Four-quark states in QCD

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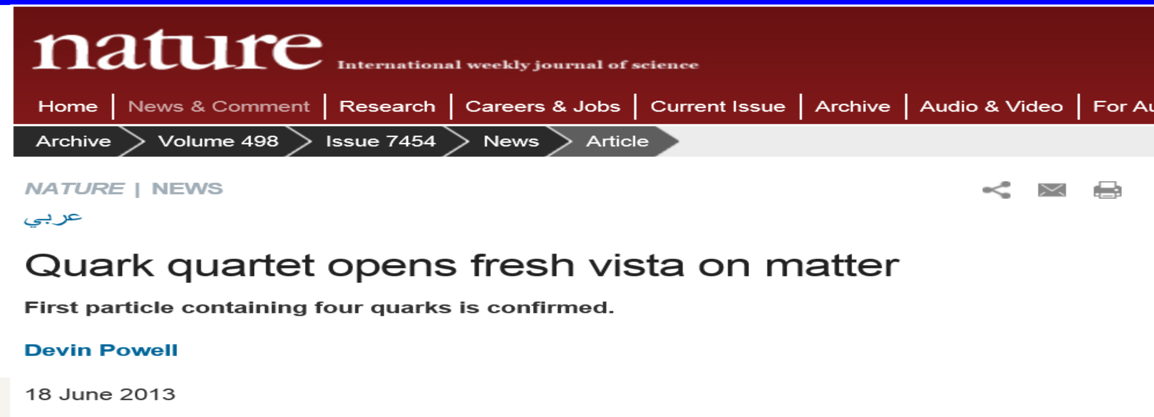
3 March, 2015

Outline

- 1. Four-quark state in constituent quark model
- 2. QCD sum rule
- 3. “Candidates” of four-quark states
- 4. Conclusions and discussions

1. Four-quark state in constituent quark model

Nature 498, 280 (2013)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NATURE | NEWS

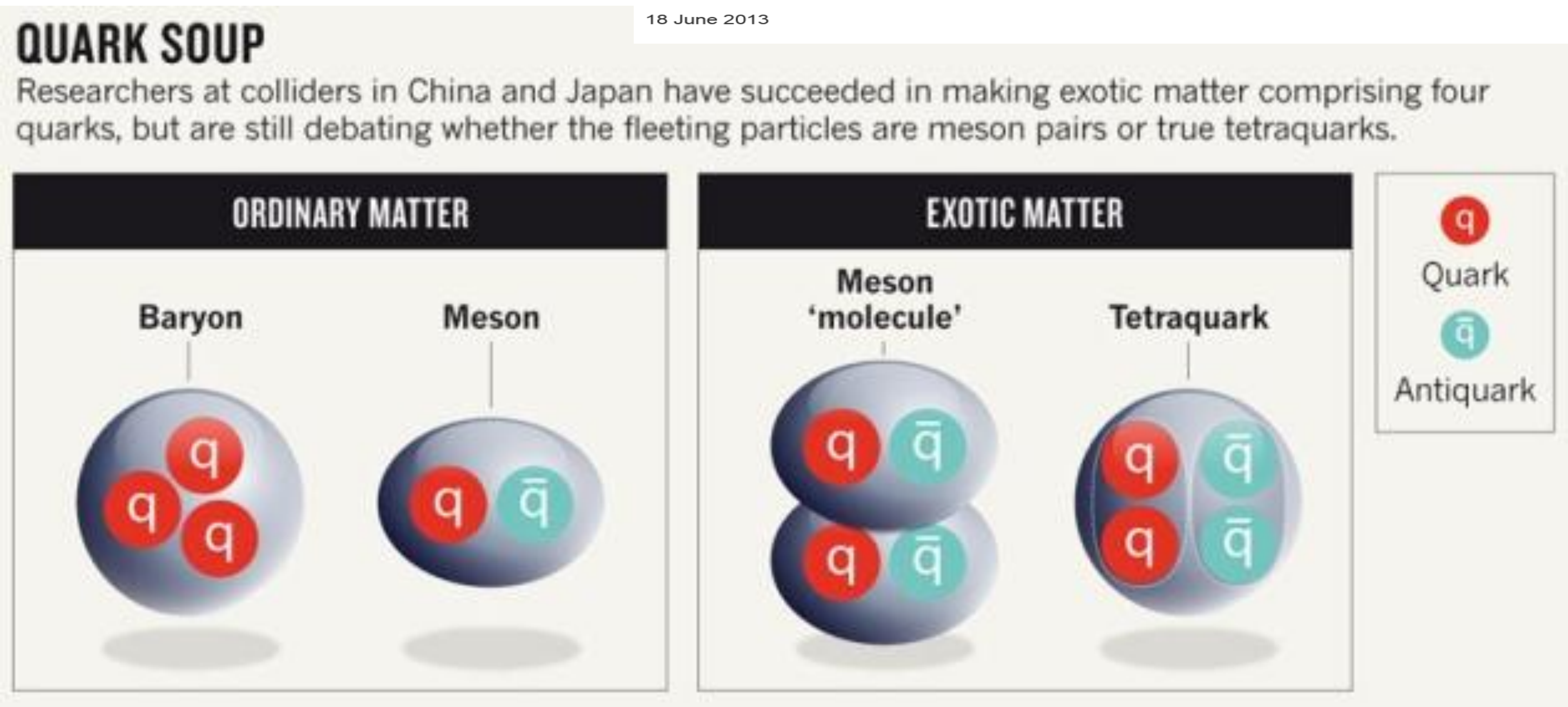
عربي

Quark quartet opens fresh vista on matter

First particle containing four quarks is confirmed.

Devin Powell

18 June 2013



Motivation

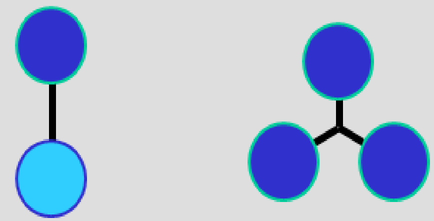
Quark Model

Quantum Chromodynamics (QCD)

QCD is the Theory of the Strong Interaction

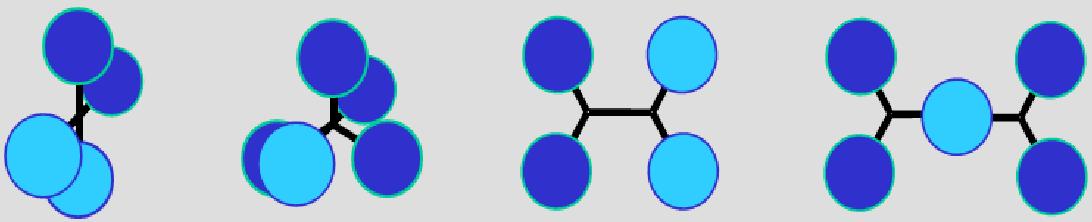
We know

mesons and baryons

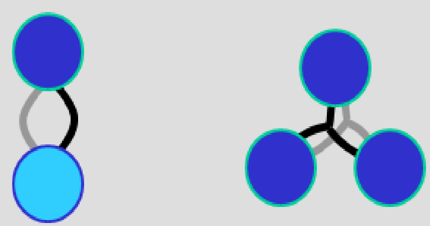


QCD also allows

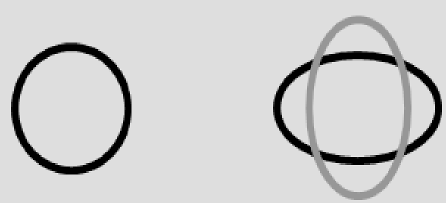
molecules/multi-quarks



hybrids



glueballs



and more

Hadron scattering amplitudes: four-quark state

J.L. Rosner, Phys. Rev. Lett. 21, 950 (1968)

Reference

MIT bag model:

R.L. Jaffe, Phys. Rev. D15, 267 (1977); D15, 281 (1977)

Color junction model:

Hong-Mo Chan and H. Hogaasen, Phys. Lett. B72, 121 (1977)

Potential model:

J. Weinstein and N. Isgur, Phys. Rev. Lett, 48, 659; Phys.Rev. D27, 588 (1983)

J. Weinstein and N. Isgur, Phys.Rev. D41, 2236 (1990)

N.A. Tornqvist, Phys. Rev. Lett, 67, 556 (1991)(deuteron-like meson-meson states,one-pion exchange)

L.Y. Glozman and D. O. Riska, Phys. Rept, 268, 263 (1996) (pseudoscalar mesons(SU(3)F octet) exchange interaction)

Effective Lagrangian:

D. Black, A.H. Fariborz, J. Schechter, Phys. Rev. D59, 074026 (1999)

Relativistic quark model:

D. Ebert, R.N. Faustov, V.O. Galkin, Phys. Lett. B634, 214 (2006)

QCD sum rules:

Ailin Zhang, Phys. Rev. D61, 114021 (2000)

Thomas Schafer, Phys. Rev. D68, 114017 (2003)

M.E. Bracco, A. Lozea, R.D. Matheus, *et al., Phys. Lett. B624, 217 (2005)*

Hungchong Kim and Yongseok Oh, Phys. Rev. D72, 074012 (2005)

Hua-Xing Chen, A. Hosaka and Shi-Lin Zhu, Phys. Rev. D74 , 054001 (2006)

Ailin Zhang, Tao Huang and Tom. Steele, Phys. Rev. D76, 036004 (2007)

Fernando S.Navarra, Marina Nielsen and Su Houng Lee, Phys.lett. B649, 166(2007)

Chun-Yu Cui, Yong-Lu Liu and Ming-Qiu Huang, Phys.Rev. D85, 074014(2012)

R. T. Kleiv, T. G. Steele, Ailin Zhang and Ian Blokland, Phys.Rev. D87, 125018 (2013)

....

Other models

N.N. Achasov, S.A. Devyanin and G.N. Shestakov, Phys. Lett. B108, 134 (1982)

L. Maiani, F. Piccinini, A.D. Polosa and V. Riquer, Phys. Rev. Lett. 19, 212002 (2004); Phys. Rev. D71, 014028 (2005)

……

Reviews:

S. Godfrey and J. Napolitano, Rev. Mod. Phys. 71, 1411 (1999)

C. Amsler and N.A. TÖrnqvist, Phys. Rept, 389, 61 (2004)

R.L. Jaffe, Phys. Rept. 409, 1 (2005)

Marina Nielsen, Fernando S. Navarra and Su Houng Lee, Phys.Rept. 497 (2010) 41-83

♠ Four-quark states

Four-quark state: consists of four quarks and anti-quarks

Intrinsic quarks/anti-quarks may make clusters

Degrees of freedom of quark: color, flavor, spin, $etc.$

♢ $(qq)(\bar{q}\bar{q})$ (tetraquark state, baryonium)

Quark dynamics

Spin-independent interaction(Coulombic + linear confinement)

Spin-dependent interaction(color magnetic spin-spin interaction between the quarks(one gluon exchange))

$\diamondsuit$ $(q\bar{q})(q\bar{q})$ (molecule)

$(q\bar{q})$ **is kept together by hadron exchange forces (two-gluon exchange forces, or one-pion exchange forces)**

Color 8×8 $(q\bar{q})(q\bar{q})$ state: ??

Hadrons are in color singlet, $(qq)(\bar{q}\bar{q})$ may mix with $(q\bar{q})(q\bar{q})$ four-quark state may mix with normal q anti-q meson

♠ Mixing

Crypto-exotic states

$$|meson>=|q\bar{q}>+|(qq)(\bar{q}\bar{q})>+|(q\bar{q})(q\bar{q})>$$

+......

Intrinsic color, flavor configurations could not be distinguished except that special observable is established.

Unfortunately, no such an observable has been definitely set up

2. QCD sum rule

♠ QCD (SVZ) sum rules

M.A.Shifman, A.I. Vainshtein and V.I. Zakharov, Nucl. Phys. B147, 385(1979)

QCD & Vacuum $\overline{\underline{sum\ rule}}$ Hadron

Nonperturbative method of relating fundamental parameters of QCD lagrangian and vacuum to parameters of hadrons

- Correlator

$$i\int d^4x e^{iqx}\langle 0|T(j_\Gamma(x)j_\Gamma^\dagger(0))|0\rangle$$

$j_\Gamma(x)$: interpolating current

- OPE(Operator Product Expansion)

$$i\int d^4x e^{iqx}\langle 0|T(j_\Gamma(x)j_\Gamma^\dagger(0))|0\rangle = \sum_n C_n^\Gamma(q^2)O_n$$

Hard (coefficients)+soft (condensates)

Fundamental parameters of QCD lagrangian+condensates (universal parameters)

- Dispersion relation

$$\Pi_P(q^2) = \frac{1}{\pi} \int ds \frac{Im\Pi(s)}{s - q^2 - i\epsilon}$$

- Spectral density

$$Im\Pi(s) \sim \text{bound state (or resonance)+continuum}$$

Continuum contribution approximation

$$Im\Pi(s) = Im\Pi^{QCD}(s),\ s > s_0 \text{ (threshold)}$$

Duality relation!

To extract reliable information of the resonance

- Borel transformation

$$\hat{B} = \lim_{\substack{-q^2, n \to \infty \\ -q^2/n = M^2}} \frac{(-q^2)^{(n+1)}}{n!} \left(\frac{d}{dq^2} \right)^n$$

Semi-phenomenological method inspired by QCD

♠ Interpolating currents

Ailin Zhang, Phys. Rev. **D61**, 114021 (2000): "Four-quark state in QCD"

- $(q\bar{q})(q\bar{q})$

$$
\begin{aligned}
j_1(x) &= (\bar{q}\Gamma\Lambda^m q)(\bar{q}\Gamma\Lambda^n q), \\
j_2(x) &= f^{ab_1c_1} f^{ab_2c_2}(\bar{q}^{b_1}\Gamma\Lambda^m q^{c_1})(\bar{q}^{b_2}\Gamma\Lambda^n q^{c_2}), \\
j_3(x) &= (\bar{q}\Gamma h_v)(\bar{q}\Gamma\Lambda^m q), \\
j_4(x) &= f^{ab1c1} f^{ab2c2}(\bar{q}^{b1}\Gamma h_v^{c1})(\bar{q}^{b2}\Gamma\Lambda^m q^{c2}).
\end{aligned}
$$

where for the pseudoscalar quark pairs, $\Gamma = \gamma_5$, while $\Gamma = \gamma_\mu$ for the vector pairs. Λ^m is the generator of flavor $SU(3)$

Light four-quark state

$$(q\bar{q})(q\bar{q}): \quad 700 \sim 900 \text{ MeV}$$

Heavy-light four-quark state with one heavy quark

$$(c\bar{q})(q\bar{q}): \quad 1.8 \sim 1.9 \text{ GeV}$$

$$(m_c = 1.3 \text{ GeV})$$

$$(b\bar{q})(q\bar{q}): \; 5.2 \sim 5.3 \text{ GeV}$$

$$(m_b = 4.7 \text{ GeV})$$

- $(ud)(\bar{s}\bar{s})$

Hua-Xing Chen, A. Hosaka and Shi-Lin Zhu, Phys. Rev. **D74**, 054001 (2006): "Exotic tetraquark $ud\bar{s}\bar{s}$ of $J^P = 0^+$ in the QCD sum rule"

$$S_{abcd} = (\bar{s}_a \gamma_5 C \bar{s}_b^T)(u_c^T C \gamma_5 d_d)\,,$$

$$V_{abcd} = (\bar{s}_a \gamma_\mu \gamma_5 C \bar{s}_b^T)(u_c^T C \gamma^\mu \gamma_5 d_d)\,,$$

$$T_{abcd} = (\bar{s}_a \sigma_{\mu\nu} C \bar{s}_b^T)(u_c^T C \sigma^{\mu\nu} d_d)\,,$$

$$A_{abcd} = (\bar{s}_a \gamma_\mu C \bar{s}_b^T)(u_c^T C \gamma^\mu d_d)\,,$$

$$P_{abcd} = (\bar{s}_a C \bar{s}_b^T)(u_c^T C d_d)\,.$$

~ 1.5 GeV

$B^*\bar{B}$ and $[bd][\bar{b}\bar{u}]$

Chun-Yu, Yong-Lu Liu and Ming-Qiu Huang, Phys.Rev. D85, 074014(2012)

$$j^{\mu} = \frac{1}{\sqrt{2}}[(\bar{u}i\gamma^5 b)(\bar{b}\gamma_{\mu}d) + (\bar{u}_a\gamma_{\mu}b_a)(\bar{b}_b i\gamma^5 d_b)]$$

$$M_Z = (10.44 \pm 0.23)\ \mathrm{GeV}$$

$$j_{\mu} = \frac{\epsilon_{abc}\epsilon_{dec}}{\sqrt{2}}[(d_a^T C\gamma_5 b_b)(\bar{u}_d\gamma_{\mu}C\bar{b}_e^T) - (d_a^T C\gamma_{\mu}b_b) \times (\bar{u}_d\gamma_5 C\bar{b}_e^T)].$$

$$M_Z = (10.5 \pm 0.19)\ \mathrm{GeV}$$

Four quark in operator picture → Diquark in constituent quark picture? ? ?

Problems:

♣ Fierz transformation (rearrangement)

$(qq)(\bar{q}\bar{q}) \to (q\bar{q})(q\bar{q})$

T. Schafer, Phys. Rev. D68, 114017 (2003)

♣ Renormalization group improvement

All the currents may mix with each other under renormalization

Problems:

♣ Coupling

The coupling is a coupling of a current with a hadron

instead of a current quark with a constituent quark

The interpolating current is in color singlet, while the quark inside has color

Can the quark operator with color create Fock state directly?

1, In view of the sum rule approach, the internal color structure of multi-quark state can not be detected through the couplings of interpolating currents to hadrons

2, In principle, there is no direct way to turn the operator picture into the constituent quark picture

3, Diquark: meaningful in constituent quark picture; Not meaningful in operator picture in the framework of QCD sum rules

Baryon sum rules

Interpolating currents: Color SU(3), Flavor SU(3), Lorentz

Unique way for baryons color structure, different ways for the flavor and Lorentz structure

B.L. Ioffe,

Nuclear Physics B188 (1981) 317–341

$$\eta(x) = (u^a(x) C\gamma_\mu u^b(x))\gamma_5\gamma_\mu d^c(x)\varepsilon^{abc}$$

$$M_N = 985 \text{ MeV}$$

Y. Chung, H.G. Dosch, M. Kremer and D. Schall

Nuclear Physics B197 (1982) 55–75

$$\psi^{\mu} = a(u^{\mathrm{T}}C\gamma^{5}d)\gamma^{\mu}u + b(u^{\mathrm{T}}Cd)\gamma^{\mu}\gamma^{5}u + c(u^{\mathrm{T}}C\gamma^{5}\gamma_{\rho}d)[(g^{\mu\rho} - \tfrac{1}{4}\gamma^{\mu}\gamma^{\rho})u]$$

$$m_{\mathrm{N}} \approx 1240\ \mathrm{MeV}$$

Diquark + QCD sum rule

0^+ qq or qs diquark

Ailin Zhang, Tao Huang and Tom Steele, Phys. Rev. D76, 036004 (2007)

qq: 400 MeV

qs: 460 MeV

With spin-dependent interaction switched on

0^{++} four-quark state

$[\bar{q}\,\bar{q}][qq]$, ~490 MeV

$[\bar{q}\,\bar{q}][sq]$ ($[\bar{s}\,\bar{q}][qq]$) ~610 MeV

$[\bar{s}\,\bar{q}][sq]$ ~730 MeV

1^{--} four-quark state

$[\bar{q}\,\bar{q}][qq]$, ~490+B'_q MeV

$[\bar{q}\,\bar{q}][sq]$ $([\bar{s}\,\bar{q}][qq])$ ~610+B'_q MeV

$[\bar{s}\,\bar{q}][sq]$ ~730+B'_q MeV

◇ Scalar: $f_0(600)$ (or σ), $f_0(980)$, $a_0(980)$ and the unconfirmed $\kappa(800)$?

Cq diquark

R. T. Kleiv, T. G. Steele, Ailin Zhang and Ian Blokland, Phys.Rev. D87, 125018 (2013)

0^+: 1.86 $\pm$0.05 GeV

1^+: 1.87 $\pm$0.10 GeV

Bq diquark

$0^+,1^+$: 5.08 $\pm$0.04 GeV

X(3872) and Y_b(10890) are very possibly the $J^{PC}=0^{++}$ tetraquark states

3. Candidates of four-quark state

Light hadrons

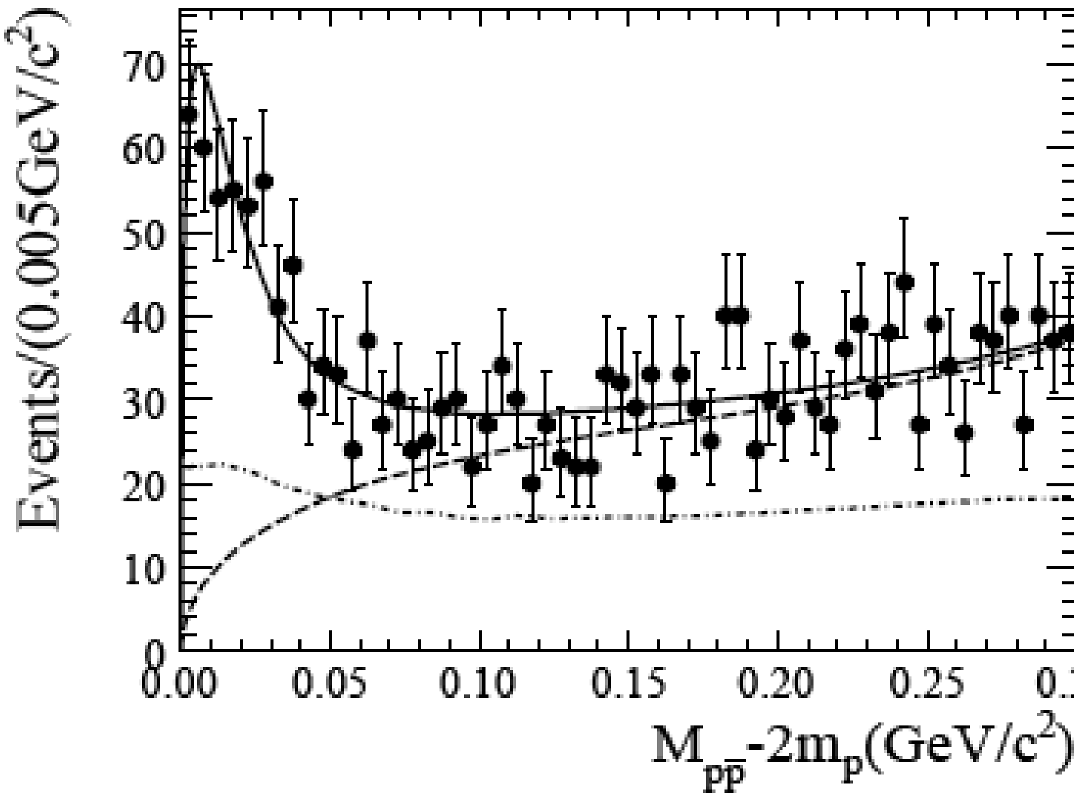
◇ Scalar: $f_0(600)$ (or σ), $f_0(980)$, $a_0(980)$ and the unconfirmed $\kappa(800)$?

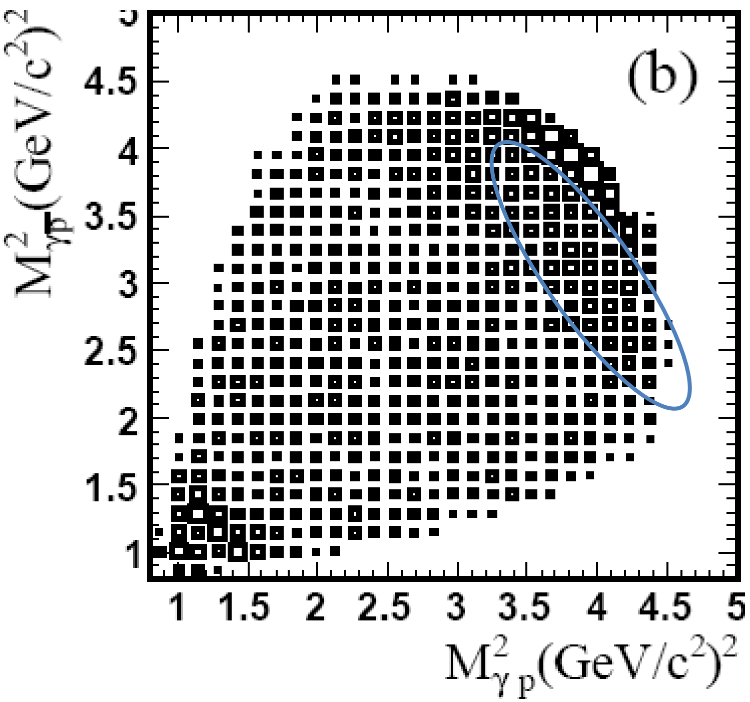
◇ **X(1860)**

anomalous enhancement near the threshold of $p\bar{p}$ **mass spectrum at BES III**

J. Z. Bai, et al., (BES Collaboration), Phys. Rev. Lett. 91, 022001 (2003); Chin.Phys.C34, 421(2010)

$\psi' \to \pi\pi J/\psi, J/\psi \to \gamma p\bar{p}$ @ BESIII

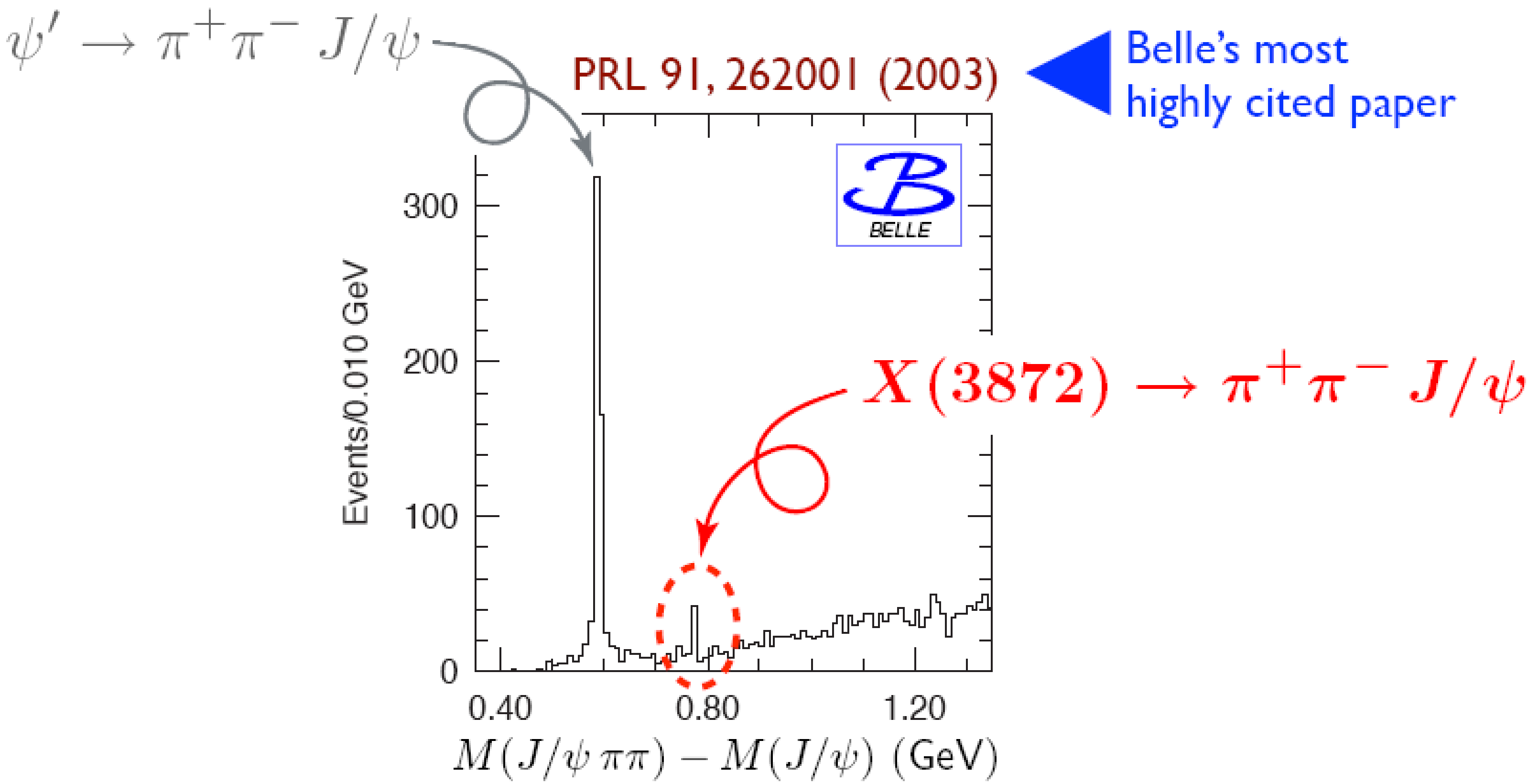




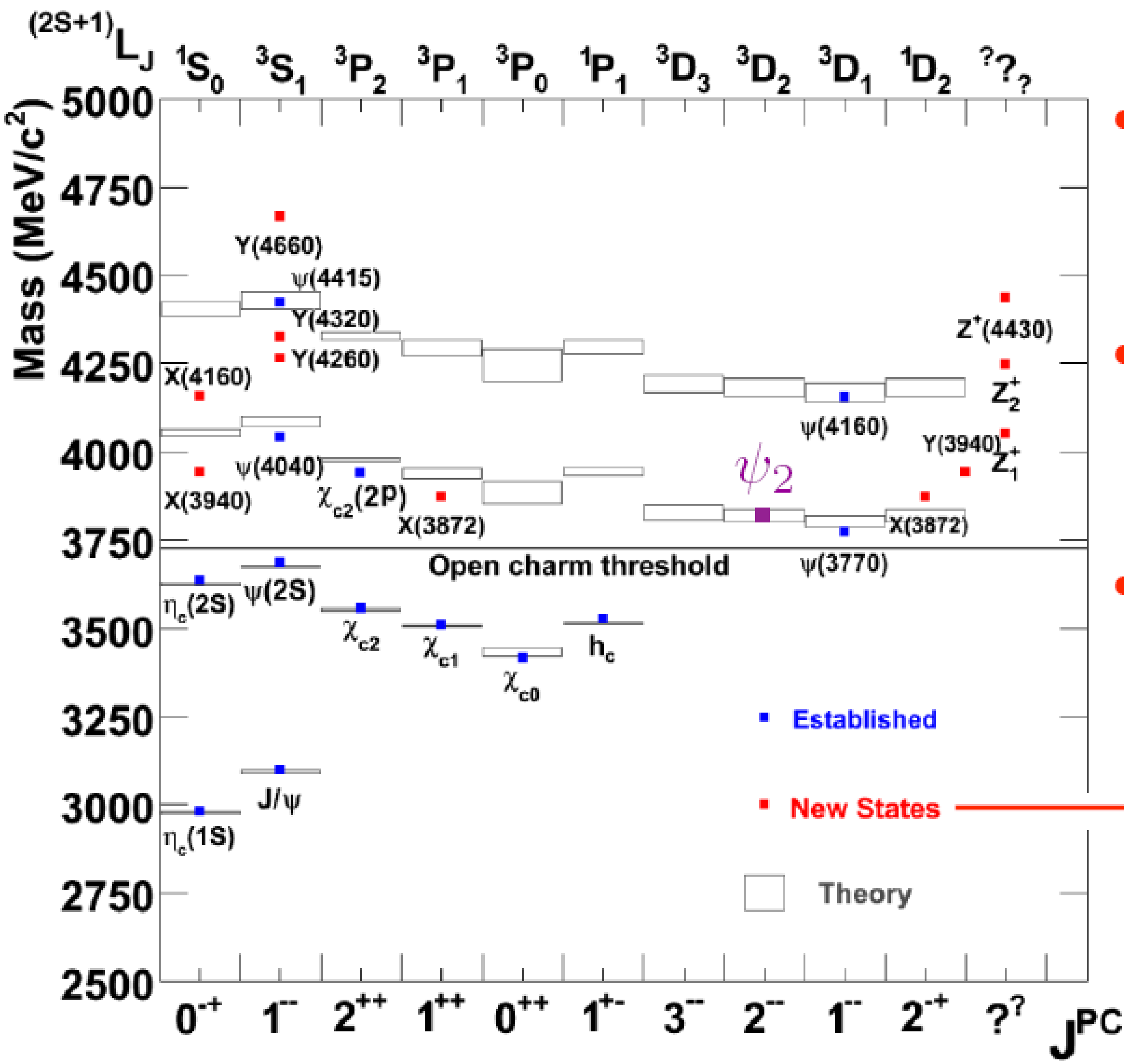
Fitted with a S-wave BW, M=1861$^{+6}_{-13}$ (stat)$^{+7}_{-26}$ (syst) MeV/c^2
Γ < 38 MeV/c^2 (90% CL)

Charmonium-like

$X(3872)$



Exotic charmonium-like spectroscopy



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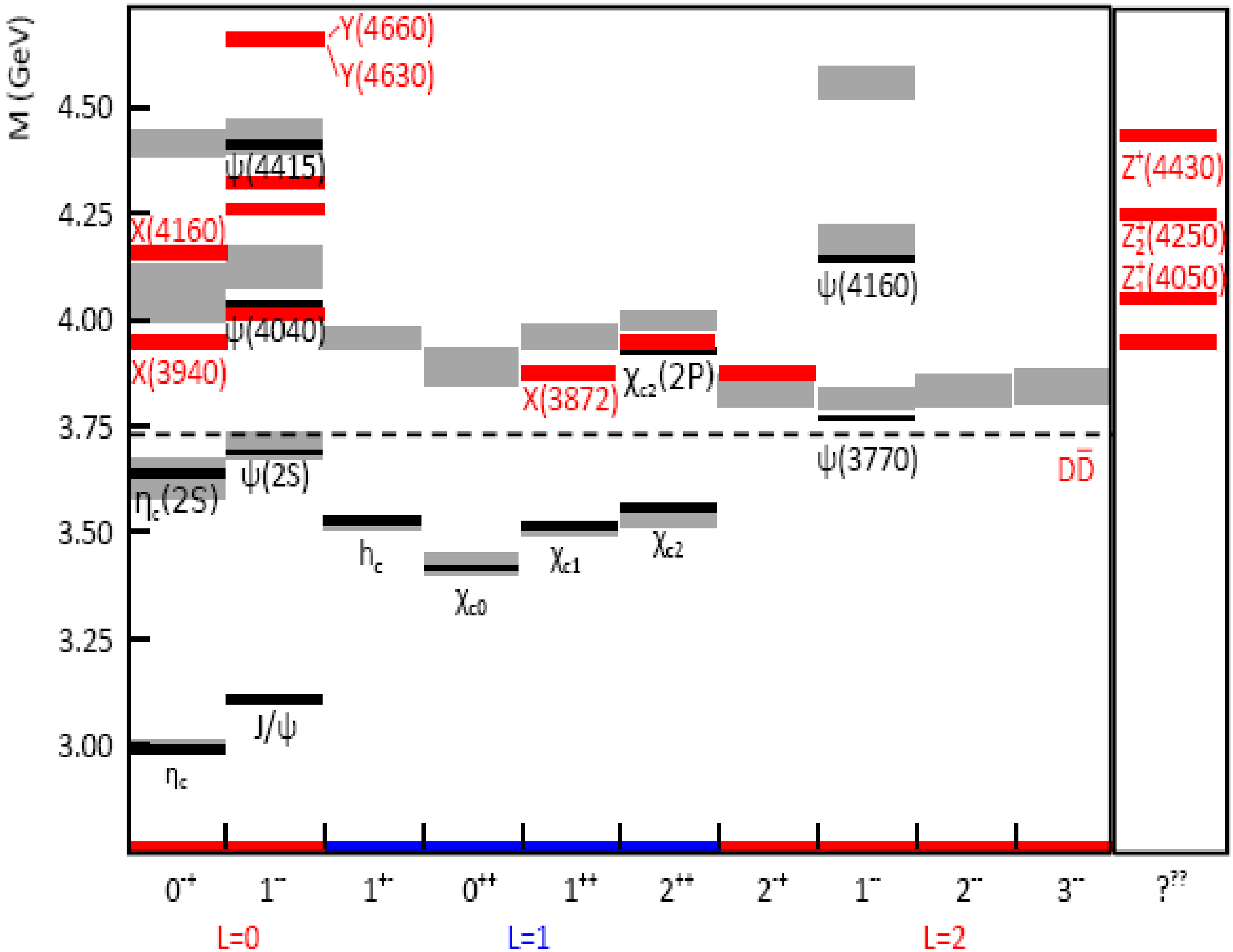
- Many *new states* seen, starting with $X(3872)$ in 2003
- Hard to match many of them with $c\bar{c}$ predictions
- Charged states cannot be $c\bar{c}$

State	M, MeV	Γ, MeV	J^{PC}	Process
$X(3872)$	3871.52 ± 0.20	1.3 ± 0.6	$1^{++}/2^{-+}$	$B \to K(\pi^+\pi^- J/\psi)$
		(< 2.2)		$p\bar{p} \to (\pi^+\pi^- J/\psi) + \ldots$
				$B \to K(\omega J/\psi)$
				$B \to K(D^{*0}D^0)$
				$B \to K(\gamma J/\psi)$
				$B \to K(\gamma\psi(2S))$
$X(3915)$	3915.6 ± 3.1	28 ± 10	$0/2^{?+}$	$B \to K(\omega J/\psi)$
				$\gamma\gamma \to (\omega J/\psi)$
$X(3940)$	3942^{+9}_{-8}	37^{+27}_{-17}	$?^{?+}$	$e^+e^- \to J/\psi(D\bar{D}^*)$
				$e^+e^- \to J/\psi\ (\ldots)$
$Y(4008)$	4008^{+121}_{-49}	226 ± 97	1^{--}	$e^+e^- \to \gamma(\pi^+\pi^- J/\psi)$
$Z_1(4050)^+$	4051^{+24}_{-43}	82^{+51}_{-55}	?	$B \to K(\pi^+\chi_{c1}(1P))$
$Y(4140)$	4143.4 ± 3.0	15^{+11}_{-7}	$?^{?+}$	$B \to K(\phi J/\psi)$
$X(4160)$	4156^{+29}_{-25}	139^{+113}_{-65}	$?^{?+}$	$e^+e^- \to J/\psi(D\bar{D}^*)$
$Z_2(4250)^+$	4248^{+185}_{-45}	177^{+321}_{-72}	?	$B \to K(\pi^+\chi_{c1}(1P))$
$Y(4260)$	4263 ± 5	108 ± 14	1^{--}	$e^+e^- \to \gamma(\pi^+\pi^- J/\psi)$
				$e^+e^- \to (\pi^+\pi^- J/\psi)$
				$e^+e^- \to (\pi^0\pi^0 J/\psi)$
$Y(4360)$	4353 ± 11	96 ± 42	1^{--}	$e^+e^- \to \gamma(\pi^+\pi^- \psi')$
$Z(4430)^+$	4443^{+24}_{-18}	107^{+113}_{-71}	?	$B \to K(\pi^+\psi(2S))$
$X(4630)$	4634^{+9}_{-11}	92^{+41}_{-32}	1^{--}	$e^+e^- \to \gamma(\Lambda_c^+\Lambda_c^-)$
$Y(4660)$	4664 ± 12	48 ± 15	1^{--}	$e^+e^- \to \gamma(\pi^+\pi^- \psi(2S))$

Eur.Phys.J.C71,1534 (2011)



Godfrey & Isgur,
Phys. Rev. D **32**, 189 (1985)

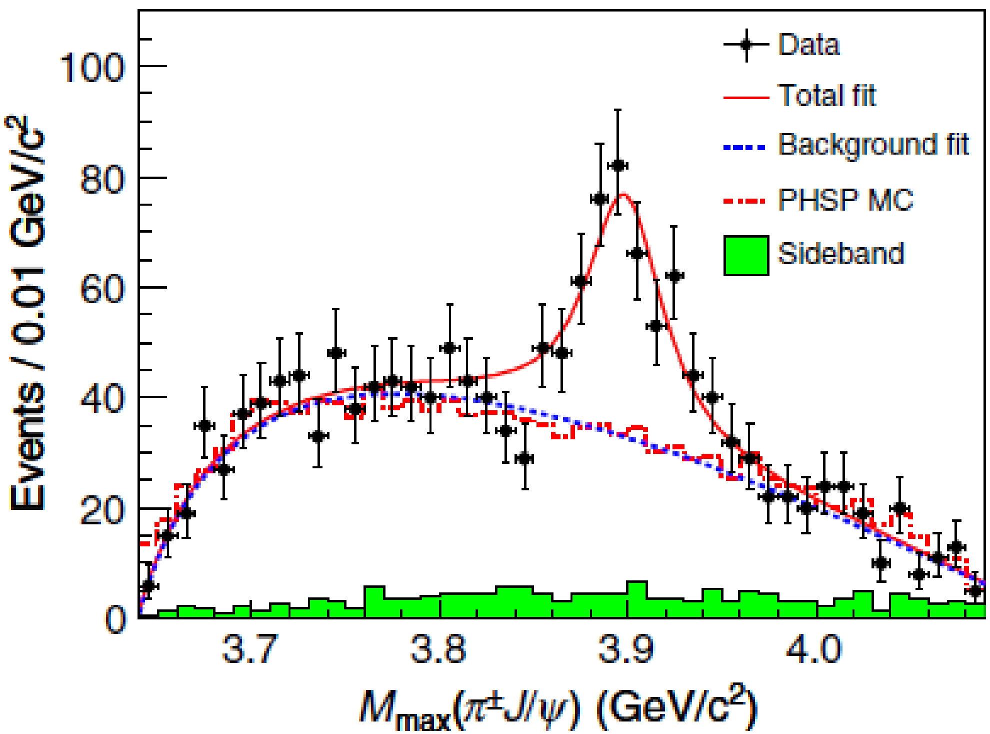
Wolfgang Gradl, Talk at Charm2012

Zc(3900)

BESIII Collaboration, Phys.Rev.Lett,110,252001(2013)

$$e^+e^- \rightarrow \pi^{\pm}Z_c(3900)^{\mp} \rightarrow \pi^+\pi^- J/\psi$$

PRL **110,** 252001 (2013) PHYSICAL



M=3899.0 ±3.6 ±4.9 MeV

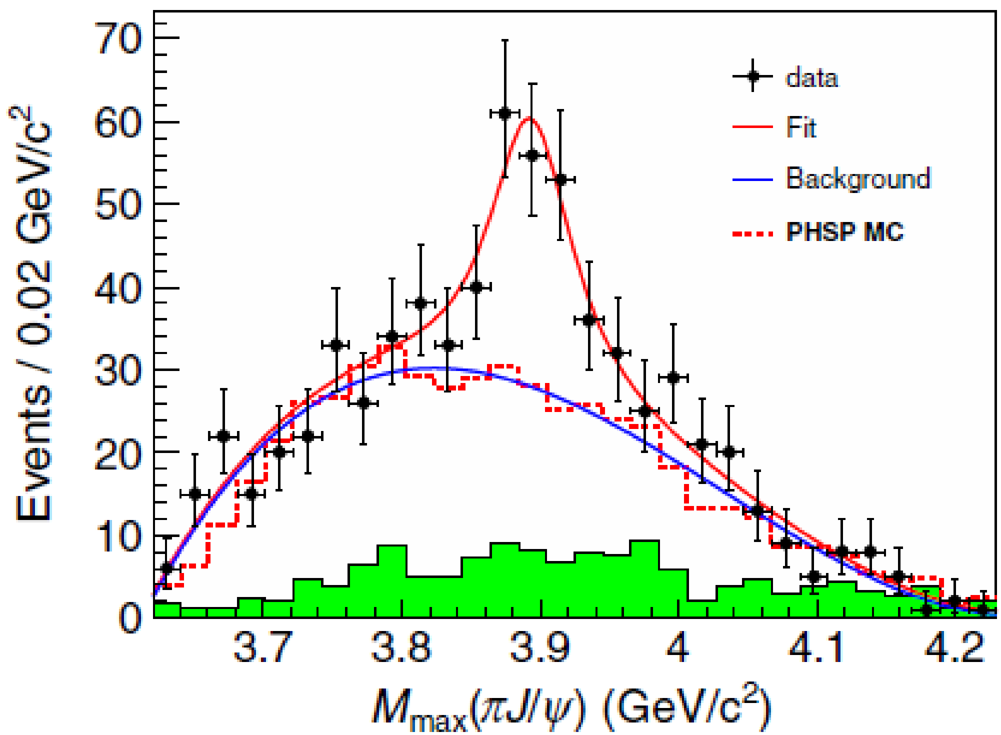
Γ=46 ±10 ±20 MeV

> 8 σ

Confirmed by Belle and CLEO-c

Belle Collaboration, PRL,110,252002 (2013)

PRL **110**, 252002 (2013) PHYSICAL



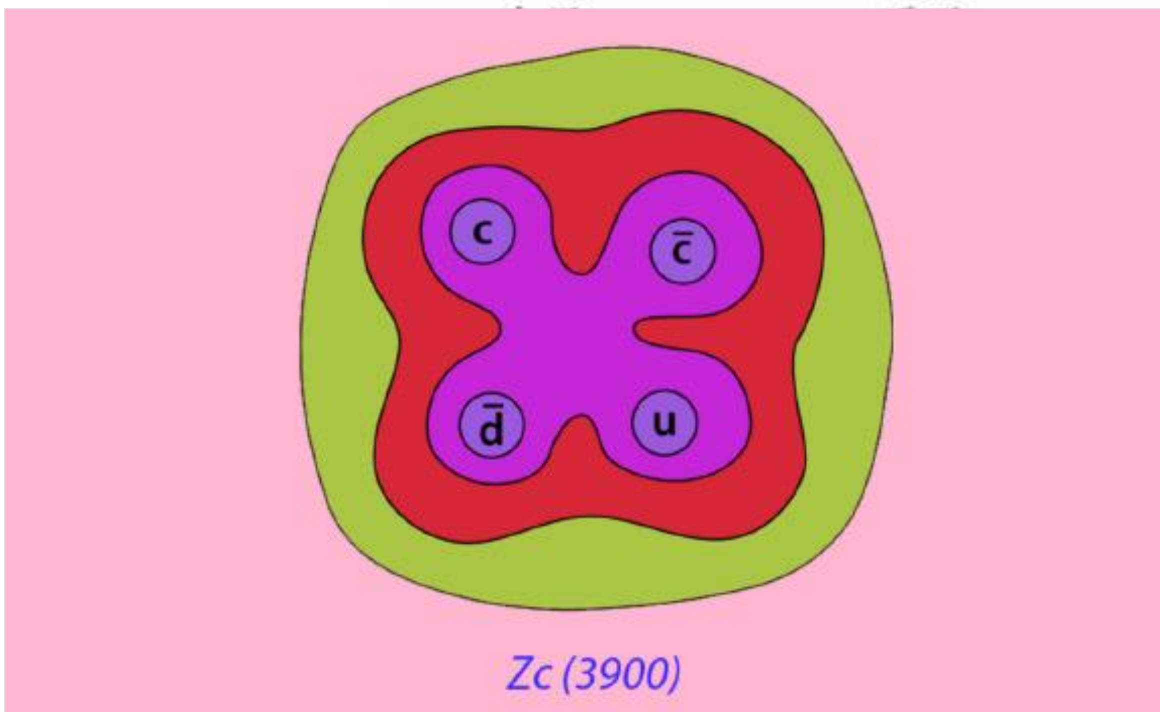
M=3894.5 ±6.6 ±4.5 MeV

Γ=63 ±24 ±26 MeV

> 5.2 σ

Confirmed by Belle and CLEO-c

Two experiments have detected the signature of a new particle, which may combine quarks in a way not seen before--Eric Swanson



Confirmed by Belle and CLEO-c

CLEO-c results, PLB,727,366 (2013)

Physics Letters B 727 (2013) 366–370

Contents lists available at ScienceDirect

Physics Letters B

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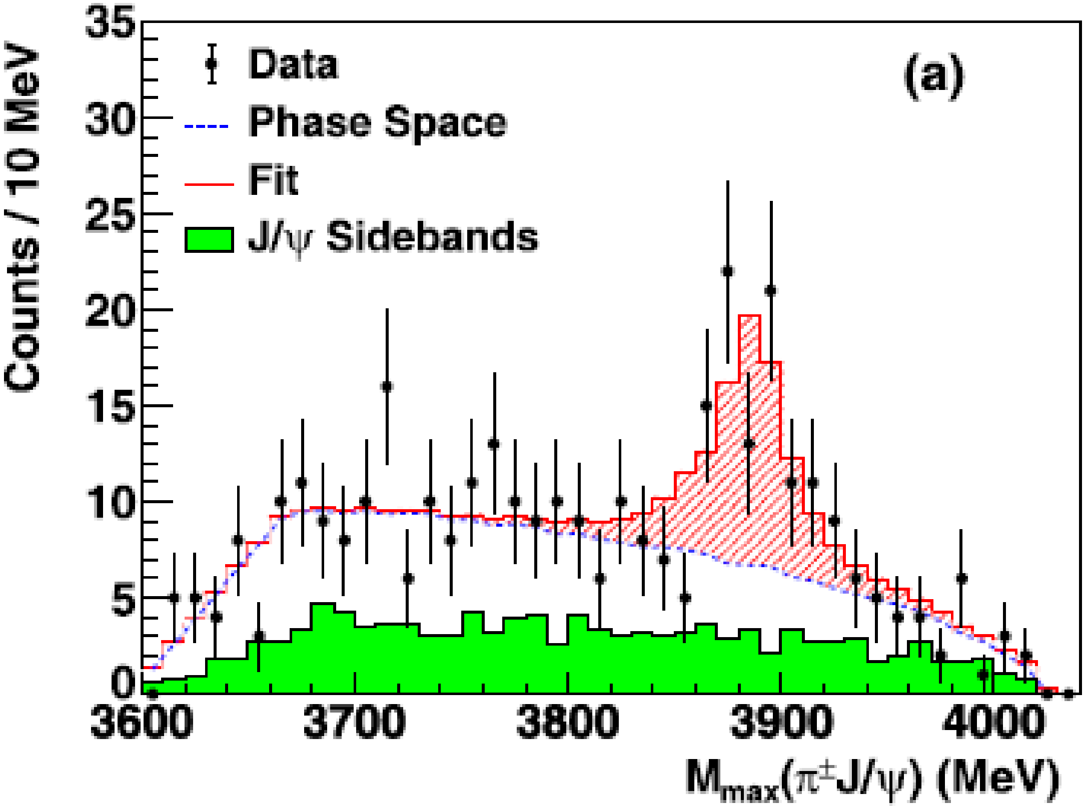
Observation of the charged hadron $Z_c^{\pm}(3900)$ and evidence for the neutral $Z_c^0(3900)$ in $e^+e^- \to \pi\pi J/\psi$ at $\sqrt{s} = 4170$ MeV

Xiao, S. Dobbs, A. Tomaradze, Kamal K. Seth *

hwestern University, Evanston, IL 60208, USA



M=3886 ±4 ±2 MeV

Γ=37 ±4 ±8 MeV

Summary of fit results for $Z_c^{\pm}$ and Z_c^0. The second uncertainties in $M(Z_c)$, $\Gamma(Z_c)$ and R are systematic. The log-likelihood determined significance levels for the present results have been calculated including systematic errors.

		Significance	$N(Z_c)$	$\langle\sigma(e^+e^- \to \pi Z_c \to \pi\pi J/\psi)\rangle$, pb	$M(Z_c)$ MeV	$\Gamma(Z_c)$ MeV	R %
BES III [1]	$\pi^+\pi^-$	$>8\sigma$	307 ± 48	13.5 ± 2.1	$3899\pm4\pm5$	$46\pm10\pm20$	$22\pm3\pm8$
Belle [2]	$\pi^+\pi^-$	$>5.2\sigma$	159 ± 49	-	$3895\pm7\pm5$	$63\pm24\pm26$	29 ± 9
Present:							
$(M^2(\pi^+\pi^-)$ – all)	$\pi^+\pi^-$	5.1σ	71 ± 15	$2.7\pm0.6\pm0.8$	$3886\pm4\pm2$	$33\pm6\pm7$	$32\pm8\pm10$
$(M^2(\pi^+\pi^-)<0.65$ GeV)	$\pi^+\pi^-$	5.7σ	81 ± 16	$3.9\pm0.8\pm0.8$	$3886\pm4\pm2$	$37\pm4\pm8$	$52\pm12\pm10$
$(M^2(\pi^0\pi^0)<0.65$ GeV)	$\pi^0\pi^0$	3.5σ	25 ± 7	$3.2\pm0.8\pm0.6$	$3904\pm9\pm5$	37 (fixed)	$63\pm21\pm11$

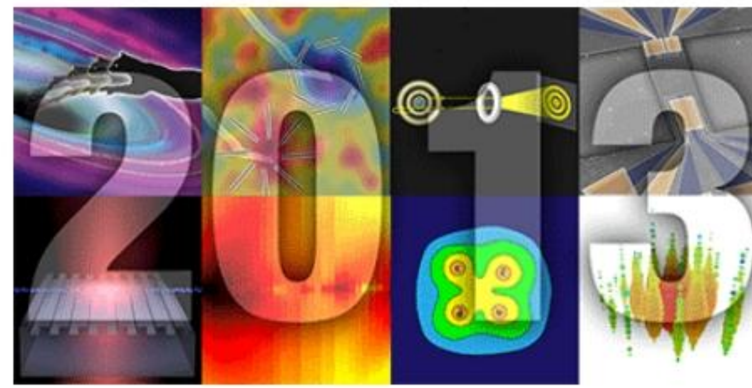
Notes from the Editors: Highlights of the Year

Published December 30, 2013 | Physics **6**, 139 (2013) | DOI: 10.1103/Physics.6.139

***Physics* looks back at the standout stories of 2013.**

As 2013 draws to a close, we look back on the research covered in *Physics* that really made waves in and beyond the physics community. In thinking about which stories to highlight, we considered a combination of factors: popularity on the website, a clear element of surprise or discovery, or signs that the work could lead to better technology. On behalf of the *Physics* staff, we wish everyone an excellent New Year.

– Matteo Rini and Jessica Thomas



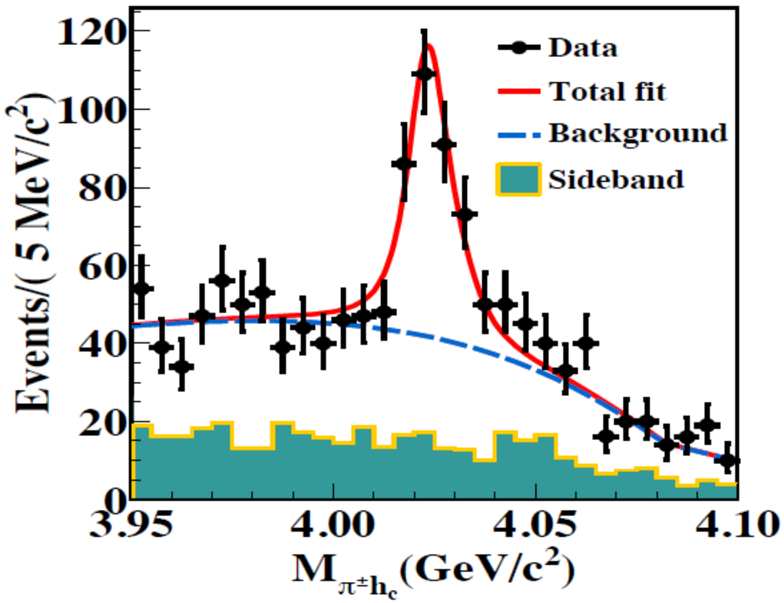
Images from popular *Physics* stories in 2013.

Four-Quark Matter

Quarks come in twos and threes—or so nearly every experiment has told us. This summer, the BESIII Collaboration in China and the Belle Collaboration in Japan reported they had sorted through the debris of high-energy electron-positron collisions and seen a mysterious particle that appeared to contain four quarks. Though other explanations for the nature of the particle, dubbed $Z_c(3900)$, are possible, the "tetraquark" interpretation may be gaining traction: BESIII has since seen a series of other particles that appear to contain four quarks.

$Z_c(4020)$

BESIII Collaboration, Phys.Rev.Lett,111,242001(2013)



- Mass:

  4022.9±0.8±2.7 MeV/c^2

- Width:

  7.9±2.7±2.6 MeV

- $Z_c(4020)$ signals:

  114±25 at 4230 MeV;

  72±17 at 4260 MeV;

  67±15 at 4360 MeV

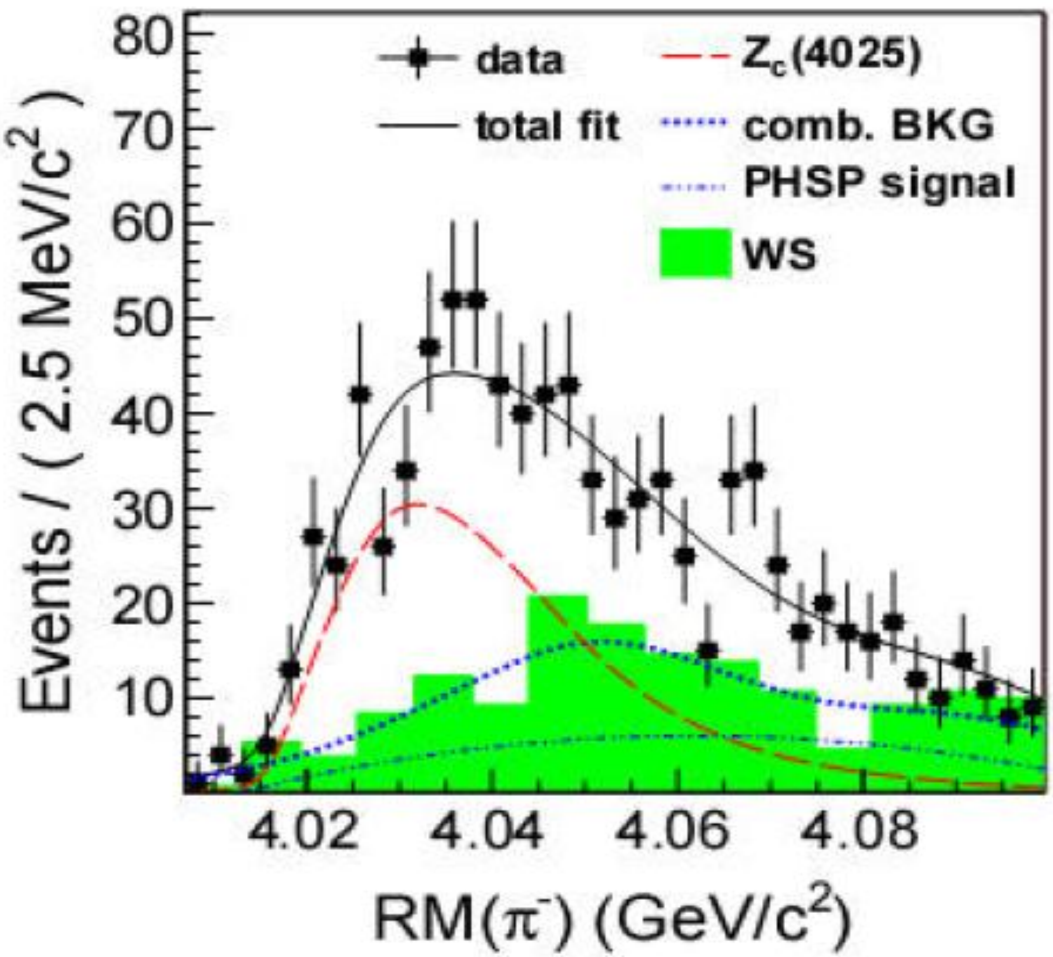
significance : 8.9 σ

- Fit the three data samples separately
- Fit the π^+h_c and π^-h_c mass spectrum separately

fit yields consistent

$Z_c^+(4025)$

BESIII Collaboration, Phys.Rev.Lett,112,132001(2014)

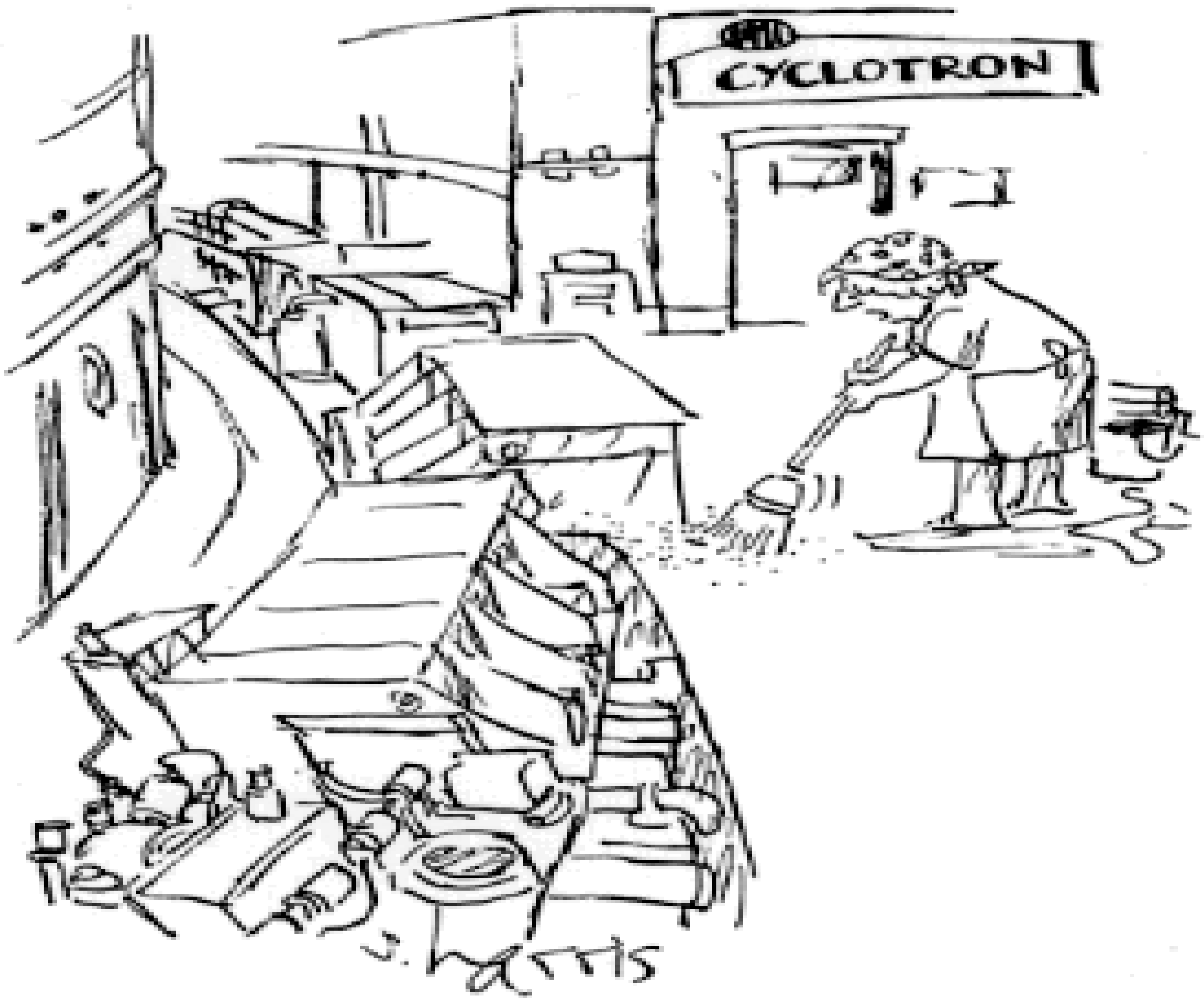


$M = 4026.3 \pm 2.6\ MeV$,

$\Gamma = 24.8 \pm 5.6\ MeV$, $e^+e^- \to (D^*\bar{D}^*)^{\pm}\pi^{\mp}$

Alternative explanations of the data exist that are based on less exotic quark-based interactions. One possibility is that the Zc is not a new particle but is an interaction between two D mesons. These D mesons are a combination of a charm quark with an up or down quark, so they give essentially the same quark content as in Fig. 1(c). Some models predict that these mesons will be attracted to each other with sufficient strength to explain the data. The difference between this D meson interaction and a new four-quark particle is only a matter of degree, but future experiments studying how the D mesons interact might be able to settle the issue. From the theory side, continued efforts at solving QCD might reveal whether four or more quarks can naturally come together to form a particle. If the four-quark explanation is confirmed, our particle physics zoo will need to be enlarged to include new species. And our understanding of quark taxonomy will have expanded into a new realm

X, Y, Z ?



"Particles, particles, particles."

4. Conclusions and discussions

- 1. Four-quark state has been established?
- 2. The properties of the decays of four-quark state? The mechanism of hadronic decays of four-quark states?
- 3. Theoretical study of four-quark state is not satisfactory, the principle (except for flavor, charge) of identification of four-quark state has not been established
- 4. Reasonable way to study multi-quark states in QCD ? Lattice theory?

Thanks !