

BESIII: the latest data harvest

Wolfgang Gradl

on behalf of the BESIII collaboration

53rd International Winter Meeting on Nuclear Physics
Bormio
27th January 2015



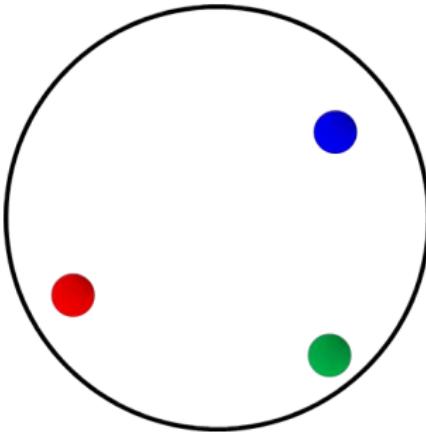
The big question

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?

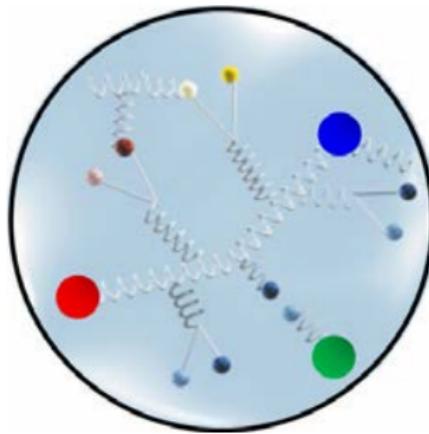
Proton consists of 3 quarks

But:

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

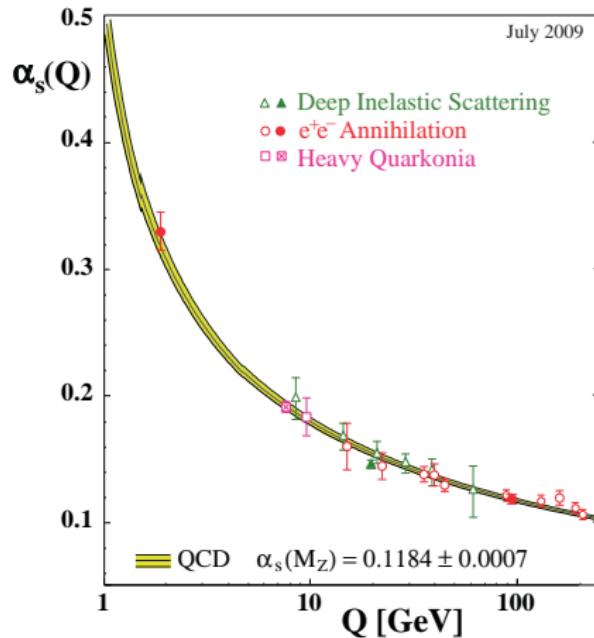
Inner structure of hadrons?

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



QCD bound systems

States found in nature: colour-neutral combinations

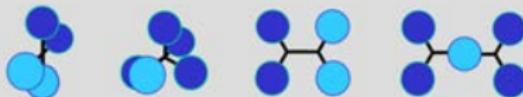
We know

mesons and baryons



QCD also allows

molecules/multi-quarks



hybrids



glueballs



and more

Totalitarian principle of quantum mechanics:

Everything not forbidden is compulsory

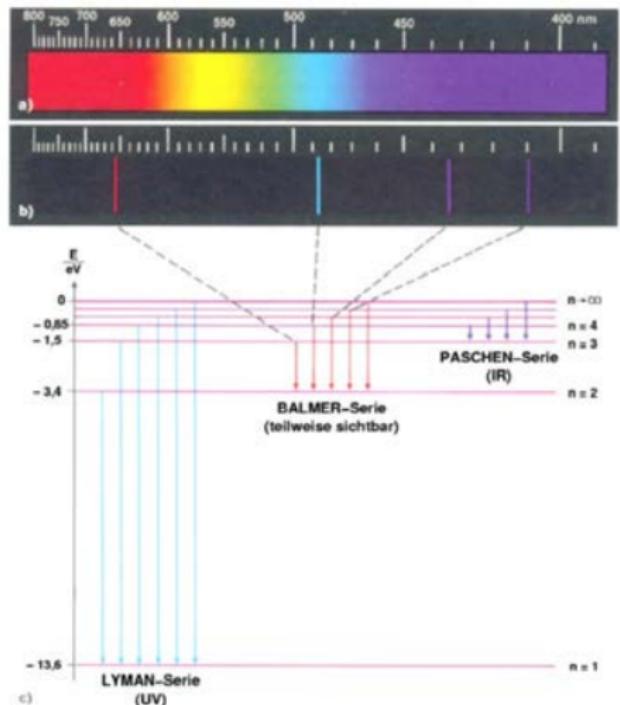
'...while mesons are made out of $(q\bar{q})$, $(qq\bar{q}\bar{q})$, etc.'

Gell-Mann, Phys. Lett. **8**, 214 (1964)



Charmonium Spectroscopy

Analogy: Atomic spectroscopy



Information on bound systems by observing

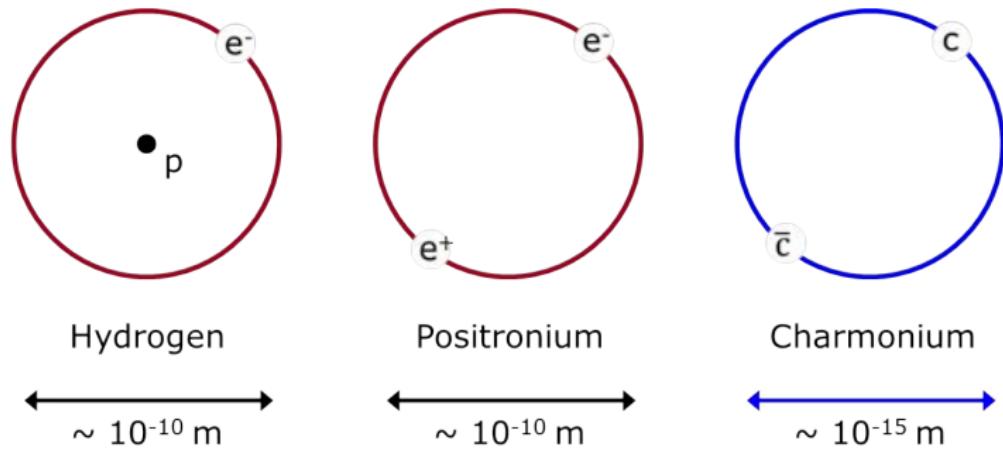
- Energy levels
- Transitions between levels (selection rules ...)

Discovery of discrete spectral lines
→ Discrete energy levels in atoms

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

Precision measurements
→ Fine structure, Lamb shift ...

Hadron spectroscopy: Charmonium



Observables in hadron spectroscopy

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

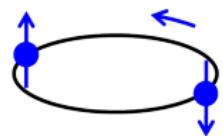
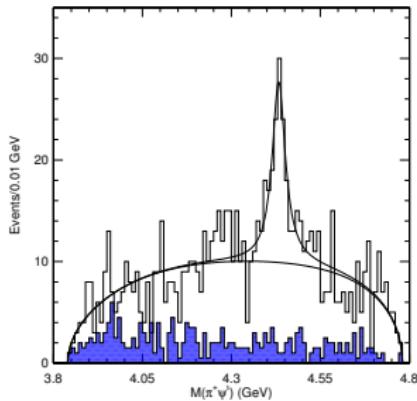
Classify states according to

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

S total spin (\sim sum of quark spins)

L orbital angular momentum

J total angular momentum, $J = |L - S|, \dots, L + S$



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

Example; J/ψ (1^3S_1): $L = 0, S = 1 \Rightarrow J^{PC} = 1^{--}$

‘Natural’ quantum numbers: accessible for $q\bar{q}$
 $J^{PC} = 0^{++}, 0^{-+}, 1^{--}, 1^{++}, 1^{+-}, 2^{++} \dots$

‘Exotic’ quantum numbers: cannot be made from $q\bar{q}$
 $J^{PC} = 0^{+-}, 1^{-+}, 2^{+-}, \dots$

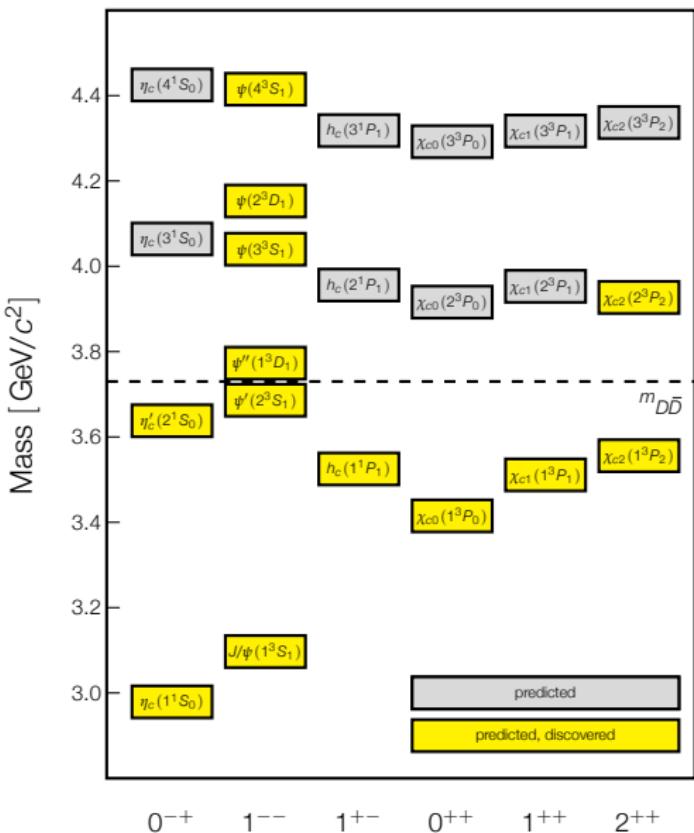
The hunt for new states

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
Charmonium and charmonium-like states useful for this search:

- $m_c \approx 1.4$ 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^-
- Exciting possibility to find exotics among new states

Charmonium spectrum



Charmonium: $c\bar{c}$

Example potential

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

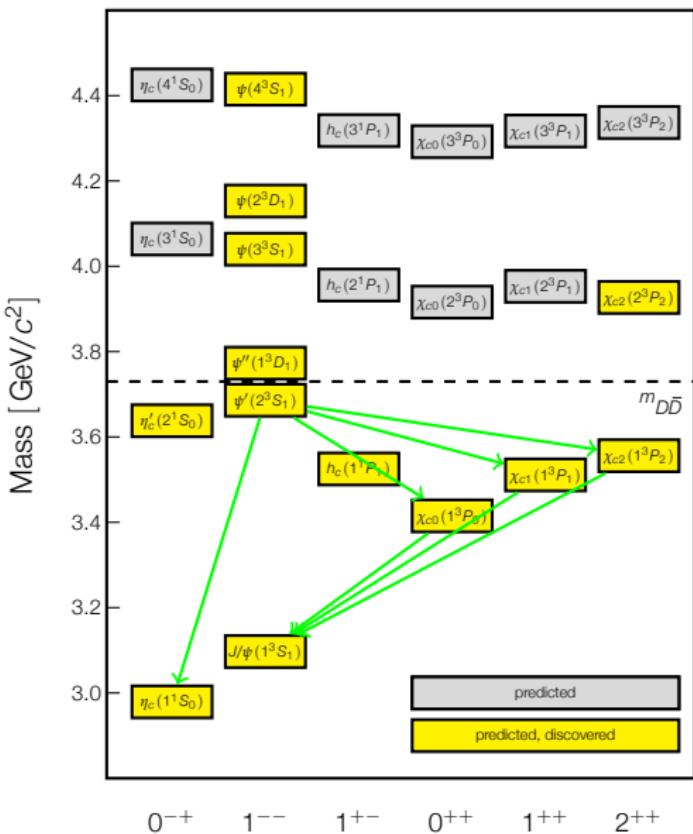
$$V_{\text{spin-dep.}} = \frac{1}{m_c^2} \left[\left(\frac{2\alpha_s}{r^3} - \frac{b}{2r} \right) \vec{L} \cdot \vec{S} + \frac{4\alpha_s}{r^3} T \right]$$

Barnes, Godfrey & Swanson,
PRD 72, 054026

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

→ Remarkably good description

Charmonium spectrum



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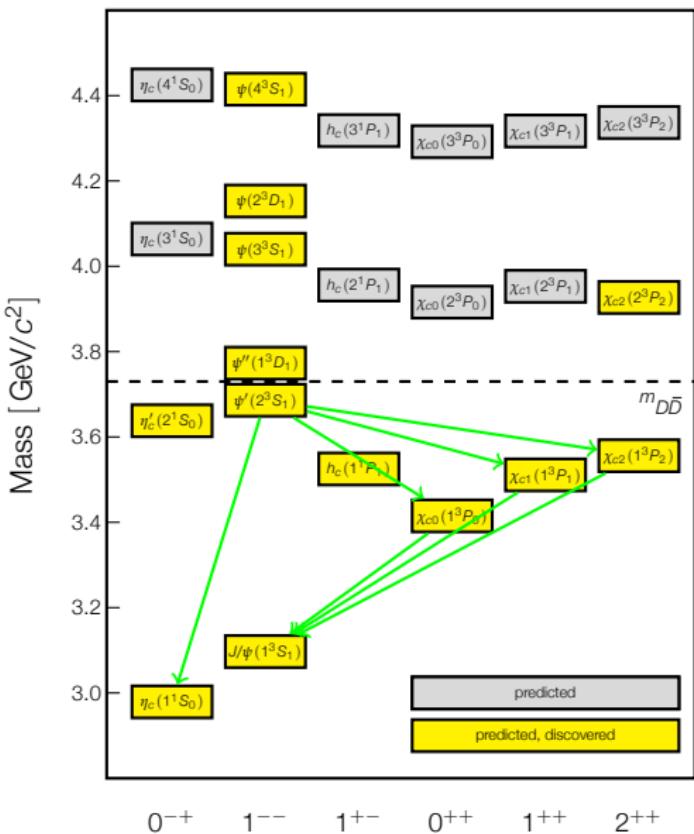
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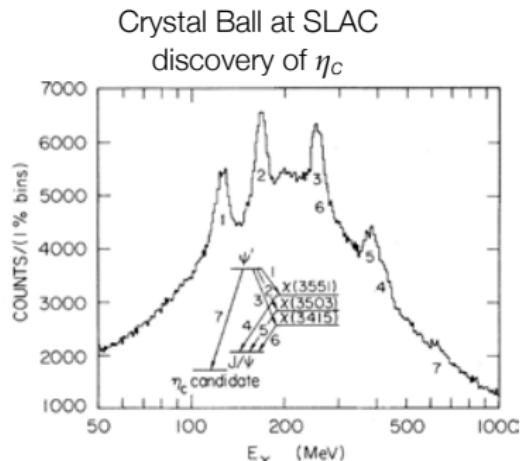
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Charmonium spectrum



Charmonium: $c\bar{c}$

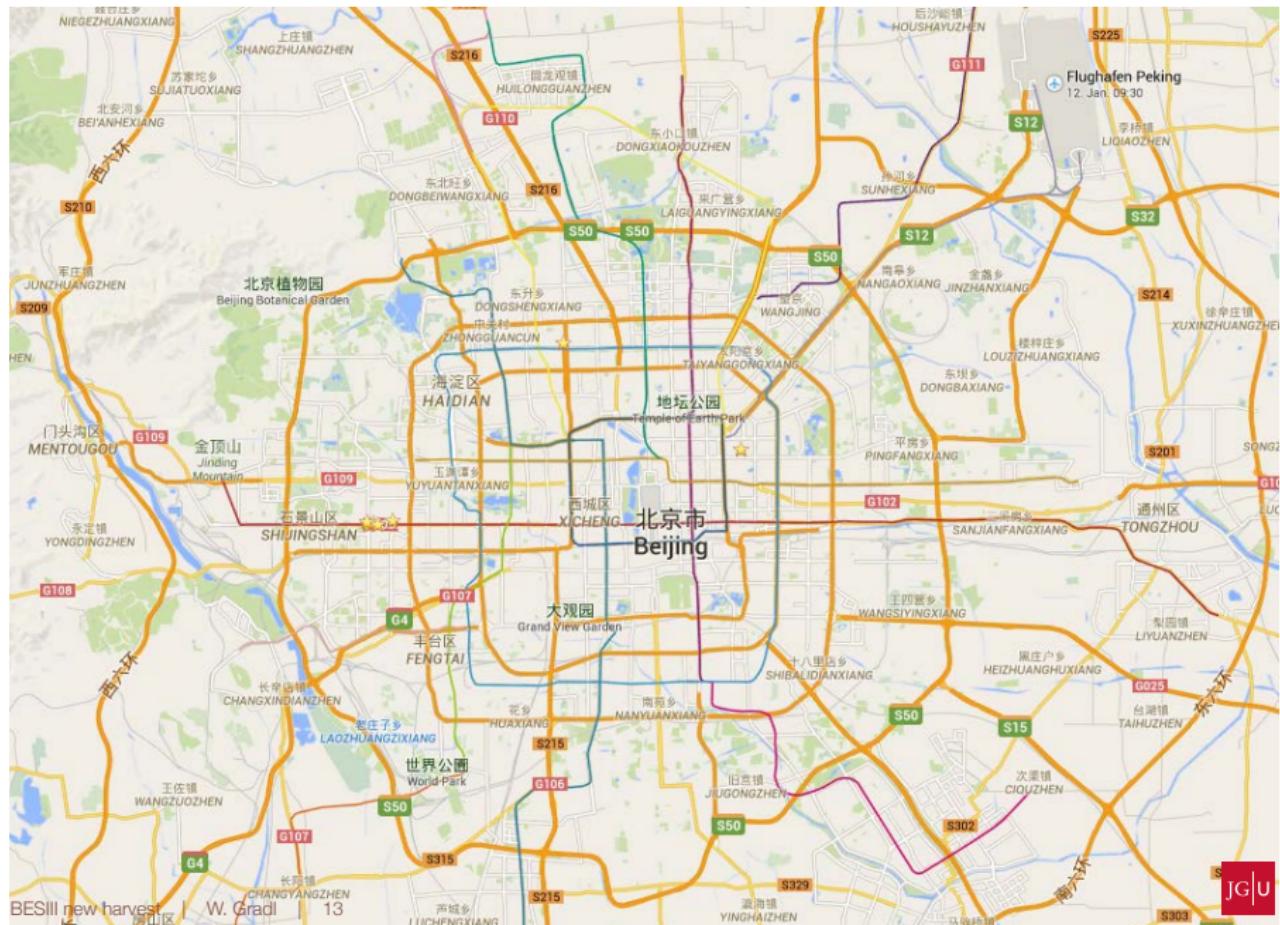


PRL 45, 1150 (1980)

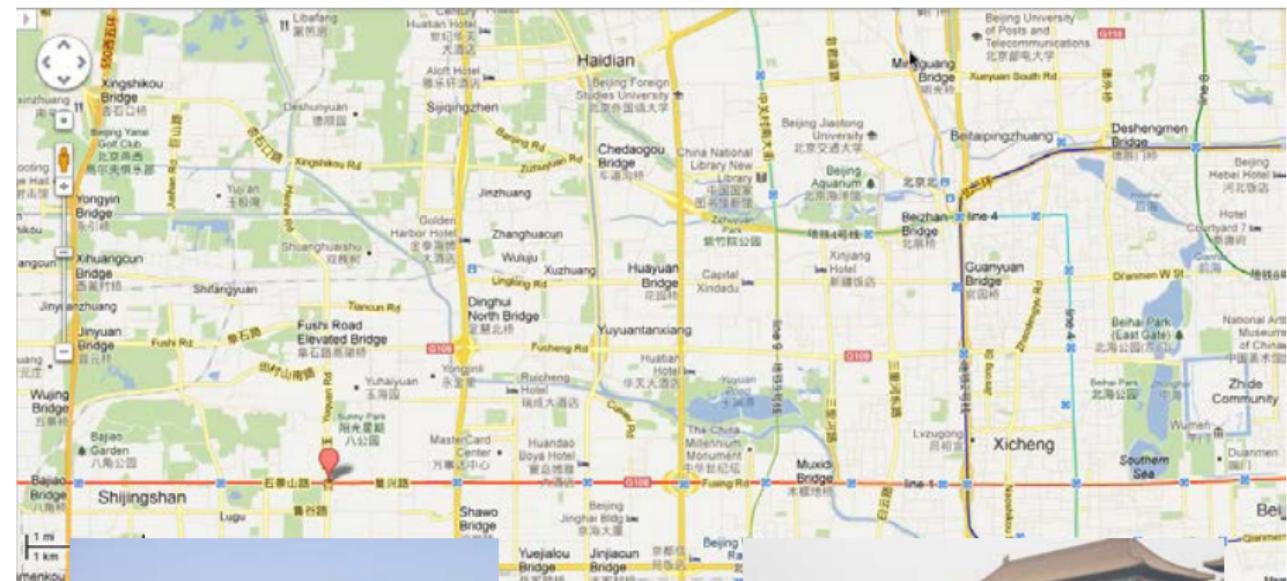
A black and white photograph of the Great Wall of China. The wall, made of stone and brick, winds its way across the frame, starting from the bottom left and curving upwards towards the top left. It is set against a backdrop of dark, misty mountains. In the distance, several watchtowers stand prominently on the ridges of the mountains. The sky is overcast and hazy.

BESIII: a τ -charm factory

BEPCII and BESIII



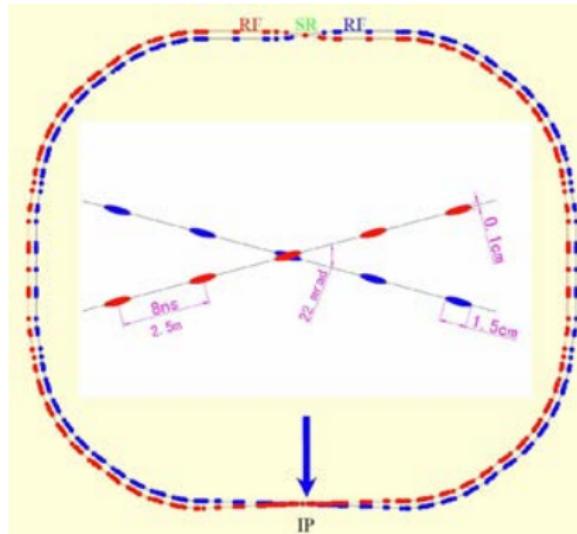
BEPCL and BESIII



BEPCII and BESIII



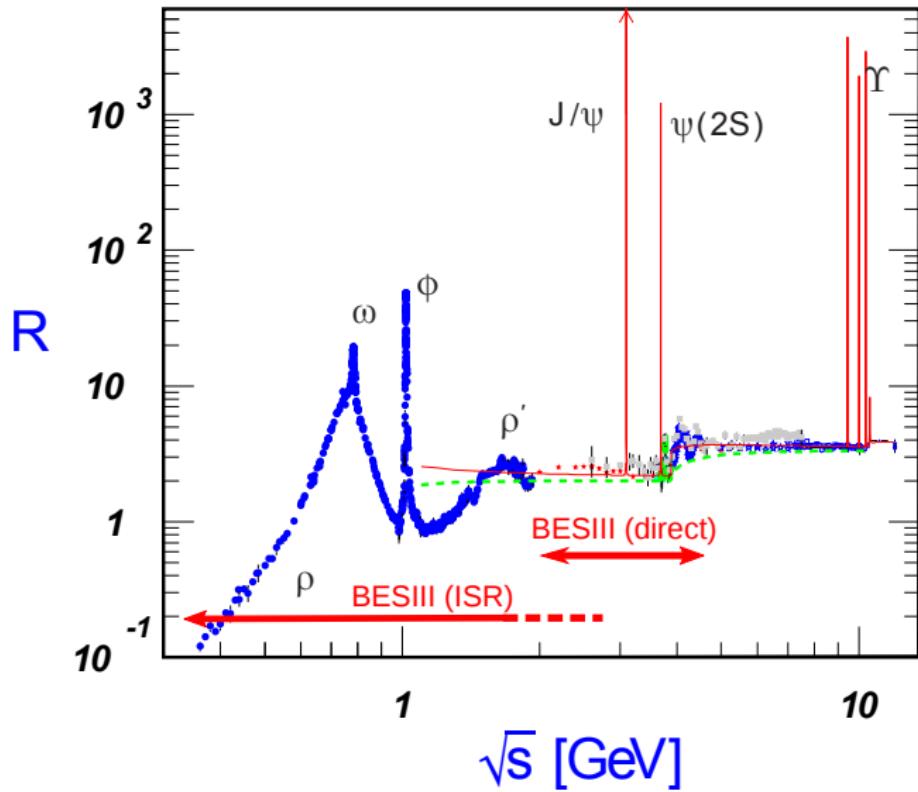
BEPCII storage rings: a τ -charm factory



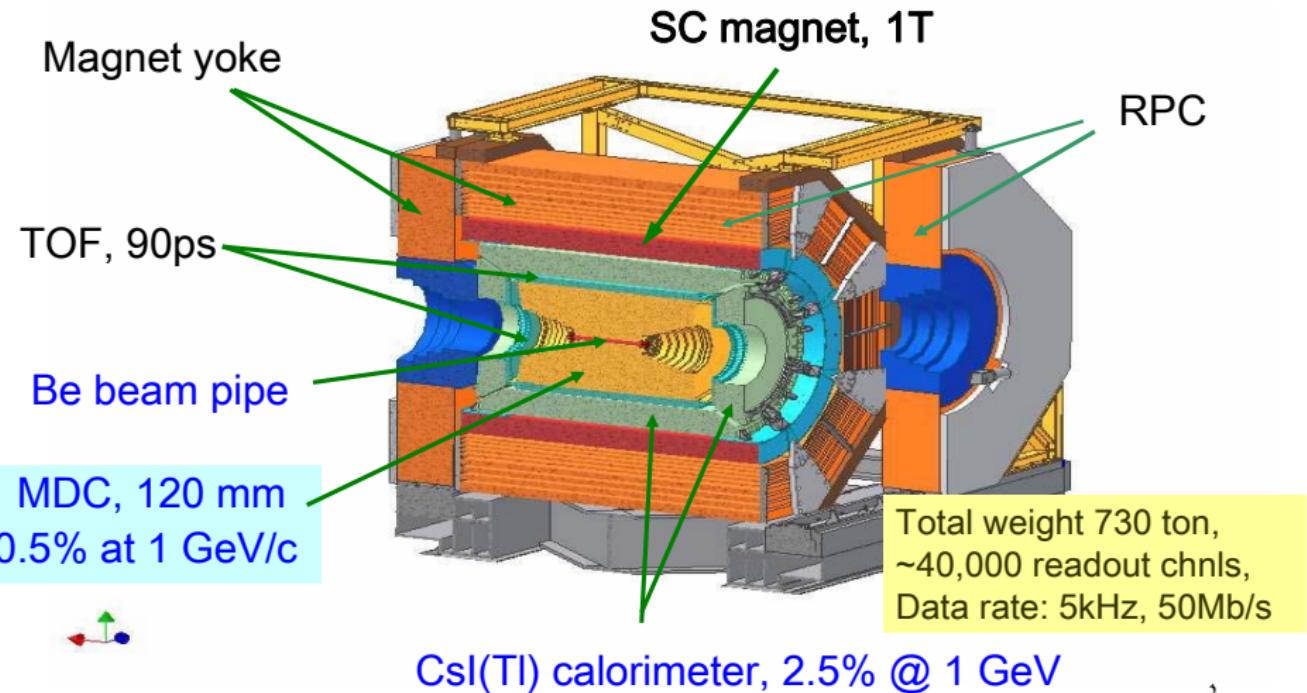
Upgrade of BEPC (started 2004,
first collisions July 2008)
Beam energy 1 ... 2.3 GeV
Optimum energy 1.89 GeV
Single beam current 0.91 A
Crossing angle: ± 11 mrad

Design luminosity: $10^{33} \text{ cm}^{-2}\text{s}^{-1}$
Achieved: $8 \times 10^{32} \text{ cm}^{-2}\text{s}^{-1}$
Beam energy measurement:
Laser compton backscattering
 $\Delta E/E \approx 5 \times 10^{-5}$
(≈ 50 keV at τ threshold)

A τ -charm factory



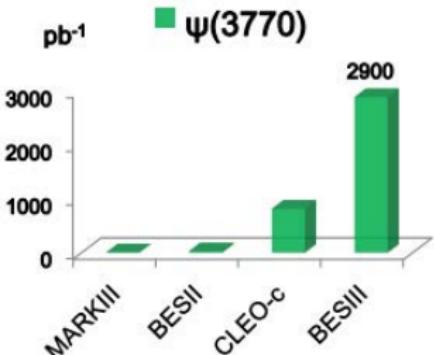
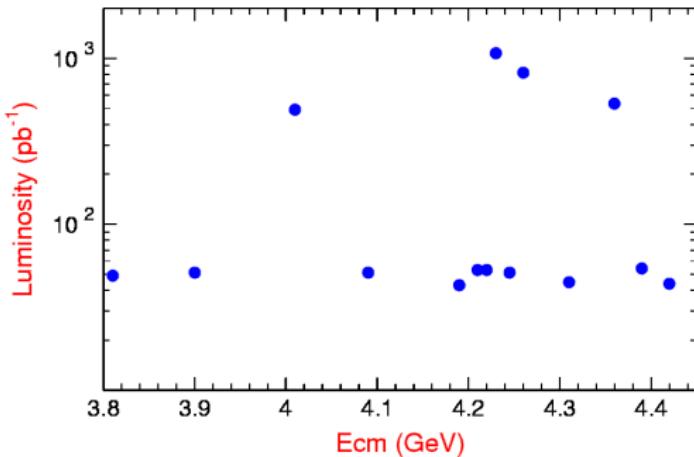
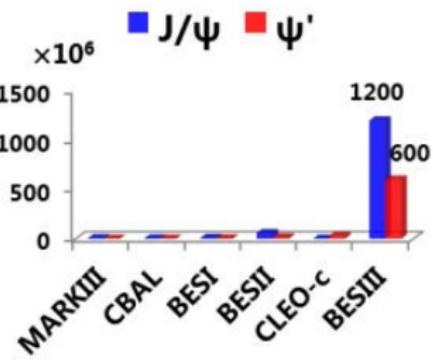
BESIII detector



Completely new detector

Comparable performance to CLEO-c, + muon ID

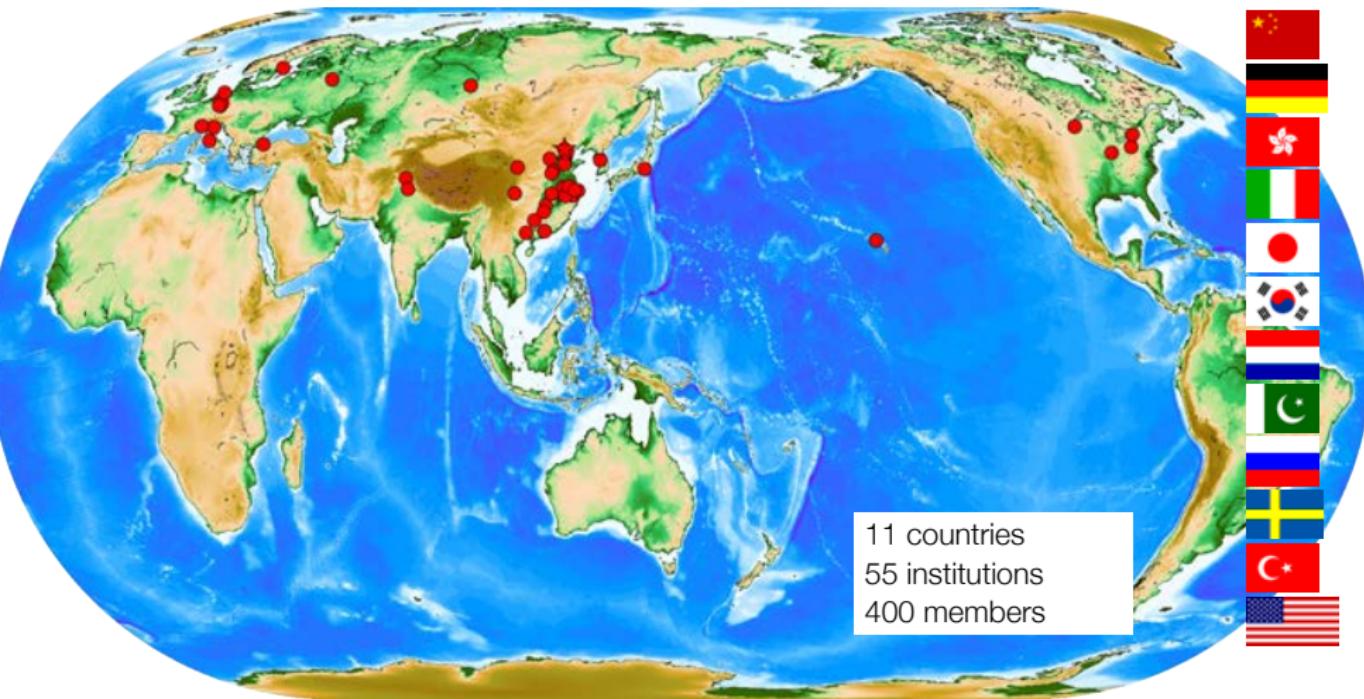
BESIII data sets



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

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

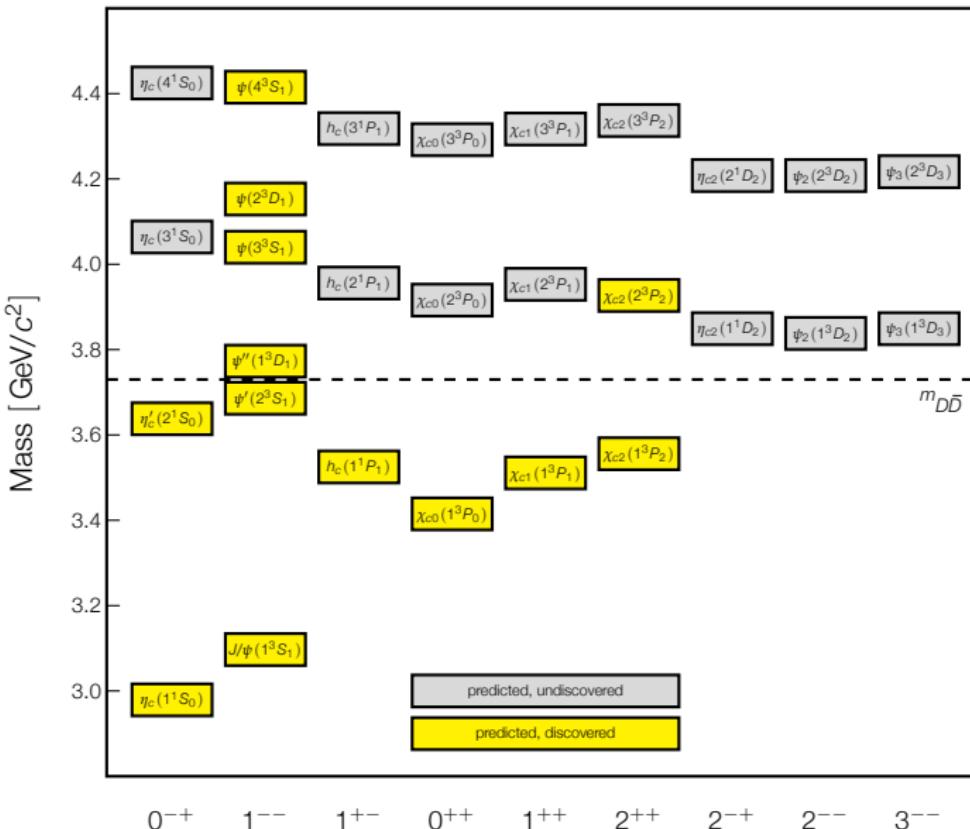
The BESIII Collaboration





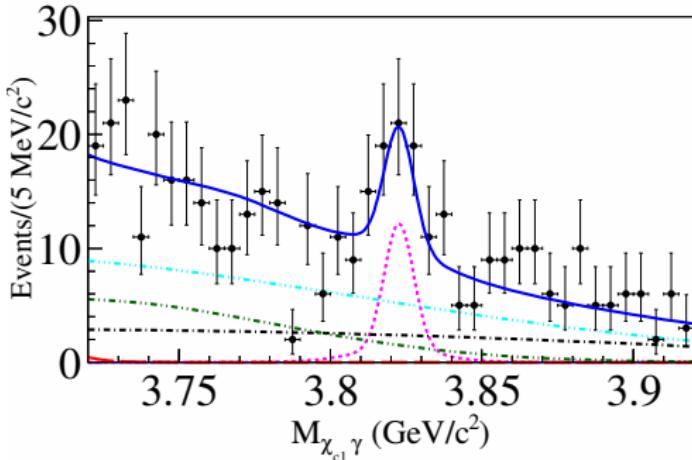
Conventional $c\bar{c}$

Higher charmonium states



The $X(3823)$ at Belle

PRL 111, 032001 (2013)



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

$B \rightarrow K\gamma\chi_{c1}$

simultaneous fit to B^+ and B^0

3.8 σ evidence

$$M = 3832.1 \pm 1.8 \pm 0.7 \text{ MeV}$$

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

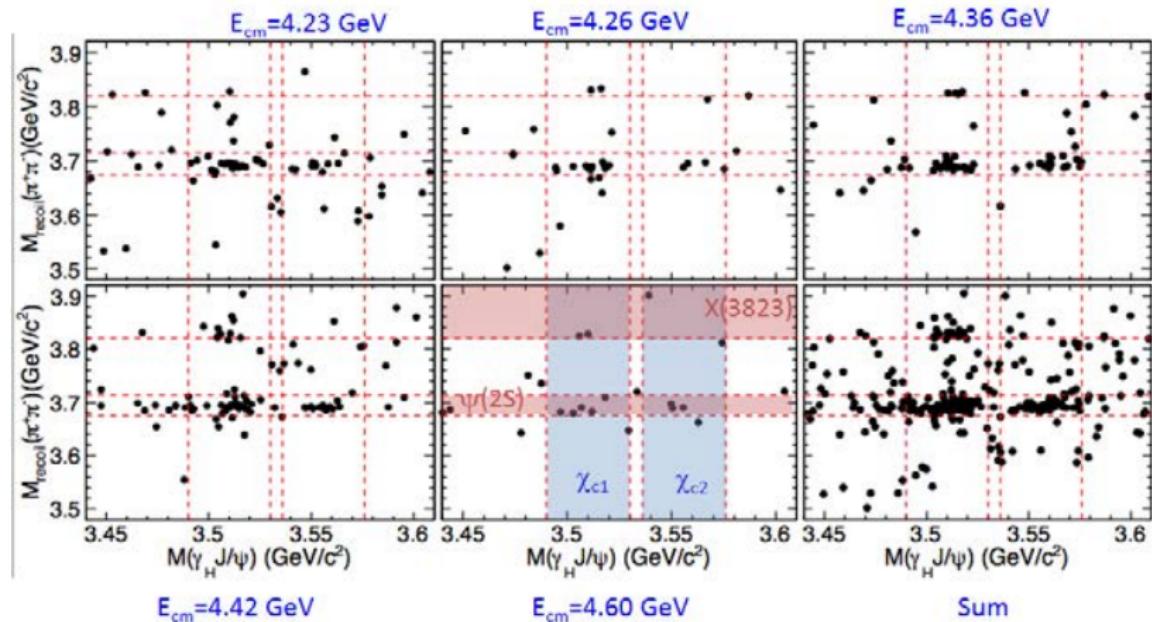
Search for $e^+e^- \rightarrow \pi^+\pi^-X(3823) \rightarrow \pi^+\pi^-\gamma\chi_{c1}$

BESIII
preliminary

reconstruct $\chi_{c1,2} \rightarrow \gamma J/\psi \rightarrow \gamma\ell^+\ell^-$

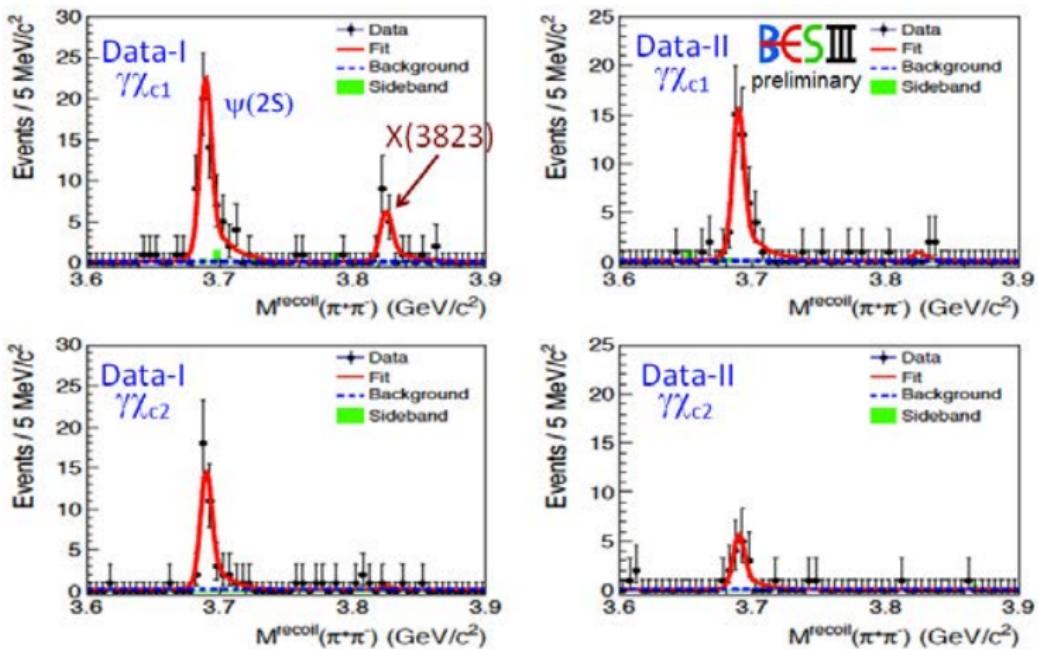
look in mass recoiling against $\pi^+\pi^-$ system, $M_{\text{recoil}}(\pi^+\pi^-)$

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



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

BESIII
preliminary



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

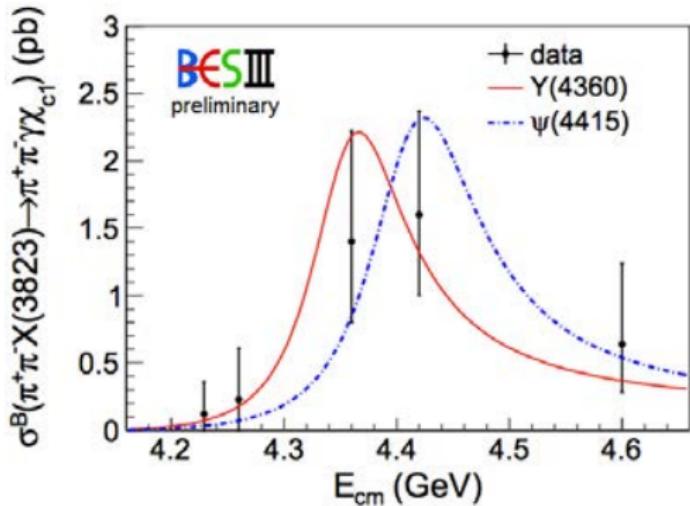
$M = 3821.7 \pm 1.3 \pm 0.7 \text{ MeV}$, significance 6.7σ

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

BESIII
preliminary

Energy-dependent cross section for

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



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

Mass and width \sim in agreement
with potential model

Production ratio

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

~ 0.2 prediction

< 0.43 at 90% C.L.

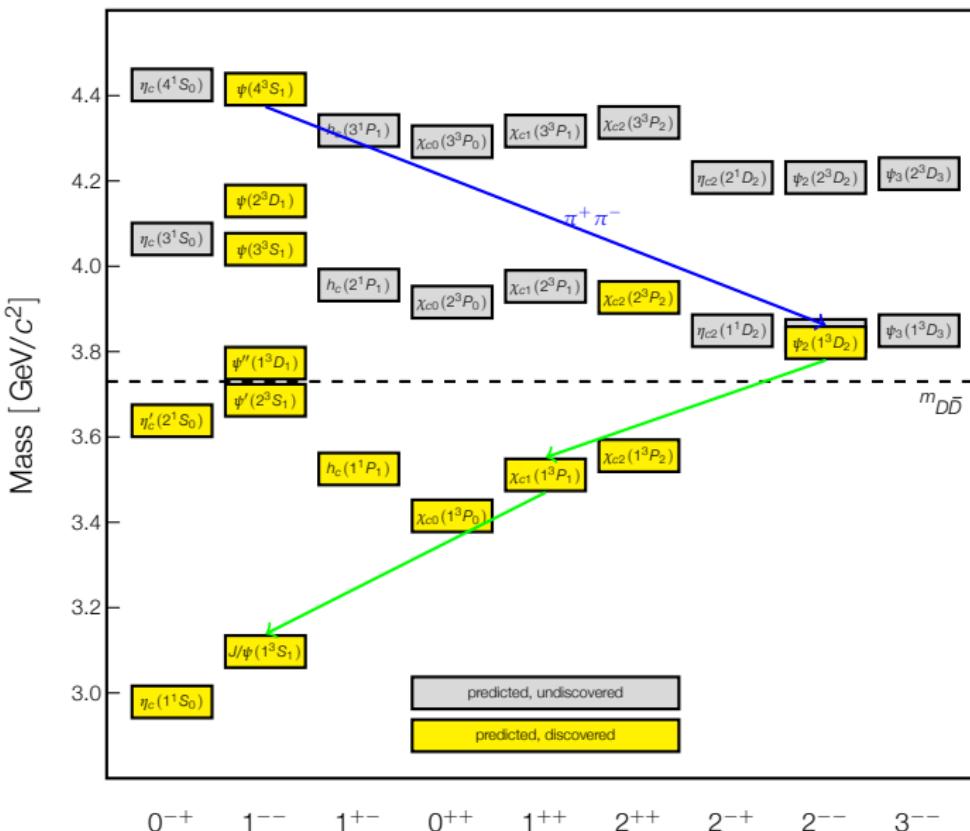
Exclusion:

$1^1D_2 \rightarrow \gamma\chi_{c1}$ forbidden

$1^3D_3 \rightarrow \gamma\chi_{c1}$ has zero amplitude

Not enough statistics to distinguish
 S and D wave from data

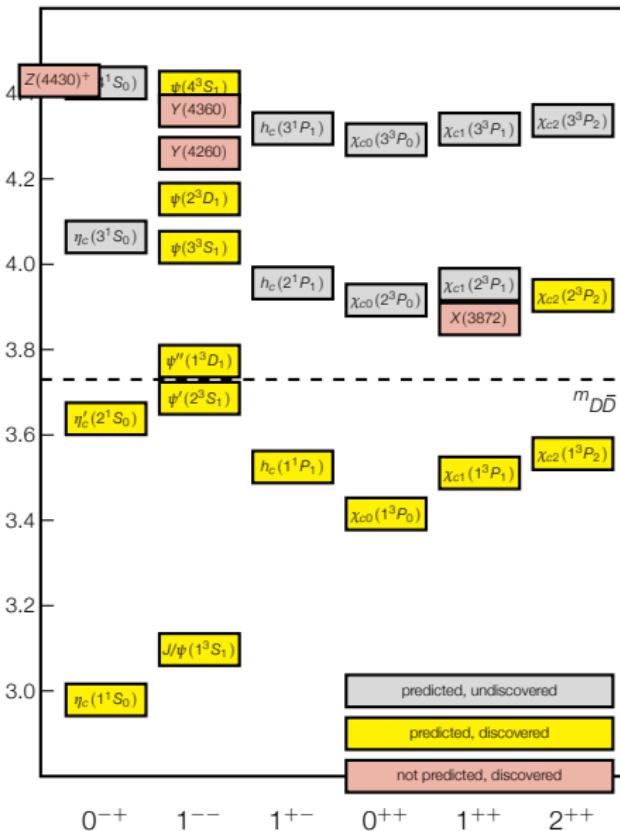
Higher charmonium states – new family member?



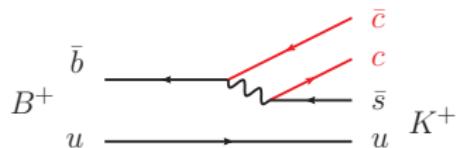


Exotic states

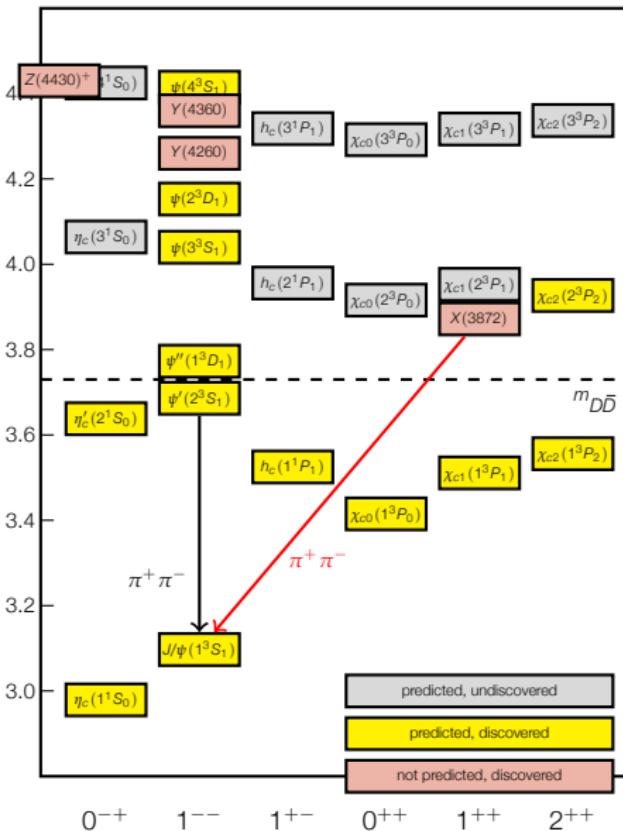
Surprising discoveries: the XYZ states



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

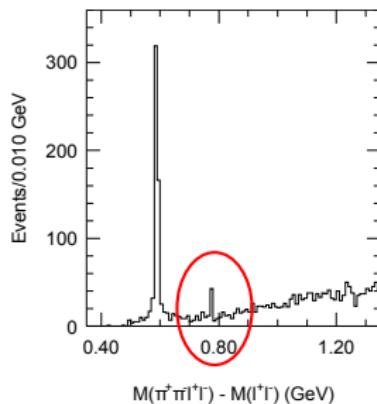


Surprising discoveries: the XYZ states



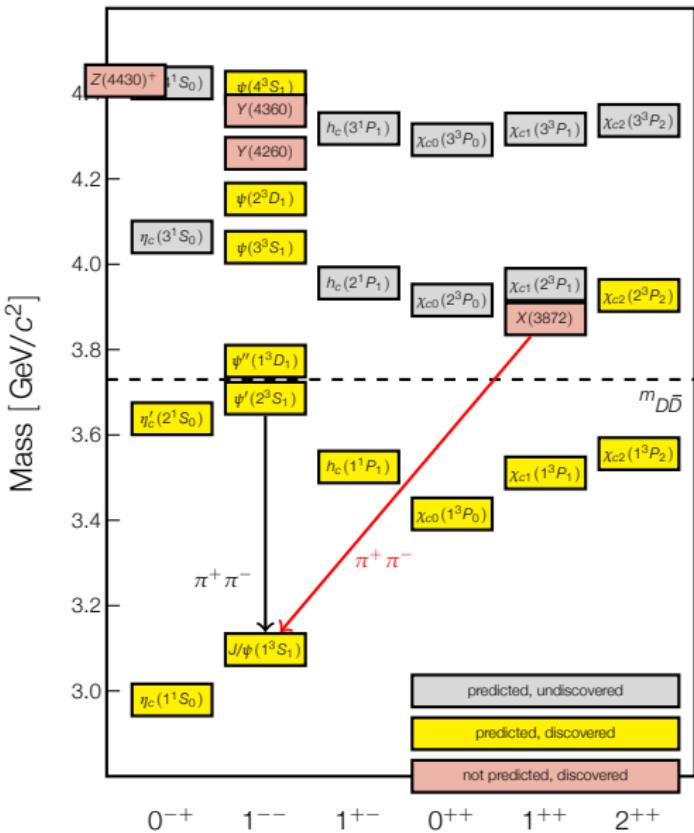
Most of the ‘XYZ’ states discovered at Belle and BABAR in e^+e^- collisions in bottomonium region

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

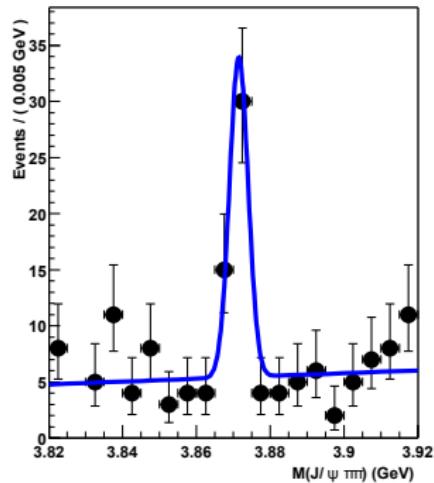


Belle, PRL 91, 262001 (2003)

The $X(3872)$



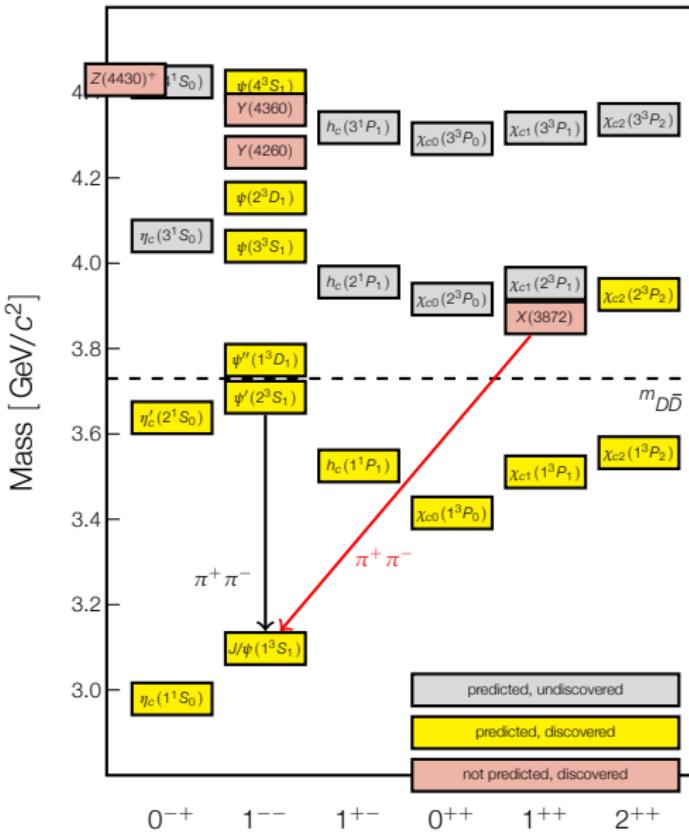
Extremely narrow, sits at or just below the $D\bar{D}^*$ threshold



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

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

The $X(3872)$



Seen by BABAR, CDF, D0, LHCb,

...

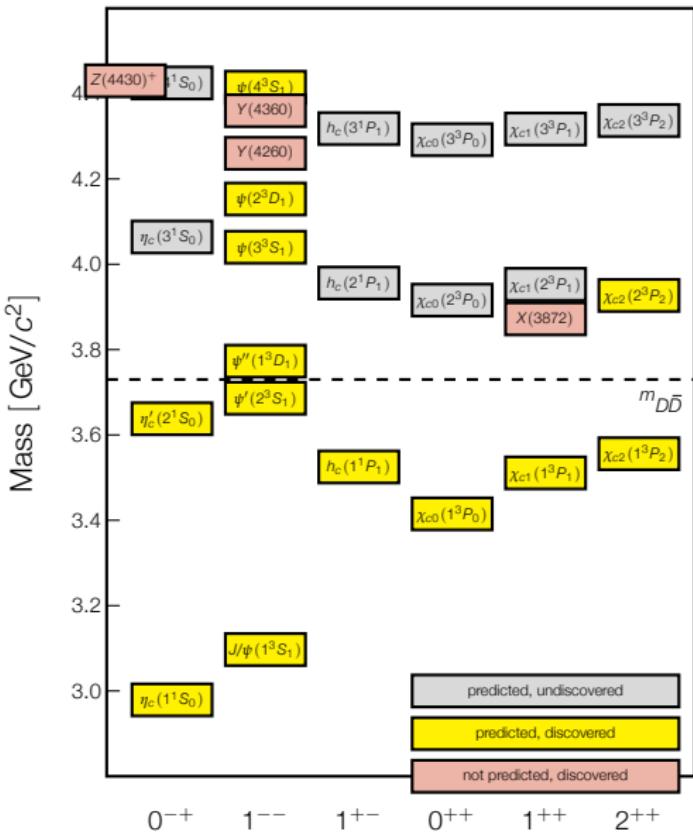
Decays into $J/\psi\pi^+\pi^-$, $D^0\bar{D}^0\pi^0$,
 $\gamma J/\psi$, $\gamma\psi(2S)$

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

no obvious place in spectrum
 ~ 50 MeV too light to be $\chi_{c1}(2P)$?

but see Achasov and Rogozina,
[arXiv:1501.03583](https://arxiv.org/abs/1501.03583)

The $\Upsilon(4260) \rightarrow J/\psi \pi^+ \pi^-$

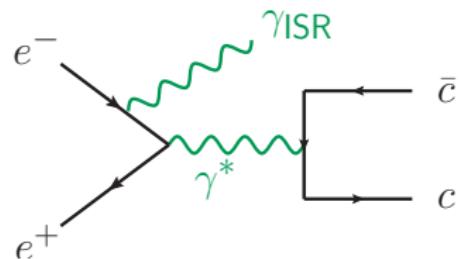


e⁺e⁻ collisions near $\Upsilon(4S)$

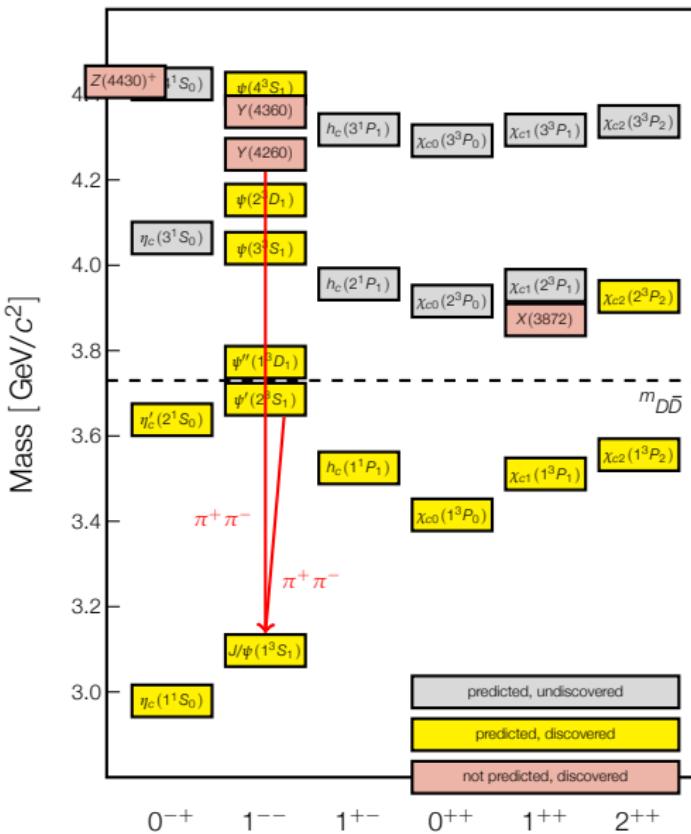
in ISR production

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

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



The $\Upsilon(4260) \rightarrow J/\psi \pi^+ \pi^-$

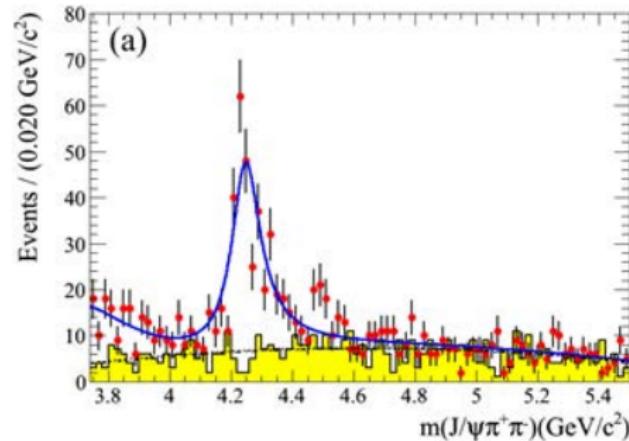


e⁺e⁻ collisions near $\Upsilon(4S)$

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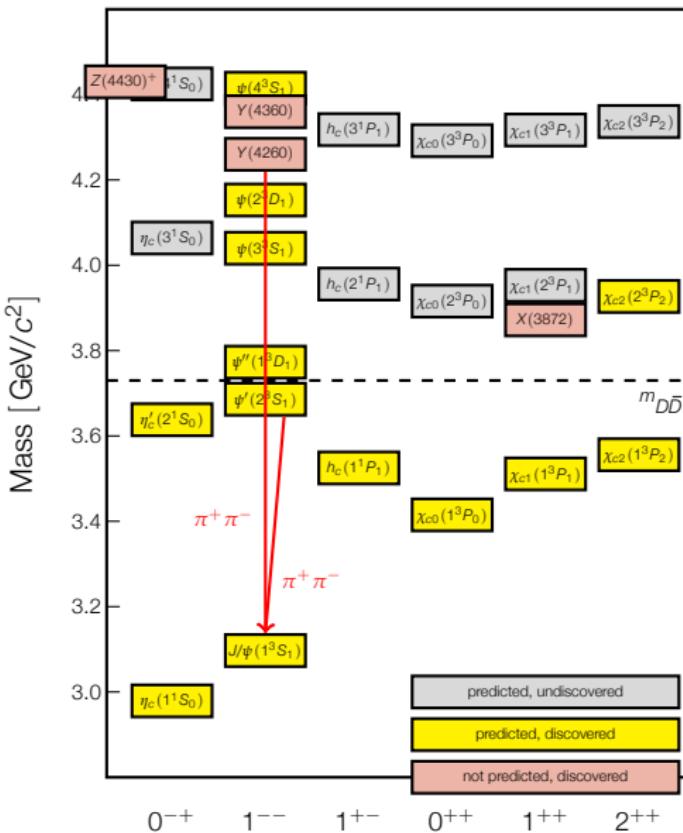
$$e^+e^- \rightarrow \gamma_{\text{ISR}} J/\psi \pi^+ \pi^-$$

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



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

The $\Upsilon(4260) \rightarrow J/\psi \pi^+ \pi^-$



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

in ISR production

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

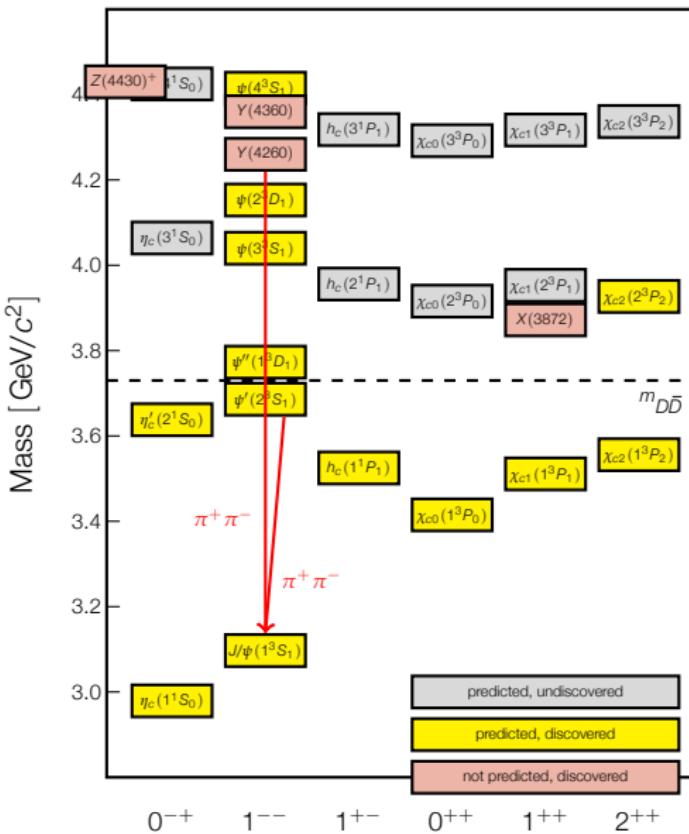
$$\Rightarrow J^{PC} = 1^{--}$$

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

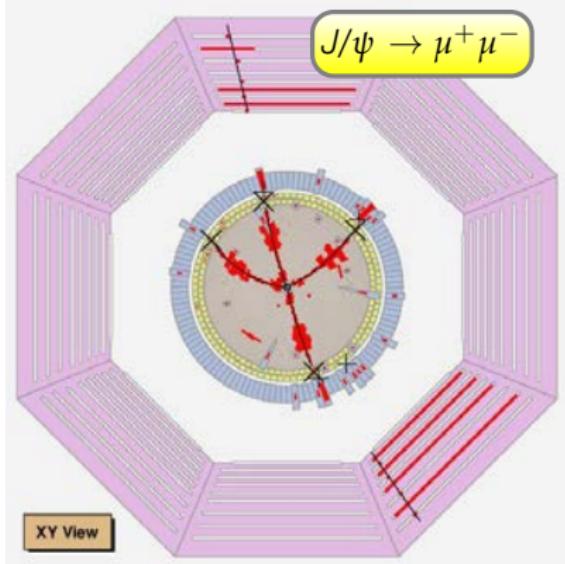
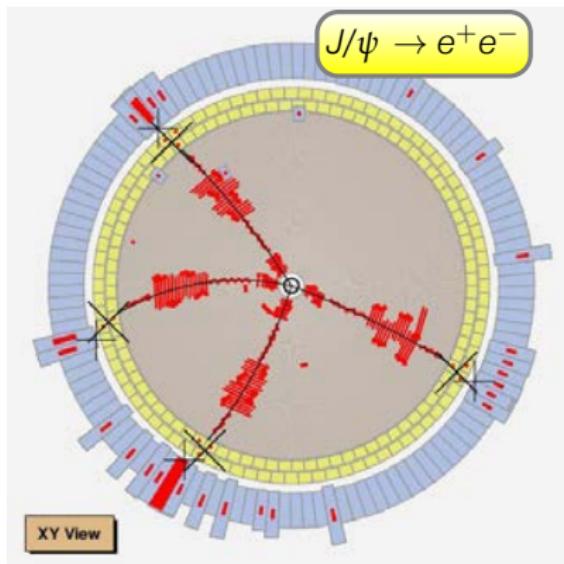
$$\frac{\mathcal{B}(Y(4260) \rightarrow D\bar{D})}{\mathcal{B}(Y(4260) \rightarrow J/\psi \pi^+ \pi^-)} < 4$$

compare with
 ≈ 500 for $\psi(3770)$

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



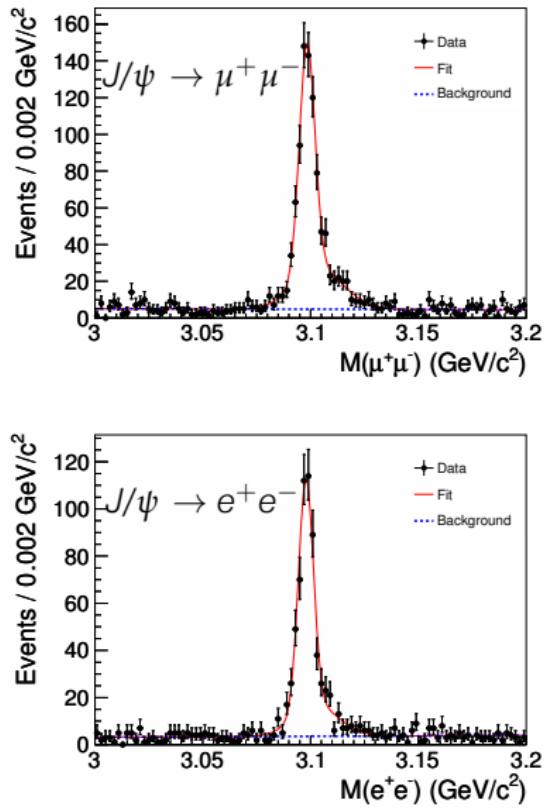
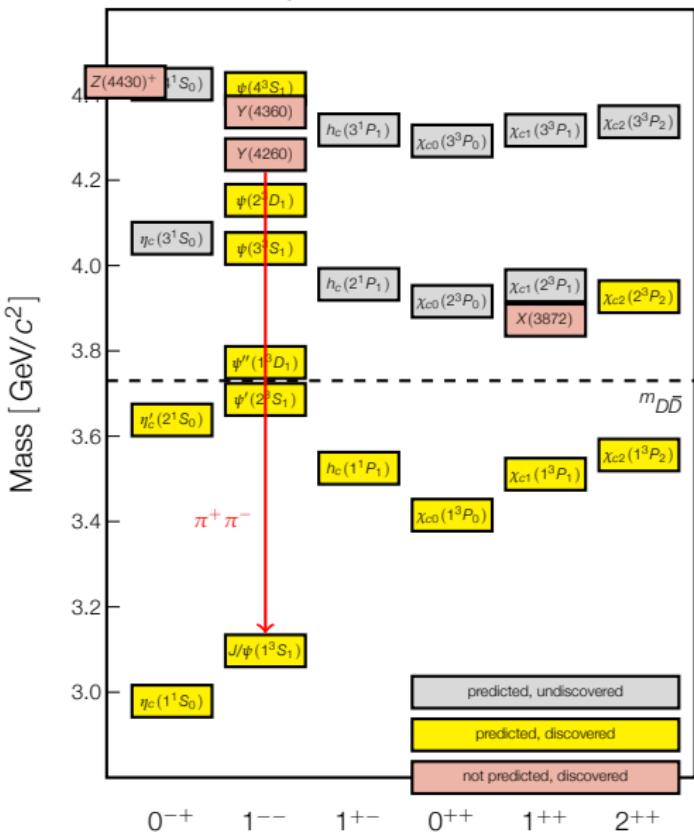
- ... $Y(4260) \rightarrow J/\psi \pi^+ \pi^-$
- ... $Y(4360) \rightarrow \psi(2S) \pi^+ \pi^-$
- ... additional state at 4460 MeV
- Do not correspond to peaks in $\sigma(e^+e^- \rightarrow \text{hadrons})$
- But: BESIII can run at these energies;
maybe produce them directly?



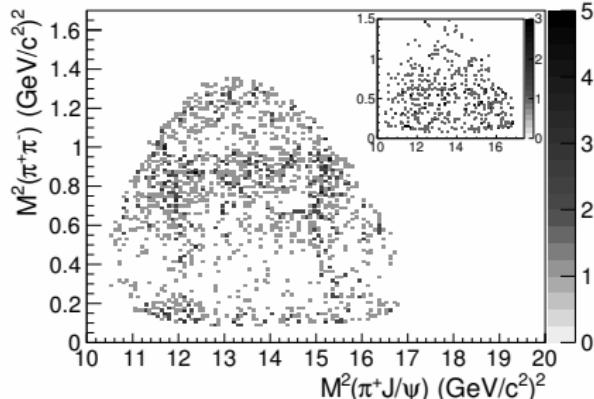
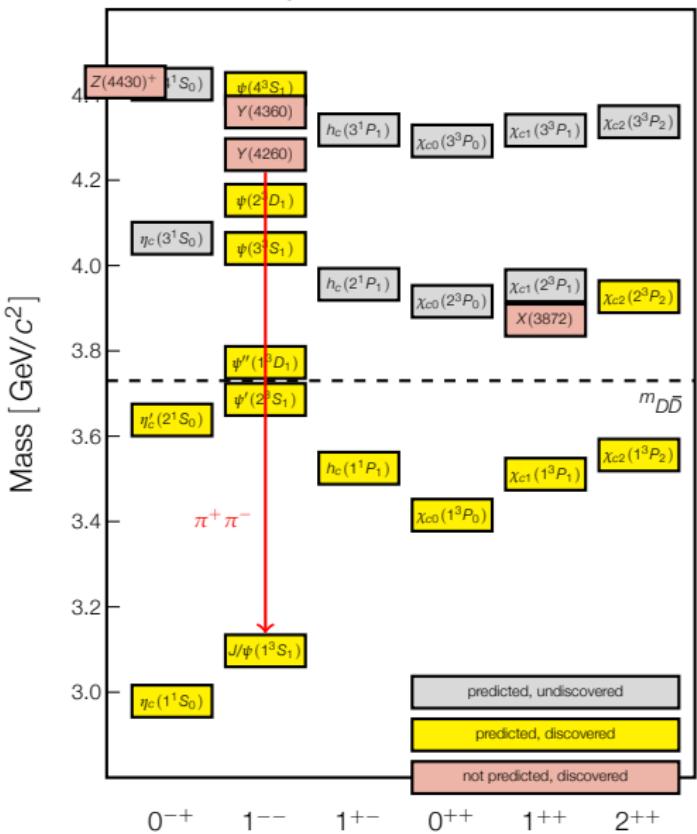
- Running at $\sqrt{s} = 4260$ MeV: simple and straightforward
- $J/\psi (\rightarrow \ell^+\ell^-)\pi^+\pi^-$: four charged tracks
- very clean sample, high efficiency, reliable MC simulation
- dominant background: continuum $e^+e^- \rightarrow \pi^+\pi^-\pi^+\pi^-$

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

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



...have hundreds of events!

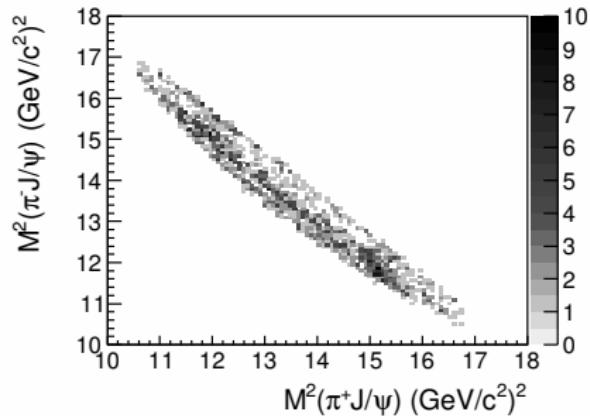
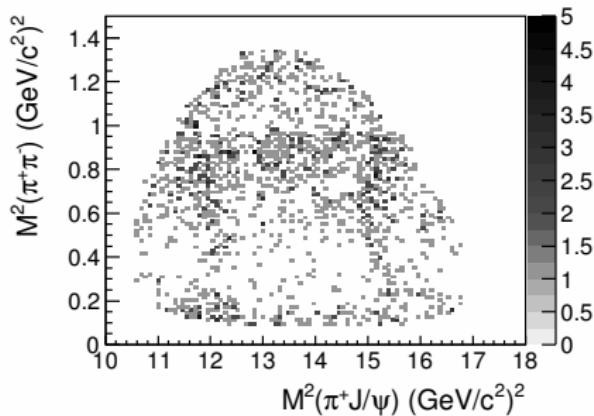


Non-trivial substructure in
 $J/\psi\pi^+\pi^-$ Dalitz plot

Resonant substructure in decay!

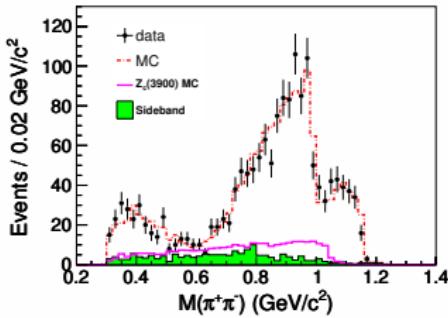
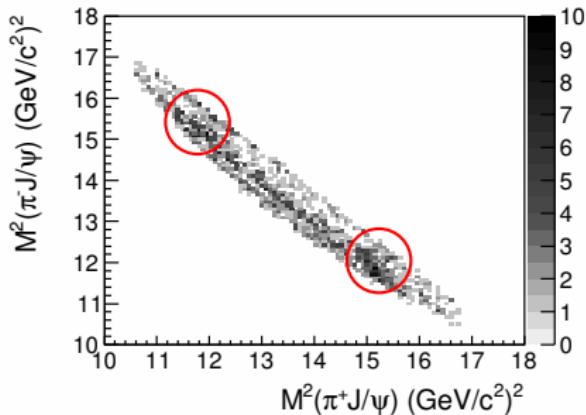
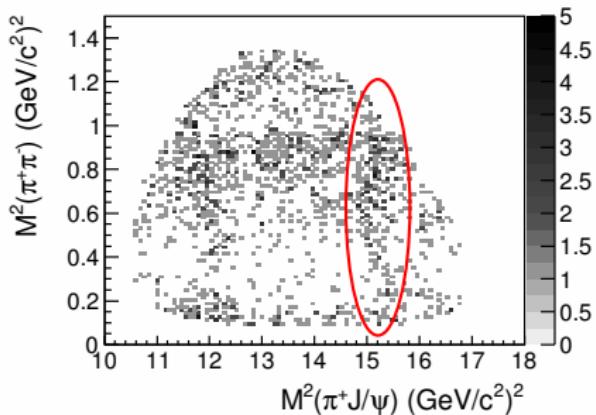
$J/\psi \pi^+ \pi^-$ Dalitz plot

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



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

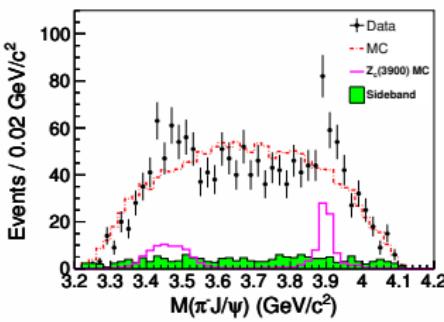
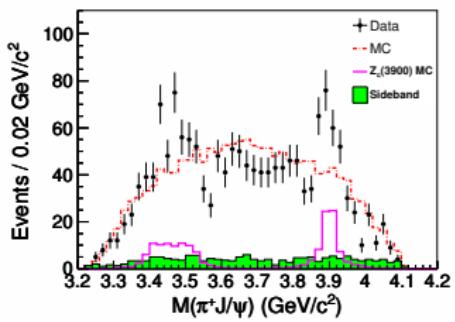
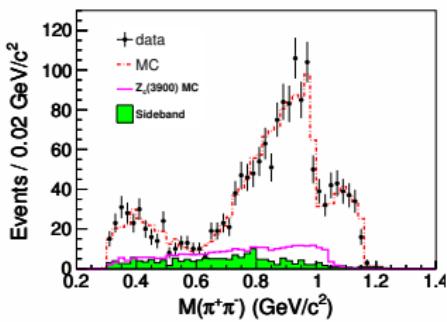
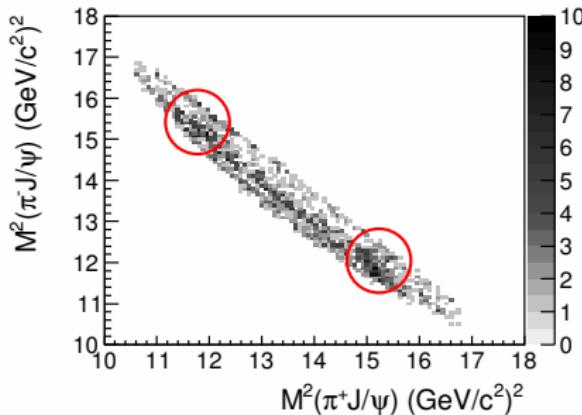
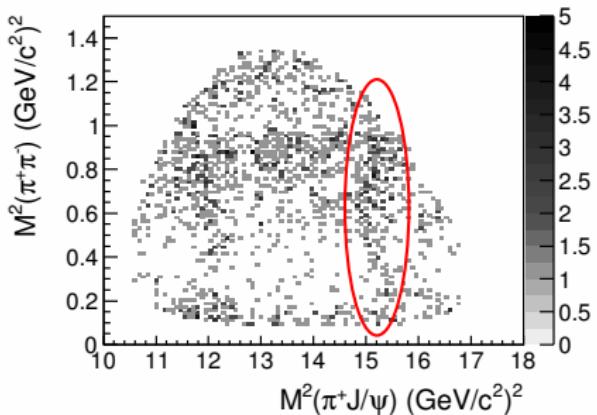
BESIII, PRL **110**, 252001 (2013)

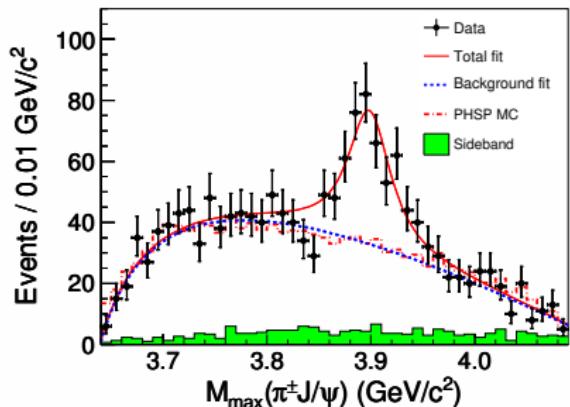
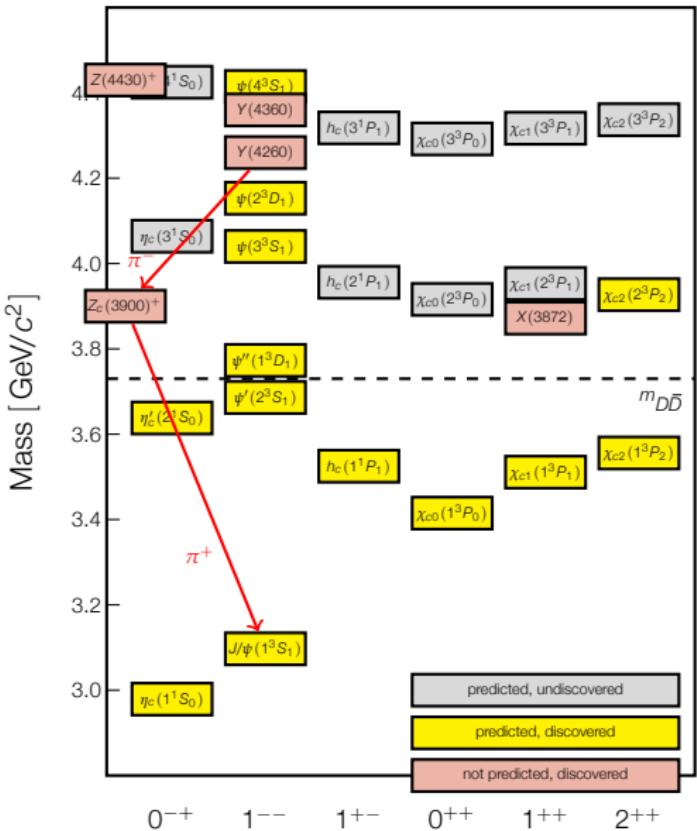


Model $\pi^+ \pi^-$ -system with known structure:
 $f_0(500)$, $f_0(980)$, non-resonant
obtain good fit of $\pi^+ \pi^-$ mass projection

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

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





Charged charmonium-like structure

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

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

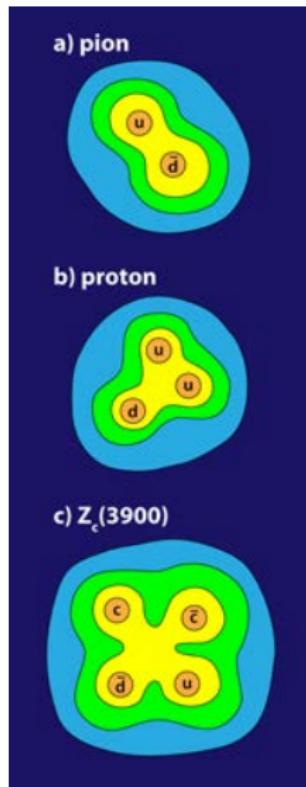
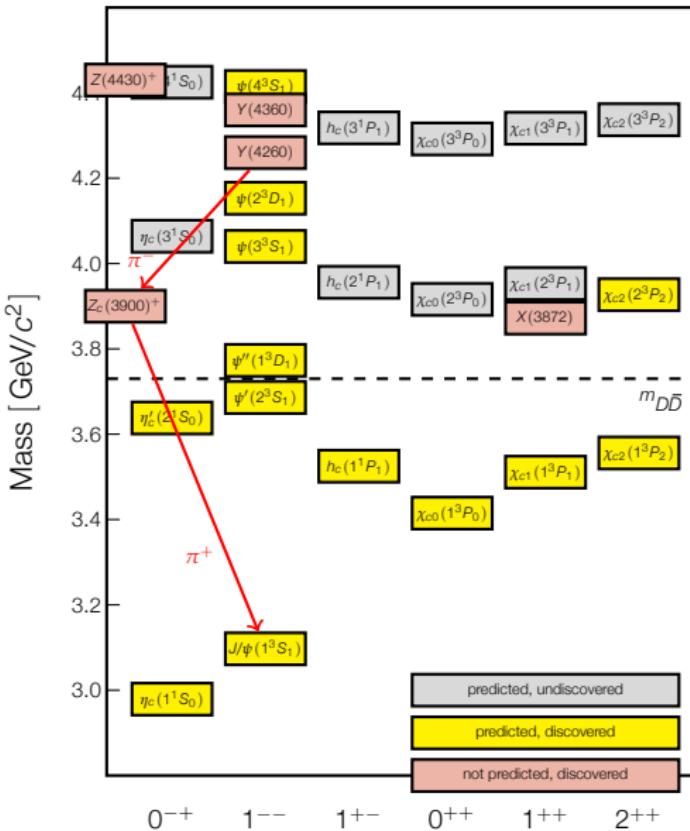
Confirmed by Belle PRL 110, 252002
and with CLEOc data PLB 727, 366

Close to $D\bar{D}^*$ threshold

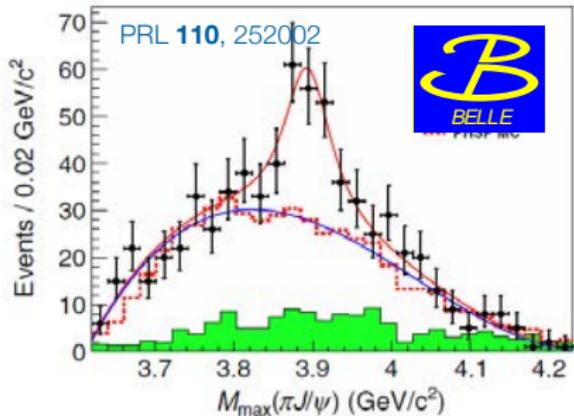
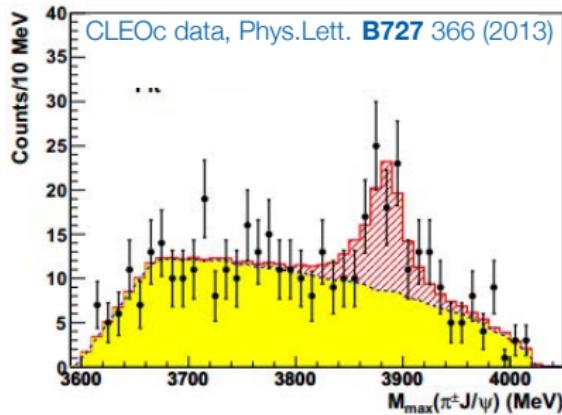
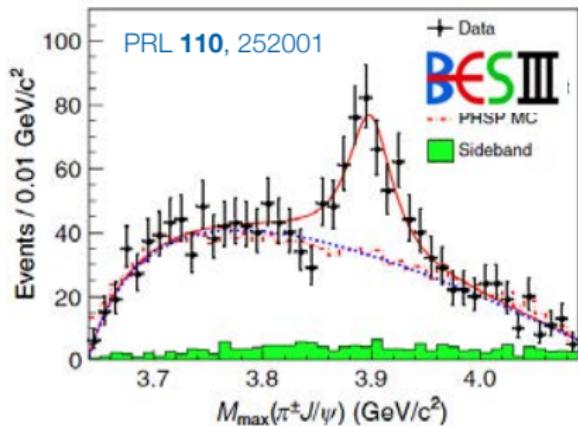
$e^+e^- \rightarrow J/\psi\pi^+\pi^-$ at 4.26 GeV

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

One of
APS highlights of 2013



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

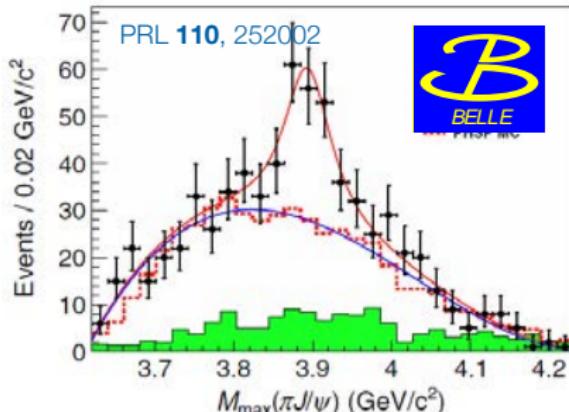
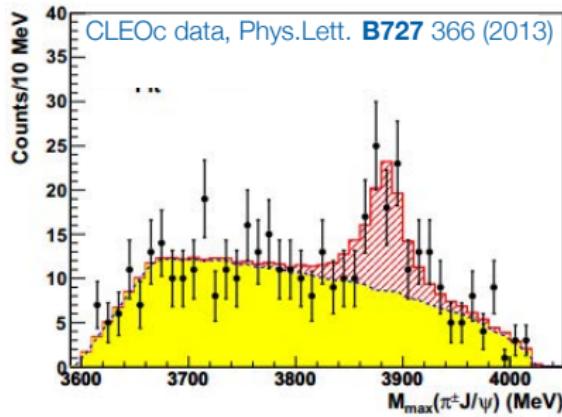
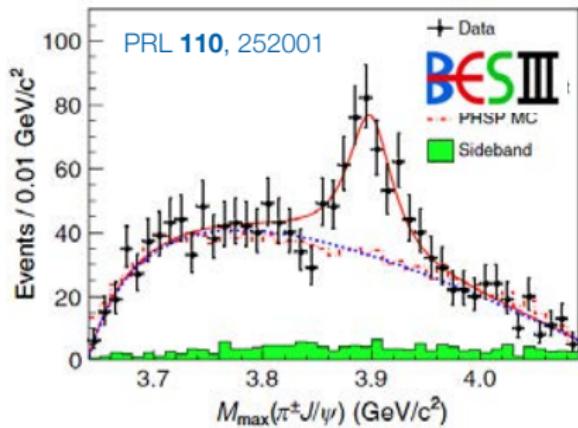


	m / MeV	Γ / MeV
BESIII	$3899.0 \pm 3.6 \pm 4.9$	$46 \pm 10 \pm 20$
Belle	$3894.5 \pm 6.6 \pm 4.5$	$63 \pm 24 \pm 26$
CLEOc	$3885 \pm 5 \pm 1$	$34 \pm 12 \pm 4$

Belle: $e^+e^- \rightarrow \gamma_{ISR} J/\psi \pi^+\pi^-$,
in $Y(4260)$ region

CLEOc data: $\sqrt{s} = 4.170$ GeV

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



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

Interpretation of $Z_c(3900)$?

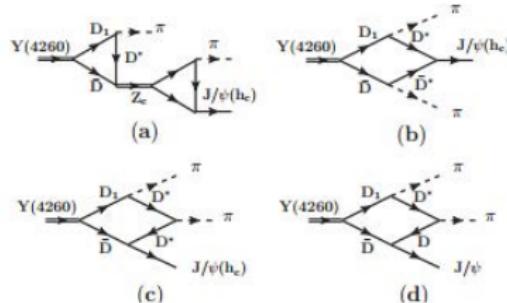
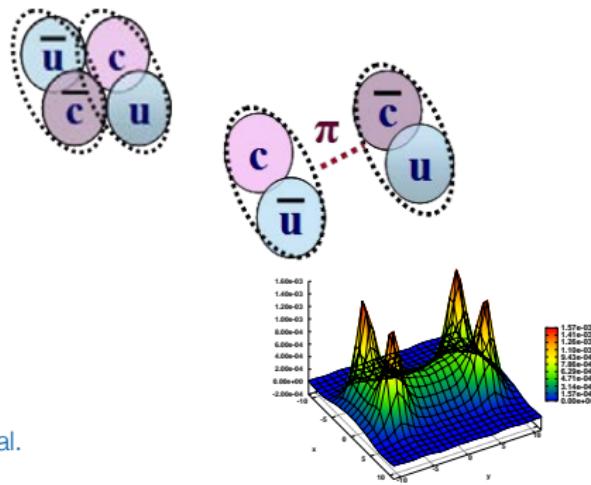
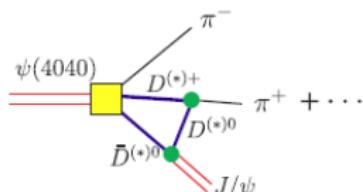
- Mass close to DD^* threshold
 - Couples strongly to $c\bar{c}$
 - Has electric charge
 - If new particle:
 - ➡ necessarily exotic,
- quark contents at least $c\bar{c}u\bar{d}$

Interpretation of $Z_c(3900)$?

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- Has electric charge
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So, what is it?

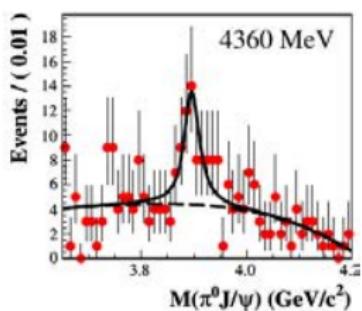
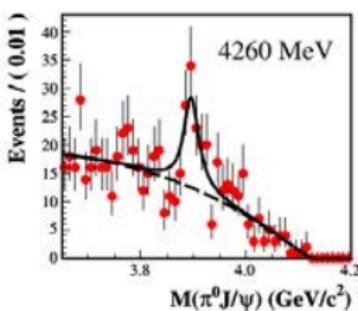
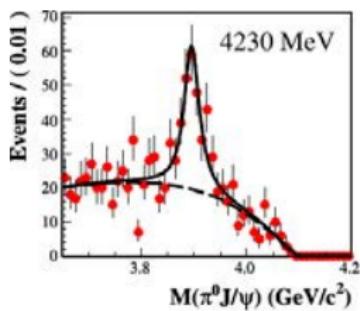
- Tetraquark L. Maiani, A. Ali et al.
- Hadronic molecule U.-G. Meissner, F.K. Guo et al.
- Hadro-charmonium M. B. Voloshin
- Meson loop Q. Zhao et al.
- ISPE model X. Liu et al.
- ...



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

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

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

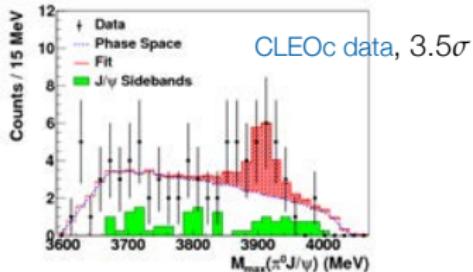


Structure in $\pi^0 J/\psi$ invariant mass
clearly visible at all energies

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

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

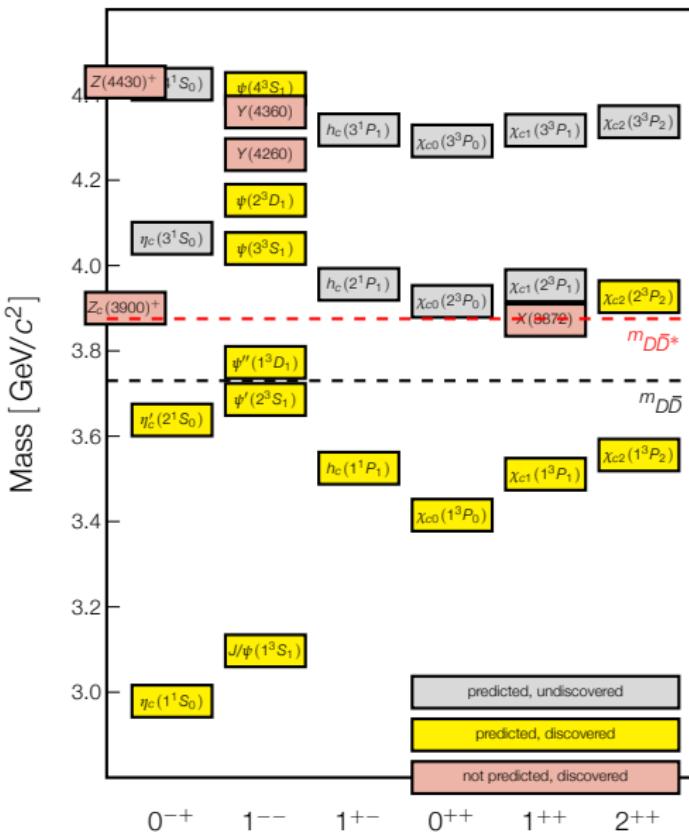
Significance = 10σ



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

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

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



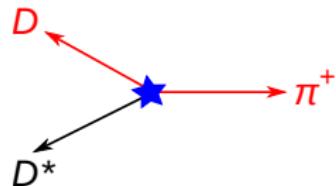
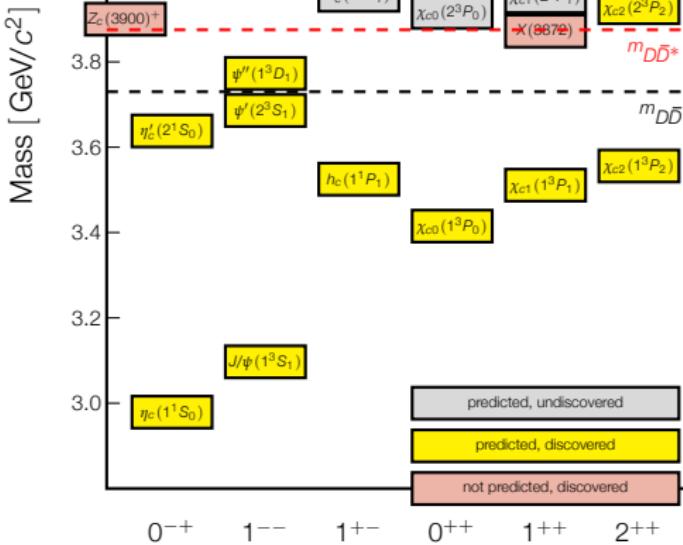
$Z_c(3900)^+$ at $D\bar{D}^*$ threshold

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

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

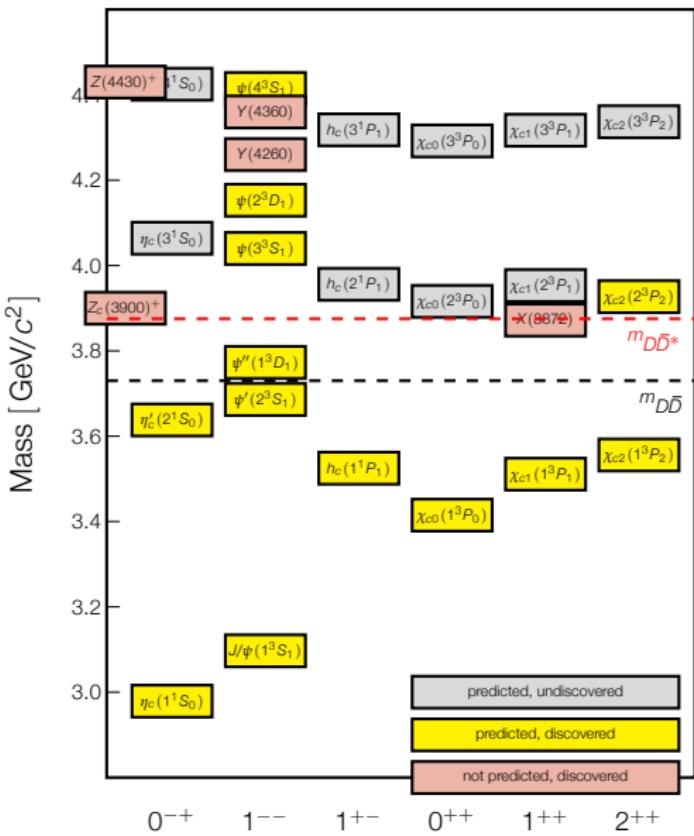
Single tag analysis:

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

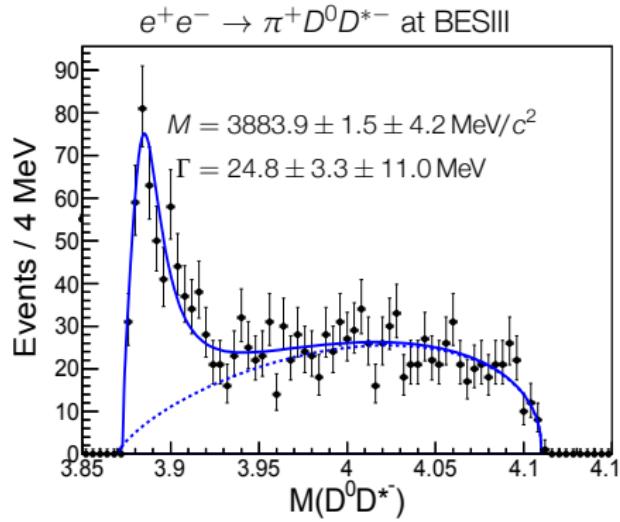


$Z_c(3900)^+$ at $D\bar{D}^*$ threshold

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

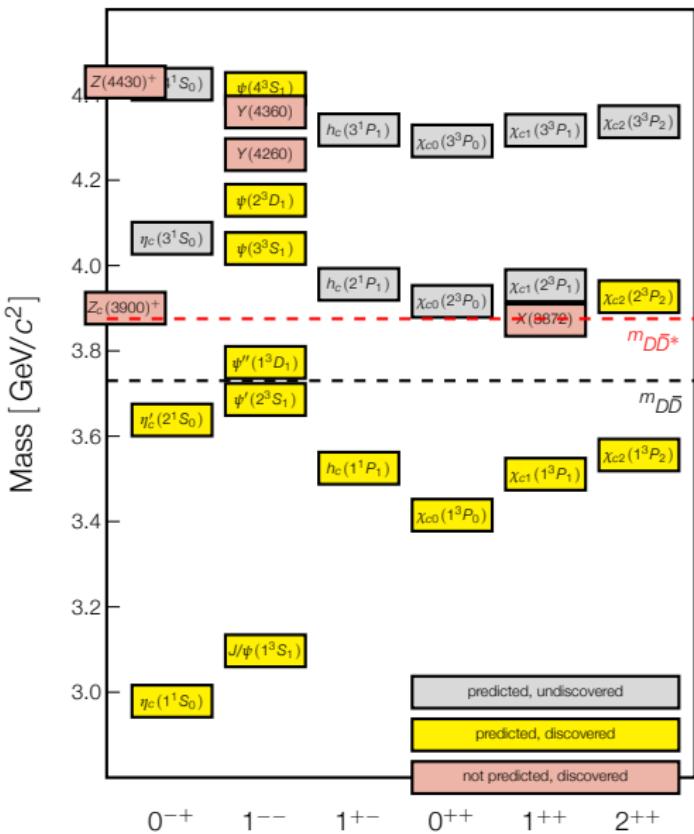


Decay mode $Z_c(3900)^+ \rightarrow (D\bar{D}^*)^+?$



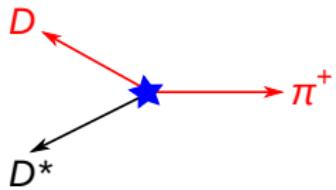
...and BESIII sees structure in DD^*

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



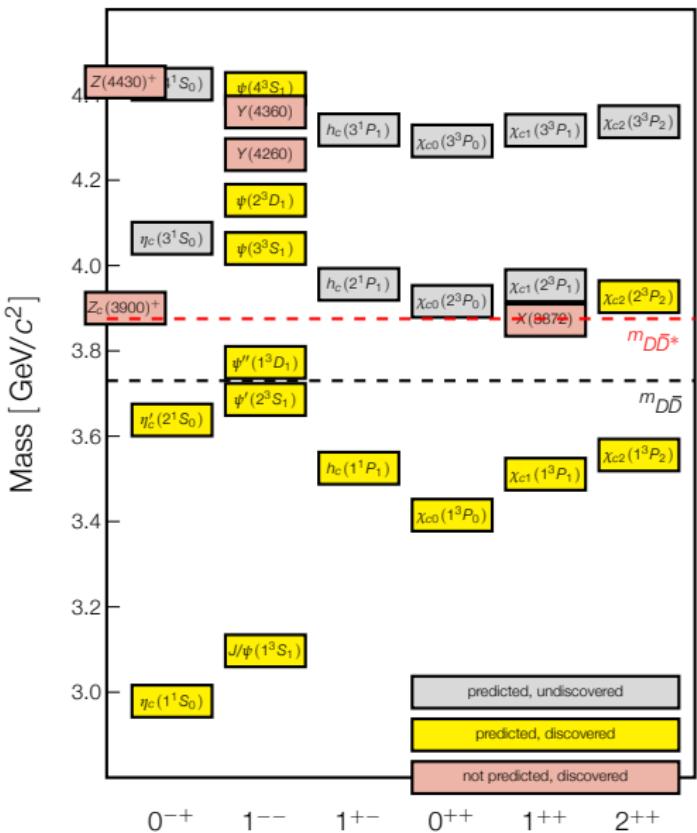
New: Double tag analysis

- 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

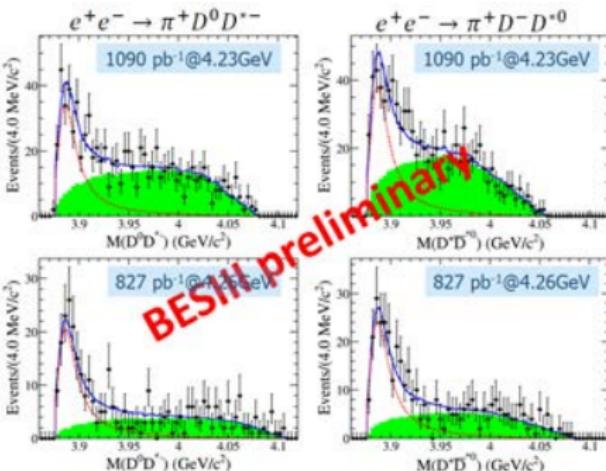
BESIII
preliminary



$e^+e^- \rightarrow \pi^+ D^0 D^{*-}$ 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?

$\cos \theta_\pi$: angle between bachelor pion and beam axis in CMS

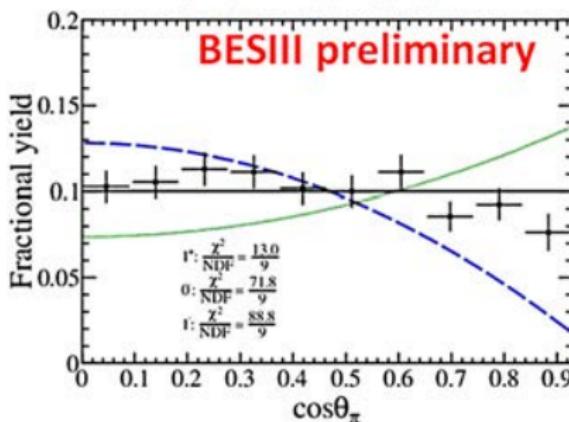
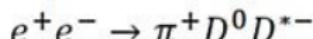
0^+ excluded by parity conservation

0^- π and $Z_c(3885)$ in P -wave, with $J_z = \pm 1$ $\Rightarrow dN/d\cos \theta_\pi \propto 1 - \cos^2 \theta_\pi$

1^- π and $Z_c(3885)$ in P -wave $\Rightarrow dN/d\cos \theta_\pi \propto 1 + \cos^2 \theta_\pi$

1^+ π and $Z_c(3885)$ in S or D wave. Assume D wave small near threshold: flat distribution in $\cos \theta_\pi$.

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 $Z_c(3885)$

	$Z_c(3885) \rightarrow D\bar{D}^*$	$Z_c(3900) \rightarrow \pi J/\psi$
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!

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

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

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

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

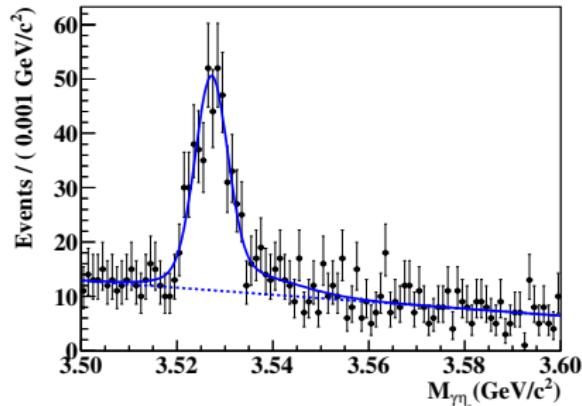
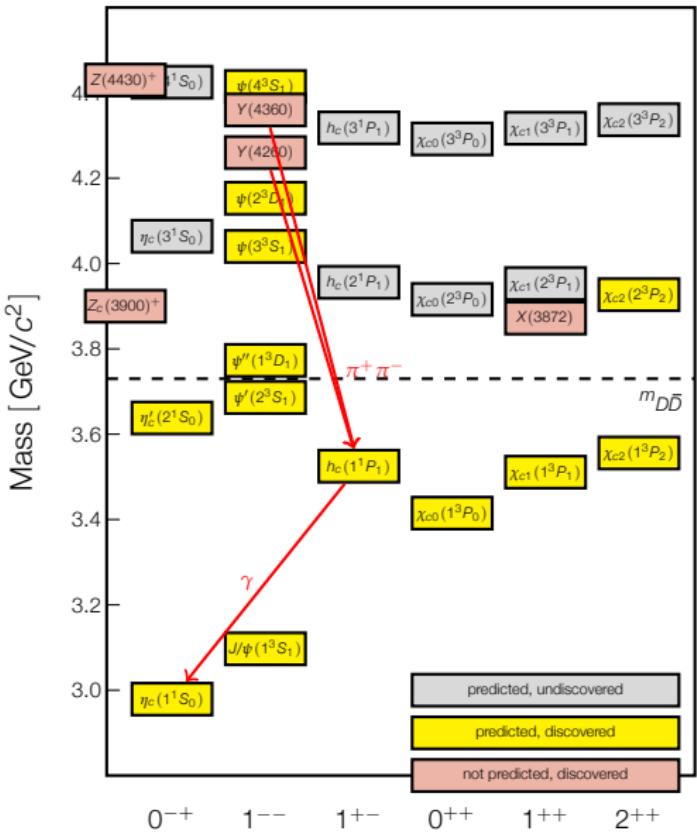
BESIII, PRL **111**, 242001 (2013)

Exclusively reconstruct the process

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

$$h_c(1P) \rightarrow \gamma\eta_c(1S)$$

$\eta_c(1S) \rightarrow 16$ decay channels



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

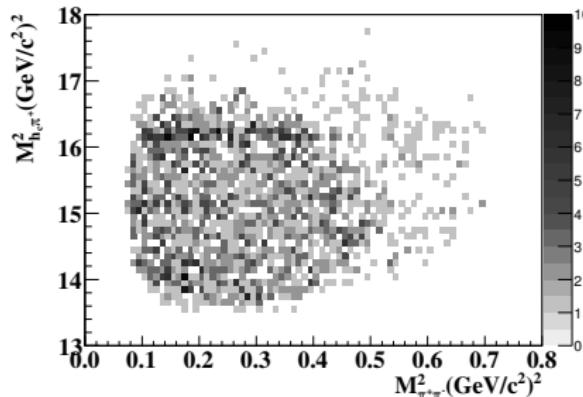
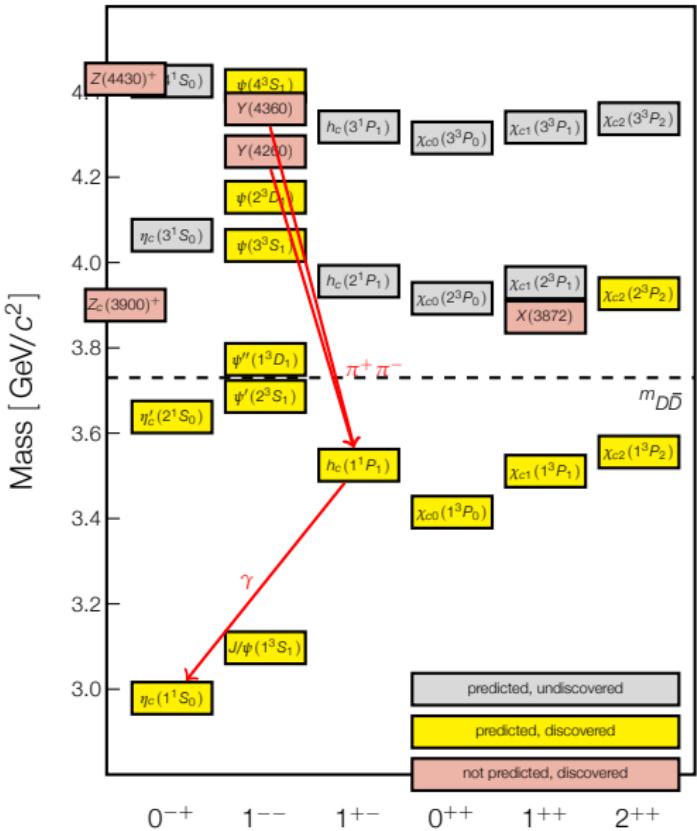
BESIII, PRL **111**, 242001 (2013)

Exclusively reconstruct the process

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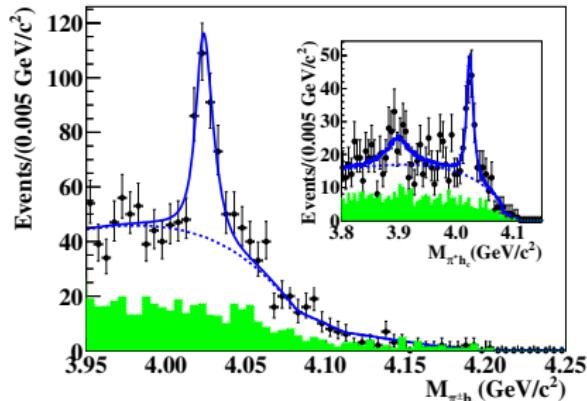
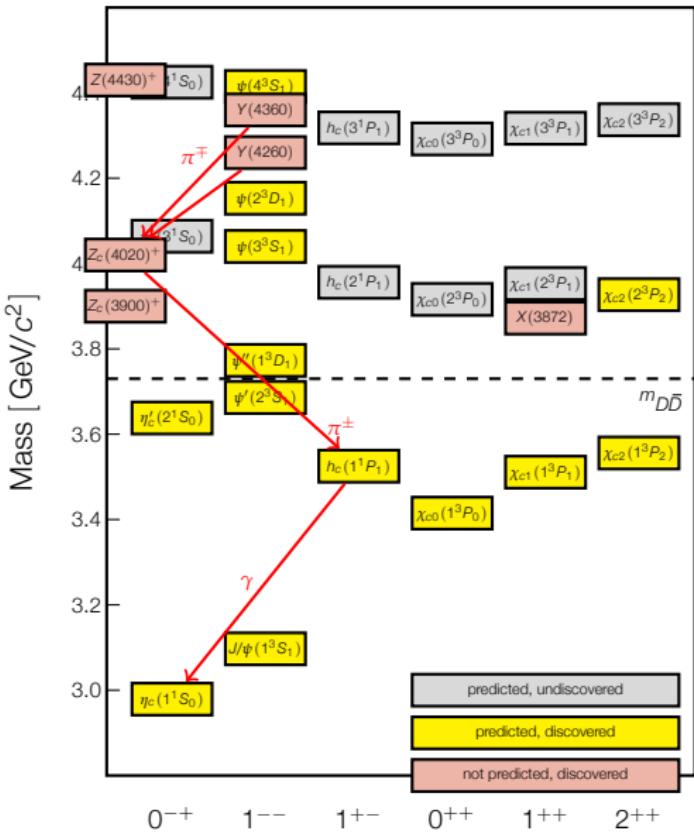
$$h_c(1P) \rightarrow \gamma\eta_c(1S)$$

$\eta_c(1S) \rightarrow 16$ decay channels



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

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



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

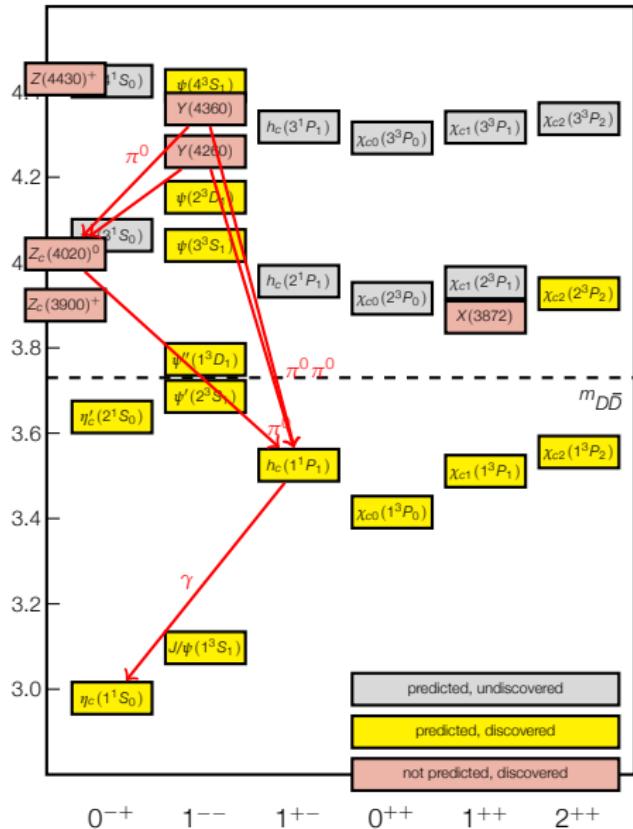
$$M = 4022.9 \pm 0.8 \pm 2.7 \text{ MeV}/c^2$$

$$\Gamma = 7.9 \pm 2.7 \pm 2.6 \text{ MeV}$$

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

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

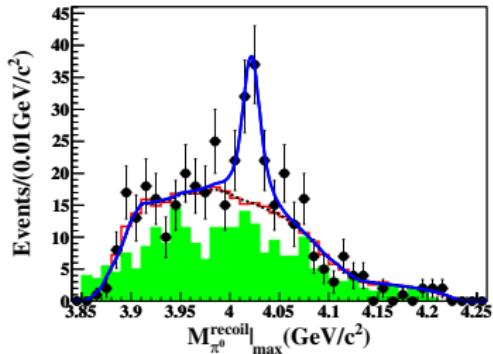
BESIII, PRL **113**, 212002 (2014)



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

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

Neutral partner to $Z_c(4020)^+$



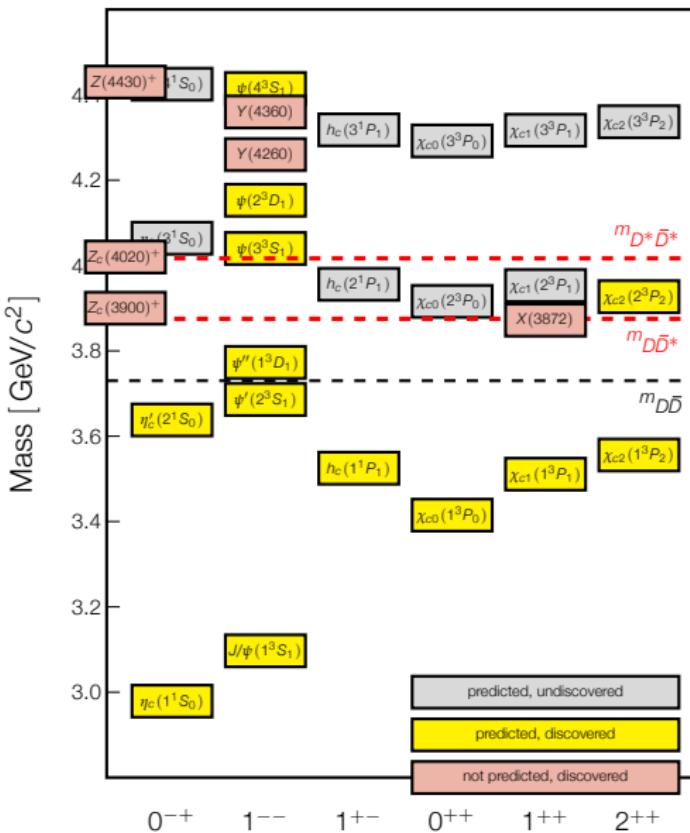
$$M = 4023.6 \pm 4.5 \text{ MeV}/c^2$$

Isospin triplet found!

Yet another mass threshold ...

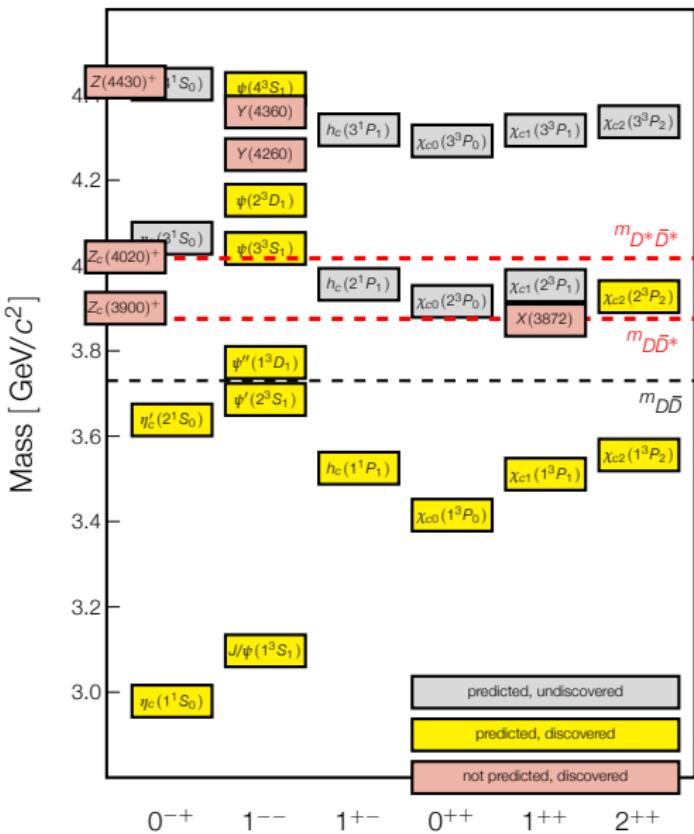
BESIII, PRL **112**, 132001 (2014)

$Z_c(4020)$ at $D^* \bar{D}^*$ threshold

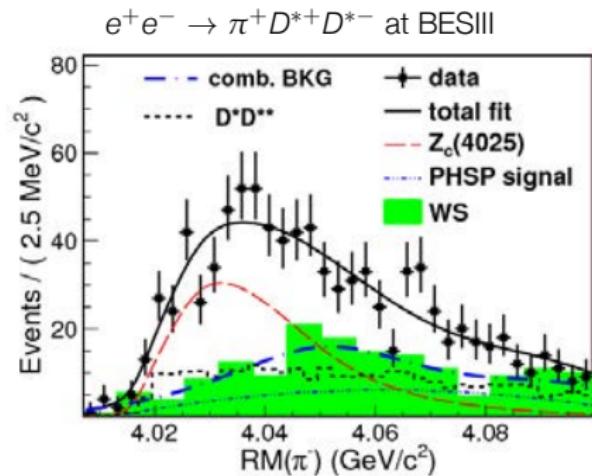


Yet another mass threshold ...

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



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

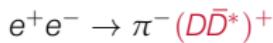
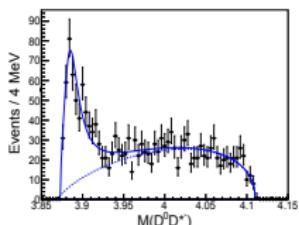
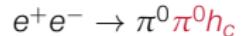
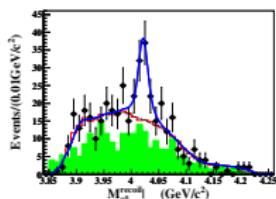
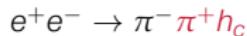
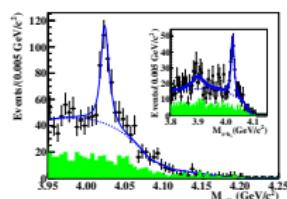
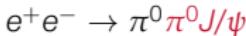
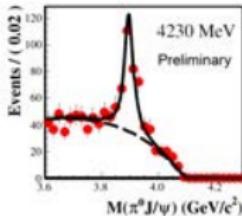
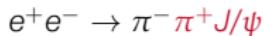
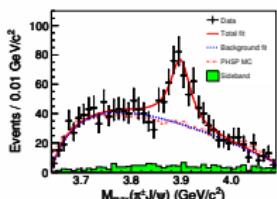


...and BESIII sees structure in $D^* D^*$

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

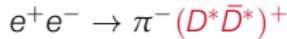
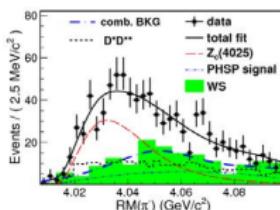
$$\Gamma = 24.8 \pm 5.6 \pm 7.7 \text{ MeV}$$

All the Z_c s from BESIII near $\sqrt{s} = 4.3$ GeV



$Z_c(3900)^+?$

$Z_c(3900)^0?$



$Z_c(4020)^+?$

$Z_c(4020)^0?$

Nature of these states? Isospin triplets?

Different decay channels of the same states observed?

Other decay modes?

Even more surprises

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

- $Z_c(4430)^+ \rightarrow \psi(2S)\pi^+$

Seen by Belle in 2008 in B decays, not confirmed by BABAR,
recently confirmed by LHCb [PRL 112, 222002 \(2014\)](#)

- $Z_1(4050)^+, Z_2(4250)^+ \rightarrow \chi_{c1}\pi^+$

Seen by Belle in B decays, not significant in BABAR data

- $Z_c(4200)^+ \rightarrow J/\psi\pi^+$

Belle, in $\bar{B}^0 \rightarrow J/\psi K^- \pi^+$ [Phys. Rev. D 90, 112009 \(2014\)](#) very broad!
no $Z_c(3900)^+$ visible here?!

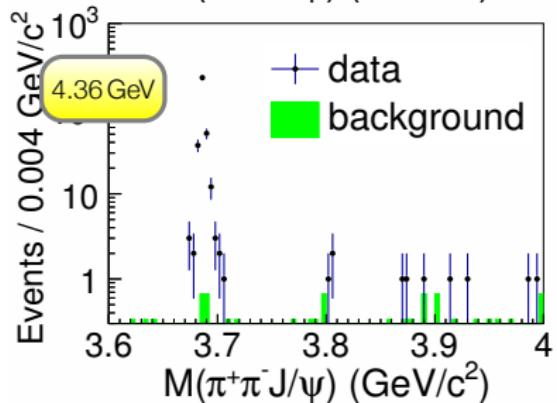
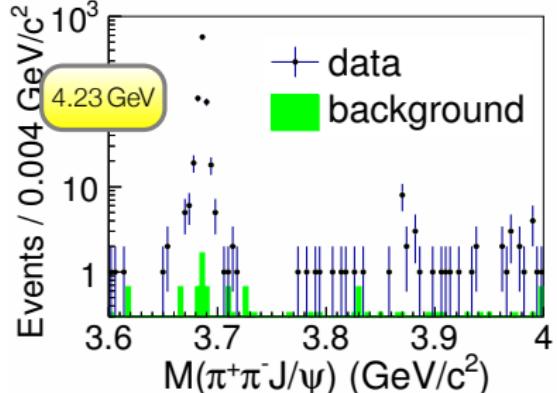
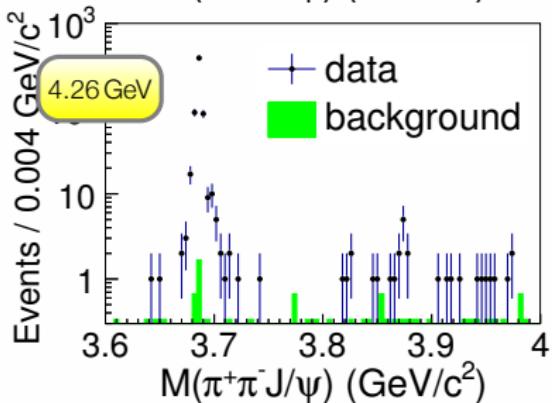
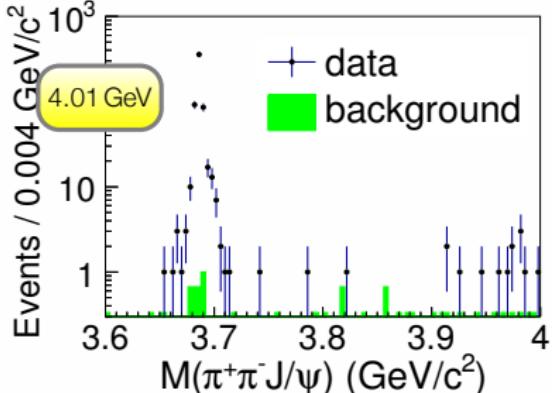
- $Z_b(10610)^+$ and $Z_b(10650)^+ \rightarrow Y(2,3S)\pi^+$

seen in $b\bar{b}$ sector ([PRL 108, 122001 \(2012\)](#))

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

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

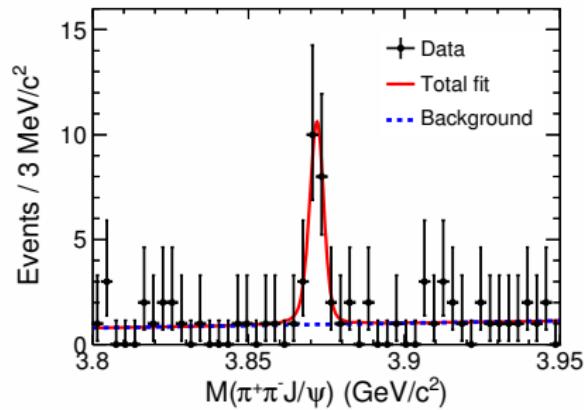
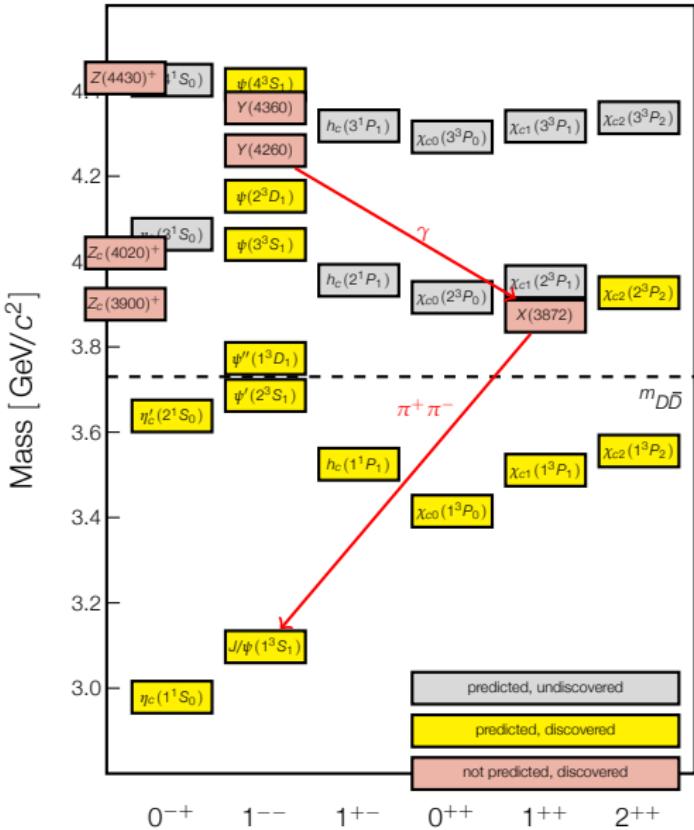
BESIII, PRL **112**, 092001 (2014)



Clear ISR ψ' signal for validation
X(3872) signal around 4.23 – 4.26 GeV

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

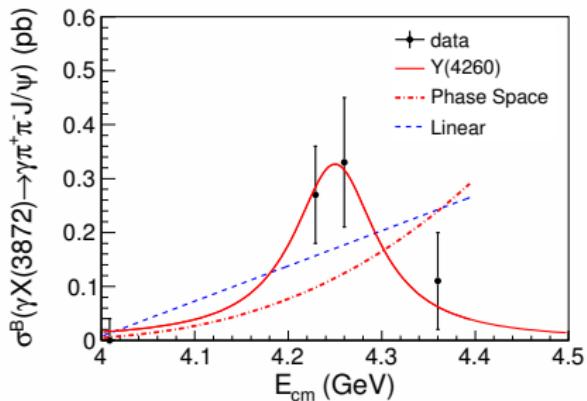
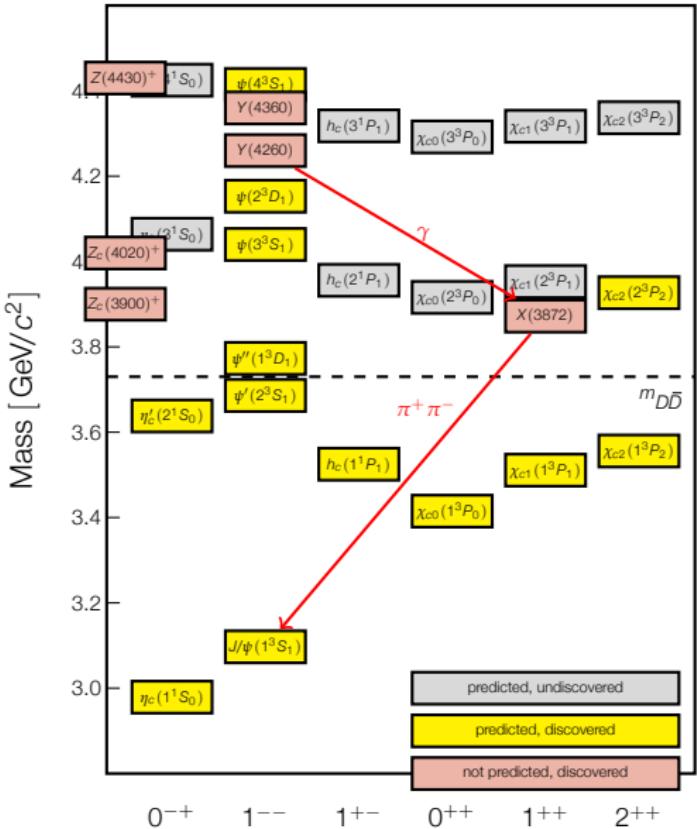
BESIII, PRL **112**, 092001 (2014)



20.1 ± 4.5 events
significance 6.3σ
 $M = 3871.9 \pm 0.7 \pm 0.2 \text{ MeV}/c^2$

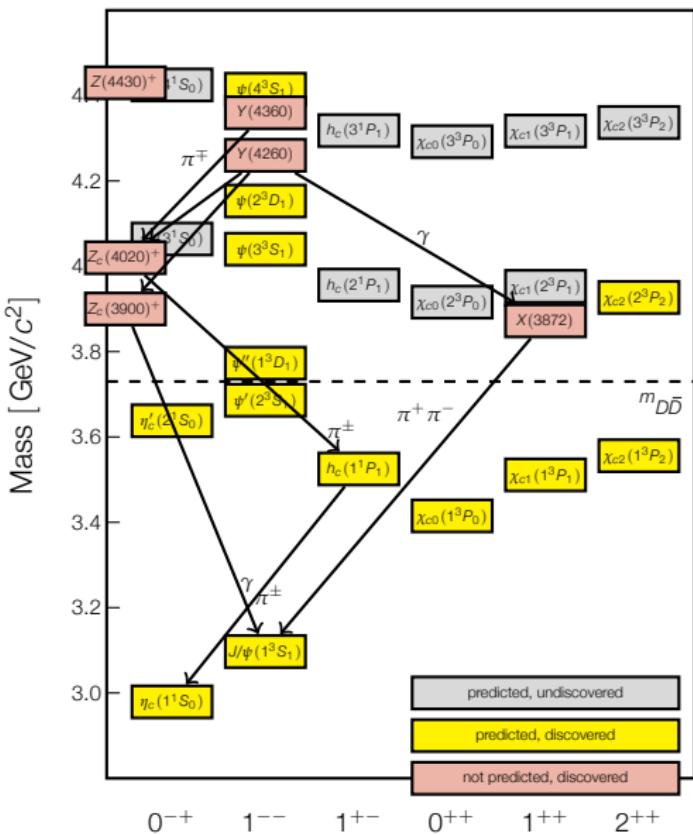
$$e^+e^- \rightarrow \gamma X(3872) \rightarrow \gamma J/\psi \pi^+ \pi^-$$

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



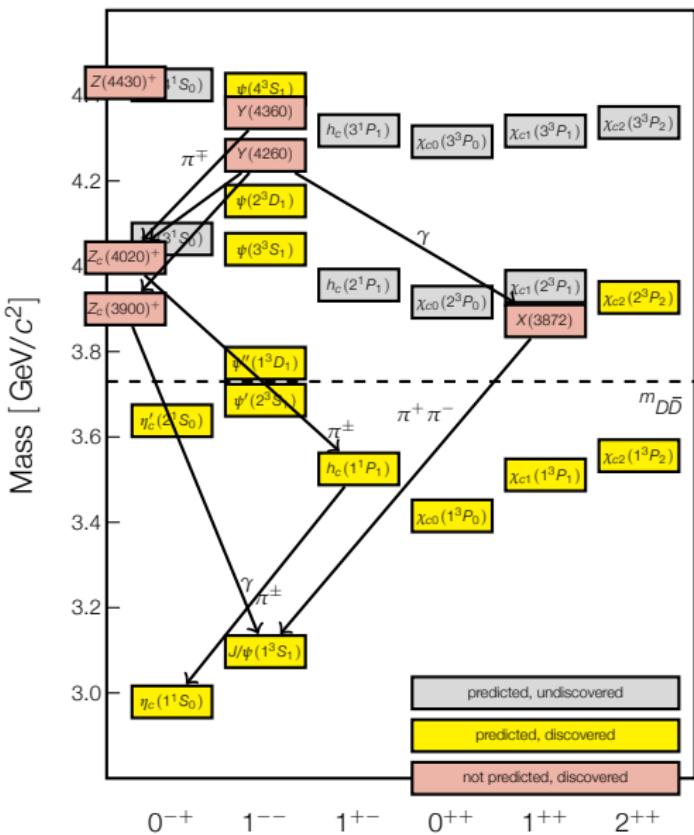
Suggestive of
 $Y(4260) \rightarrow \gamma X(3872)$

Summary



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

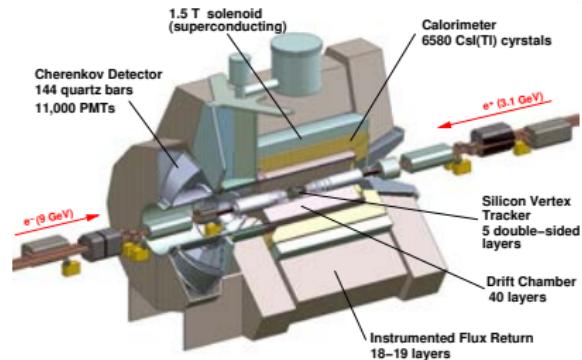
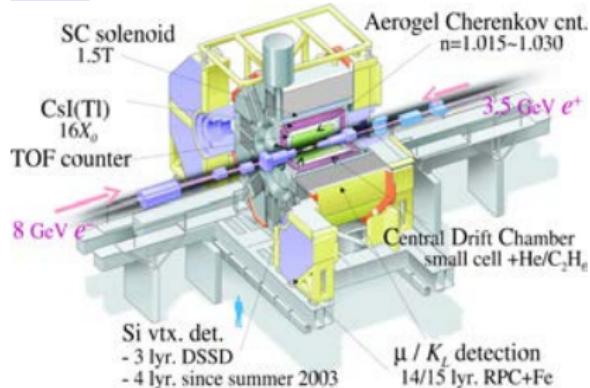


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The B factories Belle and BABAR



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

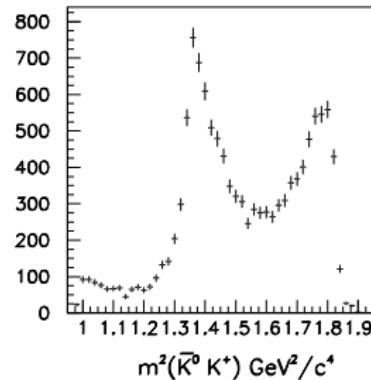
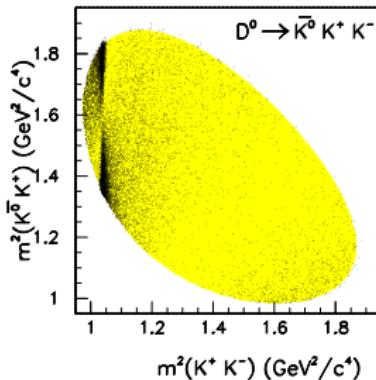
- KEK-B: 8 GeV e⁻ × 3.5 GeV e⁺
- $\mathcal{L}_{\text{int}} \approx 1 \text{ ab}^{-1}$
- Data taking finished 2010
- PEP-II: 9 GeV e⁻ × 3.1 GeV e⁺
- $\mathcal{L}_{\text{int}} \approx 530 \text{ fb}^{-1}$
- Data taking finished 2008

Reflections

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

Striking example provided by $D^0 \rightarrow \bar{K}^0 K^+ K^-$

BABAR, Phys. Rev. D **72**, 052008 (2005)



No resonances in $K^+ \bar{K}^0$ channel.

Structures visible in projection created from resonances in $K^+ K^-$.

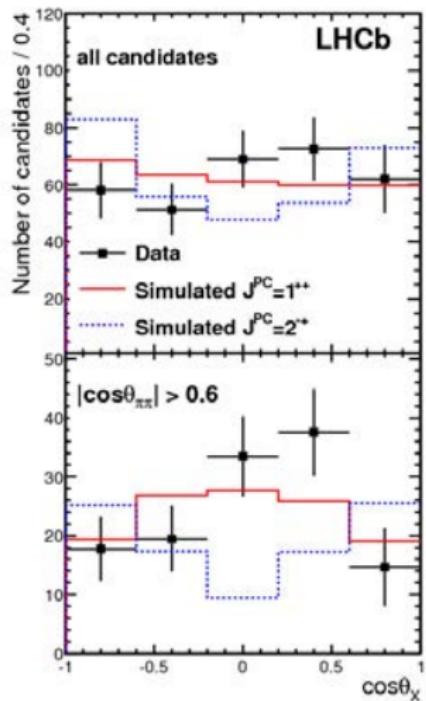
Note: Decays like $B \rightarrow \psi(2S) K\pi$ more complicated: Two kinematic variables of Dalitz plot not sufficient to describe kinematics

e.g. *BABAR* $B \rightarrow J/\psi K\pi$, Phys. Rev. D **71**, 032005 (2005)

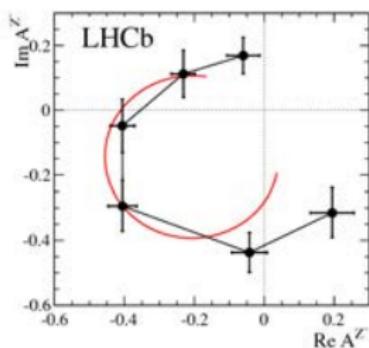
The $Z_c(4430)^+$ in $B^0 \rightarrow \psi' K^+ \pi^-$

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

Spin-Parity assignment



Phase motion



behaves like a 'true' resonance

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