Four-quark states and QCD sum rules

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11 Jul, 2015

HNP2015, Krabi

Outline

- 1. Four-quark state in constituent quark model
- 2. QCD sum rules
- 3. “Candidates” of four-quark states
- 4. Discussions

1. Four-quark state in constituent quark model

Nature 498, 280 (2013)

nature International weekly journal of science

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NATURE | NEWS

عربي

Quark quartet opens fresh vista on matter

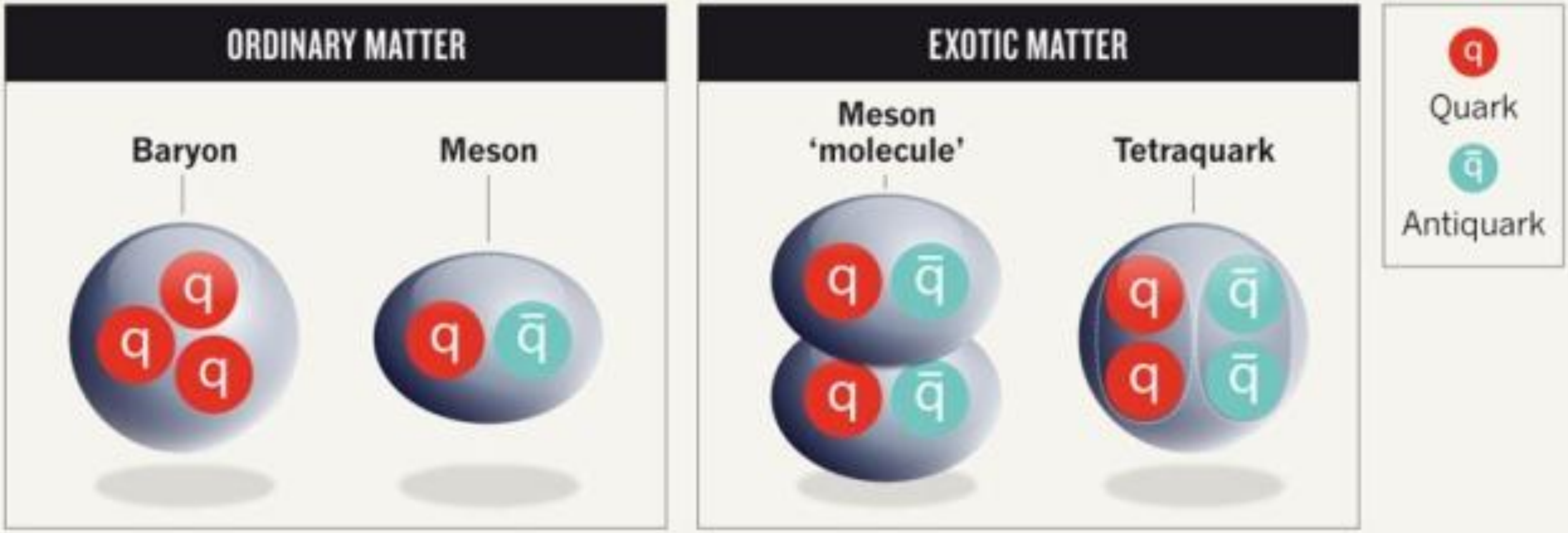
First particle containing four quarks is confirmed.

Devin Powell

18 June 2013

QUARK SOUP

Researchers at colliders in China and Japan have succeeded in making exotic matter comprising four quarks, but are still debating whether the fleeting particles are meson pairs or true tetraquarks.



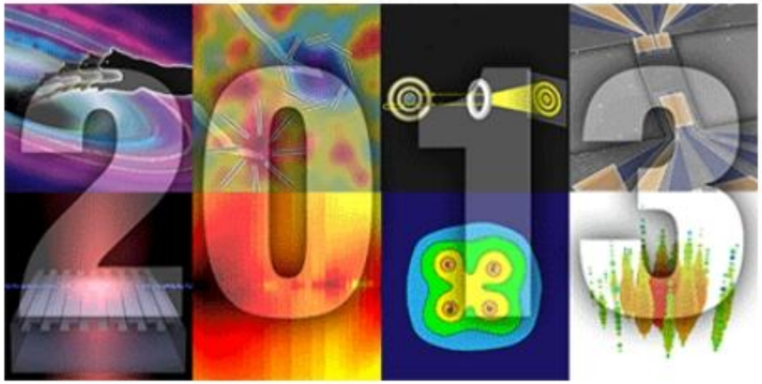
Notes from the Editors: Highlights of the Year

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

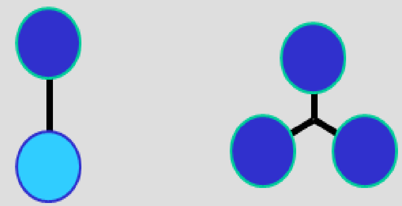
Quarks come in twos and threes—or so nearly every experiment has told us. This summer, the BESIII Collaboration in China and the Belle Collaboration in Japan reported they had sorted through the debris of high-energy electron-positron collisions and seen a mysterious particle that appeared to contain 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.

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

Quark Model

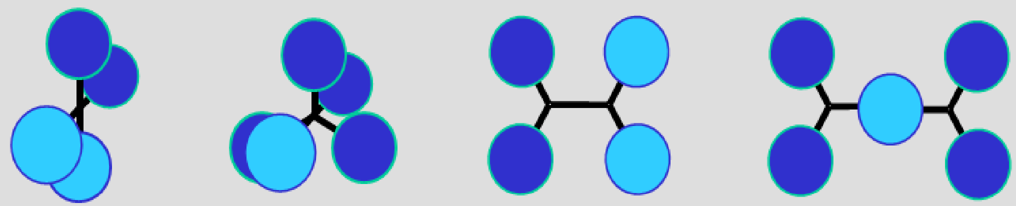
We know

mesons and baryons

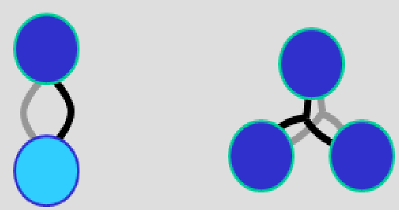


QCD also allows

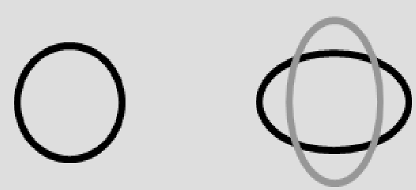
molecules/multi-quarks



hybrids



glueballs



and more

Four-quark state was first introduced through hadron scattering amplitudes:

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

Some models related to four-quark states:

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)

......

Related reviews to four-quark states:

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

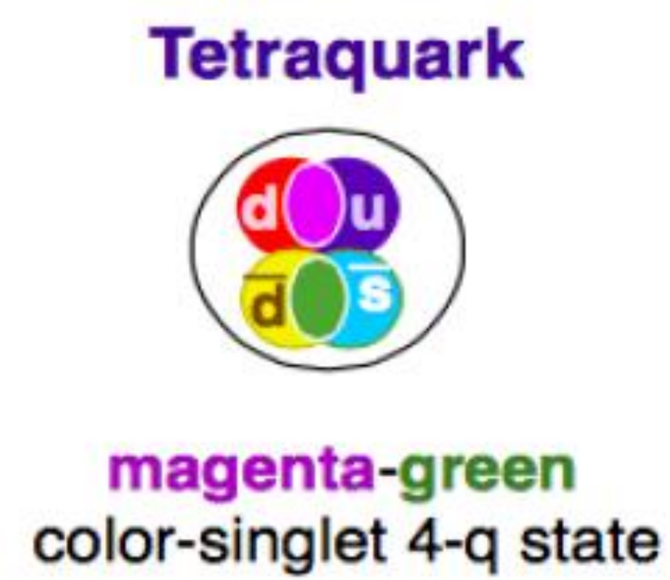
Four-quark state: consists of four quarks and anti-quarks

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

Intrinsic quarks/anti-quarks may make clusters

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

Quark dynamics

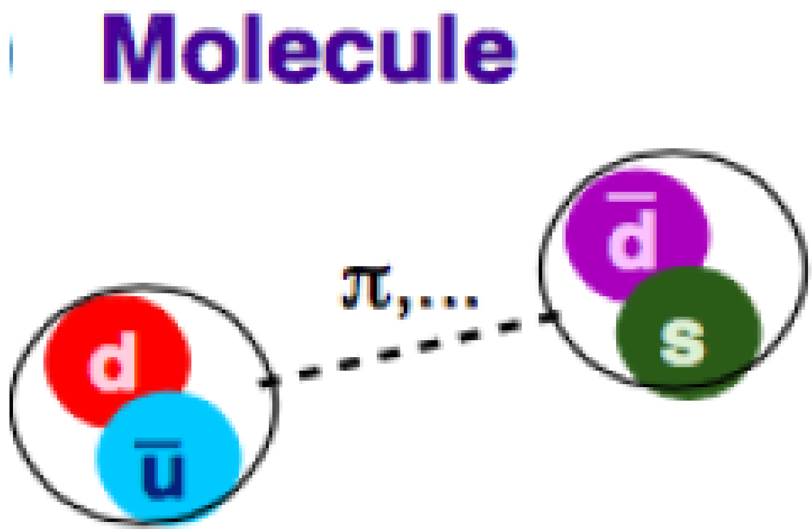


Diquark-antidiquark with gluon exchange

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)



2 color-neutral mesons with soft pion exchange

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

Color singlet from $8 \times 8 \; (q\bar{q})(q\bar{q})$ **?**

Mixing

Hadrons are in color singlets

1, $(qq)(\bar{q}\bar{q})$ **may mix with** $(q\bar{q})(q\bar{q})$
2, **four-quark state may mix with normal** $q\bar{q}$ **meson**

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

Morgan's pole counting rule (D. Morgan, Nucl.Phys.A543,632 (1992))

2. QCD sum rules

◇ QCD (SVZ) sum rules

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

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

△ In principle, it is a nonperturbative method of relating fundamental parameters of QCD Lagrangian and vacuum to parameters of hadrons

Calculable: QCD at short distances by perturbation theory
OPE

Measurable: Properties of resonances, cross section, etc
at long distance

Analyticity →despersion relation:

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

Analyticity relates \`sum over measurable\` to \`Caculable\`

△ Semi-phenomenological method inspired by QCD

- 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!

The spectral density is expressed through the coupling!

Couplings!

A coupling is the coupling of a current with a hadron instead of a current quark with a constituent quark

The quark operator with color cannot create the Fock state directly!

♠ Interpolating currents

1, $(q\bar{q})(q\bar{q})$ **Molecule-like**

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

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

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

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

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

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

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

2, $(qq)(\bar{q}\bar{q})$ **Tetraquark-like**

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"

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

$$
\begin{aligned}
S_{abcd} &= (\bar{s}_a \gamma_5 C \bar{s}_b^T)(u_c^T C \gamma_5 d_d)\,, \\
V_{abcd} &= (\bar{s}_a \gamma_\mu \gamma_5 C \bar{s}_b^T)(u_c^T C \gamma^\mu \gamma_5 d_d)\,, \\
T_{abcd} &= (\bar{s}_a \sigma_{\mu\nu} C \bar{s}_b^T)(u_c^T C \sigma^{\mu\nu} d_d)\,, \\
A_{abcd} &= (\bar{s}_a \gamma_\mu C \bar{s}_b^T)(u_c^T C \gamma^\mu d_d)\,, \\
P_{abcd} &= (\bar{s}_a C \bar{s}_b^T)(u_c^T C d_d)\,.
\end{aligned}
$$

~ 1.5 GeV

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

$$[bd][\bar{b}\bar{u}]$$

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

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

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

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

3, Diquark

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

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

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

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

However, there may be problems with physical interpretation

♣ Fierz transformation (rearrangement)

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

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

♣ Renormalization group improvement

All the currents may mix with each other in the lowest order of perturbation theory under renormalization

A color singlet current (with different combinations of quark operators) may coupling with a color singlet hadron (with different internal quark clusters and dynamics)

QCD sum rules present us the calculation, but have no thing to do with the hadron dynamics!

Do calculations
Let dynamics be!

A general large-N argument due to Coleman (1985):

Using Fierz transform the 4-quark operators can always be reduced to products of colorless bilinears $B_i = (\bar{q}\Gamma_i q)$ (Γ_i are spin-flavor structures):

$$j(x) = \sum_{ik} C_{ik}\, B_i(x) B_k(x) \ ,$$

where C_{ij} are symmetric coefficients.

Correlator

$$\langle j(x) j^\dagger(y)\rangle_0 = \sum_{iklm} C_{ik} C^*_{lm} \left[\langle B_i(x) B^\dagger_l(y)\rangle_0 \langle B_k(x) B^\dagger_m(y)\rangle_0 + \langle B_i(x) B_k(x) B^\dagger_l(y) B^\dagger_m(y)\rangle_{0,\text{connected}}\right]$$

The first term is the fall-apart contribution- a meson pair rather than exotics. The exotic resonances contribute only to the connected part.

The contribution of the exotic resonances is suppressed at large N

M. Voloshin (QNP2015):

Sum rules are a time tested approach to calculate properties of the lowest state in a J^{PC} channel, but look not helpful for studies of multiquark exotic resonances

M.Shifman 2006, communication
P, Colangelo, discussion face to face

3. Candidates of four-quark state

Light hadrons

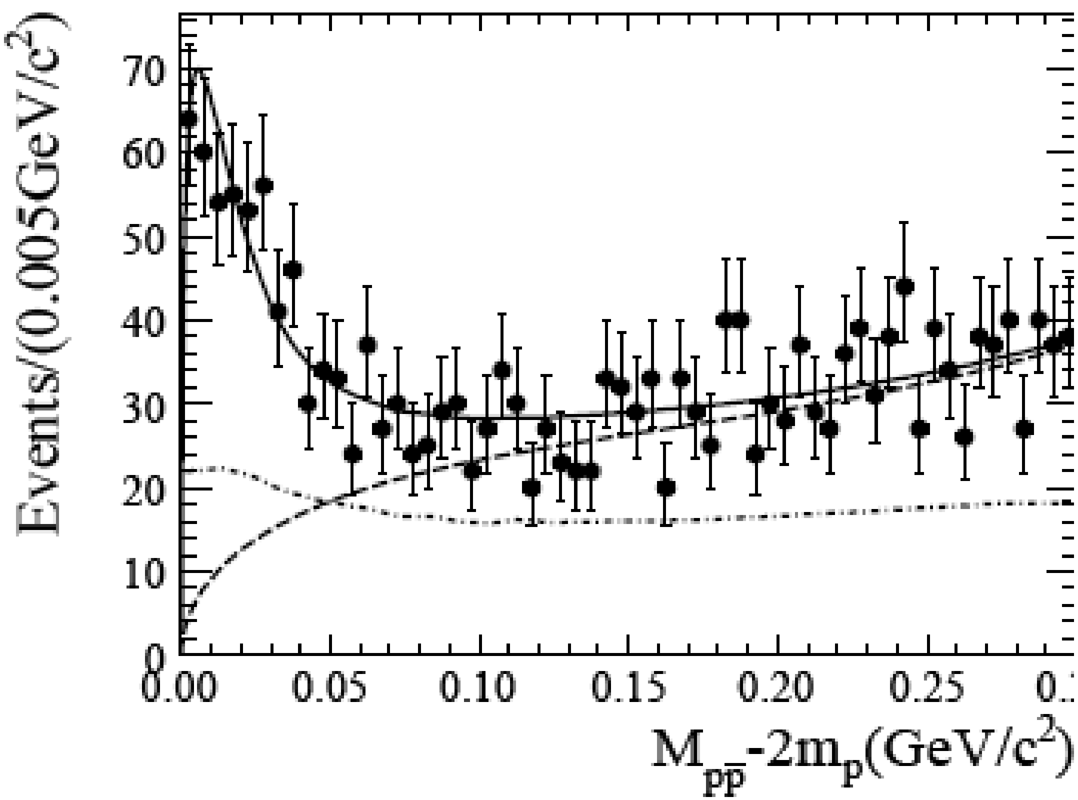
◇ Scalar: $f_0(600)$ (or σ), $f_0(980)$, $a_0(980)$ and the unconfirmed $\kappa(800)$?

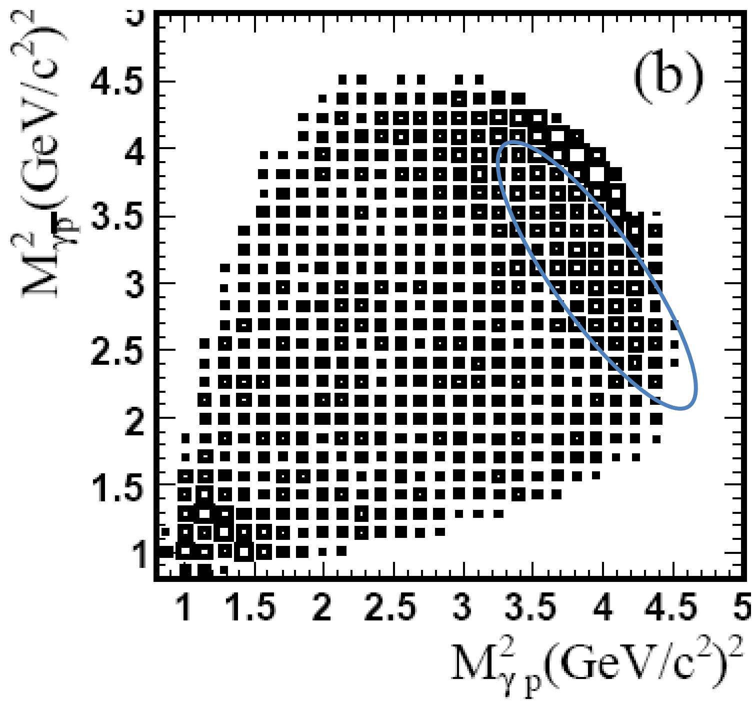
◇ X(1860)

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
$\Gamma < 38$ MeV/c^2 (90% CL)

The observations at BES

- ★ X(1840): J^P unknown,$J/\psi\to\gamma\ 3(\pi^+\ \pi^-)$ **PRD 88, 091502**
- ○ X(1870): J^P unknown, $J/\psi\to\ \omega\ (\eta\pi\pi)$ PRL107, 182001
- ▲ X(1835): $J^P=0^-$, $J/\psi\to\gamma\ (\eta'\pi\pi)$ PRL106, 072002
- ■ $X(p\ \bar{p})$: $J^P=0^-$, $J/\psi\to\gamma\ (p\ \bar{p})$ PRL108,112003
- + X(1810): $J^P=0^+$,J $J/\psi\to\gamma\ (\omega\phi)$ PRD 87, 032008

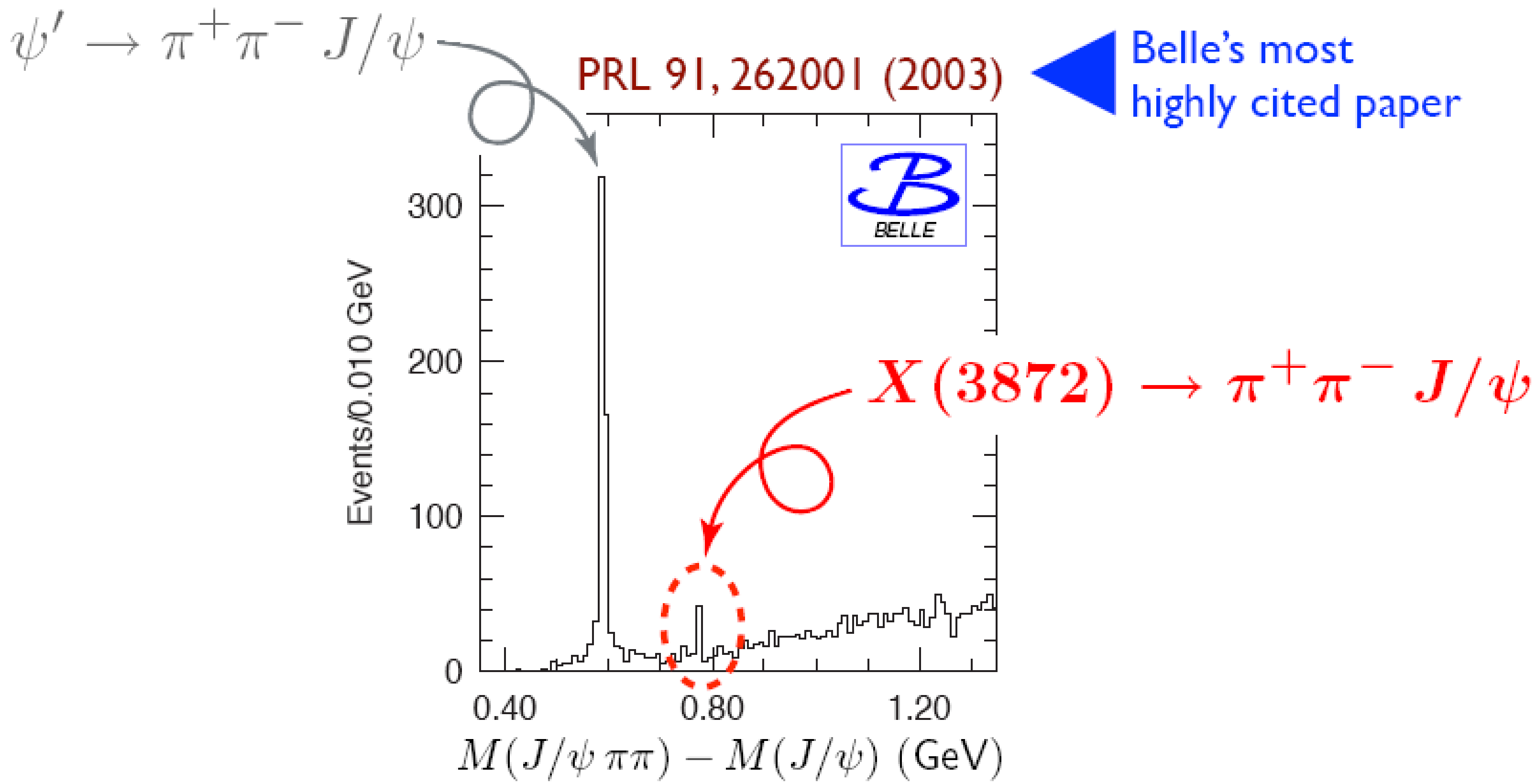
X(18??) are close to the threshold of proton and anti-proton

Identified?

The same resonance?

Charmonium-like

$X(3872)$



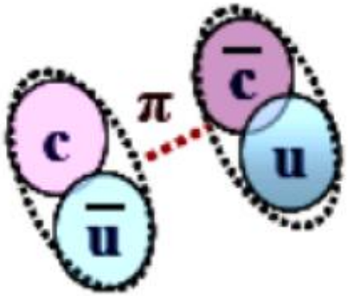
Belle's most highly cited paper

Explanations to X(3872)

$J^{PC} = 1^{++}$

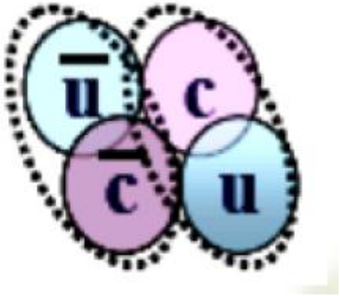
<u>D^0D^{*0} molecular state:</u>

E.S.Swanson, F.E.Close and P.R. Page, M.B.Voloshin...



<u>Tetraquark (cq)($\overline{cq}$):</u>

L.Maiani, A.D.Polosa, V.Riquer, F.Piccini; D.Ebert, R.N.Faustov, V.O.Galkin



<u>Hybrid (ccg)</u> *F.E.Close and P.R. Page*

<u>Threshold cusp</u> *D.V.Bugg*

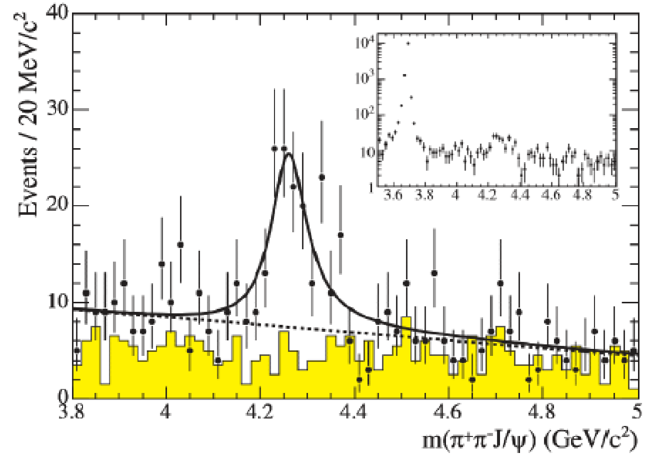
$X(3872)$: a dominant $c\bar{c}$ component with some admixture of $D^0\bar{D}^{*0} + \bar{D}^0 D^{*0}$

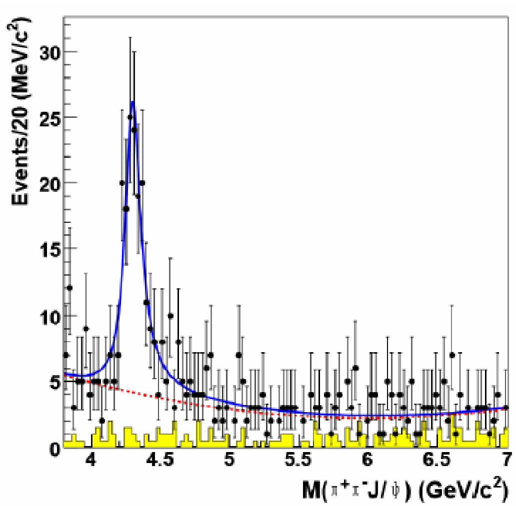
- Suzuki, PRD72, 114013
- Meng, Chao, arXiv:hep-ph/0506222
- Zhu, IJMP, E17, 283
- Liu, Liu, Deng, Zhu, EPJC56, 63

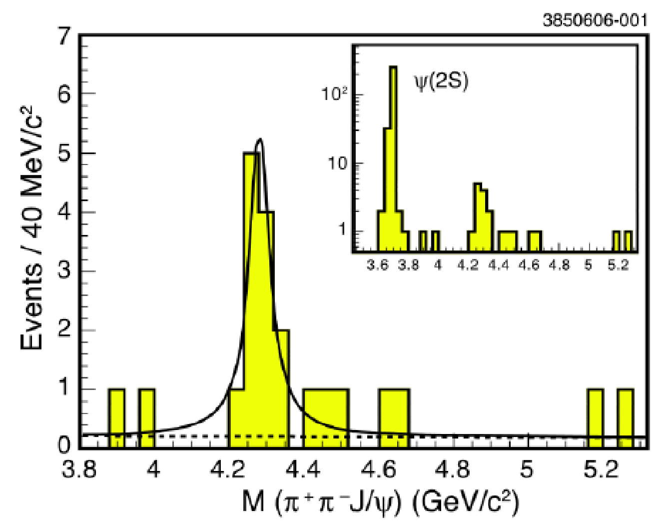
X(4260)

X(4260) in $e^+e^- \rightarrow \gamma_{isr}\pi\pi J/\psi$

- BaBar first observed in initial state radiation process.
  - Phys. Rev. Lett. 95, 142001 (2005)
- Confirmed by Belle and CLEO.







Explanations to X(4260)

Charmonium:

$J^{PC} = 1^{--}$

F.J.Llanes-Estrada,PRD72(2005)031503
B.-Q.Li and K.-T.Chao,PRD79 (2009) 094004

Molecule:

Xiang Liu, et al.,PRD72 (2005) 054023
C.Z.Yuan, et al.,PLB634(2006)399
Q.Wang, et al., PRL111(2013)132003

Tetraquark:

L. Maiani, F. Piccinini, A. D. Polosa, and V. Riquer, Phys.Rev. D72 (2005) 031502

Hybrid:

S.-L.Zhu,PLB625 (2005) 212

Non-resonance:

E.Van Beveren, G.Rupp,PRD79(2005)111501
D.Y.Chen, J.He, X.Liu,PRD83(2011)054021

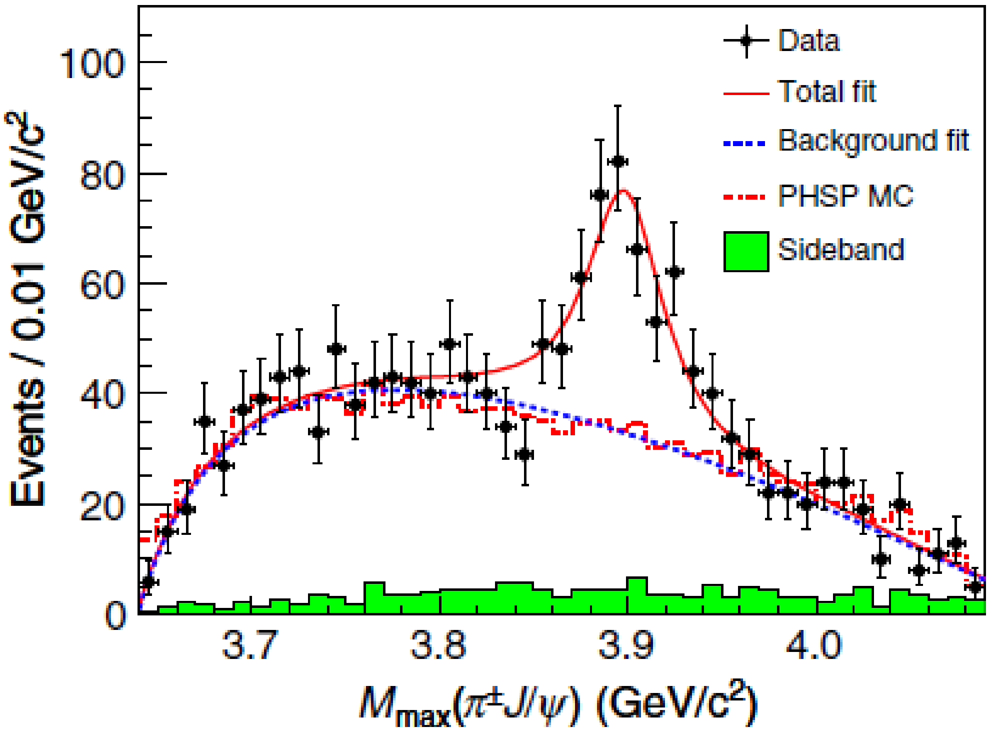
X(3900)

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

Zc(3900)



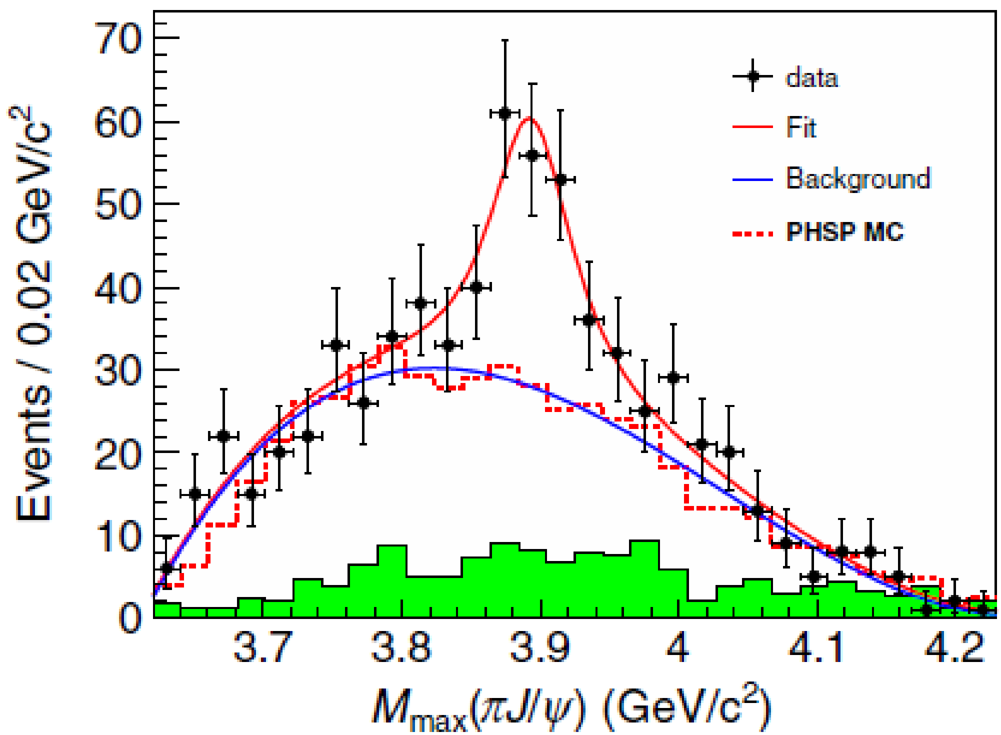
M=3899.0 ±3.6 ±4.9 MeV
Γ=46 ±10 ±20 MeV
> 8 σ

Close to D $\bar{D}$*
threshold (3875 MeV)

Confirmed by Belle

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 CLEO-c

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

Physics Letters B 727 (2013) 366–370

Contents lists available at ScienceDirect

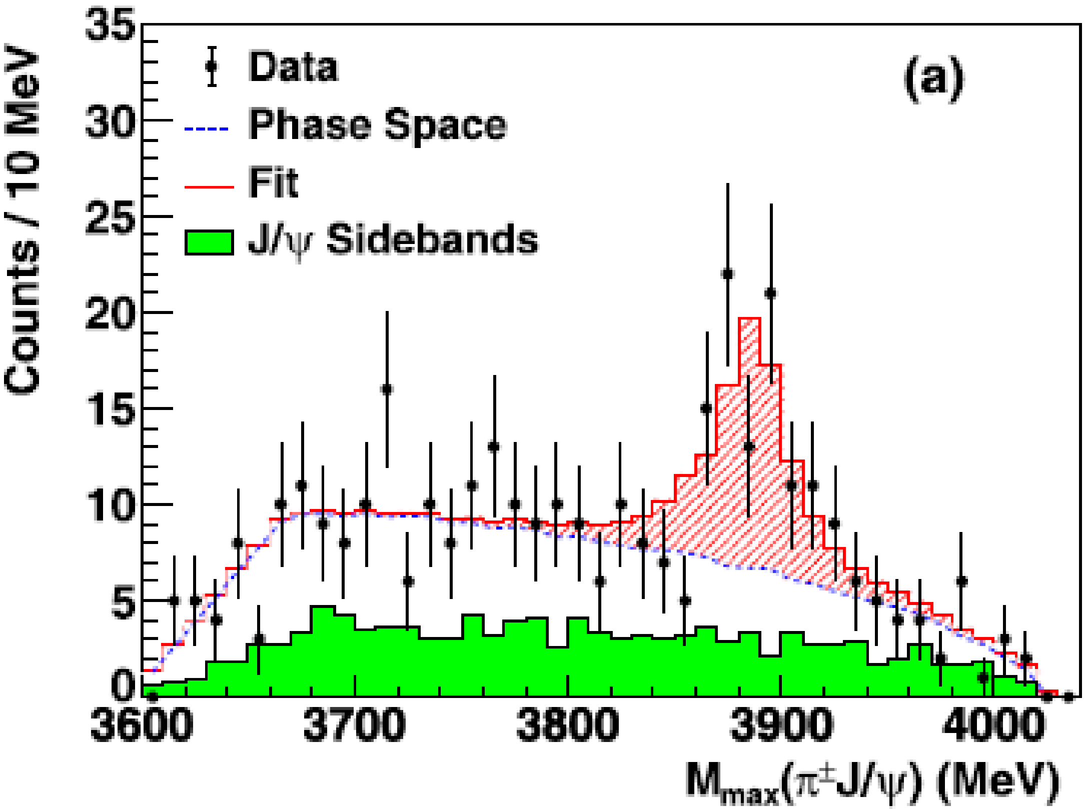
Physics Letters B

www.elsevier.com/locate/physletb

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

Explanations to X(3900)

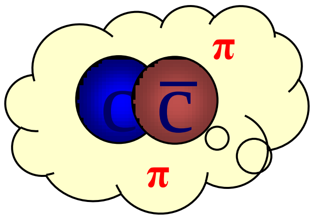
D*D molecular state:

F-K Guo, Phys.Rev. D88 (2013) 054007
C-Y Cui, et al., J.Phys. G41 (2014) 075003, QCD sum rule

Tetraquark state:

L.Maiani, et al.,Phys.Rev. D87 (2013)111102(R）
J.M.Dias, et al., Phys.Rev. D88 (2013), 016004, QCD sum rule
C.-F.Qiao and L.Tang, Eur.Phys.J. C74 (2014), 3122, QCD sum rule

Hadron-charmonium:



M.B.Voloshin,Phys.Rev. D87 (2013) 091501

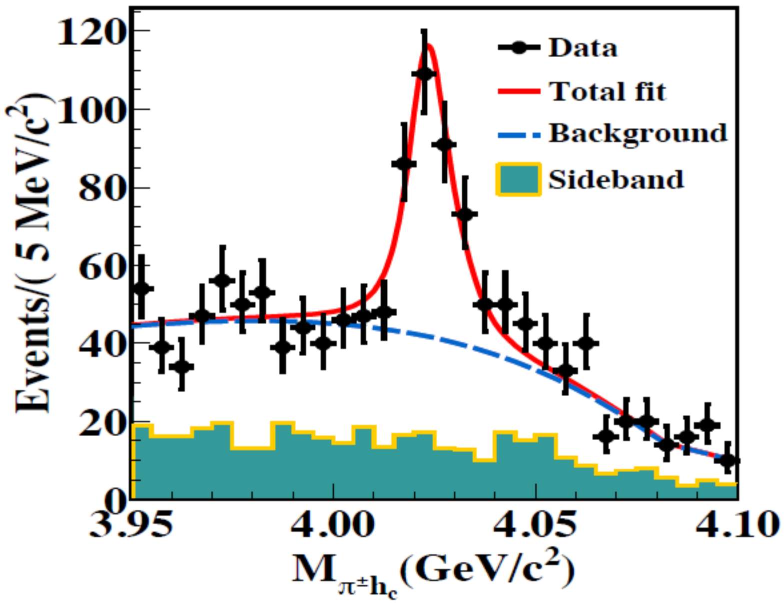
charmonium embedded into light hadron

Initial single pion emission :

D.Y.Chen and X.Liu,Phys.Rev. D84 (2011) 034032

X(4020)

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



$Z_c(4020)$

- 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

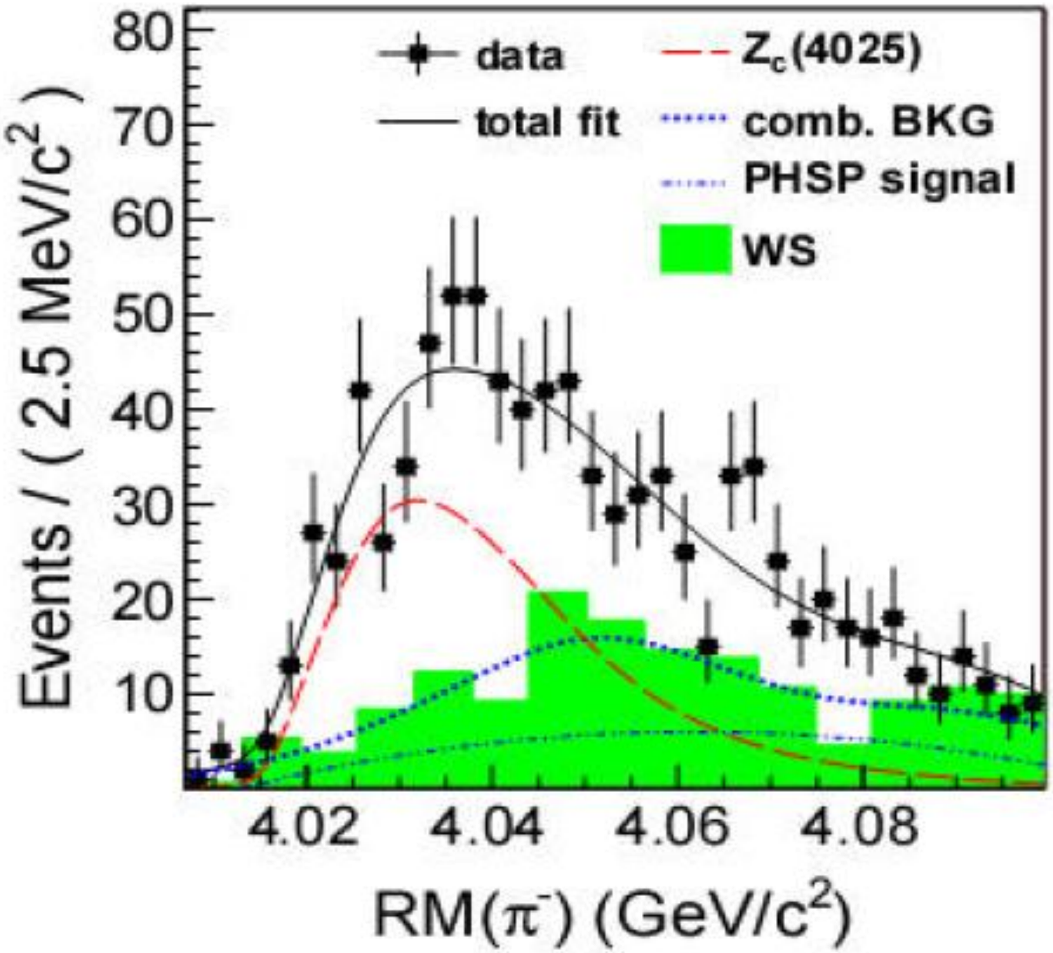
- Fit the three data samples separately
- Fit the π^+h_c and π^-h_c mass spectrum separately

fit yields consistent

Close to $D^* \bar{D}^*$ threshold (4017 MeV)

X(4020)

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



$Z_c^+(4025)$

$\mathbf{M=4026.3 \pm 2.6}$ ***MeV***,

$\mathbf{\Gamma=24.8\pm5.6}$ ***MeV***, $e^+e^- \to (D^*\bar{D}^*)^\pm\pi^\mp$

Explanations to X(4020)

D*D molecular state:

K. P. Khemchandani, A. Martínez Torres, M. Nielsen, and F. S. Navarra， Phys. Rev. D 89（2014）, 014029， QCD sum rules

Tetraquark state:

C.F.Qiao and L.Tang, Eur.Phys.J. C74 (2014), 2810, QCD sum rule
Chengrong Deng, Jialun Ping, Fan Wang, PRD 90 (2014) , 054009

Coupled channel cusp:

E.S.Swanson, Phys.ReV.D91 (2015) 034009
F-K Guo, C.Hanhart,Q.Wang,Q.Zhao, Phys.ReV.D91 (2015) 051504(R)

Could the near-threshold XYZ states be simply kinematic effects?

X(4430)

Z(4430)

- *Belle observed a broad charged state $Z(4430)^+$ in $B \to \psi(2S)\, \pi^+ K^-$*
  - *Not a simple $c\bar{c}$ state, quark content as least $(c\bar{c})u\bar{d}$*

$$M_{Z(4430)} = (4433 \pm 4 \pm 2)\ \text{MeV}$$

$$\Gamma_{Z(4430)} = (45\ {}^{+18}_{-13}\ {}^{+30}_{-13})\ \text{MeV}$$

$$B(B^0 \to K^{\mp} Z^{\pm}) \times B(Z^{\pm} \to \psi' \pi^{\pm}) = (4.1 \pm 1.0 \pm 1.4) \times 10^{-5}$$

- *BaBar looks for Z(4430) in charged and neutral B decays to $\psi(2S)\ \pi K$ and $J/\psi\ \pi K$ (PRD 79,112001 (2009))*
  - *All samples are consistent with no Z(4430)*

$$B(B^0 \to K^{\mp} Z^{\pm}) \times B(Z^{\pm} \to \psi' \pi^{\pm}) = (1.9 \pm 0.8) \times 10^{-5}$$

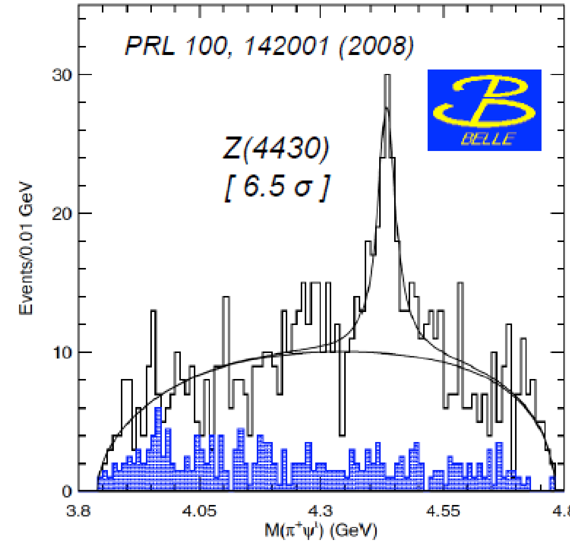
$$< 3.1 \times 10^{-5}\ (90\%\ \text{C.L.})$$

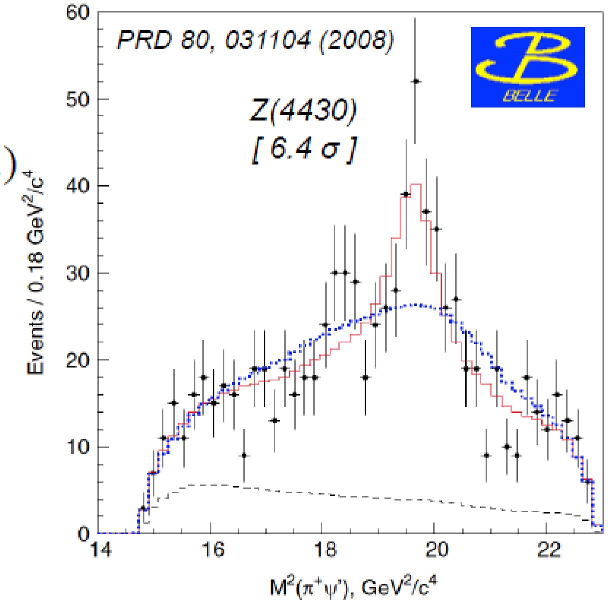
- *Belle sees no evidence for Z(4430) in $B \to J/\psi\ \pi K$*
- *Belle does a Dalitz re-analysis of $B \to \psi(2S)\ \pi K$ and confirms the Z*

$$M_{Z(4430)} = (4443^{+15}_{-12}\ {}^{+19}_{-13})\ \text{MeV}$$

$$\Gamma_{Z(4430)} = (107\ {}^{+86}_{-43}\ {}^{+74}_{-56})\ \text{MeV}$$

$$B(B^0 \to K^{\mp} Z^{\pm}) \times B(Z^{\pm} \to \psi' \pi^{\pm}) = (3.2^{+1.8}_{-0.9}\ {}^{+5.3}_{-1.6}) \times 10^{-5}$$





•The theoretical explanations for X(4430)

Rosner	S-wave threshold effect of D1(2420)-D*(2010)
(Meng, Chao), Ding	D1(2420)D*(2010) molecule
(Maiania, Polosa, Riquerd) and (Gershtein, Likhoded, Pronko)	Tetraquark state **Phys.Rev. D89 (2014) 11, 114010**
Cheuanga, Keung, Yuan	Bottom analog of *Z*(4430) assuming it is a tetraquark bound state
Lee, Mihara, Navarra, Nielsen	QSR D1(2420)D*(2010)
Bugg	Cusp effect
(Braatten, Lu)	Studying the Line shape of *Z*(4430)
Li, Lv, Wang	Partners of Z(4430) and Productions in B Decays
Qiao	
Liu, Zhao, Close	The photoproduction of Z(4430)

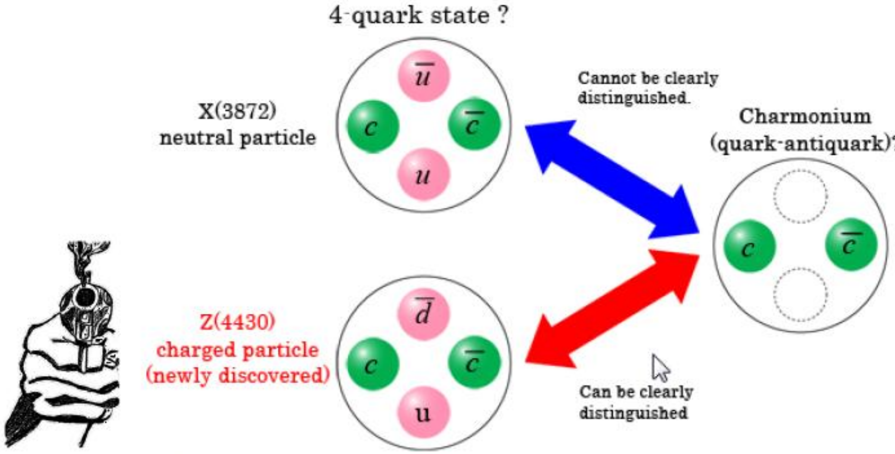
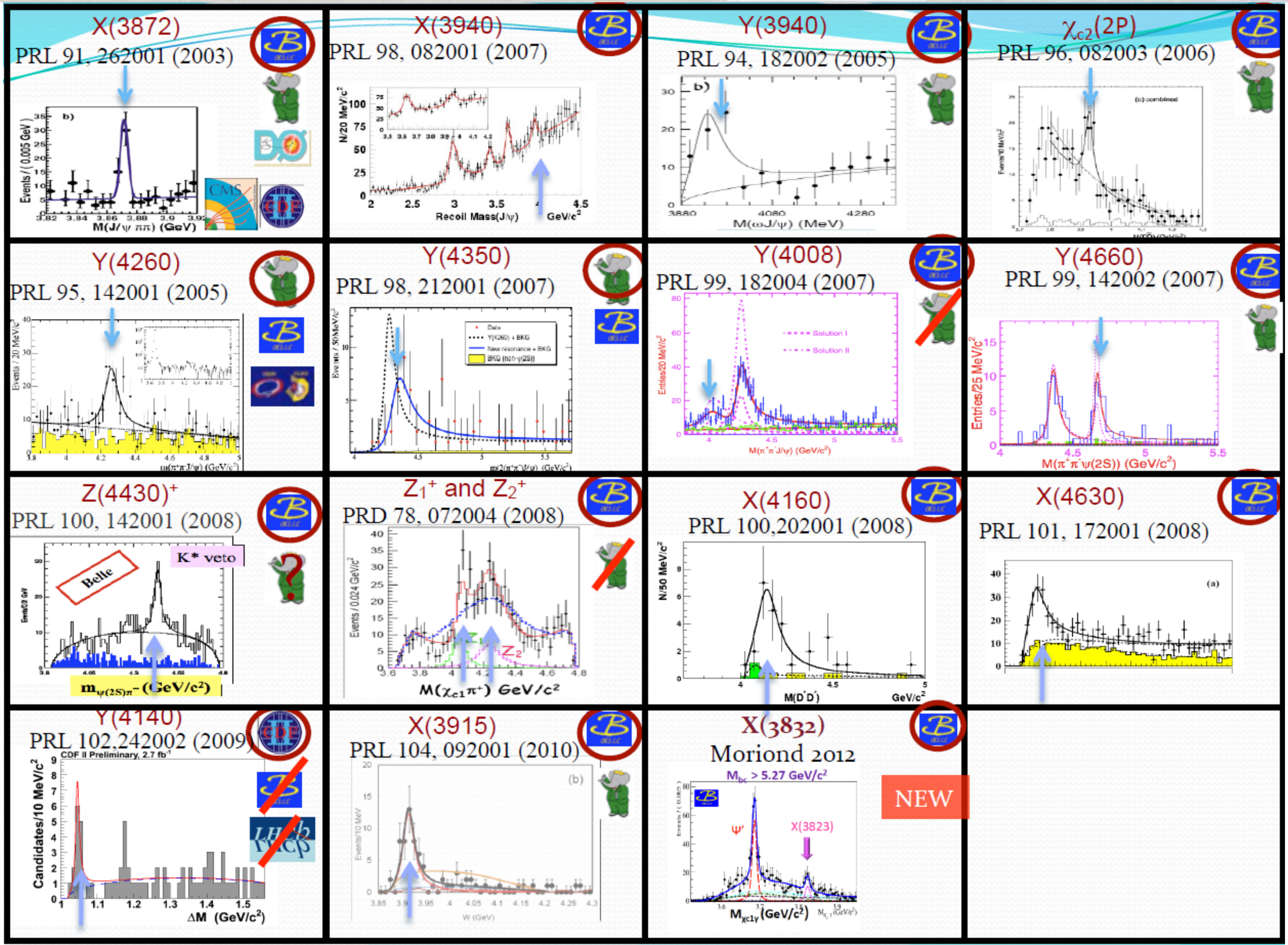


Figure 3: The X(3872) particle, which is electrically neutral, cannot be clearly distinguished from an unusual charmonium meson. On the other hand, the newly found Z(4430), which is electrically charged, can be clearly distinguished from all charmonium mesons.


X(3872)
PRL 91, 262001 (2003)
X(3940)
PRL 98, 082001 (2007)
Y(3940)
PRL 94, 182002 (2005)
χc2(2P)
PRL 96, 082003 (2006)
Y(4260)
PRL 95, 142001 (2005)
Y(4350)
PRL 98, 212001 (2007)
Y(4008)
PRL 99, 182004 (2007)
Y(4660)
PRL 99, 142002 (2007)
Z(4430)+
PRL 100, 142001 (2008)
K* veto
Belle
Z1+ and Z2+
PRD 78, 072004 (2008)
X(4160)
PRL 100,202001 (2008)
X(4630)
PRL 101, 172001 (2008)
Y(4140)
PRL 102,242002 (2009)
CDF II Preliminary, 2.7 fb-1
X(3915)
PRL 104, 092001 (2010)
X(3832)
Moriond 2012
Mbc > 5.27 GeV/c2
ψ'
X(3823)
NEW

Bottomonium-like

X(10610) & X(10650)

Belle discovered two charged bottomonium-like resonances: PRL108,122001(2011)

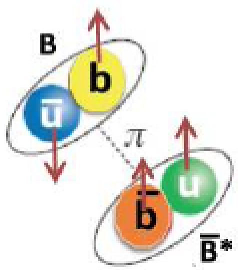
Zb(10610) and Zb(10650)

Z(10610)

M=10607.2±2.0 MeV

Γ=18.4±2.4 MeV

$\mathbf{M_B + M_{B^*} = 10604.5 \pm 0.6\ MeV}$



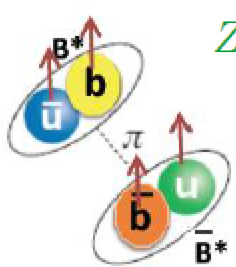
$Z_b^{\pm}(10610) \to \Upsilon(nS)\,\pi^{\pm}\ ,\quad Z_b^{\pm}(10610) \to h_b(kP)\,\pi^{\pm}$

Z(10650)

M=10652.2±1.5 MeV

Γ=11.5±2.2 MeV

$\mathbf{M_{B^*} + M_{B^*} = 10650.2 \pm 1.0\ MeV}$



$Z_b^{\pm}(10650) \to \Upsilon(nS)\,\pi^{\pm}\ ,\quad Z_b^{\pm}(10650) \to h_b(kP)\,\pi^{\pm}$

Alternative explanations of the data exist that are based on less exotic quark-based interactions?

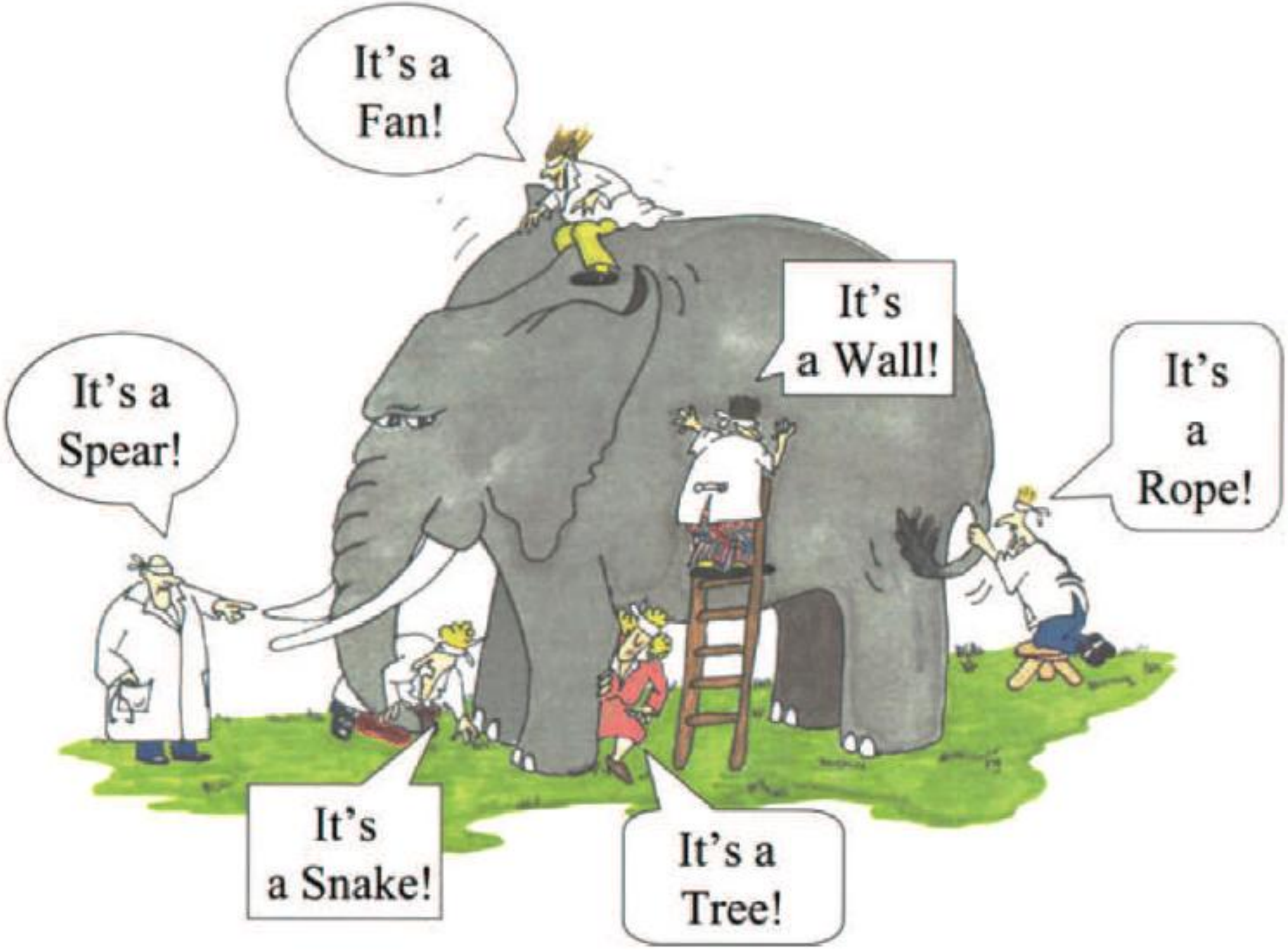
Kinematics effect?

Final state interactions?

Threshold effect?

…

The study of exotics:



Discussions

- Are these observations real resonances?
- Where is the four-quark state?
- QCD sum rules suitable for study of multi-quark states?
- Reasonable way to study multi-quark states?

Thanks!