News from BESIII and what can be learned

Wolfgang Gradl

on behalf of the BESIII collaboration

EMMI Rapid reaction taskforce
GSI, 14th October 2015

SFB 1044 THE LOW-ENERGY FRONTIER OF THE STANDARD MODEL

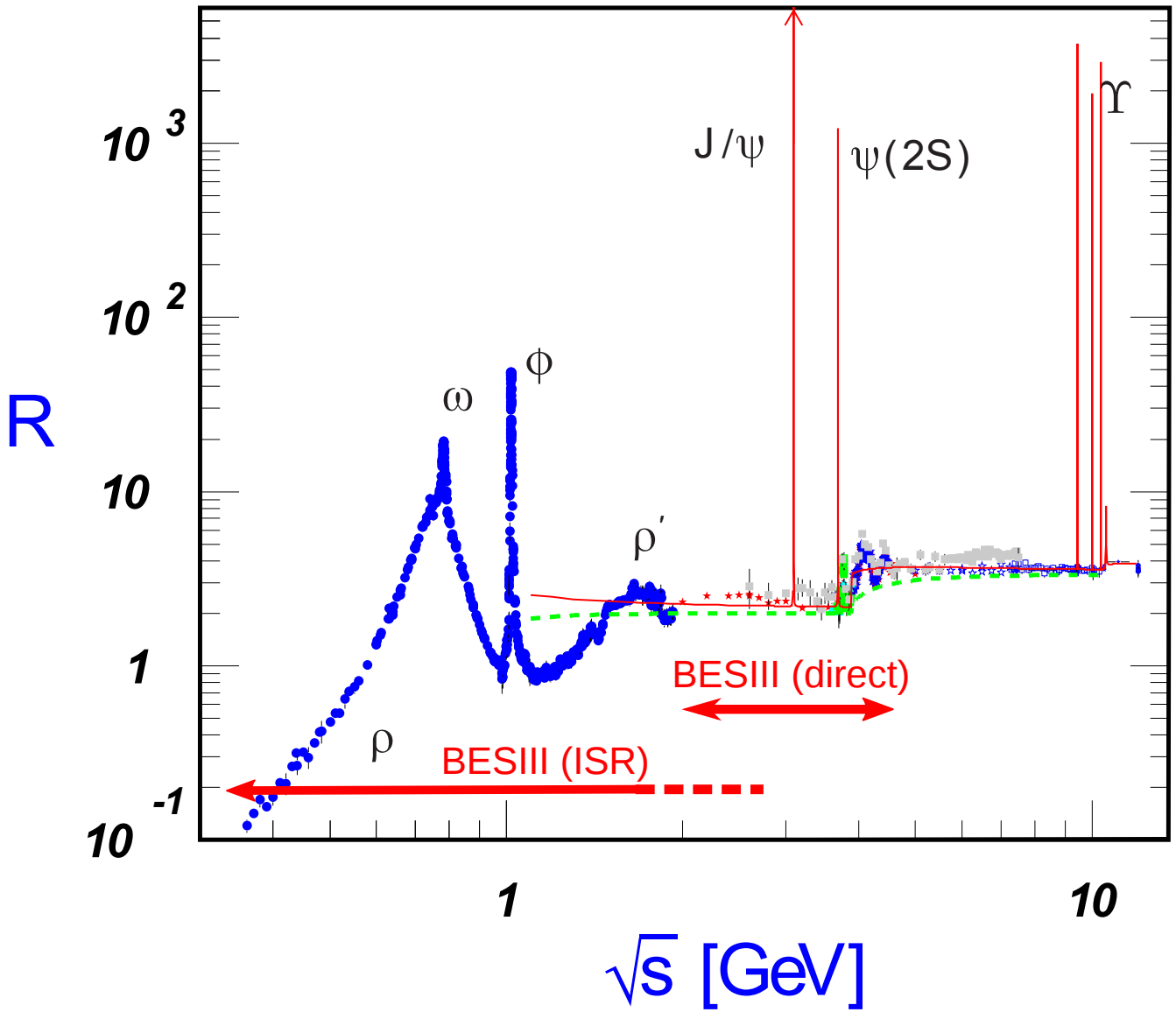
JG|U JOHANNES GUTENBERG UNIVERSITÄT MAINZ

PRISMA

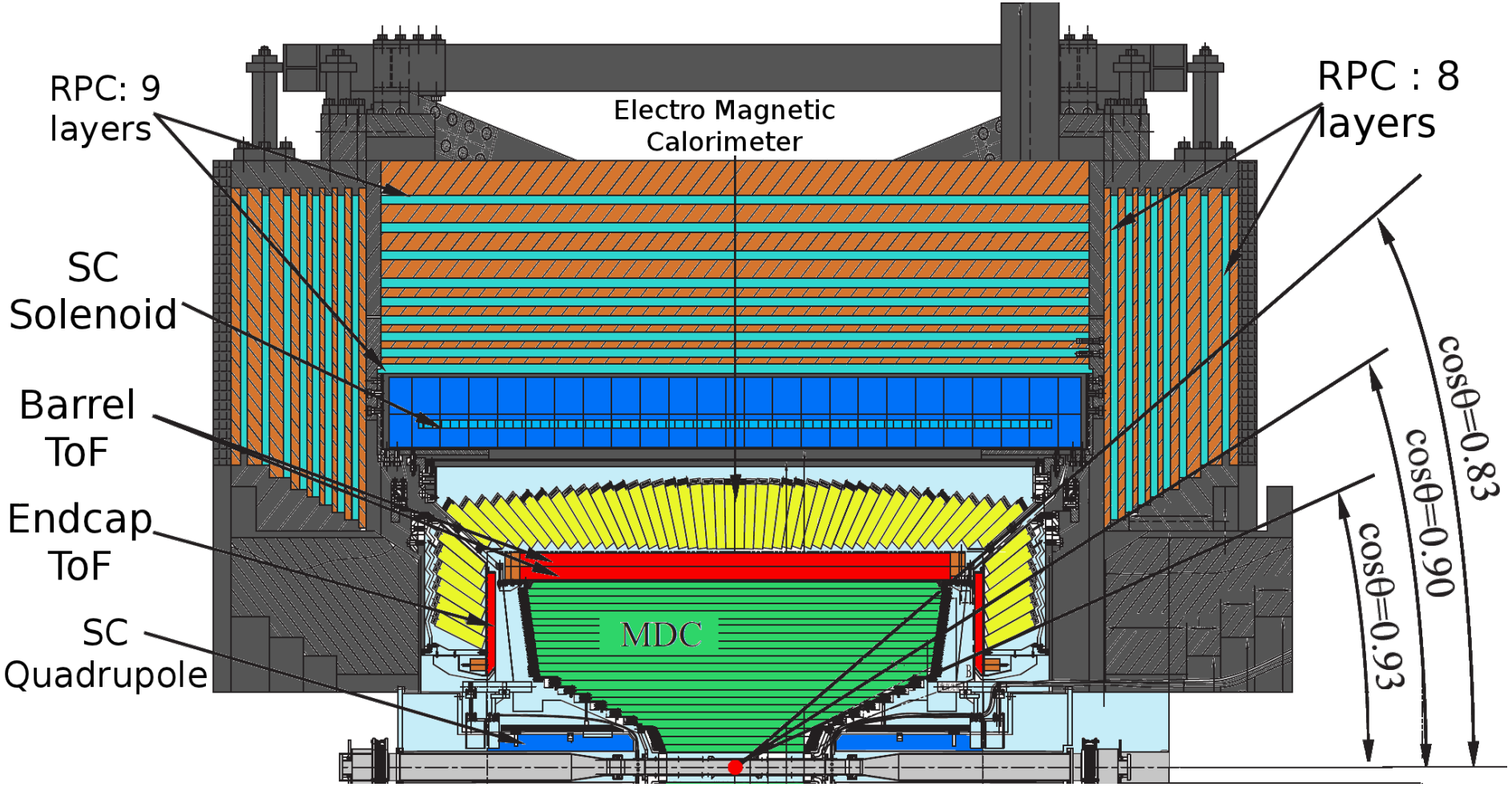
BESIII: a τ-charm factory

BEPCII and BESIII

A τ-charm factory



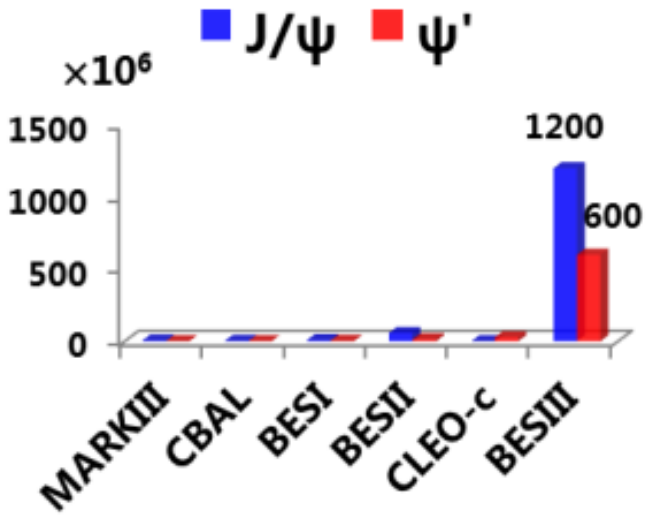
BESIII detector

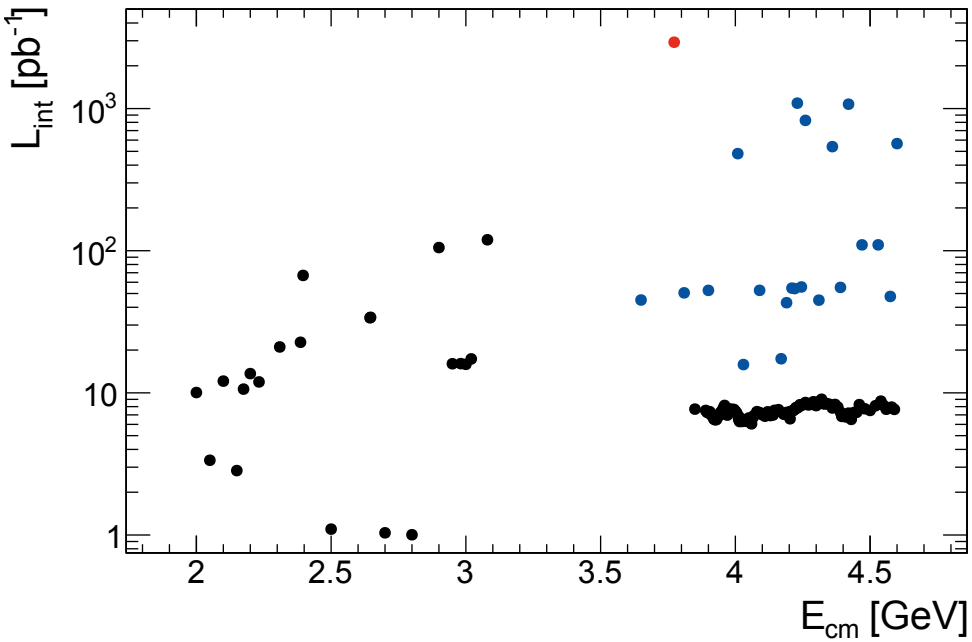


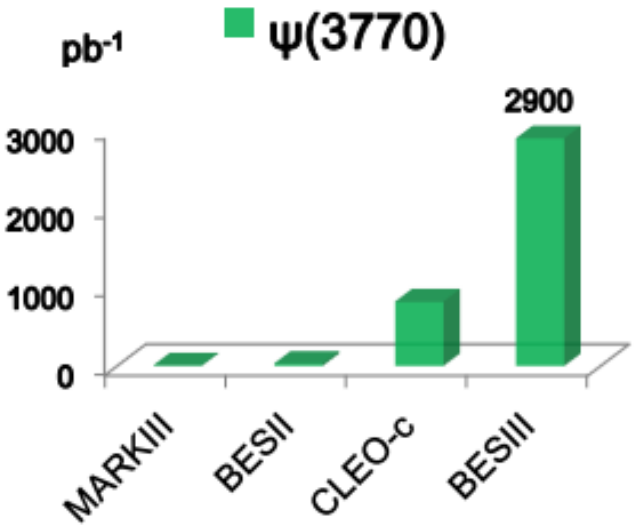
Completely new detector

Comparable performance to CLEO-c, + muon ID

Unique BESIII data set







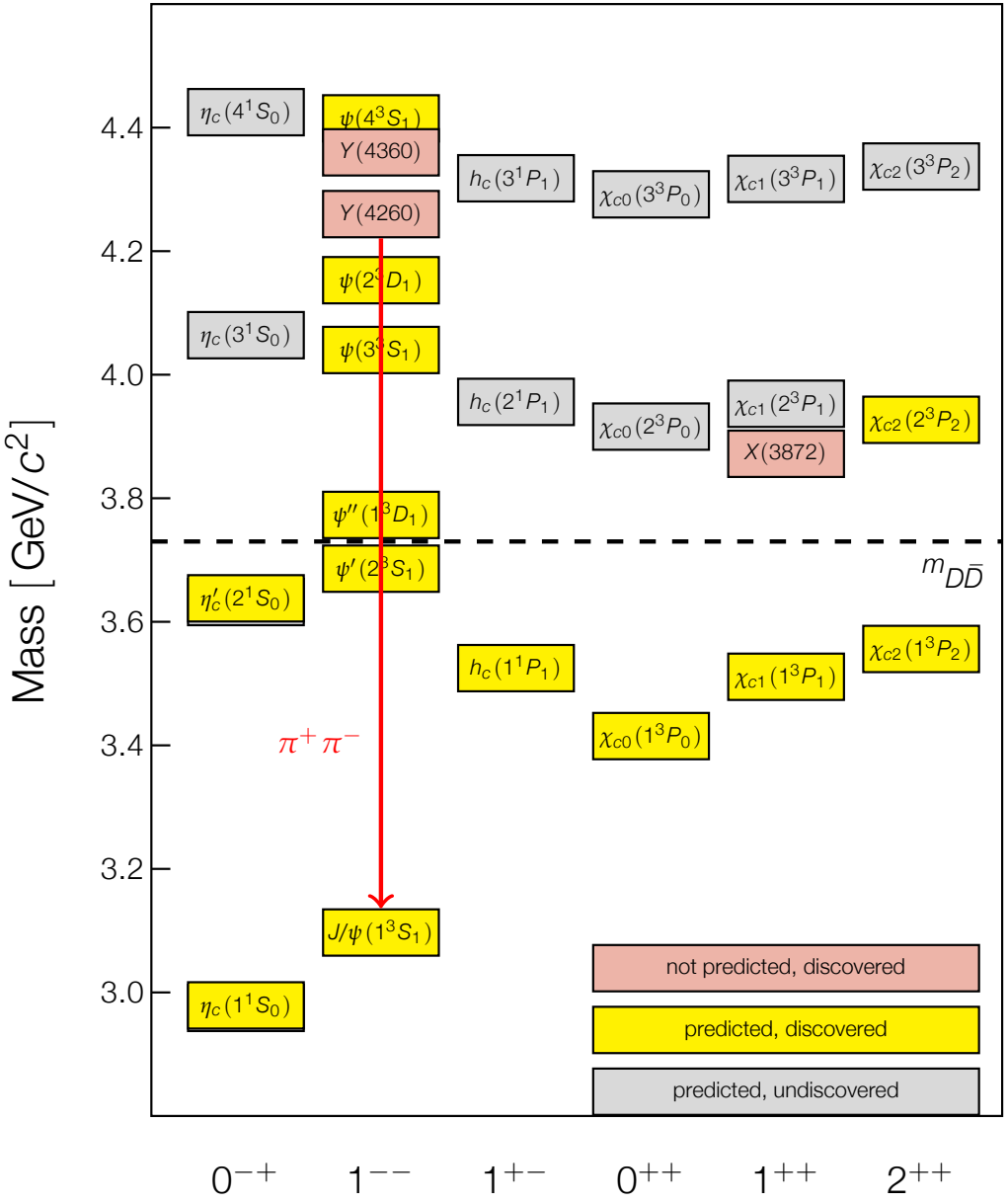
large data sets of $\approx 4\,\mathrm{fb}^{-1}$ above 3.8 GeV for
$+$ 104 energy points between 3.85 and 4.59 GeV
$+ \sim$ 20 energy points between 2.0 and 3.1 GeV

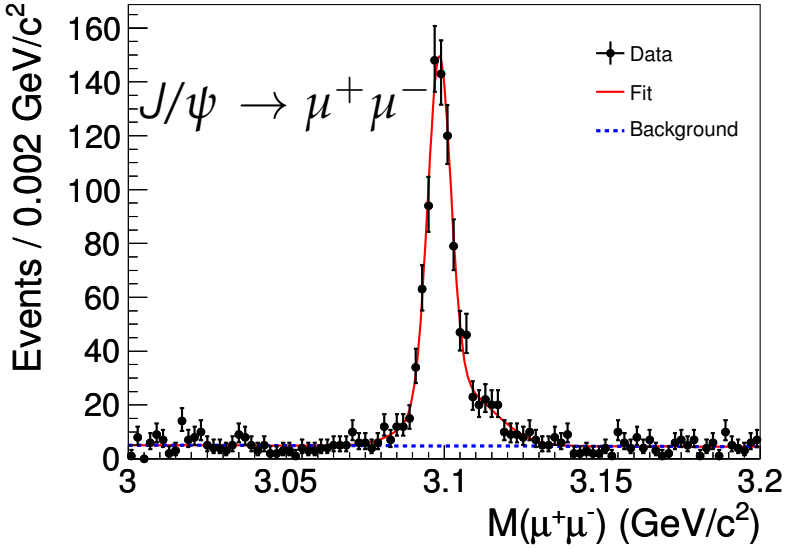
Direct production of 1^{--} states studied
with world's largest scan dataset

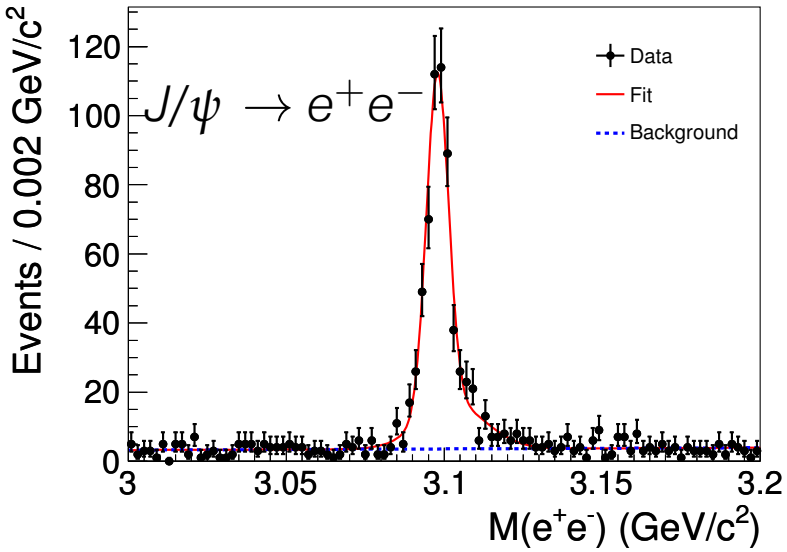
The Z_c family

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

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



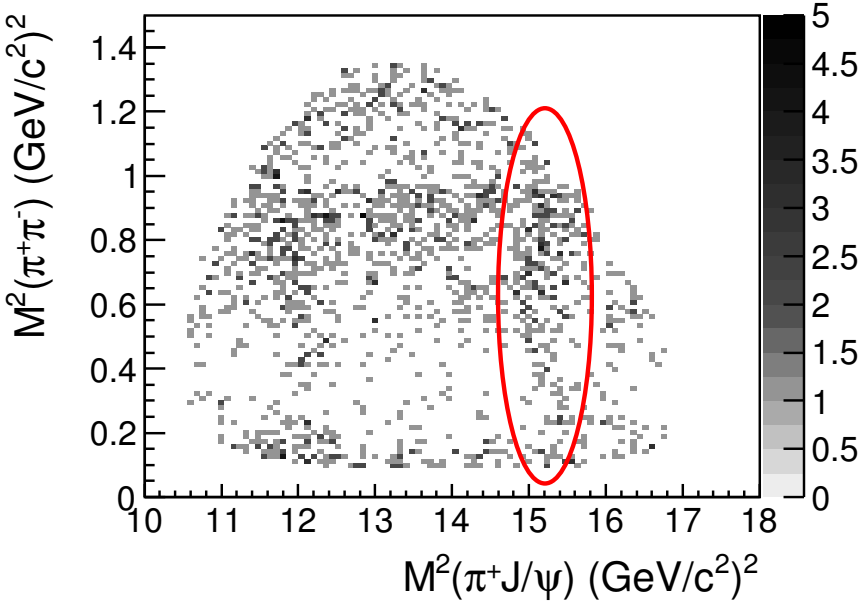


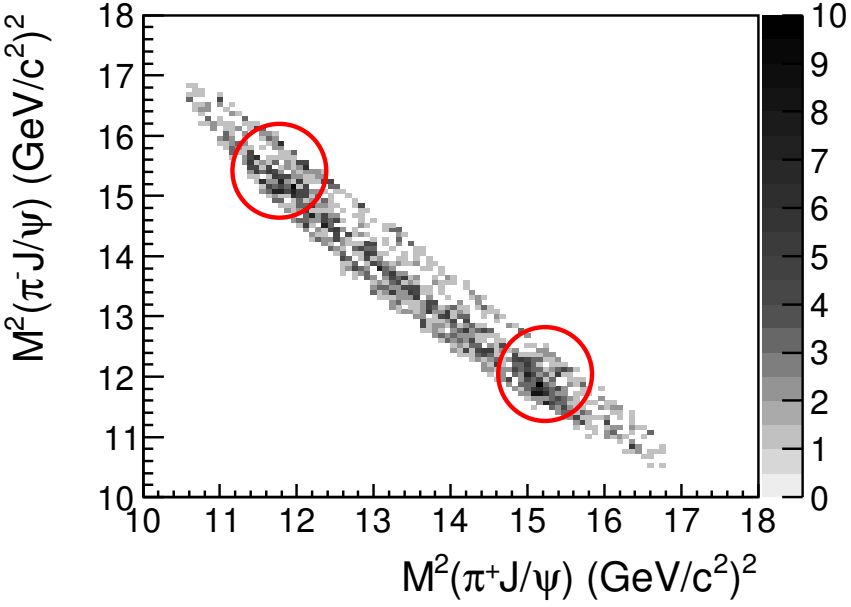


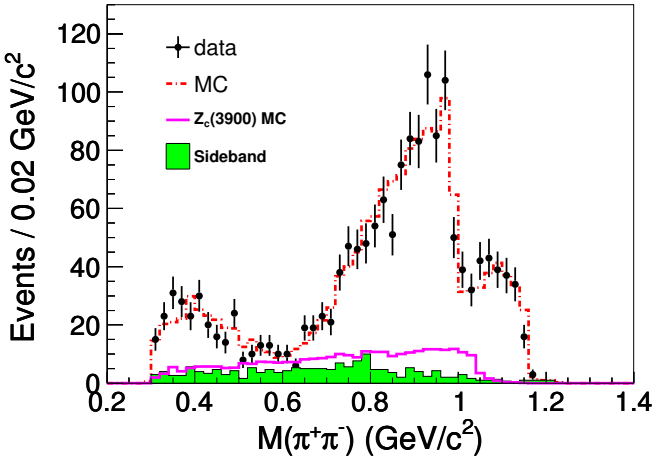
…have hundreds of events!

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

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



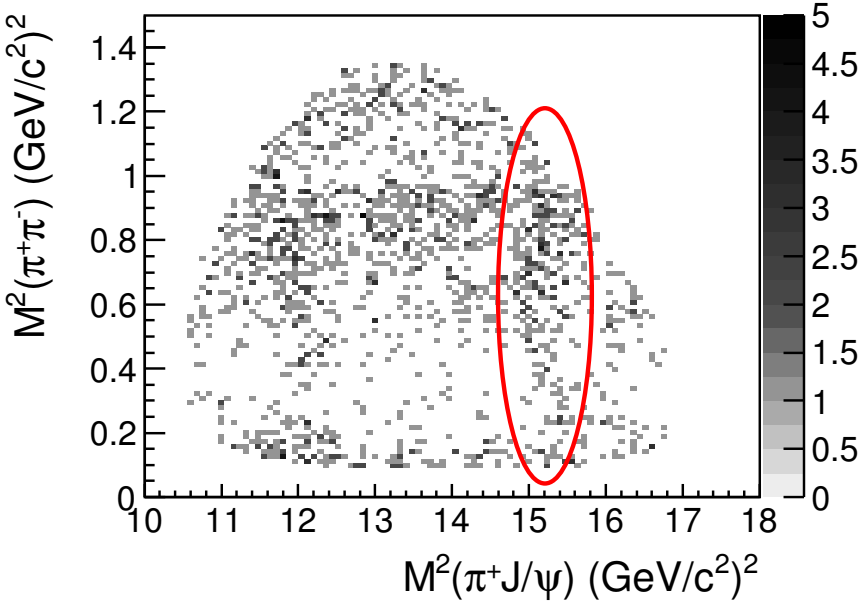


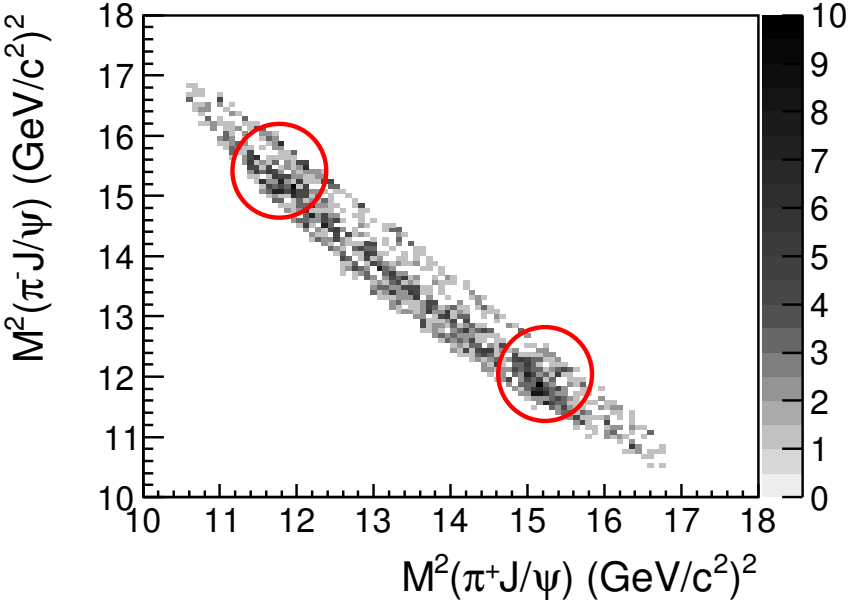


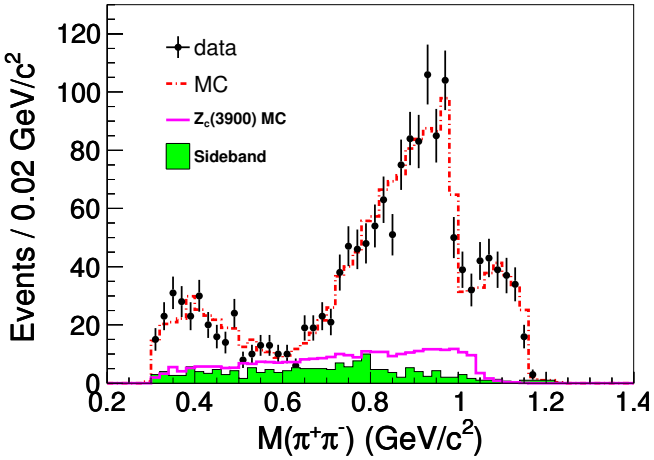
Model $\pi^+\pi^-$-system with known structure:
$f_0(500)$, $f_0(980)$, non-resonant
obtain good fit of $\pi^+\pi^-$ mass projection

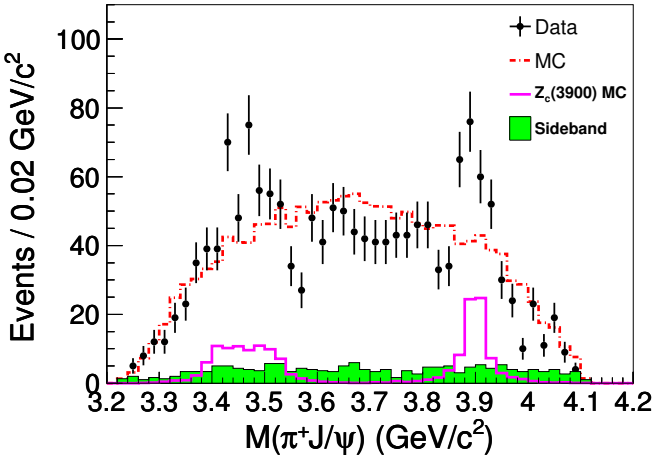
$J/\psi\,\pi^+\pi^-$ Dalitz plot

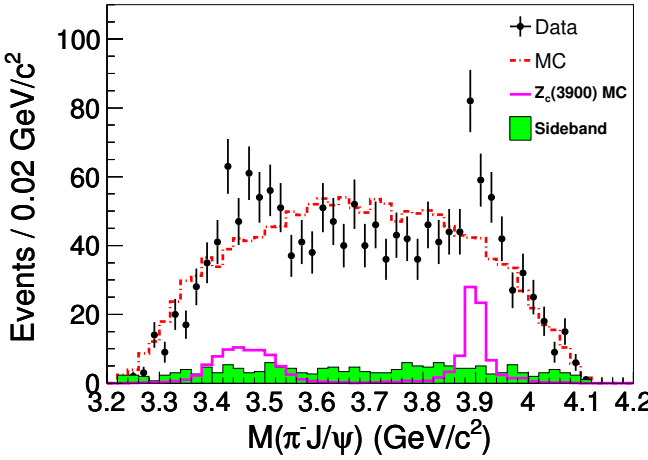
BESIII, PRL **110**, 252001 (2013)





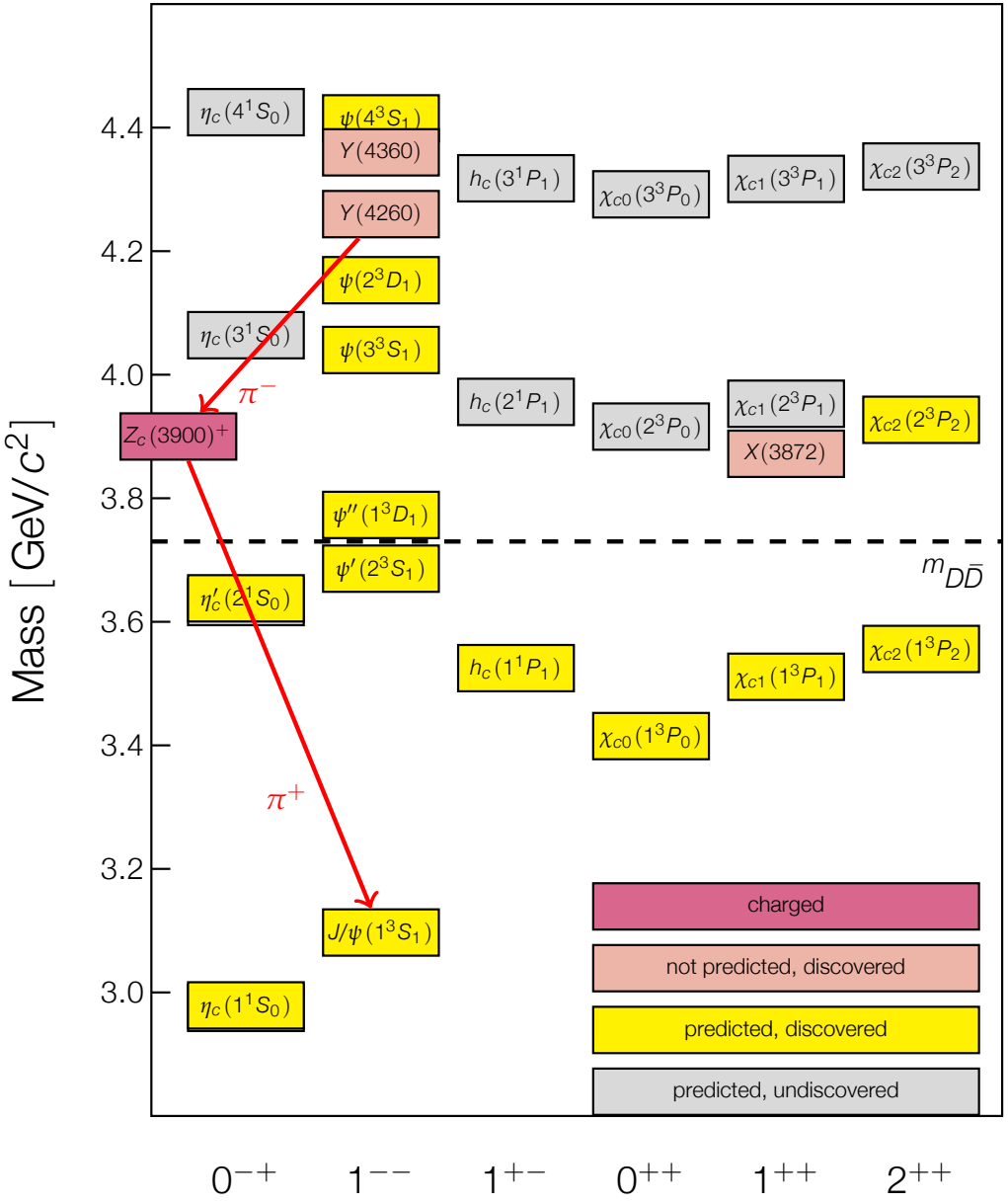


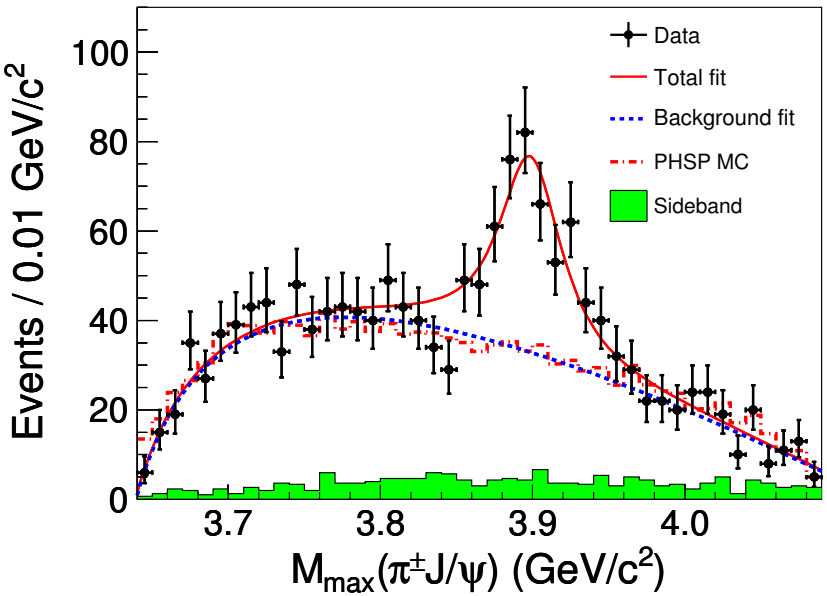




$e^+e^- \to J/\psi\,\pi^+\pi^-$ at 4.26 GeV

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





Charged charmonium-like structure

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

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

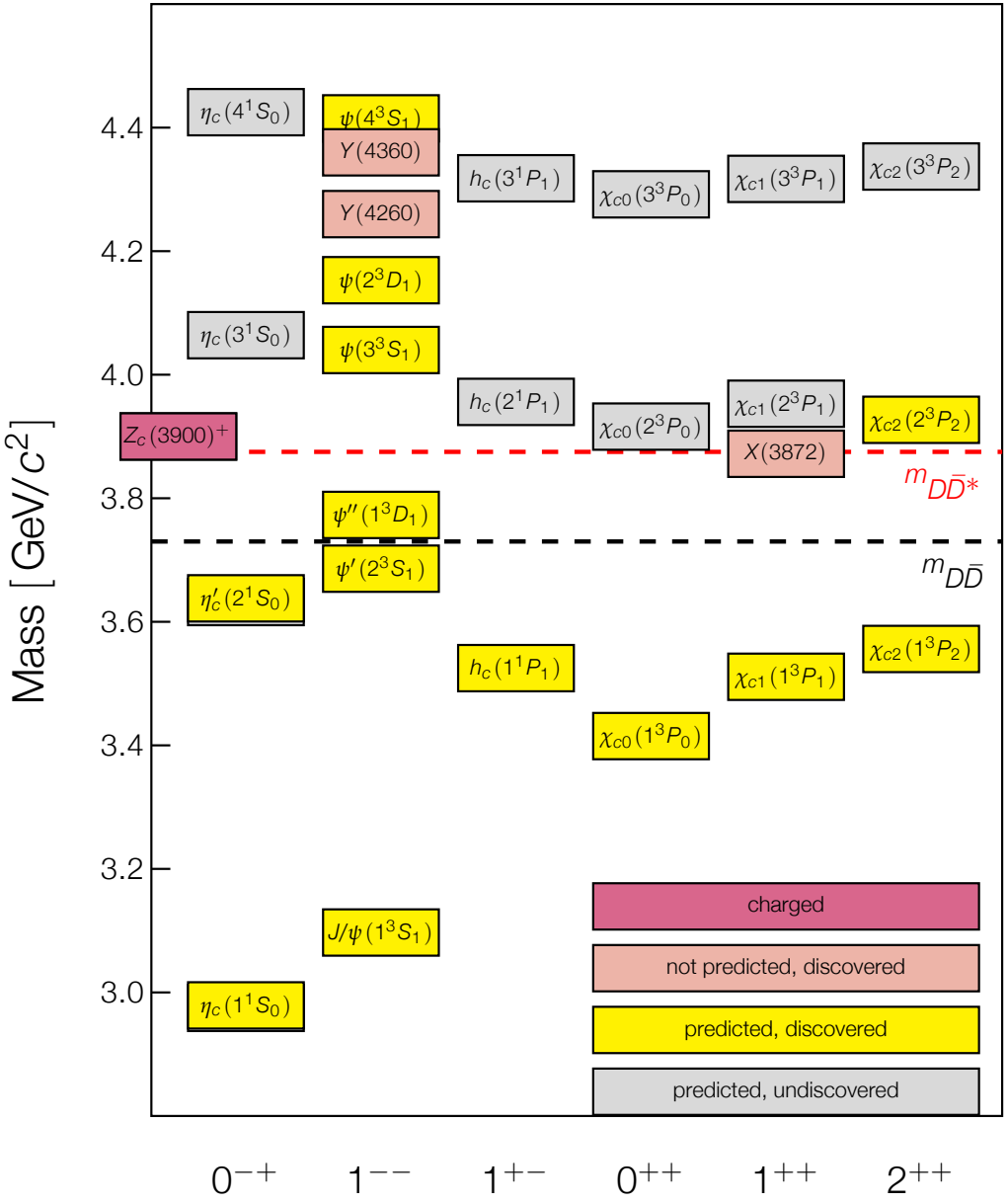
Confirmed by Belle PRL **110**, 252002
and with CLEOc data PLB 727, 366

Close to DD^* threshold
Interpretation?

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

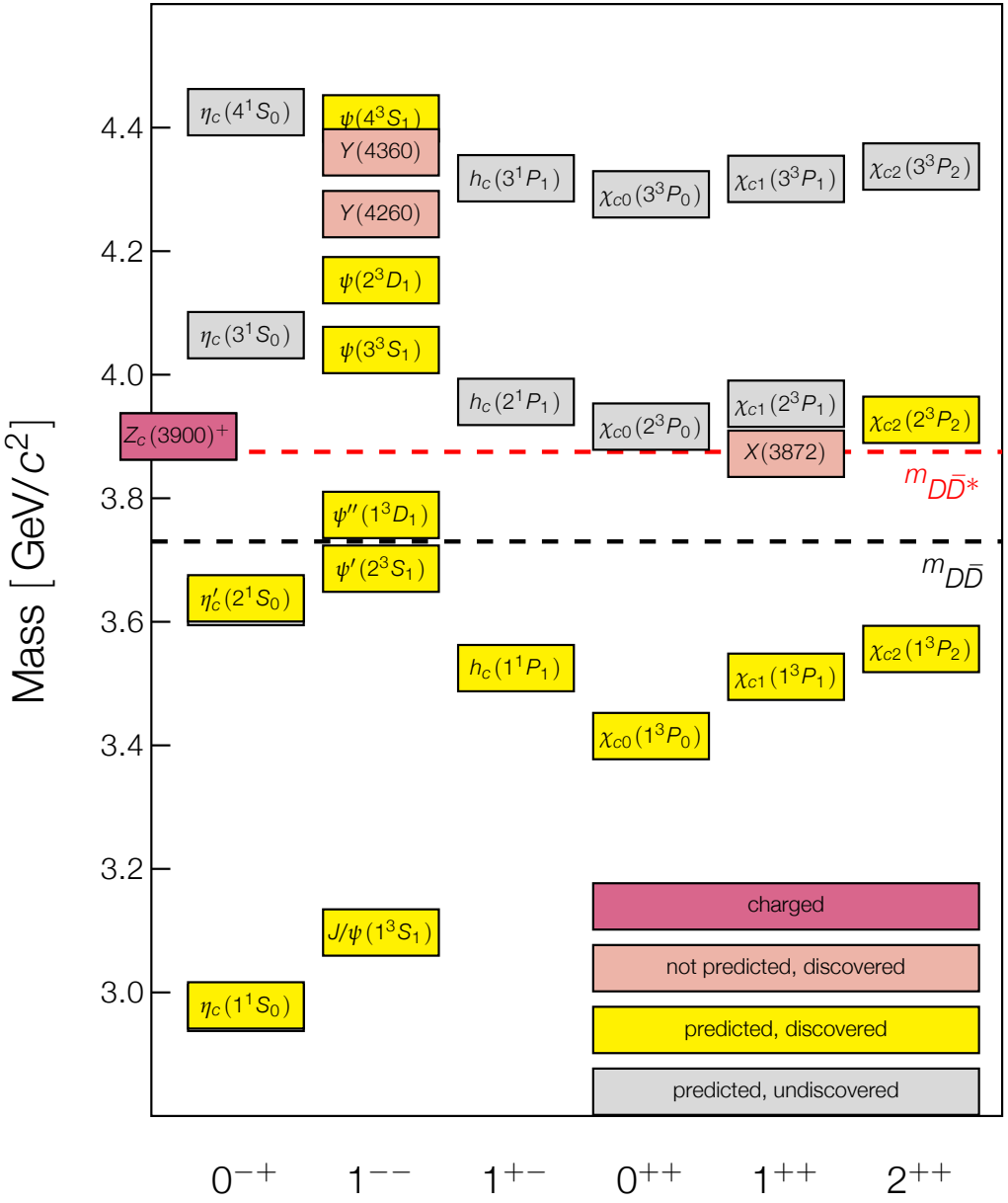
BESIII, PRL **112**, 022001 (2014)

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



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

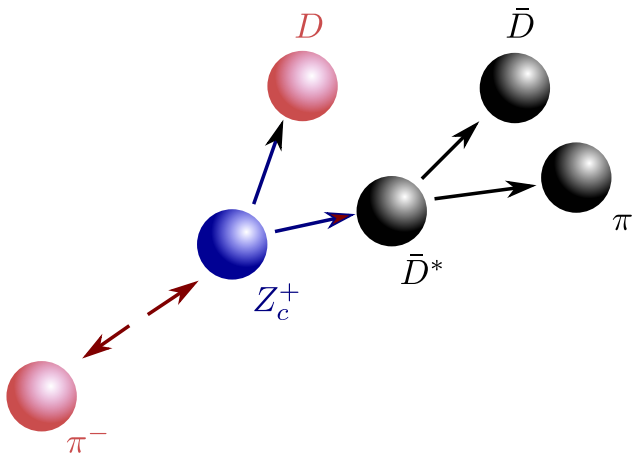
BESIII, PRL **112**, 022001 (2014)



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

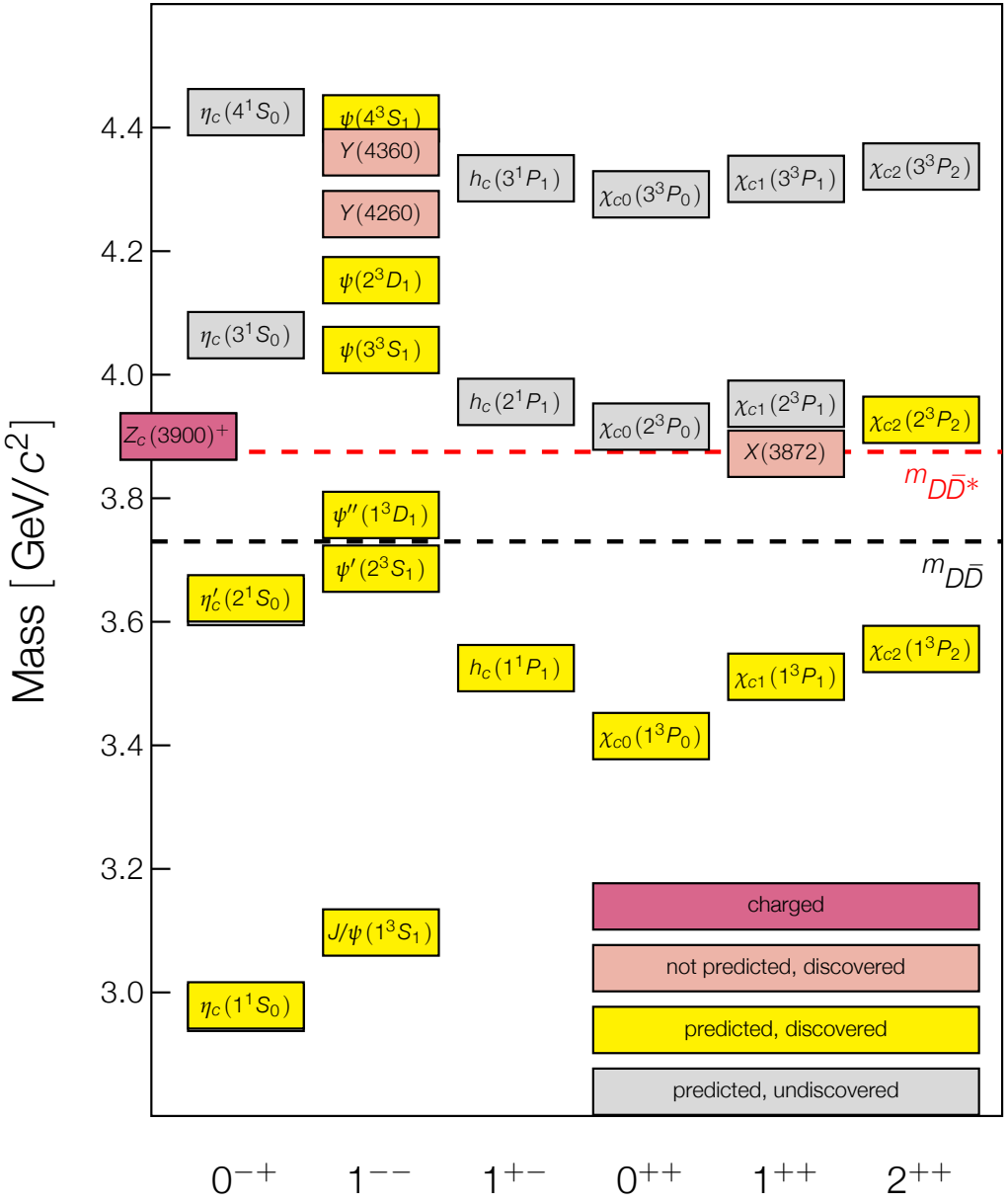
Single tag analysis:

- 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^+



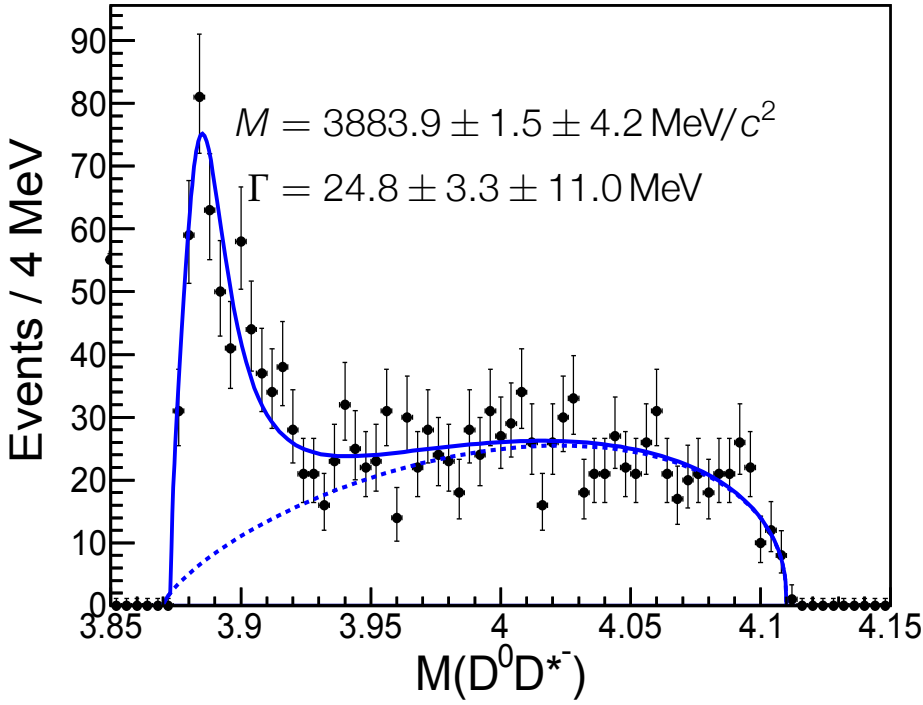
$Z_c(3900)^+$ at $D\bar{D}^*$ threshold

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



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

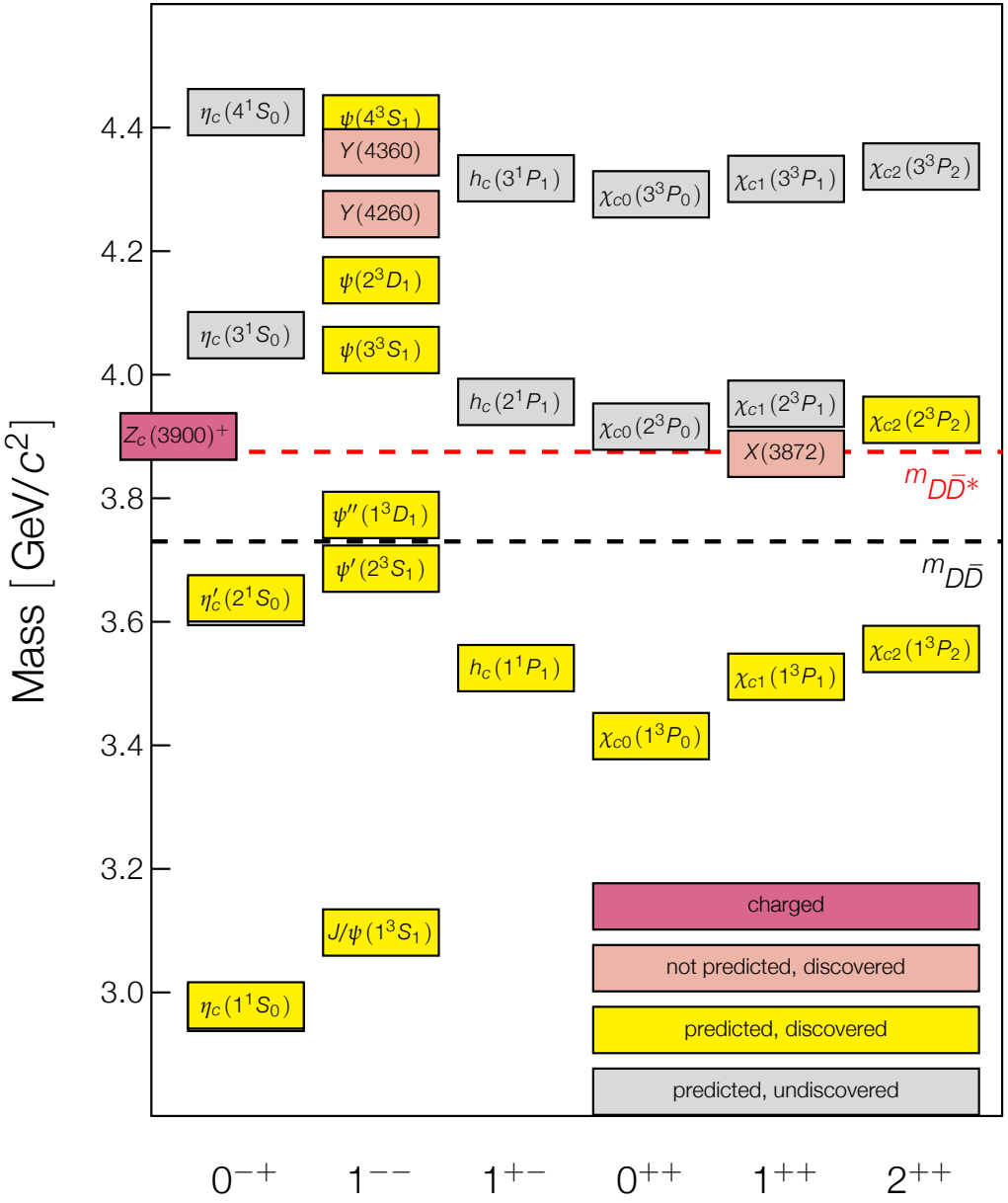
$e^+e^- \to \pi^+ D^0 D^{*-}$ at BESIII



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

Large systematics due to non-Z_c signal shape

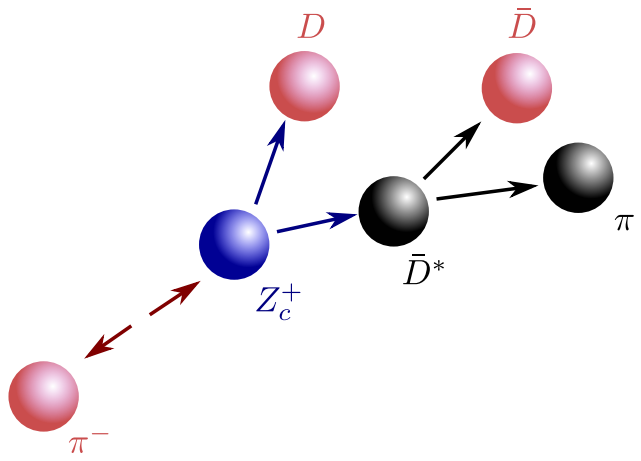
$Z_c(3900)^+$ at $D\bar{D}^*$ threshold



BESIII
preliminary
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

preliminary
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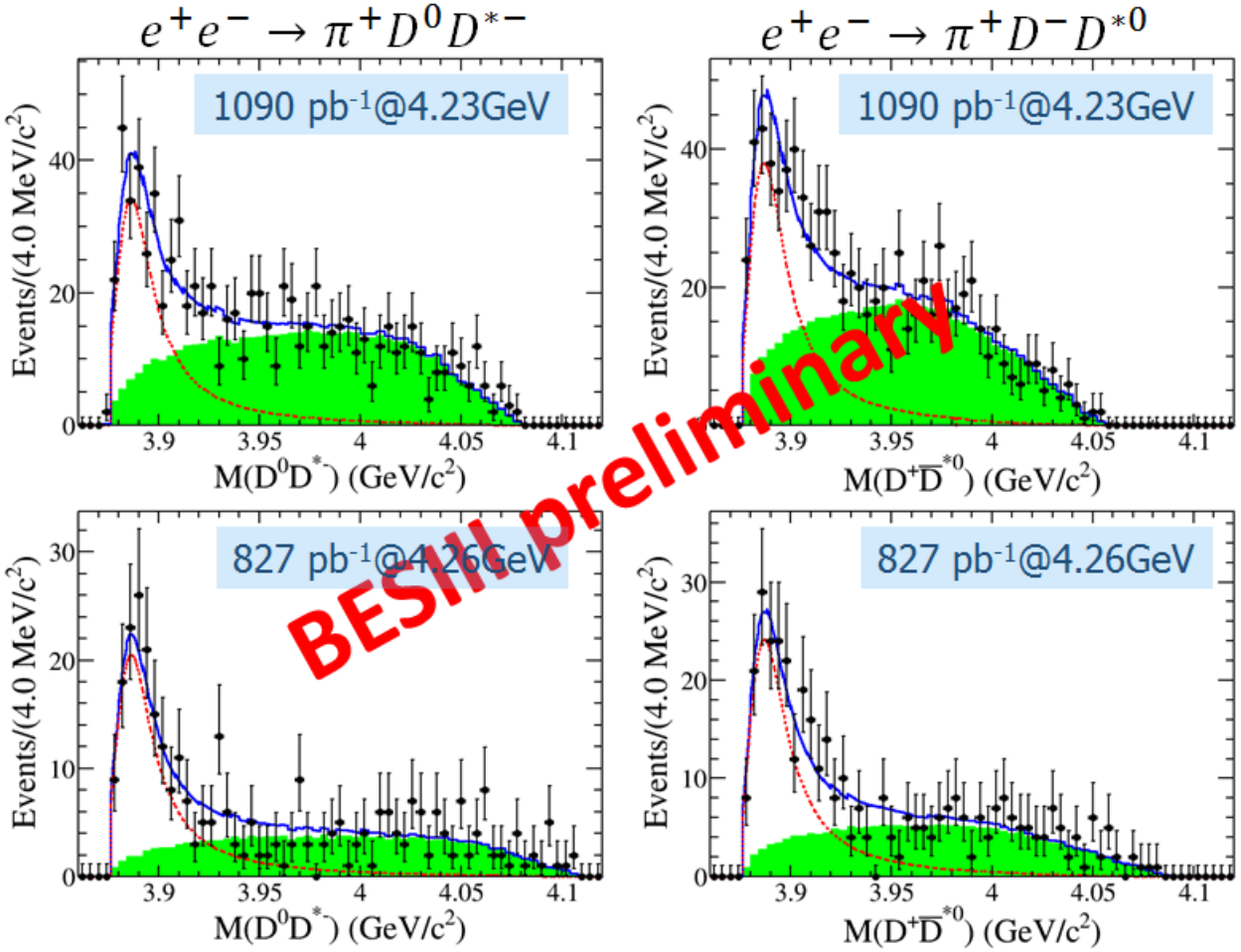


Simultaneous fit with phase space shape + $(BW \otimes \mathcal{R}) \times \varepsilon$

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

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

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

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

preliminary
1509.01398

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

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

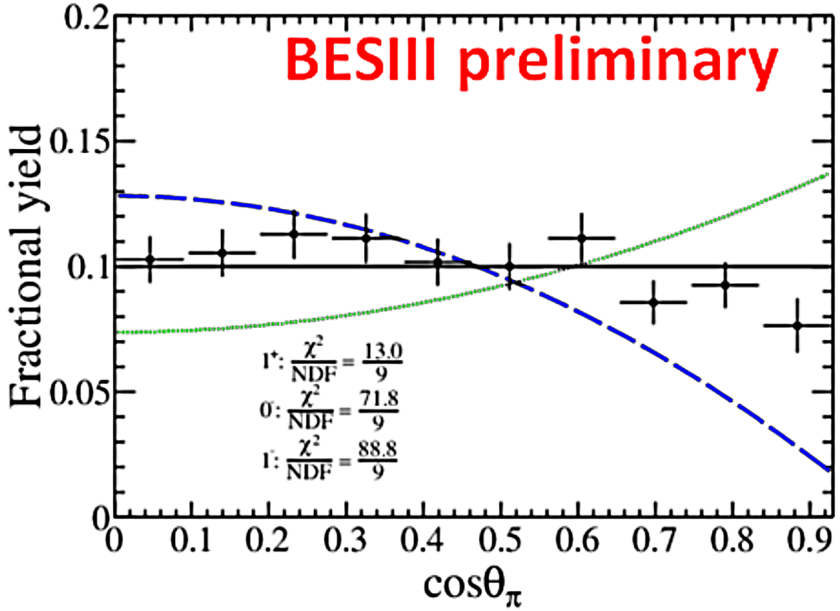
$Z_c(3885)^+$ Quantum numbers?

preliminary
1509.01398

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

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

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



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 $Z_c(3900)^0 \to \pi^0 J/\psi$

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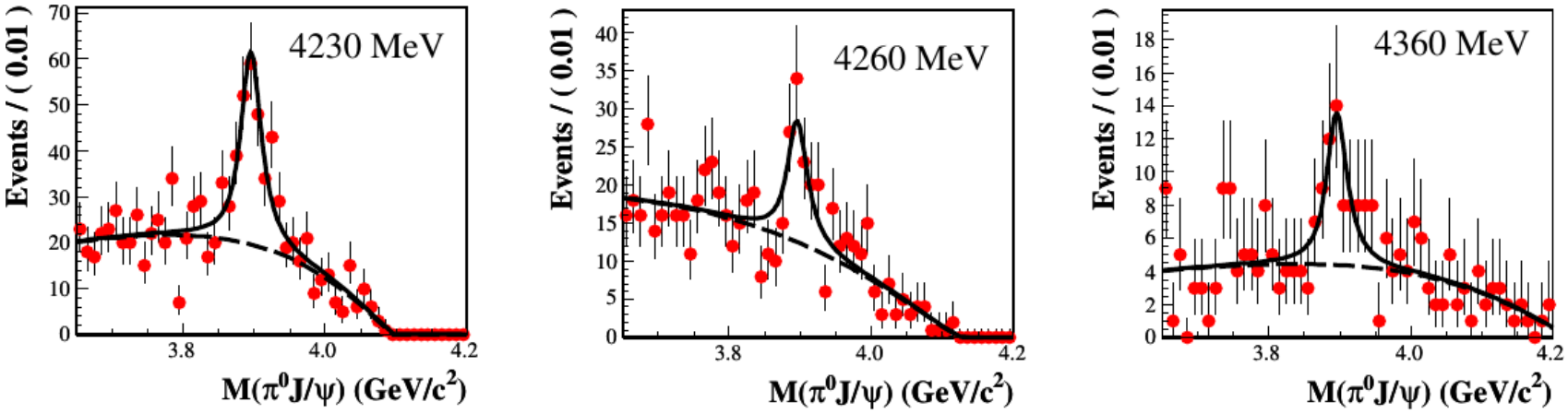
Study $e^+e^- \to \pi^0\pi^0 J/\psi$ with large data sets at three different $\sqrt{s}$

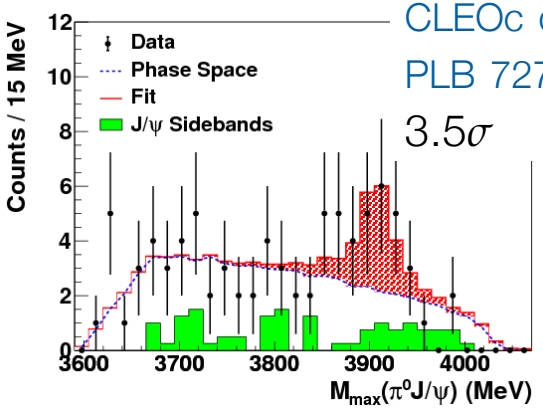


Structure in $\pi^0 J/\psi$ invariant mass
clearly visible at all energies

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

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

Significance 10σ



CLEOc data,
PLB 727, 366 (2013)
3.5σ

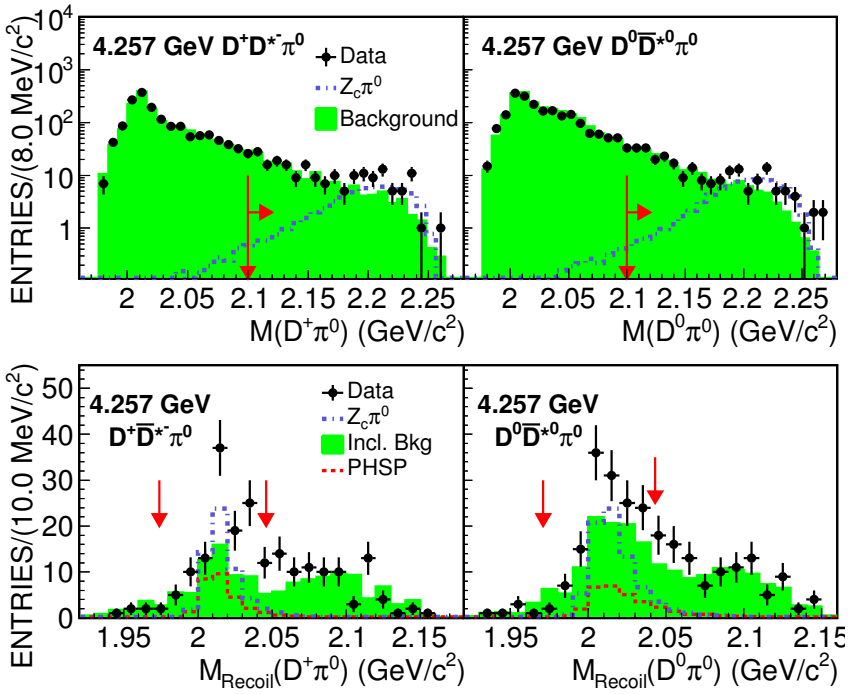
$Z_c(3885)^0$ in $e^+e^- \to (D\bar{D}^*)^0\pi^0$

Partial reconstruction technique:

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

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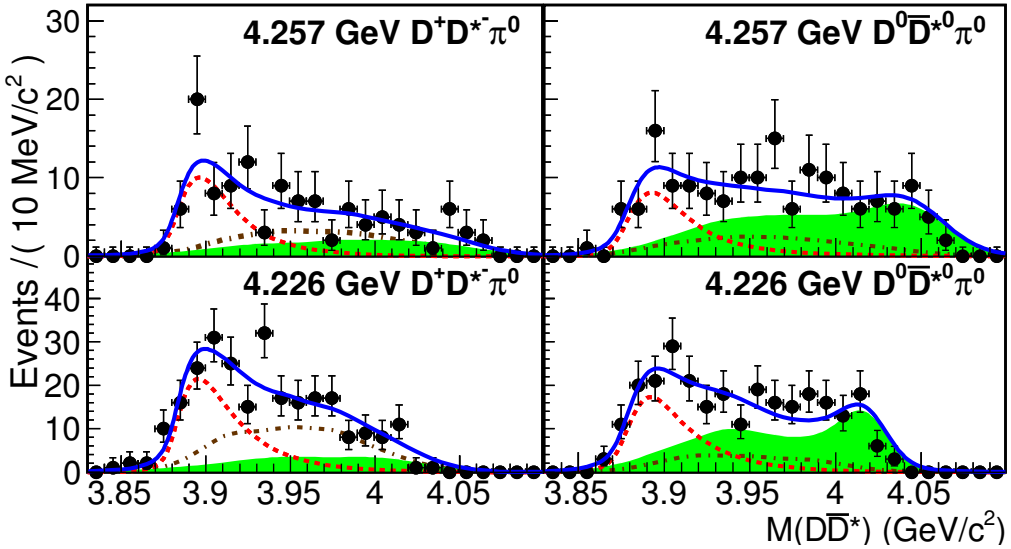
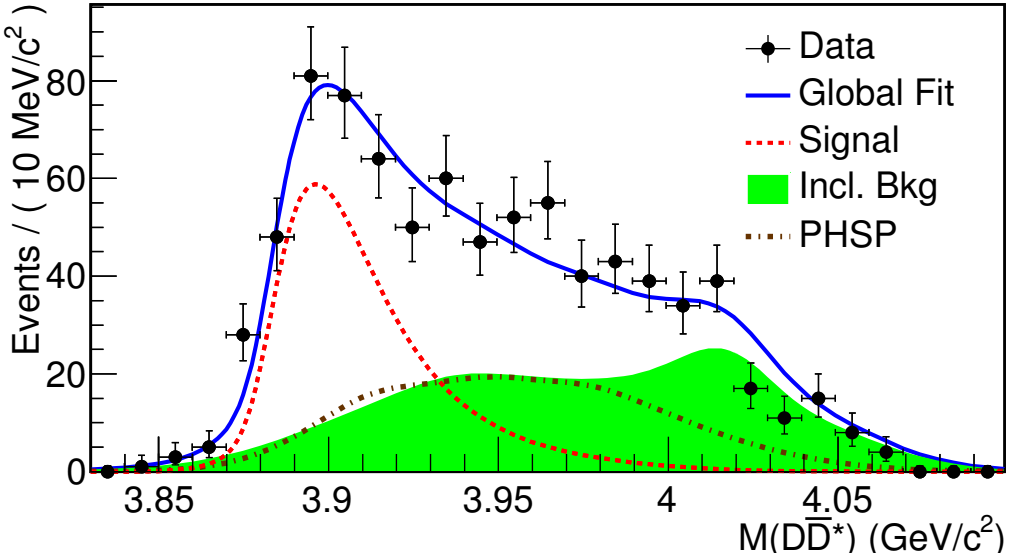




Simultaneous fit to both charge combinations
in two large datasets at $\sqrt{s} = 4.226$ and 4.257 GeV

Significance $> 10\sigma$

Pole parameters of rel. BW:

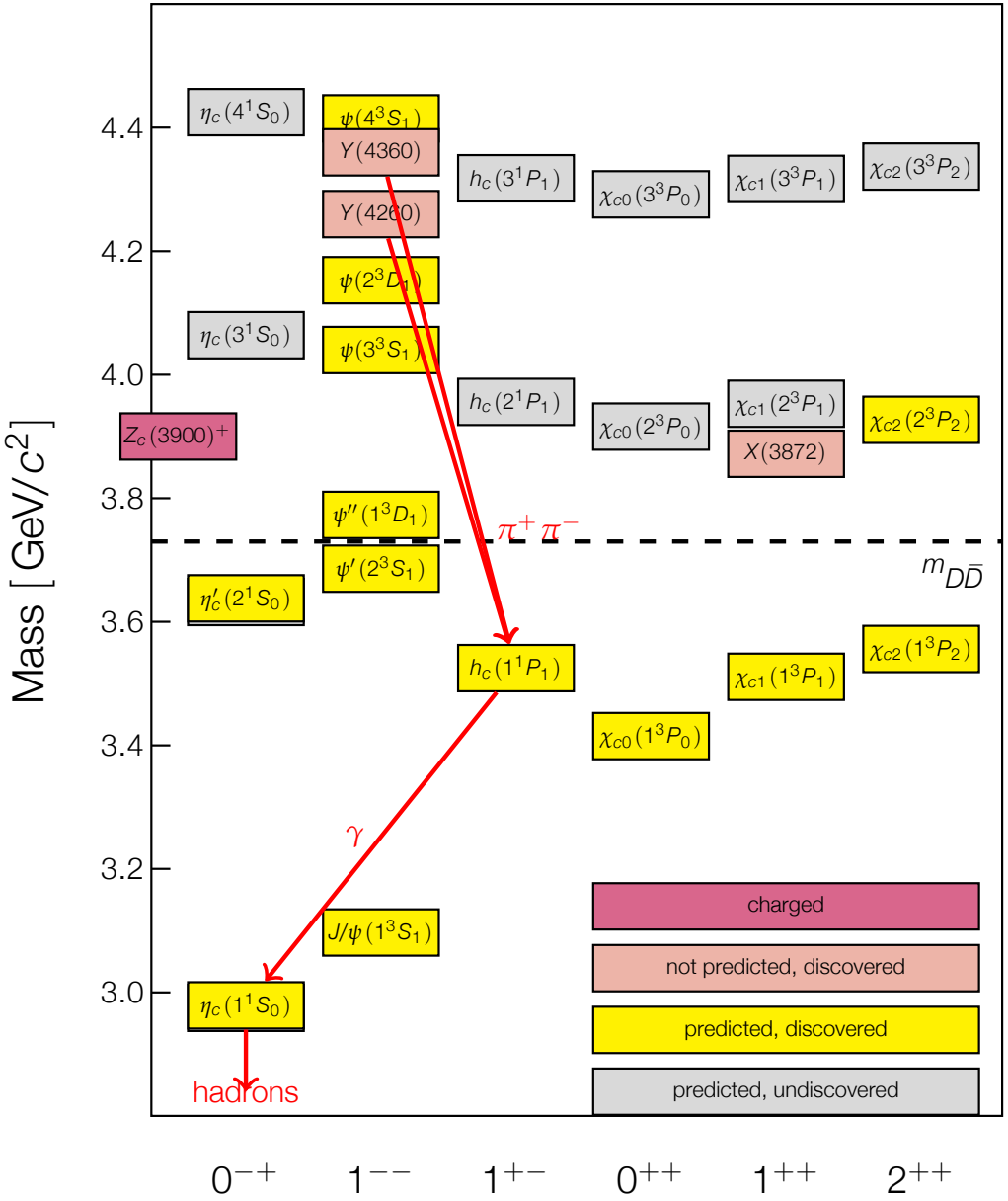
$$M = (3885.7^{+4.3}_{-5.7}(\text{stat.}) \pm 8.4(\text{syst.}))\ \text{MeV}/c^2$$

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

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

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

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

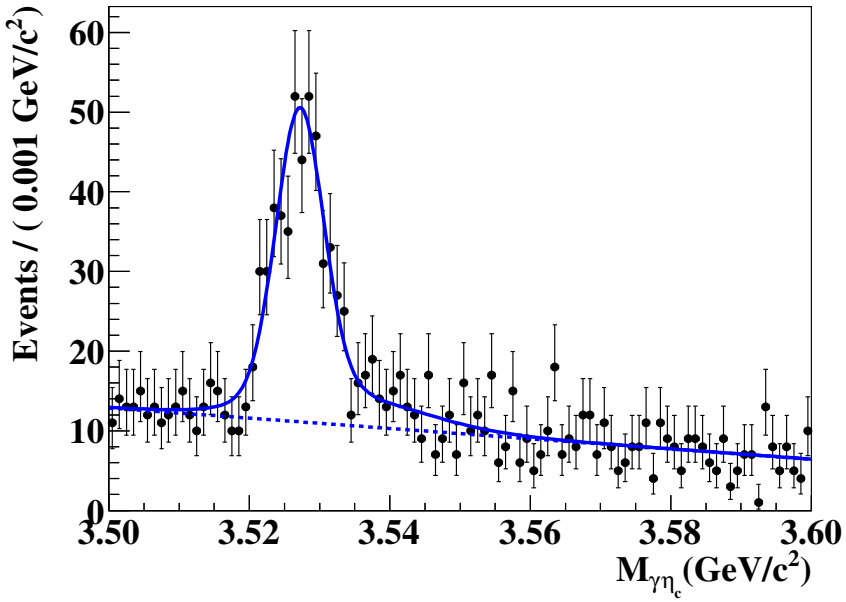


Exclusively reconstruct the process

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

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

$$\eta_c(1S) \to 16 \text{ decay channels}$$



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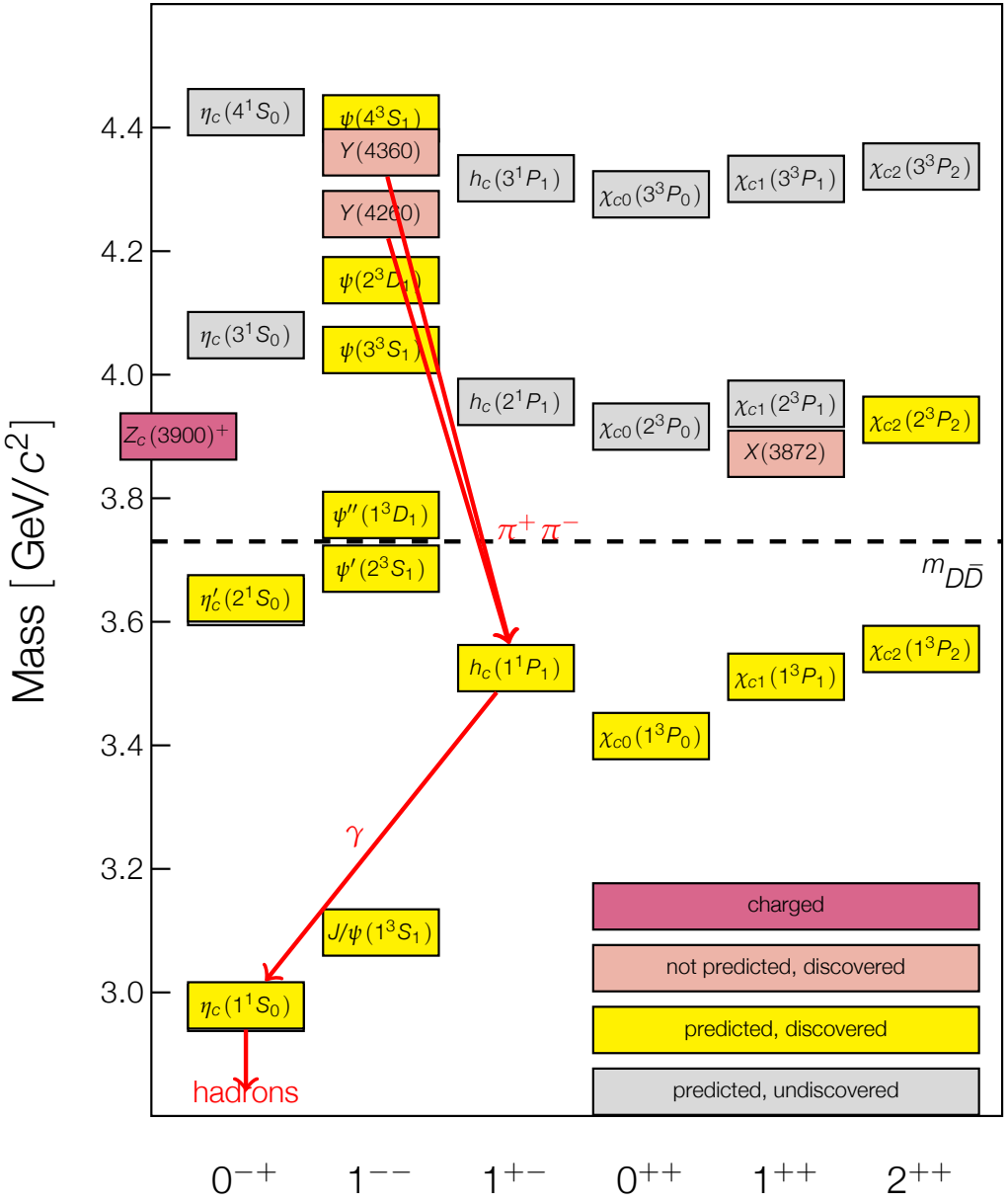
BESIII, PRL **111**, 242001 (2013)



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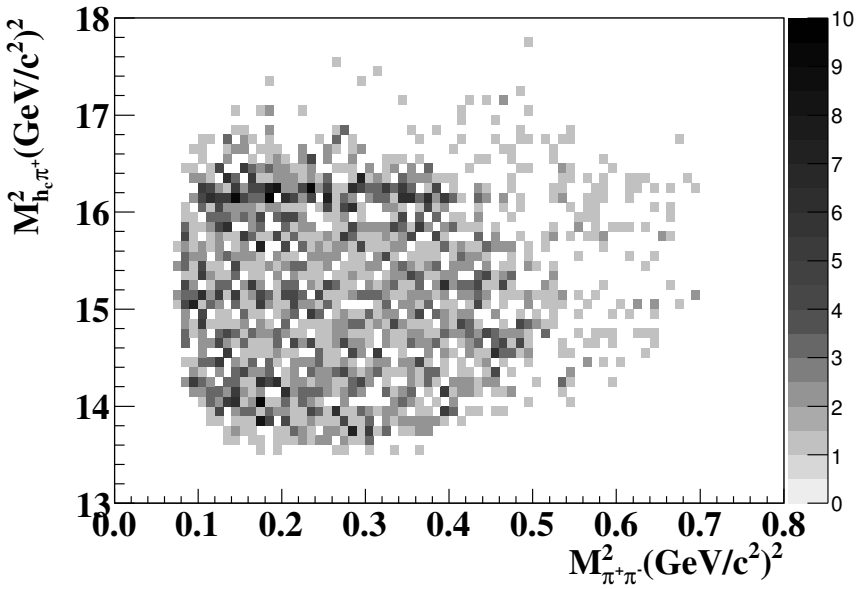
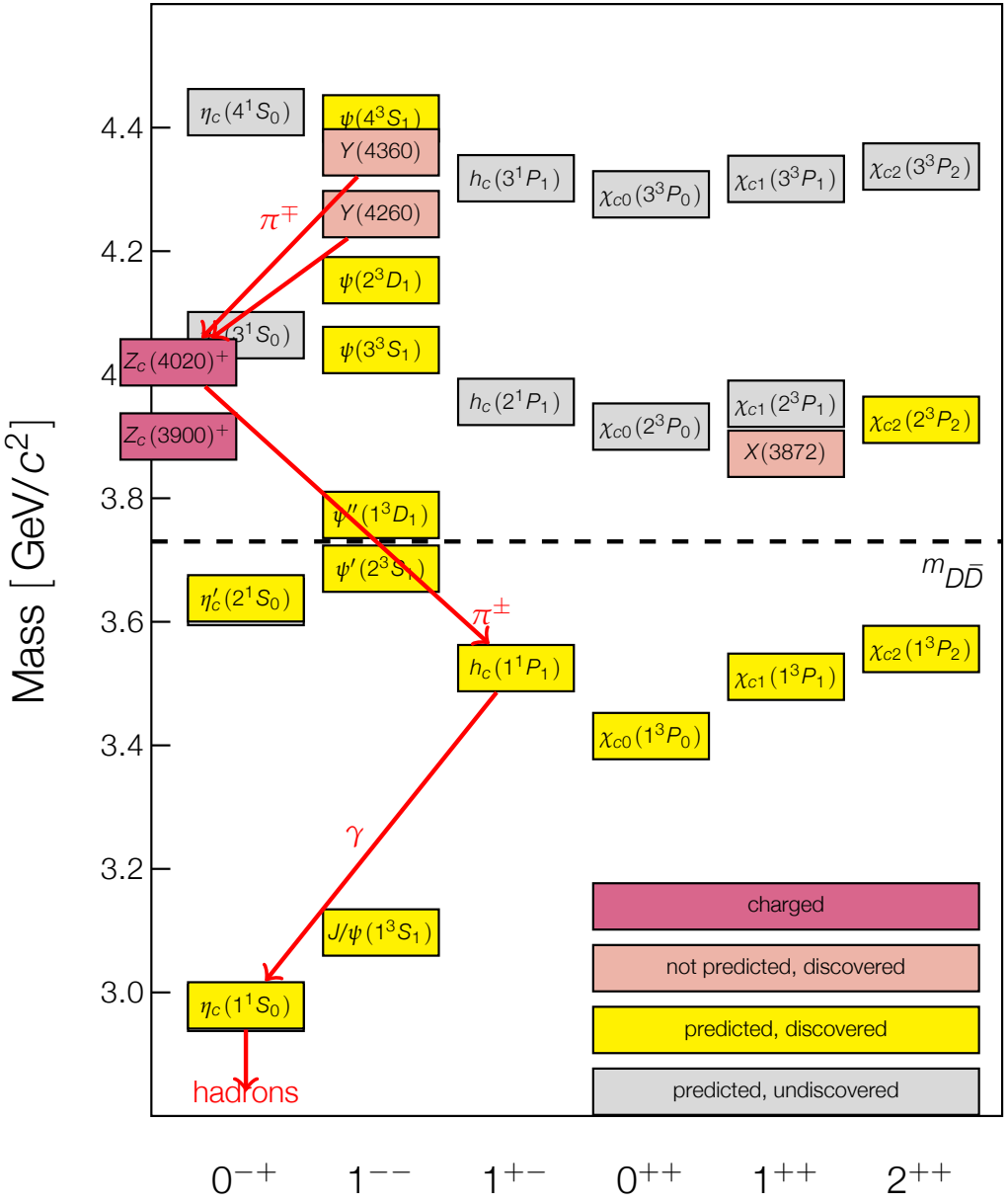
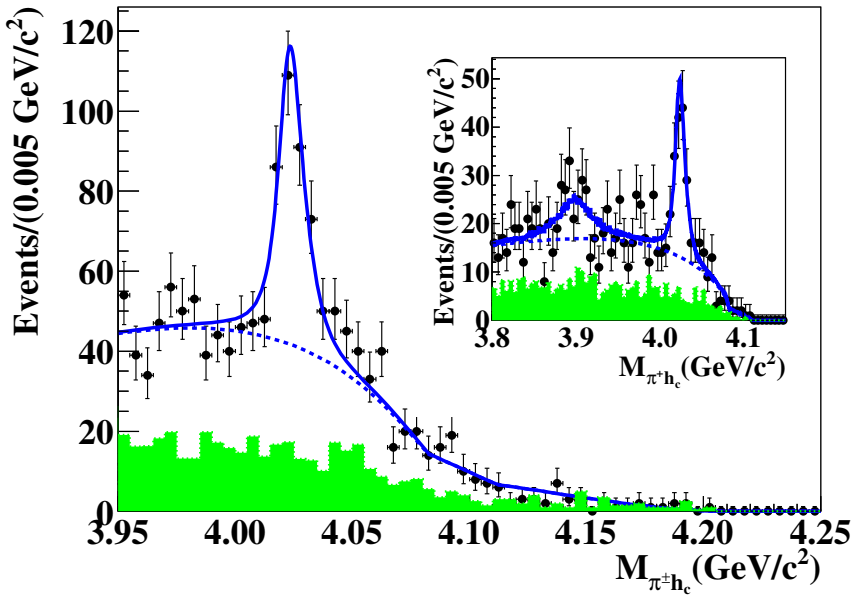


$e^+e^- \to h_c(1P)\pi^+\pi^-$

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





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

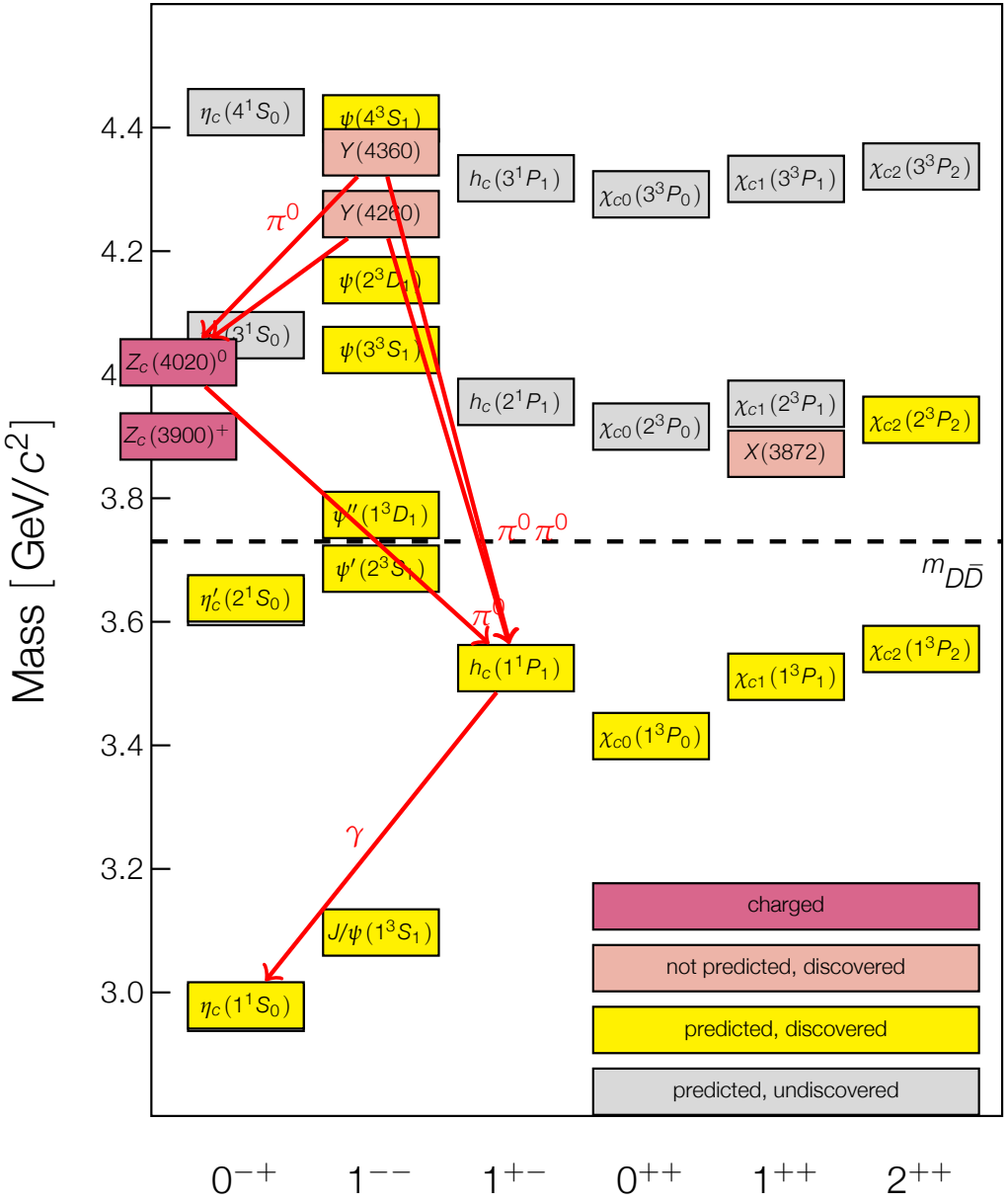
$$M = 4022.9 \pm 0.8 \pm 2.7\,\text{MeV}/c^2$$

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

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

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

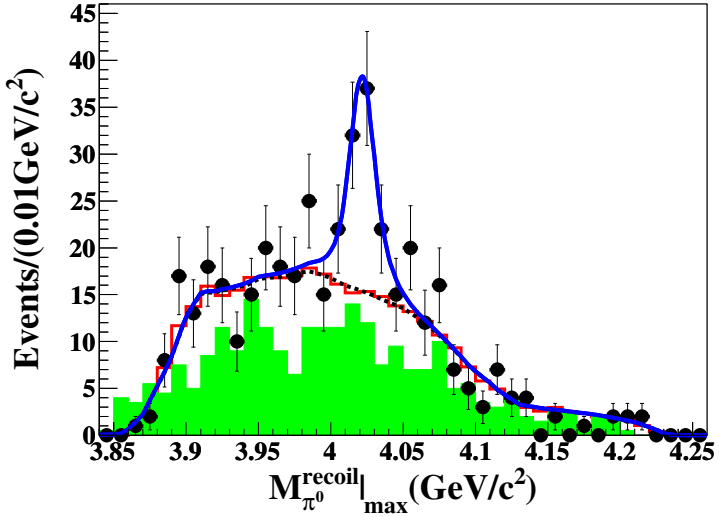
BESIII, PRL **113**, 212002 (2014)



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 $Z_c(4020)^+$



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

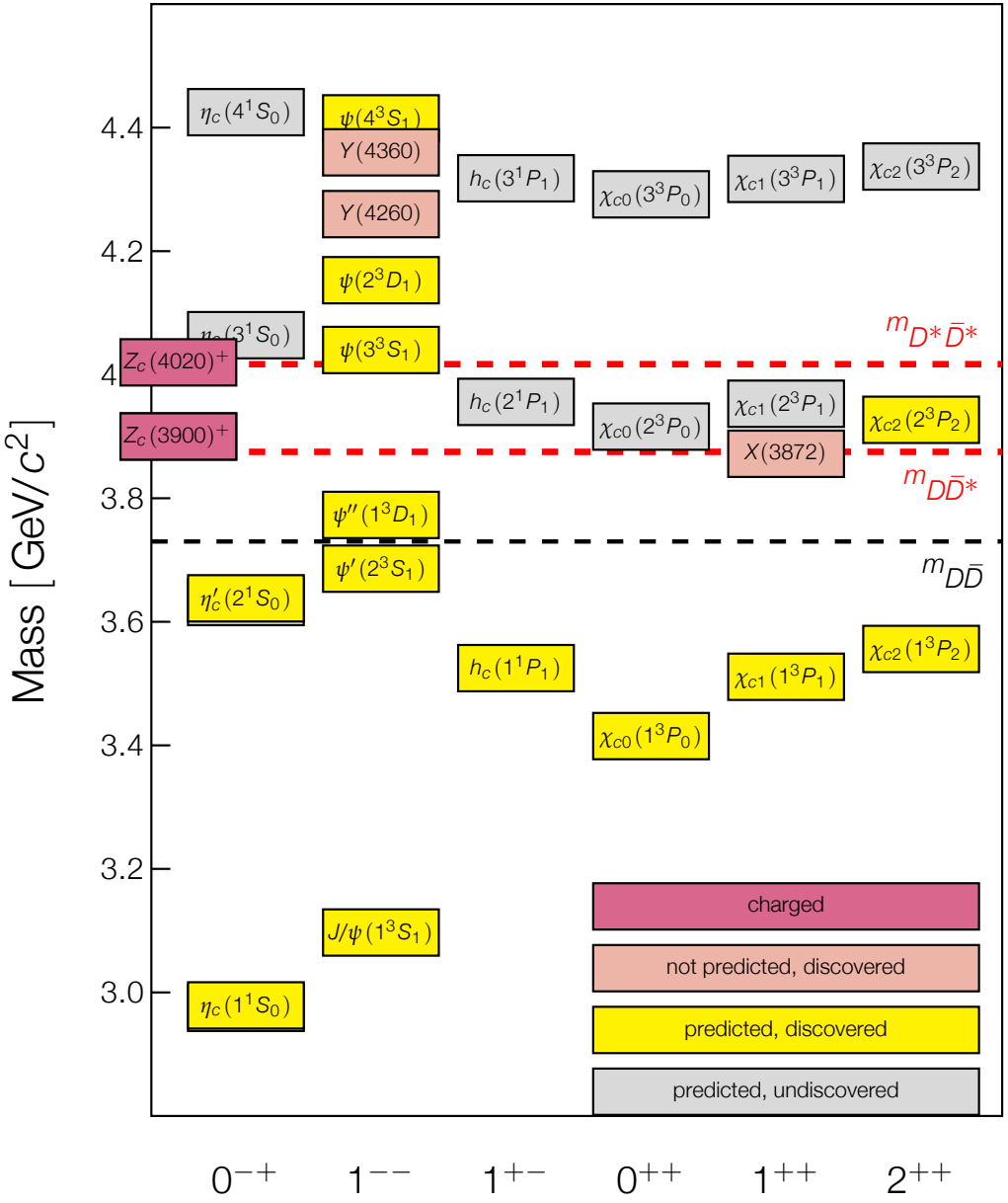
Γ fixed in the fit

Isospin triplet found!

Yet another mass threshold …

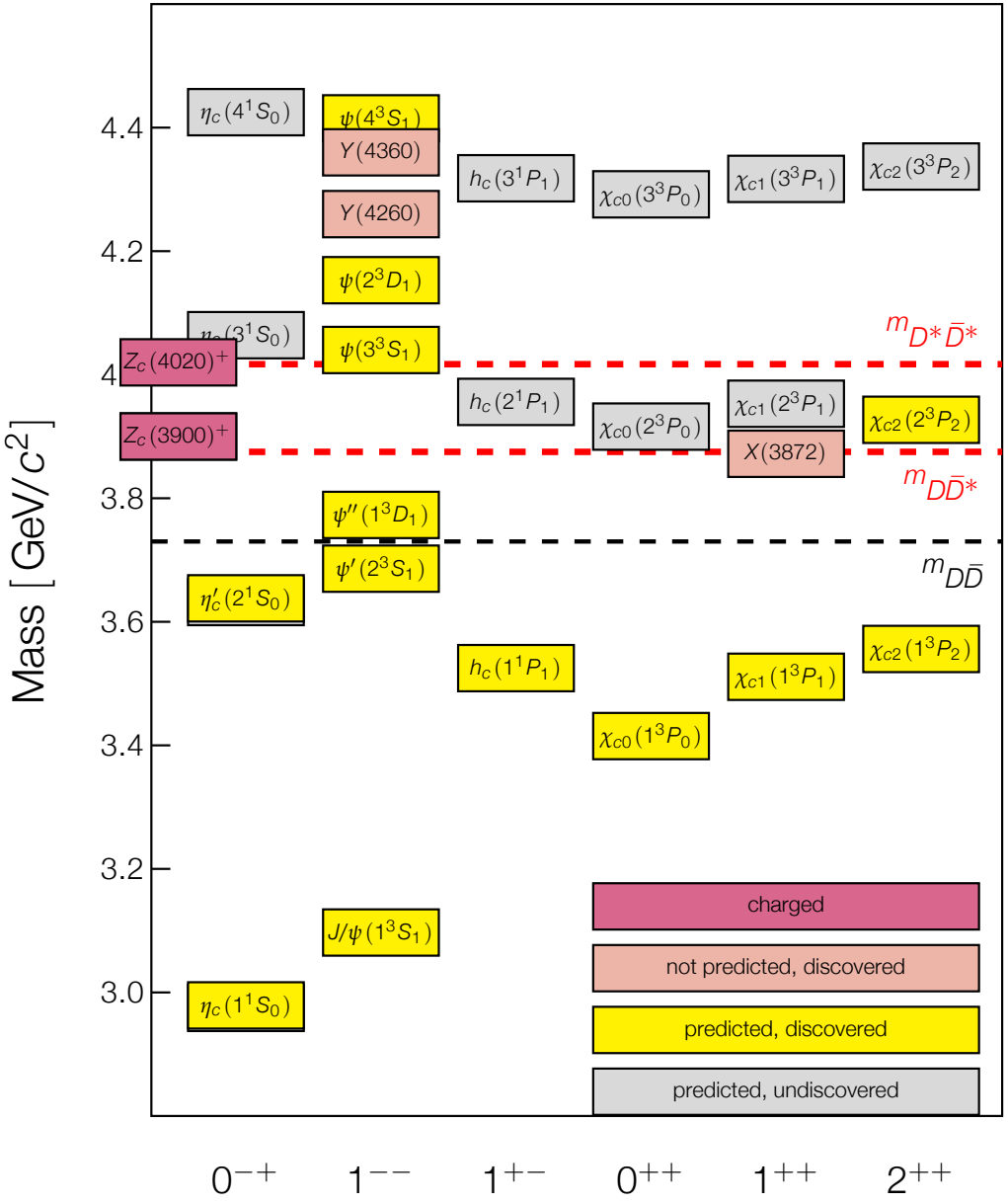
BESIII, PRL **112**, 132001 (2014)

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



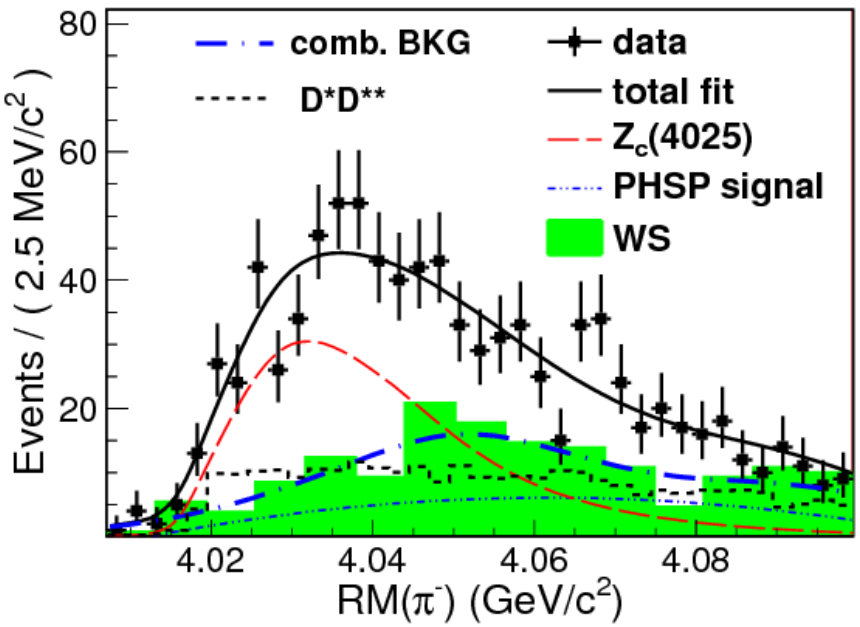
Yet another mass threshold …

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



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

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



…and BESIII sees structure in D^*D^*

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

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

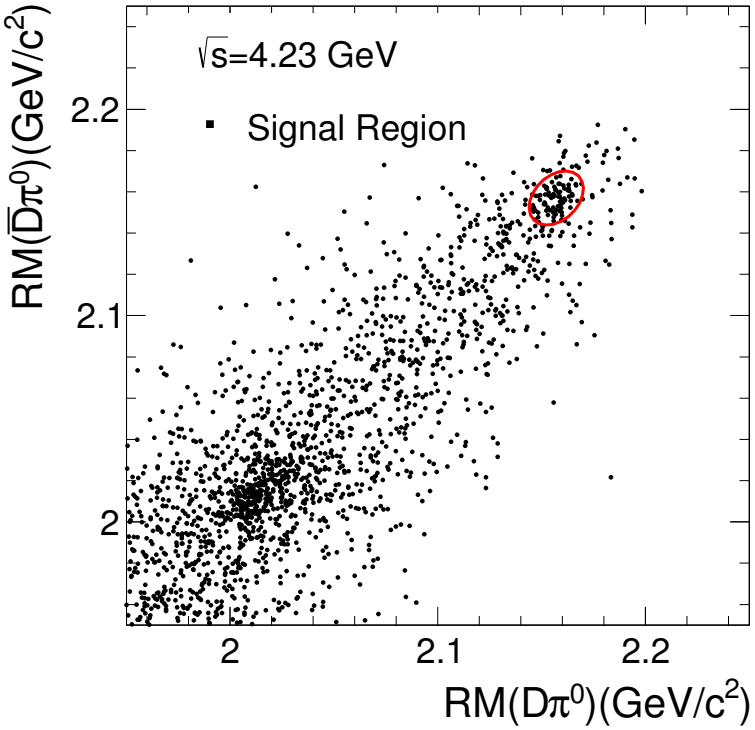
… and the neutral partner: $Z_c(4025)^0$

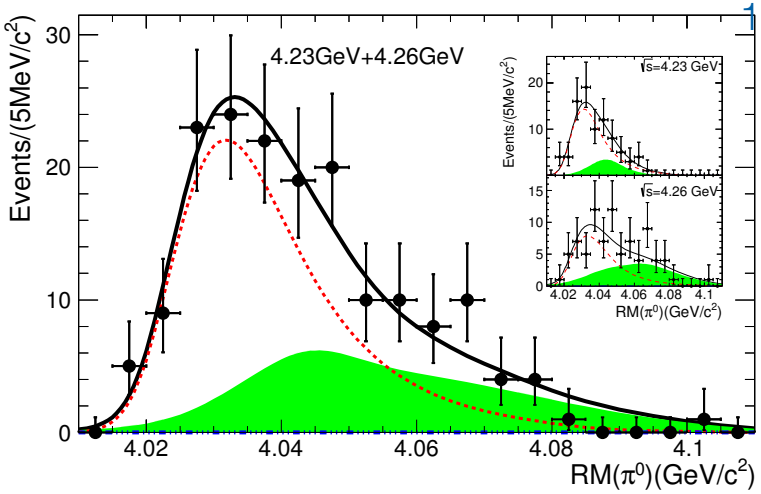
preliminary
1507.02404

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

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: $Z_c(4025)^0$

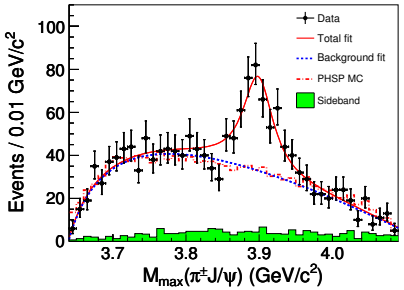
preliminary
1507.02404

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

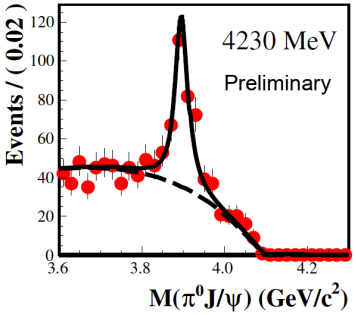
	Mass [MeV/c^2]	**Width [MeV]**	$\sigma(\mathbf{e^+e^- \to Z_c\pi \to D^*\bar{D}^*\pi})$ **[pb]**
$Z_c(4025)^+$	$4026.3 \pm 2.6 \pm 3.7$	$24.8 \pm 5.6 \pm 7.7$	$42.2 \pm 2.8 \pm 4.6$
$Z_c(4025)^0$	$4025.5^{+2.0}_{-4.7} \pm 3.1$	$23.0 \pm 6.0 \pm 1.0$	$43.4 \pm 8.0 \pm 5.4$

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

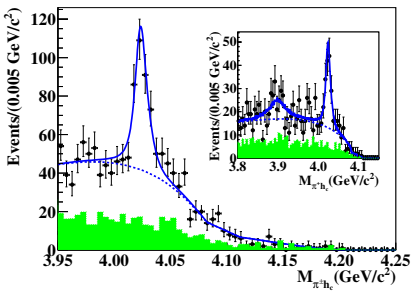
All the Z_cs from BESIII near $\sqrt{s} = 4.3\,\mathrm{GeV}$



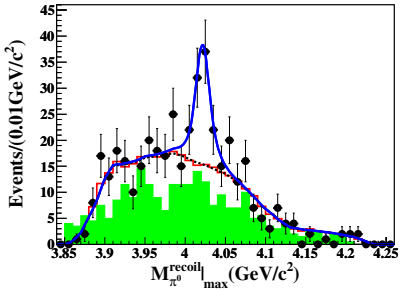
$e^+e^- \to \pi^-\pi^+ J/\psi$



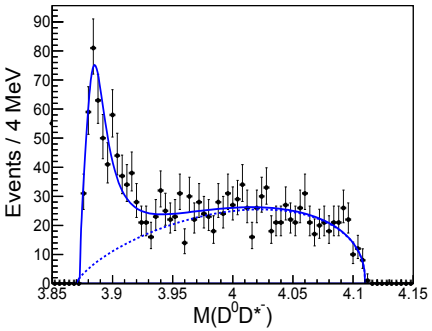
$e^+e^- \to \pi^0\pi^0 J/\psi$



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

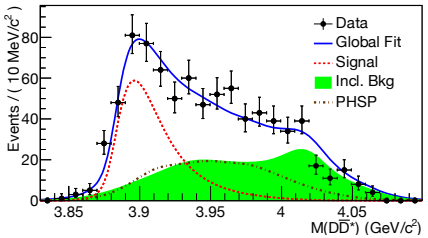


$e^+e^- \to \pi^0\pi^0 h_c$

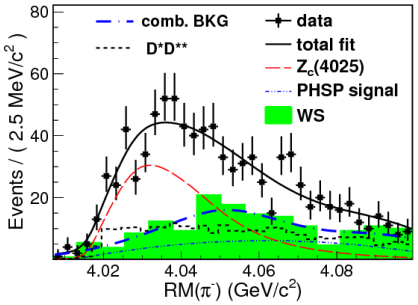


$e^+e^- \to \pi^-(D\bar{D}^*)^+$

$Z_c(3900)^+$?

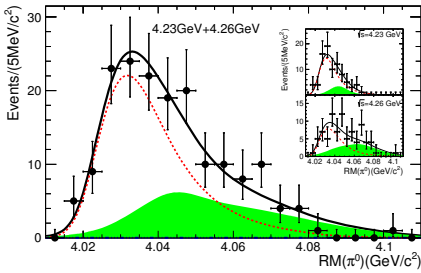


$Z_c(3900)^0$?



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

$Z_c(4020)^+$?

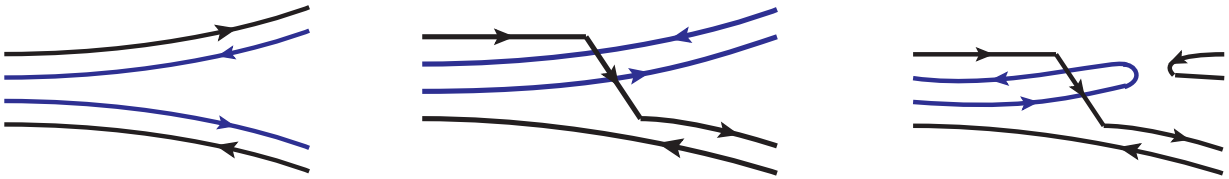


$Z_c(4020)^0$?

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

Other decay modes?

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



open charm hidden charm light mesons

threshold effects!

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

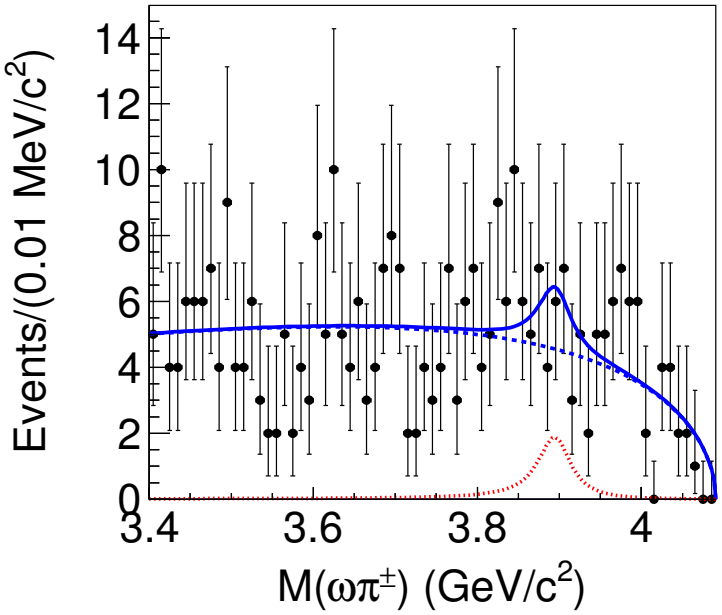
If $c\bar{c}$ in S-wave, annihilation could be 'easy' …

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

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

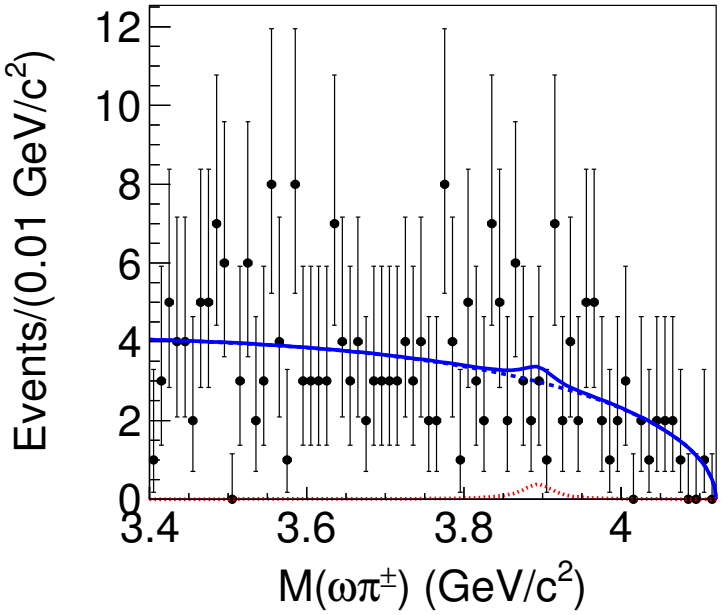
BESIII, PRD **92**, 032009 (2015)

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



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

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



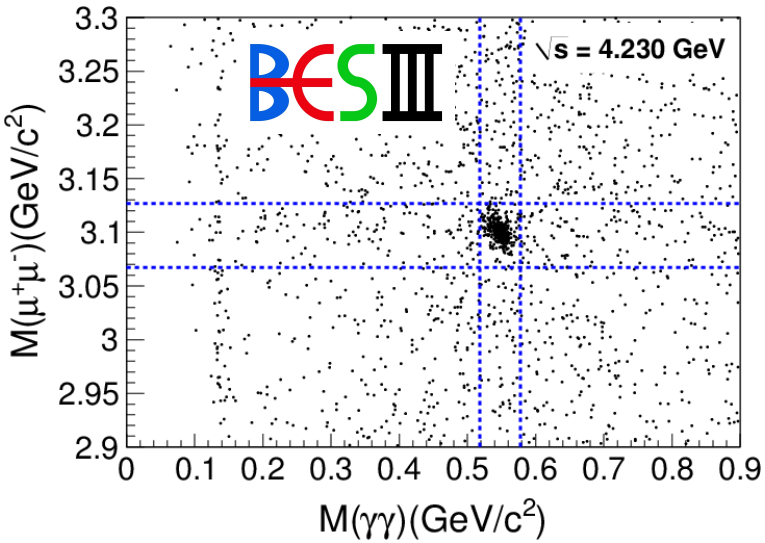
$\sigma(e^+e^- \to Z_c^+\pi^-, Z_c^+ \to \omega\pi^+) < 0.18\,\text{pb}$

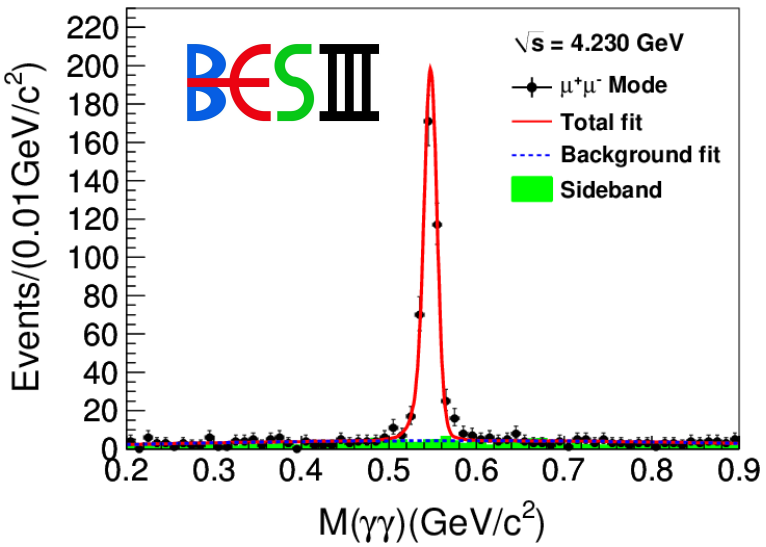
Compared to sum of $Z_c^+ \to J/\psi\,\pi^+$ and $Z_c^+ \to (D\bar{D}^*)^+$:

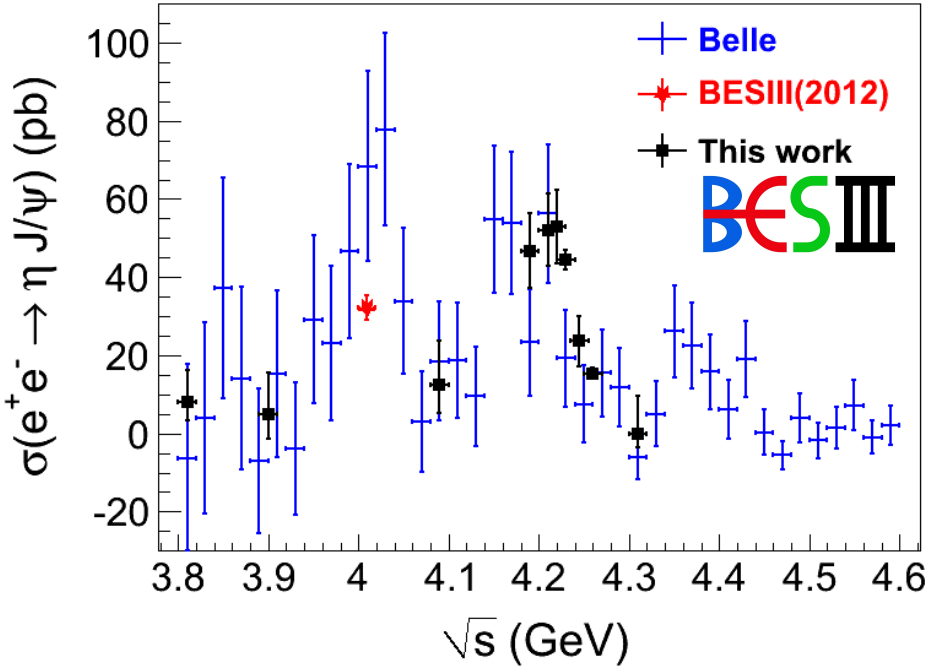
$$\Gamma(Z_c^+ \to \omega\pi^+) < 0.2\%\Gamma_{\text{tot}}$$

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

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







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

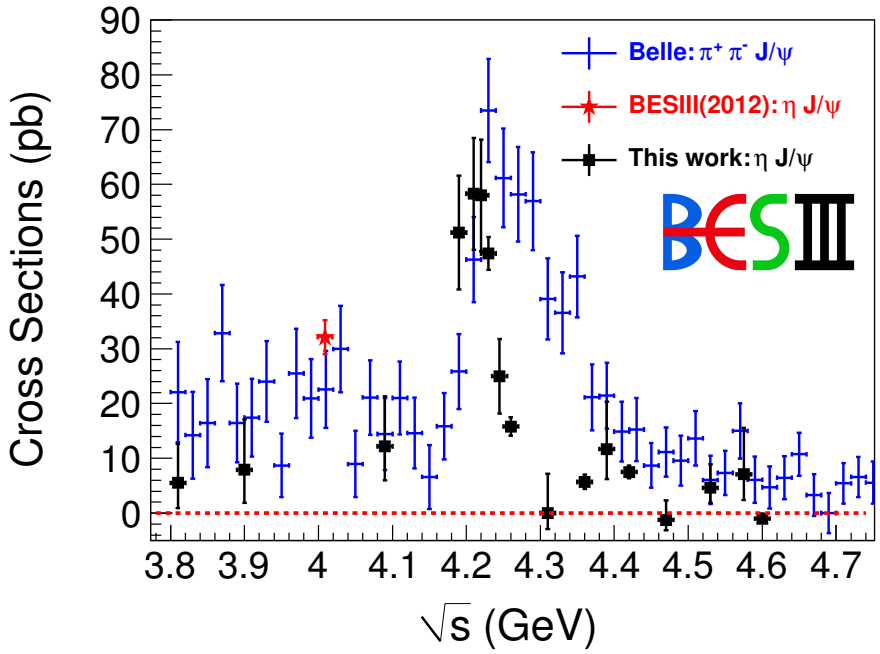
Good agreement,
significantly better precision

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)

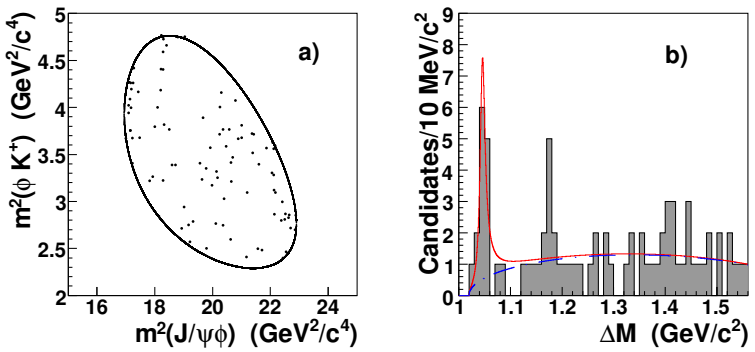


Compare to $e^+e^- \to \gamma_{\rm ISR}\pi^+\pi^- J/\psi$ from Belle, PRL **110**, 252002 (2013)

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

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

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

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

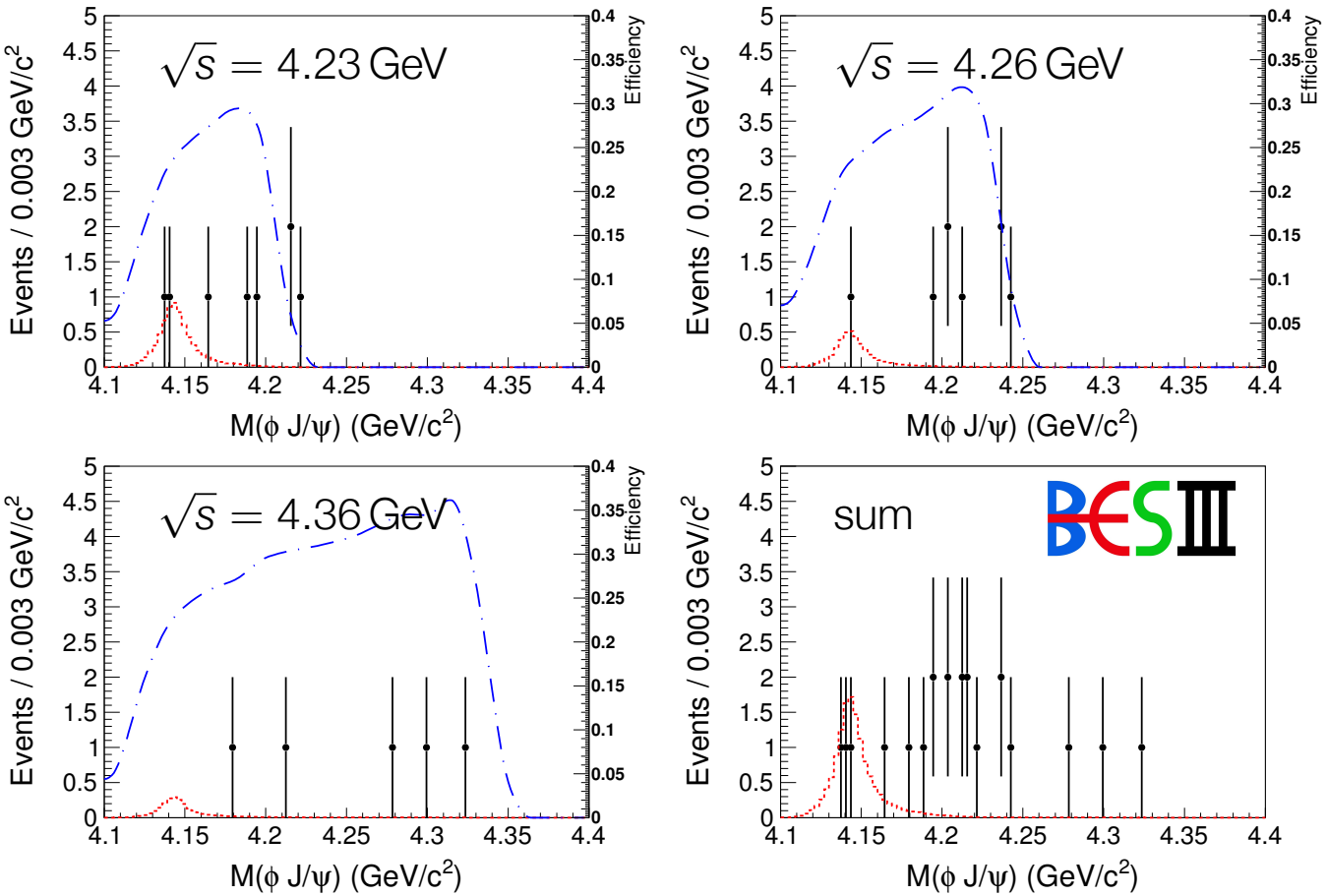
If both $Y(4260)$ and $Y(4140)$ are *charmonium hybrids*:
partial width of $Y(4260) \to \gamma Y(4140)$ may be up to several tens of keV
N. Mahajan, PLB **679**, 228 (2009)

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

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

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

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



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

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

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

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

$\sqrt{s}$/ GeV	4.23	4.26	4.36
$\sigma \times \mathcal{B}(X(3872))$/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 $\mathcal{B}(X(3872) \to J/\psi\pi^+\pi^-) \sim 5\%$:

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

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 $B^0 \to J/\psi\,\pi^+K^-$!)
- 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 ($\Delta E \sim 100\,\text{MeV}$) with $0.5\,\text{fb}^{-1}$ per point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