Radiative Transitions in Charmonia at CLEO

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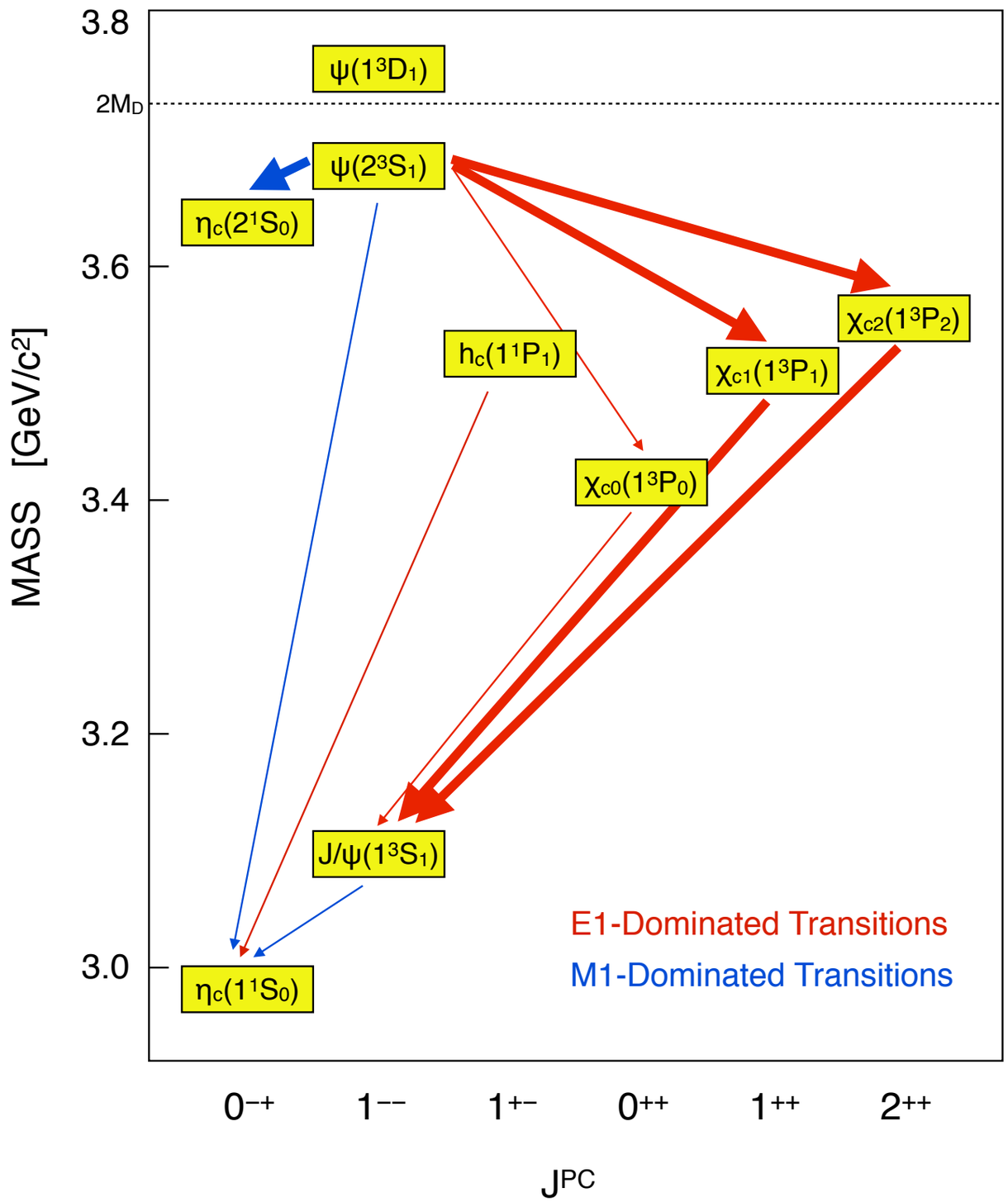
New Measurements from CLEO-c



CLEO-c final data set:

$(25.9 \pm 0.5) \times 10^6$ $\psi(2S)$ decays

(divided into two runs).

I. Higher multipoles in $\psi(2S) \to \gamma\chi_{cJ}$; $\chi_{cJ} \to \gamma J/\psi$ (PRD80, 112003 (2009))

- E1-dominated, but M2 contributions expected
- M2 sensitive to the anomalous magnetic moment of the charm quark
- old experimental discrepancies
- $(24.5 \pm 0.5) \times 10^6$ $\psi(2S)$ decays

II. Search for $\psi(2S) \to \gamma\eta_c(2S)$ (PRD81, 052002 (2010))

- allowed M1 transition
- old (1982) Crystal Ball report ruled out
- use exclusive $\eta_c(2S)$ decays and $\eta_c(2S) \to \pi^+\pi^-\eta_c(1S)$
- $(25.9 \pm 0.5) \times 10^6$ $\psi(2S)$ decays

I. Higher Multipoles in $\psi(2S) \to \gamma\chi_{cJ}$; $\chi_{cJ} \to \gamma J/\psi$

non-relativistic theoretical expectations for multipole amplitudes:

$\psi(2S) \to \gamma\chi_{c1}$ ⟶

$$b_2^{J=1} \equiv \frac{M2}{\sqrt{E1^2 + M2^2}} = \frac{E_{\gamma'}}{4m_c}(1 + \kappa_c)$$

$\psi(2S) \to \gamma\chi_{c2}$ ⟶

$$b_2^{J=2} \equiv \frac{M2}{\sqrt{E1^2 + M2^2 + E3^2}} = \frac{3}{\sqrt{5}}\frac{E_{\gamma'}}{4m_c}(1 + \kappa_c)$$

$\chi_{c1} \to \gamma J/\psi$ ⟶

$$a_2^{J=1} \equiv \frac{M2}{\sqrt{E1^2 + M2^2}} = -\frac{E_\gamma}{4m_c}(1 + \kappa_c)$$

$\chi_{c2} \to \gamma J/\psi$ ⟶

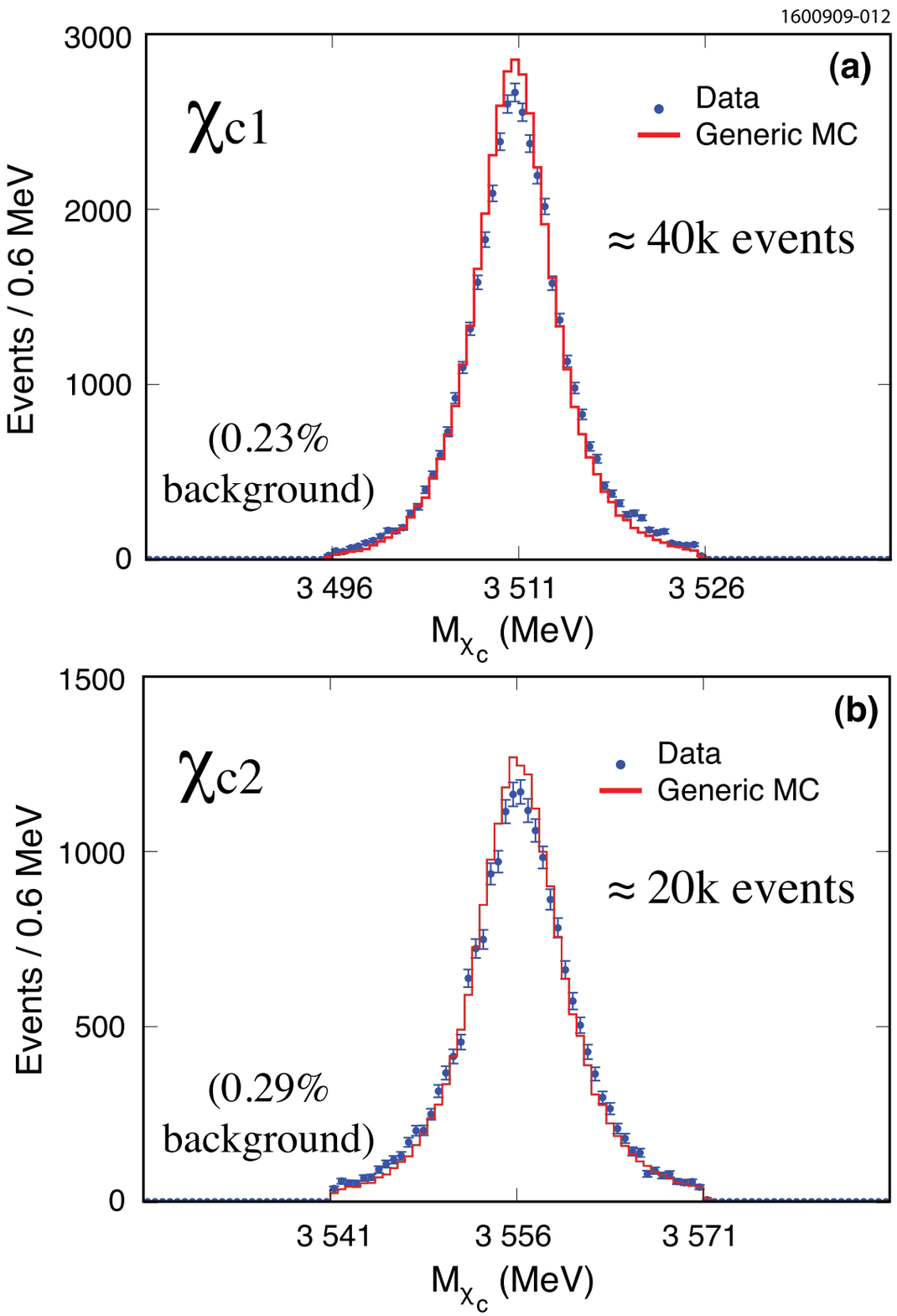
$$a_2^{J=2} \equiv \frac{M2}{\sqrt{E1^2 + M2^2 + E3^2}} = -\frac{3}{\sqrt{5}}\frac{E_\gamma}{4m_c}(1 + \kappa_c)$$

b: "before the χ_c"
a: "after the χ_c"
κ_c: anomalous magnetic moment of charm quark
m_c: mass of charm quark
$E_{\gamma'}$: photon energy from $\psi(2S) \to \gamma\chi_{cJ}$
E_γ: photon energy from $\chi_{cJ} \to \gamma J/\psi$

Notes:

- sensitivity to κ_c (anomalous magnetic moment of charm quark)
- E3 expected to be zero, but allowed if there is S-D ($\psi(2S)$) or P-F ($\chi(1P)$) mixing
- also recent lattice calculations (Dudek et al., PRD73, 074507 (2006), PRD79, 094504 (2009))

CLEO $\psi(2S) \to \gamma\chi_{cJ}$; $\chi_{cJ} \to \gamma J/\psi$ Data Samples



Event Selection:

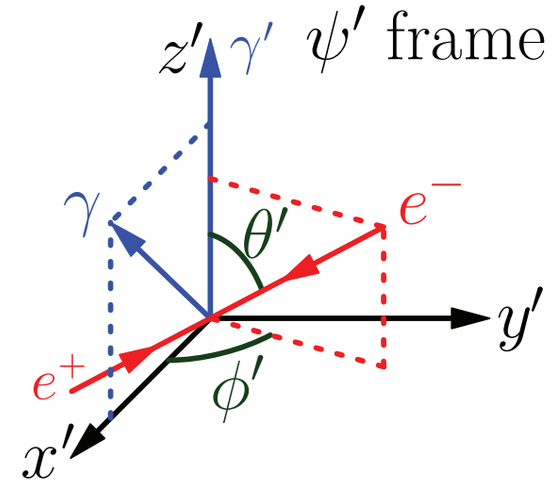
- decay chains:
  $\psi(2S) \to \gamma\chi_{cJ}$; $\chi_{cJ} \to \gamma J/\psi$; $J/\psi \to e^+e^-, \mu^+\mu^-$
- at least 2 tracks, 2 showers
- lepton identification via E/p
- kinematic fit to J/ψ mass (1C) and $\psi(2S)$ 4-momentum (4C)
- suppression of $\psi(2S) \to (\pi^0,\eta)J/\psi$ using J/ψ momentum

$\Rightarrow$ *clean samples well-described by MC*

Measuring Multipoles with Angular Distributions

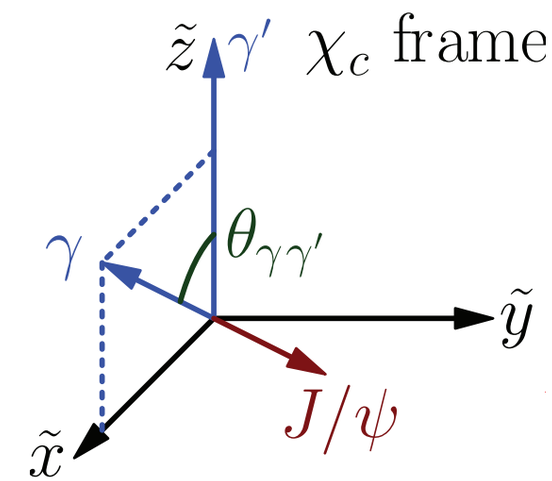
Angular distribution in the helicity formalism (depending on five angles):

$$W(\cos\theta', \phi', \cos\theta_{\gamma\gamma'}, \cos\theta, \phi)$$
$$\propto \sum_{\substack{\nu'\tilde{\nu}';\mu'=\pm1\\ \nu\tilde{\nu};\mu=\pm1}} \rho^{(\mu'-\nu',\mu'-\tilde{\nu}')}(\theta', \phi') B_{|\nu'|} B_{|\tilde{\nu}'|} d^{J_\chi}_{-\nu'\nu}(\theta_{\gamma\gamma'})$$
$$\times\, d^{J_\chi}_{-\tilde{\nu}'\tilde{\nu}}(\theta_{\gamma\gamma'}) A_{|\nu|} A_{|\tilde{\nu}|} \rho^{*(\nu-\mu,\tilde{\nu}-\mu)}(\theta, \phi),$$

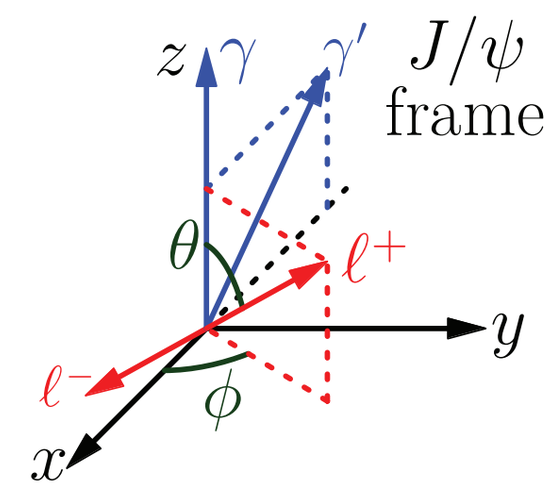


Relationship between helicity and multipole amplitudes:

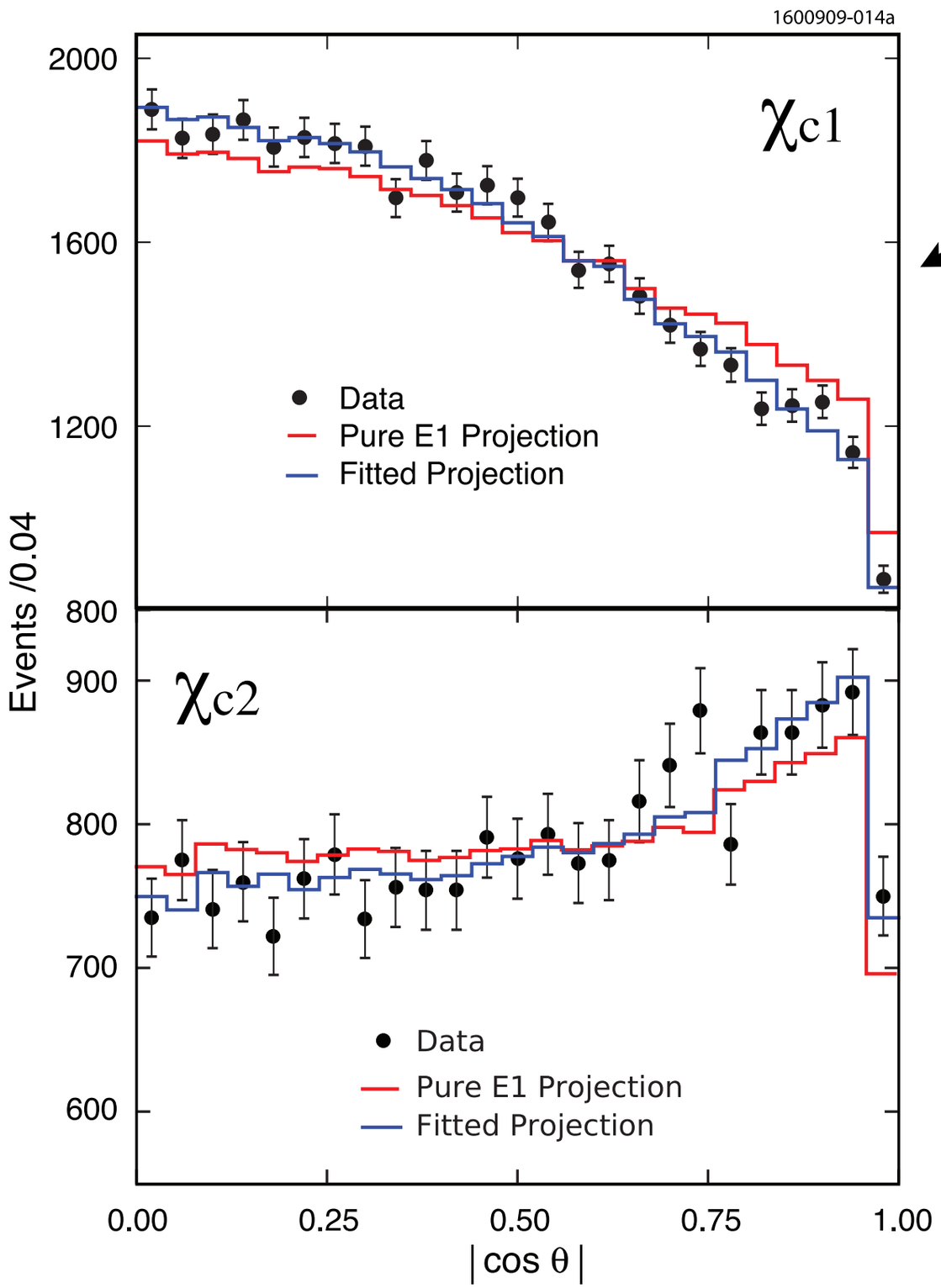
$$A^{J_\chi}_{\nu} = \sum_{J_\gamma} \sqrt{\frac{2J_\gamma+1}{2J_\chi+1}}\, a^{J_\chi}_{J_\gamma} \langle J_\gamma, 1; 1, \nu-1 | J_\chi, \nu\rangle$$



$\Rightarrow$ *Fit angular distributions to data using an unbinned maximum likelihood fit.*



Multipole Fit Projections



projection of cosine of angle between l^+ and γ from χ_{cJ} decay in J/ψ frame

⇒ *Significant differences between E1,M2 and pure E1 fits*

⇒ *Non-zero M2 amplitudes*

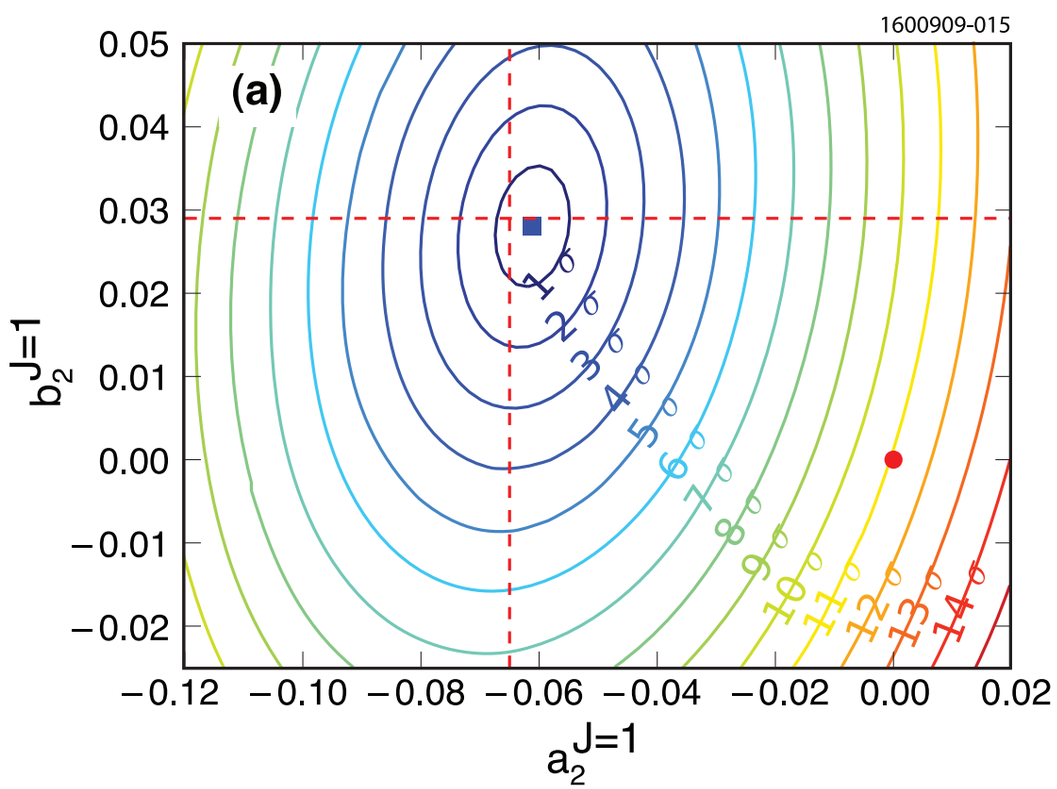
Statistical Results

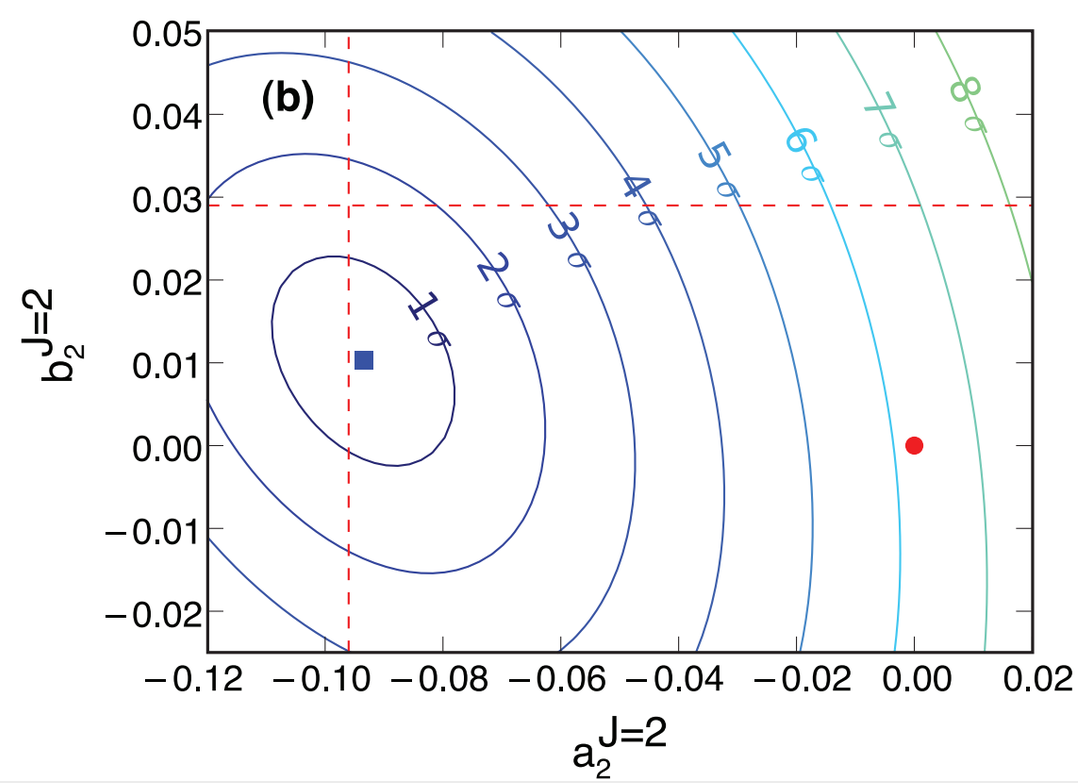
χ_{c1}

Fit	$a_2^{J=1}$ (10^{-2})	$b_2^{J=1}$ (10^{-2})	χ_{E1}
Two-parameter	-6.11 ± 0.63	2.81 ± 0.73	11.1
One-parameter ($a_2/b_2 = -2.274$)	-6.15 ± 0.55	2.71 ± 0.24	11.1
Theory ($m_c = 1.5$ GeV)	$-6.5(1 + \kappa_c)$	$2.9(1 + \kappa_c)$	

χ_{c2}

Fit	$a_2^{J=2}$ (10^{-2})	$b_2^{J=2}$ (10^{-2})	$a_3^{J=2}$ (10^{-2})	$b_3^{J=2}$ (10^{-2})	χ_{E1}
Two-parameter	-9.3 ± 1.6	1.0 ± 1.3	0	0	6.2
Three-parameter	-9.3 ± 1.6	0.7 ± 1.3	0	-0.8 ± 1.2	6.3
Two-parameter ($b_2 = \frac{-a_2}{3.367}$)	-9.2 ± 1.6	2.7 ± 0.5	0	-0.1 ± 1.1	6.1
Four-parameter	-7.9 ± 1.9	0.2 ± 1.4	1.7 ± 1.4	-0.8 ± 1.2	6.4
Theory ($m_c = 1.5$ GeV)	$-9.6(1 + \kappa_c)$	$2.9(1 + \kappa_c)$	0	Model dep.	





Cross-Checks and Systematic Errors

Cross-Checks:

- many toy MC fits
- varying size of MC sample used to calculate the "efficiency integral"
- separate fits for $J/\psi \rightarrow e^+e^-$ and $\mu^+\mu^-$
- etc.

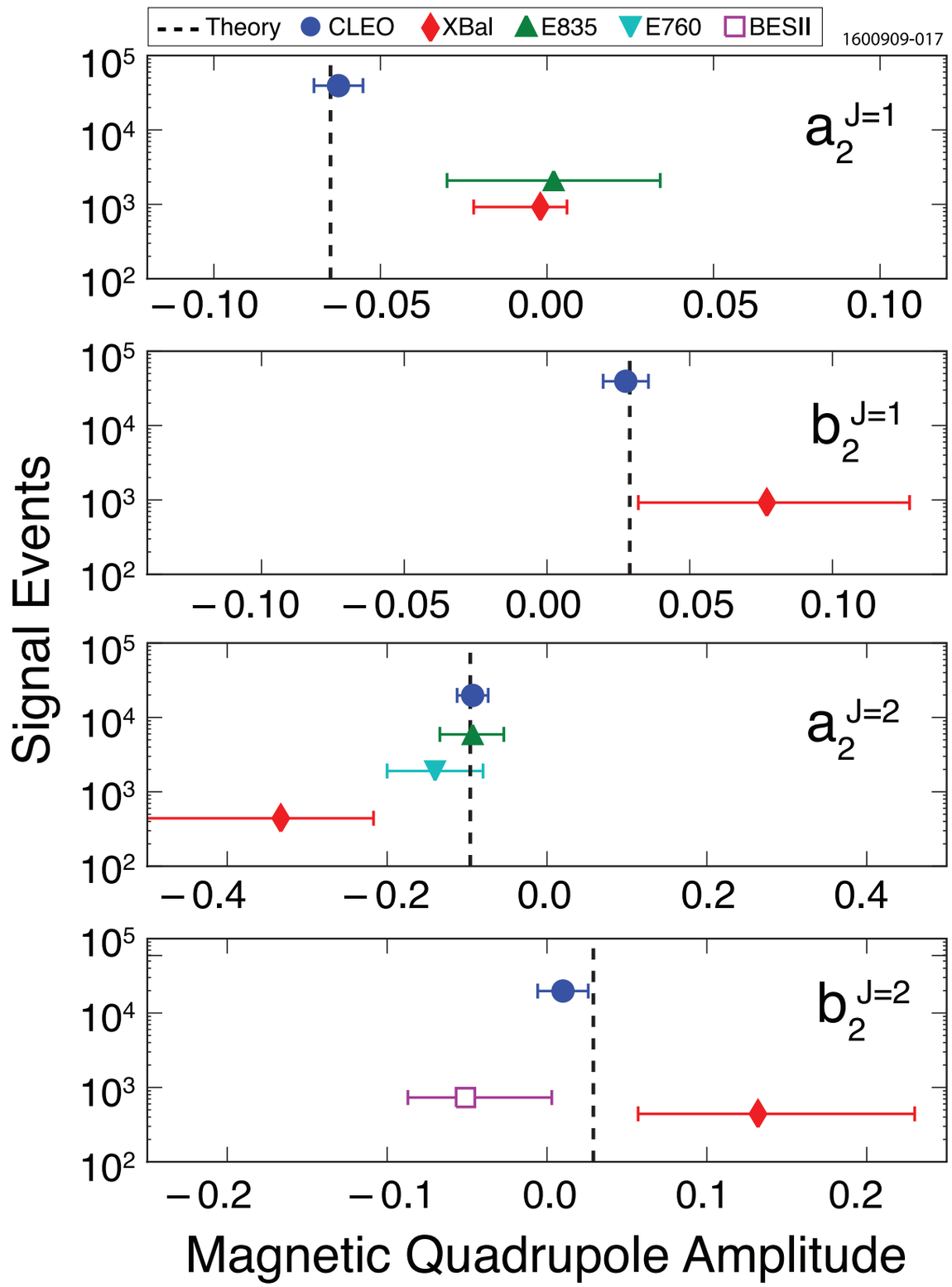
Systematic Errors:

- "Generic MC impurities" -- MC fits with and without predicted backgrounds
- "Selection criteria" -- ensembles of fits with variations on the selection criteria

systematic errors for J = 1; the J = 2 case is similar (except no biases):

Systematic uncertainty	$a_2^{J=1}$		$b_2^{J=1}$	
	Uncertainty (10^{-2})	Bias (10^{-2})	Uncertainty (10^{-2})	Bias (10^{-2})
Generic MC impurities	0.15	0.15	0.05	0.05
Selection criteria	0.19	-	0.22	-
Total systematic uncert.	0.24	0.15	0.23	0.05
Statistical uncertainty	0.63	-	0.73	-

Final Results (I)



CLEO's results:

χ_{c1}:

$$a_2^{J=1} = (-6.26 \pm 0.63 \pm 0.24) \times 10^{-2}$$

$$b_2^{J=1} = (2.76 \pm 0.73 \pm 0.23) \times 10^{-2}$$

χ_{c2} (E3 terms fixed to zero):

$$a_2^{J=2} = (-9.3 \pm 1.6 \pm 0.3) \times 10^{-2}$$

$$b_2^{J=2} = (1.0 \pm 1.3 \pm 0.3) \times 10^{-2}$$

$\Rightarrow$ *Good agreement with theory*
(m_c = 1.5 GeV/c^2, k_c = 0)

Final Results (II)

- E3 terms consistent with zero in all fit variations
  e.g. in the full 4-parameter fit:

$$a_3^{J=2} = (1.7 \pm 1.4 \pm 0.3) \times 10^{-2},$$

$$b_3^{J=2} = (-0.8 \pm 1.2 \pm 0.2) \times 10^{-2}$$

- Sensitivity to anomalous magnetic moment -- use:

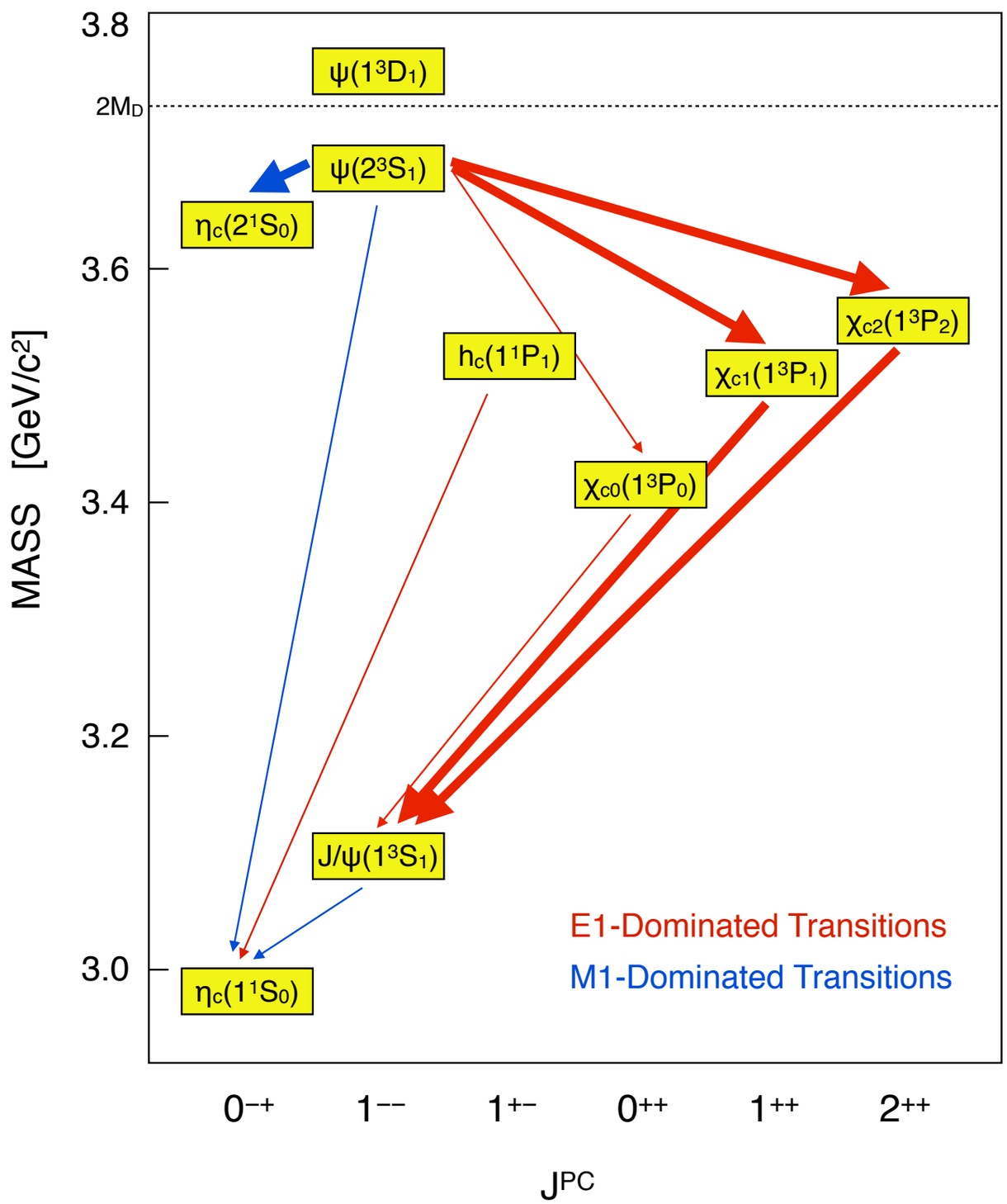
$$a_2^{J=1} = -\frac{E_\gamma}{4m_c}(1 + \kappa_c) = (1 + \kappa_c)/\xi$$

to measure (assuming $m_c = 1.5 \pm 0.3$ GeV/c^2):

$$1 + \kappa_c = \xi a_2^{J=1} = 0.877 \pm 0.088 \pm 0.034 \pm 0.175$$

$\Rightarrow$ *anomalous magnetic moment of charm quark consistent with zero*

II. Search for $\psi(2S) \to \gamma\eta_c(2S)$



Properties of the $\eta_c(2S)$:

- $\eta_c(2S)$ observed in B decays, $\gamma\gamma$ fusion, and $e^+e^- \to J/\psi X$
- only decay mode observed is $K_S K\pi$
- $M(\eta_c(2S)) = 3637 \pm 4$ MeV/c^2 [PDG 2009]
- $\Gamma(\eta_c(2S)) = 14 \pm 7$ MeV/c^2 [PDG 2009]

Search for $\psi(2S) \to \gamma\eta_c(2S)$:

- allowed M1 transition
- predicted BF from $(0.1 - 6.2) \times 10^{-4}$
- use exclusive decays of the $\eta_c(2S)$
- also look for $\eta_c(2S) \to \pi\pi\eta_c(1S)$

Analysis Strategy

1. Reconstruct $\psi(2S) \to \gamma X$, where X is one of many exclusive channels:

Channel	χ^2/d.o.f.	ϵ (%)
$K_S^0 K^\pm \pi^\mp$	<3.5	14.09 ± 0.10
$K^+ K^- \pi^0$	<4.0	17.55 ± 0.14
$K\bar{K}\pi$	$\cdots$	7.63 ± 0.04
$2(\pi^+\pi^-)$	<4.5	20.48 ± 0.16
$3(\pi^+\pi^-)$	<5.0	14.22 ± 0.14
$K^+K^-\pi^+\pi^-$	<4.0	19.50 ± 0.15
$K^+K^-\pi^+\pi^-\pi^0$	<2.5	8.68 ± 0.11
$K^+K^-2(\pi^+\pi^-)$	<4.0	9.93 ± 0.11
$K_S^0 K^\pm \pi^\mp \pi^+\pi^-$	<4.0	7.84 ± 0.09
$\pi^+\pi^-\eta,\ \eta \to \gamma\gamma$	<2.0	4.03 ± 0.04
$\pi^+\pi^-\eta,\ \eta \to \pi^+\pi^-\pi^0$	<3.0	1.65 ± 0.02
$\pi^+\pi^-\eta$	$\cdots$	5.68 ± 0.05
$K^+K^-\eta,\ \eta \to \gamma\gamma$	<3.5	4.55 ± 0.05
$K^+K^-\eta,\ \eta \to \pi^+\pi^-\pi^0$	<5.0	1.92 ± 0.02
$K^+K^-\eta$	$\cdots$	6.48 ± 0.05
$\pi^+\pi^-\eta'$	<3.0	1.42 ± 0.02

2. Look at photon energy spectrum down to 30 MeV

Event Selection:

- kinematic fit to $\psi(2S)$ 4-momentum, select on χ^2/d.o.f.
- $\Delta M \equiv M(\psi(2S)) - M(\text{hadrons})$ between 0 and 100 MeV/c^2
- J/ψ suppression
- etc.

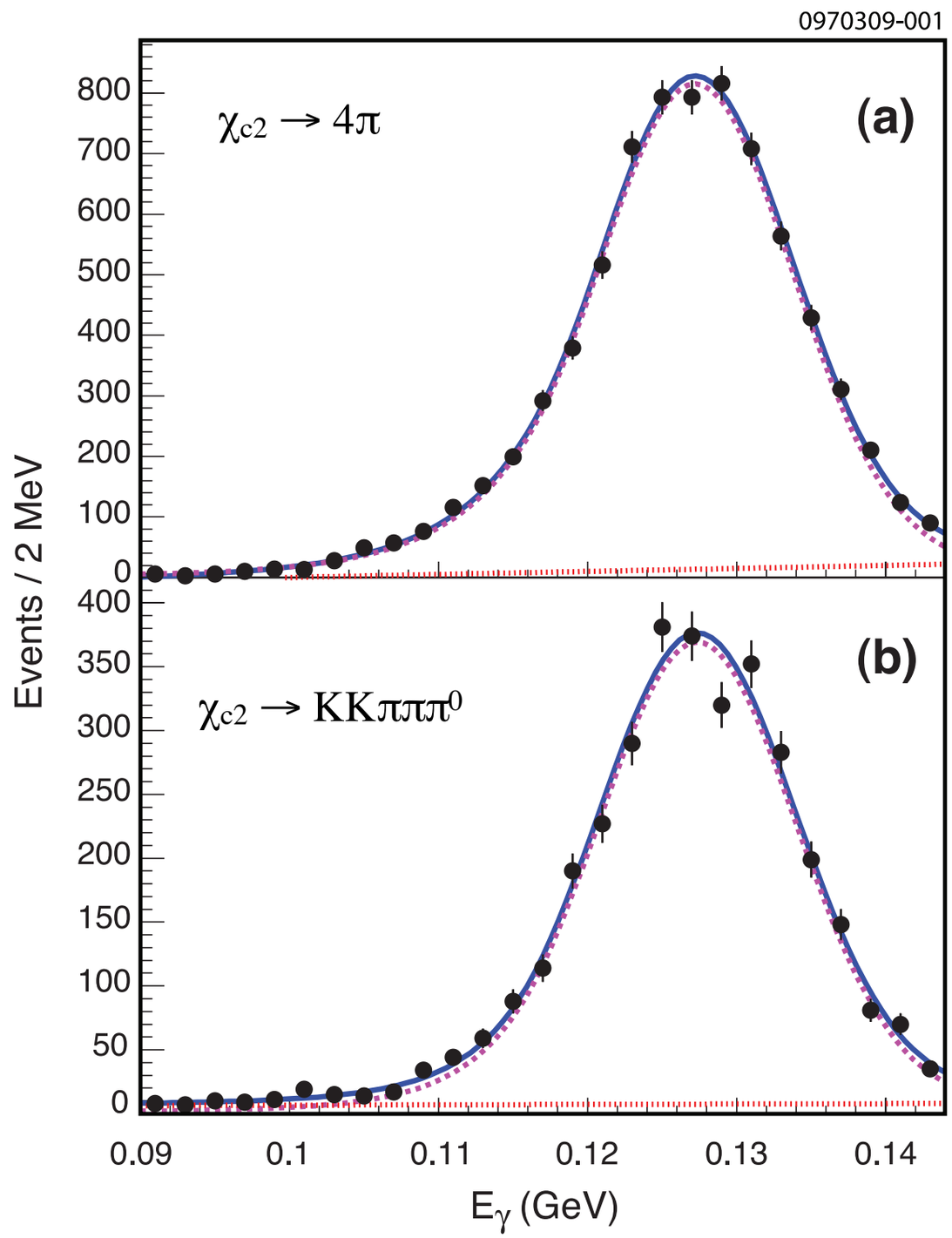
Background Determination:

- shape from MC
- floating normalization

Cross-checks:

- signal fitting checked with $\psi(2S) \to \gamma\chi_{c2};\ \chi_{c2} \to X$
- background shape checked with $\psi(2S) \to \pi\pi J/\psi;\ J/\psi \to X$

Using $\psi(2S) \to \gamma\chi_{c2}$; $\chi_{c2} \to X$ as a Cross-Check

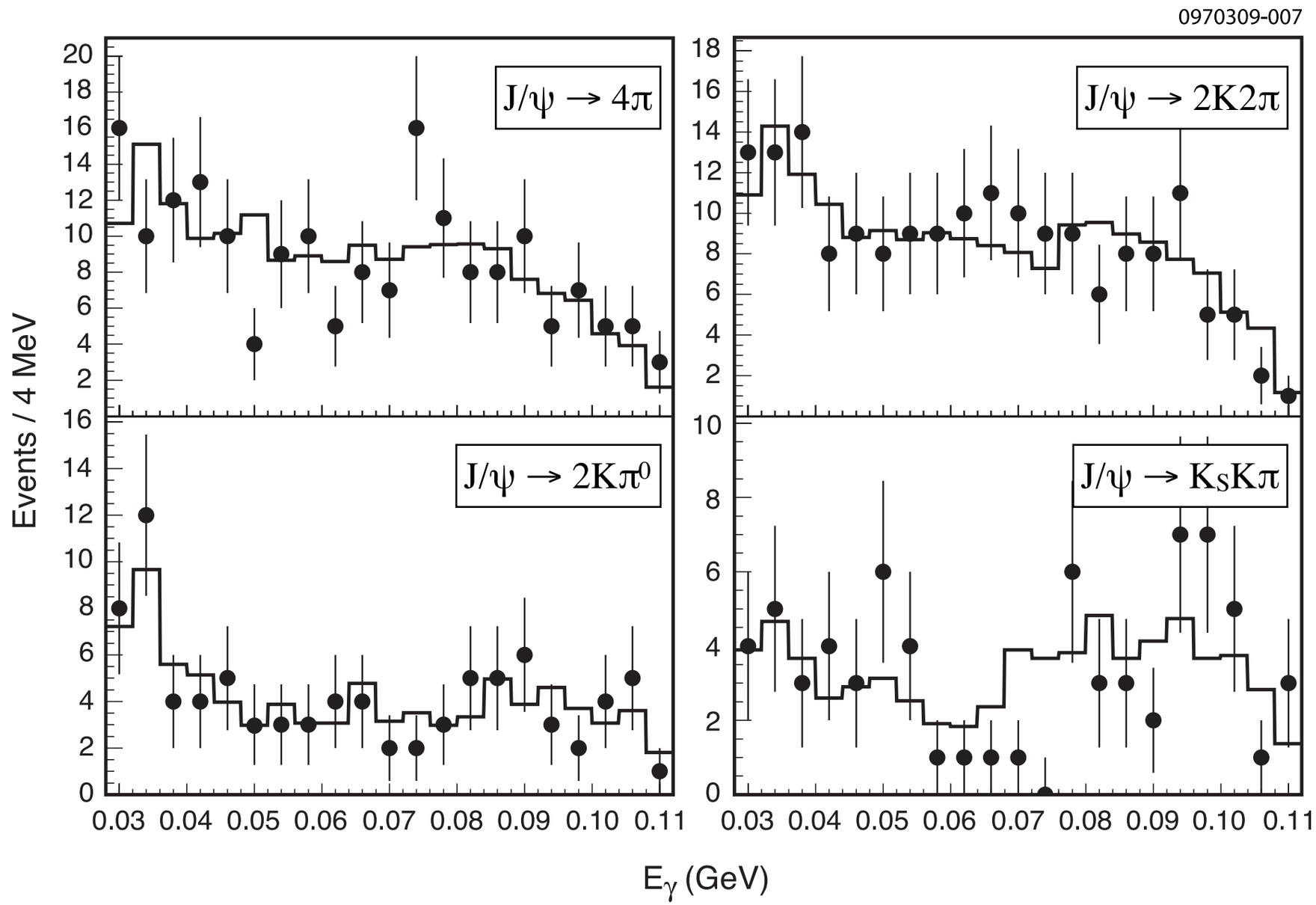


- Reconstruct $\psi(2S) \to \gamma X$, where X = same modes as before
- Remove ΔM requirement, look at higher photon energies
- Results:
  - Good fits $\Rightarrow$ good understanding of resolution function
  - Product BF's consistent with PDG

Using J/ψ Decays to Check Low-Energy Showers

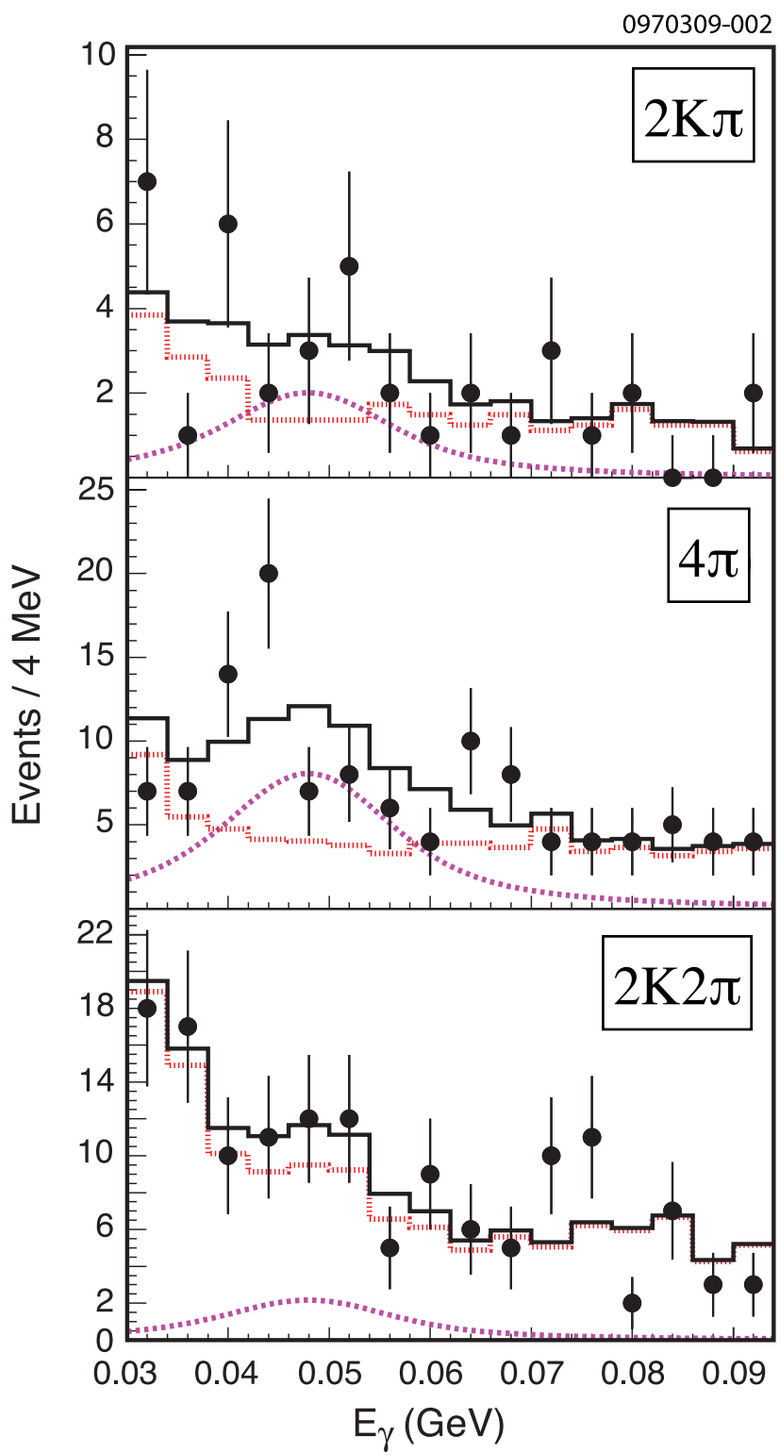
Reconstruct $\psi(2S) \to \pi\pi J/\psi$; $J/\psi \to X$

- showers due to FSR and hadronic "split-offs"
- "photon" energy spectrum reproduced well in MC



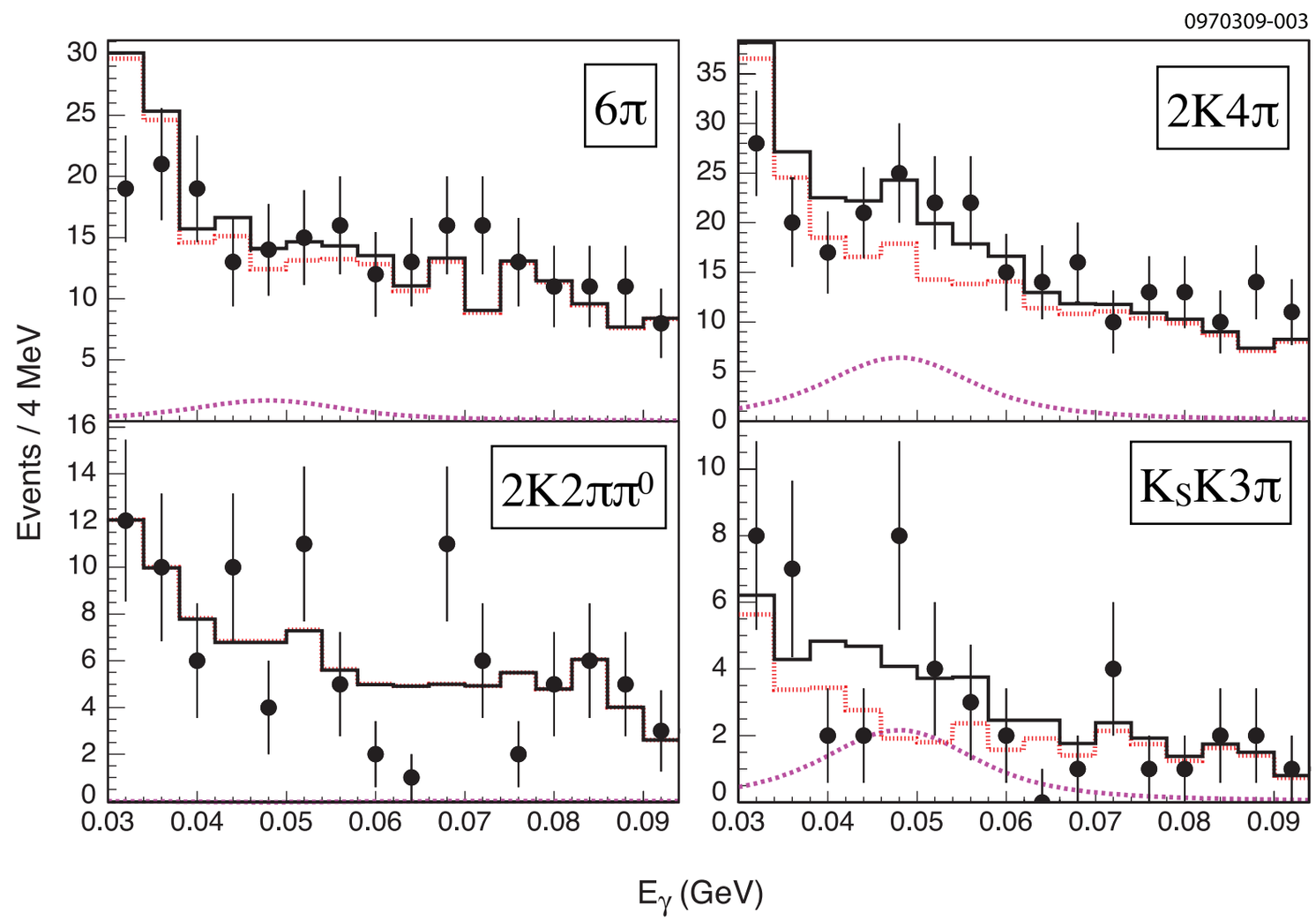
⇒ *trust MC to predict background in* $\psi(2S) \to \gamma\eta_c(2S)$

Looking in the Signal Region



Fit components:

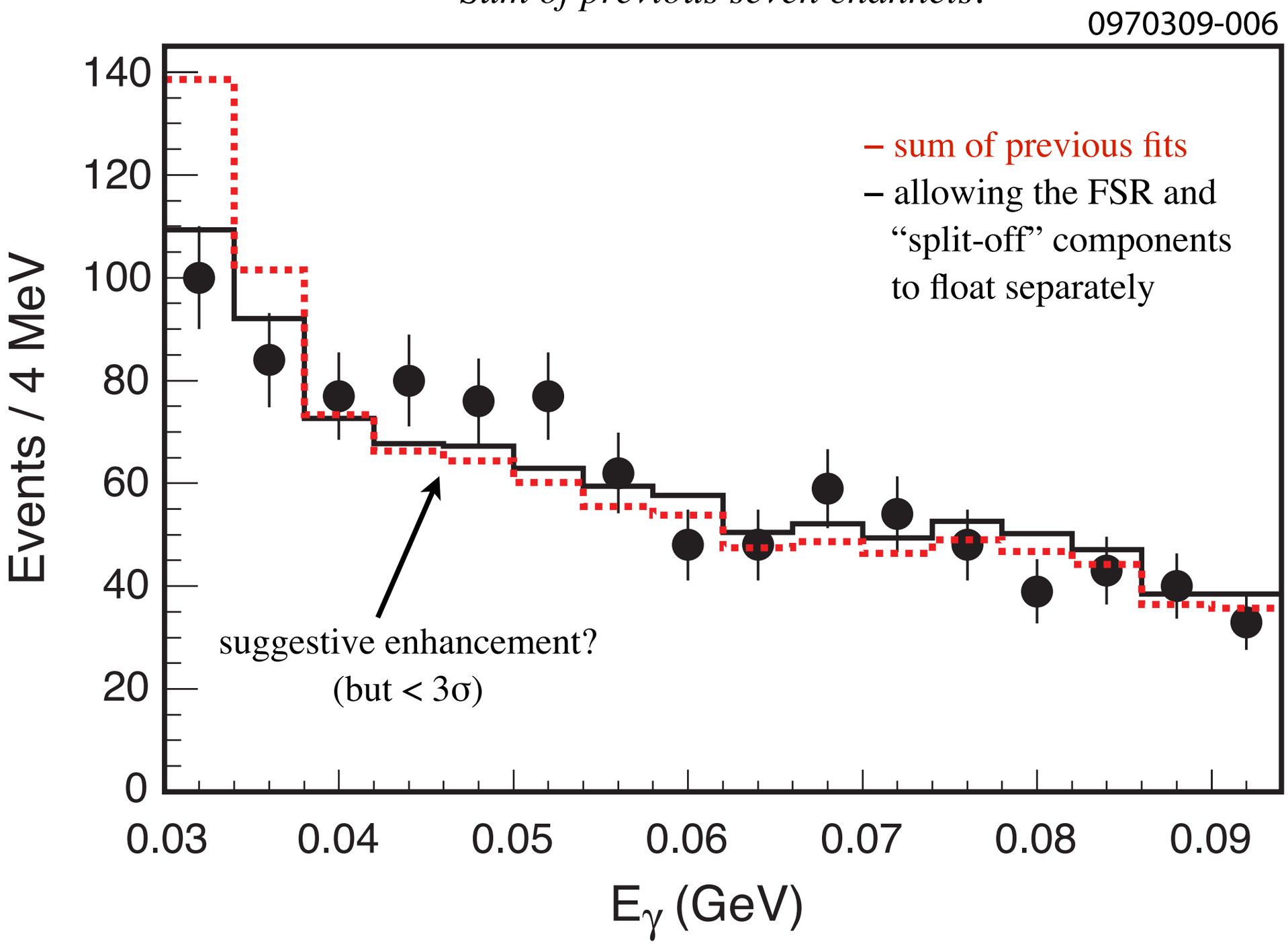
- signal (PDG mass and width convolved with resolution function)
- MC-predicted background (dominated by FSR and "split-offs")



⇒ *no significant signals seen*

Looking in the Signal Region

Sum of previous seven channels:



Results and Systematic Errors (I)

Table of final results for seven channels:

Channel	N_{sig}	χ^2/d.o.f.	Systematic uncertainties (%) A	B	C	D	E	Other	Total	B_1B_2 ($\times 10^{-6}$)	(90% C.L.)
$K\bar{K}\pi$	$11.7^{+7.8}_{-7.0}$	9.7/14	15.2	16.9	12.2	13.3	8.2	5.6	30.7	$5.9^{+4.0}_{-3.5} \pm 1.8$	<14.5
$2(\pi^+\pi^-)$	$47.9^{+13.6}_{-13.0}$	14.1/14	2.5	6.1	11.8	11.7	4.4	5.0	19.1	$9.0^{+2.6}_{-2.5} \pm 1.7$	<14.6
$3(\pi^+\pi^-)$	$10.1^{+18.1}_{-17.6}$	11.2/14	16.6	20.4	14.6	12.1	3.6	5.1	33.0	$2.7^{+4.9}_{-4.8} \pm 0.9$	<13.2
$K^+K^-\pi^+\pi^-$	$12.8^{+15.8}_{-15.6}$	9.2/14	7.7	32.6	7.1	13.8	4.4	4.5	37.2	$2.5^{+3.1}_{-3.1} \pm 0.9$	<9.6
$K^+K^-\pi^+\pi^-\pi^0$	$37.5^{+21.3}_{-20.8}$	13.8/14	22.7	15.2	29.7	24.5	0.9	7.2	47.8	$16.7^{+9.5}_{-9.3} \pm 8.0$	<43.0
$K^+K^-2(\pi^+\pi^-)$	$-0.3^{+12.6}_{-12.2}$	13.2/14	0.8	6.8	14.8	11.0	4.3	5.3	20.8	$-0.1^{+4.9}_{-4.7} \pm 0.1$	<9.7
$K^0_SK^\pm\pi^\mp\pi^+\pi^-$	$12.9^{+8.3}_{-7.5}$	11.9/14	13.2	17.8	16.3	5.6	5.2	5.0	29.0	$6.4^{+4.1}_{-3.7} \pm 1.8$	<15.2

Dominant uncertainties:

A. ΔM selection (remove selection and redo fits)

B. background parameterization (use 1st order polynomial)

C. $M(\eta_c(2S))$ (vary by 1σ around PDG value)

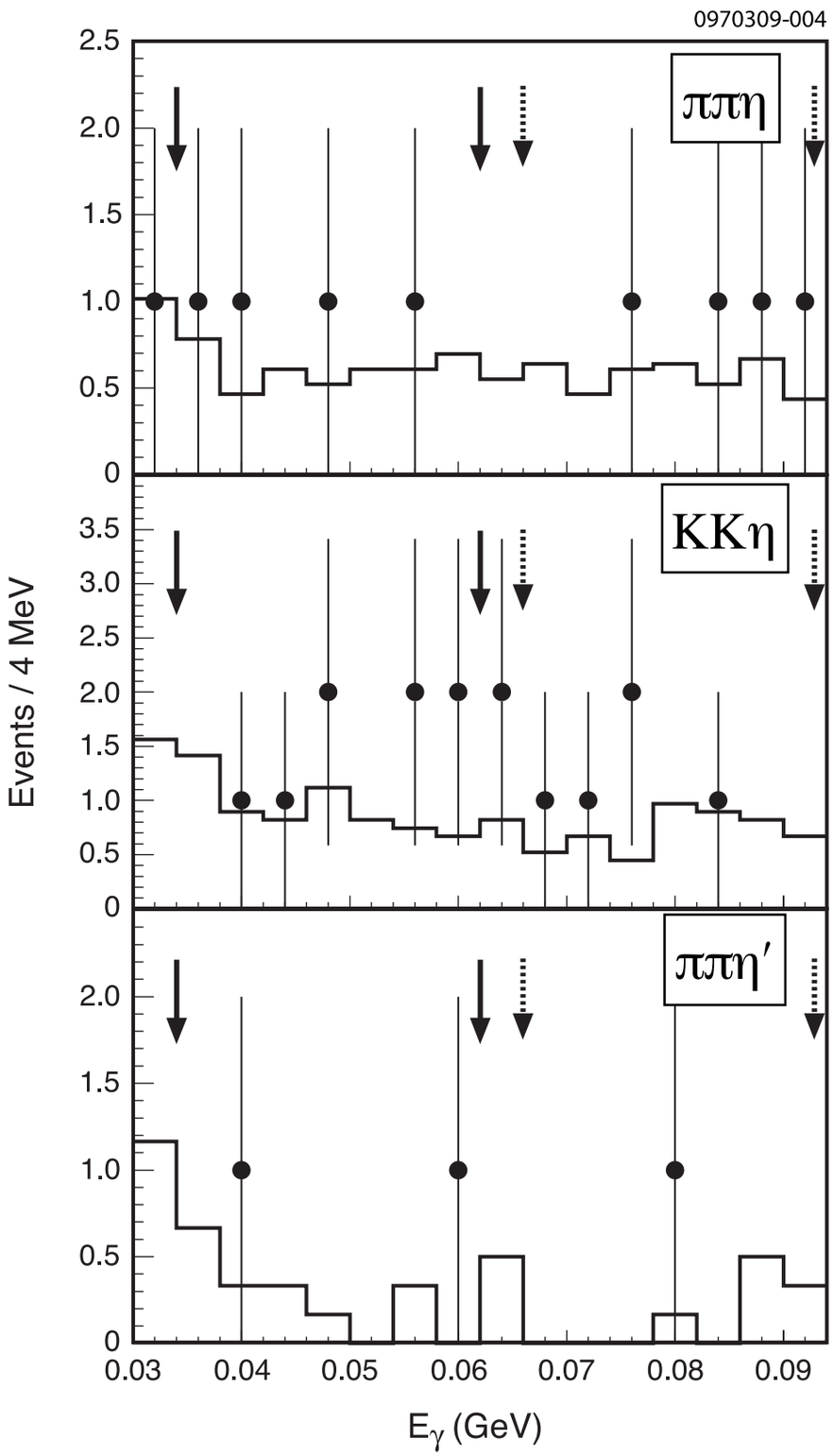
D. signal region (vary lower and upper bounds of fit range)

E. non-resonant background (fits to off-resonance data)

track and shower reconstruction efficiencies, $N(\psi(2S))$, etc.

NB: upper limits are also published as a function of $\Gamma(\eta_c(2S))$

Results and Systematic Errors (II)



Channels with η are handled differently:

- use sidebands to normalize background
- count signal and background events in the signal region

Table of final results for channels with η
(systematic uncertainties as before)

Channel	N_{obs}/N_{bg}	N_{sig}/ϵ (90% C.L.)	Systematic uncertainties (%) A	B	C	Other	Total	B_1B_2 ($\times 10^{-6}$) (90% C.L.)
$\pi^+\pi^-\eta$	4/4.3	<75.4	6.1	46.5	3.0	8.1	47.7	<4.3
$K^+K^-\eta$	8/6.5	<115.7	9.2	29.8	3.9	7.6	32.3	<5.9
$\pi^+\pi^-\eta'$	2/1.8	<287.9	8.9	24.5	3.7	7.4	27.3	<14.2

⇒ *no significant signals seen here either*

Search for $\eta_c(2S) \to \pi^+\pi^-\eta_c(1S)$

- Look for the chain:

  $\psi(2S) \to \gamma\eta_c(2S)$;

  $\eta_c(2S) \to \pi^+\pi^-\eta_c(1S)$;

  $\eta_c(1S) \to X$,

  where X =

  $K_SK\pi$, $KK\pi^0$,

  4π, $2K2\pi$

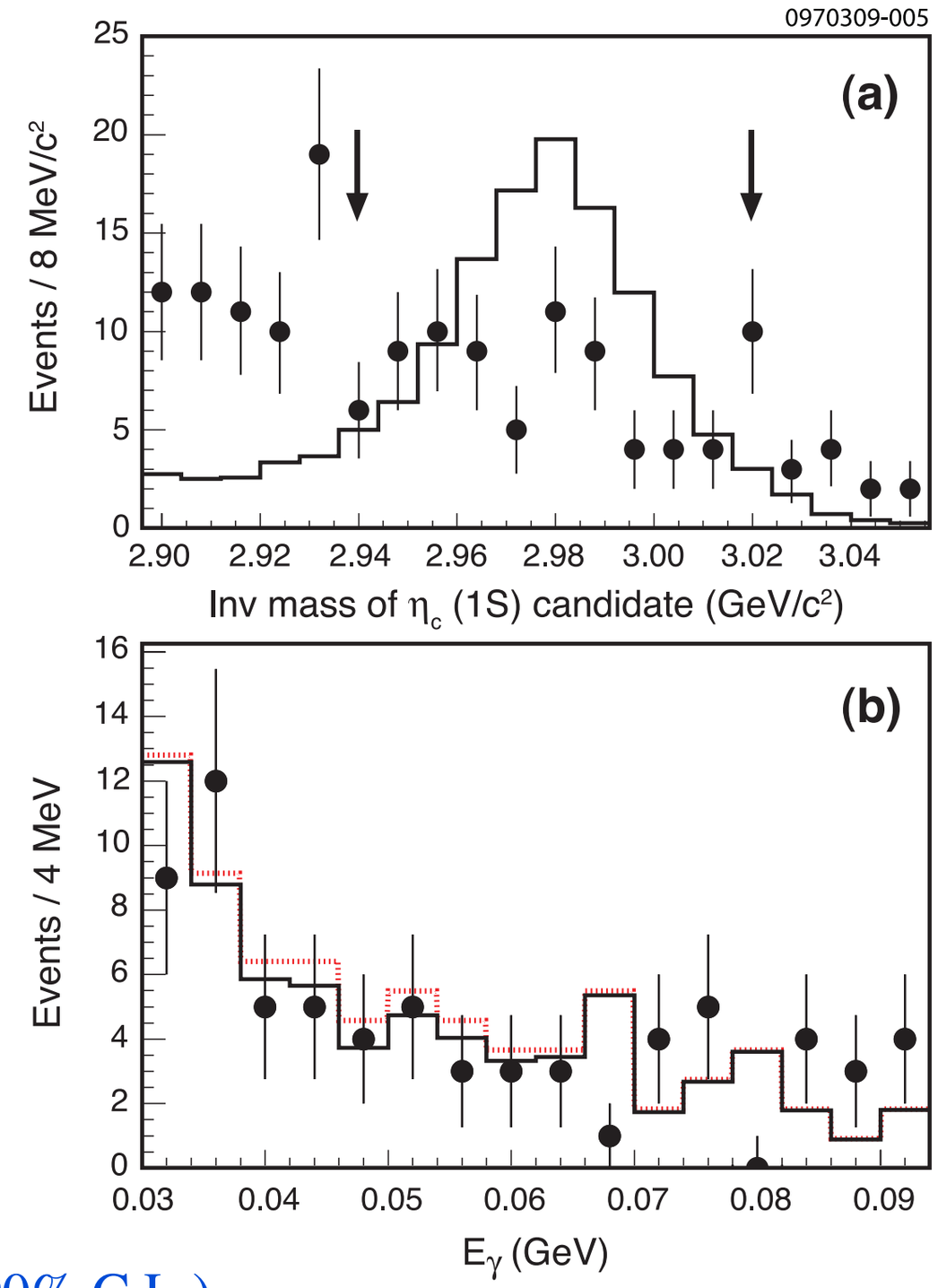
- Select $\eta_c(1S)$ mass

- Look at shower energy

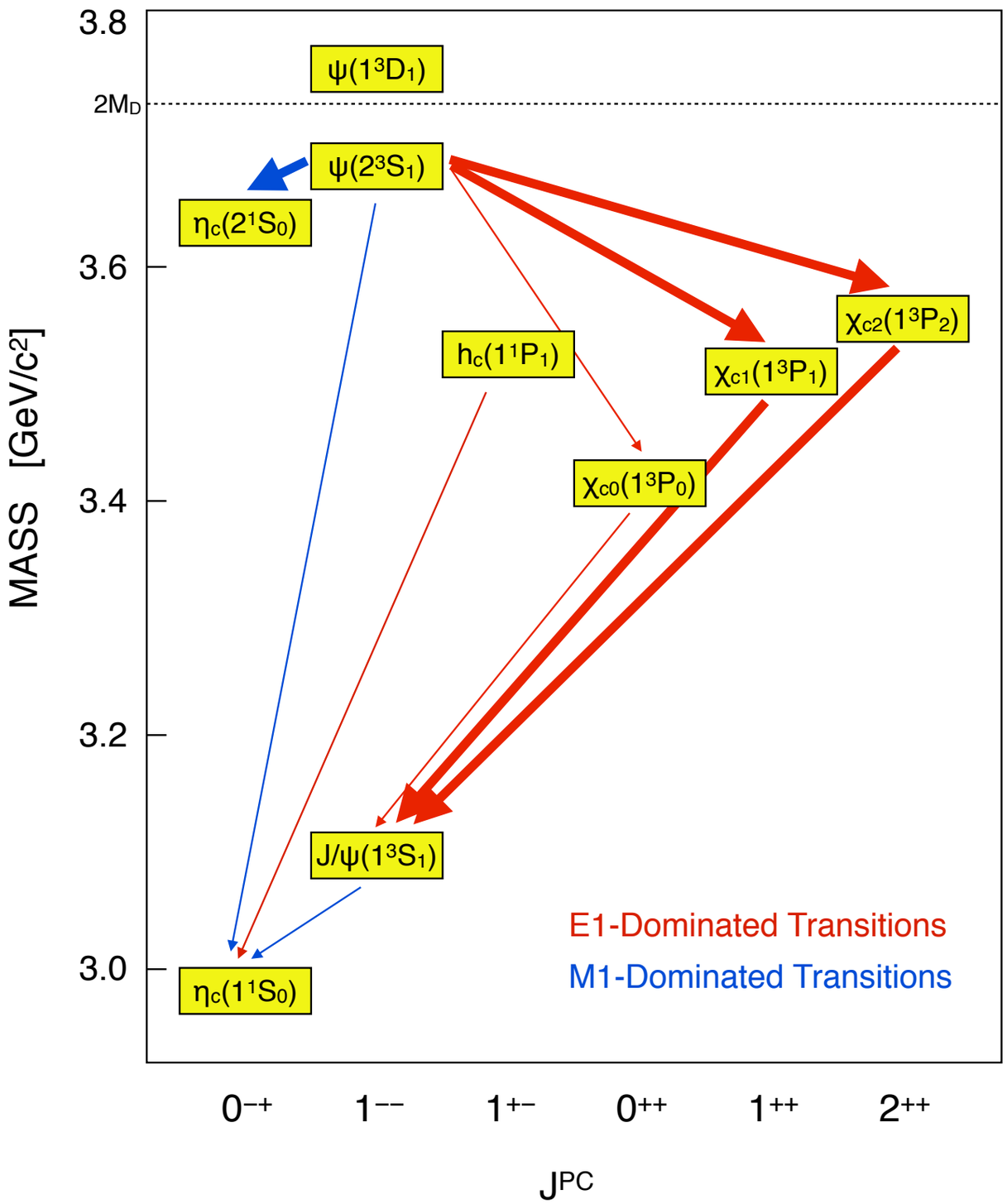
- Upper limits:

$$\mathcal{B}(\psi(2S) \to \gamma\eta_c(2S))\mathcal{B}(\eta_c(2S) \to \pi^+\pi^-\eta_c(1S)) = \frac{N_{\rm sig}}{N_{\psi(2S)}[\sum_i \epsilon_i \times \mathcal{B}_i(\eta_c(1S))]},$$

$= (-0.39^{+0.83}_{-0.76} \pm 0.18) \times 10^{-4} < 1.7 \times 10^{-4}$ (90% C.L.)



Summary



I. Higher multipoles in $\psi(2S) \to \gamma\chi_{cJ}$; $\chi_{cJ} \to \gamma J/\psi$
(PRD80, 112003 (2009))

- discrepancies with theory resolved
- significant M2 amplitudes
- no significant E3 amplitudes
- anomalous magnetic moment of charm quark consistent with zero

II. Search for $\psi(2S) \to \gamma\eta_c(2S)$
(PRD81, 052002 (2010))

- no signals
- upper limits on product branching fractions on the order of 10^{-5}