XYZ states at BESIII

Wolfgang Gradl

on behalf of the BESIII collaboration

HISKP Kolloquium
Bonn, 14th July 2015

THE LOW-ENERGY FRONTIER
OF THE STANDARD MODEL

JOHANNES GUTENBERG
UNIVERSITÄT MAINZ

Outline

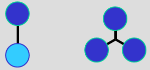
- Introduction: charmonium spectroscopy
- New (conventional) charmonium state: $\psi_2(1^3D_2)$
- Exotic charmonium(-like) states: the X, Y, $\&Z$
- Summary and Outlook

QCD bound systems

States found in nature: colour-neutral combinations

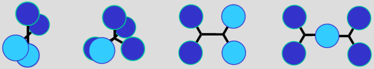
We know

mesons and baryons

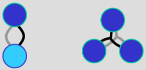


QCD also allows

molecules/multi-quarks



hybrids



glueballs

and more

Totalitarian principle of quantum mechanics:

Everything not forbidden is compulsory

Gell-Mann, borrowing from T. H. White *The once and future king*

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-

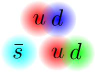
ber $n_t - n_{\bar{t}}$ would be zero for all known baryons and mesons. The most interesting example of such a model is one in which the triplet has spin $\frac{1}{2}$ and $z = -1$, so that the four particles d^-, s^-, u^0 and b^0 exhibit a parallel with the leptons.

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**.

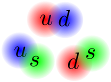
A formal mathematical model based on field theory can be built up for the quarks exactly as for

Multiquark states from QCD diquarks

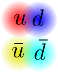
have a new (anti-)triplet of coloured objects: combine them into colour-neutral objects?



pentaquark



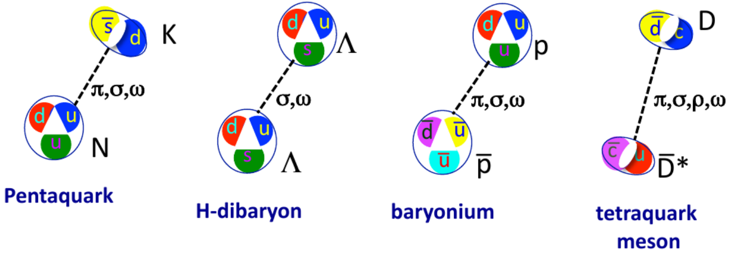
H-dibaryon



tetraquark

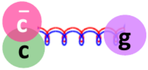
‘exotic hadrons’ loved by particle theorists

Multiquark states from ‘molecules’



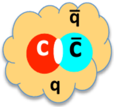
…loved by nuclear theorists

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

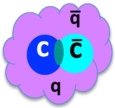


QCD hybrid

Glueball



hadrocharmonium



adjoint charmonium

Where are they?

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 T. Barnes, hep-ph/0510365

Where are they?

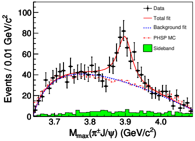
The absence of exotics is one of the most obvious features of QCD.

R. Jaffe, hep-ph/0409065

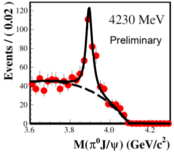
The story of the pentaquark shows how poorly we understand QCD.

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

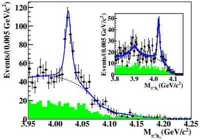
in the past few years, compelling evidence for states beyond simple $q\bar{q}$!



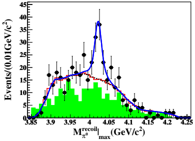
$e^+e^- \to \pi^-\pi^+J/\psi$



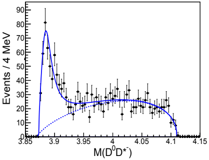
$e^+e^- \to \pi^0\pi^0J/\psi$



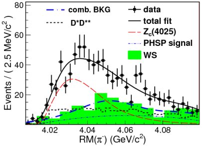
$e^+e^- \to \pi^-\pi^+h_c$



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



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

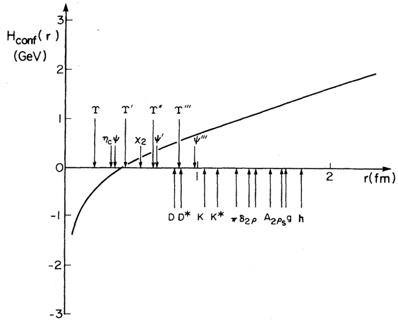


$e^+e^- \to \pi^-(D^*\bar{D}^*)^+$

Charmonium Spectroscopy

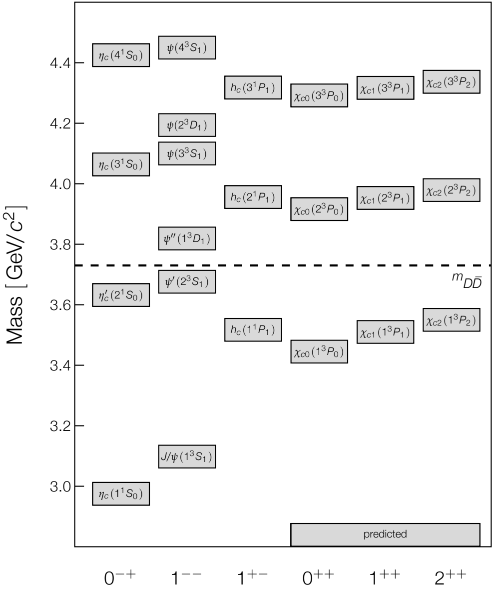
Charmonium and charmonium-like states useful for this search:

- $m_c \approx 1.3\,\text{GeV}$: 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 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!

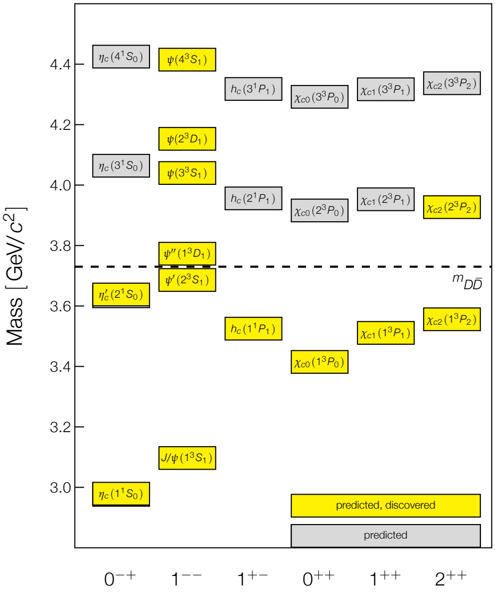
Godfrey & Isgur, PRD 32, 189 (1985);
Barnes, Godfrey & Swanson,
PRD 72, 054026 (2005)

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!

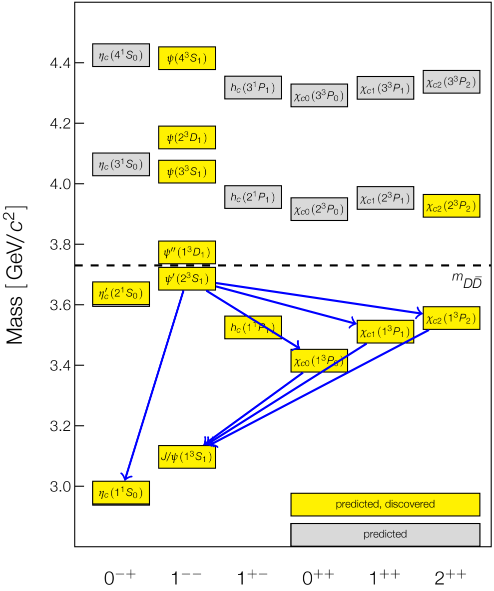
Godfrey & Isgur, PRD 32, 189 (1985);
Barnes, Godfrey & Swanson,
PRD 72, 054026 (2005)

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!

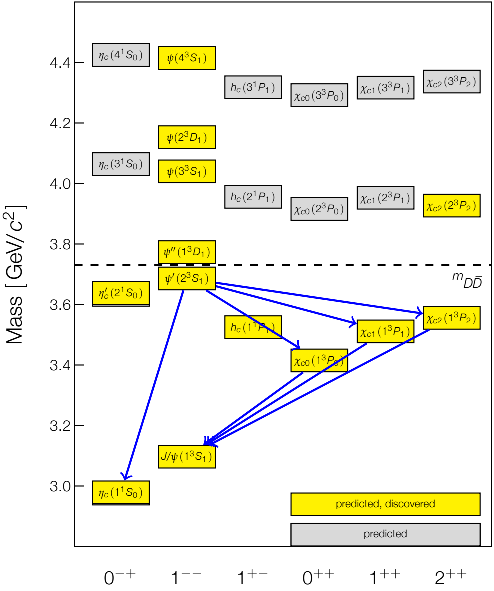
Godfrey & Isgur, PRD 32, 189 (1985);
Barnes, Godfrey & Swanson,
PRD 72, 054026 (2005)

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

➡ Remarkably good description

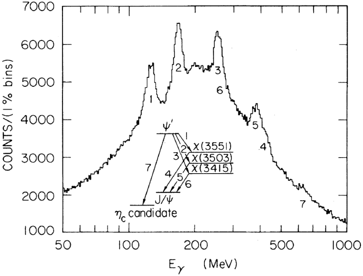
above $D\bar{D}$ threshold: some mass shifts

Charmonium spectrum



Charmonium: $c\bar{c}$

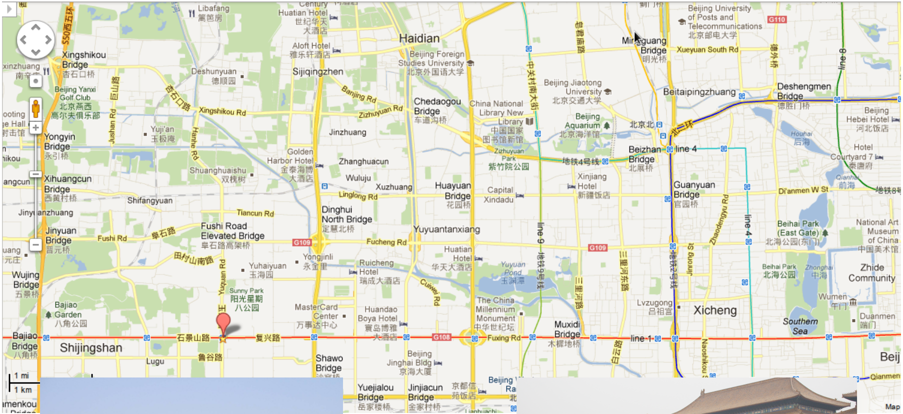
Crystal Ball at SLAC
discovery of η_c



PRL 45, 1150 (1980)

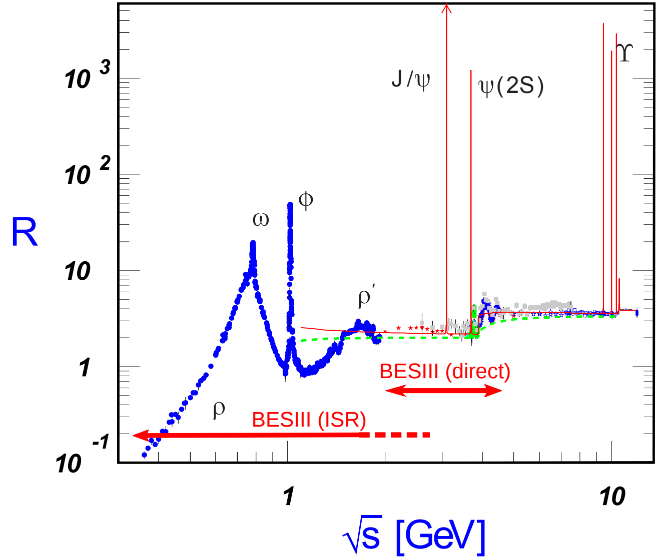
BESIII: a τ-charm factory

BEPCII and BESIII

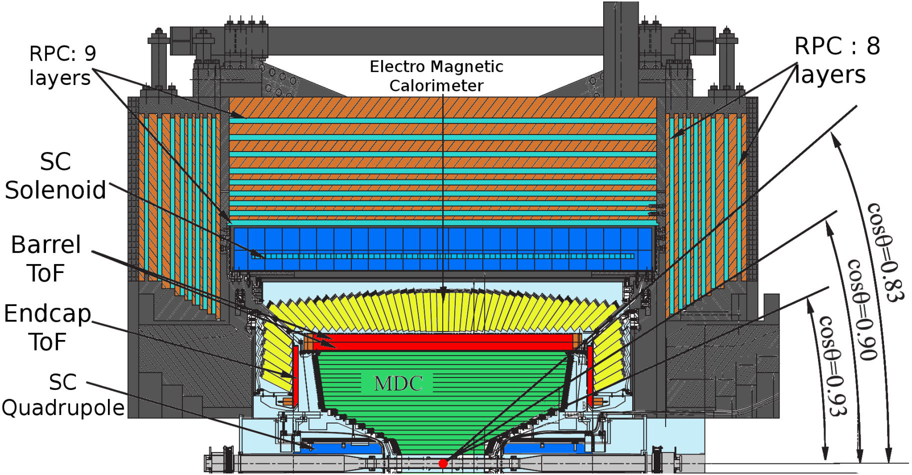


BEPCII and BESIII

A τ-charm factory



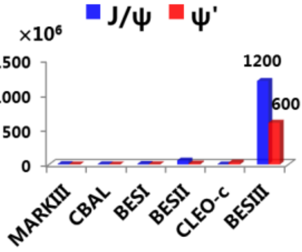
BESIII detector

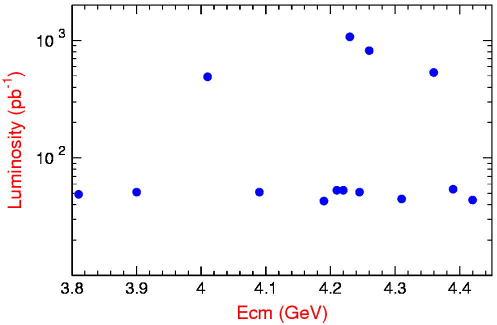


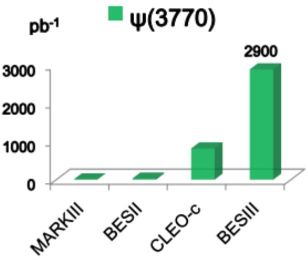
Completely new detector

Comparable performance to CLEO-c, + muon ID

BESIII data sets





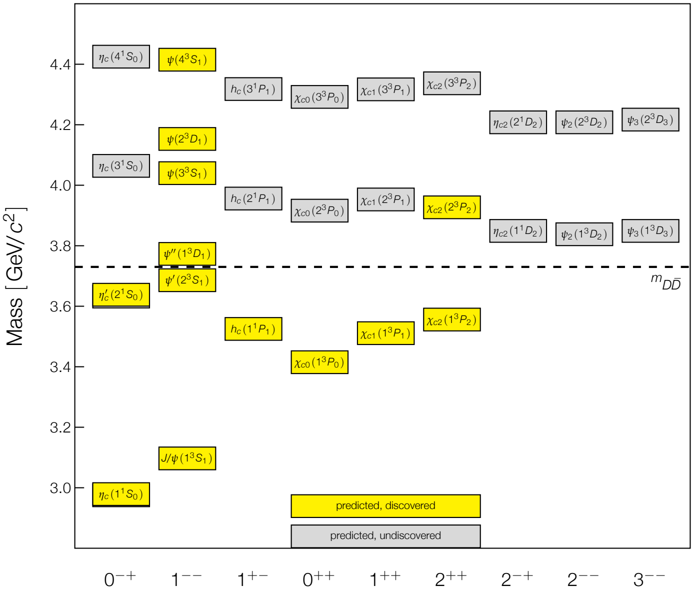


+ 104 energy points between 3.85 and 4.59 GeV
+ ~ 20 energy points between 2.0 and 3.1 GeV

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

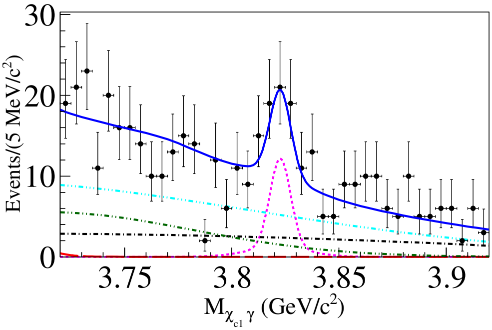
A new conventional $c\bar{c}$ state

Higher charmonium states



The $X(3823)$ at Belle

PRL **111**, 032001 (2013)



Using full Belle data set of $772 \times 10^6 B\bar{B}$

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

3.8σ evidence

$M = 3823.1 \pm 1.8 \pm 0.7\,\mathrm{MeV}$

very narrow

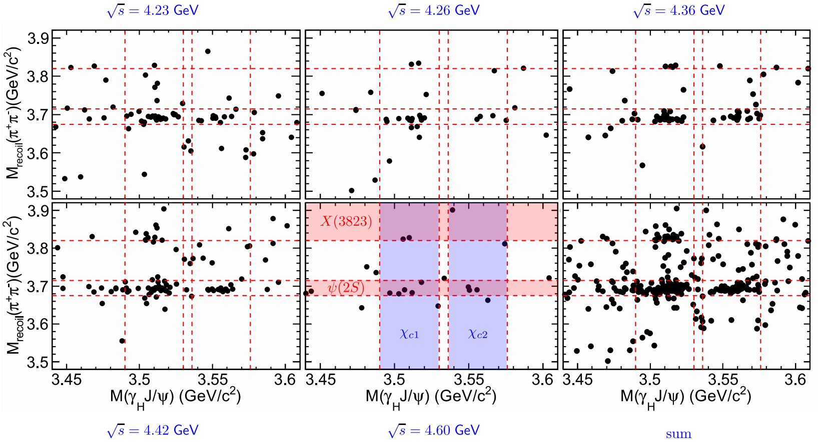
Mass (and width) compatible with $\psi_2(1^3D_2)$ state

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

PRL **115**, 011803

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

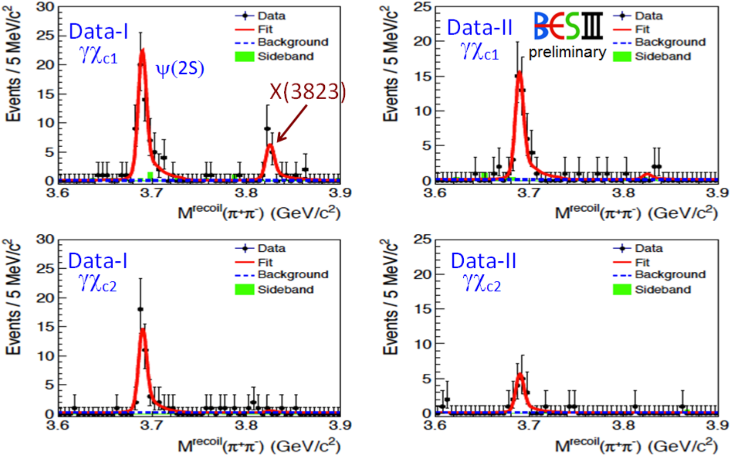
Use 5 large data sets (total luminosity $\sim 4.1\,\text{fb}^{-1}$)



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

$\sqrt{s} \geq 4.36\,\mathrm{GeV}$ $\sqrt{s} = 4.23, 4.26\,\mathrm{GeV}$

PRL **115**, 011803



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

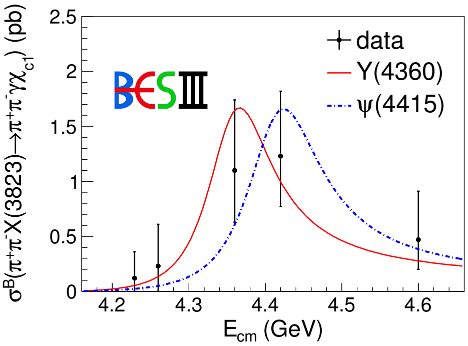
$\Gamma < 16\,\mathrm{MeV}$ at 90% C.L.

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

PRL **115**, 011803

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 prediction for 1^3D_2
predicted to be narrow!

Production ratio

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

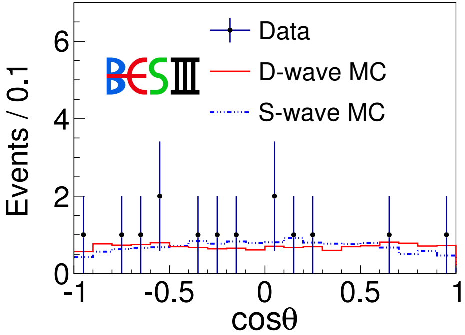
~ 0.2 prediction

< 0.43 at 90% C.L.

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

PRL **115**, 011803

Angular distribution $\theta \equiv \angle(\pi\pi, \psi_2)$
assuming $\pi\pi$ system in S-wave: $1 + \cos^2\theta$ for spin 2



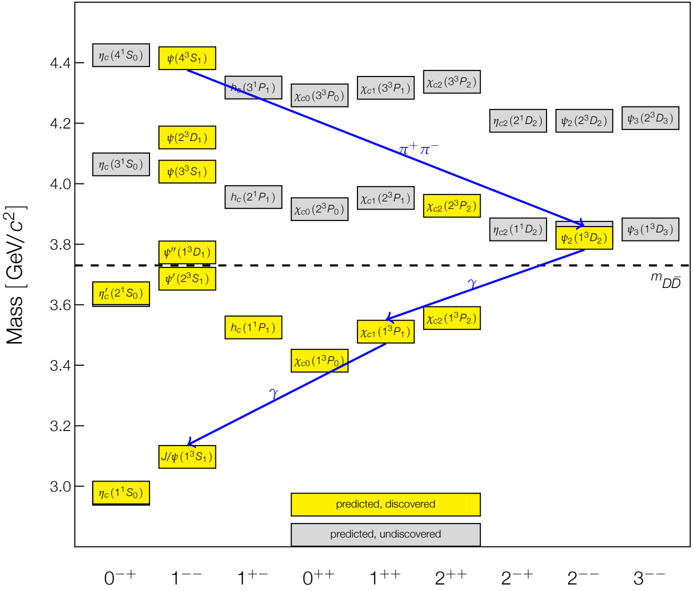
Mass and width $\sim$ in agreement with potential model prediction for 1^3D_2
predicted to be narrow!

J^P by exclusion:
$1^1D_2 \to \gamma\chi_{c1}$ forbidden
$1^3D_3 \to \gamma\chi_{c1}$ has zero amplitude

Good candidate for $\psi_2(1^3D_2)$

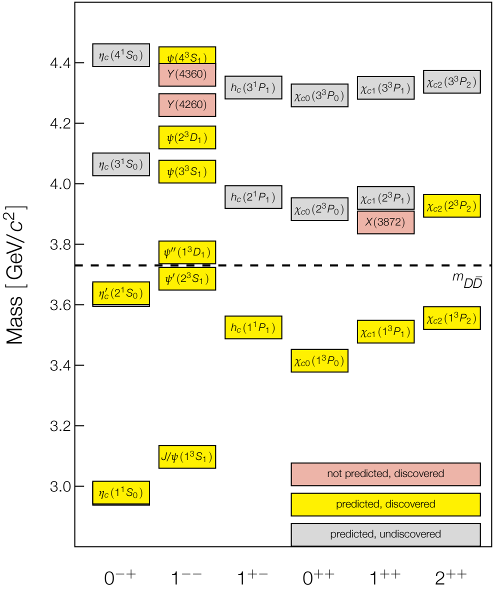
Not enough statistics to distinguish S and D wave from data

Higher charmonium states — a new family member!

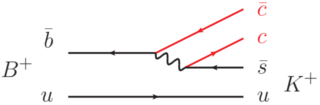


Exotic states: the *X* and *Y*

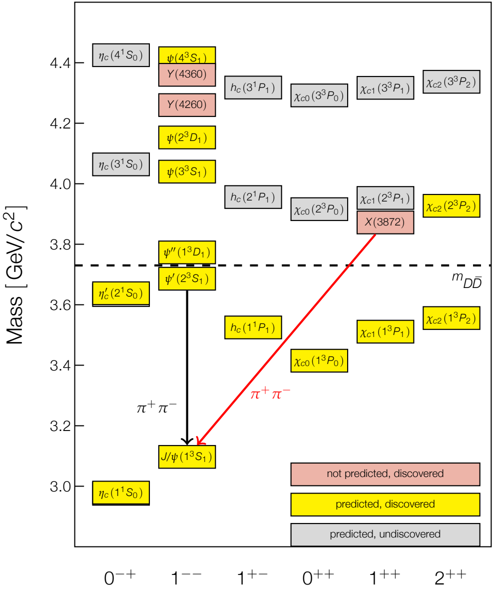
Surprising discoveries: the XYZ states



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

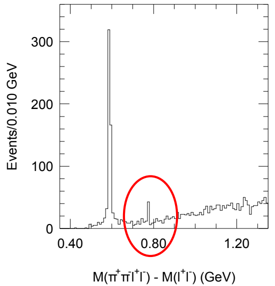


Surprising discoveries: the XYZ states



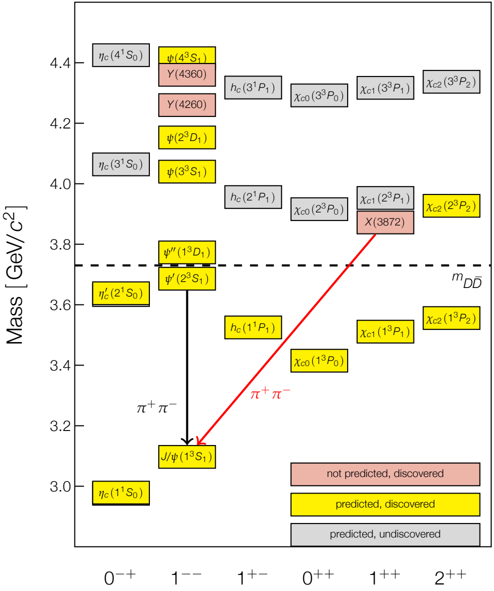
Most of the ‘XYZ’ states discovered at Belle and BABAR in e^+e^- collisions in bottomonium region

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

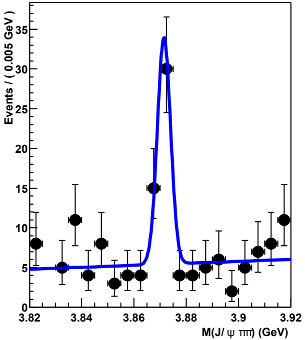


Belle, PRL 91, 262001 (2003)

The $X(3872)$



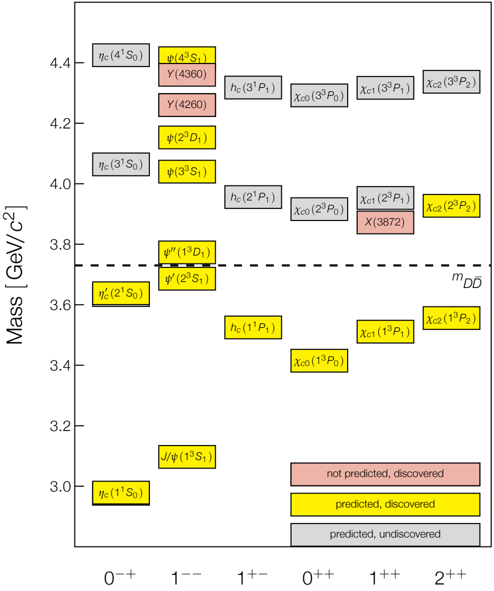
Extremely narrow, sits at or just below the DD^* threshold



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

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

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

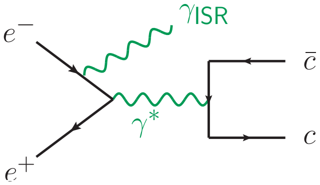


e^+e^- collisions near $\Upsilon(4S)$

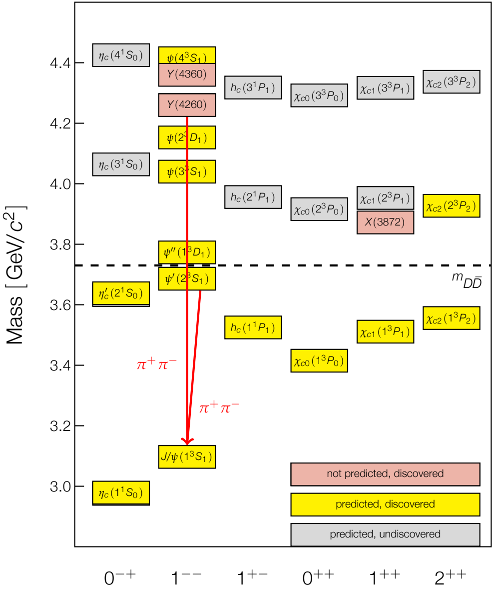
in ISR production

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

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



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

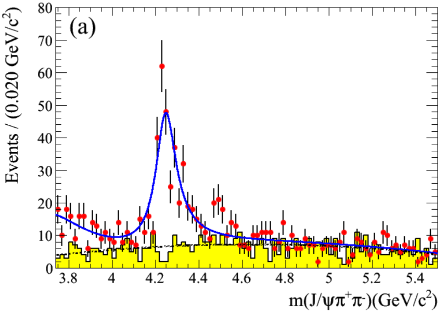


e^+e^- collisions near $\Upsilon(4S)$

in ISR production

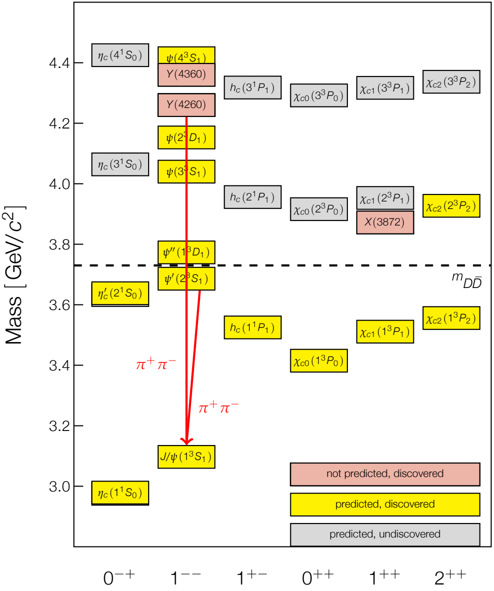
$e^+e^- \to \gamma_{\text{ISR}} J/\psi\, \pi^+\pi^-$

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



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

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



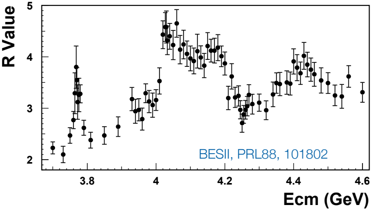
… $Y(4260) \to J/\psi\, \pi^+\pi^-$

… $Y(4360) \to \psi(2S)\pi^+\pi^-$

… additional state at 4660 MeV

- supernumerary states:
  all 1^{--} slots already taken

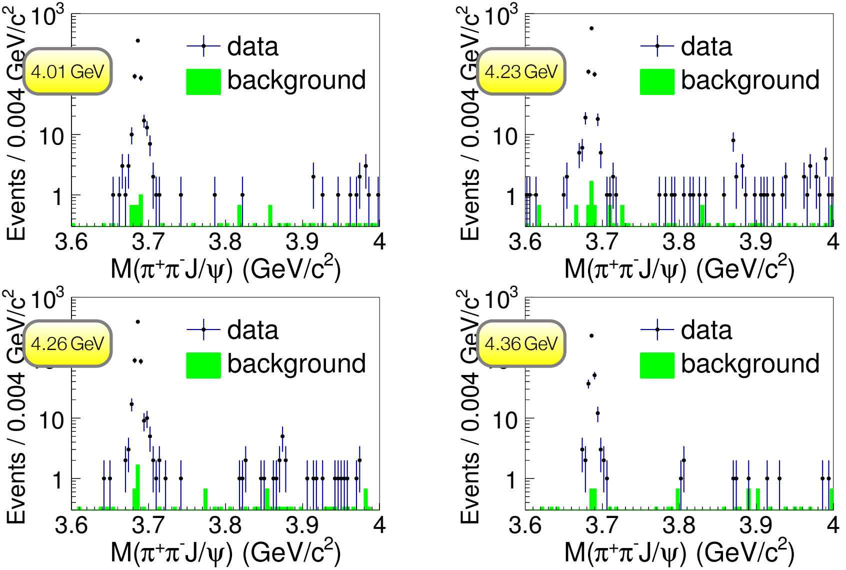
➡ do not correspond to peaks in $\sigma(e^+e^- \to \text{hadrons})$



➡ produce them directly at BESIII!

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

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

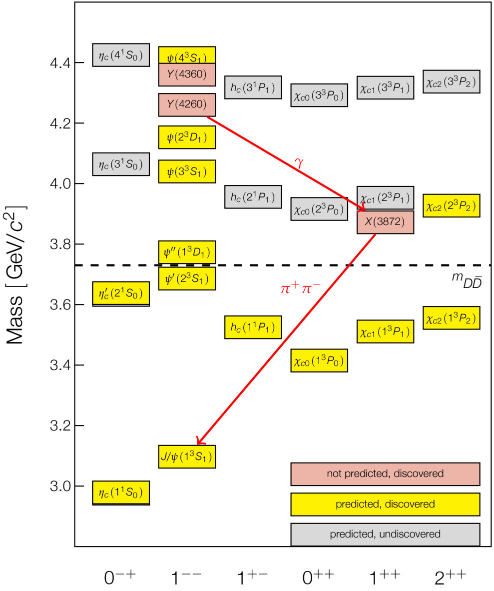


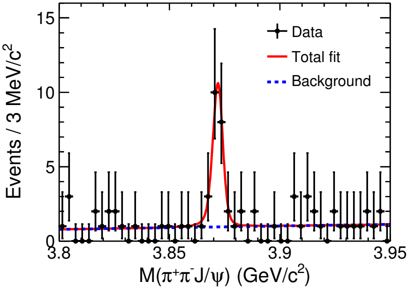
Clear ISR ψ' signal for validation

$X(3872)$ 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

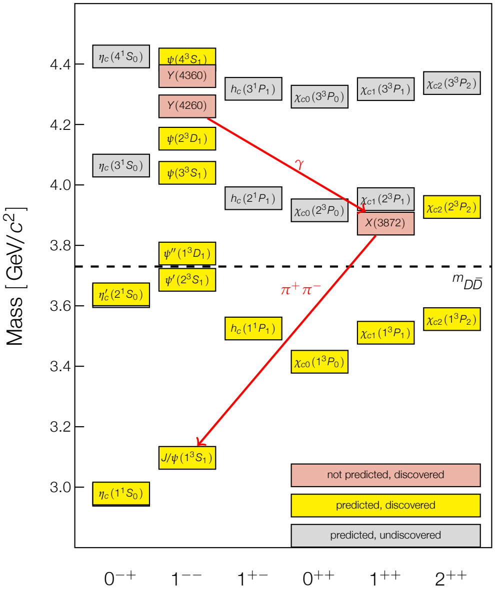
significance 6.3σ

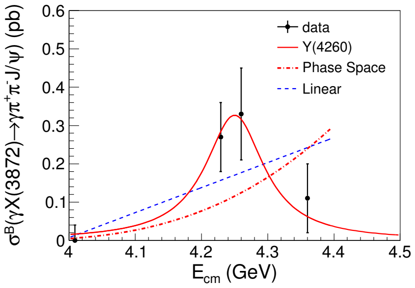
$M = 3871.9 \pm 0.7 \pm 0.2\,\mathrm{MeV}/c^2$

[PDG2013:
$3871.68 \pm 0.17\,\mathrm{MeV}/c^2$]

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

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





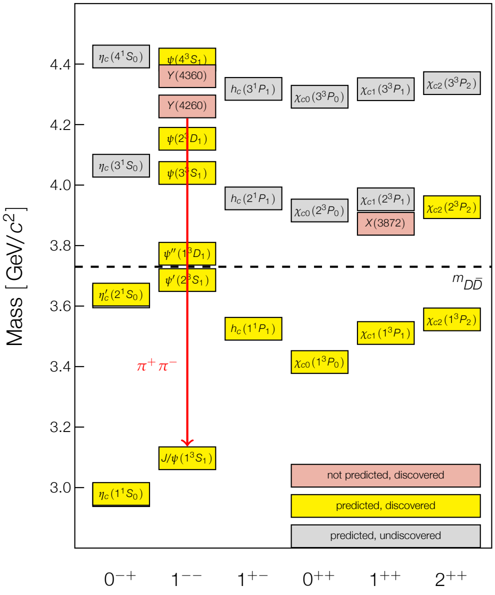
Suggestive of radiative transition
$Y(4260) \to \gamma X(3872)$

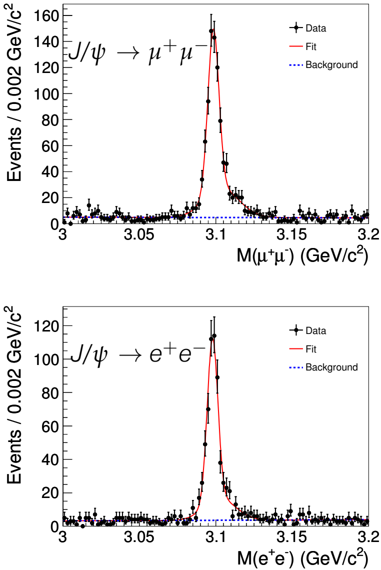
Direct connection between the two states?

The Z_c family

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

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

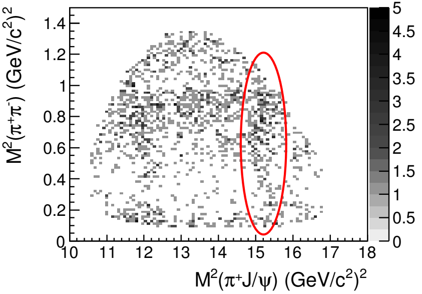


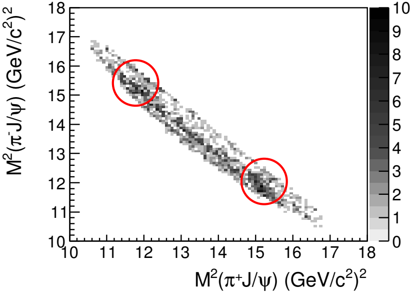


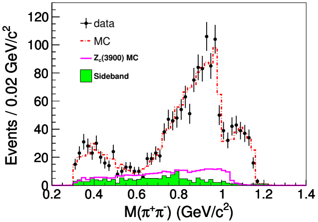
…have hundreds of events!

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

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



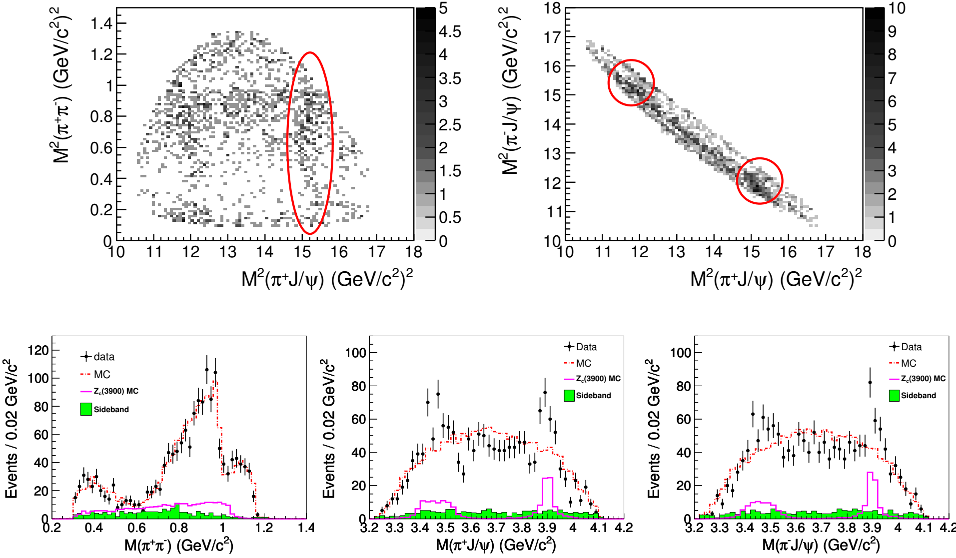




Model $\pi^+\pi^-$-system with known structure:
$f_0(500)$, $f_0(980)$, non-resonant
obtain good fit of $\pi^+\pi^-$ mass projection

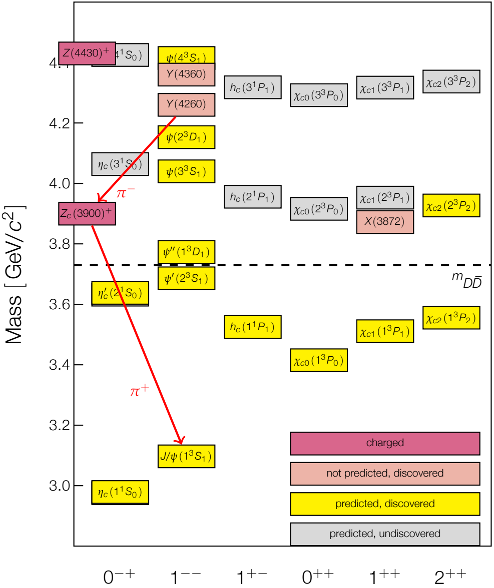
$J/\psi\,\pi^+\pi^-$ Dalitz plot

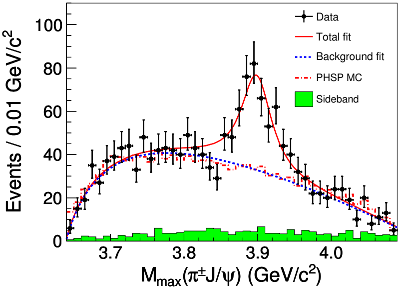
BESIII, PRL **110**, 252001 (2013)



$e^+e^- \to J/\psi\, \pi^+\pi^-$ 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
Interpretation?

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

preliminary
arXiv:1506.06018

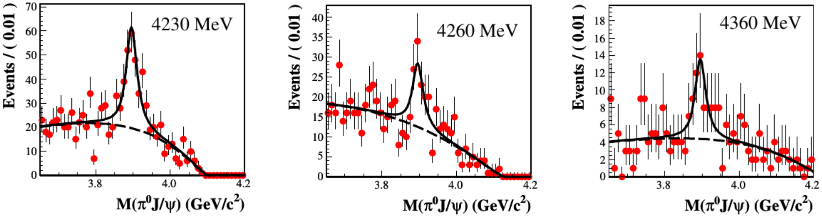
If $Z_c(3900)^+$ is not just an artefact of analysis:
expect state completing isospin triplet, with decay $Z_c(3900)^0 \to \pi^0 J/\psi$

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

BESIII
preliminary
arXiv:1506.06018

If $Z_c(3900)^+$ is not just an artefact of analysis:
expect state completing isospin triplet, with decay $Z_c(3900)^0 \to \pi^0 J/\psi$

Study $e^+e^- \to \pi^0\pi^0 J/\psi$ with large data sets at three different $\sqrt{s}$

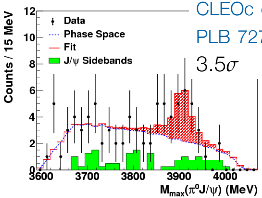


Structure in $\pi^0 J/\psi$ invariant mass clearly visible at all energies

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

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

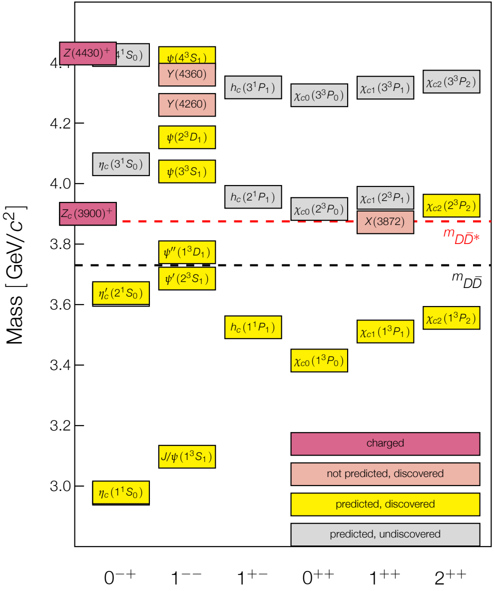
Significance 10σ



CLEOc data,
PLB 727, 366 (2013)
3.5σ

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

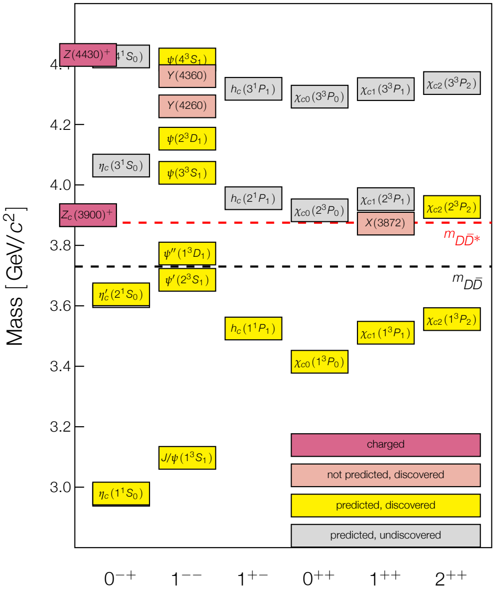
BESIII, PRL **112**, 022001 (2014)



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

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

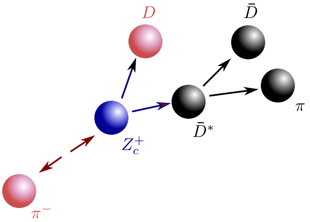
BESIII, PRL **112**, 022001 (2014)



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

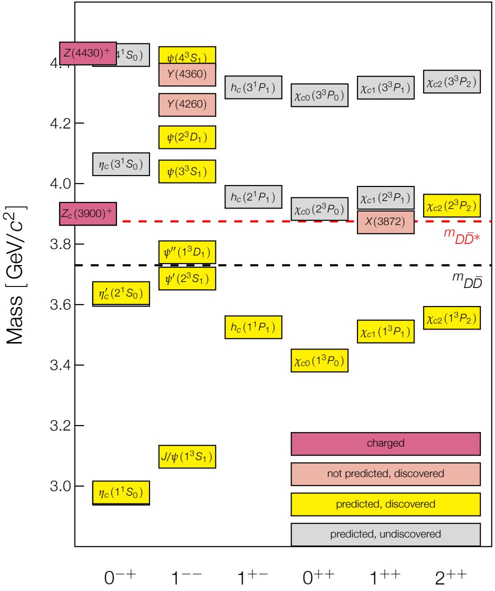
Single tag analysis:

- 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^+

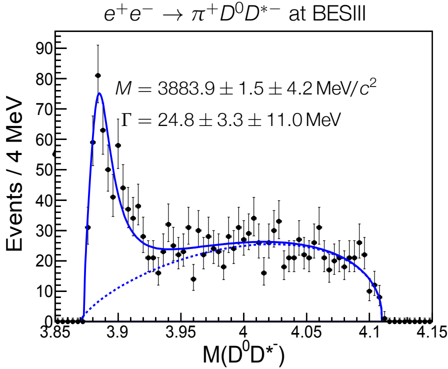


$Z_c(3900)^+$ at $D\bar{D}^*$ threshold

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



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

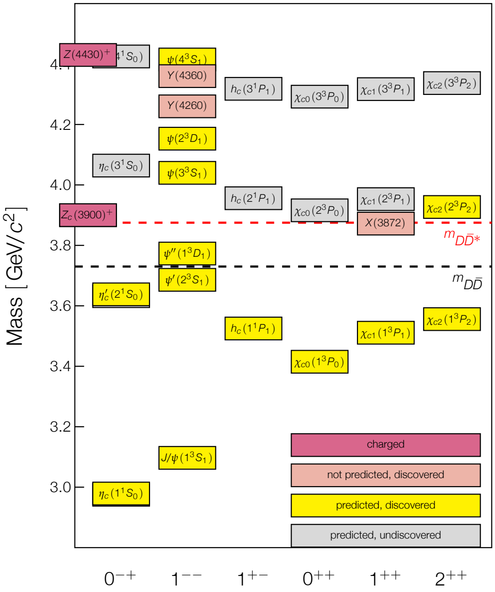


…and BESIII sees structure in $(DD^*)^{\pm}$

Large systematics due to non-Z_c signal shape

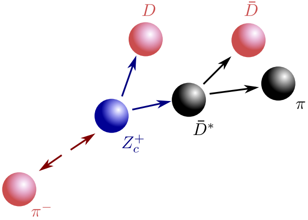
$Z_c(3900)^+$ at $D\bar{D}^*$ threshold

BESIII preliminary



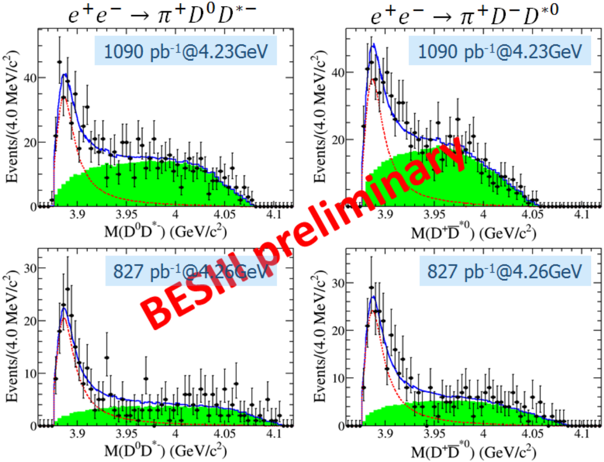
New: Double tag analysis

- reconstruct 'bachelor' π^+ and D^0, D^- in 4 or 6 decay modes
- kinematic fit, requiring π from D^* in missing mass essentially background-free D^*
- improved statistics, much better control over background shape, improved systematics
- $M^{\text{recoil}}(\pi^+) = M(D\bar{D}^*)$



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

preliminary



Simultaneous fit with phase space shape + $(BW \otimes \mathcal{R}) \times \varepsilon$
Compatible with, but significantly more precise, than single-tag analysis

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

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

$e^+e^- \to \pi^+(D\bar{D}^*)^-$ with double tags: Results

BESIII preliminary

		BESIII single D tags PRL 112, 022001	BESIII double D tags preliminary
$M_{\text{pole}}\,[\text{MeV}/c^2]$		$3883.9 \pm 1.5(\text{stat}) \pm 4.2(\text{syst})$	$3884.3 \pm 1.2(\text{stat}) \pm 1.5(\text{syst})$
$\Gamma_{\text{pole}}\,[\text{MeV}]$		$24.8 \pm 3.3(\text{stat}) \pm 11.0(\text{syst})$	$23.8 \pm 2.1(\text{stat}) \pm 2.6(\text{syst})$
$\sigma \times \mathcal{B}[\text{pb}]$	4.23 GeV		$106.8 \pm 7.1(\text{stat}) \pm 9.5(\text{syst})$
	4.26 GeV	$83.5 \pm 6.6(\text{stat}) \pm 22.0(\text{syst})$	$88.0 \pm 6.1(\text{stat}) \pm 7.9(\text{syst})$

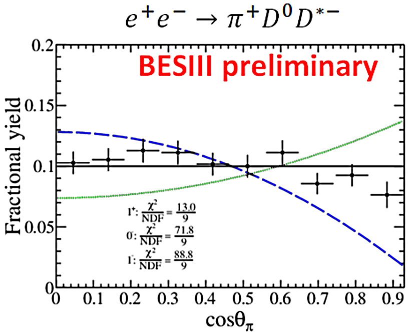
$$\sigma \times \mathcal{B} \equiv \sigma(e^+e^- \to \pi^\pm Z_c(3885)^\mp) \times \mathcal{B}(Z_c(3885)^\mp \to (D\bar{D}^*)^\mp)$$

$Z_c(3885)^+$ Quantum numbers?

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: ➡ $dN/d\cos\theta_\pi \propto 1$



Efficiency corrected event yield in 10 bins in $|\cos\theta_\pi|$

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

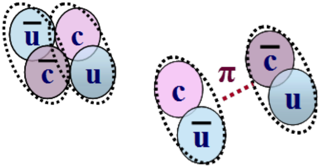
confirms J^P for $Z_c(3885)$ from single-tags

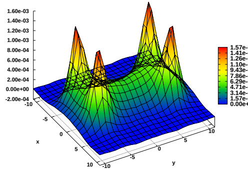
Interpretation of $Z_c(3900)$?

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

Interpretation of $Z_c(3900)$?

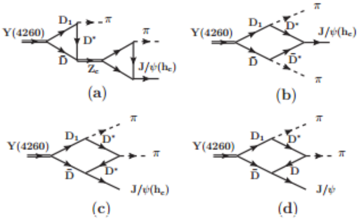
- Mass close to DD^* threshold
- Couples strongly to $c\bar{c}$
- Has electric charge
- If new particle:
  ➡ necessarily exotic,
  quark contents at least $c\bar{c}u\bar{d}$

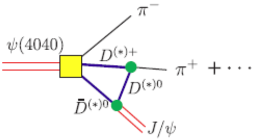




So, what is it?

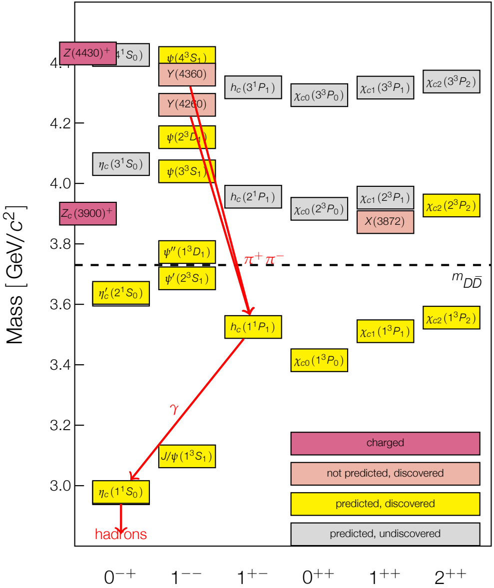
- Tetraquark L. Maiani, A. Ali et al.
- Hadronic molecule U.-G. Meissner, F.K. Guo et al.
- Hadro-charmonium M. B. Voloshin
- Meson loop Q. Zhao et al.
- ISPE model X. Liu et al.
- Threshold cusp E. Swanson
- …





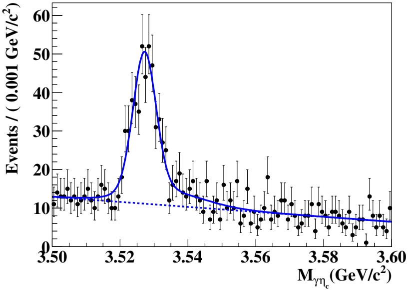
$e^+e^- \to h_c(1P)\pi^+\pi^-$

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



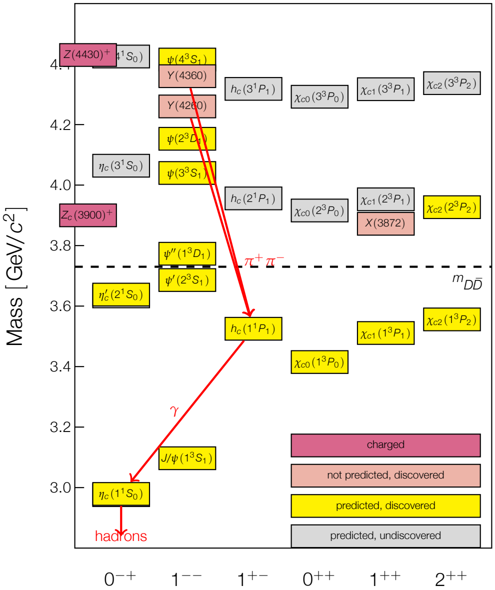
Exclusively reconstruct the process

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



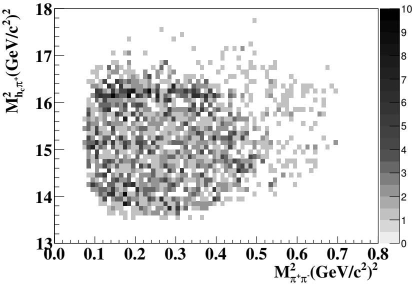
$e^+e^- \to h_c(1P)\pi^+\pi^-$

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



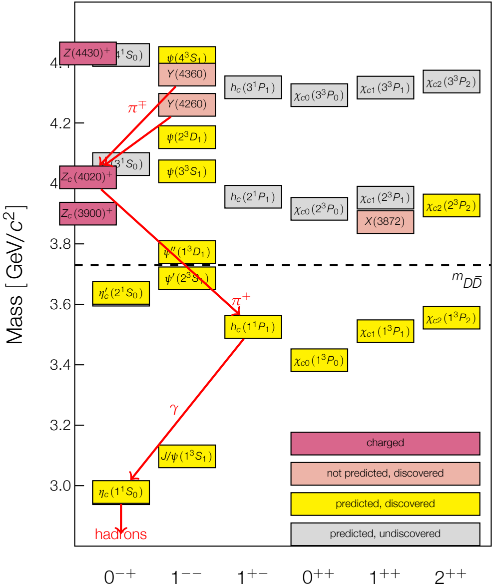
Exclusively reconstruct the process

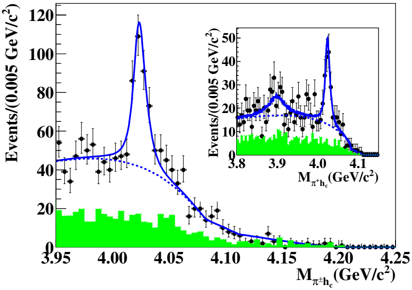
$$e^+e^- \to \pi^+\pi^- h_c(1P)$$
$$h_c(1P) \to \gamma\eta_c(1S)$$
$$\eta_c(1S) \to \text{16 decay channels}$$



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

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





Charged charmonium-like structure
close to $D^*\bar{D}^*$ threshold

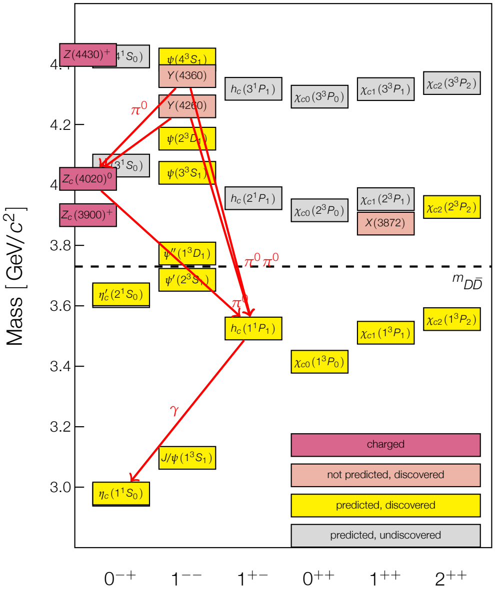
$$M = 4022.9 \pm 0.8 \pm 2.7\,\mathrm{MeV}/c^2$$

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

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

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

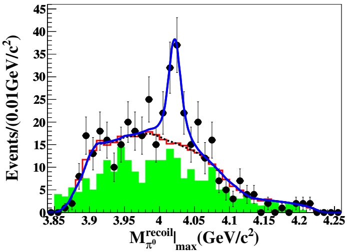
BESIII, PRL **113**, 212002 (2014)



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 $Z_c(4020)^+$



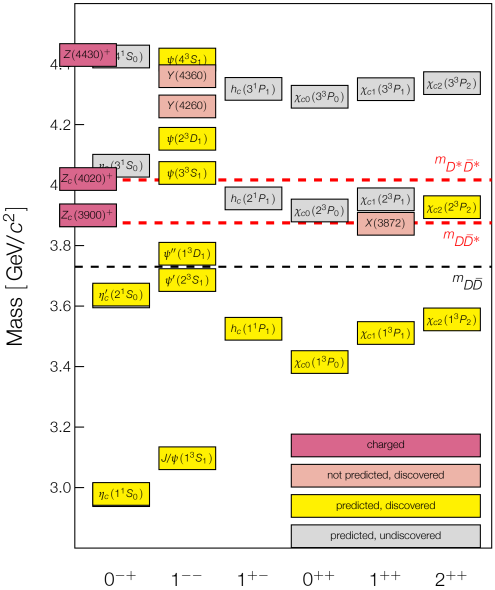
$M = 4023.6 \pm 4.5\,\mathrm{MeV}/c^2$

Γ fixed in the fit

Isospin triplet found!

Yet another mass threshold …

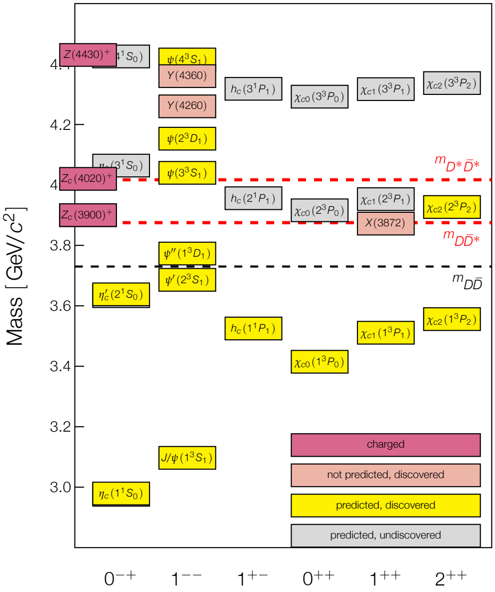
BESIII, PRL **112**, 132001 (2014)



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

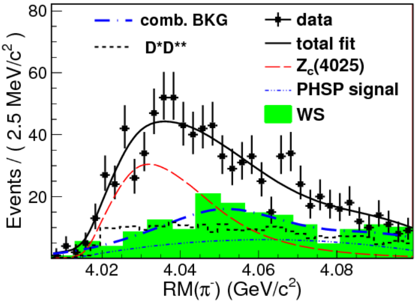
Yet another mass threshold …

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



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

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



…and BESIII sees structure in D^*D^*

$$M = 4026.3 \pm 2.6 \pm 3.7\,\mathrm{MeV}/c^2$$

$$\Gamma = 24.8 \pm 5.6 \pm 7.7\,\mathrm{MeV}$$

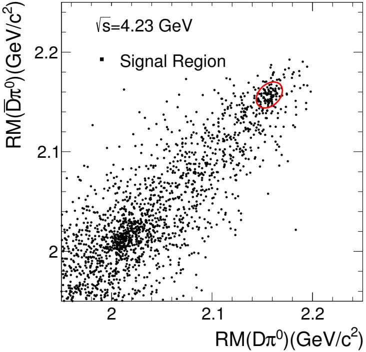
… and a neutral partner: $Z_c(4025)^0$

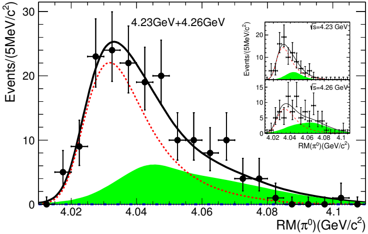
BESIII preliminary

$$e^+e^- \to (D^*\bar{D}^*)^0\pi^0$$
$$\to (D^{*0}\bar{D}^{*0})\pi^0 + (D^{*+}D^{*-})\pi^0$$

Use partial reconstruction technique:

- Reconstruct D, $\bar{D}$, and bachelor π^0
- Infer presence of D^* by selecting on mass recoiling against $\bar{D}\pi^0$





Combine data sets at $\sqrt{s} = 4.23,\ 4.26\,\text{GeV}$

Enhancement at threshold visible

No non-resonant process needed

Fit with $BW \otimes \mathcal{R}$, extract pole position

$$M_{\text{pole}} = (4025.5^{+2.0}_{-4.7} \pm 3.1)\,\text{MeV}/c^2$$
$$\Gamma_{\text{pole}} = (23.0 \pm 6.0 \pm 1.0)\,\text{MeV}$$

… and the neutral partner: $Z_c(4025)^0$

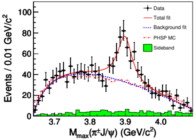
preliminary

Comparison with the $Z_c(4025)^+ \to (D^* \bar{D}^*)^+$:

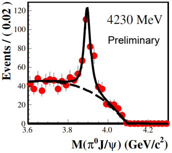
	Mass [MeV/c^2]	**Width [MeV]**	$\sigma(e^+e^- \to Z_c\pi \to D^*\bar{D}^*\pi)$ [pb]
$Z_c(4025)^+$	$4026.3 \pm 2.6 \pm 3.7$	$24.8 \pm 5.6 \pm 7.7$	$42.2 \pm 2.8 \pm 4.6$
$Z_c(4025)^0$	$4025.5^{+2.0}_{-4.7} \pm 3.1$	$23.0 \pm 6.0 \pm 1.0$	$43.4 \pm 8.0 \pm 5.4$

- Almost perfect agreement in resonance parameters
- and cross sections
- very small isospin violation?!

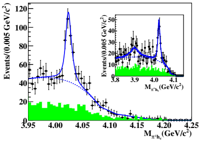
All the Z_cs from BESIII near $\sqrt{s} = 4.3\,\text{GeV}$



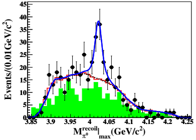
$e^+e^- \to \pi^-\pi^+J/\psi$



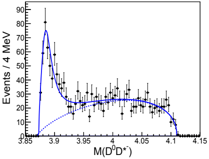
$e^+e^- \to \pi^0\pi^0J/\psi$



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



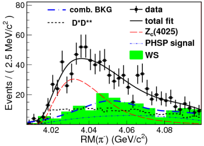
$e^+e^- \to \pi^0\pi^0h_c$



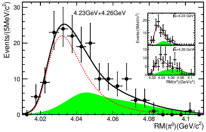
$e^+e^- \to \pi^-(D\bar{D}^*)^+$

BESIII

in progress



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

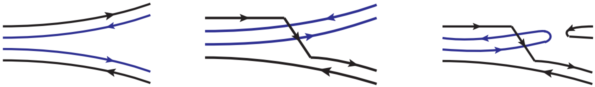


$Z_c(3900)^+$? $Z_c(3900)^0$? $Z_c(4020)^+$? $Z_c(4020)^0$?

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

Other decay modes?

Exploring new decay modes can help to identify nature of structures close to threshold



open charm hidden charm light mesons

threshold effects!

Decay modes with $c\bar{c}$ annihilation does not involve hidden or open charm final states!

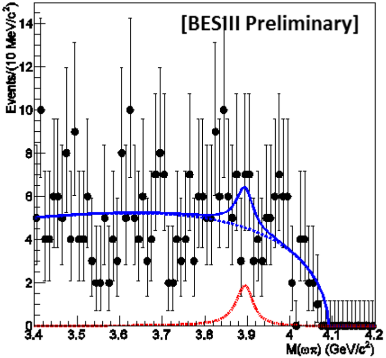
If $c\bar{c}$ in S-wave, annihilation could be 'easy' …

but theoretical predictions very difficult,
order-of-magnitude only

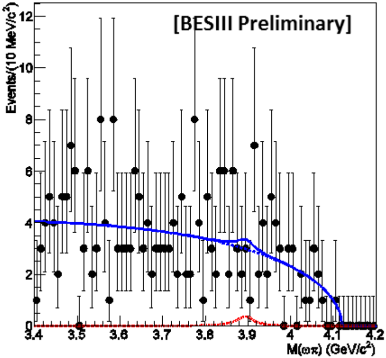
$Z_c(3900)^+ \to \omega\pi^+ \to (\pi^+\pi^-\pi^0)\,\pi^+$

preliminary

$\sqrt{s} = 4.230\,\text{GeV}$



$\sqrt{s} = 4.260\,\text{GeV}$



$\sigma(e^+e^- \to Z_c^+\pi^-, Z_c^+ \to \omega\pi^+) < 0.27\,\text{pb}$ $\sigma(e^+e^- \to Z_c^+\pi^-, Z_c^+ \to \omega\pi^+) < 0.18\,\text{pb}$

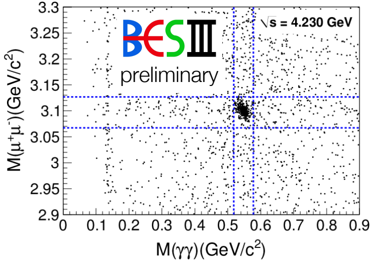
Compared to sum of $Z_c^+ \to J/\psi\,\pi^+$ and $Z_c^+ \to (D\bar{D}^*)^+$:

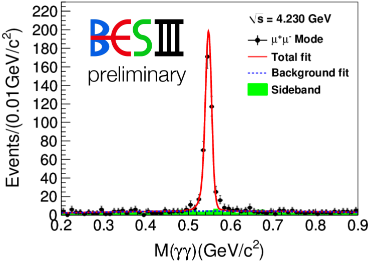
$$\Gamma(Z_c^+ \to \omega\pi^+) < 0.2\%\Gamma_{\text{tot}}$$

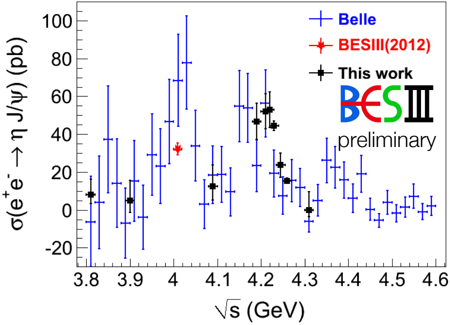

Search for other Y states

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

BESIII preliminary, arXiv:1503.06644 [hep-ex]







Compare to $e^+e^- \to \gamma_{ISR}\eta J/\psi$ from
Belle, Phys. Rev. D 87, 051101(R) (2013)

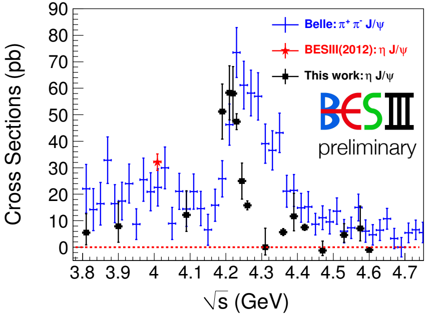
Good agreement,
significantly better precision

Cross section peaks around 4.2 GeV

Also searched for $e^+e^- \to \pi^0 J/\psi$:
no significant signal found

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

BESIII preliminary,
arXiv:1503.06644 [hep-ex]



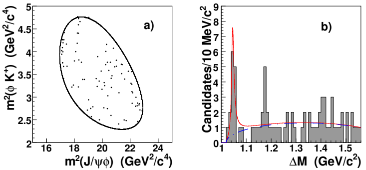
Compare to $e^+e^- \to \gamma_{\mathrm{ISR}}\pi^+\pi^- J/\psi$ from
Belle, Phys. Rev. Lett. **110**, 252002 (2013)

Very different line shape

➡ Different dynamics at work in
$e^+e^- \to \eta J/\psi$ compared to
$e^+e^- \to \pi^+\pi^- J/\psi$

Search for $Y(4140) \to J/\psi\phi$

CDF first reported evidence for
$Y(4140) \to J/\psi\phi$ in $B^+ \to J/\psi\phi K^+$,
also claimed by D0 and CMS



CDF, PRL **102**, 242002, (2009)

Not seen by LHCb, Belle (B decays and $\gamma\gamma$ events), or BABAR

$J/\psi\phi$ system has $C = +1$: search in radiative transitions of charmonium or $Y(4260)$

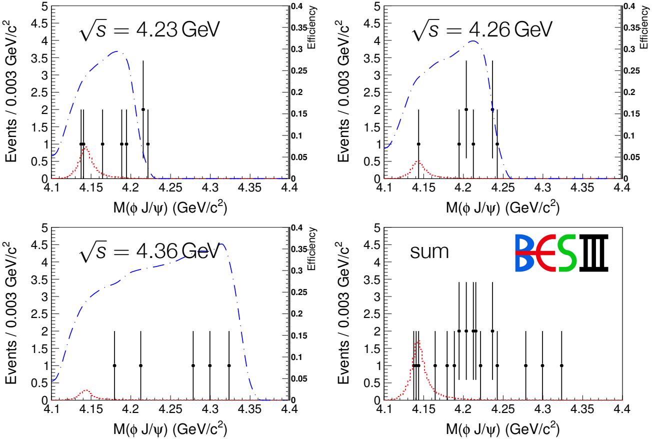
If both $Y(4260)$ and $Y(4140)$ are *charmonium hybrids*:
partial width of $Y(4260) \to \gamma Y(4140)$ may be up to several tens of keV
N. Mahajan, PLB **679**, 228 (2009)

Search for $Y(4140) \to J/\psi\,\phi$

BESIII, PRD **91**, 032002 (2015)

Use BESIII's large data samples from 4.23 – 4.36 GeV (2.47 fb^{-1} in total)

$$e^+e^- \to \gamma J/\psi\,\phi$$
$$J/\psi \to e^+e^-, \mu^+\mu^-,$$
$$\phi \to K^+K^-, K_S^0K_L^0, \pi^+\pi^-\pi^0$$



Search for $Y(4140) \to J/\psi\,\phi$

BESIII, PRD **91**, 032002 (2015)

No significant signal found; place upper limits on
$\sigma(e^+e^- \to \gamma Y(4140)) \times \mathcal{B}(Y(4140) \to J/\psi\,\phi)$

Compare sensitivity to $e^+e^- \to \gamma X(3872) \times \mathcal{B}(X(3872) \to J/\psi\,\pi^+\pi^-)$

$\sqrt{s}$ / GeV	4.23	4.26	4.36
$\sigma \times \mathcal{B}(X(3872))/\mathrm{pb}$	0.27 ± 0.09	0.33 ± 0.12	0.11 ± 0.09
$\sigma \times \mathcal{B}(Y(4140))/\mathrm{pb}$	< 0.35	< 0.28	< 0.33

Assuming $\mathcal{B}(Y(4140) \to J/\psi\,\phi) \sim 30\%$ and $\mathcal{B}(X(3872) \to J/\psi\,\pi^+\pi^-) \sim 5\%$:

$$\frac{\sigma[e^+e^- \to \gamma Y(4140)]}{\sigma[e^+e^- \to \gamma X(3872)]} < 0.1 \quad \text{at 4.23, 4.26 GeV}$$

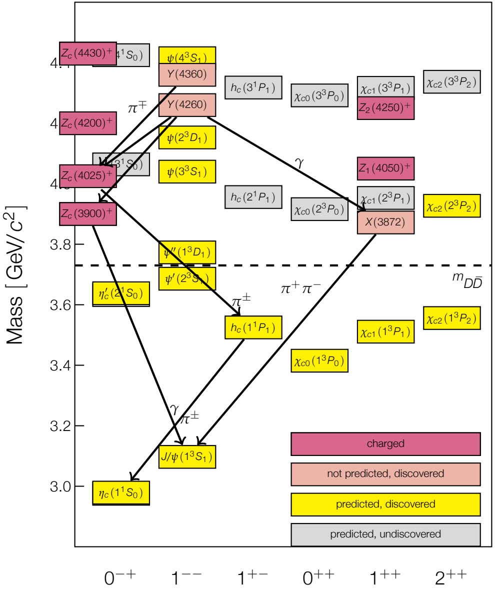
Even more surprises

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

Summary

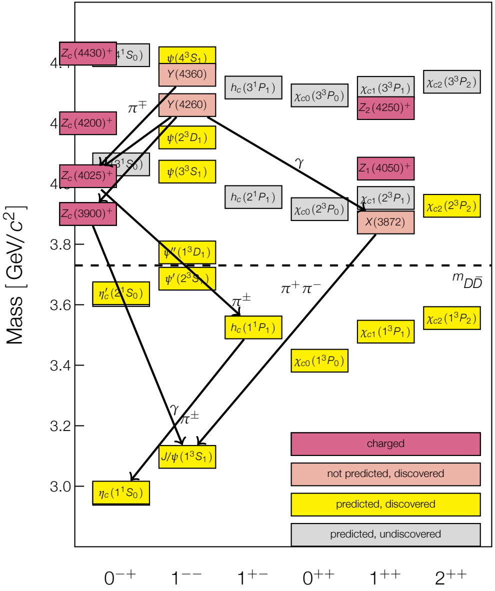


- Quark model describes charmonium states $c\bar{c}$ reasonably well
- *XYZ* states: unexpected, point to non-conventional states ($c\bar{c}g$, $cq\overline{qc}$, $(\bar{c}q)(\bar{q}c)$, $c\bar{c}\pi\pi$ …)
- Observation of transitions between *XYZ* states

➡ Start making connections between new, exotic states

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

Summary

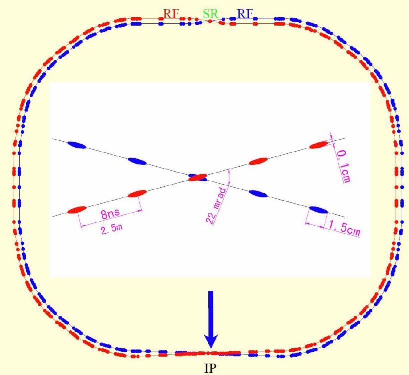


- Structure of *XYZ* to be clarified; learn more about strongly bound systems
- More detailed studies (PWA, other channels …) at BESIII ongoing

- Future:
  More data from BESIII
  LHCb spectroscopy
  Belle-II will start 2017
  PANDA
- Exciting times ahead

謝謝！

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**

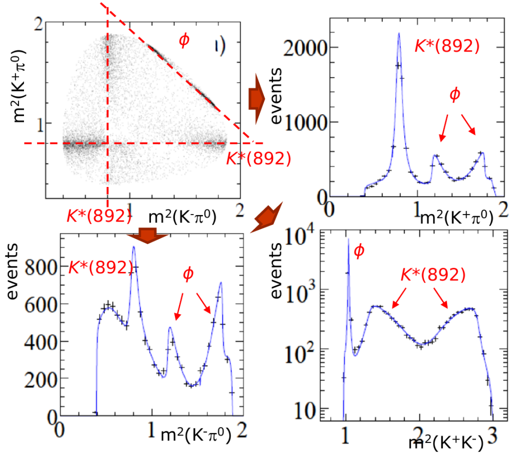
Design luminosity	**$10^{33}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$**
Achieved	**$8 \times 10^{32}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$**

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

Kinematic reflections

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

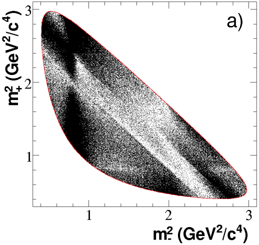
For example $D^0 \to K^+K^-\pi^0$: relatively easy to understand



Kinematic reflections

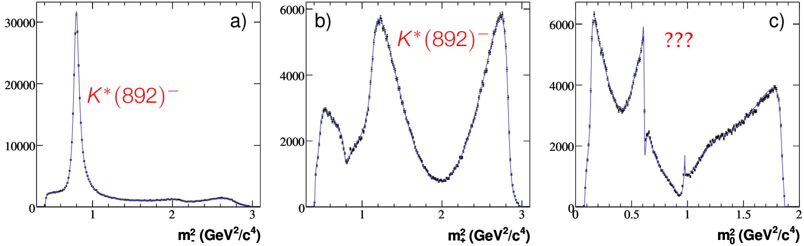
But can be much less obvious

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

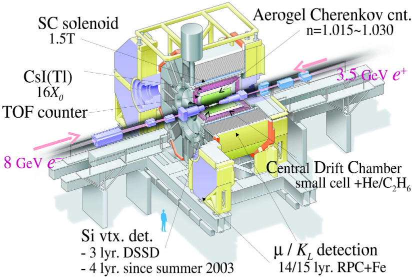


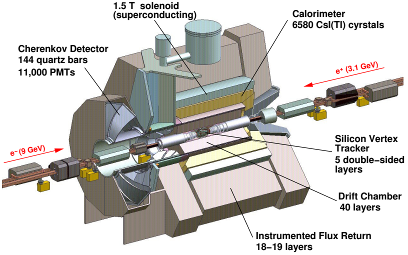
$$\mathcal{A}_D(m_-^2, m_+^2) = \sum_r a_r e^{i\phi_r} \mathcal{A}_r(m_-^2, m_+^2) + a_{\mathrm{NR}} e^{i\phi_{\mathrm{NR}}}$$

Using 10 resonant amplitudes



The B factories Belle and BABAR





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

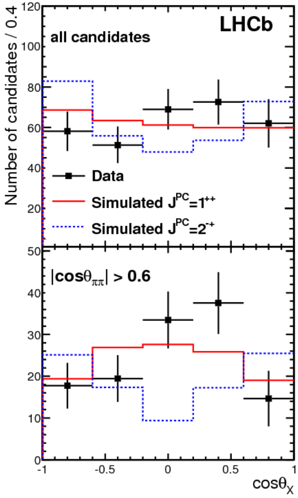
- KEK-B: 8 GeV e^- × 3.5 GeV e^+
- $\mathcal{L}_{\text{int}} \approx 1\,\text{ab}^{-1}$
- Data taking finished 2010

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

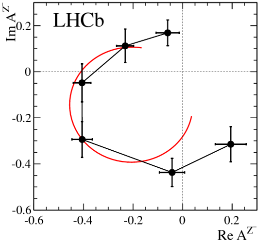
The $Z_c(4430)^+$ in $B^0 \to \psi' K^+ \pi^-$

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

Spin-Parity assignment



Phase motion



behaves like a 'true' resonance

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