Heavy quarkonia: an overview of recent results

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Hadron 2007 Frascati

Outline

Heavy Quarkonium production puzzles in hadronic collisions

Spectroscopy: naming the zoo (above open charm threshold)

B-factories as the perfect charmonium discovery tool:

- B decays and tetraquarks
- Double ccbar : another challenge for NRQCD
- Radiative return: how to turn a drawback in a success
- 2 photon physics ... finally !

Decays: EM and hadronic transitions

Hot searches : spin singlets

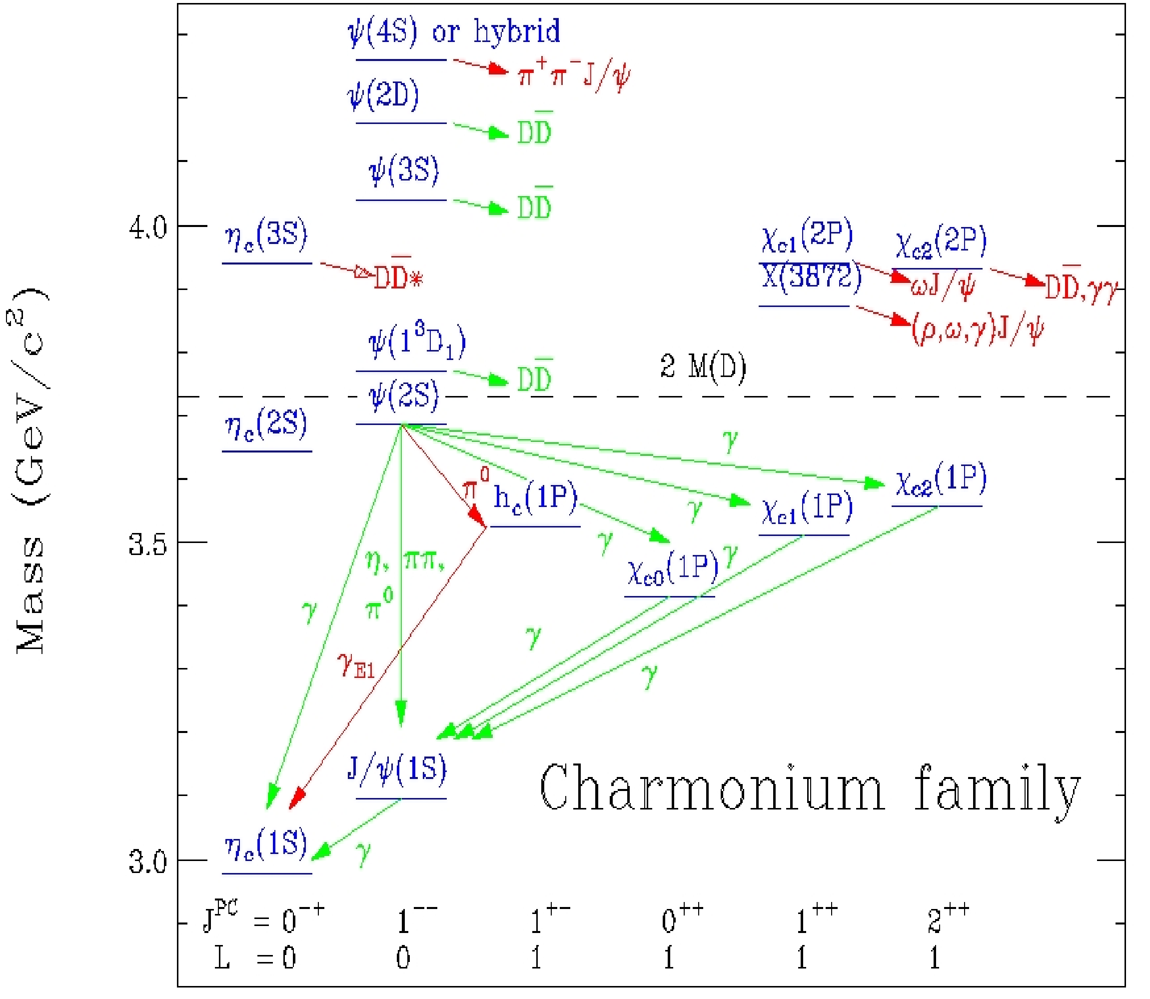
Charmonium

$c\bar{c}$ bound state
quasi relativistic system
in *quasi* perturbative regime
$\alpha_S \sim 0.2–0.3$

Good quantum numbers: J,S
D wave mixing with S wave

S=0 : *para*charmonium (η_C)
$\Gamma_S \sim 30$ MeV ; $\Gamma_P \sim 1$ MeV

S=1 : *orto*charmonium (J/ψ , ψ')
$\Gamma_S \sim 0.1,0.3$ MeV; $\Gamma_P \sim 1–10$ MeV



Hyperfine Splitting : 112 MeV (1S), 40-50 MeV (2S)
Fine Splitting : 45-100 MeV (1P)

Bottomonium

$b\bar{b}$ bound state

non-relativistic quark motion,

in perturbative regime

$\alpha_S \sim 0.1$–0.2

J,S,L are good quantum numbers

S=0 : *para*bottomonium

Not yet observed

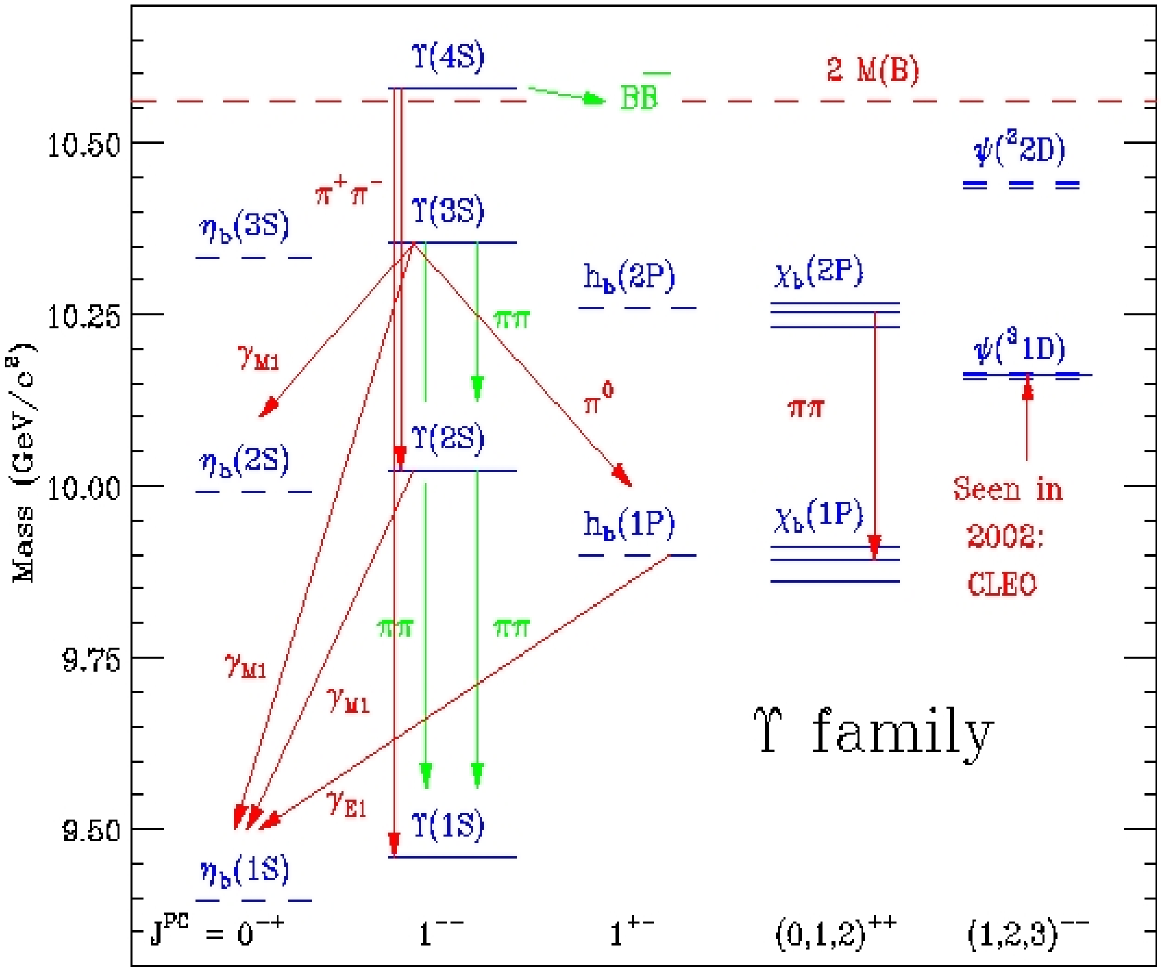
S=1 : *orto*bottomonium

$\Gamma[\Upsilon(1,2,3S)]$ = 53, 44, 26 keV

$\Gamma_P \sim$ few MeV (not measured)

Hyperfine Splitting : unknown

Fine Splitting : 15-30 MeV (1P)



Quarkonium Working Group Activities

YELLOW REPORT : CERN-2005-005 (hep-ph/0412158)

QWG Workshops on Heavy Quarkonium:

QWG1: CERN, November 8 to 10, 2002

QWG2: Fermilab, September 20 to 22, 2003

QWG School: ITP Beijing, October 8 to 11, 2004

QWG3: Beijing, October 12 to 15, 2004

QWG4: Brookhaven, June 27 to 30, 2006

QWG5: DESY Hamburg: Oct 17 to 20, 2007 (next week!)

www.qwg.to.infn.it

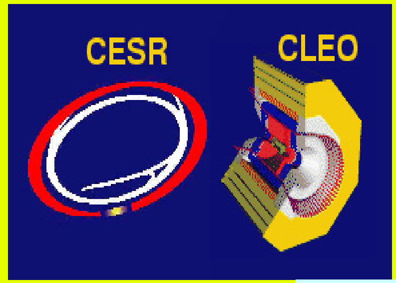
Experiments

Beauty Factories : Belle, BaBar, CLEO

657 M $\Upsilon(4S)$
11 M $\Upsilon(3S)$

6.6M $\Upsilon(5S)$

383M $\Upsilon(4S)$



12M $\Upsilon(4S)$
6M $\Upsilon(3S)$
9M $\Upsilon(2S)$
28M $\Upsilon(1S)$

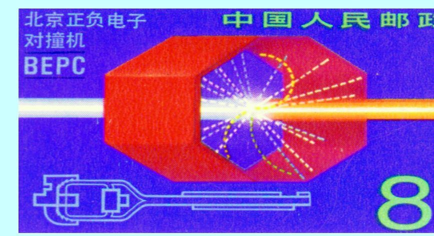
Hadron Colliders: CDF, D0

CDF: 0.8 fb-1

D0: 1.3 fb-1

τ-charm factories: CLEO-c, BES-II

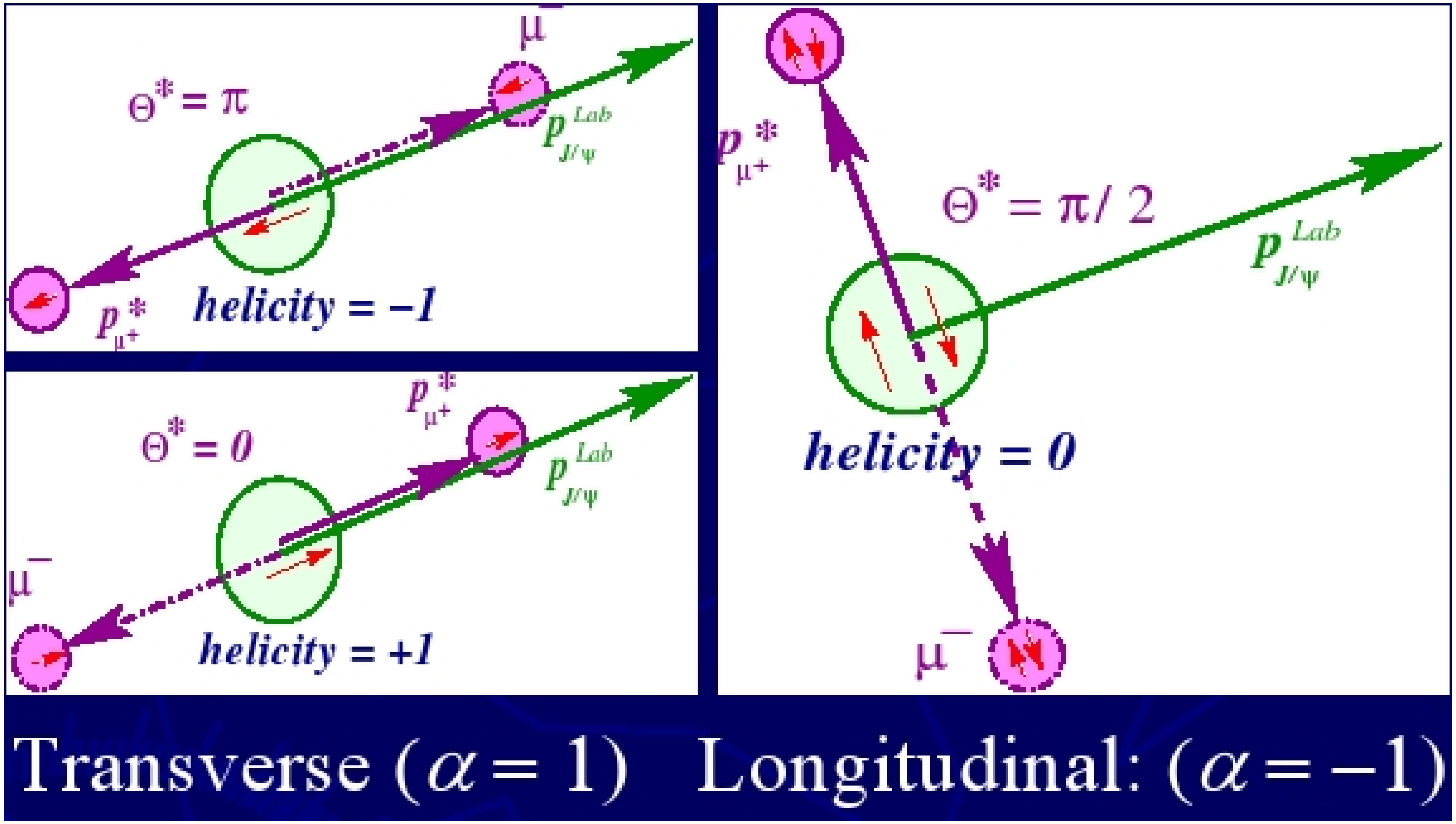
29M $\Psi(2S)$
1.8M $\Psi(3770)$



14M $\Psi(2S)$
58M J/Ψ

but also:
e-p colliders : Hera-B, H1, Zeus at DESY
ppbar to charmonium : E760/835 at FNAL
heavy ion collisions: Star-Phenix at RHIC, NA50/60 at CERN SPS

Polarization of heavy quarkonia at Tevatron



$$\frac{d\Gamma}{d\cos\theta^*} \propto 1 + \alpha\cos^2\theta^* \quad (-1 \le \alpha \le 1)$$

Polarization of heavy quarkonia at Tevatron

Run 1 : NRQCD succesfully explained the production of heavy quarkonia at high Pt

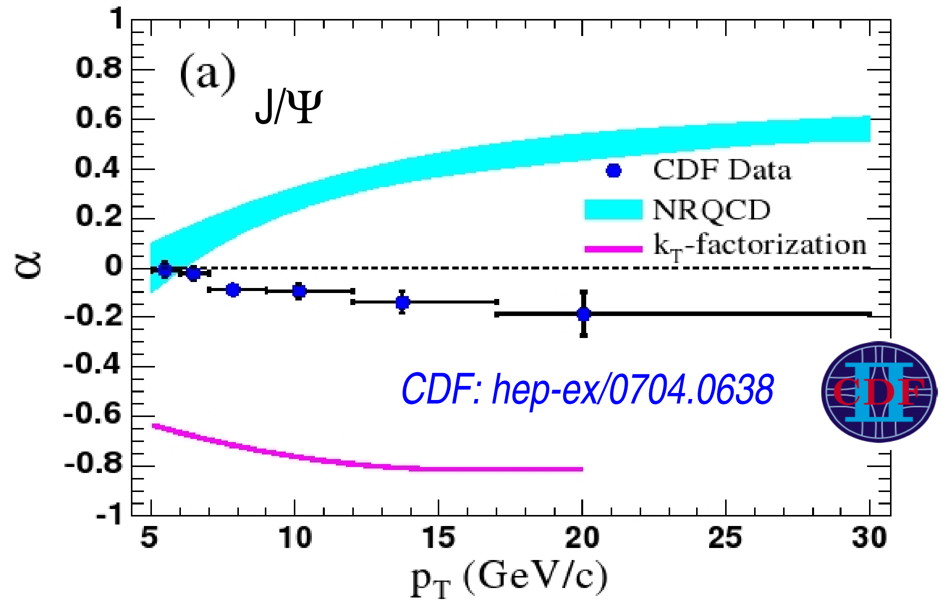
Run 2: New results on charmonium AND bottomonium polarization vs Pt challenge theory :

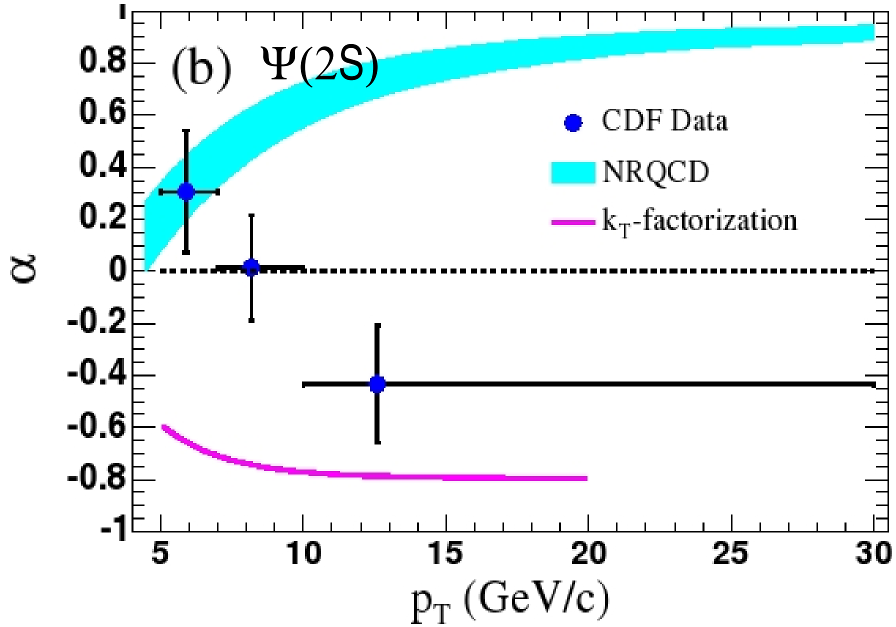
- NRQCD predictions
  [Braaten, Lee: PRD 63, 071501 (2001)]
- K_T Factorization approach

  A: quark spin conservation

  B: full quark spin depolarisation

  [Baranov hep-ph/0707.0253]





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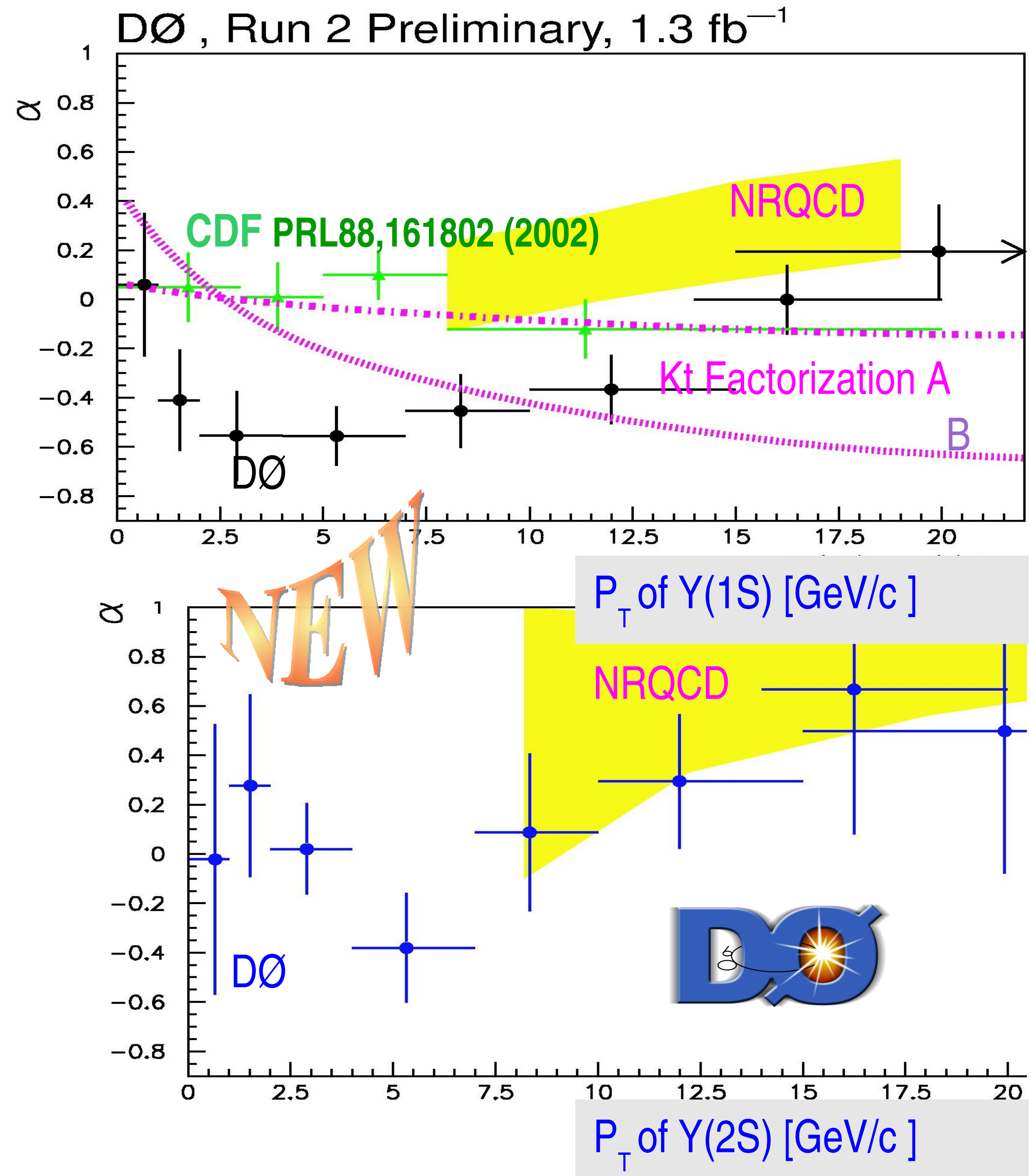
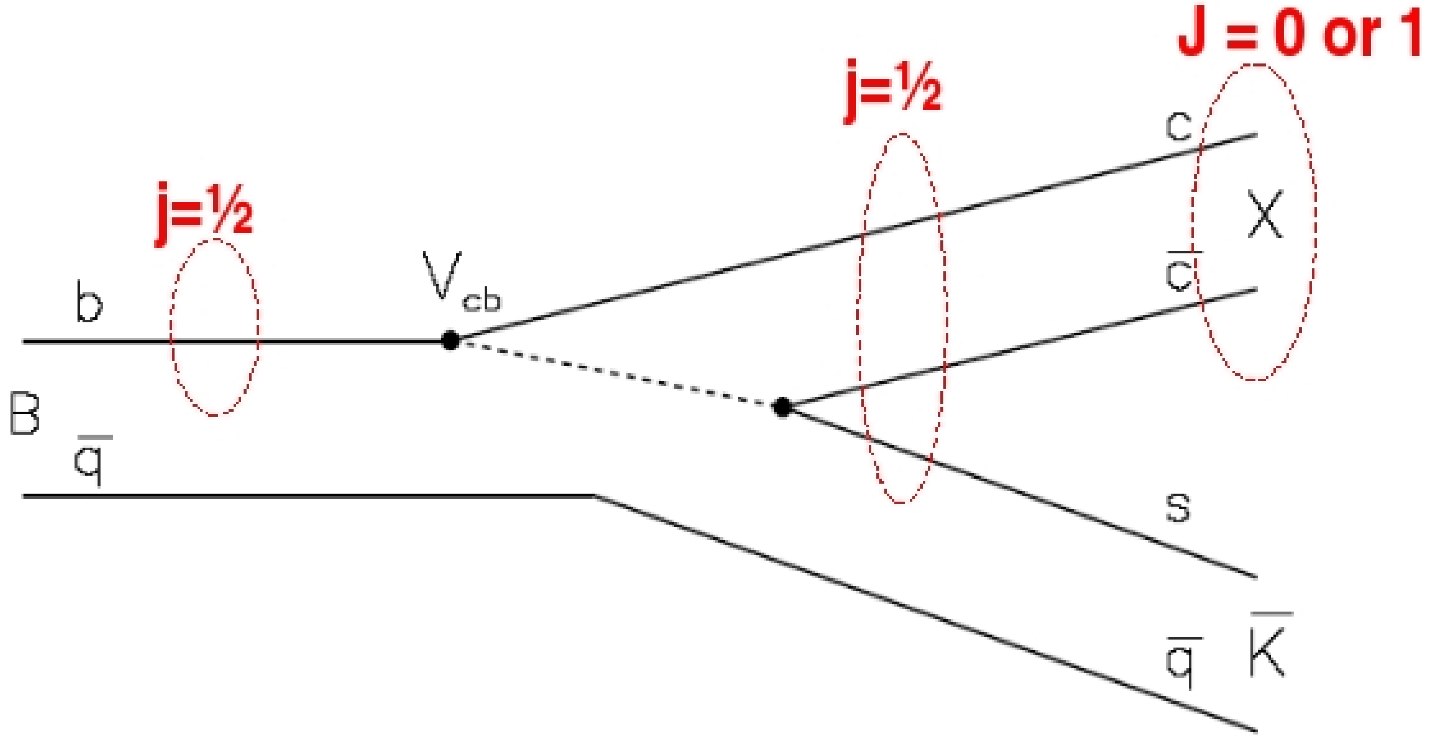
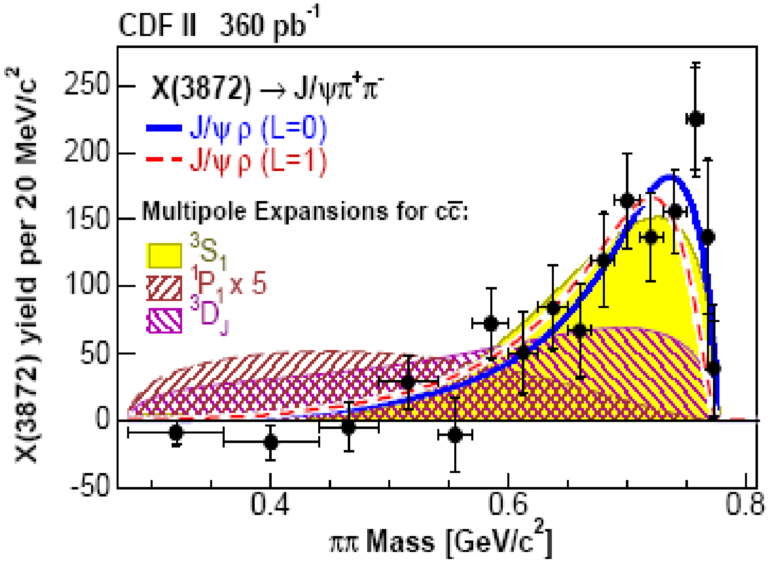


B decays to K + charmonium



B to K J/ ψ $\pi\pi$

X(3872): established facts



Discovered (2003) in B decays $\to$ K $J/\psi\pi\pi$

Prompt production dominant at Tevatron:

(only 16% are from B$\to$ K $J/\psi\pi\pi$)

$M_{\pi\pi}$ consistent with $J/\psi\rho$ (I=1)

X(3872) $\to$ $J/\psi\,\gamma$ observed by Belle and BaBar; confirms C=+1

C=+1 implies $I_{\pi\pi}$=1 $\to$ isospin violation in $J/\psi\pi\pi$ decay

It is NOT observed in $\gamma\gamma$

It is NOT observed in e^+e^- (ISR)

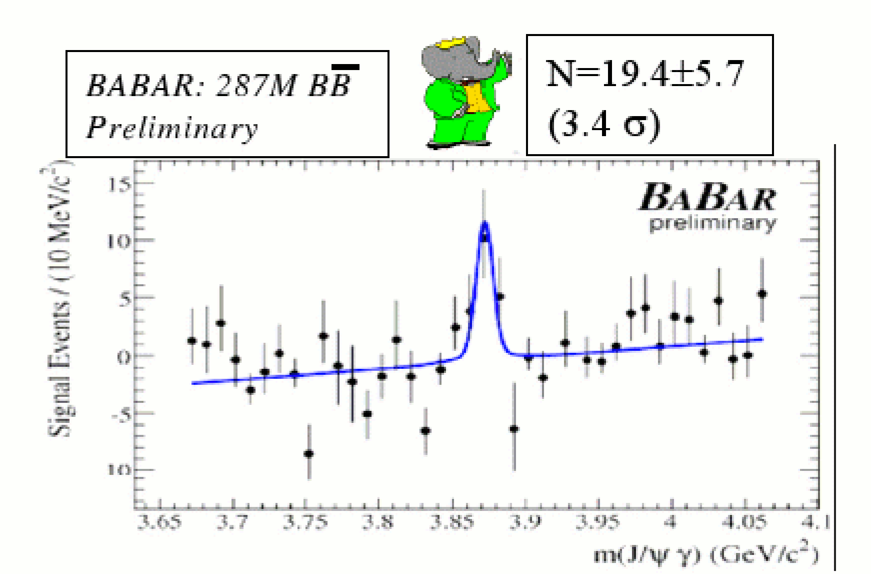
Angular distributions favor $J^{PC} = 1^{++}$ or 2^{-+}

Observation in B decay suggests $J^{PC} = 1^{++}$

Mass (PDG2006) = 3871.4±0.6 MeV/c^2

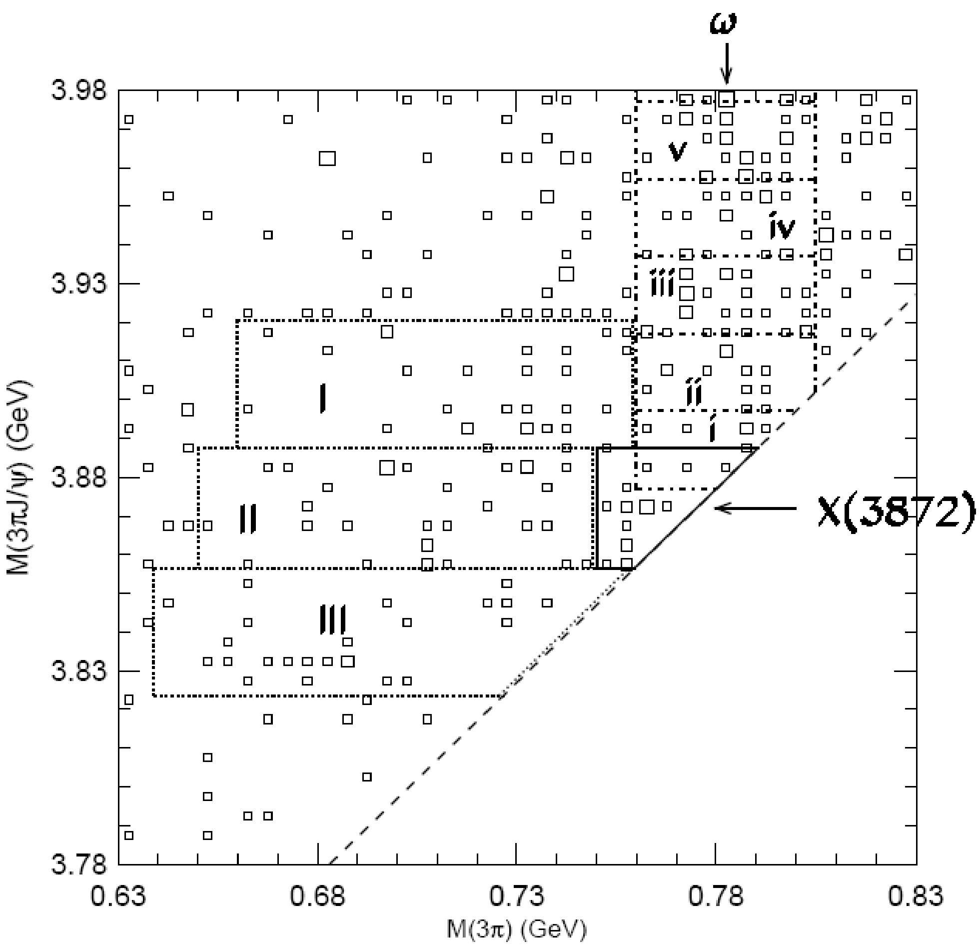
[M(D^0+D^0) = 3871.81±0.36 MeV/c^2]*

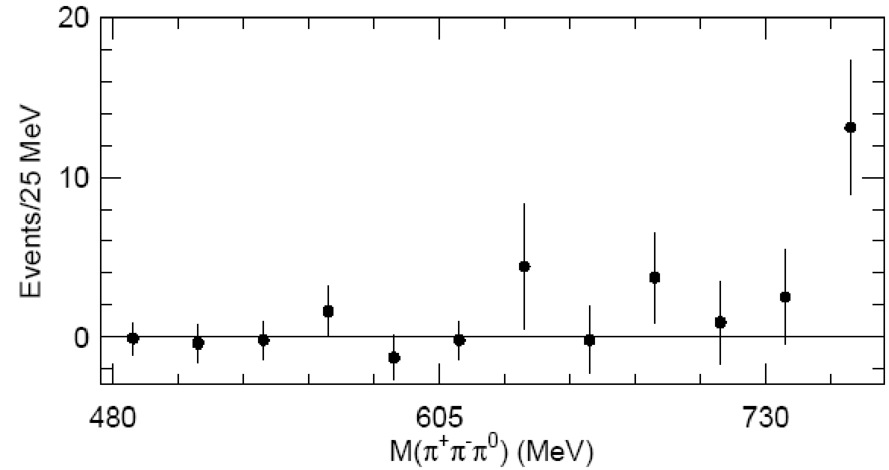
Width (PDG2006) < 2.3 MeV (90%CL)



X(3872) in $B \to K (\pi^0 \pi^+ \pi^- J/\psi)$

Belle, 256 fb^{-1}: hep-ex/0505037





Below ω threshold: 12.4 ± 4.2 evts

$$\frac{Br(X \to J/\psi\ 3\pi)}{Br(X \to J/\psi\ \pi\pi)} \sim 1$$

Controversial evidence:

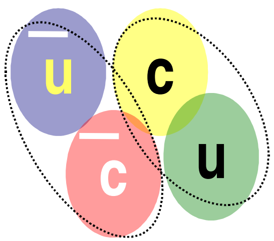
BaBar does not confirm it

X(3872): a tetraquark doublet?

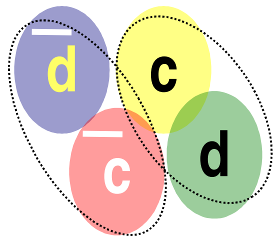
Maiani et al PRD 71,014028 (2005)

$\Delta M = M(X_u) - M(X_d) = (7 \pm 2)\cos(2\theta)$ MeV

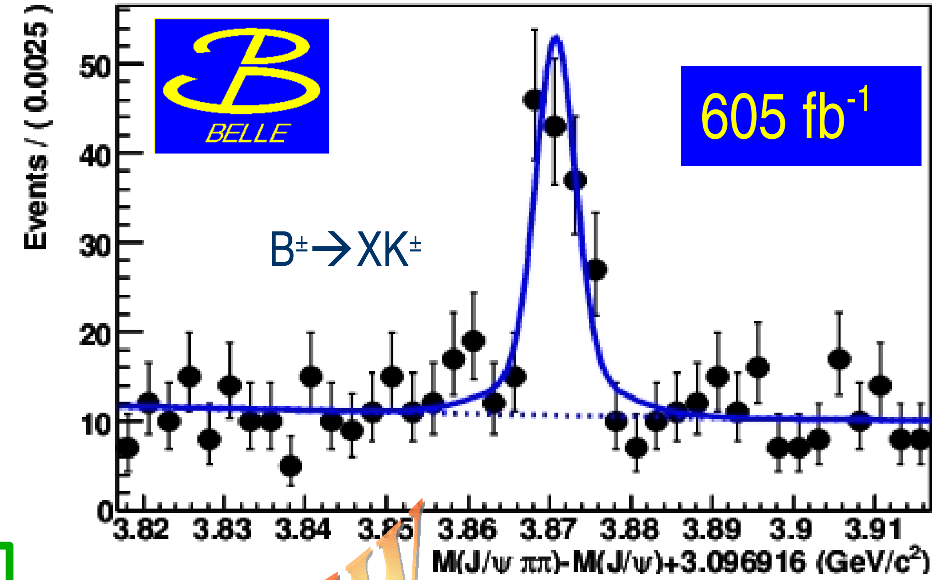
$X_u =$

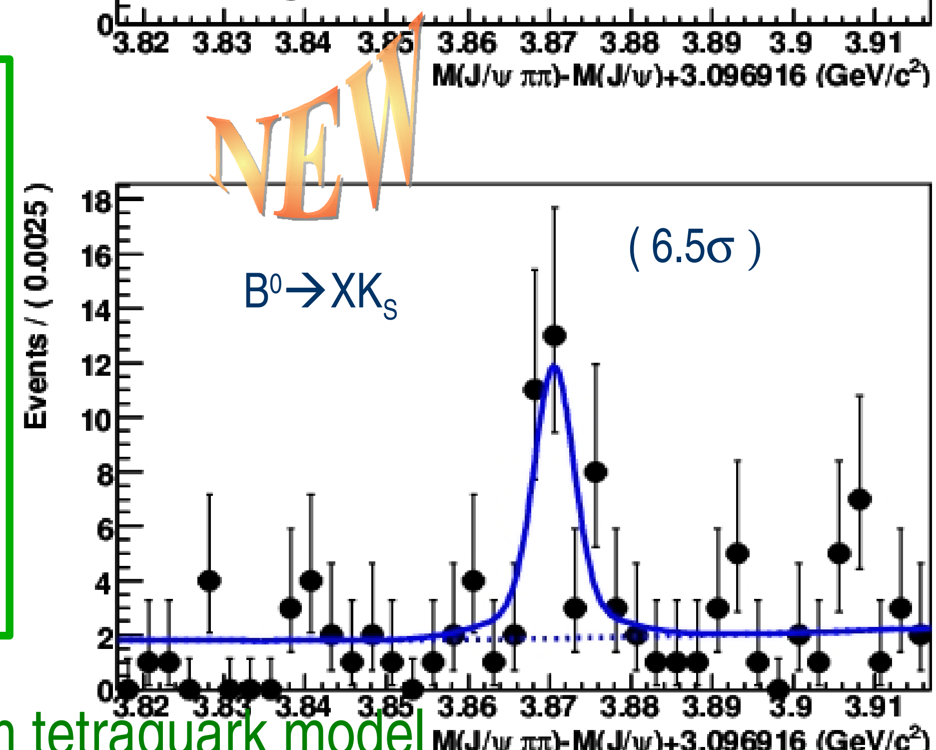


$X_d =$



	$\frac{\mathcal{B}(B^0 \to K^0 X(3872))}{\mathcal{B}(B^- \to K^- X(3872))}$	ΔM [MeV/c^2]
BaBar	0.61±0.36±0.06 *PRD73, 011101 (2006)*	2.7±1.3±0.2
BELLE	0.94±0.24±0.10 *BELLE-CONF-0711*	0.22±0.90±0.27





No evidence of mass splitting expected from tetraquark model

No evidence of rate asymmetry: molecule model predicts 1/10

B to K $\underline{D}$ $D^{(*)}$

X(3875) in B decays to $\pi D^0 \bar{D}^0$

$Br(B \to KX) Br(X \to \pi^0 D^0 \bar{D}^0)$:

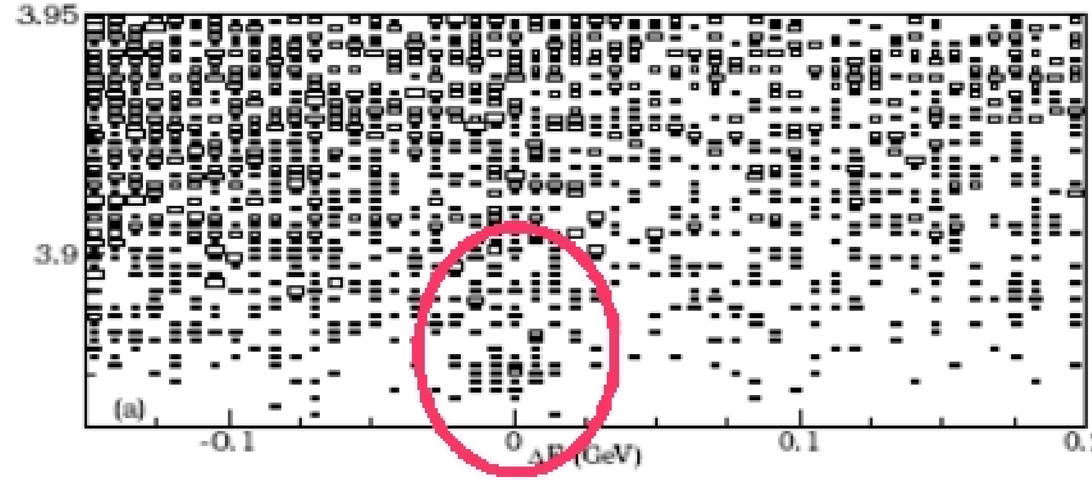
$(1.27 \pm 0.31 \ ^{+0.22}_{-0.39}) \times 10^{-4}$

10 x$Br(J/\psi\pi\pi)$

Mass:

$3875.4 \pm 0.7^{+0.7}_{-1.7} \pm 0.8$ MeV/c^2

Phys.Rev.D97,162002(2006)



BaBar: hep-ex/0708.1565

$Br(B \to KX) Br(X \to \pi^0 D^0 \bar{D}^0)$:

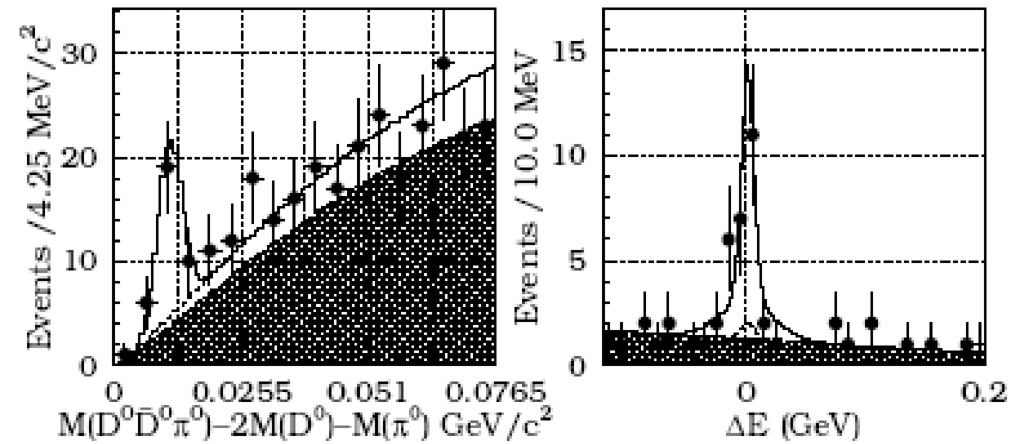
$(1.67 \pm 0.36 \pm 0.58) \times 10^{-4}$

Mass:

$3875.1 \pm 1.1 \pm 0.5$ MeV/c^2

Width:

$3.0^{+4.6}_{-2.3} \pm 0.9$ MeV

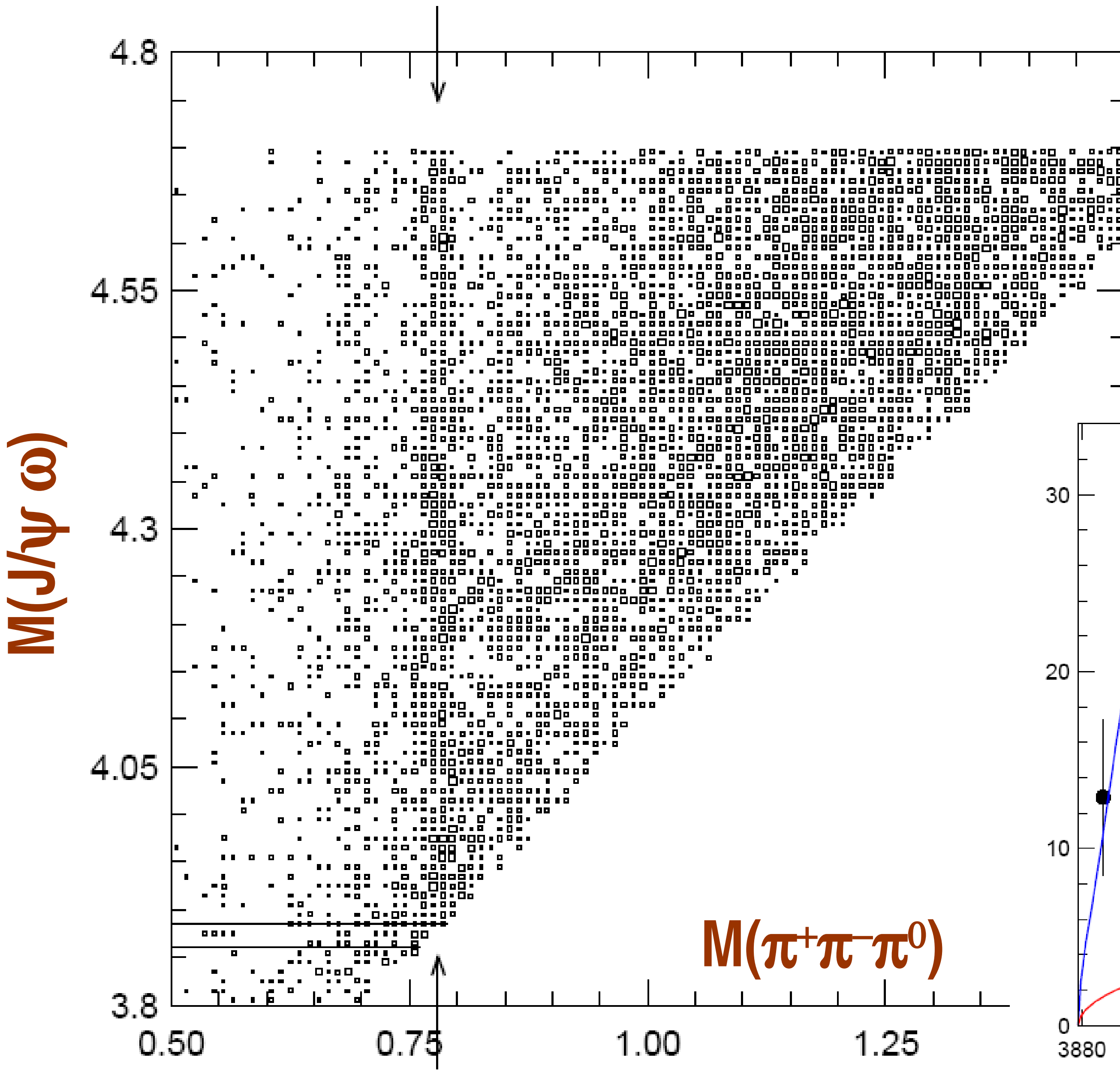


$B \to K \gamma D^0 \bar{D}^0$ / $B \to K \pi D^0 \bar{D}^0$ consistent with D^{*0} decay BR's.

Angular distribution consistent with 1^+

B to K J/ ψ $\pi\pi\pi$

Y(3940) in B decays to K ω J/ψ



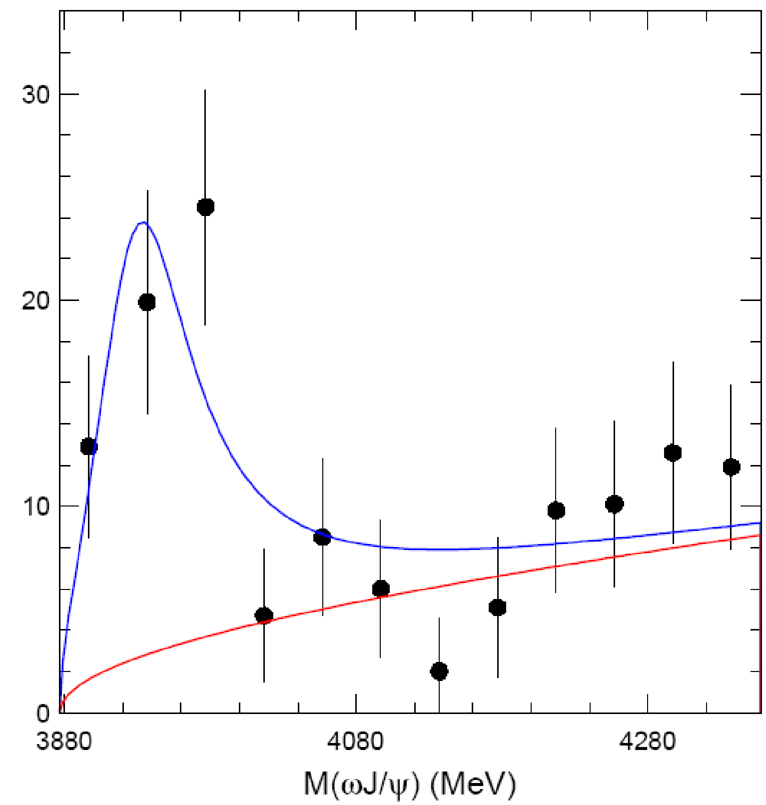
B→K ω J/ψ

255 fb^{-1} : PRL94, 182002 (2005)

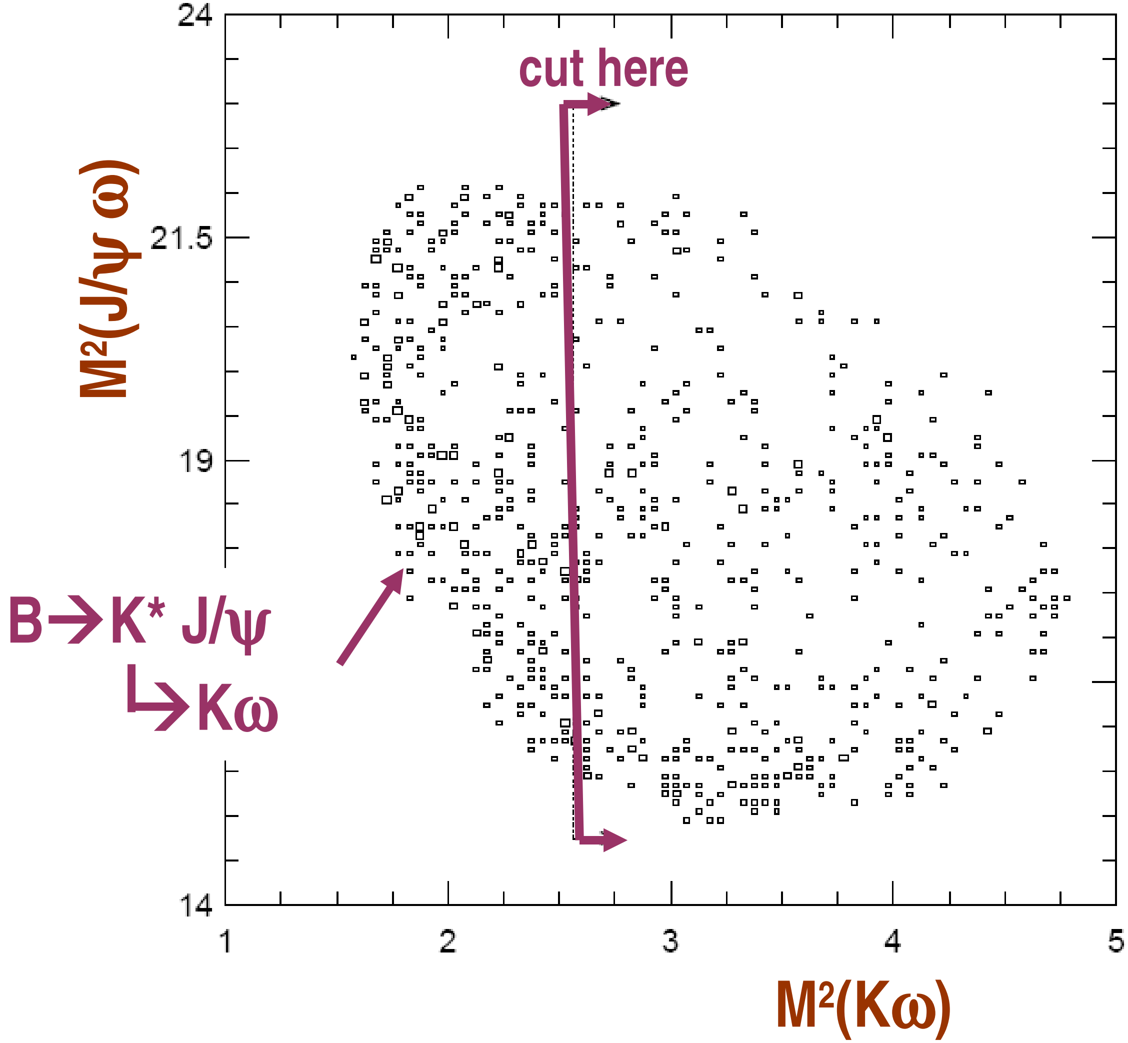
M = 3940 ± 11 MeV

Γ = 92 ± 24 MeV

Γ(Y(3940)→ωJ/ψ) > 7 MeV??



Y(3940) : Dalitz plot $B \to K\,\omega\,J/\psi$

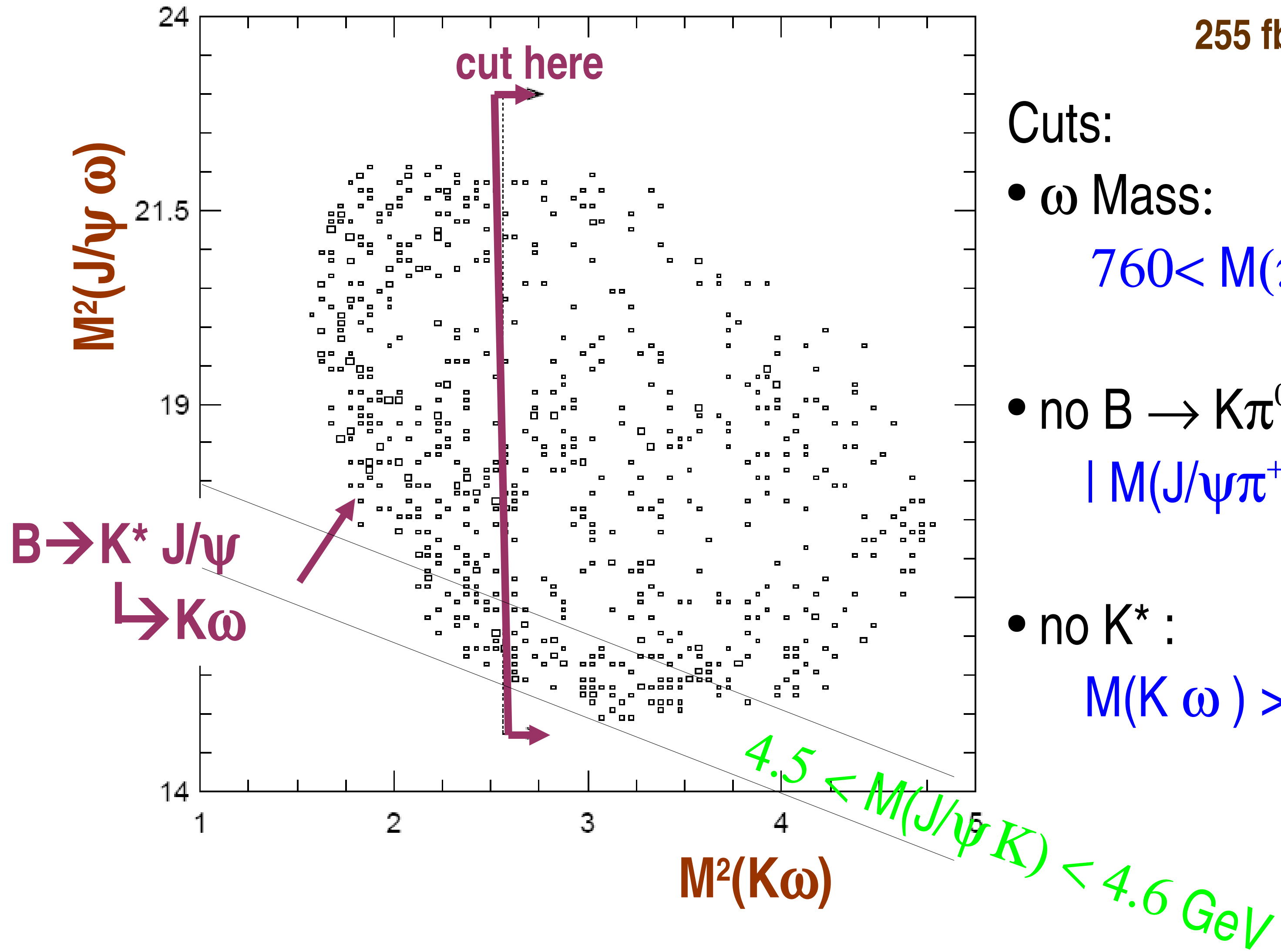


255 fb^{-1}: PRL94, 182002 (2005)

Cuts:

- ω Mass:
  $760 < M(\pi^+\pi^-\pi^0) < 805$ MeV
- no $B \to K\pi^0\psi'$:
  $|M(J/\psi\pi^+\pi^-) - M(\psi')| > 3\sigma$
- no K* :
  $M(K\,\omega) > 1.6$ GeV

Y(3940) : Dalitz plot B→ K ω J/ψ

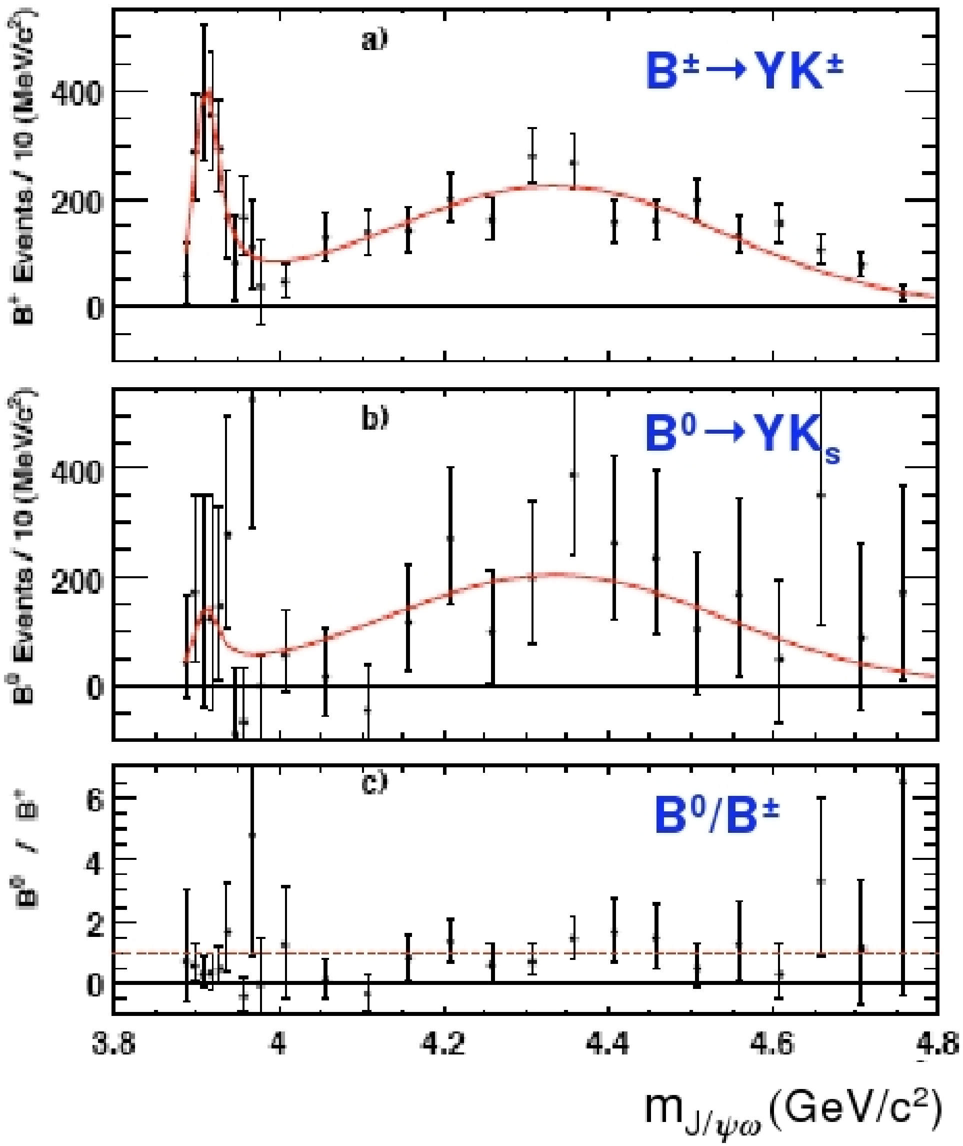


255 fb^{-1}: PRL94, 182002 (2005)

Cuts:

- ω Mass:
  $760 < M(\pi^+\pi^-\pi^0) < 805$ MeV
- no B → $K\pi^0\psi'$:
  $| M(J/\psi\pi^+\pi^-) - M(\psi') | > 3\sigma$
- no K* :
  M(K ω) > 1.6 GeV

Y(3940) in B decays to K ω J/ψ

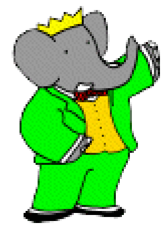


350 fb^{-1} : EPS2007

$M = 3914.3 \pm^{3.4}_{3.8} \pm 1.6$ MeV

$\Gamma = 33 \pm^{12}_{8} \pm 6$ MeV

BR(B to YK) ~ 10-5



BaBar confirms Belle result, but...:

Y(3940) much narrower

Mass shifted 30 MeV below

$M = 3943 \pm 11 \pm 13$ MeV

$\Gamma = 87 \pm 22 \pm 26$ MeV

$Z^{\pm}(4430)$ in $B \to K \pi^{\pm} \psi'$

NEW

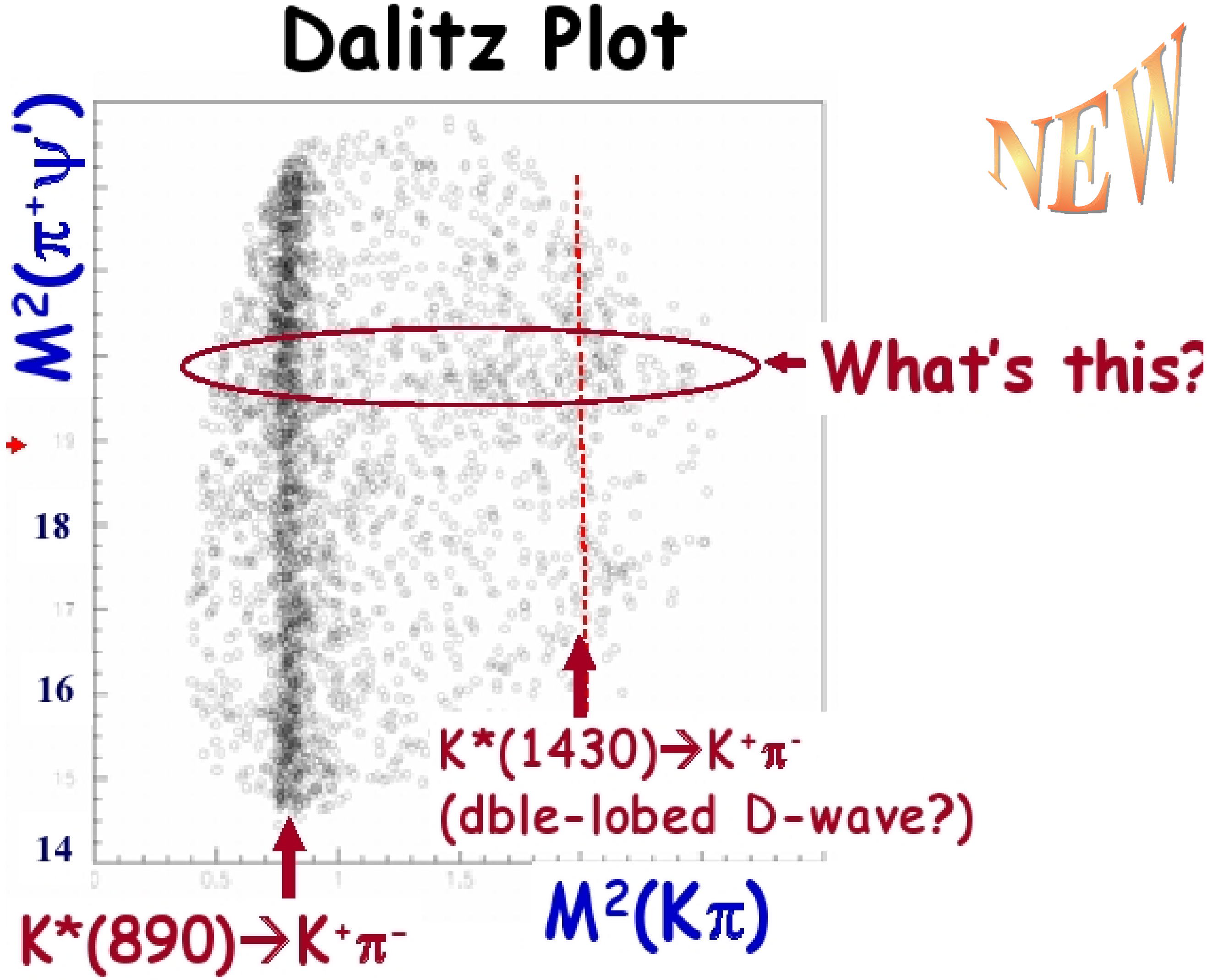
From the analysis of the full Dalitz plot for the channel:

$$B \to K \pi^{\pm} \psi'$$

with reconstruction of

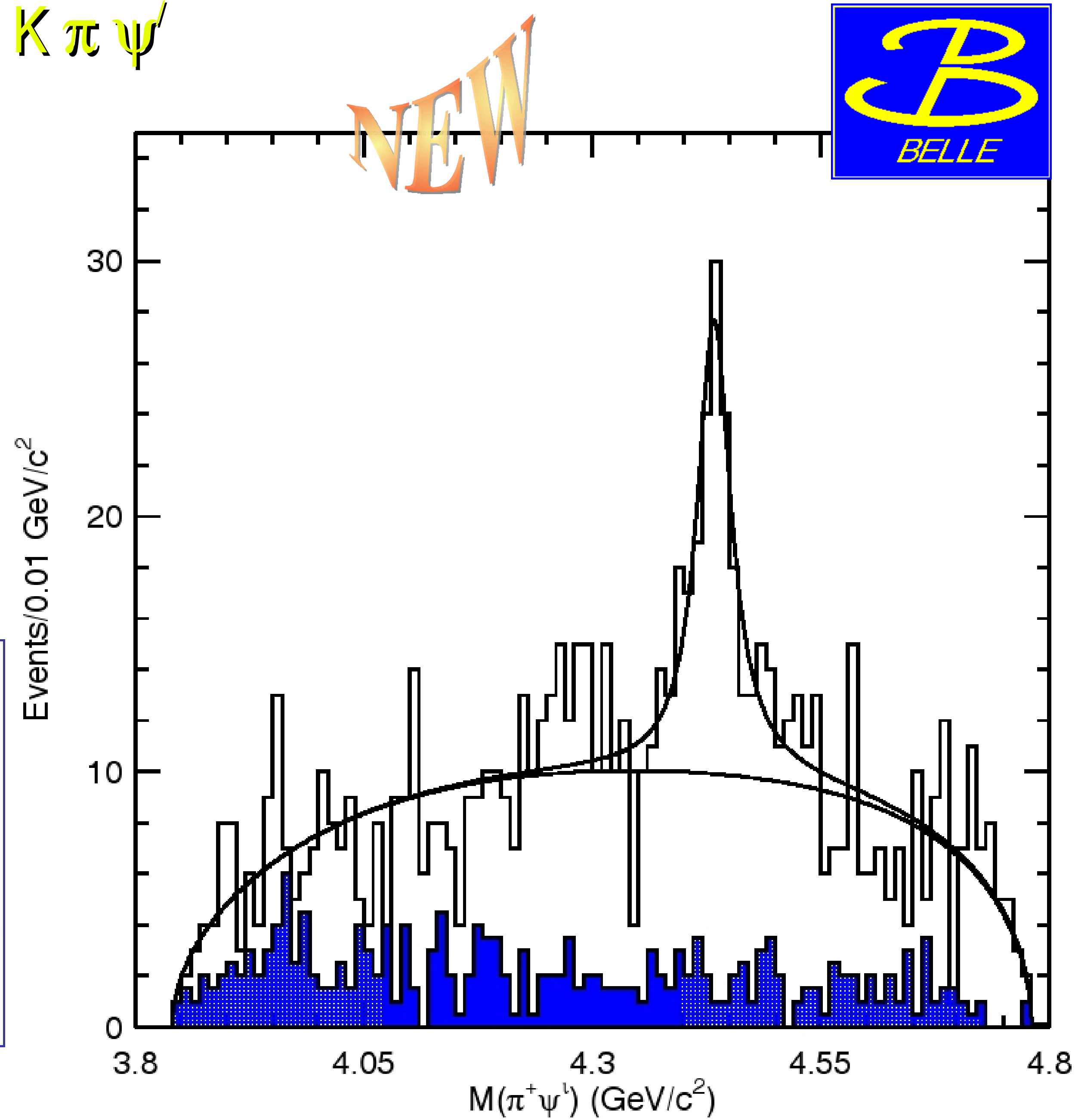
- $\psi' \to (ee,\mu\mu)$
- $\psi' \to (ee,\mu\mu)\ \pi\pi$

decay modes and with both neutral and charged K.



Z(4430) in $B \rightarrow K \pi \psi'$

After cutting +/- 100 MeV around the K*(890) and K*(1400) masses, this peak shown up.

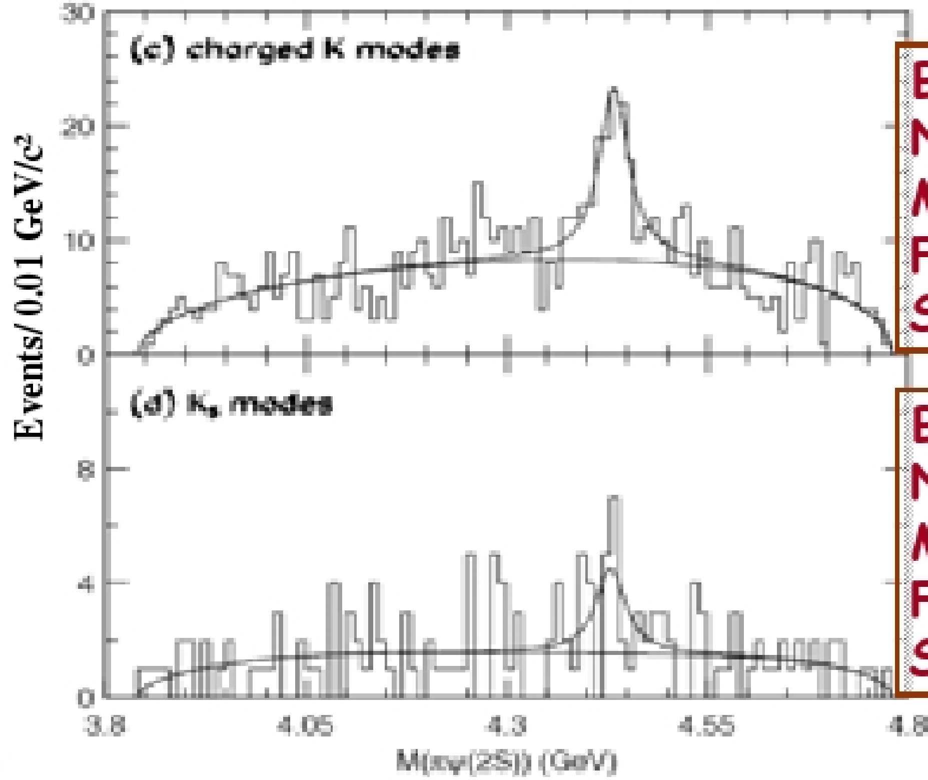


BW Fit Results

N_{signal} = 124.4 ± 30.8 evts
Mass = 4433 ± 4 MeV
FWHM $\Gamma = 44^{+17}_{-13}$ MeV
χ^2/dof = 72.3/94.0 (95.3% CL)
Significance = 7.3 σ

Z(4430) in $B \to K \pi \psi'$

Compare data subsamples
$B^0 \to K^- \pi^+ \psi'$ *vs* $B^+ \to K_S \pi + \psi'$



$B^0 \to K^- \pi^+ \psi'$
N_{signal} = 107 ± 27 evts
Mass = 4434 ± 5 MeV
FWHM Γ = 46^{+17}_{-13} MeV
Signif = 6.6 σ

$B^+ \to K_S \pi^+ \psi'$
N_{signal} = 21 ± 8 evts
Mass = 4430 ± 9 MeV
FWHM Γ = 46 MeV(fixed)
Signif = 3.0 σ

For equal B^+/B^0 Bf's, expect: $N(K_S)/N(K^-)=0.19$ in agreement with measurement: 0.20 +- 0.09

B decays to K + charmonium

BR($B^{\pm} \rightarrow K^{\pm}$ charmonium)*10^4

BR($B^0 \rightarrow K^0$ charmonium)*10^4

	η	ψ	h_c	χ_{C0}	χ_{C1}	χ_{C2}
Upper state, $B^{\pm}$	3.4±1.8	6.48±0.45				
Upper state, B^0		6.2±0.6				
$B^{\pm}$				1.6±0.5	5.3±0.7	
B^0				<5	3.9±0.4	
Lower state, $B^{\pm}$	9.1±1.3	10.08±0.35				
Lower state, B^0	9.9±1.9	8.72±0.33				

BR(B→K "new states")

10^4 *BR(Z4430) *BR($\psi\pi$) = 0.41±0.18

10^4 *BR(Y3940) *BR($\psi\omega$) = 0.71±0.34

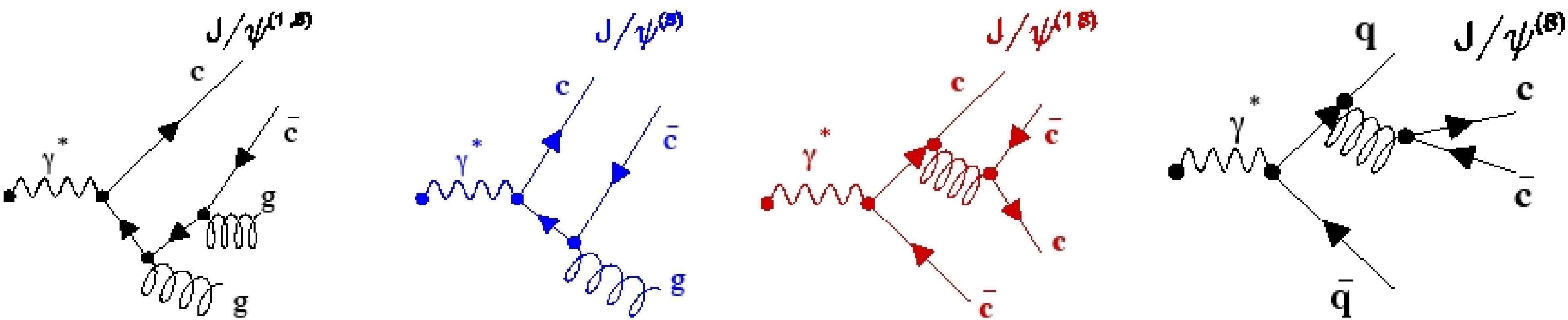
10^4 *BR(X3875) *BR($DD\pi$) = 1.3±0.4

10^4 *BR(X3872) *BR($\psi\pi\pi$) = 0.114±0.020

Double ccbar: a challenge for theory

NRQCD expectations (before 2002)

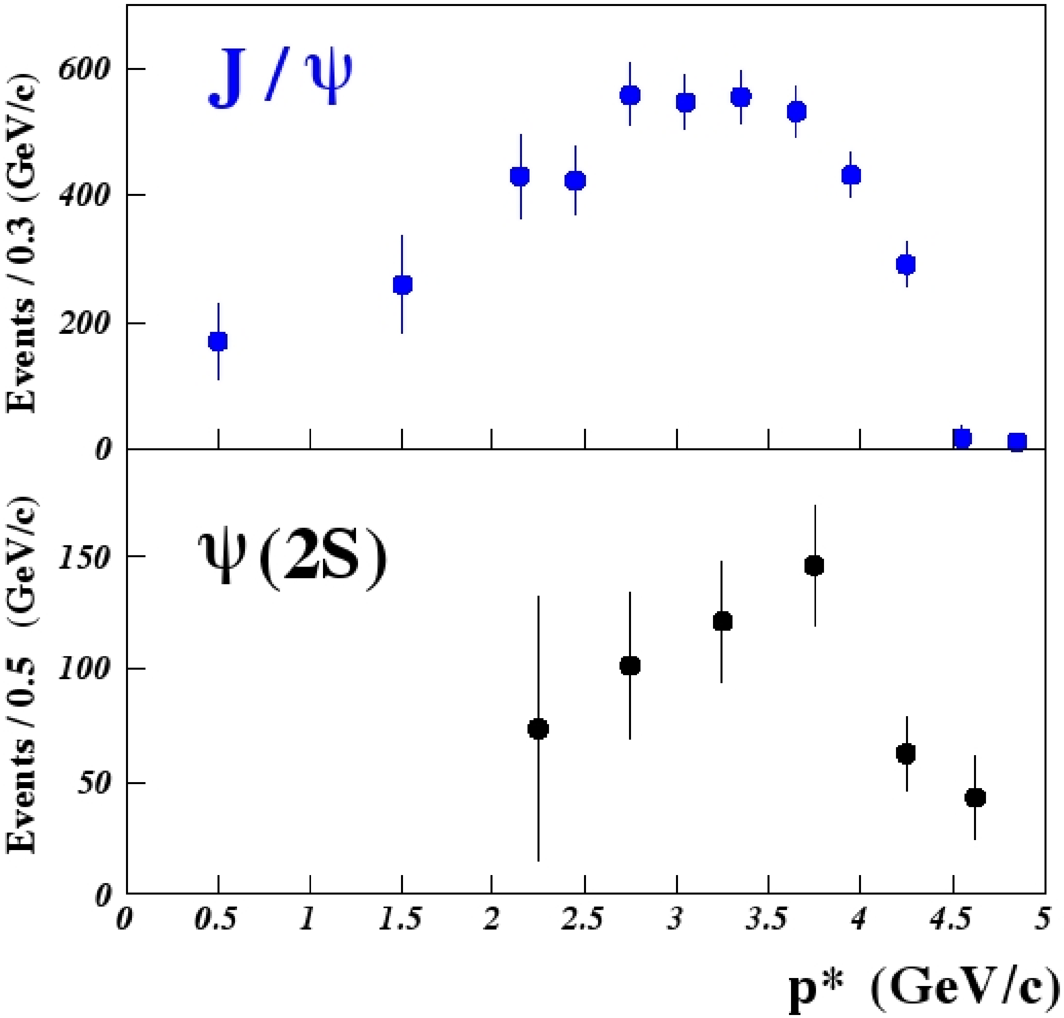
$e^+e^- \to \psi\, gg$ | $\to \psi\, g$ | $\to \psi\, c\bar{c}$ | $\to \psi\, q\bar{q}$



[octet] (for $\to \psi\, g$) | [octet] (for $\to \psi\, q\bar{q}$)

DOMINANT for $\sqrt{s} \approx 10.6\,\mathrm{GeV}$ | dominant at p^* endpoint | $\mathcal{O}(10\%)$ | small

Double ccbar: a challenge for theory



Why the p* spectrum of J/ψ ends before the kinematic limit?

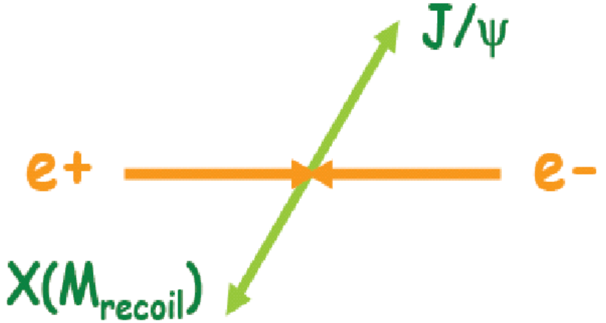
Why octet terms do not show up at the endpoint?

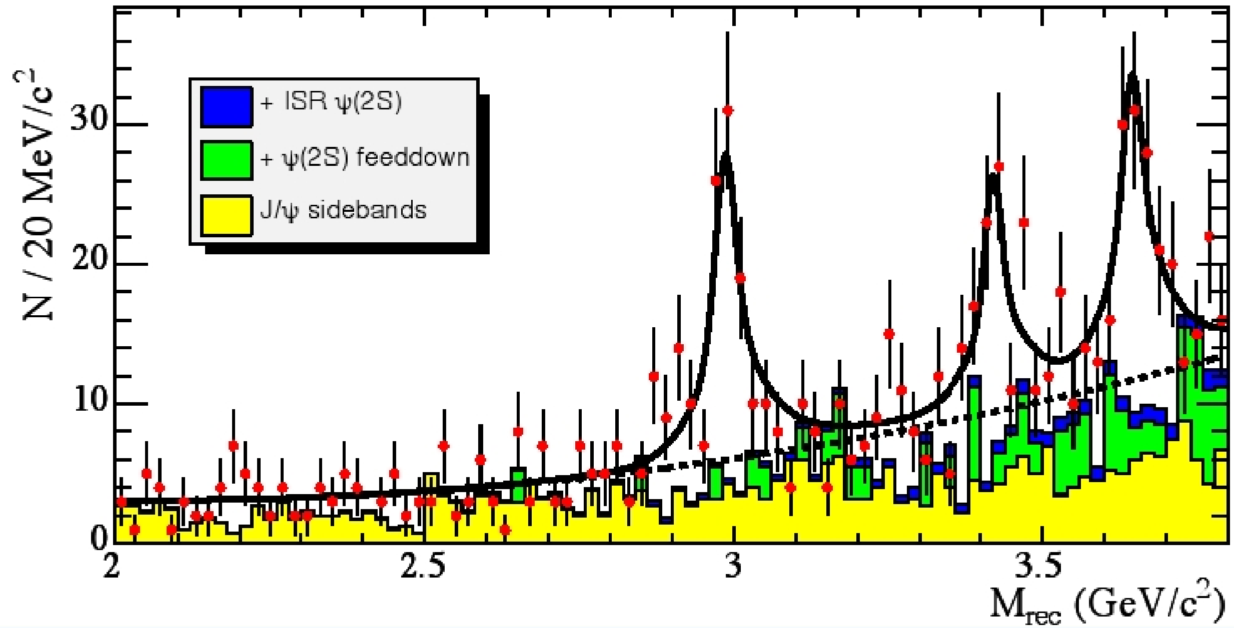
NRQCD predictions are totally wrong?

Plot as a function of $M_{recoil}(J/\psi)$:

$$M_{\rm recoil}(\psi) = \sqrt{(\sqrt{s} - E^*_\psi)^2 - (p^*_\psi)^2}$$

Scanning charmonia with J/ψ recoil





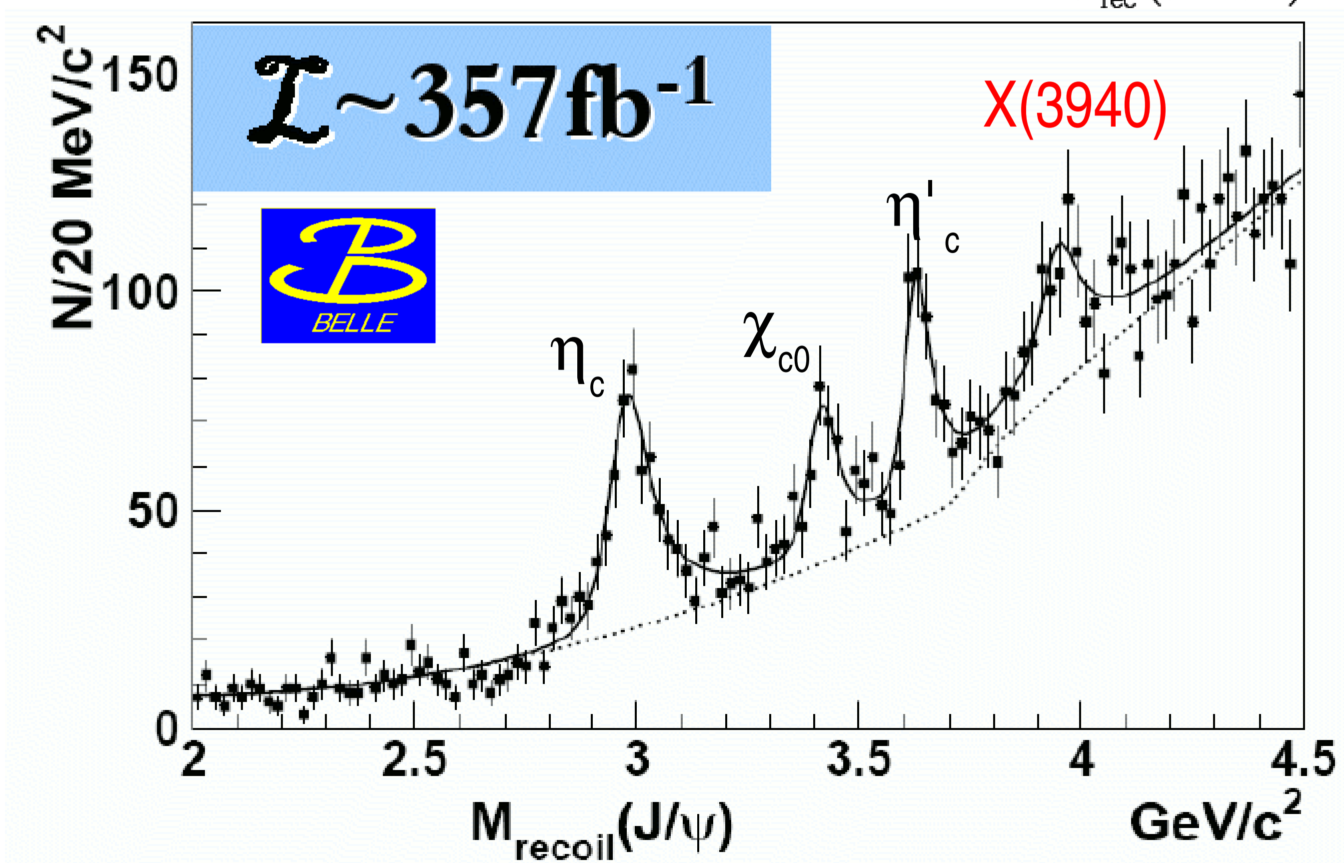
First: 3 peaks, from J=0 charmonia, with 2nd evidence of $\eta_c(2S)$:

Belle: PR D 70, 071102(R) (2004)

BaBar: PR D 72, 031101(R) (2005)

Then: discovery of X(3940) :

Belle: PRL 98, 082001 (2007)



NRQCD crisis ?

$J/\psi\,(c\bar{c})_{res}$		$\eta_c(1S)$	χ_{c0}	$\eta_c(2S)$
Belle	$\sigma \times \mathcal{B}_{>2}$ [fb]	$25.6 \pm 2.8 \pm 3.4$	$6.4 \pm 1.7 \pm 1.0$	$16.5 \pm 3.0 \pm 2.4$
BaBar	$\sigma \times \mathcal{B}_{>2}$ [fb]	$17.6 \pm 2.8^{+1.5}_{-2.1}$	$10.3 \pm 2.5^{+1.4}_{-1.8}$	$16.4 \pm 3.7^{+2.4}_{-3.0}$
NRQCD:	σ [fb]			
Braaten&Lee[1]		3.78 ± 1.26	2.40 ± 1.02	1.57 ± 0.52
...with relativistic corr^{ns}:		$7.4^{+10.9}_{-4.1}$	–	$7.6^{+11.8}_{-4.1}$
Liu,He,&Chao[2]		5.5	6.9	3.7
Zhang,Gao,&Chao[3]		14.1	–	–
				–

- **The K-factor from the resummed relativistic corrections is greater than that from the QCD NLO corrections found by Zhang, Gao, and Chao.**

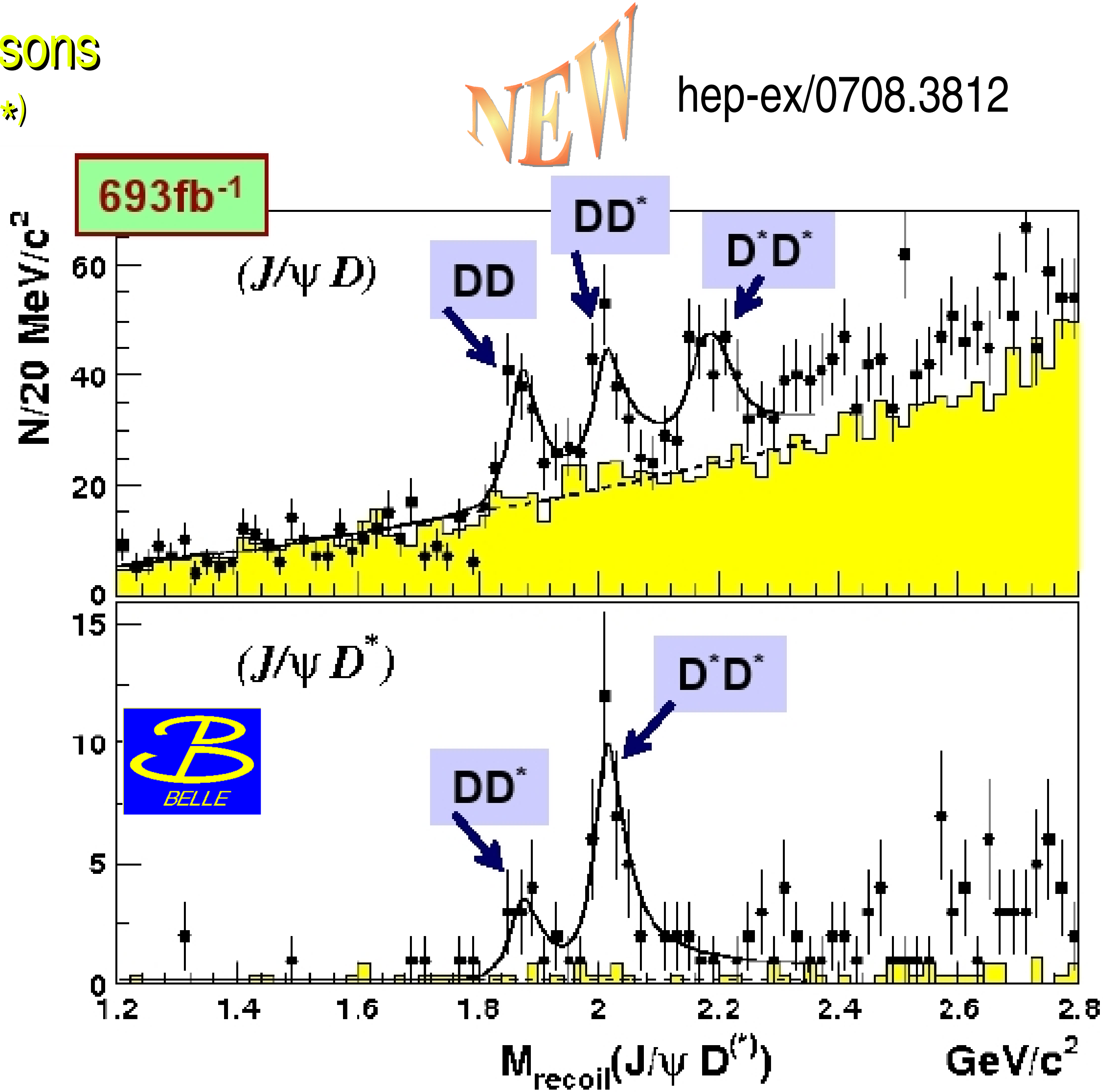
$$\text{K-Factor} = (1 + \underbrace{0.8}_{\text{QCD NLO}}) \times (1 + \underbrace{1.45 \pm 0.61}_{v^2\ \text{Resummation}})$$

- Without (QCD NLO)$\times$(v^2 Resum.) term:
  $(3.78\ \text{fb})_{\text{LO}} \times (3.25 \pm 0.61) = \mathbf{12.3 \pm 2.3}$ fb
- With estimated (QCD NLO)$\times$(v^2 Resum.) term:
  $(3.78\ \text{fb})_{\text{LO}} \times (4.41 \pm 1.10) = \mathbf{16.7 \pm 4.2}$ fb

Braaten & Lee (QWG2006)

Scanning charmed mesons recoiling on $J/\psi+D^{(*)}$

hep-ex/0708.3812



Another development:

D^+ reconstructed in 3 decay modes (12%):

$K^-\pi^+\pi^-$, $K^+K^-\pi^+$, $K_S^0\pi^+$

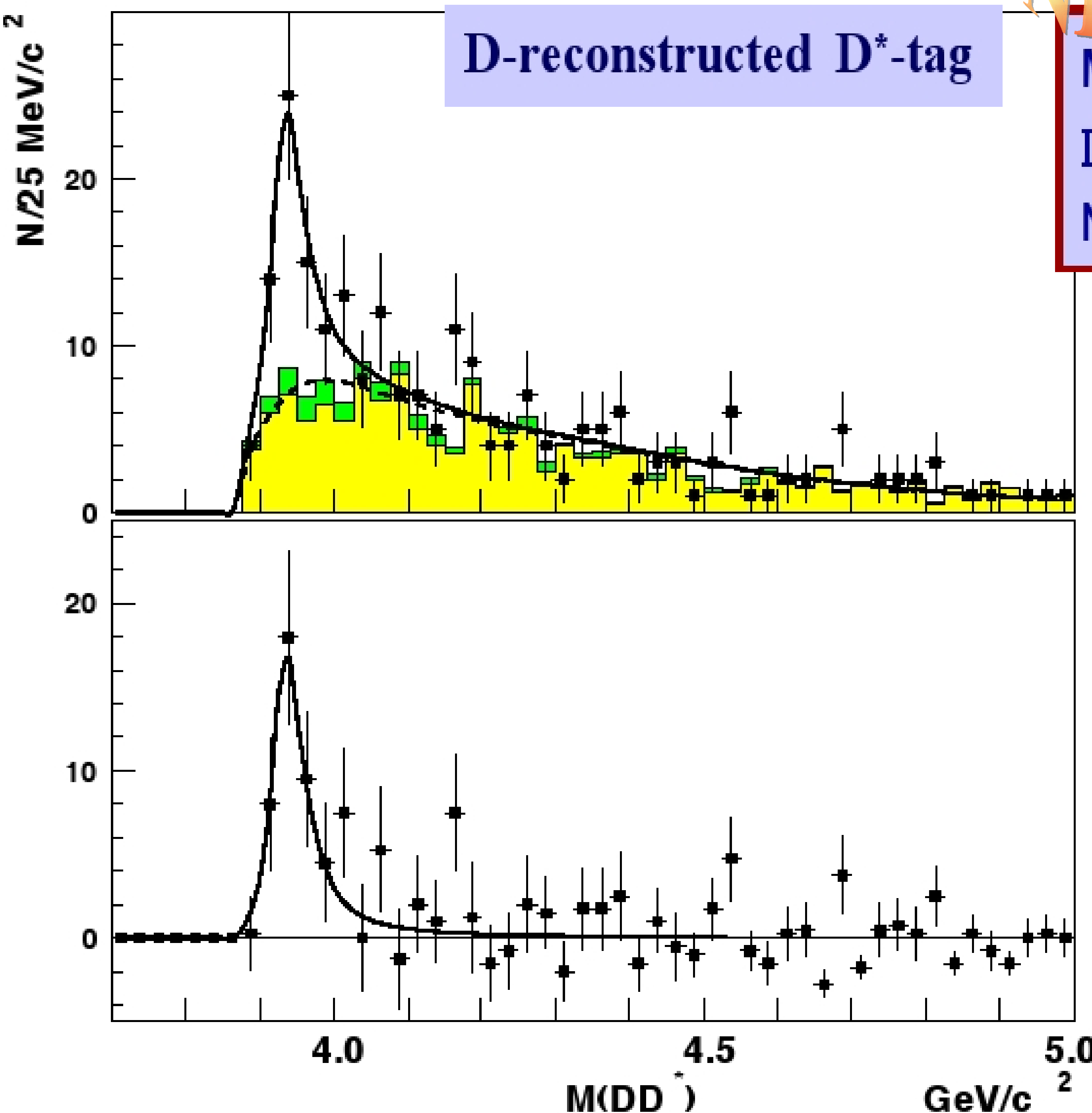
D^0 reconstructed in 5 decay modes (29%):

$K^-\pi^+$, K^+K^-, $K^-\pi^+\pi^-\pi^+$, $K_S^0\pi^+\pi^-$, $K^+K^-\pi^0$

(Details in Eidelman's talk)

X(3940) parameters

[hep-ex/0708.3812]



NEW

$M = 3942^{+7}_{-6} \pm 6$ MeV

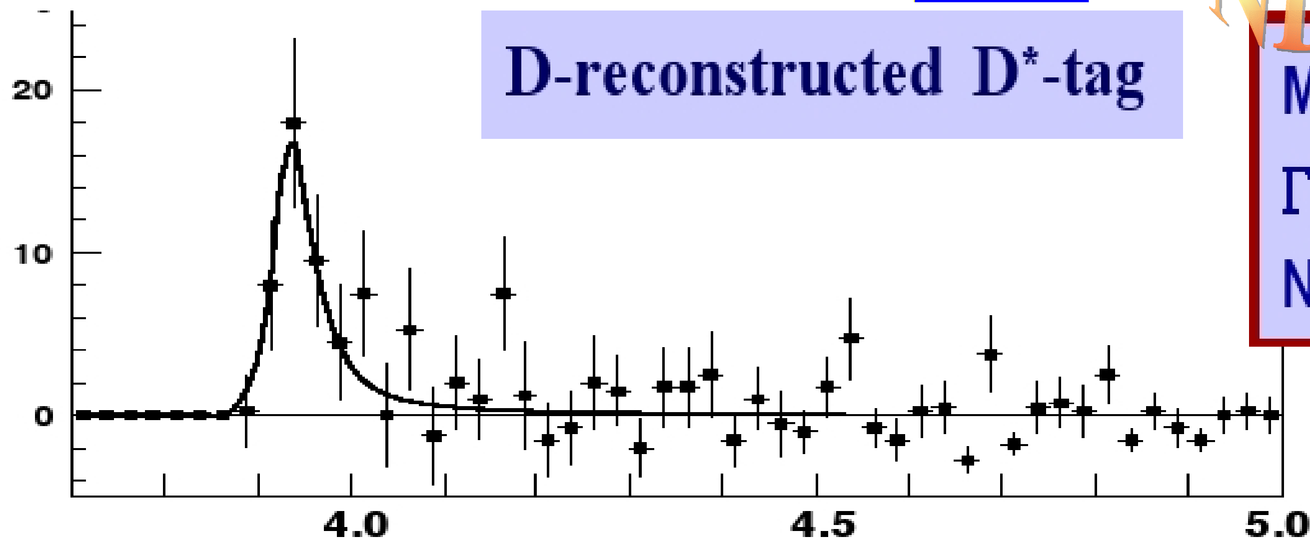
$\Gamma_{tot} = 37^{+26}_{-15} \pm 12$ MeV

$N_{ev} = 52^{+24}_{-16} \pm 11$

J^{PC} (X3940)$\neq 0^{++}, 2^{++}$

.... and a new discovery!

[hep-ex/0708.3812]



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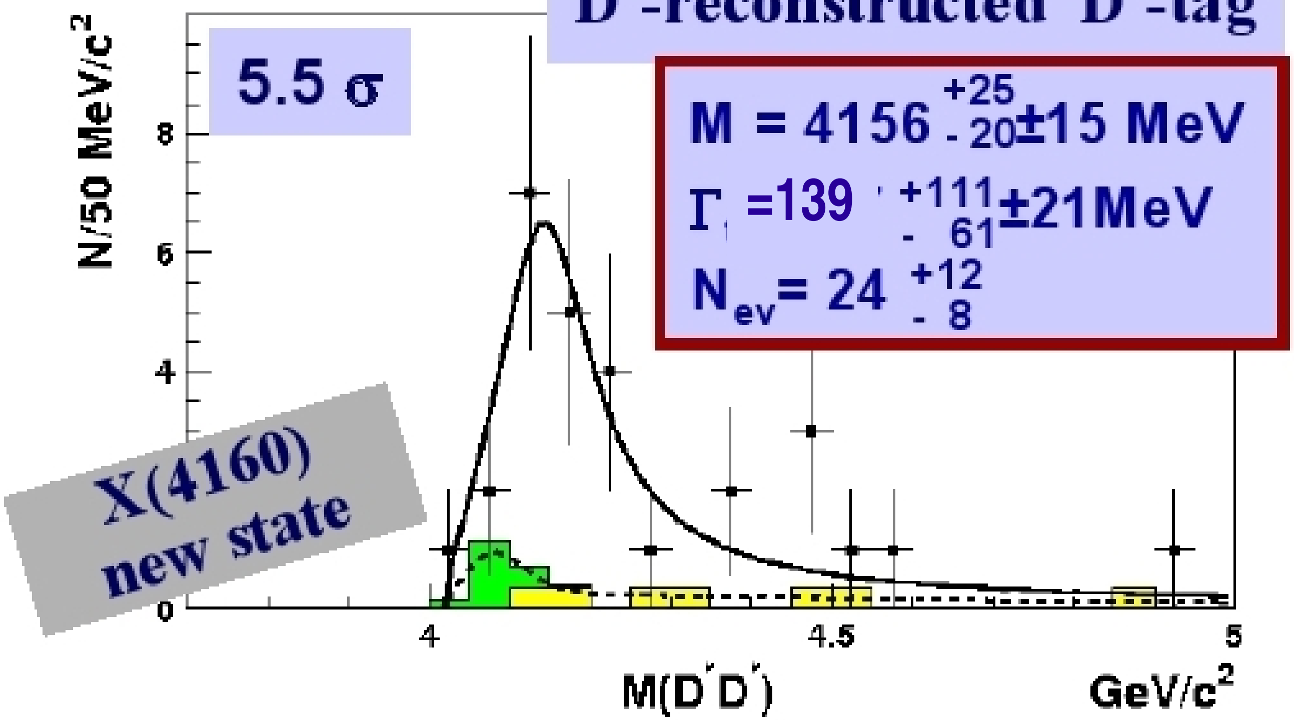


$M = 4156^{+25}_{-20} \pm 15$ MeV

$\Gamma_t = 139^{+111}_{-61} \pm 21$ MeV

$N_{ev} = 24^{+12}_{-8}$

Charmonium candidates in range ? $\eta_c(3S)$?

Double ccbar cross sections

		$J/\psi\ (c\bar{c})_{res}$	$\eta_c(1S)$	χ_{c0}	$\eta_c(2S)$
Belle	$\sigma \times \mathcal{B}_{>2}$ [fb]		$25.6 \pm 2.8 \pm 3.4$	$6.4 \pm 1.7 \pm 1.0$	$16.5 \pm 3.0 \pm 2.4$
BaBar	$\sigma \times \mathcal{B}_{>2}$ [fb]		$17.6 \pm 2.8^{+1.5}_{-2.1}$	$10.3 \pm 2.5^{+1.4}_{-1.8}$	$16.4 \pm 3.7^{+2.4}_{-3.0}$

BELLE

$\sigma(\psi(2S)\,(c\bar{c})_{res}) \times \mathcal{B}_{>0}$ [fb]	$16.3 \pm 4.6 \pm 3.9$	$12.5 \pm 3.8 \pm 3.1$	$16.0 \pm 5.1 \pm 3.8$

$$\sigma(e^+e^- \to J/\psi X(3940))\mathcal{B}_{D^*\overline{D}} = (13.9^{+6.4}_{-4.1} \pm 2.2)\,\mathrm{fb}$$

$$\sigma(e^+e^- \to J/\psi X(4160))\mathcal{B}_{D^*\overline{D}^*} = (24.7^{+12.8}_{-\ \ 8.3} \pm 5.0)\,\mathrm{fb}.$$

Double ccbar cross sections:

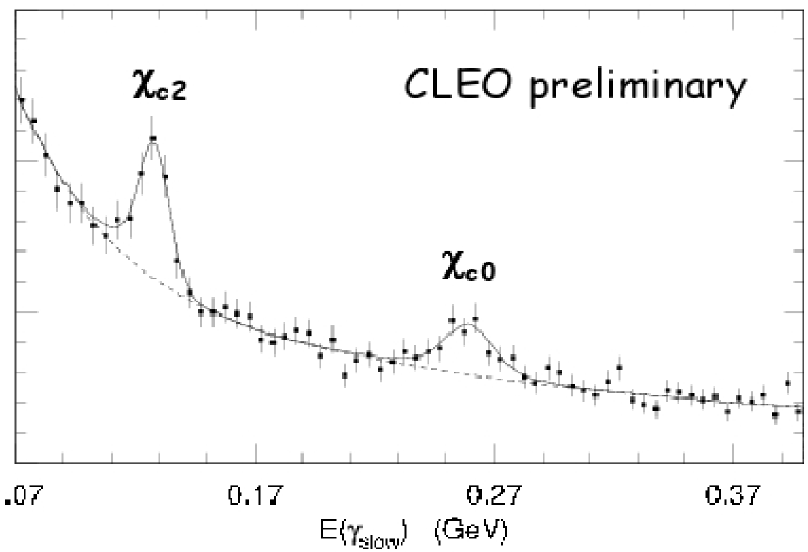
a) do not decrease in ψ(2s) recoil

b) do not decrease if higher masses recoil on J/ψ

2γ physics: precision studies in decays and spectroscopy

First evidence of $\chi_{c0,2}(1P) \to \gamma\gamma$

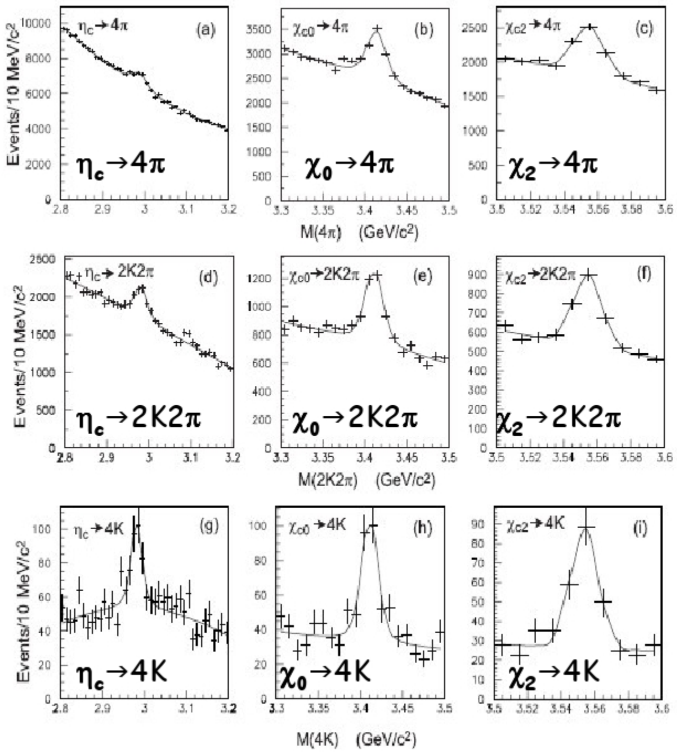
from 28M $\psi(2S)$ decays to $\gamma\gamma\gamma$



(check for news in Shepherd's talk)

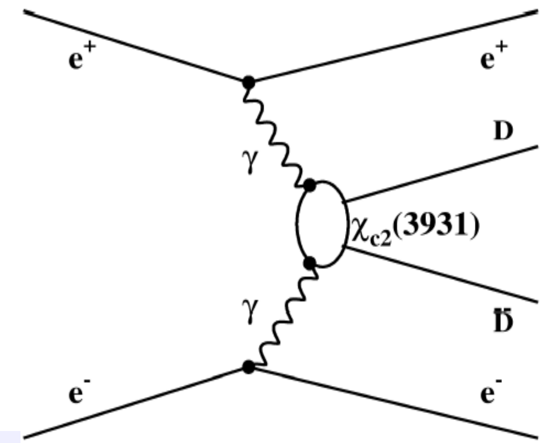
thorough study of

$\gamma\gamma \to \eta_c(1,2S), \chi_{c0,2}(1P)$



(details in Eidelman's talk)

Z(3930) in $\gamma\gamma$ fusion



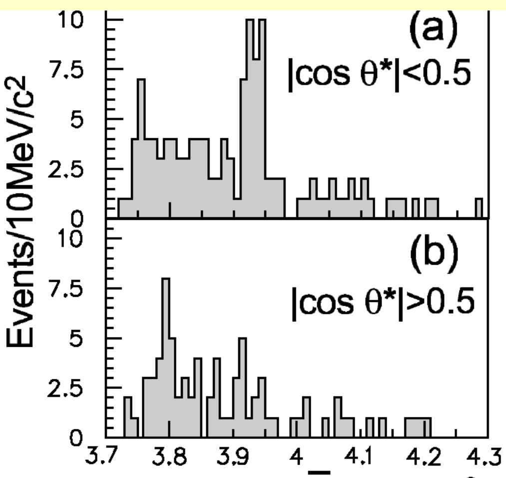
Belle, 395 fb^{-1}: PRL 96 (2006), 82003 (hep-ex/0507033)

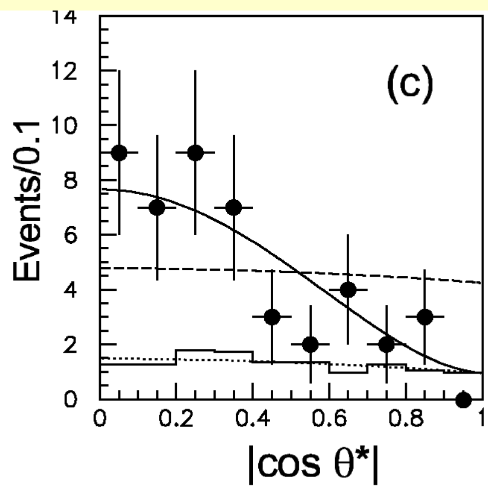
M=3929 ± 5 ± 2 MeV ; Γ=29±10 ±2 MeV

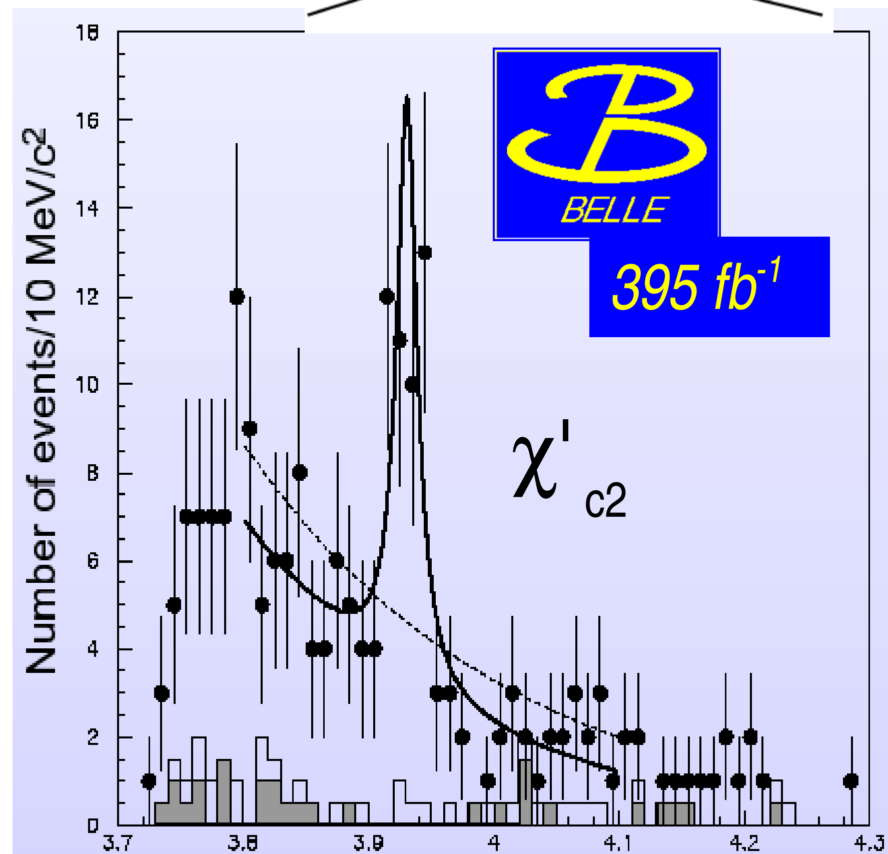
$\Gamma_{\gamma\gamma}$·BR(Z→D$\underline{D}$) = **180±50±30 eV**

64± 18 evts (5.3σ significance)

Angular distributions favor J^{PC} = 2^{++}







Fits charmonium hypothesis as χ'_{c2}(2P)

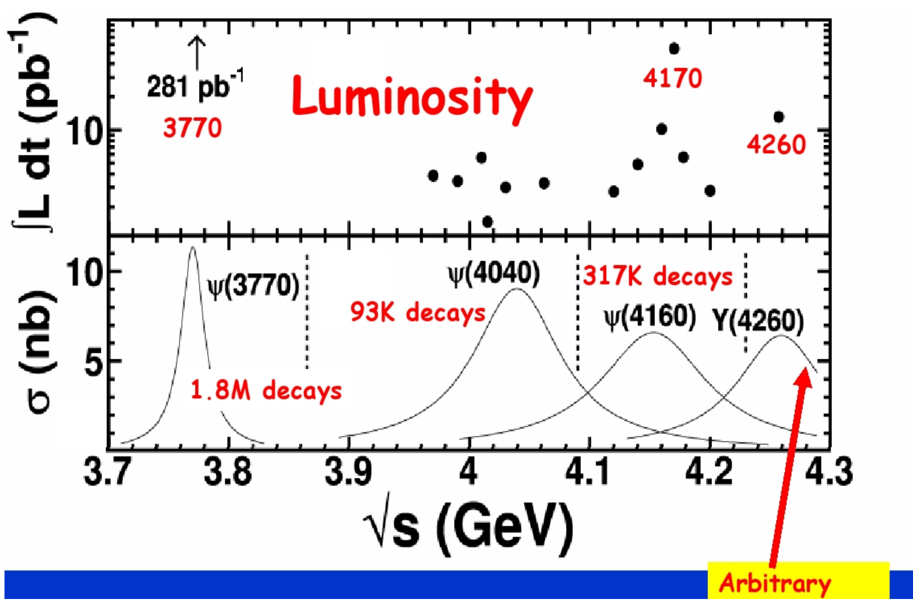
NEED: CONFIRMATION BY BaBar , DD : D*D* ratio

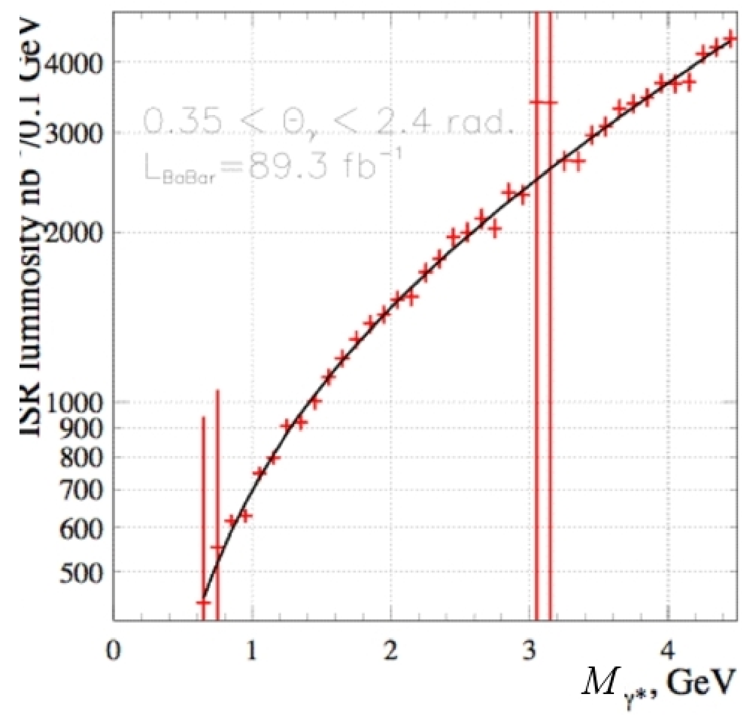
ISR scanning:

Radiative return yields vs direct scanning:

	Y(4S) Ldt [fb^{-1}]	Y(3S) [10^6]	Y(2S) [10^6]	Y(1S) [10^6]	dL/dE@4 GeV pb^{-1}/100MeV
BaBar	500	12	8	15	22
Belle	700	17	11.2	21	31
CLEO-III		6	9	29	

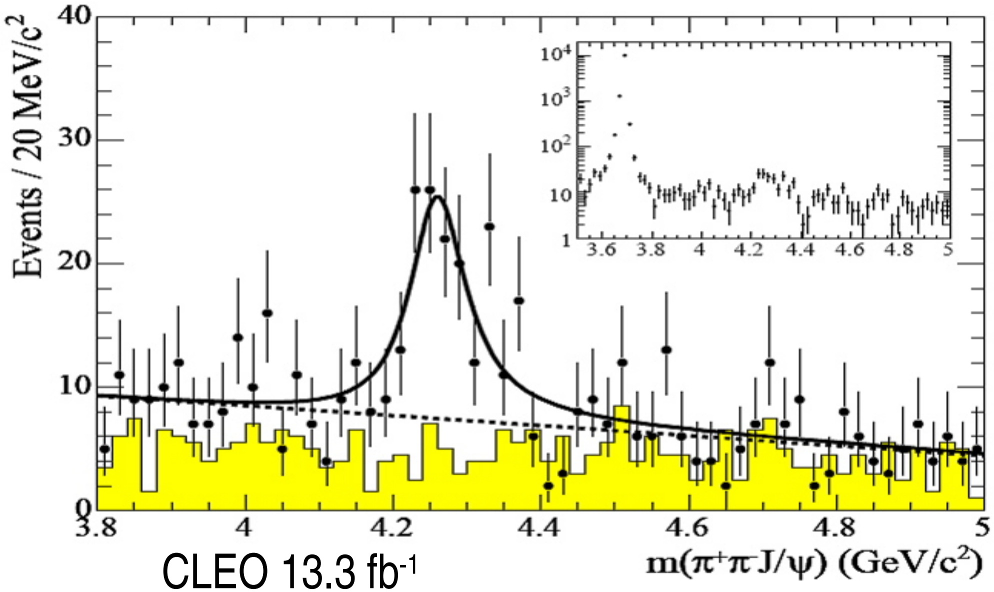
CLEO-c



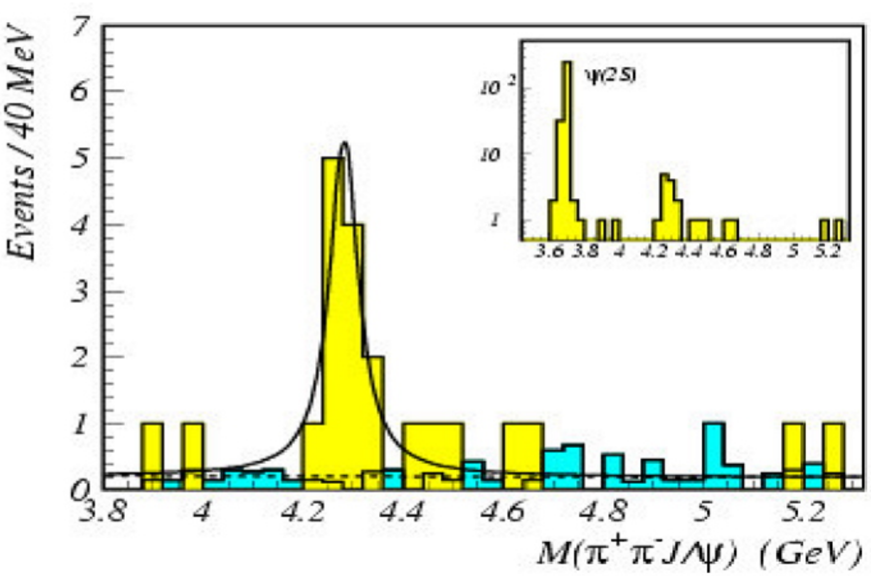


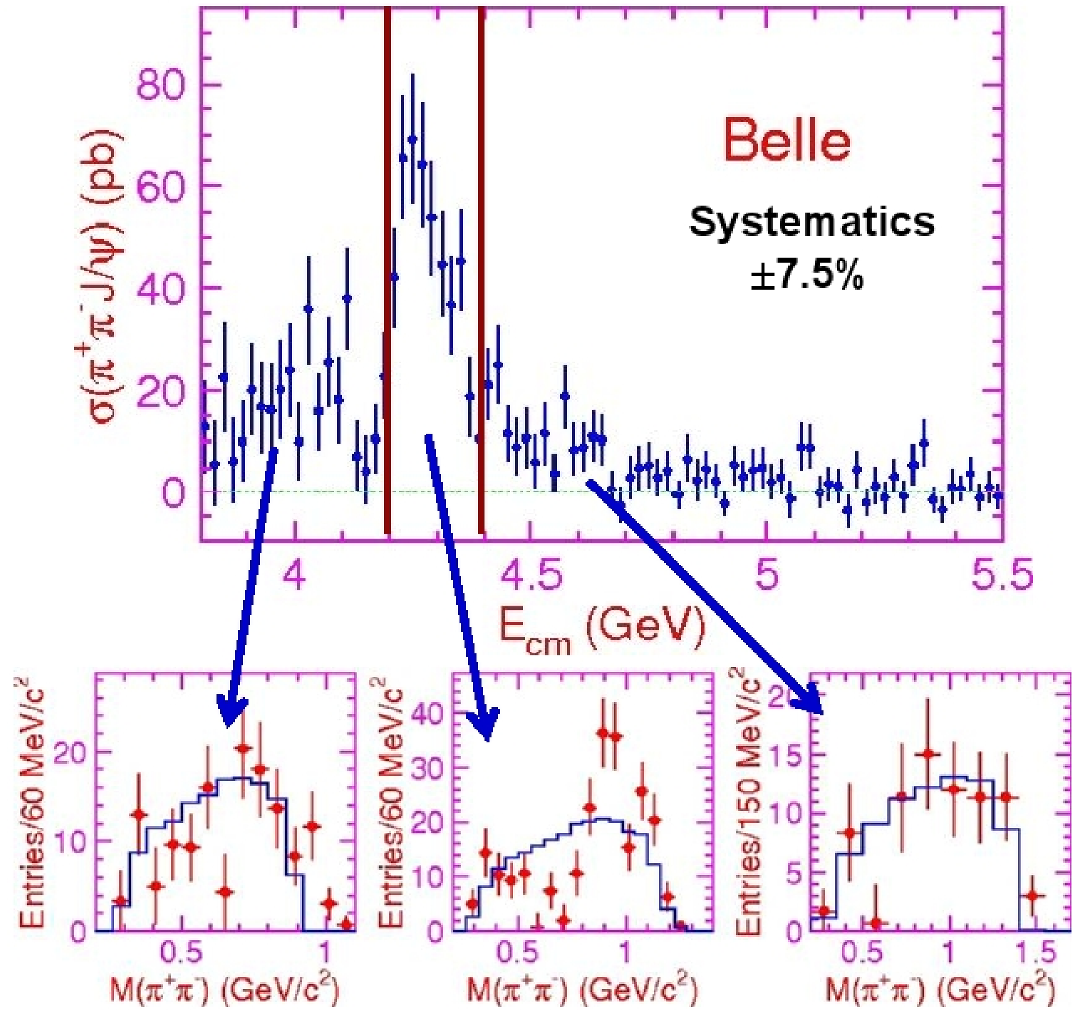
Y(4260) in $e^+e^- \to \pi^+\pi^- J/\psi$

BaBar PRL95, 142001 (2005): 233 fb^{-1}



CLEO 13.3 fb^{-1}





Exp	Mass(MeV)	Width(MeV)
BaBar	$4259 \pm 8^{+2}_{-6}$	$88 \pm 23^{+6}_{-4}$
CLEO	$4283^{+17}_{-16} \pm 4$	$70^{+40}_{-25} \pm 5$
Belle	$4247 \pm 12^{+17}_{-26}$	$108 \pm 9^{+8}_{-10}$

(previous result superseded)

Y(4360) in $e^+e^- \rightarrow \pi^+ \pi^- \psi'$

BaBar (ICHEP 2006) shows a peak in

$\pi^+ \pi^- \psi'$

which does not match the expected Y(4260) state mass and width.

Belle confirms it, and finds a new one :

Y(4360)

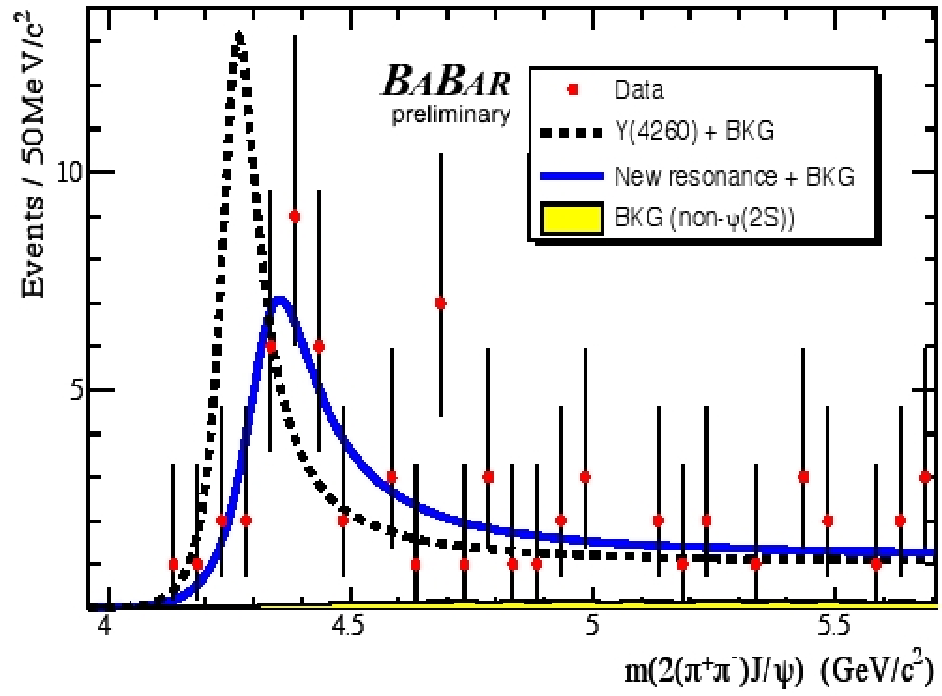
Mass = 4361±9±9 MeV/c^2

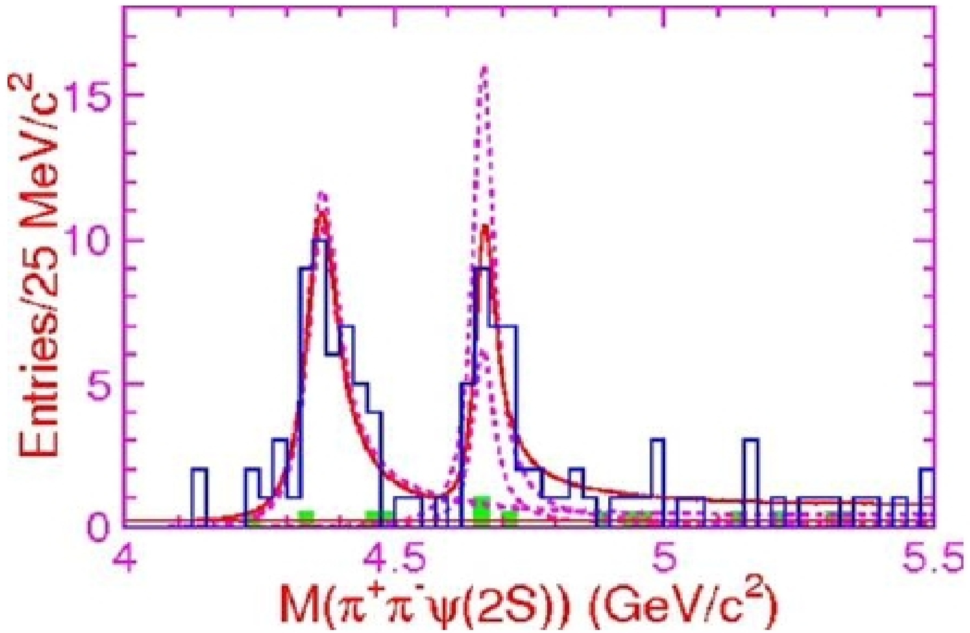
Width = 74±15±15 MeV

Y(4660)

Mass = 4664±11±5 MeV/c^2

Width = 48±15±3 MeV





Understanding the R ratio from 3.8 to 5 GeV

CLEO-c : hep-ex/0606016

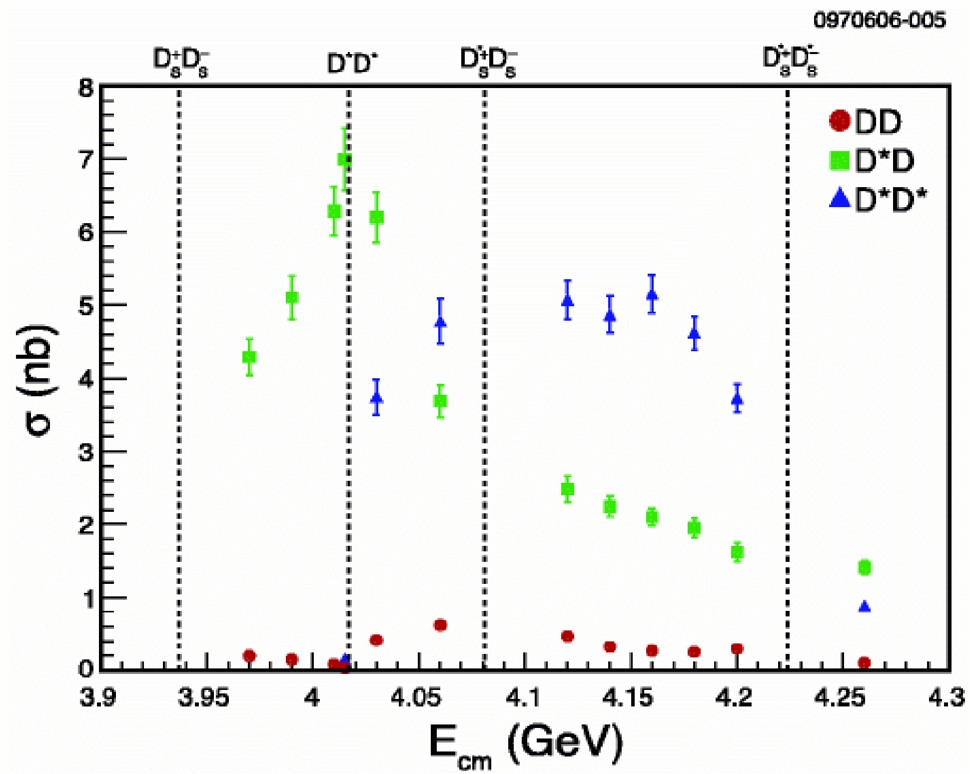


Figure 8: Cross sections for $D\bar{D}$, $D\bar{D}^*$, and $D^*\bar{D}^*$ from the CLEO-c scan run.

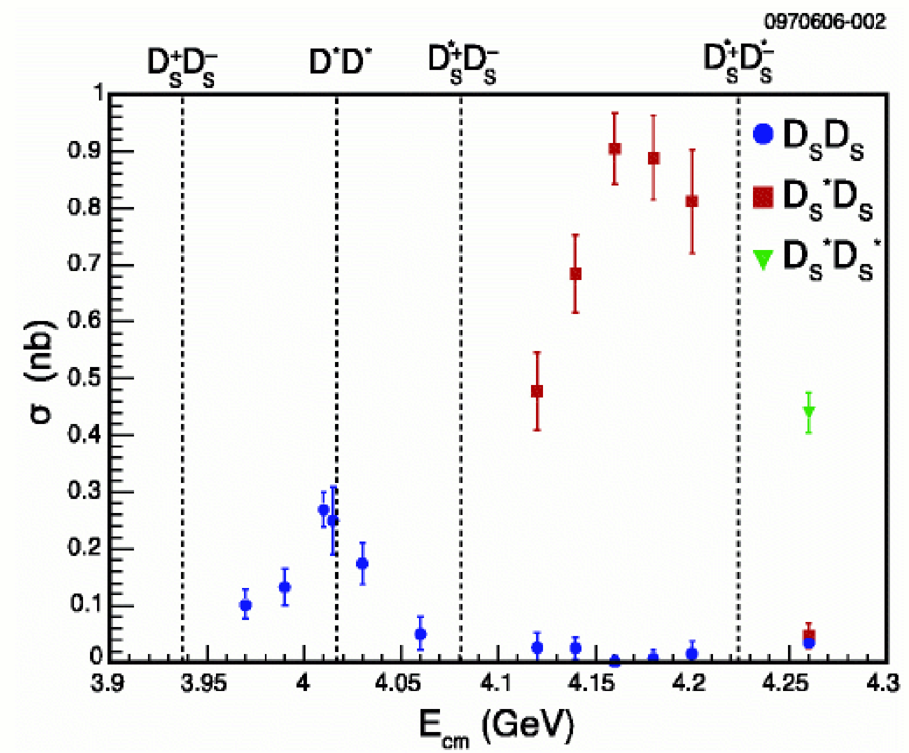
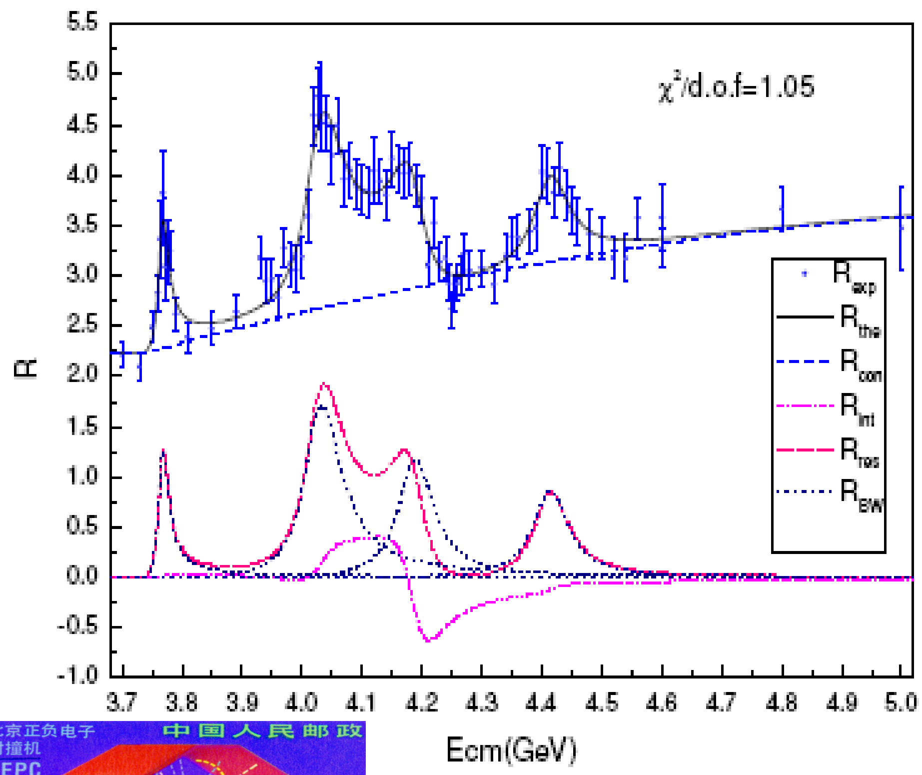


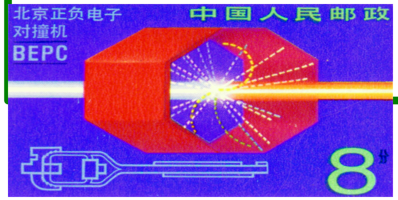
Figure 9: Cross sections for $D_s\bar{D}_s$, $D_s\bar{D}_s^*$, and $D_s^*\bar{D}_s^*$ (only accessible at the highest point) from the CLEO-c scan run.

Theory: Cornell Coupled Channel (CCC) model has to be retuned to fit the new datasets.

Refitting the R ratio from 3.8 to 5 GeV .... and rescanning it in ISR!

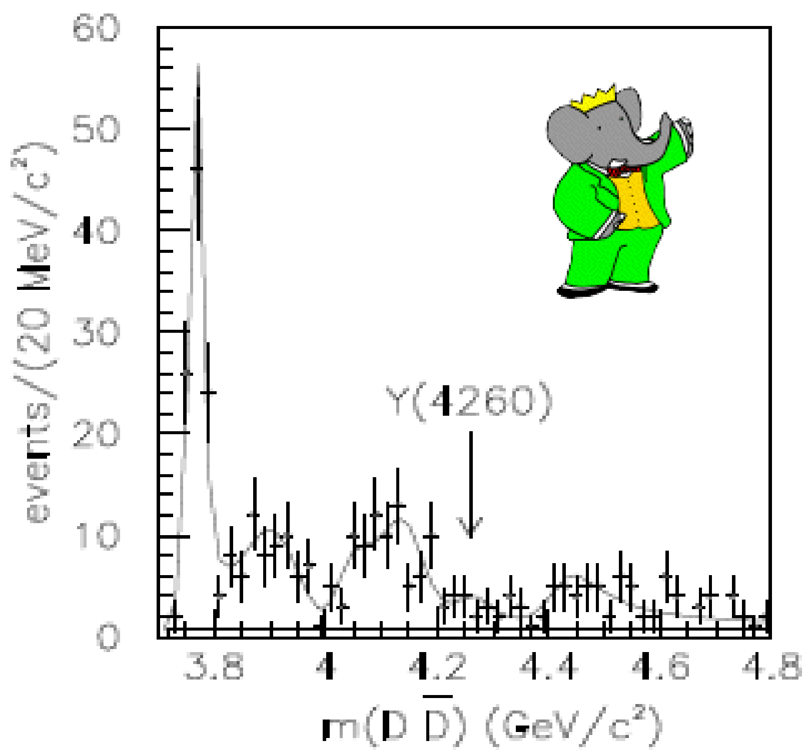
Full refitting of the BES scans, including interference terms





hep-ex/0705.4500 (see Yuan's talk)

First D$\underline{D}$ cross section in ISR

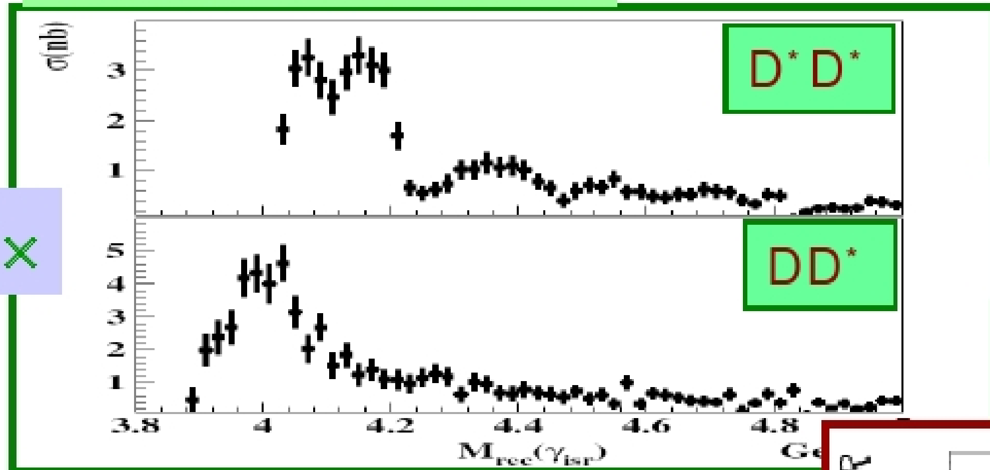


hep-ex/0607083

Complete decomposition of R ratio from 3.8 to 5 GeV

Phys. Rev. Lett. 98, 092001 (2007)

2×



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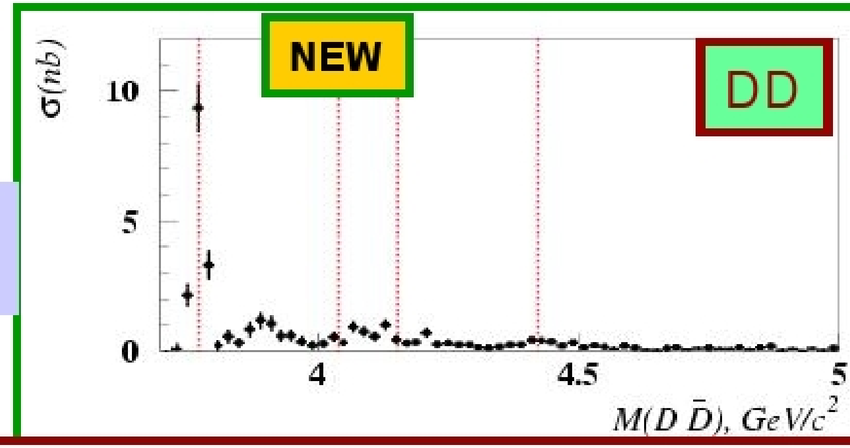

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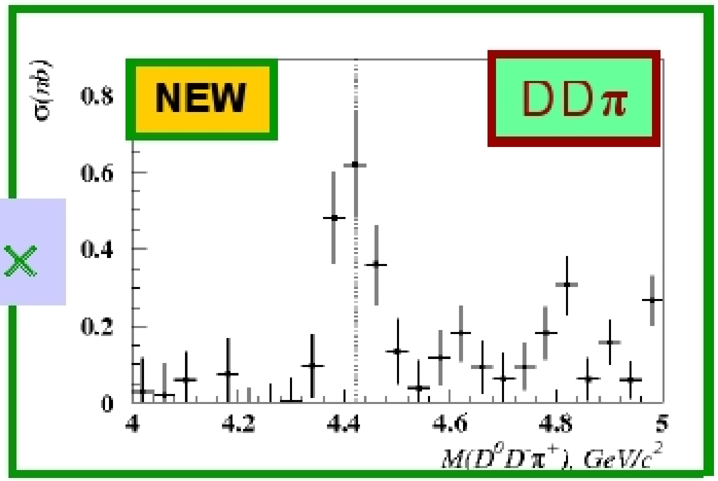

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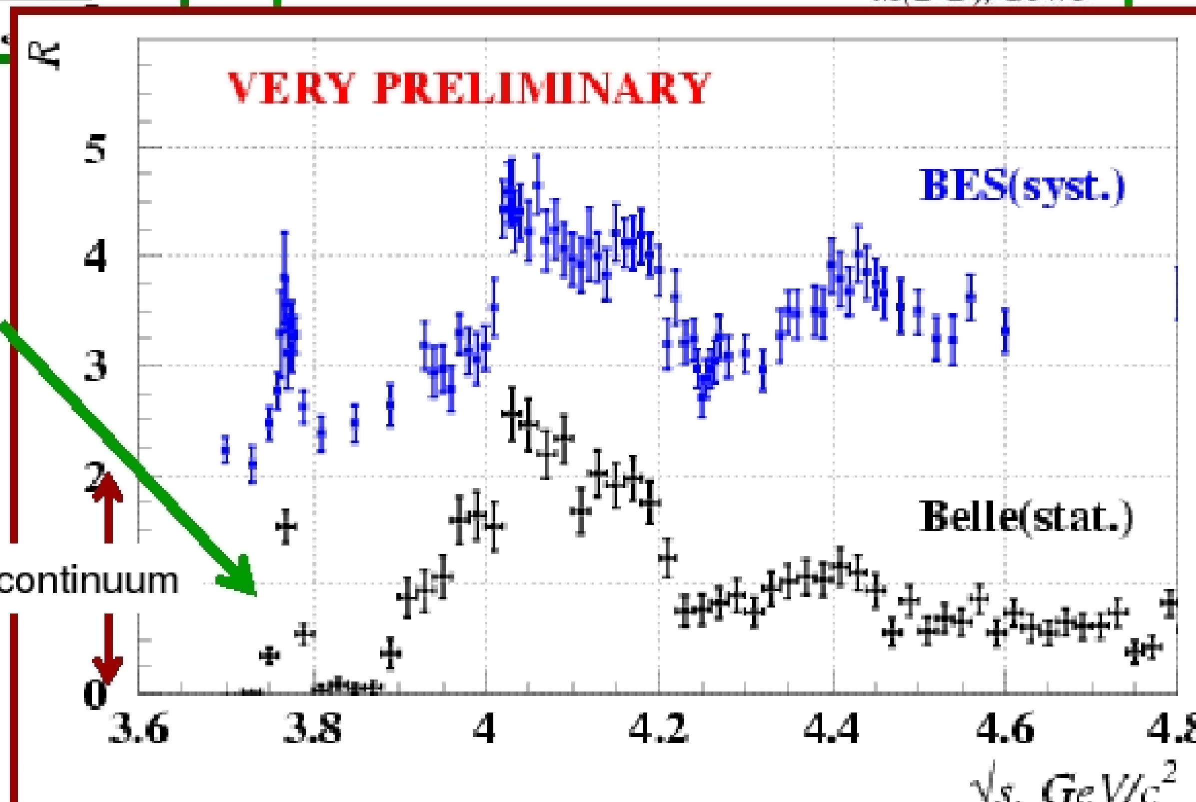


uds-continuum

These 4 final states almost saturate inclusive cross section

Naming the Vector Zoo: summary and prospects

4.02 : D*D* threshold, decays mainly to D*D , and $\underline{D}_S D_S$, maybe also J/ψ ππ

4.16: strong interference effects between $\underline{D}$*D and $\underline{D}$*D*, clear peak in $\underline{D}_S{}^*D_S$

4.26: Decays to J/ψ ππ ; unclear if it peaks in $\underline{D}_S{}^*D^*{}_S$

4.35: Decays to ψ(2S)ππ

4.42: Decays to $\underline{D}D_2$(2420) and nothing else : D wave ?

4.66: Decays to ψ(2S)ππ

Belle and CLEO- c : J/ψ KK is another fertile field: more statistics needed!

Further insights will come from:

- CLEO-c large dataset at Ecm = 4.17 GeV
- BaBar, Belle: full ISR deconvolution of $\underline{D}_S{}^{(*)}D_S{}^{(*)(*)}$

Tevatron experiments may find further peaks in J/ψ ππ and ψ(2S)ππ

What can we learn from Y(5S) running? *Don't miss Hou's talk, this afternoon !!!*

Precision studies on the lower states

Outstanding problems in spectroscopy of states below threshold:

-- Find the missing J=2 D waves in charmonium

-- Precise Mass and Width of h_c

-- Solve current inconsistencies between $\eta_c(1,2S)$ mass and width measurements with different experimental techniques.

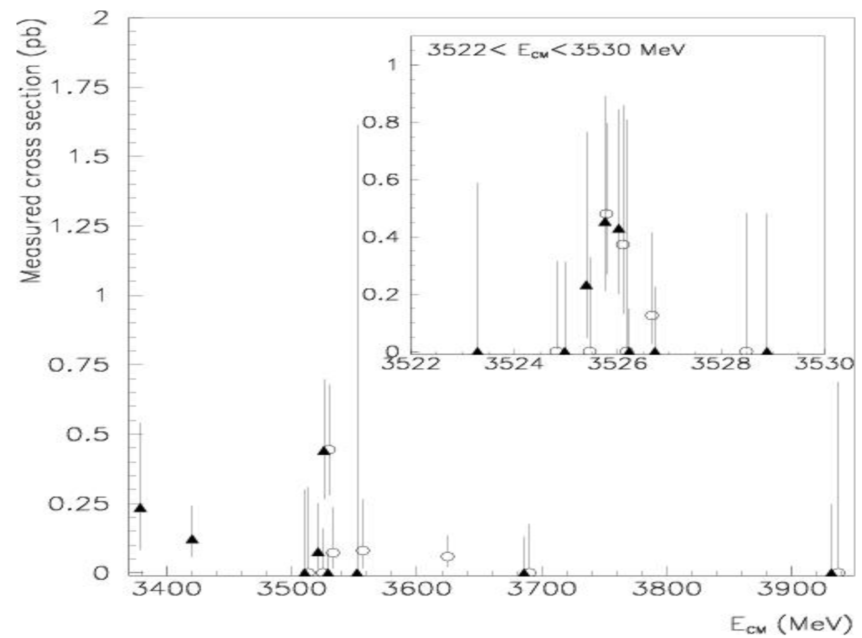
-- FIND ALL THE PARABOTTOMONIA

The h_c ($^1P_1$) saga

- E835 signal: *PRD72, 032001 (2005)*

  $p\bar{p} \to h_c \to \eta_c \gamma \to \gamma\gamma\gamma$

- $\Gamma_{in} B_{out} = (3.1\pm1.1\pm1.0)\text{x}10^{-3}$ eV
- M = 3525.8±0.2(stat)±0.2(syst) MeV



- CLEO-c signal, with 3M ψ' :

  $\psi' \to h_c \pi \to \eta_c \gamma \pi$

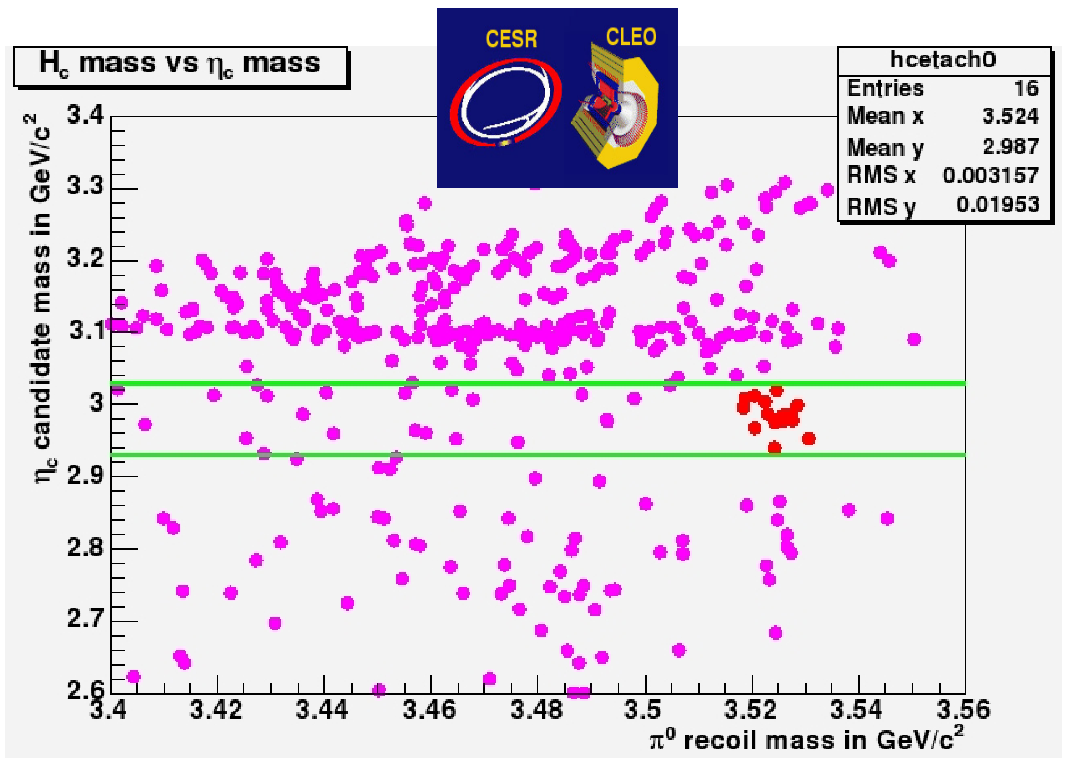
  Inclusive AND exclusive evidence (5σ)

  $BR(\psi' \to \pi h_c) * BR(h_c \to \gamma\eta_c) = (4.0\pm0.8\pm0.7)*10^{-4}$

M = 3524.9±0.7(stat)±0.4(syst) *[incl]*

= 3524.4±0.6(stat)±0.4(syst)*[all]*

PRD72(2005),092004 ; PRL95(2005),102003



NRQCD Estimates on η_b Parameters

Calculation at NLL of $M(\eta_b)$:

$M(\eta_b) = 9421 \pm 10(th) \pm 9(\delta\alpha_s)$ MeV/c^2

Kniehl et al., PRL 92(2004),242001

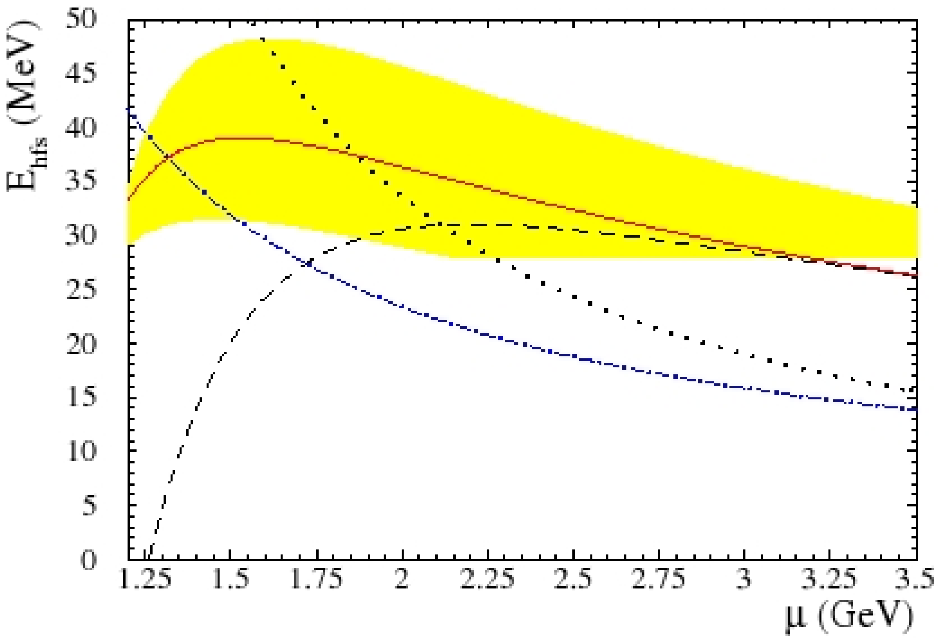


FIG. 1: HFS of 1S bottomonium as a function of the renormalization scale μ in the LO (dotted line), NLO (dashed line), LL (dot-dashed line), and NLL (solid line) approximations. For the NLL result, the band reflects the errors due to $\alpha_s(M_Z) = 0.118 \pm 0.003$.

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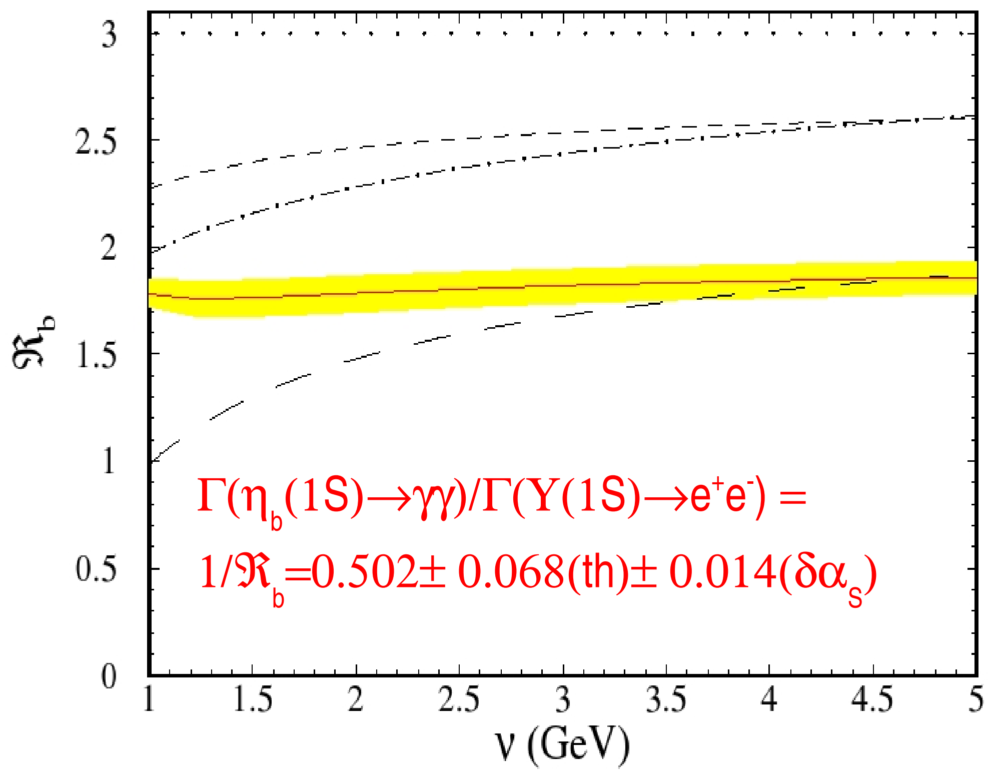

Figure 3: The spin ratio as the function of the renormalization scale ν in LO≡LL (dotted line), NLO (short-dashed line), NNLO (long-dashed line), NLL (dot-dashed line), and NNLL (solid line) approximation for the bottomonium ground state with $\nu_h = m_b$. For the NNLL result the band reflects the errors due to $\alpha_s(M_Z) = 0.118 \pm 0.003$.

Two photons width at NNLL:

$$\Gamma(\eta_b(1S) \to \gamma\gamma) = 0.659 \pm 0.089(\text{th.})^{+0.019}_{-0.018}(\delta\alpha_s) \pm 0.015(\text{exp.})\ \text{keV}$$

Penin et al., NP B699 (2004),183

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Penin et al., NP B699 (2004),183

Light Hadrons Width at NLO: done for charmonium, promised for η_b

$\Gamma(\eta_c \to gg)/\Gamma(\eta_c \to \gamma\gamma) = 3.1 \pm 0.5(\text{th}) \pm 0.3(\delta\alpha_S) * 10^3$ Exp$= 3.6 \pm 1.2 * 10^3$

Bodwin, Chen, PRD64(2001),114008

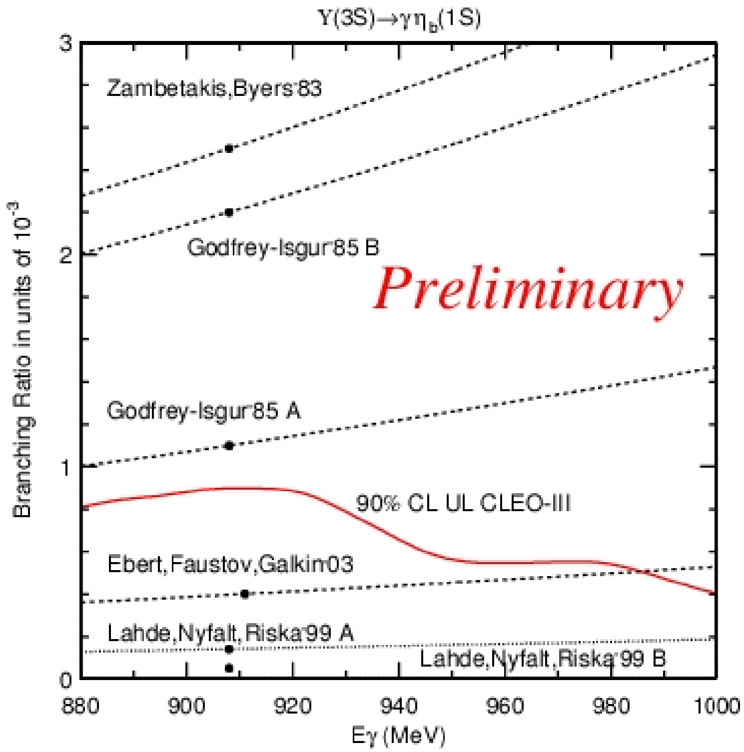
Bodwin, Petrelli, PRD66(2002),094011

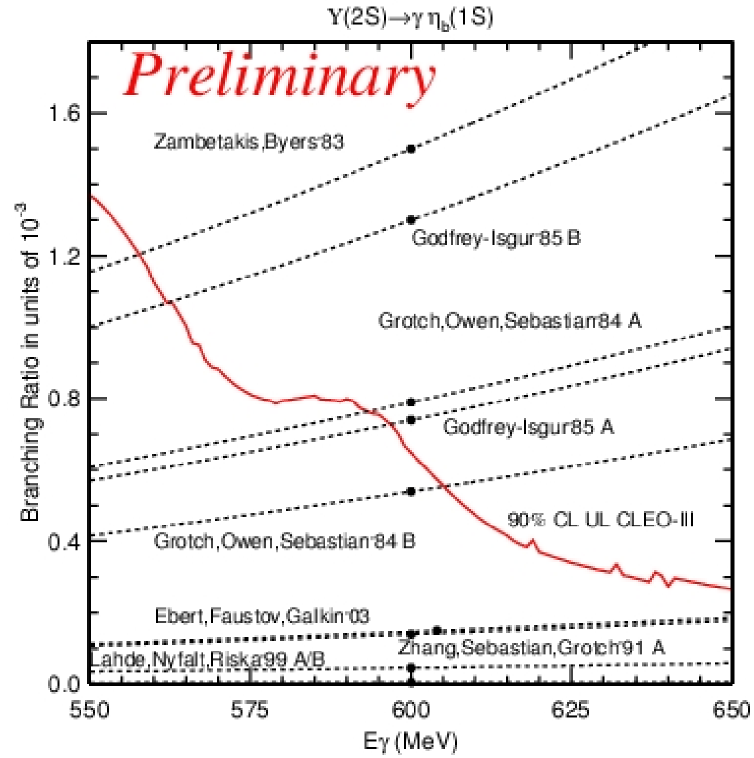
Exp.Limits: $\eta_b(1,2S)$ $h_b(1P)$

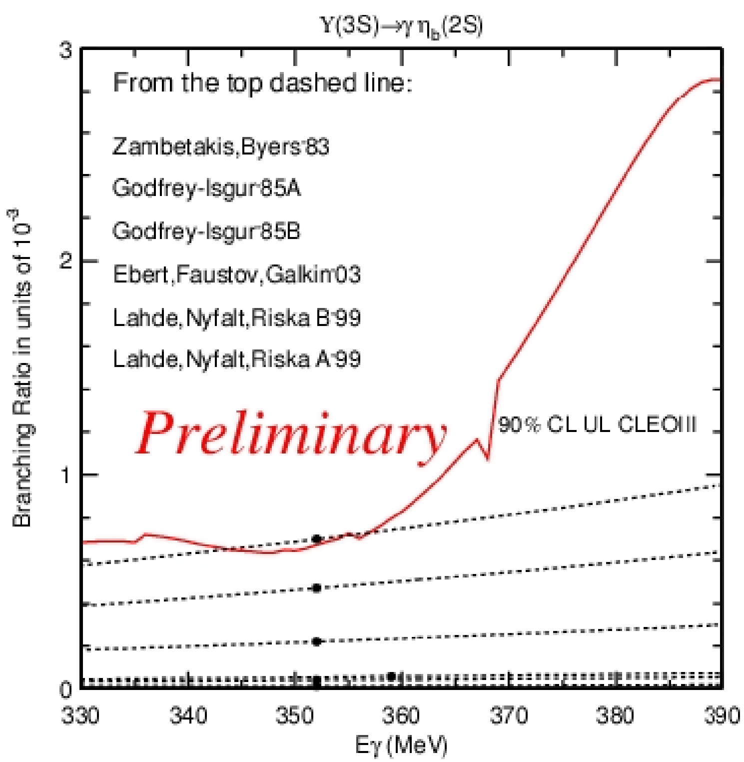
Inclusive searches need running on narrow states

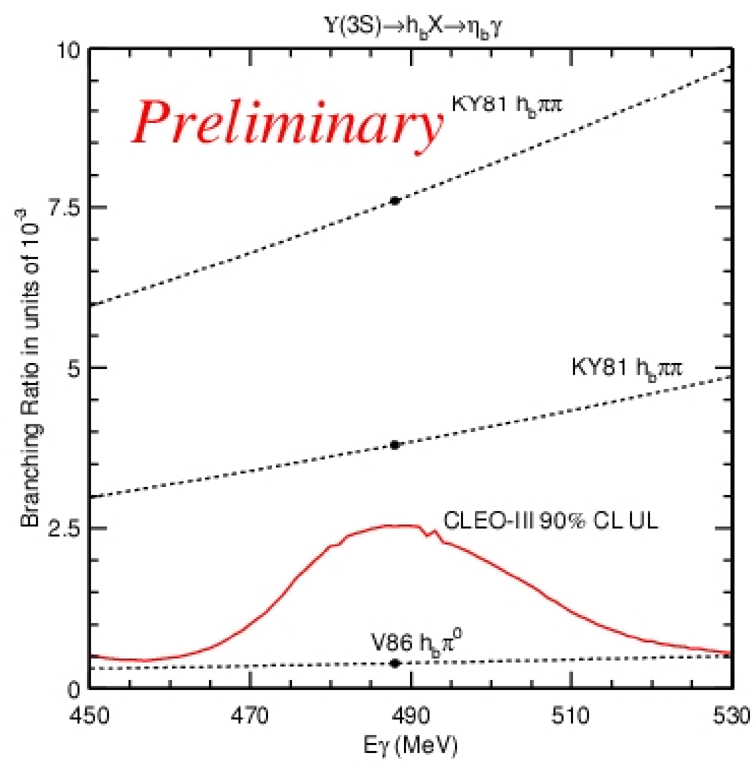
Exclusive searches can be immediately checked by Belle and BaBar.

A major effort is under way at CLEO to extract evidence of singlet states in *bottomonia* : expect results soon!

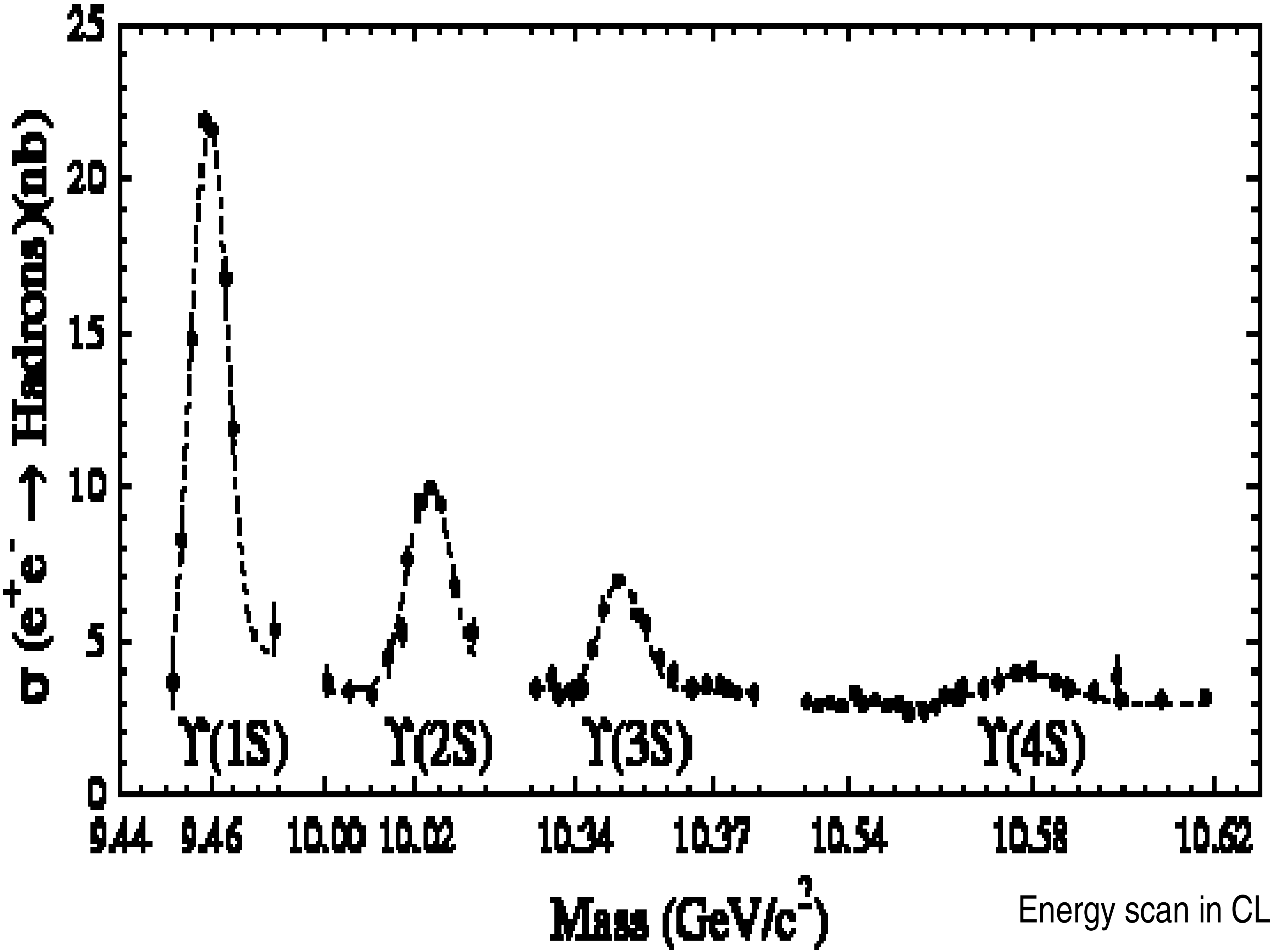






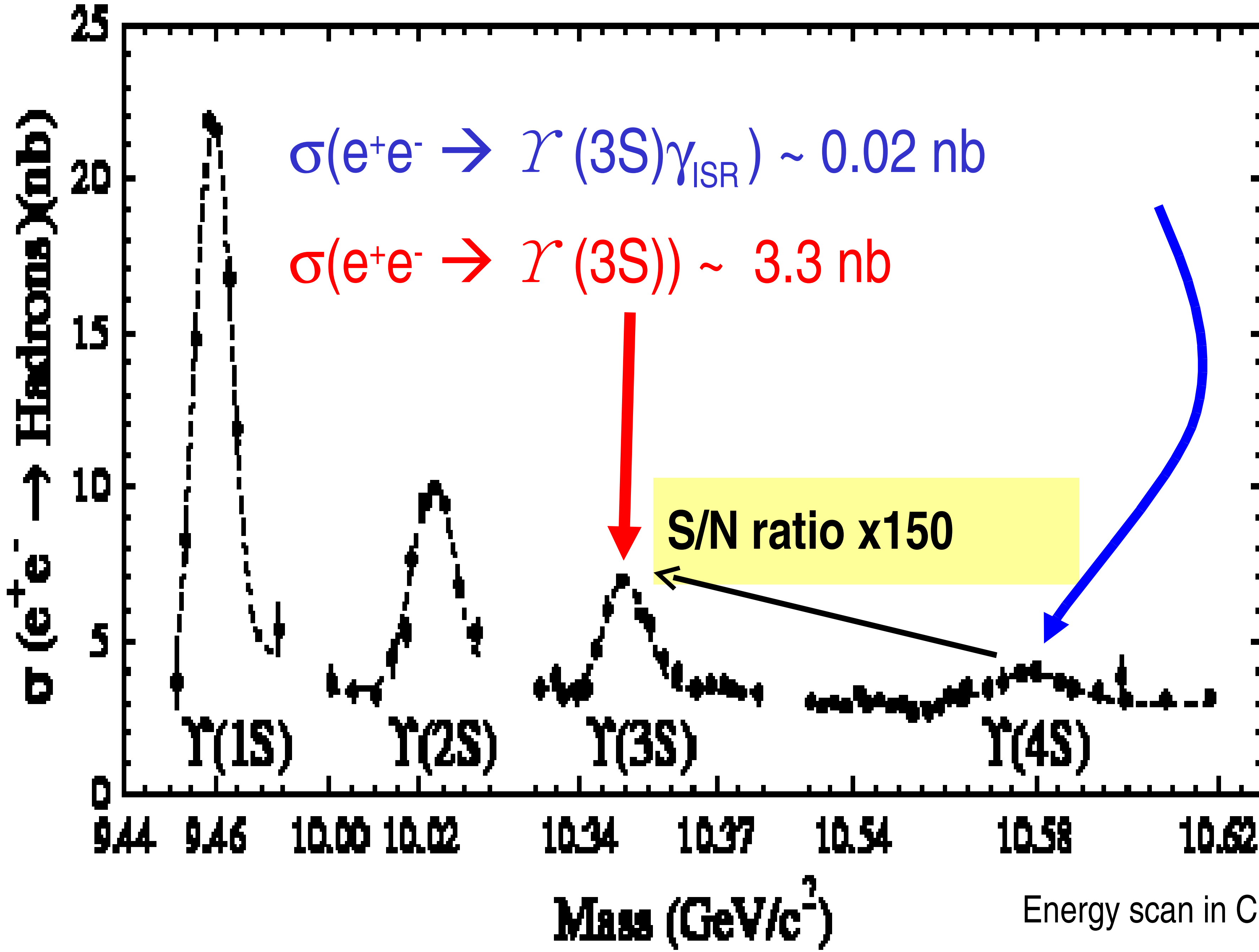


Bottomonium formation in e+e- annihilations



Energy scan in CLEO

Dedicated Peak Running at Narrow Υ(nS)



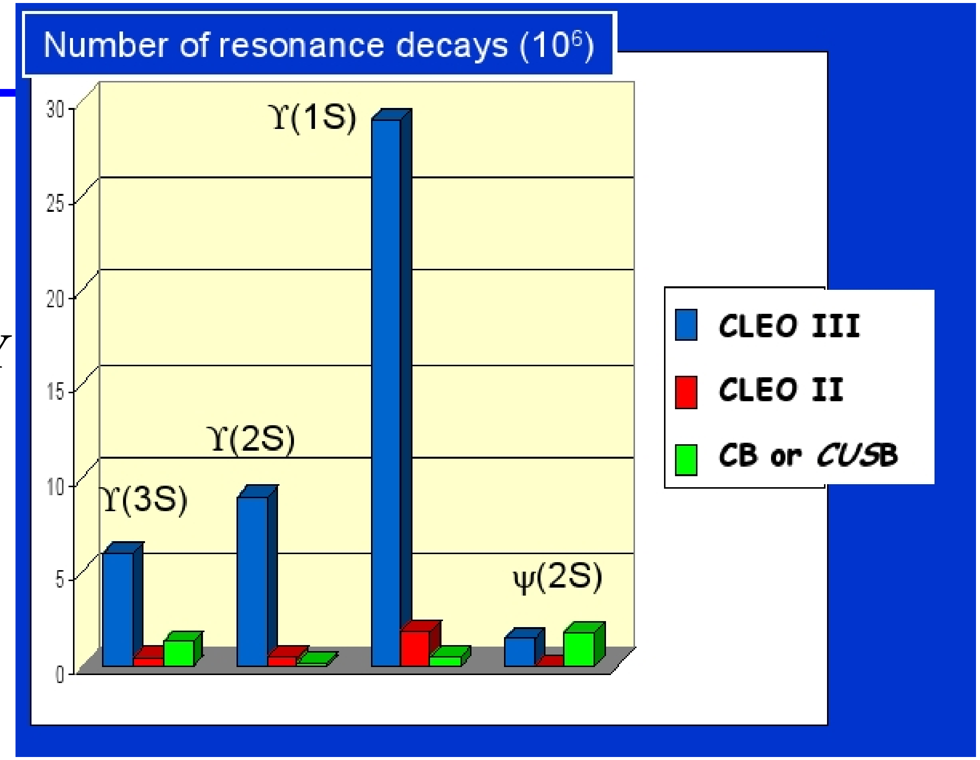
Energy scan in CLEO

Υ(3S) runs at B factories

CLEO:
1.46 fb^{-1},
6M Υ(3S)

- discovery of Υ(1D)
- χ_b (2P)→ ω Υ
- χ_b (2P) →χ_b (1P) ππ
- Double cascades Υ →$\gamma\chi_b$ → γγΥ
- Υ(1,2,3S) to e^+e^-, $\mu^+\mu^-$, $\tau^+\tau^-$
  PRL96(2006),092003
- limits on LFV in Υ(1,2,3S) to μτ
  hep-ex/0610089
- DM searches :

Υ(1S) to invisible < 0.39% (90%CL)
PRD75(2007),031104



New results soon !

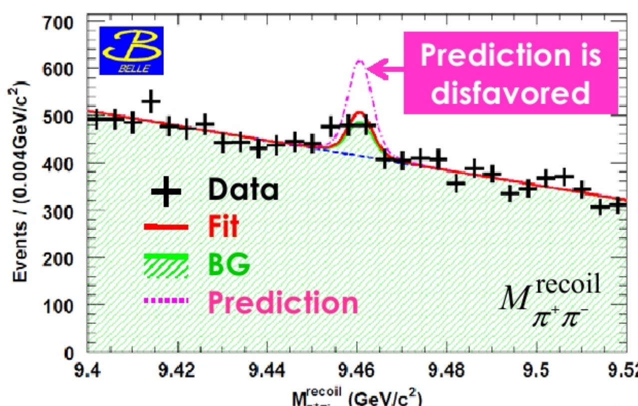
BELLE:
2.9 fb^{-1} (*)
11 M Υ(3S)

(*) BELLE 1.7fb^{-1}/day,
BABAR 0.9 fb^{-1}/day

DM searches
hep-ex/0611041

from here as well !

N_{sig} = 38 □ 39(stat) ⇔ 0 consistent



@ 2.9fb^{-1}

syst. included

Br(Υ(1S) → invisible) < 2.5 x 10^{-3} (@90%C.L.)

Summary

Lots of new "charmonia" in the last 5 years : a new spectroscopy?

2 (η_c' and h_c) long sought , while 2 narrow D waves yet missing

9-11 puzzling ones , 1 even charged:

X(3872) & X(3875) : lowest tetraquark doublet?

X(3940) & X(4160) : candidates for η_c(3S), or χ_{c0}(3P) ?

Z(3930): probably the χ_{c2}(2P), but 40-50 MeV below theory

Y(3940): experimental evidence still to be fully understood

The Vector Zoo: Y(4008?,4260,4350,4660). Hybrids, tetraquarks?

Z(4430) : the first charged tetraquark?

Major progress in deconvolution of R scans between 3.8 and 5 GeV

Y(ns) to Y(mS) hadronic transitions are a gold mine

ParaBottomonia : major searches underway

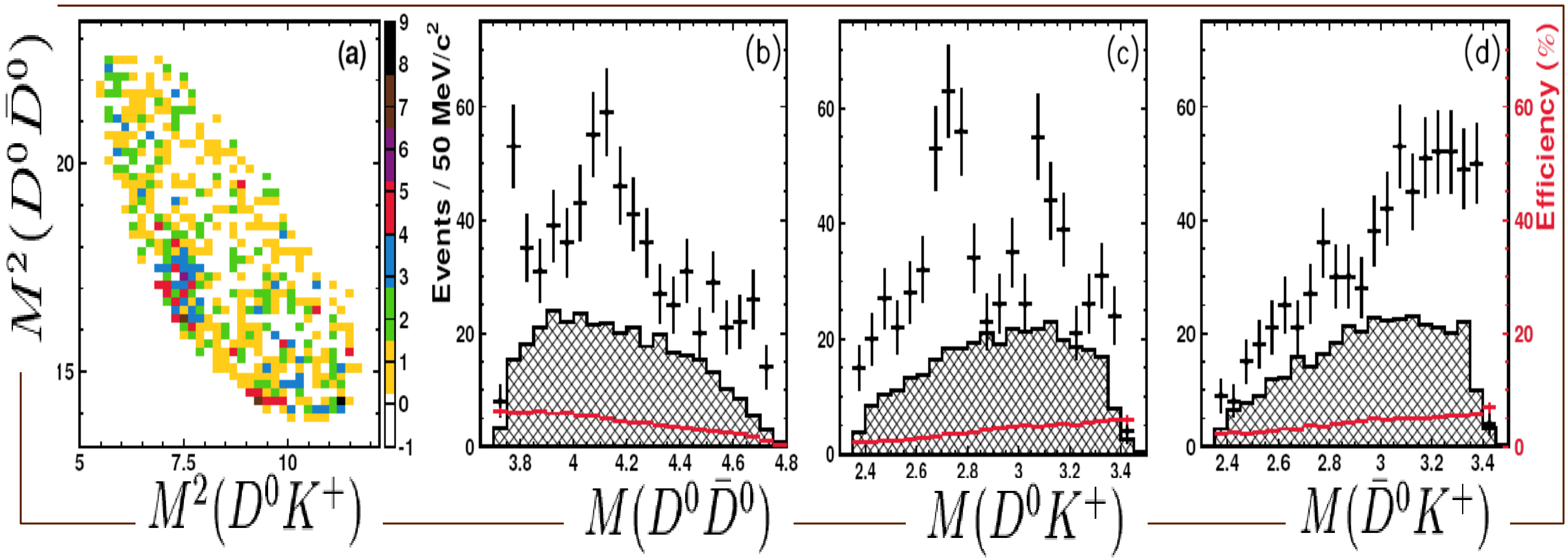
$B^\pm$ decays to $D^0\bar{D}^0K^\pm$

414 fb^{-1}: hep-ex/0707.3491 (2007)

$B^\pm \to K^\pm\,\psi(3770) \to K^\pm D^0 \bar{D}^0$

$B^\pm \to K^\pm\,\psi(4160) \to K^\pm D^0 \bar{D}^0$

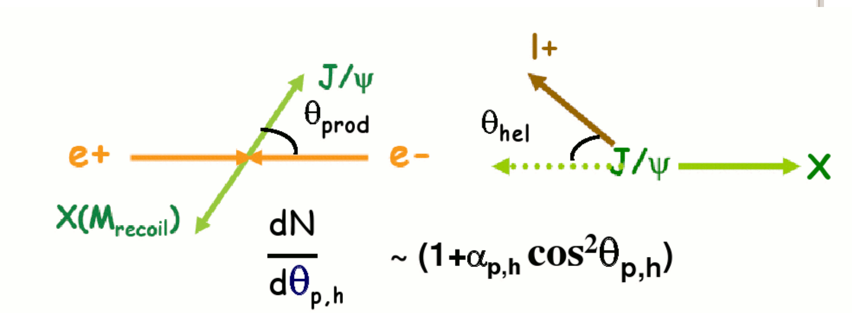
$B^\pm \to D_s^\pm(2700)\,\bar{D}^0 \to K^\pm D^0 \bar{D}^0$

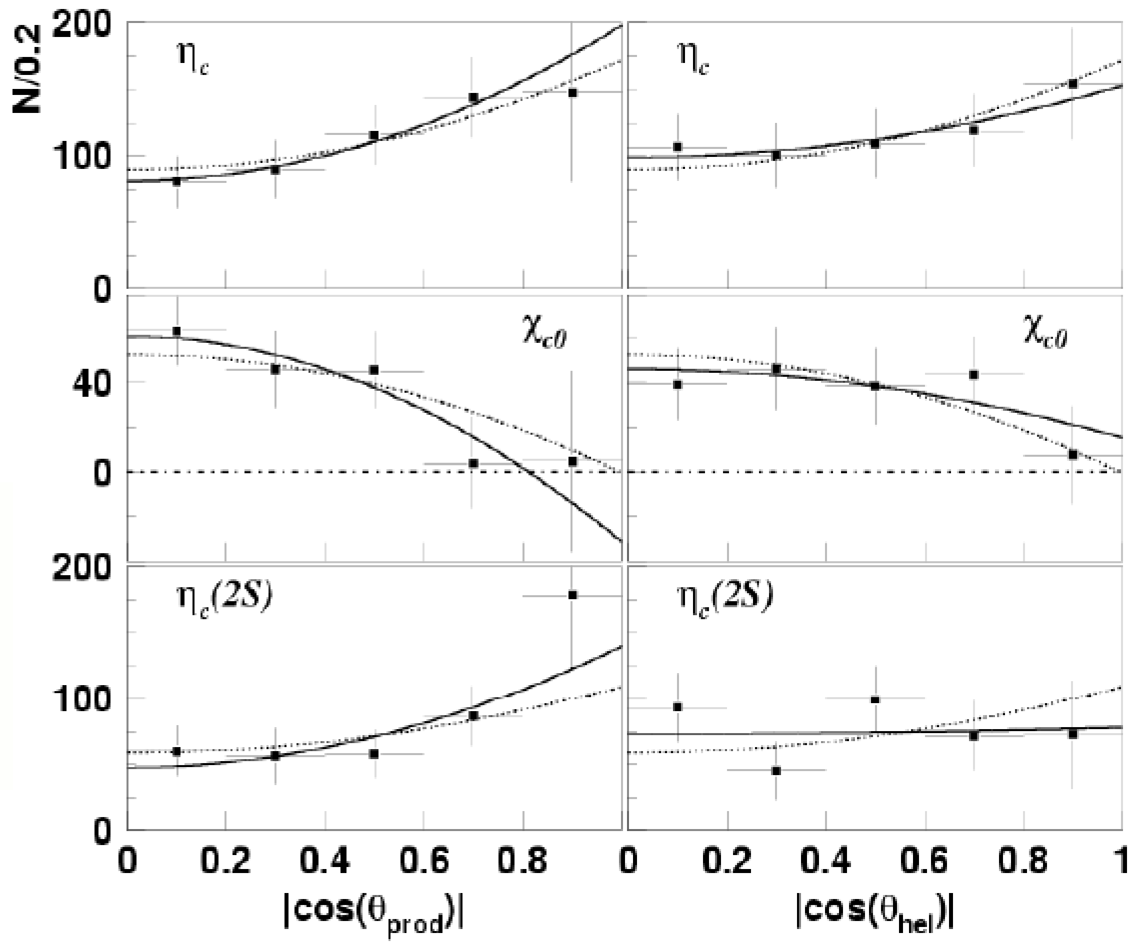


Full helicity amplitude analysis of the Dalitz plot: contribution from Ds(2700) overlaps exactly on $\psi(4160)$

X(3940) in double charmonium : 0^{-+} vs 0^{++}

Angular distributions can cast some light on X(3940) quantum numbers :

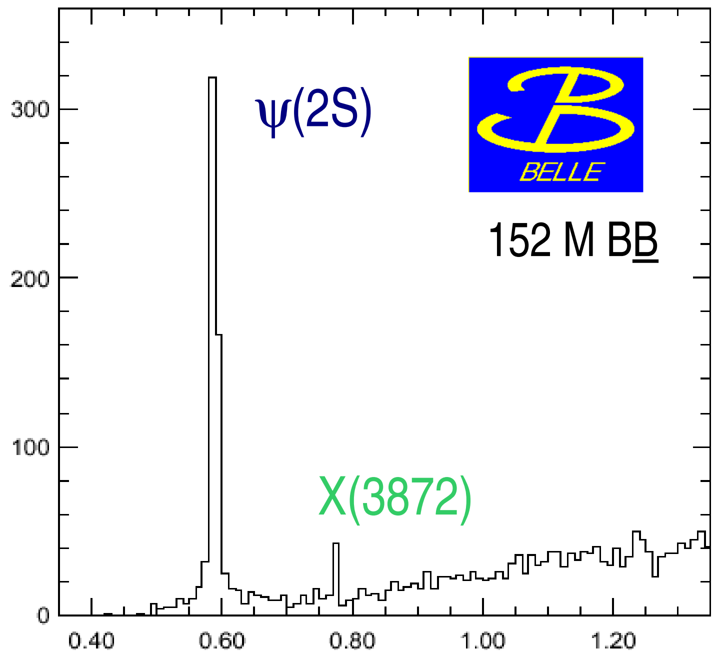




X(3872): discovery in $B \to K (\pi^+ \pi^- J/\psi)$

LP2003, August '03

Discovery in B decays $\to K\, J/\psi \pi\pi$



Belle : PRL91,262001(2003)
[hep-ex/0309032]

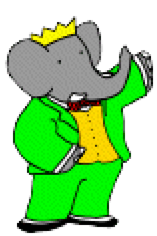
$M = 3872.0 \pm 0.6 \pm 0.5$ MeV/c^2

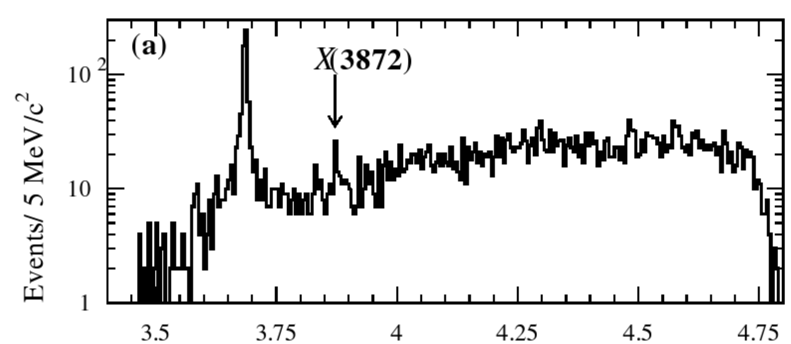
$\Gamma < 2.3$ MeV (90%CL)

$$\frac{Br(B^+ \to K^+ X) * Br(X \to J/\psi\, \pi\pi)}{Br(B^+ \to K^+ \psi') * Br(\psi' \to J/\psi\, \pi\pi)} = 6.3 \pm 1.2 \pm 0.7\ \%$$

PHYSICAL REVIEW D **71,** 071103 (2005)

BaBar: PRD71,071103(2005)
[hep-ex/0406022]



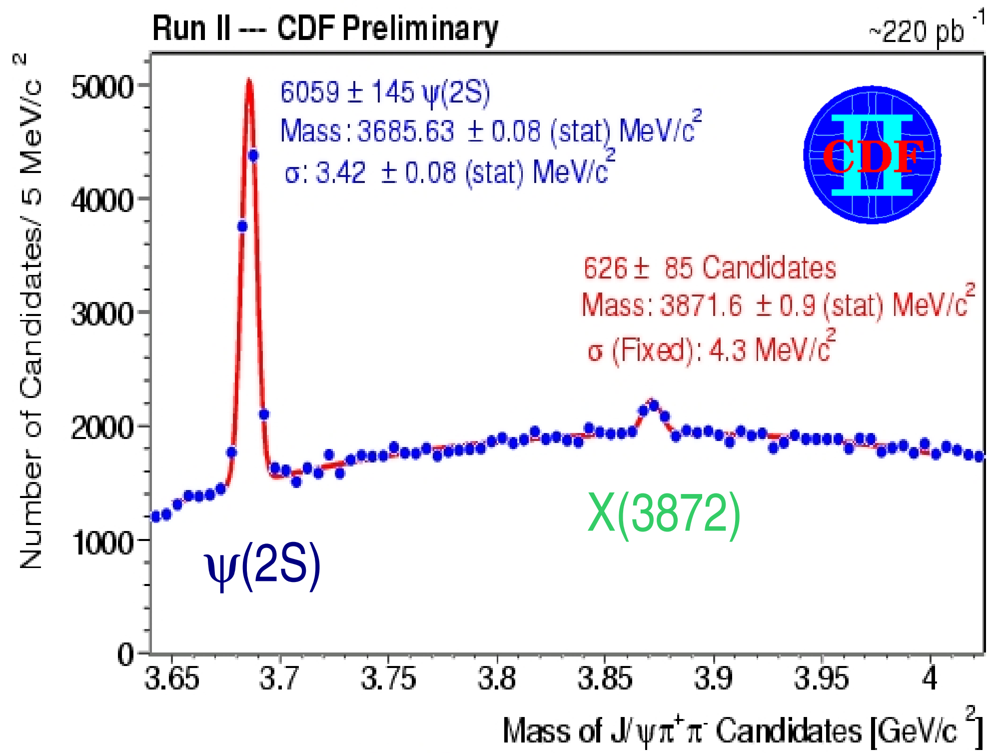


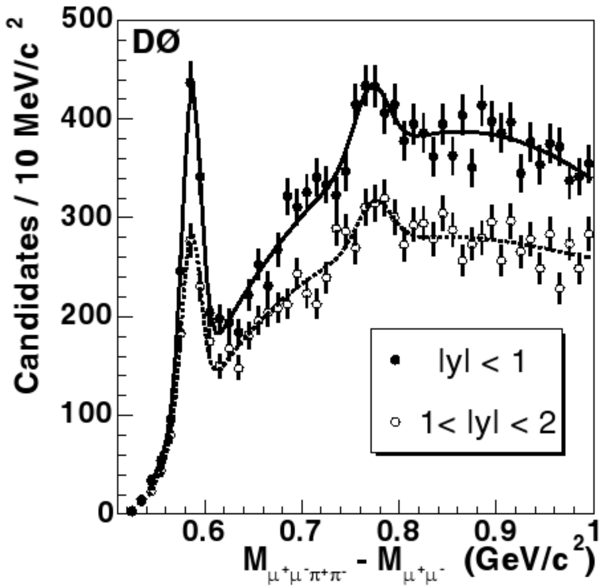
X(3872): production in $p\bar{p}$ annihilations

CDF: PRL93,072001(2004)
[hep-ex/0312021]

Prompt X(3872) is dominant:
only 16% from B→ K J/ψππ

• Use ~ 220 pb^{-1} Run II Data





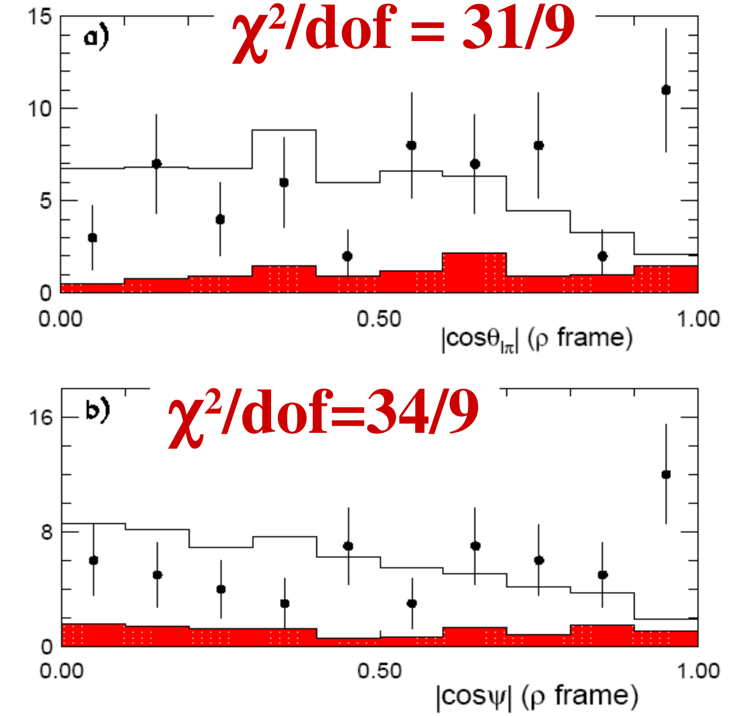
PRL93,162002(2004)
[hep-ex/0405004]

X(3872) production vs pseudo-rapidity

X(3872) – $\pi^+ \pi^- J/\psi$ angular distribution

not 0^{++} $\varepsilon_\rho \cdot \varepsilon_{J/\psi}$

neither 0^{-+} $k \cdot (\varepsilon_\rho x \varepsilon_{J/\psi})$

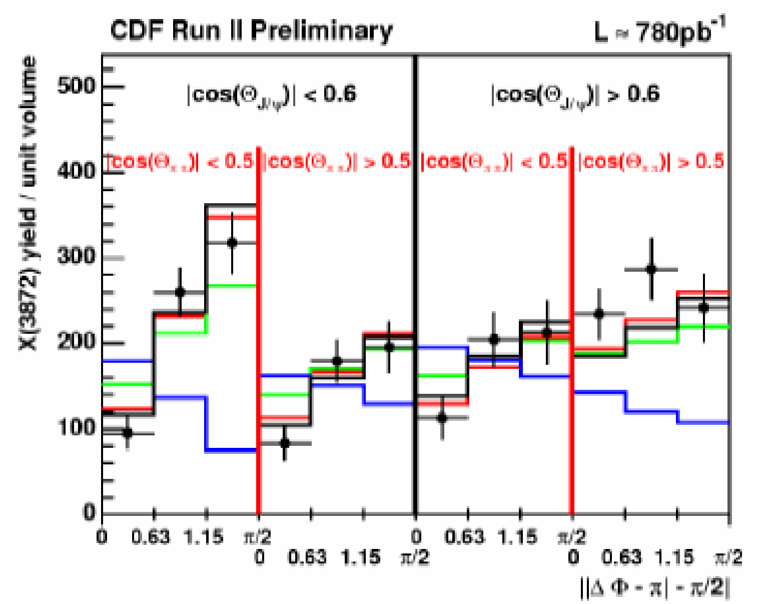


(CDF reference)

X(3872)
• data points

acc. corrected prediction for
0^{++}_P
1^{--}_S
1^{++}_P
2^{-+}_P

J^{PC}	χ^2 prob.
1^{++}	27.8%
2^{-+}	25.8%
1^{--}	0.02%
2^{+-}	$5.5 \cdot 10^{-5}$
1^{+-}	$3.8 \cdot 10^{-5}$
2^{--}	$3.8 \cdot 10^{-5}$
3^{+-}	$3.8 \cdot 10^{-5}$
3^{--}	$2.4 \cdot 10^{-5}$
2^{++}	$1.1 \cdot 10^{-5}$
1^{-+}	$4.1 \cdot 10^{-6}$
0^{-+}	$3.5 \cdot 10^{-17}$
0^{+-}	$< 1 \cdot 10^{-20}$
0^{++}	$< 1 \cdot 10^{-20}$



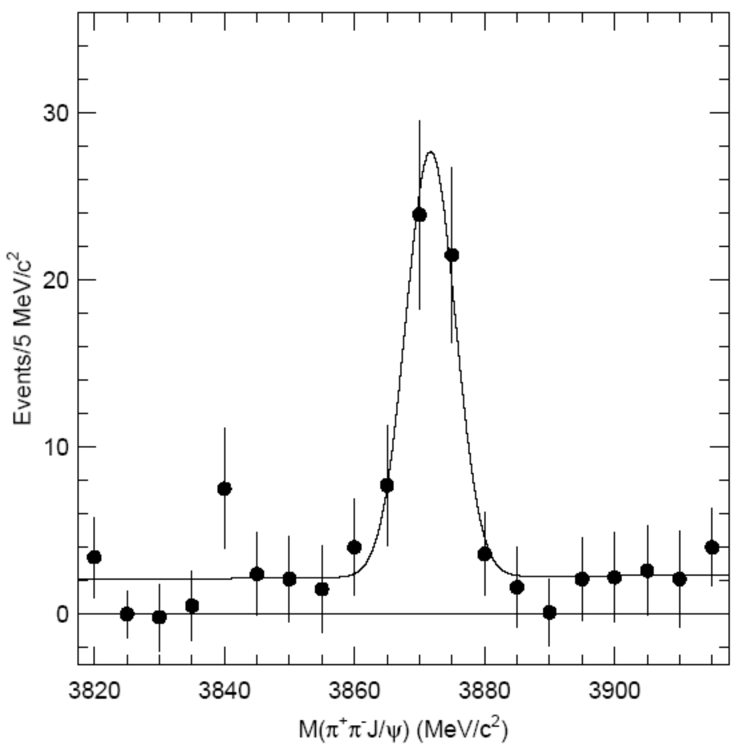
Favors

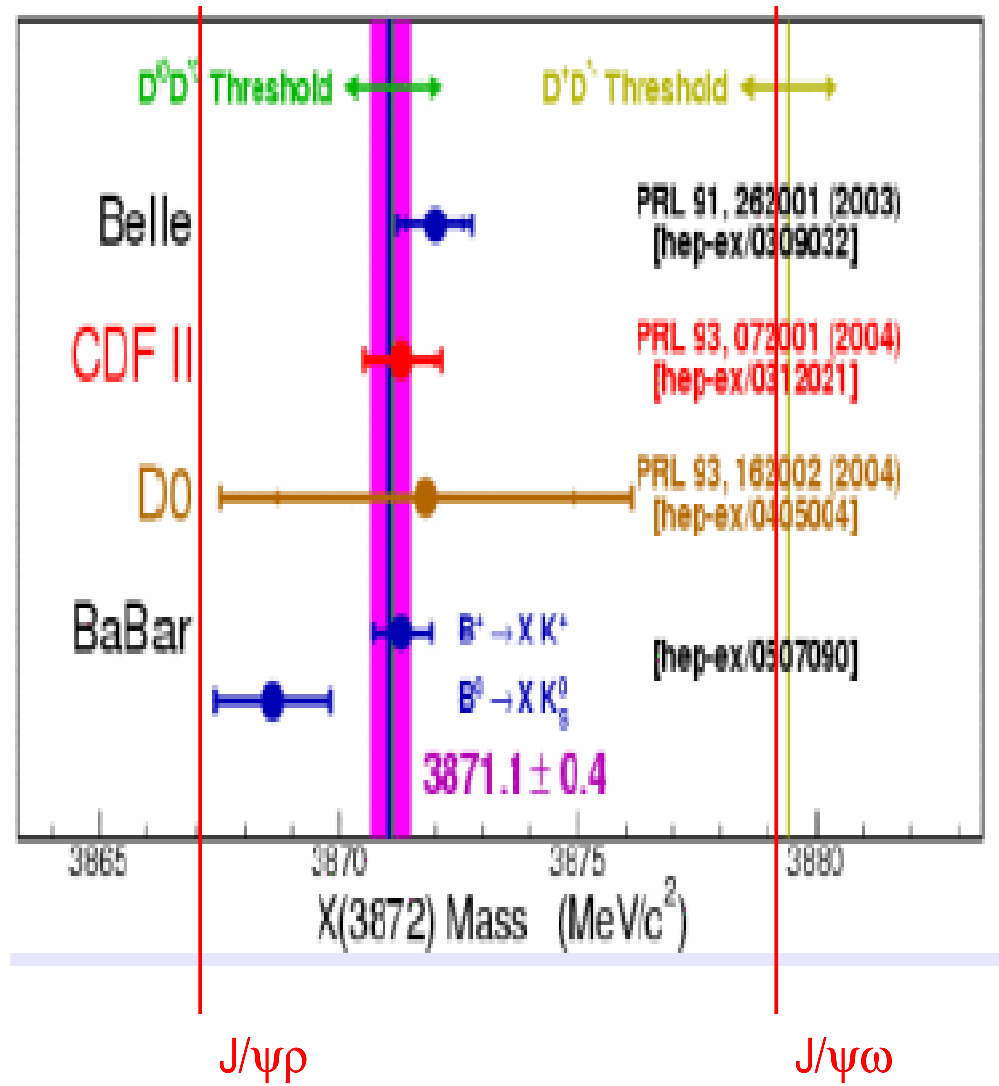
$J = 1^{++}$ or 2^{-+}

(But J=2 unseen, in B to K charmonium)

X(3872) vs DD* threshold

BELLE latest update (Beijing 10/04):
[258 fb^{-1} , 48.6 ±7.8 events]
M = 3872.4 ± 0.7 MeV





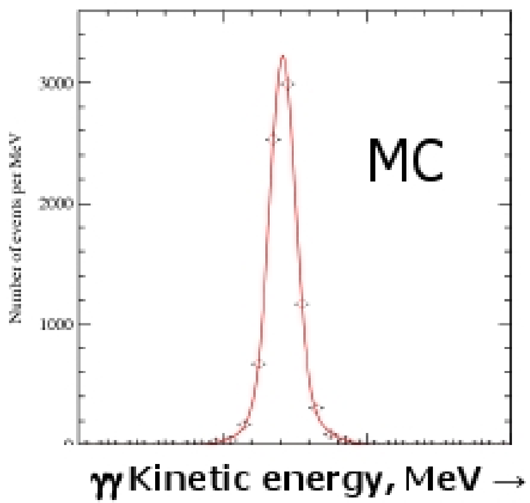
Prospects on $\chi_{C1,2}$ or X(3872) recoil?

$$\sigma(e^+e^- \to X(3872)X) \cdot \mathcal{B}(X(3872) \to \gamma J/\psi) \cdot \mathcal{B}(X \to (N_{ch} > 2))$$

$$= (-2.7 \pm 3.7 \pm 1.0)\ \text{fb} \quad (< 5.1\ \text{fb}\ @90\%\ C.L.).$$

In charmonium $\psi(2S)\to\eta J/\psi$ is (surprisingly) large ~3%

Kuang [hep-ph10601044 v2] scales $\Gamma \sim (p^*)^3/m_Q^4$ to predict



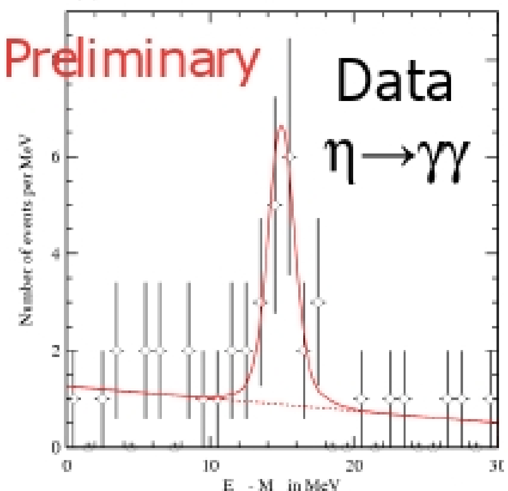
$B(\Upsilon(2S)\to\eta\Upsilon(1S)) = (8.1 \pm 0.8) \times 10^{-4}$

$B(\Upsilon(3S)\to\eta\Upsilon(1S)) = (6.7 \pm 0.7) \times 10^{-4}$

CLEO seeks $\Upsilon(2S)\to\eta\Upsilon(1S)$ with
$\Upsilon(1S) \to \mu\mu$ or ee, and $\eta\to\gamma\gamma$ or $\pi^+\pi^-\pi^0$

Sees preliminary ~5σ evidence

$B(\Upsilon(2S)\to\eta\Upsilon(1S)) = (2.5 \pm 0.7 \pm 0.5) \times 10^{-4}$



Also 3 events in $\eta\to\pi^+\pi^-\pi^0$ mode

Also seek π^0, find no excess over background

$B(\Upsilon(2S)\to \pi^0\Upsilon(1S)) < 2.1 \times 10^{-4}$
consistent with expected ratio to η (.16)