Charmonium Spectroscopy and Decays

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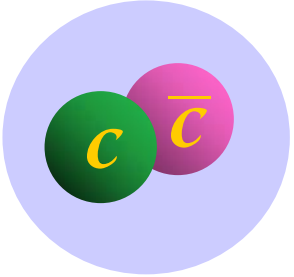
Outline

- Introduction to charmonium
- Spectroscopy
  - *Conventional charmonium states*

    $h_c,\ \eta_c,\ \eta_c(2S)$
  - *Charmonium-like states*

    X(3872), Y
- Decays
- Summary

Charmonium



- Charmed-quark anticharmed-quark bound states ($c\bar{c}$)
- c-quarks are heavy, velocities small: v/c~1/4, the system is non-relativistic.
- The energy levels are found by solving a non-relativistic Schrodinger equation. (+ relativistic corrections & other effects)
- <u>The potential</u>:

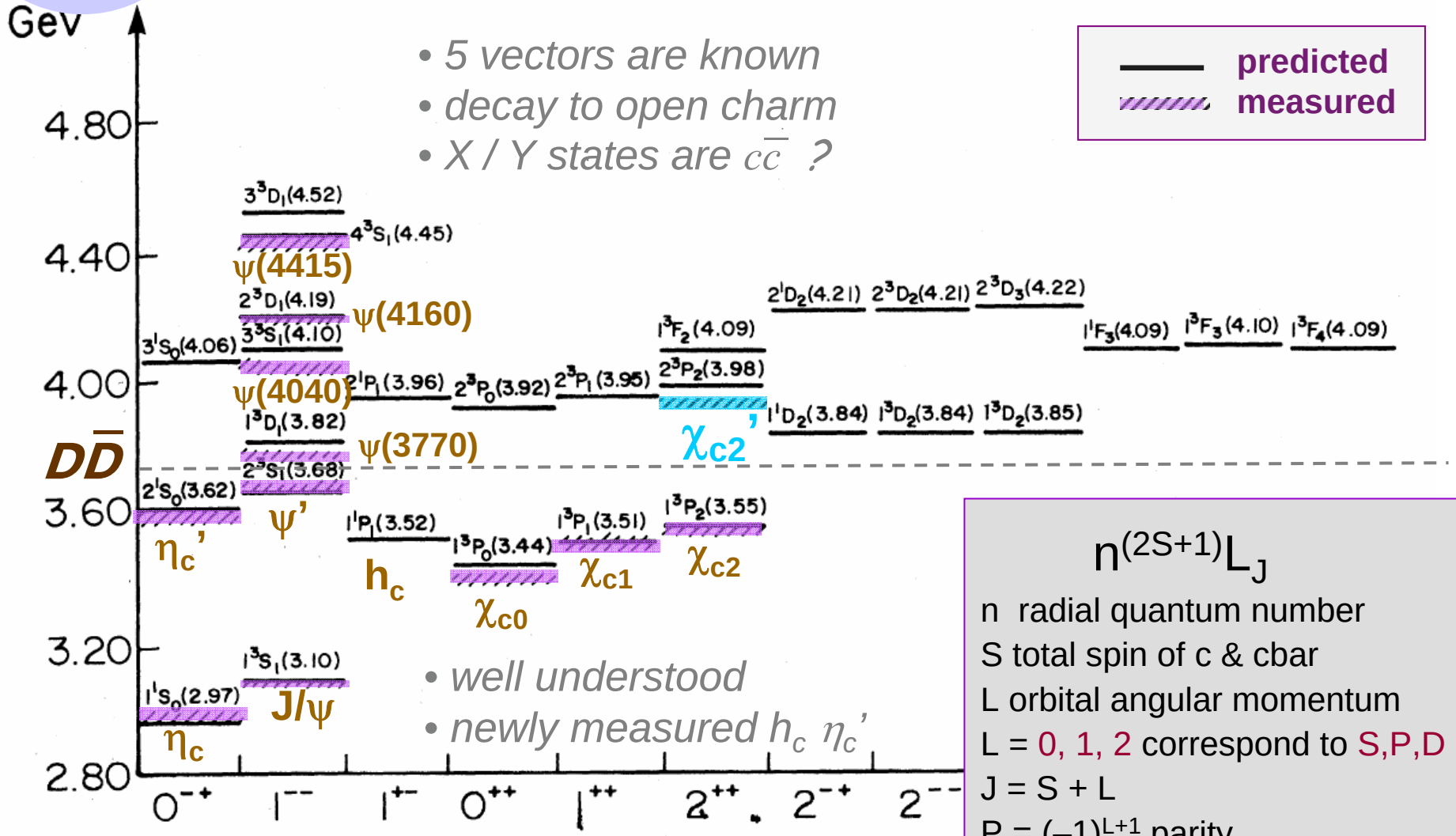
  a short distance behavior: *dominated by single-gluon-exchange*, ~ <u>*Coulombic*</u>

  at large separation: *dominated by* <u>*a linearly increasing confining potential*</u>

Charmonium Spectroscopy

Godfrey & Isgur, PRD32, 189 (1985)

- *5 vectors are known*
- *decay to open charm*
- *X / Y states are $c\bar{c}$?*



- *well understood*
- *newly measured h_c η_c'*

$n^{(2S+1)}L_J$

n radial quantum number

S total spin of c & cbar

L orbital angular momentum

L = 0, 1, 2 correspond to S,P,D

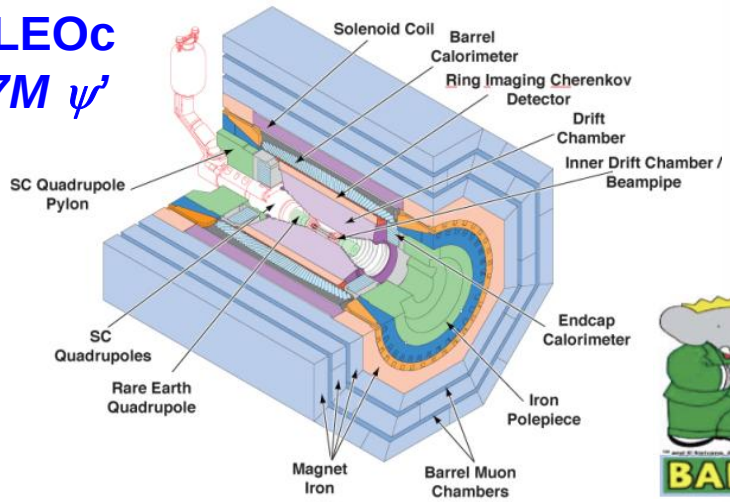
J = S + L

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

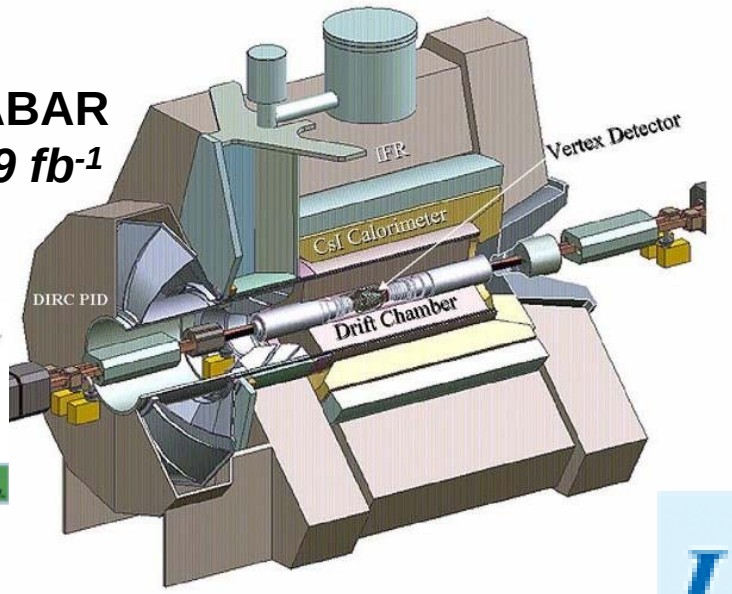
$C = (-1)^{L+S}$ charge conj.

Experiments

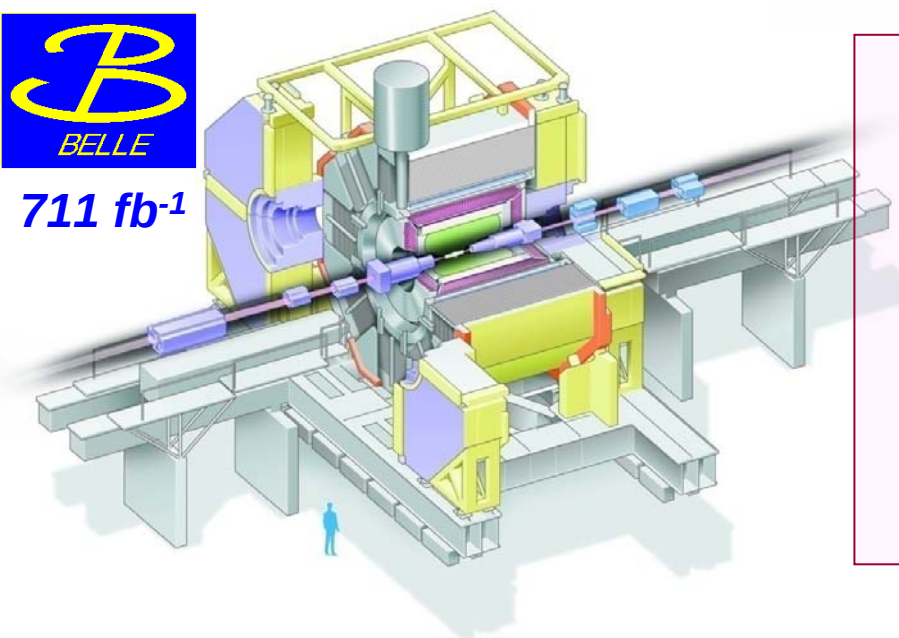
CLEOc
27M ψ'



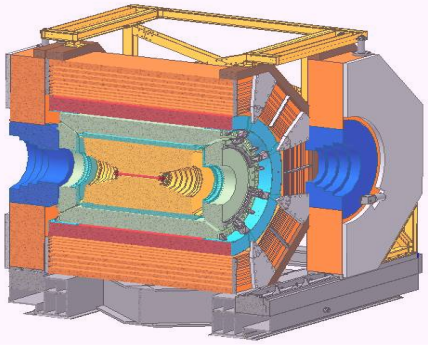
BABAR
519 fb^{-1}



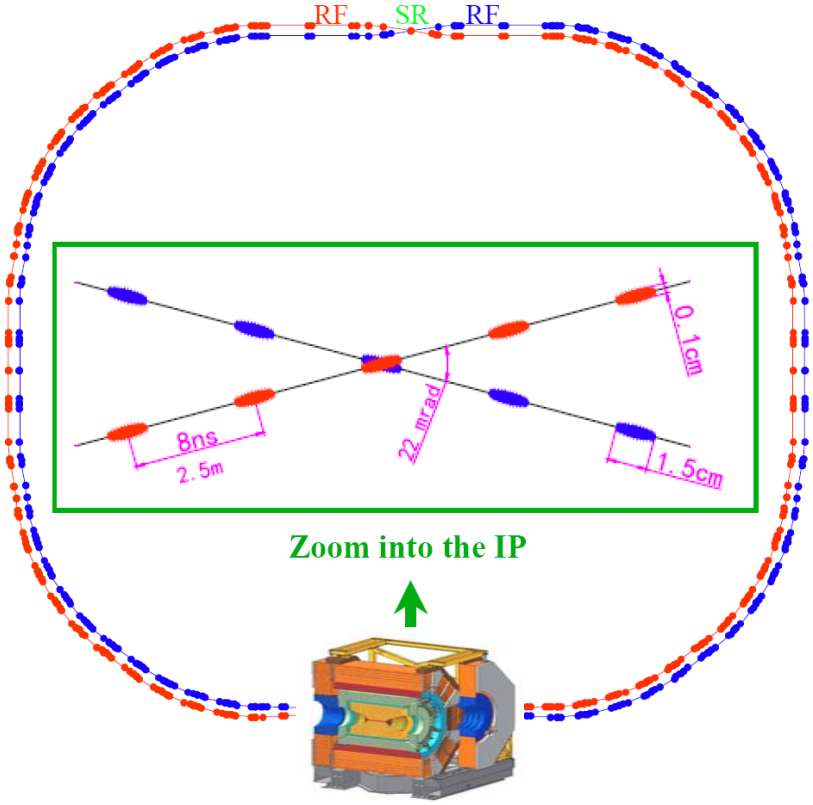
711 fb^{-1}



BESIII ***106 M ψ'***
225 M J/ψ



BEPCII storage rings



Beam energy: 1.0 − 2.3 GeV

Peak Luminosity:

Design: 1×10^{33} $cm^{-2}s^{-1}$

Achieved: **0.65×10^{33} $cm^{-2}s^{-1}$**

Optimum energy: 1.89 GeV

Energy spread: 5.16×10^{-4}

Circumference: 237 m

Beam energy measurement:

Using Compton backscattering technique. Accuracy up to **5×10^{-5}**

Data samples collected:

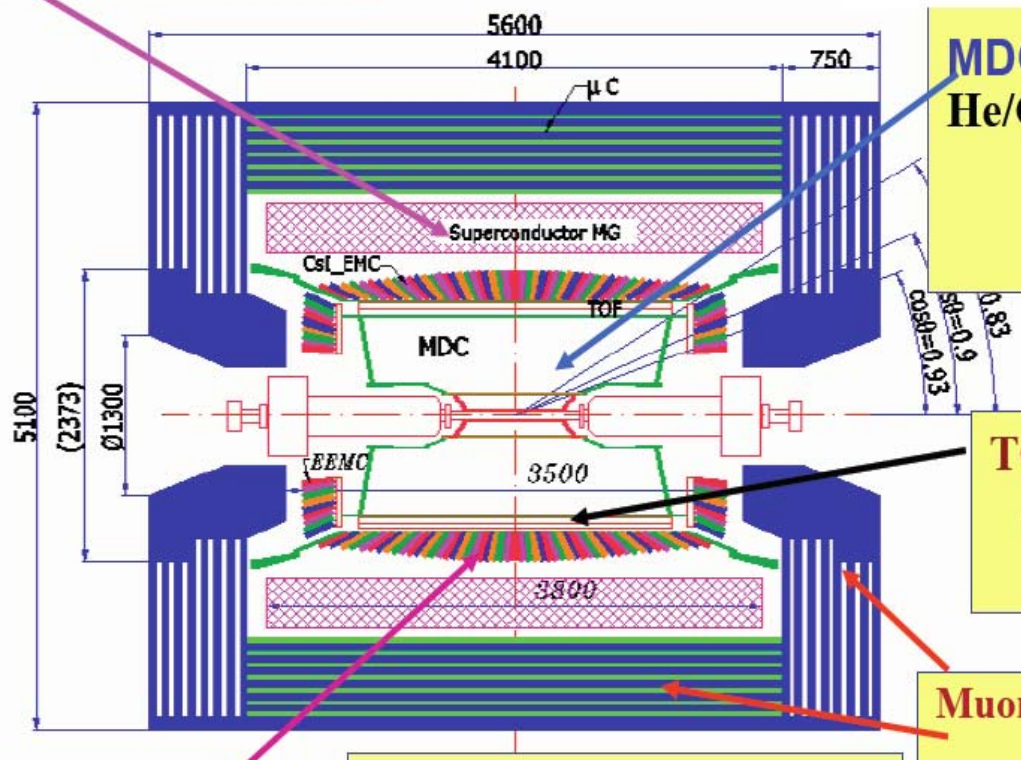
- **225 M J/ψ**
- **106 M ψ'**
- **2.9 fb^{-1} ψ(3770)**
- **0.5 fb^{-1} @4010 MeV**

BESIII Detector

BESIII detector: all new !

CsI calorimeter
Precision tracking
Time-of-flight + dE/dx PID

Magnet: 1 T Super conducting



MDC: small cell & Gas:
He/C_3H_8 (60/40), 43 layers
σ_{xy}=130 μm
σ_p/p = 0.5% @1GeV
dE/dx=6%

TOF:
σ_T = 100 ps Barrel
110 ps Endcap

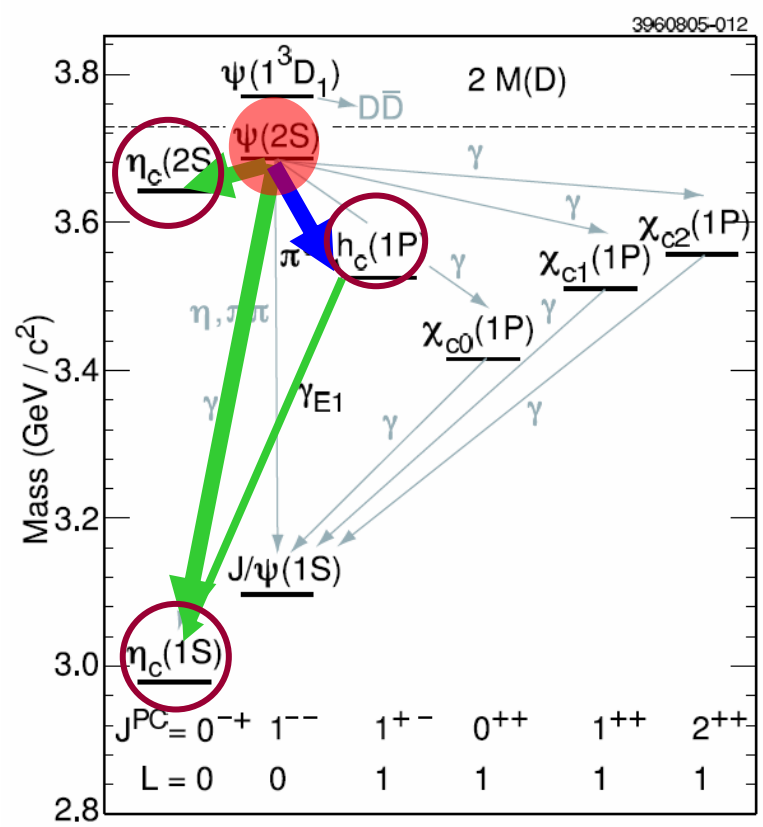
Muon ID: 9 layers RPC
8 layers for endcap

EMC: CsI crystal, 28 cm
$\Delta E/E$ = 2.5% @1 GeV
$\sigma z = 0.6$ cm/$\sqrt{E}$

Data Acquisition:
Event rate = 4 kHz
Total data volume ~ 50 MB/s

Conventional charmonium states

h_c , $\eta_c(1S)$, $\eta_c(2S)$



$h_c(^1P_1)$

- Spin singlet P wave (S=0, L=1)
- Potential model: if non-vanishing spin-spin interaction,

  $\Delta M_{hf}(1P) = M(h_c) - \langle m(1\ ^3P_J)\rangle \neq 0$

  where $\langle m(1\ ^3P_J)\rangle = [(M(\chi_{c0})+3M(\chi_{c1})+5M(\chi_{c2})]/9$,
- E835 found evidence for h_c in $p\bar{p} \rightarrow h_c \rightarrow \gamma\eta_c$
- CLEOc observed h_c in $ee \rightarrow \psi' \rightarrow \pi^0 h_c$, $h_c \rightarrow \gamma\eta_c$ *PRL 101 182003 (2008)*

  $\Delta M_{hf}(1P)=0.08\pm0.18\pm0.12$ MeV/c^2

  Consistent to 1P hypefine splitting of 0.

Theoretical prediction:

$BF(\psi(2S) \rightarrow \pi^0 h_c) = (0.4\text{-}1.3) \times 10^{-4}$

$BF(h_c \rightarrow \gamma\eta_c) = 48\%$ (NRQCD)

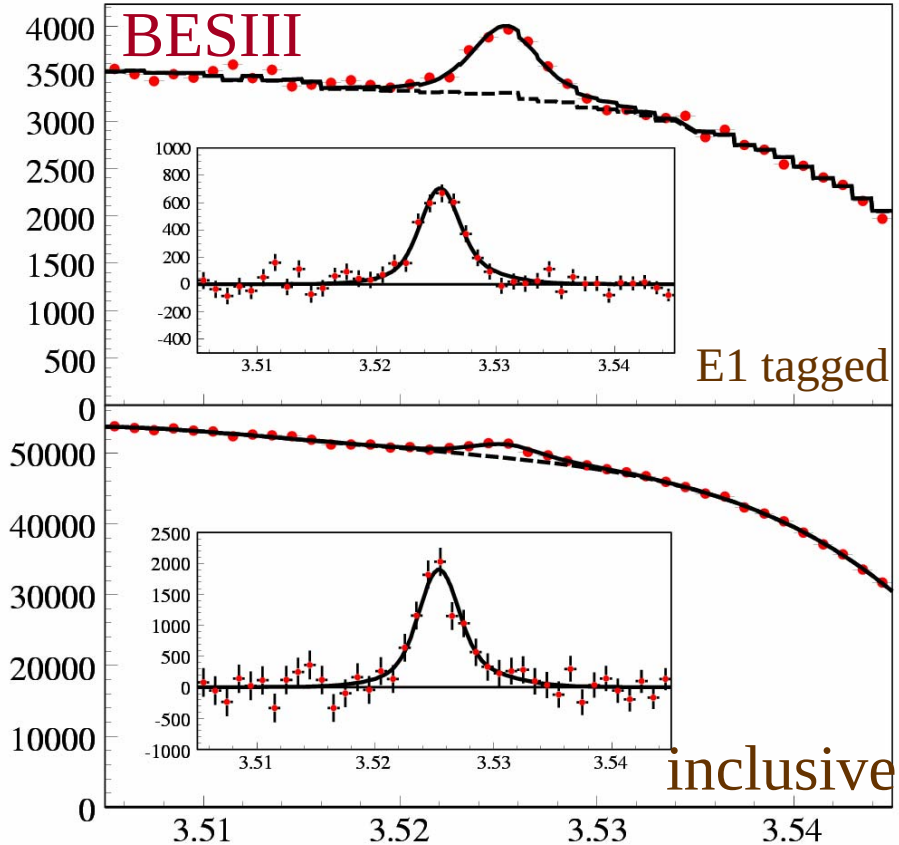
$BF(h_c \rightarrow \gamma\eta_c) = 88\%$ (PQCD)

Kuang, PR D65 094024 (2002)

$BF(h_c \rightarrow \gamma\eta_c) = 38\%$

Godfrey and Rosner, PR D66 014012(2002)

$\psi(2S) \rightarrow \pi^0 h_c$, $h_c \rightarrow \gamma \eta_c$



BESIII: PRL 104 132002 (2010)

Mass = **3525.40±0.13±0.18** MeV/c^2

Width = **0.73±0.45±0.28** MeV

<1.44 MeV @90%

CLEOc: PRL 101 182003 (2008)

Mass = **3525.28±0.19±0.12** MeV

Width: fixed at 0.9 MeV

Hyperfine mass splitting

$\Delta M_{hf}(1P) = M(h_c) - \langle m(1\ 3P_J) \rangle$

BESIII: ***0.10±0.13±0.18*** MeV/c^2

CLEOc: ***0.02±0.19±0.13*** **MeV/c^2**

<u>By combining inclusive results with E1-photon tagged results</u>

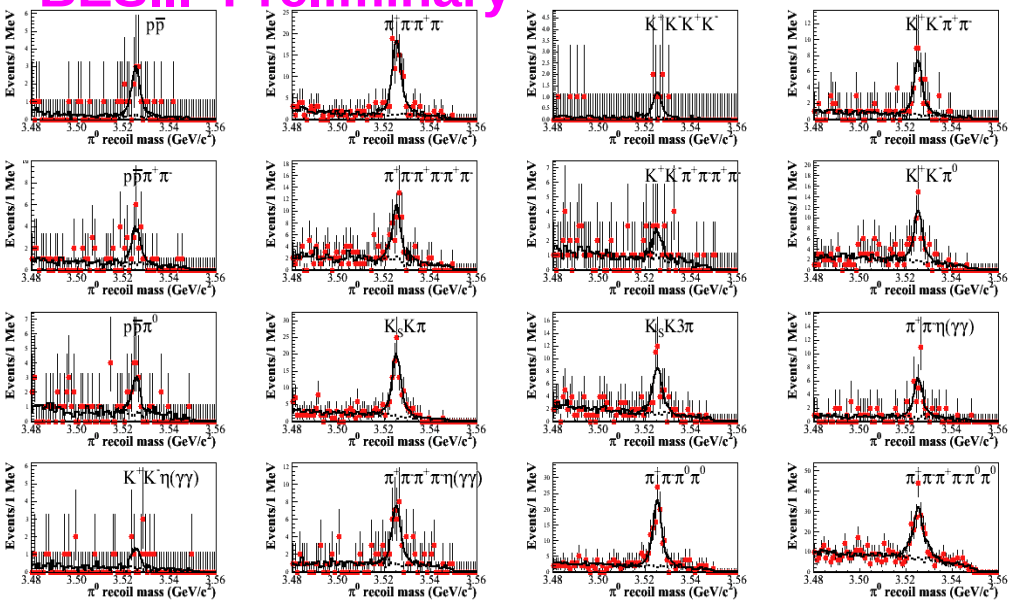
BF($\psi' \rightarrow \pi^0 h_c$) = **(8.4±1.3±1.0) ×10^{-4}**

BF($h_c \rightarrow \gamma \eta_c$) = **(54.3±6.7±5.2)%**

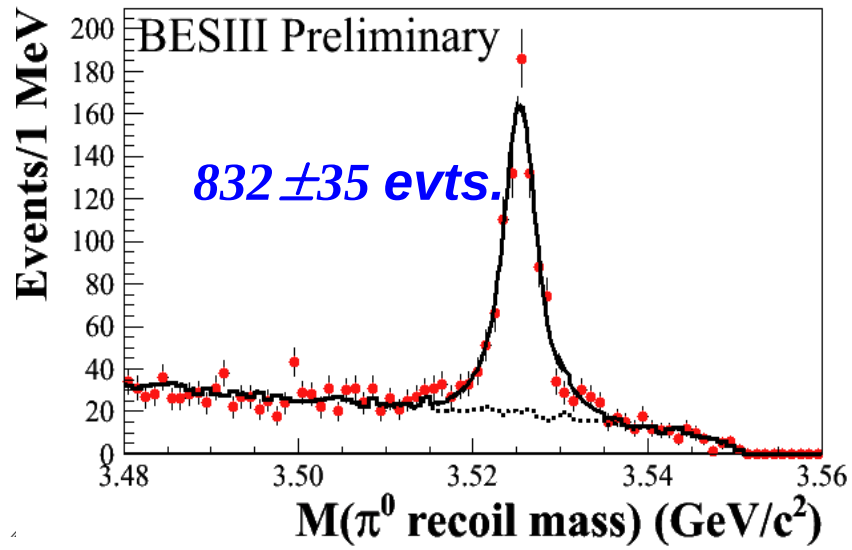
<u>Agree with prediction</u> from Kuang, Godgrey, Dude et al.

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

BESIII Preliminary



Summed distribution



Simultaneous fit to π^0 recoiling mass

χ^2/d.o.f. = 32/46

Mass = **3525.31±0.11±0.15** MeV/c^2

Width = **0.70±0.28±0.25** MeV

Consistent with BESIII inclusive results

Mass = **3525.40±0.13±0.18** MeV/c^2

Width = **0.73±0.45±0.28** MeV

CLEOc exclusive results

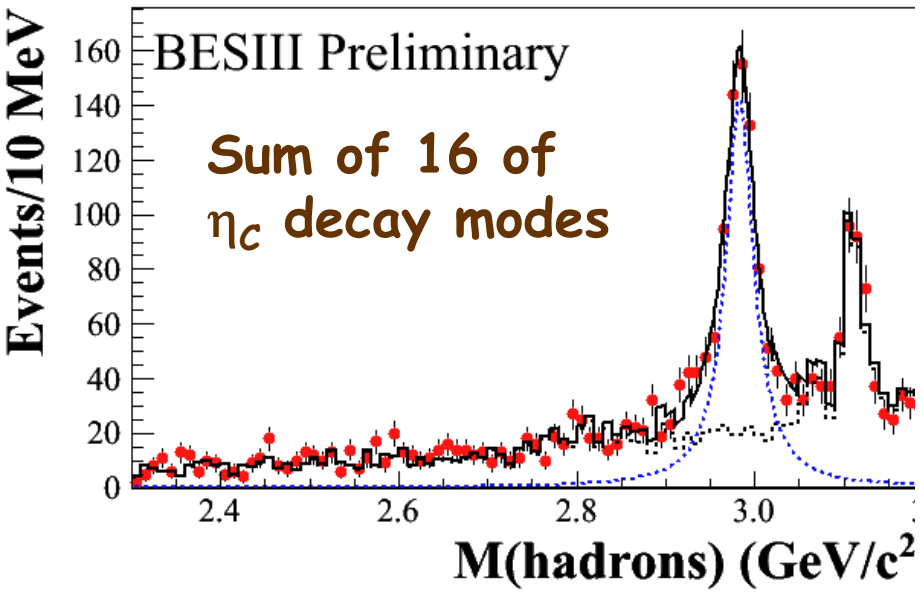
Mass =**3525.21±0.27±0.14** MeV/c^2

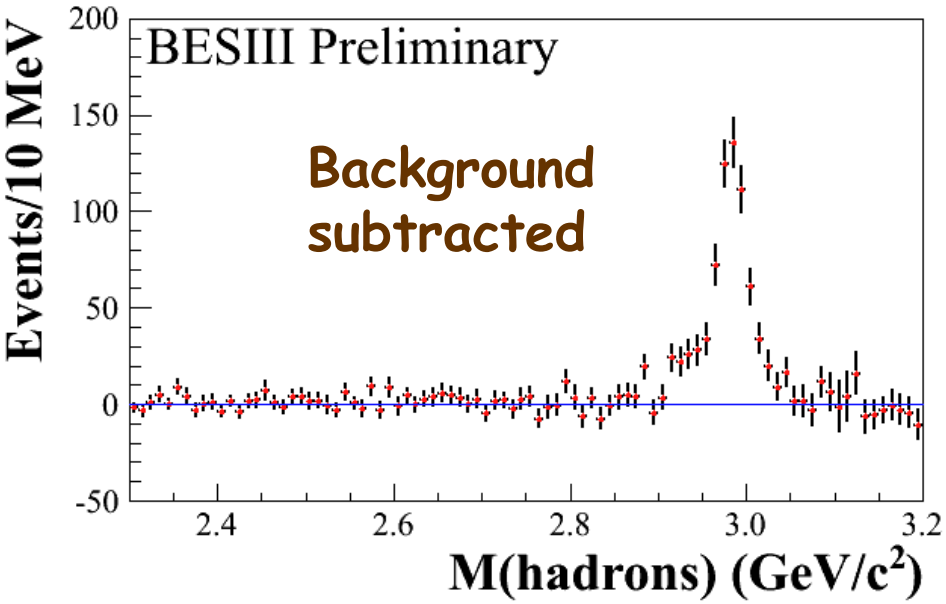
evts. =**136±14**

BESIII: PRL 104 132002 (2010)

CLEOc: PRL 101 182003 (2008)

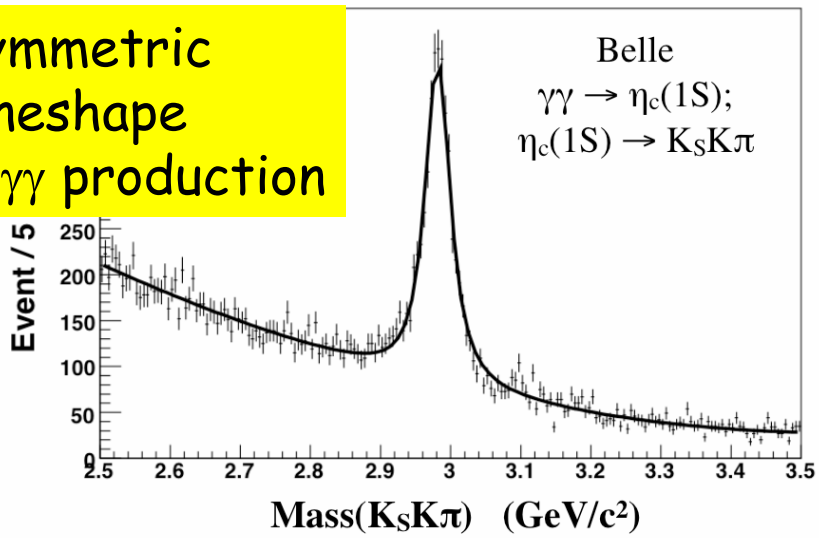
η_c lineshape from $\psi' \rightarrow \pi^0 h_c$, $h_c \rightarrow \gamma \eta_c$

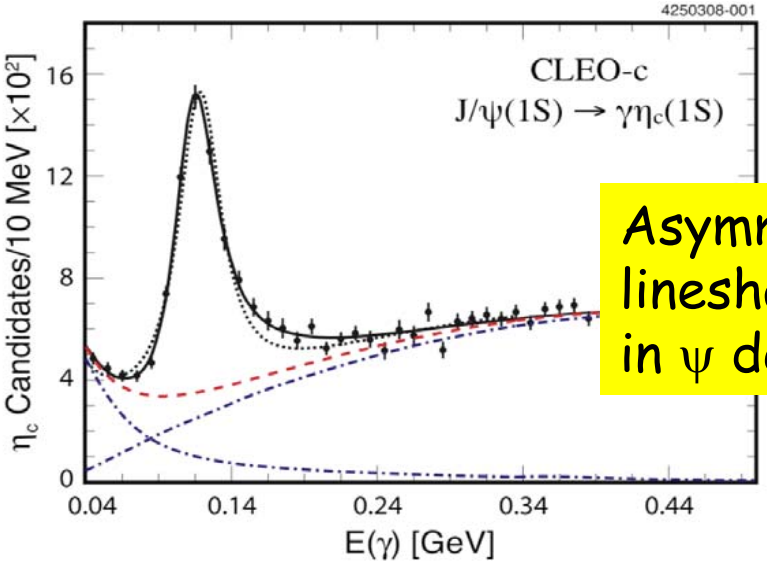




The η_C lineshape is not distorted in the $h_c \rightarrow \gamma \eta_c$

Symmetric lineshape in $\gamma\gamma$ production





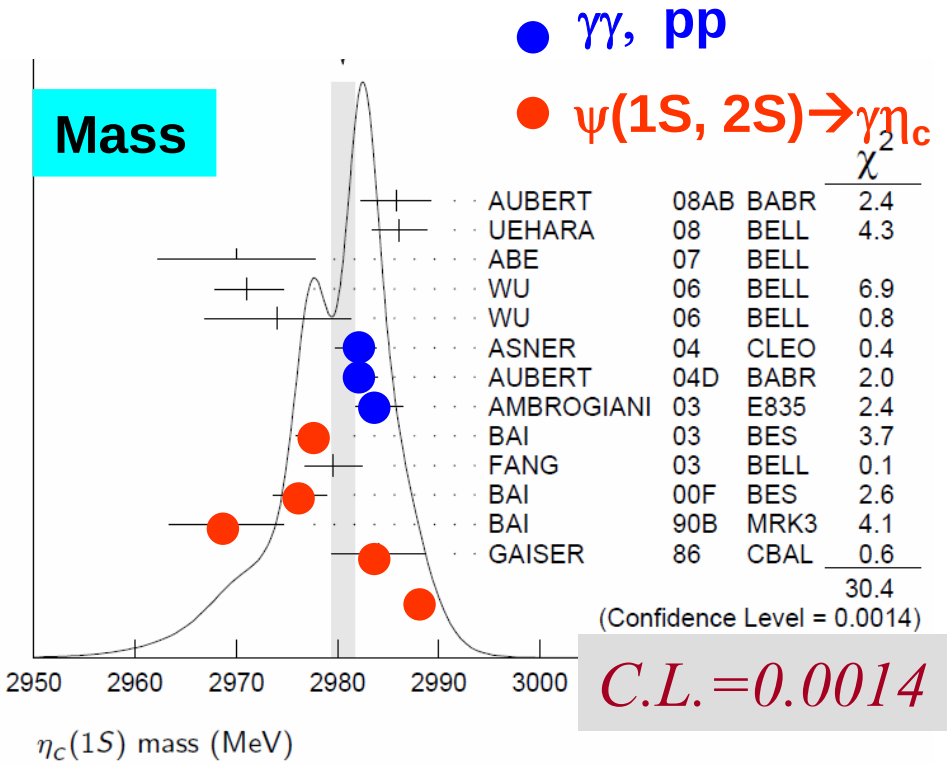
Asymmetric lineshape in ψ decay

$\eta_c(1S)$

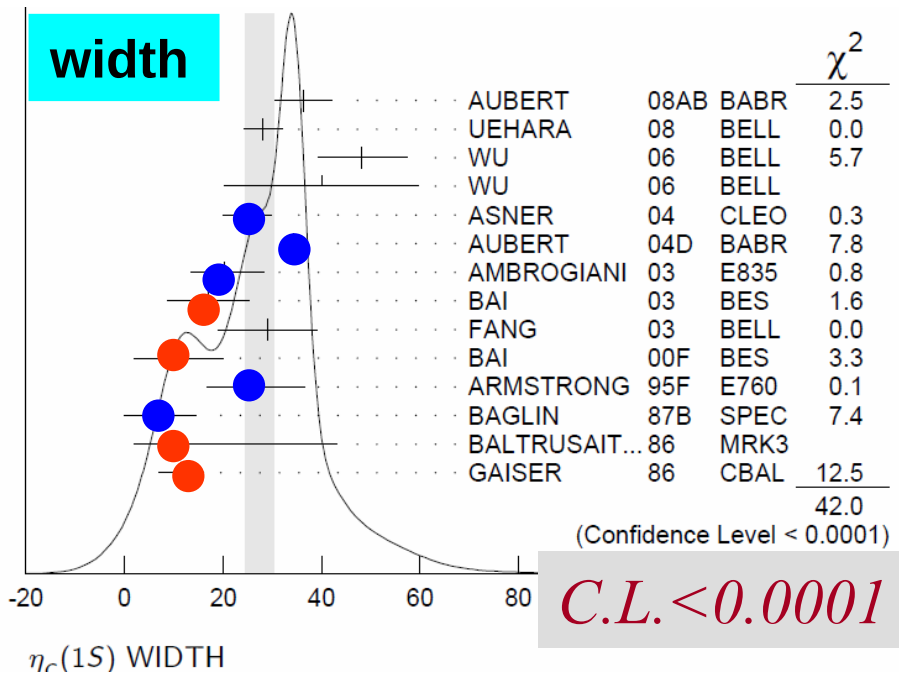
- The lowest lying S-wave spin singlet charmonium, discovered in 1980 by MarkII
- Parameters:

  J/ψ radiative transition: M ~ 2978.0MeV/c^2, Γ ~ 10MeV

  γγ process: M = 2983.1±1.0 MeV/c^2, Γ = 31.3±1.9 MeV
- CLEOc found the distortion of the η_c line shape in ψ' decays.



C.L.=0.0014



C.L.<0.0001

$\eta_c(2S)$

Crystal Ball's "first observation" of $\psi' \to \gamma X$ never been confirmed
PRL 48 70 (1982)

Observed in different production mechanisms,

1. $B \to K \eta_c(2S)$
2. $\gamma\gamma \to \eta_c(2S) \to KK\pi$
3. double charmonium production

Belle: PRL 89 102001 (2002)
CLEOc: PRL 92 142001 (2004)
Belle: NPPS.184 220 (2008); PRL 98 082001(2007)
BaBar: PRL 92 142002 (2004); PR D72 031101(2005)
BaBar: PR D84 012004 (2011)

M1 transition $\psi' \to \gamma \eta_c(2S)$

CLEO found no signals in 25M ψ'.

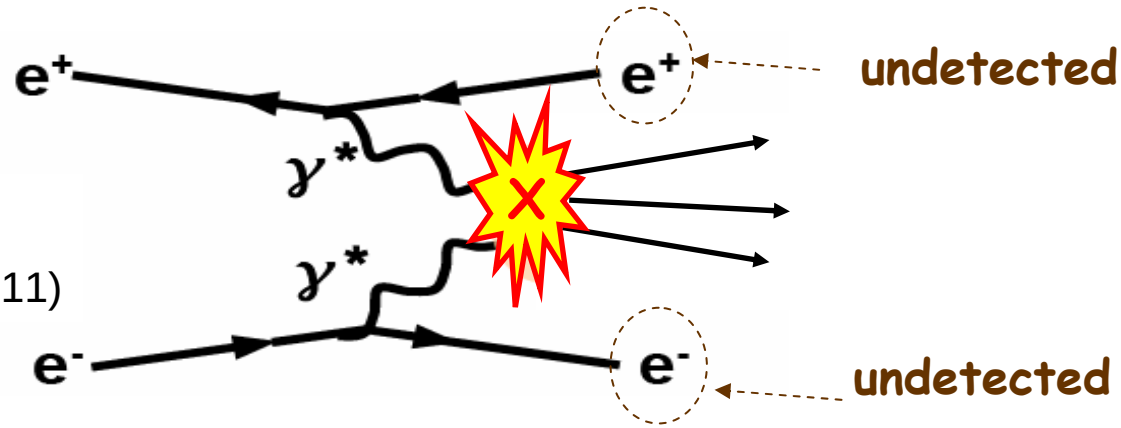
$BF(\psi' \to \gamma \eta_c(2S)) < 7.6 \times 10^{-4}$ CLEO: PRD 81 052002 (2010)

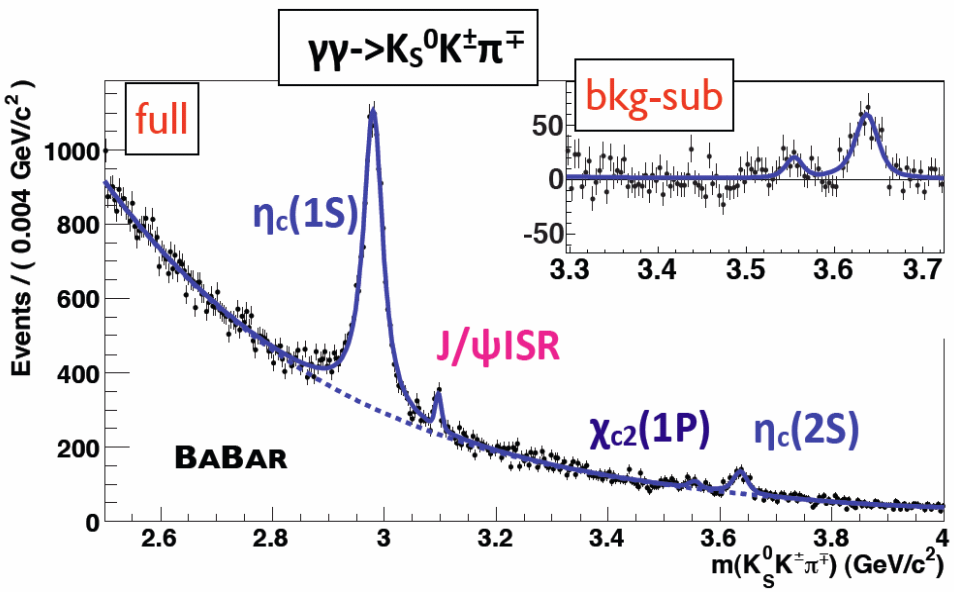
Experimental challenge : search for photons of 50 MeV

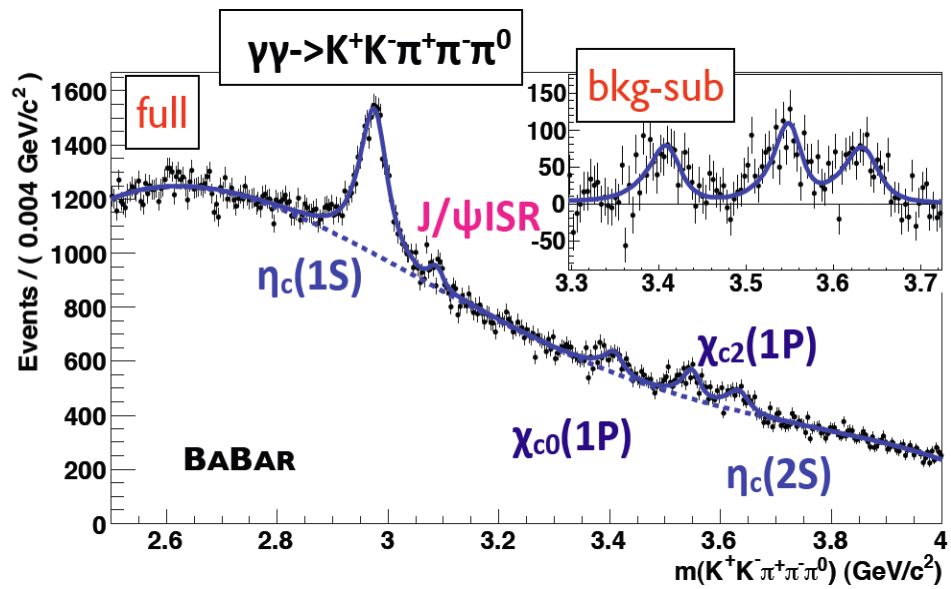
$\gamma\gamma \rightarrow \eta_c(1S/2S) \rightarrow K_S K\pi$; $KK3\pi$

519 fb^{-1}

PR D84 012004 (2011)







- $M(\eta_c(1S)) = 2982.5 \pm 0.4_{(stat)} \pm 1.4_{(syst)}$ MeV/c^2
- $\Gamma(\eta_c(1S)) = 32.1 \pm 1.1_{(stat)} \pm 1.3_{(syst)}$ MeV

precise mass and width measurements: *from* $\eta_c \to K_s K \pi$

- $M(\eta_c(2S)) = 3638.5 \pm 1.5_{(stat)} \pm 0.8_{(syst)}$ MeV/c^2
- $\Gamma(\eta_c(2S)) = 13.4 \pm 4.6_{(stat)} \pm 3.2_{(syst)}$ MeV

PR D84 012004 (2011)

BABAR

Branching Fractions

ULs are 90% CL Bayesian with uniform priors)

Process	$\Gamma_{\gamma\gamma} \times \mathcal{B}$ (keV)
$\eta_c(1S) \to K\overline{K}\pi$	$0.386 \pm 0.008 \pm 0.021$
$\chi_{c2}(1P) \to K\overline{K}\pi$	$(1.8 \pm 0.5 \pm 0.2) \times 10^{-3}$
$\eta_c(2S) \to K\overline{K}\pi$	$0.041 \pm 0.004 \pm 0.006$
$\chi_{c2}(2P) \to K\overline{K}\pi$	$< 2.1 \times 10^{-3}$
$\eta_c(1S) \to K^+K^-\pi^+\pi^-\pi^0$	$0.190 \pm 0.006 \pm 0.028$
$\chi_{c0}(1P) \to K^+K^-\pi^+\pi^-\pi^0$	$0.026 \pm 0.004 \pm 0.004$
$\chi_{c2}(1P) \to K^+K^-\pi^+\pi^-\pi^0$	$(6.5 \pm 0.9 \pm 1.5) \times 10^{-3}$
$\eta_c(2S) \to K^+K^-\pi^+\pi^-\pi^0$	$0.030 \pm 0.006 \pm 0.005$
$\chi_{c2}(2P) \to K^+K^-\pi^+\pi^-\pi^0$	$< 3.4 \times 10^{-3}$

First observations

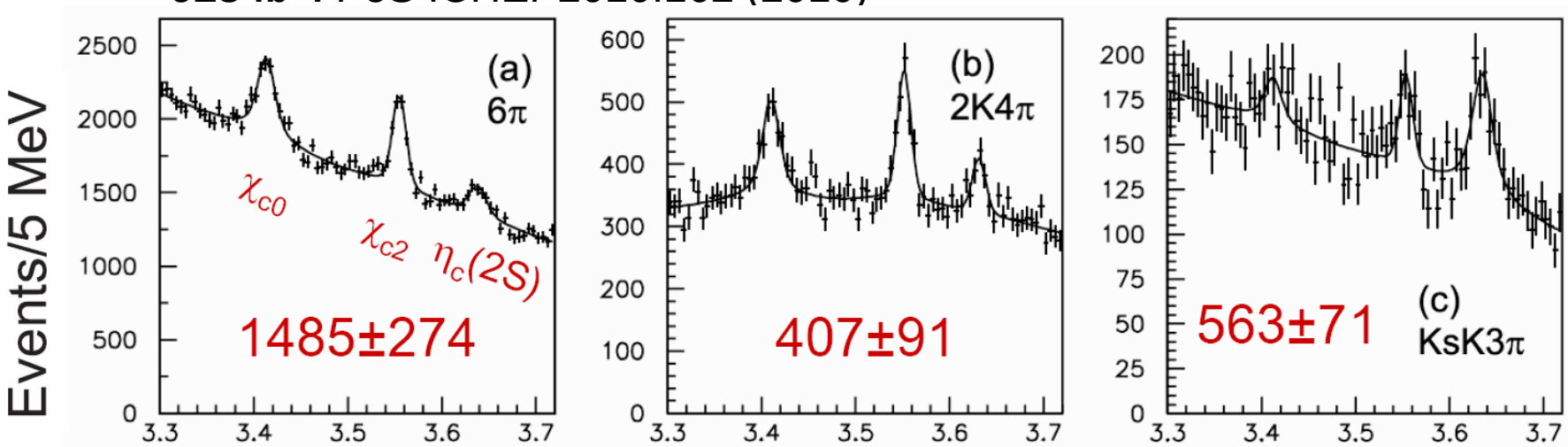
First evidence

18.1σ, 5.4σ, 4.0σ, 5.3σ

In particular, first $\eta_c(2S)$ exclusive hadronic decay other than to $K\overline{K}\pi$

$\gamma\gamma \rightarrow \eta_c(2S) \rightarrow$ 6 prongs

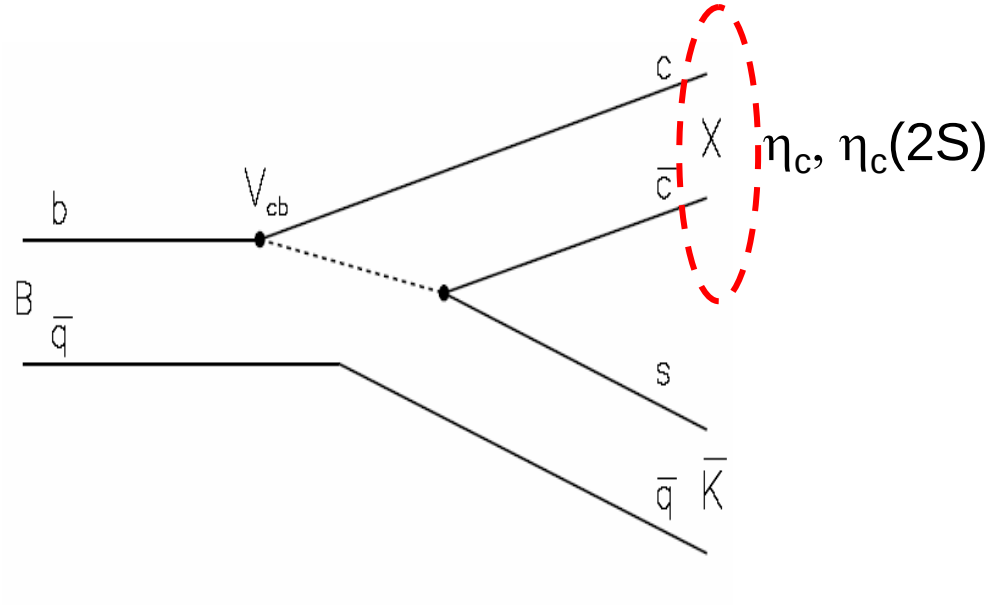
923 fb^{-1}: PoS ICHEP2010:162 (2010)



	Mass (MeV)	Γ (MeV)
6π	$3638.9\pm1.6\pm2.3$	10.7 ± 4.9
$2K4\pi$	$3634.7\pm1.6\pm2.8$	$1.4^{+6.3}_{-1.4}$, <13 (@90%)
$K_sK3\pi$	$3636.5\pm1.8\pm2.4$	15.9 ± 5.7
Ave.	$3636.9\pm1.1\pm2.5\pm5.0$	$9.9\pm3.2\pm2.6\pm2.0$

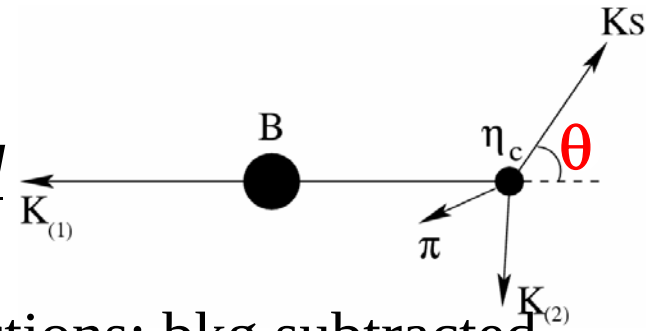
The third uncertainty from possible interference

$B \rightarrow \eta_c(1S, 2S)\ K$

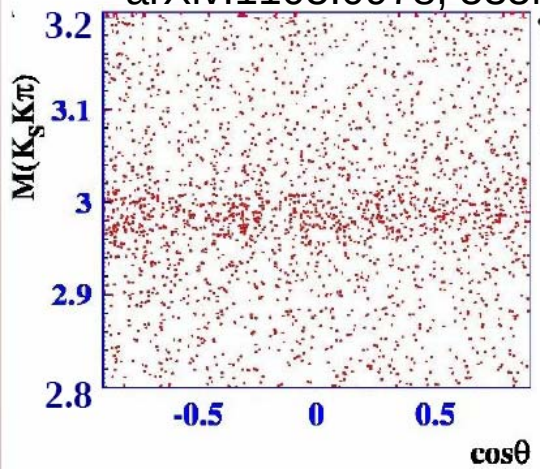


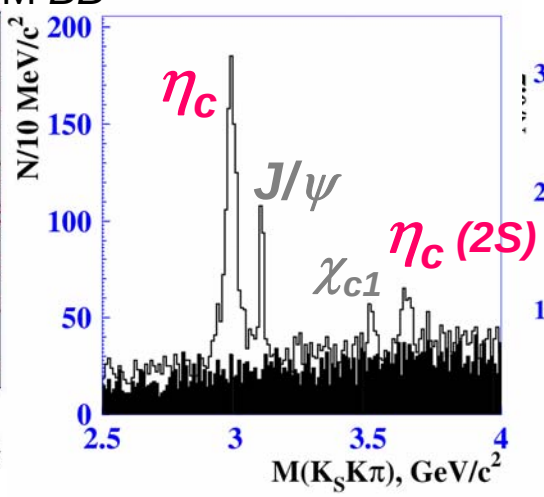
$B \to K\eta_c(1S,2S) \to K(K_s K\pi)$

- *Perform a $M(K_s K\pi)$ & $\cos\theta$ 2D fit*
- *Interference btw signal & NR considered*

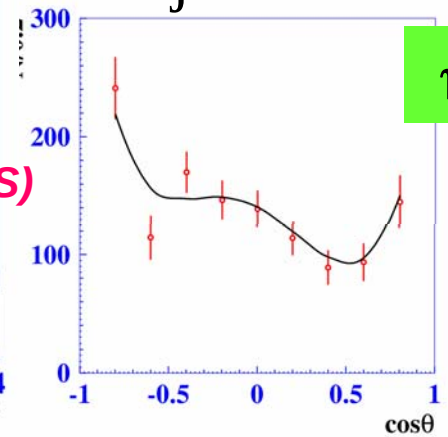


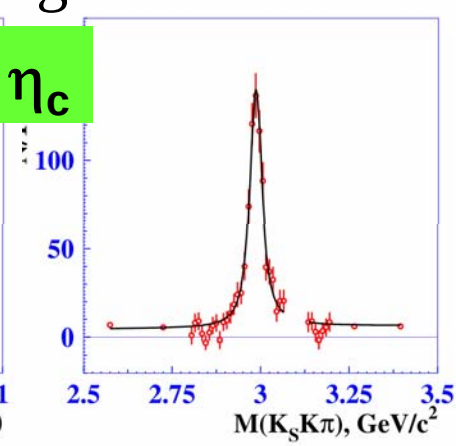
arXiv:1105.0978; 535M *BB*

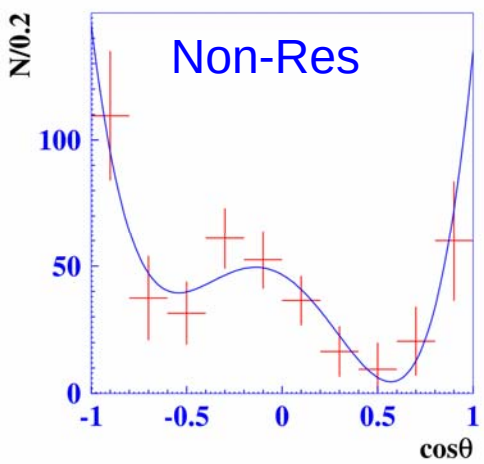


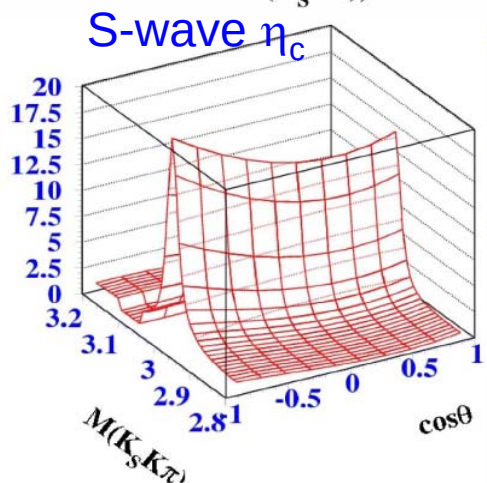


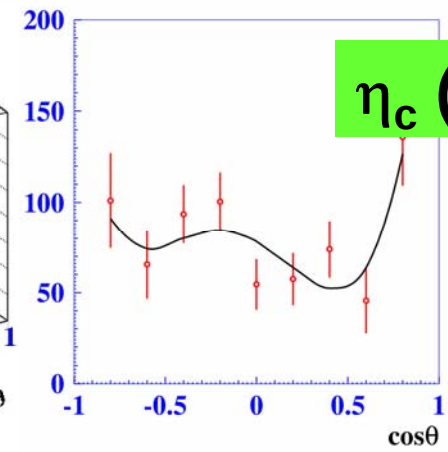
Projections: bkg subtracted

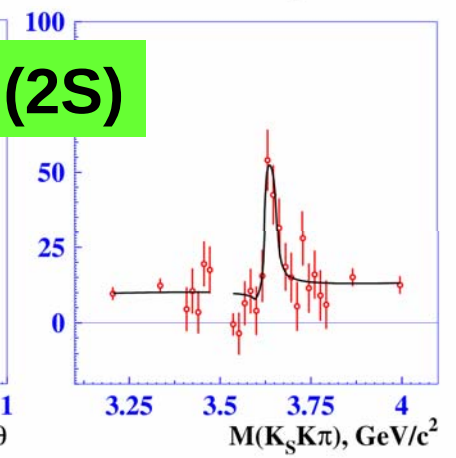












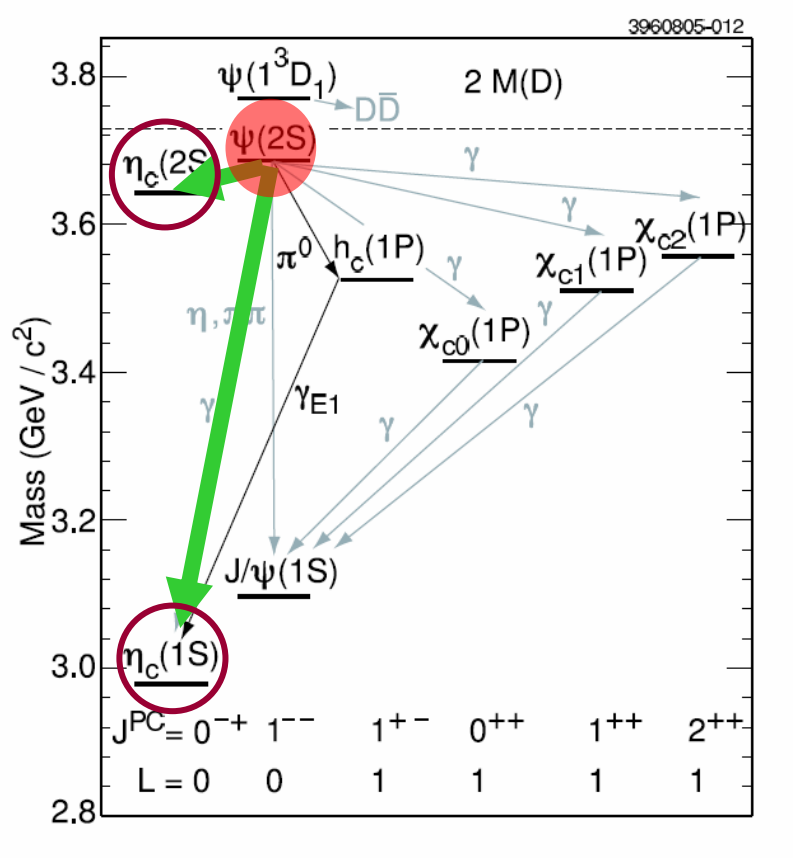
$B \to K\eta_c(1S,2S) \to K(K_s K\pi)$

arXiv:1105.0978

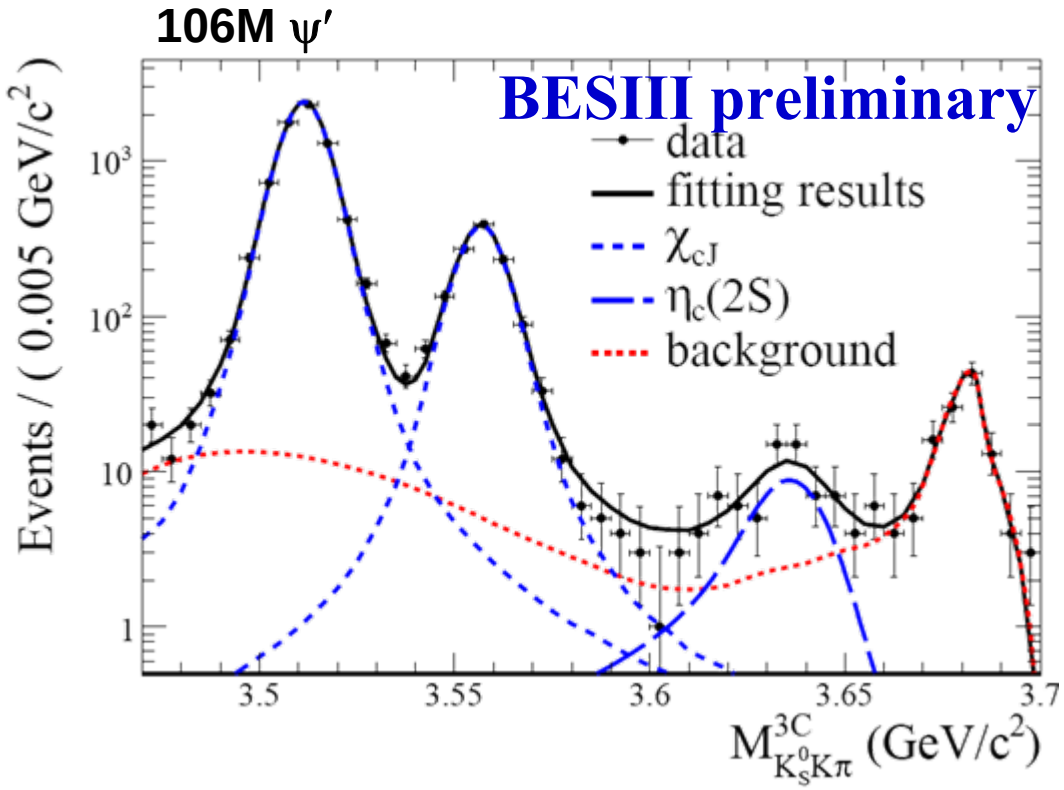
$B \to K\eta_c(1S)$; $\eta_c(1S) \to K(K_s K\pi)$	
η_c mass	$2985.4 \pm 1.5^{+0.2}_{-2.0}$
η_c width	$35.1 \pm 3.1^{+1.0}_{-1.6}$
$BF \times BF$ (10^{-6})	$26.7 \pm 1.4^{+2.9}_{-2.6} \pm 4.9$ (model)
$B \to K\eta_c(2S)$; $\eta_c(2S) \to K(K_s K\pi)$	
η_c (2S) mass	$3636.1^{+3.9}_{-4.2}{}^{+0.5}_{-2.0}$
η_c (2S) width	$6.6^{+8.4}_{-5.1}{}^{+2.6}_{-0.9}$
$BF \times BF$ (10^{-6})	$3.4^{+2.2}_{-1.5}{}^{+0.5}_{-0.4}$

- Take interference into account. No assumptions on the phase or absolute value of the interference
- Consistent with most accurate measurements.

$\psi' \rightarrow \gamma \eta_c(2S)$



Observation of $\psi' \to \gamma\eta_c(2S) \to \gamma(K_S K\pi)$



Width fixed to 12 MeV (world ave.)

Events: **50.6±9.7**; Significance >6.0σ!

Mass = **3638.5±2.3±1.0** MeV/c²

$BF(\psi' \to \gamma\eta_c(2S) \to \gamma K_S K\pi)$

$=(2.98 \pm 0.57 \pm 0.48) \times 10^{-6}$

$BF(\eta_c(2S) \to K\bar{K}\pi) = (1.9 \pm 0.4 \pm 1.1)\%$

BaBar: PR D78 012006 (2008)

$BF(\psi' \to \gamma\eta_c(2S))$

$= (4.7 \pm 0.9 \pm 3.0) \times 10^{-4}$

CLEOc: **$<7.6\times10^{-4}$**

PR D81 052002 (2010)

Potential model predicts

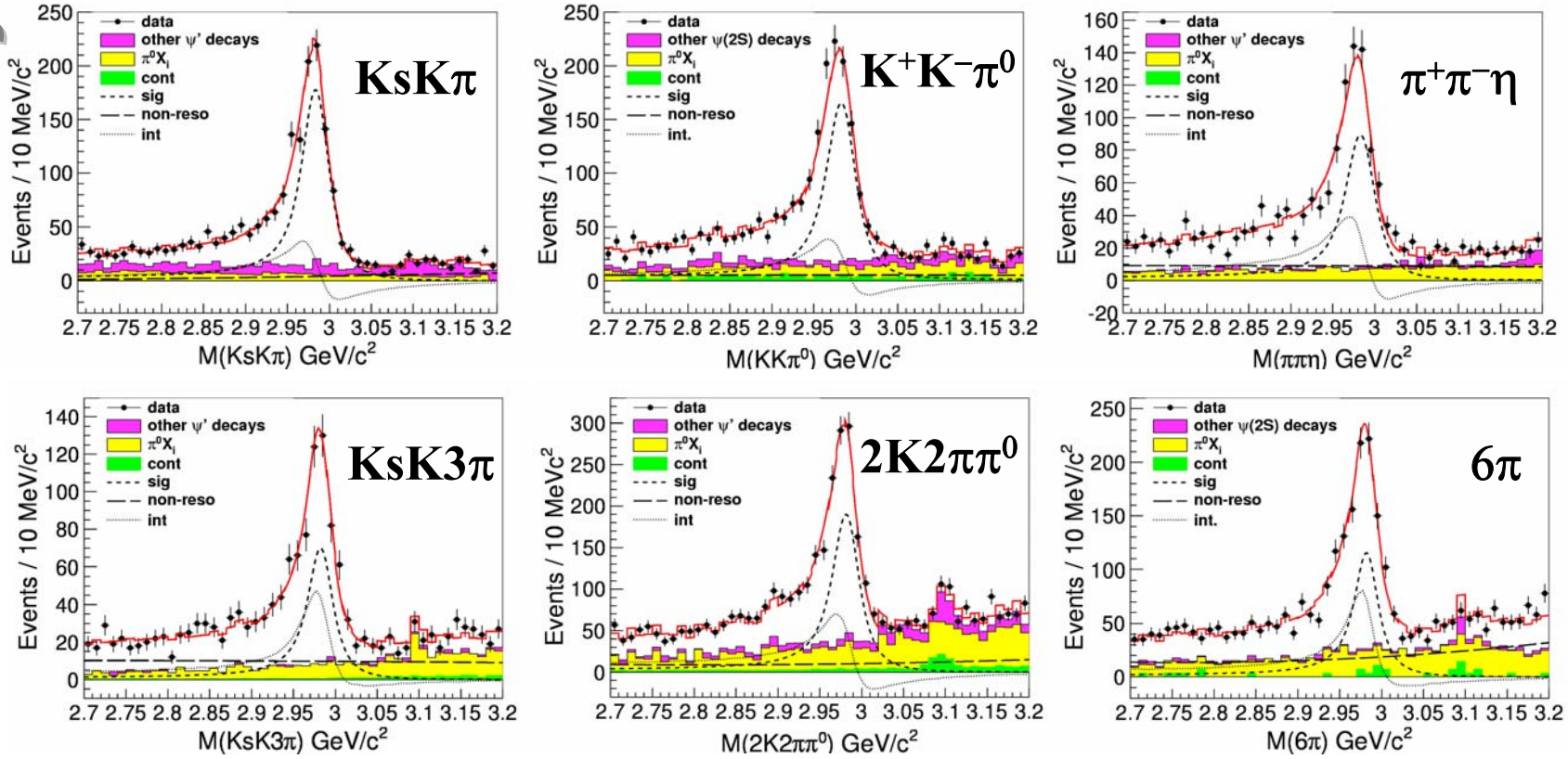
$(0.1 \sim 6.2)\times10^{-4}$

PRL 89 162002 (2002)

$\psi' \rightarrow \gamma\eta_c$, η_c exclusive decays

Possible interference has been take into account

BESIII Preliminary



Relative phase ϕ values from each mode are consistent within 3σ,

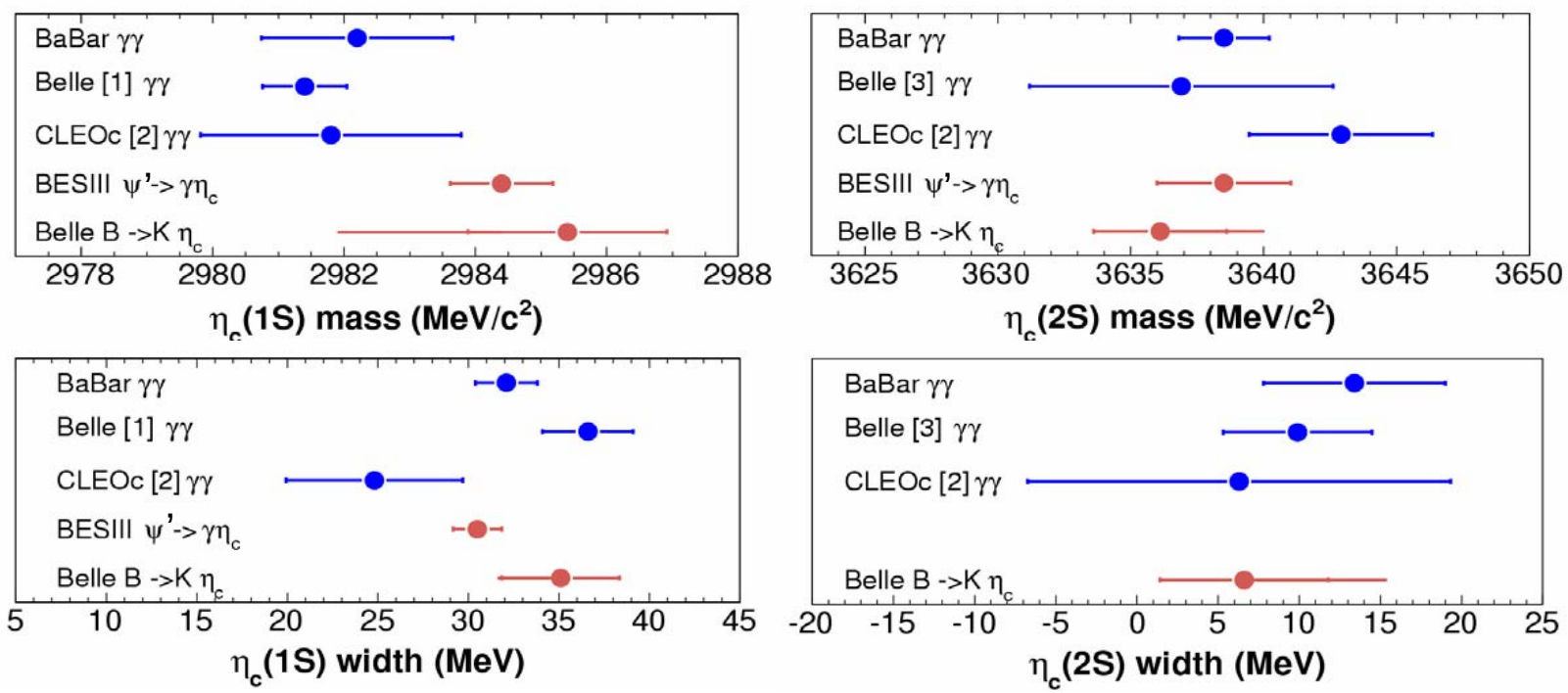
➔ use a common phase value in the simultaneous fit.

M: **2984.4±0.5±0.6** MeV/c^2

width: **30.5±1.0±0.9** MeV

ϕ: **2.35±0.05±0.04** rad

Summary for $\eta_c/\eta_c(2S)$



[1] NPPS 184 220(2008); [2] PRL 92 142001; [3] PoS ICHEP2010:162, 2010

Hyperfine splitting: $\Delta M(1S)$ = **112.5 ± 0.8** MeV;

$\Delta M(2S)$ = **47.6 ± 1.7** MeV

$$\Delta M_{hf}(nS) = M(n^3S_1) - M(n^1S_0) = \frac{32\pi\alpha_s(m_q)}{9}(\psi(0)/m_q)^2 \ , \ L=0 \rightarrow$$

$\Delta M(1S) \approx 118$ MeV
$\Delta M(2S) \approx 68$ MeV

$$\Delta M_{hf}(nL) = M(n^3L) - M(n^1L) = 0, \qquad L \neq 0 \rightarrow$$

$\Delta M(1P) = 0$ MeV

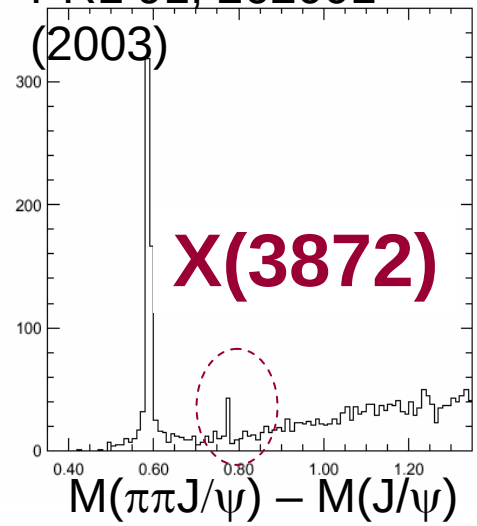
K. Seth hadron11

Charmonium-like state

X(3872)

Overview the X(3872)

PRL 91, 262001 (2003)



- First observed in $B \rightarrow K(J/\psi\pi^+\pi^-)$ by Belle in 2003
  - *mass is very close to the $D^{*0}\bar{D}^0$ threshold*
  - *width is less than exp. resolution*

Confirmed by Babar, CDF and D0

- Quantum number

  M(ππ) likes look a ρ ; X(3872) $\rightarrow \gamma\, J/\psi$ ➔ C =+1

  ππJ/ψ angular analysis by CDF ➔ 1^{++} or 2^{-+}

Belle: hep-ex/0505038
CDF: PRL 96 102002
Belle: arXiv 1105.0177
BaBar: PRL 102 132001
CDF: PRL 98 132002

Interpretations:

- charmonium state:

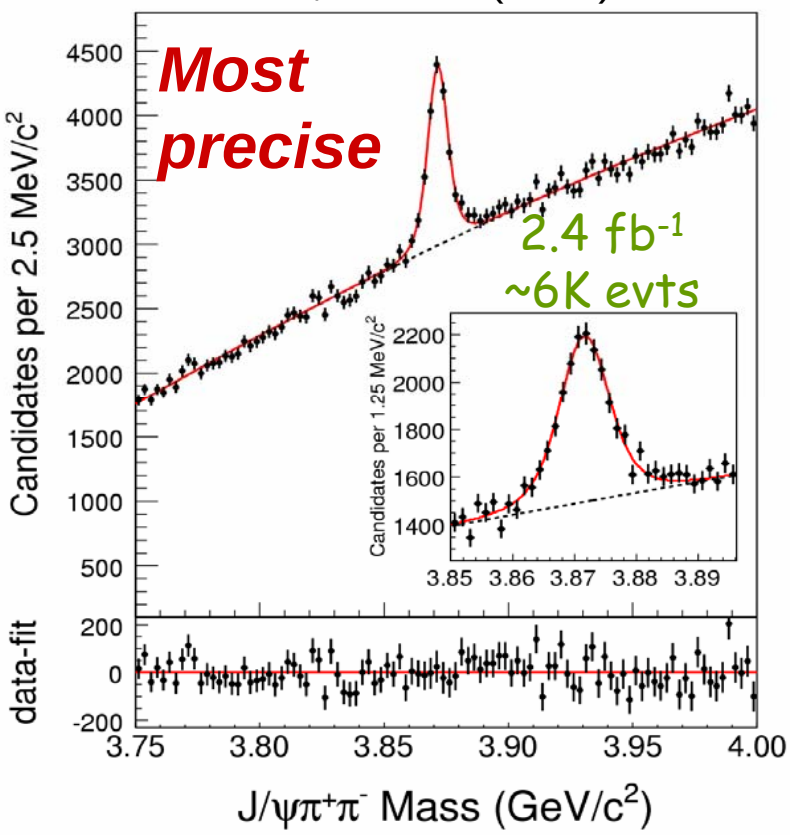
  1^{++} $\chi_{c1}(2P)$: *large BF($\chi_{c1}(2P) \rightarrow J/\psi\, \gamma$) expected*

  2^{-+} $\eta_{c2}(^1D_2)$: *large width expected*

- DD* molecule: *hard to explain the large radiative decay rate, $\pi\pi J/\psi$ rate and the production in $p\bar{p}$*
- diquark-diantiquarks: *no partner or charged partner was found*
- cc-gluon hybrids: *mass too low*

The mass of *X(3872)*

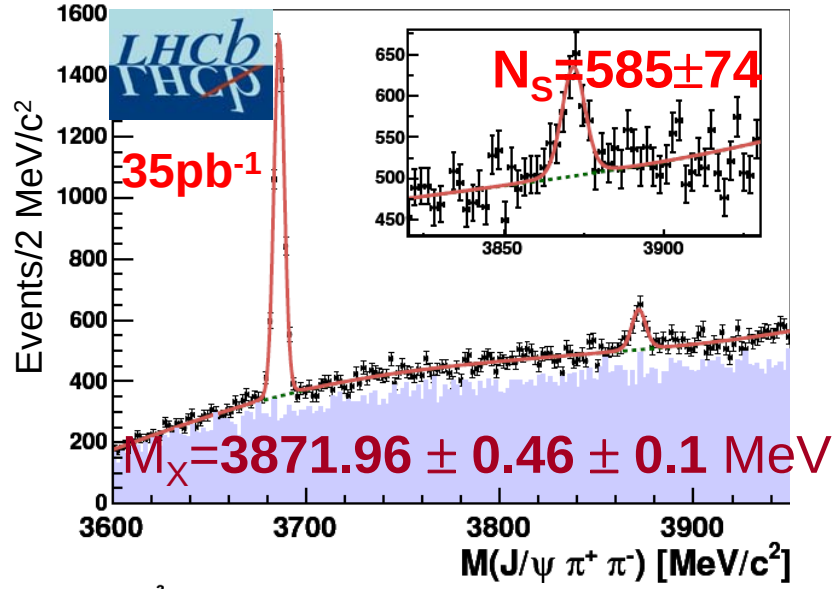
PRL103, 152001 (2009)

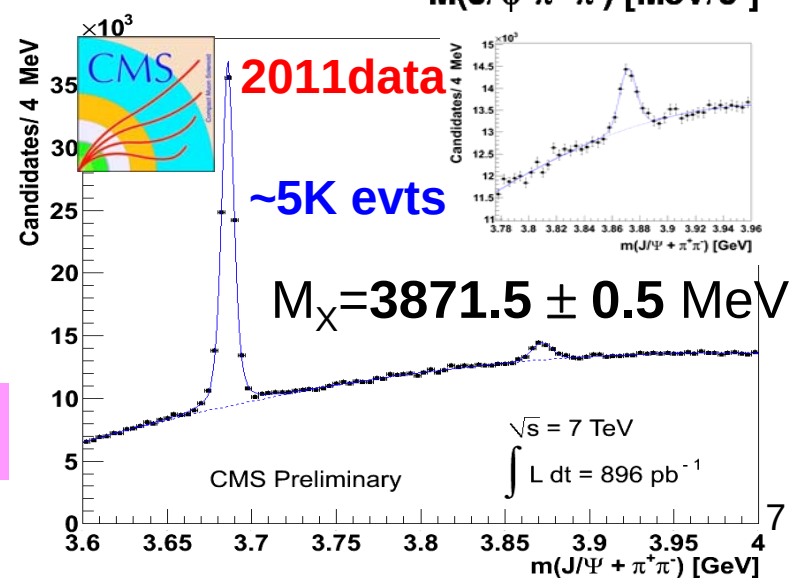


Width was fixed at 1.34 MeV

M_X = 3871.61 ± 0.16 ± 0.19 MeV

Y. Zhang EPS2011

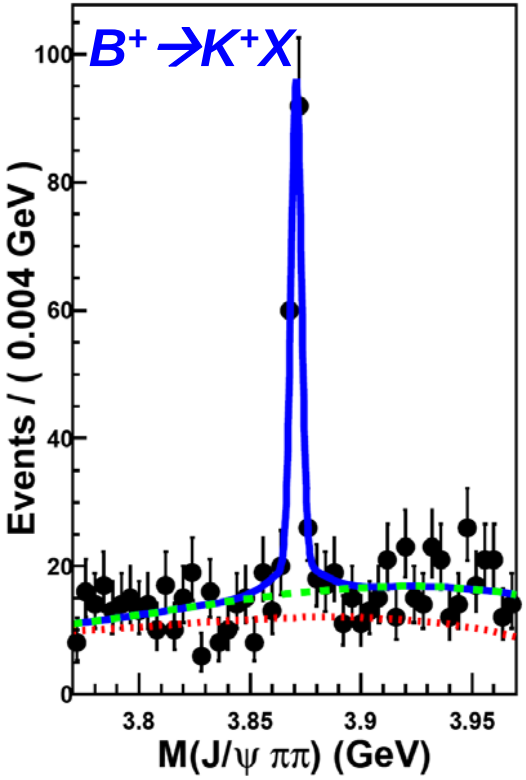


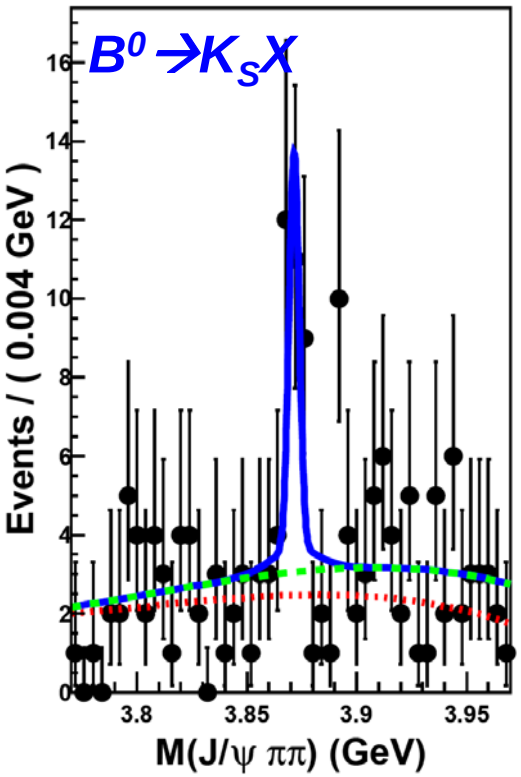


711 fb^{-1}

New $X(3872) \rightarrow \pi\pi J/\psi$

Diquark-antidiquark model predicts a mass difference ΔM_X





Belle arXiv:1107.0163

ΔM_X = -0.69 ±0.97± 0.19 MeV

Consistent with 0

BaBar: PRD 77 111101 (2008)

ΔM_X = **2.7 ± 1.6 ± 0.4** MeV

Mass= **3871.84 ±0.27 ±0.19** MeV

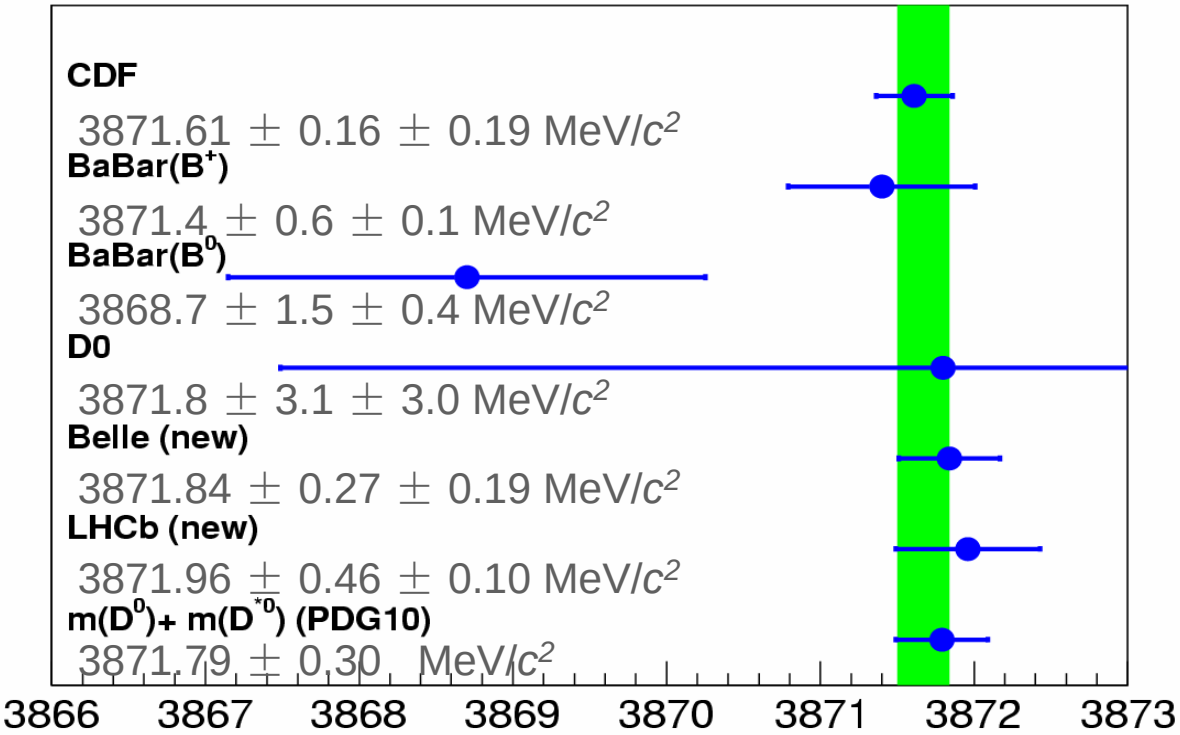
Width **< 1.2 MeV @ 90% C.L**

$BF(B^+ \rightarrow KX) \times BF(X \rightarrow J/\psi\pi^+\pi^-)$ = **(8.61± 0.82 ± 0.52)×10^{-6}**

$BF(B^0 \rightarrow K^0 X) / BF(B^+ \rightarrow K^+ X)$ = **0.50 ± 0.14 ± 0.04**

X(3872) mass in $\pi^+\pi^- J/\psi$ channel only

new average: **3871.67 ± 0.17 MeV/c^2**



Binding energy getting smaller

Old: Δm **= -0.32 ± 0.35** MeV/c^2

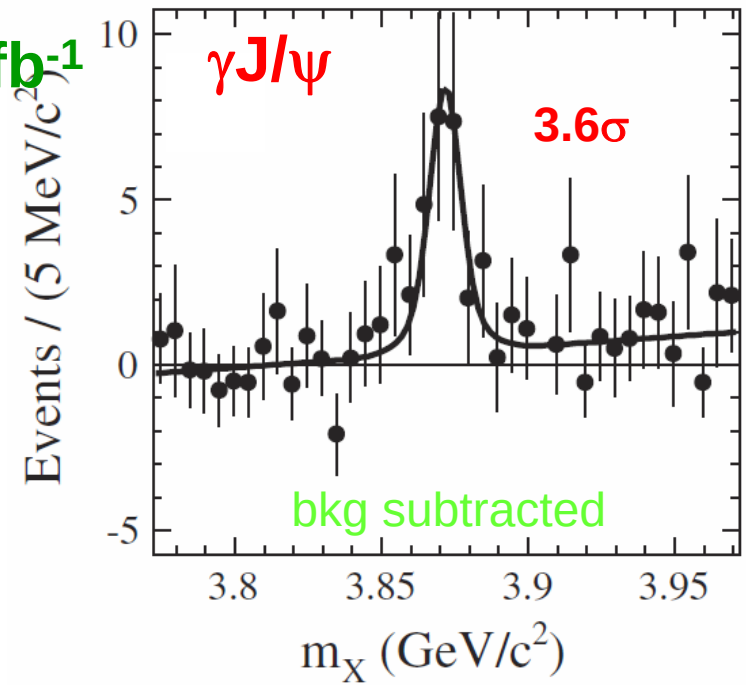
New: Δm **= -0.12 ± 0.35** MeV/c^2

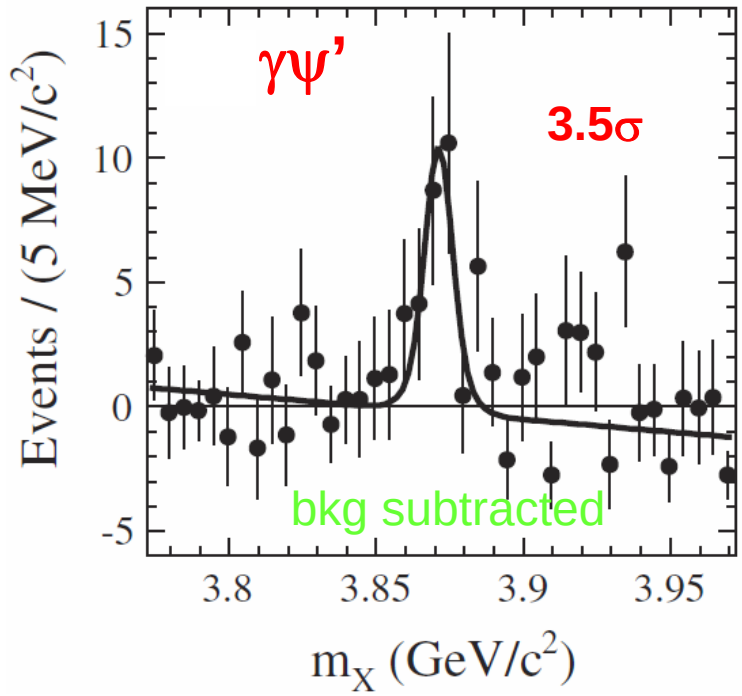
Δm**(deuteron) = -2.2** MeV/c^2

$X(3872) \rightarrow \gamma J/\psi(\psi')$

PRL 102 132001(2009)

424 fb^{-1}





$BF(B^+ \rightarrow K^+X) \times BF(X \rightarrow \gamma J/\psi) = (2.8 \pm 0.8) \times 10^{-6}$

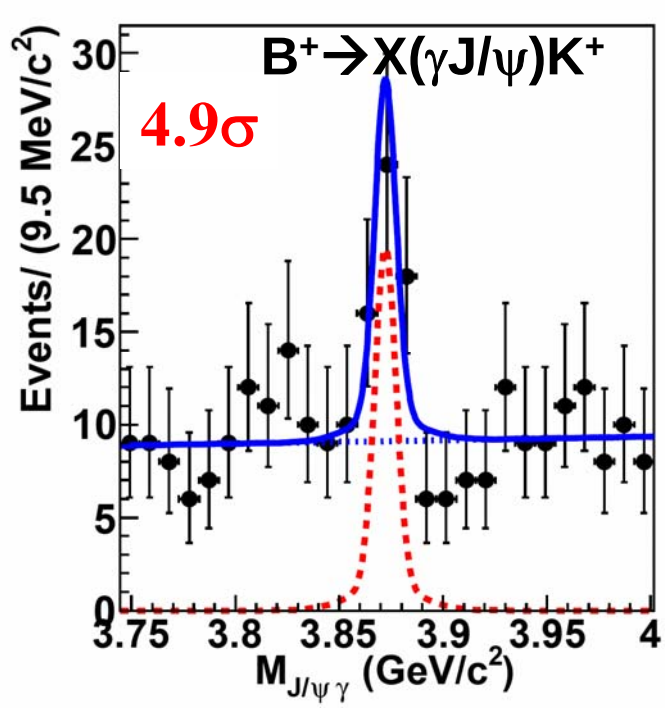
$BF(B^+ \rightarrow K^+X) \times BF(X \rightarrow \gamma\psi') = (9.5 \pm 2.8) \times 10^{-6}$

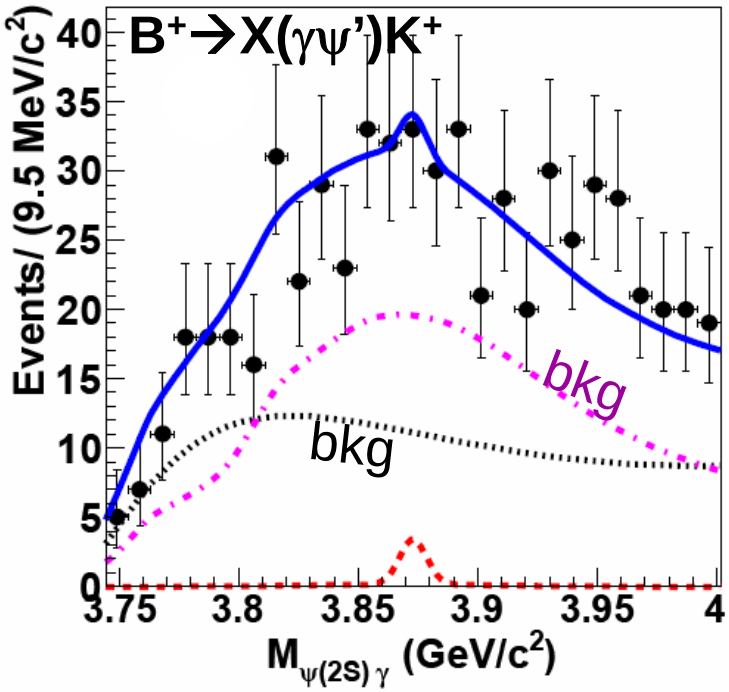
$$\frac{BF(X_{3872} \rightarrow \gamma\psi')}{BF(X_{3872} \rightarrow \gamma J/\psi)} = 3.4 \pm 1.4$$

- *C-parity = +1*
- $BF(X_{3872} \rightarrow \gamma\psi') > BF(X_{3872} \rightarrow \gamma J/\psi)$ ← *For molecular X, it should be very small !!*

$X(3872) \rightarrow \gamma J/\psi(\psi')$

arXiv 1105.0177 (2010)





$BFxBF=(1.78^{+0.48}_{-0.44} \pm 0.12)x10^{-6}$

Agreement

$BFxBF < 3.45\ x10^{-6}$

Disagreement

BaBar: $(9.5 \pm 2.8)\ x10^{-6}$

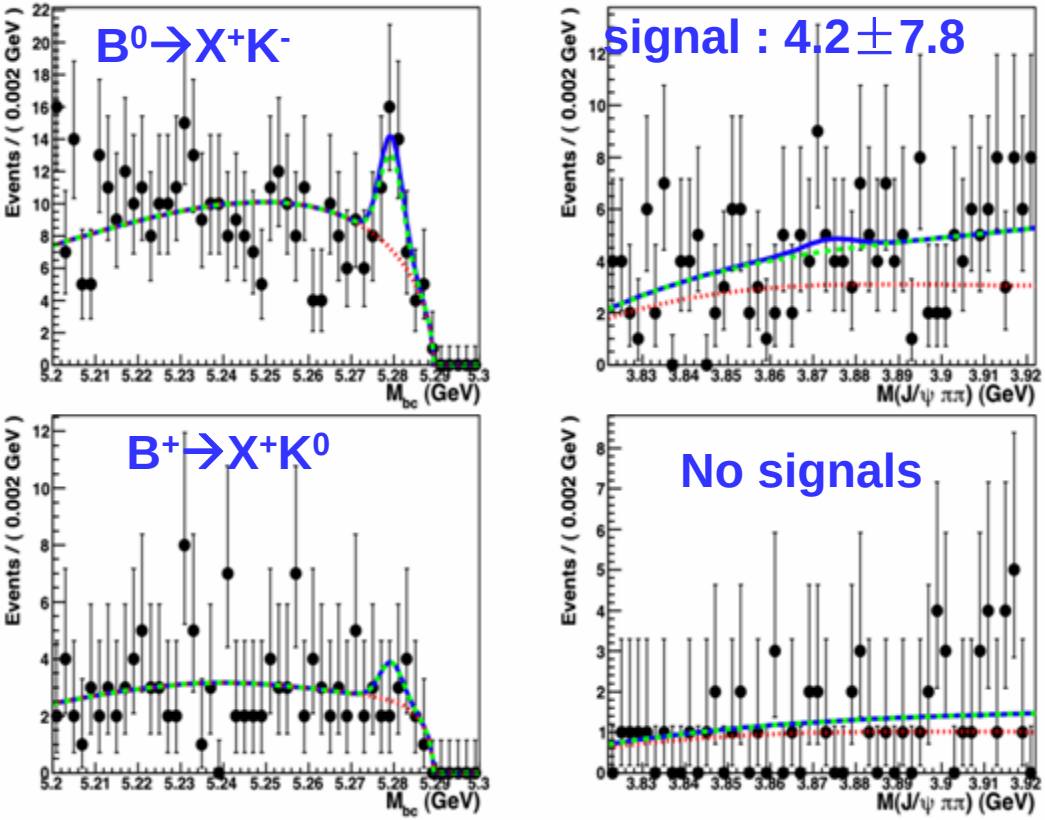
$$\frac{BF(X_{3872} \rightarrow \gamma\psi')}{BF(X_{3872} \rightarrow \gamma J/\psi)} < 2.1\ (90\%)$$

BaBar: 3.4 ± 1.4

Charged partner of the X(3872) ?

Diquark-antidiquark model predicts charged X^+

2D Fit



$BF(B^0 \to K^- X^+) \times BF(X^+ \to \rho^+ J/\psi)$
$< 4.2 \times 10^{-6}$

$BF(B^+ \to K^0 X^+) \times BF(X^+ \to \rho^+ J/\psi)$
$< 6.1 \times 10^{-6}$

No evidence of charge partner X^+ .
Rule out isospin triplet model

XBall fcn (for Mx), parameters are fixed at values returned from fit to MC

Belle arXiv:1107.0163

BaBar PR D71,031501

$BF(B^0 \to K^- X^+) \times BF(X^+ \to \rho^+ J/\psi) < 5.4 \times 10^{-6}$

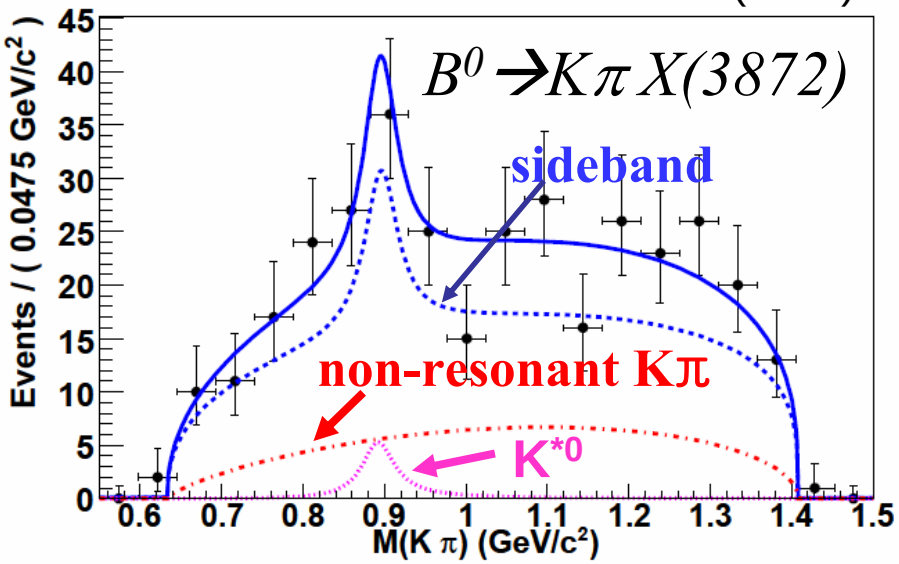
$BF(B^+ \to K^0 X^+) \times BF(X^+ \to \rho^+ J/\psi) < 22 \times 10^{-6}$

$B^0 \to K\pi X(3872)$ is diff. to $B \to K\pi (c\bar{c})$

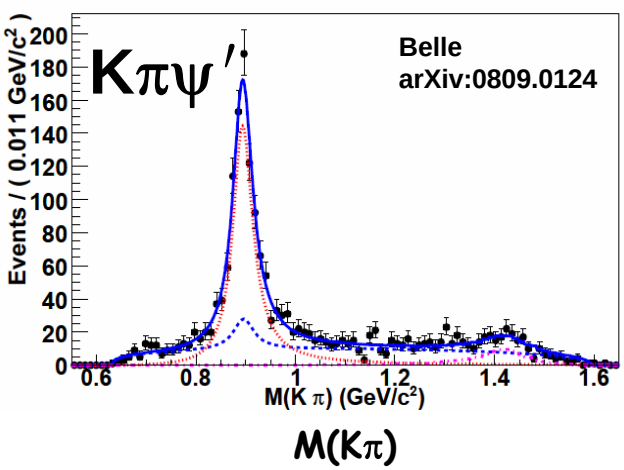
arXiv:0809.1224(2008)

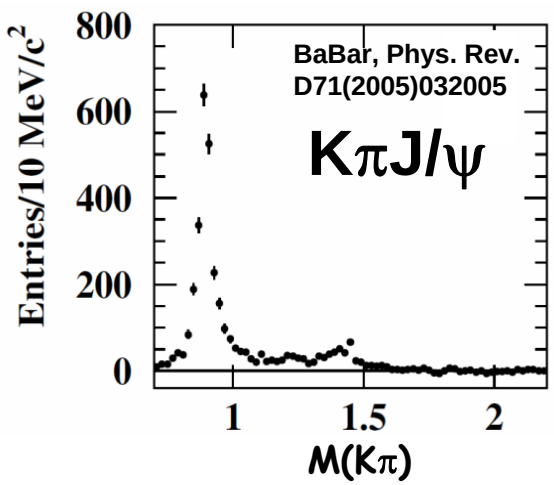
All K* comes from sideband

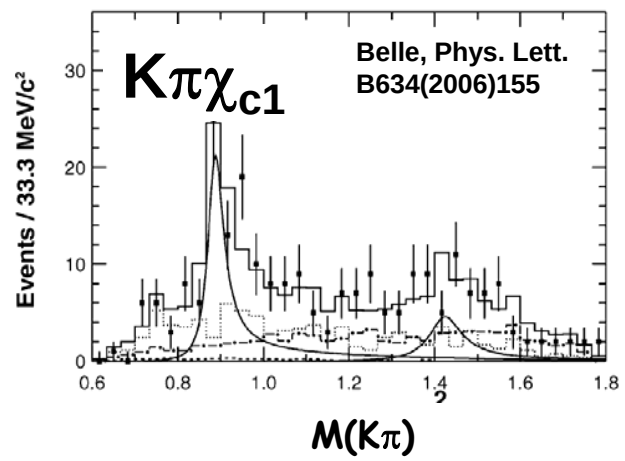
$BF(K^{*0}X(3872); X \to \pi\pi J/\psi) < 3.4\times10^{-6}$ @90% CL



$B \to K\pi + c\bar{c}$





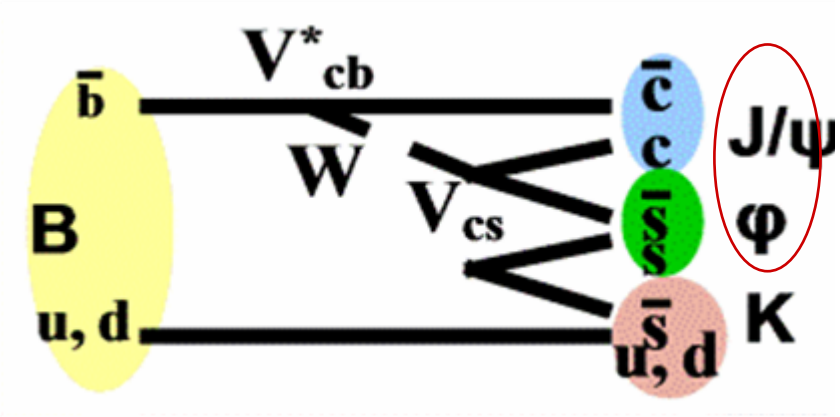


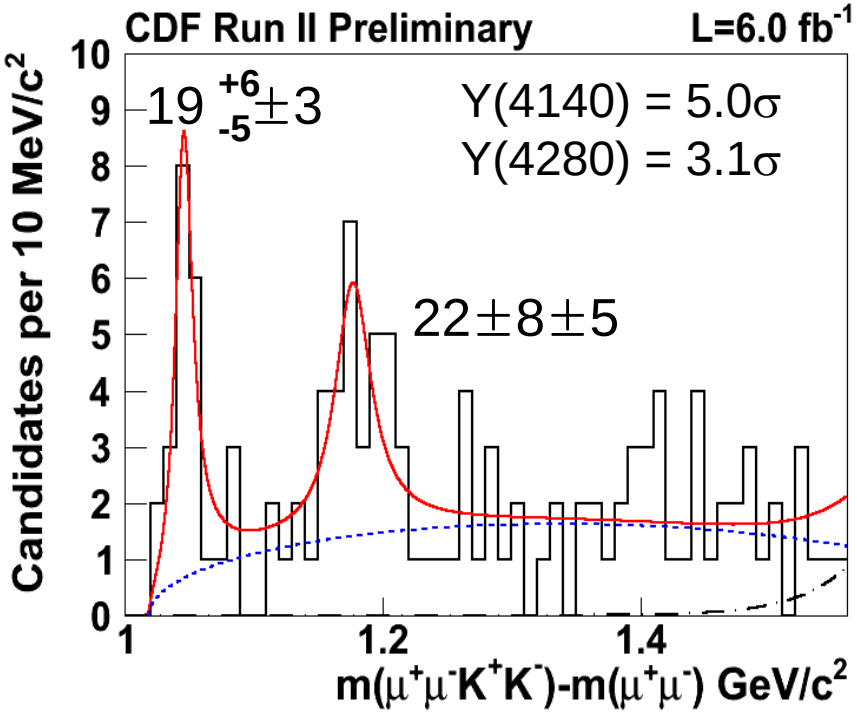
In all $B \to K\pi + c\bar{c}$ modes, K* dominates.

X(3872) summary

- Mass: very close to $D^{*0}\bar{D}^0$ threshold
- Width: very narrow, < 3 MeV
- $J^{PC}=1^{++}$ *or* 2^{-+} *?* Large sample *LHCb* will allow separation.
- No evidence for charged partner ➔ $I=0$
- Production
  - in $p\bar{p}$ collision – similar to charmonia
  - In B decays – KX similar to $c\bar{c}$, K^*X smaller than $c\bar{c}$
- Decay: open charm ~ *50%,* charmonium ~O*(%)*
- Nature (very likely exotic)
  - Loosely $D^{*0}\bar{D}^0$ bound state (like deuteron?)?
  - Mixture of excited χ_{c1} and $D^{*0}\bar{D}^0$ bound state?
  - Other possibilities

The Y(4140)→φJ/ψ





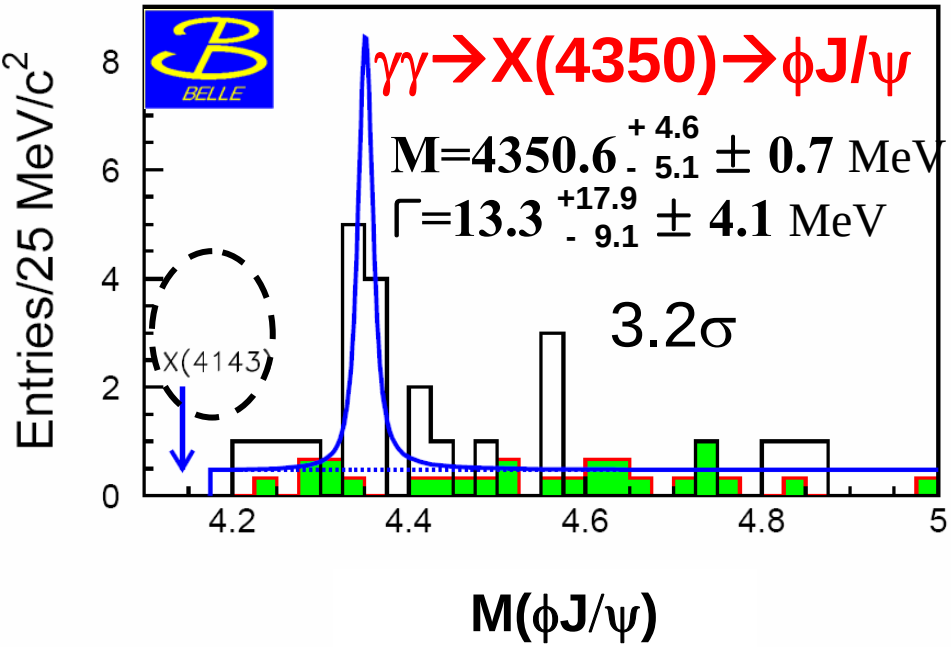
The two enhancements remain unconfirmed.

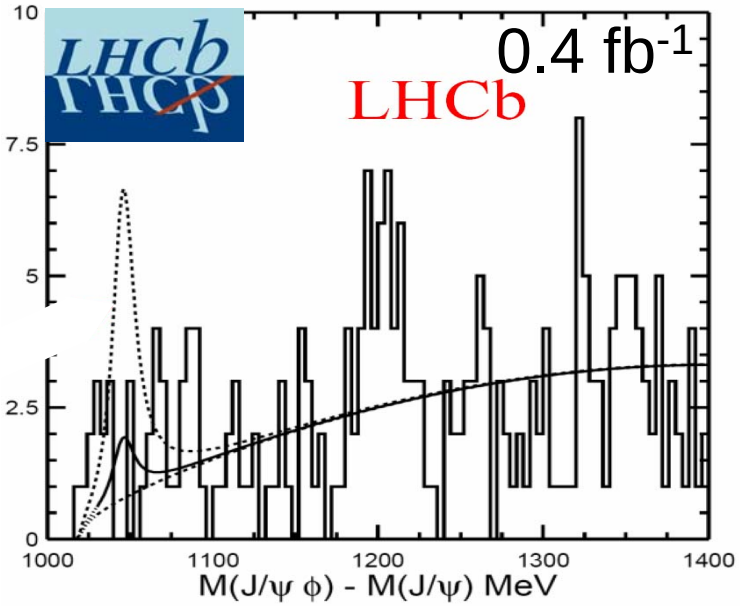
CDF arXiv: 1101.6058 (2011)

Y(4140)→ϕ J/ψ @ LHCb

825 fb^{-1}

Belle: PRL104 112004(2010)





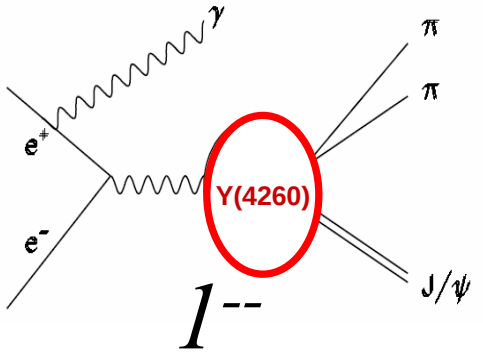
No evidence for Y(4140)

Low eff. near J/ψϕ threshold

Evidence for a new X(4350)

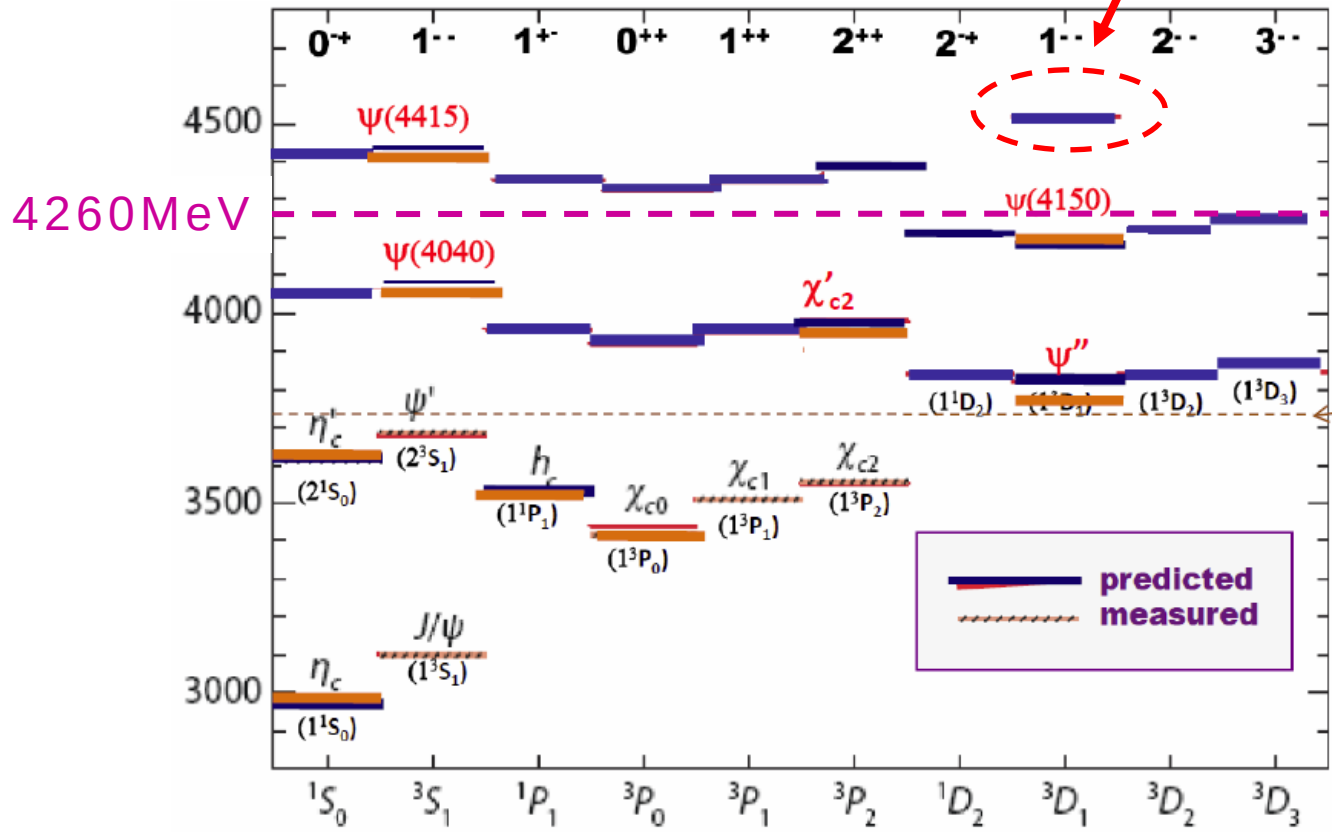
LHCb does not confirm Y(4140).

The 1^{--} states

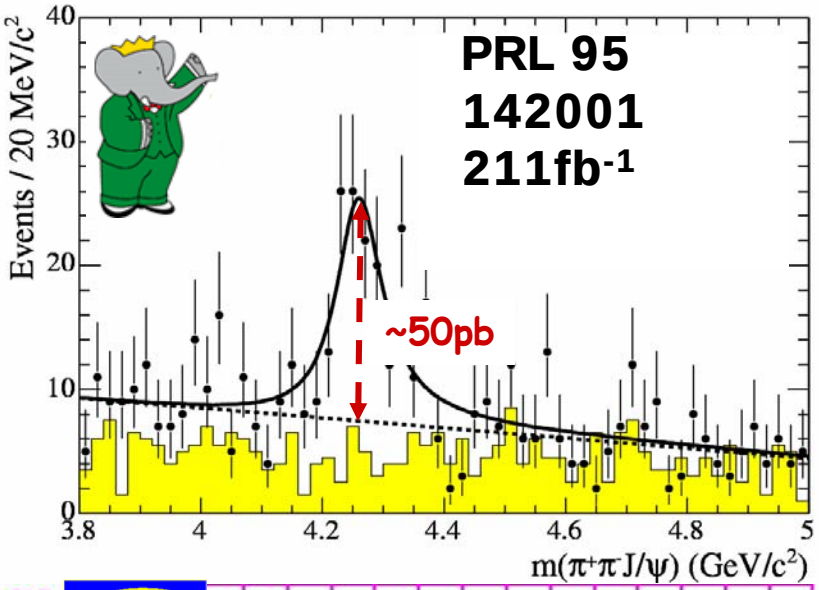


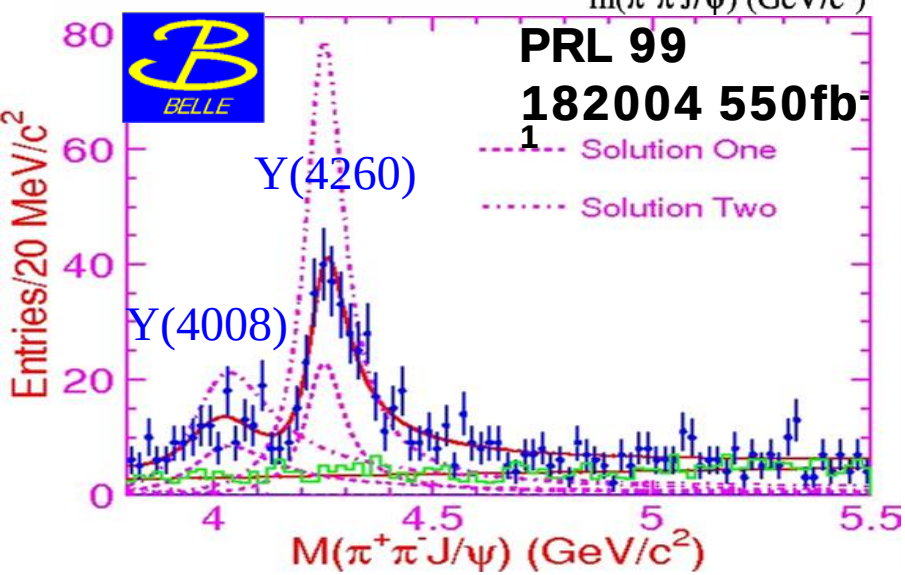
$e^+e^- \rightarrow \gamma_{ISR} Y$

only unfilled 1^{--} state left

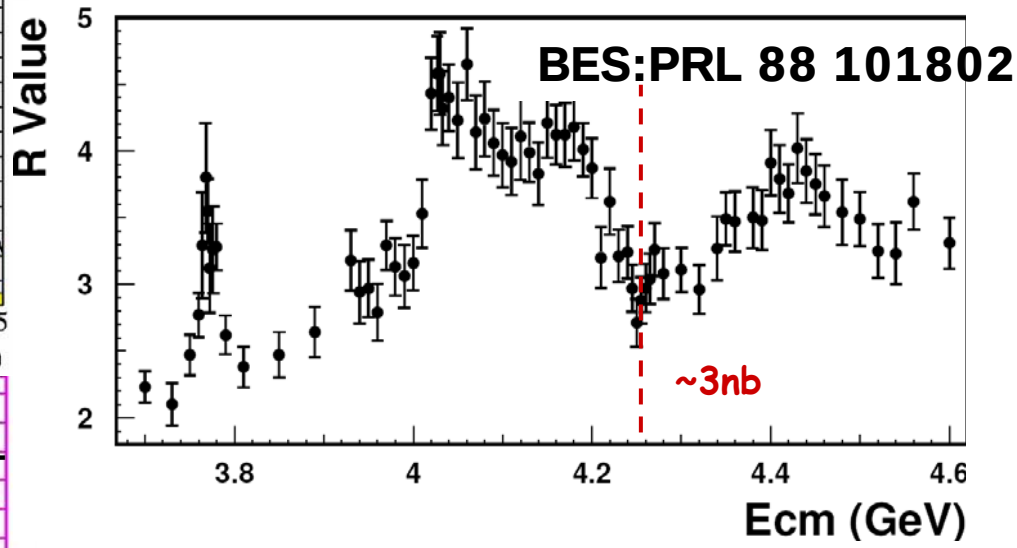


$Y(4260) \rightarrow \pi^+\pi^- J/\psi$





	Babar	Belle
M:	$4259 \pm 8\ ^{+2}_{-6}$ MeV	$4247 \pm 12\ ^{+17}_{-32}$ MeV
Γ :	$88 \pm 23\ ^{+6}_{-9}$ MeV	$108 \pm 19 \pm 10$ MeV



No sign of $Y(4260) \rightarrow D^{(*)}D^{(*)}$

PL B640, 182 (2006)

$\Gamma(Y_{4260} \rightarrow \pi^+\pi^- J/\psi) > 0.508$ **MeV** @ 90%

Much larger than measured $c\bar{c}$ widths

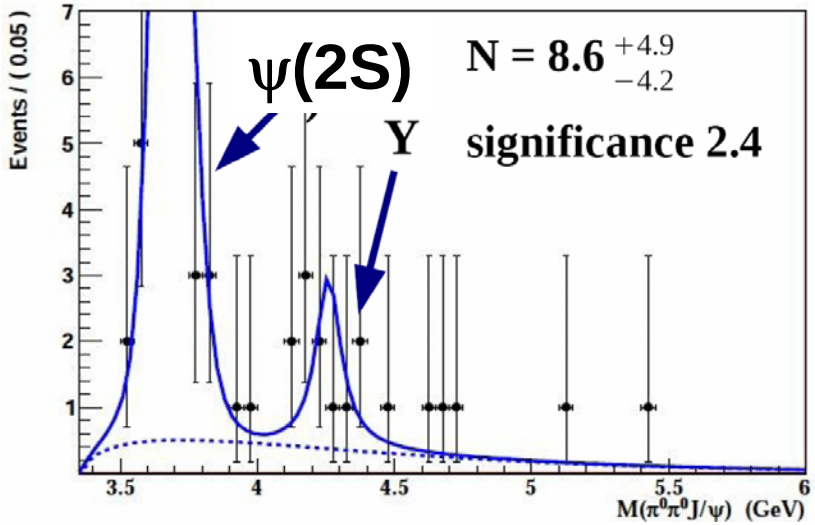
e.g.

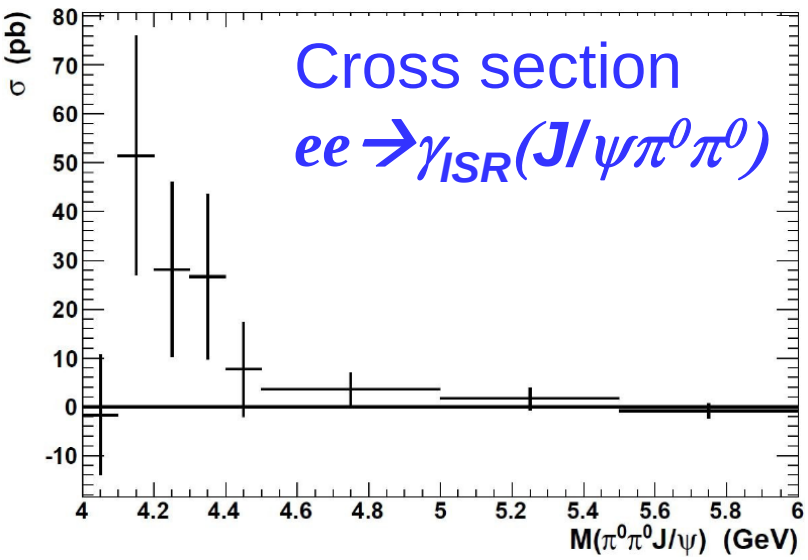
$\Gamma(\psi' \rightarrow \pi^+\pi^- J/\psi) = 0.104 \pm 0.004$ MeV

$\Gamma(\psi'' \rightarrow \pi^+\pi^- J/\psi) = 0.044 \pm 0.008$ MeV

$Y(4260) \rightarrow \pi^0\pi^0 J/\psi$

790fb^{-1}





A. Vinokurova EPS 2011,

Γ_{ee} BF($J/\psi\pi^0\pi^0$) =3.19 $^{+1.82+0.64}_{-1.53-0.35}$ eV

PDG: Γ_{ee} BF($J/\psi\pi^+\pi^-$) =(5.9 $^{+1.2}_{-0.9}$) eV

It implies that the Y(4260) has I=0, as expected for a $c\bar{c}$ state.

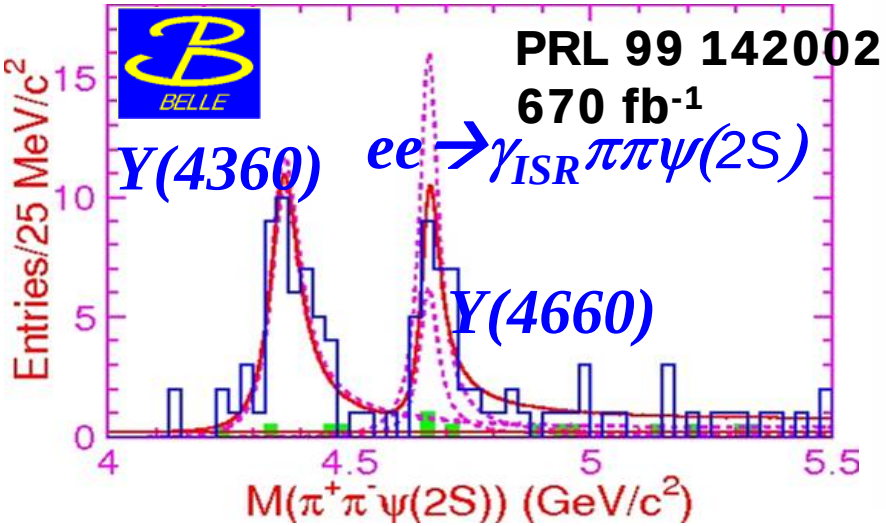
CLEO: PRL 96 162003 (2006)

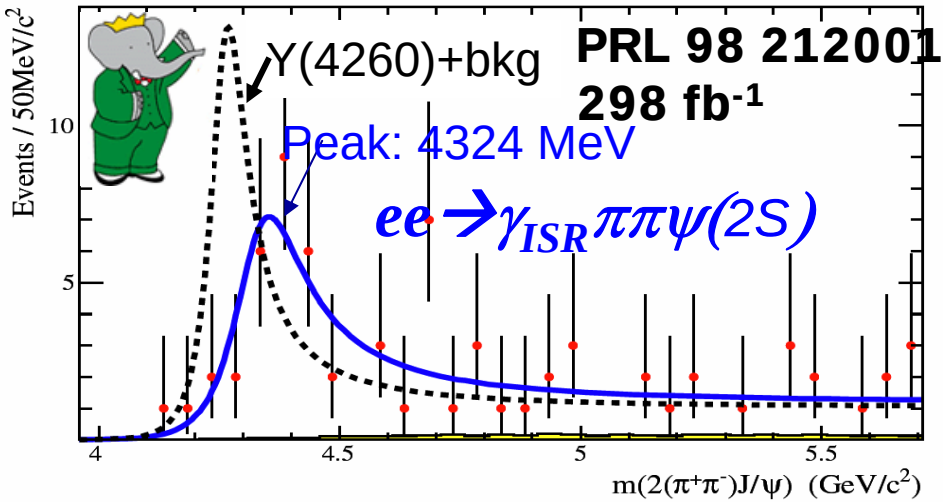
From e^+e^- collision

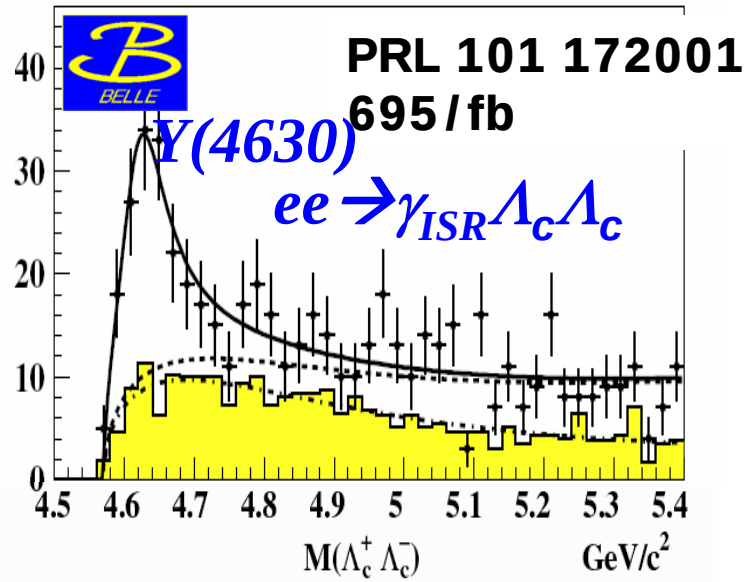
***BF*(J/$\psi\pi^0\pi^0$)/ *BF*(J/$\psi\pi^+\pi^+$) ~ 0.5**

1^{--}

More Y states





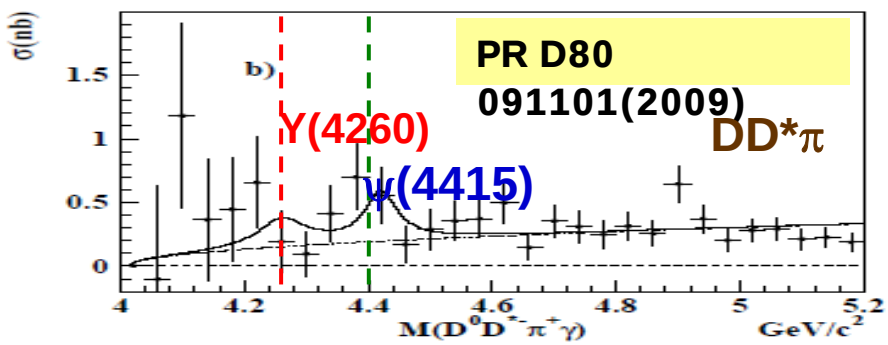


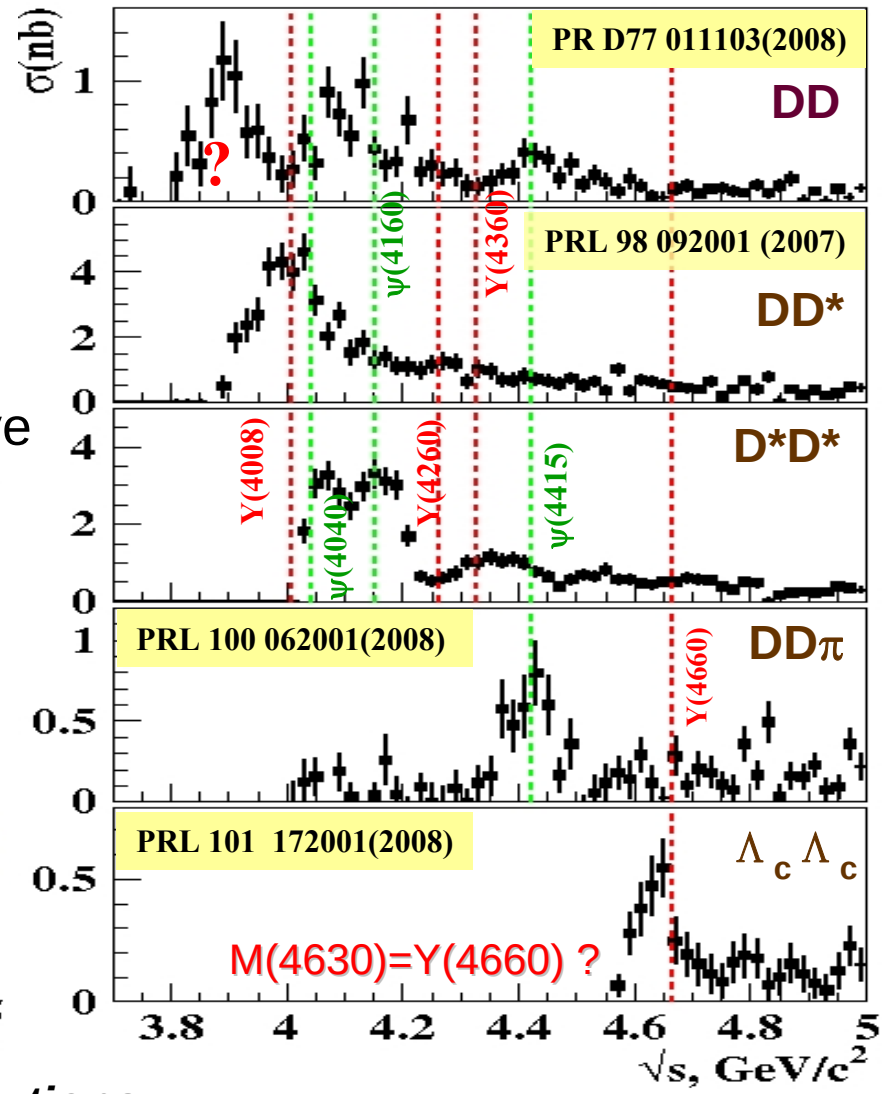
Y(4008) Y(4260) Y(4360) Y(4660) Y(4630) peaks are seen

Only one state left for 1^{--} ; no room in the spectrum for all.

Large $\pi^+\pi^-J/\psi$ ($\pi^+\pi^-\psi'$) partial width.

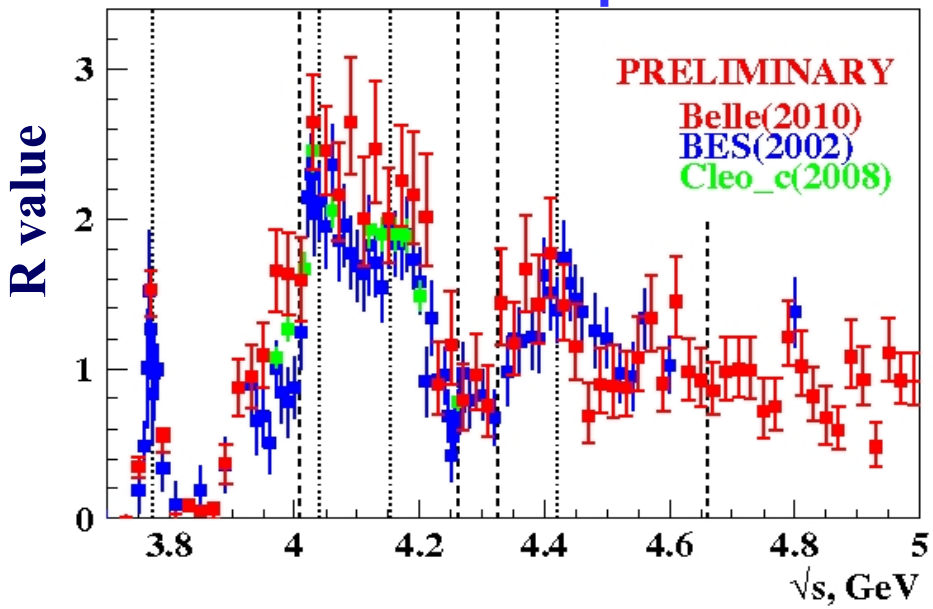
Y states don't match $D^{(*)}\bar{D}^{(*)}$ peaks





∑ exclusive

BES inclusive



Only small room for unaccounted contributions

Limited inclusive data above 4.5 GeV

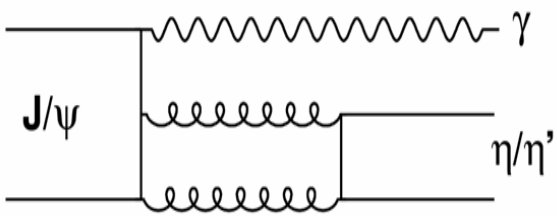
<u>No evidence for any 1^{--} $Y \rightarrow D^{(*)}D^{(*)}$</u>

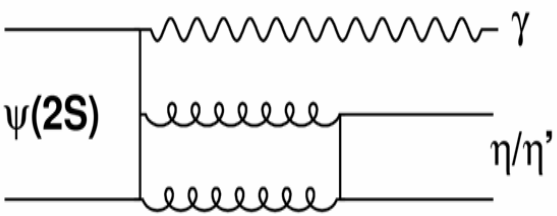
Charmonium decays

$\psi' \to \gamma P(\pi^0, \eta, \eta')$

$V \to \gamma P$ test various mechanisms:

Vector meson Dominance Model (VDM); Couplings & form factor;
Mixing of η-η' (-η_c);





LO-pQCD predicts $R_1 \approx R_2$

PRP 112 173 (1984)

$$R_n \equiv \frac{BF(\psi(nS) \to \gamma\eta)}{BF(\psi(nS) \to \gamma\eta')}$$

CLEOc found R_2 surprisingly small ! PR D79 111101(2009)

R_1 = (21.1 ± 0.9)% R_2< 1.8% at 90% CL

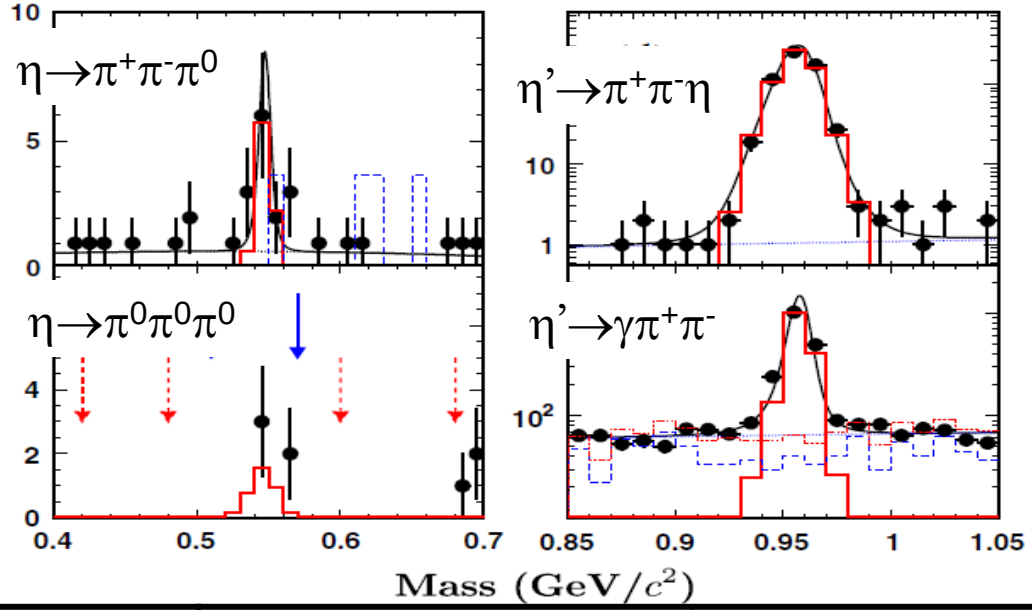
Other processes contribute?
Or related to the "ρπ puzzle"?

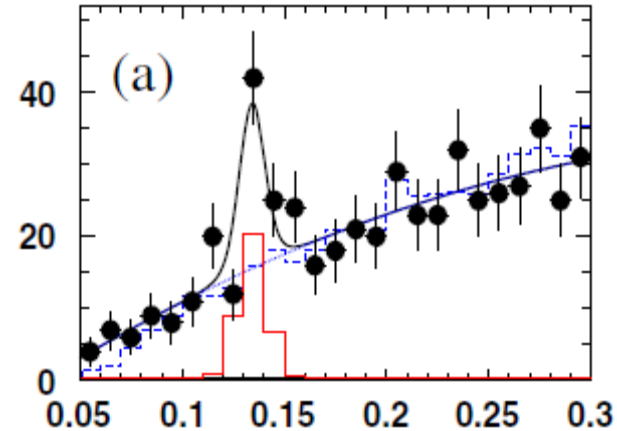
$$Q = \frac{BF(\psi' \to X)}{BF(J/\psi \to X)} \sim 12\%$$

Results from BESIII

BESIII PRL 105, 261801 (2010)

$\psi' \to \gamma\eta$ $\psi' \to \gamma\eta'$ $\psi' \to \gamma\pi^0$





$$R = \frac{BF(V \to \gamma\eta)}{BF(V \to \gamma\eta')}$$

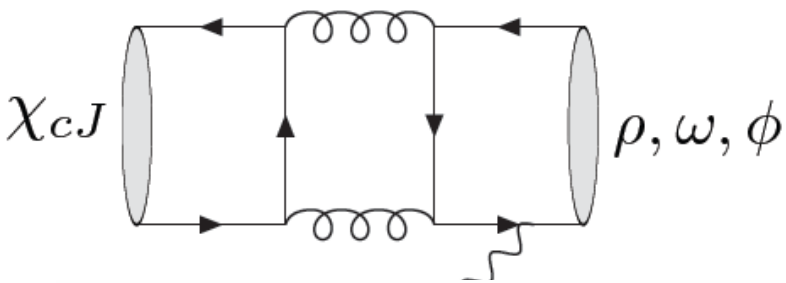
Mode	$BF(\psi')$ [x10^{-6}]	PDG $BF(J/\psi)$ [x10^{-4}]	Q (%)
$\gamma\pi^0$	1.58 ± 0.42	0.35 ± 0.03	4.5 ± 1.3
$\gamma\eta$	1.38 ± 0.49	11.04 ± 0.34	0.13 ± 0.04
$\gamma\eta'$	126 ± 9	52.8 ± 1.5	2.4 ± 0.2
$R_{1/2}$	(1.10±0.39) % <<	20.9 ± 0.9) %	-

VDM associate with Mixing of η_c-$\eta(\eta')$?

Phys. Lett. B697, 52 (2011)

Large $\chi_{cJ} \to \gamma V(\rho, \omega, \phi)$

pQCD prediction much lower than experiment



- Information of C-even state
- Two gluon coupling
- Possible glue-ball or hybrid states
- Hadronization

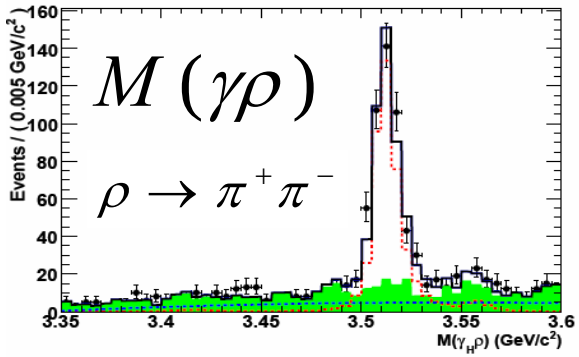
Mode	CLEO[1]	pQCD[2]	QCD[3]	QCD+QED[3]
$\chi_{c0} \to \gamma\rho^0$	< 9.6	1.2	3.2	2.0
$\chi_{c1} \to \gamma\rho^0$	$243 \pm 19 \pm 22$	14	41	42
$\chi_{c2} \to \gamma\rho^0$	< 50	4.4	13	38
$\chi_{c0} \to \gamma\omega$	< 8.8	0.13	0.35	0.22
$\chi_{c1} \to \gamma\omega$	$83 \pm 15 \pm 12$	1.6	4.6	4.7
$\chi_{c2} \to \gamma\omega$	< 7.0	0.5	1.5	4.2
$\chi_{c0} \to \gamma\phi$	< 6.4	0.46	1.3	0.03
$\chi_{c1} \to \gamma\phi$	< 26	3.6	11	11
$\chi_{c2} \to \gamma\phi$	< 13	1.1	3.3	6.5

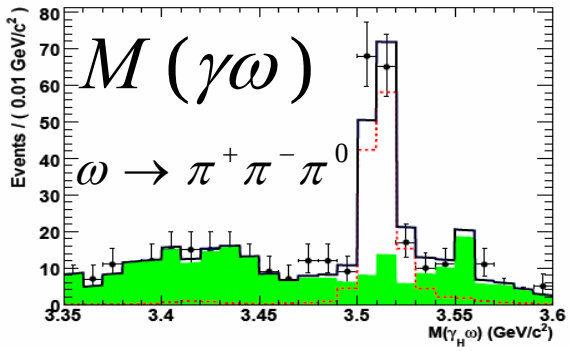
In unit of 10^{-6}

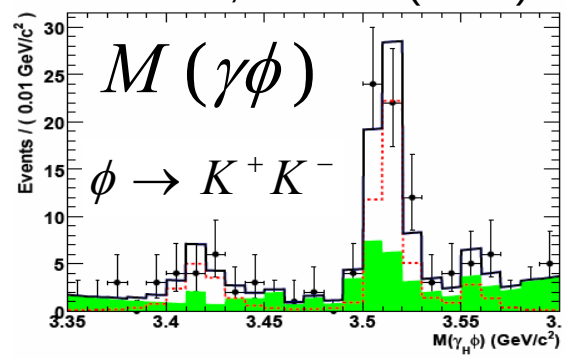
1. PRL 101,151801 (2008). 2. Chin. Phys. Lett. 23, 2376 (2006). 3. hep-ph/0701009

Results form BESIII

Phys. Rev. D 83, 112005 (2011)







Mode	CLEO[1]	pQCD[2]	QCD[3]	QCD+QED[3]	**BESIII**
$\chi_{c0} \to \gamma\rho^0$	< 9.6	1.2	3.2	2.0	**<10.5**
$\chi_{c1} \to \gamma\rho^0$	$243 \pm 19 \pm 22$	14	41	42	**228±13±16**
$\chi_{c2} \to \gamma\rho^0$	< 50	4.4	13	38	**<20.8**
$\chi_{c0} \to \gamma\omega$	< 8.8	0.13	0.35	0.22	**<12.9**
$\chi_{c1} \to \gamma\omega$	$83 \pm 15 \pm 12$	1.6	4.6	4.7	**69.7±7.2±5.6**
$\chi_{c2} \to \gamma\omega$	< 7.0	0.5	1.5	4.2	**<6.1**
$\chi_{c0} \to \gamma\phi$	< 6.4	0.46	1.3	0.03	**<16.2**
$\chi_{c1} \to \gamma\phi$	< 26	3.6	11	11	**25.8±5.2±2.0**
$\chi_{c2} \to \gamma\phi$	< 13	1.1	3.3	6.5	**<8.1**

First observation

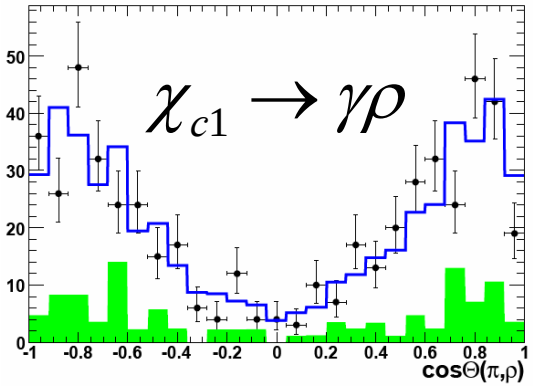
An non-pQCD explanation: "hadronic loop correction"

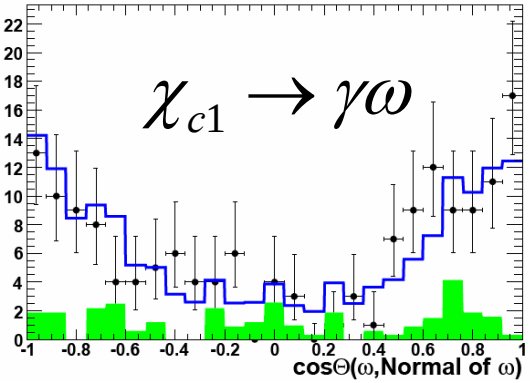
arXiv:1005.0066; EPJC70, 177-182 (2010);

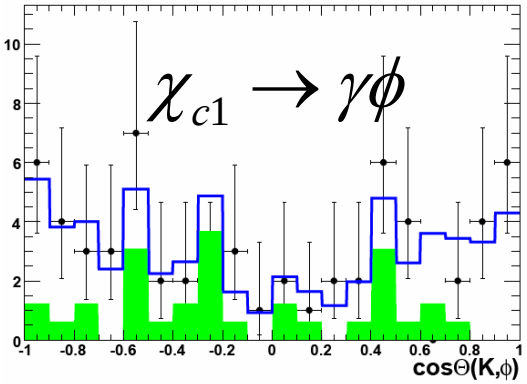
Polarization of $\chi_{c1} \to \gamma V(\rho, \omega, \phi)$

Longitudinal polarization (f_L);
Transverse polarization (f_T); θ : Helicity angle

$$\frac{d\Gamma}{\Gamma d\cos\theta} \propto (1 - f_T)\cos^2\theta + \frac{1}{2} f_T \sin^2\theta \qquad f_T = \frac{|A_T|^2}{|A_T|^2 + |A_L|^2}$$







$f_T = 0.158 \pm 0.034^{+0.015}_{-0.014}$ $\qquad$ $f_T = 0.247^{+0.090+0.044}_{-0.087-0.026}$ $\qquad$ $f_T = 0.29^{+0.13+0.10}_{-0.12-0.09}$

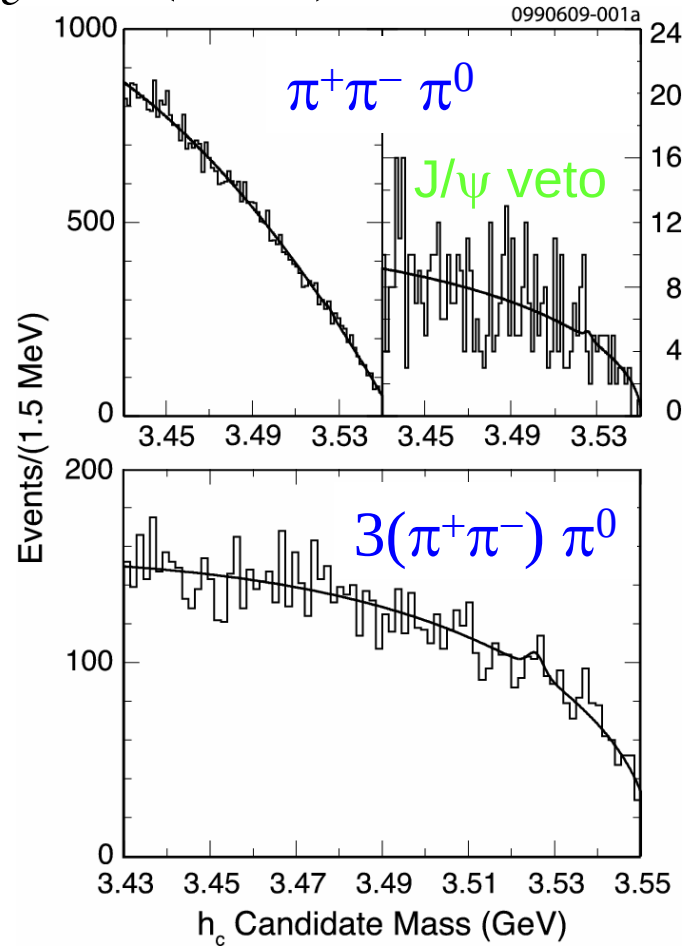
<u>*Longitudinal polarization dominates, consistent with theoretical prediction*</u>

Z. Phys. C 66, **71** (1995)
Phys. Rev. **77**, 242 (1950)

Evidence of h_c hadronic decay

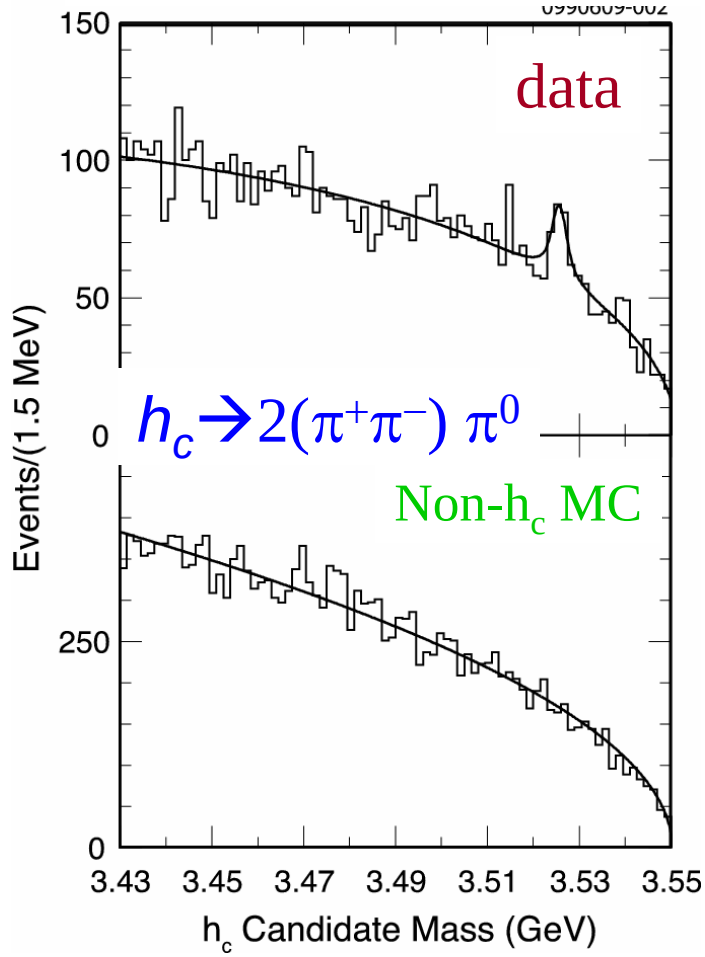
Look for $\psi' \rightarrow \pi^0 h_c$

$h_c \rightarrow n(\pi^+\pi^-)\,\pi^0$, n=1,2,3



First evidence for $h_c \rightarrow 2(\pi^+\pi^-)\,\pi^0$

CLEOc PR D80 051106 (2009)



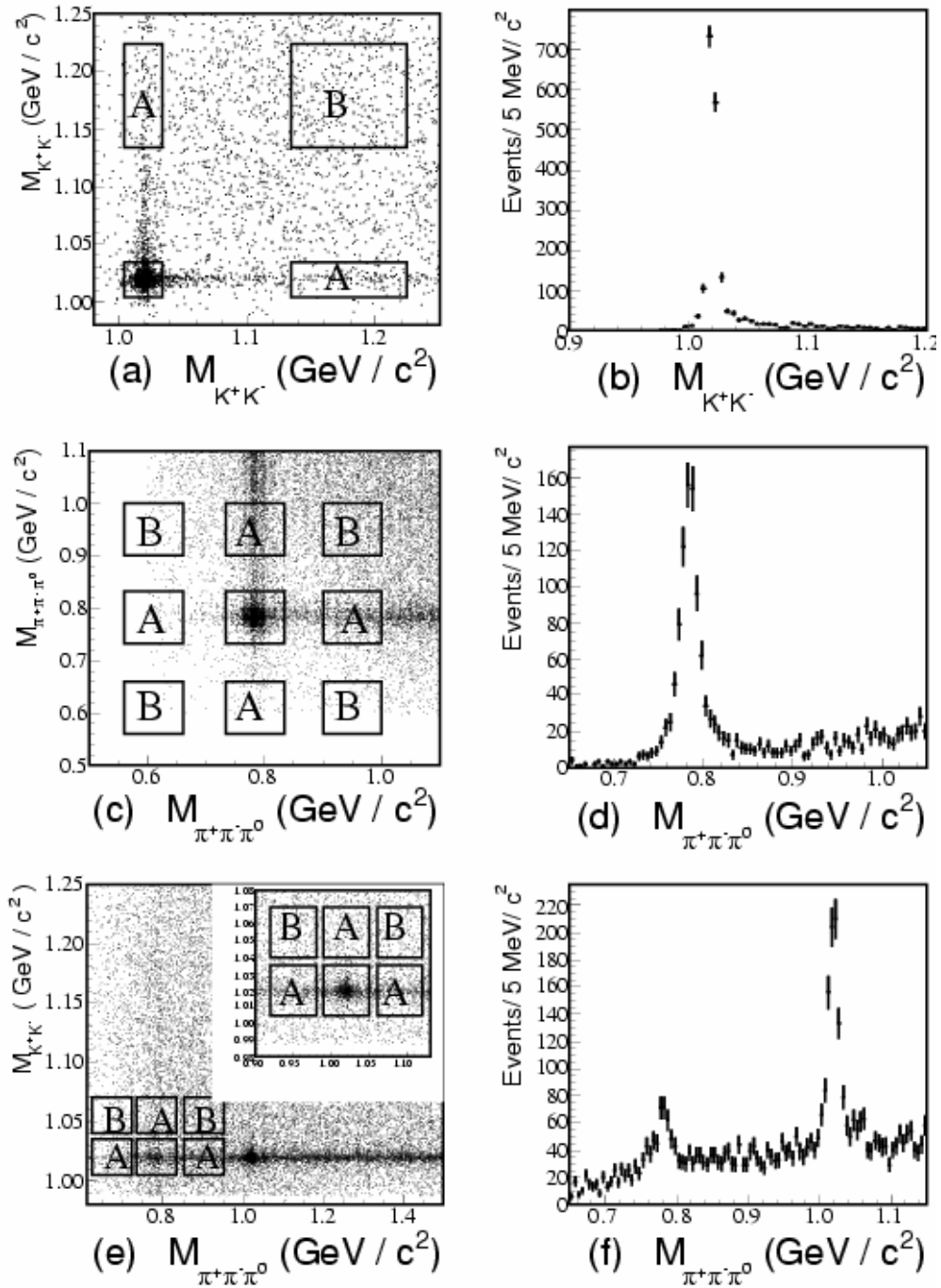
$\chi_{cJ} \rightarrow VV(V: \omega, \phi)$

- $\chi_{cJ} \rightarrow \phi\phi$ and $\chi_{cJ} \rightarrow \omega\omega$ are Singly OZI suppressed
- $\chi_{c1} \rightarrow \phi\phi$ and $\chi_{c1} \rightarrow \omega\omega$ is suppressed by helicity selection rule.
- $\chi_{cJ} \rightarrow \phi\omega$ is doubly OZI suppressed, not measured yet

Reconstruct

$\phi \rightarrow K^+K^-$

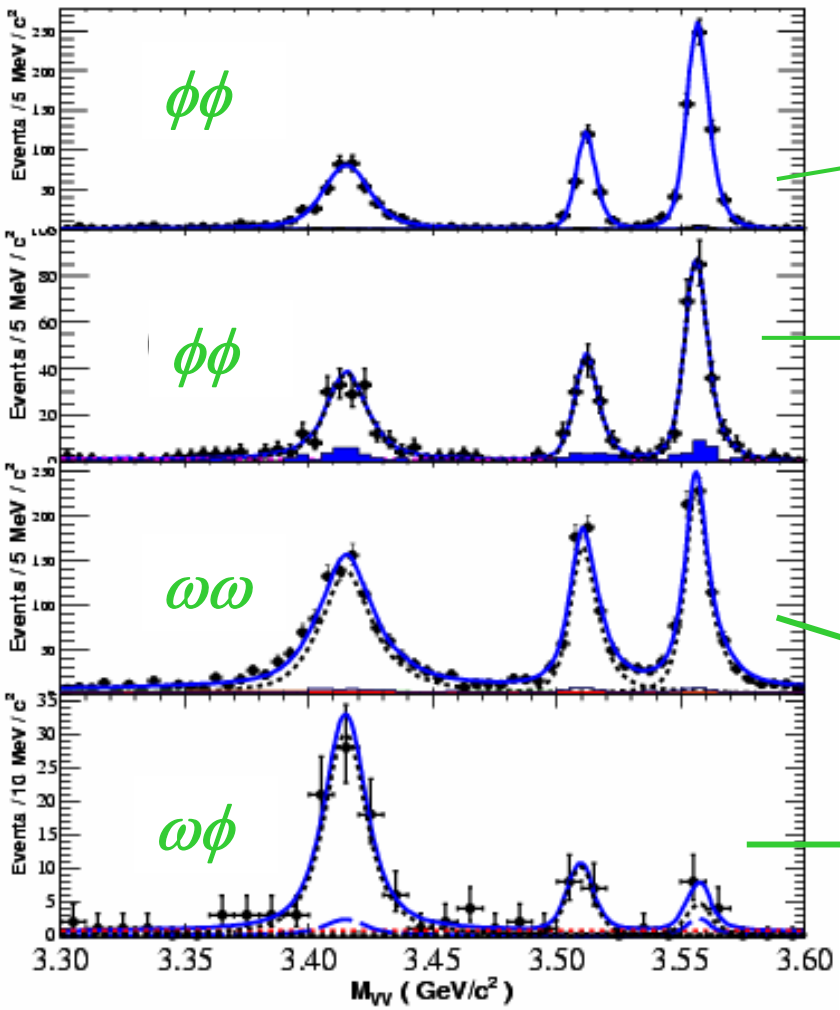
$\omega \rightarrow \pi^+\pi^-\pi^0$



BESIII PRL 107 091803(2011)

$\chi_{cJ} \to VV$ at BESIII

arXiv:1104.5068



Mode	$N_{\rm net}$	ϵ (%)	$\mathcal{B}(\times 10^{-4})$
$\chi_{c0} \to \phi\phi$	433 ± 23	22.4	$7.8 \pm 0.4 \pm 0.8$
$\chi_{c1} \to \phi\phi$	254 ± 17	26.4	$4.1 \pm 0.3 \pm 0.4$
$\chi_{c2} \to \phi\phi$	630 ± 26	26.1	$10.7 \pm 0.4 \pm 1.1$
$\to 2(K^+K^-)$			
$\chi_{c0} \to \phi\phi$	179 ± 16	1.9	$9.2 \pm 0.7 \pm 1.0$
$\chi_{c1} \to \phi\phi$	112 ± 12	2.3	$5.0 \pm 0.5 \pm 0.6$
$\chi_{c2} \to \phi\phi$	219 ± 16	2.2	$10.7 \pm 0.7 \pm 1.2$
$\to K^+K^-\pi^+\pi^-\pi^0$			
Combined:			
$\chi_{c0} \to \phi\phi$	—	—	$8.0 \pm 0.3 \pm 0.8$
$\chi_{c1} \to \phi\phi$	—	—	$4.4 \pm 0.3 \pm 0.5$
$\chi_{c2} \to \phi\phi$	—	—	$10.7 \pm 0.3 \pm 1.2$
$\chi_{c0} \to \omega\omega$	991 ± 38	13.1	$9.5 \pm 0.3 \pm 1.1$
$\chi_{c1} \to \omega\omega$	597 ± 29	13.2	$6.0 \pm 0.3 \pm 0.7$
$\chi_{c2} \to \omega\omega$	762 ± 31	11.9	$8.9 \pm 0.3 \pm 1.1$
$\to 2(\pi^+\pi^-\pi^0)$			
$\chi_{c0} \to \omega\phi$	76 ± 11	14.7	$1.2 \pm 0.1 \pm 0.2$
$\chi_{c1} \to \omega\phi$	15 ± 4	16.2	$0.22 \pm 0.06 \pm 0.02$
$\chi_{c2} \to \omega\phi$	< 13	15.7	< 0.2
$\to K^+K^-\pi^+\pi^-\pi^0$			

Evidence

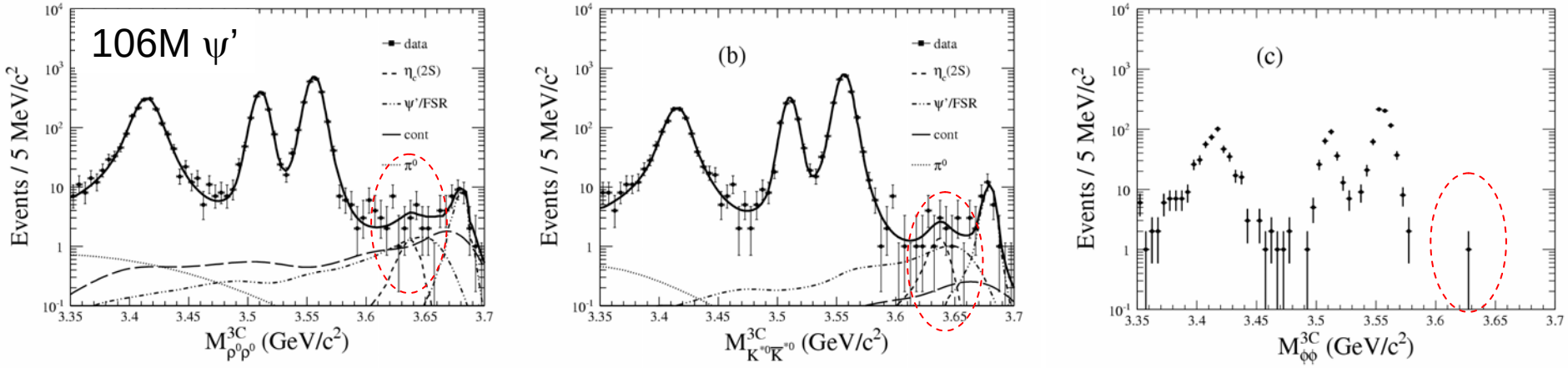
First observation

Long distance transitions could contribute via the intermediate meson loops.

PR D81 014017 (2010)
PR D81 074006 (2010)

Search for $\eta_c(2S) \rightarrow VV$ @BESIII

Test for the "Intermediate charmed meson loops"



	BF($\psi' \rightarrow \gamma\eta_c' \rightarrow \gamma VV$) ($10^{-7}$)	BF($\eta_c' \rightarrow VV$) (10^{-3})	Theory BF($\eta_c' \rightarrow VV$) (10^{-3})
$\rho^0\rho^0$	<11.4	<3.1	6.4 ~ 28.9
$K^{*0}K^{*0}$	<19.4	<5.3	7.9 ~ 35.8
$\phi\phi$	<7.8	<2.0	2.1 ~ 9.8

No signals observed in $\eta_c \rightarrow \rho\rho$, $K^{*0}K^{*0}$, $\phi\phi$; more stringent UL's are set.

arXiv: 1010.1343

Summary

- Charmonium is the "best understood" hadronic system
  - All the lowest-lying charmonium states have been found; the long-anticipated states have been measured with high precision.
  - Agreement between their measured properties and theory.
  - Higher-mass charmonium meson searches have produced surprises; unanticipated states showed up.

- Enormous progress has been achieved on charmonium decays
  - Measurements of BFs, width and mass have attained high precision,
  - Provides crucial anchors for theoretical approaches.

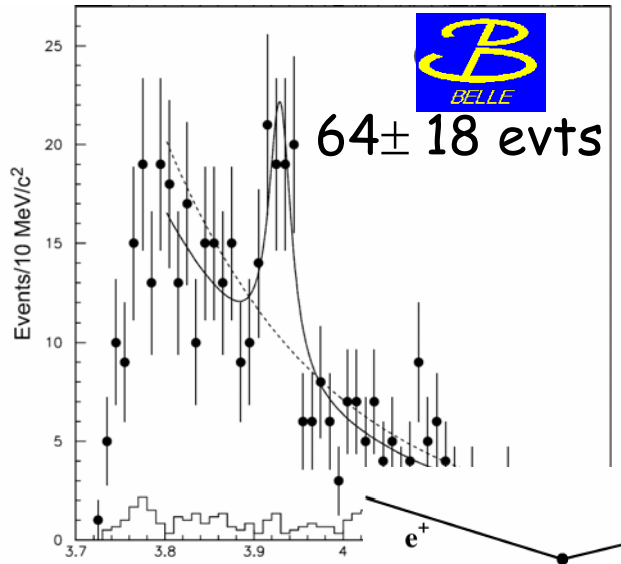
- Outlook
  - BESIII will continue to investigate charmonium spectroscopy and decay.
  - LHC starts to produce physics results. Large data samples from LHC will allow to identify the X,Y,Z, measure production, and polarization.
  - Future experiments (PANDA etc.) will complement the activities at other labs.

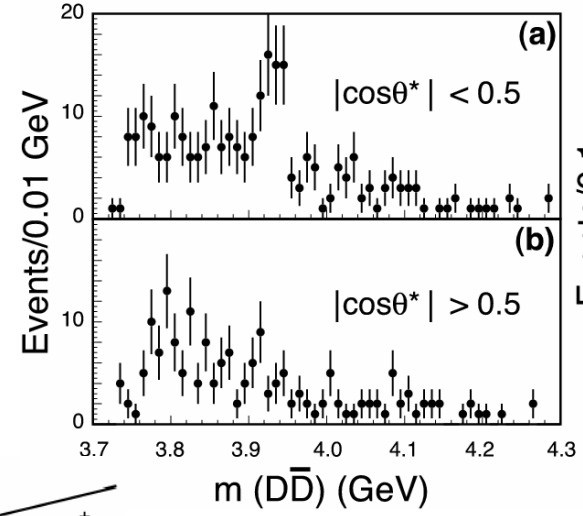
Backup

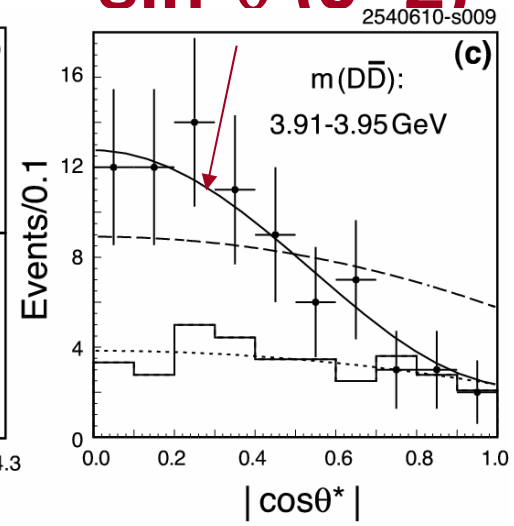
$\gamma\gamma \rightarrow \chi_{c2}(2P) \rightarrow D\bar{D}$

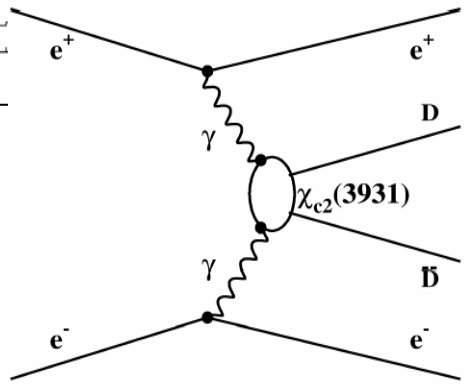
used name *Z(3930)*

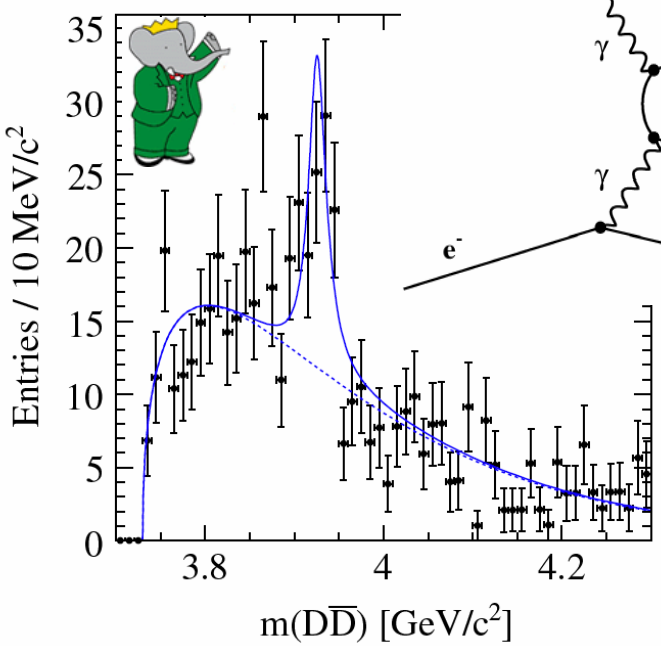
$\sin^4\theta$ (J=2)











$J^{PC} = 0^{++}, 2^{++}$

Belle PRL 96 082003

M=3929 ± 5 ± 2 MeV

Γ=29 ± 10 ± 2 MeV

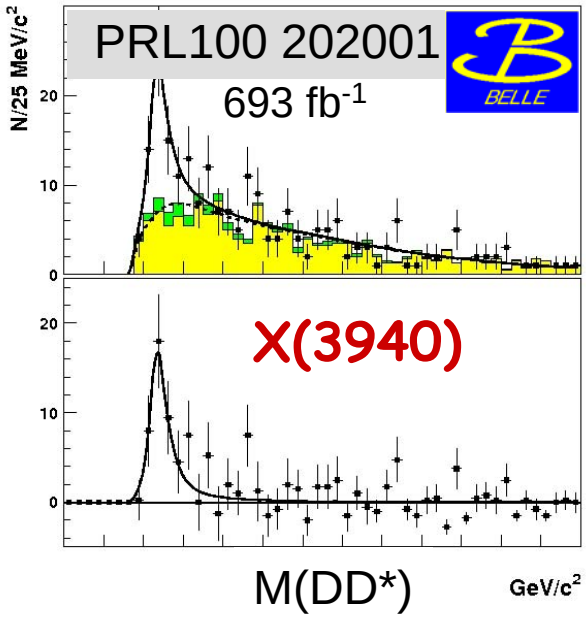
BaBar: PRD 81, 092003

M = 3926.7±2.7±1.1 MeV

G = 21.3±6.8±3.6 MeV

The states near 3940 MeV

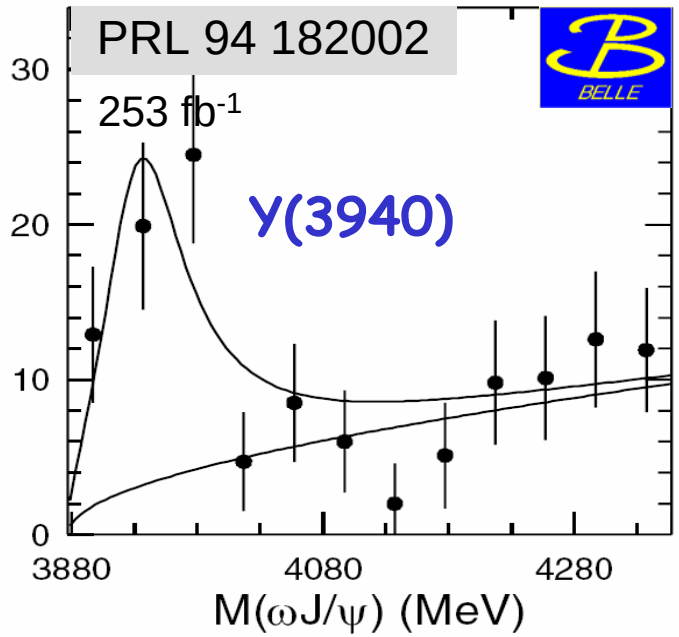
$e^+e^- \to J/\psi\ DD^*$



$M = 3942^{+7}_{-6} \pm 6$ MeV

$\Gamma_{tot} = 37^{+26}_{-15} \pm 12$ MeV

$B \to K\ \omega J/\psi$



$M \approx 3943 \pm 11 \pm 13$ MeV

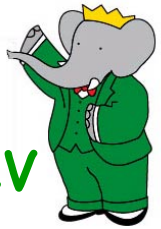
$\Gamma_{tot} \approx 87 \pm 22 \pm 26$ MeV

X(3940) not seen in $\omega J/\psi$;
Y(3940) not seen in DD^*

BaBar PRD 82, 011101; 426 fb^{-1}

$M \approx 3919.1^{+3.8}_{-3.5} \pm 2.0$ MeV

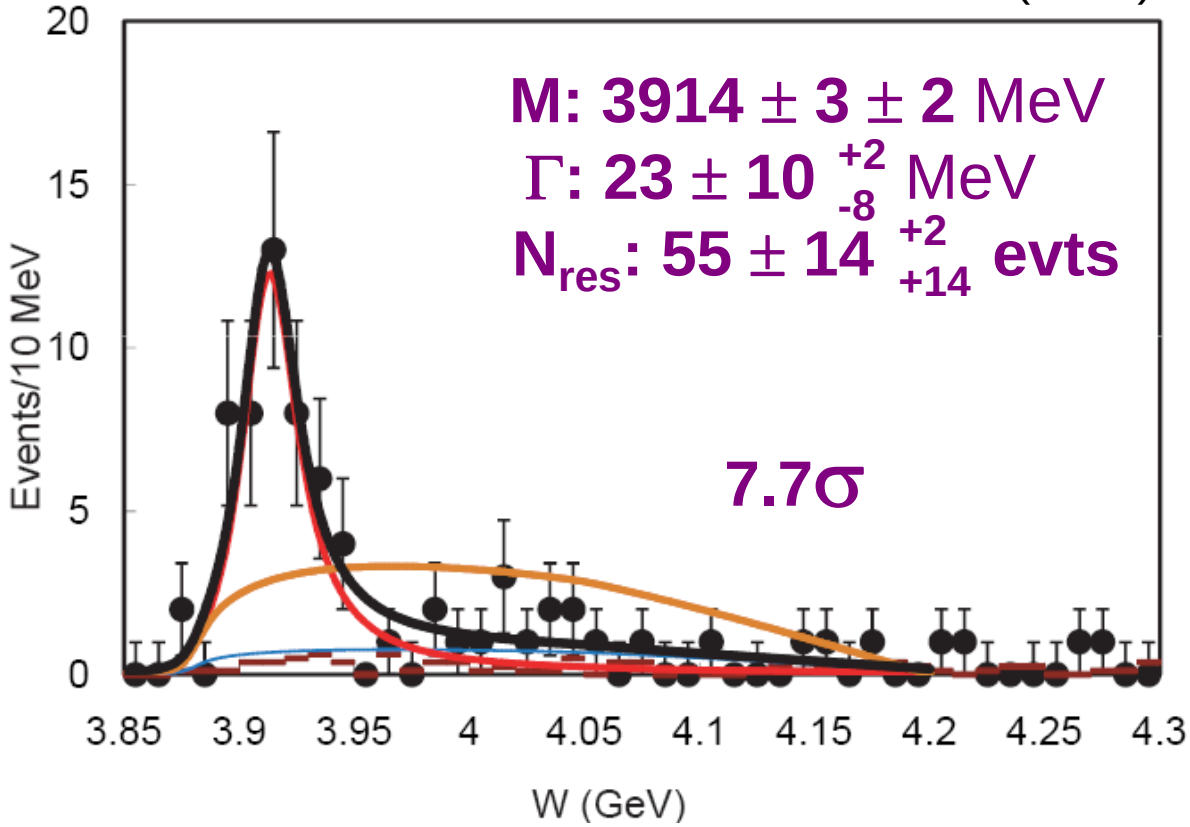
$\Gamma \approx 31^{+10}_{-8} \pm 5$ MeV



X(3940) Y(3940) probably are different

X(3915) in $\gamma\gamma \rightarrow \omega J/\psi$

PRL 104 092001 (2010)



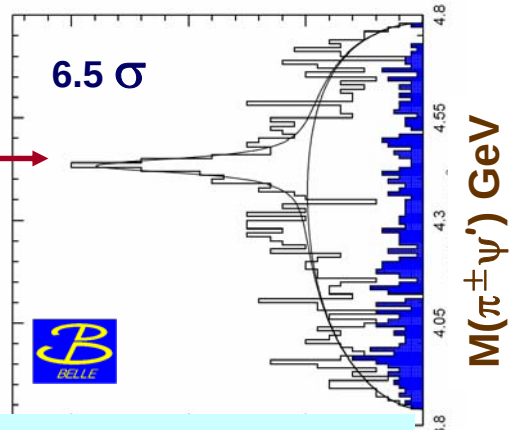
$W = M_5 - M_{ll} + M(J/\psi)$

X(3915) = Y(3940) ?

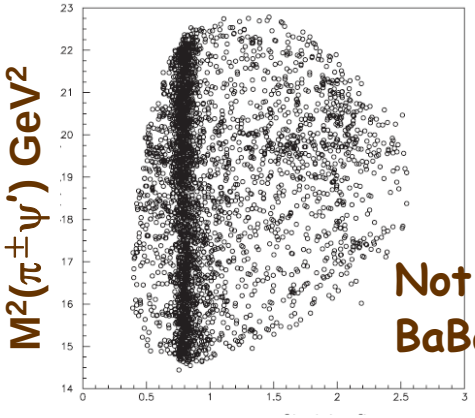
The Z^+ meson candidates

$B \to K\, \pi^+ \psi'$

$Z(4430)^+$



(Belle) PRl 100, 142001

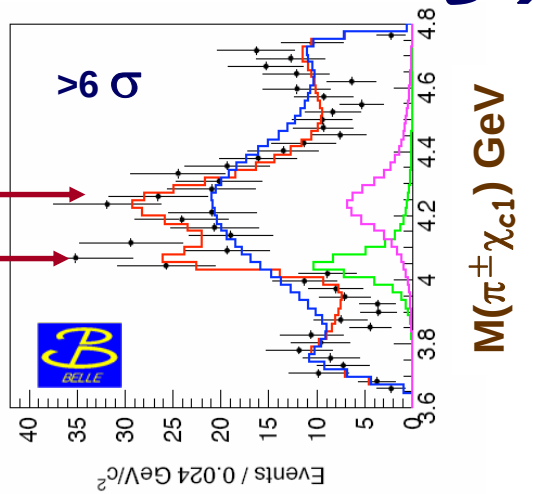


Not confirmed by BaBar arXiv:0811.0564

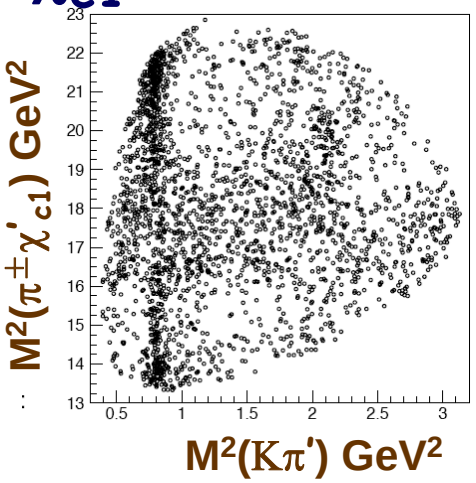
$B \to K\, \pi^+ \chi_{c1}$

$Z_2(4250)^+$

$Z_1(4050)^+$

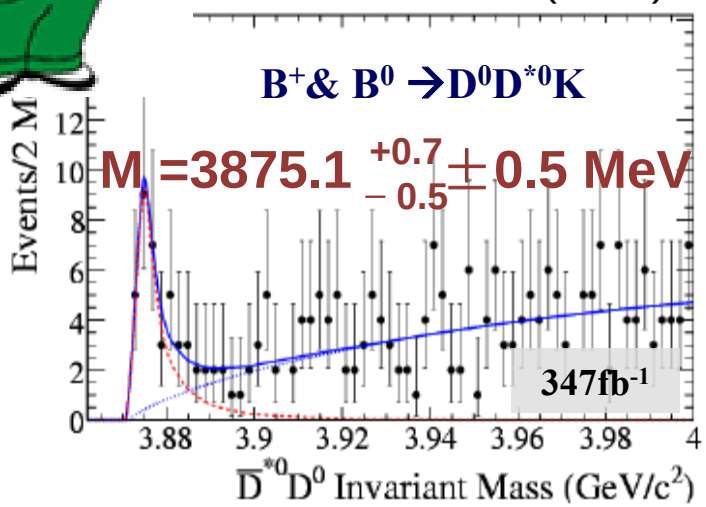


(Belle) PRD 78, 072004



Strong decay X(3872)→D$\overline{D}$*

PR D77 011102(2008)



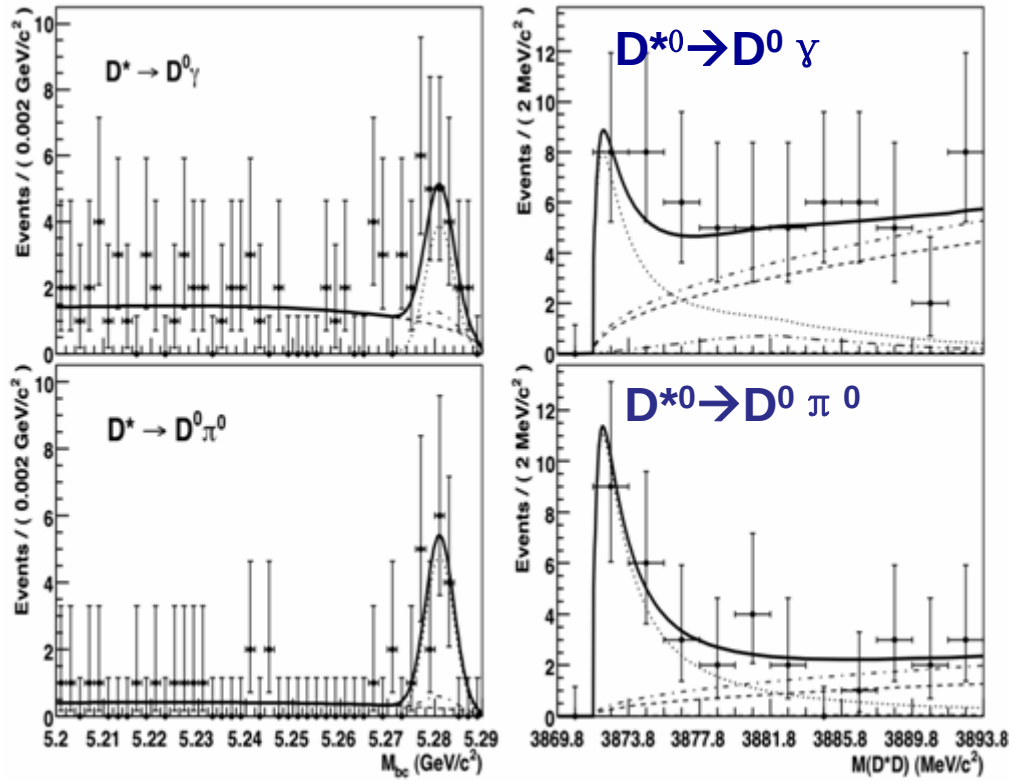
Belle PRL97, 162002(2006)

Saw a higher mass value

BF(DD) ≈ 10 × BF($\pi^+\pi^-J/\psi$)*

B →K D^0D^{*0}

2D fit; 605 fb^{-1}



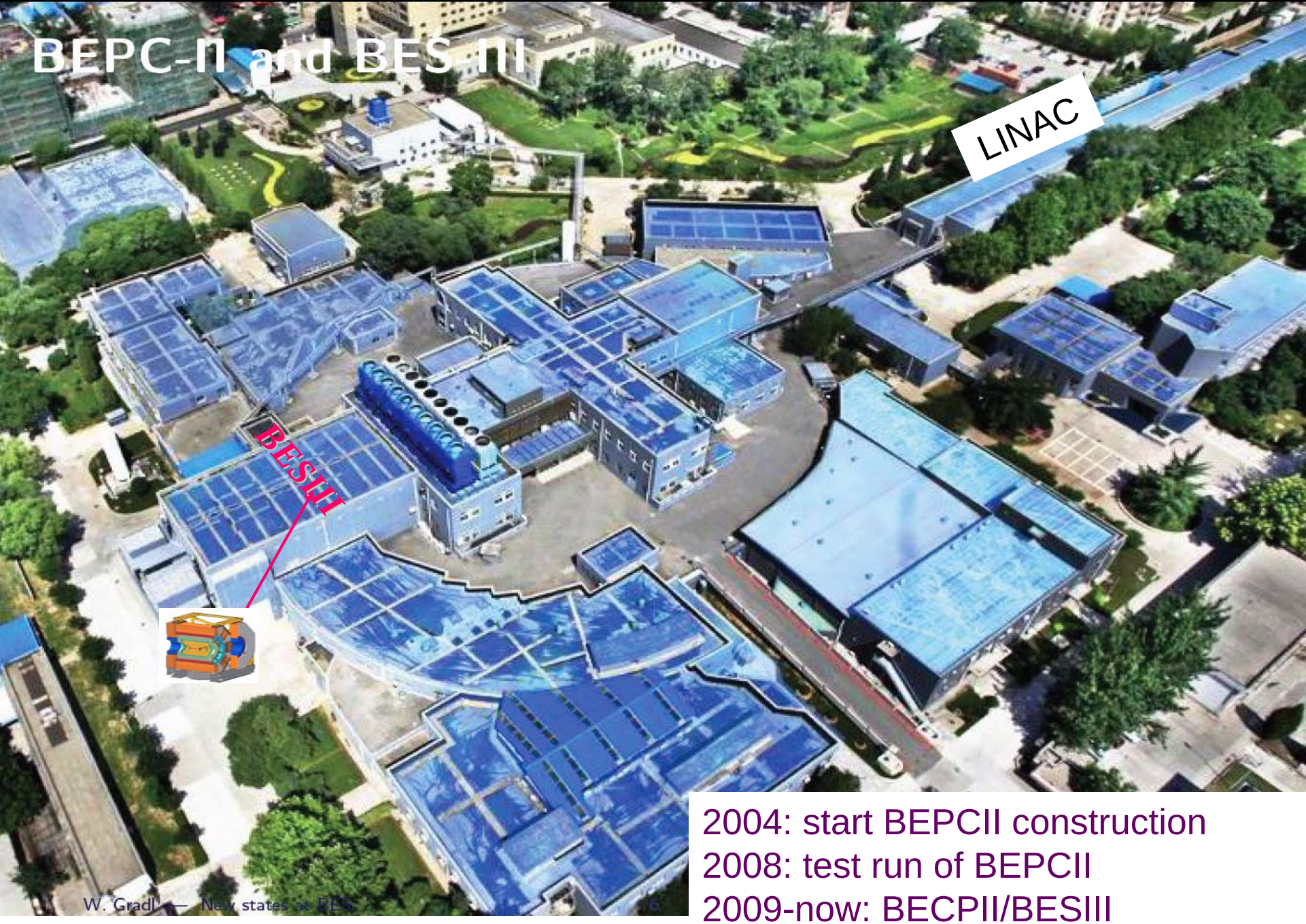
Mass = **3872.9** $^{+0.6+0.4}_{-0.4-0.5}$ MeV

Γ(BW) = **3.9** $^{+2.8+0.2}_{-1.4+1.1}$ MeV

$\mathcal{BF}(B \to K\ X) \times \mathcal{BF}(X \to D^{*0}D^0)$ = **(0.80 ± 0.20 ± 0.10)×10^{-4}**

PRD81, 031103 (R) (2010)

BEPC-II and BES-III



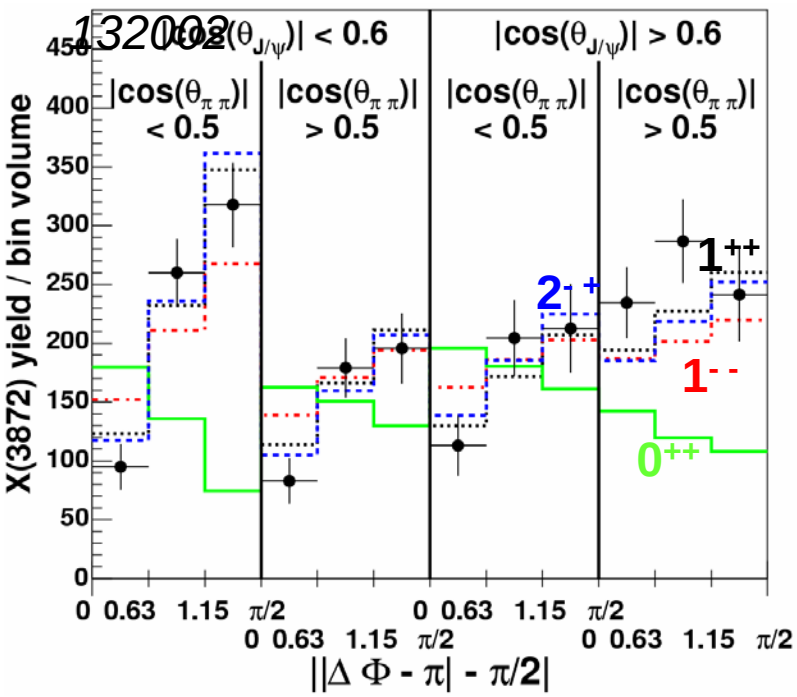
2004: start BEPCII construction
2008: test run of BEPCII
2009-now: BECPII/BESIII
data taking

BEPCII /BESIII

J^{pc} ?

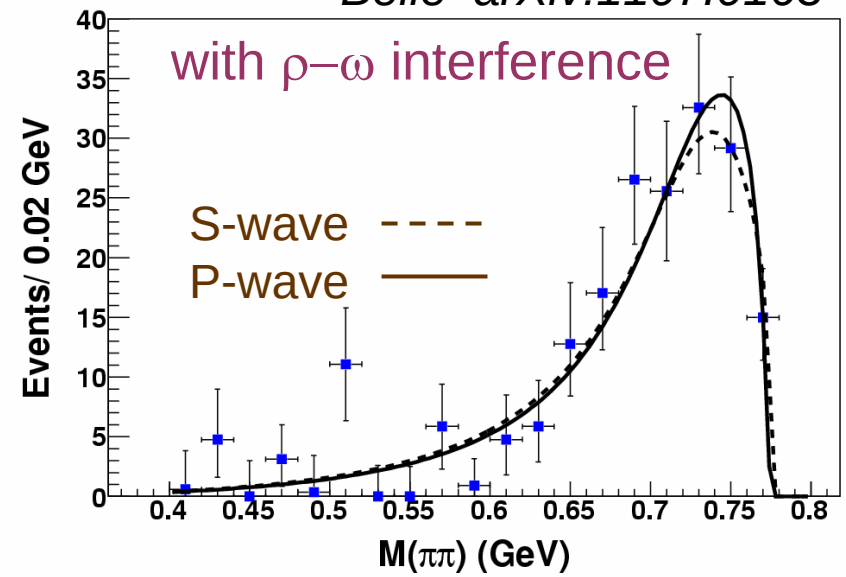
Angular analysis

CDF: PRL 98 132002



Fits to $M(\pi^+\pi^-)$

Belle arXiv:1107.0163



bkg is subtracted & weighted by acceptance

All J^{PC} values other than 1^{++} or 2^{-+} are ruled out.

Angular analyses or $M(\pi\pi)$ fits can not distinguish 1^{++} and 2^{-+} hypotheses with current data.