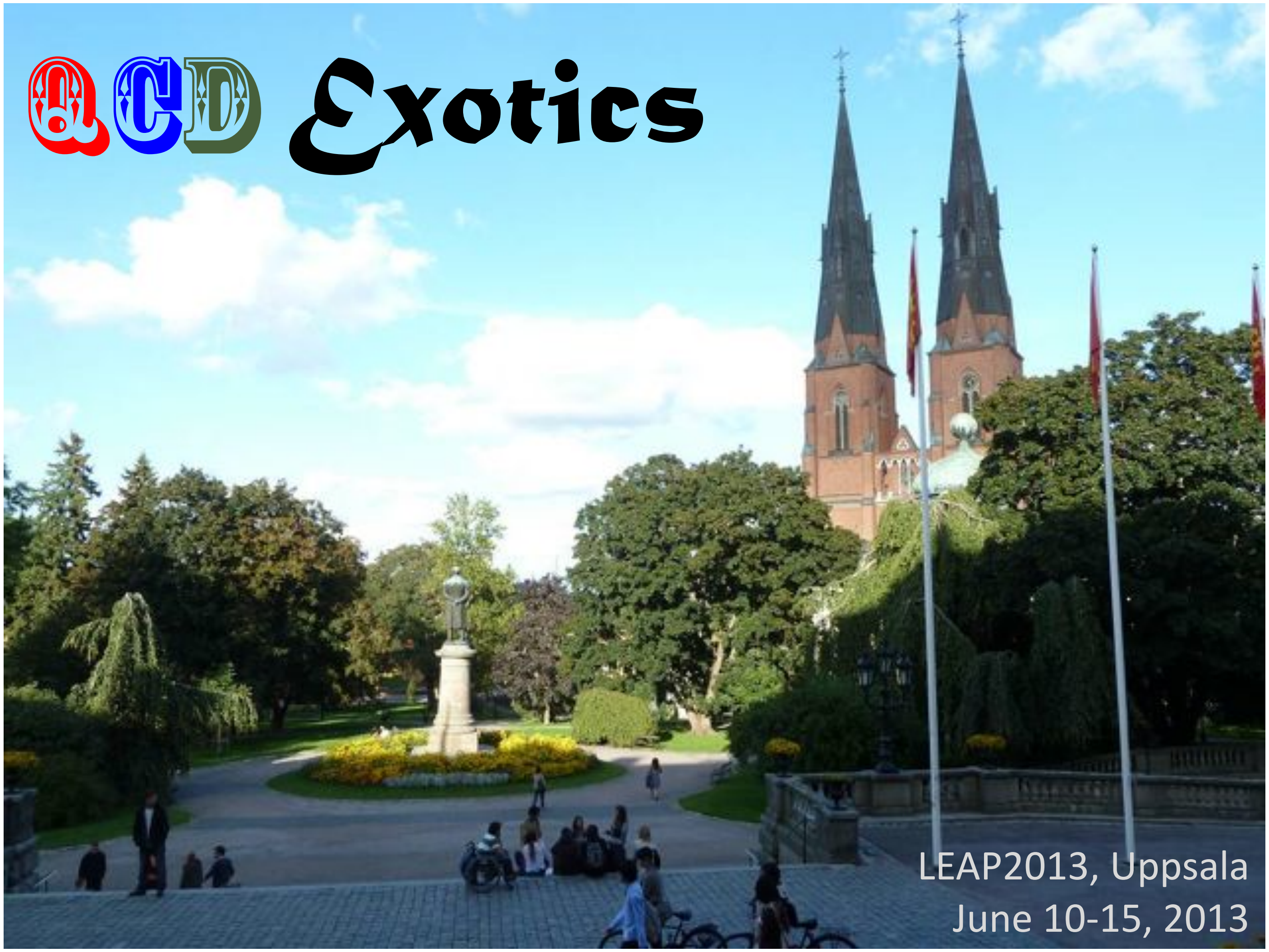


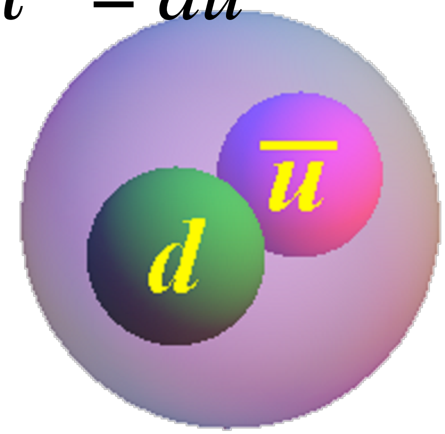
Stephen Lars Olsen

Seoul National University

Constituent Quark Model

1964 The model was proposed independently by Gell-Mann and Zweig
Three fundamental building blocks 1960's (p,n,λ) $\Rightarrow$ 1970's (u,d,s)

$\pi^- = d\bar{u}$



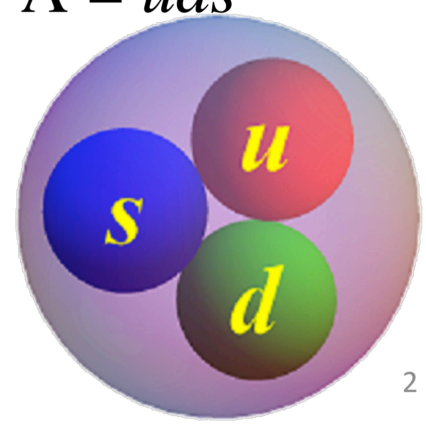
mesons are bound states of a of quark and anti-quark:

$$\pi^+ = u\bar{d} \qquad \pi^0 = \tfrac{1}{\sqrt{2}}(u\bar{u} - d\bar{d}) \quad \pi^- = d\bar{u}$$

$$K^+ = u\bar{s} \quad K^0 = d\bar{s} \quad \overline{K}^0 = s\bar{d} \quad K^- = s\bar{u}$$

baryons are bound state of 3 quarks:

$\Lambda = uds$

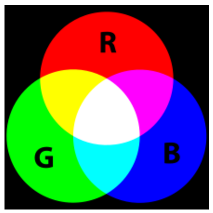


$$p = uud \qquad n = udd \quad \Lambda = uds$$

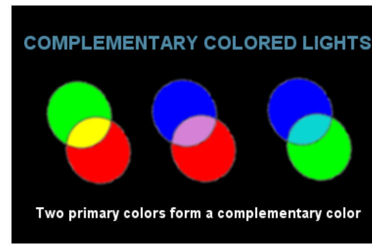
$$\bar{p} = \bar{u}\bar{u}\bar{d} \quad \bar{n} = \bar{u}\bar{d}\bar{d} \quad \overline{\Lambda} = \bar{u}\bar{d}\bar{s}$$

QPM Superseded by QCD in the 1970s: observed particles are color singlets

3 primary colors → **white**

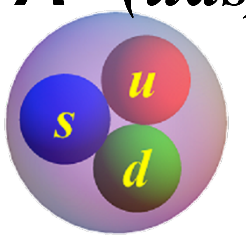


color + complementary **color** → **white**



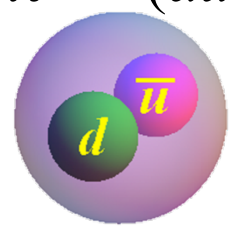
blue-yellow
green-magenta
red-cyan

$\Lambda = (uds)$



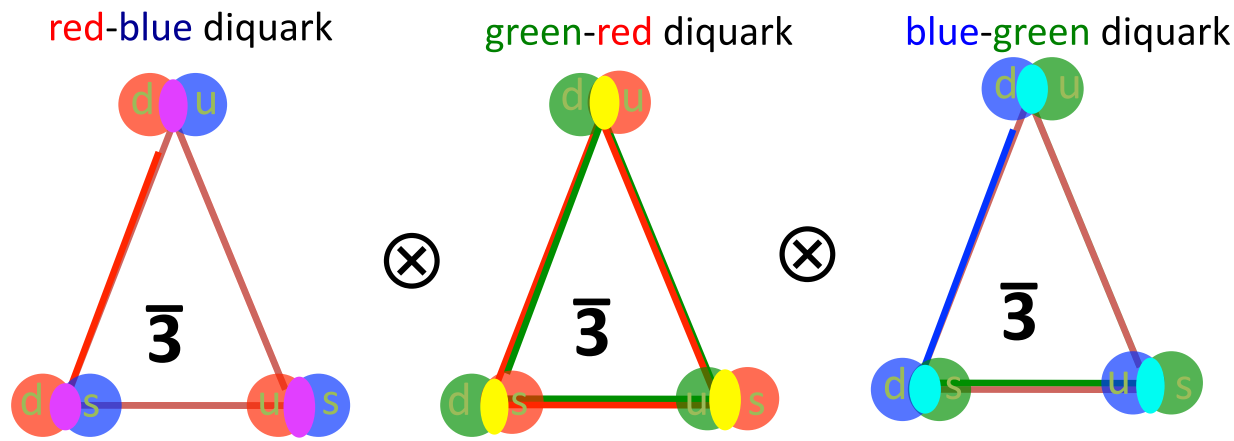
Baryons are red-blue-green triplets

$\pi^- = (d\bar{u})$



Mesons are color-anticolorpairs

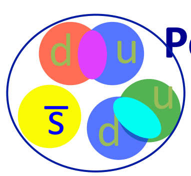
multiquark states from diquarks & diantiquarks



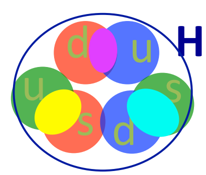
magenta (anti-green)
anti-triplet

yellow (anti-blue)
anti-triplet

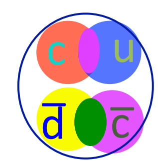
cyan (anti-red)
anti-triplet



Pentaquark



H-dibaryon



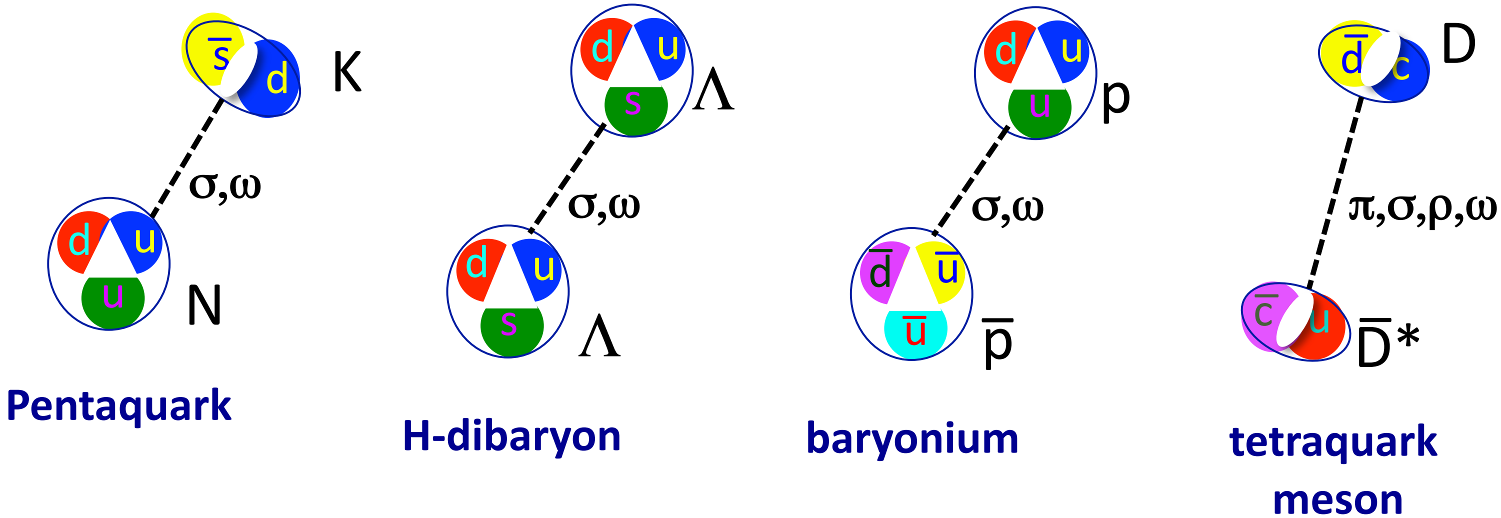
tetraquark meson

magenta-cyan-yellow
color singlet 5-q state

magenta-cyan-yellow
color singlet 6-q state

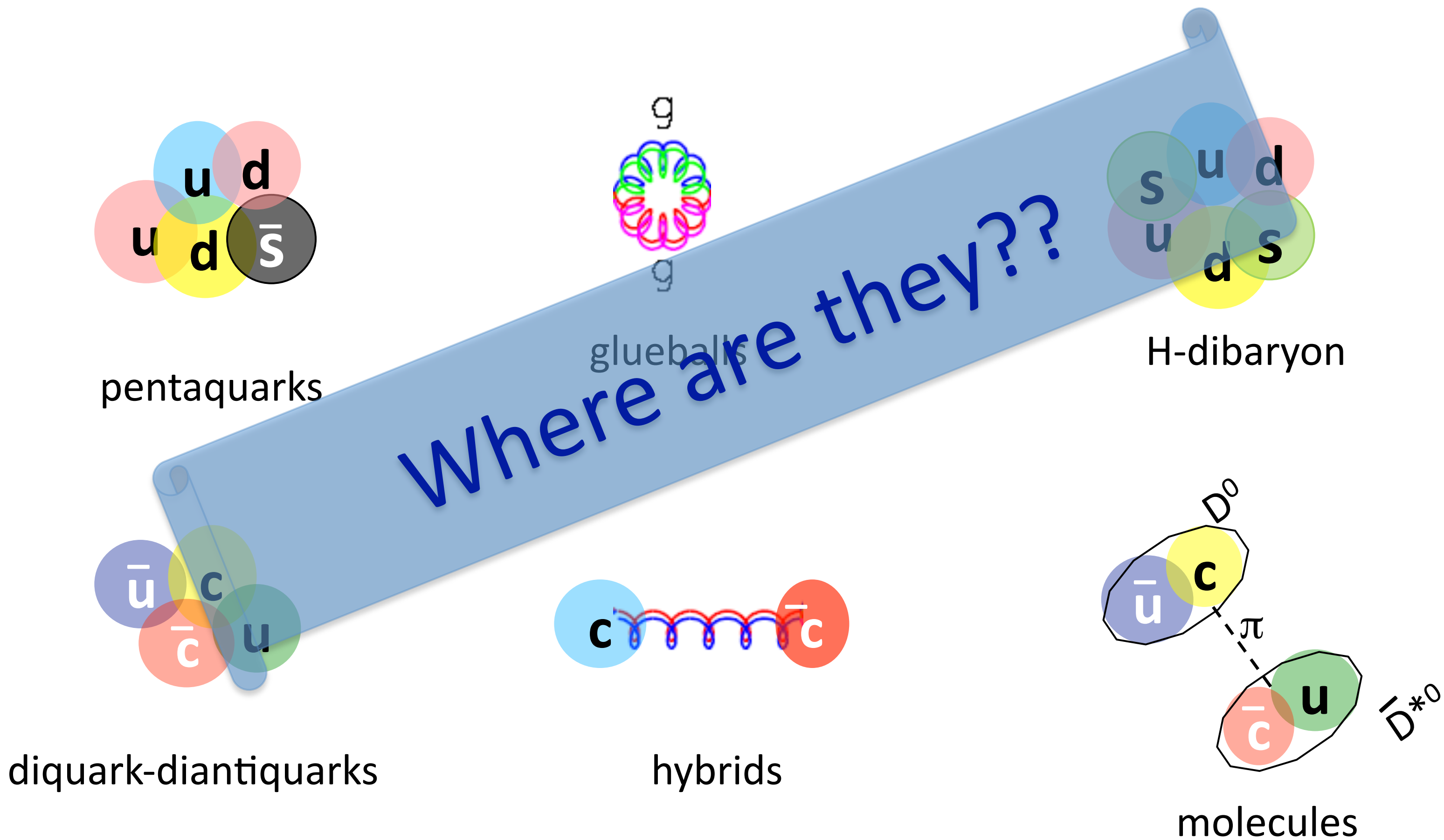
green-magenta (anti-green)
color singlet 4-q state

multiquark states from "molecules"



-new dimensions to Nuclear Physics-

Non-$q\bar{q}$ mesons or non-qqq baryons predicted by `QCD-motivated' models

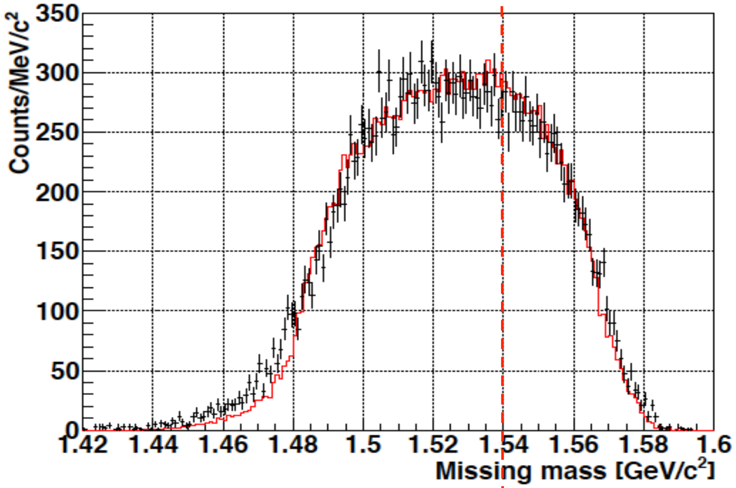


non-$q\bar{q}$ & non-qqq color-singlet combinations

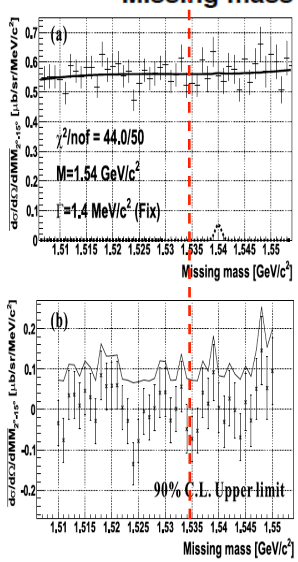
No Pentaquarks

J-PARC E19 - 2012 PRL 109, 132002

$$\pi^- p \to K^- X \;@\; 1.92 GeV/c$$

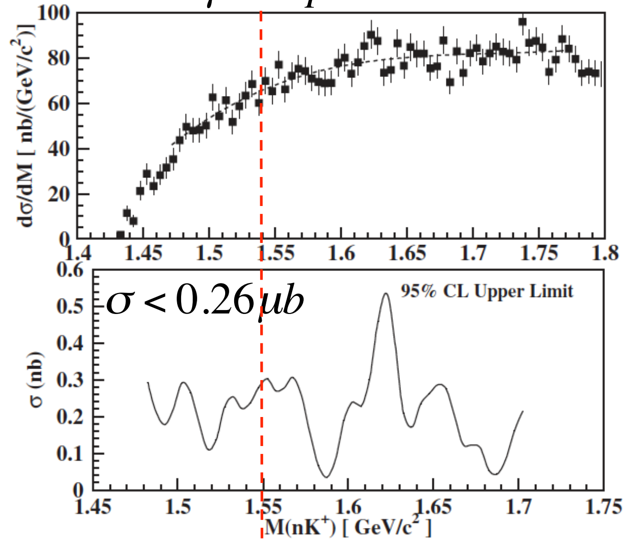


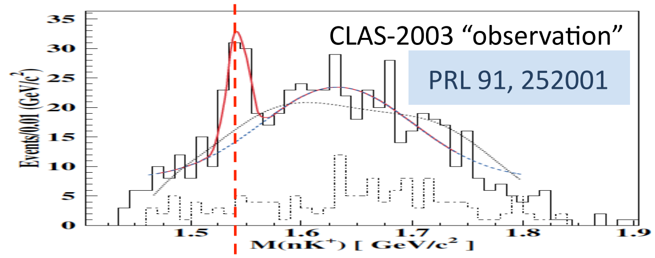
$$\frac{d\sigma}{d\Omega} < 0.26 \mu b / sr$$



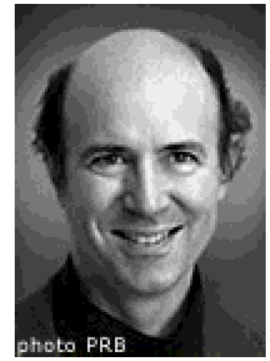
JLab CLAS -2006 PRL 96, 212001

$$\gamma d \to p K^- K^+ n$$





“The story of pentaquark shows how poorly we understand QCD” – F. Wilczek, 2005

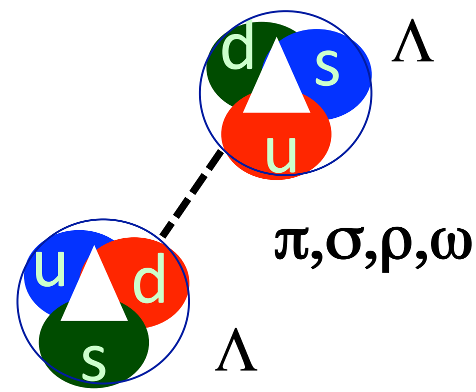


Frank Wilczek

How about the H dibaryon?

Tightly bound
diquark triplet

or



Hyperon-hyperon
molecular state

R.L. Jaffee, PRL 38, 195 (1977): $J^P = 0^+$ **di-hyperon with** $M_H \approx 2m_\Lambda - 80$ **MeV**

models predict $M_H \approx 2m_\Lambda$

long-lived
cτ > 3 cm!!

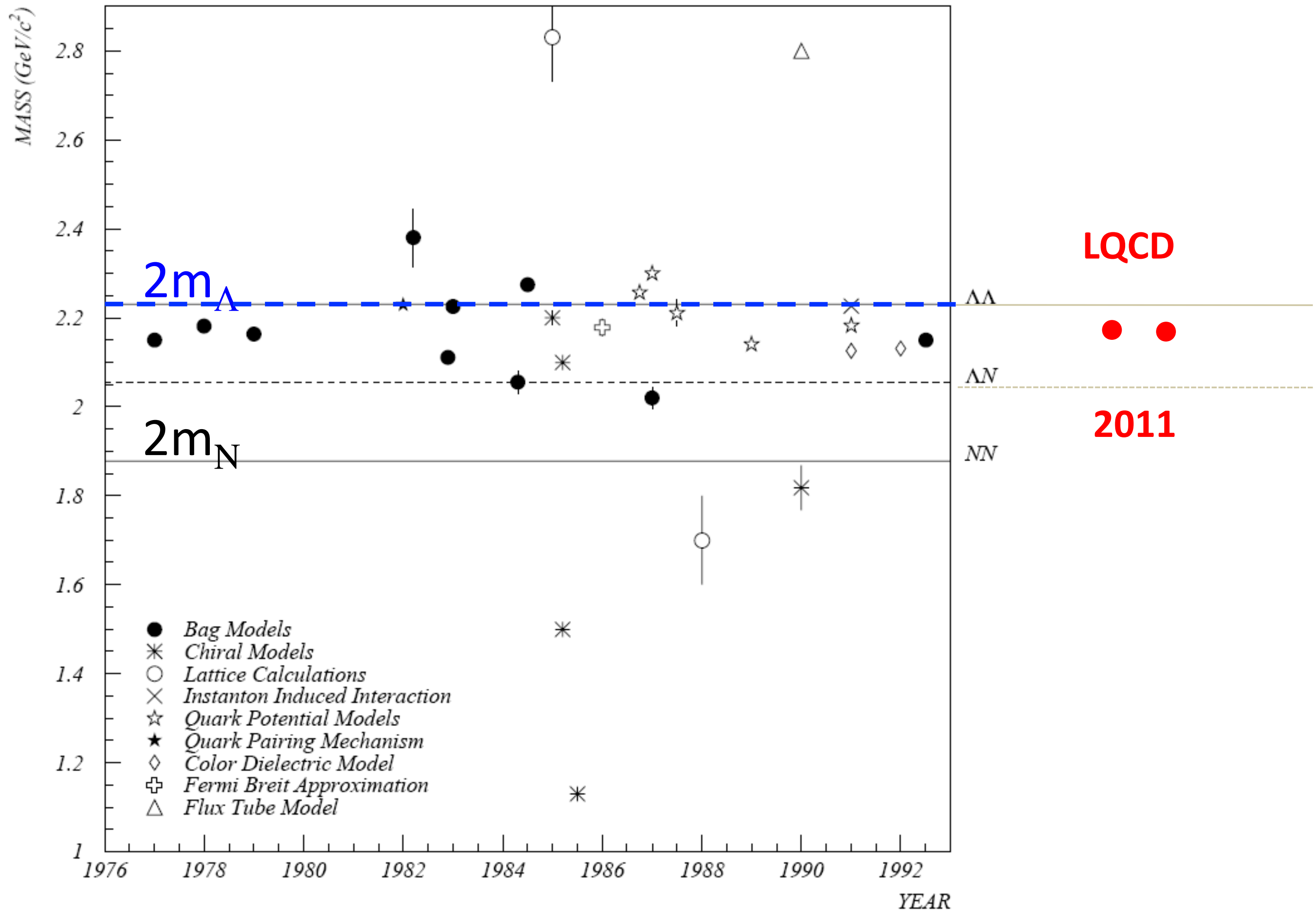


Figure 1: Theoretical predictions for the mass of the H-dibaryon as a function of year of prediction

Recent Lattice QCD calculations

S.R. Beane *et al* (NPLQCD) PRL 106, 062001 (2011)

T. Inoue *et al* (NPLQCD) PRL 106, 062002 (2011)

Evidence for a Bound H-dibaryon from Lattice QCD

S.R. Beane,[1,2] E. Chang,[3] W. Detmold,[4,5] B. Joo,[5] H.W. Lin,[6] T.C. Luu,[7] K. Orginos,[4,5] A. Parreño,[3] M.J. Savage,[6] A. Torok,[8] and A. Walker-Loud[9]
(NPLQCD Collaboration)

[1] *Albert Einstein Zentrum für Fundamentale Physik, Institut für theoretische Physik, Sidlerstrasse 5, CH-3012 Bern, Switzerland*
[2] *Department of Physics, University of New Hampshire, Durham, NH 03824-3568, USA*
[3] *Dept. d'Estructura i Constituents de la Matèria. Institut de Ciències del Cosmos (ICC), Universitat de Barcelona, Martí Franquès 1, E08028-Spain*
[4] *Department of Physics, College of William and Mary, Williamsburg, VA 23187-8795, USA*
[5] *Jefferson Laboratory, 12000 Jefferson Avenue, Newport News, VA 23606, USA*
[6] *Department of Physics, University of Washington, Box 351560, Seattle, WA 98195, USA*
[7] *N Division, Lawrence Livermore National Laboratory, Livermore, CA 94551, USA*
[8] *Department of Physics, Indiana University, Bloomington, IN 47405, USA*
[9] *Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA*

(Dated: December 20, 2010)

$M_H = 2m_\Lambda - 16.1 \pm 2.1 \pm 4.6$ MeV

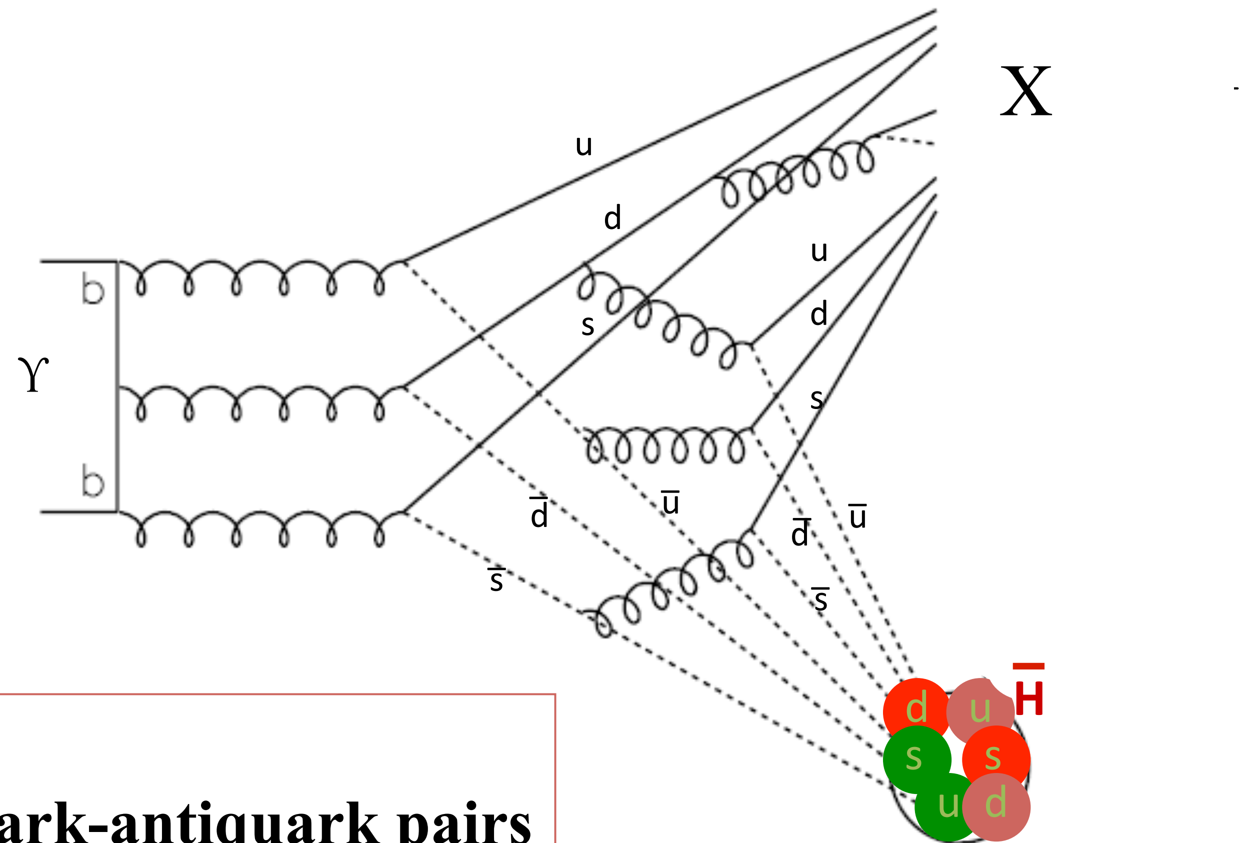
Bound H-dibaryon in Flavor SU(3) Limit of Lattice QCD

Takashi Inoue[1] Noriyoshi Ishii[2], Sinya Aoki[2,3], Takumi Doi[3], Tetsuo Hatsuda[4,5], Yoichi Ikeda[6], Keiko Murano[7], Hidekatsu Nemura[8], Kenji Sasaki[3]
(HAL QCD Collaboration)

[1] *Nihon University, College of Bioresource Sciences, Fujisawa 252-0880, Japan*
[2] *Center for Computational Sciences, University of Tsukuba, Tsukuba 305-8577, Japan*
[3] *Graduate School of Pure and Applied Sciences, University of Tsukuba, Tsukuba 305-8571, Japan*
[4] *Department of Physics, The University of Tokyo, Tokyo 113-0033, Japan*
[5] *IPMU, The University of Tokyo, Kashiwa 277-8583, Japan*
[6] *Nishina Center for Accelerator-Based Science, Institute for Physical and Chemical Research (RIKEN), Wako 351-0198, Japan*
[7] *High Energy Accelerator Research Organization (KEK), Tsukuba 305-0801, Japan*
[8] *Department of Physics, Tohoku University, Sendai 980-8578, Japan*

$M_H = 2m_\Lambda$ – "(30~40) MeV"

Production via gluons in Υ(1S) decays



Need to:

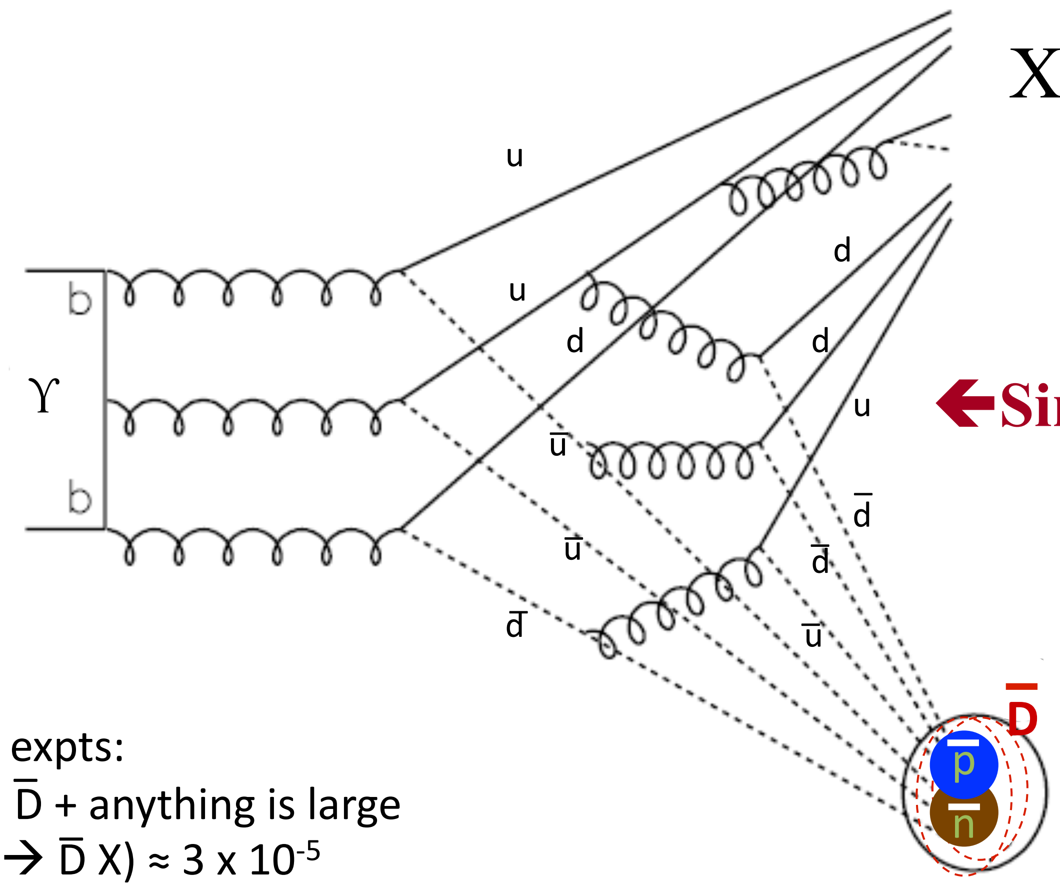
produce 6 quark-antiquark pairs

(including two $s\bar{s}$ quark pairs)

very close in phase space

← Is this likely???

Anti-deuteron production in $\Upsilon(1S)$ decays



← **Similar process!!**

ARGUS & CLEO expts:

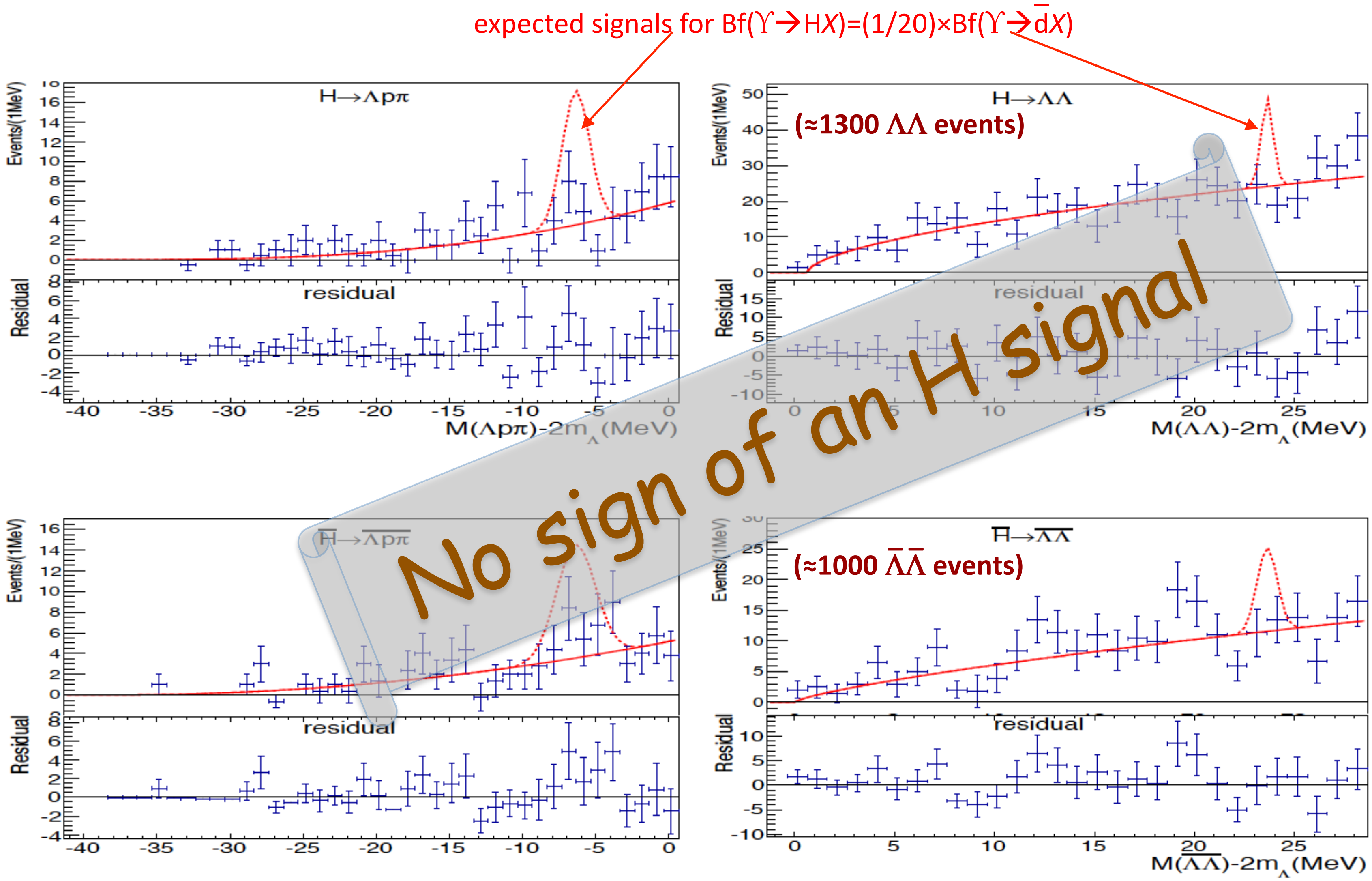
$\Upsilon(1,2S) \rightarrow \bar{D}$ + anything is large

$Bf(\Upsilon(1,2S) \rightarrow \bar{D}\,X) \approx 3 \times 10^{-5}$

H. Albrecht *et al* (ARGUS) PRB 236, 102 (1990)
D.M. Asner *et al* (CLEO) PRD 75, 012009 (2007)

Belle data samples: 100×10^{6} $\Upsilon(1S)$ decays + 160×10^{6} $\Upsilon(2S)$ decays

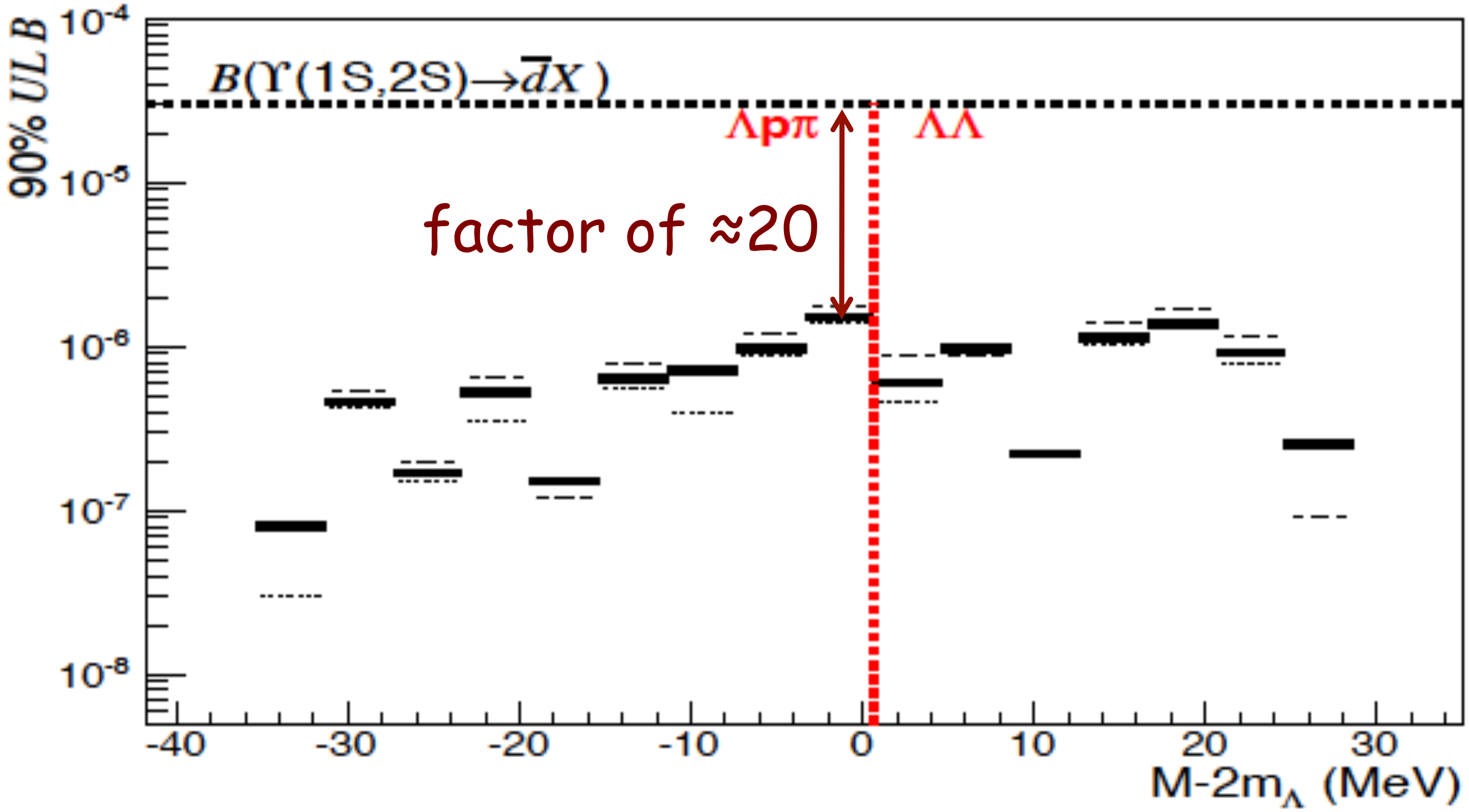
$\Upsilon(1,2S) \to \Lambda p \pi^- X$ & $\Upsilon(1,2S) \to \Lambda\Lambda X$



$M(\Lambda p \pi^-)$-$2m_\Lambda$

$M(\Lambda\Lambda)$-$2m_\Lambda$

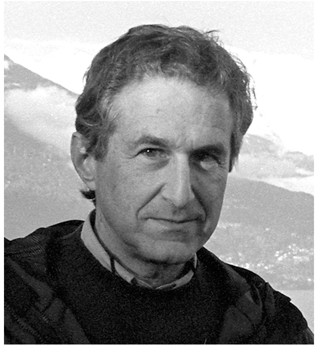
90% CL upper limits on Υ(1S,2S)→H X



B.H. Kim *et al* (Belle) PRL 110, 222002 (2013) ← last week

QCD-motivated multiquark states are not seen!

“The absence of exotics is one of the most obvious features of QCD, R. Jaffe 2005



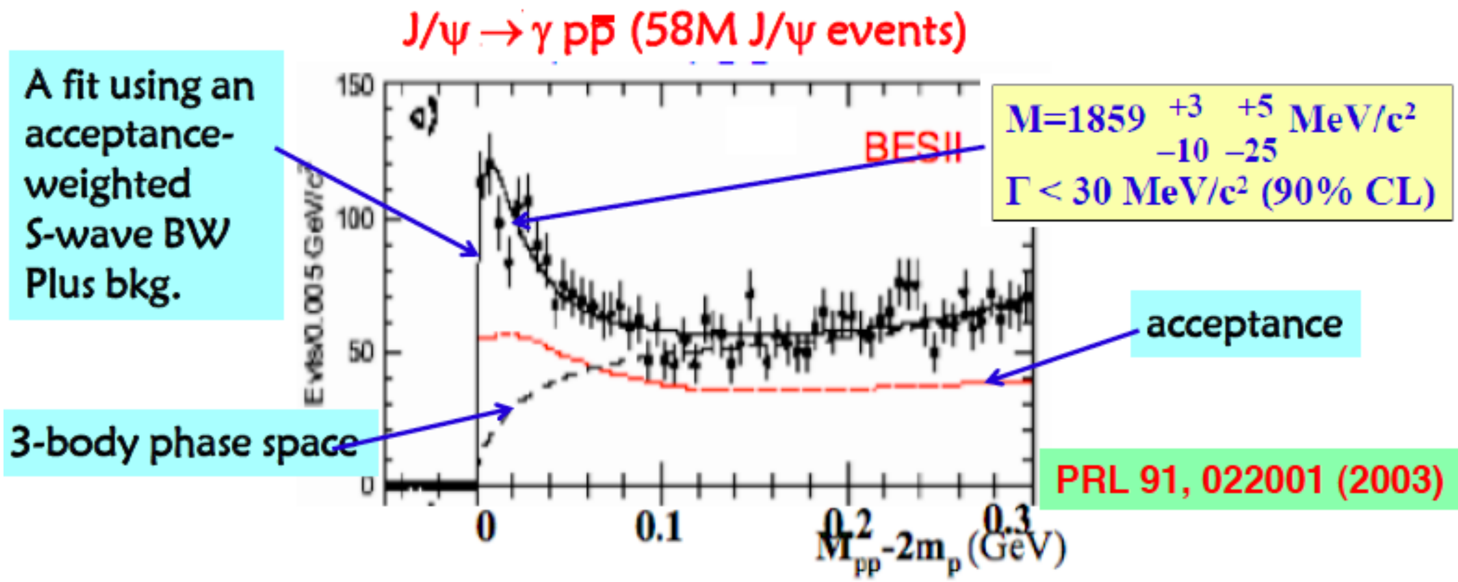
Robert Jaffe

What do we see?

- Baryonium?
- XYZ mesons

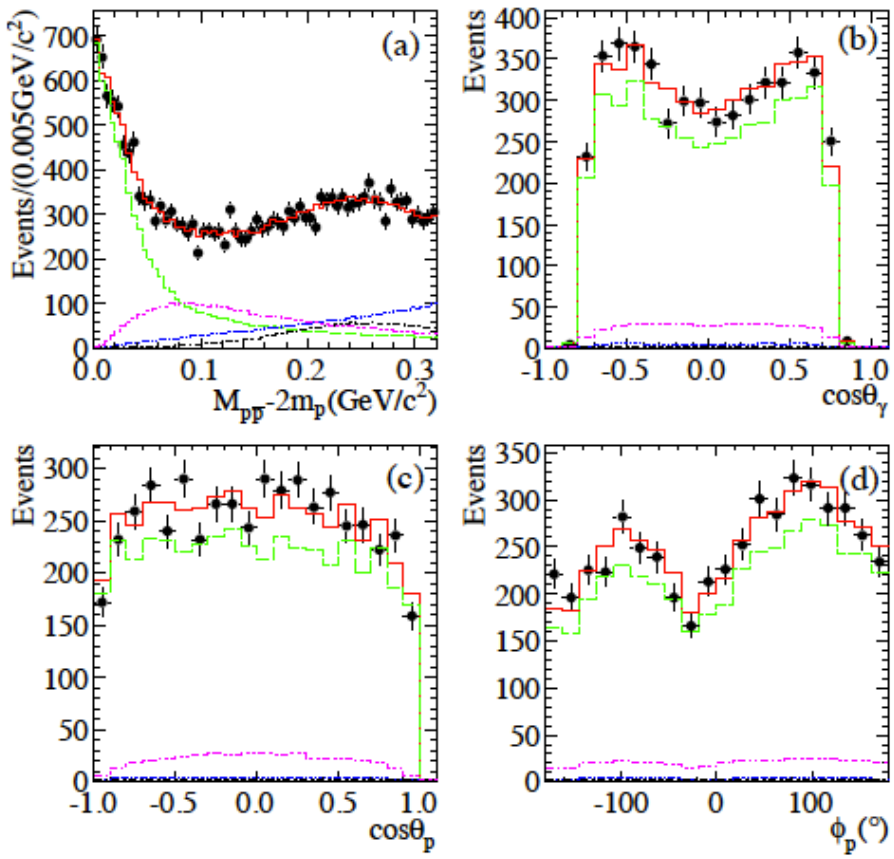
$p\bar{p}$ bound state in $J/\psi \rightarrow \gamma p\bar{p}$?

BESII -- 10 years ago --



2012, with 5x more data

$J/\psi \rightarrow \gamma p\bar{p}$

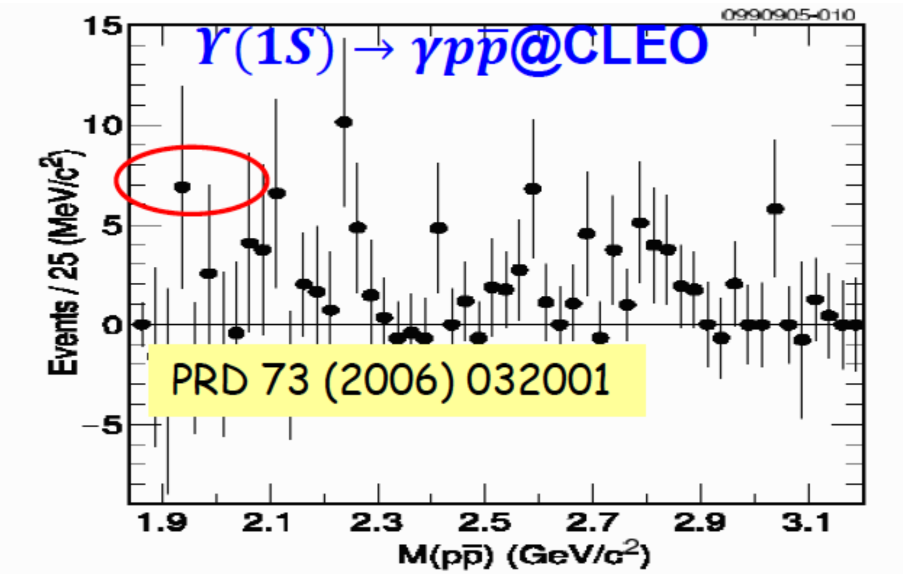


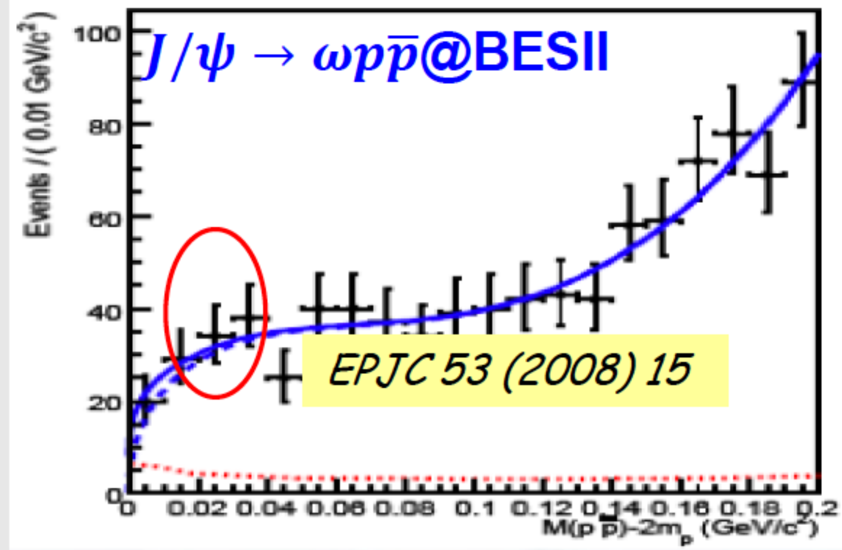
PRL 108, 112003 (2012)

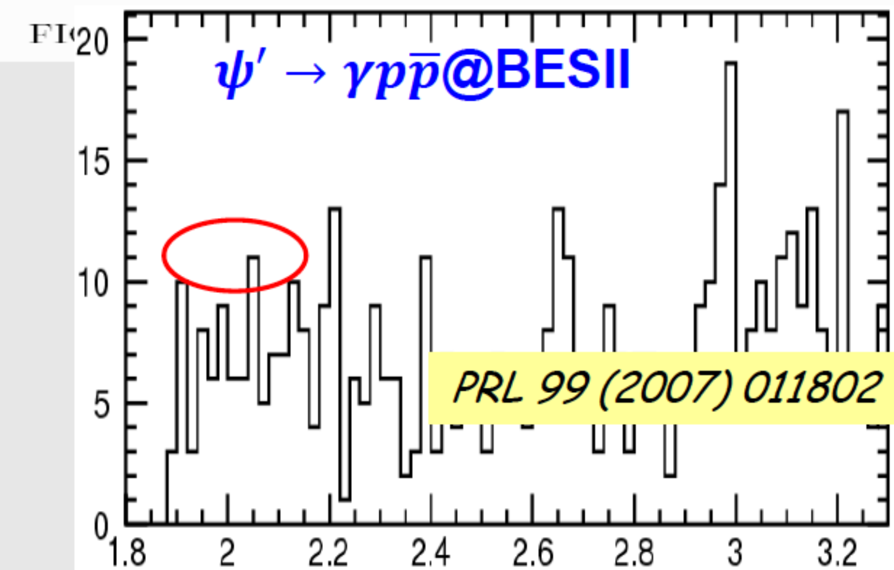
Partial Wave Analysis:

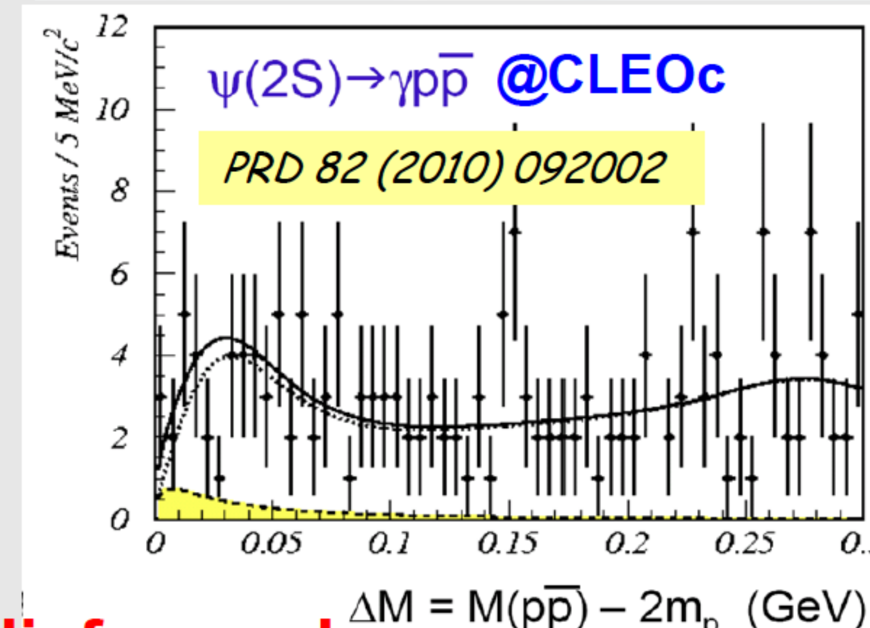
- $J^{PC} = 0^{-+}$ >6.8σ better than other assignments
- I=0 FSI improves the fit quality by ~7σ
- $M = 1832^{+19}_{-5}\,^{+18}_{-33} \pm 19_{model}$ MeV
  ($\approx 2m_p$-40 MeV)
- $\Gamma <$ 76 MeV
- $Bf(J/\psi \rightarrow \gamma X) \times Bf(X \rightarrow p\bar{p}) =$
  $(9.0^{+0.4}_{-1.1}\,^{+1.5}_{-5.0} \pm 2.3_{model}) \times 10^{-5}$
  ➔ suggests $Bf(X \rightarrow p\bar{p})$~large

Some non-observations









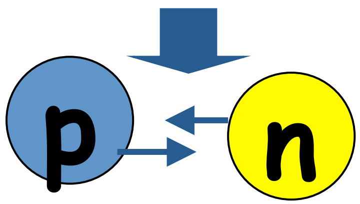
Pure FSI interpretation is disfavored

A $p\bar{p}$ bound state (baryonium)?

There is lots & lots of literature about this possibility

deuteron:

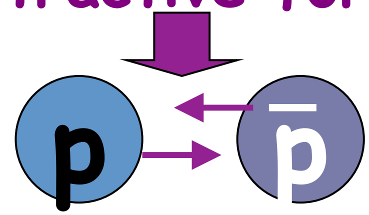
attractive nuclear force



loosely bound
3-q 3-q color
singlets with
$M_d = 2m_p - \varepsilon$

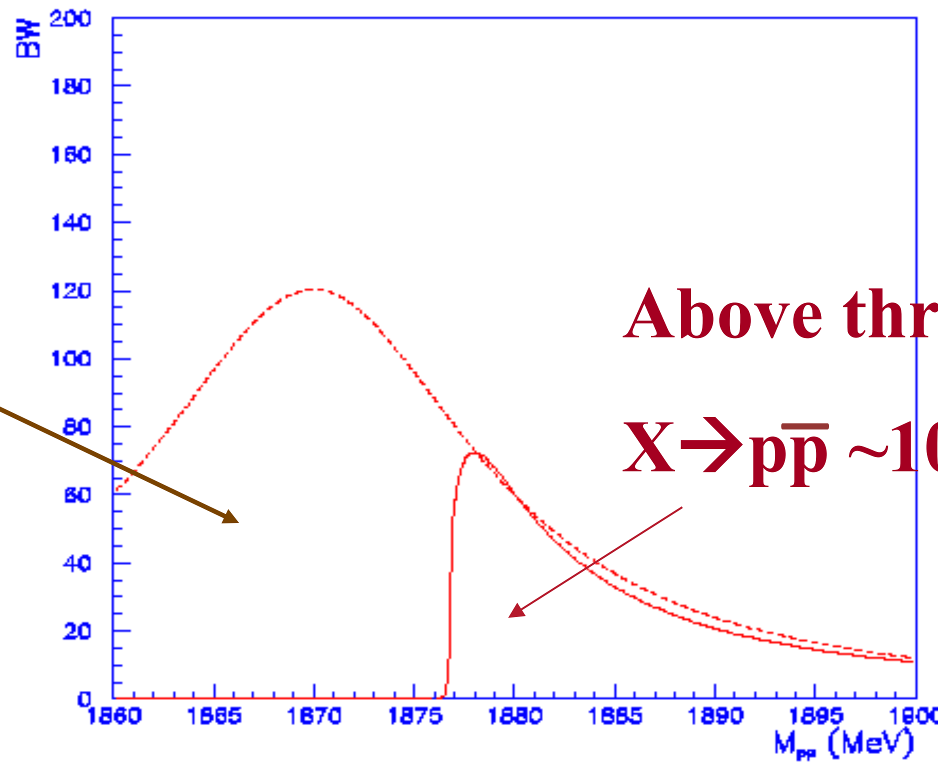
baryonium:

attractive force?



loosely bound
3-q 3-$\bar{q}$ color
singlets with
$M_b = 2m_p - \delta$?

Expectation for $p\bar{p}$ bound state



below-threshold p and $\bar{p}$ annihilate to mesons

Above threshold

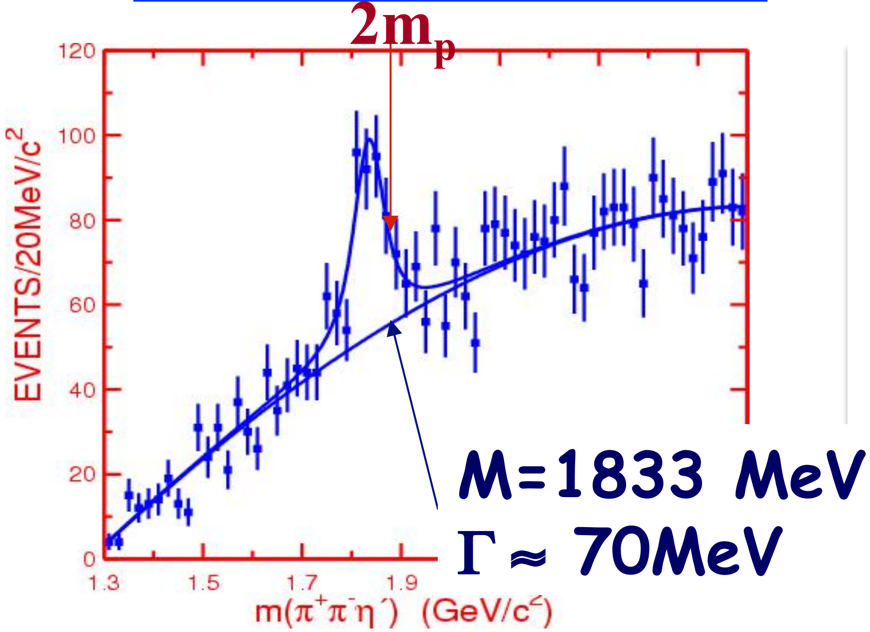
$X \rightarrow p\bar{p}$ ~100%

$m_p + m_p$

I=0, $J^{PC}=0^{-+}$ init. state: $p\bar{p} \rightarrow \pi^+\pi^-\eta'$ and $3(\pi^+\pi^-)$ are common

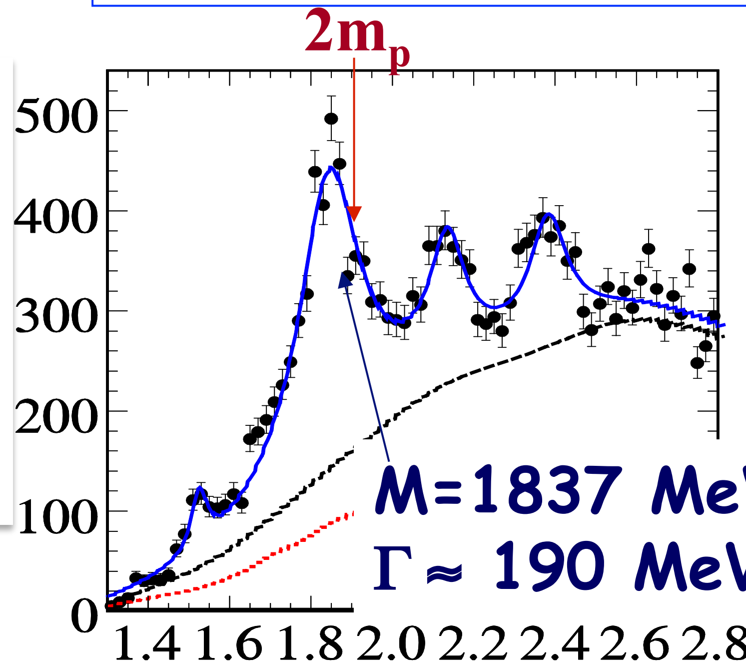
$J/\psi \rightarrow \gamma X(1835) \rightarrow \gamma(\pi^+\pi^-\eta')$

BESII PRL 95, 262001 (2005)



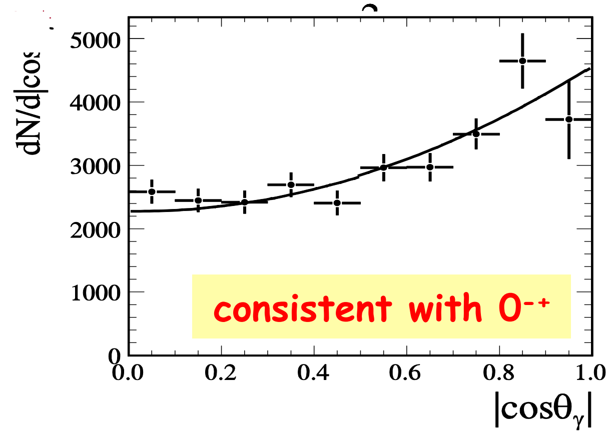
M=1833 MeV
$\Gamma \approx$ 70MeV

BESIII PRL 106, 072002 (2011)



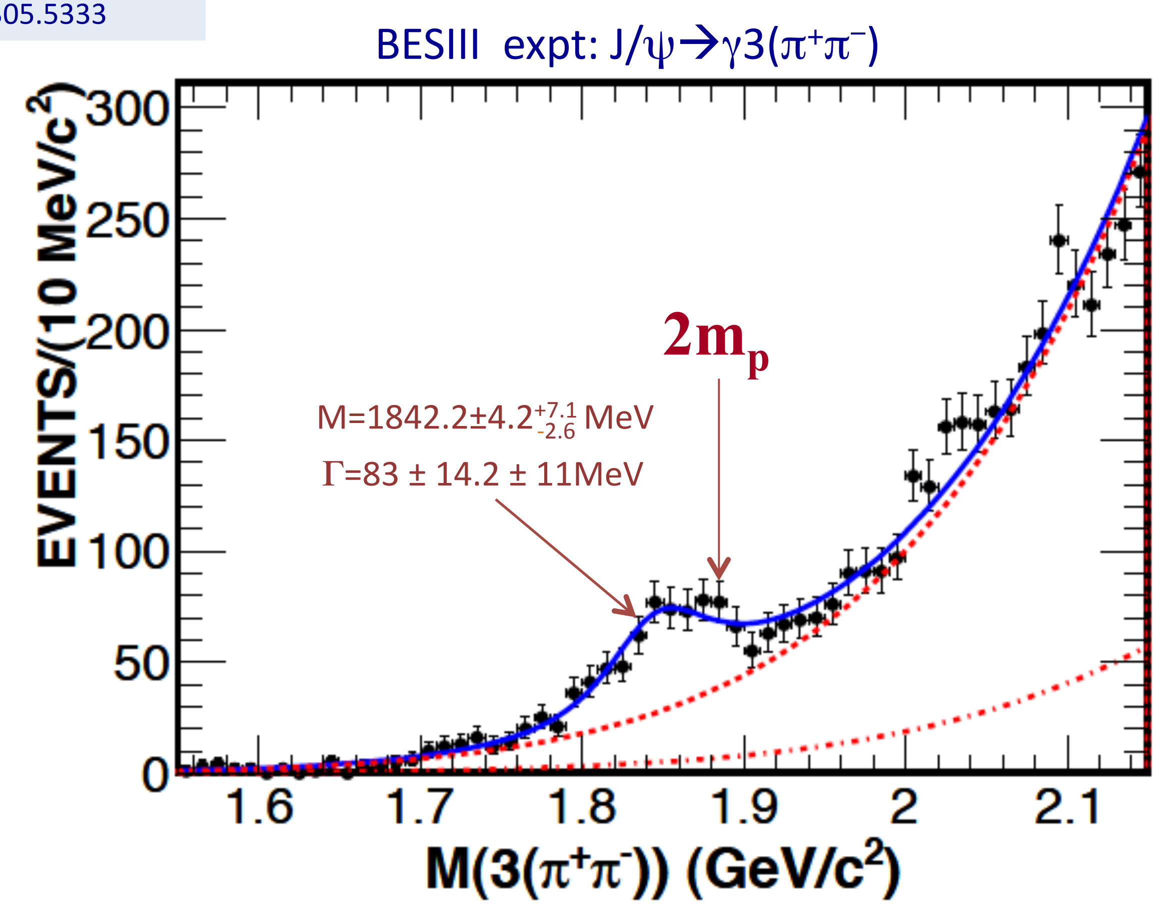
M=1837 MeV
$\Gamma \approx$ 190 MeV

$M(\pi^+\pi^-\eta')$



$J/\psi \rightarrow \gamma X(1835)$; $X \rightarrow 3(\pi^+\pi^-)$?

BESIII arXiv:1305.5333



Are the $p\bar{p}$, $\pi^+\pi^-\eta'$ & $3(\pi^+\pi^-)$ peaks all from the same state?

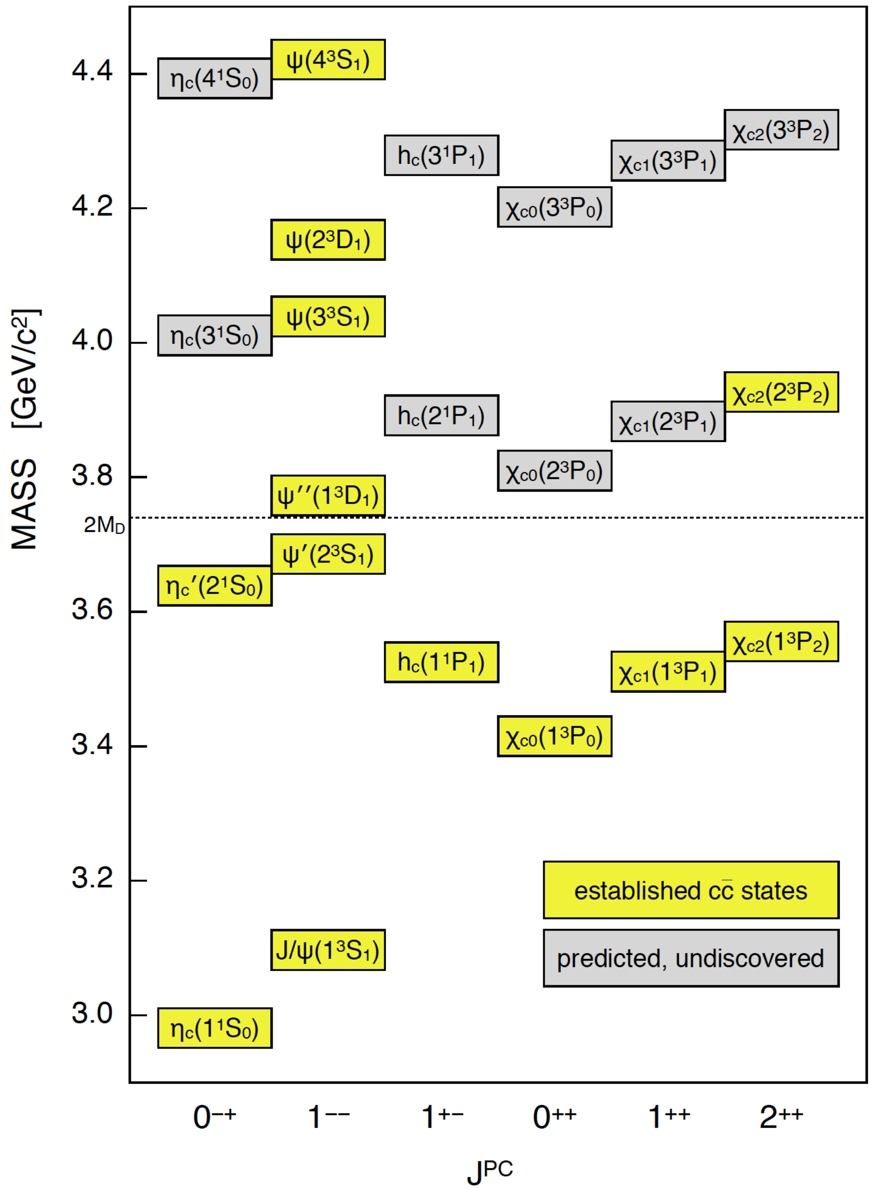
channel	M (Mev)	Γ (MeV)	J^{PC}	$Bf(J/\psi \rightarrow \gamma X) \times Bf(X \rightarrow f\,i)$
$p\bar{p}$	1832^{+32}_{-38}	13^{+25}_{-13}	0^{-+}	$(0.9^{+0.3}_{-0.5})\times10^{-4}$
$\pi^+\pi^-\eta'$	1837^{+7}_{-4}	190^{+39}_{-37}	0^{-+}(?)	$(2.9\pm0.1)\times10^{-4}$
$3(\pi^+\pi^-)$	1842^{+8}_{-5}	83 ± 17	$?^{?+}$	$(0.24\pm0.08)\times10^{-4}$

Need: J^{PC} measurement for the $X(1842) \rightarrow 3(\pi^+\pi^-)$ signal
better measurements of widths & line shapes

Some of this will be done soon with BESIII's 1.2B J/ψ event data sample,

The XYZ quarkonium-like mesons

Charmonium spectrum



Any meson that decays to a c and c quark should fit in one of the (gray) unassigned states.

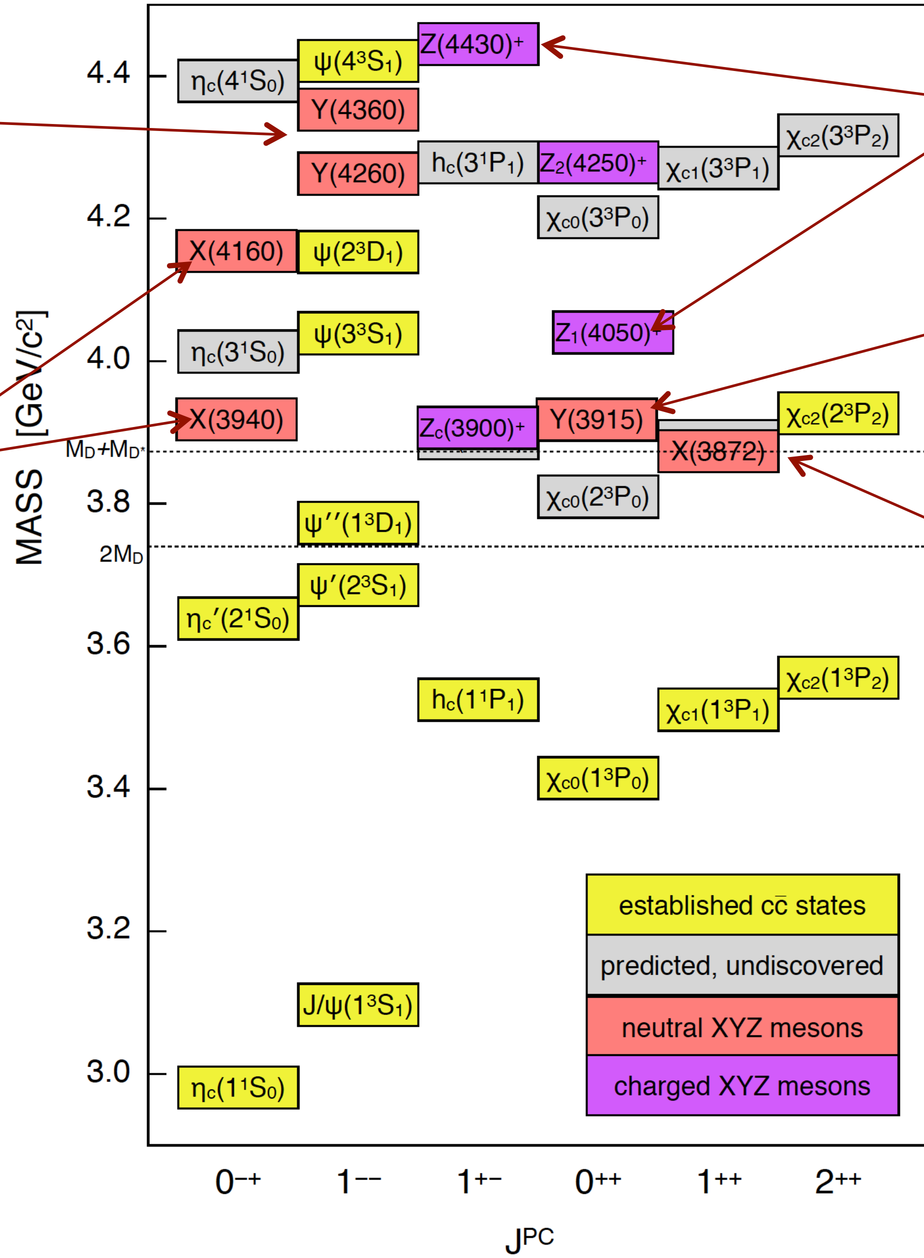
XYZ charmoniumlike mesons

State	m (MeV)	Γ (MeV)	J^{PC}	Process (mode)
$X(3872)$	3871.52 ± 0.20	1.3 ± 0.6	1^{++}	$B \to K(\pi^+\pi^- J/\psi)$
		(<2.2)		$p\bar{p} \to (\pi^+\pi^- J/\psi) + \cdots$
				$B \to K(\omega J/\psi)$
				$B \to K(D^{*0}\bar{D}^0)$
				$B \to K(\gamma J/\psi)$
$Z_c(3900)^+$	3899 ± 6	46 ± 22	$1^{+(-)}$	$Y(4260) \to \pi^-(\pi^+ J/\psi)$
$X(3915)$	3915.6 ± 3.1	28 ± 10	0^{++}	$B \to K(\omega J/\psi)$
				$e^+e^- \to e^+e^-(\omega J/\psi)$
$X(3940)$	3942^{+9}_{-8}	37^{+27}_{-17}	0^{-+}	$e^+e^- \to J/\psi(D\bar{D}^*)$
				$e^+e^- \to J/\psi\ (\ldots)$
$G(3900)$	3943 ± 21	52 ± 11	1^{--}	$e^+e^- \to \gamma(D\bar{D})$
$Y(4008)$	4008^{+121}_{-49}	226 ± 97	1^{--}	$e^+e^- \to \gamma(\pi^+\pi^- J/\psi)$
$Z_1(4050)^+$	4051^{+24}_{-43}	82^{+51}_{-55}	$0^{+(+)}/1^{-(+)}$	$B \to K(\pi^+\chi_{c1}(1P))$
$Y(4140)$	4143.4 ± 3.0	15^{+11}_{-7}	$?^{?+}$	$B \to K(\phi J/\psi)$
$X(4160)$	4156^{+29}_{-25}	139^{+113}_{-65}	0^{-+}	$e^+e^- \to J/\psi(D\bar{D}^*)$
$Z_2(4250)^+$	4248^{+185}_{-45}	177^{+321}_{-72}	$0^{+(+)}/1^{-(+)}$	$B \to K(\pi^+\chi_{c1}(1P))$
$Y(4260)$	4263 ± 5	108 ± 14	1^{--}	$e^+e^- \to \gamma(\pi^+\pi^- J/\psi)$
				$e^+e^- \to (\pi^+\pi^- J/\psi)$
				$e^+e^- \to (\pi^0\pi^0 J/\psi)$
$Y(4274)$	$4274.4^{+8.4}_{-6.7}$	32^{+22}_{-15}	$?^{?+}$	$B \to K(\phi J/\psi)$
$X(4350)$	$4350.6^{+4.6}_{-5.1}$	$13.3^{+18.4}_{-10.0}$	$0,2^{++}$	$e^+e^- \to e^+e^-(\phi J/\psi)$
$Y(4360)$	4353 ± 11	96 ± 42	1^{--}	$e^+e^- \to \gamma(\pi^+\pi^-\psi(2S))$
$Z(4430)^+$	4443^{+24}_{-18}	107^{+113}_{-71}	$1^{+(-)}$	$B \to K(\pi^+\psi(2S))$
$X(4630)$	4634^{+9}_{-11}	92^{+41}_{-32}	1^{--}	$e^+e^- \to \gamma(\Lambda_c^+\Lambda_c^-)$

$c\bar{c}$ assignments for the XYZ mesons?

no unassigned levels for the 1^{--} Y(4260) & Y(4360)

the X(3940) & X(4160) as the $\eta_c(3S)$ & $\eta_c(4S)$ would imply huge hyperfine splittings for n=3&4



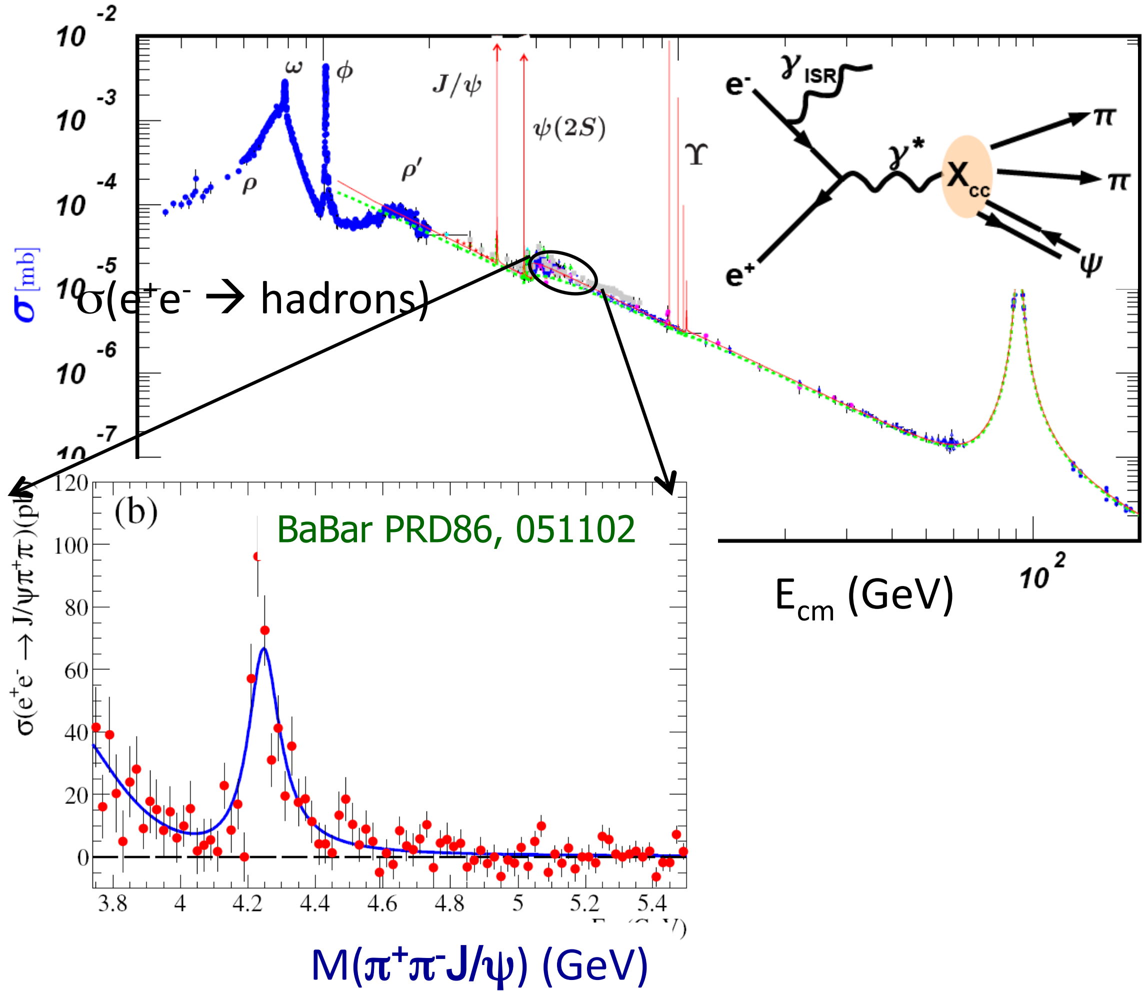
the (4) charged Zs must have a minimal quark content of $c\bar{c}u\bar{d}$

the Y(3915) mass and $\Gamma(Y \rightarrow \omega J/\psi)$ are too high for the $\chi_{c0}(2P)$

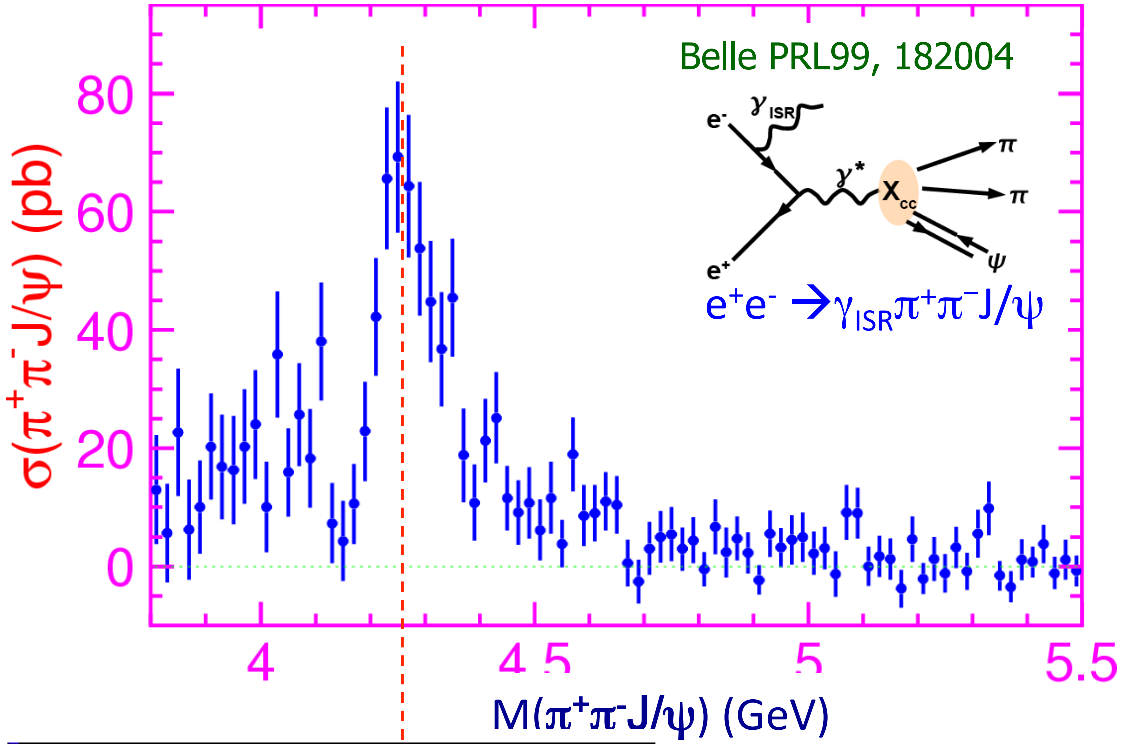
the X(3872) is a long complex story

the Y(4260)

found by BaBar in $e^+e^- \rightarrow \gamma_{ISR}\pi^+\pi^- J/\psi$

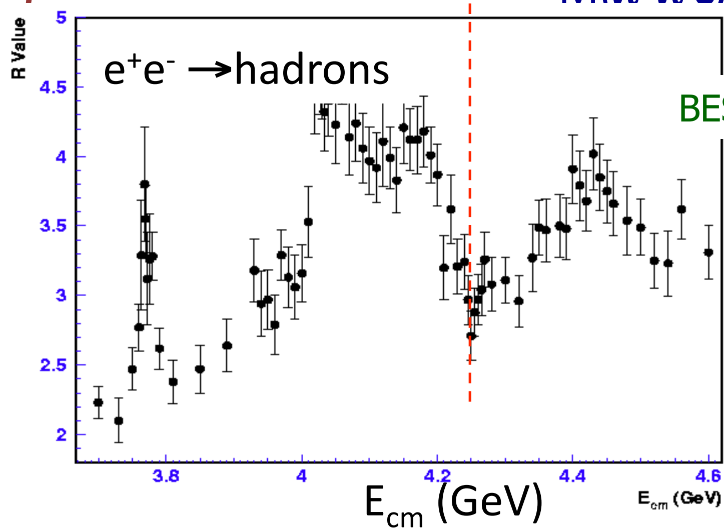


Y(4260) → $\pi^+\pi^- J/\psi$ confirmed by Belle



No sign of Y(4260) → $D^{(*)}D^{(*)}$

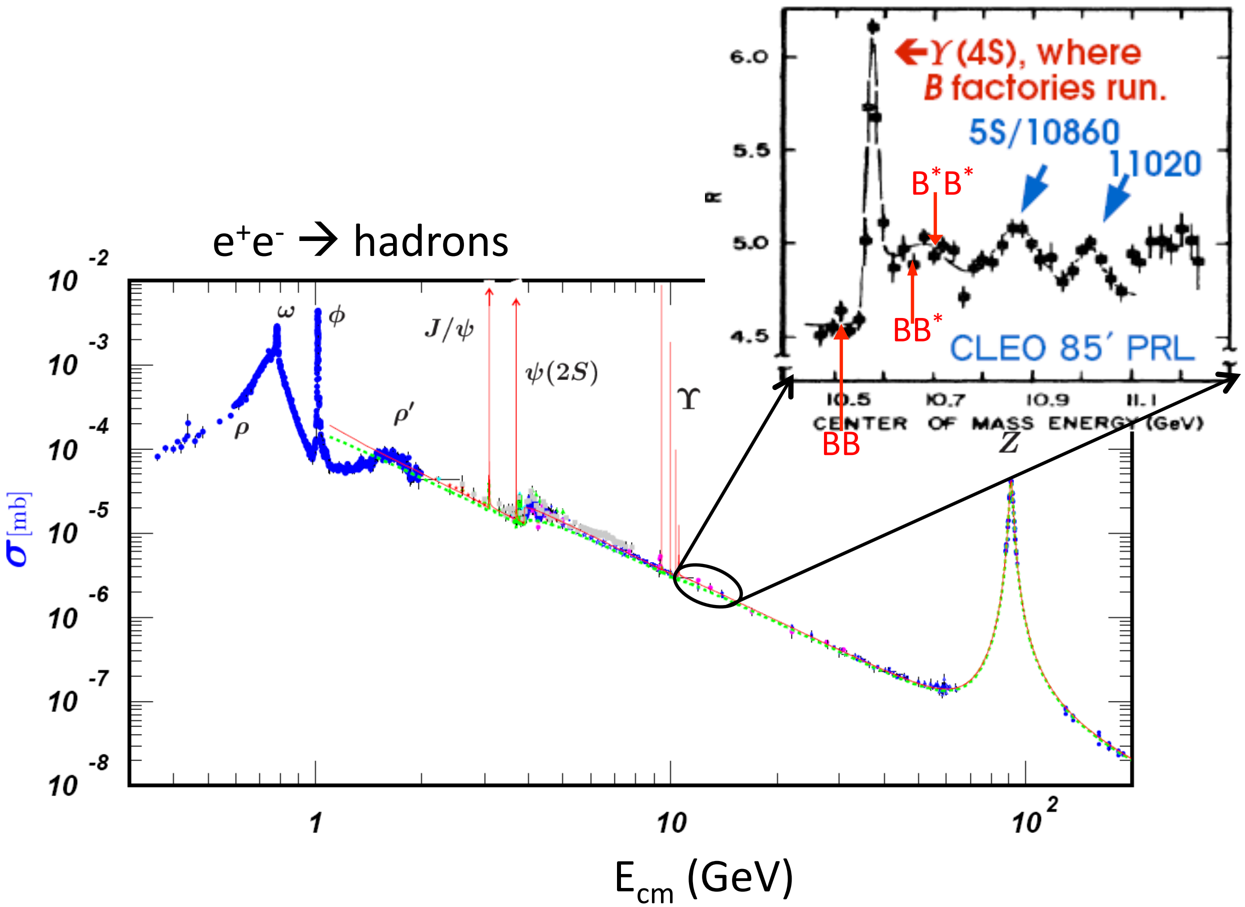
Y(4260) peak in $\sigma(\pi^+\pi^- J/\psi)$ occurs at a dip in $\sigma(D^{(*)}D^{(*)})$



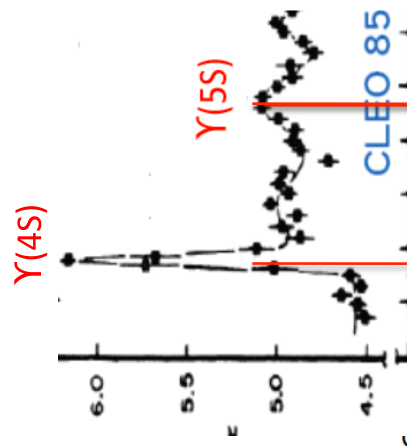
→ $\Gamma(\pi^+\pi^- J/\psi)$ is large, 10~100 × charmonium

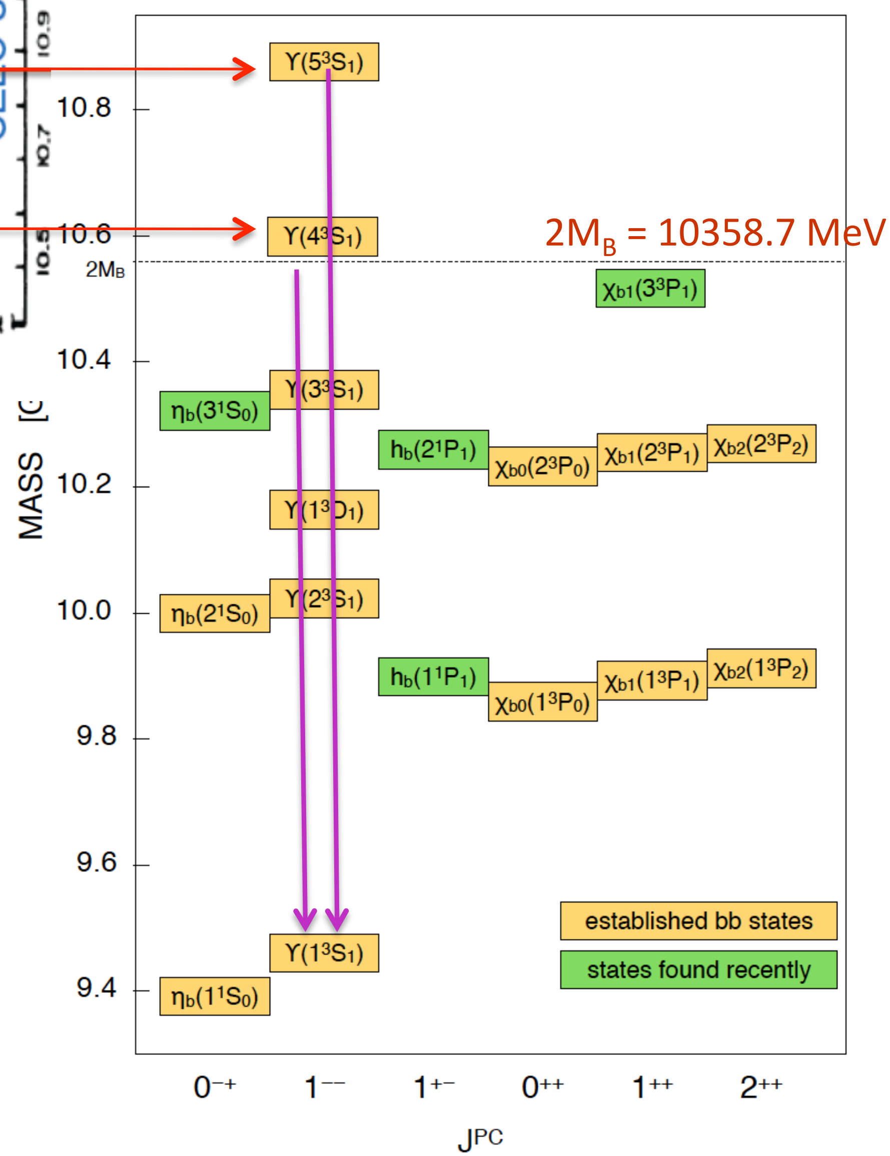
X. H. Mo et al., PLB 640, 182

Is there a b-quark version of Y(4260)?



“bottomonium” $b\bar{b}$ mesons





Is there any anomaly in $\Upsilon(4S,5S) \rightarrow \pi^+\pi^- \Upsilon(1S)$?

$\Gamma_{\Upsilon(4S)\rightarrow\pi^+\pi^-\Upsilon(1S)}$

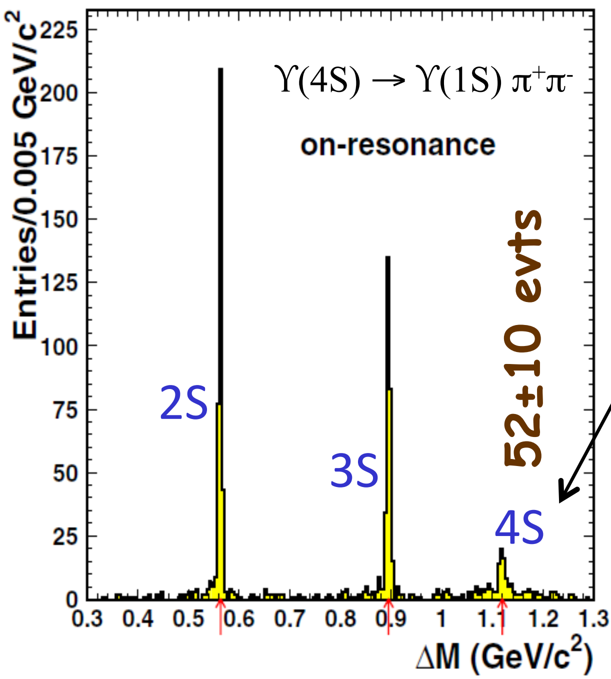
Belle: PRD 75 071103

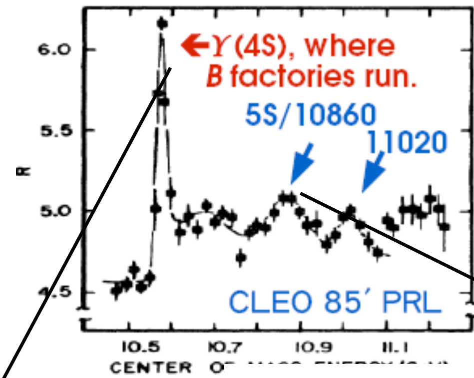
477 fb^{-1}

$\Gamma_{"\Upsilon(5S)"\rightarrow\pi^+\pi^-\Upsilon(1S)}$

Belle: PRL 100 112001

23.6 fb^{-1}



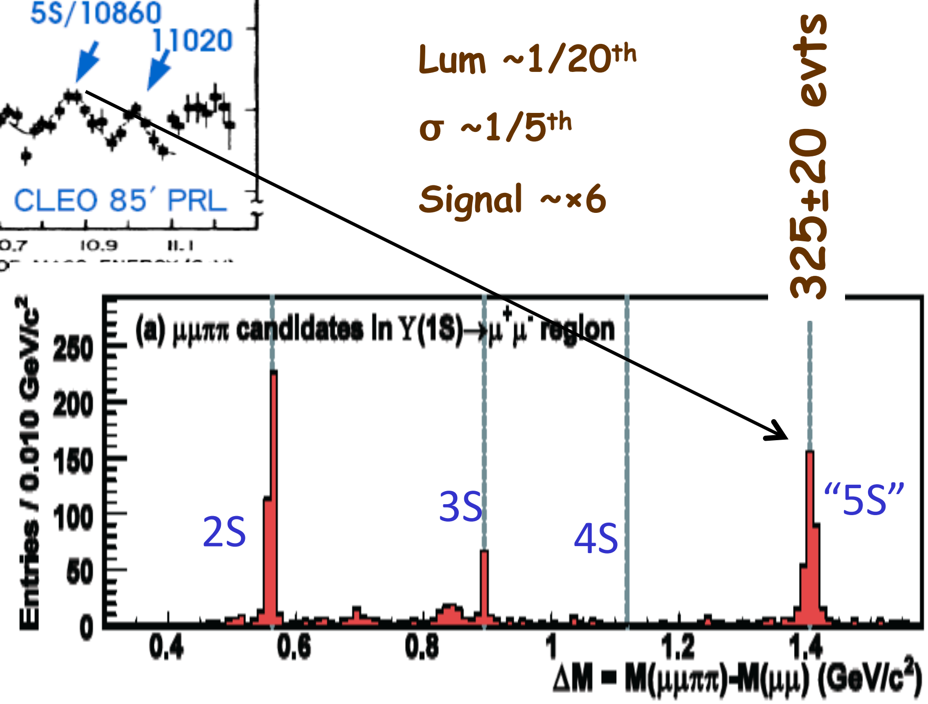


Signal

Lum ~1/20th

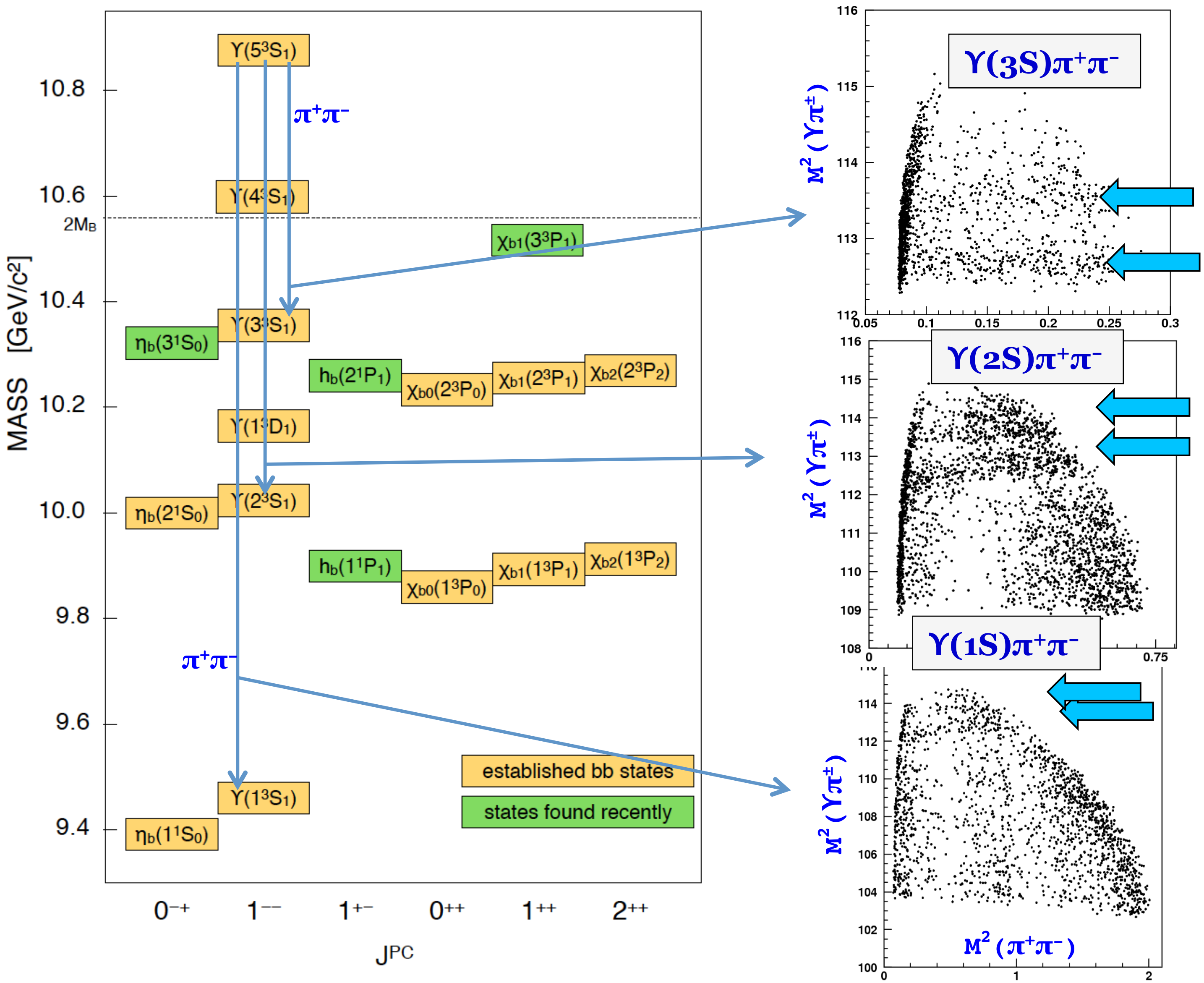
σ ~1/5th

Signal ~×6



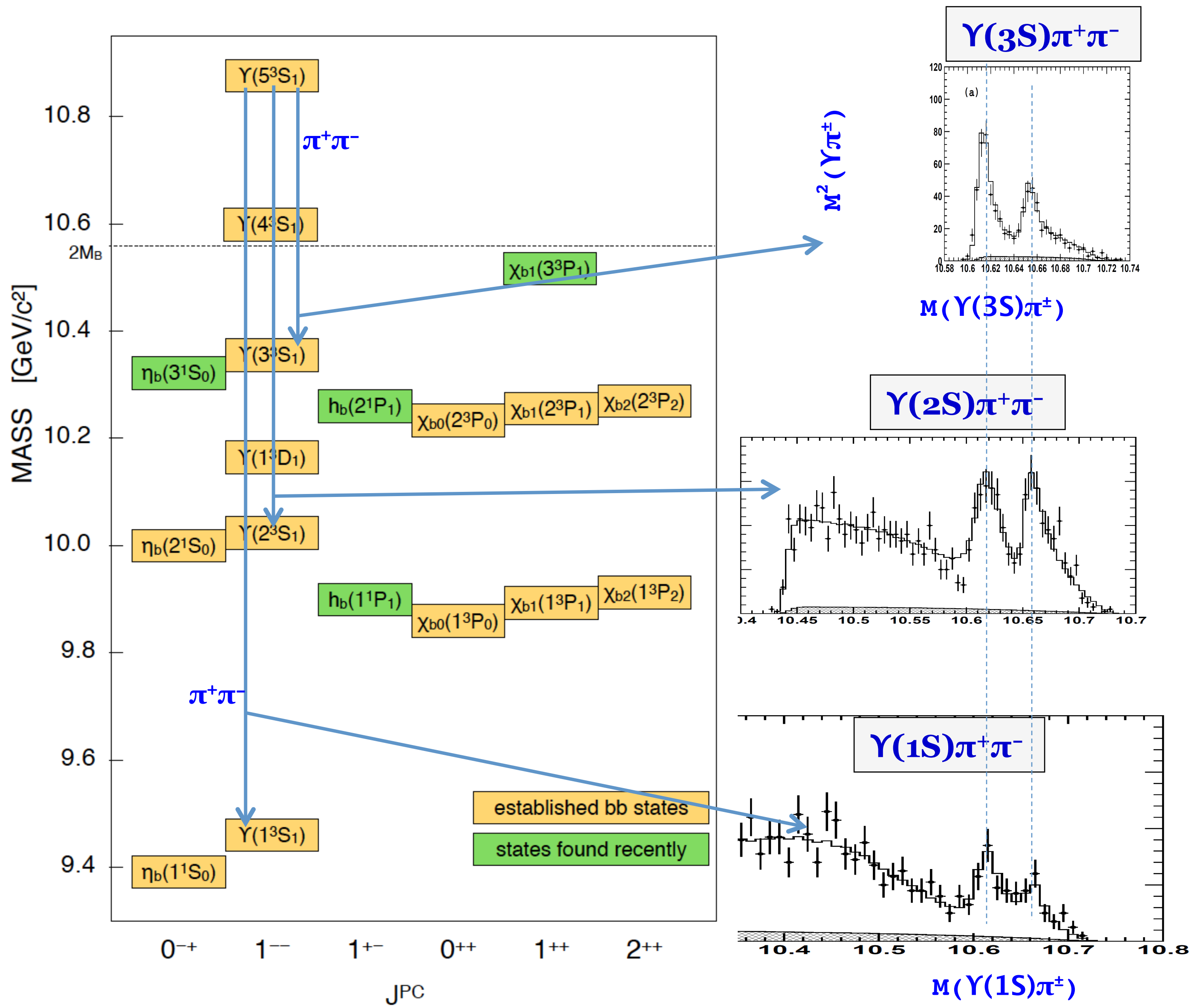
parent	$N(\pi^+\pi^-\Upsilon(1S))$	$\Gamma(Y_{4S}\rightarrow\pi\pi\Upsilon_{1S})$	Γ_{theory}
$\Upsilon(4S)$	52±10	1.75 ± 0.35 keV	1.47±0.03 keV
"$\Upsilon(5S)$"	325±20	590 ± 110 keV	<1.5 keV

"Υ(5S)" → $\pi^+\pi^-$ Υ (1S) ?



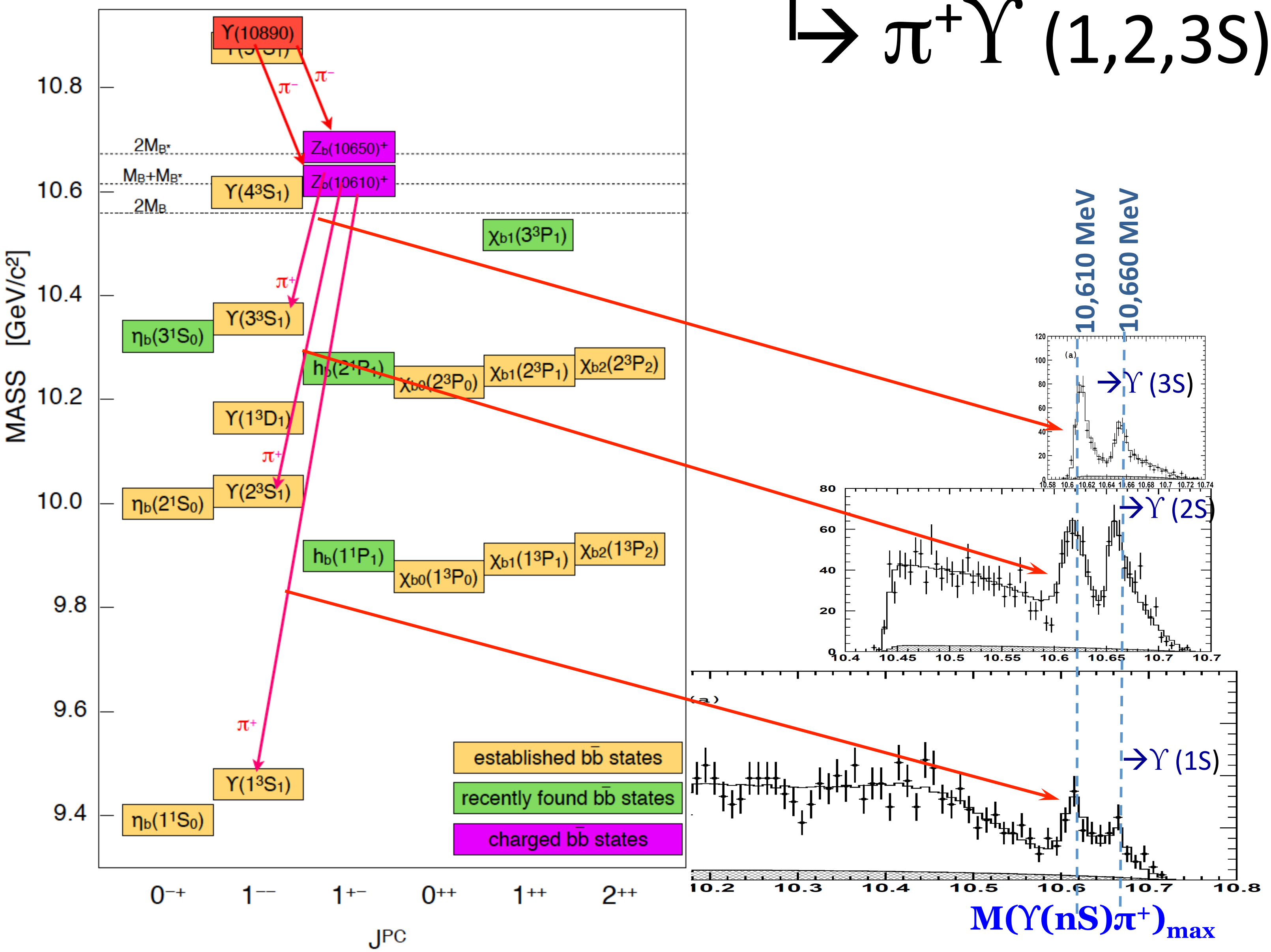
Υ(5³S₁)
Υ(4³S₁)
Υ(3³S₁)
Υ(1³D₁)
Υ(2³S₁)
Υ(1³S₁)
ηb(3¹S₀)
ηb(2¹S₀)
ηb(1¹S₀)
χb1(3³P₁)
hb(2¹P₁)
χb0(2³P₀)
χb1(2³P₁)
χb2(2³P₂)
hb(1¹P₁)
χb0(1³P₀)
χb1(1³P₁)
χb2(1³P₂)
π⁺π⁻
π⁺π⁻
2MB
MASS [GeV/c²]
JPC
0−+
1−−
1+−
0++
1++
2++
established bb states
states found recently
Υ(3S)π⁺π⁻
Υ(2S)π⁺π⁻
Υ(1S)π⁺π⁻
M² (Υπ±)
M² (π⁺π⁻)

"ϒ(5S)" → $\pi^+\pi^-$ ϒ (1S) ?

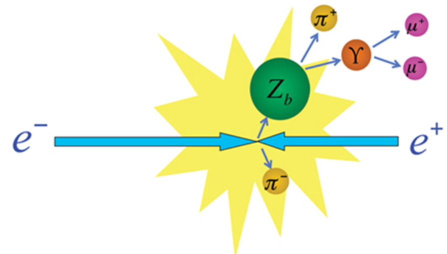

ϒ(5³S₁)
ϒ(4³S₁)
ϒ(3³S₁)
ϒ(2³S₁)
ϒ(1³S₁)
ϒ(1³D₁)
ηb(3¹S₀)
ηb(2¹S₀)
ηb(1¹S₀)
hb(2¹P₁)
hb(1¹P₁)
χb0(2³P₀)
χb1(2³P₁)
χb2(2³P₂)
χb0(1³P₀)
χb1(1³P₁)
χb2(1³P₂)
χb1(3³P₁)
2MB
π+π−
π+π−
MASS [GeV/c²]
10.8
10.6
10.4
10.2
10.0
9.8
9.6
9.4
0−+
1−−
1+−
0++
1++
2++
JPC
established bb states
states found recently
ϒ(3S)π+π−
M²(ϒπ±)
M(ϒ(3S)π±)
ϒ(2S)π+π−
ϒ(1S)π+π−
M(ϒ(1S)π±)

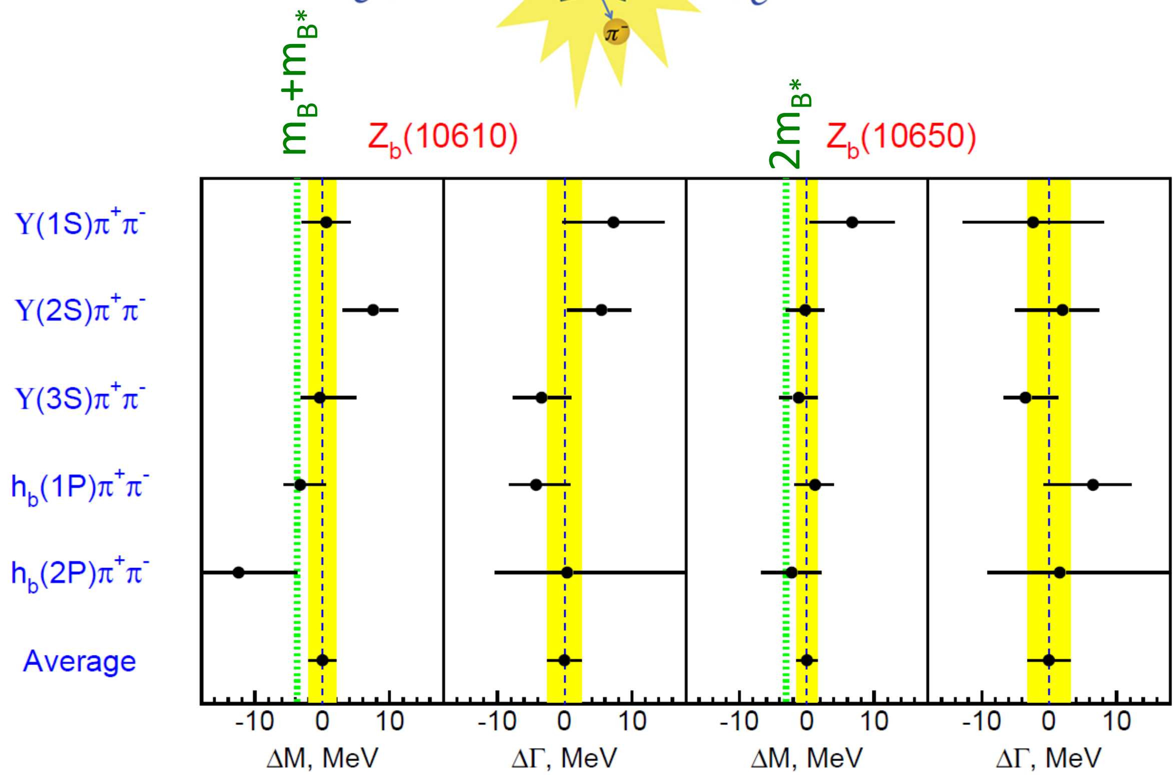
"$\Upsilon(5S)$" → $\pi^- Z^+_{b1,2}$ → $\pi^+\Upsilon(1,2,3S)$

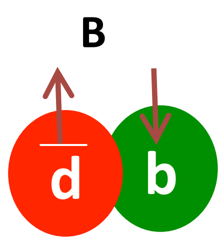
Belle PRL 108, 122001 (2012)
121.4 fb^{-1}

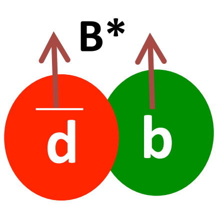


Summary of parameter measurements









$Z_b(10610)$

M=10608±2 MeV

Γ=18.4±2.4 MeV

$Z_b(10650)$

M=10653±2 MeV

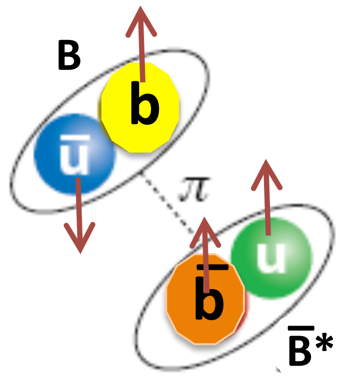
Γ=11.5±2.2 MeV

Belle PRL 108, 122001

March 2012

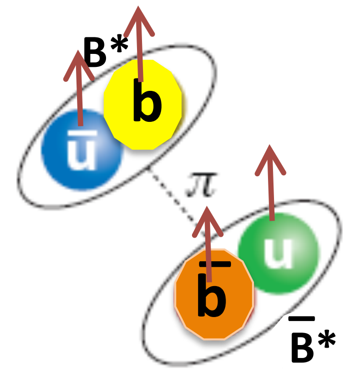
B-$\bar{B}$* & B*-$\bar{B}$* molecules??

$Z_b(106010)^{\pm}$



B-$\bar{B}$* "molecule"

$Z_b(106050)^{\pm}$



B*-$\bar{B}$* "molecule"

$M_{Z_b(106010)} - (M_B + M_{B*}) = +\,3.6 \pm 1.8$ MeV

$M_{Z_b(106010)} - 2M_{B*} = +\,3.1 \pm 1.8$ MeV

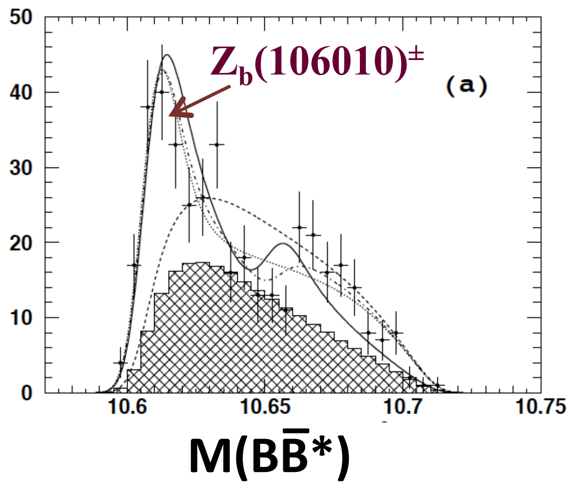
Slightly unbound threshold resonances??

Belle: M=10608.1±1.7 MeV, Γ=15.5±2.4 MeV; M=10653.3±1.5 MeV, Γ=14.0±2.8 MeV

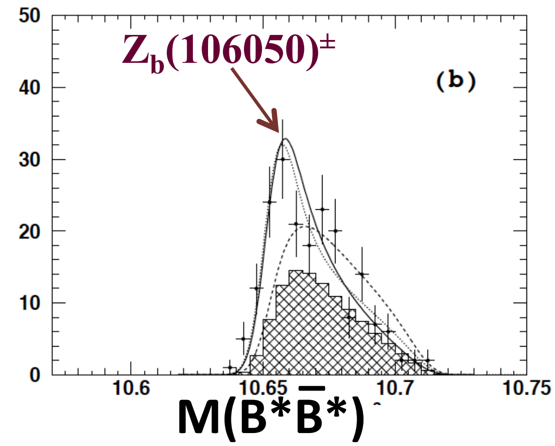
PDG: $M_B + M_{B*} = 10604.5 \pm 0.6$ MeV; $M_{B*} + M_{B*} = 10650.2 \pm 1.0$ MeV

$Z_b(10610) \rightarrow B\bar{B}^*$ & $Z_b(10650) \rightarrow B^*\bar{B}^*$

"$\Upsilon(5S)$" $\rightarrow \pi^-(B\bar{B}^*)^+$



"$\Upsilon(5S)$" $\rightarrow \pi^-(B^*\bar{B}^*)^+$

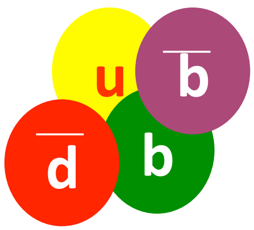


$$\frac{Bf(Z_b(10610) \rightarrow B\bar{B}^*}{Bf(Z_b(10610) \rightarrow \pi^+(b\bar{b})} = 6.1 \pm 0.4$$

Channel	Fraction, %	
	$Z_b(10610)$	$Z_b(10650)$
$\Upsilon(1S)\pi^+$	0.32 ± 0.09	0.24 ± 0.07
$\Upsilon(2S)\pi^+$	4.38 ± 1.21	2.40 ± 0.63
$\Upsilon(3S)\pi^+$	2.15 ± 0.56	1.64 ± 0.40
$h_b(1P)\pi^+$	2.81 ± 1.10	7.43 ± 2.70
$h_b(2P)\pi^+$	4.34 ± 2.07	14.8 ± 6.22
$B^+\bar{B}^{*0} + \bar{B}^0 B^{*+}$	86.0 ± 3.6	–
$B^{*+}\bar{B}^{*0}$	–	73.4 ± 7.0

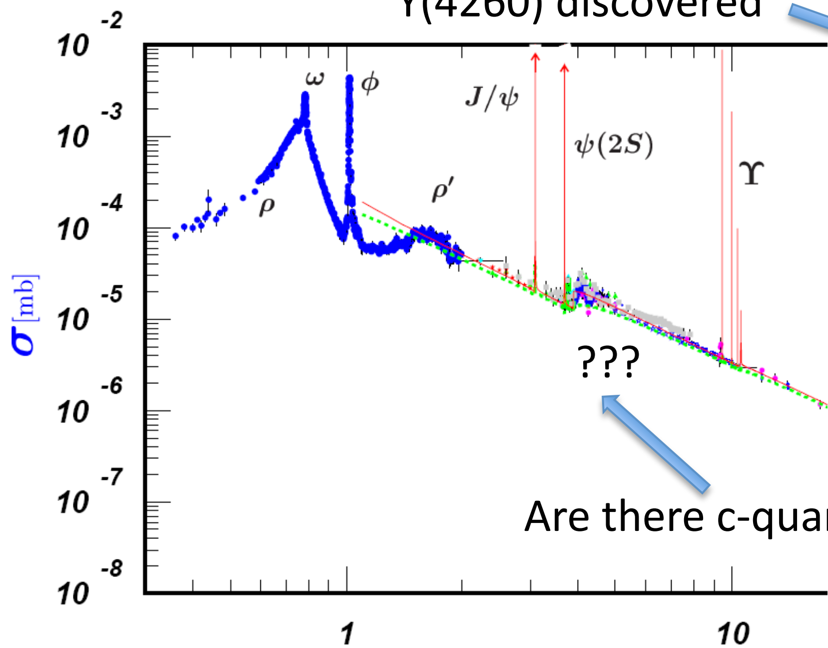
$$\frac{Bf(Z_b(10610) \rightarrow B^*\bar{B}^*}{Bf(Z_b(10610) \rightarrow \pi^+(b\bar{b})} = 2.8 \pm 0.4$$

Z_{b1} & Z_{b2}, "smoking guns" for non-$q\bar{q}$ mesons



- decays to Υ(nS) & h_b(nP) ➔ must contain $b\bar{b}$ pair
- electrically charged ➔ must contain $u\bar{d}$ pair

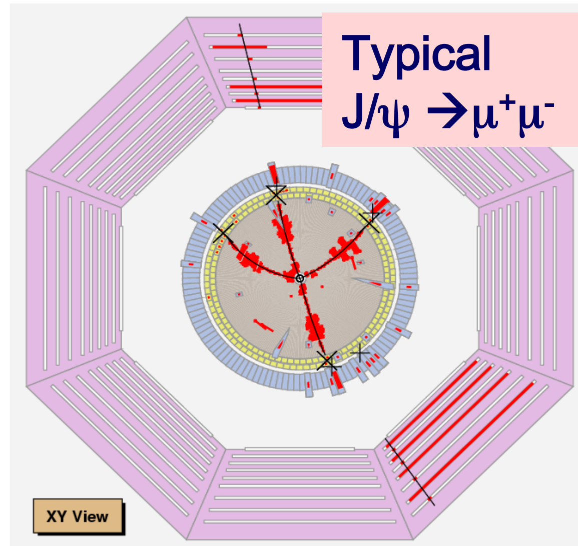
Are there c-quark versions of Z_b's

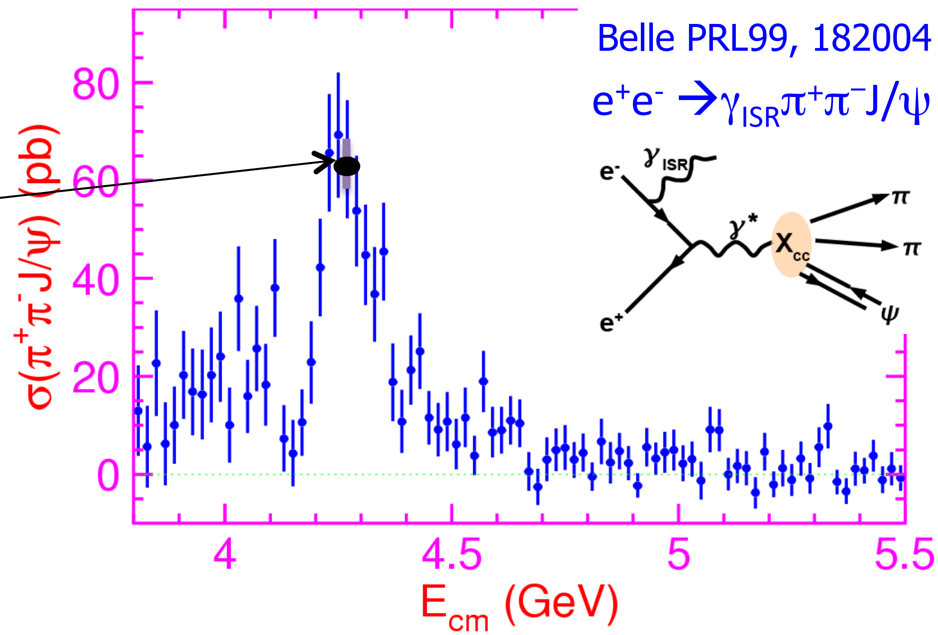


run BEPCII/BESIII as a Y(4260) factory

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

@E_{cm}=4260 MeV

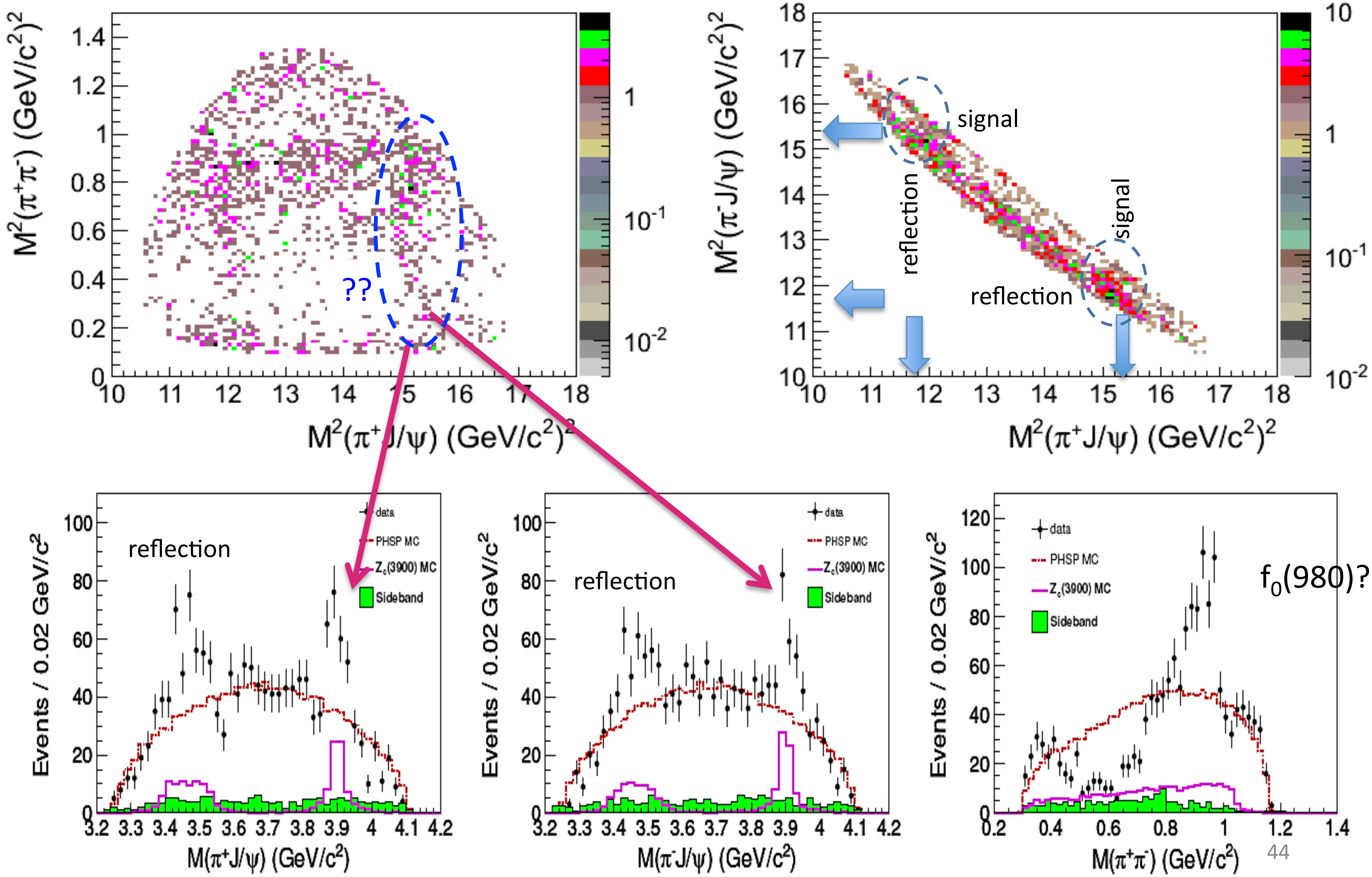




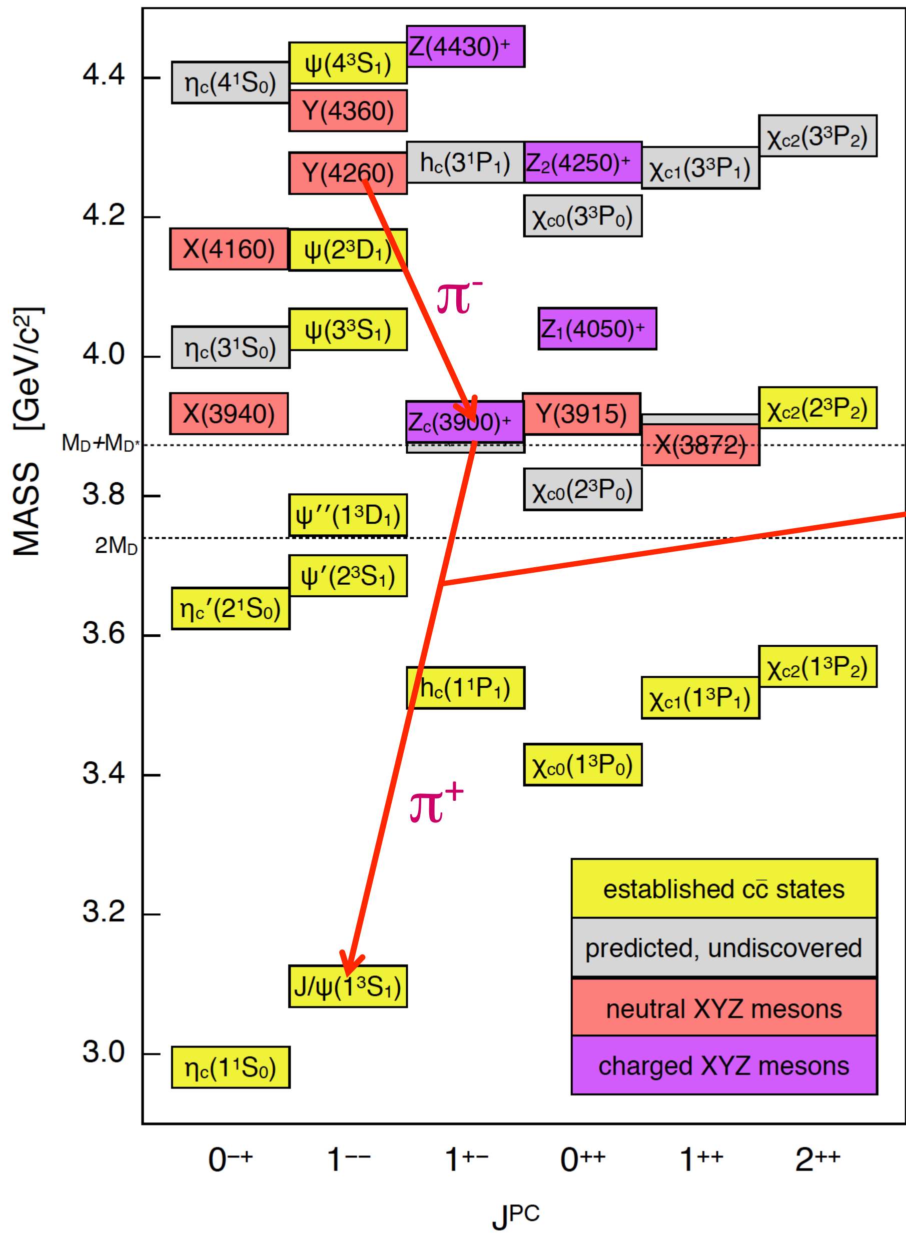
BESIII: arXiv:1303.5949

$\sigma(e^+e^- \to \pi^+\pi^- J/\psi)$ = (62.9±1.9±3.7) pb

Dalitz plots & 1D projections

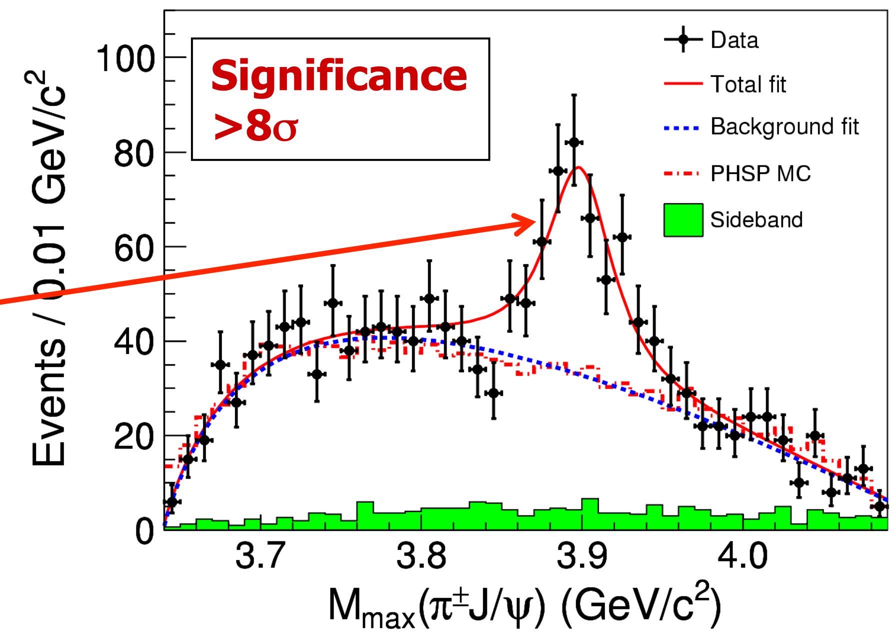


$Y(4260) \rightarrow \pi^- Z_c(3900)^+ \rightarrow \pi^+ J/\psi$



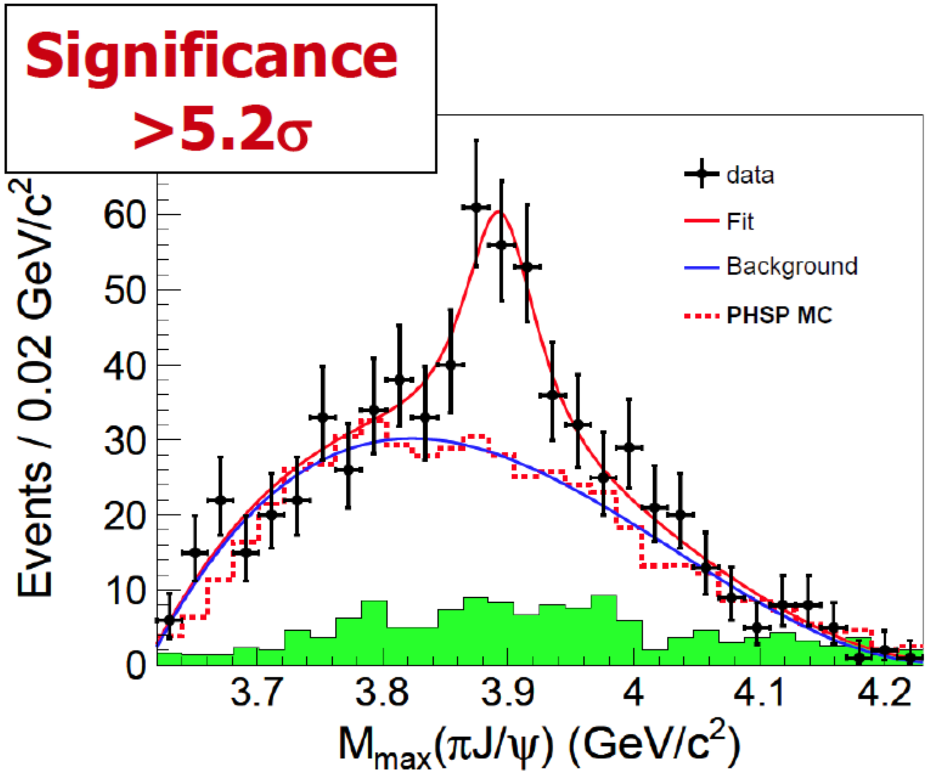
BESIII: arXiv:1303.5949

to appear in PRL

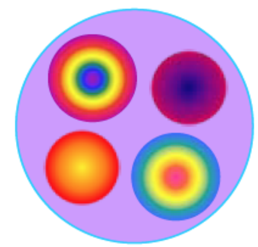


- Mass = (3899.0±3.6±4.9) MeV
- Width = (46±10±20) MeV
- Fraction = (21.5±3.3±7.5)%

$Z_c(3900)$ confirmed by Belle



- Couples to $\bar{c}c$
- Has electric charge
- At least 4-quarks
- What is its nature?



Belle arXiv: 1304.0121
to appear in PRL

- Mass = (3894.5 ± 6.6 ± 4.5) MeV
- Width = (63 ± 24 ± 26) MeV
- Fraction = (29.0 ± 8.9)% (stat. error only)

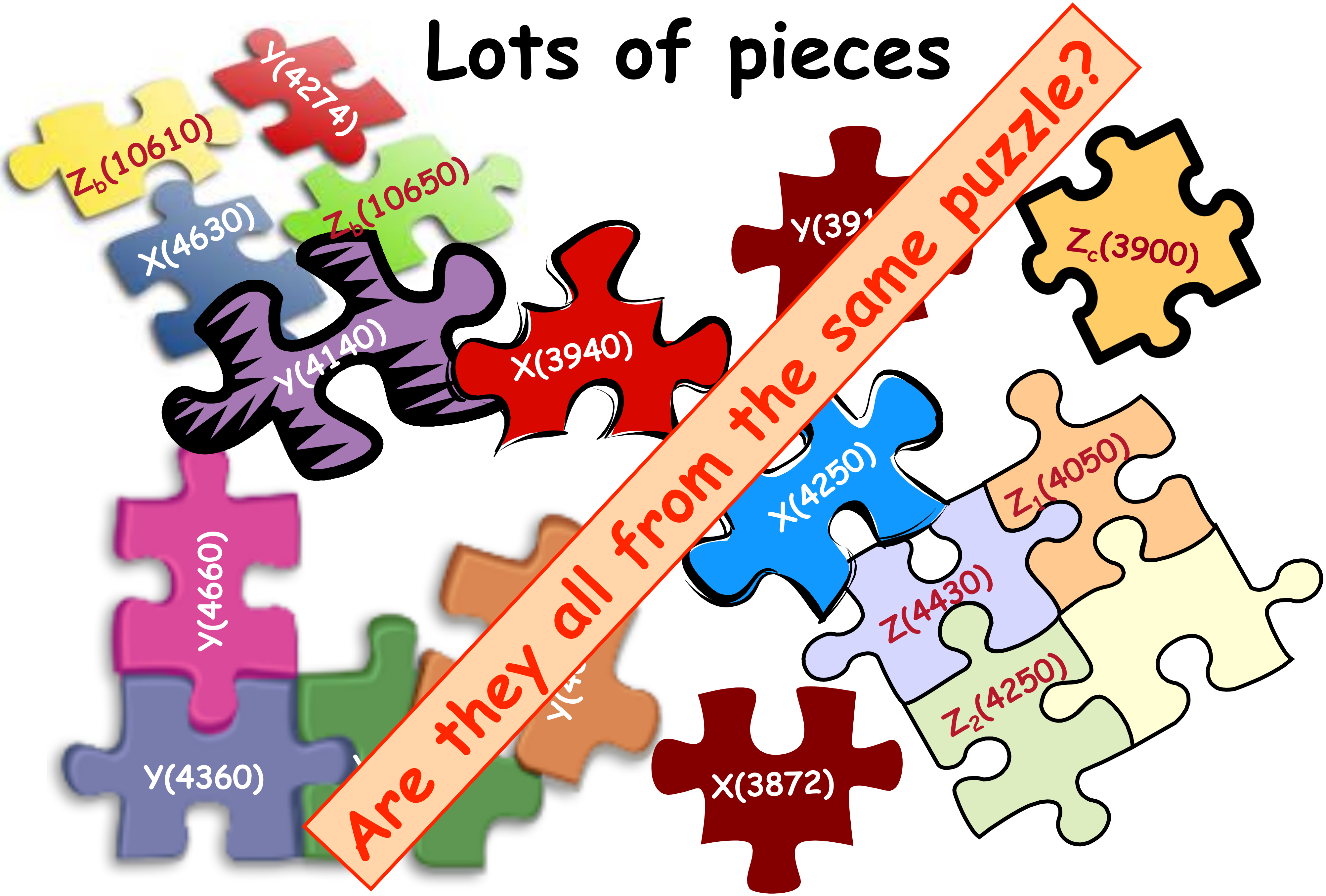
Summary

- QCD "exotics" most favored by theorists do not seem to exist
  - evidence for Pentaquarks has disappeared
  - H-dibaryon with mass near $2m_\Lambda$ is excluded at stringent levels

- Numerous non-$q\bar{q}$ mesons not specific to QCD have been found
  - Baryonium in $J/\psi \rightarrow \gamma p\bar{p}$ at BESII and BESIII
  - XYZ mesons containing $c\bar{c}$ and $b\bar{b}$ pairs

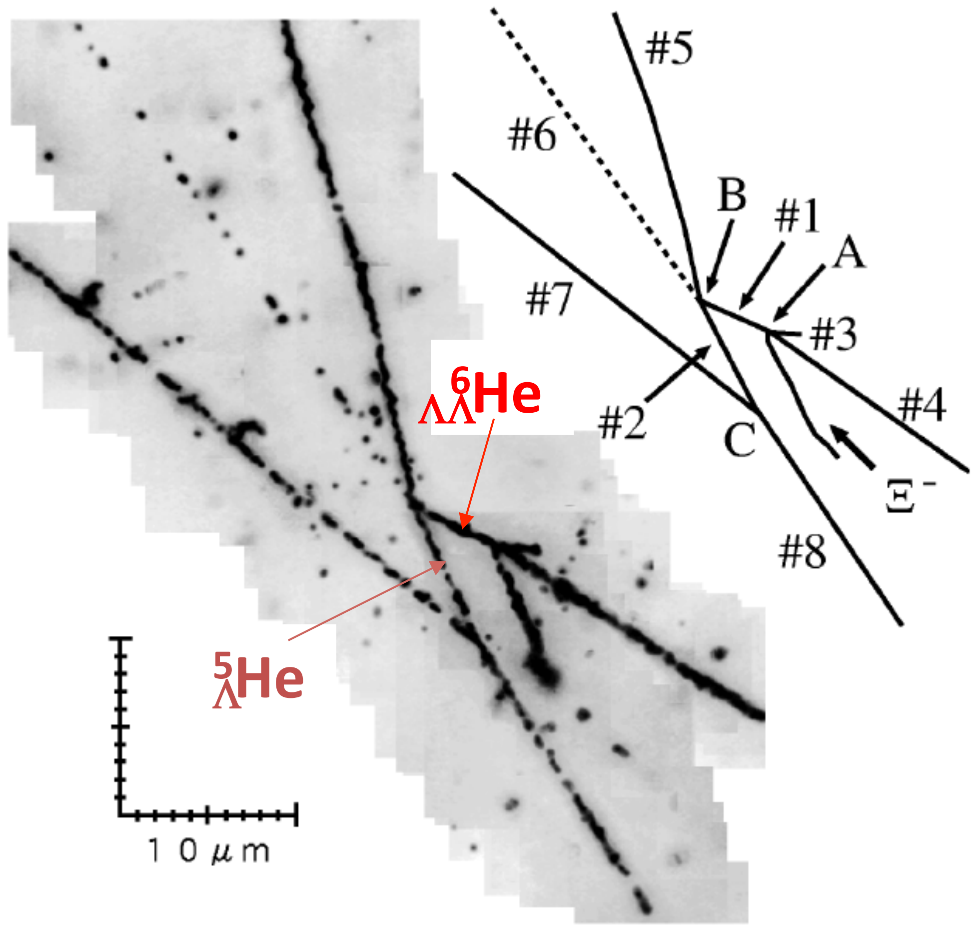
- The $J^{PC}=1^{--}$ Y(4260) and "$\Upsilon(5S)$" have no compelling interpretation
  - strong couplings to $\pi^+\pi^- J/\psi$ ($\pi^+\pi^- \Upsilon(nS)$)
  - strong sources of charged Z_c (Z_b) states with M near $m_D+m_{D^*}$ ($m_{B(*)}+m_{B^*}$)

Lots of pieces



Back-up slides

The "Nagara" $^{6}_{\Lambda\Lambda}$He event



H. Takahashi *et al*, PRL 87, 215502 (1977): $M_H > 2m_\Lambda$-7.7 MeV

X(1835) confirmed at BESIII

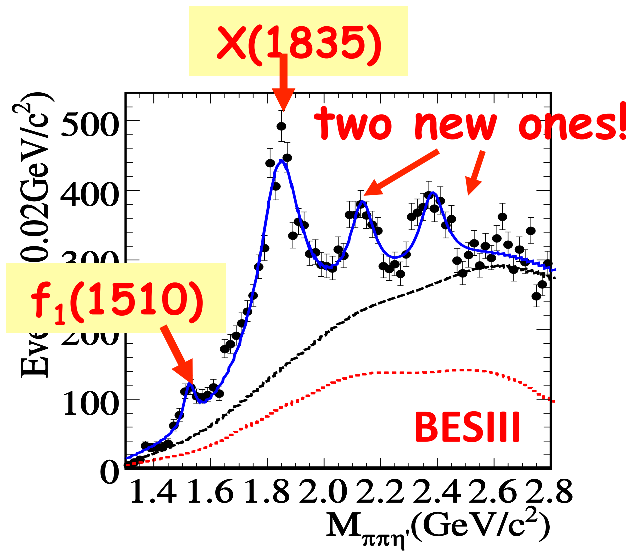
(+ two new structures with M>2GeV)

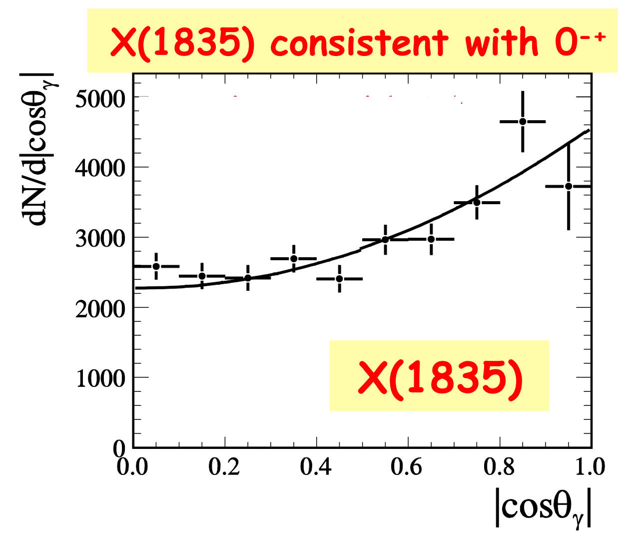
BESIII PRL 106, 072002 (2011)

$J/\psi \to \gamma\eta'\pi^+\pi^-$

$\eta' \to \eta\pi^+\pi^-$

$\eta' \to \gamma\pi^+\pi^-$





X(1835): same mass and J^{PC} as the $p\bar{p}$ peak, but larger width

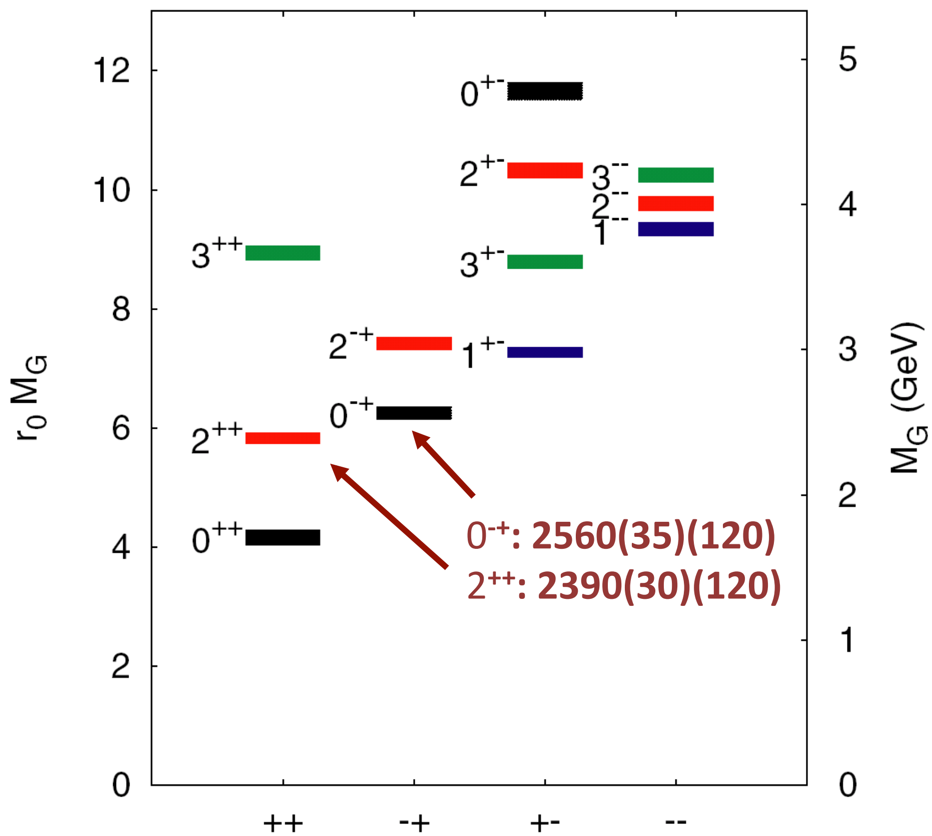
Resonance	M(MeV/c²)	Γ(MeV/c²)	Stat.Sig.
X(1835)	$1836.5\pm3.0^{+5.6}_{-2.1}$	$190.1\pm9.0^{+38}_{-36}$	>20σ
X(2120)	$2122.4\pm6.7^{+4.7}_{-2.7}$	$83\pm16^{+31}_{-11}$	7.2σ
X(2370)	$2376.3\pm8.7^{+3.2}_{-4.3}$	$83\pm17^{+44}_{-6}$	6.4σ

narrow!!

What are these new structures?

way above threshold, but narrow!!

PRD73,014516(2006) Y.Chen et al



- ✓ first distinct resonant structures observed above 2 GeV:

  -LQCD predicts that the lowest –lying pseudoscalar glueball: around 2.3 GeV

  -$J/\psi \to \gamma\eta'\pi^+\pi^-$ is a good decay channel for finding 0^{-+} glueballs.

- ✓ X(2120)/X(2370) possibilities:

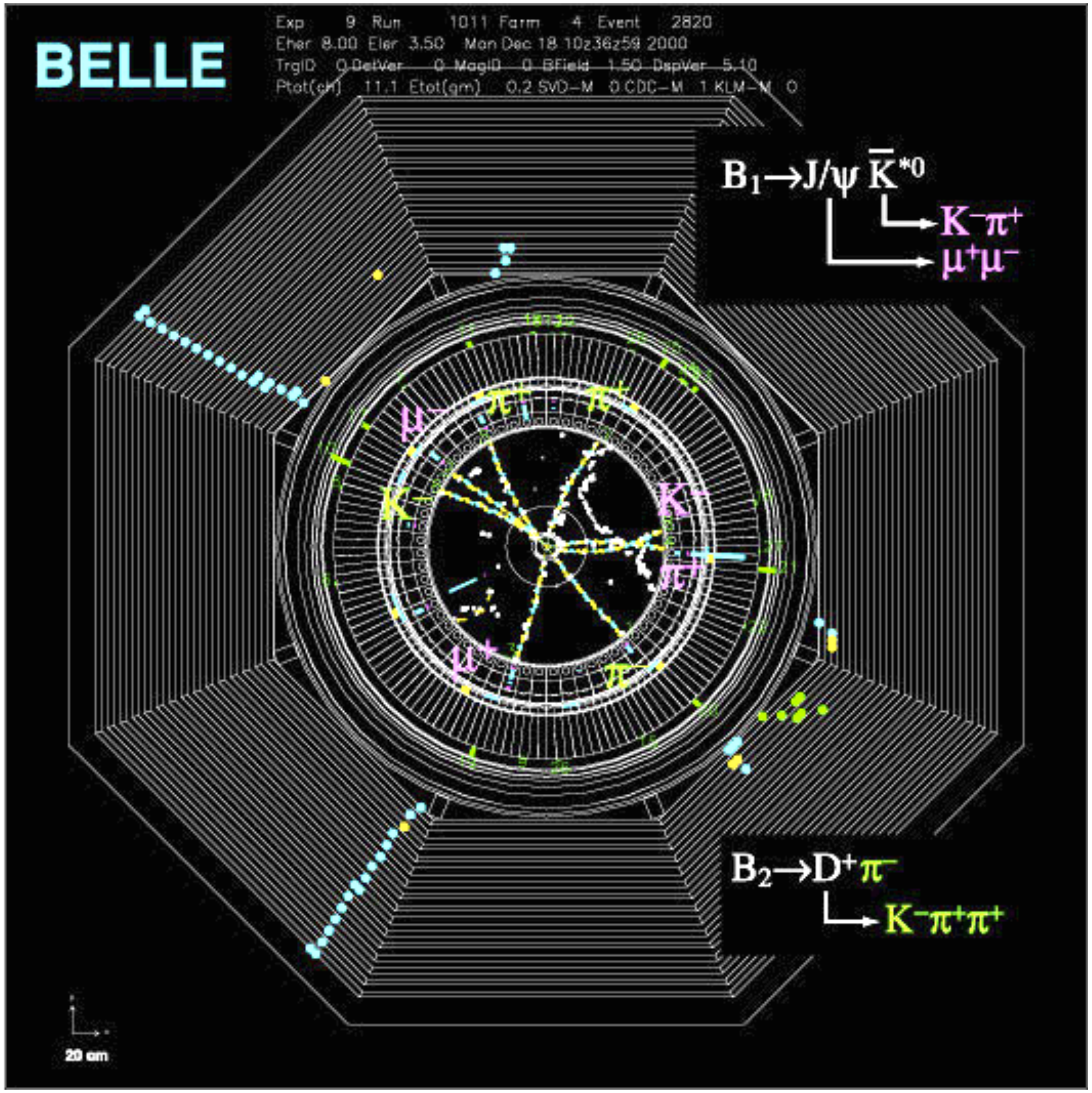
  -pseudoscalar & tensor glueball ?

  -η/η' excited states?

- ✓ Need spin-parity analyses

PRD82,074026,2010 J.F. Liu, G.J. Ding and M.L.Yan
PRD83:114007,2011 (J.S. Yu, Z.-F. Sun, X. Liu, Q. Zhao)

Event in the Belle Detector



2^{-+} $c\bar{c}$ assignment? η_{c2}?

pinned to:
$M\psi''=3770$ MeV
$\&M\psi_2=3823$ MeV

- Mass is too high?:
  - 3872 *vs* 3837 MeV

- Expt: $\dfrac{\Gamma(\eta_{c2}\to\rho^0 J/\psi)}{\Gamma\eta_{c2}\to\gamma J/\psi)} = 3.4 \pm 1.2$

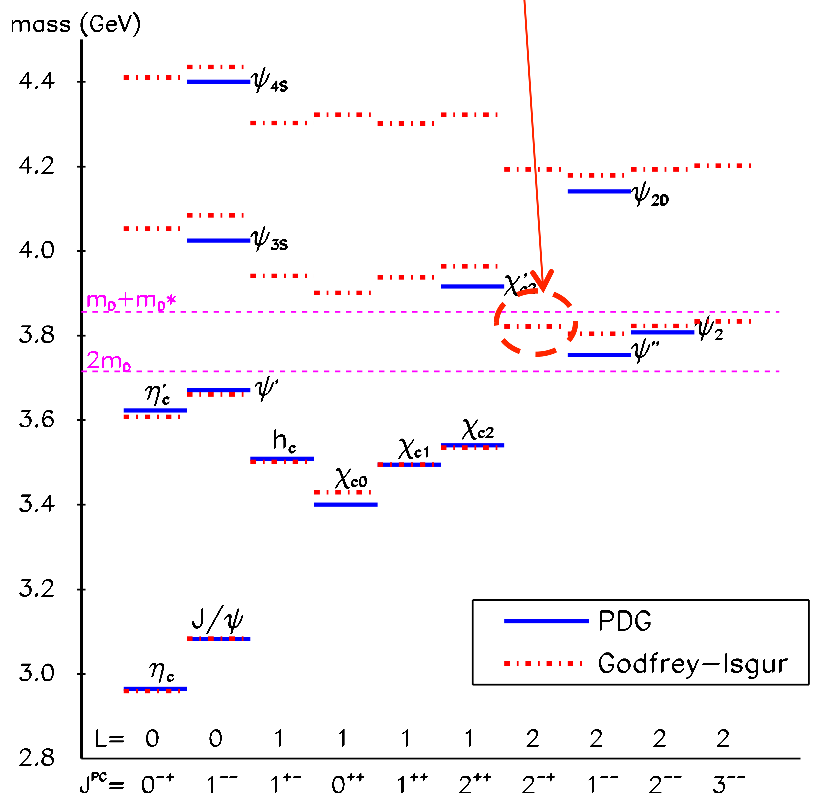
  use theory: $\Gamma(\eta_{c2}\to\gamma J/\psi)\approx 9\mathrm{keV}$
  Y. Jia*et al* arXiv:0107.4541

  $\Rightarrow \Gamma(\eta_{c2}\to\rho^0 J/\psi)\approx 30\mathrm{keV}$

  ***c.f.*: $\Gamma(\psi'\to\pi^0 J/\psi)\approx 0.4$ keV**

- Theor: $B\to K\eta_{c2}$ violates factorization
  - $B\to Kh_c$ not seen
  - $B\to K\chi_{c2}$ barely seen

- Theor: $\eta_{c2}\to D\bar{D}^*$ expected to be tiny
  Y. Kalasnikova*et al* arXiv:1008.2895
  - Belle & BaBar::
  $\Gamma(X\to D\bar{D}^*)/\Gamma(X\to\pi^+\pi^- J/\psi)=9.5\pm3.1$



$\eta_{c2}\to\gamma h_c(1S)$ & $\pi\pi\eta_c$ modes expected to dominate

"$\Upsilon(5S)$" is very different from other Υ states

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

Belle PRL 100, 112001 (2008)
23.6 fb^{-1}

	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

X10^{-2}

$$Bf(\Upsilon(4S) \to \pi^+\pi^-\Upsilon(1S)) = (0.008 \pm 0.0003)\%$$

$$Bf(Y(5S) \to \pi^+\pi^-\Upsilon(1S)) = (0.53 \pm 0.06)\%$$

Recall Y(4260) with anomalous $\Gamma(J/\psi\,\pi^+\pi^-)$

$\Rightarrow$ Is there a Y_b equivalent close to $\Upsilon(5S)$

The "XYZ" mesons

State	M (MeV)	Γ (MeV)	J^{PC}	Decay Modes	Production Modes
$Y_s(2175)$	2175 ± 8	58 ± 26	1^{--}	$\phi f_0(980)$	e^+e^- (ISR) $J/\psi \to \eta Y_s(2175)$
$X(3872)$	3871.4 ± 0.6	< 2.3	1^{++}	$\pi^+\pi^- J/\psi$, $\gamma J/\psi, D\bar{D}^*$	$B \to KX(3872)$, $p\bar{p}$
$X(3915)$	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 $D\bar{D}^*$)	$B \to KY(3940)$
$Y(4008)$	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)
$Y(4350)$	4361 ± 13	74 ± 18	1^{--}	$\pi^+\pi^- \psi'$	e^+e^-(ISR)
$X(4630)$	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^{--}	$\pi^+\pi^- \Upsilon(1,2,3S)$	$e^+e^- \to Y_b$
$Z_{b1}(10610)$	10,607±2	18±2	1^-	$\pi^\pm\Upsilon(1,2,3S)/h_b(1,2S)$; BB*	`$\Upsilon(5S)$' $\to \pi^\pm Z_{b1}$
$Z_{b2}(10650)$	10,653±2	12±2	1^-	$\pi^\pm\Upsilon(1,2,3S)/h_b(1,2S)$;B*B*	`$\Upsilon(5S)$' $\to \pi^\pm Z_{b2}$