Charmonium(-like) Spectroscopy with BESIII

Precision Physics of “Simple” Subatomic Systems

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on behalf of the BESIII Collaboration
The Standard Model

Subatomic Systems and QCD

Leptons

Quarks

Force Carriers

+Higgs
Subatomic Systems and QCD

The Standard Model

\[ \mathcal{L}_{\text{QCD}} = \sum q \left( i \gamma_\mu D_\mu - m_q \right) q - \frac{1}{4} G_{\mu \nu}^\mu G_{\mu \nu} \]

Quarks and **gluons** carry **color** charge

QCD – Quantum Chromo Dynamics

Greenberg, Han, Nambu, …
Subatomic Systems and QCD

The Standard Model

Self-interaction of force carriers!

Color confinement

+Higgs
Charmonium - the “positronium” of QCD

S = S₁ + S₂
J = L + S
P = (-1)^(L+1)
C = (-1)^(L+S)

+radial excitations
Charmonium - the "positronium" of QCD

Potential models: 

\[ V^{(c\bar{c})}(r) = -\frac{4\alpha_s}{3r} + br + \frac{32\pi\alpha_s}{9m_c^2} \delta(r) \hat{S} \cdot \hat{S} \]

(Coulomb + Confinement + Contact)

\[ V_{\text{spin-dep}} = \frac{1}{m_c^2} \left[ \frac{2\alpha_s}{r^3} - \frac{b}{2r} \right] \hat{L} \cdot \hat{S} + \frac{4\alpha_s}{r^3} T \]

(Spin-Orbit + Tensor)

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Example from Barnes, Godfrey, Swanson:

- \( \psi' \)
- \( \psi'' \)
- \( \eta_c(2^1S_0) \)
- \( \psi'(2^3S_1) \)
- \( \psi(1^3D_1) \)
- \( \chi_c(1^3P_1) \)
- \( \chi_c(1^3P_0) \)
- \( \chi_c(1^3P_2) \)
- \( \eta_c(1^1P_1) \)
- \( \eta_c(1^1S_0) \)
- \( \eta_c(1^3S_0) \)

- established \( c\bar{c} \) states
- Open charm threshold

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**BRD72, 054026 (2005)**
Charmonium - the “positronium” of QCD

- Symmetric $e^+e^-$ collider:
  - $\sqrt{s} = 2.0 - 4.6$ GeV
- Design luminosity:
  - $1 \times 10^{33} \text{ cm}^{-2}\text{s}^{-1}$ (at $\psi(3770)$, achieved in 04/2016)
- Data taking started in 2009
A few “2012 highlights” of BESIII
A few "2012 highlights" of BESIII

- DD and charm physics
- ψ and charmonium physics
- Spectroscopy of light hadrons

Resolved long-standing discrepancy between experiments and Lattice QCD

PRL 108, 222002 (2012)
Introduction to the BESIII Experiment

phenomenology and theory

We assume that all the sources of systematic uncertainty were found between the default reference in the total branching ratio, and from uncertainty in the choice of the background. A few "2012 highlights" of BESIII Experiment.

now discovered in radiative transitions!

resolved long-standing discrepancy between experiments and Lattice QCD
phenomenology

and theory

Introduction to the BESIII Experiment

TABLE I: The absolute systematic uncertainties in the 

(3686) events in our data sample [17].

- Particle identification - 1.3
- Fitting range 0.1 0.4 1.3
- Damping function 0.7 4.0 19.6

We assume that all the sources of systematic uncertain-

ness contribute to the uncertainty on the mass of the

ψ(2S) now discovered in radiative transitions!

~150 keV mass accuracy & 1st lifetime determination

resolved long-standing discrepancy between experiments and Lattice QCD
**A few “2012 highlights” of BESIII**

- **~150 keV mass accuracy & 1st lifetime determination**
- **now discovered in radiative transitions!**
- **resolved long-standing discrepancy between experiments and Lattice QCD**

... and many more!

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**[PRL 109, 042003 (2012)]**

**[PRL 108, 222002 (2012)]

**[PRL 104, 132002 (2010), PRD 86, 092009 (2012)]**
Charmonium-like particles - terra incognita

2013

Discovery

Open charm threshold

Precision

“XYZ” Puzzle

established cc states
predicted, undiscovered
neutral XYZ mesons
charged XYZ mesons

$\eta_c(1^{1S}_0)$
$\psi(1^{2S}_1)$
$\psi'(2^{3S}_1)$
$\eta_c(2^{1P}_0)$
$\eta_c(1^{1P}_1)$
$\chi_{c1}(1^{3P}_0)$
$\chi_{c0}(1^{3P}_0)$
$\chi_{c1}(2^{3P}_0)$
$\chi_{c0}(2^{3P}_0)$
$\chi_{c0}(3^{3P}_2)$
$\psi(4^{3S}_1)$
$\psi'(1^{3D}_1)$
$X(4160)$
$Y(4260)$
$Y(4360)$
$X(3940)$
$Z(3900)^+$
$X(3915)$
$X(3872)$
Charmonium-like particles - terra incognita

New XYZ results from BESIII

Myroslav Kavatsyuk
KVI – Center for Advanced Radiation Technology,
University of Groningen
For the BESIII collaboration
Charmonium-like particles - terra incognita

New XYZ results from BESIII
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PRL110, 252001, 252002 (2013)
Charmonium-like particles - terra incognita

A charged and charmonium-rich state
At least 4 quarks involved
Confirmed by Belle and CLEO-c data
Many more found shortly afterwards
Charmonium-like particles - terra incognita

A charged and charmonium-rich state
At least 4 quarks involved
Confirmed by Belle and CLEO-c data
Many more found shortly afterwards

Z_c(3900): PRL110, 252001 (2013)
Z_c(4040): PRL112, 132001 (2014)
Z_c(3885): PRL112, 022001 (2014)
X(3872): PRL112, 092001 (2014)
Z_c(4020)^0: PRL113, 212002 (2014)
Z_c(3900)^0: PRL115, 112003 (2015)
Z_c(4025)^0: PRL115, 182002 (2015)
Z_c(3885)^0: PRL115, 222002 (2015)
Charmonium-like particles - terra incognita

At least 4 quarks involved
Confirmed by Belle and CLEO-c data
Many more found shortly afterwards

Multiplet(s) of new matter discovered!
Break-through! It is just the beginning…

XYZ particles: tip of the iceberg?

Internal structure?

Level scheme?

Spin-parity $J^{PC}$?

Production and decay?

What is $Z_c^{(3900)}$?

Charged → It is not a conventional $c\bar{c}$!

Tetraquark

Hadronic molecule

$\text{arXiv:1110.1333, 1303.6857}$

$\text{arXiv:1304.0345, 1304.1301}$

$\text{arXiv:1303.6608, 1304.2882, 1304.1850}$

Most popular models

Are they exotic hadrons?

Exotic means non $qq\star$ or $qqq$ structures ...

Strongly interacting clusters of hadrons: molecules

[Voloshin; Tornqvist; Close; Braaten; Swanson…]

Tetraquark mesons, Pentaquarks, ...

[Maiani,Piccinini,Polosa,Riquer …]

Hybrids

[Close, Kou&Pene, …]

Hadrocharmonium

[Voloshin]

Many exotic candidates have been identified among the so-called $XYZ$ particles.
From discovery towards precision

- XYZ region: 3.8 \sim 4.6 \text{ GeV}, integrated luminosity: \textbf{12 fb}^{-1}
- 104 energy points between 3.85 and 4.59 \text{ GeV} (R scan)
- \sim20 energy points between 2.0 and 3.1 \text{ GeV}
Spin-parity of $Z_c(3900)$, Partial Wave Analysis

$e^+ e^- \rightarrow Z_c(3900) \pm \pi^\pm$ - PWA of $/\psi\pi\pi$

- Amplitude analysis (helicity formalism)
  - $\pi\pi$-spectrum: $\sigma$, $f_0(980)$, $f_2(1270)$, $f_0(1370)$
  - $Z_c(3900)\pm$ (Flatte, $J^P = 1^+$ in nominal fit)
  - Non-resonant $/\psi\pi\pm$

- Simultaneous fit to data at 4.23 and 4.26 GeV
  - $= (3901.5 \pm 2.7 \pm 38.0) /2$
  - Consistent with the mass for $Z_c(3885)$\pm

$E^+ e^- \rightarrow J/\psi(1^{+}S_0) \rightarrow \pi^\pm$ - PWA of $/\psi\pi\pi$

- $\pi^\pm$-spectrum: $\sigma$, $f_0(980)$, $f_2(1270)$, $f_0(1370)$
  - $Z_c(3900)\pm$ (Flatte, $J^P = 1^+$ in nominal fit)
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  - Consistent with the mass for $Z_c(3885)$\pm

\[PRL 119 (2017) 072001\]
\[PRL 112, 022001 (2014) \]
\[PRD 92, 092006 (2015) \]
Spin-parity of $Z_c(3900)$, Partial Wave Analysis

- Polar angle of $Z_c$ = $\theta_{Zc}$, helicity angle of $\psi\pi\pi$
- Data favours $J^P = 1^+$ for $Z_c$ over others (>8 $\sigma$)
- Consistent with $Z(3885)^\pm$ "$D_0D^*\pm$ (single-tag, re-confirmed in double-tag analysis)
- Also BR open vs. hidden charm found in consistency:
  - [PRL 119 (2017) 072001]
  - [PRL 112, 022001 (2014)]
Spin-parity of $Z_c(3900)$, Partial Wave Analysis

Hypothesis | $\Delta(-2 \ln L)$ | $\Delta(\text{ndf})$ | Significance
---|---|---|---
$1^+$ over $0^-$ | 94.0 | 13 | 7.6$\sigma$
$1^+$ over $1^-$ | 158.3 | 13 | 10.8$\sigma$
$1^+$ over $2^-$ | 151.9 | 13 | 10.5$\sigma$
$1^+$ over $2^+$ | 96.0 | 13 | 7.7$\sigma$
The mysterious “Y” states: Y(4260, 4360)

New XYZ results from BESIII

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The mysterious “Y” states: energy scan

Two resonances & no Y(4008) needed
The mysterious “Y” states: energy scan

[PRL 118, 092002 (2017)]

\[ \text{e}^+\text{e}^- \rightarrow h_c \pi^+\pi^- \]

Dressed Cross section ( pb)

\( \tilde{s} \) (GeV)

\[ \text{e}^+\text{e}^- \rightarrow J/\psi \pi^+\pi^- \]

\( \sigma(\text{e}^+\text{e}^- \rightarrow \pi^+\pi^- \text{J}/\psi) \) ( pb)

\( \tilde{s} \) (GeV)

\[ \text{e}^+\text{e}^- \rightarrow D^0D^{*-} \pi^+ \]

BESIII Preliminary

\( \sigma_{\text{dress}} \) ( pb)

\( E_{CM} \) (GeV)

\[ \text{e}^+\text{e}^- \rightarrow \psi(2S) \pi^+\pi^- \]

Cross Section ( pb)

\( \sqrt{s} \) (GeV)

BESIII

Belle

BaBar

[PRD 96, 032004 (2017)]
The mysterious “Y” states: energy scan

Consistent observation of two resonances: Y(4220) and Y(4390)
Charmonium(-like) Spectroscopy with BESIII

Precision Physics of “Simple” Subatomic Systems
Charmonium(-like) Spectroscopy with BESIII

Precision Physics of “Simple” Subatomic Systems

Charmonium(-like) systems revealed many insights in the dynamics of the strong force...

...from the discovery of “charm” in the 70s till the recent discovery of exotic hadrons

BESIII is a leading player in the field, using $e^+e^-$ annihilation in the charmonium regime

High statistics samples have (recently) been obtained to unambiguously measure the properties of various XYZ states

...and to make new discoveries in this exciting field of hadron physics

“This could be the discovery of the century. Depending, of course, on how far down it goes.”
The BESIII Collaboration

14 countries
61 institutions
~ 450 members
The BESIII Collaboration

Thanks for listening!

14 countries
61 institutions
~ 450 members
The mysterious “Y” states: Y(4260)

For the BESIII collaboration

ψ/π⁺π⁻ using ISR at BaBar?

Some Update,

ψ/π⁺π⁻ states:

Low mass peak “Y(4008)”?

Using ISR at Belle

ψ/π⁺π⁻ peak, “Y(4008)”?

[BesIII]

From [PRL 110, 252002 (2013)]

Results

May 8, 2017

Low mass peak “Y(4008)”?

Asymmetric shape?

[Babar]

Energy scan using ISR at BaBar

[Belle]

π⁺π⁻, “Y(4008)”?

[BesIII]

έπ(4ςSn) J/ψ(4360)

έπ(3ςP₁) Z(4200) X₀(3ςP₁)

έπ(3ςP₁) Z(4090)

έπ(3ςP₁) Z(4020) Z(4000) X₀(3ςP₁)

έπ(2ςP₀)

ε(4ςSn) Y(4360)

ε(3ςP₁) Z(4250) X₀(3ςP₁)

ε(2ςP₀)

ε(2ςP₀) X₀(2ςP₀)

ε(2ςP₀) X₀(1ςP₀)

ε(1ςP₁) X₀(1ςP₀)

ε(1ςP₁) X₀(1ςP₀)

ε(0ςP₁) Z(3900) X₀(2ςP₀)

ε(0ςP₁) Z(3915) X₀(1ςP₀)

ε(0ςP₁) Z(3972) X₀(1ςP₀)

ε(0ςP₁) X₀(1ςP₀)

ε(0ςP₁) X₀(1ςP₀)

ε(0ςP₁) X₀(1ςP₀)

ε(0ςP₁) X₀(1ςP₀)

ε(0ςP₁) X₀(1ςP₀)

ε(0ςP₁) X₀(1ςP₀)

ε(0ςP₁) X₀(1ςP₀)

ε(0ςP₁) X₀(1ςP₀)

ε(0ςP₁) X₀(1ςP₀)

ε(0ςP₁) X₀(1ςP₀)

ε(0ςP₁) X₀(1ςP₀)

ε(0ςP₁) X₀(1ςP₀)

ε(0ςP₁) X₀(1ςP₀)

ε(0ςP₁) X₀(1ςP₀)

ε(0ςP₁) X₀(1ςP₀)

ε(0ςP₁) X₀(1ςP₀)
The mysterious "Y" states: Y(4360)

- \[ Y(4360) \]
- \[ \psi(4S) \]
- \[ \eta(4S) \]
- \[ \chi_c(4S) \]
- \[ \chi_c(3P) \]
- \[ \pi^+ \pi^- \]

**BaBar**

- \[ \psi(2S) \rightarrow J/\psi \pi^+ \pi^- \]
- \[ \psi(2S) \rightarrow l^+ l^- \]

**Belle**

- \[ M[\pi^+ \pi^- \psi(2S)] \] (GeV/c^2)
Probing QCD at various distance scales

Color confinement: observed particles are colorless SU(3) singlets

Heavy bag, mostly pure binding energy

Light bag of “free” quarks
The mysterious “Y” states: Y(4260, 4360)

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The mysterious “Y” states: \( Y(4260, 4360) \)

**Lattice calculations**

Hadron Spectrum Collaboration

\[ \text{JHEP 1207, 126 (2012)} \]

mass of ground state used as input