Heavy Quarkonia
$c\bar{c}$, $b\bar{b}$

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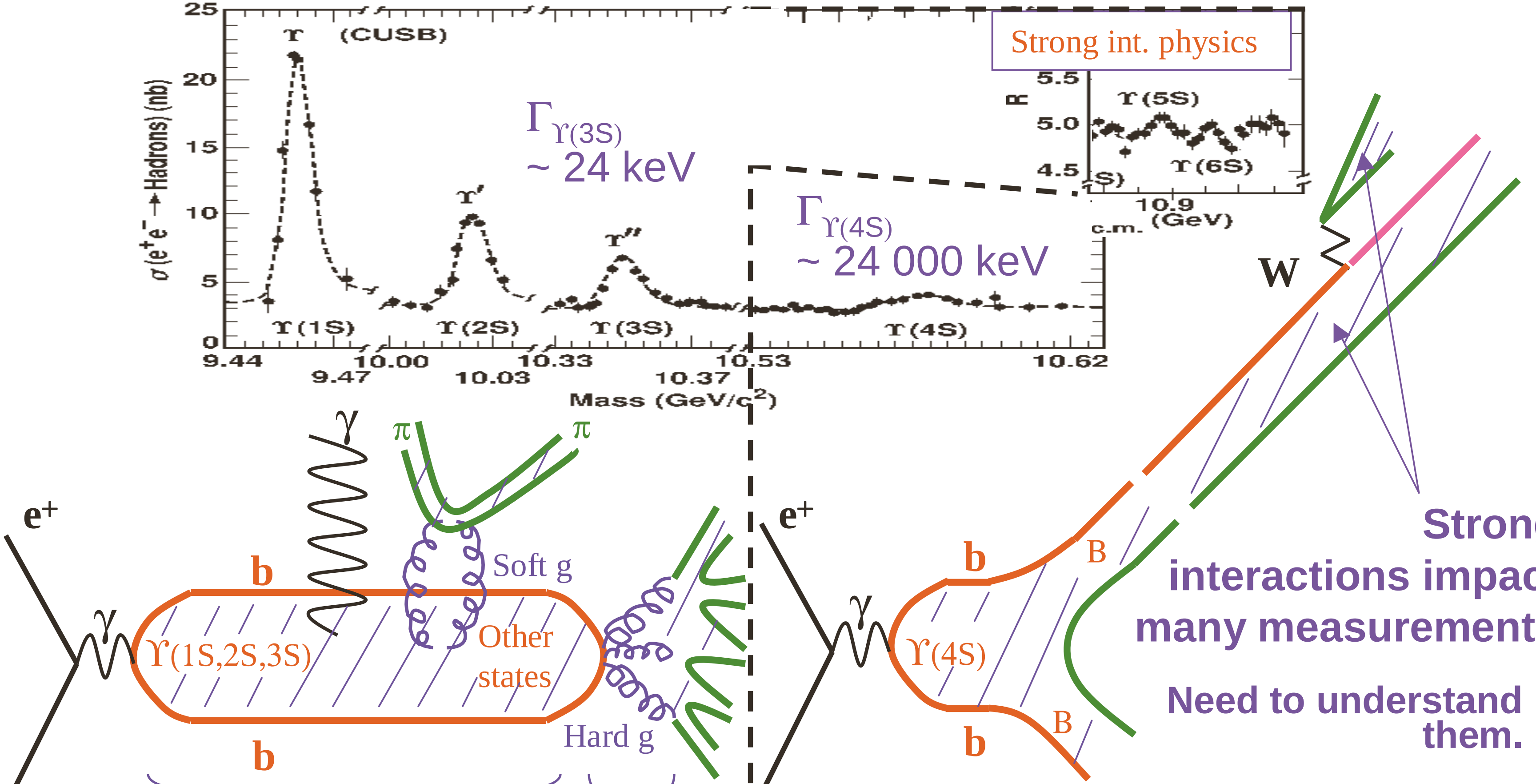
Long and Short-lived Quarkonia

Use $b\bar{b}$ as an example

Laboratory of strong interactions

Factory of weakly decaying heavy flavors



Long distance interactions

Short distance interactions

Strong interactions impact many measurements

Need to understand them.

Old Physics but still not completely understood

Strong interactions

New physics can be strongly coupled.

Weak interactions

New Physics ?

Onia

FORCES			System	**Ground triplet state 1^3S_1**			**$(v/c)^2$**	Number of states below dissociation energy	
binding	decay			Name	Γ (MeV)	Mass (GeV)		n^3S_1	all
POSITRONIUM									
EM	EM		e^+e^-	Ortho-	$5\ 10^{-15}$	0.001	**~0.0**	2	8
QUARKONIUM									
STRONG	STRONG		$u\bar{u},d\bar{d}$	ρ	150.00	0.8	**~1.0**	0	0
			$s\bar{s}$	φ	4.40	1.0	**~0.8**	"1"	"2"
		EM	$c\bar{c}$	ψ	0.09	3.1	**~0.25**	**2**	**8**
			$b\bar{b}$	ϒ	0.05	9.5	**~0.08**	**3**	**30**
	weak		$\bar{t}t$		(3000.0)	(360.)	<0.01	0	0

Toponium is not a lab for QCD

Consequences of **large m_Q**:

- velocities of constituents are small
- strong coupling constant in annihilation and production is small

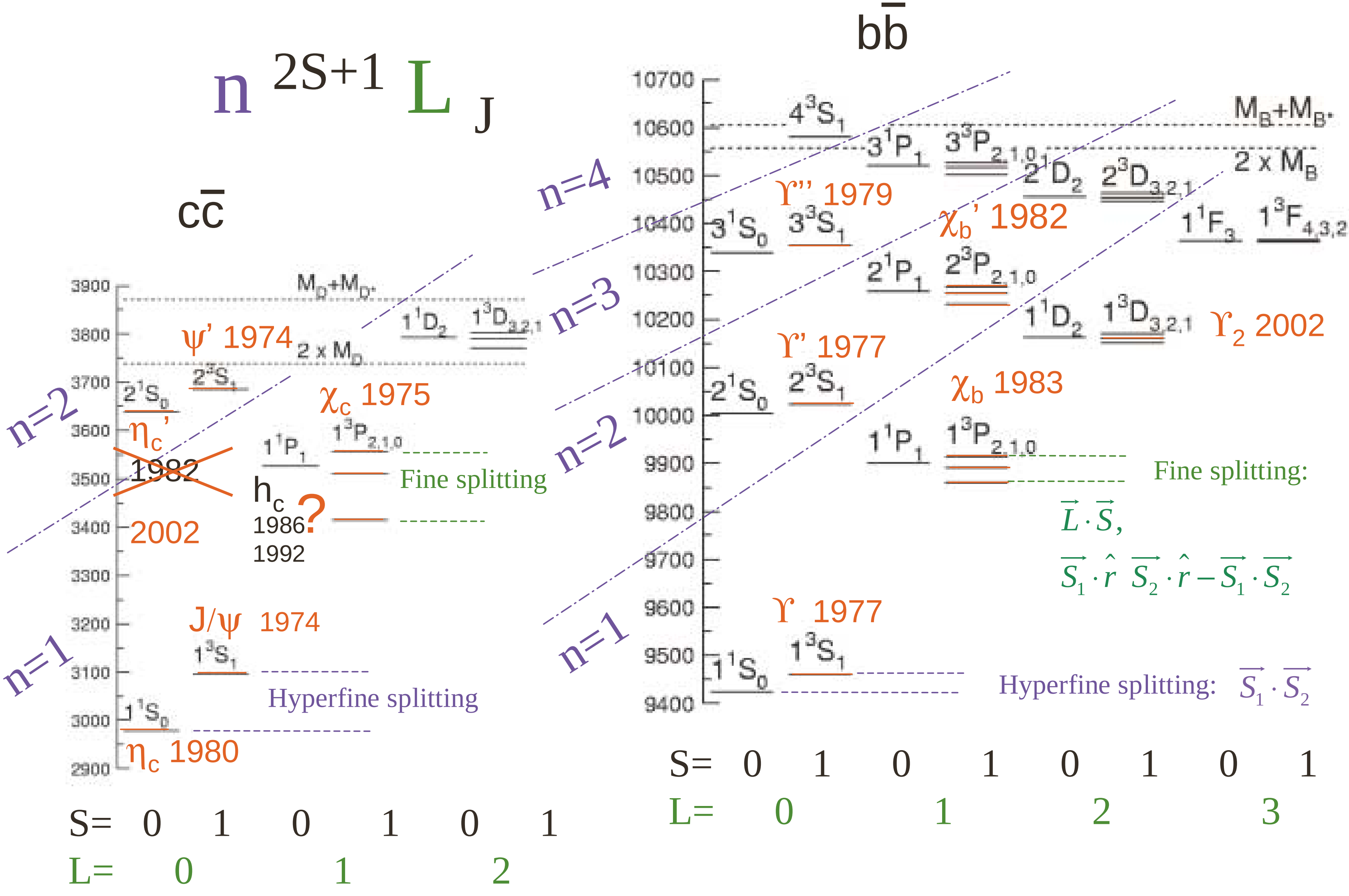
v
α_s
Expansion parameters

This opens avenues for **effective theories** of strong interactions:

- purely phenomenological potential models
- more recently NRQCD and much improved QCD on Lattice

Predicted States

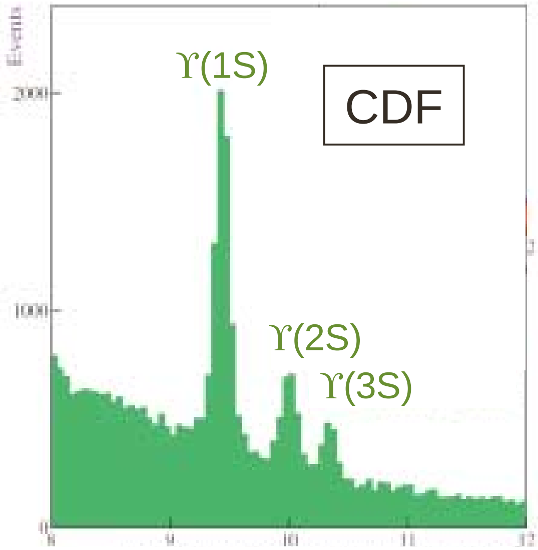
$$n\,^{2S+1}L_J$$



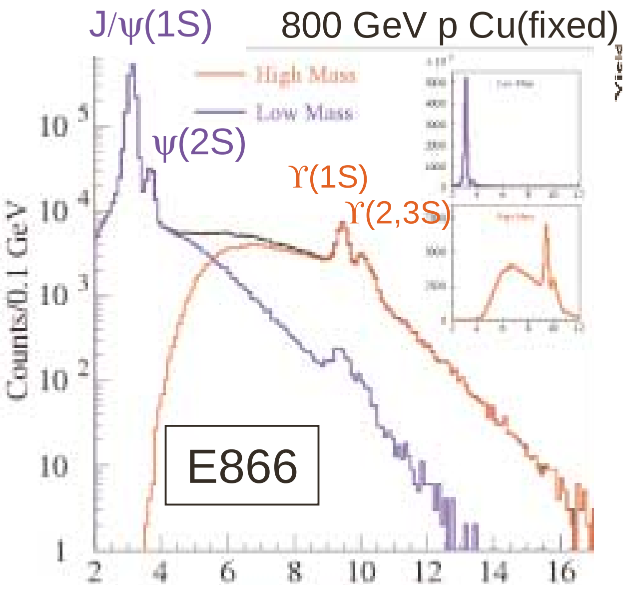
Hadro-production

- Annihilation of n^3S_1-- (ψ,Υ) to $\mu^+\mu^-$ (e^+e^-) makes it possible for experimentalists to fish heavy quarkonia states out. This is how they were (co)discovered!
- Access to $1^3P_{2,1}^{++}$ (χ) by adding a photon
- So far not a player in spectroscopy (except for the discovery) or decay studies
- Physics in **production mechanism**
- Used also as **a probe** for a structure of the target (e.g. gluon content)

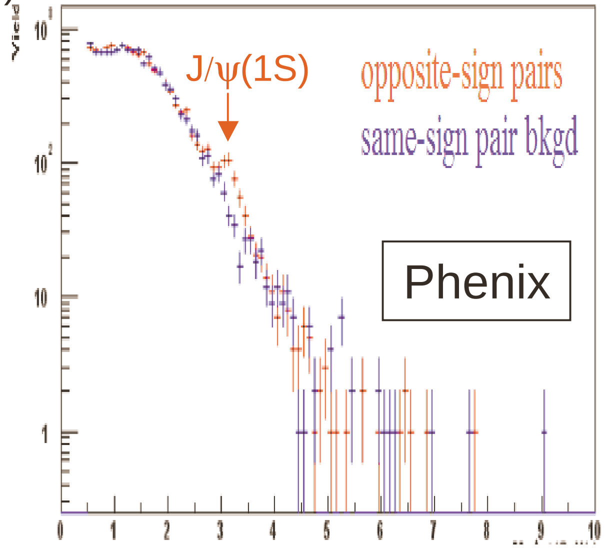
1.8 TeV p $\bar{p}$



800 GeV p Cu(fixed)

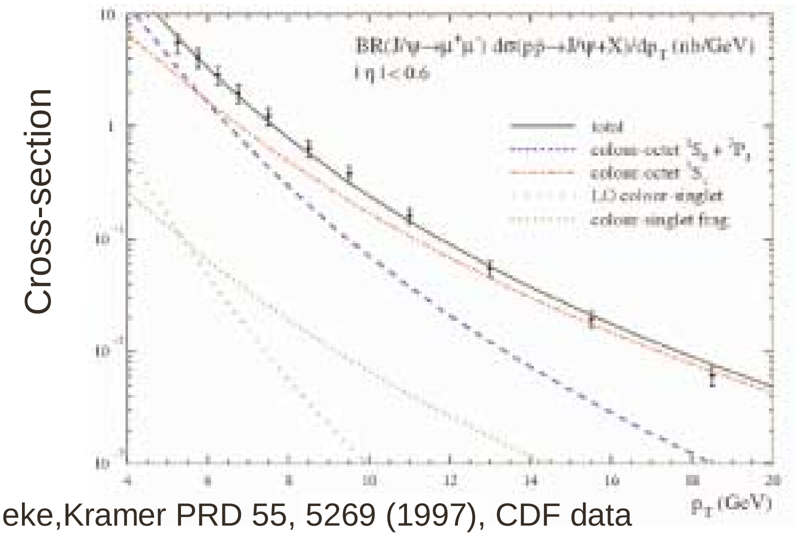


200 GeV d Au



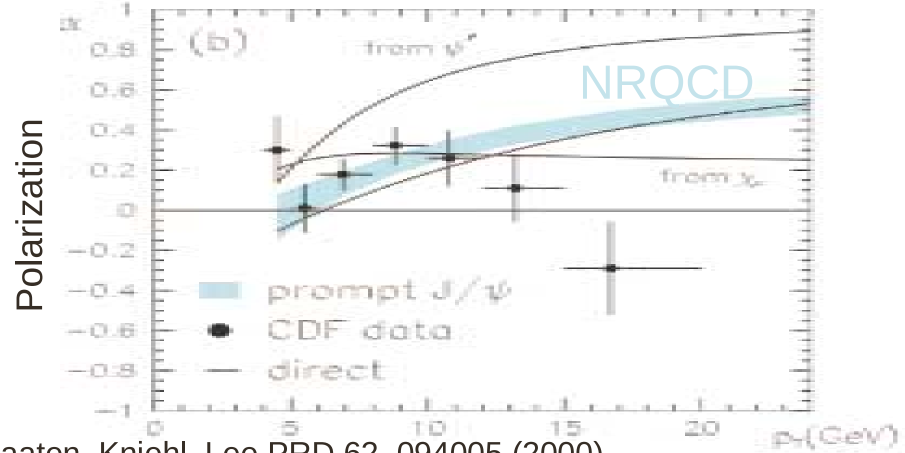
M($\mu^+\mu^-$) GeV

Hadro-production



Beneke,Kramer PRD 55, 5269 (1997), CDF data

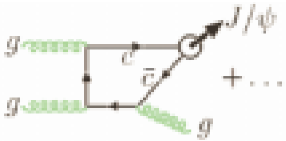
Old news: color-octet contributions are important
potential problem with polarization data



Braaten, Kniehl, Lee PRD 62, 094005 (2000)

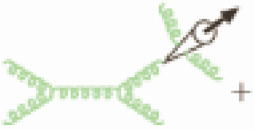
- NRQCD (leading order)

leading-order colour-singlet: $g + g \to c\bar{c}[^3S_1^{(1)}] + g$



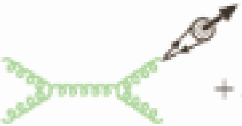
$+\ldots \qquad \sim \alpha_s^3 \frac{(2m_c)^4}{p_t^8}$

colour-singlet fragmentation: $g + g \to [c\bar{c}[^3S_1^{(1)}] + gg] + g$



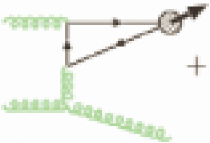
$+\ldots \qquad \sim \alpha_s^5 \frac{1}{p_t^4}$

colour-octet fragmentation: $g + g \to c\bar{c}[^3S_1^{(8)}] + g$



$+\ldots \qquad \sim \alpha_s^3 \frac{1}{p_t^4} v^4$

colour-octet fusion: $g + g \to c\bar{c}[^1S_0^{(8)}, {}^3P_J^{(8)}] + g$

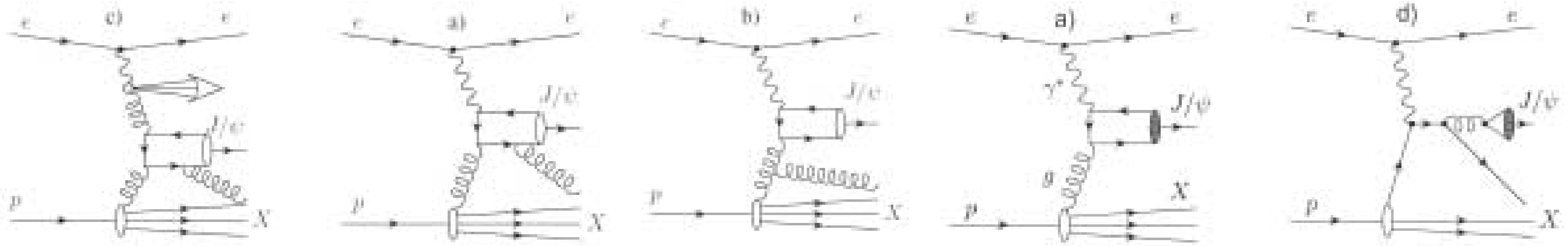


$+\ldots \qquad \sim \alpha_s^3 \frac{(2m_c)^2}{p_t^6} v^4$

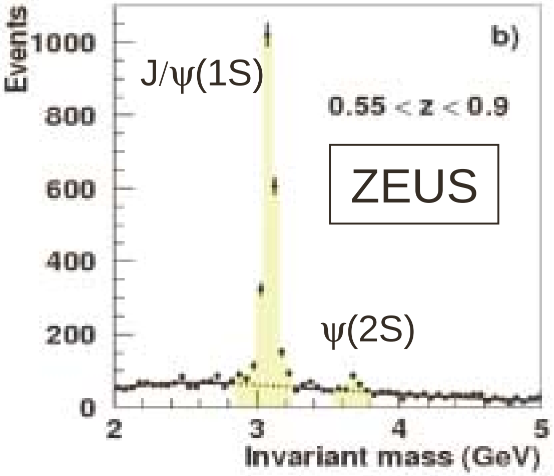
new: CDF Run-II data: http://www-cdf.fnal.gov/physics/new/bottom/030327.blessed-jpsixsec/xsec_html/

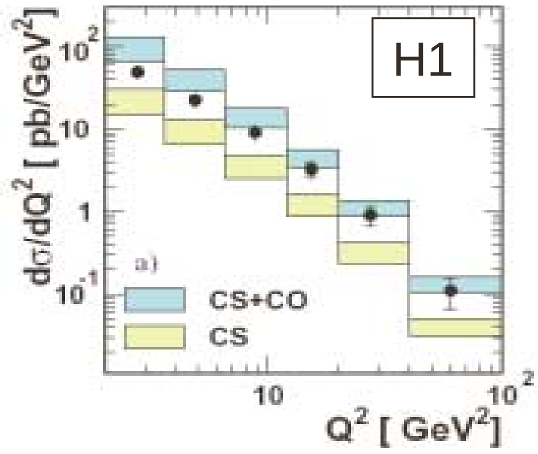
Photo- and Electro-production

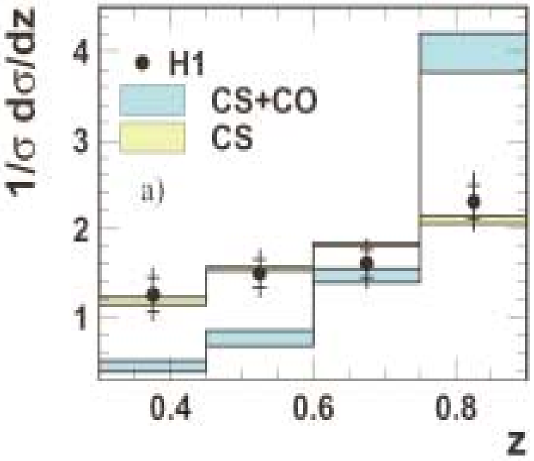
- Large range of kinematical regimes and differential cross sections to inspect at HERA



Large number of contributed papers by H1 and ZEUS!







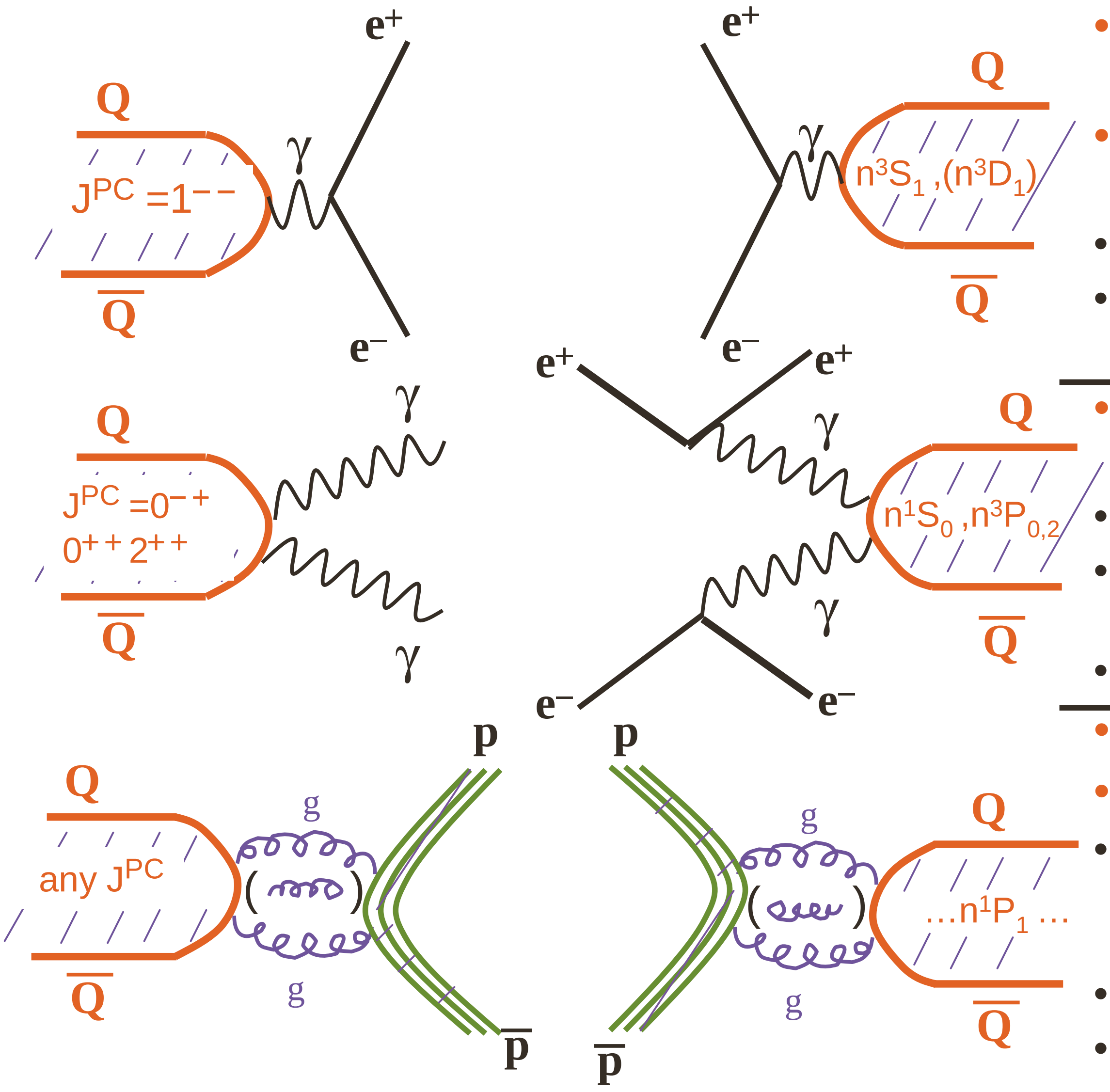
- Difficult to reconcile all data with consistent theoretical approach (charm not heavy enough ?)

For a more complete review see e.g. Arnd Meyer at QWG Workshop CERN Nov.02

http://alephwww.physik.uni-siegen.de/~quarkonium/WS-nov02/WStalks/meyer.pdf

Clean production environments

Most of what we know about quarkonia states and their decays comes from experiments at clean production environments, which are reversals of simple decay modes



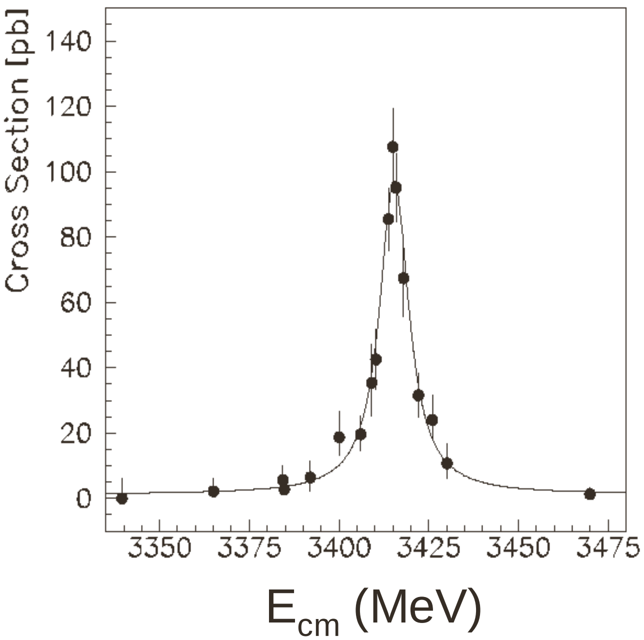
- Large production rates
  - Can study even small BR
- Small backgrounds - inclusive and exclusive decay modes
- Works only for vector states.
- Dedicated runs needed (one state at a time).

- Get them for free at e^+e^- machines
- Production rates are small
- Backgrounds - exclusive decay modes with large BR only
- So far only charmonium states

- All states can be formed
- Rates can be high
- Large backgrounds can be defeated by constrained kinematics –exclusive decays only.
- Works for charmonium states only
- Dedicated runs needed (one state at a time)

$\bar{p}p$ Annihilation Results

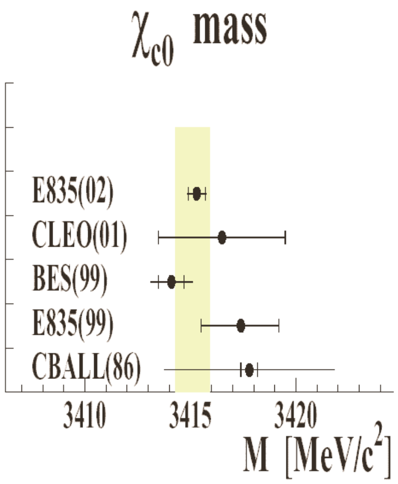
- E835 experiment at FNAL (1996-97, 2000)
  - non-magnetic detector (γ and e detector)
  - Extremely precise determinations of $\chi_c(1^3P_{2,1,0})$ masses and widths

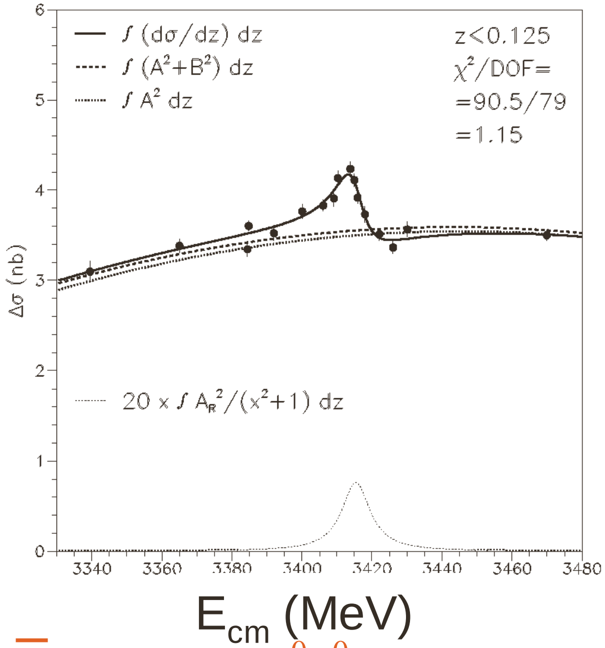


$\bar{p}p \to \chi_{c0} \to \gamma J/\psi, J/\psi \to e^+e^-$

PL B533, 237 (2002)

Example



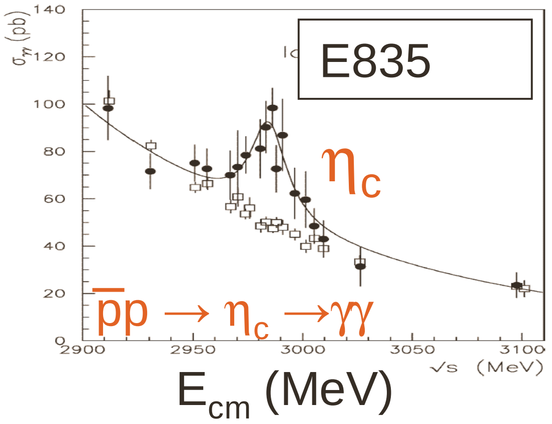


$\bar{p}p \to \chi_{c0} \to \pi^0\pi^0$
interfering with $\bar{p}p \to \pi^0\pi^0$

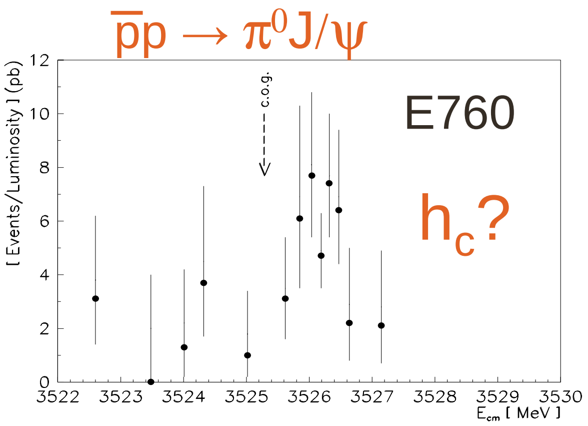
Submitted to PRL

They are also analyzing 1M $\psi(2S)$ decays

Singlet States at $\bar{p}p$ Annihilation



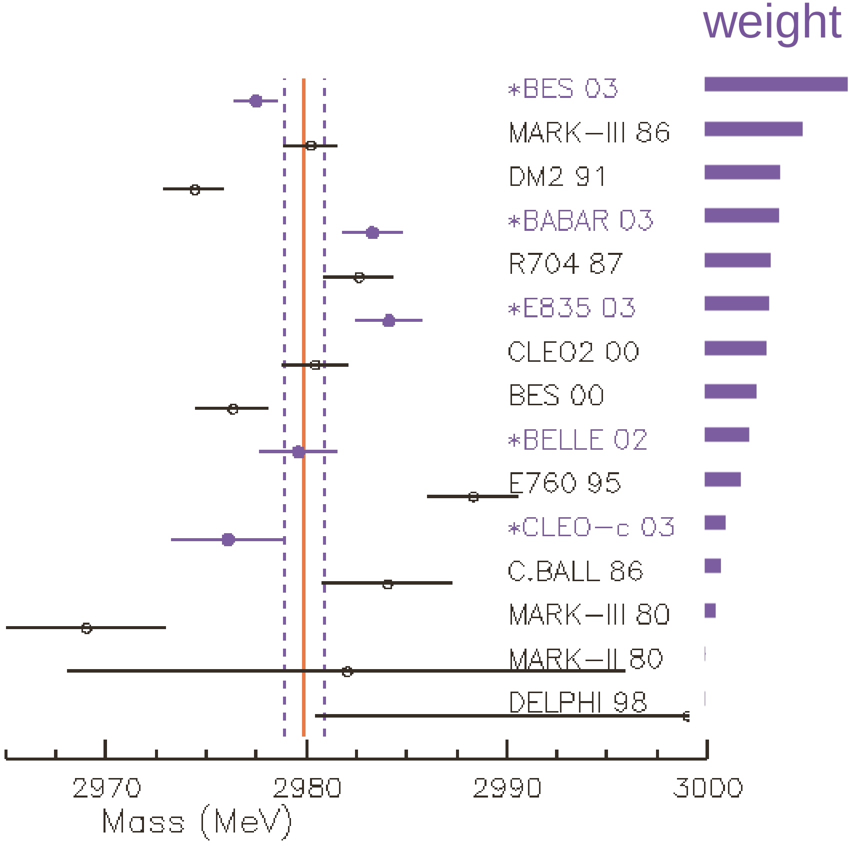
- Recent measurement of $\eta_c(1^1S_0)$ mass by E835 PL B566, 45 (2003)
- Non-observation of $\eta_c(2^1S_0)$ by E760 and E835 PRD62, 052002 (2000)
- Saga of $h_c(1^1P_1)$
  - Inconclusive evidence from R704 at ISR (1984)
  - Better evidence claimed by E760 (1989-91) in $\bar{p}p \rightarrow h_c \rightarrow \pi^0 J/\psi$, $J/\psi \rightarrow e^+e^-$. Mass close to the center-of-gravity of the triplet P-states (as expected if there are no long range spin-spin interactions)
  - More statistics taken by E835 (also a better detector):
    - Rumors of "disappearance" recently in print CERN Cour.43N3:17-18,2003 and other preprints (non-E835 authors)
    - Official statement from the collaboration:
      - Looking at all available channels
      - Not ready to report any results yet



Mass of η_c(1S)

- Five new measurements

2979.9±1.0 MeV

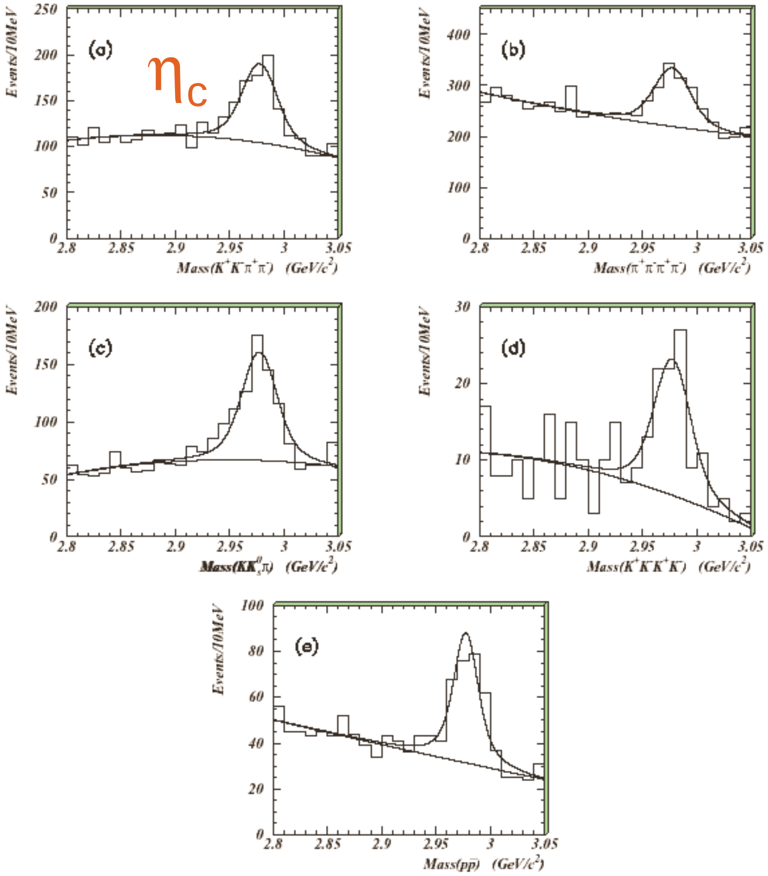


CL=0.5% scale factor=1.5

Consistency problem

BES-II 58M J/ψ

Phys.Lett. B555, 174 (2003)

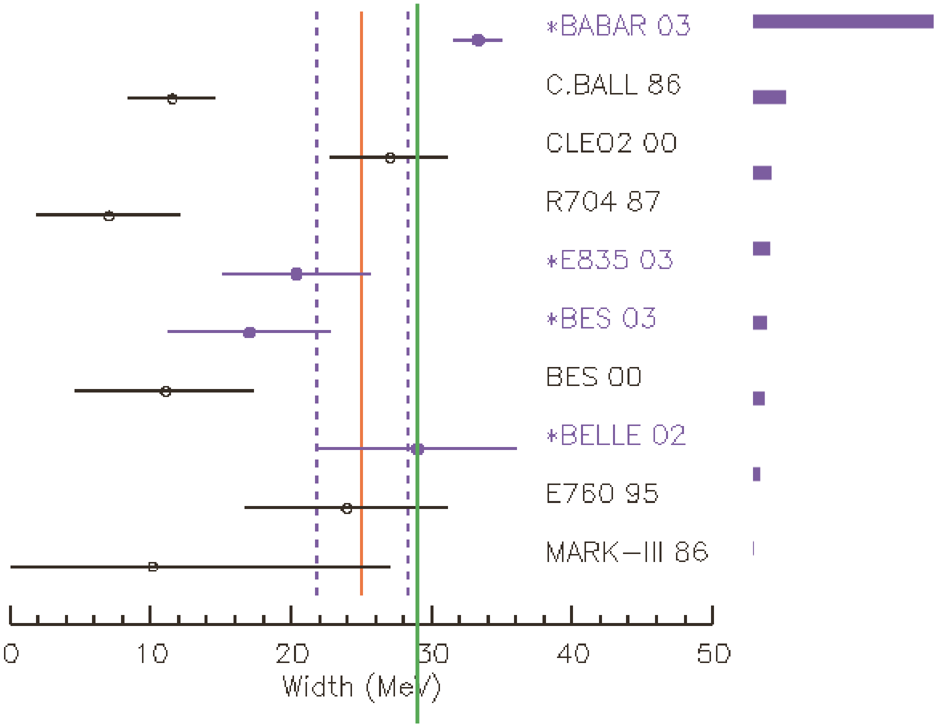


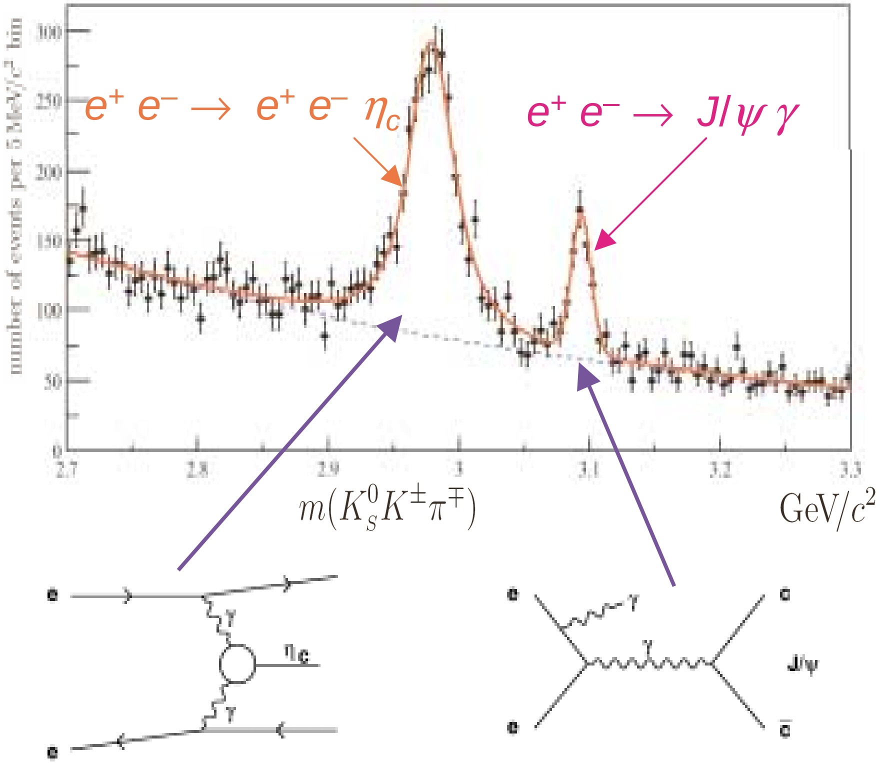
Width of $\eta_c(1S)$

- Four new measurements

25.0±3.3 MeV PDG: 16.1±3.1 MeV

BaBar 88 fb^{-1} *Preliminary*





CL=0.05% scale factor=1.8

Serious consistency problem!

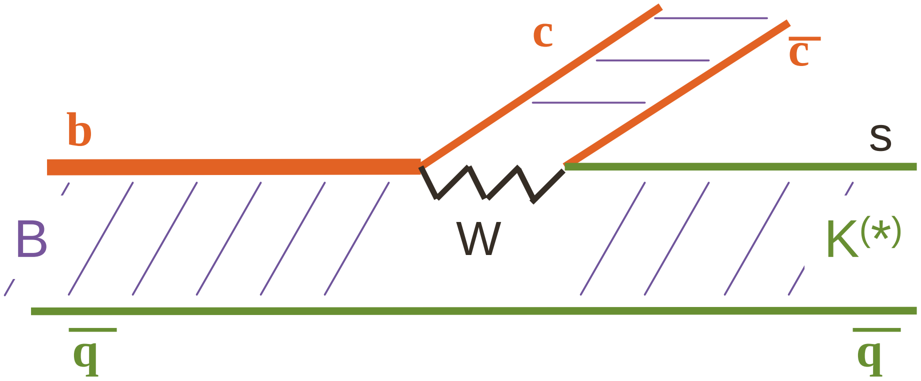
$$\Gamma_{tot}(\eta_c) = (33.3 \pm 2.5 \pm 0.8)\ \mathrm{MeV}$$

29.1±2.5 MeV *CL=15%*

Excluding R704 and C.BALL

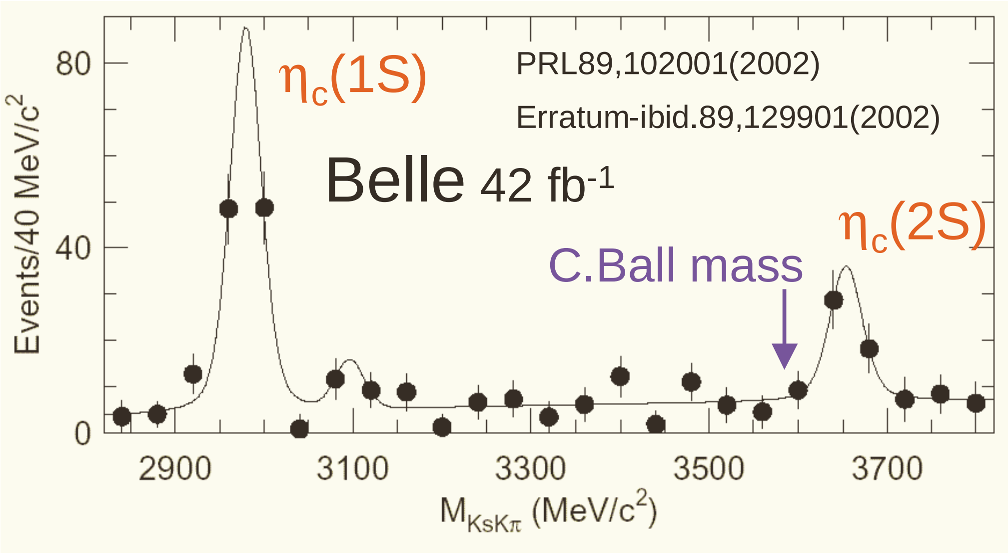
Rediscovery of $\eta_c(2^1S_0)$

- B-meson gateway to charmonium states



- All states can be formed
- Backgrounds can be suppressed by B meson mass constraint. Additional constraint at e^+e^- : $E_B=E_{beam}$.
- Get them for free when doing B physics
- Rates can be very low
- Exclusive final states

$B\rightarrow K(K_sK^+\pi^-)$



3654 ± 6 ± 8 MeV

Double charm production at Belle

$e^+e^- \to J/\psi\eta_c$:

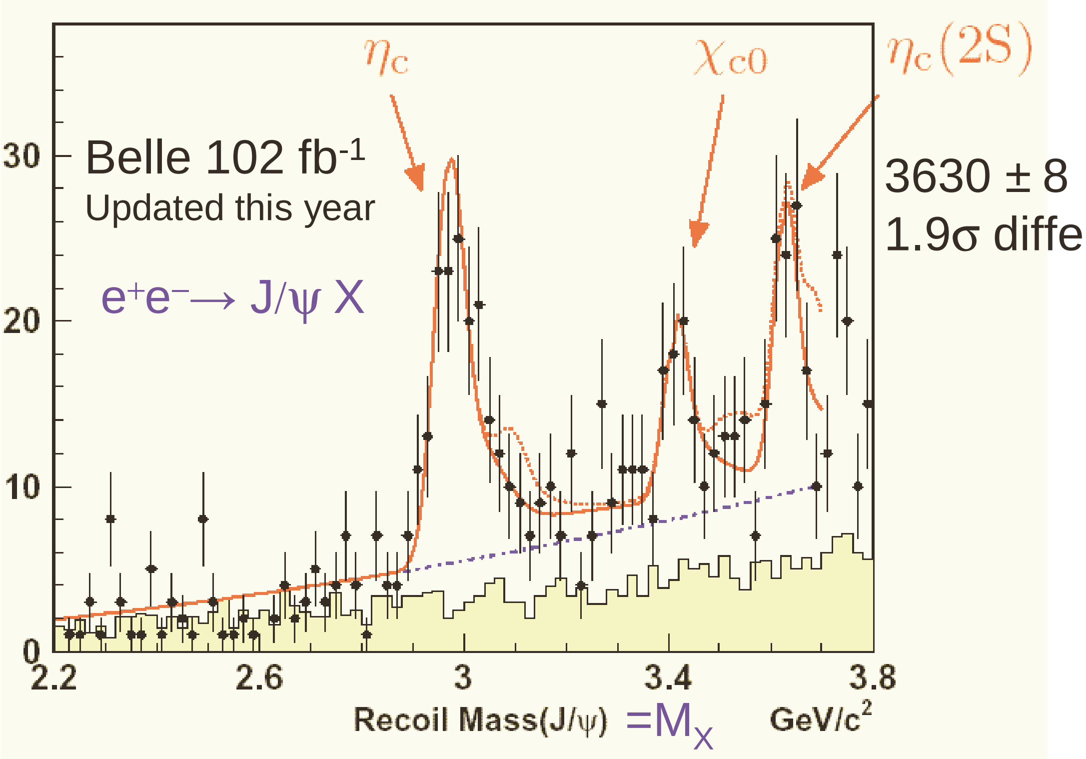
$$\boxed{\sigma(e^+e^- \to J/\psi\,\eta_c)\times\mathcal{B}(\eta_c \to> 2\ \text{charged}) = (0.033^{+0.007}_{-0.006} \pm 0.009)\text{pb}}$$

$e^+e^-\to J/\psi D^0 X$
$e^+e^-\to J/\psi D^{*+} X$:

$$\boxed{\sigma(e^+e^- \to J/\psi\, c\bar{c})/\sigma(e^+e^- \to J/\psi\, X) = 0.59^{+0.15}_{-0.13} \pm 0.12}$$

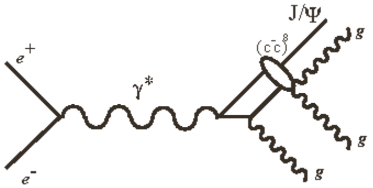
2002 results

~10 times larger than expected

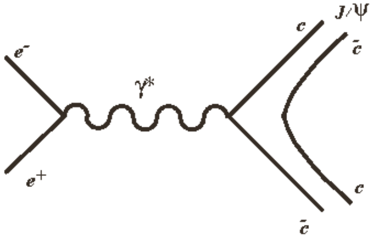


3630 ± 8 MeV
1.9σ different

~ 1 pb



~ 0.06 pb



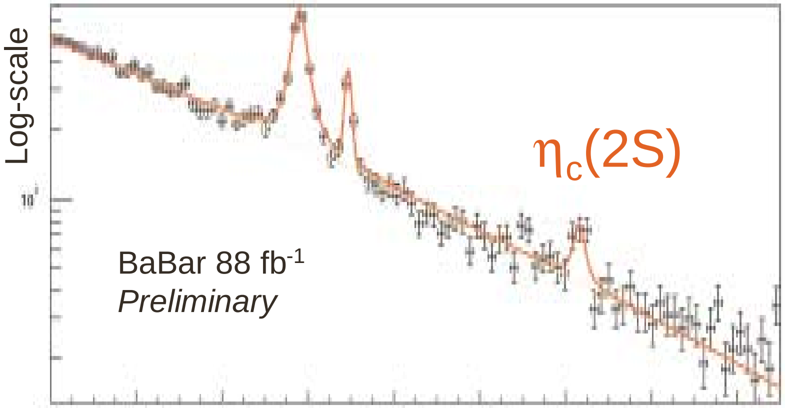
~ 0.06 pb

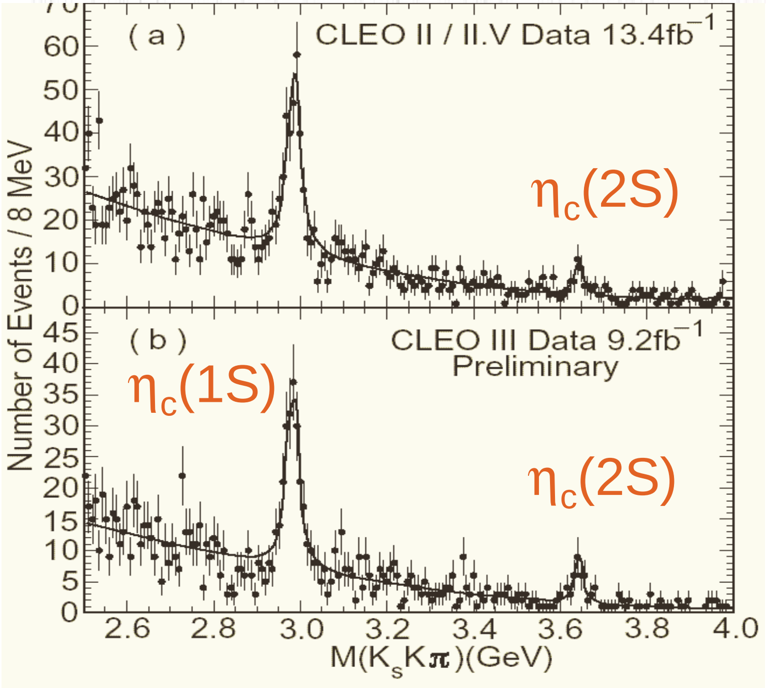
$$\boxed{\left.\frac{\sigma(e^+e^-\to J/\psi\, c\bar{c})}{\sigma(e^+e^-\to J/\psi\, X)}\right|_{P_{J/\psi}>2.0\,\text{GeV}/c} = \frac{0.5(N_{D^0}+N_{D^+}+N_{D_s^+}+N_{\Lambda_c})+N_{(c\bar{c})res}}{N_{J/\psi}} = 0.82 \pm 0.15 \pm 0.14}$$

Preliminary

- Much debated theoretical puzzle!

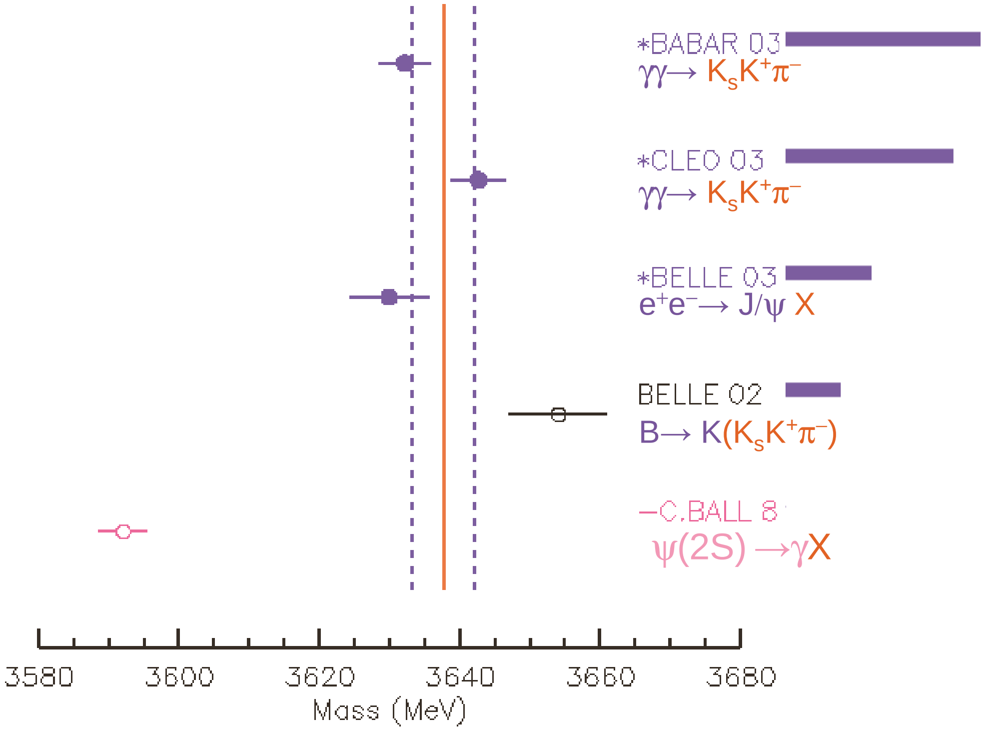
Confirmation of $\eta_c(2^1S_0)$ in $\gamma\gamma$-collisions





$$\frac{\Gamma_{\gamma\gamma}(\eta_c') \times B(\eta_c' \to K_S K\pi)}{\Gamma_{\gamma\gamma}(\eta_c) \times B(\eta_c \to K_S K\pi)} = 0.17^{+0.07}_{-0.06}(stat) \ \pm 0.04(syst)$$

3637.7±4.4 MeV



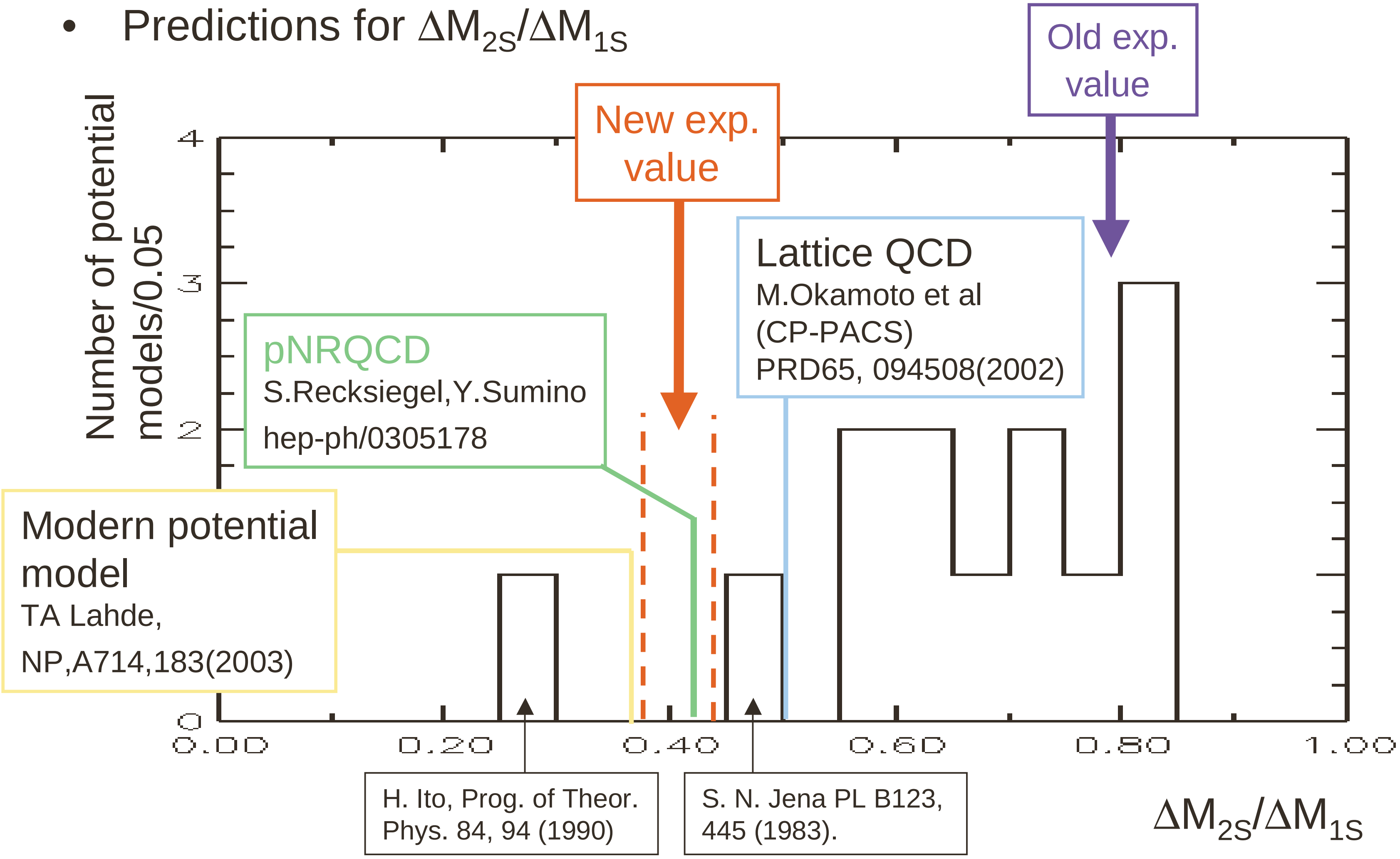
CL=14% scale factor=1.3

New measurements of mass are consistent

$\Gamma_{tot}(\eta_c(2S))$ = (19±10) MeV

Predictions for hyperfine splitting ratio

- For 20 years theorists were exposed to the experimental value of ΔM_{2S}=M(ψ(2S))-M(η_c(2S)) which was wrong by a factor of 2
- Predictions for $\Delta M_{2S}/\Delta M_{1S}$



Old exp. value

New exp. value

Lattice QCD
M.Okamoto et al
(CP-PACS)
PRD65, 094508(2002)

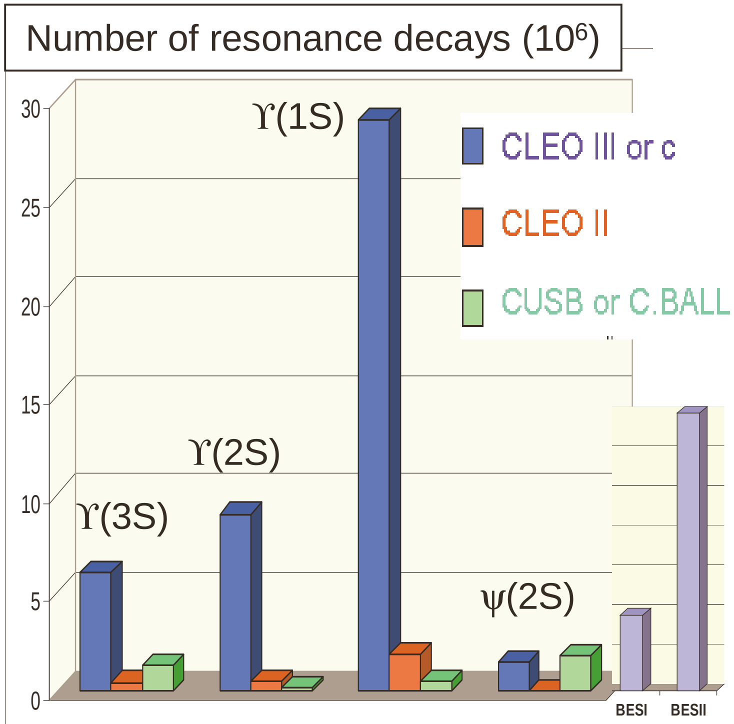
pNRQCD
S.Recksiegel,Y.Sumino
hep-ph/0305178

Modern potential model
TA Lahde,
NP,A714,183(2003)

H. Ito, Prog. of Theor. Phys. 84, 94 (1990)

S. N. Jena PL B123, 445 (1983).

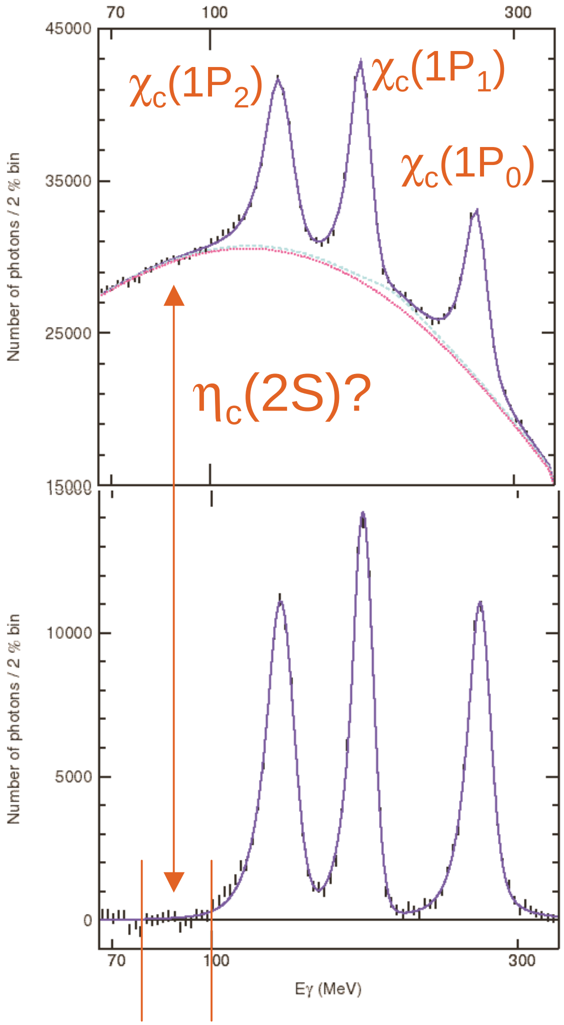
First CLEO-c Results



Number of resonance decays (10^6)

Detector	Calorimeter crystals	$\sigma_{E\gamma}$ resolution at Eγ=100 MeV
CLEO-III or c	CsI(Tl)	4.5 MeV
CUSB-II	BGO	4.2 MeV
Crystal Ball	NaI(Tl)	4.8 MeV
BES-II	Not crystalic	70 MeV

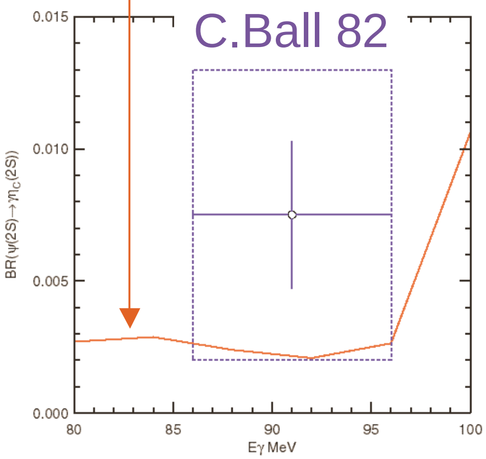
CLEO-c is the first experiment since the Crystal Ball which is able to look at **inclusive** photons from ψ(2S)



Preliminary

2.7 pb^{-1}
1.5M ψ(2S)

CLEO-c 2003
90% CL U.L. limit on
$BR(\psi(2S) \rightarrow \gamma\eta_c(2S))$



- C.Ball'82 signal directly ruled out

E1 and M1 transitions from $\psi(2S)$

Preliminary

BR($\psi(2S) \to \gamma\, \chi_c(1P_J)$) in %

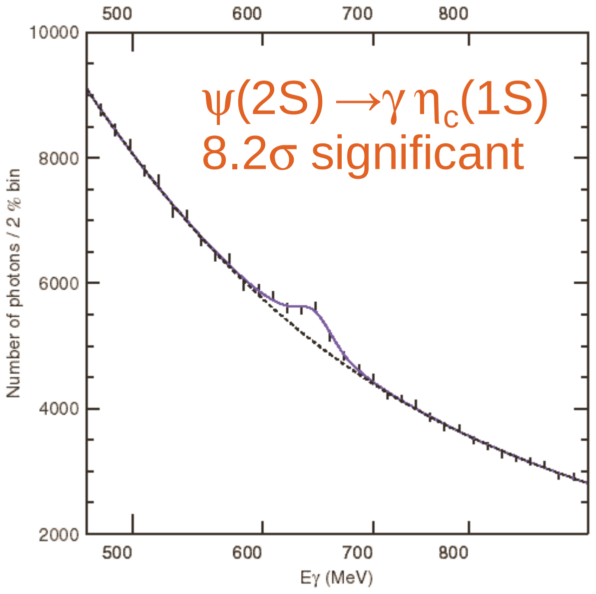
BR($\psi(2S) \to \gamma\, \eta_c(1S)$) in %

	E1 lines			Hindered M1 line
	$J = 2$	$J = 1$	$J = 0$	$J = 0$
CLEO	$9.75 \pm 0.14 \pm 1.17$	$9.64 \pm 0.11 \pm 0.69$	$9.83 \pm 0.13 \pm 0.87$	$0.278 \pm 0.033 \pm 0.049$
C.Ball	$8.0 \pm 0.5 \pm 0.7$	$9.0 \pm 0.5 \pm 0.7$	$9.9 \pm 0.5 \pm 0.8$	0.28 ± 0.06
PDG	7.8 ± 0.8	8.7 ± 0.8	9.3 ± 0.8	0.28 ± 0.06
ratio	1.25 ± 0.20	1.11 ± 0.13	1.06 ± 0.13	0.99 ± 0.30

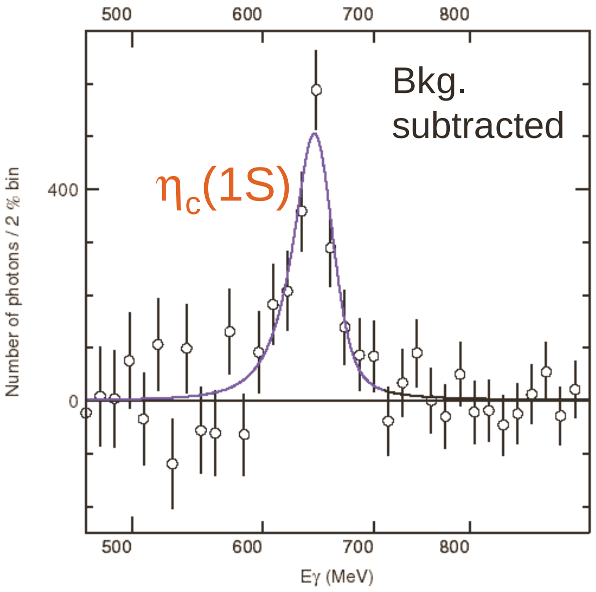
Eγ in MeV

	E1 lines			Hindered M1 line
	$J = 2$	$J = 1$	$J = 0$	$J = 0$
CLEO	$128.00 \pm 0.08 \pm 0.09 \pm 0.64$	$172.05 \pm 0.08 \pm 0.16 \pm 0.86$	$261.99 \pm 0.14 \pm 0.27 \pm 1.31$	$641.5 \pm 2.4 \pm 3.3$
PDG	127.50 ± 0.01	171.27 ± 0.01	260.72 ± 0.03	639.00 ± 0.28
ratio	$1.0039 \pm 0.0009 \pm 0.0050$	$1.0046 \pm 0.0010 \pm 0.0050$	$1.0049 \pm 0.0011 \pm 0.0050$	1.0039 ± 0.064

- Good agreement on branching ratios
- Hindered M1 transition confirmed!
- E1 photons will fix absolute energy scale for $\chi_b(1P_J,2P_J)$ mass measurements



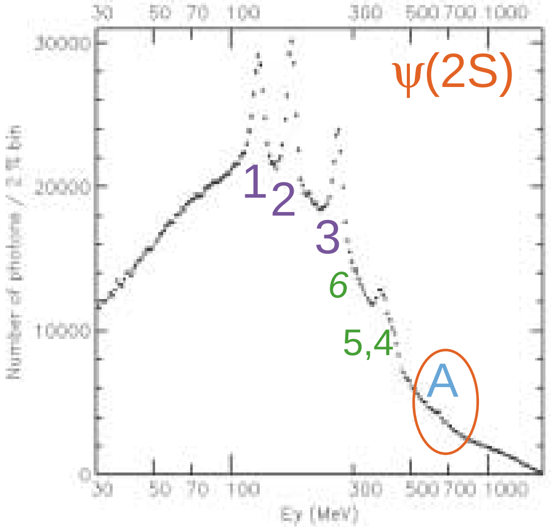
$\psi(2S) \to \gamma\, \eta_c(1S)$
8.2σ significant

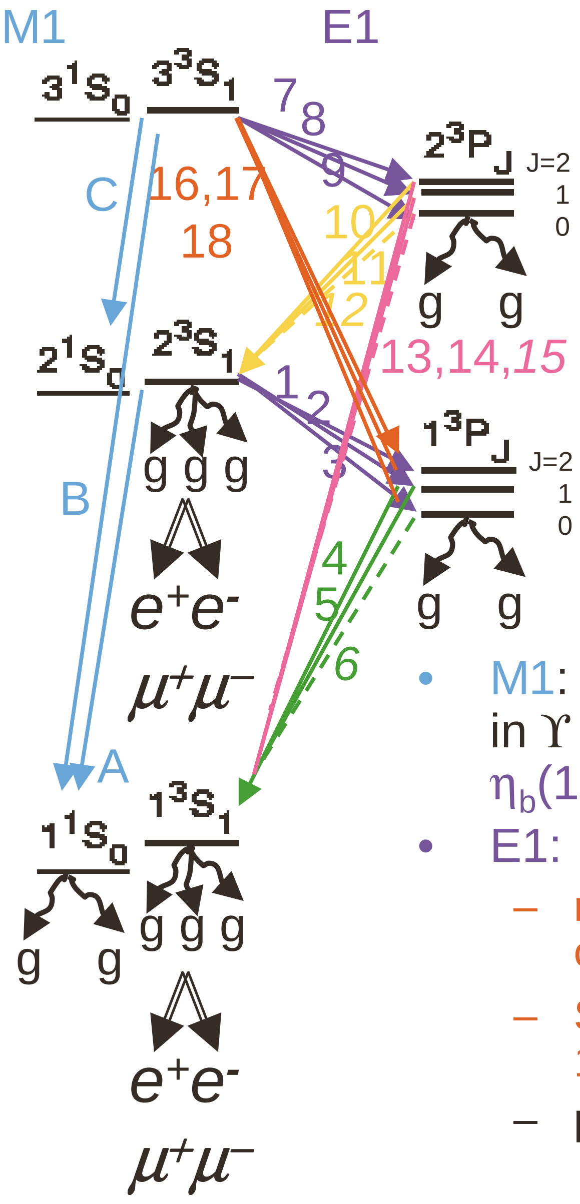


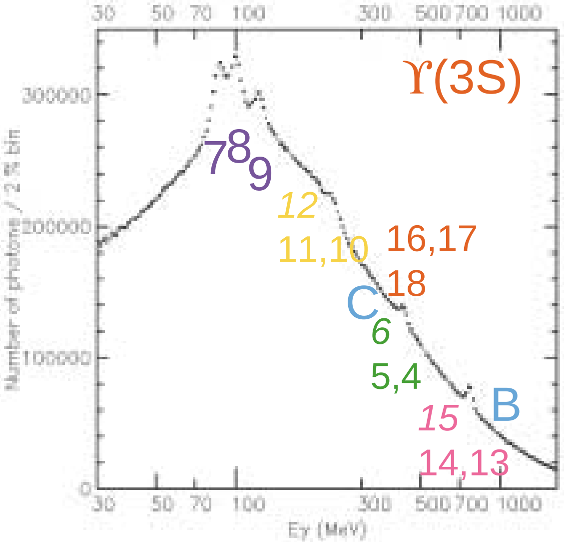
$\eta_c(1S)$

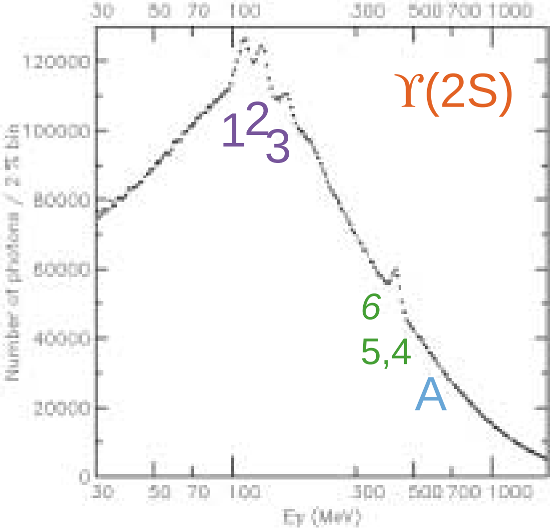
Bkg. subtracted

Photon Spectroscopy in CLEO







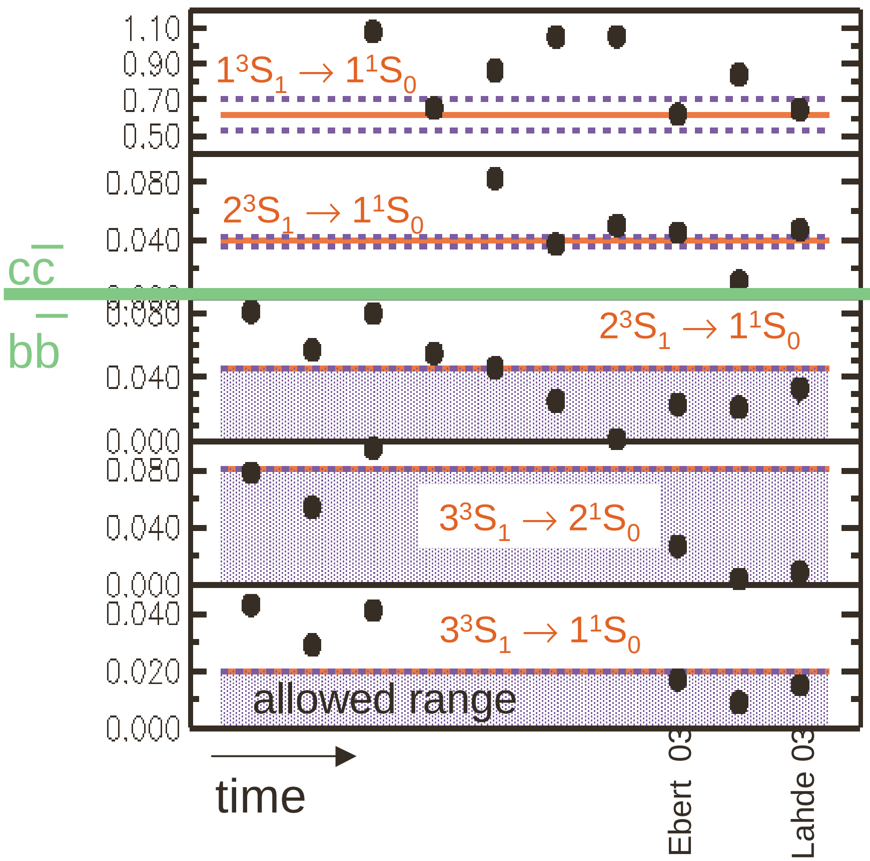


- M1: no hindered transitions detected in Υ decays (no observations of $\eta_b(1S,2S)$)
- E1:
  - rare $\Upsilon(3^3S_1) \rightarrow \gamma\, \chi_b(1^3P_J)$ transitions observed with good statistics
  - Suppressed $\chi_b(2,1^3P_0) \rightarrow \gamma\, \Upsilon\,(2^3S_1, 1^3S_1)$ also observed
  - precision measurements in progress

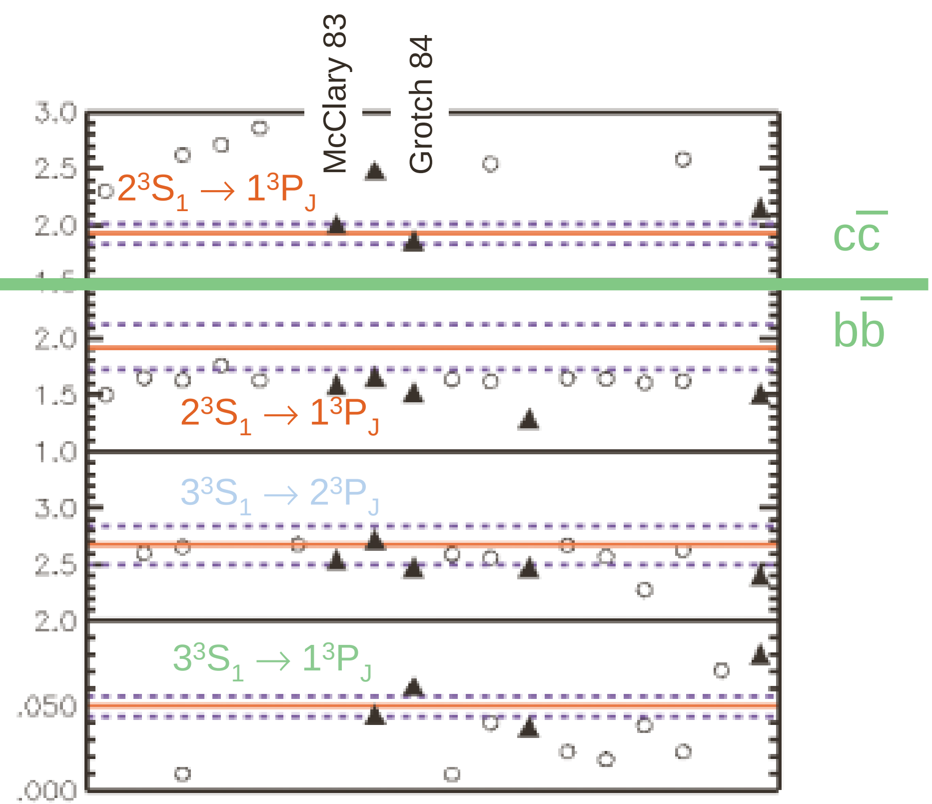
$$E\gamma \longrightarrow M(n^3P_J)$$
$$BR\gamma * \Gamma_{tot} \longrightarrow \Gamma_{E1}$$

E1,M1 rates vs predictions

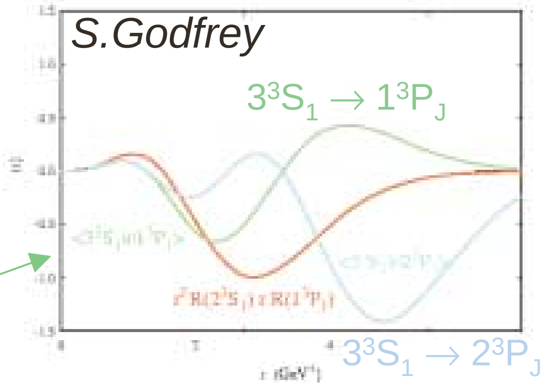
M1 matrix elements



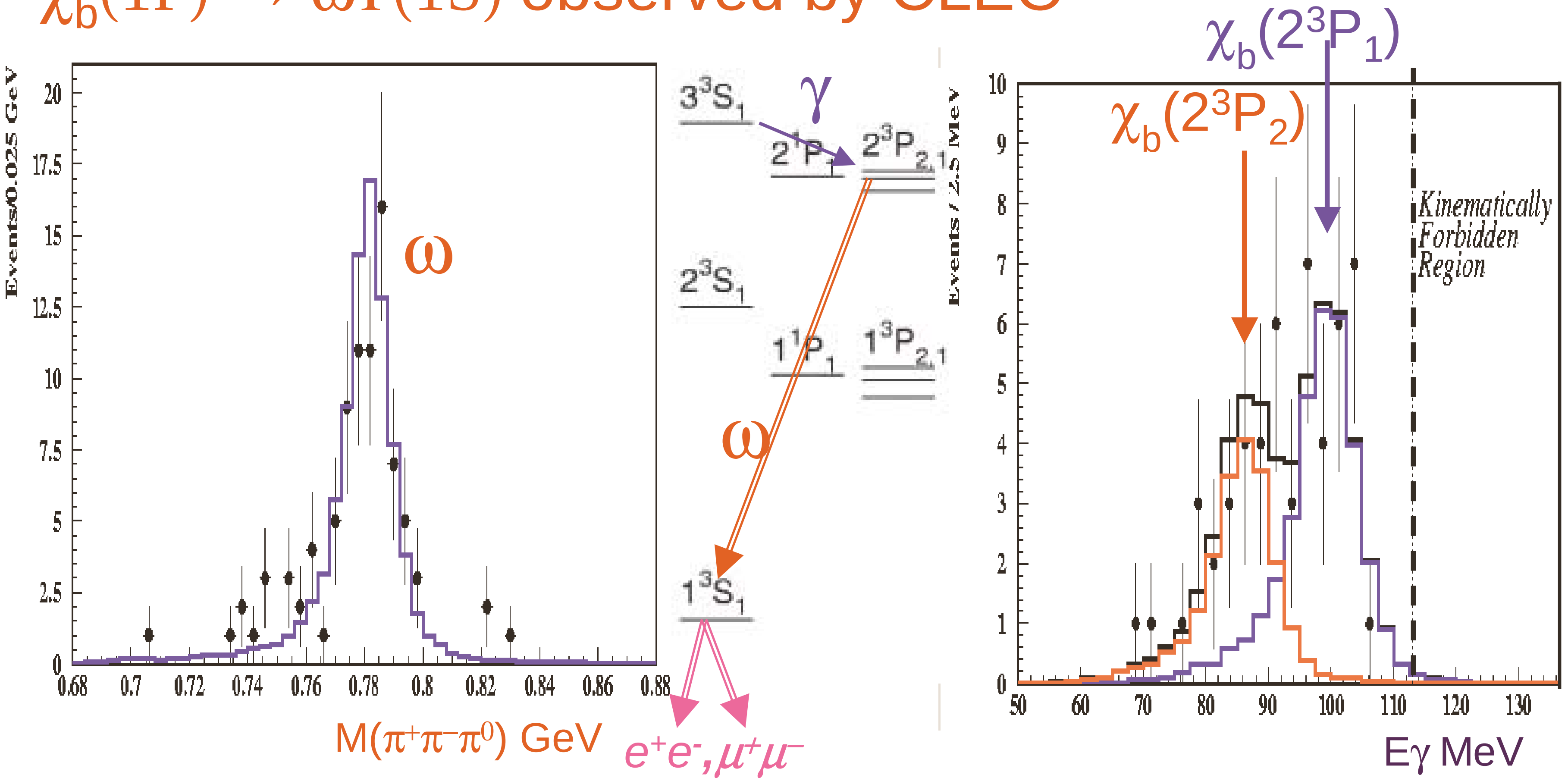
E1 matrix elements (GeV^{-1})



- Only recent calculations of M1 rates consistent with all the data
- Relativistic corrections needed (triangles) to describe E1 rates in charmonium. Corrections small in bottomonium.
- Small matrix element $3^3S_1 \rightarrow 1^3P_J$ difficult to predict (cancellations)



$\chi_b(1P) \rightarrow \omega\Upsilon(1S)$ observed by CLEO



$BR(\chi_b(1P_2) \rightarrow \omega\Upsilon(1S)) = (1.1\pm0.3\pm0.1)\%$ $BR(\chi_b(1P_1) \rightarrow \omega\Upsilon(1S)) = (1.6\pm0.3\pm0.2)\%$

- First observed hadronic transistion in heavy quarkonia, which is not between triplet-S states. First new transition in about 20 years.
- E1*E1*E1 type. No spin dependence (Voloshin) – consistent with the data
- No theoretical predictions for the rate of this transition

New state observed by Belle

- $B^\pm \to K^\pm(J/\psi\, \pi^+\pi^-)$

  ↳ e^+e^- *or* $\mu^+\mu^-$

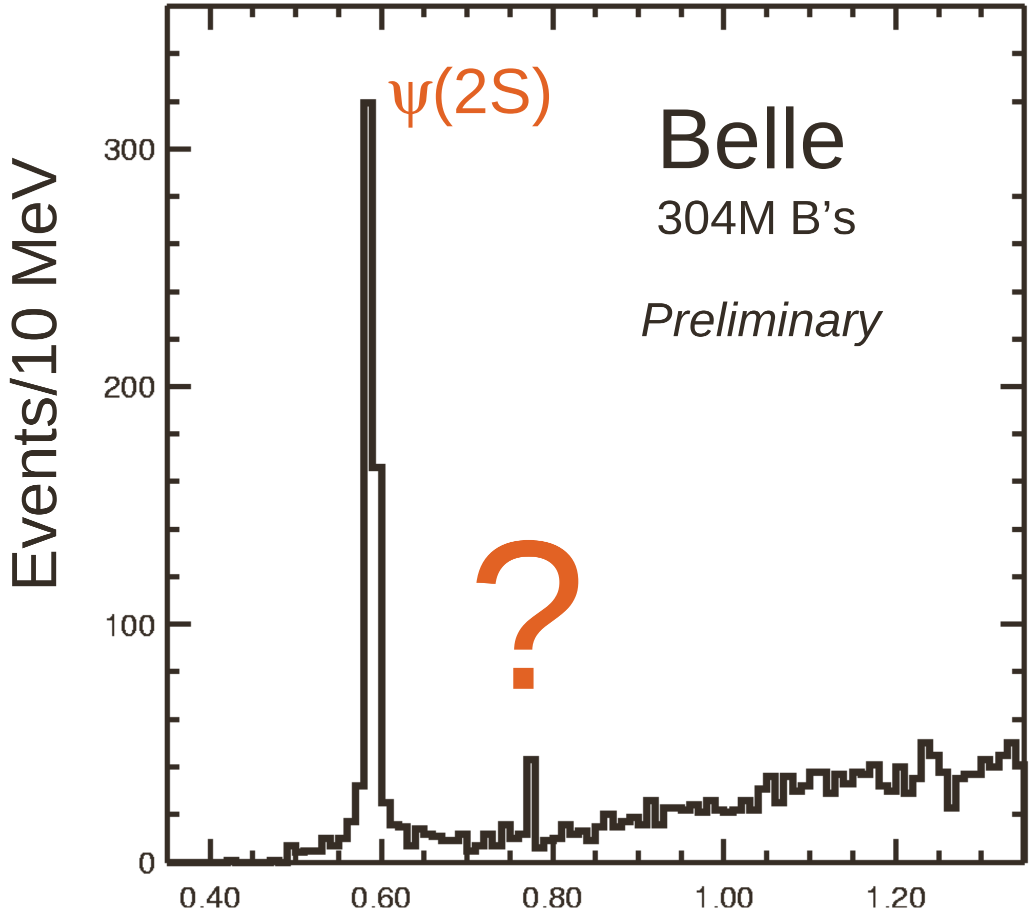
hadronic event
$R_2 < 0.4$
$|\cos\theta_B| < 0.8$

In CMS of the e^+e^- collision:

$$|E(K^\pm J/\psi\, \pi^+\pi^-) - E_{beam}| < 2.5\sigma$$

$$\Big|\underbrace{\sqrt{E_{beam}^2 - p(K^\pm J/\psi\, \pi^+\pi^-)^2}}_{M_{b.c.}} - M_B\Big| < 3\sigma$$

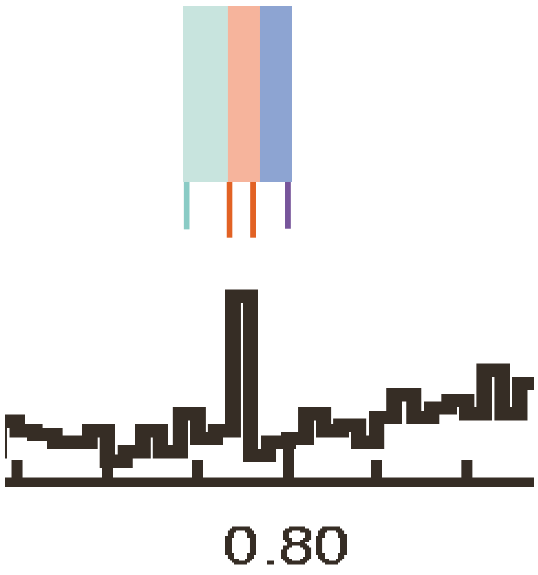
$$|M(\ell^+\ell^-) - M_{J/\psi}| < 20\text{ MeV}$$

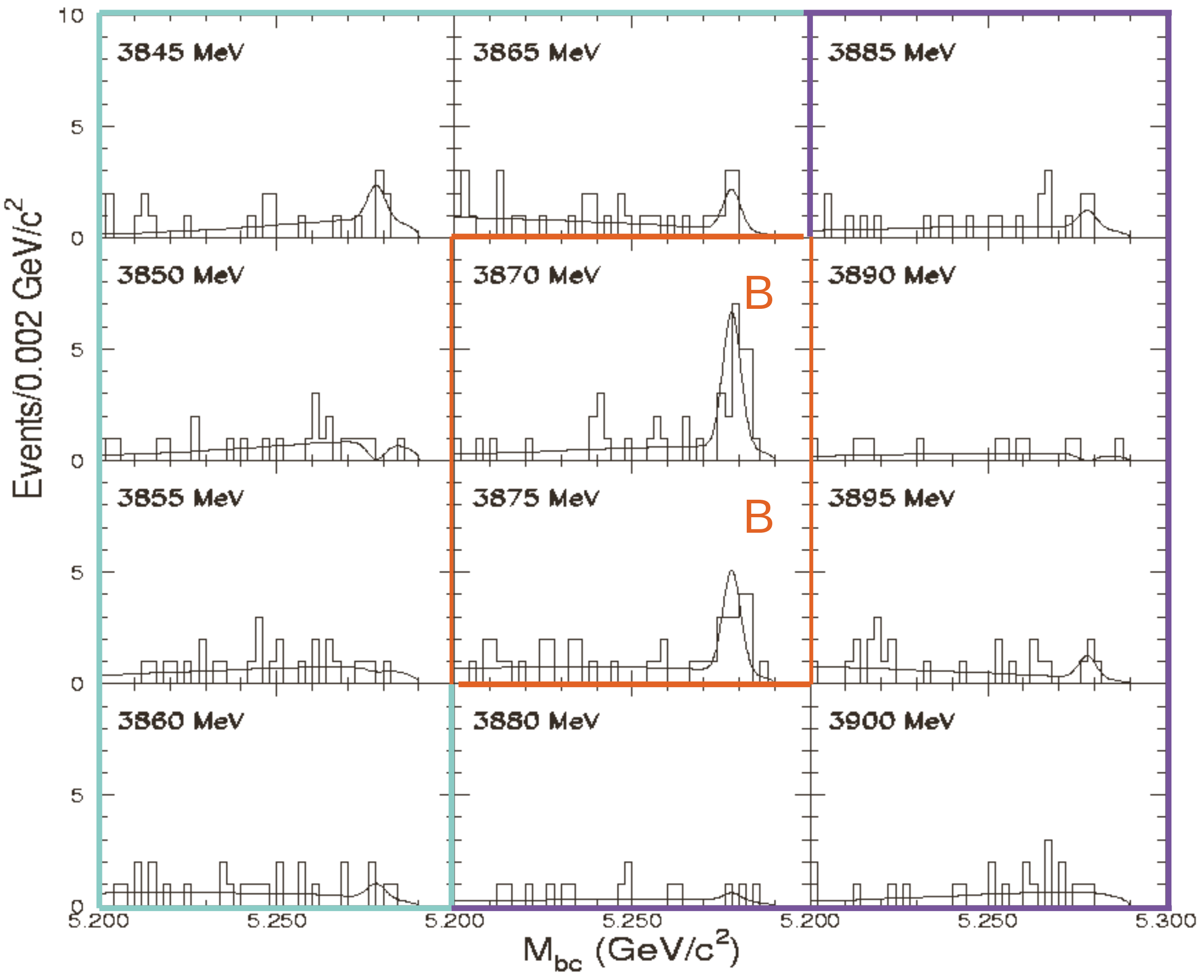


$\Delta M = M(J/\psi\, \pi^+\pi^-) - M(J/\psi)$ GeV

Signal is clearly from B decays

- Fit beam-constrained mass ($M_{b.c.}$) in bins of the mass of the produced system ($M_{J/\psi}+\Delta M$)

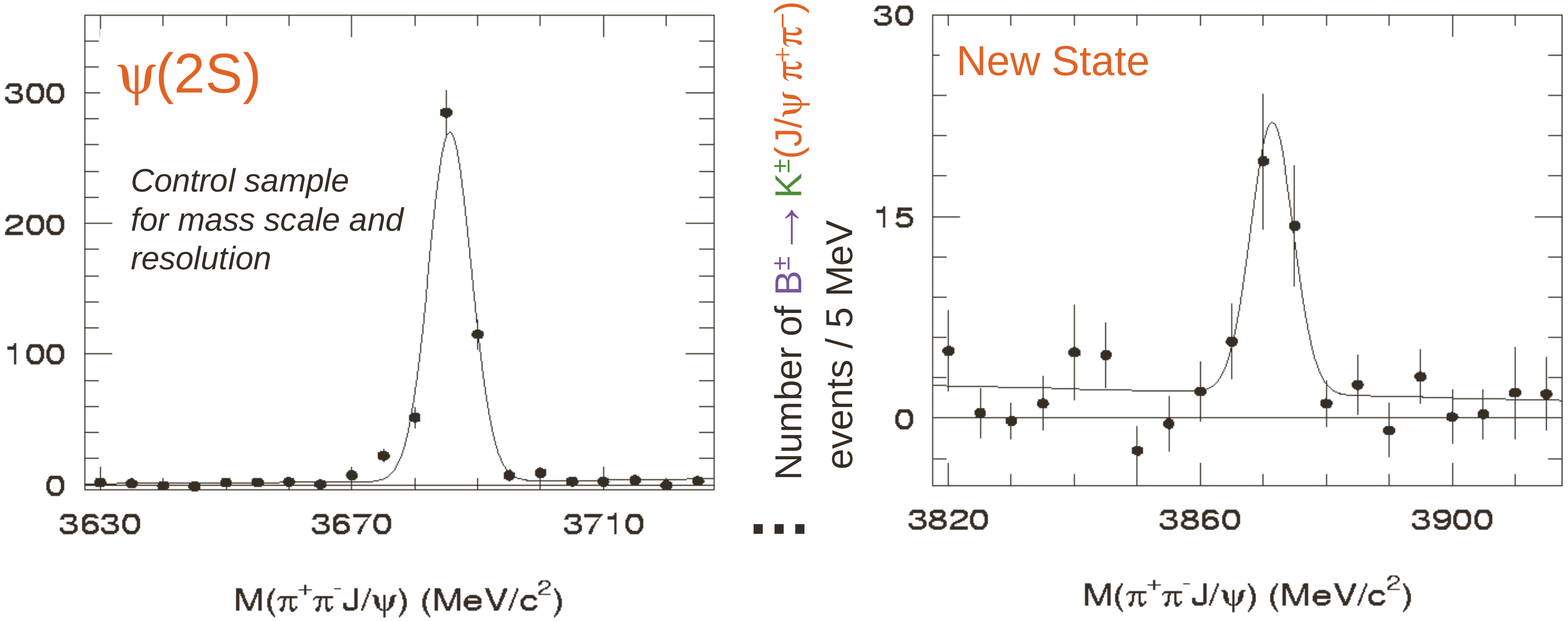




Belle

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

Properties of the state



Control sample for mass scale and resolution

- 34.4±6.5 events, statistical significance 8.6σ
- Mass: 3871.8±0.7±0.4 MeV
- Observed width consistent with the detector resolution.
- Natural width < 3.5 MeV at 90% C.L.

Belle

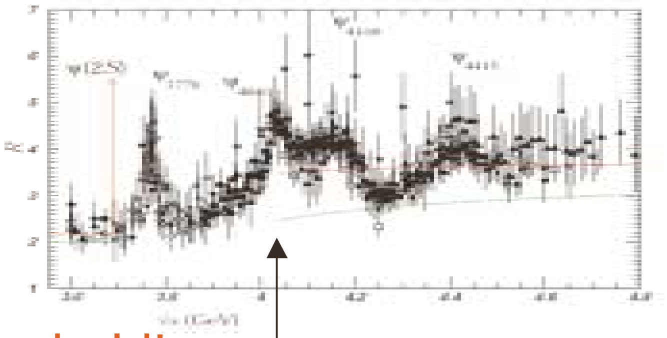
$B^{\pm} \to K^{\pm}(J/\psi\ \pi^{+}\pi^{-})$

Preliminary

$$\frac{\mathcal{B}(B^+ \to K^+ X) \times \mathcal{B}(X \to \pi^+\pi^- J/\psi)}{\mathcal{B}(B^+ \to K^+ \psi') \times \mathcal{B}(\psi' \to \pi^+\pi^- J/\psi)} = 0.075 \pm 0.014(\mathrm{stat}) \pm 0.007(\mathrm{syst}).$$

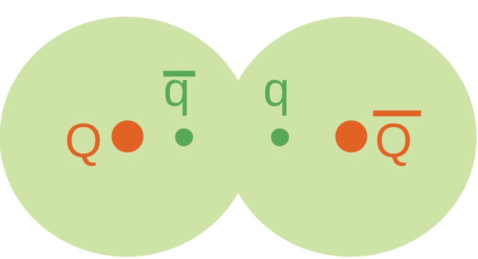
Possible interpretations

Quantity	MeV	$M_X - M_{threshold}$
M_X	3871.8±0.7±0.4	
$M_{D^0} + M_{D^{*0}}$	3871.5±0.7	+0.3±1.1
$M_{D^+} + M_{D^{*+}}$	3879.5±0.7	−7.7±1.1



- The mass of the state is right at the $D^0\bar{D}^{*0}$ threshold!
- This suggests a loosely bound $D^0\bar{D}^{*0}$ molecule, right below the dissociation energy
- "Molecular Charmonium" discussed in literature since 1975:
  - Triggered by complicated structure of $\sigma(e^+e^- \rightarrow \text{hadrons})$ observed at SPEAR
    - M. Bander, G.L. Shaw, P. Thomas, PRL 36, 695 (1976)
    - M.B. Voloshin, L.B. Okun JETP Lett. 23, (1976), Pisma Zh.Eksp.Teor.Fiz.23, 369 (1976)
    - A.De Rujula, H.Georgi, S.L.Glashow, PRL 38 (1977)
  - Interactions described by pion-exchange give attractive force for $D\bar{D}^*$, $B\bar{B}^*$
    - N.A. Tornqvist, PRL 67, 556 (1991), Z.Phys. C61, 525(1994)
    - A.V. Manohar, M.B. Wise,Nucl.Phys. B339, 17(1993)

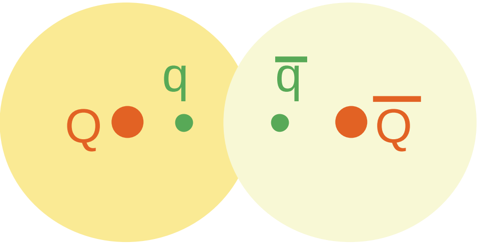
$D^0\bar{D}^{*0}$ molecule



Loose binding

Decays to $(Q\bar{Q})$+(light mesons) via quark rearrangement which suppresses the width.

A different idea from that time:



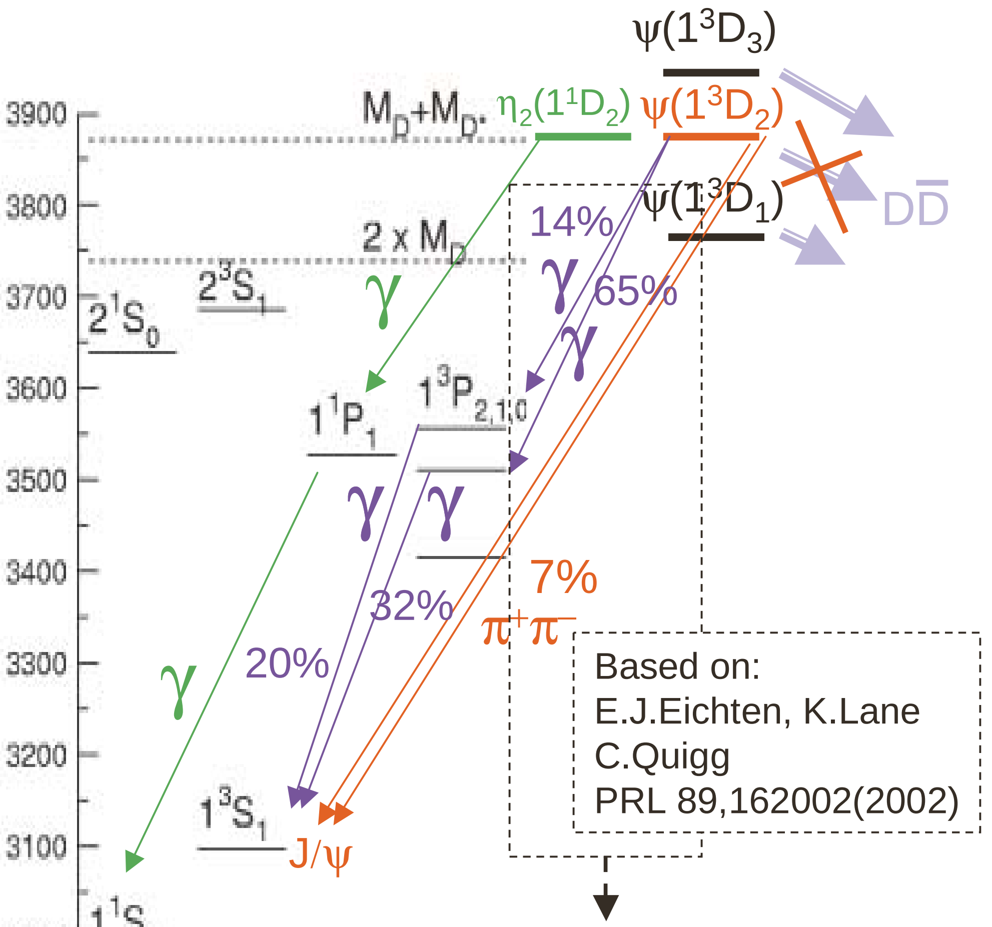
Stronger binding

Diquark Model *(Qq) are colored*

e.g.
C.Rosenzweig
PRL 36,697 (76)

Possible interpretations

- A $\psi(1^3D_2)$ state:
  - Because D-states have negative parity, spin-2 states cannot decay to $D\bar{D}$
  - They are narrow as long as below the $D\bar{D}^*$ threshold
  - $\eta_2(1^1D_2)$ preferentially decays to $h_c(1^1P_1)$. Decays to $\pi^+\pi^- J/\psi$ would be of magnetic type and are suppressed.
  - Some models predict large widths for $\psi(1^3D_2) \longrightarrow \pi^+\pi^- J/\psi$
  - All models predict even larger widths for $\psi(1^3D_2) \longrightarrow \gamma\,\chi_c\,(1^3P_{2,1})$ Should easily see $\psi(1^3D_2) \longrightarrow \gamma\gamma\, J/\psi$.
    - Discovery of the signal is very recent. Belle is working on this channel but is not ready to present any results.

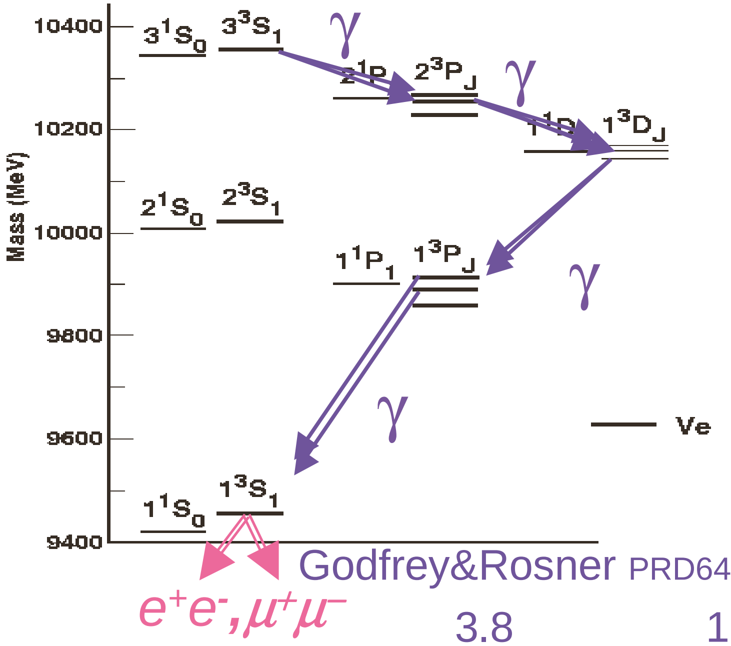


Based on:
E.J.Eichten, K.Lane
C.Quigg
PRL 89,162002(2002)

$$\frac{BR(\psi(1^3D_2)\to\gamma\gamma J/\psi)}{BR(\psi(1^3D_2)\to\pi^+\pi^- J/\psi)}\sim 3$$

CLEO has observed $\Upsilon(1^3D_2)$

- Preliminary results presented at ICHEP'02
- Update: more data and better background suppression



Godfrey&Rosner PRD64,097501(2001)

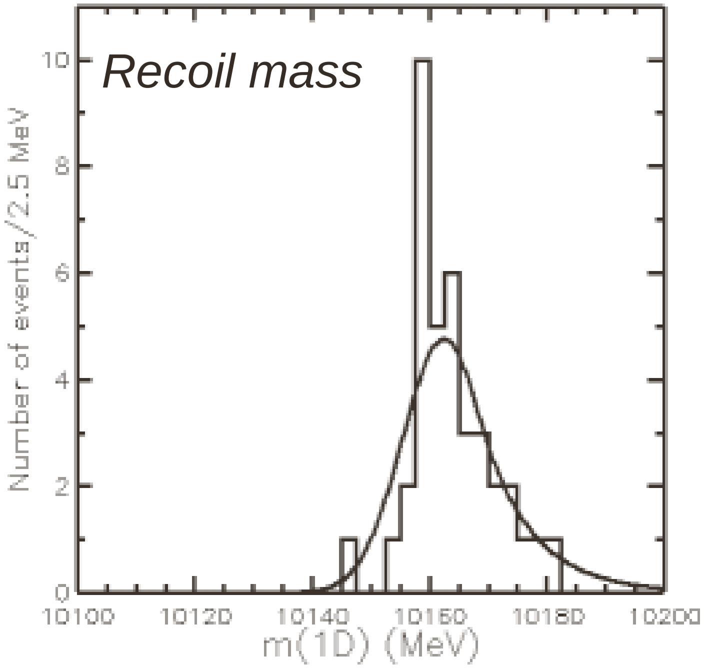
3.8 10^{-5}

$B(\Upsilon(3S) \to \gamma\gamma\Upsilon(1D) \to \gamma\gamma\gamma\ \Upsilon(1S) \to \gamma\gamma\gamma\ell^+\ell^-)$

$=(2.6\pm0.5\pm0.5)\ 10^{-5}$

$BR(\Upsilon(3S) \to \gamma\gamma\Upsilon(1D_J)) \times BR(\Upsilon(1D_J) \to \eta\Upsilon(1S)) < 2.3\ 10^{-4}$

$$\frac{BR(\Upsilon(1D_2) \to \eta\ \ \Upsilon(1S))}{BR(\Upsilon(1D_2) \to \gamma\gamma\ \Upsilon(1S))} < 0.25\ (90\%\ C.L.)$$



$M(\Upsilon(1^3D_2))= 10161.1\pm0.6\pm1.6$ MeV

Scaling to $c\bar{c}$ using M(2S)-M(1S):

$M(\psi(1^3D_2))\sim3831$ MeV

Scaling to $c\bar{c}$ using M(1P)-M(1S):

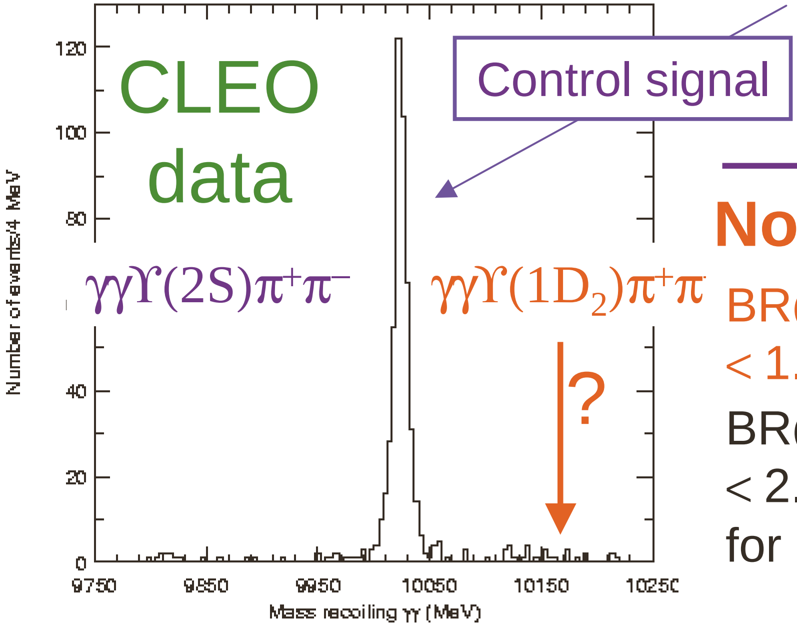
$M(\psi(1^3D_2))\sim3780$ MeV

vs

$M_X = 3872$ MeV

Search for $\Upsilon(1^3D_2) \to \pi^+\pi^-\Upsilon(1S)$

$\Upsilon(3S) \to \gamma\gamma\,\pi^+\pi^-\,\Upsilon(1S)$,
$\Upsilon(1S) \to \ell^+\ell^-$



$BR(\Upsilon(3S) \to \gamma\gamma\Upsilon(2S))$ x $BR(\Upsilon(2S) \to \pi^+\pi^-\Upsilon(1S))$
$=(0.95 \pm 0.05)10^{-2}$ (statistical error only)

Ratio to PDG based value: 1.20±0.18

No signal is observed. At 90% C.L.:

$BR(\Upsilon(3S) \to \gamma\gamma\Upsilon(1D_2))$ x $BR(\Upsilon(1D_2) \to \pi^+\pi^-\Upsilon(1S))$
$< 1.1\ 10^{-4}$

$BR(\Upsilon(3S) \to \gamma\gamma\Upsilon(1D_J))$ x $BR(\Upsilon(1D_J) \to \pi^+\pi^-\Upsilon(1S))$
$< 2.7\ 10^{-4}$
for $M(1D_J)$ in 10140-10180

$$\frac{BR(\Upsilon(1D_2) \to \pi^+\pi^-\Upsilon(1S))}{BR(\Upsilon(1D_2) \to \gamma\gamma\quad\Upsilon(1S))} <1.2\ (90\%\ C.L.)$$

			Voloshin et al approach	
	CLEO 90% CL	Kuang-Yan	Moxhay	Ko
$\Upsilon(1D_2)$	<1.1	9.2	0.049	0.39
$\Upsilon(1D_J)$	<2.7	17.7	0.094	0.75

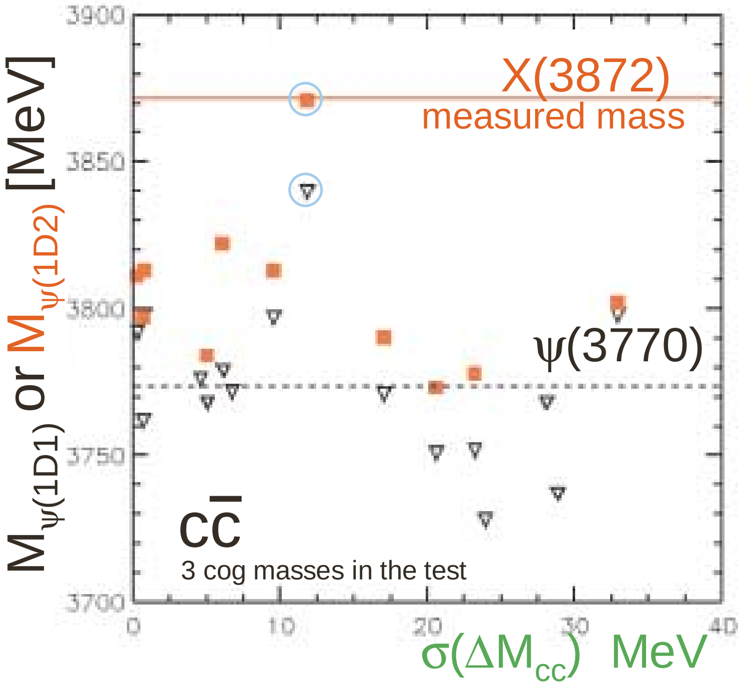
With Rosner's production rates

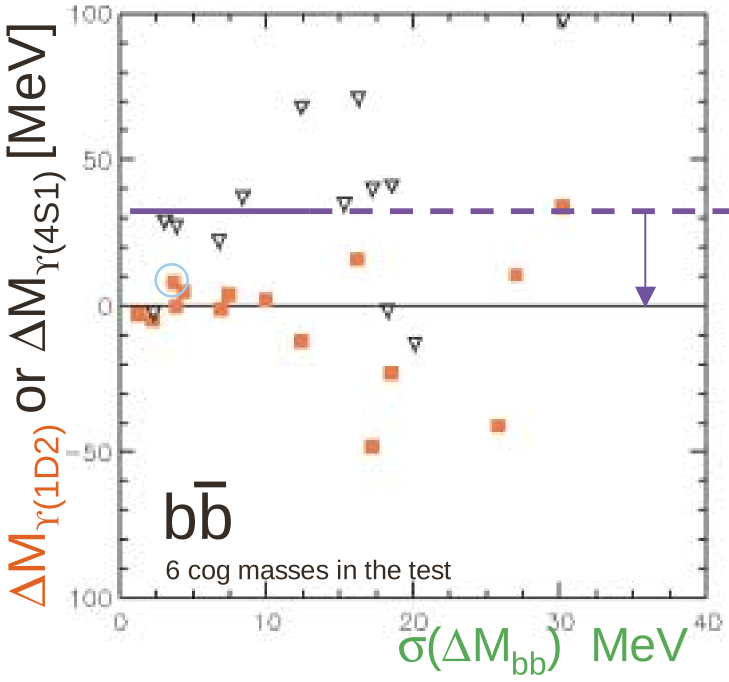
The $\Upsilon(1D_2)$ results confirm that photon transitions are the dominant decays of D-state heavy quarkonia below the open flavor threshold

Potential Models Mass Predictions

What do potential models say about mass of ψ(1^3D_2), ϒ(1^3D_2) ?

Plot predictions for 1^3D_2 states, and for the observed states above flavor threshold, ψ(3770), ϒ(4S) ,vs. “quality of a model” (RMS of ΔM= M_{theory}-M_{data} for states below the flavor threshold)



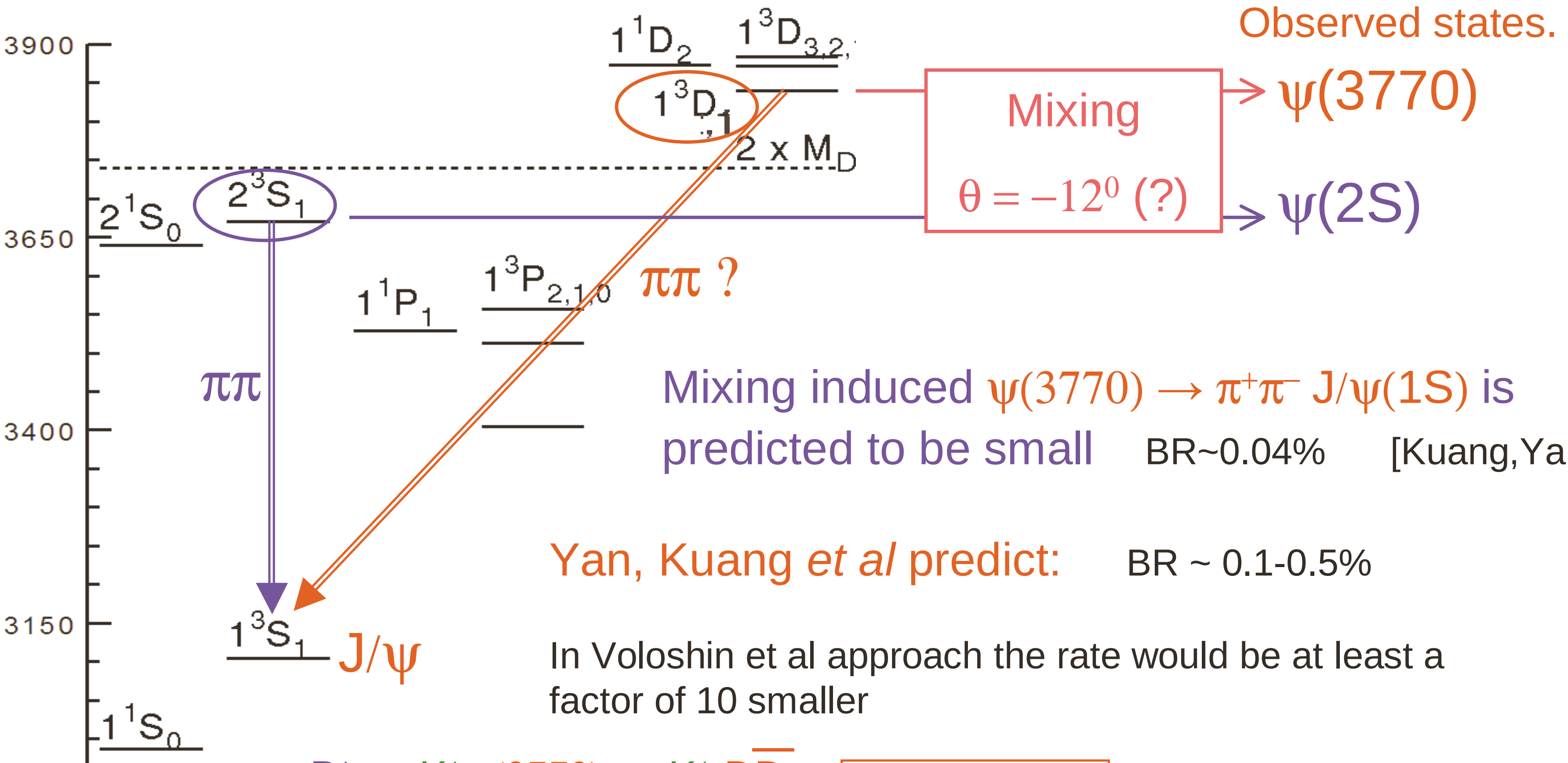


~30 MeV correction needed to the ϒ(4S) mass

- All models expect for Fulcher, PRD44,2079(91), predict ψ(1^3D_2) mass to be ~70 MeV lower than the measured X(3872) mass. At the same time good quality models reproduce ϒ(1^3D_2) mass very well.
- Coupled channel effects would push the Fulcher’s predictions down >30 MeV.
- None of the models can accommodate ψ(3770) and X(3872) in the same 1^3D_J triplet! Can coupled channel effects and ψ(1^3D_1)–ψ(2^3S_1) mixing change this?

Relation of $\psi(1^3D_2) \rightarrow \pi^+\pi^-$ J/ψ to ψ(3770) → $\pi^+\pi^-$ J/ψ

These are E1*E1 transitions. No spin dependence. Width for $\psi(1^3D_2) \rightarrow \pi^+\pi^-$ J/ψ should differ from $\psi(1^3D_2) \rightarrow \pi^+\pi^-$ J/ψ mostly by the phase space factor.



Mixing induced ψ(3770) → $\pi^+\pi^-$ J/ψ(1S) is predicted to be small BR~0.04% [Kuang,Yan]

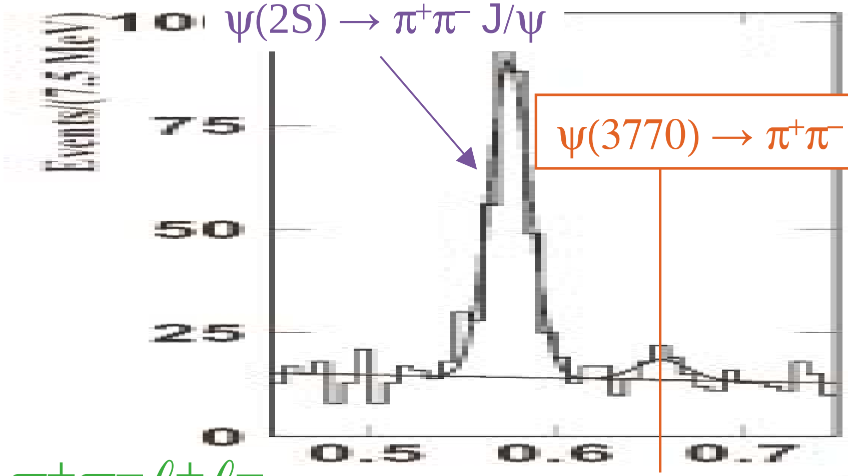
Yan, Kuang *et al* predict: BR ~ 0.1-0.5%

In Voloshin et al approach the rate would be at least a factor of 10 smaller

$B^\pm \rightarrow K^\pm\psi(3770) \rightarrow K^\pm D\overline{D}$

	Belle	MARK I	DELCO	MARK II
$M(\psi(3770))$, MeV/c^2	$3778.4 \pm 3.0 \pm 0.8$	3772 ± 6	3770 ± 6	3764 ± 5
$\Delta m = M(\psi(3770)) - M(\psi(2S))$, MeV/$c^2$	$92.4 \pm 3.0 \pm 0.8$	88 ± 3	86 ± 2	80 ± 2

$\psi(3770) \rightarrow \pi^+\pi^- J/\psi$ at BES II



$e^+e^- \rightarrow \gamma\, \psi(2S)$, $\psi(2S) \rightarrow \pi^+\pi^- J/\psi$

$\psi(3770) \rightarrow \pi^+\pi^- J/\psi$

$E(\pi^+\pi^-)$ GeV

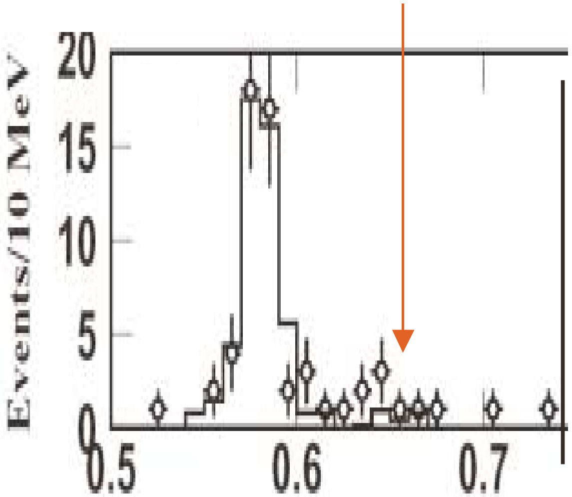
- Data sample: 8.0±0.5 pb^{-1} (20% scan), $(5.7\pm1.3)10^4$ $\psi(3770)$ decays

  Efficiency: 17.1%
- Claim 9 events including 2.2±0.4 background events

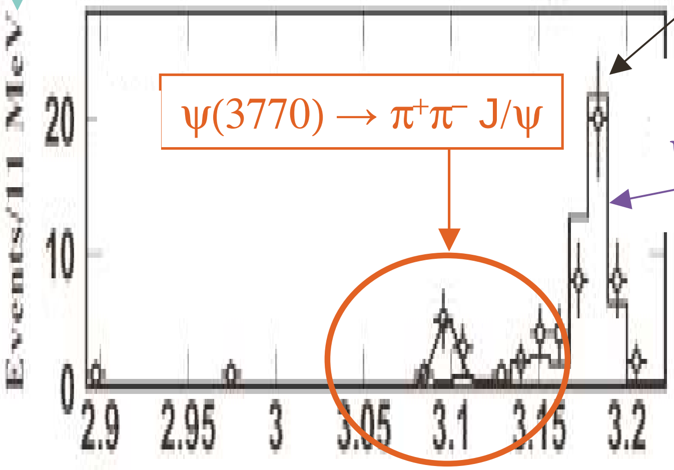
$BR(\psi(3770)\rightarrow\pi^+\pi^- J/\psi(1S))$
$=(0.59\pm0.26\pm0.16)$ % LARGE!

$\pi^+\pi^-\ell^+\ell^-$ events

4C fit $(E=E_{cm},\vec{P}=0)$



$E(\pi^+\pi^-)$ GeV



data

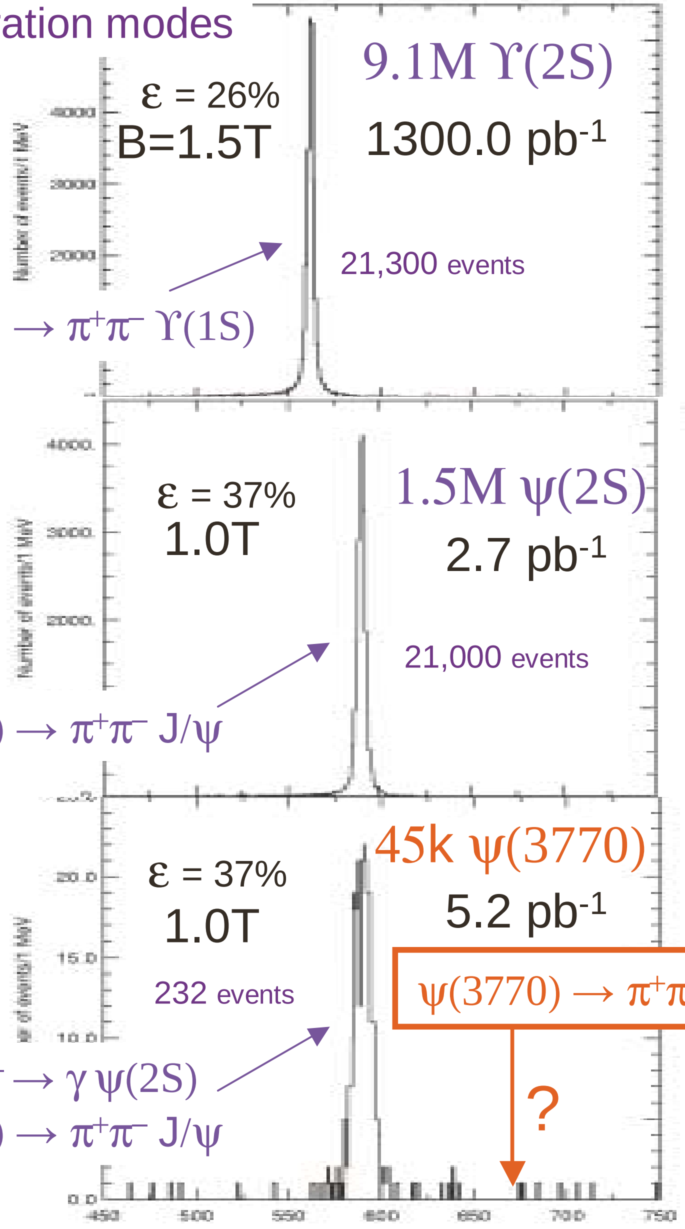
$\psi(3770) \rightarrow \pi^+\pi^- J/\psi$

$e^+e^- \rightarrow \gamma\, \psi(2S)$, $\psi(2S) \rightarrow \pi^+\pi^- J/\psi$ MC

$M(\ell^+\ell^-)$ GeV

$\psi(3770) \rightarrow \pi^+\pi^- J/\psi$ at CLEO-c

calibration modes



ε = 26%
B=1.5T

9.1M $\Upsilon(2S)$
1300.0 pb^{-1}

21,300 events

$\Upsilon(2S) \rightarrow \pi^+\pi^- \Upsilon(1S)$

ε = 37%
1.0T

1.5M $\psi(2S)$
2.7 pb^{-1}

21,000 events

$\psi(2S) \rightarrow \pi^+\pi^- J/\psi$

ε = 37%
1.0T

45k $\psi(3770)$
5.2 pb^{-1}

232 events

$\psi(3770) \rightarrow \pi^+\pi^- J/\psi$

?

$e^+e^- \rightarrow \gamma\, \psi(2S)$
$\psi(2S) \rightarrow \pi^+\pi^- J/\psi$

Ecm -Mass recoiling $\pi^+\pi^-$

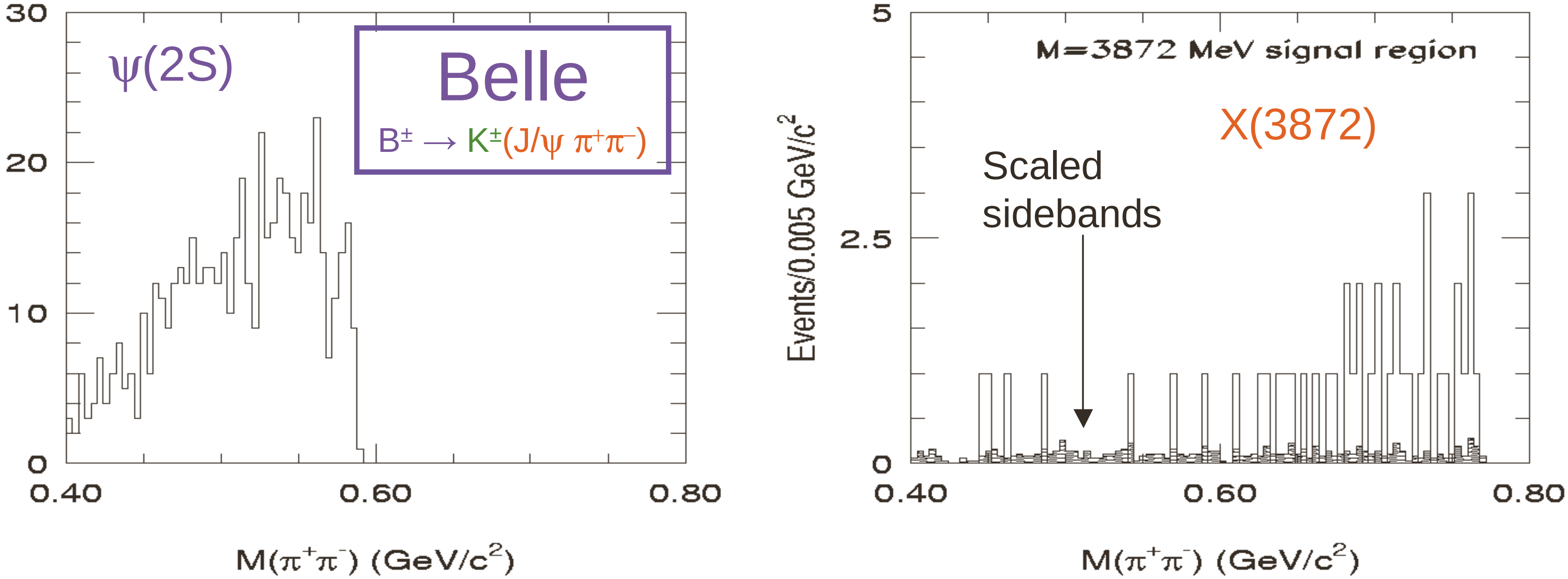
- Data sample: 5.2±0.2 pb^{-1}, $(4.5\pm0.4)10^4$ $\psi(3770)$ decays
- Efficiency: 37.1%
- < 4.75 events at 90% C.L.

BR($\psi(3770) \rightarrow \pi^+\pi^- J/\psi(1S)$)
<0.26% at 90% C.L.

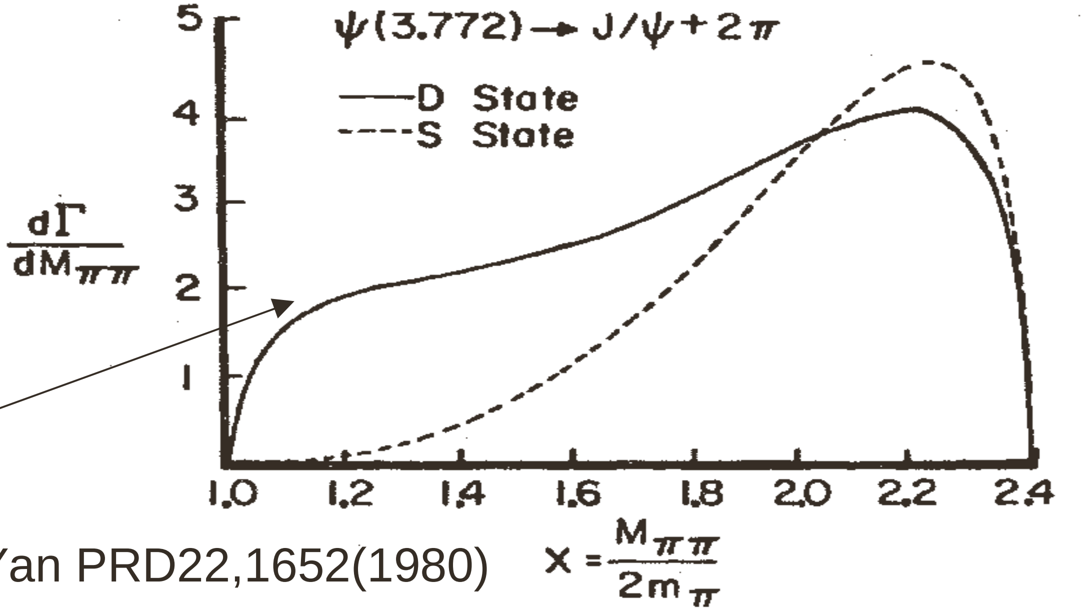
More data coming:
BES-II is analyzing additional 12 pb^{-1}
CLEO-c is scheduled to take 50 pb^{-1} this fall
eventually 2 fb^{-1} (to study D-decays)

$\pi^+\pi^-\ell^+\ell^-$ events
After cuts on $M(\ell^+\ell^-)$ to make
it near M(J/ψ) or M($\Upsilon(2S)$)

Dipion mass distribution in Belle's data



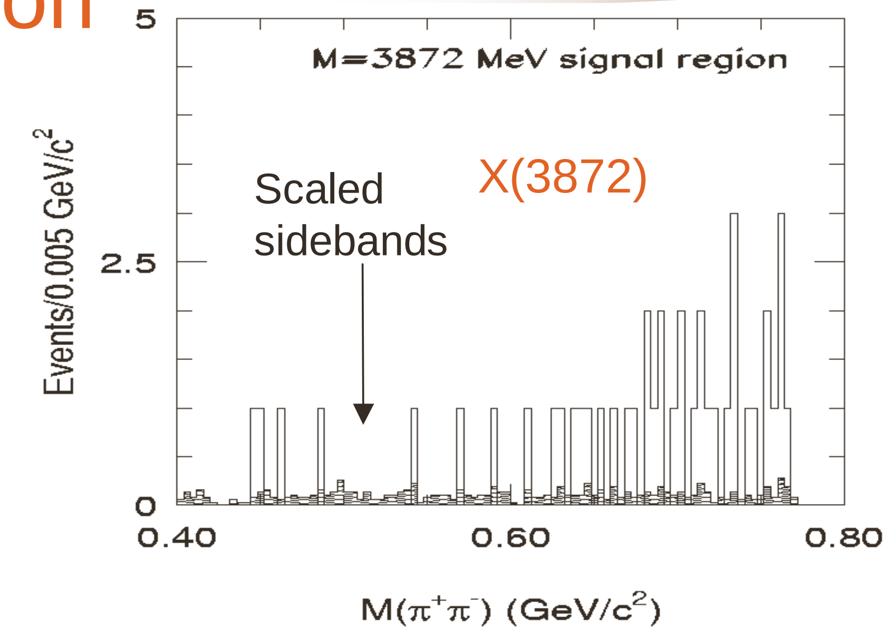
- Peaking at high values of $M(\pi^+\pi^-)$ for $\psi(2S) \to J/\psi(2S)\pi^+\pi^-$ can be explained in the multipole expansion model
- For $\psi(1D) \to J/\psi(2S)\pi^+\pi^-$ the mutipole model predicts less pronounced peaking.



T.M.Yan PRD22,1652(1980)

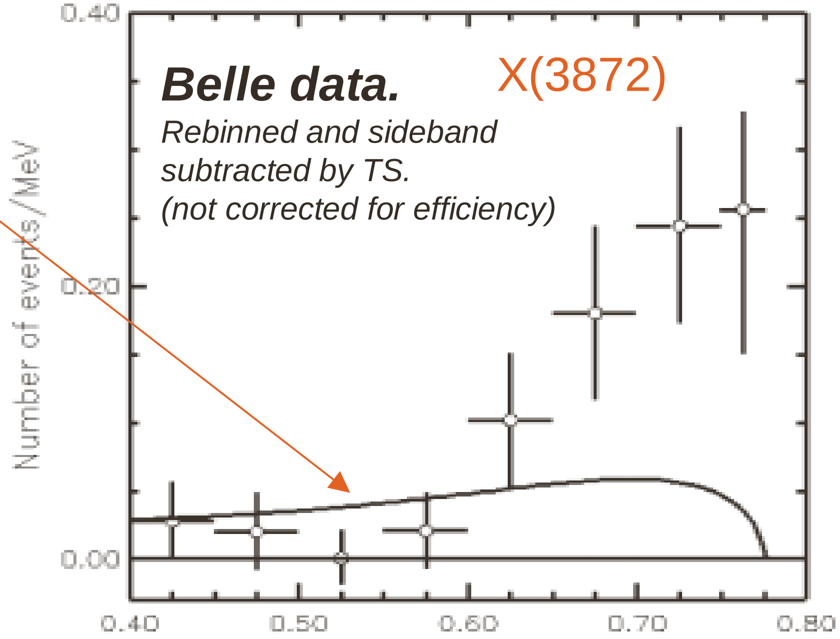
Dipion mass distribution

- Data for the new X(3872) state is very strongly peaked at high M($\pi^+\pi^-$) values. Even stronger peaking than for 2S → 1S $\pi^+\pi^-$ transitions.
- Fit of the shape predicted for ψ(1D) → J/ψ(2S)$\pi^+\pi^-$ by Yan gives low confidence level – 0.5%
- Either multipole expansion model fails here or X(3872) is not a $\psi(1^3D_2)$ state



Scaled sidebands

X(3872)



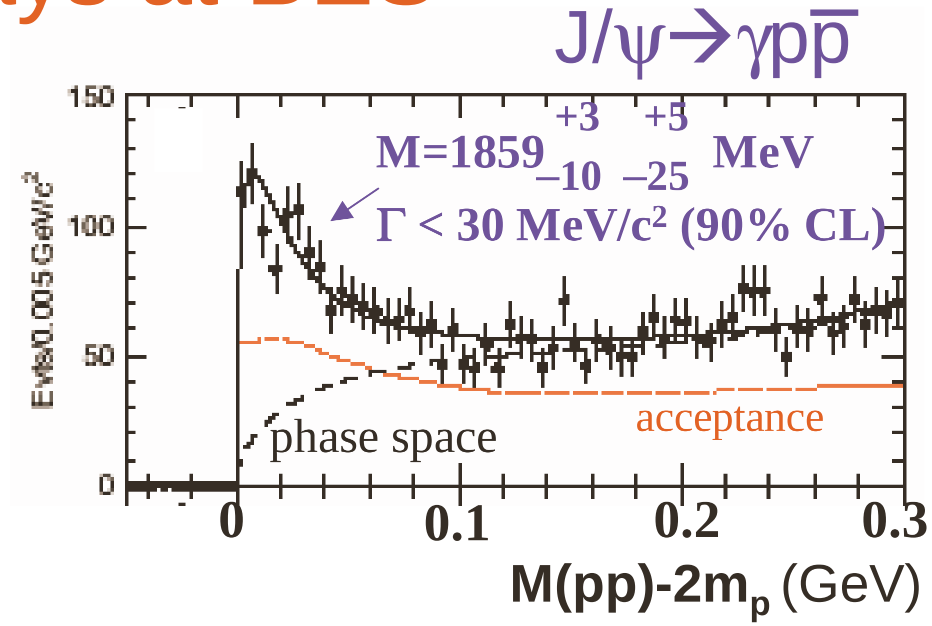
Belle data.

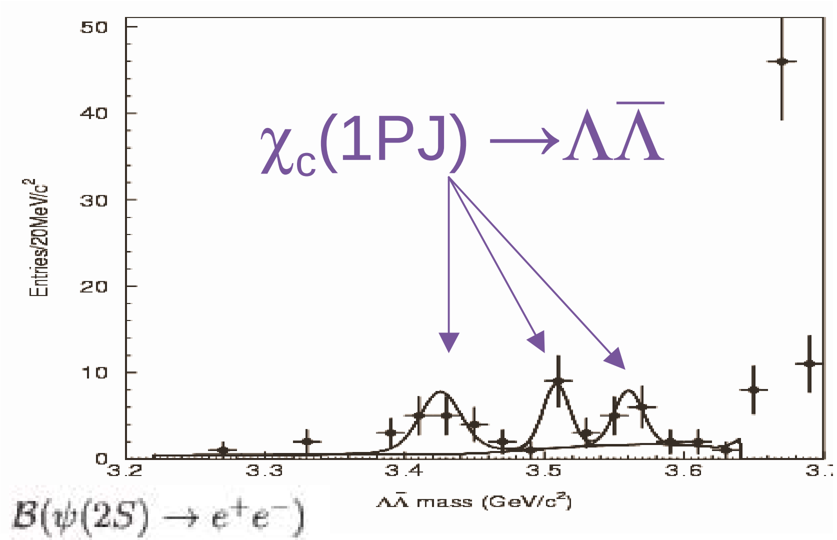
Rebinned and sideband subtracted by TS. (not corrected for efficiency)

X(3872)

J/ψ and ψ(2S) decays at BES

- Gateway to light hadron spectroscopy
- “ρπ” puzzle
- BES-II has the largest samples (58M J/ψ , 14M ψ(2S))
- Recent results:
  - Confirm resonant structure at the $p\bar{p}$ threshold
  - Observe χ_c(1PJ) →$\Lambda\bar{\Lambda}$. Branching ratios larger than expected.
  - Improved measurements of J/ψ and ψ(2S) → $K_S^0K_L^0$ rates

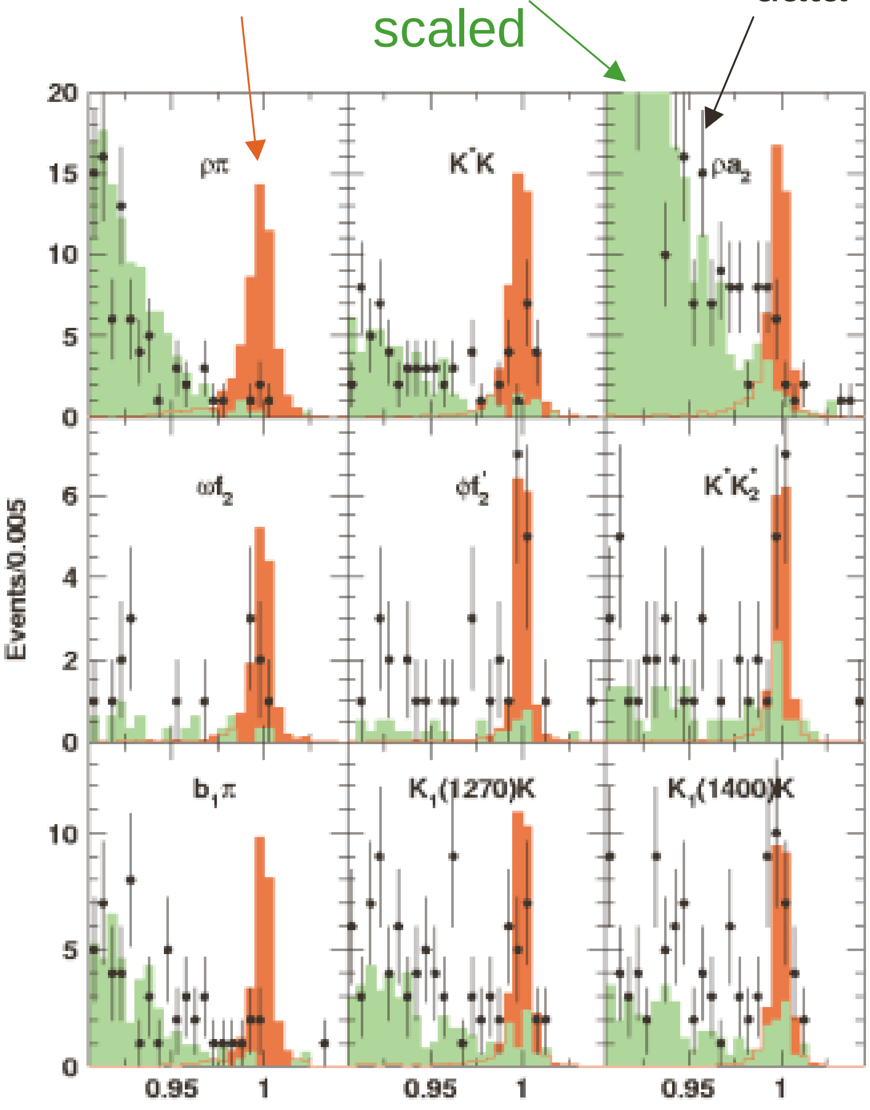




$$Q_h = \frac{\mathcal{B}(\psi(2S)\to K_S^0K_L^0)}{\mathcal{B}(J/\psi\to K_S^0K_L^0)} = (28.2\pm4.7)\% > 12\% = \frac{\mathcal{B}(\psi(2S)\to e^+e^-)}{\mathcal{B}(J/\psi\to e^+e^-)}$$

Υ(1S), Υ(2S), and Υ(3S), decays at CLEO

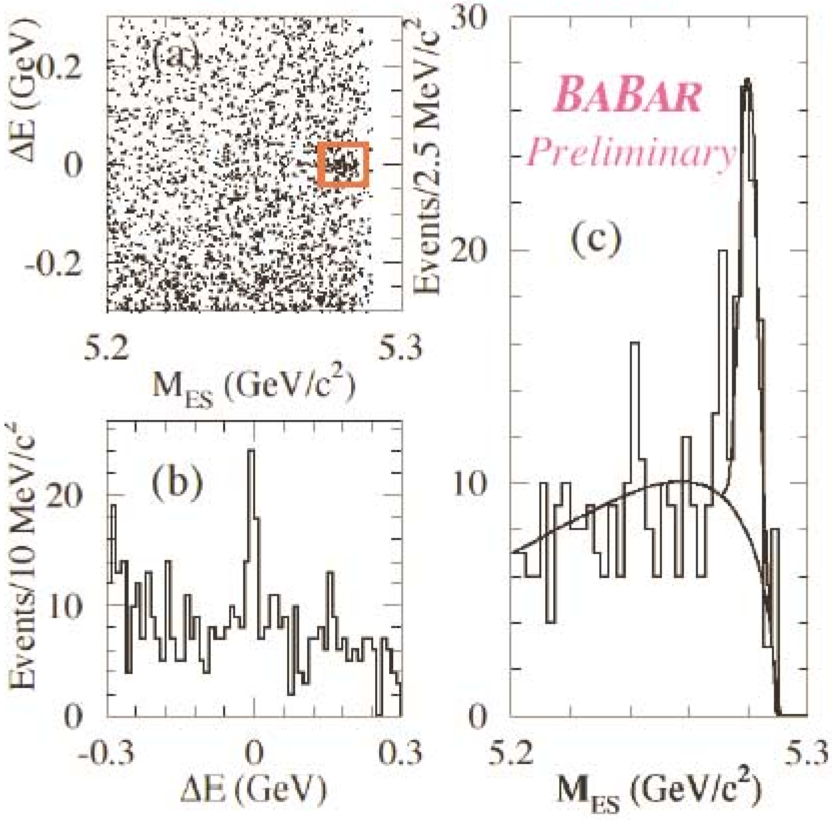
- Can Upsilon decays shed some light at the “ρπ” puzzle in charmonium?
- CLEO-III has the largest samples (21M Υ(1S), 9M Υ(2S), 5M Υ(3S))
- Preliminary results on two-body decays:
  - Observe signals for $\Upsilon(1S) \rightarrow \phi f_2'(1525)$ and K1(1400)K, BR ~ 10^{-5}
  - Set limits for the others
  - Tightest limit: BR($\Upsilon(1S) \rightarrow \rho\pi$)< 4 10^{-6} .More than $(M_{J/\psi}/M_{\Upsilon(1S)})^6$ suppression relative to the charmonium.



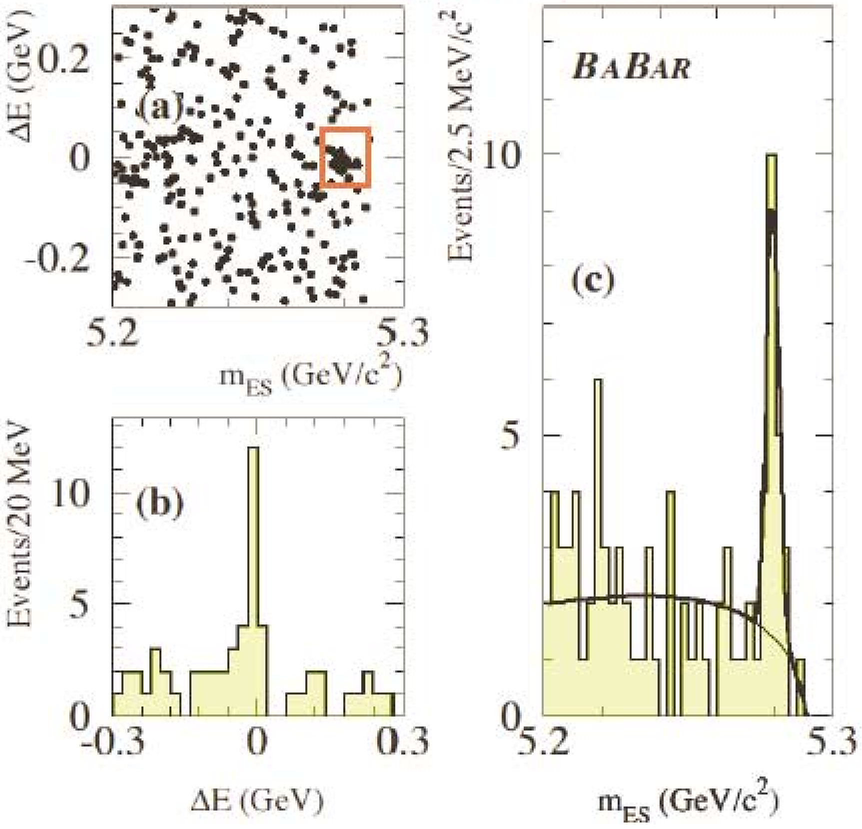
E_{tot}/E_{CM}

Other BaBar results

$B^+ \to J/\psi\,\eta\,K^+$ (data)



$B^+ \to J/\psi\,\phi\,K^+$ (data)



Comparable rates

- Also:
  - $B^\pm \to K^\pm \eta_c \to K^\pm p\bar{p}\,\pi^+\pi^-$
  - Mass, width and Γ_{ee} of $\Upsilon(4S)$

Summary and Outlook

- Heavy quarkonium physics has been experimentally revitalized:
  - Large data samples collected for quarkonia in e^+e^- annihilation by BES-II ($c\bar{c}$) and CLEO-III ($b\bar{b}$). Also E835 $p\bar{p}$ ($c\bar{c}$). Still being analyzed.
  - CLEO-c program has started (first ψ' and ψ'' results from 1 wiggler runs)
  - B-gateway to charmonium now wide open with ~300M B decays at Belle and BaBar
- Similar progress in theory (NRQCD, Lattice QCD)
- Longer range outlook:
  - Charmonium results from BES-II, CLEO-c/CESR-c (L~ 1-5 10^{32} cm^{-2} s^{-1}) and later from BES-III/BEPC-II (approved in Feb.03! L~10^{33} cm^{-2} s^{-1}. 2007-)
  - Belle and BaBar will continue to produce charmonium results from even more B-meson decays
  - Charmonium physics from B mesons produced at hadronic machines? (Run II, BTeV and LHCb)
  - Charmonium at dedicated $p\bar{p}$ machine? PANDA project at GSI: (675 M€, >2008-)
  - More Upsilon runs at CESR??? Upsilon runs at SLAC and KEK???
- X(3872) discovered by Belle is a good looking candidate for $D\bar{D}^*$ molecule:
  - Charmonium played crucial role in establishing $q\bar{q}$ model for mesons. It may be now telling us that we need to go beyond it to describe all hadronic bound state phenomena. Only a **heavy** quarkonium system can provide a convincing proof for existence of both forms.