Hadron Spectroscopy in 2009

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Outline

1. Theoretical framework
2. New Hadrons with Heavy Quarks
   - η_b , $\Upsilon(1D)$
   - Ω_b , Ξ_b , Σ_b , Σ^*_b
3. Charmonium-like XYZ States
   - *Y(4140), Z^+(4430), X(3872), Y(4260), Y(4630)…*
4. Final Comments

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2. New Hadrons with Heavy Quarks
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3. Charmonium-like XYZ States
   - *Y(4140), Z^+(4430), X(3872), Y(4260), Y(4630)...*
4. Final Comments

Apology: Too many results to cover in a short overview. I apologize for all the topics that I do not cover.

Parallel Talks:

A. Zupanc	H. Egiyan
K. Yi	T. Lee
E. Braaten	L. Dong
D. Kaplan	V. Papadimitriou
S. Behari	E. Swanson

Some recent reviews:

F.A. Harris, arXiv:0810.3045
G.V. Pakhlova, arXiv:0810.4114
SG & S. Olsen, Ann. Rev. Nucl. Part. Sci. 58, 51 (2008)
E. Eichten *et al*., Rev. Mod. Phys. 80, 1161 (2008)

Introduction

Quantum Chromodynamics theory of strong interactions

Hadrons

- reflect QCD in the non-perturbative regions
- Laboratory for precision tests of lattice QCD, effective field theory, chiral dynamics, quark model,…

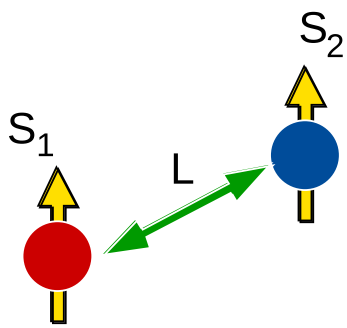
Much progress over the last several years

Many newly discovered states have puzzling properties

Will use quark potential models for comparison

Conventional Mesons & Potential Models

Meson quantum numbers characterized by given J^{PC}:



$S = S_1 + S_2$

$J = L + S$

$P = (-1)^{L+1}$

$C = (-1)^{L+S}$

Allowed:

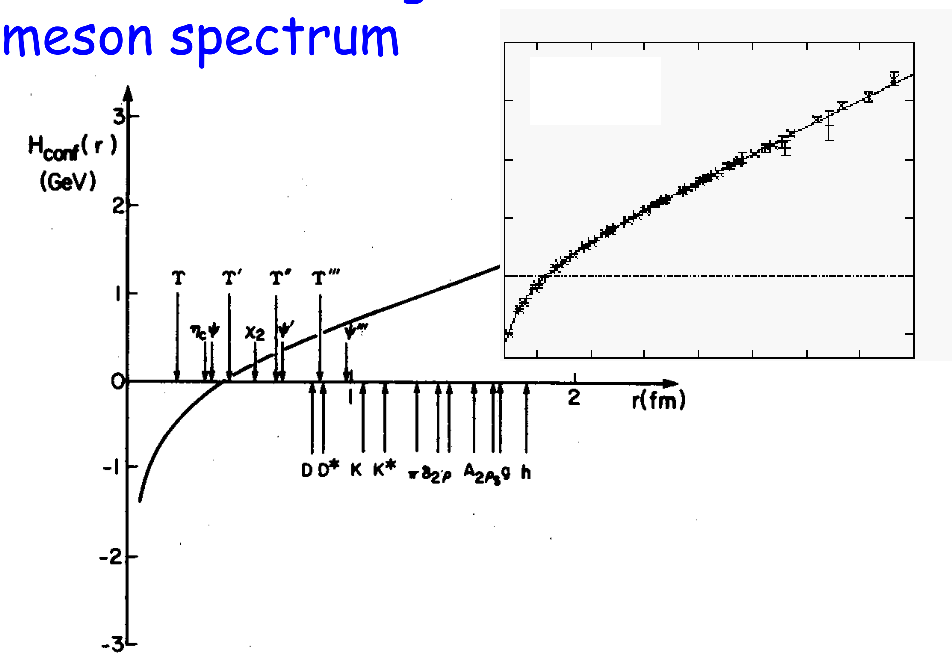
$J^{PC} = 0^{-+}\ \ 1^{--}\ \ 1^{+-}\ \ 0^{++}\ \ 1^{++}\ \ 2^{++}\ \ldots$

Not allowed: exotic combinations:

$J^{PC} = 0^{--}\ \ 0^{+-}\ \ 1^{-+}\ \ 2^{+-}\ \ldots$

For given spin and orbital angular momentum configurations & radial excitations generate the meson spectrum

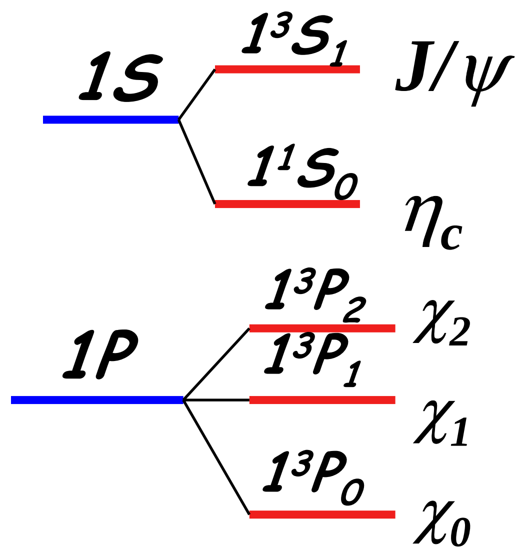
$$V(r) = -\frac{4}{3}\frac{\alpha_s(r)}{r} + br$$



Conventional Mesons & Potential Models

Spin-dependent potentials:

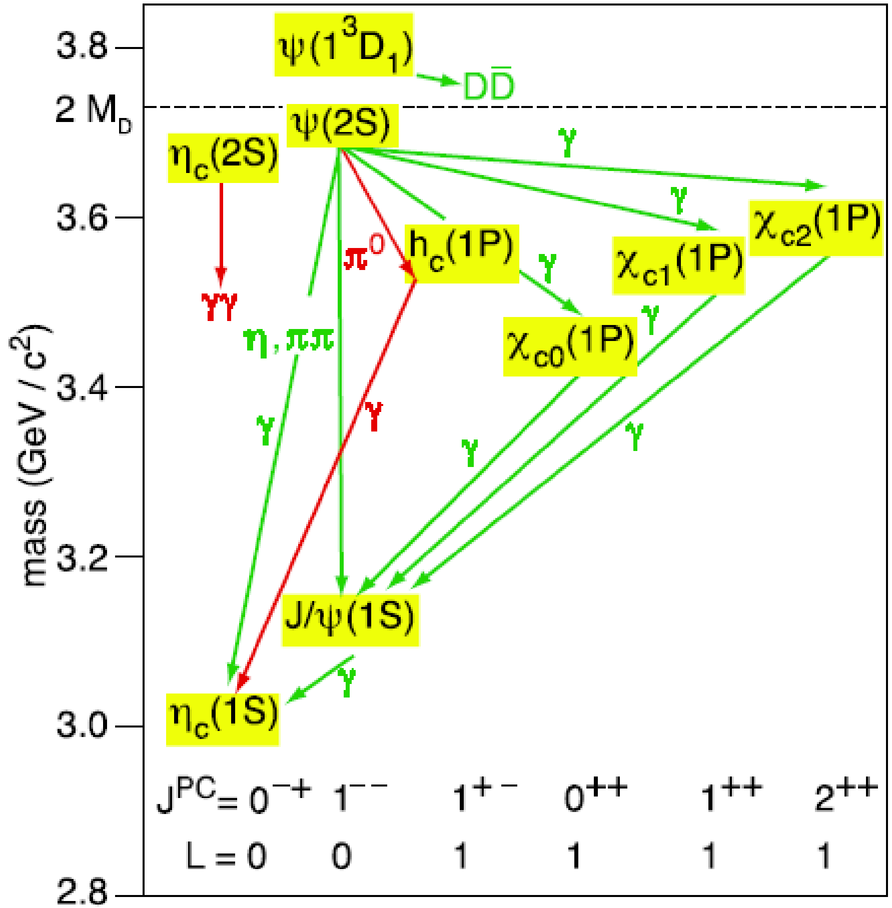
- Lorentz vector 1-gluon exchange + scalar confinement
- Spin-dependent interactions are $(v/c)^2$ corrections
  - Spin-spin interactions:
  - Spin-orbit interactions:



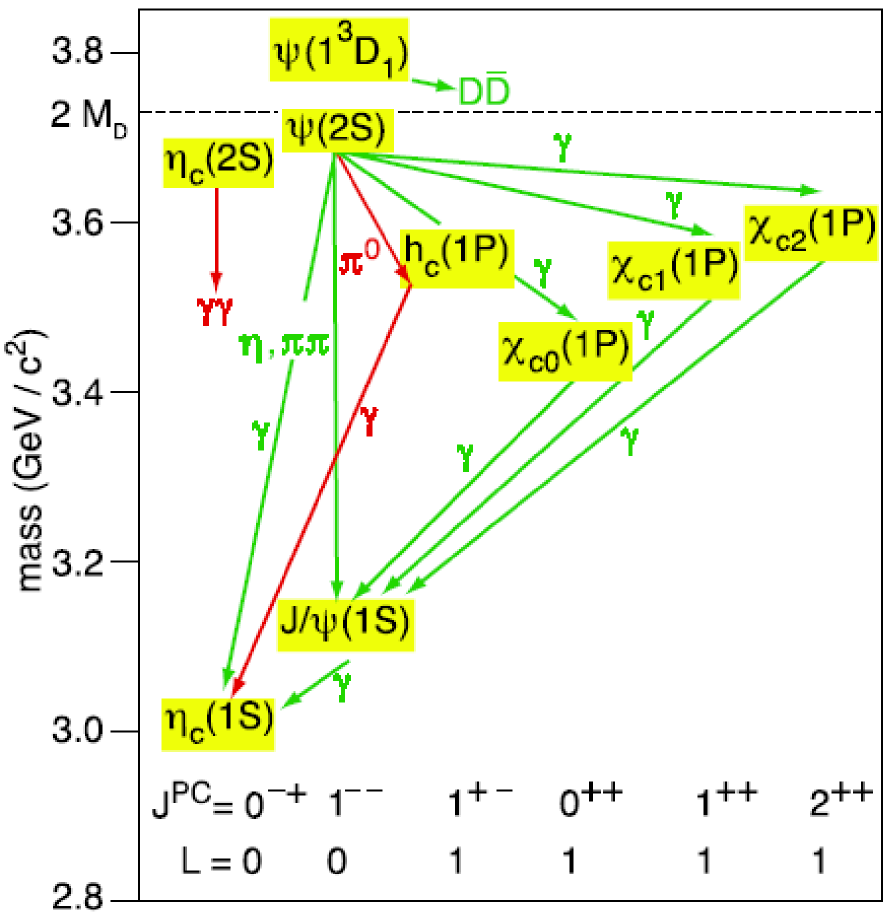
Decays:

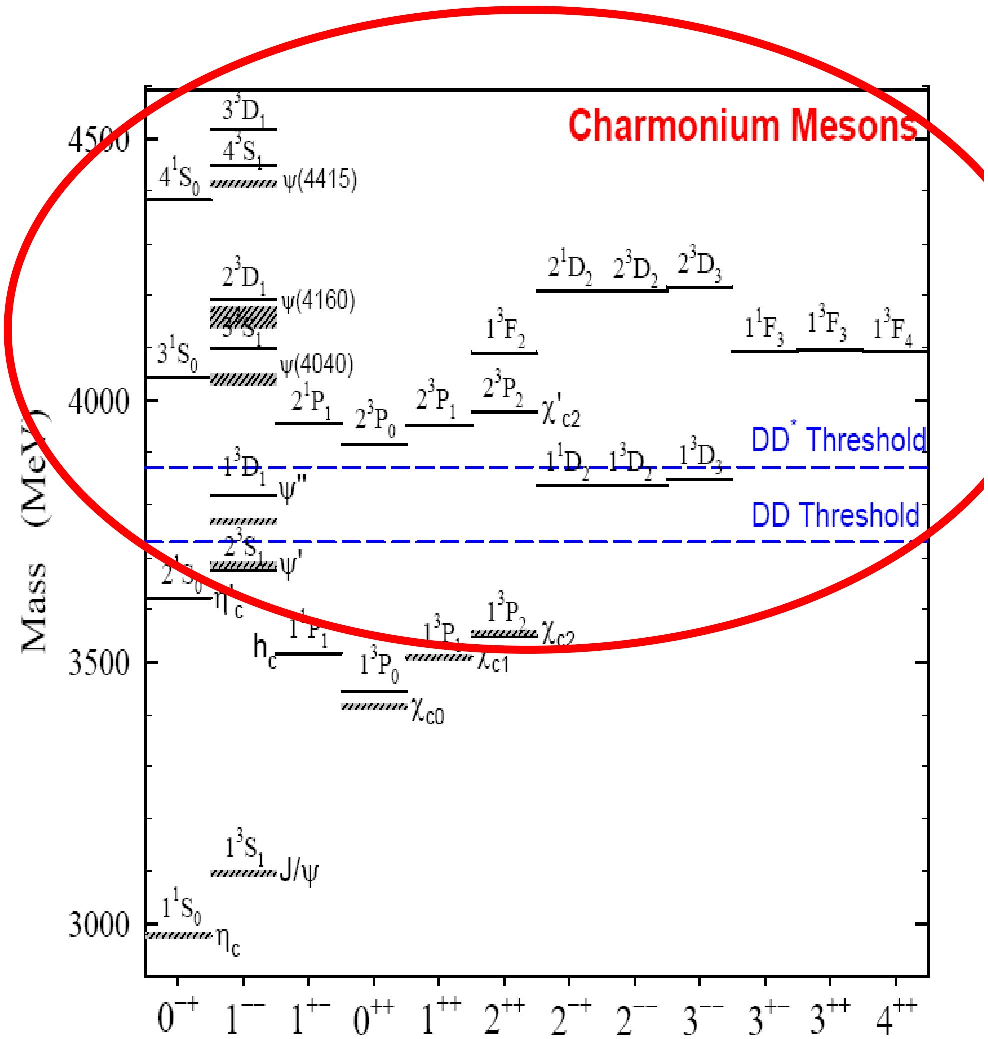
- Zweig allowed strong Decays: Well described by $^3P_0$ decay model
- Annihilation Decays
- Hadronic Transitions
- Electromagnetic Transitions: E1 & M1

Conventional (Charmonium) States



Conventional (Charmonium) States





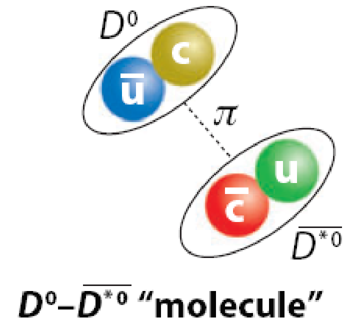
"Exotic States"

Hybrids

•States with excited gluonic degrees of freedom
•Distinctive decay modes

Multiquark States

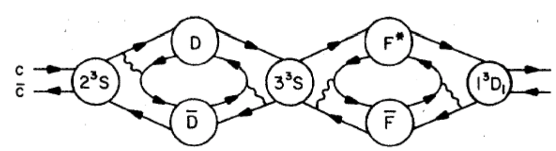
•Molecular state
- -loosely bound pair of mesons near threshold
- -Exhibit large isospin violations



•Tetraquarks
- -tightly bound diquark-diantiquark states
- -expect flavour multiplet of states

Threshold-effects

•Rescattering near threshold due to interactions between two outgoing mesons
•Mass shifts due to thresholds
•Coupled channel effects mixing 2-meson states with resonances



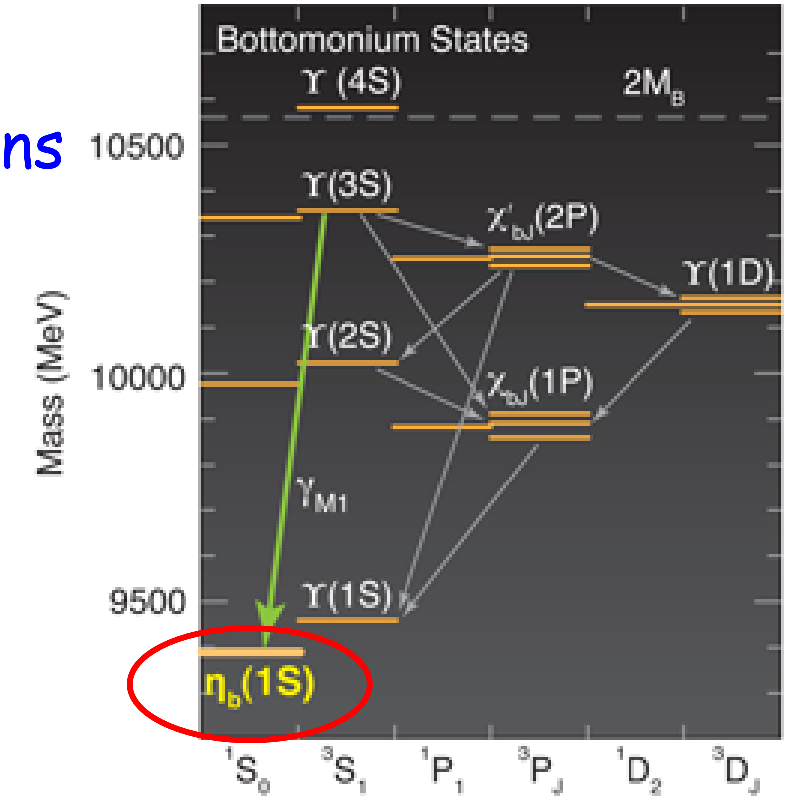
Bottomonium: $\eta(n^1S_0)$ states

Observation of η_b important test of lattice QCD and other calculations

Proceeds via magnetic dipole (M1) transitions:

$$\Upsilon(n^3S_1)\rightarrow\eta(n'S) + \gamma$$

$$\Gamma(^3S_1\rightarrow{}^1S_0+\gamma)=\frac{4}{3}\alpha\frac{e_Q^2}{m_Q^2}\left|\langle f\,|\,j_0(kr/2)|\,i\rangle\right|^2\omega^3$$



- Hindered transitions have large phase space
- Relativistic corrections resulting in differences in $^3S_1$ and $^1S_0$ wavefunctions due to hyperfine interaction

See SG+Rosner, PRD64, 074011 (2001)
SG, Physics 1, 11(2008).

Bottomonium: $\eta(n^1S_0)$ states

- BaBar accumulated 109×10^6 $\Upsilon(3S)$'s
- Searched for $\Upsilon(3S) \to \gamma\eta_b$
- Find:

$$\mathcal{B}(\Upsilon(3S) \to \gamma\eta_b) = (4.8 \pm 0.5 \pm 1.2) \times 10^{-4}$$
$$M(\eta_b) = 9388.9^{+3.1}_{-2.3} \pm 2.7 \text{ MeV}$$
$$M(\Upsilon(1S)) - M(\eta_b) = 71.4^{+2.3}_{-3.1} \pm 2.7) \text{ MeV}$$

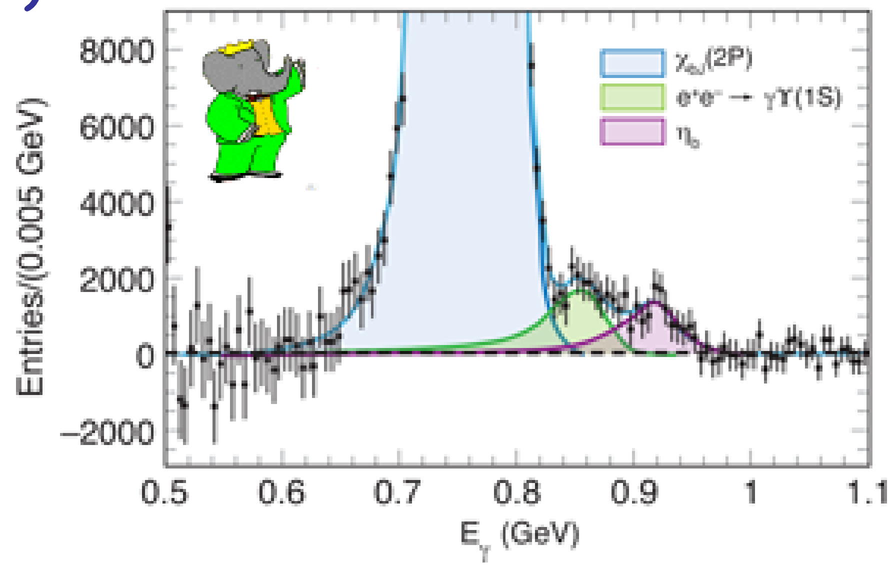
- In agreement with Lattice QCD and QCD based models

- Confirmed by looking in $\Upsilon(2S) \to \gamma\eta_b$
- Find

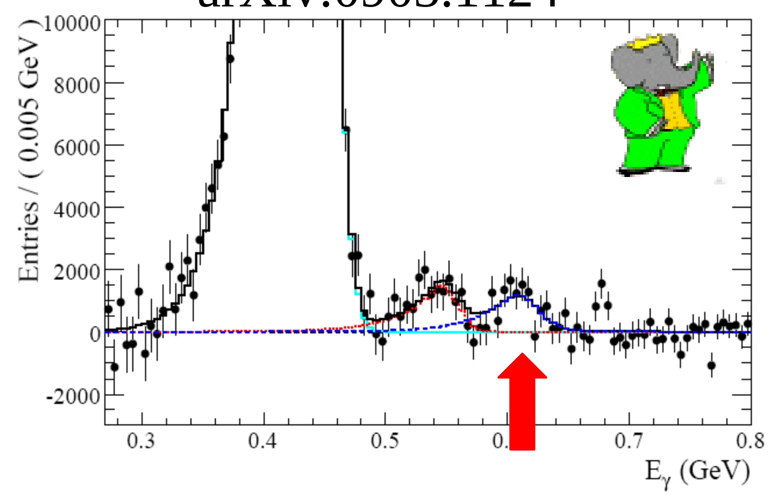
$$M(\eta_b) = 9392.9^{+4.6}_{-4.8} \pm 1.8 \text{ MeV}$$
$$\mathcal{B}(\Upsilon(2S) \to \gamma\eta_b) = (4.2^{+1.1}_{-1.0} \pm 0.9) \times 10^{-4}$$

- Average: $M(\eta_b) = 9390.4 \pm 3.1$ MeV

PRL101, 071801(2008)

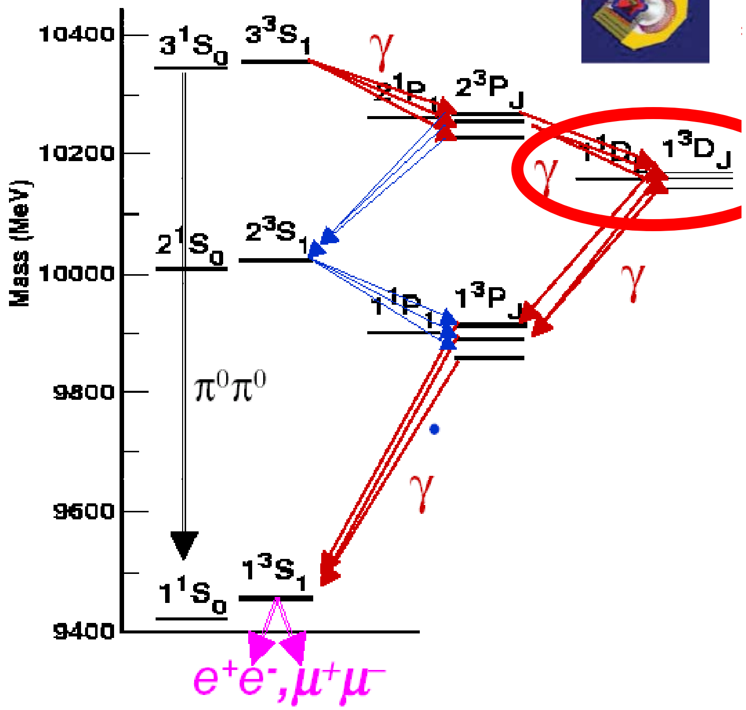


arXiv:0903.1124



Bottomonium: $\Upsilon(1D)$ CLEO: Phys. Rev. D70,032001 (2004)

- Observations test predictions
- Use for 4γ E1 cascade to search for $\Upsilon(1^3D_J)$



- Estimate the radiative widths and BR using quark model

Cascade	Events/10^6 $\Upsilon(3S)$
$3^3S_1 \to 2^3P_2 \to 1^3D_3 \to 1^3P_2 \to 1^3S_1$	7.8
$3^3S_1 \to 2^3P_2 \to 1^3D_2 \to 1^3P_1 \to 1^3S_1$	2.7
$3^3S_1 \to 2^3P_1 \to 1^3D_2 \to 1^3P_1 \to 1^3S_1$	20
$3^3S_1 \to 2^3P_1 \to 1^3D_1 \to 1^3P_1 \to 1^3S_1$	3.3

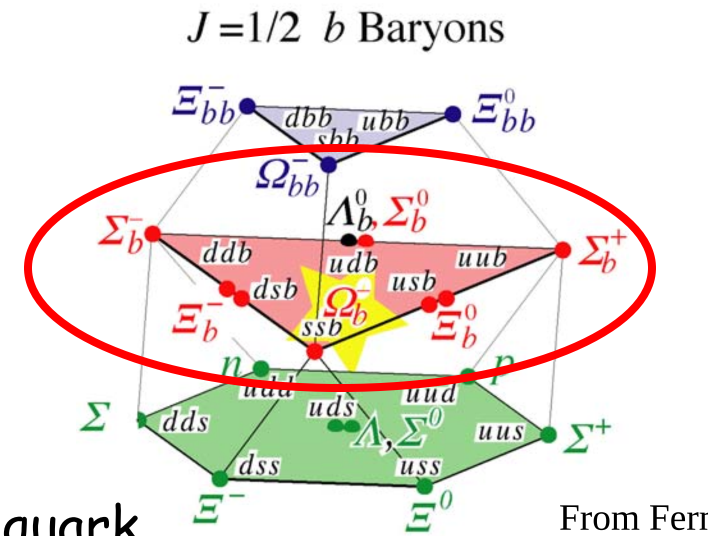
M=10161.1$\pm$ 0.6(stat) $\pm$ 1.6(syst) MeV
In agreement with potential models and Lattice QCD
BR=$(2.5\pm0.5\pm0.5)\times10^{-5}$ vs 2.6×10^{-5}

CLEO's discovery based on 5.8×10^6 $\Upsilon(3S)$'s
BaBar has $109\pm1 \times 10^6$ $\Upsilon(3S)$'s

Heavy Baryons

Satyajit Behari, parallel talk

$$\Lambda_b^0 = |bud\rangle$$
$$\Sigma_b^{(*)+} = |buu\rangle$$
$$\Xi_b^{(*,\prime)-} = |bsd\rangle$$
$$\Omega_b^{(*)} = |bss\rangle$$



From Fermilab

Heavy quark surrounded by light quark or diquark

"Hydrogenlike" system ⇒ **Test Lattice QCD, HQET, QM,…**

Colour Hyperfine: $\Delta H_{ij}^{hyp} = \frac{16\pi\alpha_s}{9m_i m_j} \vec{S}_i \cdot \vec{S}_j \, \langle \delta^3(\vec{r}_{ij}) \rangle \sim \gamma \frac{\vec{S}_i \cdot \vec{S}_j}{m_i m_j}$

$$M(\Sigma_b^*) - M(\Sigma_b) = [M(\Sigma_c^*) - M(\Sigma_c)] \times \left(\frac{m_c}{m_b}\right) \simeq 25 \text{ MeV vs } 21.2^{+2.0}_{-1.9} \text{ MeV}$$

$$M(\Sigma_b) - M(\Lambda_b) = [M(\Sigma_c) - M(\Lambda_c)] \times \frac{(1-m_u/m_b)}{(1-m_u/m_c)} \simeq 192 \text{ MeV vs } 192 \text{ MeV}$$

Karliner et al. predict:
(Annals Phys. 324, 2 (2009))

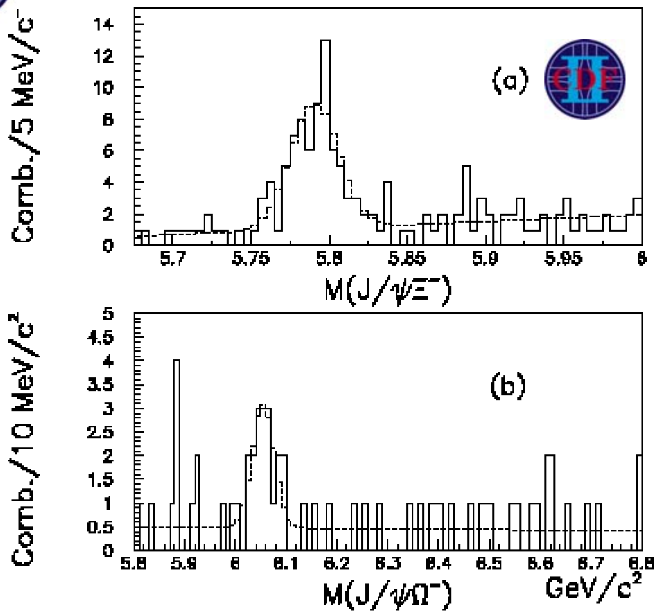
$$M(\Omega_b) = 6052.1 \pm 5.6 \text{ MeV}$$
$$M(\Omega_b^*) = 6082.8 \pm 5.6 \text{ MeV}$$
$$M(\Xi_b^*) = 5786.7 \pm 3.0 \text{ MeV}$$

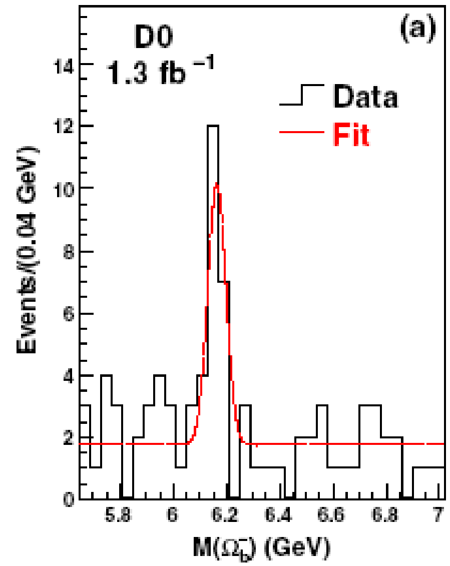
Heavy Baryons: Ω_b , Ξ_b & Σ_b

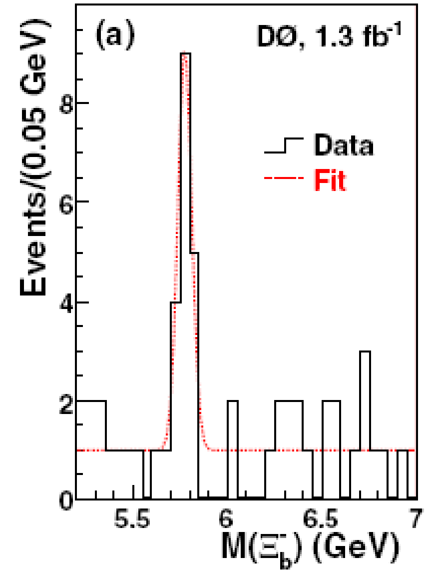
arxiv:0905.3123

PRL101, 232002 (2008)

PRL99, 052001 (2007)







$$M(\Omega_b) = 6054.4 \pm 6.8\ (stat)\ \pm 0.9\ (sys)\ \mathrm{MeV}$$
$$M(\Xi_b) = 5790.9 \pm 2.6 \pm 0.9\ \mathrm{MeV}$$

$$M(\Omega_b) = 6165 \pm 10 \pm 13\ \mathrm{MeV}$$
$$M(\Xi_b) = 5774 \pm 11 \pm 15\ \mathrm{MeV}$$

Heavy Baryons: Ω_b , Ξ_b &Σ_b

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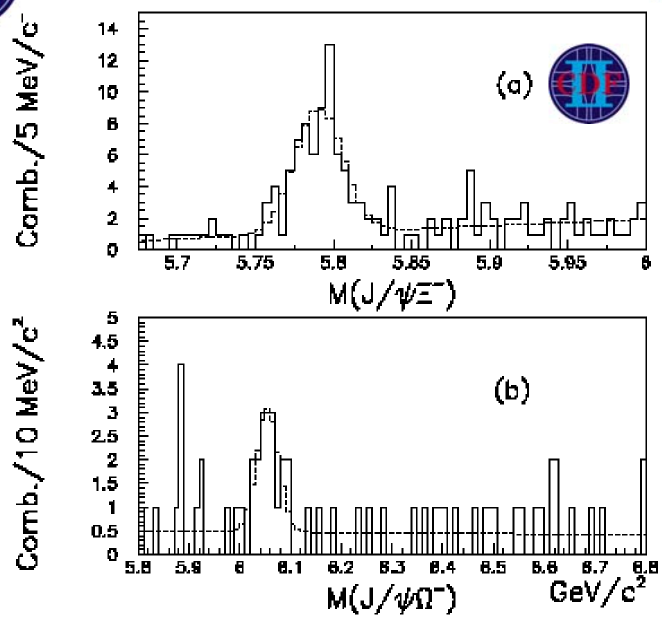
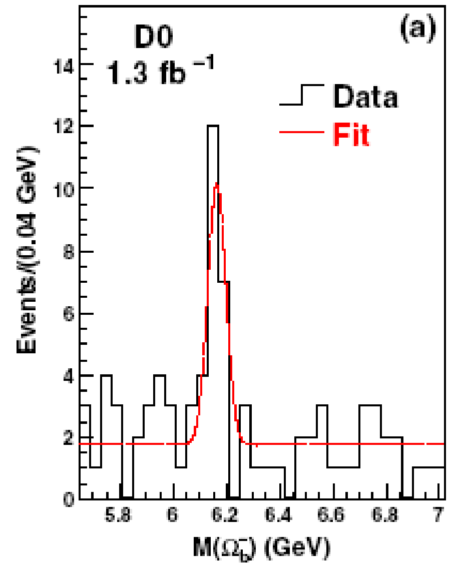
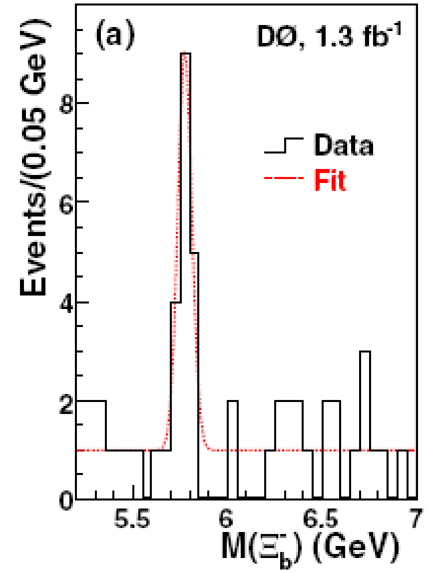


PRL101, 232002 (2008)



PRL99, 052001 (2007)



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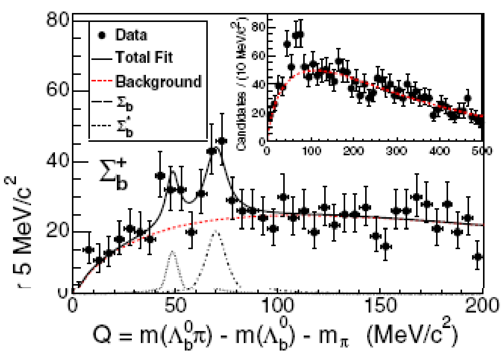


CDF PRL99, 202001 (2007)

$M(\Sigma_b^+) = 5807.8^{+2.0}_{-2.2} \pm 1.7$ MeV

$M(\Sigma_b^-) = 5815.2 \pm 1.0 \pm 1.7$ MeV

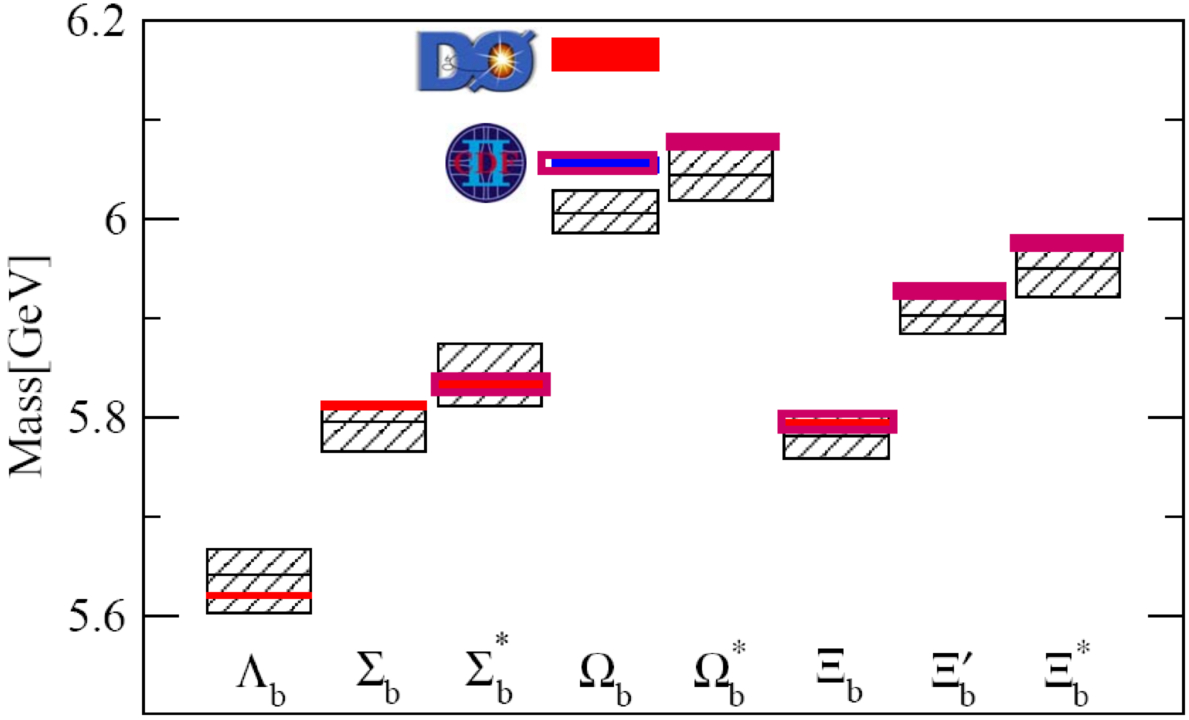
$M(\Sigma_b^{*+}) = 5829.0^{+1.6+1.7}_{-1.8-1.8}$ MeV

$M(\Sigma_b^{*-}) = 5829.0 \pm 2.0^{+1.8}_{1.7}$ MeV

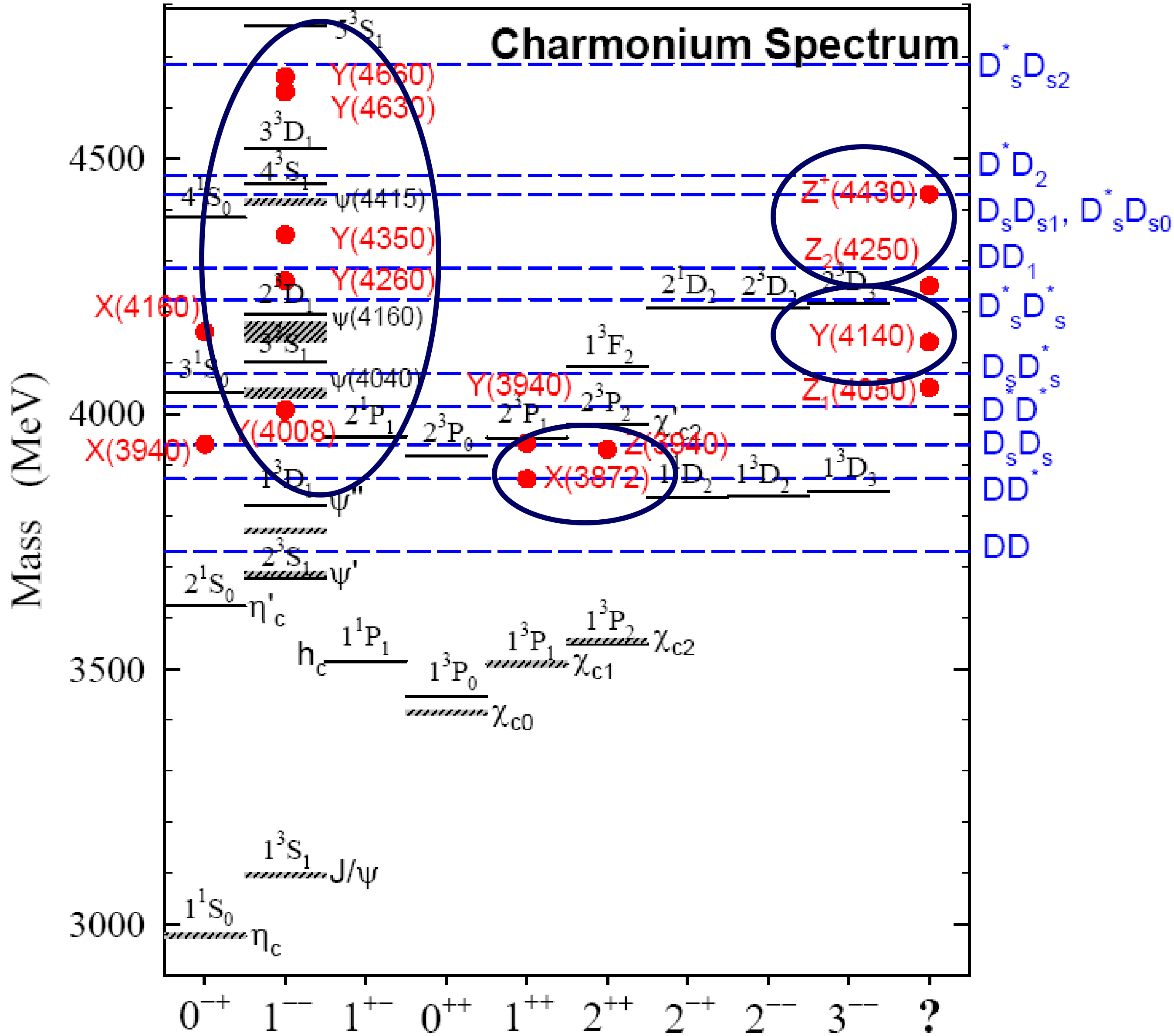
Heavy Baryons

Lattice results from Lewis & Woloshyn, PRD79, 014502 (2009)

Quark Model results from Karliner et al. (Annals Phys. 324, 2 (2009))



New Charmonium like states "XYZ"states



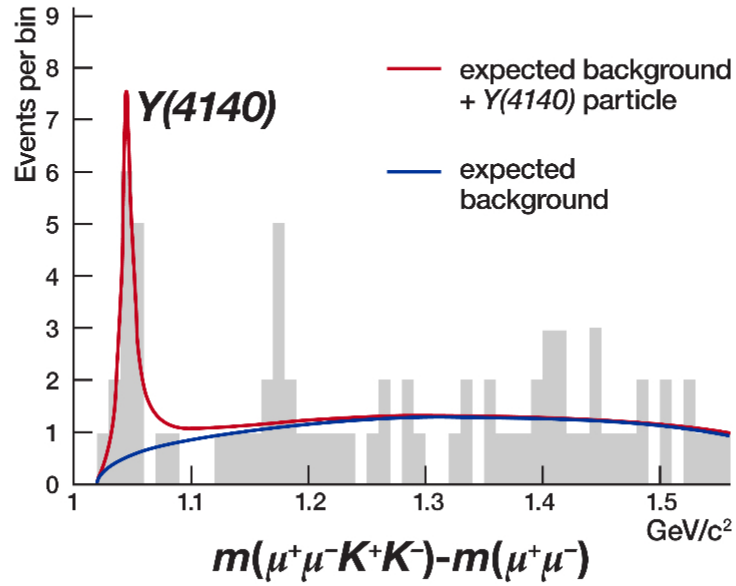
New Charmonium-like states – X, Y, Z's

Anze Zupanc, parallel talk

State	M (MeV)	Γ (MeV)	J^{PC}	Decay Modes	Production Modes	Observed also by
$Y_s(2175)$	2175 ± 8	58 ± 26	1^{--}	$\phi f_0(980)$	e^+e^- (ISR) $J/\psi \to \eta Y_s(2175)$	BaBar, BESII
$X(3872)$	3871.4 ± 0.6	< 2.3	1^{++}	$\pi^+\pi^- J/\psi$, $\gamma J/\psi, D\bar{D}*$	$B \to KX(3872)$, $p\bar{p}$	BaBar CDF, D0,
$X(3915)$	3914 ± 4	23 ± 9	$0/2^{++}$	$\omega J/\psi$	$\gamma\gamma \to X(3915)$	
$Z(3930)$	3929 ± 5	29 ± 10	2^{++}	$D\bar{D}$	$\gamma\gamma \to Z(3940)$	
$X(3940)$	3942 ± 9	37 ± 17	$0^{?+}$	$D\bar{D}*$ (not $D\bar{D}$ or $\omega J/\psi$)	$e^+e^- \to J/\psi X(3940)$	
$Y(3940)$	3943 ± 17	87 ± 34	$?^{?+}$	$\omega J/\psi$ (not $D\bar{D}*$)	$B \to KY(3940)$	BaBar
$Y(4008)$	4008^{+82}_{-49}	226^{+97}_{-80}	1^{--}	$\pi^+\pi^- J/\psi$	e^+e^-(ISR)	
$X(4160)$	4156 ± 29	139^{+113}_{-65}	$0^{?+}$	$D^*\bar{D}^*$ (not $D\bar{D}$)	$e^+e^- \to J/\psi X(4160)$	
$Y(4260)$	4264 ± 12	83 ± 22	1^{--}	$\pi^+\pi^- J/\psi$	e^+e^-(ISR)	BaBar, CLEO
$Y(4350)$	4361 ± 13	74 ± 18	1^{--}	$\pi^+\pi^- \psi'$	e^+e^-(ISR)	BaBar
$X(4630)$	4634^{+9}_{-11}	92^{+41}_{-32}	1^{--}	$\Lambda_c^+\Lambda_c^-$	e^+e^-(ISR)	
$Y(4660)$	4664 ± 12	48 ± 15	1^{--}	$\pi^+\pi^- \psi'$	e^+e^-(ISR)	
$Z(4050)$	4051^{+24}_{-23}	82^{+51}_{-29}	?	$\pi^\pm \chi_{c1}$	$B \to KZ^\pm(4050)$	
$Z(4250)$	4248^{+185}_{-45}	177^{+320}_{-72}	?	$\pi^\pm \chi_{c1}$	$B \to KZ^\pm(4250)$	
$Z(4430)$	4433 ± 5	45^{+35}_{-18}	?	$\pi^\pm \psi'$	$B \to KZ^\pm(4430)$	
$Y_b(10890)$	$10,890 \pm 3$	55 ± 9	1^{--}	$\pi^+\pi^- \Upsilon(1,2,3S)$	$e^+e^- \to Y_b$	

Table taken from arxiv:arXiv:0901.2371 (S. Olsen's proc. to PANIC08) + added two more states ($X(3915)$ and $X(4630)$).

Looked for structure in $J/\psi\ \phi$ invariant mass in $B^+ \rightarrow J/\psi\ \phi\ K^+$



Find evidence for a state with significance of 3.8σ near $J/\psi\ \phi$ threshold

$M=4143.0 \pm 2.9 \pm 1.2$ MeV/c^2
$\Gamma=11.7\ ^{+8.3}_{-5.0} \pm 3.7$ MeV/c^2

Both J/ψ and ϕ have $J^{PC}=1^{-}$ so Y has +ve C parity

Some argue similarity to Y(3940) in $B \rightarrow J/\psi\ \omega\ K$

What is it?

Y(4140): What is it?

Conventional state

- Above open charm threshold so expect to have large width
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$c\bar{c}s\bar{s}$ tetraquark Mahajan arXiv:0903:3107, Liu & Zhu arXiv:0903:2529, Stancu arXiv:0906:2485

- Expect larger width via rearrangement of quarks ~100 MeV
- Generally expect similar widths to both hidden and open charm

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Charmonium hybrid Mahajan arXiv:0903:3107,

- Predict with masses ~4.0-4.4 GeV
- Could be $J^{PC}=1^{-+}$ exotic
- If below $D^{**}D$ threshold could be narrow with decays to DD suppressed
- D^*D is important mode to search for

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Rescattering via $D_sD^*_s$? Rosner PR D76, 114002 (2007)

Opening of channel Van Beveren & Rupp arXiv:0906:2278; 0905.1595

Y(4140)

- $D_s^{*+} D_s^{*-}$ molecule

Mahajan 0903:3107, Branz, Gutsche, Lyubovitskij 0903.5424, Zhang, Huang 0906.0090
Liu & Zhu 0903.2529, Albuquerque, Bracco & Nielson 0903.5540, Ding 0904.1782

  - Threshold ~ 4225 MeV so binding energy ~80 MeV
  - Argue similar binding if Y(3940) is $D^* \bar{D}^*$ molecule with similar decay Y → J/ψ ω but question of width
  - Decays proceed via rescattering with decays to hidden and open charm final states equally probable so search for open modes: $D\bar{D}$, $D\bar{D}^*$ etc final states
  - Search for $Y(4140) \to D_s^{*+} D_s^- \gamma,\ D_s^+ D_s^{*-} \gamma$

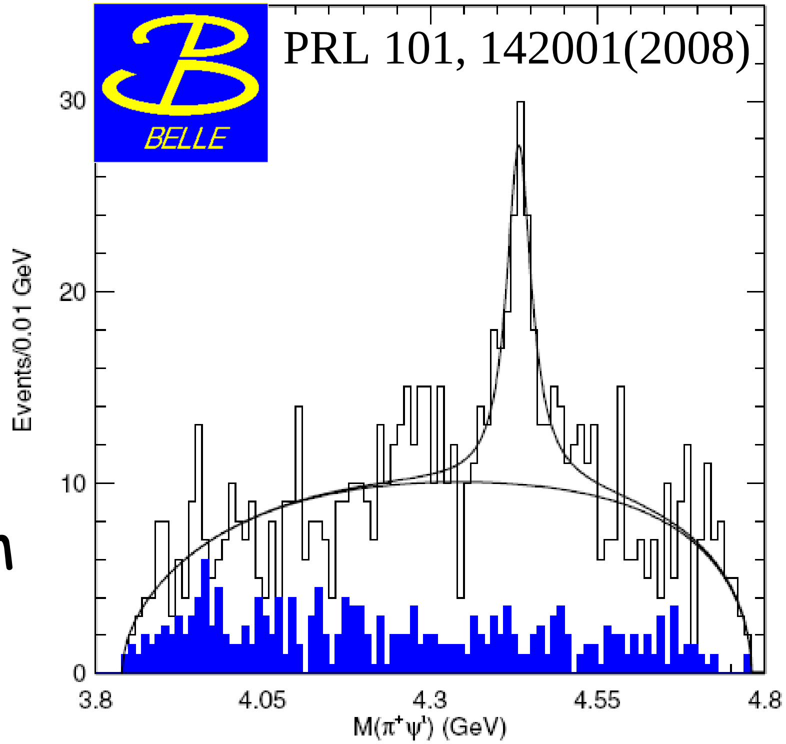
Liu & Ke arXiv:0907:1349

  - Predict other molecules $D^{*+} D_s^{*-}$ with M~4040 MeV search for in J/ψ ρ final state???

$Z^+(4430)$, $Z_1^+(4050)$, $Z_2^+(4250)$ Belle

New state in $B \to K\pi^{\pm}\psi(2S)$

$$M = 4433 \pm 4 \pm 2 \text{ MeV}$$
$$\Gamma = 45^{+18}_{-12}{}^{+30}_{-13} \text{ MeV}$$
$$\mathcal{B}(B^0 \to K^{\mp}Z^{\pm}) \times \mathcal{B}(Z^{\pm} \to \pi^{\pm}\psi') = (4.1 \pm 1.0 \pm 1.4) \times 10^{-5}$$



Charged and hidden charm

so cannot be conventional charmonium or hybrid

The usual suspects:

- $[cu][\bar{c}\bar{d}]$ Tetraquark Maiani et al0708.3997
- $D^*\bar{D}_1(2420)$ Threshold effect Rosner PR D76, 114002 (2007)
- $D^*\bar{D}_1(2420)$ $J^P=0^-, 1^-$ Molecule Meng, Chao 0708.4222

Molecule predict:

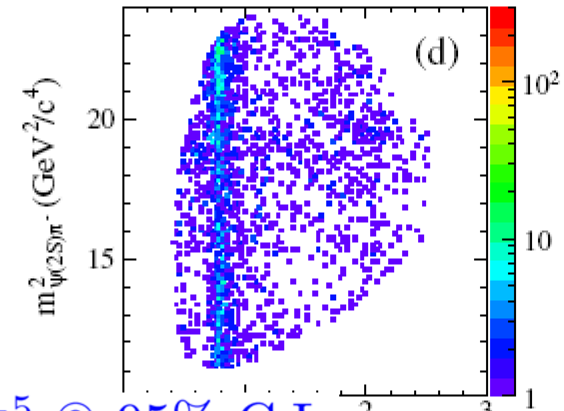
- decays into $D^*D^*\pi$
- Rescattering into $\psi'\ \pi$

$Z^{+}(4430)$ search by BaBar

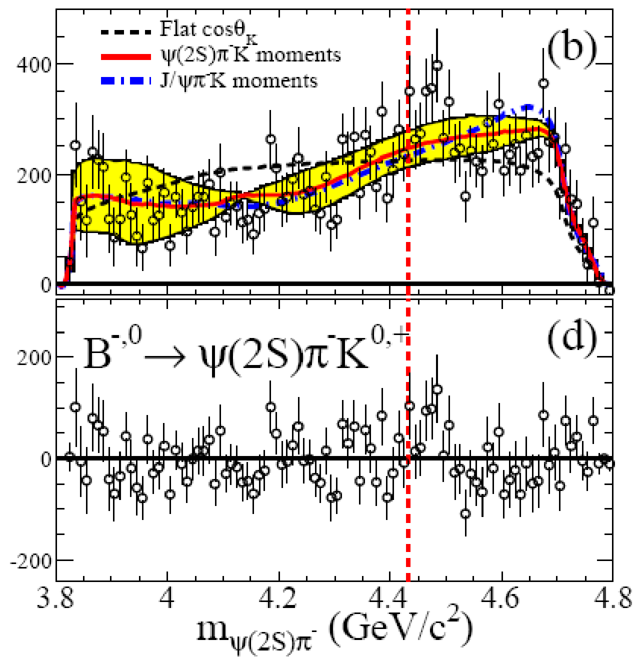
PR D79, 112001 (2009)

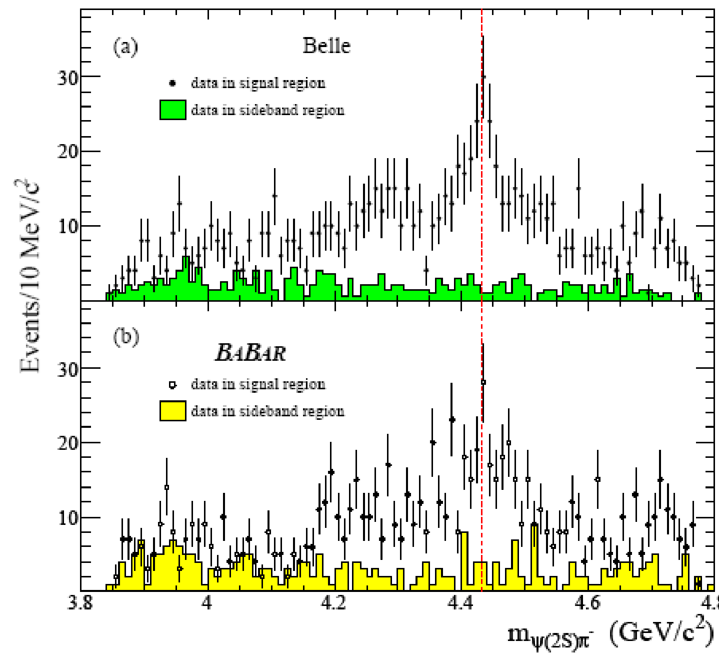
$B \rightarrow K\pi^{\pm}\psi(2S)$

- Detailed study of $K\pi^{-}$ system
- Correct for efficiency
- Includes S, P, and D waves



$\mathcal{B}(B^0 \rightarrow K^+Z^- \rightarrow \psi(2S)\pi^-K^+) < 3.1 \times 10^{-5}$ @ 95% C.L.



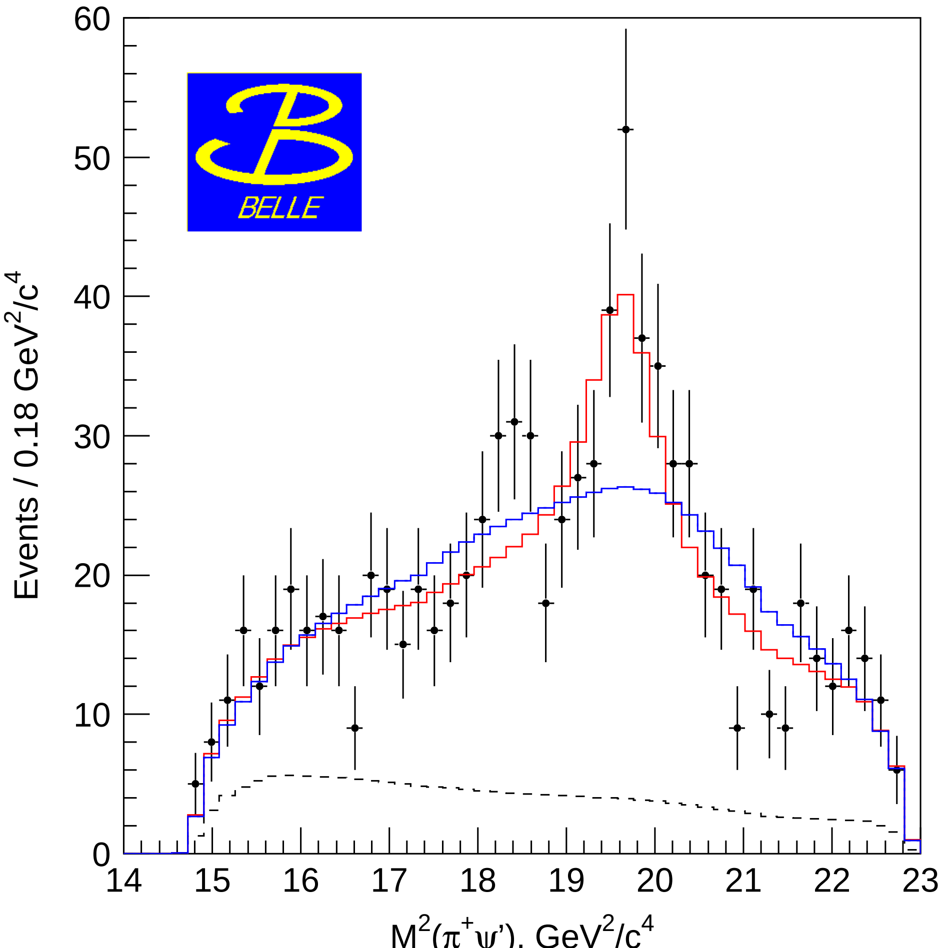


No conclusive evidence by BaBar for the Z^{-} (4430)

$Z^+(4430)$: Complete Dalitz analysis by Belle

Belle confirms the original result on $Z(4430)^+$

Anze Zupanc, parallel talk
arXiv:0905.2869



$$M = (4443^{+15}_{-12}{}^{+17}_{-13})\ \mathrm{MeV}/c^2,$$

$$\Gamma = (109^{+86}_{-43}{}^{+57}_{-52})\ \mathrm{MeV},$$

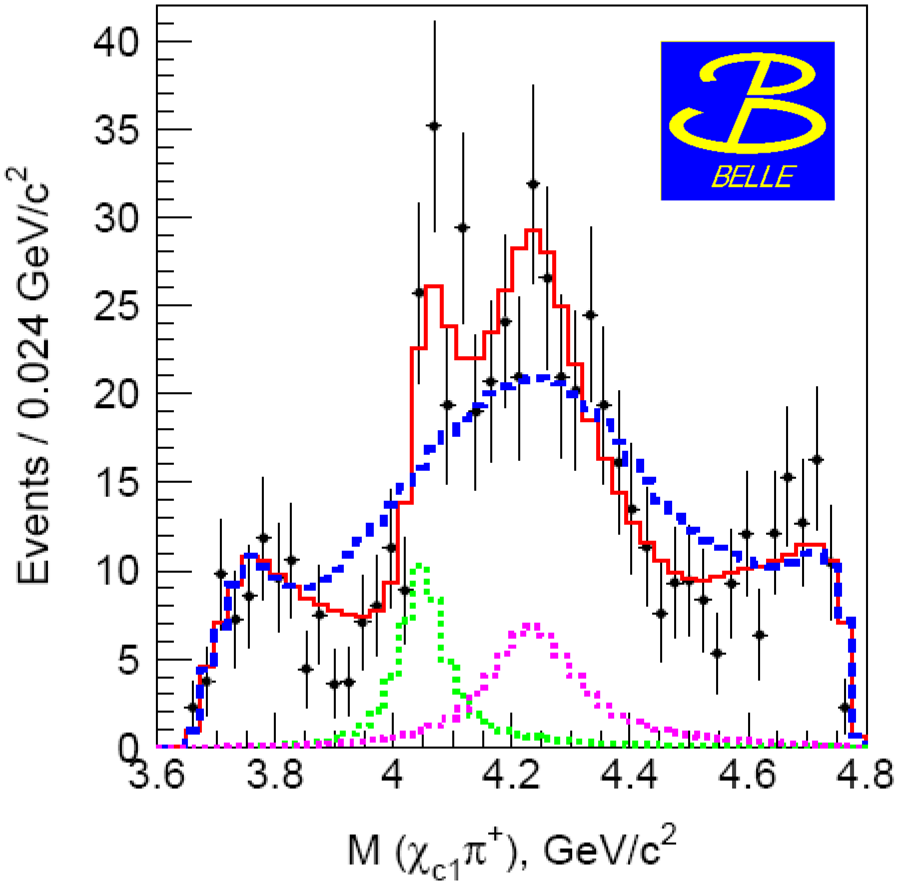
Width is larger than original but uncertainties are large

$Z_1^+(4050)$, $Z_2^+(4250)$ Belle PR D78, 072004 (2008)

Two resonance like structures in $\pi^+\chi_{c1}$ mass distributions

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

$$M_1 = (4051 \pm 14^{+20}_{-41})\ \mathrm{MeV}$$
$$\Gamma_1 = (82^{+21+47}_{-17-22})\ \mathrm{MeV}$$
$$M_2 = (4248^{+44+180}_{-29-35})\ \mathrm{MeV}$$
$$\Gamma_2 = (177^{+54+316}_{-39-61})\ \mathrm{MeV}$$



Evidence for three charged charmonium-like objects

Need experimental confirmation for all three of them

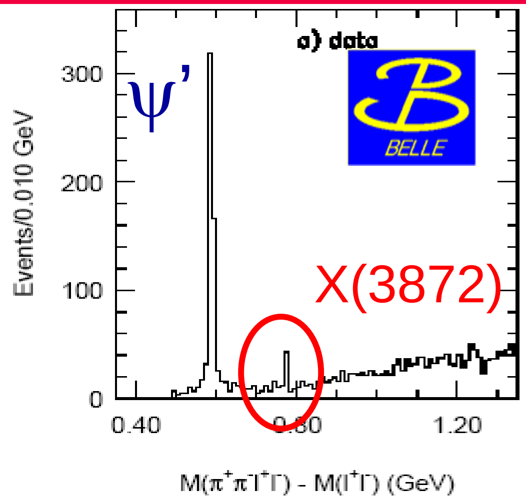
X(3872)

Kai Yi, parallel talk
Eric Braaten, parallel talk

First observed by Belle PRL 91, 262001(2003)

Confirmed by:

- CDF PRL 93, 072001 (2004)
- D0 PRL 93, 162002 (2004)
- BABAR PR D71, 071103 (2005)



$M = 3872.0 \pm 0.6 \pm 0.5$ MeV

$\Gamma < 2.3$ MeV at 90% C.L. consistent with detector resolution.

- $X(3872) \to \gamma J/\psi$ implies C=+ Belle [hep-ex/0505037]
  BaBar PR D74, 071101 (2006)

Angular distributions favour $J^{PC}=1^{++}$ Belle [hep-ex/0505038]

Higher statistics by CDF allow $J^{PC}=1^{++}$ or 2^{-+} PRL 98, 132002 (2007)

- $X(3872) \to D^0 \bar{D}^0 \pi^0$ seen [Belle PRL 97, 162002 (2006)]
- $X(3872) \to D^0 \bar{D}^0 \gamma$ seen [BaBar PR D77, 011102R (2008)]
- Implies decays predominantly to $D^0 \bar{D}^{*0}$

X(3872)

1. Conventional Charmonium

Barnes, Godfrey, PR D69, 050400 (2004)
Eichten, Lane, Quigg, PR D69, 094019 (2004)
Barnes, Godfrey, Swanson, PR D 054026 (2005)

- 1^1D_2 or 2^3P_1 only possible conventional states with correct quantum numbers close enough in mass
- But identification of Z(3931) with 2^3P_2 implies 2P mass ~ 3940 MeV
- $X(3872) \to \gamma J/\psi, \gamma\psi'$ disfavours 1^1D_2

X(3872)

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2. Tetraquark Maiani et al PR D71, 014028 (2008)

- Predict more nearly degenerate states including charged states which have not been seen
  - High statistics study by CDF of X(3872) mass and width and tested hypothesis of two states and find $\Delta m < 3.6$ (95% C.L.) $M=3871.61 \pm 0.16 \pm 0.19$ MeV/c^2

Mass splitting between X(3872) from charged and neutral B mesons consistent with zero. See K. Yi, parallel talk & [0906.5218]

Disfavours tetraquark models

X(3872)

3. D^0D^{*0} molecule   see talk by Braaten

Close, Page PLB 578, 119 (2004)
Voloshin PLB 579, 316(2004)
Swanson PLB 588, 189(2004)
Braaten Kusunoki PR D72 054022(2005

- Close to D^0D^{*0} threshold so might be S-wave D^0D^{*0} bound state "molecule"

$$X(3872) \to \rho J/\psi \sim X(3872) \to \omega J/\psi$$

So large isospin violation indicative of molecule

But decays $X(3872) \to \gamma J/\psi$ & $X(3872) \to \gamma \psi'$
implies ccbar content

BaBar: PRL 102,132001(2009)

Probably mixing with χ'_{c1} explains both X(3872) and Y(3940) properties as admixtures of molecule and 2^3P_1 states

Danilin & Simonov, 0907.1088; SG hep-ph/0605152;
Ortega et al, 0907.3997, Matheus et al 0907.2683

Y states in ISR ($J^{PC}=1^{--}$)

$$e^+e^- \to \gamma_{ISR} Y$$

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

BaBar: PRL 95, 142001(2005)

$Y(4008) \to J/\psi\, \pi^+\pi^-$

Belle: PRL 99, 182004(2007)

$Y(4325) \to \psi(2S)\, \pi^+\pi^-$

BaBar: PRL 98, 212001(2007)

$Y(4360) \to \psi(2S)\, \pi^+\pi^-$

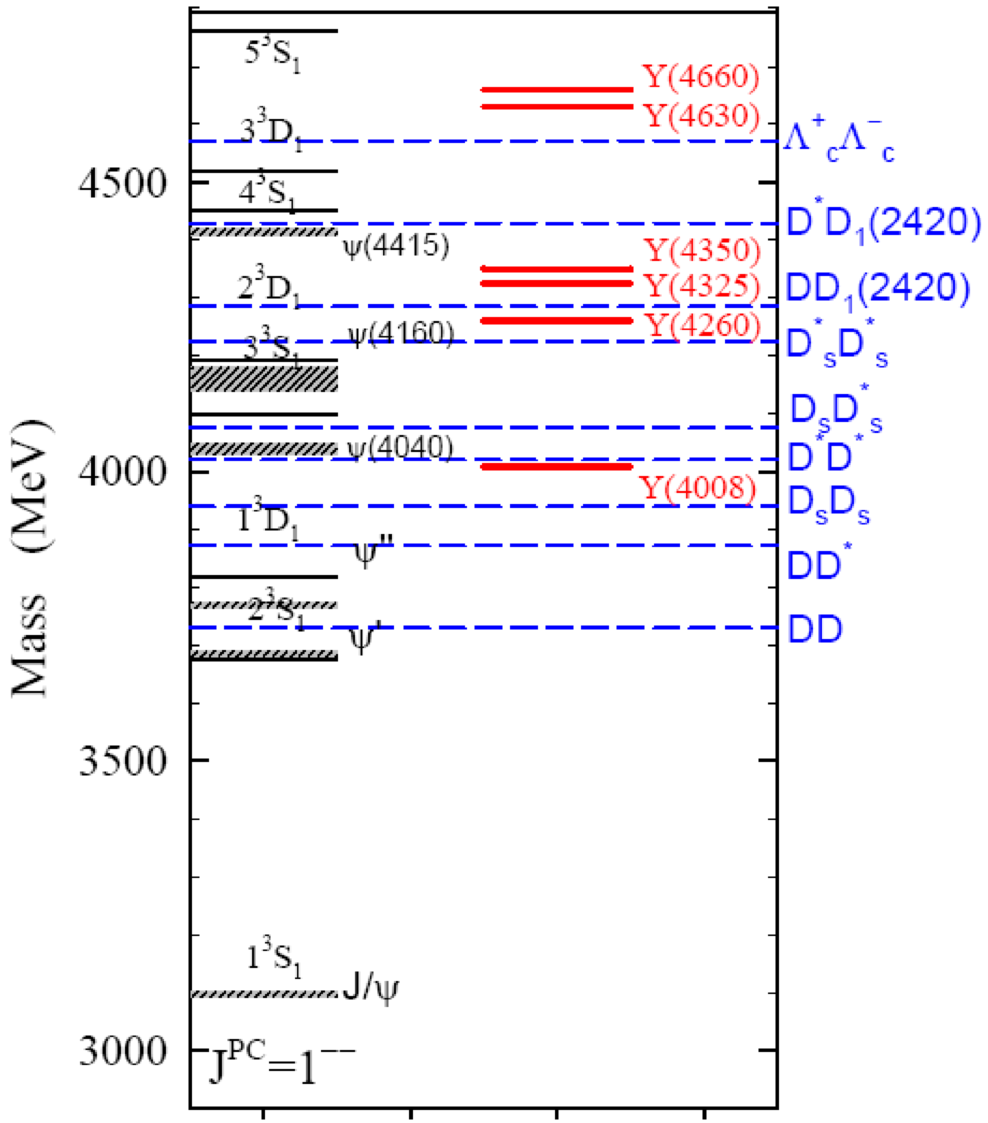
Belle: PRL 99, 142002(2007)

$Y(4630) \to \Lambda_c^+ \Lambda_c^-$

Belle: PRL 101, 172001(2008)

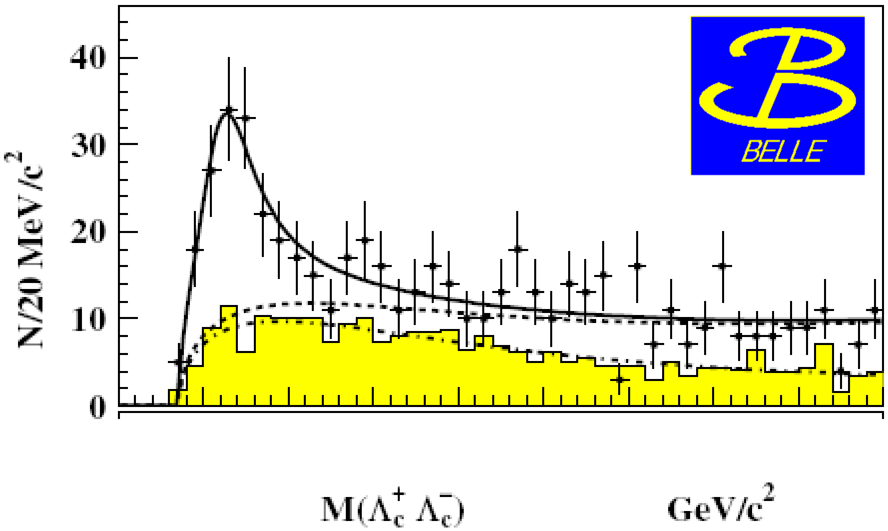
$Y(4660) \to \psi(2S)\, \pi^+\pi^-$

Belle: PRL 99, 142002(2007)



$e^+e^- \to \Lambda_c^+\Lambda_c^-\gamma_{ISR}$

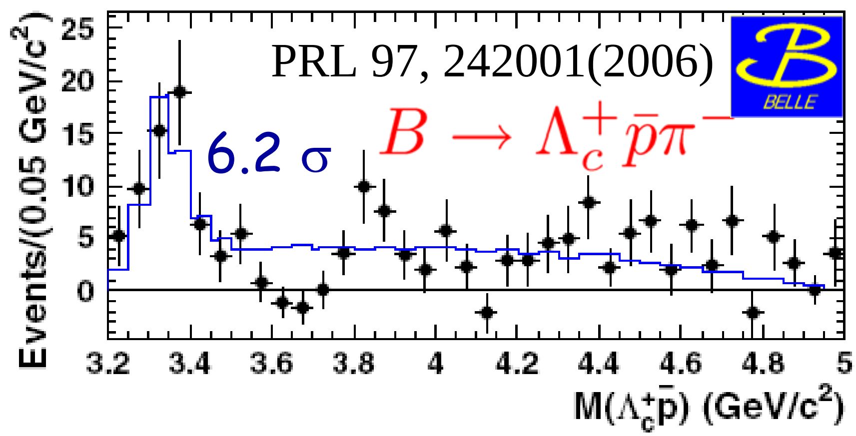
Belle: PRL 101, 172001(2008)



$$M = 4634^{+8+5}_{-7-8}$$
$$\Gamma = 92^{+40+10}_{-24-21}$$

Dibaryon threshold effect?

- Dibaryonic peak near threshold



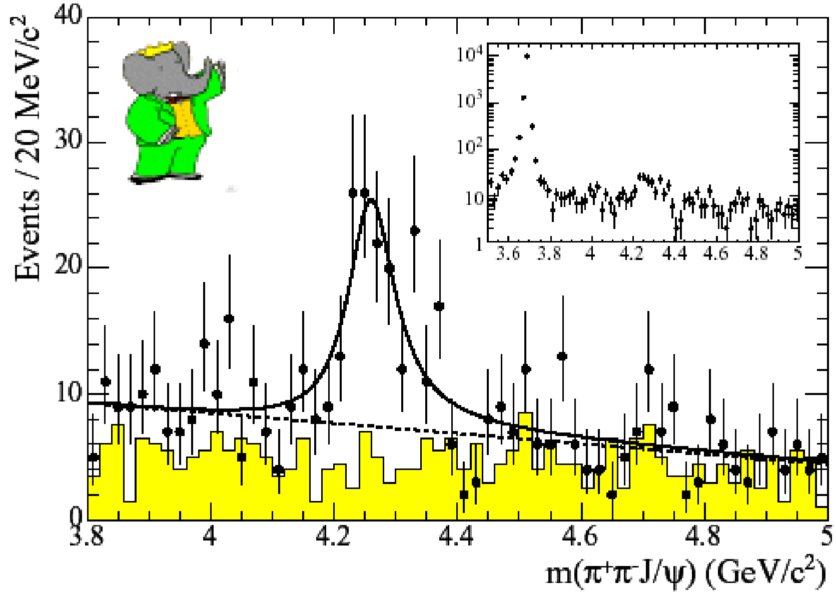
X(4630)=Y(4660)?

5^3S_1 charmonium state?

- M~4670 MeV

Y(4260)

Discovered by Babar as enhancement in $\pi\pi$ J/ψ subsystem in $e^+e^- \rightarrow \gamma_{ISR}\, \psi\pi\pi$ PRL 95, 142001(2005)



M=4259 $\pm$ 8 $\pm$ 4 MeV

Γ =88 $\pm$ 23 $\pm$ 5 MeV

$\Gamma_{ee} \times BR(Y \rightarrow \pi^+\pi^- J/\psi)$=5.5 $\pm$ 1.0$\pm$0.8 eV

ISR production tells us $J^{PC}=1^{--}$

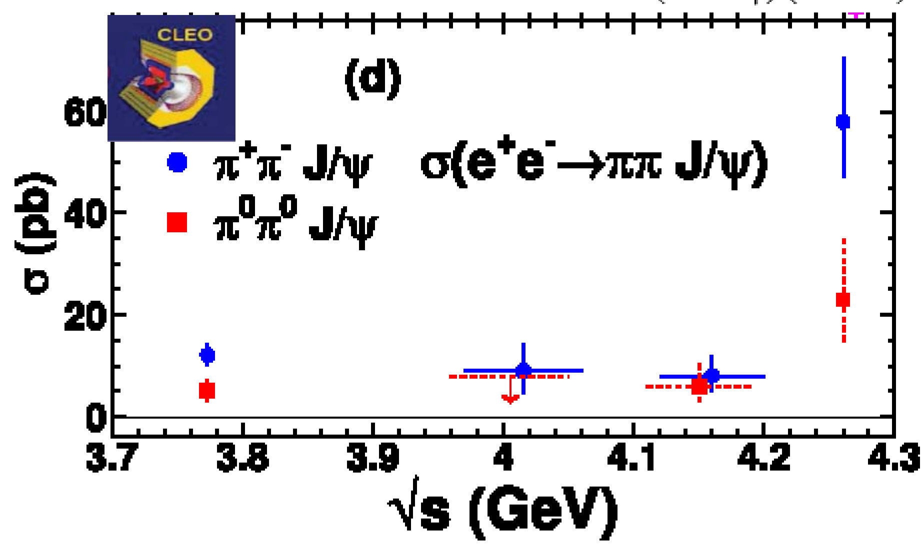
Further evidence in

$B \rightarrow K(\pi^+\pi^- J/\psi)$ PR D73, 011101(2006)

Confirmed by

CLEO PRL 96, 162003 (2006)

Belle PRL 99, 182004 (2007)



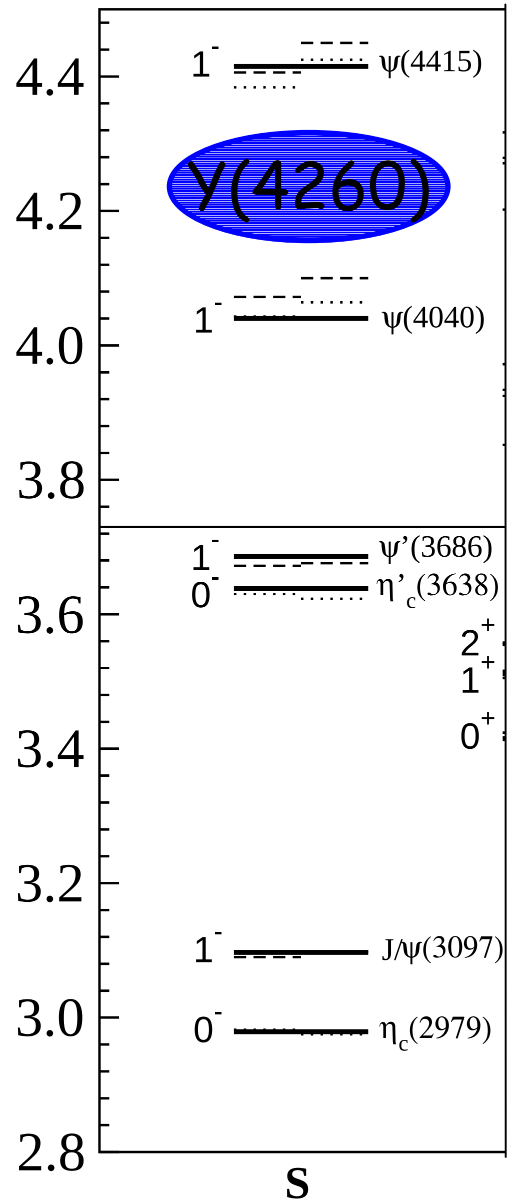
Y(4260)

Conventional Charmonium:

- The first unaccounted 1^{--} state is the $\psi(3D)$
- Quark models estimate $M(\psi(3D))$~4500 MeV much too heavy for the Y(4260)
- Y(4260) represents an overpopulation of expected 1^{-} states
- Absence of open charm production also against conventional cc state

Other explanations are:

- . $\psi(4S)$ Phys Rev D72, 031503 (2005)
- Tetraquark Phys Rev D72, 031502 (2005)
- D_1D^* Bound state PRL 102, 242003
- cc hybrid Phys Lett B625, 212 (2005); Phys Lett B628, 215 (2005) Phys Lett B631, 164 (2005)



Y(4260): Hybrid?

- Flux tube model predicts lowest cc hybrid at 4200 MeV
- LGT expects lowest cc hybrid at 4200 MeV [Phys Lett B401, 308 (1997)]

  - LGT study suggest searching for other closed charm modes with $J^{PC}=1^{--}$ $J/\psi\eta,\ J/\psi\eta',\ \chi_J\omega\ldots$
  - The dominant decay mode expected to be $D+D_1(2420)$
    $D_1(2420)$ has width ~300 MeV and decays to $D^*\pi$
    - **Suggests search for Y(4260) in $DD^*\pi$**
  - Evidence of large $DD_1(2420)$ signal would be strong evidence for hybrid

- Search for Partner States: (fill in the multiplet)
  - Identify J^{PC} partners of the hybrid candidate nearby in mass.
  - The F-T model expects:

$$\mathbf{0^{+-},\ 1^{-+},\ 2^{+-},\ 0^{-+},\ 1^{+-},\ 2^{-+},\ 1^{++},\ 1^{--}}$$

Y states in ISR: What are they?

- Conventional states?
  - Don't match the peaks in $D^{(*)}D^{(*)}$ cross-sections
  - No room unless predictions way off

- Are Y states threshold effects?
  - Opening up of channels
  - Coupled-channel effects
  - rescattering of charmed meson pairs could shift masses, cause binding and account for observed spectrum

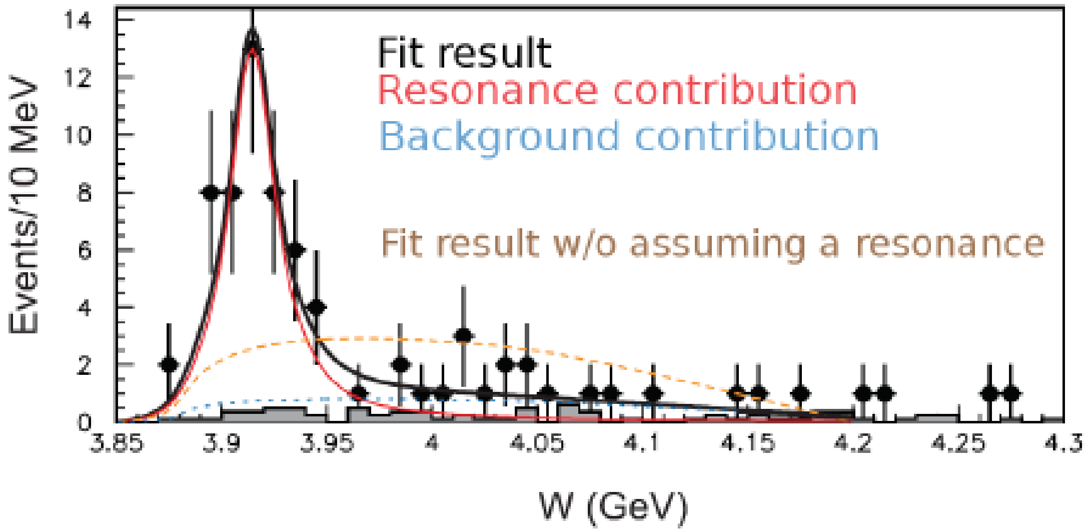
Voloshin hep-ph/0602233; Close & Downum, PRL 102, 242003(2009); Danilin & Simonov, 0907.1088; van Beveren & Rupp 0904.4351

- Charmonium hybrids
- Multiquark states

Most need to be confirmed

The Y(4260) is the most robust and might be hybrid

New peak in $\gamma\gamma \to \omega J/\psi$ @ 3915 GeV (Belle preliminary)



X(3915)

$$M = 3914 \pm 3 \pm 2 \;\; \text{MeV}$$
$$\Gamma = 23 \pm 9^{+2}_{-3} \;\; \text{MeV}$$
$$N_{\text{sig}} = 54 \pm 11 \pm 4$$
$$\text{Significance} = 7.5\sigma$$

$\hookrightarrow$ consistent with $Y(3940)$ values!

Product of decay width and $\mathcal{B}$

J^P	$\Gamma_{\gamma\gamma}\mathcal{B}(X(3915) \to \omega J/\psi)$
0^+	$69 \pm 16^{+7}_{-18}$ eV
2^+	$21 \pm 4^{+2}_{-5}$ eV

For comparison:

$\Gamma_{\gamma\gamma}\mathcal{B}(Z(3930) \to D\overline{D})$
$= 180 \pm 50 \pm 30$ eV

If $X(39$ ... $)=$ ... 2

... reshold

... $c\bar{c}$ candidates for
X ... 40), $Y(3940)$ and $X(3915)$.

Some of the many topics left out

- f_{Ds} puzzle and new physics — Aida El-Khadra talk
- $D_{sJ}(2317)$ & $D_{sJ}(2460)$
- Hadronic transitions in Quarkonium — CLEO: PRL101, 192001(2008)
- BESIII results for J/ψ decays
- $Y(2175)$, B_c, $Y_b(10890)$ …
- Quarkonium annihilation decays — CLEO: PR D78, 091103 (2008)
  PR D78, 092007 (2008)
- N^* Program at Jefferson Lab — V.D. Burkert, 0907.0661

Summary

- Many hadrons with heavy quarks have been observed with properties in good agreement with theory

- Many new charmonium-like states observed, not clear how they fit in
  - A few are strong candidates for molecules & hybrids
  - Many need confirmation and measure properties
  - Coupled channel effects, threshold effects need to be better understood

- Future is promising with many new experiments in the future:

  BaBar, Belle, BESIII, JLab, PANDA, LHC…