Charmonium Spectroscopy and $Z_c^{\pm}(3900)$

Workshop on Tau-Charm at High Luminosity

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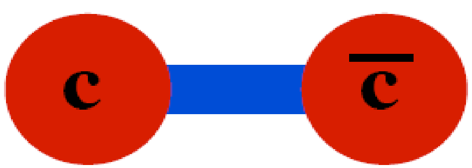
OUTLINE

- Introduction
- Precision charmonium measurements
  - η_c
  - $\eta_c(2S)$
  - h_c
  - $\Psi' \to \pi^0/\eta J/\Psi$
  - $\chi_{c0,2} \to \gamma\gamma$
  - $\Psi' \to \gamma\gamma J/\Psi$
- XYZ physics
  - $Y(4260)$
  - $Z_c(3900)$
- Future
- Summary



CHARMONIUM

Charmonium Spectroscopy

- Charmonium is one of the simplest bound states in QCD. Like positronium in QED.
- Importance of charmonium:
  - Provides detailed information on QCD in the perturbative and non-perturbative regions.
  - Provides laboratory for precision tests of lattice QCD and effective field theory calculations.
  - Provides clean laboratory for studies of hadronic decays and searches for exotic states, hybrids, glueballs, and rare decays.
  - Provides laboratory for study of baryons and excited-baryons ($I = \frac{1}{2}$ filter).
  - Understanding necessary to understand XYZ states.

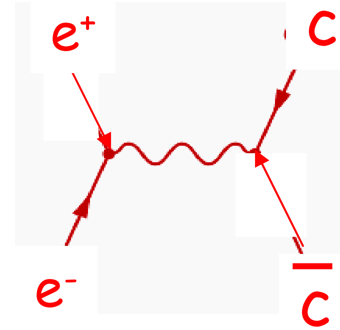
In following, $\Psi' = \Psi(2S)$

Charmonium Spectroscopy

Apology:

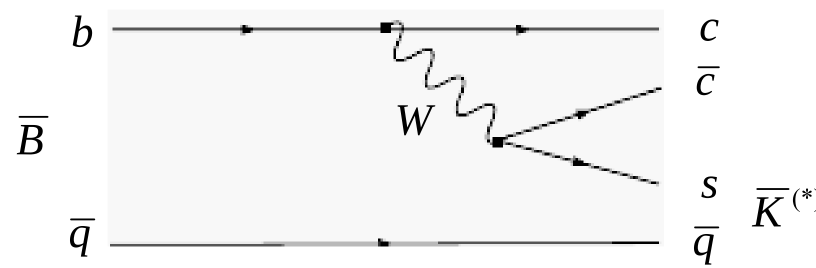
In the following I will cover mostly results from BESIII and only a small subset of those.

Important Processes

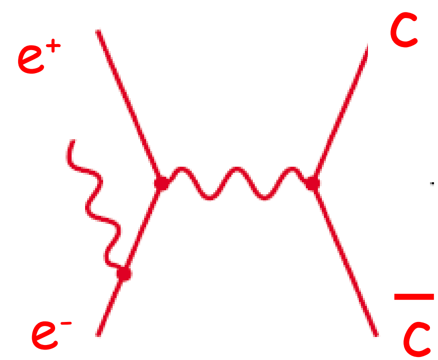


- e+e- annihilation

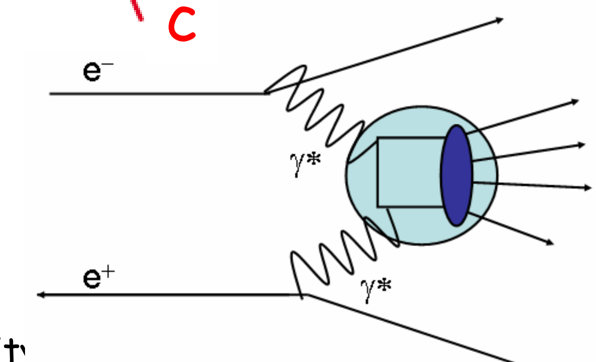
- B decay



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

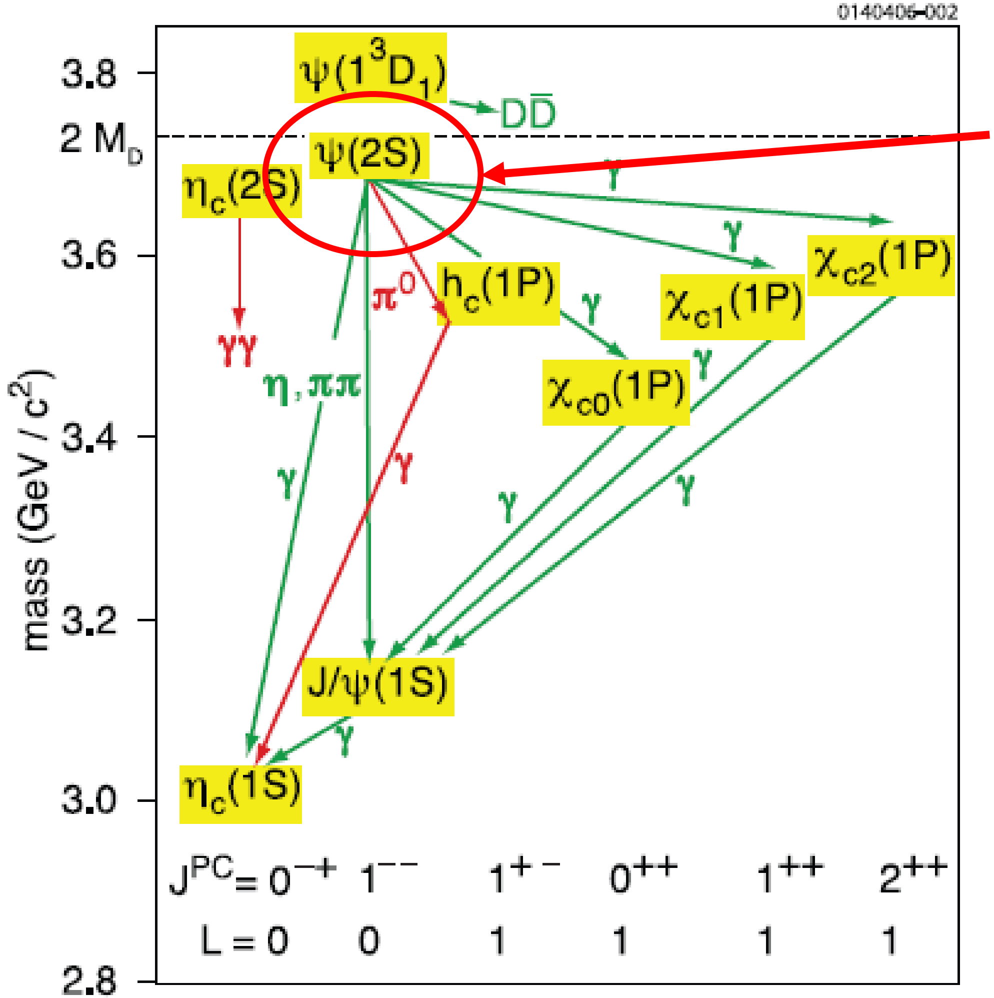


- 2 photon
  - even spin mesons
  - anti glueball filter.



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

Charmonium spectrum below open charm



BESIII: 106 M Ψ′ events. Will be used for following analyses.

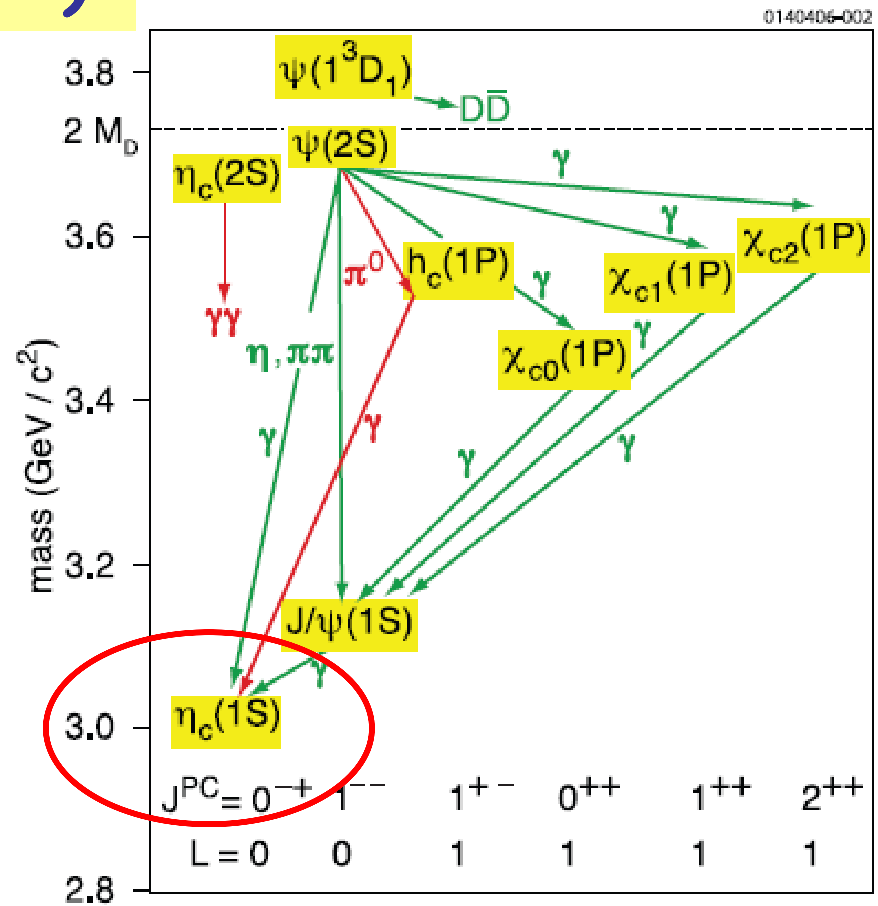
Only J/ψ and ψ′ produced directly in e^+e^- collisions, but states below ψ′ produced through radiative and hadronic transitions.


η_c

$\eta_c(1s)$

S wave spin singlet ground state of charmonium.

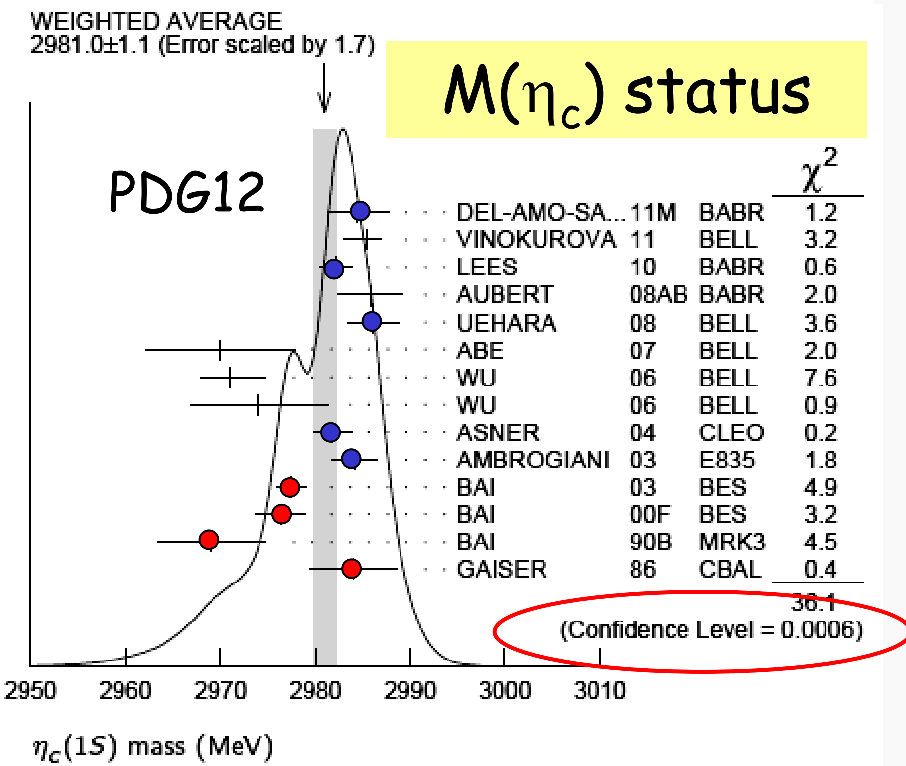
Known for long time.

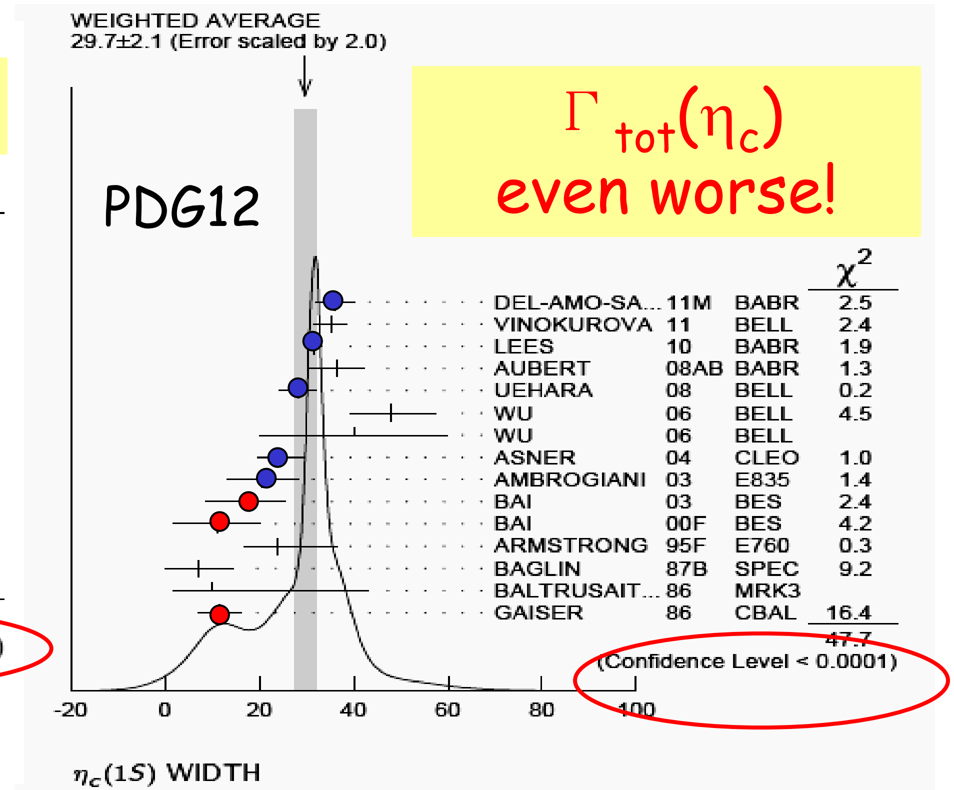


Precise measurement of η_c mass provides information on the hyperfine (Δ M(1S)) splitting of η_c and J/ψ. Also important to check lattice QCD calculations.

$\eta_c(1s)$

But: mass and width poorly determined.





- For $J/\Psi, \Psi' \rightarrow \gamma\eta_c$, average = 2978.5 ± 1.3 MeV/c^2.
- For $\gamma\gamma$ or $p\bar{p}$ production, average = 2983.3 ± 1.0 MeV/c^2.

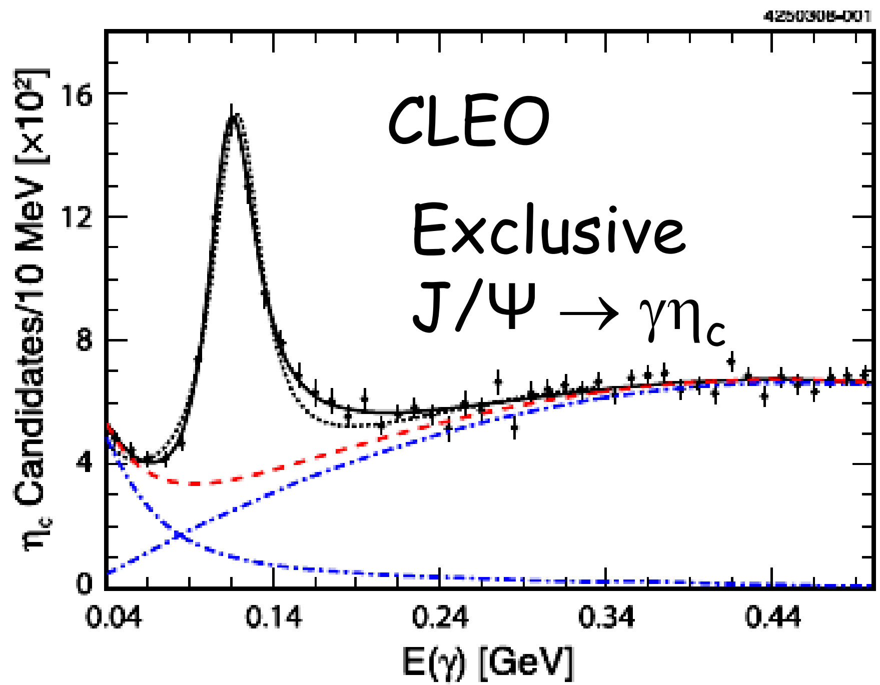
3 σ difference. Discrepancy pointed out by CLEOc.

$\eta_c(1s)$

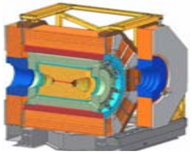
CLEOc: J/Ψ and Ψ′ → $\gamma\eta_c$

- Investigated with 24.5 M Ψ′ decays. Used 12 η_c exclusive decays to determine γ line shape in J/Ψ → $\gamma\eta_c$.
- Shape can not be explained by simple BW + resolution.
- Used empirical form.
- May explain 3σ difference with mass from $\gamma\gamma$ fusion and p-pbar annihilation.

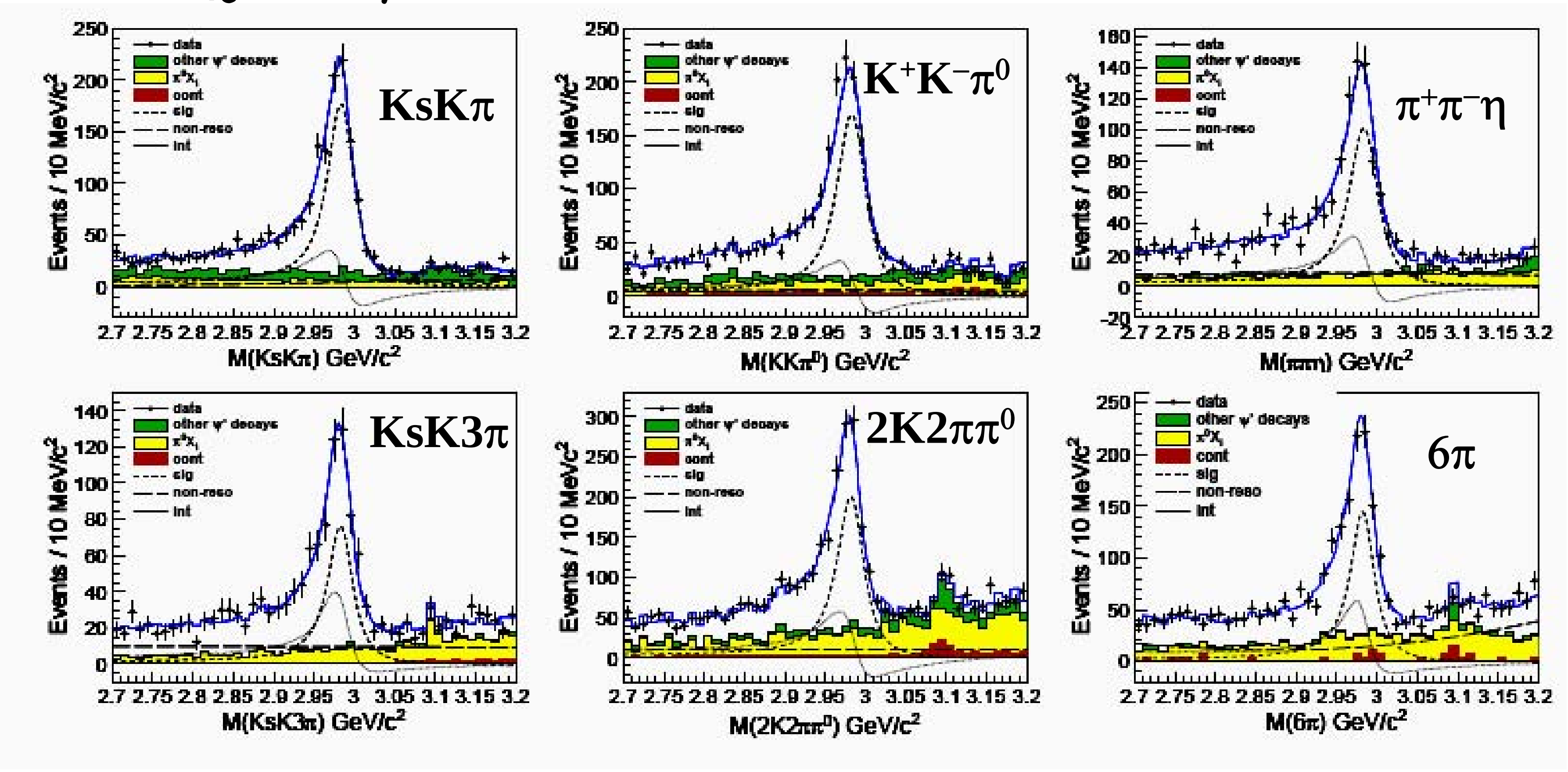
CLEO, PRL 102, 011801 (2009)



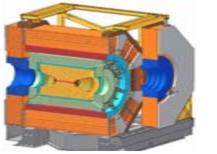
$\eta_c(1s)$


BESIII

- BESIII: Studied $\Psi' \rightarrow \gamma\eta_c$, η_c exclusive decays.
- Did simultaneous fit with distorted lineshape (hindered M1) with significant **interference** (15 σ) between η_c and non-η_c decays.



Mass and Width of η_c



BESIII

- mass = $2984.3 \pm 0.6_{stat} \pm 0.6_{syst}$ MeV/c^2
- width = $32.0 \pm 1.2_{stat} \pm 1.0_{syst}$ MeV
- X^2/ndf = 283/274 for fit.

BESIII, PRL 108, 222002 (2012); arXiv:1111.0398

- Now consistent with γγ and p-pbar production.
- Currently BESIII is the most precise measurement
- $\Delta M_{hf}(1S)_{cc\text{-}bar} = M(J/\Psi) - M(\eta_c) = 112.6 \pm 0.8$ MeV/c^2.
- In good agreement with recent LQCD calculations:

  $\Delta M_{hf}(1S)_{cc\text{-}bar}$ 108 – 117 MeV/c^2.

LQCD theorists much happier.

T. Burch *et al.*, PRD **81**, 034508 (2010)
T. Kawanai and S. Sasaki, PRD 85, 091503 (2012)
D. Mohler, arXiv:1209.5790 (2012)
C. Davies *et al.*, arXiv:1301.7203 (2013)

$\eta_c(2S)$

- First "observation" by Crystal Ball in 1982 (M=3.592GeV, from $\psi' \rightarrow \gamma X$) never confirmed.
- First observed by Belle in $B^{\pm} \rightarrow K^{\pm} \eta_c(2S)$, $\eta_c(2S) \rightarrow K_S K^{\pm} \pi^{\mp}$.
- Published results (PDG2012): All B-factory/CLEO!

$\eta_c(2S)$ MASS

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
3638.9±1.3 OUR AVERAGE					
3638.5±1.5±0.8	624	[1] DEL-AMO-SA..11M		BABR	$\gamma\gamma \rightarrow K^0_S K^{\pm}\pi^{\mp}$
3640.5±3.2±2.5	1201	[1] DEL-AMO-SA..11M		BABR	$\gamma\gamma \rightarrow K^+ K^- \pi^+ \pi^- \pi^0$
$3636.1^{+3.9}_{-4.2}{}^{+0.7}_{-2.0}$	128	[2] VINOKUROVA	11	BELL	$B^{\pm} \rightarrow K^{\pm}(K^0_S K^{\pm}\pi^{\mp})$
3626 ±5 ±6	311	[3] ABE	07	BELL	$e^+ e^- \rightarrow J/\psi(c\overline{c})$
$3645.0\pm5.5^{+4.9}_{-7.8}$	121 ± 27	AUBERT	05C	BABR	$e^+ e^- \rightarrow J/\psi c\overline{c}$
3642.9±3.1±1.5	61	ASNER	04	CLEO	$\gamma\gamma \rightarrow \eta_c \rightarrow K^0_S K^{\pm}\pi^{\mp}$

$\eta_c(2S)$ WIDTH

VALUE (MeV)	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
10 ± 4 OUR AVERAGE						
13.4± 4.6±3.2		624	[8] DEL-AMO-SA..11M		BABR	$\gamma\gamma \rightarrow K^0_S K^{\pm}\pi^{\mp}$
$6.6^{+8.4}_{-5.1}{}^{+2.6}_{-0.9}$		128	[9] VINOKUROVA	11	BELL	$B^{\pm} \rightarrow K^{\pm}(K^0_S K^{\pm}\pi^{\mp})$
6.3±12.4±4.0		61	ASNER	04	CLEO	$\gamma\gamma \rightarrow \eta_c \rightarrow K^0_S K^{\pm}\pi^{\mp}$

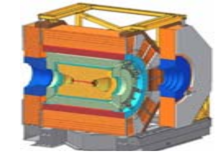
$\eta_c(2S)$

$\eta_c(2S)$ DECAY MODES

PDG2012

	Mode	Fraction (Γ_i/Γ)	
Γ_1	hadrons	not seen	
Γ_2	$K\overline{K}\pi$	(1.9 ± 1.2) %	←
Γ_3	$2\pi^+2\pi^-$	not seen	
Γ_4	$\rho^0\rho^0$	$< 3.1 \times 10^{-3}$	← UL BESIII PRD 84, 091102 (2011)
Γ_5	$3\pi^+3\pi^-$	not seen	
Γ_6	$K^+K^-\pi^+\pi^-$	not seen	
Γ_7	$K^{*0}\overline{K}^{*0}$	$< 5.3 \times 10^{-3}$	← UL BESIII
Γ_8	$K^+K^-\pi^+\pi^-\pi^0$	(1.4 ± 1.0) %	←
Γ_9	$K^+K^-2\pi^+2\pi^-$	not seen	
Γ_{10}	$K^0_SK^-2\pi^+\pi^- +$ c.c.	not seen	
Γ_{11}	$2K^+2K^-$	not seen	
Γ_{12}	$\phi\phi$	$< 2 \times 10^{-3}$	← UL BESIII
Γ_{13}	$p\overline{p}$		
Γ_{14}	$\gamma\gamma$	$< 5 \times 10^{-4}$	
Γ_{15}	$\pi^+\pi^-\eta$	not seen	
Γ_{16}	$\pi^+\pi^-\eta'$	not seen	
Γ_{17}	$K^+K^-\eta$	not seen	
Γ_{18}	$\pi^+\pi^-\eta_c(1S)$	not seen	

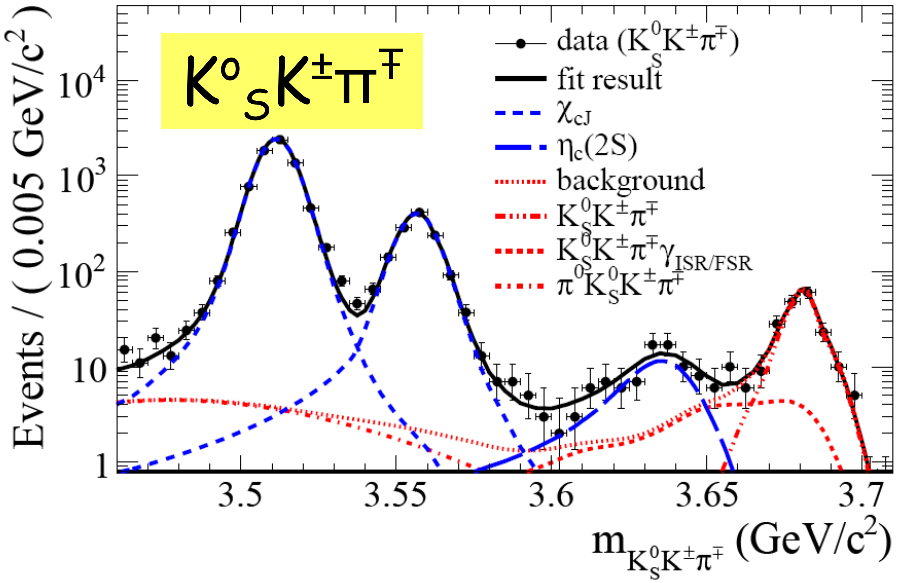
First observation of $\psi' \to \gamma\eta_c(2S)$

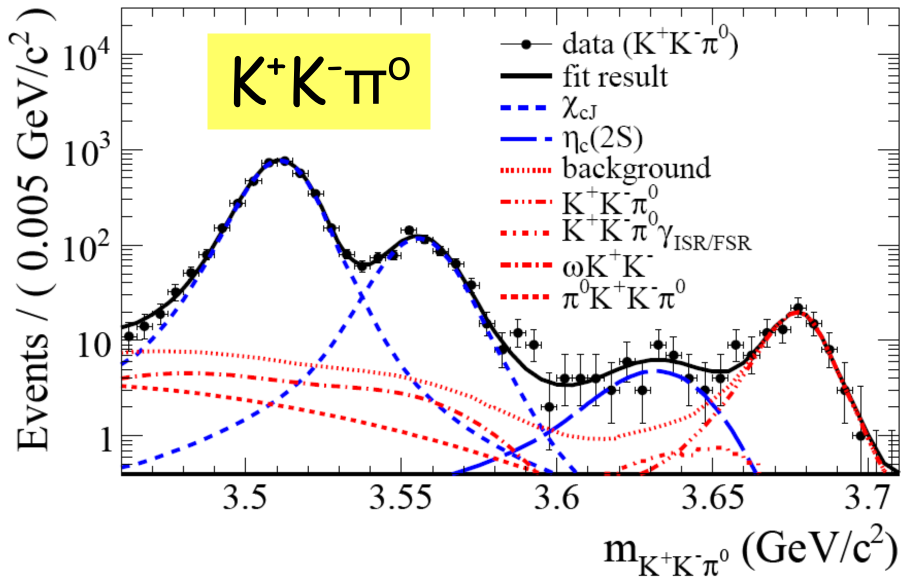


BESIII

BESIII studies: $\psi' \to \gamma\eta_c(2S) \to \gamma K_s K \pi$, $K^+K^- \pi^0$.

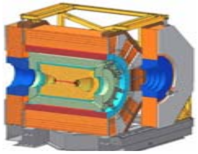
Difficult since E_γ = 48 MeV. Detailed analysis of backgrounds necessary.





- Simultaneous fit of $\eta_c(2S)$ and χ_{cJ}
- $\eta_c(2S)$ signal: modified BW (M1).
- $N(\eta_c(2S)) = 127 \pm 18$
- statistical significance 11σ
- $\chi^2/ndf=0.9$

$\psi' \to \gamma\eta_c(2S) \to \gamma KK\pi$



BESIII

$M(\eta_c(2S)) = 3637.6 \pm 2.9 \pm 1.6$ MeV/c^2
$\Gamma(\eta_c(2S)) = 16.9 \pm 6.4 \pm 4.8$ MeV
$B(\psi' \to \gamma\eta_c(2S)) \times B(\eta_c(2S) \to KK\pi) = 1.30 \pm 0.20 \pm 0.30) \times 10^{-5}$

Using $Br(\eta_c(2S) \to KK\pi) = (1.9 \pm 0.4 \pm 1.1)\%$ from BaBar

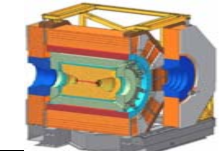
- $Br(\psi' \to \gamma\eta_c(2S)) = (6.8 \pm 1.1_{stat} \pm 4.5_{sys}) \times 10^{-4}$

BESIII, PRL 109, 042003 (2012).

CLEO-c: $< 7.6 \times 10^{-4}$ (PRD81,052002(2010))
Predictions for $B(\psi' \to \gamma\eta_c(2S))$: $(0.1 - 6.2) \times 10^{-4}$
[see compilation in arXiv:0909.2812 (2009)].

BESIII discovers this transition after 18 years of searching.

$\eta_c(2S)$



BESIII

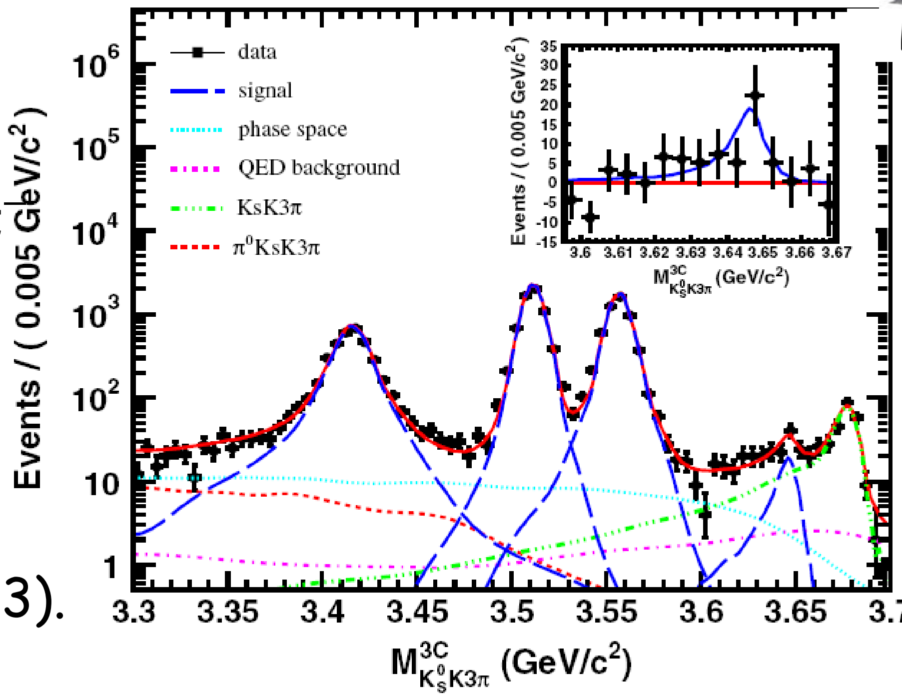
BESIII also studies:

$\psi' \rightarrow \gamma\eta_c(2S) \rightarrow \gamma K_s K^{\pm}\pi^{\mp}\pi^{+}\pi^{-}$

$N(\eta_c(2S))$ = 57 ± 17

significance 4.2 σ

BESIII, PRD 87, 052005 (2013).



$M(\eta_c(2S))$ = 3646.9 ± 1.6 ± 3.6 MeV/c^2

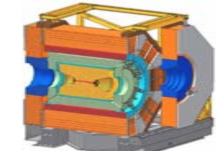
$\Gamma(\eta_c(2S))$ = 9.9 ± 4.8 ± 2.9 MeV

$B(\psi' \rightarrow \gamma\eta_c(2S)) \times B(\eta_c(2S) \rightarrow K_S K^{\pm}\pi^{\mp}\pi^{+}\pi^{-})$ =

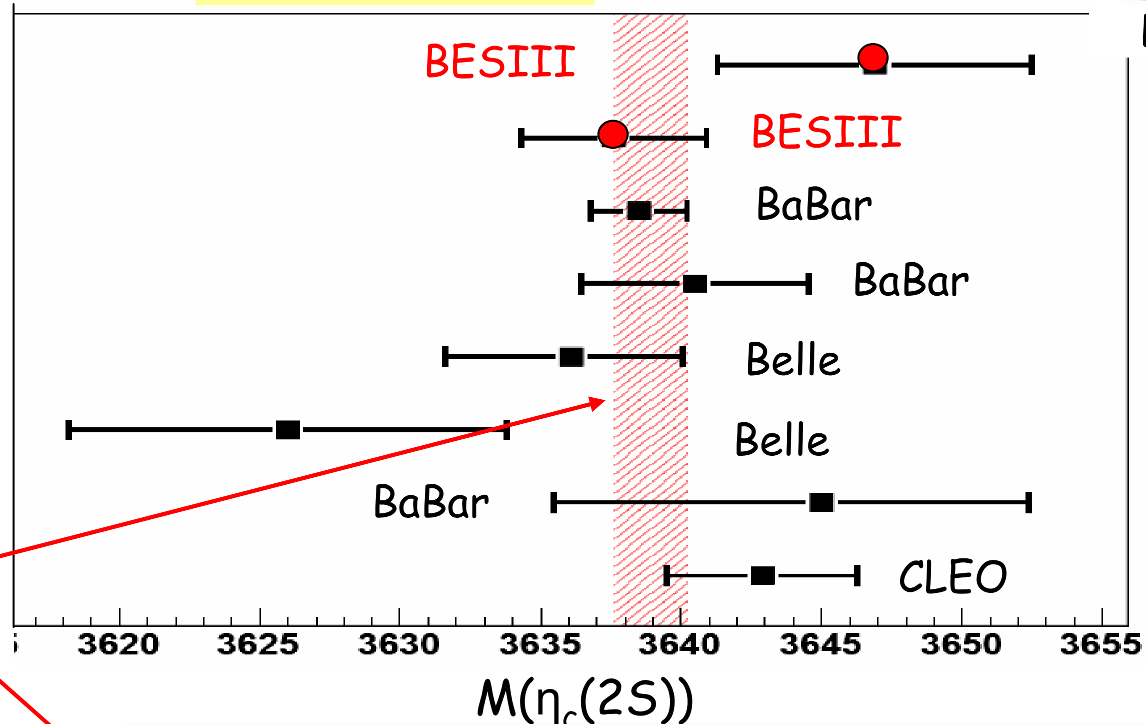
7.03 ± 2.10 ± 0.70)x10^{-6}

- $\Delta M_{hf}(2S) = M(\Psi(3686)) - M(\eta_c(2S))$ = 47.2 ± 1.3 MeV/c^2 [PDG2012]
- LQCD calculation: $\Delta M_{hf}(1S)_{cc\text{-}bar}$ 57.9 ± 2.0 MeV/c^2.
  D. Mohler, CHARM2012, arXiv:1209.5790 (2012).

$\eta_c(2S)$

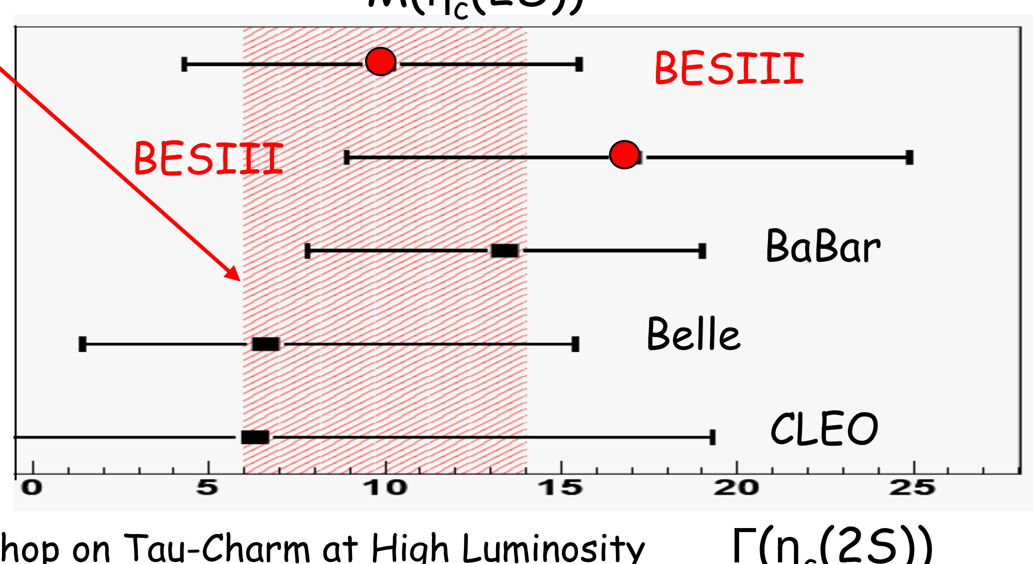


$\eta_c(2S)$ mass



PDG2012 compilation values

$\eta_c(2S)$ width



BESIII will be able to improve mass and width values.


h_c

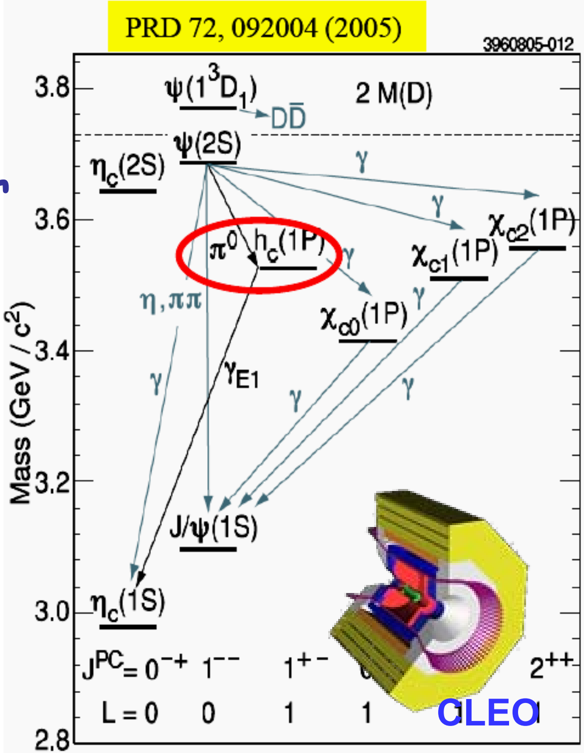
$h_c(^1P_1)$

$M(h_c)$ important to learn about hyperfine interaction of P wave states.

Hyperfine or triplet-singlet splitting determined by spin-spin term in QCD potential models. Expected to be ~ 0 for P wave states.

Not in PDG summary table until 2008.

CLEOc used $\psi' \to \pi^0 h_c$, $h_c \to \gamma\eta_c$ and obtained:



$M(h_c)_{AVG} = 3525.20 \pm 0.18 \pm 0.12$ MeV/c^2
$(B_1 \times B_2)_{AVG} = (4.16 \pm 0.30 \pm 0.37) \times 10^{-4}$

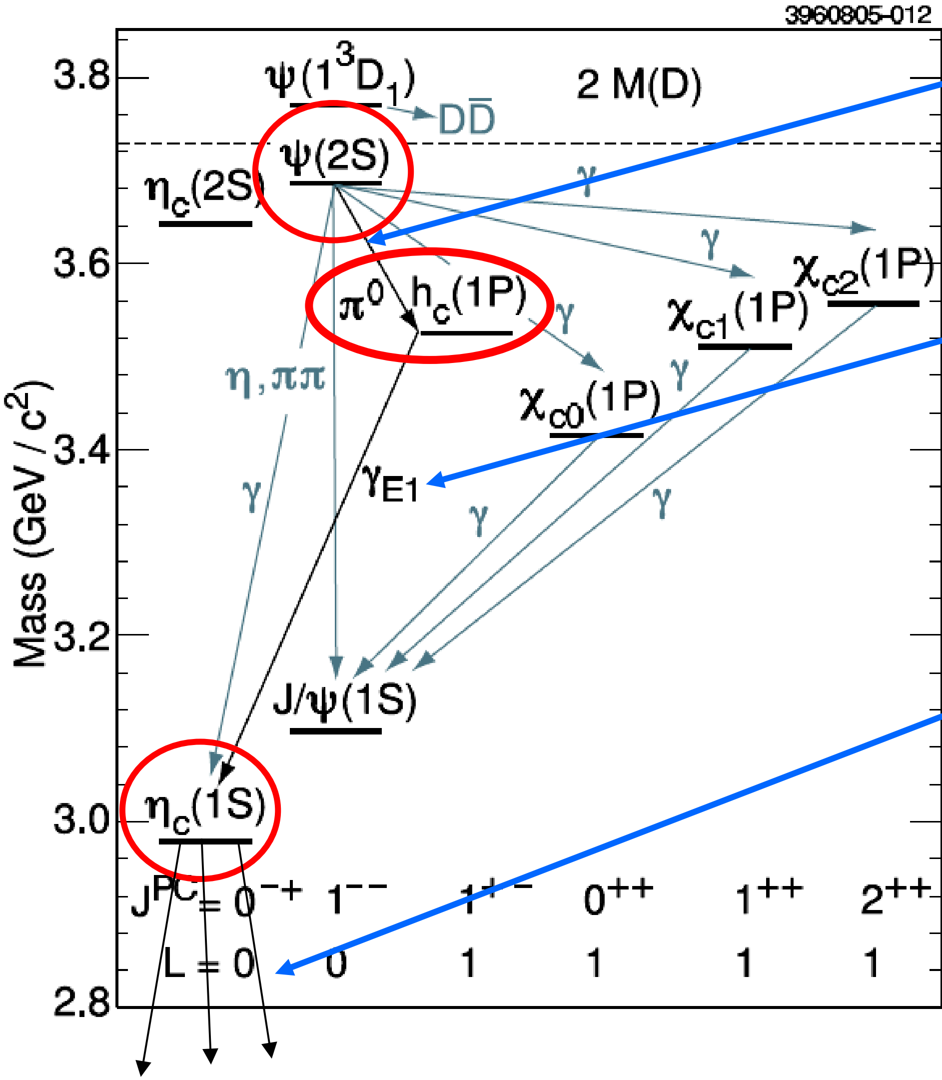
PRL 101, 182003 (2008).

$\Delta M_{hf}(1P) = \langle M(^3P_J)\rangle - M(^1P_1) = +0.08 \pm 0.18 \pm 0.12$ MeV,
where $\langle M(^3P_J)\rangle$ = spin weighted centroid of ^3P_J states

$$= [M(\chi_{cJ}) + 3{*}M(\chi_{cJ}) + 5{*}M(\chi_{cJ})]/9$$

Consistent with lowest order expectation of 0.

Methods to study h_c



Only detect π^0 : inclusive.

Rate ~ $B(\psi' \to \pi^o h_c)$

BESIII, PRL 104, 132002 (2010)

Detect π^0 and γ: E_1 tagged.

Rate ~ $B(\psi' \to \pi^o h_c)$ x $B(h_c \to \gamma\eta_c)$

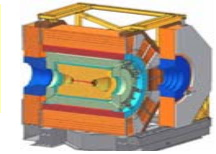
BESIII, PRL 104, 132002 (2010)

Detect π^0, γ, and η_c decay: exclusive.

Rate ~ $B(\psi' \to \pi^o h_c)$ x $B(h_c \to \gamma\eta_c)$ x $B(\eta_c \to X)$

Exclusive η_c decays

$\psi' \to \pi^0 h_c$, $h_c \to \gamma\eta_c$, η_c exclusive decays



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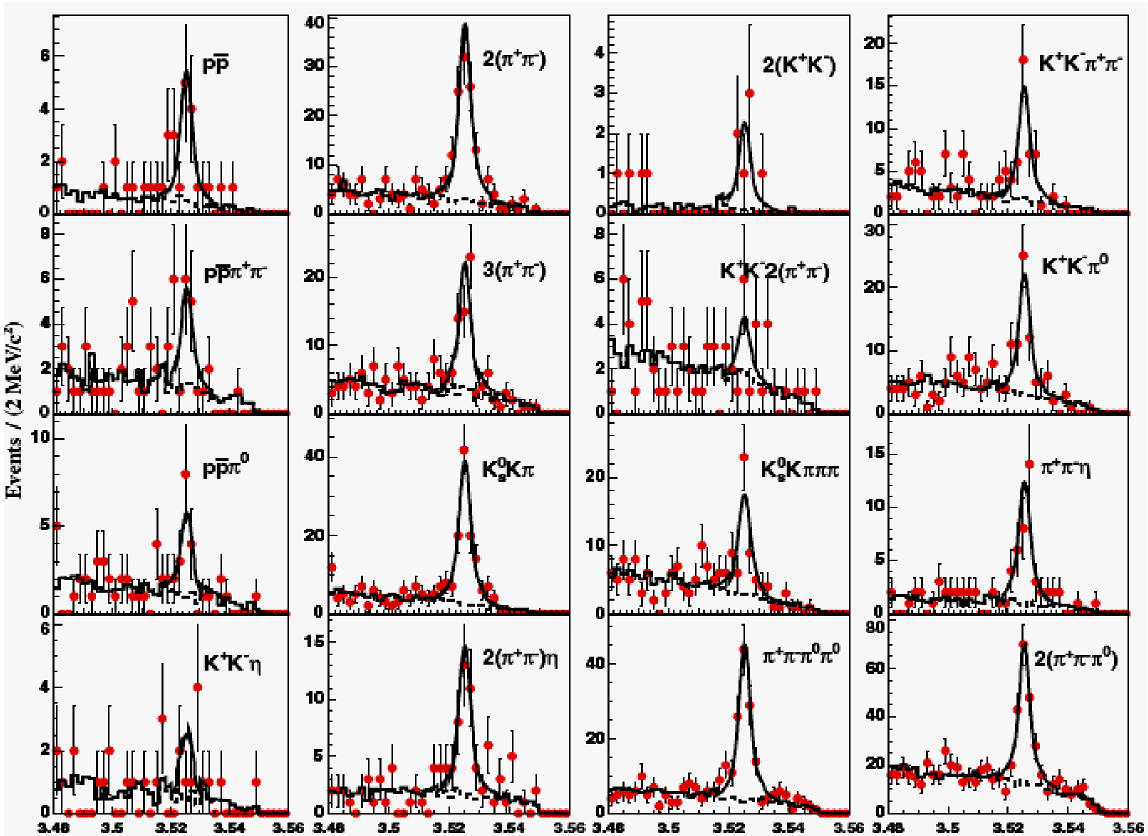


mass recoiling from π^0 (GeV/c^2)

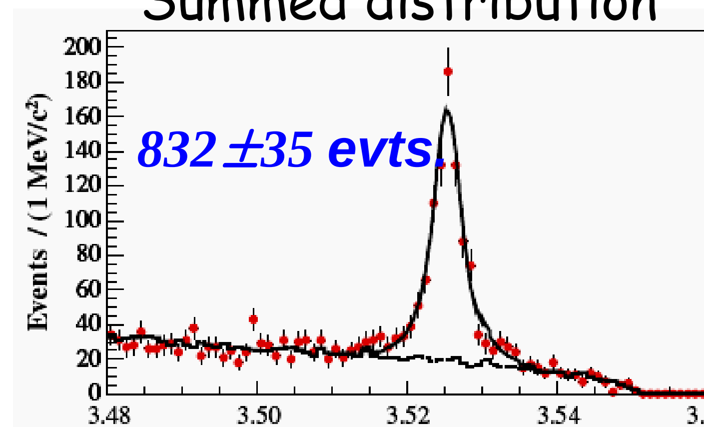
Require:

$450 < E(\gamma_{E1}) < 550$ MeV

π^0: 3480 – 3570 MeV/c^2

$2.9 < M(\eta_c) < 3.05$ GeV/c^2.

Summed distribution



mass recoiling from π^0 (GeV/c^2)

Consistent with BESIII inclusive and CLEOc

Mass = $3525.31 \pm 0.11 \pm 0.14$ MeV/c^2

Width = $0.70 \pm 0.28 \pm 0.22$ MeV

$\Delta M_{hf}(1P)$ [MeV/c^2] = $-0.01 \pm 0.11 \pm 0.15$ MeV/c^2

BESIII Collaboration, PRD 86, 092009 (2012)

Currently the most precise measurements

h_c : analysis summary

	BESIII Exclusive	BESIII Tagged	CLEOc
$Br(\psi' \to \pi^0 h_c) \times Br(h_c \to \gamma\eta_c)$ [10^{-4}]		$4.58 \pm 0.40 \pm 0.50$	$4.16 \pm 0.30 \pm 0.37$
M [MeV/c^2]	3525.31±0.11±0.14	3525.40 ±0.13±0.18	3525.20 ±0.18±0.12
Γ [MeV]	0.70±0.28±0.22	$0.73 \pm 0.45 \pm 0.28$	
$\Delta M_{hf}(1P)$ [MeV/c^2]	-0.01±0.11±0.15	$0.10 \pm 0.13 \pm 0.18$	$0.08 \pm 0.18 \pm 0.12$

	BESIII	theoretical predictions
$Br(\psi' \to \pi^0 h_c)$ [10^{-4}]	$8.4 \pm 1.3 \pm 1.0$	4 - 13 Kuang
$Br(h_c \to \gamma\eta_c)$ [%]	54.3±6.7±5.2	41 (NRQCD) Kuang 88 (PQCD) Kuang 38 Godfrey, Rosner
Γ [MeV]	0.70±0.28±0.22 $0.73 \pm 0.45 \pm 0.28$	1.1 (NRQCD) Kuang 0.51 (PQCD) Kuang 0.601 ± 0.055†

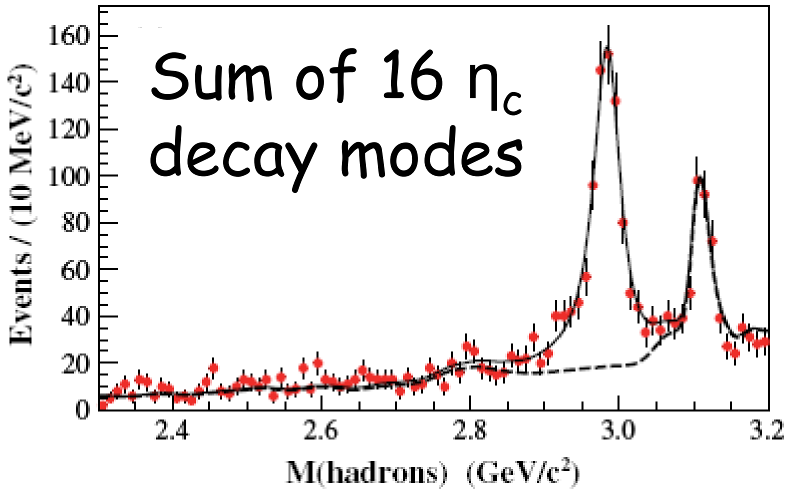
Theoretical predictions:
Kuang, PRD65, 094024(2002),
Godfrey & Rosner, PRD 66, 014012 (2002)
†Lattice: Duek, *et al*, PRD 73, 074507 (2006).

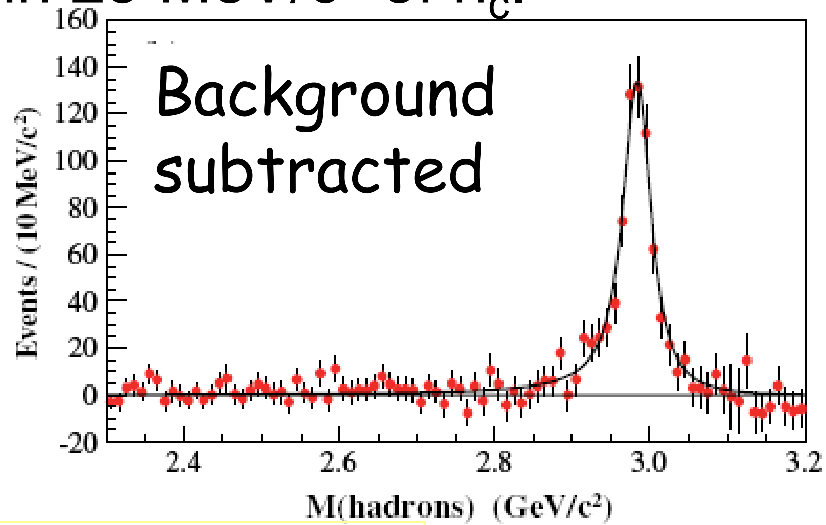
CLEO, PRL 101, 182003 (2008)
BESIII, PRL 104, 132002 (2010)
BESIII, PRD 86, 092009 (2012)

η_c lineshape from $\psi' \to \pi^0 h_c$, $h_c \to \gamma\eta_c$

BESIII

Events with π^0 recoil mass within ±5 MeV/c^2 of h_c.





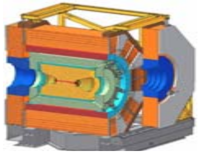
From simultaneous fit to mass spectra. χ^2/d.o.f. = 1.5

	From $h_c \to \gamma\eta_c$	From $\Psi' \to \gamma\ \eta_c$
$M(\eta_c)$ [MeV/c^2]	2984.49±1.16±0.52	2984.3 ±0.06±0.06
$\Gamma(\eta_c)$ [MeV]	36.4±3.2±1.7	32.0±1.2±1.7

Lineshape is much less distorted than for J/ψ, $\psi' \to \gamma\eta_c$: the non-resonant interfering background is small. This channel much better for determining the η_c resonance parameters.

BESIII Collaboration, PRD 86, 092009 (2012)

$B(\eta_c \rightarrow X_i)$ from $\psi' \rightarrow \pi^0 h_c,\ h_c \rightarrow \gamma\eta_c$


BESIII

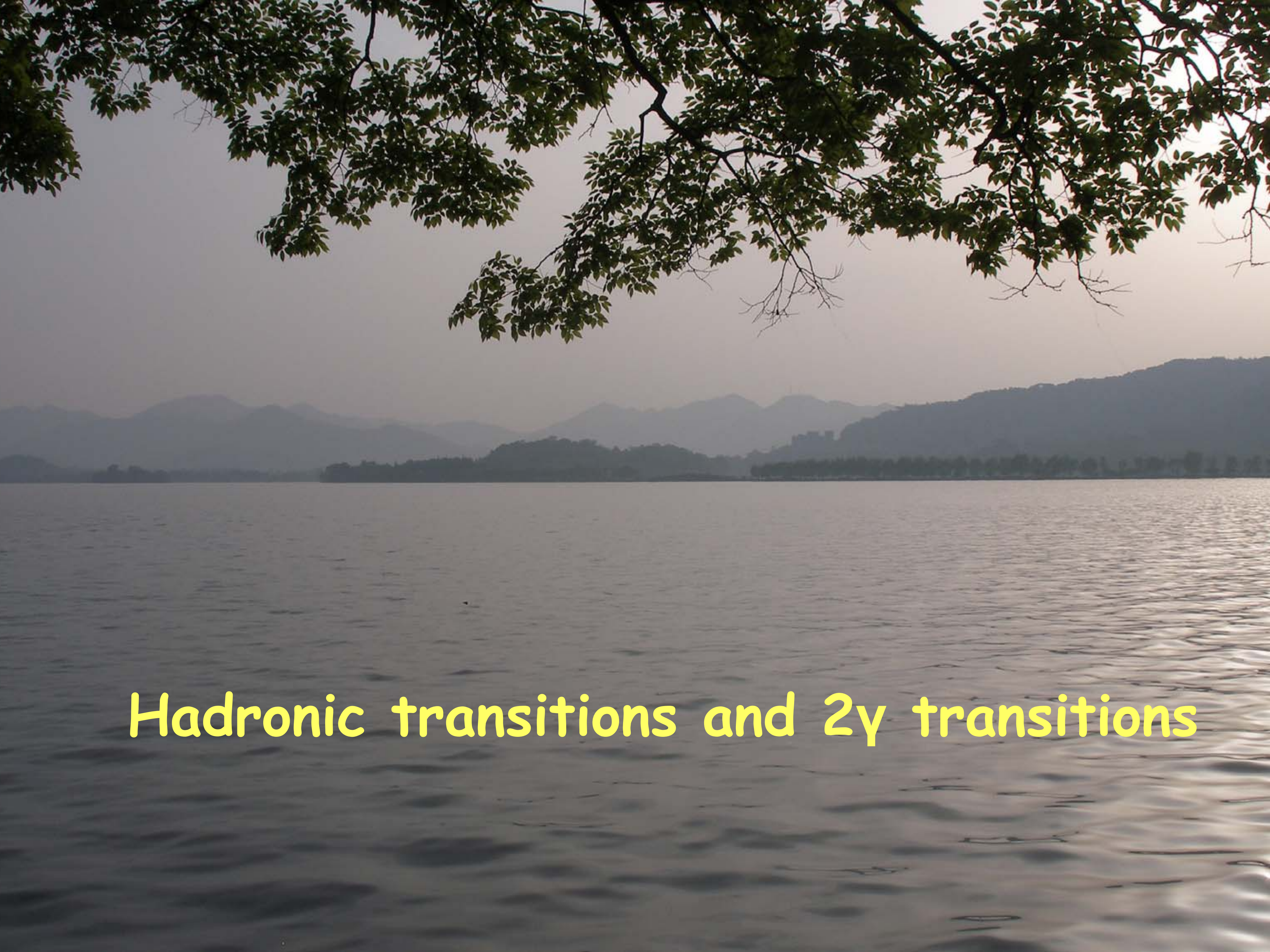
$B_1(\Psi' \rightarrow \pi^0 h_c) \times B_2(h_c \rightarrow \gamma\eta_c) \times B_3(\eta_c \rightarrow X_i)$

The third errors in B are the systematic errors due to uncertainty of $B_2(h_c \rightarrow \gamma\eta_c) \times B_3(\eta_c \rightarrow X_i)$.

X_i	$\mathcal{B}_1 \times \mathcal{B}_2 \times \mathcal{B}_3 (\times 10^{-6})$	$\mathcal{B}_3$ (%)	$\mathcal{B}_3$ in PDG (%)
$p\bar{p}$	$0.65 \pm 0.19 \pm 0.10$	$0.15 \pm 0.04 \pm 0.02 \pm 0.01$	0.141 ± 0.017
$\pi^+\pi^-\pi^+\pi^-$	$7.51 \pm 0.85 \pm 1.11$	$1.72 \pm 0.19 \pm 0.25 \pm 0.17$	0.86 ± 0.13
$K^+K^-K^+K^-$	$0.94 \pm 0.37 \pm 0.14$	$0.22 \pm 0.08 \pm 0.03 \pm 0.02$	0.134 ± 0.032
$K^+K^-\pi^+\pi^-$	$4.16 \pm 0.76 \pm 0.59$	$0.95 \pm 0.17 \pm 0.13 \pm 0.09$	0.61 ± 0.12
$p\bar{p}\pi^+\pi^-$	$2.30 \pm 0.65 \pm 0.36$	$0.53 \pm 0.15 \pm 0.08 \pm 0.05$	<1.2 (at 90% C.L.)
$\pi^+\pi^-\pi^+\pi^-\pi^+\pi^-$	$8.82 \pm 1.57 \pm 1.59$	$2.02 \pm 0.36 \pm 0.36 \pm 0.19$	1.5 ± 0.50
$K^+K^-\pi^+\pi^-\pi^-\pi^-$	$3.60 \pm 1.71 \pm 0.64$	$0.83 \pm 0.39 \pm 0.15 \pm 0.08$	0.71 ± 0.29
$K^+K^-\pi^0$	$4.54 \pm 0.76 \pm 0.48$	$1.04 \pm 0.17 \pm 0.11 \pm 0.10$	1.2 ± 0.1
$p\bar{p}\pi^0$	$1.53 \pm 0.49 \pm 0.23$	$0.35 \pm 0.11 \pm 0.05 \pm 0.03$	...
$K_S^0K^\pm\pi^\mp$	$11.35 \pm 1.25 \pm 1.50$	$2.60 \pm 0.29 \pm 0.34 \pm 0.25$	2.4 ± 0.2
$K_S^0K^\pm\pi^\mp\pi^\pm\pi^\mp$	$12.01 \pm 2.22 \pm 2.04$	$2.75 \pm 0.51 \pm 0.47 \pm 0.27$	...
$\pi^+\pi^-\eta$	$7.22 \pm 1.47 \pm 1.11$	$1.66 \pm 0.34 \pm 0.26 \pm 0.16$	4.9 ± 1.8
$K^+K^-\eta$	$2.11 \pm 1.01 \pm 0.32$	$0.48 \pm 0.23 \pm 0.07 \pm 0.05$	<1.5 (at 90% C.L.)
$\pi^+\pi^-\pi^+\pi^-\eta$	$19.17 \pm 3.77 \pm 3.72$	$4.40 \pm 0.86 \pm 0.85 \pm 0.42$	...
$\pi^+\pi^-\pi^0\pi^0$	$20.31 \pm 2.20 \pm 3.33$	$4.66 \pm 0.50 \pm 0.76 \pm 0.45$	...
$\pi^+\pi^-\pi^+\pi^-\pi^0\pi^0$	$75.13 \pm 7.42 \pm 9.99$	$17.23 \pm 1.70 \pm 2.29 \pm 1.66$	...

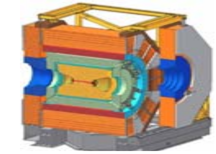
Some branching ratios measured for first time.

BESIII Collaboration, PRD 86, 092009 (2012)



Hadronic transitions and 2γ transitions

Hadronic transitions $\Psi' \to \eta J/\Psi$, $\pi^0 J/\Psi$



BESIII

$\Psi' \to \pi^0 J/\Psi$ - isospin violating decay

$R = B(\Psi' \to \pi^0 J/\Psi)/B(\Psi' \to \eta J/\Psi)$ suggested as way to measure m_u/m_d. [Phys. Lett. 95B, 99 (1980)]

Theoretical predictions:

$R = 1.6\%$ using QCD multipole expansion and axial anomaly [Phys Rep. 194, 1 (1990)]

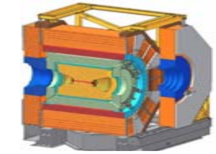
$R = (11 \pm 6)\%$ using charmed meson loops in chiral perturbation theory [PRL 103, 082003 (2009); 104, 10990 (2010)]

	BESIII	PDG2012
$B(\Psi' \to \pi^0 J/\Psi)$ ($\times 10^{-3}$)	$1.26 \pm 0.02 \pm 0.03$	1.30 ± 0.10
$B(\Psi' \to \eta J/\Psi)$ ($\times 10^{-3}$)	$33.75 \pm 0.17 \pm 0.86$	32.8 ± 0.7
R (%)	$3.74 \pm 0.06 \pm 0.04$	3.96 ± 0.42

Branching ratios will place constraints on meson loop contributions.

BESIII Collaboration, PRD 86, 092008 (2012)

$X_{c0,2} \to \gamma\gamma$

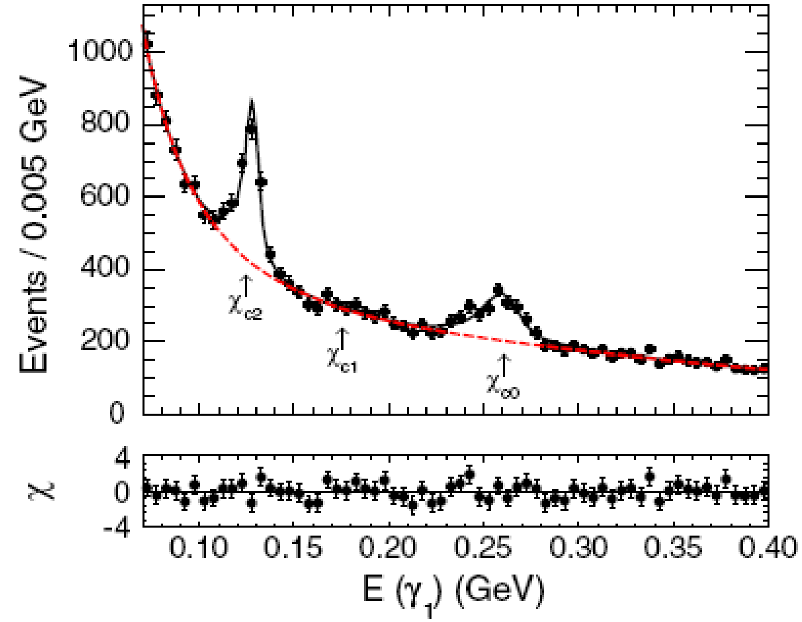


BESIII

Analog to P-wave triplet states in positronium.

Lowest order predicts:

$R = \Gamma(X_{c2} \to \gamma\gamma)/\Gamma(X_{c0} \to \gamma\gamma) = 0.27$
[Phys. Lett. B60, 183 (1976)]
$R = 0.09$ to 0.36 with high order corrections [PRD 54, 2075 (1996)]



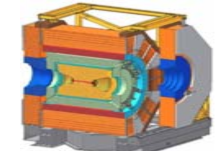
Quantity	X_{c0}	X_{c2}
$B_1 \times B_2 \times 10^5$	2.17±0.17±0.12	2.81±0.17±0.15
$B_2 \times 10^4$	2.24±0.19±0.12±0.08	3.21±0.18±0.17±0.13
$\Gamma_{\gamma\gamma}$ (keV)	2.33±0.20±0.13±0.17	0.63±0.04±0.04±0.04
R	0.271±0.029±0.013±0.027	

$B_1 = B(\Psi' \to \gamma X_{c0,2})$
$B_2 = B(X_{c0,2} \to \gamma\gamma)$
$R = \Gamma_{\gamma\gamma}(X_{c2})/\Gamma_{\gamma\gamma}(X_{c0})$

BESIII, PRD 85, 112008 (2012)

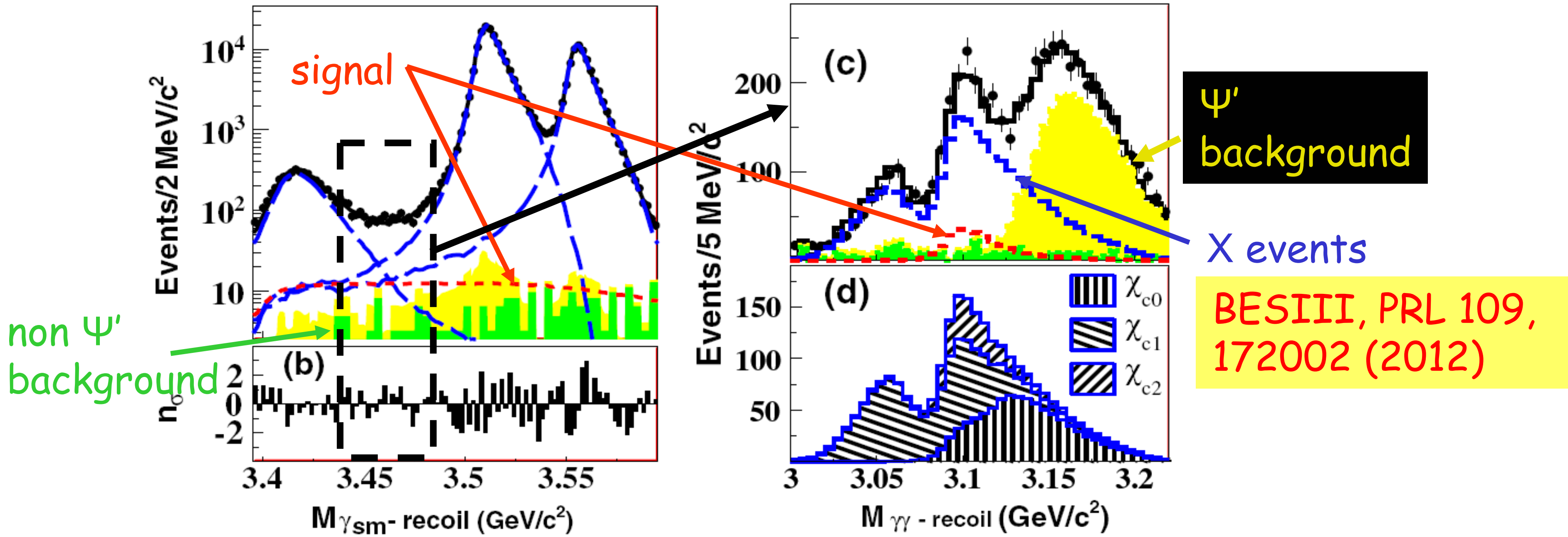
R is consistent with lowest order prediction.

First evidence for $\Psi' \to \gamma\gamma J/\Psi$



BESIII

May be sensitive to charm hadronic loop effects.
[PRD 83, 054028 (2011)]

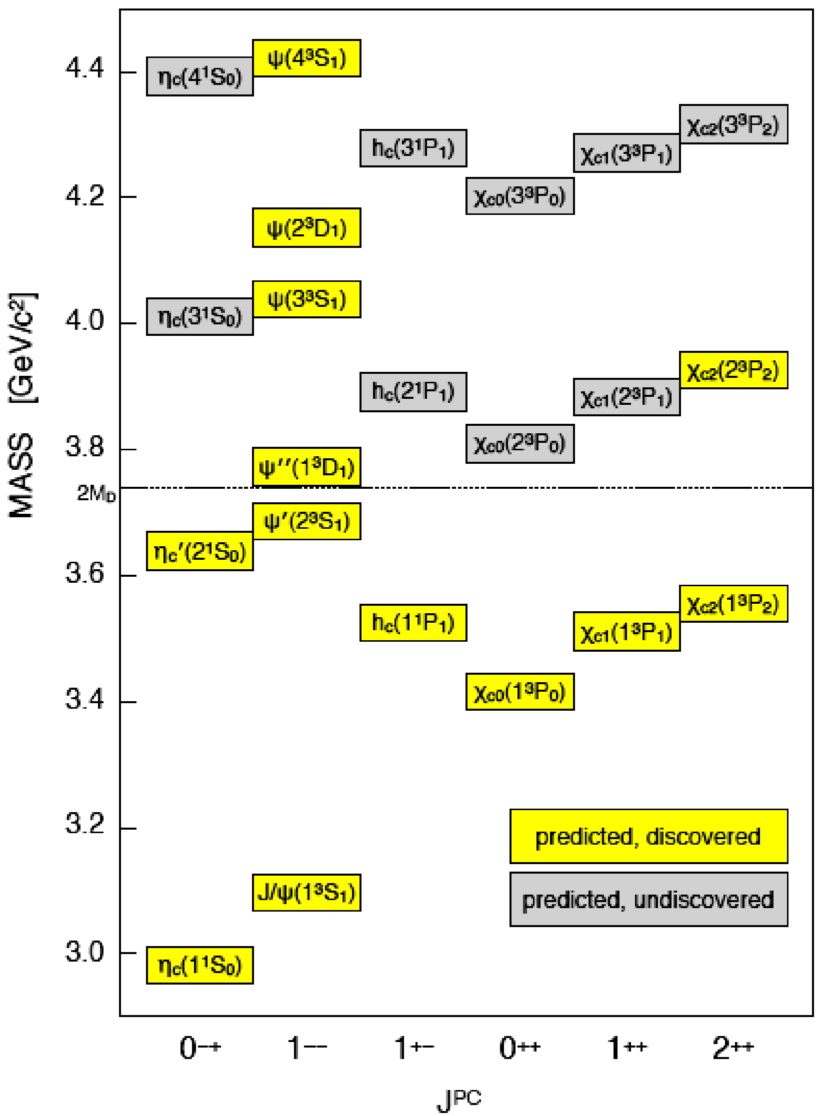


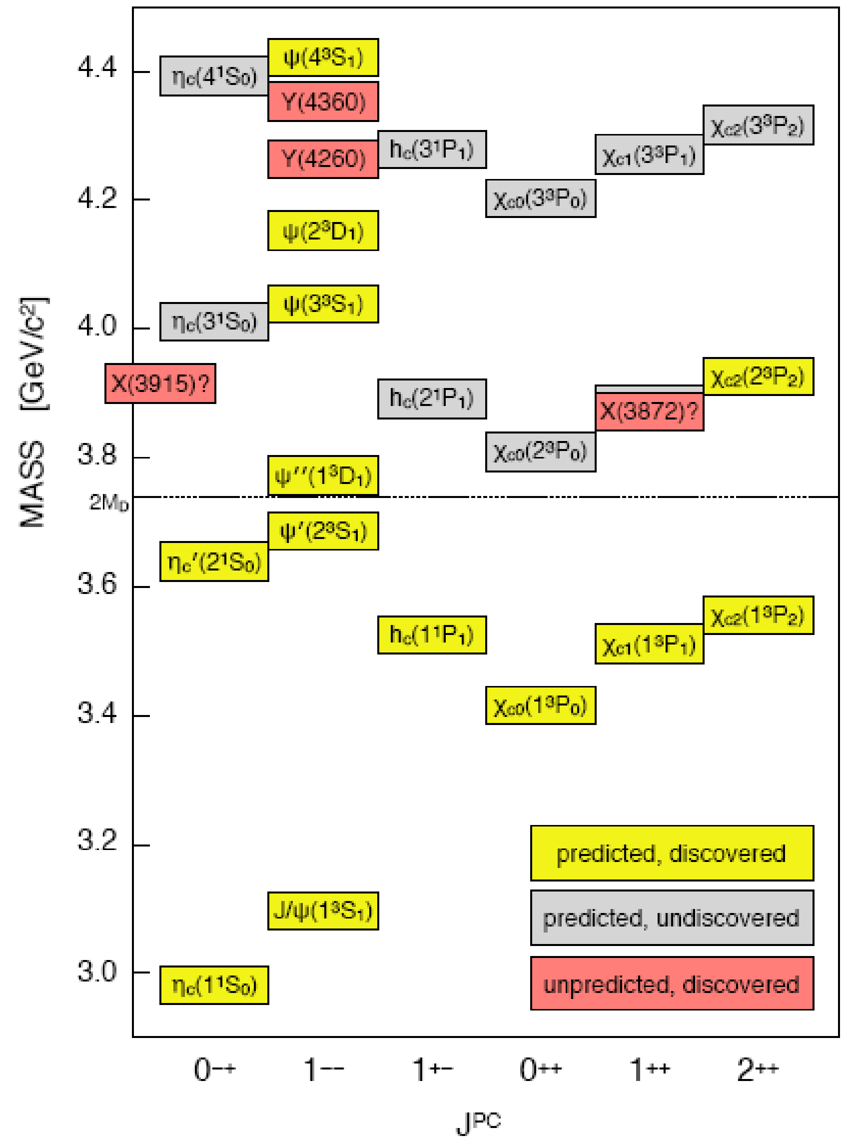
	BESIII	PDG2012
$B(\Psi' \to \gamma\gamma J/\Psi)$	$(3.1\pm0.6^{+0.8}_{-1.0}) \times 10^{-4}$	
$B(\Psi' \to \gamma X_{c0}, X_{c0} \to \gamma J/\Psi)$	$(15.1\pm0.3\pm1.0) \times 10^{-4}$	$(11.3\pm0.8) \times 10^{-4}$
$B(\Psi' \to \gamma X_{c1}, X_{c1} \to \gamma J/\Psi)$	$(337.7\pm0.9\pm18.3) \times 10^{-4}$	$(318\pm8) \times 10^{-4}$
$B(\Psi' \to \gamma X_{c2}, X_{c2} \to \gamma J/\Psi)$	$(187.4\pm0.7\pm10.2) \times 10^{-4}$	$(170\pm4) \times 10^{-4}$

CLEO: $B(\Psi' \to \gamma\gamma J/\Psi) < 1 \times 10^{-4}$ [PRD 78, 011102 (2008)]

XYZ States and Y(4260)

XYZ States

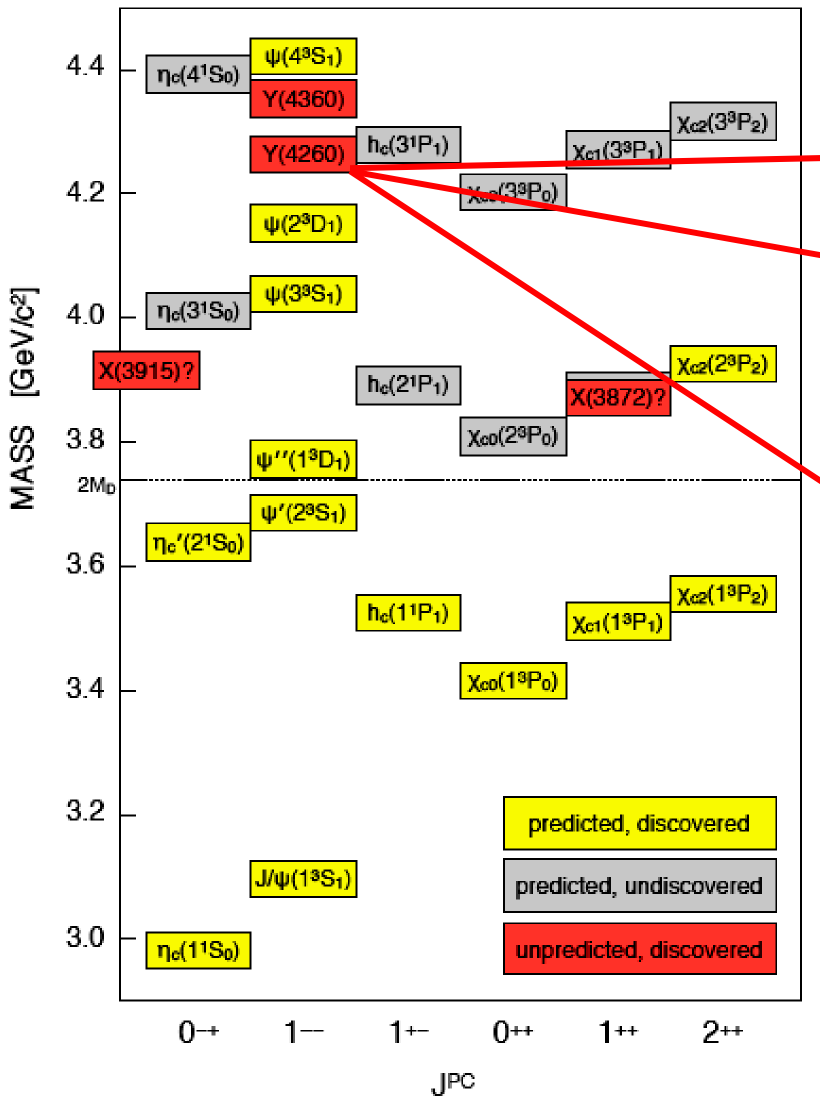

MASS [GeV/c^2]
4.4
4.2
4.0
3.8
$2M_D$
3.6
3.4
3.2
3.0
$\eta_c(4^1S_0)$
$\psi(4^3S_1)$
$h_c(3^1P_1)$
$\chi_{c2}(3^3P_2)$
$\chi_{c1}(3^3P_1)$
$\chi_{c0}(3^3P_0)$
$\psi(2^3D_1)$
$\eta_c(3^1S_0)$
$\psi(3^3S_1)$
$h_c(2^1P_1)$
$\chi_{c2}(2^3P_2)$
$\chi_{c1}(2^3P_1)$
$\chi_{c0}(2^3P_0)$
$\psi''(1^3D_1)$
$\psi'(2^3S_1)$
$\eta_c'(2^1S_0)$
$h_c(1^1P_1)$
$\chi_{c2}(1^3P_2)$
$\chi_{c1}(1^3P_1)$
$\chi_{c0}(1^3P_0)$
$J/\psi(1^3S_1)$
$\eta_c(1^1S_0)$
predicted, discovered
predicted, undiscovered
0^{-+} 1^{--} 1^{+-} 0^{++} 1^{++} 2^{++}
J^{PC}


MASS [GeV/c^2]
4.4
4.2
4.0
3.8
$2M_D$
3.6
3.4
3.2
3.0
$\eta_c(4^1S_0)$
$\psi(4^3S_1)$
Y(4360)
Y(4260)
$h_c(3^1P_1)$
$\chi_{c2}(3^3P_2)$
$\chi_{c1}(3^3P_1)$
$\chi_{c0}(3^3P_0)$
$\psi(2^3D_1)$
$\eta_c(3^1S_0)$
$\psi(3^3S_1)$
X(3915)?
$h_c(2^1P_1)$
X(3872)?
$\chi_{c2}(2^3P_2)$
$\chi_{c0}(2^3P_0)$
$\psi''(1^3D_1)$
$\psi'(2^3S_1)$
$\eta_c'(2^1S_0)$
$h_c(1^1P_1)$
$\chi_{c2}(1^3P_2)$
$\chi_{c1}(1^3P_1)$
$\chi_{c0}(1^3P_0)$
$J/\psi(1^3S_1)$
$\eta_c(1^1S_0)$
predicted, discovered
predicted, undiscovered
unpredicted, discovered
0^{-+} 1^{--} 1^{+-} 0^{++} 1^{++} 2^{++}
J^{PC}

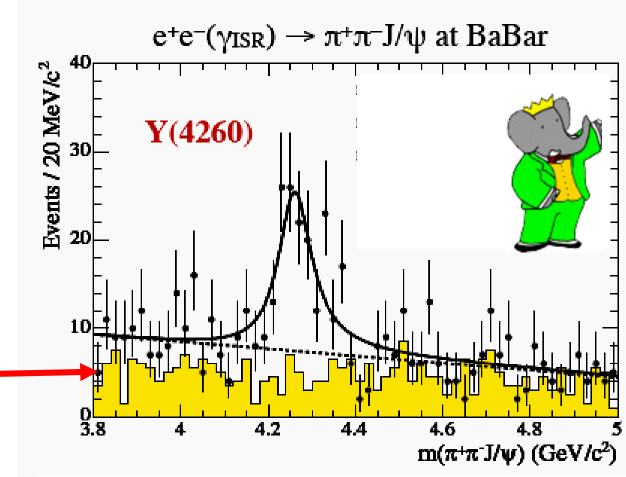
XYZ States (EPJ C71, 1534 (2011))

State	m (MeV)	Γ (MeV)	J^{PC}	Process (mode)	Experiment (#σ)	Year	Status
$X(3872)$	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!
$Y(4260)$	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!

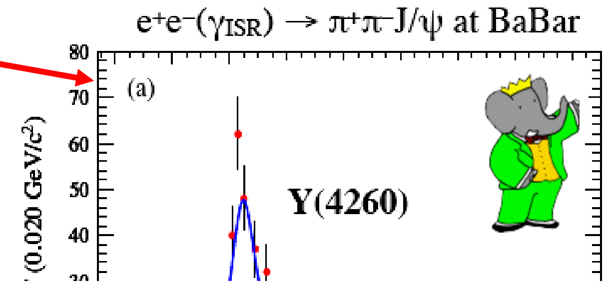
Y(4260)



BaBar, PRL 95, 142001 (2005)

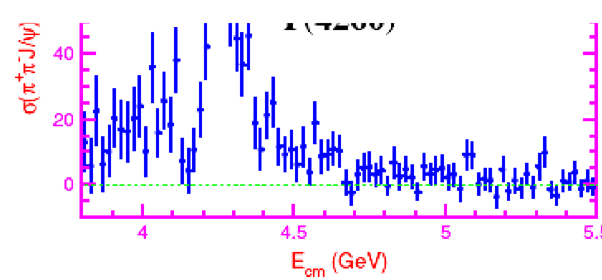


BaBar, PRD 86, 051102 (2012)



Not only does Y(4260) not fit in normal quark model, it decays to $\pi^+\pi^- J/\Psi$ even though it is above DD-bar threshold.

Bel 182004 (2007)



Y(4260)

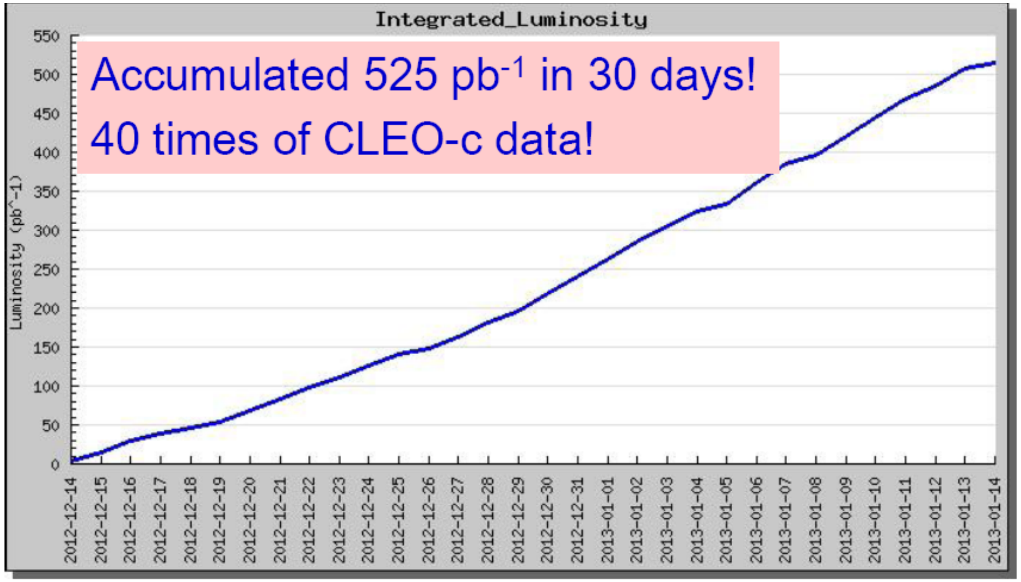
New XYZ era has generated many, many theoretical papers.

Some theoretical ideas for Y(4260):

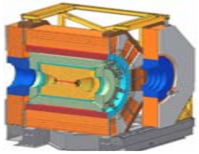
- DD^* bound state [NPA815, 53 (2009)].
- $J/\Psi\ f_0$ bound state (with $KK \rightarrow \pi\pi$) [PRD80, 094012 (2009)].
- Tetraquarks (or two diquarks) [PRD72, 031502 (2005)].
- Hadrocharmonium [PLB666, 215 (2008)].
- Hybrid charmonium [PLB628, 215 (2005), PRD78, 094505 (2008), PLB625, 212 (2005)].

On Dec. 14, 2012, BESIII began running with a CM energy of 4260 MeV.

Also took data at 4360 MeV.



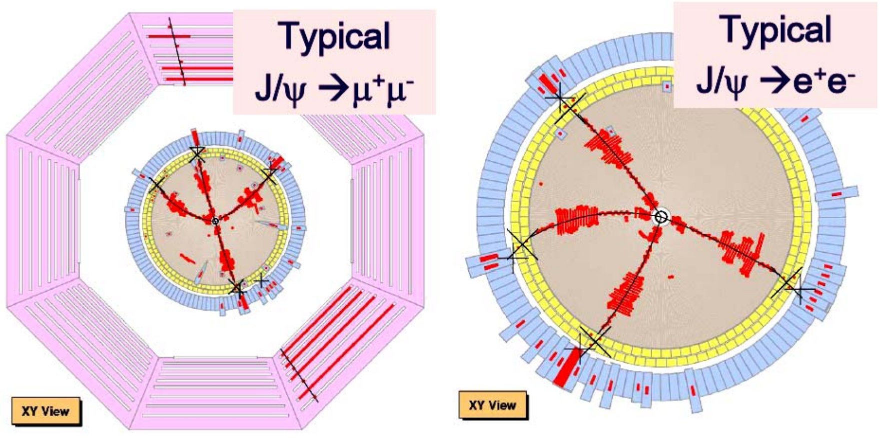
Y(4260)

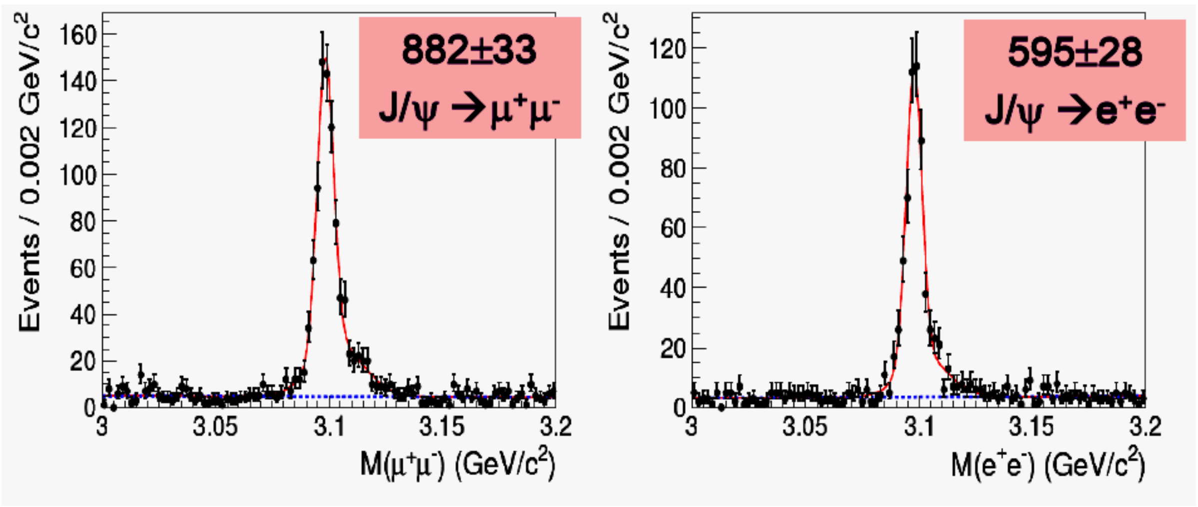


Select $e^+e^- \rightarrow \pi^+\pi^- J/\Psi$, $J/\Psi \rightarrow l^+l^-$ events.

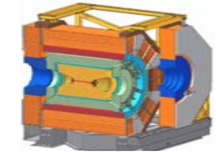
1477 events found.

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

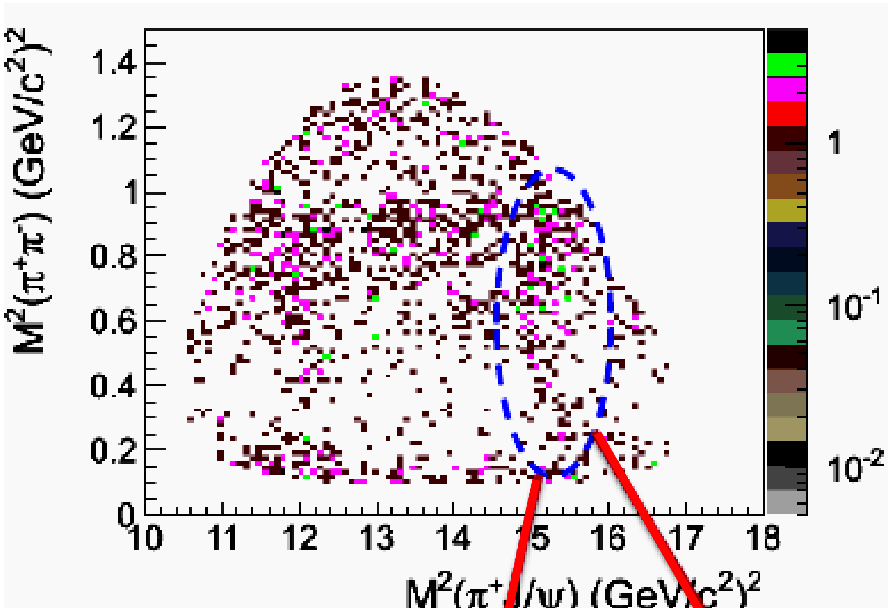




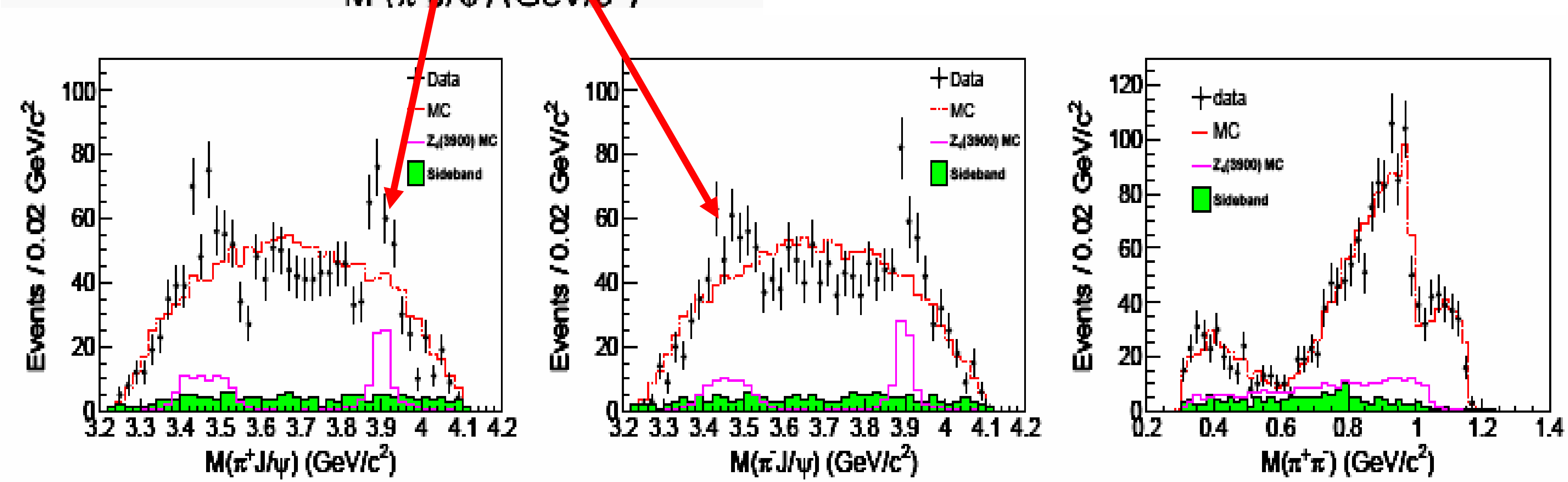
Y(4260)



BESIII

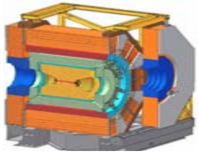


A structure around 3.9 GeV/c is observed in the $\pi^\pm$ J/Ψ mass spectrum. If interpreted as a particle, it carries charge and couples to charmonium.



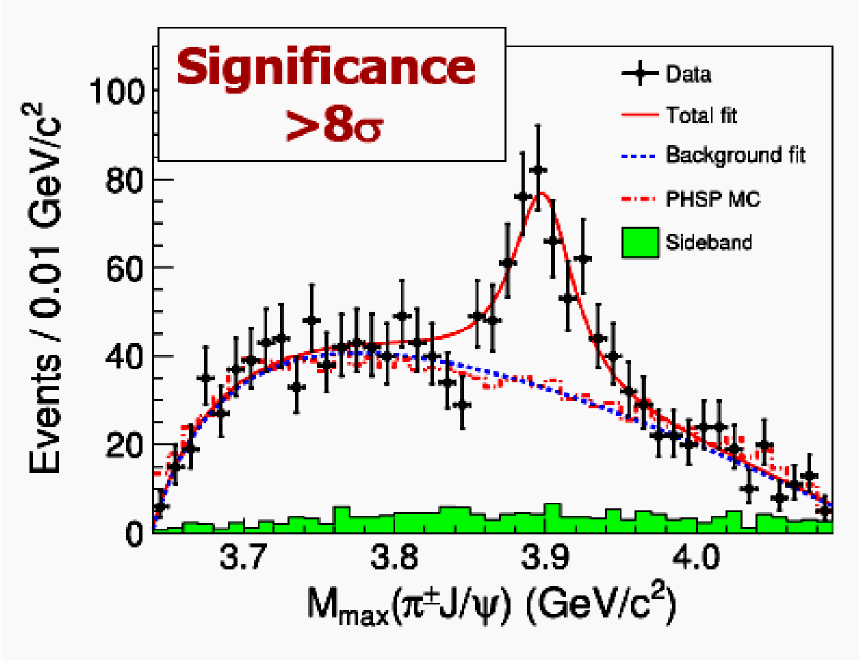
MC: σ, f(980), NR

$Z_c(3900)$



Plot maximimum of $M(\pi^+ J/\Psi)$ and $M(\pi^- J/\Psi)$ for each event. Fit with BW convolved with Gaussian resolution function; neglect interference with background.

$N(Z_c(3900)) = 307 \pm 48$
$M(Zc(3900)) =$
$(3899.0 \pm 3.6 \pm 4.9)$ MeV/c^2
$\Gamma(Z_c(3900)) = (46 \pm 10 \pm 20)$ MeV

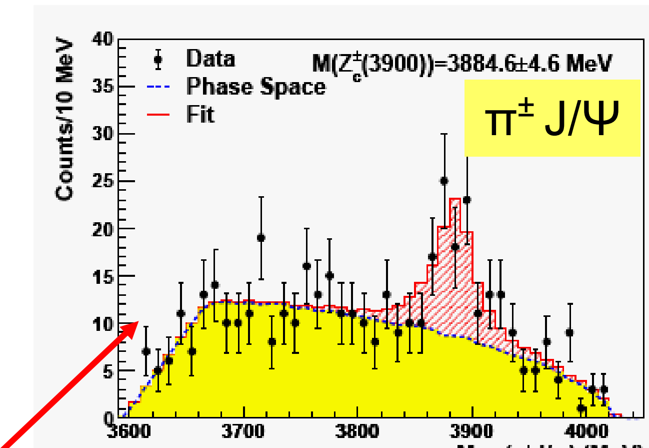


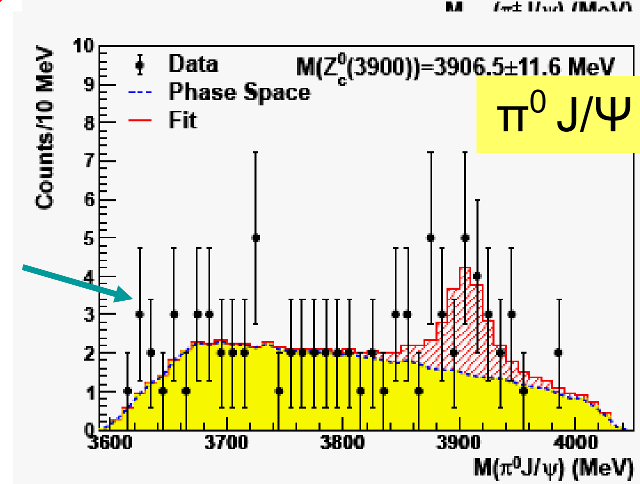
Structure has charge and couples to charmonium. Suggestive of a state containing more than just a C and C-bar quark.

$Z_c(3900)$

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 $Z_c(3900)$ has already been confirmed by Belle [arXiv:1304.0121] in ISR Y(4260) production and by Kam Seth [arXiv:1304.3036] using 586 pb^{-1} of CLEO data taken at a CM energy of 4170 MeV [$\Psi(4170)$]. Seth also sees a peak in $\pi^0 J/\Psi$, a neutral $Z_c(3900)$.





$Z_c(3900)$

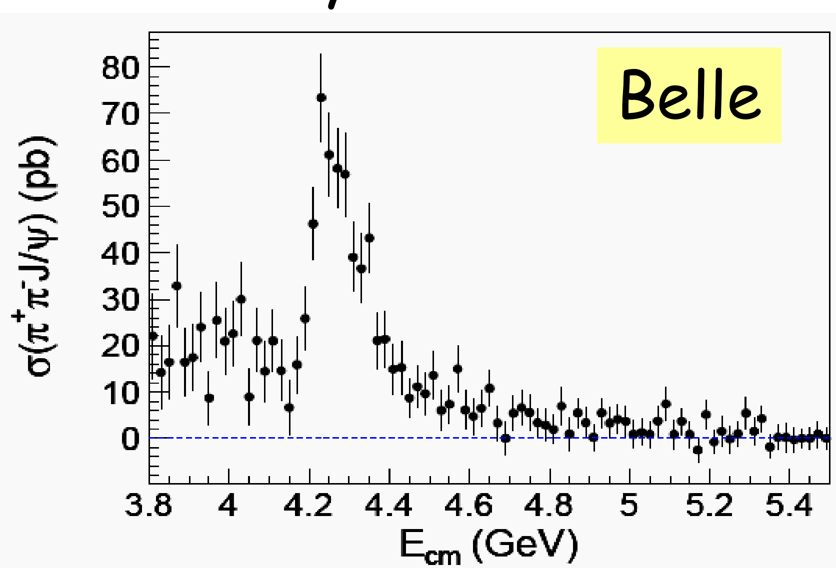
		$\sqrt{s}$ (GeV)	$\sigma(ee \to \pi\pi J/\Psi)$, pb	$N(Z_c)$	$M(Z_c)$ MeV/c^2	$\Gamma(Z_c)$ MeV	R %
BESIII	$\pi^+\pi^-$	4.26	62.9 ± 1.9	307	3899 ± 6	46 ± 22	22 ± 3
Belle	$\pi^+\pi^-$	3.8 – 5.5		159	3895 ± 8	63 ± 35	29 ± 9
Seth	$\pi^+\pi^-$	4.17	8.6 ± 0.7	81	3885 ± 5	34 ± 13	35 ± 11
Seth	$\pi^0\pi^0$	4.17	5.7 ± 0.8	17	3907 ± 12	34 ± 29	25 ± 15

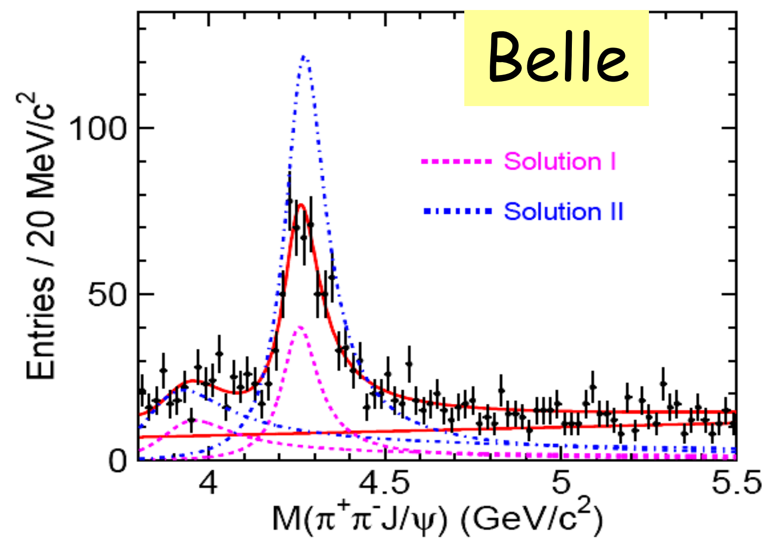
$R = B(Y(e^+e^- \to Z_c\pi) \cdot B(Z_c \to \pi J/\Psi)/B(e^+e^- \to \pi\pi J/\Psi)$

- Measurements agree well.
- Seth not at peak of Y(4260), but at peak of 2^3D_1 state of charmonium, E_{CM} = 4170 MeV. "Do not need to attribute unusual properties to initial state of Y(4260)".

$Z_c(3900)$

- Belle also measures cross section in latest work.
- Belle has claimed two resonances in this region: Y(4260) and Y(4008); Belle, PRL99, 182004 (2007).
- However BaBar uses a different background description and does not confirm the Y(4008); BaBar, PRD86, 051102 (2012).
- Therefore situation at E_{CM} = 4170 GeV unclear.
- BESIII will be able to clarify and study many more decay modes of the Y(4260). Accumulating more data.





The nature of the $Z_c(3900)$?

From Spires April 21:

1. Tetraquarks

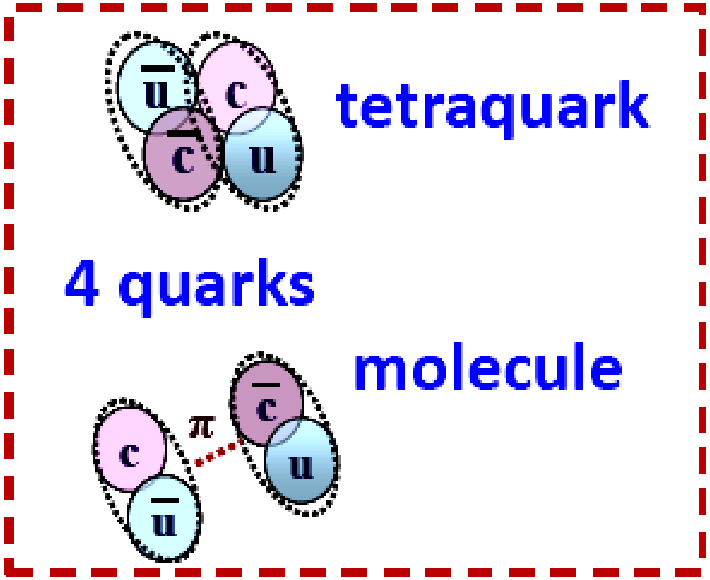
- arXiv:1110.1333, 1303.6857
- arXiv:1304.0345, 1304.1301

2. Hadronic molecules:

- arXiv:1303.6608, 1304.2882
- arXiv:1304.1850

3. Four quark state (1 or 2)

- arXiv:1304.0380



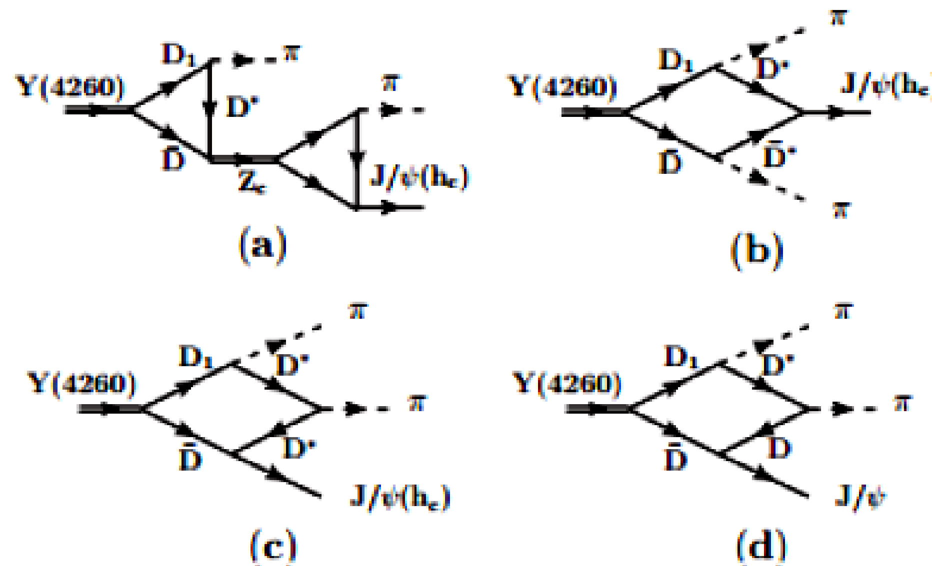
Exotic!

The nature of the $Z_c(3900)$?

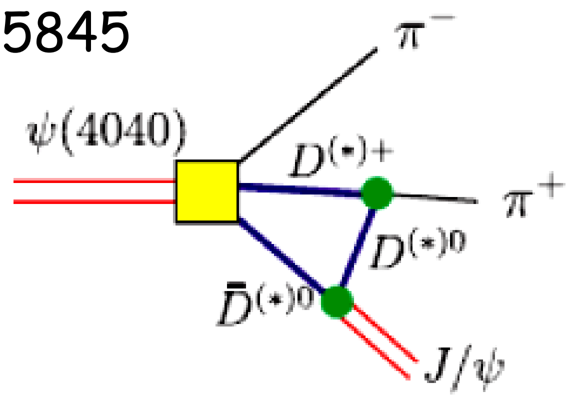
4. Meson loop
- arXiv:1303.6355
- arXiv:1304.4458

5. Initial Single Pion Emission (ISPE) model
- arXiv:1208.2411
- arXiv:1303.6842
- arXiv:1304.5845

6. ???



Meson loop

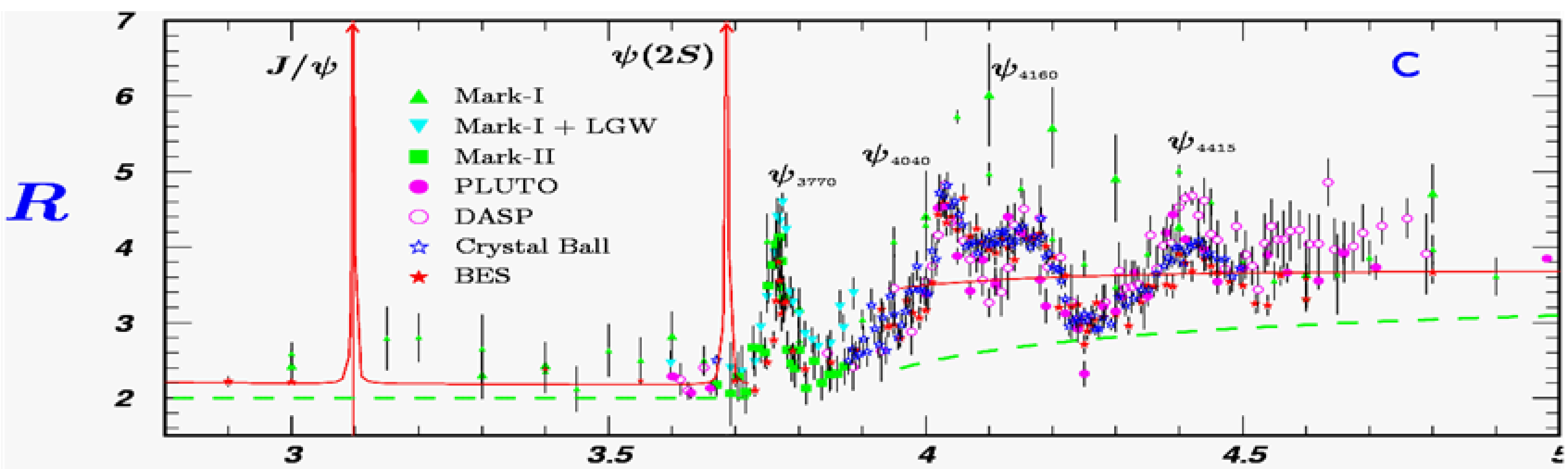


ISPE model

BESIII data sets and future plans

BESIII data taking status & plan

	Previous data	BESIII present & future	Goal
J/ψ	BESII 58M	1.2 B 20*BESII	10 B
ψ′	CLEO: 28 M	0.5 B 20*CLEOc	3B
ψ″	CLEO: 0.8 /fb	2.9/fb 3.5*CLEOc	20 /fb
Above open charm	CLEO: 0.6/fb @ ψ(4160)	2011: 0.4/fb @ ψ(4040) 2013: 1/fb@4260, 4360	5-10 /fb
R scan & Tau	BESII	2012: 12/pb@2.23,2.4,2.8,3.4 25/pb, τ scan 2013, 2014: @4260, R scan, …	

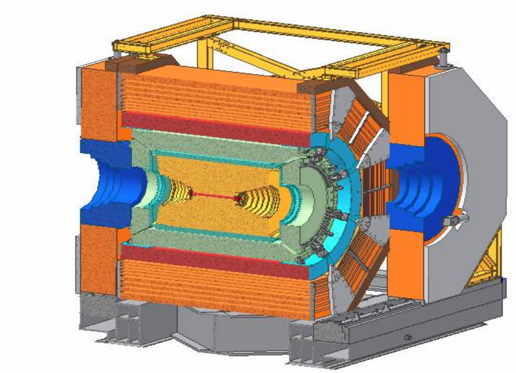


Future

- BESIII has many years of data taking to reach goals. Considering now upgrades necessary to run until 2020.
- Goals may change due to competition from LHCb and Belle-II.
- Tau-charm energy region will continue to be interesting due to large variety of physics possible:
  - XYZ physics
  - Charmonium
  - Charm
  - Detailed R scan
  - precision tau mass
  - etc.

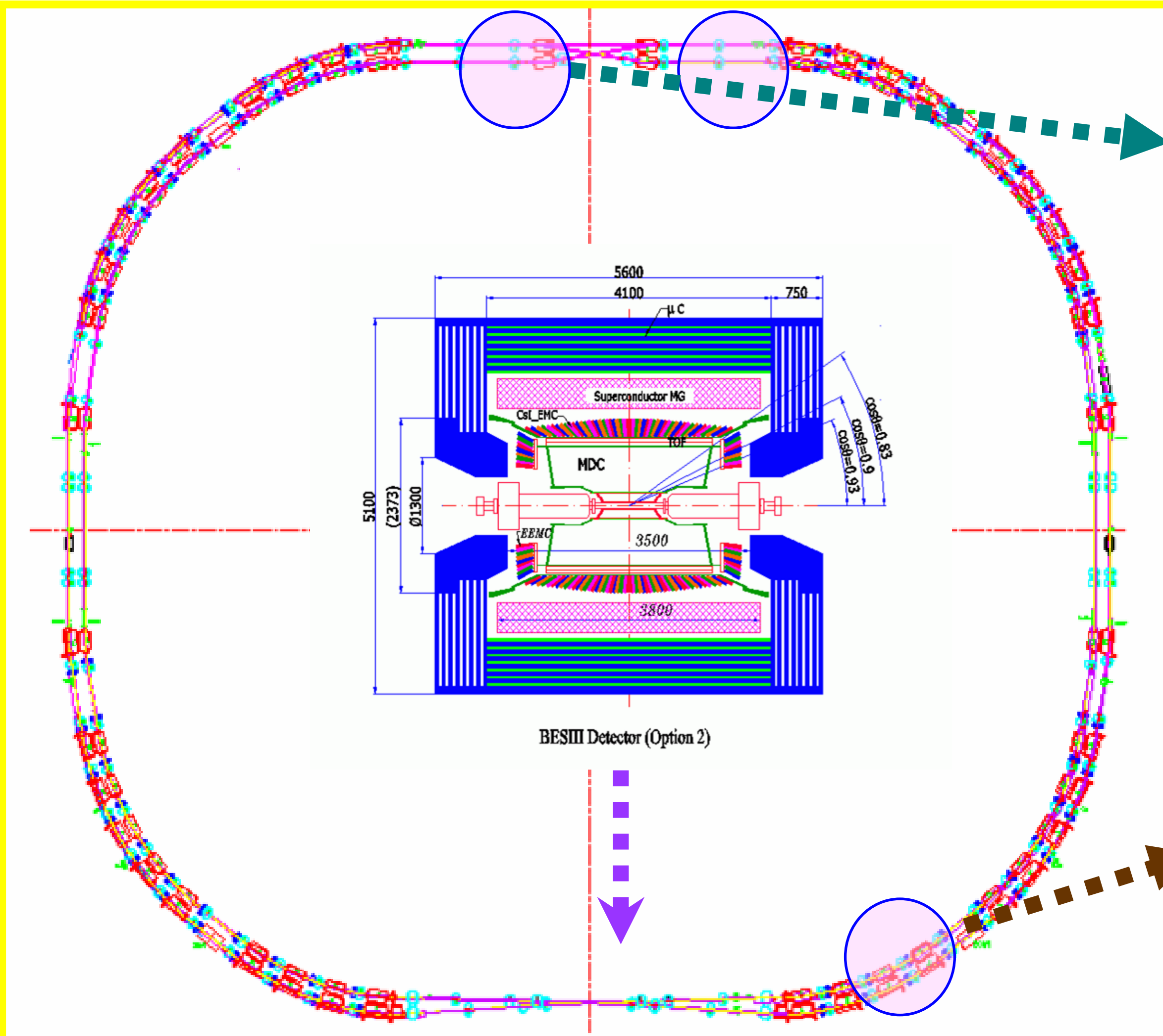
Summary

- Charmonium results have entered the precision era.
  - Mass and width problems of $\eta_c(1S)$ understood?
  - Have good handle now on $\eta_c(2S)$ from Ψ' decays. More events will improve mass and width measurements.
- There is still much to do.
  - Improve measurements of charmonium below charm threshold to test/calibrate LQCD.
  - Understand states above charm threshold.
  - XYZ states and higher mass charmonium states need to be disentangled.



Grazie

BEPCII: a high luminosity double-ring collider



SC RF

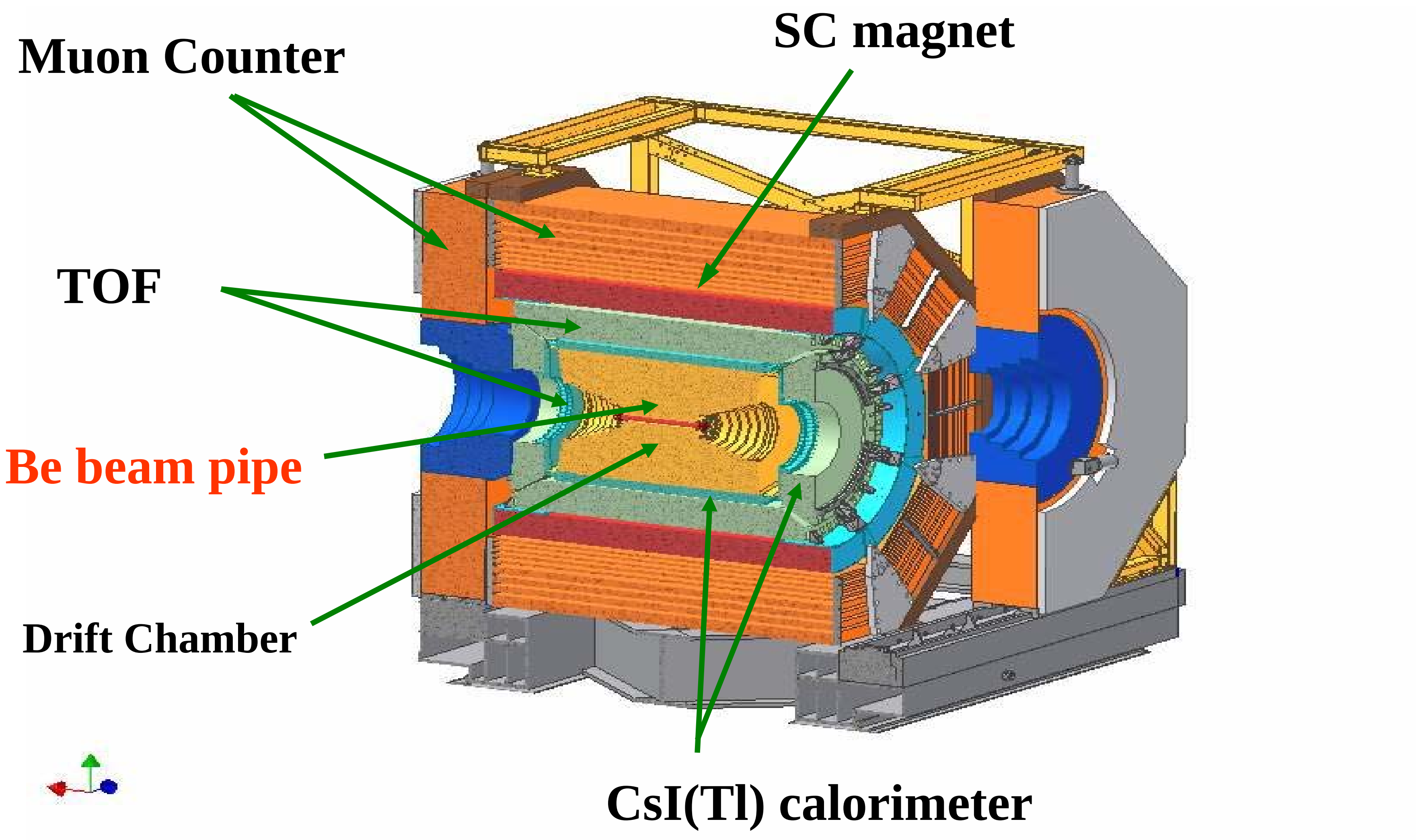
Beam magnets

CM Energy: 2 – 4.4 GeV

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

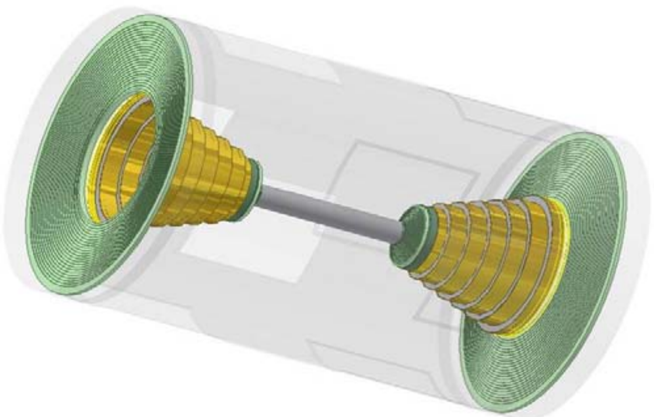
Uses 93 bunches and SC mini-beta.

BESIII Detector



BESIII Detector

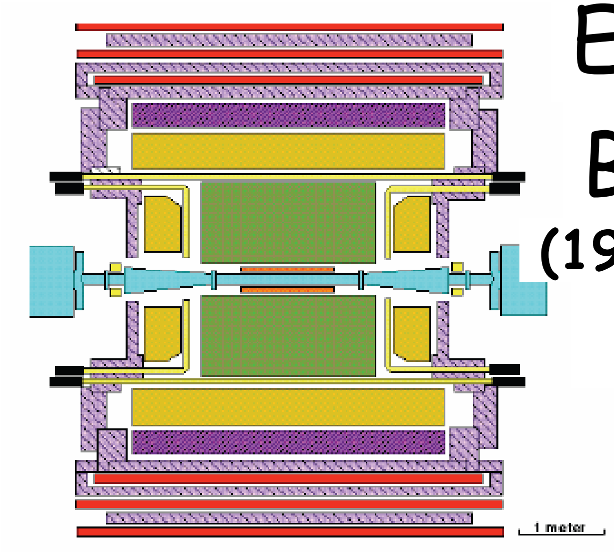
Berylium beam pipe
Small-celled, helium-based MDC:
  $|\cos\theta| < 0.83$ (all layers), < 0.93 (20 layers)
  $\sigma_p/p = 0.5$ % at 1 GeV/c; $\sigma_{dE/dx}$ /dE/dx = 6% at 1 GeV/c
TOF (2 layers in barrel; 1 layer endcap)
  σ_T = 100 ps barrel; σ_T = 110 ps endcap
CsI electromagnetic calorimeter
  crystal length: 28 cm (15 X_0)
  energy: 2.5%, space 0.6 cm at 1 GeV
Superconducting Magnet – 1 T
Muon Counter
  9 layers of RPCs in barrel; 8 in endcap



For details, see talk by F. Harris at Meson2008.

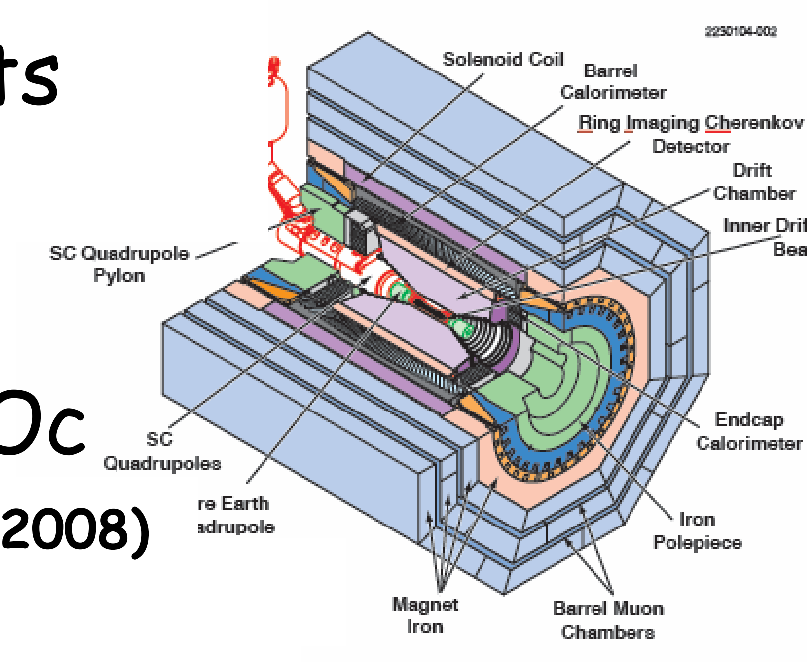
10 billion J/Ψ per year.

Experiments



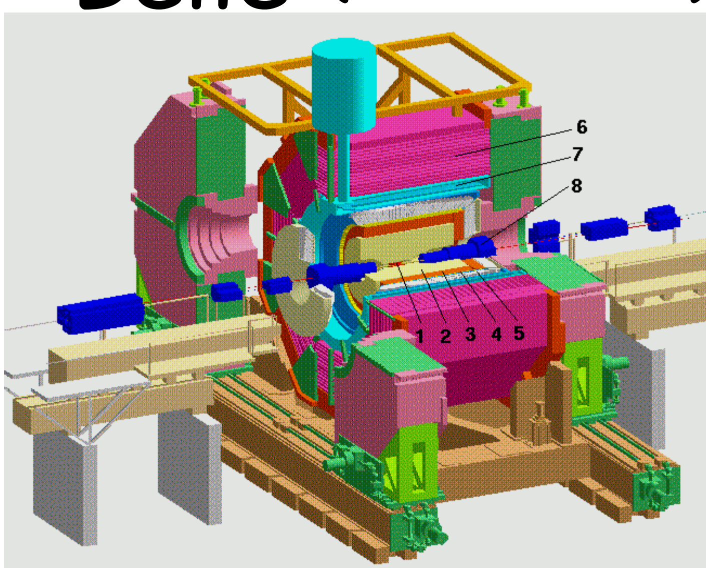
BESII
(1996 - 2004)

CLEOc
(2003 - 2008)



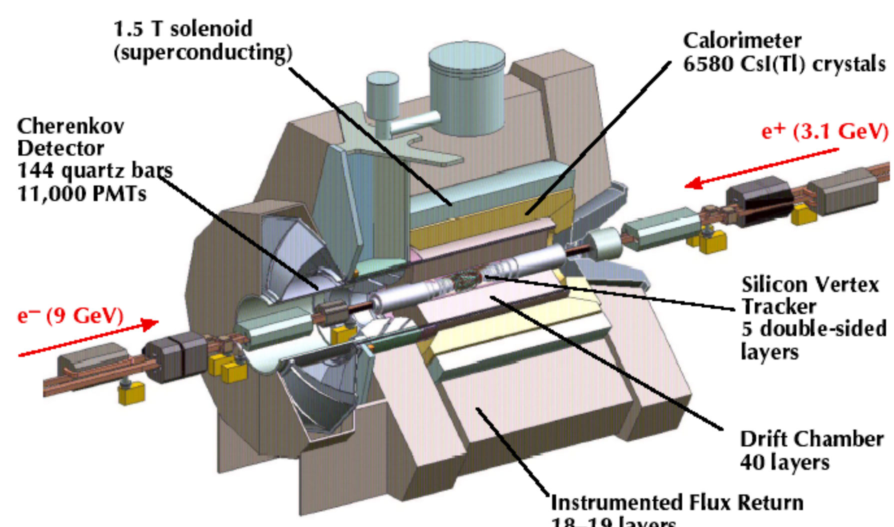
e^+e^-

Belle (1998 - 2010)

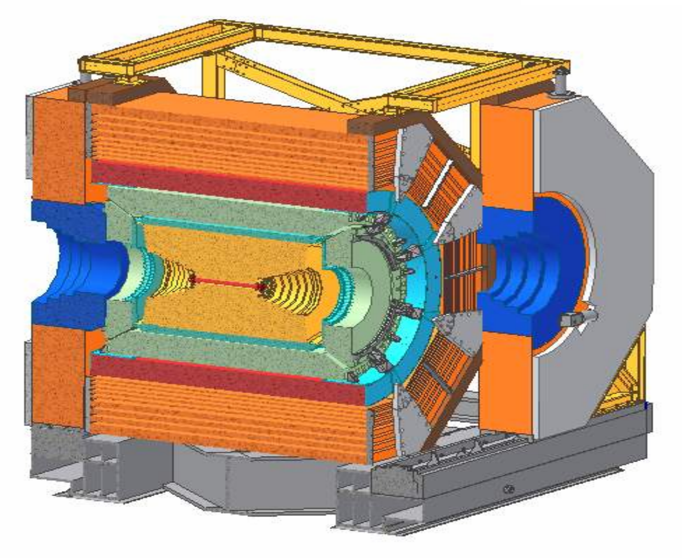


BABAR (1998 - 2008)

The BaBar Detector

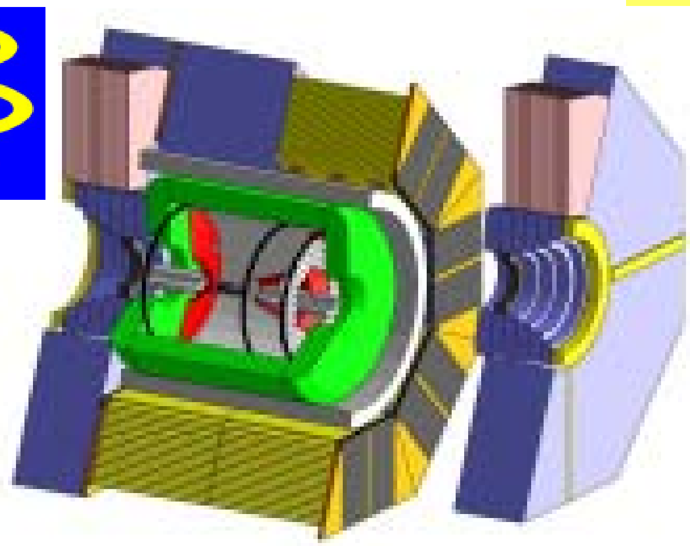


Experiments



BESIII
(2009 -)

e^+e^-



Belle II
(2016? -)

Others:
- D0
- CDF
- SND
- CMD3
- LHCb
- ATLAS
- CMS
- Panda