

# **Light hadron and Charmonium(-like) & Bottomonium(-like) states**

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**Hai-Bo Li**

**Institute of High Energy Physics, CAS**

**Beijing China**

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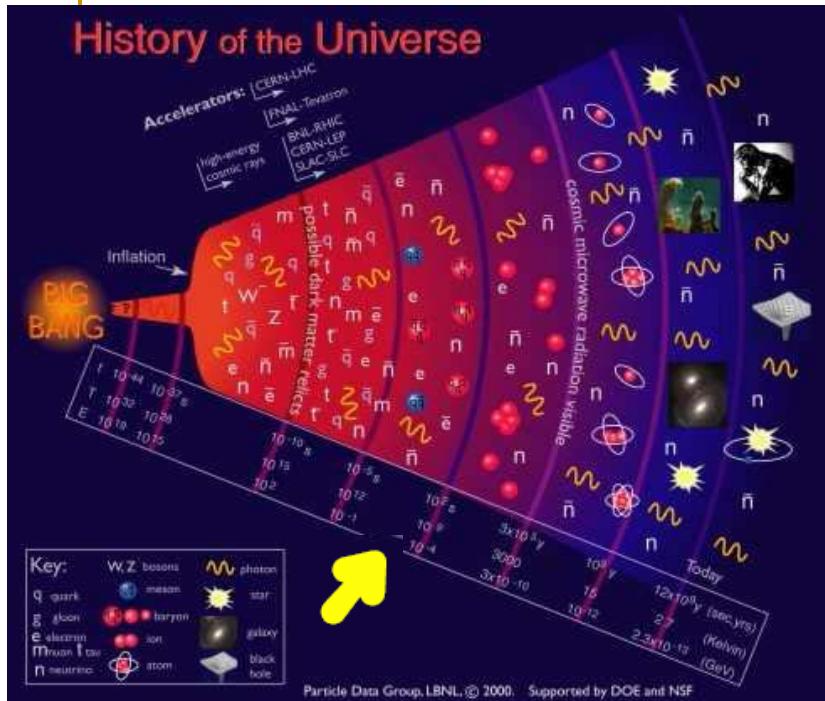
**August 22 – 27, 2011**

# Outline

- **Introduction**
- **Light meson spectroscopy and decays**
- **Charmonium-(like) states**
- **Bottomonium(-like) states**
- **Summary**

# Introduction – QCD and confinement

## History of the Universe

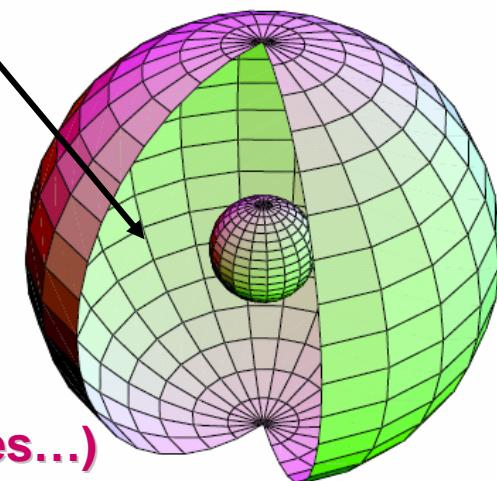


From about  $10^{-6}$  s on, all quark and anti-quark became confined inside the hadron matters. Only proton and neutron remained after about 1 second.

No matter how hard one strikes the proton,  
One cannot liberate an individual quark/gluon

Interaction between quarks unknown  
throughout 98% of the hadron volume

Courtesy of Craig Roberts, Argonne



How does QCD give rise to hadrons?

What's the role of gluon inside hadron?

What are the properties of predicted states beyond the quark-anti-quark systems (hybrid, glueball, multi-quark states...)

Need to map out spectrum, new states using experiments and theory

# Introduction – experiments

## ➤ B factories: BABAR and Belle experiments

- Large sample of  $\Upsilon(nS)$  and B mesons
- Also large sample of charm and charmonia :  $\sigma(e^+e^- \rightarrow c\bar{c}) = 1.3 \text{ nb}$
- Charm and Charmonium from B decays, ISR and  $\gamma\gamma$  processes.

Samples	$\Upsilon(1S)$	$\Upsilon(2S)$	$\Upsilon(3S)$	$\Upsilon(4S)$	$\Upsilon(5S)$
 BaBar		$14 \text{ fb}^{-1}$	$30 \text{ fb}^{-1}$	$433 \text{ fb}^{-1}$	$3.2 \text{ fb}^{-1} (\text{scan})$
 Belle	$6 \text{ fb}^{-1}$	$24 \text{ fb}^{-1}$	$3 \text{ fb}^{-1}$	$711 \text{ fb}^{-1}$	$121 \text{ fb}^{-1}$

## ➤ Charm factories: CLEO-c and BES-III $e^+e^- \rightarrow J/\psi, \psi(2S), \psi(3770)$ scan 2.0-4.8 GeV

- BEPCII/BESIII: designed:  $L \sim 10^{33}/\text{cm}^2/\text{s}$ ;
- reached peak Luminosity:  $6.4 \times 10^{32}/\text{cm}^2/\text{s}$
- Dedicated to charm/charmonia,
- BESIII is a factory for light hadron in charmonium decays

## ➤ Tevatron: DØ and CDF

pp collider  $\sqrt{s} \sim 1.96 \text{ TeV}$ ,  $L \sim 10 \text{ fb}^{-1}$  per experiment

Good place to study  $B_c$ , b-baryons as well as charmonium/charm states

## ➤ Many experiments for light hadron and charm/charmonia : KEDR/KLOE/COMPASS/...

## ➤ Experiments at LHC,

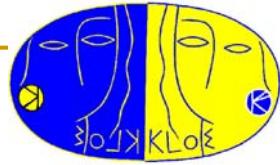
LHCb, CMS and ATLAS are also important for charmonium and bottomonium states

Future: PANDA, GlueX/JLab, Belle-II, Super-B abd LHCb upgrade...

Sorry, cannot cover all of them!

# **Light meson spectroscopy and decays most recent results**

# $\eta$ meson decays at KLOE

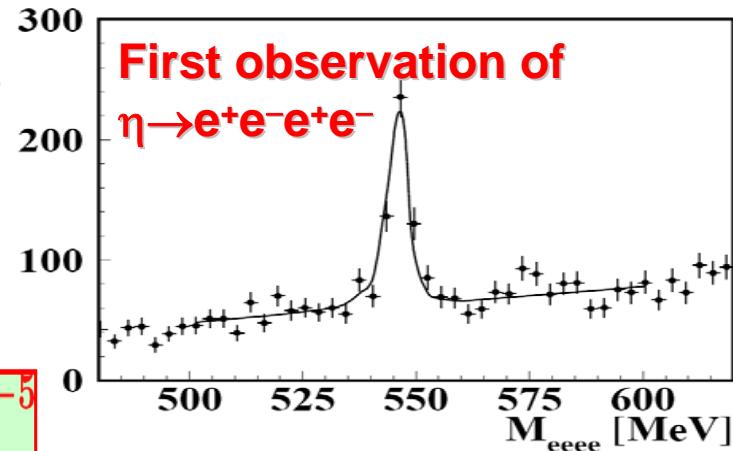


Test of ChPT at low energy

theoretical prediction:  $\text{BR}(\eta \rightarrow 4e) = (2.4 - 2.7) \times 10^{-5}$   
 [ J. Bijnens and F. Perrsson, hep-ph/0106130 ]

KLOE results based on  $1.7\text{fb}^{-1}$  on  $\phi$  peak  
 [arXiv:1105.6067]:

$$\text{BR}(\eta \rightarrow e^+ e^- e^+ e^-(\gamma)) = (2.4 \pm 0.2_{\text{stat}} \pm 0.1_{\text{syst}}) \times 10^{-5}$$



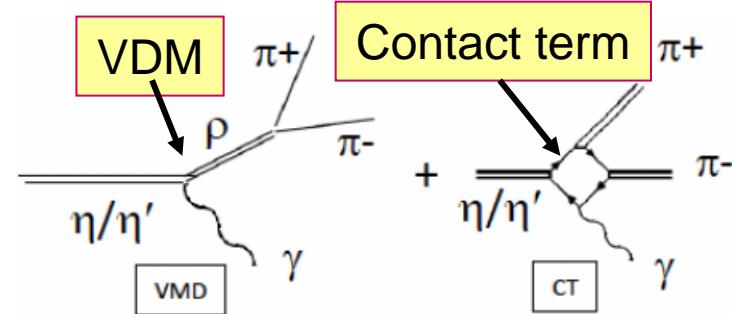
Precision measurement of : [arXiv:1107.5733]

$$\Gamma(\eta \rightarrow \pi^+ \pi^- \gamma) / \Gamma(\eta \rightarrow \pi^+ \pi^- \pi^0)$$

value	events	author	year
$0.203 \pm 0.008$		PDG average	
$0.175 \pm 0.007 \pm 0.006$	859	CLEO	2007



CLEO result (2007) is  
 2 – 3  $\sigma$  lower than PDG:

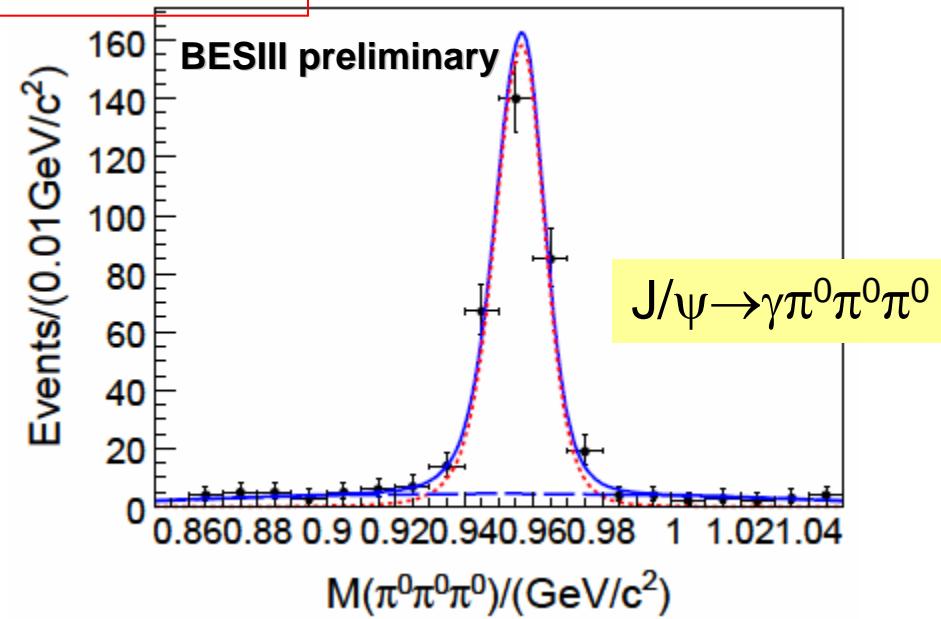
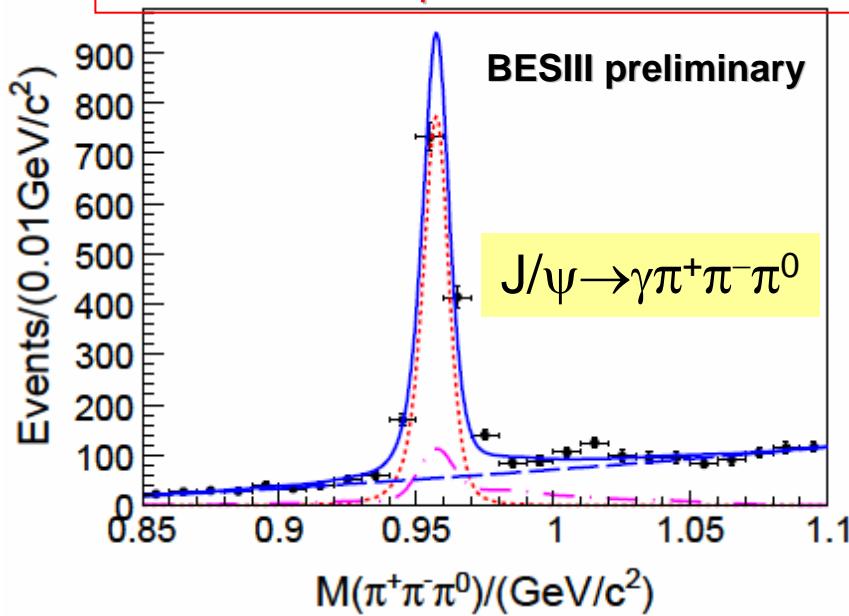


Based on  $558\text{pb}^{-1}$  on  $\phi$  peak,  
 KLOE preliminary result:

$$\frac{\Gamma(\eta \rightarrow \pi^+ \pi^- \gamma)}{\Gamma(\eta \rightarrow \pi^+ \pi^- \pi^0)} = (0.1838 \pm 0.0005_{\text{stat}} \pm 0.0030_{\text{sys}})$$

# New results on $\eta' \rightarrow 3\pi$ in $J/\psi \rightarrow \gamma\pi\pi\pi$ at BESIII

With 225M  $J/\psi$  collected in one and half month



## Preliminary results:

Improved by factor of 3

$$\left\{ \begin{array}{l} Br(\eta' \rightarrow \pi^+\pi^-\pi^0) = (3.83 \pm 0.15(stat.) \pm 0.39(sys.)) \times 10^{-3} \\ \text{PDG2010: } (3.6^{+1.1}_{-0.9}) \times 10^{-3} \text{ (2009 CLEO-c)} \end{array} \right.$$

Two times of PDG 2010 value

$$\left\{ \begin{array}{l} Br(\eta' \rightarrow 3\pi^0) = (3.56 \pm 0.22(stat.) \pm 0.34(sys.)) \times 10^{-3} \\ \text{PDG2010: } (1.68 \pm 0.22) \times 10^{-3} \text{ (1984: GAM2)} \end{array} \right.$$

# Search for spin exotic states

## Constituent quark model

- color neutral  $q\bar{q}$  systems
- Quantum numbers  $I^G J^{PC}$
- $P = (-1)^{L+1}$     $C = (-1)^{L+S}$     $G = (-1)^{I+L+1}$
- $J^{PC}$  multiplets:  $0^{++}, 0^{-+}, 1^{--}, 1^{+-}, 1^{++}, 2^{++}, \dots$
- **Forbidden:**  $0^{--}, 0^{+-}, 1^{-+}, 2^{+-}, 3^{-+}, \dots$

## Hybrid candidates ( $1.3 - 2.2 \text{ GeV}/c^2$ ):

lightest hybrid predicted: **exotic  $J^{PC} = 1^{-+}$**

- $\pi_1(1400)$ : VES, E852, Crystal Barrel  $\rightarrow \eta\pi$
- $\pi_1(1600)$ : E852, VES  $\rightarrow \rho\pi, \eta'\pi, f_1\pi, b_1\pi$
- $\pi_1(2000)$ : E852  $\rightarrow f_1(1285)\pi, b_1(1235)\pi$
- .... still controversial  $\rightarrow$  COMPASS

COMPASS (2004):  $\pi^- \text{Pb} \rightarrow \pi^- \pi^+ \pi^- \text{Pb}$

BW for  $\pi_1(1600)$  + background:

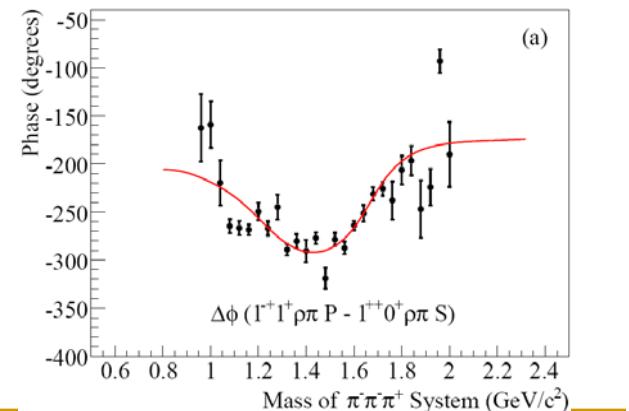
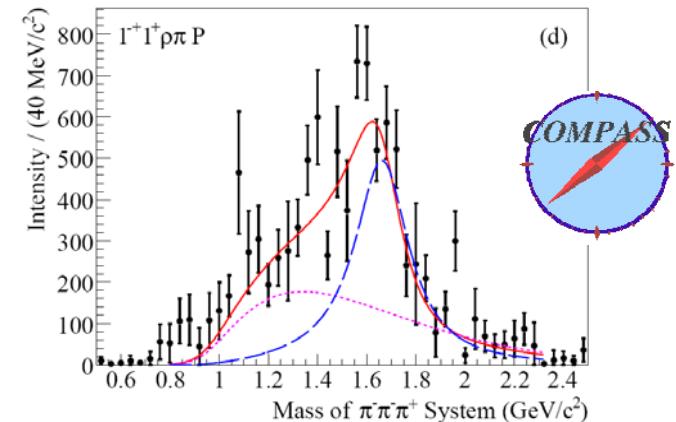
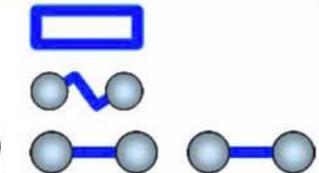
$$M = (1.660 \pm 0.010 {}^{+0.000}_{-0.064}) \text{ GeV}/c^2$$

$$\Gamma = (0.269 \pm 0.021 {}^{+0.042}_{-0.064}) \text{ GeV}/c^2$$

$\Rightarrow$  Confirm the  $1^{-+} \pi_1(1600)$

## QCD: meson states beyond

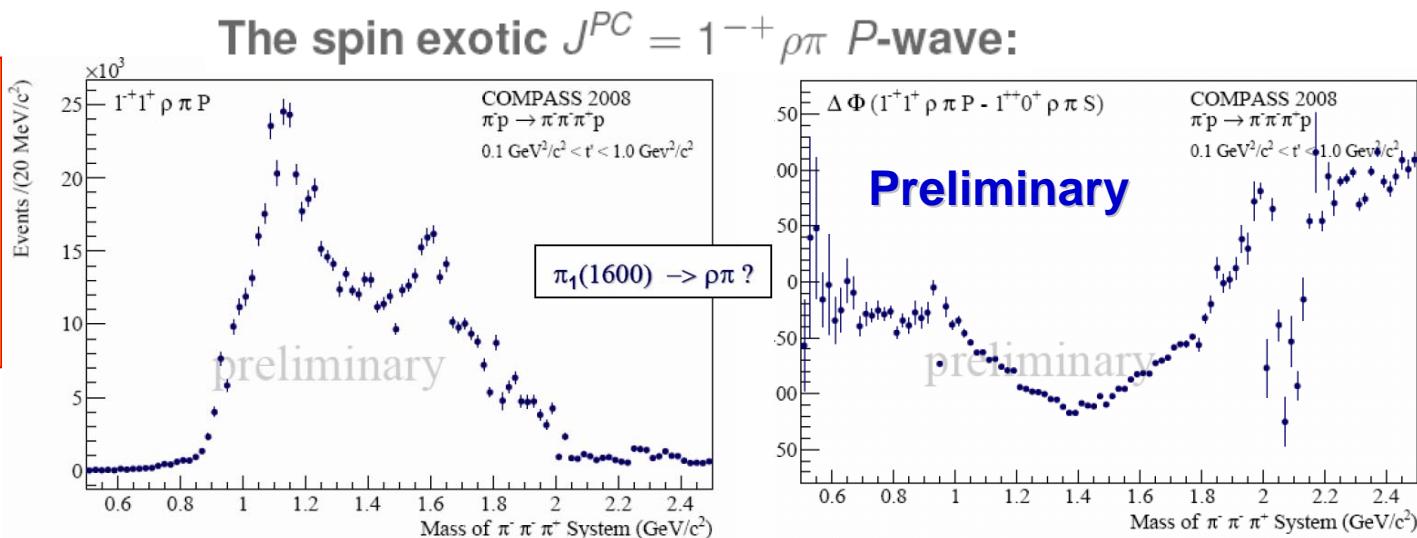
- Glueballs:  $gg, ggg$
- Hybrids:  $q\bar{q}g$
- Tetraquarks:  $(q\bar{q})(q\bar{q})$



COMPASS: PRL 104 (2010) 241803

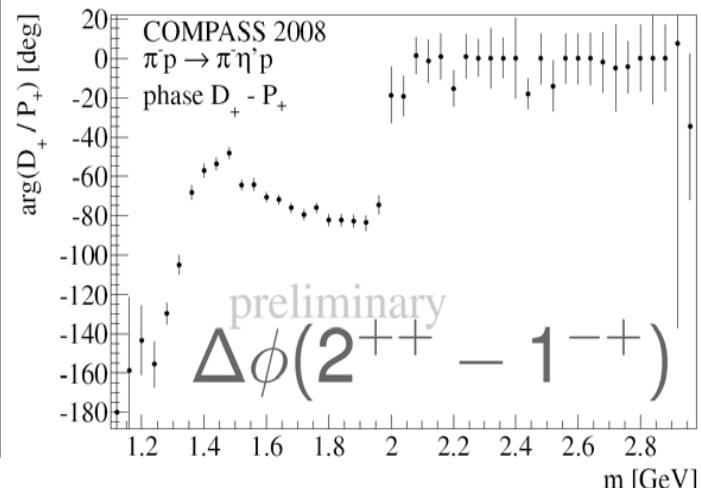
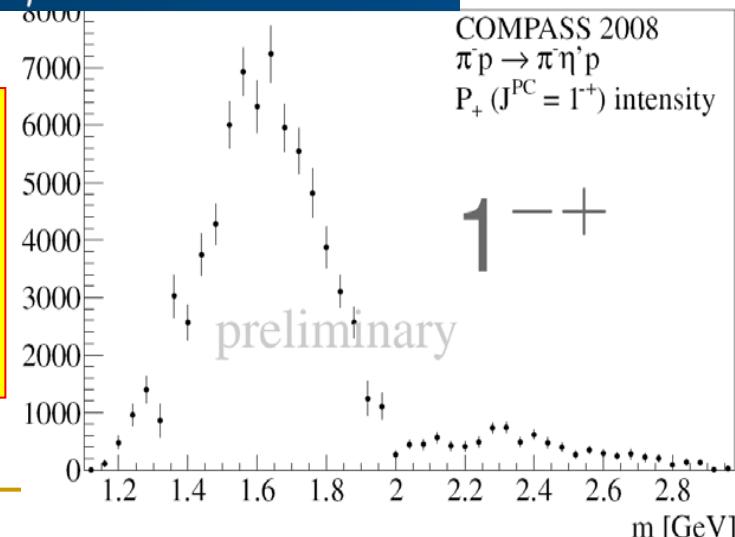
# Confirm $\pi_1(1600)$ at COMPASS

2008 run:  
**190 GeV  $\pi^-$  beam  
on liquid H<sub>2</sub>**  
 $\pi^- + p \rightarrow \pi^- \pi^- \pi^+ + p$   
**100 M events**



COMPASS:  $\pi^- + p \rightarrow \eta'\pi + p$   
The spin exotic  $J^{PC} = 1^{-+}$   $\eta'\pi$  P-wave

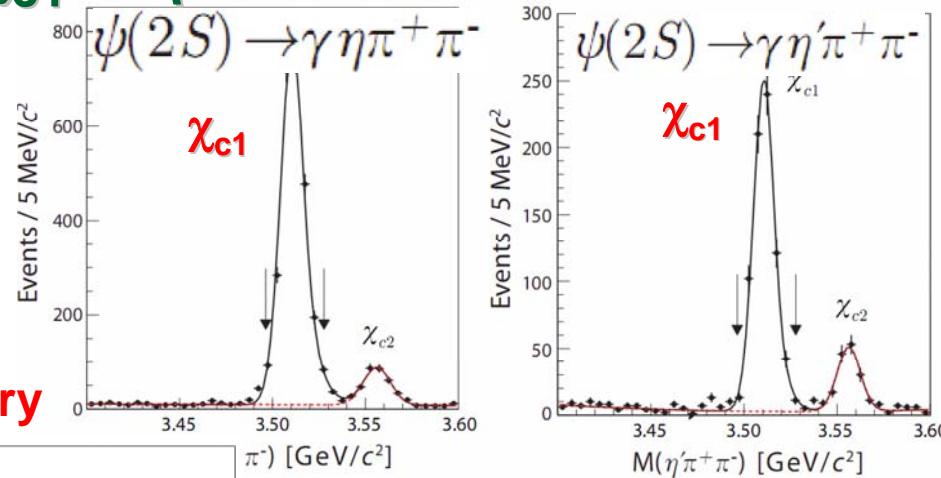
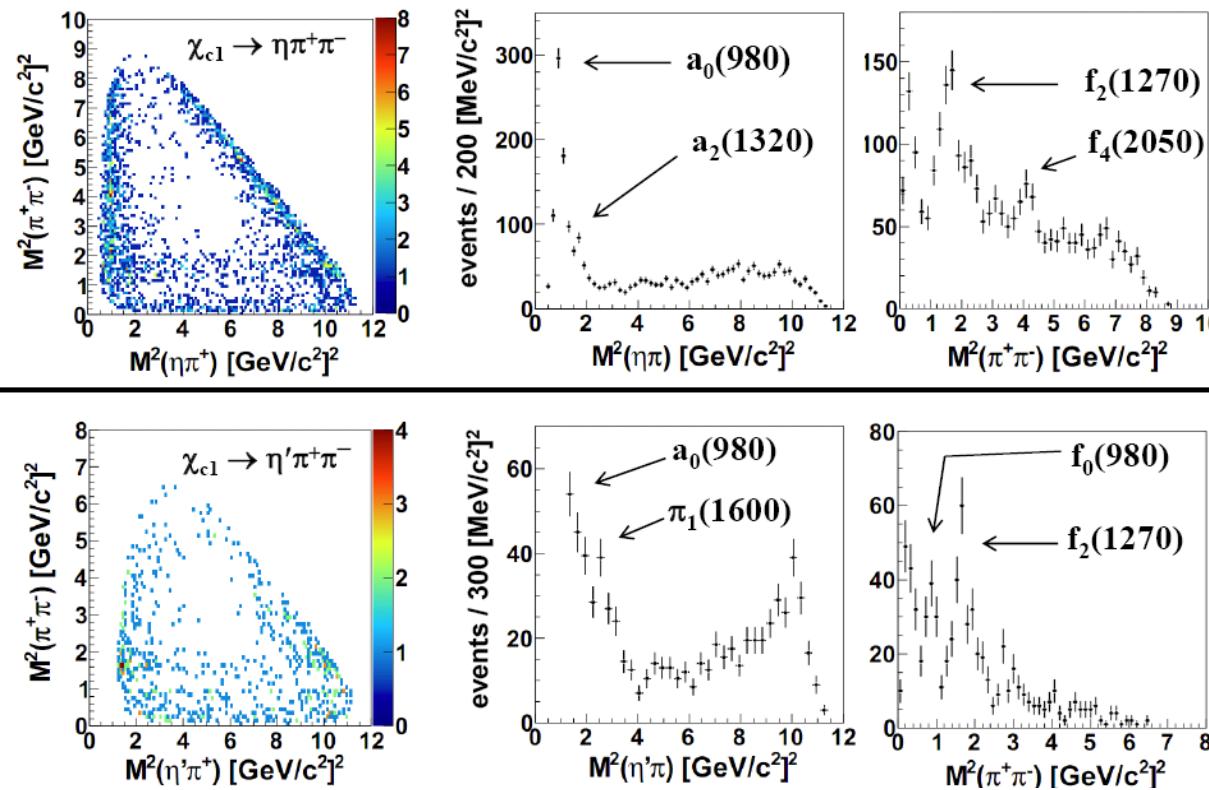
2008 run:  
**190 GeV  $\pi^-$  beam  
on liquid H<sub>2</sub>**  
 $\pi^- + p \rightarrow \eta' \pi^- + p$   
**Strong 1<sup>-+</sup> signal**



# Evidence for $\pi_1(1600)$ in $\chi_{c1} \rightarrow \eta' \pi^+ \pi^-$ at CLEO-c

- ✓ Very low background in  $\psi' \rightarrow \gamma \chi_{c1} \rightarrow \eta^{(\prime)} \pi^+ \pi^-$
- ✓ Opportunity to study  $\chi_{c1} \rightarrow \eta^{(\prime)} \pi^+ \pi^-$ 
  - study  $(\pi\pi)$ -S-wave
  - search for spin exotic,  $1^+$ ,  $\eta\pi$  or  $\eta'\pi$  states

CLEO-c preliminary



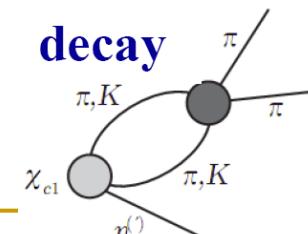
A full amplitude analysis  
with isobar model :

$\chi_{c1} \rightarrow$  isobar + bachelor hadron

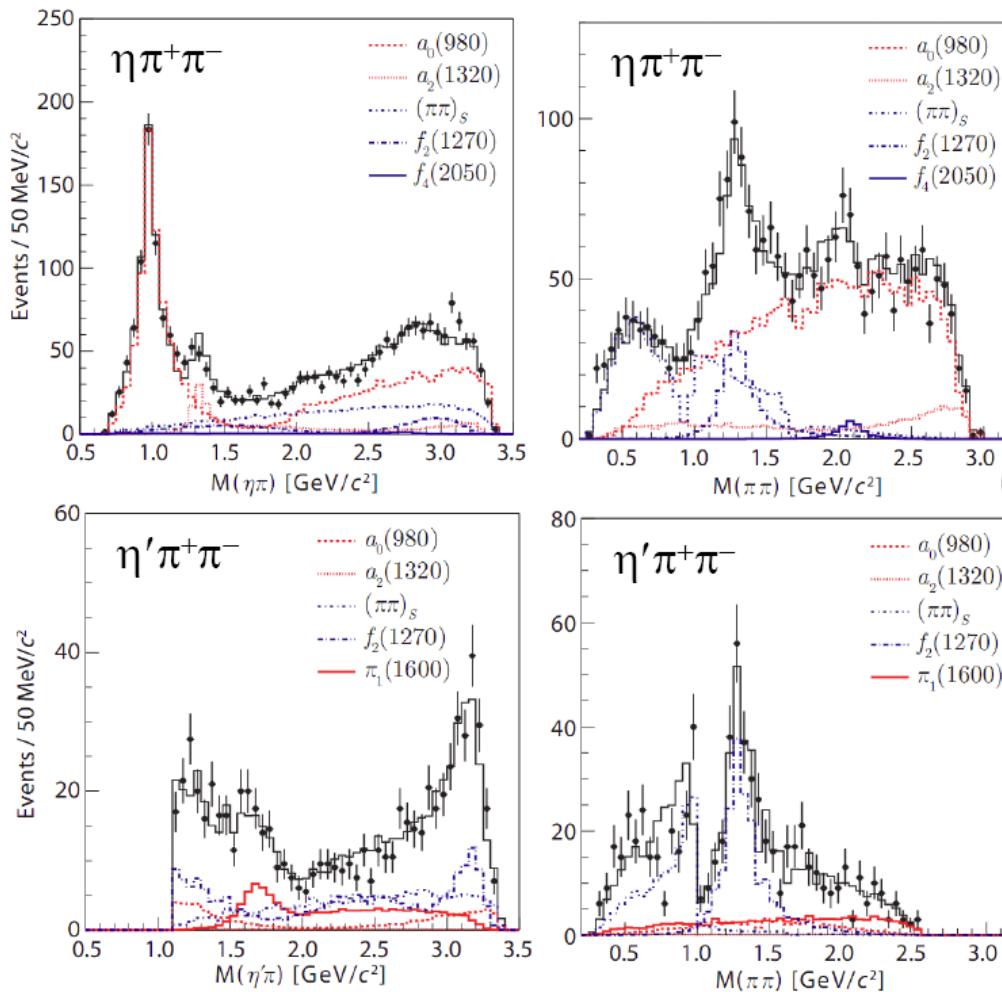
BW for most of resonances

Flatte:  $a_0(980)$

$\pi\pi$  S wave : KK,  $\pi\pi$  scattering



M. Kornicer  
PANIC11



$A_\alpha(x)$	$F [\%]$
$a_0(980)\pi$	$66.2 \pm 1.2 \pm 1.1$
$a_2(1320)\pi$	$9.8 \pm 0.8 \pm 1.0$
$(\pi\pi)_S\eta$	$22.5 \pm 1.3 \pm 2.4$
$f_2(1270)\eta$	$7.4 \pm 0.8 \pm 0.7$
$f_4(2050)\eta$	$1.0 \pm 0.3 \pm 0.3$

CLEO-c PRELIMINARY

$A_\alpha(x)$	$F [\%]$
$a_0(980)\pi$	$11.0 \pm 2.3 \pm 1.8$
$a_2(1320)\pi$	$0.4 \pm 0.5 \pm 0.6$
$(\pi\pi)_S\eta'$	$21.6 \pm 2.7 \pm 1.4$
$f_2(1270)\eta'$	$27.0 \pm 2.9 \pm 1.8$
$\pi_1(1600)\pi$	$15.1 \pm 2.7 \pm 3.2$

Assuming BW shape for  $1^+$ :  
 $M = 1670 \pm 30 \pm 20 \text{ MeV}/c^2$   
 $\Gamma = 240 \pm 50 \pm 60 \text{ MeV}$   
Significance  $> 4.0 \sigma$

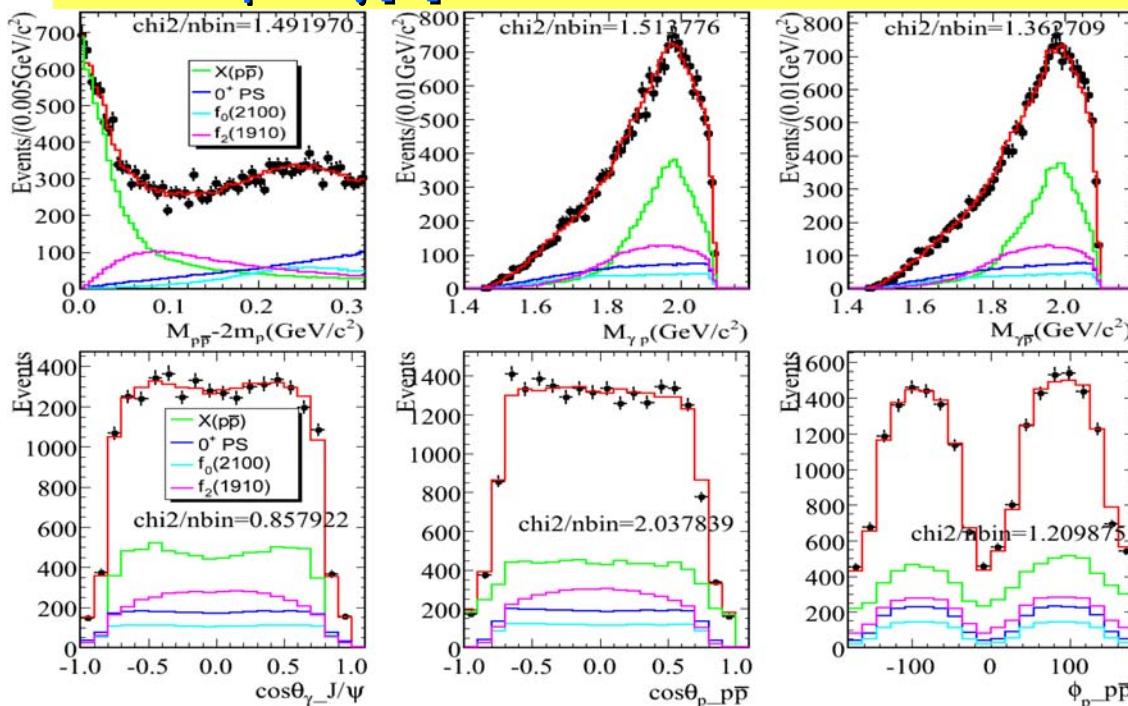
First evidence in charmonium decays Bo Li (IHEP)

First evidence for  $a_0 \rightarrow \eta'\pi$ :  

$$\frac{B(a_0(980) \rightarrow \eta'\pi)}{B(a_0(980) \rightarrow \eta\pi)} = 0.064 \pm 0.013 \pm 0.012$$

M. Kornicer PANIC11

# First Partial Wave Analysis near $p\bar{p}$ threshold in $J/\psi \rightarrow \gamma p\bar{p}$ at BESIII Preliminary



Spin-parity, mass, width and B.R. of  $X(p\bar{p})$ :

$J^{pc} = 0^{-+}$  >6.8  $\sigma$  better than other  $J^{pc}$  assignments.

$$M = 1832 \pm 5(\text{stat})^{+19}_{-17}(\text{syst}) \pm 19(\text{mod}) \text{ MeV}/c^2$$

$$\Gamma = 13 \pm 20(\text{stat})^{+11}_{-33}(\text{syst}) \pm 4(\text{mod}) \text{ MeV}/c^2 \text{ or } \Gamma < 48 \text{ MeV}/c^2 @ 90\% C.L.$$

$$B(J/\psi \rightarrow \gamma X(p\bar{p})) B(X(p\bar{p}) \rightarrow p\bar{p}) = (9.0 \pm 0.7(\text{stat})^{+1.5}_{-5.1}(\text{syst}) \pm 2.3(\text{mod})) \times 10^{-5}$$

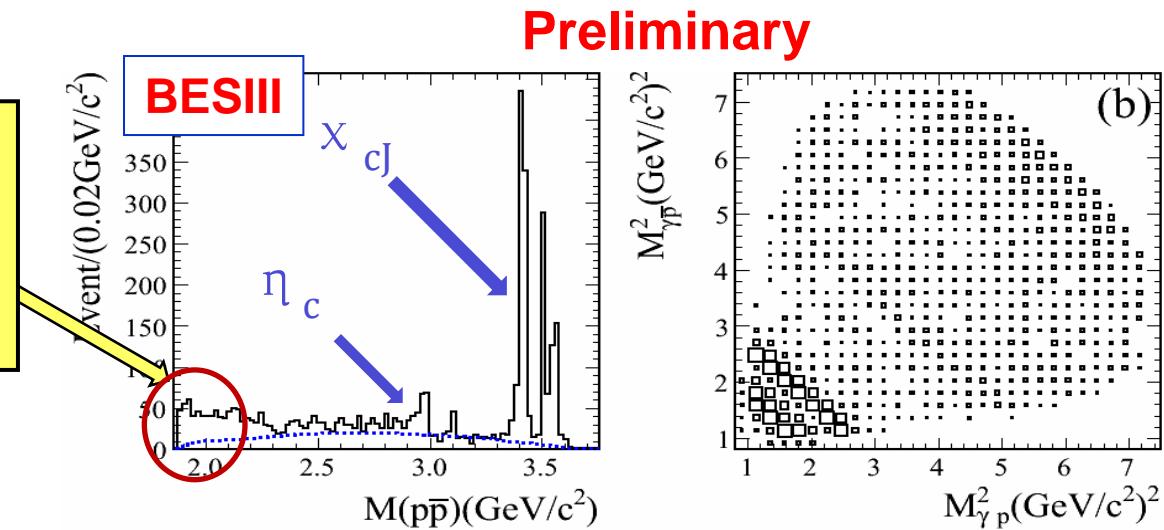
$f_0(2100)$  and  $f_2(1910)$  fixed to PDG.  
Significance of  $X(p\bar{p}) >> 30\sigma$

- The fit with a BW and S-wave FSI( $I=0$ ) factor can well describe ppb mass threshold structure.
- It is much better than that without FSI effect, and  $\Delta 2\ln L = 51 \Rightarrow 7.1\sigma$ .

Different FSI models → Model dependent uncertainty

# PWA on the $p\bar{p}$ mass threshold structure in $\psi' \rightarrow \gamma p\bar{p}$

Obviously different line shape of  $p\bar{p}$  mass spectrum near threshold from that in  $J/\psi$  decays



## PWA results:

- Significance of  $X(pp)$  is larger than  $6.9\sigma$ .
- The production ratio  $R$ :

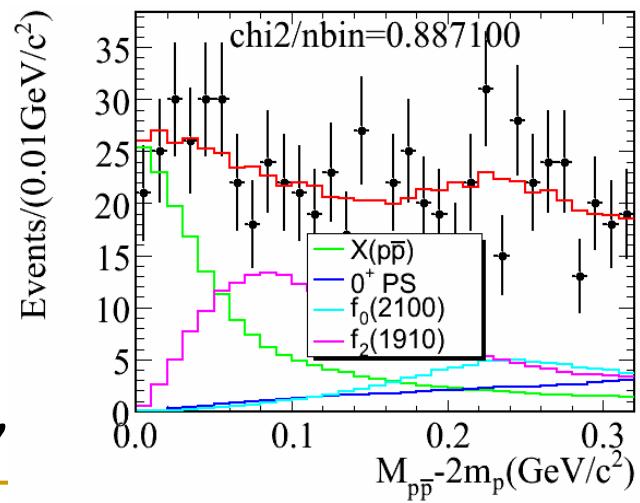
$$R = \frac{B(\psi' \rightarrow \gamma X(p\bar{p}))}{B(J/\psi \rightarrow \gamma X(p\bar{p}))}$$

$$= (5.08 \pm 0.56(\text{stat})^{+0.72}_{-3.83}(\text{syst}) \pm 0.12(\text{mod}))\%$$

- It is suppressed compared with “12% rule”

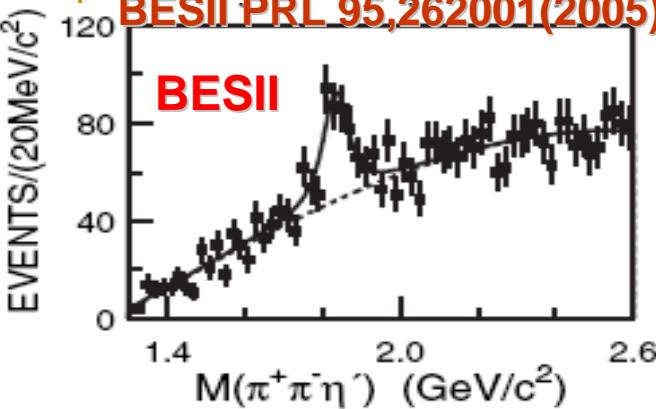
first measurement

## PWA Projection:



# Confirmation of X(1835) and two new structures at BESIII

BESII PRL 95,262001(2005)



BESII result (Stat. sig.  $\sim 7.7\sigma$ ):

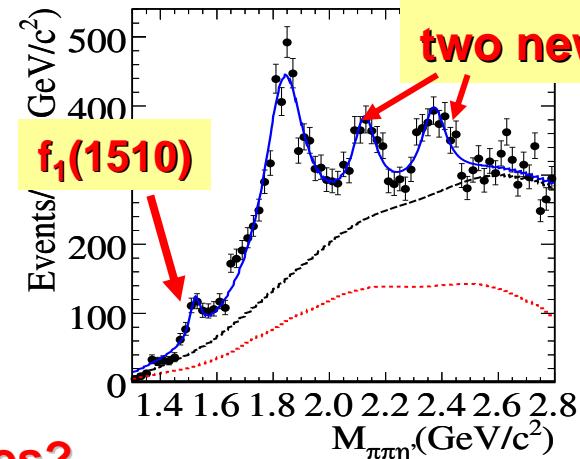
$$M = 1833.7 \pm 6.1(\text{stat}) \pm 2.7(\text{syst}) \text{ MeV}$$

$$\Gamma = 67.7 \pm 20.3(\text{stat}) \pm 7.7(\text{syst}) \text{ MeV}$$

**BESIII: 225M  
J/ψ events:**

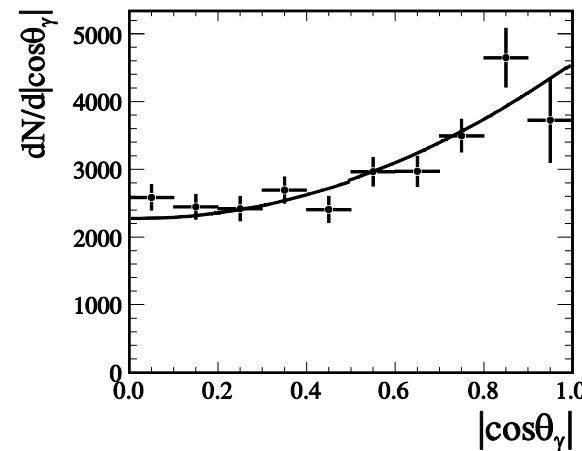
$$\begin{aligned} J/\psi &\rightarrow \gamma \eta' \pi^+ \pi^- \\ \eta' &\rightarrow \eta \pi^+ \pi^- \\ \eta' &\rightarrow \gamma \rho \end{aligned}$$

BESIII: PRL 106, 072002(2011)



**η' excited states?  
Glueball candidates?**

**The same state  
as that in p̄p enhancement?**



**X(1835) consistent with  
0<sup>+</sup>, but the others are  
not excluded**

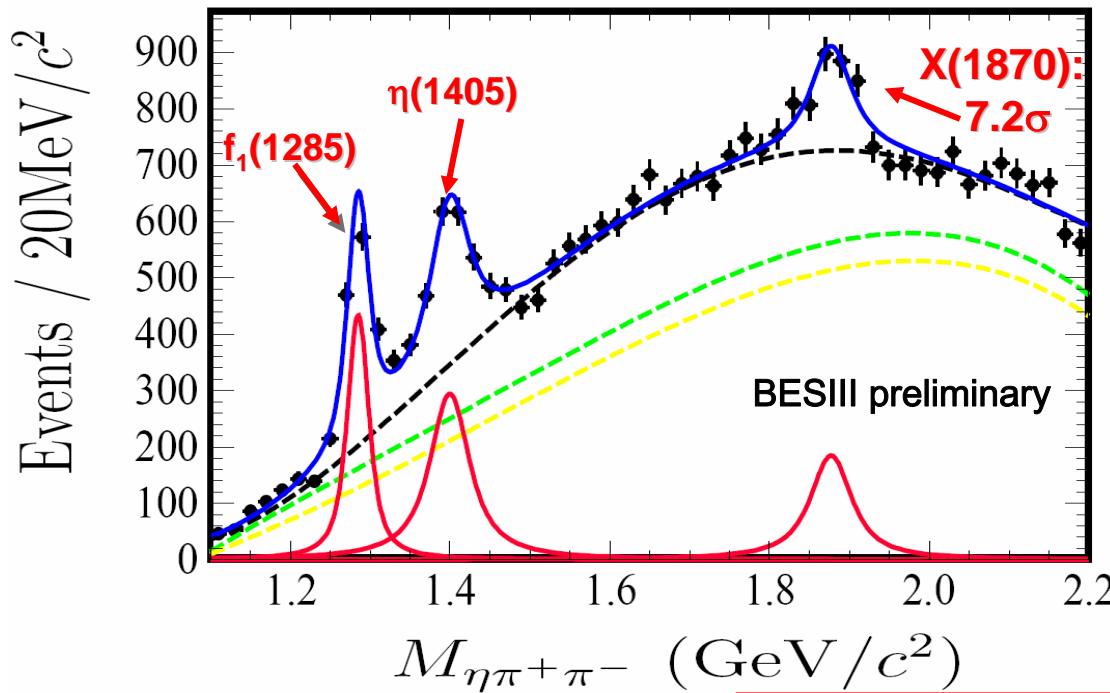
**BESIII fit results:**

Resonance	M (MeV/c²)	Γ (MeV/c²)	Stat.Sig.
X(1835)	$1836.5 \pm 3.0^{+5.6}_{-2.1}$	$190.1 \pm 9.0^{+38}_{-36}$	$>20\sigma$
X(2120)	$2122.4 \pm 6.7^{+4.7}_{-2.7}$	$83 \pm 16^{+31}_{-11}$	$7.2\sigma$
X(2370)	$2376.3 \pm 8.7^{+3.2}_{-4.3}$	$83 \pm 17^{+44}_{-6}$	$6.4\sigma$

An amplitude analysis will help with  
interpretation for the additional new structures!  
Mostly are candidates of η excited states.

# X(1870) in $J/\psi \rightarrow \omega X$ , $X \rightarrow a_0(980)\pi$ ( $a_0 \rightarrow \eta\pi^\pm$ ) at BESIII

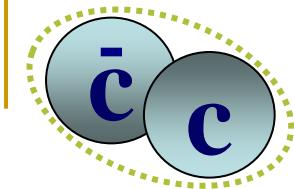
$J/\psi \rightarrow \omega\eta\pi^+\pi^-$ ,  $a_0(980)$  reconstructed in  $\eta\pi^\pm$



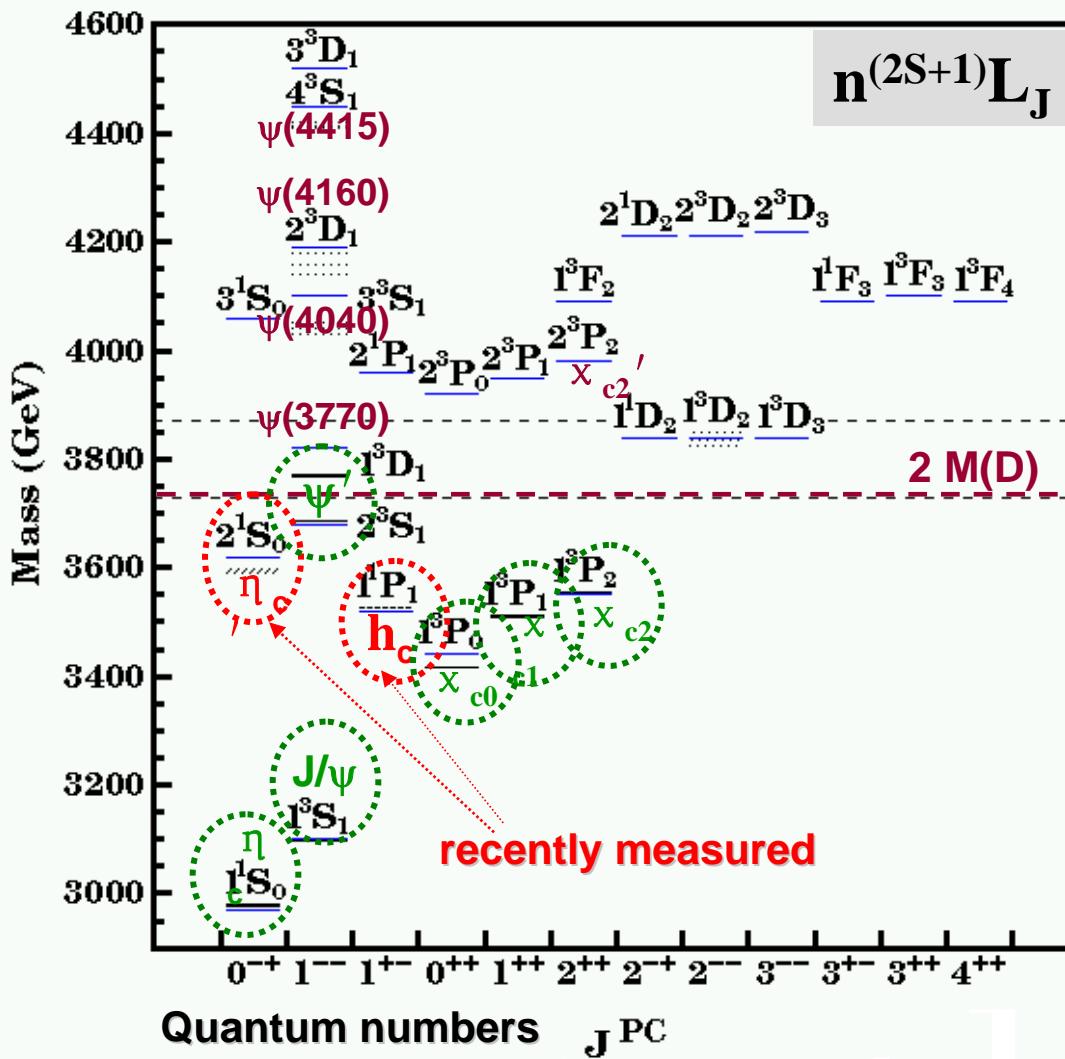
Identification of  $X(1870)$ :  
 $0^+(?)$   
It is  $X(1835)$ ?  
Need PWA!

$\text{BR}(J/\psi \rightarrow \omega X, X \rightarrow a_0^\pm(980)\pi^\mp)$

Resonance	Mass ( $\text{MeV}/c^2$ )	Width ( $\text{MeV}/c^2$ )	Branch ratio ( $10^{-4}$ )
$f_1(1285)$	$1285.1 \pm 1.0^{+1.6}_{-0.3}$	$22.0 \pm 3.1^{+2.0}_{-1.5}$	$1.25 \pm 0.10^{+0.19}_{-0.20}$
$\eta(1405)$	$1399.8 \pm 2.2^{+2.8}_{-0.1}$	$52.8 \pm 7.6^{+0.1}_{-7.6}$	$1.89 \pm 0.21^{+0.21}_{-0.23}$
$X(1870)$	$1877.3 \pm 6.3^{+3.4}_{-7.4}$	$57 \pm 12^{+19}_{-4}$	$1.50 \pm 0.26^{+0.72}_{-0.36}$



# Charmonia



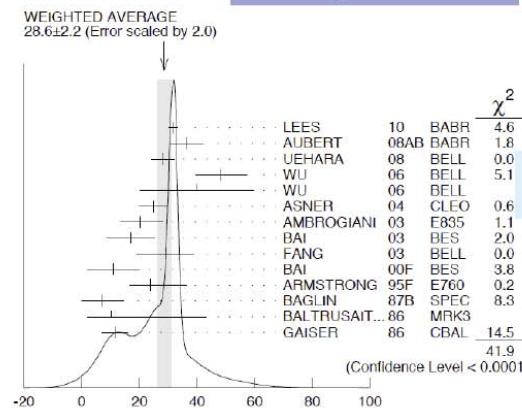
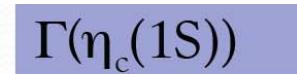
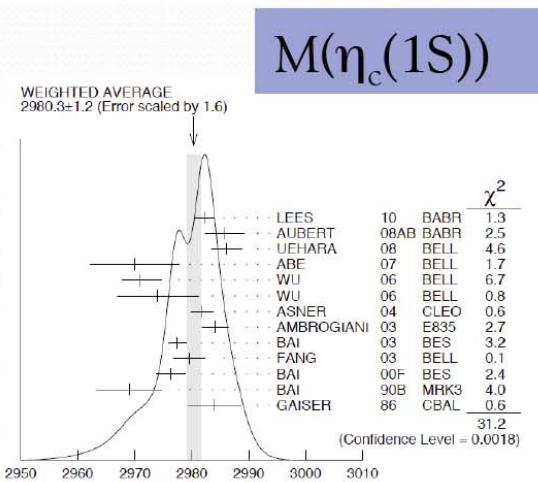
New measurements of mass and width for  $\eta_c(1S)/\eta_c(2S)/h_c(1P)$

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

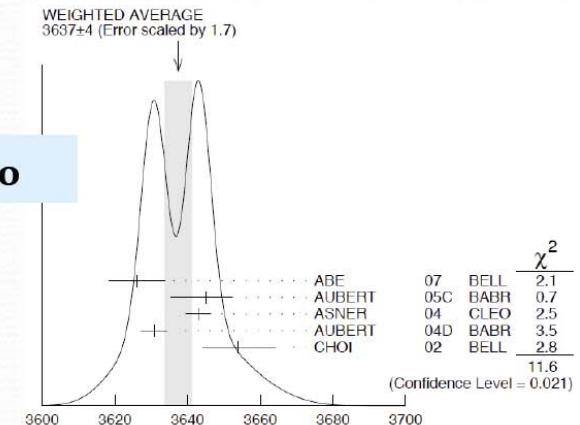
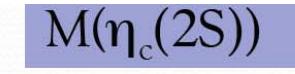
Observation of new  $\eta_c(2S)$  decay mode

Determination of resonant parameters for  $J/\psi$ ,  $\psi(2S)$  and  $\psi(3770)$

# Status of $\eta_c(1S)$ and $\eta_c(2S)$



PDG 2010



$\eta_c(1S)$  observed by several experiments, but there is a large spread in mass and width measurements

$$\Gamma(\eta_c(1S)) \approx 15 \text{ MeV}$$

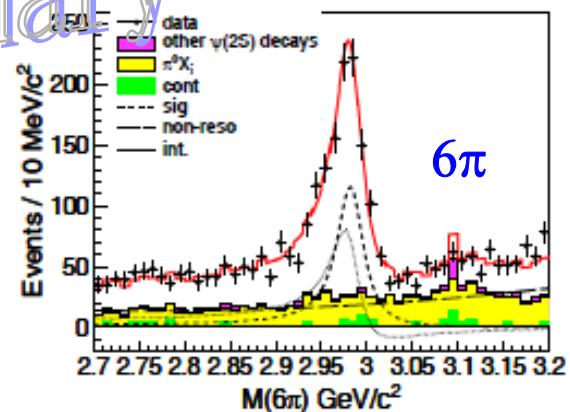
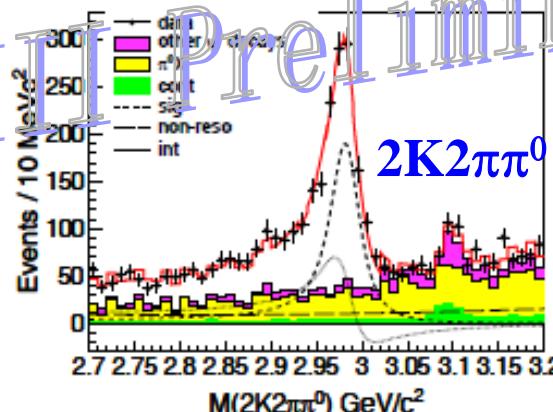
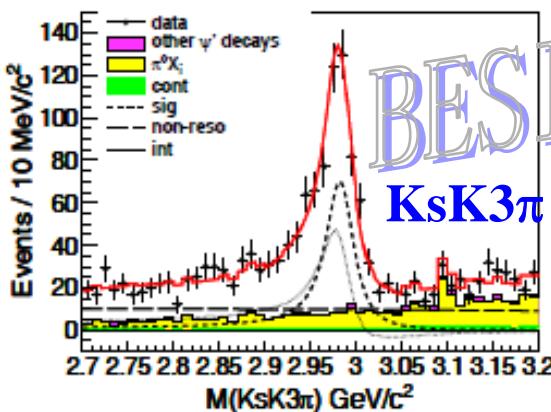
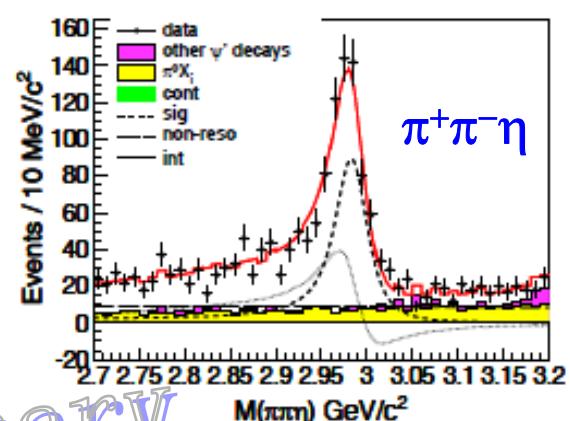
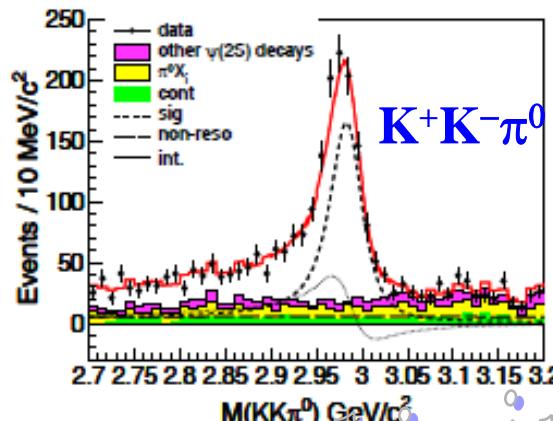
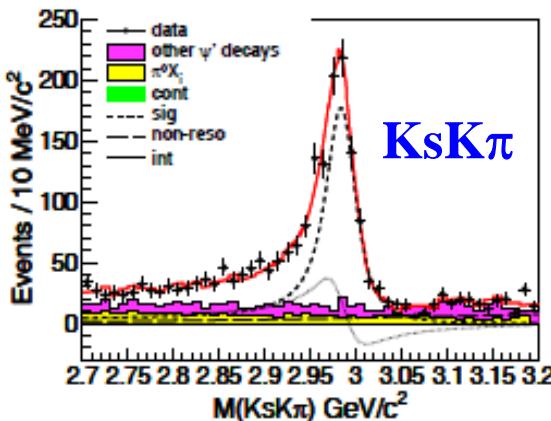
(J/ $\psi$ ,  $\psi(2S)$  radiative decays)

$$\Gamma(\eta_c(1S)) \approx 30 \text{ MeV}$$

(B decays /  $\gamma\gamma$  productions )

Until recently has been only observed in exclusive decay  $K\bar{K}\pi$ . Precise measurement of  $\eta_c(2S)$  parameters will help discriminate among different charmonium model.

# $\eta_c$ resonance parameters from $\psi' \rightarrow \gamma \eta_c$ at BESIII



Considering the interference between  $\eta_c$  and non-resonant decays,

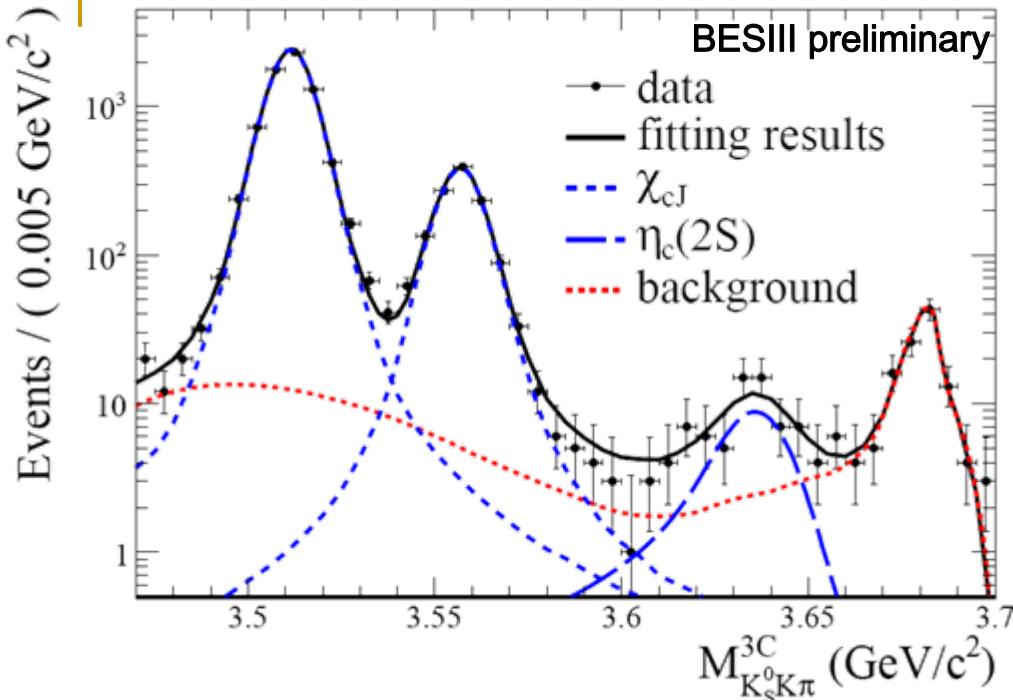
mass:  $2984.4 \pm 0.5_{\text{stat}} \pm 0.6_{\text{sys}} \text{ MeV}/c^2$

width:  $30.5 \pm 1.0_{\text{stat}} \pm 0.9_{\text{sys}} \text{ MeV}$

$\phi$ :  $2.35 \pm 0.05_{\text{stat}} \pm 0.04_{\text{sys}} \text{ rad}$

$\phi$ : relative phase between  $\eta_c$  and non-resonant component. An universal phase for different modes is used.

# First observation of $\eta_c(2S)$ in $\psi' \rightarrow \gamma \eta_c(2S), \eta_c(2S) \rightarrow K_s K\pi$



$$(E_\gamma^3 \times BW(m) \times damping(E_\gamma)) \otimes Gauss(0, \sigma)$$

M1 transition

$$\frac{E_0^2}{E_\gamma E_0 + (E_\gamma - E_0)^2}$$

With 106M  $\psi'$  events at BESIII:

$$M(\eta_c(2S)) = (3638.5 \pm 2.3 \pm 1.0) \text{ MeV}/c^2$$

$$N(\eta_c(2S)) = 50.6 \pm 9.7$$

Statistical significance larger than  $6.0\sigma$ !

$$\begin{aligned} Br(\psi' \rightarrow \gamma \eta_c(2S) \rightarrow \gamma K_s K\pi) \\ = (2.98 \pm 0.57_{\text{stat}} \pm 0.48_{\text{sys}}) \times 10^{-6} \end{aligned}$$

+

$$\begin{aligned} Br(\eta_c(2S) \rightarrow K_s K\pi) &= (1.9 \pm 0.4 \pm 1.1)\% \\ \text{From BABAR(PRD78,012006)} \end{aligned}$$



$$\begin{aligned} Br(\psi' \rightarrow \gamma \eta_c(2S)) \\ = (4.7 \pm 0.9_{\text{stat}} \pm 3.0_{\text{sys}}) \times 10^{-4} \end{aligned}$$

CLEO-c:  $< 7.6 \times 10^{-4}$  PRD81,052002(2010)

Potential model:  $(0.1 - 6.2) \times 10^{-4}$   
PRL89,162002(2002)

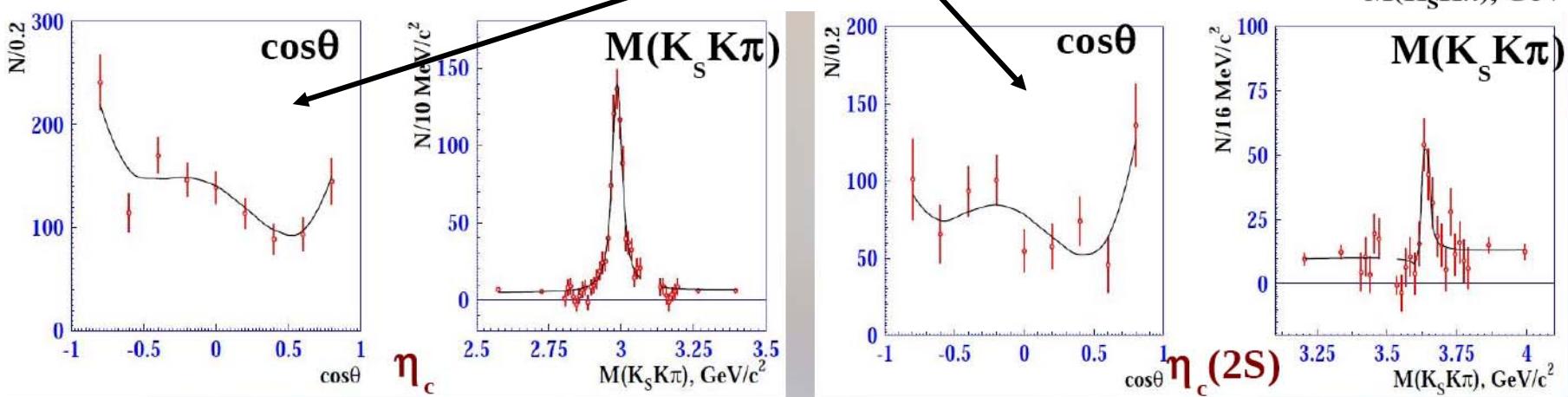
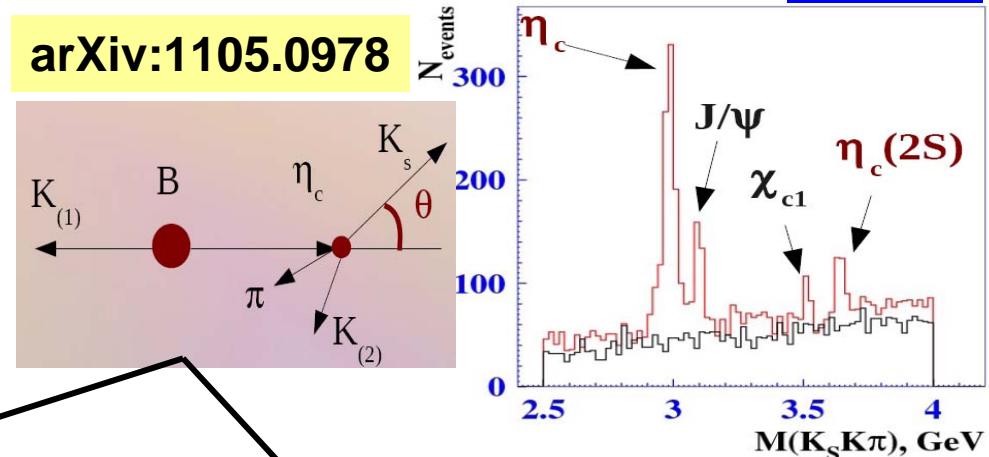
$\Gamma(\eta_c(2S))$  fixed to 12MeV (world average)

# $\eta_c$ and $\eta_c(2S)$ in $B^\pm \rightarrow K^\pm(K_S K\pi)^0$ at Belle



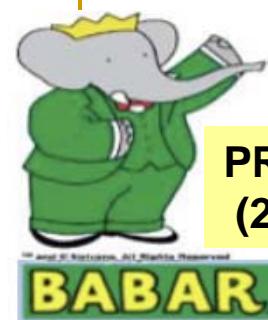
Considering the interference between  $\eta_c/\eta_c(2S)$  signal and non-resonance

Using  $M(K_S K\pi)$  and  $\cos(\theta)$  distributions to distinguish signal from non-resonant backgrounds  $\Rightarrow$  2D-fit

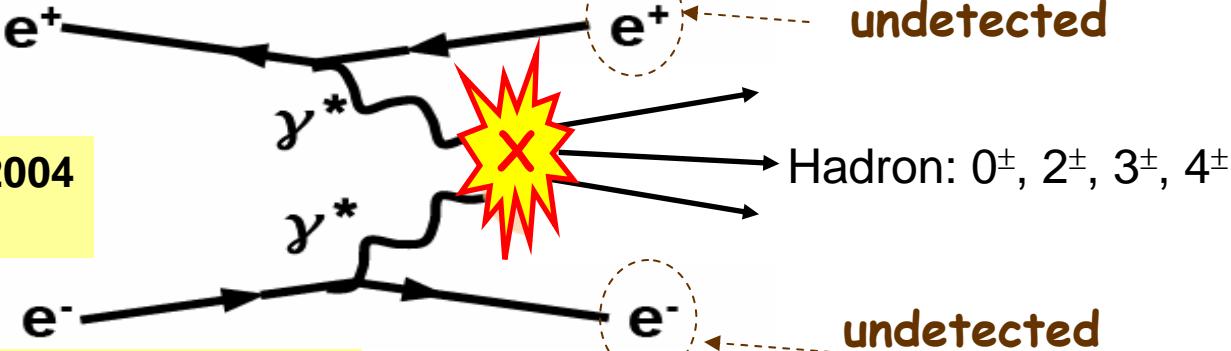


$M(\eta_c)$ , MeV	$2985.4 \pm 1.5 (\text{stat})^{+0.2}_{-2.0} (\text{syst})$	$M(\eta_c(2S))$ , MeV	$3636.1^{+3.9}_{-4.2} (\text{stat+model})^{+0.5}_{-2.0} (\text{syst})$
$\Gamma(\eta_c)$ , MeV	$35.1 \pm 3.1 (\text{stat})^{+1.0}_{-1.6} (\text{syst})$	$\Gamma(\eta_c(2S))$ , MeV	$6.6^{+8.4}_{-5.1} (\text{stat+model})^{+2.6}_{-0.9} (\text{syst})$

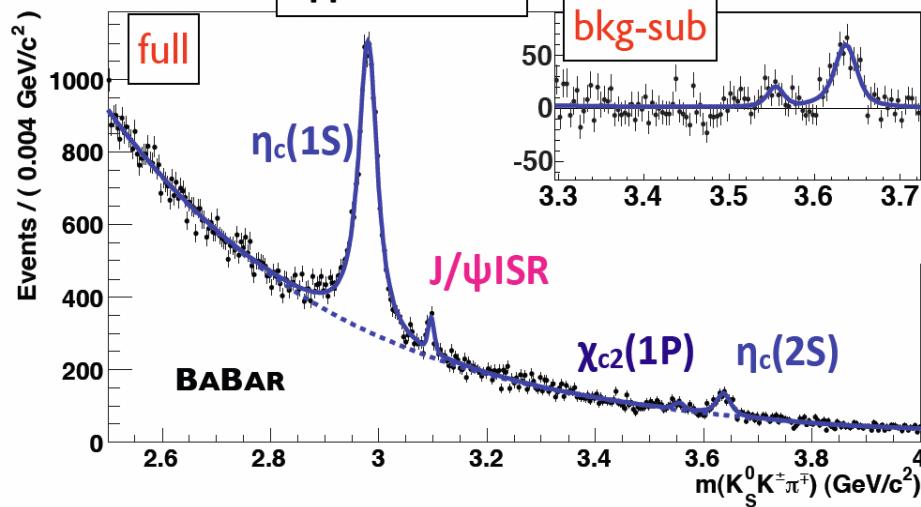
# $\eta_c(1S)/\eta_c(2S)$ in two photon fusion at BABAR



PRD 84, 012004  
(2011)

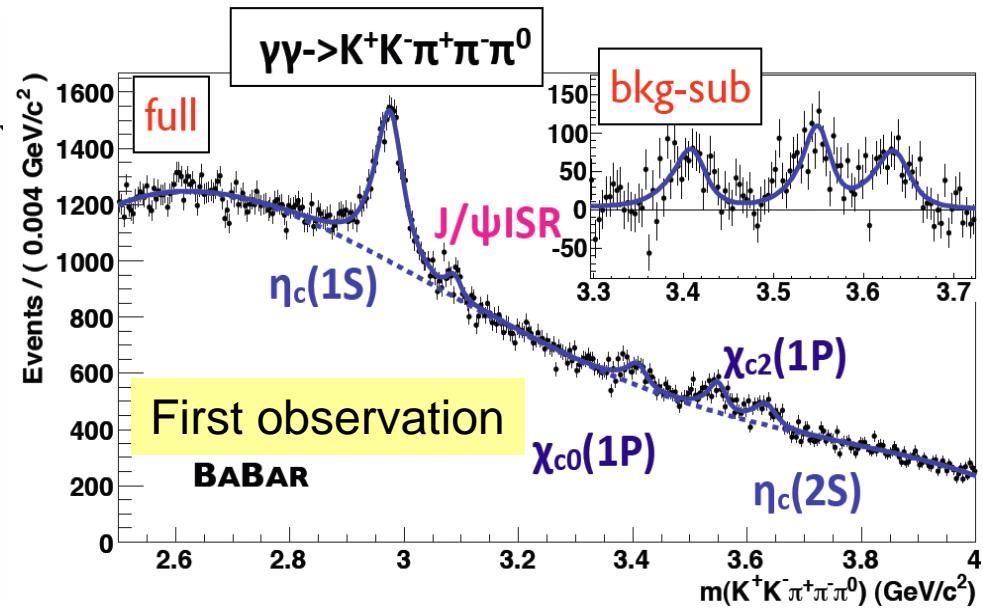


Full data set at BABAR:  $519 \text{ fb}^{-1}$



$$M(\eta_c(1S)) = 2982.2 \pm 0.4 \pm 1.4 \text{ MeV}/c^2$$

$$\Gamma(\eta_c(1S)) = 32.1 \pm 1.1 \pm 1.3 \text{ MeV}$$



$$M(\eta_c(2S)) = 3638.5 \pm 1.5 \pm 0.8 \text{ MeV}/c^2$$

$$\Gamma(\eta_c(2S)) = 13.4 \pm 4.6 \pm 3.2 \text{ MeV}$$

Most precise measurement for  $\eta_c(2S)$

# Comparison of the mass and width for $\eta_c/\eta_c(2S)$

	BESIII [2011] preliminary $\psi(2S) \rightarrow \gamma \eta_c/\eta_c(2S)$	Belle[2011] arXiv:1105.0978 B decays	BABAR[2011] PRD 84 012004 $\gamma\gamma$ fusion	PDG 2011
$M(\eta_c)$ , MeV/c <sup>2</sup>	<b>2984.4 ± 0.5 ± 0.6</b>	$2985.4 \pm 1.5^{+0.2}_{-2.0}$	<b>2982.2 ± 0.4 ± 1.4</b>	<b>2980.3 ± 1.2</b>
$\Gamma(\eta_c)$ , MeV	<b>30.5 ± 1.0 ± 0.9</b>	$35.1 \pm 3.1^{+1.0}_{-1.6}$	<b>32.1 ± 1.1 ± 1.3</b>	<b>28.6 ± 2.2</b>
$M(\eta_c(2S))$ , MeV	<b>3638.5 ± 2.3 ± 1.0</b>	$3636.1^{+3.9}_{-1.5} {}^{+0.5}_{-2.0}$	<b>3638.5 ± 1.5 ± 0.8</b>	<b>3637 ± 4</b>
$\Gamma(\eta_c(2S))$ , MeV	<b>12 (fixed)</b>	$6.6^{+8.4}_{-5.1} {}^{+2.6}_{-0.9}$	<b>13.4 ± 4.6 ± 3.2</b>	<b>14 ± 7</b>

- First observation of  $\eta_c(2S)$  in  $\psi(2S)$  radiative decay from BESIII
- Most precise measurement for  $\eta_c$  parameters is from BESIII
- Most precise measurement for  $\eta_c(2S)$  parameters is from BABAR  $\gamma\gamma$  fusion
- Hyperfine splitting:  $\Delta M(1S) = 112.5 \pm 0.8$  MeV;  $\Delta M(2S) = 47.6 \pm 1.7$  MeV

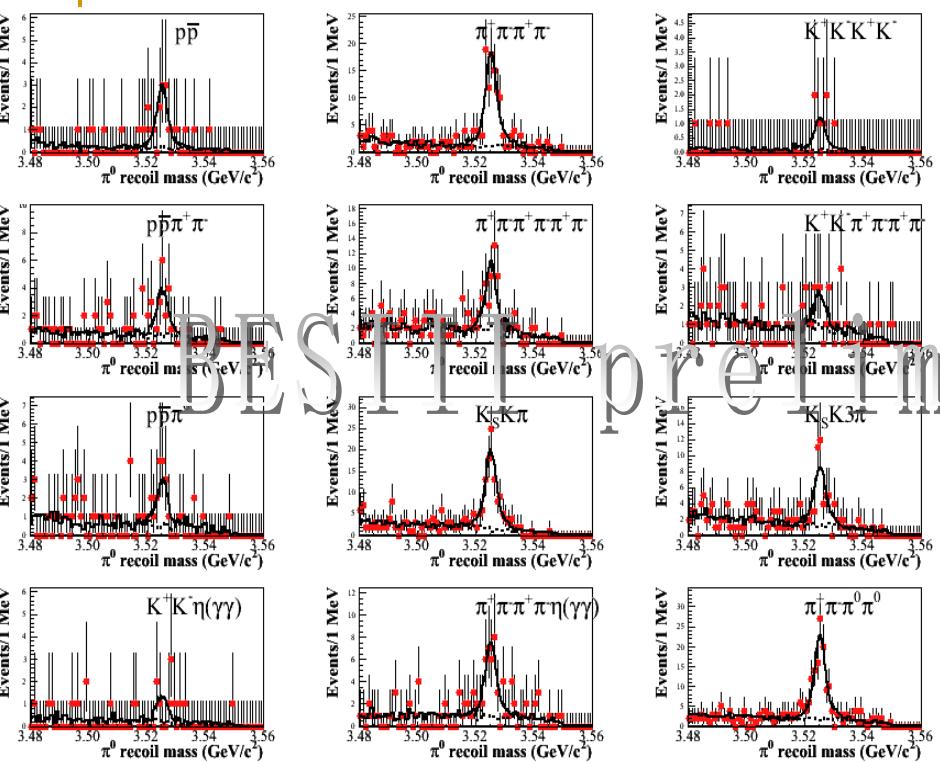
$$\Delta M_{hf}(nS) \equiv M(n^3S_1) - M(n^1S_0) = \frac{32\pi\alpha_S}{9m_1m_2} |\psi_n(0)|^2$$

K. Seth, arXiv:0912.2776

$$\begin{aligned}\Delta M(1S) &\approx 118 \text{ MeV} \\ \Delta M(2S) &\approx 68 \text{ MeV}\end{aligned}$$

Discrepancies on  $M(\eta_c)$  and  $\Gamma(\eta_c)$  disappear in different production processes.

# $h_c(1^1P_1)$ in $\psi' \rightarrow \pi^0 h_c$ , $h_c \rightarrow \gamma \eta_c$ , $\eta_c \rightarrow X_i$ (16 $\eta_c$ modes)



Simultaneous fit to  $\pi^0$  recoiling mass  
in 106M  $\psi'$  sample:

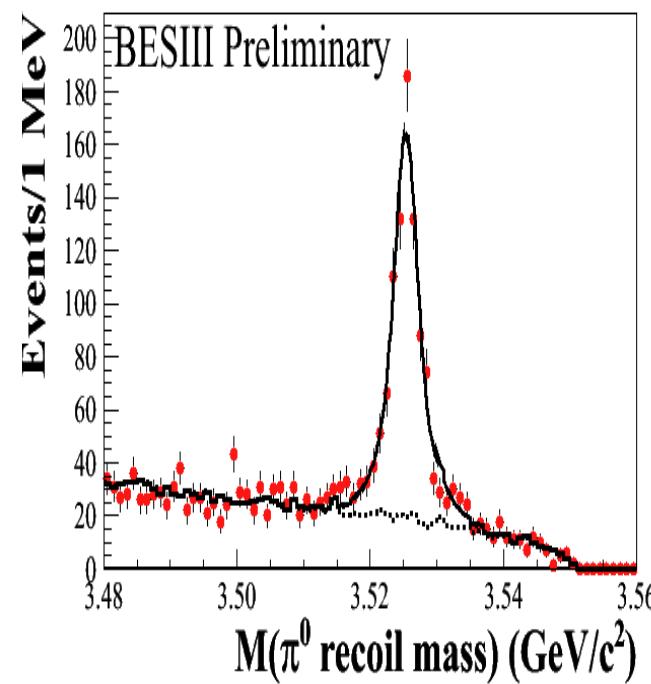
$$M(h_c) = 3525.31 \pm 0.11_{\text{(stat)}} \pm 0.15_{\text{(sys)}} \text{ MeV}/c^2$$

$$\Gamma(h_c) = 0.70 \pm 0.28_{\text{(stat)}} \pm 0.25_{\text{(sys)}} \text{ MeV}$$

$$N = 832 \pm 35$$

$$\Delta M_{\text{hf}} = -0.01 \pm 0.11 \pm 0.14 \text{ MeV} \text{ (Hypfine splitting)}$$

Sum of  $\pi^0$  recoil mass



Consistent with BESIII inclusive results PRL104,132002(2010)

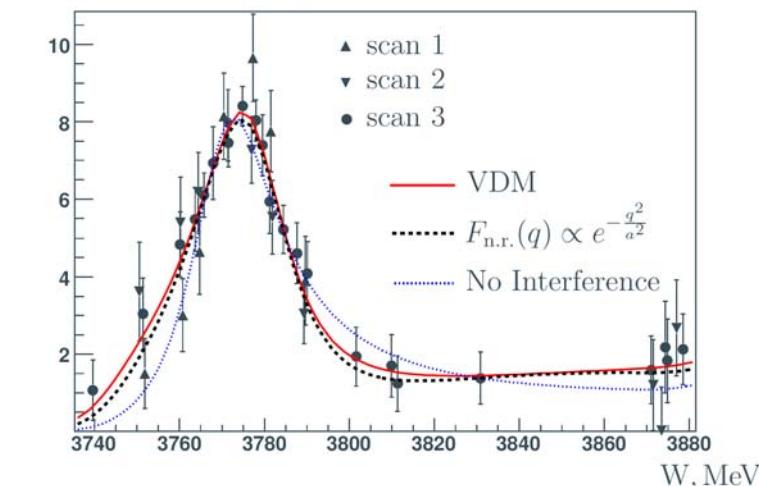
CLEO-c exclusive results:  
 $M(h_c) = 3525.21 \pm 0.27 \pm 0.14 \text{ MeV}/c^2$   
 $N = 136 \pm 14$

# Determination of $\psi(3770)$ parameters by KEDR/VEPP-4M

$e^+e^- \rightarrow \text{hadrons}$ , light quarks contribution is subtracted

$$\sigma_{D\bar{D}} \propto |A_{\psi(3770)} e^{i\phi} + F_{\text{n.r.}}|^2$$

$$\sigma_{D\bar{D}} \propto |A_{\psi(3770)} e^{i\phi} + A_{\psi(2S)} + B|^2$$



Interference between  $A_{\psi(3770)}$  and  $A_{\psi(2S)}$  is important, and was firstly considered in Mod.Phys.Lett. A 23, 3113 (2008) [Yang] and PRD 81, 011501(R) [LI, Qin and Yang]

Two solutions with close  $M$ ,  $\Gamma$  and different  $(\phi, \Gamma_{ee})$

	solution 1	solution 2	No Interf.
$M$ , MeV	$3779.6 \pm 1.8$	$3779.4 \pm 1.8$	$3773.0 \pm 0.5$
$\Gamma$ , MeV	$24.7 \pm 4.4$	$24.7 \pm 4.1$	$24.0 \pm 2.4$
$\Gamma_{ee}$ , eV	$142 \pm 79$	$508 \pm 68$	$306 \pm 29$
$\phi$ , degrees	$155. \pm 35.$	$254. \pm 14.$	—
$P(\chi^2)$ , %	18.8	19.1	1.8

Interference between resonance and continuum is important for mass and  $\Gamma_{ee}$

PDG:  $\Gamma_{ee} = (259 \pm 16)$  keV w/o interference

Anomalous lineshape is not observed

BESII observed lineshape anomaly  
[BESII, PRL 101, 102004(2008)]

KEDR final results on  $\psi(3770)$  parameters:

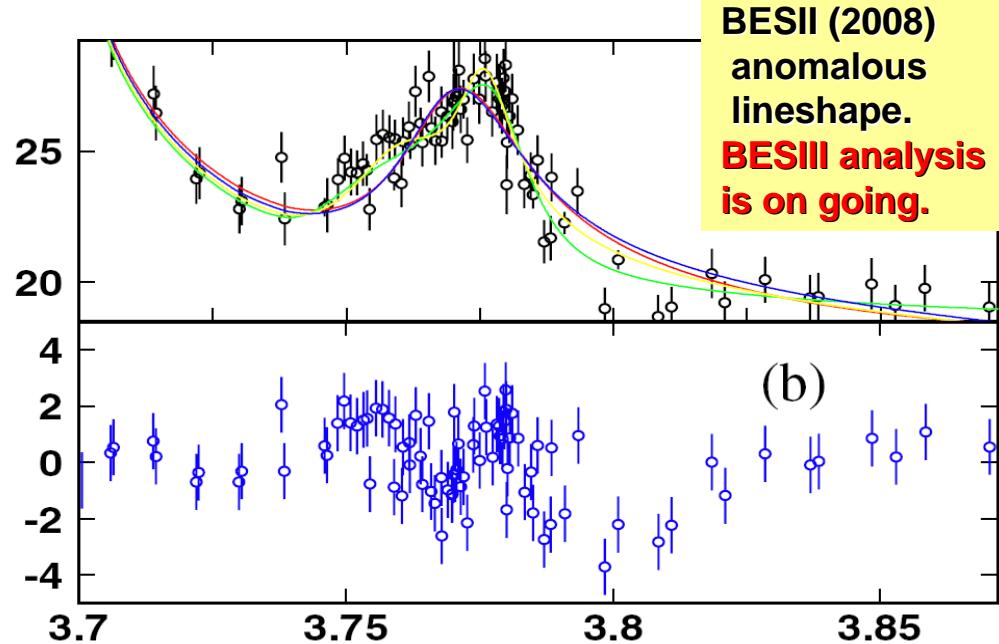
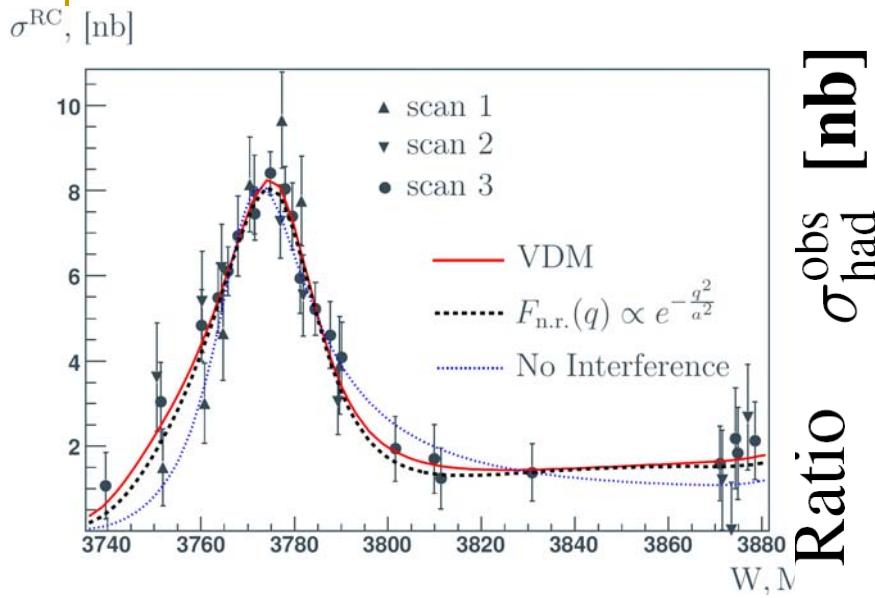
$$M = 3779.5 \pm 1.8 \pm 0.6^{+0.2}_{-0.3} \text{ MeV},$$

$$\Gamma = 24.7 \pm 4.4 \pm 0.3^{+1.5}_{-0.1} \text{ MeV}.$$

- (1)  $\Gamma_{ee} = 142 \pm 79 \pm 13^{+50}_{-10}$  eV,
- (2)  $\Gamma_{ee} = 508 \pm 68 \pm 46^{+200}_{-10}$  eV.

The potential model favors low  $\Gamma_{ee}$

# Determination of $\psi(3770)$ parameters by KEDR/VEPP-4M



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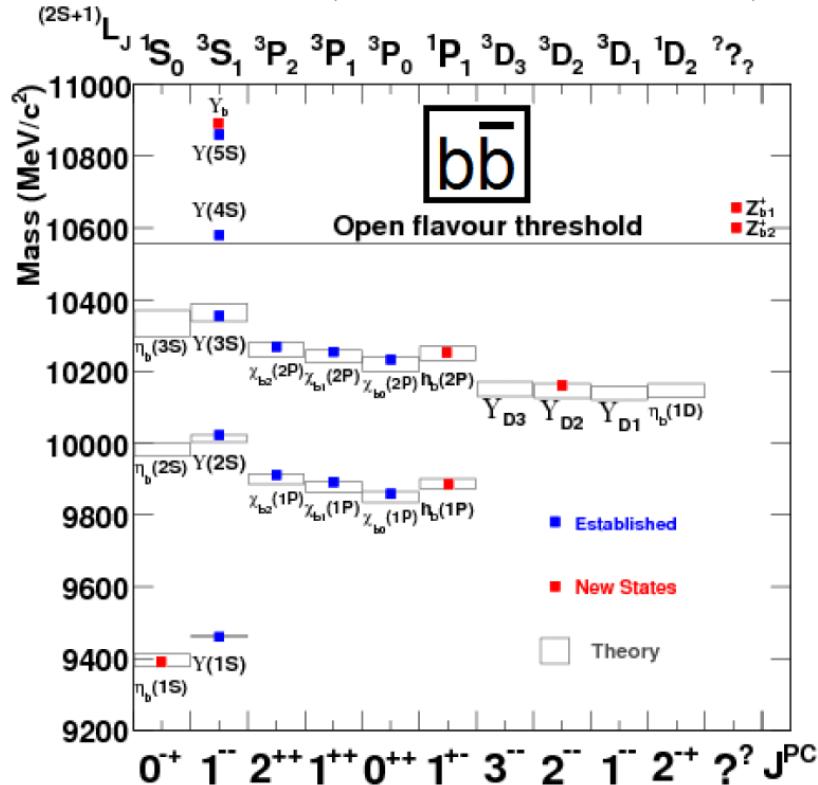
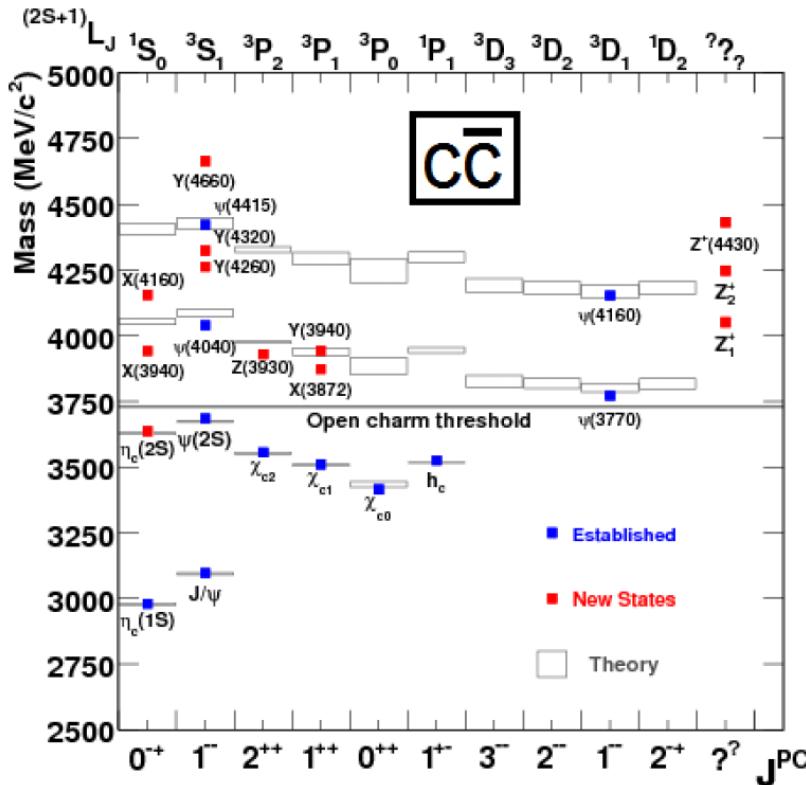
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The potential model favors low  $\Gamma_{ee}$

# Charmonium-like and Bottomonium-like states



**XYZ from B factories cannot fill into the empty slots.**

**New results**

**X(3872) from Belle, CMS and LHCb**

**X(4260) from B factories**

**X(4140) from LHCb**

**Indication of  $(XYZ)_b$  like states from factories.**

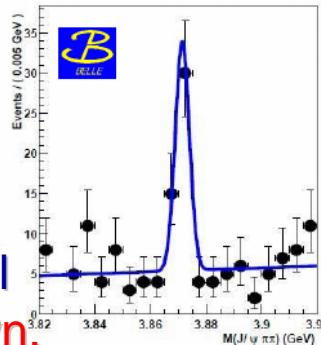
**New observations:**

**$h_b(1P)$ ,  $h_b(2P)$ , charged  $Z_{b1}$  and  $Z_{b2}$**

# X(3872) properties

X(3872) first observed by Belle in 2003 in  $B \rightarrow K X, X \rightarrow J/\psi \pi^+ \pi^-$ .

Mass is close to the ( $D^0$  anti $D^{*0}$ ) threshold. Width is less than experimental resolution. Confirmed by BABAR, CDF, D0, LHCb, CMS. **Nature not known.**



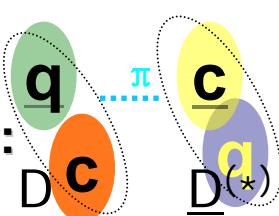
Determination of quantum numbers of X(3872)

- Evidence for  $X(3872) \rightarrow J/\psi \gamma$  established  $C = +1$   
[Belle arXiv:1105.0177; BABAR PRL 102 132001]
- $X(3872) \rightarrow J/\psi \pi^+ \pi^-$  by CDF  $\Rightarrow 1^{++}$  or  $2^{-+}$  [PRL 98 132002]
- $X(3872)$  not seen  $\chi_{c1}\gamma, \chi_{c2}\gamma$  and  $J/\psi \eta$  modes  
**indicate that X may be not a conventional cc state**
- $X(3872) \rightarrow J/\psi \omega$  by BABAR favors  $2^{-+}$  [PRD 82 011101]

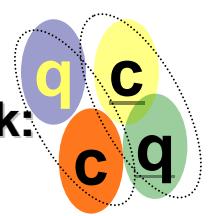
Conventional:



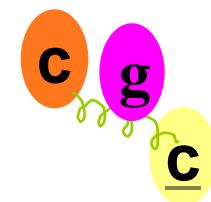
Molecular:



Tetraquark:



Hybrid :



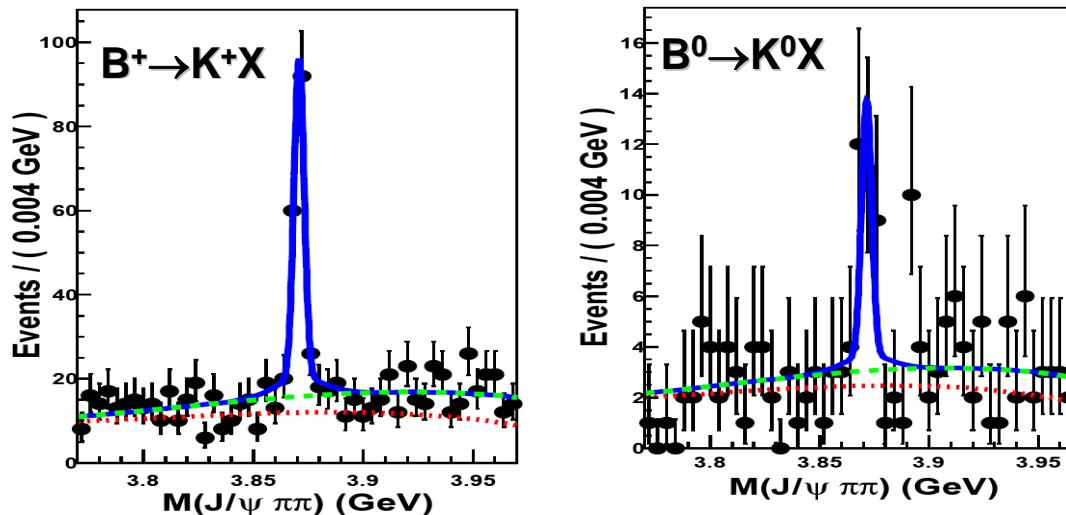
Still experimental results appear:  
new results from full Belle data sample:  $711 \text{ fb}^{-1}$

# Update of $X(3872) \rightarrow J/\psi \pi^+ \pi^-$ in B decay at Belle

arXiv:1107.0163

Full Belle data sample:  $711 \text{ fb}^{-1}$

Diquark-antidiquark model predicts mass difference  $\Delta M_X$  on the X mass in the two modes  $B^+ \rightarrow K^+(J/\psi \pi^+ \pi^-)$  and  $B^0 \rightarrow K^0(J/\psi \pi^+ \pi^-)$



$\Delta M_X = (-0.69 \pm 0.97 \pm 0.19) \text{ MeV} \Rightarrow$  is consistent with zero, the same particle.

$M_X = (3871.84 \pm 0.27 \pm 0.19) \text{ MeV} \quad \Gamma_X < 1.2 \text{ MeV (90\% C.L.)}$

CDF:  $M_X = (3871.61 \pm 0.16 \pm 0.19) \text{ MeV [PRL103,152001]}$

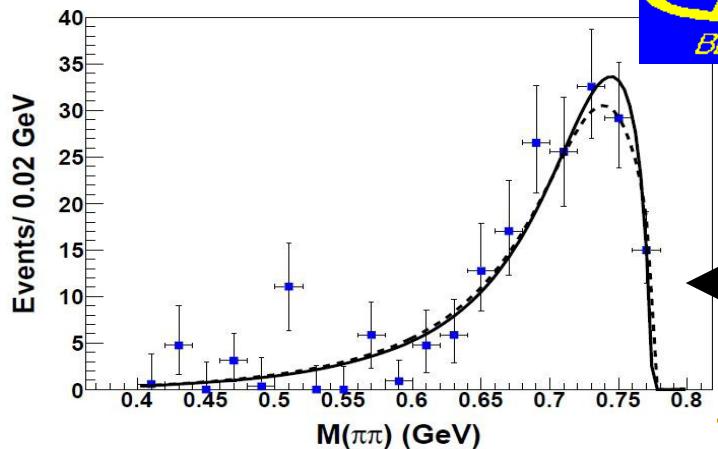
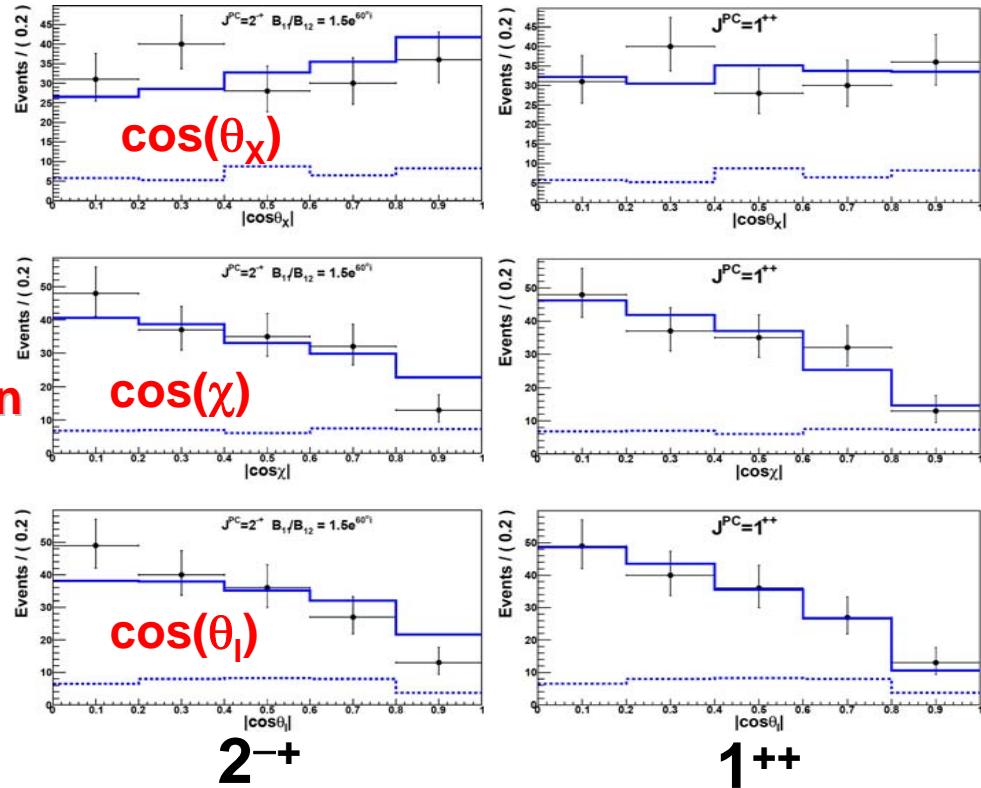
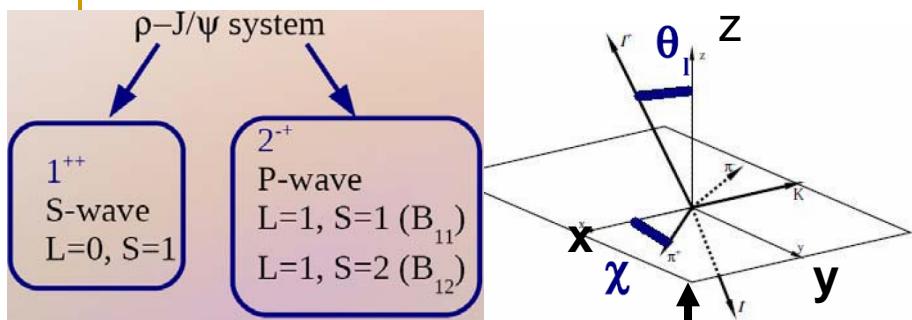
Improved the previous UL on the width by a factor of 2

$$B(B^+ \rightarrow K^+ X) \times B(X \rightarrow J/\psi \pi^+ \pi^-) = (8.61 \pm 0.82 \pm 0.52) \times 10^{-6}$$

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

# Angular analysis of $X(3872) \rightarrow J/\psi \pi^+ \pi^-$ at Belle

arXiv:1107.0163



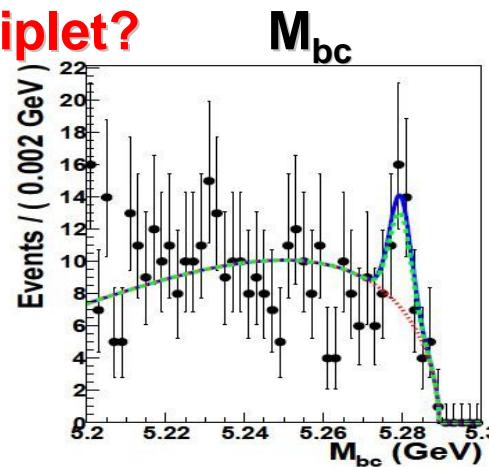
Fit to the  $M(\pi^+\pi^-)$  distribution taking  $\rho - \omega$  mixing into account  $\Rightarrow 1^{++}$  and  $2^{+}$  are both possible

# Search for charged $X^+ \rightarrow J/\psi \pi^+ \pi^0$

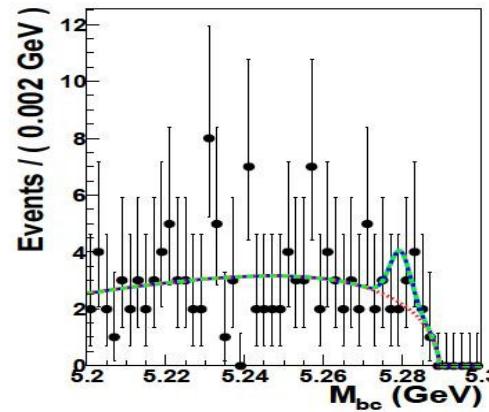
arXiv:1107.0163

$X(3872)$ : singlet or triplet?

$B^0 \rightarrow K^- X^+$



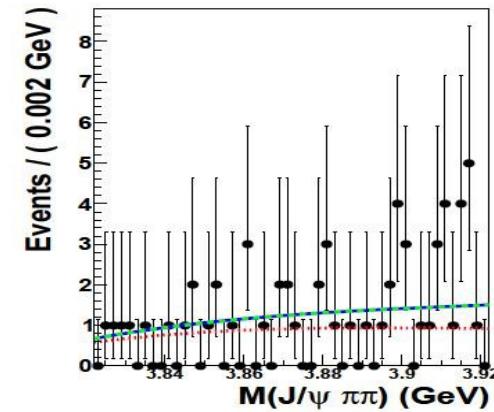
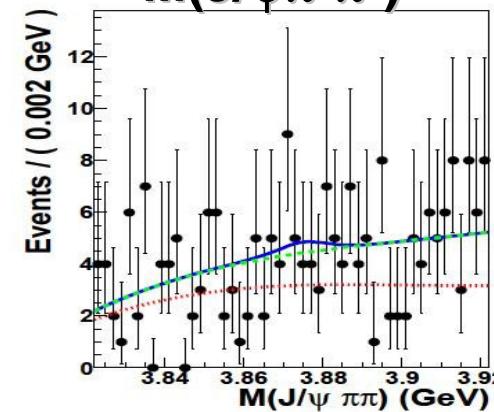
$B^+ \rightarrow K^0 X^+$



$$BR(B^0 \rightarrow K^- X^+) \times BR(X^+ \rightarrow J/\psi \pi^+ \pi^0) < 4.2 \times 10^{-6} \text{ (90%CL)}$$

$$BR(B^+ \rightarrow K^0 X^+) \times BR(X^+ \rightarrow J/\psi \pi^+ \pi^0) < 6.1 \times 10^{-6} \text{ (90%CL)}$$

$M(J/\psi \pi^+ \pi^0)$



No evidence for charged partner  $\Rightarrow I = 0$

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



Belle: arXiv:1105.0177

Molecular model: X  $\rightarrow$   $\psi'\gamma$  is highly suppressed compared to X  $\rightarrow$  J/ $\psi\gamma$ .

BABAR results:  $B(X \rightarrow \psi'\gamma)$  is 3 times larger than  $B(X \rightarrow J/\psi\gamma)$  [PRL 102 132001]

Can be an indication of a (c anti-c) admixture with a ( $D^0$  anti- $D^{*0}$ ) component.

Using full data at Belle: 711 fb $^{-1}$

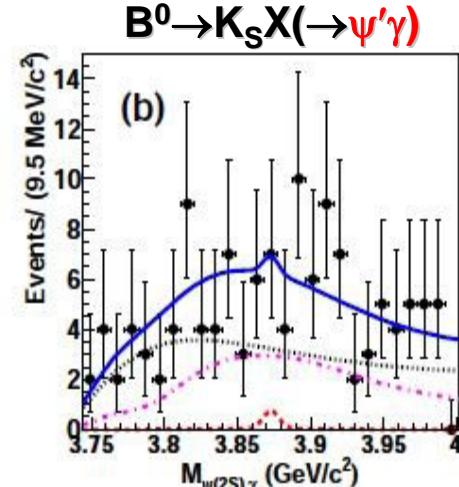
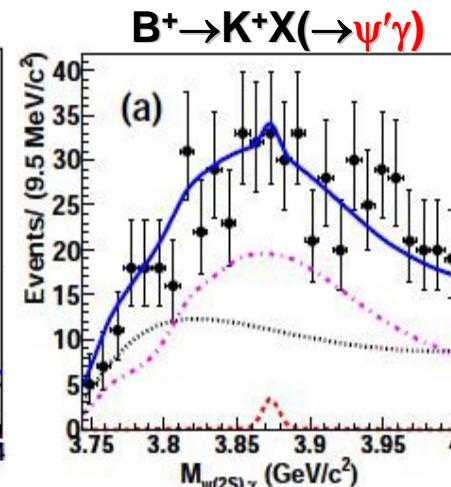
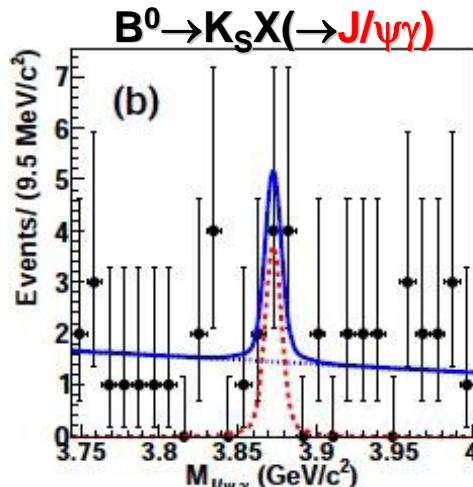
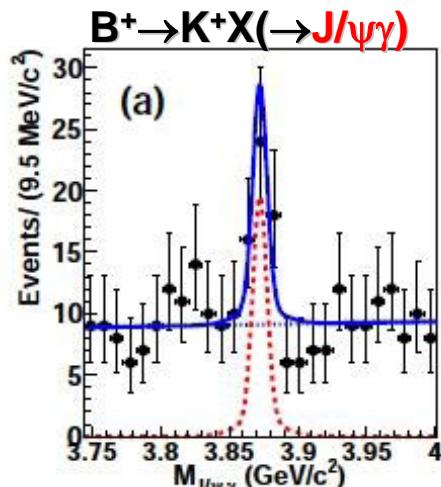
$$B(B^+ \rightarrow XK^+) \bullet B(X \rightarrow J/\psi\gamma) = (1.78_{-0.44}^{+0.48} \pm 0.12) \times 10^{-6}$$

$$B(B^+ \rightarrow XK^+) \bullet B(X \rightarrow \psi'\gamma) < 3.45 \times 10^{-6} \text{ (90% CL)}$$

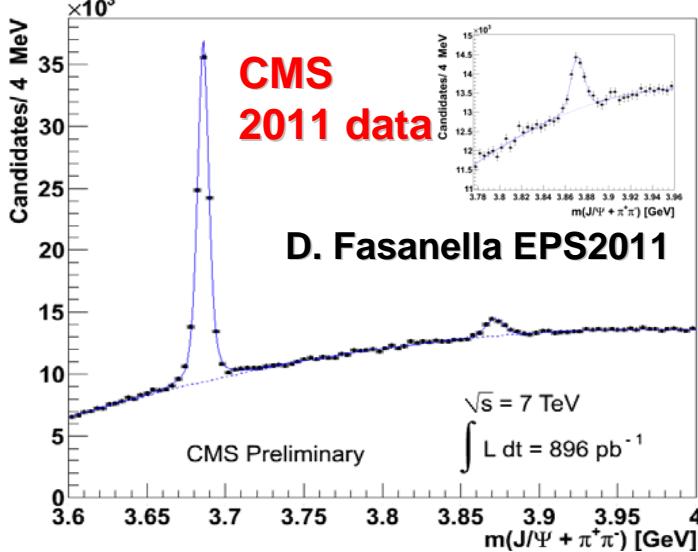
**B(X  $\rightarrow$   $\psi'\gamma$ ) / B(X  $\rightarrow$  J/ $\psi\gamma$ ) < 2.1 (90% CL)**

**BABAR: B(X  $\rightarrow$   $\psi'\gamma$ ) / B(X  $\rightarrow$  J/ $\psi\gamma$ ) = 3.4  $\pm$  1.4**

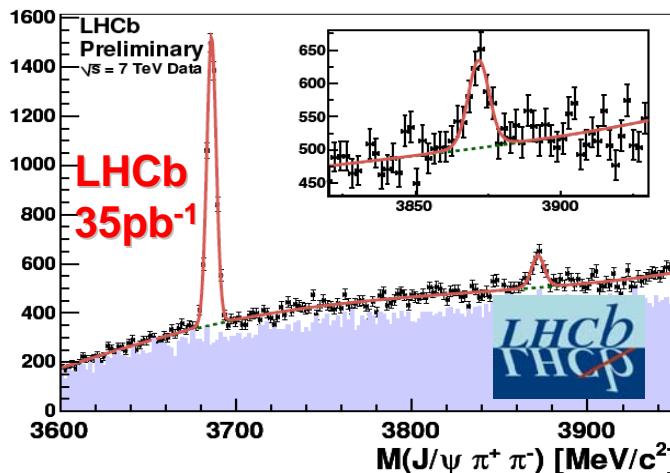
**X(3872) may not have a (c anti-c) admixture with a ( $D^0$  anti- $D^{*0}$ ) molecular**



# X(3872) at LHCb and CMS and comparison



CMS:  $M_x = 3871.5 \pm 0.5 \text{ MeV}/c^2$



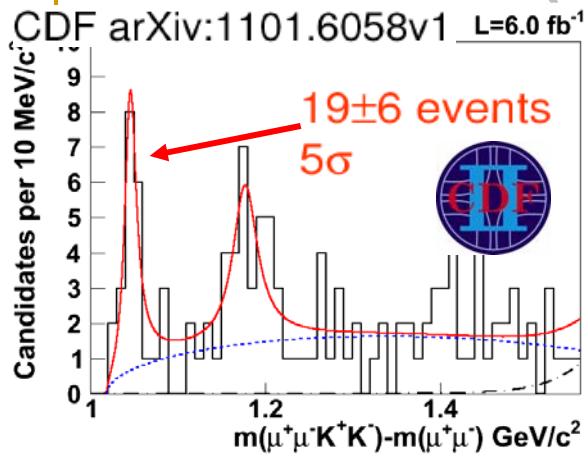
LHCb:  $M_x = 3871.96 \pm 0.46 \pm 0.10 \text{ MeV}/c^2$

S. Choi, FPCP2011

Experiment	X mass ( $\text{MeV}/c^2$ )
CDF II	$3871.61 \pm 0.16 \pm 0.19$
BABAR ( $B^+$ )	$3871.4 \pm 0.6 \pm 0.1$
BABAR ( $B^0$ )	$3868.7 \pm 1.5 \pm 0.4$
D0	$3871.8 \pm 3.1 \pm 3.0$
Belle (full dataset)	$3871.84 \pm 0.27 \pm 0.19$
World Average	$3871.62 \pm 0.19$
LHCb (new)	$3871.96 \pm 0.46 \pm 0.10$
World Average again	$3871.67 \pm 0.17$
$M(D^0) + M(D^{*0})$ PDG2010	$3871.79 \pm 0.30$

Indistinguishable from  $DD^*$  threshold  
New:  $\Delta m = -0.12 \pm 0.35 \text{ MeV}$   
Binding energy becomes smaller.

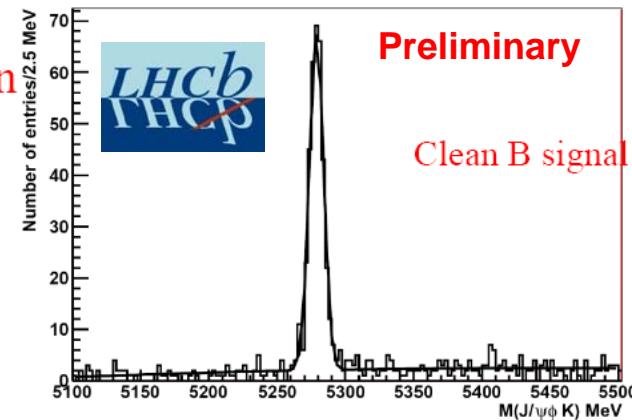
# Search for Y(4140) at LHCb



CDF observed structure ( $J/\psi\phi$ ) in  $B^+ \rightarrow J/\psi\phi K^+$  ( $\phi \rightarrow K^+K^-$ ) decay

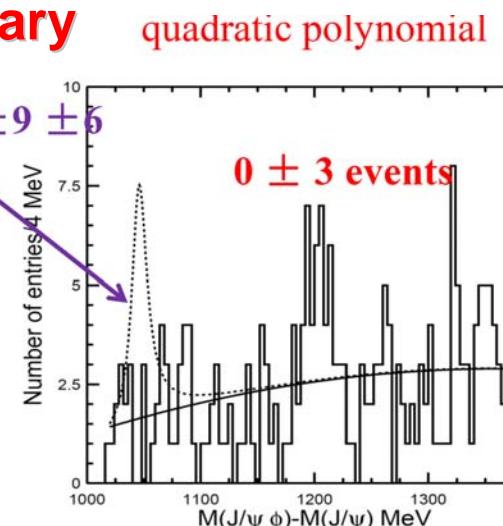
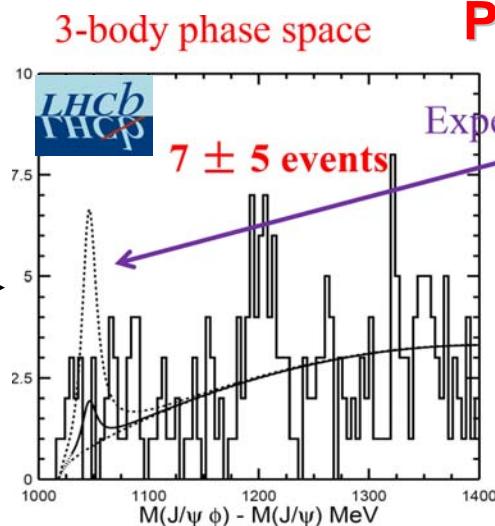
**CDF 6.0 fb<sup>-1</sup>:**  
 $B^+$ :  $115 \pm 12$  events

**LHCb (2010+2011 0.4 fb<sup>-1</sup>)**  
 $B^+$ :  $381 \pm 22$  events



$M(J/\psi\phi) - M(J/\psi)$

Y. Zhang, EPS2011



$$\frac{Br(B^+ \rightarrow X(4140)K^+, X(4140) \rightarrow J/\psi\phi)}{Br(B^+ \rightarrow J/\psi\phi K^+)}$$

**LHCb does not confirm Y(4140)**

< 0.07 for 3 - body phasespace (90% C.L.)  
< 0.04 for quadratic polynomial (90% C.L.)

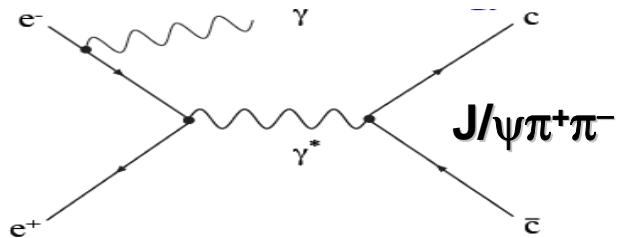
CDF:  $0.149 \pm 0.039 \pm 0.024$

# **Y(4260) properties**

First observed by BABAR in 2005 in  $e^+e^- \rightarrow (J/\psi\pi^+\pi^-)$  ISR  
Confirmed by Belle and CLEO.

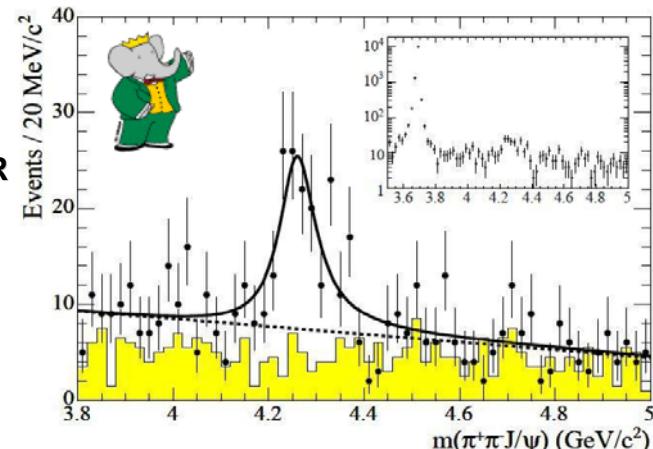
Production in ISR

$$\Rightarrow J^{PC} = 1^-$$



Family of 4 Y resonances from Belle

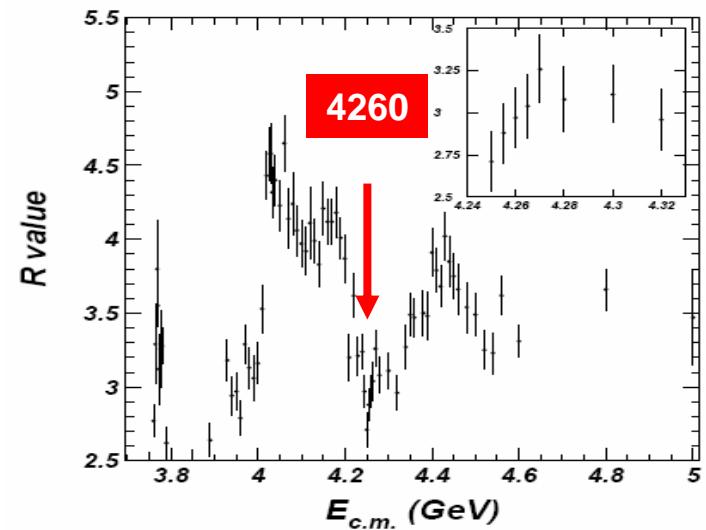
- ◆  $e^+e^- \rightarrow (J/\psi\pi^+\pi^-)$  ISR: Y(4008), Y(4260)
- ◆  $e^+e^- \rightarrow (\psi(2S)\pi^+\pi^-)$  ISR: Y(4360), Y(4660)



**BABAR: PRL 95 142001**

Possible interpretation:

- Undiscovered Charmonium states but cannot fit into spectrum
- Hybrid ?
- Tetraquarks ?
- (D anti-D<sub>1</sub>) or (D<sup>0</sup> anti-D<sup>\*0</sup>) molecules ?
- f<sub>0</sub>(980) $\psi(2S)$  molecule for Y(4660) ?



**BES PRL 88, 101802 (2006)**

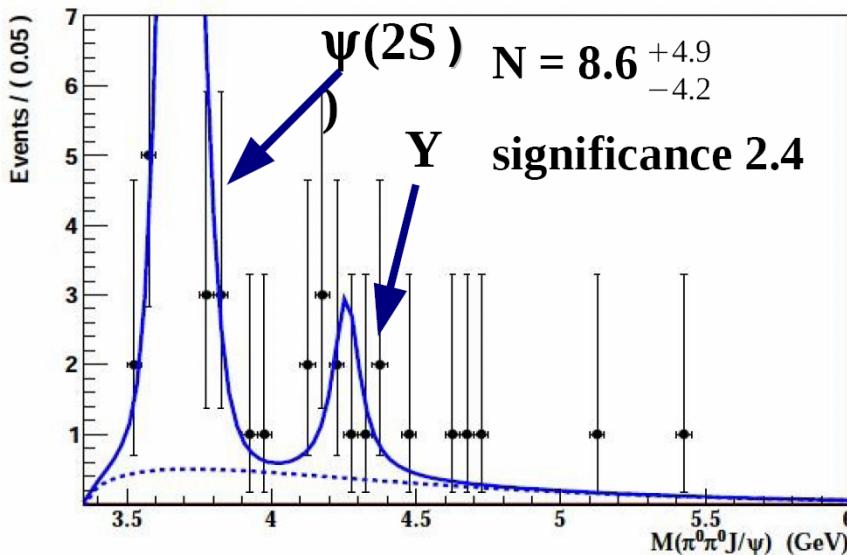
# Search for $Y(4260) \rightarrow J/\psi \pi^0 \pi^0$



Isospin symmetry  $\Rightarrow Y(4260) \rightarrow J/\psi \pi^0 \pi^0$  should be half the rate of  $J/\psi \pi^+ \pi^-$

Large isospin symmetry violation could be a strong evidence of the exotic nature of  $Y$ .

Study of the cross-section  $e^+e^- \rightarrow J/\psi \pi^0 \pi^0$  as a function of mass based on  $790 \text{ fb}^{-1}$

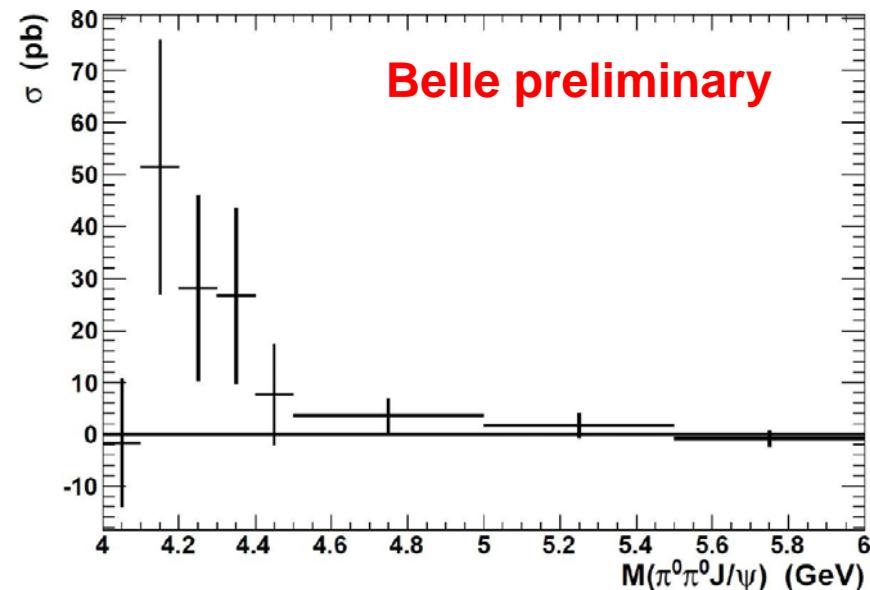


$$\Gamma_{ee} \times B(J/\psi \pi^0 \pi^0) = (3.19^{+1.82+0.64}_{-1.53-0.35}) \text{ eV}$$

$$\Gamma_{ee} \times B(J/\psi \pi^+ \pi^-) = 2 \times (3.0^{+0.6}_{-0.5}) \text{ eV [PDG]}$$

Consistency with isospin expectation.

$\Gamma_{ee}(\psi(2S)) = (2.30 \pm 0.10) \text{ keV}$   
consistent with PDG:  
 $\Gamma_{ee}(\psi(2S)) = (2.35 \pm 0.04) \text{ keV}$



# Puzzles of $\Upsilon(5S)$ decays



Anomalous production of  $\Upsilon(nS)\pi^+\pi^-$  with  $21.7 \text{ fb}^{-1}$

PRD82,091106R(2010)

PRL100,112001(2008)

	$\Gamma(\text{MeV})$
$\Upsilon(5S) \rightarrow \Upsilon(1S)\pi^+\pi^-$	$0.59 \pm 0.04 \pm 0.09$
$\Upsilon(5S) \rightarrow \Upsilon(2S)\pi^+\pi^-$	$0.85 \pm 0.07 \pm 0.16$
$\Upsilon(5S) \rightarrow \Upsilon(3S)\pi^+\pi^-$	$0.52^{+0.20}_{-0.17} \pm 0.10$
$\Upsilon(2S) \rightarrow \Upsilon(1S)\pi^+\pi^-$	0.0060
$\Upsilon(3S) \rightarrow \Upsilon(1S)\pi^+\pi^-$	0.0009
$\Upsilon(4S) \rightarrow \Upsilon(1S)\pi^+\pi^-$	0.0019

10<sup>2</sup>

(1) Rescattering  $\Upsilon(5S) \rightarrow BB\pi\pi \rightarrow \Upsilon(nS)\pi\pi$

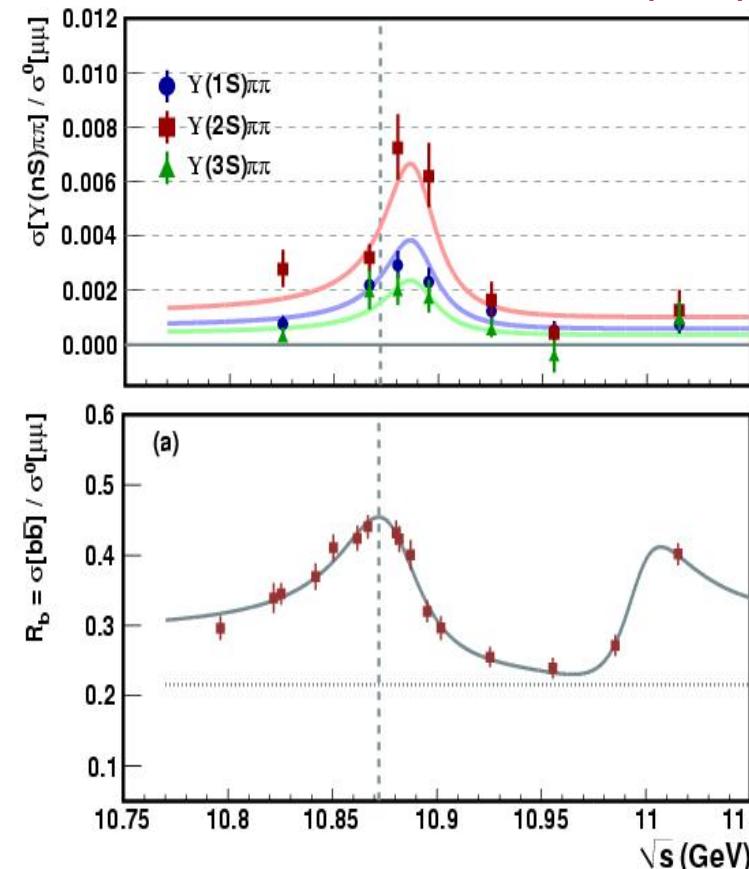
Simonov JETP Lett 87,147(2008)

(2) Exotic resonance  $\mathbf{Y}_b$  near  $\Upsilon(5S)$

analogue of  $\Upsilon(4260)$  resonance  
with anomalous  $\Gamma(J/\psi\pi^+\pi^-)$  ?

Dedicated energy scan  $\Rightarrow$   
shapes of  $R_b$  and  $\sigma(\Upsilon\pi\pi)$  different ( $2\sigma$ )

$\Upsilon(5S)$  is very interesting and not yet understood  
Finally Belle recorded  $121.4 \text{ fb}^{-1}$  data set at  $\Upsilon(5S)$

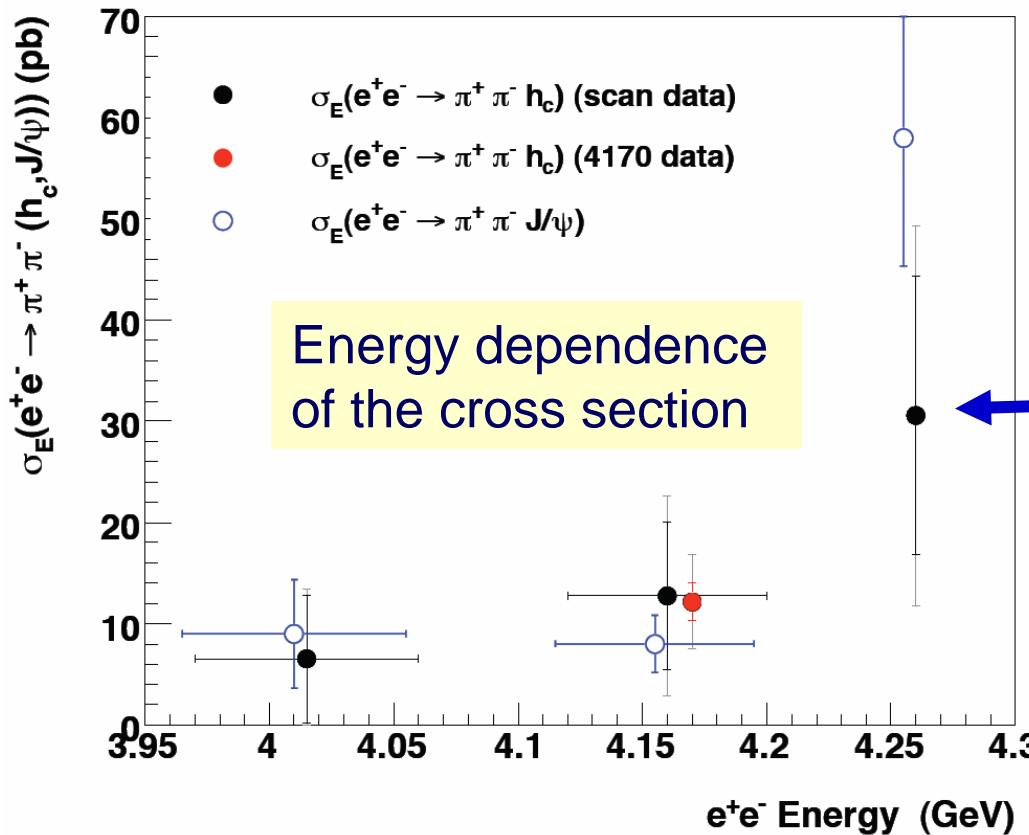


A. Bondar  
FPCP2011

# Motivation for looking at $\Upsilon(5S) \rightarrow h_b(nP)\pi\pi$

Observation of  $e^+e^- \rightarrow \pi^+\pi^- h_c$  by CLEO-c

arXiv:1104.2025



FPCP 2011, J.Rosner

Enhancement of  $\sigma(h_c \pi^+\pi^-)$  @  $\Upsilon(4260)$

$\sigma(h_b \pi^+\pi^-)$  is enhanced @  $\Upsilon_b$ ?

⇒ Belle search for  $h_b$  in  $\Upsilon(5S)$  data

# Introduction to $h_b(nP)$

$(b\bar{b}) : S=0 \ L=1 \ J^{PC}=1^{+-}$

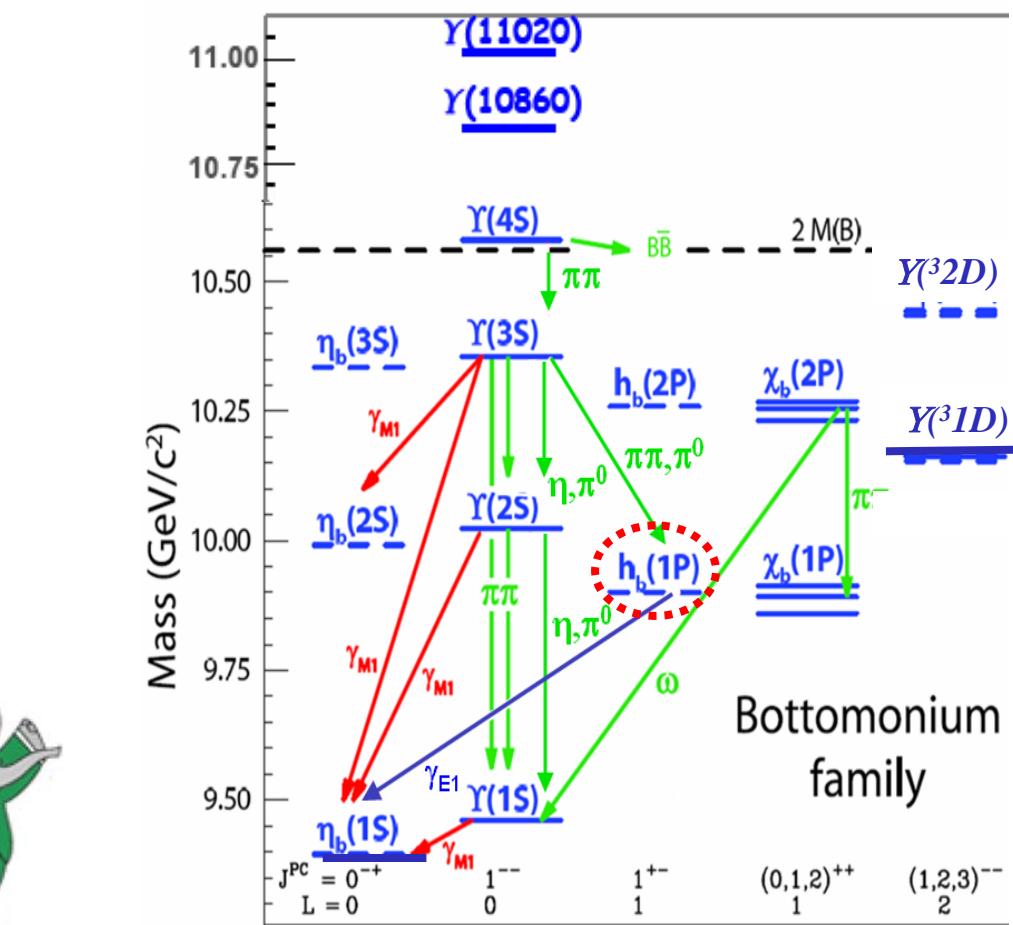
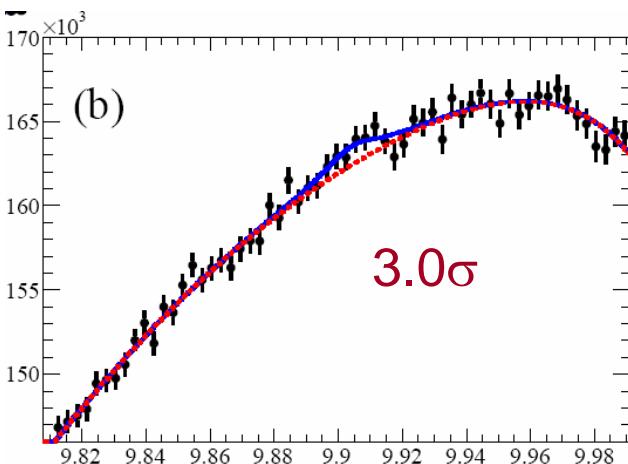
Expected mass (CoG of  $\chi_{bJ}$ )

$$\approx (M_{\chi_{b0}} + 3 M_{\chi_{b1}} + 5 M_{\chi_{b2}}) / 9$$

$\Delta M_{HF} \Rightarrow$  test of hyperfine interaction

Evidence from BaBar arXiv:1102.4565

$$\Upsilon(3S) \rightarrow \pi^0 h_b(1P) \rightarrow \pi^0 \gamma \eta_b(1S)$$



$$m(h_b) = 9902 \pm 4_{\text{(stat)}} \pm 1_{\text{(syst)}} \text{ MeV}/c^2$$

$$B(\Upsilon(3S) \rightarrow \pi^0 h_b) \times B(h_b \rightarrow \gamma \eta_b) = (3.7 \pm 1.1 \pm 0.7) \times 10^{-4}$$

# Observation of $\Upsilon(5S) \rightarrow h_b(nP)\pi^+\pi^-$ at Belle

**Method :**  
**missing mass**  
**technique**

Search for signal  $\Upsilon(5S) \rightarrow h_b(nP)\pi^+\pi^-$

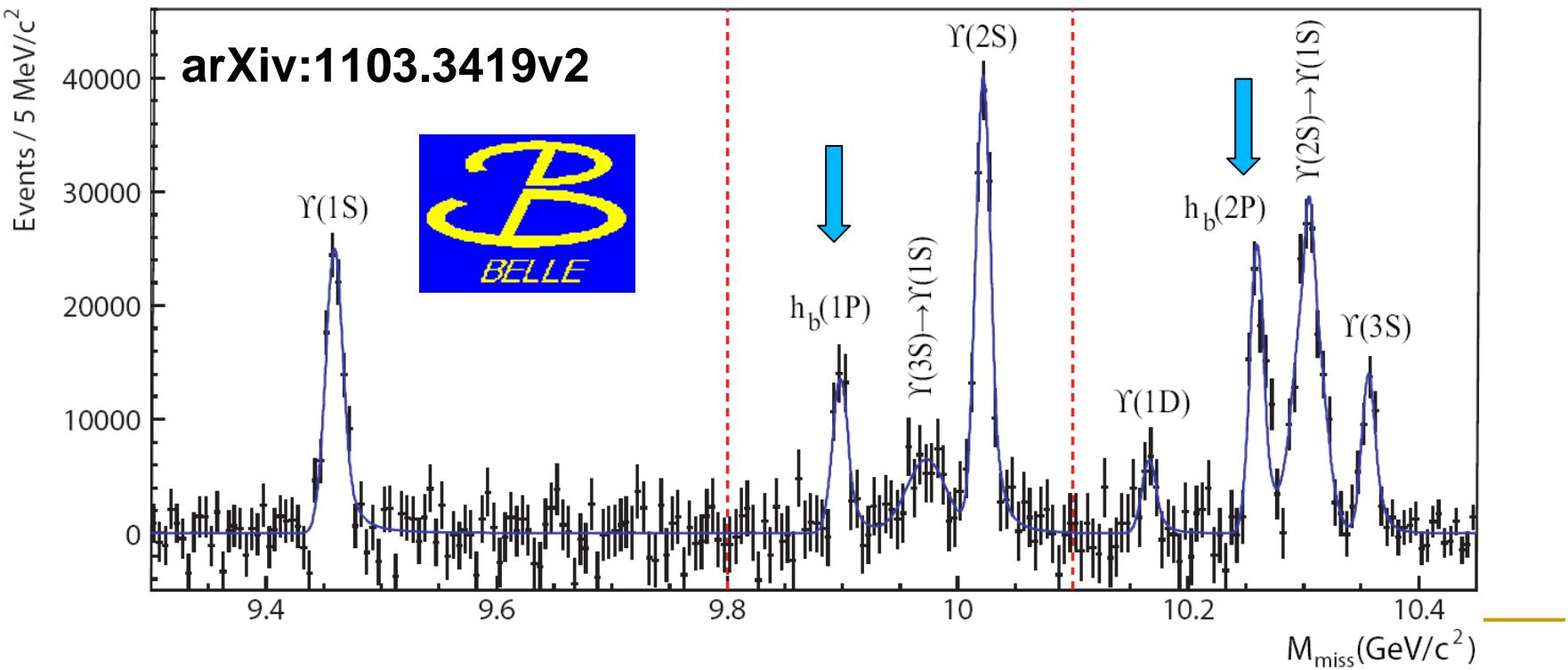
$P_{\Upsilon(5S)}$  is given by  
c.m. energy and boost

$P_{\pi^+\pi^-}$  is measured

$$M_{hb(nP)} = \sqrt{(P_{\Upsilon(5S)} - P_{\pi^+\pi^-})^2} \equiv MM(\pi^+\pi^-)$$

⇒ Search for  $h_b(nP)$  peaks in  $MM(\pi^+\pi^-)$  spectrum

⇒ reconstruct  $\mu^+\mu^-$  in addition to  $\pi^+\pi^-$  to suppress background



# Mass measurements in $\Upsilon(5S) \rightarrow h_b(nP)/\Upsilon(nS) \pi\pi$

arXiv:1103.3419v2

Significance w/ systematics

$h_b(1P)$   $5.5\sigma$ ;  $h_b(2P)$   $11.2\sigma$

Deviations from CoG of  
 $\chi_{bJ}$  masses:  $\Delta M_{HF}$

$h_b(1P)$ :  $(+1.6 \pm 1.5)$  MeV/ $c^2$

$h_b(2P)$ :  $(+0.5^{+1.6}_{-1.2})$  MeV/ $c^2$

Agree with expected zero!

	Yield, $10^3$	Mass, MeV/ $c^2$	Significance
$\Upsilon(1S)$	$105.2 \pm 5.8 \pm 3.0$	$9459.4 \pm 0.5 \pm 1.0$	$18.2\sigma$
$h_b(1P)$	$50.4 \pm 7.8^{+4.5}_{-9.1}$	$9898.3 \pm 1.1^{+1.0}_{-1.1}$	$6.2\sigma$
$3S \rightarrow 1S$	$56 \pm 19$	$9973.01$	$2.9\sigma$
$\Upsilon(2S)$	$143.5 \pm 8.7 \pm 6.8$	$10022.3 \pm 0.4 \pm 1.0$	$16.6\sigma$
$\Upsilon(1D)$	$22.0 \pm 7.8$	$10166.2 \pm 2.6$	$2.4\sigma$
$h_b(2P)$	$84.4 \pm 6.8^{+23.1}_{-10.1}$	$10259.8 \pm 0.6^{+1.4}_{-1.0}$	$12.4\sigma$
$2S \rightarrow 1S$	$151.7 \pm 9.7^{+9.0}_{-20.1}$	$10304.6 \pm 0.6 \pm 1.0$	$15.7\sigma$
$\Upsilon(3S)$	$45.6 \pm 5.2 \pm 5.1$	$10356.7 \pm 0.9 \pm 1.1$	$8.5\sigma$

$$\frac{\Gamma[\Upsilon(5S) \rightarrow h_b(nP) \pi^+ \pi^-]}{\Gamma[\Upsilon(5S) \rightarrow \Upsilon(2S) \pi^+ \pi^-]} = \begin{cases} 0.46 \pm 0.08^{+0.07}_{-0.12} \\ 0.77 \pm 0.08^{+0.22}_{-0.17} \end{cases}$$

$S(h_b) = 0 \Rightarrow$  spin-flip  
no spin-flip

Process with spin-flip of heavy quark is not suppressed

for  $h_b(1P)$

for  $h_b(2P)$

No  $h_b$  signal at  $\Upsilon(4S)$

⇒ Mechanism of  $\Upsilon(5S) \rightarrow h_b(nP) \pi^+ \pi^-$  decay is exotic!

This is the motivation to study resonant substructure of this process

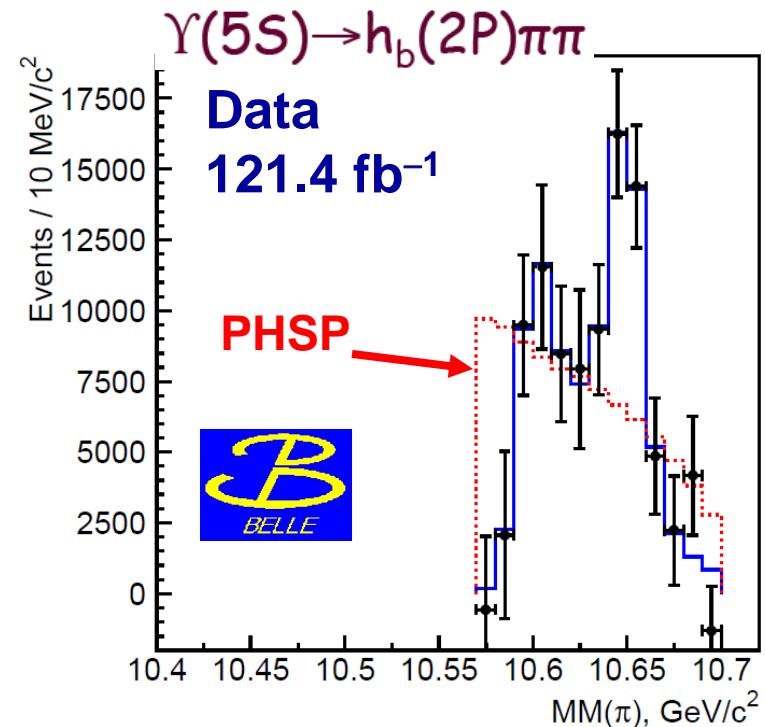
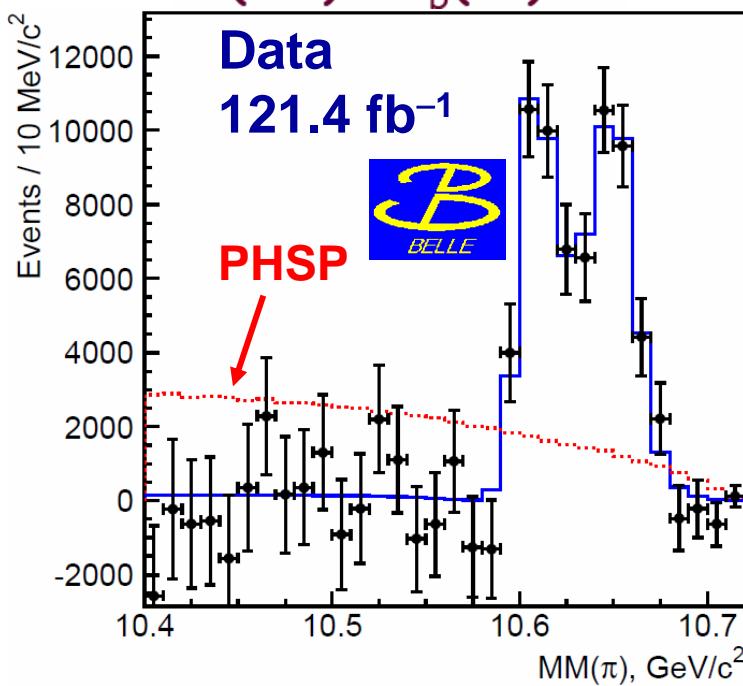
A. Bondar  
FPCP2011

# Resonant substructure of $\Upsilon(5S) \rightarrow h_b(nP) \pi^+ \pi^-$

$P(h_b) = P_{\Upsilon(5S)} - P(\pi^+ \pi^-) \Rightarrow M(h_b \pi^+) = MM(\pi^-) \Rightarrow$  measure  $\Upsilon(5S) \rightarrow h_b \pi \pi$  yield

$\Upsilon(5S) \rightarrow h_b(1P) \pi \pi$

in bins of  $MM(\pi)$



**Fit function:**  $|BW(s, M_1, \Gamma_1) + ae^{i\phi} BW(s, M_2, \Gamma_2) + be^{i\psi}|^2 \frac{qp}{\sqrt{s}}$

arXiv: 1105.4583

# Fit results

arXiv: 1105.4583



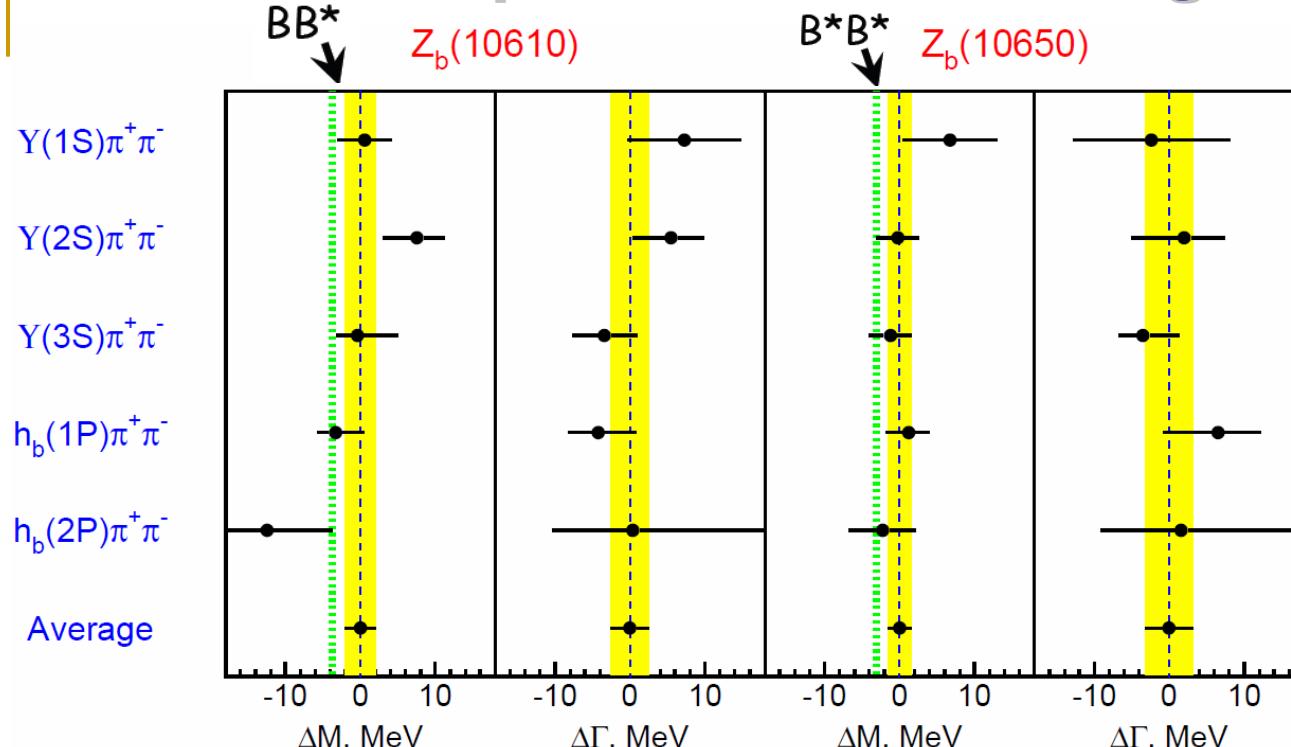
	$h_b(1P)\pi^\pm\pi^\mp$	$h_b(2P)\pi^\pm\pi^\mp$	
$M_1$ (MeV/c <sup>2</sup> )	$10605.1 \pm 2.2^{+3.0}_{-1.0}$	$10596 \pm 7^{+5}_{-2}$	$Z_{b1}$ ~ $B\bar{B}^*$ threshold
$\Gamma_1$ (MeV)	$11.4^{+4.5+2.1}_{-3.9-1.2}$	$16^{+16+13}_{-10-14}$	
$M_2$ (MeV/c <sup>2</sup> )	$10654.5 \pm 2.5^{+1.0}_{-1.9}$	$10651 \pm 4 \pm 2$	$Z_{b2}$ ~ $B^*\bar{B}^*$ threshold
$\Gamma_2$ (MeV)	$20.9^{+5.4+2.1}_{-1.7-5.7}$	$12^{+11+8}_{-9-2}$	
$a$	$1.8^{+1.0+0.1}_{-0.7-0.5}$	$1.3^{+3.1+0.4}_{-1.1-0.7}$	
$\phi$ (°)	$188^{+44+4}_{-58-9}$	$255^{+56+12}_{-72-183}$	
$b$	$\approx 0$	$\approx 0$	

- Good agreement between  $h_b(1P)$  and  $h_b(2P)$
- Non-resonant part  $\sim 0$ : nearly all  $h_b(nP)$  produced via

$$\Upsilon(5S) \rightarrow Z^\pm \pi^\mp \rightarrow h_b(nP)\pi^\pm\pi^\mp$$

$Z_{b1}$  and  $Z_{b2}$  are also observed in  $\Upsilon(5S) \rightarrow \Upsilon(nS)\pi^+\pi^-$  decays (n=1,2,3)

# Summary of parameters of charged $Z_b$ states



$Z_{b1}(10610)$

$M=10608.4\pm2.0$  MeV

$\Gamma=15.6\pm2.5$  MeV

$Z_{b2}(10650)$

$M=10653.2\pm1.5$  MeV

$\Gamma=14.4\pm3.2$  MeV

- Relative phases:  $Y(\approx 0^\circ)$ ,  $h_b(\approx 180^\circ)$
- Mass just above  $B^*B$  and  $B^*B^*$  thresholds
- Angular analysis favors  $J^P=1^+$   
Indicates  $Z_b$ 's could be molecules

arXiv: 1105.4583

Many theoretical papers:  
molecules interpretations:  
[arXiv:1106.2968](https://arxiv.org/abs/1106.2968) , [arXiv:1105.5935](https://arxiv.org/abs/1105.5935)  
[arXiv:1105.5829](https://arxiv.org/abs/1105.5829), [arXiv:1107.0254](https://arxiv.org/abs/1107.0254)  
 X. Liu, S.L.Zhu, G. Ding et. al  
tetraquark states  
[arXiv:1108.2197](https://arxiv.org/abs/1108.2197) A. Ali (beauty11)  
 cusp effect:  
[arXiv:1105.5492](https://arxiv.org/abs/1105.5492) D. Bugg

# Summary

- New results on spin exotic  $1^{-+}$ ,  $\pi_1(1600)$ , first evidence in charmonium decays
- BESIII providing exciting data on light hadron and charmonia
  - The spin-parity of the ppbar mass threshold enhancement in  $J/\psi \rightarrow \gamma \text{ppbar}$  was first determined as  $0^{++}$ .
  - Two new structures above 2.0 GeV observed in  $J/\psi \rightarrow \gamma \eta' \pi^+ \pi^-$  decays
  - The first observation of  $\eta_c(2S)$  in  $\psi' \rightarrow \gamma \eta_c(2S)$  decay.
  - Precision measurements of  $\eta_c(1S)$  parameters in  $\psi' \rightarrow \gamma \eta_c(1S)$ .
- B factories gave a dramatic contributions to heavy flavor spectroscopy, still analyzing data, charmonium-like XYZ states are still mystery
- Updated results on X(3872) from B factories,
  - isospin test favors  $I=0$ , and  $J^{PC}$  is  $1^{++}$  or  $2^{-+}$
  - Still statistical limited
- Indication for  $(XYZ)_b$  in b-anti-b sector, exotic states  $Z_{b1}$  and  $Z_{b2}$
- LHC starting exploit their data: X(3872) is confirmed by both CMS and LHCb
  - Y(4140) is not observed by LHCb with 3.2 times larger B sample than that of CDF
- Super-flavor factories (Belle-II, superB, LHC-b upgrade, PANDA...) being expected to identify the charmonium-like and bottomonium-like states.

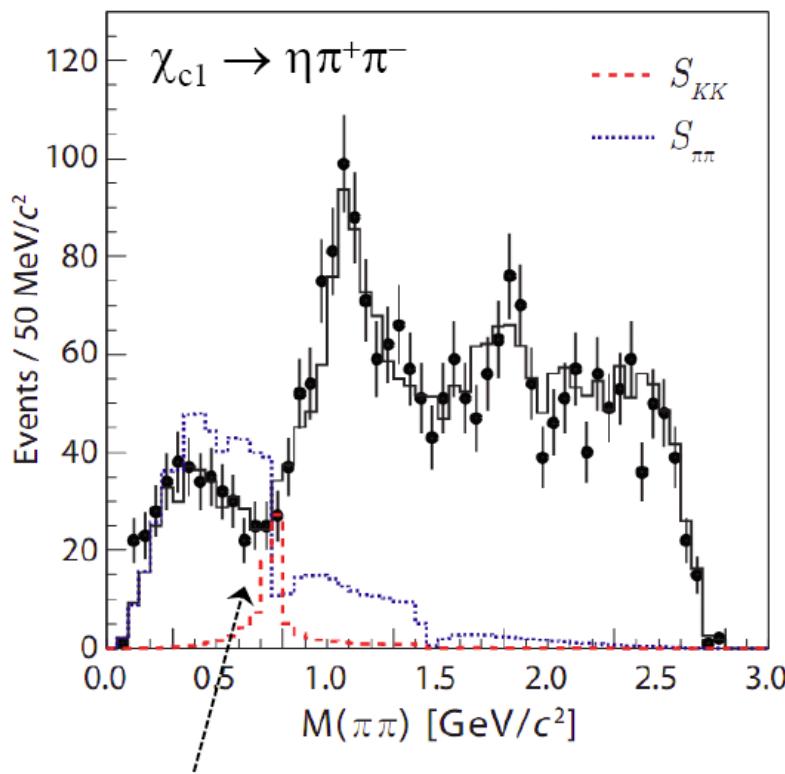
# Finally, I would thank my colleagues:

- **Torsten Schröder from BABAR**
- **Karim Trabelsi, A. Bondar, S. Choi from Belle**
- **Roy A. Briere, K. Seth, M. Kornicer from CLEO**
- **Diego Tonelli, Giovanni Punzi, Robert M Roser, Robert Harr from CDF and D0**
- **Y.N. Gao from LHCb**
- **Hal Evans for ATLAS and CMS**
- **Simon I. Eidelman, Evgeny Baldin from KEDR**
- **Simona Giovannella, Paolo Gauzzi from KLOE**
- **H.S.Chen, Y.F. Wang, S. Jin, X.Y.Shen ,C.Z.Yuan, Y.H.Zheng, J.Z. Zhang from BESIII**

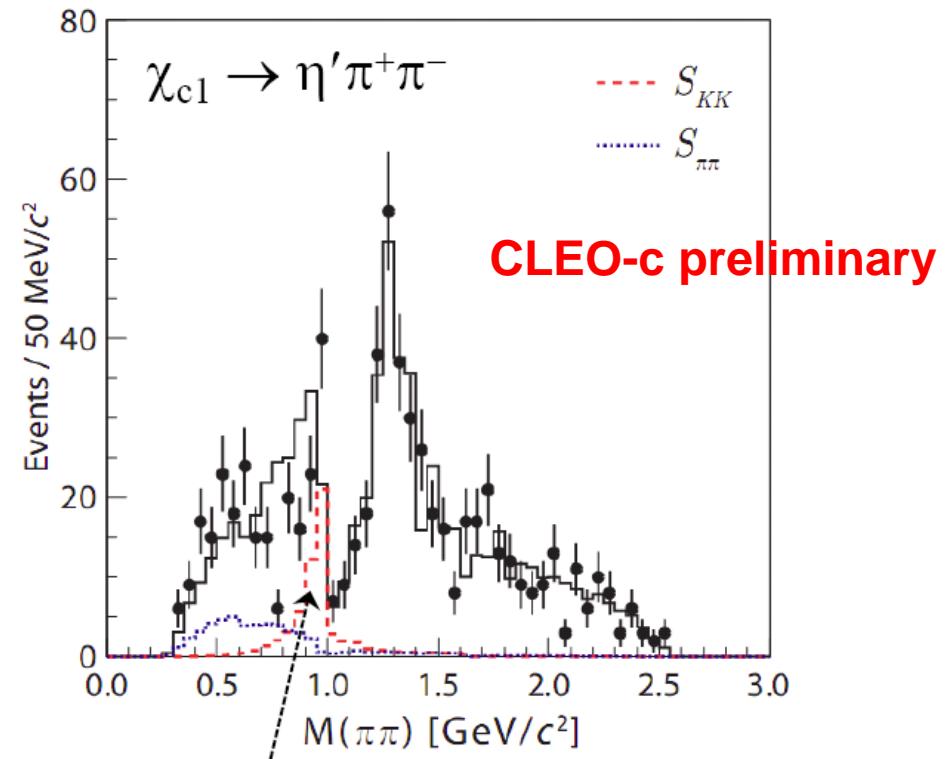
**Thank you!**

# Back up

# $(\pi\pi)$ S wave in $\chi_{c1} \rightarrow \eta^{(\prime)}\pi^+\pi^-$ at CLEO-c



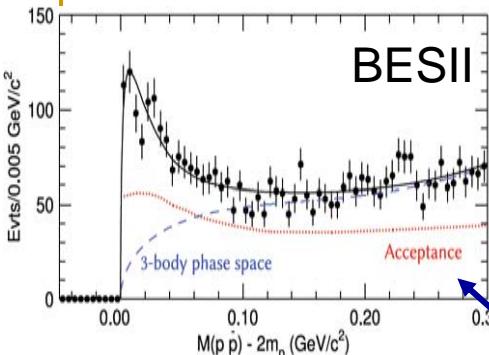
❖ dip in  $\pi^+\pi^-$  spectra @ 1 GeV



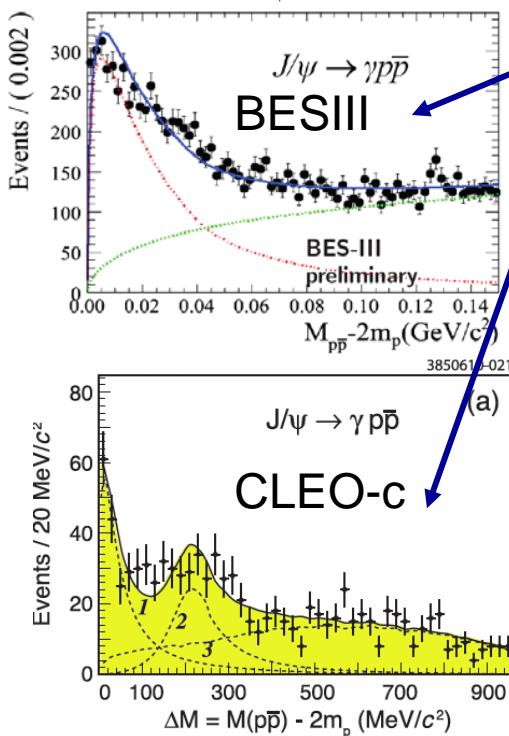
❖  $f_0(980)$ -like peak from S-wave  
 $KK \rightarrow \pi\pi$  production

Note:  $B(\chi_{c1} \rightarrow S_{KK}\eta) \approx B(\chi_{c1} \rightarrow S_{KK}\eta')$  while  
 $B(\chi_{c1} \rightarrow S_{\pi\pi}\eta')$  is suppressed compared to  $B(\chi_{c1} \rightarrow S_{\pi\pi}\eta)$

# Threshold enhancement in $p\bar{p}$ mass

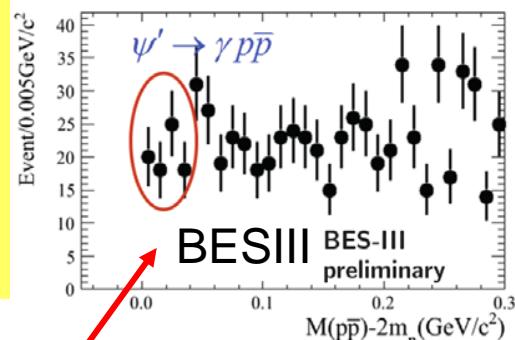
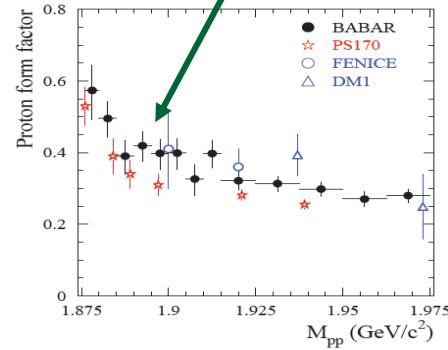
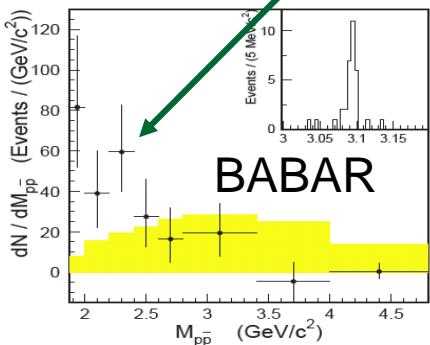


**FSI effect**  
**Baryonium (i.e. proton-antiproton bound state)**  
**Something of both**  
**...**

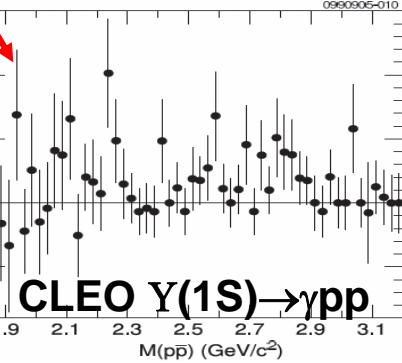
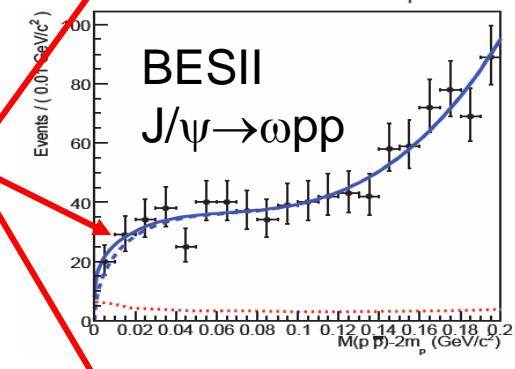


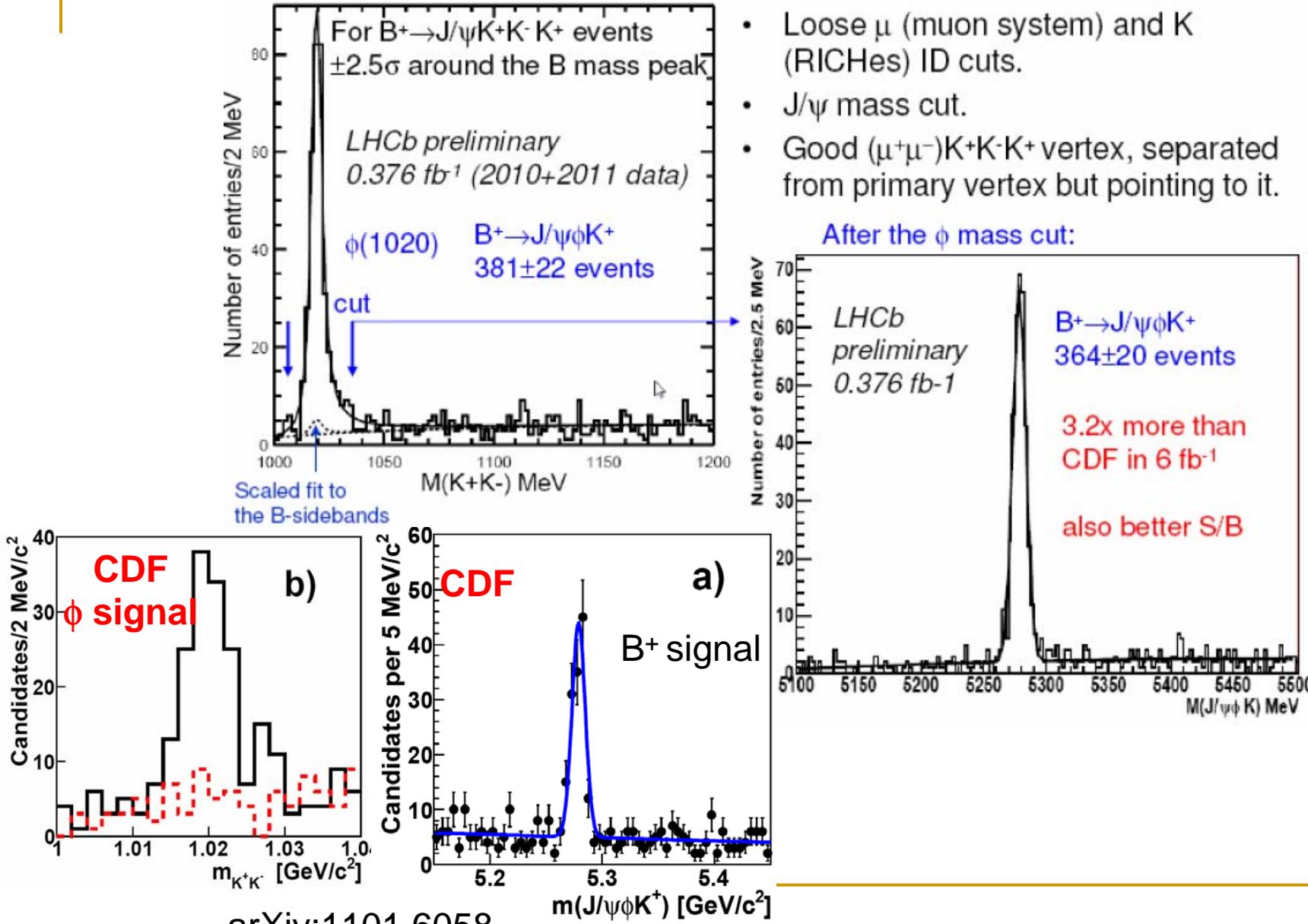
Compatible with BES-II results

**First seen in  $J/\psi \rightarrow \gamma p\bar{p}$  by BESII**  
**Confirmed by BESIII and CLEO-c**  
**Not seen in  $\psi' \rightarrow \gamma p\bar{p}$ ,  $J/\psi \rightarrow \omega p\bar{p}$  and  $\Upsilon(1S) \rightarrow \gamma p\bar{p}$**   
**Enhancement seen in  $e^+e^- \rightarrow p\bar{p}$  and  $B^+ \rightarrow K^+ p\bar{p}$**



**BESII**  
 $J/\psi \rightarrow \omega p\bar{p}$

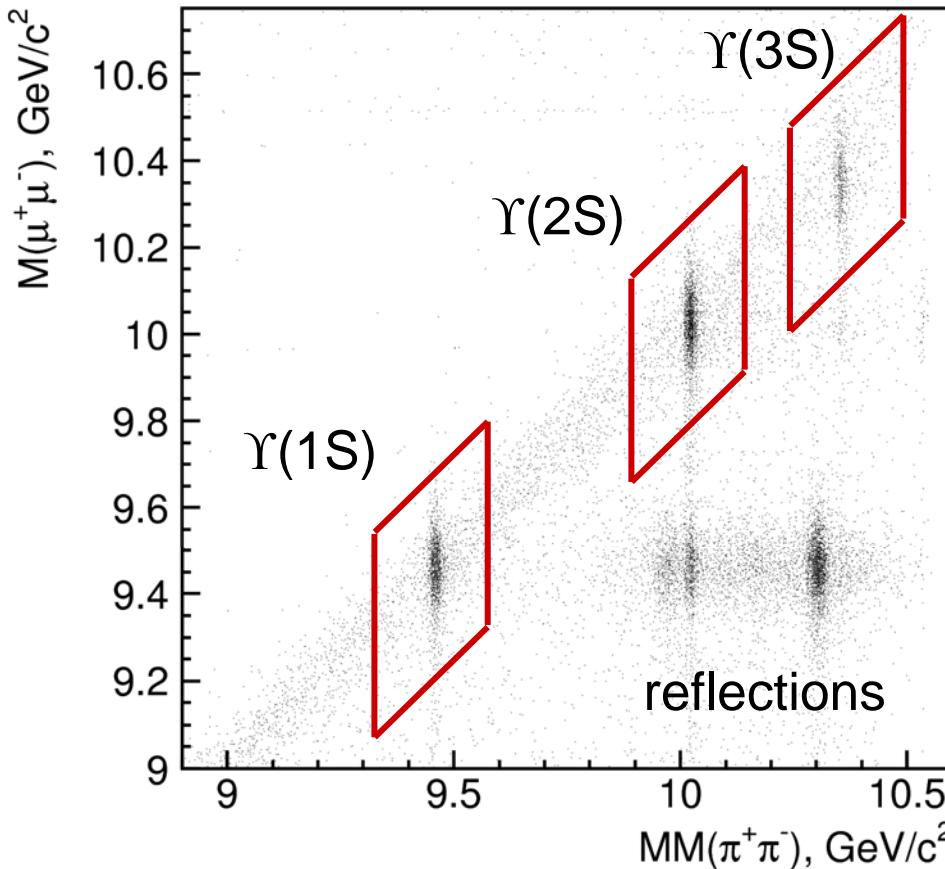


LHCb search for X(4140):  $B^+ \rightarrow J/\psi \phi K^+$  sample

# Exclusive $\Upsilon(5S) \rightarrow \Upsilon(nS) \pi^+ \pi^-$

$$\begin{aligned}\Upsilon(5S) &\rightarrow \Upsilon(nS) \pi^+ \pi^- \\ \Upsilon(nS) &\rightarrow \mu^+ \mu^-\end{aligned} \quad (n = 1, 2, 3)$$

arXiv: 1105.4583



Full reconstructions  
Clear signal  
⇒ Dalitz analysis

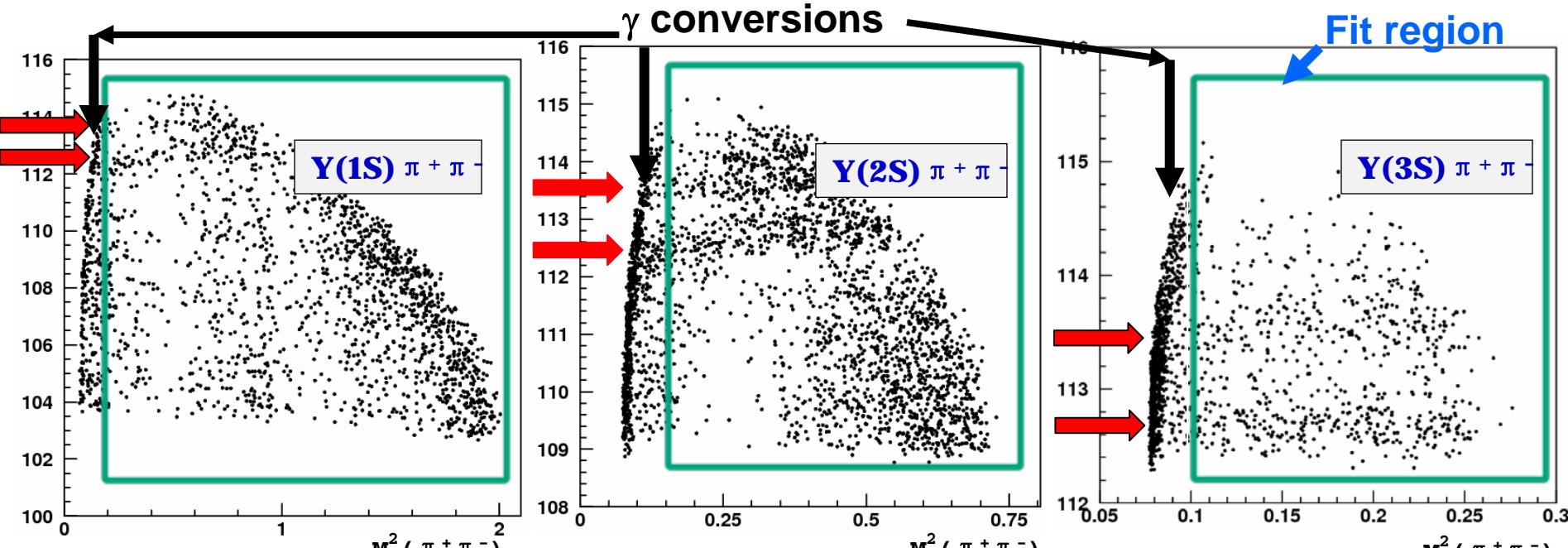
# $\Upsilon(5S) \rightarrow \Upsilon(nS) \pi^+ \pi^-$ Dalitz plots

Dalitz distributions for events in  $\Upsilon(nS)$  signal regions.

$9.43 \text{ GeV} < \text{MM}(\pi^+ \pi^-) < 9.48 \text{ GeV}$

$10.05 \text{ GeV} < \text{MM}(\pi^+ \pi^-) < 10.10 \text{ GeV}$

$10.33 \text{ GeV} < \text{MM}(\pi^+ \pi^-) < 10.38 \text{ GeV}$



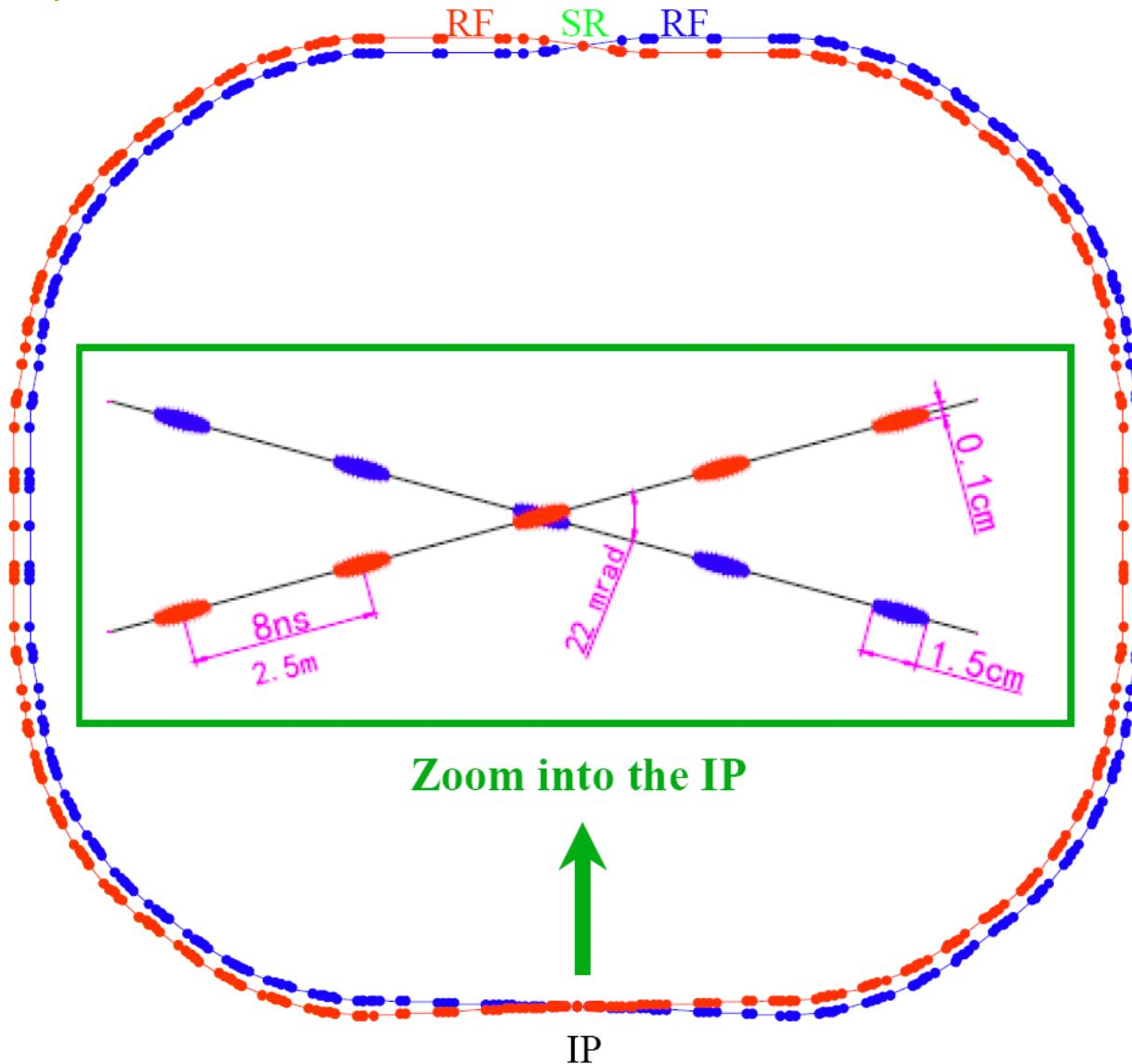
$$\text{Fit function: } S(s_1, s_2) = |A_{Z_{b1}} + A_{Z_{b2}} + A_{\text{NR}} + A_{f_0(980)} + A_{f_2(1275)}|^2$$

$$s_i = M_{\pi_i \Upsilon}^2 \quad A_{Z_{bk}} = \frac{\sqrt{M_k \Gamma_k}}{M_k^2 - s_1 + i M_k \Gamma_k} + \frac{a_k e^{i \phi_k} \sqrt{M_k \Gamma_k}}{M_k^2 - s_2 + i M_k \Gamma_k}$$

$$A_{\text{NR}} = c_1 + c_2 M_{\pi\pi}^2$$

A. Voloshin, PRD74, 054022 (2006);  
Prog. Part. Nucl. Phys. 61, 455 (2008)

# BEPCII storage rings



**Beam energy:**  
**1.0-2.3 GeV**

**Design Luminosity:**  
 $1 \times 10^{33} \text{ cm}^{-2}\text{s}^{-1}$

**Optimum energy:**  
**1.89 GeV**

**Energy spread:**  
 $5.16 \times 10^{-4}$

**No. of bunches:**  
**93**

**Bunch length:**  
**1.5 cm**

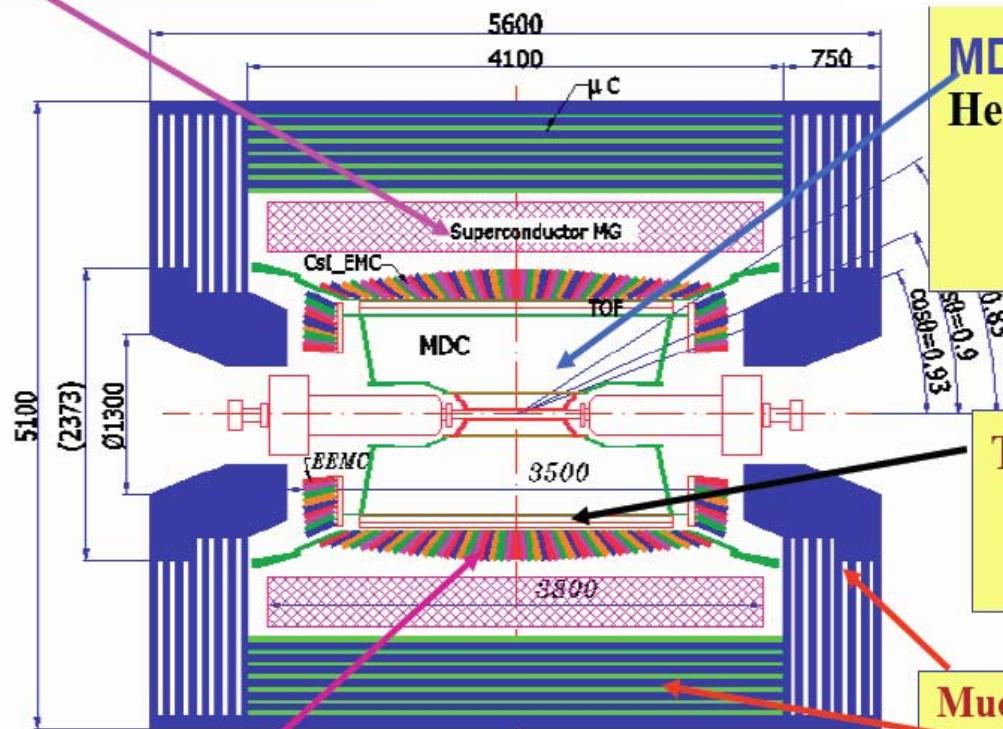
**Total current:**  
**0.91 A**

**Circumference :**  
**237m**

# BESIII detector: all new !

## BESIII Detector

Magnet: 1 T Super conducting



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

Data Acquisition:  
Event rate = 4 kHz  
Total data volume  $\sim 50 \text{ MB/s}$

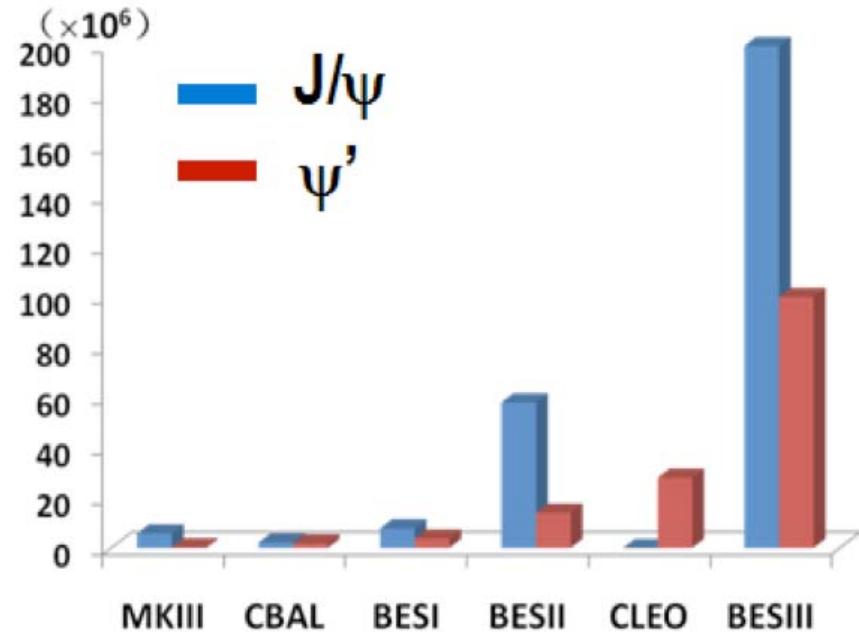
MDC: small cell & Gas:  
 $\text{He/C}_3\text{H}_8 (60/40)$ , 43 layers  
 $\sigma_{xy} = 130 \mu\text{m}$   
 $\sigma_p/p = 0.5\% @ 1 \text{ GeV}$   
 $dE/dx = 6\%$

TOF:  
 $\sigma_t = 100 \text{ ps}$  Barrel  
 $110 \text{ ps}$  Endcap

Muon ID: 9 layers RPC  
8 layers for endcap

# Data samples

- So far BESIII has collected :
  - 2009: 225 Million  $J/\psi$
  - 2009: 106 Million  $\psi'$
  - 2010-11:  $2.9 \text{ fb}^{-1}$   $\psi(3770)$   
( $3.5 \times \text{CLEO-c } 0.818 \text{ fb}^{-1}$ )
  - May 2011:  $0.5 \text{ fb}^{-1}$  @4010 MeV  
(one month) for Ds and XYZ spectroscopy
- BESIII will also collect:
  - more  $J/\psi$ ,  $\psi'$ ,  $\psi(3770)$
  - data at higher energies (for XYZ searches, R scan and Ds physics)



# luminosity since startup

Note that luminosity is lower at  $J/\psi$ ,  
and machine is optimal near  $\psi(3770)$

