Heavy Flavour Spectroscopy

Eric Swanson

spectroscopy

atomic spectroscopy ⇒ quantum mechanics

nuclear spectroscopy ⇒ shell model

hadron spectroscopy ⇒ Eightfold way ⇒ QCD

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)

theoretical issues

gluonics

hybrids
glueballs
strong decays

vacuum structure

chiral symmetry breaking
confinement
instantons/vortices/monopoles

short range interactions

gluon exchange
pion exchange
instantons
coupled channels

long range interactions

pomeron exchange
pion exchange
gluonic multipoles
coupled channels
confinement
emergence of nuclear physics

beyond the SM

- CP violation in J/ψ decays

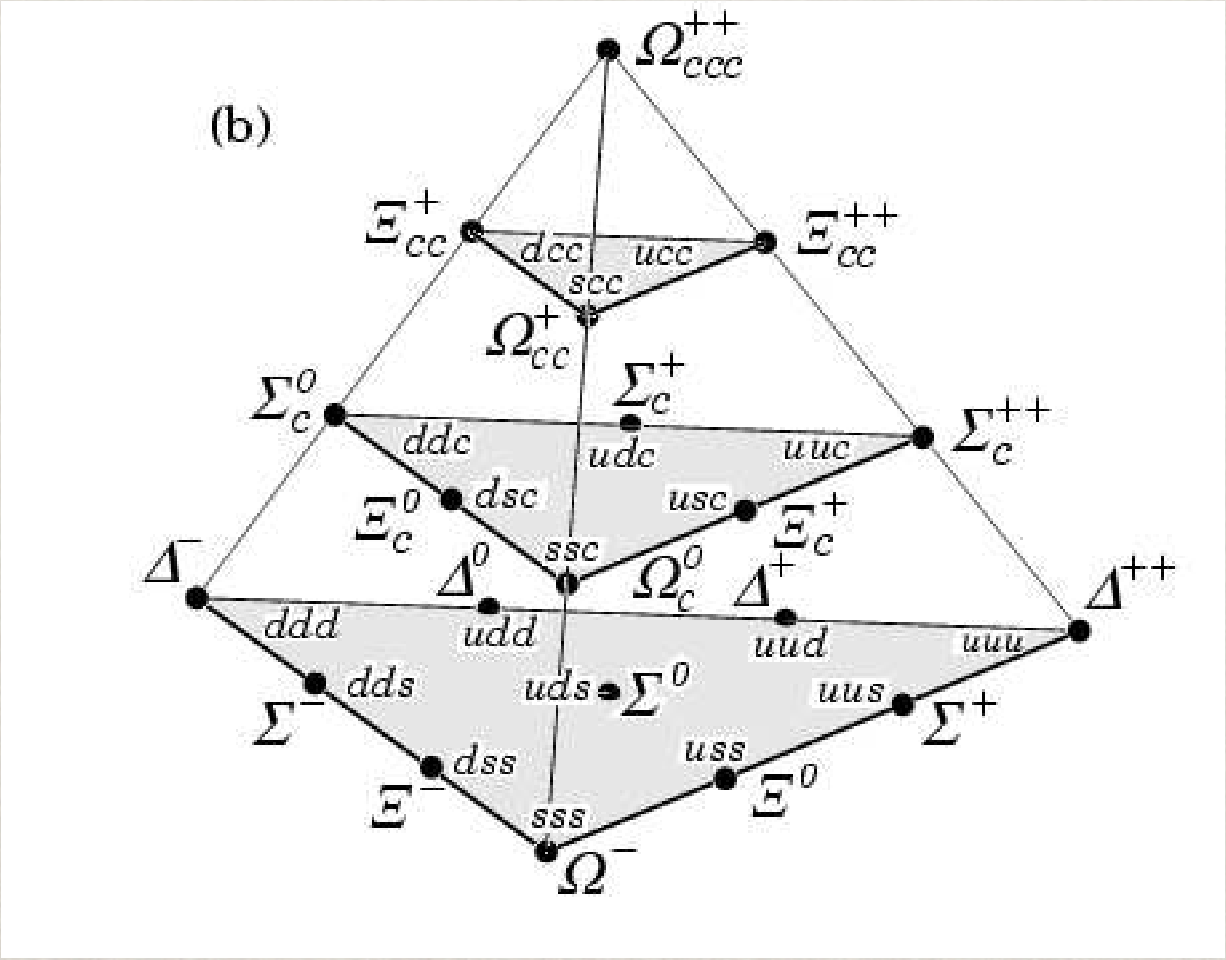
$$\mathcal{L}_{CP} = -i\frac{d_c}{2}\bar{c}\gamma_5\sigma_{\mu\nu}G^{\mu\nu}c$$

- 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
- charged Higgs/leptoquarks in f_{Ds}

“hadrons are simple”



“hadrons are irreducible complexity”

theoretical tools

- effective field theory
  - SCET, NRQCD,pNRQCD
- lattice gauge theory
- perturbative QCD

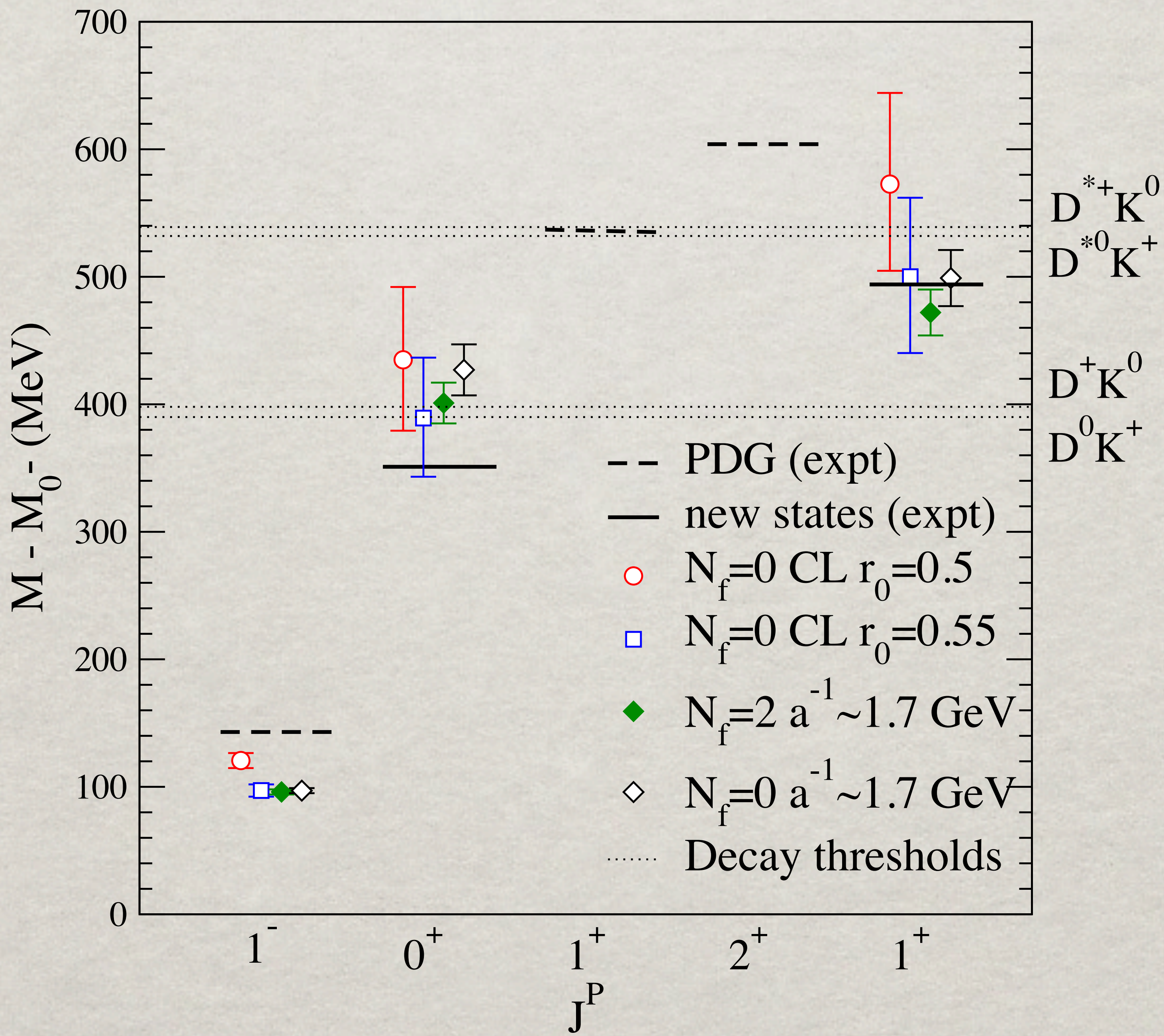
NRQCD

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

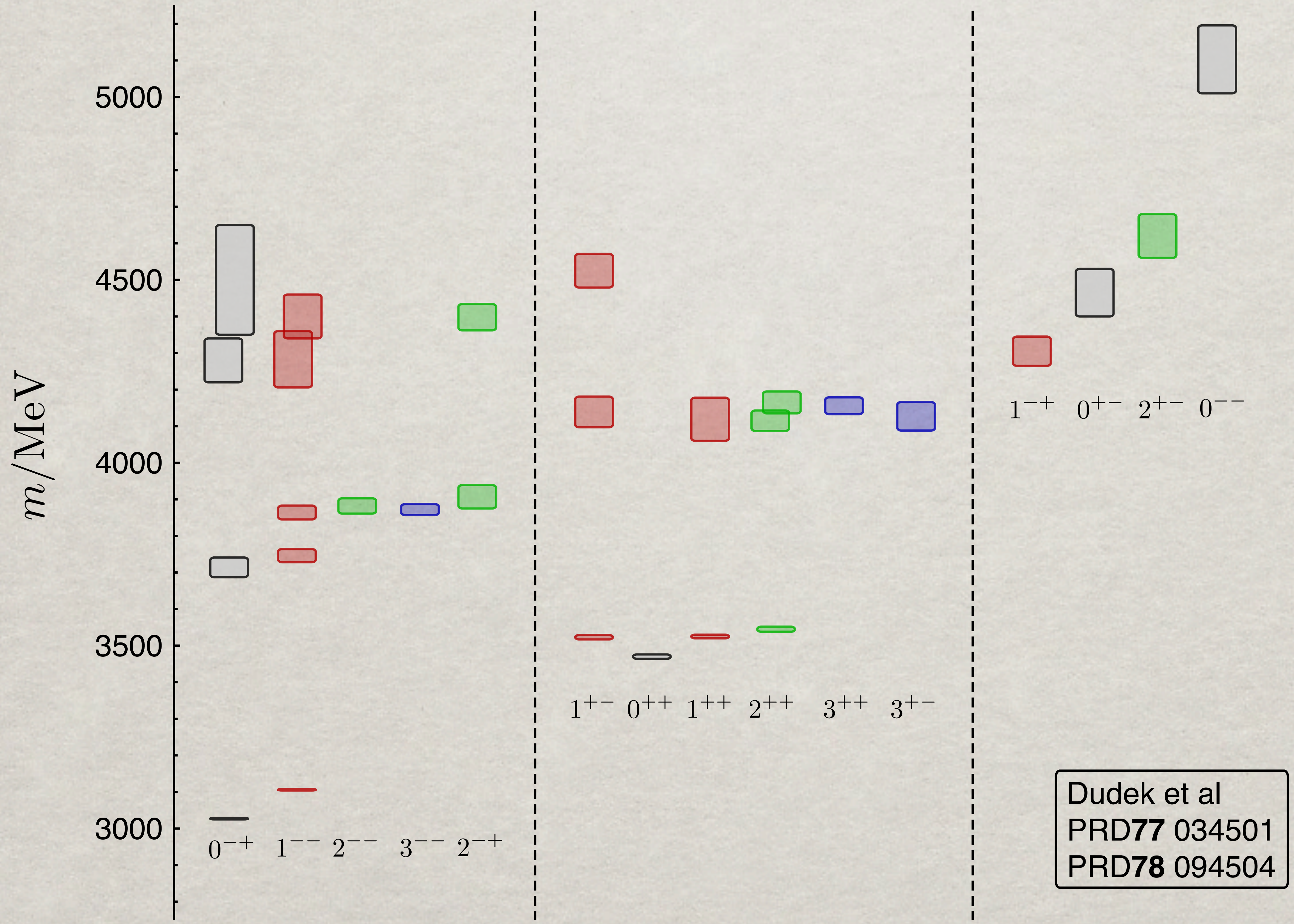
lattice

$D_{s0}(2317)$



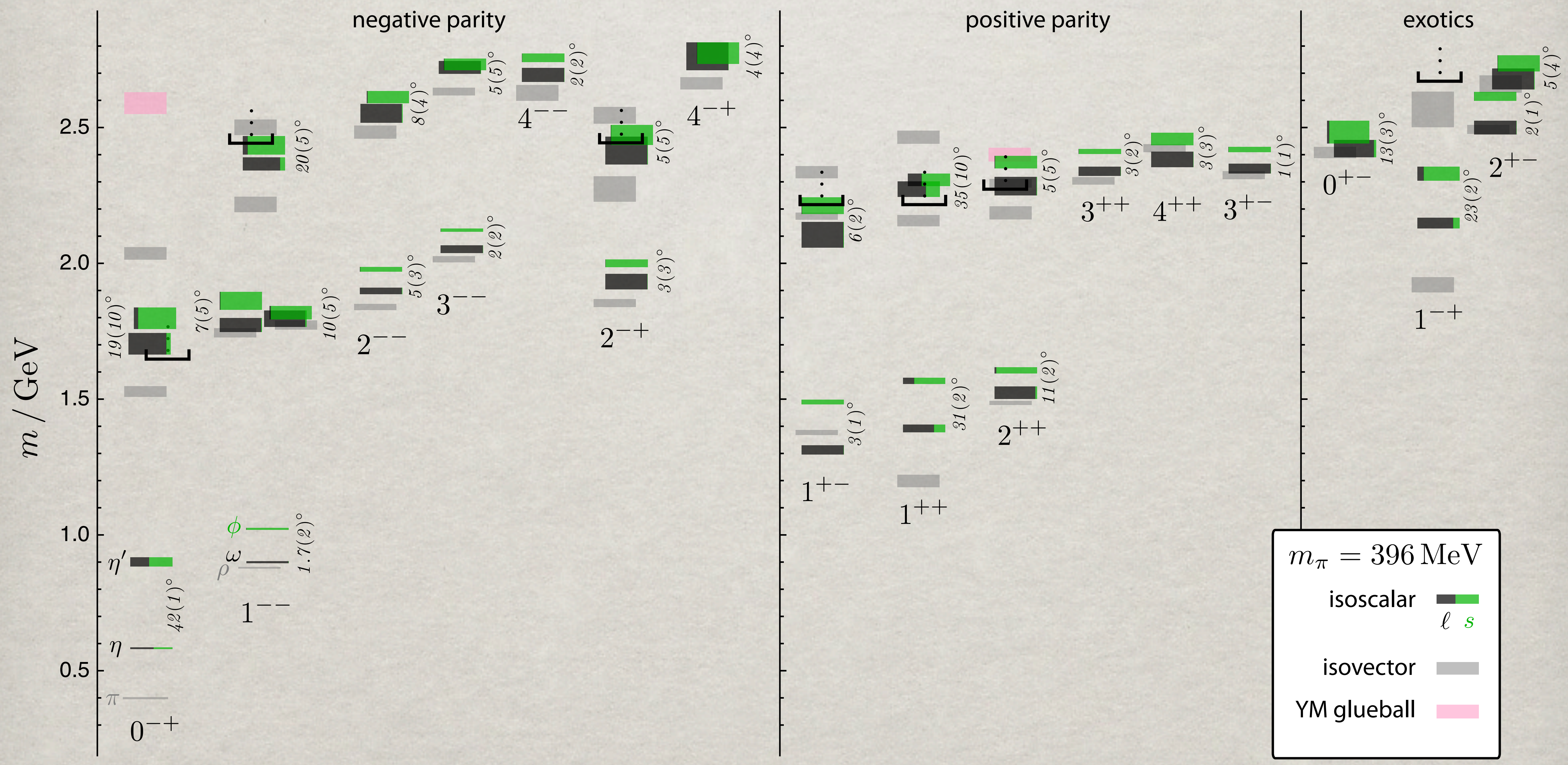
lattice

charmonium



lattice

light isoscalars



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

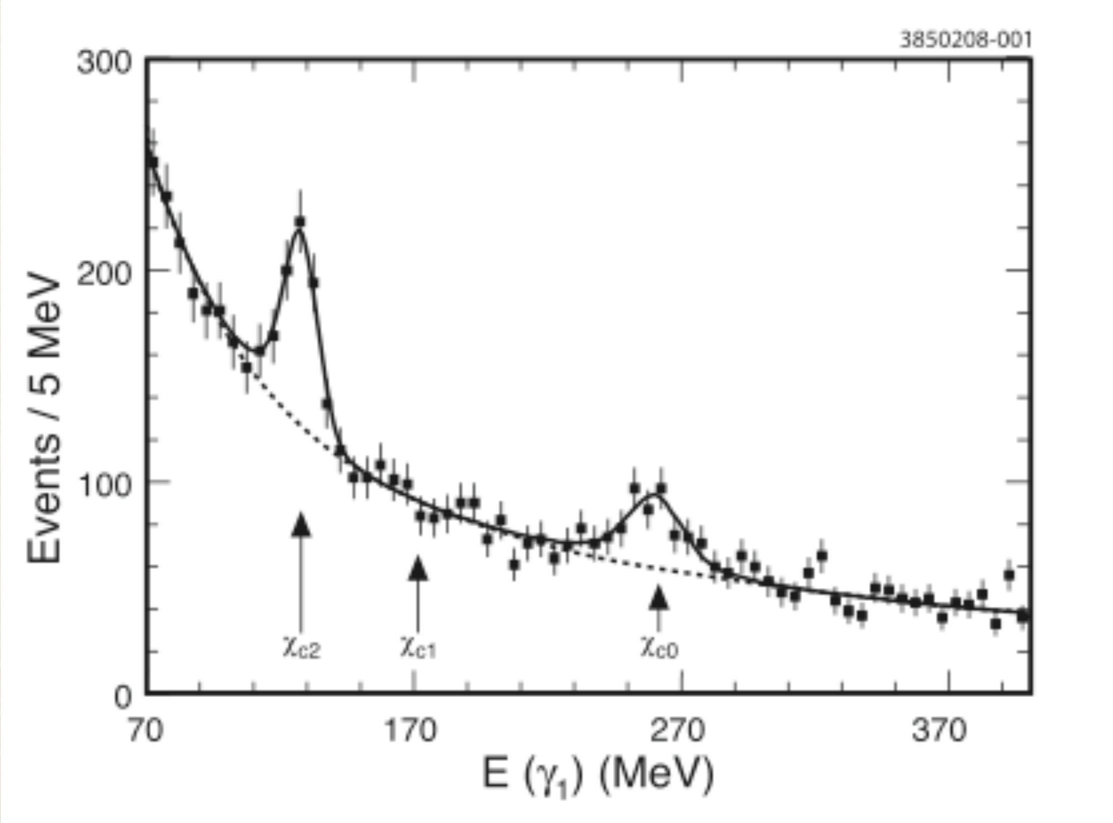
perturbative QCD

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

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

e^+e^- widths

van Royen and Weisskopf

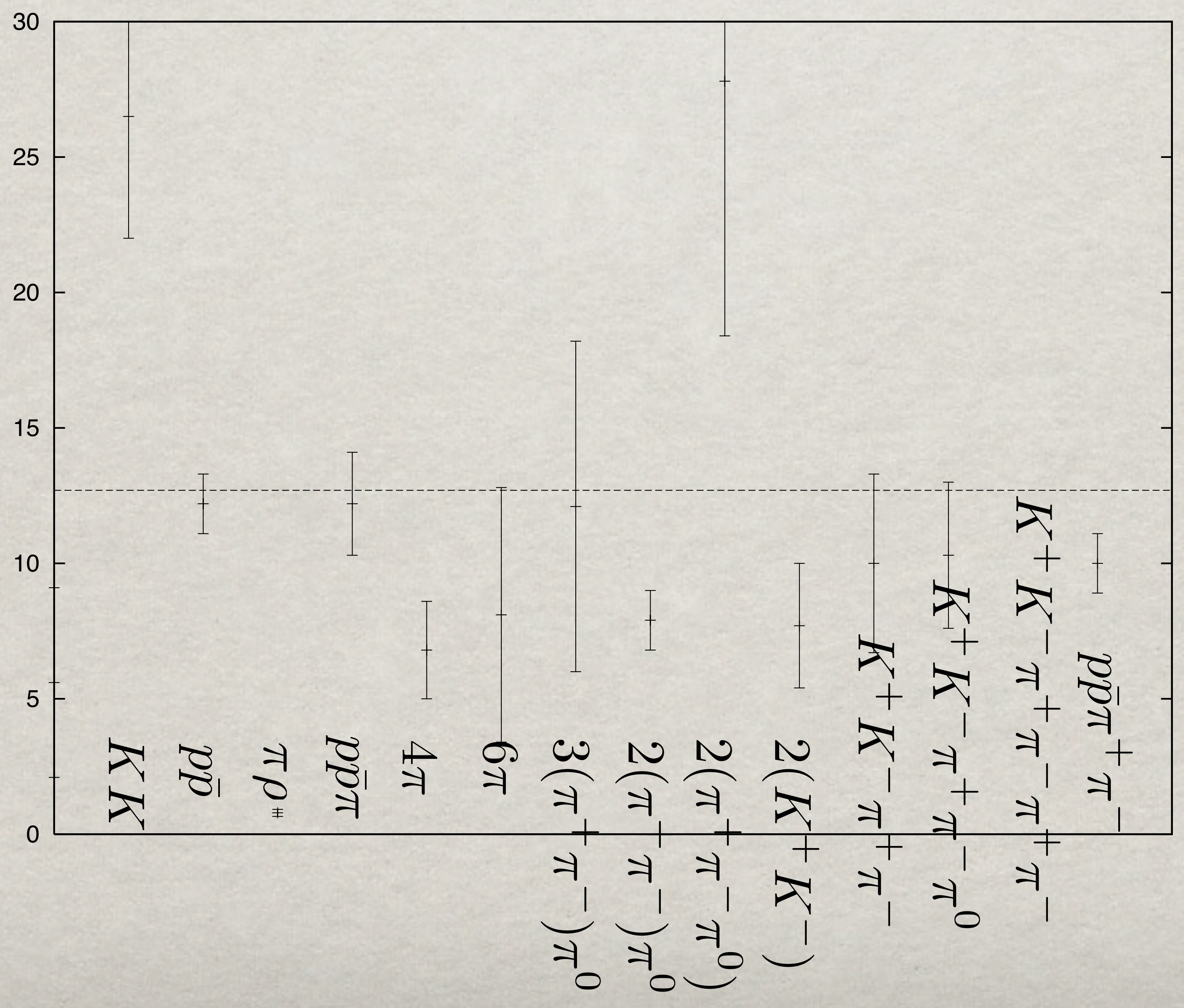
$$\Gamma(^3S_1 \to e^+e^-) = 16\alpha_s^2 Q^2 \frac{|\psi(0)|^2}{M^2}$$

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

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)	
$\psi(4040)$	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

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



some experiment

T. Pedlar [CLEO], Moriond, 2009
M. Shepherd [CLEO], GHP09

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

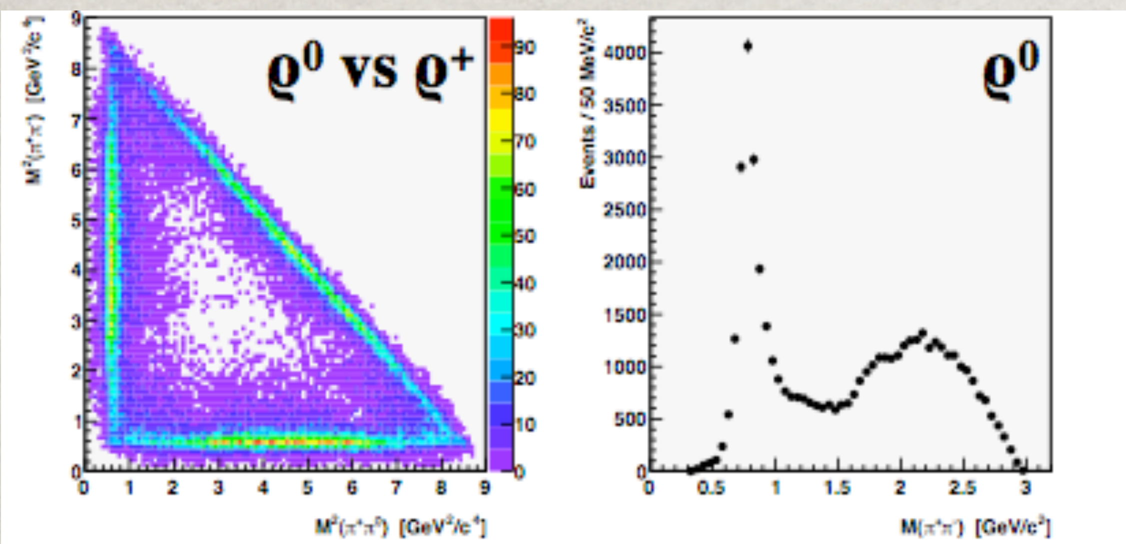
$*10^{-4}$

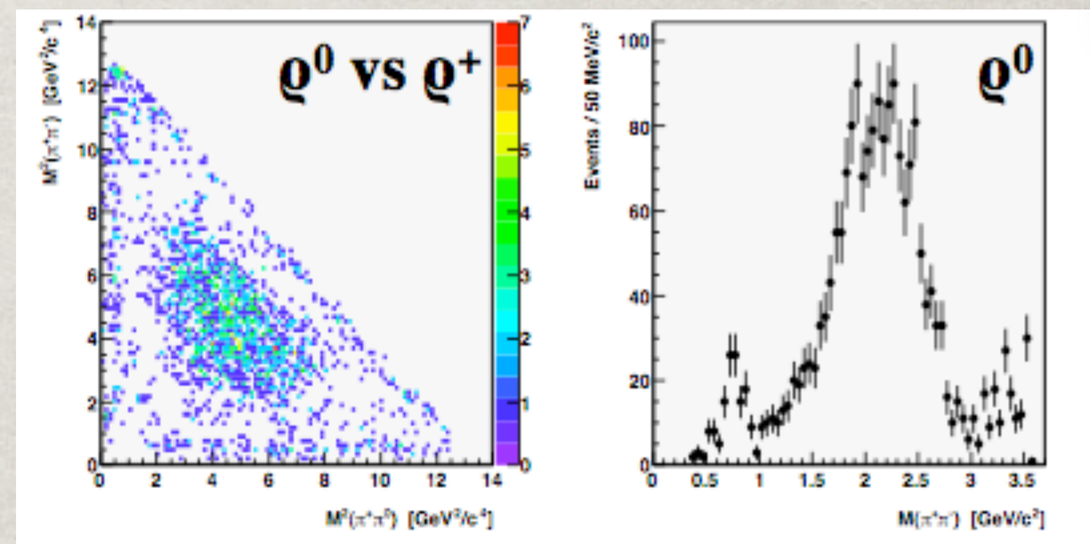
$$\frac{Bf(\psi(2S) \to \gamma\eta)}{Bf(\psi(2S) \to \gamma\eta')} = \frac{< 0.02}{1.19 \pm 0.08 \pm 0.03} < 0.018$$

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

$J/\psi \to \pi\pi\pi$

$\psi(2S) \to \pi\pi\pi$





memory of the initial state survives annihilation?

Puzzles of $\Upsilon(5S)$ decays

1. Anomalous production of $\Upsilon(nS)\,\pi^+\pi^-$

PRL100,112001(2008)	Γ(MeV)
$\Upsilon(5S) \to \Upsilon(1S)\pi^+\pi^-$	$0.59 \pm 0.04 \pm 0.09$
$\Upsilon(5S) \to \Upsilon(2S)\pi^+\pi^-$	$0.85 \pm 0.07 \pm 0.16$
$\Upsilon(5S) \to \Upsilon(3S)\pi^+\pi^-$	$0.52^{+0.20}_{-0.17} \pm 0.10$
$\Upsilon(2S) \to \Upsilon(1S)\pi^+\pi^-$	0.0060
$\Upsilon(3S) \to \Upsilon(1S)\pi^+\pi^-$	0.0009
$\Upsilon(4S) \to \Upsilon(1S)\pi^+\pi^-$	0.0019

10^2

Simonov JETP Lett 87,147(2008)

(1) Rescattering $\Upsilon(5S) \to BB\pi\pi \to \Upsilon(nS)\pi\pi$

(2) Exotic resonance Y_b near $\Upsilon(5S)$

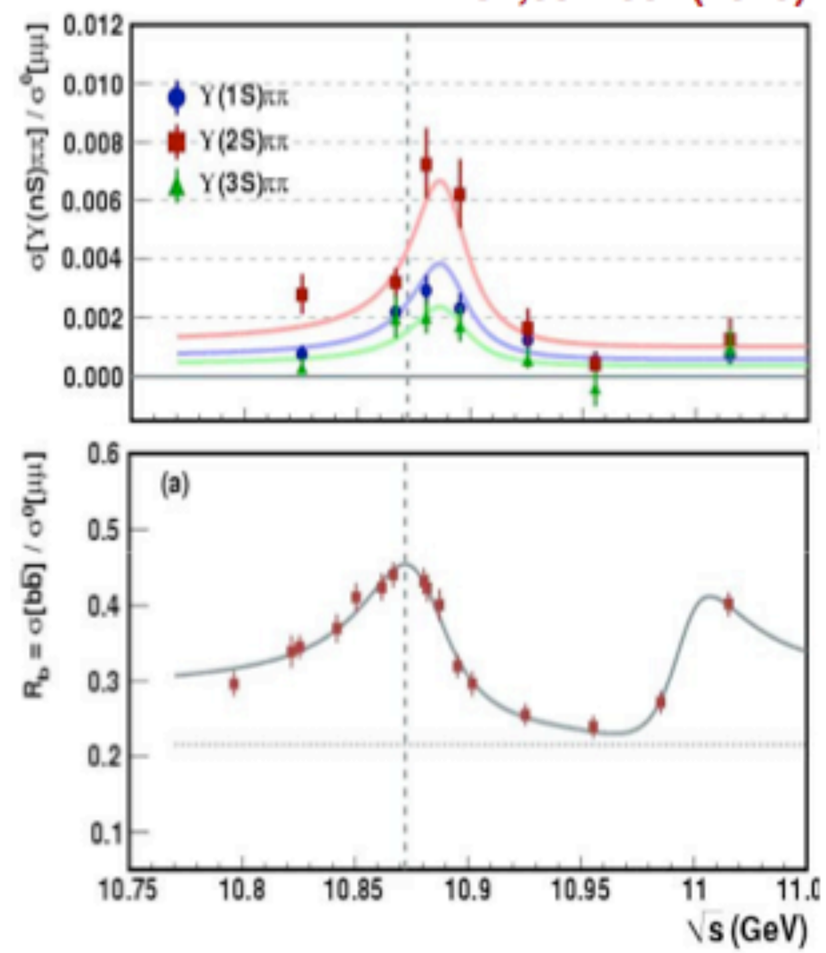
analog of Y(4260) resonance

with anomalous $\Gamma(J/\psi\,\pi^+\pi^-)$

Energy scan $\Rightarrow$

shapes of R_b and $\sigma(\Upsilon\pi\pi)$ different (2σ)

PRD82,091106R(2010)



PRD81,112003(2010)

2. $BF[\Upsilon(5S) \to B^*\bar{B}\pi] = (7.3\,^{+2.3}_{-2.1} \pm 0.8)\,\%$ *>10 times higher than expectations*

$\Upsilon(5S)$ is very interesting and not yet understood region

$$\frac{\Gamma[\Upsilon(5S) \to h_b(nP)\,\pi^+\pi^-]}{\Gamma[\Upsilon(5S) \to \Upsilon(2S)\,\pi^+\pi^-]} = \begin{cases} 0.407 \pm 0.079^{+0.043}_{-0.076} & \text{for } h_b(1P) \\ 0.78 \pm 0.09^{+0.22}_{-0.10} & \text{for } h_b(2P) \end{cases}$$

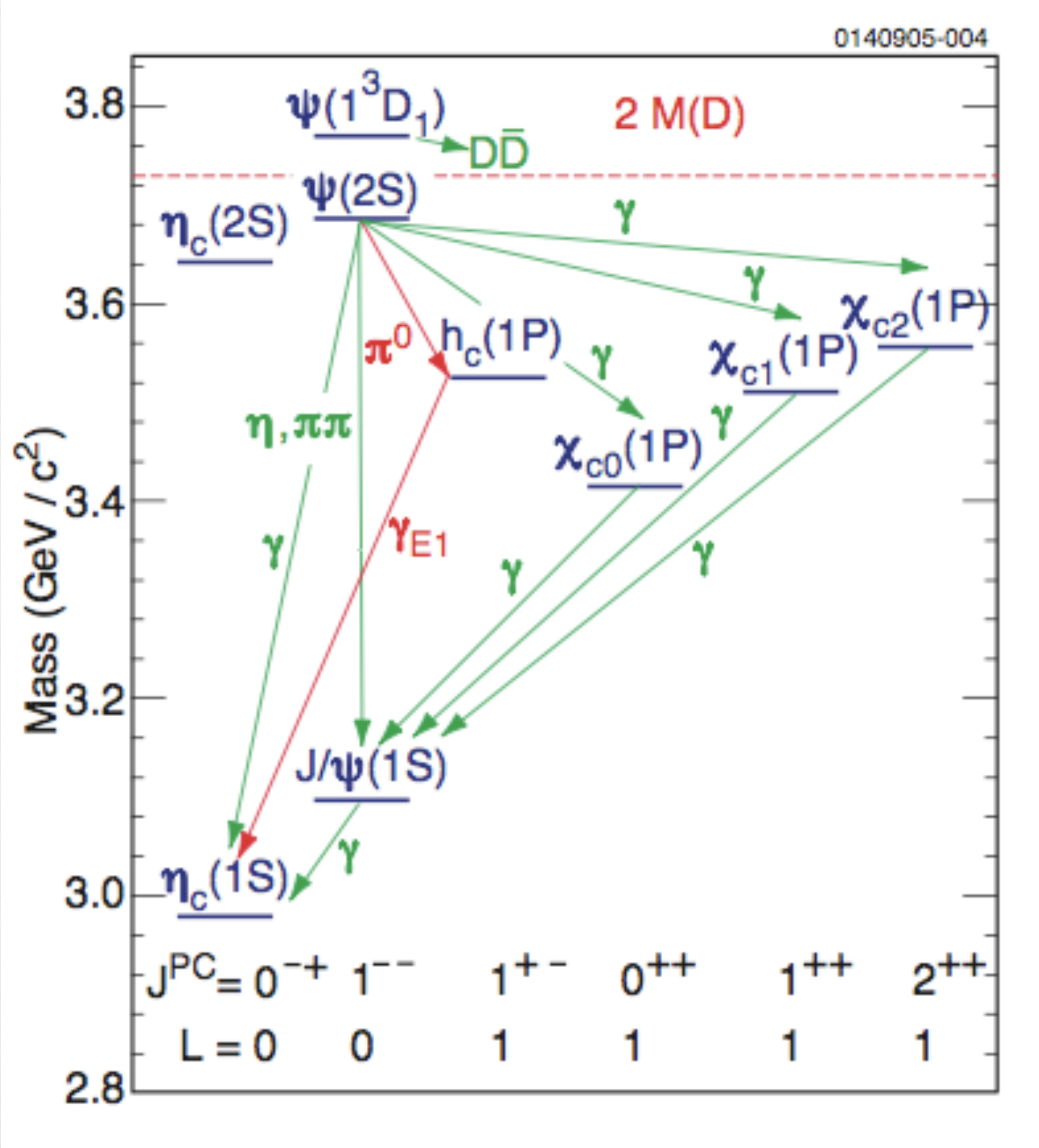
Spin h_b = 0 ⇒ spin-flip

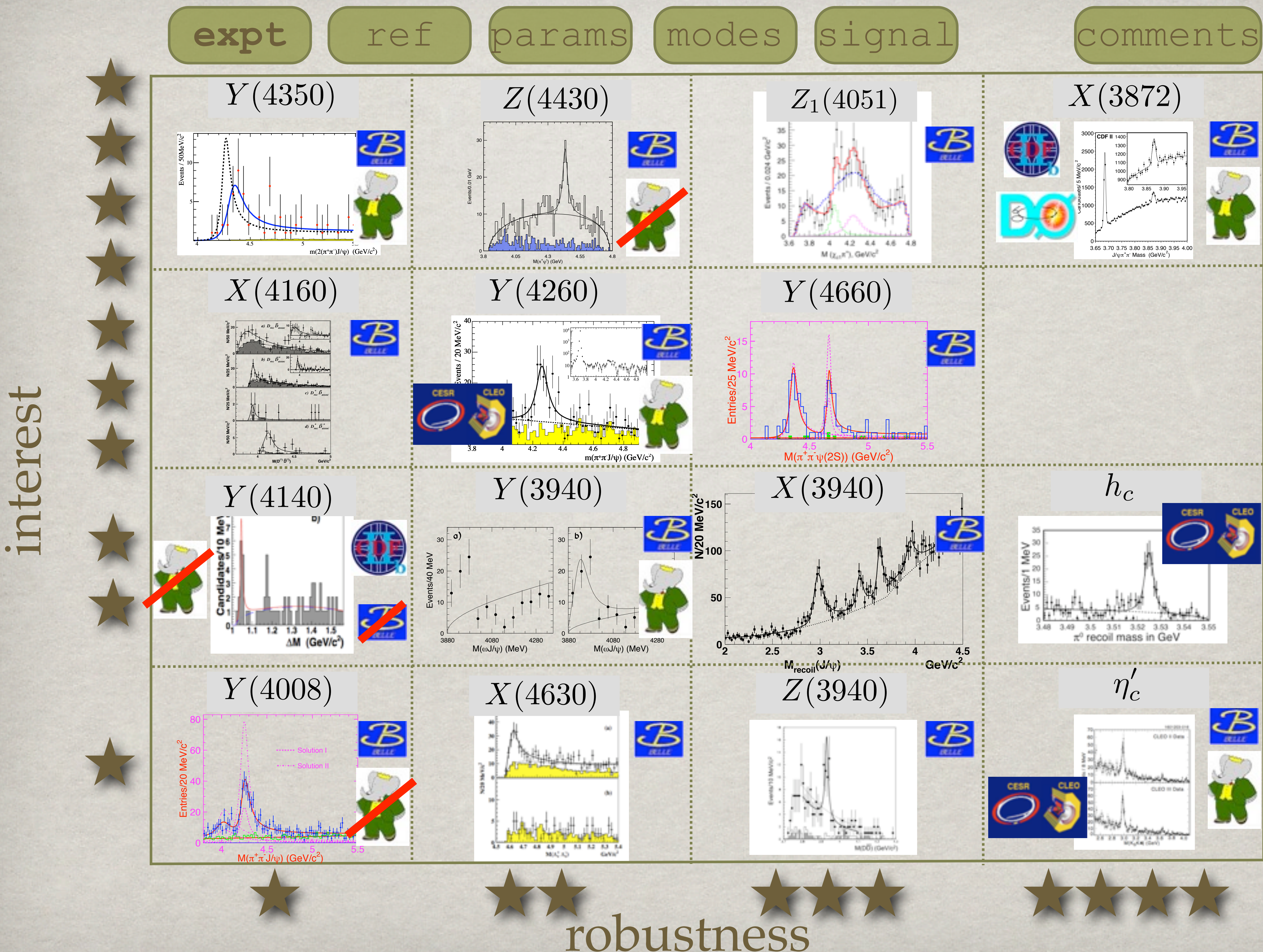
no spin-flip

Process with spin-flip of heavy quark is not suppressed

and some spectroscopy...

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





expt
ref
params
modes
signal
comments
interest
robustness
Y(4350)
Z(4430)
Z1(4051)
X(3872)
X(4160)
Y(4260)
Y(4660)
Y(4140)
Y(3940)
X(3940)
hc
Y(4008)
X(4630)
Z(3940)
η′c

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

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

interest

robustness

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

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

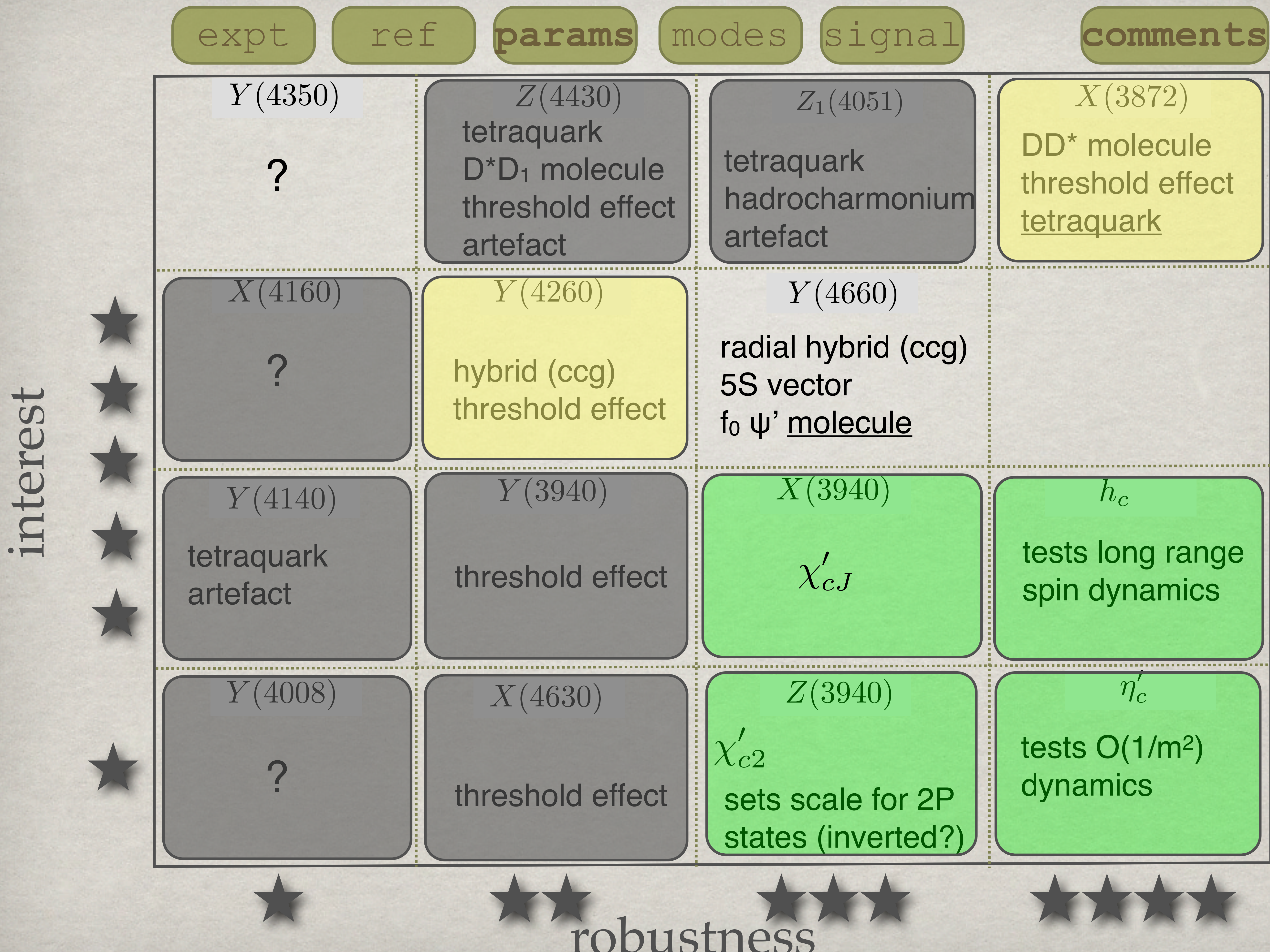
robustness

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

interest \ robustness	★	★★	★★★	★★★★
★★★★	$Y(4350)$?	$Z(4430)$ 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 Ds*Ds* 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
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comments
$Y(4350)$
?
$Z(4430)$
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	★	★★	★★★	★★★★
★★★★★★★★★				
★★★★★★★★				
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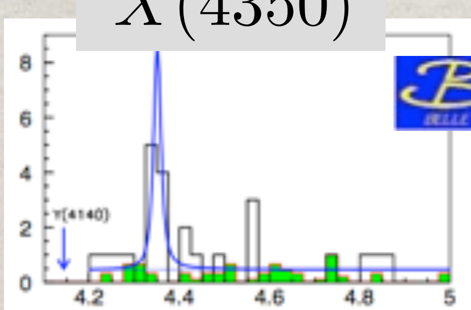
★★★				
★★	$X(4350)$ 	$X(3915)$	$G(3900)$	$Y(4274)$
★				

interest

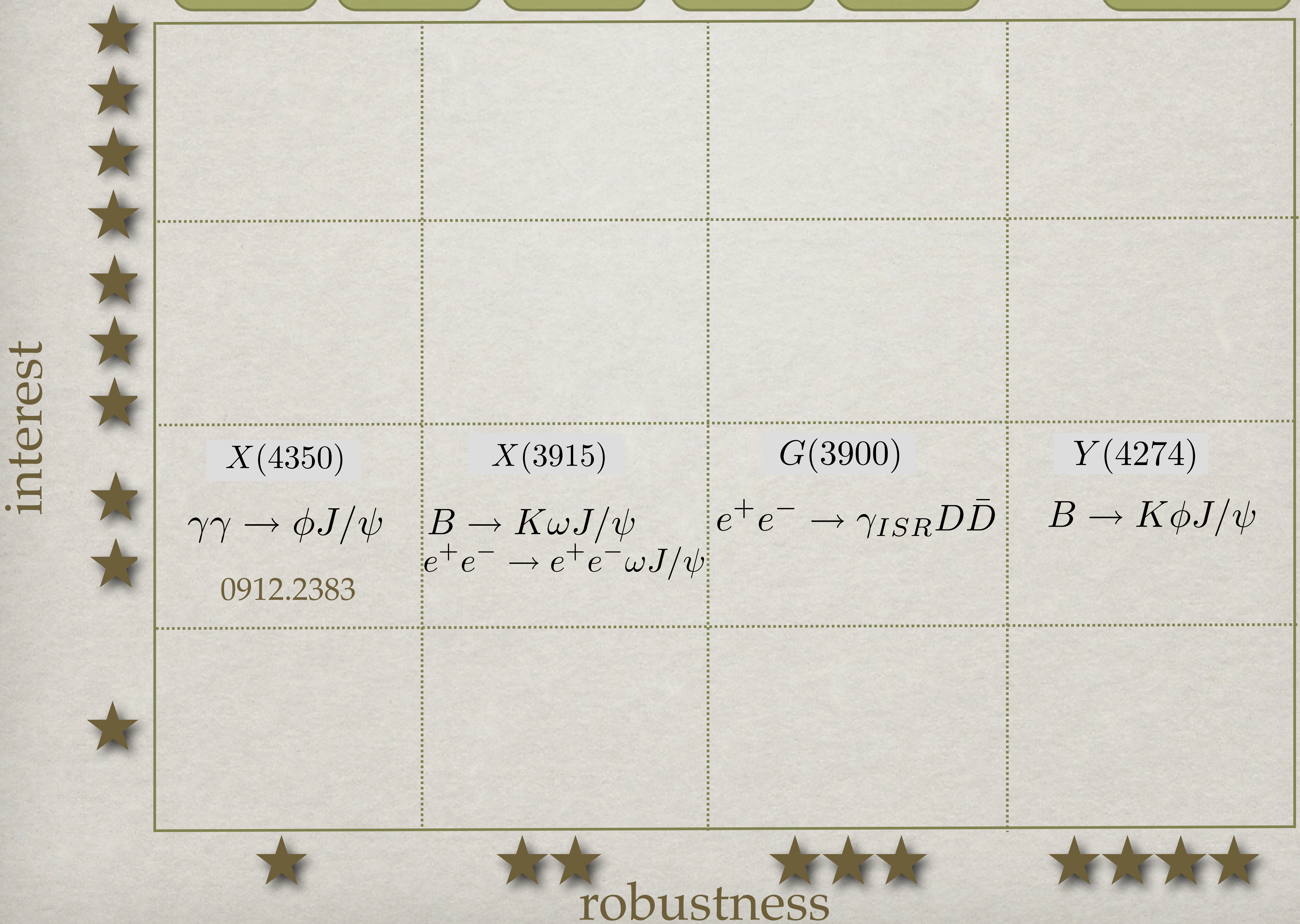
robustness

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

interest	★	★★	★★★	★★★★
★★	$X(4350)$ $M = 4350.6 \pm 5 \pm 0.7$ $\Gamma = 13.3 \pm 12 \pm 4$ $\sigma = 3.2$	$X(3915)$ $M = 3915.6 \pm 3.1$ $\Gamma = 28 \pm 10$	$G(3900)$ $M = 3043 \pm 10$ $\Gamma = 52 \pm 11$	$Y(4274)$ $M = 4274.4 \pm 7$ $\Gamma = 32 \pm 18$

robustness

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



a word on the X(3872)

the X(3872) in 1992!

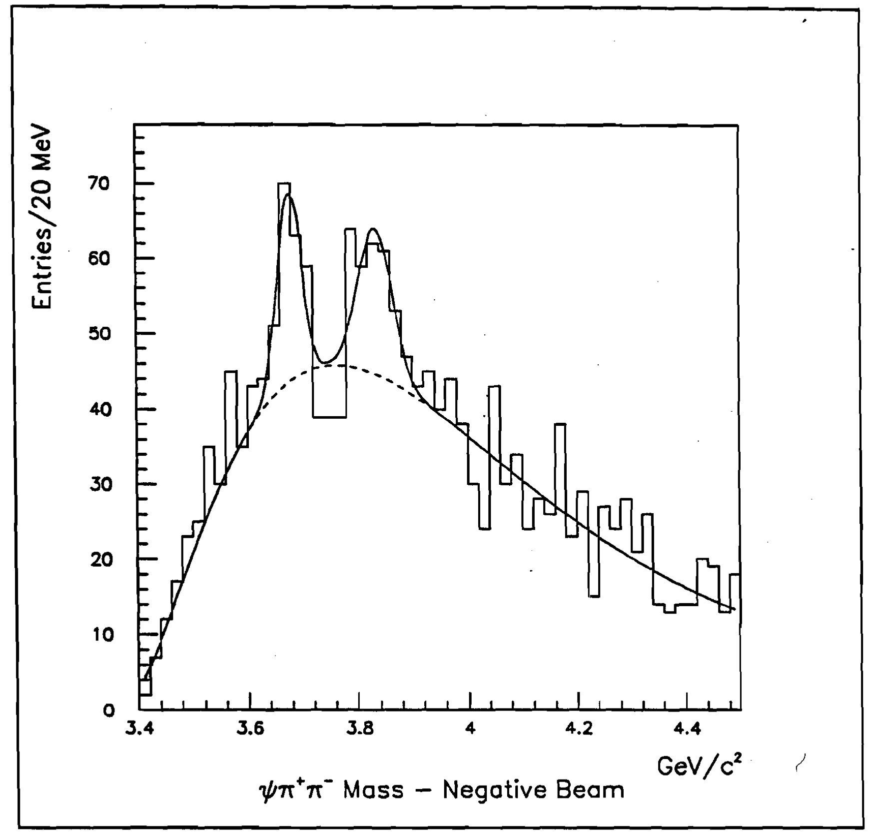


Figure 6.12 ψππ mass spectrum, standard cuts, negative beam.

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

a word on the X(3872)

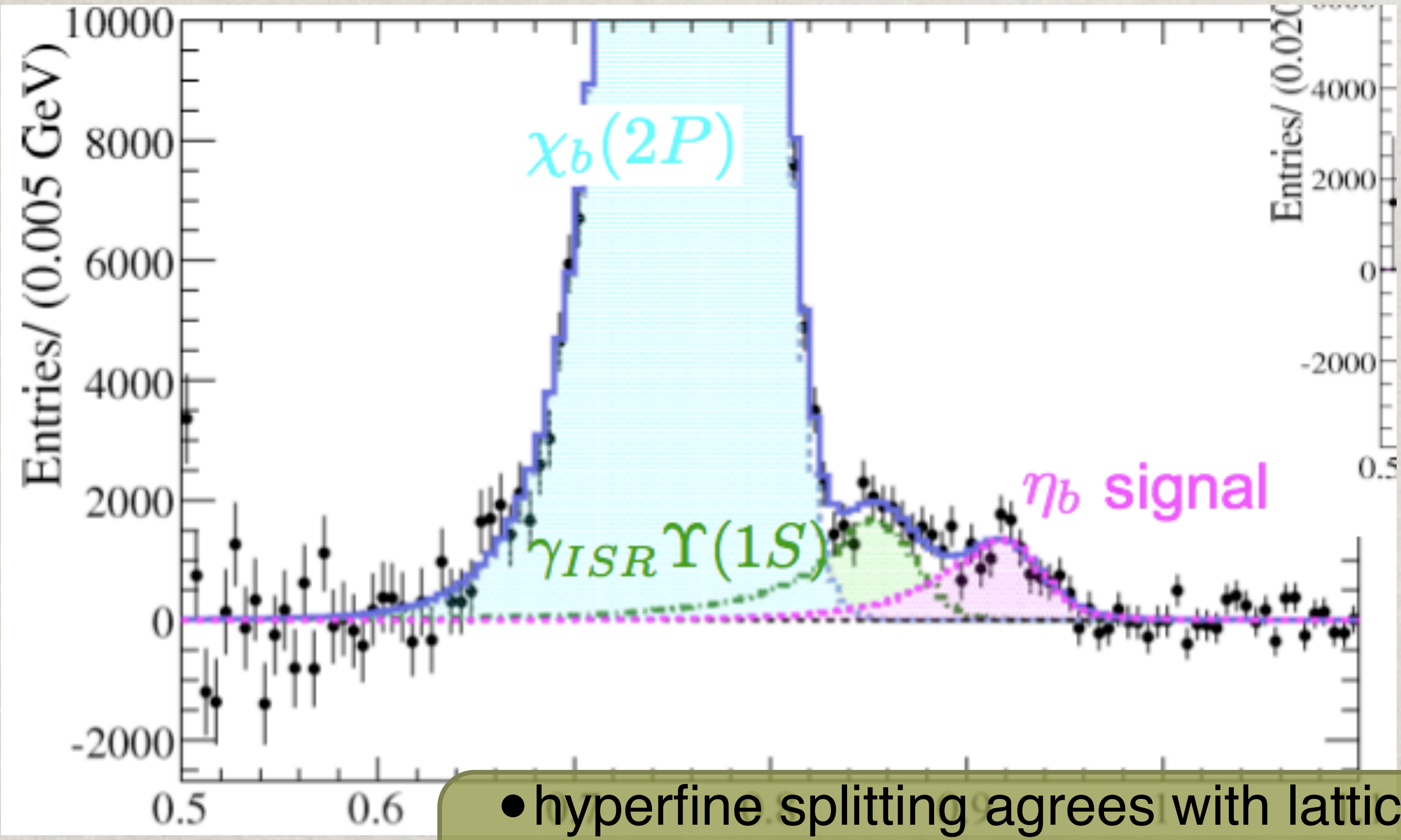
- firm up $\frac{X \to D\bar{D}\pi}{X \to \pi\pi J/\psi}$ (DDπ mass?)
- firm up $\frac{B^0 \to K^0 X}{B^+ \to K^+ X}$ $\frac{X \to \gamma J/\psi}{X \to \gamma\psi(2S)}$
- test cusp effect/ tetraquark

$$B^0 \to K^+ D^- D^{*0} \quad B^+ \to K^0 D^0 D^{*+}$$

- new molecules?

$$(D^* \bar{D}^*) \to \omega J/\psi$$

discovery of 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

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

$M = 9392.9 \pm 5 \pm 2$

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

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

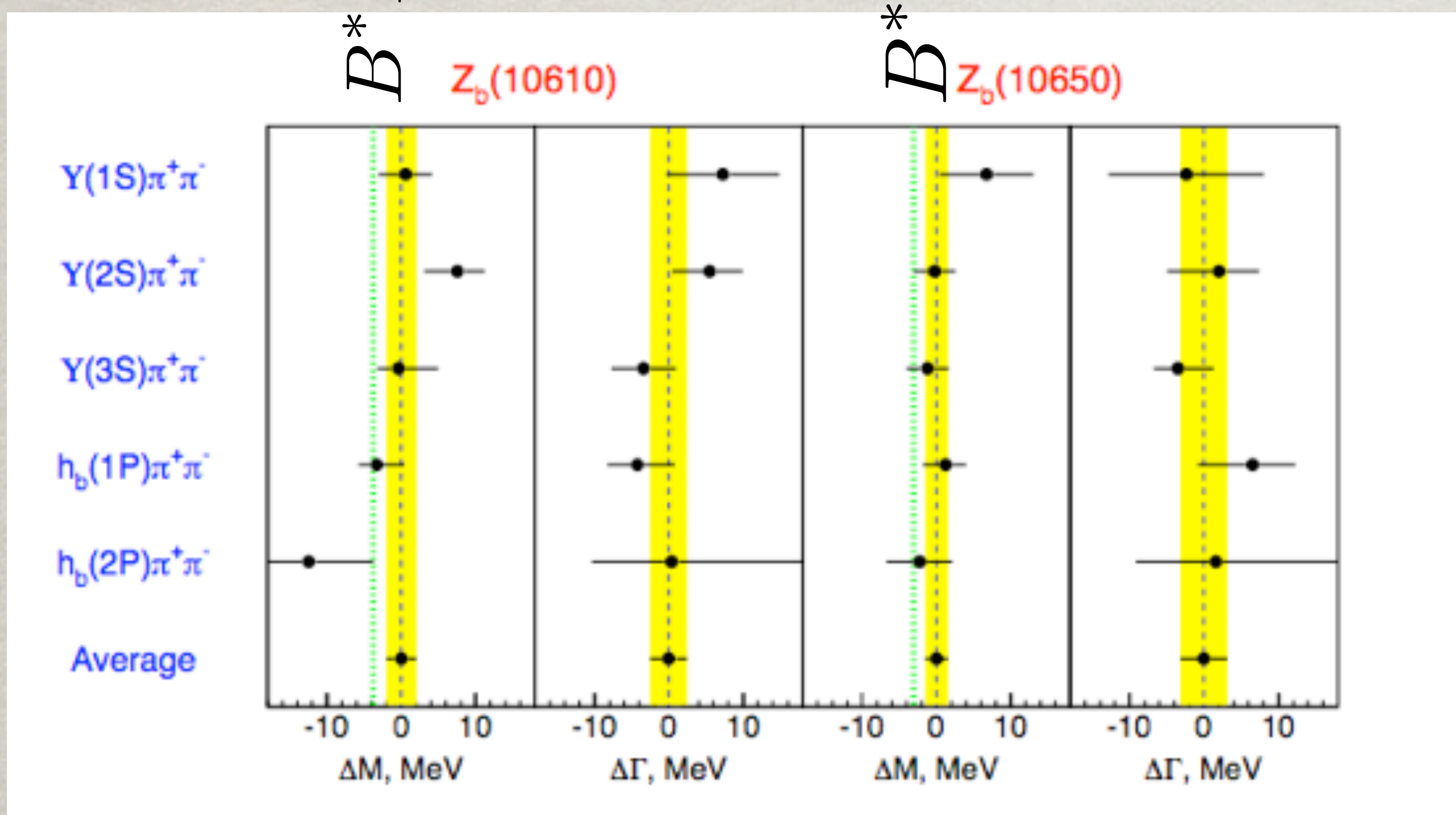
- hyperfine splitting agrees with lattice
- hyperfine splitting disagrees with pNRQCD
- hyperfine splitting gives $\alpha_s(M_{\eta_b})$
- test NRQCD
- test mixing with A_0

$Z_b^+(10610)$ $\quad$ $Z_b^+(10650)$

Adachi et al. [Belle] 1105.4583

$$I^G J^P = 1^+ 1^+$$

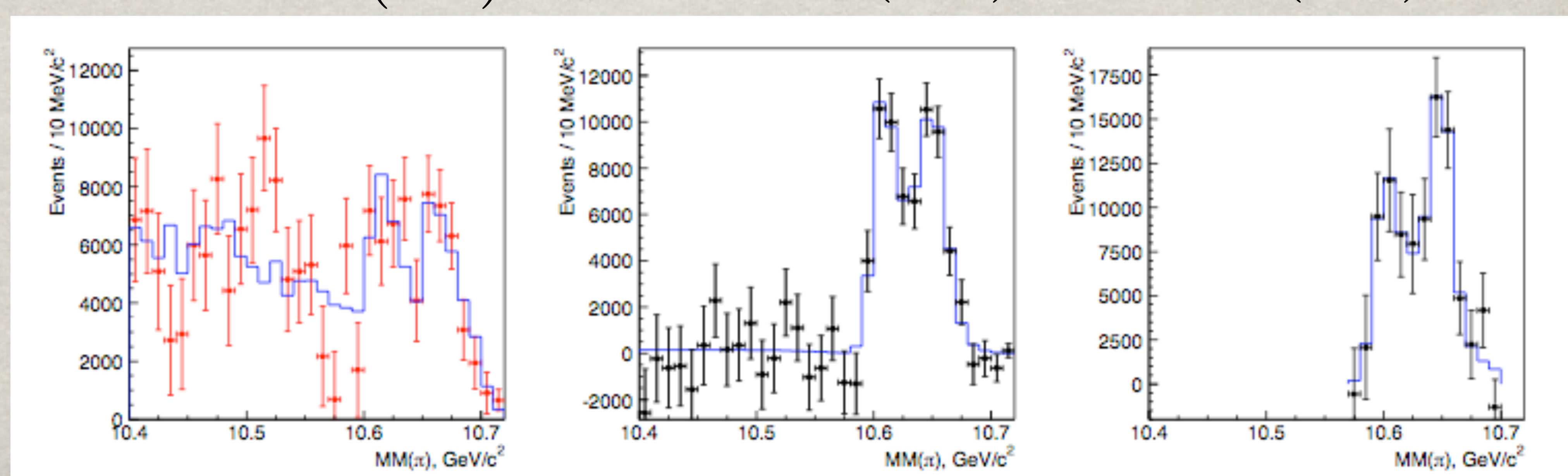
$B^*\bar{B}$ $\quad$ $B^*\bar{B}^*$



$Y_b(10888)$ $\quad$ 1^{--}

$e^+e^- \to \pi\pi\Upsilon(nS)$

$\Upsilon(2S)$ $\quad$ $h_b(1P)$ $\quad$ $h_b(2P)$



CONCLUSIONS

- Hadrons and QCD provide one the few tools to learn about nonperturbative quantum field theory.
- pQCD and EFT are not fully developed
- lattice is getting there rapidly (coupled channel resonance effects, large operator bases, hairpin diagrams,...)
- still many experimental anomalies and states to straighten out (look to JPARC, superB, COMPASS, PANDA/FAIR, & LHC)

✢ ÆRIC MEC HEHT GEWYRCAN