E835 results on excited S=1 states of charmonium

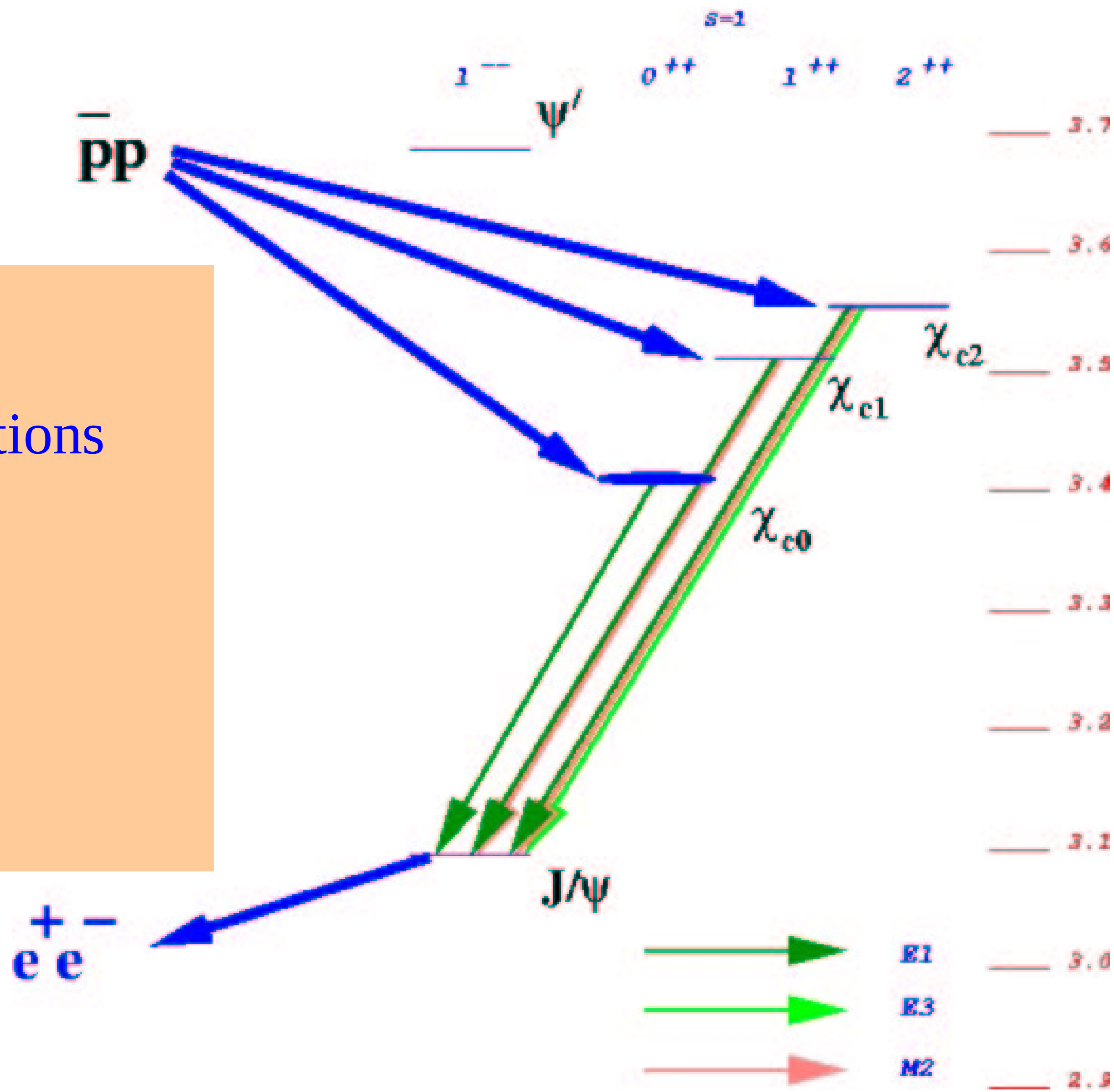
Roberto Mussa
(on behalf of E835)

ICHEP 2002, Amsterdam, July 24-31

Outline

- Total χ_{c0} Width
- Radiative Transitions

  $\chi_c \rightarrow \gamma\, J/\psi$



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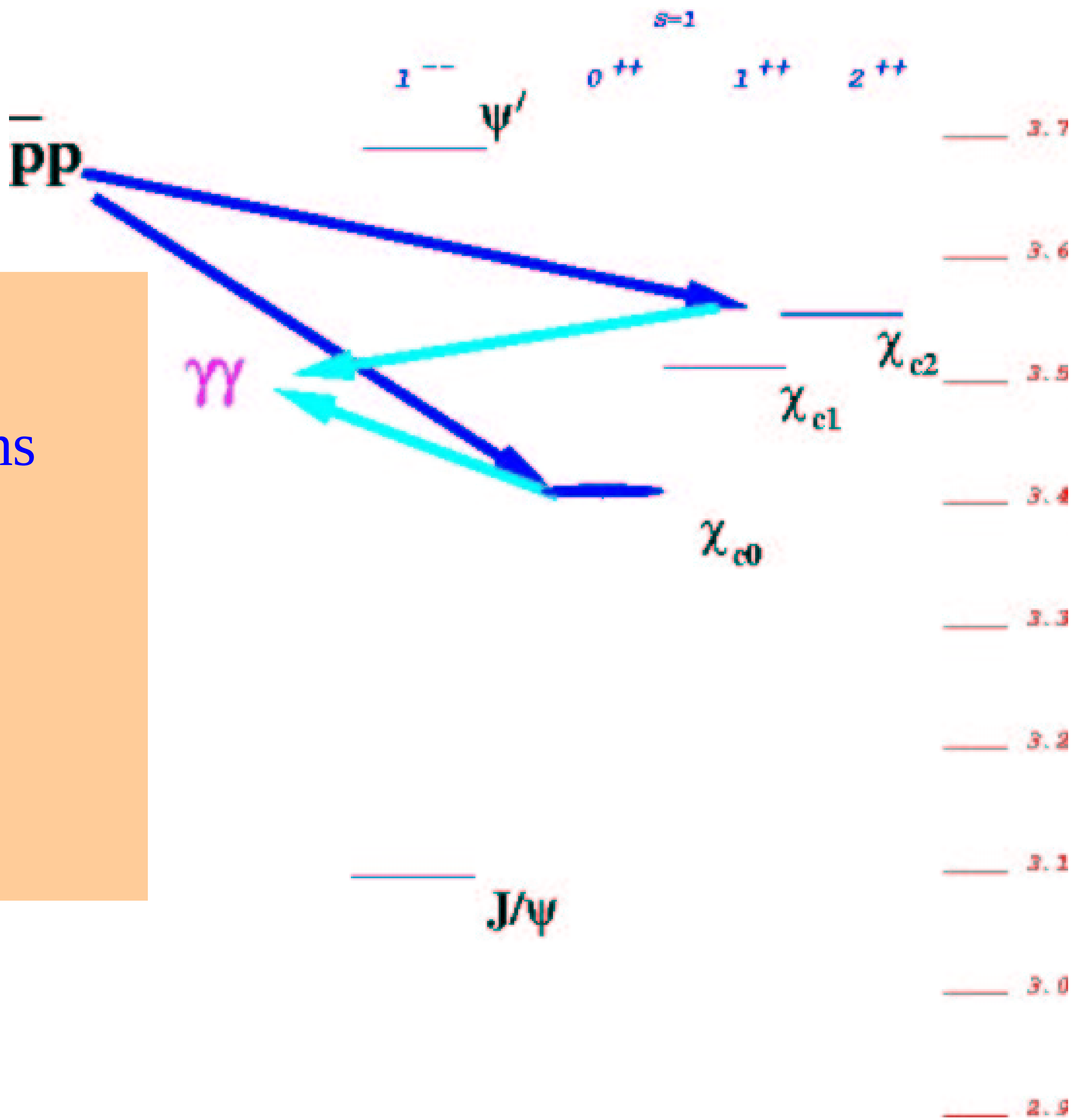
- $\Gamma(\chi_{c0,2} \rightarrow \gamma\gamma)$



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  $\chi_c \rightarrow \gamma J/\psi$
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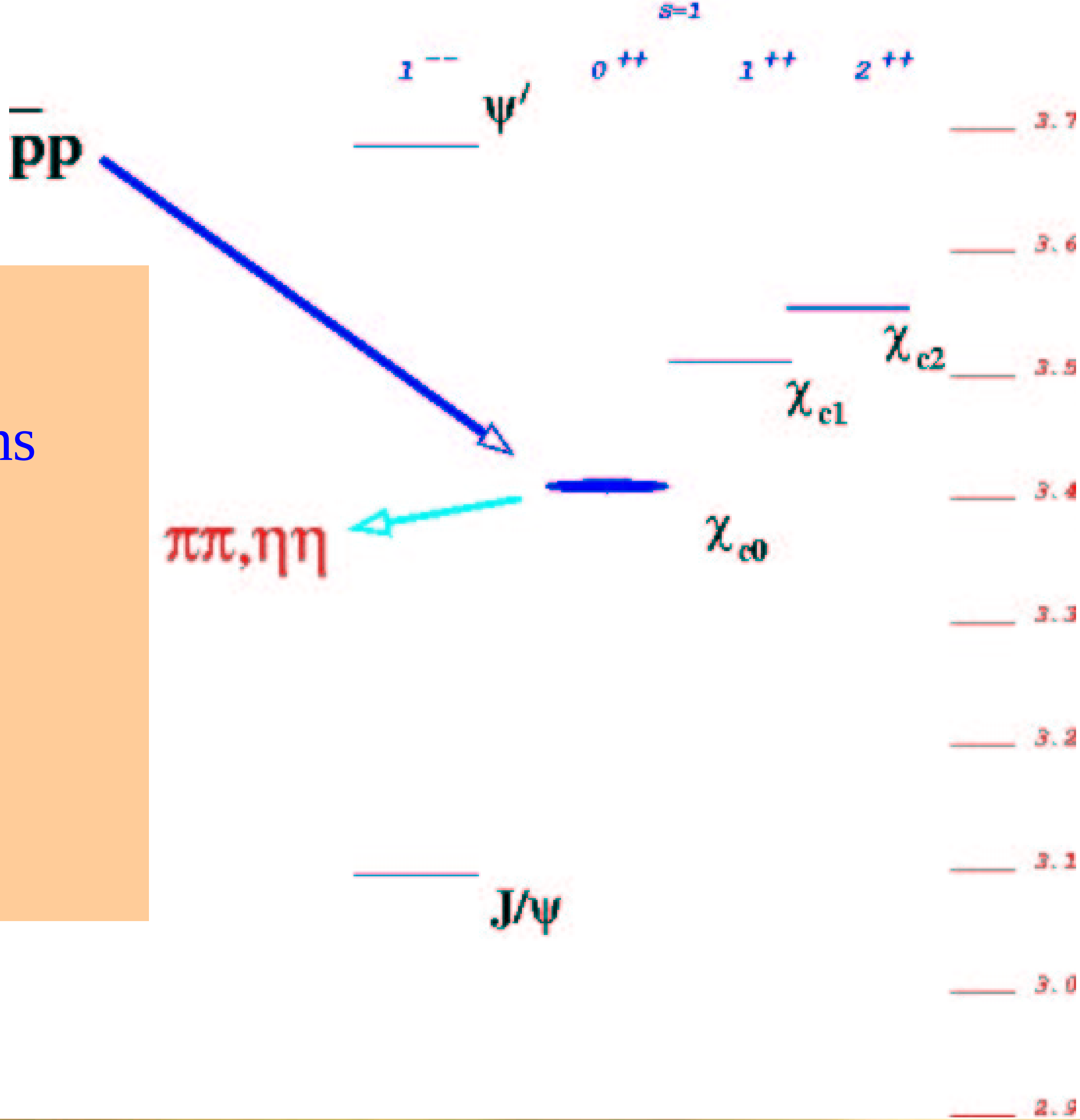
- $BR(\chi_{c0} \rightarrow \pi\pi, \eta\eta)$



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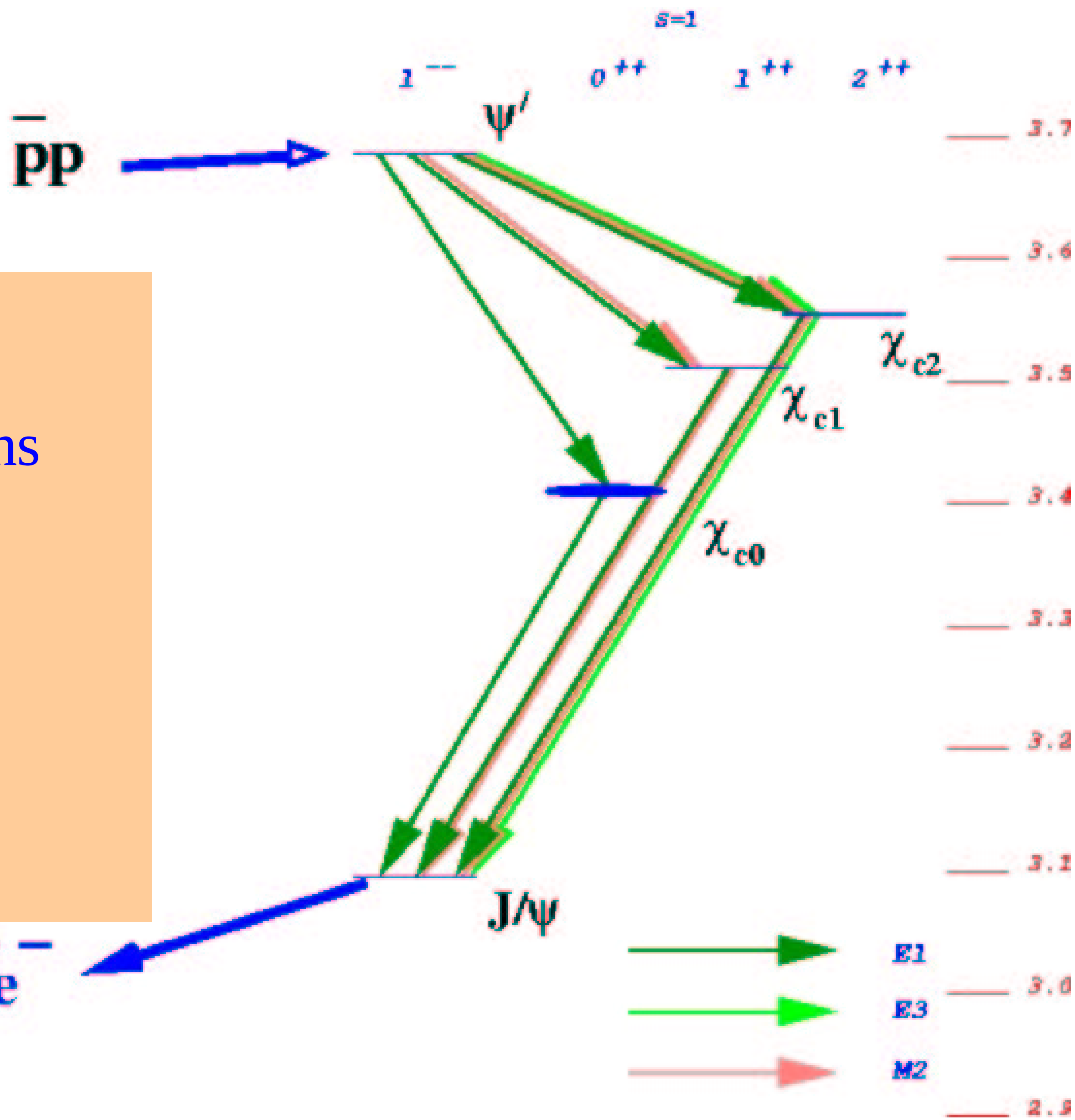
  $\chi_c \rightarrow \gamma\, J/\psi$
- $\Gamma(\chi_{c0,2} \rightarrow \gamma\gamma)$
- $BR(\chi_{c0} \rightarrow \pi\pi, \eta\eta)$
- $\psi' \rightarrow J/\psi\, \gamma\gamma$, e^+e^-, ...



Charmonium sources

Precise measurements of charmonium spectroscopy in the last 2 decades were done using the following processes:

1) e^+e^- annihilations (Mark-III, Crystal Ball, DM2, BES ... CLEO-c):
   - directly only $J^{PC}=1^{--}$;
   - access to hadronic and EM decay modes ;
   - Initial state radiation
2) $\gamma\gamma,\gamma\gamma^*$ scattering, from $e^+e^- \rightarrow e^+e^-\gamma\gamma$ (CLEO,LEP,B factories)
   - Only on states with positive C
3) $\bar{p}\,p$ annihilations (R704 at CERN, E760/835 at Fermilab)
   - direct on all J^{PC} ;
   - only EM decay modes (huge hadronic background)
   - Very good $\delta p/p$ (stochastic cooling)
4) B decays, via b->$c\bar{c}$s (B factories)
5) e^+e^- annihilations in double charmonia (Belle) NEW!

E760+E835 data samples on P states

The table summarizes the samples collected by E760/E835 in the channels $\bar{p}p \to \chi_{c0,1,2} \to \gamma J/\psi \to \gamma e^+e^-$

From each resonance scan, 3 observables are extracted: Mass, Total Width Γtot, and the product

ΓiBo= Γtot*BRin*BRout . If Γtot >> Γbeam, σ_{peak} ~ BRin*BRout . If Γtot ~ Γbeam, the correlation between Γtot and Brin*BRout depends on the scanning strategy.

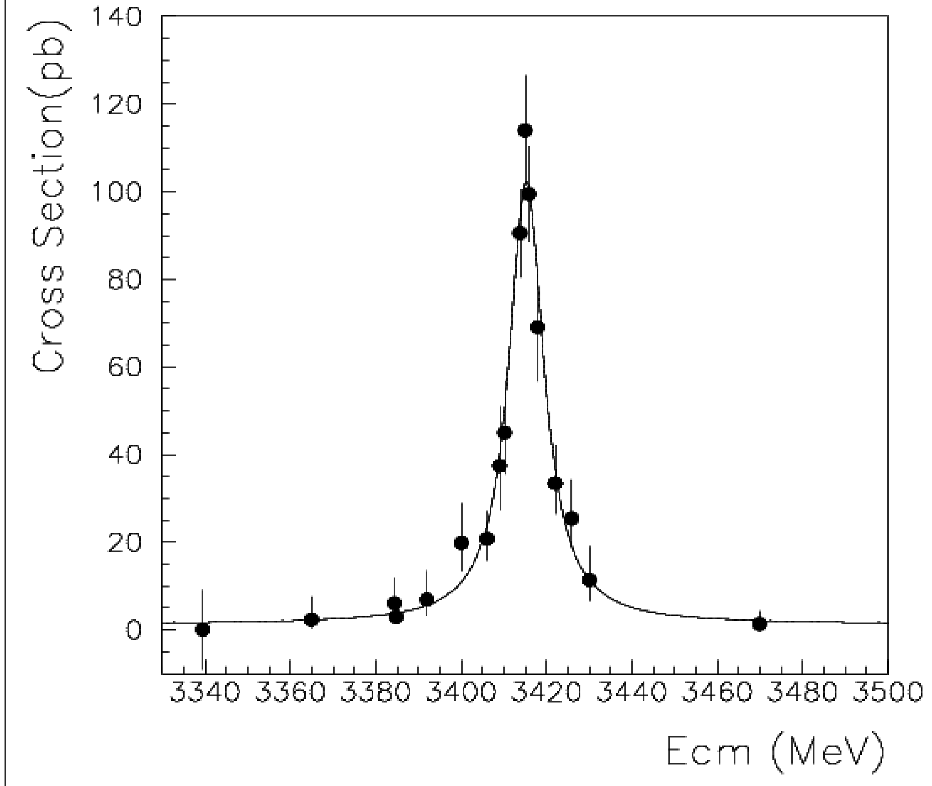
Experiment	Resonance	Ldt /nb^{-1}	Nevents	Γtot/MeV	Fractional error Stat.	Fractional error Syst	Γi*Bo/eV	Fractional error Stat	Fractional error Syst	Mass/MeV/c2	Error on Mass Stat	Error on Mass Syst
E760												
	CHI2	1160	585	1.98	9% ⊕	4%	1.67	5% ⊕	7%	3556.15	0.07 ⊕	0.12
	CHI1	1030	513	0.88	13% ⊕	9%	1.29	9% ⊕	10%	3510.53	0.04 ⊕	0.12
E835/96												
	CHI2	12392	~7000	Data used for Angular Distributions and $\Gamma(\chi_{c2} \to \gamma\gamma)$ only:								
	CHI1	7256	~3500	large syst. errors in the Beam Energy Calibration								
	CHI0	2573	69	16.6	31%		2.7	23%		3417.4	1.9 ⊕	0.2
E835/00												
	CHI2	1053	~300	2.39	12% ⊕	4%	1.63	15% ⊕	4%	*(preliminary)*		
	CHI1	1330	~1250	0.91	7% ⊕	10%	1.11	4% ⊕	5%	*(preliminary)*		
	CHI0	32785	392	9.9	10% ⊕	1%	1.7	9% ⊕	4%	3415.4	0.4 ⊕	0.2

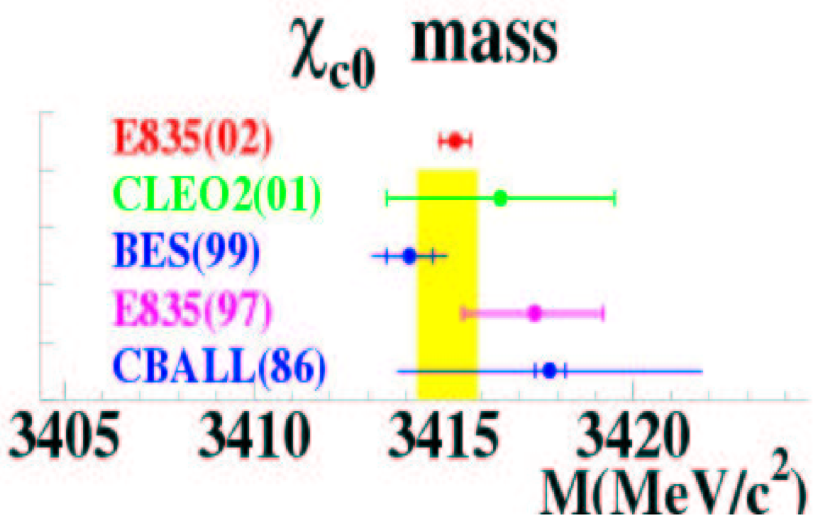
Total width and Mass of χ_{c0}

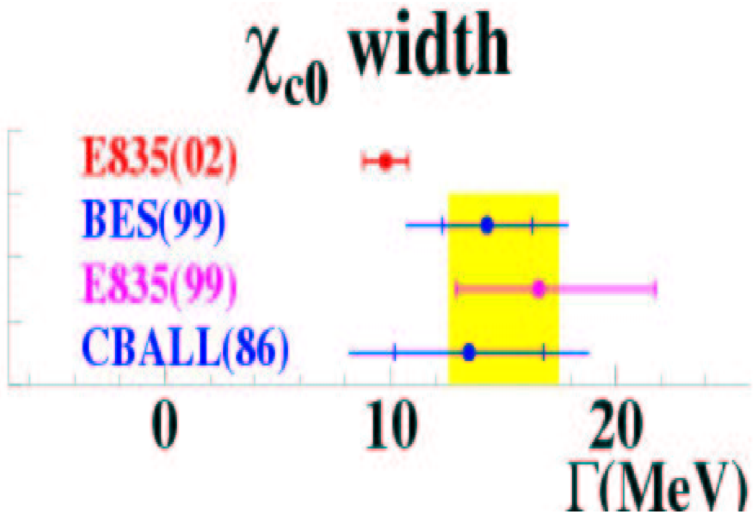
E835/00 sample = 6x E835/97

Bagnasco et al., Phys.Lett.B533(2002),237

Increased statistics (x 6)







Multipole structure of the $\chi_{c1,2}$ radiative decay

When $J_i \otimes J_f \neq 0$, higher multipoles can be measured, through the interference terms in angular distributions:

e.g.: $d\Gamma(\Omega)/d\Omega = |E1|^2 f_{E1}(\Omega) + E1{*}M2\, f_{12}(\Omega) + E1{*}E3\, f_{13}(\Omega) + \ldots$

Measurements exist for the processes:

From $\bar{p}\,p \to \chi_{c1,2} \to \gamma\, J/\psi \to \gamma\, e^+e^-$

R704: C.Baglin et al., Phys.Lett. B195,85 (1987)
E760: T.Armstrong et al., Phys.Rev. D48,3037 (1993)
E835: M.Ambrogiani et. al., Phys.Rev.D65:052002 (2002)

From $e^+e^- \to \psi' \to \gamma\,\chi_{c1,2} \to \gamma\,\gamma\, J/\psi \to \gamma\,\gamma\, e^+e^-$

Crystal Ball: M.Oreglia et al., Phys.Rev.D25,2259(1982).

- Angular distributions allow also the extraction of the helicity zero contribution to $\Gamma(\chi_{c2} \to \bar{p}\,p)$.

Multipole structure of the $\chi_{c1,2}$ radiative decay: results

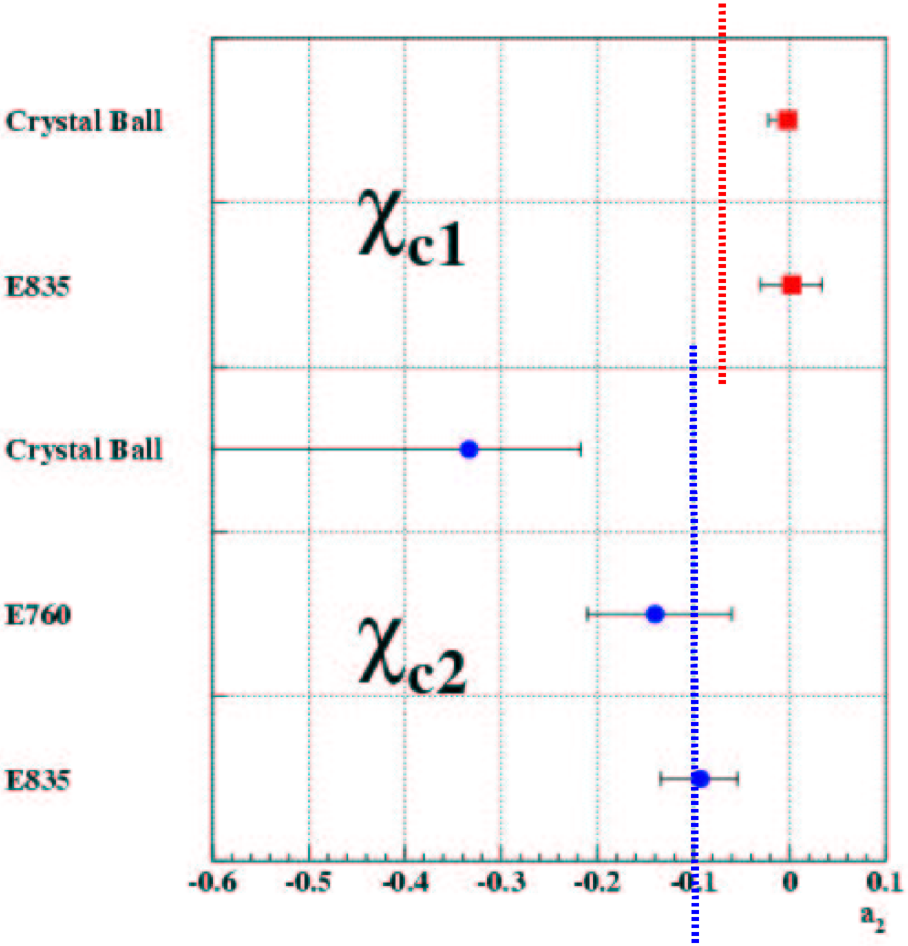
The anomalous magnetic moment of the charm quark, κ_c , can be extracted from the fractional M2 amplitude, using the expressions:

$$a_2(\chi_{c1}) = -(1+\kappa_c)\frac{E_\gamma}{4m_c}$$

$$a_2(\chi_{c2}) = -(1+\kappa_c)\frac{3}{\sqrt{5}}\frac{E_\gamma}{4m_c}$$

The ratio $a_2(\chi_{c1})/a_2(\chi_{c2})$ should then be 0.68, canceling out any κ_c or m_c dependence.

Helicity zero contribution to $\Gamma(\chi_{c2} \to \bar{p}p)$ is measured to be $B_0^2 = 13 \pm 8\%$.



$\Gamma(\chi_{c0,2} \rightarrow \gamma\gamma)$

- E835/97 measurement of

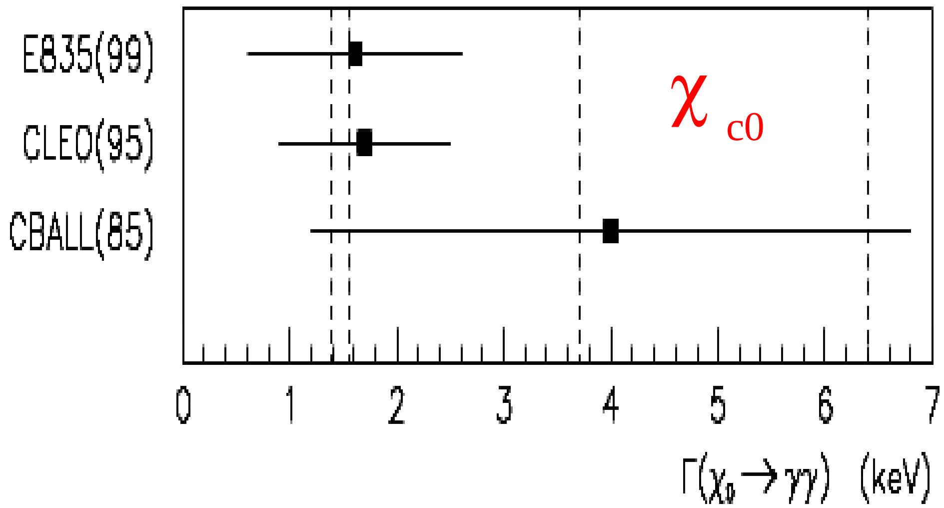
$$R_{\gamma\gamma}(\chi_{cJ}) = \frac{BR(\chi_{cJ} \rightarrow \gamma\gamma)}{BR(\chi_{cJ} \rightarrow \gamma\psi)}$$

Ambrogiani et al., Phys.Rev.D62(2000):052002

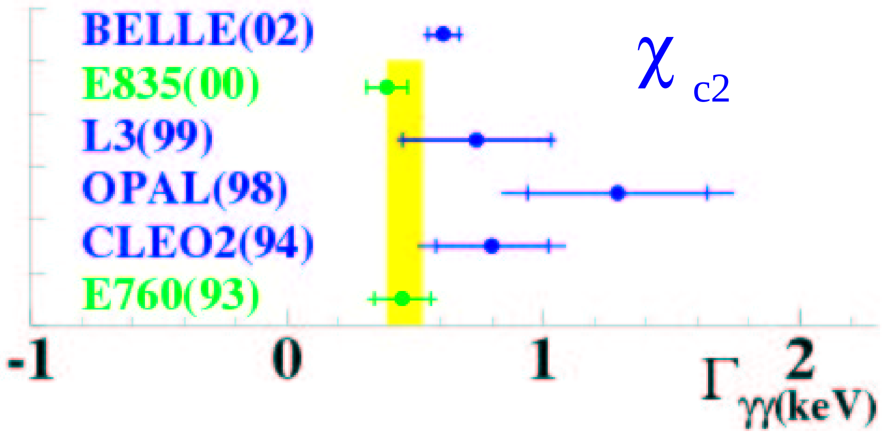
$R_{\gamma\gamma}(\chi_{c0}) = (24.4 \pm 12.5) * 10^{-2}$

$R_{\gamma\gamma}(\chi_{c2}) = (1.67 \pm 0.30) * 10^{-2}$

- Analysis of the 2000 χ_{c0} data set is in progress(> 6x more statistics).



- The global refit in PDG 2002 reduces the discrepancy on $\Gamma(\chi_{c2} \rightarrow \gamma\gamma)$ between $\bar{p}p$ and e^+e^- experiments.

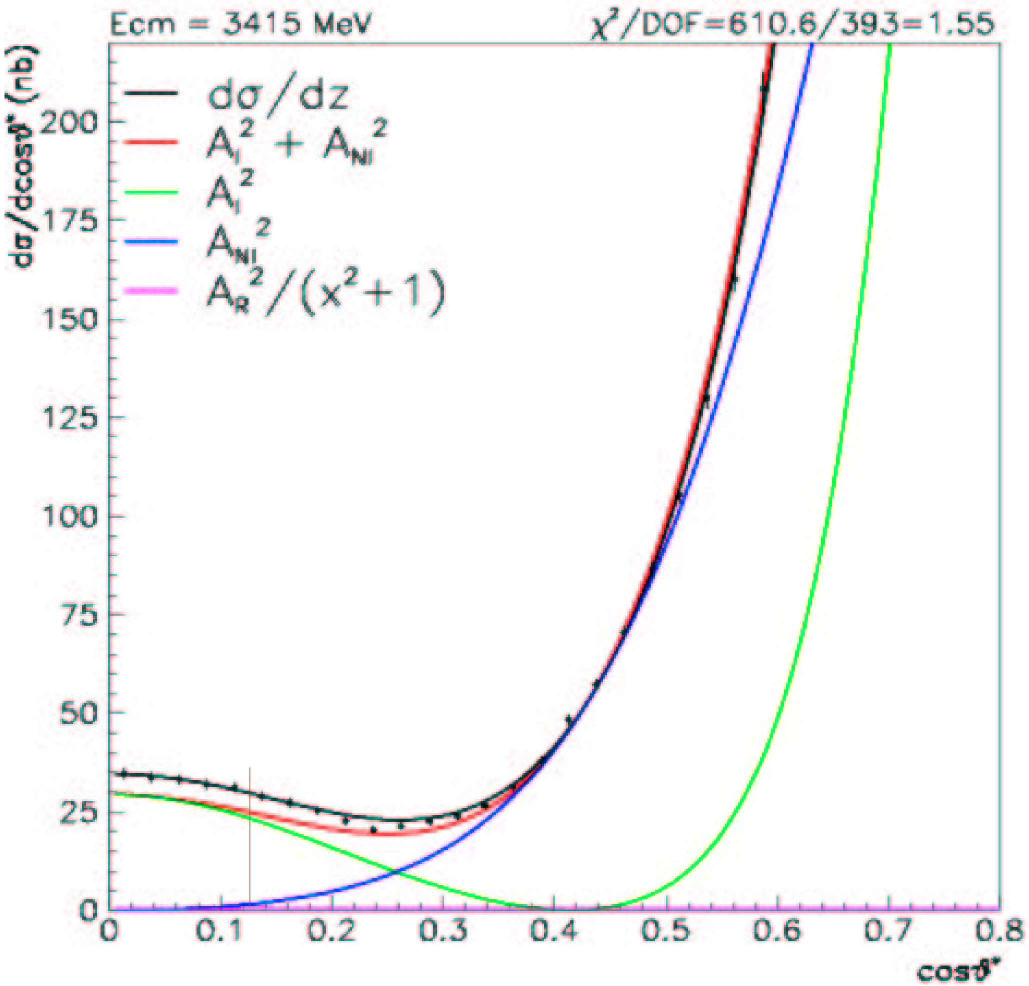


- Recent result from $\gamma\gamma \rightarrow \chi_{c2} \rightarrow \gamma J/\psi$ at Belle is ~consistent with the new average.

Abe et al., hep/ex-0205100 (2002)

$BR(\chi_{c0} \rightarrow \pi\pi)$

- Despite the large hadronic continuum cross-section, the interference between resonant and continuum behavior gives a sizeable signal, at $\cos\vartheta_{cm} \sim 0$, at the χ_{c0} peak energy.
- The angular distribution at the peak is shown in the figure, and illustrates the separate contributions from interfering (helicity 0), non interfering (helicity 1), resonant amplitudes.The excess of events above the red curve is due to the interference between resonant and continuum behaviour.
- The distribution is given by the expression:



$$\frac{d\sigma}{dz}(x,z) = \left| \frac{-A_R}{x+i} + A_I(x,z)\, e^{i\delta_I(z)} \right|^2 + \left| A_{NI}(x,z) \right|^2$$

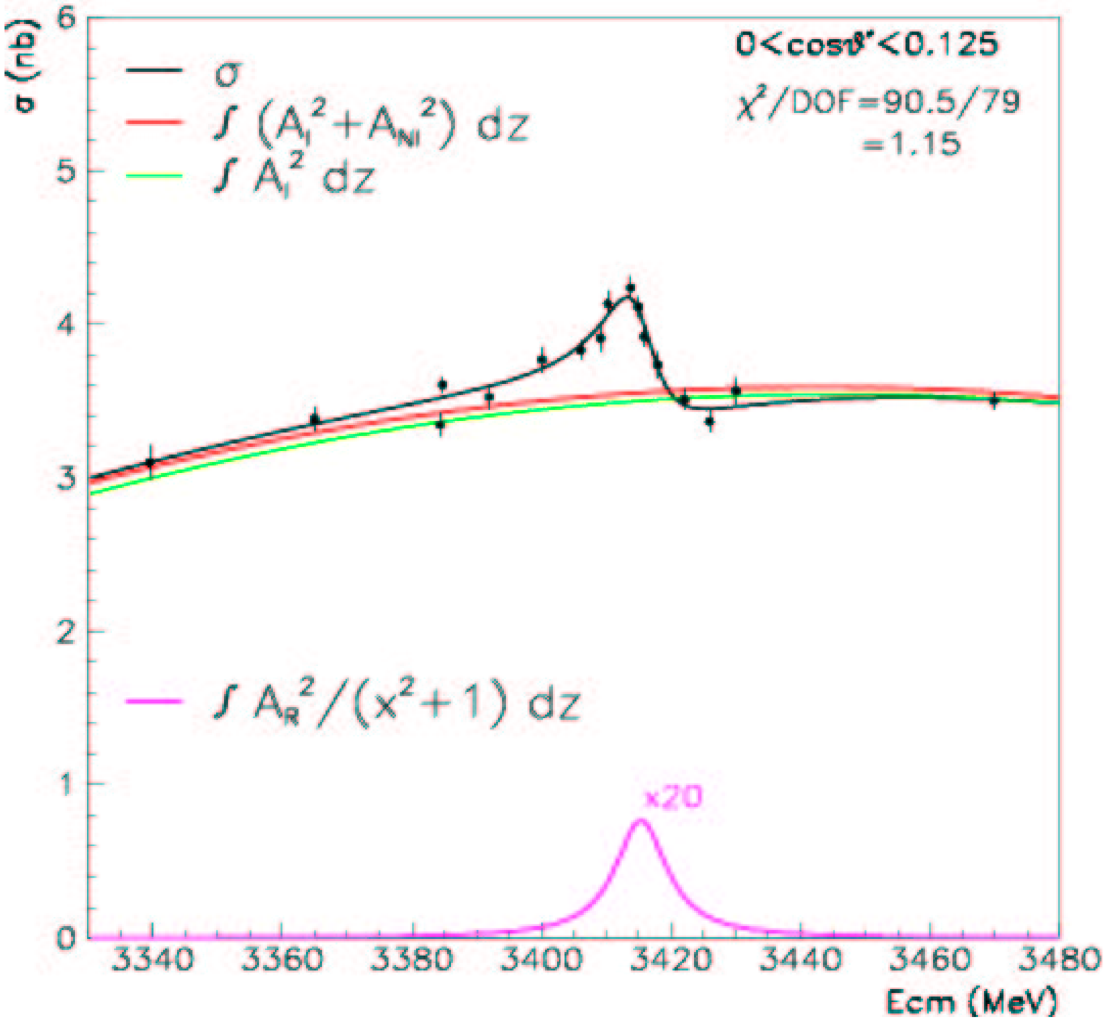
where $x = 2\frac{(E_{CM} - M_R)}{\Gamma_R}, z = \cos(\theta_{cm})$

BR($\chi_{c0} \to \pi\pi$)

★ The interference between resonant and continuum behavior gives a sizeable, asymmetric, signal: the figure describes cross section vs energy, for $|\cos\theta|<0.125$.

★The expected contribution from the pure resonance (symmetric Breit-Wigner) is shown also, *magnified by 20.*

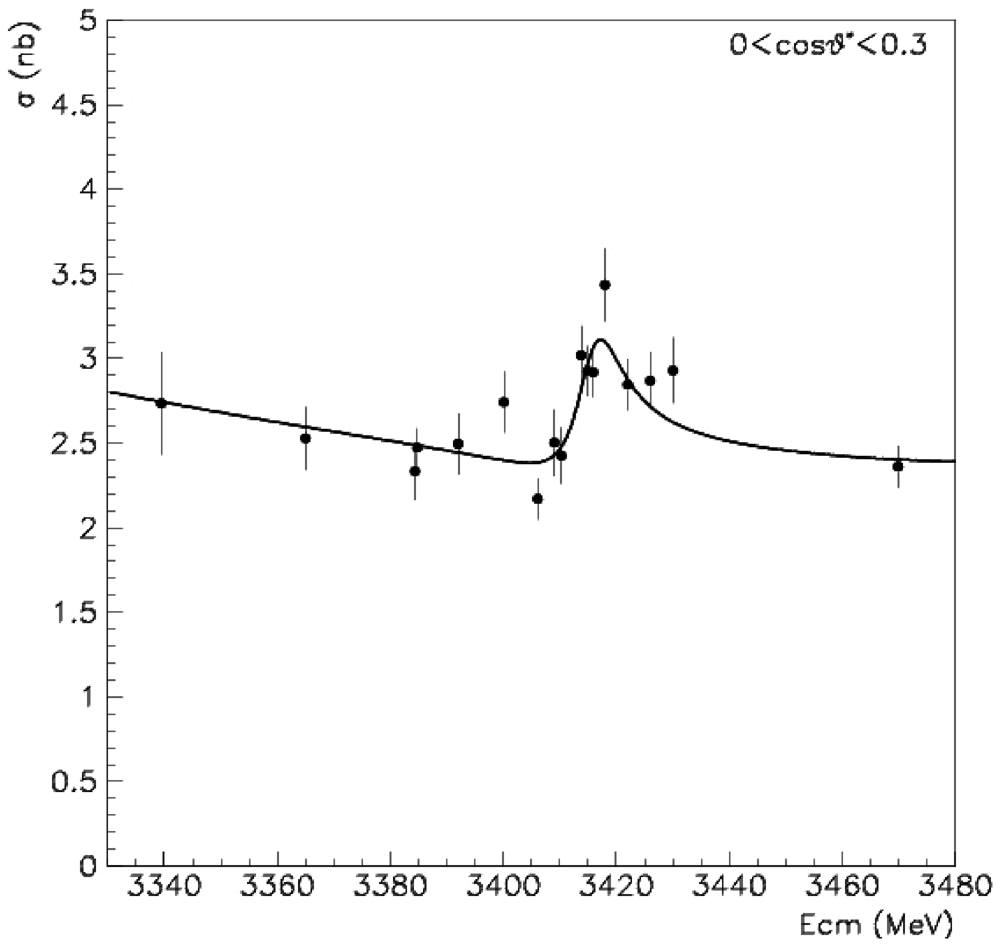
★From the fit to this data set , we can extract a measure of the product of branching fractions:



$BR(\chi_{c0} \to \pi^0\pi^0) * BR(\chi_{c0} \to p\bar{p}) = (5.09 \pm 0.81) * 10^{-7}$ *(preliminary)*

BR($\chi_{c0} \to \eta\eta$)

- Analysis of the $\eta\eta$ channel is under way ....
the phase looks opposite to $\pi^0\pi^0$

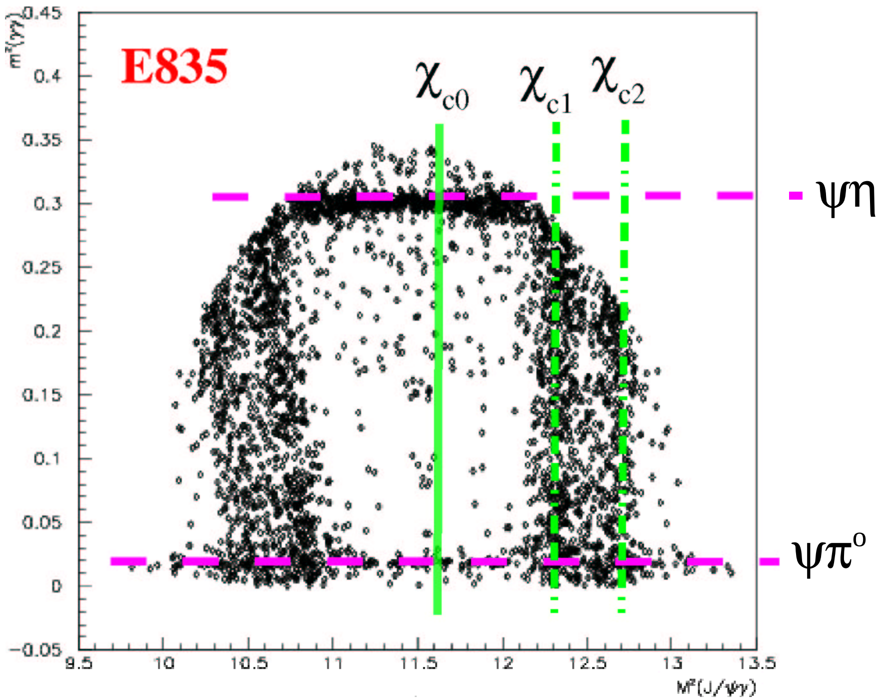


$\psi' \to J/\psi\ \gamma\gamma$

- Samples:

Experiments	Events	PSI' produced
CRYSTAL BALL	*2920*	*0.8 (+1) M*
E835/96+00	*2080*	*1.0 M*
BES		*4.0 M*

- Access to $\gamma\chi_c, \psi\pi^o, \psi\eta$.
- ECAL:NaI(C.Ball), PbG(E835)



- Analysis under way in E835:
  - ✭ $BR(\psi' \to \gamma\chi_{c0})$* $BR(\chi_{c0} \to \gamma\ J/\psi)$
  - ✭ angular distributions

➜ Further studies on 2000 data: $\psi' \to J/\psi\ \pi\pi$, e^+e^-, $\gamma\phi\phi$

Conclusions

- The study of charmonium P states in $p\bar{p}$ is close to completion; only a new generation of experiments can reduce the current statistical and systematic errors.

- 33 pb^{-1} of data were taken by E835 in year 2000 at the χ_{c0} energy, yielding samples of $\psi\gamma$, $\gamma\gamma$, $\pi\pi$, $\eta\eta$ events.
  - The total width of the χ_{c0} is now known at 10% level.
  - The first charmonium signal in pure hadronic channels ($p\bar{p} \rightarrow \pi\pi, \eta\eta$) was observed, exploiting interference in scattering at 90° in CM frame.

- The study of $\chi_{c1,2}$ and ψ' angular distributions shed light in the multipolarity of radiative transitions , and on the helicity structure of the $p\bar{p}$ coupling to charmomium.

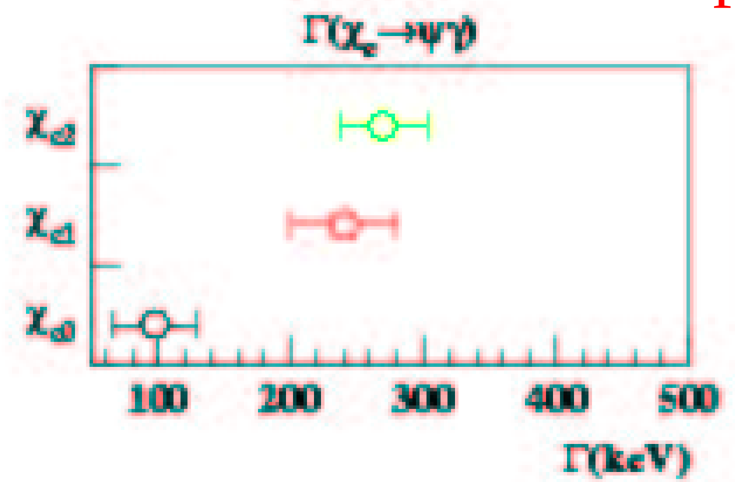
- To fully exploit the stat accuracy of $p\bar{p}$ measurements on products of BR's, new e^+e^- data on their ratios are needed.

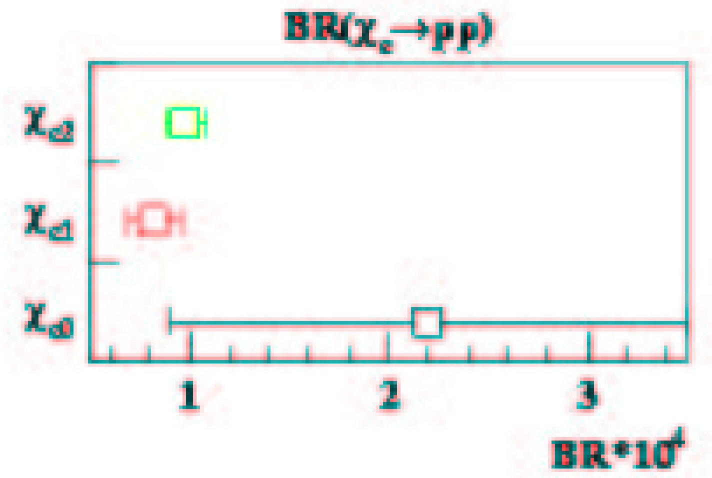
Extra slides

Global refitting in PDG 2002

The PDG 2002 shows a substantial change in the overall pattern of branching ratios and radiative widths of P states as a result of a global refitting of all χ_c and ψ' data , accounting correctly for all the correlations between different experiments. The variety of sources of exclusive charmonium data provides a powerful set of crosschecks, which is crucial to allow the extraction of parameters about a single process from data who normally involve 2 or more reactions.
(see also *C.Patrignani,Phys. Rev. D 64(2001) 034017*)

PDG2000





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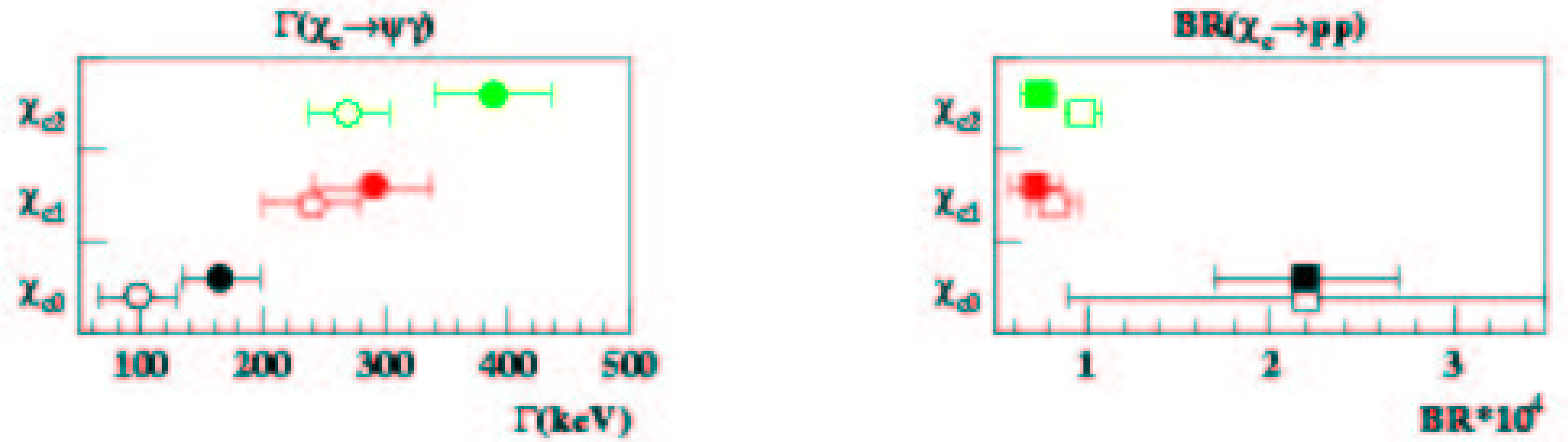
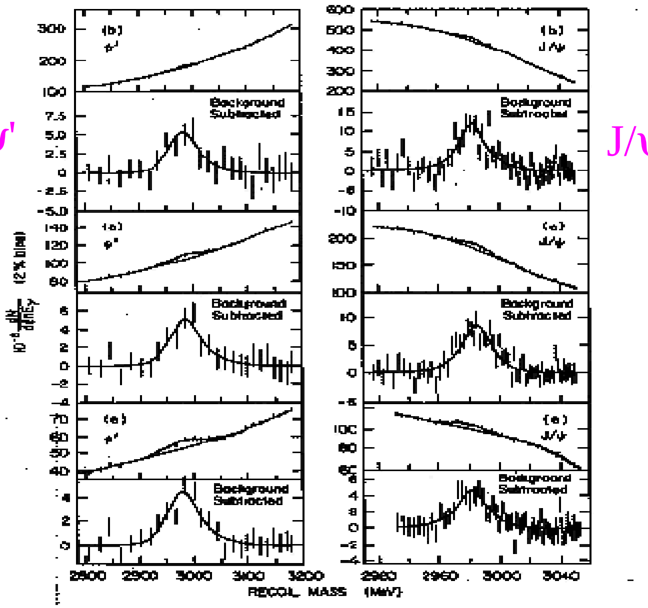
PDG2002



Syst errors from inclusive photon spectra

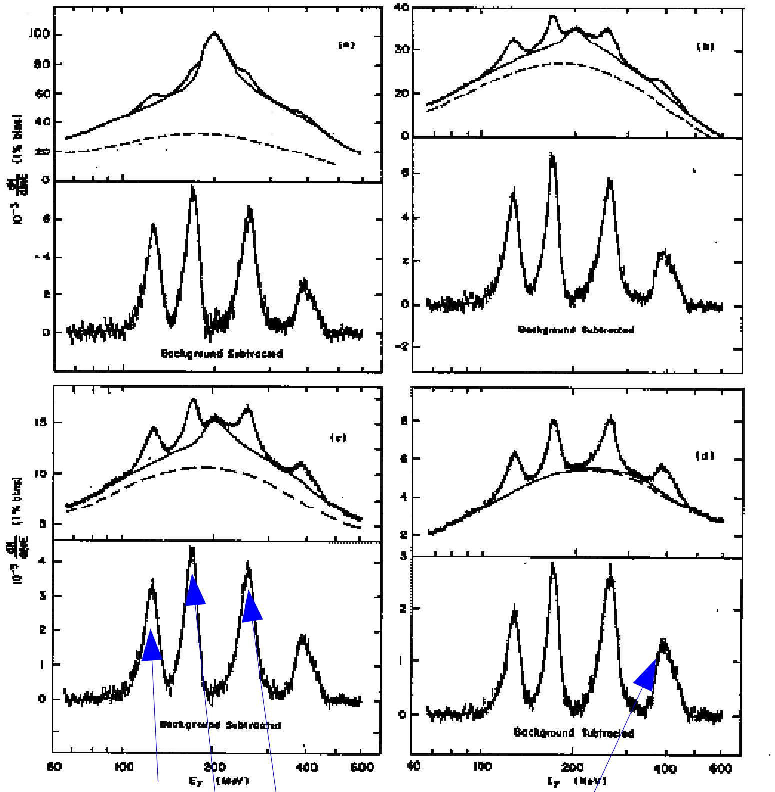
- *All* BR(η_c,χ_c→hadrons) measured from e+e- annihilations *depend* on BR(J/ψ,ψ'→γ+...), measured by Crystal Ball. *Gaiser et al. Ph. Rev. D34,711 (1986)*
- Crystal Ball's charged tracking inefficiency: 20% syst error on BR(ψ'→γχ_c)?
- Low statistics of M1 transitions: 30% stat error on BR(J/ψ,ψ'→γη_c)

ψ'



J/ψ

FIG. 8. Simultaneous fits to the η_c mass in the ψ' and J/ψ inclusive photon spectra. The data are plotted in 2% bins in the photon energy. The preferred resolution value of σ_0=2.7% is used in the fit. The spectra labeled (b) and (c) correspond to the photon selection criteria of the χ analysis. The spectra labeled (e) employ a modified cut on the lateral photon energy pattern as described in the text.



ψ'→ γ χ_{c2}, χ_{c1},χ_{c0}

χ_{c2}, χ_{c1} → J/ψ

$\Gamma(\chi_{c2} \to \gamma\gamma)$

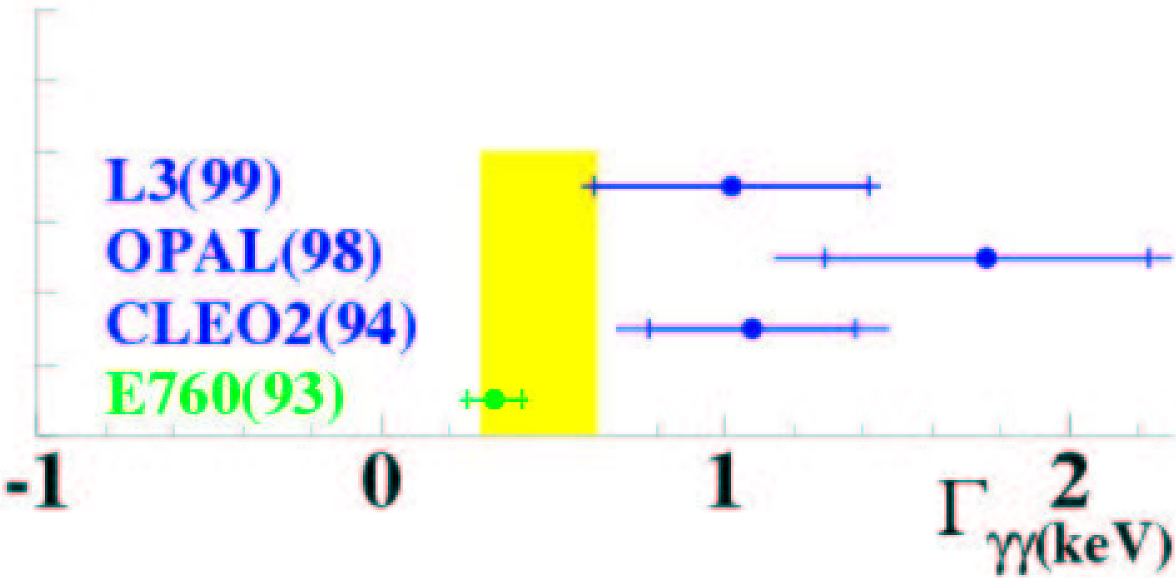
The determination of this quantity depends directly from two processes:

- $p\bar{p} \to \chi_{c2} \to \gamma\gamma$: R704,E760,E835/97 *(Ambrogiani et al., Phys.Rev.D62(2000):052002)*
- $\gamma\gamma \to \chi_{c2} \to \gamma J/\psi$, hadrons : CLEO, L3, OPAL, BELLE (new:*Abe et al., hep/ex-0205100 (2002)*)

And indirectly from various other quantities, deduced from :

- $\psi' \to \gamma + \chi_c \to \gamma\gamma J/\psi$
- $\psi' \to \pi\pi J/\psi$
- $\bar{p}p \to \chi_{c2} \to \gamma J/\psi$

PDG 2000 outlined a big discrepancy between the measurements coming from different reactions.



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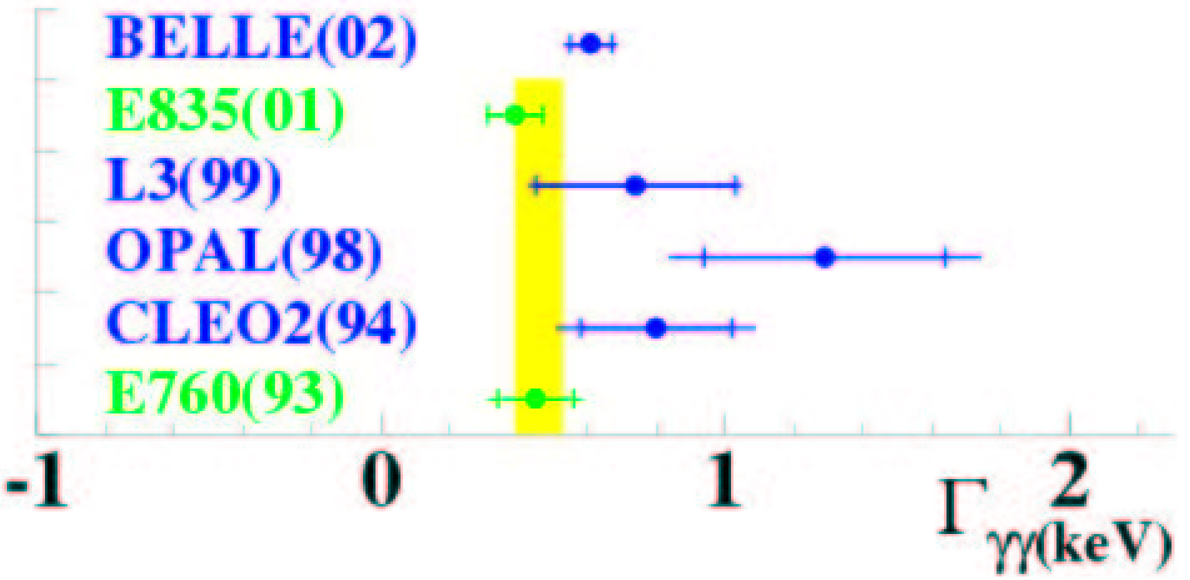
- $\psi' \to \gamma + \chi_c \to \gamma\gamma J/\psi$
- $\psi' \to \pi\pi J/\psi$
- $\bar{p}p \to \chi_{c2} \to \gamma J/\psi$

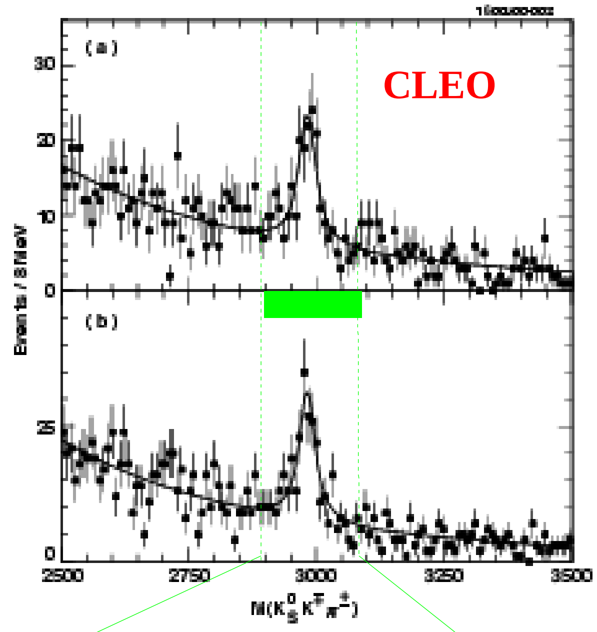
The global fit of all previous data (PDG 2002) substantially reduces the discrepancy between the measurements from the two different processes, as the $BR(\chi_{c2} \to \gamma J/\psi)$ is raised from 13.6% to 18.7% (38% increase)

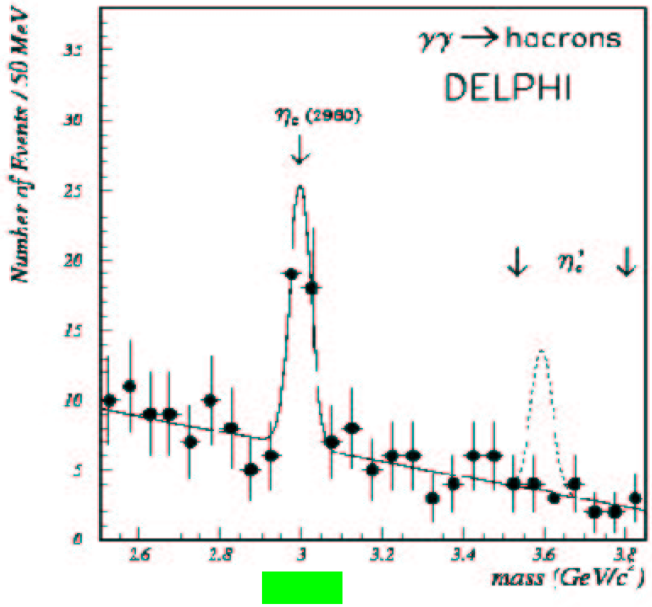


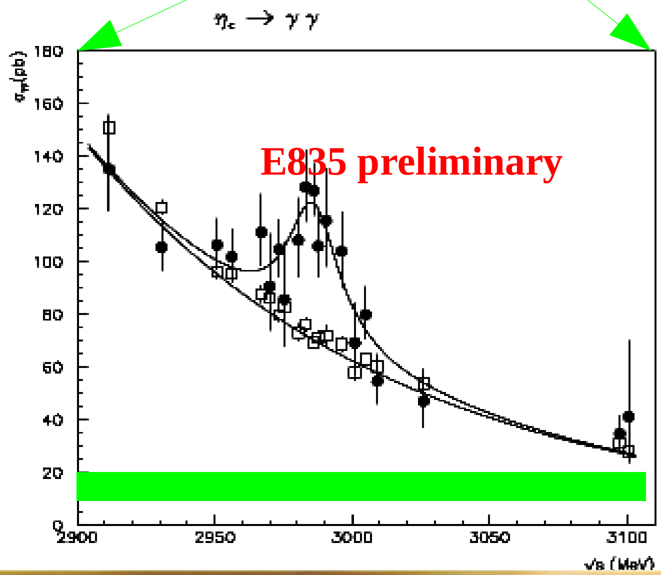
η_c mass and width

- *Quasi* recent data from:
  - *CLEO: Brandenburg et al. Phys.RevLett. 85 (2000) 3095*
  - *BES: Bai et al. Phys.Rev.D60(1999) 072001*
  - *DELPHI: Abreu et al., Phys.Lett. B441(1998) 479*
- *Still preliminary* data from E835

  Studying syst errors from energy dependence of $p\bar{p} \to \pi^0\pi^0 + \pi^0\gamma$ feeddown .







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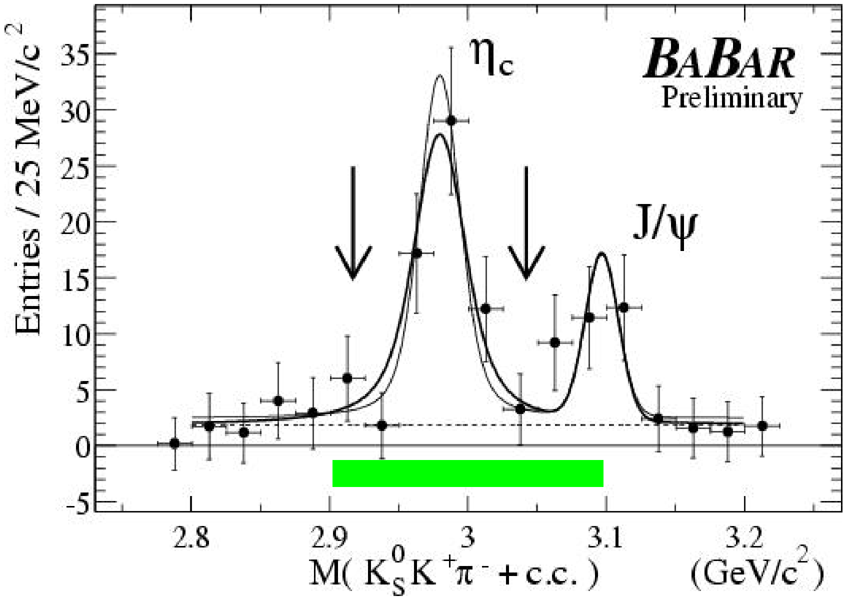
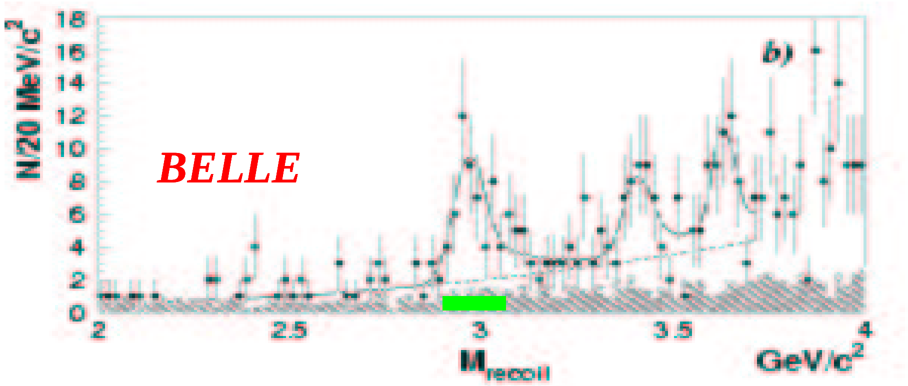
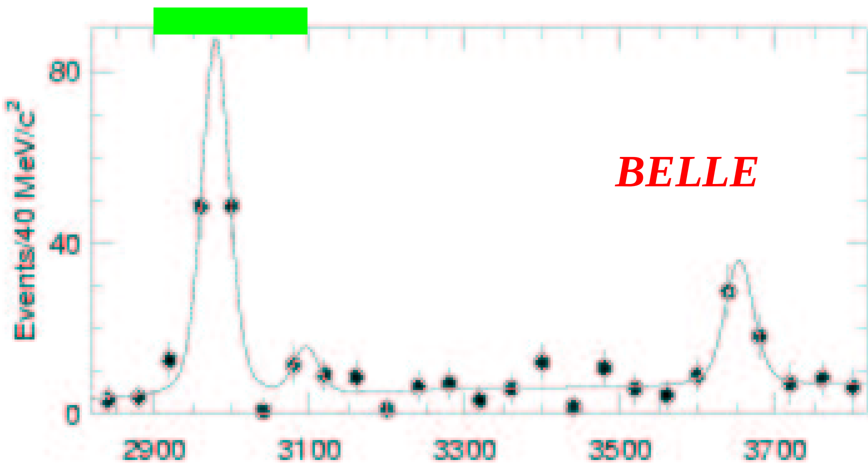
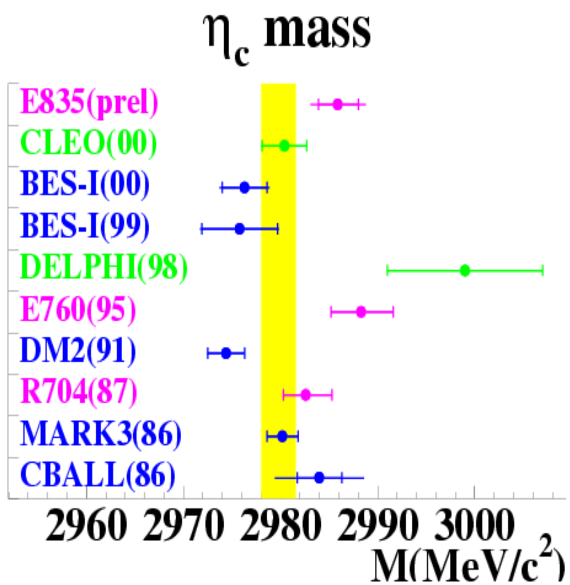
- *Still preliminary* data from E835
  - Energy dependence of $p\bar{p} \rightarrow \pi^0\pi^0 + \pi^0\gamma$ feeddown.
  - Interference with $\gamma\gamma$ continuum?
- *New* data from B factories look promising but statistically still poor:
  - *BaBar: Aubert et al. Phys.RevLett. 85 (2000) 3095*
  - *Belle: Choi et al. Hep-ex/0206002 (2002)*
  - *Belle: Abe et al. Hep-ex/0205104 (2002)*







η_c mass and width



★Recent data:
E835,BES,CLEO,LEP,BELLE,BABAR

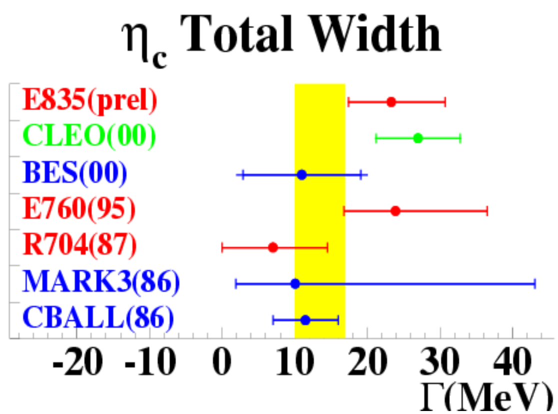
- MASS:

Hyperfine splitting:

$M(J/\psi)-M(\eta_c) = 117\pm2$ MeV/c^2

Bad overall χ^2 on PDG:

M($p\bar{p}$)>M(e^+e^-)?



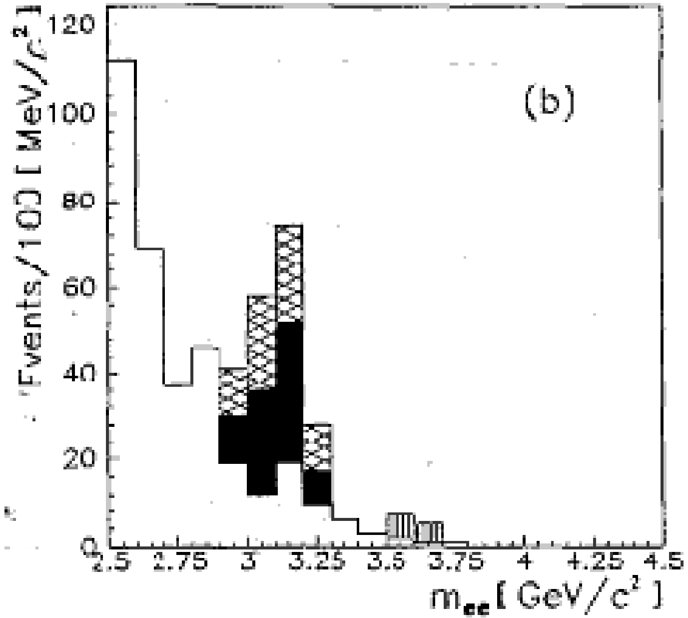
- TOTAL WIDTH=$\Gamma(\eta_c \to gg)$

BES-I data from ψ and ψ' sample

$\delta\Gamma/\Gamma$~25% ?? Bad χ^2 casts doubts on PDG2000

$^1P_1$ (*a.k.a. h_c*) search

- E760 data: 16 pb^{-1} in the M_{cog} region
  - Observed a state at M=3526.2±0.15±0.20 in $p\bar{p} \to h_c \to J/\psi\, \pi^0$
  - Not seen in $p\bar{p} \to h_c \to J/\psi\, \pi\pi$, and $p\bar{p} \to h_c \to \gamma\eta_c \to \gamma\gamma\gamma$
  - Large amount of cross-calibration data: $\chi_{c1,2}$ scans, J/ψ,ψ' double scans.
- E835 data: 47pb^{-1} (in 96-97) and 50 pb^{-1} (in 2000) in the M_{cog} region
  - Careful study on the stability of E_{beam} measurements (at a level of few hundred keV) under way .



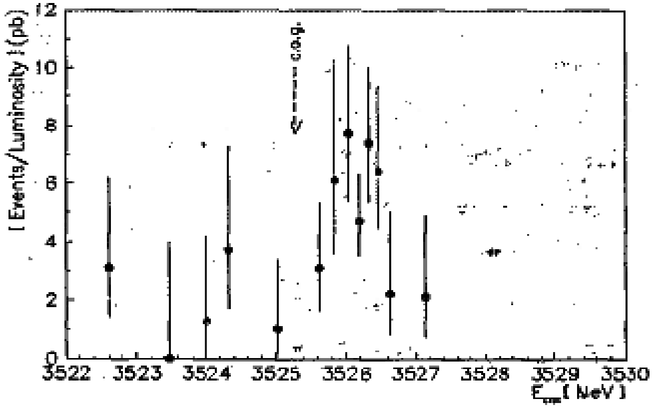


FIG. 2. Number of events per integrated luminosity vs center-of-mass energy; data are binned in 150-keV intervals in the average center-of-mass energy.

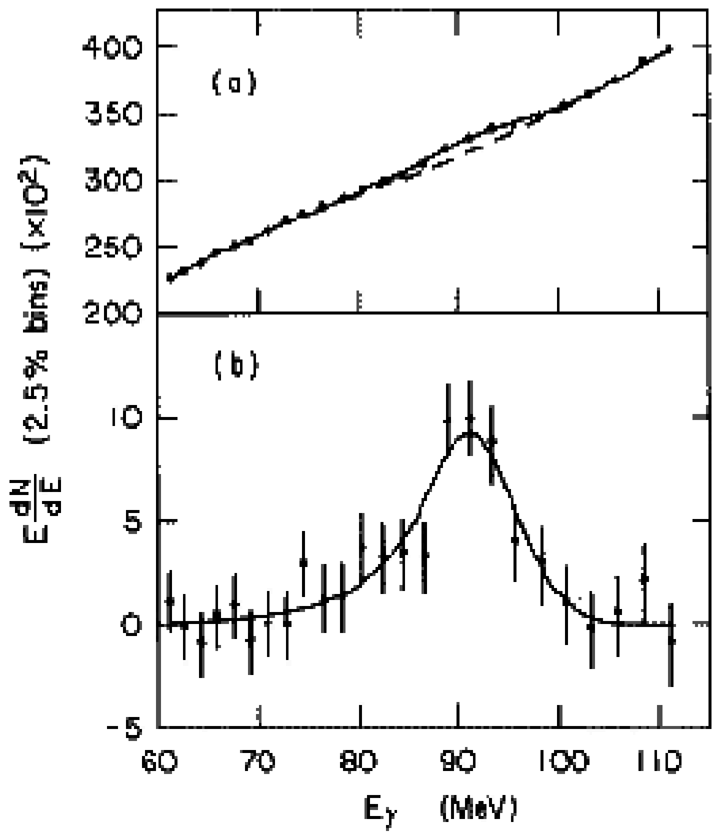
η_c' searches

- A $^1S_0(n=2)$ candidate at 3594±5 MeV/c^2 wasobserved by Crystal Ball in

  $e^+e^- \to \gamma + X$

  Edwards et al., Phys.Rev.Lett.48(1982),70

  ... but never confirmed



η_c' searches

⭐A $^1S_0(n=2)$ candidate at 3594±5 MeV/c^2 wasobserved by Crystal Ball in

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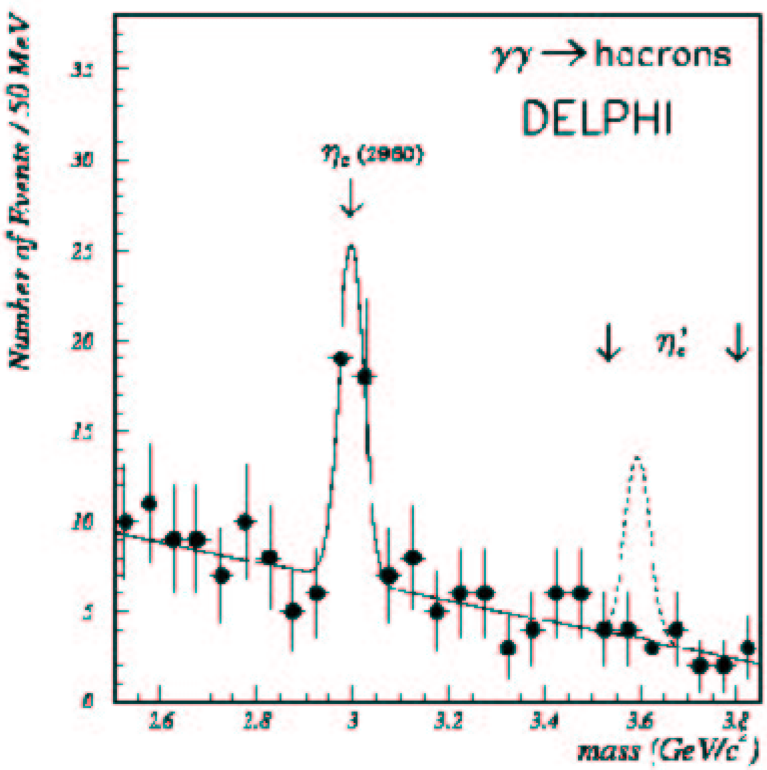

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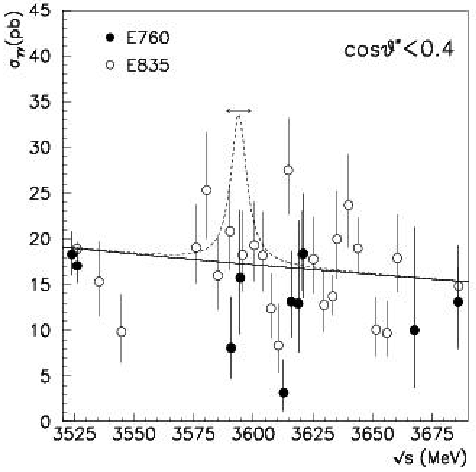
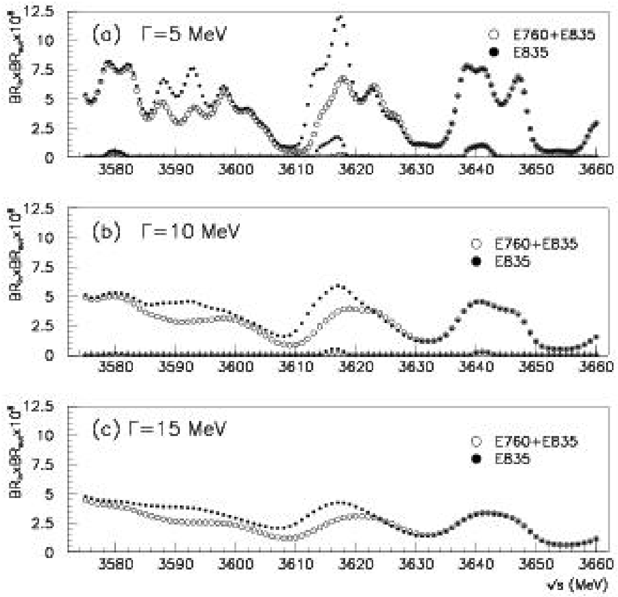
  Upper limits at 90%CL on BR($p\bar{p}$)*BR($\gamma\gamma$) with Γ=5,10,15 MeV are given.





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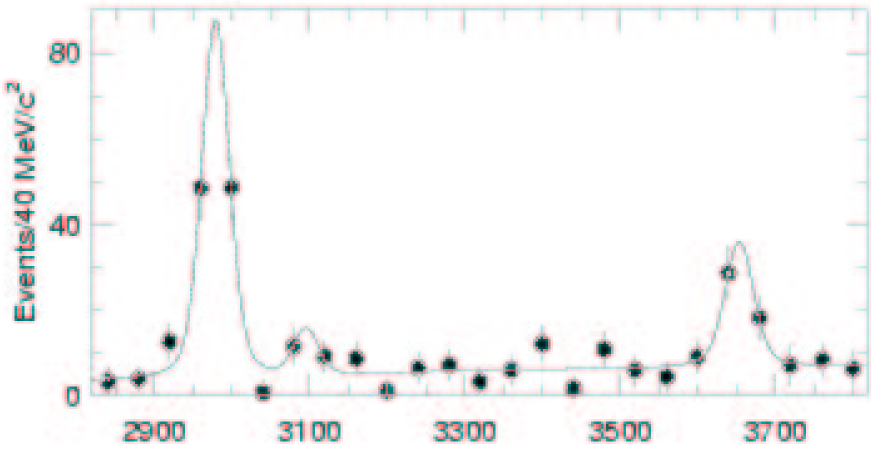

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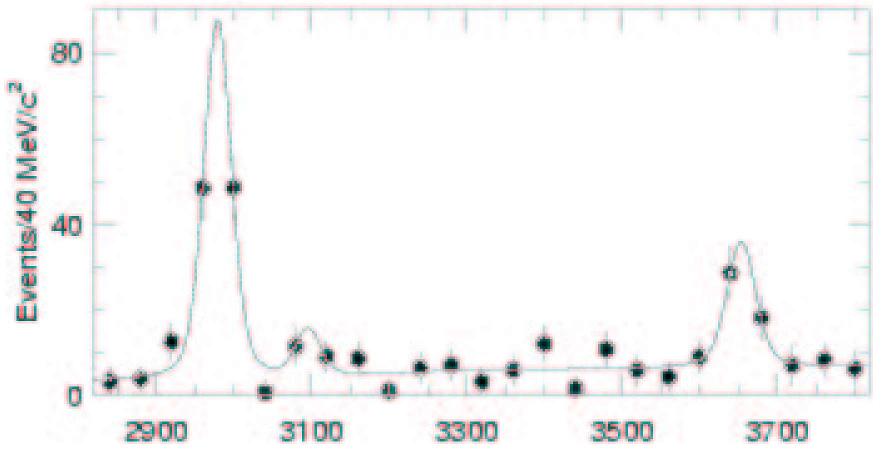
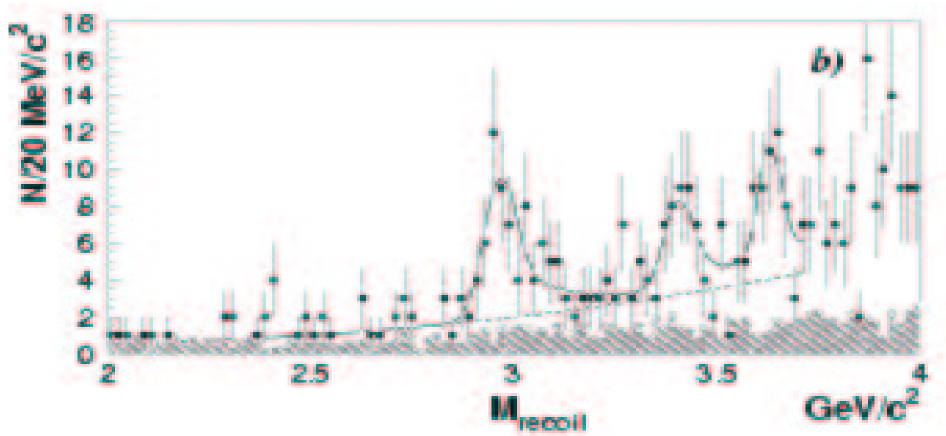
..... and/or at *3622±12 MeV/c^2!?!*

in $e^+e^- \rightarrow \gamma^* \rightarrow J/\psi + X$

Abe et al. Hep-ex/0205104 (2002)





Quarkonium Working Group

The Genoa mini-workshop on charmonium, in June 2001, has triggered a very constructive and collaborative effort between experimentalists and theoreticians, who are eager to fully benefit from the wealth of heavy quarkonium data who are becoming available in the present and near future.
During the winter, N.Brambilla and myself, with help from A.Vairo(CERN), A.Boehrer (Siegen), M.Kraemer(Edinburgh) and D.Gromes (Heidelberg), wrote down a proposal for the formation of a

Joint experimental-theoretical working group on heavy quarkonium physics, aiming to a unified QCD-based formalization of all the aspects of its dynamics: production, decays, spectroscopy, interactions with nuclear matter .

The proposal, circulated in February-March, received a wide-spread enthusiastic support from most theoreticians and/but a cooler response from experimenters. Nevertheless, we succeeded to get responses from at least 1 person of each running or future experiment.

We are now preparing for a first workshop to be held at CERN in November , and requested funding for a second workshop in Turin, June 03.

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