New Hadronic States at BESIII

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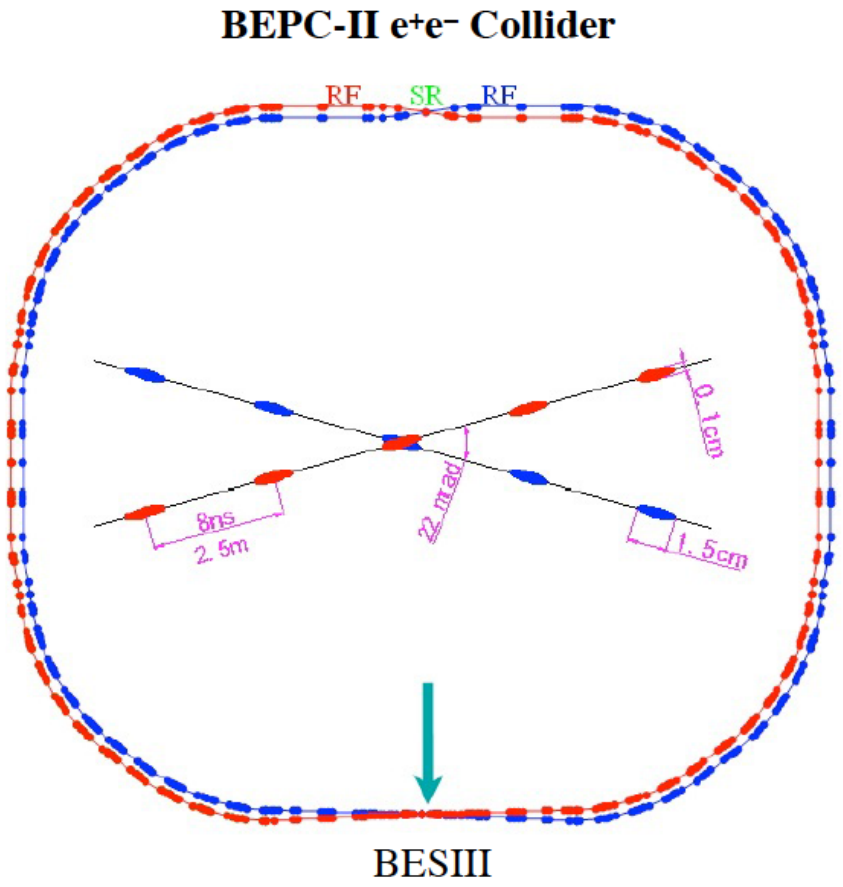
Carnegie Mellon

BESIII

BESIII at BEPCII

- The physics goals of BESIII cover a diverse range:
  - Light hadron spectroscopy, charm physics, τ physics, charmonium physics
- e^+e^- collisions in the charmonium region
  - Use the properties and decays of charmonium states to study QCD



BESIII at BEPCII

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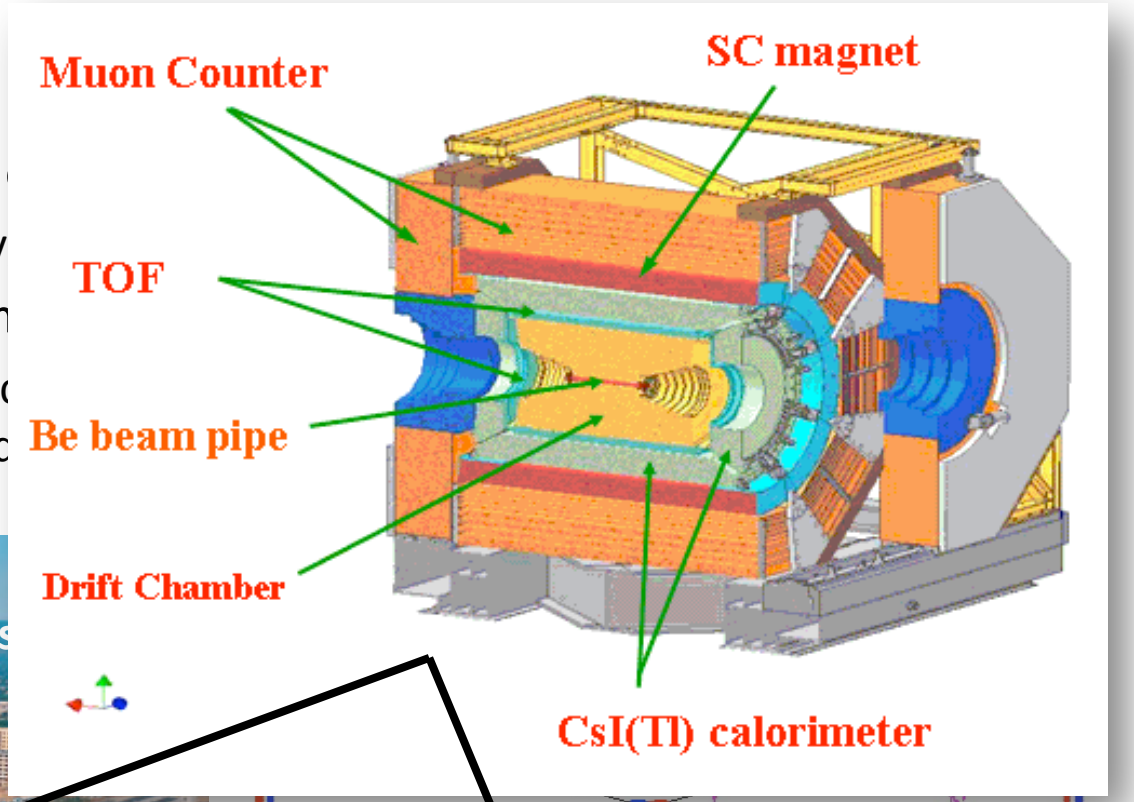

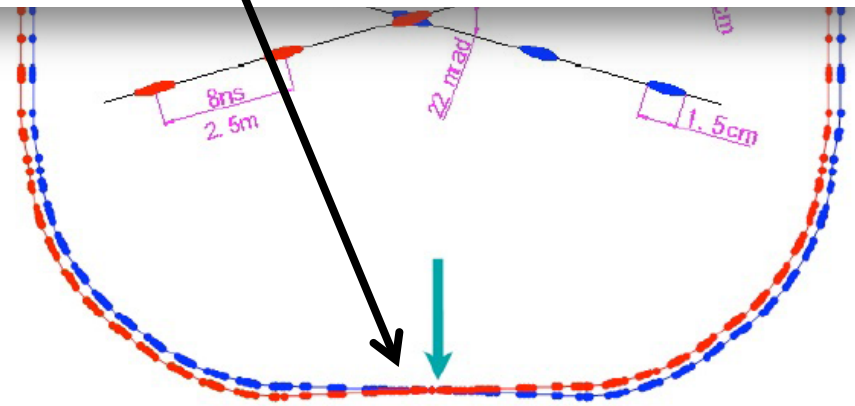

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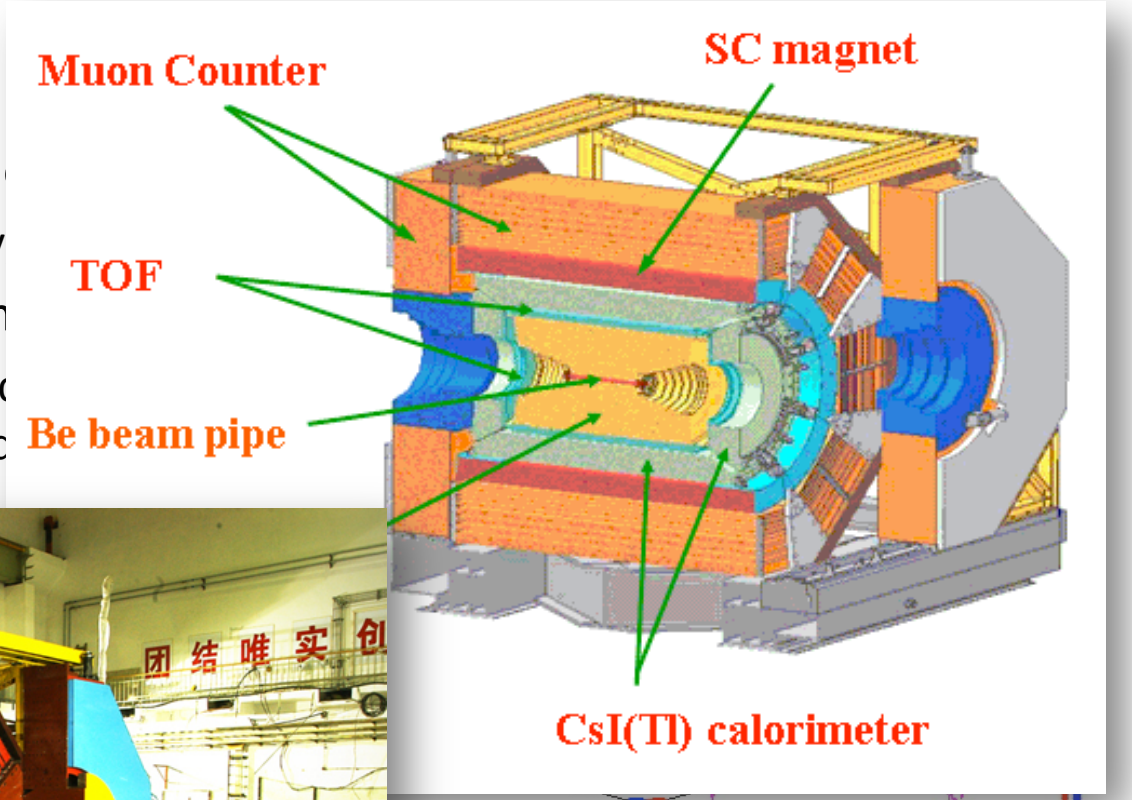
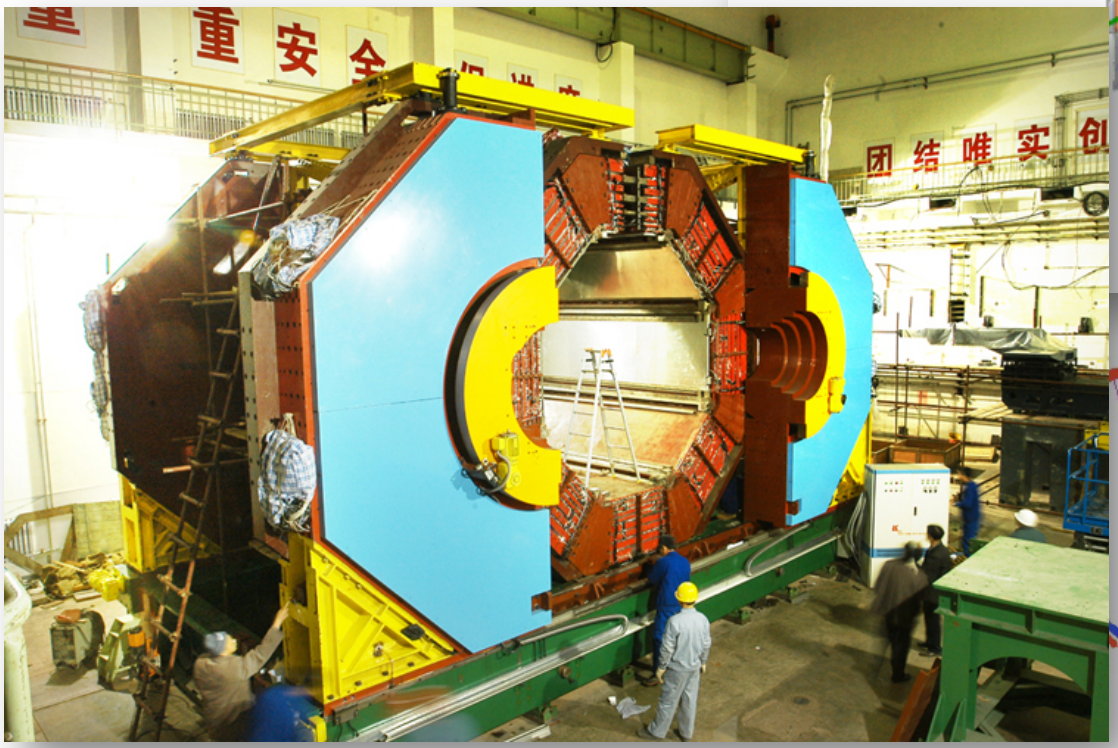
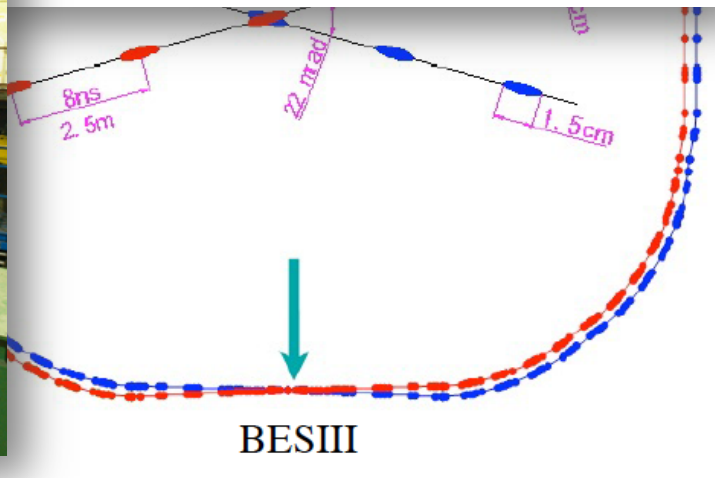


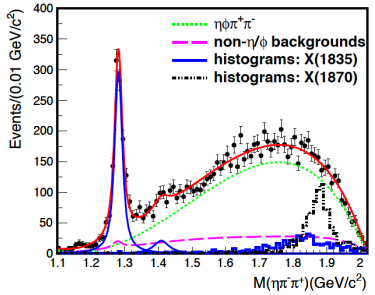




BESIII at BEPCII

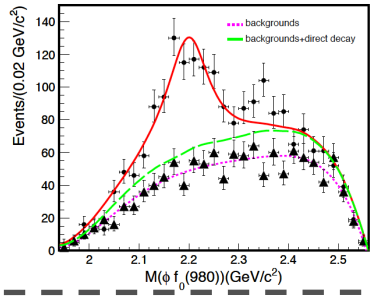
- The physics goals of BESIII cover a diverse range:
  - **Light hadron spectroscopy,** charm physics, τ physics, charmonium physics

BESIII, arXiv:1412.5258

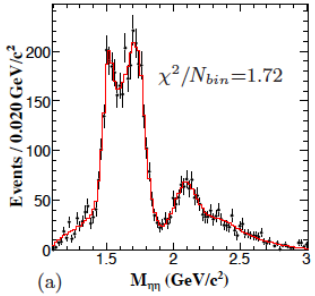


$$J/\psi \to \eta\phi\pi^+\pi^-$$

- Observed Y(2175): possible strangeonium counterpart of Y(4260)
- Observed η(1295): existence is questionable

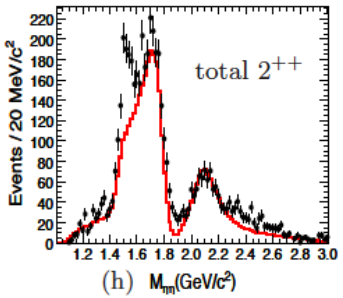


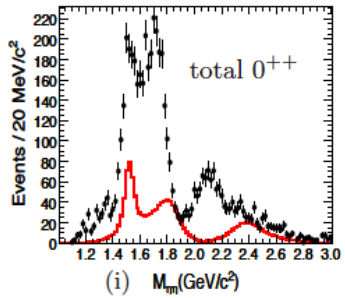
PRD 87, 092009 (2013)



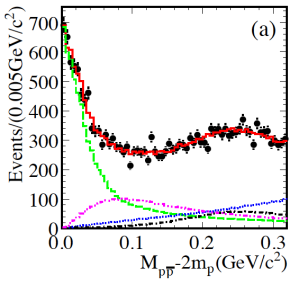
Partial wave analysis of $J/\psi \to \gamma\eta\eta$

- $f_0(1710)$ and $f_0(2100)$ are dominant scalars
- $f_0(1500)$ exists (8.2σ)
- $f_2'(1525)$ is the dominant tensor
- $f_2(1810)$ and $f_2(2340)$ exist (6.4 and 7.6σ)
- No evidence for $f_J(2220)$



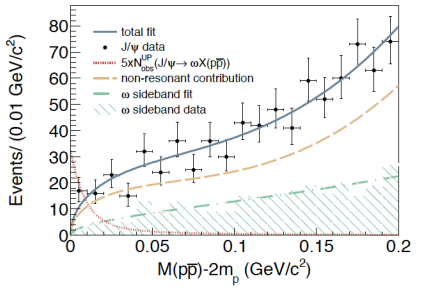


PRL 108, 112003 (2012)



Spin-Parity Analysis of $p\bar{p}$ Mass Threshold Structure in J/ψ and ψ' Radiative Decays

- 0^{-+} structure observed in pp̄ spectra
- Not apparent in J/ψ → ωpp̄



PRD 87, 112004 (2013)

BESIII at BEPCII

- The physics goals of BESIII cover a diverse range:
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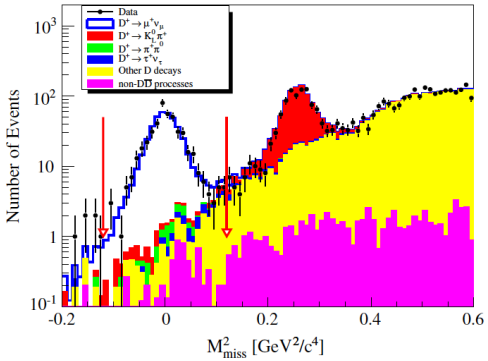
Precision measurements of $B(D^+ \to \mu^+\nu_\mu)$

$$B(D^+ \to \mu^+\nu_\mu) = [3.71 \pm 0.19(\text{stat}) \pm 0.06(\text{sys})] \times 10^{-4}$$

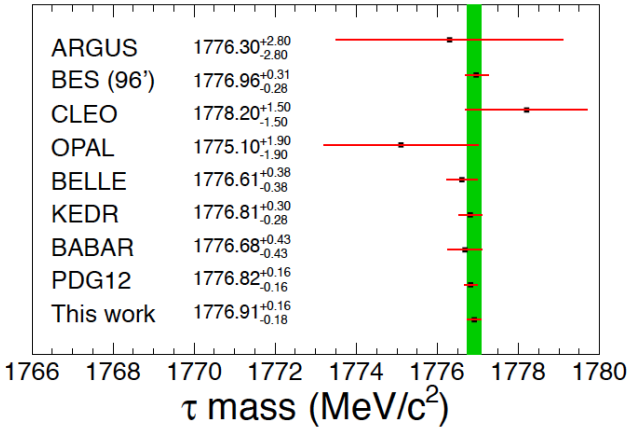
- Using $|V_{cd}|$ from global SM fit, f_{D+} = (203.2 ± 5.3 ± 1.8) MeV
- Using lattice QCD prediction for f_{D+}, $|V_{cd}|$ = 0.2210 ± 0.0058 ± 0.0047
- In either case, these are the most precise results for these quantities

BESIII: PRD 89, 051104(R) (2014)

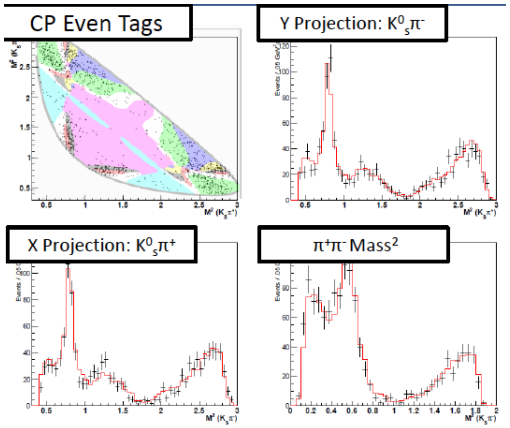


Precision Measurement of the Mass of the τ Lepton

BESIII: PRD 90, 012001 (2014)



Measurement of the relative strong-phase



- Model independent measurement of the strong phase difference between D^0 and $\bar{D}^0$ decays to $K^0\pi^+\pi^-$
- Significant improvement in a previously statistically limited measurement

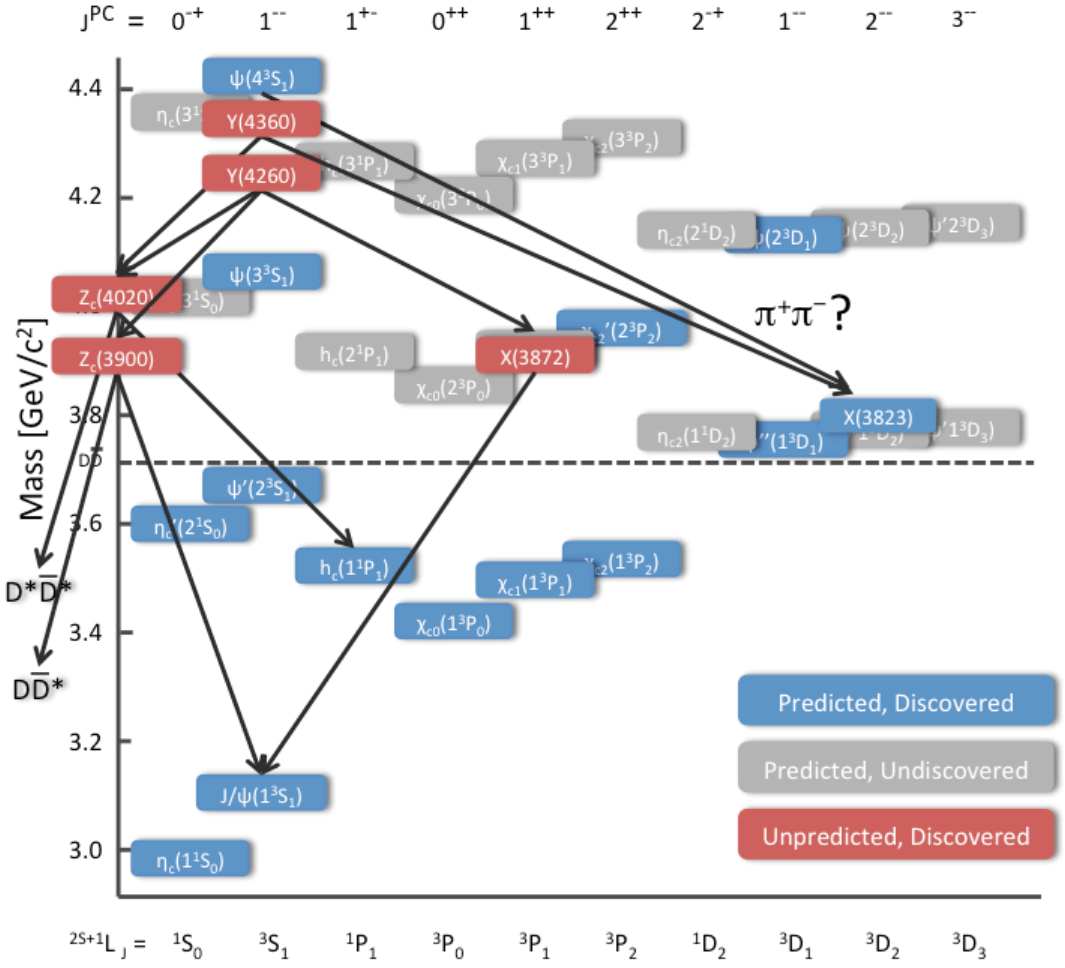
BESIII

Preliminary

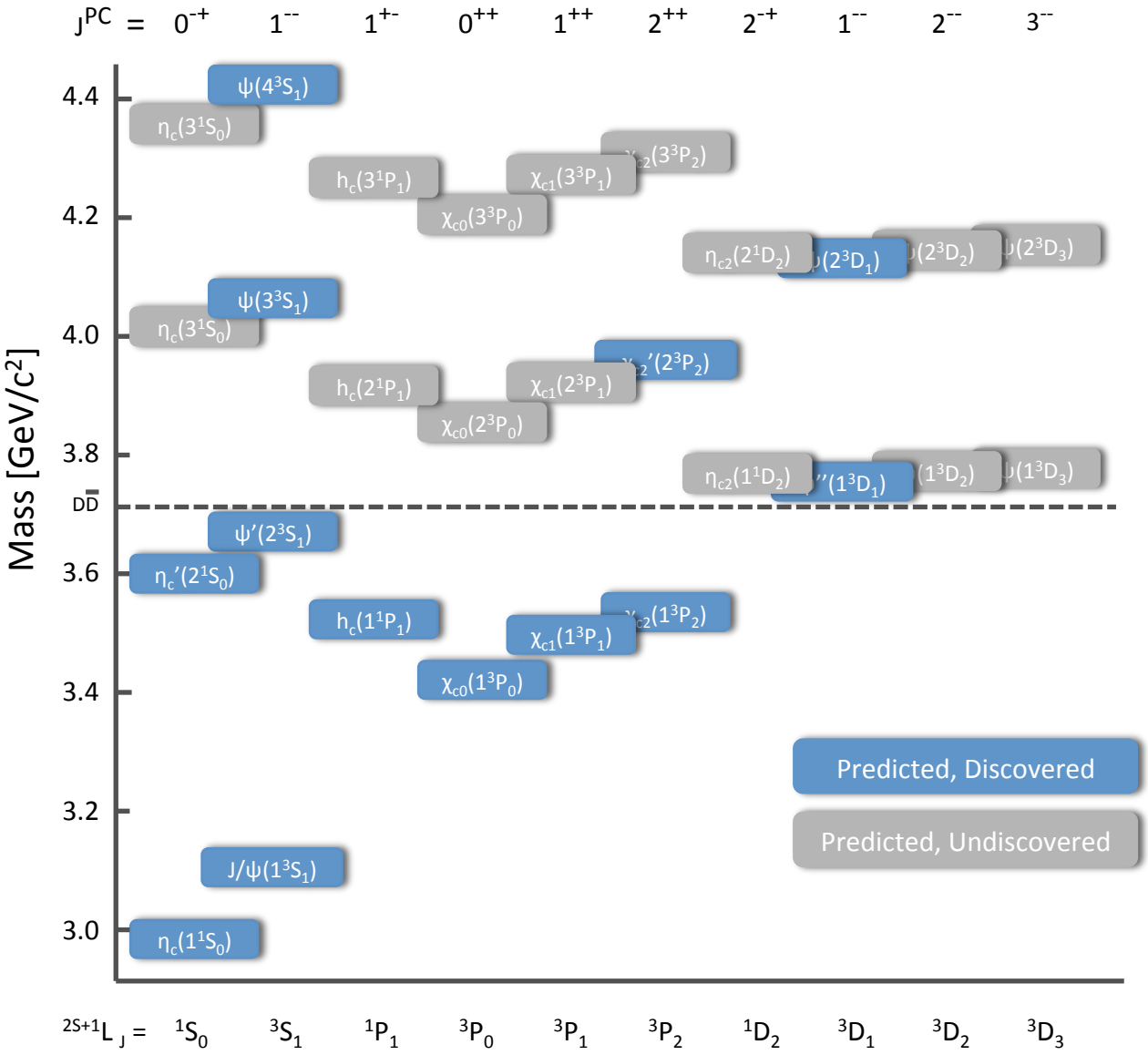
BESIII at BEPCII

- The physics goals of BESIII cover a diverse range:
  - Light hadron spectroscopy, charm physics, τ physics, **charmonium physics**

- XYZ physics:
  - $Z_c(3900)^{\pm}$ to $\pi^+\pi^- J/\psi$ (2013)
  - *$Z_c(3900)^0$ to $\pi^0\pi^0 J/\psi$ (Prelim.)*
  - *$Z_c(3885)^{\pm}$ to $(D\bar{D}^*)^{\pm}$ (2014, Prelim.)*
  - $Z_c(4020)^{\pm}$ to $\pi^+\pi^- h_c$ (2013)
  - $Z_c(4020)^0$ to $\pi^0\pi^0 h_c$ (2014)
  - $Z_c(4025)^{\pm}$ to $(D^*\bar{D}^*)^{\pm}$ (2014)
  - Observation of X(3823) (2015)
  - Y(4260) to γX(3872) (2014)
  - *e^+e^- to $\pi^+\pi^-\omega$ (Prelim.)*
  - Y(4260) to $\omega\chi_{c0}$ (2015)
  - e^+e^- to (η/π^0) J/ψ (2015)
  - *e^+e^- to η' J/ψ (Prelim.)*



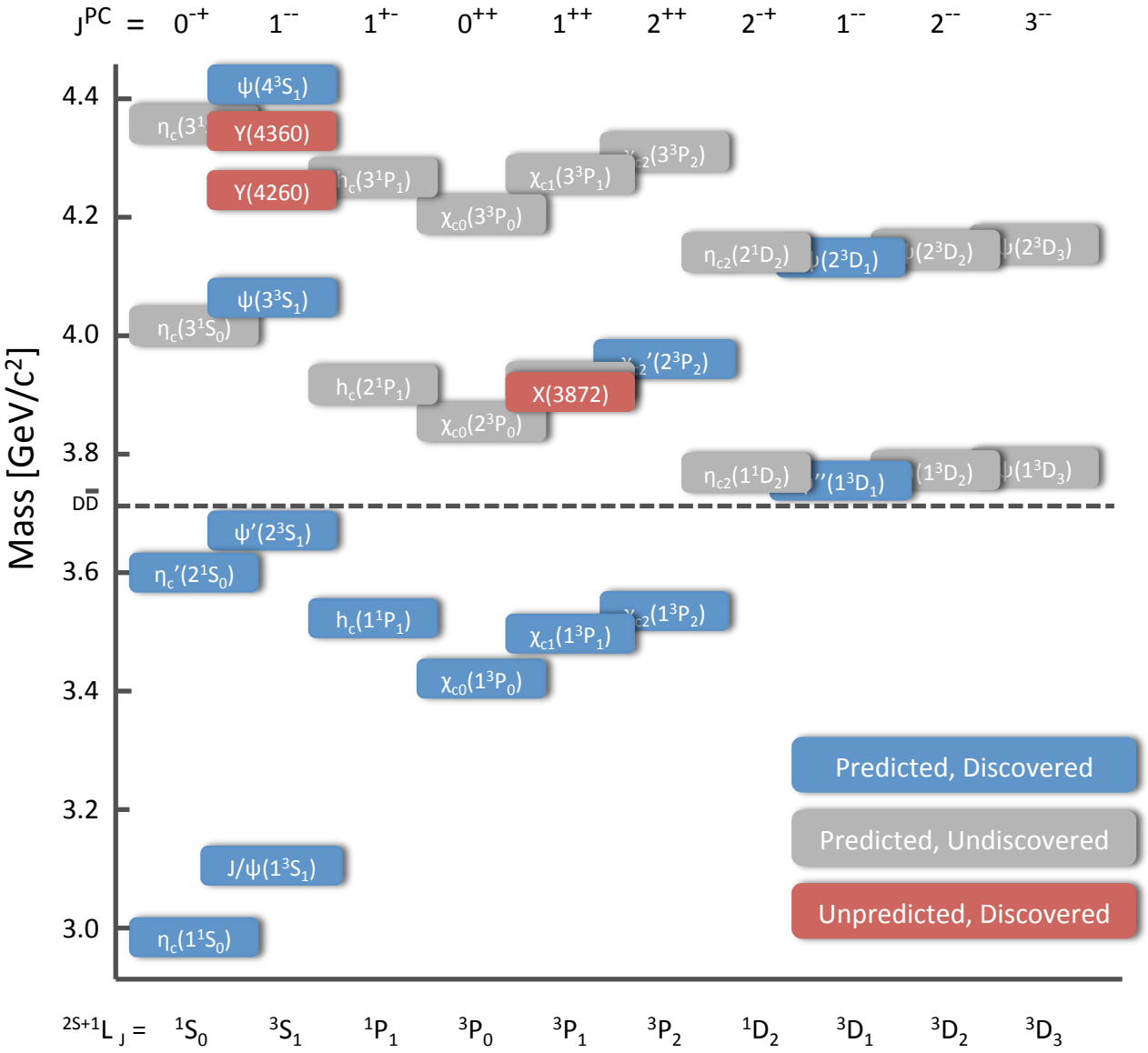
The charmonium spectrum



- Below $D\bar{D}$ threshold, all states have been observed
  - Charm anti-charm potential model describes these states well
- Goal: Obtain a better understanding of charmonium and charmonium-like states
- Method: Study pattern of masses, transitions between states, etc.

Predictions from: Barnes, Swanson, and Godfrey, PRD 72 054026 (2005)

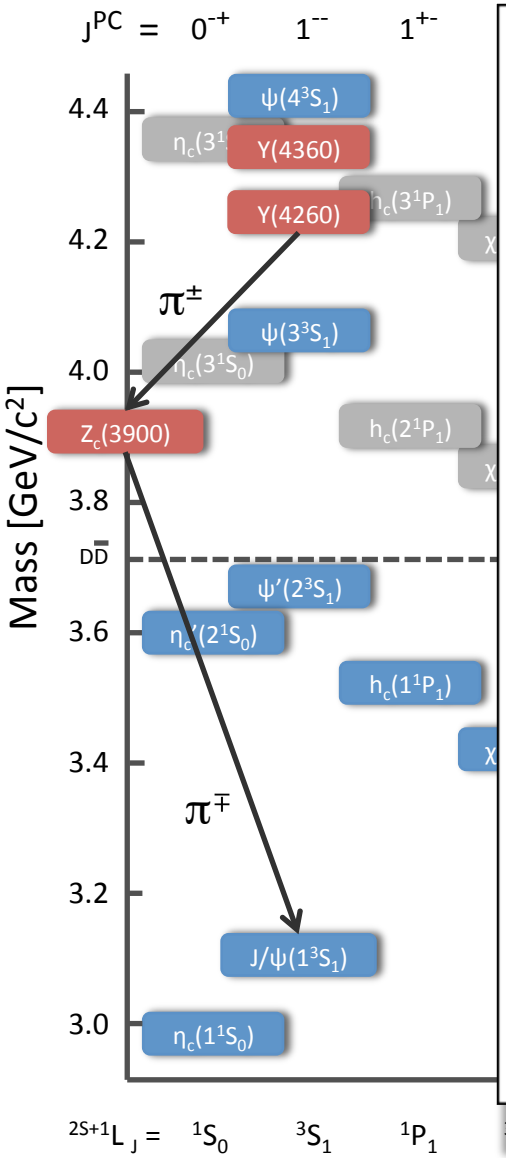
The charmonium spectrum



- More than a decade ago, unconventional charmonium-like states began appearing
  - Unexpectedly small decay widths to open charm
- Y(4260)
  - $\sigma(D\bar{D}):\sigma(\pi\pi J/\psi) \sim 4:1$
  - Compare with ~ 500:1 for $\psi(3770)$!
  - Quantum numbers 1^{--}
    - Perfect for study at BESIII
- Similarly for Y(4360)
  - Decays dominantly to $\pi\pi\psi'$

Predictions from: Barnes, Swanson, and Godfrey, PRD 72 054026 (2005)

The charmonium spectrum



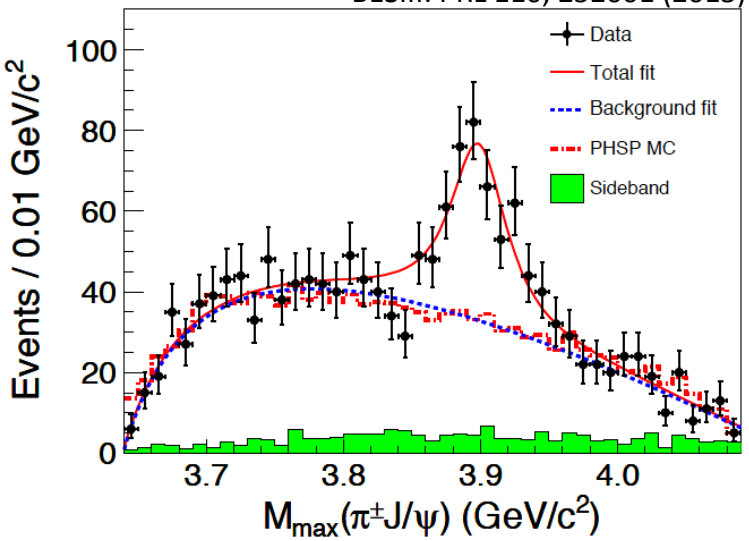
- Study e^+e^- annihilation to $\pi^+\pi^- J/\psi$ at $E_{CM} = 4.260$ GeV

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

$\Gamma = (46 \pm 10 \pm 20)$ MeV

Significance $> 8\sigma$

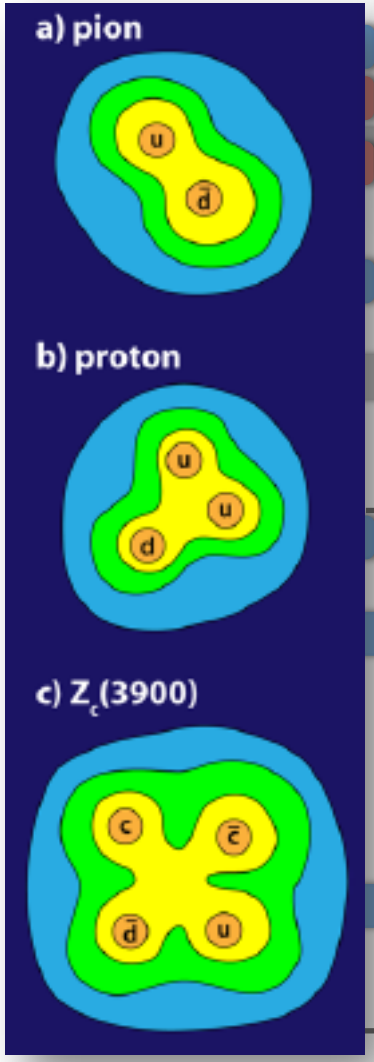
BESIII: PRL 110, 252001 (2013)



- Charged charmonium-like structure, $Z_c(3900)^{\pm}$
- Confirmed by Belle: PRL 110, 252002 (2013) and CLEO: PLB 727, 366 (2013)

The charmonium spectrum

J^{PC} = 0^{-+} 1^{--}

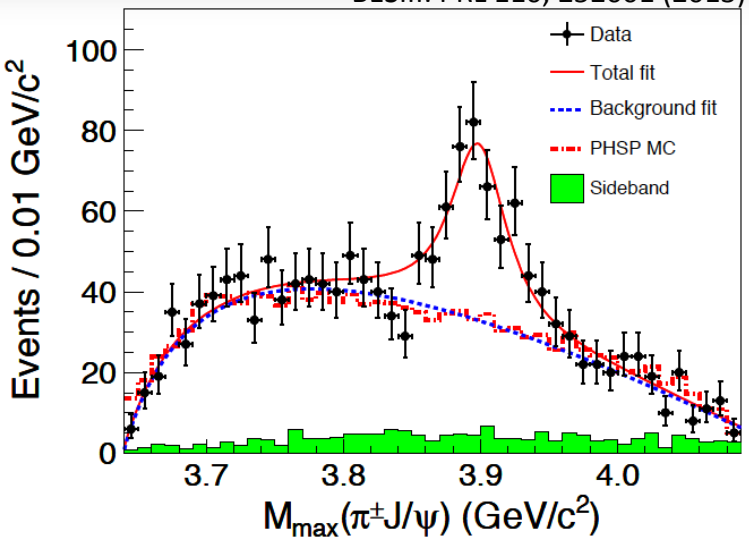


Viewpoint: New Particle Hints at Four-Quark Matter

Eric Swanson, *University of Pittsburgh, Pittsburgh, PA 15260, USA*

Published June 17, 2013 | Physics **6**, 69 (2013) | DOI: 10.1103/Physics.6.69

BESIII: PRL 110, 252001 (2013)



- Charged charmonium-like structure, $Z_c(3900)^{\pm}$
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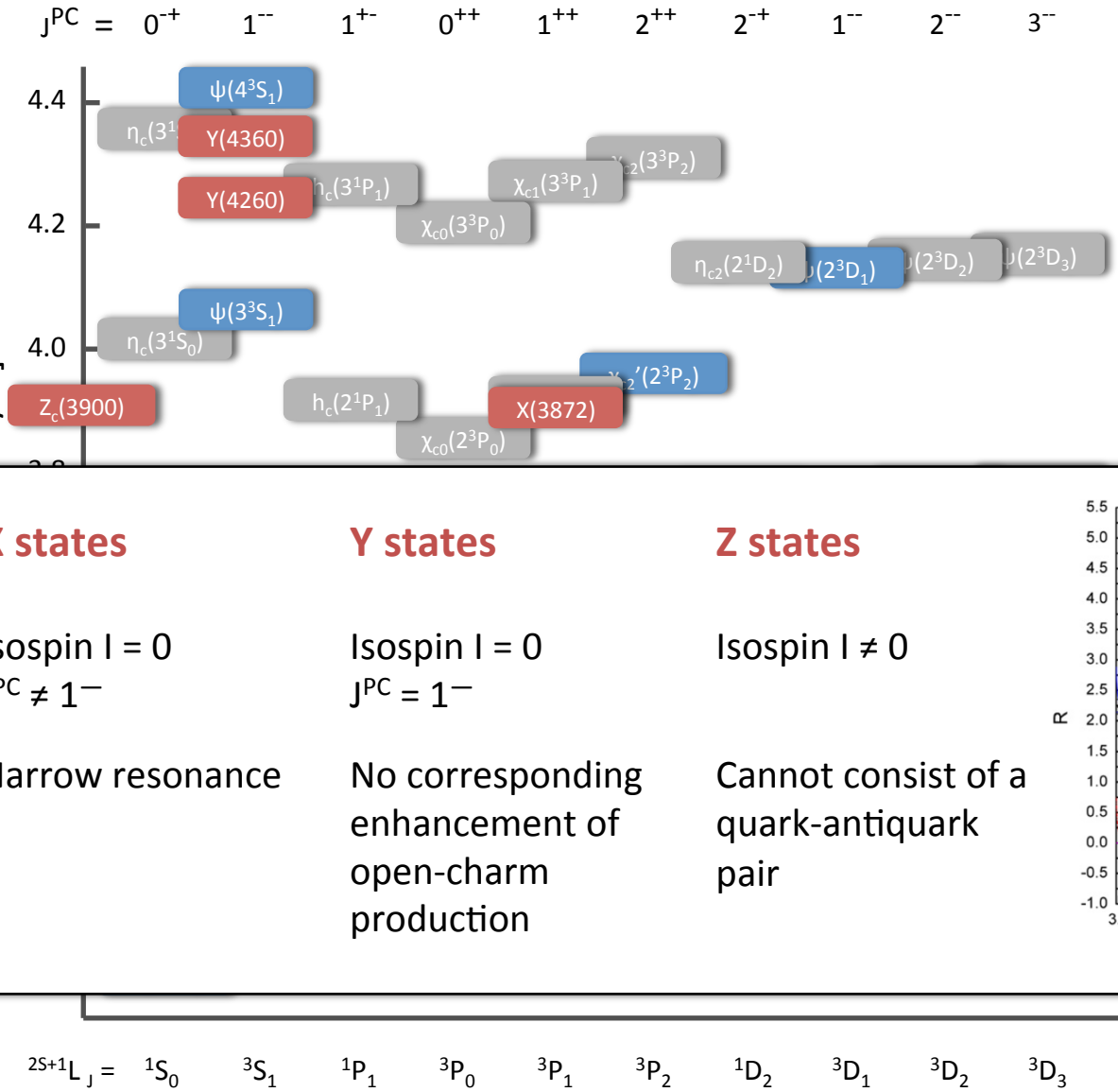
$^{2S+1}L_J$ = $^1S_0$ $^3S_1$ $^1P_1$ $^3P_0$ $^3P_1$ $^3P_2$ $^1D_2$ $^3D_1$ $^3D_2$ $^3D_3$

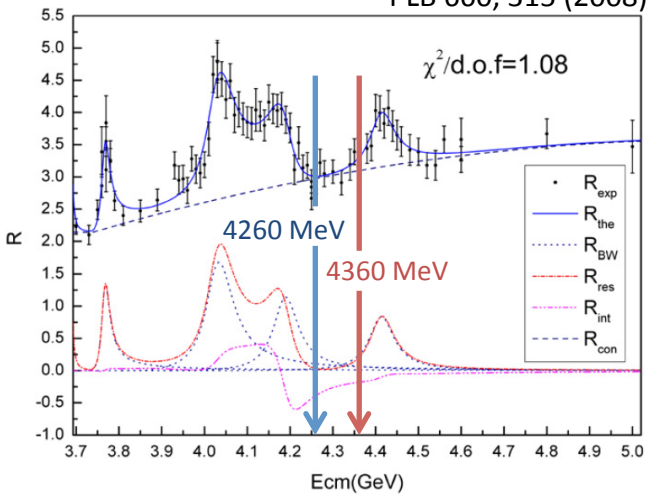
The charmonium spectrum



- More than a decade ago, unconventional charmonium-like states began appearing
- Y states:
  - Unexpectedly small decay widths to open charm
  - Dominantly to ππψ'

X states	Y states	Z states
Isospin I = 0 $J^{PC} \neq 1^-$	Isospin I = 0 $J^{PC} = 1^-$	Isospin I ≠ 0
Narrow resonance	No corresponding enhancement of open-charm production	Cannot consist of a quark-antiquark pair

PLB 660, 315 (2008)

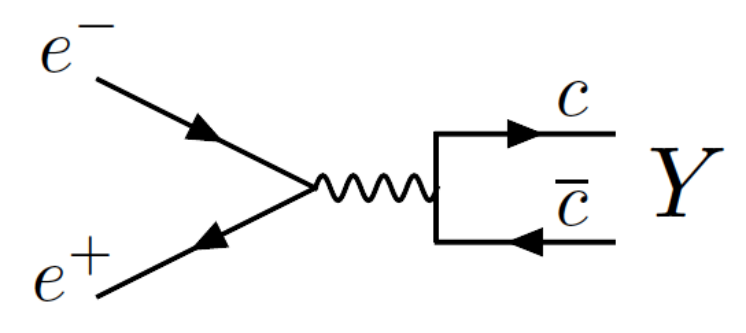


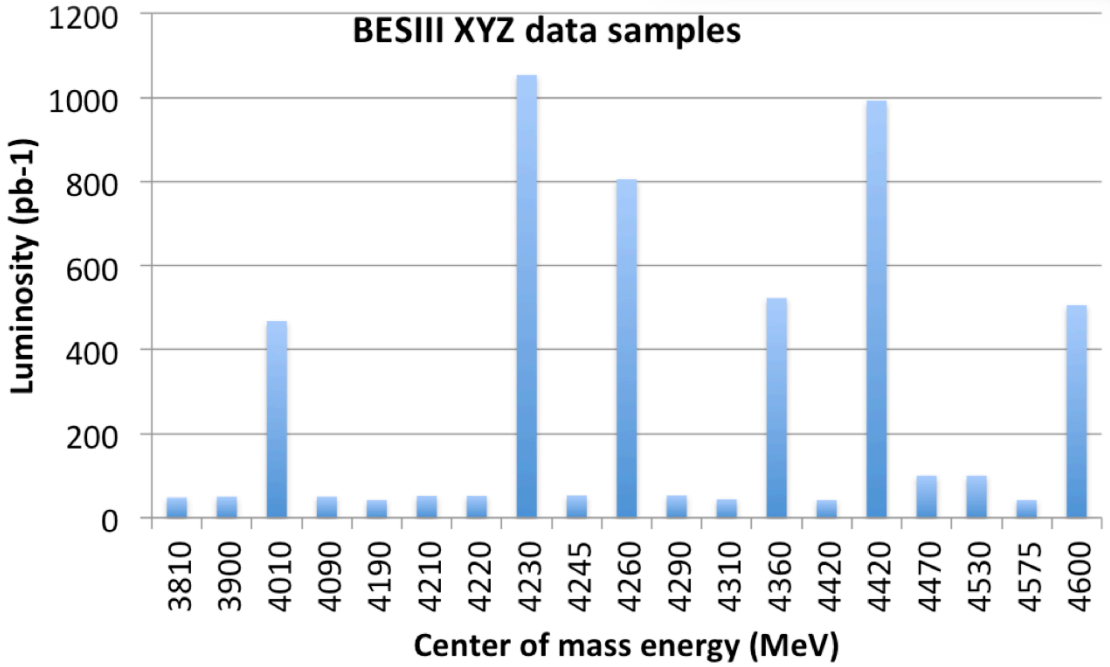
The charmonium spectrum

BESIII can produce Y states directly in e^+e^- annihilation

Search for new exotic states Y decays

Investigate the hidden and open charm decays of XYZ states



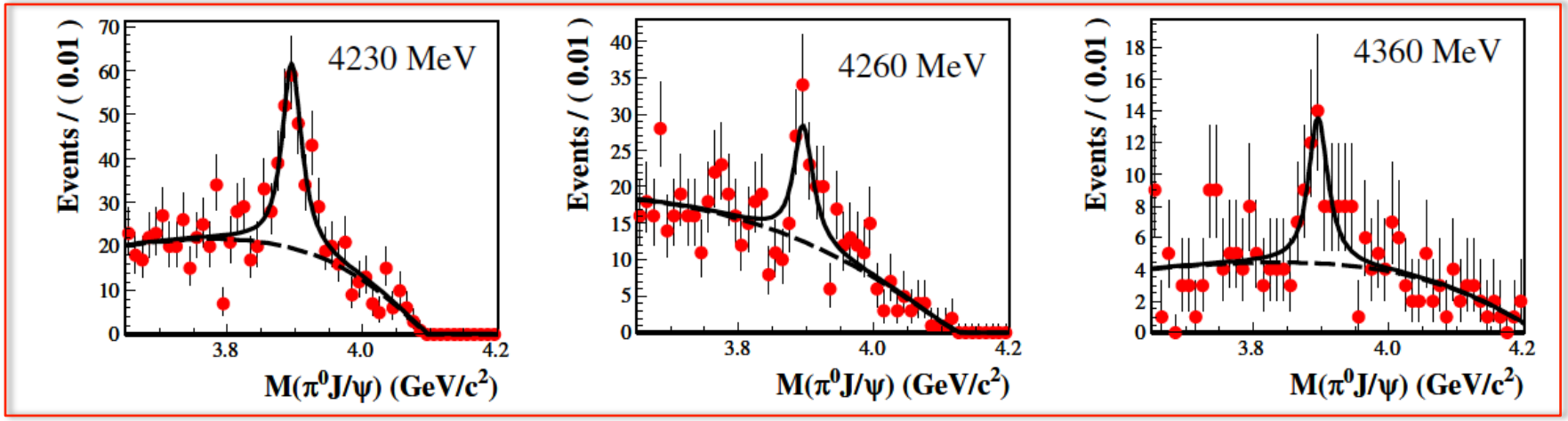


Search for neutral $Z_c(3900)$ isospin partner

- Study e^+e^- to $\pi^0\pi^0 J/\psi$
  - 2.5 fb^{-1} at E_{CM} = 4.23, 4.26 and 4.36 GeV
  - Simultaneous fit to $\pi^0 J/\psi$ spectrum

BESIII

Preliminary



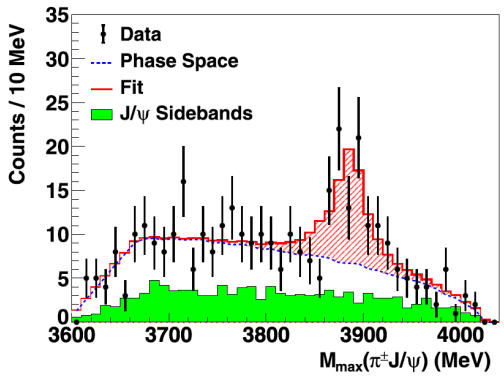
$M = (3894.8 \pm 2.3 \pm 2.7)$ MeV/c^2

$\Gamma = (29.6 \pm 8.2 \pm 8.2)$ MeV

Significance = 10.4σ

Consistent with CLEO-c evidence with 586 pb^{-1} at E_{CM} = 4.17

PLB 727, 366 (2013)



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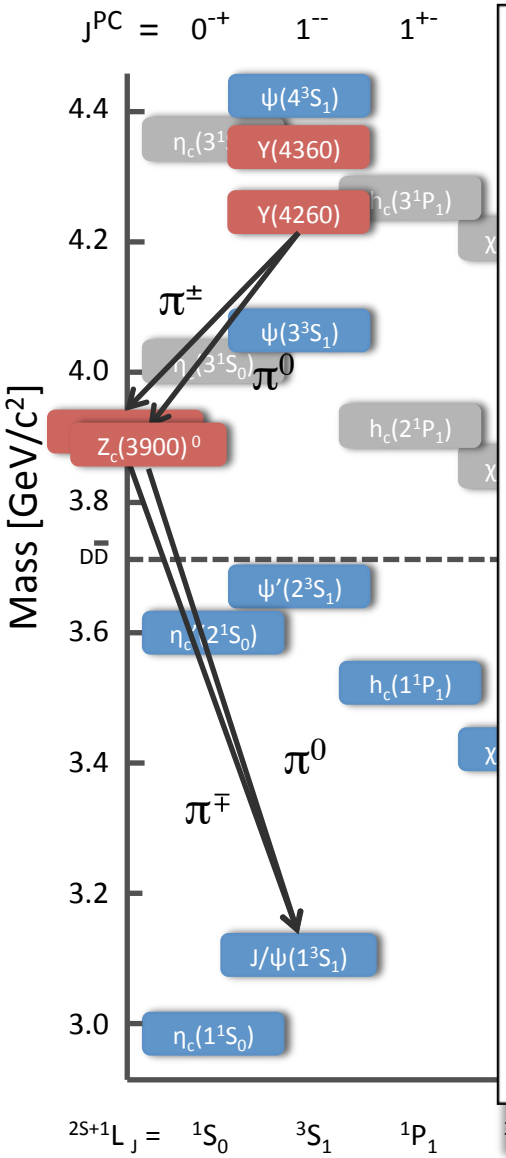
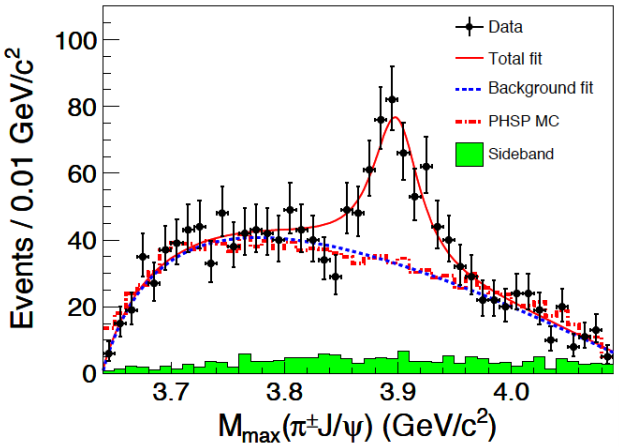


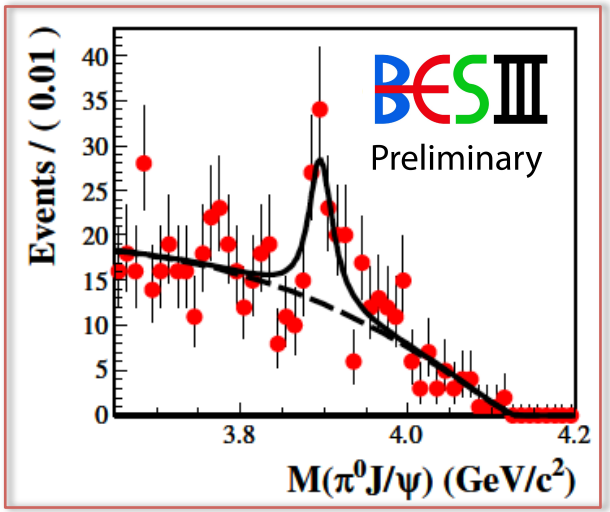
Isospin triplet $Z_c(3900)$ is established!

BESIII: PRL 110, 252001 (2013)



$Z_c(3900)^{\pm}$
$M = (3899.0 \pm 3.6 \pm 4.9)$ MeV/c^2
$\Gamma = (46 \pm 10 \pm 20)$ MeV
Significance > 8σ

$Z_c(3900)^0$
$M = (3894.8 \pm 2.3 \pm 2.7)$ MeV/c^2
$\Gamma = (29.6 \pm 8.2 \pm 8.2)$ MeV
Significance > 10σ



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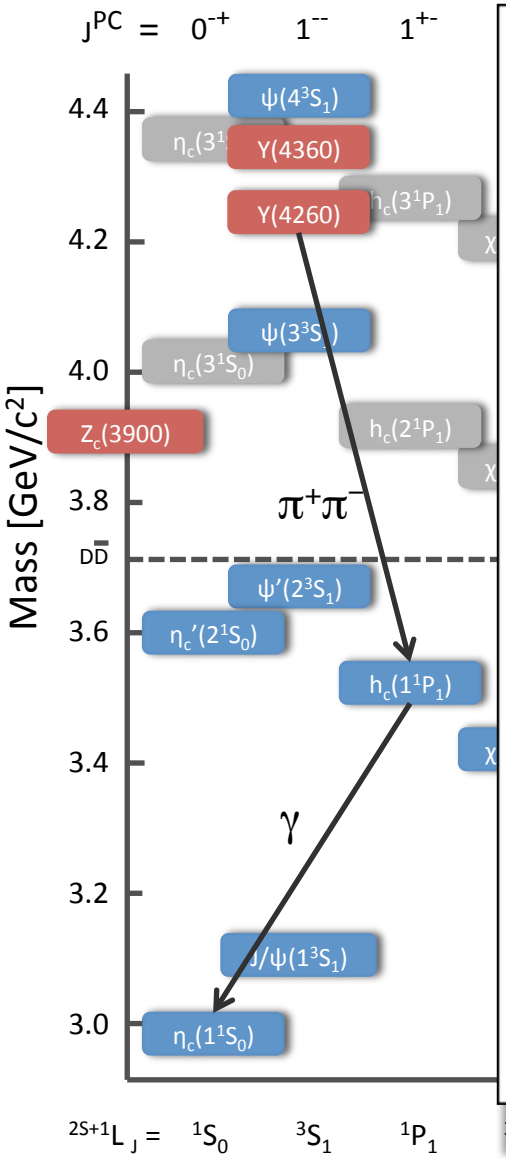
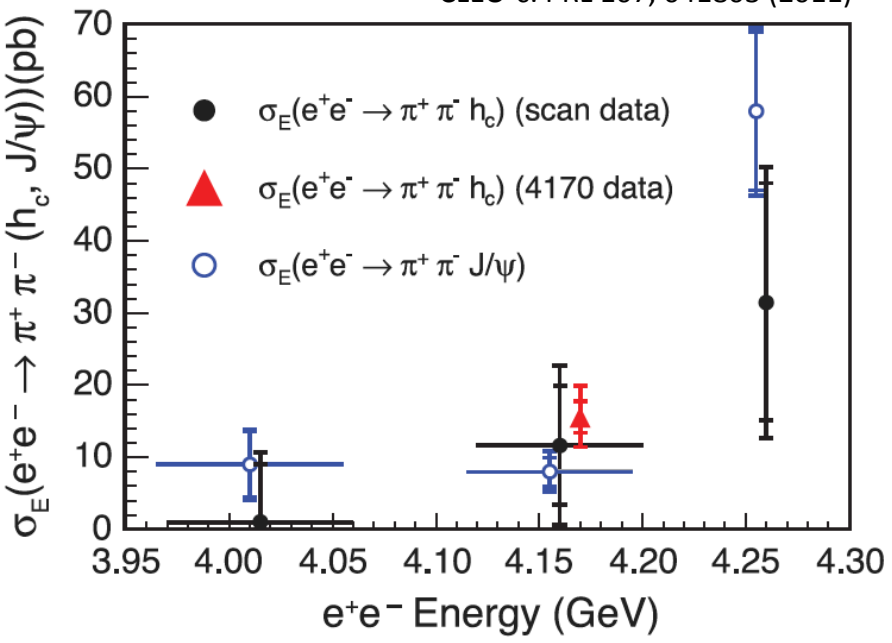


What about other reactions?

- CLEO-c saw hint of a rising cross section near 4.26 GeV for $\pi^+\pi^- h_c$

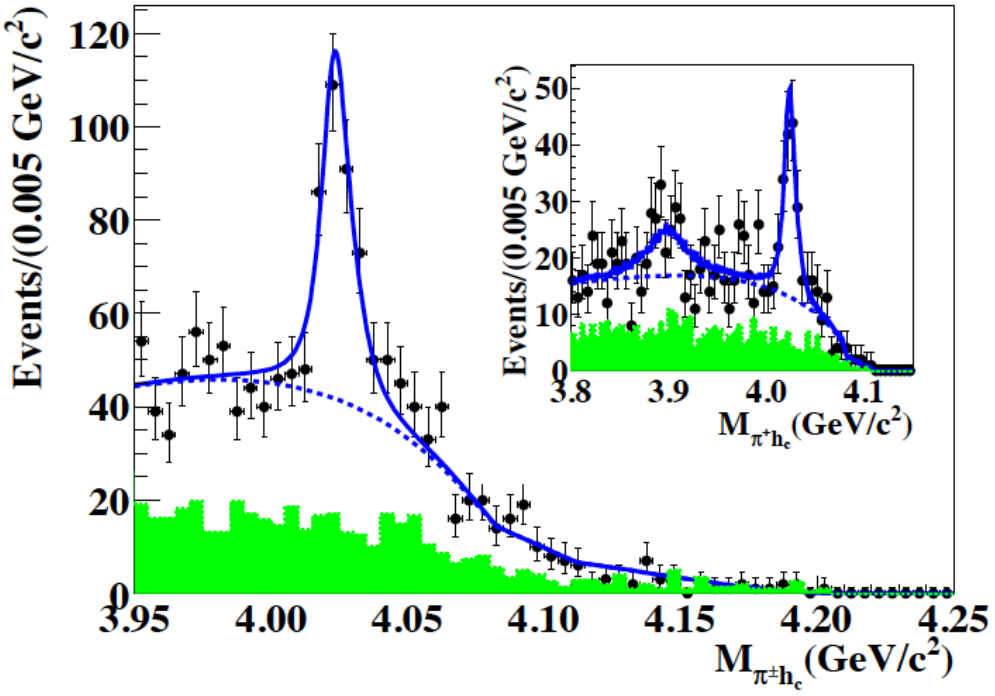
CLEO-c: PRL 107, 041803 (2011)



Observation of charged charmonium-like structure in $\pi^+\pi^- h_c$

- Study e^+e^- annihilation to $\pi^+\pi^- h_c$
  - h_c decaying to $\gamma\eta_c$; η_c reconstructed through 16 hadronic decay modes
- Simultaneous fit to $M(\pi^\pm h_c)$ at E_{CM} = 4.23, 4.26, and 4.36 GeV

BESIII: PRL 111, 242001 (2013)

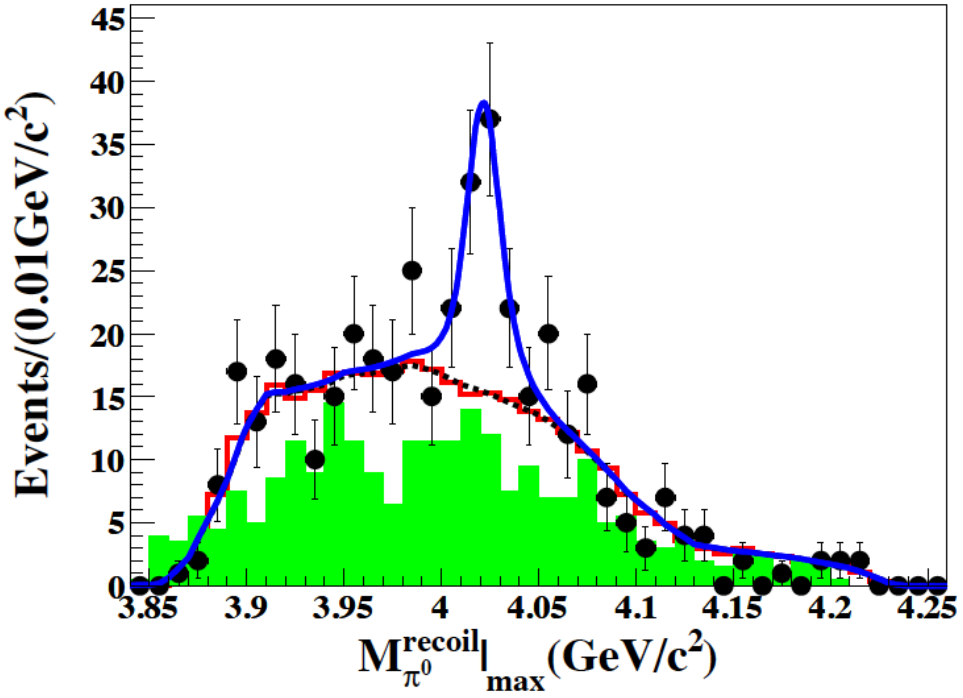


- Visible $Z_c(4020)^\pm$
  - $M = (4022.9 \pm 0.8 \pm 2.7)$ MeV/c^2
  - $\Gamma = (7.9 \pm 2.7 \pm 2.6)$ MeV
  - Significance = 8.9σ
- No evidence for $Z_c(3900)^\pm$
  - Significance = 2.1σ
  - Upper limits determined

Observation of neutral charmonium-like structure in $\pi^0\pi^0 h_c$

- Study e^+e^- annihilation to $\pi^0\pi^0 h_c$
  - h_c decaying to $\gamma\eta_c$; η_c reconstructed through 16 hadronic decay modes
- Simultaneous fit to $M(\pi^0 h_c)$ at E_{CM} = 4.23, 4.26, and 4.36 GeV

BESIII: PRL 113, 212002 (2014)

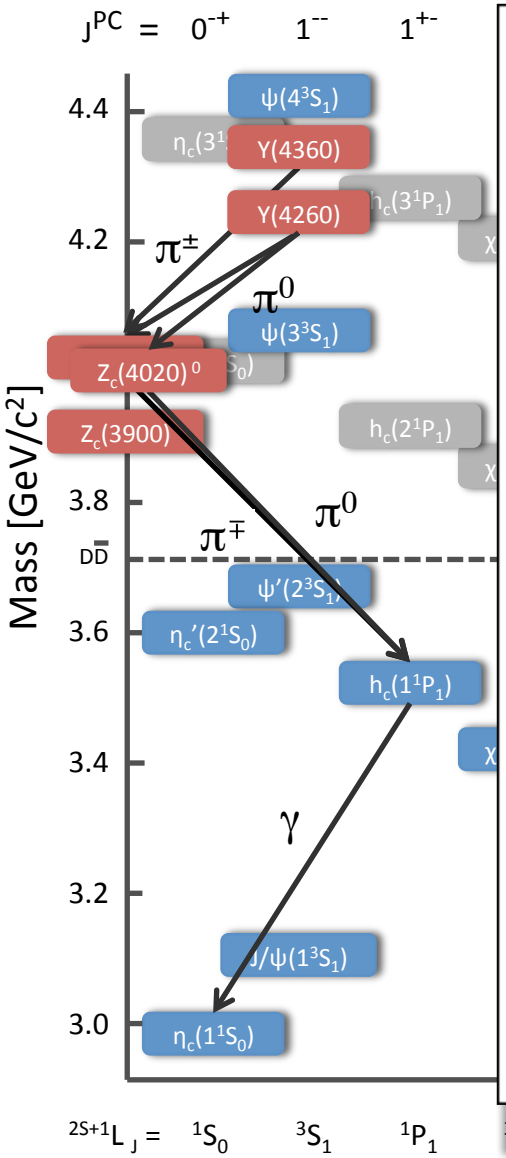


- $Z_c(4020)^0$
  - M = (4023.9 ± 2.2 ± 3.8) MeV/c^2
  - Γ fixed to Γ($Z_c(4020)^{\pm}$)
  - Significance > 5σ
- Born cross sections agree with expectations from isospin symmetry

$$\frac{\sigma(e^+e^- \to \pi^0\pi^0 h_c)}{\sigma(e^+e^- \to \pi^+\pi^- h_c)} = 0.63 \pm 0.9$$

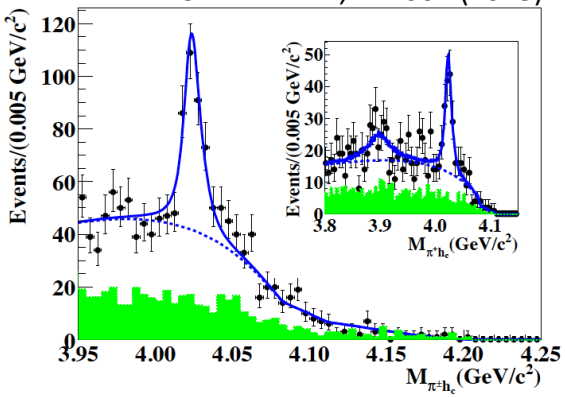
$$(\text{expect } 0.5)$$

The charmonium spectrum



Isospin triplet $Z_c(4020)$ is established!

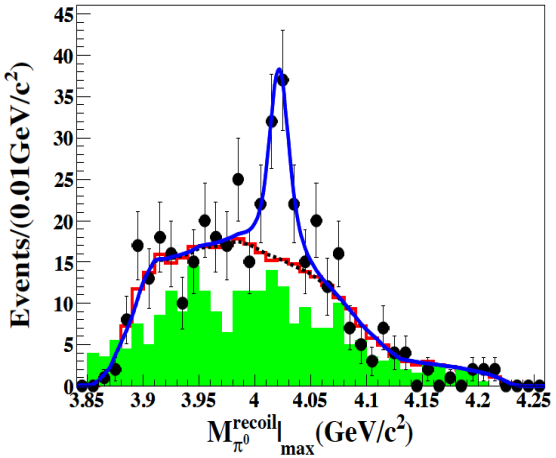
BESIII: PRL 111, 242001 (2013)



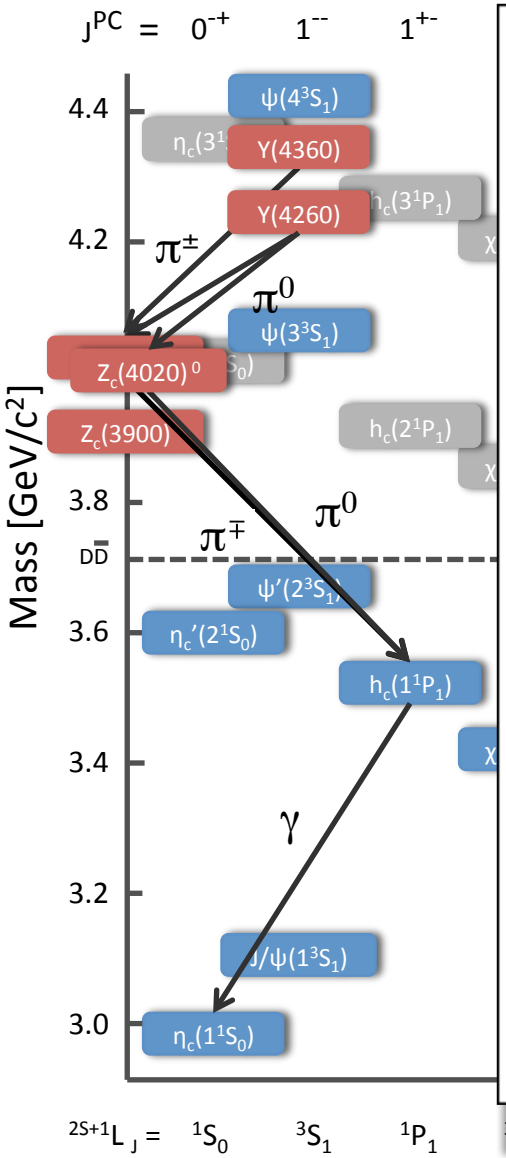
$Z_c(4020)^{\pm}$
$M = (4022.9 \pm 0.8 \pm 2.7)$ MeV/c²
$\Gamma = (7.9 \pm 2.7 \pm 2.6)$ MeV
Significance > 8σ

$Z_c(4020)^0$
$M = (4023.9 \pm 2.2 \pm 3.8)$ MeV/c²
Γ fixed to $\Gamma(Z_c(4020)^{\pm})$
Significance > 5σ

BESIII: PRL 113, 212002 (2014)



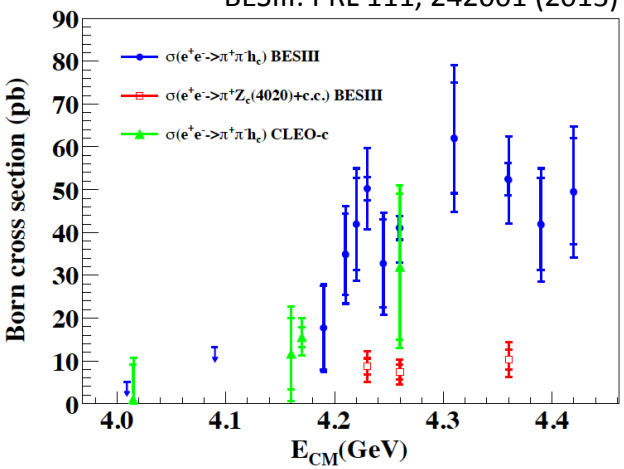
The charmonium spectrum



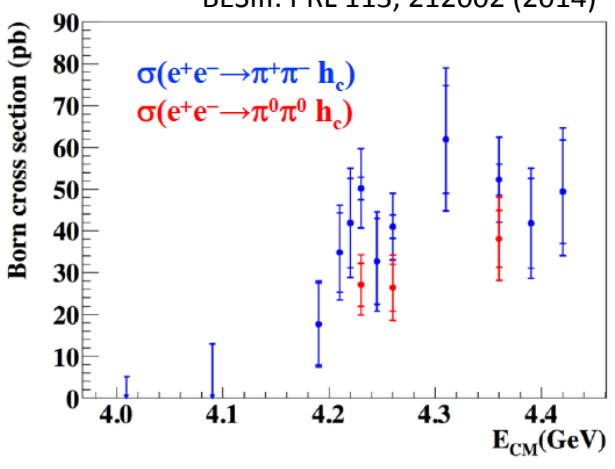
… but the cross section seems complicated

- Correlation of $\pi\pi h_c$ with Y(4260) and Y(4360) is unclear
- Is it a combination of both or something else altogether?

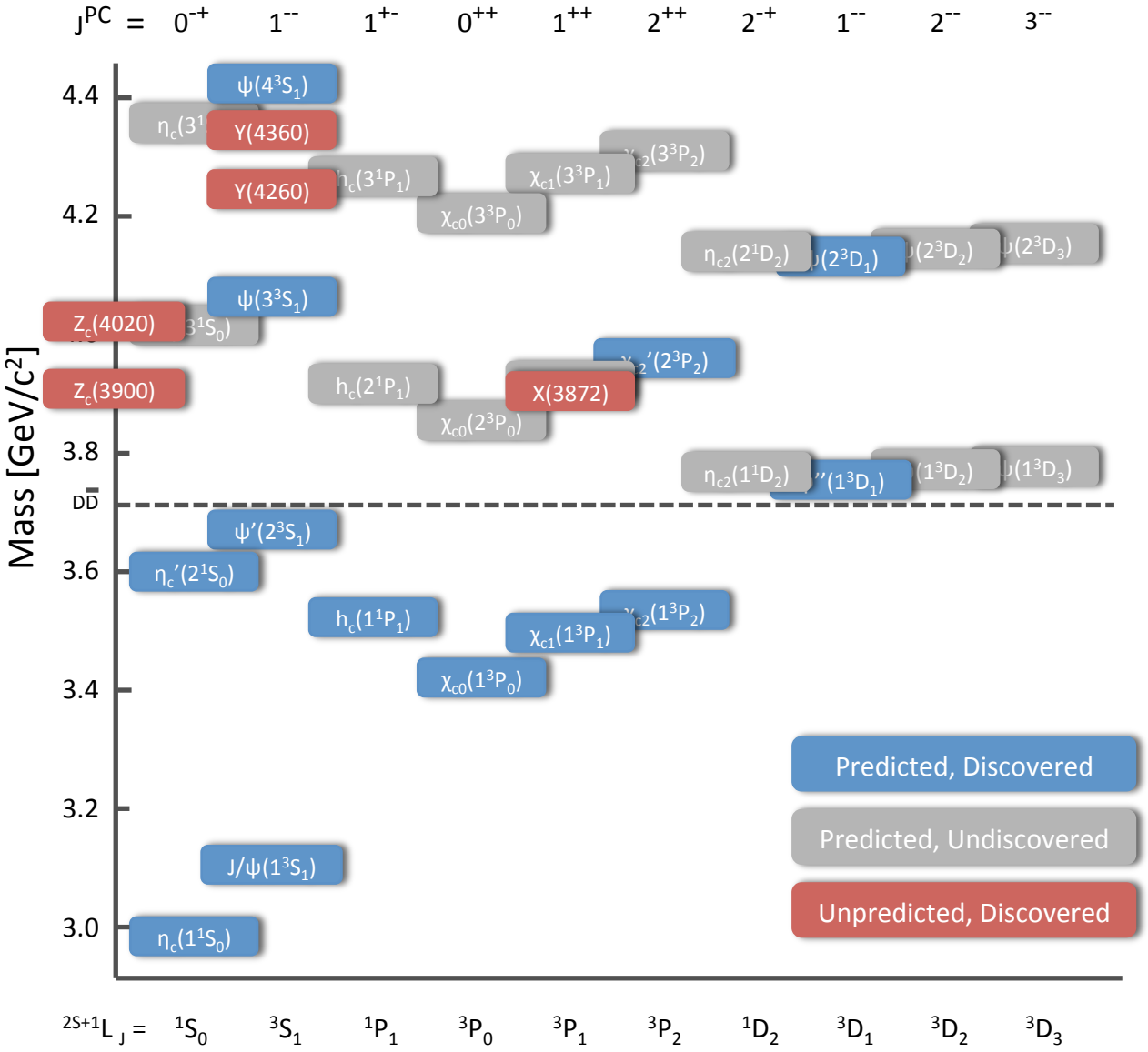
BESIII: PRL 111, 242001 (2013)



BESIII: PRL 113, 212002 (2014)



The charmonium spectrum



- Z states appear near open charm thresholds

$Z_c(3900)$ mass is ~20 MeV above $D\bar{D}^*$ threshold

$Z_c(4020)$ mass is ~5 MeV above $D^*\bar{D}^*$ threshold

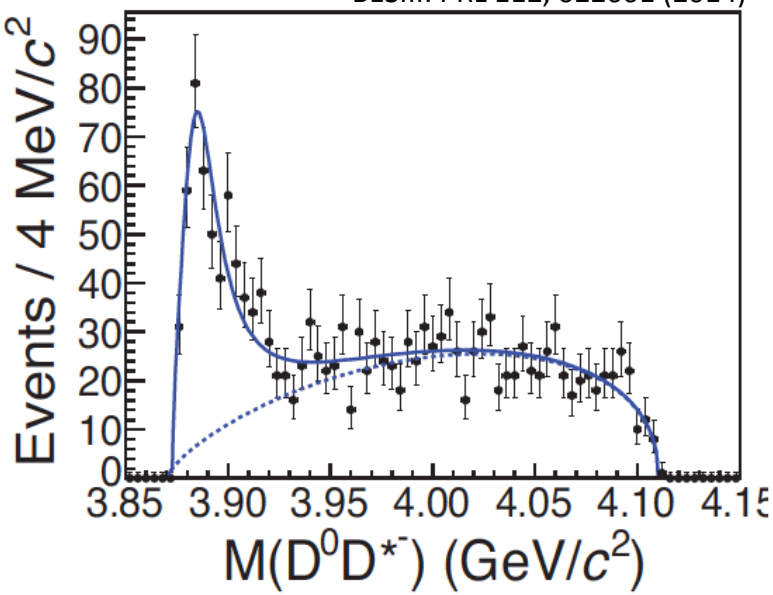
- Neither measurement considers interference with a coherent non-resonant background (may shift the results)

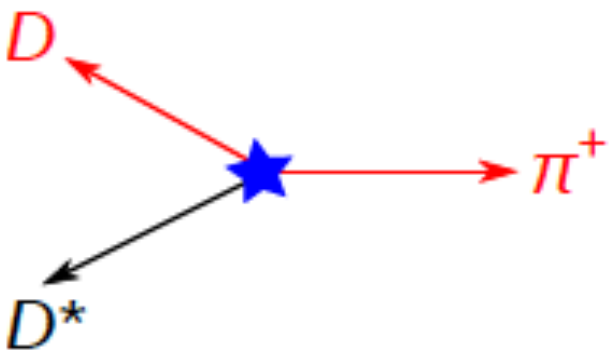
- Natural question:
  Do the Z states decay to open charm?

Observation of a charged structure in $(D\bar{D}^*)^{\pm}$

- Study e^+e^- to $(D\bar{D}^*)^{\pm}\pi^{\mp}$ at E_{CM} = 4.26 GeV (525 pb^{-1})
- 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^+

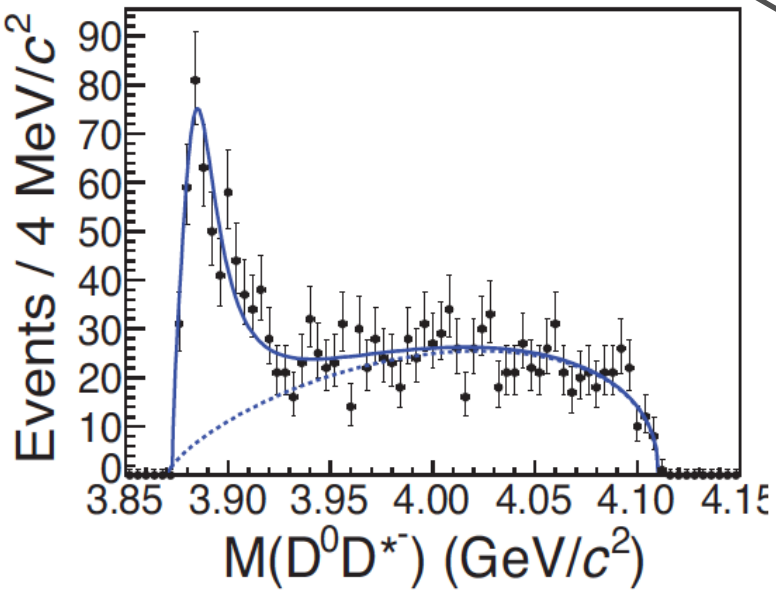
BESIII: PRL 112, 022001 (2014)

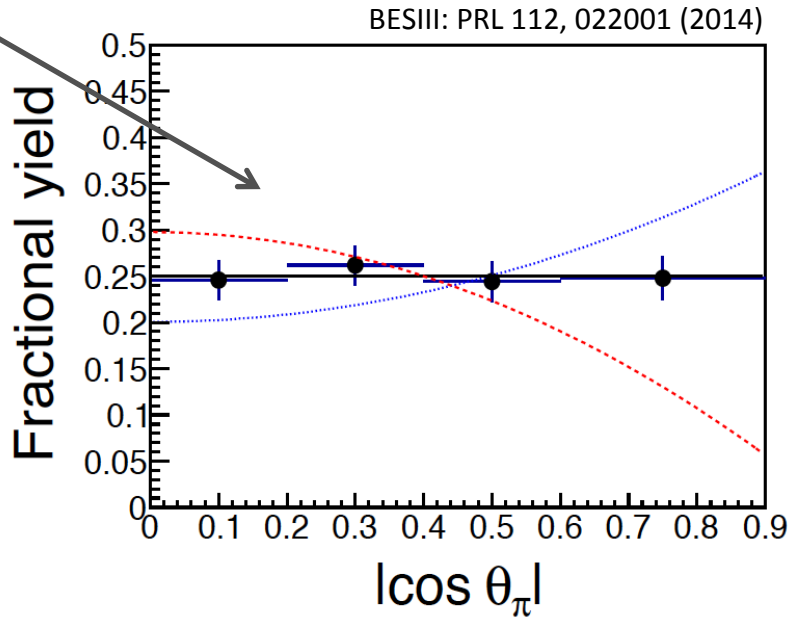




Observation of a charged structure in $(D\bar{D}^*)^{\pm}$

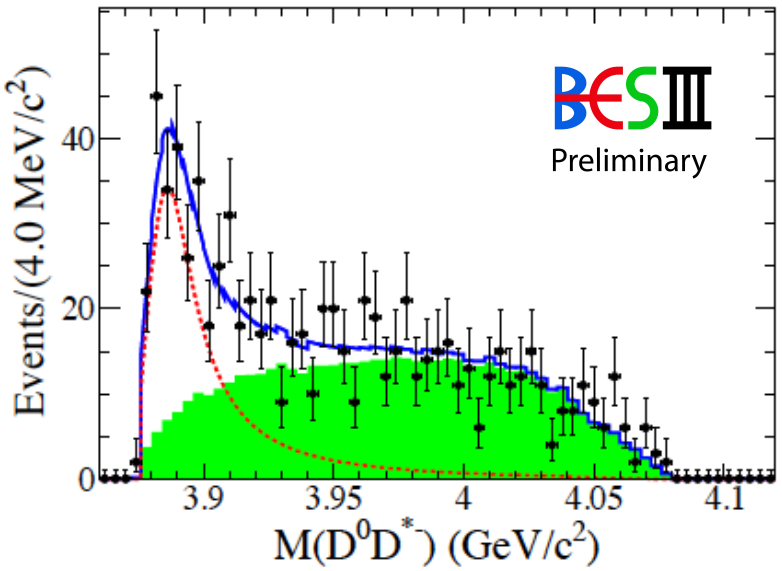
- Study e^+e^- to $(D\bar{D}^*)^{\pm}\pi^{\mp}$ at E_{CM} = 4.26 GeV (525 pb^{-1})
- Single tag analysis
- Structure apparent in $(D\bar{D}^*)^{\pm}$
  - M = 3883.9 ± 1.5 ± 4.2 MeV/c^2
  - Γ = 24.8 ± 3.3 ± 11.0 MeV
  - Significance > 18σ
  - Favors $J^P = 1^+$ (disfavors 0^- and 1^-)

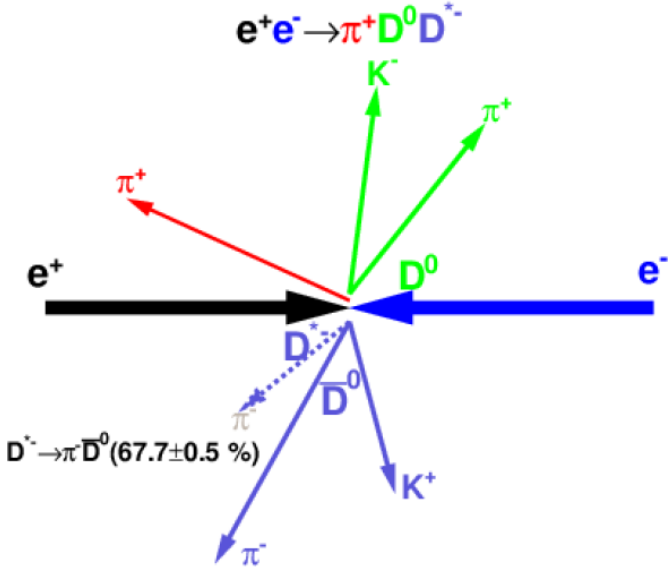




Observation of a charged structure in $(D\bar{D}^*)^{\pm}$

- Study e^+e^- to $(D\bar{D}^*)^{\pm}\pi^{\mp}$ at E_{CM} = 4.26 GeV (525 pb^{-1})
- Double tag analysis
  - Reconstruct bachelor π^+, D^0 (4 decay modes) and D^- (6 decay modes)
  - Improved statistics, systematics; better control over background shape
  - Apply kinematic fit: look in mass recoiling against π^+

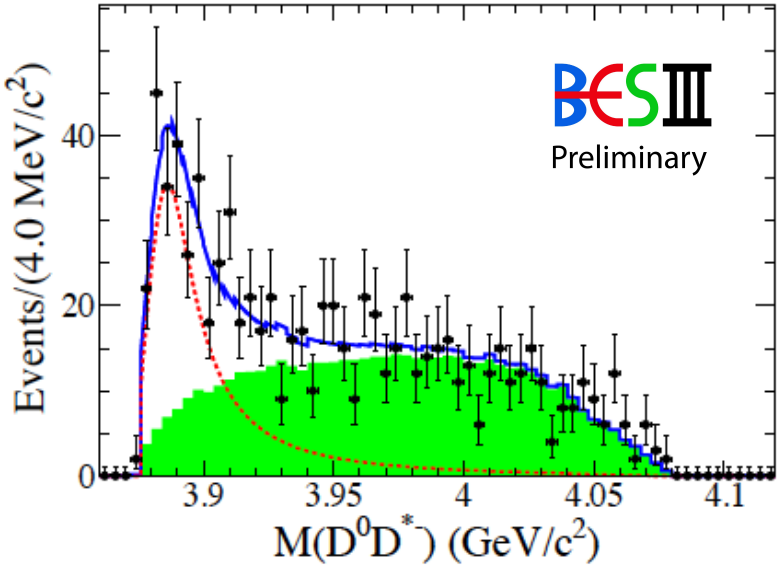


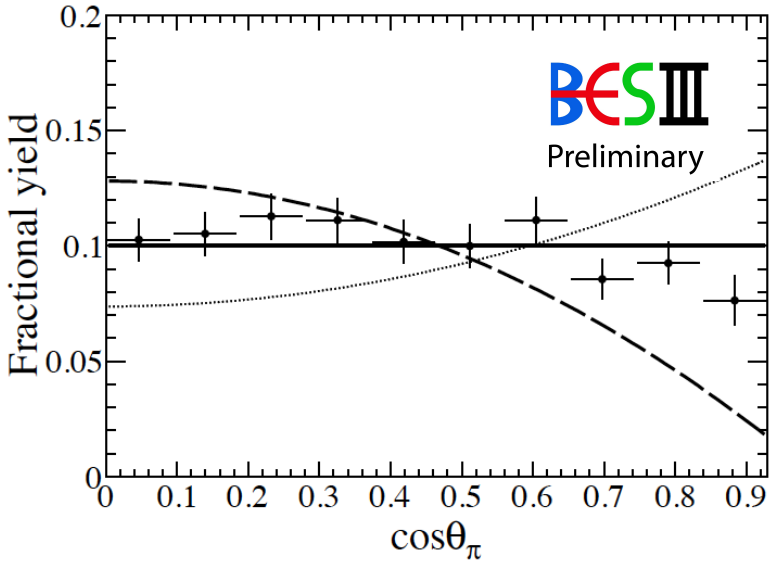


Observation of a charged structure in $(D\bar{D}^*)^{\pm}$

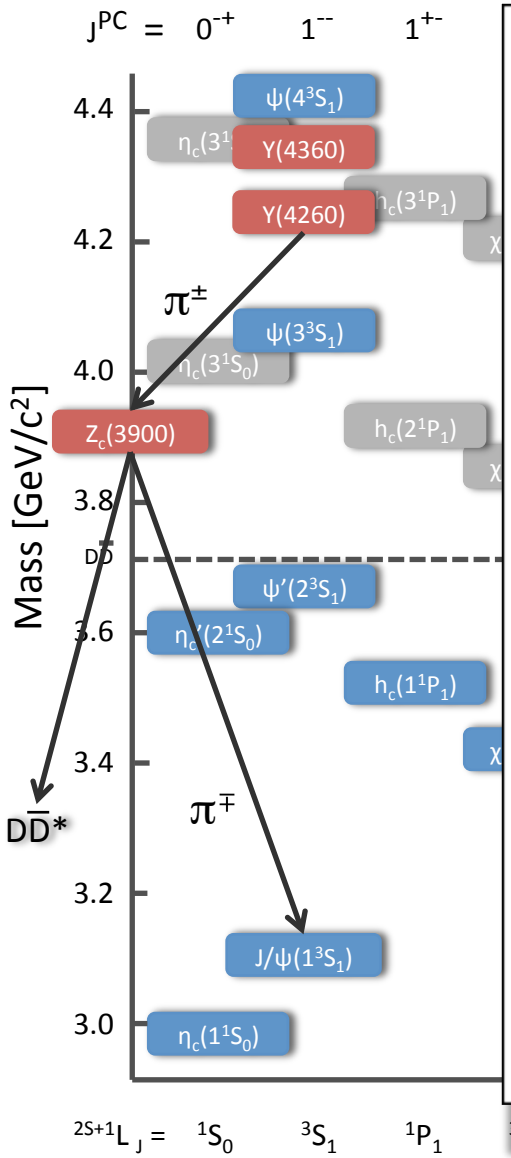
- Study e^+e^- to $(D\bar{D}^*)^{\pm}\pi^{\mp}$ at E_{CM} = 4.23 (1090 pb^{-1}) and 4.26 GeV (827 pb^{-1})
- Double tag analysis
- Structure apparent in $(D\bar{D}^*)^{\pm}$
  - M = 3884.3 ± 1.2 ± 1.8 MeV/c^2
  - Γ = 23.8 ± 2.1 ± 2.6 MeV
  - Significance > 10σ
  - Favors $J^P = 1^+$ (disfavors 0^- and 1^-)

Compatible with, but more precise than, the single tag analysis results
M = 3883.9 ± 1.5 ± 4.2 MeV/c^2
Γ = 24.8 ± 3.3 ± 11.0 MeV





The charmonium spectrum



Comparisons 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 ± 6.1	13.5 ± 2.1

Masses and widths are consistent within ~2σ, but…

If the $Z_c(3900)$ and $Z_c(3885)$ are the same state, the ratio of partial widths is reduced relative to typical charmonium decays.

$$\frac{\Gamma(Z_c(3885) \to D\bar{D}^*)}{\Gamma(Z_c(3900) \to \pi J/\psi)} = 6.5 \pm 1.1$$

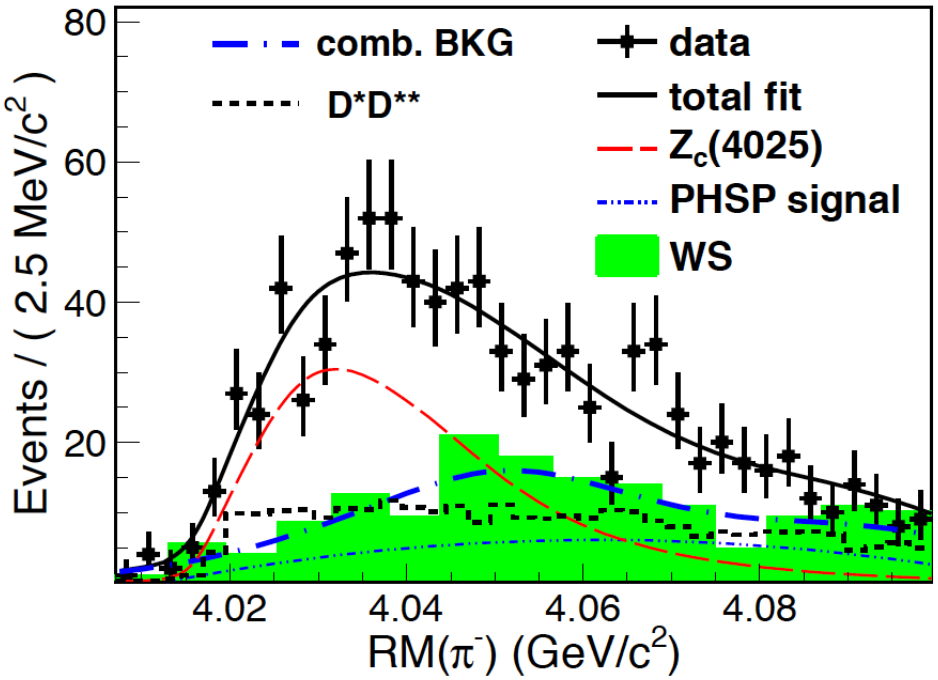
$$\frac{\Gamma(\psi(4040) \to D^*\bar{D}^*)}{\Gamma(\psi(4040) \to \eta J/\psi)} \approx 283$$

Open charm decays are suppressed!
Dynamics of Y(4260) – $Z_c(3900)$ system are different than conventional charmonium

Observation of a charged structure in $(D^*\bar{D}^*)^{\pm}$

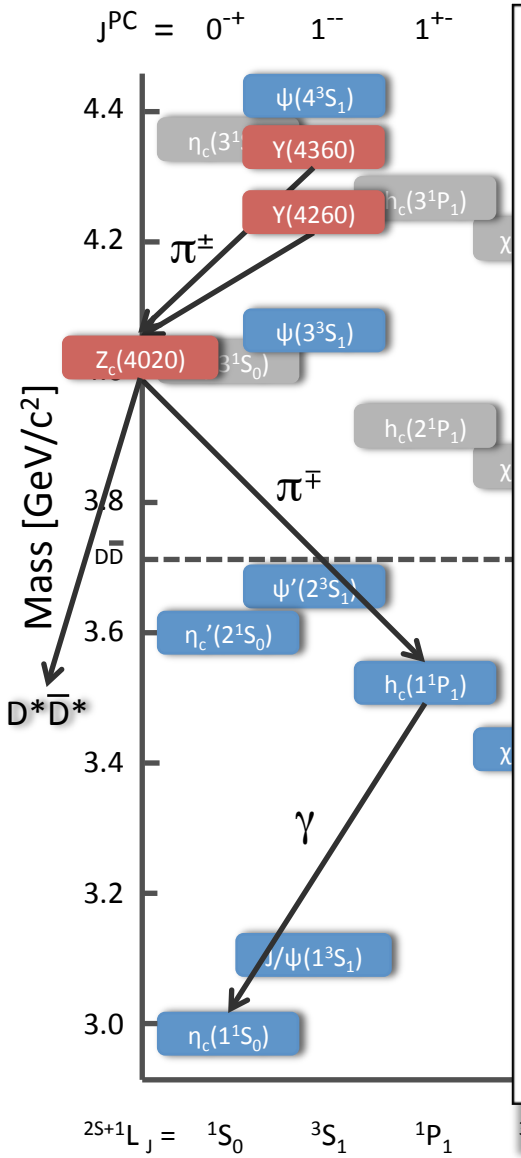
- Study e^+e^- to $(D^*\bar{D}^*)^{\pm}\pi^{\mp}$ at E_{CM} = 4.26 GeV (827 pb^{-1})
- Structure apparent in $(D^*\bar{D}^*)^{\pm}$

BESIII: PRL 112, 132001 (2014)



- $Z_c(4025)^{\pm}$
  - M = 4026.3 ± 2.6 ± 3.7 MeV/c^2
  - Γ = 24.8 ± 5.6 ± 7.7 MeV
  - Significance = 13σ
  - Assuming $J^P = 1^+$ (others not ruled out)
  - Cross section = 83.5 ± 6.6 ± 22.0 pb

The charmonium spectrum



Comparisons between $Z_c(4020)$ and $Z_c(4025)$

	$Z_c(4025) \to D^*D^*$	$Z_c(4020) \to \pi h_c$
Mass / MeV/c^2	$4026.3 \pm 2.6 \pm 3.7$	$4022.9 \pm 0.8 \pm 2.7$
Width / MeV	$24.8 \pm 5.6 \pm 7.7$	$7.9 \pm 2.7 \pm 2.6$
$\sigma \times \mathcal{B}$ / pb	89.0 ± 12.3	7.4 ± 1.7 (at 4260 MeV)

Masses and widths are consistent within ~2σ, but…

If the $Z_c(4020)$ and $Z_c(4025)$ are the same state, the ratio of partial widths is reduced relative to typical charmonium decays.

$$\frac{\Gamma(Z_c(4025)\to D^*\bar{D}^*)}{\Gamma(Z_c(4020)\to \pi h_c)} = 12.0 \pm 3.2$$

$$\frac{\Gamma(\psi(4040)\to D^*\bar{D}^*)}{\Gamma(\psi(4040)\to \eta J/\psi)} \approx 283$$

Open charm decays are suppressed!
Dynamics of Y(4260) – $Z_c(4020)$ system are different than conventional charmonium

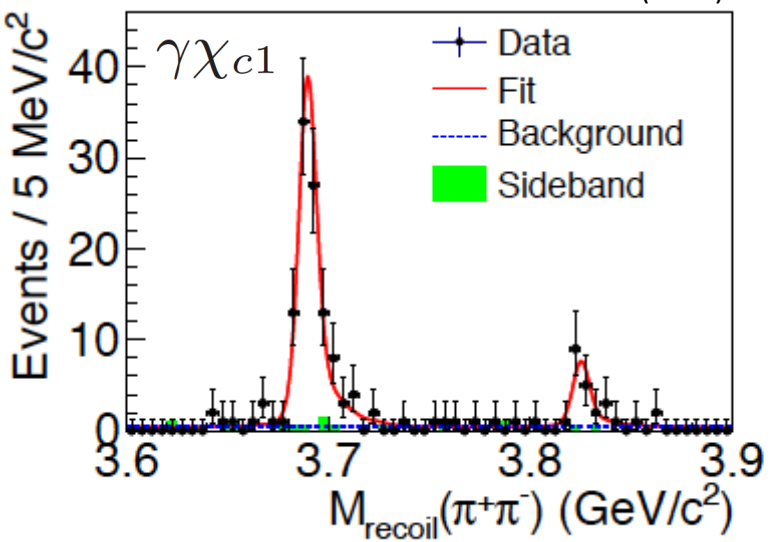
Observation of X(3823)

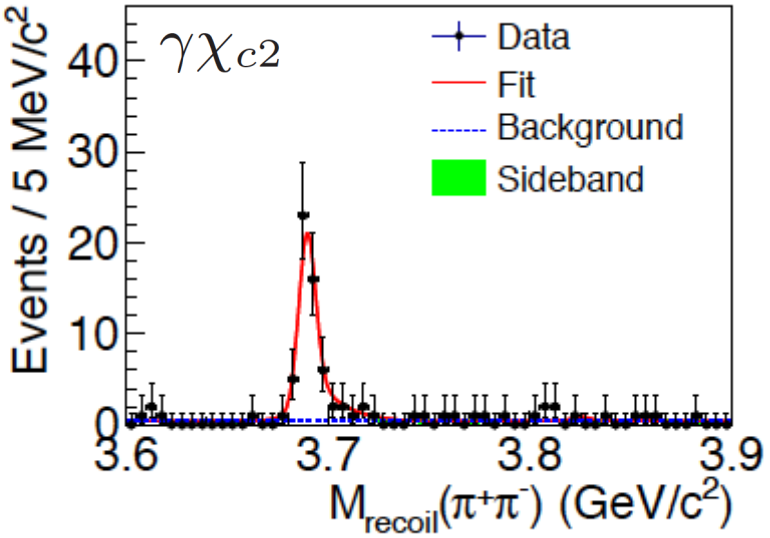
- e^+e^- to $\pi^+\pi^-\gamma\chi_{c1}$ from 4.19 to 4.6 GeV
  - M = 3821.7 ± 1.3 ± 0.7 MeV/c^2
  - $\Gamma < 16$ MeV
  - Significance = 6.7σ
- Measurements in good agreement with potential model prediction of the X(3823) as the 1^3D_2 charmonium state

$$\frac{\mathcal{B}(X \to \gamma\chi_{c1})}{\mathcal{B}(X \to \gamma\chi_{c2})} < 0.43$$

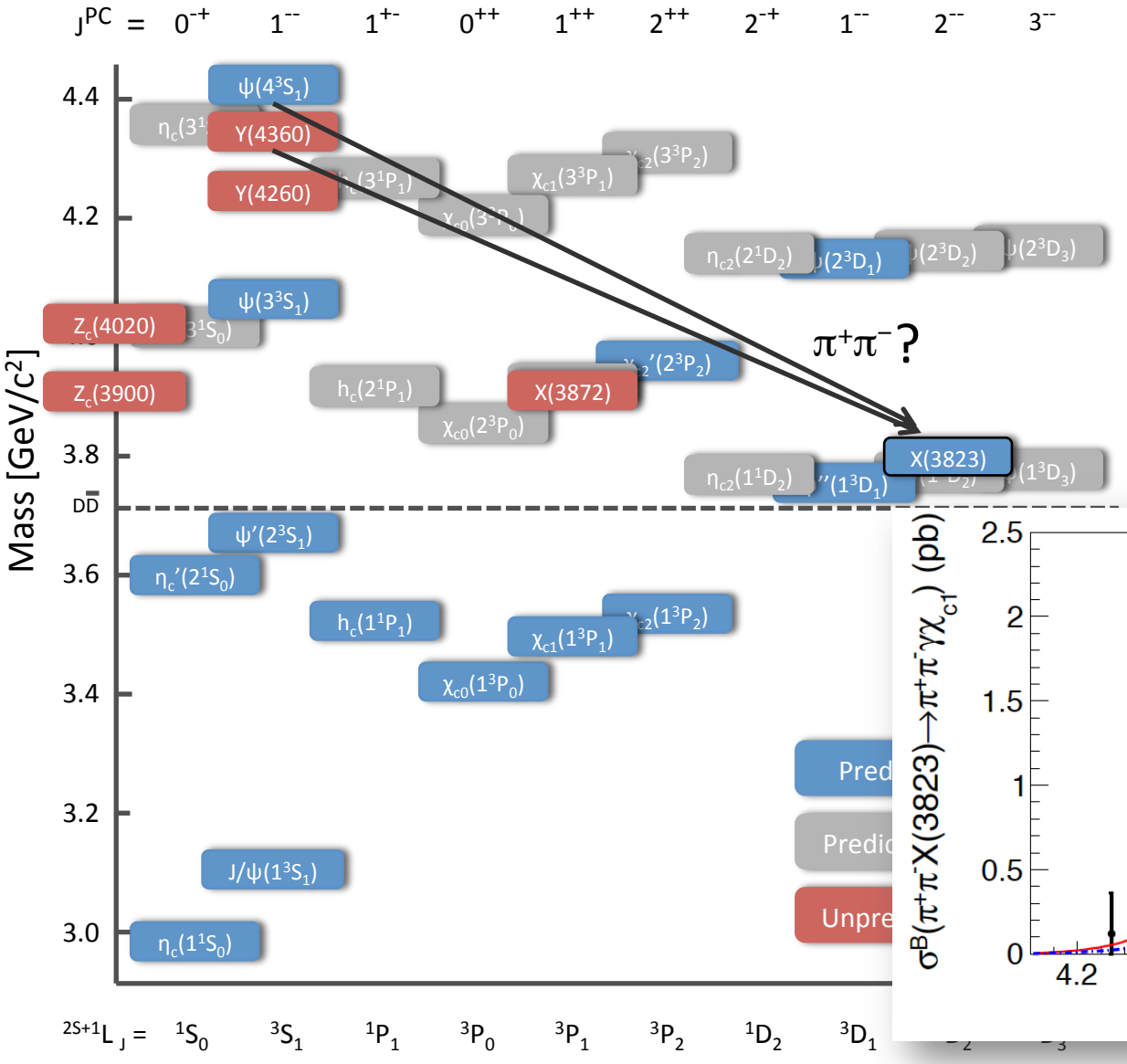
Consistent with prediction ~ 0.2

BESIII: arXiv:1503.08203 (2015)



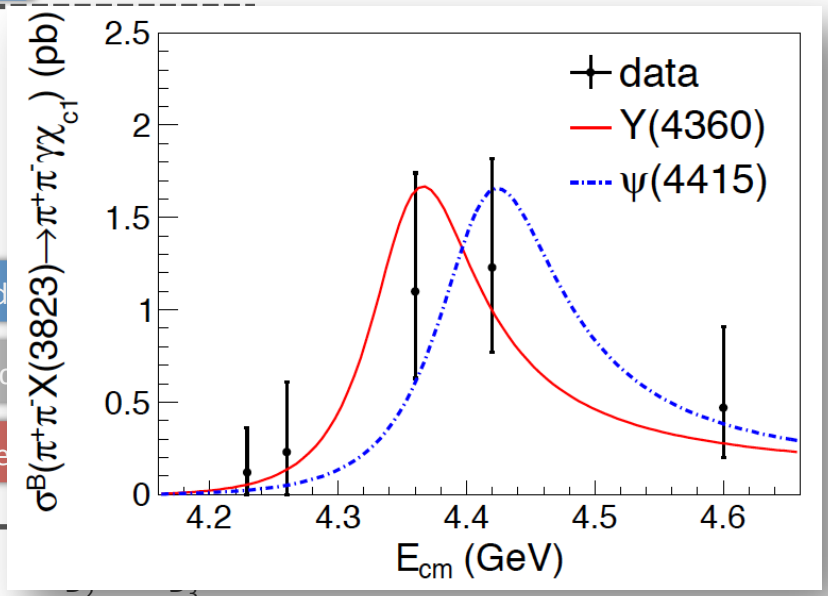


Observation of X(3823)



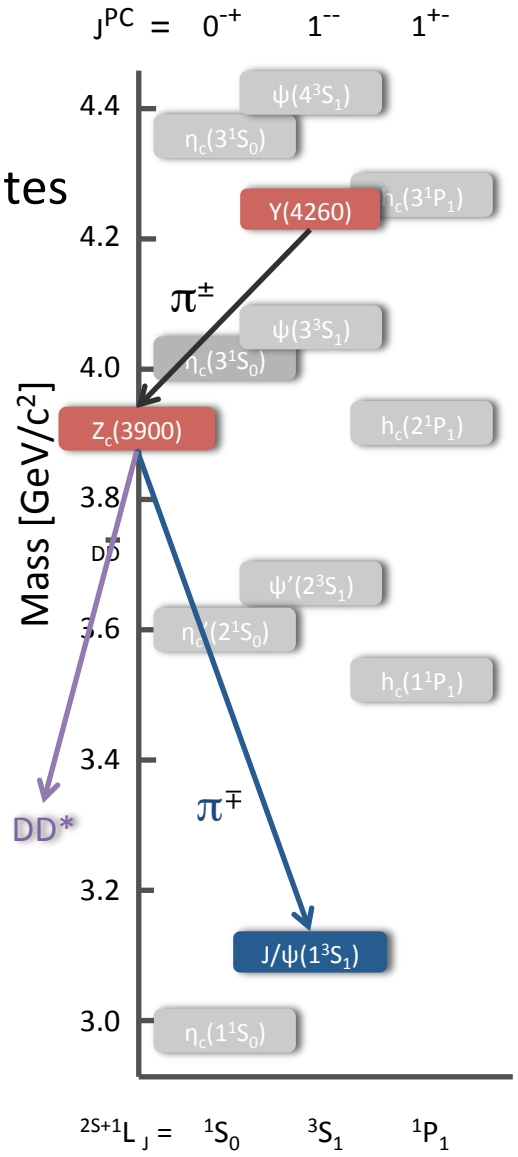
- Line shape consistent with both Y(4360) and ψ(4415)
- Not enough statistics to distinguish between S and D wave

BESIII: arXiv:1503.08203 (2015)



Making connections

- Decay properties provide useful information
- Three important decay modes for charmonium-like states
  - fall-apart to open charm mesons
  - cascade to hidden charm mesons
  - decays to light hadrons via intermediate gluons

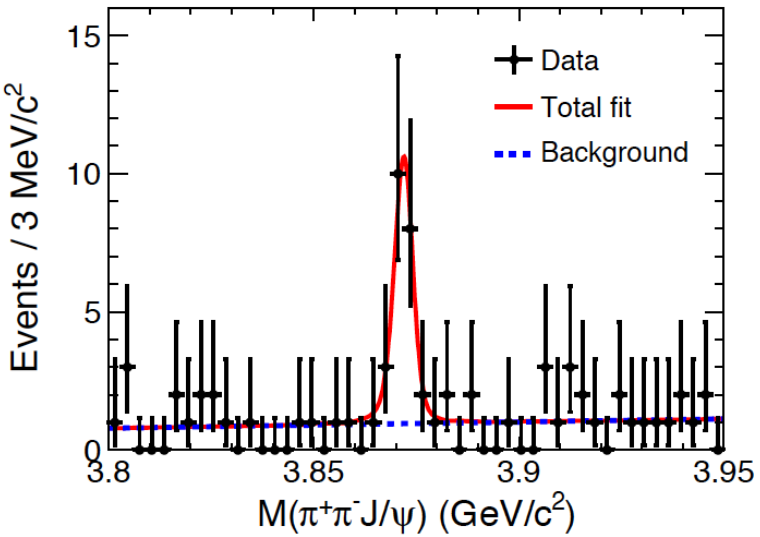


e^+e^- to $\gamma X(3872)$ at energies between 4.009 and 4.42 GeV

- Decay properties provide useful information
- Three important decay modes for charmonium-like states
  - fall-apart to open charm mesons
  - **cascade to hidden charm mesons**
  - decays to light hadrons via intermediate gluons

- Y(4260) and Y(4360) only observed in final states with charmonium plus $\pi^+\pi^-$
  - Couple with other exotic states like Z_c
- e^+e^- to $\gamma X(3872)$; X(3872) to $\pi^+\pi^-$ J/ψ at energies between 4.009 and 4.42 GeV
  - Previously only observed in B decays and hadronic collisions

BESIII: PRL 112, 092001 (2014)

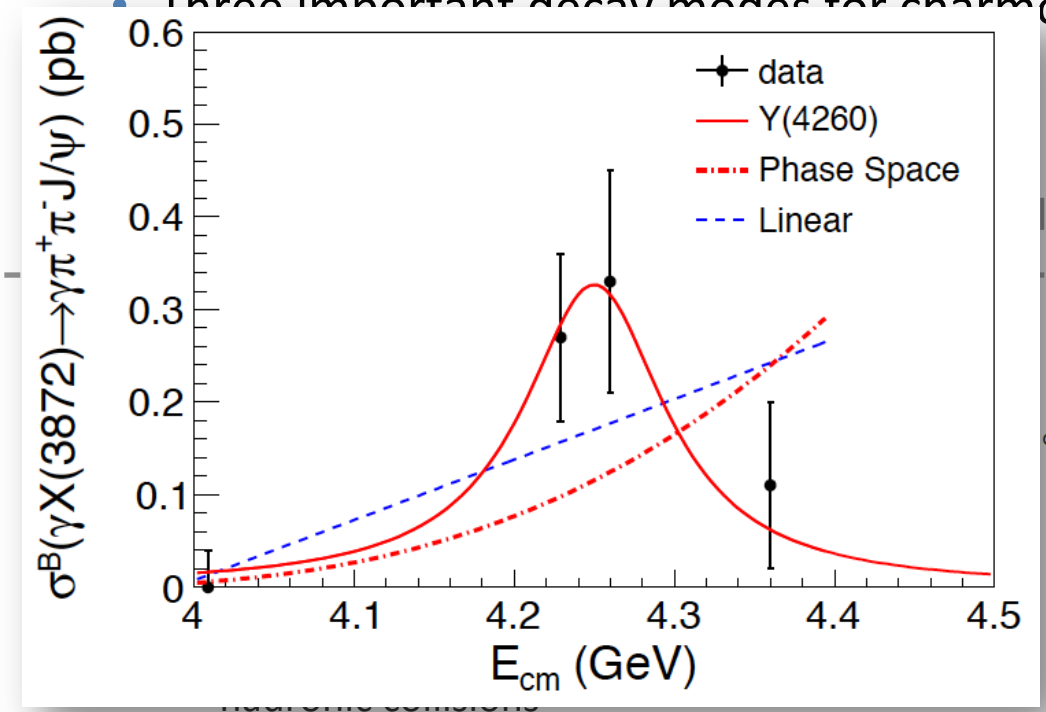


$M = 3871.9 \pm 0.7 \pm 0.2$ MeV/c^2

Significance = 6.3σ

e^+e^- to $\gamma X(3872)$ at energies between 4.009 and 4.42 GeV

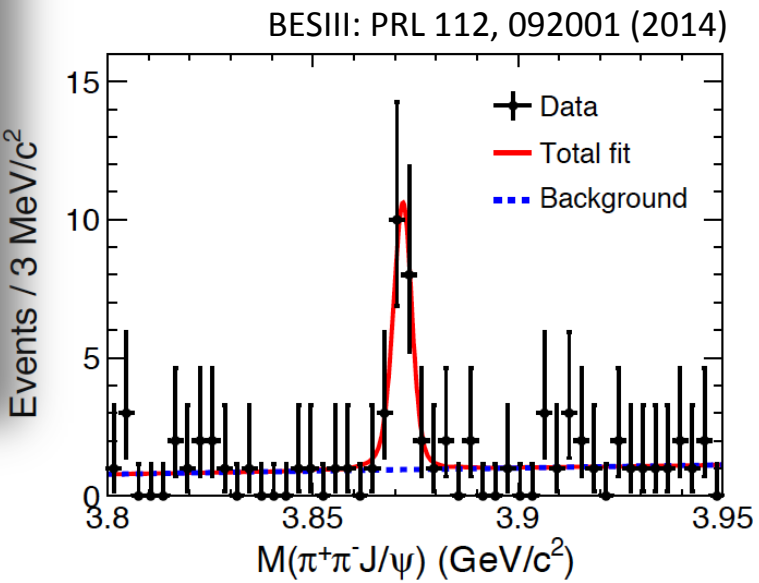
- Decay properties provide useful information
- Three important decay modes for charmonium-like states



luons

- Cross section consistent with expectations for radiative transition from Y(4260)

BESIII: PRL 112, 092001 (2014)



$M = 3871.9 \pm 0.7 \pm 0.2$ MeV/c^2

Significance = 6.3σ

e^+e^- to $\pi^+\pi^-\omega$ at 4.23 and 4.26 GeV

- Decay properties provide useful information
- Three important decay modes for charmonium-like states
  - fall-apart to open charm mesons
  - cascade to hidden charm mesons
  - **decays to light hadrons via intermediate gluons**

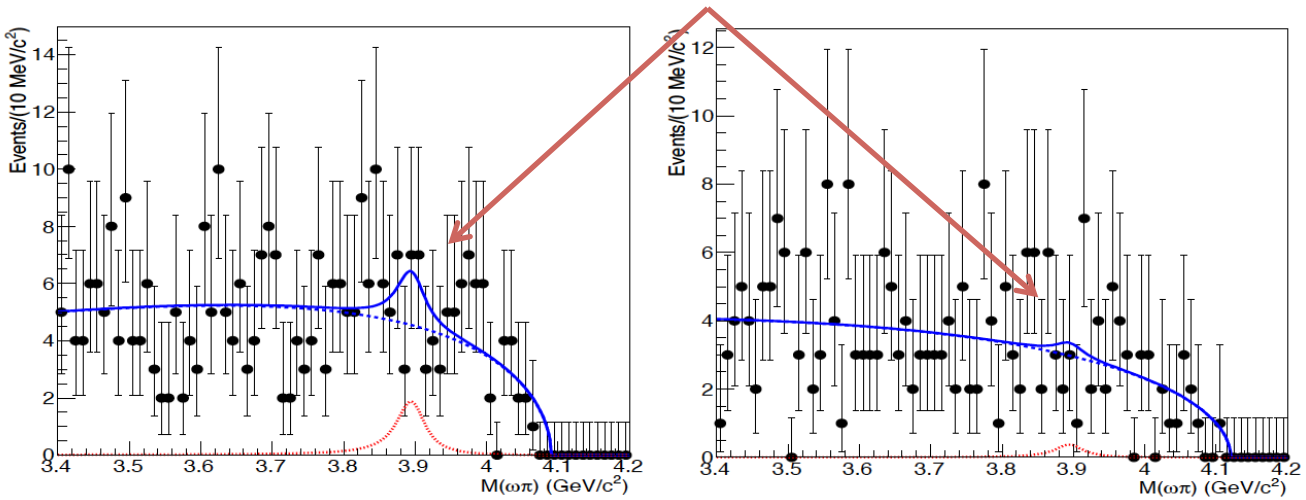
- Rescattering in hidden and open charm final states could enhance the $D\bar{D}^*$ threshold*
  - $Z_c(3900)$ decays to light hadrons will play a unique role in distinguishing a resonance from threshold effects

*PRL 111, 78 132003 (2013), PRL 80 110, 232001 (2013)

e^+e^- to $\pi^+\pi^-\omega$ at 4.23 and 4.26 GeV

- Decay properties provide useful information
- Three important decay modes for charmonium-like states
  - fall-apart to open charm mesons
  - cascade to hidden charm mesons
  - **decays to light hadrons via intermediate gluons**

- e^+e^- to $\pi^+\pi^-\omega$ at 4.23 and 4.26 GeV
  - A typical decay mode of a 1^{+-} resonance
  - No significant signal for $Z_c(3900)$

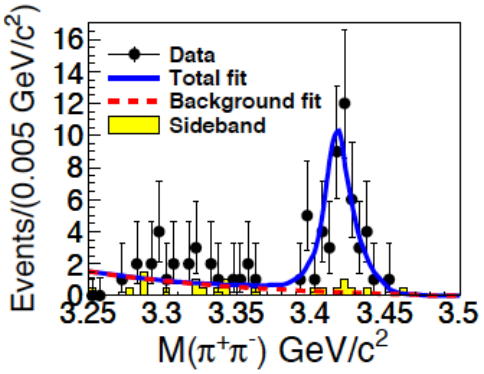


BESIII

Preliminary

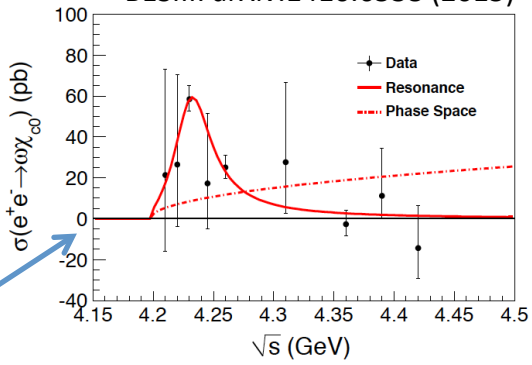
May indicate that $c\bar{c}$ annihilation in $Z_c(3900)$ decays is suppressed

Making connections

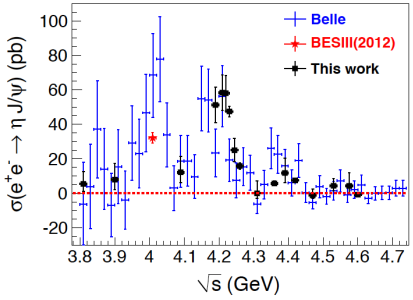


- Coupling of Y(4260) to $\omega\chi_{c0}$ predicted to be sizeable – ratio of Y(4260) decays to $\omega\chi_{cJ}$ (J = 0:1:2) predicted to be 4:3:5*
- e^+e^- to $\omega\chi_{cJ}$ between 4.21 and 4.42 GeV
  - Only $\omega\chi_{c0}$ observed!
- M = 4230 ± 8 ± 6 MeV/c^2; Γ = 38 ± 12 ± 2 MeV
  - Inconsistent with Y(4260) production!

BESIII: arXiv:1410.6538 (2015)

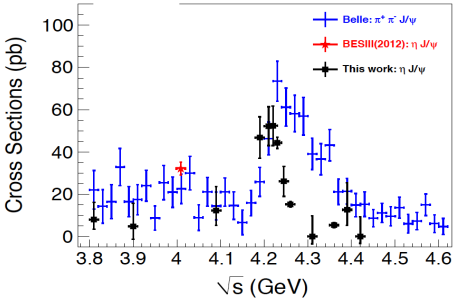


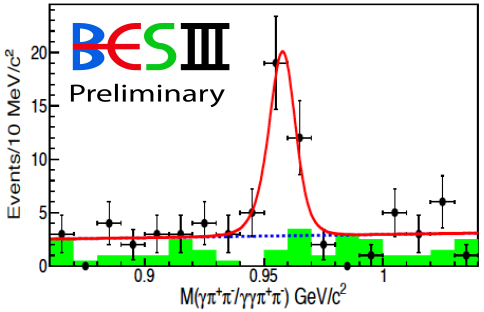
*Prediction from L. Ma, X. H. Liu, X. Liu, S. L. Zhu, arXiv:1406.6879.



- e^+e^- to η J/ψ (No significant signal for π^0 J/ψ)
- Hadronic transitions (by an η or π^0) to lower charmonia are regarded as sensitive probes to study the properties of Y-states
- Cross sections for these reactions are predicted to have line shapes that are strongly affected by open charm effects

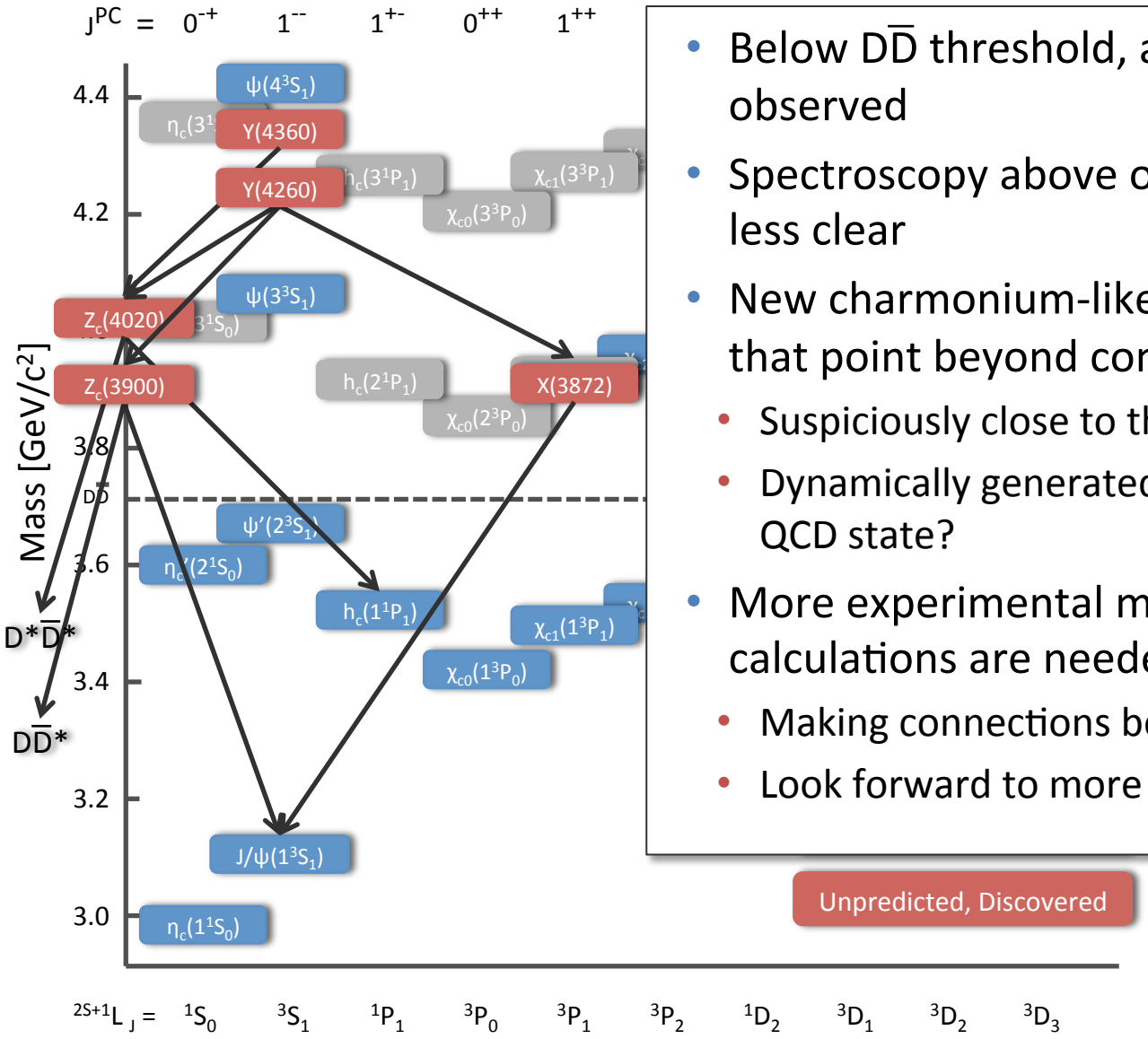
BESIII: arXiv:1503.06644 (2015)





- Cross section to η' J/ψ is lower than that of η J/ψ and theoretical predictions
  - Significance of 9σ at 4.23 GeV, σ_B = 3.1 ± 0.6 ± 0.3 pb
  - Significance of 7.7σ at 4.26, σ_B = 3.9 ± 0.8 ± 0.4 pb
  - Higher order effects may be significant, or gluonium component contributions may affect the results significantly

Summary



- Below $D\bar{D}$ threshold, all states have been observed
- Spectroscopy above open charm threshold less clear
- New charmonium-like states with properties that point beyond conventional charmonium
  - Suspiciously close to thresholds
  - Dynamically generated structure or new type of QCD state?
- More experimental measurements and theory calculations are needed to clarify spectrum
  - Making connections between the XYZ states
  - Look forward to more detailed studies from BESIII

Unpredicted, Discovered