Recent Charmonium Results from CLEO-c

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on behalf of the CLEO-c Collaboration

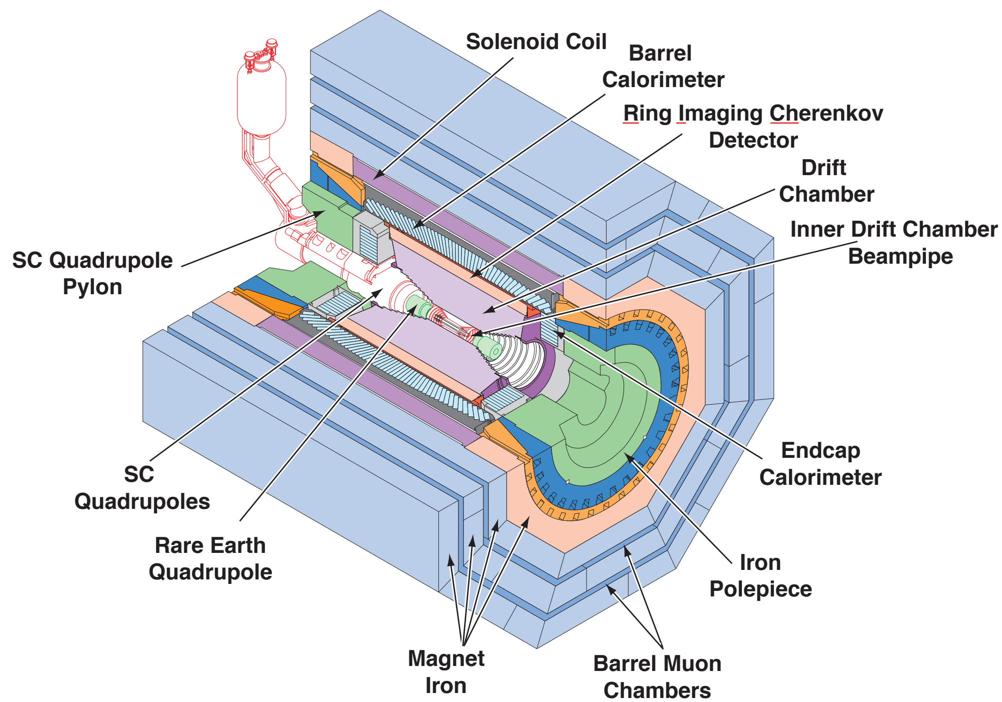
The Laboratory: CLEO-c & CESR

Cornell Electron Storage Ring

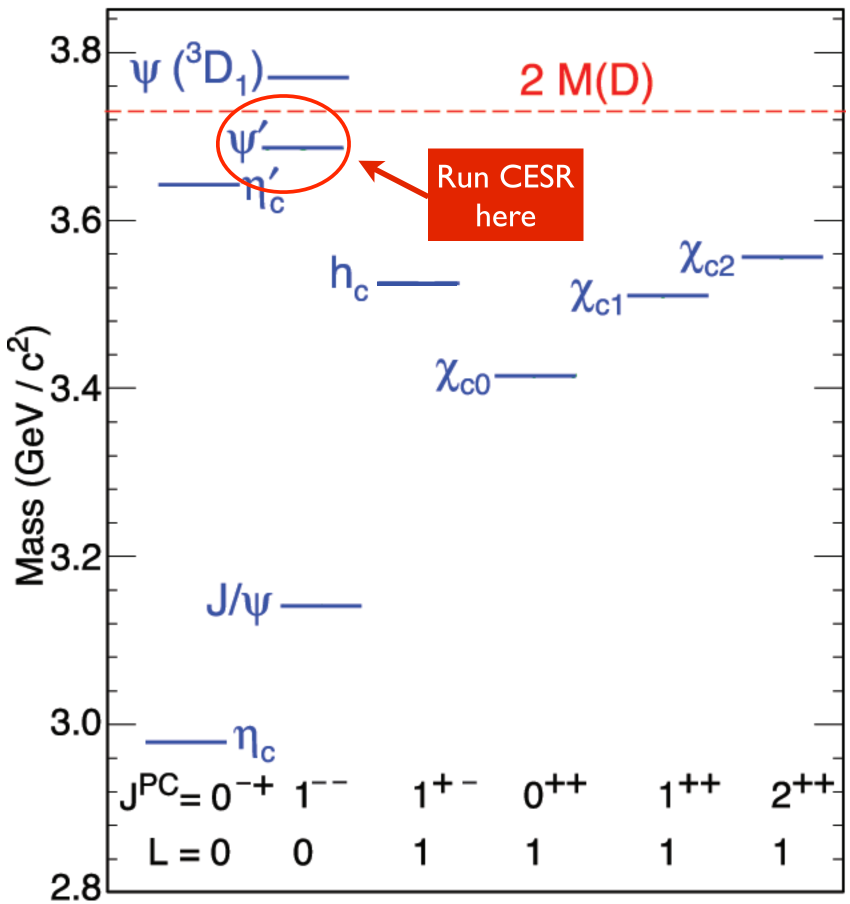
- e^+e^- collider
- $\sqrt{s}$ = 3-11 GeV
- Home to CLEO experiment since 1975

CLEO-c: A general purpose hermetic detector

- 93% of 4π coverage
- 1Tesla superconducting solenoid encasing:
  - CsI calorimeter
    ΔE/E ~ 5% at 100 MeV
  - Drift chamber, dE/dx
    Δp/p ~ 0.6% at 1 GeV
  - RICH



The Laboratory: Charmonium Spectrum



NB ψ'≡ψ(2S)

CLEO-c Data Samples

Open charm

600 pb^{-1} at 4170 MeV

818 pb^{-1} at ψ(3770)

This talk

54 pb^{-1} at ψ(2S)

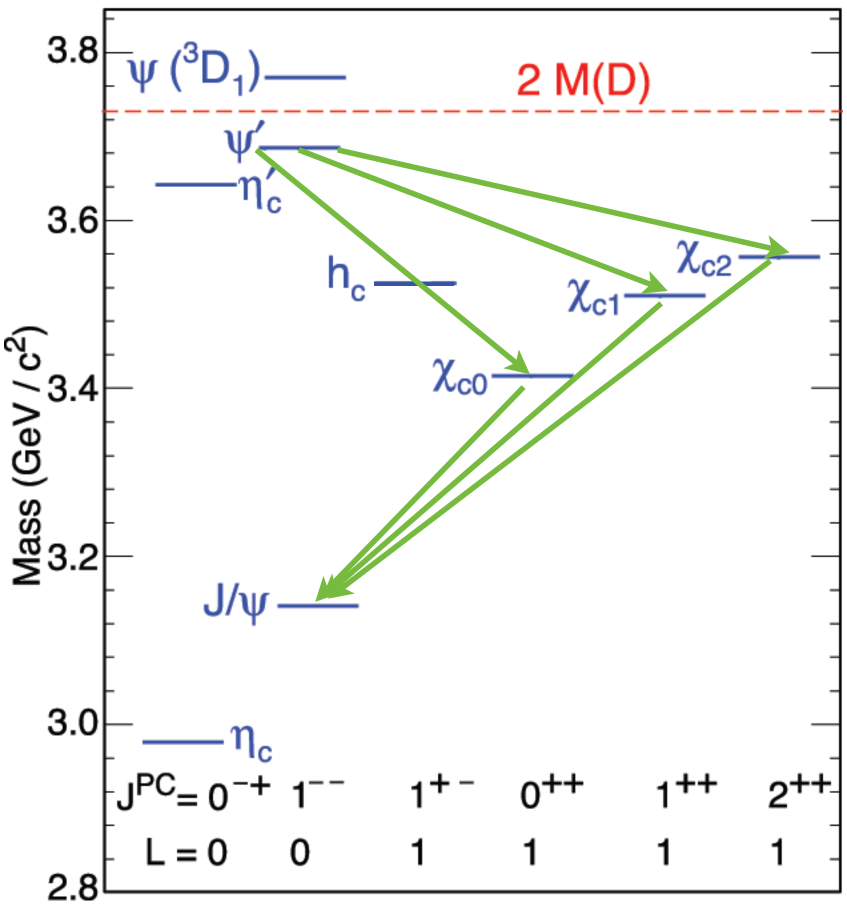
- 27M ψ(2S) *Largest world sample (pre-BESIII)*
- + χ_{cJ} [B(ψ → χ_{cJ} X) ~30%]
- + J/ψ [B(ψ → J/ψ X) ~60%]

Able to study:

- Spectroscopy
- Hadronic Transitions
- EM Transitions
- Hadronic Decays etc...

Final CLEO-c data taken March 2008

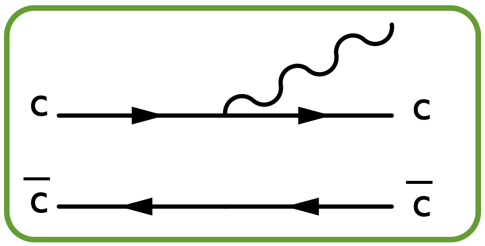
This Talk



Higher Order Multipole Amplitudes in Charmonium Radiative Transitions

Inclusive Radiative ψ(2S) Decays

Exclusive χ_{cJ} Decays



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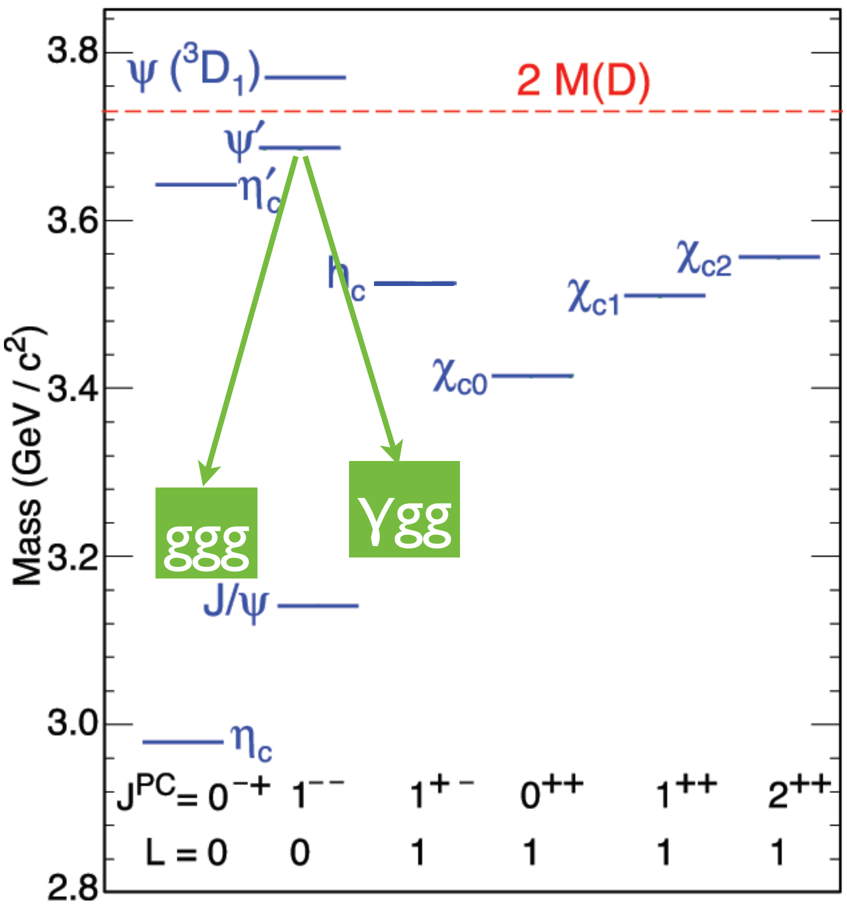

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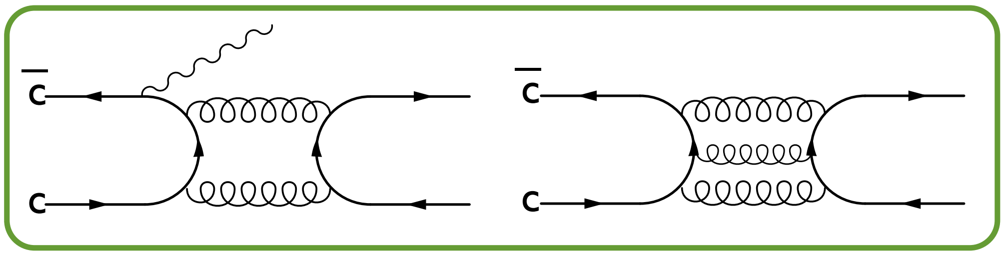

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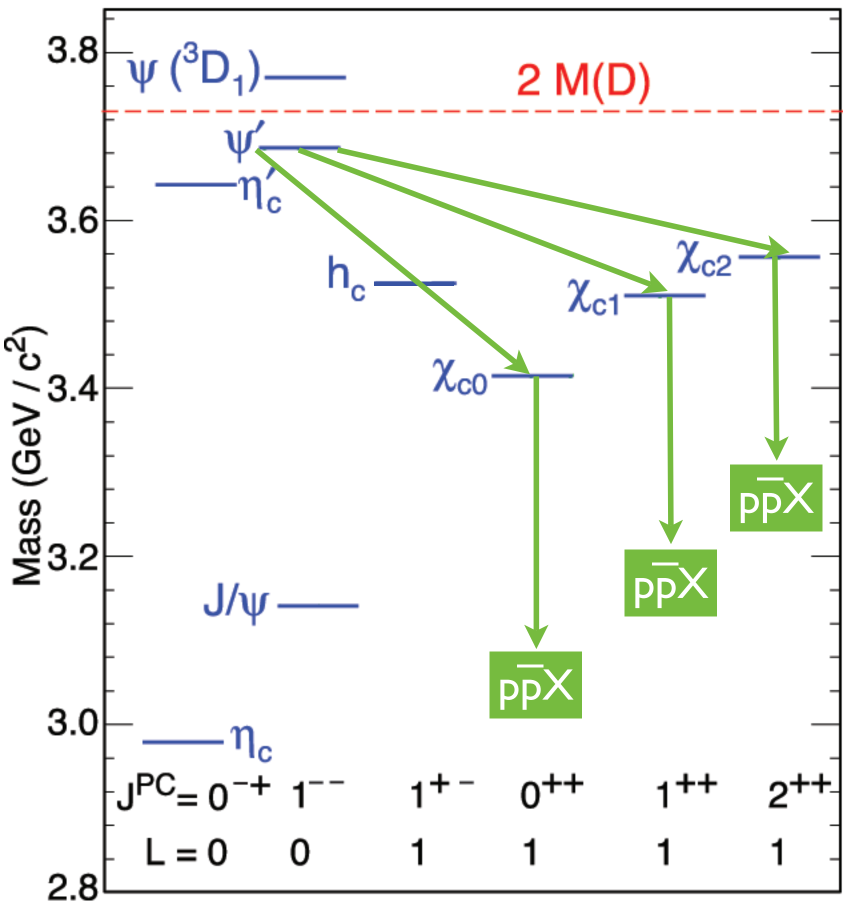
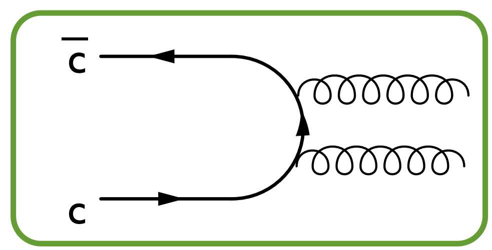


Higher Order Multipole Amplitudes in Charmonium Radiative Transitions

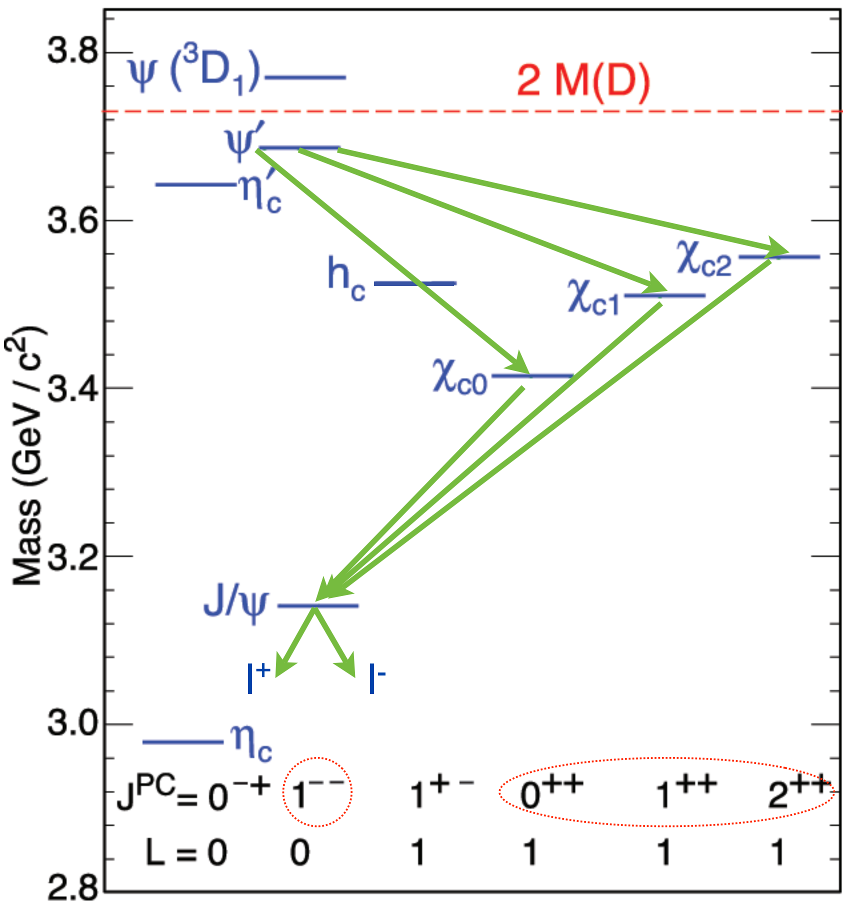
Inclusive Radiative $\psi(2S)$ Decays

Exclusive χ_{cJ} Decays

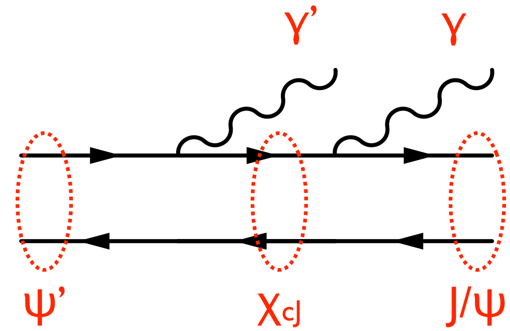


Higher Order Multipole Amplitudes in Charmonium Radiative Transitions

PRD 80 112003 (2009)



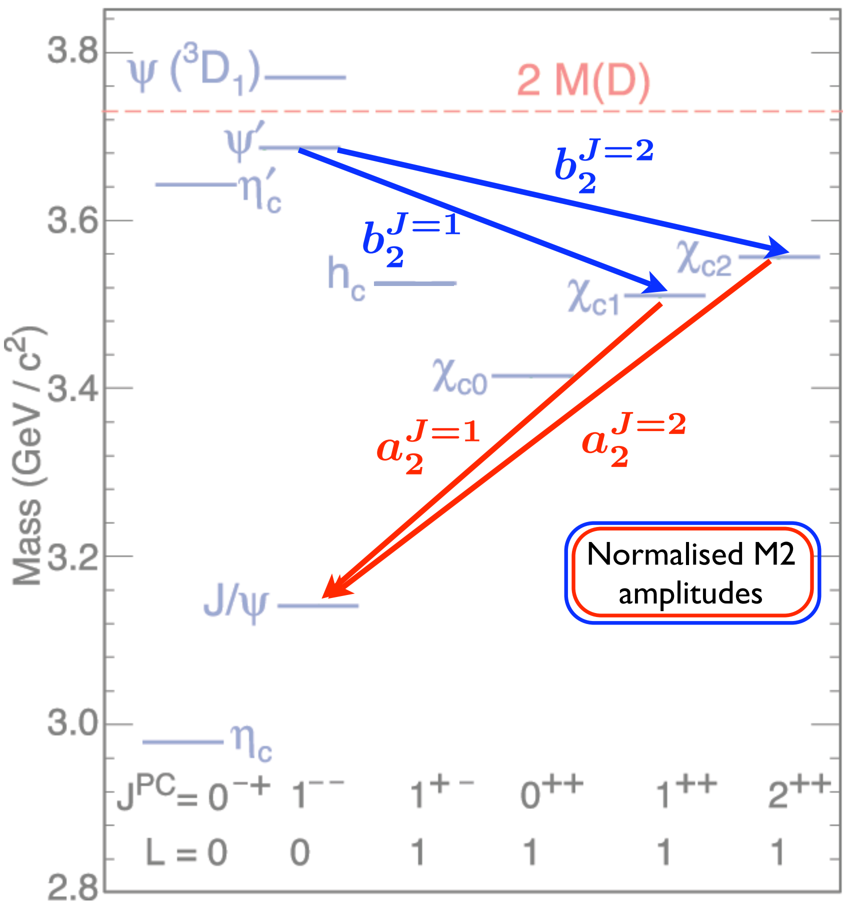
$$e^+e^- \rightarrow \gamma^* \rightarrow \psi'$$
$$\psi' \rightarrow \gamma' \chi_c$$
$$\chi_c \rightarrow \gamma J/\psi$$
$$J/\psi \rightarrow l^+l^-$$



- Dominated by E1 transitions but M2 and E3 allowed.
  - Only E1 allowed for χ_{c0} sequence.
  - E1 and M2 allowed for χ_{c1}, χ_{c2} sequences.
  - E3 should be zero in absence of ψ’ S-D mixing.
- Previous experimental measurements of M2 amplitudes (going back to 1980) are in disagreement with theory.
- Magnetic transition: spin of one quark interacting with magnetic field of the other. M2 is sensitive to the *magnetic moment* of *c quark.*

Higher Order Multipole Amplitudes in Charmonium Radiative Transitions

PRD 80 112003 (2009)



- Assuming ψ(1S), ψ(2S) are pure S states and χ_{c1}, χ_{c2} are pure P states and the interaction Hamiltonian:

vector potential of emitted photon

$$H = -\frac{e_c}{2m_c}\left(\mathbf{A}^* \cdot \mathbf{p} + \mathbf{p} \cdot \mathbf{A}^*\right) - \mu\sigma \cdot \mathbf{H}^*$$

H* = ∇ x A*

$$\left[\mu = \frac{e_c}{2m_c}(1+\kappa_c)\right]$$

- The fraction decaying via M2 (to first order in E_γ/m_c):

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

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

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

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

Anomalous magnetic moment of the charm quark

- Ratios of amplitudes are *independent of κ_c , m_c*.

Higher Order Multipole Amplitudes in Charmonium Radiative Transitions

PRD 80 112003 (2009)

$$e^+e^- \to \gamma^* \to \psi'$$
$$\psi'(\lambda') \to \gamma'(\mu')\chi_c(\nu')$$
$$\chi_c(\nu) \to \gamma(\mu)J/\psi(\lambda)$$
$$J/\psi \to l^+l^-$$

Helicities:

$\lambda' = \mu' - \nu'$

$\nu = \mu - \lambda$

- Use the helicity formalism to construct the joint angular distribution of the 2 photons γ and γ'.

ψ' spin density matrix

Helicity Amplitudes

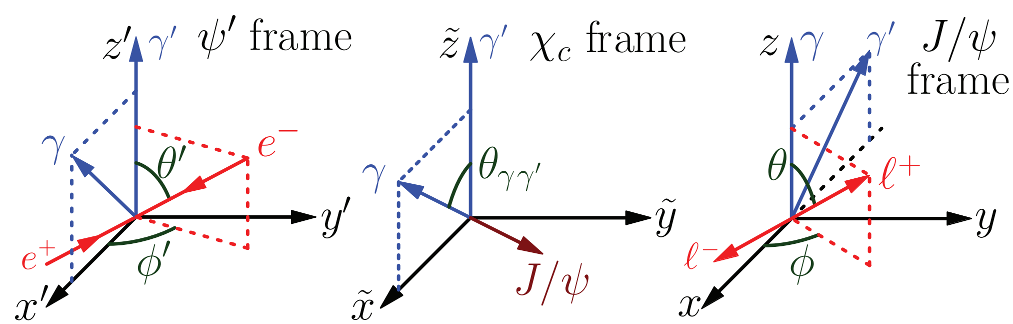
$$W(cos\theta', \phi', cos\theta_{\gamma\gamma'}, cos\theta, \phi)$$
$$\propto \sum \rho^{(\mu'-\nu',\mu'-\bar{\nu}')}(\theta',\phi')B_{|\nu'|}B_{|\bar{\nu}'|}d^{J_\chi}_{-\nu'\nu}(\theta_{\gamma\gamma'})$$
$$\times\, d^{J_\chi}_{-\bar{\nu}'\bar{\nu}}(\theta_{\gamma\gamma'})A_{|\nu|}A_{|\bar{\nu}|}\rho^{*(\nu-\mu,\nu-\bar{\mu})}(\theta,\phi)$$

Coherent sum over allowed helicities

J/ψ spin density matrix

- 2 step decay is completely defined by θ',φ' $\theta_{\gamma\gamma}$, θ, φ [Φ].

θ',φ' sensitive to ψ' polarisation



θ, φ sensitive to J/ψ polarisation

$\theta_{\gamma\gamma'}$ gives rotation between two frames

Higher Order Multipole Amplitudes in Charmonium Radiative Transitions

PRD 80 112003 (2009)

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ψ' spin density matrix

Helicity Amplitudes

Coherent sum over allowed helicities

J/ψ spin density matrix

$$W\left(cos\theta', \phi', cos\theta_{\gamma\gamma'}, cos\theta, \phi\right) \propto \sum \rho^{(\mu'-\nu',\mu'-\bar{\nu}')}(\theta',\phi')B_{|\nu'|}B_{|\bar{\nu}'|}d^{J_\chi}_{-\nu'\nu}(\theta_{\gamma\gamma'}) \times d^{J_\chi}_{-\bar{\nu}'\bar{\nu}}(\theta_{\gamma\gamma'})A_{|\nu|}A_{|\bar{\nu}|}\rho^{*(\nu-\mu,\nu-\bar{\mu})}(\theta,\phi)$$

- 2 step decay is completely defined by θ',φ' $\theta_{\gamma\gamma}$, θ, φ [Φ].

- Perform an unbinned maximum likelihood fit in 5 parameter Φ to extract the helicity amplitudes.

Minimise the log likelihood

Sum over data

Acceptance

$$-2ln\mathcal{L} = -\sum_{i=1}^{N} ln\left(W\left(\Phi_i\right)\right) + \int W\left(\Phi\right)\eta\left(\Phi\right)d\Phi$$

Higher Order Multipole Amplitudes in Charmonium Radiative Transitions

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ψ' spin density matrix

Coherent sum over allowed helicities

Helicity Amplitudes

J/ψ spin density matrix

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Minimise the log likelihood

Sum over data

Acceptance

$$-2ln\mathcal{L} = -\sum_{i=1}^{N} ln(W(\Phi_i)) + \int W(\Phi)\eta(\Phi)d\Phi$$

• Recover multipole amplitudes via:

Helicity amplitudes

Multipole amplitudes

$$\begin{pmatrix} A_0^{J=2} \\ A_1^{J=2} \\ A_2^{J=2} \end{pmatrix} = \begin{pmatrix} \sqrt{\frac{1}{10}} & \sqrt{\frac{1}{2}} & \sqrt{\frac{2}{5}} \\ \sqrt{\frac{3}{10}} & \sqrt{\frac{1}{6}} & -\sqrt{\frac{8}{15}} \\ \sqrt{\frac{3}{5}} & -\sqrt{\frac{1}{3}} & \sqrt{\frac{1}{15}} \end{pmatrix} \begin{pmatrix} a_1^{J=2} \\ a_2^{J=2} \\ a_3^{J=2} \end{pmatrix}$$

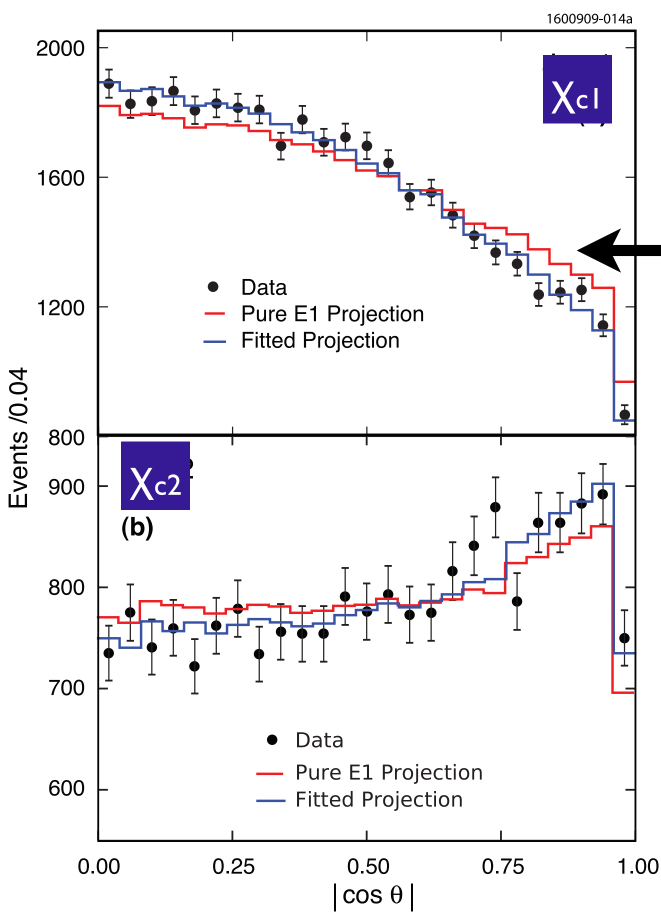
Clebsch Gordon Coefficients

Higher Order Multipole Amplitudes in Charmonium Radiative Transitions

PRD 80 112003 (2009)

Results

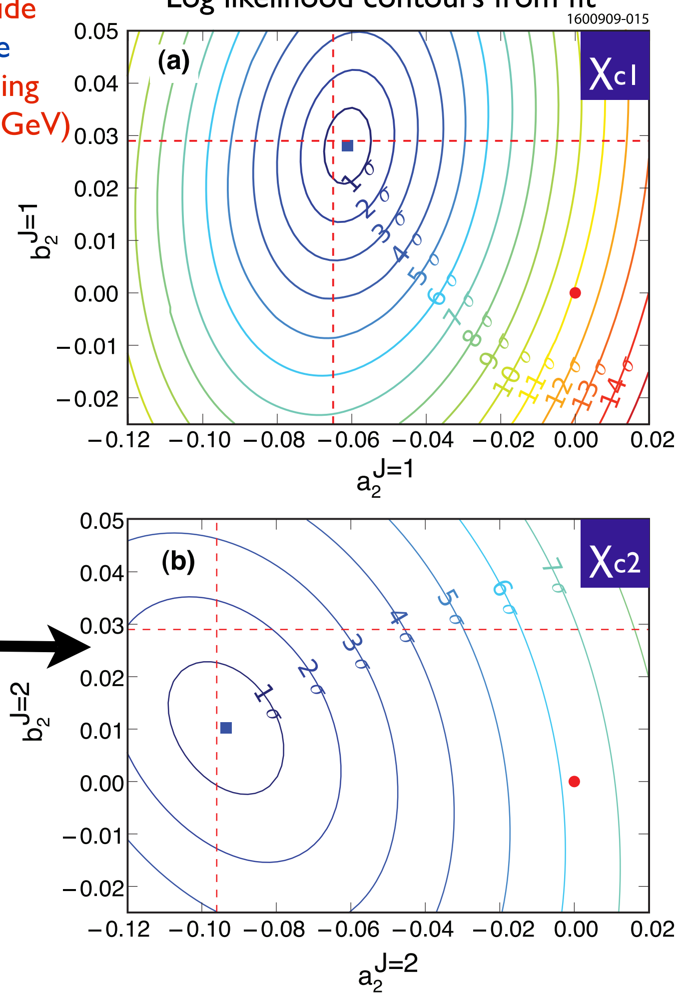
Projecting from the unbinned fit onto cosθ:



Evident in projections that a pure E1 amplitude does not fit the data well.

● Pure E1 amplitude
■ E1+ M2 mixture
········ Theory (Assuming $\kappa_c = 0$, $m_c = 1.5$GeV)

Log likelihood contours from fit



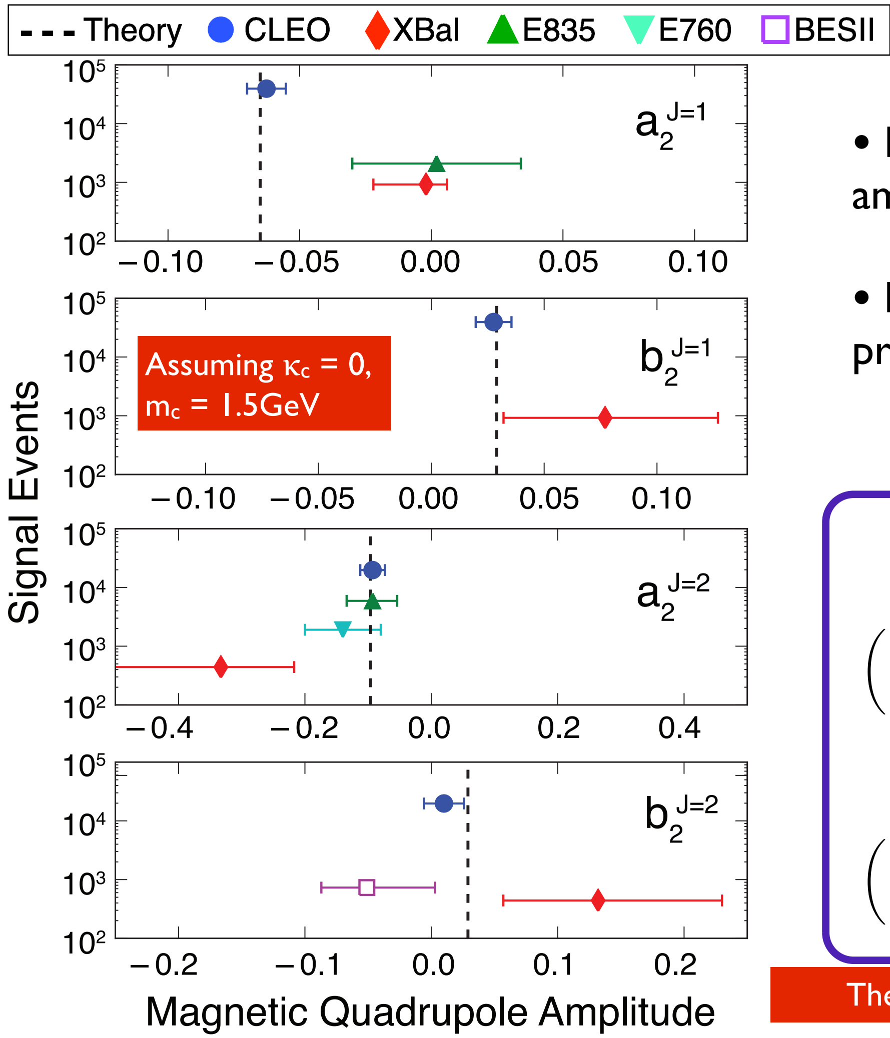
Pure E1 amplitudes are inconsistent with data at the 11σ and 6σ level.

(E3 amplitude fixed to 0 in these fits)

Higher Order Multipole Amplitudes in Charmonium Radiative Transitions

PRD 80 112003 (2009)

Results



- Results show strong of evidence of non-zero M2 amplitudes.

- Excellent agreement with theory - resolves previous experimental/theoretical disagreement.

$$\left(\frac{a_2^{J=1}}{a_2^{J=2}}\right)_{CLEO} = 0.67^{+0.19}_{-0.13} \stackrel{?}{=} \left(\frac{a_2^{J=1}}{a_2^{J=2}}\right)_{th} = 0.676 \pm 0.071$$

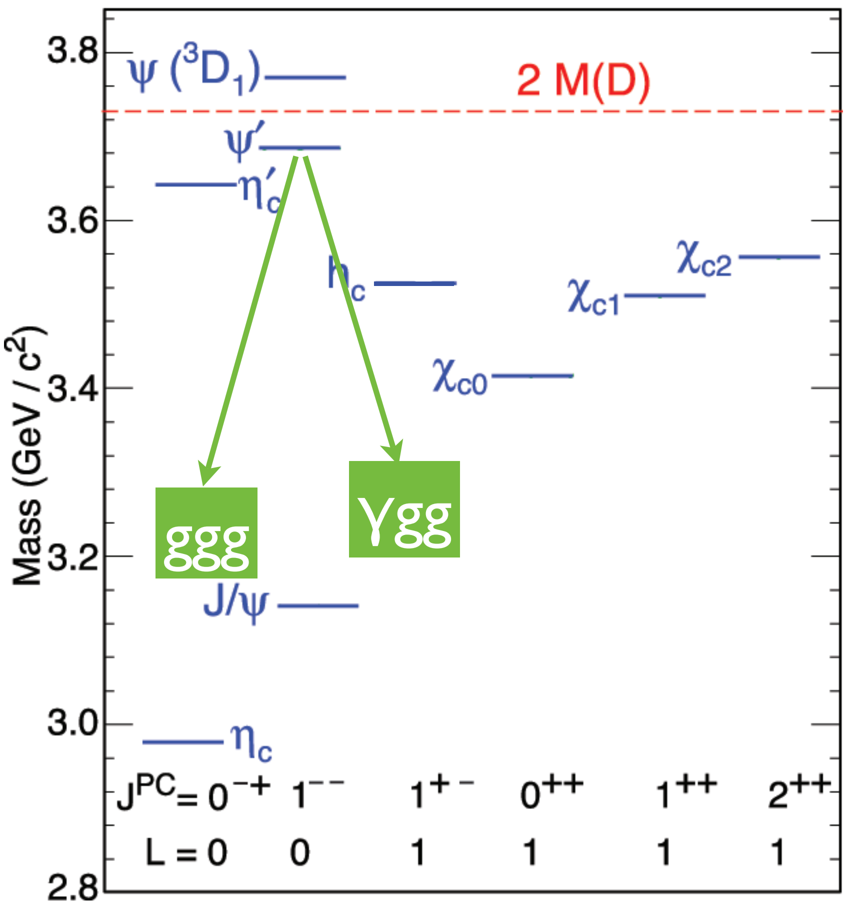
$$\left(\frac{a_2^{J=1}}{b_2^{J=1}}\right)_{CLEO} = -2.27^{+0.57}_{-0.99} \stackrel{?}{=} \left(\frac{a_2^{J=1}}{b_2^{J=1}}\right)_{th} = -2.27 \pm 0.16$$

$$\left(\frac{b_2^{J=2}}{b_2^{J=1}}\right)_{CLEO} = 0.37^{+0.53}_{-0.47} \stackrel{?}{=} \left(\frac{b_2^{J=2}}{b_2^{J=1}}\right)_{th} = 1.000 \pm 0.015$$

$$\left(\frac{b_2^{J=2}}{a_2^{J=2}}\right)_{CLEO} = -0.11^{+0.14}_{-0.15} \stackrel{?}{=} \left(\frac{b_2^{J=2}}{a_2^{J=2}}\right)_{th} = -0.297 \pm 0.025$$

Theoretical comparison of M2 ampliutde ratios - independent of κ_c, m_c

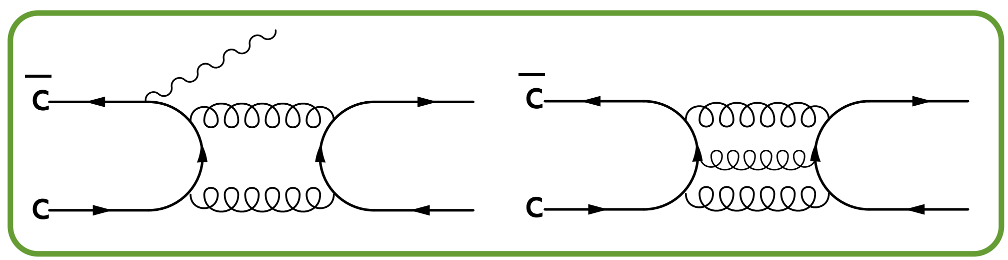
This Talk



Higher Order Multipole Amplitudes in Charmonium Radiative Transitions

Inclusive Radiative ψ(2S) Decays

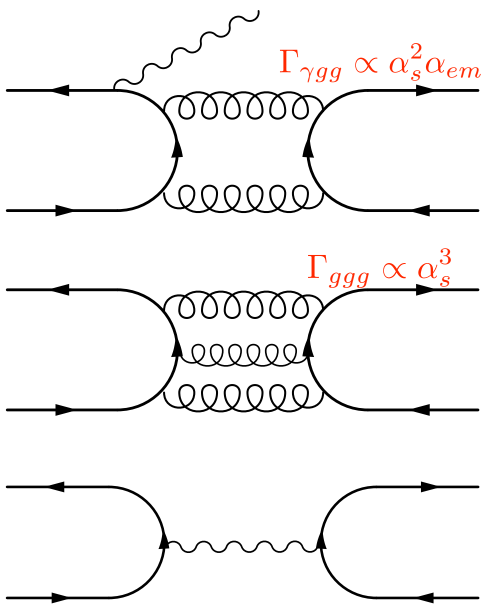
Exclusive χ_{cJ} Decays



Inclusive ψ(2S) Decays

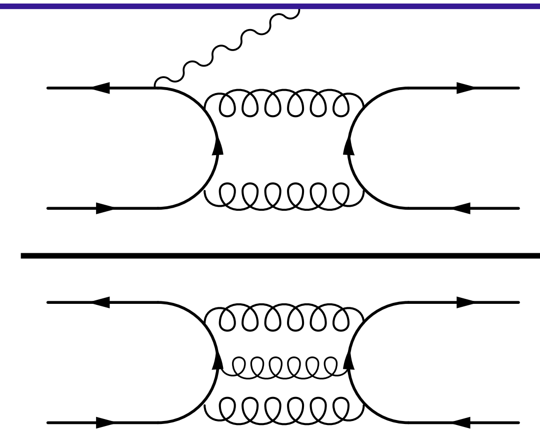
PRD 80 072002 (2009)

- OZI rule tells us that $c\bar{c}$ would prefer to decay to open charm.
- Not energetically possible for states below $D\bar{D}$ threshold.
- Next lowest order decay processes are:



Goal is to measure:

$$R_\gamma = \frac{\Gamma(\psi(2S) \rightarrow \gamma gg)}{\Gamma(\psi(2S) \rightarrow ggg)} =$$



No previous results for ψ(2S), but plenty of other CLEO measurements in last 4 years:

$R_\gamma(J/\psi)$	$(0.137 \pm 0.001 \pm 0.016)$	PRD 78 032012 (2008) (CLEO)
$R_\gamma(\Upsilon(1S))$	$(0.027 \pm 0.001 \pm 0.003)$	PRD 74 012003 (2006) (CLEO)
$R_\gamma(\Upsilon(2S))$	$(0.032 \pm 0.001 \pm 0.005)$	PRD 74 012003 (2006) (CLEO)
$R_\gamma(\Upsilon(3S))$	$(0.027 \pm 0.001 \pm 0.005)$	PRD 74 012003 (2006) (CLEO)

Naively expect: $R_\gamma(\ \psi(2S)\ ) = R_\gamma(\ J/\psi\ )$

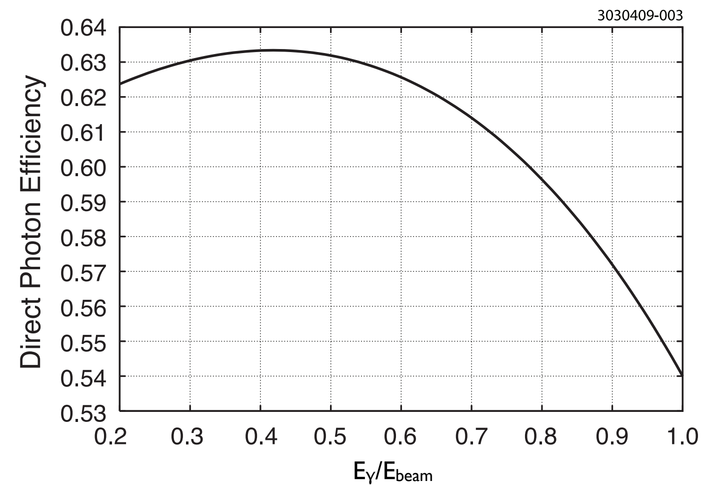
Inclusive ψ(2S) Decays

PRD 80 072002 (2009)

Approach:

- Measure direct photon spectrum.
- Subtract off everything that isn't $\psi(2S)\rightarrow\gamma gg$
- Use known $B(\psi' \rightarrow \gamma\, c\bar{c})$ etc.

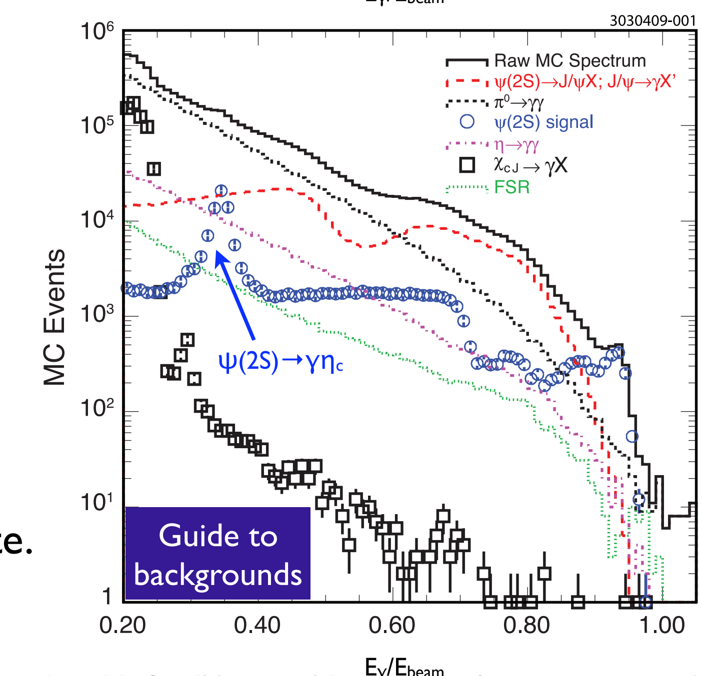
Direct photon efficiency



Integral of direct photon spectrum

$$R_\gamma = \frac{N_{\gamma gg}}{N_{ggg} \times \epsilon_{\gamma gg}}$$

From previously measured $\Gamma(\psi(2S)\rightarrow ggg)$
CLEO PRD 78 1011102 (2008)



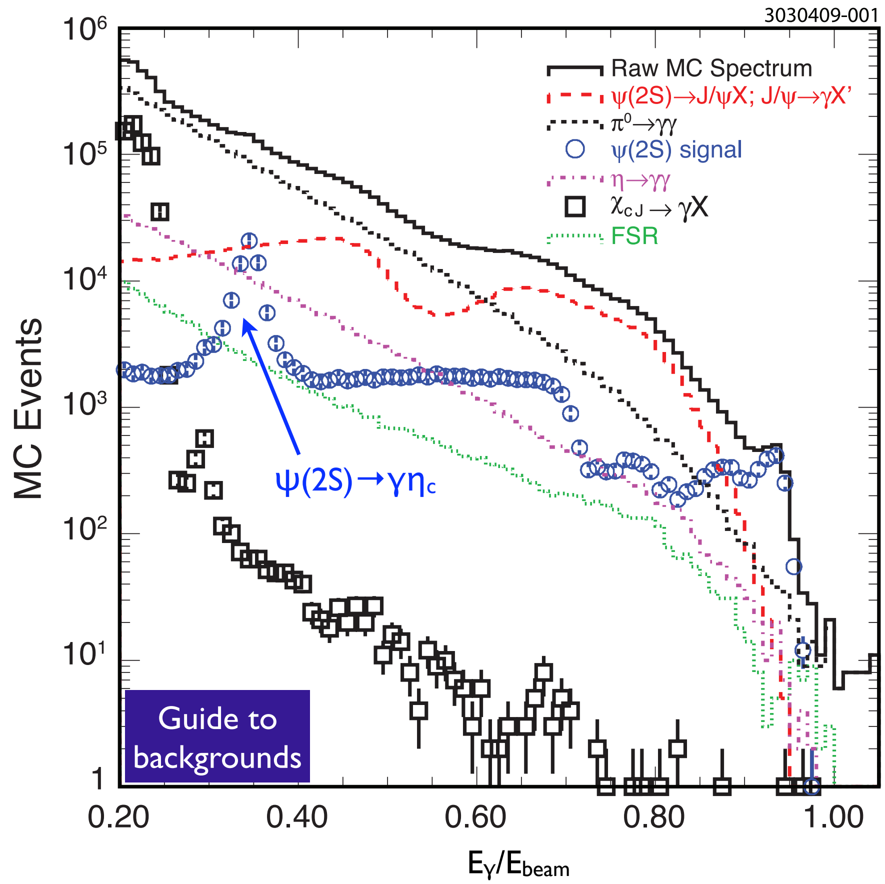
Main challenge:

- Backgrounds: low signal to noise ratio.
- 85% of ψ(2S) decays are transitions to lower mass $c\bar{c}$.
- Photons from π^0s, ηs in the final state and J/ψ decays dominate.

Inclusive ψ(2S) Decays

PRD 80 072002 (2009)

Backgrounds



ψ(2S)→ J/ψ X; J/ψ → γ X

- J/ψ → γgg photon spectrum measured in data.
PRD 78 032012 (2008)
- Subtract off directly.

π^0 → γγ and η → γγ

Method 1: Exponential Fit

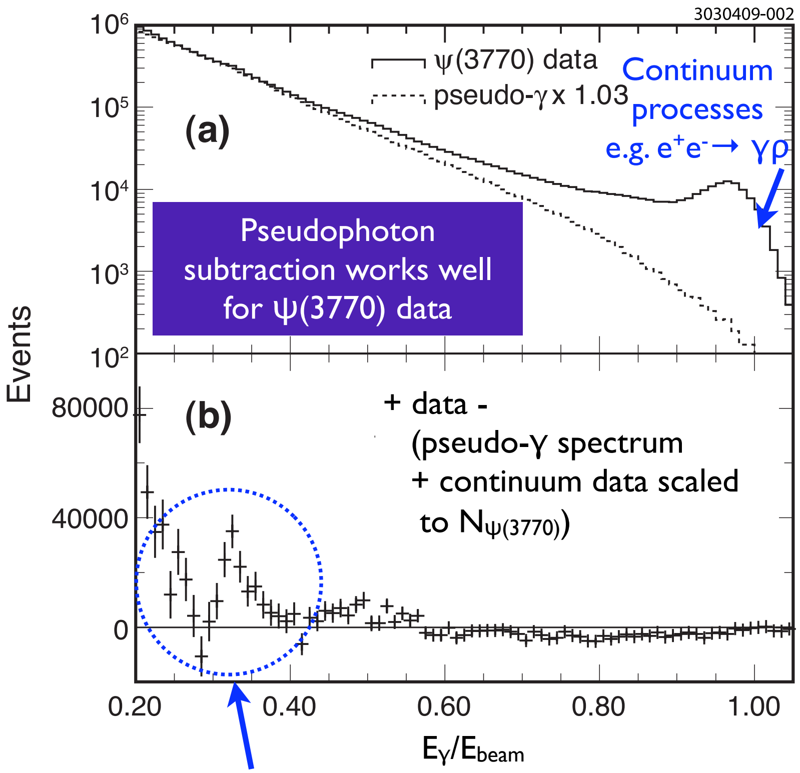
- Fit an exponential where π^0 bkg dominates:
E_γ/E_{beam} = 0.27 - 0.32 GeV
- Extrapolate to the high E_γ region.

Inclusive ψ(2S) Decays

PRD 80 072002 (2009)

Backgrounds

Cross check of pseudophoton background subtraction



$\psi(3770) \to J/\psi\, X;\ J/\psi \to \gamma X'$
Continuum data taken ~100MeV below ψ(3770) - leads to offset in E_γ/E_{beam}.

$\pi^0 \to \gamma\gamma$ and $\eta \to \gamma\gamma$ (cont)

Method 2: Generate a pseudophoton distribution

- Exploit isospin relationship between π^+, π^-, π^0
- Use distribution of π^+, π^- in data to predict π^0 distribution and therefore γγ distribution.

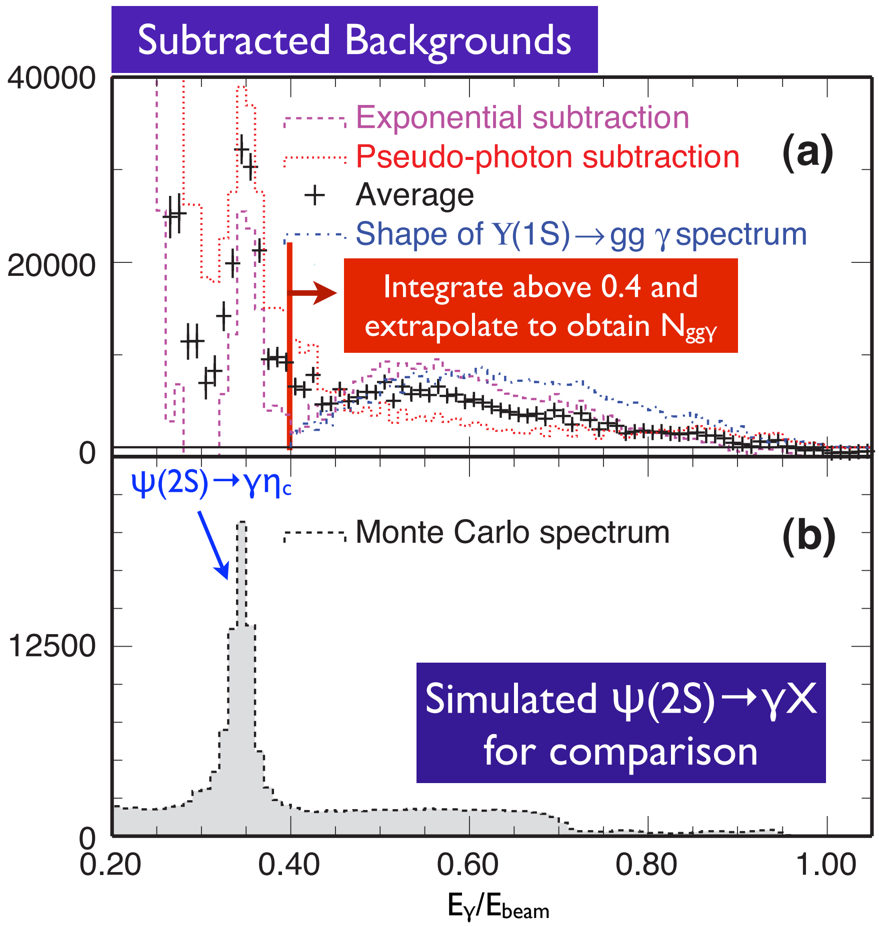
Pseudophoton Cross-check

- Apply pseudophoton subtraction to ψ(3770) data.
- $\Gamma(\psi(3770) \to \gamma gg)$ should be immeasurably small.
- Pseudophoton spectrum should be a good approximation of ψ(3770) spectrum.

Inclusive ψ(2S) Decays

PRD 80 072002 (2009)

Results



Extraction of R_γ

Method 1: Extrapolate to $E_\gamma/E_{beam} = 0$

- Integrate subtracted spectrum for $E_\gamma/E_{beam} > 0.4$.
- Extrapolate to $E_\gamma/E_{beam} = 0$ to obtain $N_{gg\gamma}$:

Method 2: Normalise to $\psi(2S)\to\gamma\eta_c$

- Background removal can result in over/under subtraction.
- Fit prominent η_c line to obtain $N_{\eta c}$ observed.
- Use known B($\psi(2S)\to\gamma\eta_c$) to obtain scale factor for integral of photon spectrum ($E_\gamma/E_{beam} >$ 0.4).

Take average of methods 1 and 2

Inclusive ψ(2S) Decays

PRD 80 072002 (2009)

Results

- Average 3 methods and compare to previous results:

$R_\gamma(J/\psi)$	$(0.137 \pm 0.001 \pm 0.016)$	PRD 78 032012 (2008) CLEO
$R_\gamma(\psi(2S))$	$(0.097 \pm 0.002 \pm 0.026)$	PRD 80 072002 (2009) CLEO
$R_\gamma(\Upsilon(1S))$	$(0.027 \pm 0.001 \pm 0.003)$	PRD 74 012003 (2006) CLEO
$R_\gamma(\Upsilon(2S))$	$(0.032 \pm 0.001 \pm 0.005)$	PRD 74 012003 (2006) CLEO
$R_\gamma(\Upsilon(3S))$	$(0.027 \pm 0.001 \pm 0.005)$	PRD 74 012003 (2006) CLEO

$$R_\gamma(\ \psi(2S)\ ) \stackrel{?}{=} R_\gamma(\ J/\psi\ )$$

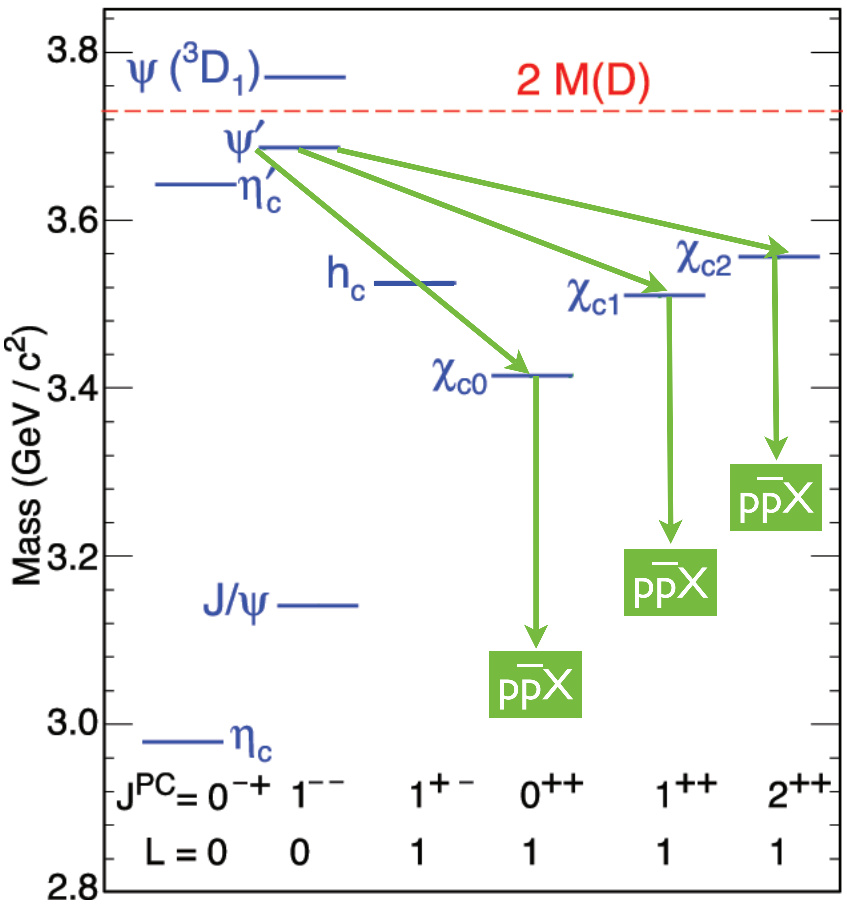
- Naive expectation that R_γ is the same for 1S, 2S, 3S states is validated in ϒ.

- Completes the set of R_γ for ψ 1^{--} states.

- Another example of unexpected ψ(2S) to J/ψ partial width ratios?

  e.g.
  - B(ψ(2S) → ρπ) / B(J/ψ → ρπ) - the "ρπ puzzle" *PRD 63 114019 (2001)*
  - B(ψ(2S) → γη) / B(ψ(2S) → γη') << B(J/ψ → γη) / B(J/ψ → γη') *PRD 79 111101 (2009)*

This Talk



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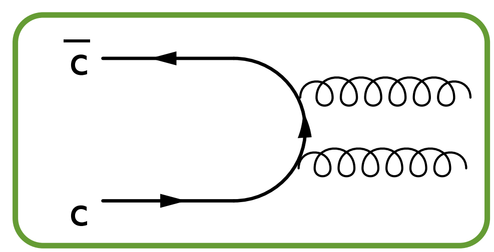
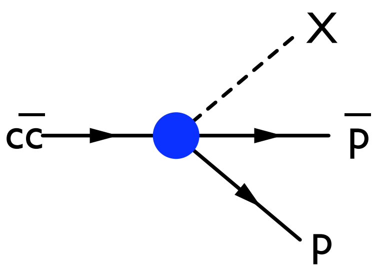
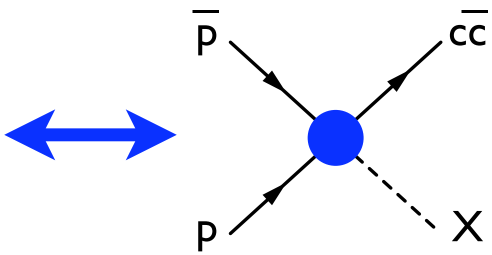
Exclusive χ_{cJ} Decays



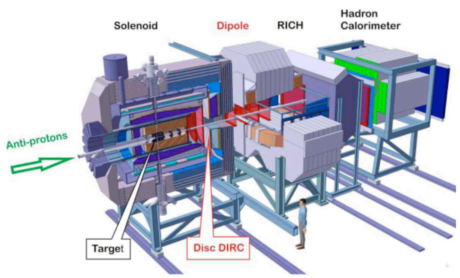
Exclusive $\chi_{cJ} \rightarrow p\bar{p}X$



Charmonium Decay



Associated charmonium production



PANDA (antiProton ANnihilation at DArmstadt)

- χ_{cJ} decays are glue rich: an ideal environment for investigations of possible glueball dynamics.
- $p\bar{p}X$ final states are particularly interesting - recent calculations linking:

$$\Gamma(\, c\bar{c} \rightarrow p\bar{p}X\,) \text{ to } \sigma(\, p\bar{p} \rightarrow c\bar{c}\,X\,)$$

PRD 73 096003 (2006)
PRD 75 054018 (2007)
PRD 77 056001 (2008)
arXiv:1001.1335 (2010)
} *Ted Barnes et al.*

- Predictions of $\sigma(\, p\bar{p} \rightarrow c\bar{c}\,X\,)$ of particular interest to PANDA (new $p\bar{p}$ annihilation experiment @ FAIR).

- CLEO has reported the first $\chi_{cJ} \rightarrow p\bar{p}X$ branching fractions using 3M ψ'.
- Use 10x increase in statistics to do precision studies.

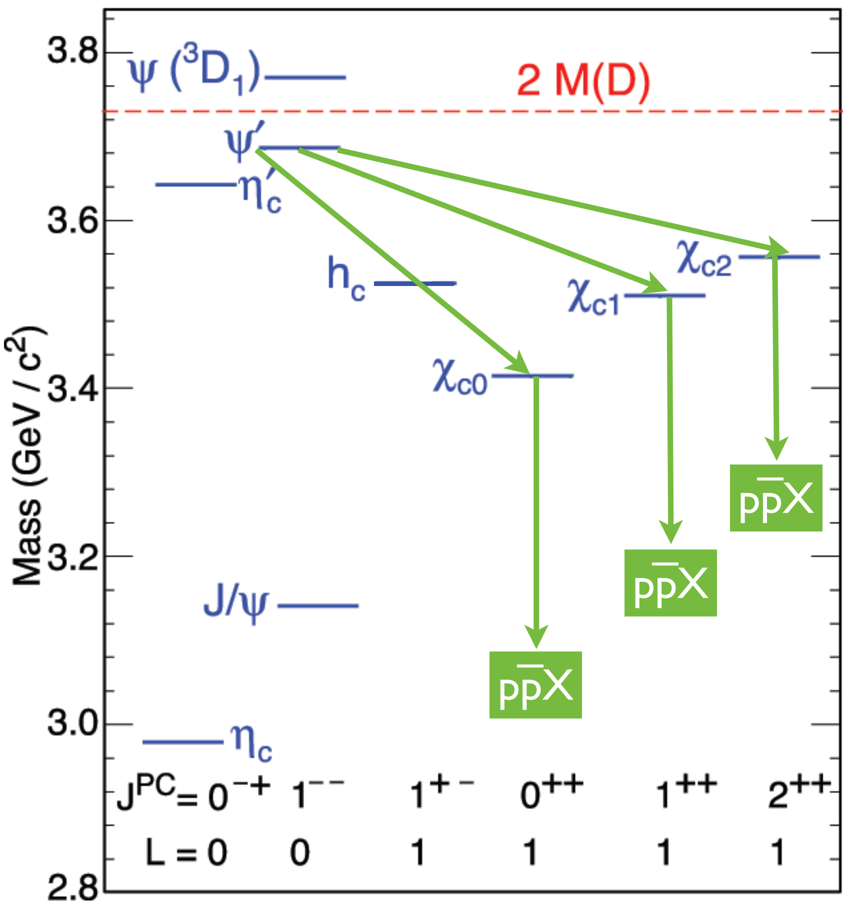
PHYSICAL REVIEW D **75,** 032002 (2007)

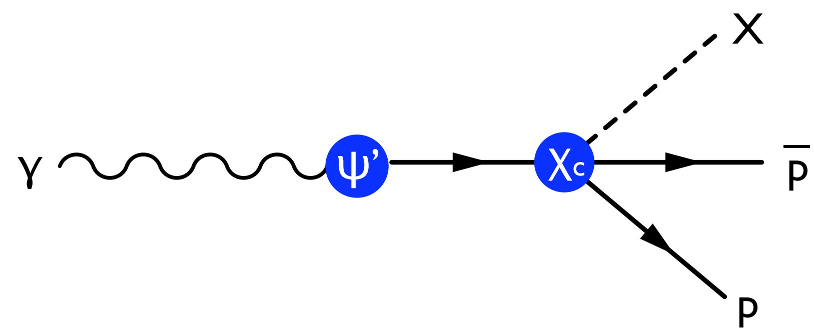
χ_{cJ} decays to $h^+h^-h^0$

$(\times 10^{-4})$	χ_{c0}	χ_{c1}	χ_{c2}
$\mathcal{B}(\chi_{cJ} \rightarrow p\bar{p}\pi^0)_{exp}$	$5.9 \pm 1.0 \pm 0.7 \pm 0.3$	$1.2 \pm 0.5 \pm 0.1 \pm 0.1$	$4.4 \pm 0.8 \pm 0.4 \pm 0.3$
$\mathcal{B}(\chi_{cJ} \rightarrow p\bar{p}\eta)_{exp}$	$3.9 \pm 1.1 \pm 0.4 \pm 0.2$	< 1.6	$1.9 \pm 0.7 \pm 0.2 \pm 0.1$

Exclusive $\chi_{cJ} \rightarrow p\bar{p}X$

CLEO-c PRELIMINARY





Basic Approach:

- Kinematically fit γ, p, $\bar{p}$, X, to $\psi(2S)$ 4-momentum.
- Extract $N_{p\bar{p}X}$ via fit to χ_{cJ} candidate mass: $M(p\bar{p}X)$.

Exclusive $\chi_{cJ} \to p\bar{p}X$

Consider two final states

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

$\chi_{cJ} \to p\bar{p}\pi^+\pi^-\pi^0$

Allows us to reconstruct

$\chi_{cJ} \to p\bar{p}\pi^0$

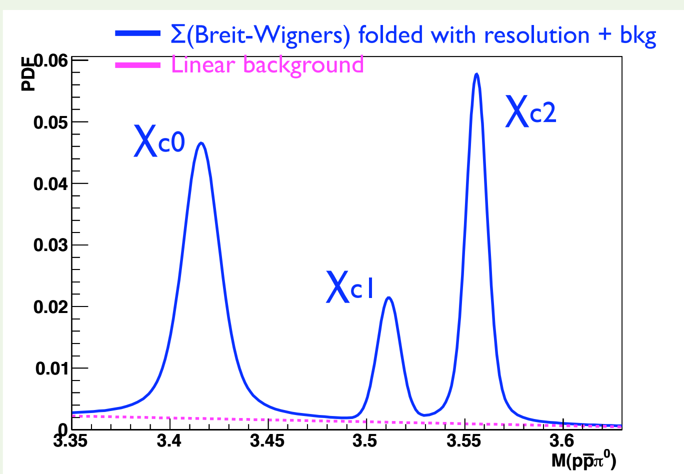
$\chi_{cJ} \to p\bar{p}\eta$

$\chi_{cJ} \to p\bar{p}\eta$

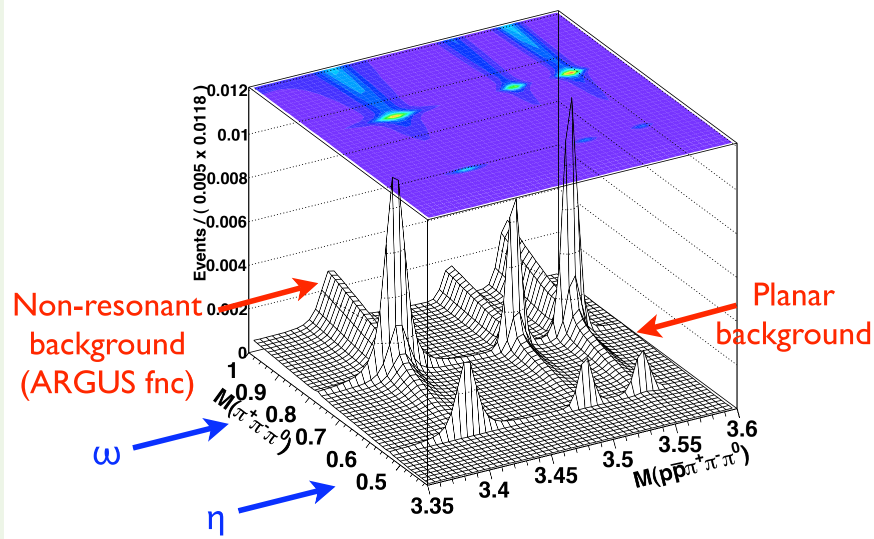
$\chi_{cJ} \to p\bar{p}\omega$

Provides us with cross check

- Perform a 1D extended maximum likelihood fit to $M(p\bar{p}X)$:



- Large non-resonant $\chi_{cJ} \to p\bar{p}\pi^+\pi^-\pi^0$ background.
- Perform 2D unbinned extended maximum likelihood fit in $M(p\bar{p}\pi^+\pi^-\pi^0)$ and $M(\pi^+\pi^-\pi^0)$.
- Simultaneously extract $\chi_{cJ} \to p\bar{p}\eta$, $\chi_{cJ} \to p\bar{p}\omega$.



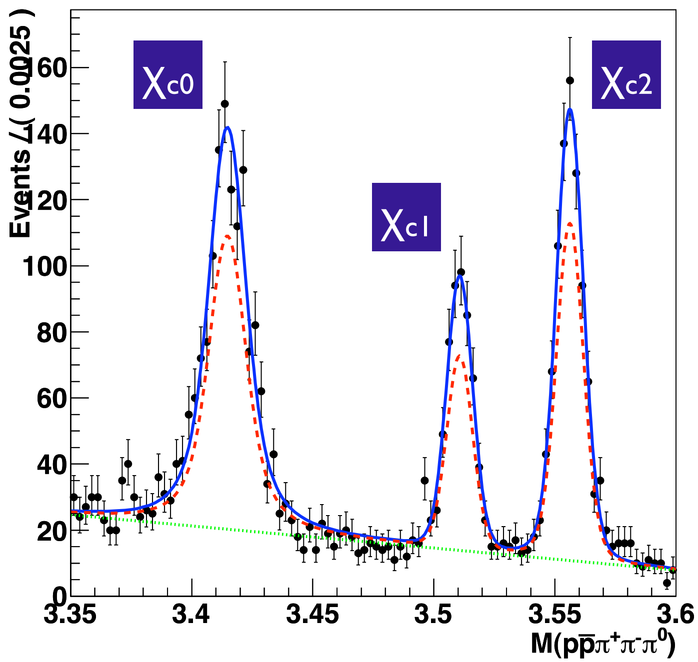
Exclusive $\chi_{cJ} \rightarrow p\bar{p}X$

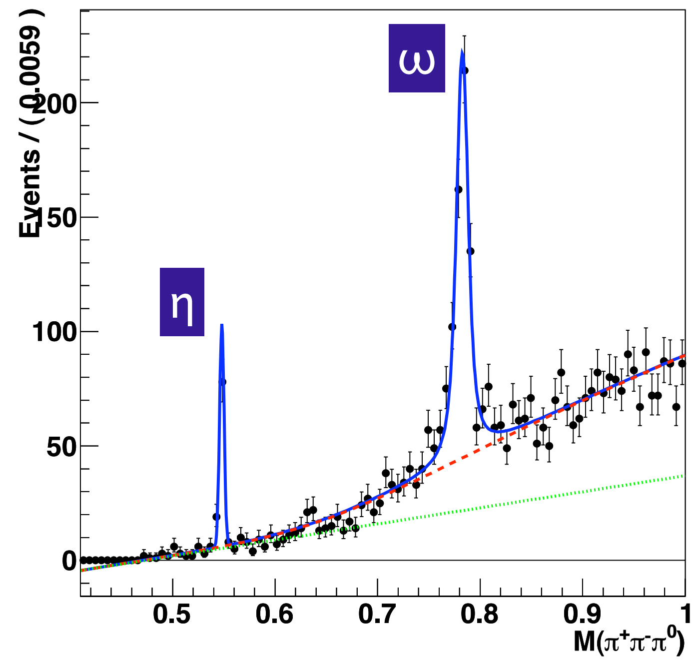
CLEO-c PRELIMINARY

$\chi_{cJ} \rightarrow p\bar{p}\pi^+\pi^-\pi^0$

Preliminary

- Results of 2-D Extended Maximum Likelihood Fit.
- Global features of data reproduced well....





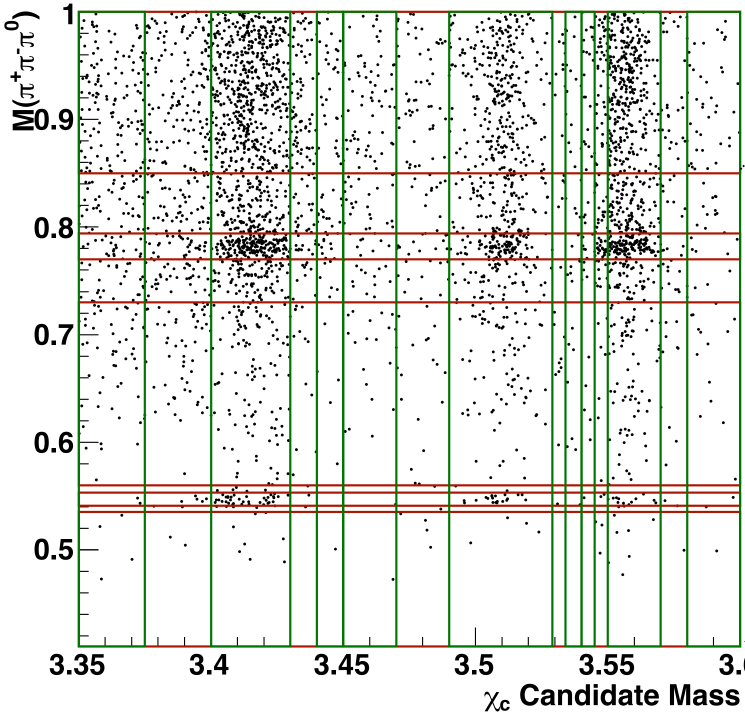
Total PDF
Non-resonant Background
Polynomial Background

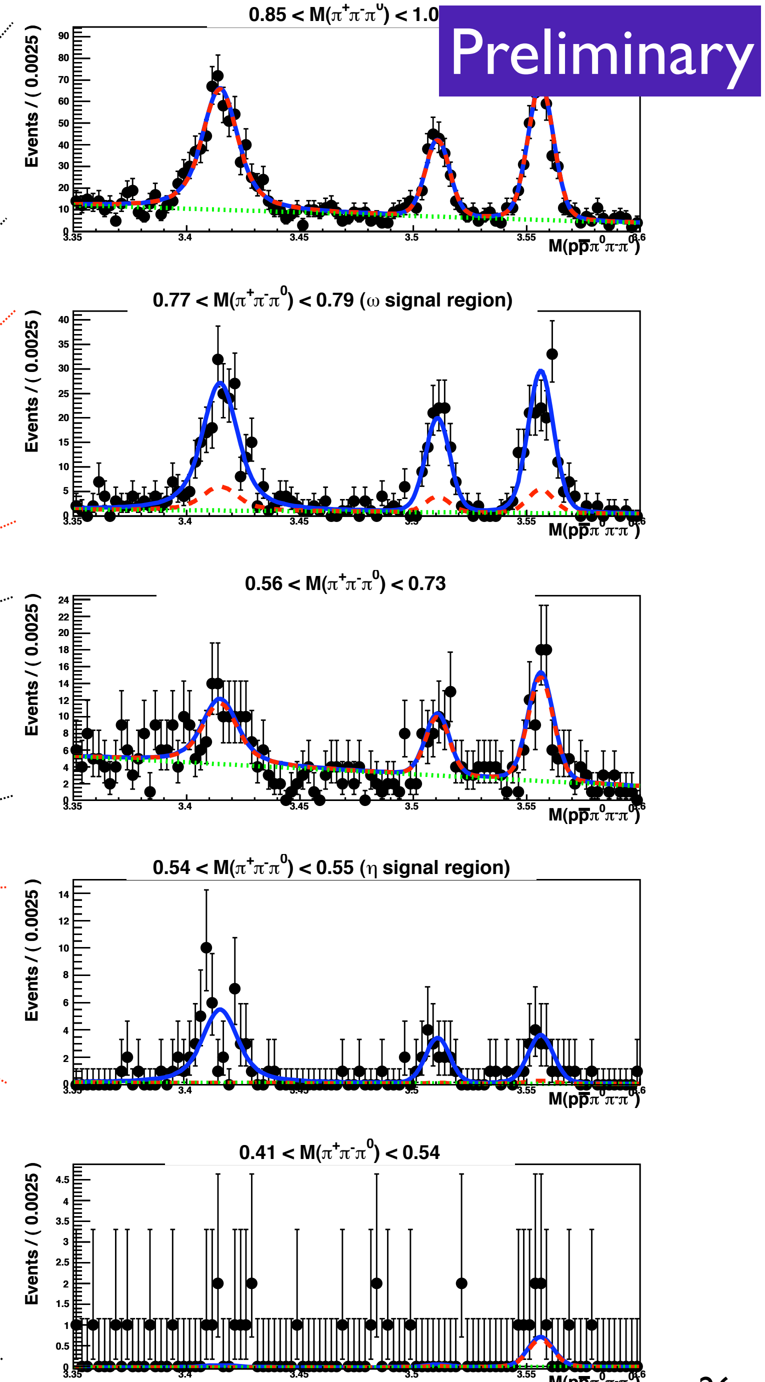
Exclusive $\chi_{cJ} \to p\bar{p}X$

CLEO-c
PRELIMINARY

$\chi_{cJ} \to p\bar{p}\pi^+\pi^-\pi^0$

- Details are also well reproduced...





Total PDF

Non-resonant Background

Polynomial Background

Exclusive $\chi_{cJ} \to p\bar{p}X$

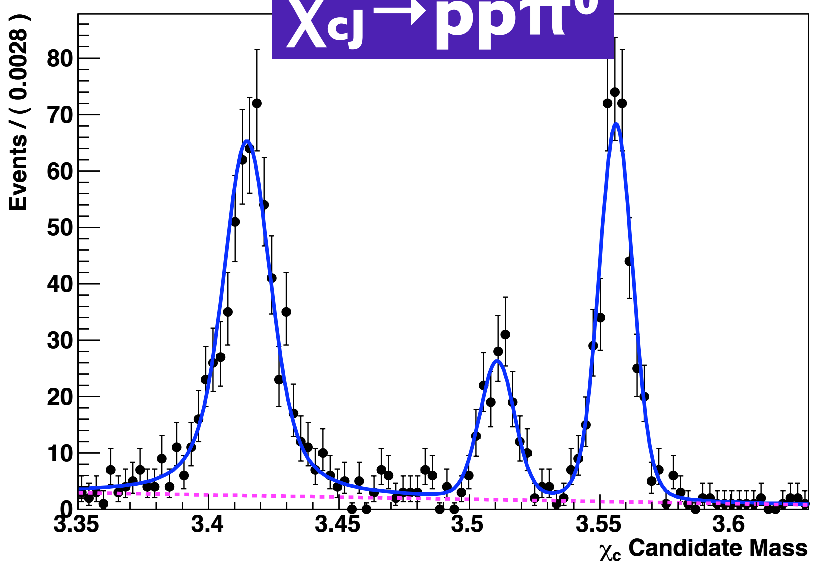
CLEO-c PRELIMINARY

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

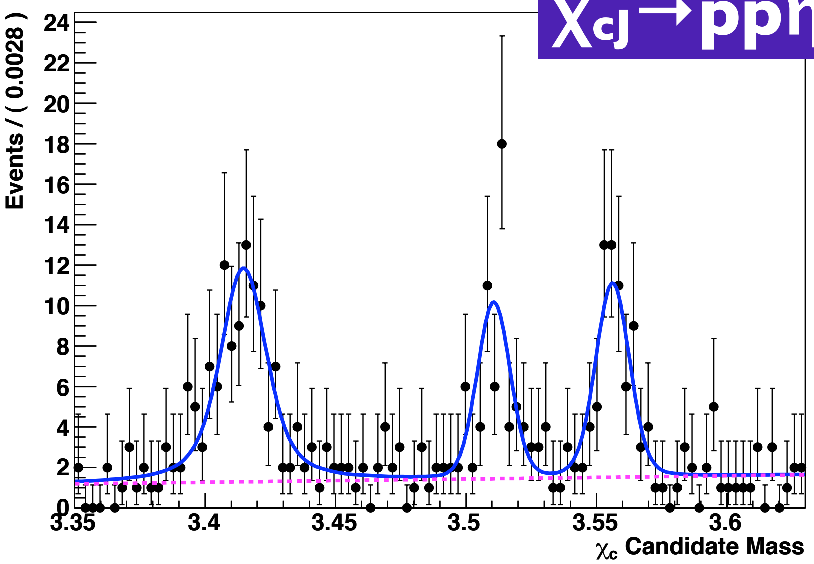
Preliminary

- Results of 1-D Extended Maximum Likelihood Fit:

$\chi_{cJ} \to p\bar{p}\pi^0$



$\chi_{cJ} \to p\bar{p}\eta$



Total PDF: Σ(Breit-Wigners) folded with resolution + bkg

Linear Background

Exclusive $\chi_{cJ} \to p\bar{p}X$

CLEO-c PRELIMINARY

Preliminary Branching Fractions for $\chi_{cJ} \to p\bar{p}X$

Errors are statistical then systematic then a separate systematic due to uncertainties in $B(\psi(2S) \to \gamma\chi_{cJ})$

$(\times 10^{-4})$	χ_{c0}	χ_{c1}	χ_{c2}
$p\bar{p}\pi^0$	$(7.76 \pm 0.37 \pm 0.51 \pm 0.39)$	$(1.75 \pm 0.16 \pm 0.13 \pm 0.11)$	$(4.83 \pm 0.25 \pm 0.35 \pm 0.31)$
$p\bar{p}\eta[\gamma\gamma]$	$(3.45 \pm 0.45 \pm 0.25 \pm 0.17)$	$(1.63 \pm 0.27 \pm 0.19 \pm 0.10)$	$(1.84 \pm 0.29 \pm 0.17 \pm 0.12)$
$p\bar{p}\eta[\pi^0\pi^+\pi^-]$	$(4.51 \pm 0.67 \pm 0.51 \pm 0.23)$	$(1.46 \pm 0.37 \pm 0.14 \pm 0.09)$	$(1.62 \pm 0.40 \pm 0.13 \pm 0.11)$
$p\bar{p}\eta[\text{mean}]$	$(3.73 \pm 0.38 \pm 0.28 \pm 0.19)$	$(1.56 \pm 0.22 \pm 0.14 \pm 0.10)$	$(1.76 \pm 0.23 \pm 0.14 \pm 0.11)$
$p\bar{p}\omega$	$(5.57 \pm 0.48 \pm 0.50 \pm 0.28)$	$(2.28 \pm 0.28 \pm 0.20 \pm 0.14)$	$(3.68 \pm 0.35 \pm 0.31 \pm 0.24)$

- First measurement of $\chi_{cJ} \to p\bar{p}\omega$
- Comparison with previous experiment / theory:

Reference	$(\times 10^{-4})$	χ_{c0}	χ_{c1}	χ_{c2}
arXiv:1001.1335 (2010)	$\mathcal{B}(\chi_{cJ} \to p\bar{p}\pi^0)_{theory}$	2.5	0.2	-
PRD 75 032002 (2007)	$\mathcal{B}(\chi_{cJ} \to p\bar{p}\pi^0)_{exp}$	$5.9 \pm 1.0 \pm 0.7 \pm 0.3$	$1.2 \pm 0.5 \pm 0.1 \pm 0.1$	$4.4 \pm 0.8 \pm 0.4 \pm 0.3$
PRD 75 032002 (2007)	$\mathcal{B}(\chi_{cJ} \to p\bar{p}\eta)_{exp}$	$3.9 \pm 1.1 \pm 0.4 \pm 0.2$	< 1.6	$1.9 \pm 0.7 \pm 0.2 \pm 0.1$

Errors are statistical then systematical then a separate systematic due to uncertainties in $B(\psi(2S) \to \gamma\chi_{cJ})$

Summary

- Rich program of charmonium studies have been completed and published with CLEO-c data.

- A few of the latest presented here:
  - Precision measurements of higher order multipole amplitudes.
  - Precision measurements of $\chi_{cJ} \rightarrow p\bar{p}X$ branching fractions.
  - Final measurement of R_Υ completing the set for the ψ and Υ states.

- With BESIII now online, analyses are being wrapped up - but more publications still to come.

END

BACKUP

PRD 80 112003 (2009)

polarisation vector with helicity λ $m^i \equiv (sin\theta cos\phi, sin\theta sin\phi, cos\theta)$

J/ψ spin density matrix

$$\rho^{(\lambda,\bar{\lambda})}(\theta,\phi) \equiv \sum_{i,j} \epsilon_i^{*(\lambda)} \epsilon_j^{(\bar{\lambda})} (\delta^{ij} - m^i m^j)$$

Systematics - M2 amplitudes

- Fitting Procedure: *4% for $a^{J=1}$*, *11% for $b^{J=1}$*
  - Generate Toy MC (i.e. know a_2, b_2), vary fitting technique
- Phase Space MC Sample Size:
  - Test the necessary size of phase space needed for the efficiency integrals
- MC Impurities:
  - Using Generic MC test the effect of impurities on the fitted amplitudes
- Final State Radiation: *5% for $a^{J=1}$*, *17% for $b^{J=1}$*
  - Compare fits of the generator level four-vectors with and without Final State Radiation added via PHOTOS.
- Kinematic Fit:
  - Test different Types of Kinematic Fits
- Cut Variations:
  - Compare small variations in Cuts

BACKUP

PRD 80 112003 (2009)

- E3 amplitude was fixed to zero in fits shown.
- If E3 is not fixed to zero, then M2 amplitudes from 4 parameter fit are consistent with 3 parameter fit (within errors).

- Use most sensitive M2 amplitude to calculate κ_c - find $(1+\kappa_c) = 0.877$.

BACKUP

PRD 80 072002 (2009)

Inclusive ψ(2S) Decays Systematic Errors

Source	$\delta R_\gamma / R_\gamma (\%)$
Background normalization	27
$z_\gamma \to 0$ extrapolation	1
Angular distribution uncertainties	2.2
K_L^0 + antineutrino contamination	4
Trigger efficiency	1
Photon-finding	2
$\psi(2S) \to J/\psi X$ normalization	2
Three-gluon event efficiency	2
Input branching fractions	15
Total Systematic Error	$\pm 27 \pm 15$

BACKUP

PRD 80 072002 (2009)

Inclusive ψ(2S) Decays: Branching Fractions used in background subtraction

TABLE I. Inputs to calculations and extracted signal results. Note that the branching fractions to the χ_{cJ} states have had cascades to the J/ψ ($\chi_{cJ} \to J/\psi\gamma$) removed to avoid double-counting, as indicated.

Quantity	Value	Comment
Number $\psi(2S)$ decays produced	27.4 M	CLEO-2008
$\mathcal{B}(\psi(2S) \to \pi^+\pi^- J/\psi)$	$(35.4 \pm 0.5)\%$	CLEO-2008
$\mathcal{B}(\psi(2S) \to J/\psi X)/\mathcal{B}(\psi(2S) \to \pi^+\pi^- J/\psi)$	$1.784 \pm 0.003 \pm 0.02$	CLEO-2008
$\mathcal{B}(\psi(2S) \to e^+e^-)$	$(0.765 \pm 0.017)\%$	PDG08
$\mathcal{B}(\psi(2S) \to \mu^+\mu^-)$	$(0.76 \pm 0.08)\%$	PDG08
$\mathcal{B}(\psi(2S) \to \tau^+\tau^-)$	$(0.3 \pm 0.04)\%$	PDG08
$\mathcal{B}(\psi(2S) \to \gamma^* \to \text{hadrons})$	$(1.75 \pm 0.14)\%$	PDG08
$\mathcal{B}(\psi(2S) \to \gamma\chi_{c0}) \times (1 - \mathcal{B}(\chi_{c0} \to \gamma J/\psi))$	$[(9.42 \pm 0.31) \times 0.99]\%$	PDG08
$\mathcal{B}(\psi(2S) \to \gamma\chi_{c1}) \times (1 - \mathcal{B}(\chi_{c1} \to \gamma J/\psi))$	$[(9.2 \pm 0.4) \times 0.66]\%$	PDG08
$\mathcal{B}(\psi(2S) \to \gamma\chi_{c2}) \times (1 - \mathcal{B}(\chi_{c2} \to \gamma J/\psi))$	$[(8.69 \pm 0.35) \times 0.8]\%$	PDG08
$\mathcal{B}(\psi(2S) \to \gamma\eta_c)$	$(0.43 \pm 0.06)\%$	CLEO
f_z	0.725	$z_\gamma \geq 0.4$ fraction of entire γgg spectrum
N_{ggg}	2.9 M	
$N_\gamma(z_\gamma \geq 0.4)$	162 K	pseudophoton subtraction
$N_\gamma(z_\gamma \geq 0.4)$	232 K	exponential subtraction
$R_\gamma(z_\gamma \geq 0.4)$	$(5.65 \pm 0.03)\%$	pseudophoton subtraction
$R_\gamma(z_\gamma \geq 0.4)$	$(8.34 \pm 0.04)\%$	exponential subtraction
$N_{\gamma\eta_c}$	130 K	from fit to photon line (averaged plot)
$R_\gamma(z_\gamma \geq 0.4)$	$(7.07 \pm 0.8)\%$	normalized to $\mathcal{B}(\psi(2S) \to \gamma\eta_c)$

BACKUP

CLEO-c PRELIMINARY

$$B(\psi(2S)\rightarrow\gamma\chi_{cJ}) \times B(\chi_{cJ}\rightarrow p\bar{p}X)$$

Errors are statistical then systematic

$(\times 10^{-5})$	χ_{c0}	χ_{c1}	χ_{c2}
$p\bar{p}\pi^0$	$(7.15 \pm 0.34 \pm 0.47)$	$(1.59 \pm 0.15 \pm 0.12)$	$(4.51 \pm 0.24 \pm 0.33)$
$p\bar{p}\eta$[mean]	$(3.43 \pm 0.35 \pm 0.26)$	$(1.42 \pm 0.20 \pm 0.13)$	$(1.64 \pm 0.22 \pm 0.13)$
$p\bar{p}\omega$	$(5.13 \pm 0.44 \pm 0.45)$	$(2.07 \pm 0.25 \pm 0.18)$	$(3.44 \pm 0.32 \pm 0.29)$

BACKUP

CLEO-c PRELIMINARY

Exclusive $\chi_{cJ} \to p\bar{p}X$ Systematic Errors

(%)	$\chi_{cJ} \to p\bar{p}\pi^0$			$\chi_{cJ} \to p\bar{p}\eta$		
	χ_{c0}	χ_{c1}	χ_{c2}	χ_{c0}	χ_{c1}	χ_{c2}
Fitting	1	3	1	1	8	3
Tracking ($p\bar{p}$)	1	1	1	1	1	1
Photon Efficiency	6	6	6	6	6	6
χ^2_{4C}/dof cut	0	0	0	0	3	1
Number of $\psi(2S)$	2	2	2	2	2	2
$\mathcal{B}(\psi(2S) \to \gamma\chi_{cJ})$	5	6	7	5	6	7
Dalitz Plot	0	1	4	3	5	5
Total	8	9	10	9	13	11

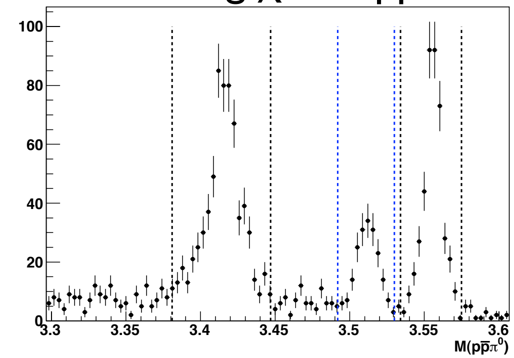
(%)	$\chi_{cJ} \to p\bar{p}\eta$			$\chi_{cJ} \to p\bar{p}\omega$		
	χ_{c0}	χ_{c1}	χ_{c2}	χ_{c0}	χ_{c1}	χ_{c2}
Fitting	1	5	4	3	2	2
Tracking ($p\bar{p}$)	1	1	1	1	1	1
Tracking ($\pi^+\pi^-$)	1	1	1	1	1	1
Photon Efficiency	6	6	6	6	6	6
χ^2_{4C}/dof cut	1	2	0	1	0	0
Number of $\psi(2S)$	2	2	2	2	2	2
$\mathcal{B}(\psi(2S) \to \gamma\chi_{cJ})$	5	6	7	5	6	7
Dalitz Plot	9	4	2	5	5	5
Total	12	11	10	10	10	11

BACKUP

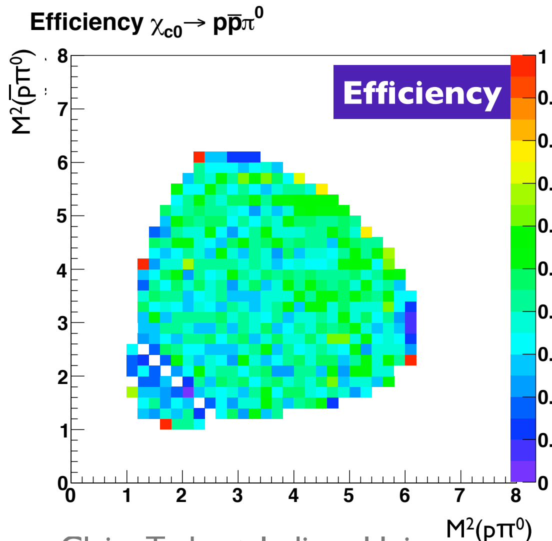
CLEO-c PRELIMINARY

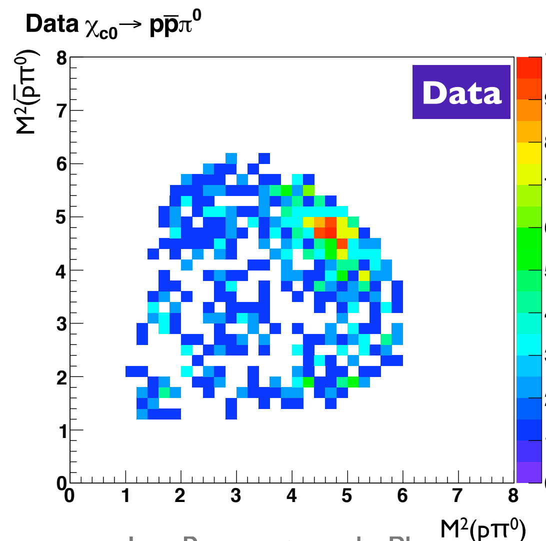
To get a rough idea of how much efficiency variations affect yield:

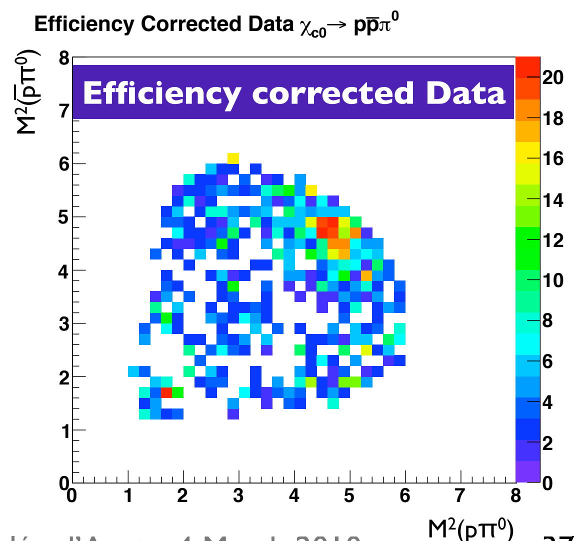
Selecting $\chi_{c0} \rightarrow p\bar{p}\pi^0$



- Select $\chi_{c0} \rightarrow p\bar{p}\pi^0$ in data and signal MC via rough cut on M($p\bar{p}\pi^0$).
- Plot Dalitz plot for data and plot ϵ_{det} as function of $M^2(p\pi^0)$ vs $M^2(\bar{p}\pi^0)$.
- Correct data as a function of $M^2(p\pi^0)$ vs $M^2(\bar{p}\pi^0)$ and integrate to obtain total efficiency corrected yield.
- Compare to efficiency corrected yield calculated using average of ϵ_{det} across Dalitz plot -- assign difference as systematic error.







BACKUP

CLEO-c PRELIMINARY

Barnes et al. arXiv:1001.1335 (2010)

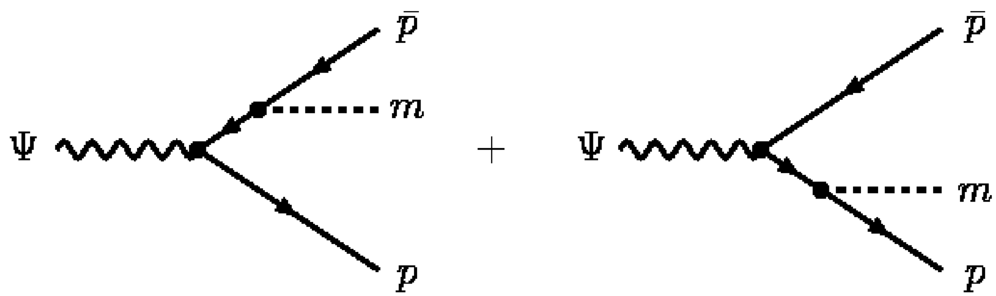


FIG. 1: Feynman diagrams of the meson emission model.

- "Actual relative importance of this process is unclear at the moment."
- Model doesn't currently include N* resonances i.e. no Dalitz plot structure.