Review on low and high mass spectroscopy

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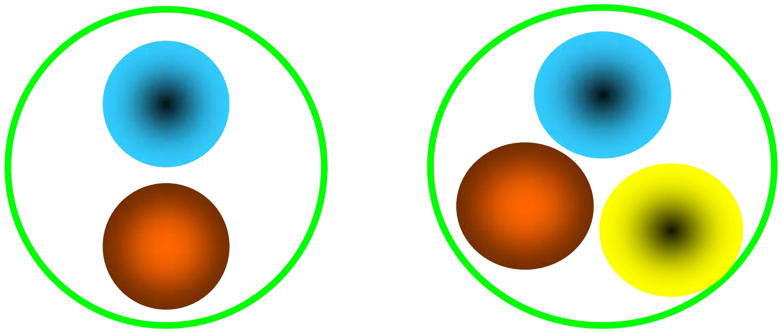
Hadrons： normal & exotic

- Hadrons are composed from 2 (meson) or 3 (baryon) quarks

Quark model



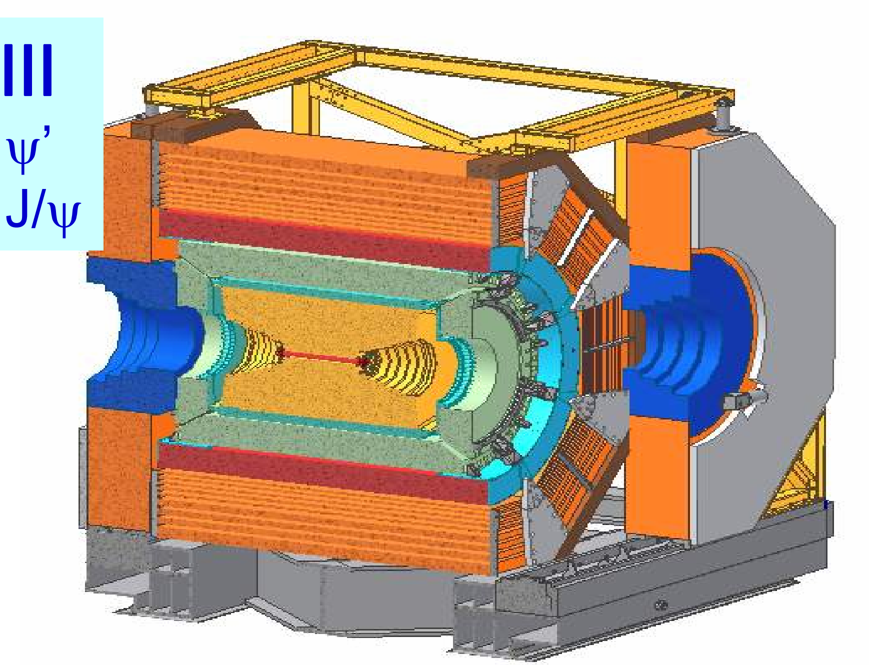
- QCD allows hadrons with $N_{quarks} \neq 2, 3$
  - glueball : $N_{quarks} = 0$ (gg, ggg, …)
  - hybrid : $N_{quarks} = 2$ + excited gluon
  - Multiquark state : $N_{quarks} > 3$
  - molecule : bound state of more than 2 hadrons

Outline

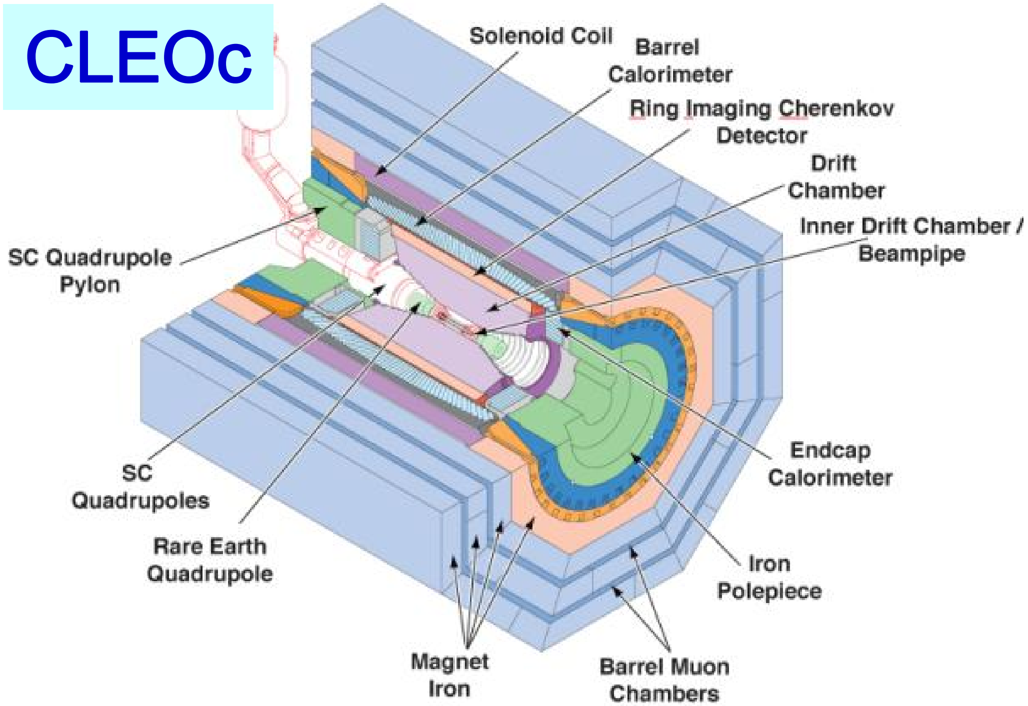
- Light hadrons
  - States with exotic quantum number: $\pi_1(1600)$
  - states decay into ppbar, $\eta\pi\pi$, and $\eta'\pi\pi$
- Spin-singlet quarkonium states
  - $h_c(^1P_1)$, η_c, η_c', $h_b(^1P_1)$, η_b
- Charmonium-like XYZ states
  - X(3872) – molecular state?
  - XYZ(3940) & X(3915) – charmonia?
  - Y(4140)/Y(4280) & X(4350) – tetraquark states?
  - Y states and excited ψ's – hybrids?
- Multiple solutions in extracting parameters from experimental data

Most states from e^+e^- experiments

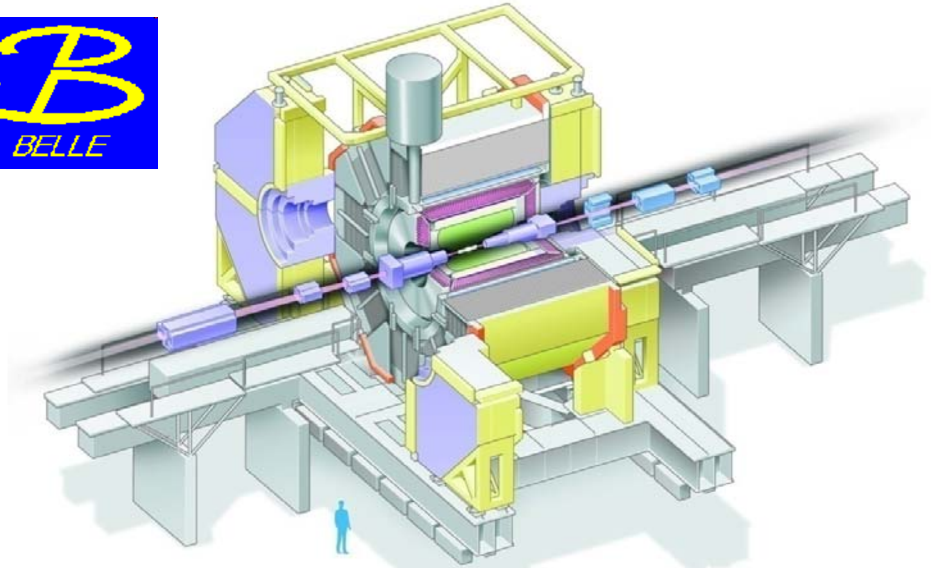
BESIII
106M ψ'
226M J/ψ



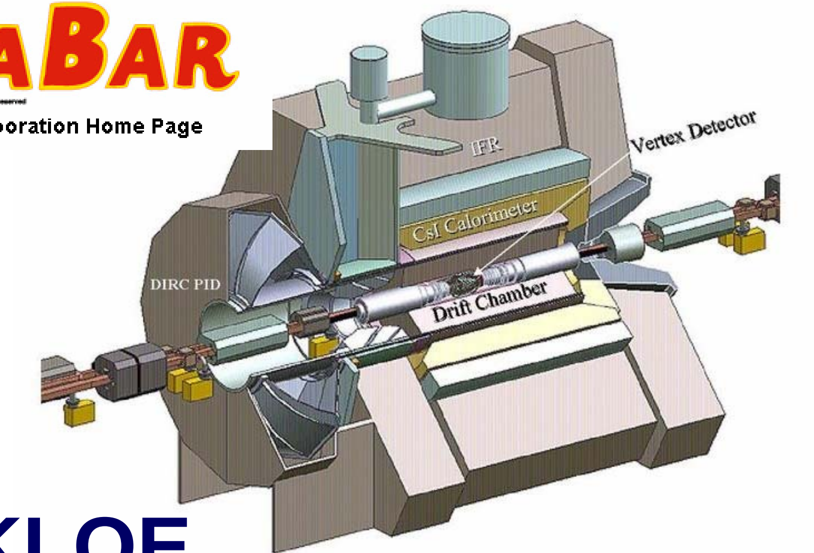
CLEOc



BELLE



BABAR
Collaboration Home Page

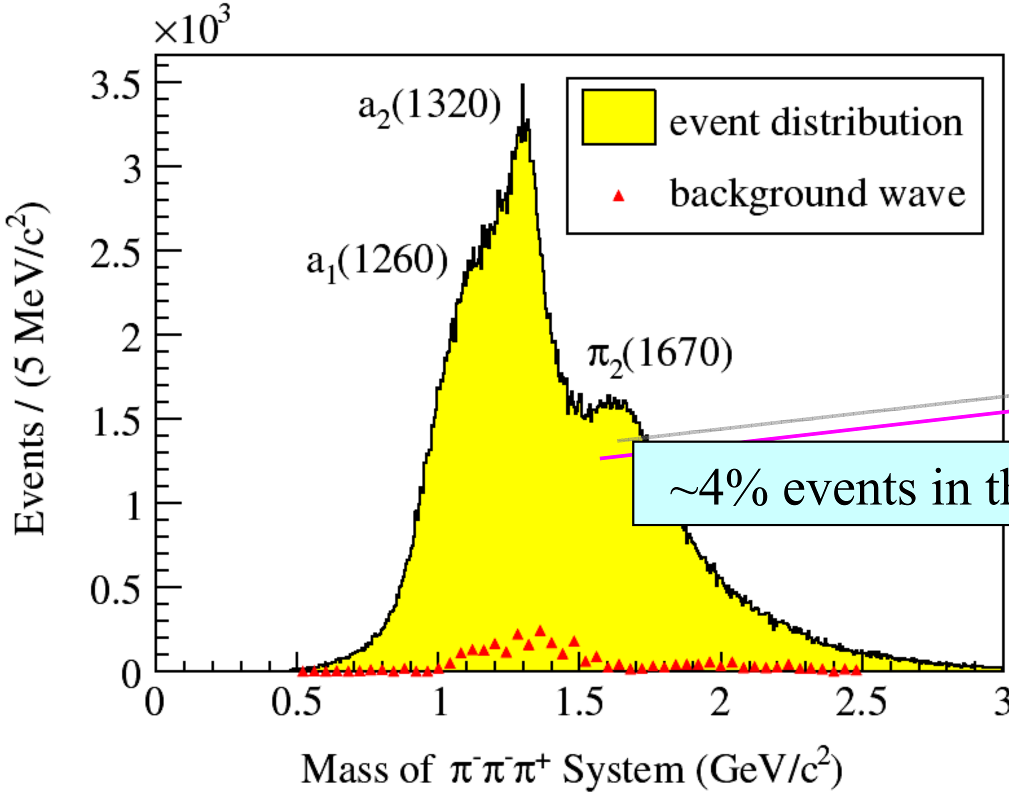


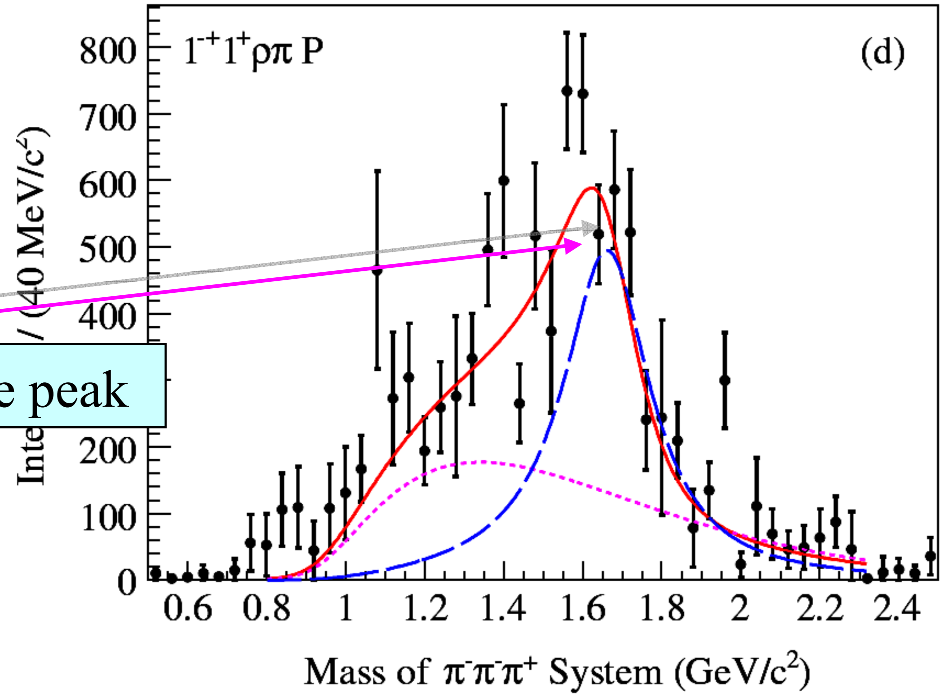
+ CDF, Compass, KLOE, …

Light hadrons

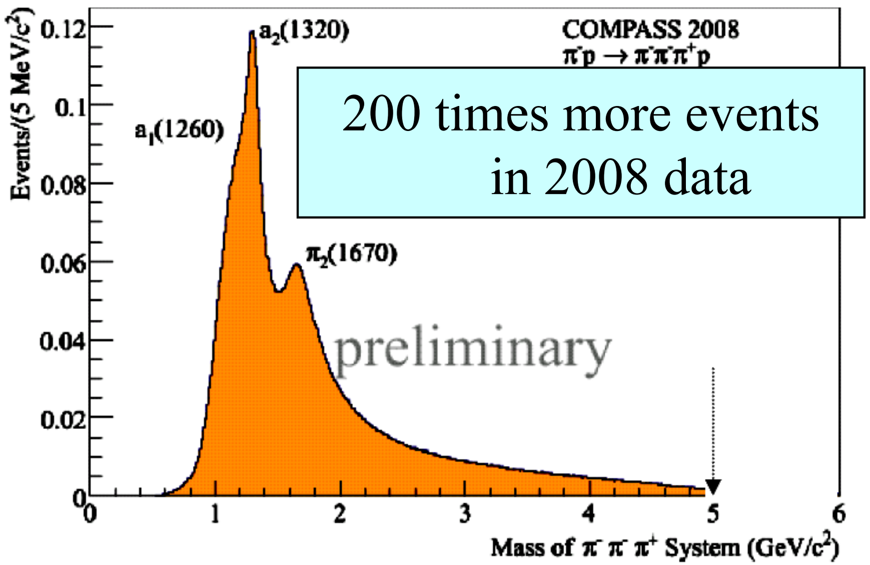
$\pi_1(1600)$: exotic state $J^{PC}=1^{-+}$

COMPASS: PRL 104, 241803 (2010)





~4% events in the peak

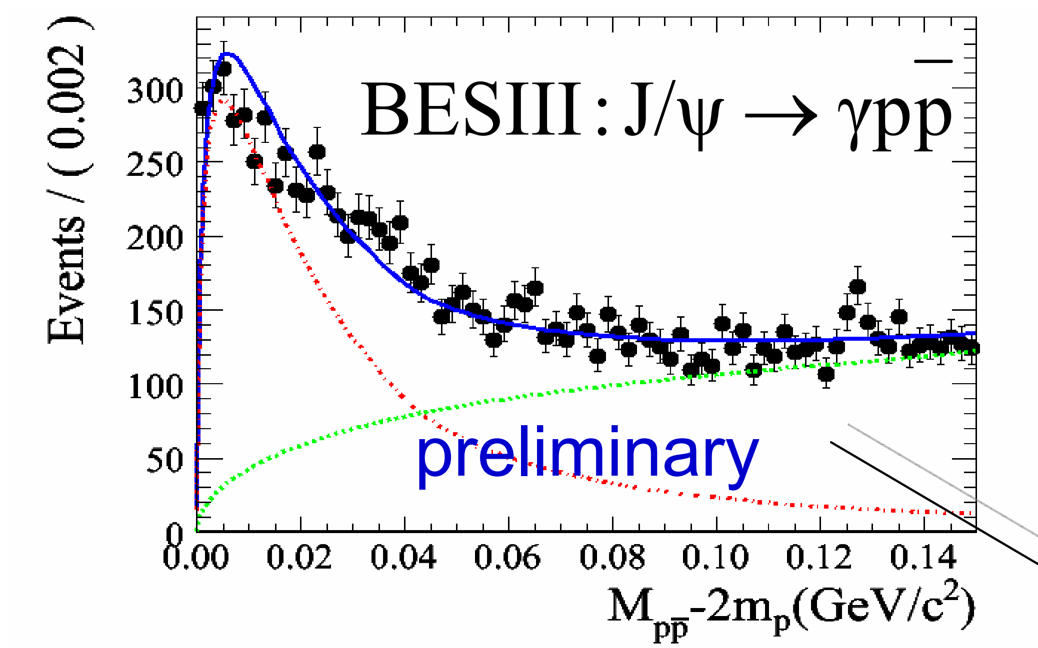


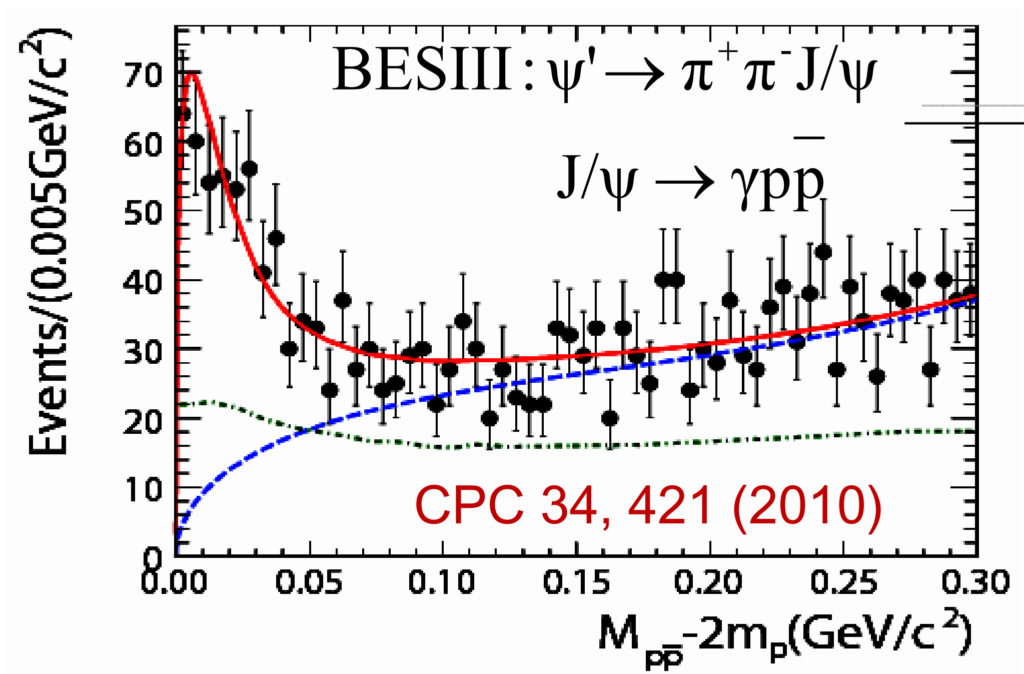
200 times more events in 2008 data

$M=1660 \pm 10^{+0}_{-64}$ MeV
$\Gamma= 269 \pm 21^{+42}_{-64}$ MeV
agrees with E852 & VES.
Candidate for lightest hybrid state.

Talk by Nerling

BESIII: enhancement at ppbar threshold

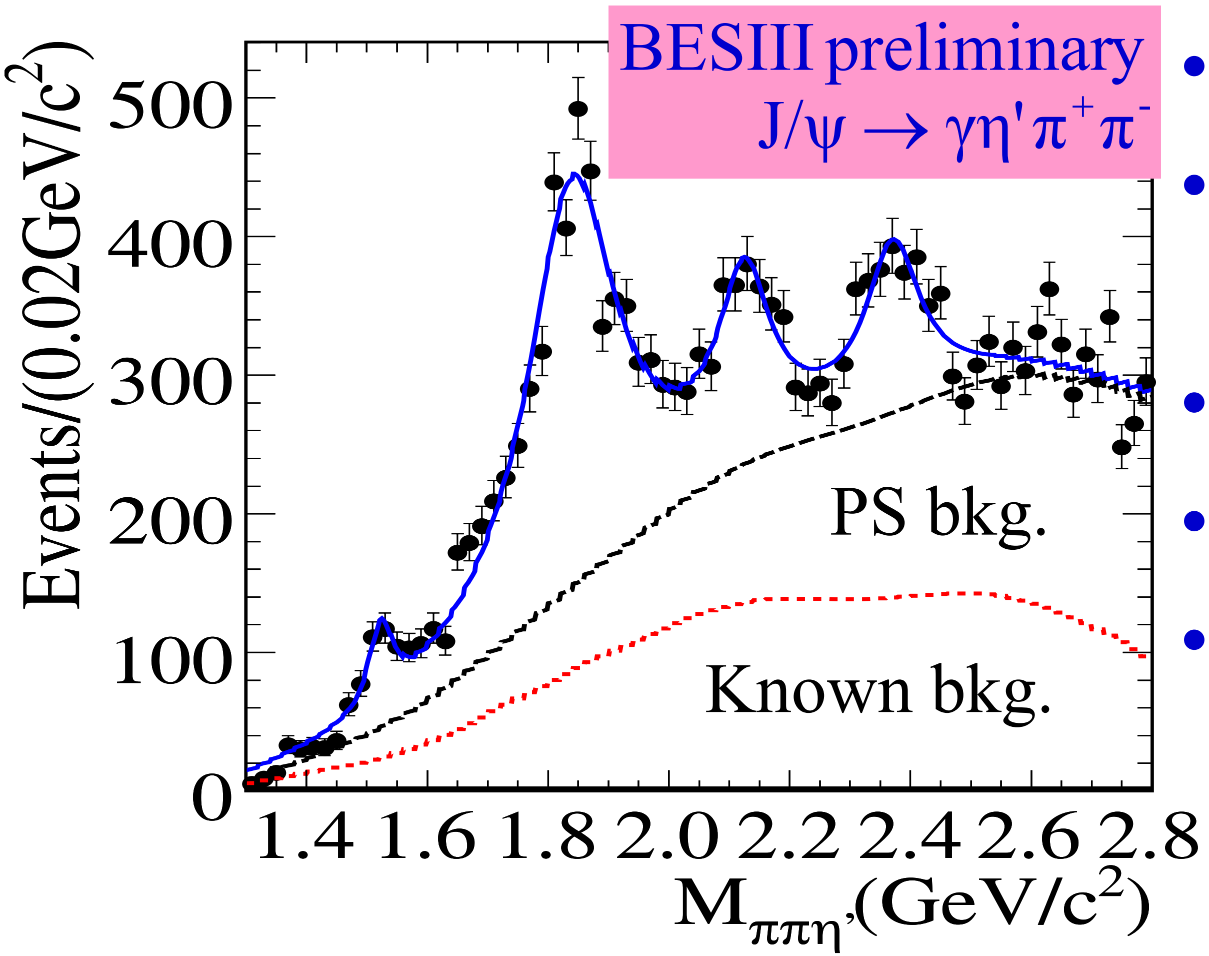




- Observed at BESII in 2003
  - PRL91, 022001
  - $M=1861^{+3}_{-10}{}^{+5}_{-25}$ MeV
  - Width < 38 MeV (90% CL)
  - JPC=0-+
- Confirmed at BESIII (& CLEOc)
  - M=1861.6±0.8 (stat.) MeV
  - Width<8 MeV @ 90% C.L.
  - $M=1859^{+6}_{-13}{}^{+7}_{-26}$ MeV
  - Width < 30 MeV (90% CL)
- Many possibilities:
  - Normal meson?
  - ppbar bound state/ multiquark/ glueball/ …

Talk by Huang

BESIII: more states decays into $\eta'\pi^+\pi^-$



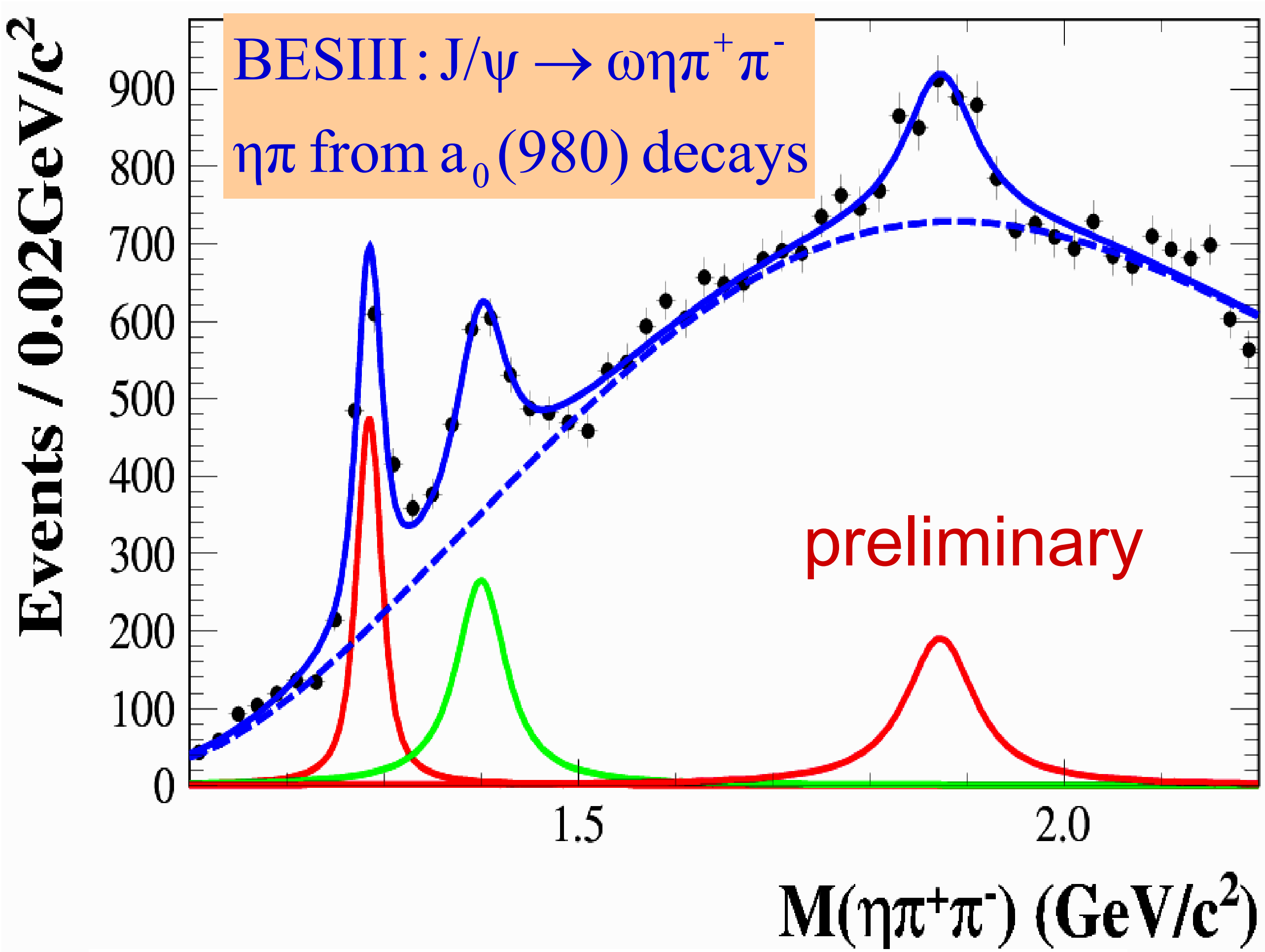
- X(1835) at BESII
- Confirmed at BESIII, width much larger
- Two more peaks !!
- JP unknown
- Nature?
  - X1835=X1859?
  - Excited η or η' states?

resonance	M(MeV/c^2)	Γ(MeV/c^2)	Stat. sig.
X(1835)	1838.1 ± 2.8	179.5 ± 9.1	$> 25\sigma$
X(2120)	2124.8 ± 5.6	101 ± 14	$> 7.2\sigma$
X(2370)	2371.0 ± 6.4	108 ± 15	$> 6.7\sigma$

BESII X(1835):
$M = 1833.7 \pm 6.1 \pm 2.7$ MeV/c^2
$\Gamma = 67.7 \pm 20.3 \pm 7.7$ MeV/c^2

Talk by Huang

BESIII: states decay into $\eta\pi^+\pi^-$



resonance	M(MeV/c^2)	Γ(MeV/c^2)
$f_1(1285)$	1285.0 ± 1.0	20.9 ± 2.9
$\eta(1405)$	1400.2 ± 2.5	56.5 ± 8.4
$X(1870)$	1872.7 ± 10.6	81.5 ± 18.6

- JP unknown
- Nature?
  - X1870=X1835?
  - $\eta_2(1870)$?
  - Excited η, η' states?

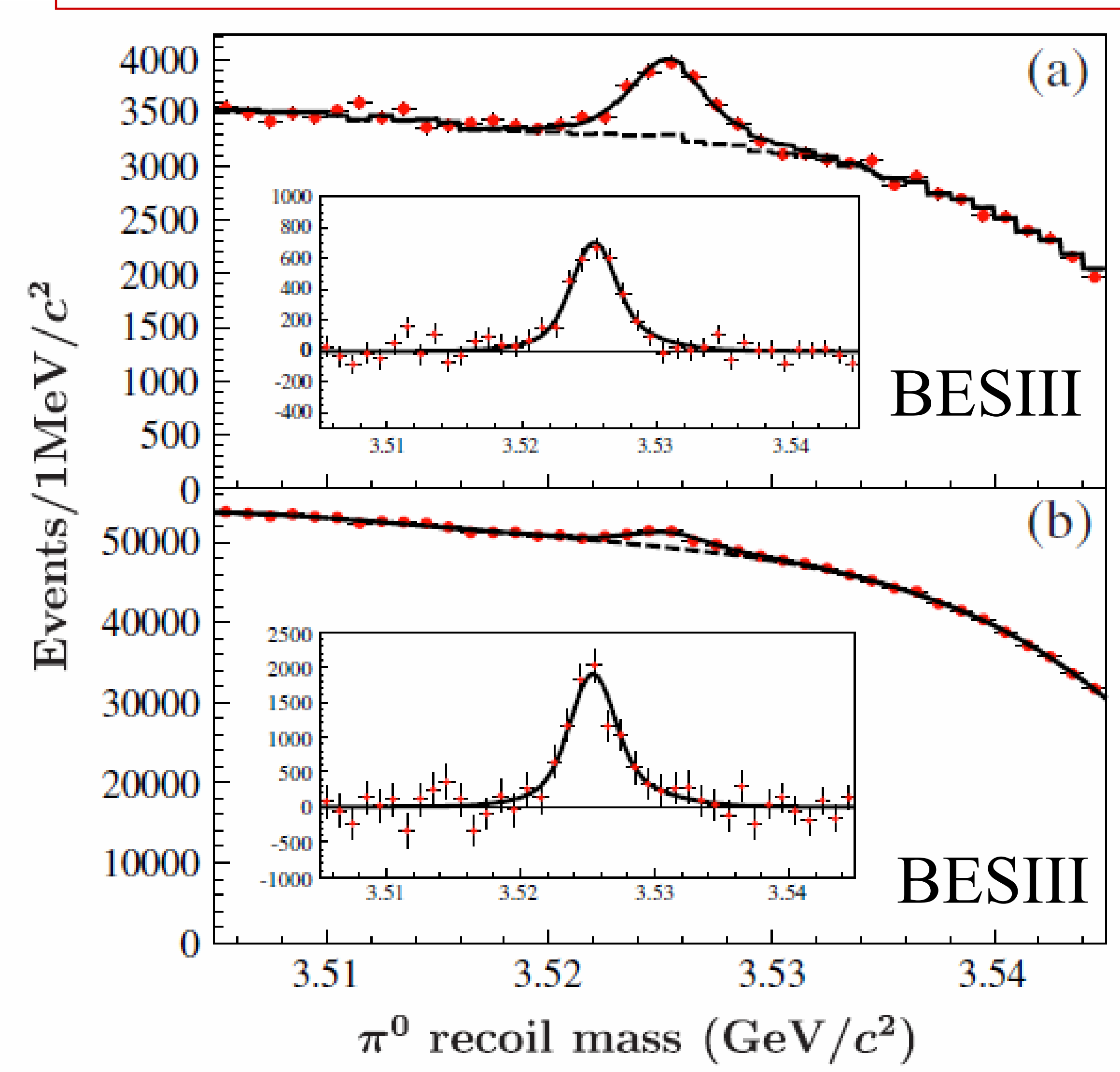
BESII X(1835):
$M = 1833.7 \pm 6.1 \pm 2.7$ MeV
$\Gamma = 67.7 \pm 20.3 \pm 7.7$ MeV

BESIII X(1835):
$M = 1838.1 \pm 2.8(stat.)$ MeV
$\Gamma = 178 \pm 9(stat.)$ MeV

Talk by Huang

Spin-singlet quarkonia

BESIII: $\psi(2S) \rightarrow \pi^0 h_c$ transition



BESIII: PRL 104, 132002 (2010)
Mass: 3525.40±0.13±0.18 MeV
Width: 0.73±0.45±0.28 MeV
(<1.44 MeV @ 90% C.L.)

CLEOc: PRL101, 182003 (2008)
Mass: 3525.28±0.19±0.12 MeV
Width: fixed to 0.9 MeV

ΔM_{hf}= <$M(^3P_J)$>-$M(^1P_1)$
Agrees with zero within ~0.5 MeV

Information on spin-spin interaction.

Combined inclusive and E1-photon-tagged spectrum (First measurements)

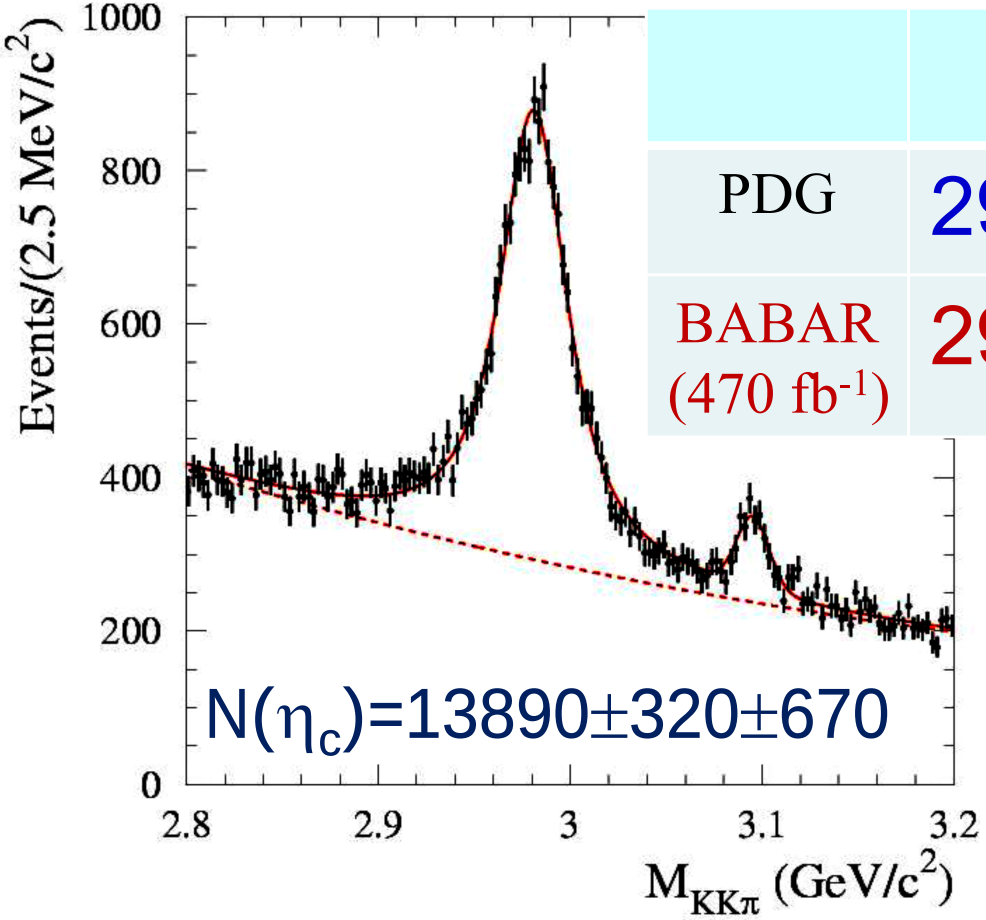
$B(\psi' \rightarrow \pi^0 h_c) = [\ 8.4 \pm 1.3(\text{stat.}) \pm 1.0(\text{syst.})] \times 10^{-4}$

$B(h_c \rightarrow \gamma \eta_c) = [54.3 \pm 6.7(\text{stat.}) \pm 5.2(\text{syst.})]\ \%$

Agree with predictions of Kuang, Godfrey, Dudek, et al.

$\gamma\gamma \rightarrow \eta_c \rightarrow K_S K^+ \pi^- + c.c.$

Widest charmonium below charm threshold, mass and width are known to large uncertainties.



	Mass (MeV)	Width (MeV)
PDG	2980.5 ± 1.2	27.4 ± 2.9
BABAR (470 fb^{-1})	$2982.2\pm0.4\pm1.5$	$31.7\pm1.2\pm0.8$

$\Gamma(\eta_c\rightarrow\gamma\gamma)B(\eta_c\rightarrow KK\pi)$:

$0.379\pm0.009\pm0.031$ keV: BaBar

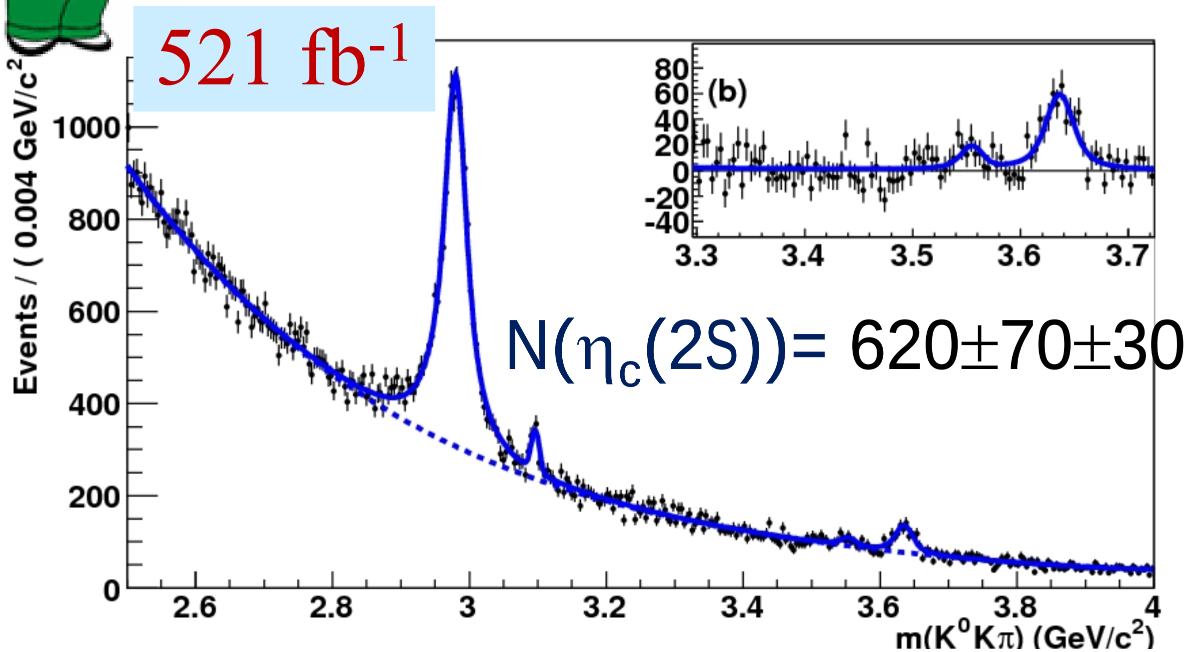
0.44 ± 0.04 keV : PDG

$0.407\pm0.022\pm0.028$ keV: CLEO

BaBar, PRD**81,** 052010 (2010)

Talk by Druzhinin

$\gamma\gamma \rightarrow \eta_c(2S) \rightarrow K_S K\pi / K^+K^-\pi^+\pi^-\pi^0$

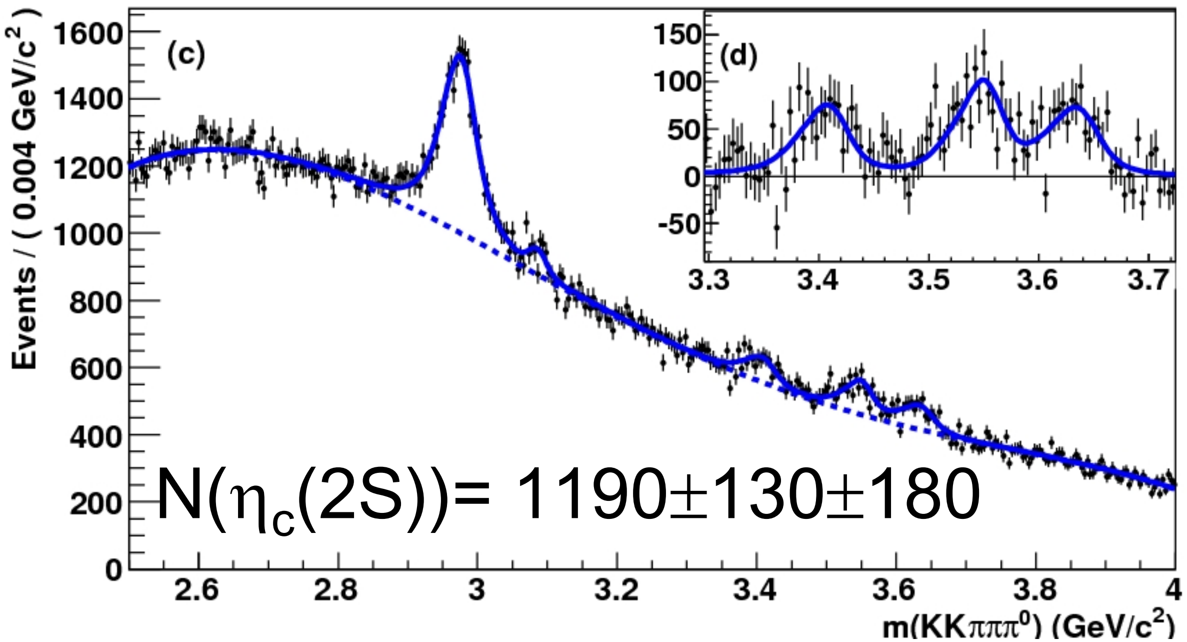


First observation of $K^+K^-\pi^+\pi^-\pi^0$!

From KsKπ mode:

M=3638.3±1.5±0.5 MeV

Γ = 14.2±4.4±2.5 MeV



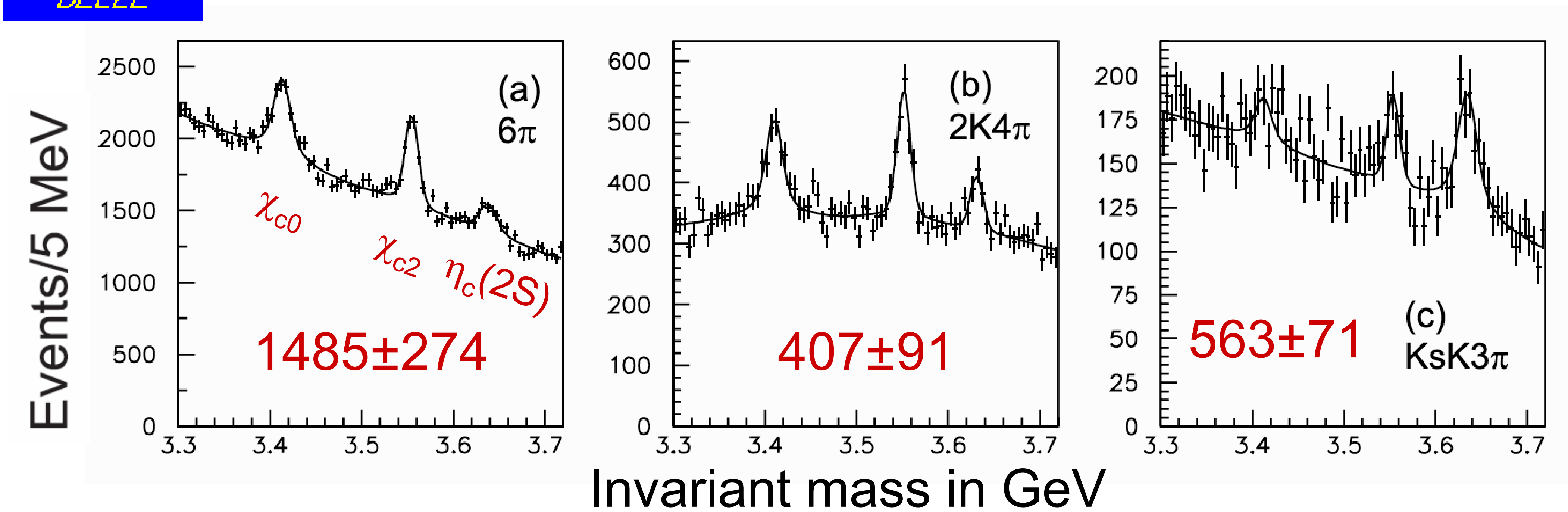
$$\frac{B(K^+K^-\pi^+\pi^-\pi^0)}{B(K_S K^\pm \pi^\mp)}:$$

$$1.44 \pm 0.06 \pm 0.26 \ \text{for}\ \eta_C,$$

$$2.2 \pm 0.4 \pm 0.5 \ \text{for}\ \eta_C(2S).$$

Talk by Druzhinin

Observation of $\eta_c(2S) \rightarrow 6$ prongs



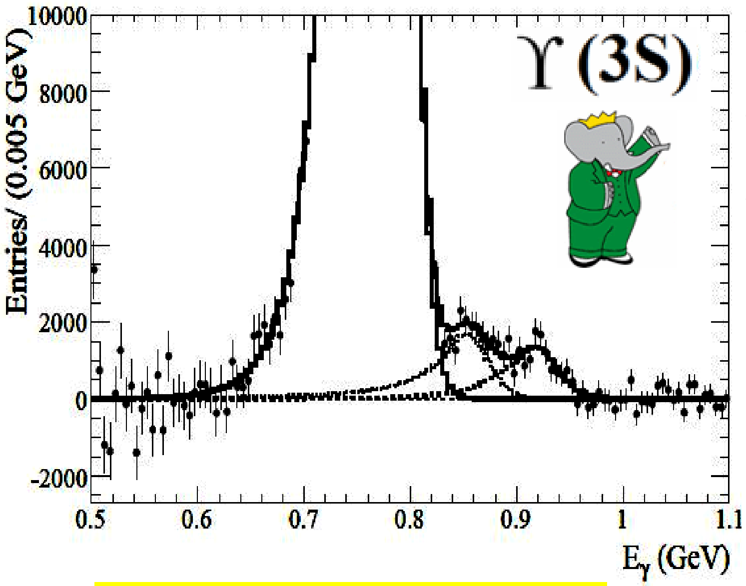
Mass (MeV)	Width (MeV)
3636.9 ± 1.1 ± 2.5 ± 5.0	9.9 ± 3.2 ± 2.6 ± 2.0

Last error due to possible interference with continuum

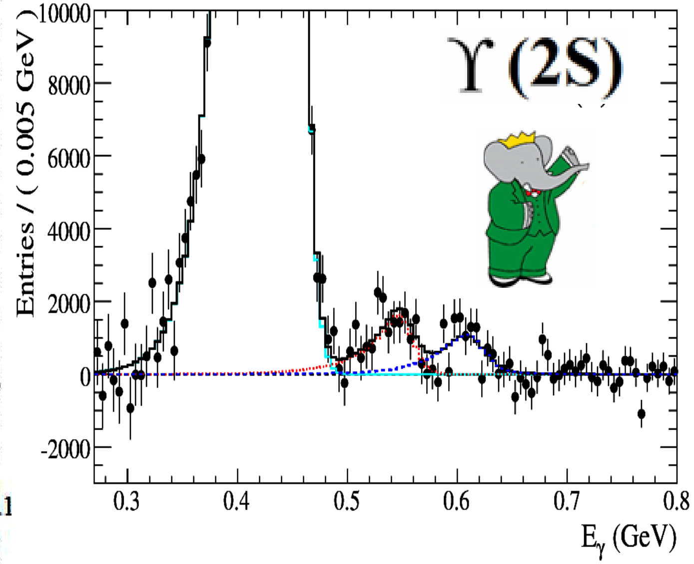
CLEOc searched for $\psi' \rightarrow \gamma\eta_c(2S)$ but not observed
BESIII with 4 times more ψ' data, is working on it.

923/fb, talk by Nakazawa

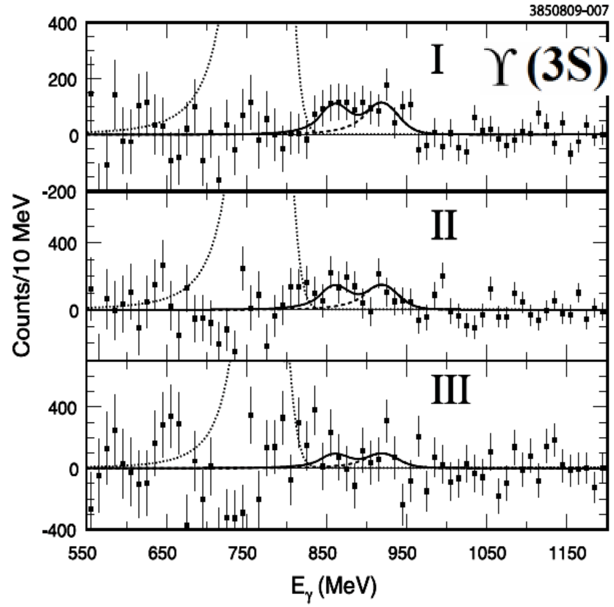
$\eta_b(1S)$ from $\Upsilon(nS)$ transition



PRL 101, 071801 (2008)



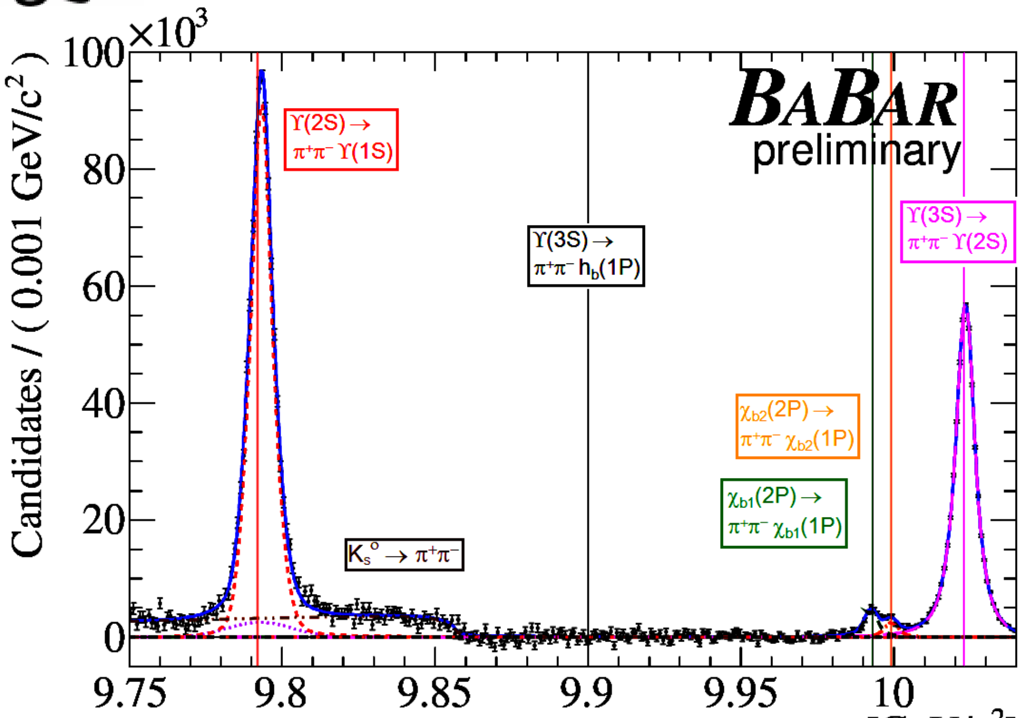
PRL 103, 161801 (2009)



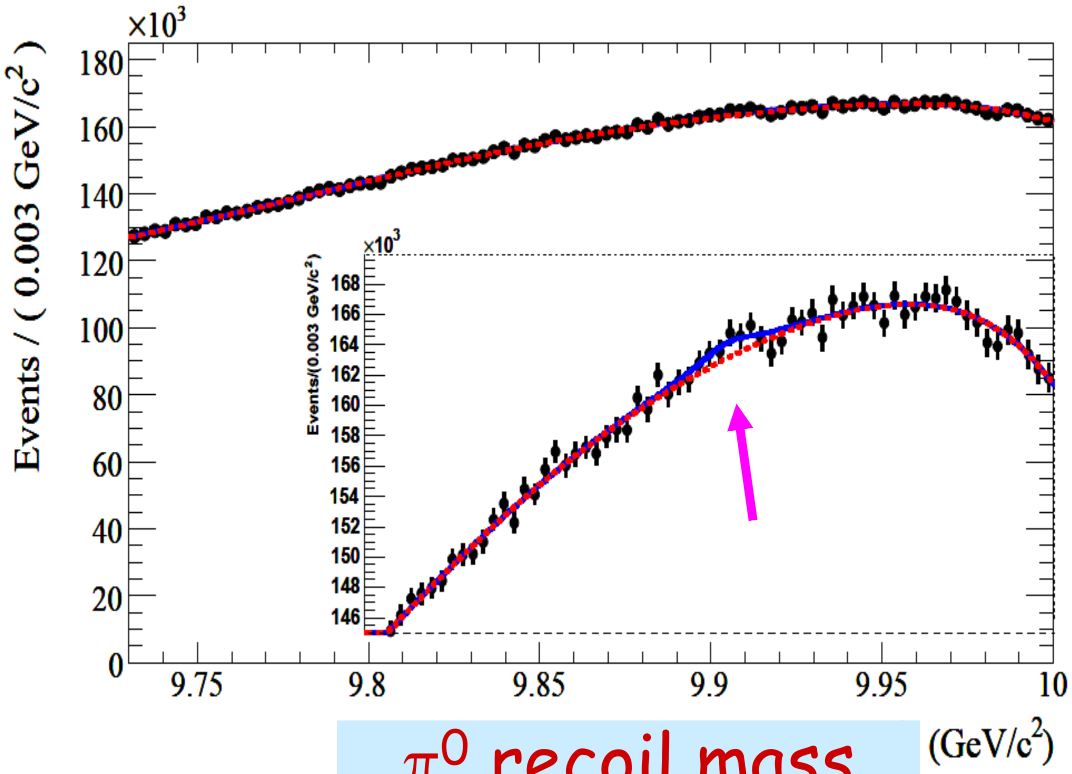
CLEOc: PRD 81, 031104 (2010)

- $B(\Upsilon(3S,2S)\to\gamma\eta_b) = (5.1\pm0.7)\times10^{-4}$ / $(3.9\pm1.5)\times10^{-4}$
- $m_{\eta_b(1S)} = 9390.9\pm2.8$ MeV, $\Gamma_{\eta_b(1S)}\approx10$ MeV
- $m_{\Upsilon(1S)} - m_{\eta_b(1S)} = 69.3\pm2.8$ MeV
- Most recent calculation on mass splitting
  - 60.3±5.5(stat.)±3.8(sys.)±2.1(exp.) MeV [Meinel, 1007.3966]
  - 23.5±4.1±1.5±0.8 MeV [prediction on 2S splitting]

$h_b(^1P_1)$ in $\Upsilon(3S)$ transition



$\pi^+\pi^-$ recoil mass



π^0 recoil mass

- No evidence for h_b signal in $\pi^+\pi^- h_b$ mode
  - $B(\Upsilon(3S) \to \pi^+\pi^- h_b) = (0.0 \pm 0.5 \pm 0.3)\times 10^{-4}$ ($<1\times 10^{-4}$ UL)
- Faint evidence at 9903 MeV in $\Upsilon(3S) \to \pi^0 + X$
  - $B(\Upsilon(3S) \to \pi^0 h_b \to \pi^0 \gamma \eta_b) = (3.1 \pm 1.1 \pm 0.4)\times 10^{-4}$ **(2.7σ)**
  - $1.5\times 10^{-4} < B(\Upsilon(3S) \to \pi^0 h_b \to \pi^0 \gamma \eta_b) < 4.9\times 10^{-4}$

Talk by Fulsom

Charmonium-like XYZ states

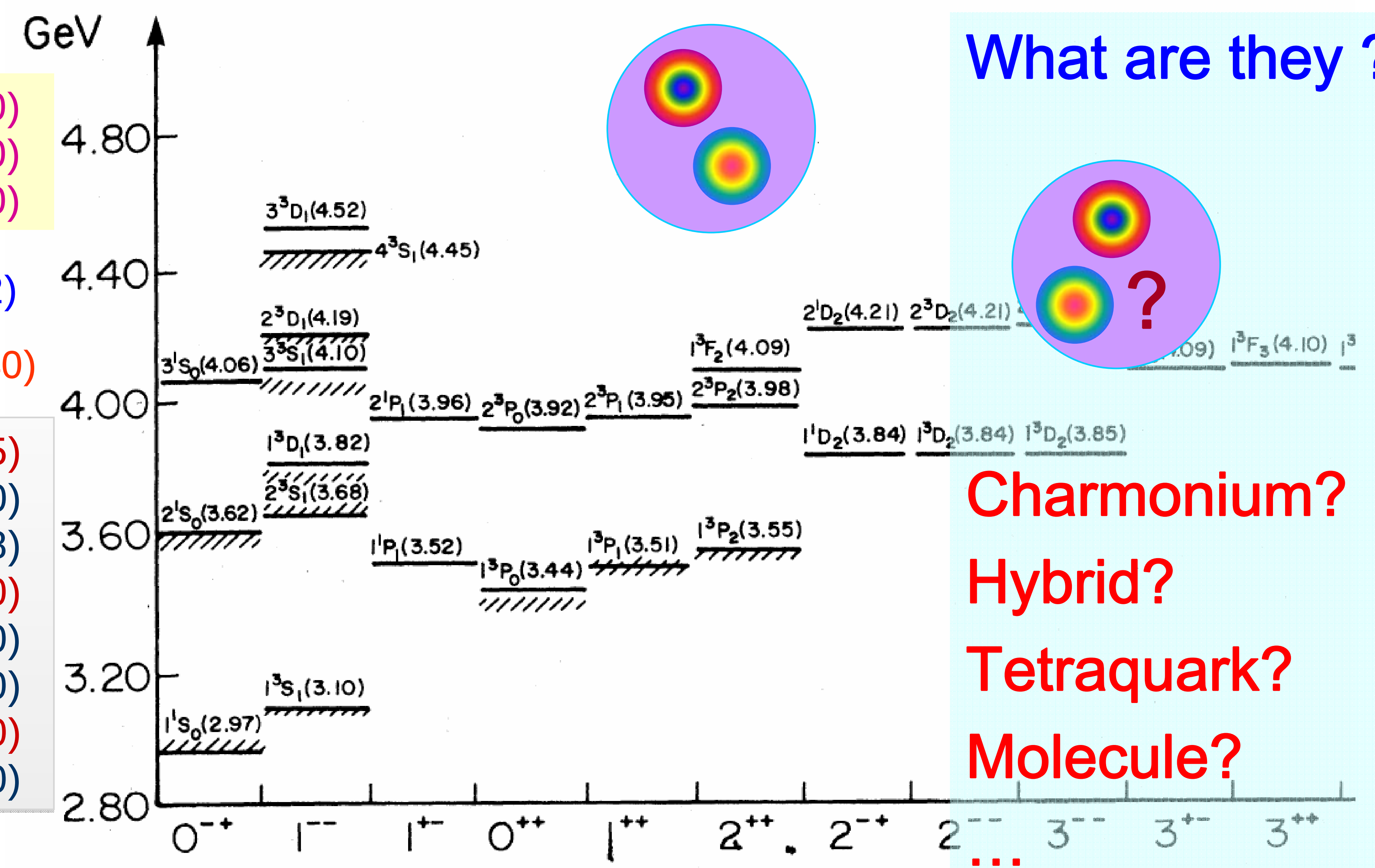
Charmonia & XYZ states

Z(4430)
Z(4250)
Z(4050)

X(3872)

XYZ(3940)

X(3915)
X(4160)
Y(4008)
Y(4140)
Y(4260)
Y(4360)
X(4350)
Y(4660)



What are they ?

Charmonium?
Hybrid?
Tetraquark?
Molecule?
…

Godfrey & Isgur, PRD32, 189 (1985)

Not all XYZ states are charmonia!

X(3872)

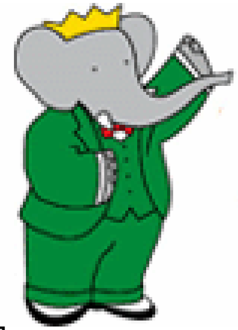
first and most puzzling state
(observed in 2003 at Belle)

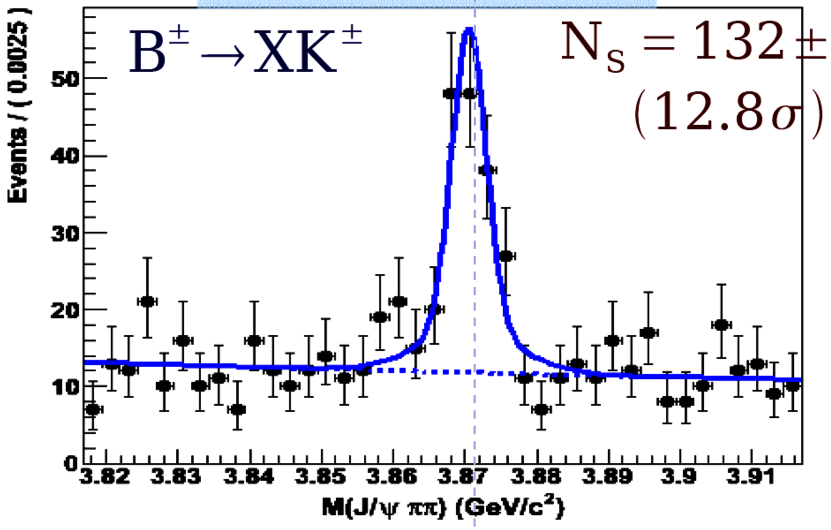
$X(3872) \rightarrow \pi^+\pi^- J/\psi$

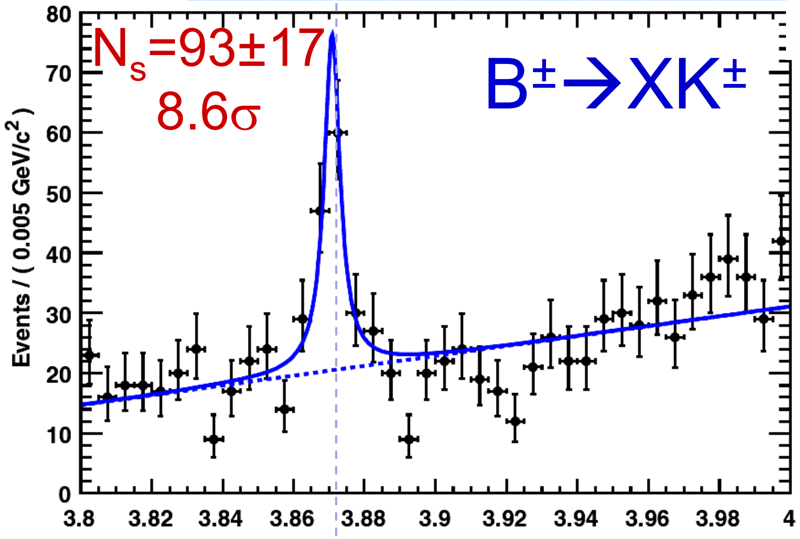
latest results

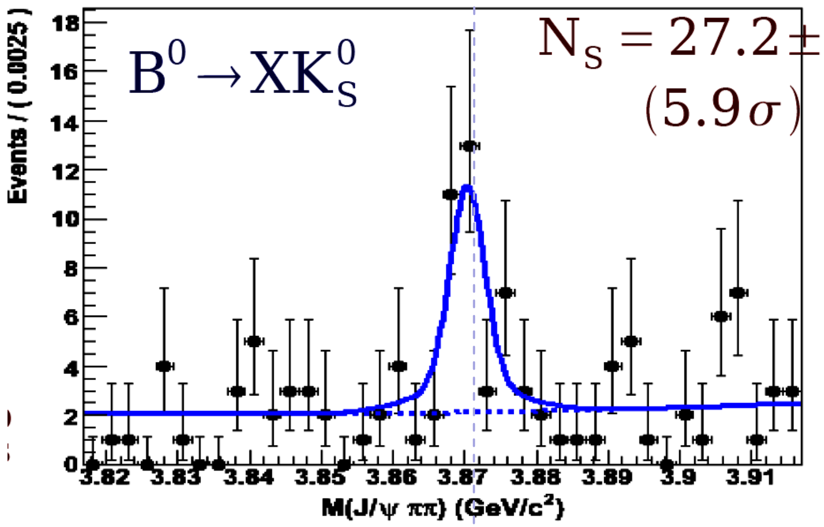
arXiv:0809.1224 605 fb^{-1}

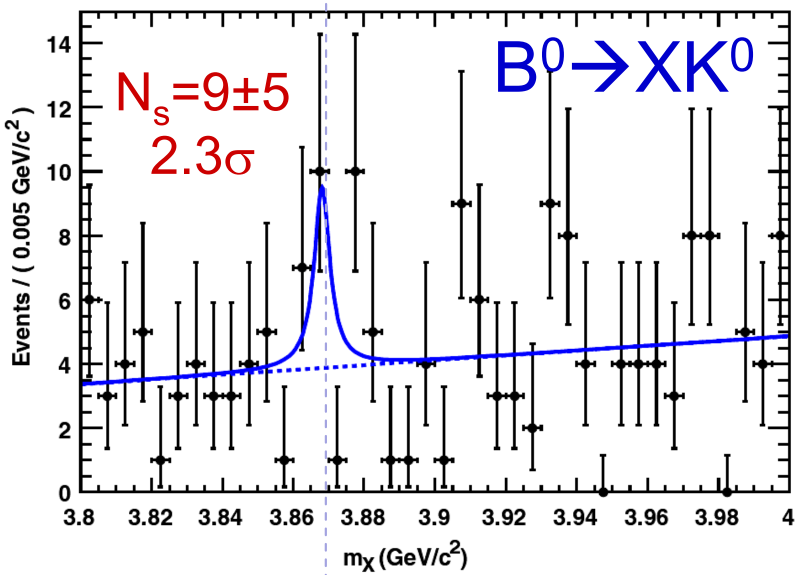
PRD77,111101 (2008) 413 fb^{-1}







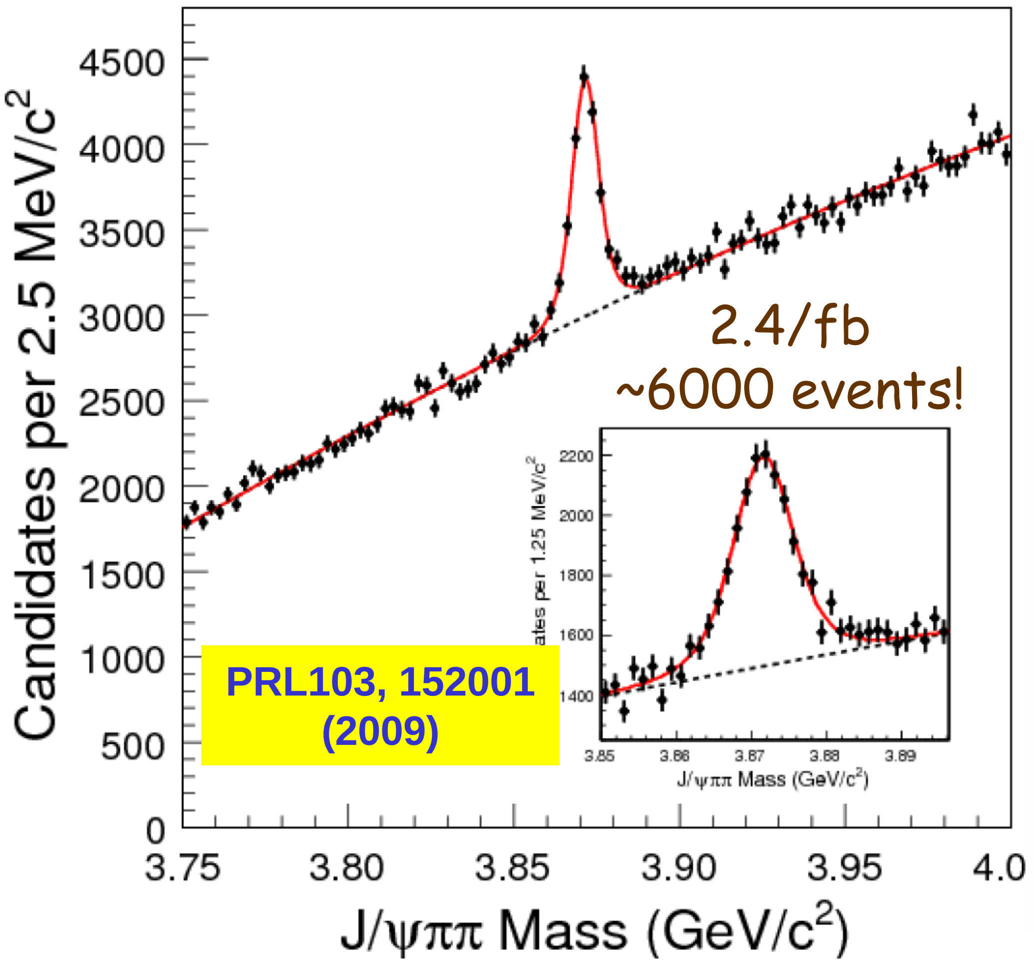




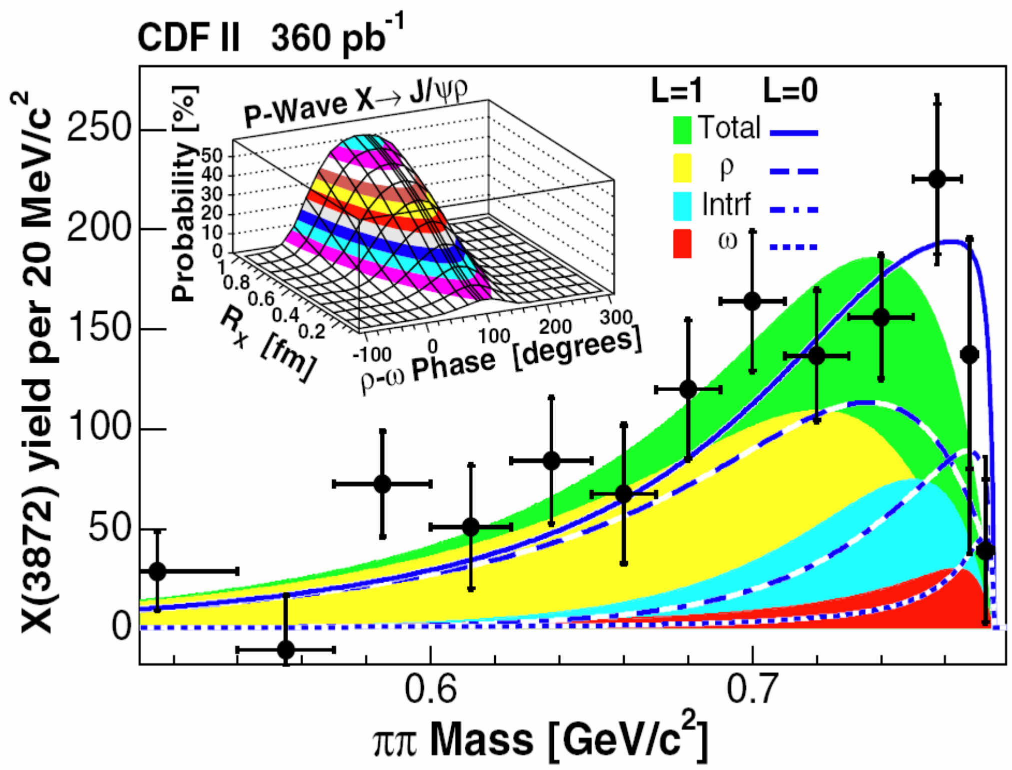
$$\delta M_X = M(X \text{ from } B^\pm) - M(X \text{ from } B^0)$$
$$= (0.18 \pm 0.89 \pm 0.26)\ \text{MeV}$$

$= (2.7 \pm 1.6 \pm 0.4)$ MeV

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



PRL96, 102002 (2006)

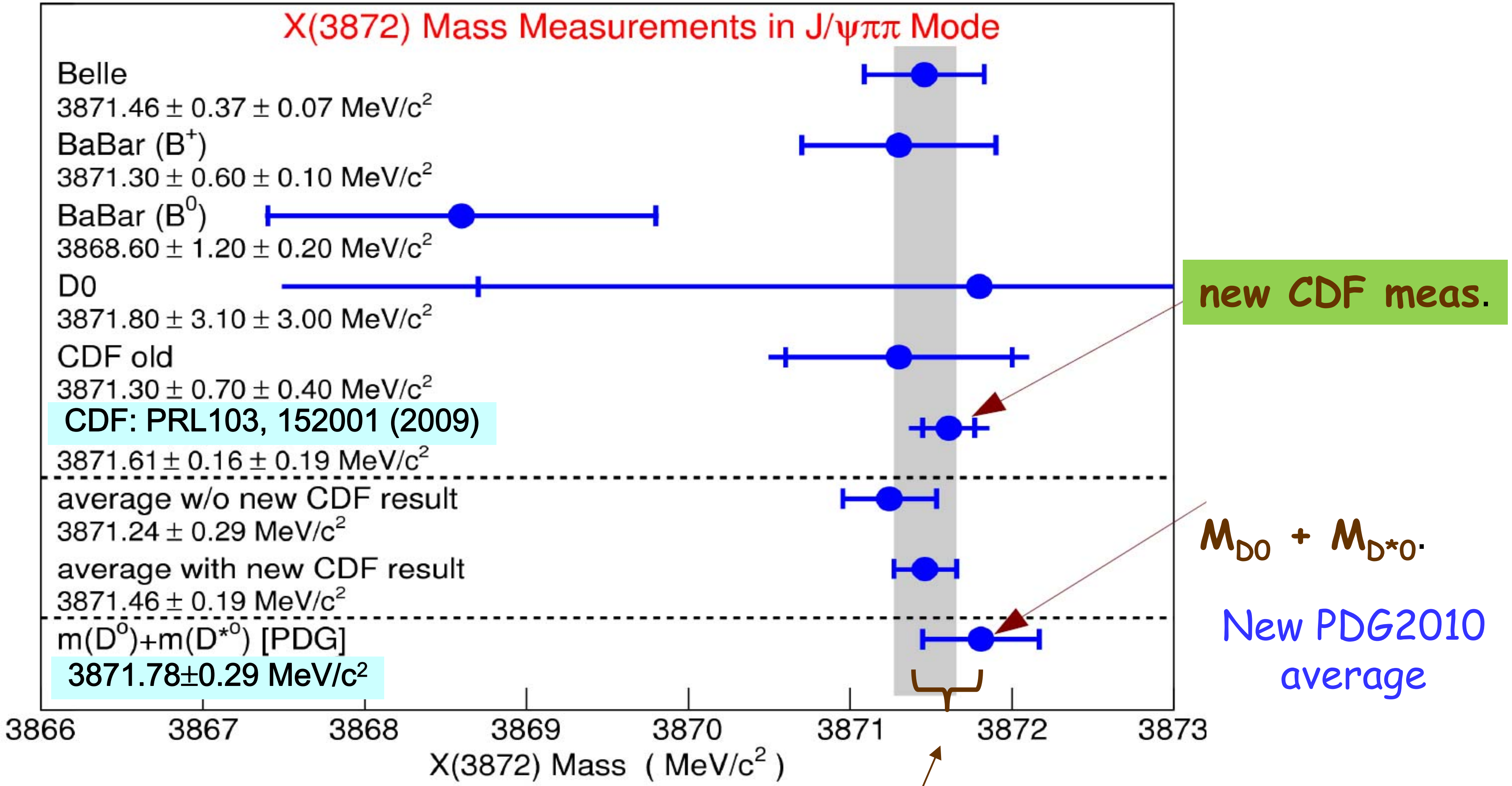


M_X = 3871.61±0.16±0.19 MeV

JPC=1++ (p=55%)
or 2-+ (p=7.7%)

M(X(3872)) vs. M(D^0D^{*0})

$\langle M_X \rangle = 3871.46 \pm 0.19$ MeV

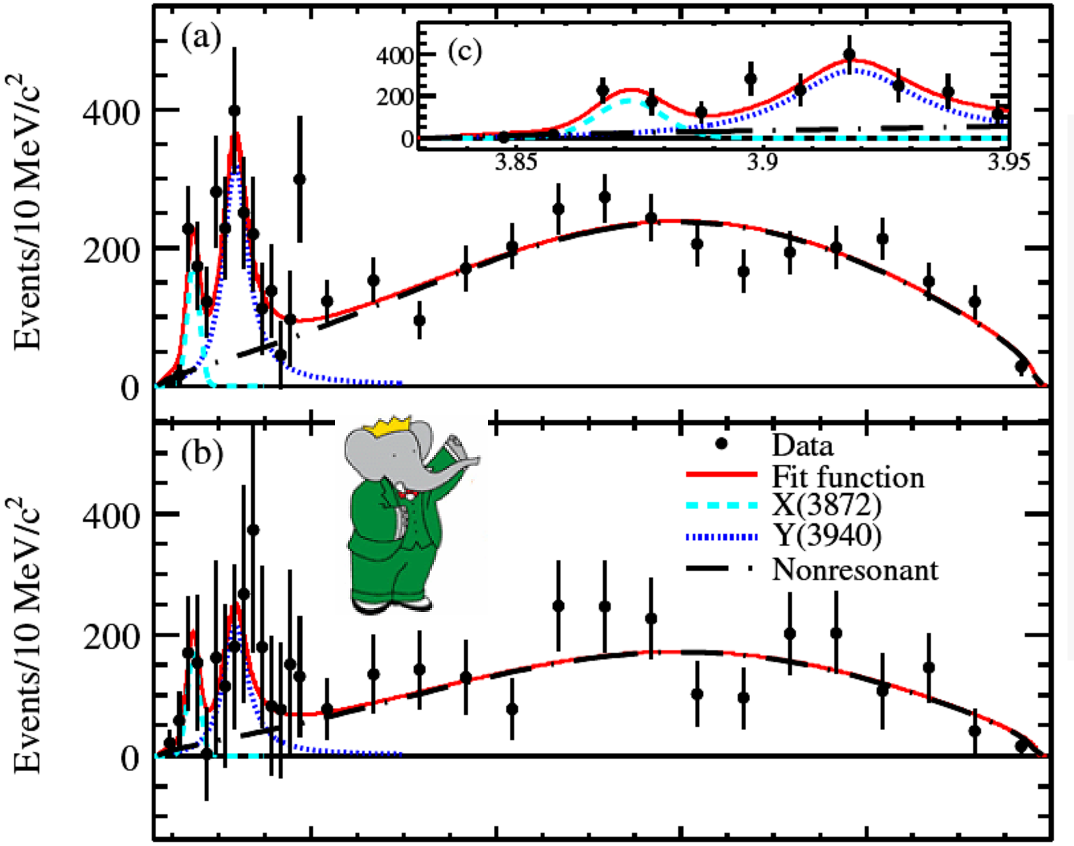


Δm(deuteron) = -2.2 MeV

$\Delta m = -0.32 \pm 0.35$ MeV

Evidence for X(3872)→ωJ/ψ

BaBar: PRD82, 011101 (2010)
426 fb^{-1}, $B^- \to K^-\pi^+\pi^-\pi^0 J/\psi$

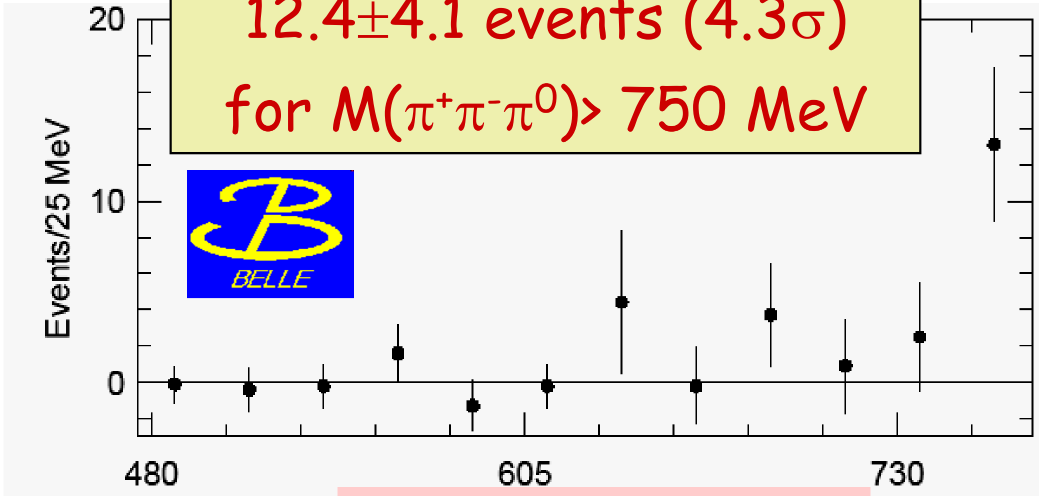


M(ωJ/ψ) [MeV]

26.7±7.6 events (4.0σ)

Belle: hep-ex/0505037
253 fb^{-1}, $B^- \to K^-\pi^+\pi^-\pi^0 J/\psi$

12.4±4.1 events (4.3σ)
for $M(\pi^+\pi^-\pi^0)$> 750 MeV

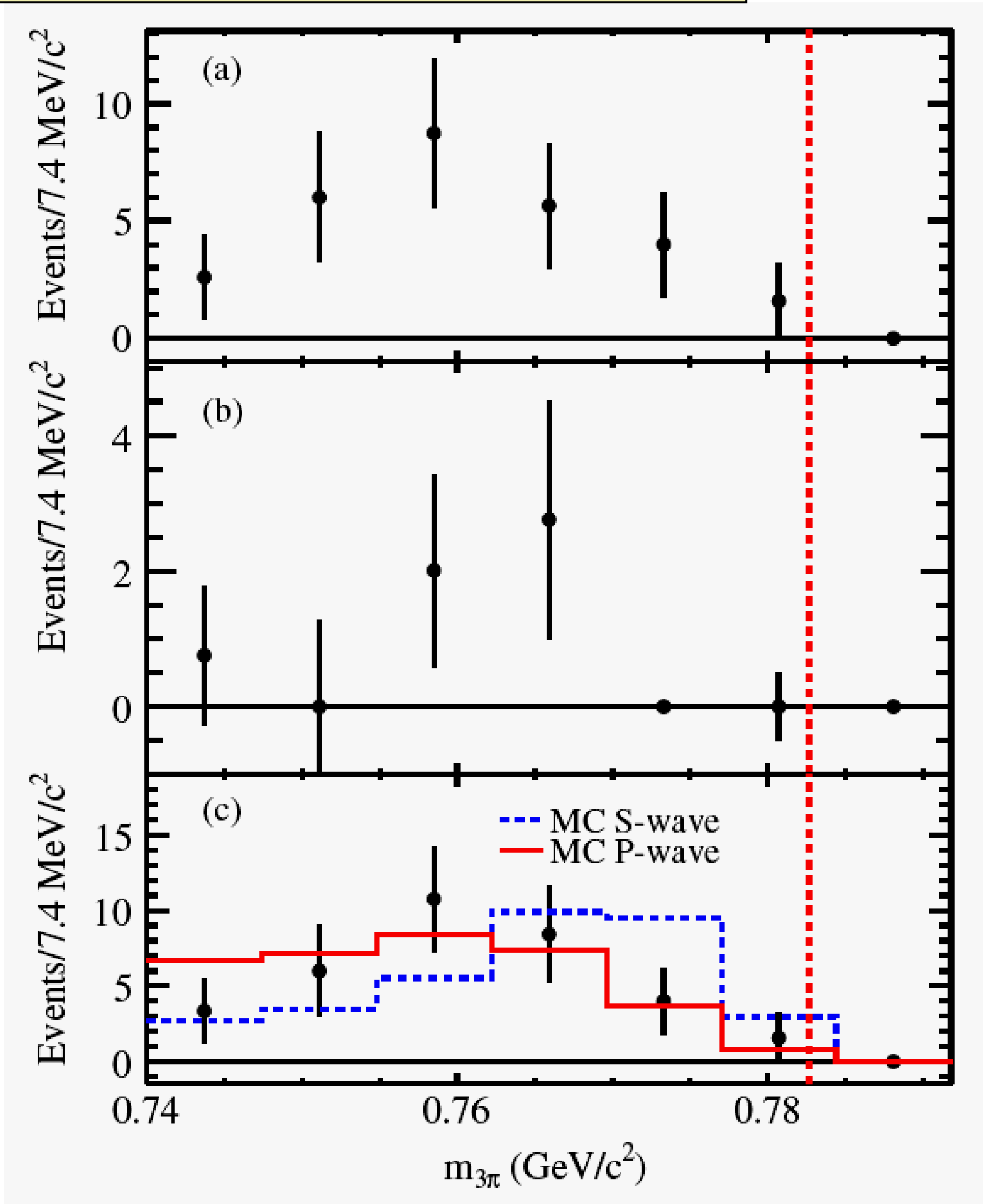


$M(\pi^+\pi^-\pi^0)$ [MeV]

Large isospin violation:
ω/ρ= 1.0±0.5 Belle
ω/ρ= 0.8±0.3 BaBar

Evidence for X(3872)→ωJ/ψ

BaBar: PRD82, 011101 (2010)



All together 34 events

S-wave between ω & J/ψ

χ^2/ndf=10.17/5, P=7.1%

P-wave between ω & J/ψ

χ^2/ndf=3.53/5, P=61.9%

JPC=2-+ favored than 1++

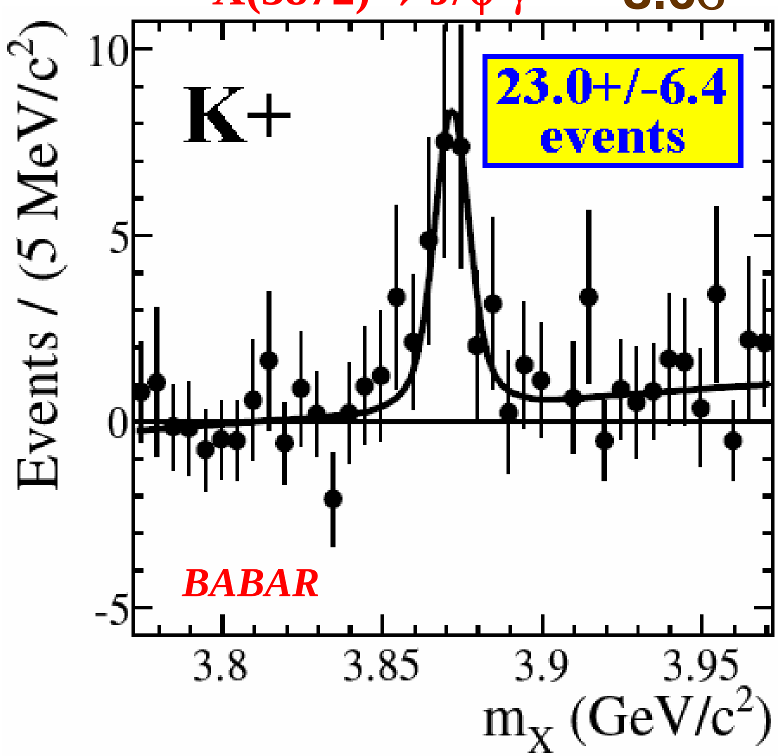
X(3872)=$\eta_{c2}(1^1D_2)$?

Potential models: 3.84 GeV!

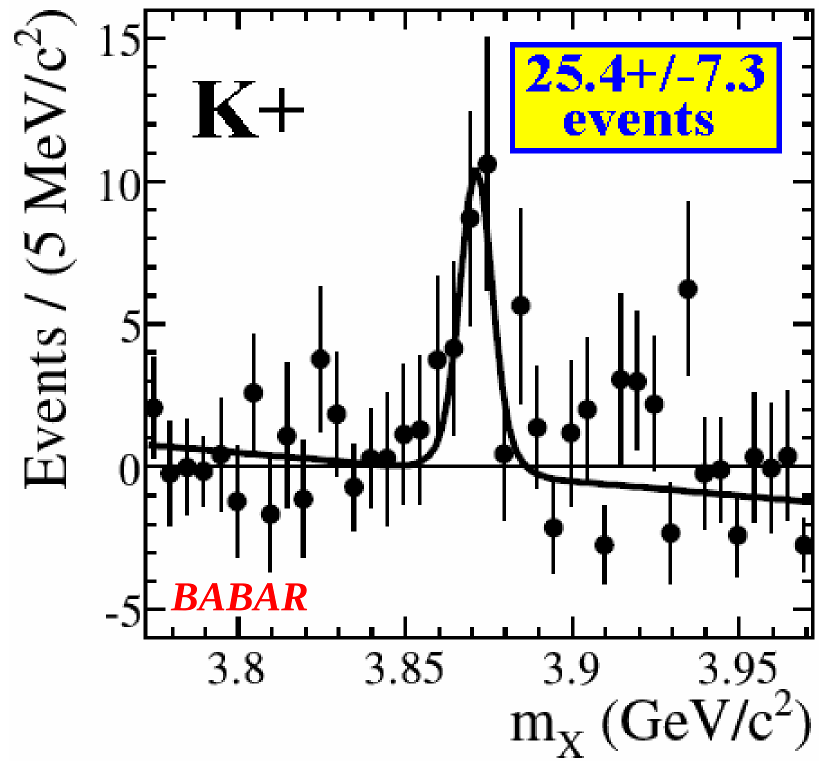
X(3872)→γJ/ψ & γψ′ from BaBar

424 fb^{-1}, PRL 102, 132001 (2009)

X(3872)→ J/ψ γ 3.6σ

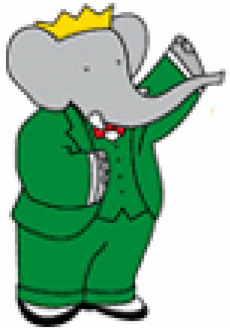


X(3872)→ ψ(2S) γ 3.5σ



$Bf(B^+ \to X_{3872}K^+) \times (X_{3872} \to J/\psi\gamma) = (2.8 \pm 0.8 \pm 0.1) \times 10^{-6}$

$Bf(B^+ \to X_{3872}K^+) \times (X_{3872} \to \psi'\gamma) = (9.5 \pm 2.7 \pm 0.6) \times 10^{-6}$

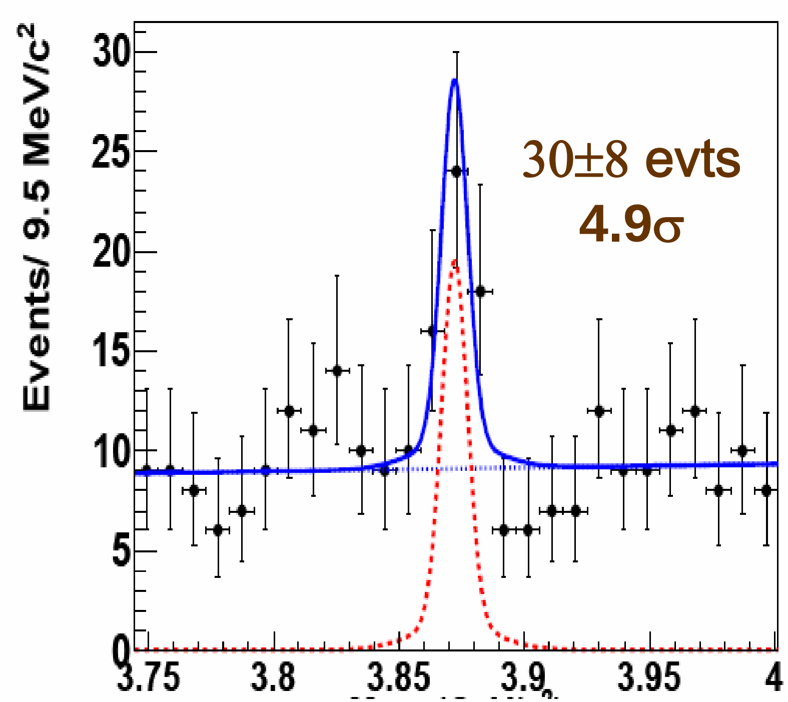


- C-parity = +1
- $J^{PC} = 2^{-+}$ disfavored ← multipole suppression
- $Bf(X_{3872} \to \gamma\psi') > Bf(X_{3872} \to \gamma J/\psi)$ ←bad for molecules

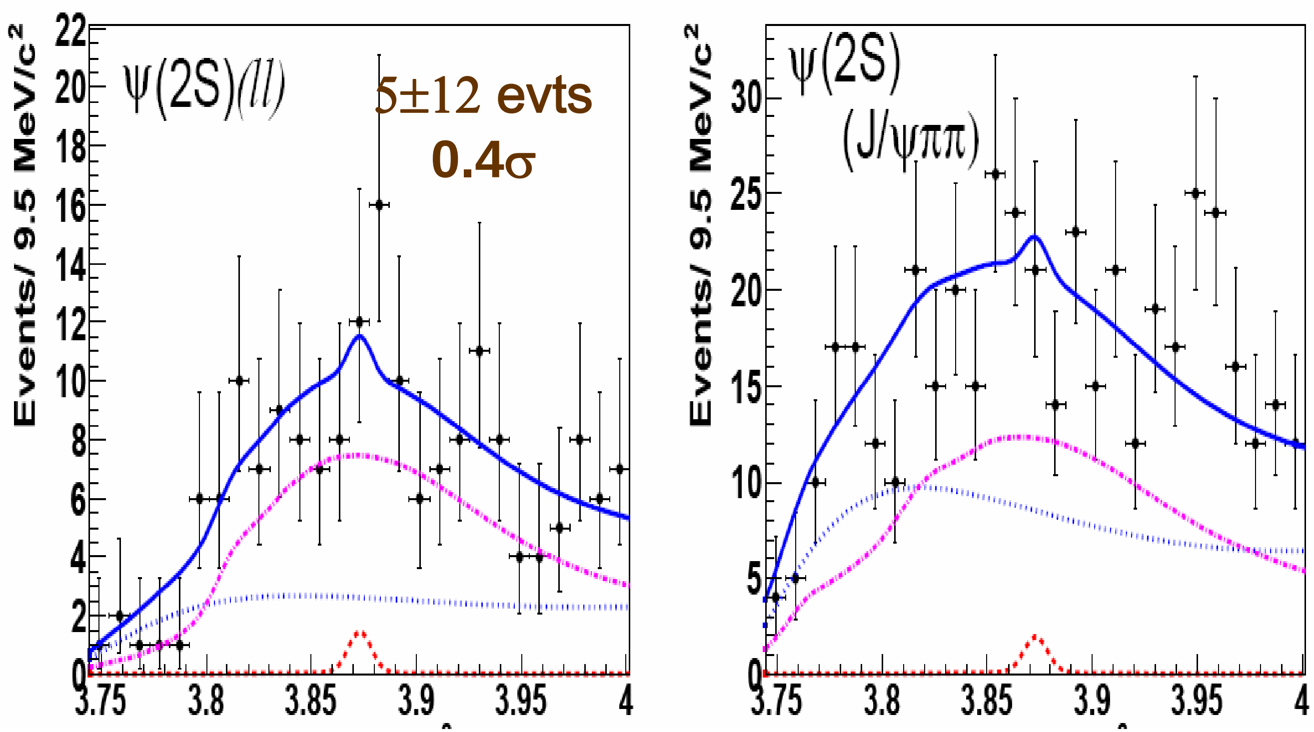
Swanson, PLB 598, 197 (2004)

X(3872)→γJ/ψ & γψ' from Belle

712 fb^{-1}, $B^+ \to K^+ X$



J/ψ γ mass (GeV)



ψ(2S) γ mass (GeV)

$Bf(B^+ \to X_{3872} K^+) \times (X_{3872} \to J/\psi\gamma)$
$= (1.78^{+0.48}_{-0.44} \pm 0.12) \times 10^{-6}$

Agrees with BaBar (2.8 ± 0.8 ± 0.1)

$Bf(B^+ \to X_{3872} K^+) \times (X_{3872} \to \psi'\gamma)$
$< 3.4 \times 10^{-6}$ @ 90% C.L.

Smaller than BaBar (9.5±2.7±0.6)

BELLE

$Bf(X_{3872} \to \gamma\psi')$ >?< $Bf(X_{3872} \to \gamma J/\psi)$

Talk by Watson

X(3872) summary

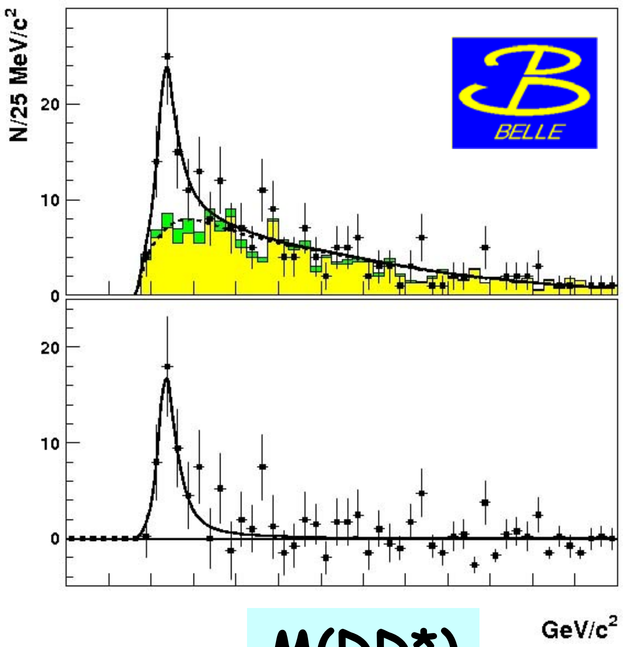
- Mass: Very close to D^0D^{*0} threshold
- Width: Very narrow, < 3 MeV
- $J^{PC}=1^{++}$ or 2^{-+} (need confirmation!)
- Production
  - in pp collison – similar to charmonia
  - In B decays – KX similar to cc, K*X smaller than cc
- Decay BR: open charm ~ 50%, charmonium~O(%)
- Nature (very likely exotic)
  - Loosely D^0D^{*0} bound state (like deuteron?)?
  - Mixture of excited χ_{c1} and D^0D^{*0} bound state?
  - Many other possibilities (if it is not χ'_{c1}, where is χ'_{c1}?)

XYZ(3940)

The states near 3940 MeV at Belle

not seen in $\omega J/\psi$ | probably different | not seen in DD^* | Probably the χ_{c2}'

X(3940) — $e^+e^- \to J/\psi\ DD^*$

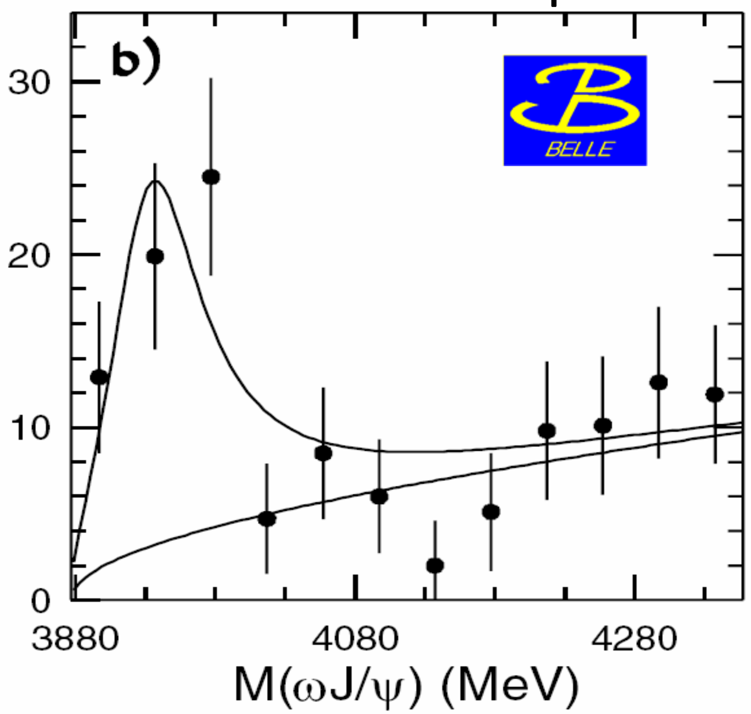


M(DD*)

$M = 3942\ ^{+7}_{-6} \pm 6$ MeV
$\Gamma_{tot} = 37\ ^{+26}_{-15} \pm 12$ MeV

693/fb, PRL 100, 202001

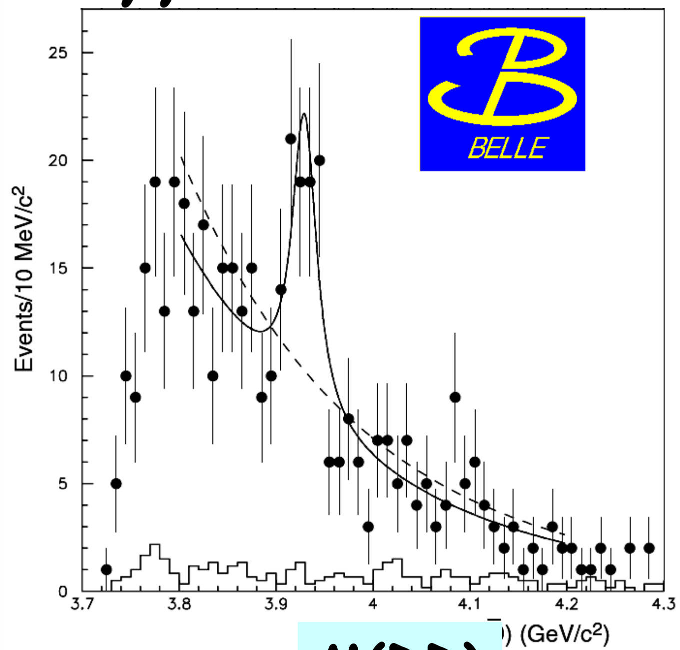
Y(3940) — $B \to K\ \omega J/\psi$



$M \approx 3943 \pm 11 \pm 13$ MeV
$\Gamma_{tot} \approx 87 \pm 22 \pm 26$ MeV

253/fb, PRL 94, 182002

Z(3930) — $\gamma\gamma \to DD$



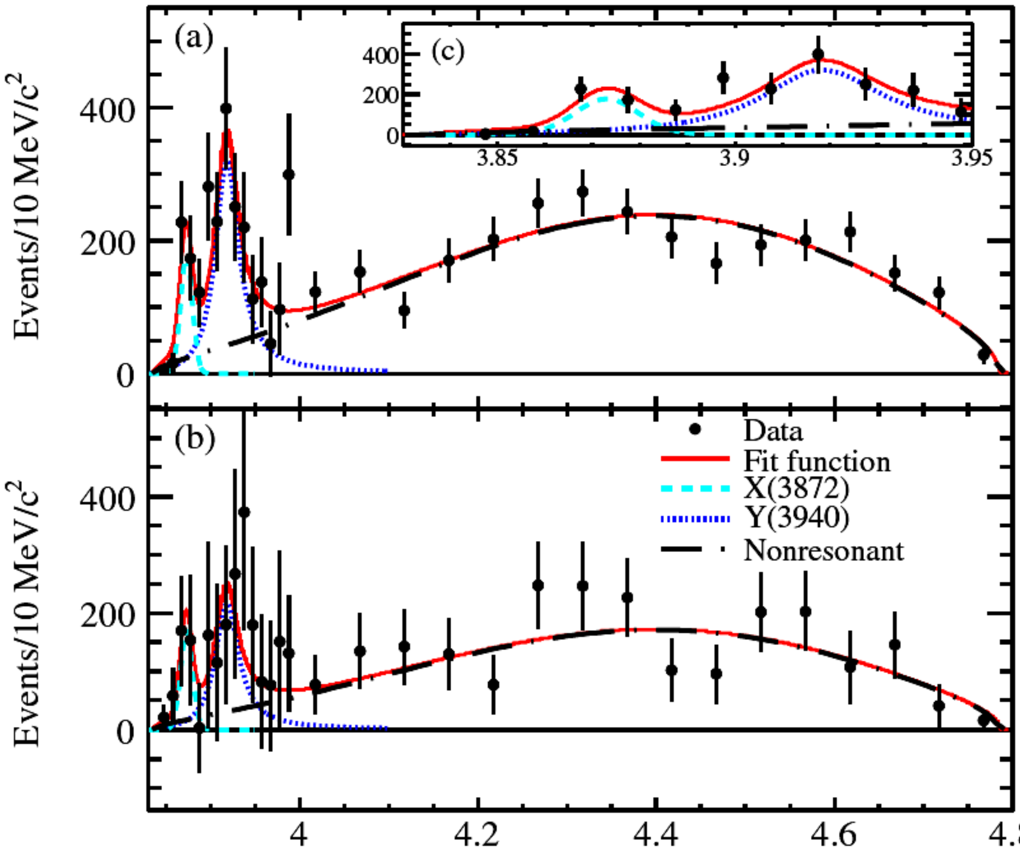
M(DD)

$M = 3929 \pm 5 \pm 2$ MeV
$\Gamma_{tot} = 29 \pm 10 \pm 2$ MeV

395/fb, PRL 96, 082003

The states near 3940 MeV at BaBar

Y(3940), B→K ωJ/ψ

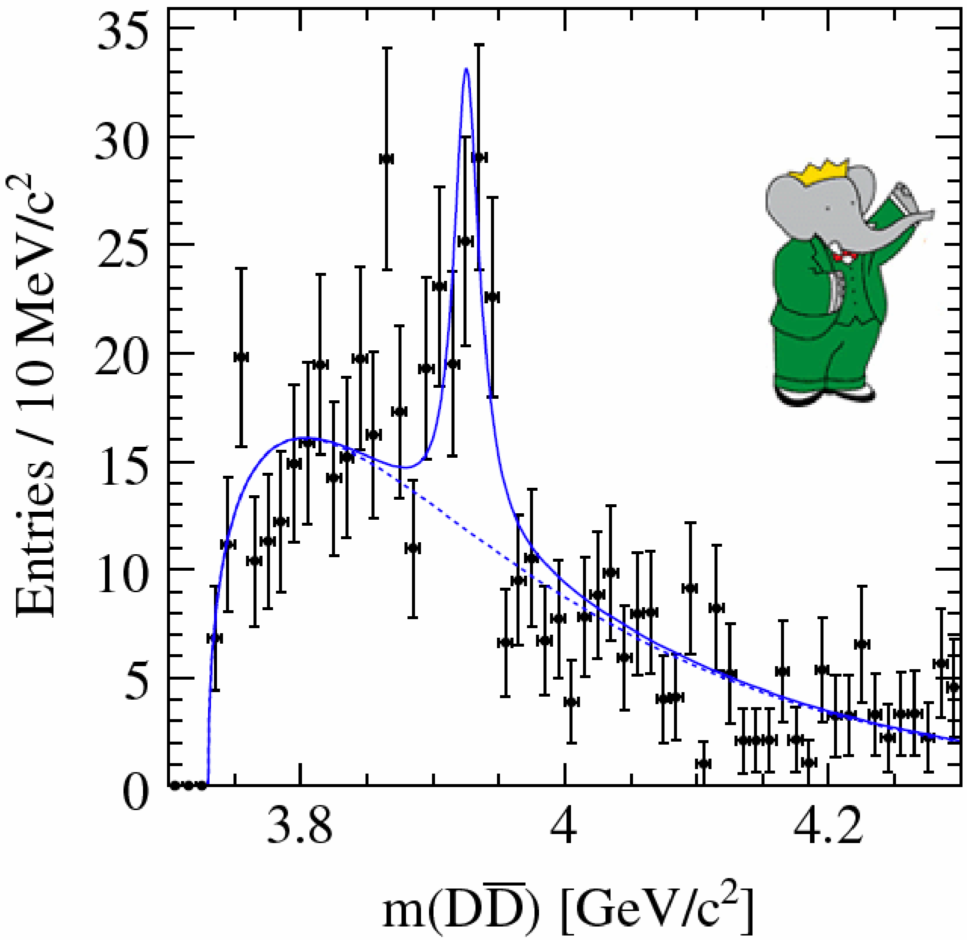


M(ωJ/ψ)

$M \approx 3919.1^{+3.8}_{-3.5} \pm 2.0$ MeV
$\Gamma \approx 31^{+10}_{-8} \pm 5$ MeV

426/fb: PRD 82, 011101

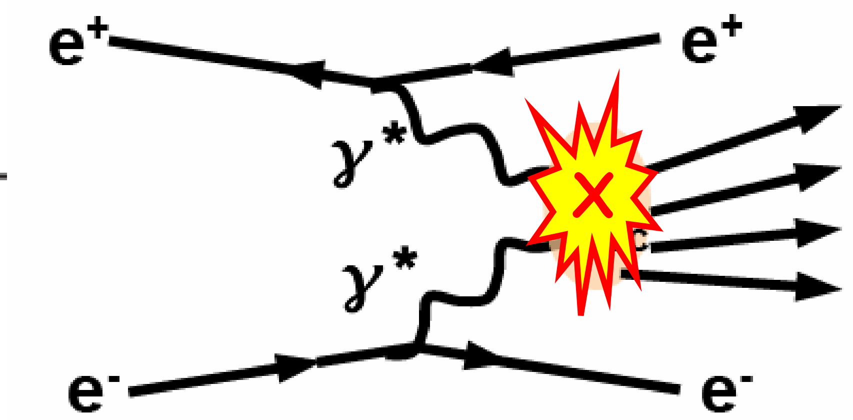
Z(3930), γγ→DD

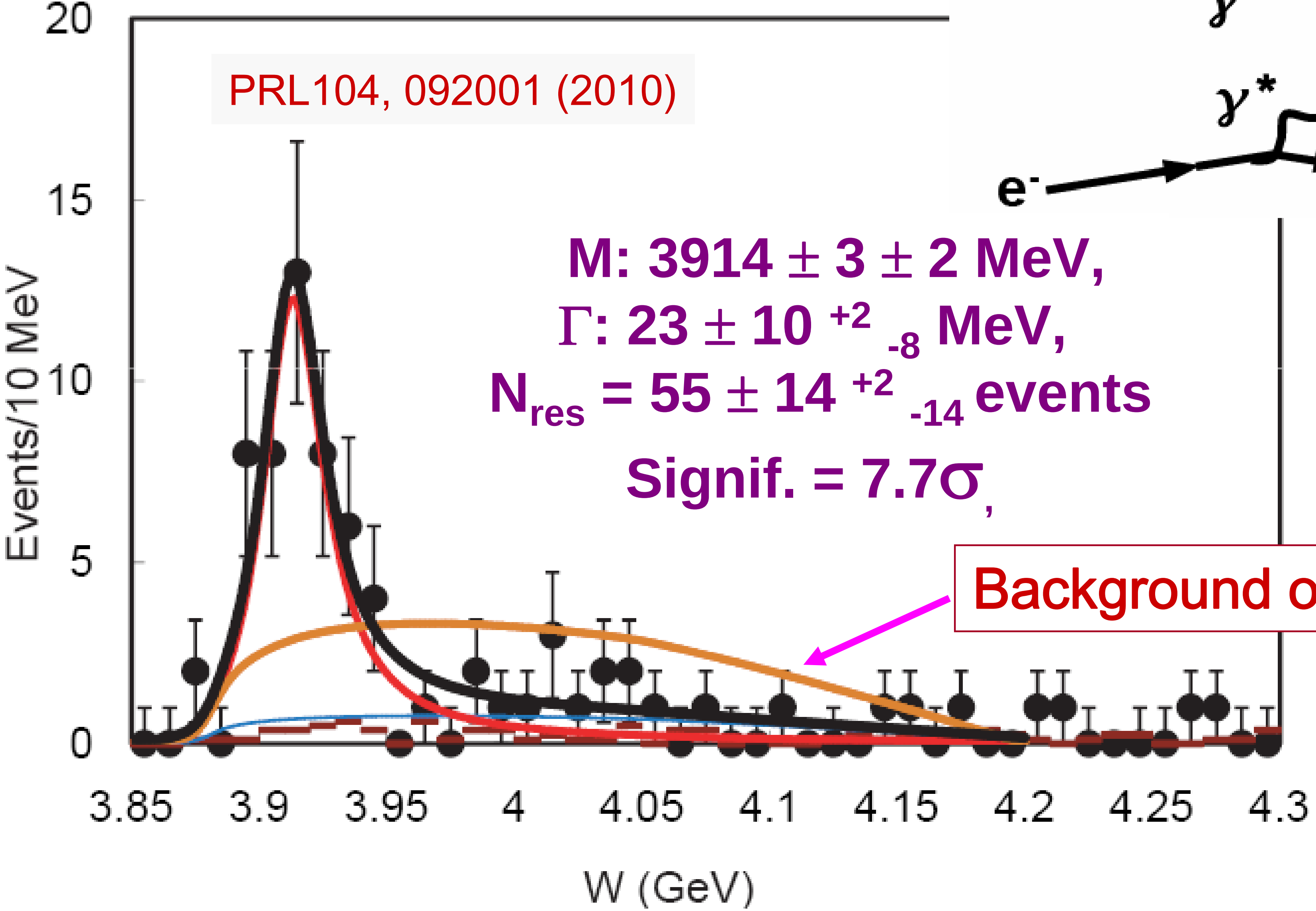


$M = 3926.7 \pm 2.7 \pm 1.1$ MeV
$\Gamma_{tot} = 21.3 \pm 6.8 \pm 3.6$ MeV

384/fb: PRD 81, 092003

New peak in $\gamma\gamma \rightarrow \omega J/\psi$





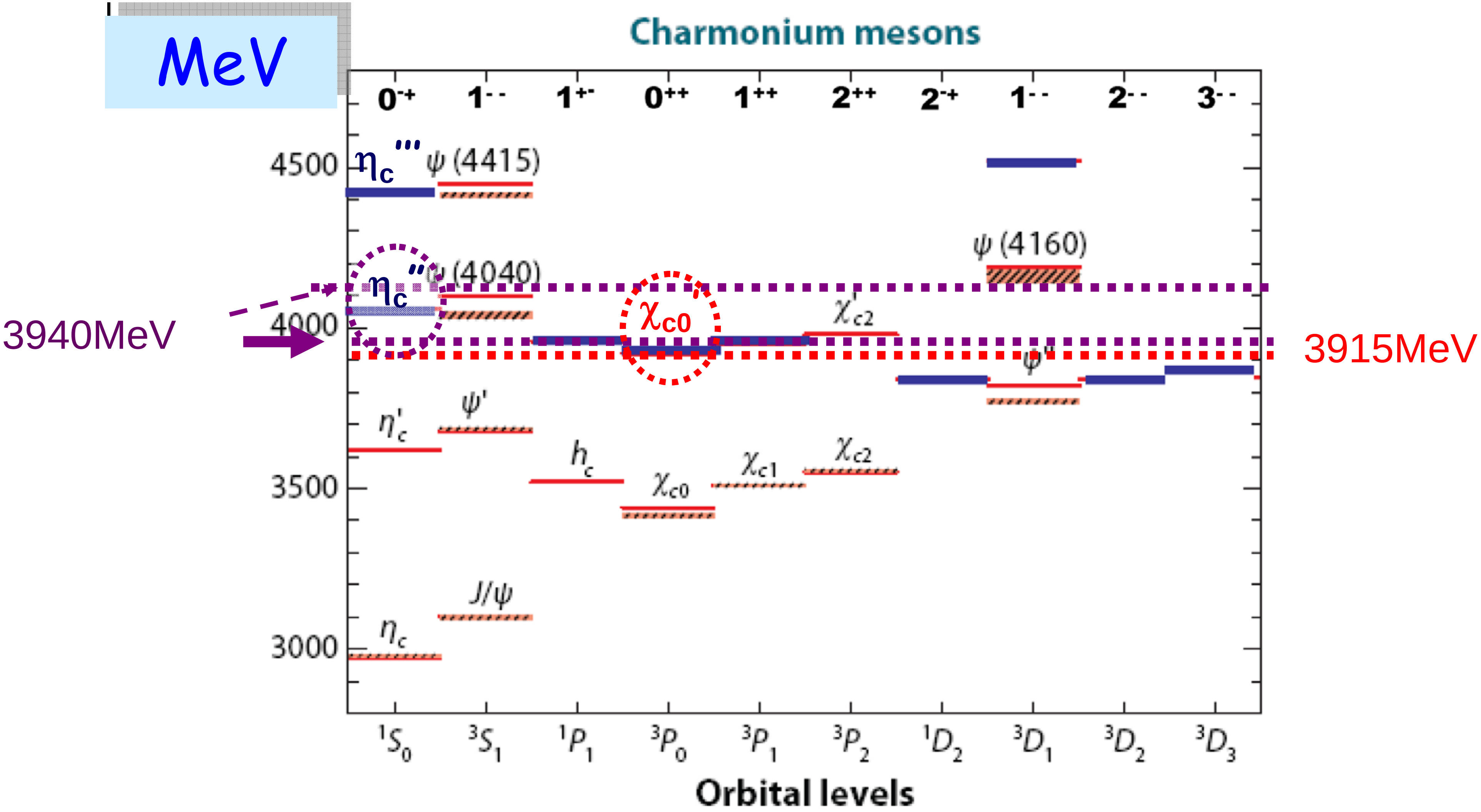
M: 3914 $\pm$ 3 $\pm$ 2 MeV,

Γ: 23 $\pm$ 10 $^{+2}_{-8}$ MeV,

N_{res} = 55 $\pm$ 14 $^{+2}_{-14}$ events

Signif. = 7.7σ,

$c\underline{c}$ assignments for X(3915), X(3940) & Y(3940)?

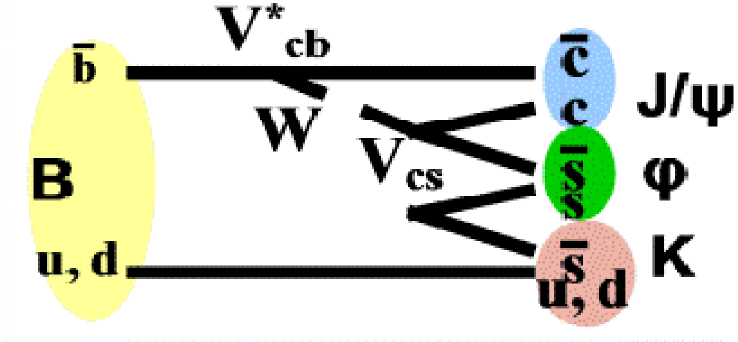


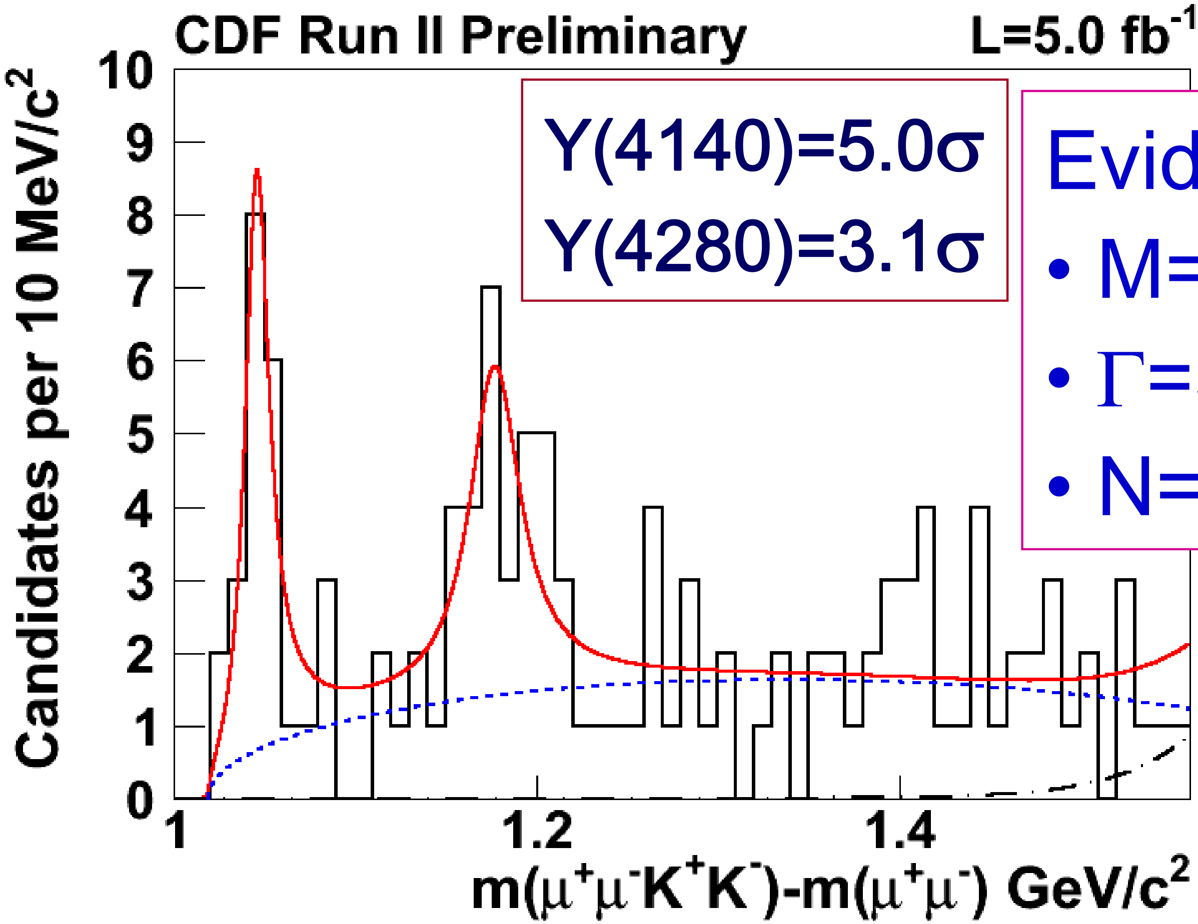
- Y(3940) = X(3915) = χ_{co}' ? ← $\Gamma(\omega J/\psi)$ too large?
- X(3940) = η_c''? ← mass too low? $\psi(3S)$=4040 MeV
- Z(3940) = χ_{c2}' ? ← ($\Delta M(J=2,0)=15\pm7$ MeV?)

States decay into $\phi J/\psi$

CDF update: Y(4140) & Y(4280)

- $M = 4143.4^{+2.9}_{-3.0} \pm 0.6$ MeV
- $\Gamma = 15.3^{+10.4}_{-6.1} \pm 2.5$ MeV
- $N = 19^{+6}_{-5} \pm 3$ (Observation!)





Y(4140)=5.0σ

Y(4280)=3.1σ

Evidence for Y(4280):

- $M = 4274.4^{+8.4}_{-6.7} \pm 1.9$ MeV
- $\Gamma = 32.3^{+21.9}_{-15.3} \pm 7.6$ MeV
- N= 22 ± 8 ± 5

2.8 fb^{-1} results in PRL102, 242002 (2009)

Talk by Yi

Y(4140)/Y(4280) not significant

- Belle: B→J/ψϕK with 772M B$\overline{B}$

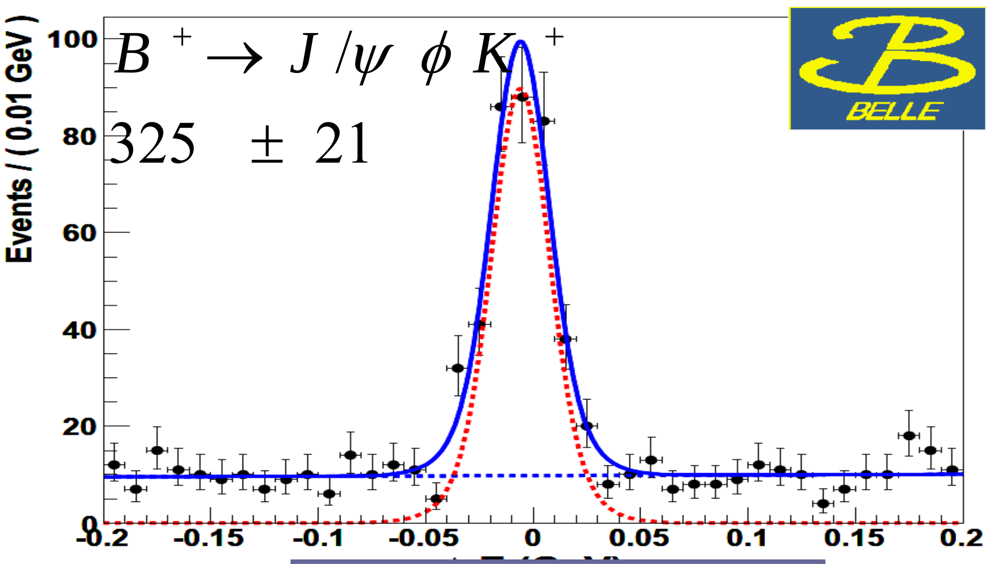
  M(J/ψϕ) fit with Y(4140) parameters fixed

  [but low effciency at J/ψϕ threshold]

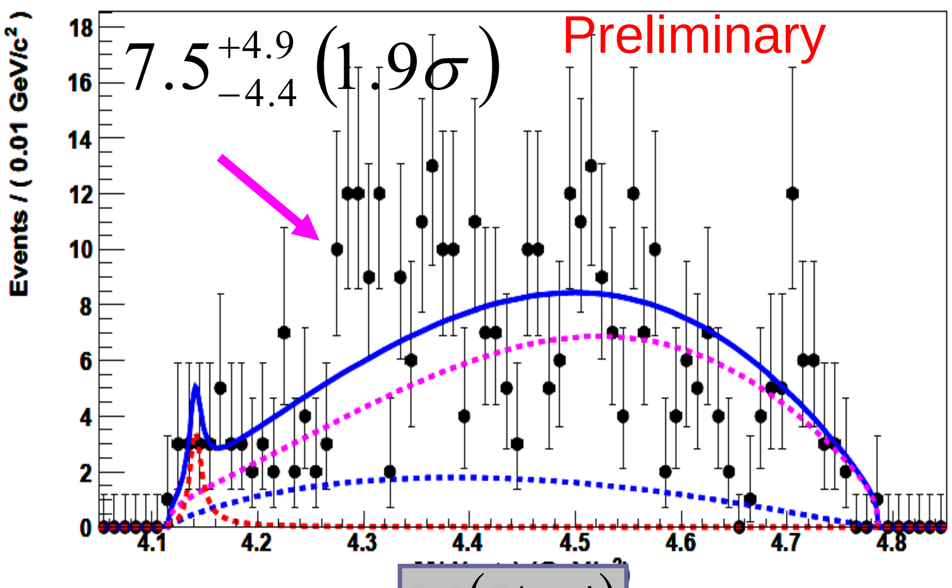
$$Br\left(B^{+}\to Y(4140)K^{+}, Y\to J/\psi\phi\right) < 6\times10^{-6}\ @\ 90\%C.L$$

CDF result (my evaluation):

$$Br\left(B^{+}\to Y(4140)K^{+}, Y\to J/\psi\phi\right) = (7.7\pm3.7)\times10^{-6}$$



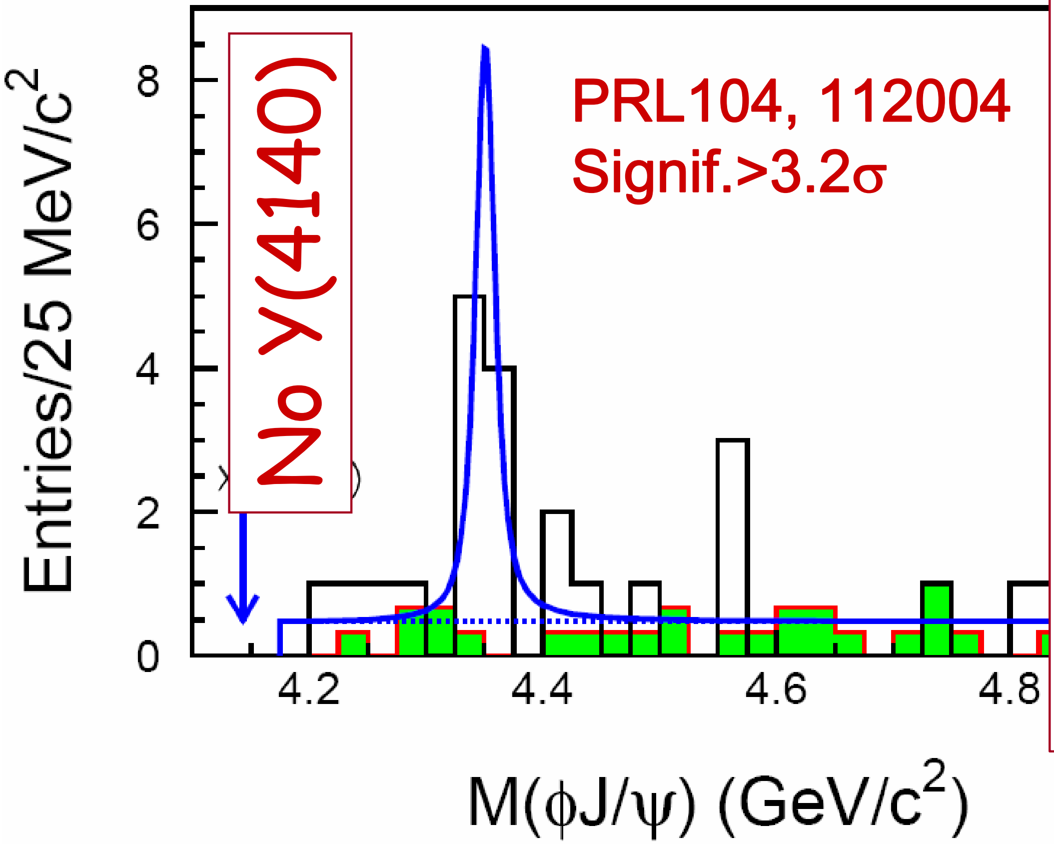
$$\Delta E = E_B - \sqrt{s}/2$$

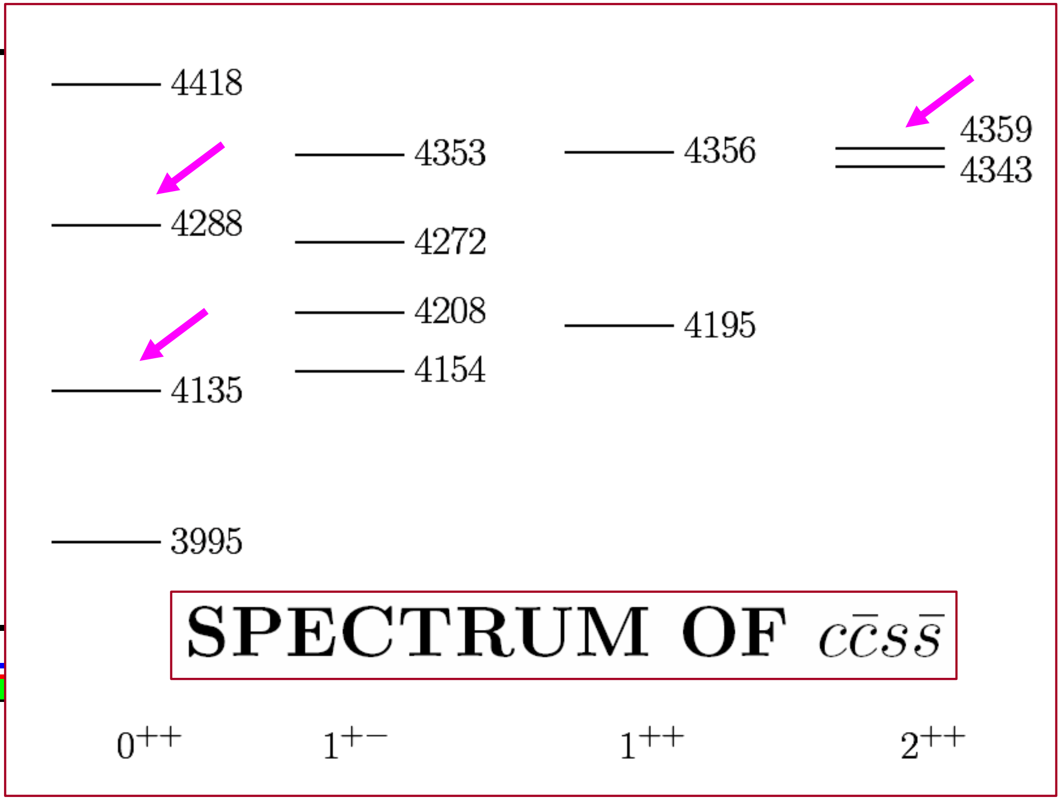


M(J/ψϕ)

Evidence for X(4350)→ϕJ/ψ

825 /fb





$M=4350.6^{+4.6}_{-5.1} \pm 0.7$ MeV

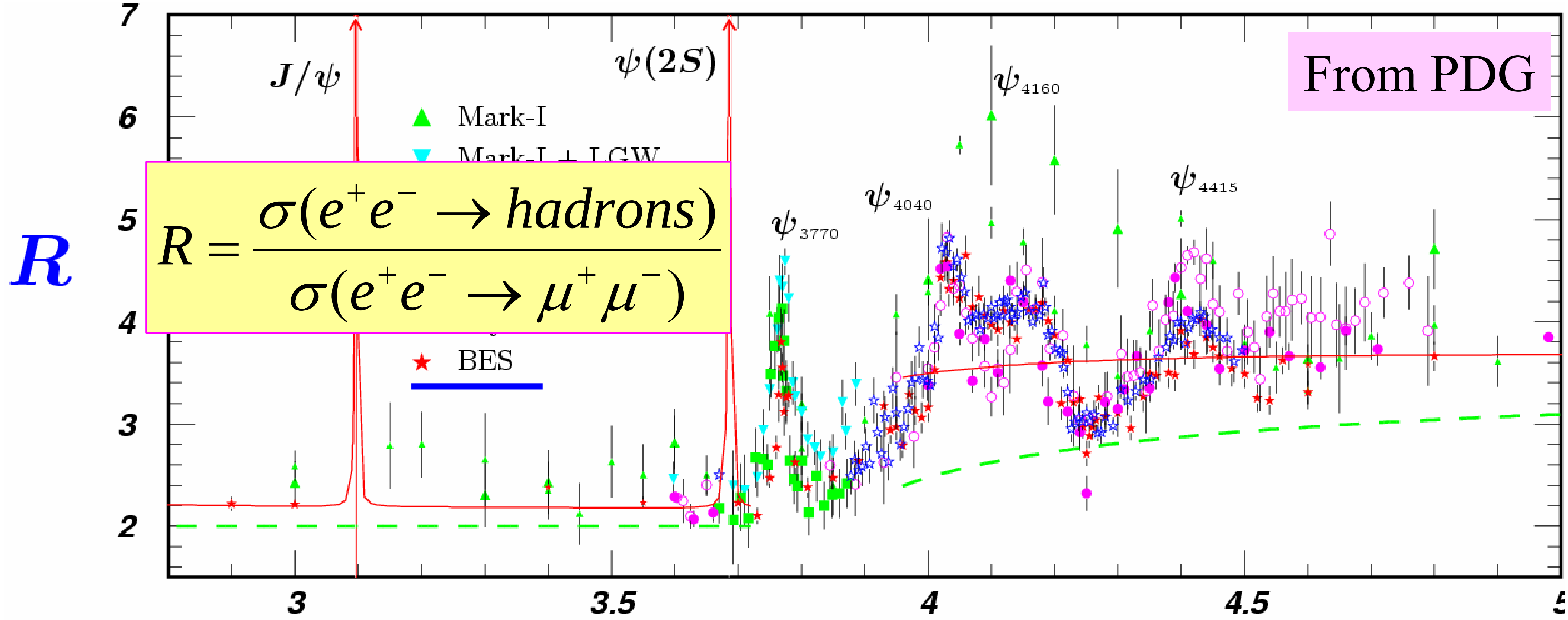
$\Gamma=13.3^{+17.9}_{-9.1} \pm 4.1$ MeV

0^+: $\Gamma_{\gamma\gamma}B(\phi J/\psi) = 6.4^{+3.1}_{-2.3} \pm 1.1$ eV

2^+: $\Gamma_{\gamma\gamma}B(\phi J/\psi) = 1.5^{+0.7}_{-0.5} \pm 0.3$ eV

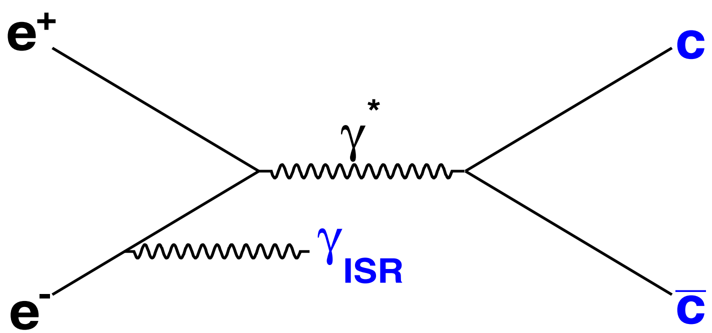
- Excited P-wave charmonium?
- Tetraquark?
  Fl. Stancu, JPG37, 075017 (2010)
- $D^*_s\underline{D}^*_{s0}$ molecule at 4.34±0.09 GeV?
  J.R.Zhang et al., arXiv:0905.4672

R values/ψ states/Y states



From PDG

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

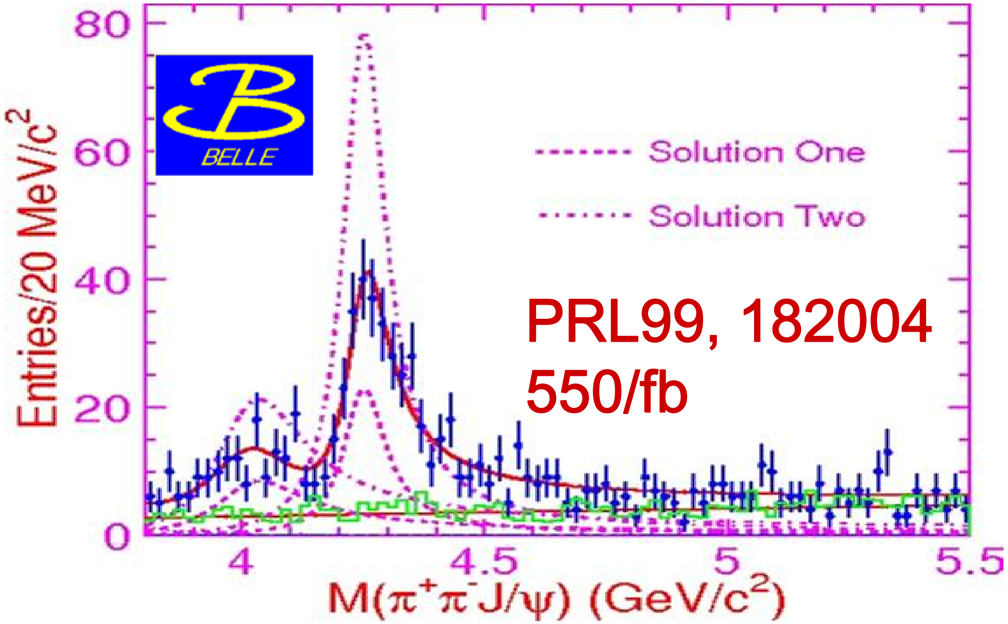


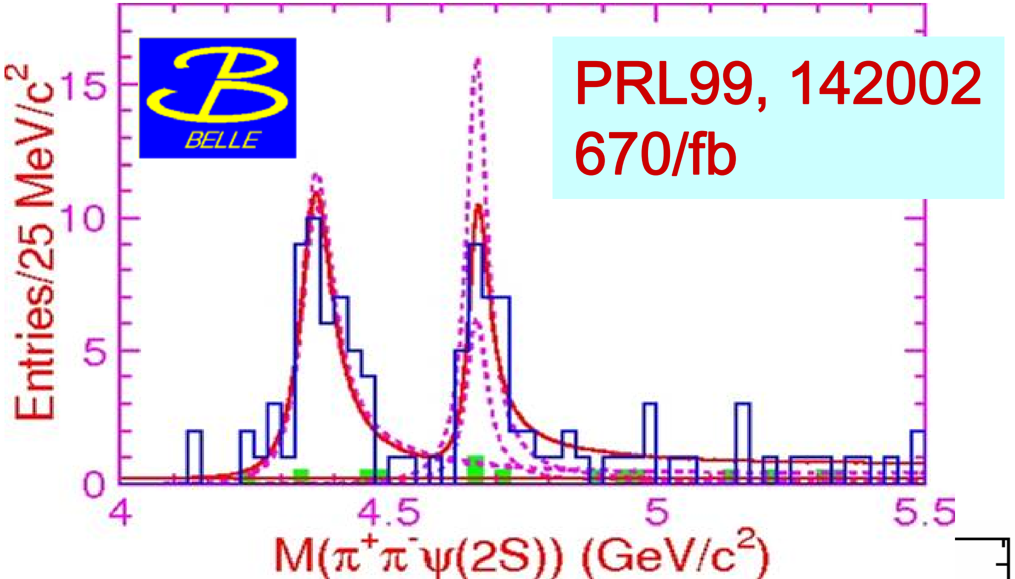
$J^{PC} = 1^{--}$

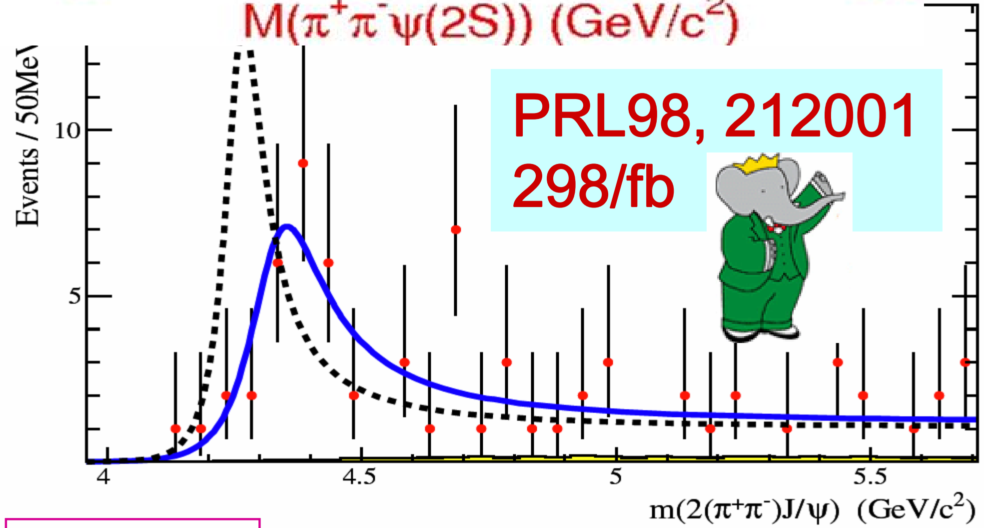
ψ', ψ'', Y…

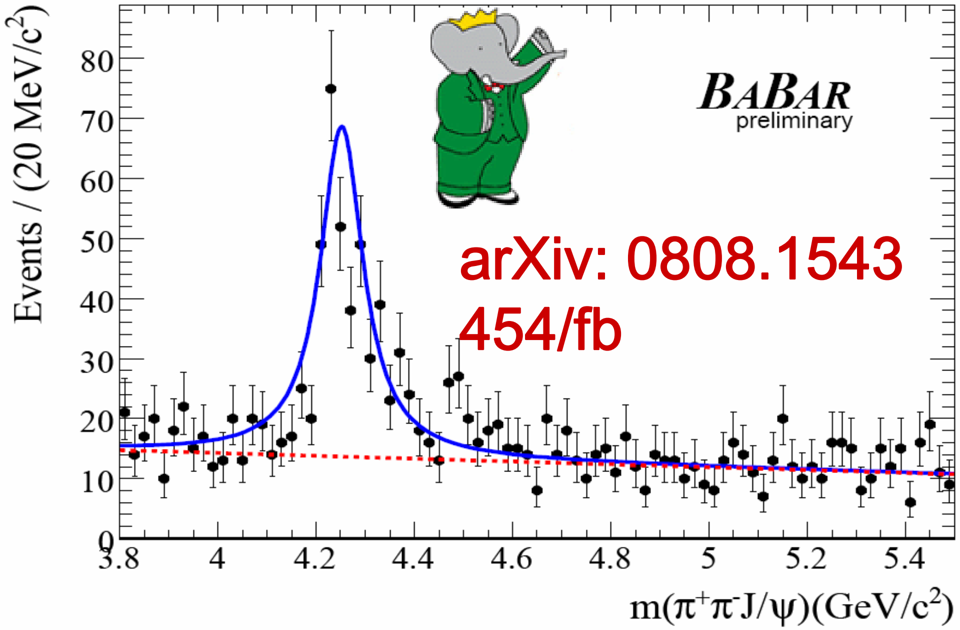
The Y states should also appear in this plot (between 4.0 and 4.7 GeV!)

The Y states

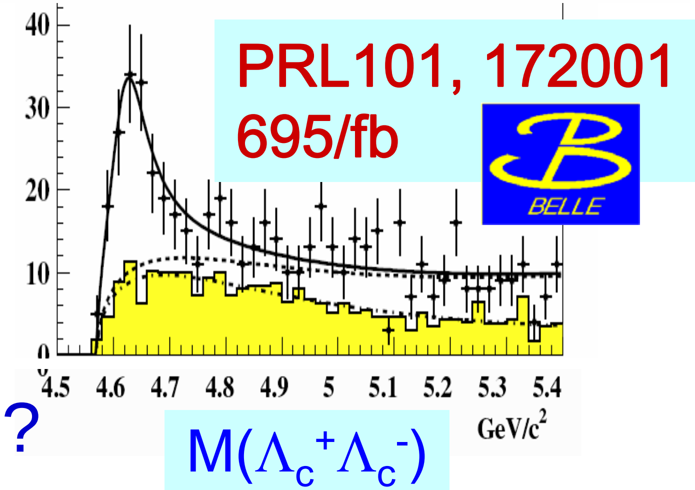






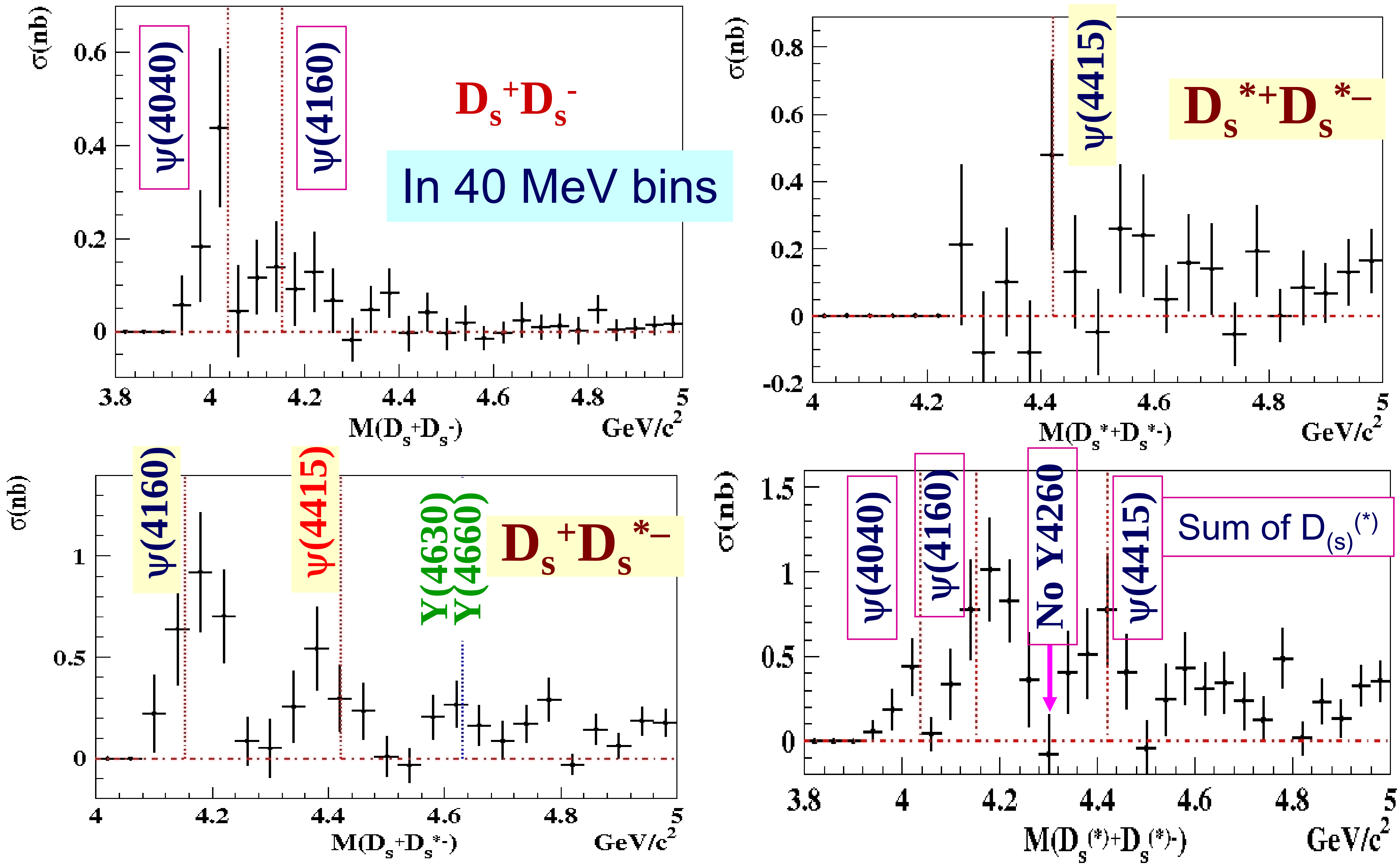


Y(4008)
Y(4260)
Y(4360)
Y(4660)
Y(4630)



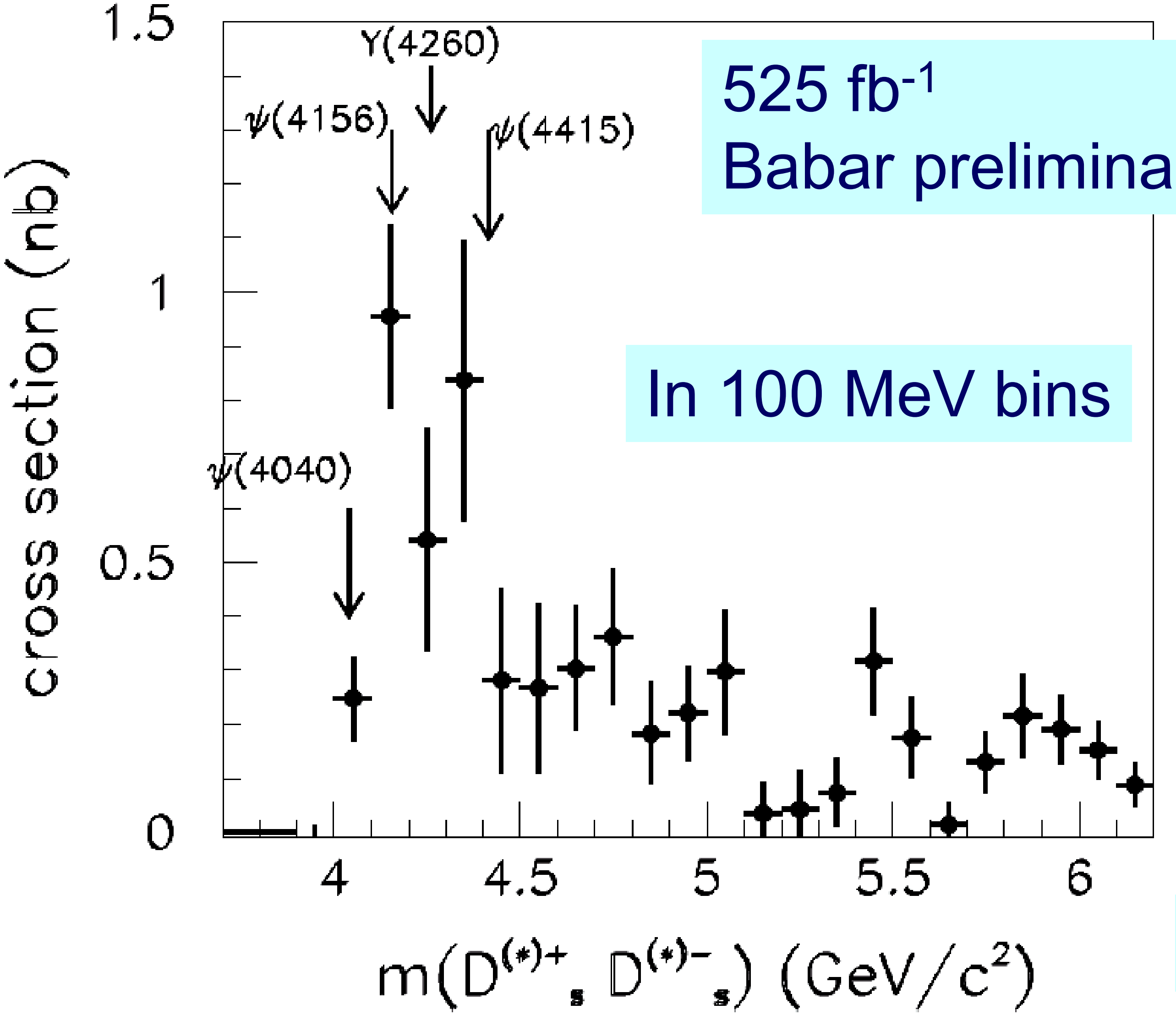
Above D$\underline{D}$ threshold, decay to open charm?

Recent meas.: $D_s^{(*)}D_s^{(*)}$ via ISR



967 fb^{-1}; Belle preliminary

Recent meas.: $D_s^{(*)}D_s^{(*)}$ via ISR



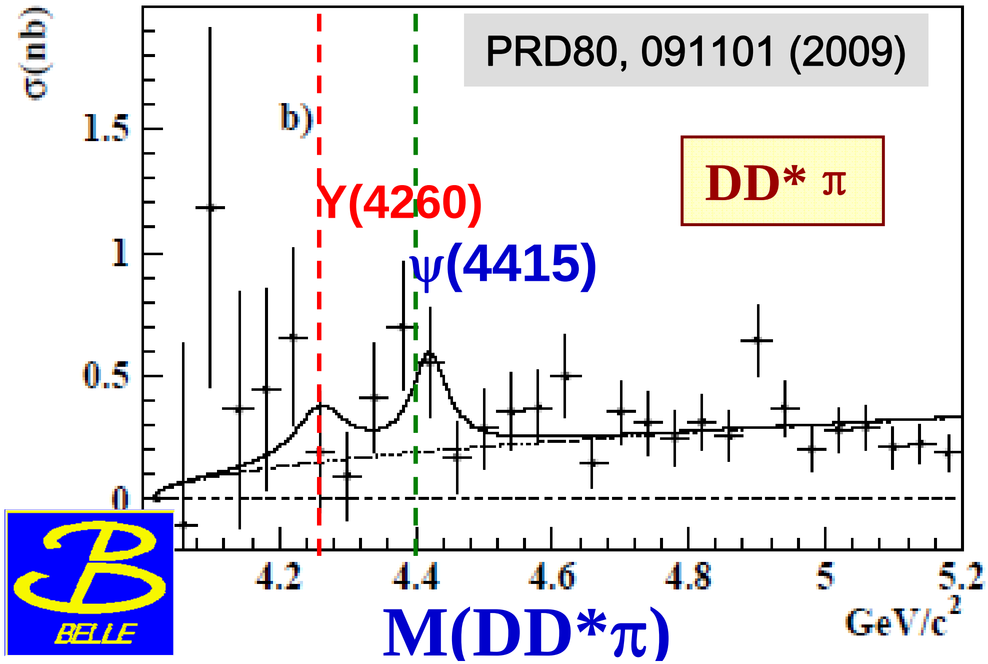
525 fb^{-1}
Babar preliminary

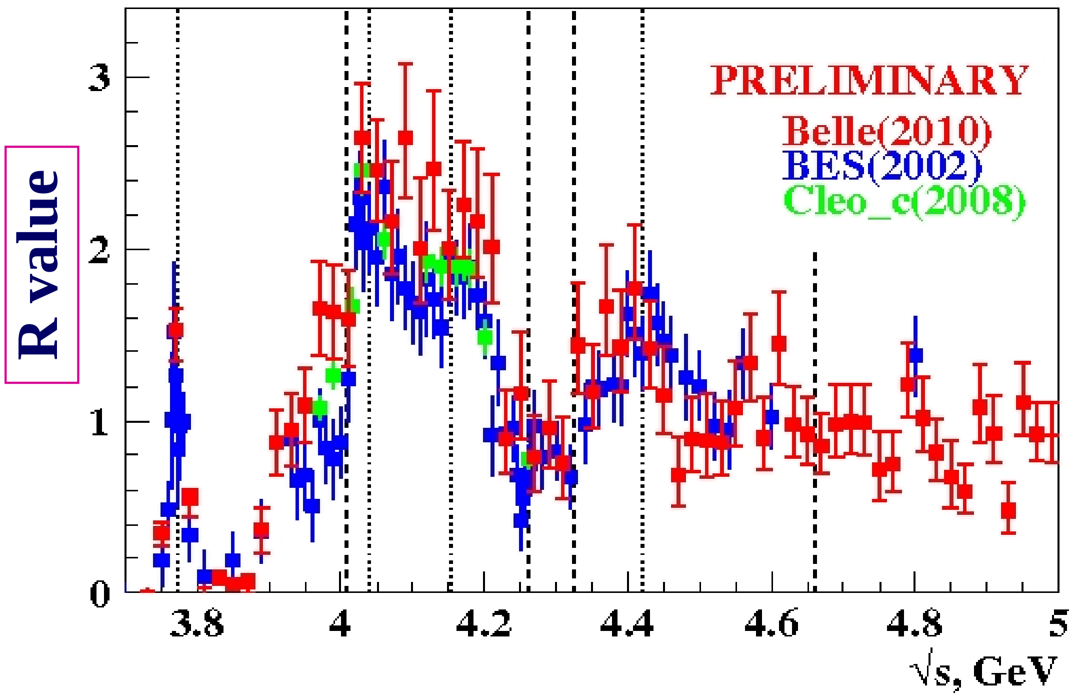
In 100 MeV bins

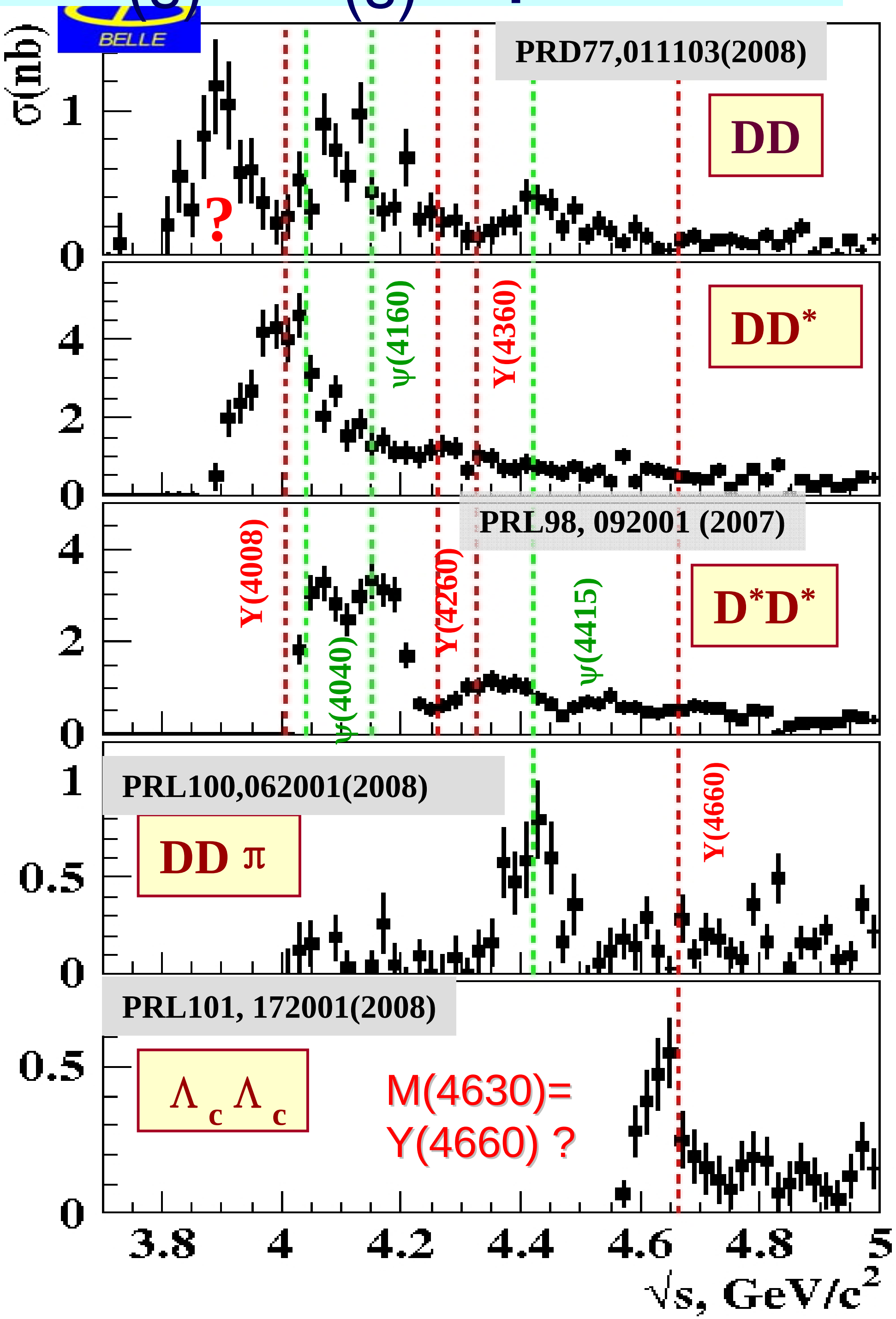
Talk By Izen

CLEOc measurements for Ecm<4.26 GeV by energy scan
PRD 80, 072001 (2009)

Y states don't match $D_{(s)}^{(*)}D_{(s)}^{(*)}$ peaks







Best ψ resonance parameters from BESII

$$R_{\text{the}} = R_{\text{con}} + R_{\text{res}}$$

Coherent sum of 4 BWs

$$R_{\text{con}} = C_0 + C_1(W - 2M_{D^\pm}) + C_2(W - 2M_{D^\pm})^2$$

$$R_{\text{res}} = \frac{\sigma_{\text{res}}}{\sigma^0_{\mu\mu}} = \frac{12\pi}{s}\left[|\mathcal{T}_{\psi'}|^2 + |\mathcal{T}_{\text{res}}|^2\right]$$

Amplitude of r → f

$$|\mathcal{T}_{\text{res}}|^2 = \sum_f \left| \sum_r \mathcal{T}_r^f(W) \right|^2$$

$$\mathcal{T}_r^f(W) = \frac{M_r\sqrt{\Gamma_r^{ee}\Gamma_r^f}}{W^2 - M_r^2 + iM_r\Gamma_r} e^{i\delta_r}$$

$\psi(3770) \Rightarrow D\bar{D}$;

$\psi(4040) \Rightarrow D\bar{D}, D^*\bar{D}^*, D\bar{D}^*, D_s\bar{D}_s$;

$\psi(4140) \Rightarrow D\bar{D}, D^*\bar{D}^*, D\bar{D}^*, D_s\bar{D}_s, D_s\bar{D}_s^*$;

$\psi(4415) \Rightarrow D\bar{D}, D^*\bar{D}^*, D\bar{D}^*, D_s\bar{D}_s, D_s\bar{D}_s^*, D_s^*\bar{D}_s^*, D\bar{D}_1, D\bar{D}_2^*$.

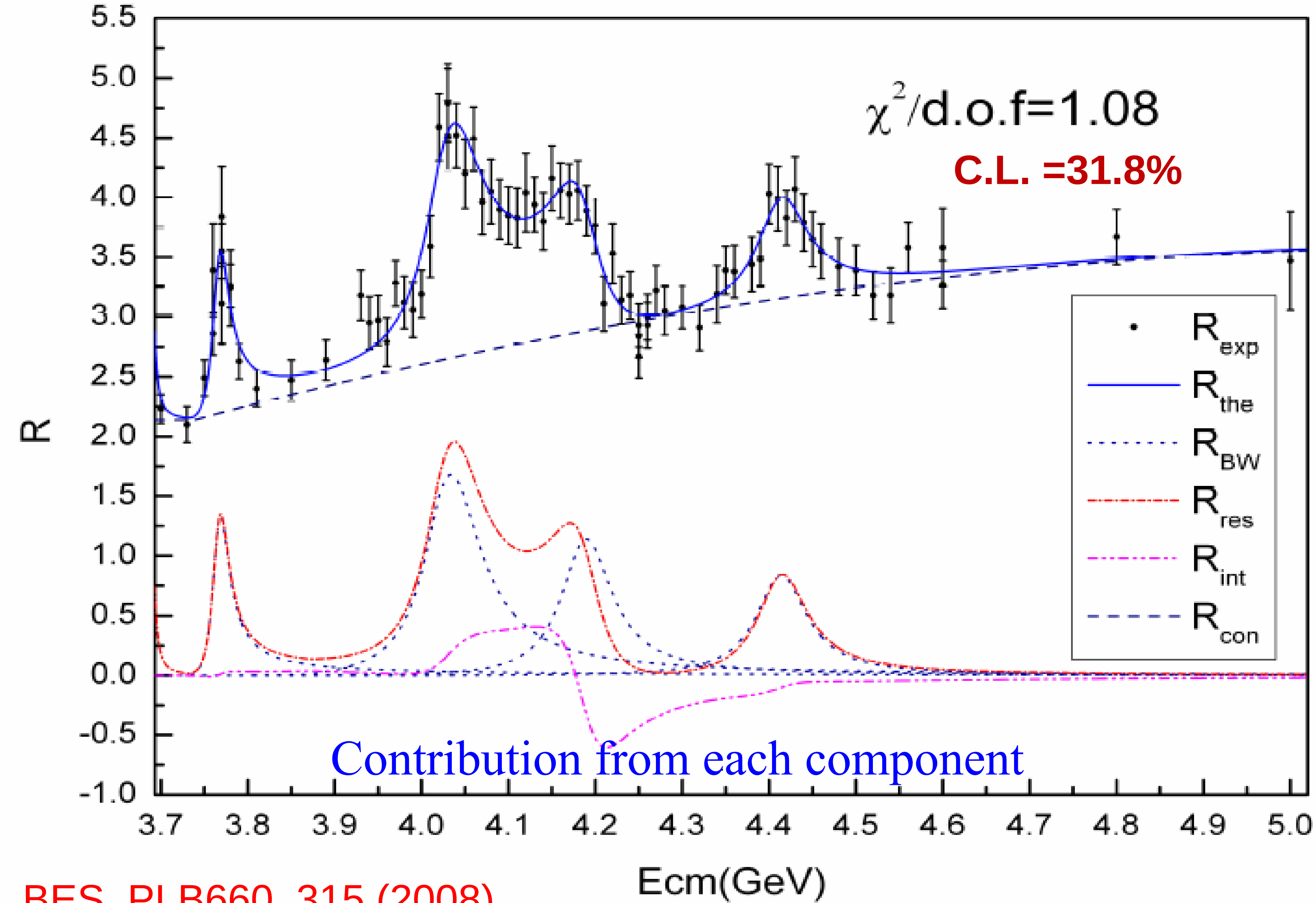
Mass dependent width

$$\Gamma_r^f(W) = \hat{\Gamma}_r \sum_L \frac{Z_f^{2L+1}}{B_L}$$

BES, PLB660, 315 (2008)

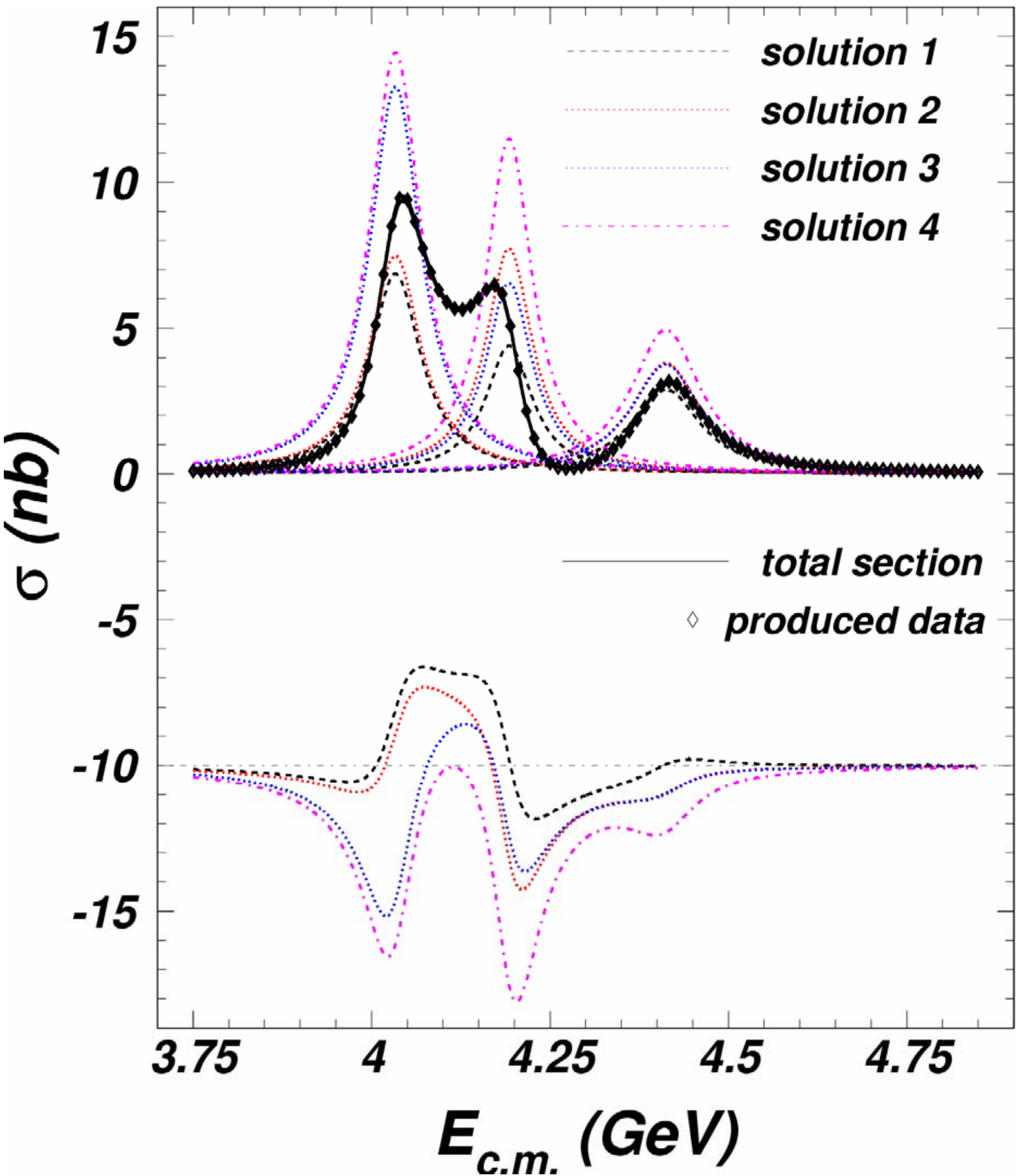
May use data now!

Fit by BESII



BES, PLB660, 315 (2008)

Multiple solutions in BESII data



Fitting Ecm>4 GeV with 3 coherent amplitudes results in 4 solutions with identical fit quality!

BESII official fit is only one of the four possible solutions!

X.H. Mo, CZY, P. Wang, arXiv: 1007.0084

Multiple solutions in BESII data

	Parameter	$\psi(4040)$	$\psi(4160)$	$\psi(4415)$
Same for all solutions	M (MeV)	4034 ± 6	4193 ± 7	4412 ± 15
	Γ_t (MeV)	87 ± 11	79 ± 14	118 ± 32
Sol. I (same as BES)	$\Gamma_{ee}^{(1)}$ (keV)	0.66 ± 0.22	0.42 ± 0.16	0.45 ± 0.13
	$\phi^{(1)}$ (radian)	0 (fixed)	2.7 ± 0.8	2.0 ± 0.9
Sol. II	$\Gamma_{ee}^{(2)}$ (keV)	0.72 ± 0.24	0.73 ± 0.18	0.60 ± 0.25
	$\phi^{(2)}$ (radian)	0 (fixed)	3.1 ± 0.7	1.4 ± 1.2
Sol.III	$\Gamma_{ee}^{(3)}$ (keV)	1.28 ± 0.45	0.62 ± 0.30	0.59 ± 0.20
	$\phi^{(3)}$ (radian)	0 (fixed)	3.7 ± 0.4	3.8 ± 0.8
Sol. IV	$\Gamma_{ee}^{(4)}$ (keV)	1.41 ± 0.12	1.10 ± 0.15	0.78 ± 0.17
	$\phi^{(4)}$ (radian)	0 (fixed)	4.1 ± 0.1	3.2 ± 0.3

X.H. Mo, CZY, P. Wang, arXiv: 1007.0084

Multiple solutions also exist in F_π fit

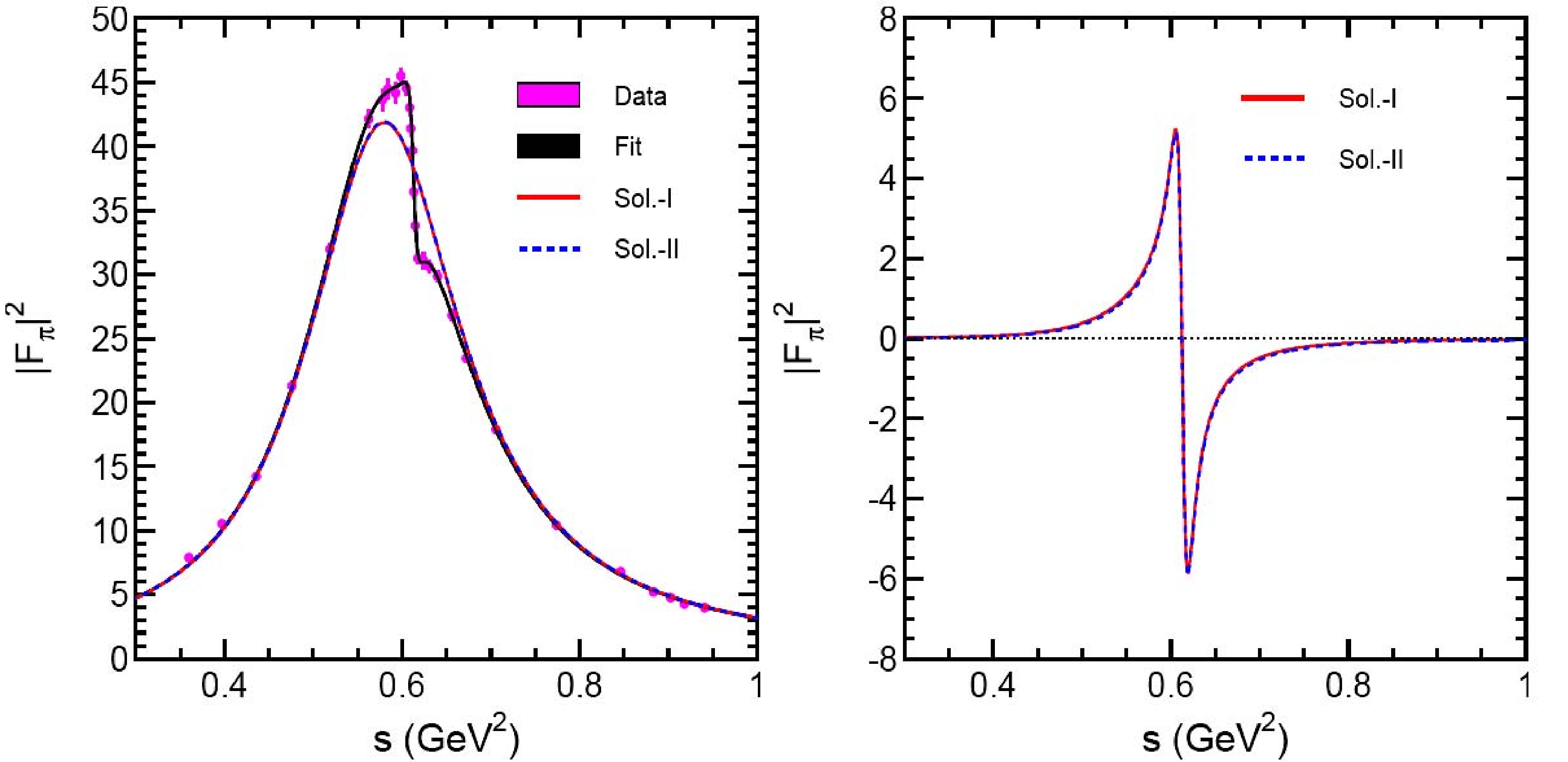
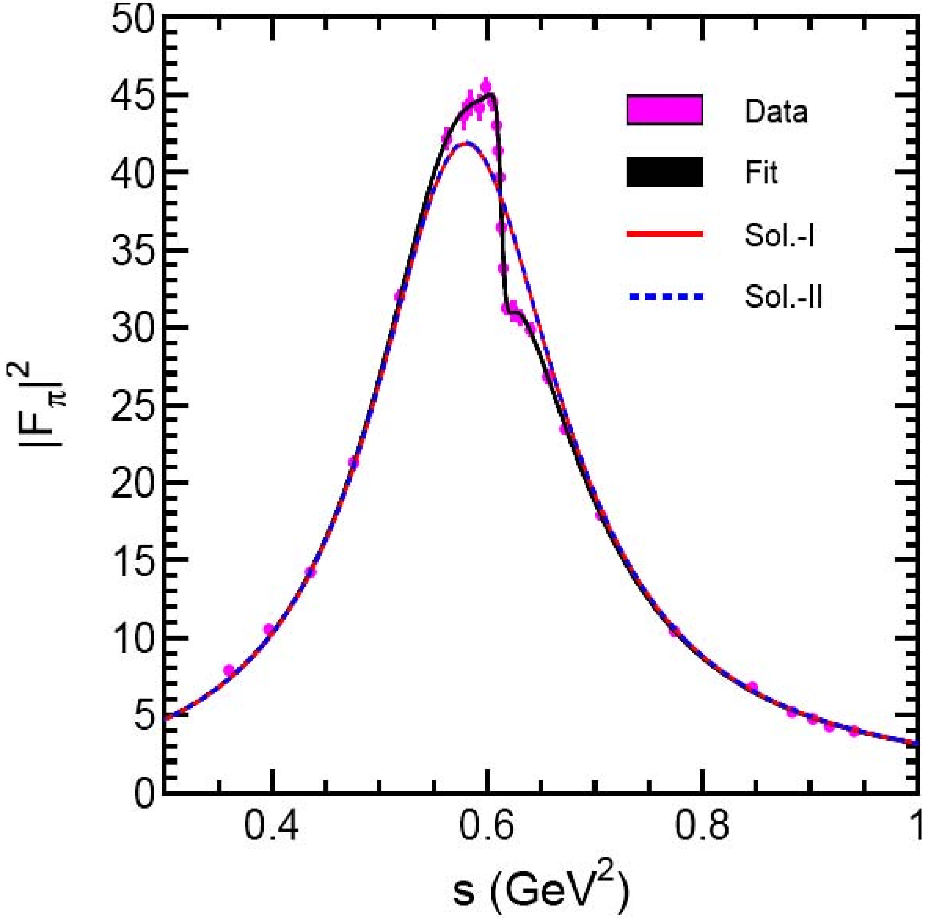
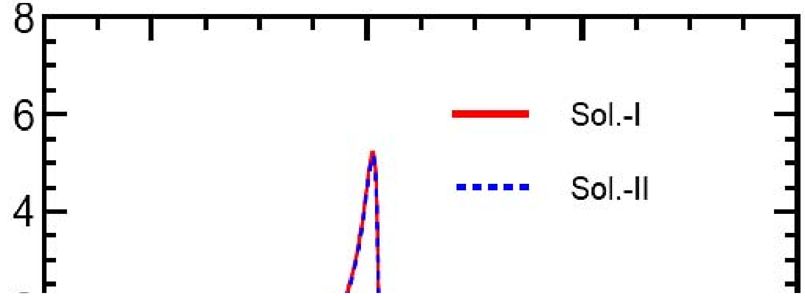


Figure 3: Fit to the $e^+e^- \to \pi^+\pi^-$ form factors below $s = 1$ GeV^2 measured at CMD2

CZY, X.H. Mo, P. Wang, arXiv:0911.4791

Multiple solutions also exist in F_π fit





Parameter	Solution I	Solution II	Davier [8]
m_ρ [MeV]	775.9 ± 0.5		–
Γ_ρ [MeV]	146.0 ± 0.8		–
$\|\delta\|$ [$\times 10^{-3}$]	1.62 ± 0.06	21.97 ± 0.04	–
ϕ_δ [°]	10.1 ± 1.4	86.56 ± 0.17	–
$\|\beta\|$	0.086 ± 0.004		–
$\Delta\mathcal{B}^{\rm mixing}$ [%]	-0.03 ± 0.01	$+0.04 \pm 0.01$	-0.01 ± 0.01
$\Delta a_\mu^{\rm mixing}$ [10^{-10}]	$+2.5 \pm 0.2$	$+1.6 \pm 0.2$	$+2.80 \pm 0.19$

s (GeV^2)

Figure 3: Fit to the $e^+e^- \to \pi^+\pi^-$ form factors below $s = 1$ GeV^2 measured at CMD2

CZY, X.H. Mo, P. Wang, arXiv:0911.4791

Summary of the talk

Many new strctures were observed in C- and B-factories and other experiments.

They could be normal hadrons (2 or 3 quarks) or exotic hadrons such as

glueballs, molecular states, multiquark states, or hybrids

or just threshold effect, FSI effect, or some other unknown QCD effect (yes, we need better QCD calculations!).

Both theorists and experimentalists should continue work hard and patiently for possibly very rare (even non-existing) exotic hadrons!

Thanks a lot.

backup

Charged state with hidden charm $Z^+(4430)$ and more

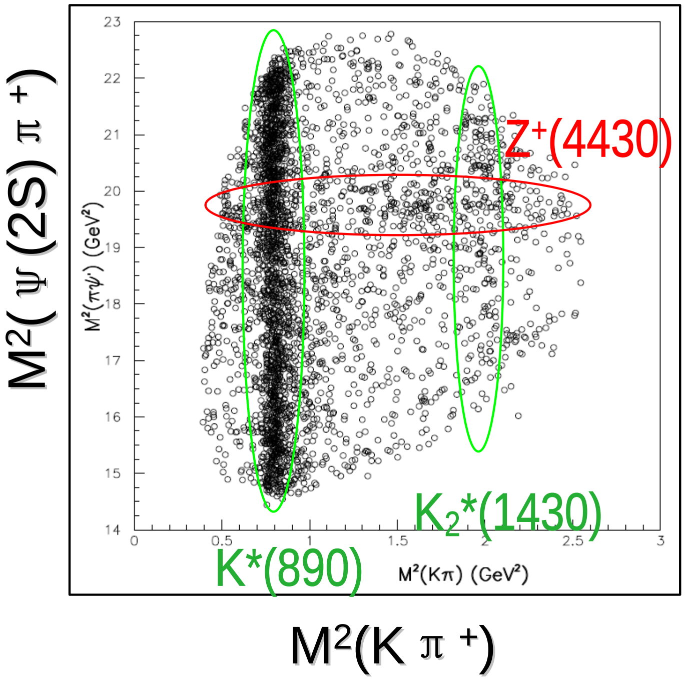
Unambiguous tetraquark state?

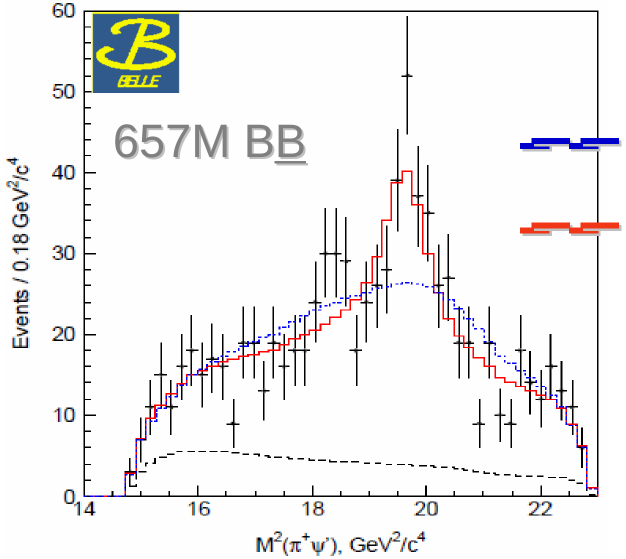
$Z(4430)^{\pm} \to \psi(2S)\pi^{\pm}$

PRL100, 142001 (2008)

- Found in $\psi(2S)\pi^+$ from $B \to \psi(2S)\pi^+ K$. Z parameters from fit to $M(\psi(2S)\pi^+)$
- Confirmed through Dalitz-plot analysis of $B \to \psi(2S)\pi^+ K$
- $B \to \psi(2S)\pi^+ K$ amplitude: coherent sum of Breit-Wigner contributions
- **Models: all known $K^* \to K\pi^+$ resonances only**

  all known $K^* \to K\pi^+$ and $Z^+ \to \psi(2S)\pi^+$ ⇨ favored by data





M²(ψ (2S) π ⁺) after K* veto

Significance: 6.4 σ

fit for model with K*'s only

fit for model with K*'s and Z

$$M = 4433 ^{+15}_{-12} {}^{+19}_{-13} \text{ MeV}$$

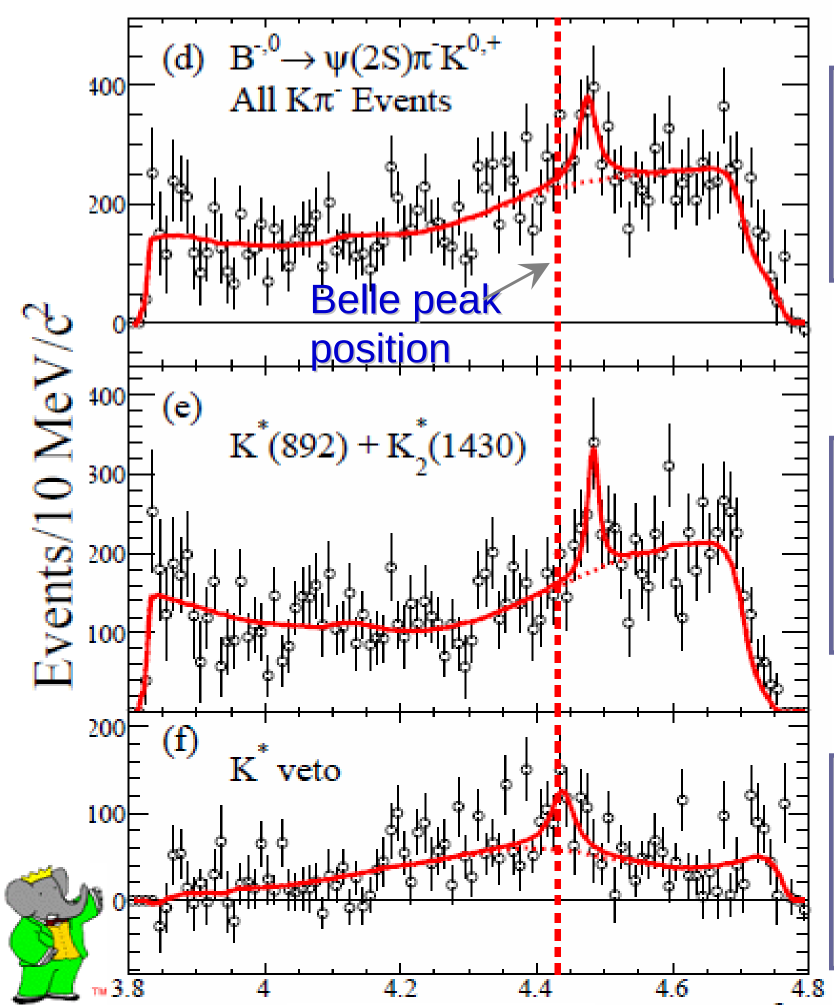
$$\Gamma = 107 ^{+86}_{-43} {}^{+74}_{-53} \text{ MeV}$$

PRD80, 031104 (2009)

- **[cu][$\underline{cd}$] tetraquark? neutral partner in $\psi'\pi^0$ expected**
- **$D^*\underline{D}_1(2420)$ molecule? should decay to $D^*\underline{D}^*\pi$**

$Z^{\pm}(4430)$ in BaBar data?

- Fits to $M(\psi(2S)\pi^+)$: no significant Z(4430) signal



$M(\psi(2S)\pi^+)$

$M_Z = 4476 \pm 8\ MeV$
$\Gamma_Z = 32 \pm 16\ MeV$
2.7σ

PRD79, 112001 (2009)

(χ^2/ndf=54.7/58)

$M_Z = 4483 \pm 3\ MeV$
$\Gamma_Z = 17 \pm 12\ MeV$
2.5σ

$M_Z = 4439 \pm 8\ Me$
$\Gamma_Z = 41 \pm 33\ MeV$
1.9σ

$Bf(B^0 \to Z^+ K) \times$
$Bf(Z^+ \to \psi(2S)\pi^+)$
$= (3.2^{+1.8+9.6}_{-0.9-1.6}) \times 10^{-5}$ Belle
$< 3.1 \times 10^{-5}$ @90% C.L BaBar

- $M(\psi(2S)\pi^+)$ is statistically consistent between BaBar & Belle
- Better to have one more experiment to examine it

Two $Z^{\pm} \to \chi_{c1}\pi^{\pm}$

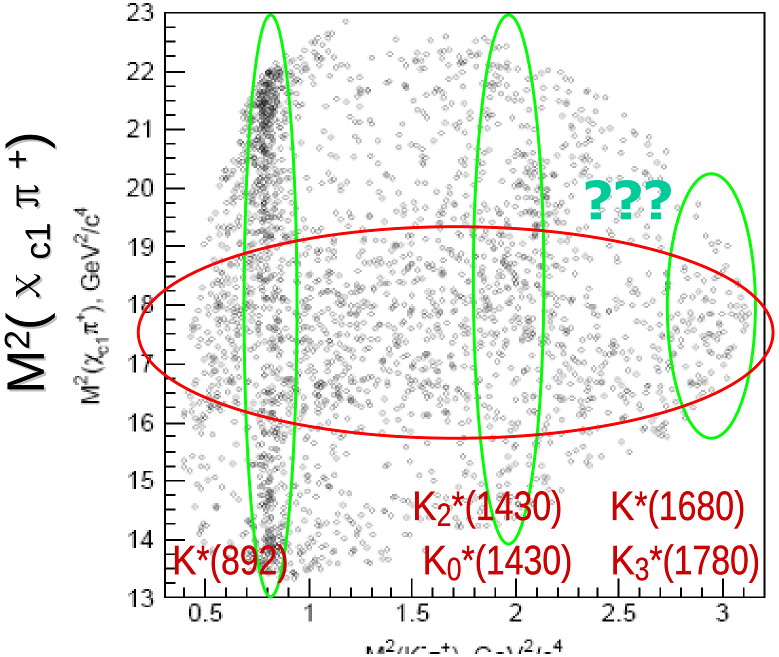
- Dalitz-plot analysis of $\underline{B}^0 \to \chi_{c1}\pi^+K^-$ $\chi_{c1} \to J/\psi\gamma$ with 657M $B\underline{B}$
- Dalitz plot models: known $K^* \to K\pi$ only

  K^*'s + one $Z \to \chi_{c1}\pi^{\pm}$

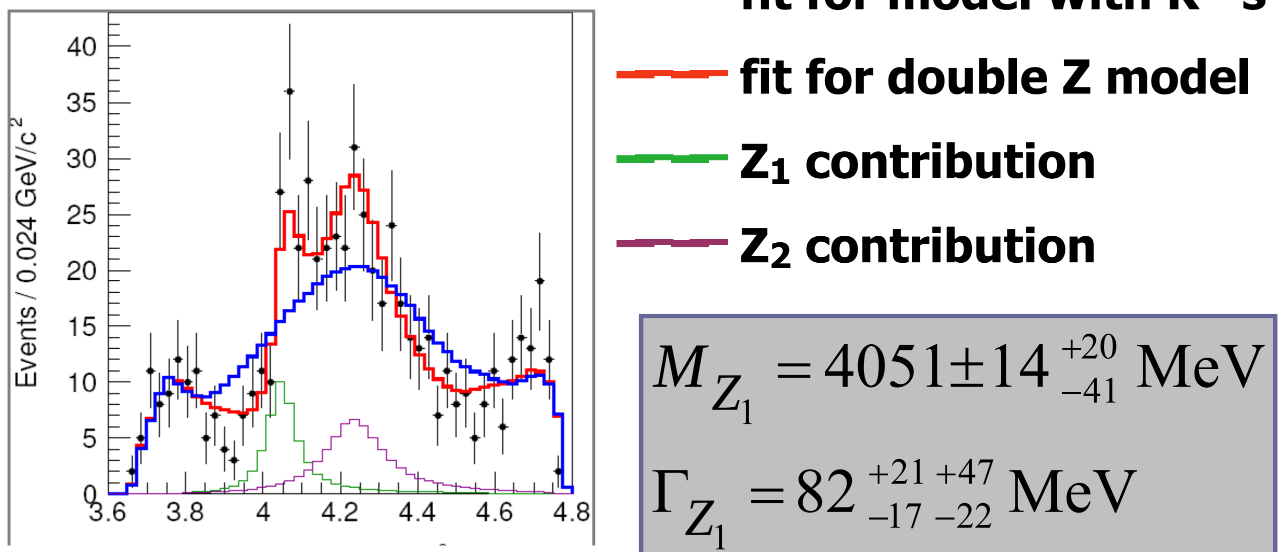
  K^*'s + two $Z^{\pm}$ states ⇨ favored by data

PRD 78, 072004 (2008)

Significance: 5.7σ



$M^2(K^-\pi^+)$



$M(\chi_{c1}\pi^+)$ for $1<M^2(K^-\pi^+)<1.75\,\mathrm{GeV}^2$

$$M_{Z_1} = 4051 \pm 14\,^{+20}_{-41}\ \mathrm{MeV}$$

$$\Gamma_{Z_1} = 82\,^{+21}_{-17}\,^{+47}_{-22}\ \mathrm{MeV}$$

$$M_{Z_2} = 4248\,^{+44}_{-29}\,^{+180}_{-35}\ \mathrm{MeV}$$

$$\Gamma_{Z_2} = 177\,^{+54}_{-39}\,^{+316}_{-61}\ \mathrm{MeV}$$

Waiting for experiments to confirm them!

Multiple solutions

Parameter	Solution I	Solution II
σ_0 [nb]	7.88 ± 0.04	7.88 ± 0.08
$\Re(Z)$	0.106 ± 0.004	0.106 ± 0.006
$\Im(Z)$	-0.103 ± 0.003	-1.90 ± 0.006
σ' [nb/MeV]	0.064 ± 0.002	0.064 ± 0.006
$\mathcal{B}(\phi \to \omega\pi^0)$	4.61×10^{-5}	7.62×10^{-3}

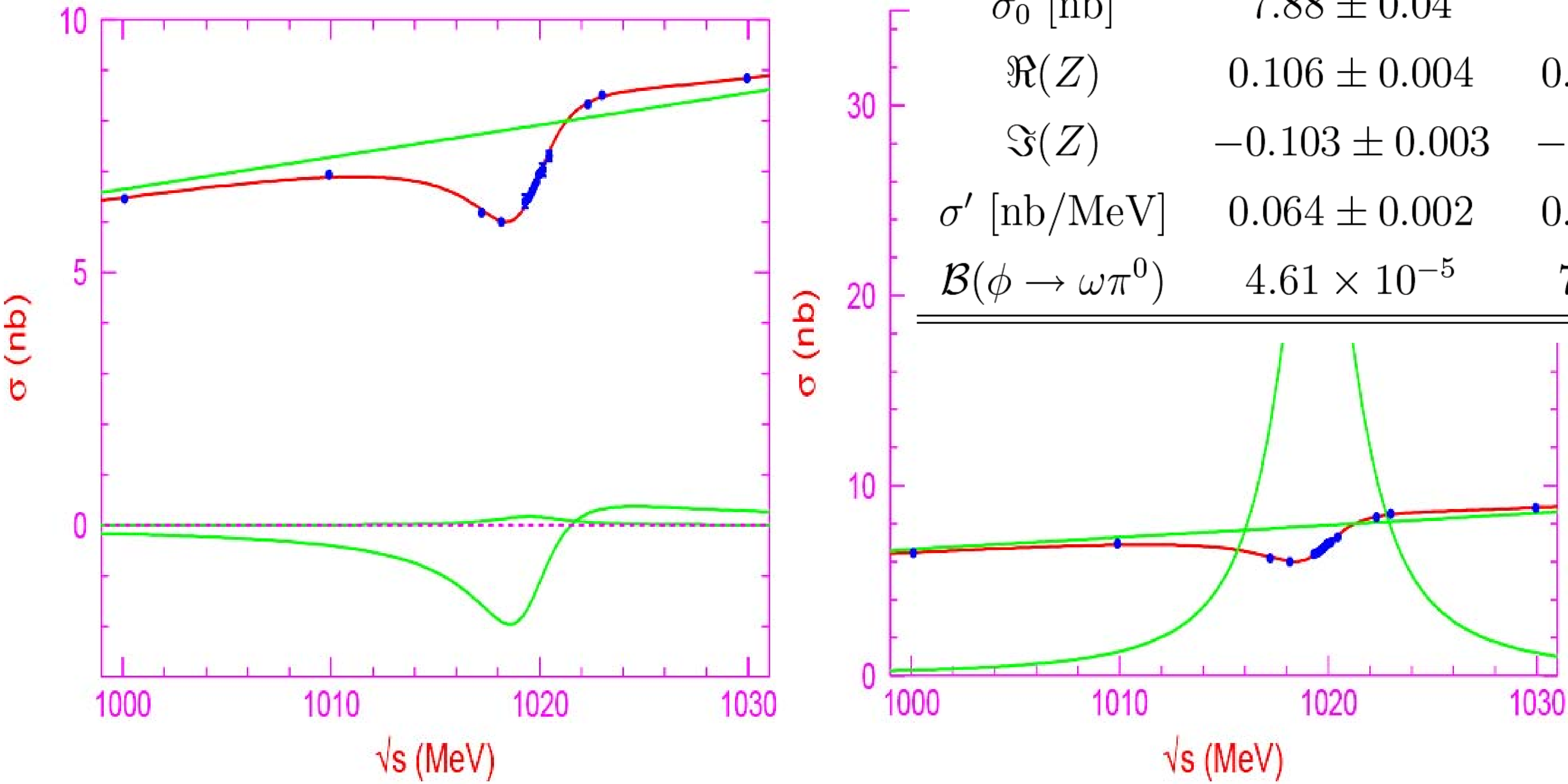
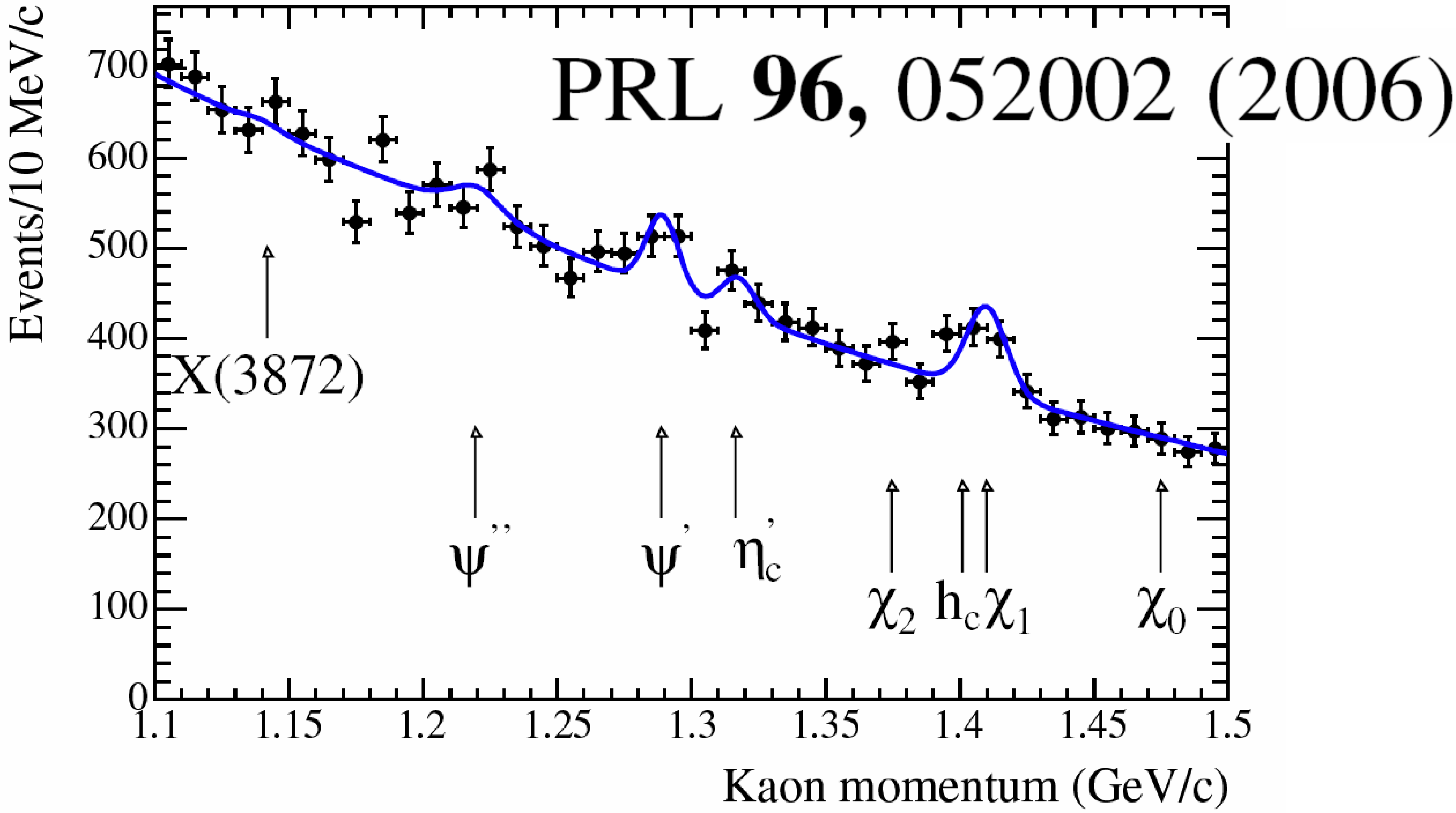


Figure 2: Fit to the $e^+e^- \to \omega\pi^0$ cross sections as a function of center-of-mass energy.

CZY, X.H. Mo, P. Wang, arXiv:0911.4791

Production of X(3872) in B decays



$$Bf\left(B^{-} \rightarrow X(3872)K^{-}\right) < 3.2\times10^{-4} \quad \text{at 90\% C.L.}$$

Decay of X(3872)

$$Bf(B^- \to XK^-)Bf(X \to J/\psi\pi^+\pi^-) = (8.20 \pm 0.93)\times 10^{-6}$$
$$Bf(B^- \to XK^-)Bf(X \to J/\psi\pi^+\pi^-\pi^0) = (8.2 \pm 4.2)\times 10^{-6}$$
$$Bf(B^- \to XK^-)Bf(X \to J/\psi\gamma) = (2.8 \pm 0.8 \pm 0.1)\times 10^{-6}$$
$$Bf(B^- \to XK^-)Bf(X \to \psi(2S)\gamma) = (9.5 \pm 2.7 \pm 0.6)\times 10^{-6}$$
$$Bf(B^- \to XK^-)Bf(X \to D^0\overline{D^{0*}} + c.c.) = (1.67 \pm 0.36 \pm 0.47)\times 10^{-4}$$

...

$$\Rightarrow Bf(X \to J/\psi\pi^+\pi^-) < \frac{8.2 + 1\sigma}{8.2 + 8.2 + 2.8 + 9.5 + 167 - 1\sigma} \approx 6.6\% \quad @90\%\,\text{C.L.}$$

$$2.3\% < Bf\left(X \to J/\psi\pi^+\pi^-\right) < 6.6\%$$
$$1.4\times 10^{-4} < Bf\left(B^- \to X(3872)K^-\right) < 3.2\times 10^{-4} \quad \text{at } 90\%\,\text{C.L.}$$

$$Bf\left(B^- \to \psi(2S)K^-\right) = \left(6.48 \pm 0.35\right)\times 10^{-4}$$
$$Bf\left(B^- \to \chi_{c1}K^-\right) = \left(4.9 \pm 0.5\right)\times 10^{-4}$$
$$Bf\left(B^- \to \eta_c K^-\right) = \left(9.1 \pm 1.3\right)\times 10^{-4}$$

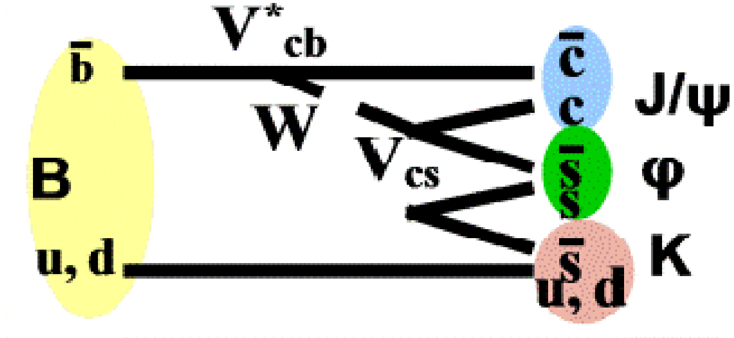
A bit history on exotics hunting

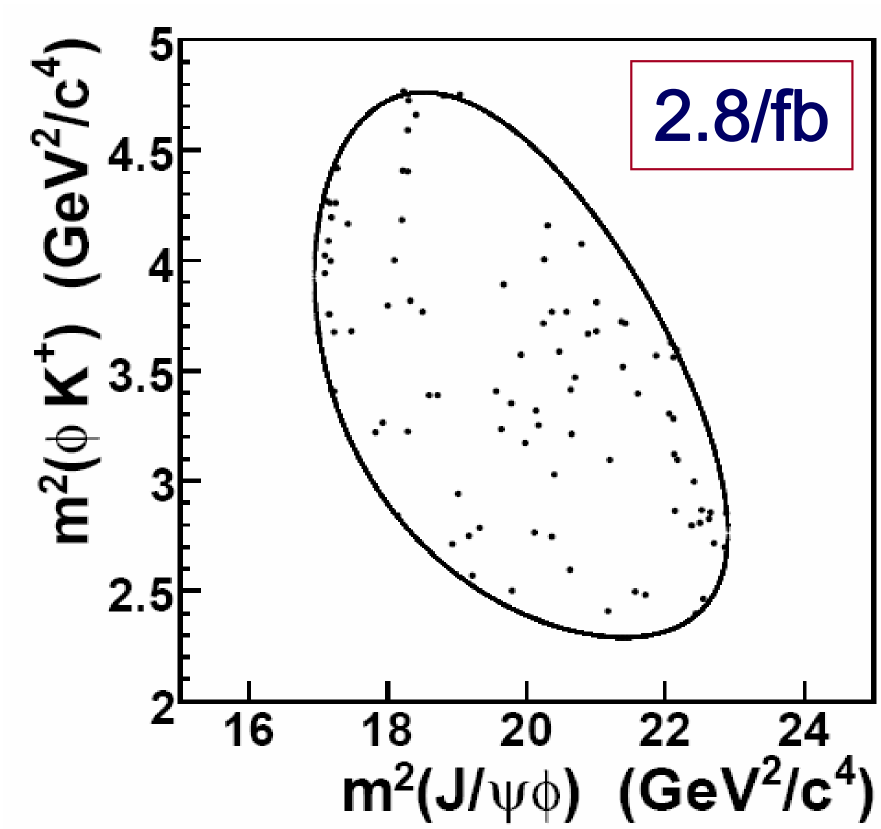
- “The absence of exotics is one of the most obvious features of QCD” – R. L. Jaffe, 2005
- Deuteron ➔ H state, d’, d*, $\Omega^-\Omega^-$ bound state
- No solid signature of glueballs
- Pentaquark state appeared and disappeared

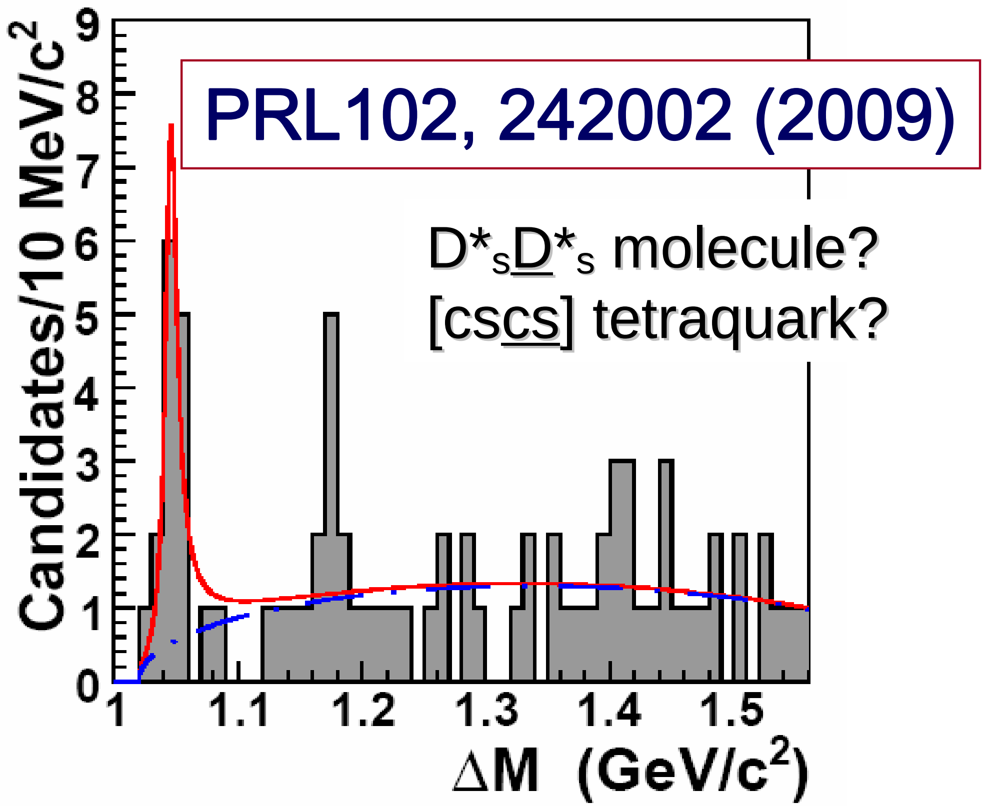
  (“The story of pentaquark shows how poorly we understand QCD” – F. Wilczek, 2005)
- There are lots of new states from low to high mass in various experiments! Are they normal or exotic?

The CDF Y(4140)→ϕJ/ψ

- $B^+ \rightarrow Y(4140)K^+$
- 14±5 events, >3.8σ
- Mass: 4143.0 ± 2.9 ± 1.2 MeV
- Width: $11.7^{+8.3}_{-5.0}$ ± 3.7 MeV (It is narrow!)

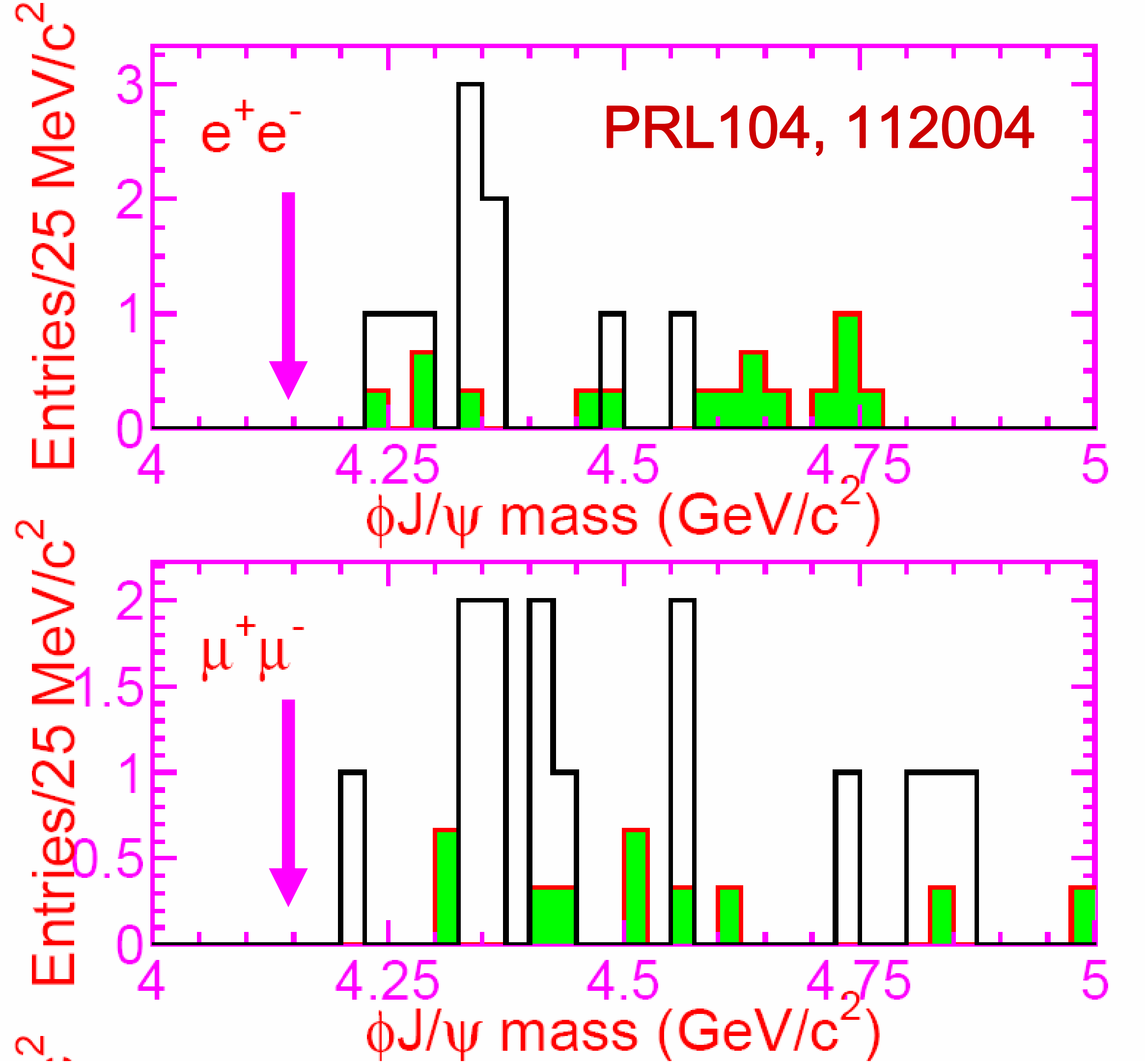


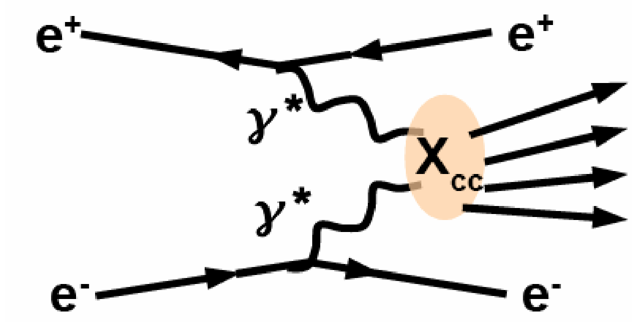




Searched for in $\gamma\gamma \to \phi J/\psi$

825 /fb





- No Y(4140)
- Disfavor $D_s^{*+}D_s^{*-}$ molecule
- Evidence for X(4350)

$J^P=0^+$: $\Gamma_{\gamma\gamma} Br(Y(4140)) \to \phi J/\psi) < 39$ eV @ 90% C.L.
$J^P=2^+$: $\Gamma_{\gamma\gamma} Br(Y(4140)) \to \phi J/\psi) < 5.7$ eV @ 90% C.L.