Experimental results from BESIII

Wolfgang Gradl

on behalf of the BESIII collaboration

INT Workshop on Modern Exotic Hadrons
Seattle, 3rd November 2015

THE LOW-ENERGY FRONTIER OF THE STANDARD MODEL

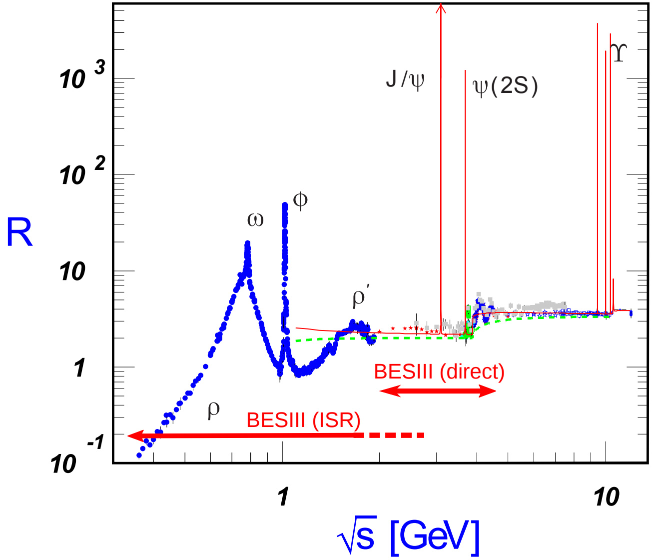
JOHANNES GUTENBERG UNIVERSITÄT MAINZ

PRISMA

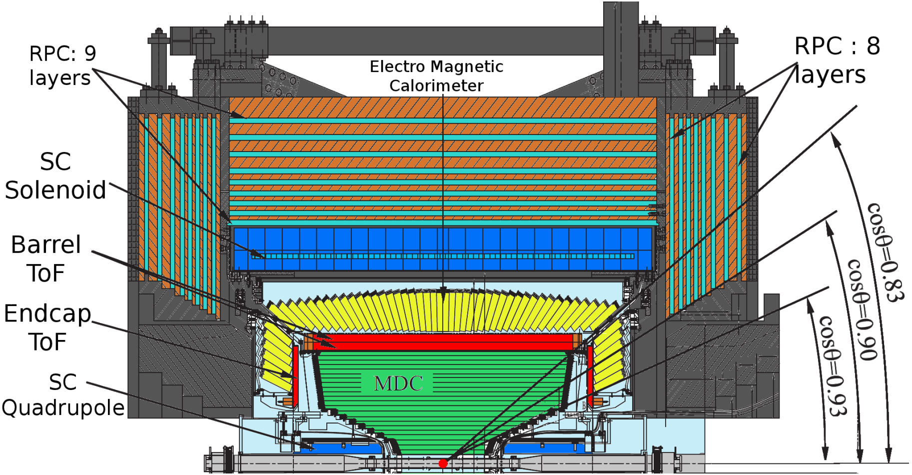
BESIII: a τ-charm factory

BEPCII and BESIII

A τ-charm factory



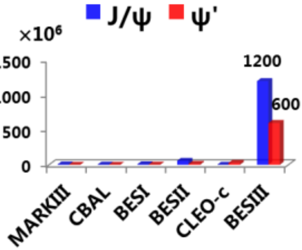
BESIII detector

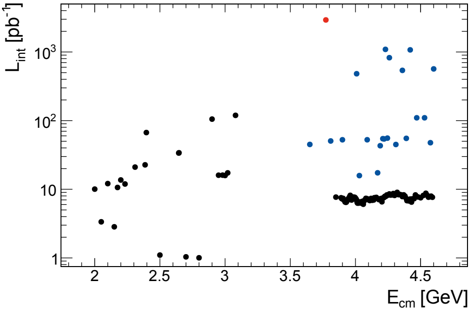


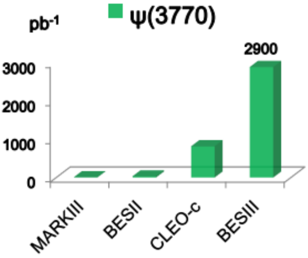
Completely new detector

Comparable performance to CLEO-c, + muon ID

Unique BESIII data set





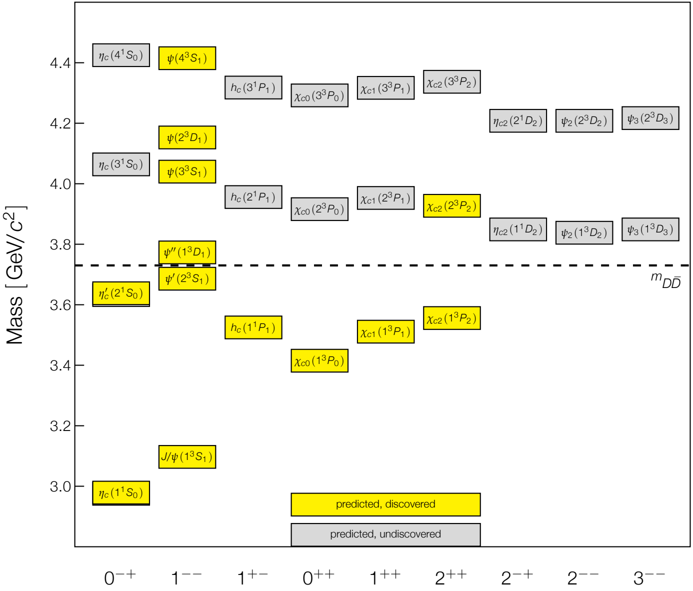


large data sets of $\approx 4\ \text{fb}^{-1}$ above 3.8 GeV for XYZ studies
+ 104 energy points between 3.85 and 4.59 GeV (*R* scan)
+ $\sim$ 20 energy points between 2.0 and 3.1 GeV

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

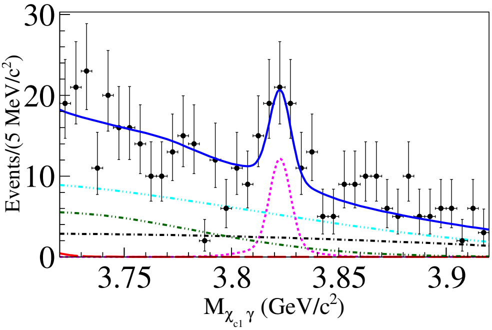
Conventional $c\bar{c}$ states

Higher charmonium states



The $X(3823)$ at Belle

PRL **111**, 032001 (2013)



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

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

3.8σ evidence

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

very narrow

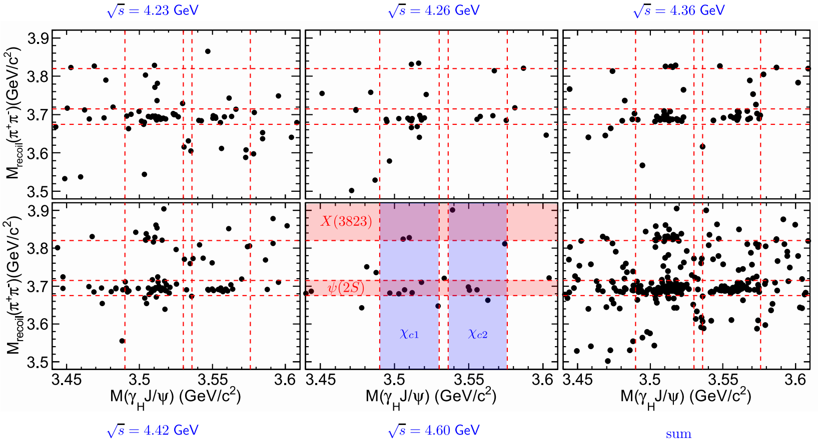
Mass (and width) compatible with $\psi_2(1^3D_2)$ state

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

PRL **115**, 011803

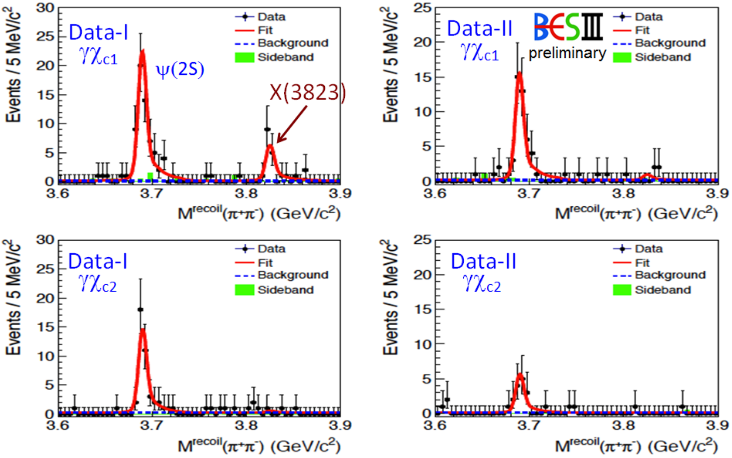
reconstruct $\chi_{c1,2} \to \gamma J/\psi \to \gamma\ell^+\ell^-$
look in mass recoiling against $\pi^+\pi^-$ system, $M_{\mathrm{recoil}}(\pi^+\pi^-)$

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



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

$\sqrt{s} \geq 4.36\,\text{GeV}$ $\sqrt{s} = 4.23, 4.26\,\text{GeV}$ PRL **115**, 011803



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

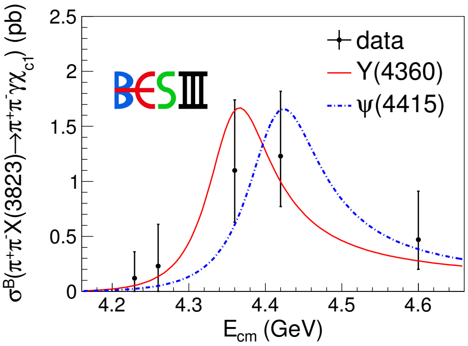
$\Gamma < 16\,\text{MeV}$ at 90% C.L.

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

PRL **115**, 011803

Energy-dependent cross section for

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



$Y(4360)$ and $\psi(4415)$ line shapes to guide the eye

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

Production ratio

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

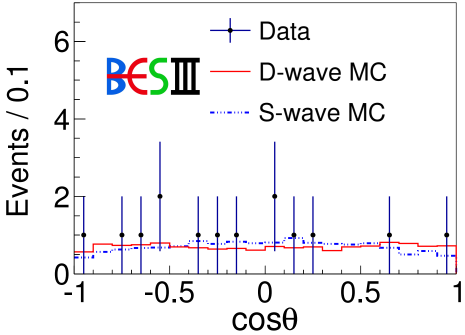
~ 0.2 prediction

< 0.43 at 90% C.L.

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

PRL **115**, 011803

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



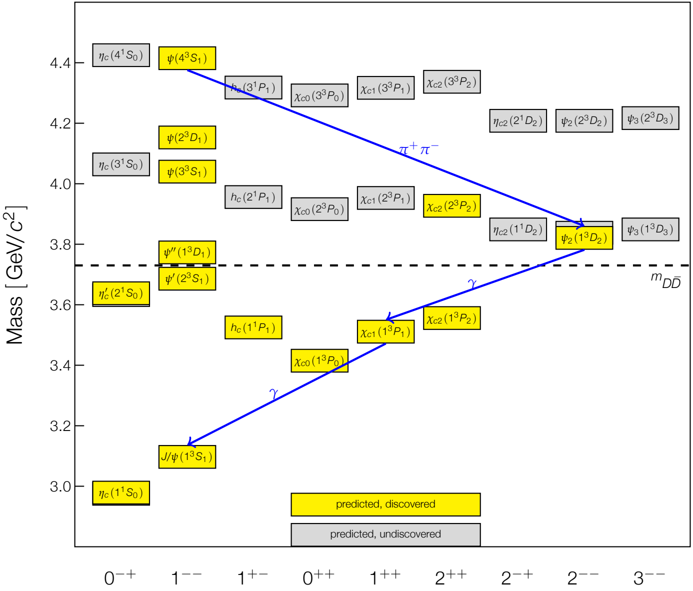
Mass and width $\sim$ in agreement with potential model prediction for 1^3D_2
predicted to be narrow!

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

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

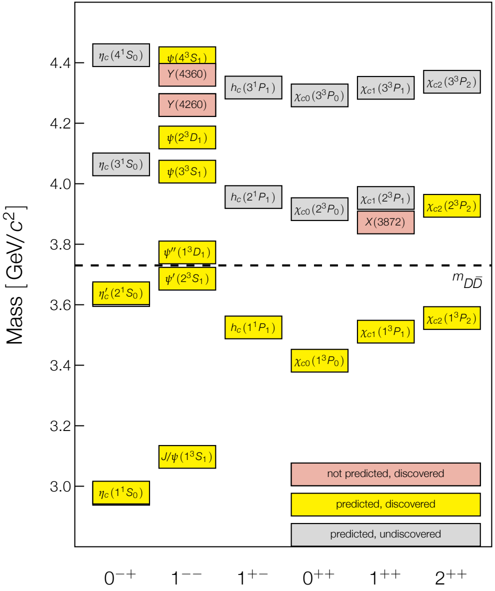
Not enough statistics to distinguish S and D wave from data

Higher charmonium states — a new family member!




Exotic states: the *X* and *Y*

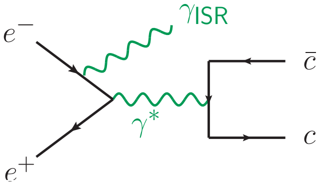
$Y(4260) \to J/\psi\, \pi^+\pi^-$



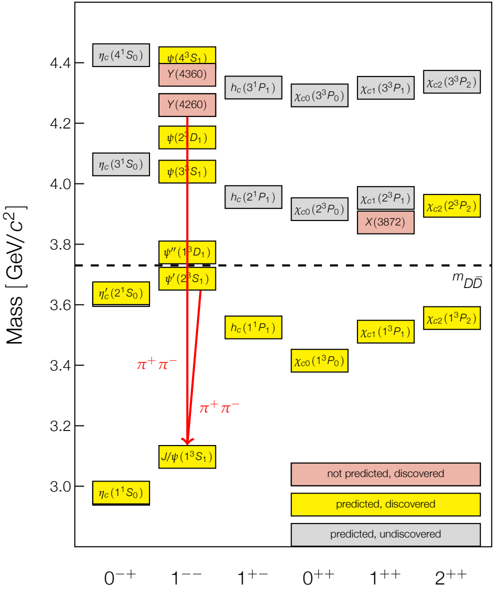
e^+e^- collisions near $\Upsilon(4S)$

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

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



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



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

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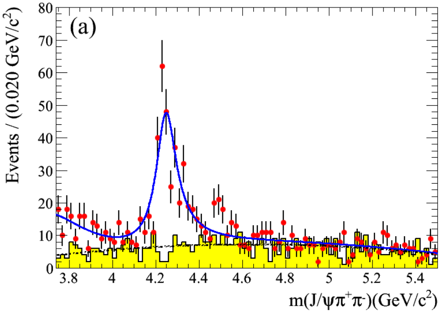
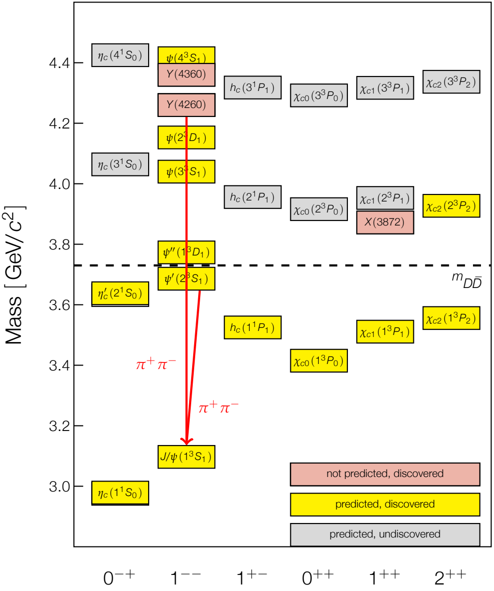
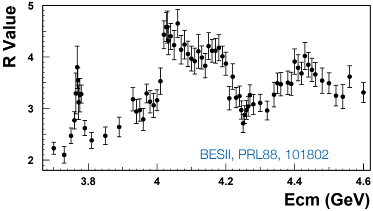


BABAR, PRD 86, 051102(R) (2012)

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



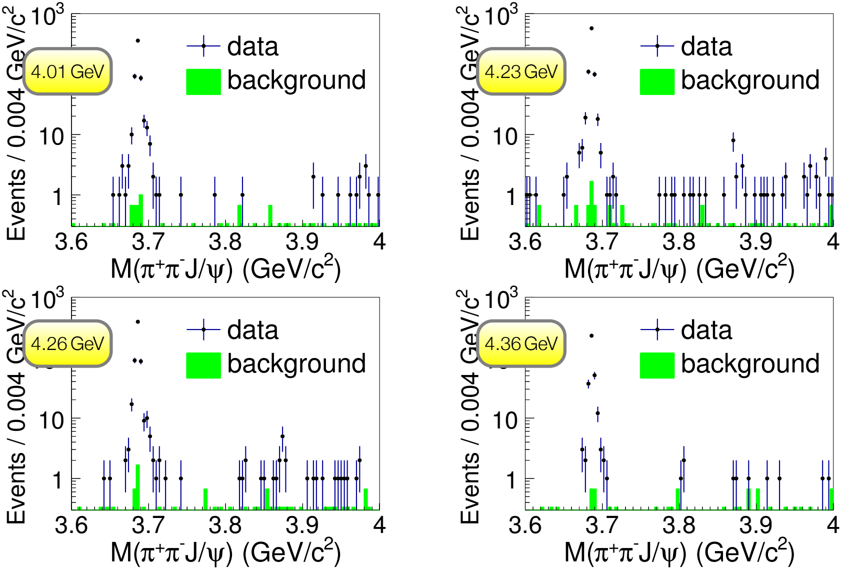
- … $Y(4260) \to J/\psi\,\pi^+\pi^-$
- … $Y(4360) \to \psi(2S)\pi^+\pi^-$
- … additional state at 4660 MeV
- supernumerary states: all 1^{--} slots already taken
- ➡ do not correspond to peaks in $\sigma(e^+e^- \to \text{hadrons})$



- ➡ produce them directly at BESIII!

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

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

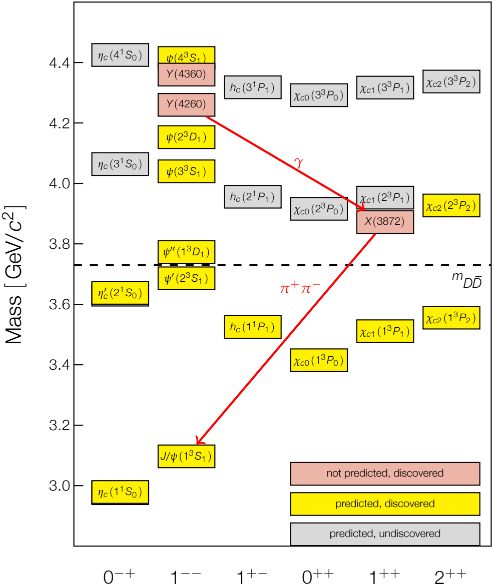


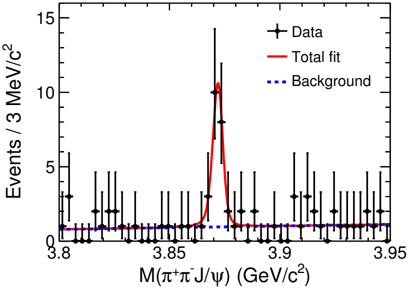
Clear ISR ψ' signal for validation

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

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

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





20.1 ± 4.5 events

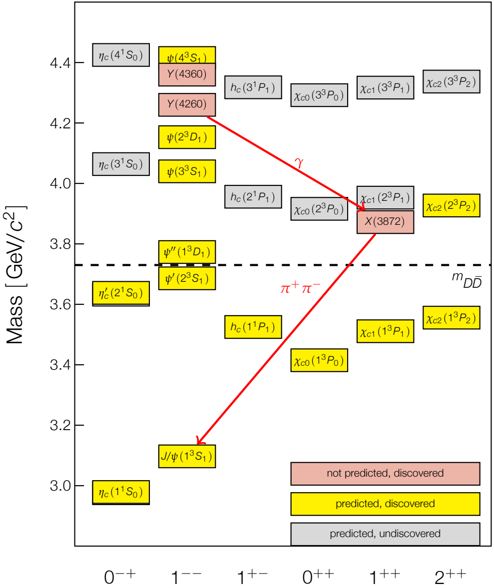
significance 6.3σ

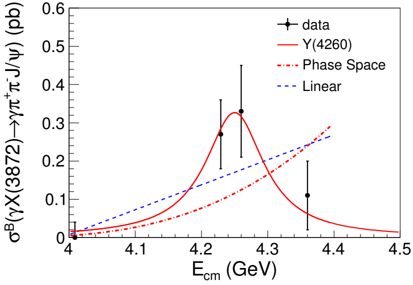
$M = 3871.9 \pm 0.7 \pm 0.2\,\mathrm{MeV}/c^2$

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

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

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





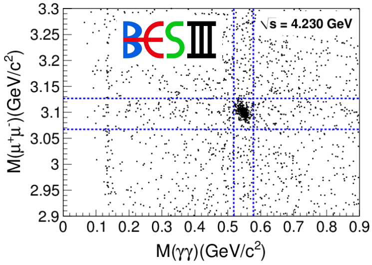
Suggestive of radiative transition
$Y(4260) \to \gamma X(3872)$

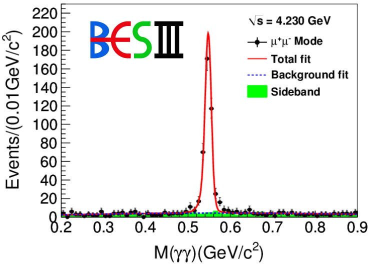
Direct connection between the two states?

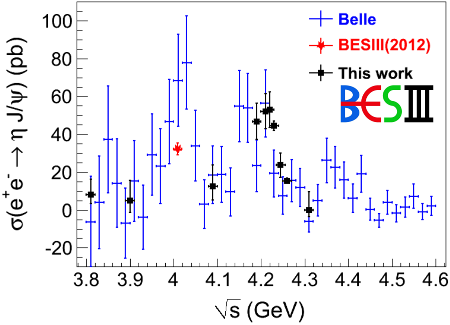
Data at 4.6 GeV to be analysed

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

BESIII, PRD **91**, 112005 (2015)







Compare to $e^+e^- \to \gamma_{\mathrm{ISR}}\eta J/\psi$ from Belle, PRD **87**, 051101(R) (2013)

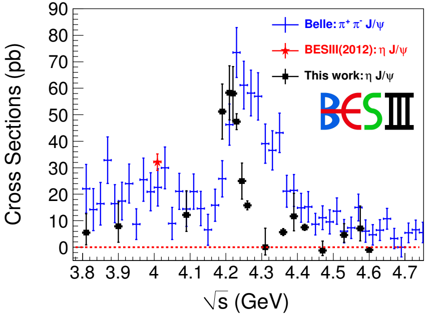
Good agreement,
significantly better precision

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, PRD **91**, 112005 (2015)



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

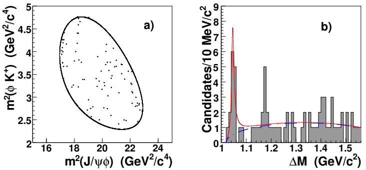
Very different line shape

➡ 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

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



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

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

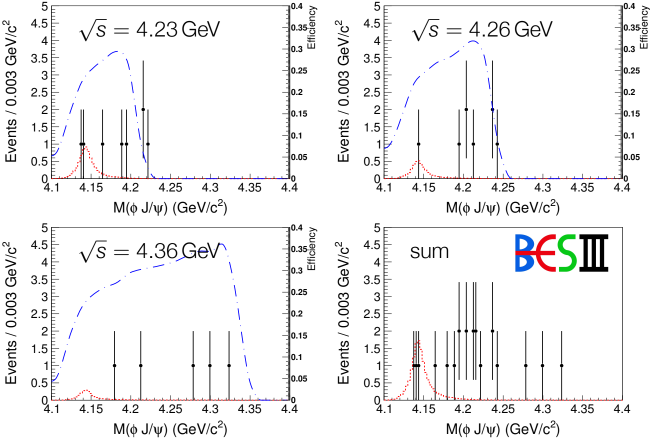
If both $Y(4260)$ and $Y(4140)$ are *charmonium hybrids*:
partial width of $Y(4260) \to \gamma Y(4140)$ may be up to several tens of keV
N. Mahajan, PLB **679**, 228 (2009)

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)

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



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

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

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

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

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

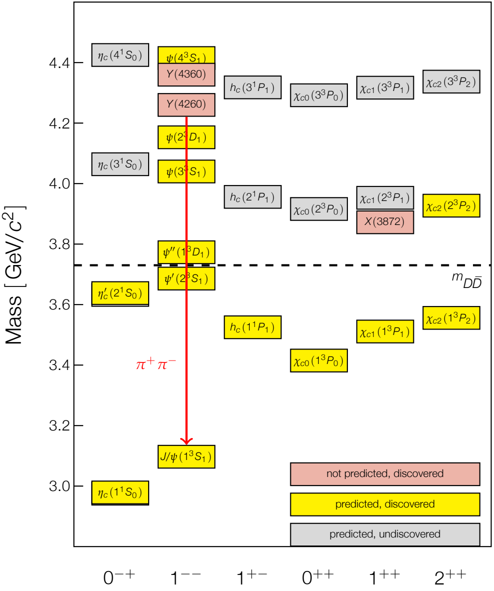
Assuming $\mathcal{B}(Y(4140) \to J/\psi\,\phi) \sim 30\%$ and $\mathcal{B}(X(3872) \to J/\psi\,\pi^+\pi^-) \sim 5\%$:

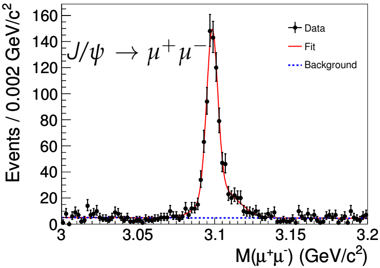
$$\frac{\sigma[e^+e^- \to \gamma Y(4140)]}{\sigma[e^+e^- \to \gamma X(3872)]} < 0.1 \quad \text{at } 4.23,\ 4.26\ \text{GeV}$$

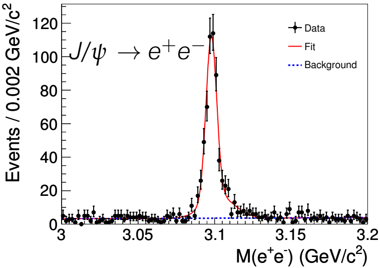
The Z_c family

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

BESIII, PRL **110**, 252001 (2013)
525 pb^{-1} at 4.26 GeV



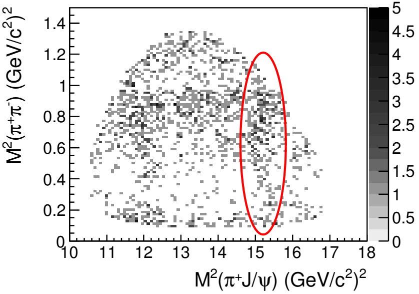


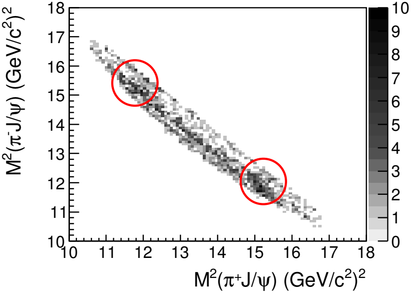


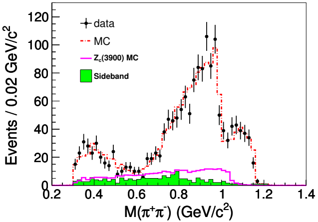
…have hundreds of events!

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

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



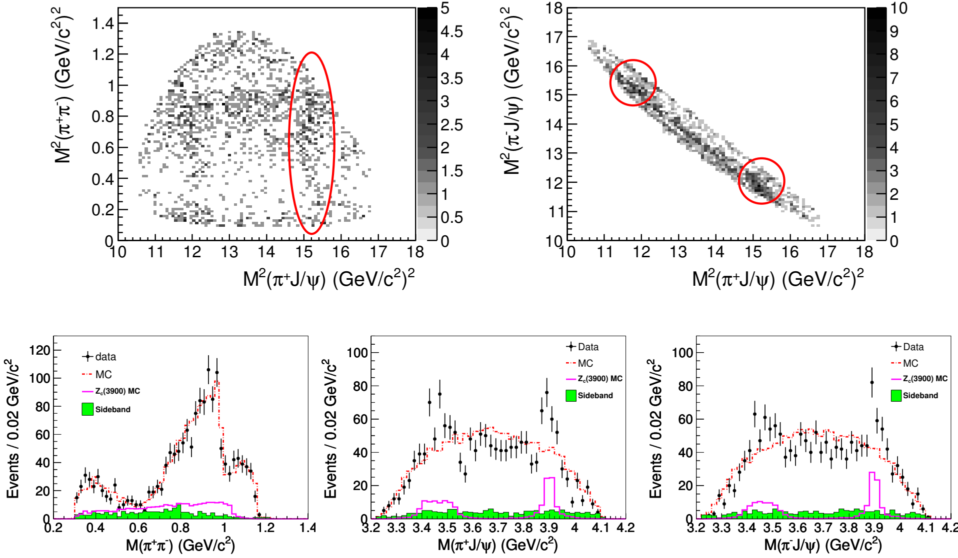




Model $\pi^+\pi^-$-system with known structure:
$f_0(500)$, $f_0(980)$, non-resonant
obtain good fit of $\pi^+\pi^-$ mass projection

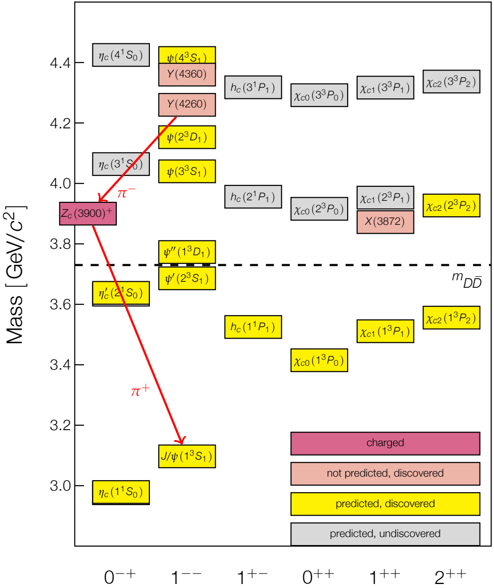
$J/\psi\,\pi^+\pi^-$ Dalitz plot

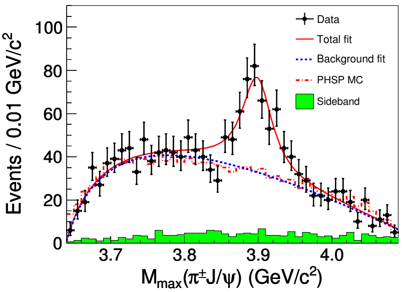
BESIII, PRL **110**, 252001 (2013)



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

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





Charged charmonium-like structure

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

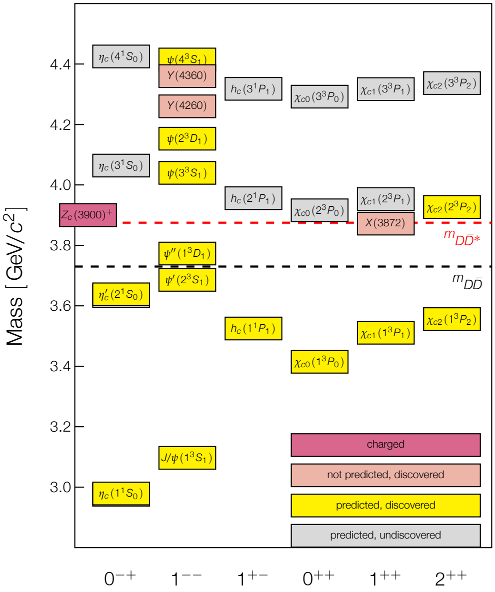
$$\Gamma = (46 \pm 10 \pm 20)\ \mathrm{MeV}$$

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

Close to DD^* threshold
Interpretation?

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

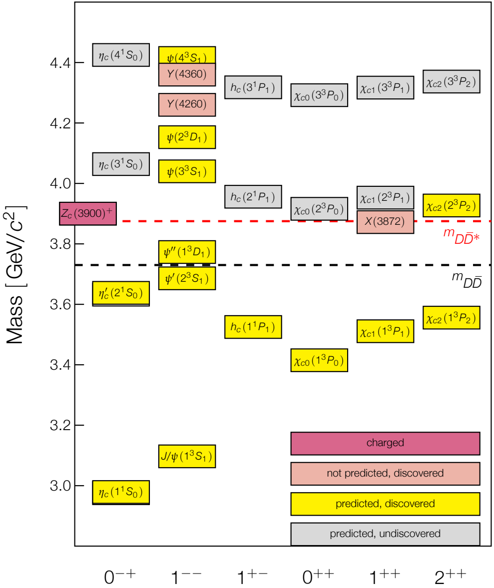
BESIII, PRL **112**, 022001 (2014)



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

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

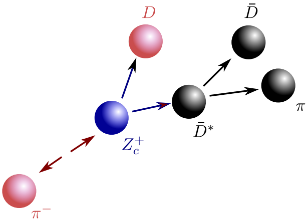
BESIII, PRL **112**, 022001 (2014)



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

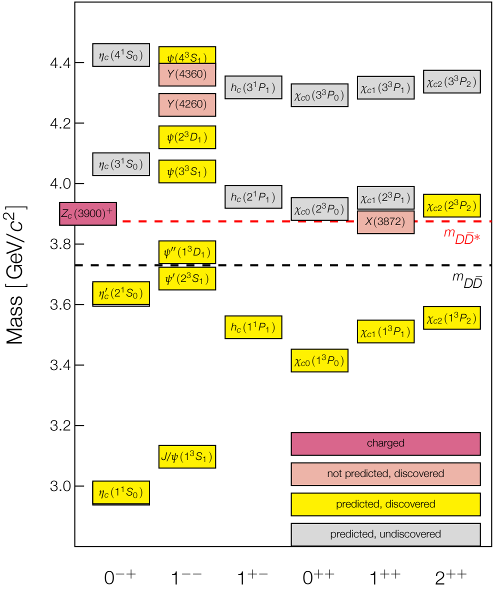
Single tag analysis:

- 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^+



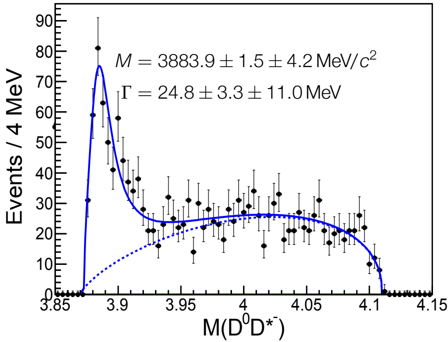
$Z_c(3900)^+$ at $D\bar{D}^*$ threshold

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



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

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



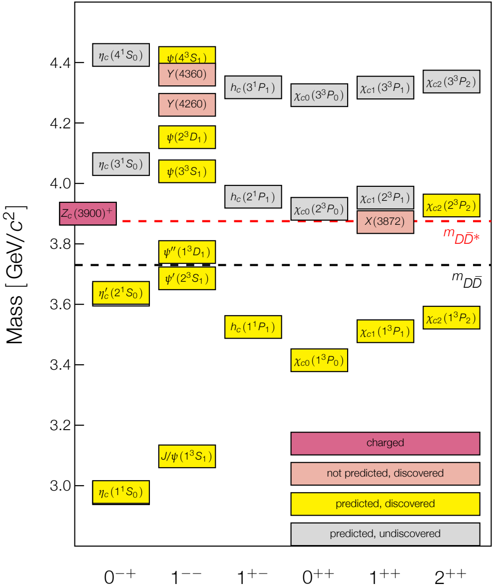
…see structure close to $(DD^*)^\pm$ threshold

Large systematics due to non-Z_c signal shape

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

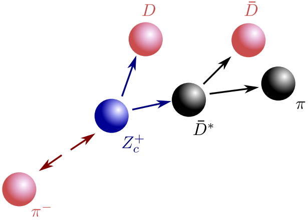
$Z_c(3900)^+$ at $D\bar{D}^*$ threshold

1509.01398



New: Double tag analysis

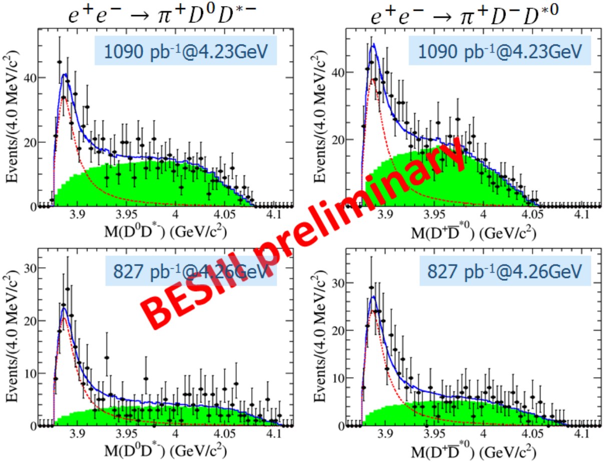
- reconstruct 'bachelor' π^+ and D^0, D^- in 4 or 6 decay modes
- kinematic fit, requiring π from D^* in missing mass essentially background-free D^*
- improved statistics, much better control over background shape, improved systematics
- $M^{\text{recoil}}(\pi^+) = M(D\bar{D}^*)$



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

BESIII

1509.01398



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

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

$$M = 3881.7 \pm 1.6 \pm 2.6\,\mathrm{MeV}/c^2$$

$$\Gamma = 26.6 \pm 2.0 \pm 2.3\,\mathrm{MeV}$$

JG|U

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

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1509.01398

Single and double tag analyses only share $\sim 9\%$ of events: samples statistically almost independent!

	$M_{\text{pole}}\,[\text{MeV}/c^2]$	$\Gamma_{\text{pole}}\,[\text{MeV}]$
Single *D* tags	$3883.9 \pm 1.5 \pm 4.2$	$24.8 \pm 3.3 \pm 11.0$
Double *D* tags	$3881.7 \pm 1.6 \pm 2.6$	$26.6 \pm 2.0 \pm 2.3$
Combined	$3882.3 \pm 1.1 \pm 1.9$	$26.5 \pm 1.7 \pm 2.3$

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$Z_c(3885)^+$ Quantum numbers?

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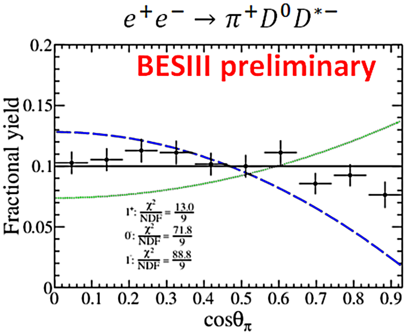
θ_π: angle between bachelor pion and beam axis in CMS
Know initial state is 1^-, with $J_z = \pm 1$. Depending on J^P of Z_c:

- 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: ➡ $\mathrm{d}N/\mathrm{d}\cos\theta_\pi \propto 1$



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

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

BESIII, PRL **115**, 112003 (2015)

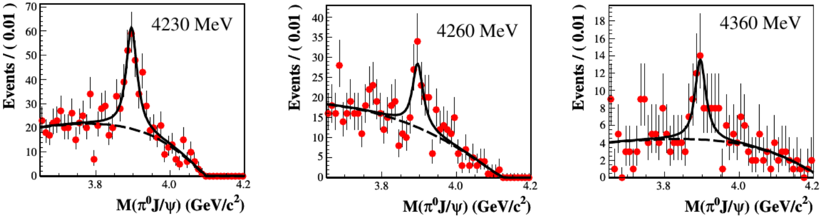
If interpretation of $Z_c(3900)^+$ as four-quark state is correct:
expect state completing isospin triplet, with decay $Z_c(3900)^0 \to \pi^0 J/\psi$

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

BESIII, PRL **115**, 112003 (2015)

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 $\sqrt{s}$

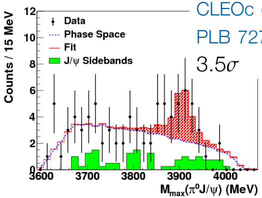


Structure in $\pi^0 J/\psi$ invariant mass clearly visible at all energies

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

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

Significance 10σ



CLEOc data,
PLB 727, 366 (2013)

3.5σ

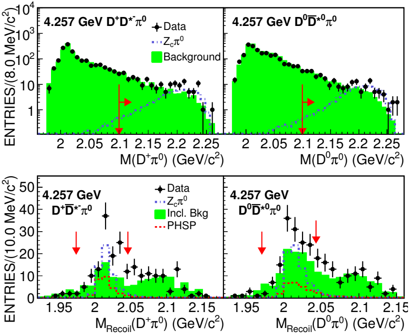
$Z_c(3885)^0$ in $e^+e^- \to (D\bar{D}^*)^0\pi^0$

Partial reconstruction technique:

BESIII preliminary 1509.05620

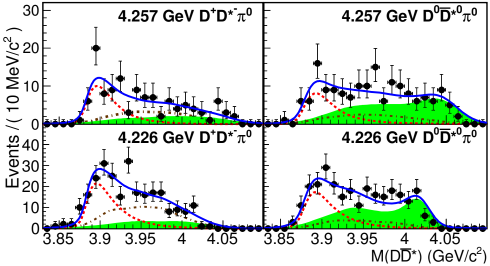
$$e^+e^- \to D^+D^{*-}\pi^0 \to D^+\bar{D}^0\pi^-\pi^0$$
$$e^+e^- \to D^0\bar{D}^{*0}\pi^0 \to D^0\bar{D}^0\pi^0\pi^0$$

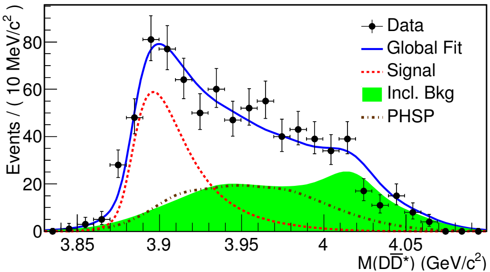
1. Reconstruct bachelor π^0
2. Reconstruct D^+ ($\bar{D}^0$) in one of five (three) hadronic decay modes
3. Infer presence of $\bar{D}^*$ by recoil mass



$Z_c(3885)^0$ in $e^+e^- \to (D\bar{D}^*)^0\pi^0$

BESIII
preliminary
1509.05620





Simultaneous fit to both charge combinations in two large datasets at $\sqrt{s} = 4.226$ and 4.257 GeV

Significance $> 10\sigma$

Pole parameters of rel. BW:

$$M = (3885.7^{+4.3}_{-5.7}(\text{stat.}) \pm 8.4(\text{syst.}))\ \text{MeV}/c^2$$

$$\Gamma = (35^{+11}_{-12}(\text{stat.}) \pm 15(\text{syst.}))\ \text{MeV}$$

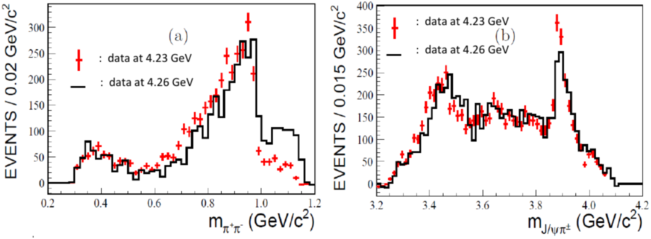
$$\mathcal{R} = \frac{\mathcal{B}(Z_c(3885)^0 \to D^+D^{*-})}{\mathcal{B}(Z_c(3885)^0 \to D^0\bar{D}^{*0})} = 0.96 \pm 0.18 \pm 0.12$$

J^P of $Z_c(3900)^+$

BESIII
NEW prelim

PWA of $e^+e^- \to J/\psi\,\pi^+\pi^-$ with full datasets at 4.23 and 4.26 GeV (1.92 fb^{-1})

Compare signal yields:



(scaled to luminosity of 4.23 GeV sample)

some differences in $\pi\pi$ system;
$Z_c(3900)^+$ production cross section appears to be larger at 4.23 GeV

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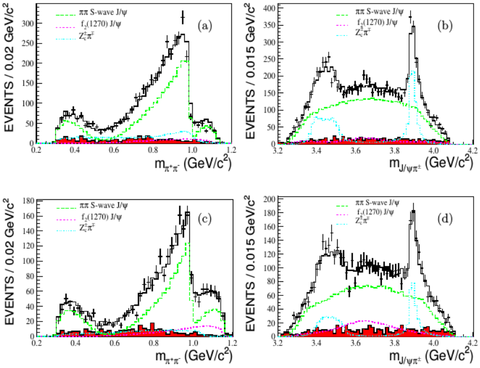
J^P of $Z_c(3900)^+$

NEW prelim

PWA of $e^+e^- \to J/\psi\,\pi^+\pi^-$ with full datasets at 4.23 and 4.26 GeV (1.92 fb^{-1})

Amplitudes in the fit:

- $\pi\pi$ $\mathcal{S}$-wave: $f_0(500)$, $f_0(980)$, $f_0(1370)$
- $f_2(1270) \to \pi^+\pi^-$
- $Z_c(3900)^+ \to J/\psi\,\pi^+ + c.c.$ (Flatté-like lineshape, nominal fit: $J^P = 1^+$)
- nonresonant $J/\psi\,\pi^+\pi^-$



J^P of $Z_c(3900)^+$

BESIII NEW prelim

PWA of $e^+e^- \to J/\psi\,\pi^+\pi^-$ with full datasets at 4.23 and 4.26 GeV (1.92 fb^{-1})

Observed signal yields and cross section
$\sigma \times \mathcal{B} \equiv \sigma(e^+e^- \to Z_c(3900)^\pm\pi^\mp \to J/\psi\,\pi^+\pi^-$ from the PWA fit:

$\sqrt{s}$	N_{sig}	$\sigma \times \mathcal{B}$ [pb]
4.23 GeV	875.2 ± 84.8	$20.3 \pm 2.0 \pm 4.8$
4.26 GeV	314.2 ± 21.2	$10.1 \pm 0.7 \pm 1.3$

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J^P of $Z_c(3900)^+$

BESIII
NEW prelim

PWA of $e^+e^- \to J/\psi\,\pi^+\pi^-$ with full datasets at 4.23 and 4.26 GeV ($1.92\,\text{fb}^{-1}$)

Test different J^P assignments for $Z_c(3900)^+$:

Replace $Z_c(3900)^+(1^+)$ with $Z_c(3900)^+(J^P)$ in the fit,
add $Z_c(3900)^+(1^+)$,
observe change in likelihood for given $\Delta(\text{ndf})$

J^P	$\Delta(-2\ln L)$	significance
1^+ over 0^-	89.0	$7.3\,\sigma$
1^+ over 1^-	214.0	$> 8\,\sigma$
1^+ over 2^-	103.6	$> 8\,\sigma$
1^+ over 2^+	387.0	$> 8\,\sigma$

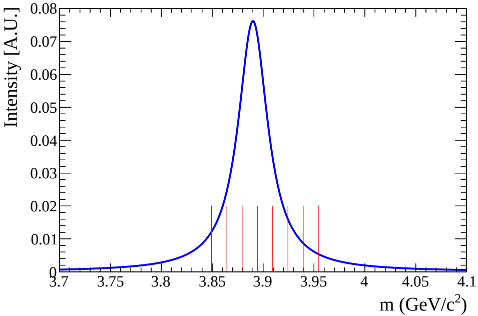
Data clearly favours $J^P = 1^+$

JG|U

J^P of $Z_c(3900)^+$

BESIII
NEW prelim

Phase motion across $Z_c(3900)^+$ peak:
in seven 15 MeV/c^2 wide bins across the $Z_c(3900)^+$ peak, replace amplitude for $Z_c(3900)^+$ by complex numbers.
Fix other constants (couplings, ...) to values from nominal fit



JG|U

J^P of $Z_c(3900)^+$

BESIII NEW preliminary

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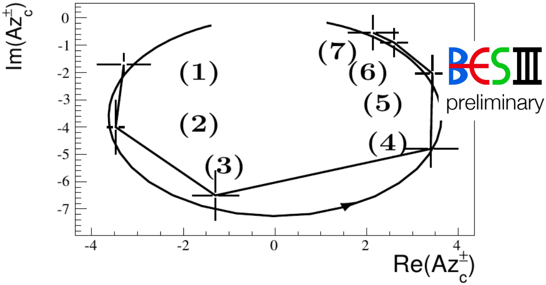


Rapid phase motion across peak; consistent with resonant behaviour

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	$3882.3 \pm 1.1 \pm 1.9$	$3899.0 \pm 3.6 \pm 4.9$
Width / MeV	$26.5 \pm 1.7 \pm 2.3$	$46 \pm 10 \pm 20$
$\sigma \times \mathcal{B}$ / pb	$88.0 \pm 6.1 \pm 7.9$	$13.5 \pm 2.1 \pm 4.8$

Both are $J^P = 1^+$; mass and width compatible within $\sim 2\sigma$

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

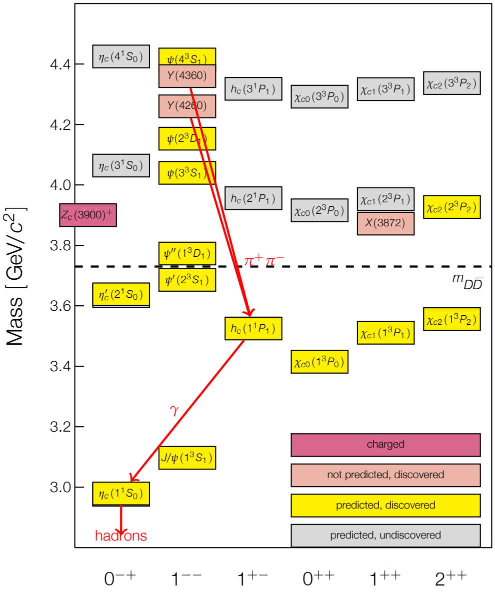
$$\frac{\mathcal{B}(\psi(4040) \to D^{(*)}\bar{D}^{(*)})}{\mathcal{B}(\psi(4040) \to J/\psi\,\eta)} = 192 \pm 27$$

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

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

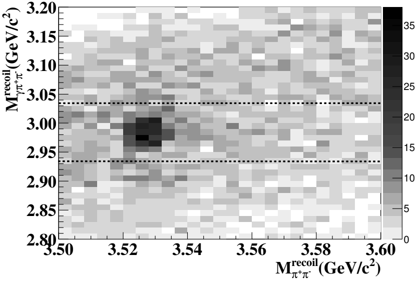
$e^+e^- \to h_c(1P)\pi^+\pi^-$

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



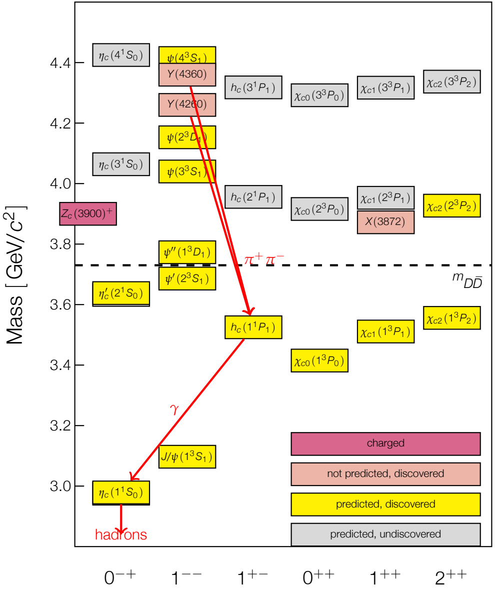
Exclusively reconstruct the process

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



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

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



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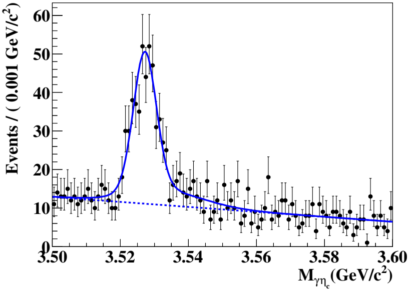
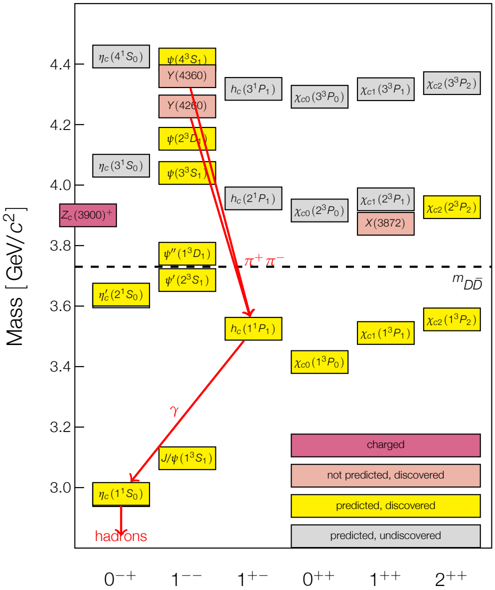


$e^+e^- \to h_c(1P)\pi^+\pi^-$

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



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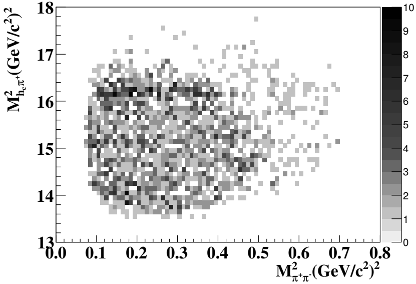
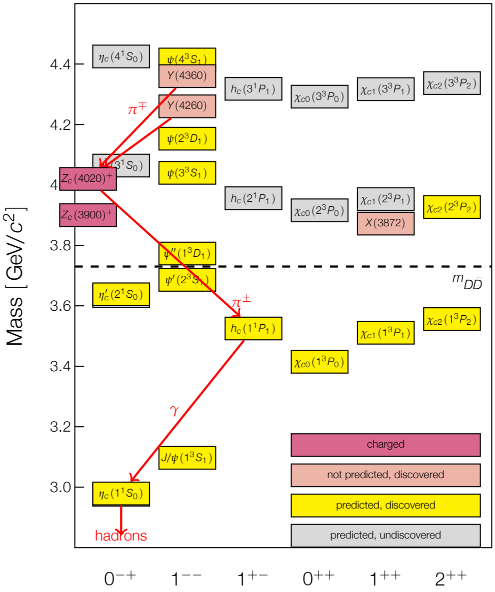
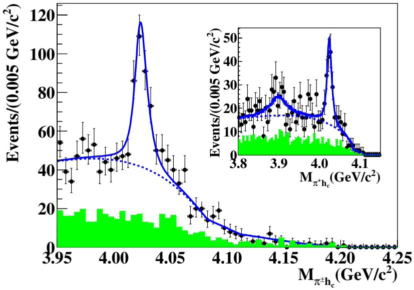


$e^+e^- \to h_c(1P)\pi^+\pi^-$

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





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

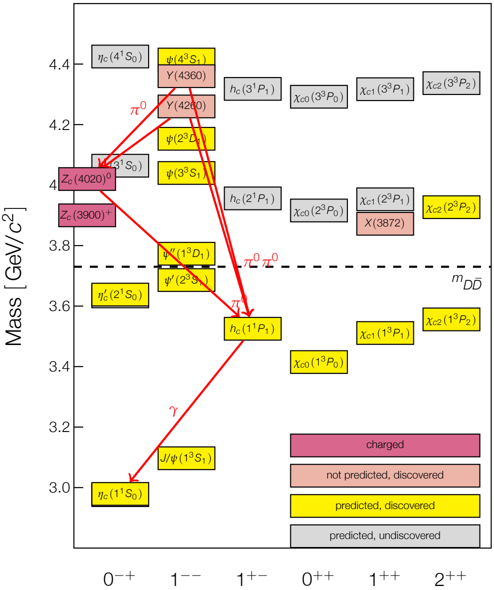
$M = 4022.9 \pm 0.8 \pm 2.7\,\mathrm{MeV}/c^2$

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

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

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

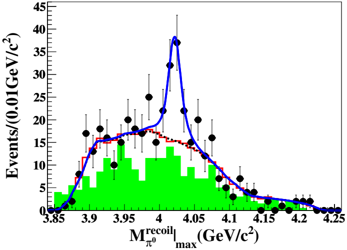
BESIII, PRL **113**, 212002 (2014)



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

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

Neutral partner to $Z_c(4020)^+$



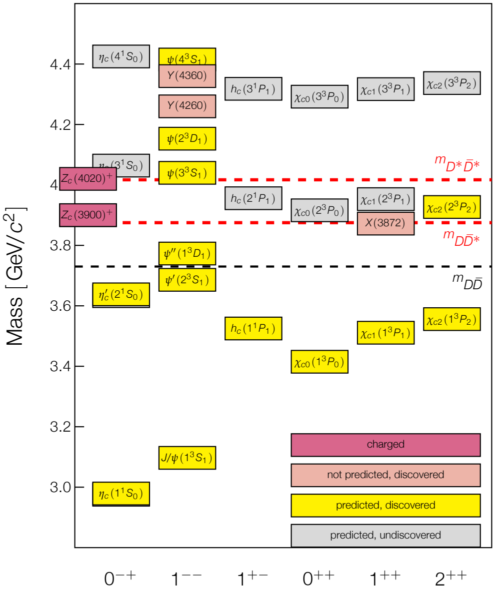
$M = 4023.6 \pm 4.5\,\mathrm{MeV}/c^2$

Γ fixed in the fit

Isospin triplet found!

Yet another mass threshold …

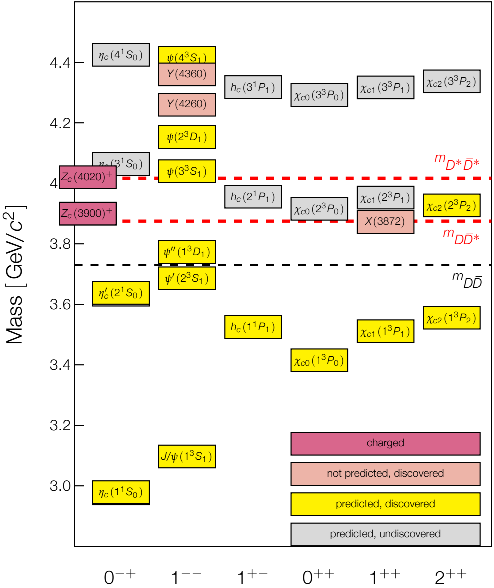
BESIII, PRL **112**, 132001 (2014)



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

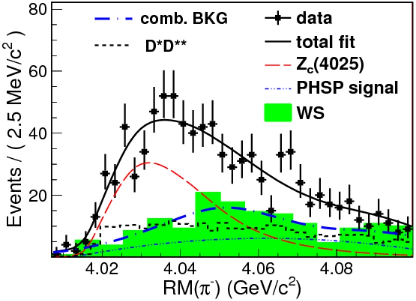
Yet another mass threshold …

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



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

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



…and BESIII sees structure in D^*D^*

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

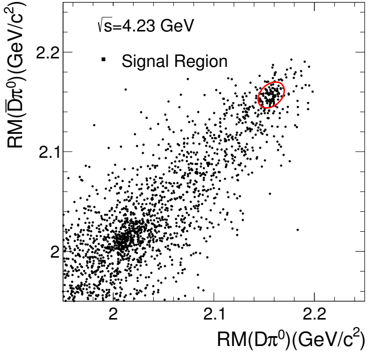
… and the neutral partner: $Z_c(4025)^0$

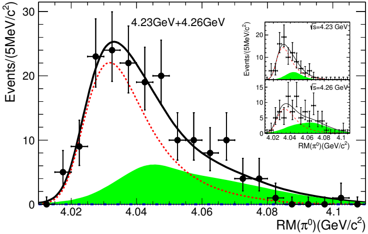
PRL **115**, 182002 (2015)

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

Use partial reconstruction technique:

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





Combine data sets at $\sqrt{s} = 4.23$, 4.26 GeV
Enhancement at threshold visible
No non-resonant process needed
Fit with $BW \otimes \mathcal{R}$, extract pole position

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

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

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

BESIII

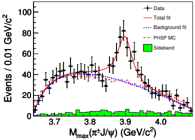
PRL **115**, 182002 (2015)

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

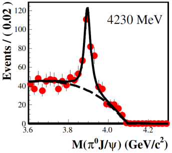
- Almost perfect agreement in resonance parameters
- and cross sections
- very small isospin violation?!

JG|U

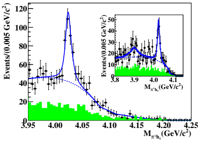
All the Z_cs from BESIII near $\sqrt{s} = 4.3$ GeV



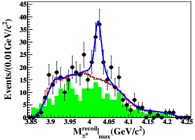
$e^+e^- \to \pi^-\pi^+J/\psi$



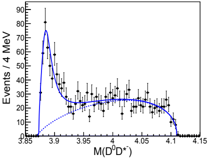
$e^+e^- \to \pi^0\pi^0 J/\psi$



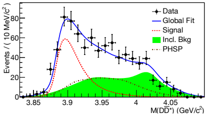
$e^+e^- \to \pi^-\pi^+h_c$

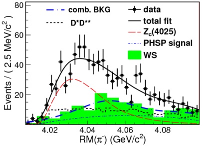


$e^+e^- \to \pi^0\pi^0 h_c$

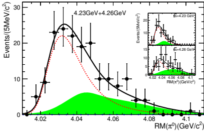


$e^+e^- \to \pi^-(D\bar{D}^*)^+$





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



$Z_c(3900)^+$?

$Z_c(3900)^0$?

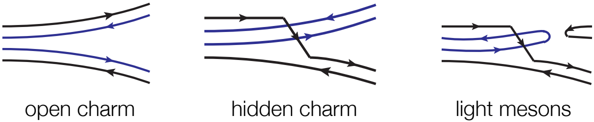
$Z_c(4020)^+$?

$Z_c(4020)^0$?

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

Other decay modes?

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



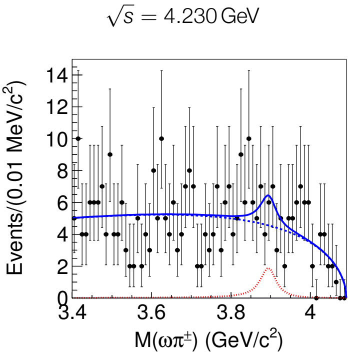
threshold effects!

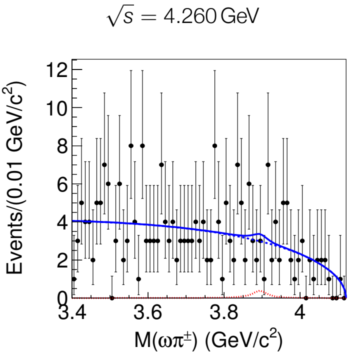
Decay modes with $c\bar{c}$ annihilation does not involve hidden or open charm final states!

If $c\bar{c}$ in S-wave, annihilation could be as 'easy' as for J/ψ ...
but theoretical predictions very difficult,
order-of-magnitude only

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

BESIII, PRD **92**, 032009 (2015)





$\sigma(e^+e^- \to Z_c^+\pi^-, Z_c^+ \to \omega\pi^+) < 0.26\,\text{pb}$

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

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

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

What have we learned?

At BESIII, together with Belle and CLEO:

- Close to $D\bar{D}^*$ and $D^*\bar{D}^*$ thresholds:
  charged charmonium-like structures decaying into $\pi^+(c\bar{c})$
- Close-by: structures in $D\bar{D}^*$ and $D^*\bar{D}^*$
- Prominently visible in data taken near $\sqrt{s} = 4.26 \cdots 4.36\,\text{GeV}$
  where 'supernumerary' 1^{--} states lie
- In each of the decay modes, also observe neutral partner

What can we learn, and how?

- J^P of the newly-discovered states?
- Other states, with other charmonia?
  Yes! $Z_c(4430)^+ \to \psi(2S)\pi^+$ (first one, Belle & LHCb, in B decays)
  $Z_c(4050)^+, Z_c(4250)^+ \to \chi_{c1}\pi^+$, Belle, in B decays (not signif. in BABAR data)
  (Belle does not see $Z_c(3900)^+ \to J/\psi\,\pi^+$ in $B^0 \to J/\psi\,\pi^+K^-$, but something else!)
- Others? E.g. with η_c, …
- Other decay modes, e.g. into light hadrons?
- If we've seen isospin triplets, are there isoscalars to be found?
- Strangeness partners? (e.g. $Y(2170) \to \phi f_0(980)$?)

Large experimental programme, which will define BESIII data taking in the next years
Suggestions include fine scan ($\Delta E \sim 100\,\mathrm{MeV}$) with $0.5\,\mathrm{fb}^{-1}$ per point


謝謝！