Phenomenology at the end of the Alphabet

- Theory Landscape
- Experimental Landscape

ESS, Phys. Rept. **539**, 243 (2006)

Eric Swanson

- we seek to deepen our understanding of the emergent phenomena associated with nonperturbative field theory (confinement, chiral symmetry breaking, topological excitations, gluonic degrees of freedom)
- can we repeat the successes in building quantum mechanics via atomic spectroscopy and QCD via hadronic spectroscopy in the gluonic sector?

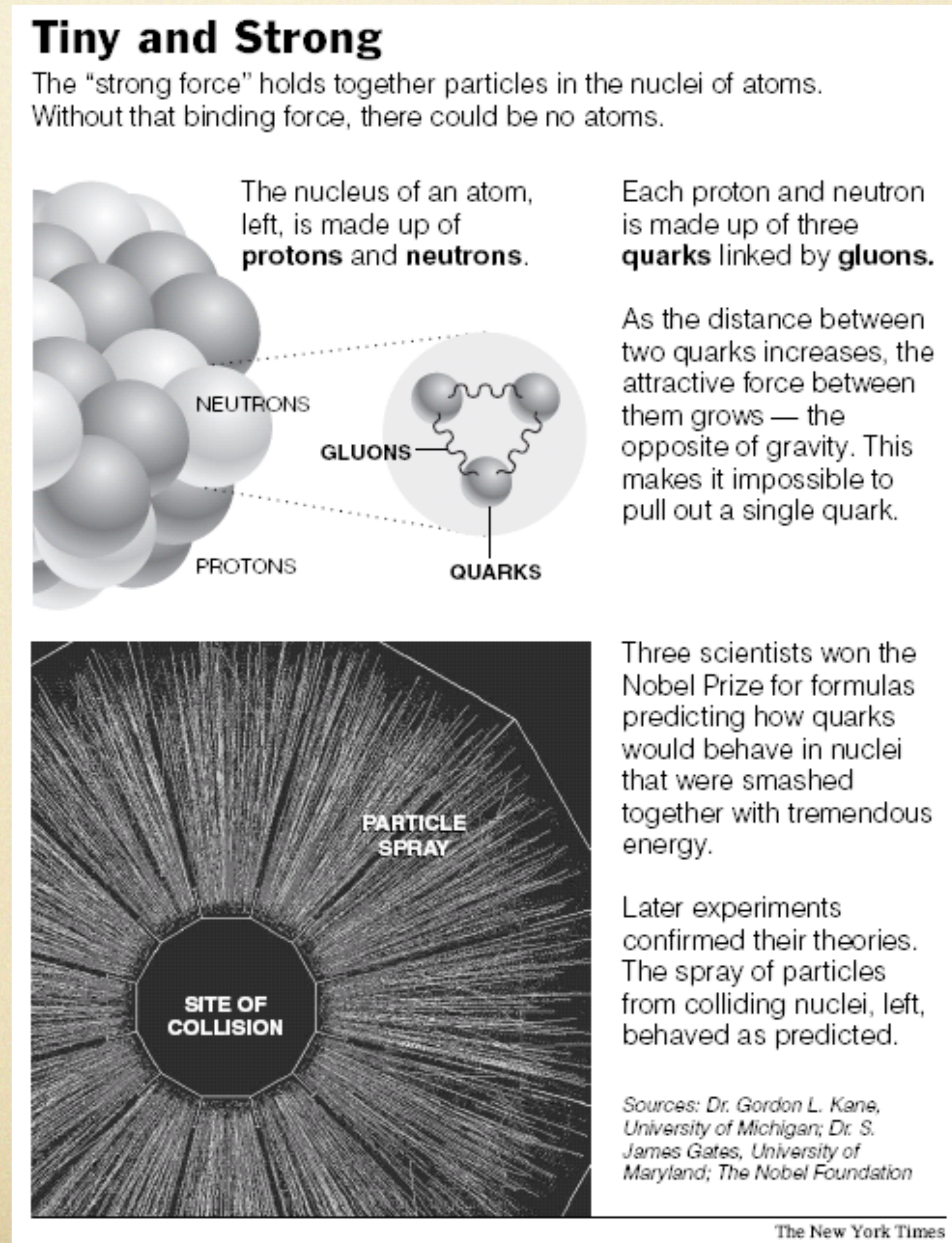
Theory Landscape

Nomenclature

quark

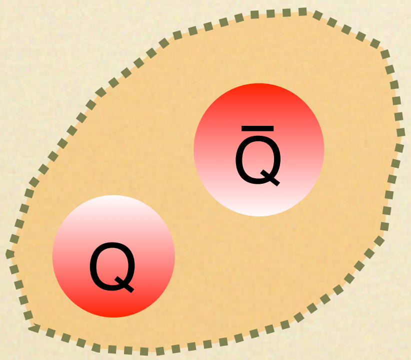
gluon

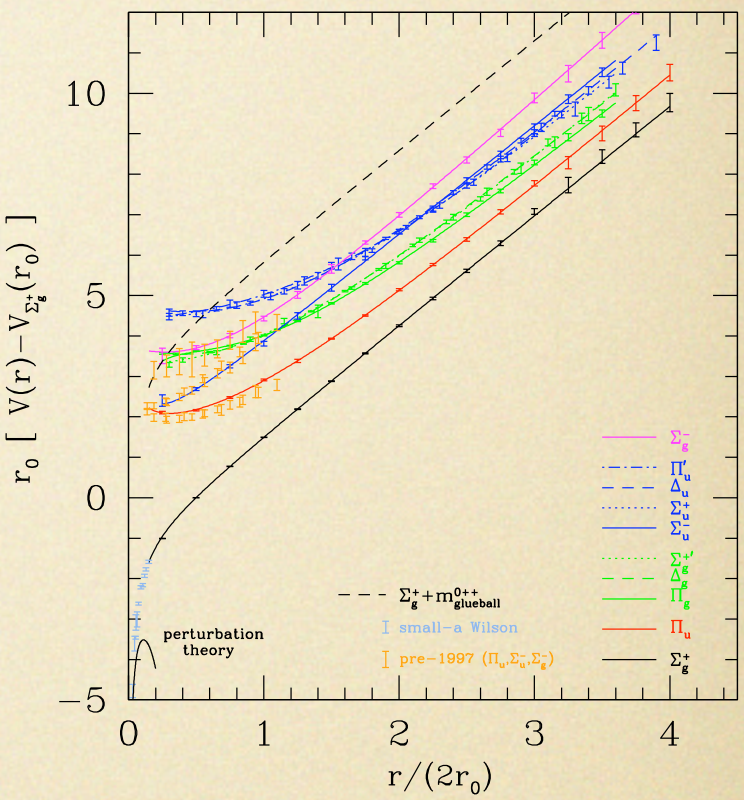
colour

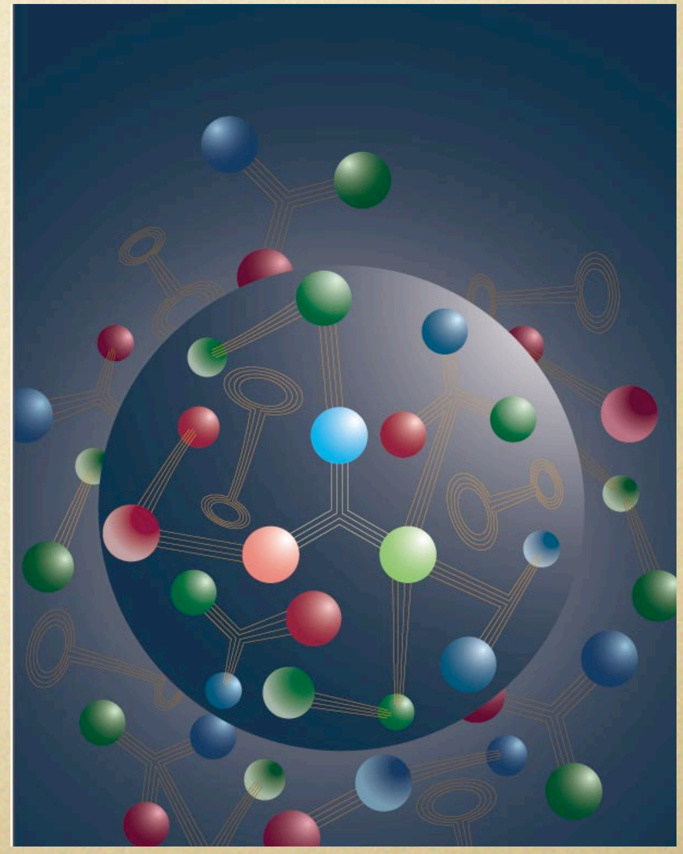


Nomenclature

meson

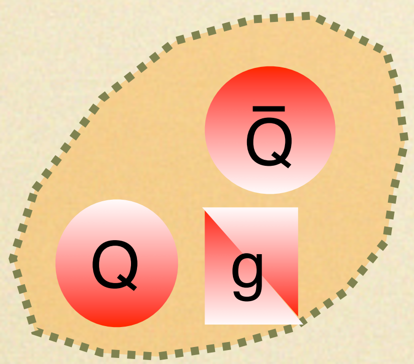




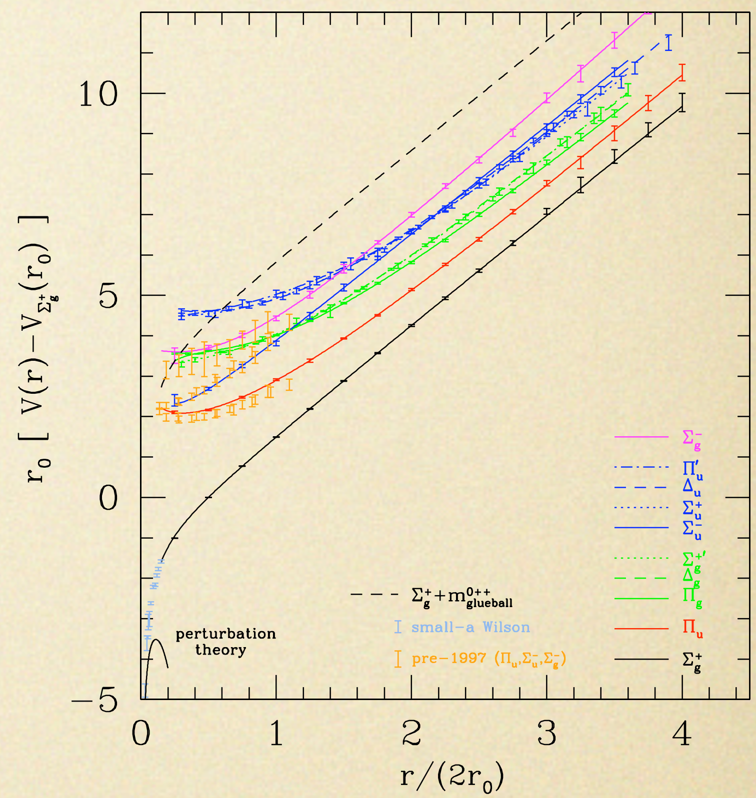


Nomenclature

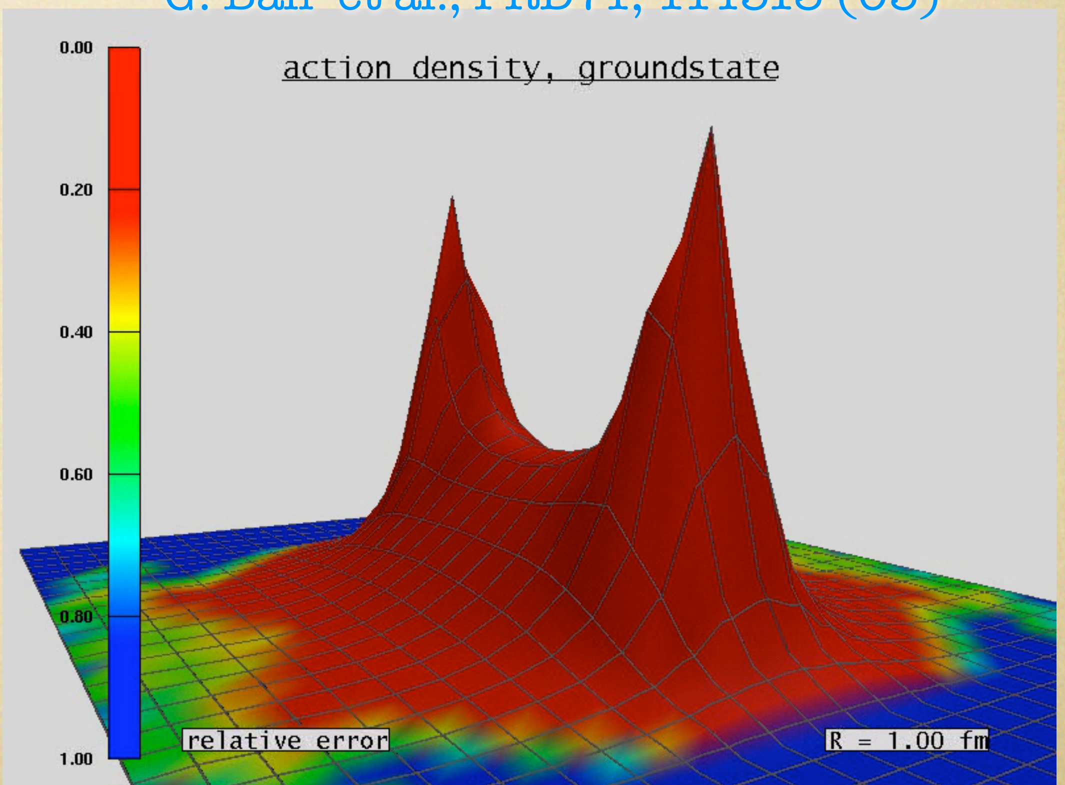
hybrid



Juge, Kuti, & Morningstar.

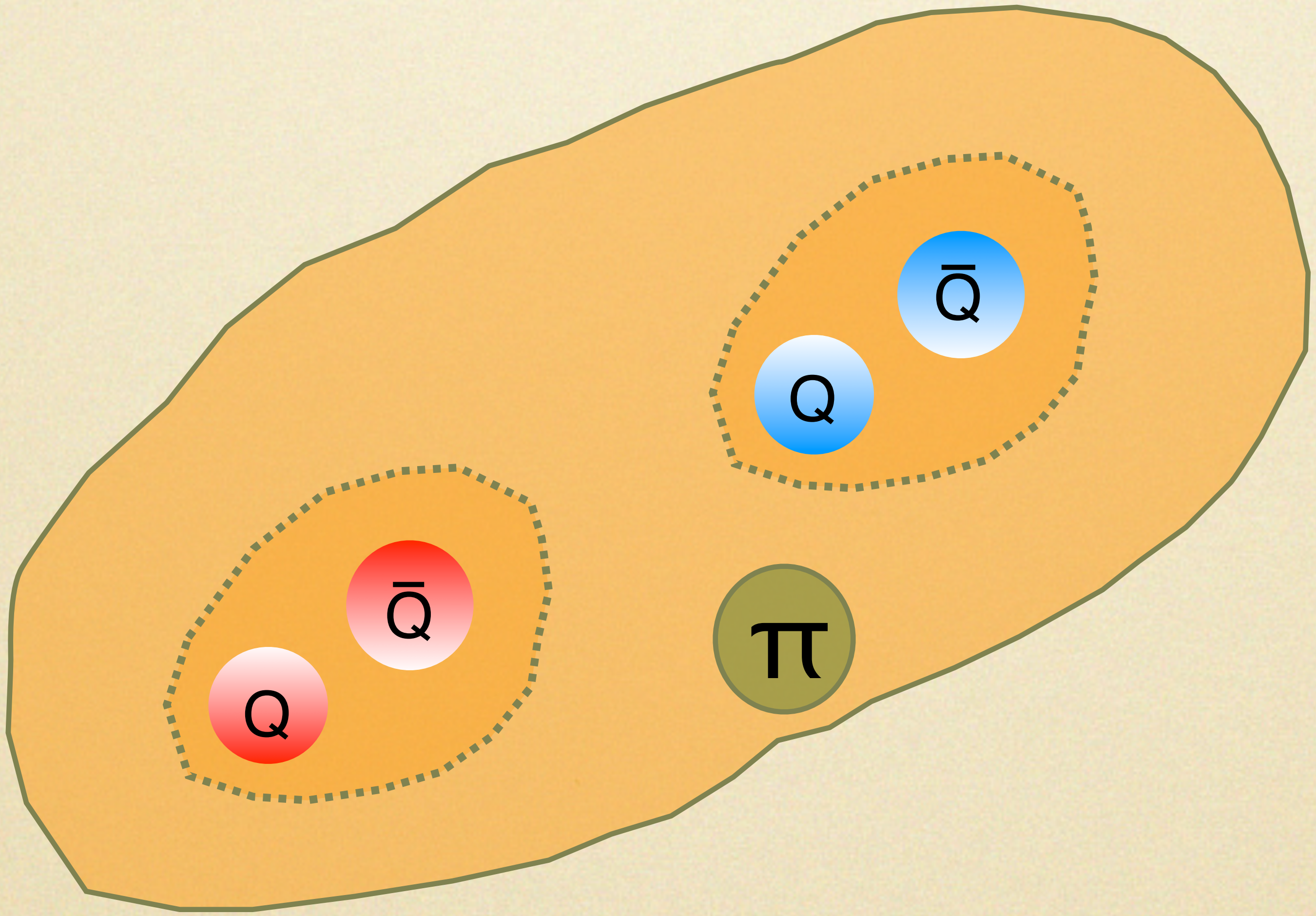


G. Bali et al., PRD71, 114513 (05)



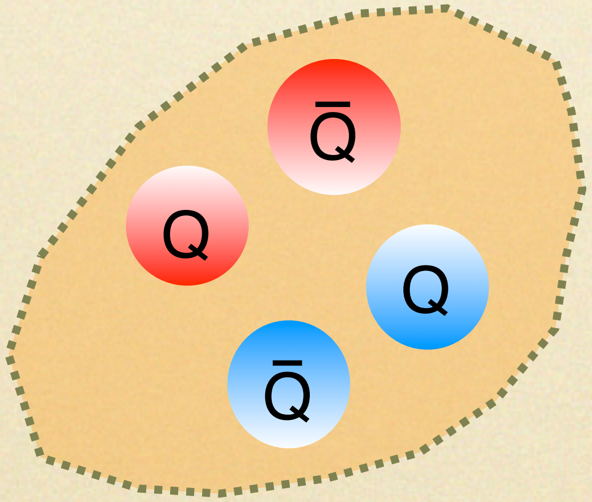
Nomenclature

molecule



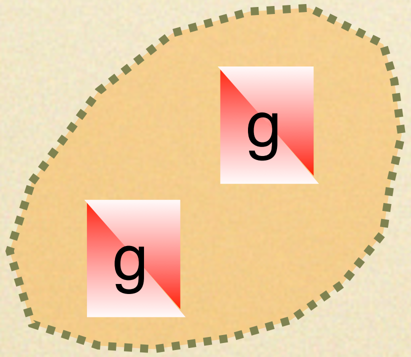
Nomenclature

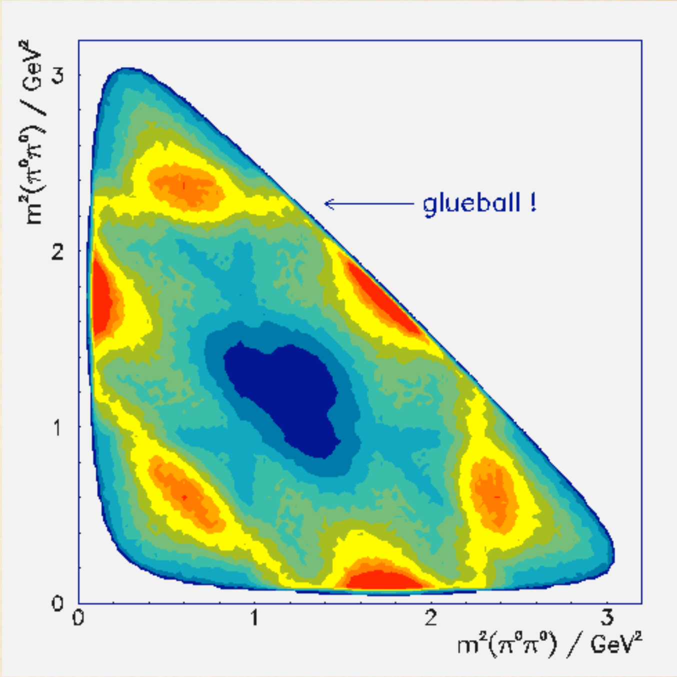
tetraquark

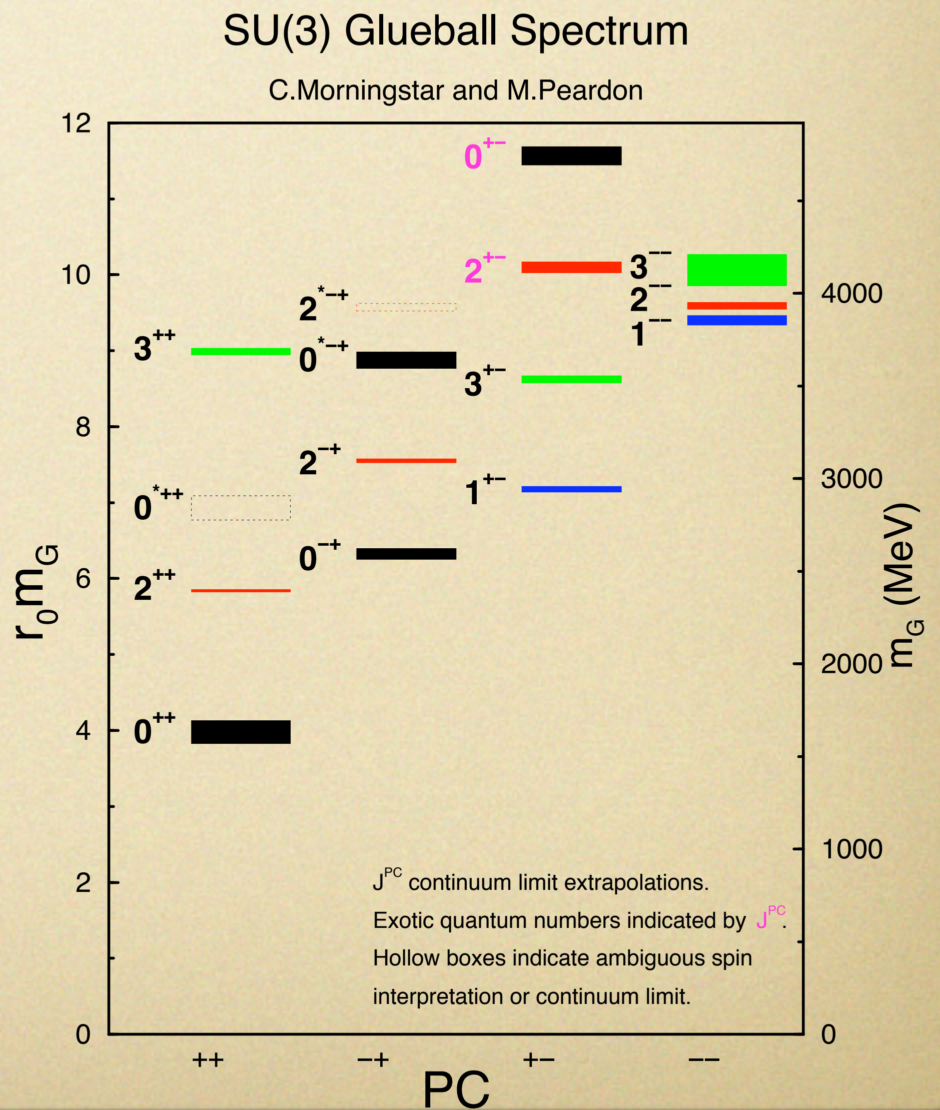


Nomenclature

glueball

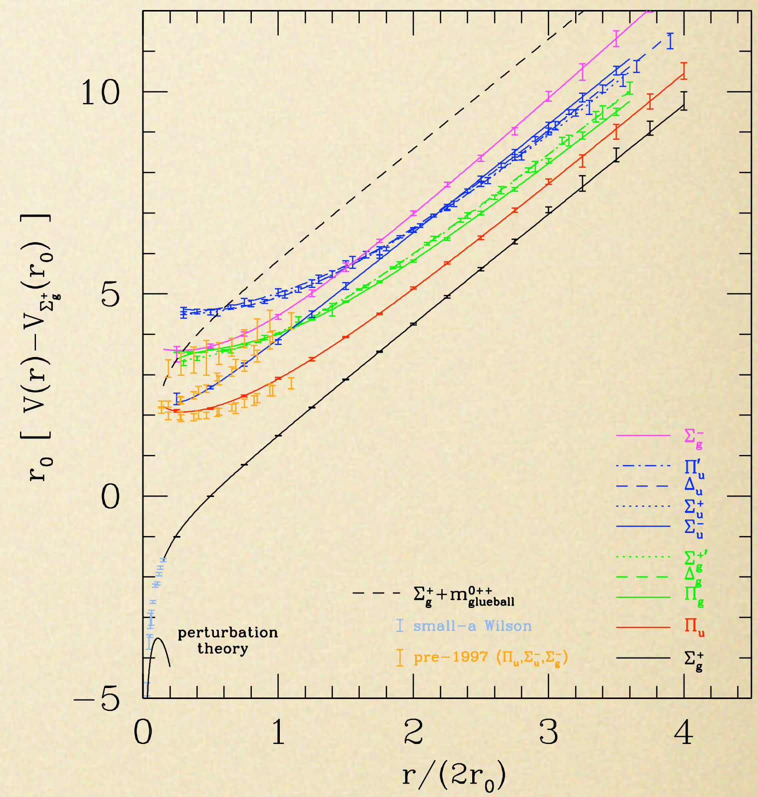






constituent quark model

$$V_{SI}(r) = -\frac{3}{4}\frac{\alpha_s}{r} + br$$

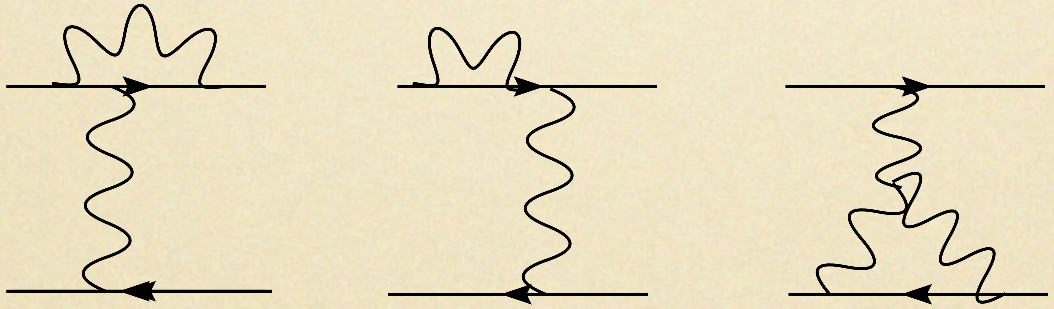


$$\begin{aligned} V_{SD}(r) \quad = \quad & \left(\frac{\sigma_q}{4m_q^2} + \frac{\sigma_{\bar{q}}}{4m_{\bar{q}}^2}\right) \cdot \mathbf{L} \left(\frac{1}{r}\frac{dV_{conf}}{dr} + \frac{2}{r}\frac{dV_1}{dr}\right) + \left(\frac{\sigma_{\bar{q}} + \sigma_q}{2m_q m_{\bar{q}}}\right) \cdot \mathbf{L} \left(\frac{1}{r}\frac{dV_2}{dr}\right) \\ & + \frac{1}{12 m_q m_{\bar{q}}}\Big(3\sigma_q \cdot \hat{\mathbf{r}}\, \sigma_{\bar{q}} \cdot \hat{\mathbf{r}} - \sigma_q \cdot \sigma_{\bar{q}}\Big) V_3 + \frac{1}{12 m_q m_{\bar{q}}} \sigma_q \cdot \sigma_{\bar{q}} V_4 \\ & + \frac{1}{2}\left[\left(\frac{\sigma_q}{m_q^2} - \frac{\sigma_{\bar{q}}}{m_{\bar{q}}^2}\right) \cdot \mathbf{L} + \left(\frac{\sigma_q - \sigma_{\bar{q}}}{m_q m_{\bar{q}}}\right) \cdot \mathbf{L}\right] V_5. \qquad (1) \end{aligned}$$

Eichten & Feinberg

constituent quark model

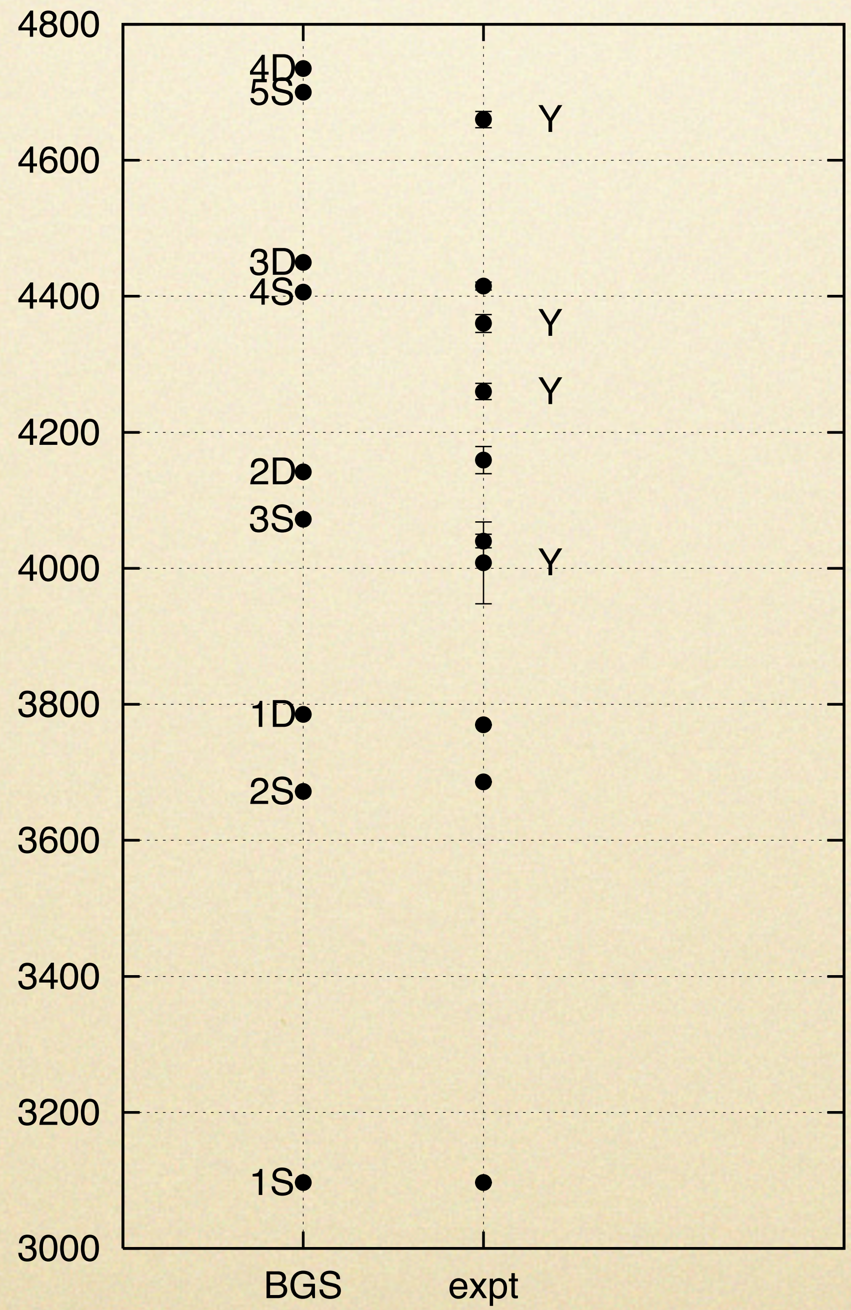
Gupta & Radford, PRD33, 777 (86)



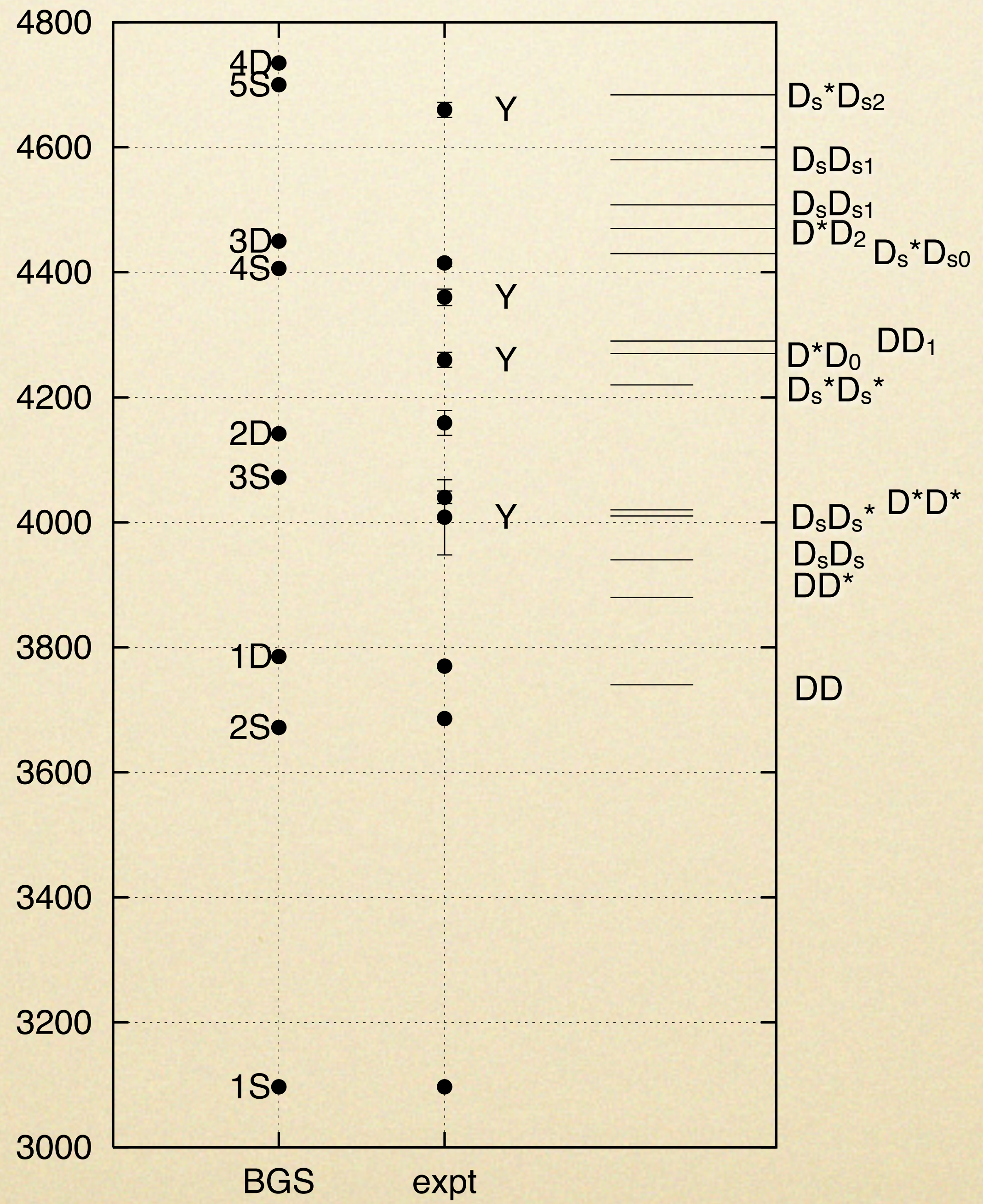
constituent quark model

$$
\begin{aligned}
V_1(m_q, m_{\bar{q}}, r) &= -br - C_F \frac{1}{2r}\frac{\alpha_s^2}{\pi}\left(C_F - C_A\left(\ln\left[(m_q m_{\bar{q}})^{1/2} r\right] + \gamma_E\right)\right) \\
V_2(m_q, m_{\bar{q}}, r) &= -\frac{1}{r} C_F \alpha_s \left[1 + \frac{\alpha_s}{\pi}\left[\frac{b_0}{2}[\ln(\mu r) + \gamma_E] + \frac{5}{12} b_0 - \frac{2}{3} C_A + \frac{1}{2}\left(C_F - C_A\left(\ln\left[(m_q m_{\bar{q}})^{1/2} r\right] + \gamma_E\right)\right)\right]\right] \\
V_3(m_q, m_{\bar{q}}, r) &= \frac{3}{r^3} C_F \alpha_s \left[1 + \frac{\alpha_s}{\pi}\left[\frac{b_0}{2}[\ln(\mu r) + \gamma_E - \frac{4}{3}] + \frac{5}{12} b_0 - \frac{2}{3} C_A + \right.\right. \\
&\quad \left.\left. + \frac{1}{2}\left(C_A + 2C_F - 2C_A\left(\ln\left[(m_q m_{\bar{q}})^{1/2} r\right] + \gamma_E - \frac{4}{3}\right)\right)\right]\right] \\
V_4(m_q, m_{\bar{q}}, r) &= \frac{32\alpha_s \sigma^3 e^{-\sigma^2 r^2}}{3\sqrt{\pi}} \\
V_5(m_q, m_{\bar{q}}, r) &= \frac{1}{4r^3} C_F C_A \frac{\alpha_s^2}{\pi} \ln\frac{m_{\bar{q}}}{m_q} \qquad (1)
\end{aligned}
$$

Charmonium Vectors -- Constituent Quark Model



Charmonium Vectors -- Constituent Quark Model



JLab lattice results

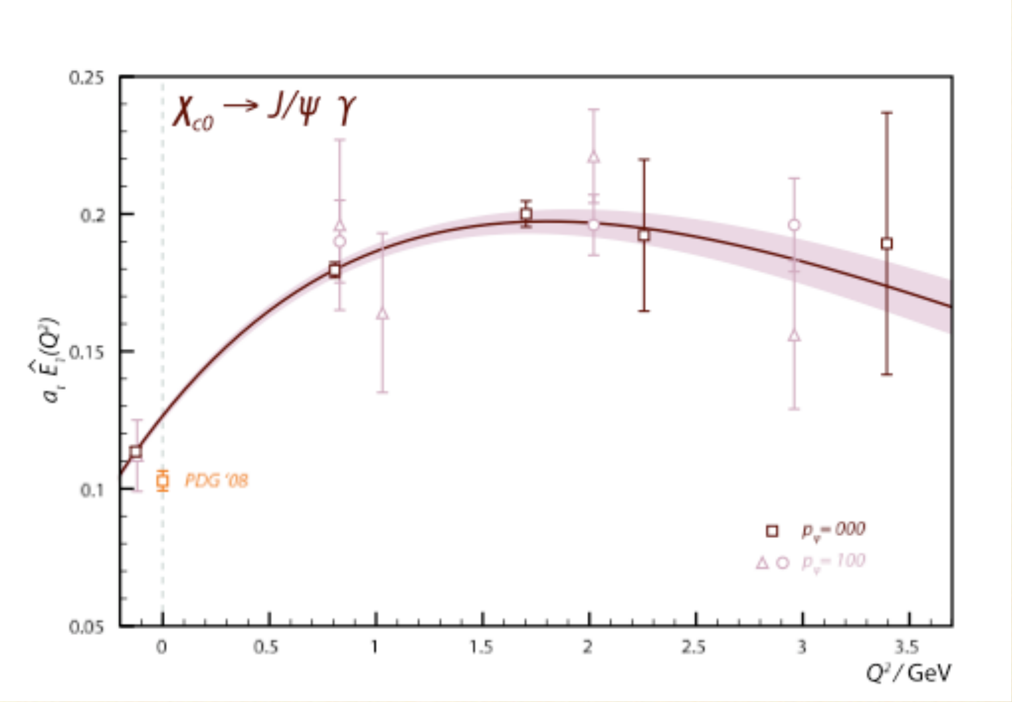
Dudek, Roberts, Thomas, 0902.2241

level	mass / MeV	suggested state	model assignment
0	3106(2)	J/ψ	$1\,{}^3S_1$
1	3746(18)	$\psi'(3686)$	$2\,{}^3S_1$
2	3846(12)	ψ_3	lat. artifact
3	3864(19)	$\psi''(3770)$	$1\,{}^3D_1$
4	4283(77)	ψ('4040')	$3\,{}^3S_1$
5	4400(60)	Y ?	hybrid

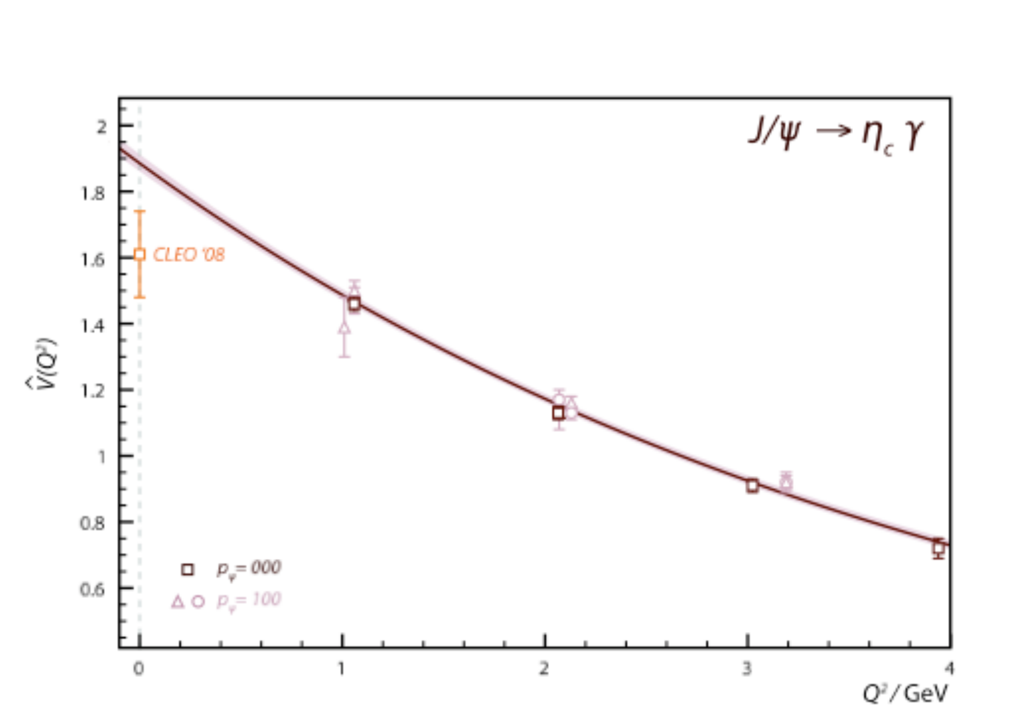
JLab lattice results

Dudek, Roberts, Thomas, 0902.2241

sink level	suggested transition	$a_t\hat{E}_1(0)$	β/MeV λ/GeV^{-2}	$\Gamma_{\rm lat}$/keV	$\Gamma_{\rm expt}$/keV
0	$\chi_{c0} \to J/\psi\gamma$	0.127(2)	409(12) 1.14(5)	199(6)	131(14)
1	$\psi' \to \chi_{c0}\gamma$	0.092(19)	164(55) 0[fixed]	26(11)	30(2)
3	$\psi'' \to \chi_{c0}\gamma$	0.265(33)	324(77) 0.58(56)	265(66)	199(26)
5	$Y_{\rm hyb.} \to \chi_{c0}\gamma$	0.00(3)	linear fit	$\lesssim 20$	-



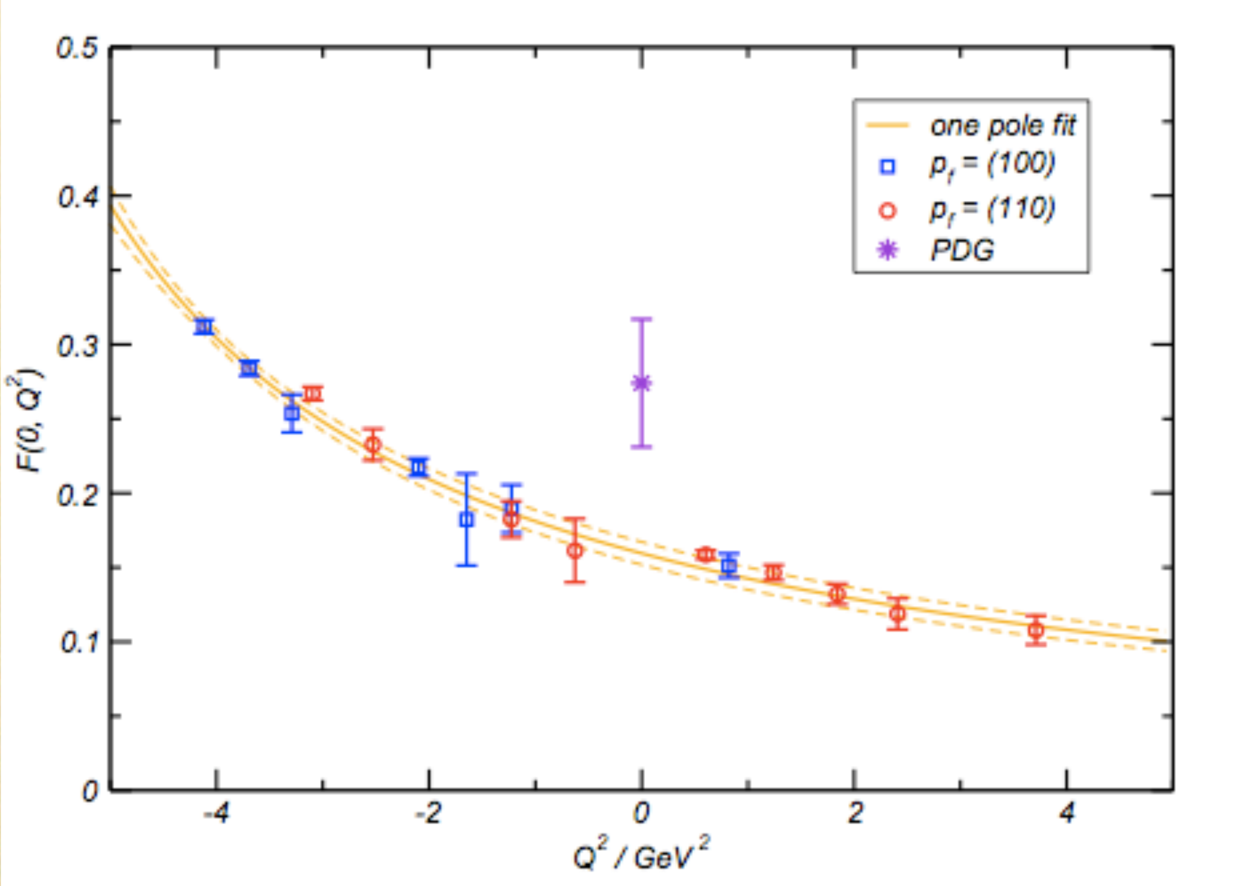
sink level	suggested transition	$\hat{V}(0)$	β/MeV λ/GeV^{-2}	$\Gamma_{\rm lat}$/keV	$\Gamma_{\rm expt}$/keV
0	$J/\psi \to \eta_c\gamma$	1.89(3)	513(7) 0[fixed]	2.51(8)	1.85(29)
1	$\psi' \to \eta_c\gamma$	0.062(64)	530(110) 4(6)	0.4(8)	0.95(16) 1.37(20)
3	$\psi'' \to \eta_c\gamma$	0.27(15)	367(55) −1.25(30)	10(11)	-
5	$Y_{\rm hyb.} \to \eta_c\gamma$	0.28(6)	250(200) 0[fixed]	42(18)	-



JLab lattice results

Dudek & Edwards, hep-ph/0607140

$$\eta_c \to \gamma\gamma^*$$



perturbative QCD

T. Pedlar [CLEO], Moriond, 2009

$$\frac{Bf(J/\psi \to \gamma\eta)}{Bf(J/\psi \to \gamma\eta')} = \frac{11.01 \pm 0.29 \pm 0.22}{52.4 \pm 1.2 \pm 1.1} = 0.21 \pm 0.04$$

$*10^{-4}$

$$\frac{Bf(\psi(2S) \to \gamma\eta)}{Bf(\psi(2S) \to \gamma\eta')} = \frac{< 0.02}{1.19 \pm 0.08 \pm 0.03} < 0.018$$

why the difference? Speculate that it is due to interference with hybrids?

perturbative QCD

T. Pedlar [CLEO], Moriond, 2009

PRL101, 101801 (2008)

$$BF(J/\psi \to \gamma\gamma\gamma) = (1.17 \pm 0.3 \pm 0.1) \cdot 10^{-5}$$

agrees with LO pQCD, but NLO is negative

perturbative QCD

T. Pedlar [CLEO], Moriond, 2009

$$\frac{\Gamma(h \to gg\gamma)}{\Gamma(h \to ggg)} = \frac{38}{5} Q^2 \frac{\alpha}{\alpha_s}[1 + (2.2 \pm 0.8)\frac{\alpha_s}{\pi}]$$

State	Ratio ($b\bar{b}$) [PRD74 012003 (2006)]	Ratio ($c\bar{c}$)
3S	$(2.72 \pm 0.06 \pm 0.32 \pm 0.37)\%$	-
2S	$(3.18 \pm 0.04 \pm 0.22 \pm 0.41)\%$	$(6.5 \pm 2.5)\%$ (PRELIMINARY)
1S	$(2.70 \pm 0.01 \pm 0.13 \pm 0.24)\%$	$(13.7 \pm 1.7)\%$ [PRD78 032012 (2008)]

perturbative QCD

Table 1: Cross Sections (fb) for $e^+e^- \to J/\psi H$ at $\sqrt{s} = 10.6$ GeV.

H	η_c	χ_{c0}	η_c'
BaBar	$17.6 \pm 2.8 \pm 2.1$	$10.3 \pm 2.5 \pm 1.8$	$16.4 \pm 3.7 \pm 3.0$
Belle	$25.6 \pm 2.8 \pm 3.4$	$6.4 \pm 1.7 \pm 1.0$	$16.5 \pm 3.0 \pm 2.4$
BL	2.31 ± 1.09	2.28 ± 1.03	0.96 ± 0.45
LHC	5.5	6.9	3.7
Bondar	~ 33		
BLL	26.7		26.6

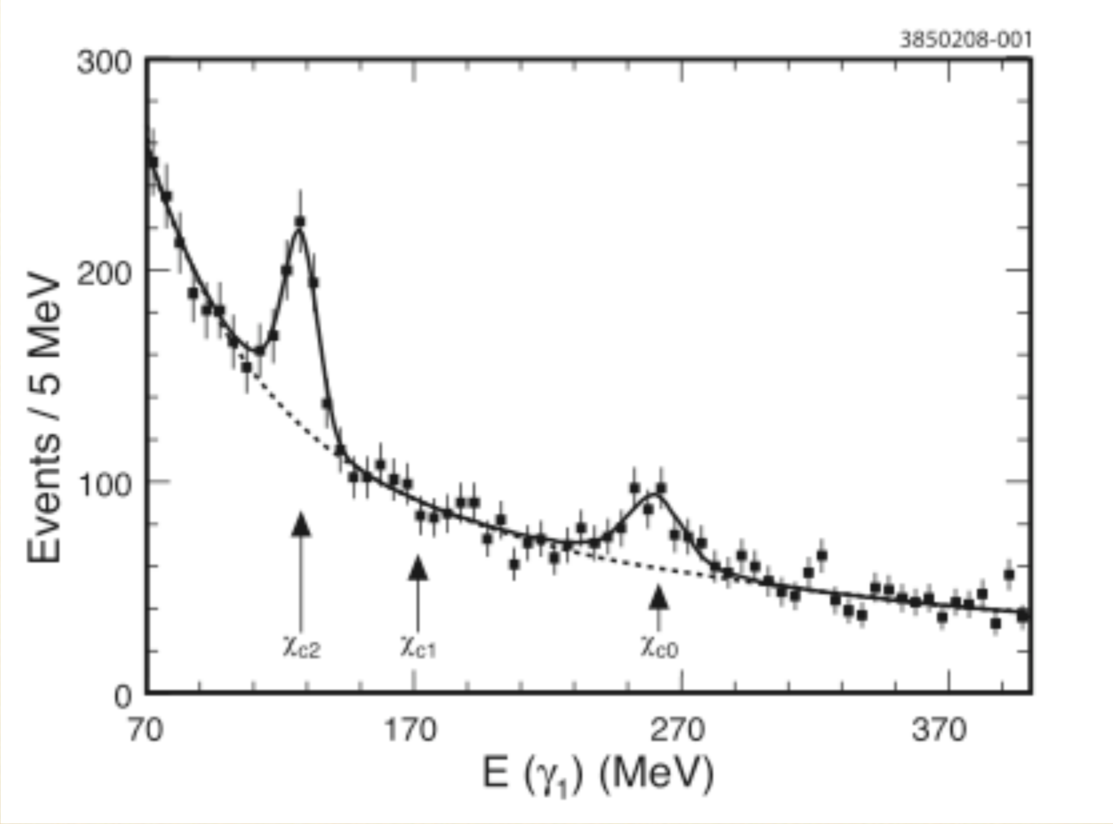
perturbative QCD

$$R = \frac{\Gamma(\chi_{c2} \to \gamma\gamma)}{\Gamma(\chi_{c0} \to \gamma\gamma)} = \frac{4}{15}(1 - 1.76\alpha_s) \; = 0.12 \; (\alpha_s = 0.32)$$

W. Bardeen et al. PRD18, 3998 (78)

$$R = \frac{0.66 \pm 0.07 \pm 0.04 \pm 0.05 \text{ keV}}{2.36 \pm 0.35 \pm 0.11 \pm 0.19 \text{ keV}} = 0.278 \pm 0.050 \pm 0.018 \pm 0.031$$

CLEO, PRD78, 091501 (2008

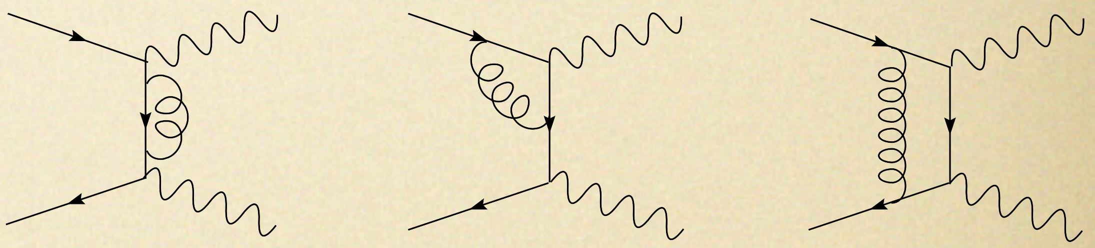


note: 4/15 = 0.27!

perturbative QCD

$$R = \frac{\Gamma(\chi_{c2} \to \gamma\gamma)}{\Gamma(\chi_{c0} \to \gamma\gamma)} = \frac{4}{15}(1 - 1.76\alpha_s)$$

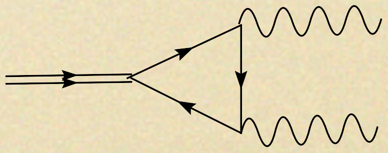
pQCD W. Bardeen et al. PRD18, 3998 (78)



NRQCD Bodwin, Braaten, Lepage, PRD51, 1125 (95)

pNRQCD N. Brambilla et al., hep-ph/0604190

pCQM Ackleh, Barnes, & Close, PRD46, 2257 (92)



bsCQM Lakhina & Swanson, PRD74, 014012 (06)

perturbative QCD

e^+e^- widths

van Royen and Weisskopf

$$\Gamma(^3S_1 \to e^+e^-) = 16\alpha_s^2 Q^2 \frac{|\psi(0)|^2}{M^2}$$

$$\Gamma(^3D_1 \to e^+e^-) = 50\alpha_s^2 Q^2 \frac{|\psi''(0)|^2}{M^2 m_c^4}$$

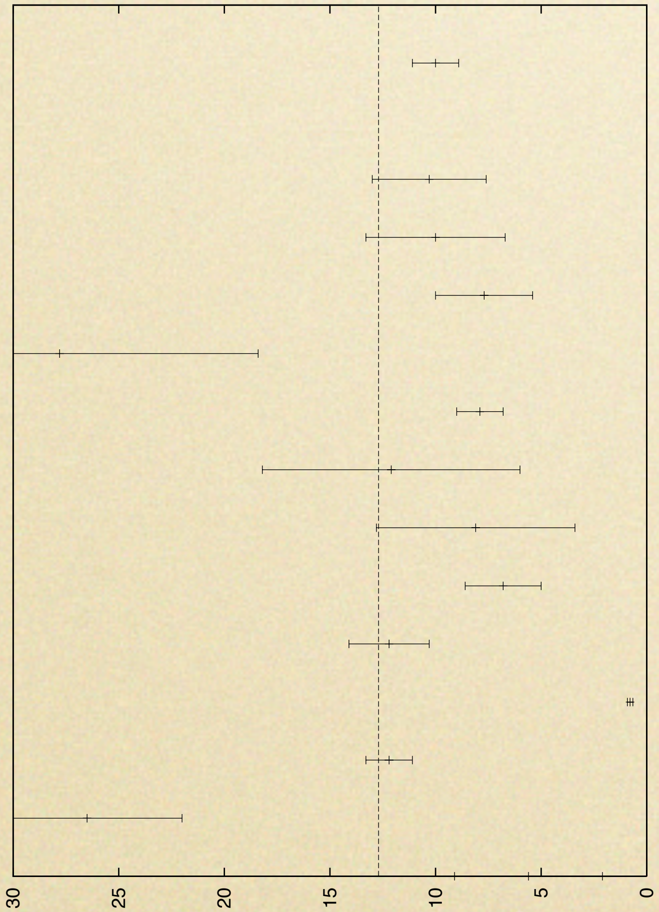
state	qn	thy (keV)	expt (keV)	
J/ψ	1^3S_1	12	5.40(17)	
ψ'	2^3S_1	5	2.12(12)	} mixing?
$\psi(3770)$	1^3D_1	0.06	0.26(4)	} mixing?
$\psi(4040)$	3^3S_1	3.5	0.75(15)	
$\psi(4159)$	2^3D_1	0.1	0.77(23)	
$\psi(4415)$	4^3S_1	2.6	0.47(10)	

perturbative QCD

the pi-rho puzzle

$$Q_h \equiv \frac{Bf(\psi' \to h)}{Bf(J/\psi \to h)} = \frac{Bf(\psi' \to e^+e^-)}{Bf(J/\psi \to e^+e^-)} \approx 12.7\%$$

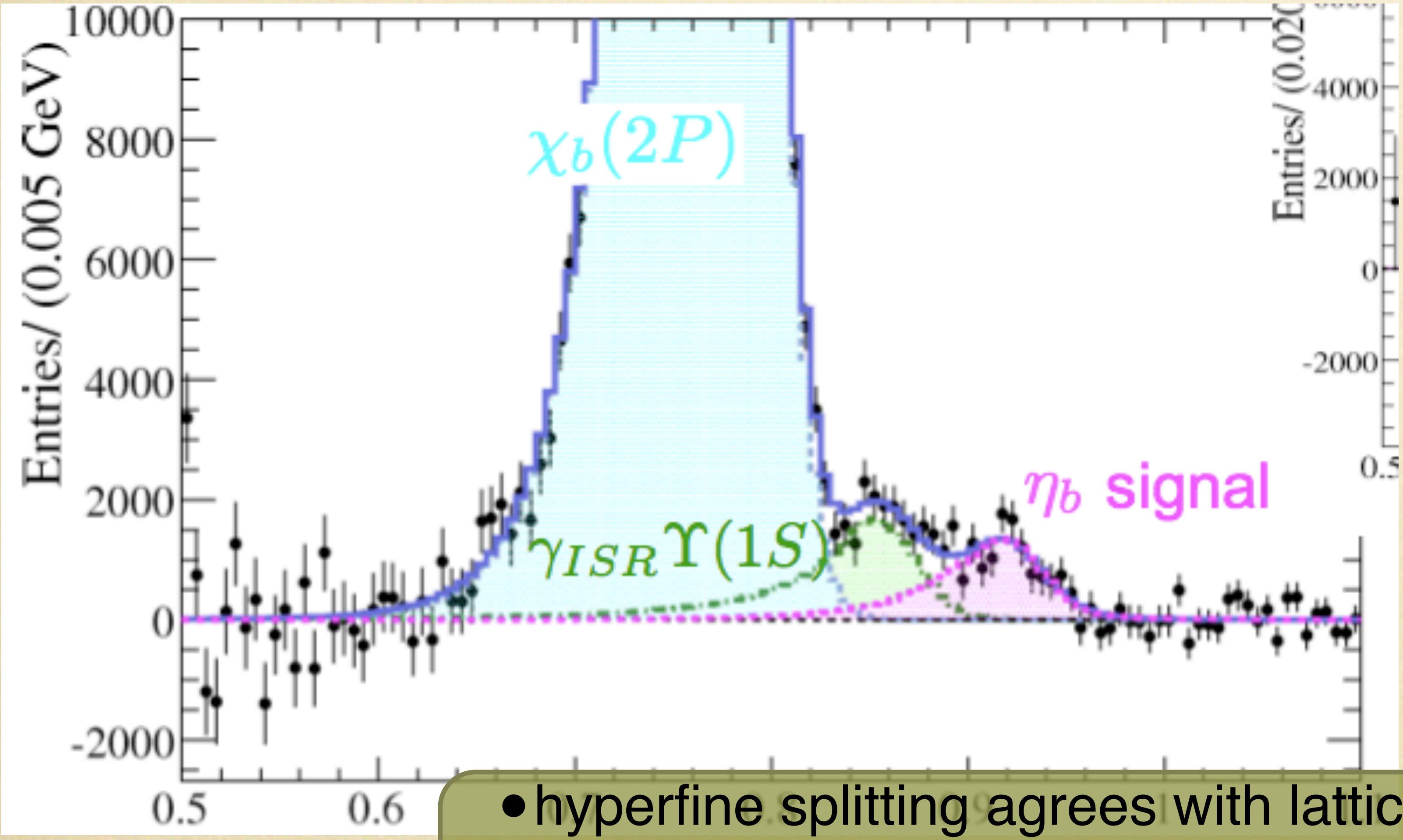
Appelquist and Politzer, PRL34, 43 (75)



Mo et al., hep-ph/0611214

Experimental Landscape

a word on the η_b



BaBar, PRD78, 091501 (2008)

$\Upsilon(3S) \to \gamma\eta_b$

$M = 9388.9 \pm 3 \pm 3$

now confirmed

arXiv:0903.1124

$\Upsilon(2S) \to \gamma\eta_b$

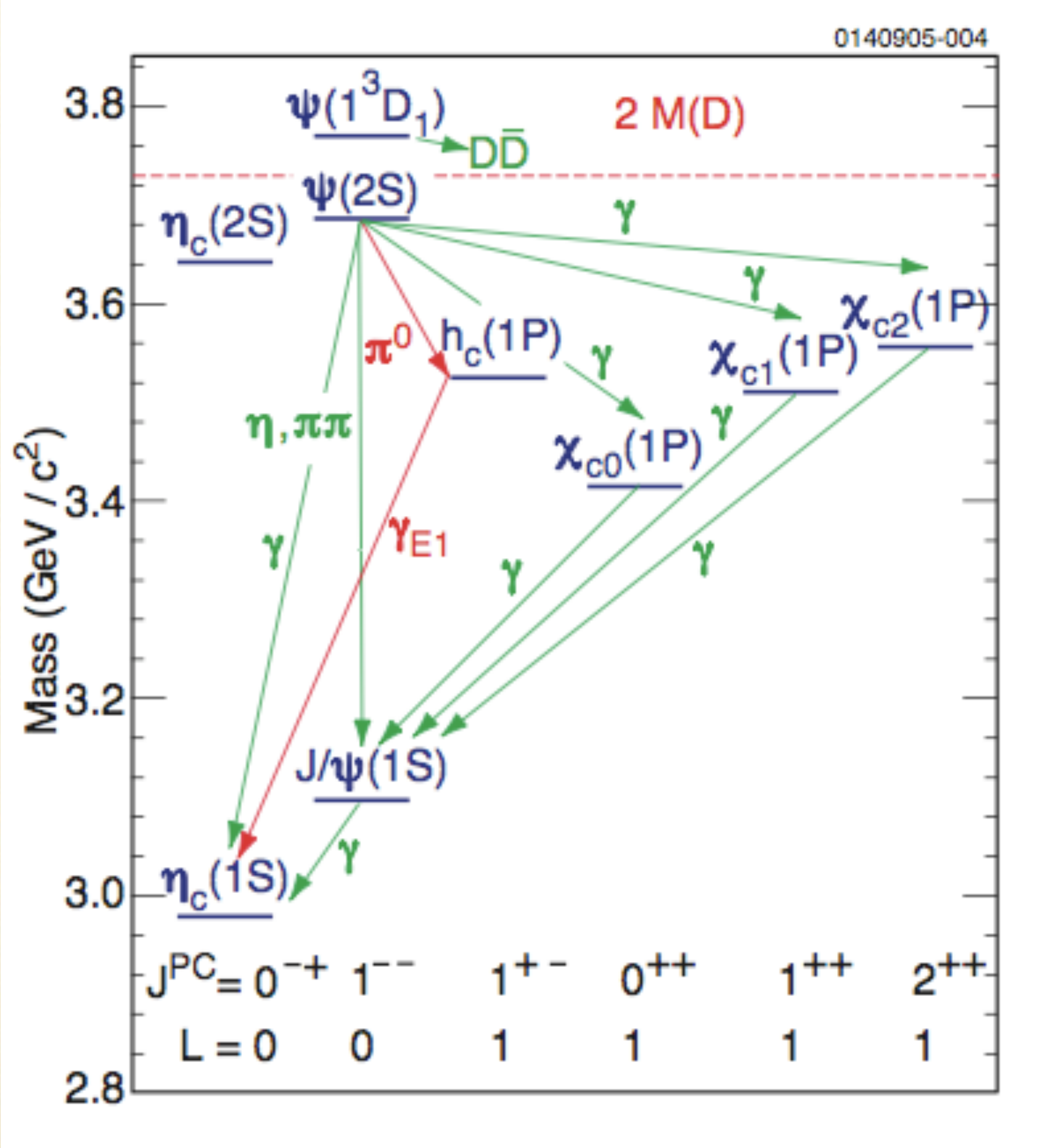
$M = 9392.9 \pm 5 \pm 2$

$M_{\rm comb} = 9390.4 \pm 3$

$\Delta M_{\rm hyp} = 69.9 \pm 3$

- hyperfine splitting agrees with lattice
- hyperfine splitting disagrees with pNRQCD
- hyperfine splitting gives $\alpha_s(M_{\eta_b})$
- test NRQCD
- test mixing with A_0

our formerly comfortable world (cf. 1932 e,p,n)



expt ref params modes signal comments

interest \ robustness	★	★★	★★★	★★★★
★★★★	$Y(4350)$	$Z(4430)$	$Z_1(4051)$	$X(3872)$
★★★	$X(4160)$	$Y(4260)$	$Y(4660)$	
★★	$Y(4140)$	$Y(3940)$	$X(3940)$	h_c
★	$Y(4008)$	$X(4630)$	$Z(3940)$	η_c'

robustness

interest

expt | ref | params | modes | signal | comments

interest \ robustness	★	★★	★★★	★★★★
★★★★	$Y(4350)$	$Z(4430)$	$Z_1(4051)$	$X(3872)$ E705
★★★	$X(4160)$	$Y(4260)$	$Y(4660)$	
★★	$Y(4140)$	$Y(3940)$	$X(3940)$	h_c
★	$Y(4008)$	$X(4630)$	$Z(3940)$	η_c'

interest

robustness

expt | **ref** | params | modes | signal | comments

interest \ robustness	★	★★	★★★	★★★★
★★★★	$Y(4350)$ hep-ex/0610057 [30]	$Z(4430)$ arXiv:0708.1790 [32]	$Z_1(4051)$ PRD78, 072004 (08)	$X(3872)$ hep-ex/0309032 [349]
★★★	$X(4160)$ arXiv:0708.3812 [13]	$Y(4260)$ hep-ex/0506081 [161]	$Y(4660)$ arXiv:0709.3699 [24]	
★★	$Y(4140)$ 0903.2229	$Y(3940)$ hep-ex/0408126 [115]	$X(3940)$ hep-ex/0408126 [77]	h_c hep-ex/0505073 [58]
★	$Y(4008)$ arXiv:0707.2541 [22]	$X(4630)$ PRL101, 172001 (08)	$Z(3940)$ hep-ex/0507033 [19]	η_c' hep-ex/0312058 [128]

robustness

expt | ref | **params** | modes | signal | comments

interest \ robustness	★	★★	★★★	★★★★
★★★★	$Y(4350)$ $J^{PC} = 1^{--}$ $M = 4361 \pm 13$ $\Gamma = 74 \pm 18$	$Z(4430)$ $J^{PC} = ?^{??}$ $M = 4433 \pm 5$ $\Gamma = 45 \pm 25$ $6.5\,\sigma$	$Z_1(4051)$ $M = 4051 \pm 20 \pm 30$ $\Gamma = 82 \pm 20 \pm 40$ $M = 4248 \pm 30 \pm 80$ $\Gamma = 177 \pm 50 \pm 100$	$X(3872)$ $J^{PC} = 1^{++}$ $M = 3871.4 \pm 0.6$ $\Gamma < 2.3$ $> 10\,\sigma$
★★★	$X(4160)$ $J^{PC} = J^{P+}$ $M = 4156 \pm 29$ $\Gamma = 139 \pm 100$ $5.1\,\sigma$	$Y(4260)$ $J^{PC} = 1^{--}$ $M = 4264 \pm 12$ $\Gamma = 83 \pm 22$	$Y(4660)$ $J^{PC} = 1^{--}$ $M = 4664 \pm 12$ $\Gamma = 48 \pm 15$	
★★	$Y(4140)$ $M = 4143 \pm 2.9 \pm 1.2$ $\Gamma = 11.7 \pm 8$ 3.8σ	$Y(3940)$ $J^{PC} = J^{P+}$ $M = 3943 \pm 17$ $\Gamma = 87 \pm 34$ $8\,\sigma$	$X(3940)$ $J^{PC} = J^{P+}$ $M = 3942 \pm 9$ $\Gamma = 37 \pm 17$ $5\,\sigma$	h_c $J^{PC} = 1^{++}$ $M = 3525.28 \pm 0.19 \pm 0.12$ $\Gamma \approx 0$ $> 5\sigma$
★	$Y(4008)$ $J^{PC} = 1^{--}$ $M = 4008 \pm 60$ $\Gamma = 226 \pm 90$	$X(4630)$ $J^{PC} = ?^{??}$ $M = 4634 \pm 8 \pm 7$ $\Gamma = 92 \pm 30 \pm 15$ $8.2\,\sigma$	$Z(3940)$ $J^{PC} = 2^{++}$ $M = 3929 \pm 5$ $\Gamma = 20 \pm 10$ $5.5\,\sigma$	η_c' $J^{PC} = 0^{-+}$ $M = 3654 \pm 6 \pm 8$ $\Gamma = 15 \pm 20$

interest

robustness

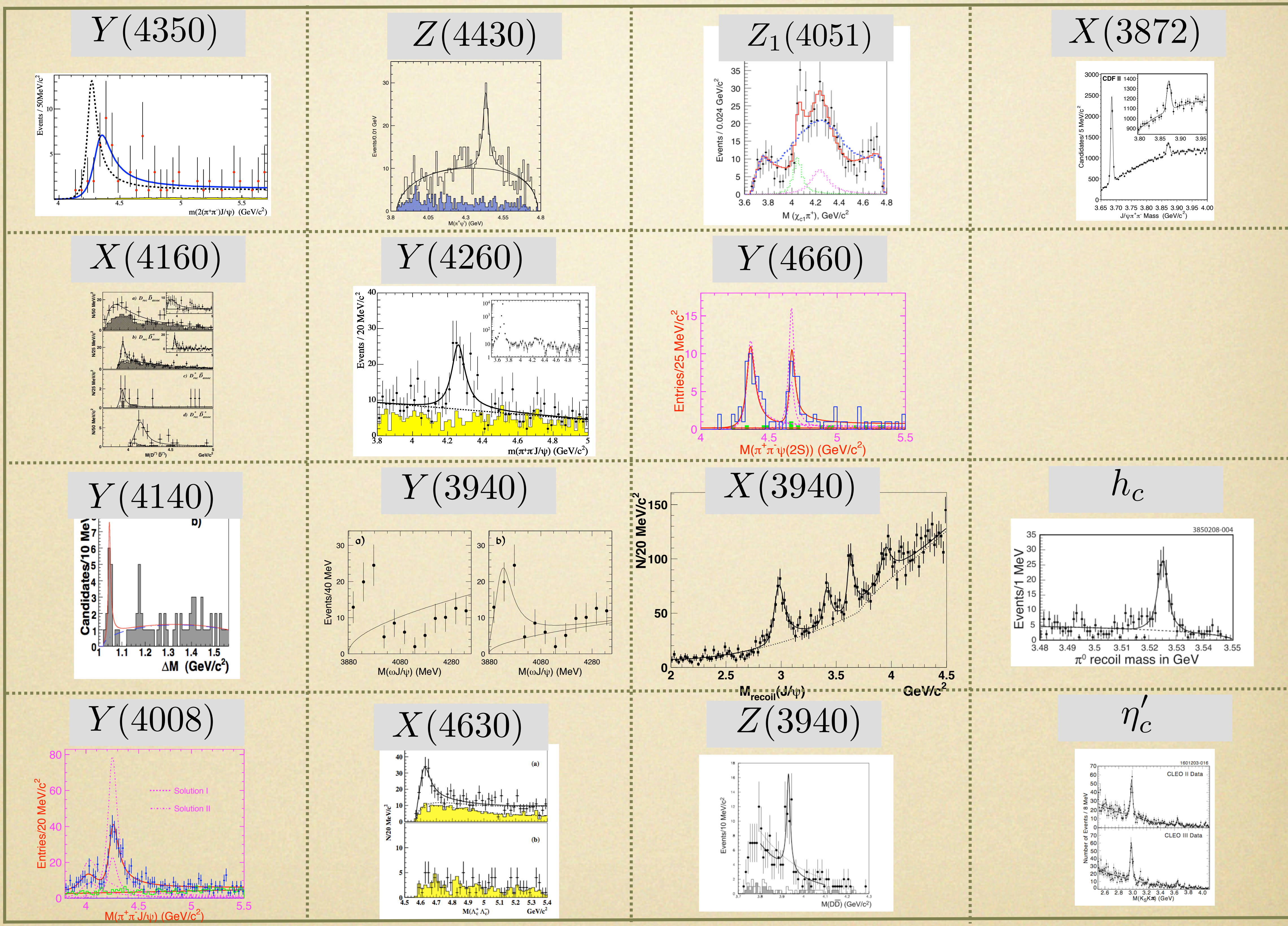
expt | ref | params | **modes** | signal | comments

interest \ robustness	★	★★	★★★	★★★★
★★★★	$Y(4350)$ $e^+e^- \to \gamma_{\rm ISR}\psi'\pi^+\pi^-$	$Z(4430)$ $B \to KZ$ $Z \to \pi^\pm\psi'$	$Z_1(4051)$ $B \to KZ_1$ $Z_1 \to \chi_{c1}\pi^\pm$	$X(3872)$ B $\to KX;\ p\bar{p}$ X $\to \pi^+\pi^- J/\psi$ X $\to \pi^+\pi^-\pi^0 J/\psi$ X $\to \gamma J/\psi;\ X \to \gamma\psi(2S)$ X(3875) $\to D^0\bar{D}^0\pi^0$
★★★	$X(4160)$ $e^+e^- \to J/\psi X$ $X \to D^*\bar{D}^*$	$Y(4260)$ $e^+e^- \to \gamma_{\rm ISR}J/\psi\pi^+\pi^-$	$Y(4660)$ $e^+e^- \to \gamma_{\rm ISR}\psi'\pi^+\pi^-$	
★★	$Y(4140)$ $p\bar{p} \to B \to J/\psi\phi K$	$Y(3940)$ $B \to KY$ $Y \to \omega J/\psi$	$X(3940)$ $e^+e^- \to J/\psi X(3940)$ $X(3940) \to D\bar{D}^*$	h_c $\psi' \to \pi^0 h_c$ $h_c \to \gamma\eta_c$
★	$Y(4008)$ $e^+e^- \to \gamma_{\rm ISR}J/\psi\pi^+\pi^-$	$X(4630)$ $e^+e^- \to \Lambda_c^+\Lambda_c^-$	$Z(3940)$ $\gamma\gamma \to D\bar{D}$	η_c' $\gamma\gamma \to \eta_c'$ $\eta_c' \to K_S^0 K^\pm\pi^\mp$

interest

robustness

expt | ref | params | modes | **signal** | comments



interest

robustness

expt | ref | params | modes | signal | comments

interest \ robustness	★	★★	★★★	★★★★
★★★★	$Y(4350)$?	$Z(4430)$ tetraquark D^*D_1 molecule threshold effect artefact	$Z_1(4051)$ tetraquark hadrocharmonium artefact	$X(3872)$ DD^* molecule threshold effect tetraquark
★★★	$X(4160)$?	$Y(4260)$ hybrid (ccg) threshold effect	$Y(4660)$ radial hybrid (ccg) 5S vector $f_0\,\psi'$ molecule	
★★	$Y(4140)$ tetraquark artefact	$Y(3940)$ threshold effect	$X(3940)$ χ'_{cJ}	h_c tests long range spin dynamics
★	$Y(4008)$?	$X(4630)$ threshold effect	$Z(3940)$ χ'_{c2} sets scale for 2P states (inverted?)	η'_c tests $O(1/m^2)$ dynamics

interest

robustness

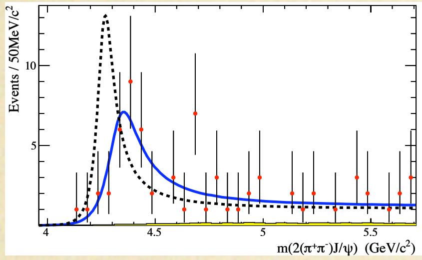
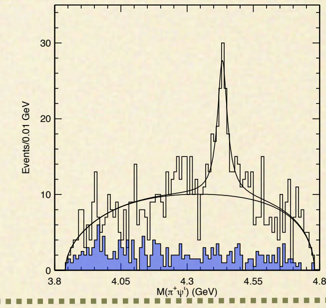
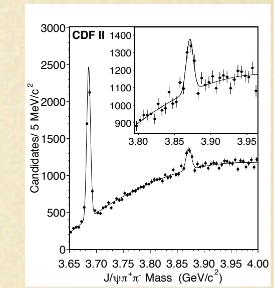
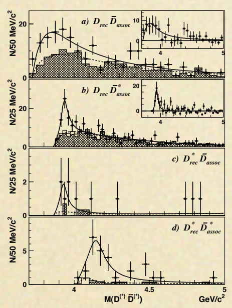
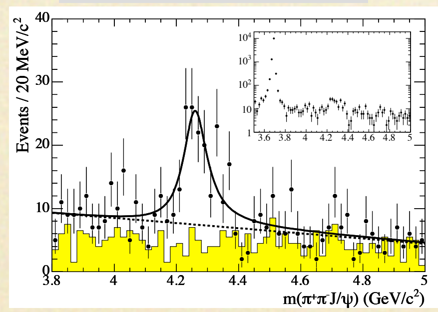
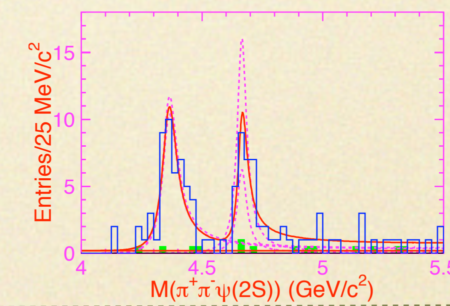
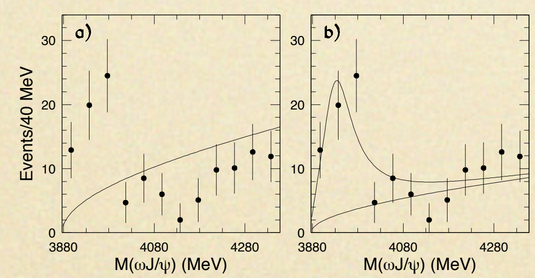
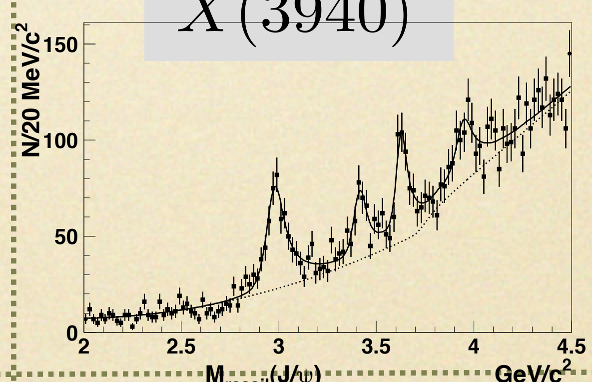
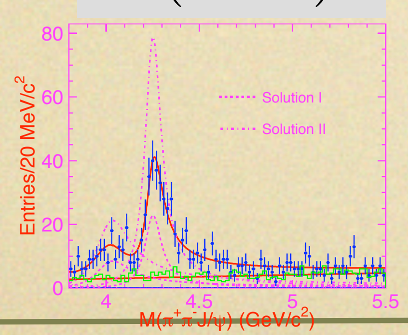
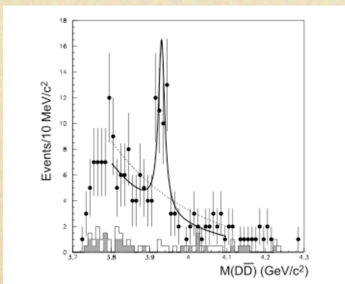
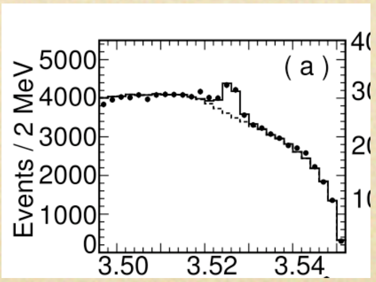
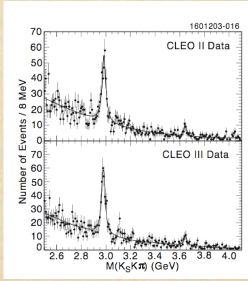
expt | ref | params | modes | signal | comments

interest \ robustness	★	★★	★★★	★★★★
★★★★	$Y(4350)$?	$Z(4430)$ tetraquark D^*D_1 molecule threshold effect artefact	$Z_1(4051)$ tetraquark hadrocharmonium artefact	$X(3872)$ DD^* molecule threshold effect tetraquark
★★★	$X(4160)$?	$Y(4260)$ hybrid (ccg) threshold effect	$Y(4660)$ radial hybrid (ccg) 5S vector f_0 ψ' molecule	
★★	$Y(4140)$ tetraquark artefact	$Y(3940)$ threshold effect	$X(3940)$ χ'_{cJ}	h_c tests long range spin dynamics
★	$Y(4008)$?	$X(4630)$ threshold effect	$Z(3940)$ χ'_{c2} sets scale for 2P states (inverted?)	η'_c tests $O(1/m^2)$ dynamics

interest

robustness

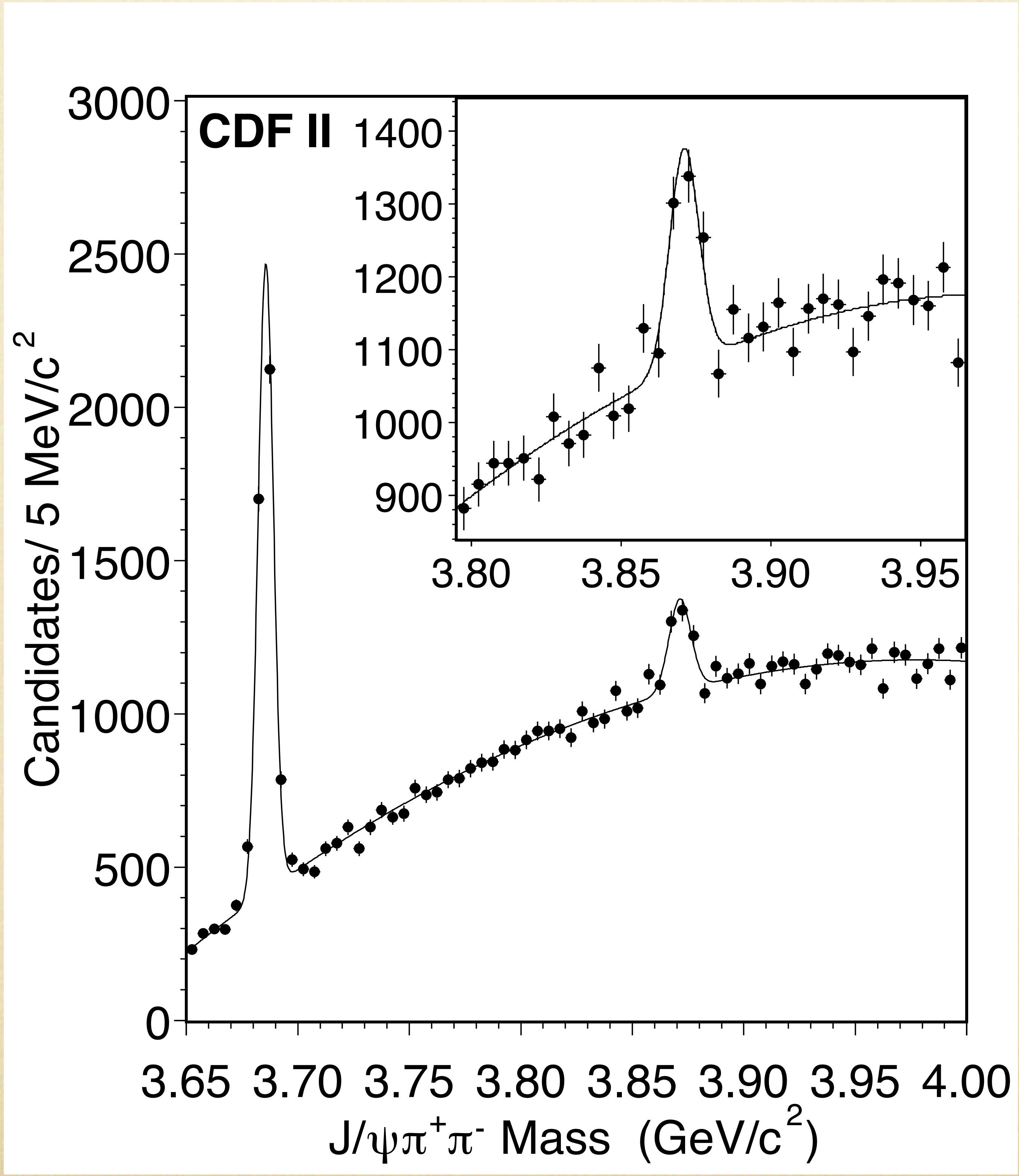
expt | ref | params | modes | **signal** | comments

interest \ robustness	★	★★	★★★	★★★★
★★★★	$Y(4350)$ 	$Z_1(4051)$	$Z(4430)$ 	$X(3872)$ 
★★★	$X(4160)$ 	$Y(4260)$ 	$Y(4660)$ 	
★★	$Y(4140)$	$Y(3940)$ 	$X(3940)$ 	
★	$Y(4008)$ 	$Z(3940)$ 	h_c 	η_c' 

interest

robustness

$X(3872)$



CDF II
Candidates/ 5 MeV/c^2
3000
2500
2000
1500
1000
500
0
3.65 3.70 3.75 3.80 3.85 3.90 3.95 4.00
J/ψπ$^+$π$^-$ Mass (GeV/c^2)
1400
1300
1200
1100
1000
900
3.80 3.85 3.90 3.95

The X(3872) in 1992

190

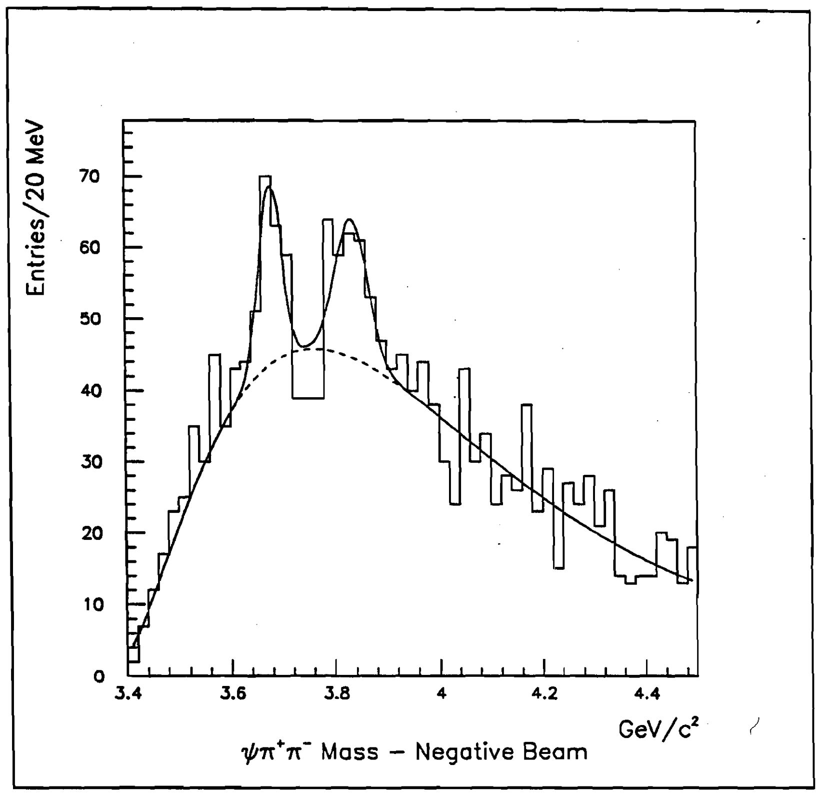


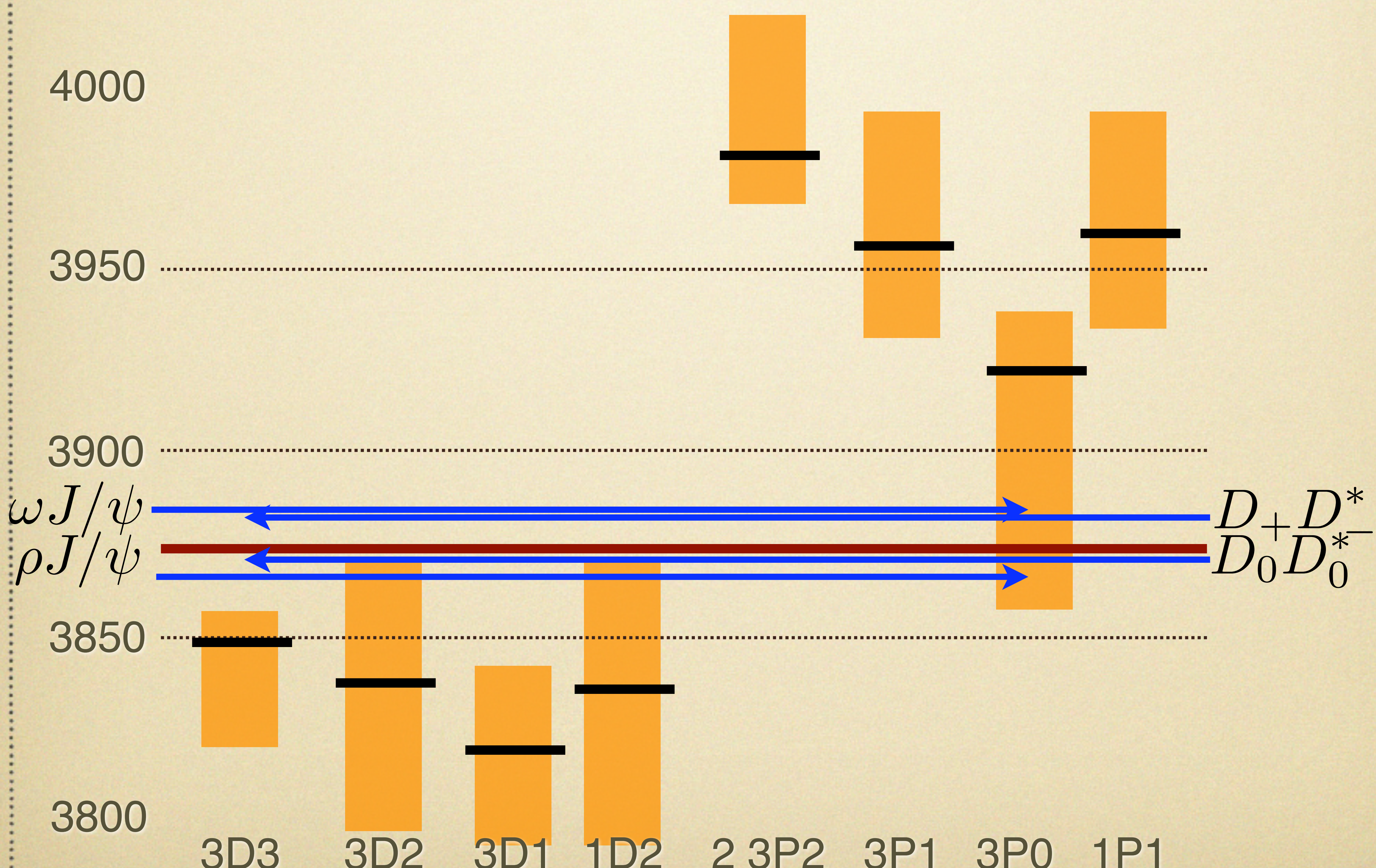
Figure 6.12 $\psi\pi\pi$ mass spectrum, standard cuts, negative beam.

A single peak above background does not fit the observed signal well. A second peak above the ψ' was added to the fit to improve this. The fit parameters are shown on the following page:

E-705

Tom LeCompte,
Northwestern thesis
E705 at FNAL

X(3872) ...



4000
3950
3900
3850
3800
$\omega J/\psi$
$\rho J/\psi$
$D_+ D^*_-$
$D_0 D^*_0$
3D3
3D2
3D1
1D2
2 3P2
3P1
3P0
1P1

Tornqvist, 0308277

Close & Page, PLB578, 119 (04)

ESS, PLB588, 189 (2004)

Molecular State (fast version)

- Model X as a $D\bar{D}^*$ state with admixture of $\omega\,\psi$ and $\rho\,\psi$
- microscopic model = oπe + quark dynamics; project onto continuum channels.
- find only one bound state with $J^{PC} = 1^{++}$
- X decays via $\rho\,\psi$ to $\pi\,\pi\,\psi$ and $\omega\,\psi$ to $\pi\,\pi\,\pi\,\psi$ with comparable strength (isospin violation is natural in this model)

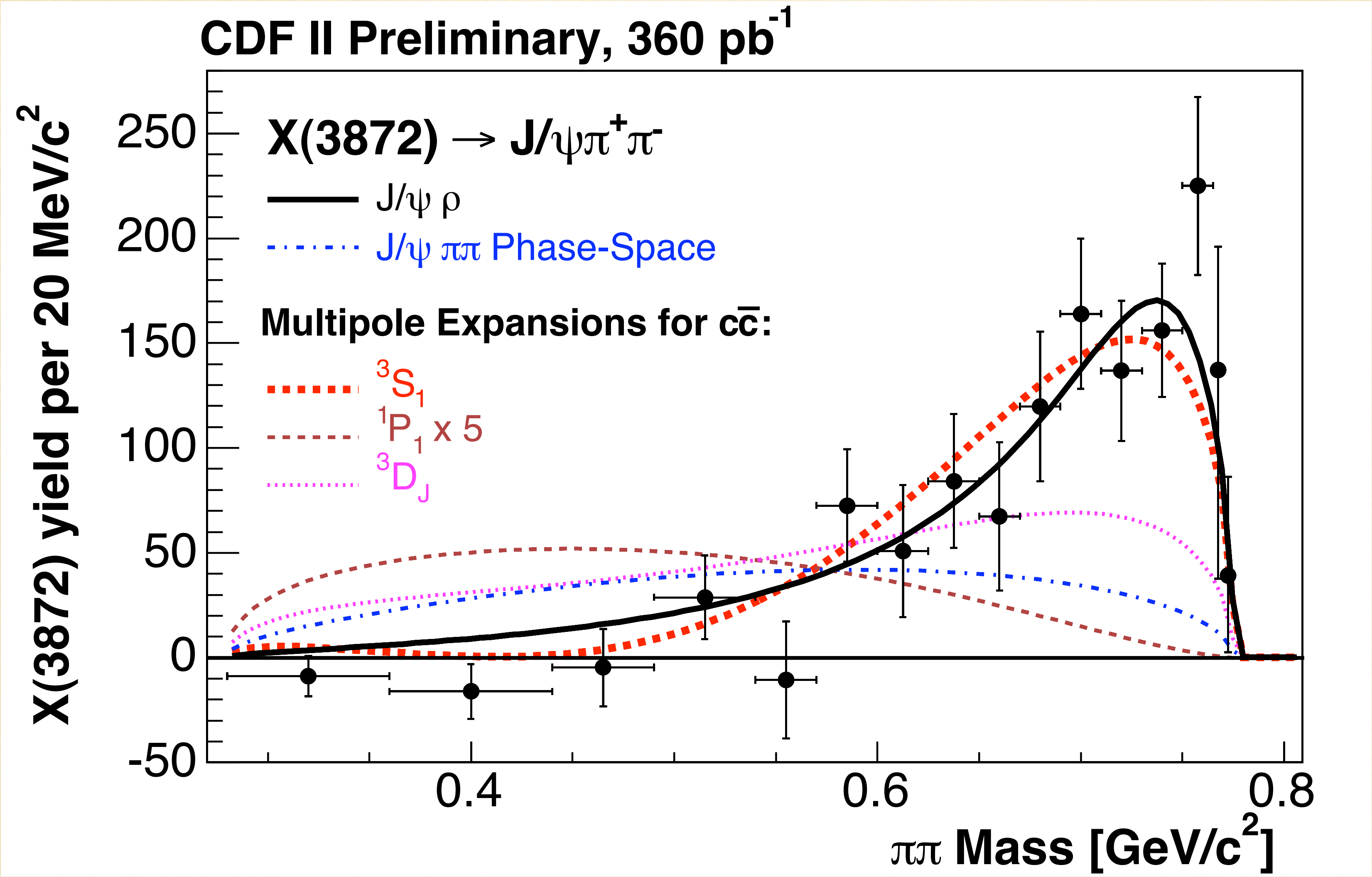
$\hat{\chi}_{c1}$ decay widths

weak binding → use free space decay widths to estimate dissociation decay modes

	D^{0*}	D^{0*}	D^{-*}	D^{-*}	D^{-*}	ρ	ρ/ω	ω	ρ/ω
B_E (MeV)	$D^0\bar{D}^0\pi^0$	$D^0\bar{D}^0\gamma$	$D^+D^-\pi^0$	$(D^+\bar{D}^0\pi^-+\text{c.c})/\sqrt{2}$	$D^+D^-\gamma$	$\pi^+\pi^-J/\psi$	$\pi^+\pi^-\gamma J/\psi$	$\pi^+\pi^-\pi^0 J/\psi$	$\pi^0\gamma J/\psi$
0.7	67	38	5.1	4.7	0.2	1290	12.9	720	70
1.0	66	36	6.4	5.8	0.3	1215	12.1	820	80
2.0	57	32	9.5	8.6	0.4	975	9.8	1040	100
3.8	52	28	12.5	11.4	0.6	690	6.9	1190	115
6.1	46	26	15.0	13.6	0.7	450	4.5	1270	120
9.0	43	24	16.9	15.3	0.8	285	2.9	1280	125
12.7	38	22	18.5	16.7	0.9	180	1.8	1240	120

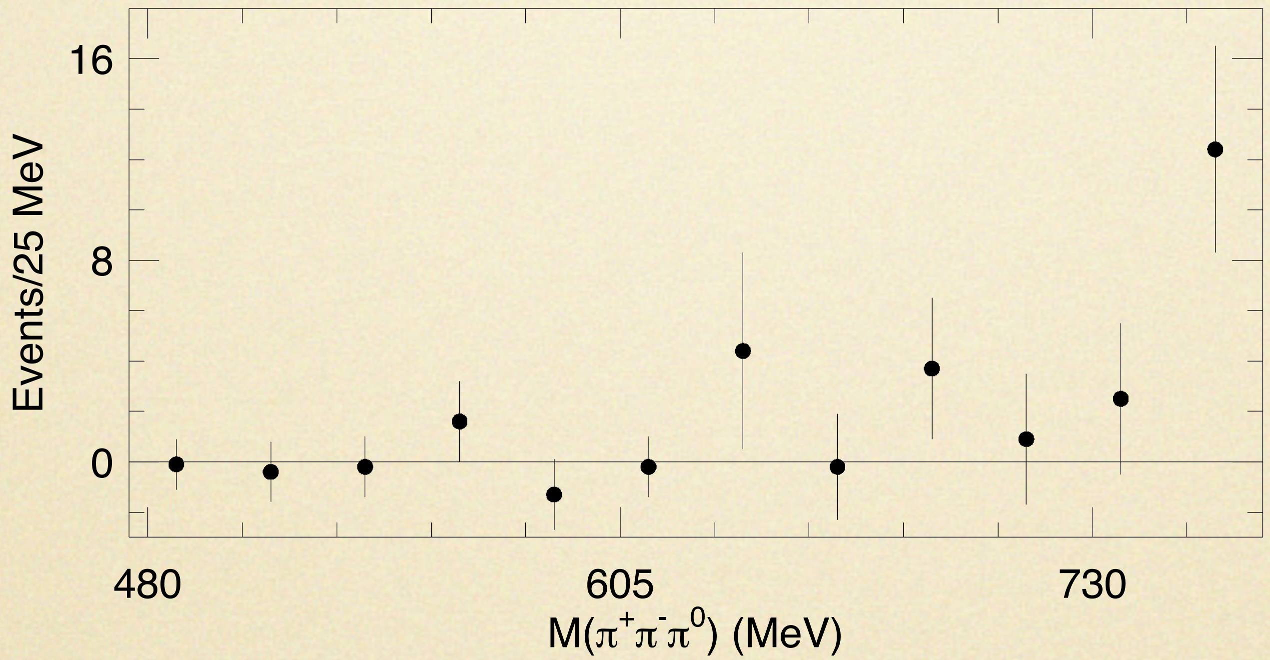
$$\frac{\Gamma(\hat{\chi} \to \pi\pi\pi J/\psi)}{\Gamma(\hat{\chi} \to \pi\pi J/\psi)} = 0.56$$

dipion spectrum



CDF note 05-03-24

$X \to 3\pi J/\psi$

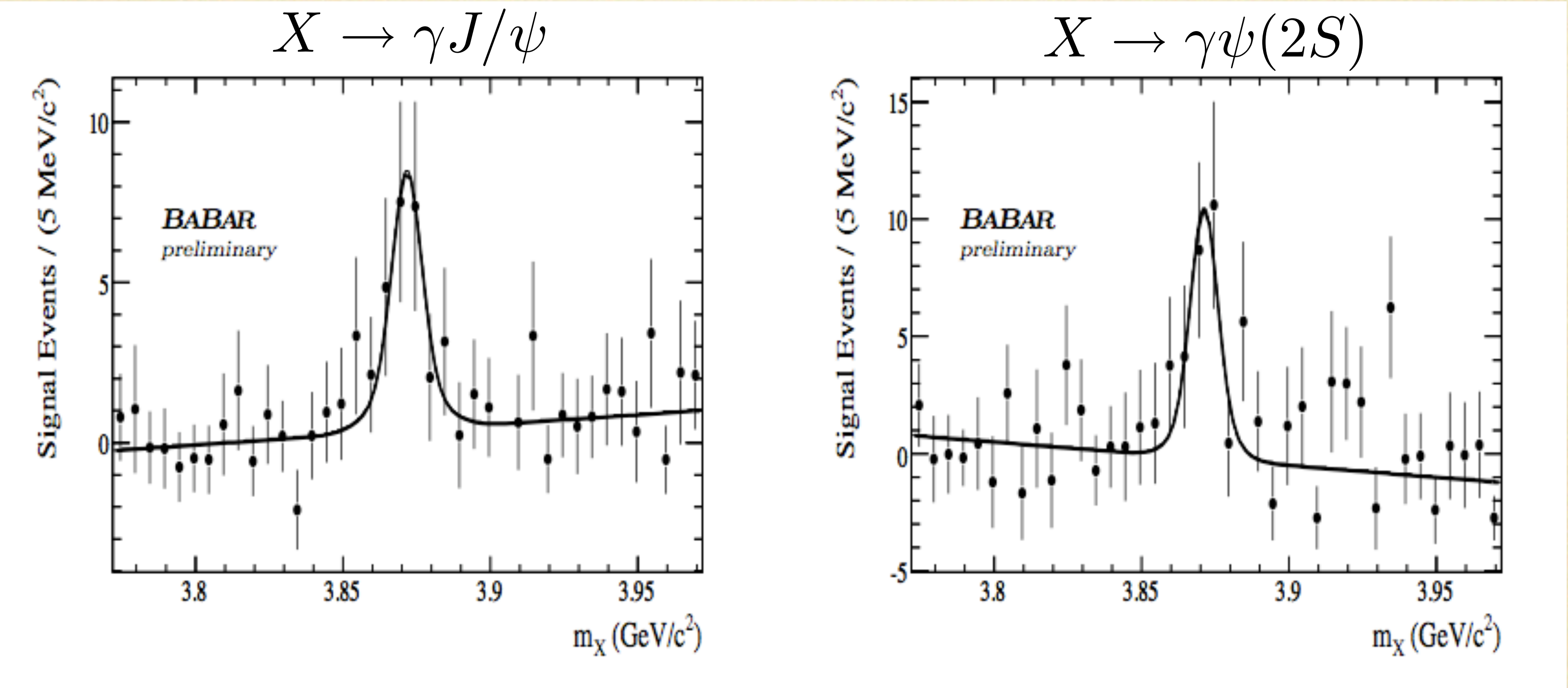


$$\frac{\Gamma(X \to \omega J/\psi)}{\Gamma(X \to \pi^+\pi^- J/\psi)} = 1.0(4)(3)$$

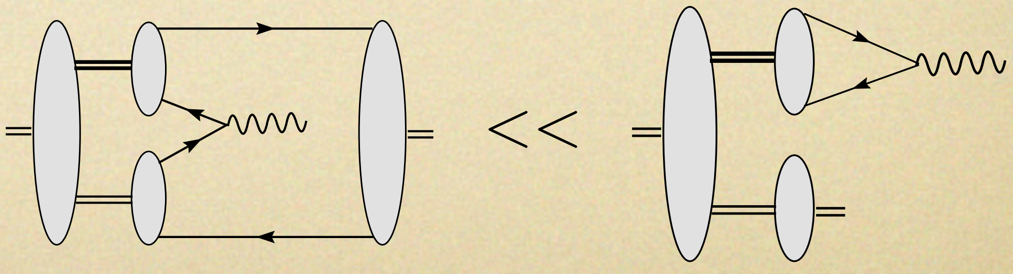
Abe et al [Belle], hep-ex/0505037

new from BaBar...

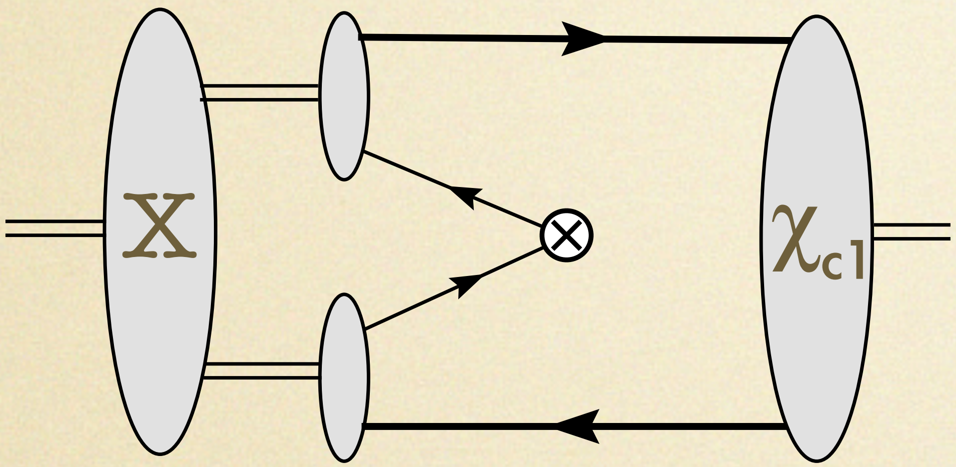
Aubert et al., 0809.0042



$$\frac{Bf(X \to \gamma\psi(2S))}{Bf(X \to \gamma J/\psi)} = 3.5(1.0)$$



Mixing



$$a_\chi = \sqrt{2} Z_{00}^{1/2} \int d^3k\, \psi_X(k) \mathcal{A}(-k)$$

state	E_B (MeV)	a (fm)	Z_{00}	a_χ (MeV)	prob
χ_{c1}	0.1	14.4	93%	94	5%
	0.5	6.4	83%	120	10%
χ'_{c1}	0.1	14.4	93%	60	100%
	0.5	6.4	83%	80	$>$ 100%

Other Molecules

ESS, probably will never complete....

I=0 D*$\bar{D}$* states

no MM mixtures

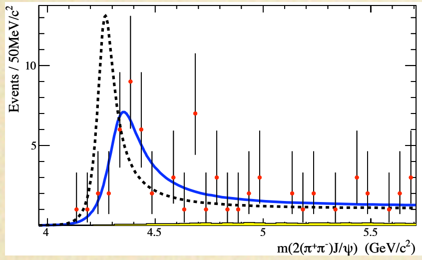
state	J^{PC}	channels	mass (MeV)	E_B
$D^*\bar{D}^*$	0^{++}	$^1S_0$, $^5D_0$	4019	1.0
$B\bar{B}^*$	0^{-+}	$^3P_0$	10543	61
$B\bar{B}^*$	1^{++}	$^3S_1$, $^3D_1$	10561	43
$B^*\bar{B}^*$	0^{++}	$^1S_0$, $^5D_0$	10579	71
$B^*\bar{B}^*$	0^{-+}	$^3P_0$	10588	62
$B^*\bar{B}^*$	1^{+-}	$^3S_1$, $^3D_1$	10606	44
$B^*\bar{B}^*$	2^{++}	$^1D_2$, $^5S_2$, $^5D_2$, $^5G_2$	10600	50

expt | ref | params | modes | **signal** | comments

interest

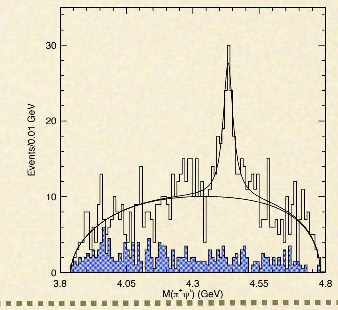
★★★★

$Y(4350)$

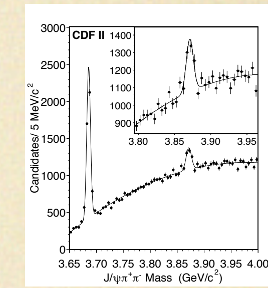


$Z_1(4051)$

$Z(4430)$

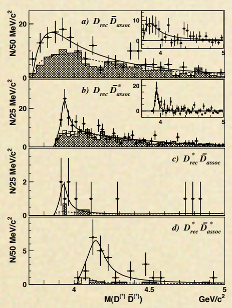


$X(3872)$

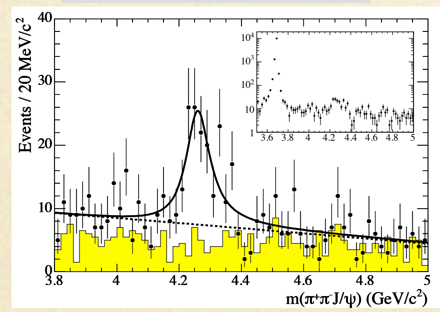


★★★

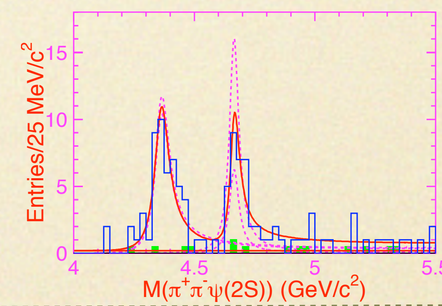
$X(4160)$



$Y(4260)$



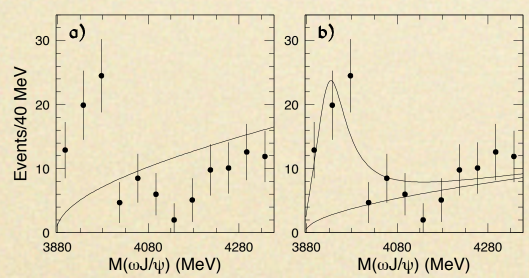
$Y(4660)$



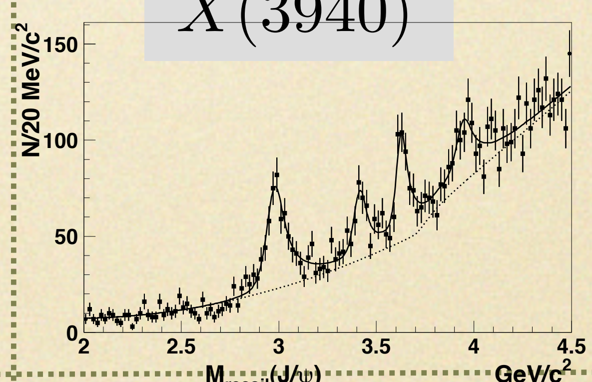
★★

$Y(4140)$

$Y(3940)$

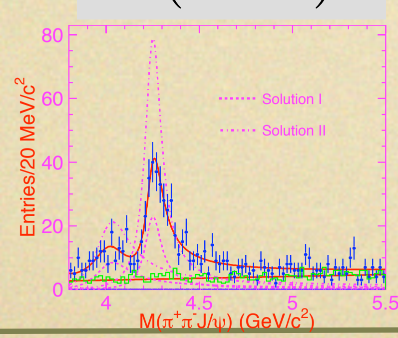


$X(3940)$

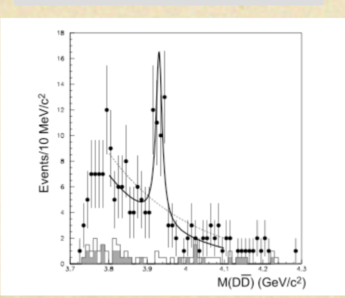


★

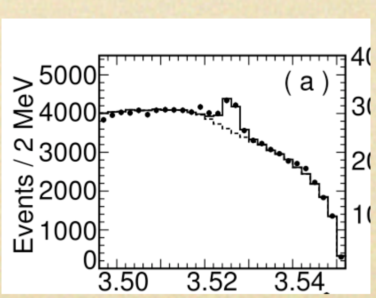
$Y(4008)$



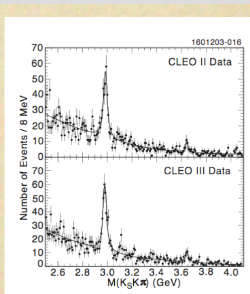
$Z(3940)$



h_c



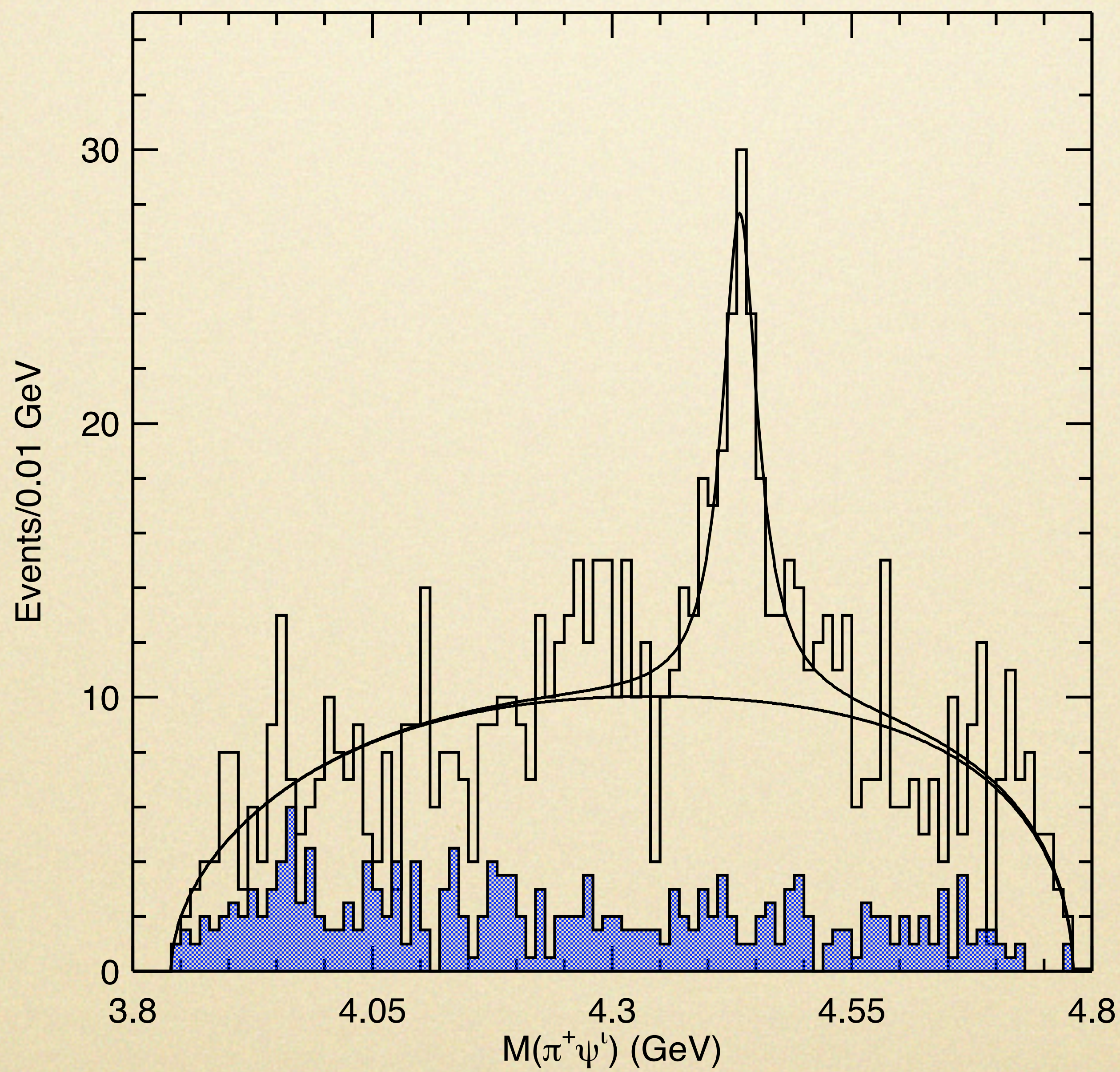
η_c'



★ | ★★ | ★★★ | ★★★★

robustness

$Z(4430)$



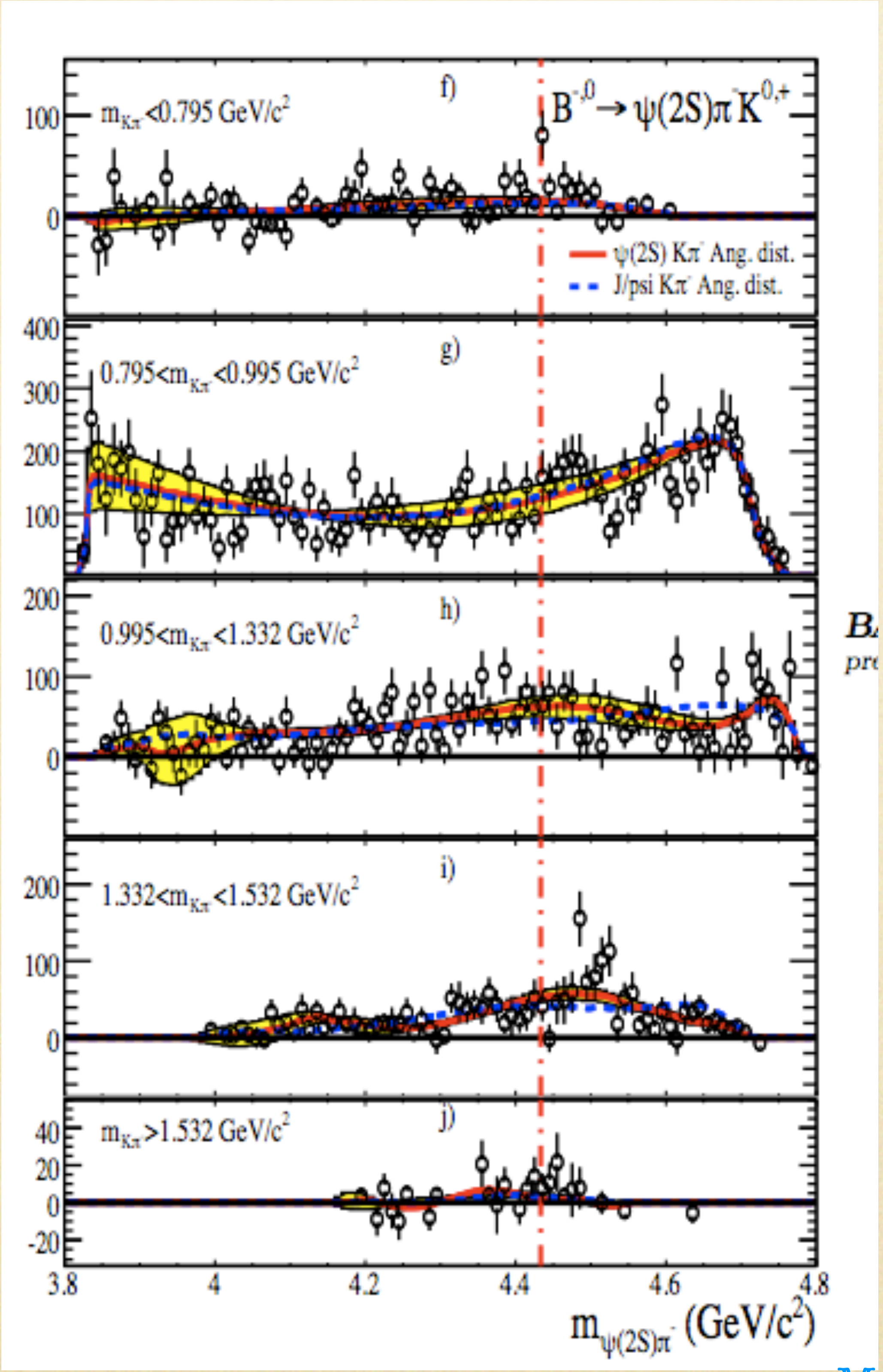
$Z^+(4430)$ ...

S.-K Choi et al. [Belle] 0708.1790

$$B \to K\pi^+\psi'$$

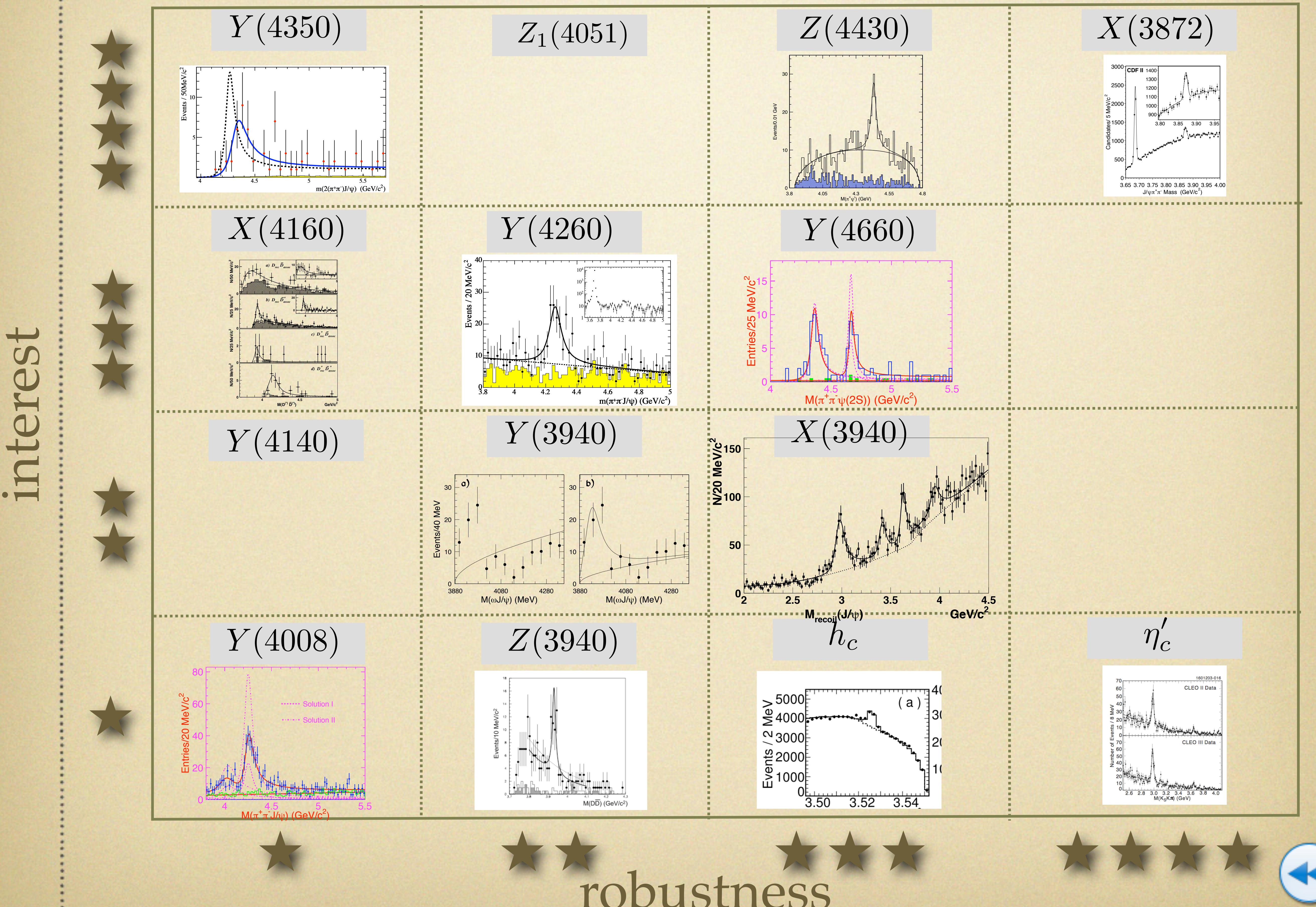
- not seen in $B \to K\pi^+ J/\psi$
- $D^*D_1(2420)$ threshold effect
- $D^*D_1(2420)$ molecule ($J^P = (2,1,0)^-$)
- $[\bar{c}\bar{u}][cd]$ tetraquark radial excitation ($J^P=1^+$)
- search for the Z in $\gamma p \to \psi'\pi^+ n$ Liu, Zhao, Close, arXiv:0802.2648
- NOT seen by BaBar

Mokhtar, 0810.1073

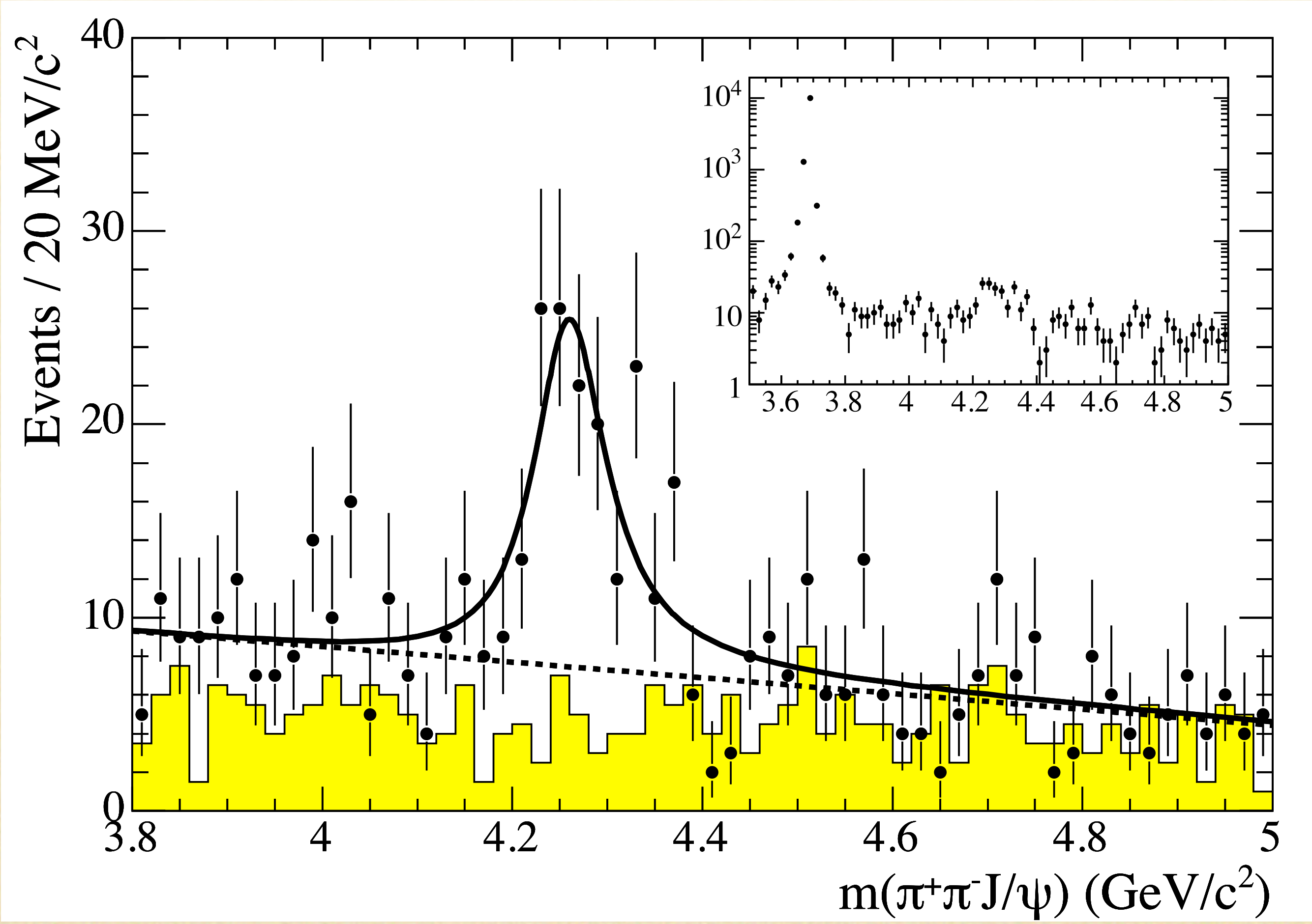


Mokhtar, 0810.1073

expt | ref | params | modes | **signal** | comments



$Y(4260)$



Interpretations

Llanes-Estrada, hep-ph/0507035

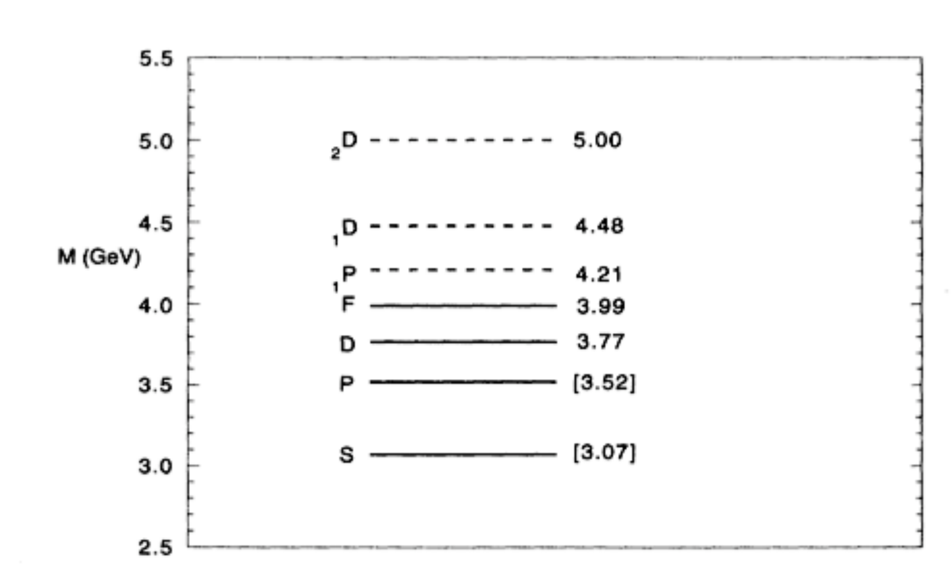
- no available vector (4S=4415, 2D=4159)

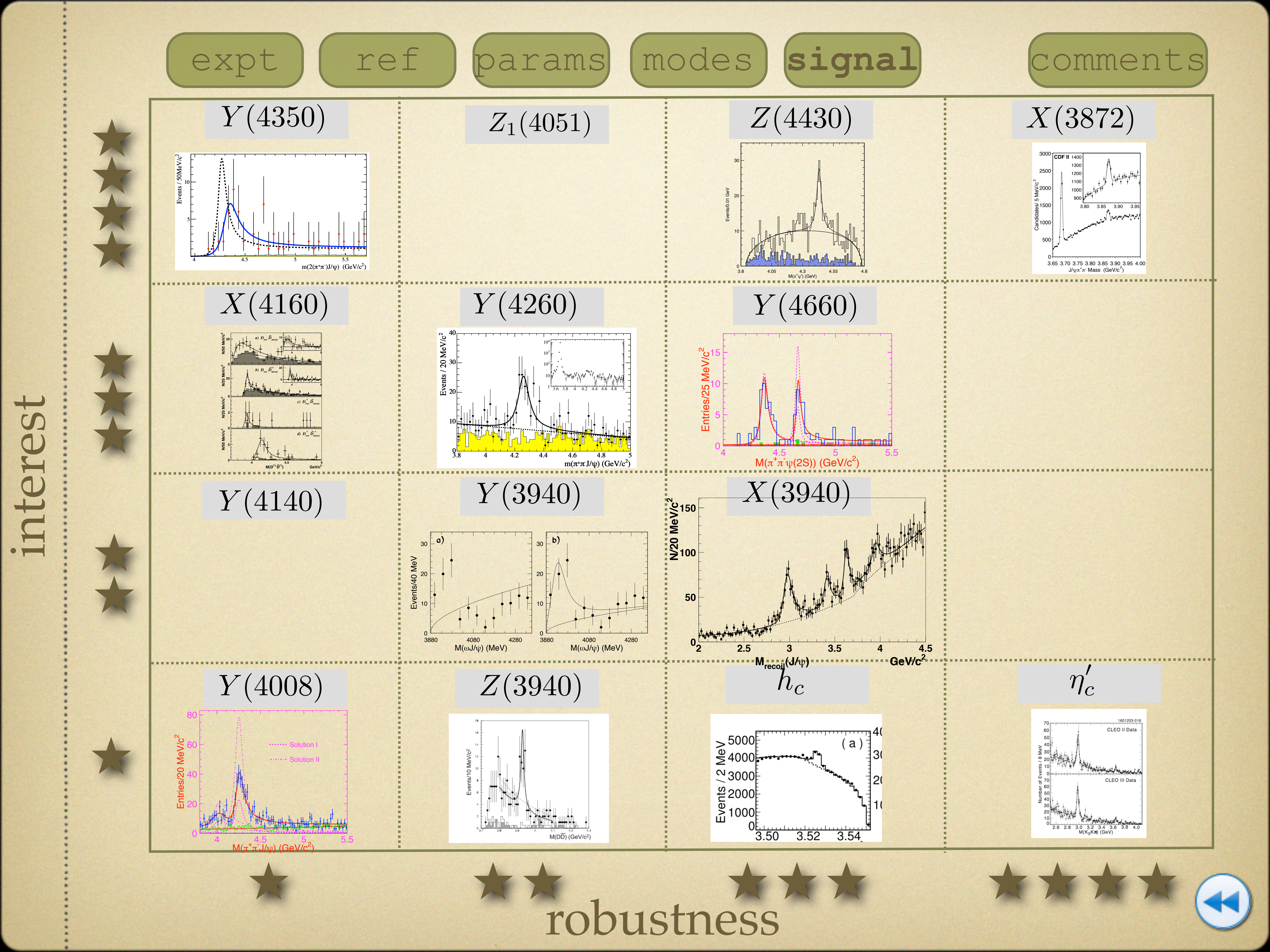
- vector hybrid [at 4200-4400]?

S-L Zhu, hep-ph/0507025

Close & Page, hep-ph/0507199

- the first vector S-wave open charm channel is at 4285 ($D\bar{D}_1'$) or 4309 ($D\bar{D}_1$): a cusp? a molecule?





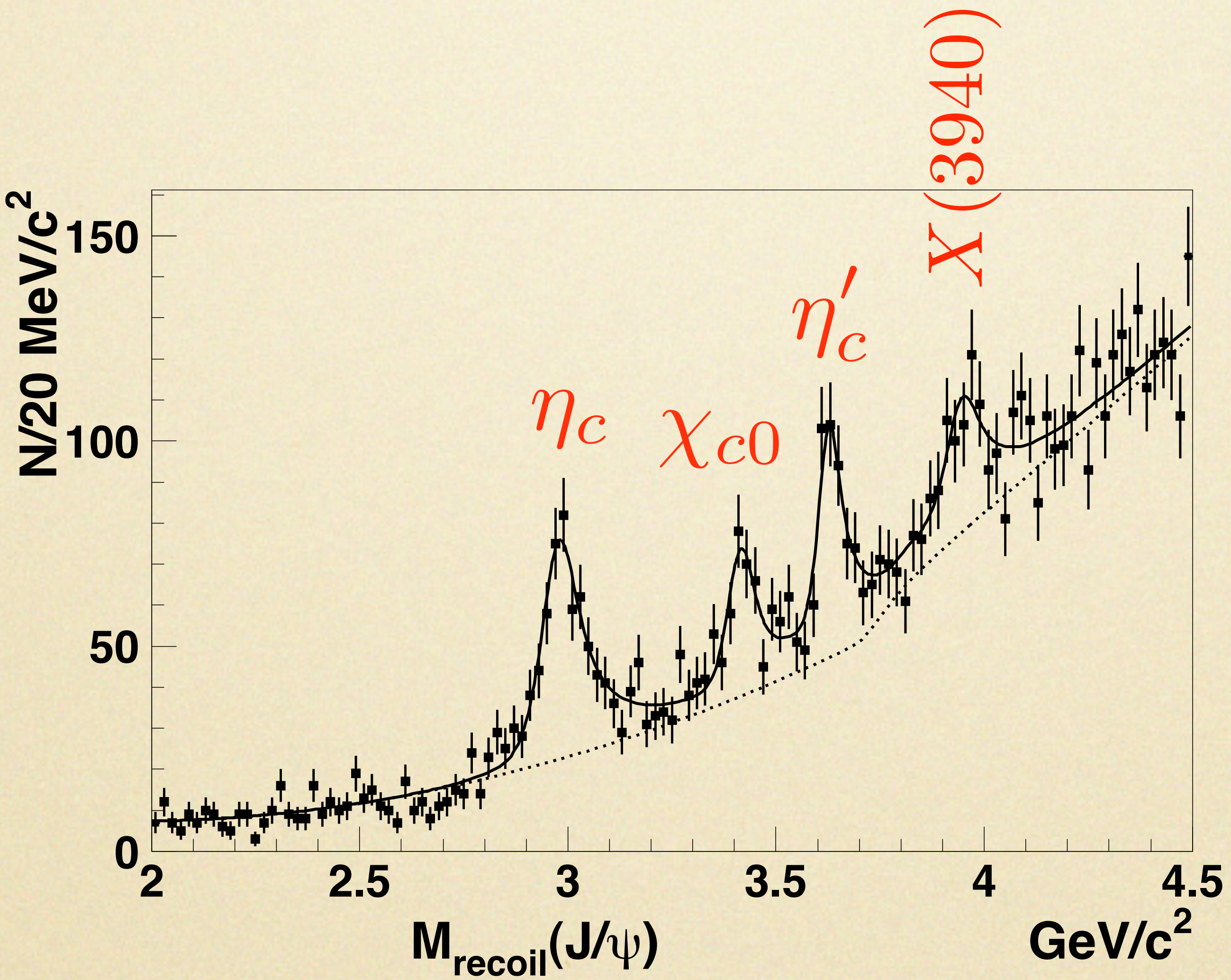
expt
ref
params
modes
signal
comments
Y(4350)
Z1(4051)
Z(4430)
X(3872)
X(4160)
Y(4260)
Y(4660)
Y(4140)
Y(3940)
X(3940)
Y(4008)
Z(3940)
hc
η′c
interest
robustness

$X(3940)$

$$e^+e^- \to J/\psi\,\text{stuff}$$

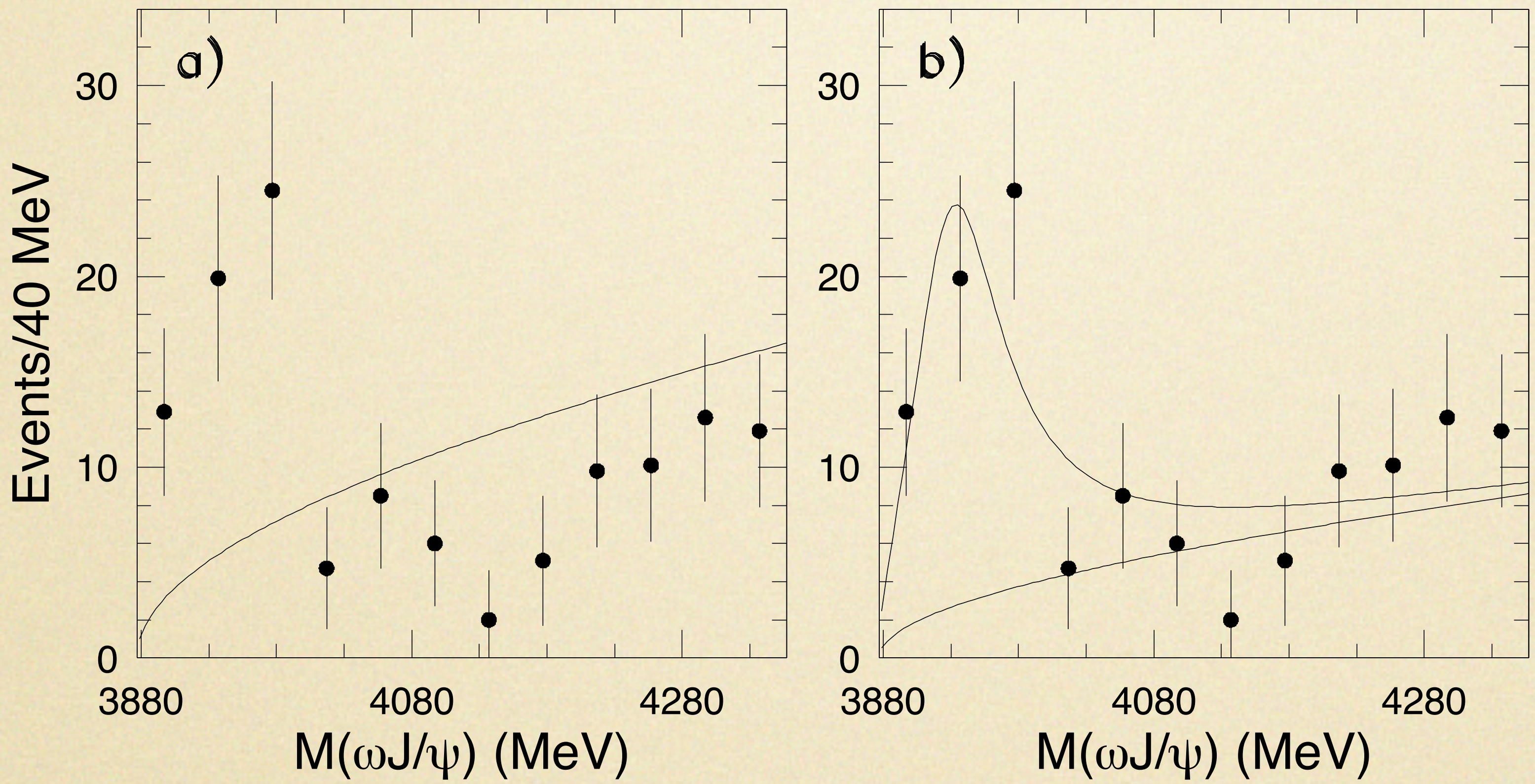
$$X \to DD^*$$

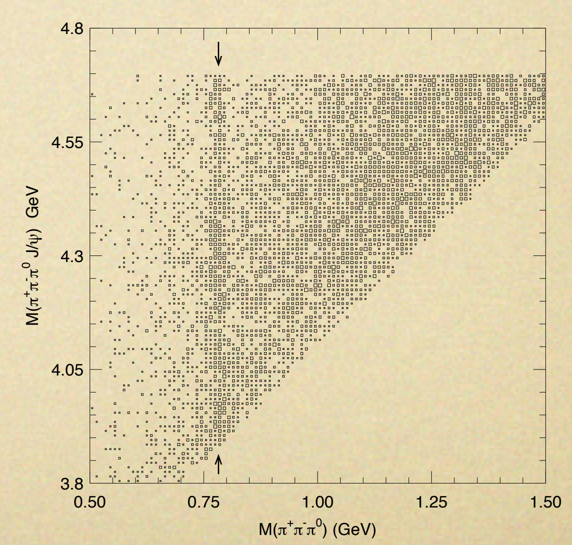
$$X \not\to \omega J/\psi$$



$Y(3940)$

$$B \to KY$$
$$Y \to \omega J/\psi$$





- too light for a ccg hybrid (@ 4200-4400)
- D*D* molecule? (0++ at 4020, but pulled down by coupling to DD and coupling to cc)

Interpretations

- possible 2P $c\bar{c}$ states

$n^{(2S+1)}L_J$	mass	width	
2^3P_2	3979	80	$\rightarrow D^*\bar{D},\ D\bar{D}$
2^3P_1	3953	165	$\rightarrow D^*\bar{D}$ ✔
2^3P_0	3916	30	$\rightarrow D\bar{D}$
2^1P_1	3956	87	$\rightarrow D^*\bar{D}$

T. Barnes, S. Godfrey, ESS, hep-ph/0505002

but Y coupling to $\omega\ \psi$?

X(3940)...

$$e^+e^- \to \psi X(3940) \to \psi D\bar{D}^*$$

$$X \stackrel{?}{=} \chi'_{c1}, \chi'_{c2}$$

But $e^+e^- \to \psi\chi_{c1}$ is not seen.

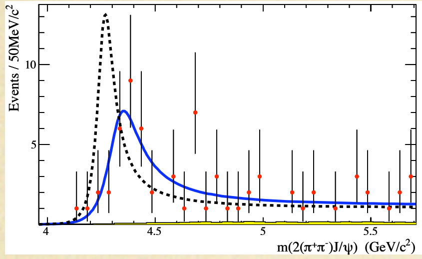
Possibly the η''_c? But M_{CQM} = 4064...

expt | ref | params | modes | **signal** | comments

interest

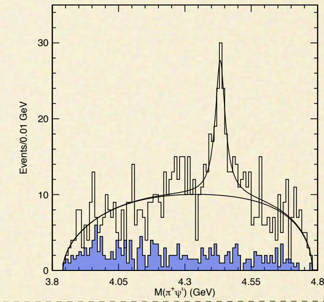
★★★★

$Y(4350)$

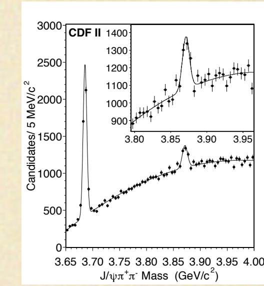


$Z_1(4051)$

$Z(4430)$

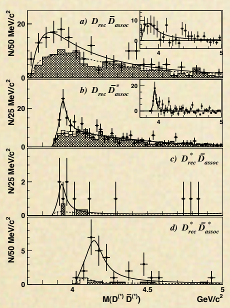


$X(3872)$

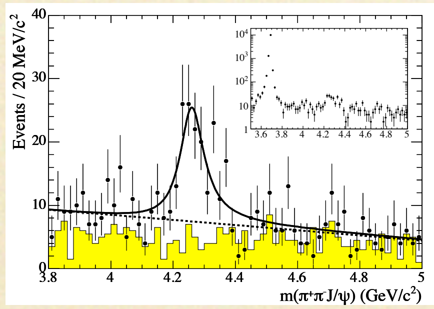


★★★

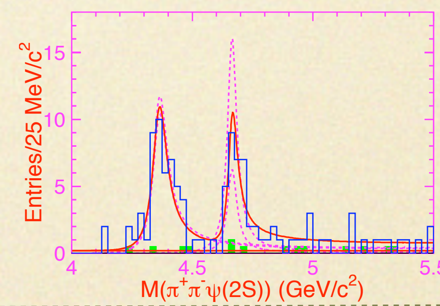
$X(4160)$



$Y(4260)$



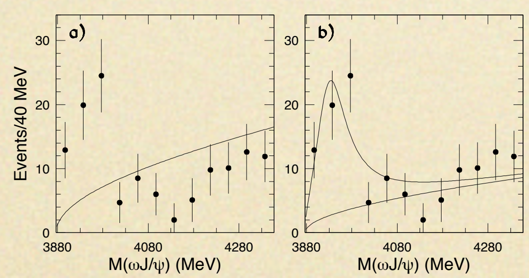
$Y(4660)$



★★

$Y(4140)$

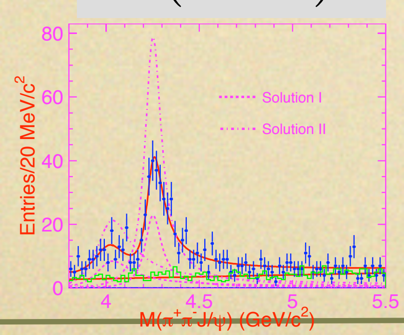
$Y(3940)$



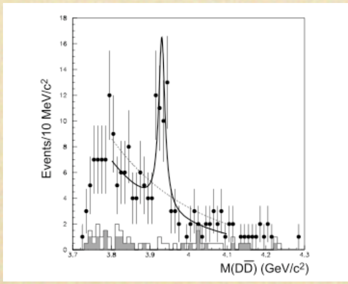
$X(3940)$

★

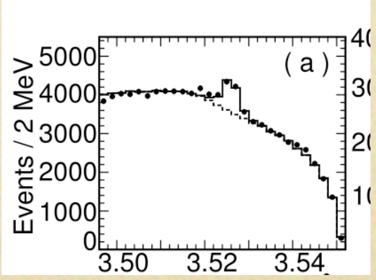
$Y(4008)$



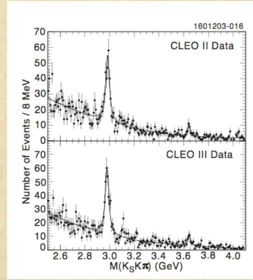
$Z(3940)$



h_c



η_c'

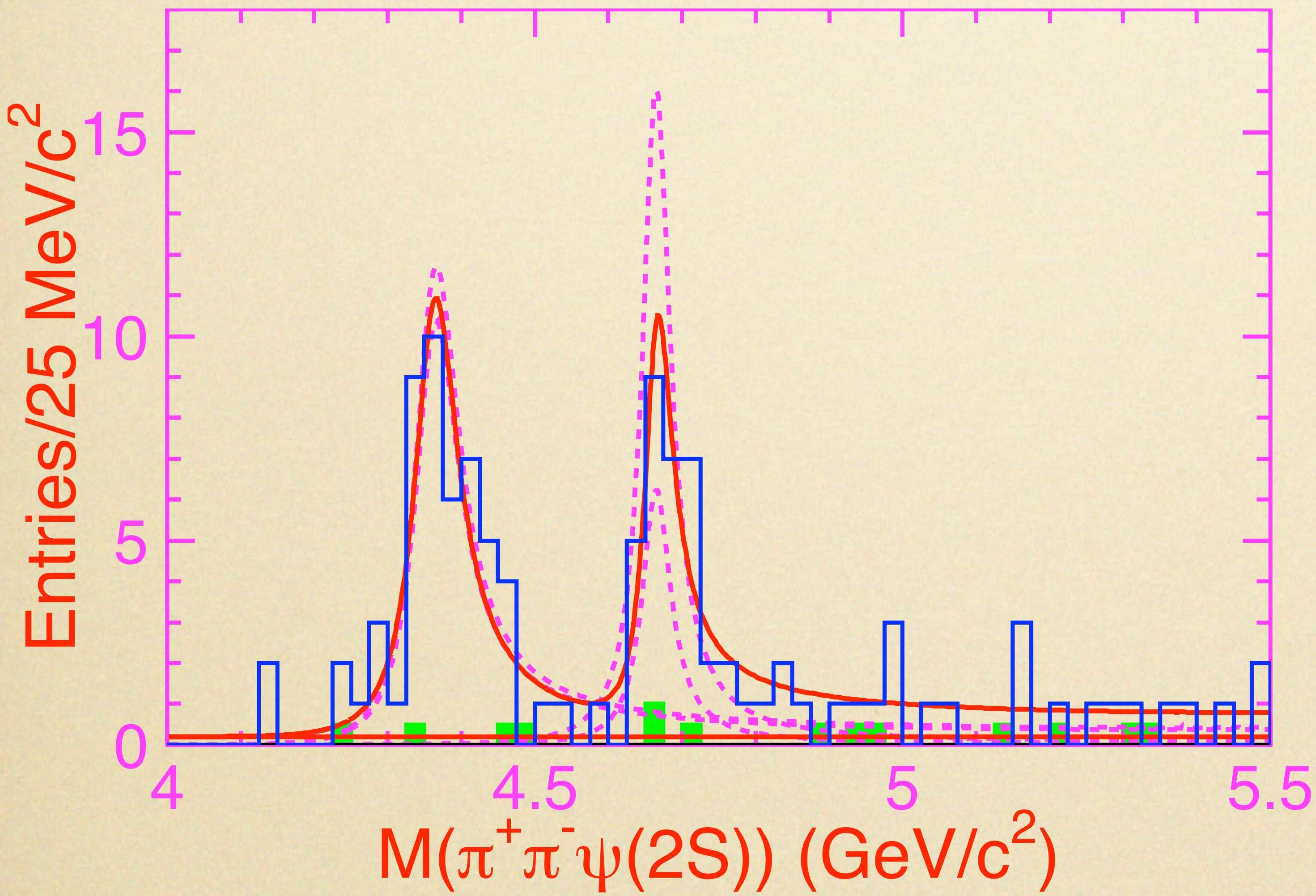


★ | ★★ | ★★★ | ★★★★

robustness

$Y(4660)$

X.-L. Wang et al. [Belle] PRL99, 142002 (2007)



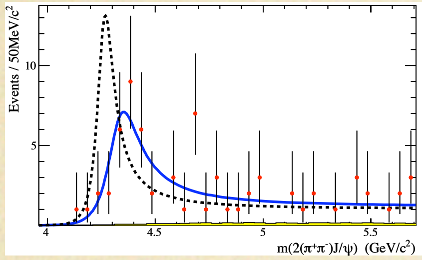
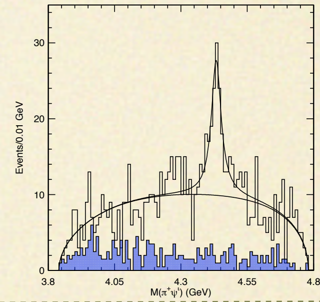
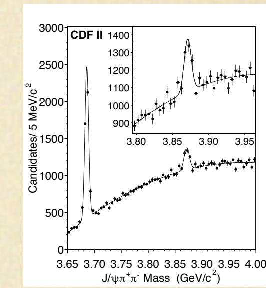
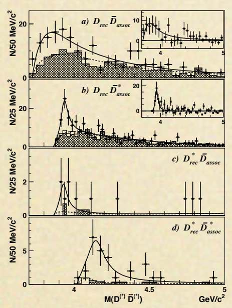
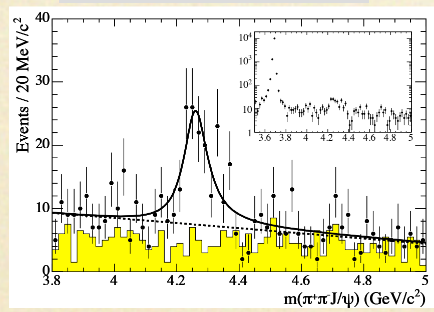
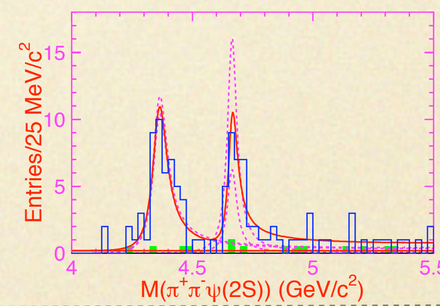
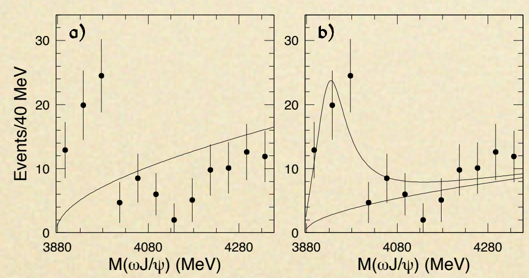
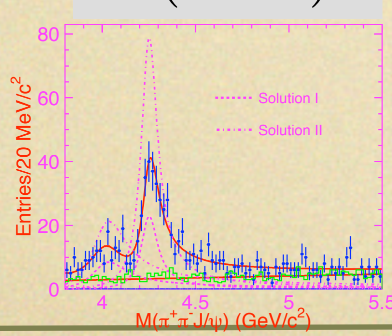
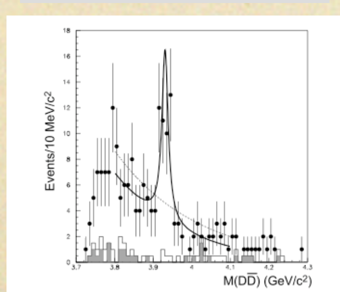
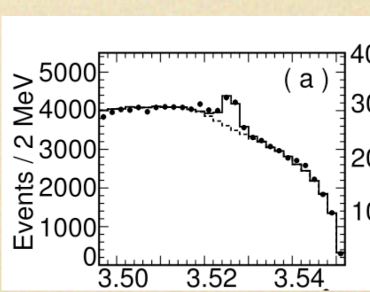
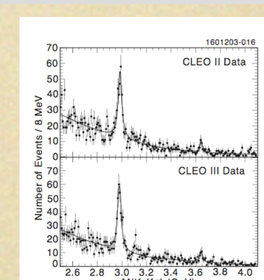
$e^+e^- \to \pi^+\pi^-\psi'$ (ISR)

$M = 4664 \pm 12$

$\Gamma = 48 \pm 15$

not seen in
$e^+e^- \to \pi^+\pi^- J/\psi$

expt | ref | params | modes | **signal** | comments

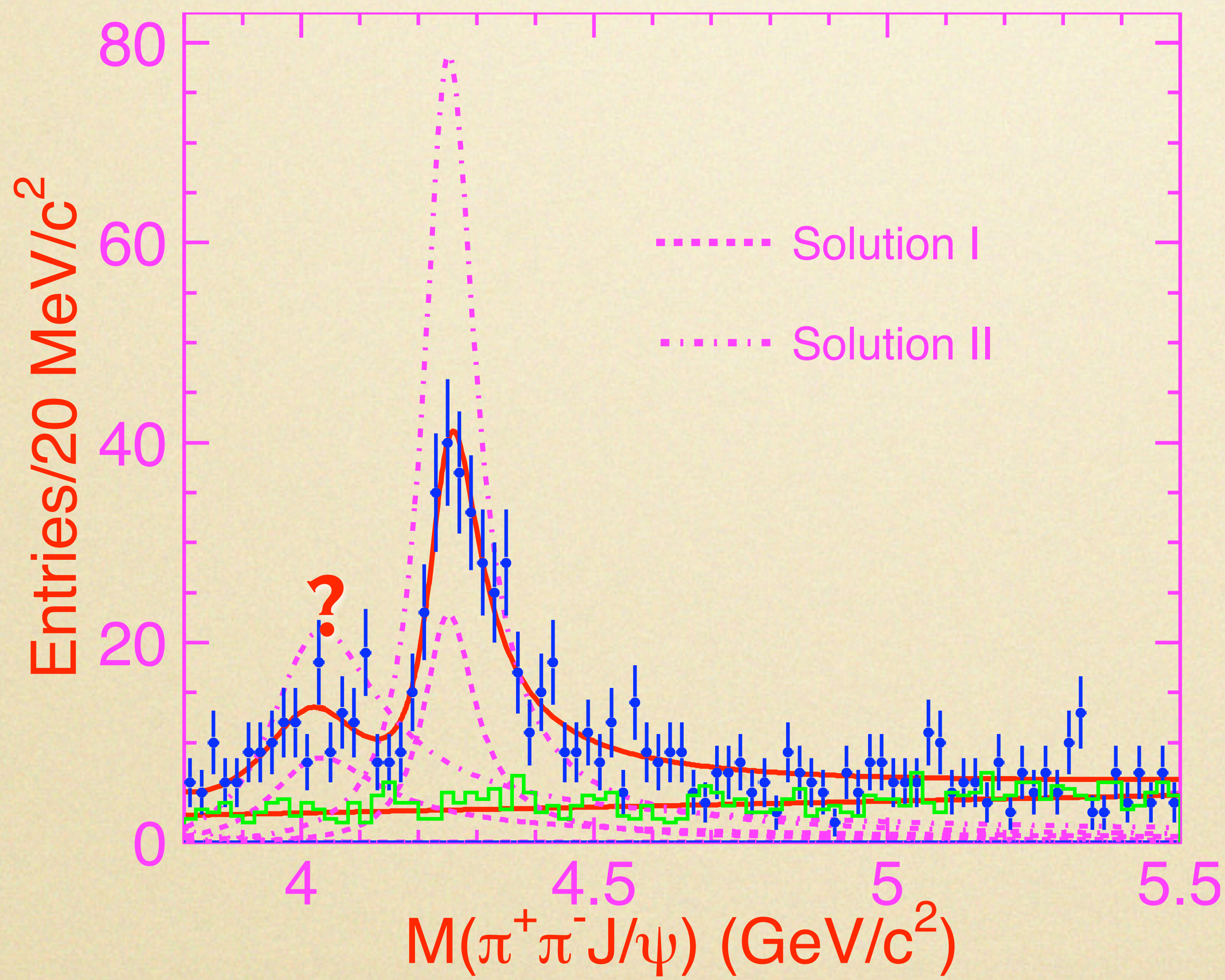
interest \ robustness	★	★★	★★★	★★★★
★★★★	$Y(4350)$ 	$Z_1(4051)$	$Z(4430)$ 	$X(3872)$ 
★★★	$X(4160)$ 	$Y(4260)$ 	$Y(4660)$ 	
★★	$Y(4140)$	$Y(3940)$ 	$X(3940)$ 	
★	$Y(4008)$ 	$Z(3940)$ 	h_c 	η_c' 

interest

robustness

$Y(4008)$

C.-Z. Yuan et al. [Belle] PRL99, 182004 (2007)



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

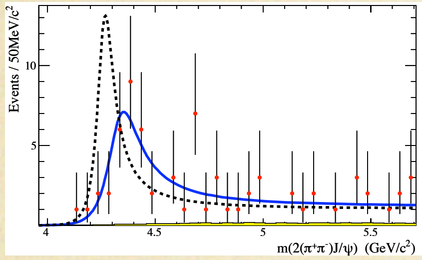
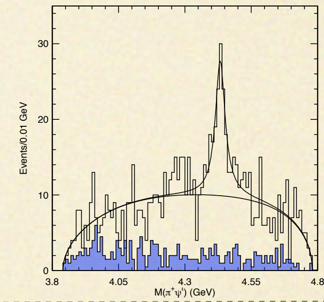
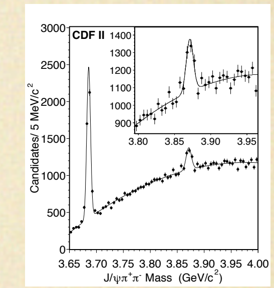
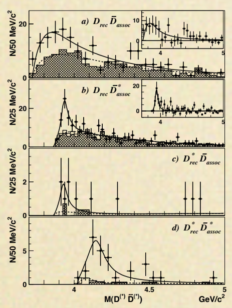
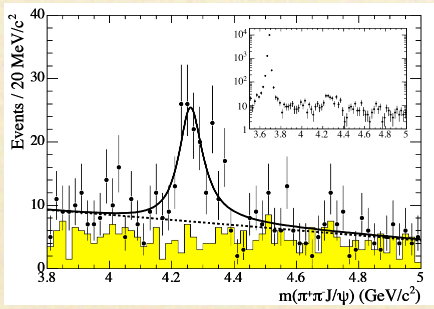
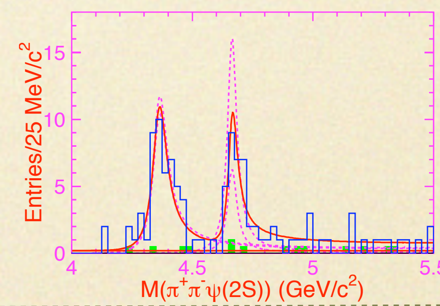
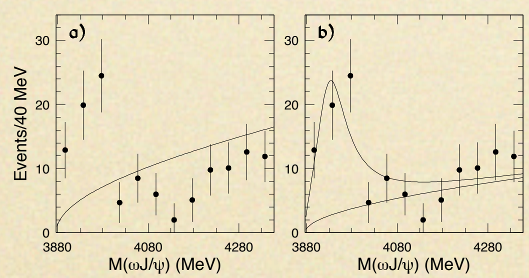
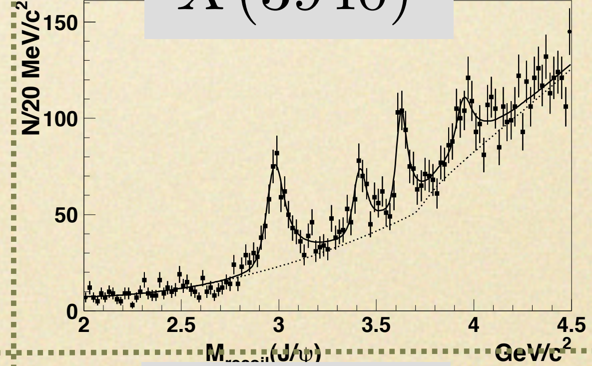
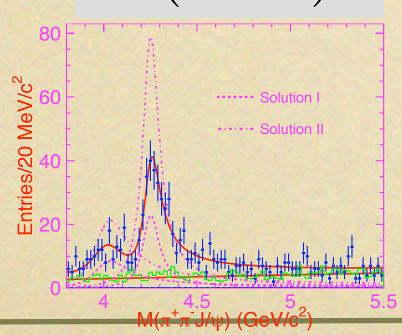
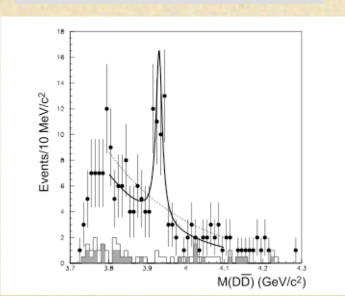
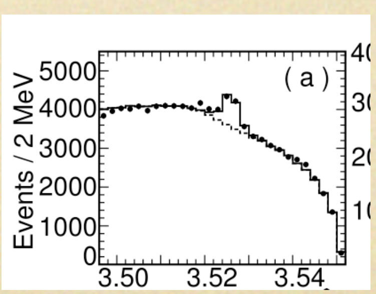
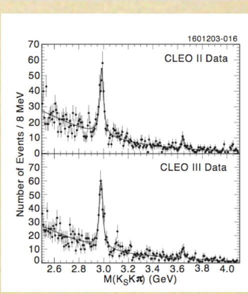
$$M = 4008 \pm 40^{+114}_{-28}$$

$$\Gamma = 226 \pm 44 \pm 87$$

BaBar claim no signal

Mokhtar, 0810.1073

expt | ref | params | modes | **signal** | comments

interest \ robustness	★	★★	★★★	★★★★
★★★★	$Y(4350)$ 	$Z_1(4051)$	$Z(4430)$ 	$X(3872)$ 
★★★	$X(4160)$ 	$Y(4260)$ 	$Y(4660)$ 	
★★	$Y(4140)$	$Y(3940)$ 	$X(3940)$ 	
★	$Y(4008)$ 	$Z(3940)$ 	h_c 	η_c' 

interest

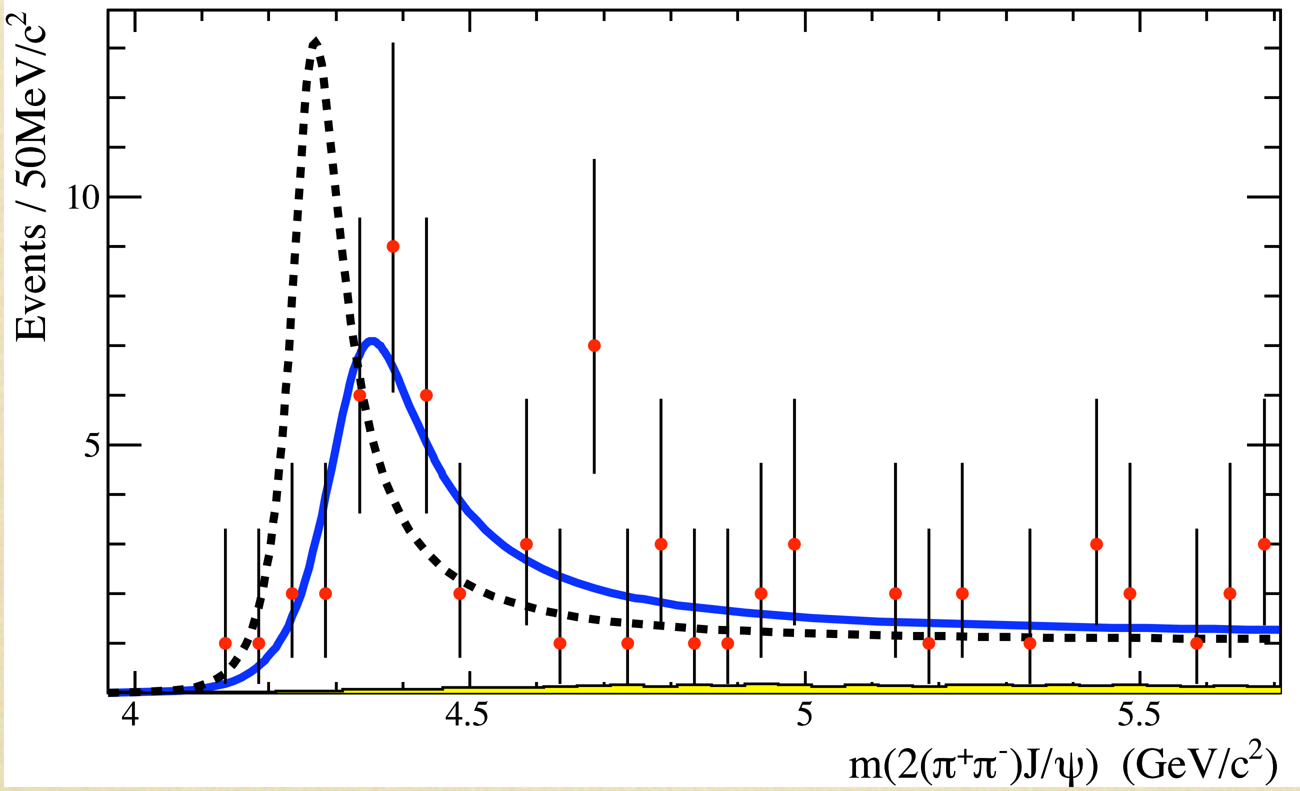
robustness

Y(4350)

BaBar, hep-ex/0610057

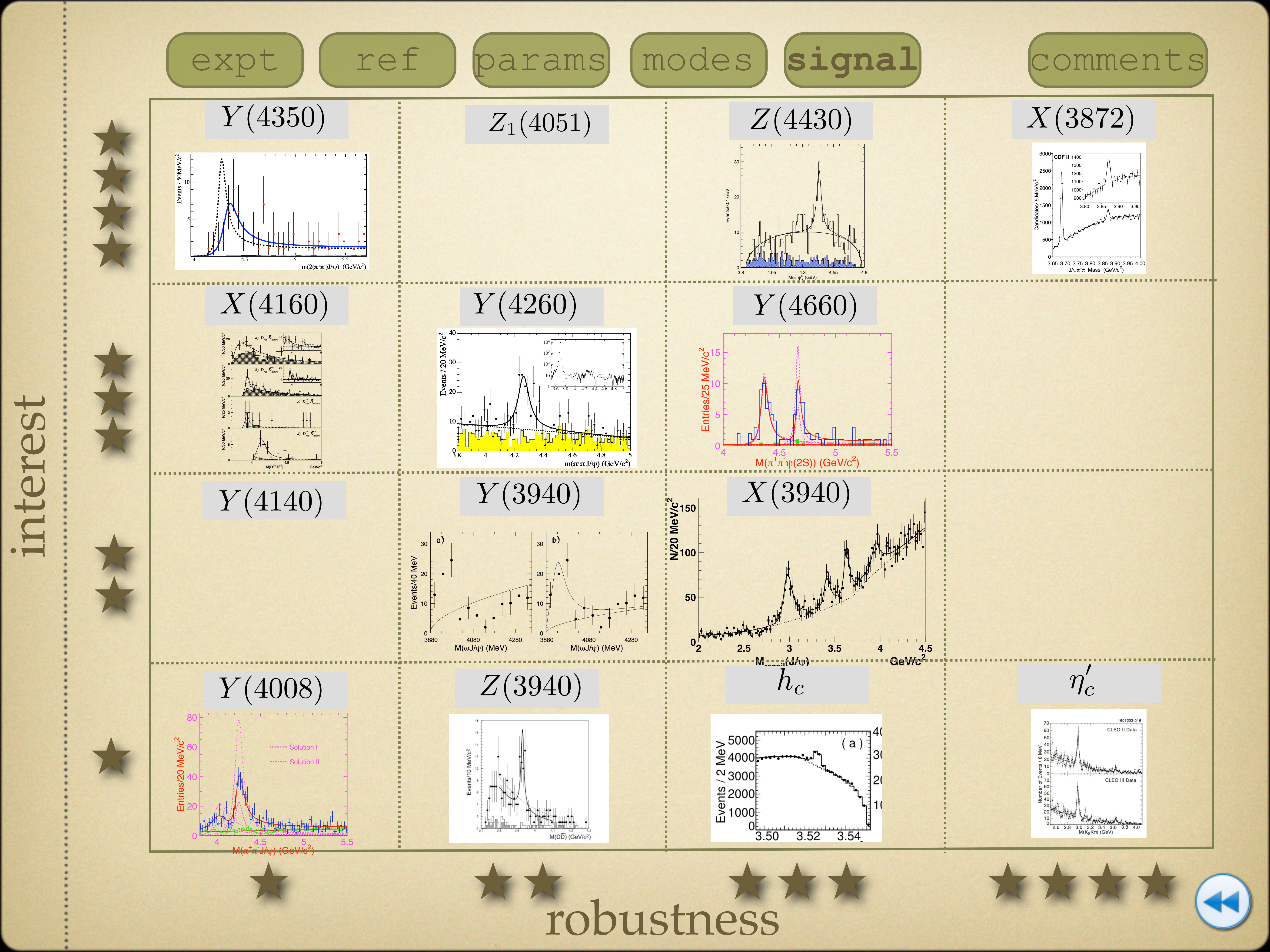
Shuwei Ye, QWG06

$$e^+e^- \to \psi(2S)\pi^+\pi^-$$



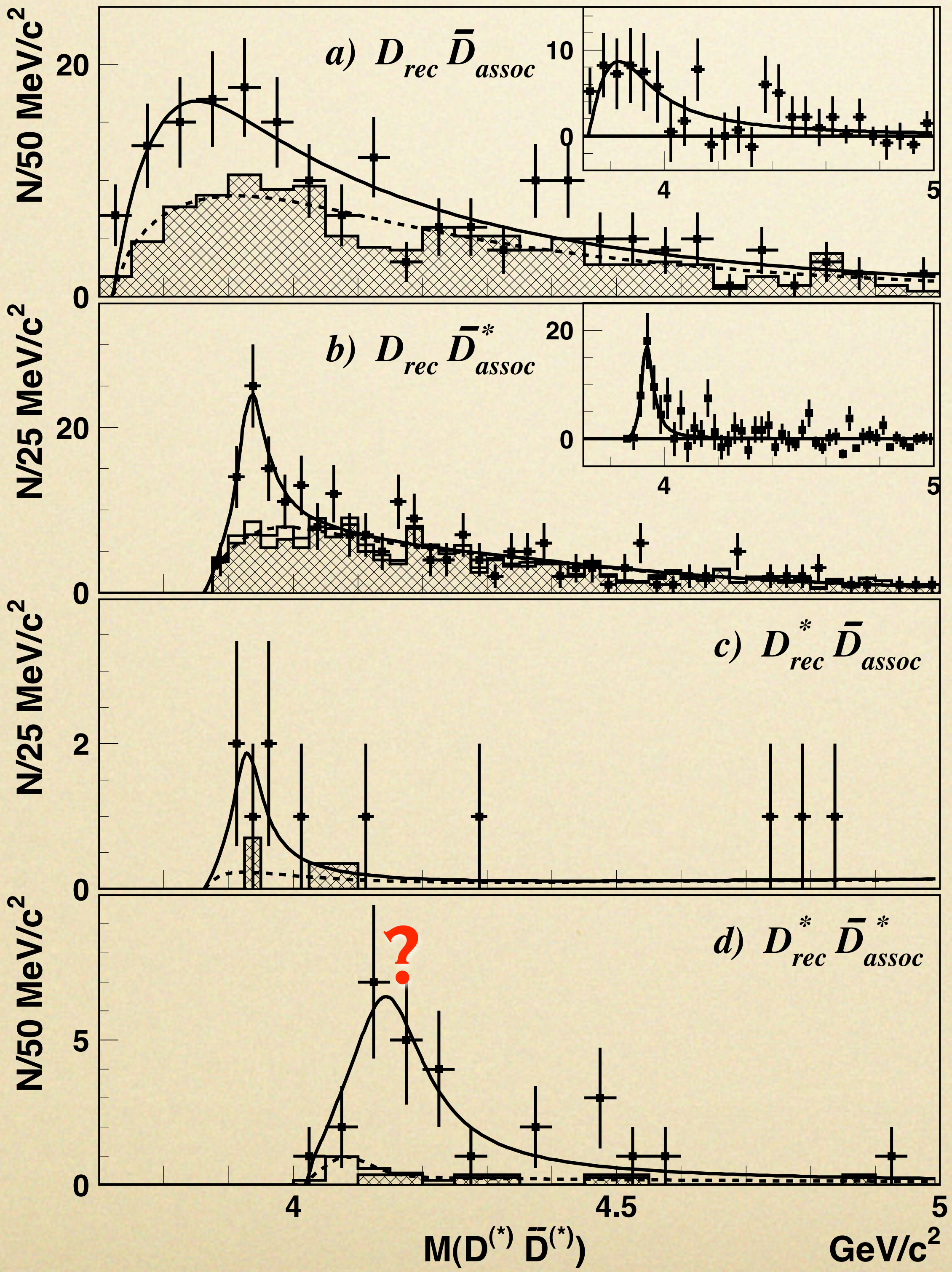
$$M = 4324 \pm 24$$
$$\Gamma = 172 \pm 33$$

[see also Y(4660)]


expt
ref
params
modes
signal
comments
$Y(4350)$
$Z_1(4051)$
$Z(4430)$
$X(3872)$
$X(4160)$
$Y(4260)$
$Y(4660)$
$Y(4140)$
$Y(3940)$
$X(3940)$
$Y(4008)$
$Z(3940)$
h_c
η_c'
CDF II
Solution I
Solution II
CLEO II Data
CLEO III Data
interest
robustness

X(4160)

I. Adachi et al. [Belle] 0708.3812

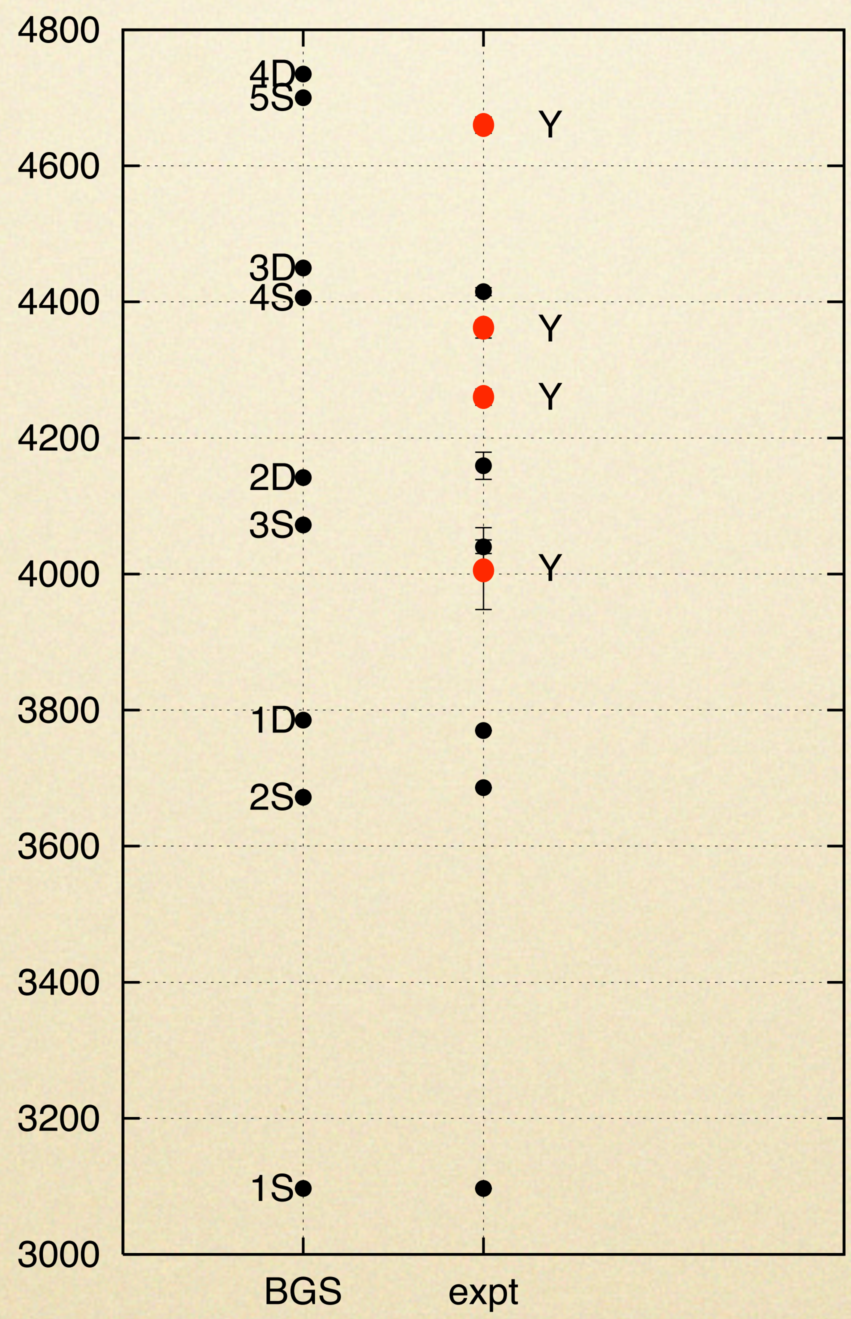


$$e^+e^- \to J/\psi D^* \bar{D}^*$$

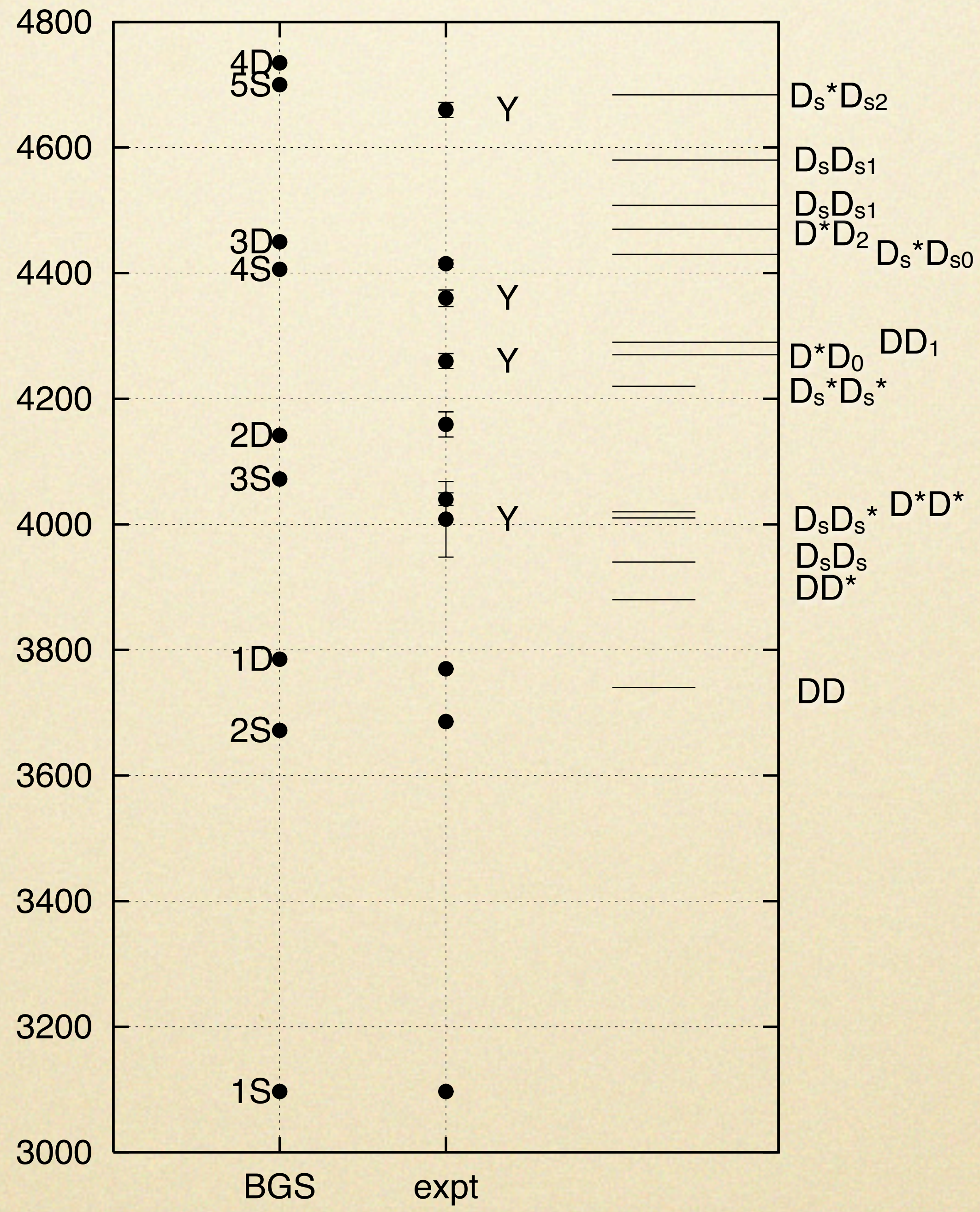
$$M = 4156 \pm 29$$

$$\Gamma = 139^{+113}_{-65}$$

Charmonium Vectors



Charmonium Vectors




Z

$Z^+(4430)$ citations

1) **The two-body open charm decays of $Z^+(4430)$.**
Xiang Liu, Bo Zhang, Shi-Lin Zhu . Mar 2008. 6pp. Temporary entry
e-Print: **arXiv:0803.4270** [hep-ph]

2) **Z+(4430) as a D(1)-prime D* (D(1) D*) molecular state.**
Xiang Liu (Peking U. & Coimbra U.) , Yan-Rui Liu (Beijing, Inst. High Energy Phys.) , Wei-Zhen Deng, Shi-Lin Zhu (Peking U.) . Mar 2008. 13pp.
e-Print: **arXiv:0803.1295** [hep-ph]

3) **D(s)D* molecule as an axial meson.**
Su Houng Lee (Yonsei U.) , Marina Nielsen (Sao Paulo U.) , Ulrich Wiedner (Ruhr U., Bochum) . Mar 2008. 5pp.
e-Print: **arXiv:0803.1168** [hep-ph]

4) **Dynamics study of Z+(4430) and X(3872) in molecular picture.**
Xiang Liu (Peking U. & Coimbra U.) , Yan-Rui Liu (Beijing, Inst. High Energy Phys.) , Wei-Zhen Deng (Peking U.) . Feb 2008. 6pp.
Contributed to Workshop on Scalar Mesons and Related Topics Honoring 70th Birthday of Michael Scadron (SCADRON 70), Lisbon, Portugal, 11-16 Feb 2008.
e-Print: **arXiv:0802.3157** [hep-ph]

5) **Search for tetraquark candidate Z(4430) in meson photoproduction.**
Xiao-Hai Liu (Beijing, Inst. High Energy Phys.) , Qiang Zhao (Beijing, Inst. High Energy Phys. & Surrey U.) , Frank E. Close (Oxford U., Theor. Phys.) . Feb 2008. 16pp.
e-Print: **arXiv:0802.2648** [hep-ph]

6) **How Resonances can synchronise with Thresholds.**
D.V. Bugg (Queen Mary, U. of London) . Feb 2008. 19pp.
Replaces 0709.1254.
e-Print: **arXiv:0802.0934** [hep-ph]

7) **Possibility of Exotic States in the Upsilon system.**
Marek Karliner (Tel Aviv U.) , Harry J. Lipkin (Tel Aviv U. & Weizmann Inst. & Argonne) . TAUP-2869-07, WIS-03-08-FEB-DPP, ANL-HEP-PR-08-7, Feb 2008. 5pp.
e-Print: **arXiv:0802.0649** [hep-ph]

8) **The Exotic XYZ Charmonium-like Mesons.**
Stephen Godfrey (Ottawa Carleton Inst. Phys. & Carleton U.) , Stephen L. Olsen (Beijing, Inst. High Energy Phys. & Hawaii U.) . Jan 2008. 28pp.
Submitted to Ann.Rev.Nucl.Part.Phys.

Diquarks and the New Charmonia

Maiani, Piccinini,Polosa, Riquer; PRD71, 014028 (2005)

Bigi, Maiani, Piccinini,Polosa, Riquer; PRD72, 114016 (2005)

Maiani, Riquer, Piccinini, Polosa; PRD72, 031502 (2005)

Maiani, Polosa, Riquer; PRL99, 182003 (2007)

Maiani, Polosa, Riquer; arXiv:0708.3997

$$M([cq]_S) = 1933$$
$$M([cq]_V) = 1933$$

Assume a spin-spin interaction

$$|0^{++}\rangle = |[cq]_S[\bar{c}\bar{q}]_S; J=0\rangle \quad (1)$$

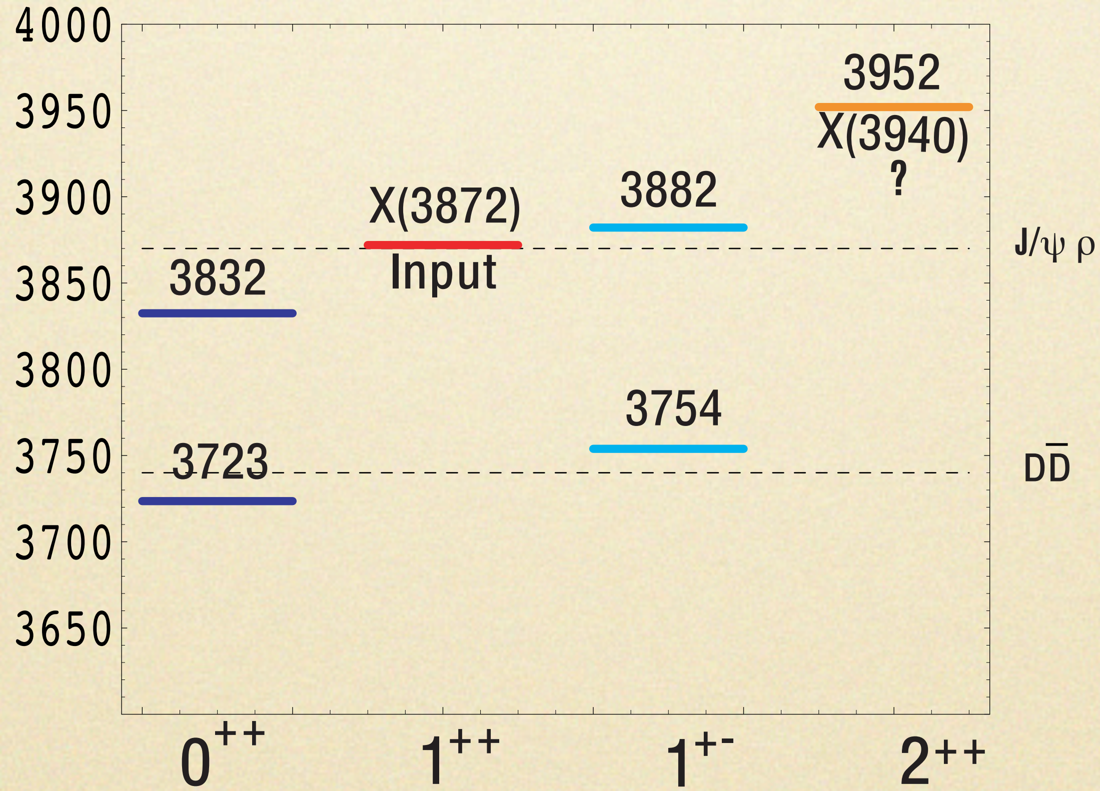
$$|0^{++\prime}\rangle = |[cq]_V[\bar{c}\bar{q}]_V; J=0\rangle \quad (2)$$

$$|1^{++}\rangle = \frac{1}{\sqrt{2}}\left(|[cq]_S[\bar{c}\bar{q}]_V; J=1\rangle + |[cq]_V[\bar{c}\bar{q}]_S; J=1\rangle\right) \quad (3)$$

$$|1^{+-}\rangle = \frac{1}{\sqrt{2}}\left(|[cq]_S[\bar{c}\bar{q}]_V; J=1\rangle - |[cq]_V[\bar{c}\bar{q}]_S; J=1\rangle\right) \quad (4)$$

$$|1^{+-\prime}\rangle = |[cq]_V[\bar{c}\bar{q}]_V; J=1\rangle \quad (5)$$

$$|2^{++}\rangle = |[cq]_V[\bar{c}\bar{q}]_V; J=2\rangle \quad (6)$$


4000
3950
3900
3850
3800
3750
3700
3650
3952
X(3940)
?
X(3872)
3882
J/ψ ρ
3832
Input
3754
3723
DD̄
0++
1++
1+-
2++

beyond the SM

- CP violation in J/ψ decays

$$\mathcal{L}_{CP} = -i\frac{d_c}{2}\bar{c}\gamma_5\sigma_{\mu\nu}G^{\mu\nu}c$$

- lepton flavour violation in J/ψ decays

$$Bf(J/\psi \to \mu\tau) < 2.0 \cdot 10^{-6}$$
$$Bf(J/\psi \to e\tau) < 8.3 \cdot 10^{-6}$$
$$Bf(J/\psi \to e\mu) < 1.1 \cdot 10^{-6}$$

- effects of a light pseudoscalar Higgs in Υ decays
- nonstandard Higgs-mediated leptonic decays of Υ

Future Opportunities

- SuperB at KEK (has received some funding, not approved yet, Japanese govt is seeking outside funding for detectors)
- PANDA at FAIR at GSI (multibillion dollar upgrade to GSI)
- LHCb: B physics at the LHC
- ATLAS and CMS: have hadronic research programmes
- JLAB 12 GeV upgrade (next month!, cost=$300M)
- BESIII upgrade
- Belle (ongoing)

Conclusions

- [the D_s spectrum and] the X's (Y's, Z's,...) "challenge our understanding of QCD"
- new states are charmonia, artefacts, threshold enhancements, hybrids, multiquarks,?...
- the constituent quark model must fail somewhere. Are we seeing it?
- Can an effective EFT approach be constructed?

✢ ÆRIC MEC HEHT GEWYRCAN

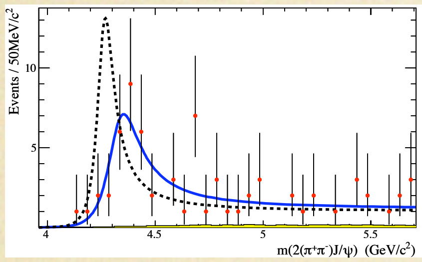
expt | ref | params | modes | **signal** | comments

interest

robustness

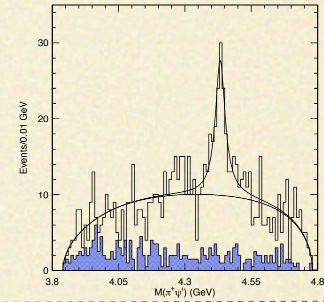
★★★★

$Y(4350)$

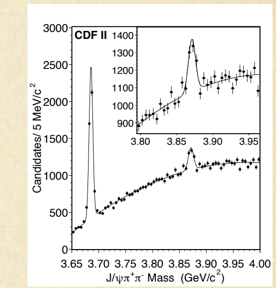


$Z_1(4051)$

$Z(4430)$

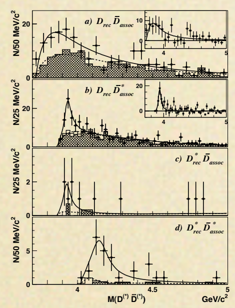


$X(3872)$

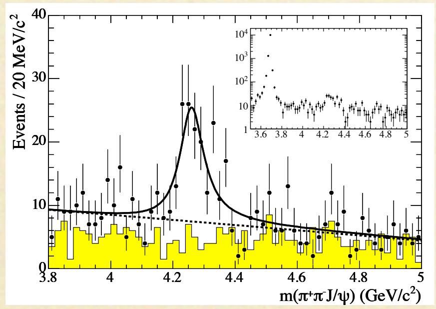


★★★

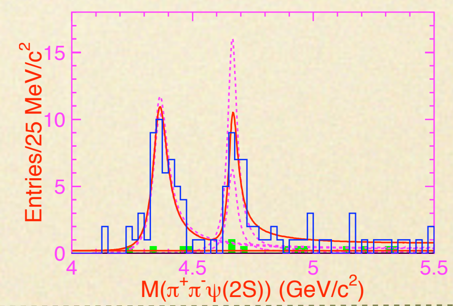
$X(4160)$



$Y(4260)$



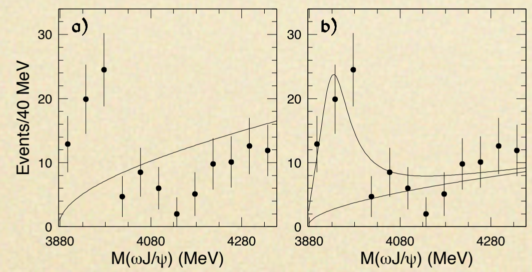
$Y(4660)$



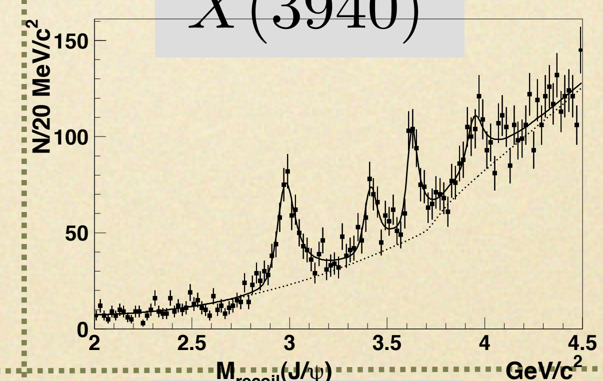
★★

$Y(4140)$

$Y(3940)$

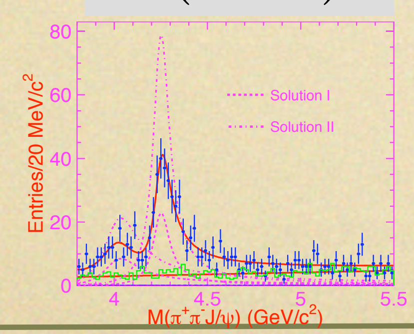


$X(3940)$

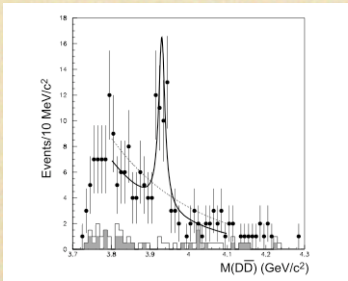


★

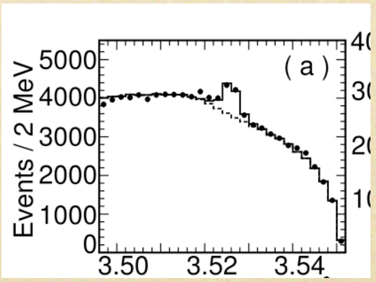
$Y(4008)$



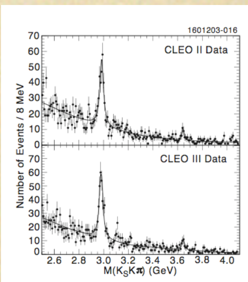
$Z(3940)$



h_c

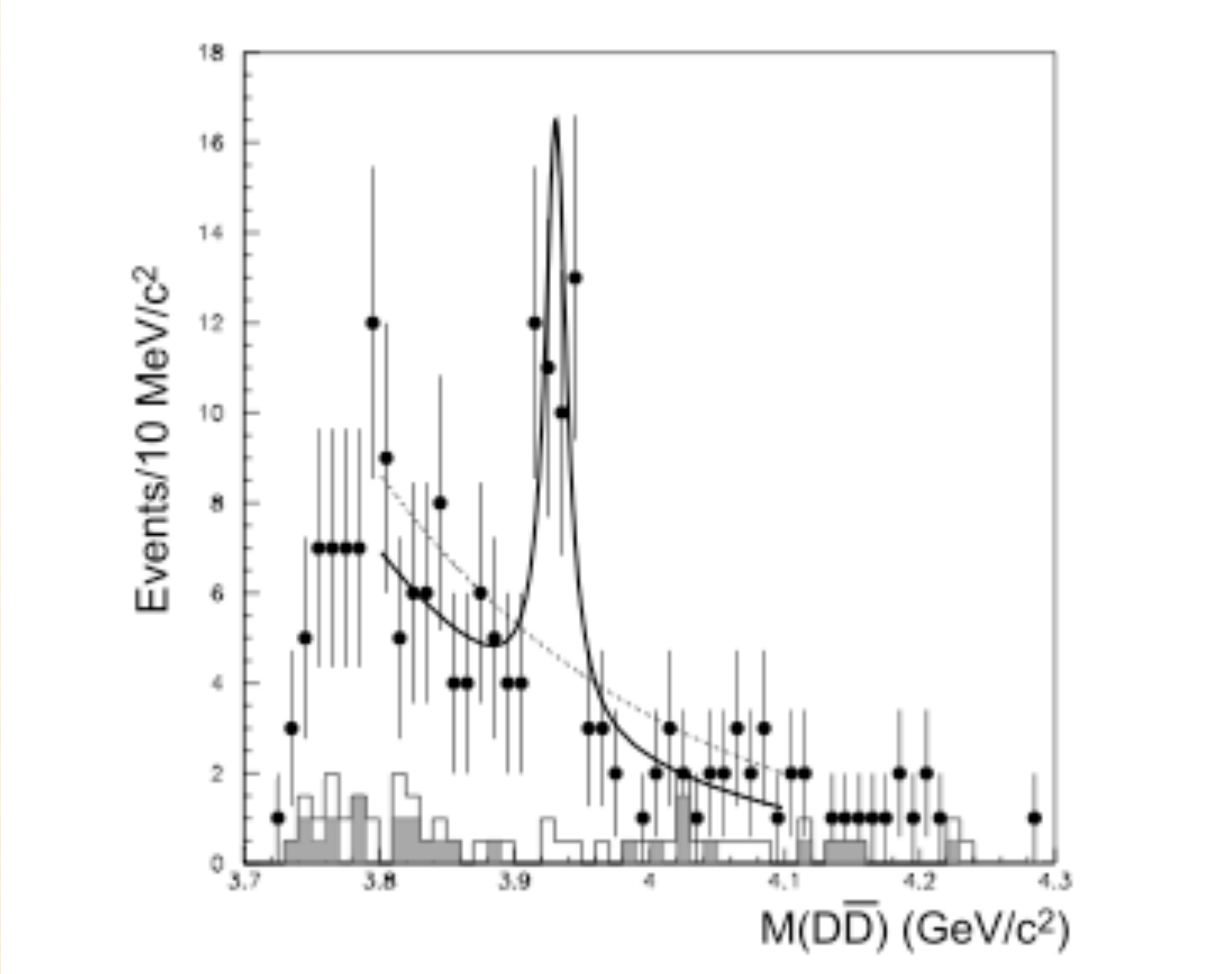


η_c'



★ ★★ ★★★ ★★★★

$Z(3940)$



K. Abe [Belle], hep-ex/0507033
T. Lesiak, H05

χ'_{c2}

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

M=3931(4) $\Gamma = 20(8)$

compare to M= ~~3972/3979~~ 3931

~~$\Gamma = 80$~~ 47

~~$Bf(D\bar{D}) = 50\%$~~ 70%

$\Gamma(\chi'_{c2} \to \gamma\psi') = 250(5)\ \text{keV}$

T. Barnes, S. Godfrey, ESS, hep-ph/0505002

η_c'

3638(4) $\Gamma = 19(10)$ CLEO, PRL92, 142001 (04)

CBALL, PRL48, 70 (82)

[3594(12)]

$J/\psi - \eta_c = 117$

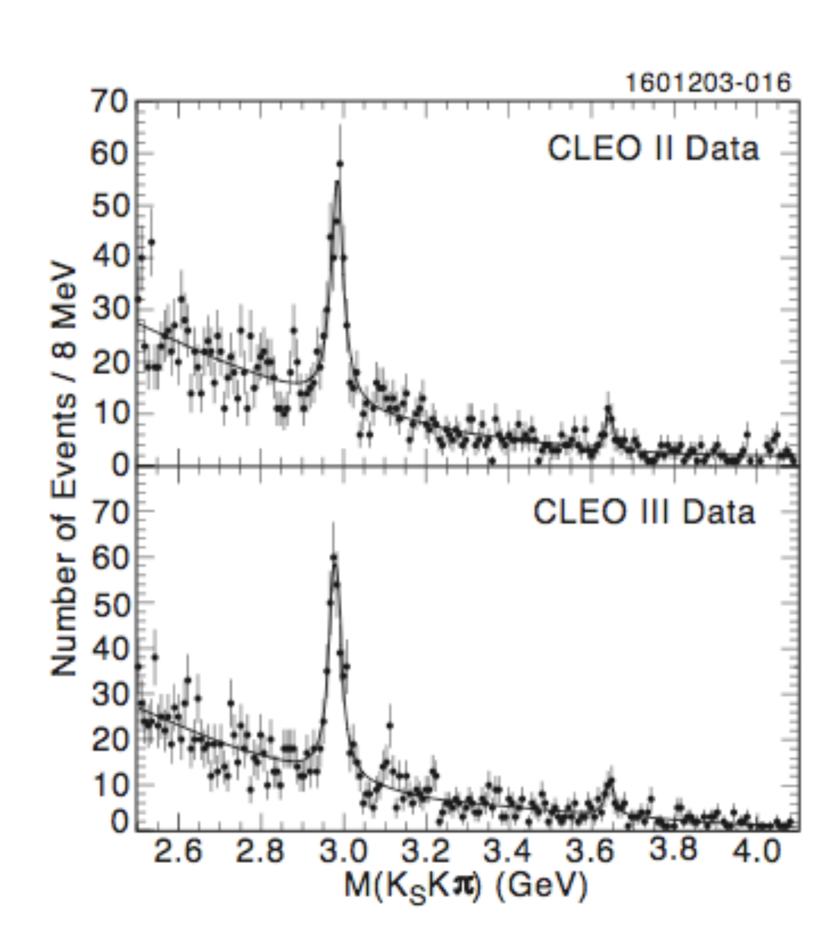
[108/123]

T. Barnes, S. Godfrey, ESS, hep-ph/0505002

$\psi' - \eta_c' = 48$

[67; 46 with loops]

Eichten, Lane, Quigg, PRD69, 094019 (04)



[42/53]

T. Barnes, S. Godfrey, ESS, hep-ph/0505002

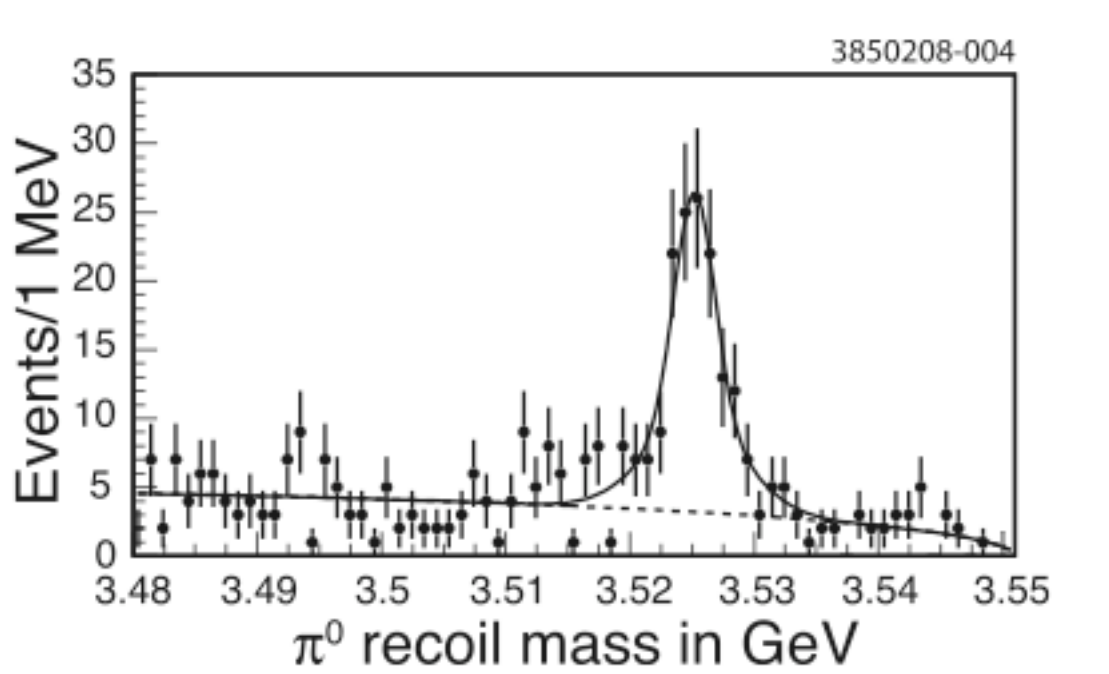
h_c 3524(1) CLEO, hep-ex/0505073

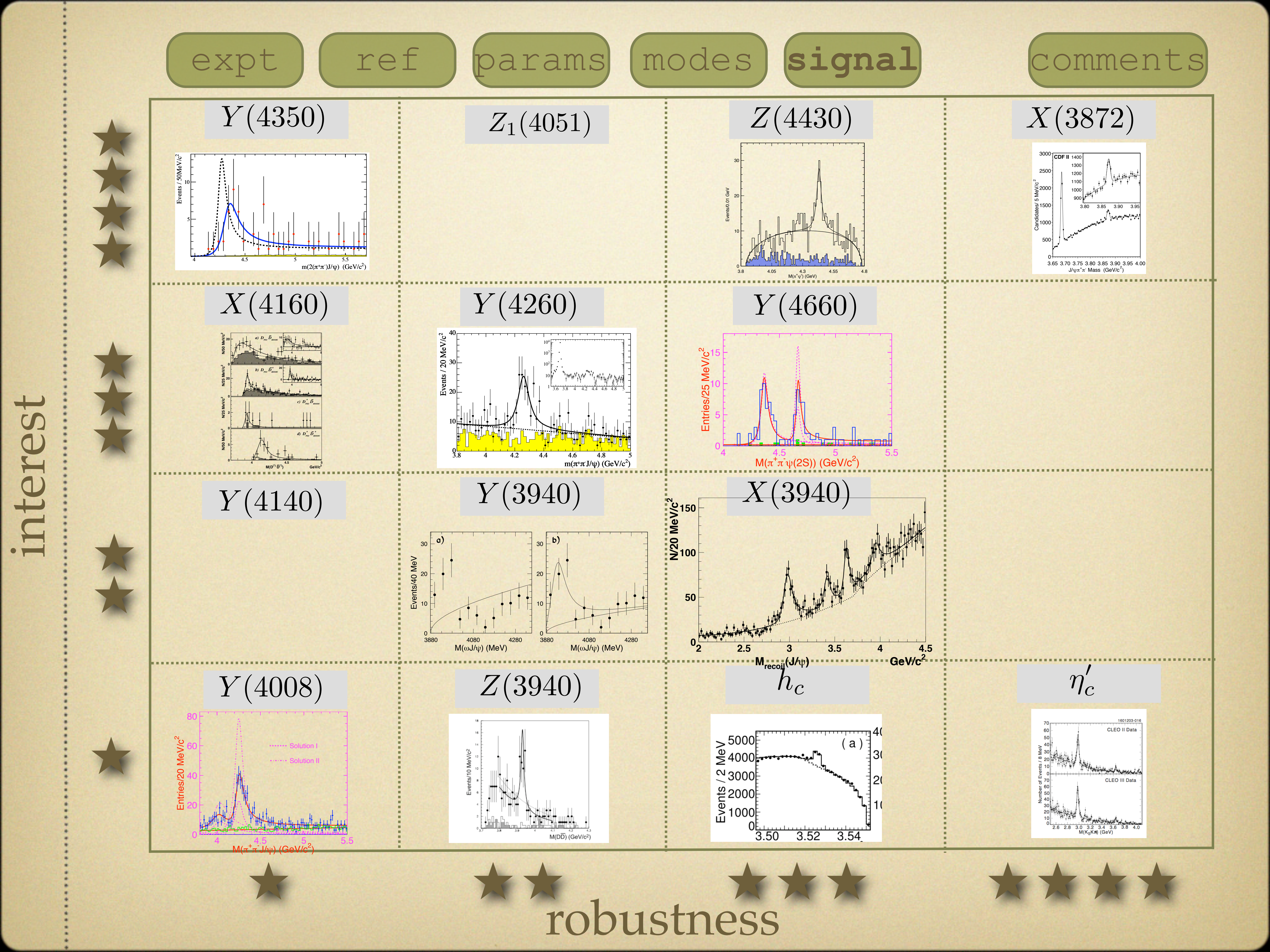
3525.28(36) CLEO, PRL101, 182003

3518 T. Barnes, S. Godfrey, ESS, hep-ph/0505002

$$\chi_{cog} = \frac{1}{9}(\chi_{c0} + 3\chi_{c1} + 5\chi_{c2}) = 3525.36$$

This tests the Dirac structure of the confining potential



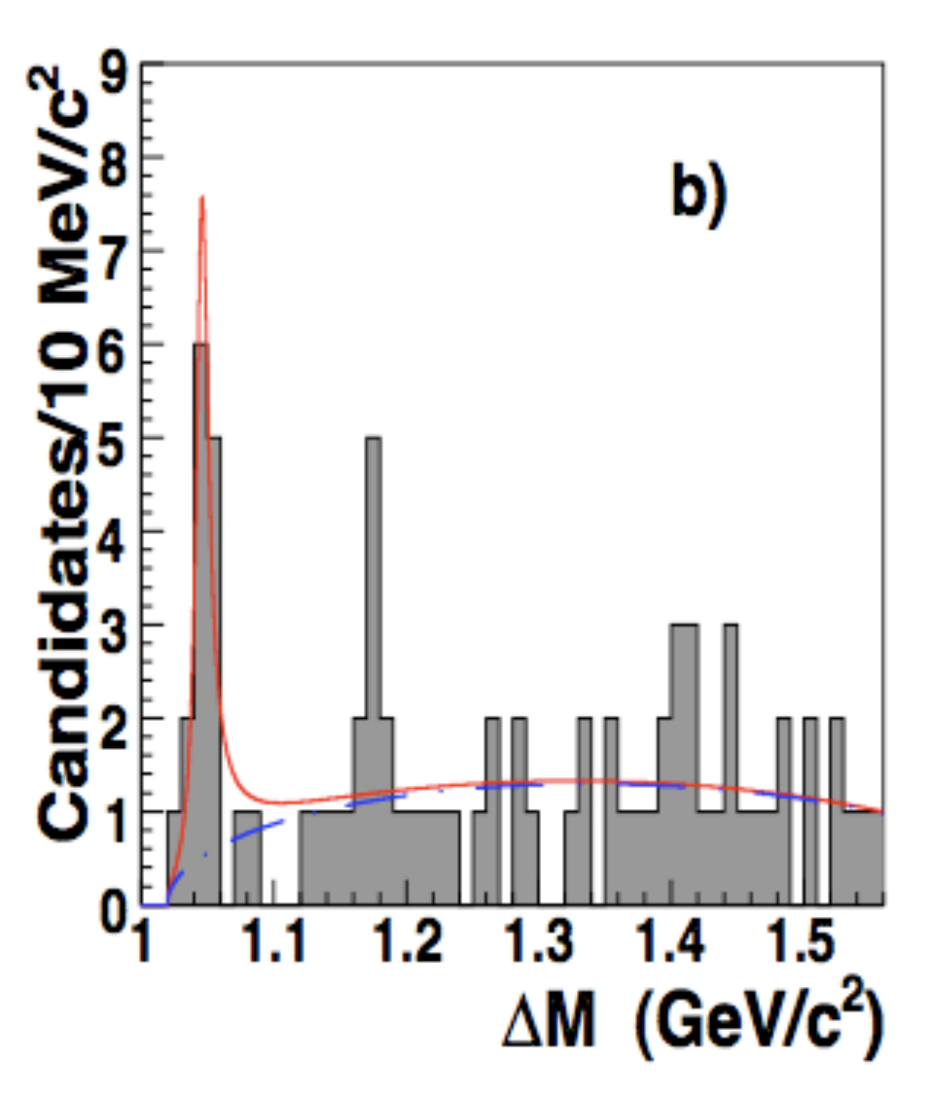


expt
ref
params
modes
signal
comments
interest
robustness
Y(4350)
Z1(4051)
Z(4430)
X(3872)
X(4160)
Y(4260)
Y(4660)
Y(4140)
Y(3940)
X(3940)
Y(4008)
Z(3940)
hc
η′c
CDF II
Solution I
Solution II
CLEO II Data
CLEO III Data

$Y(4140)$

Aaltonen et al. [CDF] arXiv:0903.2229

$$p\bar{p} \to B \to YK \to J/\psi\phi K$$



$$M = 4143.0 \pm 2.9 \pm 1.2$$
$$\Gamma = 11.7^{+8.3}_{-5.0} \pm 3.7$$
$$\sigma = 3.8$$

$D_s D_s^* = 4080$

$D_s^* D_s^* = 4220$

suspect FSI, but anomalously narrow(?!)

$Z_1(4051)$ $Z_1(4248)$

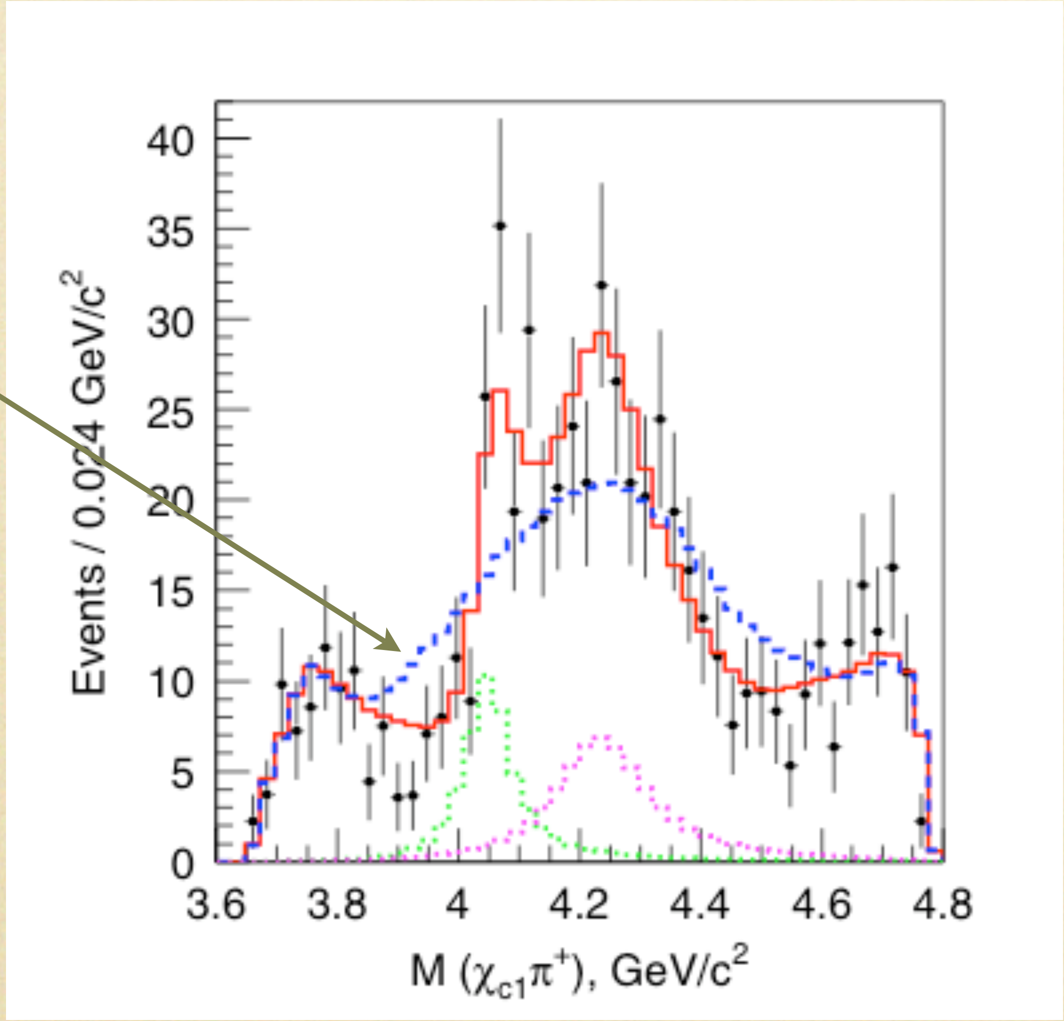
R. Mizuk et al. [Belle] PRD78, 072004 (08)

$$\bar{B}^0 \to K^- Z_1 \quad Z_1 \to \chi_{c1}\pi^+$$

$$M = 4051 \pm 14^{+20}_{-41}$$

$$\Gamma = 82^{+21+47}_{-17-22}$$

K*s only



$$M = 4248^{+44+180}_{-29-35}$$

$$\Gamma = 177^{+54+316}_{-39-61}$$

$$> 5\sigma$$

Interactions News Wire #58-08
5 August 2008 http://www.interactions.org
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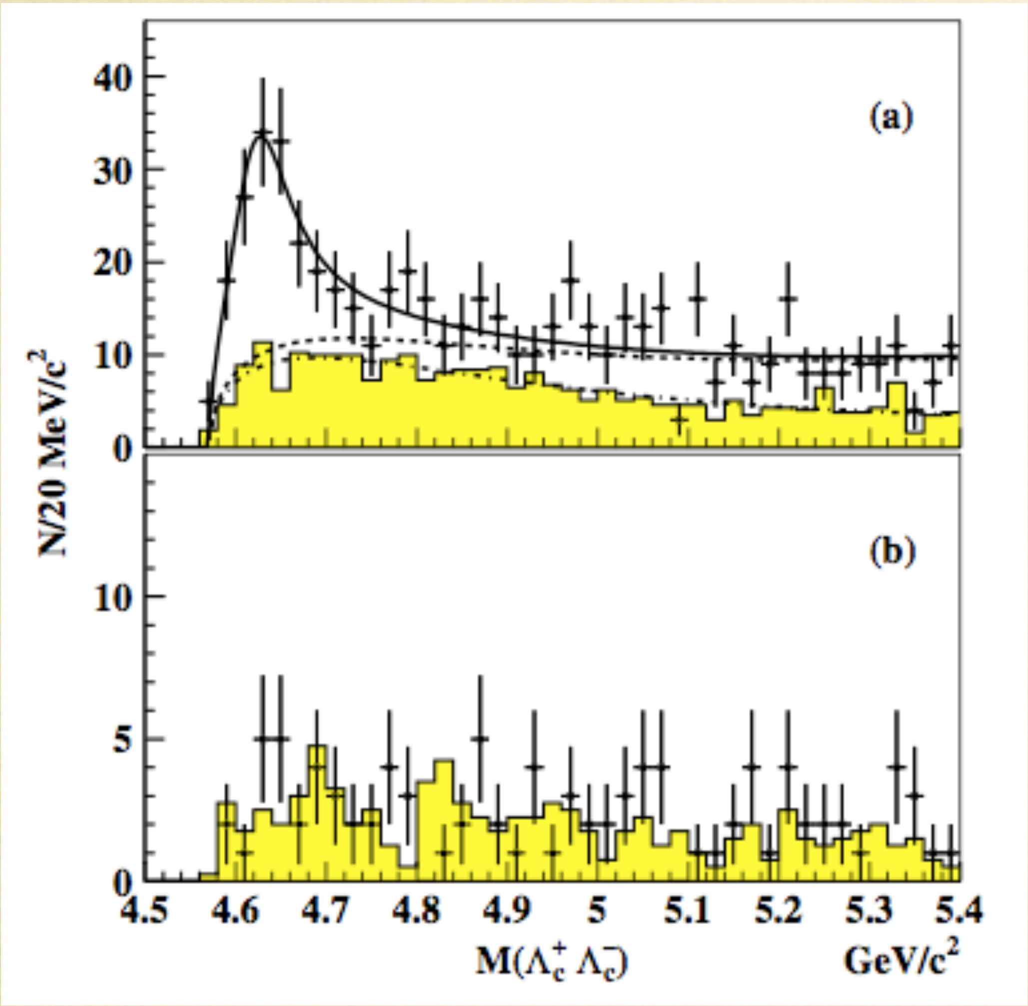
Source: KEK
Content: Press Release
Date Issued: 5 August 2008
****

Press release including graphics:
http://www.kek.jp/intra-e/press/2008/BellePress13e.html

Belle Discovers Three New Mesons

An international team of researchers at the High Energy Accelerator Research organization (KEK) in Tsukuba, Japan, the "Belle collaboration"*1, has announced the discovery of three new exotic sub-atomic particles, labeled as Z_1, Z_2 and Y_b. The Z_1 and Z_2 states have unit electric charge, by which these particles are clearly distinguished from normal quark-antiquark mesons, and thus can be identified as particles consisting of four quarks. The Y_b structure may be the first clear example of an exotic hybrid particle, which contains the bottom quark and its anti-particle (an anti-bottom quark) as in a conventional meson but with an excited gluon as well.

$X(4630)$



a classic final state interaction enhancement