First Measurement of $BR(\psi'' \to \gamma\ \chi_{cJ})$

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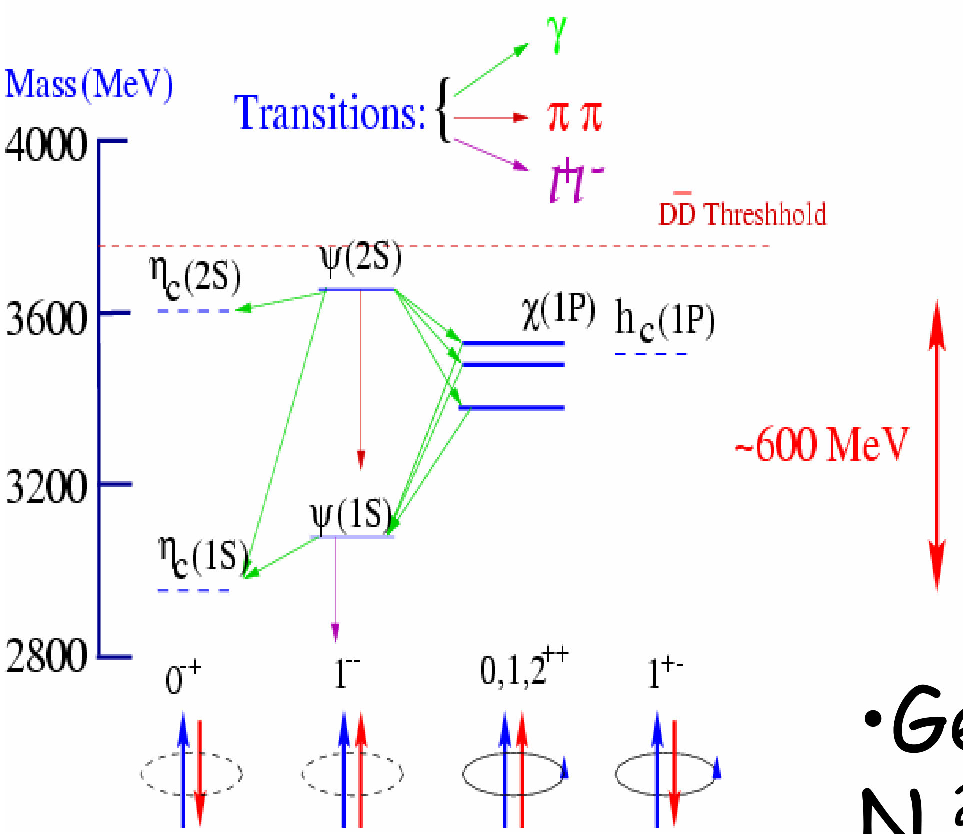
$c\bar{c}$ Spectrum



Ig(Jpc)	Name	Mass	Width
		MeV	MeV
0-(1--)	Psi''	3773	25.3
0-(1--)	Psi'	3686	0.28
0+(2++)	Xc2	3556	2.00
0+(1++)	Xc1	3510	0.88
0+(0++)	Xc0	3415	14.90
0-(1--)	J/psi	3096	0.09
0+(0-+)	EtaC	2979	17.30

- General notation

$N\ {}^{2s+1}L_J$

Motivation

1. Previous measurements did not produce significant signals

2. Impact on interpretation of X(3872)

3. Validation of Potential Model calculations above the open flavor threshold

Lack of significant previous measurements

- Before this result, no significant measurement of BR($\psi'' \to \gamma\chi_{cJ}$)

  (Unpublished results)
  - ~3/pb by MARKII
  - ~2/pb by Crystal-Ball
  - ~9/pb by MARKIII

- 281/pb; ~30times larger sample from CLEO-c

What do we know about X(3872)

A. Observed in $X(3872) \rightarrow \pi^+\pi^- J/\psi$ decay

B. Mass (3871.9 ± 0.5) MeV
   - just below the $D\bar{D}^*$ threshold

C. Width < 2.3MeV
   - Surprisingly small, since the mass is well above the $D\bar{D}$ threshold

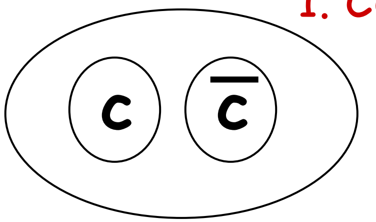
D. No radiative transitions to χ_{cJ} states have been observed
   - just an upper limit for decay to $\gamma\chi_{c1,2}$

$$\frac{\Gamma\left(X(3872) \rightarrow \gamma\chi_{c1}\right)}{\Gamma\left(X(3872) \rightarrow \pi^+\pi^-\ J/\psi\right)} < 0.9\ \textit{Belle}$$

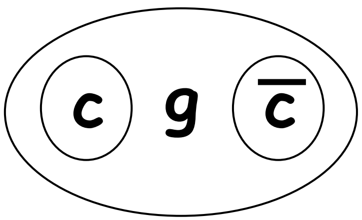
$$\frac{\Gamma\left(X(3872) \rightarrow \gamma\chi_{c2}\right)}{\Gamma\left(X(3872) \rightarrow \pi^+\pi^-\ J/\psi\right)} < 1.1\ \textit{Belle}$$

Possible interpretations of X(3872)

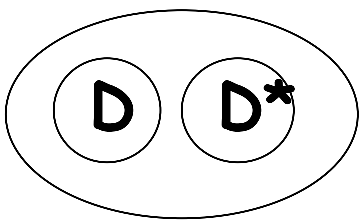
1. Conventional charmonium ($c\bar{c}$)



2. Hybrid ($c\bar{c}g$)



3.DD* molecule ($c\overline{qc}q$)



Existence of hybrids and bound states of mesons has not been experimentally proven so far

How our measurement helps?

- Conventional charmonium candidates for X(3872)
  - ψ_2 (1^3D_2), h_c' (2^1P_1), ψ_3 (1^3D_3) (C = -1)
  - η_{c2} (1^1D_2), $\chi_{c1}'(2^3P_1)$, $\eta_c''(3^1S_0)$, (C = +1)
- Nonrelativistic-case: $\langle 1D|r|1P\rangle$ is independent of J.
- $\Gamma_J = {}^4/_3 e^2\alpha\, E_\gamma^{\,3}\, C_J\, |\langle 1^3D|r|1^3P\rangle|^2$
- $1^3D_J \rightarrow \gamma\chi_{c1}$ can be measured for different J provided one is known

•Measuring 1^3D_1 $(\psi'') \rightarrow \gamma\chi_{c1}$ can shed some light on $1^3D_{2,3}$ $(\psi_2, \psi_3) \rightarrow \gamma\chi_{c1}$

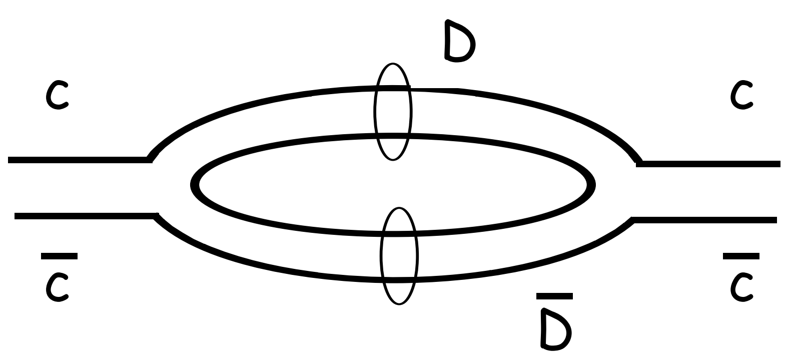
Validation of Potential Model for ψ''

- Is ψ'' a pure $c\bar{c}$ state?
  - Strong indications that X(3872) is not
  - May be all states above the flavor thresholds have complex nature?

- Radiative transitions are a good probe
  - Pure $c\bar{c}$ state: mostly 1^3D_1 (small contribution from 2^3S_1)
  - J-dependence of $\Gamma(\psi'' \rightarrow \gamma\chi_{cJ})$ is well predicted

- Are relativistic corrections important ?

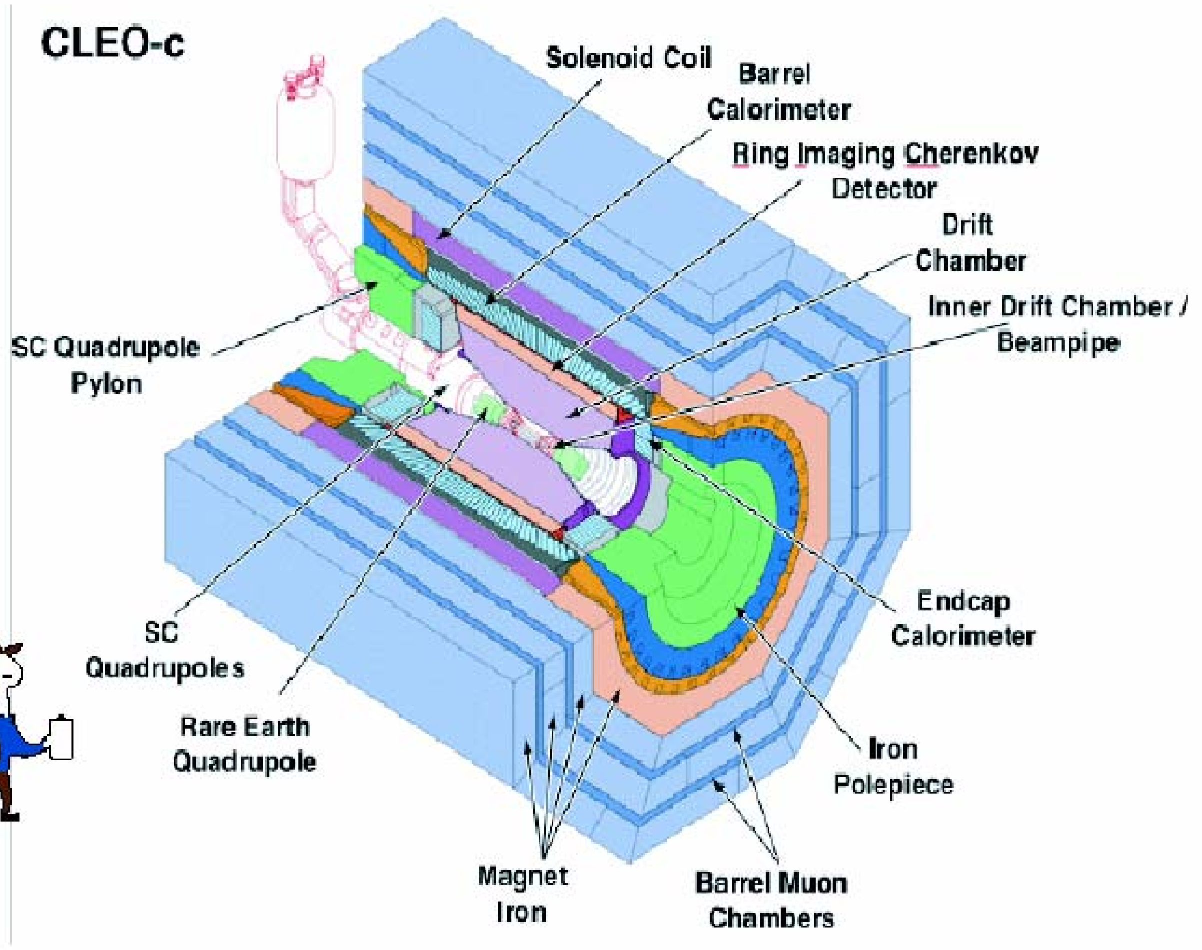
- Are coupled channel effects $c\bar{c} \rightarrow D\bar{D} \rightarrow c\bar{c}$ important?



CLEO-c

$N_{\psi'}$ =1.5M

$N_{\psi''}$ =1.8M



Analysis

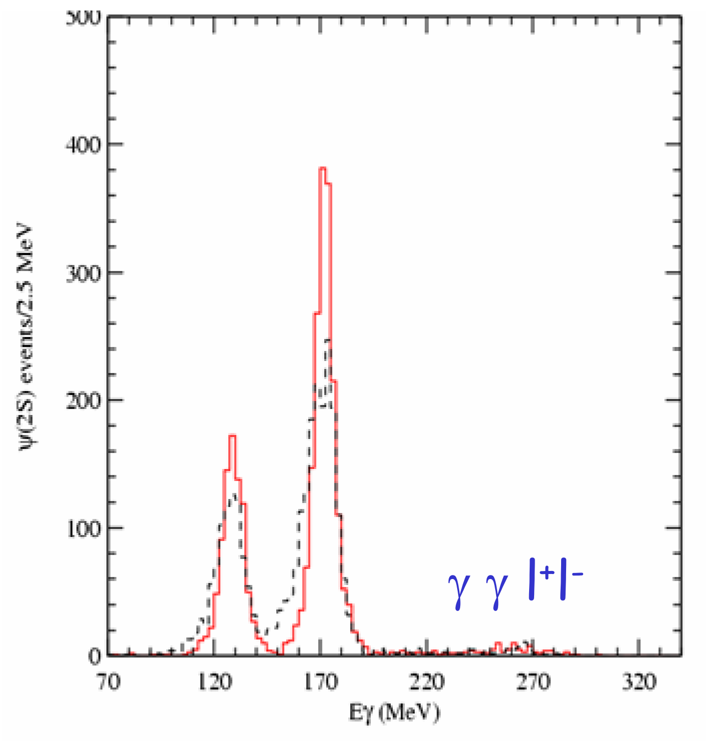
- **Method1**
- $\psi(3770) \rightarrow \gamma\chi_{cJ} \rightarrow \gamma J/\psi \rightarrow \gamma\gamma l^+l^-$
- Select events with exactly 2 photons and 2 leptons with no net charge:
  - No other photon with E > 60 MeV
  - $|P_{tot}| < 50$ MeV
  - $|E_{tot} - E_{ll} - E_{J/\psi}| < 40$ MeV
  - Electron
    - $E/p > 0.7$
  - Muon
    - $0.15 < E < 0.55$ GeV
- Signal variable: Energy of lower energy photon

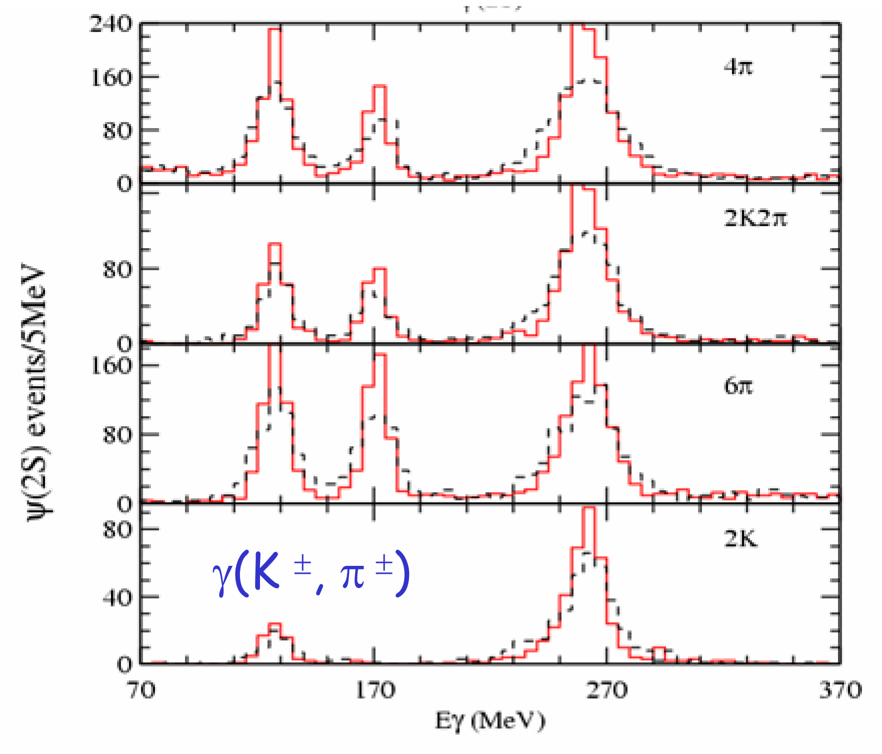
- **Method2**
- $\psi(3770) \rightarrow \gamma\chi_{cJ} \rightarrow \gamma\,(2K, 2K2\pi, 4\pi, 6\pi)$
- Select events with exactly 2,4,6 charged hadrons and a photon:
  - Highest energy neutral cluster in the calorimeter is the photon candidate
  - $|P_{tot}i - P_{cm}i| < 30$ MeV
    $i = x, y, z$
  - $|E_{tot} - E_{cm}| < 30$ MeV
  - Kaon
    - Combined log-likelihood > 0
    - $|\sigma_K| < 3$
  - Pion
    - Not a kaon
    - $|\sigma_\pi| < 3$
- Signal variable: Photon energy

Kinematic fitting

1. Constrain total energy and momentum to the expected values.
2. For $\gamma\gamma l^+l^-$ also constrain mass of l^+l^- to the J/ψ mass.

Demonstration on ψ' data



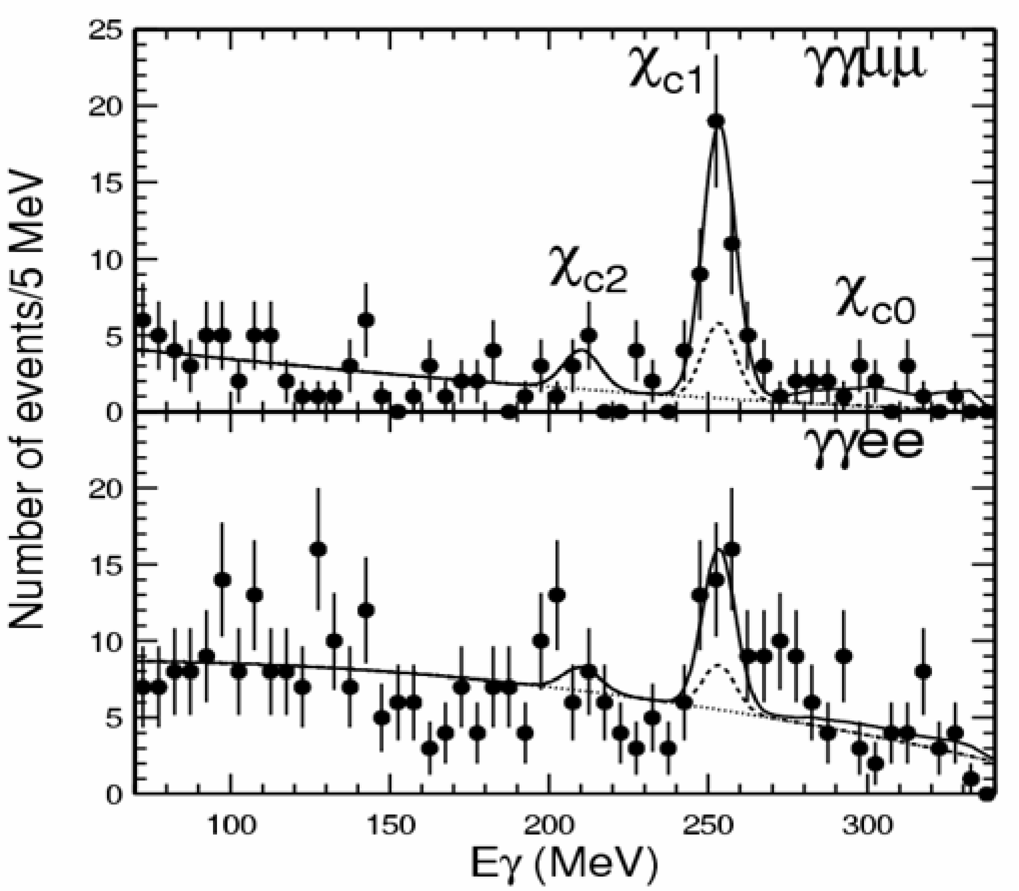


$\psi(2S)$ background in $\psi(3770)$ data

- ISR production of $\psi(2S)$ at E_{cm}=3770MeV
  - $e^+e^- \to \gamma\, \psi(2S)$
    - $\psi(2S) \to \gamma\chi_{cJ} \to \gamma J/\psi \to \gamma\, \gamma\, l^+l^-$
    - $\psi(2S) \to \gamma\chi_{cJ} \to \gamma\, (2K,\, 2K2\pi\, 2K,\, 4\pi\, ,\, 6\, \pi\,)$
- E_γ^{ISR} ~84 MeV for $\psi(2S)$ produced with its nominal mass:
  - Selection criteria and kinematic fitting gets rid of this background (E_γ^{ISR} forced to be less than about 40 MeV)
- Radiative flux peaks for $E_\gamma^{ISR} \to 0$ making the remaining background indistinguishable from the signal:
  - Estimate this background using $\psi(2S)$ measurements and theoretical formulae extrapolating the rate to the ISR peak

$\psi'' \rightarrow \gamma\gamma l^+ l^-$

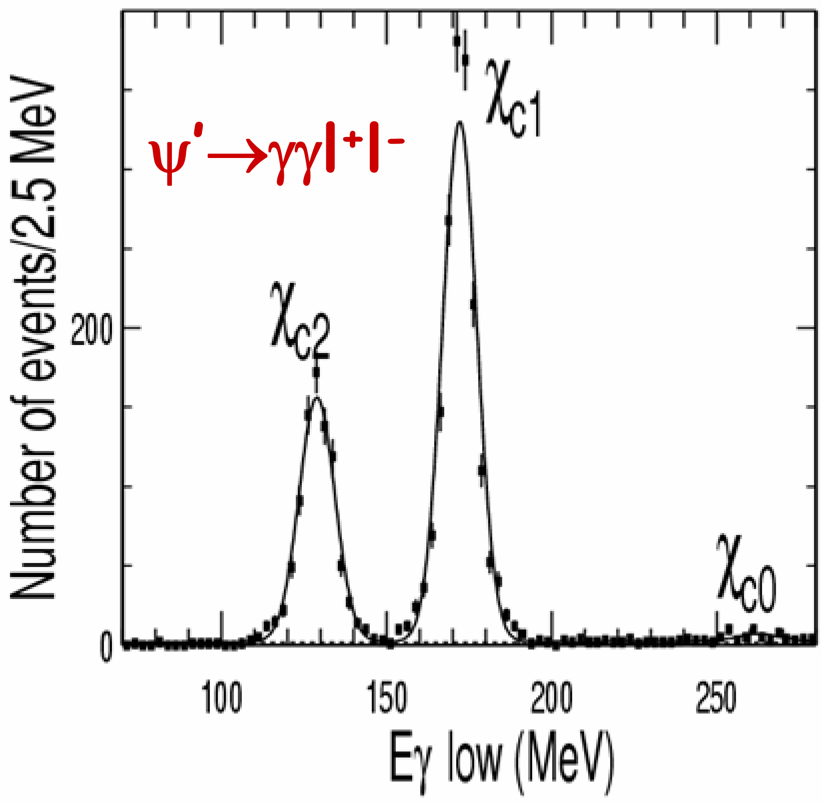
Separate $\mu\mu$ and ee data because of very different background level but fit them simultaneously



Signif.	0.0	6.6	1.7

Number of events for ψ''
A0=22±9
A1=53±10
A2=0±2.9
RR from ψ'
A0=11.7
A1=20.0
A2=0.6

Cross check of $\psi'' \to \gamma\gamma l^+l^-$ analysis by $\psi' \to \gamma\gamma l^+l^-$



Fit to gaussian shapes with linear background

Number of events for ψ'

A1=1718 ±42

A2=835 ±30

	Our measurements of BR($\psi' \to \gamma c_{cJ}$) (%)	previous CLEO-c measurement using a different technique
J=2	1.84 ±0.07	1.81 ±0.06
J=1	3.53 ±0.09	3.50 ±0.08

Results for $\gamma l^+ l^-$ Analysis

$$BR\left(\psi'' \to \gamma\chi_{cJ} \to \gamma\gamma l^+ l^-\right) = \frac{N_{events}^{(\psi''\to\gamma\gamma l^+ l^-)}}{\varepsilon_{\psi''\to\gamma\gamma l^+ l^-} \times N_{\psi''}}$$

	Results for $\psi'' \to \gamma\chi_{cJ}$		
	J=2	J=1	J=0
ε(%)	18	23	20
Branching Ratio: BR (10^{-3})	< 0.9	2.8 ±0.5 ±0.4	<44

- $B(\psi'' \to \gamma\chi_{c0})$ is predicted to be the largest, but the small $B(\chi_{c0} \to \gamma J/\psi)$ limited our sensitivity
- In order to measure we $B(\psi'' \to \gamma\chi_{c0})$ turned to hadronic decays of χ_{cJ}.

Technique for 2nd Method

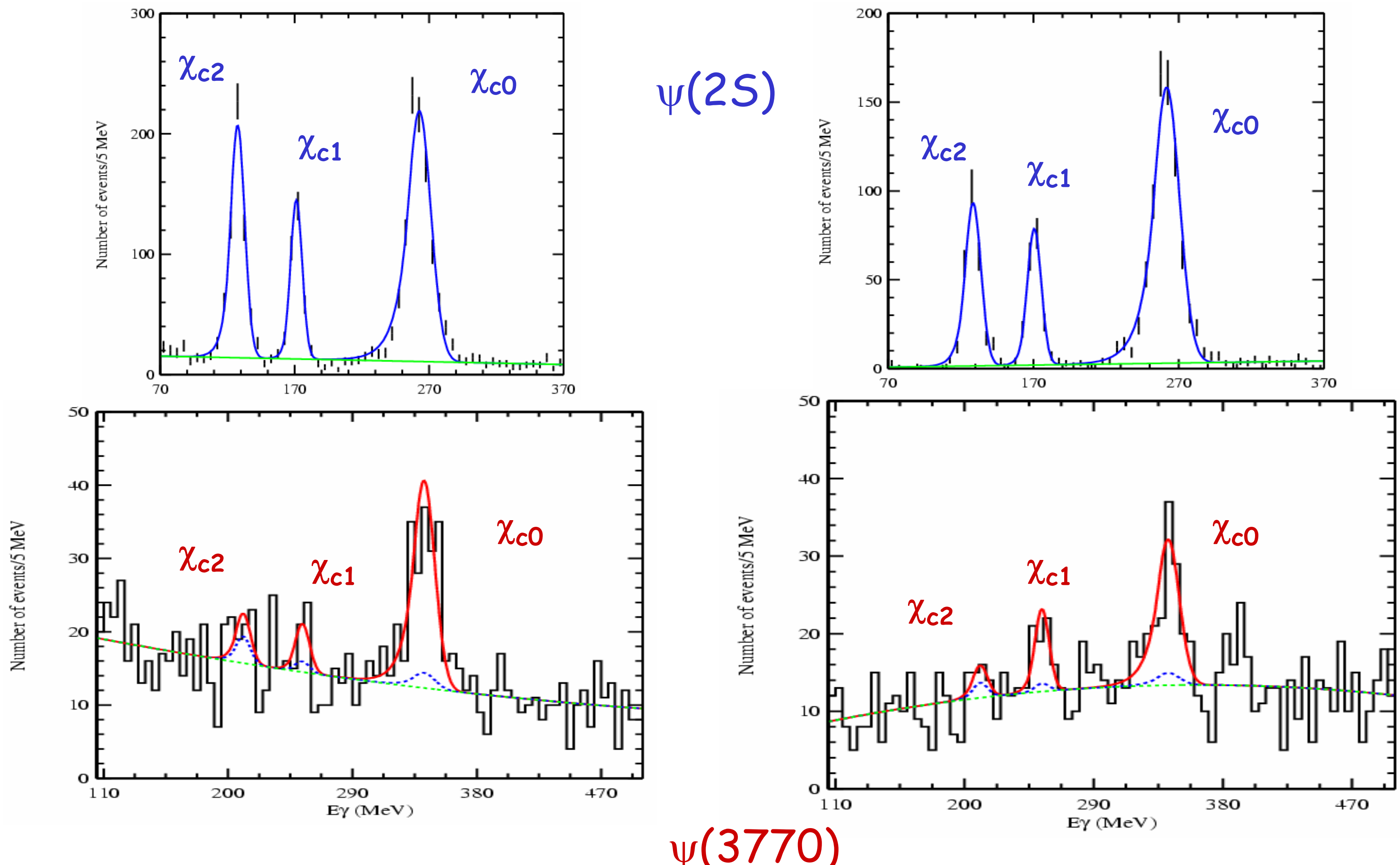
$$R = \frac{BR(\psi'' \to \gamma\chi_{cJ}, \chi_{cJ} \to \text{final state})}{BR(\psi' \to \gamma\chi_{cJ}, \chi_{cJ} \to \text{final state})}$$

$$= \frac{N_{events}^{(\psi'' \to \text{final state})}}{N_{events}^{(\psi' \to \text{final state})}} \times \frac{\varepsilon_{(\psi' \to \text{final state})}}{\varepsilon_{(\psi'' \to \text{final state})}} \times \frac{N_{\psi'}}{N_{\psi''}}$$

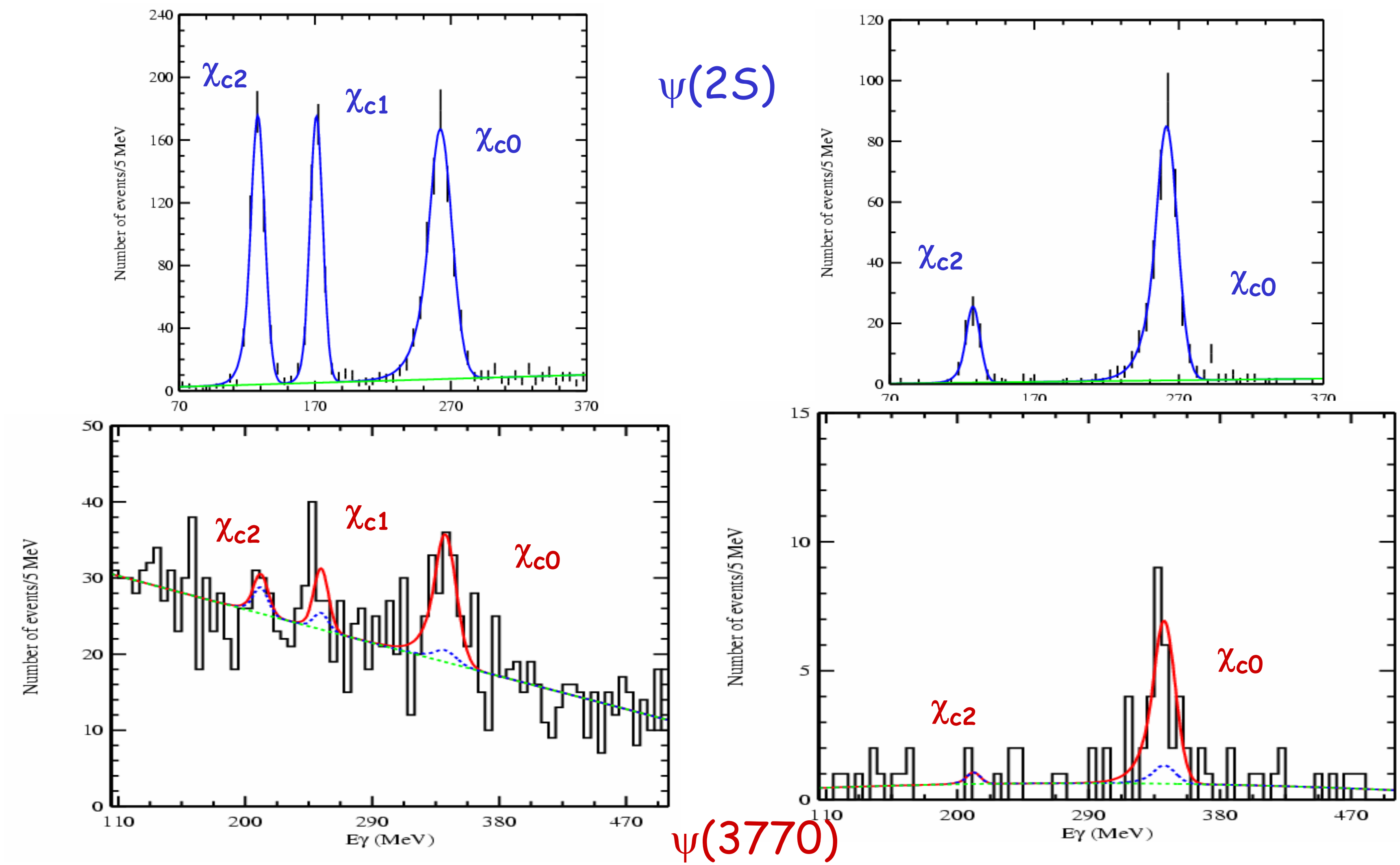
$$BR(\psi'' \to \gamma\chi_{cJ}) = R \times BR(\psi' \to \gamma\chi_{cJ})$$

PR D70, 112002(2004)

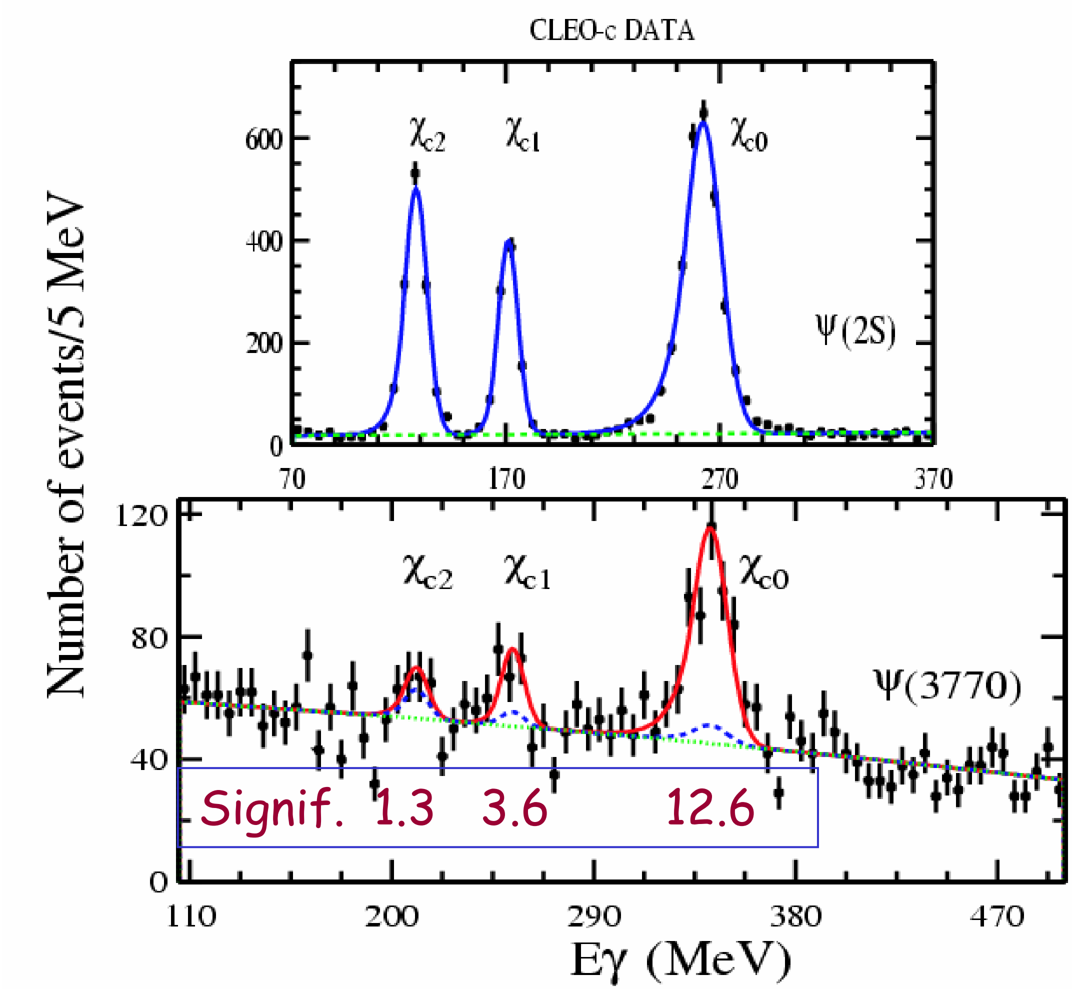
$\psi'' \rightarrow \gamma 4\pi$(left), $\gamma 2K2\pi$ (right)



$\psi'' \to \gamma 6\pi$ (left), $\gamma 2K$ (right)



Combined plots for four hadronic decay modes



Number of events for ψ'
A0=2816±58
A1= 886±32
A2=1329±40
Sum of fits (3 CBL with a linear background) to individual decay modes

Number of events for ψ''
A0=274±27
A1= 54±17
A2= 20±18
RR from ψ'
A0=25.2
A1=12.0
A2=24.9
Sum of fits (6 CBL with quadratic background)

Results for $\psi'' \to \gamma\chi_{cJ}$

	Results for $BR(\psi'' \to \gamma\chi_{cJ})$ (10^{-3})		
	J=2	J=1	J=0
2nd method	< 2.0	3.9 ±1.4 ±0.6	7.3 ±0.7 ±0.6
$\gamma\gamma ll$	< 0.9	2.8 ±0.5 ±0.4	<44
Combined	**< 0.9**	**2.9 ±0.5 ±0.6**	**7.3 ±0.7 ±0.6**

Observe significant signal for $\psi'' \to \gamma\chi_{c0,1}$ and set a 90% C.L. upper limit for $\gamma\chi_{c2}$.

Interpretation of X(3872)

$$\frac{\Gamma\left(\psi'' \to \gamma\chi_{c1}\right)}{\Gamma\left(\psi'' \to \pi^+\pi^- J/\psi\right)} = 1.56 \pm 0.37 \pm 0.37$$

PRL 96 082004 (2006)

$$\frac{\Gamma\left(\psi_2 \to \gamma\chi_{c1}\right)}{\Gamma\left(\psi_2 \to \pi^+\pi^- J/\psi\right)} \approx (2-3.5) \times \frac{\Gamma\left(\psi'' \to \gamma\chi_{c1}\right)}{\Gamma\left(\psi'' \to \pi^+\pi^- J/\psi\right)} > 2 \times 1.8$$

$$\frac{\Gamma\left(X(3872) \to \gamma\chi_{c1}\right)}{\Gamma\left(X(3872) \to \pi^+\pi^- J/\psi\right)} < 0.9 \text{ Belle}$$

X(3872) is not 1^3D_2 !

Nature of $\psi(3770)$

- Theoretically
  - $\Gamma_J = {}^4/_3 e^2 \alpha E_\gamma^3 C_J |\langle 1^3D_1|r|1^3P_J\rangle|^2$
- Non-relativistically $\langle 1^3D_1|r|1^3P_J\rangle$ is J independent
  - we can cancel it by calculating the ratios of widths
- J-dependence:
  - C_J =2/9, 1/6 and 1/90 for $1^3D_1 \rightarrow 1^3P_J$ J=0, 1 and 2
  - Measured E_γ
- Thus in non-relativistic limit expect:
  - $\Gamma_0 / \Gamma_1 = 3.2$ and $\Gamma_0 / \Gamma_2 \sim 85$
- Measured:
  - $\Gamma_0 / \Gamma_1 = 2.5 \pm 0.6$ and $\Gamma_0 / \Gamma_2 > 8$

Evidence that ψ'' is predominantly 1^3D_1 state

Beyond the naïve theory

	$\Gamma(\psi'' \to \gamma\chi_{cJ})$ **(keV)**		
	J=2	J=1	J=0
CLEO-c data	**< 20**	**70 ±17**	**172 ±30**
Rosner (non-relativistic)	24 ±4	73 ±9	523 ±12
Ding-Qin-Chao			
Non-relativistic	3.6	95	312
Relativistic	**3.0**	**72**	**199**
Eichten-Lane-Quigg			
Non-relativistic	3.2	183	254
Coupled-channel corrections	**3.9**	**59**	**225**
Barnes-Godfrey-Swanson			
Non-relativistic	4.9	125	403
Relativistic	**3.3**	**77**	**213**

- Relativistic/coupled-channel corrections in potential model calculations are important for agreement with the data

Decay width for $\psi(2S)$

	$\Gamma(\psi' \to \gamma\chi_{cJ})$ **(keV)**		
	J=2	J=1	J=0
CLEO data	**27 ±4**	**27 ±3**	**27 ±3**
Rosner (non-relativistic)	35 ±1	75 ±3	26 ±6
Ding-Qin-Chao			
Non-relativistic	42	36	25
Relativistic	**25**	**28**	**22**
Eichten-Lane-Quigg			
Non-relativistic	23	33	36
Coupled-channel corrections	**23**	**32**	**38**
Barnes-Godfrey-Swanson			
Non-relativistic	38	54	63
Relativistic	**24**	**29**	**26**

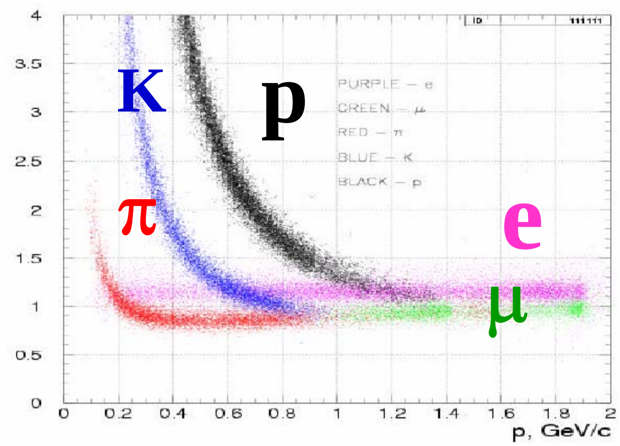
- Corrections needed in potential model calculations for agreement with the data of $\psi(2S)$ as well

Conclusions

- We have observed $\psi'' \rightarrow \gamma\chi_{c0,1}$ for the first time:
  - $\gamma\gamma ll$ results published in PRL 96, 182002 (2006)
  - results for hadronic in PR D, Rapid Communications (hep-ex/0605070)
- In view of our results the 1^3D_2 interpretation of X(3872) can be ruled out
- Spin dependence of the observed rates confirms that $\psi(3770)$ is predominantly 1^3D_1 state
- Relativistic or couple channel effects are needed for quantitative agreement between potential model calculations and the data

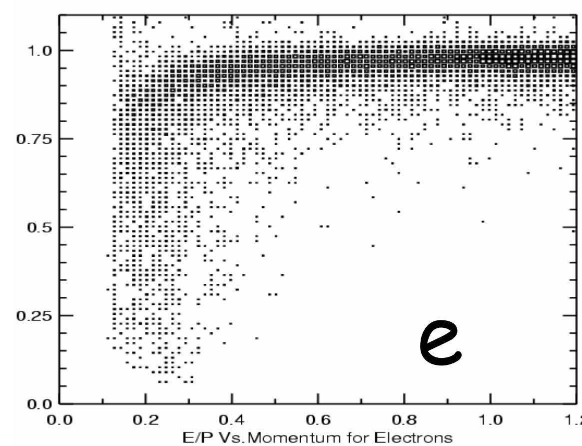
BACK UP

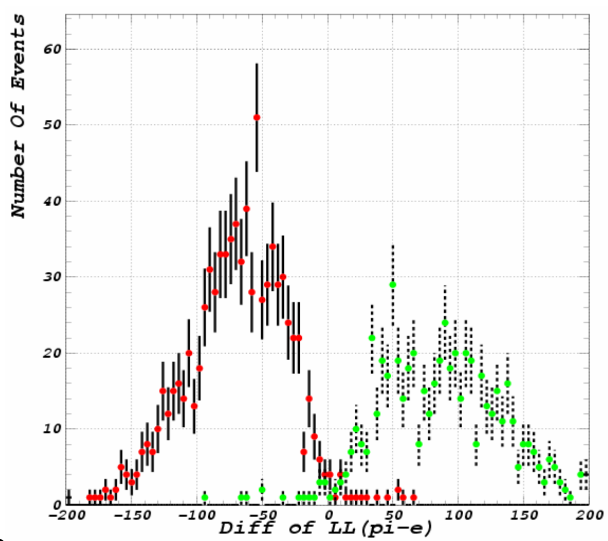
Some detector plots



DE/DX from DR

E/P



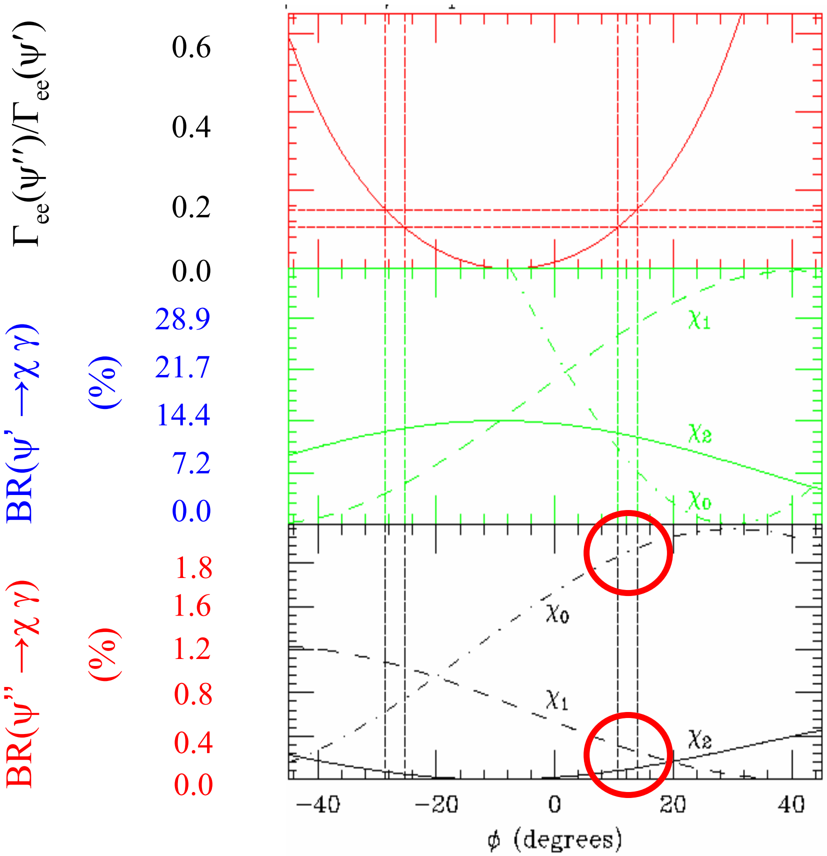


RICH

K-f Effect

- 0-ggll
  - DATA: 128.85 5.629
  - w/ k-fit: 128.93 5.337
  - w/o: 127.57 7.082
- 1-4pi
  - DATA: 127.57 5.245 fixed to MC
  - w/ k-fit w/ k-fit: 126.94 4.969 1.224
  - w/o: 127.11 6.186 0.945
- 2-2k2pi
  - DATA: 128.45 5.422 fixed to MC
  - w/ k-fit w/ k-fit: 126.83 4.835 1.265
  - w/o: 126.95 6.339 1.009
- 3-6pi
  - DATA: 127.94 5.172 fixed to MC
  - w/ k-fit w/ k-fit: 126.91 4.966 1.201
  - w/o: 127.13 6.263 0.932
- 4-2k
  - DATA: 127.54 4.851 fixed to MC
  - w/ k-fit w/ k-fit: 126.87 4.570 1.220
  - w/o: 126.93 6.305 0.986

2S1-1D1 mixing



- The measured rate for J=0 is much larger than for J=1 (which in turn is larger than J=2).
  - Confirming naïve prediction

    BR_0 □ BR_1 □ BR_2
  - Confirming D state
- Insensitive to mixing
  - Mixing needed to explain large cross-section of $\psi(3770)$ in e^+e^- experiment
  - Effects of mixing on the rates are small
  - Can be explored more with better measurement of J=2

General

- mDD*=3871.2 MeV (neutral), 3879.3 MeV (charged)
- mDD= 3729.0 MeV (neutral), 3738.0 MeV (charged)
- Eqn's of k-fit
  - Pcm=Pl+ + Pl- + Pg1 + pg2
  - Pcm=Ph+ + Ph- + Pg
- ISR background

$$N_{events}^{(\psi'\text{ in }\psi''\text{ from ISR})} = B_{(\psi'\to\text{final state})} \times \varepsilon_{(\psi''\to\text{final state})} \times L_{\psi''} \times \Gamma_{ee}(\psi') \times I(s)$$

$$= \frac{N_{events}^{(\psi'\to\text{final state})}}{N_{\psi'} \times \varepsilon_{(\psi'\to\text{final state})}} \times \varepsilon_{(\psi''\to\text{final state})} \times L_{\psi''} \times \Gamma_{ee}(\psi') \times I(s)$$

$$I(s) = \int_0^x W(s,x), b(s'(x)) F_X(s'(x)) dx$$

$$F(s') = (E_\gamma^{ISR}(s')/E_\gamma^{ISR}(M_R^2))^3$$