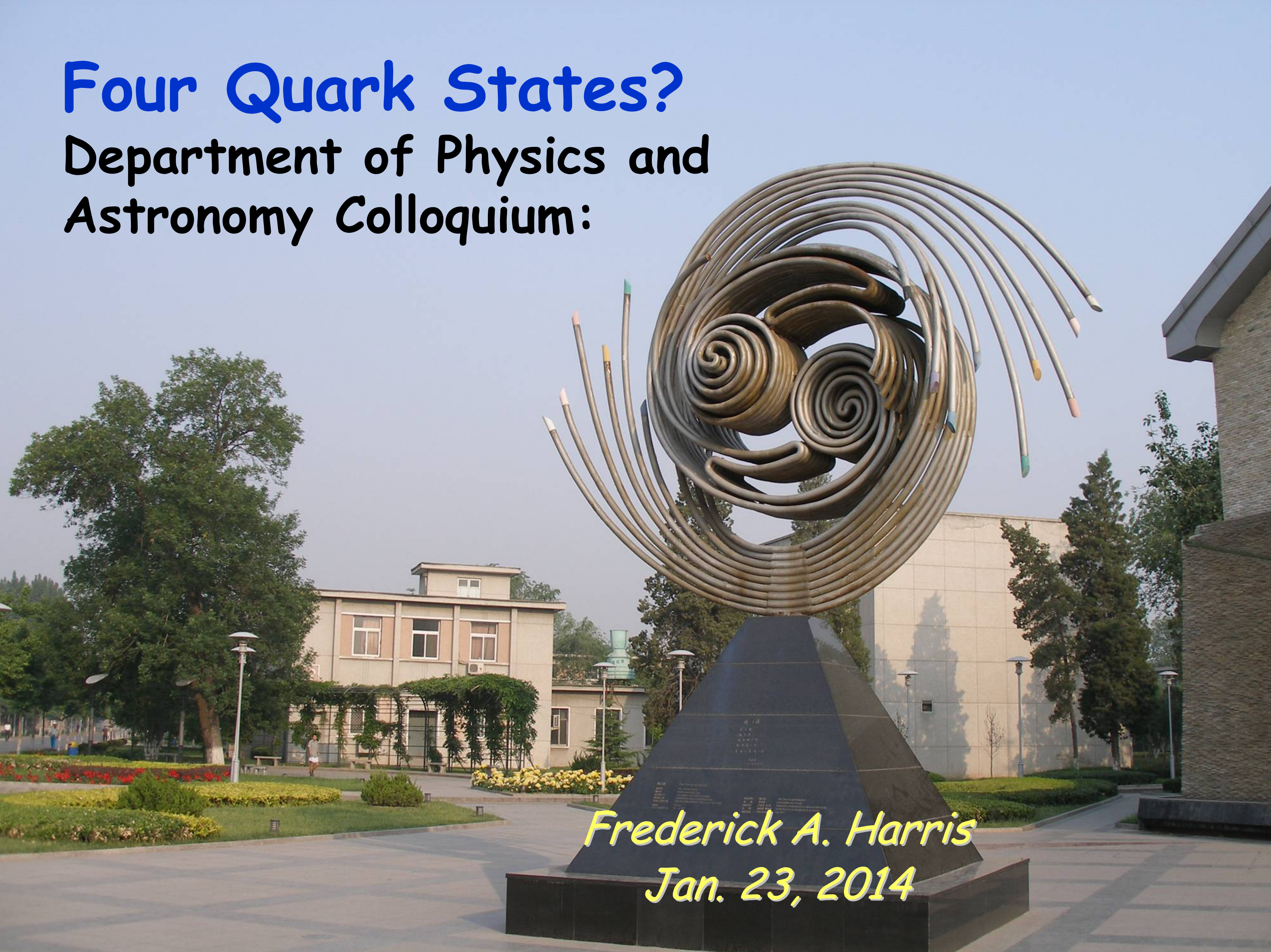
Four Quark States?

Department of Physics and Astronomy Colloquium:



Frederick A. Harris

Jan. 23, 2014

Notes from the Editors: Highlights of the Year

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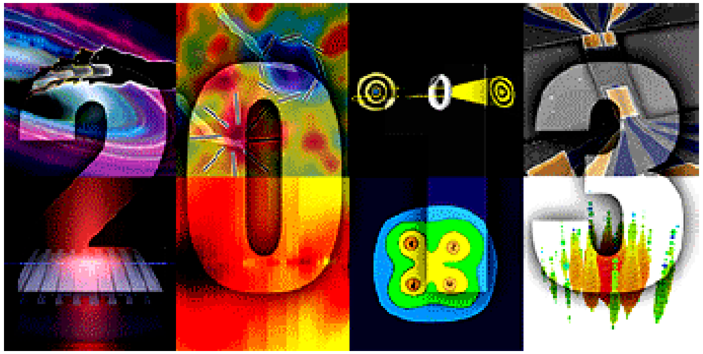
Physics looks back at the standout stories of 2013.



Images from popular *Physics* stories in 2013.

As 2013 draws to a close, we look back on the research covered in *Physics* that really made waves in and beyond the physics community. In thinking about which stories to highlight, we considered a combination of factors: popularity on the website, a clear element of surprise or discovery, or signs that the work could lead to better technology. On behalf of the *Physics* staff, we wish everyone an excellent New Year.

– Matteo Rini and Jessica Thomas

Four-Quark Matter

Quarks come in twos and threes—or so nearly every experiment has told us. This summer, the BESIII Collaboration in China and the Belle Collaboration in Japan reported they had sorted through the debris of high-energy electron-positron collisions and seen a mysterious particle that appeared to contain four quarks. Though other explanations for the nature of the particle, dubbed $Z_c(3900)$, are possible, the "tetraquark" interpretation may be gaining traction: BESIII has since seen a series of other particles that appear to contain four quarks.

OUTLINE

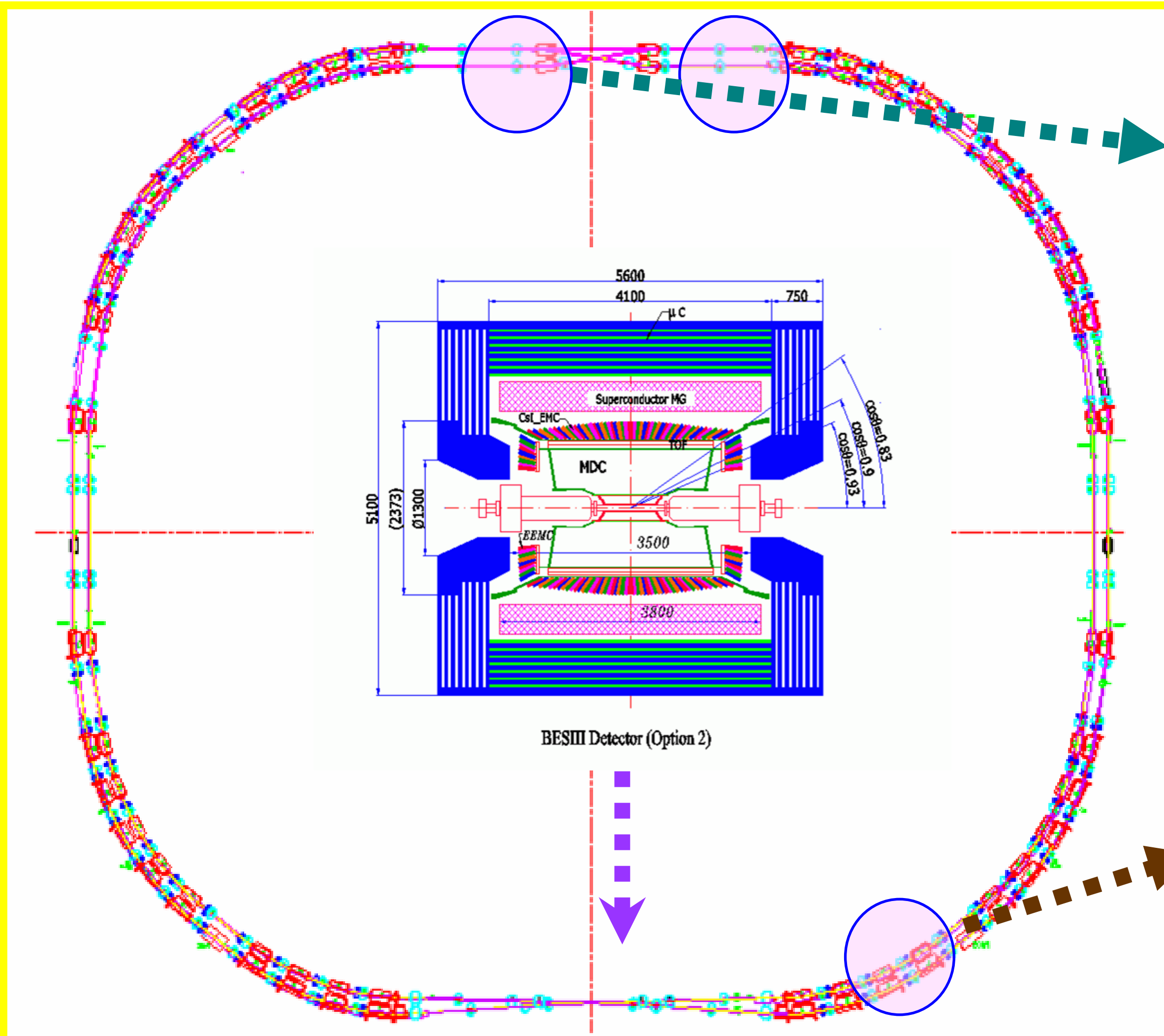
- BESIII experiment
- Charmonium
- XYZ states
  - X(3872)
  - Y(4260)
- BESIII does XYZ
  - Z_c(3900)
  - Z_c(4020)
  - Z_c(4025)
  - Z_c(3885)
  - X(3872)
- Where are we?
- Summary


BESIII

Beijing Electron Positron Collider (BEPCII)

Design luminosity: 1×10^{33} $cm^{-2}s^{-1}$

BEPCII: a high luminosity double-ring collider



SC RF

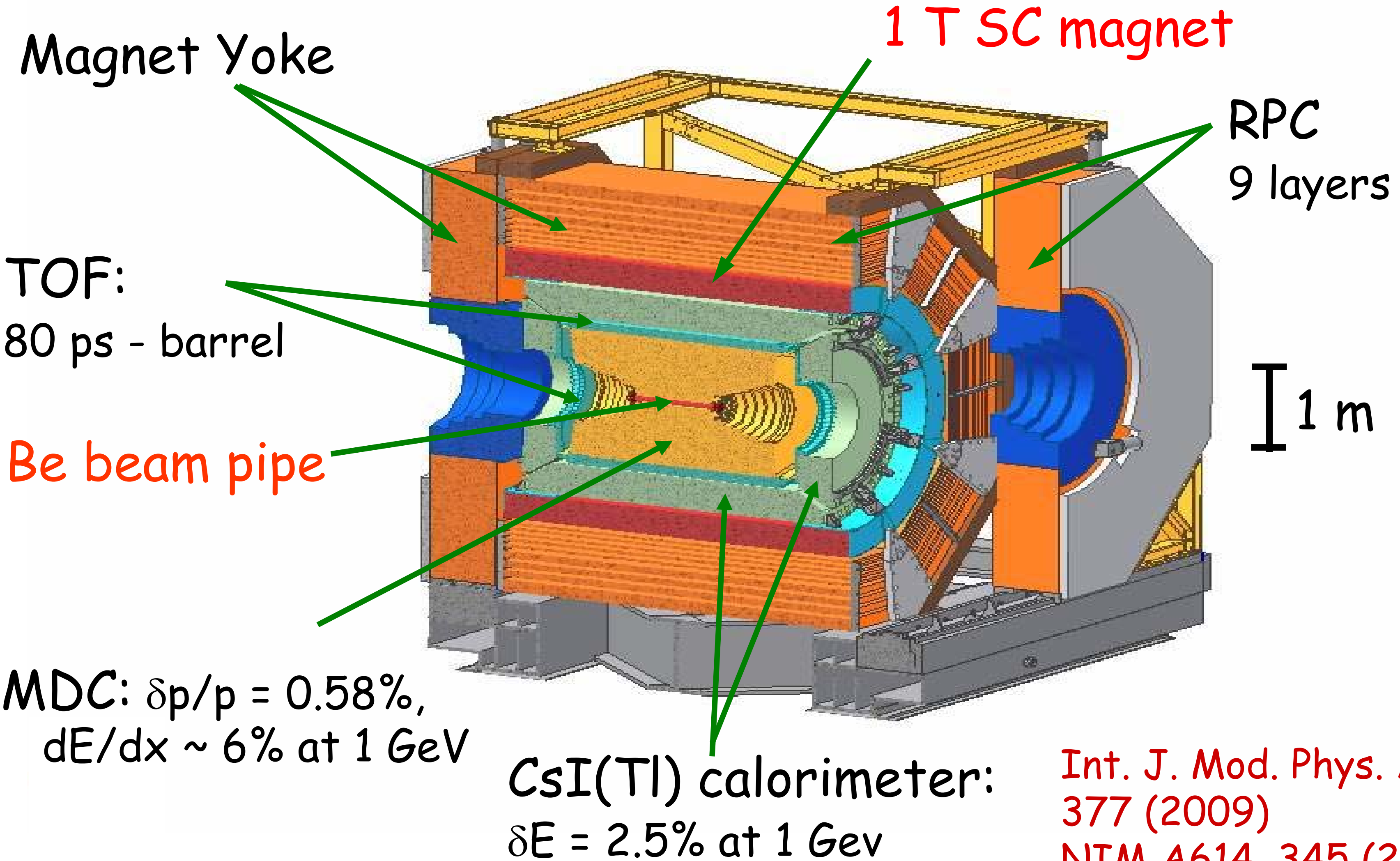
Beam magnets

CM Energy: 2 – 4.6 GeV

Luminosity: 1×10^{33} $cm^{-2}s^{-1}$ @ 1.89 GeV

Uses 93 bunches and SC mini-beta.

BESIII Detector



Int. J. Mod. Phys. A24, 377 (2009)
NIM A614, 345 (2010)

The BESIII Collaboration

Europe (13)

Germany: Univ. of Bochum,
Univ. of Giessen, GSI
Univ. of Johannes Gutenberg
Helmholtz Ins. In Mainz
Russia: JINR Dubna; BINP Novosibirsk
Italy: Univ. of Torino , Frascati Lab, Ferrara Univ.
Netherland : KVI/Univ. of Groningen
Sweden: Uppsala Univ.
Turkey: Turkey Accelerator Center

US (6)

Univ. of Hawaii
Univ. of Washington
Carnegie Mellon Univ.
Univ. of Minnesota
Univ. of Rochester
Univ. of Indiana

Korea (1)

Seoul Nat. Univ.

Japan (1)

Tokyo Univ.

Pakistan (2)

Univ. of Punjab
COMSAT CIIT

China(29)

IHEP, CCAST, GUCAS, Shandong Univ.,
Univ. of Sci. and Tech. of China
Zhejiang Univ., Huangshan Coll.
Huazhong Normal Univ., Wuhan Univ.
Zhengzhou Univ., Henan Normal Univ.
Peking Univ., Tsinghua Univ. ,
Zhongshan Univ.,Nankai Univ., Beihang Univ.
Shanxi Univ., Sichuan Univ., Univ. of South China
Hunan Univ., Liaoning Univ.
Nanjing Univ., Nanjing Normal Univ.
Guangxi Normal Univ., Guangxi Univ.
Suzhou Univ., Hangzhou Normal Univ.
Lanzhou Univ., Henan Sci. and Tech. Univ.

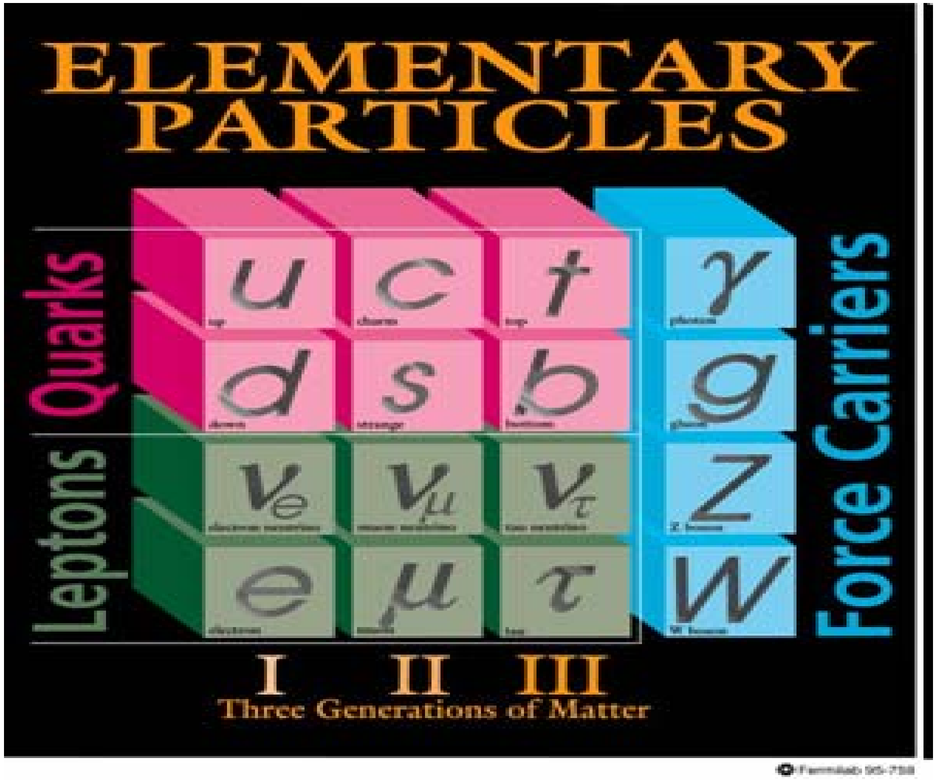
~350 members
52 institutions from
11 countries

BESIII

- Hawaii members:
  - Mihajlo Kornicer: $X_{c1} \rightarrow \eta\pi\pi$, $\eta'\pi\pi$ and τ mass studies
  - Tao Luo: τ mass studies
  - Gary Varner
- Data sets (started from 2008):
  - 1.25 B J/Ψ events
  - 125 M Ψ(3668) events
  - 2.9 fb^{-1} at Ψ(3770) for D physics
  - 500 pb^{-1} at 4.009 GeV
  - XYZ - 2.4 fb^{-1}
  - Now doing R scan from 3.8 GeV to 4.6 GeV; then more XYZ running

Introduction to charmonium

Standard Model



Standard Model particles are made of quarks, leptons, and the force carriers.

Visible matter:

$p = uud$ $n = udd$

$\pi^+ = u\bar{d}$ $\pi^- = \bar{u}d$

$D^+ = c\bar{d}$ $D^- = \bar{c}d$

Particles made of 2 or 3 quarks.

BEPCII operates in the 2 – 4.6 GeV energy region so it can study the lighter quarks (u, d, c, and s) and the leptons. "τ – charm factory"

Charmonium

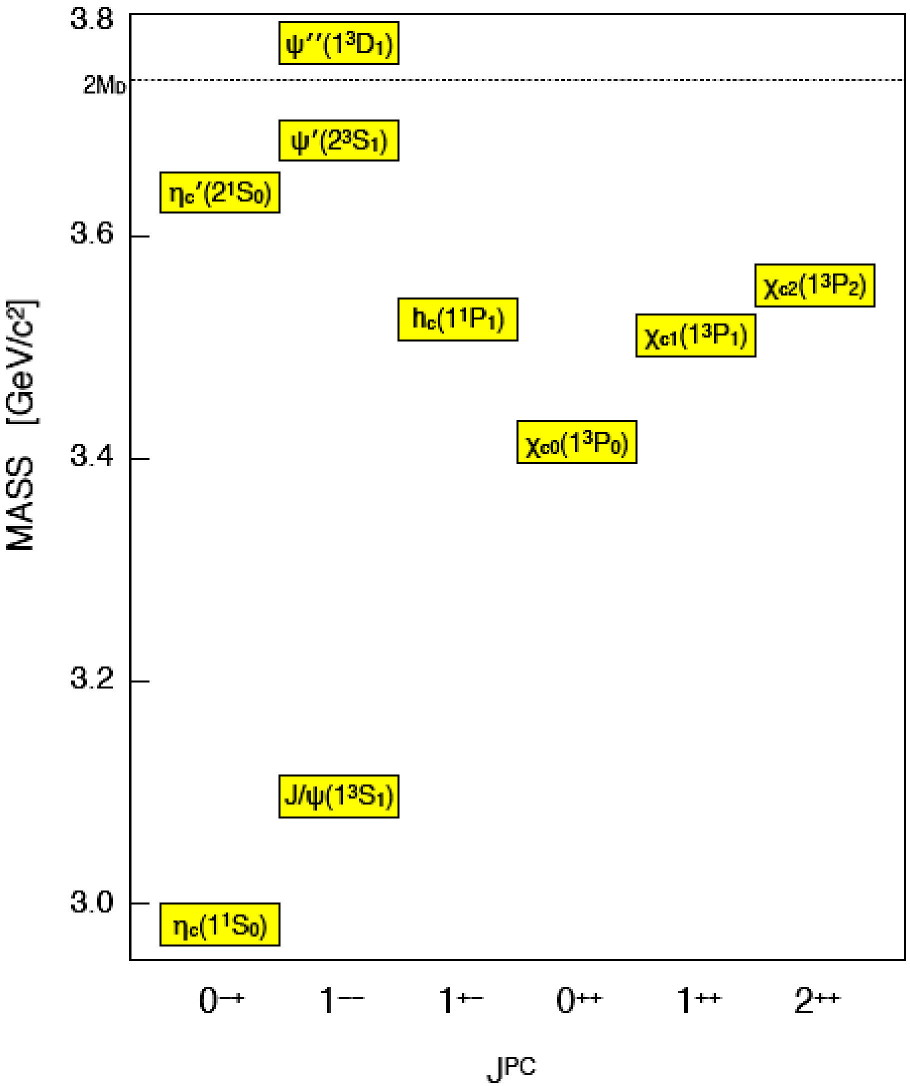
- Charmonium is one of the simplest bound states in QCD.
- Charge zero.
- Like positronium in QED.
- Classify using J^{PC}.
- Match to $n^{2S+1}L_J$ quark model states:

$$\mathbf{J} = \mathbf{L} + \mathbf{S}$$

$$P = (-1)^{L+1}$$

$$C = (-1)^{L+S}$$

$J^P = \frac{1}{2}^+$



BESIII has studied these.

Introduction to Charmonium

How to predict masses?

Potential Models
(tuned using lowest
mass states)

Example from Barnes, Godfrey, Swanson:

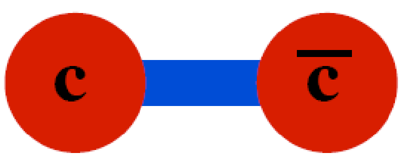
$$V_0^{(c\bar{c})}(r) = -\frac{4}{3}\frac{\alpha_s}{r} + br + \frac{32\pi\alpha_s}{9m_c^2}\tilde{\delta}_\sigma(r)\vec{\mathrm{S}}_c \cdot \vec{\mathrm{S}}_{\bar{c}}$$

(Coulomb + Confinement + Contact)

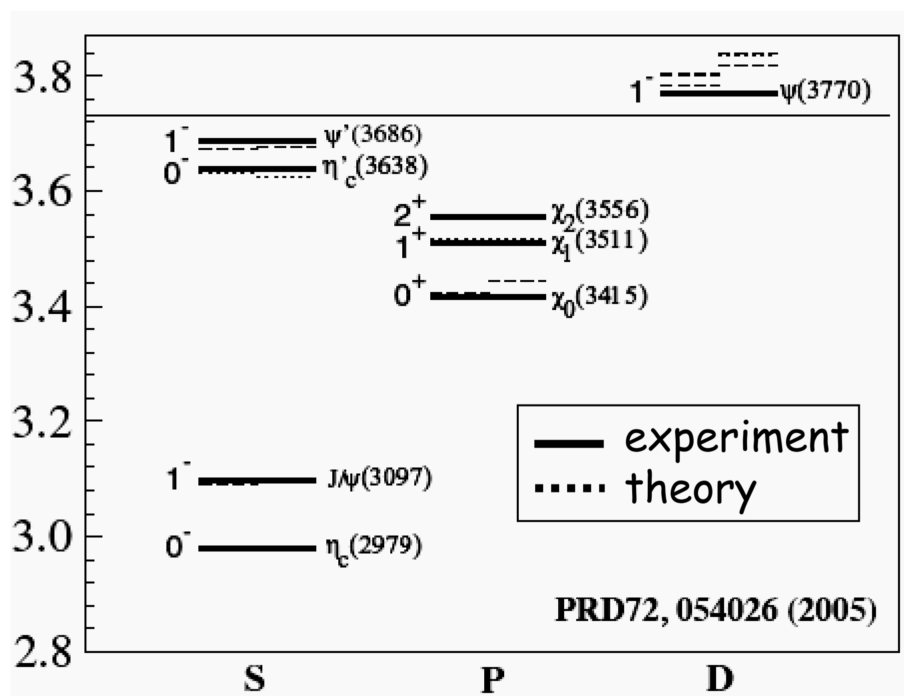
$$V_{\text{spin-dep}} = \frac{1}{m_c^2}\left[\left(\frac{2\alpha_s}{r^3} - \frac{b}{2r}\right)\vec{\mathrm{L}} \cdot \vec{\mathrm{S}} + \frac{4\alpha_s}{r^3}\mathrm{T}\right]$$

(Spin-Orbit + Tensor)

PRD72, 054026 (2005)

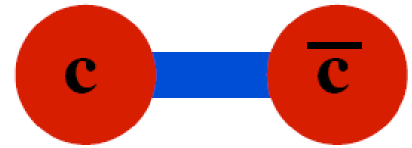


CHARMONIUM

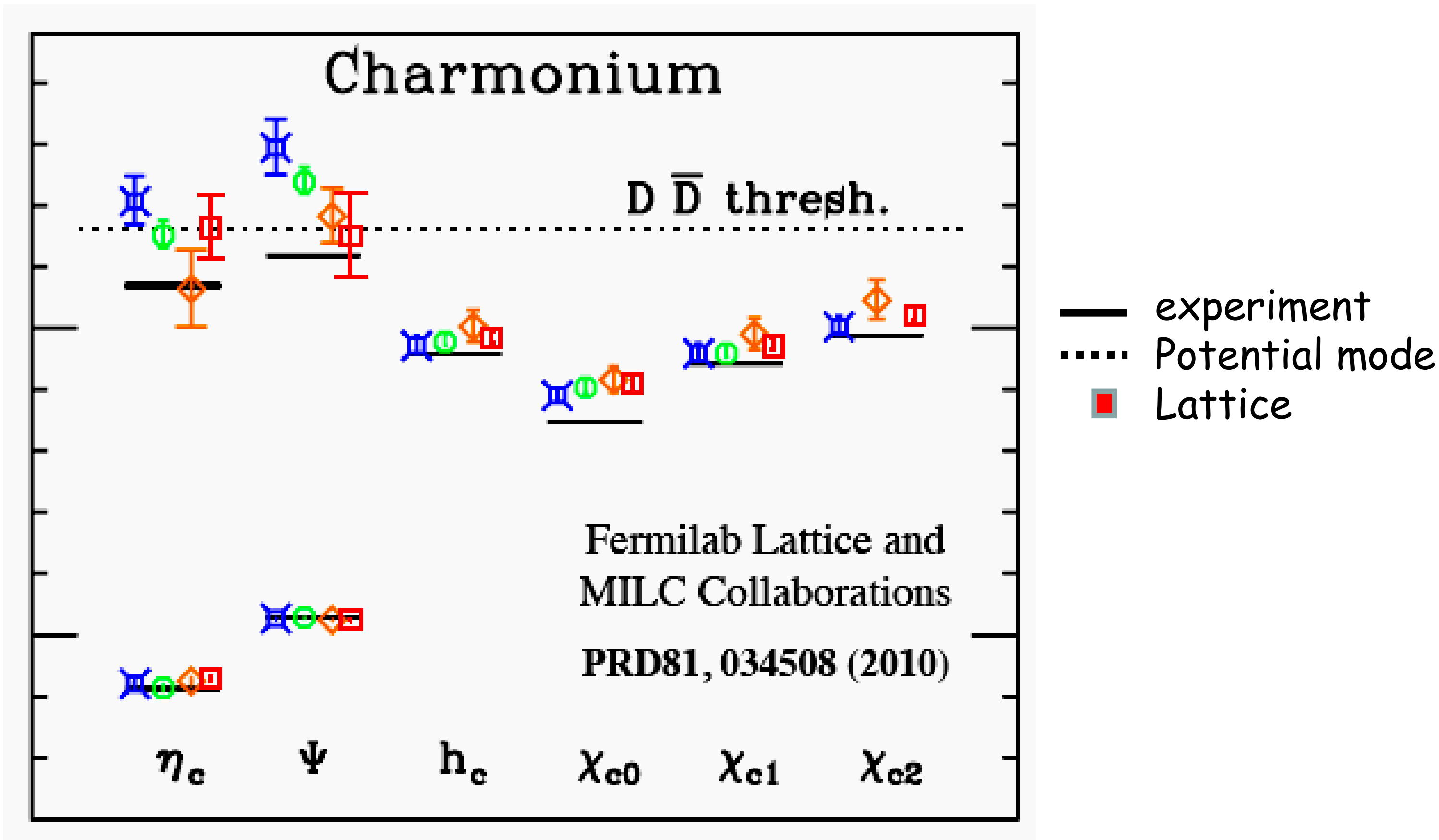


Introduction to Charmonium

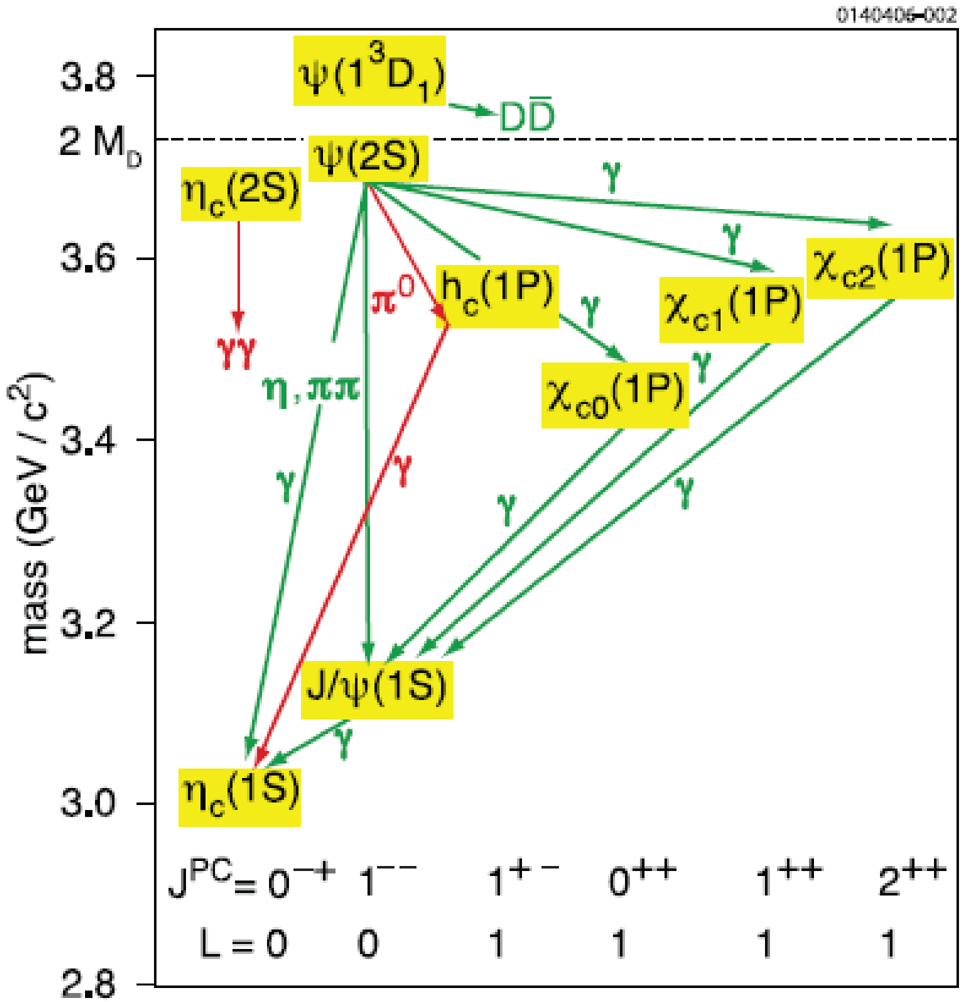
A more fundamental approach: Lattice QCD



CHARMONIUM



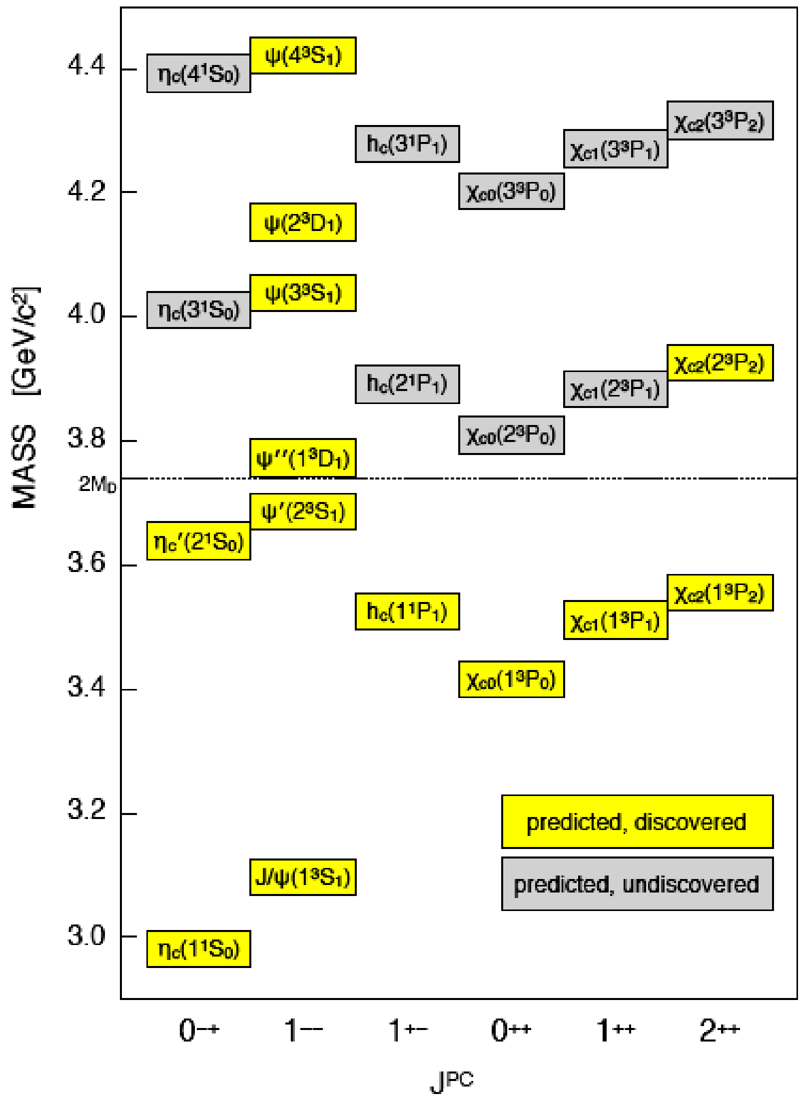
Charmonium spectrum below open charm

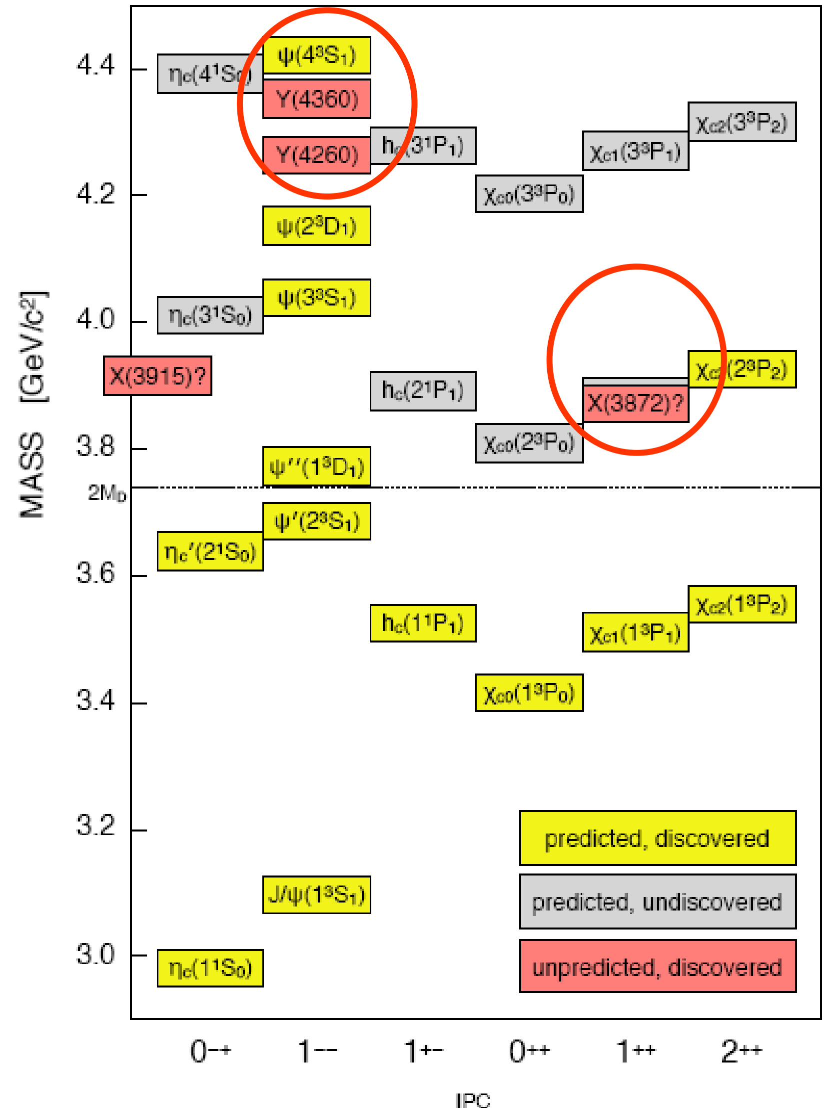


Only J/ψ and ψ' produced directly in e^+e^- collisions, but states below ψ' produced through radiative and hadronic transitions.


XYZ States

XYZ States





XYZ states not predicted by potential models.
What are they?

XYZ States (EPJ C71, 1534 (2011))

First XYZ

State	m (MeV)	Γ (MeV)	J^{PC}	Process (mode)	Experiment (#σ)	Year	Statu
$X(3872)$	3871.52 ± 0.20	1.3 ± 0.6	$1^{++}/2^{-+}$	$B \to K(\pi^+\pi^- J/\psi)$	Belle [85, 86] (12.8), *BABAR* [87] (8.6)	2003	OK
		(<2.2)		$p\bar{p} \to (\pi^+\pi^- J/\psi) + \cdots$	CDF [88–90] (np), DØ [91] (5.2)		
				$B \to K(\omega J/\psi)$	Belle [92] (4.3), *BABAR* [93] (4.0)		
				$B \to K(D^{*0}\bar{D}^0)$	Belle [94, 95] (6.4), *BABAR* [96] (4.9)		
				$B \to K(\gamma J/\psi)$	Belle [92] (4.0), *BABAR* [97, 98] (3.6)		
				$B \to K(\gamma\psi(2S))$	*BABAR* [98] (3.5), Belle [99] (0.4)		
$X(3915)$	3915.6 ± 3.1	28 ± 10	$0/2^{?+}$	$B \to K(\omega J/\psi)$	Belle [100] (8.1), *BABAR* [101] (19)	2004	OK
				$e^+e^- \to e^+e^-(\omega J/\psi)$	Belle [102] (7.7)		
$X(3940)$	3942^{+9}_{-8}	37^{+27}_{-17}	$?^{?+}$	$e^+e^- \to J/\psi(D\bar{D}^*)$	Belle [103] (6.0)	2007	NC!
				$e^+e^- \to J/\psi\ (\ldots)$	Belle [54] (5.0)		
$G(3900)$	3943 ± 21	52 ± 11	1^{--}	$e^+e^- \to \gamma(D\bar{D})$	*BABAR* [27] (np), Belle [21] (np)	2007	OK
$Y(4008)$	4008^{+121}_{-49}	226 ± 97	1^{--}	$e^+e^- \to \gamma(\pi^+\pi^- J/\psi)$	Belle [104] (7.4)	2007	NC!
$Z_1(4050)^+$	4051^{+24}_{-43}	82^{+51}_{-55}	?	$B \to K(\pi^+\chi_{c1}(1P))$	Belle [105] (5.0)	2008	NC!
$Y(4140)$	4143.4 ± 3.0	15^{+11}_{-7}	$?^{?+}$	$B \to K(\phi J/\psi)$	CDF [106, 107] (5.0)	2009	NC!
$X(4160)$	4156^{+29}_{-25}	139^{+113}_{-65}	$?^{?+}$	$e^+e^- \to J/\psi(D\bar{D}^*)$	Belle [103] (5.5)	2007	NC!
$Z_2(4250)^+$	4248^{+185}_{-45}	177^{+321}_{-72}	?	$B \to K(\pi^+\chi_{c1}(1P))$	Belle [105] (5.0)	2008	NC!

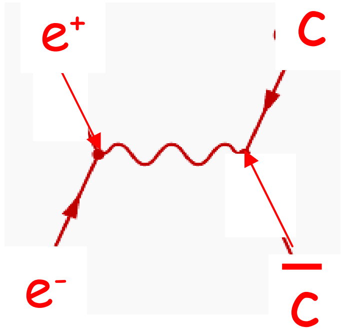
XYZ States (EPJ C71, 1534 (2011))

$Y(4260)$	4263 ± 5	108 ± 14	1^{--}	$e^+e^- \to \gamma(\pi^+\pi^- J/\psi)$	*BABAR* [108, 109] (8.0)	2005	OK
					CLEO [110] (5.4)		
					Belle [104] (15)		
				$e^+e^- \to (\pi^+\pi^- J/\psi)$	CLEO [111] (11)		
				$e^+e^- \to (\pi^0\pi^0 J/\psi)$	CLEO [111] (5.1)		
$Y(4274)$	$4274.4^{+8.4}_{-6.7}$	32^{+22}_{-15}	$?^{?+}$	$B \to K(\phi J/\psi)$	CDF [107] (3.1)	2010	NC!
$X(4350)$	$4350.6^{+4.6}_{-5.1}$	$13.3^{+18.4}_{-10.0}$	$0,2^{++}$	$e^+e^- \to e^+e^-(\phi J/\psi)$	Belle [112] (3.2)	2009	NC!
$Y(4360)$	4353 ± 11	96 ± 42	1^{--}	$e^+e^- \to \gamma(\pi^+\pi^- \psi(2S))$	*BABAR* [113] (np), Belle [114] (8.0)	2007	OK
$Z(4430)^+$	4443^{+24}_{-18}	107^{+113}_{-71}	?	$B \to K(\pi^+\psi(2S))$	Belle [115, 116] (6.4)	2007	NC!
$X(4630)$	4634^{+9}_{-11}	92^{+41}_{-32}	1^{--}	$e^+e^- \to \gamma(\Lambda_c^+\Lambda_c^-)$	Belle [25] (8.2)	2007	NC!
$Y(4660)$	4664 ± 12	48 ± 15	1^{--}	$e^+e^- \to \gamma(\pi^+\pi^- \psi(2S))$	Belle [114] (5.8)	2007	NC!
$Y_b(10888)$	10888.4 ± 3.0	$30.7^{+8.9}_{-7.7}$	1^{--}	$e^+e^- \to (\pi^+\pi^- \Upsilon(nS))$	Belle [37, 117] (3.2)	2010	NC!

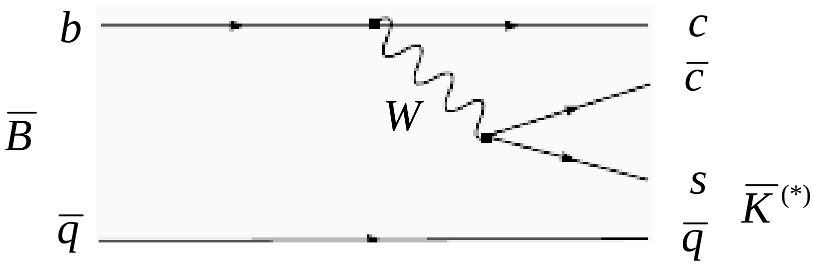
- Most discoveries by B factory experiments.
- Many states not confirmed.
- Produced indirectly by ISR production or B decay.
- Still a puzzle after 10 years.
- Much theoretical interest.

Charmonium Production Processes

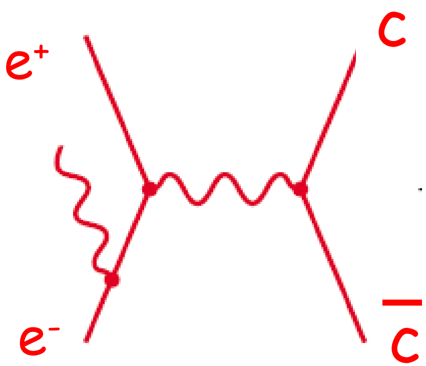
- e^+e^- annihilation



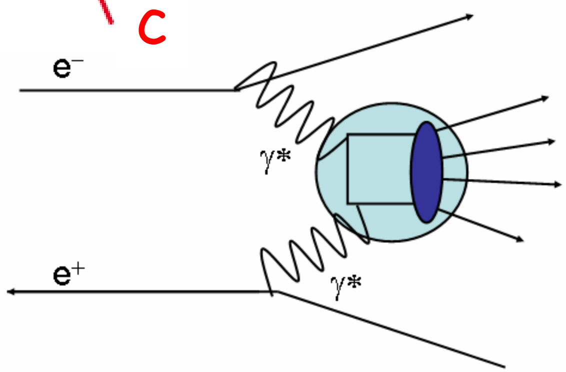
- B decay



- ISR
  - e^+e^- radiate one or more photons.
  - Measure σ over range of energies.



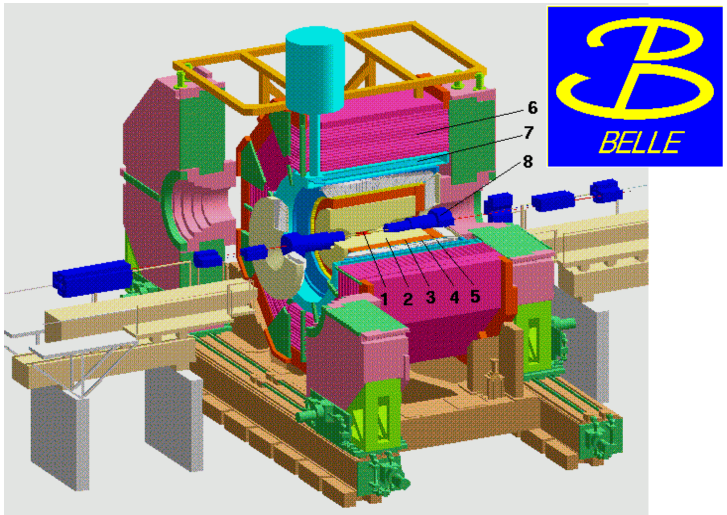
- 2 photon
  - even spin mesons
  - anti glueball filter.



High luminosities at B factories allow use of ISR and 2 photon processes.

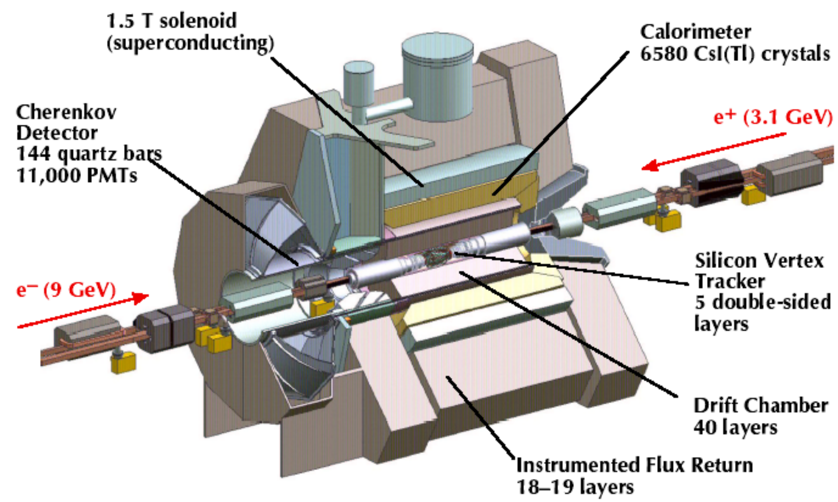
Experiments

Belle (1998 - 2010)

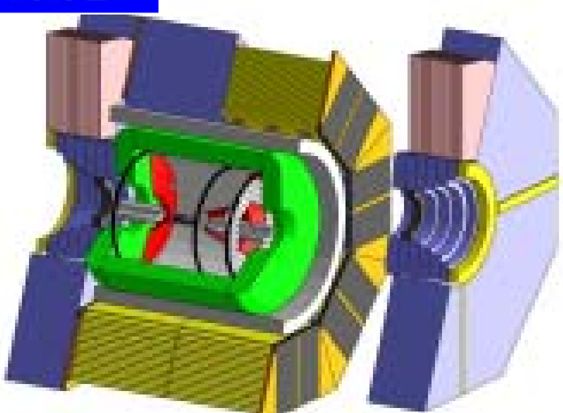


e^+e^-

BABAR (1998 - 2008)

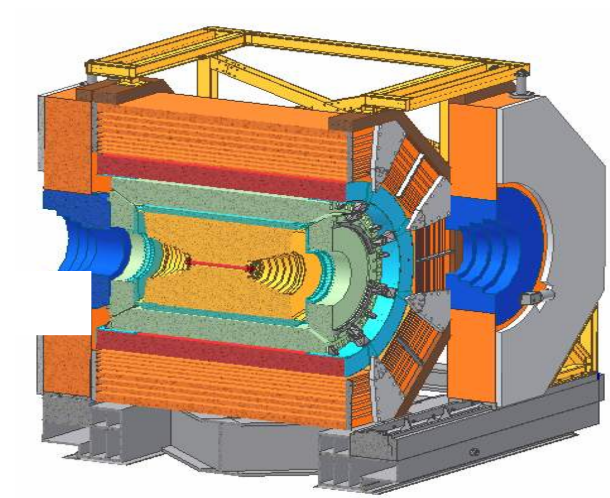


Belle II (2016? -)

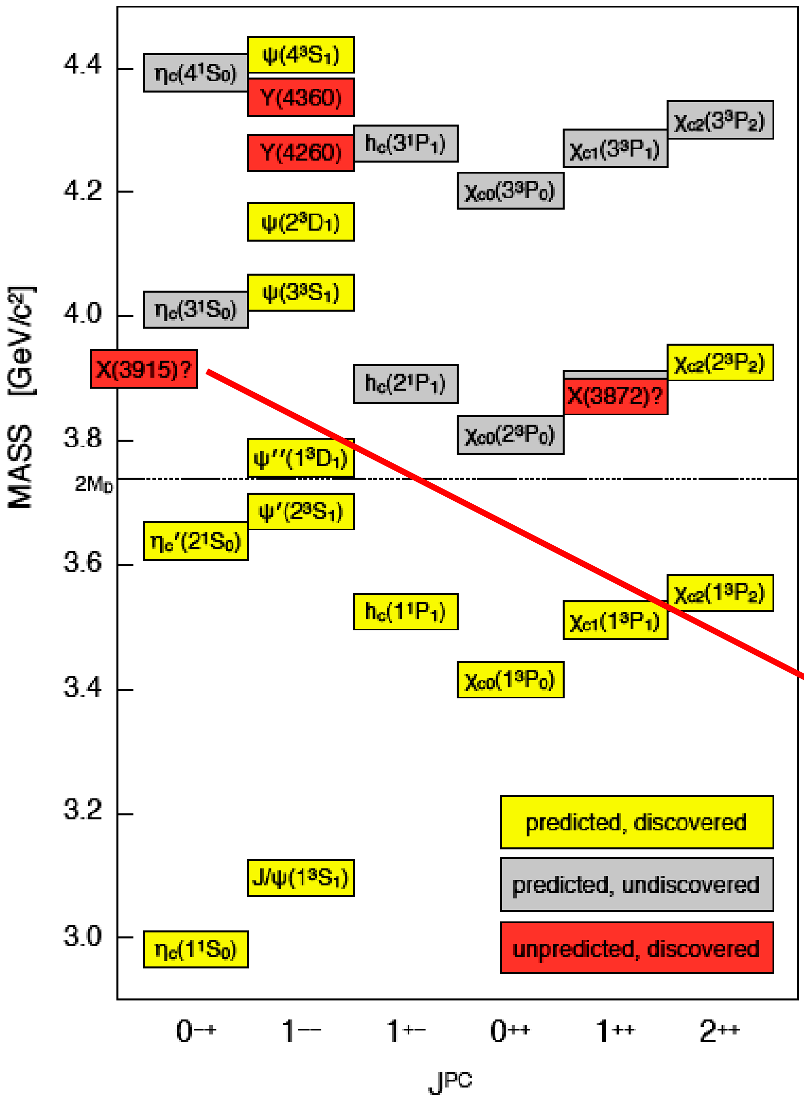


BESIII

(2009 -)

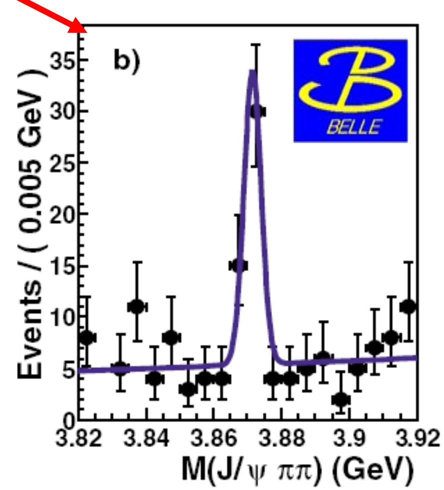


X(3872)



- Observed first by Belle in 2003 in $B^{\pm} \rightarrow K^{\pm}(\pi^{+}\pi^{-}J/\Psi)$
- Confirmed by CDF, D0, and BaBar
- Belle and BaBar observe $X(3872) \rightarrow \gamma J/\Psi$: $C = +$
- CDF and LHCb determine $J^P = 1^+$

$M = 3871.68 \pm 0.17$ MeV/c^2
$\Gamma < 1.2$ MeV



Belle, PRL 91, 262001(2003)

X(3872)

Observation of a Narrow Charmoniumlike State in Exclusive $B^{\pm} \to K^{\pm}\pi^{+}\pi^{-}J/\psi$ Decays

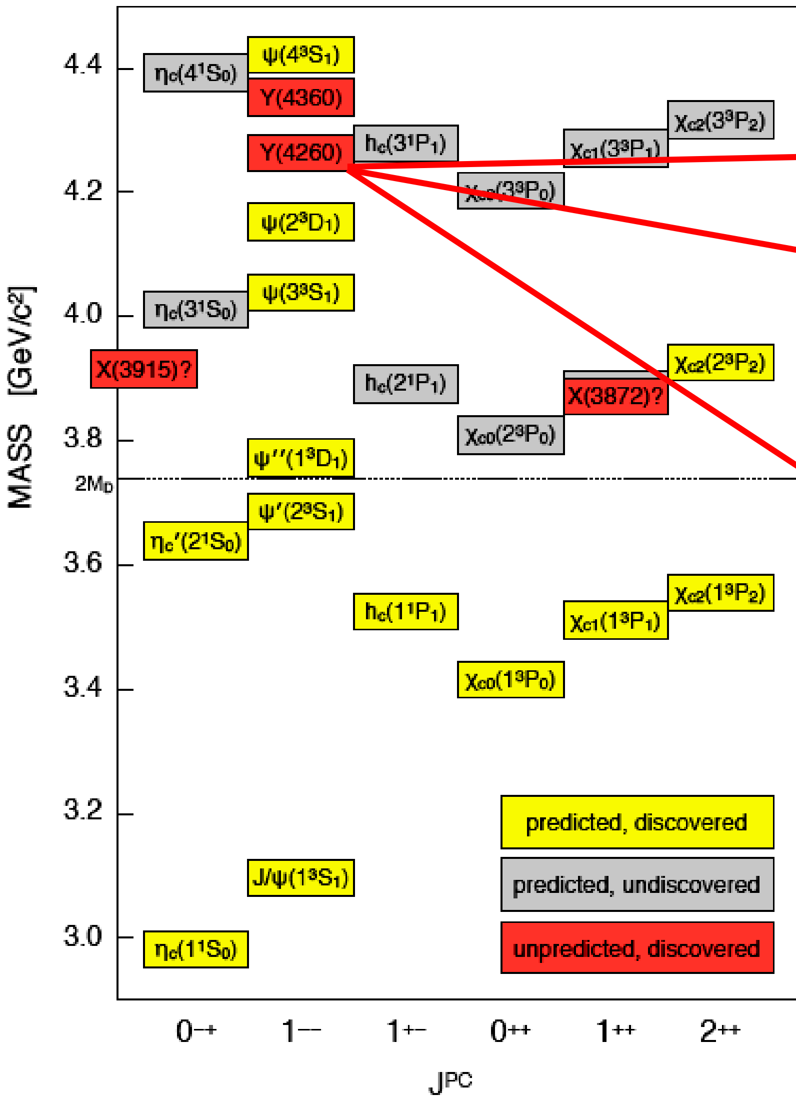
S.-K. Choi,[5] S. L. Olsen,[6] K. Abe,[7] T. Abe,[7] I. Adachi,[7] Byoung Sup Ahn,[14] H. Aihara,[43] K. Akai,[7] M. Akatsu,[20] M. Akemoto,[7] Y. Asano,[48] T. Aso,[47] V. Aulchenko,[1] T. Aushev,[11] A. M. Bakich,[38] Y. Ban,[31] S. Banerjee,[39] A. Bondar,[1] A. Bozek,[25] M. Bračko,[18,12] J. Brodzicka,[25] T. E. Browder,[6] P. Chang,[24] Y. Chao,[24] K.-F. Chen,[24] B. G. Cheon,[37] R. Chistov,[11] Y. Choi,[37] Y. K. Choi,[37] M. Danilov,[11] L. Y. Dong,[9] A. Drutskoy,[11] S. Eidelman,[1] V. Eiges,[11] J. Flanagan,[7] C. Fukunaga,[45] K. Furukawa,[7] N. Gabyshev,[7] T. Gershon,[7] B. Golob,[17,12] H. Guler,[6] R. Guo,[22] C. Hagner,[50] F. Handa,[42] T. Hara,[29] N.C. Hastings,[7] H. Hayashii,[21] M. Hazumi,[7] L. Hinz,[16] Y. Hoshi,[41] W.-S. Hou,[24] Y. B. Hsiung,[24,*] H.-C. Huang,[24] T. Iijima,[20] K. Inami,[20] A. Ishikawa,[20] R. Itoh,[7] M. Iwasaki,[43] Y. Iwasaki,[7] J. H. Kang,[52] S. U. Kataoka,[21] N. Katayama,[7] H. Kawai,[2] T. Kawasaki,[27] H. Kichimi,[7] E. Kikutani,[7] H. J. Kim,[52] Hyunwoo Kim,[14] J. H. Kim,[37] S. K. Kim,[36] K. Kinoshita,[3] H. Koiso,[7] P. Koppenburg,[7] S. Korpar,[18,12] P. Križan,[17,12] P. Krokovny,[1] S. Kumar,[30] A. Kuzmin,[1] J. S. Lange,[4,33] G. Leder,[10] S. H. Lee,[36] T. Lesiak,[25] S.-W. Lin,[24] D. Liventsev,[11] J. MacNaughton,[10] G. Majumder,[39] F. Mandl,[10] D. Marlow,[32] T. Matsumoto,[45] S. Michizono,[7] T. Mimashi,[7] W. Mitaroff,[10] K. Miyabayashi,[21] H. Miyake,[29] D. Mohapatra,[50] G. R. Moloney,[19] T. Nagamine,[42] Y. Nagasaka,[8] T. Nakadaira,[43] T. T. Nakamura,[7] M. Nakao,[7] Z. Natkaniec,[25] S. Nishida,[7] O. Nitoh,[46] T. Nozaki,[7] S. Ogawa,[40] Y. Ogawa,[7] K. Ohmi,[7] Y. Ohnishi,[7] T. Ohshima,[20] N. Ohuchi,[7] K. Oide,[7] T. Okabe,[20] S. Okuno,[13] W. Ostrowicz,[25] H. Ozaki,[7] H. Palka,[25] H. Park,[15] N. Parslow,[38] L. E. Piilonen,[50] H. Sagawa,[7] S. Saitoh,[7] Y. Sakai,[7] T. R. Sarangi,[49] M. Satapathy,[49] A. Satpathy,[7,3] O. Schneider,[16] A. J. Schwartz,[3] S. Semenov,[11] K. Senyo,[20] R. Seuster,[6] M. E. Sevior,[19] H. Shibuya,[40] T. Shidara,[7] B. Shwartz,[1] V. Sidorov,[1] N. Soni,[30] S. Stanič,[48,†] M. Starič,[12] A. Sugiyama,[34] T. Sumiyoshi,[45] S. Suzuki,[51] F. Takasaki,[7] K. Tamai,[7] N. Tamura,[27] M. Tanaka,[7] M. Tawada,[7] G. N. Taylor,[19] Y. Teramoto,[28] T. Tomura,[43] K. Trabelsi,[6] T. Tsukamoto,[7] S. Uehara,[7] K. Ueno,[24] Y. Unno,[2] S. Uno,[7] G. Varner,[6] K. E. Varvell,[38] C. C. Wang,[24] C. H. Wang,[23] J. G. Wang,[50] Y. Watanabe,[44] E. Won,[14] B. D. Yabsley,[50] Y. Yamada,[7] A. Yamaguchi,[42] Y. Yamashita,[26] H. Yanai,[27] Heyoung Yang,[36] J. Ying,[31] M. Yoshida,[7] C. C. Zhang,[9] Z. P. Zhang,[35] and D. Žontar[17,12]

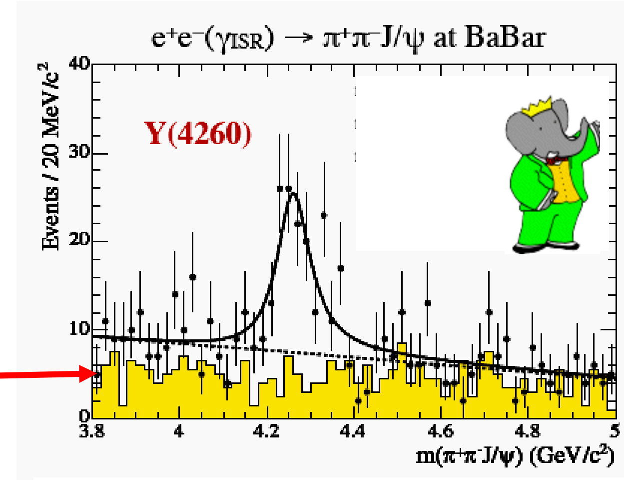
(Belle Collaboration)

Belle's most cited paper

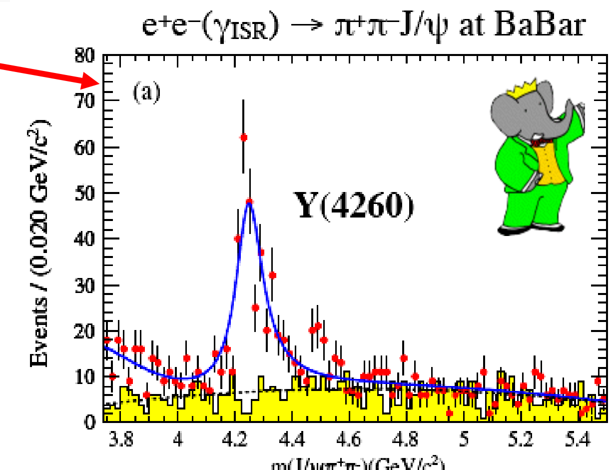
Dec. 2003

Y(4260)

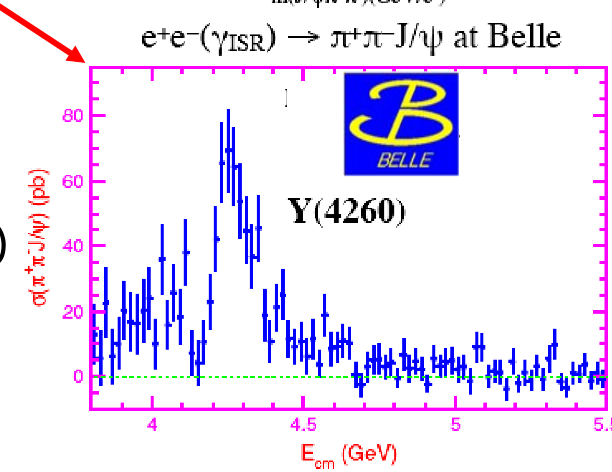




BaBar, PRL 95, 142001 (2005)



BaBar, PRD 86, 051102 (2012)



Belle, PRL 99, 182004 (2007)

$J^{PC} = 1^{--}$ since produced in ISR

X(3872) and Y(4260)

- Not only don't X(3872) and Y(4260) fit in normal quark model, they decay to $\pi^+\pi^- J/\Psi$ even though they are above DD-bar threshold.

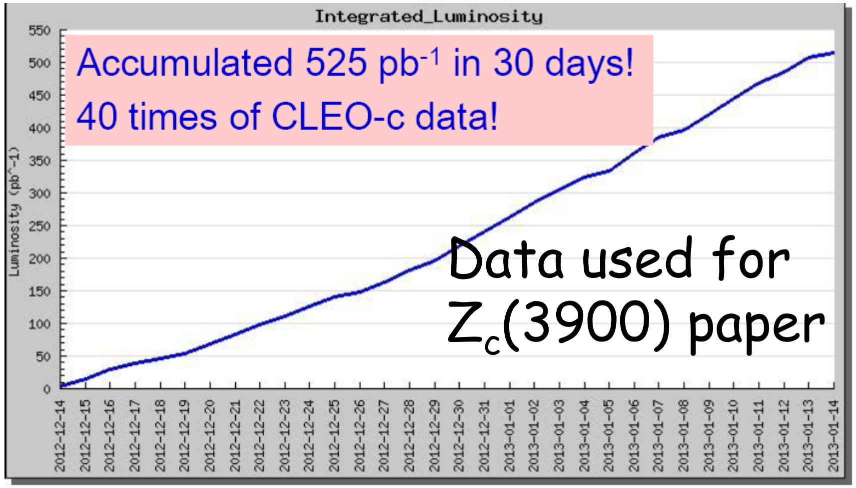
- New XYZ era has generated much excitement and many, many theoretical papers. Some theoretical ideas for Y(4260):
  - DD* bound state [NPA815, 53 (2009)].
  - J/Ψ f0 bound state (with KK $\rightarrow\pi\pi$) [PRD80, 094012 (2009)].
  - Tetraquarks (or two diquarks) [PRD72, 031502 (2005)].
  - Hadrocharmonium [PLB666, 215 (2008)].
  - Hybrid charmonium [PLB628, 215 (2005), PRD78, 094505 (2008), PLB625, 212 (2005)].

See Xiang Liu, arXiv:1312.7408 for a recent list of references.

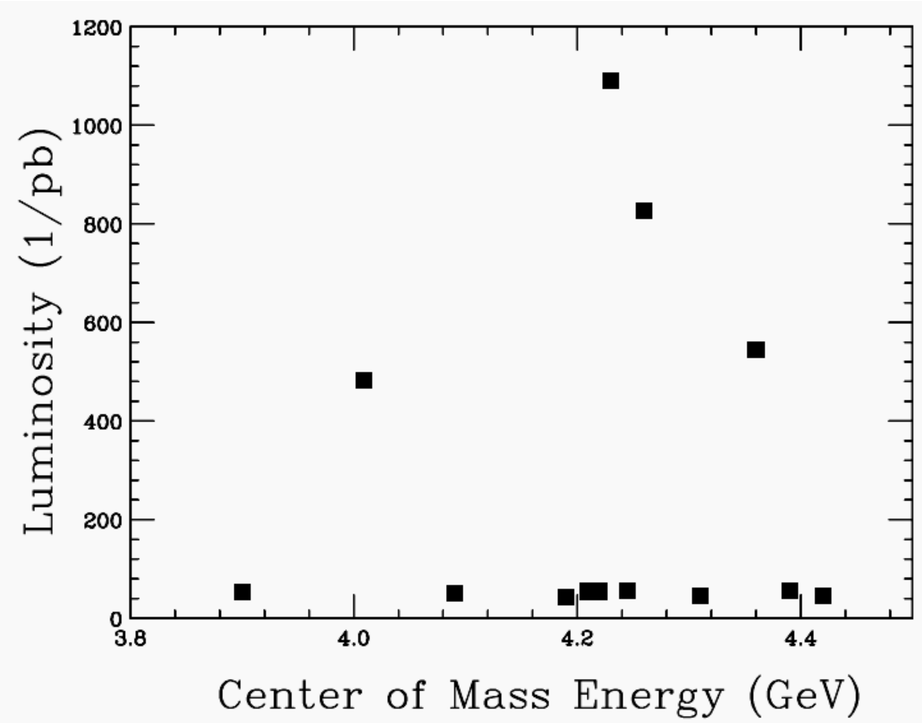

BESIII does XYZ

BES III

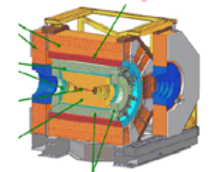
- On Dec. 14, 2012, BESIII began running with a CM energy of 4260 MeV. Produce Y(4260) directly.



- Data collection continued around Y(4260) and Y(4360) until June. Much more data collected.
- Provides excellent opportunities to understand XYZ particles.



Y(4260)

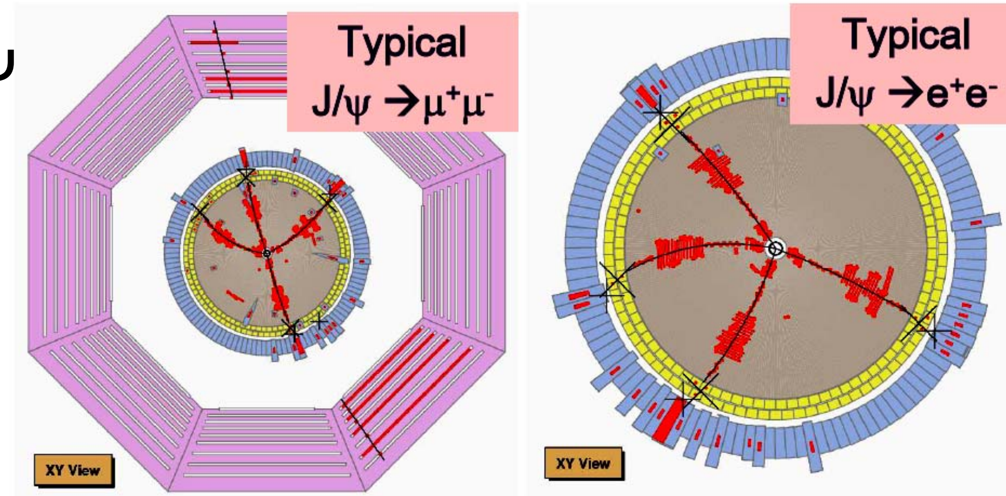


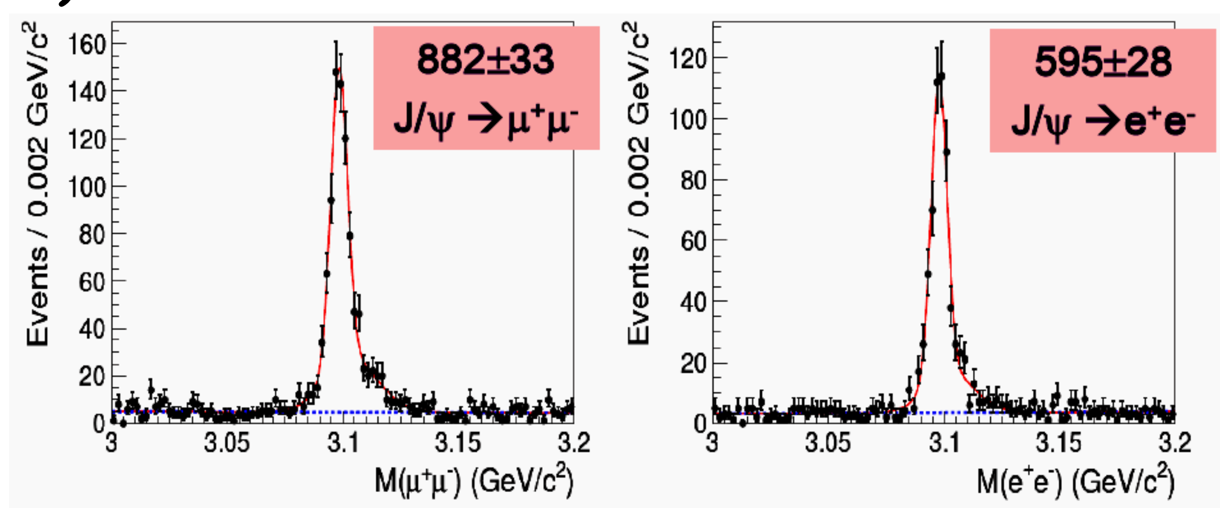
BESIII

Data: 525 pb^{-1} at 4260 MeV
Select $e^+e^- \to \pi^+\pi^- J/\Psi$, $J/\Psi \to l^+l^-$ events.

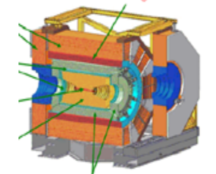
1477 events found.

Born cross section, (62.9 ± 1.9 ± 3.7) pb, consistent with production of Y(4260).



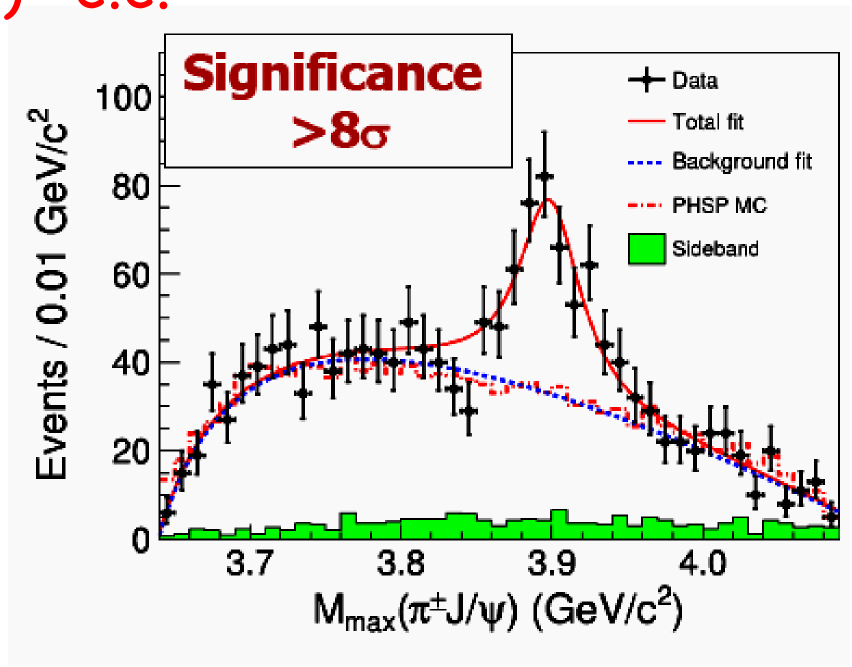


$Z_c(3900)$



Structure observed in the $\pi^{\pm} J/\Psi$ mass spectrum:
$e^+ e^- \rightarrow \pi\, Z_c(3900) \rightarrow \pi^- (\pi^+ J/\Psi)$ +c.c.

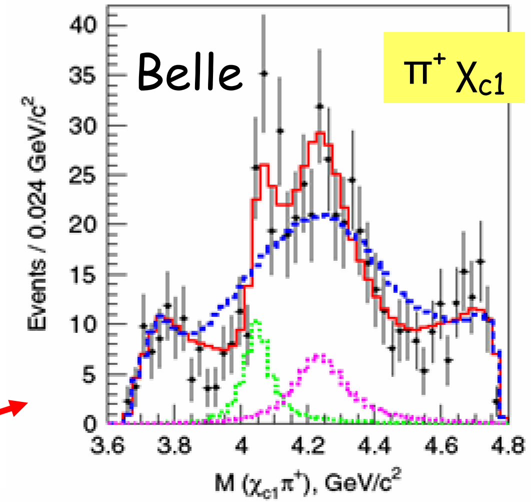
$N(Z_c(3900)) = 307 \pm 48$
$M(Z_c(3900)) = 3899.0 \pm 2.8 \pm 1.4$ MeV;
$\Gamma(Z_c(3900)) = 46 \pm 10 \pm 20$ MeV



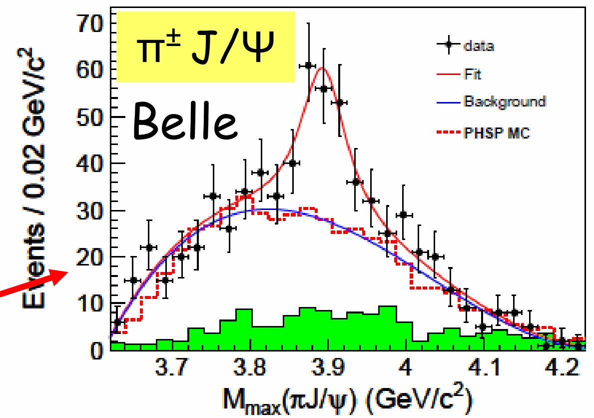
- Suggestive of a state containing more than just a C and C-bar quark. ($\pi^+ = u\bar{d}$, $J/\psi = c\bar{c}$)
- PRL **110**, 252001 (2013) with > 100 citations
- Was on top of APS Physics Highlights of 2013

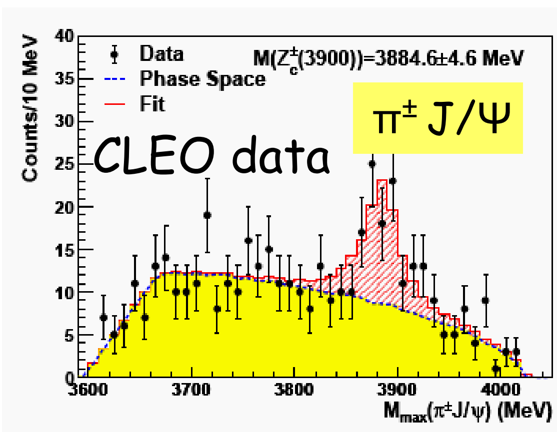
$Z_c(3900)$

Studies at B factories found unconfirmed/controversial structures in $\pi^{\pm}\Psi(3686)$, $Z^{\pm}(4430)$, [Belle, PRL 100, 142001 (2008); BaBar, PRD 79, 112001 (2009)] and $\pi^{\pm}X_{c1}$, $Z_1^{\pm}(4050)$ and $Z_2^{\pm}(4250)$, [Belle, PRD 78, 072004 (2008); BaBar, PRD 85, 052003 (2012)] systems.



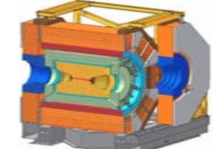
Luckily, the $Z_c(3900)$ was confirmed by Belle [PRL 110, 252002 (2013)] in ISR Y(4260) production and by Kam Seth [PLB 727, 366 (2013)] using 586 pb^{-1} of CLEO data taken at a CM energy of 4170 MeV.





$Z_c(3900)$ first confirmed charged charmonium state.

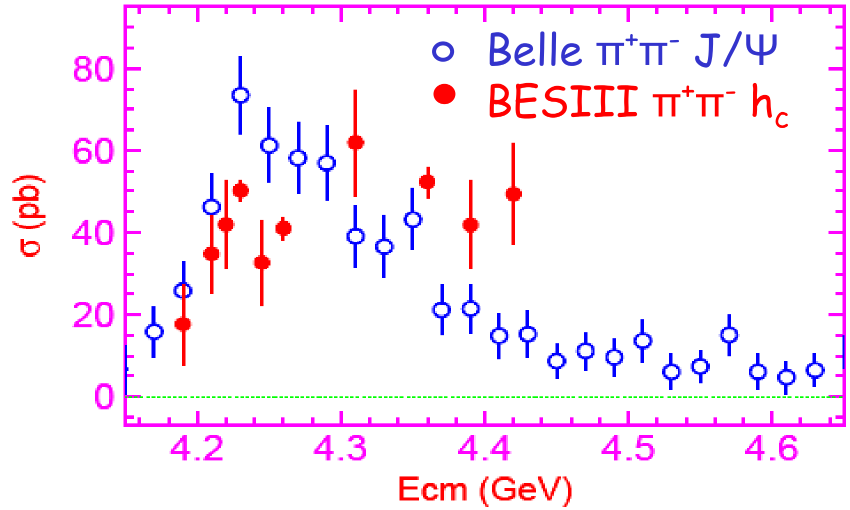
$Z_c(4020)$



BESIII

$e^+ + e^- \to \pi^+\pi^- h_c$, $h_c \to \gamma\eta_c$, $\eta_c \to$ 16 exclusive states

- Measure cross sections at 13 energies.
- Very different than $\pi^+\pi^- J/\Psi$ cross section.



C. Z. Yuan, arXiv:1312.6399

- Narrow structure near $(D^*\overline{D}^*)^+$ threshold in $\pi^\pm h_c$ mass:

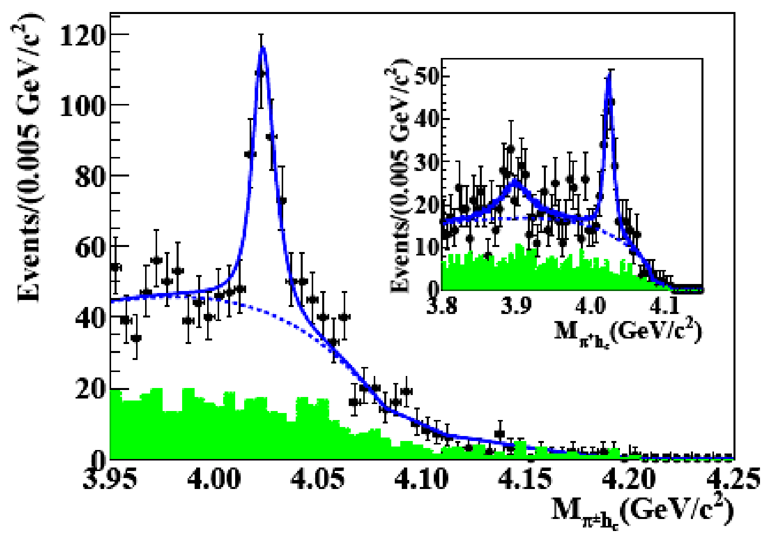
$e^+e^- \to \pi Z_c(4020) \to \pi^-(\pi^+ h_c) + c.c.$

$M(Z_c(4020)) = 4022.9 \pm 0.8 \pm 2.7$ MeV;

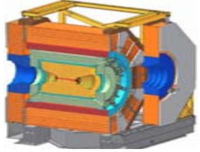
$\Gamma(Z_c(4020)) = 7.9 \pm 2.7 \pm 2.6$ MeV

$J^P = 1^+$ assumed

- No significant $Z_c(3900)$ observed.

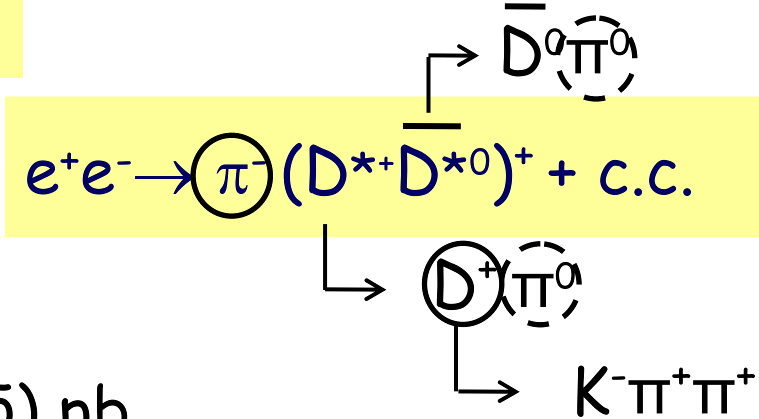


PRL **111**, 242001 (2013)
24 citations



BESIII

$Z_c(4025)$



- Partial reconstruction: detect π^-, D^+, and one π^0
- 827 pb^{-1} of data at 4.26 GeV
- Born cross section, (137 ± 9 ± 15) pb

- Structure observed in mass recoiling from π^- :

$e^+e^-\to\pi^-Z_c(4025)^+\to\pi^-(D^*\bar{D}^*)^+$ + c.c.

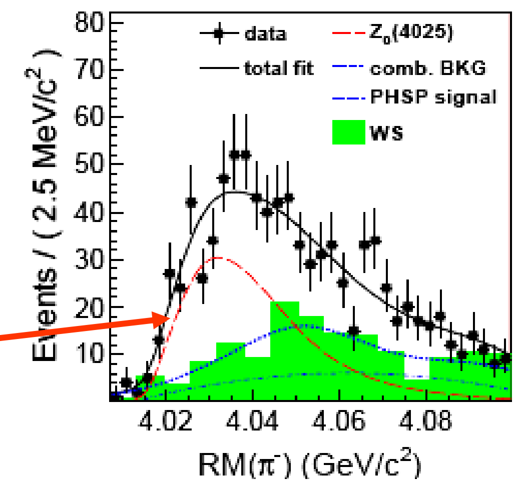
$M(Z_c(4025)) = 4026.3\pm2.6\pm3.7$ MeV/c^2;

$\Gamma(Z_c(4025)) = 24.8\pm5.6\pm7.7$ MeV

$J^P = 1^+$ assumed

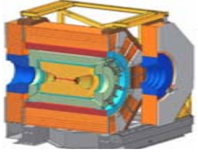
Loosely bound $D^*\bar{D}^*$ system?

$e^+e^-\to\pi Z_c(4025)$



$$\frac{\sigma(e^+e^-\to\pi^{-/+}Z_c(4025)^{+/-}\to\pi^{-/+}(D^*\bar{D}^*)^{+/-})}{\sigma(e^+e^-\to\pi^{-/+}(D^*\bar{D}^*)^{+/-})} = (65\pm9\pm6)\%$$

Submitted to PRL; arXiv1308.2760



$Z_c(3885)$

$e^+e^- \to \pi^+ (D^0 D^{*-}) + c.c.$, with $D^0 \to K^- \pi^+$

or

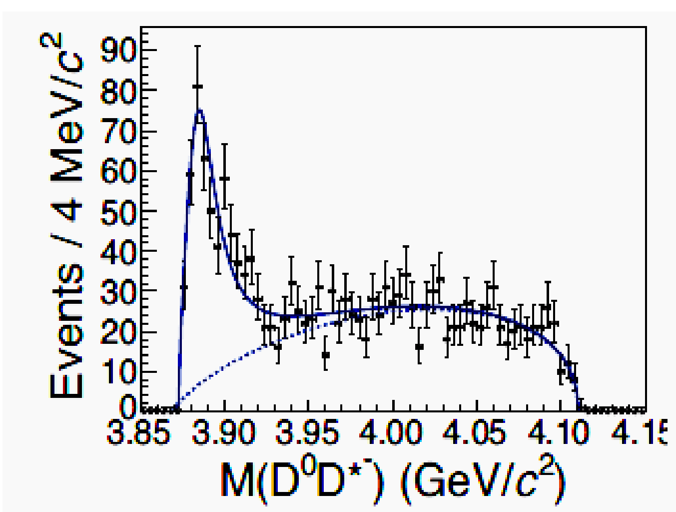
$e^+e^- \to \pi^- (D^+ \overline{D}^{*0}) + c.c.$, with $D^+ \to K^- \pi^+ \pi^+$

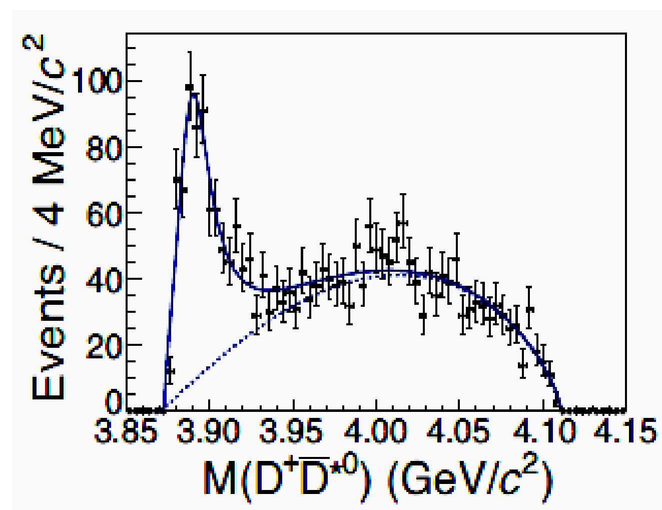
- Partial reconstruction: detect π and final state D
- 525 pb^{-1} of data at 4.26 GeV
- Born cross section, (83.5 ± 6.6 ± 22) pb
- Structure observed near $D\overline{D}^*$ threshold in mass recoiling from π:

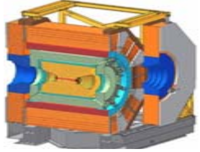
$$e^+e^- \to \pi^+ Z_c(3885)^- \to \pi^+ (D\overline{D}^*)^- + c.c.$$

$M(Z_c(3885)) = 3883.9 \pm 1.5 \pm 4.2\ MeV/c^2$;

$\Gamma(Z_c(3885)) = 24.8 \pm 3.3 \pm 11.0\ MeV$







BESIII

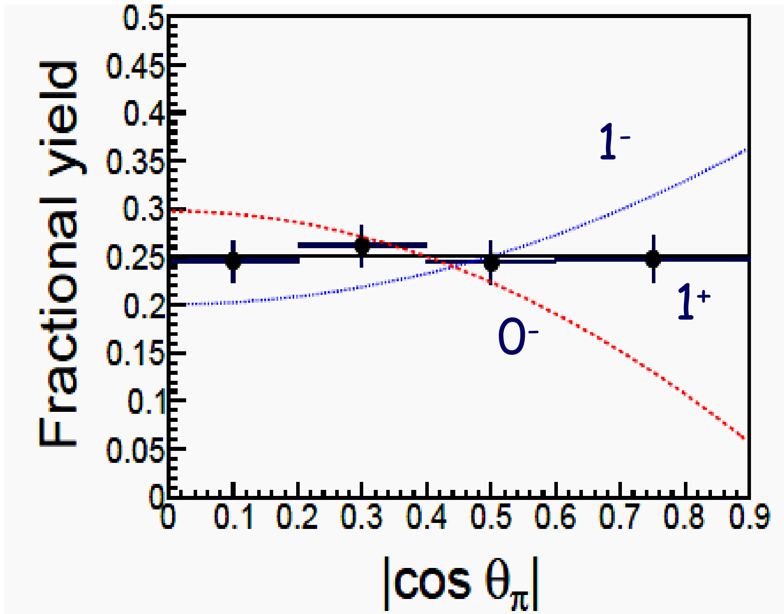
$Z_c(3885)$

$e^+e^- \to \pi^+ (D^0 D^{*-}) + c.c.$, with $D^0 \to K^- \pi^+$

or

$e^+e^- \to \pi^- (D^+ \overline{D^{*0}}) + c.c.$, with $D^+ \to K^- \pi^+ \pi^+$

- Structure prefers $J^P = 1^+$



PRL 112, 022001 (2014)

- Assuming $Z_c(3885)$ and $Z_c(3900)$ same:

$$\frac{\Gamma(Z_c(3885) \to DD^*)}{\Gamma(Z_c(3900) \to \pi J/\Psi)} = 6.2 \pm 1.1 \pm 2.7$$

Z_c Summary

		R (%)	$M(Z_c)$ (MeV/c^2)	$\Gamma(Z_c)$ (MeV)
$Z_c(3885)$	$e^+ e^- \to \pi^{+/-} Z_c^{-/+} \to \pi^{+/-} (D\bar{D}^*)^{-/+}$		3883.9 ± 1.5 ± 4.2	24.8 ± 3.3 ± 11
$Z_c(3900)$	$e^+ e^- \to \pi^{+/-} Z_c^{-/+} \to \pi^+ \pi^- J/\Psi$	21.5±3.3±7.5	3899 ± 3.6 ± 4.9	46 ± 10 ± 20
$Z_c(4020)$	$e^+ e^- \to \pi^{+/-} Z_c^{-/+} \to \pi^+ \pi^- h_c$	18	4022.9 ± 0.8 ± 2.7	7.9 ± 2.7 ± 2.6
$Z_c(4025)$	$e^+ e^- \to \pi^{+/-} Z_c^{-/+} \to \pi^{+/-} (D^*\bar{D}^*)^{-/+}$	65 ± 9 ± 6	4026.3 ± 2.6 ± 3.7	24.8 ± 5.6 ± 7.7

$R=\Gamma(e^+e^- \to Z_c\pi \to \pi \text{ f.s.})/\Gamma(e^+e^- \to \pi \text{ f.s.})$

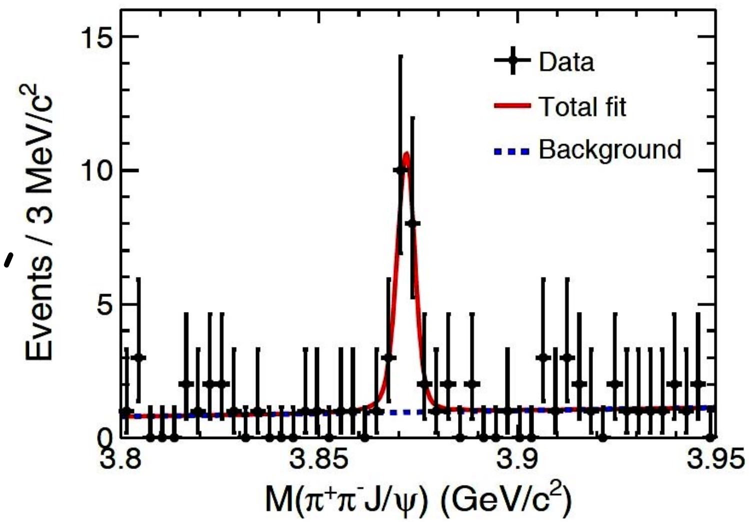
At least two states.

BESIII

X(3872)

- So far X(3872) only observed in B decays and hadron collisions.
- Since $J^{PC} = 1^{++}$, should be able to see Y(4260) radiative decay to X(3872):

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



- Combine data at 4.009, 4.229, 4.26, and 4.36 GeV:

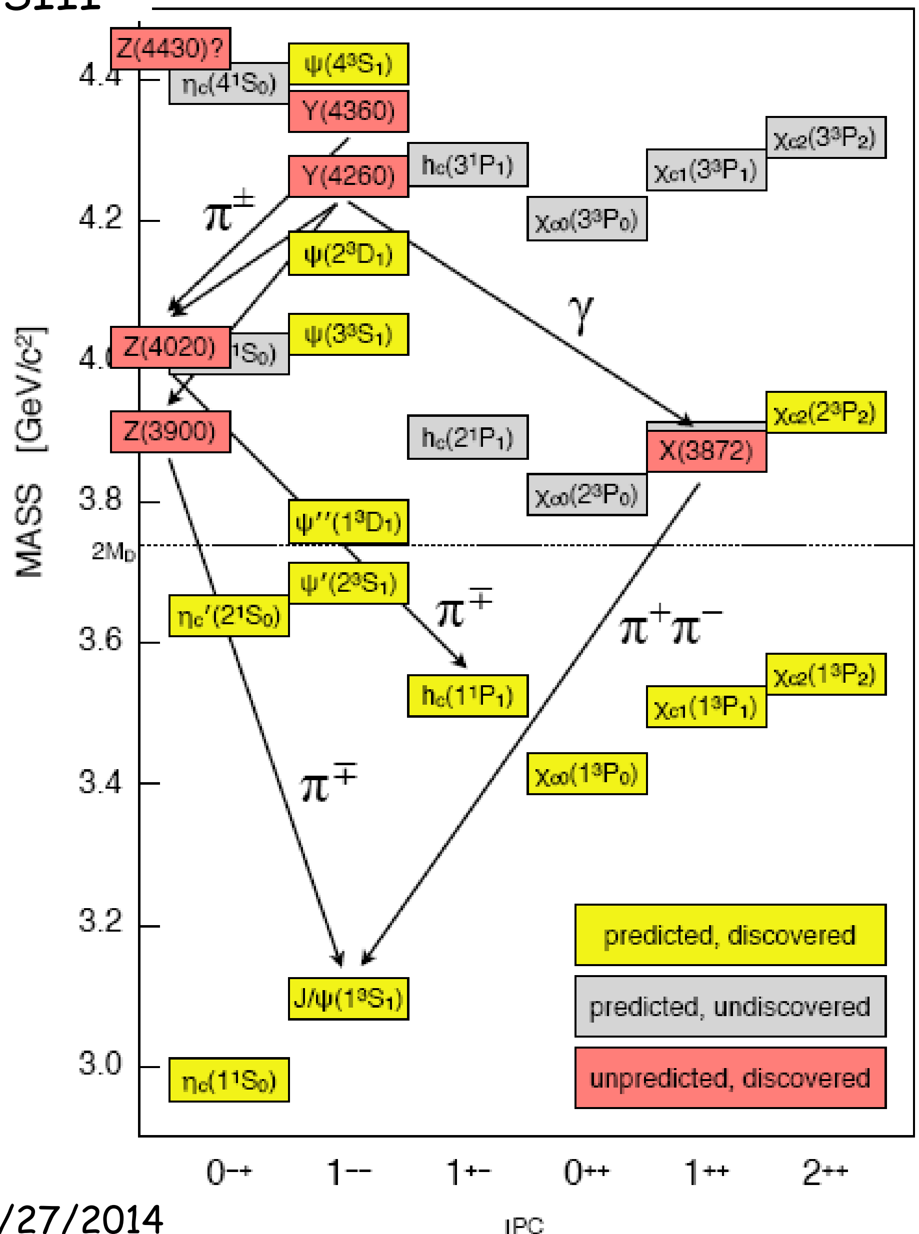
  M(X(3872)) = 3872.1±0.8±0.3 MeV

  [PDG: 3871.68 ±0.17 MeV]

- X(3872) from radiative Y(4260) decay?
- Accepted by PRL; arXiv1310.4101

BESIII

XYZ Transitions



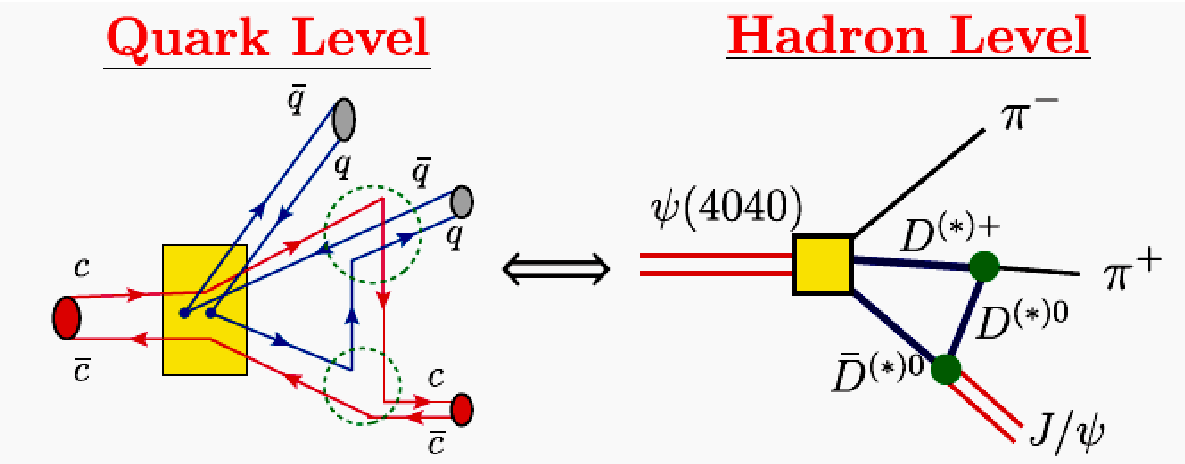
Have measured a number of transitions.
Many other analyses underway.
More data at other energy points this year.


Where are we?

Theory:

Theorists have been very busy, and many explanations have been offered for the X(3872), Y(4260), and now the Z_cs: tetraquarks, molecular states (DD* bound state), hadrocharmonium, hybrid charmonium, etc. I will only show a couple of results here.

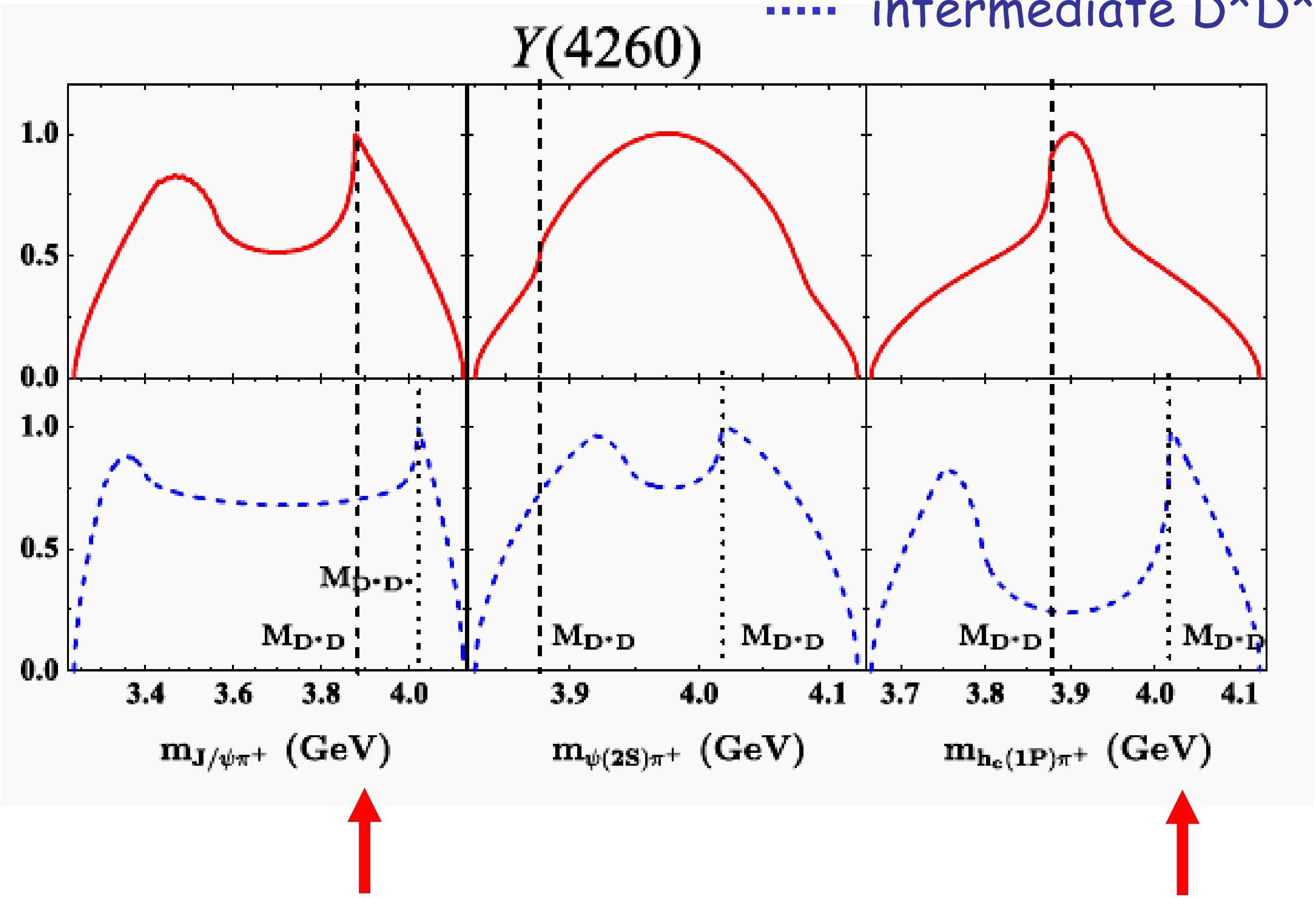
1.) Actually the Z_c states were predicted based on Z_b structures observed by Belle at 10610 and 10650 MeV/c^2 in Y decays and using the Initial Single Pion Emission mechanism (ISPE). Initial state here is charmonium.



D.Y. Chen and X. Liu, PRD 84, 034032 (2011).

ISPE mechanism:

— intermediate $D\bar{D}^*$ states
···· intermediate $D^*\bar{D}^*$ states

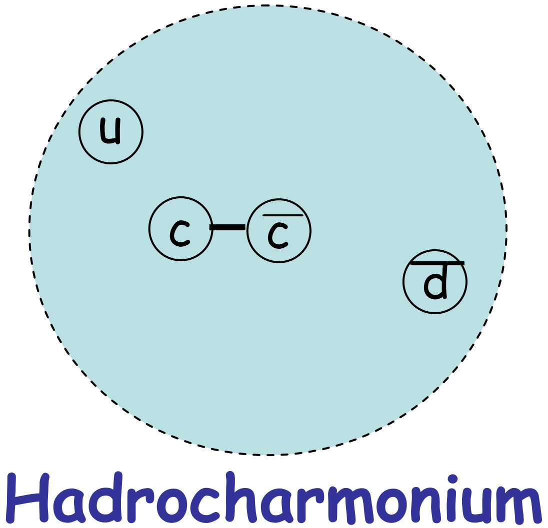


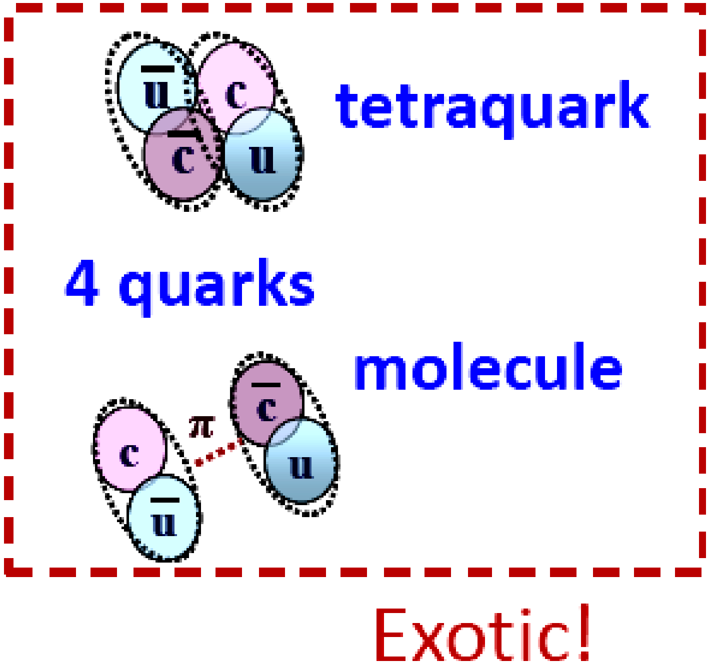
$Z_c(3900)$ $Z_c(4020)$

Initial Single Pion Emission mechanism.

Theory:

• Many of the states are near thresholds (DD*, D*D*, etc), so molecules and other 4-quark states popular.

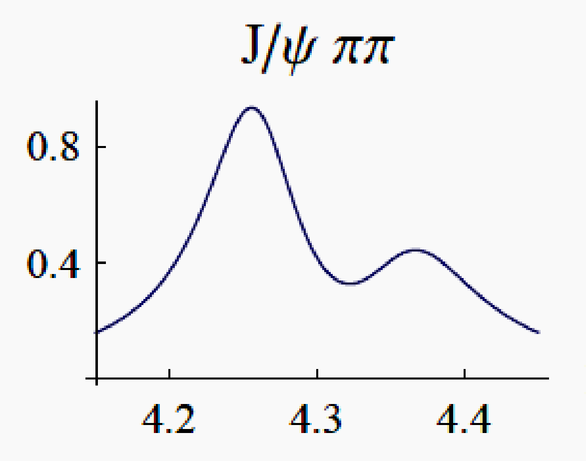


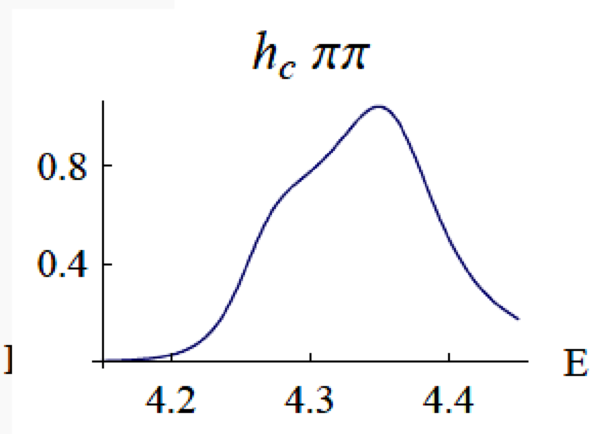


Theory:

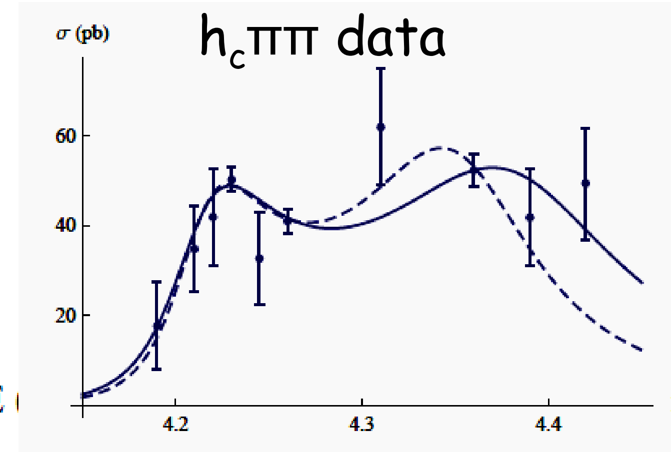
2.) Voloshin proposes that Y(4260) and Y(4360) are mixtures of two states of hadrocharmonium, one containing a spin triplet heavy quark pair and the other containing a spin singlet pair.

- Predicts line shapes:





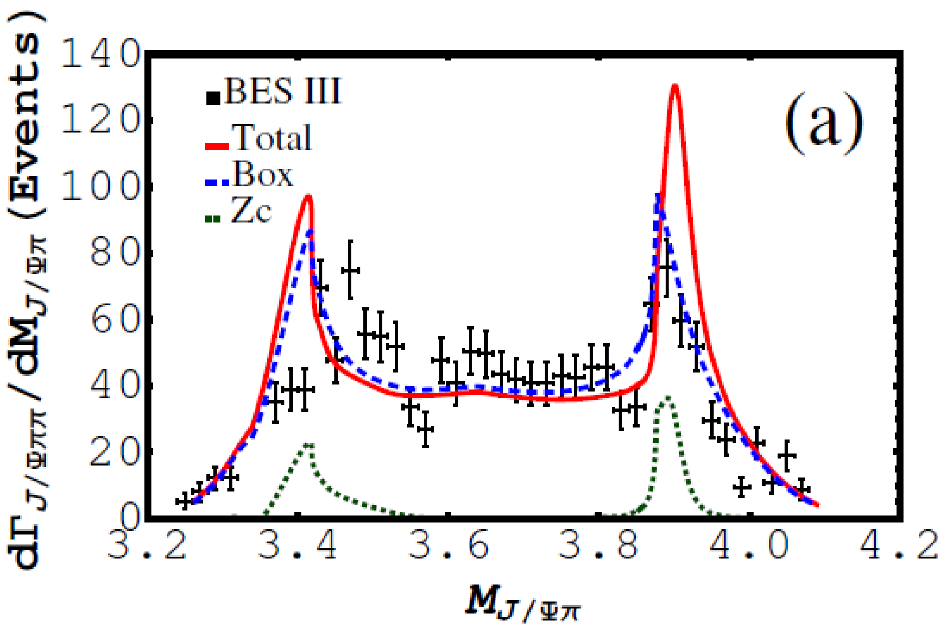
Fit to BESIII $h_c\pi\pi$ data

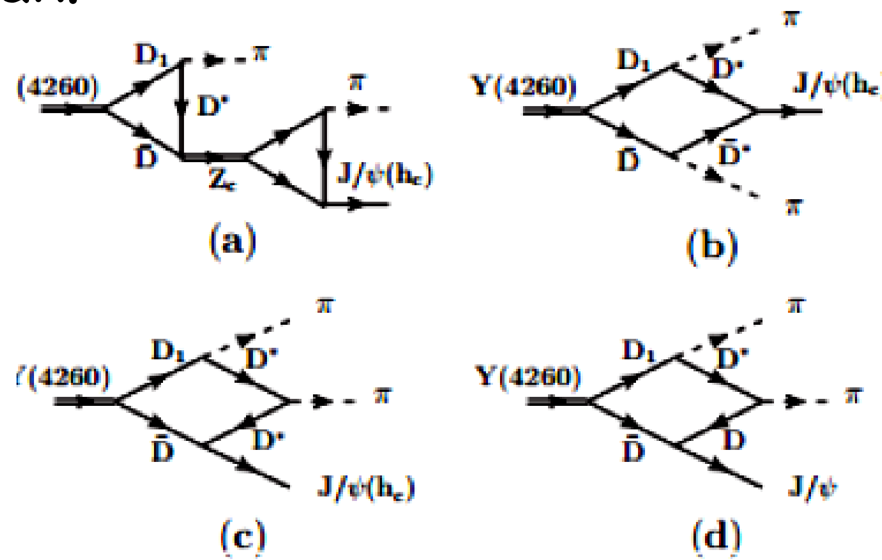


X. Li and M.B. Voloshin, arXiv:1309.1681 (2013)

Theory:

3.) Wang, Hanhart, and Zhao propose Y(4260) is a $\bar{D}D_1(2420)$ $D\bar{D}_1(2420)$ molecule. Suggests Z (3900) is a $\bar{D}D^* + D\bar{D}^*$ molecular state. Both box diagram and Z_c(3900) contribute to peak.





Meson loop

C. Wang, C. Hanhart, and C. Zhao, arXiv:1303.6355

See Xiang Liu, arXiv:1312.7408 for a recent list of references.

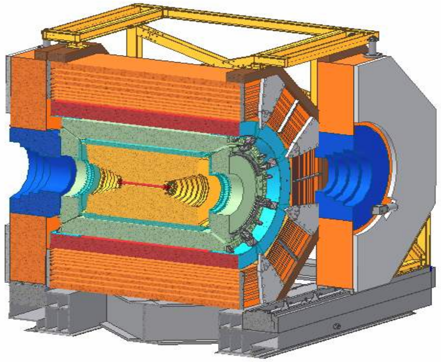
Where are we?

Do we understand everything now?

1.) What are X(3872), Y(4260), and Z_c states?
2.) Are they 4-quark states?
3.) Are they resonances? Cusps? Dynamic effects?
4.) Is there a universal explanation for XYZs?

Summary

- BESIII has begun XYZ physics running at and around the Y(4260).
- The $Z_c(3900)$ is the first confirmed charged charmonium-like state.
- Other processes have led to other narrow Z_c states.
- These have generated a lot of theoretical interest.
- However more experimental results are needed to understand the physics.
- BESIII is working on this.



Thank you