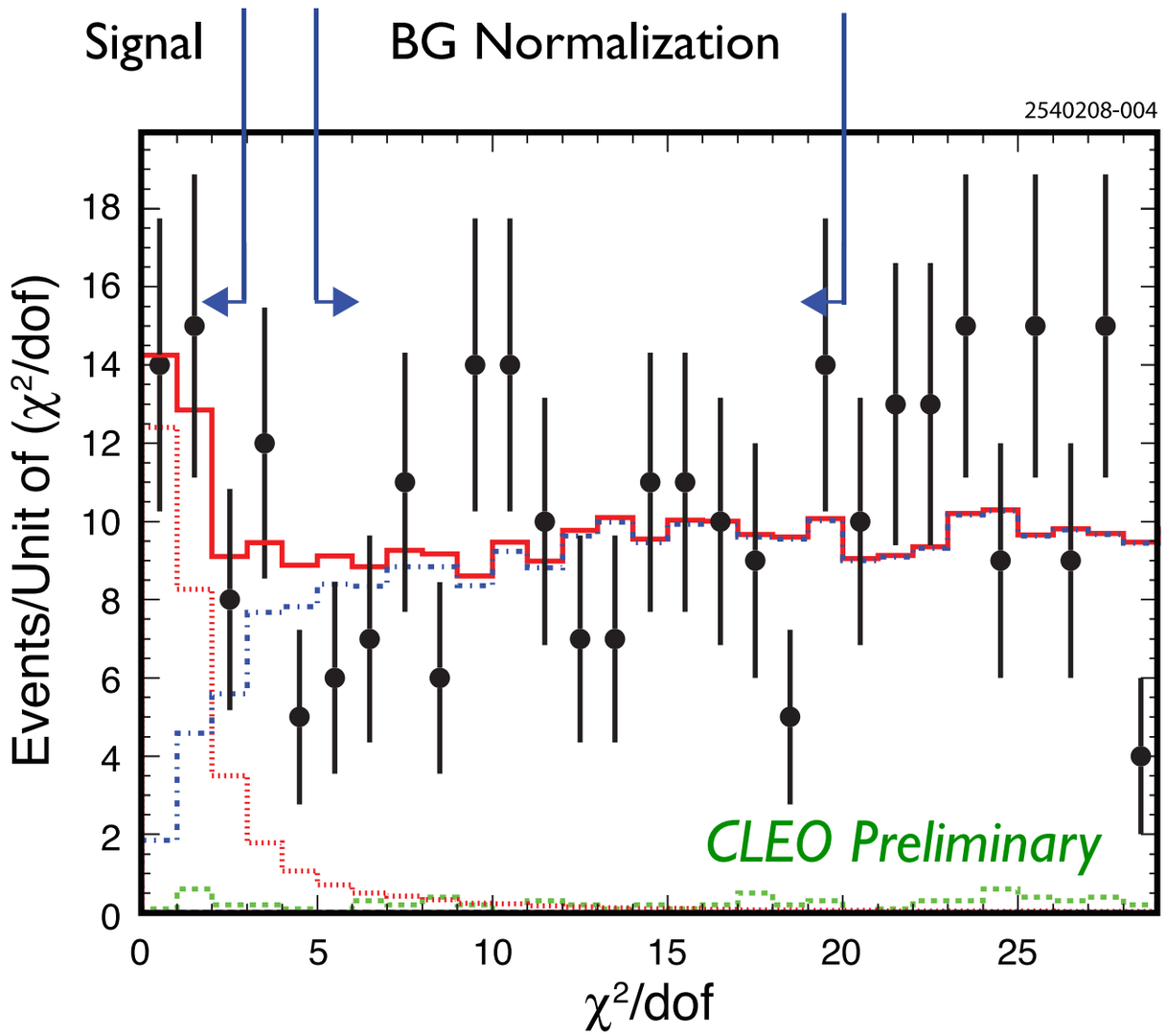
J/ψ→γγγ



- Perform a fit to the χ^2 distribution of the kinematic fit
  - signal peaks at zero
  - background from $\gamma\pi^0\pi^0$ rises away from zero
- Preliminary result:

$$\mathcal{B} = (1.17^{+0.34}_{-0.29} \pm 0.14) \times 10^{-5}\ (6\sigma)$$

- Agrees with Kwong *et al.* prediction
- First 3γ decay of any hadron!

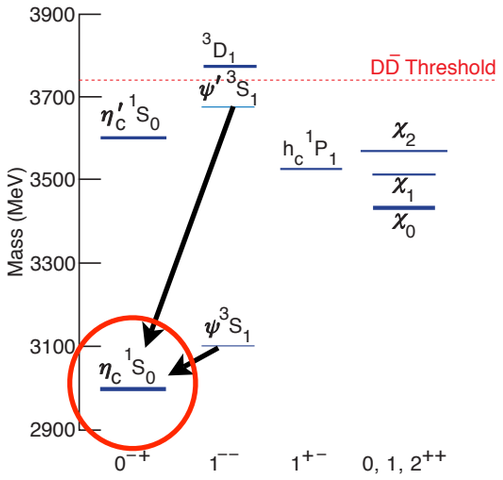


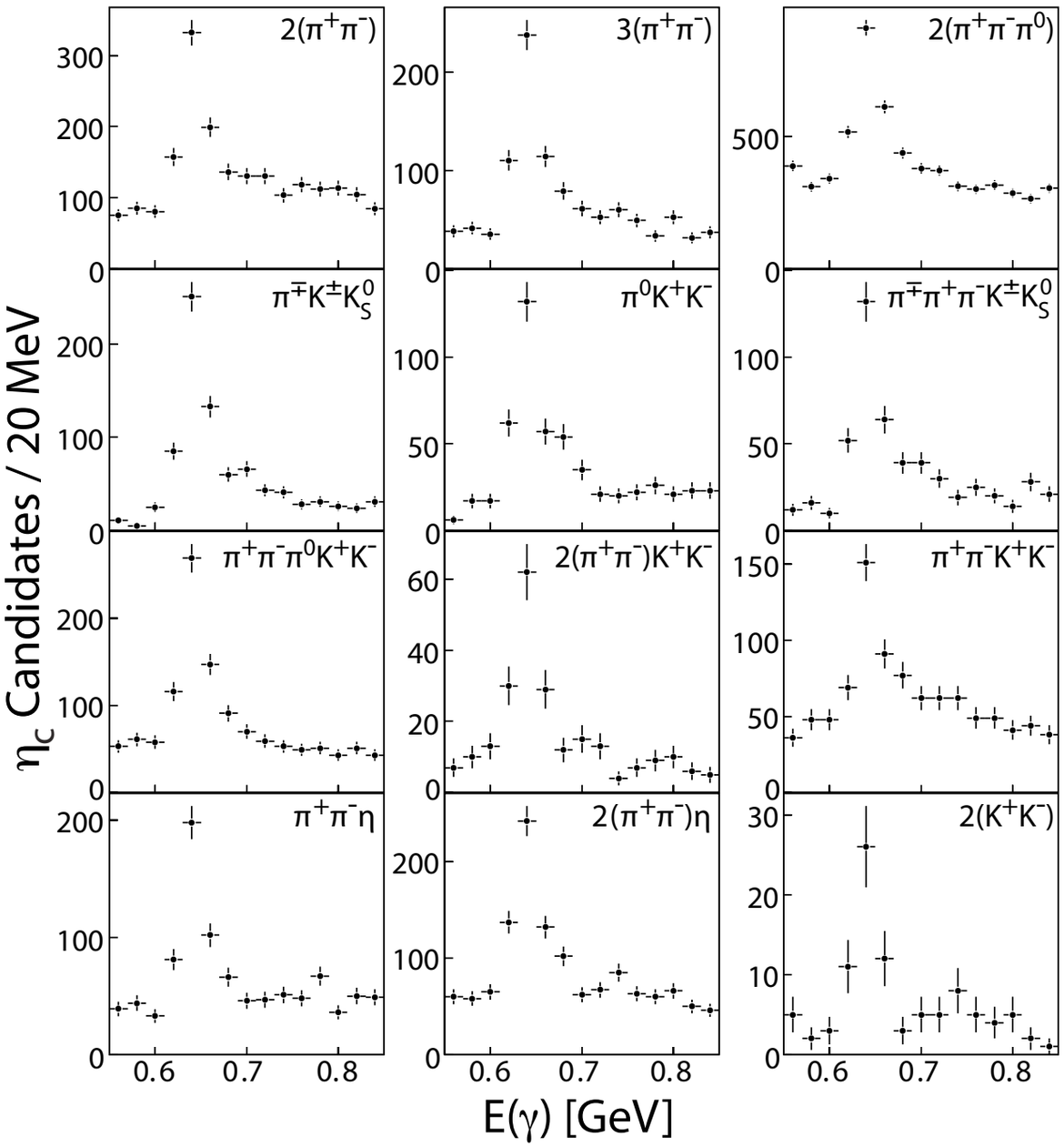
Summary

- The CLEO-c sample of ~25 M ψ' decays provides an excellent laboratory to study QCD in the heavy quark sector
- Several new exciting results:
  - most precise measurements of $J/\psi,\psi' \to \gamma\eta_c$ -- non-trival line shape may shed light on the long-standing discrepancy in measured mass and width of the η_c
  - precision measurement of the h_c mass -- hyperfine splitting in the 1P charmonium states is -0.05 ± 0.19 ± 0.16 MeV
  - measurement of purely electromagnetic decays of the χ_c and J/ψ -- the first observation of a 3γ decay of a meson
- *Analysis of world's largest ψ' sample continues -- more results soon!*

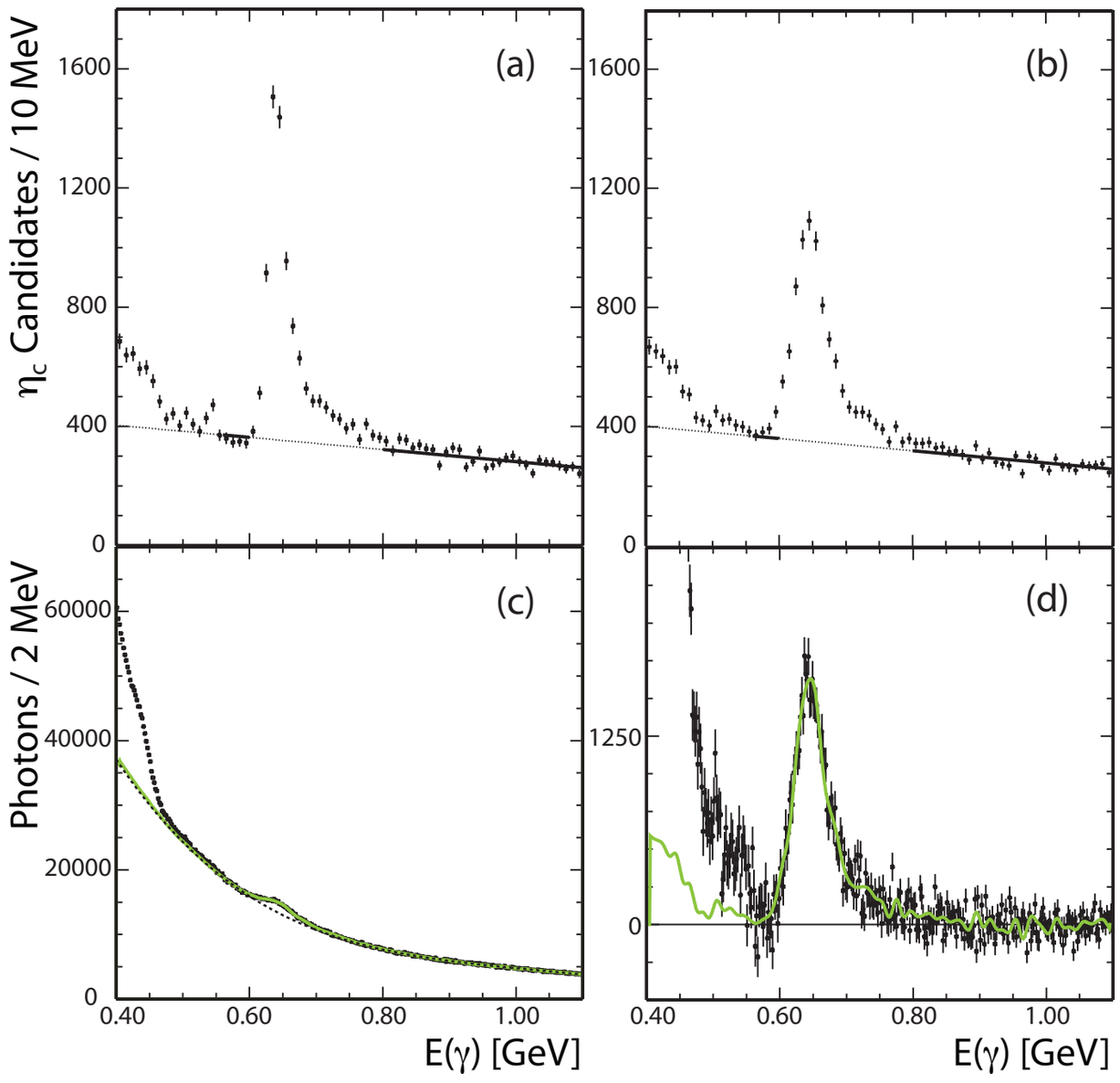
Thanks to the organizers for an enjoyable conference!

$J/\psi,\psi' \rightarrow \gamma\eta_c$





CLEO Preliminary



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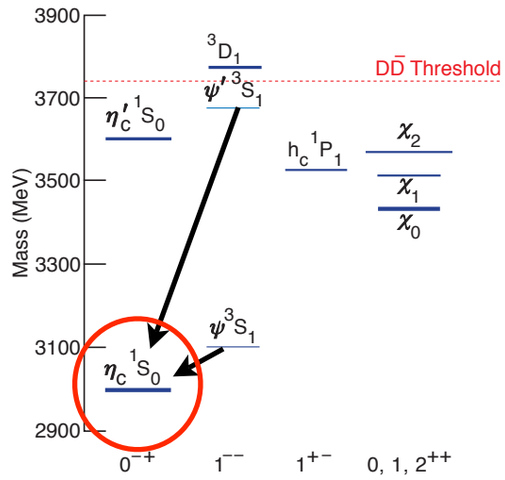
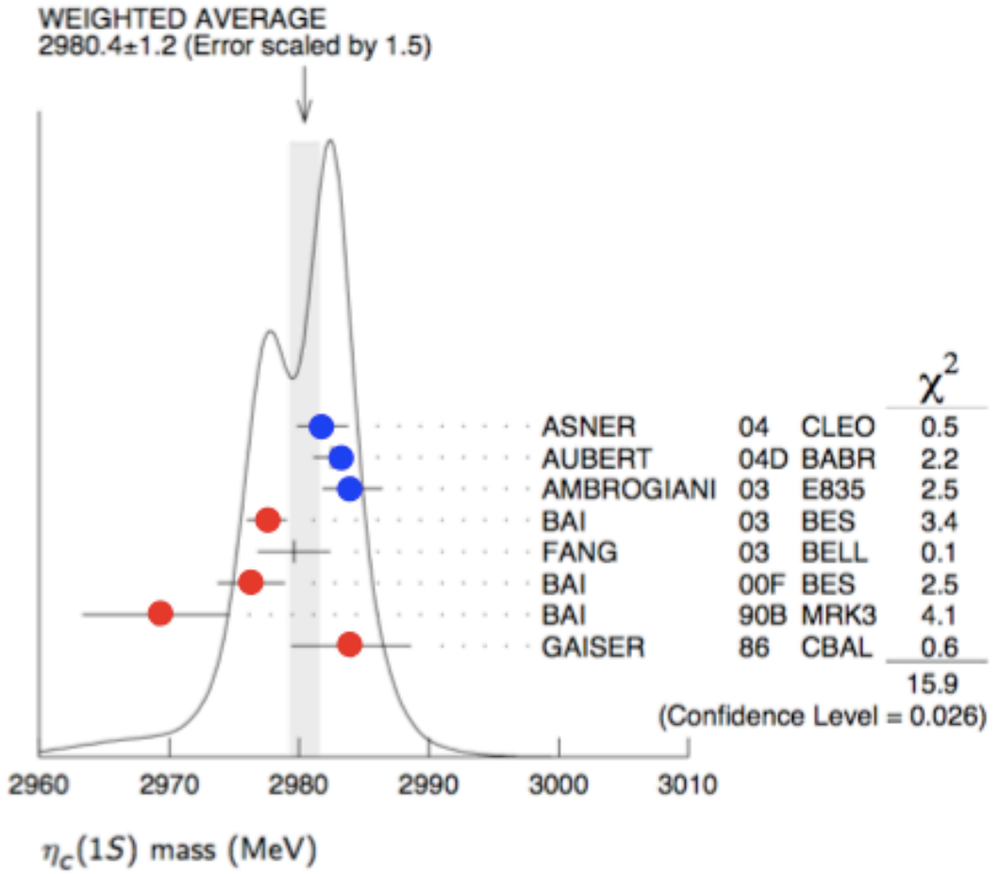
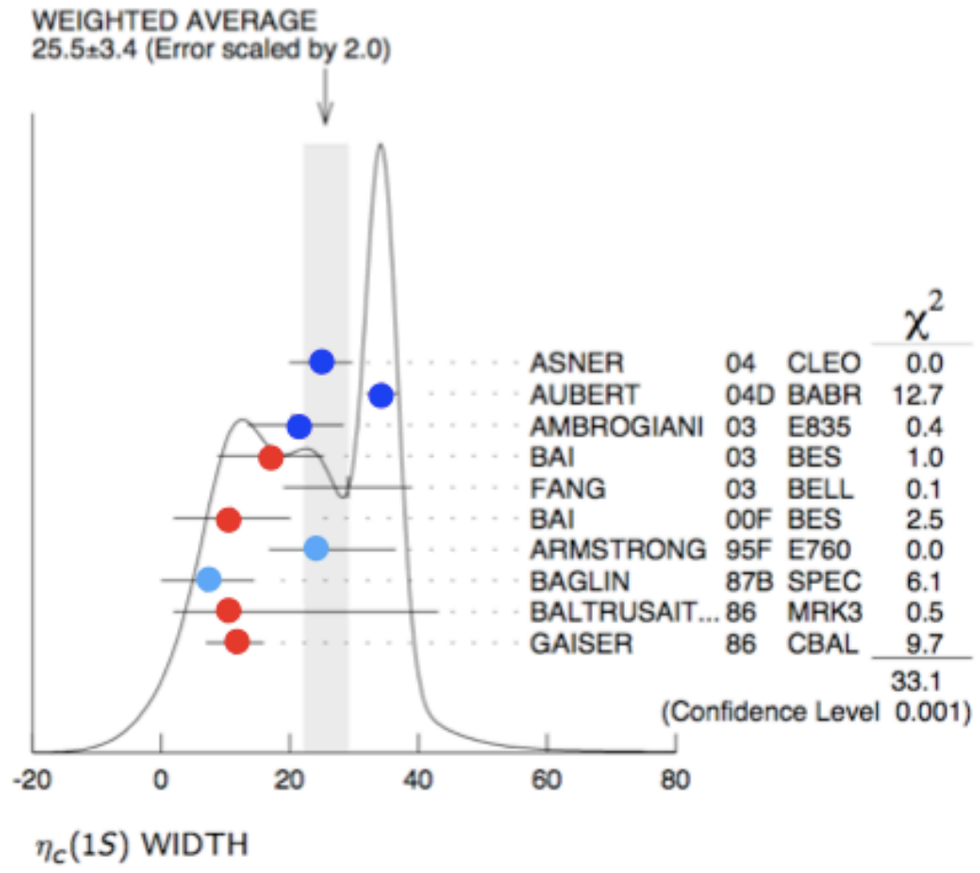
PHIPSI 08, INFN Frascati
April 10, 2008

J/ψ,ψ'→γηc







- γγ or p+p−
- γγ or p+p− (used for width, but not mass)
- ψ(1S,2S) → γηc