Recent results on XYZ states from BESIII

Wolfgang Gradl

on behalf of the BESIII collaboration

Bound States in QCD and Beyond
St. Goar, 26th March 2015

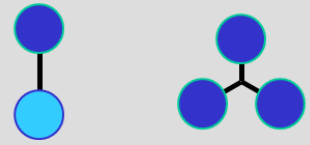
Outline

QCD bound systems

States found in nature: colour-neutral combinations

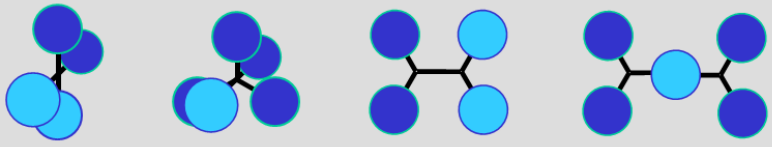
We know

mesons and baryons

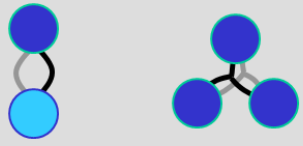


QCD also allows

molecules/multi-quarks



hybrids



glueballs

and more

Totalitarian principle of quantum mechanics:

Everything not forbidden is compulsory

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 properber $n_t - n_{\bar{t}}$ 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 (qqq), $(qqqq\bar{q})$, etc., while mesons are made out of $(q\bar{q})$, $(qq\bar{q}\bar{q})$, etc. It is assuming that the lowest baryon configuration (qqq) 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

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 hep-ph/0510365

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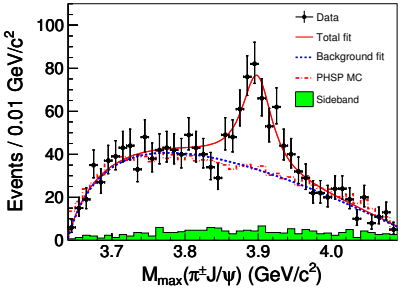
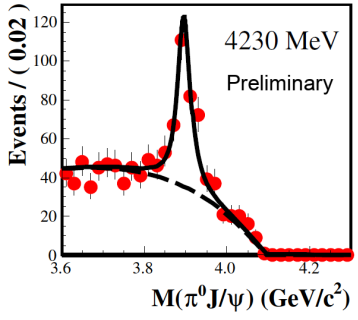
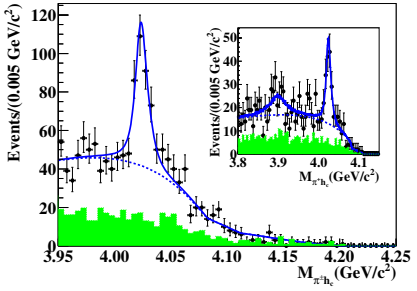
in the past few years, compelling evidence for states beyond simple $q\bar{q}$!



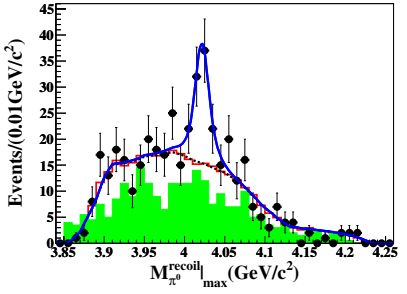
$e^+e^- \to \pi^-\pi^+ J/\psi$



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



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



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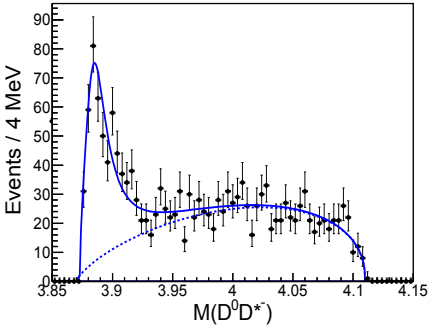
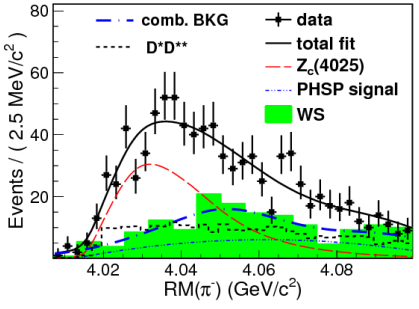


$e^+e^- \to \pi^- (D\bar{D}^*)^+$

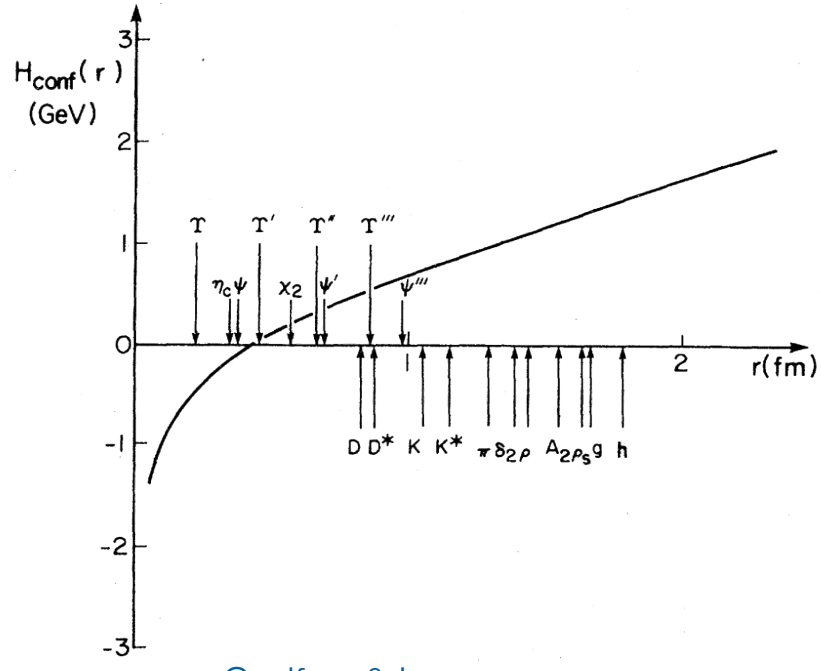


$e^+e^- \to \pi^- (D^*\bar{D}^*)^+$

A good hunting ground?

Charmonium and charmonium-like states useful for this search:

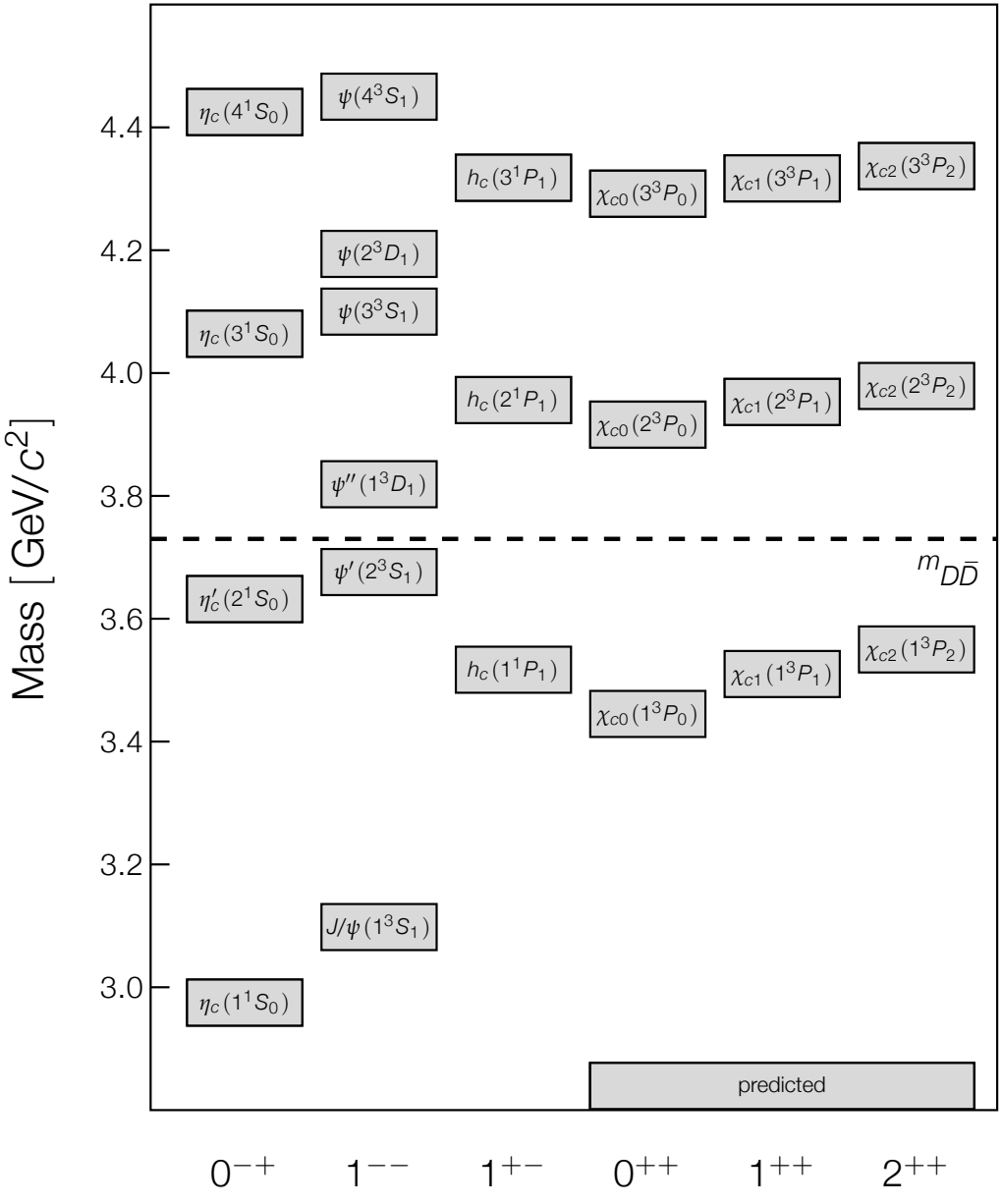
- $m_c \approx 1.3\,\text{GeV}$: probe transition region from perturbative to non-perturbative regime
- separation between states larger
- states presumably less mixed than in light quark sector
- can be produced copiously in e^+e^- collisions
- Exciting possibility to find exotics among new states



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


Charmonium Spectroscopy

Charmonium spectrum



Charmonium: $c\bar{c}$

Example potential

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

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

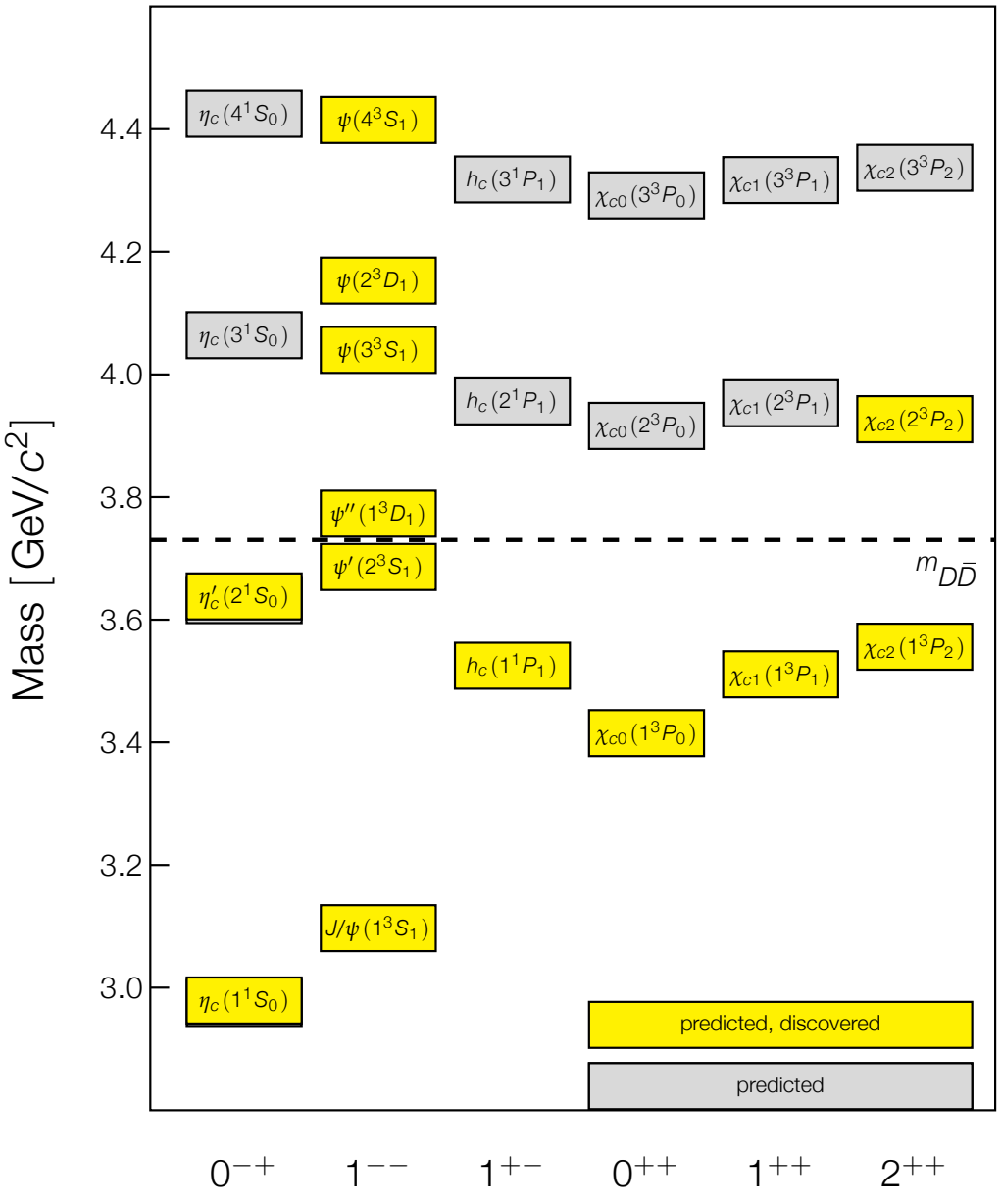
+ relativistic corrections!

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

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

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

Charmonium spectrum



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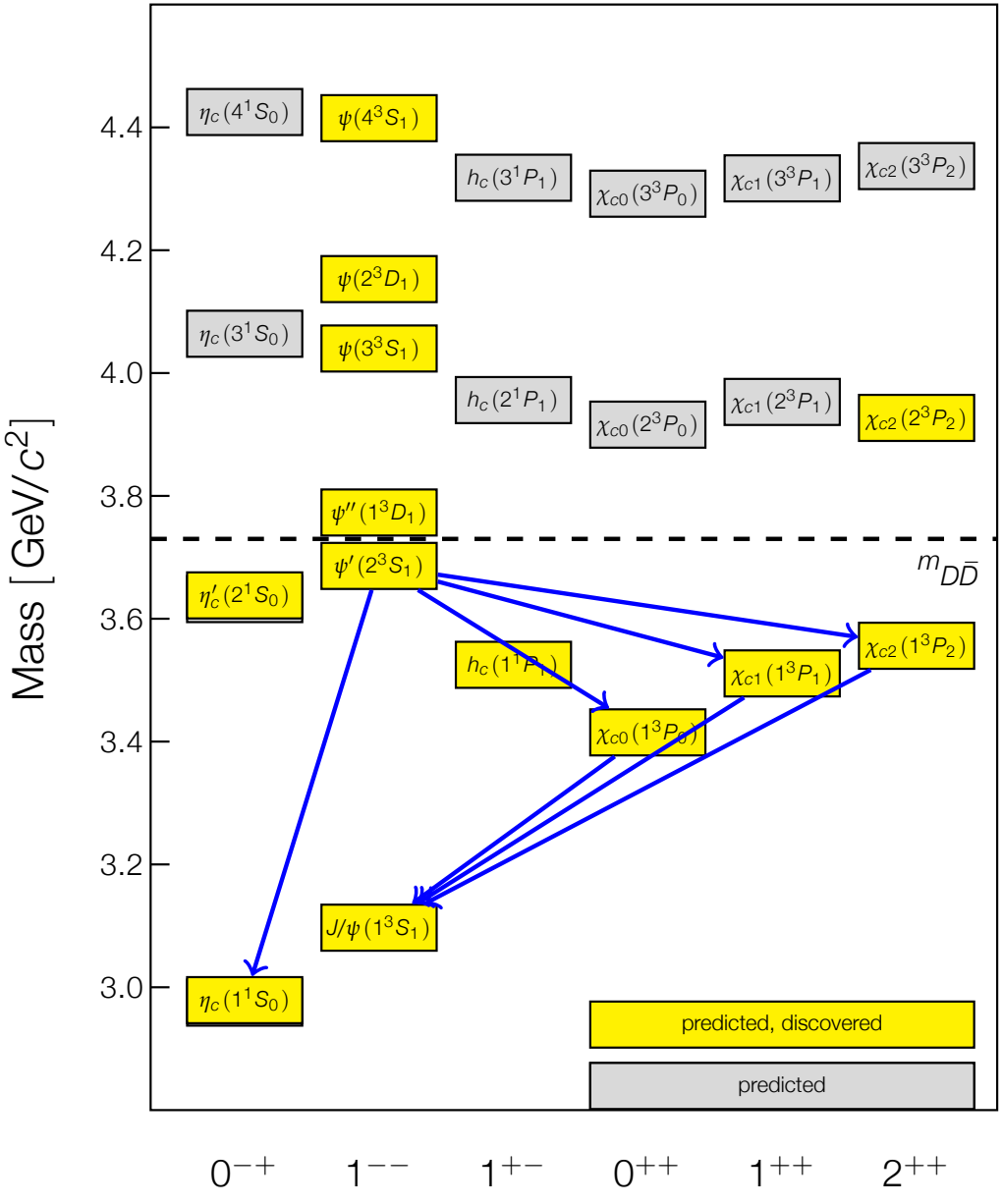

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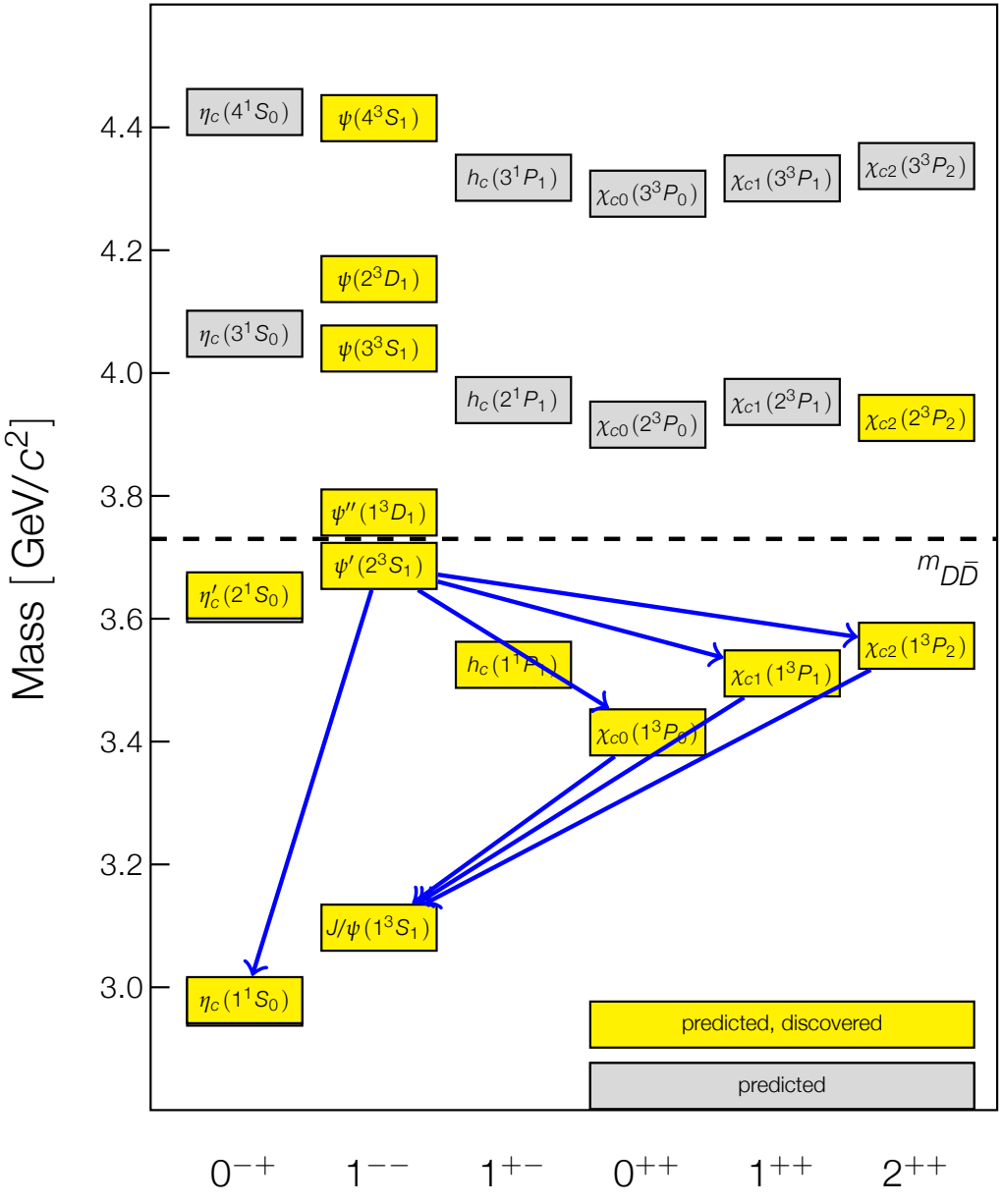
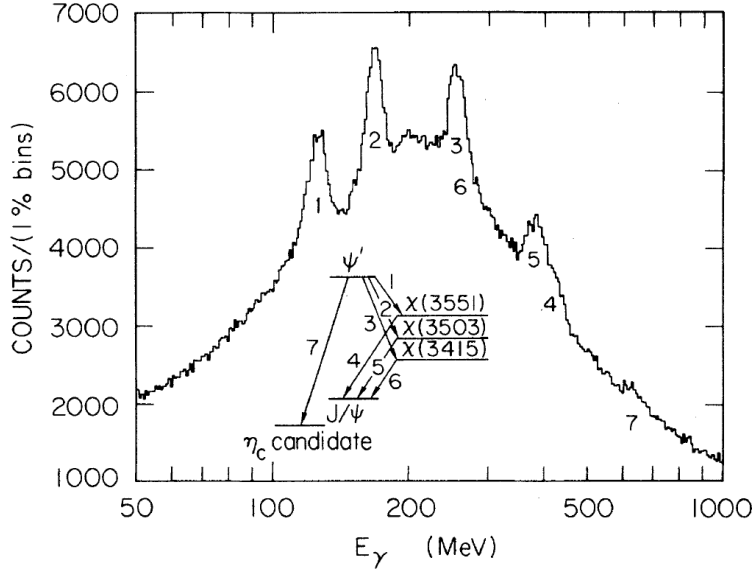


Charmonium: $c\bar{c}$

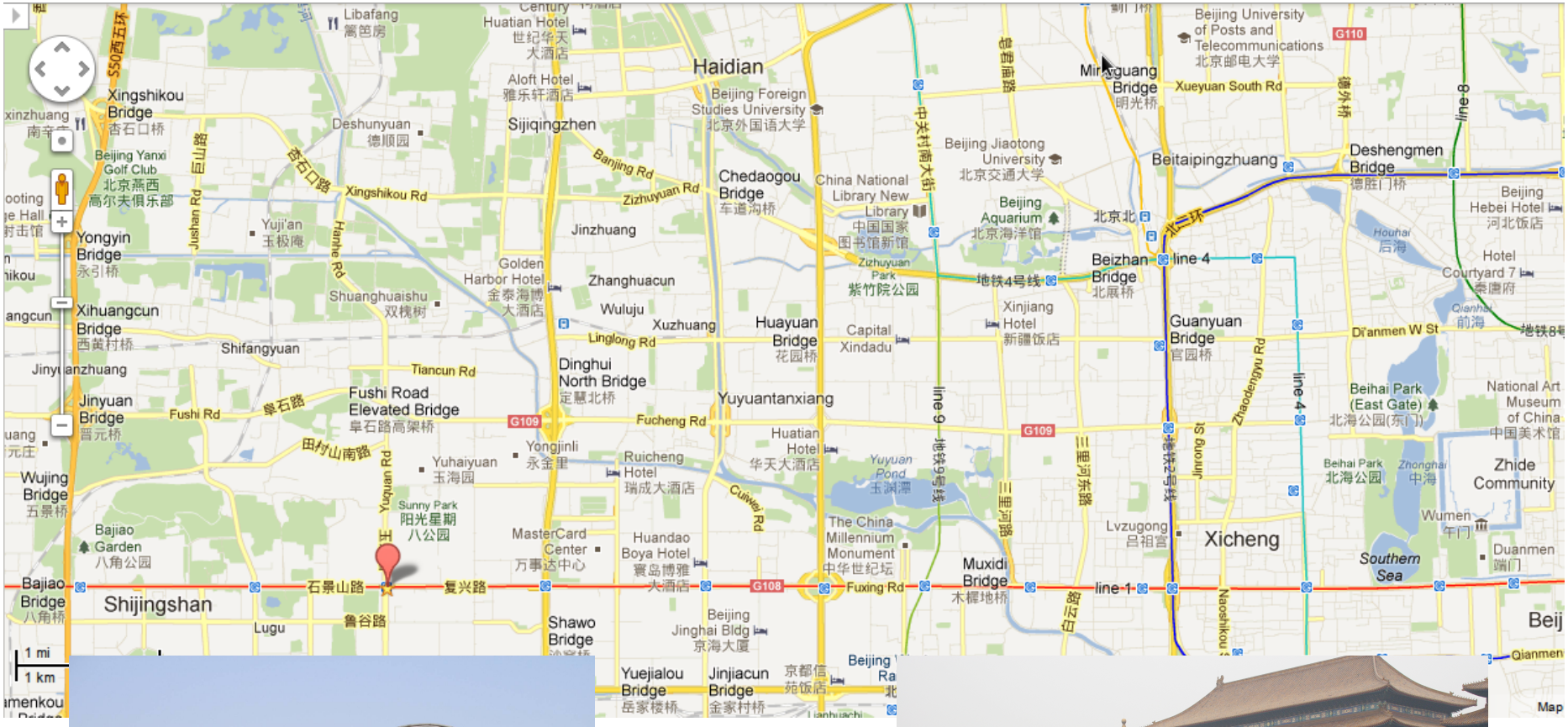
Crystal Ball at SLAC
discovery of η_C



PRL 45, 1150 (1980)

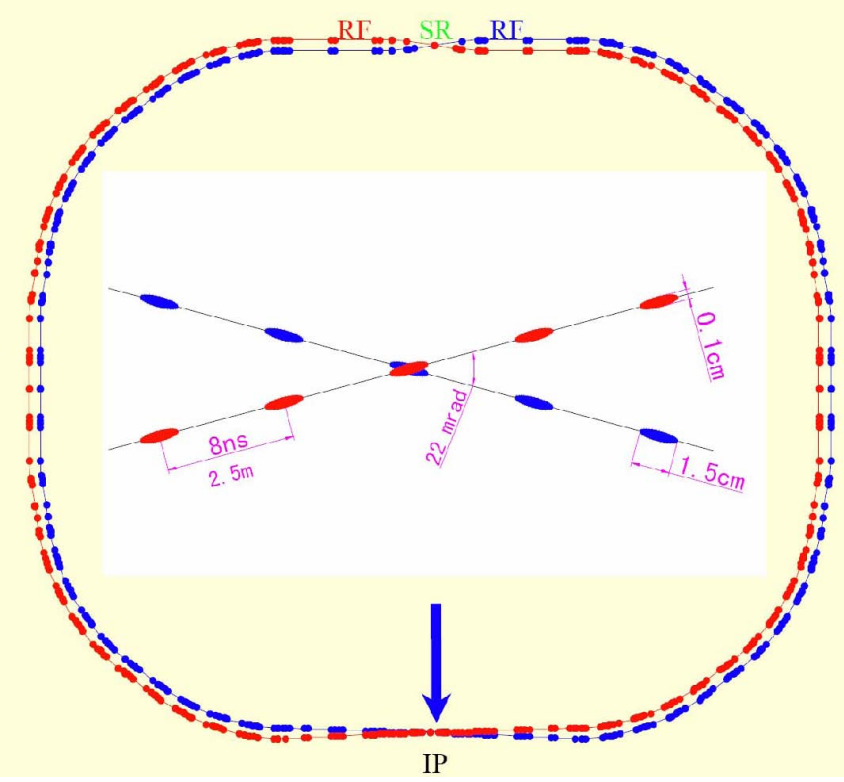

BESIII: a τ-charm factory

BEPCII and BESIII




BEPCII and BESIII
Linac
BESIII
BSRF
Tiananmen 10km

BEPCII storage rings: a τ-charm factory



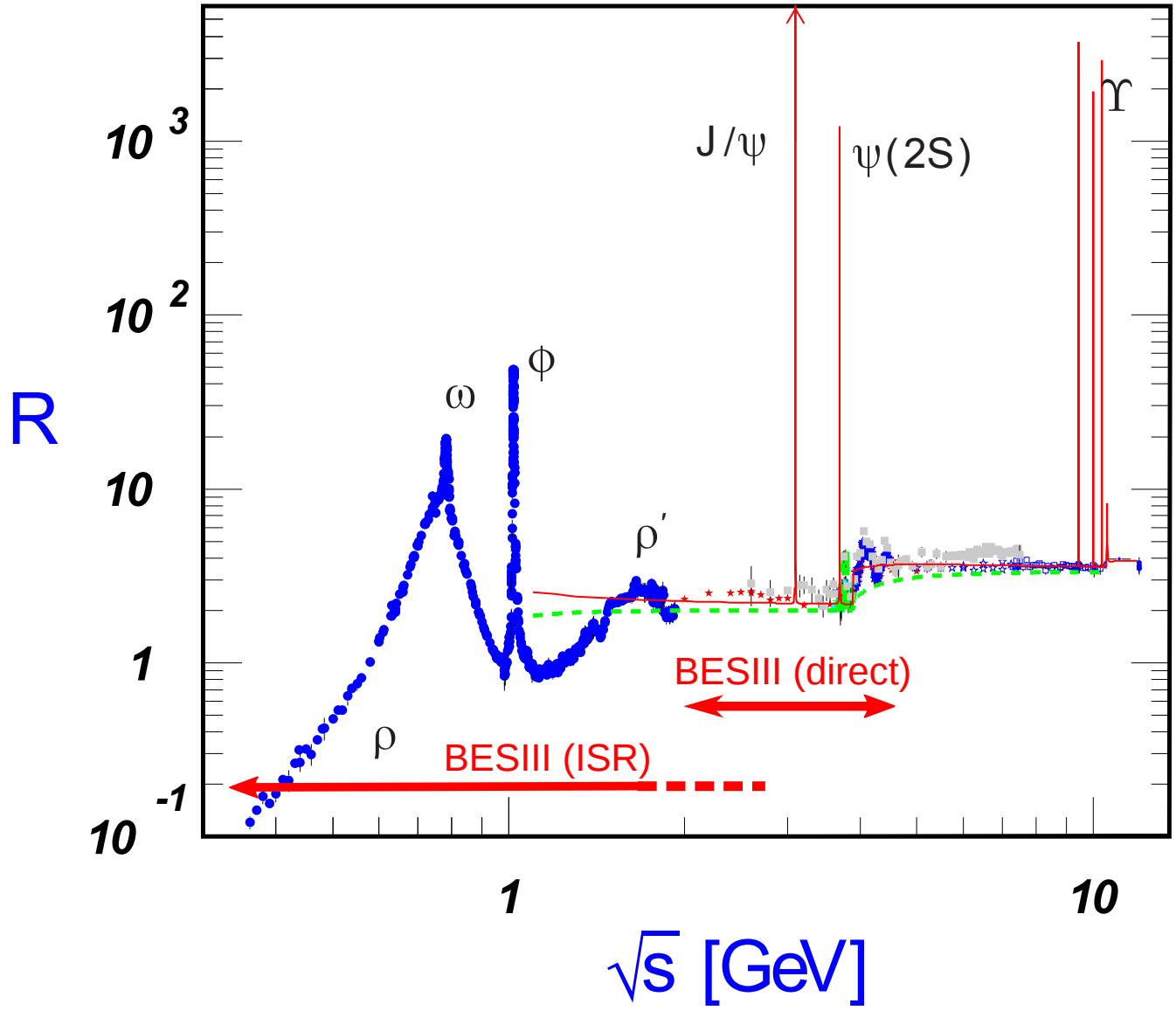
Upgrade of BEPC (started 2004, first collisions July 2008)

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

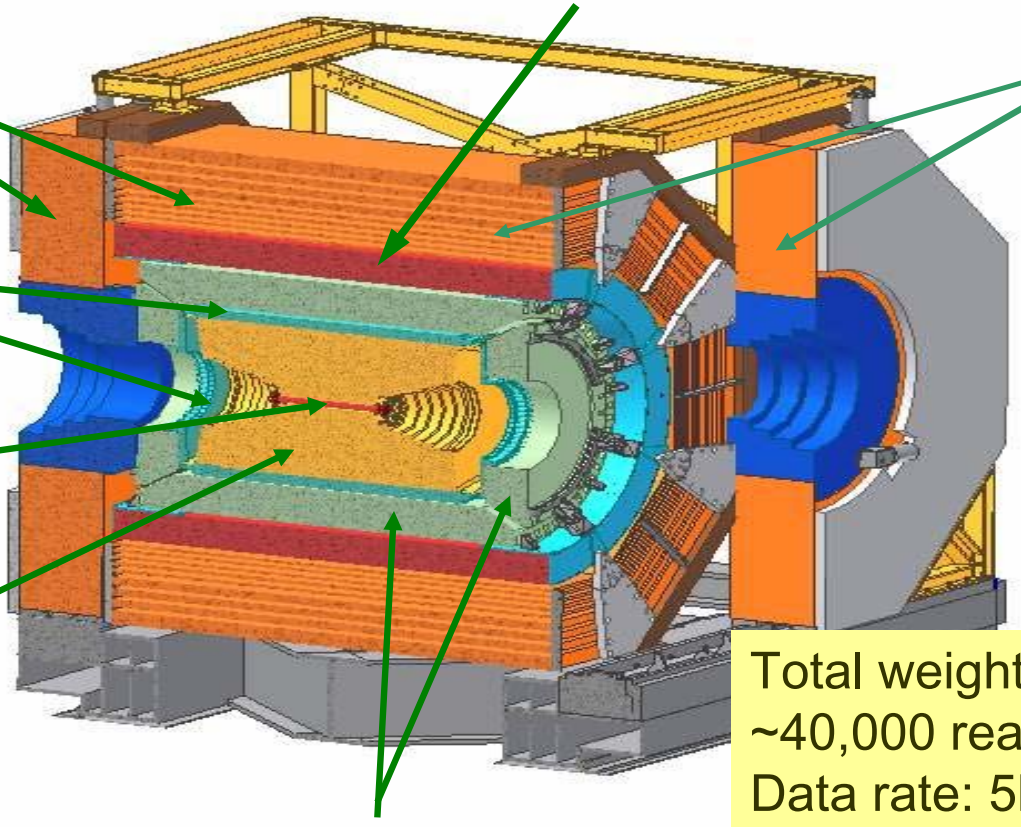
Design luminosity	$\mathbf{10^{33}\,cm^{-2}s^{-1}}$
Achieved	$\mathbf{8 \times 10^{32}\,cm^{-2}s^{-1}}$

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

A τ-charm factory



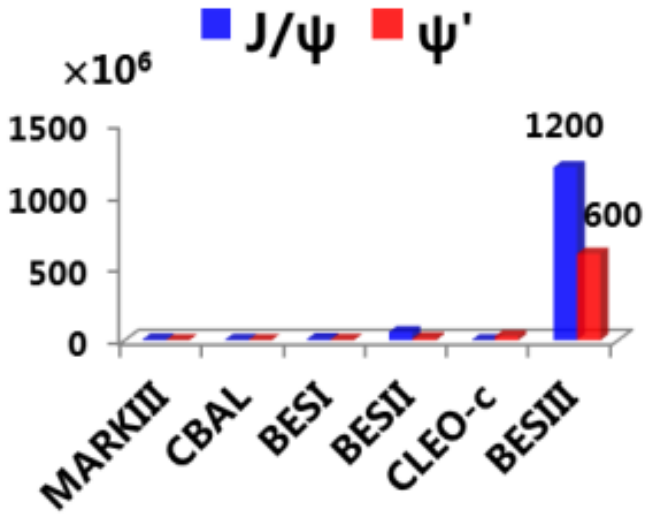
BESIII detector

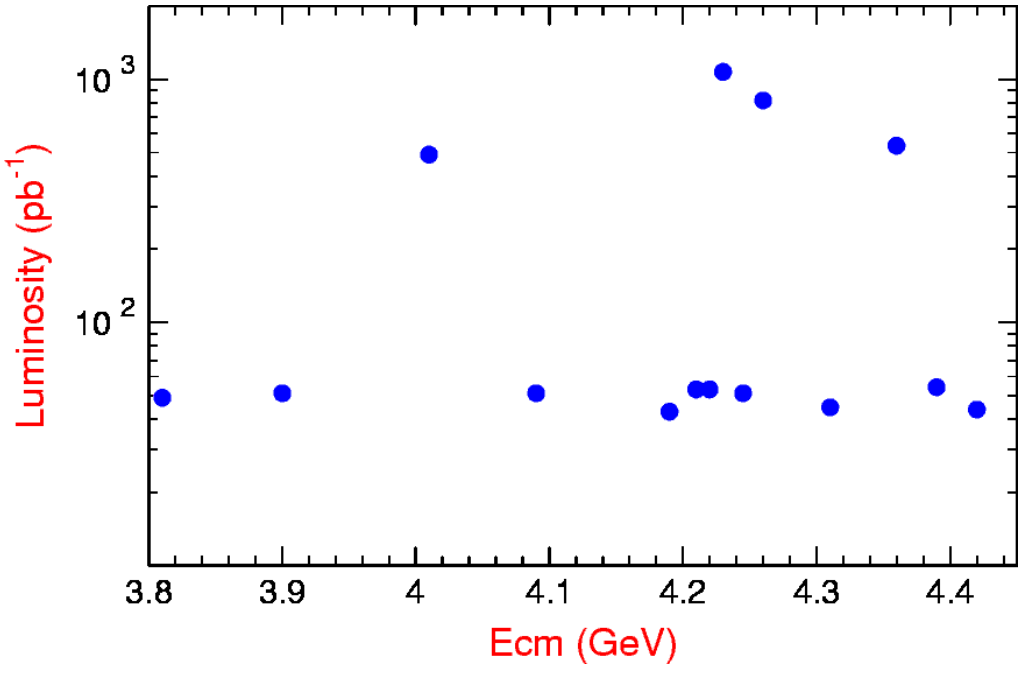


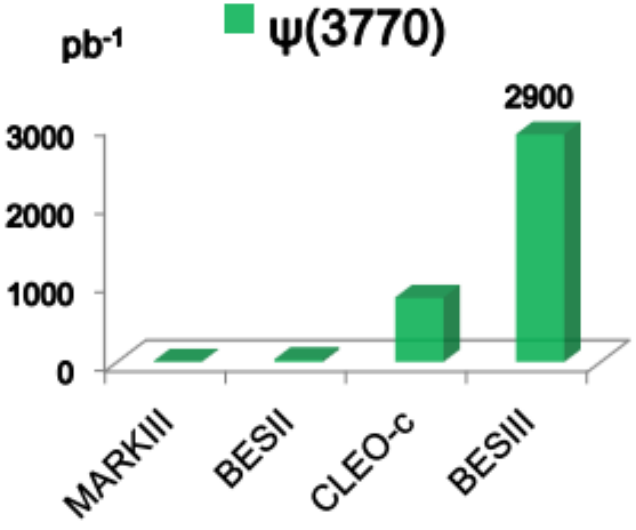
Completely new detector

Comparable performance to CLEO-c, + muon ID

BESIII data sets





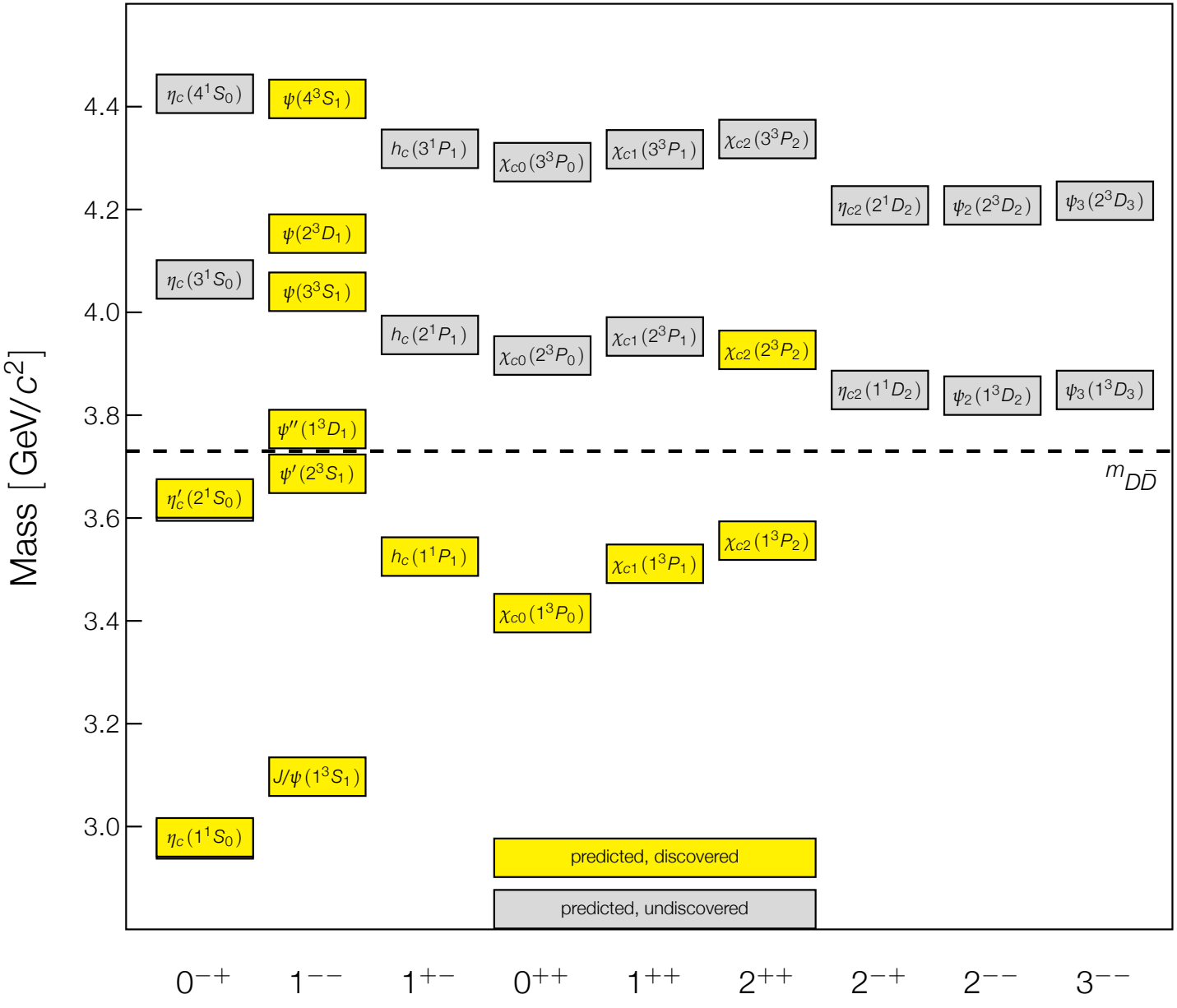


+ 104 energy points between 3.85 and 4.59 GeV
+ ~ 20 energy points between 2.0 and 3.1 GeV
(*ongoing*)

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

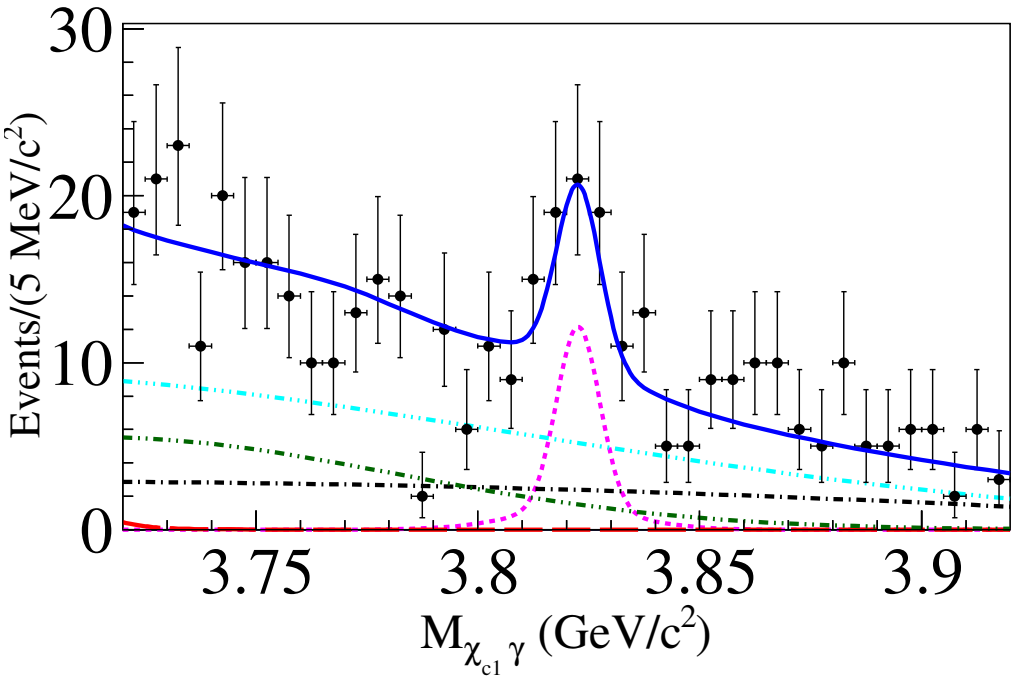

Conventional $c\bar{c}$

Higher charmonium states



The $X(3823)$ at Belle

PRL **111**, 032001 (2013)



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

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

3.8σ evidence

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

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

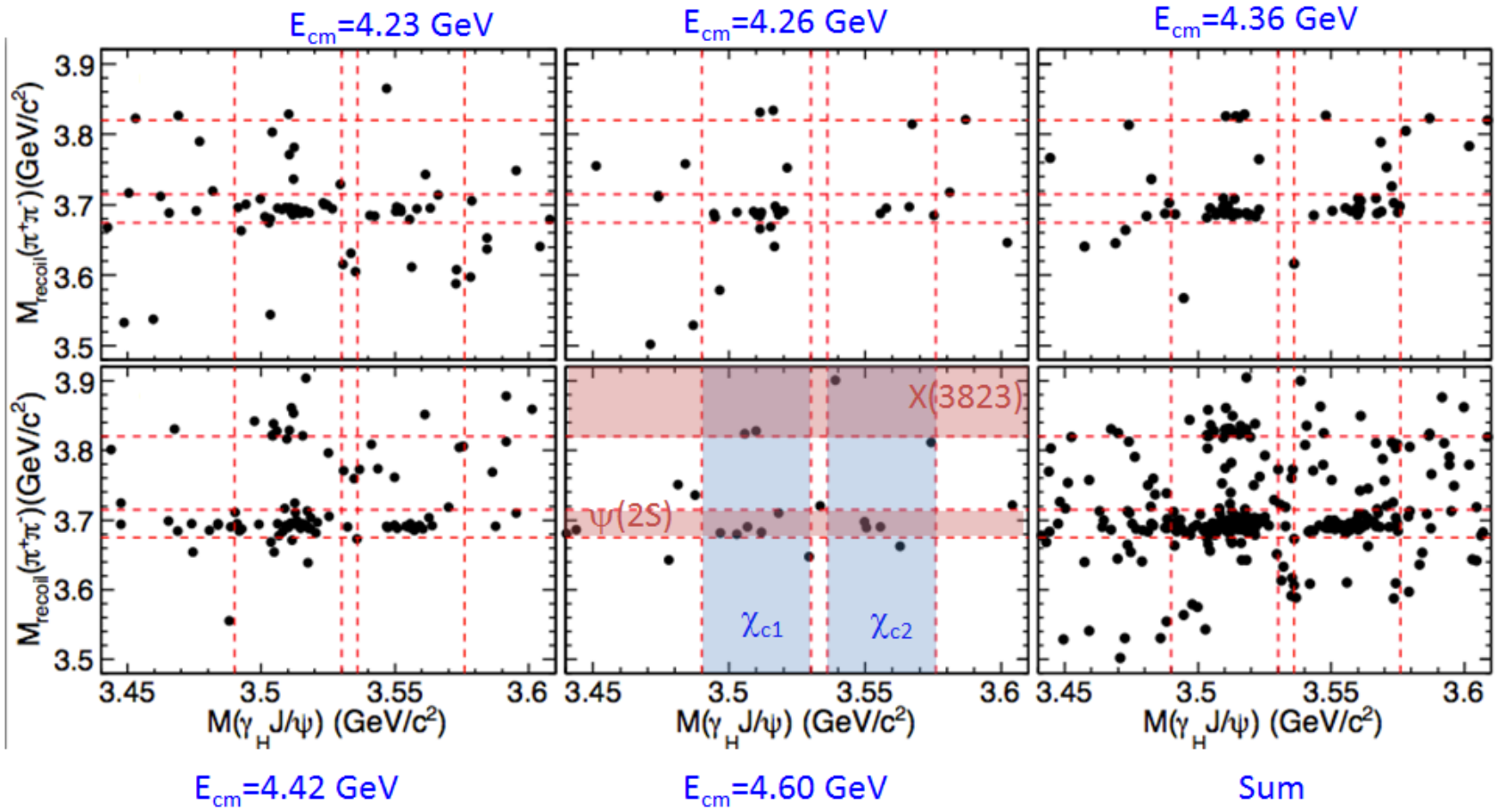
Search for $e^+e^- \to \pi^+\pi^- X(3823) \to \pi^+\pi^-\gamma\chi_{c1}$

BESIII preliminary

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

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

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



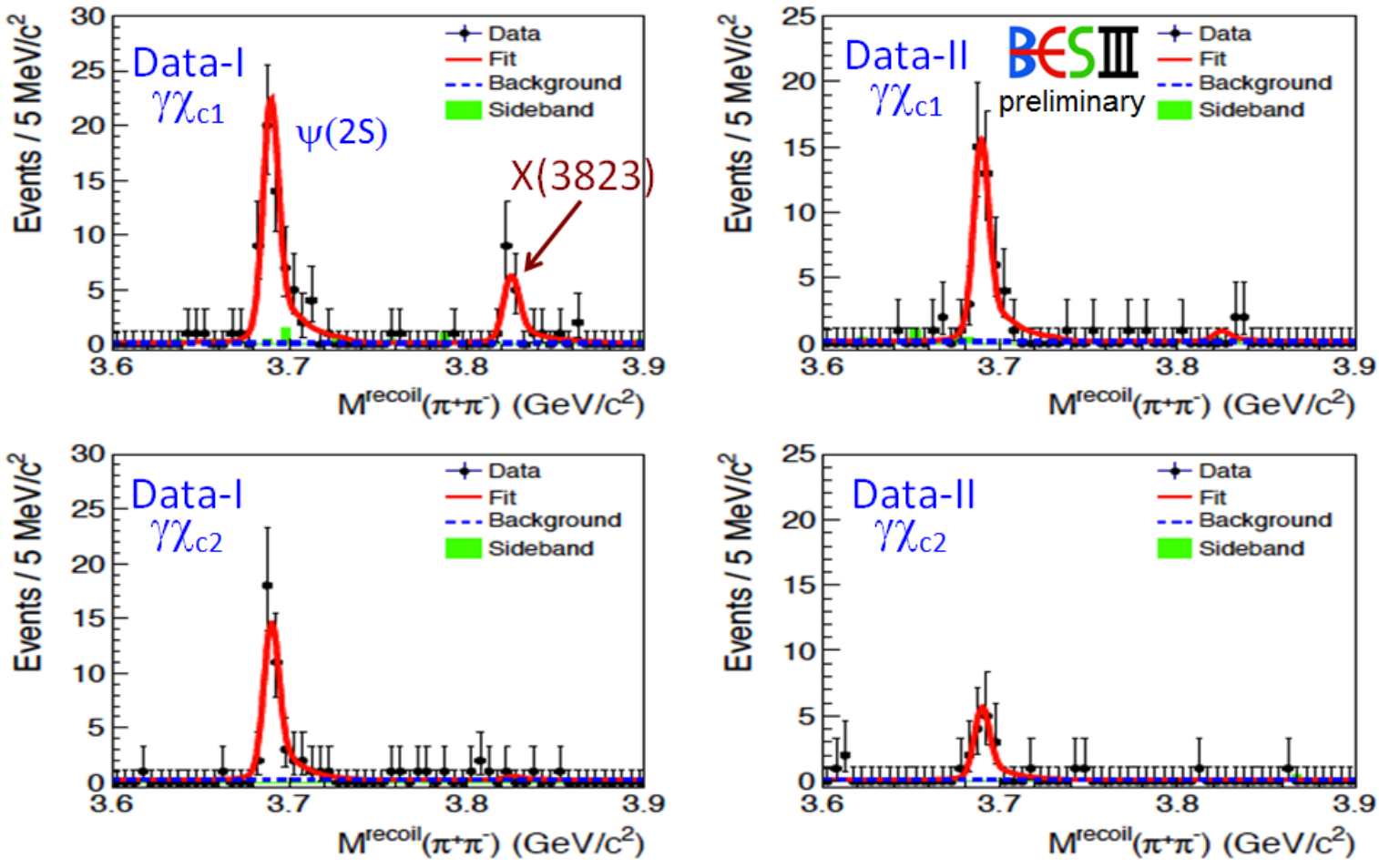
JGU

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

$\sqrt{s} \geq 4.36$ GeV

$\sqrt{s} = 4.23, 4.26$ GeV

BESIII preliminary



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

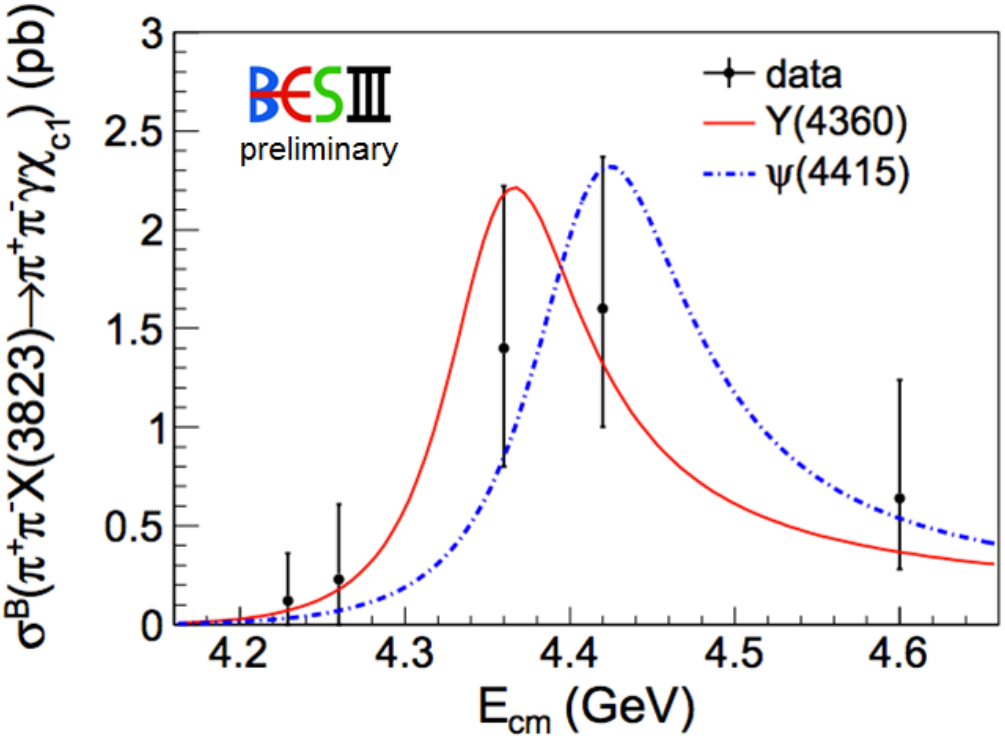
$\Gamma < 16$ MeV at 90% C.L.

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

BESIII preliminary

Energy-dependent cross section for

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



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

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

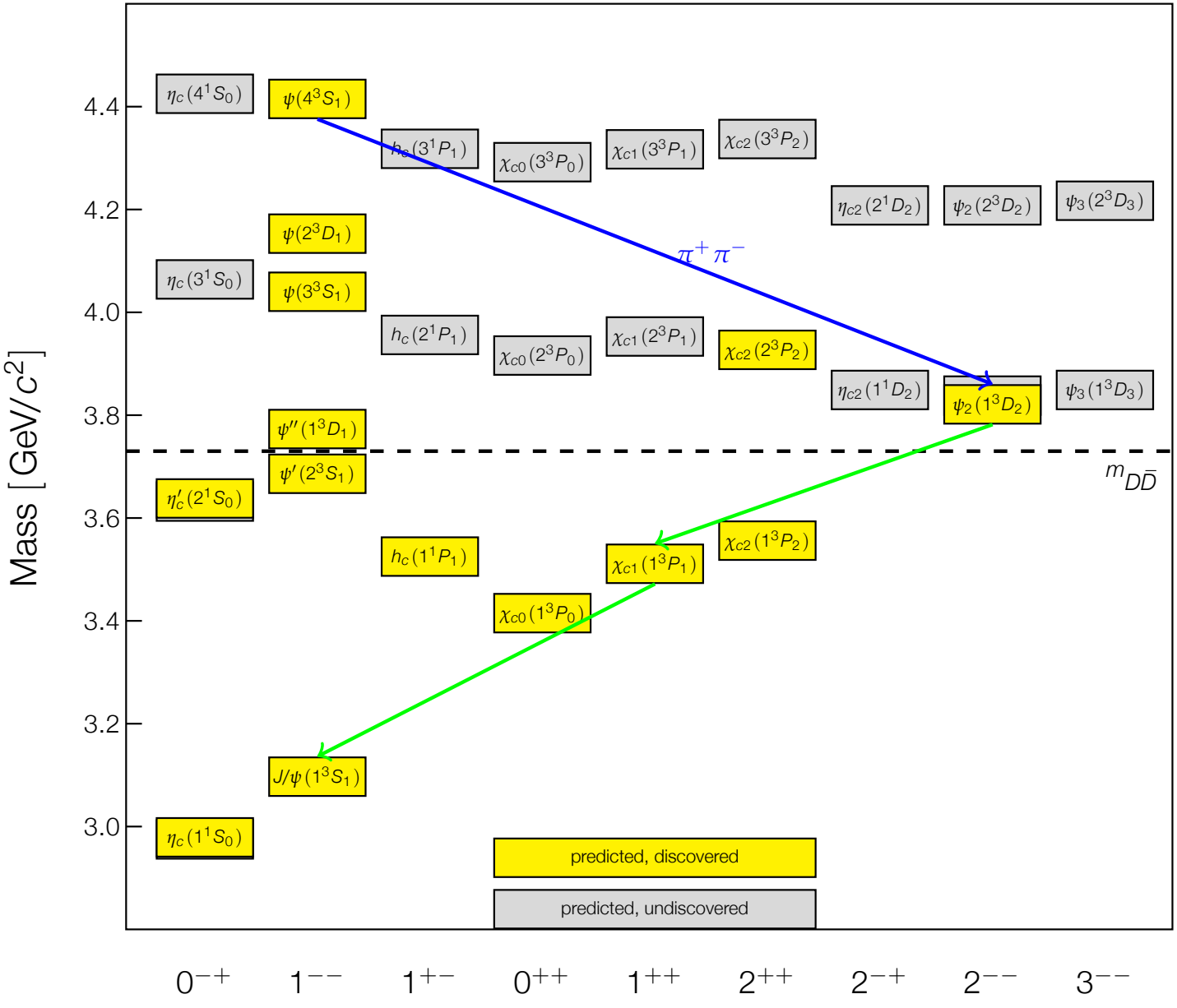
< 0.43 at 90% C.L.

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

Not enough statistics to distinguish S and D wave from data

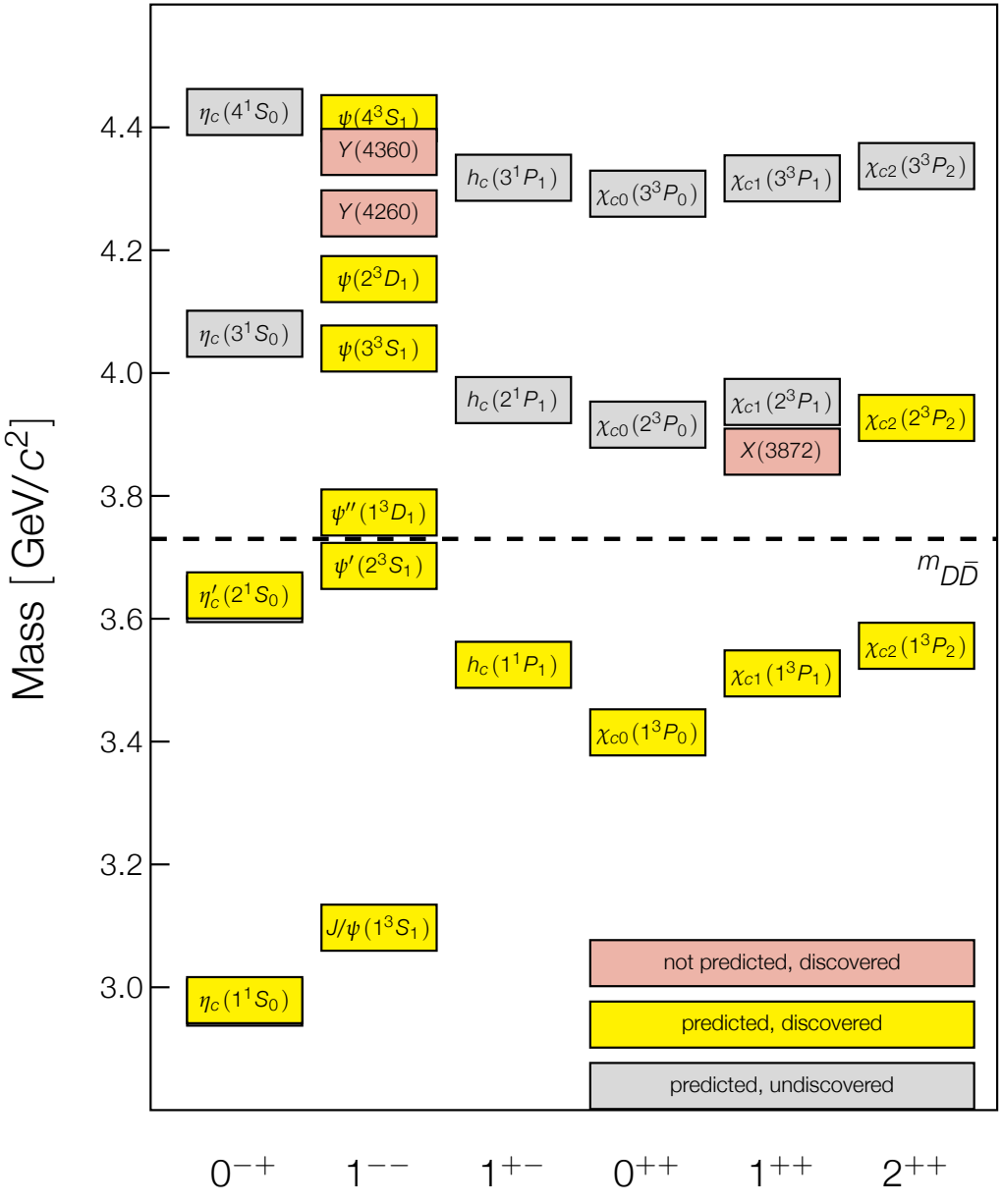
JG|U

Higher charmonium states — a new family member!

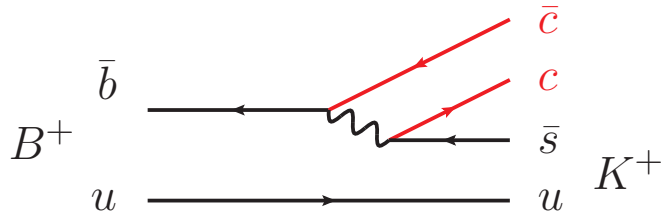



Exotic states: the X and Y

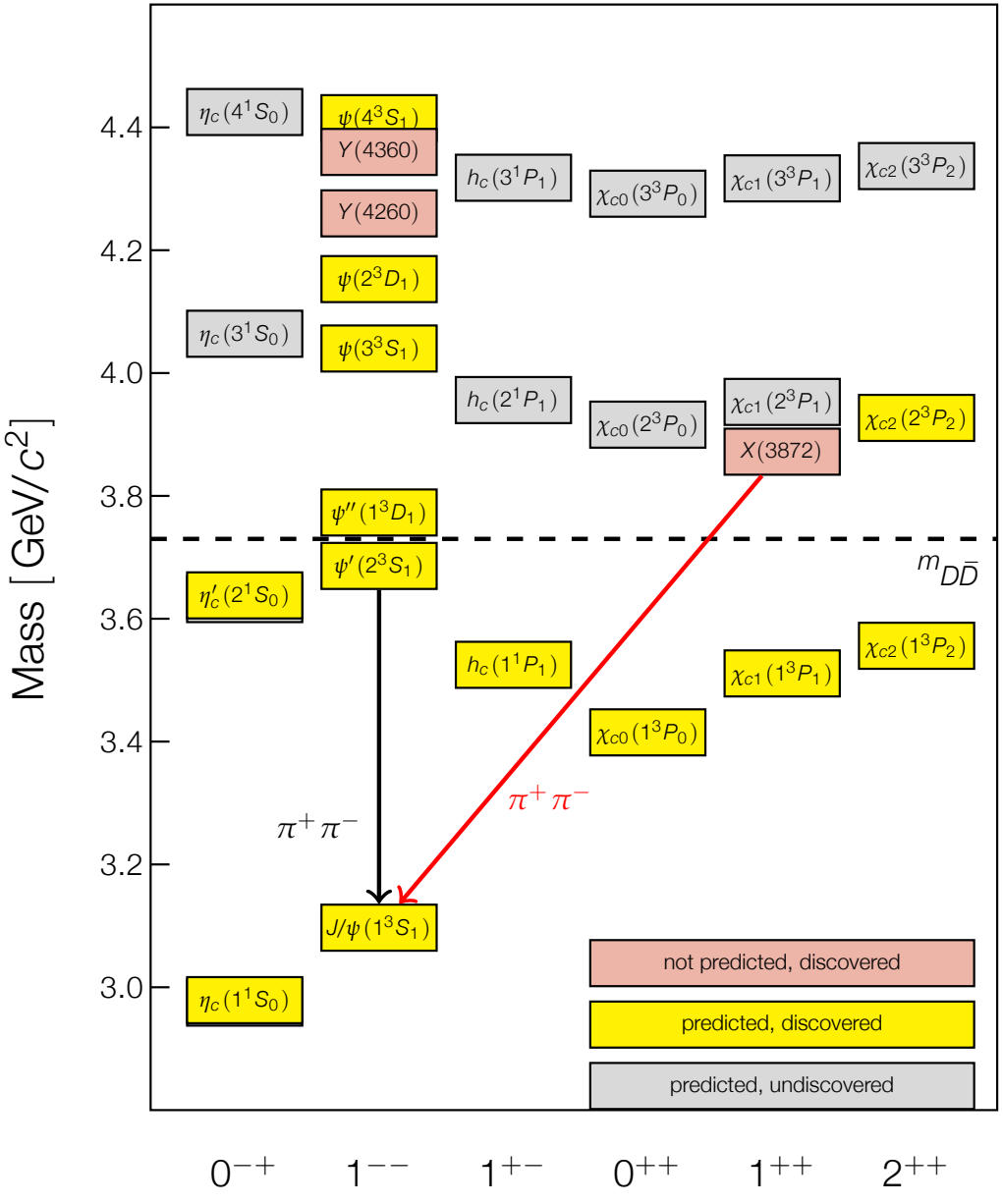
Surprising discoveries: the XYZ states



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



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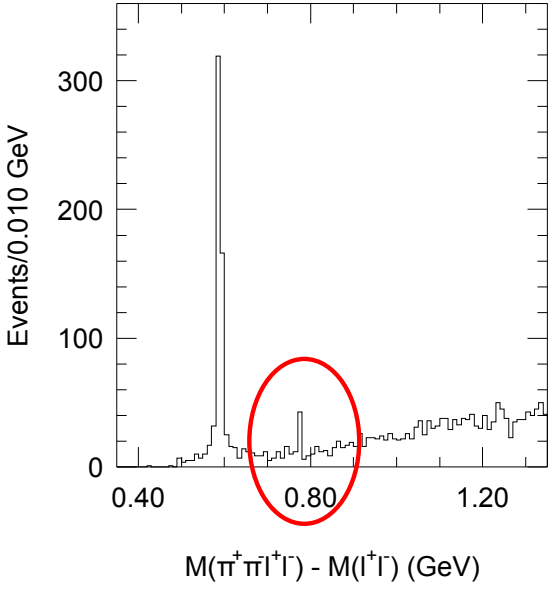
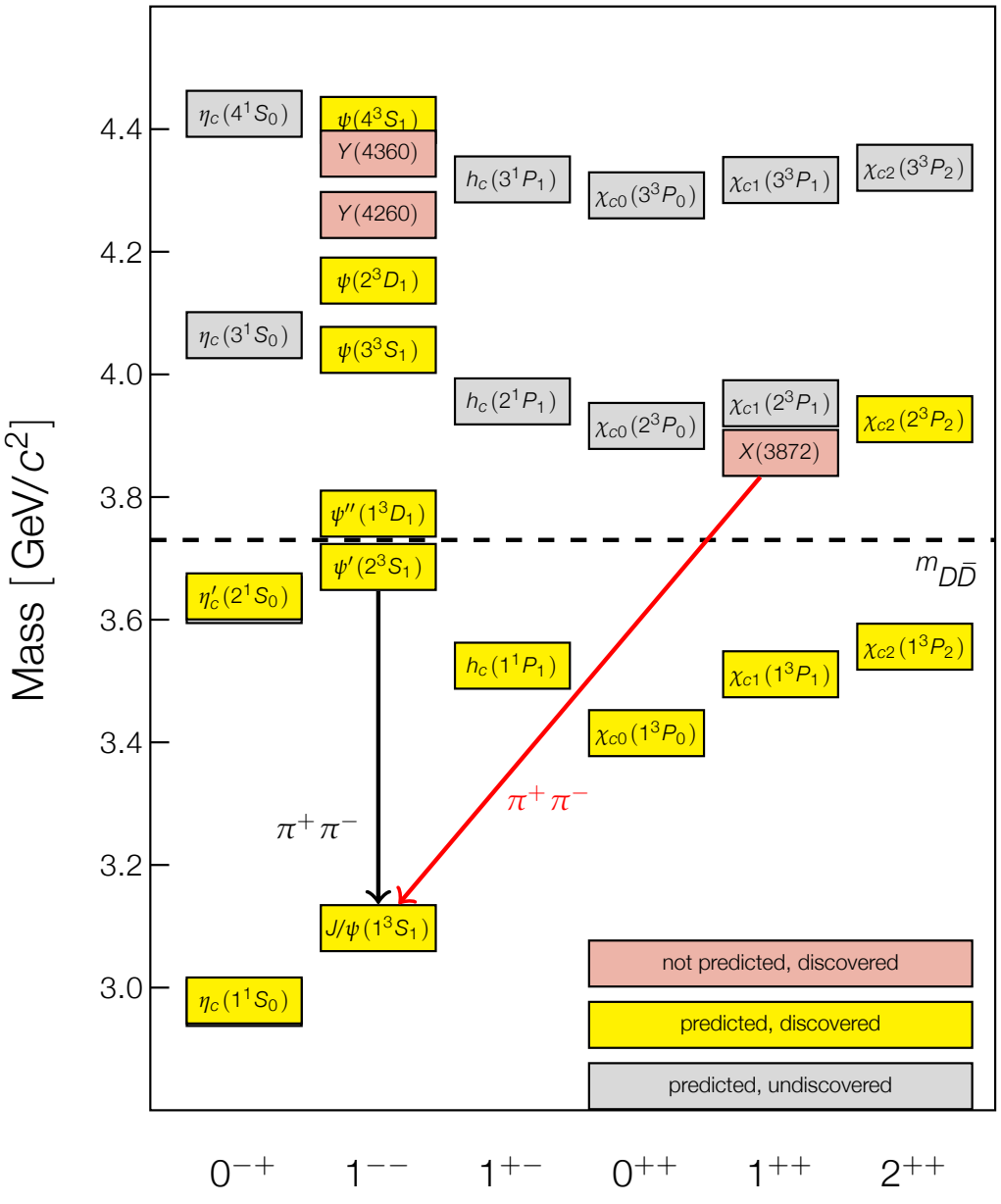
$B^+ \to K^+\pi^+\pi^- J/\psi$

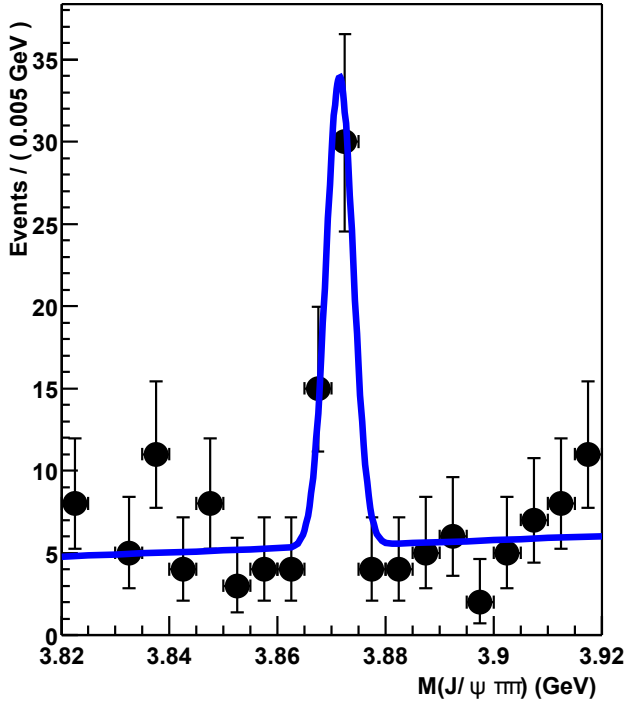


Belle, PRL 91, 262001 (2003)

The $X(3872)$



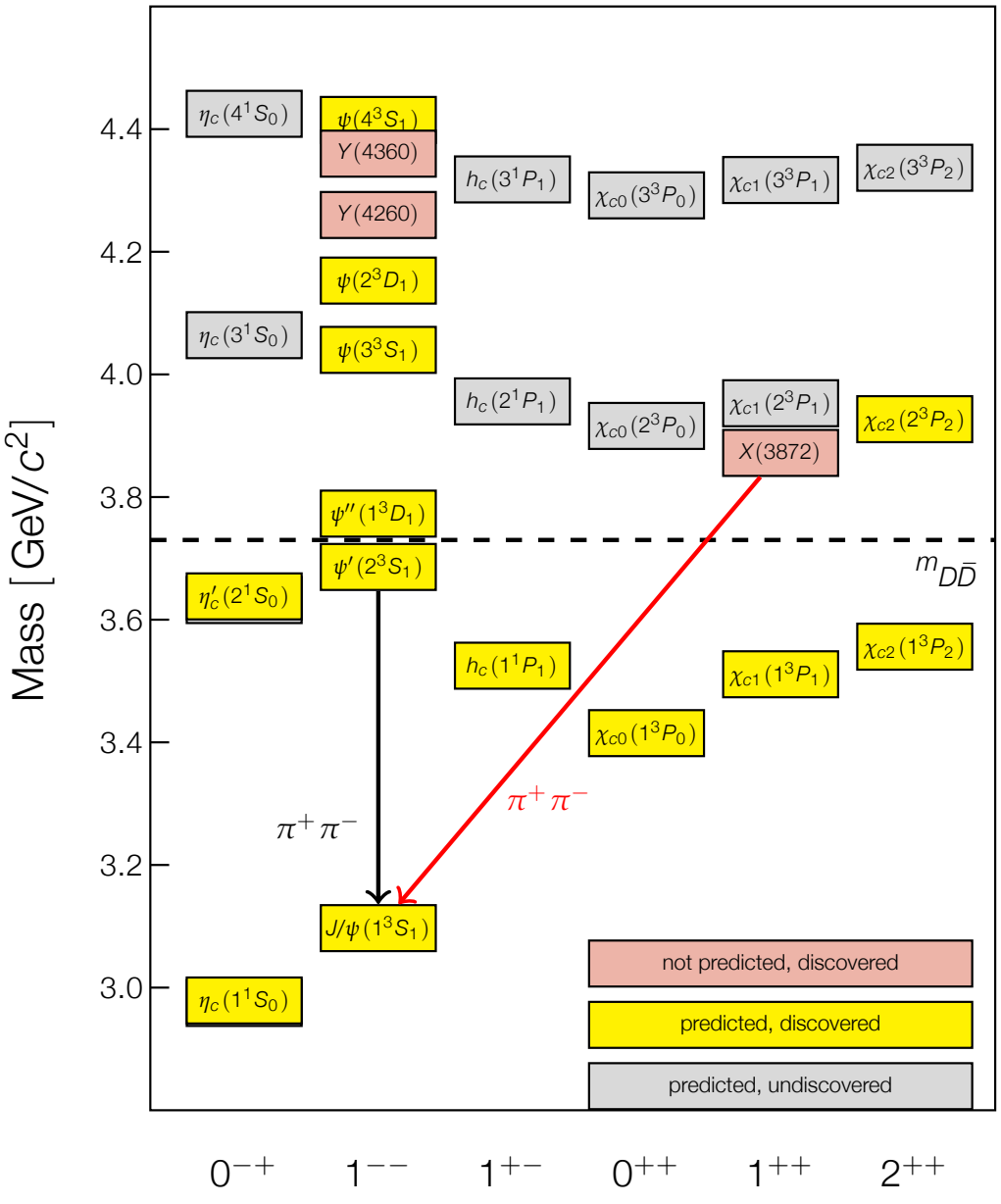
Extremely narrow, sits at or just below the DD^* threshold



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

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

The $X(3872)$



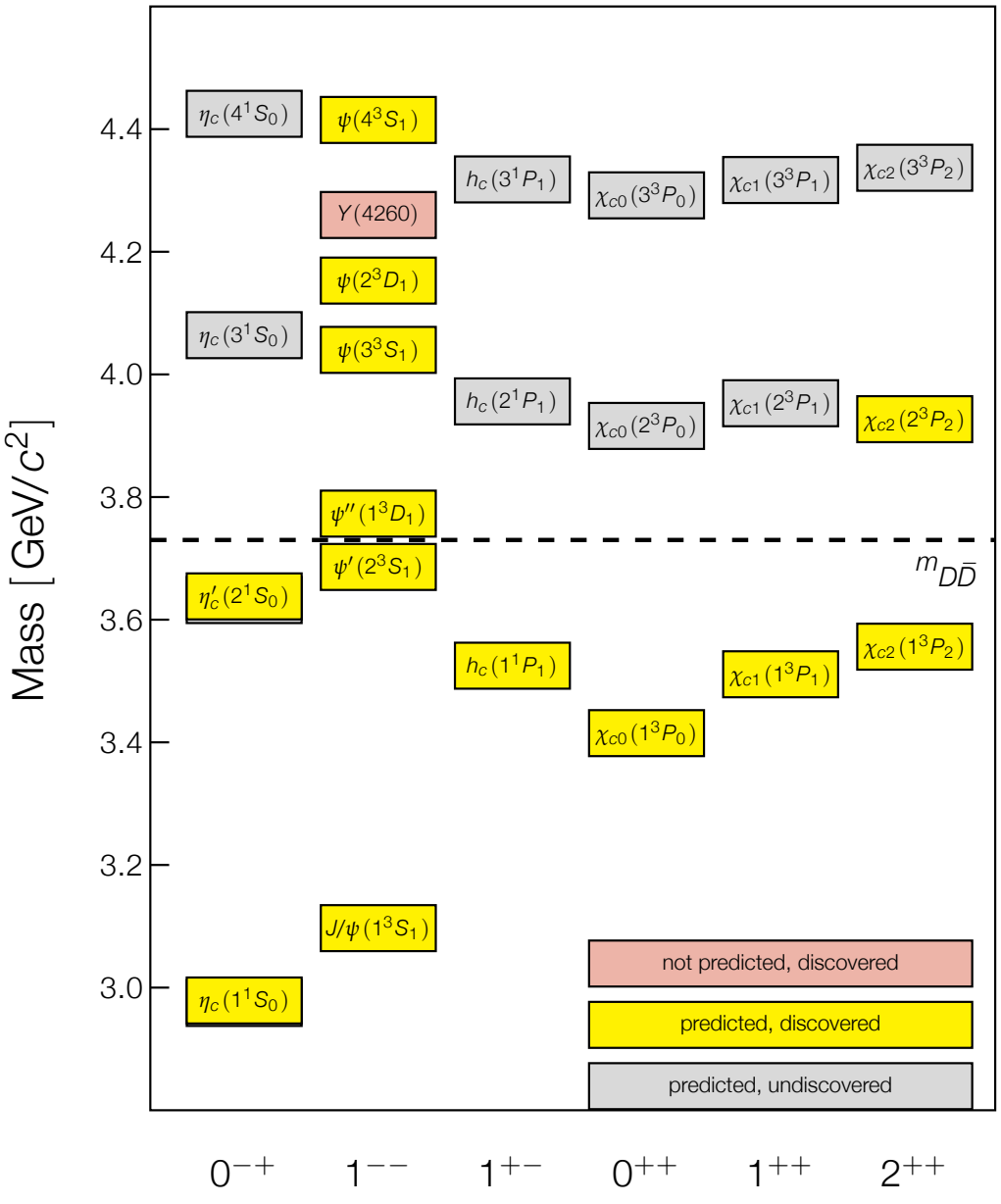
Seen by Belle, BABAR, CDF, D0, CMS, LHCb, BESIII

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

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

no obvious place in spectrum

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

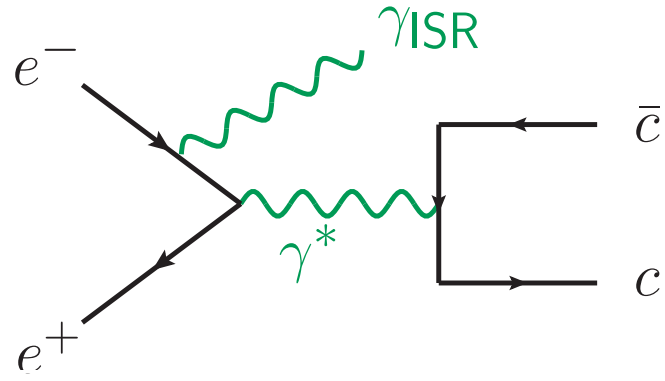


e^+e^- collisions near $\Upsilon(4S)$

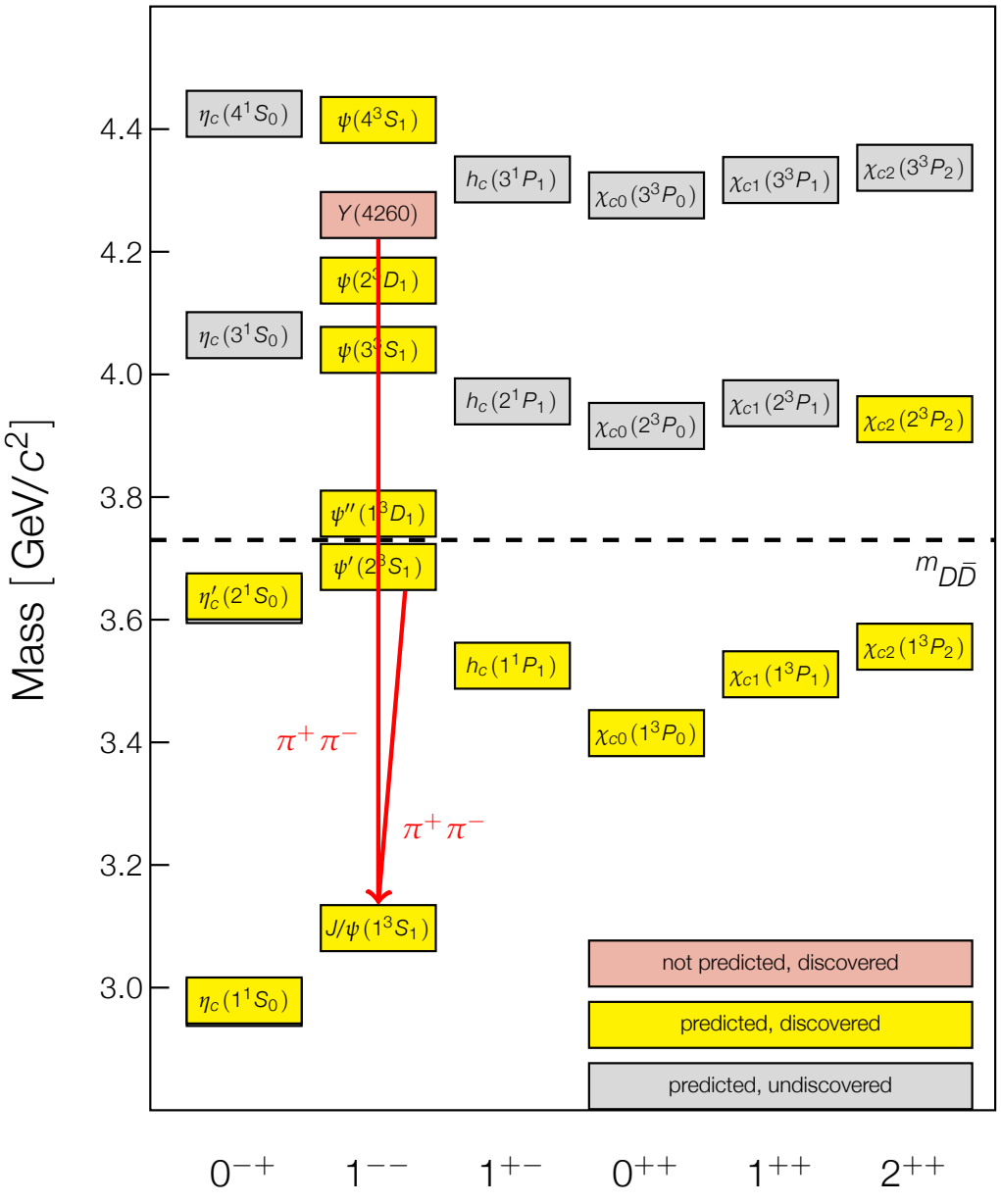
in ISR production

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

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



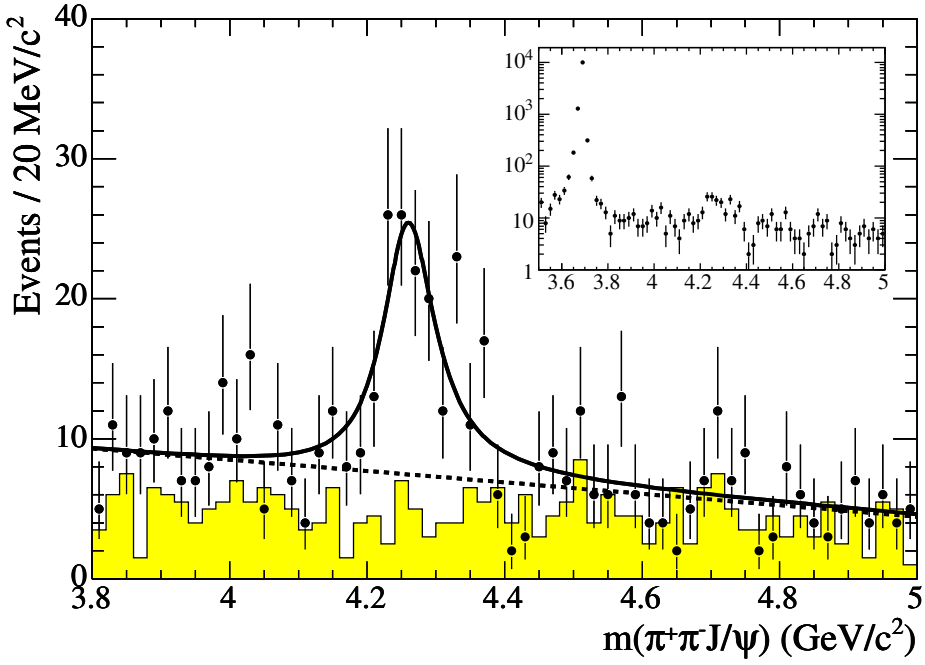
The $Y(4260) \to J/\psi\,\pi^+\pi^-$



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

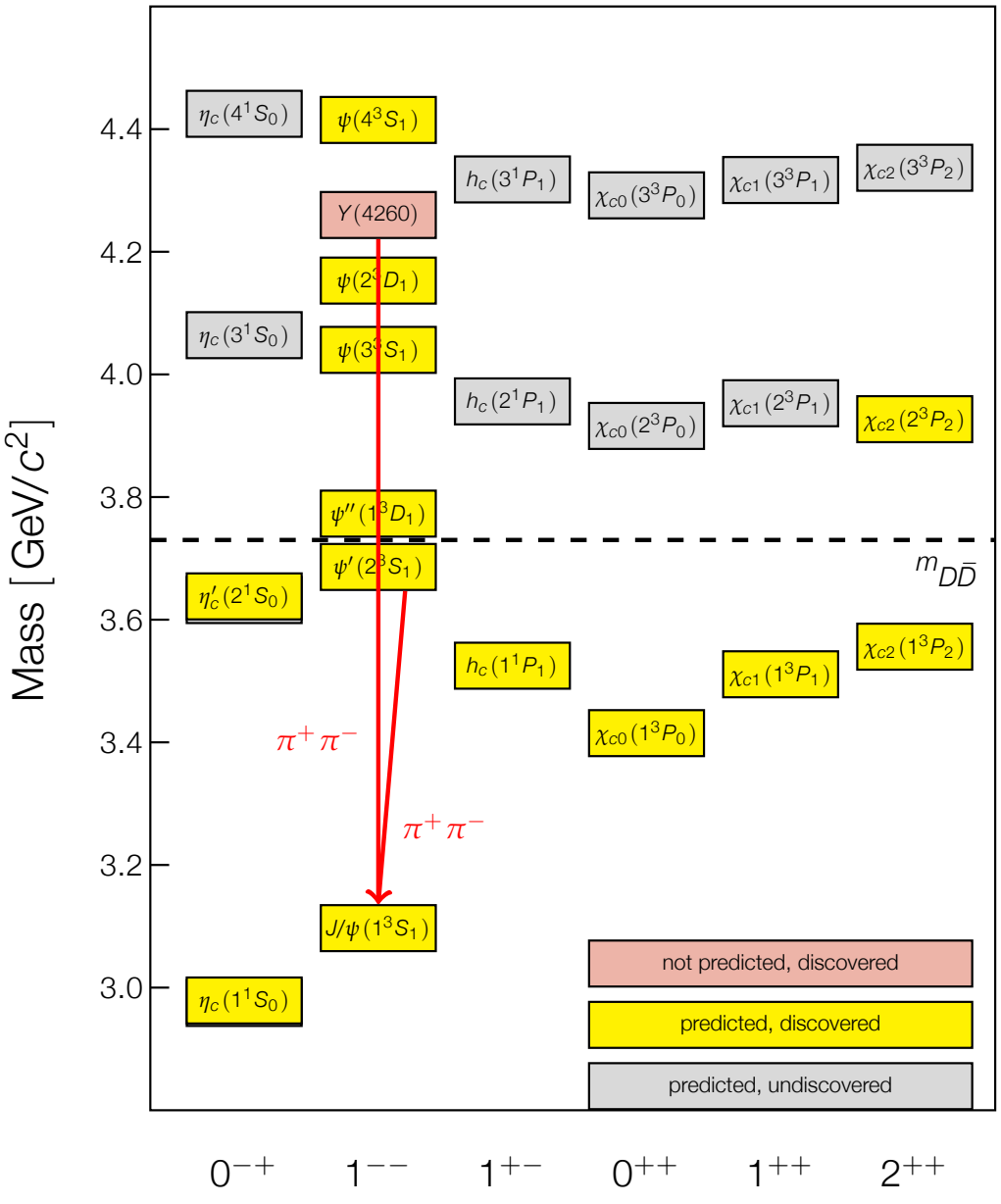
in ISR production
$e^+e^- \to \gamma_{ISR} J/\psi\,\pi^+\pi^-$

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



BABAR, PRL 95, 142001 (2005)

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



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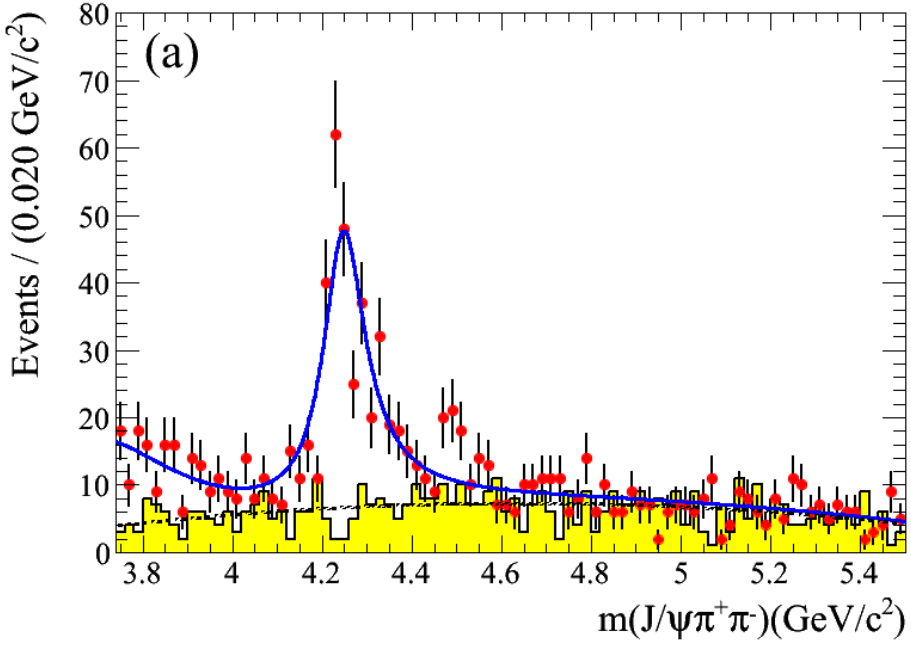
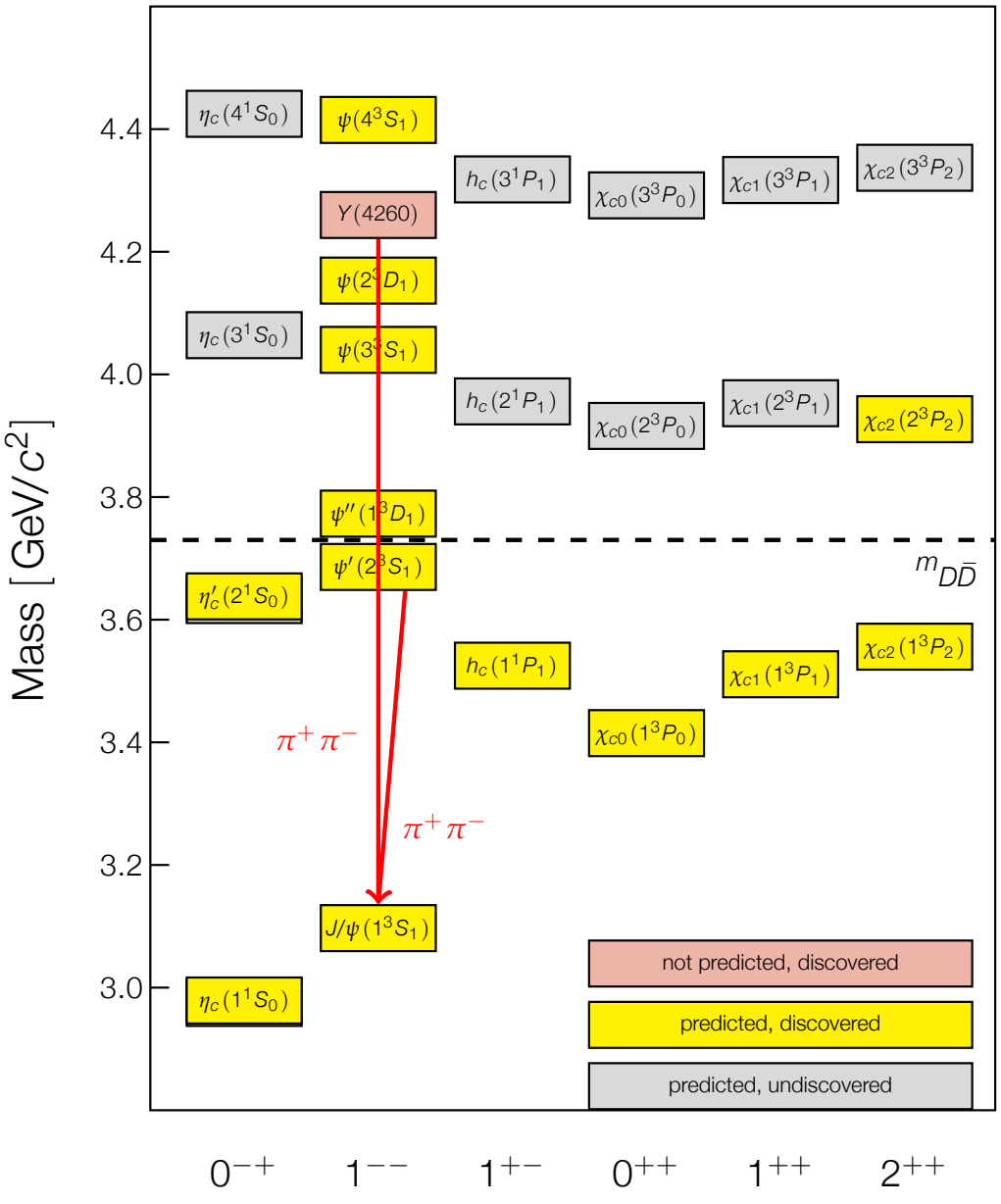


BABAR, PRD 86, 051102(R) (2012)

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



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

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

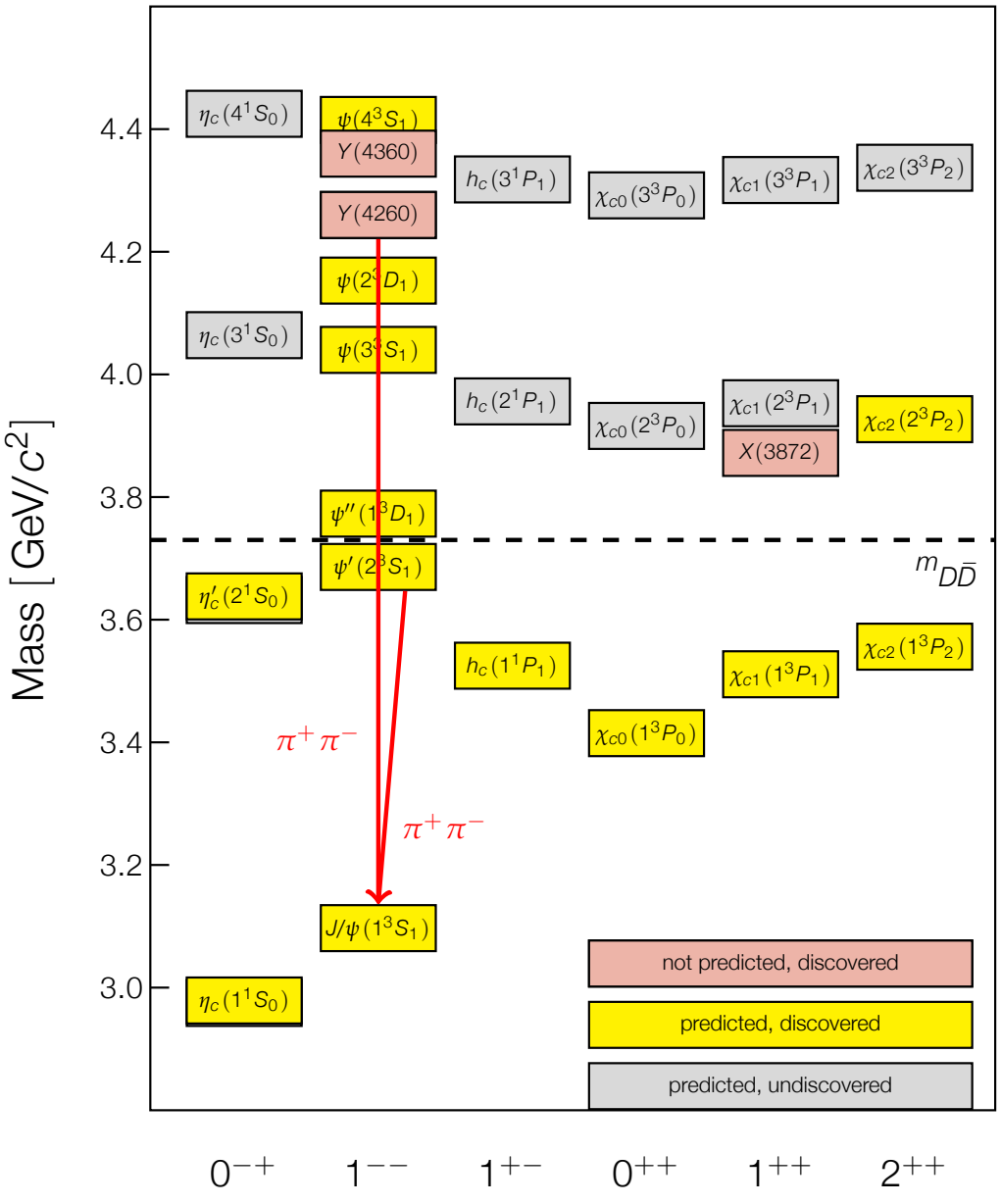
$\Rightarrow J^{PC} = 1^{--}$

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

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

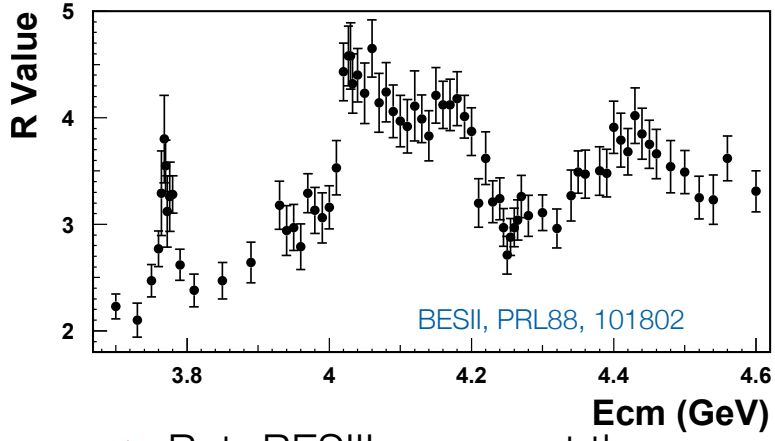
compare with
≈ 500 for $\psi(3770)$

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



- … $Y(4260) \to J/\psi\,\pi^+\pi^-$
- … $Y(4360) \to \psi(2S)\pi^+\pi^-$
- … additional state at 4660 MeV
  - supernumerary states: all 1^{--} slots already taken

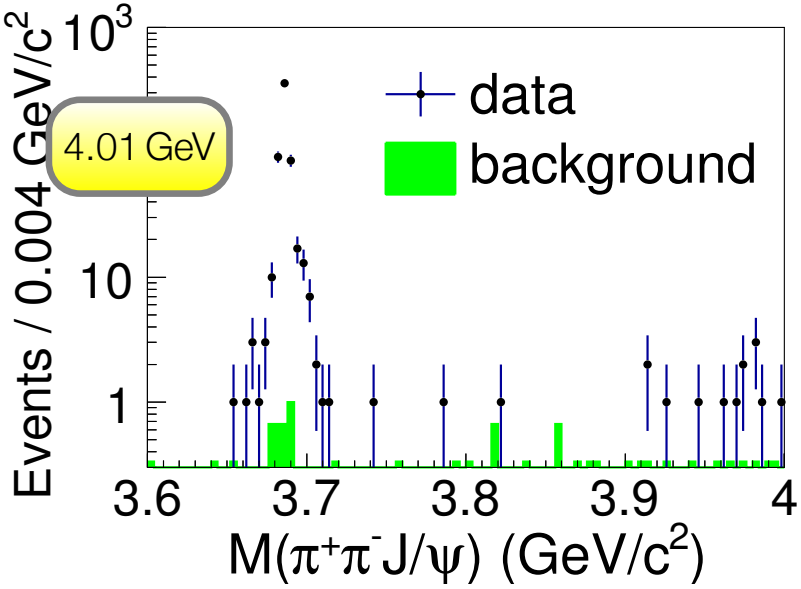
➡ do not correspond to peaks in $\sigma(e^+e^- \to \text{hadrons})$

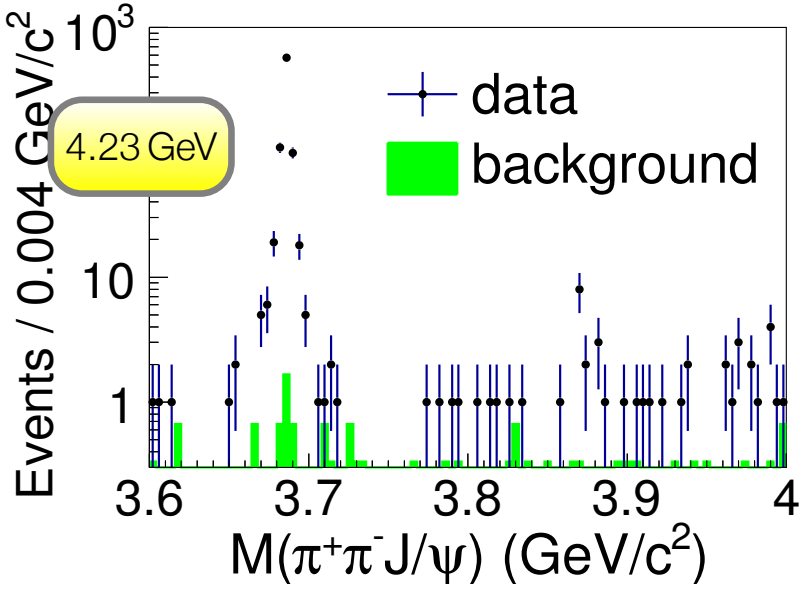


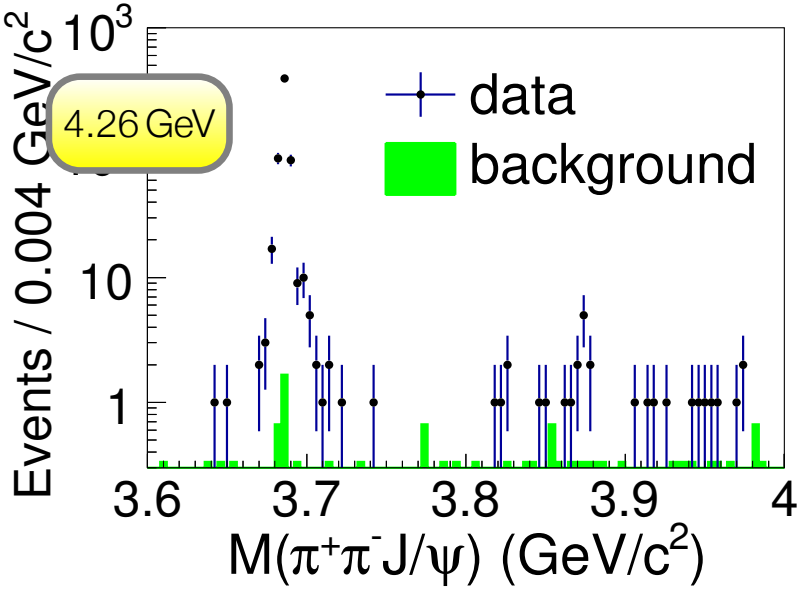
➡ But: BESIII can run at these energies;
maybe produce them directly?

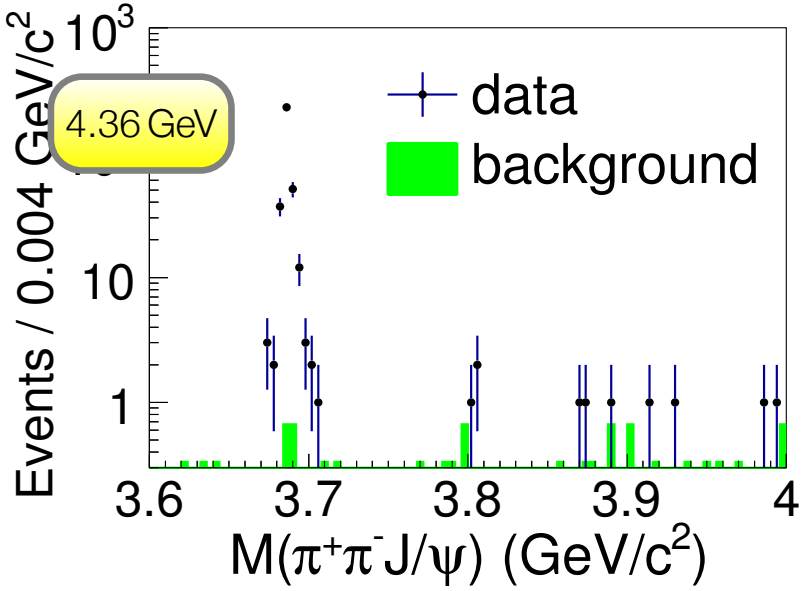
$e^+e^- \to \gamma X(3872) \to \gamma J/\psi\,\pi^+\pi^-$

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







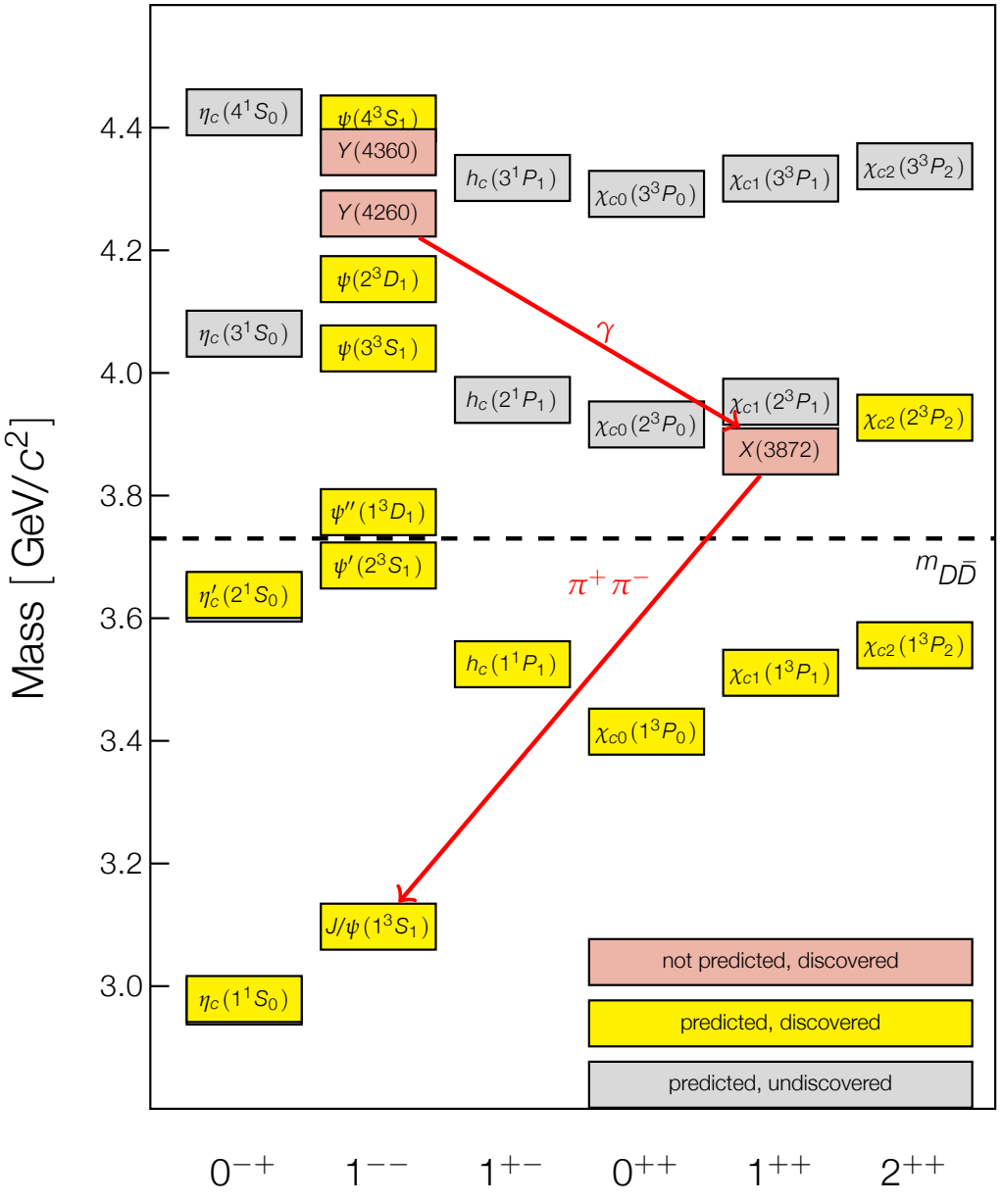


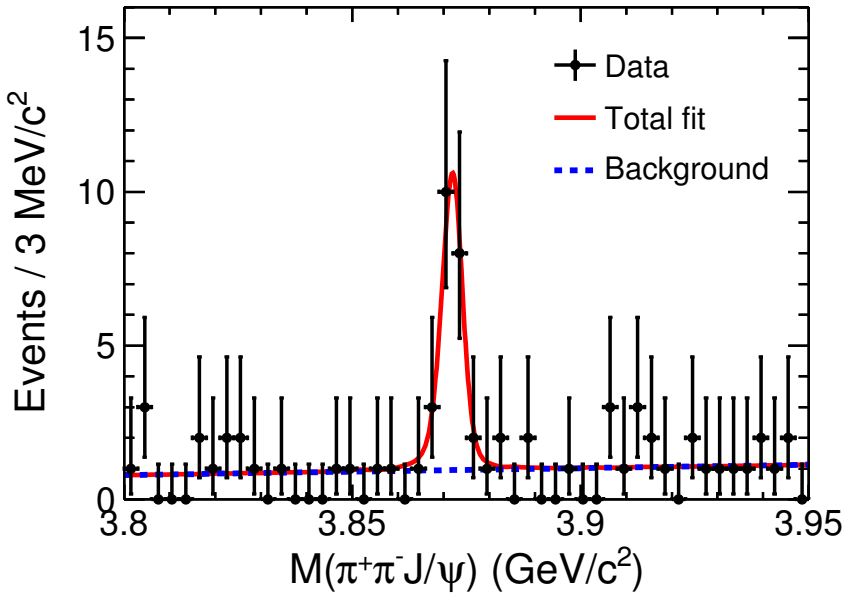
Clear ISR ψ' signal for validation

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

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

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





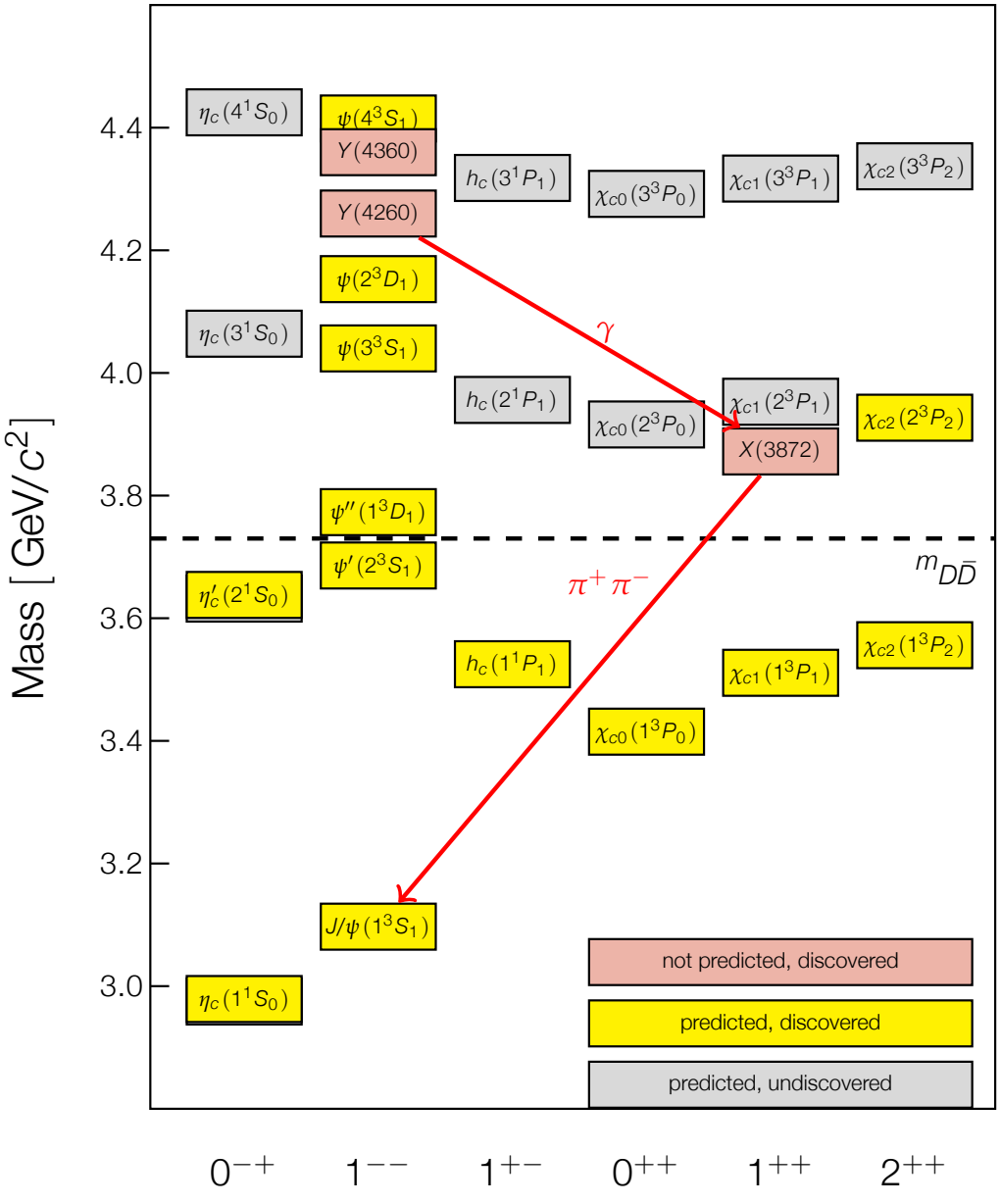
20.1 ± 4.5 events

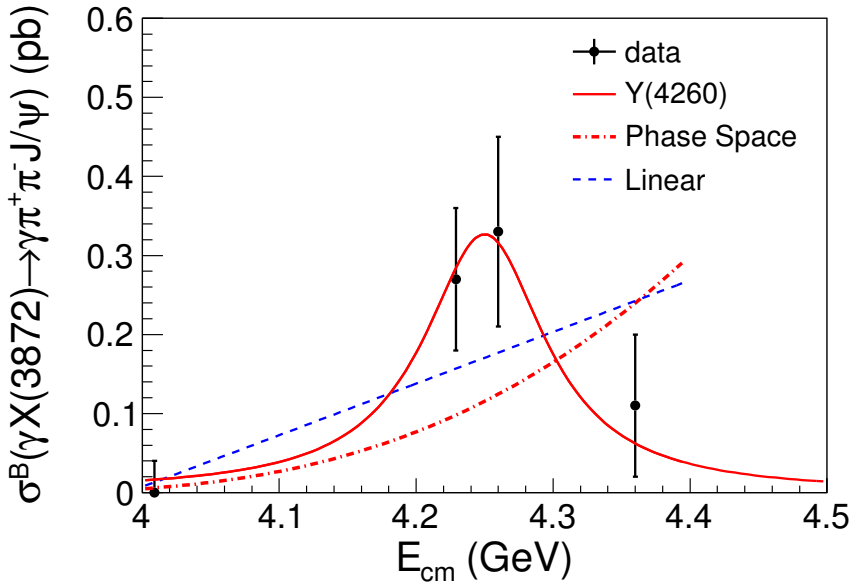
significance 6.3σ

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

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

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



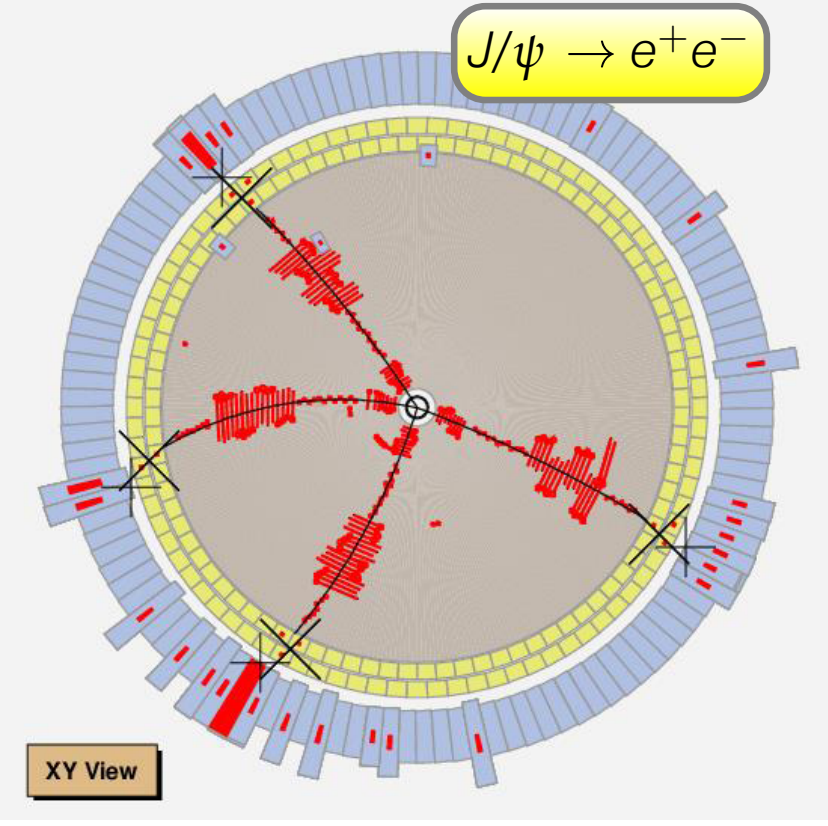


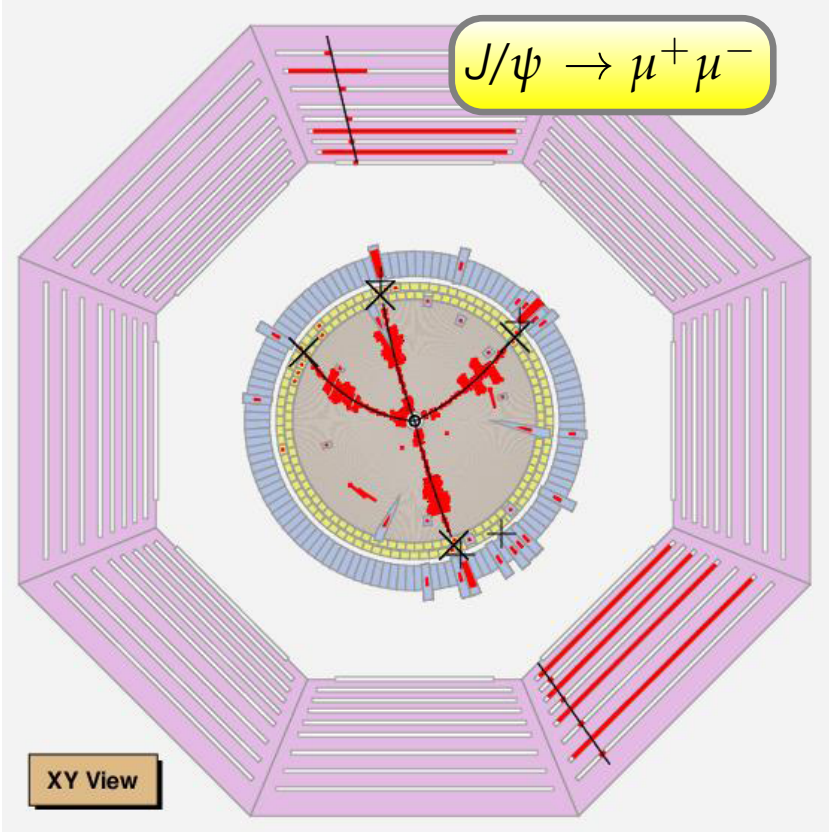
Suggestive of
$Y(4260) \to \gamma X(3872)$
Direct connection between the two states?


The Z_c family

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

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





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

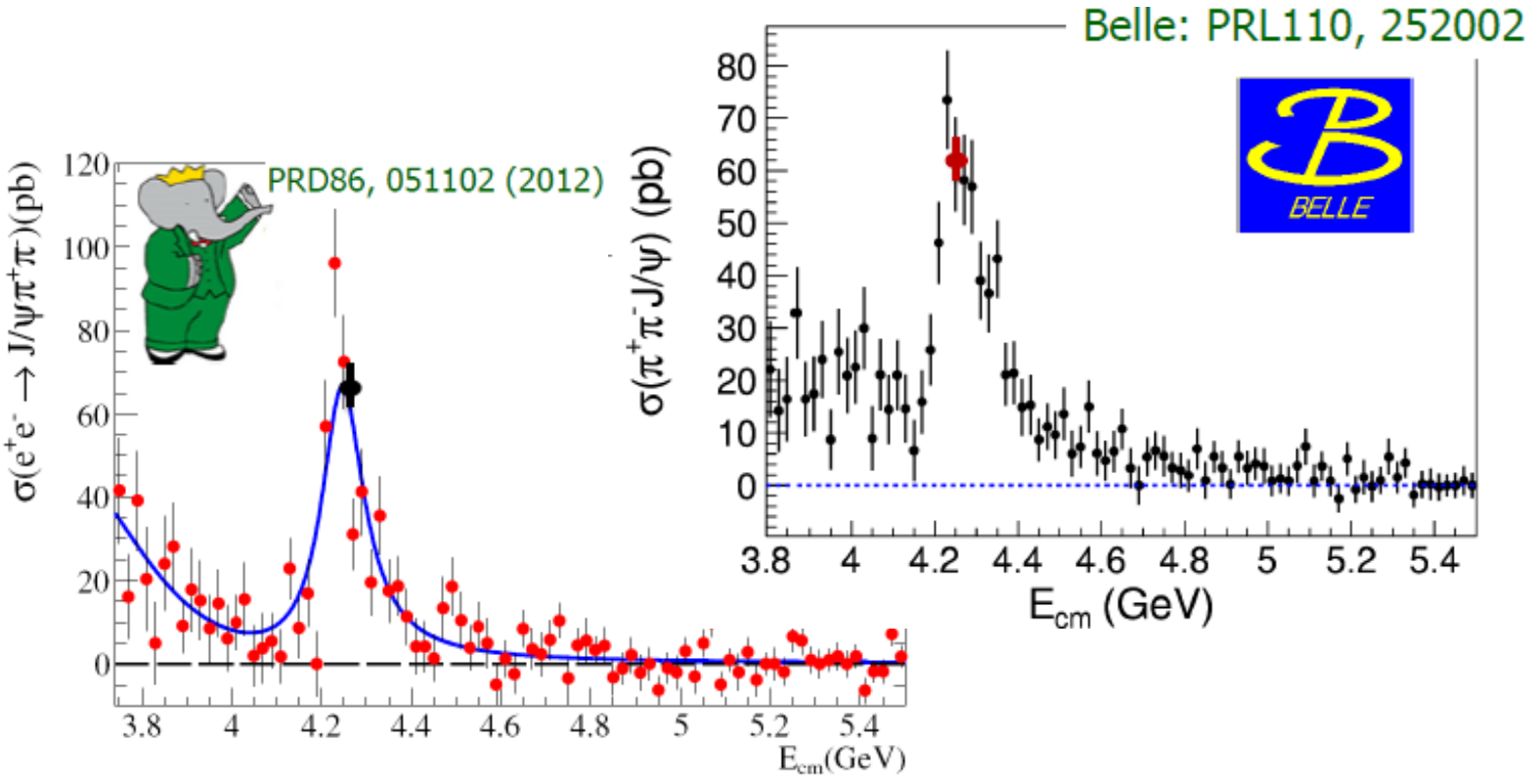
Cross section

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

BESIII measures cross section

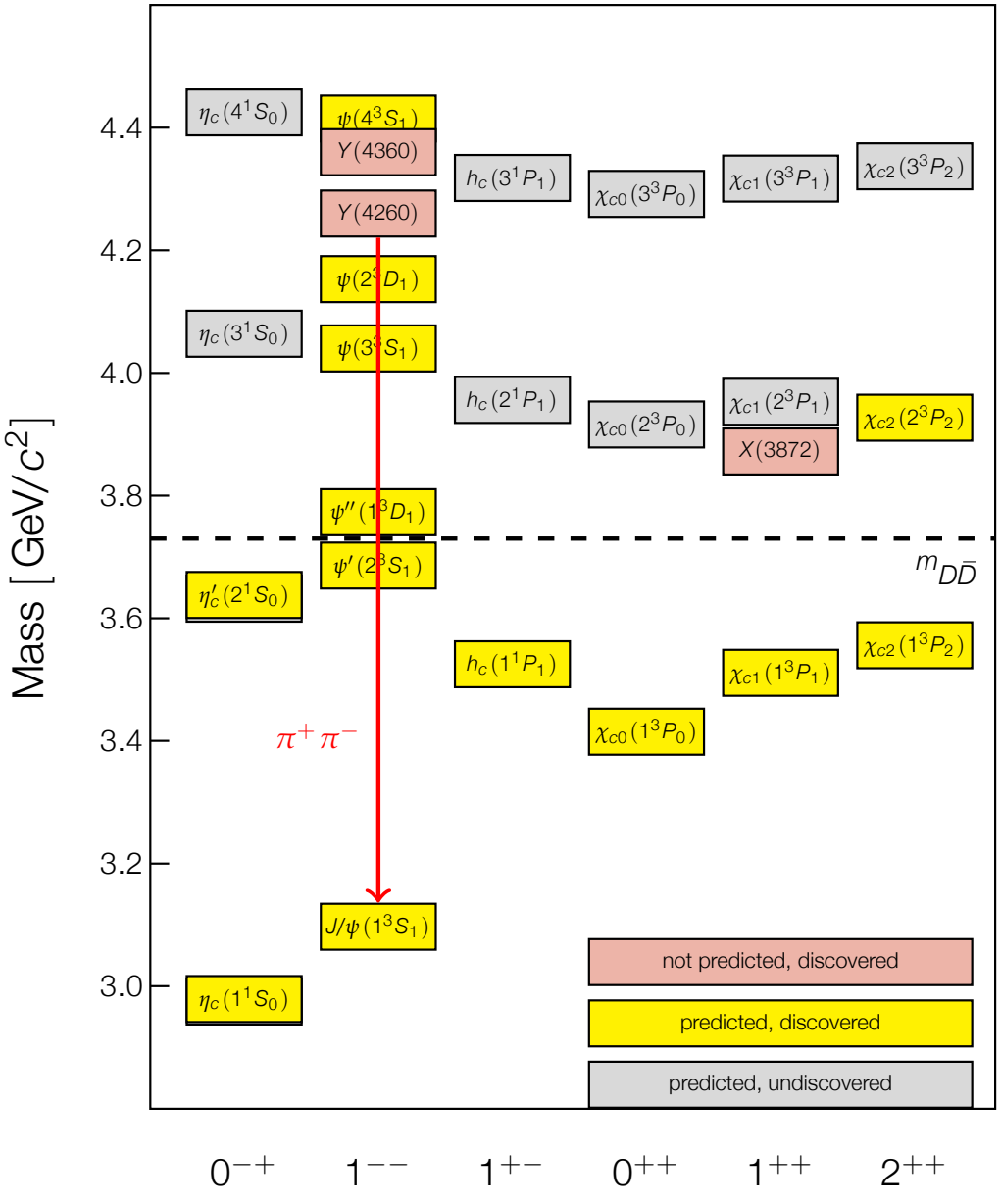
$$\sigma^B(e^+e^- \to J/\psi\,\pi^+\pi^-) = (62.9 \pm 1.9 \pm 3.7)\,\text{pb}$$

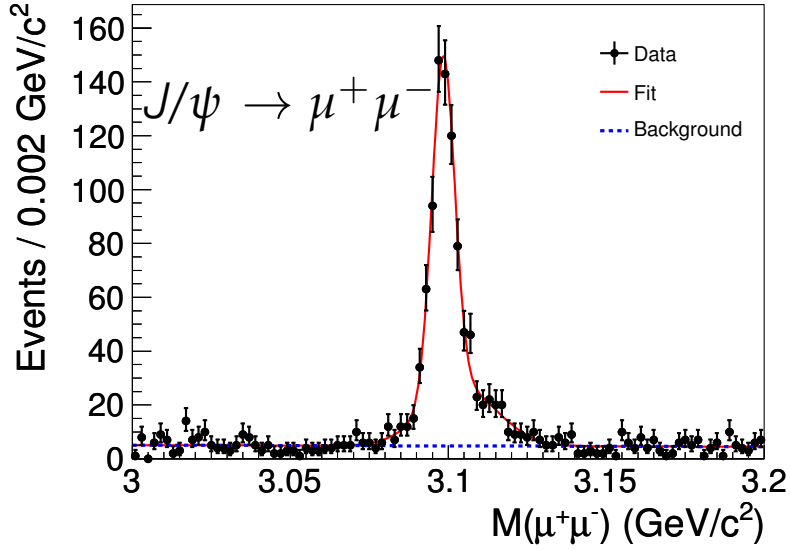
in good agreement with BABAR and Belle

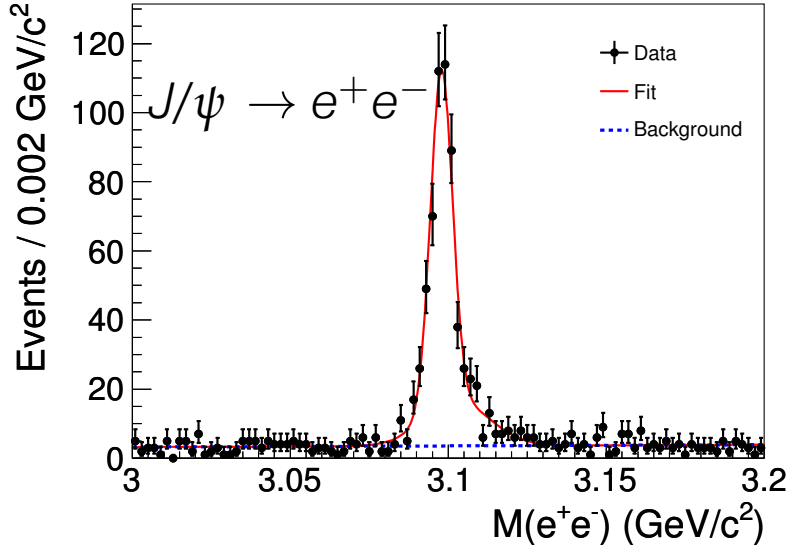


$e^+e^- \to J/\psi\,\pi^+\pi^-$ at 4.26 GeV

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



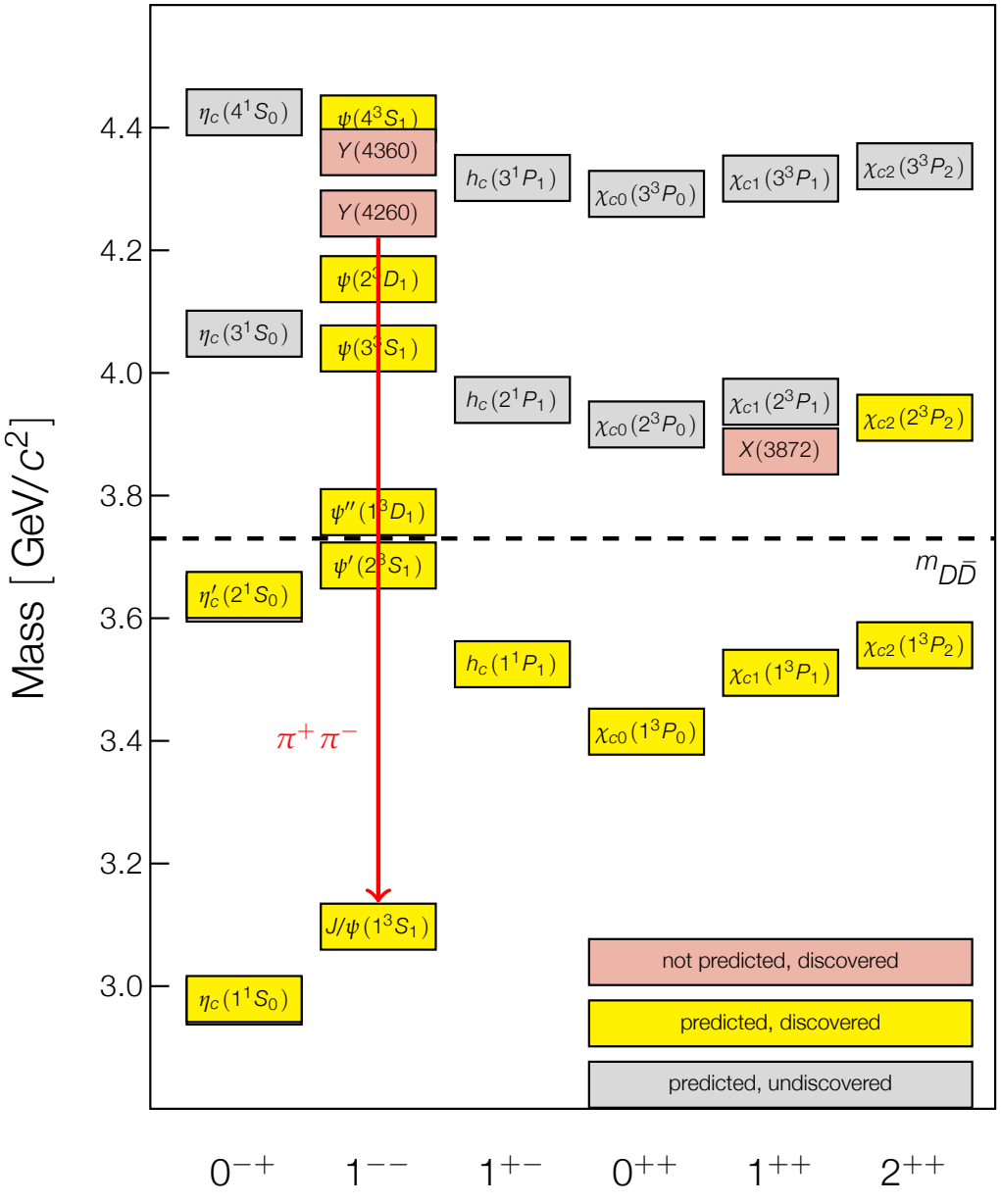


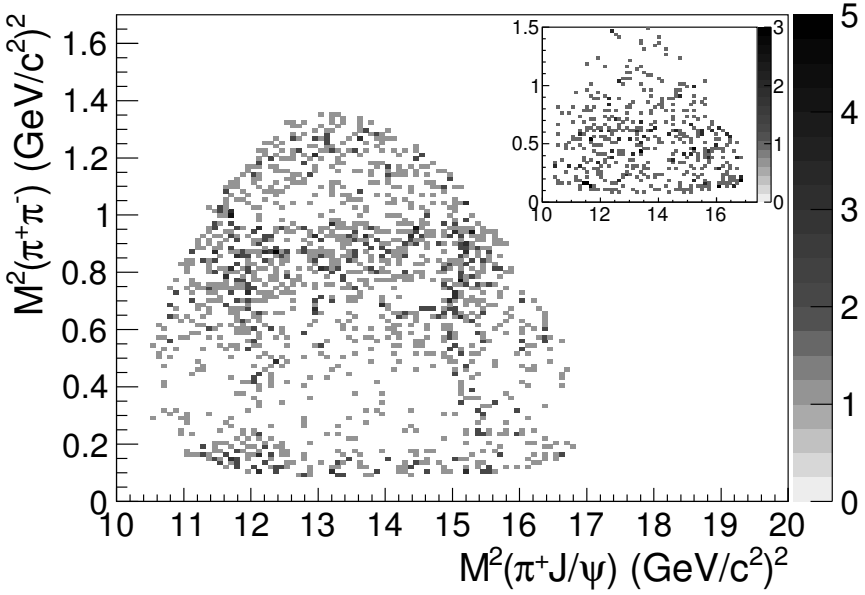


…have hundreds of events!

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

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



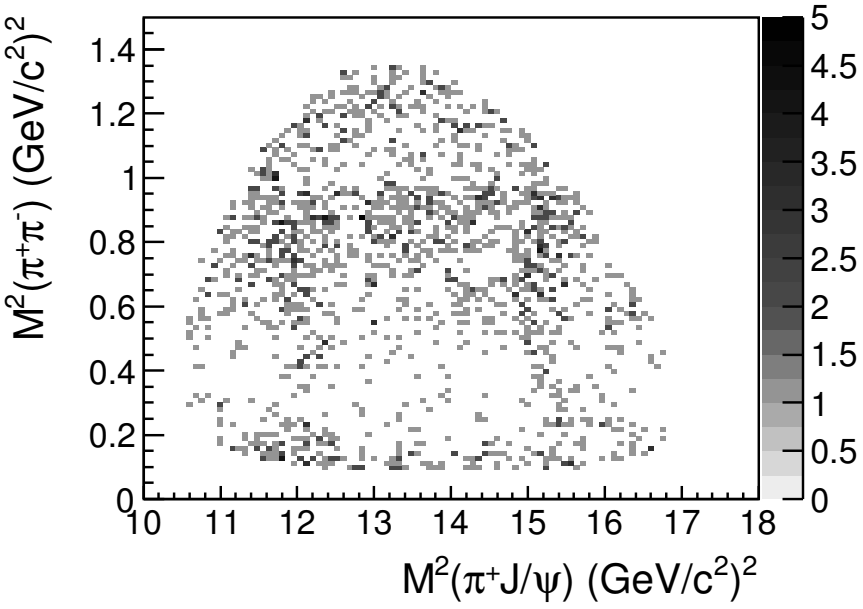


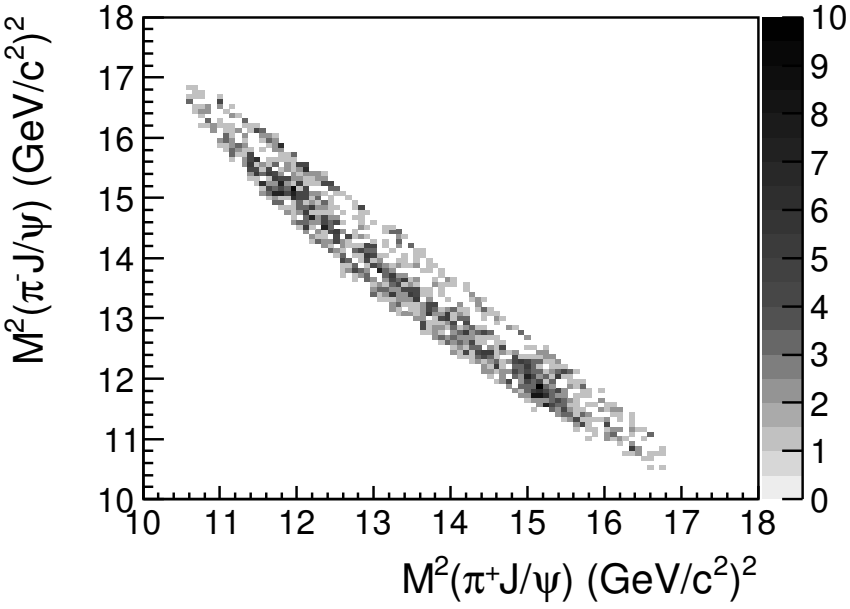
Non-trivial substructure in $J/\psi\,\pi^+\pi^-$ Dalitz plot

Resonant substructure in decay!

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

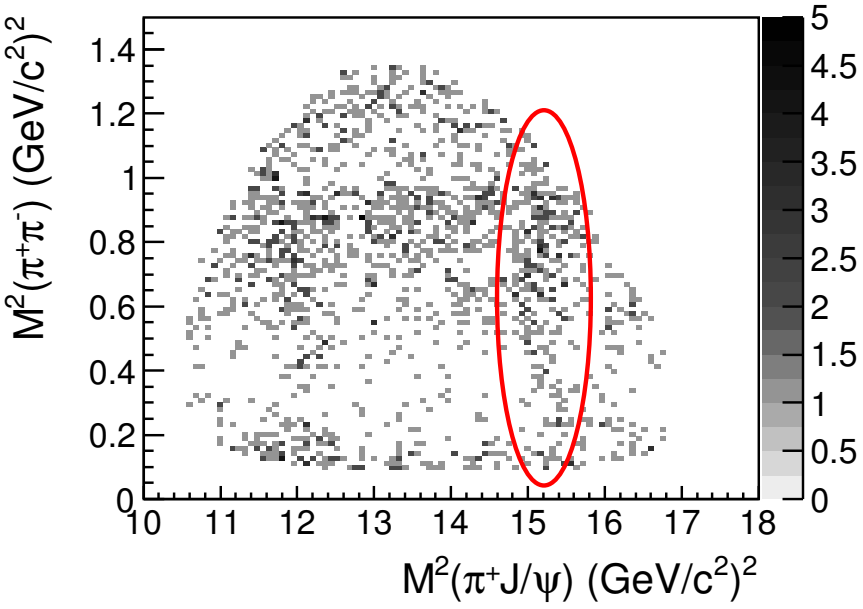
BESIII, PRL **110**, 252001 (2013)

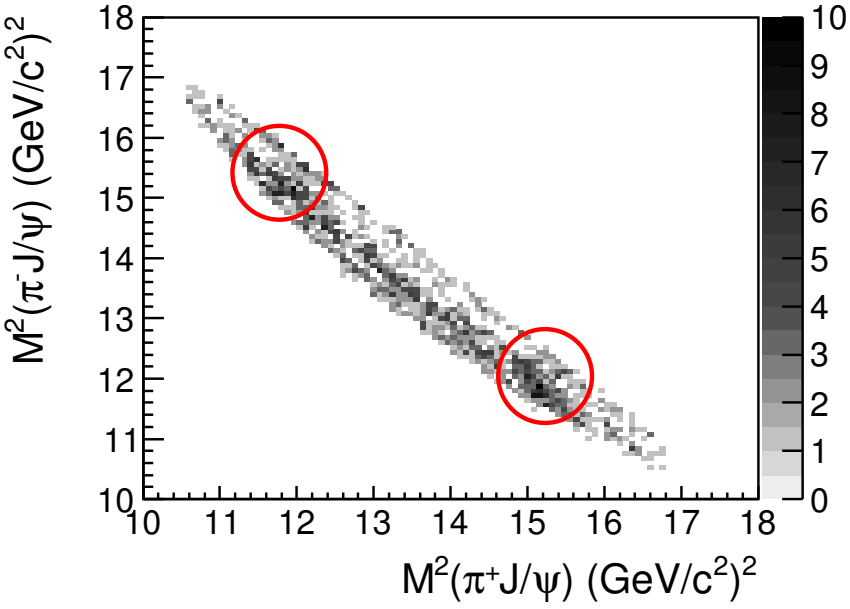


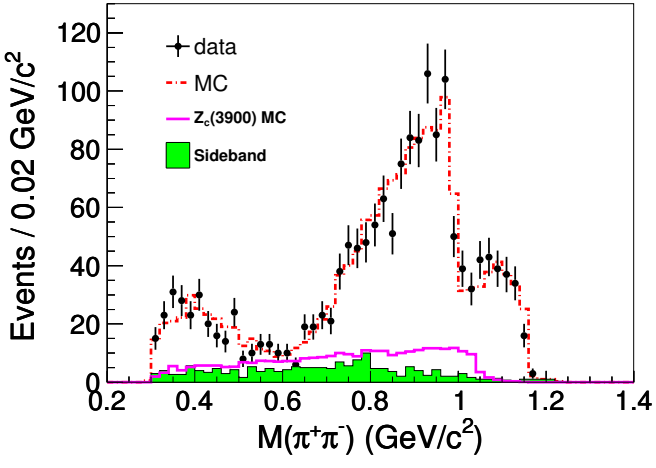


$J/\psi\,\pi^+\pi^-$ Dalitz plot

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



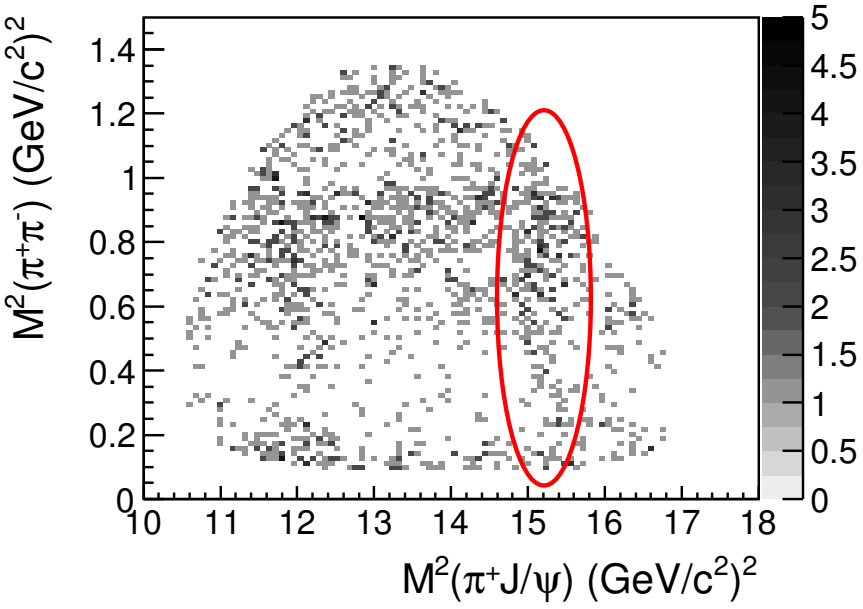


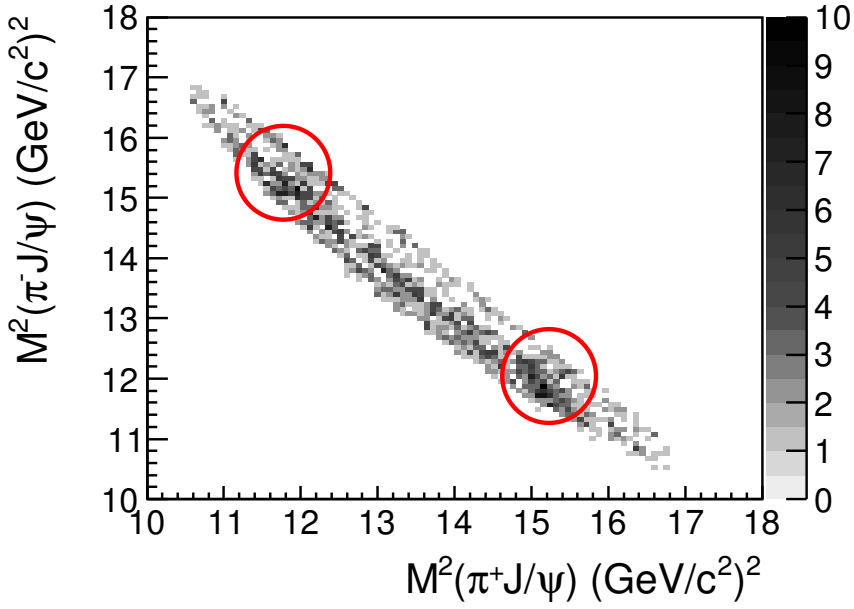


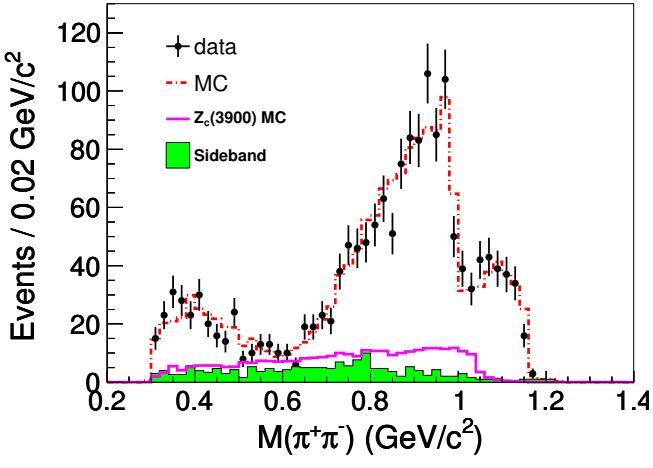
Model $\pi^+\pi^-$-system with known structure:
$f_0(500)$, $f_0(980)$, non-resonant
obtain good fit of $\pi^+\pi^-$ mass projection

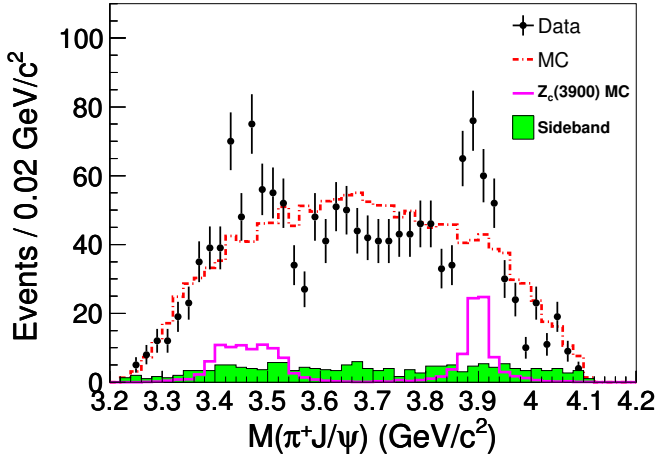
$J/\psi\,\pi^+\pi^-$ Dalitz plot

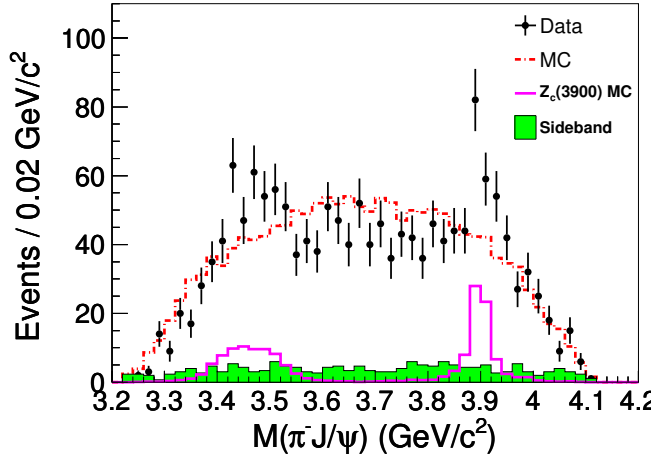
BESIII, PRL **110**, 252001 (2013)



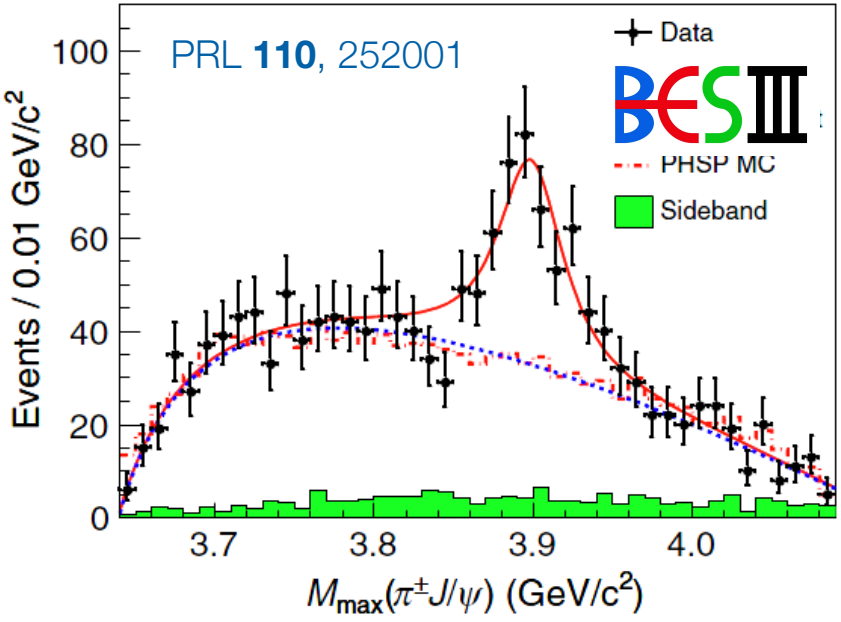


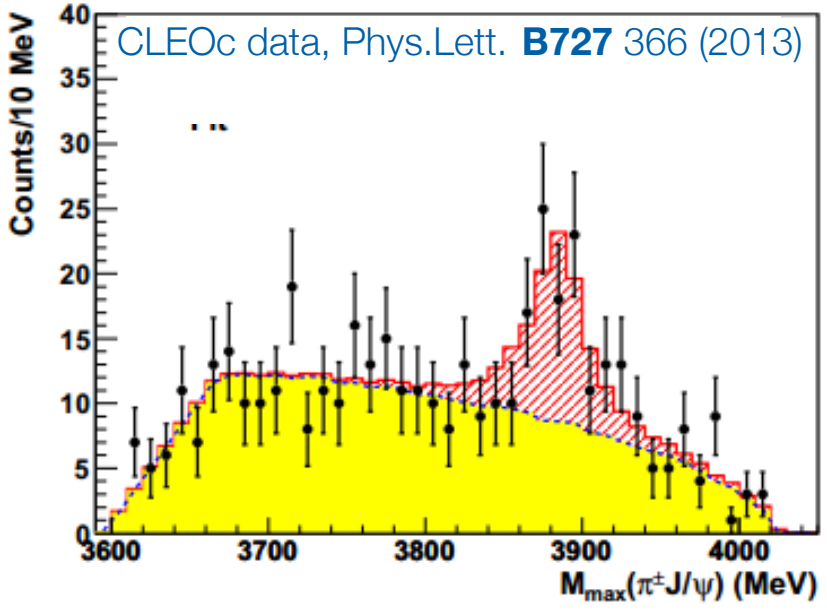


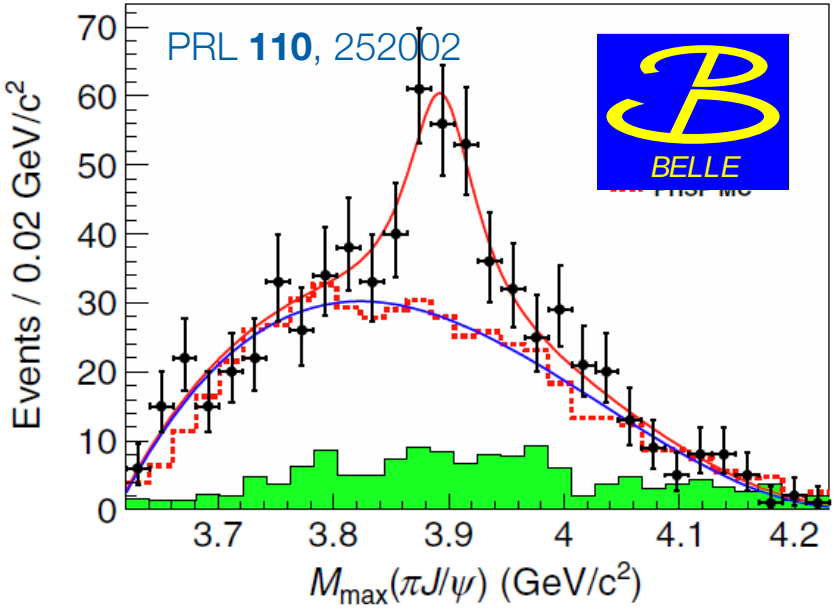




$Z_c(3900)^+$ in other datasets?



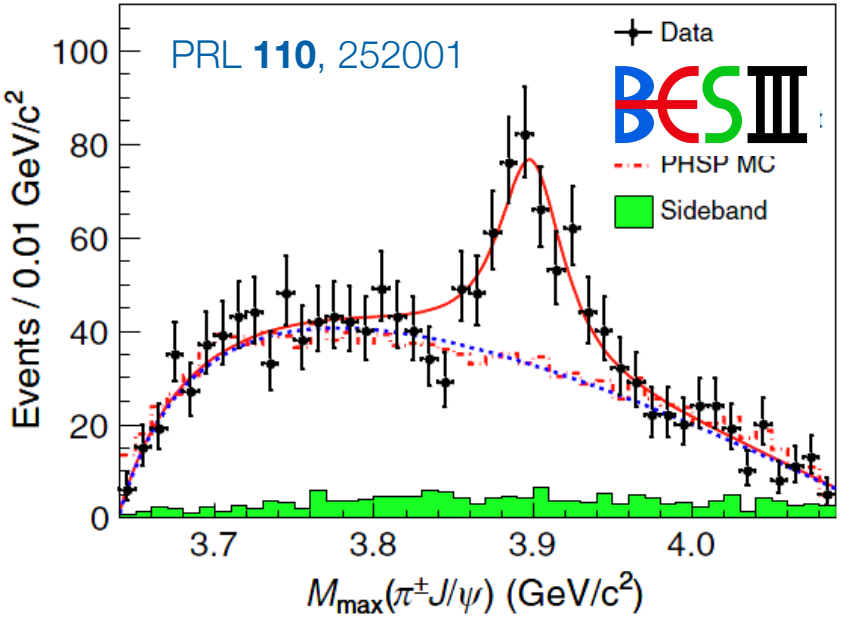


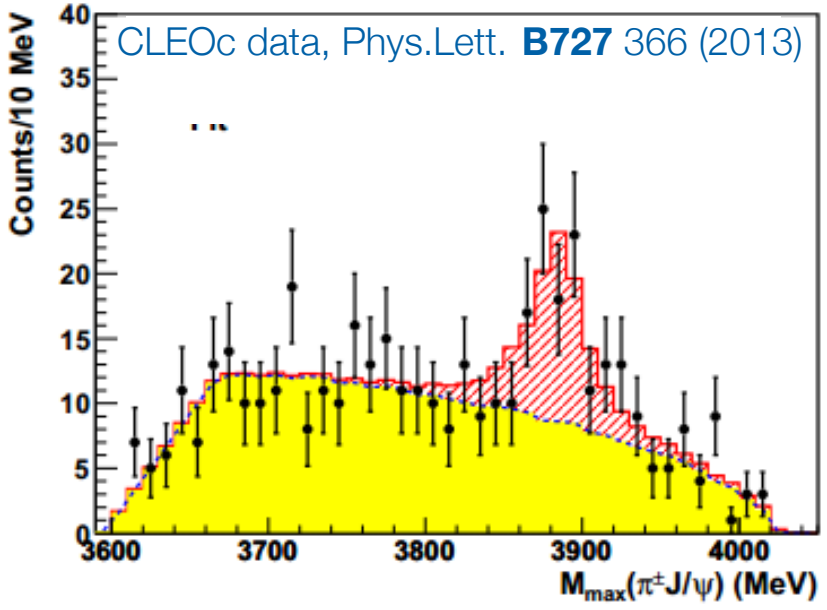


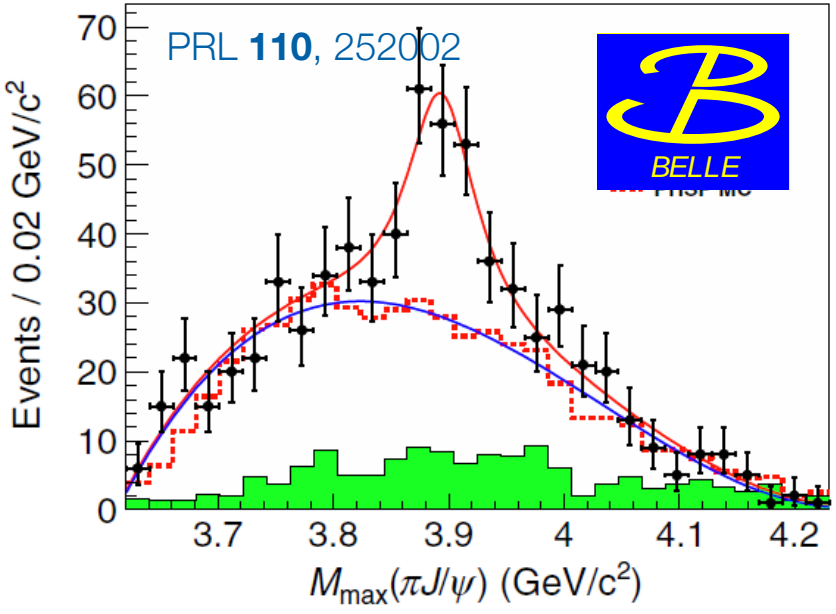
	m / MeV	Γ / MeV
BESIII	$3899.0 \pm 3.6 \pm 4.9$	$46 \pm 10 \pm 20$
Belle	$3894.5 \pm 6.6 \pm 4.5$	$63 \pm 24 \pm 26$
CLEOc	$3885 \pm 5 \pm 1$	$34 \pm 12 \pm 4$

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

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



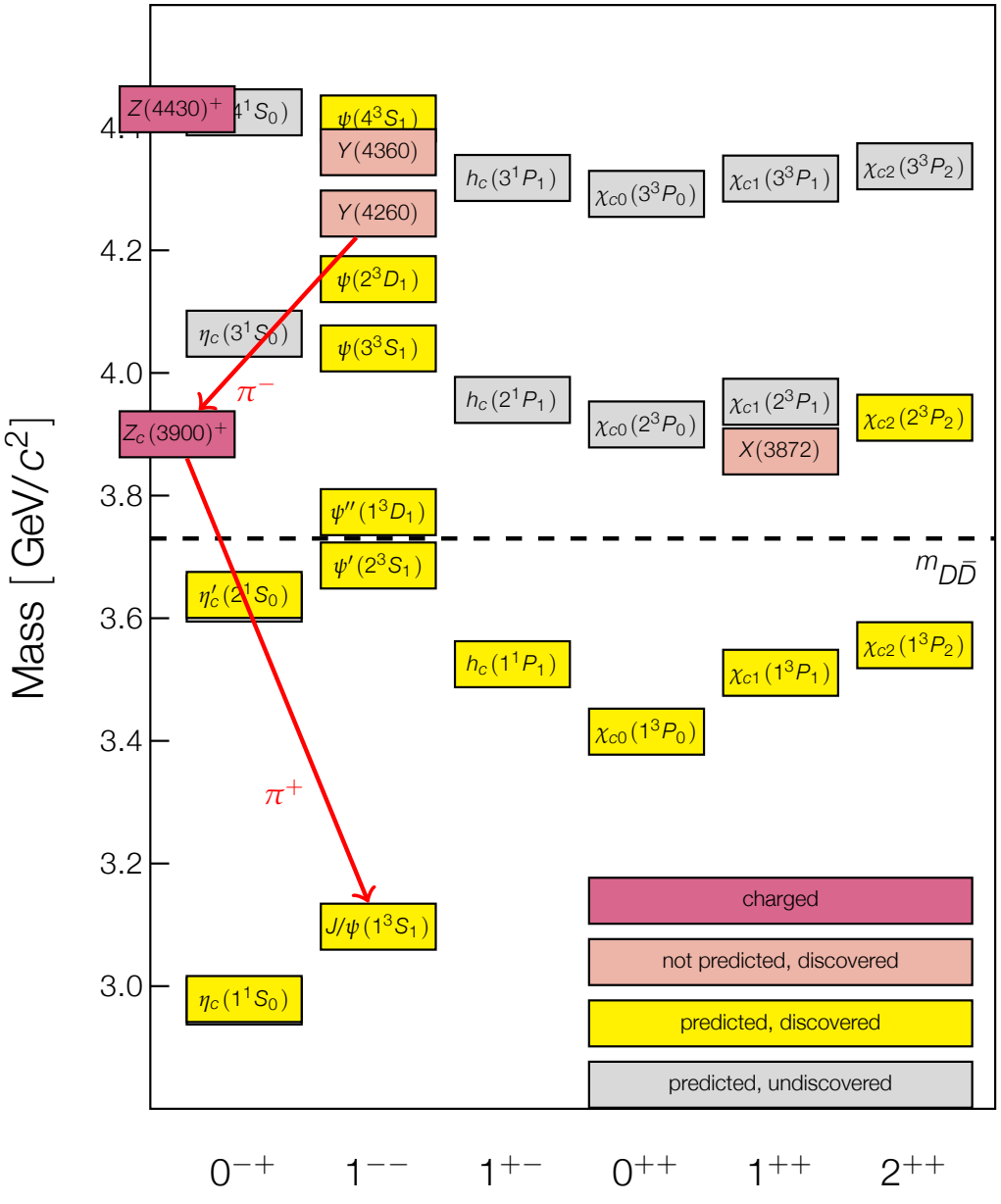


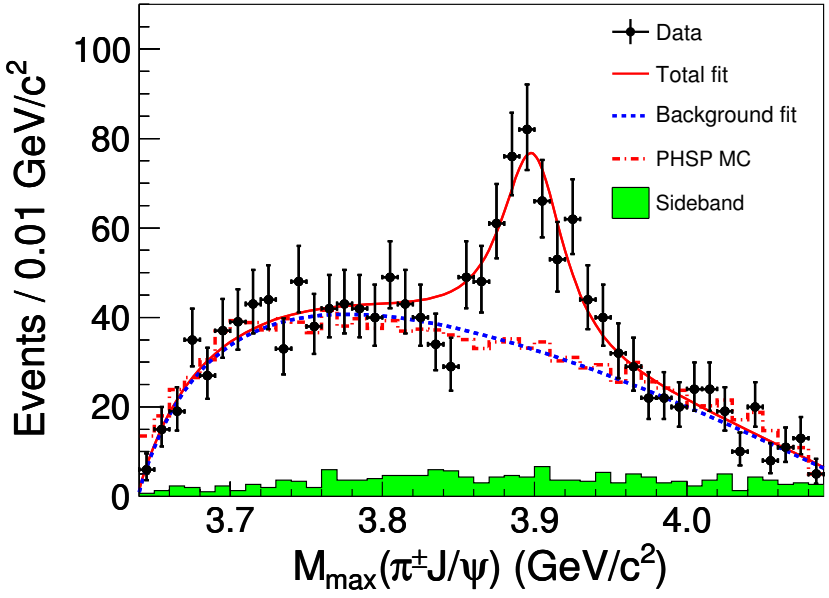


- $Z_c(3900)^+ \to J/\psi\,\pi^+$ seen at BESIII, Belle, and with CLEO-c data
- Masses and widths compatible within uncertainties
- If new state: necessarily exotic

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

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





Charged charmonium-like structure

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

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

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

Close to DD^* threshold

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

BESIII
preliminary

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

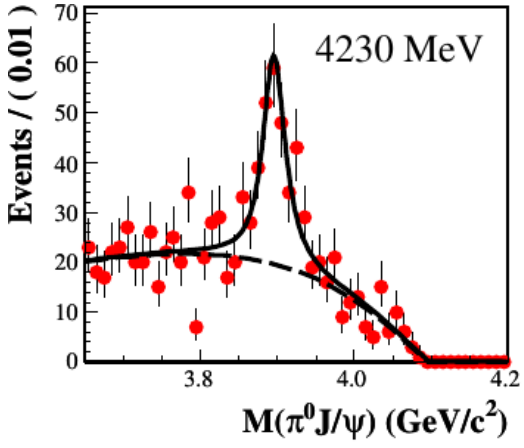
JG|U

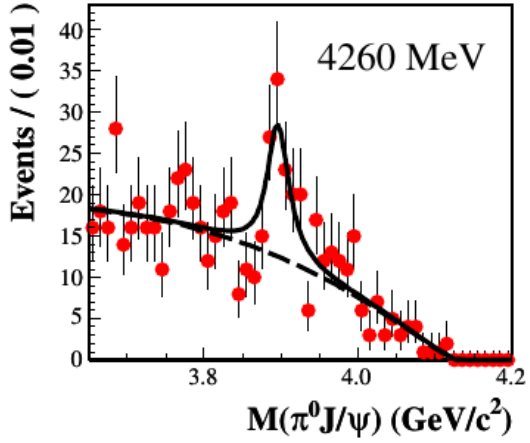
A neutral partner to the $Z_c(3900)^+$?

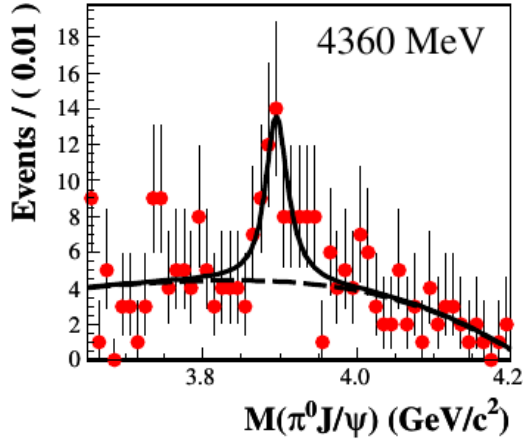
BESIII preliminary

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

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





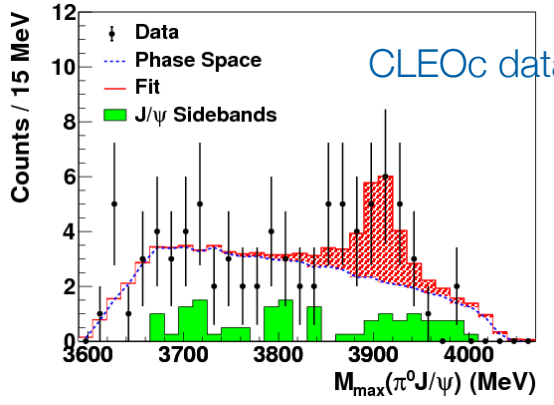


Structure in $\pi^0 J/\psi$ invariant mass clearly visible at all energies

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

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

Significance10σ

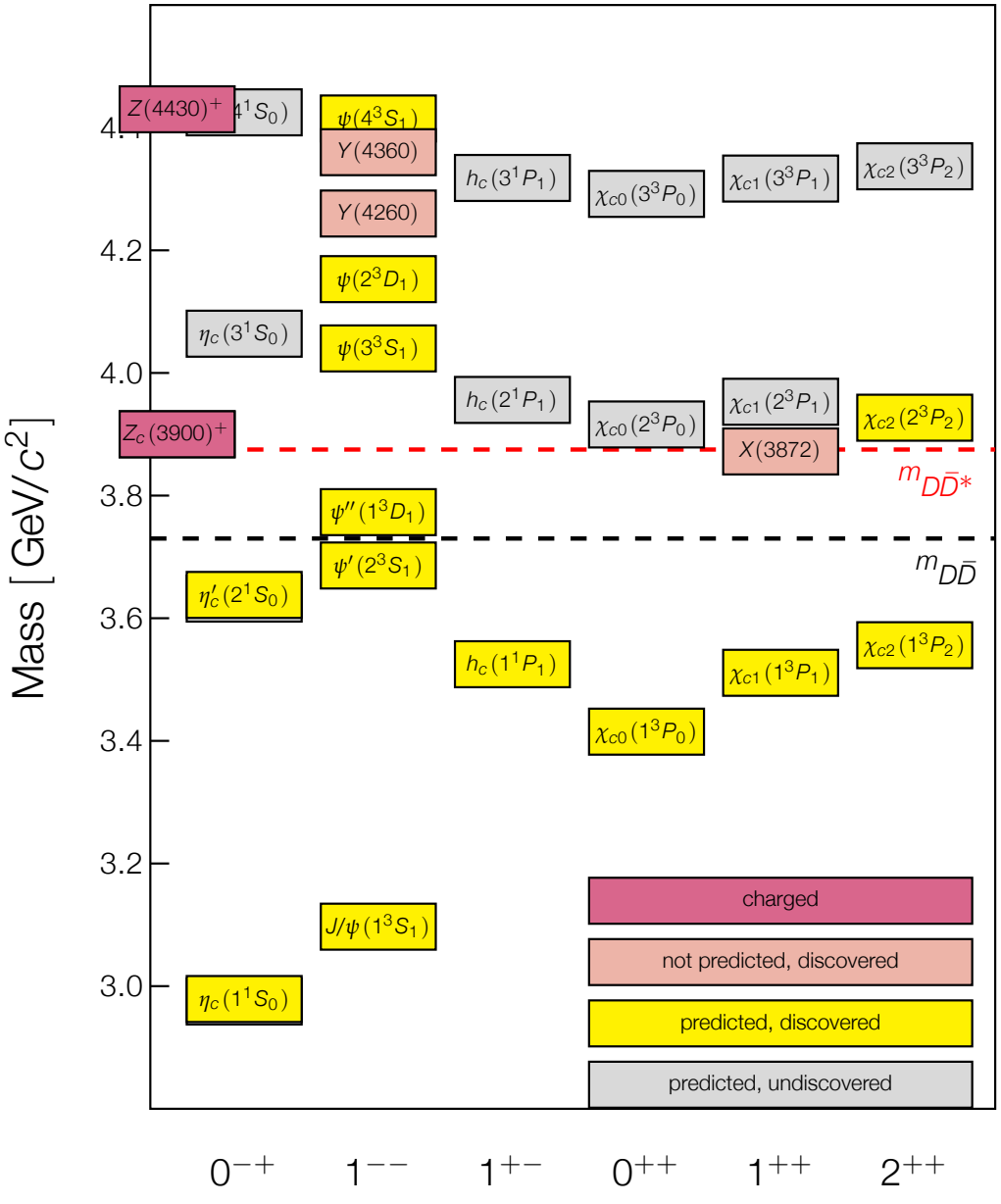


CLEOc data, 3.5σ

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

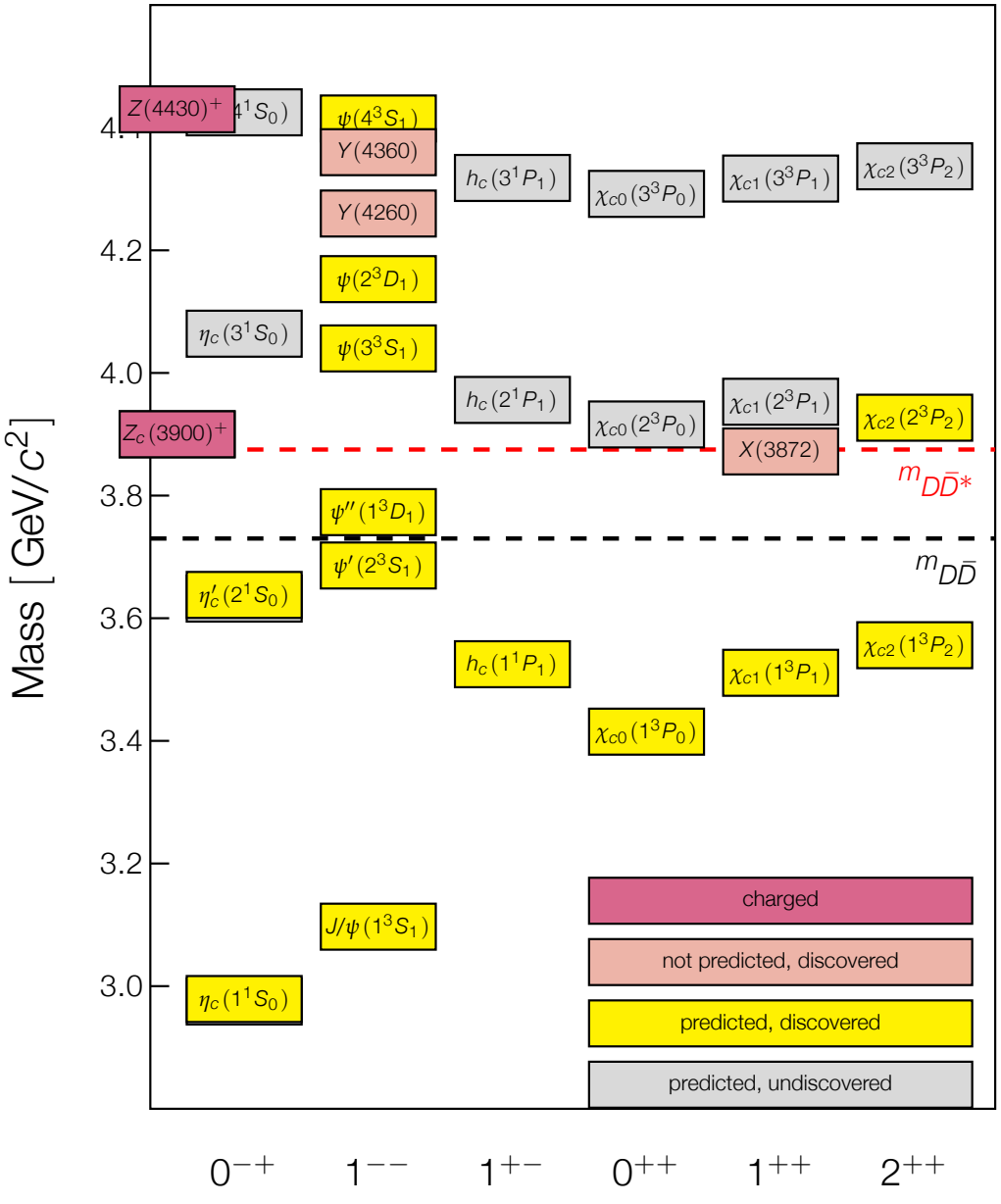
BESIII, PRL **112**, 022001 (2014)

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



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

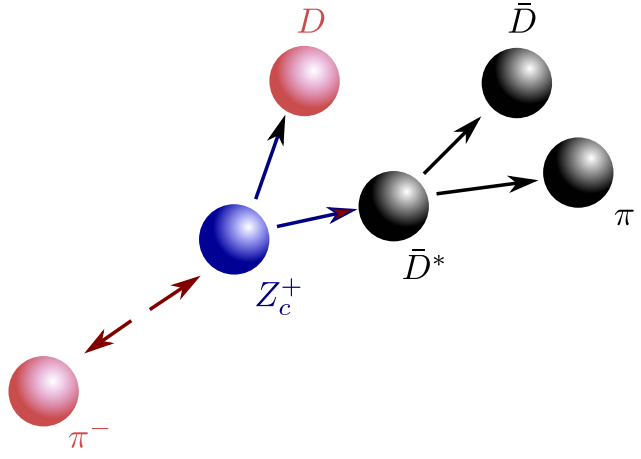
BESIII, PRL **112**, 022001 (2014)



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

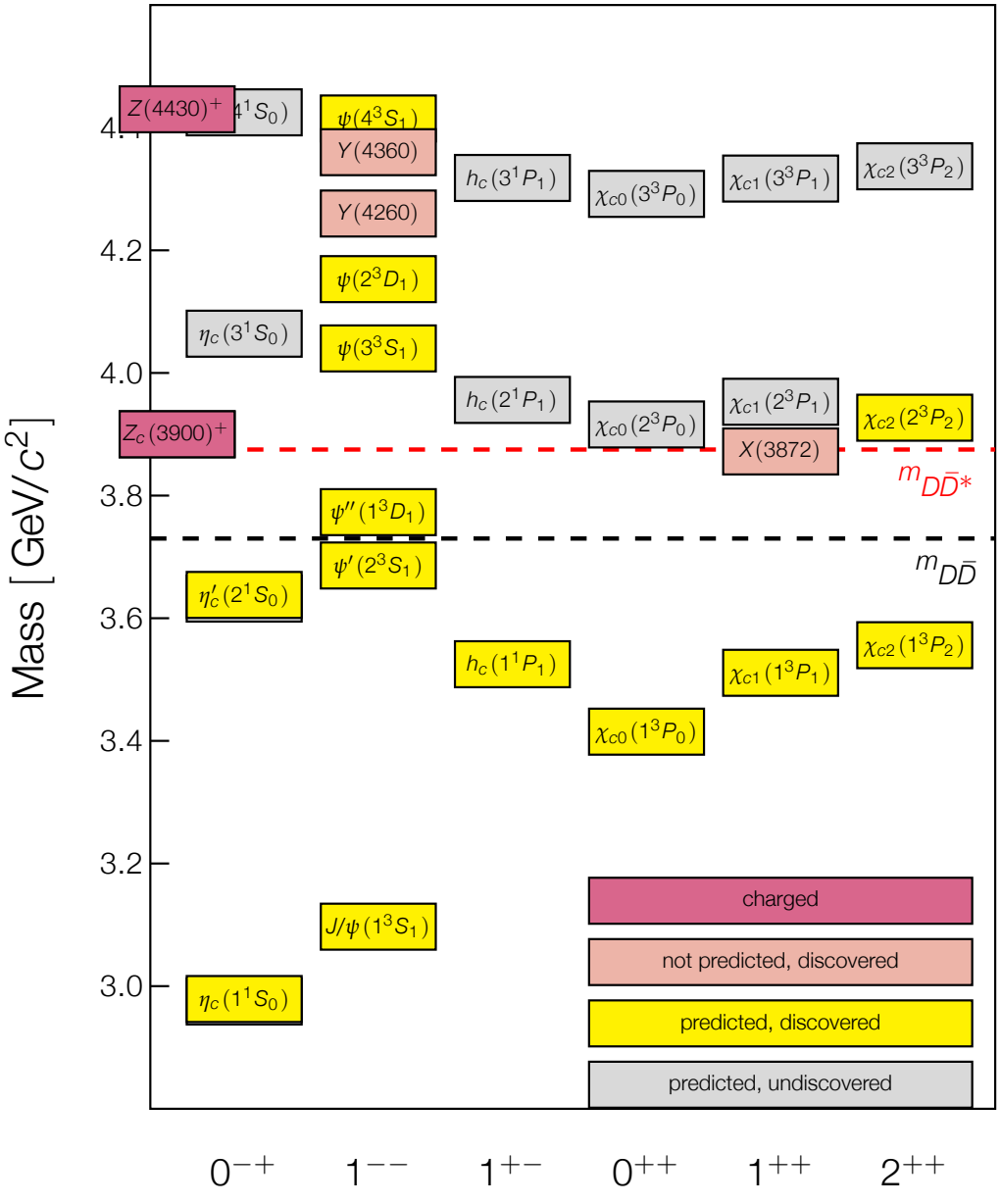
Single tag analysis:

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



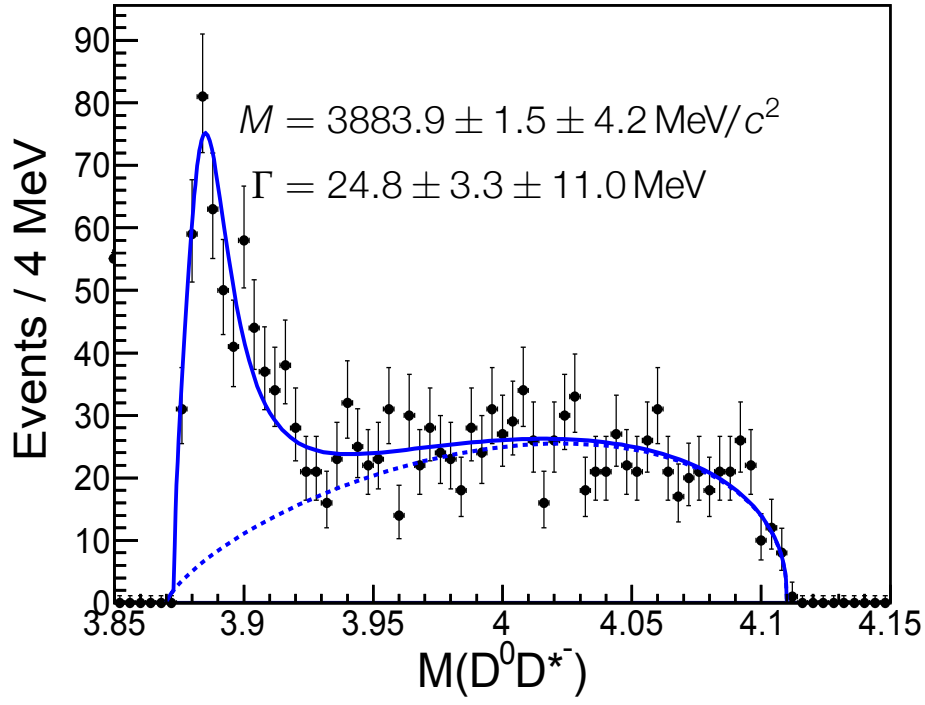
$Z_c(3900)^+$ at $D\bar{D}^*$ threshold

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



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

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

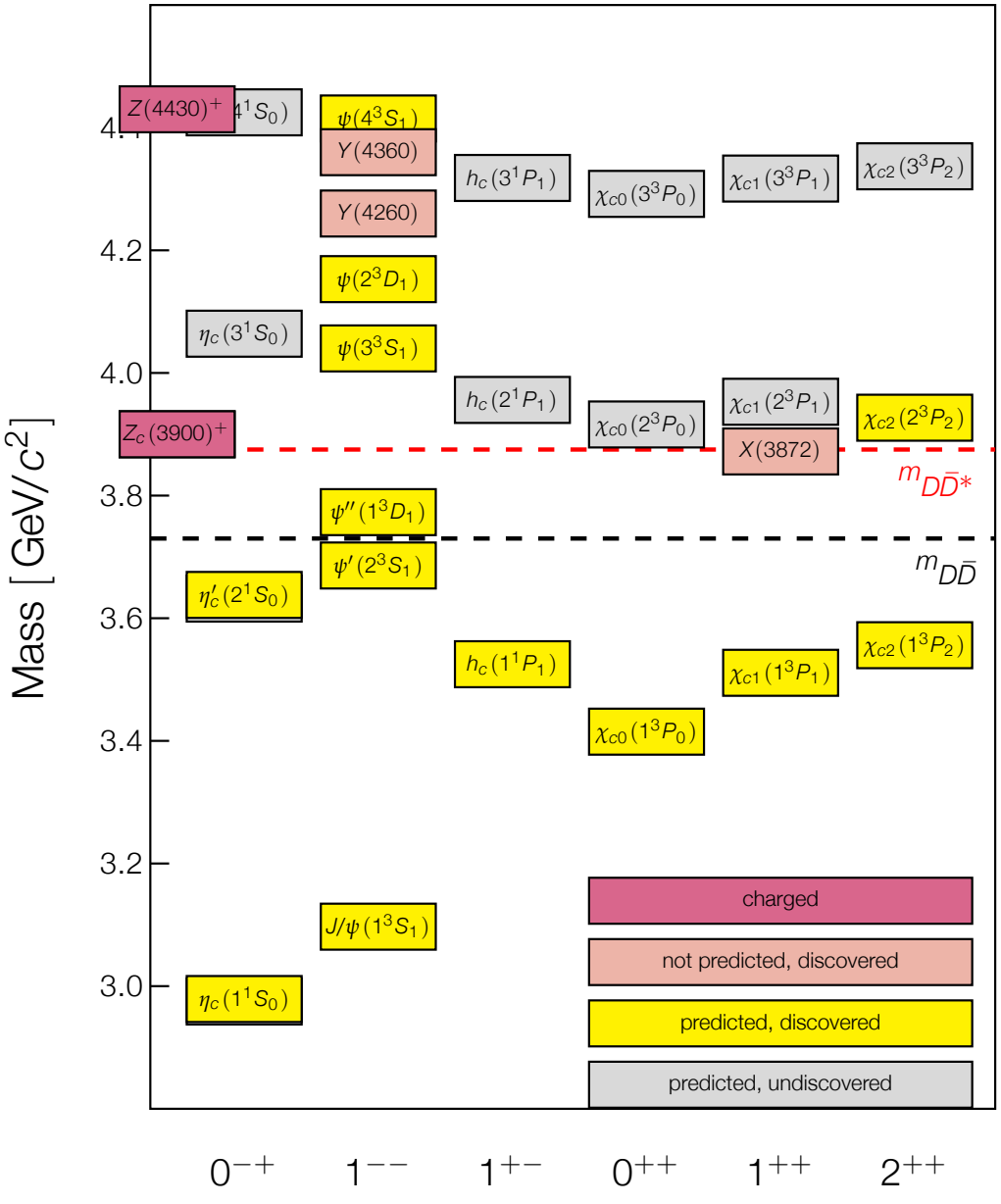


…and BESIII sees structure in $(DD^*)^\pm$

$Z_c(3885)^+$
— same state as $Z_c(3900)^+$?

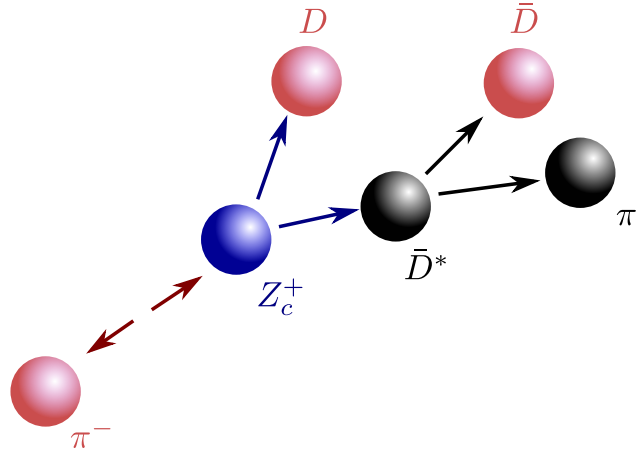
$Z_c(3900)^+$ at $D\bar{D}^*$ threshold

BESIII preliminary



New: Double tag analysis

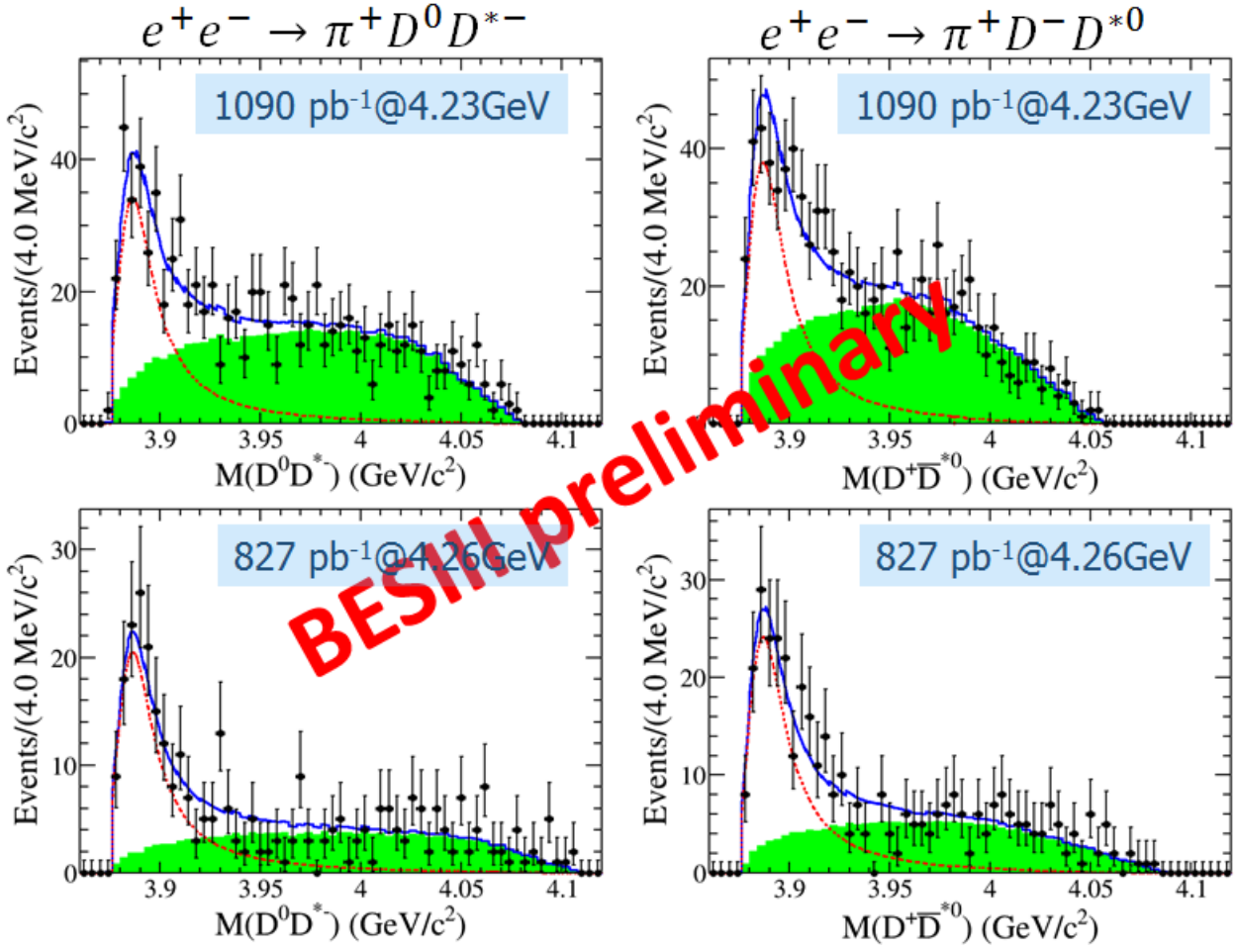
- reconstruct 'bachelor' π^+ and D^0, D^- in 4 or 6 decay modes
- kinematic fit, requiring π from D^* in missing mass essentially background-free D^*
- improved statistics, much better control over background shape improved systematics
- $M^{\text{recoil}}(\pi^+) = M(D\bar{D}^*)$



JG|U

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

BESIII preliminary



Simultaneous fit with phase space shape + $(BW \otimes \mathcal{R}) \times \varepsilon$

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

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

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

$e^+e^- \to \pi^+(D\bar{D}^*)^-$ 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	$83.5 \pm 6.6(\text{stat}) \pm 22.0(\text{syst})$	$88.0 \pm 6.1(\text{stat}) \pm 7.9(\text{syst})$

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

JG|U

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

$Z_c(3885)^+$ Quantum numbers?

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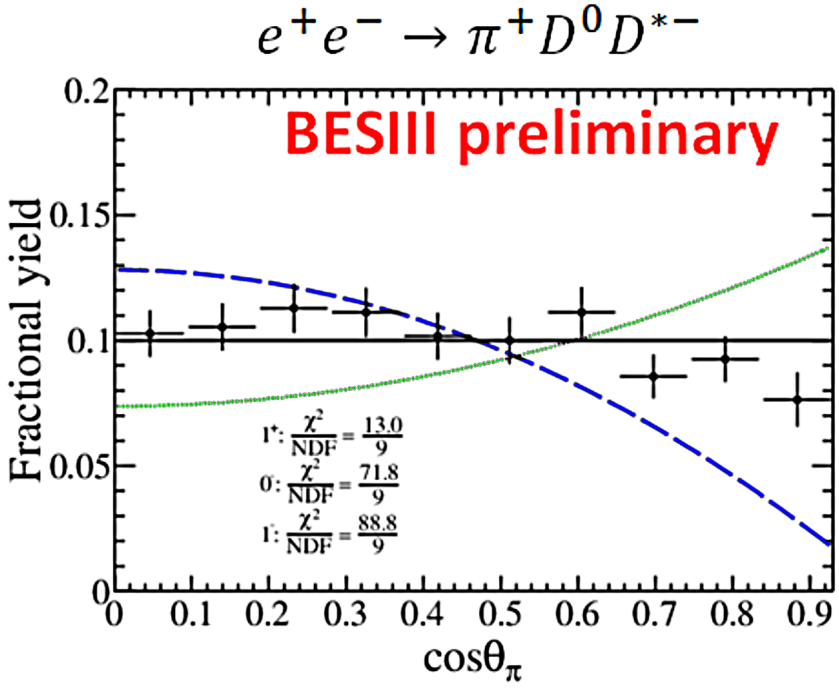

Efficiency corrected event yield in 10 bins in $|\cos\theta_\pi|$

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

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

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

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

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

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

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

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

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

Interpretation of $Z_c(3900)$?

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

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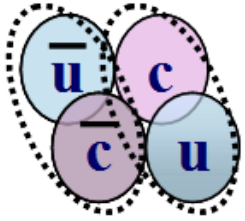
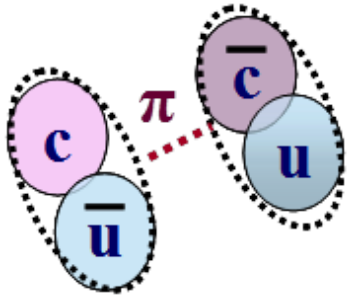
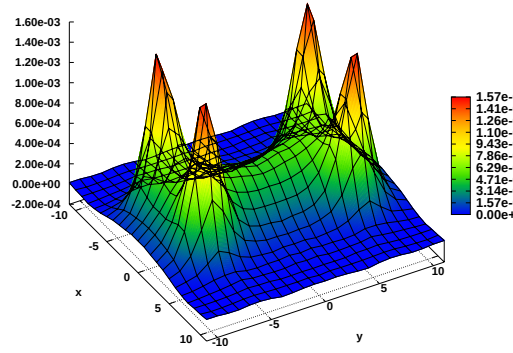
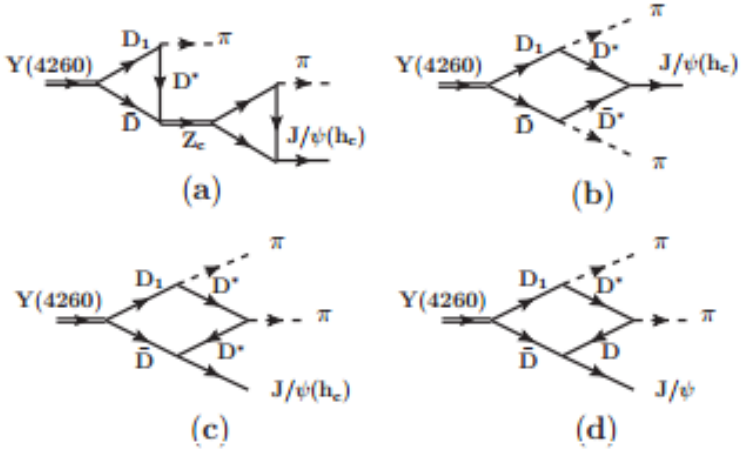
So, what is it?

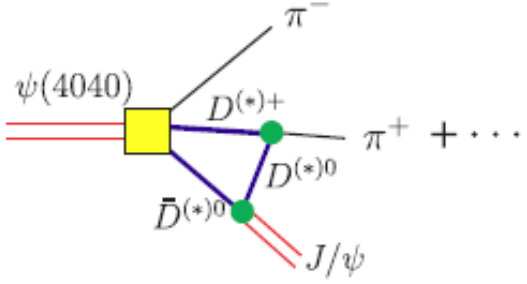
- Tetraquark L. Maiani, A. Ali et al.
- Hadronic molecule U.-G. Meissner, F.K. Guo et al.
- Hadro-charmonium M. B. Voloshin
- Meson loop Q. Zhao et al.
- ISPE model X. Liu et al.
- Threshold cusp E. Swanson
- …









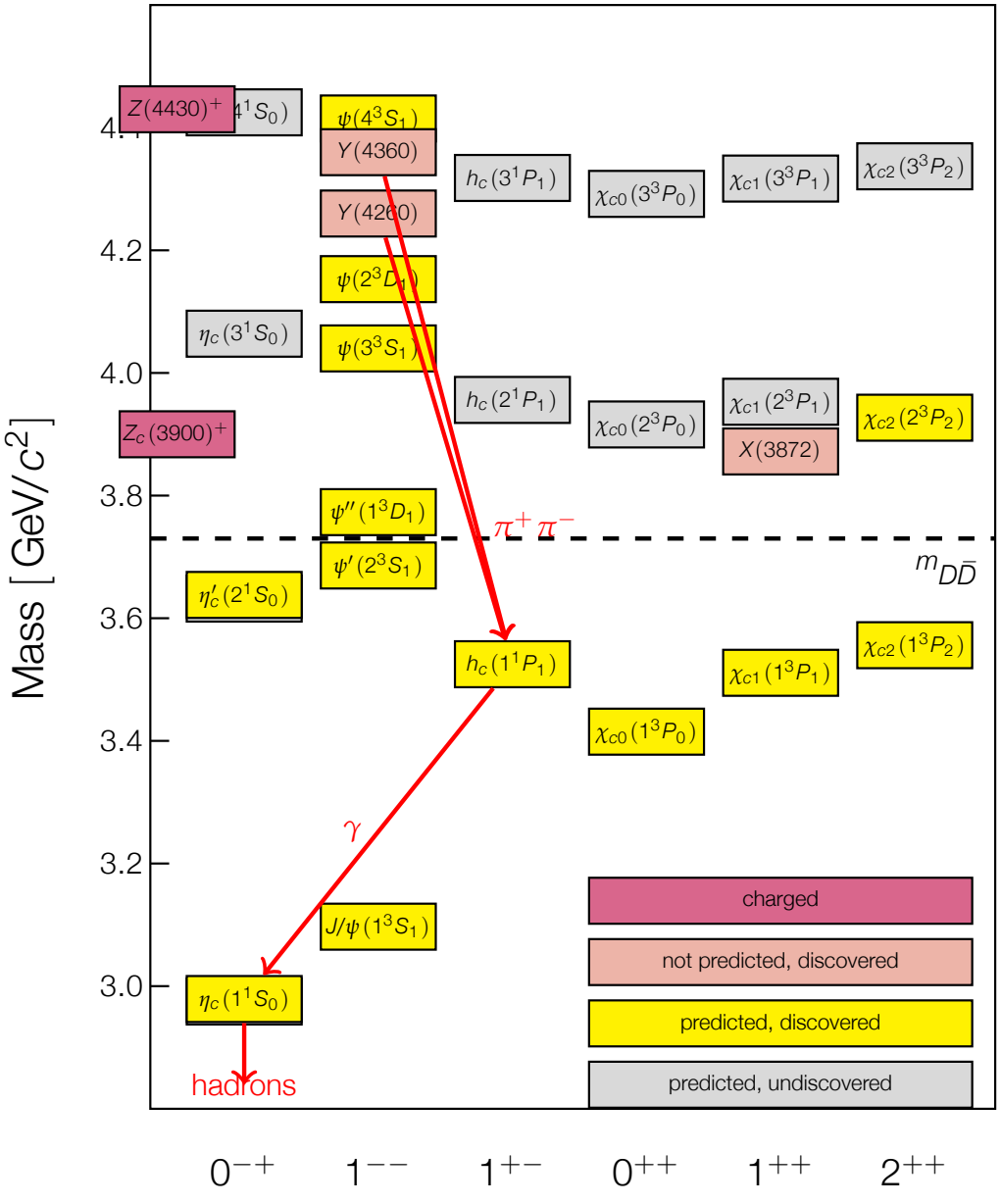


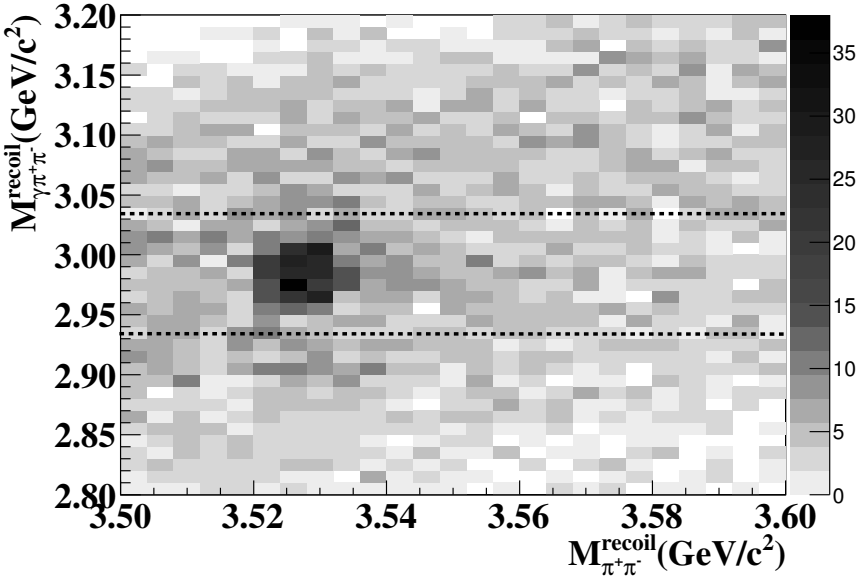
$e^+e^- \to h_c(1P)\pi^+\pi^-$

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

Exclusively reconstruct the process

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





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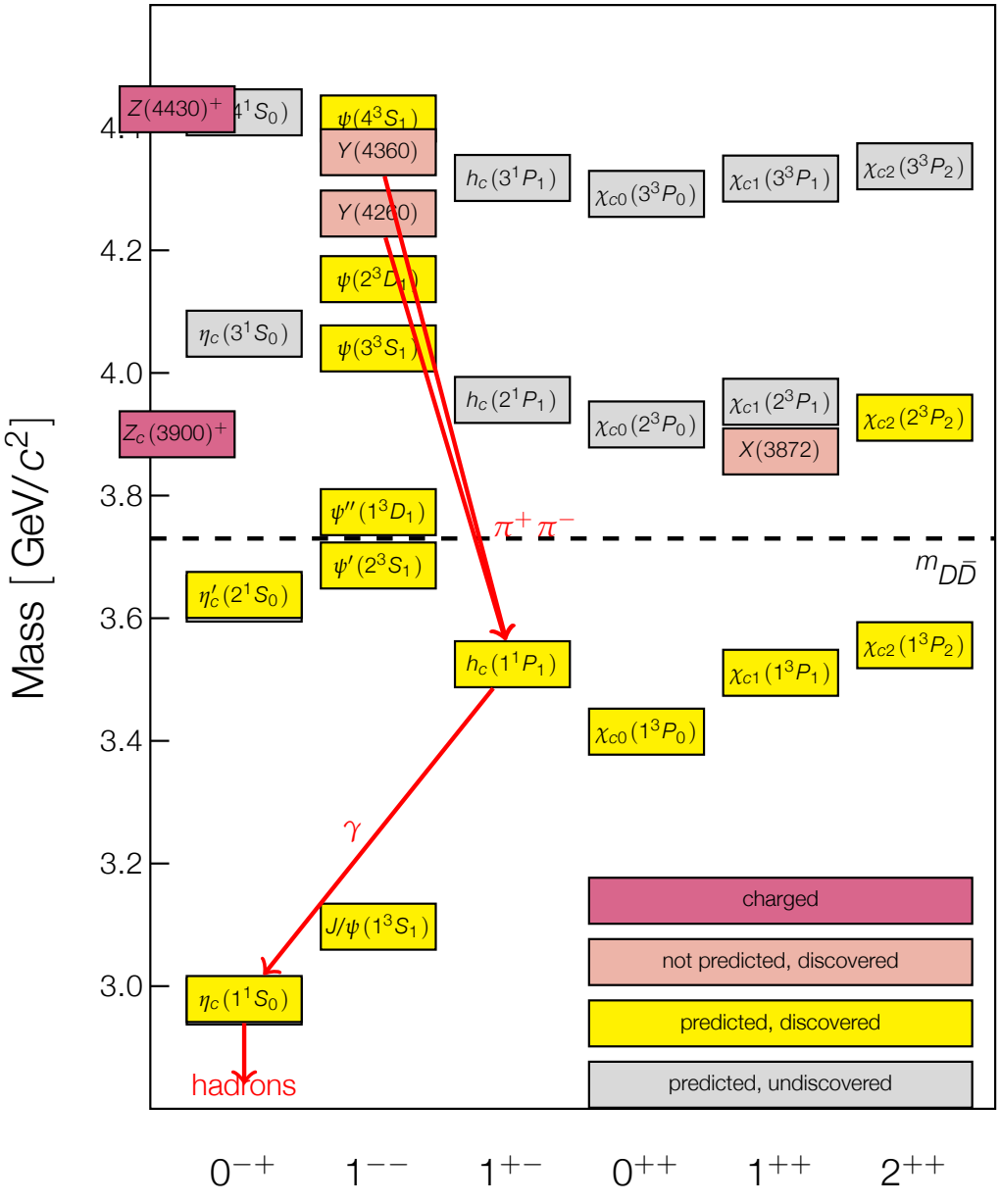

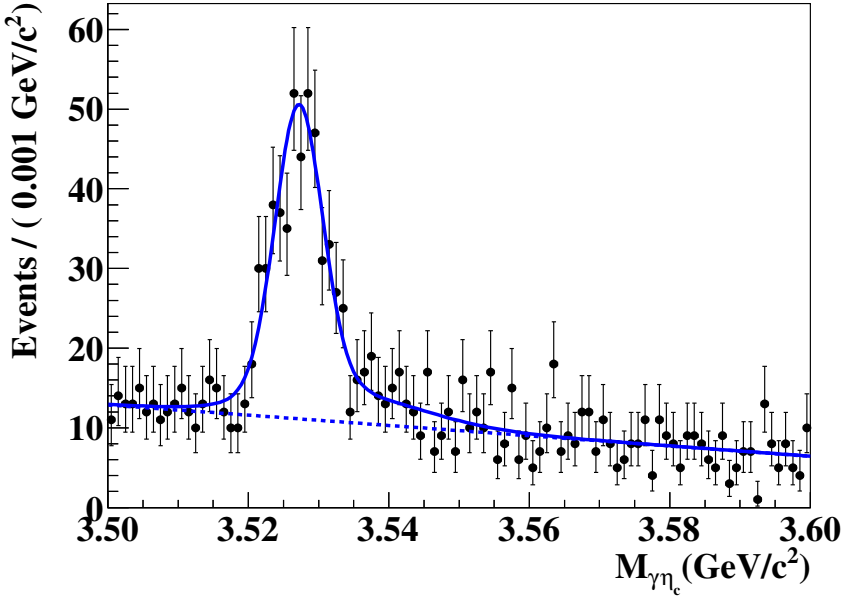

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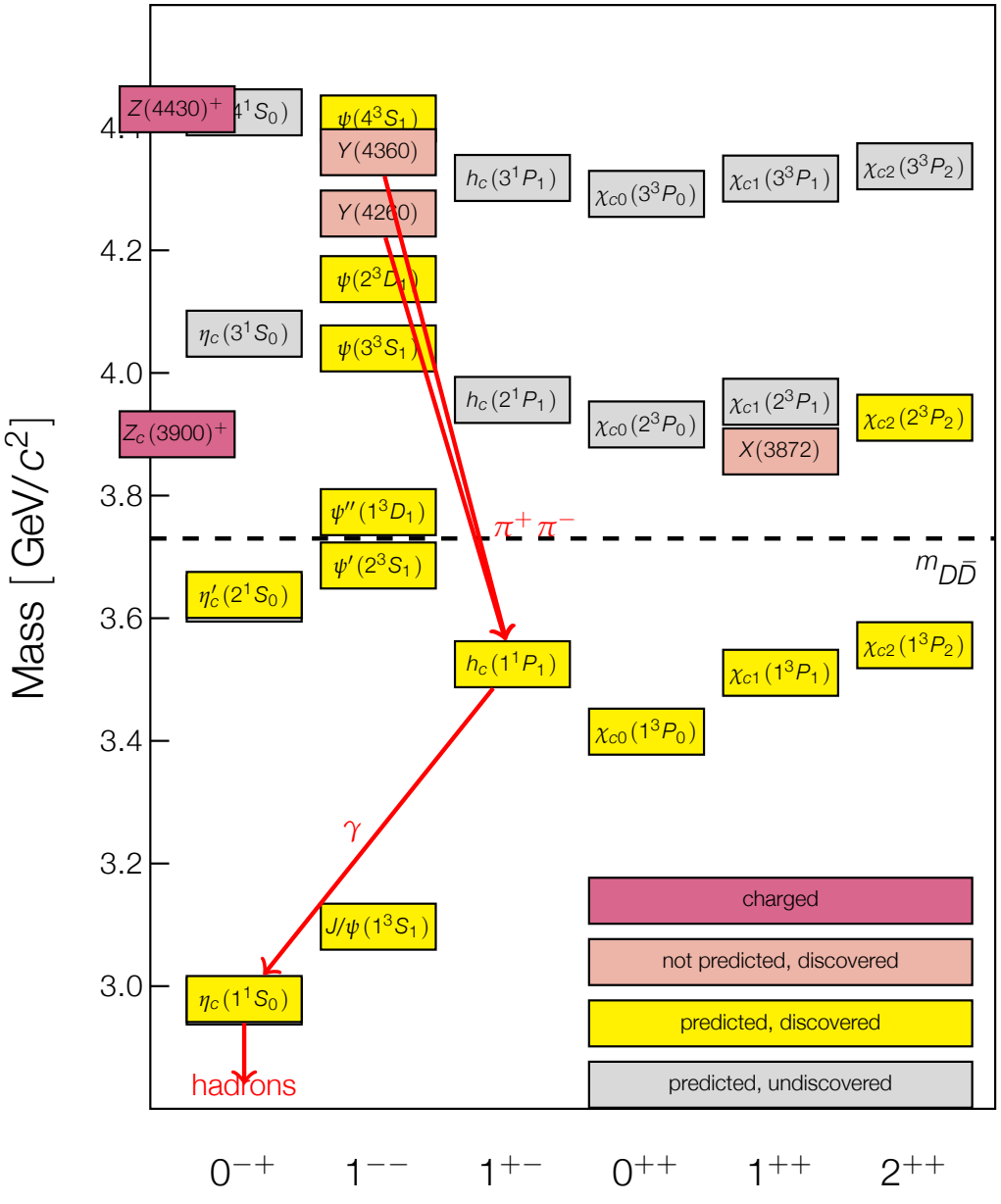

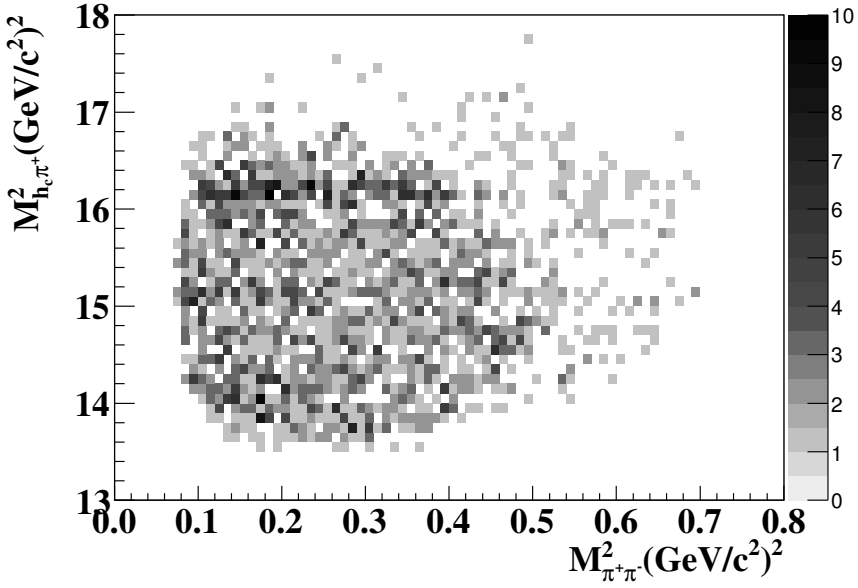

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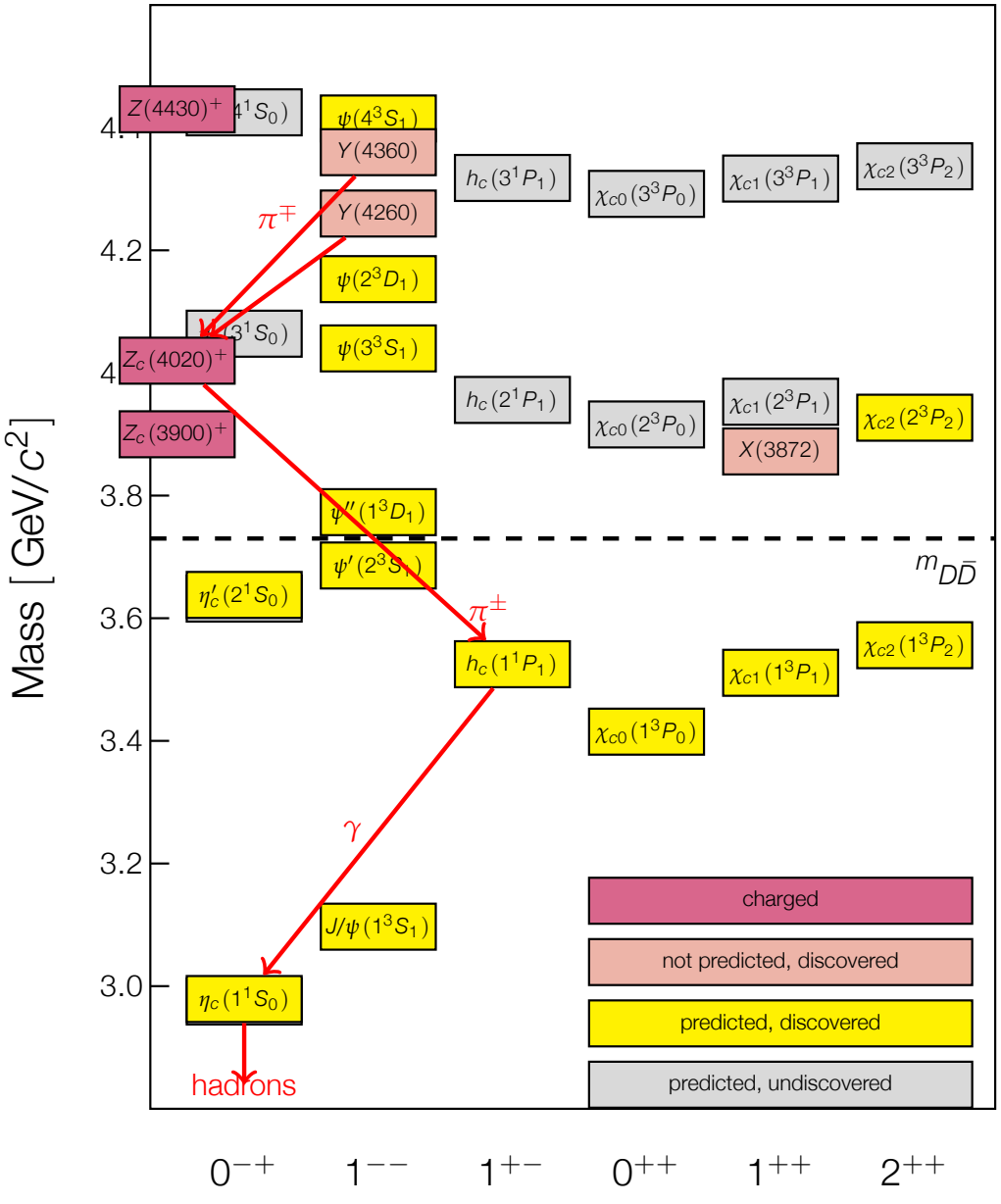
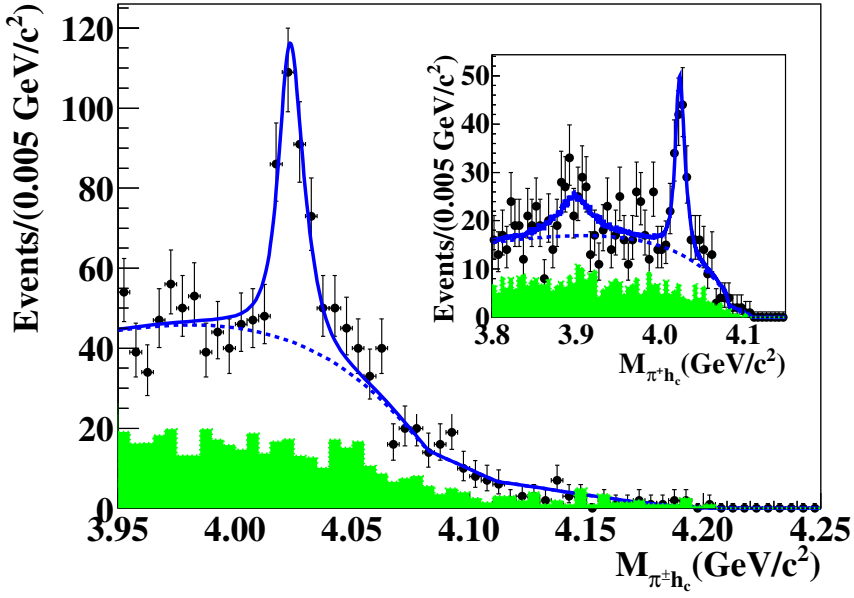
BESIII, PRL **111**, 242001 (2013)





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

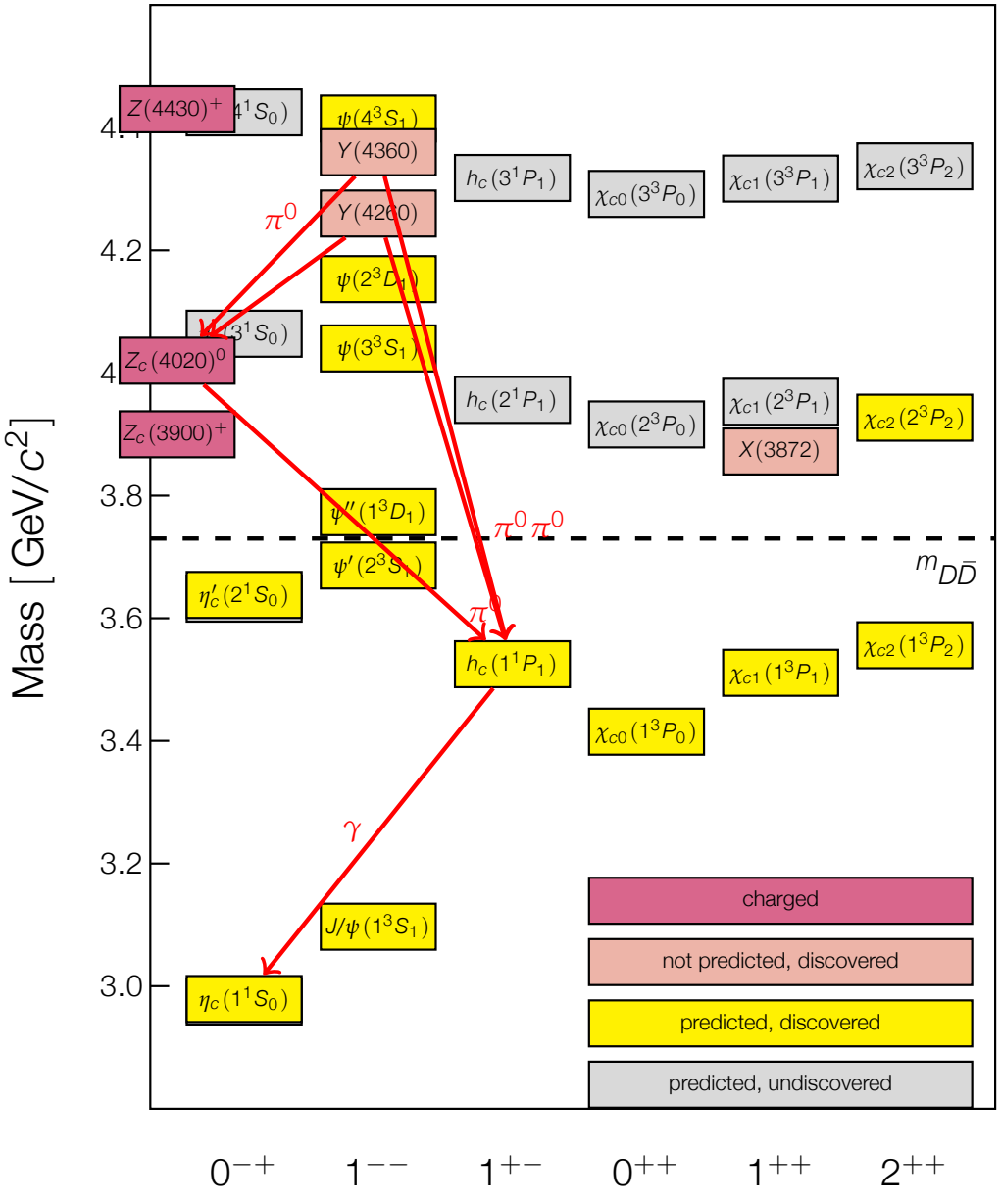
$$M = 4022.9 \pm 0.8 \pm 2.7\,\text{MeV}/c^2$$

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

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

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

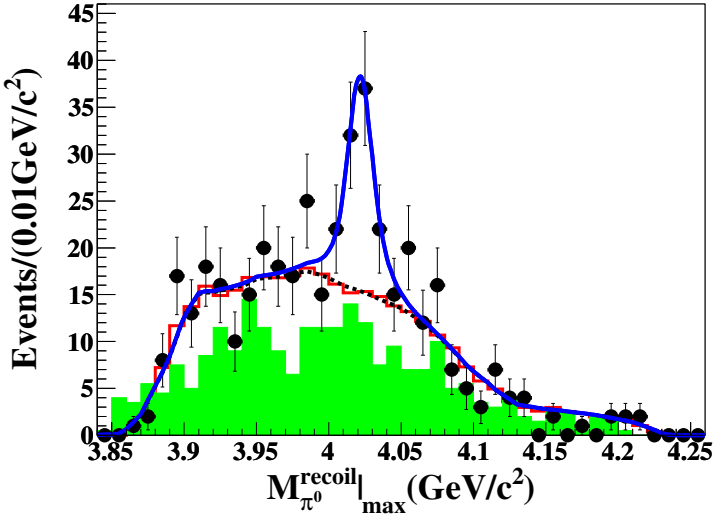
BESIII, PRL **113**, 212002 (2014)



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 $Z_c(4020)^+$



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

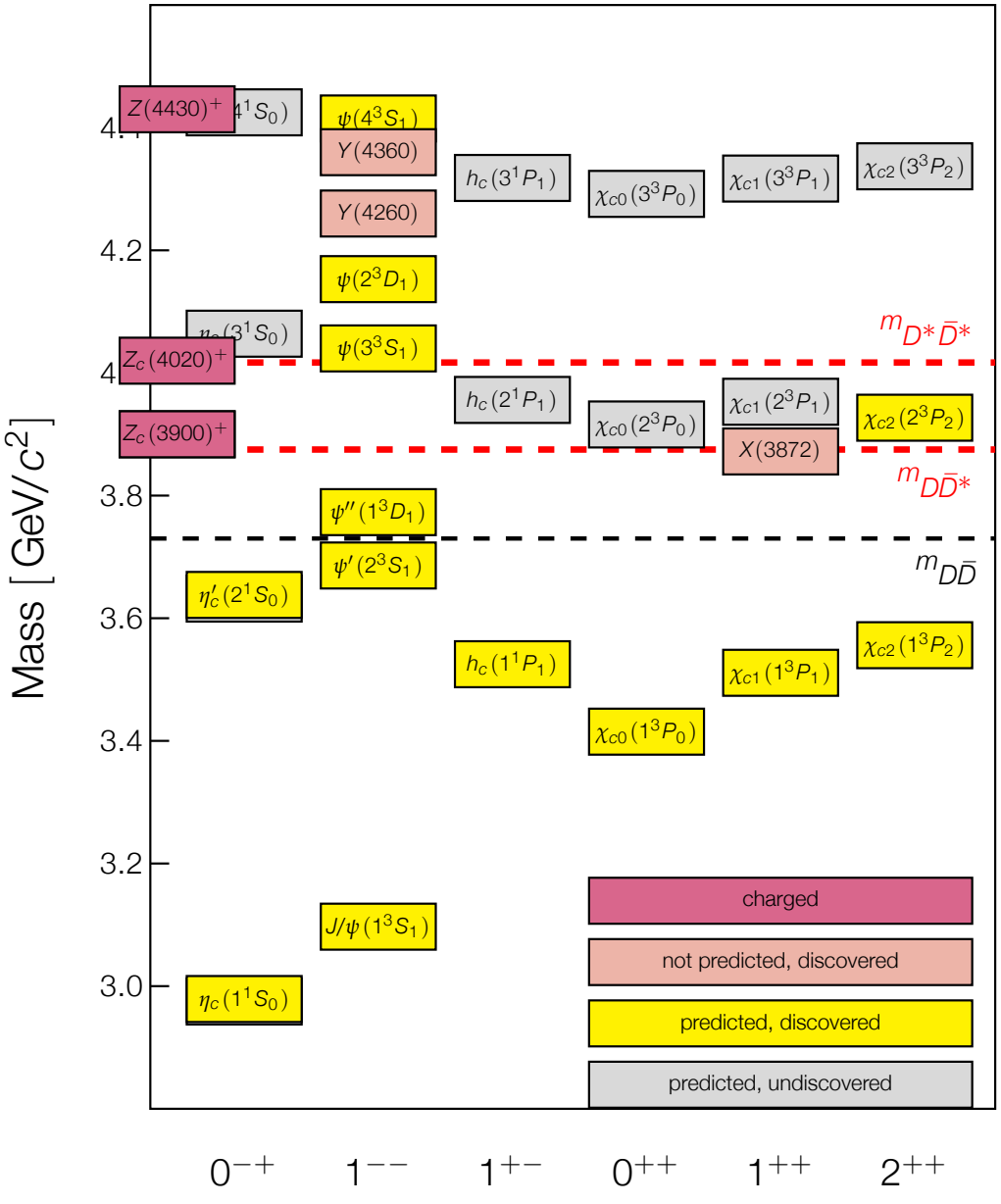
Γ fixed in the fit

Isospin triplet found!

Yet another mass threshold …

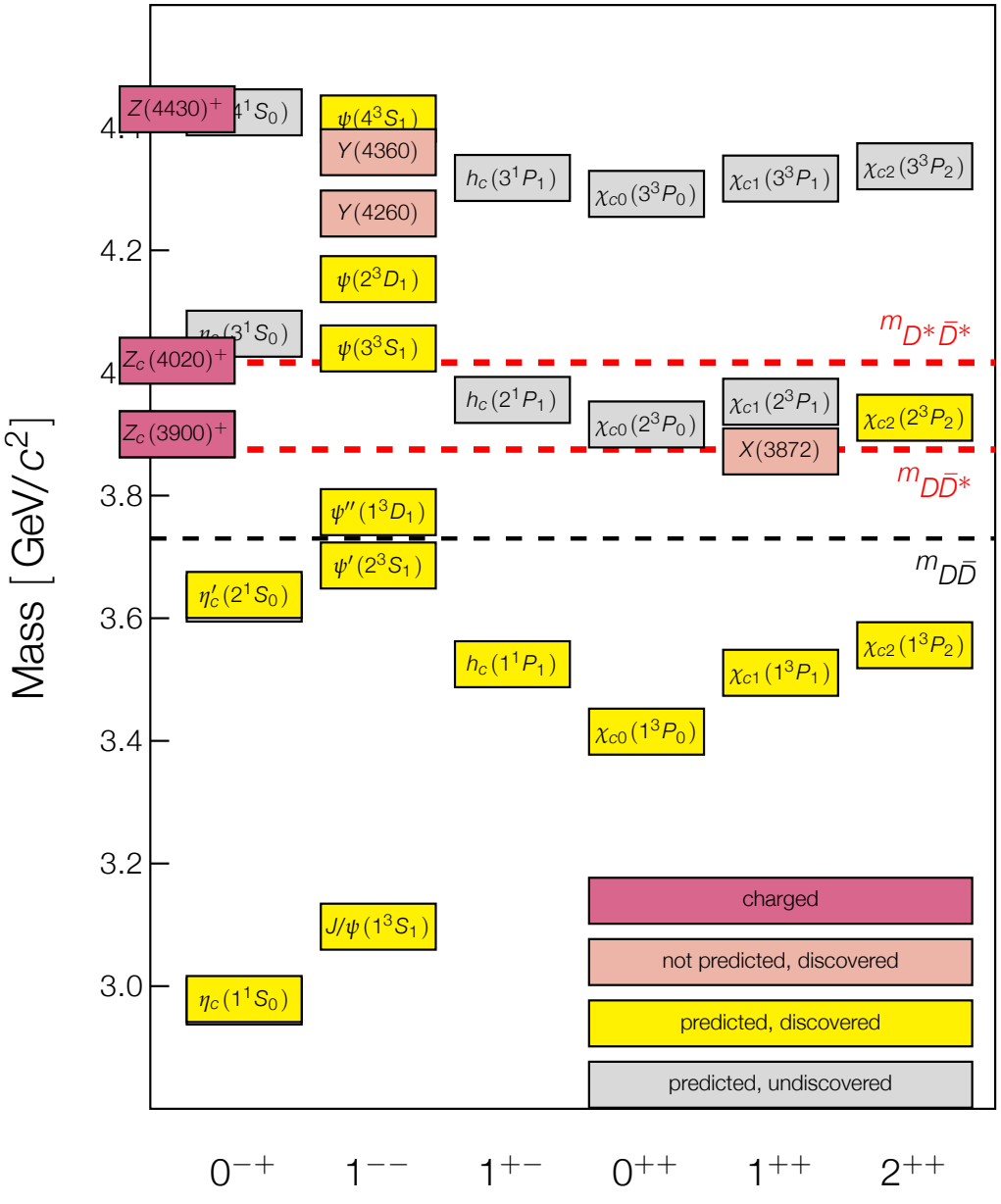
BESIII, PRL **112**, 132001 (2014)

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



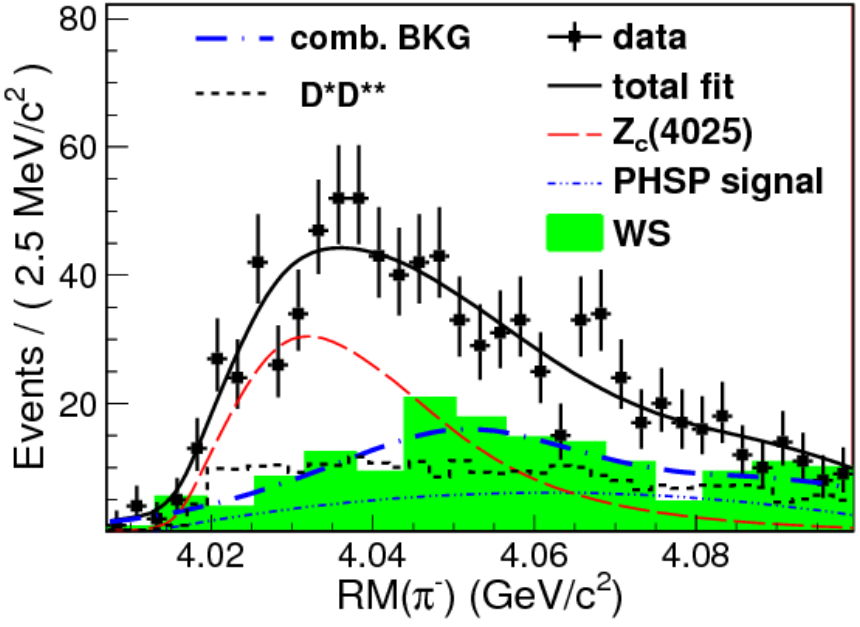
Yet another mass threshold …

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



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

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

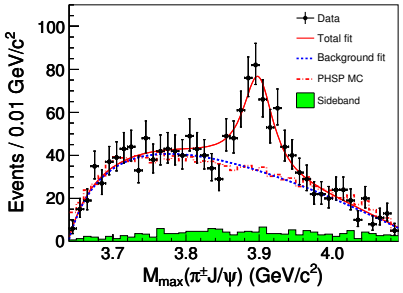


…and BESIII sees structure in D^*D^*

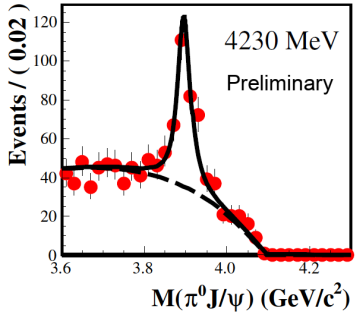
$$M = 4026.3 \pm 2.6 \pm 3.7\,\text{MeV}/c^2$$

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

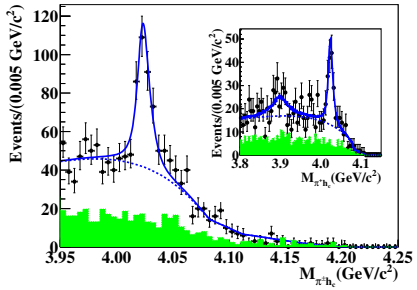
All the Z_cs from BESIII near $\sqrt{s} = 4.3\,\text{GeV}$



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



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



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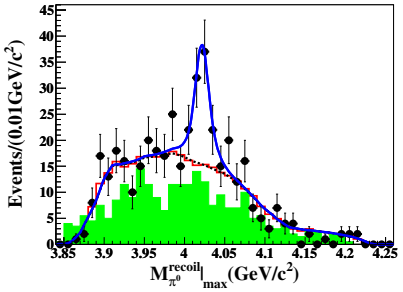

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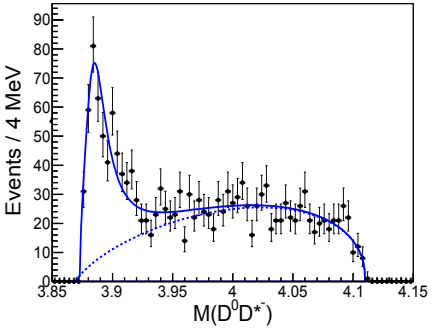
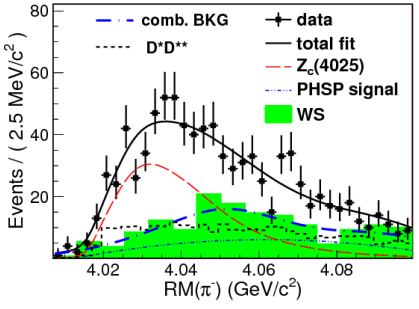


$e^+e^- \to \pi^-(D\bar{D}^*)^+$



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

$Z_c(3900)^+$?

$Z_c(3900)^0$?

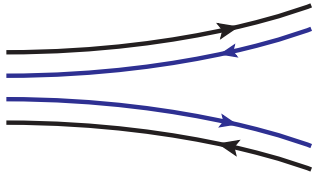
$Z_c(4020)^+$?

$Z_c(4020)^0$?

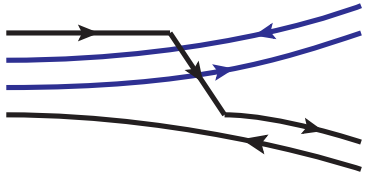
Nature of these states? Isospin triplets?
Different decay channels of the same states observed?
Other decay modes?

Other decay modes? Search for $Z_c(3900)^+ \to \omega\pi^+$

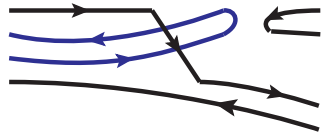
Exploring new decay modes crucial to identify nature of structures close to threshold



open charm



hidden charm



light mesons

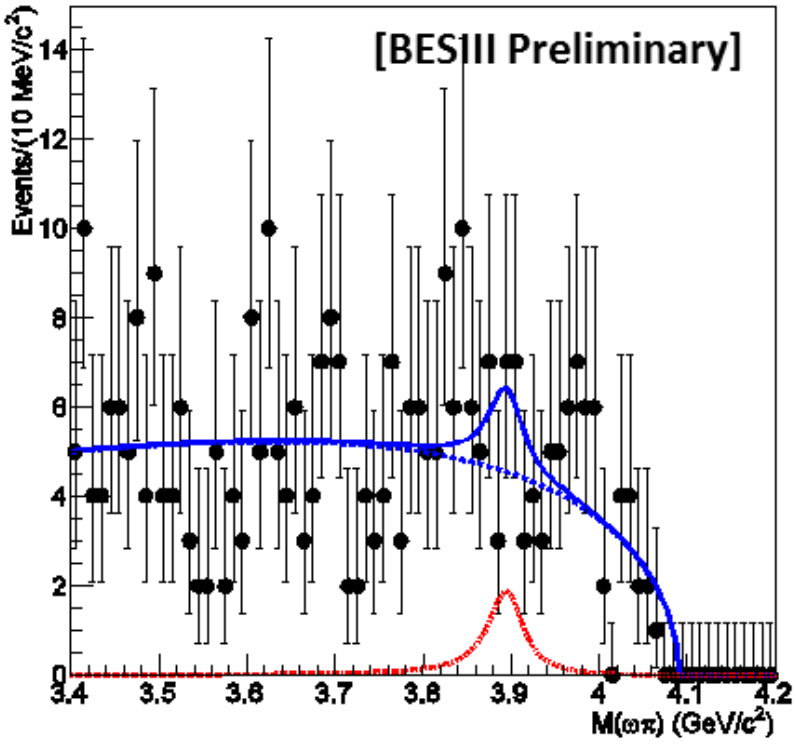
threshold effects!

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

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

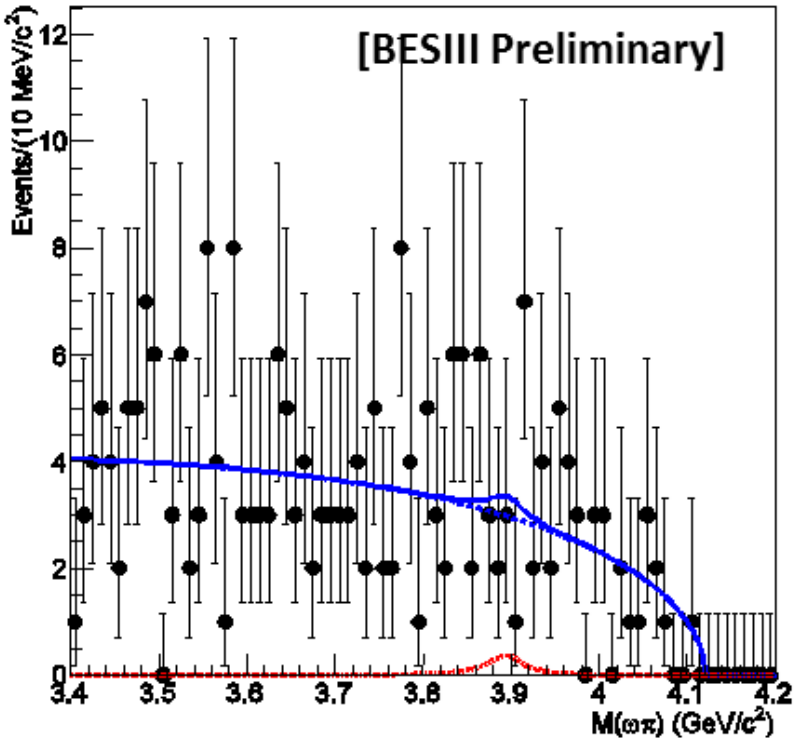
BESIII preliminary

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



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

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



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

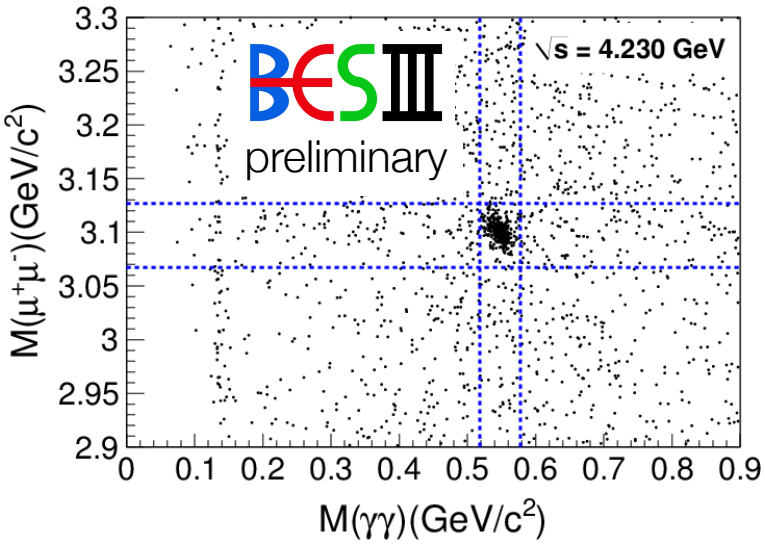
Compared to sum of $Z_c^+ \to J/\psi\,\pi^+$ and $Z_c^+ \to (D\bar{D}^*)^+$:

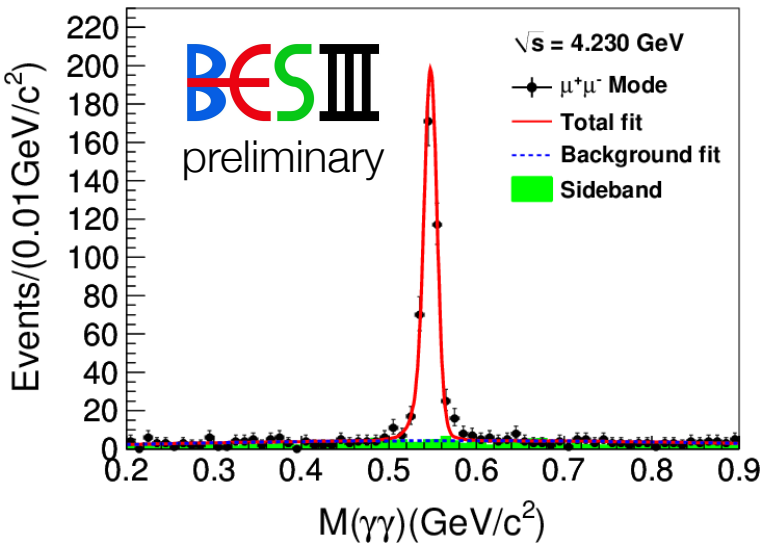
$$\Gamma(Z_c^+ \to \omega\pi^+) < 0.2\%\Gamma_{\text{tot}}$$

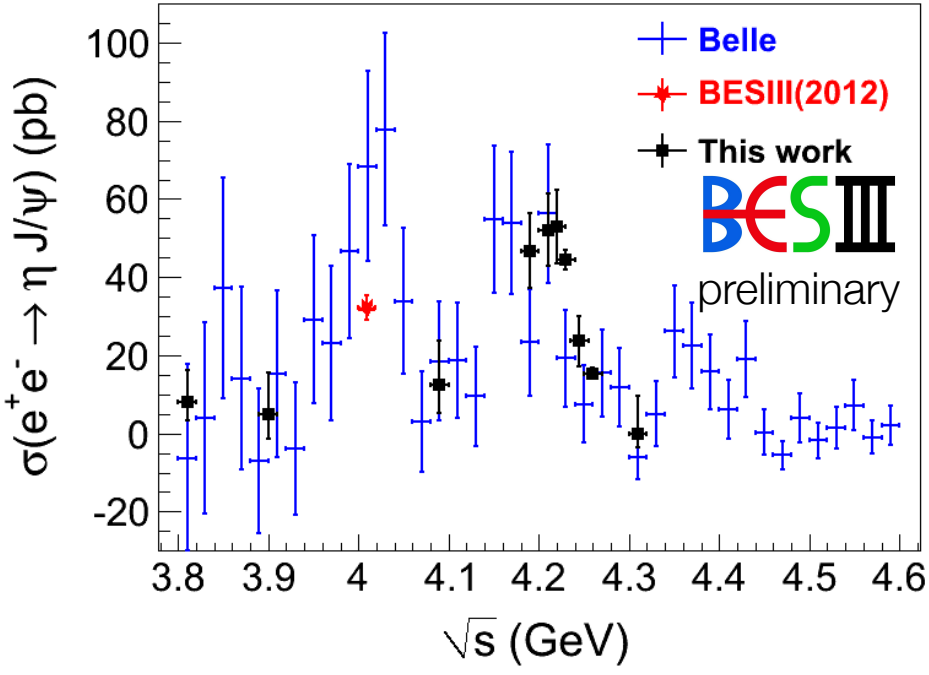
JG|U

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

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)

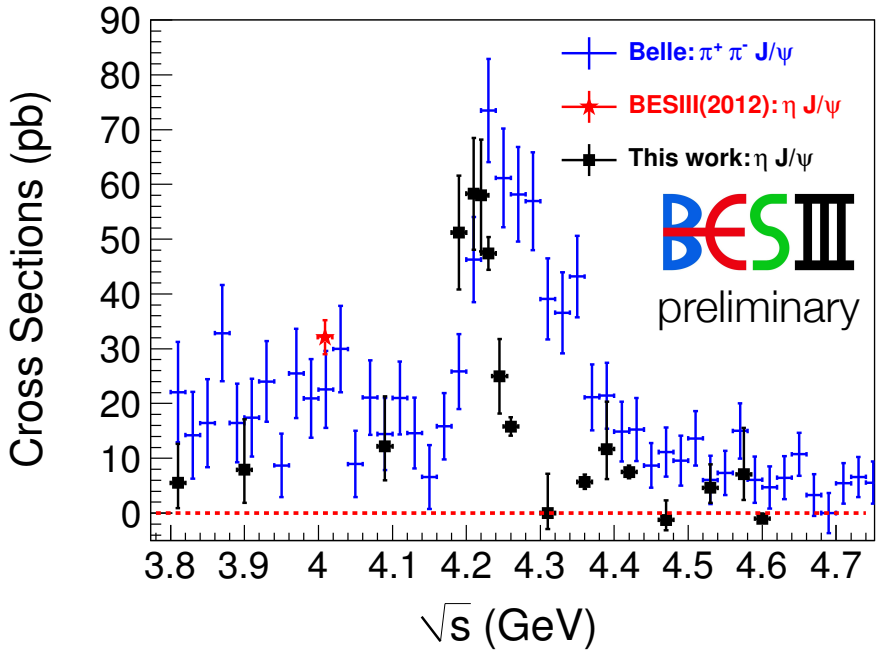
Good agreement,
significantly better precision

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]



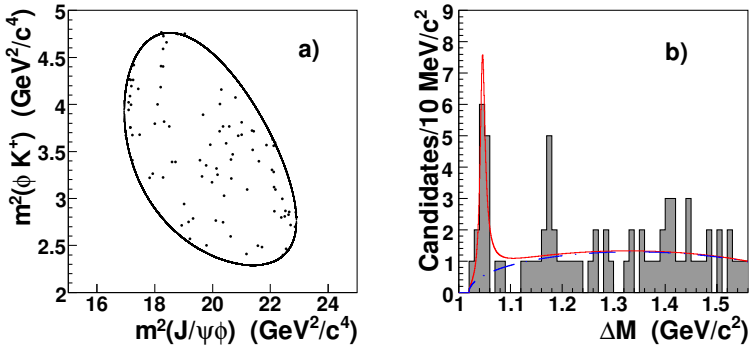
Compare to $e^+e^- \to \gamma_{ISR}\pi^+\pi^- J/\psi$ from
Belle, Phys. Rev. Lett. **110**, 252002 (2013)

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 (see G. Wormser's talk on Tuesday)

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

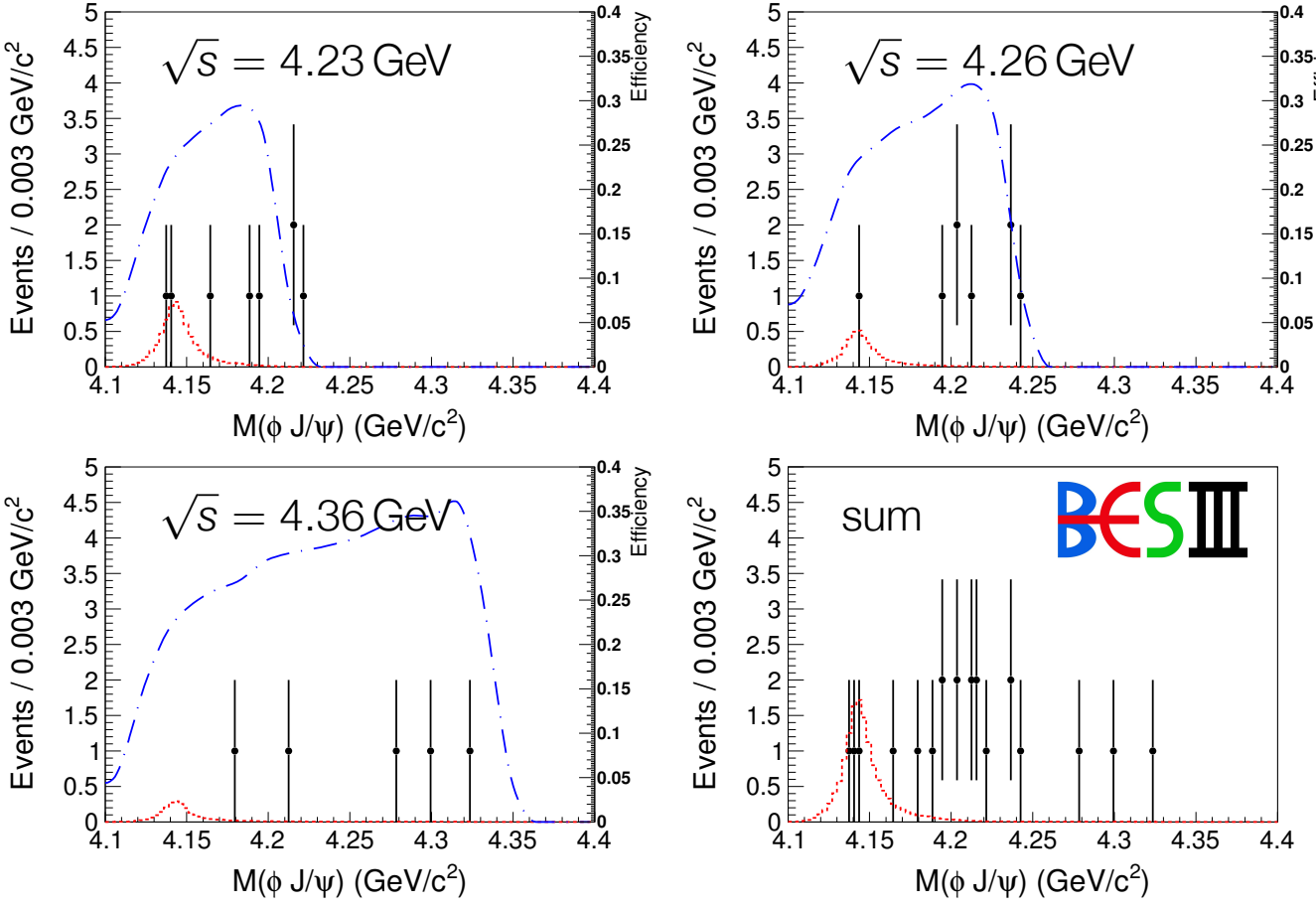
BESIII, PRD **91**, 032002 (2015)

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
$\sigma \times \mathcal{B}(X(3872))$ / pb	0.27 ± 0.09	0.33 ± 0.12	0.11 ± 0.09
$\sigma \times \mathcal{B}(Y(4140))$ / pb	< 0.35	< 0.28	< 0.33

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

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

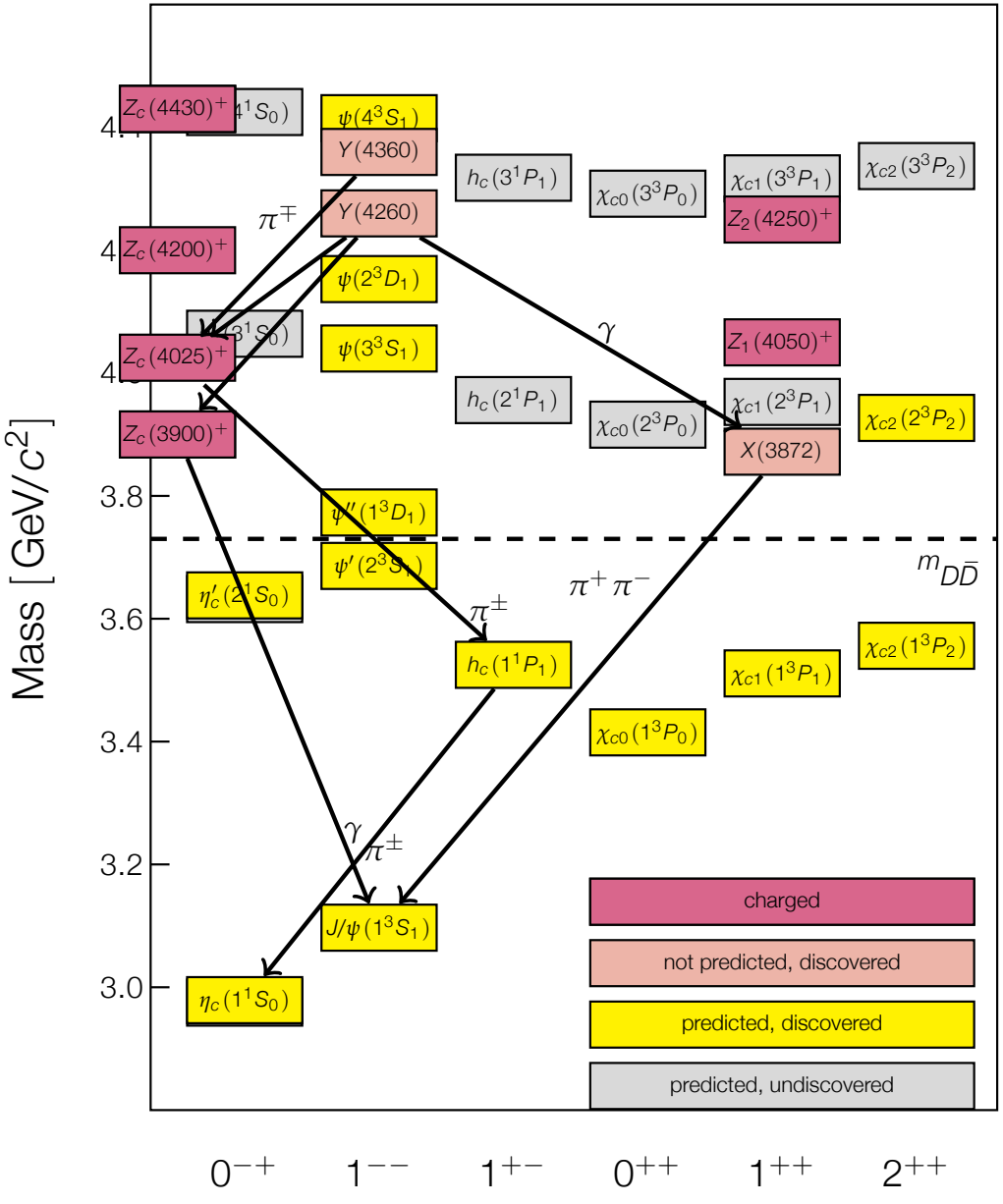
Even more surprises

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

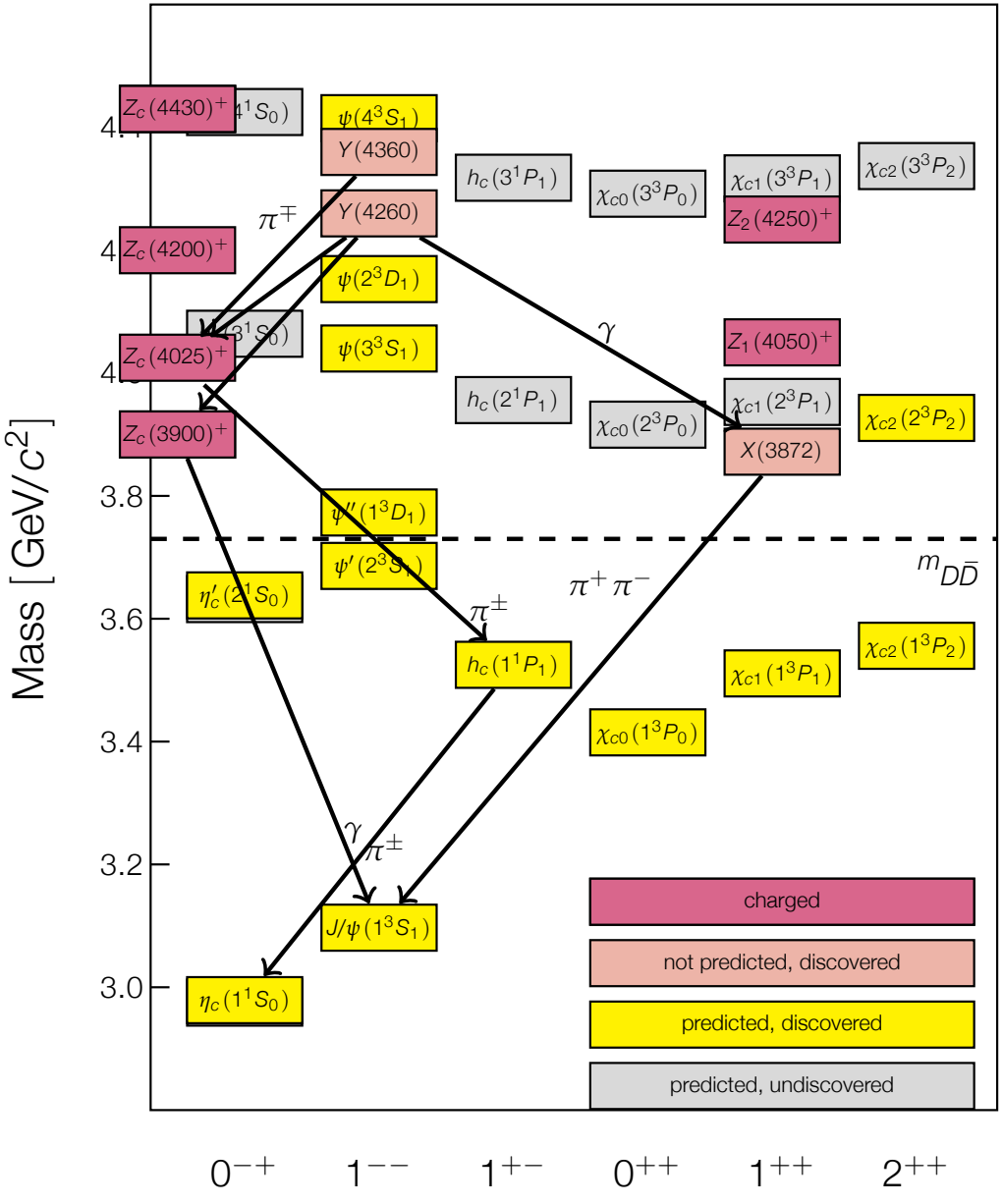


- Quark model describes charmonium states $c\bar{c}$ reasonably well
- *XYZ* states: unexpected, point to non-conventional states ($c\bar{c}g$, $cq\bar{q}\bar{c}$, $(\bar{c}q)(\bar{q}c)$, $c\bar{c}\pi\pi$ …)
- Observation of transitions between *XYZ* states

➡ Start making connections between new, exotic states

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

Summary



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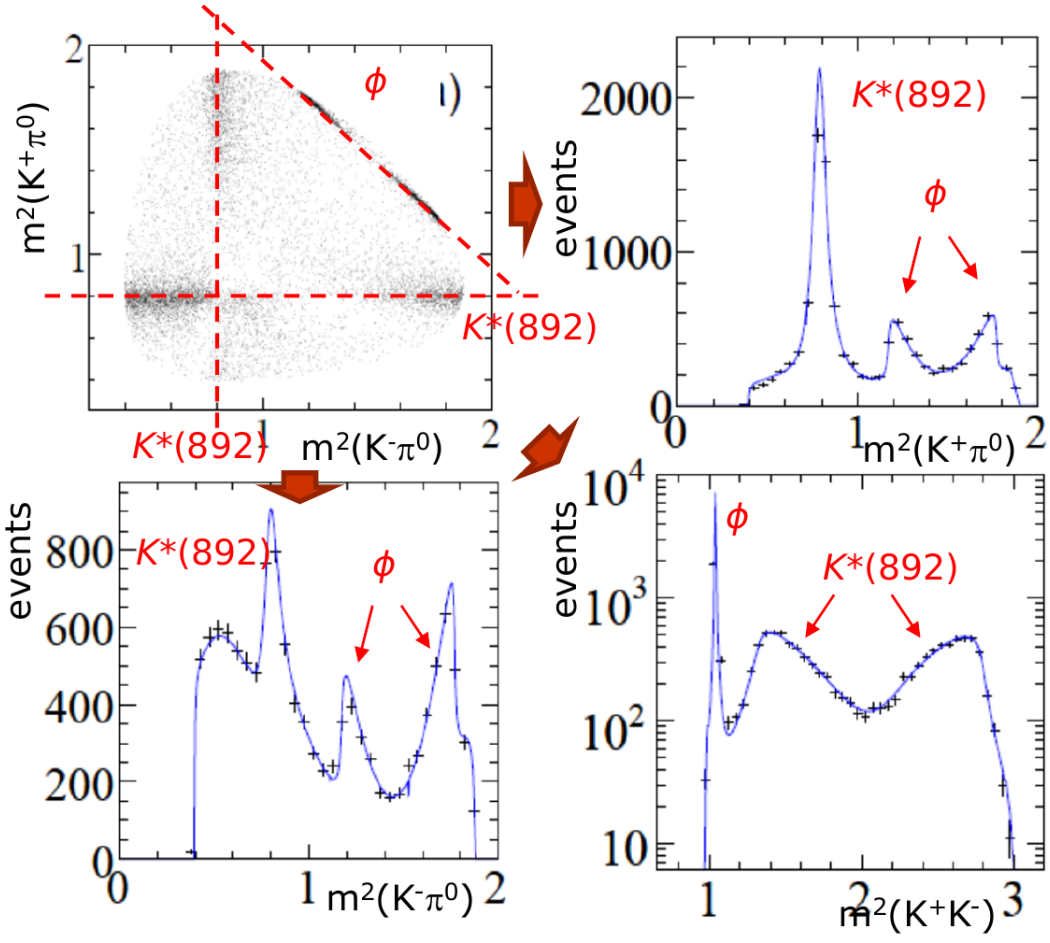
Kinematic reflections

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

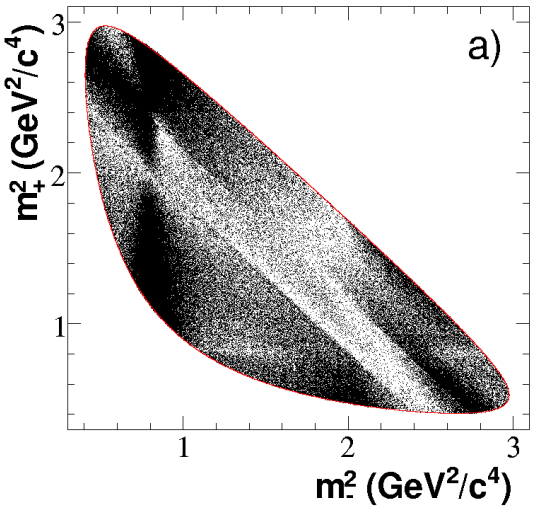
For example $D^0 \to K^+K^-\pi^0$: relatively easy to understand



Kinematic reflections

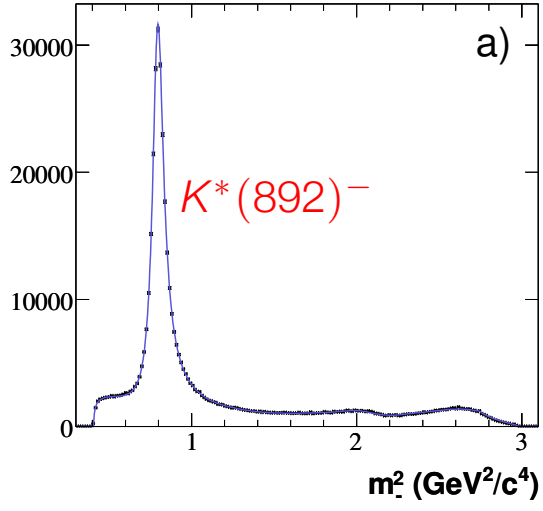
But can be much less obvious

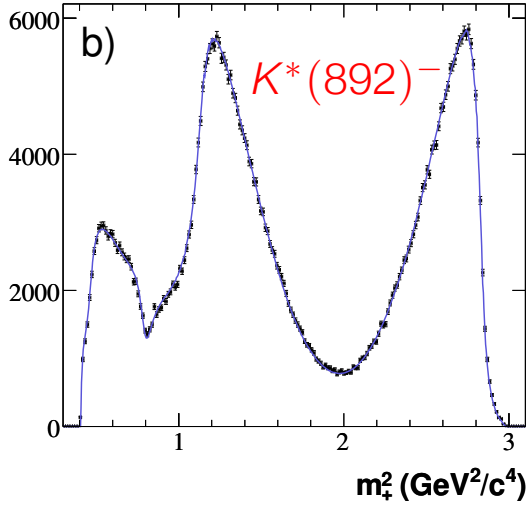
Example: high-statistics analysis of decay $D^0 \to K^0_S \pi^+ \pi^-$ BABAR, PRD78,034023 (2008)

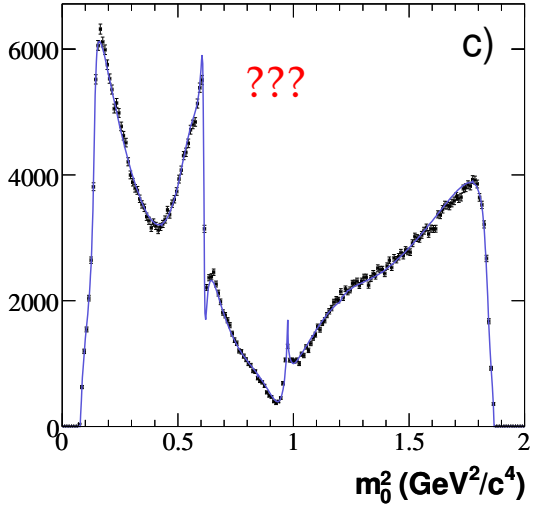


$$\mathcal{A}_D(m^2_-, m^2_+) = \sum_r a_r e^{i\phi_r} \mathcal{A}_r(m^2_-, m^2_+) + a_{\rm NR} e^{i\phi_{\rm NR}}$$

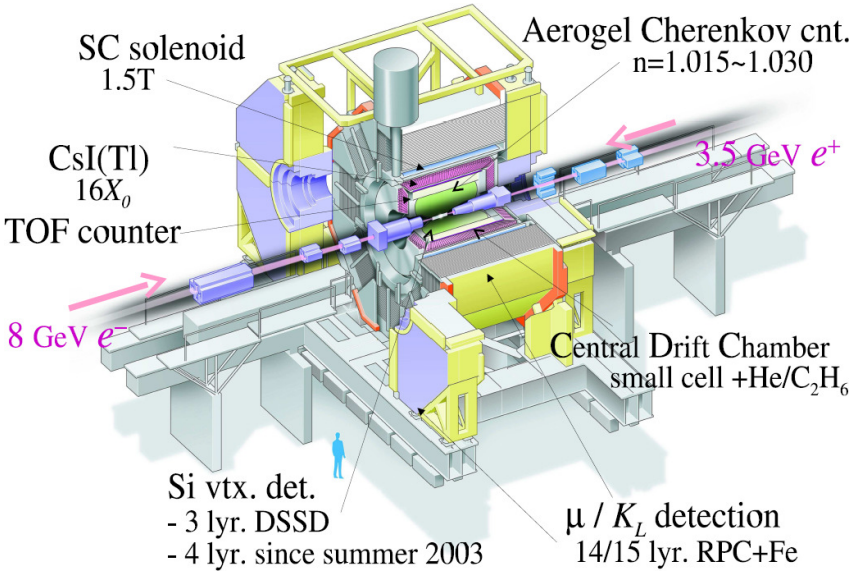
Using 10 resonant amplitudes

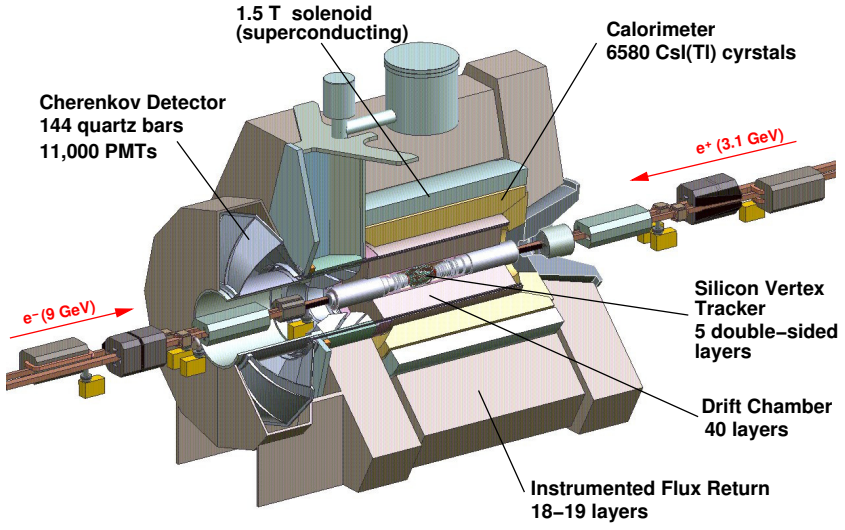






The B factories Belle and BABAR





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

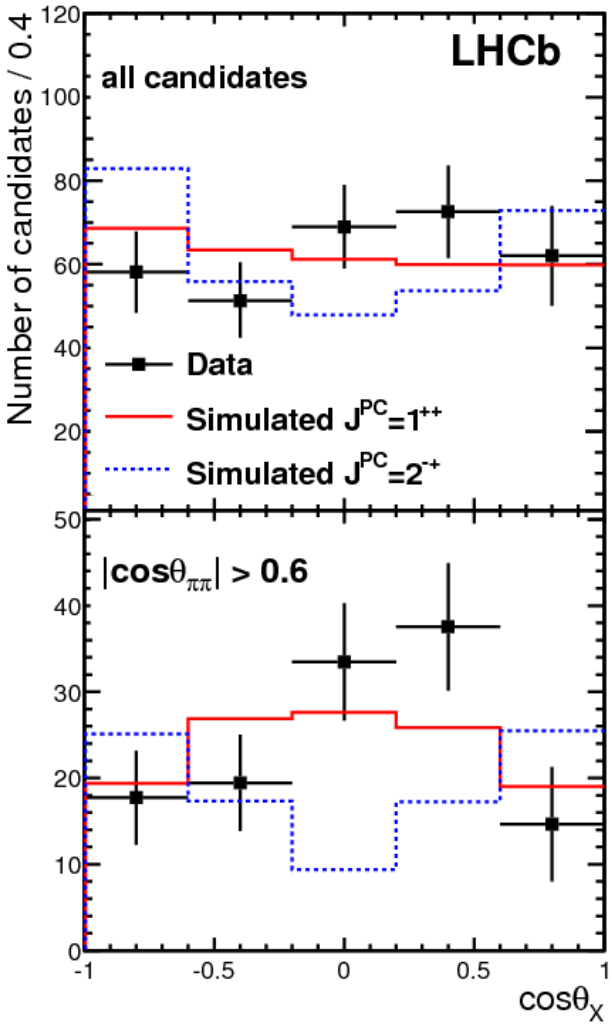
- KEK-B: 8 GeV e^- × 3.5 GeV e^+
- $\mathcal{L}_{\text{int}} \approx 1\,\text{ab}^{-1}$
- Data taking finished 2010

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

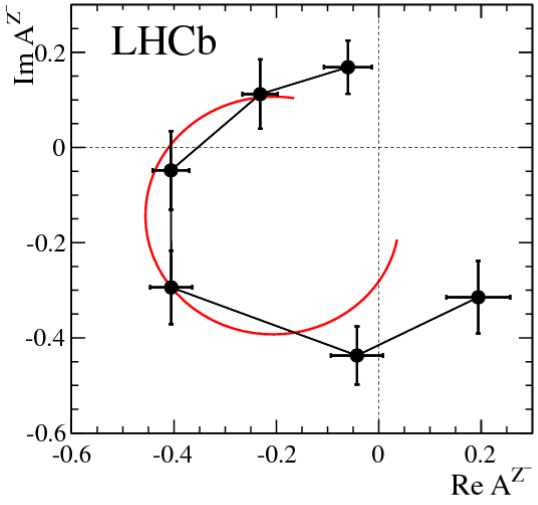
The $Z_c(4430)^+$ in $B^0 \to \psi' K^+ \pi^-$

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

Spin-Parity assignment



Phase motion



behaves like a ‘true’ resonance

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