Spectroscopy of exotic states

Wolfgang Gradl

on behalf of the BESIII collaboration

Workshop on *B* physics
19th February 2015

THE LOW-ENERGY FRONTIER OF THE STANDARD MODEL

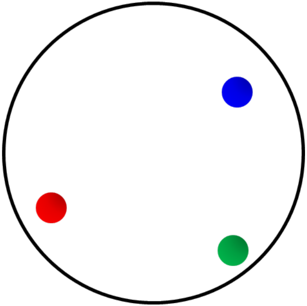
The big question

Structure and mass of proton?

Proton consists of 3 quarks

But:

- Only 2% of
  proton mass from quark masses



The big question

Structure and mass of proton?

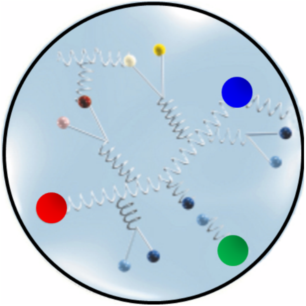
Proton consists of 3 quarks

But:

- Only 2% of
  proton mass from quark masses
- 98% from complex binding
  due to strong interaction
  not sufficiently well understood

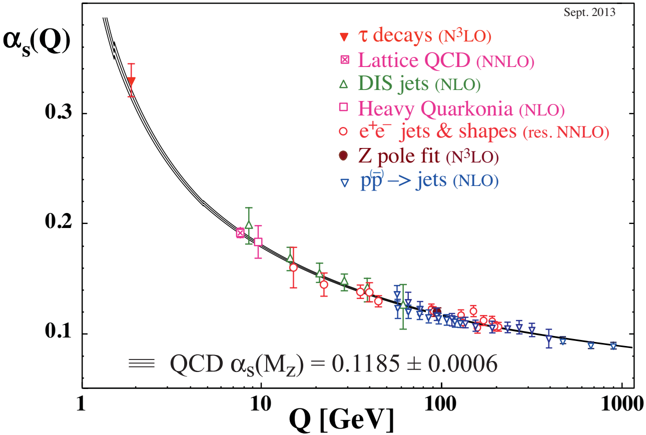
Inner structure of hadrons?

Binding force between quarks? ➠ Potential



Running coupling constant $\alpha_s(Q^2)$

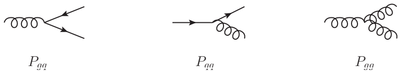
Non-abelian nature of QCD gluon self-coupling
makes α_s large at small energies $\equiv$ large distances $\Rightarrow$ confinement

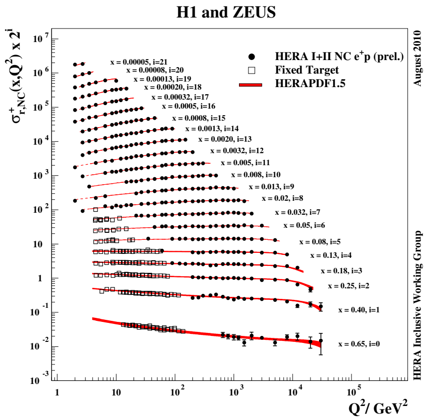


Asymptotic freedom

$\alpha_s(Q^2)$ becomes smaller at larger scales Q^2
(Asymptotic freedom; Gross, Politzer & Wilczek Nobel Prize 2004)

Together with structure of qqg, ggg vertices
predicted from theory:





Predicts evolution of quark content
inside proton

Excellent agreement between
QCD prediction
and HERA measurements
of proton structure functions

➡ perturbative QCD well understood

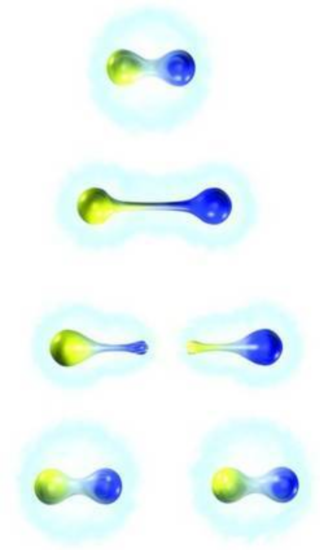
Non-perturbative end: confinement and bound states

Strong interaction at low energy scale
responsible for confinement

Trying to ‘pull apart’ a pair of quarks:
linear increase of force …

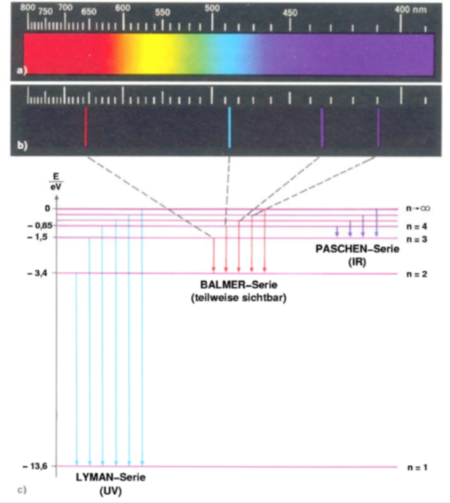
…until energy stored in string is enough to create
new $q\bar{q}$ pair: fragmentation

Mass of nucleons (proton, neutron):
only ≈ 2% from Higgs mechanism
(current quark masses)
rest from binding of quarks into nucleon



Obtaining information about bound systems

Analogy: Atomic spectroscopy



Information on bound systems by observing

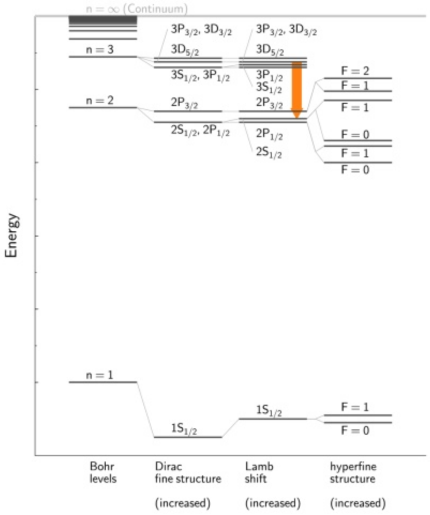
- Energy levels
- Transitions between levels (selection rules ...)

Discovery of discrete spectral lines
➡ Discrete energy levels in atoms (Bohr)

$$E_{nm} = R\left(\frac{1}{n^2} - \frac{1}{m^2}\right)$$

Obtaining information about bound systems

Analogy: Atomic spectroscopy



from backreaction.org

Information on bound systems by observing

- Energy levels
- Transitions between levels (selection rules …)

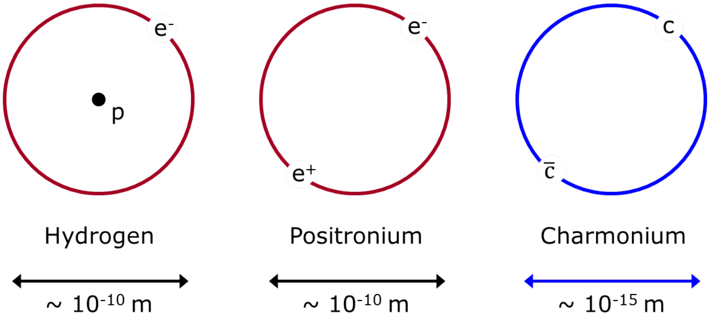
Discovery of discrete spectral lines
➡ Discrete energy levels in atoms (Bohr)

$$E_{nm} = R\left(\frac{1}{n^2} - \frac{1}{m^2}\right)$$

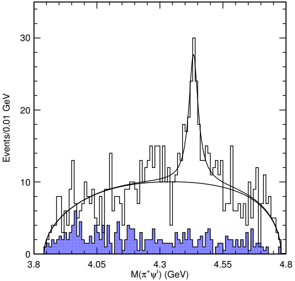
Precision measurements:

- ➡ Fine structure (*L*-*S* coupling, relativistic corrections)
- ➡ Lamb shift (vacuum polarisation)
- ➡ Hyperfine structure (*S*-*S*)

Hadron spectroscopy: quarkonia



Observables in hadron spectroscopy

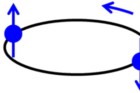


Observe states in their decays $A \to B + C(+\cdots)$
e.g. as peaks in mass spectrum (often, PWA needed)

Classify states according to

- Mass m
- Width $\Gamma \propto \tau^{-1}$ (τ: lifetime)
- Quantum numbers J^{PC}

S total spin ($\sim$ sum of quark spins)
L orbital angular momentum
J total angular momentum, $J = |L - S|, \cdots, L + S$



spectroscopic notation $n^{2S+1}L_J$
e.g. J/ψ: 1^3S_1 (ground state, spin triplet, S wave, vector particle)

Observables in hadron spectroscopy

Further, multiplicative, quantum numbers:
behaviour under space inversion P and charge conjugation C

For 'ordinary' mesons made of $q\bar{q}$:

- For elementary fermions: $P(f) = -P(\bar{f})$
- $P = (-1)^{L+1}$
- $C = (-1)^{L+S}$

E.g. J/ψ (1^3S_1): $L = 0, S = 1 \quad \Rightarrow \quad J^{PC} = 1^{--}$ (like the photon)

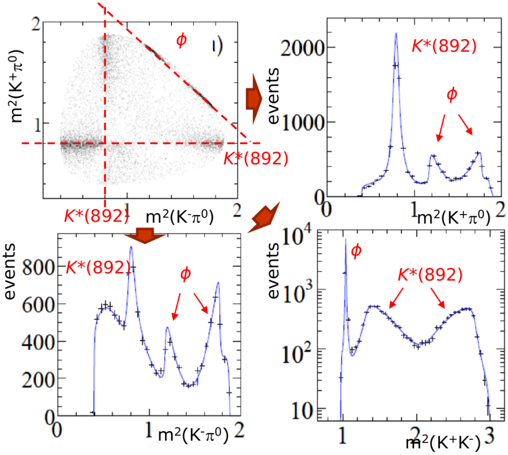
In a *non-relativistic* approximation:

- ▷ Natural quantum numbers: accessible for $q\bar{q}$
  $J^{PC} = 0^{++}, 0^{-+}, 1^{--}, 1^{++}, 1^{+-}, 2^{++} \ldots$
- ▷ Exotic quantum numbers: cannot be made from $q\bar{q}$
  $J^{PC} = 0^{+-}, 1^{-+}, 2^{+-}, \ldots$

Kinematic reflections

In multi-body decays, resonance in one subchannel can produce peaks in other mass projections (reflections)

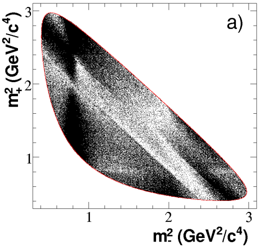
For example $D^0 \to K^+K^-\pi^0$: relatively easy to understand



Kinematic reflections

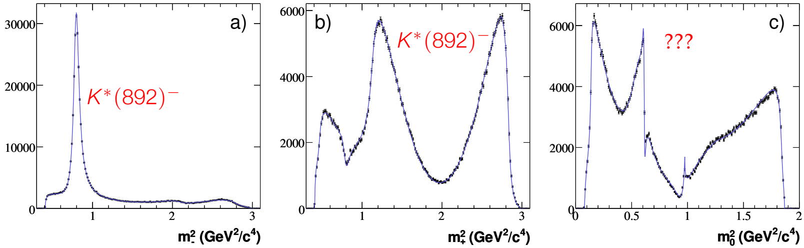
But can be much less obvious

Example: high-statistics analysis of decay $D^0 \to K^0_S \pi^+ \pi^-$ BABAR, PRD78,034023 (2008)



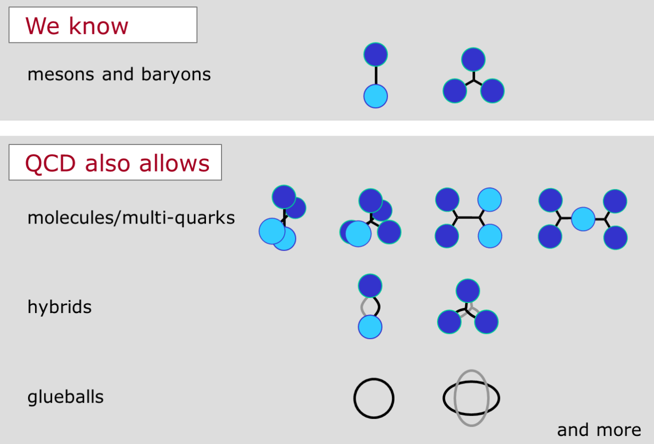
$$\mathcal{A}_D(m^2_-, m^2_+) = \sum_r a_r e^{i\phi_r} \mathcal{A}_r(m^2_-, m^2_+) + a_{\mathrm{NR}} e^{i\phi_{\mathrm{NR}}}$$

Using 10 resonant amplitudes



QCD bound systems

States found in nature: colour-neutral combinations



Totalitarian principle of quantum mechanics:

Everything not forbidden is compulsory

Multi-quark states: seen on page 1 of the quark model

Volume 8, number 3 PHYSICS LETTERS 1 February 1964

A SCHEMATIC MODEL OF BARYONS AND MESONS *

M. GELL-MANN
California Institute of Technology, Pasadena, California

Received 4 January 1964

If we assume that the strong interactions of baryons and mesons are correctly described in terms of the broken "eightfold way" [1-3], we are tempted to look for some fundamental explanation of the situation. A highly promised approach is the purely dynamical "bootstrap" model for all the strongly interacting particles within which one may try to derive isotopic spin and strangeness conservation and broken eightfold symmetry from self-consistency alone [4]. Of course, with only strong interactions, the orientation of the asymmetry in the unitary space cannot be specified; one hopes that in some way the selection of specific components of the F-spin by electromagnetism and the weak interactions determines the choice of isotopic spin and hypercharge directions.

Even if we consider the scattering amplitudes of strongly interacting particles on the mass shell only and treat the matrix elements of the weak, electromagnetic, and gravitational interactions by means of dispersion theory, there are still meaningful and important questions regarding the algebraic proper-

ber $n_t - n_{\bar{t}}$ would be zero for all known baryons and mesons. The most interesting example of such a model is one in which the triplet has spin $\frac{1}{2}$ and $z = -1$, so that the four particles d^-, s^-, u^0 and b^0 exhibit a parallel with the leptons.

A simpler and more elegant scheme can be constructed if we allow non-integral values for the charges. We can dispense entirely with the basic baryon b if we assign to the triplet t the following properties: spin $\frac{1}{2}$, $z = -\frac{1}{3}$, and baryon number $\frac{1}{3}$. We then refer to the members $u^{\frac{2}{3}}$, $d^{-\frac{1}{3}}$, and $s^{-\frac{1}{3}}$ of the triplet as "quarks" [6] q and the members of the anti-triplet as anti-quarks $\bar{q}$. Baryons can now be constructed from quarks by using the combinations $(q\,q\,q)$, $(q\,q\,q\,q\,\bar{q})$, etc., while mesons are made out of $(q\,\bar{q})$, $(q\,q\,\bar{q}\,\bar{q})$, etc. It is assuming that the lowest baryon configuration $(q\,q\,q)$ gives just the representations **1**, **8**, and **10** that have been observed, while the lowest meson configuration $(q\,\bar{q})$ similarly gives just **1** and **8**.

A formal mathematical model based on field theory can be built up for the quarks exactly as for

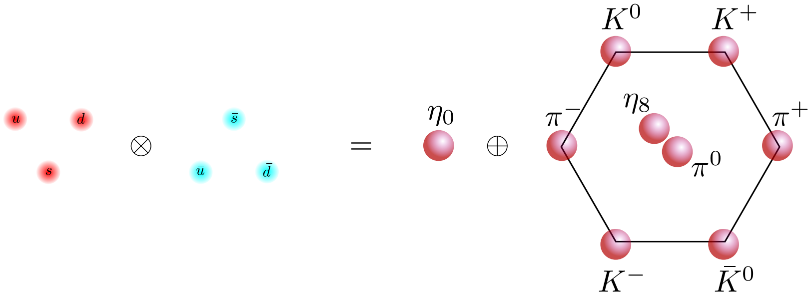
JG|U

‘Old’ Spectroscopy: $q\bar{q}$ states

Use 3 light flavours u, d, s;
approximate symmetry $SU(3)_F$ (the original $SU(3)$ of the quark model!)

Mesons = quark triplet ⊕ antiquark triplet

$$3 \otimes \bar{3} = 1 \oplus 8$$



QCD diquarks

PHYSICAL REVIEW D VOLUME 15, NUMBER 1 1 JANUARY 1977

Multiquark hadrons. I. Phenomenology of $Q^2\bar{Q}^2$ mesons*

R. J. Jaffe†

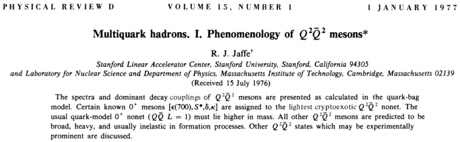
Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305
and Laboratory for Nuclear Science and Department of Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139

(Received 15 July 1976)

The spectra and dominant decay couplings of $Q^2\bar{Q}^2$ mesons are presented as calculated in the quark-bag model. Certain known 0^+ mesons [$\epsilon(700), S^*, \delta, \kappa$] are assigned to the lightest cryptoexotic $Q^2\bar{Q}^2$ nonet. The usual quark-model 0^+ nonet ($Q\bar{Q}$ $L=1$) must lie higher in mass. All other $Q^2\bar{Q}^2$ mesons are predicted to be broad, heavy, and usually inelastic in formation processes. Other $Q^2\bar{Q}^2$ states which may be experimentally prominent are discussed.

JG|U

QCD diquarks


PHYSICAL REVIEW D VOLUME 15, NUMBER 1 1 JANUARY 1977

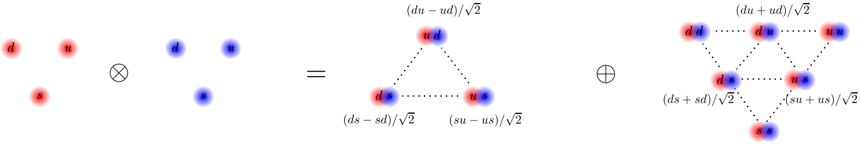
Multiquark hadrons. I. Phenomenology of $Q^2\bar{Q}^2$ mesons*

R. J. Jaffe†

Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305
and Laboratory for Nuclear Science and Department of Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139

(Received 15 July 1976)

The spectra and dominant decay couplings of $Q^2\bar{Q}^2$ mesons are presented as calculated in the quark-bag model. Certain known 0^+ mesons [$\epsilon(700), S^*, \delta, \kappa$] are assigned to the lightest cryptoexotic $Q^2\bar{Q}^2$ nonet. The usual quark-model 0^+ nonet ($Q\bar{Q}$ $L=1$) must lie higher in mass. All other $Q^2\bar{Q}^2$ mesons are predicted to be broad, heavy, and usually inelastic in formation processes. Other $Q^2\bar{Q}^2$ states which may be experimentally prominent are discussed.



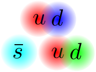
$$3 \otimes 3 = \bar{3} \oplus 6$$

anti-symmetric, anti-green, anti-triplet $\oplus$ symmetric sextet

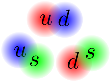
- ▷ colour force between quarks in anti-triplet attractive: bound?
- ▷ anti-triplets carry colour: can combine with other quark or antitriplet

Multiquark states from QCD diquarks

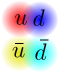
have a new (anti-)triplet of coloured objects: combine them into colour-neutral objects?



pentaquark



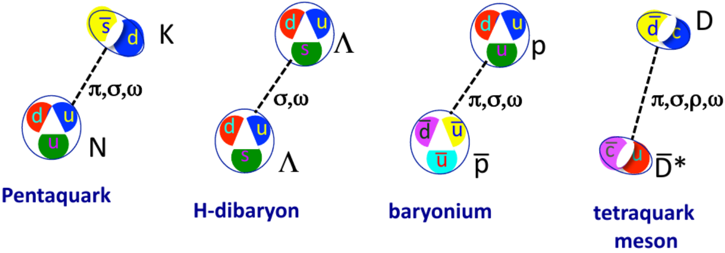
H-dibaryon



tetraquark

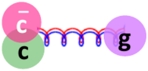
‘exotic hadrons’ loved by particle theorists

Multiquark states from ‘molecules’



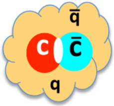
…loved by nuclear theorists

Other exotic, non-$q\bar{q}$ states

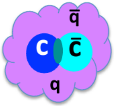


QCD hybrid

Glueball

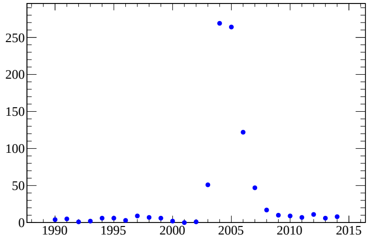


hadrocharmonium

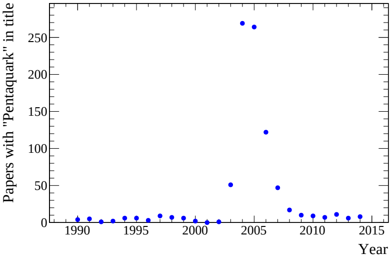


adjoint charmonium

Quiz: what's shown on this graph?



The story of the pentaquarks



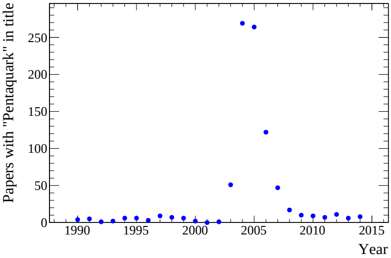
Pentaquark: first claimed to be seen in $\gamma n \to K^+ K^- n$: $\Theta^+ \to K^+ n$

baryon with anti-strangeness ($uudd\bar{s}$), with mass close to some predictions!

About 50 experimental papers, with conflicting results:

- observation / non-observation
- incompatible masses
- different states? (Θ_c)
- …

The story of the pentaquarks



Pentaquark: first claimed to be seen in $\gamma n \to K^+ K^- n$: $\Theta^+ \to K^+ n$

baryon with anti-strangeness ($uudd\bar{s}$), with mass close to some predictions!

About 50 experimental papers, with conflicting results:

- observation / non-observation
- incompatible masses
- different states? (Θ_c)
- …

Today's consensus:

> *There are two or three recent experiments that find weak evidence for signals near the nominal masses, but there is simply no point in tabulating them in view of the overwhelming evidence that the claimed pentaquarks do not exist. […] The whole story—the discoveries themselves, the tidal wave of papers by theorists and phenomenologists that followed, and the eventual "undiscovery"—is a curious episode in the history of science.* PDG 2010

A word of caution

There have been a number of incidents in the past where bold claims have not proven true

- ‘multiquark fiasco’ in the 1980s: overoptimistic models, with low-statistics experiments, led to overoptimistic claims of discoveries. None of these survived!
- pentaquark saga mid-2000s: see above.

The absence of exotics is one of the most obvious features of QCD.

R. Jaffe, hep-ph/0409065

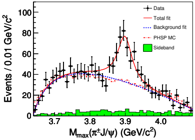
The story of the pentaquark shows how poorly we understand QCD.

attributed to F. Wilczek, see hep-ph/0510365

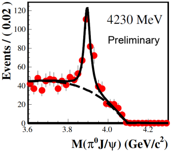
So, some caution with interpretations might be advisable …

Nevertheless …

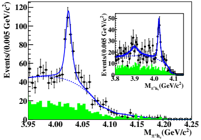
in the past few years, compelling evidence for states beyond simple $q\bar{q}$!



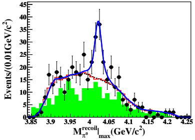
$e^+e^- \to \pi^-\pi^+J/\psi$



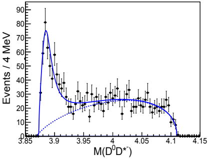
$e^+e^- \to \pi^0\pi^0J/\psi$



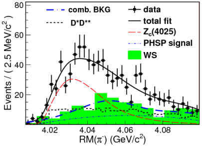
$e^+e^- \to \pi^-\pi^+h_c$



$e^+e^- \to \pi^0\pi^0h_c$



$e^+e^- \to \pi^-(D\bar{D}^*)^+$



$e^+e^- \to \pi^-(D^*\bar{D}^*)^+$

The hunt for new states

Search for non-qqq or non-$q\bar{q}$ hadrons:
some states with ‘exotic’ quantum numbers seen,
e.g. $\pi_1(1600)$, exotic 1^{-+} P-wave state (COMPASS, CLEO, …)

light hadron spectrum very complicated: broad, overlapping states

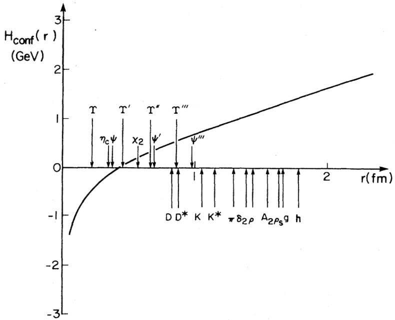
mixing of states with same quantum numbers important

Model dependence of interpretation?

A better hunting ground?

Charmonium and charmonium-like states useful for this search:

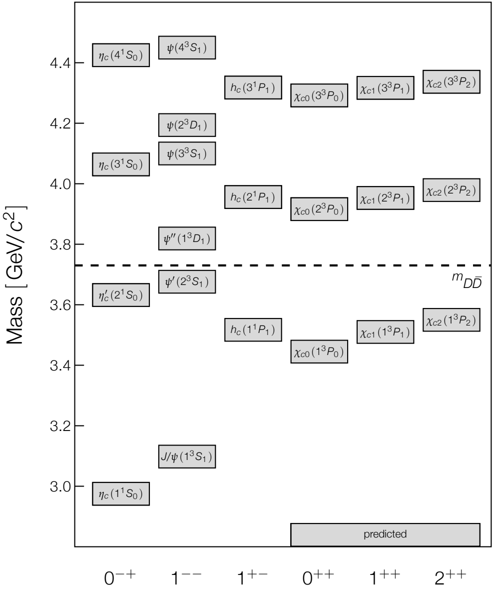
- $m_c \approx 1.3\,\text{GeV}$: probe transition region from perturbative to non-perturbative regime
- separation between states larger
- states presumably less mixed than in light quark sector
- can be produced copiously in e^+e^- collisions
- Exciting possibility to find exotics among new states



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

Charmonium Spectroscopy

Charmonium spectrum



Charmonium: $c\bar{c}$

Example potential

$$V_0^{c\bar{c}} = -\frac{4}{3}\frac{\alpha_s}{r} + br + \frac{32\pi\alpha_s}{9m_c^2}\delta(r)\vec{S}_c\vec{S}_{\bar{c}}$$

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

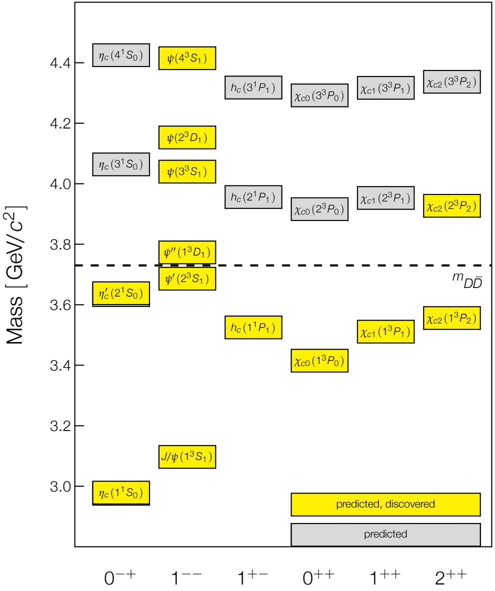
+ relativistic corrections!

Godfrey & Isgur, PRD 32, 189 (1985);
Barnes, Godfrey & Swanson,
PRD 72, 054026 (2005)

Use well-established states to fix parameters, then predict remainder of spectrum, and transitions

➡ Remarkably good description above $D\bar{D}$ threshold: some mass shifts

Charmonium spectrum



Charmonium: $c\bar{c}$

Example potential

$$V_0^{c\bar{c}} = -\frac{4}{3}\frac{\alpha_s}{r} + br + \frac{32\pi\alpha_s}{9m_c^2}\delta(r)\vec{S}_c\vec{S}_{\bar{c}}$$

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

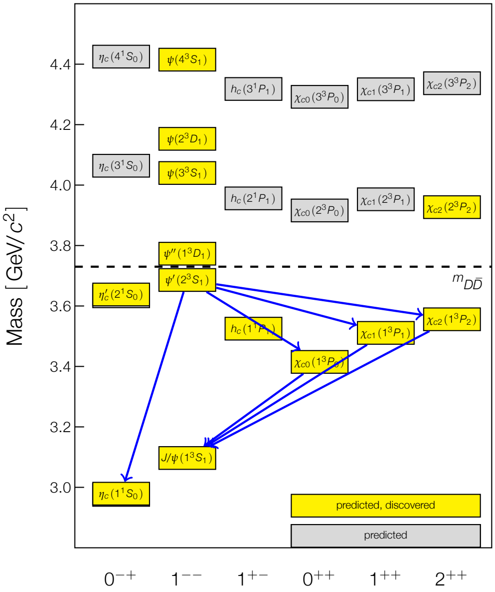
+ relativistic corrections!

Godfrey & Isgur, PRD 32, 189 (1985);
Barnes, Godfrey & Swanson,
PRD 72, 054026 (2005)

Use well-established states to fix parameters, then predict remainder of spectrum, and transitions

➡ Remarkably good description above $D\bar{D}$ threshold: some mass shifts

Charmonium spectrum



Charmonium: $c\bar{c}$

Example potential

$$V_0^{c\bar{c}} = -\frac{4}{3}\frac{\alpha_s}{r} + br + \frac{32\pi\alpha_s}{9m_c^2}\delta(r)\vec{S}_c\vec{S}_{\bar{c}}$$

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

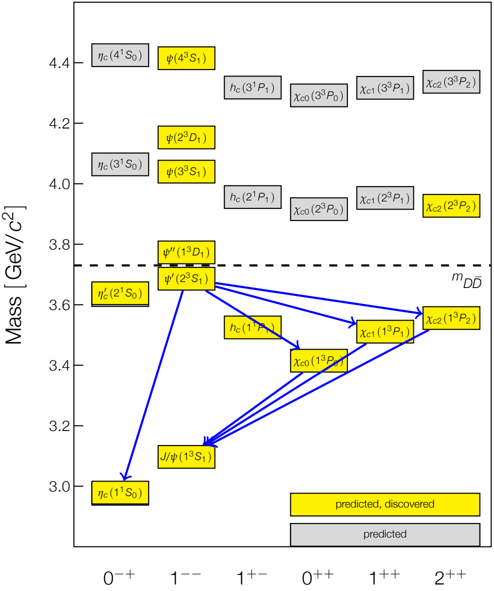
+ relativistic corrections!

Godfrey & Isgur, PRD 32, 189 (1985);
Barnes, Godfrey & Swanson, PRD 72, 054026 (2005)

Use well-established states to fix parameters, then predict remainder of spectrum, and transitions

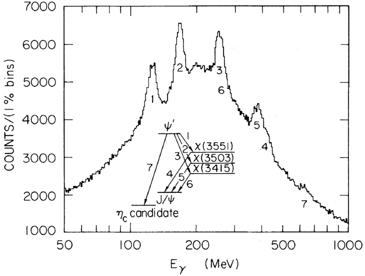
➡ Remarkably good description above $D\bar{D}$ threshold: some mass shifts

Charmonium spectrum



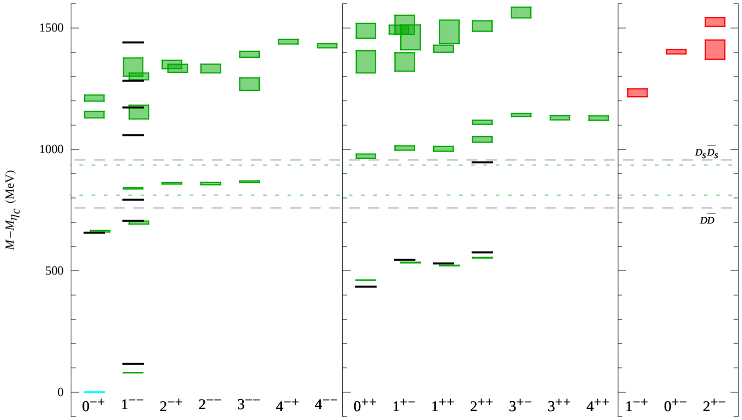
Charmonium: $c\bar{c}$

Crystal Ball at SLAC
discovery of η_c



PRL 45, 1150 (1980)

Lattice QCD?

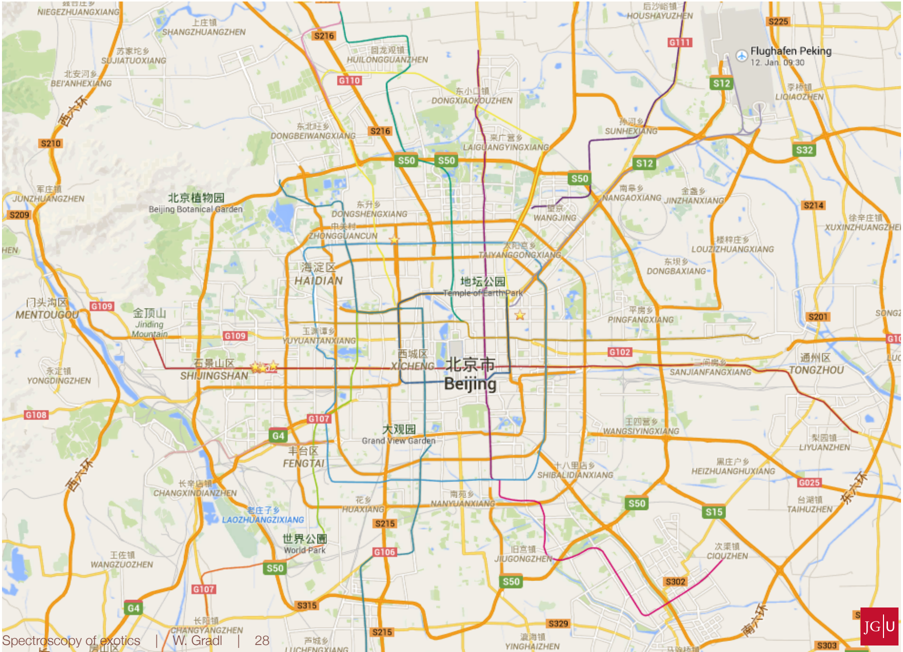


Hadron Spectrum Collab., JHEP 1207, 126 (2012)

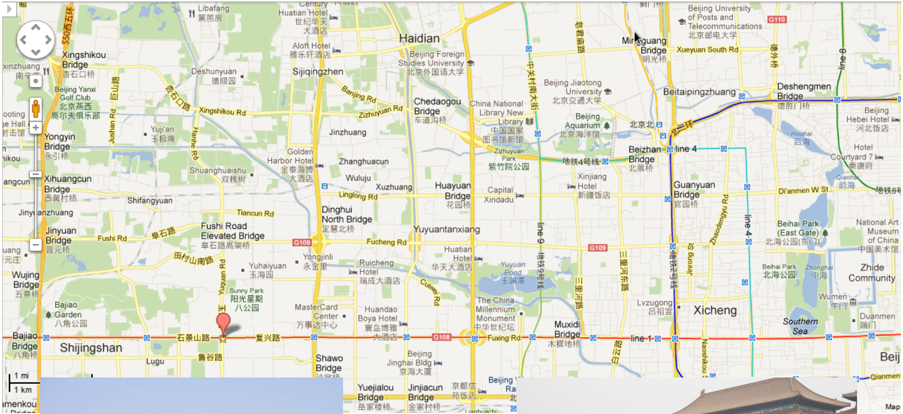
Very promising, but not quite there yet (pion mass too large, …)

BESIII: a τ-charm factory

BEPCII and BESIII

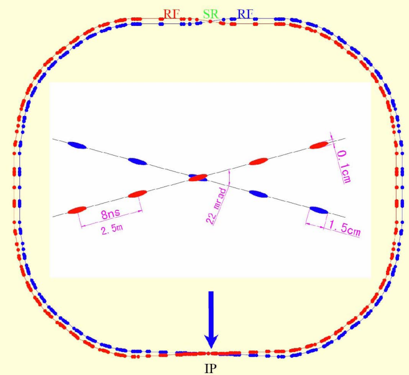


BEPCII and BESIII



BEPCII and BESIII

BEPCII storage rings: a τ-charm factory



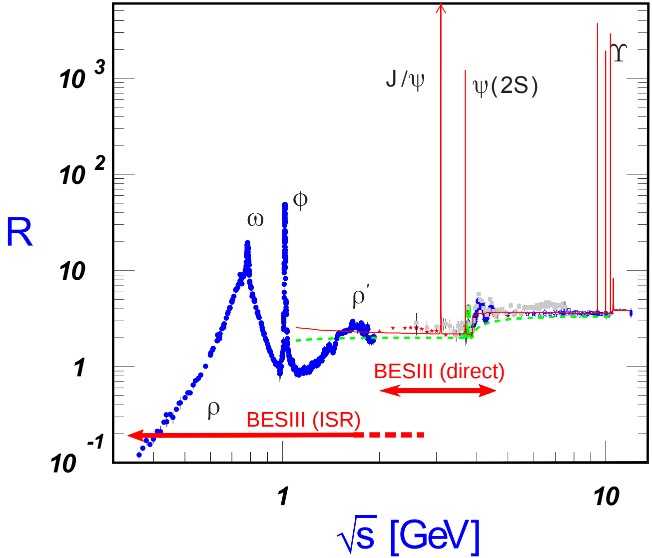
Upgrade of BEPC (started 2004,
first collisions July 2008)

Beam energy	**$1 \cdots 2.3$ GeV**
Optimum energy	**1.89 GeV**
Single beam current	**0.91 A**
Crossing angle	**± 11 mrad**

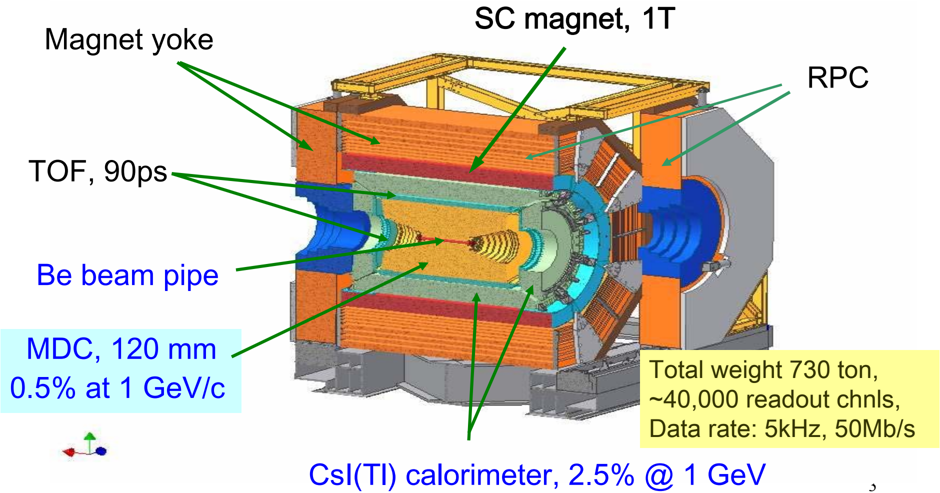
Design luminosity	**$10^{33}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$**
Achieved	**$8 \times 10^{32}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$**

Beam energy measurement:
Laser Compton backscattering
$\Delta E/E \approx 5 \times 10^{-5}$
(≈ 50 keV at τ threshhold)

A τ-charm factory



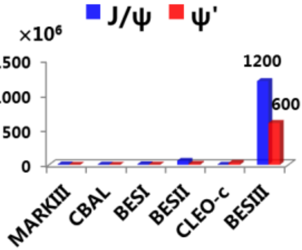
BESIII detector

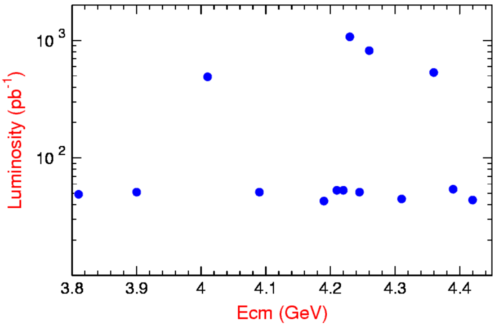


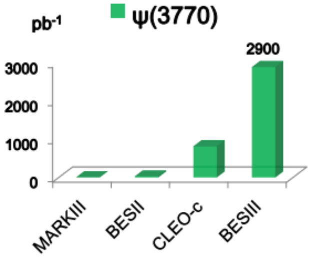
Completely new detector

Comparable performance to CLEO-c, + muon ID

BESIII data sets



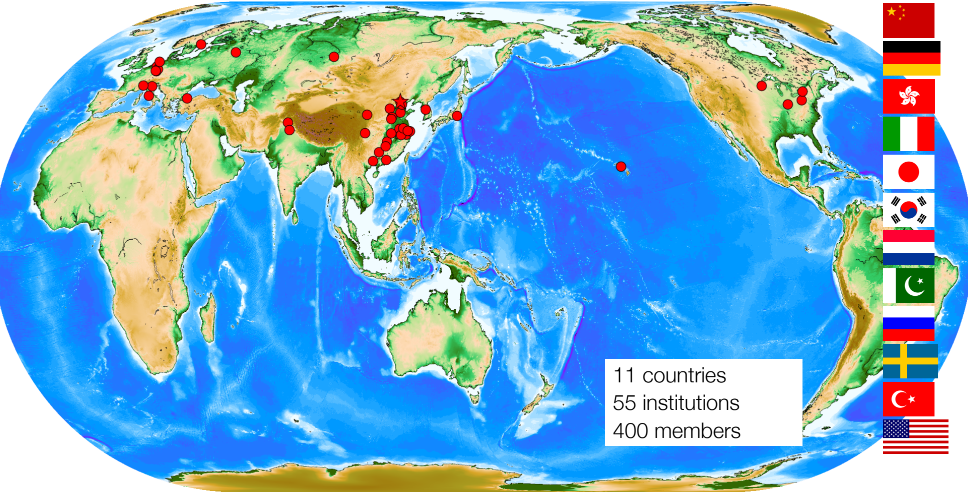




$+$ 104 energy points between 3.85 and 4.59 GeV
$+\sim$ 20 energy points between 2.0 and 3.1 GeV (*ongoing*)

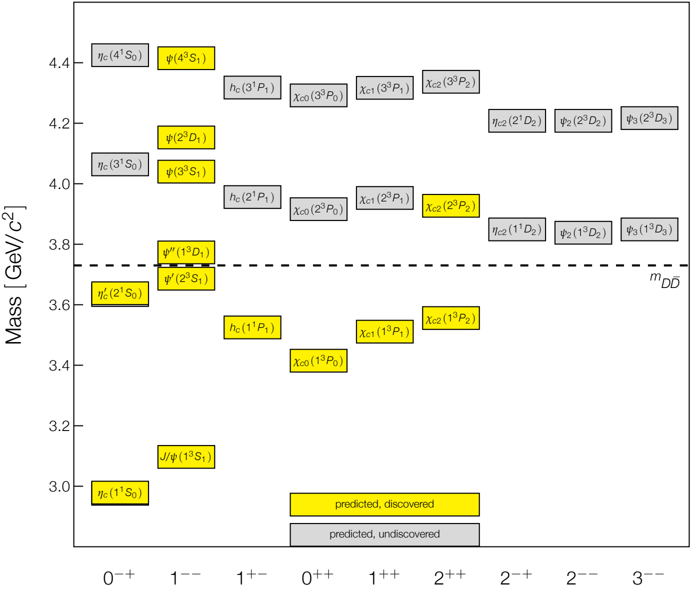
Direct production of 1^{--} states studied with world's largest scan dataset

The BESIII Collaboration



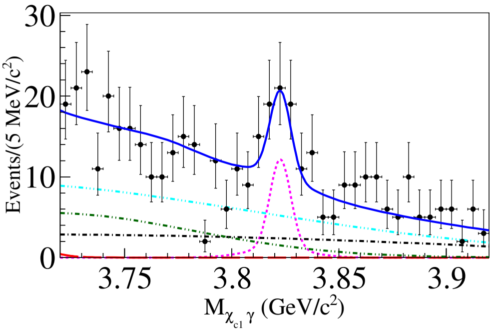

Conventional $c\bar{c}$

Higher charmonium states



The $X(3823)$ at Belle

PRL **111**, 032001 (2013)



using $772 \times 10^6 B\bar{B}$

$B \to K\gamma\chi_{c1}$
simultaneous fit to B^+ and B^0

3.8σ evidence

$$M = 3832.1 \pm 1.8 \pm 0.7\,\mathrm{MeV}$$

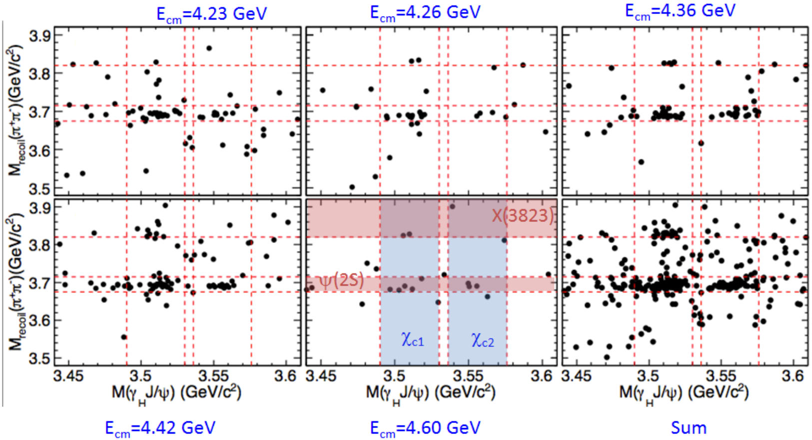
Mass (and width) compatible with $\psi_2(1^3D_2)$ state

Search for $e^+e^- \to \pi^+\pi^- X(3823) \to \pi^+\pi^-\gamma\chi_{c1}$

preliminary

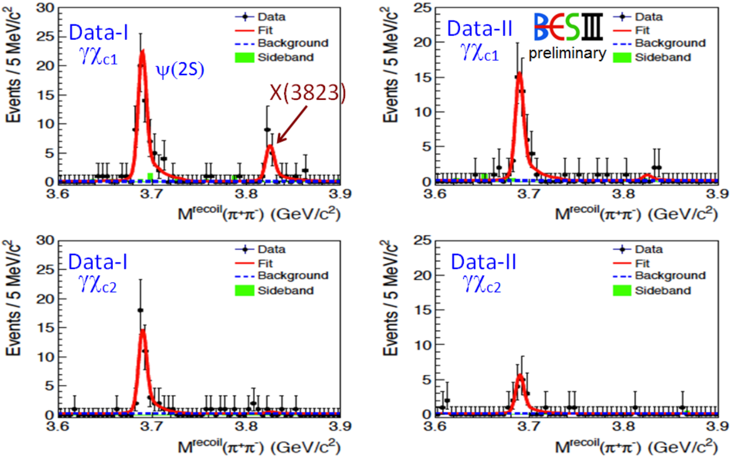
reconstruct $\chi_{c1,2} \to \gamma J/\psi \to \gamma\ell^+\ell^-$
look in mass recoiling against $\pi^+\pi^-$ system, $M_{\text{recoil}}(\pi^+\pi^-)$

Use 5 large data sets (total luminosity $\sim 4.1\,\text{fb}^{-1}$)



Search for $e^+e^- \to \pi^+\pi^- X(3823) \to \pi^+\pi^-\gamma\chi_{c1}$

preliminary



Simultaneous fit to two blocks of data (Data-I: $\geq$ 4.36 GeV, Data-II: 4.23, 4.26 GeV)

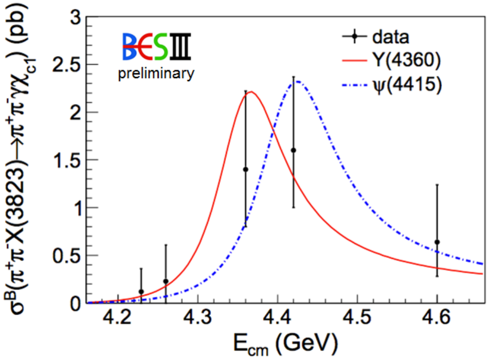
$M = 3821.7 \pm 1.3 \pm 0.7$ MeV, significance 6.7σ

Search for $e^+e^- \to \pi^+\pi^- X(3823) \to \pi^+\pi^-\gamma\chi_{c1}$

BESIII preliminary

Energy-dependent cross section for

$$e^+e^- \to \pi^+\pi^- X(3823) \to \pi^+\pi^-\gamma\chi_{c1}$$



Compatible with both $Y(4360)$ and $\psi(4415)$ line shapes

Mass and width $\sim$ in agreement with potential model

Production ratio

$$R_{21} \equiv \frac{\mathcal{B}(X(3823) \to \gamma\chi_{c2})}{\mathcal{B}(X(3823) \to \gamma\chi_{c1})}$$

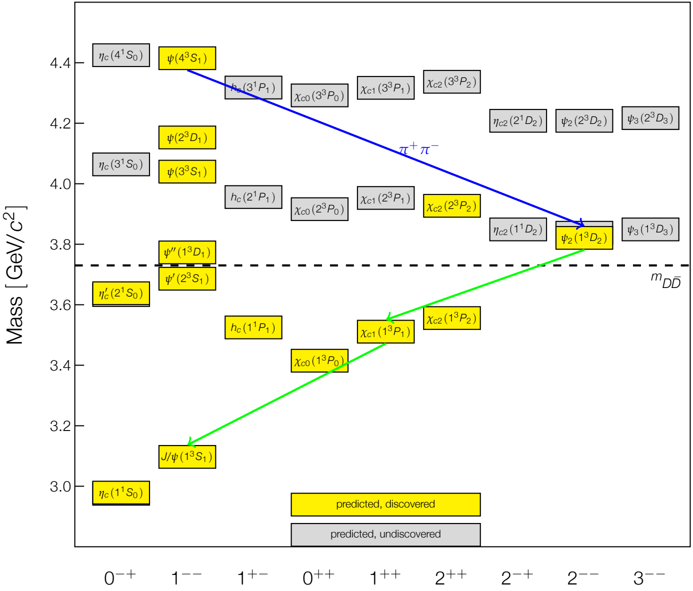
~ 0.2 prediction

< 0.43 at 90% C.L.

Exclusion:
$1^1D_2 \to \gamma\chi_{c1}$ forbidden
$1^3D_3 \to \gamma\chi_{c1}$ has zero amplitude

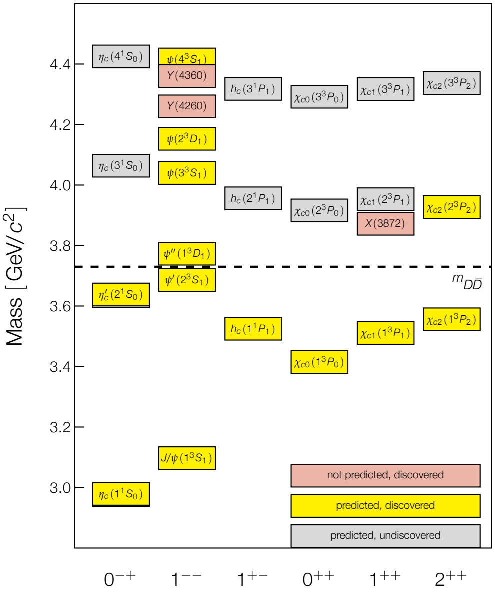
Not enough statistics to distinguish S and D wave from data

Higher charmonium states — a new family member!

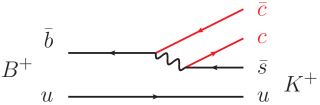



Exotic states

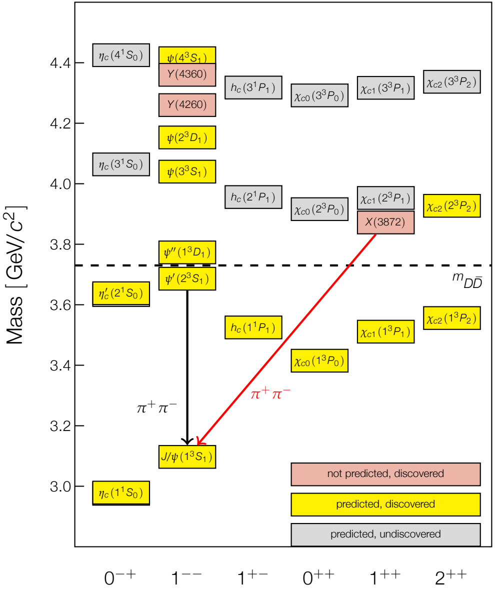
Surprising discoveries: the XYZ states



Most of the 'XYZ' states discovered at Belle and BABAR in e^+e^- collisions in bottomonium region e.g. in B decays:

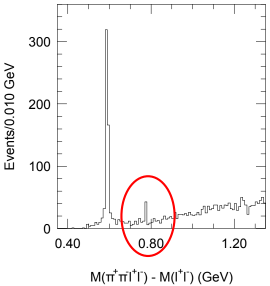


Surprising discoveries: the XYZ states



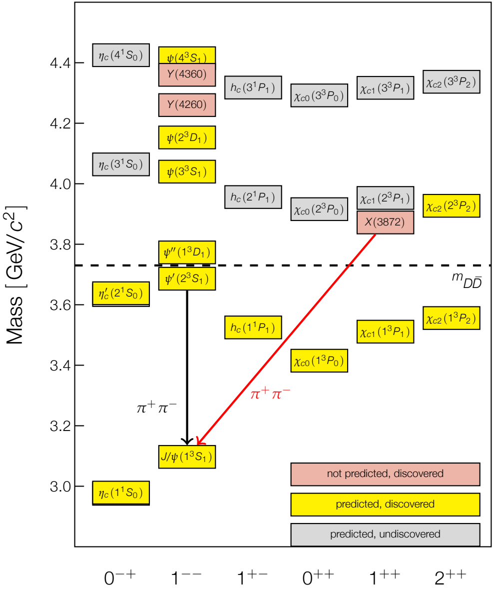
Most of the 'XYZ' states discovered at Belle and BABAR in e^+e^- collisions in bottomonium region

$B^+ \to K^+ \pi^+ \pi^- J/\psi$

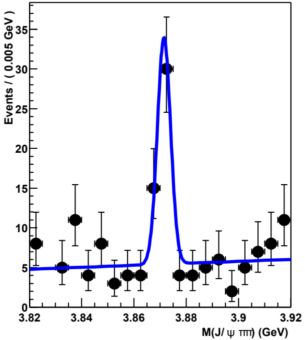


Belle, PRL 91, 262001 (2003)

The $X(3872)$



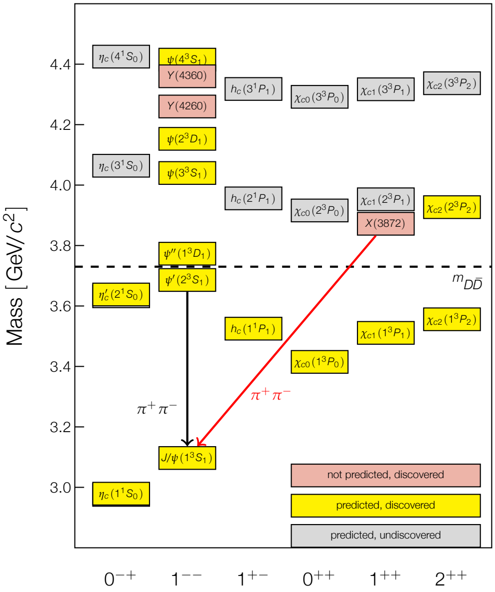
Extremely narrow, sits at or just below the DD^* threshold



$M = 3871.69 \pm 0.17\,\text{MeV}/c^2$

$\Gamma < 1.2\,\text{MeV}$

The $X(3872)$



Seen by Belle, BABAR, CDF, D0, CMS, LHCb, BESIII

Decays into $J/\psi\,\pi^+\pi^-$, $J/\psi\,\omega$, $D^0\bar{D}^0\pi^0$, $\gamma J/\psi$, $\gamma\psi(2S)$

What is known about the $X(3872)$?

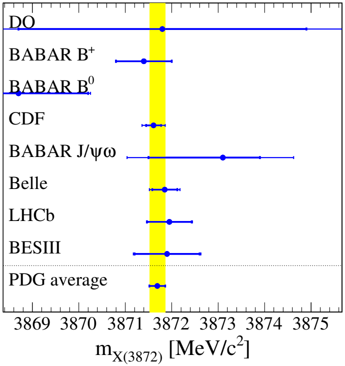
Mass and width

$$m_{X(3872)} = 3871.69 \pm 0.17\,\text{MeV}/c^2$$
$$m_{D^0} + m_{D^{*0}} = 3871.693 \pm 0.090\,\text{MeV}/c^2$$

Near equality of $m_{X(3872)}$ and $m_{D^0} + m_{D^{*0}}$: accident, or dynamics?

"Binding energy" $= 3 \pm 192\,\text{keV}$
if molecule, then very loosely bound!

(drives ever more precise measurements of m_D and m_D^*)



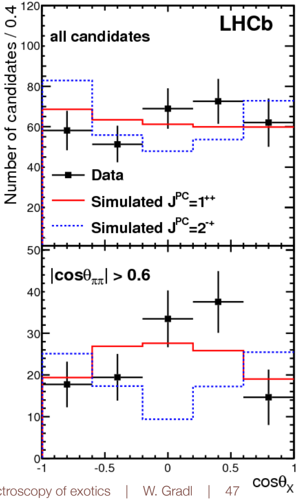
Width $< 1.2\,\text{MeV}$ at 90% C.L. (detector resolution!)

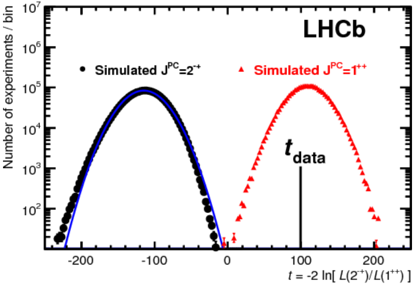
What is known about the $X(3872)$?

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

Belle: $J^{PC} = 1^{++}$ or 2^{-+} Phys. Rev. D **84**, 052004(R) (2011)

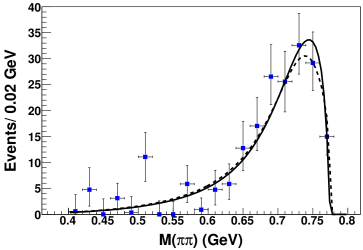
LHCb: unambiguously $J^{PC} = 1^{++}$ Phys. Rev. Lett. **110**, 222001 (2013)



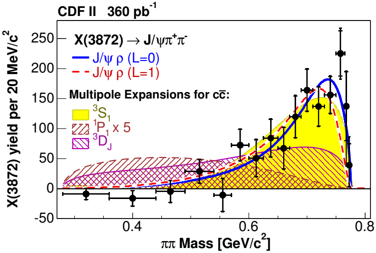


$\pi^+\pi^-$ system in $X(3872)$

$\pi^+\pi^-$ comes from $\rho^0 \to \pi^+\pi^-$:



Belle, Phys. Rev. D **84**, 052004



CDF, Phys. Rev. Lett. **96**, 102002

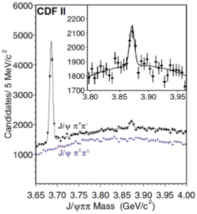
Problem: $(c\bar{c}) \to J/\psi\,\rho$ violates isospin and should be heavily suppressed.

Additionally: BABAR observes $X(3872) \to \omega J/\psi$ Phys. Rev. D **82** 011101
strong kinematic suppression (low-mass tail from ω), but $\mathcal{B}$ approx. equal!

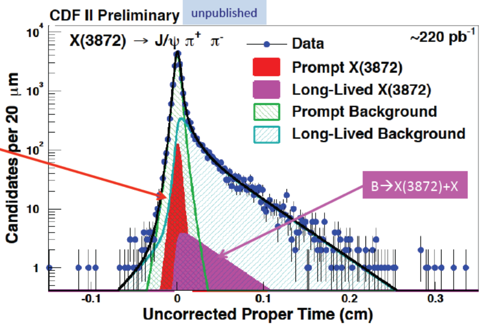
$X(3872)$ production

Production

CDF: $\approx 85\%$ of $p\bar{p} \to X(3872) + \cdots$ is prompt

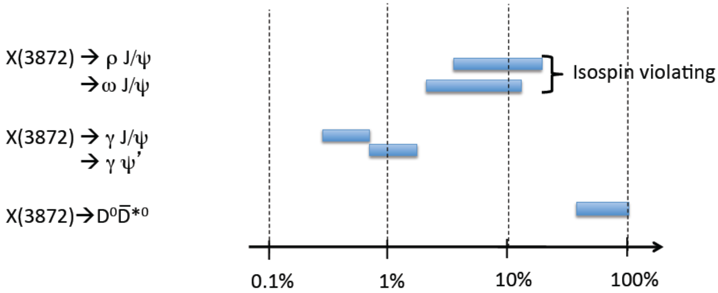


~75% @ LHC: CMS JHEP 04 (2013) 154



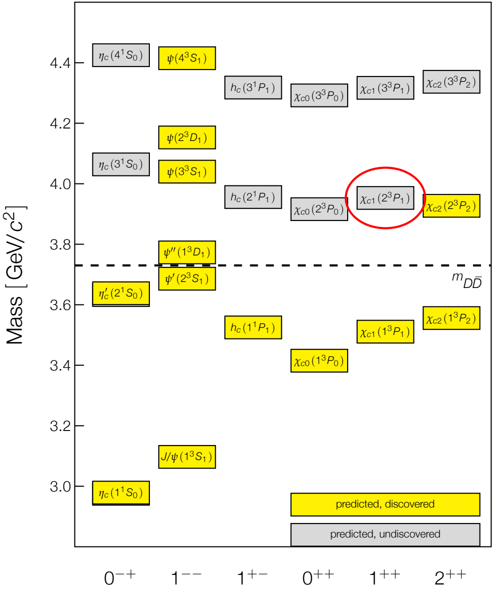
D0: $p\bar{p} \to X(3872)X \approx p\bar{p} \to \psi' X$ PRL 93, 162002

$X(3872)$ decay modes



S. Olsen

What is the $X(3872)$?



Charmonium $\chi_{c1}(2P)$?

- mass too low
  Hyperfine splitting: expect
  $\Delta M(2P) < \Delta M(1P) = 45.6\,\text{MeV}$,

  $\Delta M(2P) = 55 \pm 3\,\text{MeV}$ based on observed $\chi_{c2}(2P)$ mass
- width too narrow
  expect $\Gamma(\chi_{c1}(2P)) > 1.7\Gamma(\chi_{c1})$
  (more phase space, more decay channels)

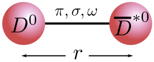
  $\Gamma(X(3872)) < 1.2\,\text{MeV} < 1.4\Gamma(\chi_{c1})$
- Isospin violation
  $\chi_{c1}(2P) \to J/\psi\,\rho$
  $\Delta I = 1$ transition;
  surprising for charmonium

JG|U

What is the $X(3872)$?

Molecule:

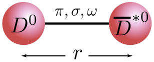
$$\frac{1}{\sqrt{2}}\left(\left|D^0\bar{D}^{*0}\right\rangle + \left|D^{*0}\bar{D}^0\right\rangle\right)$$

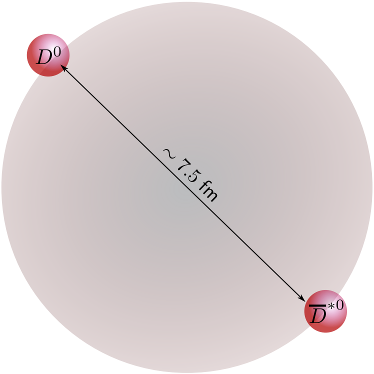


What is the $X(3872)$?

Molecule:

$$\frac{1}{\sqrt{2}}\left(\left|D^0\bar{D}^{*0}\right\rangle + \left|D^{*0}\bar{D}^0\right\rangle\right)$$





Binding energy

$$\delta M_{00} = m_{X(3872)} - (m_{D^0} + m_{D^{*0}}) < 0.2\,\text{MeV}$$

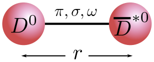
Size ≈ scattering length

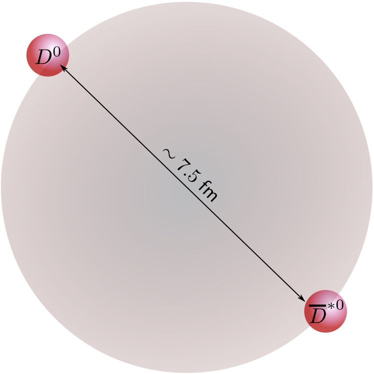
$$\langle r_{00}\rangle \approx \sqrt{\frac{1}{2m_D\delta M_{00}}} \geq 7.5\,\text{fm}$$

What is the $X(3872)$?

Molecule:

$$\frac{1}{\sqrt{2}}\left(\left|D^0\bar{D}^{*0}\right\rangle + \left|D^{*0}\bar{D}^0\right\rangle\right)$$



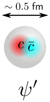


Binding energy

$$\delta M_{00} = m_{X(3872)} - (m_{D^0} + m_{D^{*0}}) < 0.2\,\text{MeV}$$

Size ≈ scattering length

$$\langle r_{00}\rangle \approx \sqrt{\frac{1}{2m_D\delta M_{00}}} \geq 7.5\,\text{fm}$$



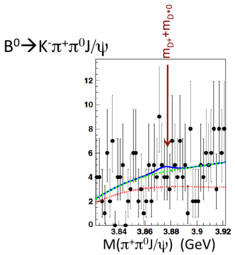
produced with similar cross sections in high-energy $p\bar{p}$ collisions?

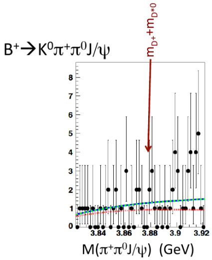
What is the $X(3872)$?

QCD tetraquark $|cq\bar{c}\bar{q}\rangle$? There should be a family:

- $X_u(3872) \sim |cu\bar{c}\bar{u}\rangle$
- $X_d(3872) \sim |cd\bar{c}\bar{d}\rangle$
- $X^+(3872) \sim |cu\bar{c}\bar{d}\rangle$
- $X^-(3872) \sim |cd\bar{c}\bar{u}\rangle$

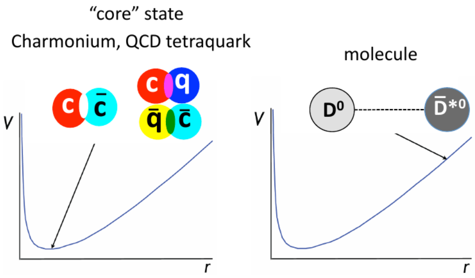
No charged partners $X^\pm(3872) \to J/\psi\,\pi^\pm\pi^0$ seen in B decays by BABAR or Belle
BABAR: PRD 71, 031501, Belle: PRD 84, 052004(R)





What is the $X(3872)$?

All of the above? QM mixture of tetraquark, charmonium, molecule

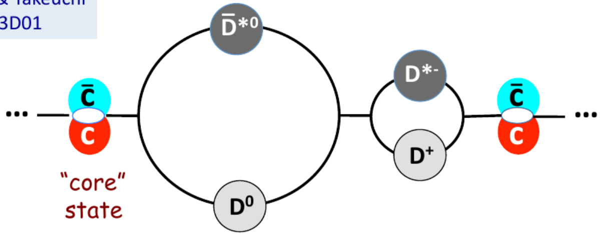


(See e.g. E. Braaten's talk at QWG'14)

What is the $X(3872)$?

Example calculation:

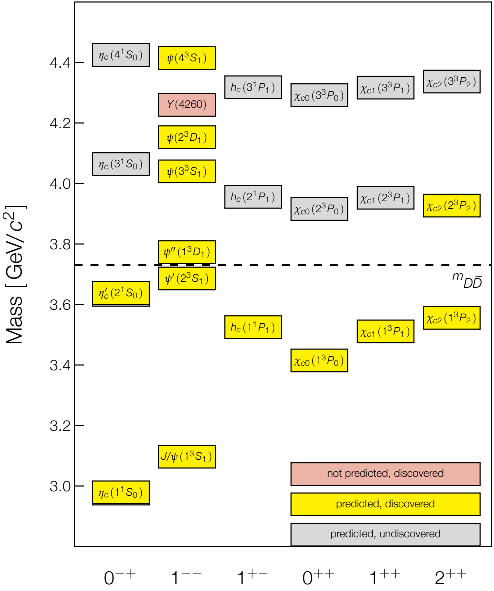
Takizawa & Takeuchi
PTEP 9, 093D01



$$|X(3872)\rangle = 0.94\left|D^0\bar{D}^{*0}\right\rangle + 0.23\left|D^+D^{*-}\right\rangle - 0.24\,|c\bar{c}\rangle$$
$$= 0.83\left|(D\bar{D}^*)_{I=0}\right\rangle + 0.51\left|(D\bar{D}^*)_{I=1}\right\rangle - 0.24\,|c\bar{c}\rangle$$

Looks like a molecule, but binding from $c\bar{c} - D\bar{D}^*$ coupling
mostly $I = 0$, but not pure isospin state

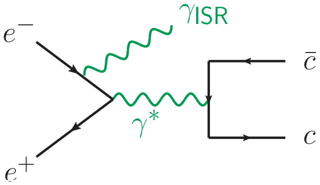
The $Y(4260) \to J/\psi\,\pi^+\pi^-$



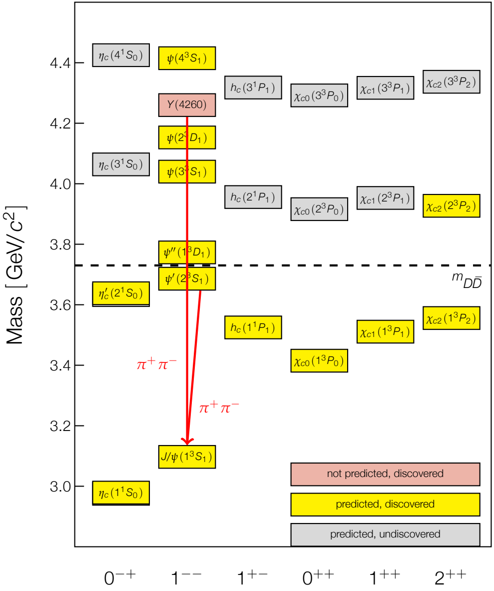
e^+e^- collisions near $\Upsilon(4S)$

in ISR production
$e^+e^- \to \gamma_{\mathrm{ISR}} J/\psi\,\pi^+\pi^-$

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



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

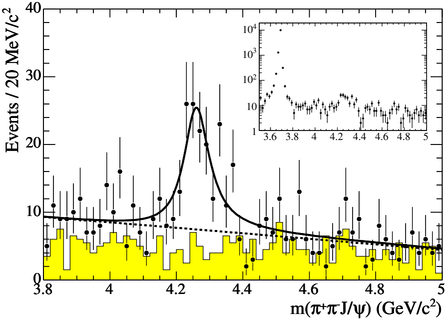


e^+e^- collisions near $\Upsilon(4S)$

in ISR production

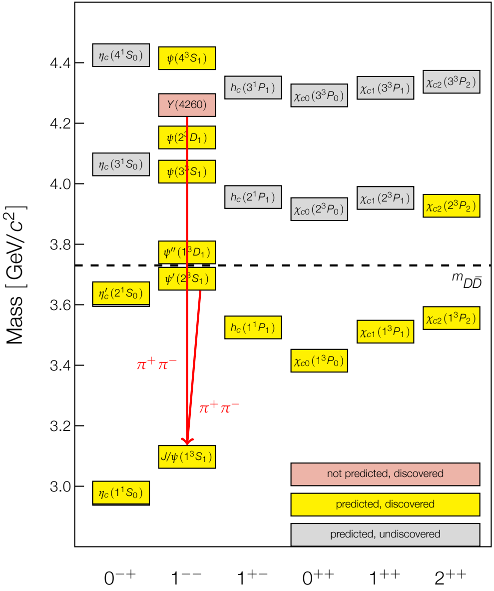
$e^+e^- \to \gamma_{ISR} J/\psi\,\pi^+\pi^-$

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



BABAR, PRL 95, 142001 (2005)

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

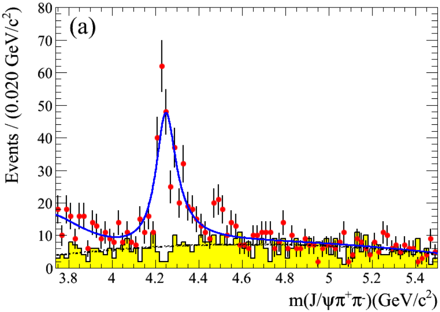


e^+e^- collisions near $\Upsilon(4S)$

in ISR production

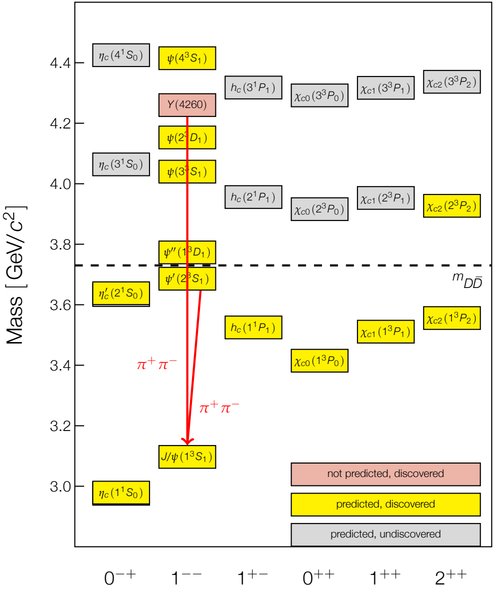
$e^+e^- \to \gamma_{ISR} J/\psi\,\pi^+\pi^-$

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



BABAR, PRD 86, 051102(R) (2012)

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



e^+e^- collisions near $\Upsilon(4S)$

in ISR production
$e^+e^- \to \gamma_{\text{ISR}} J/\psi\,\pi^+\pi^-$

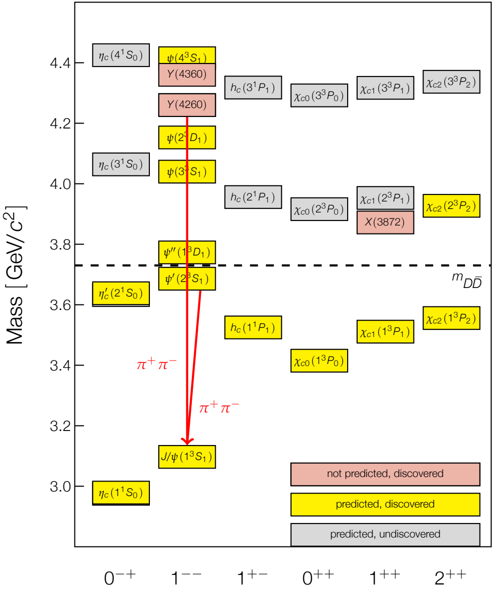
$\Rightarrow J^{PC} = 1^{--}$

Mass greater than $2m(D)$,
expect OZI favoured decay to $D\bar{D}$;
but find

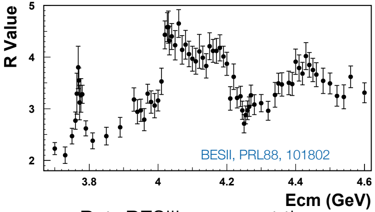
$$\frac{\mathcal{B}(Y(4260) \to D\bar{D})}{\mathcal{B}(Y(4260) \to J/\psi\,\pi^+\pi^-)} < 4$$

compare with
≈ 500 for $\psi(3770)$

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



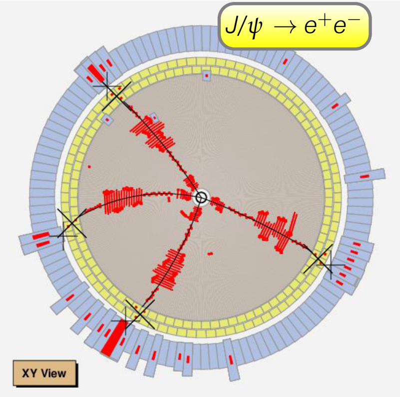
- … $Y(4260) \to J/\psi\,\pi^+\pi^-$
- … $Y(4360) \to \psi(2S)\pi^+\pi^-$
- … additional state at 4460 MeV
- supernumerary states:
  no unaccounted 1^{--} slots
- ➡ do not correspond to peaks in
  $\sigma(e^+e^- \to \text{hadrons})$

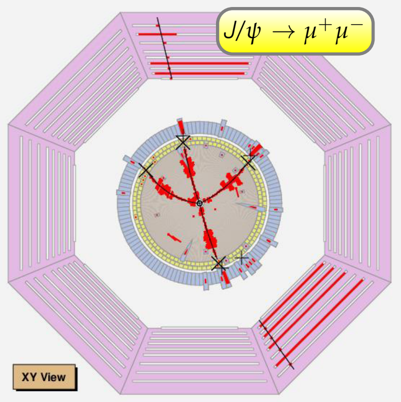


- ➡ But: BESIII can run at these energies;
  maybe produce them directly?

$e^+e^- \to J/\psi\,\pi^+\pi^-$ at 4.26 GeV

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





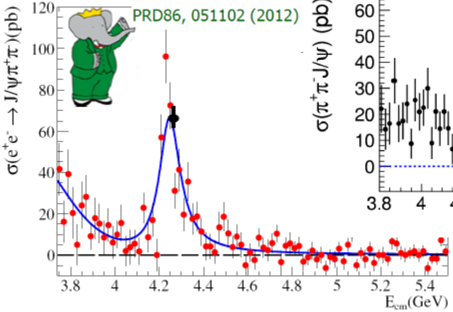
- Running at $\sqrt{s} = 4260$ MeV: simple and straightforward
- $J/\psi\,(\to \ell^+\ell^-)\pi^+\pi^-$: four charged tracks
- very clean sample, high efficiency, reliable MC simulation
- dominant background: continuum $e^+e^- \to \pi^+\pi^-\pi^+\pi^-$

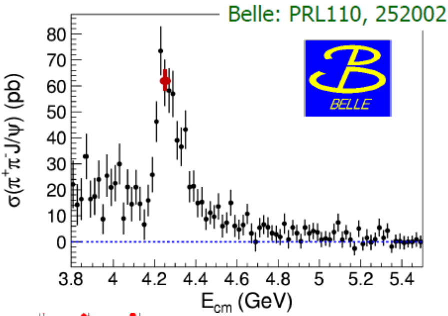
Cross section

BESIII measures cross section

$\sigma^B(e^+e^- \to J/\psi\,\pi^+\pi^-) = (62.9 \pm 1.9 \pm 3.7)\,\text{pb}$

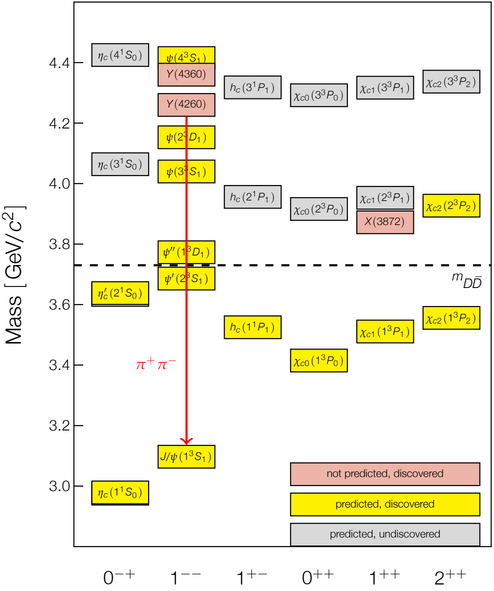
in good agreement with BABAR and Belle

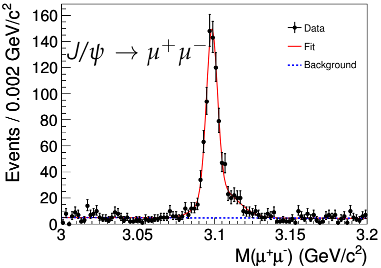


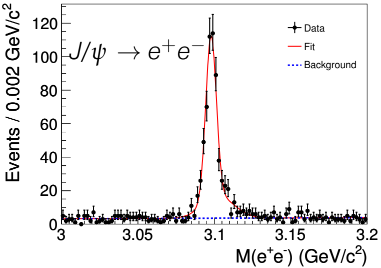


$e^+e^- \to J/\psi\,\pi^+\pi^-$ at 4.26 GeV

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



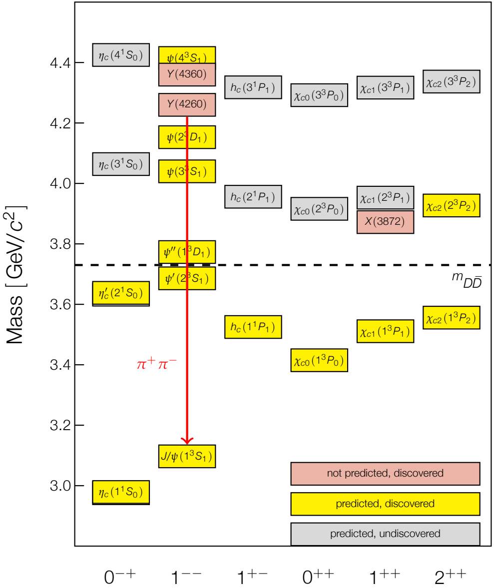


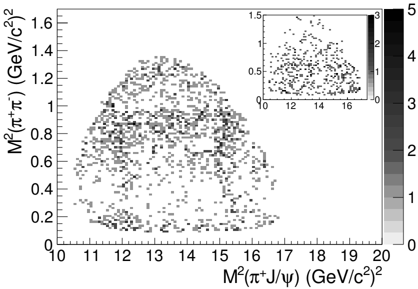


…have hundreds of events!

$e^+e^- \to J/\psi\,\pi^+\pi^-$ at 4.26 GeV

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



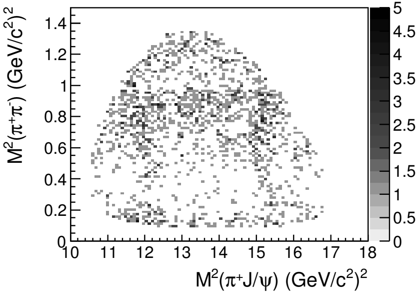


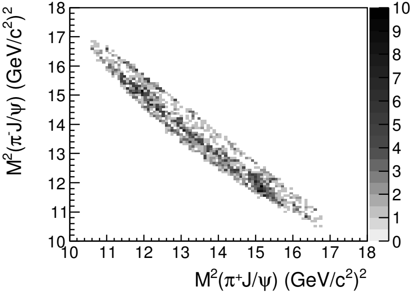
Non-trivial substructure in $J/\psi\,\pi^+\pi^-$ Dalitz plot

Resonant substructure in decay!

$J/\psi\,\pi^+\pi^-$ Dalitz plot

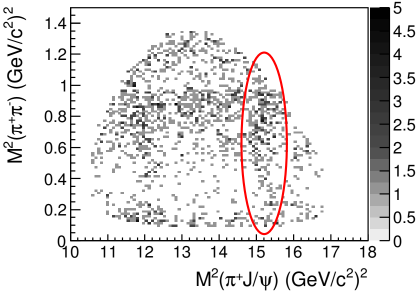
BESIII, PRL **110**, 252001 (2013)

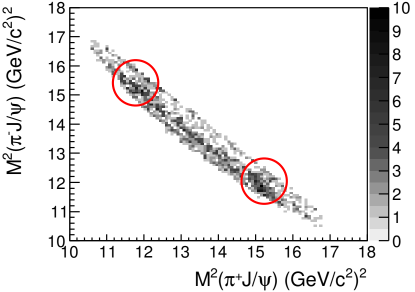


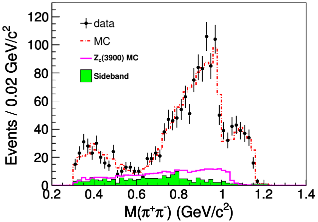


$J/\psi\,\pi^+\pi^-$ Dalitz plot

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



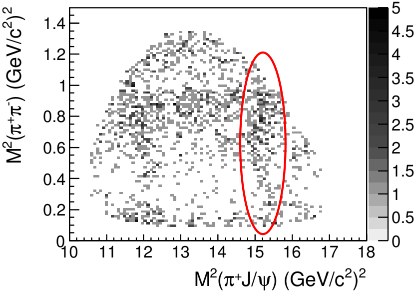


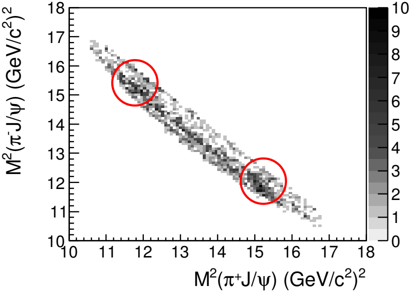


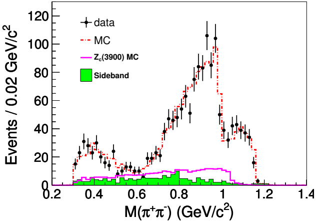
Model $\pi^+\pi^-$-system with known structure:
$f_0(500)$, $f_0(980)$, non-resonant
obtain good fit of $\pi^+\pi^-$ mass projection

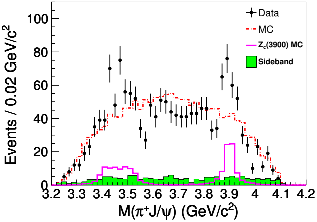
$J/\psi\,\pi^+\pi^-$ Dalitz plot

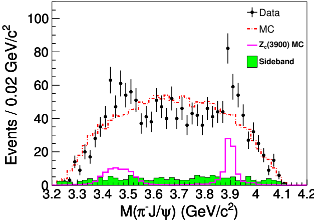
BESIII, PRL **110**, 252001 (2013)





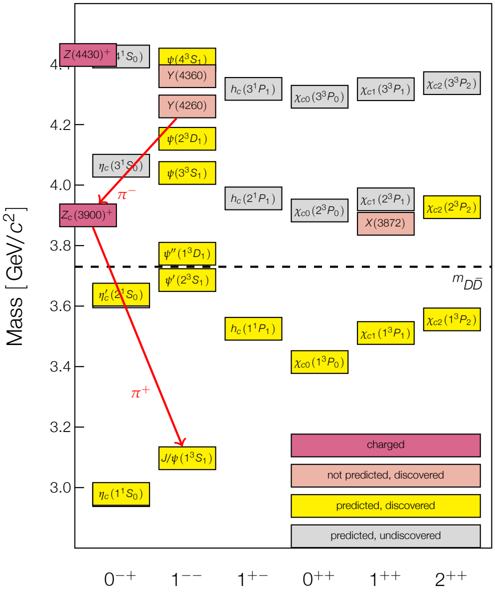


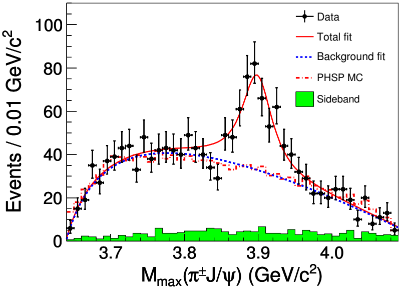




$e^+e^- \to J/\psi\,\pi^+\pi^-$ at 4.26 GeV

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





Charged charmonium-like structure

$$M = (3899.0 \pm 3.6 \pm 4.9)\ \mathrm{MeV}/c^2$$

$$\Gamma = (46 \pm 10 \pm 20)\ \mathrm{MeV}$$

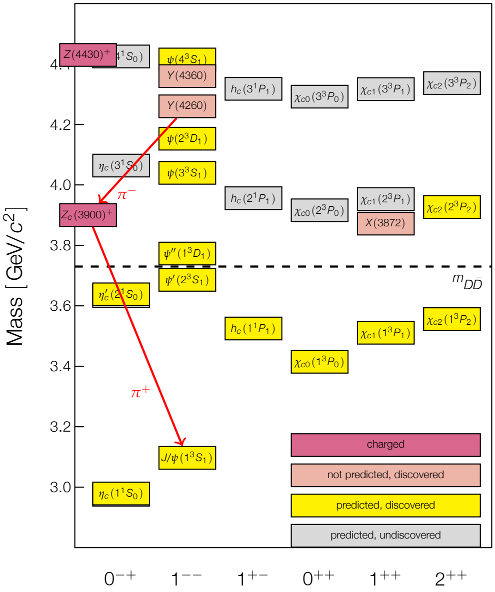
Confirmed by Belle PRL **110**, 252002
and with CLEOc data PLB 727, 366

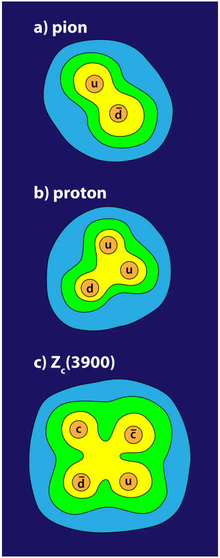
Close to DD^* threshold

$e^+e^- \to J/\psi\,\pi^+\pi^-$ at 4.26 GeV

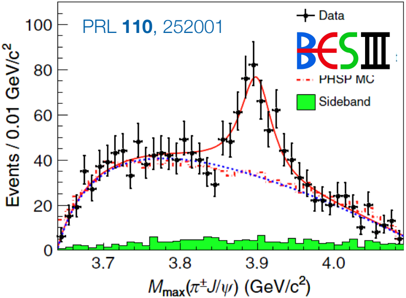
BESIII, PRL **110**, 252001 (2013)

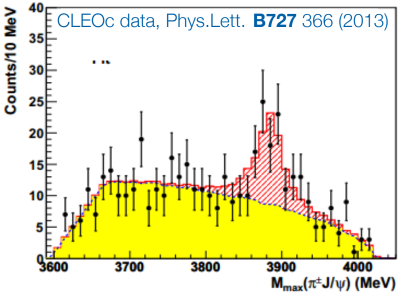
One of APS highlights of 2013

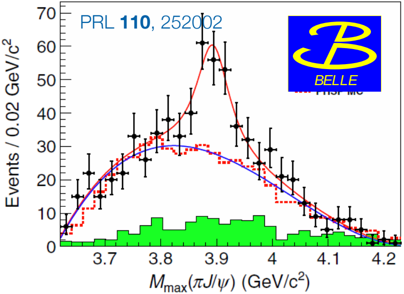




$Z_c(3900)^+$ in other datasets?



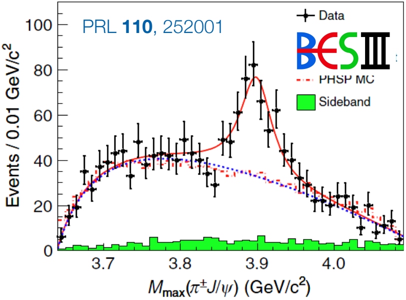


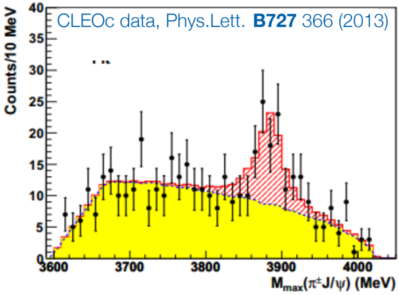


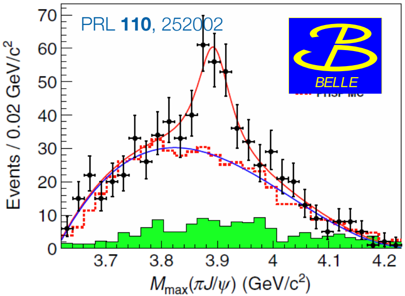
	m / MeV	Γ / MeV
BESIII	$3899.0 \pm 3.6 \pm 4.9$	$46 \pm 10 \pm 20$
Belle	$3894.5 \pm 6.6 \pm 4.5$	$63 \pm 24 \pm 26$
CLEOc	$3885 \pm 5 \pm 1$	$34 \pm 12 \pm 4$

Belle: $e^+e^- \to \gamma_{ISR} J/\psi \pi^+\pi^-$,
in $Y(4260)$ region
CLEOc data: $\sqrt{s} = 4.170$ GeV

$Z_c(3900)^+$ in other datasets?







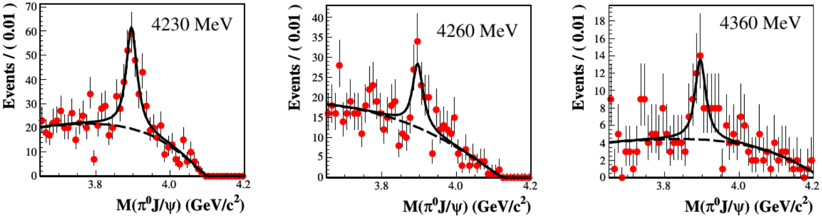
- $Z_c(3900)^+ \to J/\psi\,\pi^+$ seen at BESIII, Belle, and with CLEO-c data
- Masses and widths compatible within uncertainties

A neutral partner to the $Z_c(3900)^+$?

BESIII preliminary

If interpretation of $Z_c(3900)^+$ as four-quark state is correct:
expect state completing isospin triplet, with decay $Z_c(3900)^0 \to \pi^0 J/\psi$

Study $e^+e^- \to \pi^0\pi^0 J/\psi$ at different $\sqrt{s}$

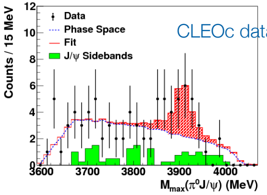


Structure in $\pi^0 J/\psi$ invariant mass clearly visible at all energies

$$M = 3894.8 \pm 2.3 \pm 2.7\,\text{MeV}/c^2$$

$$\Gamma = 29.6 \pm 8.2 \pm 8.2\,\text{MeV}$$

$$\text{Significance} = 10\sigma$$

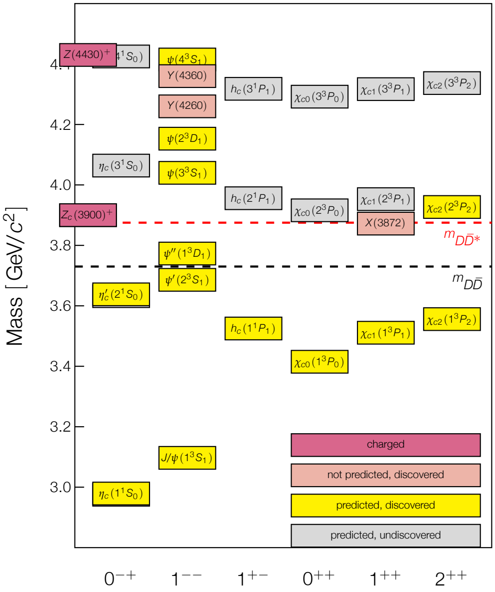


CLEOc data, 3.5σ

$Z_c(3900)^+$ at $D\bar{D}^*$ threshold

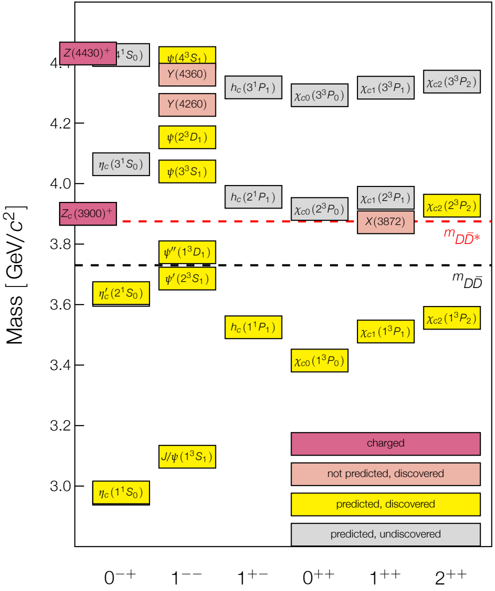
BESIII, PRL **112**, 022001 (2014)

Decay mode $Z_c(3900)^+ \to (D\bar{D}^*)^+$?



$Z_c(3900)^+$ at $D\bar{D}^*$ threshold

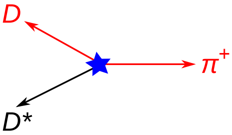
BESIII, PRL **112**, 022001 (2014)



Decay mode $Z_c(3900)^+ \to (D\bar{D}^*)^+$?

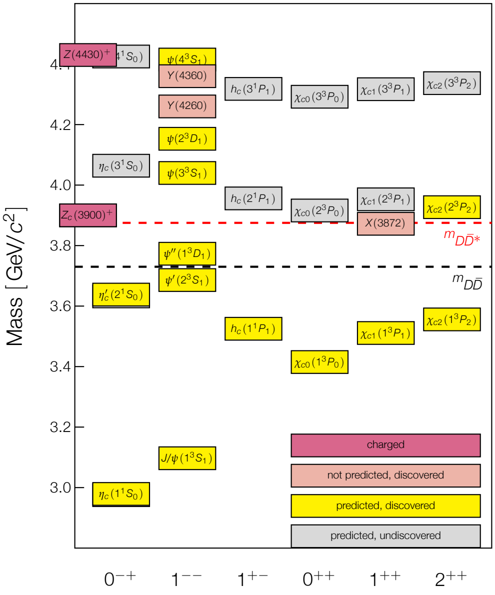
Single tag analysis:

- reconstruct 'bachelor' π^+ and $D^0 \to K^-\pi^+$ or $D^- \to K^+\pi^-\pi^-$
- require D^* in missing mass
- veto $e^+e^- \to (D^*\bar{D}^*)^0$
- apply kinematic fit; look in mass recoiling against π^+

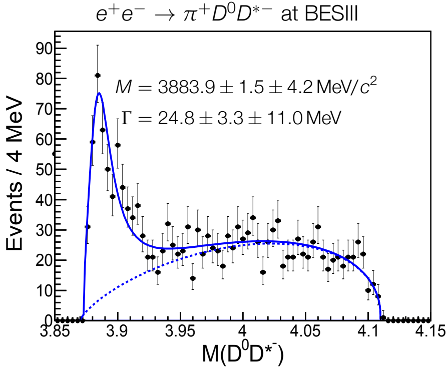


$Z_c(3900)^+$ at $D\bar{D}^*$ threshold

BESIII, PRL **112**, 022001 (2014)



Decay mode $Z_c(3900)^+ \to (D\bar{D}^*)^+$?

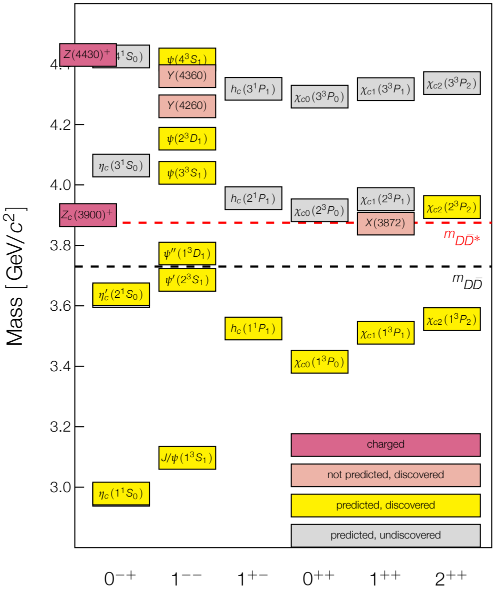


…and BESIII sees structure in $(DD^*)^\pm$

$Z_c(3885)^+$

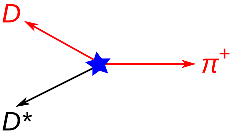
$Z_c(3900)^+$ at $D\bar{D}^*$ threshold

BESIII preliminary



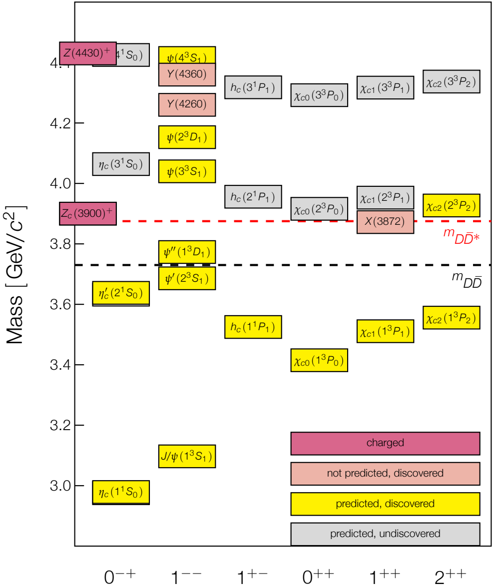
New: Double tag analysis

- reconstruct 'bachelor' π^+ and D^0, D^- in 4 or 6 decay modes
- require π from D^* in missing mass
- improved statistics, much better control over background shape improved systematics
- apply kinematic fit; look in mass recoiling against π^+



$Z_c(3900)^+$ at $D\bar{D}^*$ threshold

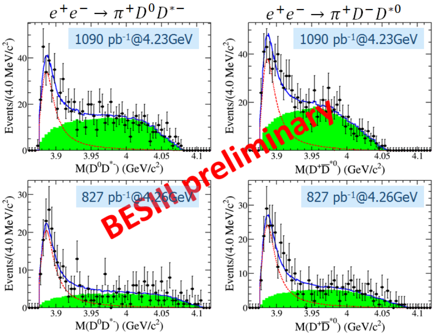
BESIII preliminary



$e^+e^- \to \pi^+ D^0 D^{*-}$ at BESIII

$$M = 3884.3 \pm 1.2 \pm 1.5\,\text{MeV}/c^2$$

$$\Gamma = 23.8 \pm 2.1 \pm 2.6\,\text{MeV}$$



Compatible with, but significantly more precise, than single-tag analysis

$Z_c(3885)^+$ Quantum numbers?

BESIII preliminary

θ_π: angle between bachelor pion and beam axis in CMS

Know initial state is 1^-, with $J_z = \pm 1$. Depending on J^P of Z_c:

- 0^+ excluded by parity conservation
- 0^- π and $Z_c(3885)$ in P-wave, with $J_z = \pm 1$ ➡ $\mathrm{d}N/\mathrm{d}\cos\theta_\pi \propto 1 - \cos^2\theta_\pi$
- 1^- π and $Z_c(3885)$ in P-wave ➡ $\mathrm{d}N/\mathrm{d}\cos\theta_\pi \propto 1 + \cos^2\theta_\pi$
- 1^+ π and $Z_c(3885)$ in S or D wave.
  Assume D wave small near threshold: ➡ $\mathrm{d}N/\mathrm{d}\cos\theta_\pi \propto 1$

$Z_c(3885)^+$ Quantum numbers?

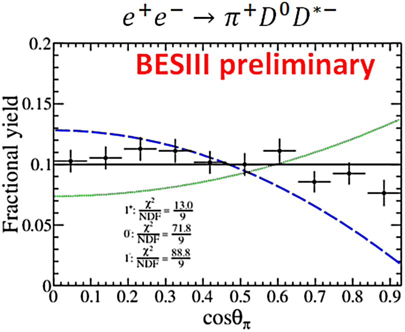
BESIII preliminary

θ_π: angle between bachelor pion and beam axis in CMS

Know initial state is 1^-, with $J_z = \pm 1$. Depending on J^P of Z_c:

- 0^+ excluded by parity conservation
- 0^- π and $Z_c(3885)$ in P-wave, with $J_z = \pm 1$ ➡ $dN/d\cos\theta_\pi \propto 1 - \cos^2\theta_\pi$
- 1^- π and $Z_c(3885)$ in P-wave ➡ $dN/d\cos\theta_\pi \propto 1 + \cos^2\theta_\pi$
- 1^+ π and $Z_c(3885)$ in S or D wave.
  Assume D wave small near threshold: ➡ $dN/d\cos\theta_\pi \propto 1$

Event yield in 10 bins in $|\cos\theta_\pi|$



data clearly favour $J^P = 1^+$ for $D\bar{D}^*$ structure

confirms J^P for $Z_c(3885)$ from single-tags

Comparison between $Z_c(3900)$ and $Z_c(3885)$

	$Z_c(3885) \to D\bar{D}^*$	$Z_c(3900) \to \pi J/\psi$
Mass / MeV/c^2	$3884.3 \pm 1.2 \pm 1.5$	$3899.0 \pm 3.6 \pm 4.9$
Width / MeV	$23.8 \pm 2.1 \pm 2.6$	$46 \pm 10 \pm 20$
$\sigma \times \mathcal{B}$ / pb	$88.0 \pm 6.1 \pm 7.9$	$13.5 \pm 2.1 \pm 4.8$

Mass and width compatible within $\sim 2\sigma$

If this is the same state decaying in two channels: open charm decays suppressed!

$$\frac{\mathcal{B}(\psi(4040) \to D^{(*)}\bar{D}^{(*)})}{\mathcal{B}(\psi(4040) \to J/\psi\,\eta)} = 192 \pm 27$$

$$\frac{\mathcal{B}(Z_c \to D\bar{D}^*)}{\mathcal{B}(Z_c \to J/\psi\,\pi)} = 6.2 \pm 2.9$$

➡ Different dynamics at work in $Y(4260) - Z_c(3900)$ system

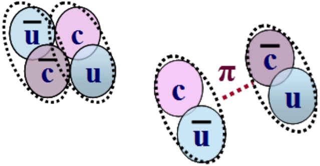
Interpretation of $Z_c(3900)$?

- Mass close to DD^* threshold
- Couples strongly to $c\bar{c}$
- Has electric charge
- If new particle:
  ➡ necessarily exotic,
  quark contents at least $c\bar{c}u\bar{d}$

JG|U

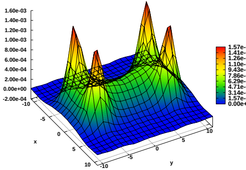
Interpretation of $Z_c(3900)$?

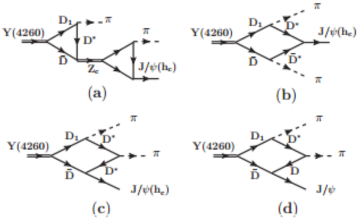
- Mass close to DD^* threshold
- Couples strongly to $c\bar{c}$
- Has electric charge
- If new particle:
  ➡ necessarily exotic,
  quark contents at least $c\bar{c}u\bar{d}$

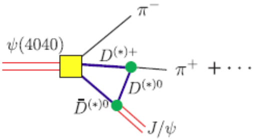


So, what is it?

- Tetraquark L. Maiani, A. Ali et al.
- Hadronic molecule U.-G. Meissner, F.K. Guo et al.
- Hadro-charmonium M. B. Voloshin
- Meson loop Q. Zhao et al.
- ISPE model X. Liu et al.
- …

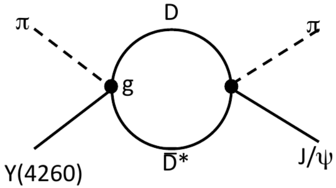


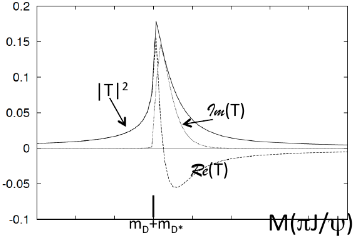




$Z_c(3900)$ just a threshold cusp?

Bugg, EPL 96, 11002 (2001); Swanson, PRD91, 034009 (2015)





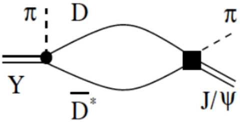
$$\Im T \propto g^2 \frac{2k}{\sqrt{s'}} FF(s')$$

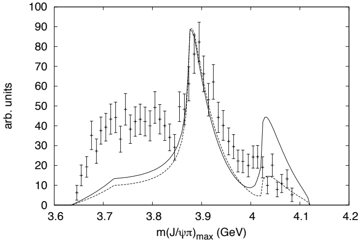
Analyticity requires also real part:

$$\Re T \propto \frac{1}{\pi} P \int_{s_{thr}}^{m_Y} \frac{ds' \Im T}{s' - s}$$

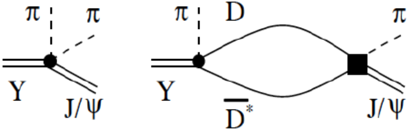
Cusp effect — comparison with data

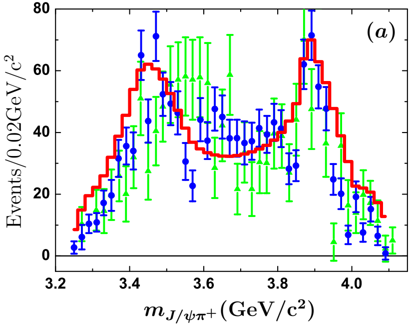
Swanson, PRD91, 034009 (2015)





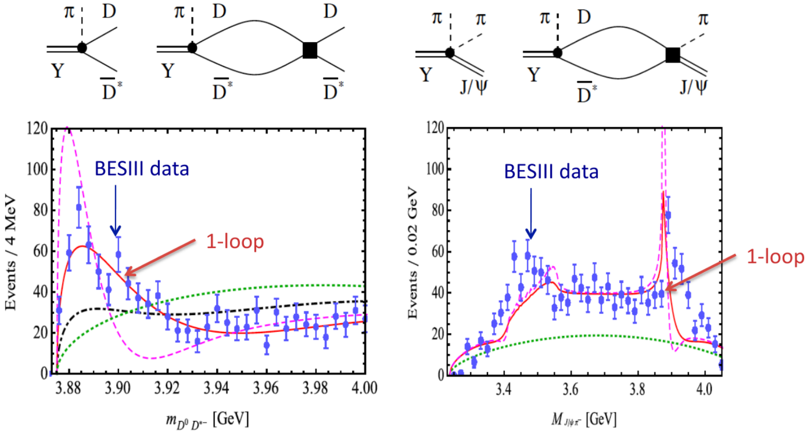
Chen et al, PRD88, 036008 (2013)





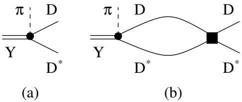
Combined fit to $J/\psi\,\pi^+$ and DD^* channels

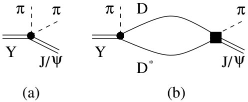
Guo, Hanhart, Wang, Zhao, arXiv:1411.5584

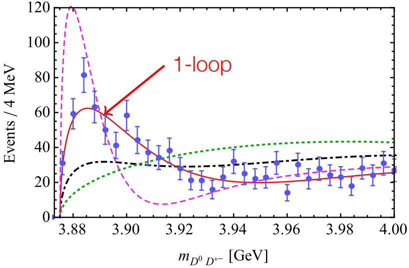


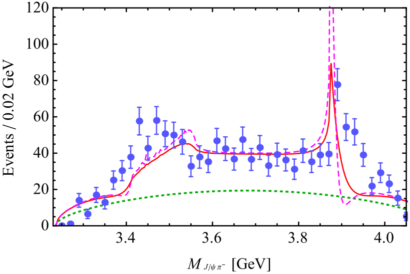
Combined fit to $J/\psi\,\pi^+$ and DD^* channels

Guo, Hanhart, Wang, Zhao, arXiv:1411.5584



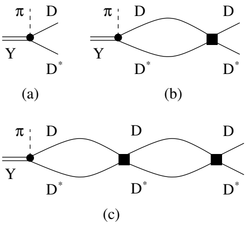


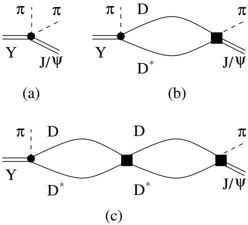


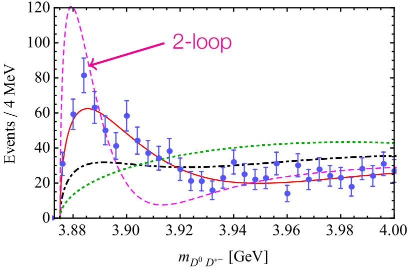


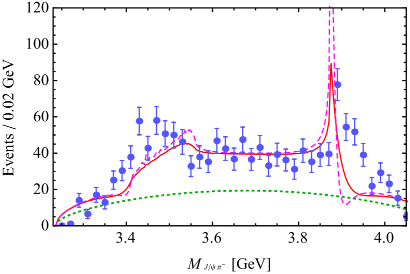
Combined fit to $J/\psi\,\pi^+$ and DD^* channels

Guo, Hanhart, Wang, Zhao, arXiv:1411.5584



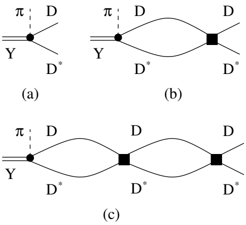


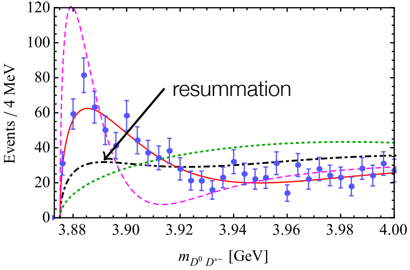




Combined fit to $J/\psi\,\pi^+$ and DD^* channels

Guo, Hanhart, Wang, Zhao, arXiv:1411.5584



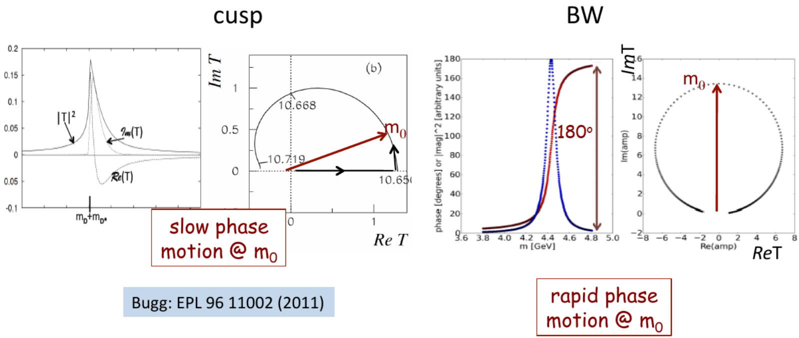


Clearly, first-order perturbation theory does not apply — inconsistent approach!

Need to resum whole series:
no peak at threshold!

Resummed series produces
bound state pole just below threshold

Cusp vs resonance phase motion

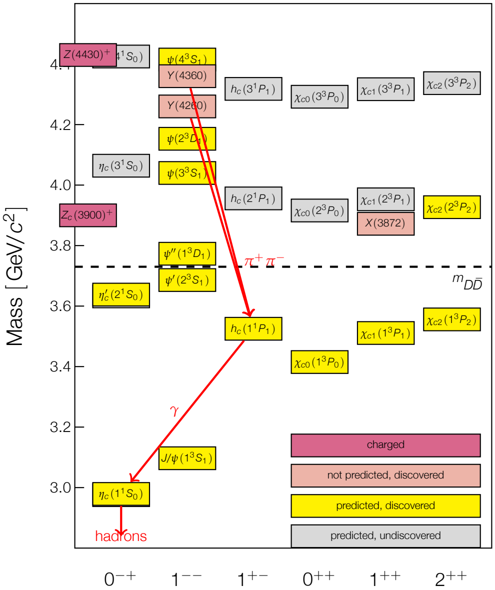


Bugg: EPL 96 11002 (2011)

Amplitude analysis of $Z_c(3900)^+ \to J/\psi\,\pi^+$ under way at BESIII; results very soon!?

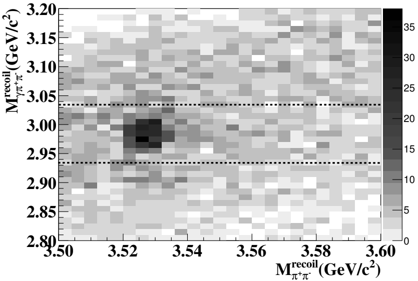
$e^+e^- \to h_c(1P)\pi^+\pi^-$

BESIII, PRL **111**, 242001 (2013)



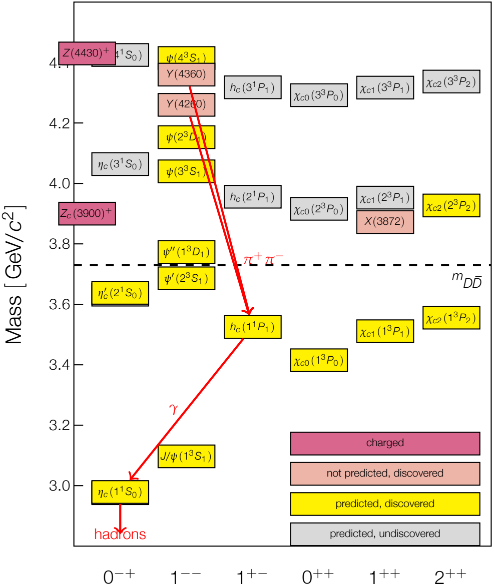
Exclusively reconstruct the process

$$e^+e^- \to \pi^+\pi^- h_c(1P)$$
$$h_c(1P) \to \gamma\eta_c(1S)$$
$$\eta_c(1S) \to \text{16 decay channels}$$



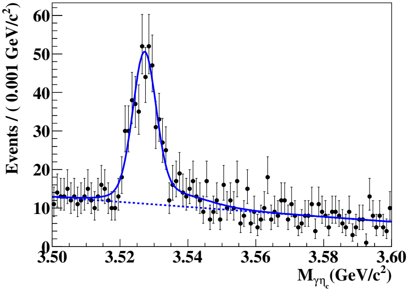
$e^+e^- \to h_c(1P)\pi^+\pi^-$

BESIII, PRL **111**, 242001 (2013)



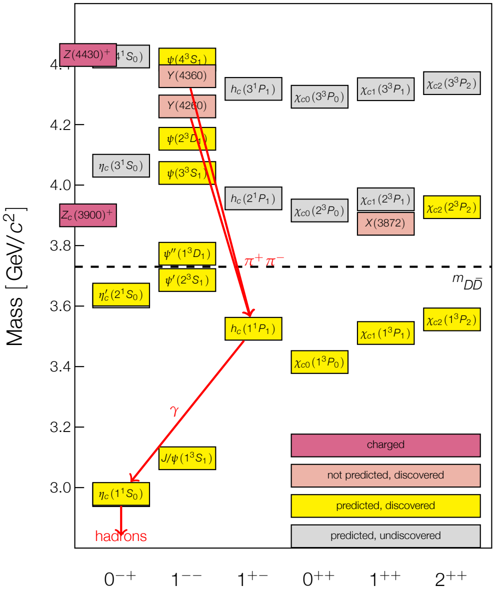
Exclusively reconstruct the process

$$e^+e^- \to \pi^+\pi^- h_c(1P)$$
$$h_c(1P) \to \gamma\eta_c(1S)$$
$$\eta_c(1S) \to \text{16 decay channels}$$



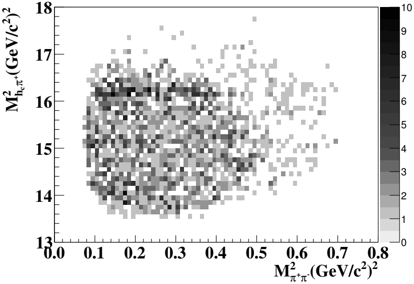
$e^+e^- \to h_c(1P)\pi^+\pi^-$

BESIII, PRL **111**, 242001 (2013)



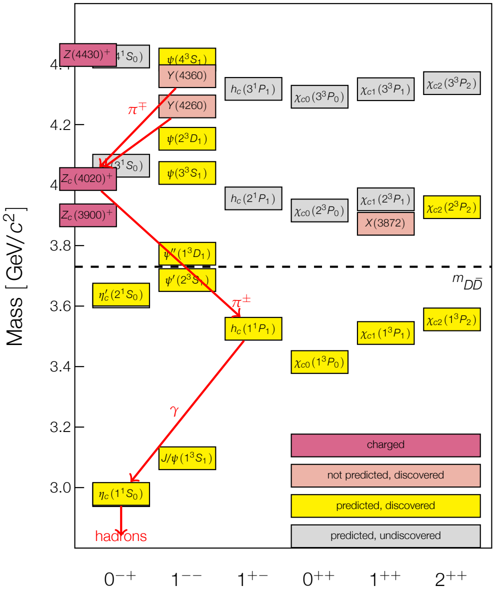
Exclusively reconstruct the process

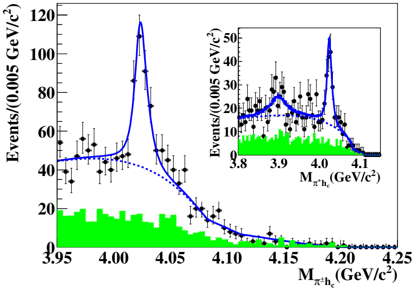
$$e^+e^- \to \pi^+\pi^- h_c(1P)$$
$$h_c(1P) \to \gamma\eta_c(1S)$$
$$\eta_c(1S) \to \text{16 decay channels}$$



$e^+e^- \to h_c(1P)\pi^+\pi^-$

BESIII, PRL **111**, 242001 (2013)





Charged charmonium-like structure
(close to D^*D^* threshold)

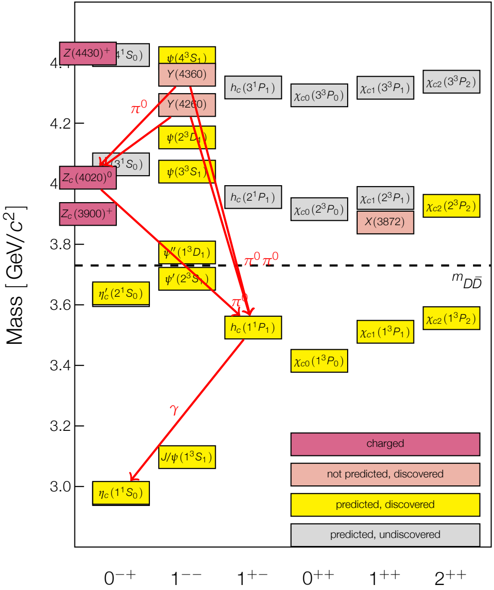
$M = 4022.9 \pm 0.8 \pm 2.7\,\mathrm{MeV}/c^2$

$\Gamma = 7.9 \pm 2.7 \pm 2.6\,\mathrm{MeV}$

Note: no significant
$Z_c(3900)^+ \to \pi^+ h_c$ seen!

$e^+e^- \to h_c(1P)\pi^0\pi^0$

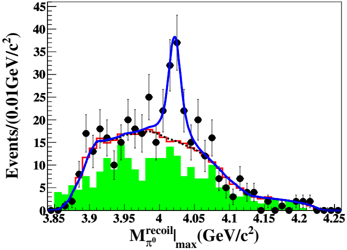
BESIII, PRL **113**, 212002 (2014)



Study $e^+e^- \to \pi^0\pi^0 h_c$ at 4.23, 4.26, 4.36 GeV

Observe structure in $h_c\pi^0$ mass distribution:

Neutral partner to $Z_c(4020)^+$

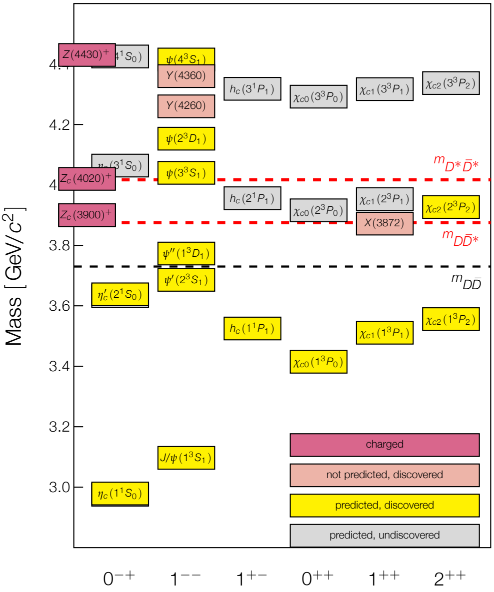


$M = 4023.6 \pm 4.5\,\text{MeV}/c^2$

Isospin triplet found!

Yet another mass threshold …

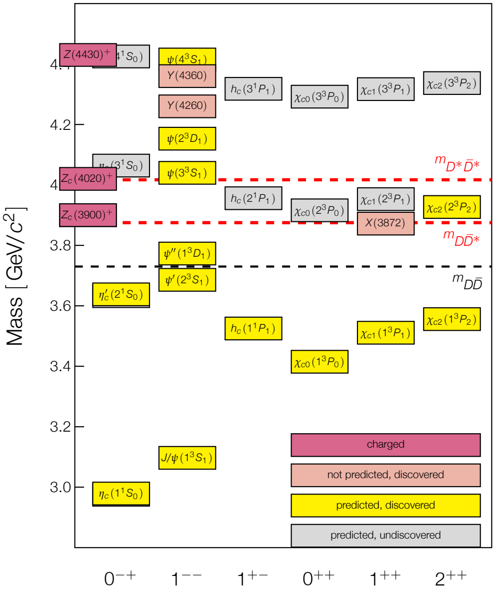
BESIII, PRL **112**, 132001 (2014)



$Z_c(4020)$ at D^*D^* threshold

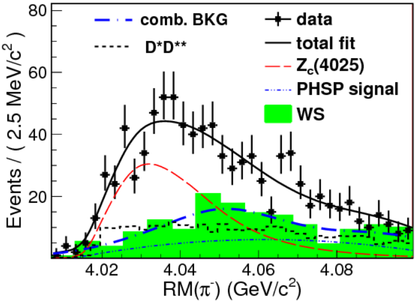
Yet another mass threshold …

BESIII, PRL **112**, 132001 (2014)



$Z_c(4020)$ at D^*D^* threshold

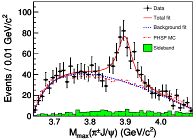
$e^+e^- \to \pi^+ D^{*+} D^{*-}$ at BESIII



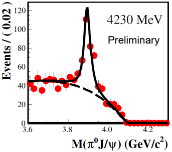
…and BESIII sees structure in D^*D^*

$$M = 4026.3 \pm 2.6 \pm 3.7\,\text{MeV}/c^2$$
$$\Gamma = 24.8 \pm 5.6 \pm 7.7\,\text{MeV}$$

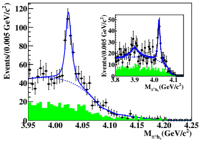
All the Z_cs from BESIII near $\sqrt{s} = 4.3\,\mathrm{GeV}$



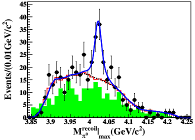
$e^+e^- \to \pi^-\pi^+ J/\psi$



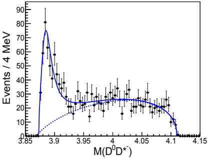
$e^+e^- \to \pi^0\pi^0 J/\psi$



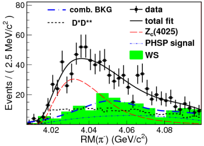
$e^+e^- \to \pi^-\pi^+ h_c$



$e^+e^- \to \pi^0\pi^0 h_c$



$e^+e^- \to \pi^-(D\bar{D}^*)^+$



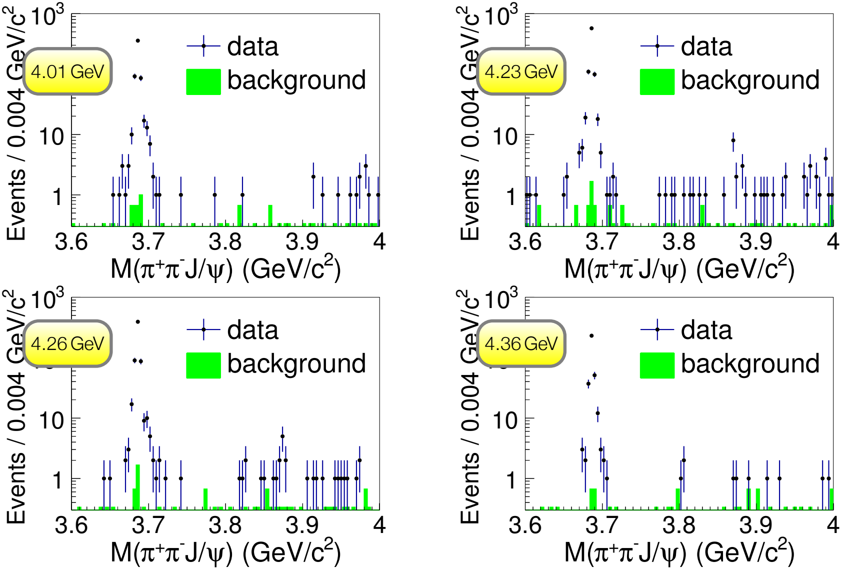
$e^+e^- \to \pi^-(D^*\bar{D}^*)^+$

$Z_c(3900)^+$? $Z_c(3900)^0$? $Z_c(4020)^+$? $Z_c(4020)^0$?

Nature of these states? Isospin triplets?
Different decay channels of the same states observed?
Other decay modes?

$e^+e^- \to \gamma X(3872) \to \gamma J/\psi\, \pi^+\pi^-$

BESIII, PRL **112**, 092001 (2014)

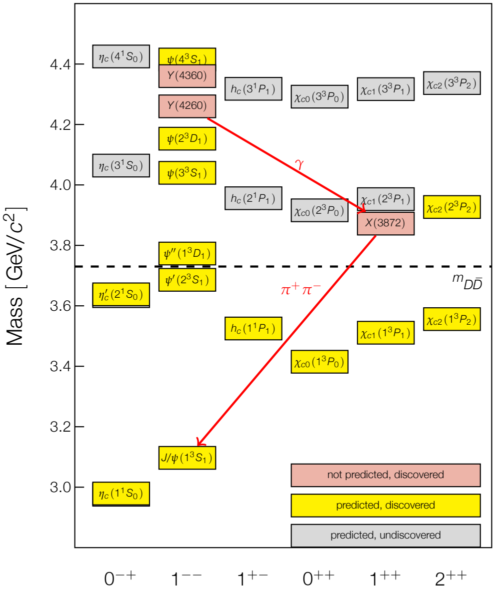


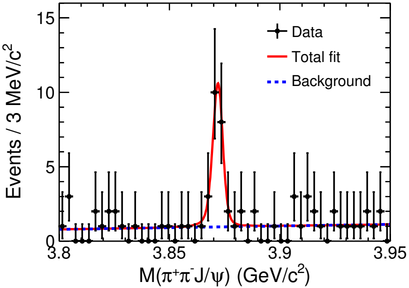
Clear ISR ψ' signal for validation

$X(3872)$ signal around 4.23 – 4.26 GeV

$e^+e^- \to \gamma X(3872) \to \gamma J/\psi\,\pi^+\pi^-$

BESIII, PRL **112**, 092001 (2014)





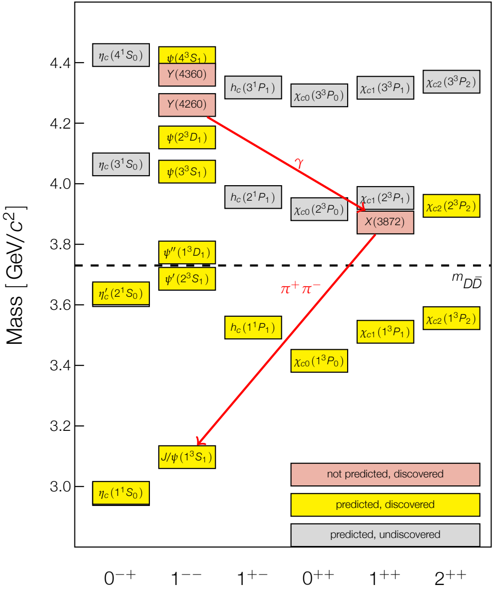
20.1 ± 4.5 events

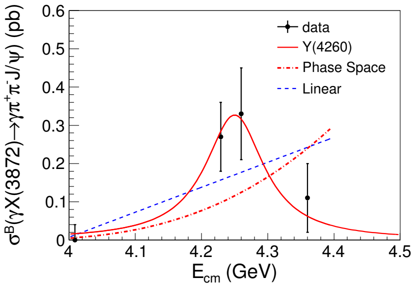
significance 6.3σ

$M = 3871.9 \pm 0.7 \pm 0.2\,\text{MeV}/c^2$

$e^+e^- \to \gamma X(3872) \to \gamma J/\psi\, \pi^+\pi^-$

BESIII, PRL **112**, 092001 (2014)





Suggestive of
$Y(4260) \to \gamma X(3872)$

Even more surprises

Quite a number of other interesting states seen, mainly by Belle collaboration:

- $Z_c(4430)^+ \to \psi(2S)\pi^+$
  Seen by Belle in 2008 in B decays, not confirmed by BABAR, recently confirmed by LHCb PRL **112**, 222002 (2014)
- $Z_1(4050)^+, Z_2(4250)^+ \to \chi_{c1}\pi^+$
  Seen by Belle in B decays, not significant in BABAR data
- $Z_c(4200)^+ \to J/\psi\,\pi^+$
  Belle, in $\bar{B}^0 \to J/\psi K^-\pi^+$ Phys. Rev. D **90**, 112009 (2014) very broad!
  no $Z_c(3900)^+$ visible here?!
- $Z_b(10610)^+$ and $Z_b(10650)^+ \to \Upsilon(2,3S)\pi^+$
  seen in $b\bar{b}$ sector (PRL **108**, 122001 (2012))

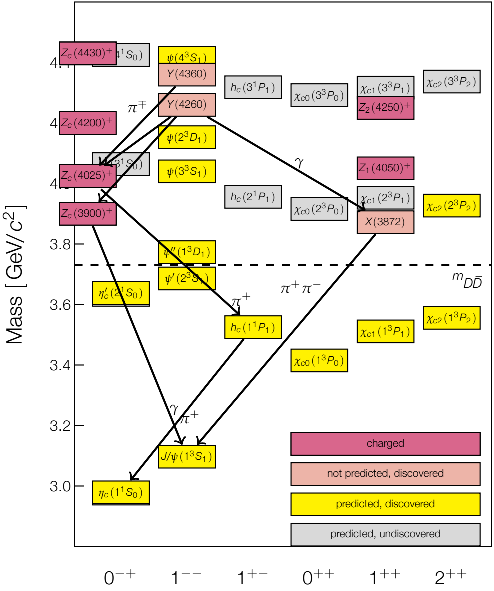
A 'zoo' of exotic (*i.e.* non-$q\bar{q}$) mesons seems to emerge

The list keeps growing …

State	M (MeV)	Γ (MeV)	J^{PC}	Process (decay mode)	Experiment
$X(3872)$	3871.68±0.17	< 1.2	1^{++}	$B \to K + (J/\psi\,\pi^+\pi^-)$	Belle [82, 89] , BaBar [85], LHCb [90]
				$p\bar{p} \to (J/\psi\,\pi^+\pi^-) + ...$	CDF [83, 91, 92, 125], D0 [84]
				$B \to K + (J/\psi\,\pi^+\pi^-\pi^0)$	Belle [94] , BaBar [59]
				$B \to K + (D^0\bar{D}^0\pi^0)$	Belle [95] , BaBar [96]
				$B \to K + (J/\psi\,\gamma)$	BaBar [126], Belle [127] , LHCb [128]
				$B \to K + (\psi'\,\gamma)$	BaBar [126], Belle [127] , LHCb [128]
				$pp \to (J/\psi\,\pi^+\pi^-) + ...$	LHCb [86], CMS [87]
$X(3915)$	3917.4 ± 2.7	$28^{+10}_{-\ 9}$	0^{++}	$B \to K + (J/\psi\,\omega)$	Belle [58] , BaBar [59]
				$e^+e^- \to e^+e^- + (J/\psi\,\omega)$	Belle [60] , BaBar [61]
$\chi_{c2}(2P)$	3927.2 ± 2.6	24±6	2^{++}	$e^+e^- \to e^+e^- + (D\bar{D})$	Belle [64] , BaBar [65]
$X(3940)$	3942^{+9}_{-8}	37^{+27}_{-17}	$0(?)^{-(?)+}$	$e^+e^- \to J/\psi + (D^*\bar{D})$	Belle [27]
				$e^+e^- \to J/\psi + (...)$	Belle [26]
$G(3900)$	3943 ± 21	52±11	1^{--}	$e^+e^- \to \gamma + (D\bar{D})$	BaBar [129], Belle [130]
$Y(4008)$	$4008^{+121}_{-\ 49}$	226±97	1^{--}	$e^+e^- \to \gamma + (J/\psi\,\pi^+\pi^-)$	Belle [32]
$Y(4140)$	4144 ± 3	17 ± 9	$?^{?+}$	$B \to K + (J/\psi\,\phi)$	CDF [74, 75], CMS [77]
$X(4160)$	4156^{+29}_{-25}	139^{+113}_{-65}	$0(?)^{-(?)+}$	$e^+e^- \to J/\psi + (D^*\bar{D})$	Belle [27]
$Y(4260)$	4263^{+8}_{-9}	95±14	1^{--}	$e^+e^- \to \gamma + (J/\psi\,\pi^+\pi^-)$	BaBar [30, 131], CLEO [132] , Belle [32]
				$e^+e^- \to (J/\psi\,\pi^+\pi^-)$	CLEO [133]
				$e^+e^- \to (J/\psi\,\pi^0\pi^0)$	CLEO [133]
$Y(4274)$	4292 ± 6	34 ± 16	$?^{?+}$	$B \to K + (J/\psi\,\phi)$	CDF [75], CMS [77]
$X(4350)$	$4350.6^{+4.6}_{-5.1}$	$13.3^{+18.4}_{-10.0}$	$0/2^{++}$	$e^+e^- \to e^+e^-\ (J/\psi\,\phi)$	Belle [81]
$Y(4360)$	4361 ± 13	74±18	1^{--}	$e^+e^- \to \gamma + (\psi'\,\pi^+\pi^-)$	BaBar [31], Belle [33]
$X(4630)$	$4634^{+\ 9}_{-11}$	92^{+41}_{-32}	1^{--}	$e^+e^- \to \gamma\,(\Lambda_c^+\Lambda_c^-)$	Belle [134]
$Y(4660)$	4664±12	48±15	1^{--}	$e^+e^- \to \gamma + (\psi'\,\pi^+\pi^-)$	Belle [33]
$Z_c^+(3900)$	3890 ± 3	33 ± 10	1^{+-}	$Y(4260) \to \pi^- + (J/\psi\,\pi^+)$	BESIII [39], Belle [40]
				$Y(4260) \to \pi^- + (D\bar{D}^*)^+$	BESIII [56]
$Z_c^+(4020)$	4024 ± 2	10 ± 3	$1(?)^{+(?)-}$	$Y(4260) \to \pi^- + (h_c\,\pi^+)$	BESIII [41]
				$Y(4260) \to \pi^- + (D^*\bar{D}^*)^+$	BESIII [42]
$Z_1^+(4050)$	4051^{+24}_{-43}	82^{+51}_{-55}	$?^{?+}$	$B \to K + (\chi_{c1}\,\pi^+)$	Belle [43], BaBar [53]
$Z^+(4200)$	4196^{+35}_{-32}	370^{+99}_{-149}	1^{+-}	$B \to K + (J/\psi\,\pi^+)$	Belle [51]
$Z_2^+(4250)$	$4248^{+185}_{-\ 45}$	$177^{+321}_{-\ 72}$	$?^{?+}$	$B \to K + (\chi_{c1}\,\pi^+)$	Belle [43], BaBar [53]
$Z^+(4430)$	4477 ± 20	181 ± 31	1^{+-}	$B \to K + (\psi'\,\pi^+)$	Belle [44, 46, 47], LHCb [48]
				$B \to K + (J\psi\,\pi^+)$	Belle [51]
$Y_b(10890)$	10888.4±3.0	$30.7^{+8.9}_{-7.7}$	1^{--}	$e^+e^- \to (\Upsilon(nS)\,\pi^+\pi^-)$	Belle [117]
$Z_b^+(10610)$	10607.2±2.0	18.4±2.4	1^{+-}	"$\Upsilon(5S)$" $\to \pi^- + (\Upsilon(nS)\,\pi^+)$, $n = 1, 2, 3$	Belle [119, 122]
				"$\Upsilon(5S)$" $\to \pi^- + (h_b(nP)\,\pi^+)$, $n = 1, 2$	Belle [119]
				"$\Upsilon(5S)$" $\to \pi^- + (B\bar{B}^*)^+$, $n = 1, 2$	Belle [123]
$Z_b^0(10610)$	10609± 6		1^{+-}	"$\Upsilon(5S)$" $\to \pi^0 + (\Upsilon(nS)\,\pi^0)$, $n = 1, 2, 3$	Belle [121]
$Z_b^+(10650)$	10652.2±1.5	11.5±2.2	1^{+-}	"$\Upsilon(5S)$" $\to \pi^- + (\Upsilon(nS)\,\pi^+)$, $n = 1, 2, 3$	Belle [119]
				"$\Upsilon(5S)$" $\to \pi^- + (h_b(nP)\,\pi^+)$, $n = 1, 2$	Belle [119]
				"$\Upsilon(5S)$" $\to \pi^- + (B^*\bar{B}^*)^+$, $n = 1, 2$	Belle [123]

S. Olsen, arXiv:1411.7738

Summary

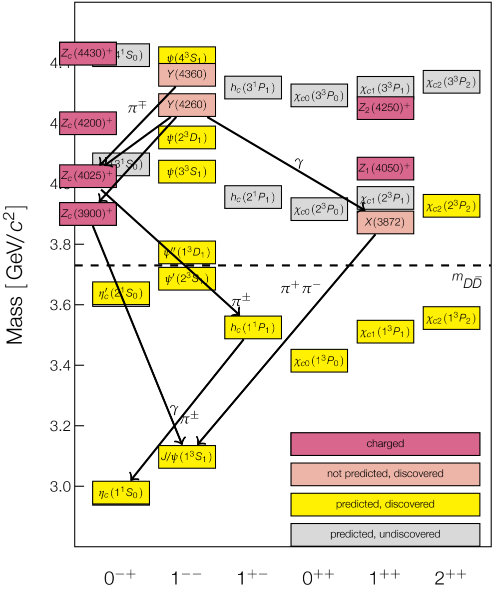


- Quark model describes charmonium states $c\bar{c}$ reasonably well
- *XYZ* states: unexpected, point to non-conventional states ($c\bar{c}g$, $cq\bar{q}\bar{c}$, $(\bar{c}q)(\bar{q}c)$, $c\bar{c}\pi\pi$ ...)
- Observation of transitions between *XYZ* states

➡ Start making connections between new, exotic states

➡ Dynamically generated at thresholds, or new kind of QCD bound states?

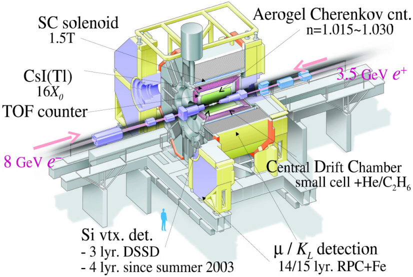
Summary

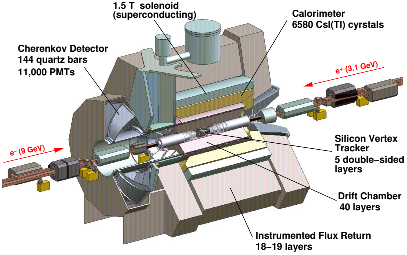


- Structure of *XYZ* to be clarified; learn more about strongly bound systems
- More detailed studies (PWA, other channels …)
  at BESIII ongoing
- Future:
  More data from BESIII
  LHCb spectroscopy
  Belle-II will start 2017
- Exciting times ahead


謝謝！

The B factories Belle and BABAR





mainly $e^+e^- \to \Upsilon(4S) \to B\bar{B}$
Asymmetric beam energies

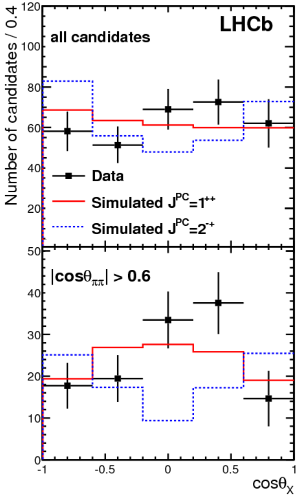
- KEK-B: 8 GeV e^- × 3.5 GeV e^+
- $\mathcal{L}_{\text{int}} \approx 1\,\text{ab}^{-1}$
- Data taking finished 2010

- PEP-II: 9 GeV e^- × 3.1 GeV e^+
- $\mathcal{L}_{\text{int}} \approx 530\,\text{fb}^{-1}$
- Data taking finished 2008

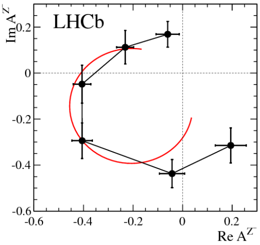
The $Z_c(4430)^+$ in $B^0 \to \psi' K^+ \pi^-$

LHCb, PRL **112**, 222002 (2014)

Spin-Parity assignment



Phase motion



behaves like a 'true' resonance

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