Charmonium Spectroscopy

Experimental overview

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ECT* Workshop
Heavy Quarkonium and Related
Heavy Quark States

Trento, 17-31 August 2006

Outline

- Why to study charmonium spectroscopy?
- Charmonium production and decay
- Conventional charmonia states
- The new states in the charmonia mass region

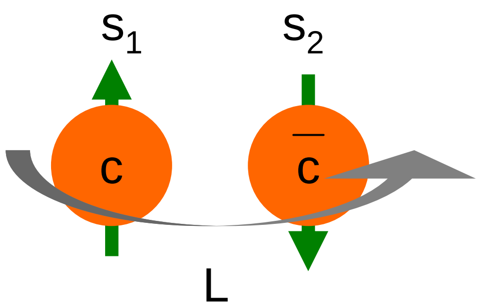
Why to study charmonium?

- $c\underline{c}$ bound state
- Powerful tool for the understanding of the strong interaction
- The high mass of the c quark (~1.5 GeV/c^2) makes it possible to perform a description of the $c\underline{c}$ dynamical properties through a non-relativistic potential model
- The parameters for the heavy quark dynamics in the charmonium state can be obtained from a fit to the data:

  $\alpha_s \sim 0.3$

  $\beta^2 \sim 0.2$

The spectroscopic notation



- The states can be described with the spectroscopic notation:

  $n^{2S+1}L_J$

  $\vec{S} = \vec{S}_1 + \vec{S}_2$

  $\vec{J} = \vec{L} + \vec{S}$

- Parity and Charge conjucation are:

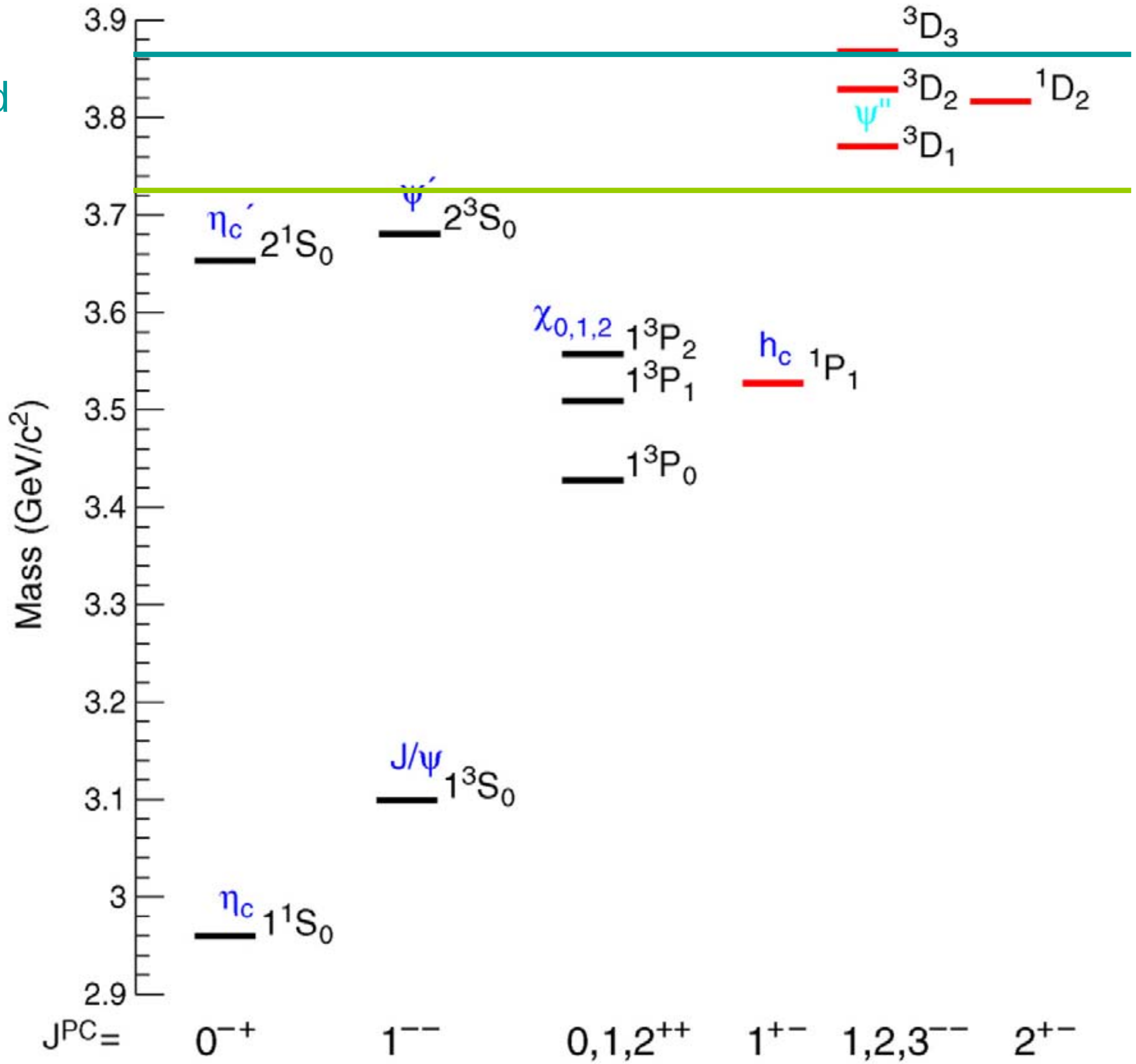
  $P = (-1)^{L+1}$

  $C = (-1)^{L+S}$

The charmonium spectrum

3.87
DD* threshold

3.73
DD threshold



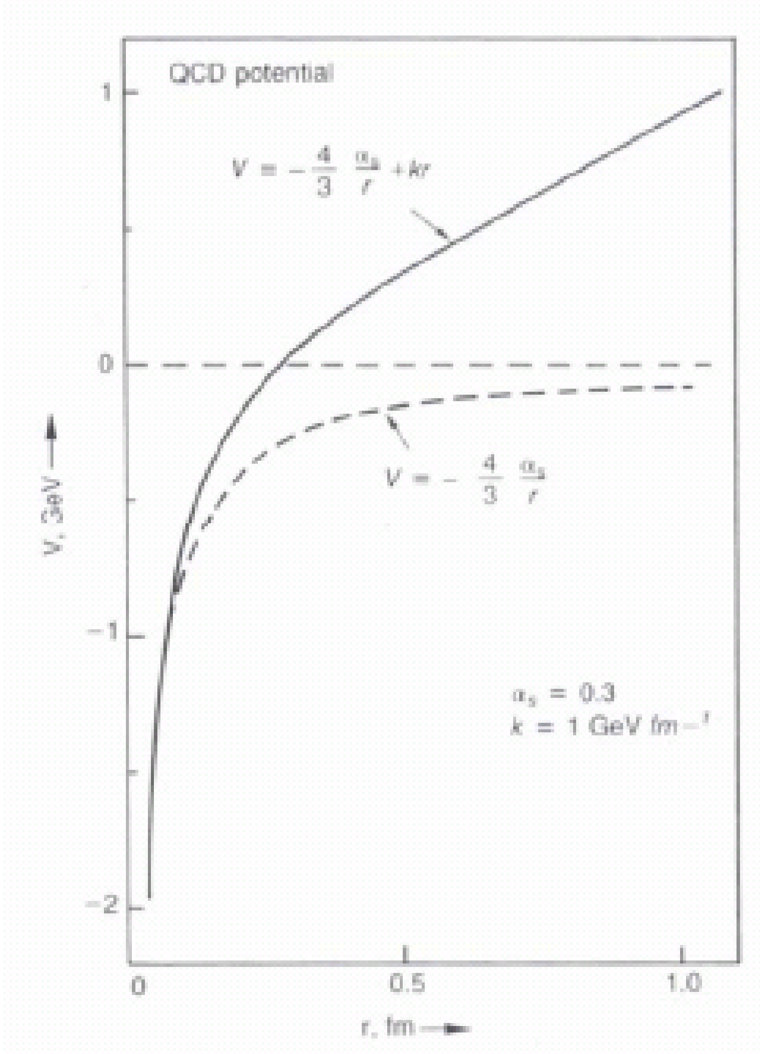
Non relativistic potential

- Short distance: asymptoic freedom

  $V(r) \sim -4/3\ \alpha_s(r)/r$

- Long distance: confinement

  $V(r) \sim kr$



Spin dependent potential

Additional spin-orbit interaction needed to explain the charmonium fine structure

$$H' = V_{LS} + V_{SS} + V_T$$

$$\begin{cases} V_{LS} = \dfrac{(\vec{L}\cdot\vec{S})}{2m_c^2 r}\left(3\dfrac{dV_V}{dr} - \dfrac{dV_S}{dr}\right) & \text{Spin-orbit} \\ V_{SS} = \dfrac{2(\vec{S_1}\cdot\vec{S_2})}{3m_c^2}\nabla^2 V_V(r) & \text{Spin-spin} \\ V_T = \dfrac{2\left[3(\vec{S}\cdot\hat{r})(\vec{S}\cdot\hat{r}) - S^2\right]}{12m_c^2}\left(\dfrac{1}{r}\dfrac{dV_V}{dr} - \dfrac{d^2V_V}{dr^2}\right) & \text{Tensor} \end{cases}$$

The Coulomb-like part of V(r) correspond to 1 gluon exchange and contributes to the vector part of the potential V_V. The scalar part V_S is due to the linear confining potential (the confining term could in principle contribute to both V_V and V_S but a fit to the χ_{cJ} masses suggests that the V_V contribution is small).

Charmonium production

- e^+e^- machines (MARK I-II-III, TPC, Crystal Ball, DASP, PLUTO, LEP, CLEO, KEDR, OLYA, CLEO-c, BES, BaBar, Belle)
  - direct formation ($J^{PC} = 1^{--}$ states)
  - $\gamma\gamma$ production
  - initial state radiation
  - B meson decay
  - double charmonium production
- $p\bar{p}$ annihilation (R704, E760, E835, PANDA)
- hadroproduction (CDF, D0, LHC)
- electroproduction (HERA-B, H1, ZEUS)

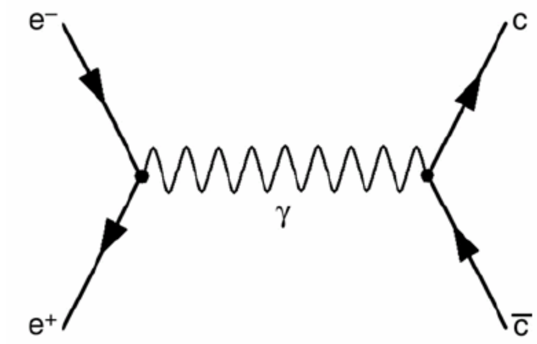
Direct formation in e^+e^- annihilation

- Only states with the photon quantum number ($J^{PC}=1^{--}$)

- Other states may be accessed through radiative decays

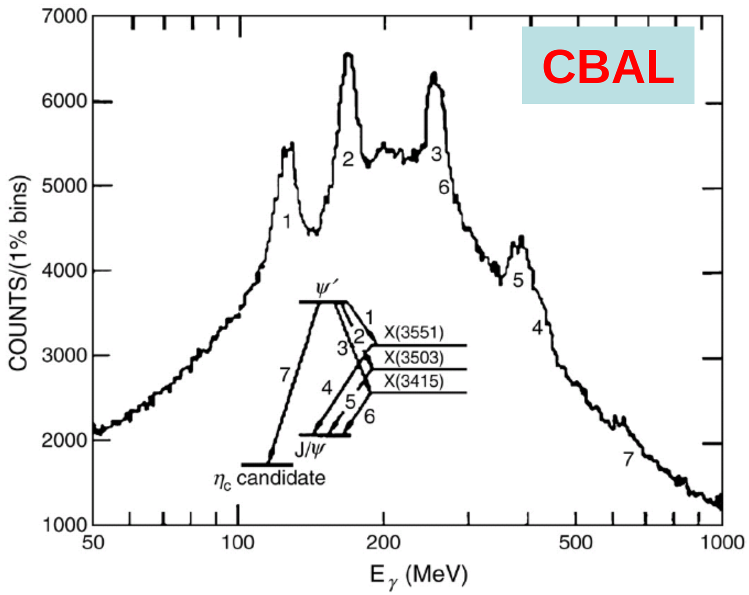
  i.e. $e^+e^- \rightarrow \psi' \rightarrow \chi_{cJ}\gamma$

$$e^+e^- \rightarrow c\bar{c}$$



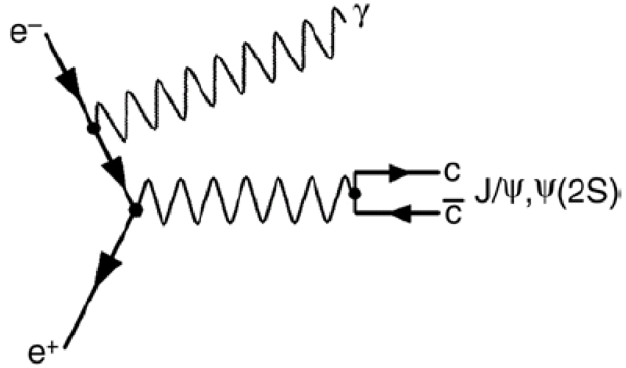
Photon spectra observed by Crystal Ball

PRL 45,1150 (1980)



Initial state radiation processes

$$e^+e^- \to \gamma_{ISR} + c\bar{c}$$

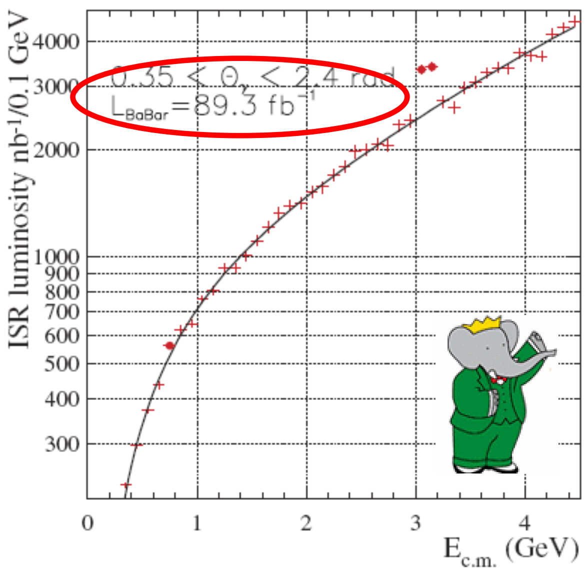


- Formation of 1^{--} states is also possible after initial state radiation (radiation of a photon from the $e^\pm$ in the initial state that lower the $\sqrt{s}$ of the interaction)
- ISR cross section for production of final state *f*:

$$\frac{d\sigma_f}{dx} = W(s,x)\cdot\sigma_f(s(1-x)) \qquad \begin{cases} x = 2E_\gamma/\sqrt{s} \\ s' = s(1-x) \end{cases}$$

Probability of ISR photon emission:

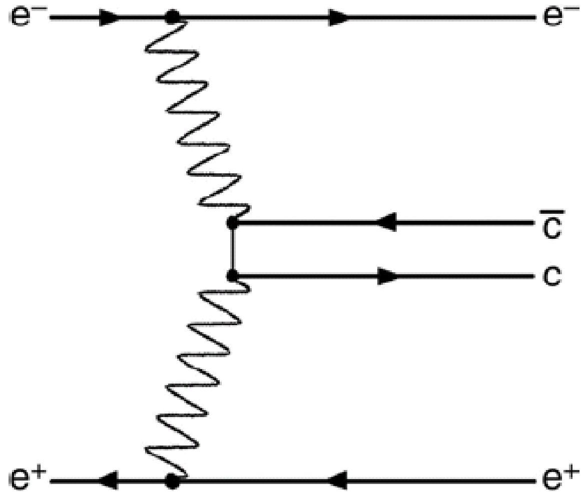
$$W(s,x) = \frac{2\alpha}{\pi \cdot x}\left(2\ln\frac{\sqrt{s}}{m_e} - 1\right)\left(1 - x + \frac{x^2}{2}\right)$$



$\gamma\gamma$ production

- Interaction of $\gamma\gamma$
- Production of C=+ states
- The state is usually identified by its hadronic decays
- The cross section for this process scales with BR($c\underline{c} \to \gamma\gamma$)

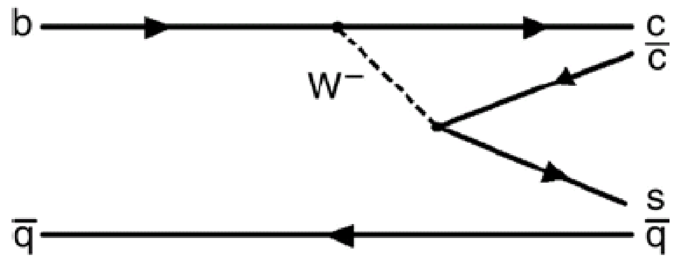
$$e^+e^- \to e^+e^- + c\bar{c}$$



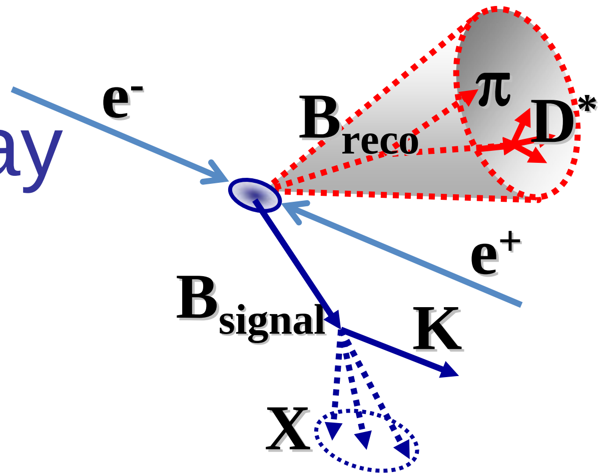
B meson decay

- Color suppressed B decays to charmonium states
- Branching ratios of the order of 10^{-4} but large samples available at the B factories
- Large discovery potential for the B factories in charmonium physics (η_c', X(3872))

$$B \rightarrow K^{(*)} + c\bar{c}$$

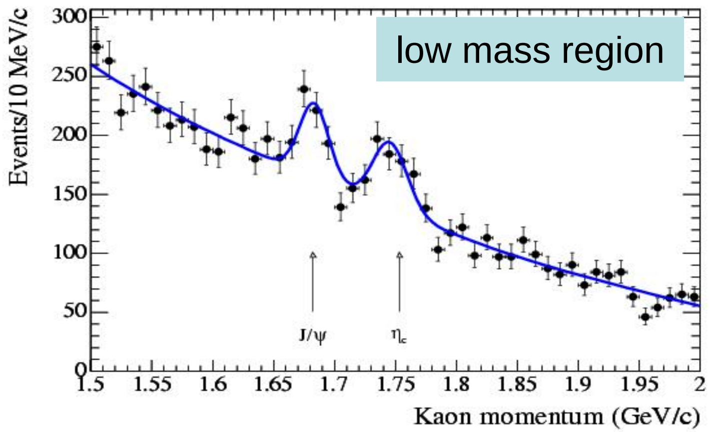


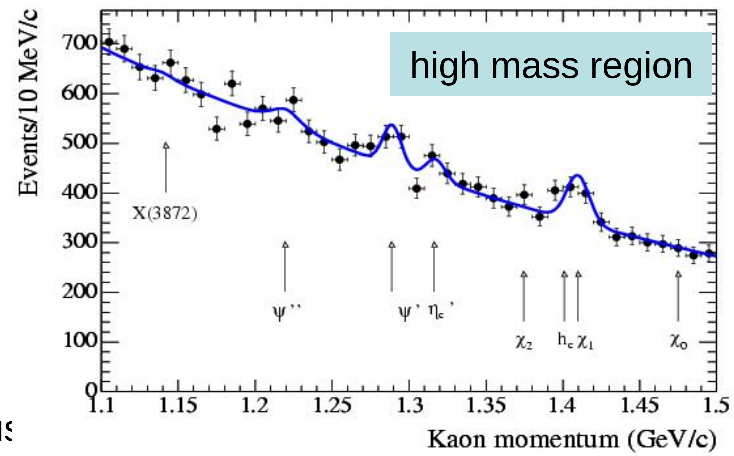
Inclusive charmonia in B decay



- Fully reconstruct B_{reco} in hadronic modes
- The X mass distribution can be obtained from the momentum distribution of $K^{\pm}$
- Huge background due to secondary $K^{\pm}$ tracks
- Observation of X states independent from the decay mode
- Absolute measurement of BR($B \to XK$)

Particle	Yield	$\mathcal{B}(10^{-4})$	Significance (σ)
η_c	273±43	8.4±1.3±0.8	7.3
J/ψ	259±41	8.1±1.3±0.7	6.9
χ_{c0}	9±21	<1.8	-
$\chi_{c1} + h_c$	227±40	8.0±1.4±0.7	6.0
χ_{c2}	0±36	<2.0	-
η_c'	98±52	3.4±1.8±0.3	1.8
ψ'	139±44	4.9±1.6±0.4	3.2
ψ''	99±69	3.5±2.5±0.3	1.4
$X(3872)$	15±39	< 3.2	-



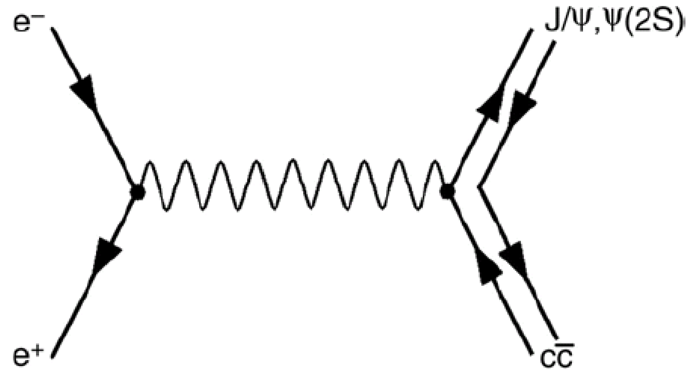


PRL 96, 052002 (2006)

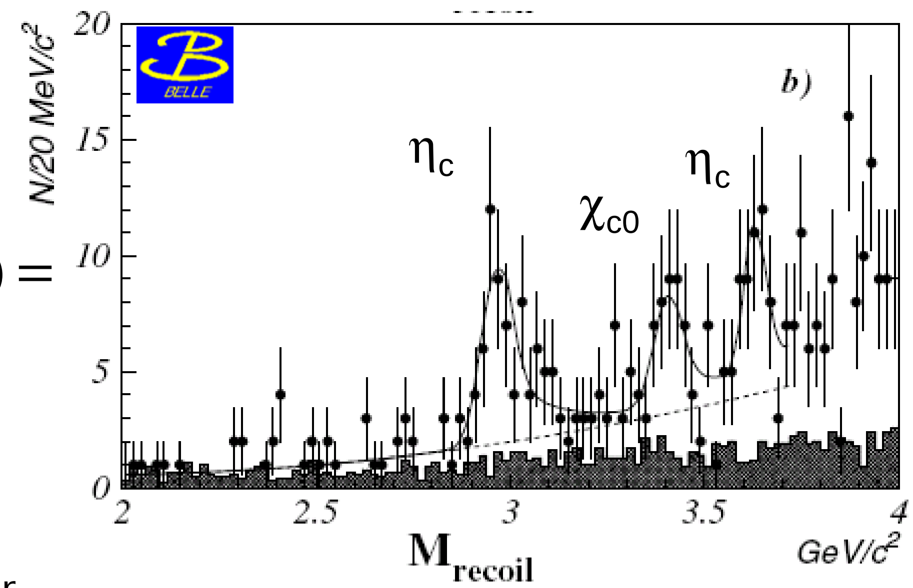
Double charmonium production

- Discovered by Belle
- Reconstruct a J/ψ and compute the recoiling invariant mass
- Observation of C=+ states
- Cross section one order of magnitude larger than NRQCD predictions

$$e^+e^- \rightarrow J/\psi + c\bar{c}$$



$$\sigma(e^+e^- \rightarrow J/\psi\eta_c)\cdot BR(\eta_c \geq 4tracks) =$$
$$= 0.033 \pm 0.011 pb$$

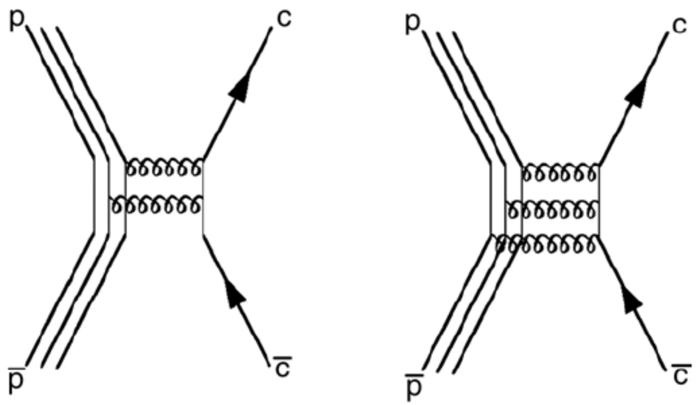


PRL 89, 142001 (2002)

Direct formation in $p\bar{p}$ annihilation

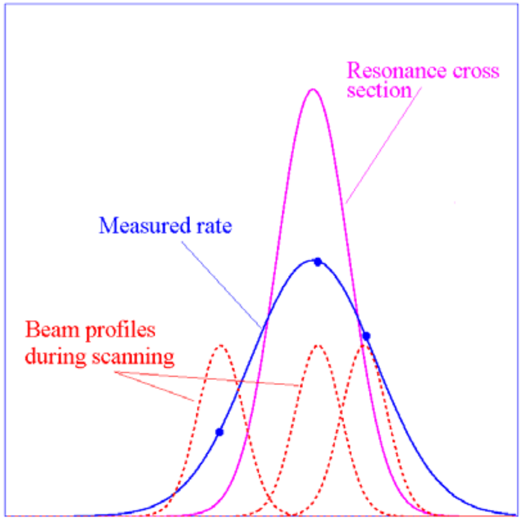
- Coherent annihilaton of the 3 quarks with the 3 antiquarks into a $c\bar{c}$ pair
- Direct formation of states with all quantum numbers
- Perform precision spectroscopy measurements through direct scan of the resonances
- Large hadronic background

$$p\bar{p} \longrightarrow c\bar{c}$$



$p\bar{p}$ annihilation: experimental technique

- Antiproton beam on H gas target
- The total energy is precisely known from the beam parameters (the detector resolution is not crucial)
  - Gaussian beam energy distribution
    σ~400 keV (ψ' width 300 keV)
- Measured cross section obtained counting events in the final state *f*
  - Convolution between resonance cross section and beam energy distribution



$$N_{ev} = Lum \cdot (\sigma_{bkg} + \int I_{beam}(E')\sigma_{BW}(E'-E)dE')$$

$$\sigma_{BW}(E) = \frac{\pi}{k^2}(2J+1)\frac{BR(p\bar{p} \to R)\cdot BR(R \to f)}{1+4(E-M_R)^2/\Gamma_R^2}$$

Beam energy and width determination

- Beam energy:

$$E_{CM} = \sqrt{2m^2(1+\gamma)} \qquad \gamma = \frac{E_{beam}}{m} = \sqrt{\frac{1}{1-\beta^2}} \qquad \beta = L \cdot f$$

$$\frac{dE_{CM}}{E_{CM}} = \frac{\beta^2\gamma^3}{2(1+\gamma)}\sqrt{\left(\frac{\delta f}{f}\right)^2 + \left(\frac{\delta L}{L}\right)^2}$$

  - m = proton mass
  - f = revolution frequency
  - L = orbit length

- η is a machine parameter (slip factor)

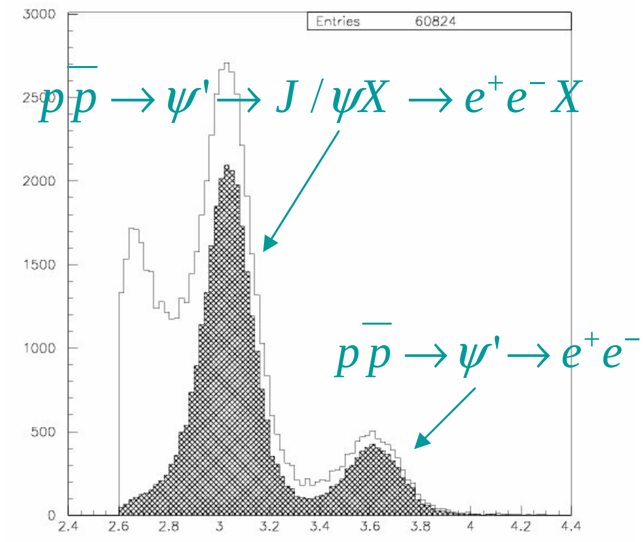
$$\frac{\delta p}{p} = -\frac{1}{\eta}\frac{\delta f}{f}$$

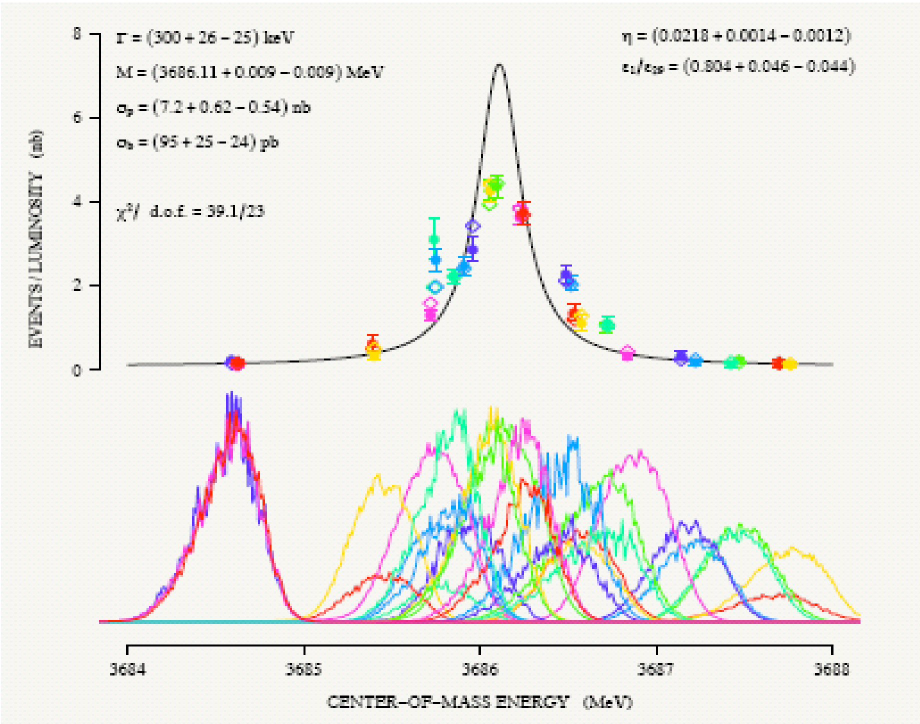
E835

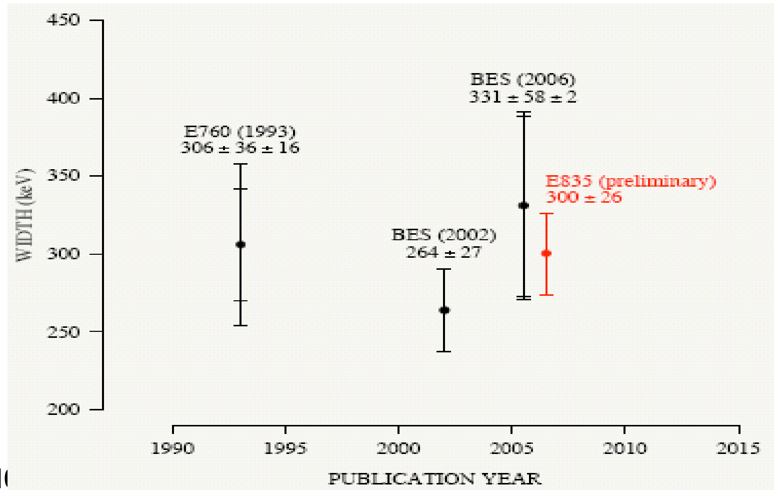
Direct measurement of the ψ' width

- E835 preliminary (G. Stancari - QWG workshop 2006)
- 2 scans performed with different techniques:
  - constant B (δf/f)
  - constant orbit (δL/L)

m_{ee} spectrum observed in the ψ' region







Charmonium decay

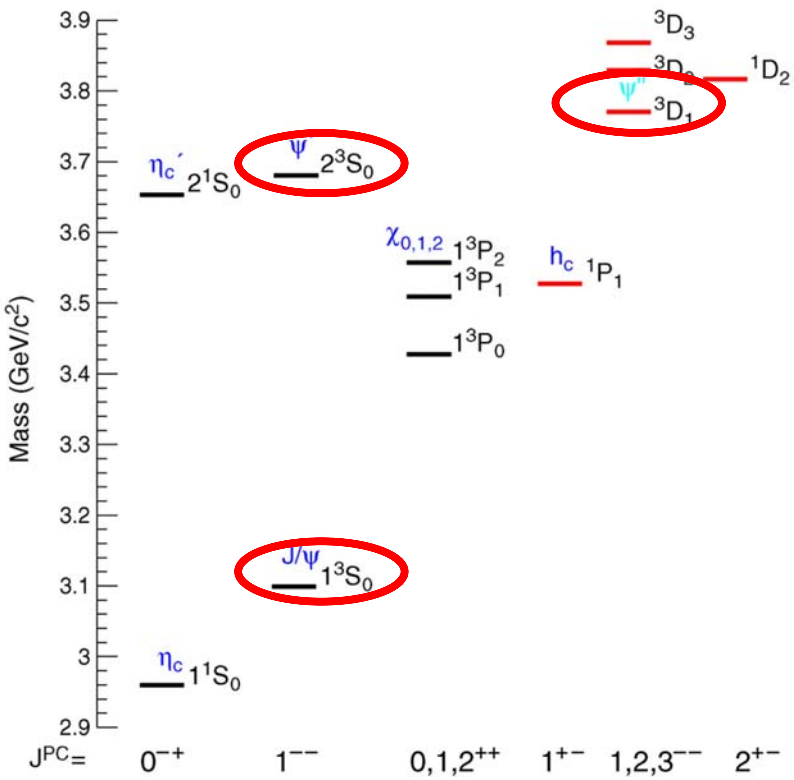
- Electromagnetic decays
  - $c\underline{c} \rightarrow e^+e^-, \mu^+\mu^-$
  - $c\underline{c} \rightarrow \gamma\gamma$
- Radiative decays
- Strong decays
  - hadronic decays
  - hadronic de-excitations

e^+e^- decay

- Possible for vector states (J/ψ, ψ')
- Described by the Van Royen - Weisskopf formula (LO in α_s):

$$\Gamma(J/\psi \rightarrow e^+e^-) = \frac{16\pi\alpha^2 e_c^2}{4m_c^2} |\Psi(0)|^2 \left(1 - \frac{16\alpha_s}{3\pi}\right)$$

- Clean decay mode at p$\bar{p}$ machines, where a large hadronic background is present



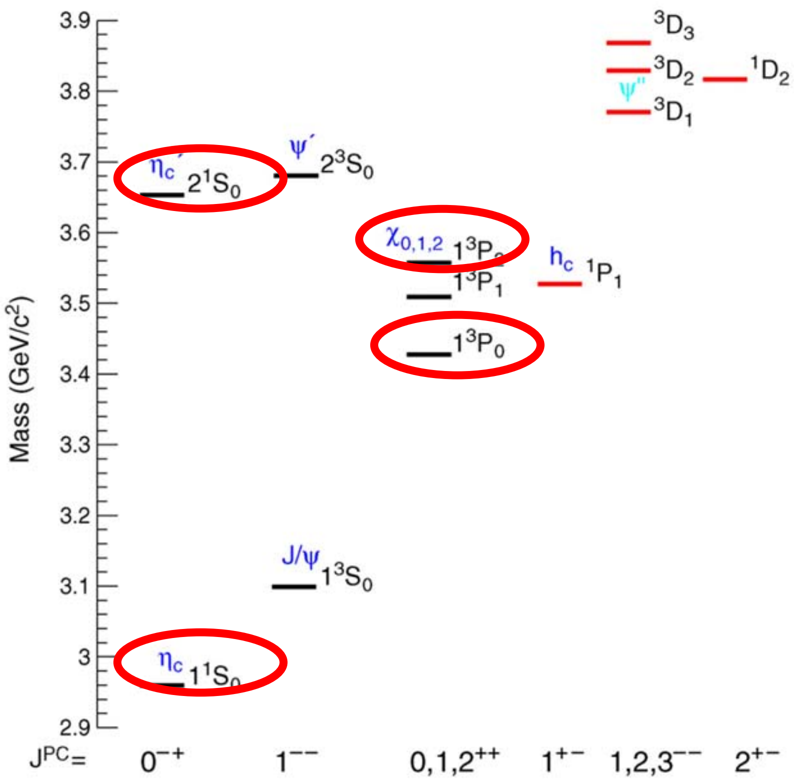
$\gamma\gamma$ decay

- C=+ states
- Forbidden for J=1 states (Yang's theorem)

$$\Gamma(\eta_c \to \gamma\gamma) = \frac{12\pi\alpha^2 e_c^4}{m_c^2} |\Psi(0)|^2 \left(1 - \frac{3.4\alpha_s}{\pi}\right)$$

$$\Gamma(\chi_{c0} \to \gamma\gamma) = \frac{27\alpha^2 e_c^4}{m_c^4} |R'(0)|^2 \left(1 + \frac{0.2\alpha_s}{\pi}\right)$$

$$\Gamma(\chi_{c2} \to \gamma\gamma) = \frac{36\alpha^2 e_c^4}{5m_c^4} |R'(0)|^2 \left(1 - \frac{16\alpha_s}{3\pi}\right)$$



$\Psi(0)$ = wavefunction at the origin
R'(0) = derivative of the non-relativistic P wavefunction at the origin

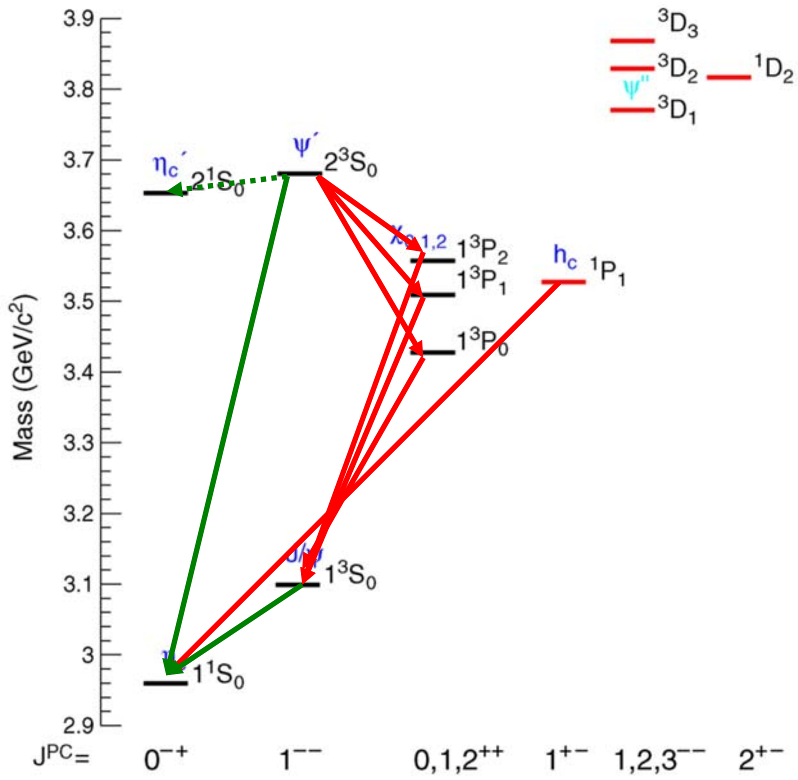
Radiative transitions

- Access to lower mass states with photon emission
  - Electric dipole (ΔL=±1 ΔS=0)

$$\Gamma(S \to P + \gamma) = \frac{2J_f + 1}{2J_i + 1} \cdot \frac{4}{9} e_c^2 \alpha k_\gamma^3 \, | E_{if} |^2$$

$$\Gamma(P \to S + \gamma) = \frac{4}{9} e_c^2 \alpha k_\gamma^3 \, | E_{if} |^2$$

$$| E_{if} | = \int_0^\infty dr r^3 R_i(r) R_f(r)$$



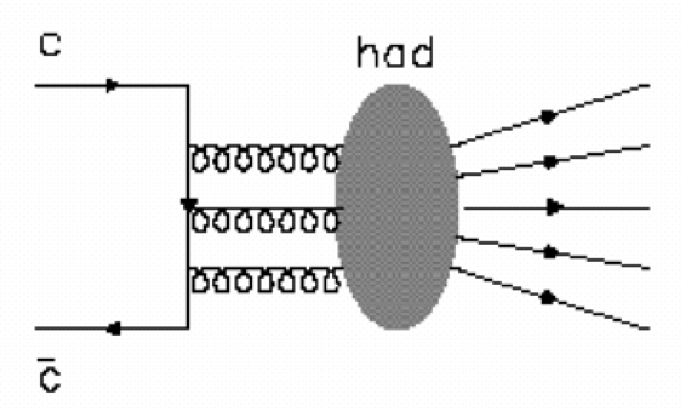
  - Magnetic dipole (ΔL=0 ΔS=±1)

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

j_0 Bessel spherical function

Hadronic decays

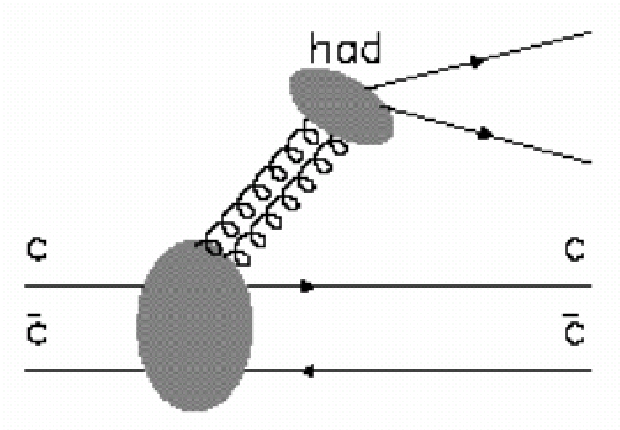
cc annihilation



Annihilation of cc pair in hard gluons, followed by hadronization.
Charmonium decay to light hadrons.
Can be treated perturbatively.
The partial width to light hadrons can be related to the partial width to $\gamma\gamma$:

$$\frac{\Gamma_{gg}}{\Gamma_{\gamma\gamma}} = \frac{2}{9}\frac{\alpha_s^2}{\alpha^2 e_c^4} \qquad \frac{\Gamma_{ggg}}{\Gamma_{\gamma\gamma\gamma}} = \frac{5}{54}\frac{\alpha_s^3}{\alpha^3 e_c^6}$$

hadronic de-excitation



Emission of soft gluons, followed by hadronization.
Transition to other charmonium state with light hadron emission ($\psi' \rightarrow J/\psi\pi\pi$).
Non perturbative process.

Charmonium decay to light hadrons

- At the NLO in α_s the width to light hadrons is given by:

$$\Gamma(\eta_c \to gg) = \frac{8\pi\alpha_s^2}{3m_c^2} |\Psi(0)|^2 \left(1 + \frac{4.8\alpha_s}{\pi}\right)$$

$$\Gamma(\chi_{c0} \to gg) = \frac{6\alpha_s^2}{m_c^4} |R'(0)|^2 \left(1 + \frac{9.5\alpha_s}{\pi}\right)$$

$$\Gamma(\chi_{c2} \to gg) = \frac{8\alpha_s^2}{5m_c^4} |R'(0)|^2 \left(1 - \frac{2.2\alpha_s}{\pi}\right)$$

5 minutes LO calculation (from PDG values)

	$\Gamma_{\gamma\gamma}$ keV	Γ_{LH} MeV	$\Gamma_{\gamma\gamma}/\Gamma_{LH}$
η_c	6.7	25.5	2.6×10^{-4}
χ_{c0}	2.9	10.4	2.8×10^{-4}
χ_{c2}	0.53	1.65	3.2×10^{-4}

Γ_{LH} is the total width for η_c while for χ_c it is obtained with subtraction of the radiative width

- For the J/ψ the LO is α_s^3:

$$\Gamma(J/\psi \to ggg) = \frac{40(\pi^2 - 9)\alpha_s^3}{81m_c^2} |\Psi(0)|^2 \left(1 - \frac{3.7\alpha_s}{\pi}\right)$$

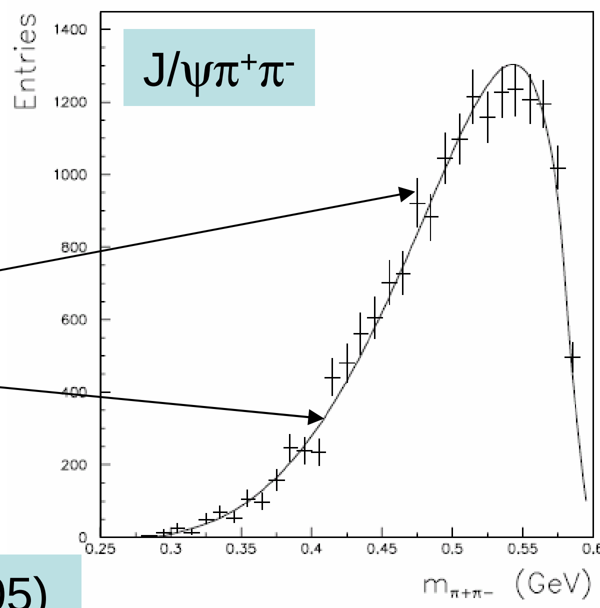
Hadronic de-excitation

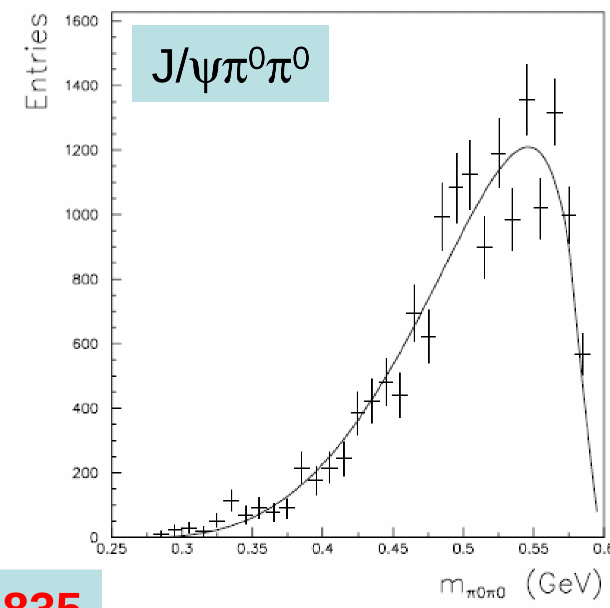
- $\psi' \rightarrow J/\psi\ \pi\pi$ has large BR (~50% of ψ' decays)
- Non perturbative QCD (soft gluon radiation)
- Some BR and the dipion invariant mass distribution can be predicted using conservation laws and the multipole expansion of the gluon field

$\pi\pi$ invariant mass distribution from E835

data

fit with multipole expansion prediction





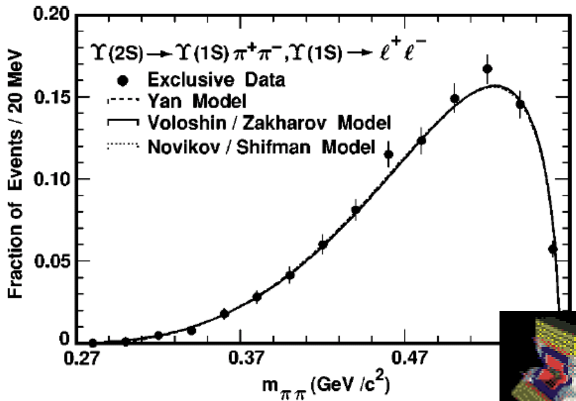
PRD 71, 032006 (2005)

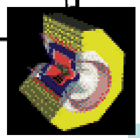
E835

A glimpse to bottomonium

- The transitions $\Upsilon(nS)\rightarrow\Upsilon(mS)\pi\pi$ are studied by many experiments
- Discrepancy with multipole expansion predictions for the dipion invariant mass distribution for some transitions
  - Excess at low invariant mass (~0.3 GeV) for $\Delta n=2$ transitions

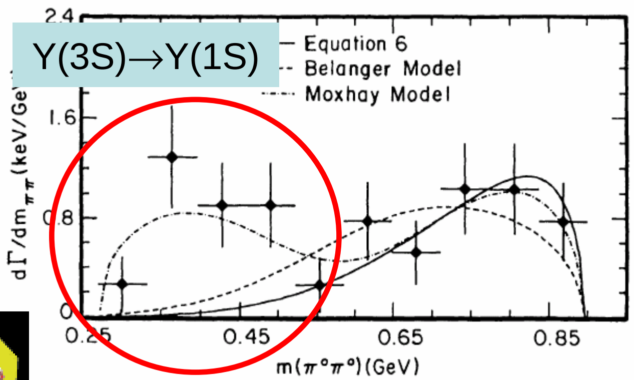
CLEO - PRD 58, 052004 (1998)

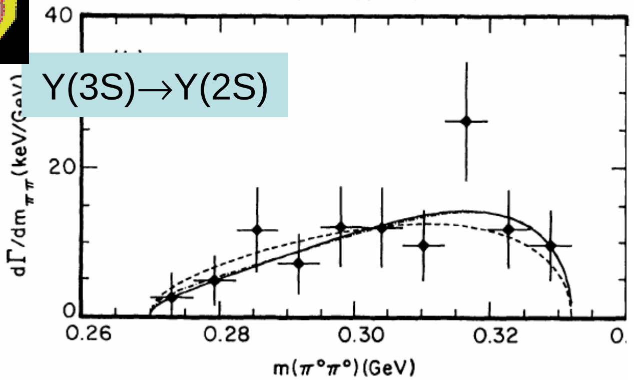




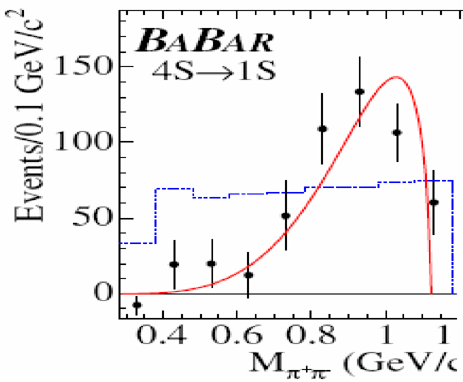
Confirmed by recent measurements by CLEO and Belle

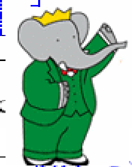
CLEO - PRD 49, 40 (1994)

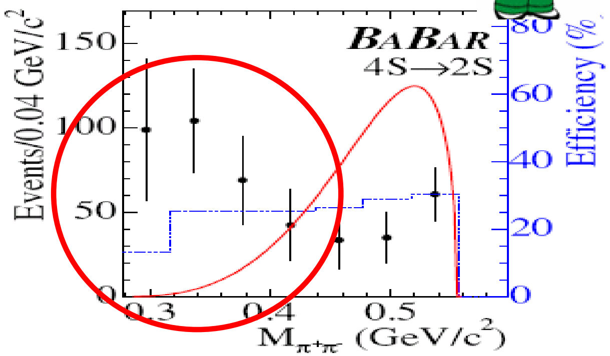




Babar - PRL 96, 232001 (2006)







The J/ψ (1^3S_1)

- Charmonium discovery in 1974
- Masses and width are well established:
  - $M(J/\psi) = 3096.916 \pm 0.011$ MeV
  - $\Gamma(J/\psi) = 93.4 \pm 2.1$ keV
- Can be used for detector and machine calibration
- Usually reconstructed in $J/\psi \rightarrow e^+e^-$, $\mu^+\mu^-$ decays

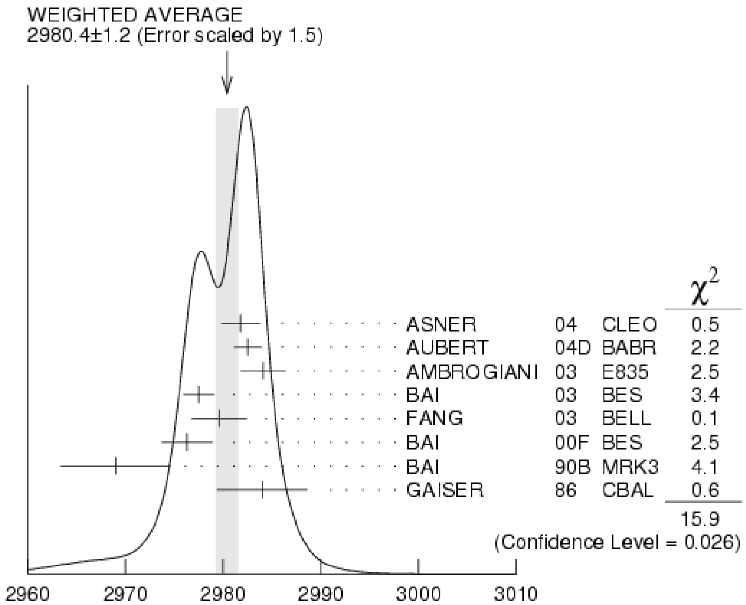
The η_c (1^1S_0)

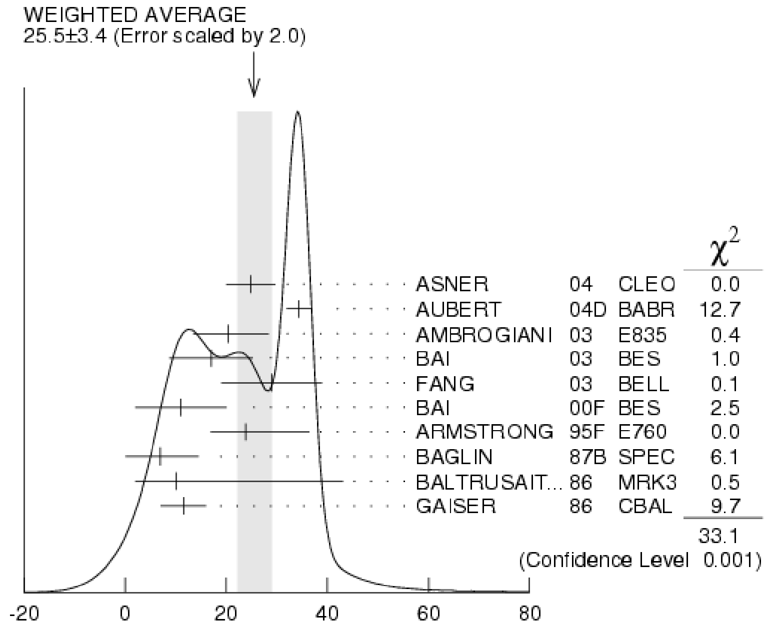
- The ground state of charmonium ($J^{PC}=0^{-+}$)
- The mass difference $M(J/\psi)-M(\eta_c)$ is a key parameter for the potential model
- Observed in:
  - M1 radiative decays of J/ψ and ψ'
  - $p\underline{p}$ annihilation
  - $\gamma\gamma$ fusion
  - B decay
  - double charmonium production

The η_c mass and width

Large width

M and Γ measured by several experiments but discrepancies still present





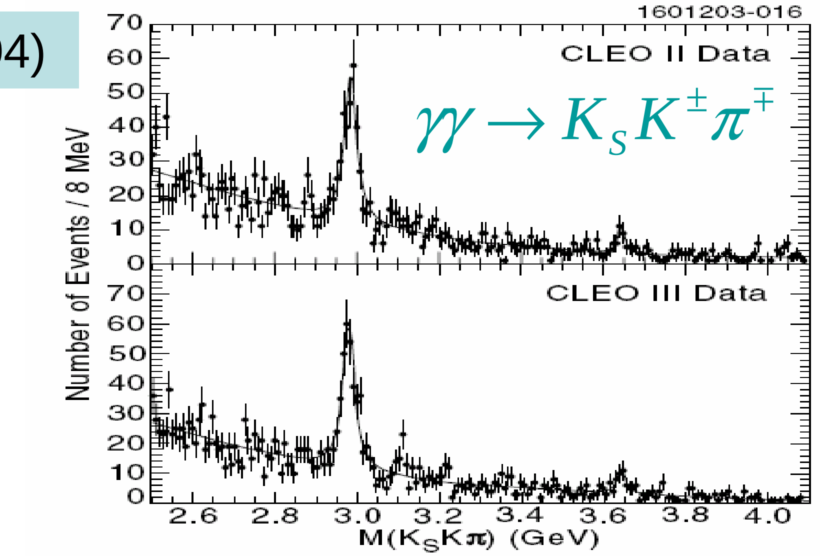
M = 2980.4±1.2 MeV

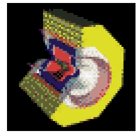
Γ = 25.5±3.4 MeV

Some recent η_c width measurements

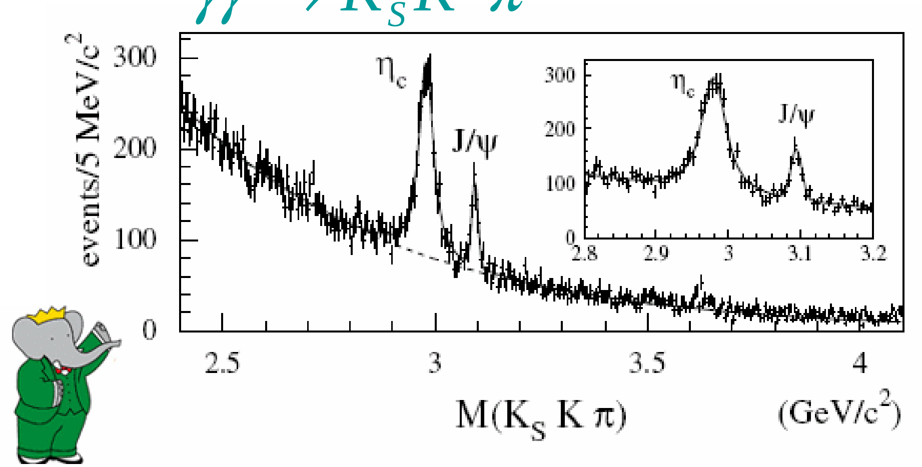
CLEO: PRL 92,142001 (2004)

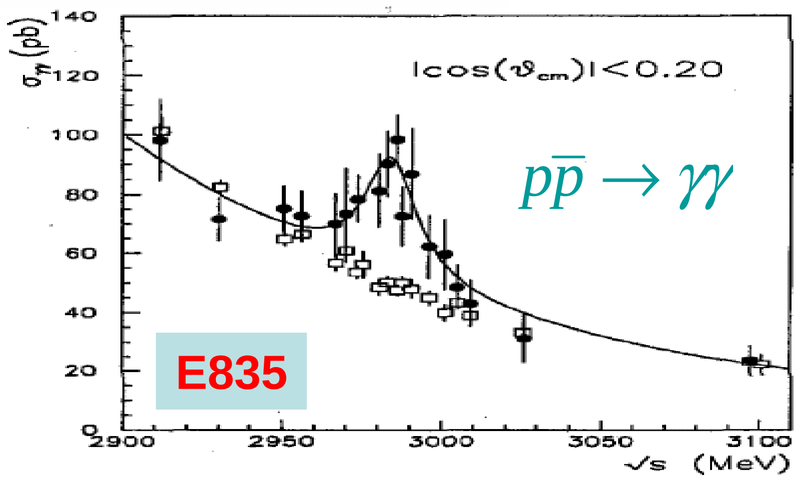
$\Gamma(\eta_c)$ = 24.8±3.4±3.5 MeV





$\gamma\gamma \to K_S K^\pm \pi^\mp$





Babar: PRL 92,142002 (2004)

$\Gamma(\eta_c)$ = 34.3±2.3±0.9 MeV

E835: PLB 566,45 (2003)

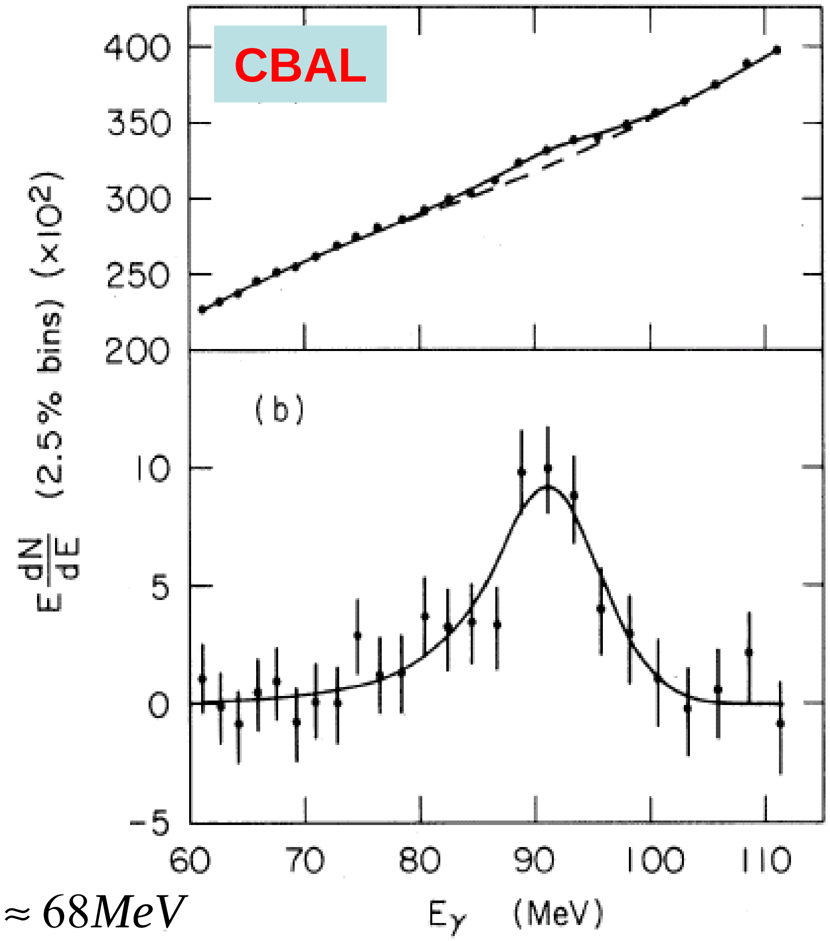
$\Gamma(\eta_c) = 20.4^{+7.7}_{-6.7} \pm 2.0$ MeV

The η_c' (2^1S_0)

- First η_c' candidate observed by Crystal Ball in 1982
  - Observation of 5582±1270 photons from $\psi' \to \eta_c' \gamma$ decay
  - M = 3594±5 MeV
  - Γ < 8 MeV (95% CL)
- Never confirmed by other experiments
- PQCD prediction for the M(ψ')-M(η_c') mass splitting:

$$\Delta M(2S) = \frac{\Gamma(\psi' \to e^+e^-)}{\Gamma(J/\psi \to e^+e^-)} \frac{M^2(\psi')}{M^2(J/\psi)} \Delta M(1S) \approx 68 MeV$$

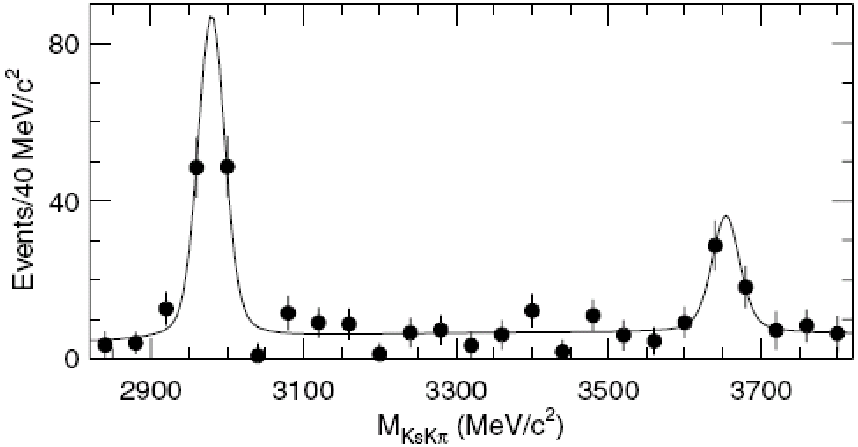
Photon energy distribution

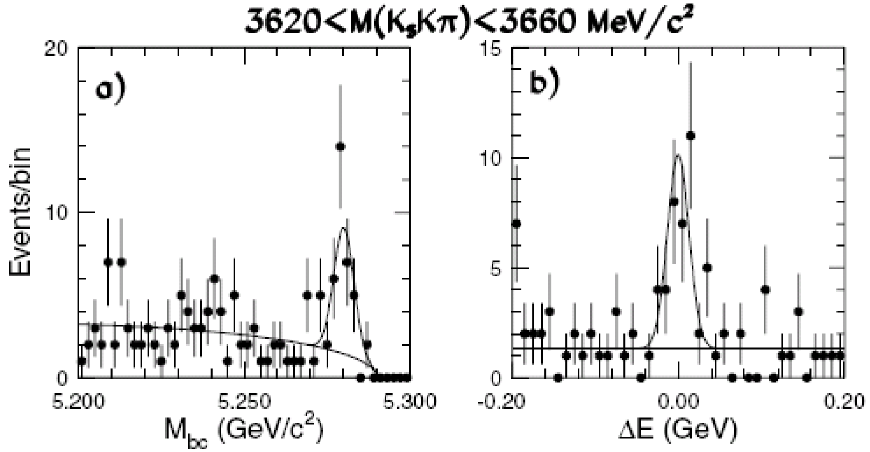


PRL 48, 70 (1982)

The η_c' (2^1S_0)

$B \to K K_S K^- \pi^+$





- Twenty years later (2002) observation of an η_c' by Belle
  - M = 3654±6±8 MeV
  - Γ < 55 MeV (90% CL)
  - Observation of 56 events with 21±2 expected background from $B \to K K_s K^- \pi^+$ decay

- Observed by Babar and CLEO and in different techniques ($\gamma\gamma$, double charmonium)

PRL 89, 102001 (2002)

The χ_{cJ} (1^3P_J)

- Produced in ψ' decay
  - BR($\psi' \to \chi_{c0}\gamma$) = 9.2±0.4%
  - BR($\psi' \to \chi_{c1}\gamma$) = 8.7±0.4%
  - BR($\psi' \to \chi_{c2}\gamma$) = 8.1±0.4%
- χ_{c0} and χ_{c1} produced in B decay
- χ_{c0} observed in double charmonium production
- χ_{c0} and χ_{c2} produced in $\gamma\gamma$ fusion
- All can be directly formed in $p\bar{p}$ annihilation

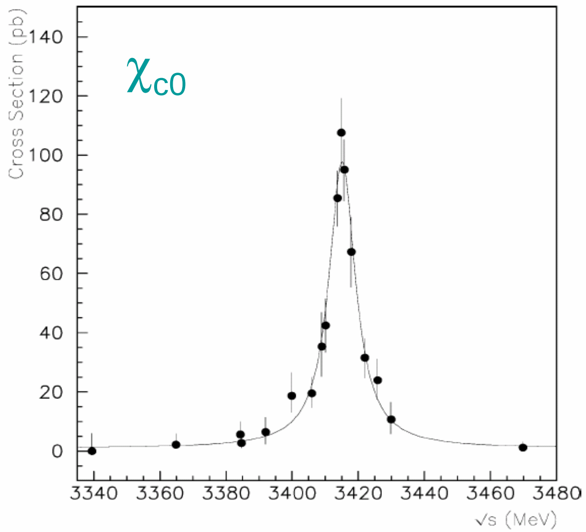
PDG06	χ_{c0}	χ_{c1}	χ_{c2}
M (MeV)	3414.76±0.35	3510.66±0.07	3556.20±0.09
Γ (MeV)	10.4±0.7	0.89±0.05	2.06±0.12

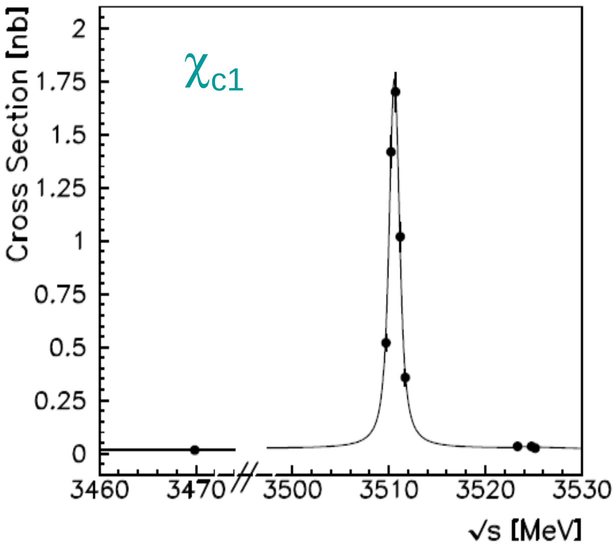
E835

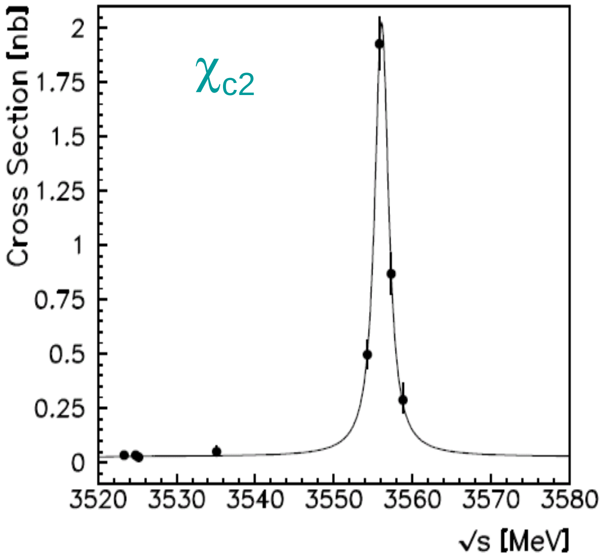
χ_{cJ} scan at $p\bar{p}$ machines

$$p\bar{p} \to \chi_{cJ} \to J/\psi\gamma$$

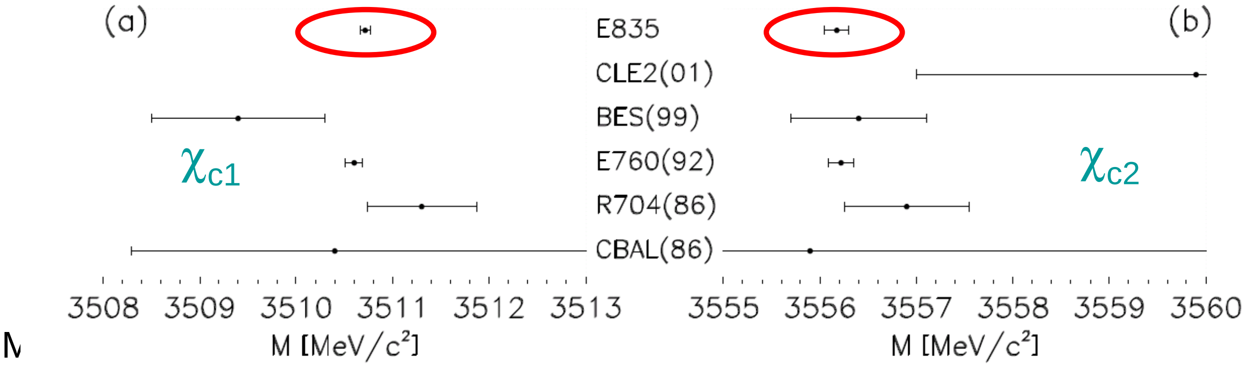
- Precision measurements of χ_{cJ} masses and widths obtained through direct scan at $p\bar{p}$ machines
- Count the number of $J/\psi \to e^+e^-$ in the final state (background ~0)







PLB 533, 237 (2002)



NPB 717, 34 (2005)

E835

PRL 91, 091801 (2003)

Interference measurement of the χ_{c0} parameters

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

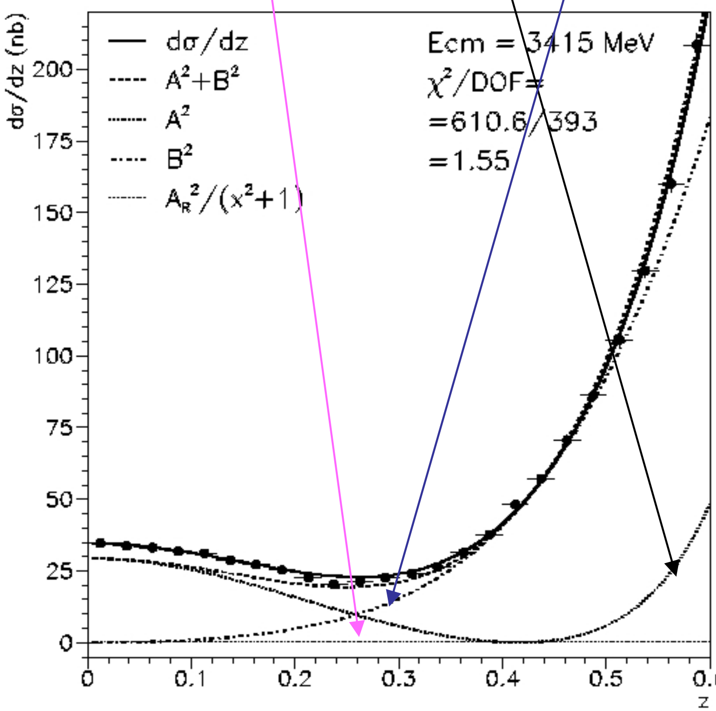
$$\frac{d\sigma}{dz}(x,z) = \left| \frac{-A_R}{x+i} + A e^{i\delta_A} \right|^2 + \left| B e^{i\delta_B} \right|^2$$

Resonant

Interfering (helicity 0)

Non-Interfering (helicity 1)

$$\begin{cases} x = \dfrac{E_{CM} - M_{\chi_0}}{\Gamma_{\chi_0}/2} \\ z = \cos\vartheta^* \end{cases}$$



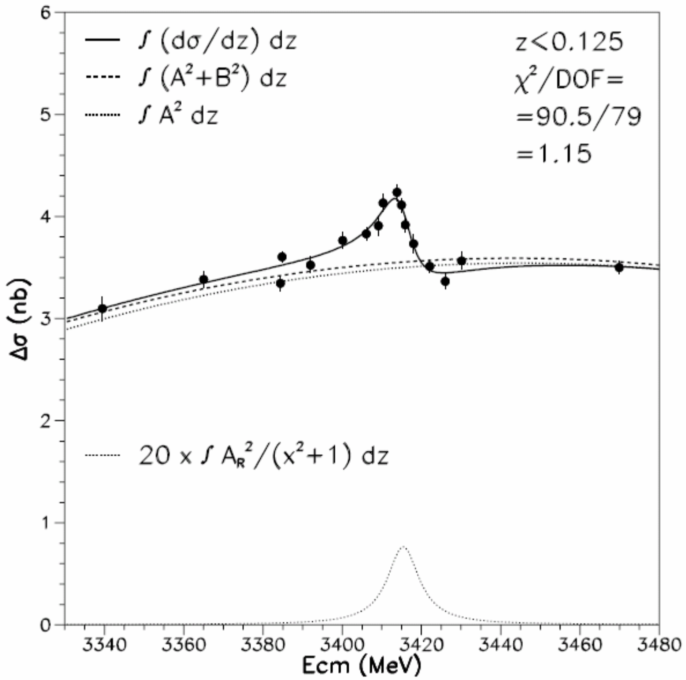


TABLE I. E835 results (errors are statistical and systematic, respectively).

$B_{\rm in} \equiv$ $B_{\rm out} \equiv$	Common channel $B(\chi_{c0} \to \bar{p}p)$ $B(\chi_{c0} \to J/\psi\,\gamma)$[a]	$B(\chi_{c0} \to \pi^0\pi^0)$
$M_{\chi_{c0}}$ (MeV/c^2)	$3415.4 \pm 0.4 \pm 0.2$[b]	$3414.7^{+0.7}_{-0.6} \pm 0.2$[c]
$\Gamma_{\chi_{c0}}$ (MeV)	$9.8 \pm 1.0 \pm 0.1$[b]	$8.6^{+1.7}_{-1.3} \pm 0.1$[c]
$B_{\rm in} \times B_{\rm out}$ (10^{-7})	$27.2 \pm 1.9 \pm 1.3$[b]	$5.42^{+0.91}_{-0.96} \pm 0.22$[c]
Final result for $B_{\rm in} \times B_{\rm out}$ (10^{-7}) and phase δ_A (degree)		$5.09 \pm 0.81 \pm 0.25$[d] $39 \pm 5 \pm 6$[d]

The h_c (1^1P_1)

- Quantum numbers: $J^{PC} = 1^{+-}$
- Expected to have small width: Γ < 1 MeV
- Hard to access. Can be produced in:
  - $p\bar{p}$ annihilation (unknown BR)
  - radiative E1 decay from η_c'
- One of the main decay modes should be $h_c \rightarrow \eta_c \gamma$
- Precision measurements of the h_c parameters give unique possibility to test the hyperfine splitting potential. The h_c is expected to be within a few MeV from the center of gravity of the χ_{cJ} states:

$$M(h_c) \cong \frac{M(\chi_{c0}) + 3M(\chi_{c1}) + 5M(\chi_{c2})}{9}$$

E835

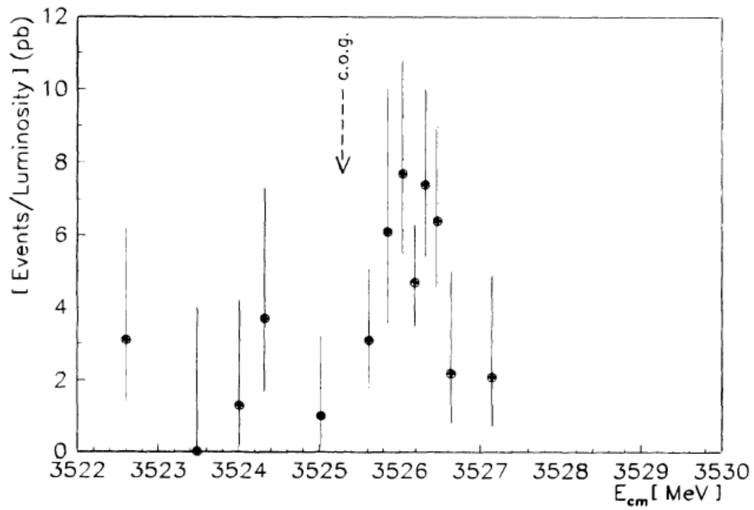
PRL 69, 2337 (1992)

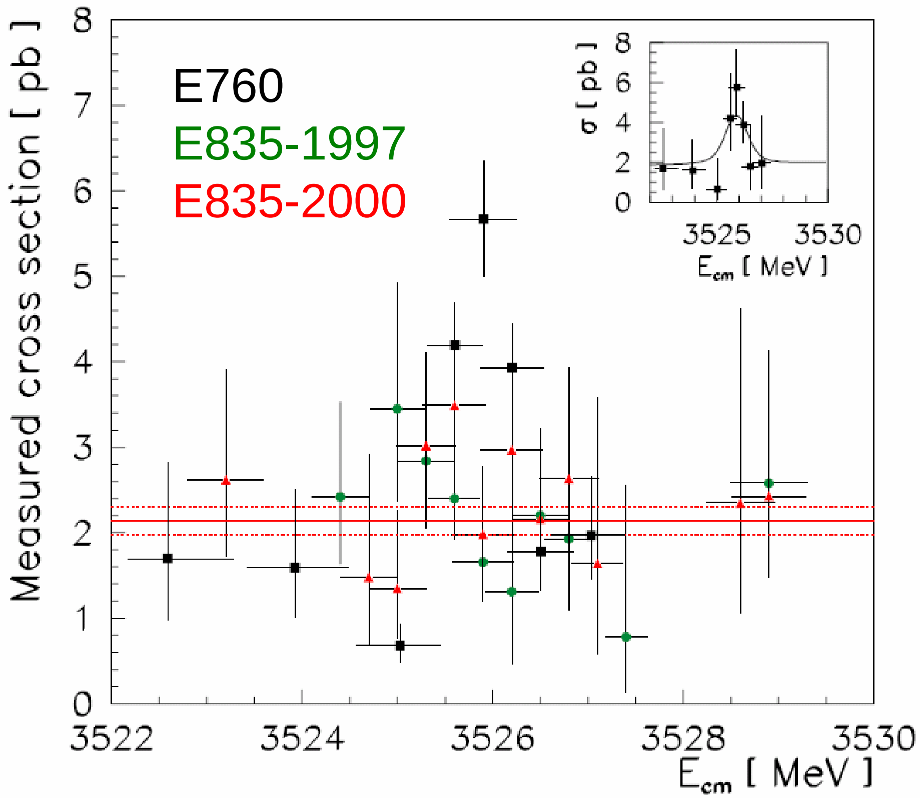
PRD 72, 032001 (2005)

The h_c (1^1P_1)

Observation by E760 of $p\bar{p} \to h_c \to J/\psi\pi^0$
The decay is isospin violating
Not confirmed by E835 with larger statistics (2 running periods)

E760:
M = 3526.3±0.2±0.2 MeV
Narrow (Γ < 1.1 MeV at 90% CL)





E835

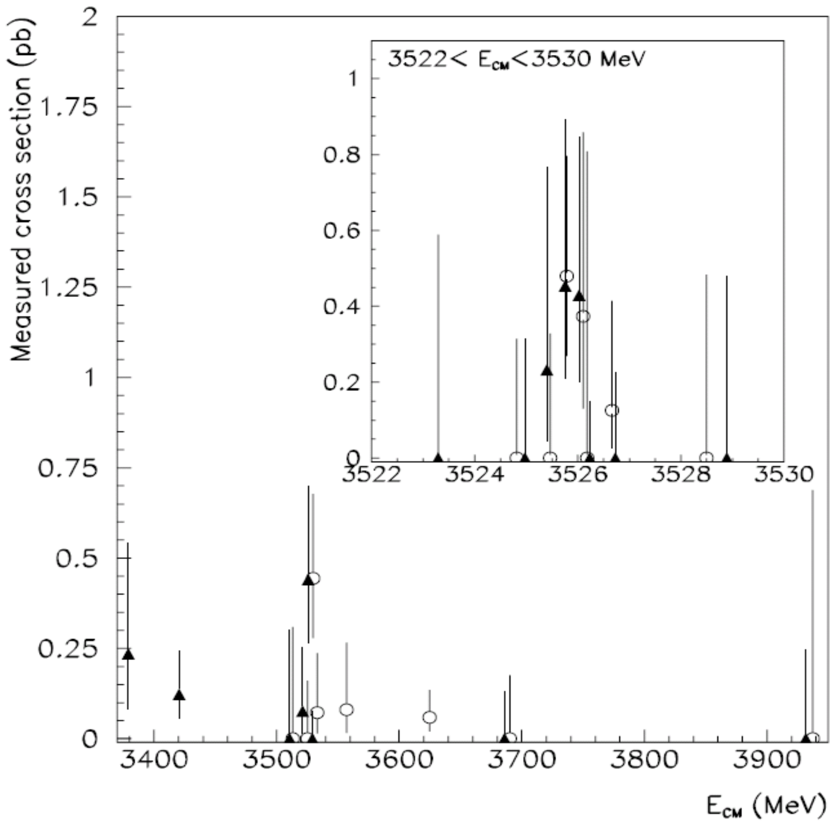
PRD 72, 032001 (2005)

$h_c \rightarrow \eta_c\gamma$ - E835

Excess of $h_c \rightarrow \eta_c\gamma$, $\eta_c \rightarrow \gamma\gamma$ events observed by E835

M = 3525.8±0.2±0.2 MeV
Narrow (Γ < 1 MeV)

$\Gamma(p\bar{p})BR(\eta_c\gamma)$ ~ 12.0±4.5 eV
compatible with expectations

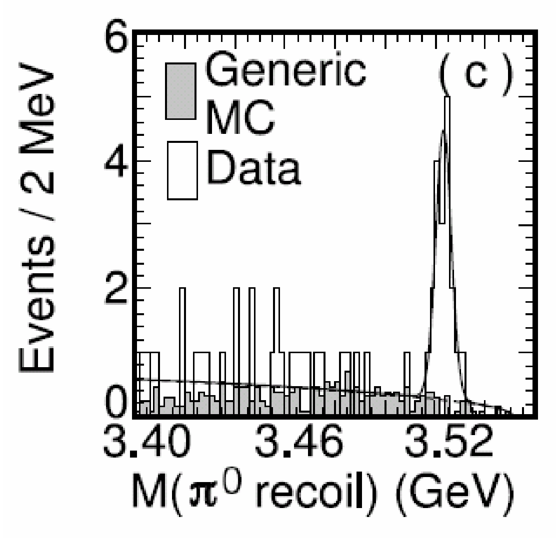


PRL 95, 102003 (2005)

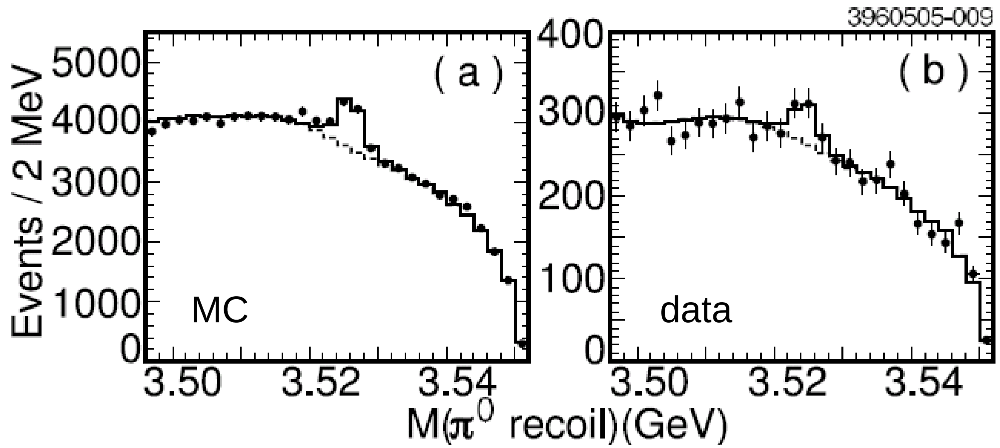
$h_c \to \eta_c\gamma$ - CLEO

$e^+e^- \to \psi' \to \pi^0 h_c \to (\gamma\gamma)(\gamma\eta_c)$ The ψ' decay mode is isospin violating

Exclusive analysis ($\eta_c \to$ hadrons)
The η_c is reconstructed in 7 decay modes (sum of BR ~ 10%)



Inclusive analysis
Invariant mass recoiling against a π^0 (after background rejection for events consistent with a radiative decay to η_c)



CLEO results:

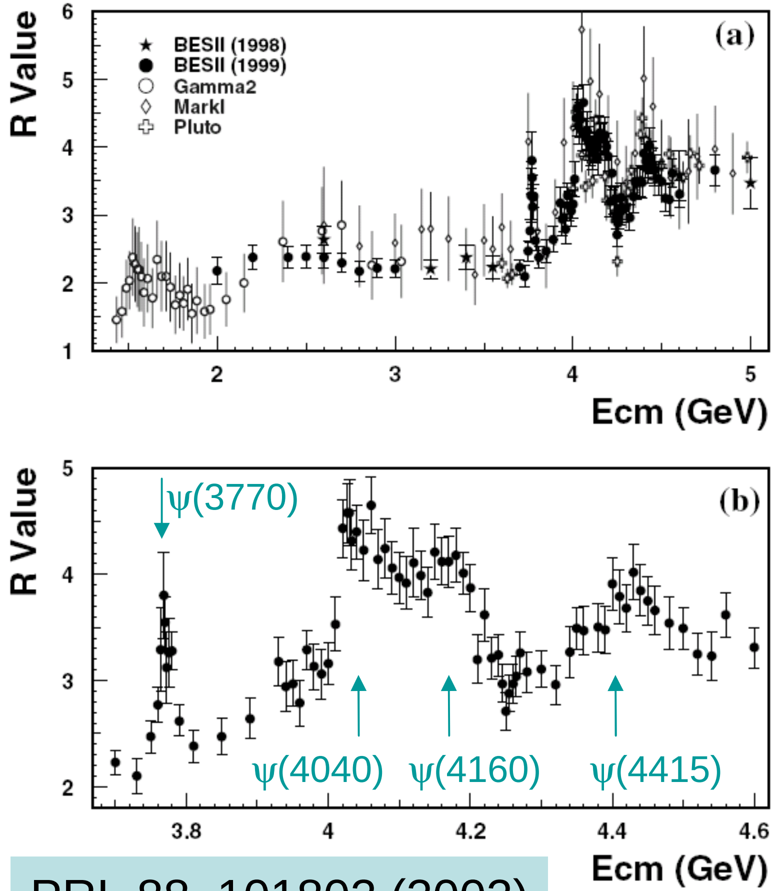
	Inclusive	Exclusive
Counts	150 ± 40	17.5 ± 4.5
Significance	$\sim 3.8\sigma$	6.1σ
$M(h_c)$ (MeV)	$3524.9 \pm 0.7 \pm 0.4$	$3523.6 \pm 0.9 \pm 0.5$
$\mathcal{B}_\psi \mathcal{B}_h$ (10^{-4})	$3.5 \pm 1.0 \pm 0.7$	$5.3 \pm 1.5 \pm 1.0$

BES

Charmonium states above the $D\underline{D}$ threshold

- Region above $D\underline{D}$ mass threshold (3.72 GeV) is poorly known
- Interesting region, rich of new states
- Excited vector states investigated at e^+e^- machines (latest results by BES)
- Only ψ(3770) clearly observed
  - considered to be the $^3D_1$ charmonium state

Compilation of R measurements in the region 2-5 GeV and latest BES measurement in the region 3.7-4.6 GeV



PRL 88, 101802 (2002)

The new states

- New states in the charmonium mass region have been recently observed at the B factories
- Their nature is still unknown
- Several hypothesis:
  - Charmonium [1],[2],[3]
  - D-$D^{(*)}$ molecules [4],[5]
  - Diquark-antidiquark (cu-cu) state [6]
  - Threshold effects
  - ... and others!

Need experimental result to test models:

- Quantum numbers
- Decay modes
- Branching ratios
- Angular distributions
- Charged partners?

(1) Barnes and Godfrey, PRD 69, 054008 (2004)

(2) Eichten, Lane and Quigg, PRD 69, 094019 (2004)

(3) Suzuki, PRD 72, 114013 (2005)

(4) Swanson, PLB 588, 189 (2004)

(5) Tornqvist, PLB 590, 209 (2004)

(6) Maiani, *et. al.*, PRD 71, 014028 (2005)

X(3872)

Discovered by Belle

$B^+ \rightarrow K^+ X(3872)$

$X(3872) \rightarrow J/\psi\ \pi^+\pi^-$

(compatible with $J/\psi\ \rho^0$)

$M_X = 3871.9 \pm 0.5\ MeV/c^2$

$\Gamma_X < 2.3\ MeV/c^2$ at 90%CL

at $D^0\overline{D}^{0*}$ threshold

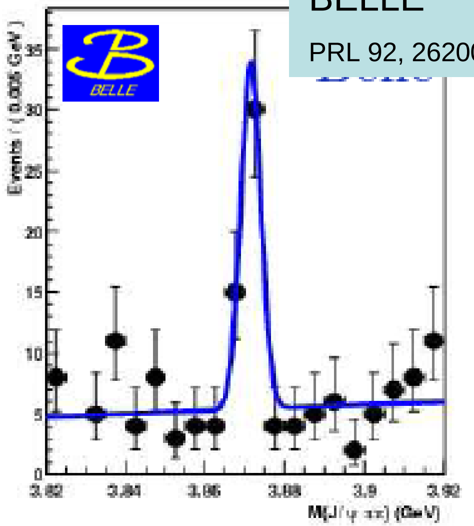
$J^{PC} = 1^{++}$ favored

Confirmed by:

- CDF
- D0
- BaBar

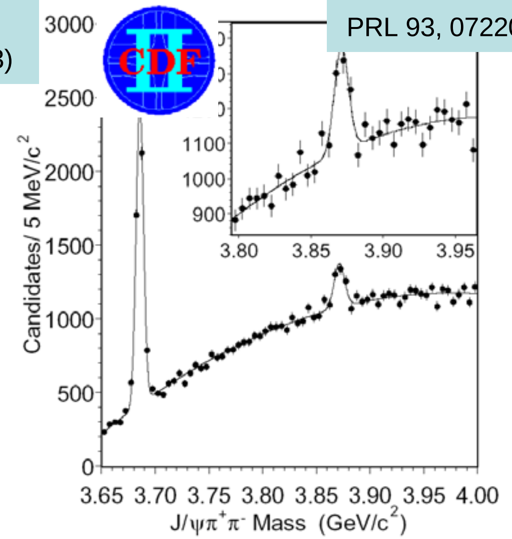
BELLE

PRL 92, 262001 (2003)



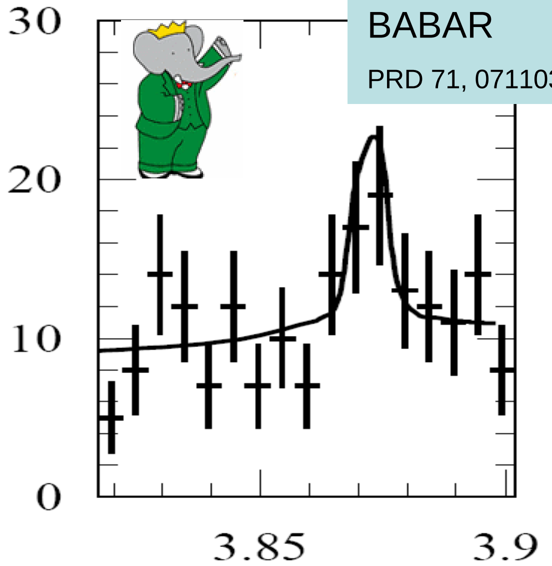
CDF

PRL 93, 072201 (2004)



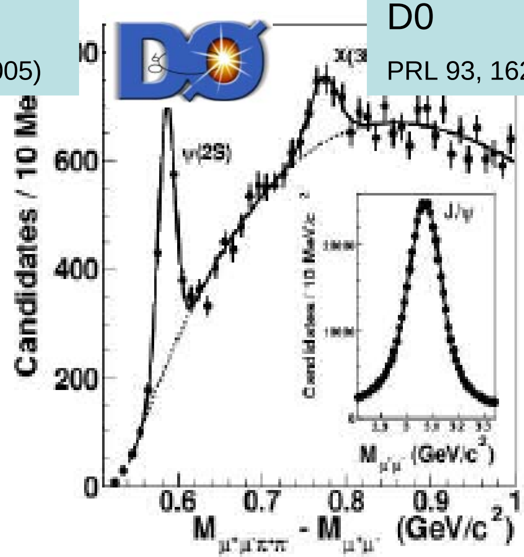
BABAR

PRD 71, 071103 (2005)



D0

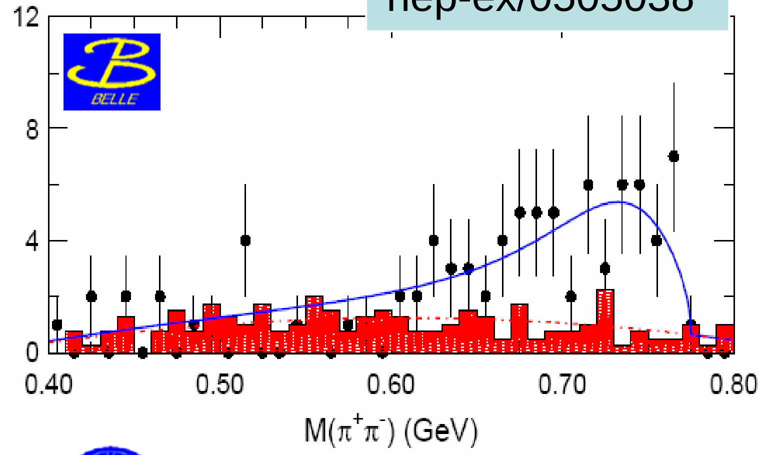
PRL 93, 162002 (2004)



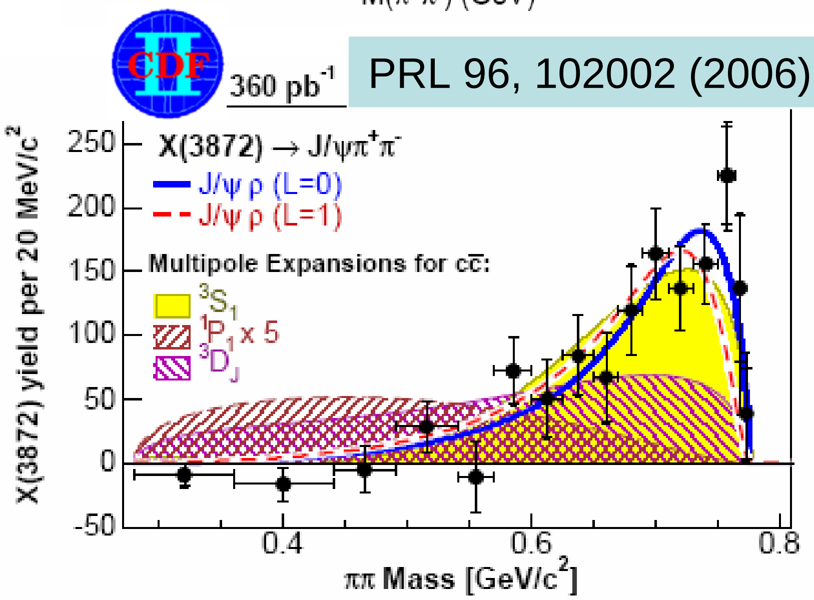
X(3872) - $\pi^+\pi^-$ mass distribution

The $\pi\pi$ invariant mass distribution is consistent with $J/\psi\rho^0$ decay (isospin I=1)

hep-ex/0505038



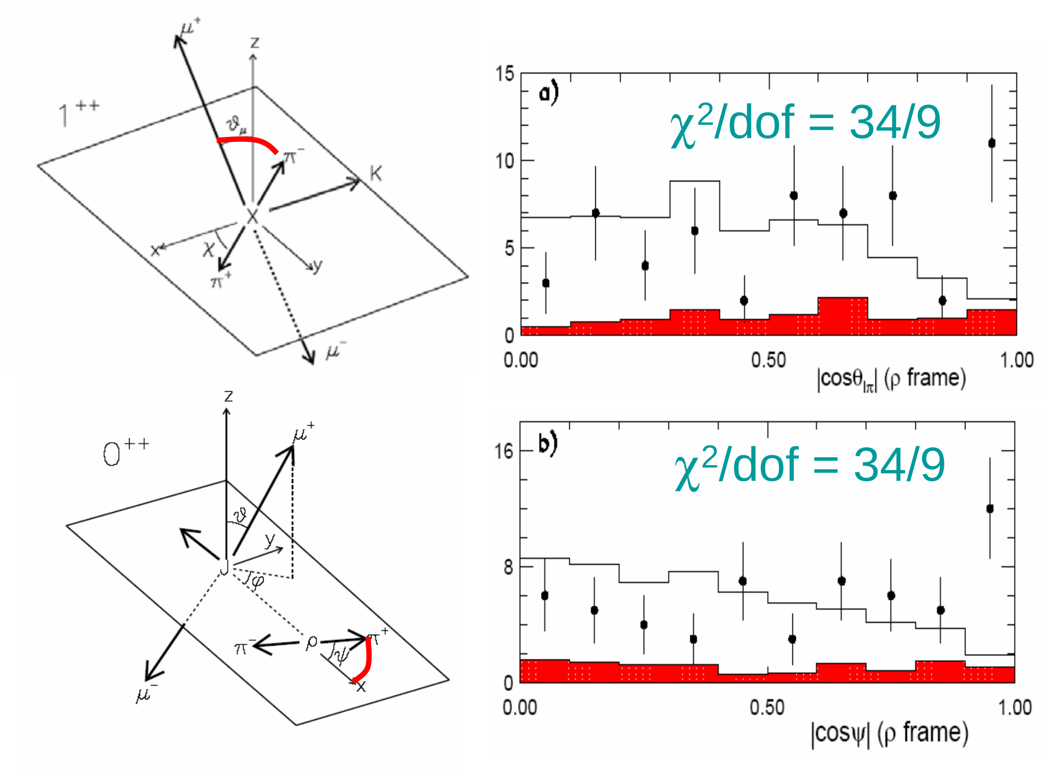
PRL 96, 102002 (2006)

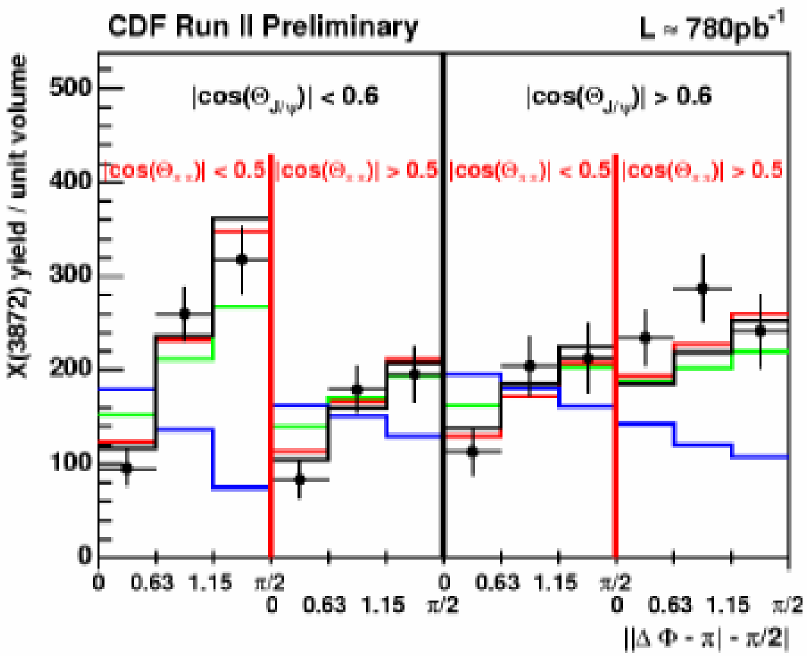


X(3872) - angular distribution

0^{++} and 0^{-+} ruled out by Belle

1^{++} and 2^{-+} favored by CDF

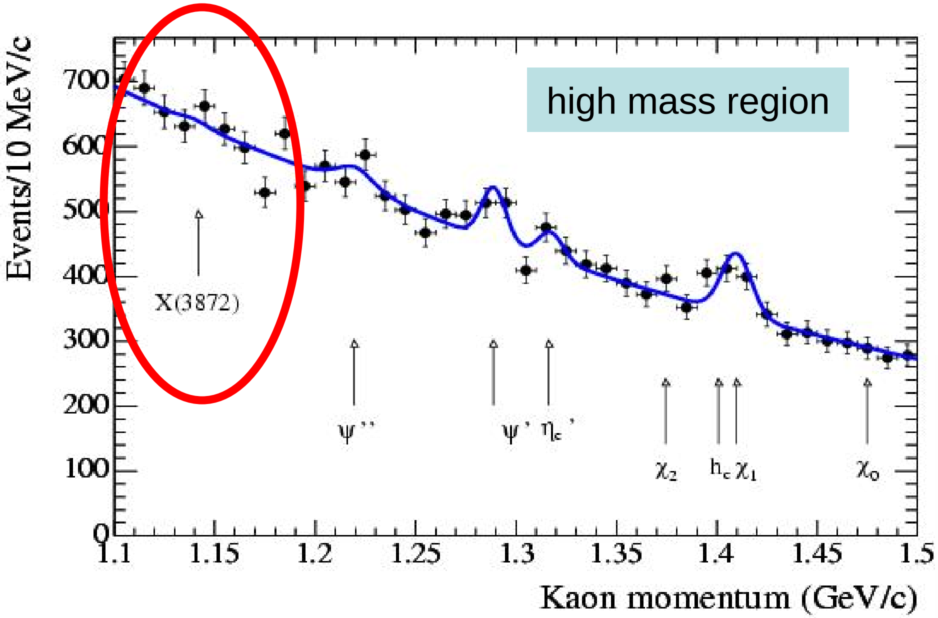


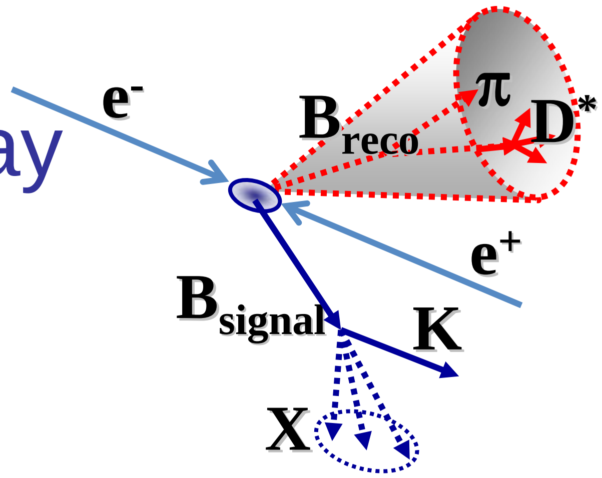


hep-ex/0505038

hep-ex/0605076

Inclusive charmonia in B decay





Particle	Yield	$\mathcal{B}(10^{-4})$	Significance (σ)
η_c	273±43	8.4±1.3±0.8	7.3
J/ψ	259±41	8.1±1.3±0.7	6.9
χ_{c0}	9±21	<1.8	-
$\chi_{c1}+h_c$	227±40	8.0±1.4±0.7	6.0
χ_{c2}	0±36	<2.0	-
η_c'	98±52	3.4±1.8±0.3	1.8
ψ'	139±44	4.9±1.6±0.4	3.2
ψ''	99±69	3.5±2.5±0.3	1.4
$X(3872)$	15±39	< 3.2	-

No X(3872) signal observed

BR($B^{\pm}\rightarrow X(3872)K^{\pm}$)<$3.2\cdot10^{-4}$ at 90% CL

From BaBar-Belle average:

BR($B^{\pm}\rightarrow X(3872)K^{\pm}$, $X(3872)\rightarrow J/\psi\pi^{+}\pi^{-}$)=

=$(13.3\pm2.5)\cdot10^{-6}$

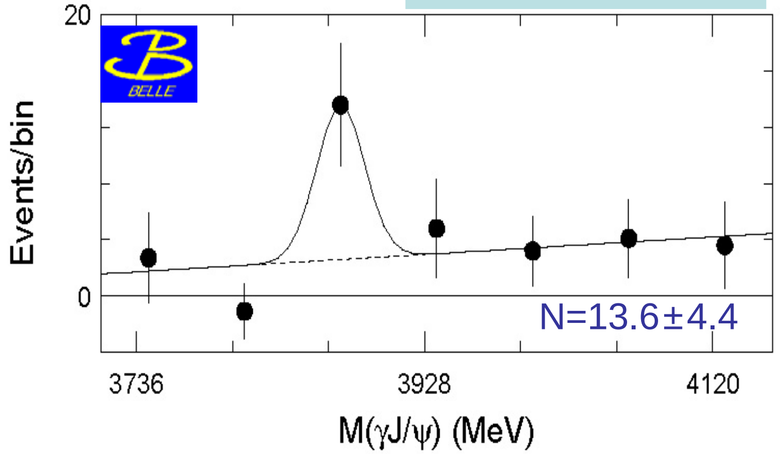
BR($X(3872)\rightarrow J/\psi\pi^{+}\pi^{-}$)>4.2% at 90% CL

PRL 96, 052002 (2006)

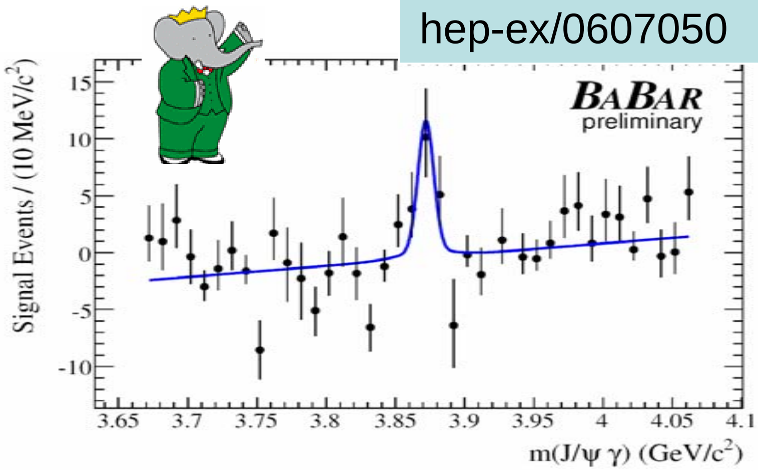
$X(3872) \to J/\psi\,\gamma$

Belle and BaBar see $J/\psi\gamma$ decay of X(3872) in B decays ($B \to J/\psi\,\gamma\,K$)

hep-ex/0505037



hep-ex/0607050



$$B(B^+ \to X(3872)K^+, X \to \psi\gamma) = (1.8 \pm 0.6 \pm 0.1)\times 10^{-6}$$

$$B(B^+ \to X(3872)K^+, X \to \psi\gamma) = (3.4 \pm 1.0 \pm 0.3)\times 10^{-6}$$

Implications:

- C=+ for the X(3872)
- I=1 for the $(\pi\pi)$ in $J/\psi\pi^+\pi^-$
- forbidden $J/\psi\pi^0\pi^0$, $J/\psi\pi^0$, and $J/\psi\eta$ decays

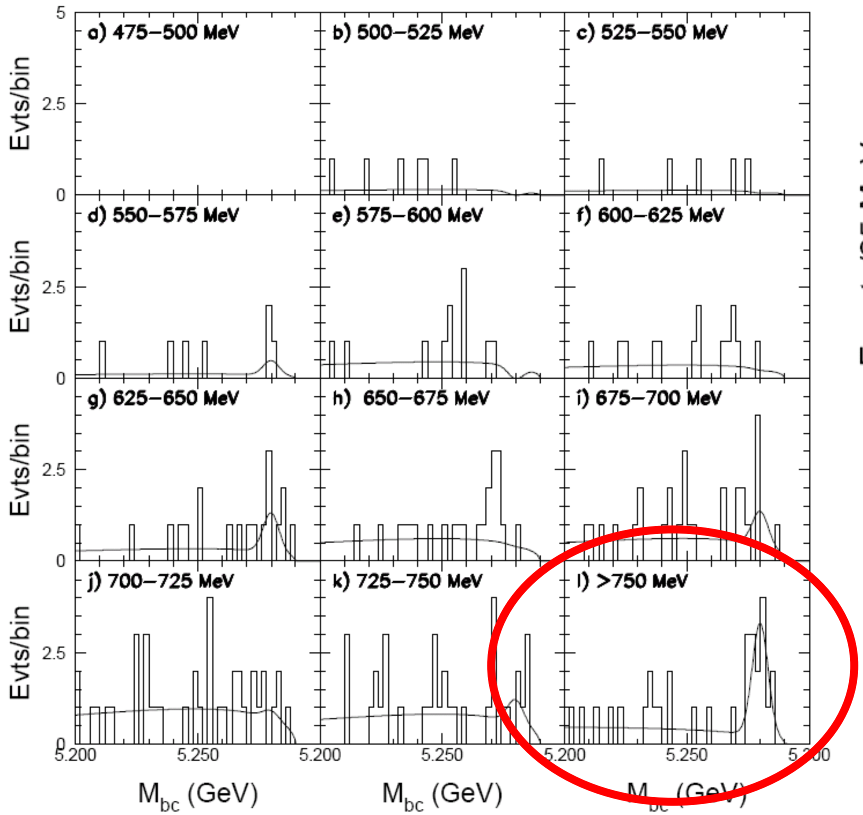
$$\frac{B(X(3872) \to \psi\gamma)}{B(X(3872) \to \psi\pi^+\pi^-)} = 0.34 \pm 0.14$$

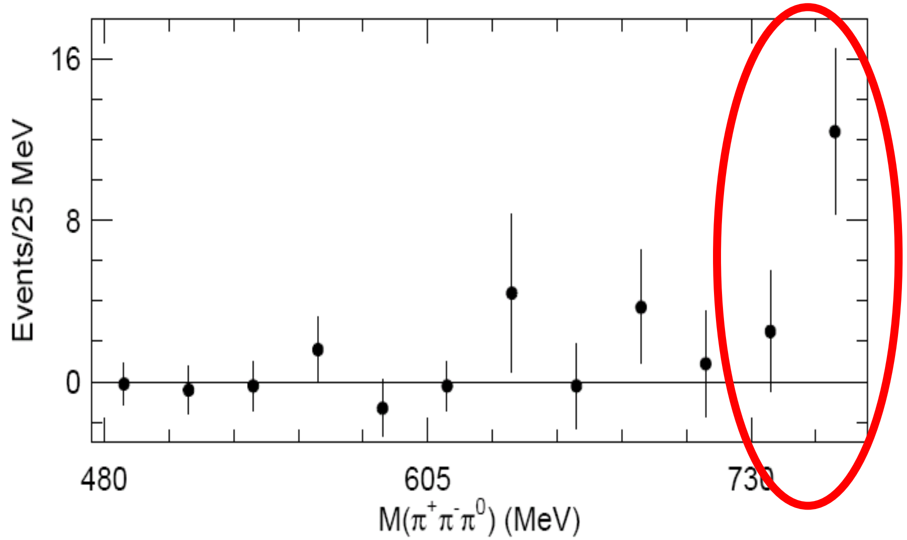
I=0 favored for X(3872), therefore the $J/\psi\pi^+\pi^-$ decay must occur with isospin violation (small width)

X(3872) → J/ψ ω

hep-ex/0505037

Observation of J/ψω decay by Belle in B decays (B → J/ψ ω K, ω → $\pi^+\pi^-\pi^0$)



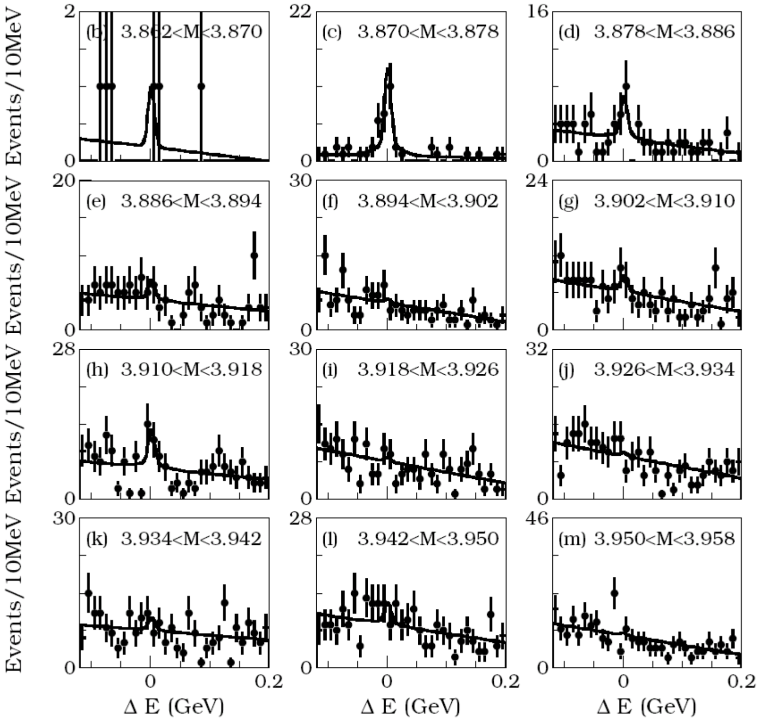


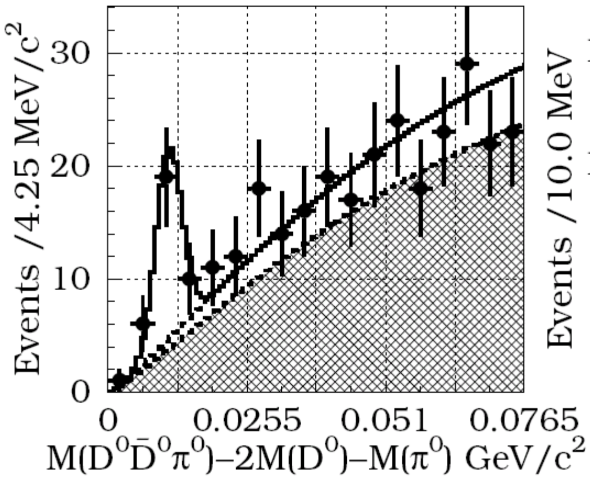
$$\frac{BR(X(3872)\to J/\psi 3\pi)}{BR(X(3872)\to J/\psi\pi^+\pi^-)}\sim 1$$

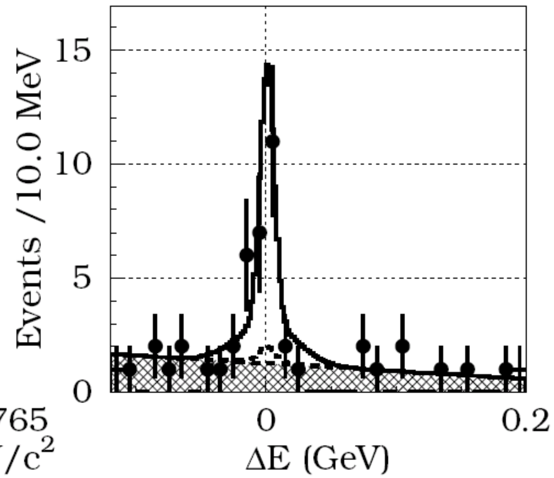
X (3872) → $D^0\bar{D}^0\pi^0$

hep-ex/0606055

Observation of $D^0\bar{D}^0\pi^0$ decay of X(3872) in B decays ($B \rightarrow K D^0\bar{D}^0\pi^0$)







M = $3875.4 \pm 0.7^{+0.4}_{-1.7} \pm 0.9$ MeV

Significance: 6.4σ

$$\frac{BR(X(3872) \rightarrow D^0\bar{D}^0\pi^0)}{BR(X(3872) \rightarrow J/\psi\pi^+\pi^-)} \sim 10$$

$J^{PC}=1^{++}$ favored (the DDp decay is expected to be be suppressed for J=2 states)

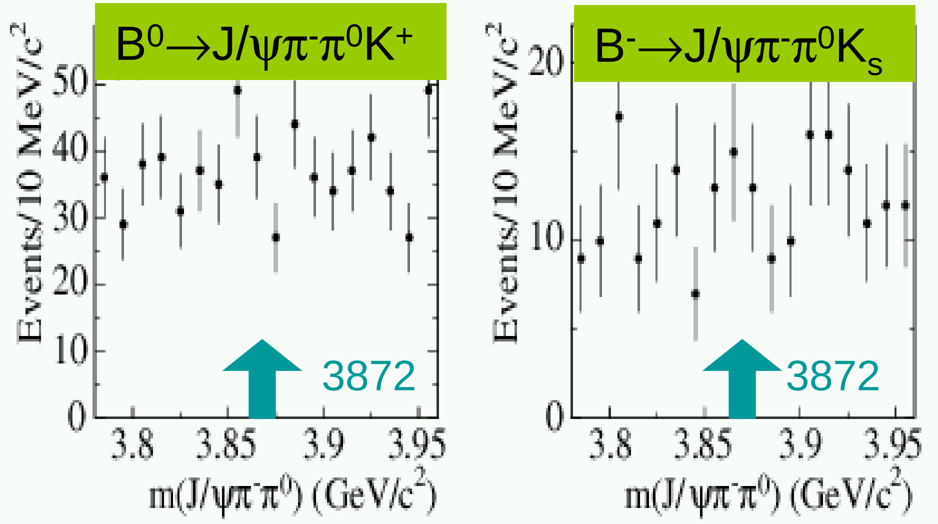
But the measured mass is ~2σ above the X(3872) measured mass

X(3872) decays

- The decay to $\chi_{c1,2}\ \gamma$ has been searched by Belle but not observed
- The decay to $J/\psi\ \eta$ was searched by Babar but not observed
- The charmonium interpretation starts being in trouble

Search for X(3872) charged partners

1. Exclusive reconstruction technique



PRD 71, 031501 (2005)

No charged partner observed

$BR(B^0 \to X(3872)^-K^+, X(3872)^- \to J/\psi\pi^-\pi^0)$ $<5.4\cdot10^{-6}$ at 90% CL

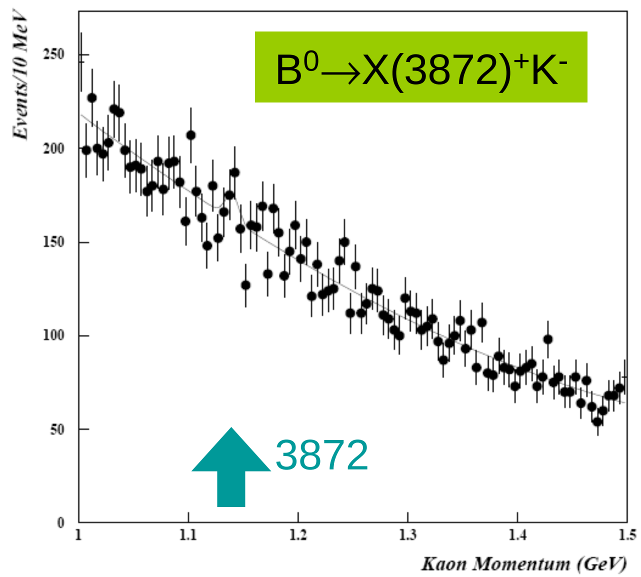
$BR(B^- \to X(3872)^-\overline{K^0}, X(3872)^- \to J/\psi\pi^-\pi^0)$ $<22\cdot10^{-6}$ at 90% CL

2. Inclusive search using recoil technique

PRL 96, 052002 (2006)

Inclusive $K^\pm$ momentum on B^0 recoil
No signal is observed for charged partners

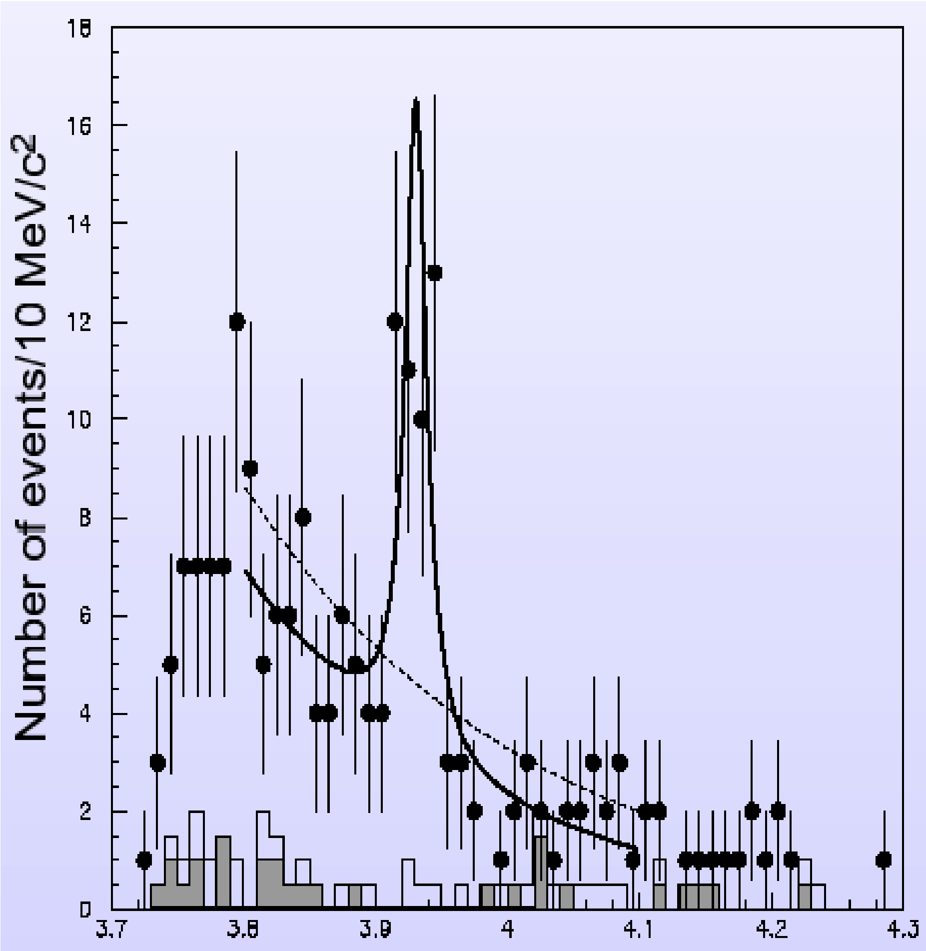
$BR(B^0 \to X(3872)^+K^-) < 5\cdot10^{-4}$ at 90% CL

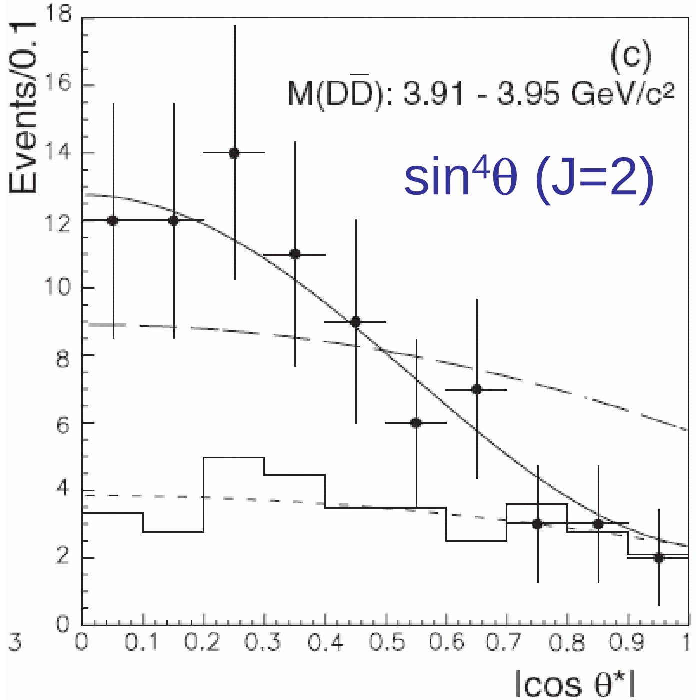


Z(3930)

PRL 96, 082003 (2006)

$\gamma\gamma \to D\bar{D}$





M = 3929±5±2 MeV

Γ = 29±5±2 MeV

N = 64±18 events

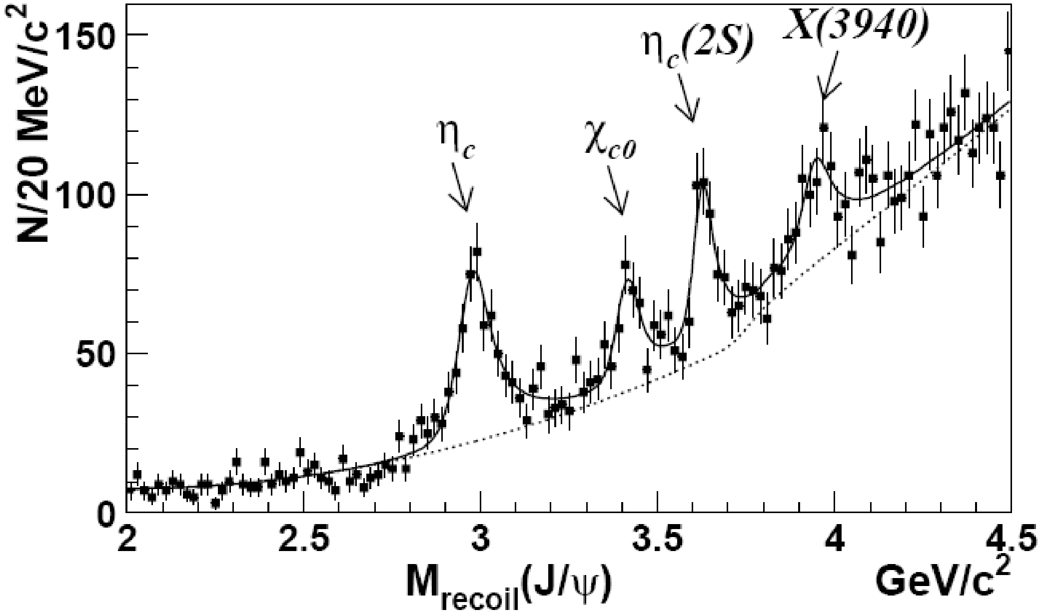
Significance: 5.3σ

Consistent with χ_{c2}'

X(3940)

hep-ex/0507019

$$e^+e^- \to J/\psi X$$



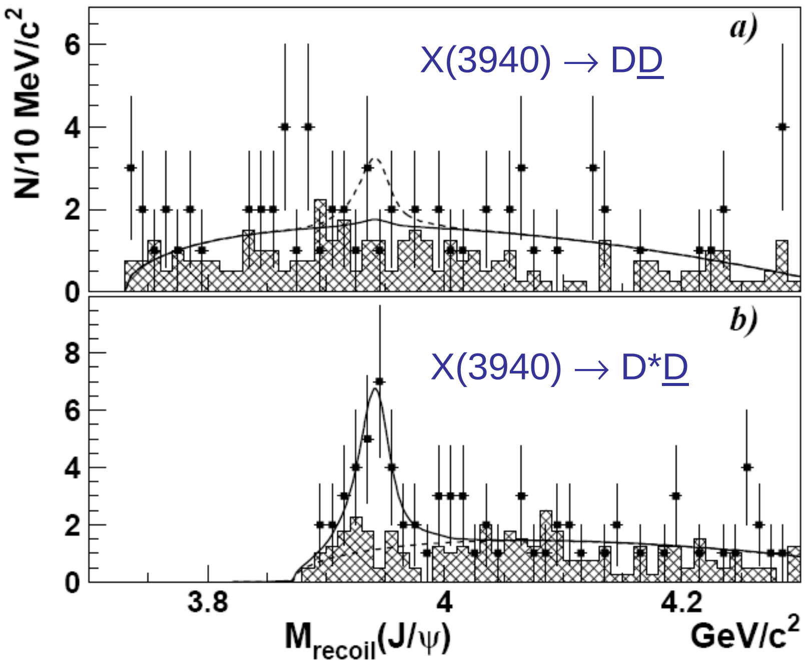
M = 3936±14 MeV

Γ < 50 MeV

N = 266±63 events

Significance: 5σ

Candidate for $\eta_c''(3^1S_0)$



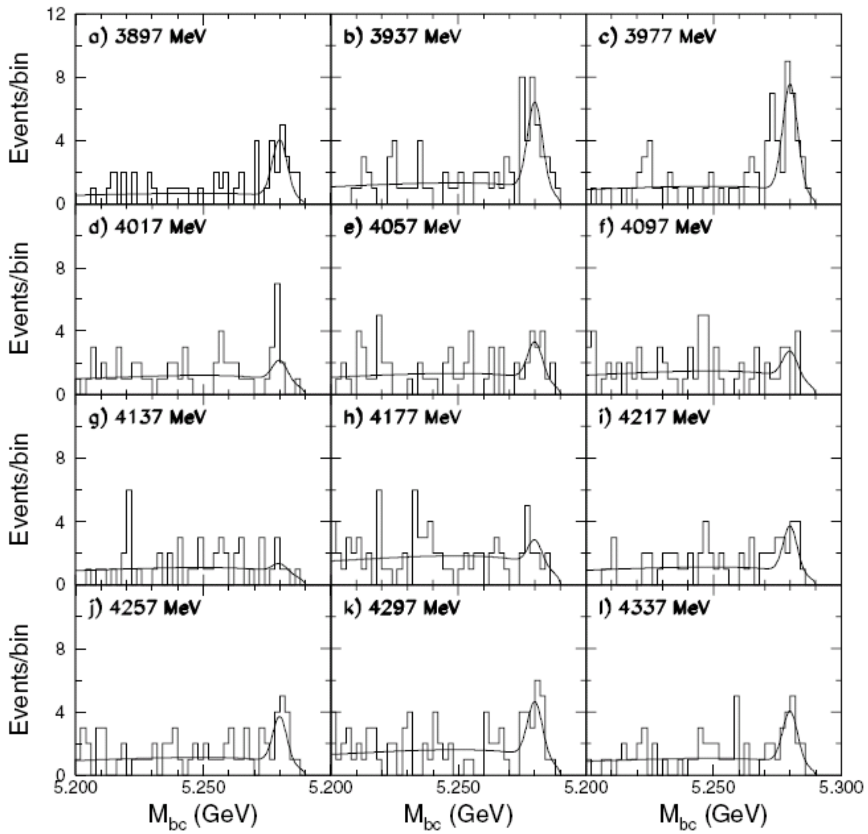
X(3940) $\to$ D$\underline{\text{D}}$ not seen

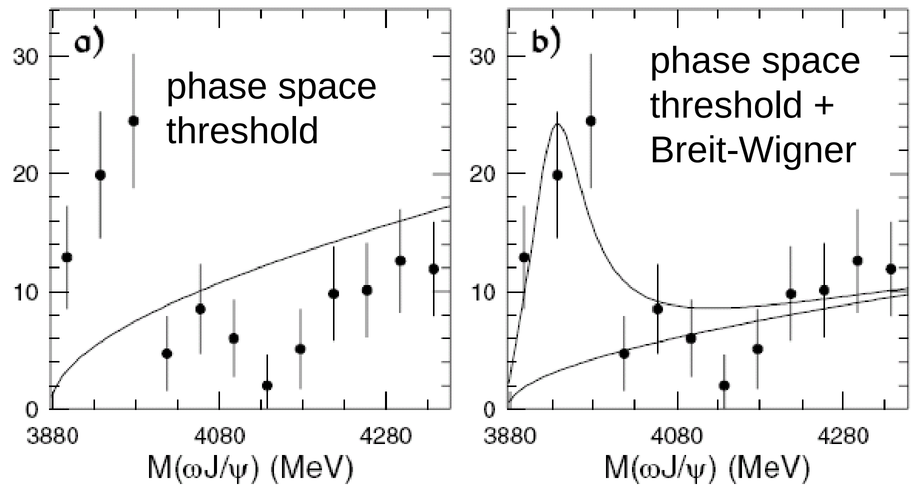
X(3940) $\to$ D*$\underline{\text{D}}$ seen

PRL 94, 182002 (2005)

Y(3940)

$B \to K\omega J/\psi$





M = 3943±11±13 MeV

Γ = 87±22±26 MeV

N = 58±11 events

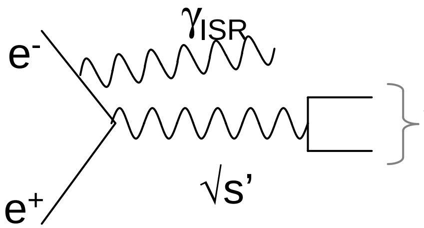
Significance: 8.1σ

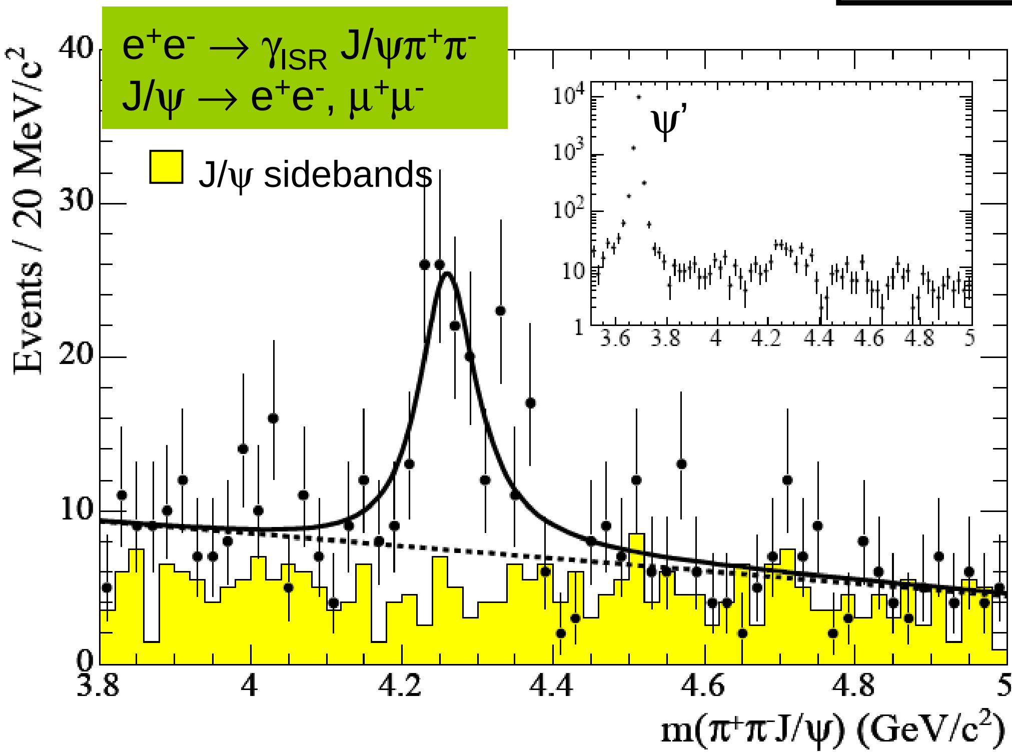
Candidate for χ_{c1}' ?

Y(4260)

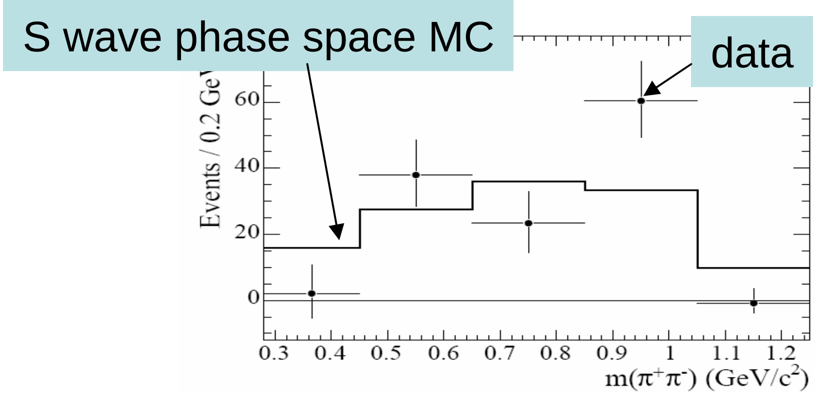
PRL 95, 142001 (2005)

233 fb^{-1}





Study of $J/\psi\pi^+\pi^-$ production in ISR
- γ_{ISR} not necessarily detected
- Small mass recoiling against final state
- Low missing transverse momentum
- Well known benchmark channel (ψ')

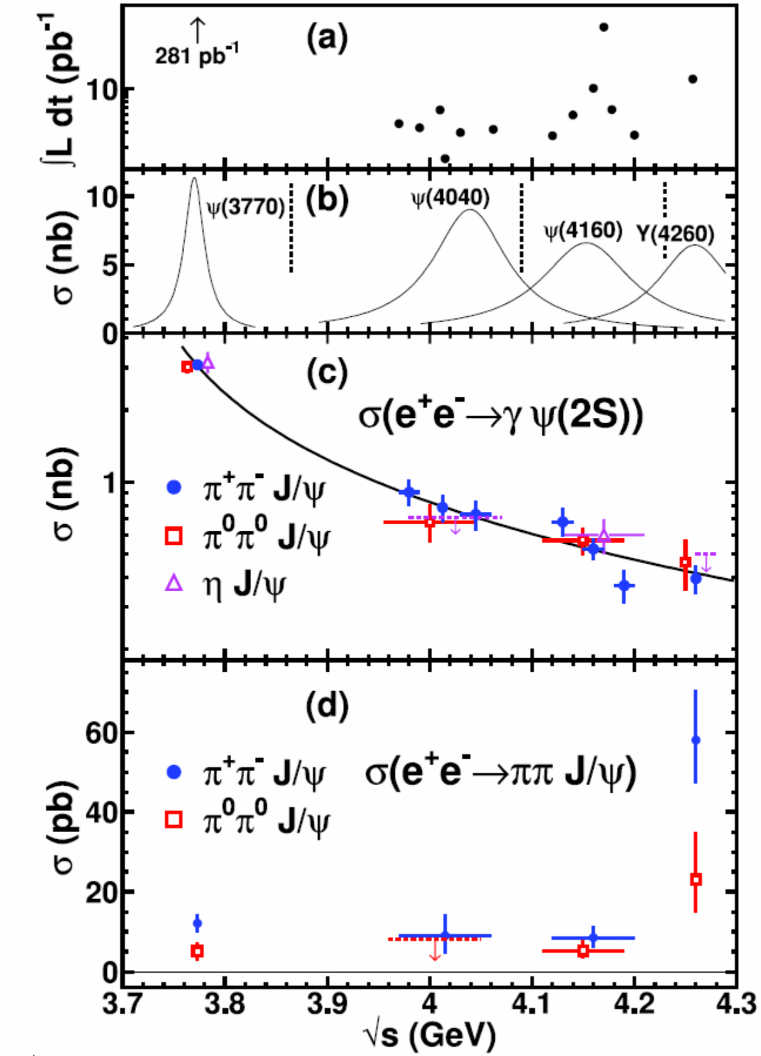


- Broad structure Y(4260):
- N=125±23
- $M_Y=4259\pm8^{+2}_{-6}$ MeV/c^2
- $\Gamma_Y=88\pm23^{+6}_{-4}$ MeV
- $J^{PC}=1^{--}$

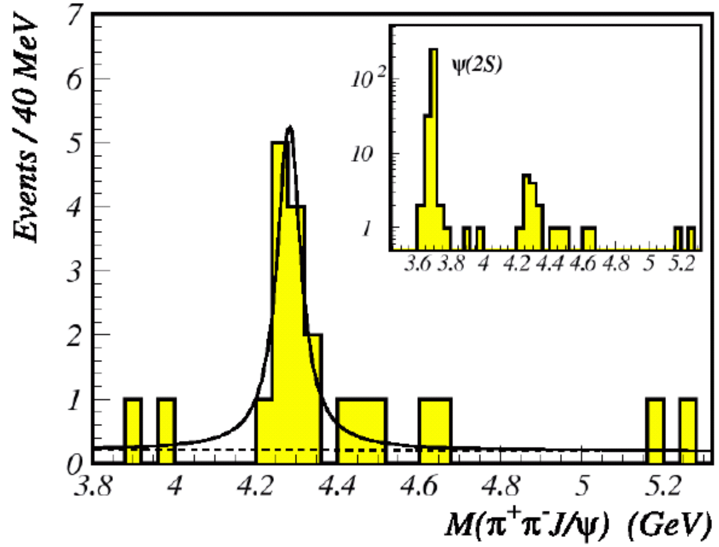
Y(4260) - CLEO

hep-ex/0606016

CLEO-c direct scan



CLEO-III ISR



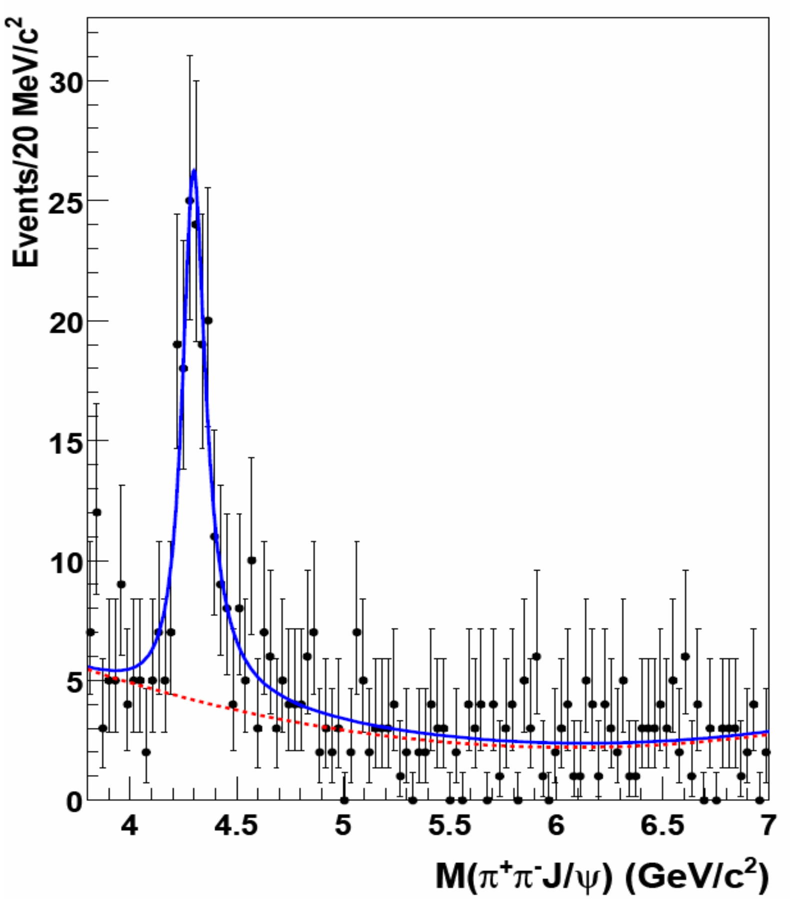
Consistent with Babar result

Observation of $J/\psi\pi^+\pi^-$ and $J/\psi\pi^0\pi^0$

PRL 96, 162003 (2006)

Y(4260) - Belle

Preliminary Belle result



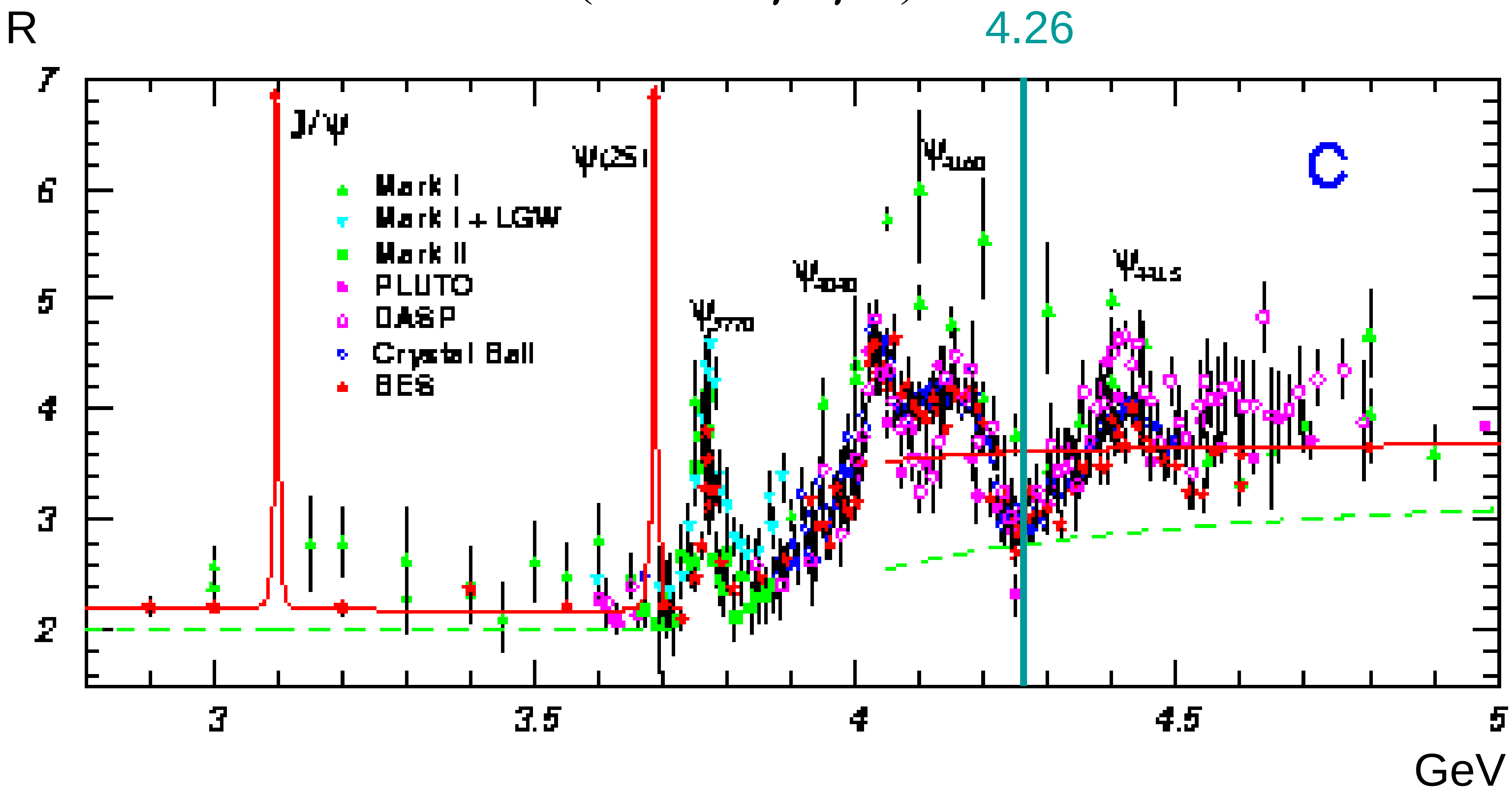
Mass higher than Babar

$M = 4295 \pm 10^{+11}_{-5}$ MeV
$\Gamma = 133 \pm 26^{+13}_{-6}$ MeV
N = 165±24 events

http://www.qwg.to.infn.it/WS-jun06/WS4talks/Tuesday_AM/Olsen.ppt

No Y(4260) observed in R scan

$$R = \frac{\sigma(e^+e^- \rightarrow hadrons)}{\sigma(e^+e^- \rightarrow \mu^+\mu^-)}$$

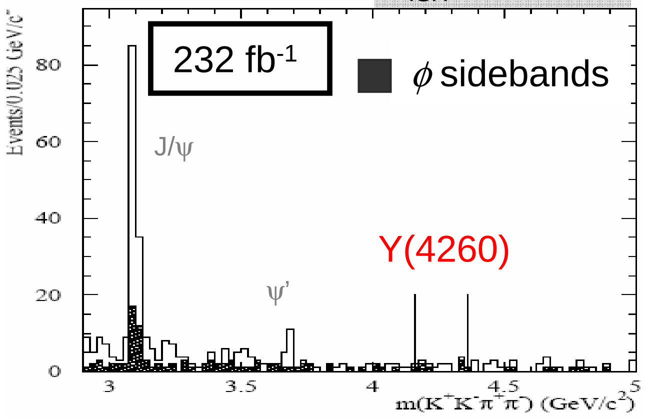


Search for other Y(4260) decays

Preliminary

$\phi\pi^+\pi^-$

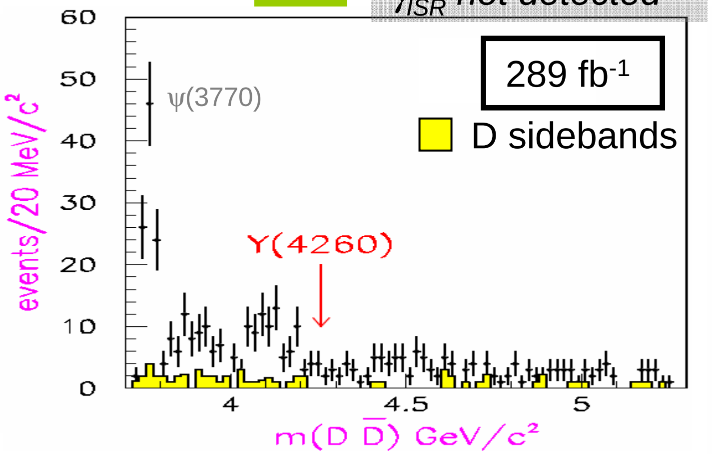
γ_{ISR} *detected*



Preliminary

$D\bar{D}$

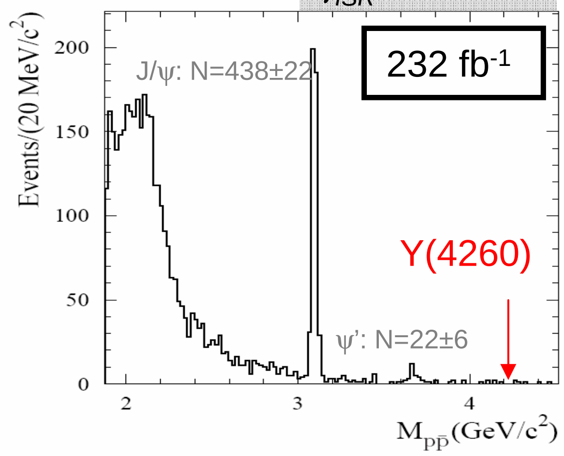
γ_{ISR} *not detected*



PRD 73, 012005 (2006)

$p\bar{p}$

γ_{ISR} *detected*



$$\Gamma_{ee}^{Y}\times B(Y(4260)\to\pi^+\pi^-\varphi) < 0.4\,\mathrm{eV} \quad 90\%\,\mathrm{CL}$$

No signal

$$\frac{B(Y(4260)\to D\bar{D})}{B(Y(4260)\to\pi^+\pi^-\psi)} < 7.6 \quad 95\%\ \mathrm{CL}$$

No signal

$$\frac{B(Y(4260)\to p\bar{p})}{B(Y(4260)\to\pi^+\pi^-\psi)} < 0.13 \quad 90\%\ \mathrm{CL}$$

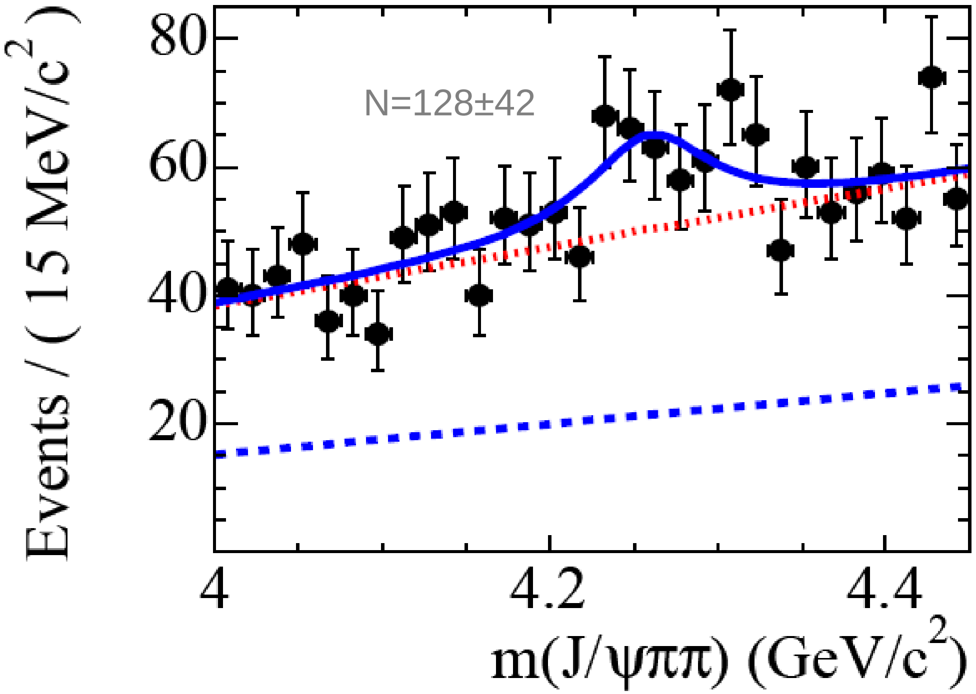
No signal

Hints for Y(4260) production in B decay

PRD 73,011101 (2006)

$B^{\pm} \to Y(4260)K^{\pm}$
$Y(4260) \to J/\psi\ \pi^{+}\pi^{-}$

211 fb^{-1}



$$B(B^{-} \to Y(4260)K^{-}) \times B(Y(4260) \to \psi\pi^{+}\pi^{-}) =$$
$$= (2.0 \pm 0.7 \pm 0.2) \times 10^{-5}$$

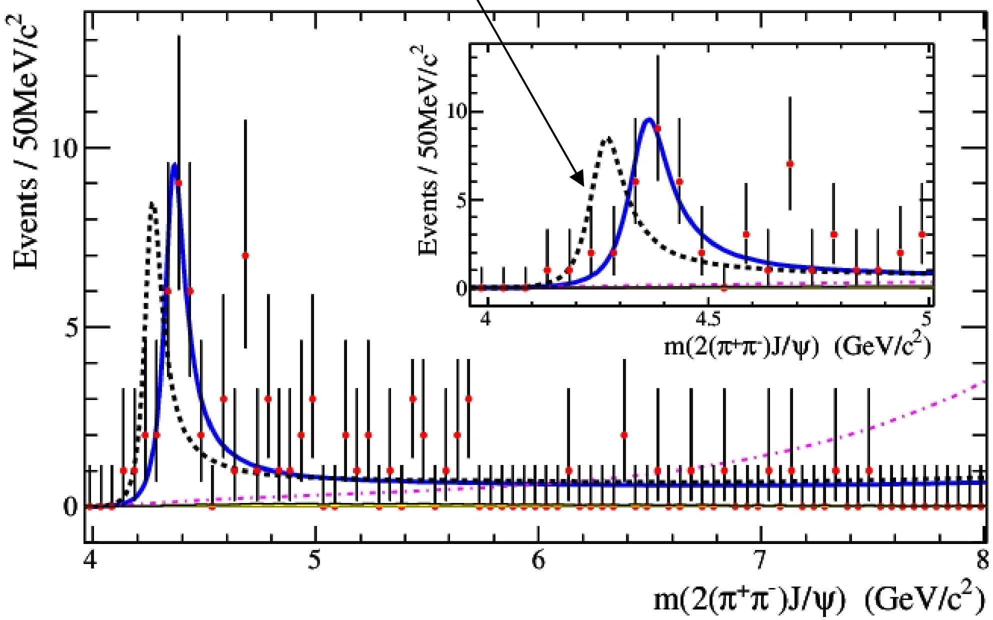
3σ excess

A new structure at 4350 MeV/c^2

Preliminary Babar result

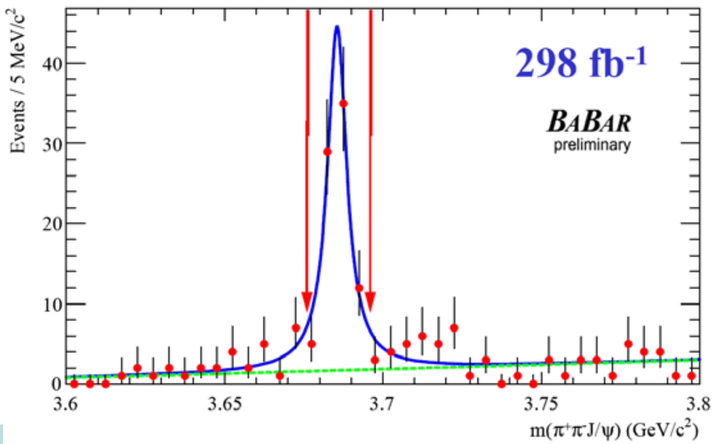
- Recently a new structure has been observed by Babar in $\psi'\pi^+\pi^-$ decays in ISR events
- Mass significantly larger with respect to the Y(4260)

Does not fit with a Y(4260) peak



M = 4354±16 MeV
Γ = 106±19 MeV

Clean $\psi'\to J/\psi\pi^+\pi^-$ signal



http://www.qwg.to.infn.it/WS-jun06/WS4talks/Tuesday_AM/Ye.pdf

Summary

- After more than 30 years from its discovery, charmonium spectroscopy is still an interesting and active research field, with challenging experimental issues
- Precision measurements of the charmonium states are obtained by experiments at e^+e^- and $p\underline{p}$ machines
- New states in the charmonium mass region have been recently observed at the B factories. More experimental results are needed to shed light on their nature
- A systematic high-precision study of the charmonium spectrum in $p\underline{p}$ interaction will be carried out by the PANDA experiment