

Exotic Heavy quarkonium: towards a new spectroscopy

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Anacapri

Beyond the “standard spectroscopy”

- Search for states with 2 quarks+“something else”
 - New forms of aggregation
 - Expected but never identified!!!
- Hybrids: $qq+n$ gluons
 - Lowest state 1^{++} (forbidden for quarkonium)
 - Dominant decay $H \rightarrow DD^{**}$
- Tetraquarks: $[\bar{q}\bar{q}'][q\bar{q}]$
 - Large amount of states
 - small widths also above threshold
- Molecules: $M[\bar{q}\bar{q}]M[q'\bar{q}']$
 - Smaller number of states but still small widths also above threshold

Search for resonances:

- with non-quarkonium J^{PC}
- unnaturally small widths
- not null charge: clear indication of something new going on

Building a new spectroscopy

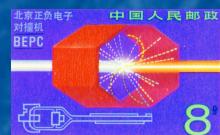
1. Find structures
2. Measure quantum numbers (mass, JPC from production and decay properties)
3. “walks like a dog, smells like a dog ...”
 - Several possible scenarios (hybrids, molecules, tetraquarks,...)
4. Quantify models and fit data to it
5. Search missing states to complete the picture

Strong interplay between theory and experiment

Experiments

- $e^+e^- \rightarrow$ Charmonium (CLEO-c, BES)

- $L \sim 10^{33}/cm^2/s$
 - $E = 3.0\text{--}4.3 \text{ GeV}$



- $e^+e^- \rightarrow Y(4S)$: (BaBar, Belle, CLEO)

- $L \sim 10^{34}/cm^2/s$
 - Charmonium in B decays, ISR and $\gamma\gamma$ production
 - Capability to measure J^{PC} also in production



- pp colliders (CDF, D0)

- High Xsection \rightarrow copious production
 - Extremely high backgrounds



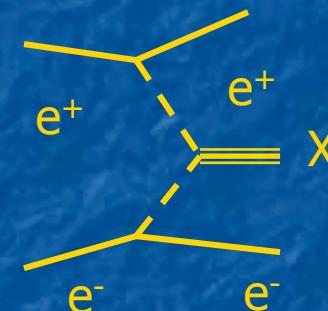
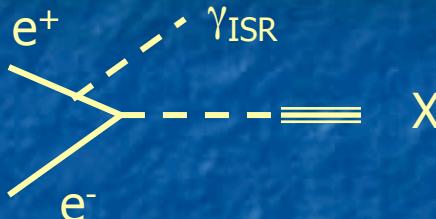
Measuring the quantum numbers

■ Production:

- ISR only produces with same quantum numbers as the photon ($J^{PC}=1^{-+}$)
- $\gamma\gamma$ only produces with $C=+$
- Double charmonium production

$$e^+e^- \rightarrow \gamma^* \rightarrow X_{cc}^{-1}X_{cc}^{-2}$$

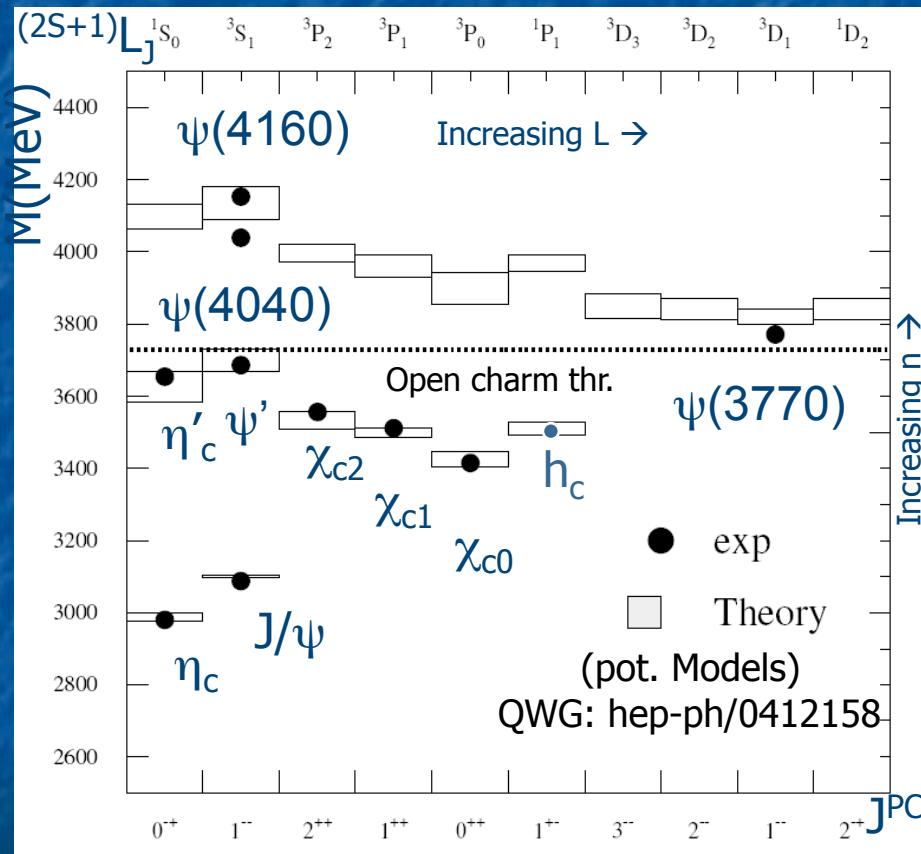
Possible only if quantum numbers of the two charmonia can be combined to give a 1^{-+} .



■ Decay:

- Angular distributions of decay products depend on J^P .
- Strong decay into C eigenstates (C_1 and C_2) implies $C=C_1*C_2$
- Selection rules
 - Conservation of J
 - Conservation of P,C in strong and electromagnetic decays

Charmonium: state of the art



All states below the open charm threshold are observed and explained

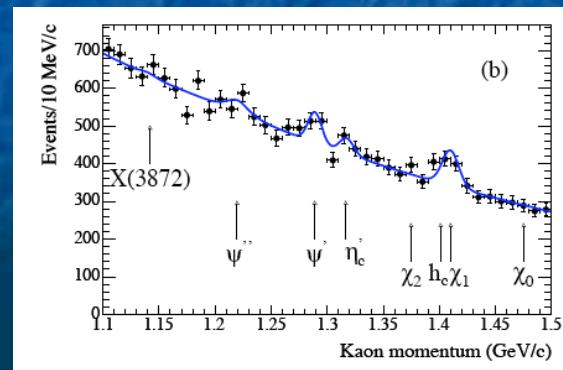
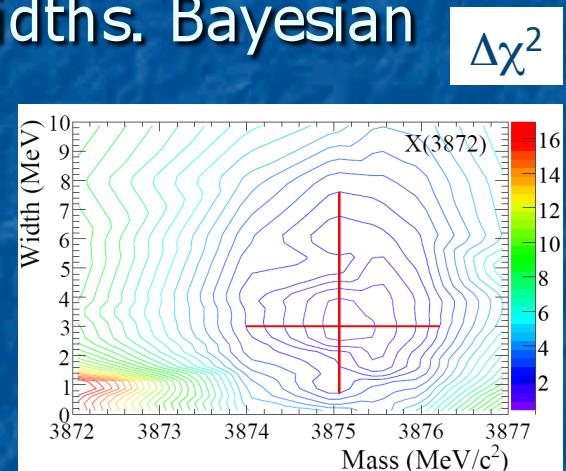
The new Charmonium zoology

- X(3872)
 - The 3940 Family
 - The 4150 Family
 - The 1-- family
 - The charged states
- 
- C=+

X(3872)

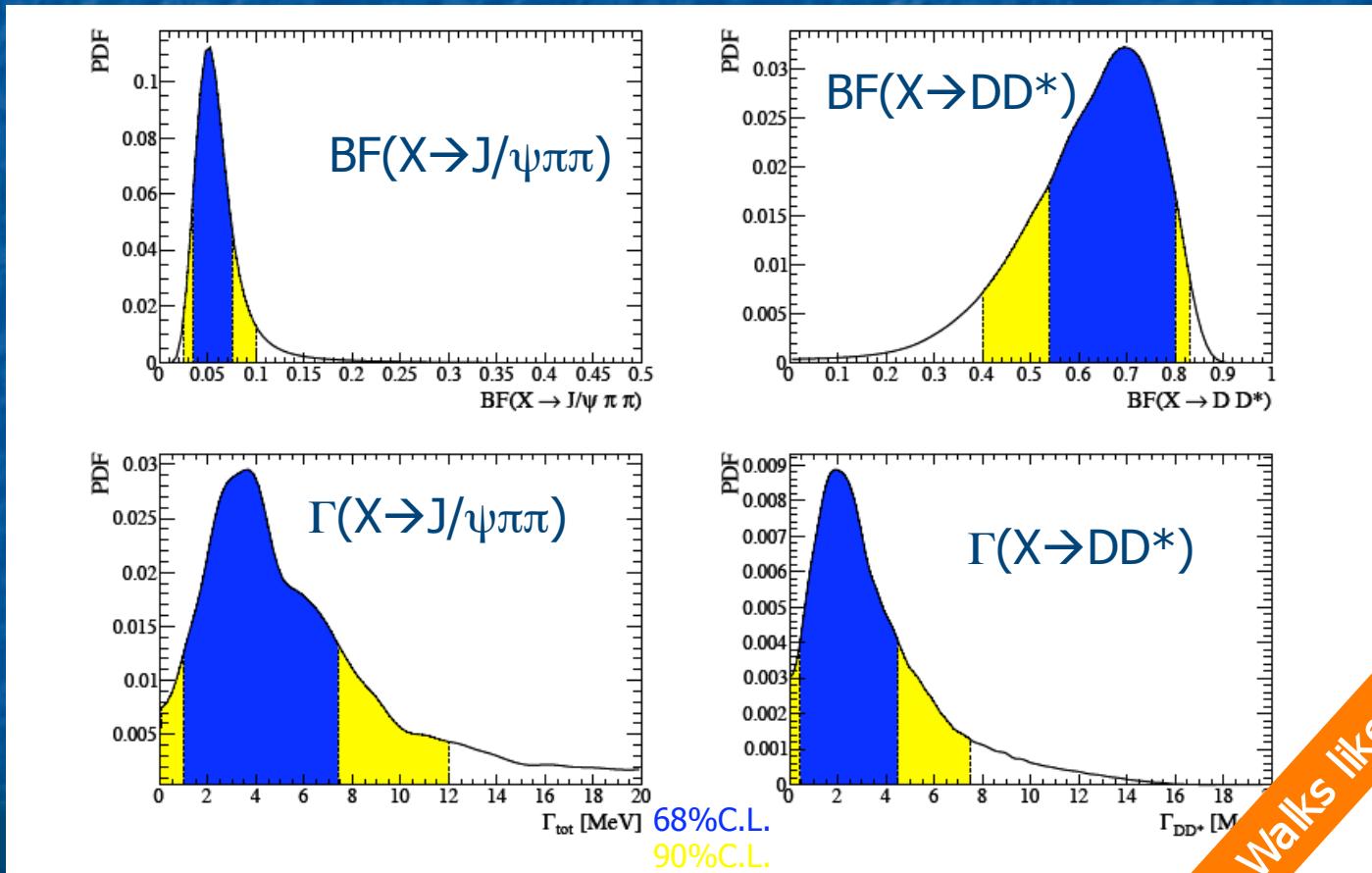
- Best known new state, $M \sim 3872$ MeV, $J^{CP} = 1^{++}$ or 2^{+-}
- Only seen in B decays so far ($B \rightarrow XK$)
- Possibility to measure absolute BF and widths. Bayesian likelihood combination of:
 - Product $\text{BF}(B \rightarrow XK) \times \text{BF}(X \rightarrow f)$
 - $f = J/\psi \pi\pi, D^{*0}D^0, J/\psi \gamma, \psi(2S)\gamma, J/\psi \pi^+\pi^-\pi^0, \chi_c\gamma, \gamma\gamma, J/\psi \eta$
 - Measured Γ (BaBar)

$$\Gamma = (3.6_{-2.3}^{+4.6} \pm 0.9) \text{ MeV}$$
 - Upper limit on $\text{BF}(B \rightarrow XK)$ from K inclusive spectrum on the recoil of fully reconstructed B decays (BaBar).



2. Measure quantum numbers

Combined BF and widths



3. Walks like a dog (?)

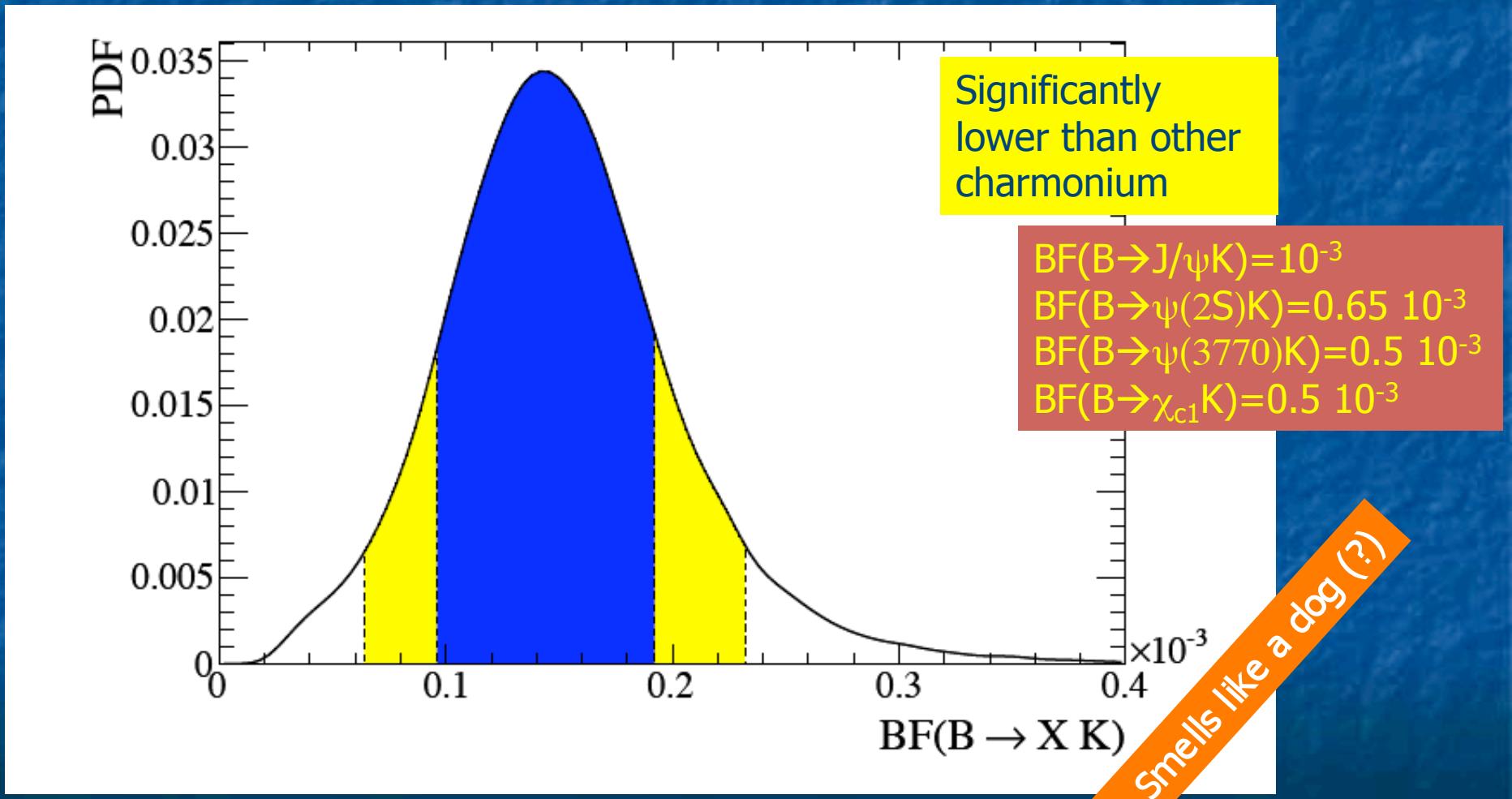
Large DD^* BF and Γ : $\text{Prob}(\Gamma(X \rightarrow DD^*) < \Gamma(D^*) = 0.7\%$

Test against molecular nature

Summary of BF

B Decay mode	X decay mode	B_{fit}	$B/B_{J/\psi\pi\pi}$
XK^\pm	$X \rightarrow J/\psi\pi\pi$	[0.035, 0.075]	N/A
XK^0	$X \rightarrow J/\psi\pi\pi$	—	N/A
XK^\pm	$X \rightarrow D^{*0}D^0$	[0.54, 0.8]	[3.9, 18.9]
XK^0	$X \rightarrow D^{*0}D^0$	—	—
XK	$X \rightarrow J/\psi\gamma$	[0.0075, 0.0195]	[0.19, 0.32]
XK	$X \rightarrow \psi(2S)\gamma$	[0.03, 0.09]	[0.75, 1.55]
XK	$X \rightarrow \gamma\gamma$	< 0.0004	< 0.0078
XK	$X \rightarrow J/\psi\eta$	< 0.098	< 1.9
XK	$X \rightarrow J/\psi\pi\pi\pi^0$	[0.015, 0.08]	[0.45, 1.44]

$\text{BF}(\text{B} \rightarrow \text{XK})$

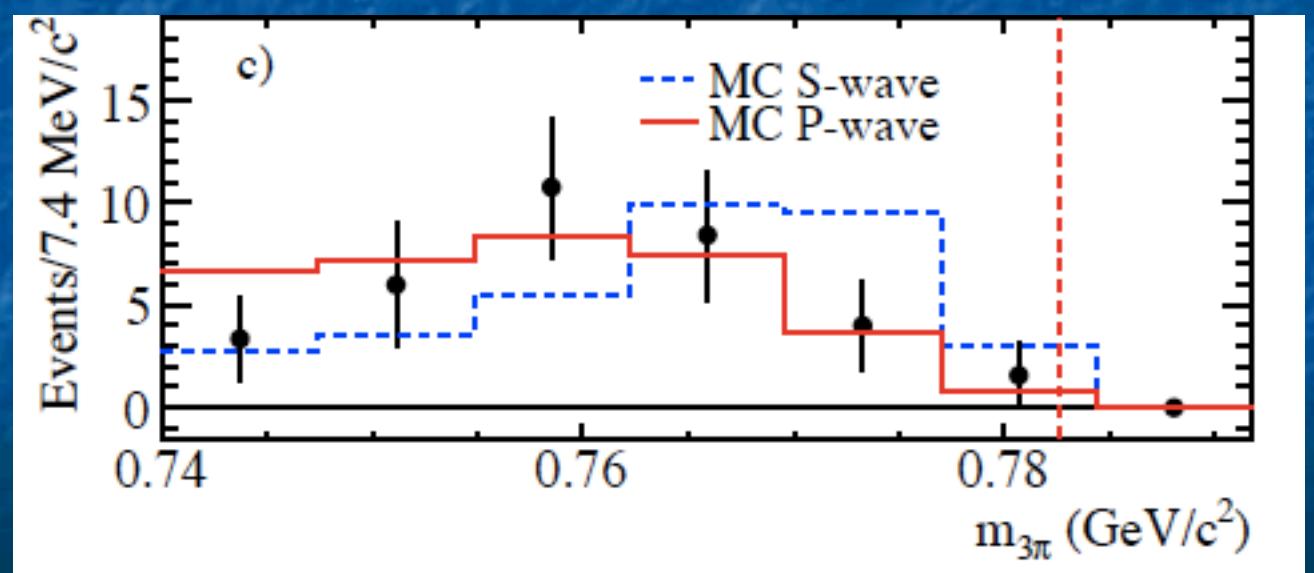


Very Recent development

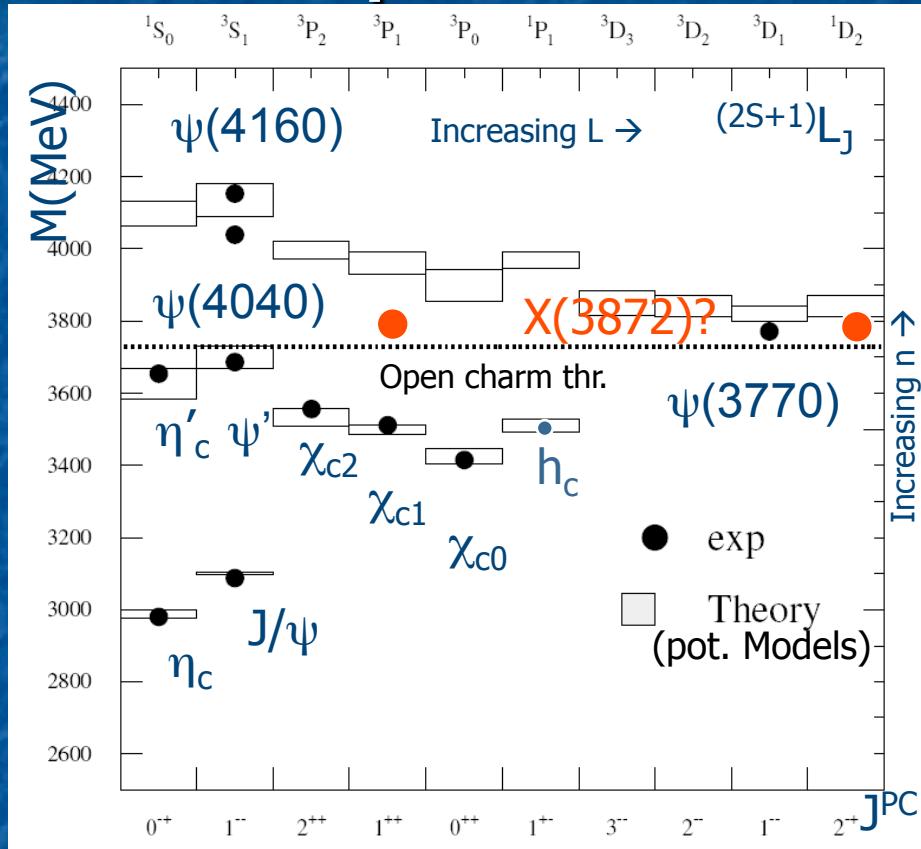
- Observation of $B \rightarrow X K$, $X \rightarrow J/\psi \pi$
- Test of J^{CP} assignment by checking centrifugal barrier on the ω mass spectrum

$J^{CP}=1^{++} :$
 $\chi^2/DOF=10/5$
 Prob=7%

$J^{CP}=2^{+-} :$
 $\chi^2/DOF=3.5/5$
 Prob=61%



The X(3872) puzzle



Charmonium:

- Cons
 - narrow to be above threshold
 - large BF in isospin violating $J/\psi\bar{p}$
 - low $BF(B \rightarrow XK)$

Molecules:

- Pros
 - Close to threshold
 - favors DD^* decays

- Cons
 - above threshold!
 - narrow
 - hard to match production Xsections in pp

Tetraquark :

- Pros:
 - explains small width
 - Any mass allowed
- Cons:
 - Several unobserved states predicted

Omitting dozens of theory references 13

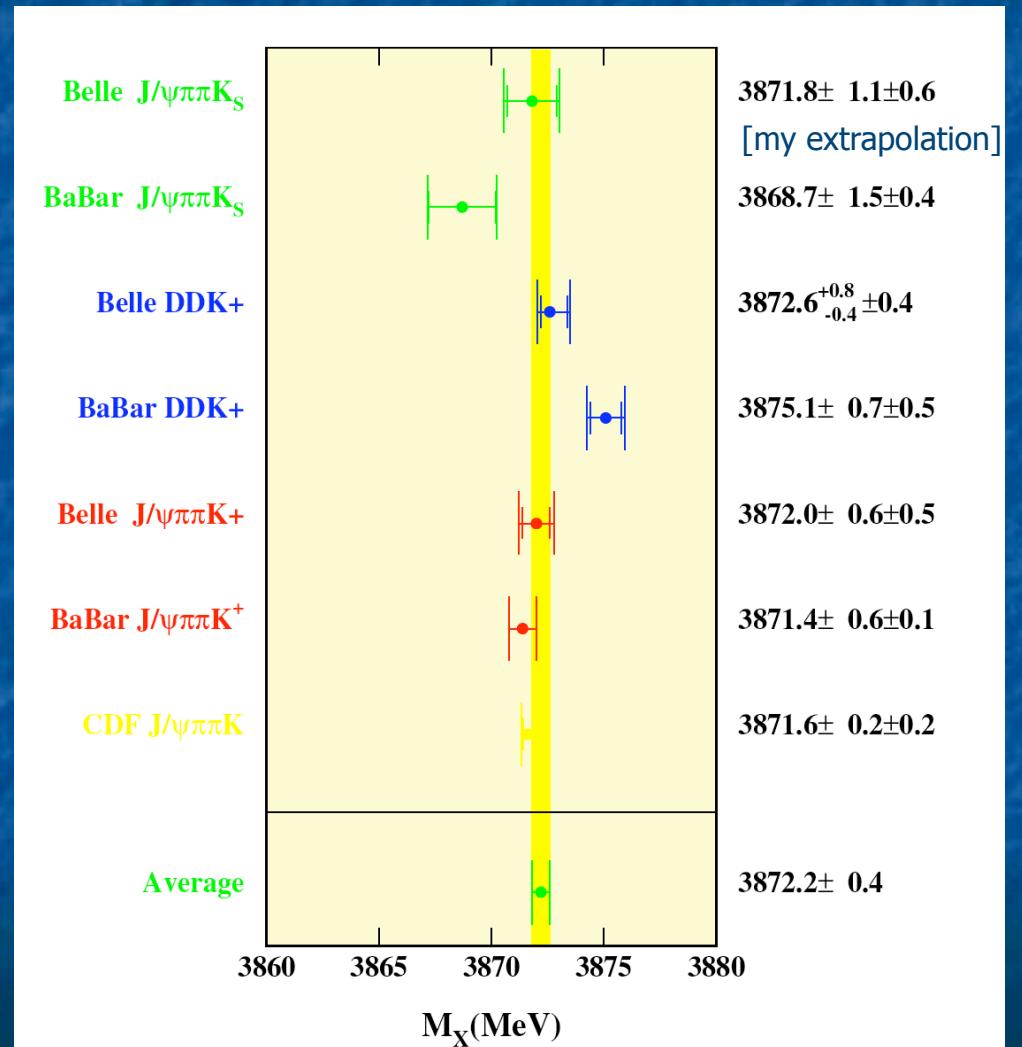
X(3872) mass in several final states

Poor agreement among
mass measurements:
 $X \rightarrow J/\psi\pi\pi$ and $X \rightarrow DD^{(*)}$
differ by $\sim 3.5\sigma$

TWO STATES? X(3872) & X(3876) ?

Predicted by tetraquark model
(but why so close to threshold?)

PRL 103:152001,2009
CDF inclusive $J/\psi\pi\pi$
 $\Delta M < 3.2$ MeV @90% C.L.



The new Charmonium zoology

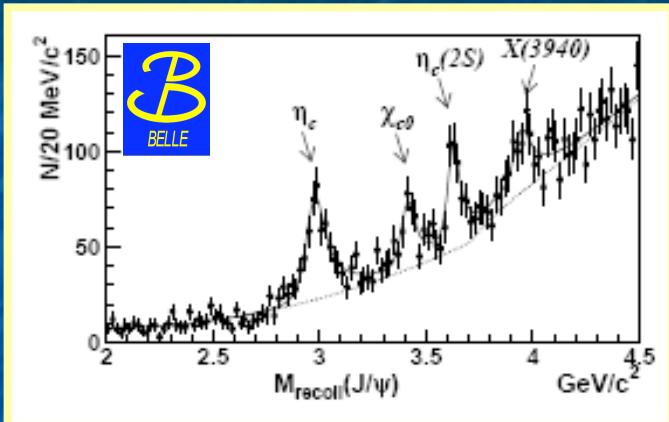
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- C=+

The 3940 family

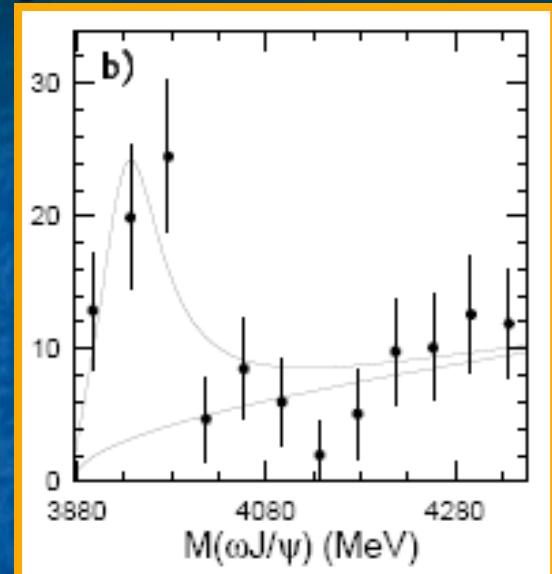
PRL 94, 182002 (2005)
PRL 101, 082001 (2008)



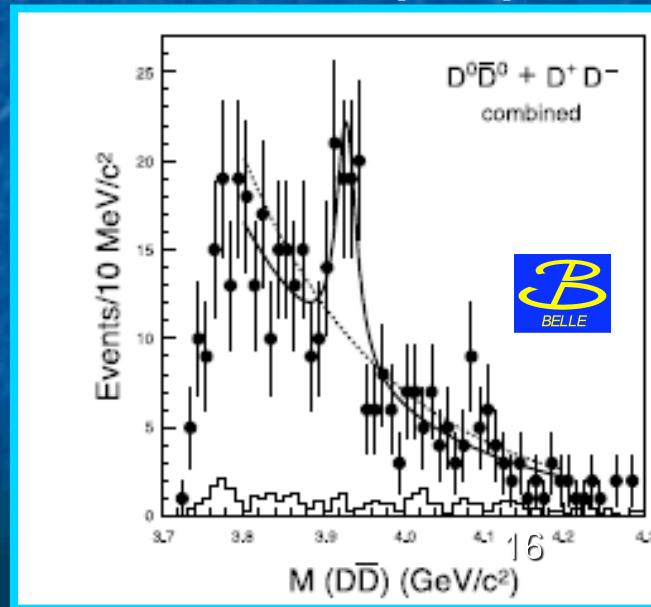
PRL 98, 082001 (2007)



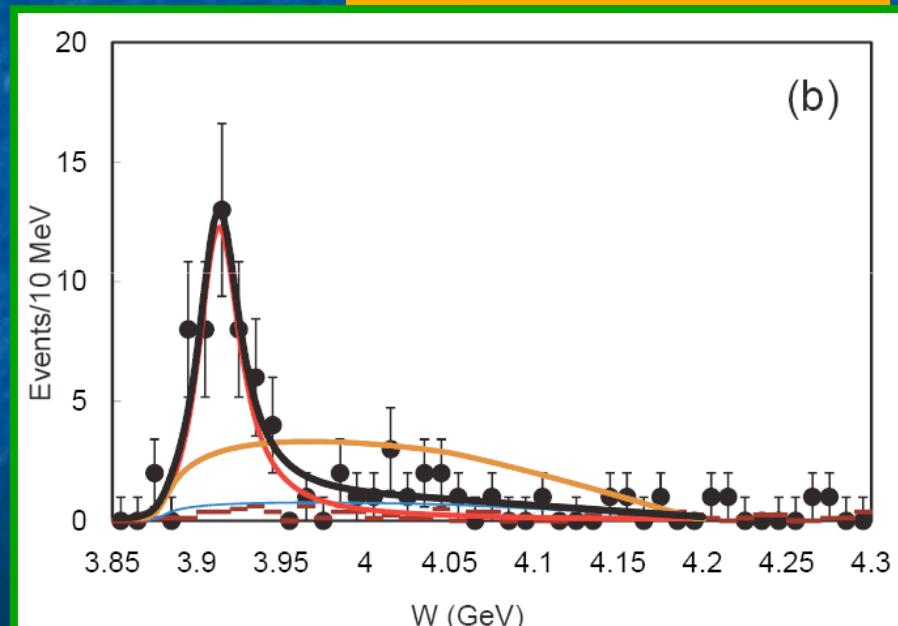
$B \rightarrow YK$
 $Y(3940) \rightarrow J/\psi \omega$



PRL 96, 082003 (2006)

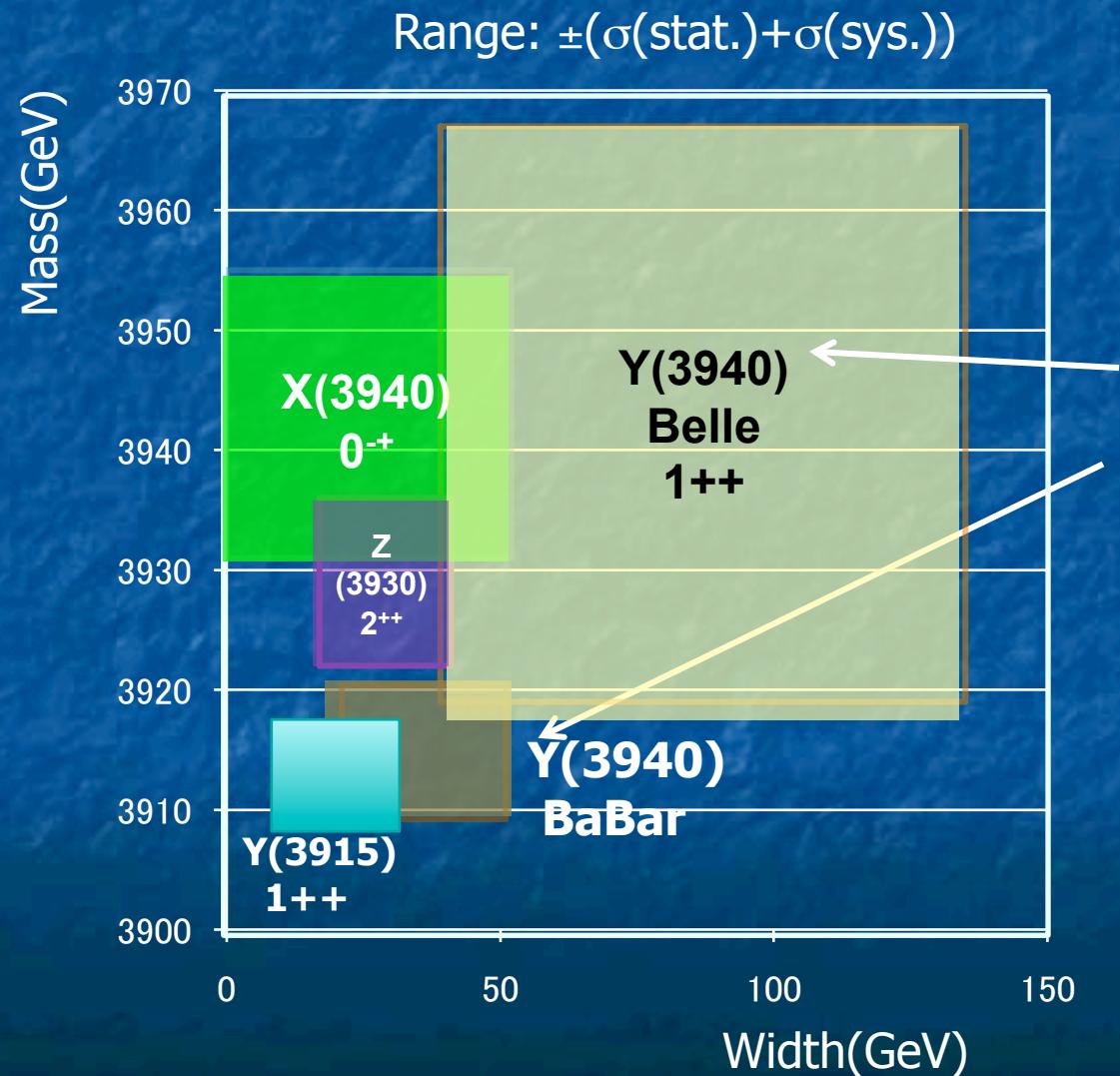


$\gamma\gamma \rightarrow Z$ $Z(3940) \rightarrow DD$



$\gamma\gamma \rightarrow Y$ $Y(3940) \rightarrow J/\psi \omega$

The 4 states near 3940



Better analysis of
the $J/\psi \omega$ mass
spectrum needed!!

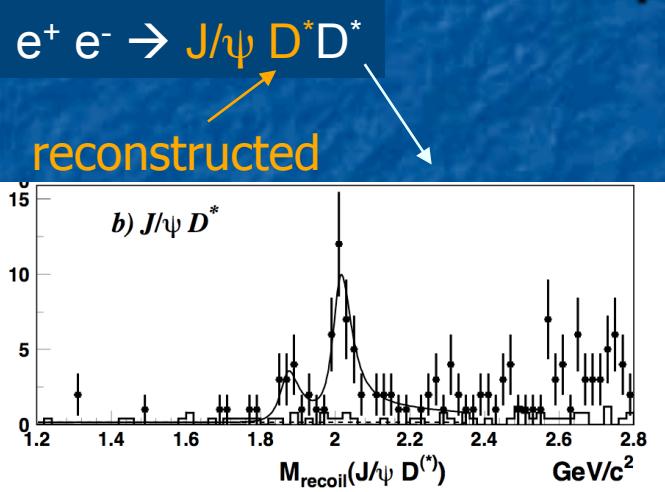
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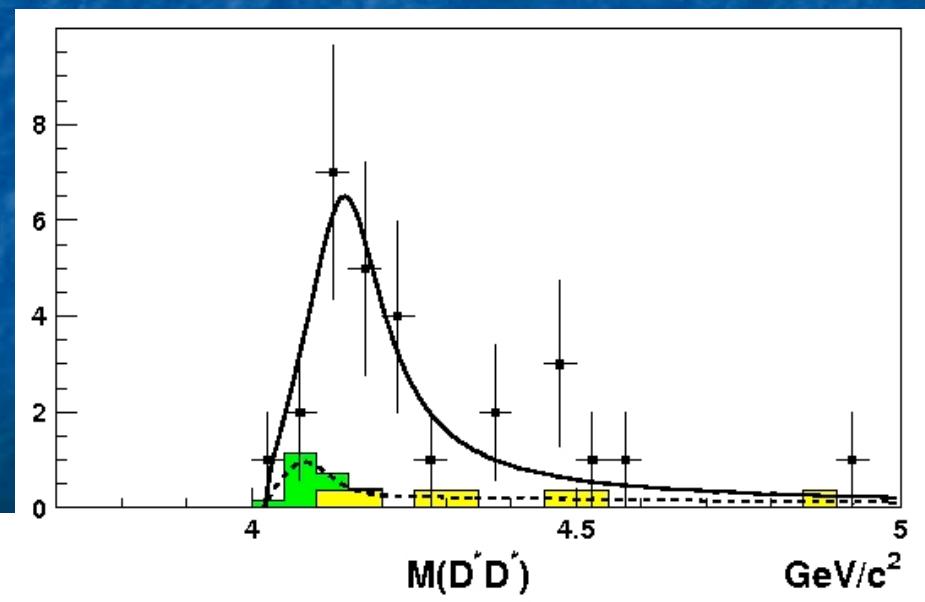
X(4160)

- Produced in $e^+e^- \rightarrow J/\psi X(4160)$
- Observed in $X(4160) \rightarrow D^*D^*$ with partial reco technique $J^{PC}=0^{\pm\pm}, 2^{\pm\pm}$



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

$$\Gamma_{\text{tot}} = 137^{+111}_{-61} \pm 21 \text{ MeV}$$

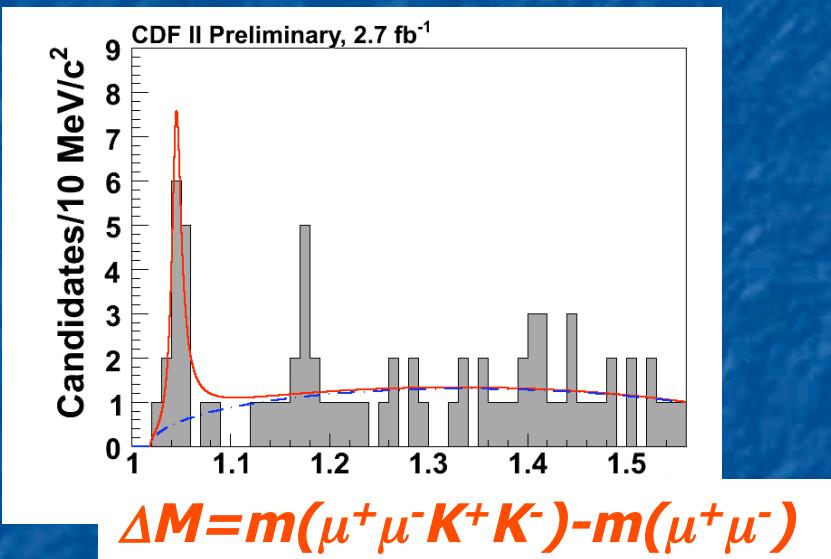




$\Upsilon(4140)$

PRL 102:242002, 2009

Search for $B \rightarrow YK$ $Y \rightarrow J/\psi\phi$



M: $4143.0 \pm 2.9 \pm 1.2 \text{ MeV}$,

Γ : $11.7^{+8.3}_{-5.0} \pm 3.7 \text{ MeV}$,

Signif. $> 3.8\sigma$

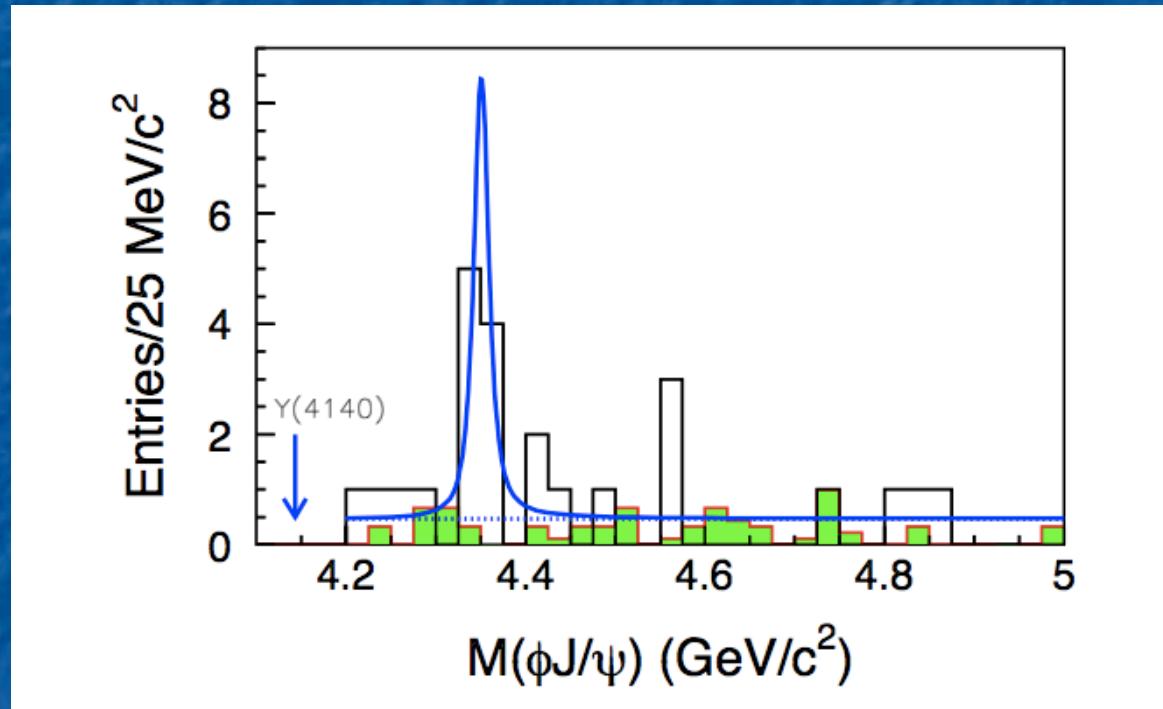
Interpretation

- Possible $J^{PC}=0^{++}, 1^{-+}, 2^{++}$
- Non Charmonium J^{CP} → hybrid
(lowest state predicted ~ 4100 MeV)
- Another 'edge' state, better candidate molecule

$\Upsilon(4140)$ in $\gamma\gamma \rightarrow X(4350)$



PRL104:112004, 2010



M: 4350 ± 5 MeV,
 Γ : $13^{+18}_{-9} \pm 4$ MeV,

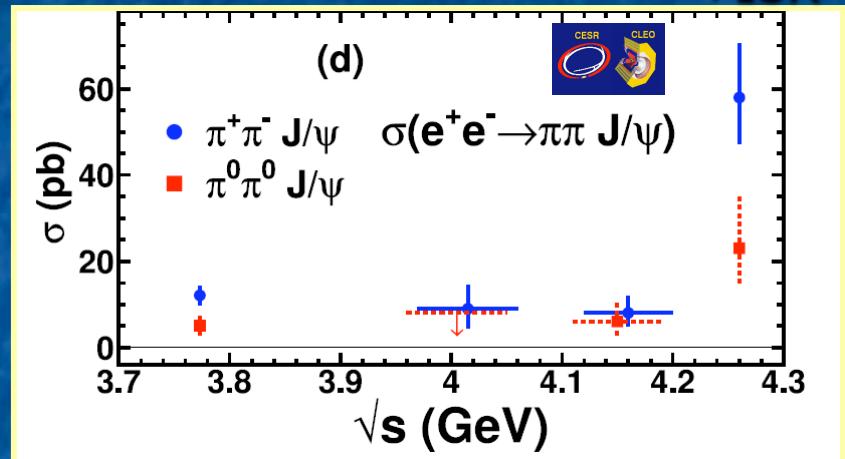
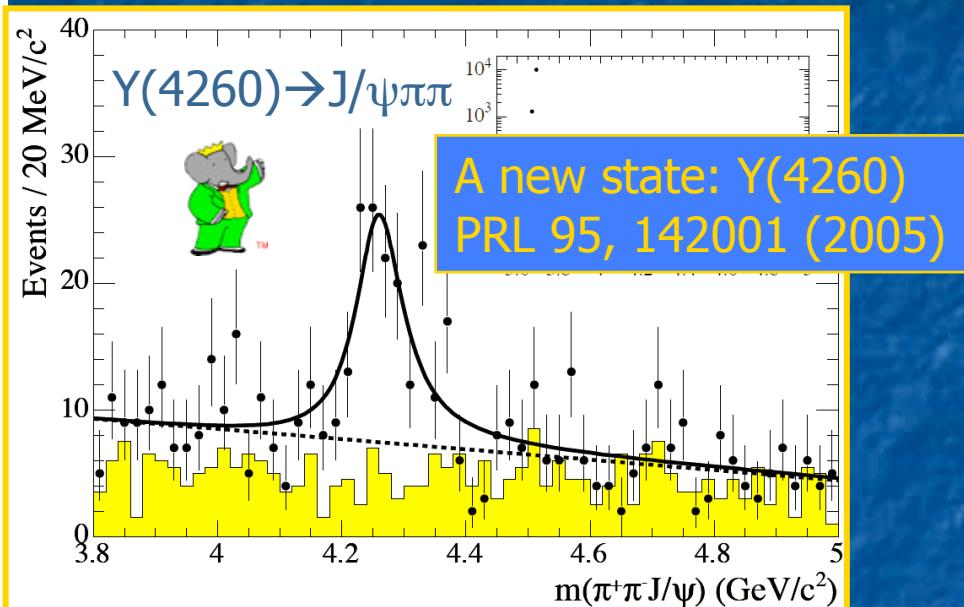
Signif. = 3.2σ

The new Charmonium zoology

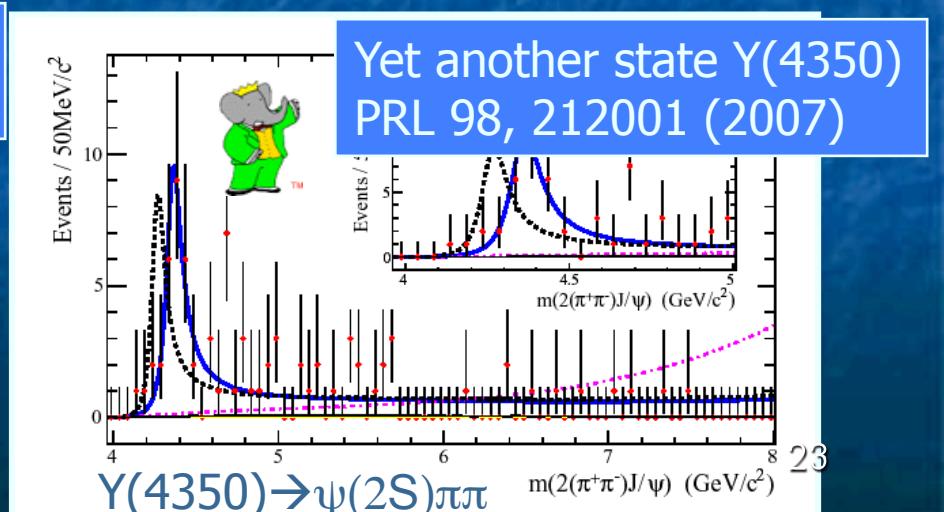
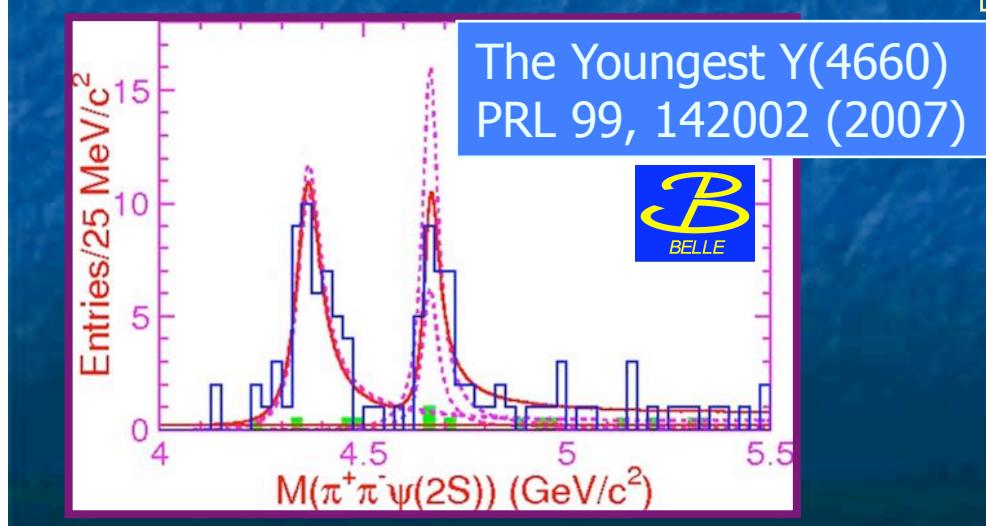
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The 1^{--} family

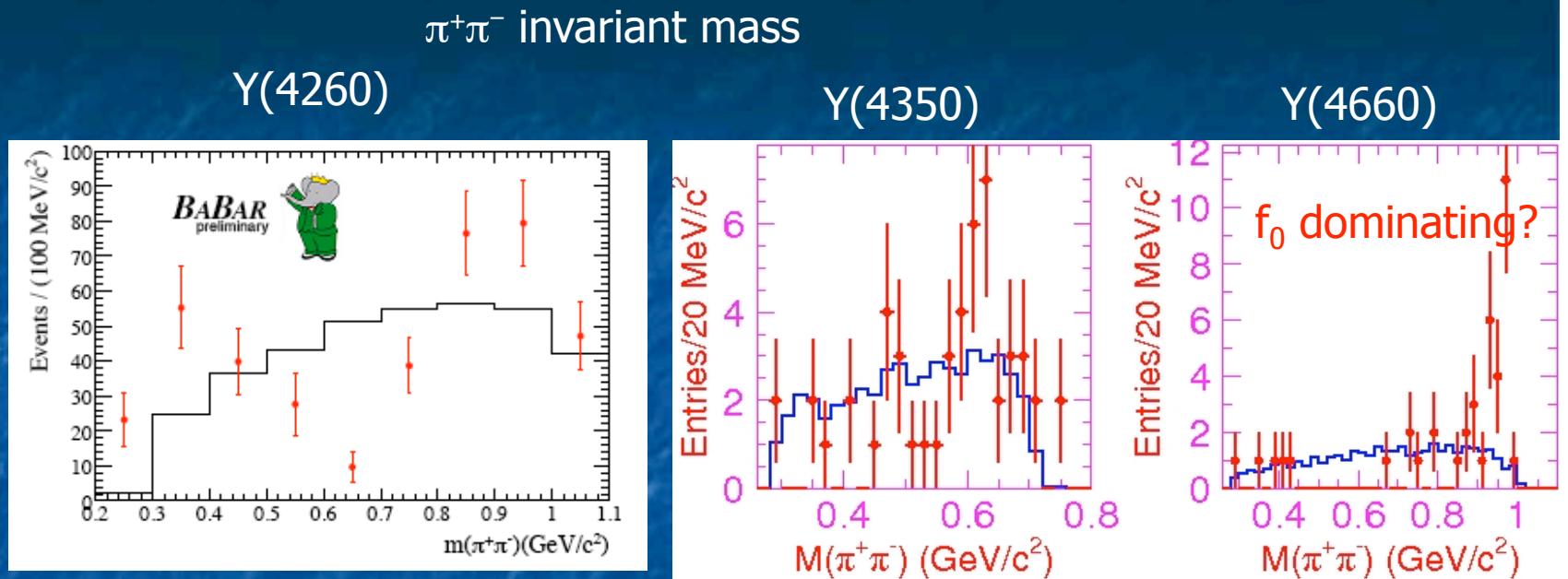
Several resonances observed in $e^+e^- \rightarrow Y\gamma_{\text{ISR}}$



Confirmation + $J/\psi \pi^0\pi^0$:
CLEO PRD74, 091104 (2006)
CLEO-c PRL 96, 162003 (2006)



DECAY PROPERTIES



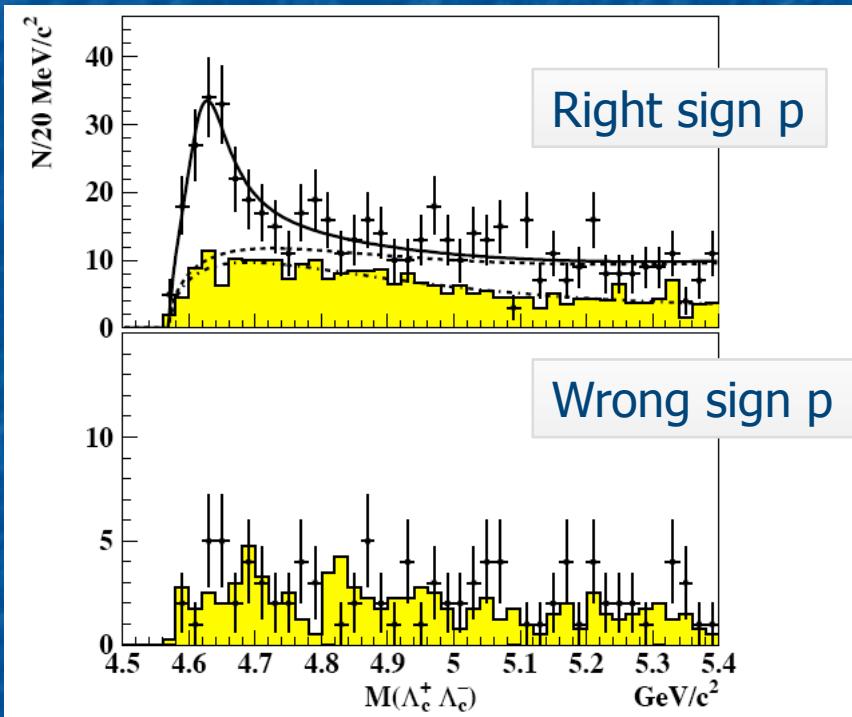
Also, why would $\Upsilon(4350)$ and $\Upsilon(4660)$ prefer $\psi(2S)\pi\pi$?

Radial or orbital excitation of tetraquarks would prefer $\psi(2S)$

n_r	ℓ	$R(\Upsilon/\psi - \psi)$
1	1	0.07
0	3	0.2
0	1	3.5

$\Upsilon(4660) \rightarrow \Lambda_c \bar{\Lambda}_c$

■ Search for ISR $e^+e^- \rightarrow \Lambda_c \bar{\Lambda}_c \gamma$ events



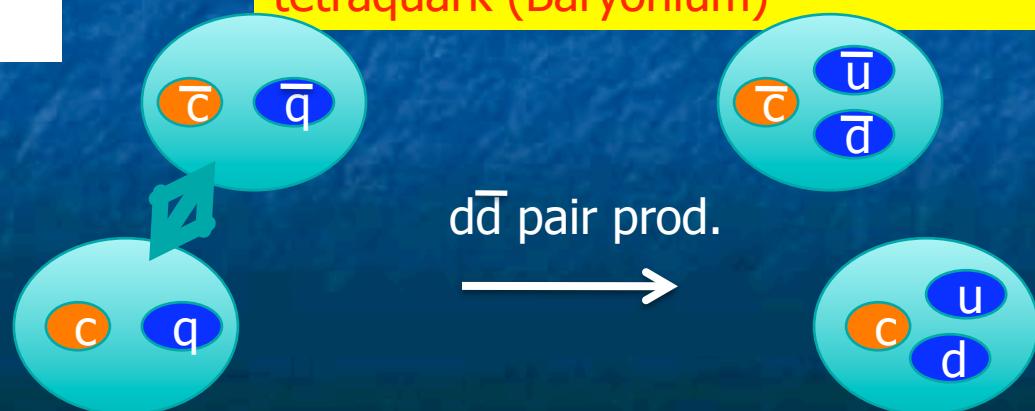
Cotugno, RF, Polosa, Sabelli

PRL104, 132005 (2010)

- simultaneous fit to $\psi(2S)\pi\pi$ and $\Lambda_c \bar{\Lambda}_c$ modes has good χ^2
- $M=4661 \pm 9$ MeV $\Gamma=61 \pm 23$ MeV
- Large preference of the baryonic decay model!

$$\mathcal{B}(Y_B \rightarrow \Lambda_c \bar{\Lambda}_c) / \mathcal{B}(Y_B \rightarrow \psi(2S)\pi\pi) = 117 \pm 44$$

$\Upsilon(4660)$ good candidate for a tetraquark (Baryonium)



The new Charmonium zoology

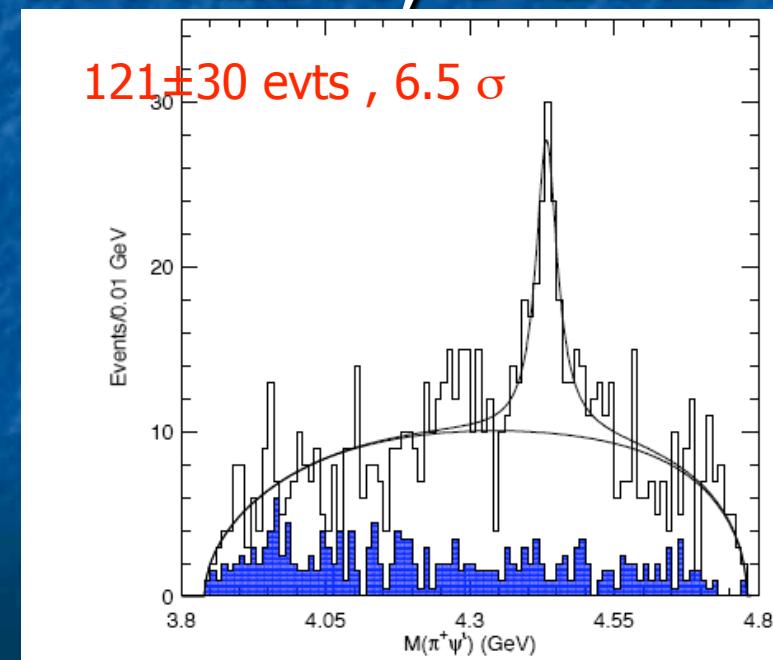
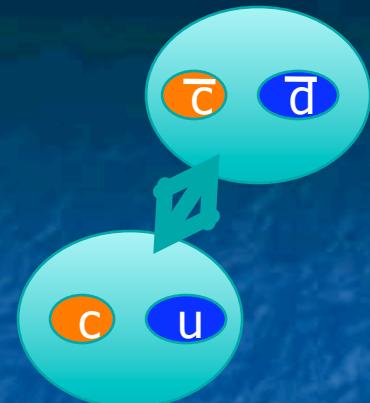
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The Z(4430)⁺

- Charged states a strong prediction of the tetra-quark model
- First observed by Belle in PRL100, 142001 (2008)
- Search for $Z^\pm \rightarrow J/\psi$ or $\psi(2S) + \pi^\pm$
In $B \rightarrow \psi\pi^\pm K$ decays

M=4433±4±2 MeV

$\Gamma=45^{+18}_{-13} {}^{+30}_{-13}$ MeV



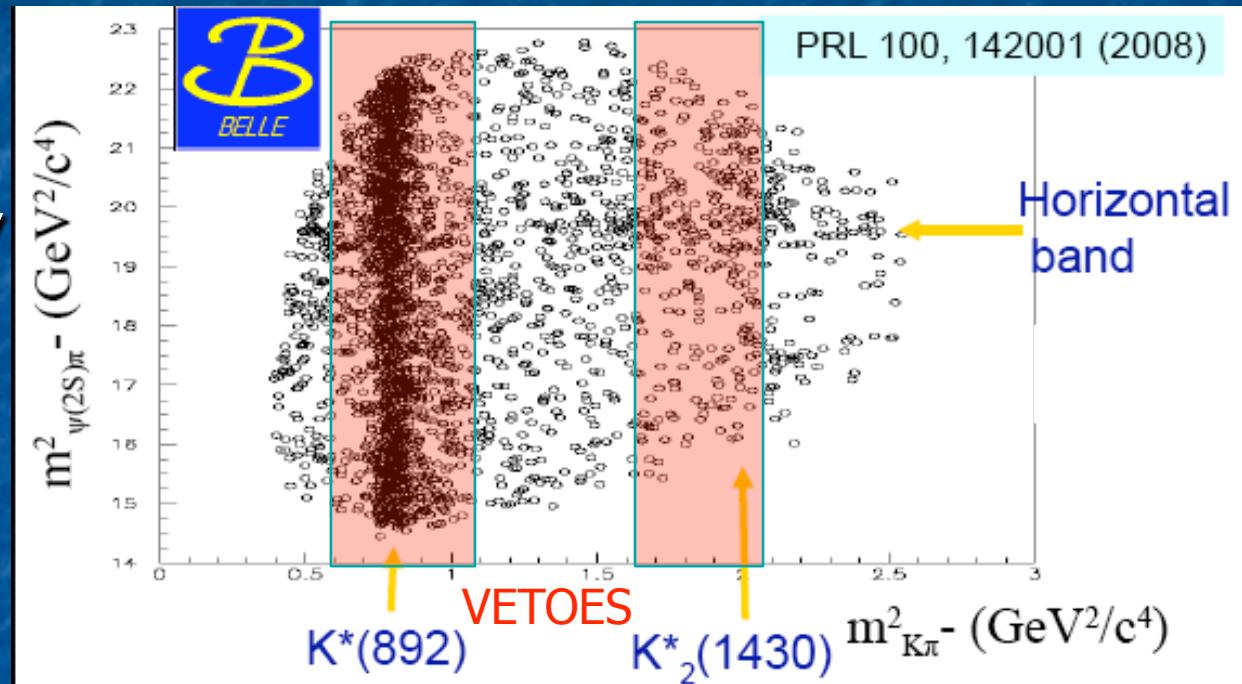
Criticisms to “discovery analysis”

- Only “global” efficiency correction

- Poor

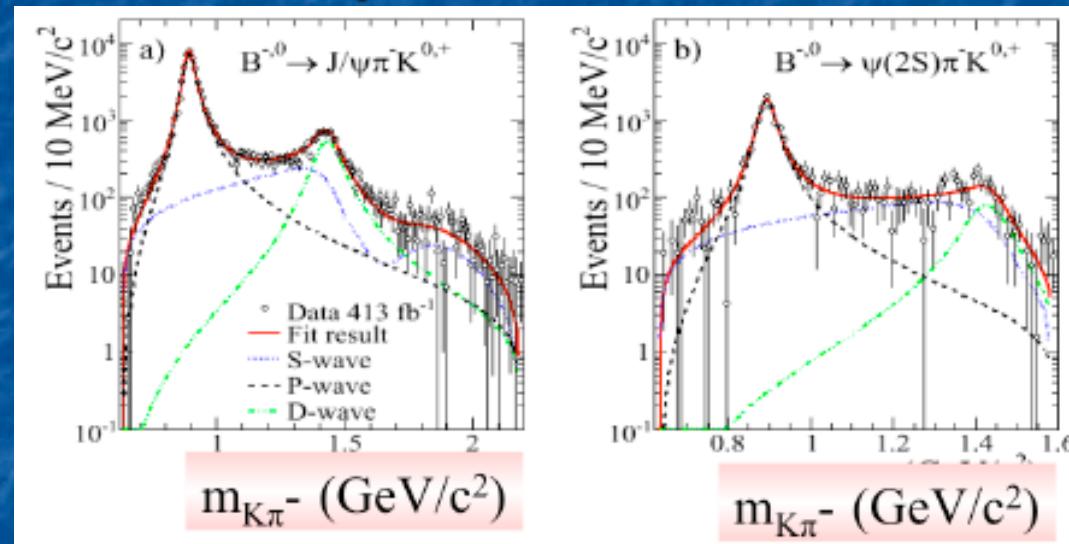
treatment of 3-body decays (cut away dominant resonances – no interference/reflections)

- Arbitrary choice of background shape



BaBar Analysis

- Event-by-event efficiency correction
- Describe the $K\pi$ system in detail
 - Mass



- Angular distributions fitted with Legendre Polynomials

BaBar results

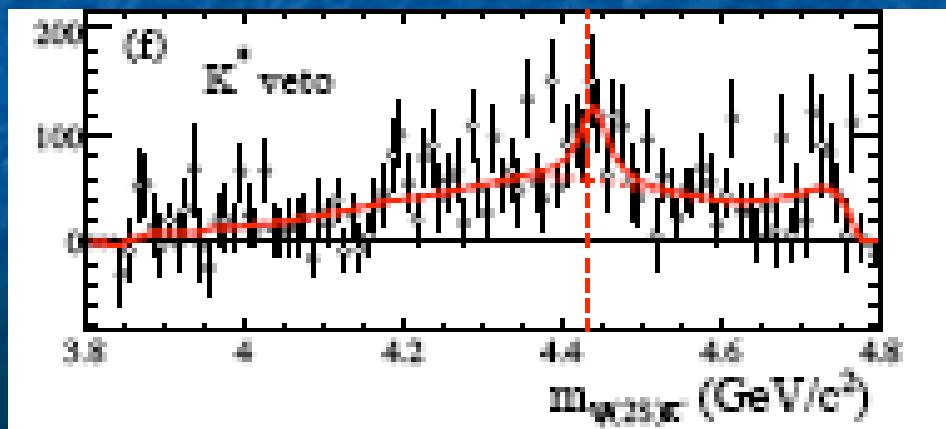
■ Fitting without vetoes

$m = 4476 \pm 8 \text{ MeV}/c^2$; $\Gamma = 32 \pm 16 \text{ MeV}$; signal size: 2.7σ

[offset of $43 \pm 9 \text{ MeV}$ w.r.t. Belle]

■ Same vetoes as Belle

$m = 4439 \pm 8 \text{ MeV}/c^2$; $\Gamma = 41 \pm 33 \text{ MeV}$; signal size 1.9σ

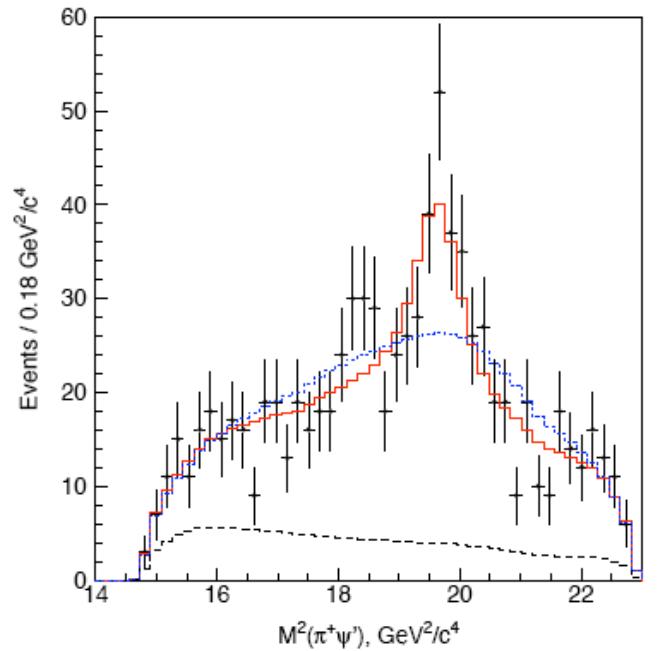


Conclusions:

- mistreatment of background might enhance significance
- veto might bias signal mass measurement

Belle Dalitz Plot Analysis

- Belle's observation confirmed, but errors increase
- Including $\psi(2S)W$



$W =$	Fit fraction (%)	Significance
$Z(4430)^+$	$5.7^{+3.1}_{-1.6}$	6.4σ
κ	$4.1^{+3.4}_{-1.1}$	1.5σ
$K^*(892)$	$64.8^{+3.8}_{-3.5}$	large
$K^*(1410)$	$5.5^{+8.8}_{-1.5}$	0.5σ
$K_0^*(1430)$	5.3 ± 2.6	1.3σ
$K_2^*(1430)$	$5.5^{+1.6}_{-1.4}$	3.1σ
$K^*(1680)$	$2.8^{+5.8}_{-1.0}$	1.2σ

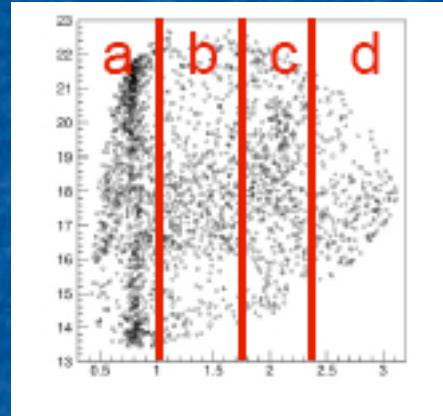
$$\begin{aligned} m &= 4443^{+24}_{-18} \text{ MeV} \\ \Gamma &= 109^{+113}_{-71} \text{ MeV} \end{aligned}$$

$$\mathcal{B}(\bar{B}^0 \rightarrow K^- Z(4430)^+) \times \mathcal{B}(Z(4430)^+ \rightarrow \pi^+ \psi')$$

CFR. BaBar excludes 3.1×10^{-5} @90% C.L.

$$= (3.2^{+1.8+5.3}_{-0.9-1.6}) \times 10^{-5}$$

Z^1 and $Z^2 \rightarrow \chi_{c1}\pi$



$\xrightarrow{b+d}$

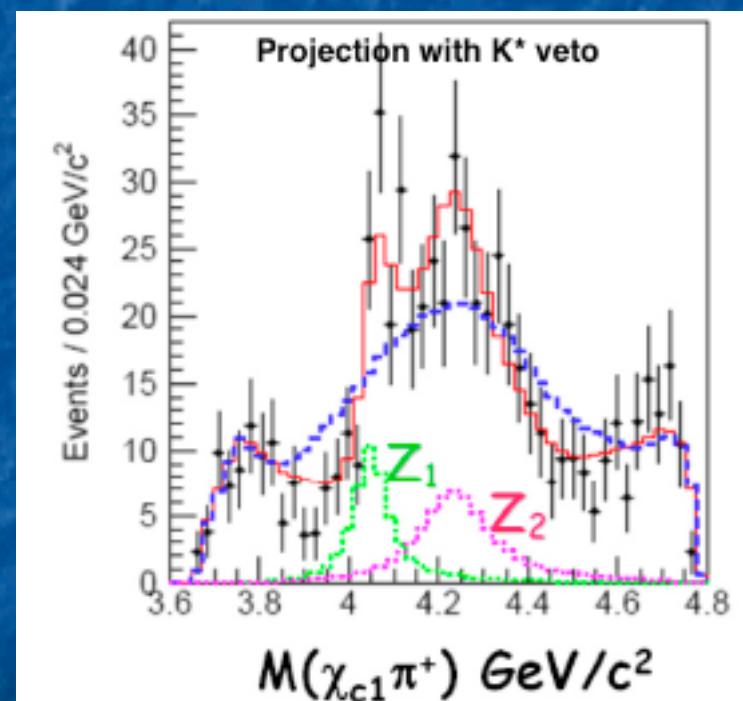
$$M_1 = (4051 \pm 14^{+20}_{-41}) \text{ MeV}/c^2,$$

$$\Gamma_1 = (82^{+21+47}_{-17-22}) \text{ MeV},$$

$$M_2 = (4248^{+44+180}_{-29-35}) \text{ MeV}/c^2,$$

$$\Gamma_2 = (177^{+54+316}_{-39-61}) \text{ MeV},$$

Same analysis strategy



$$\mathcal{B}(\bar{B}^0 \rightarrow K^- Z_1^+) \times \mathcal{B}(Z_1^+ \rightarrow \pi^+ \chi_{c1}) = (3.0^{+1.5+3.7}_{-0.8-1.6}) \times 10^{-5},$$

$$\mathcal{B}(\bar{B}^0 \rightarrow K^- Z_2^+) \times \mathcal{B}(Z_2^+ \rightarrow \pi^+ \chi_{c1}) = (4.0^{+2.3+19.7}_{-0.9-0.5}) \times 10^{-5}.$$

$J^P=1^-$ assuming $L=0$

Summary (I)

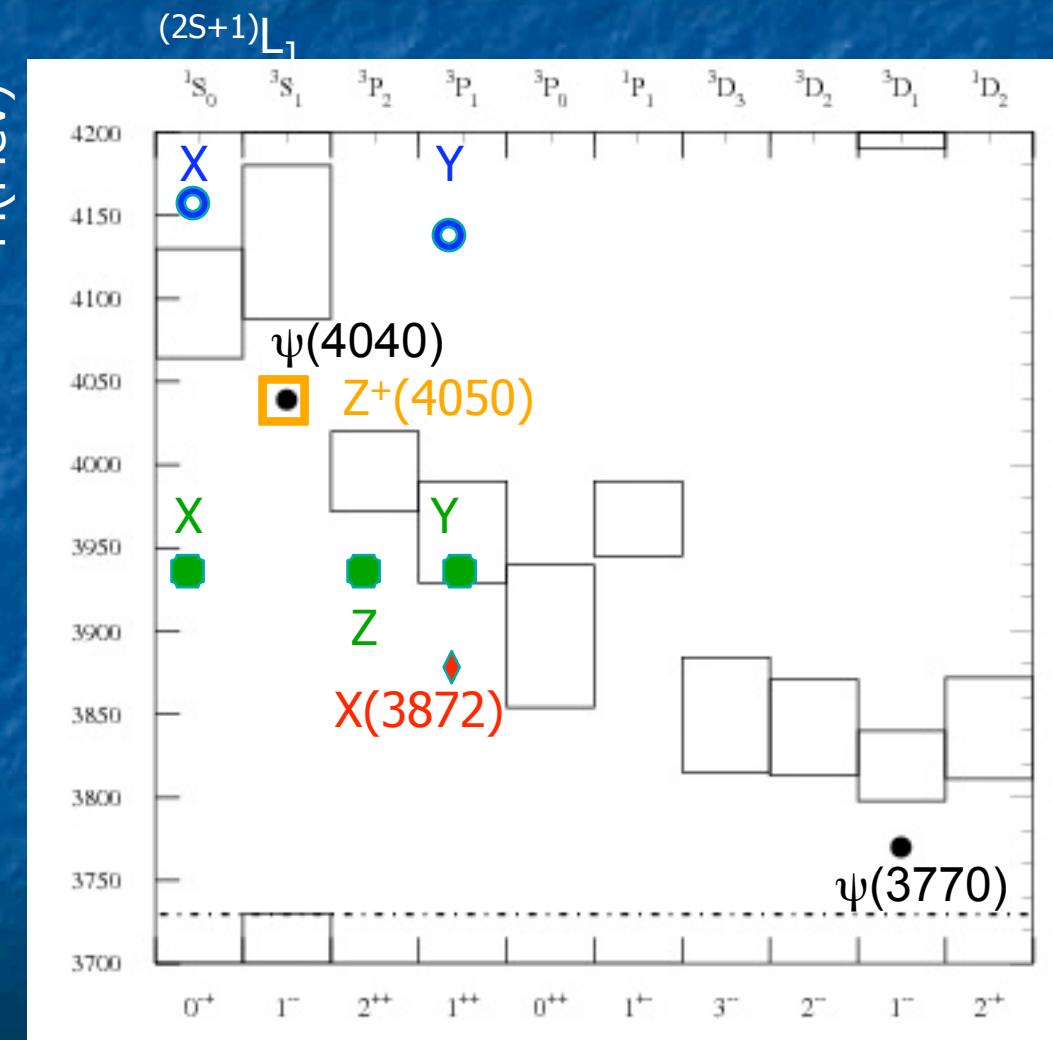
$\psi(4040)$ and $Z\pm(4050)$ and
isospin triplet?!?

X(4140): candidate $\eta_c(3S)$
Y(4160): candidate hybrid

3940 family:
X candidate tetraquark
Y,Z candidate $\chi(2P)_{1,2}$

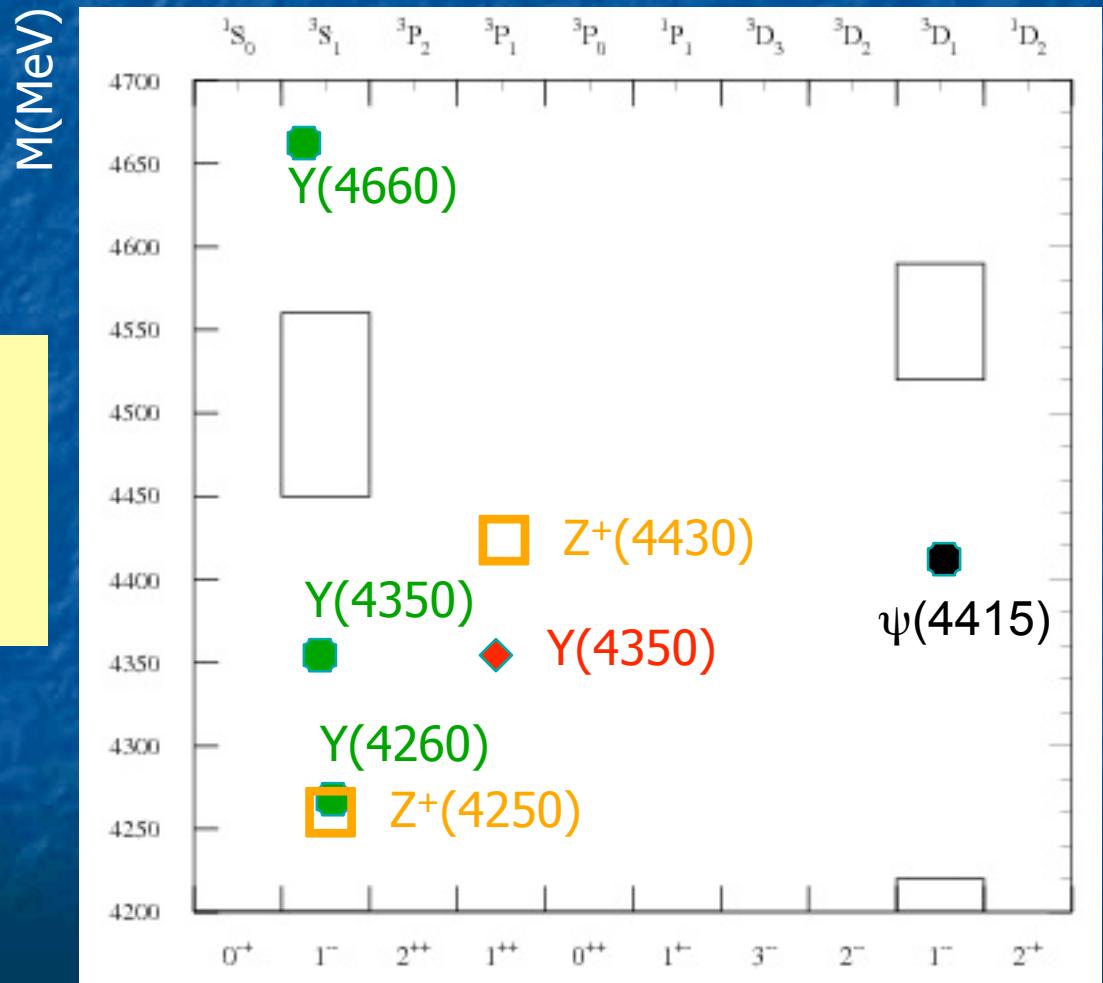
X: the most debated
(tetraquark vs DD*
molecule)

M(MeV)



Summary (II)

$(2S+1)L_J$



1^- family:

$Y(4660)$ best tetraquark candidate

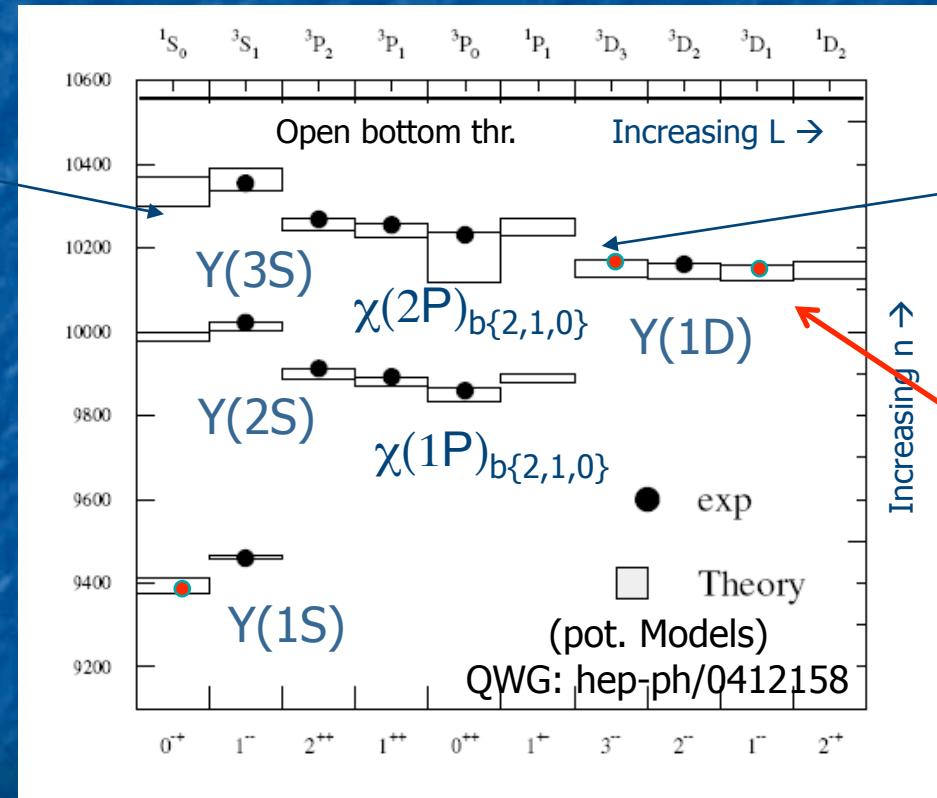
$Y(4260)$ and $Z^\pm(4250)$ an isospin triplet?!?



The new Bottomonium zoology

Bottomonium: state of the art

η_b (x2)
completely
missing



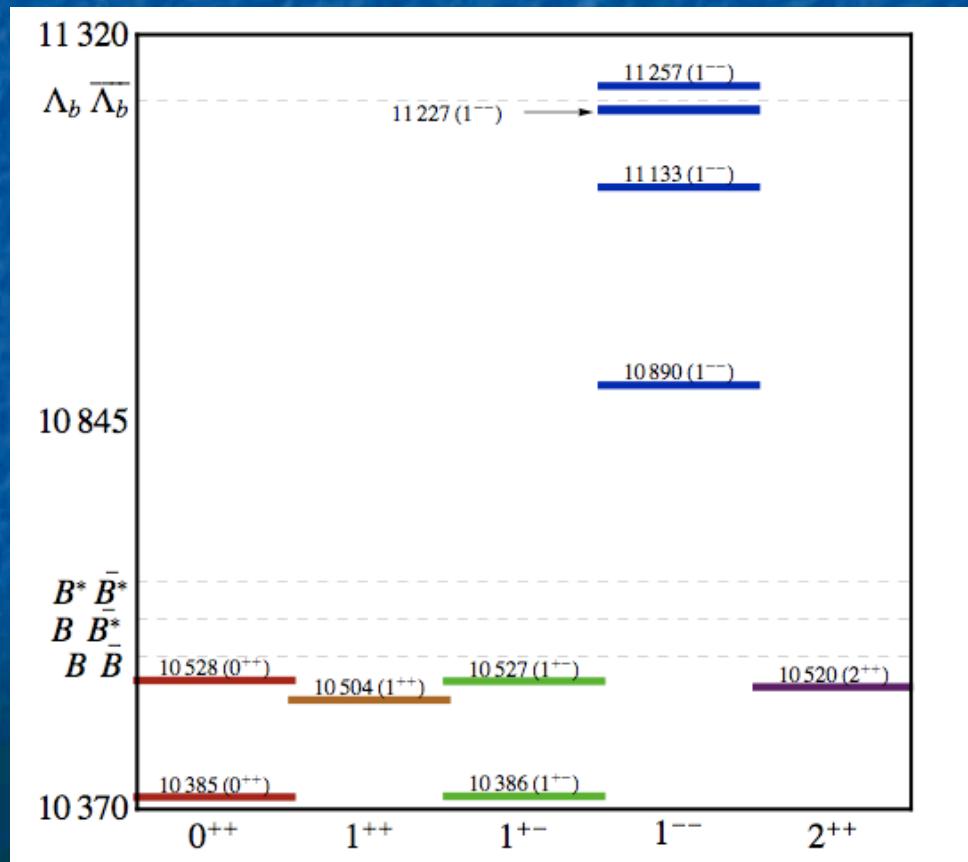
2 h_b states and a
D state are
narrow but not
observed

Recent Observations:
 η_b , 3D_J

5 narrow resonances still missing !

Exotic states

- Several unexpected 1^- charmonium-like states [$\Upsilon(4260)$, $\Upsilon(4350)$, $\Upsilon(4660)$] have been observed decaying into J/ψ or $\psi(2S)$ and two pions
 - Exotic particles, candidates for tetraquarks and hybrids / new spectroscopy in general
- Sitting at their center of mass allows a much better understanding of their decay properties → Mostly sensible to 1^- states

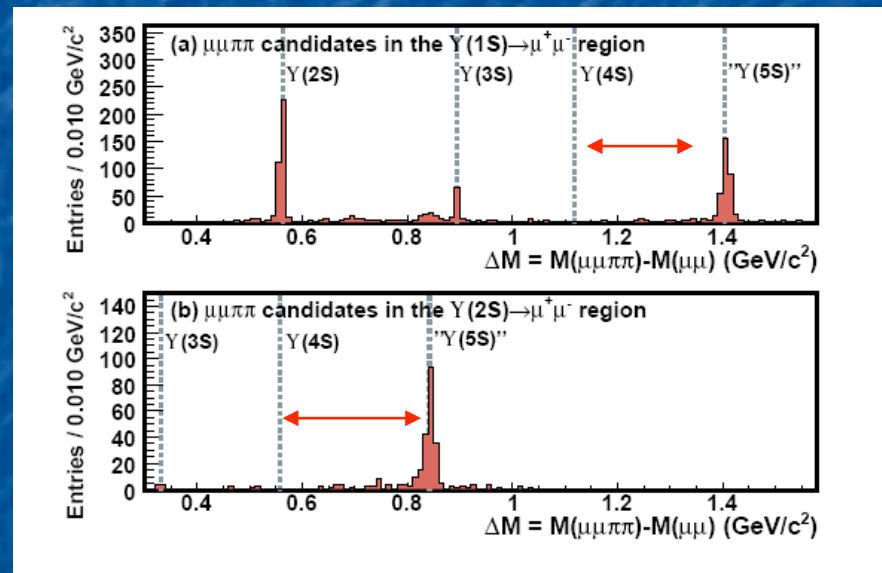


Expected tetraquark spectrum
PLB684:28,2010

Tetraquark candidates: Y(5S)

Recent observation from Belle of unusual behaviour of Y(5S) in its decay to Y(nS) $\pi\pi$

- Y(5S) good tetraquark candidate
- Expect to see other resonances with such an excess

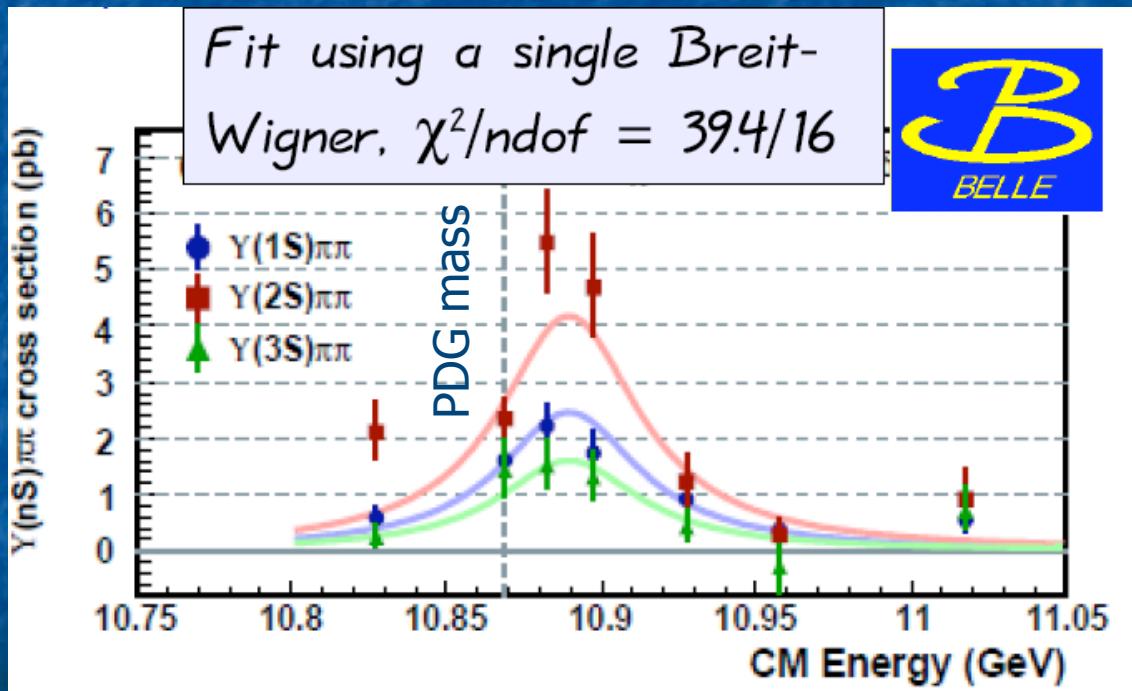


Belle: $L=21\text{fb}^{-1}$ @ Y(5S)

- This measurement also tells us that $\sigma^* \text{BF}(Y_b \rightarrow Y(1S)\pi\pi) \leq 10 \text{ pb}$

Scan around $\Upsilon(5S)$

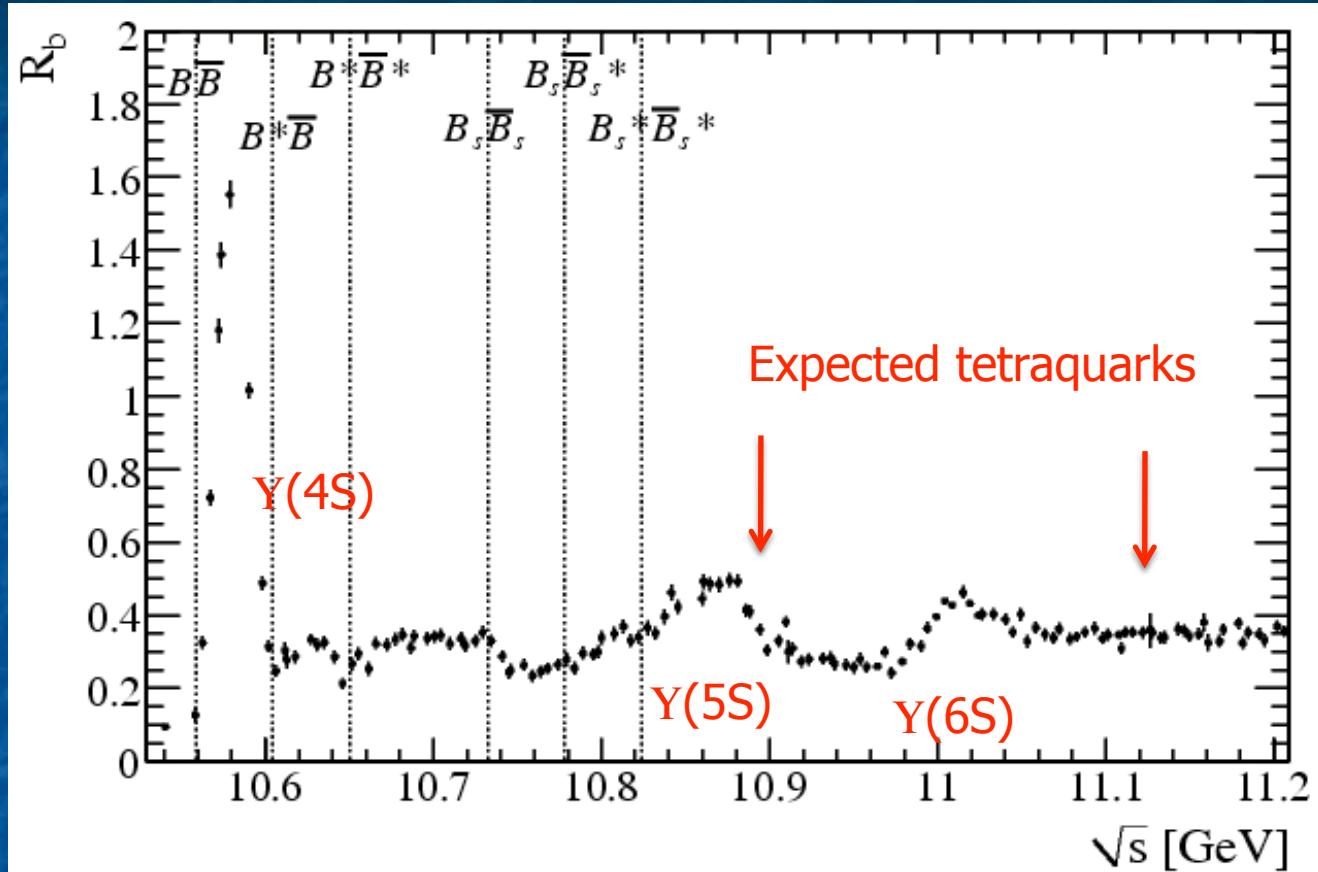
- Search for $\Upsilon \rightarrow \Psi(nS)\pi\pi$ in analogy to $\Upsilon \rightarrow \psi\pi\pi$



$$M_Y = (10889 \pm 2) \text{ MeV}$$

$$\Gamma_Y = (55 \pm 9) \text{ MeV}$$

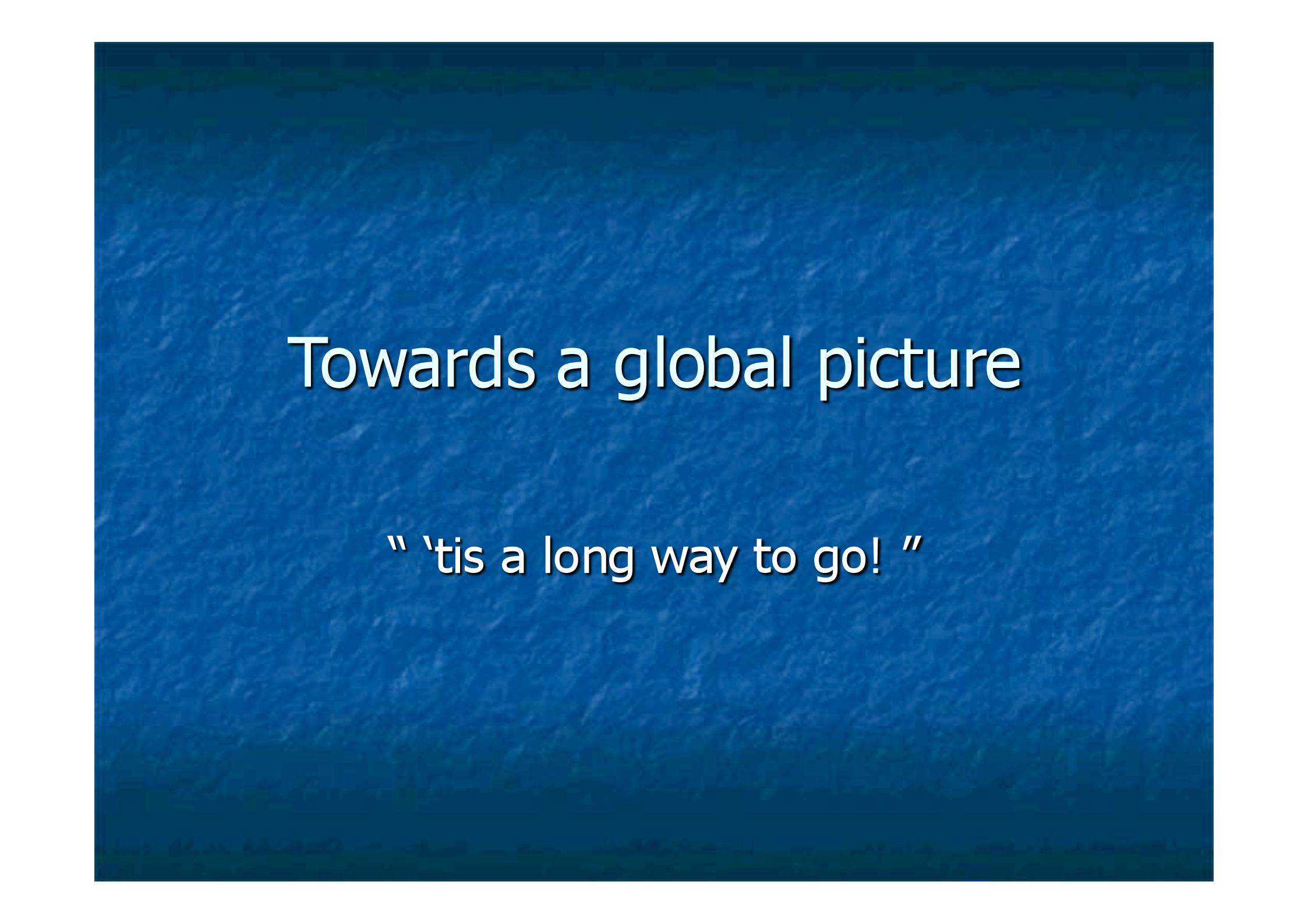
Scan between $\Upsilon(4S)$ and $\Lambda_b \bar{\Lambda}_b$



PRL 102, 012001 (2009)

Main result: $\Upsilon(5,6S)$
inconsistent with PDG

	$\Upsilon(5S)$	$\Upsilon(6S)$
$M [MeV]$	10876 ± 2	10960 ± 2
$\Gamma [MeV]$	43 ± 4	37 ± 3
$\phi [rad]$	2.11 ± 0.12	0.12 ± 0.07
$M_{PDG} [MeV]$	10865 ± 8	11019 ± 8
$\Gamma_{PDG} [MeV]$	110 ± 13	79 ± 16

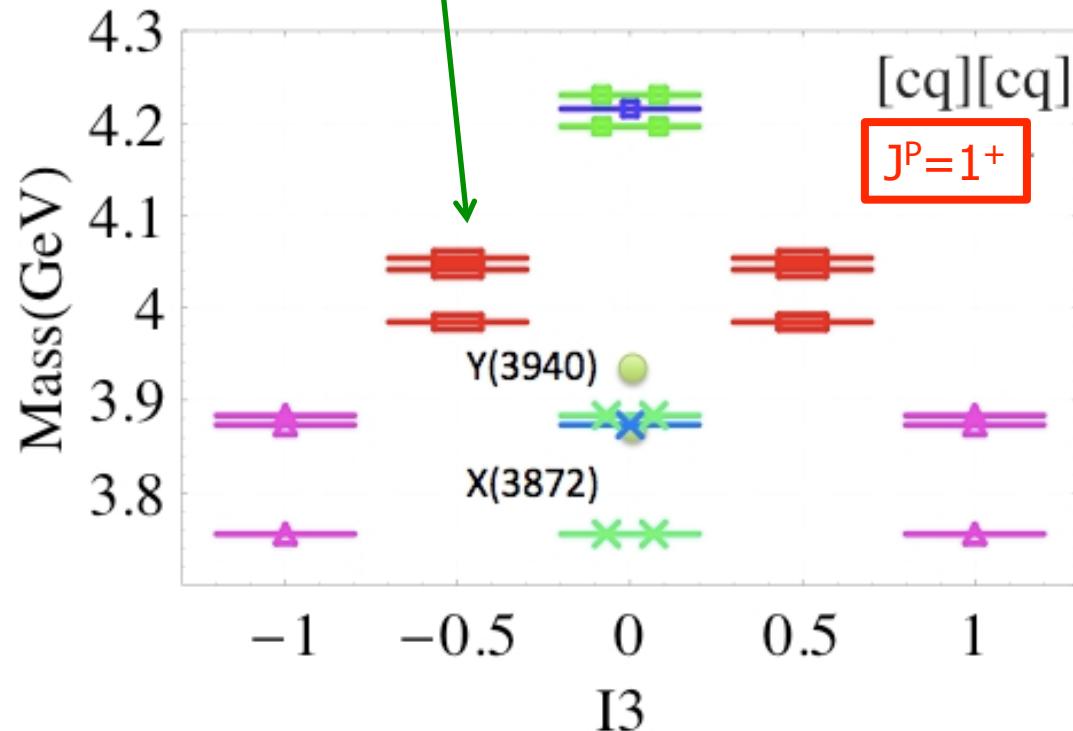


Towards a global picture

" 'tis a long way to go! "

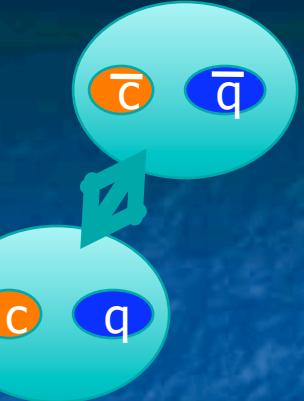
Interpretative hazards: tetraquarks

States decaying into
 ψK , never looked for !

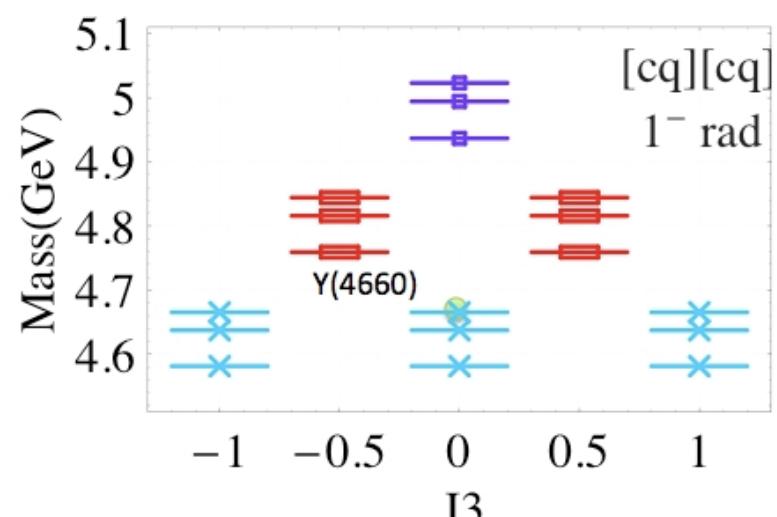
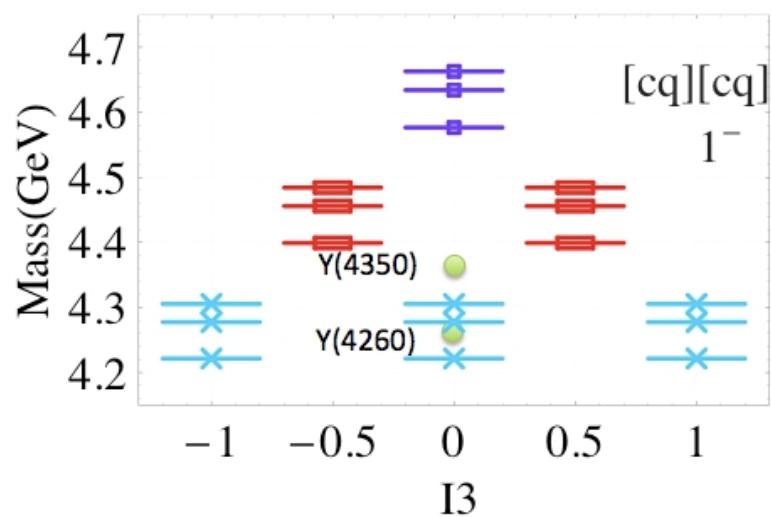
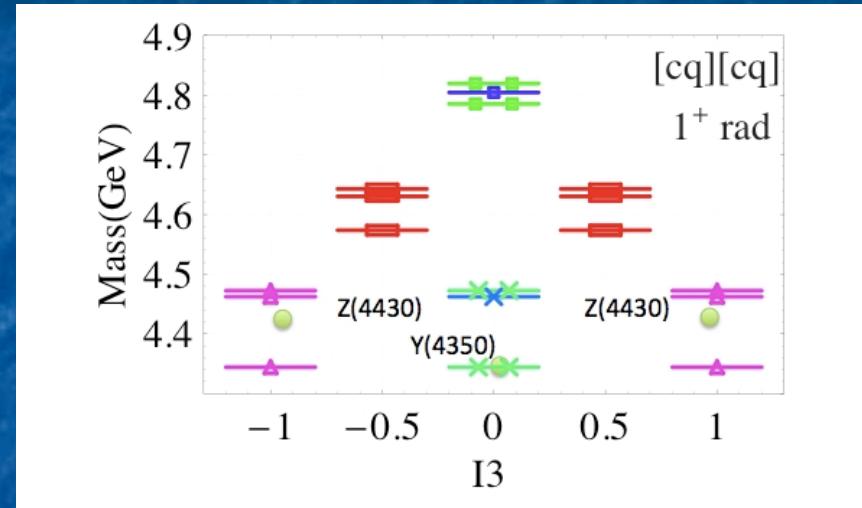


Spectra based on :

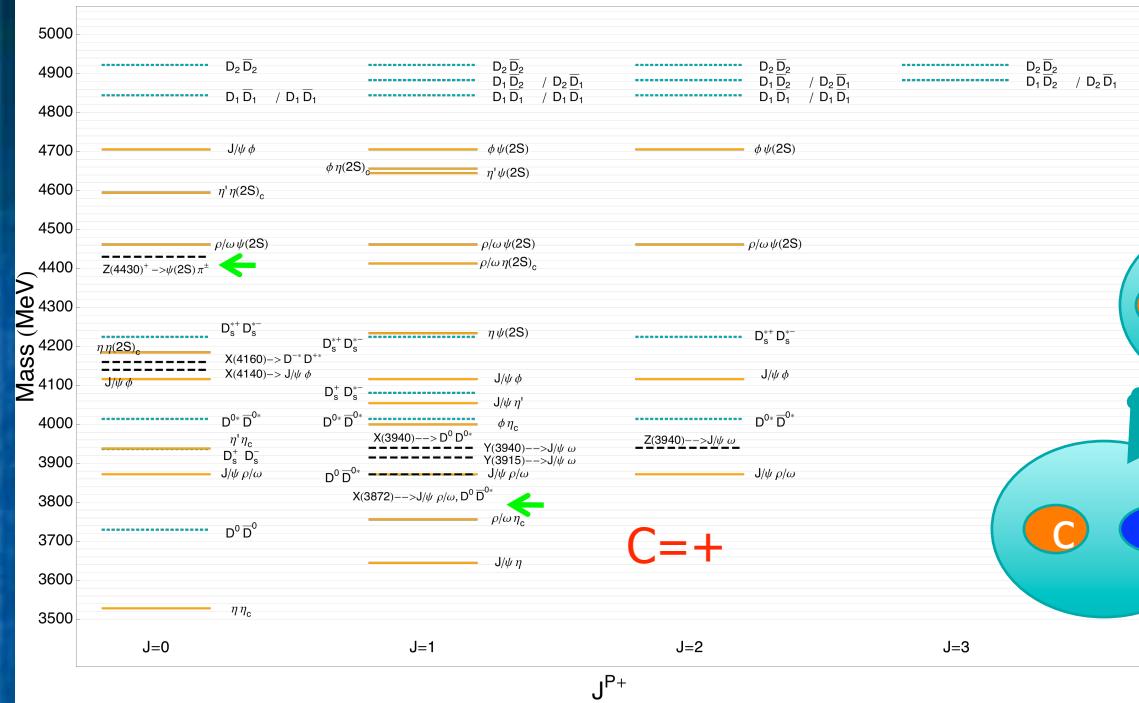
1. Quark constituent model (as in Maiani et al,
2. orbital excitations based on Chew-Frautschi as in [hep-ph/0602128](#)
3. radial excitations taken from standard charmonium



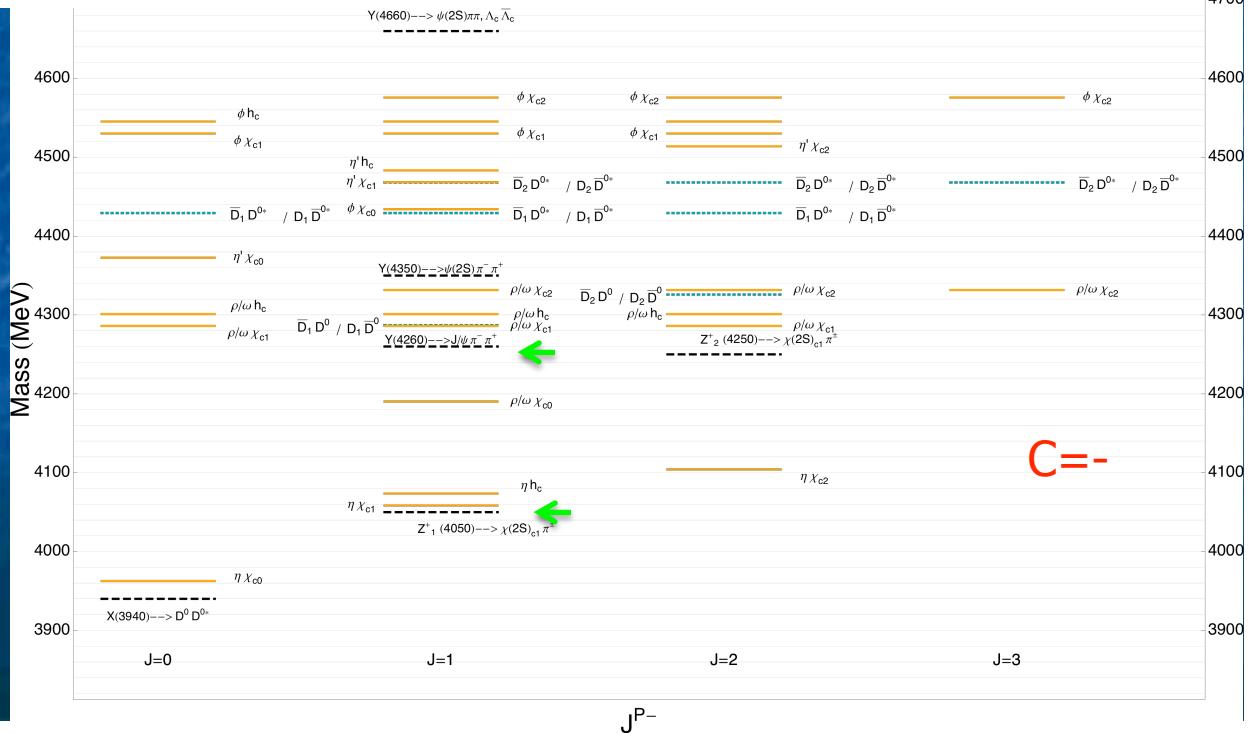
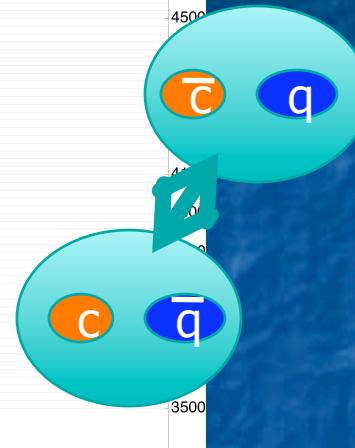
More tetraquark spectra



Interpretative hazards: molecules



$C=+$



$C=-$

Legenda

- charm – charm
- charmonium - light

- - - - data

Interesting states: right below a threshold (\rightarrow)

Outlook

B decays	JP/C	J/ψππ	J/ψω	J/ψγ	J/ψΦ	J/ψη	ψ(2S)ππ	ψ(2S)ω	ψ(2S)γ	χcγ	pp	ΛΛ	ΔcΔc	DD	DD*	D*D*	Ds(*)Ds(*)	γγ
X(3872)	1++ [2- +]	S	S*	S	N/A	N/S	N/A	N/A	S	N/S	M/F	M/F	N/A	N/A	S	N/A	N/A	N/S
X,Y (3940)	0+-	M/F	S	N/S	N/A	N/A	N/A	N/A	M/F	N/A	M/F	M/F	N/A	M/F	N/S	N/A	N	N
Z(3940)	2++	M/F	S?^	N/S	N/A	N/A	N/A	N/A	M/F	N/A	M/F	M/F	N/A	M/F	M/F	N/A	N	N
Y(4140)	JP+	M/F	M/F	N	S	N/A	N	N/A	N	N/A	M/F	M/F	N/A	M/F	N	N	N	N
X(4160)	OP+	M/F	M/F^	N	M/F	N/A	N	N/A	N	N/A	M/F	M/F	N/A	M/F	N	N	N	N
Y(4260)	1--	S	N/A	N/A	N/A	M/F	N	N/A	N/A	N	M/F	M/F	N/A	N	N	N	N/A	N/A
X(4350)	JP+	M/F	M/F^	N	M/F	N/A	N	N	N	N/A	M/F	M/F	N/A	N	N	N	N	N
Y(4350)	1--	M/F	N/A	N/A	N/A	M/F	N	N/A	N/A	N	M/F	M/F	N/A	N	N	N	N	N/A
Y(4660)	1--	N	N/A	N/A	N/A	M/F	N	N/A	N/A	N	M/F	M/F	M/F^	N	N	N	N	N/A

ISR	JP/C	J/ψππ	ψ(2S)ππ	J/ψη	χcγ	pp	ΛΛ	ΔcΔc	DD	DD*	D*D*	Ds(*)Ds(*)	legenda
Y(4260)	1--	S	N/S	N/S	N/S	N/S	M/F	N/A	N/S	N/S	N/S	N	S: seen
Y(4350)	1--	N/S	S	M/F	M/F	M/F	M/F	N/A	M/F	M/F	M/F	N	M/F: missing fit
Y(4660)	1--	N/S	S	M/F	M/F	M/F	M/F	S	M/F	M/F	M/F	N	N/S: not seen

N/A: not applicable
N/F: not feasible

pp incl	JP/C	J/ψππ	J/ψω	J/ψγ	J/ψΦ	J/ψη	ψ(2S)ππ	ψ(2S)ω	ψ(2S)γ	χcγ	pp	ΛΛ	ΔcΔc	DD	DD*	D*D*	Ds(*)Ds(*)
X(3872)	1++ [2- +]	S	N	N/F	N/A	N/A	N/A	N/A	N/F	N/A	N	N	N/A	N/A	N	N/A	N/A
X,Y (3940)	0+- [JP+(1)]	N/S	N	N/F	N/A	N/A	N/A	N/A	N/F	N/A	N	N	N/A	N	N	N/A	N
Z(3940)	2++	N/S	N	N/F	N/A	N/A	N/A	N/A	N/F	N/A	N	N	N/A	N	N	N	N
Y(4140)	JP+	N	N	N/F	N	N/A	N	N/A	N/F	N/A	N	N	N/A	N	N	N	N
X(4160)	OP+	N	N	N/F	N	N/A	N	N/A	N/F	N/A	N	N	N/A	N	N	N	N
Y(4260)	1--	N	N/A	N/A	N/A	N	N	N/A	N/A	N/F	N	N	N/A	N	N	N	N
X(4350)	JP+	N	N	N/F	N	N/A	N	N	N/F	N/A	N	N	N/A	N	N	N	N
Y(4350)	1--	N	N/A	N/A	N/A	N	N	N/A	N/A	N/F	N	N	N/A	N	N	N	N
Y(4660)	1--	N	N/A	N/A	N/A	N	N	N/A	N/A	N/F	N	N	N	N	N	N	N

Plenty of states seen with low stat and in only one channel
 → next generation [SuperB(elle)?] needed