Hadron Spectroscopy

— Experimental Progress on Charmonium–like Studies —

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Topics can be covered

- **Light hadron**
  - Scalar mesons spectroscopy
  - Quantum number exotic states, glueball, multi-quarks
  - Excited baryon
  - ……..
- **Charmonium**
  - Conventional charmonium spectroscopy
  - Charmonium-like states
  - Transition and production
  - ……
- **Buttomnium**

–

- ……..

Spectroscopy Results @ ICHEP2014

LHCb	Radiative decays of X(3872) Amplitude fits of Zc(4430) Production of χ_b(1P, 2P, 3P) states	T. Skwarnichi
Belle	Bottomonia transitions via h meson Observation of $e^+e^- \to \chi_b\omega$ Rb scan Observation of $Z^+(4200)$ in $B \to J/\psi\, K\, \pi$ Search for X-like states in decays with η_c Search for Y(1,2S) decay to double-charmonia Search for $e^+e^- \to \chi_c\gamma$	P. Krokovny
Babar	Study of $B^{0,\pm} \to J/\psi K^+K^-K^{0,\pm}$ and search for structure in the $J/\psi\phi$ system Bottomonium spectroscopy and radiative transition involving the χ_{bJ}(1P,2P)	V. Santoro
Belle& Babar	$Y(nS) \to \bar{d} + X$ $\Lambda_c^+ \to pK^-\pi^+$ Mass and width of $\Sigma_c(2455)^{0/++}$, $\Sigma_c(2525)^{0/++}$ Search for $\Xi_{cc}^{+(+)}$, Ξ_c $Y(1S, 2S) \to \Lambda\bar{\Lambda}X$	M. Z. Wang

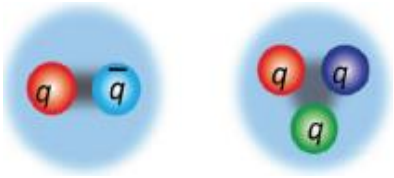
Spectroscopy Results @ ICHEP2014

BESIII	Observation of X(1840) in $J/\psi\to\gamma 3(\pi^+\pi^-)$	S. S. Fang
	PWA of $J/\psi\to\gamma\omega\phi$	
	PWA of $J/\psi\to\gamma\eta\eta$	
	η and η' physics	
	PWA results on N* Baryons in $\psi'\to\pi^0 pp$	
	Observation of $Z_c(3900)$	
	Observation of $Z_c(4020)$ in $e^+e^-\to\pi\pi h_c$	
	Observation of $Z_c(3885)$ and $Z_c(4025)$	
ATLAS&CMS	Quarkonium production at LHC ATLAS&CMS	H. K. Wohri
VEPP-2000	Results on $e^+e^-\to$hadrons cross section	T. V. Dimova
Babar	Study of e^+e^- annihilation to hadrons with ISR method	V. Druzhinin
	Measurement of collins asymmetries in inclusive production of pion pairs	
	……	

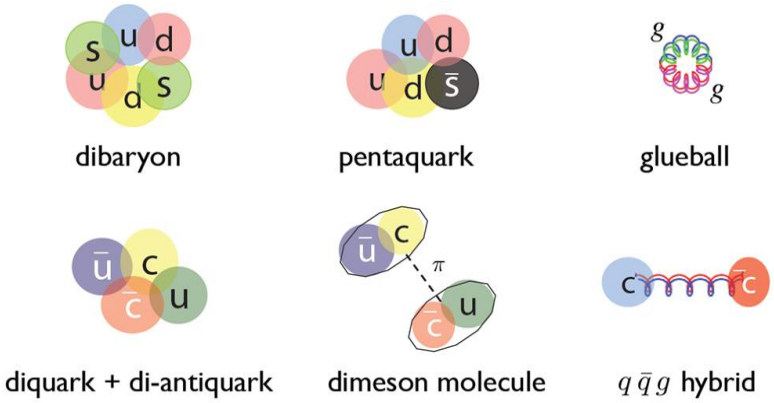
- **This talk : Charmonium-like states**
- **Apologies : I can not cover all results**

Hadrons : Normal & Exotic

- **Experiments :**
  - Hadrons are composed of 2 (meson) or 3 (baryon) quarks
  - Described very well in quark model (QM)



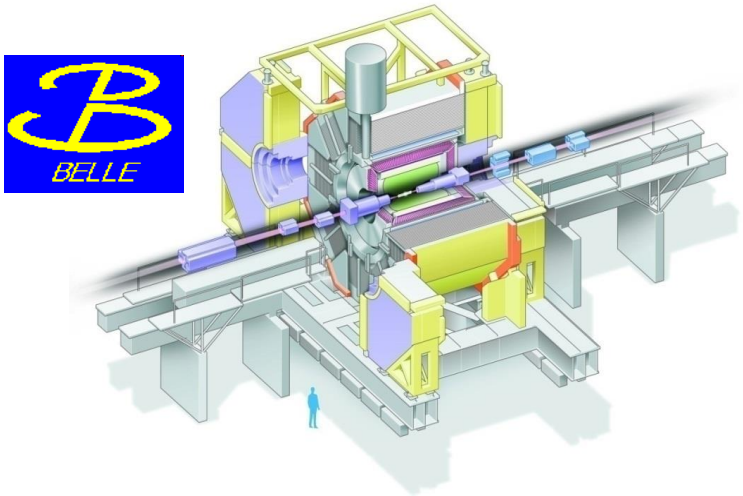
- **QCD suggests:**
  - Confinement : stable hadrons need to be colorless
  - Gluon-gluon interactions : hadron with gluons (hybrids and glueballs) could exist
  - Allow hadrons with $N_{quarks} \neq 2, 3$ (multi-quarks)

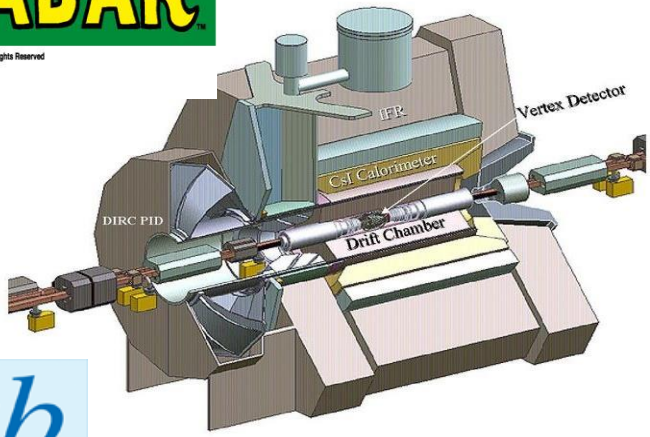


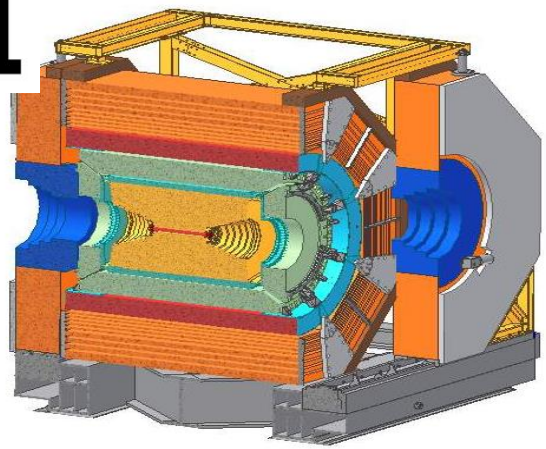
Can we find evidence for these interesting exotic hadrons?

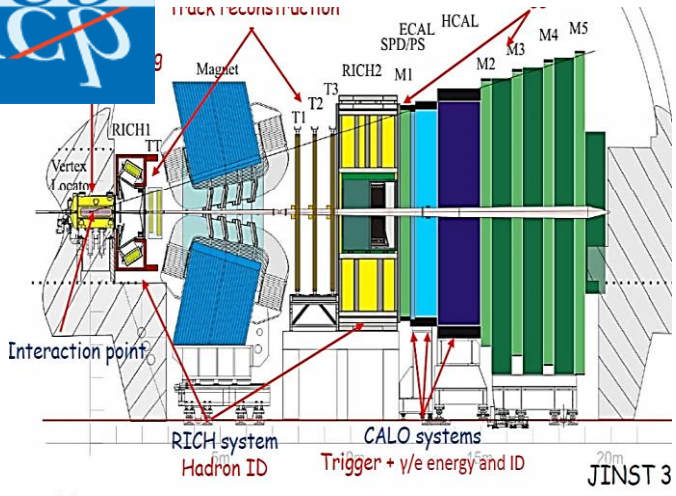
A long history of searching for the exotic hadron,
no solid conclusion was reached in past a few decades,
some hints on charmomium-like and bottomnium-like particles, recently.

Results from These Experiments









+ CLEOc, CDF, CMS/ATLAS …

Charmonium Spectroscopy

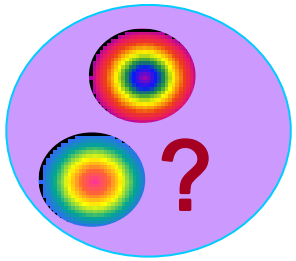
played important role in establishing QCD as theory of strong interactions

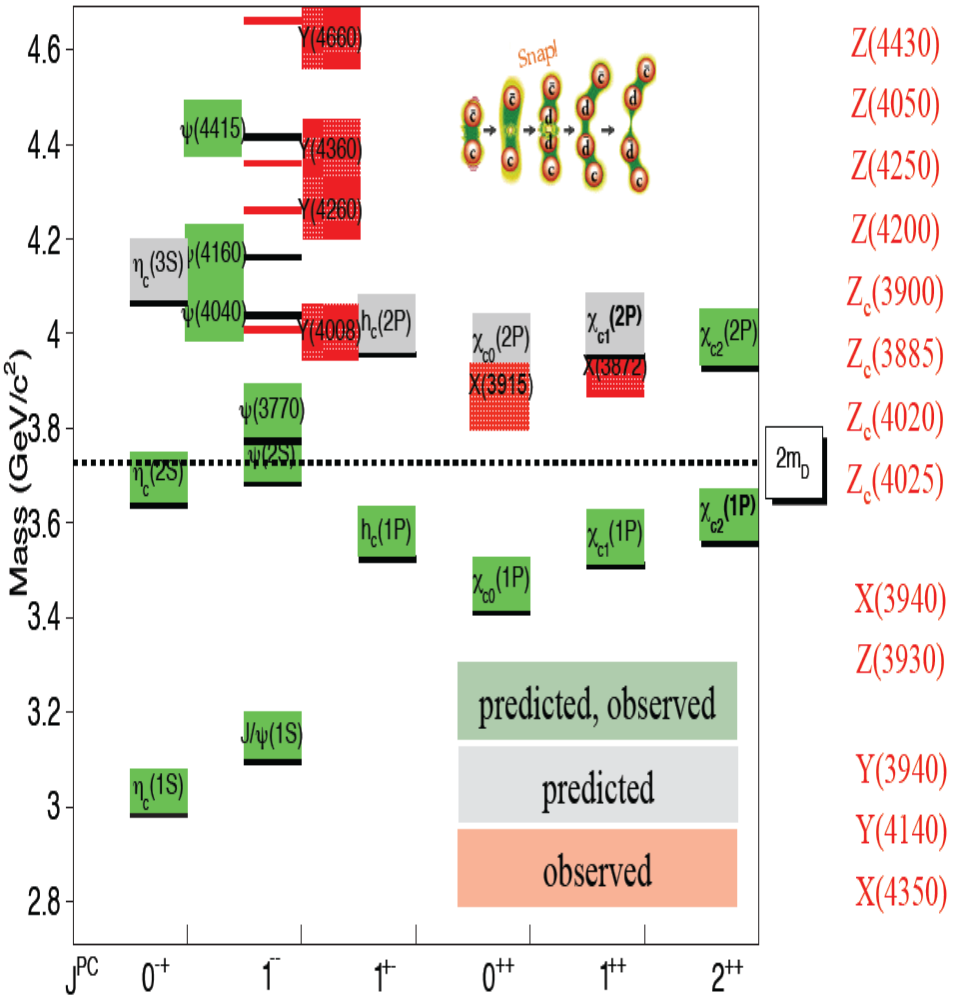
- All States below charm threshold have been observed
  - Charm anti-charm potential model described spectrum very well
- Many missing states above charm threshold.
- New states above charm threshold appear
  - Charmonium in final states
  - Not an obvious charmonium state

Not all of them are charmonia!

What are they?

- Charmonium?
- Hybrid?
- Tetraquark?
- Molecule?
- Non-resonance?

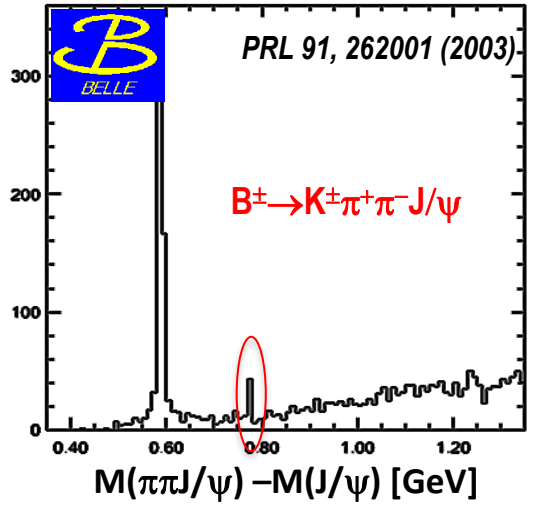


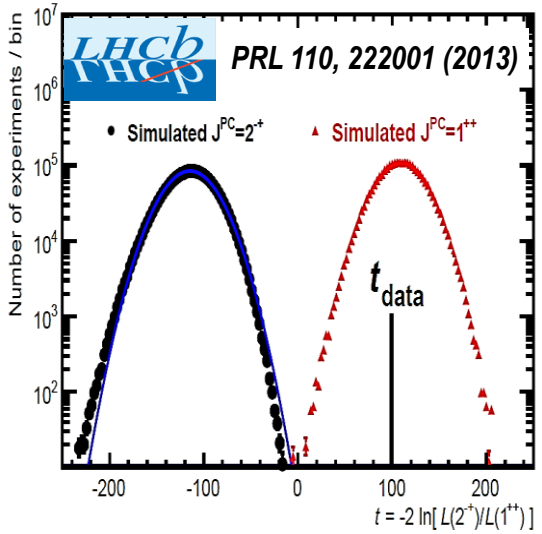


What is X(3872) ?

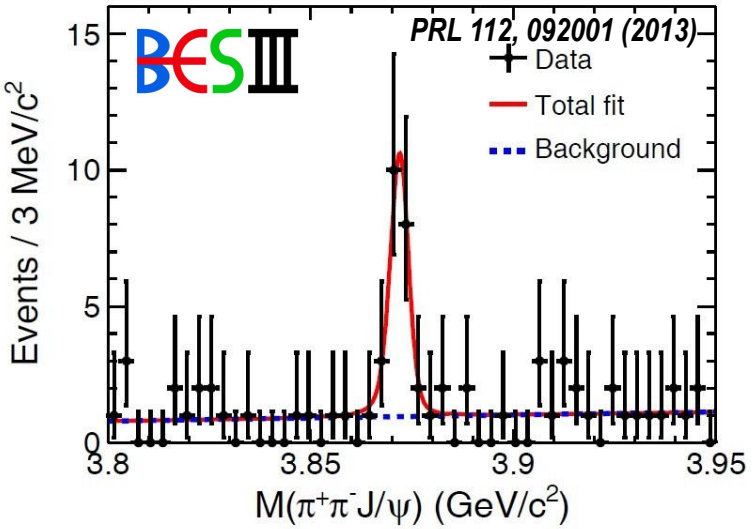
What is X(3872)

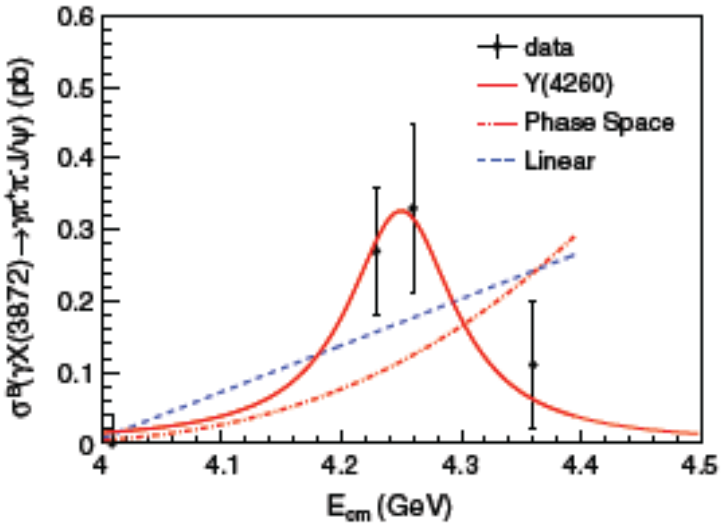
- **Observed by Belle, confirmed by several experiments**
  - Very close to $\bar{D}^0 D^{*0}$ threshold,
  - Very narrow, < 1.2 MeV
- **$J^{PC}=1^{++}$, a definitive determination by LHCb :**
  - Decay to $\gamma J/\psi$ or $\psi(2S)$ indicate C-parity as + *[Belle, Babar, LHCb]*
  - Reduce possibility to 1^{++}, 2^{-+} by CDF *[PRL 98, 132002 (2007)]*
- **Production :**
  - In B decays – KX similar to charmonia,
    - K*X smaller than charmonia
    - $K\pi X$ *(see Pavel Krokovny's talk on last Tursday)*
  - In pp/$p\bar{p}$ collision – rate similar to charmonia
  - Radiative transition of the excited vector charmonium(like)? – $J^{PC}=1^{++}$
- **Decay modes :**
  - $\pi^+\pi^-(\rho)J/\psi$, $\pi^+\pi^-\pi^0(\omega)J/\psi$,
  - $\gamma J/\psi$, $\gamma\psi(2S)$
  - $D^0\bar{D}^0\pi^0$, $D^0\bar{D}^{*0}$
  - Not observed in $\eta_c h$ decay *(see Pavel Krokovny's talk last Tursday)*





Observation of $e^+e^- \to \gamma X(3872)$





- Observed signal @E_{cm} = 4230, 4260, 4360MeV [2.4fb^{-1}]
  - Significance : 6.3σ
  - Mass : 3871.9±0.7±0.2MeV
    [PDG : 3871.68±0.17MeV]
  - Width : <2.4MeV with 90%C.L.

- X-sec. is an order higher than NRQCD calculation of continuum process.
- The radiative transition production in Y(4260) decay suggestive, but not conclusive
- Assume $B(X(3872)\to\pi^+\pi^- J/\psi) = 5\%$

$$\frac{\sigma(Y(4260)\to\gamma X(3872))}{\sigma(Y(4260)\to\pi^+\pi^- J/\psi)} \sim 11\%, \text{ large ratio !}$$

A new decay mode of Y(4260)?

Any commonality in nature of Y(4260), $Z_c(3900)$ and X(3872)?

The Nature of X(3872)

Possible Theory Speculation

- Loosely $\bar{D}^0 D^{*0}$ bound state (like deuteron?)?
- Mixture of χ'_{c1} and $\bar{D}^0 D^{*0}$ bound state?
- Many other possibilities

Isospin violation

	Relative BF
$J/\psi\rho$	1
$J/\psi\omega$	0.8 ± 0.3
$J/\psi\gamma$	0.21 ± 0.06
$D^0\bar{D}^{*0}$	~10

Comparable BF → a $D\bar{D}^*$ molecule

Ratio of $X(3872) \to \gamma\psi(2S)$ to $\gamma J/\psi$

BABAR, PRD 74, 071101(2006)

$$\frac{\mathcal{B}(X(3872) \to \gamma\psi(2S))}{\mathcal{B}(X(3872) \to \gamma J/\psi)} = 3.4 \pm 1.4$$

BELLE, PRL 107, 091803 (2011)

$$\frac{\mathcal{B}(X(3872) \to \gamma\psi(2S))}{\mathcal{B}(X(3872) \to \gamma J/\psi)} < 2.1 \text{ @ 90\% C.L.}$$

LHCb, arXiv:1404.0275

$$\frac{\mathcal{B}(X(3872) \to \gamma\psi(2S))}{\mathcal{B}(X(3872) \to \gamma J/\psi)} = 2.46 \pm 0.64 \pm 0.29$$

see Tomasz. Skwarnicki's talk on last Thursday

Theoretical predictions :

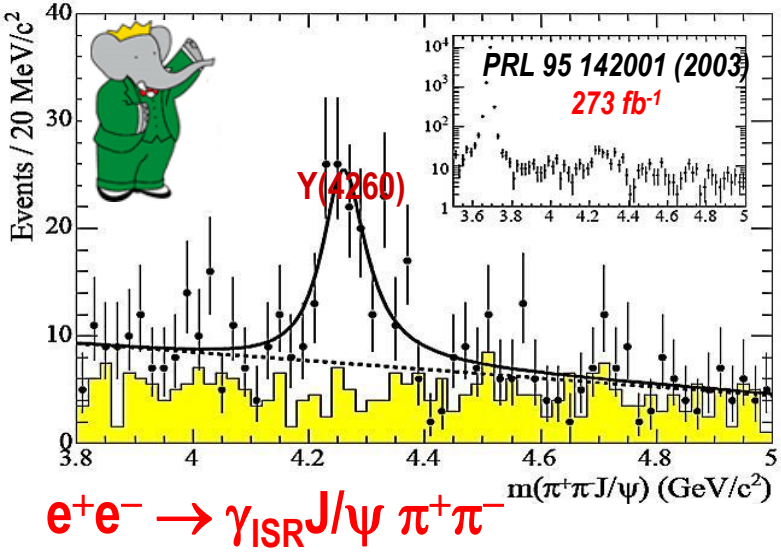
- $D\bar{D}^*$ molecule : $(3\text{-}4)\times10^{-3}$
- Charmonium : 1.2–15
- Mixture : 0.5–5

→ Not a pure $D\bar{D}^*$ molecule

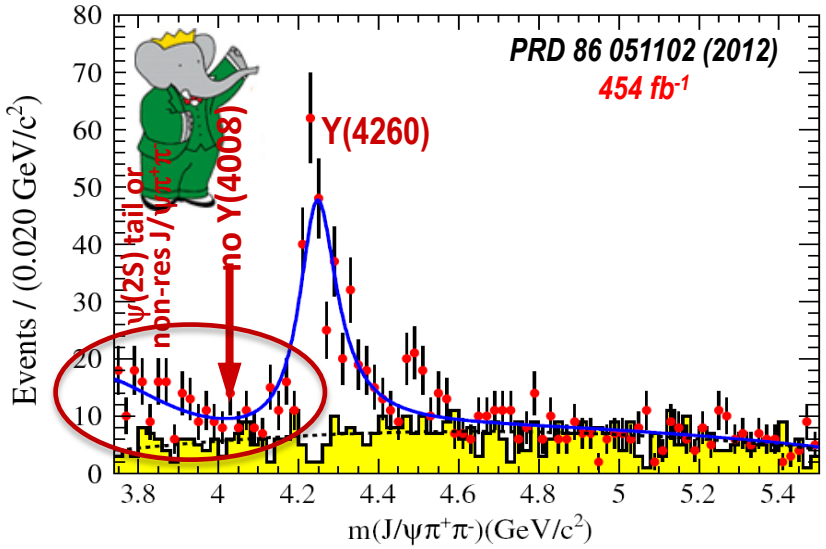
A mixture of a $D\bar{D}^*$ molecule and a χ_{c1}' charmonium ?

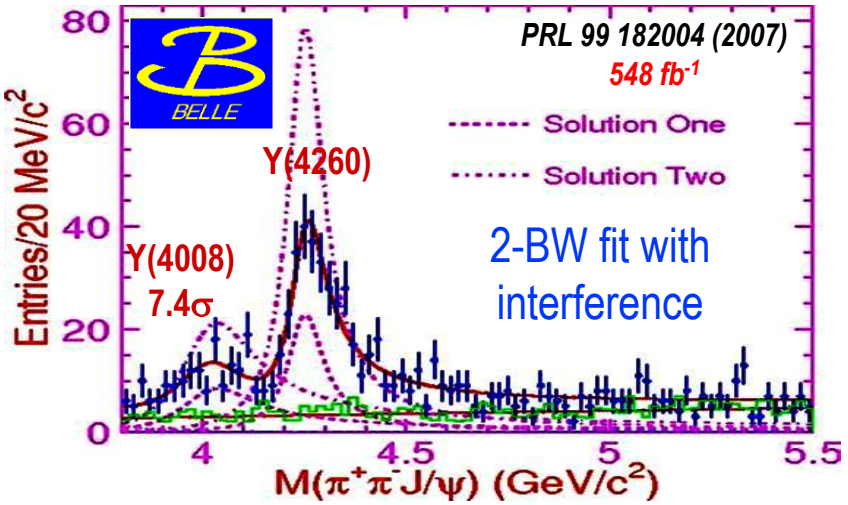
Y-family States

The history : Y(4260)/Y(4008)



$e^+e^- \to \gamma_{ISR} J/\psi\, \pi^+\pi^-$

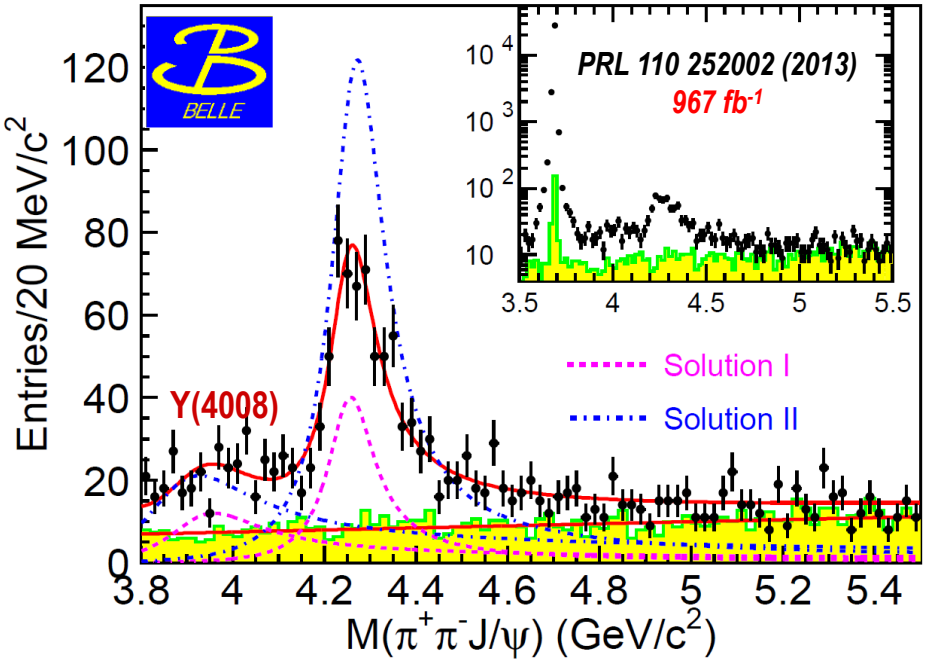




- Y(4260) first observed in $J/\psi\pi^+\pi^-$ by BaBar, and confirmed by CLEO and Belle
- Belle observed additional Y(4008)
- BaBar updated with more data, no Y(4008) observed,
- J/ψ is the only firmly established decay mode
  - Belle result limits $\sigma(KKJ/\psi)$ to about 1/10 of $\pi\pi J/\psi$

[PRD 89, 072015 (2014)]

Y(4260)/Y(4008)



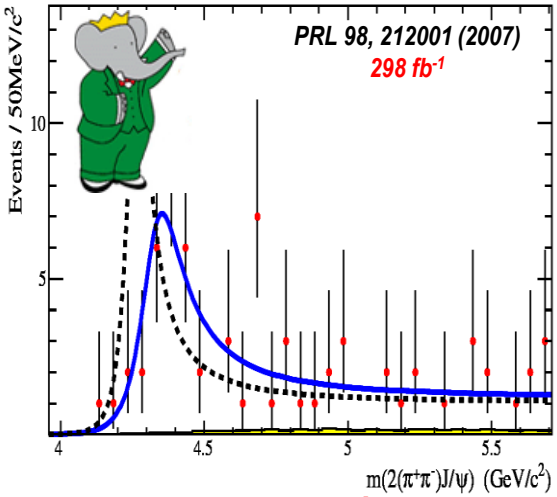
R_1=Y(4008), R_2=Y(4260)

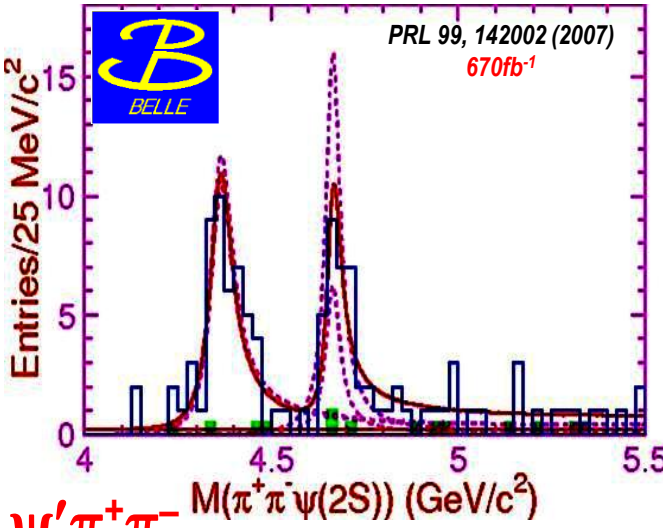
Parameters	Solution I	Solution II
$M(R_1)$	$3890.8 \pm 40.5 \pm 11.5$	
$\Gamma_{\rm tot}(R_1)$	$254.5 \pm 39.5 \pm 13.6$	
$\Gamma_{ee}\mathcal{B}(R_1 \to \pi^+\pi^- J/\psi)$	$(3.8 \pm 0.6 \pm 0.4)$	$(8.4 \pm 1.2 \pm 1.1)$
$M(R_2)$	$4258.6 \pm 8.3 \pm 12.1$	
$\Gamma_{\rm tot}(R_2)$	$134.1 \pm 16.4 \pm 5.5$	
$\Gamma_{ee}\mathcal{B}(R_2 \to \pi^+\pi^- J/\psi)$	$(6.4 \pm 0.8 \pm 0.6)$	$(20.5 \pm 1.4 \pm 2.0)$
ϕ	$59 \pm 17 \pm 11$	$-116 \pm 6 \pm 11$

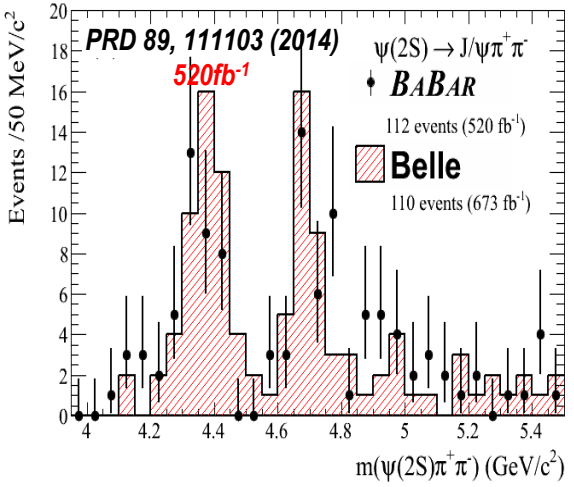
- Fit with two coherent resonances $|BW_1+BW_2*\exp(if)|^2$+bkg.
- Mass of Y(4008) is lower than previous measurement
- Fit quality: χ^2/ndf=101/84, confidence level is 9.3%

Confirmed two resonances, agrees with Belle's previous results.
Inconsistent on Y(4008) : BESIII data can clarify

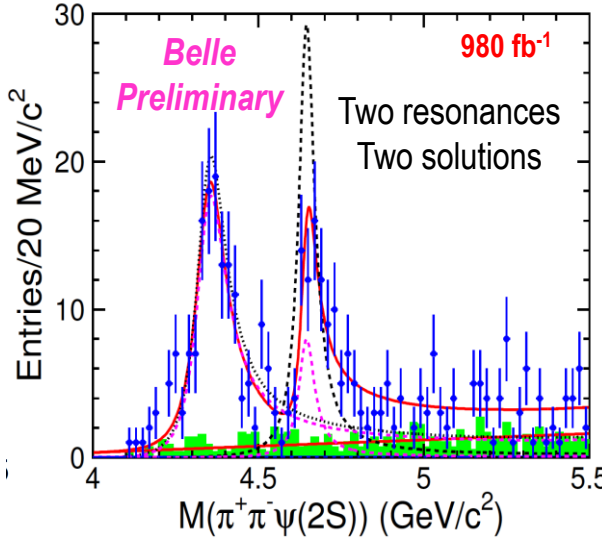
Y(4360)/Y(4660)

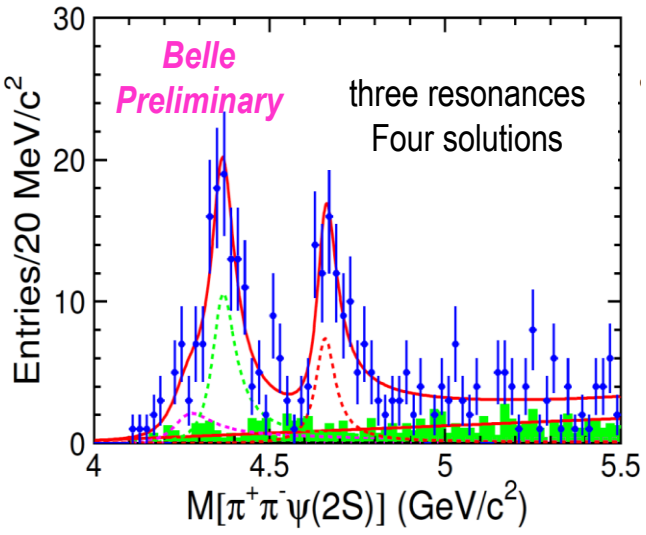






$e^+e^- \to \gamma_{ISR}\psi'\pi^+\pi^-$

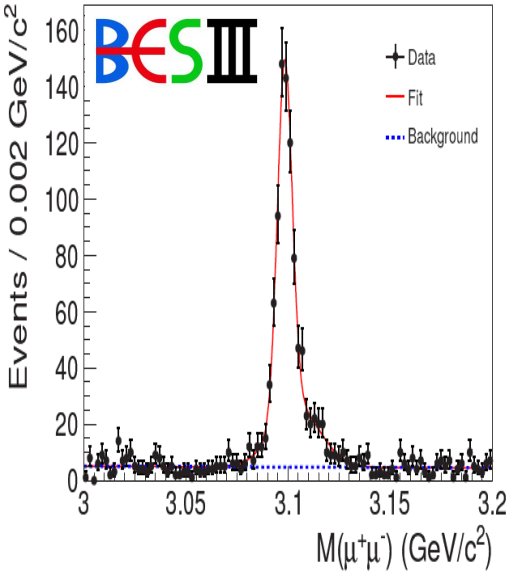


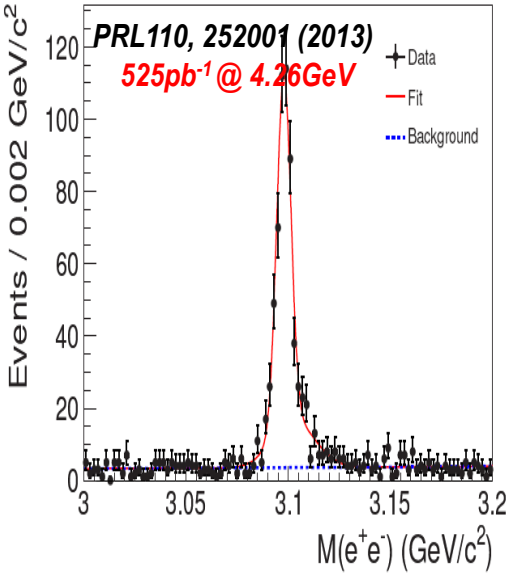


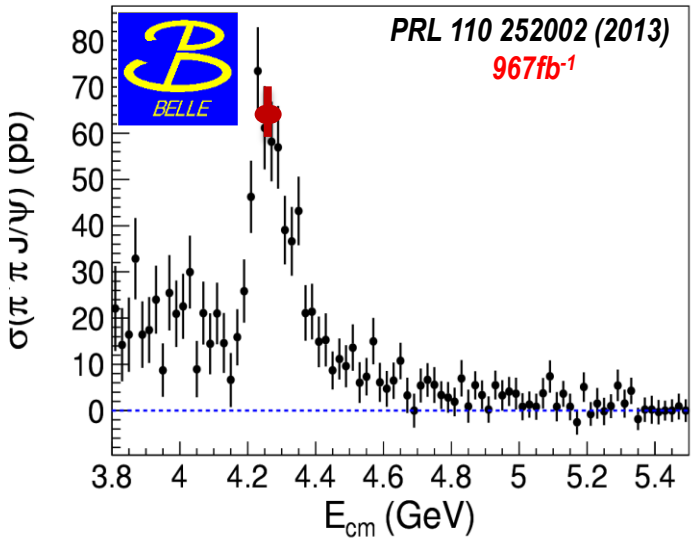
- BaBar and Belle observed Y(4360)
- Belle with additional Y(4660)
- BaBar updated results in good agreement with Belle

  Y(4660) confirmed
- Belle preliminary results in good agreement with previous results, Y(4260) significance 2.1σ only.

$e^+e^- \to \pi^+\pi^- J/\psi$ @BESIII







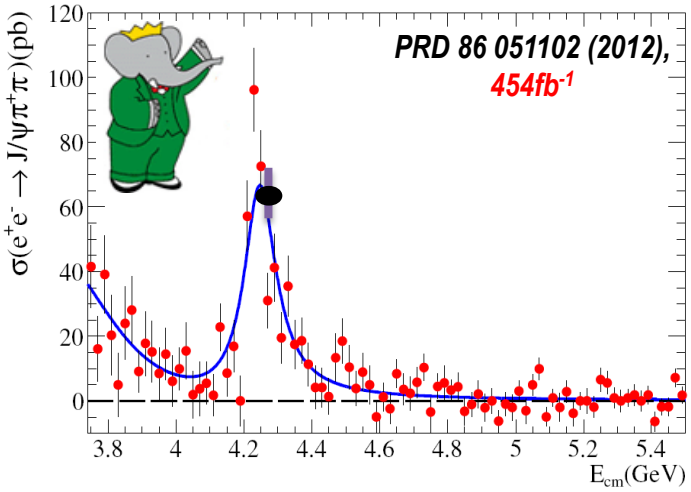
$\sigma(e^+e^- \to \pi^+\pi^- J/\psi) = (62.9 \pm 1.9 \pm 3.7)$ pb

Agree with BaBar & Belle!

Best precision!

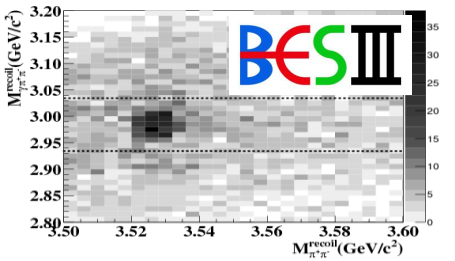
The line shape measurement is ongoing,

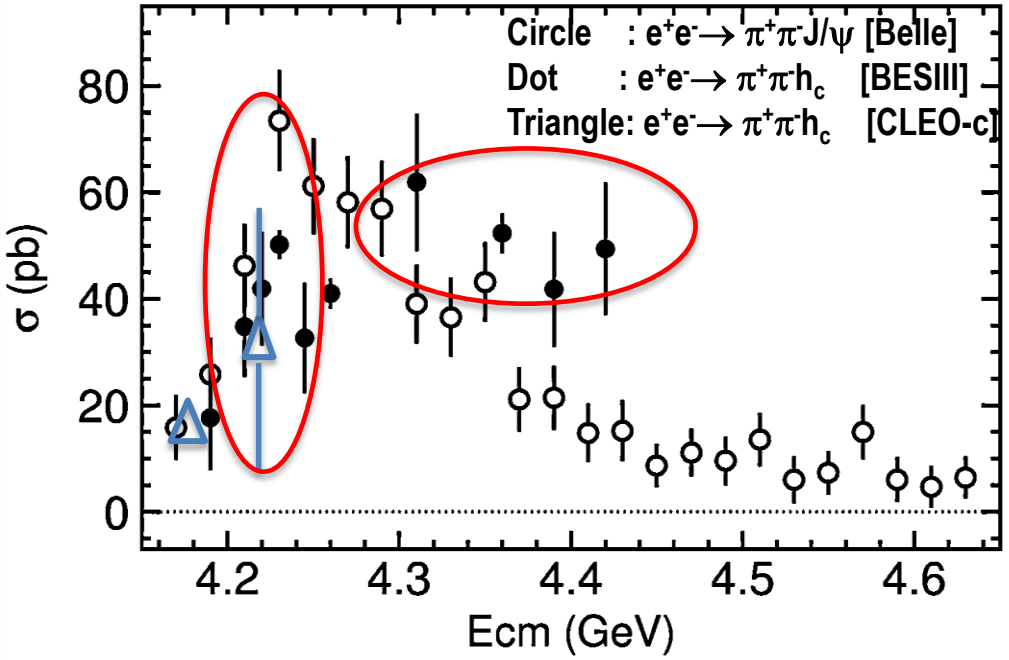
To validate the existence of Y(4008)



$e^+e^- \to \pi^+\pi^- h_c$ @BESIII

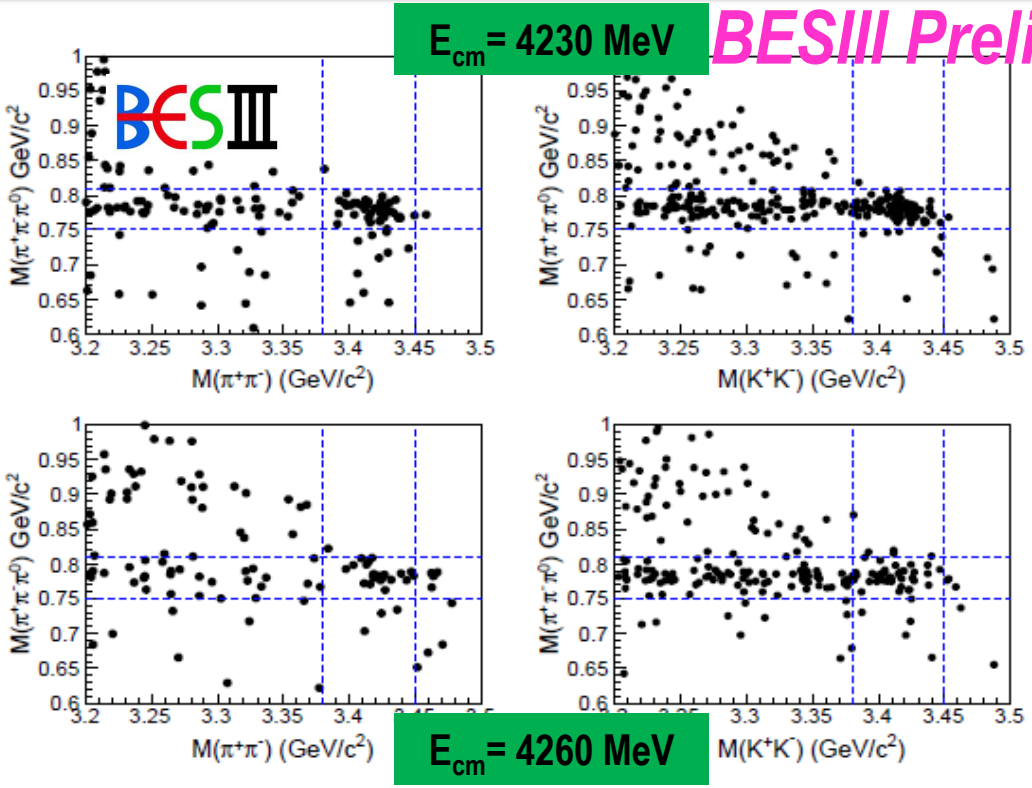
- Significant $\pi^+\pi^- h_c$ production reported by CLEO @ 4170MeV [PRL 107, 041803 (2011)]
  - Correlated with observed Y(4260) or others charmonium states?
- 3.3fb^{-1} data at 13 energy points from 3900~4420 GeV [$h_c \to \gamma\eta_c$, $\eta_c \to$hadrons, 16 exclusive decay modes]

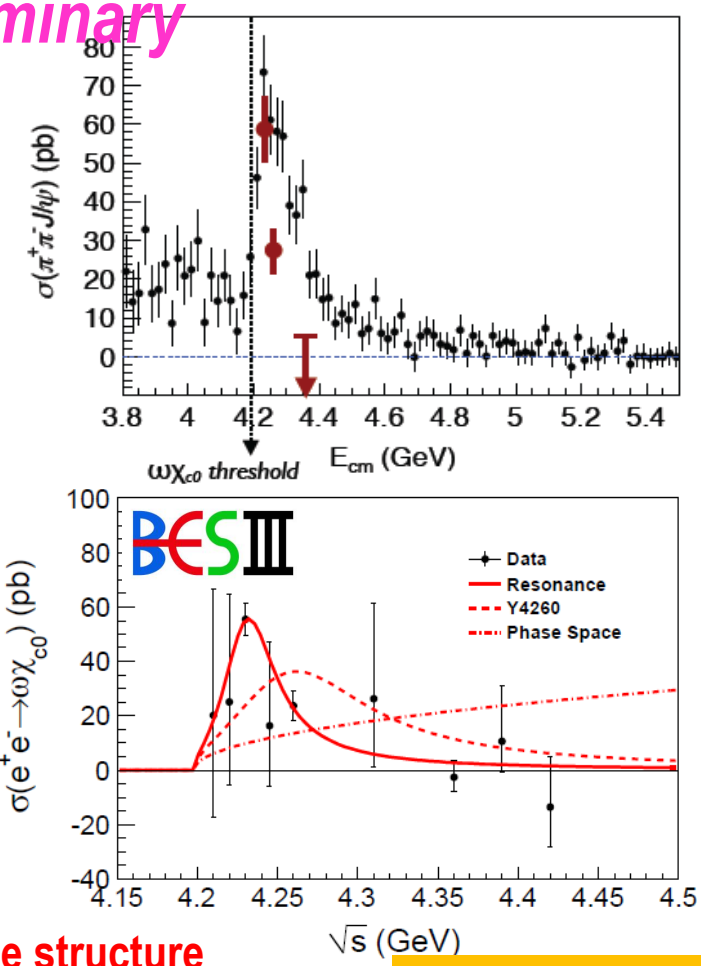




- $\sigma(e^+e^- \to \pi^+\pi^- h_c) \sim \sigma(e^+e^- \to \pi^+\pi^- J/\psi)$, but different line shape.
- Local maximum ~ 4230 MeV, broad structure at ~ 4400 MeV?
- Correlation with Y(4260) or Y(4360) is unclear
- More data around 4230MeV and above 4400MeV is very help.

$e^+e^- \to \omega\chi_{c0}$ @ BESIII





- The mass of Y(4260) is very close to $\omega\chi_{cJ}$ mass threshold
- Observation of $\omega\chi_{c0}$ at 4230, 4260 MeV data
- No evidence at 4360MeV
- Line shape seems inconsistent with Y(4260)
- a BW fitting get a narrow structure around 4230MeV.

A fine structure at 4230MeV?

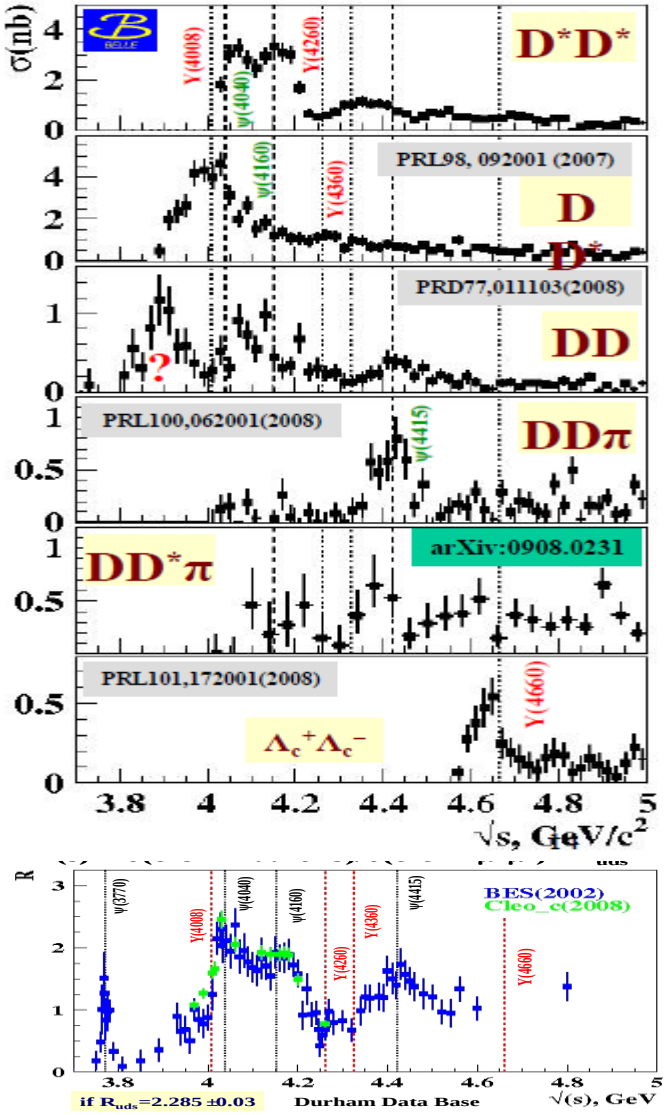
M=4229±11±6MeV

Γ=40±14±2MeV

Y states

- In QM, five states expected between 4 and 4.7GeV
  - 3S/Y(4040), 2D/Y(4160), 4S/Y(4415), 3D, 5S
- But seven states observed:
  - Y(4008), Y(4040), Y(4160), Y(4260), Y(4360), Y(4415), Y(4660)
- Y(4260), Y(4360) and Y(4660) have similar properties
  - All produced in e^+e^- collisions
  - narrow structure above charm threshold
  - Strongly couple to charmonium states
  - No evidence in open-charm process and R-value scan,
    Large BESIII R value data sample may confirm/improve
- $e^+e^- \to \pi^+\pi^- h_c$ and $\omega\chi_{c0}$ cross section line shape
  - Makes situation more complicate
  - Have fine structures at 4230MeV, strong couple to $\omega\chi_{c0}$?
- What are these Y states
  - Hybrid? Molecule? Threshold effect? …..

Unclear, need to be understood



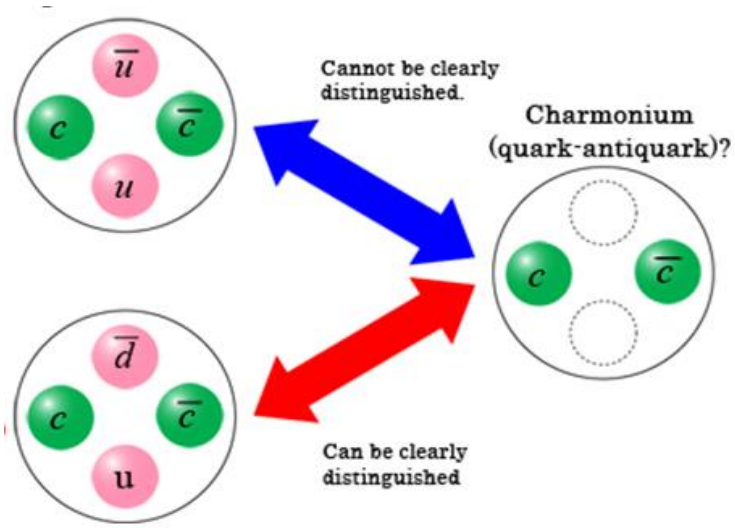
Z_c States

Z_c States

The most promising way to searching for the exotic hadrons

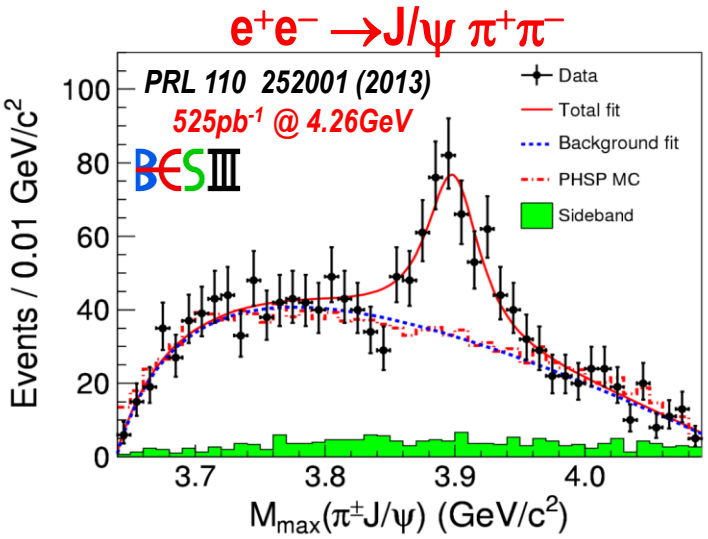
- Decay into a charmonium or $D^{(*)}\bar{D}^{(*)}$ pair
  - thus contains hidden-$c\bar{c}$ pair
- Have electric charge,
  - thus has two more light quarks

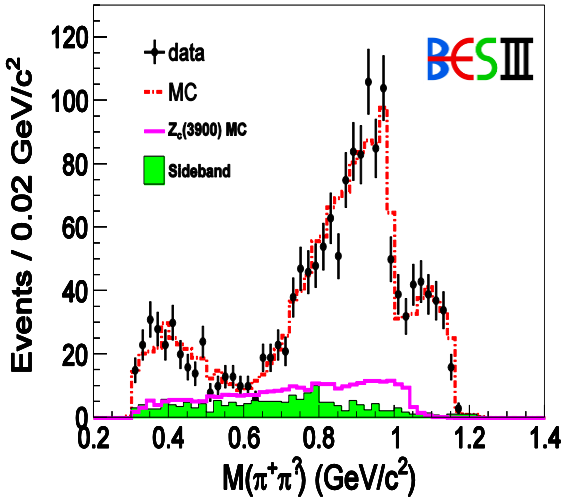
At least 4 quarks, not a conventional meson

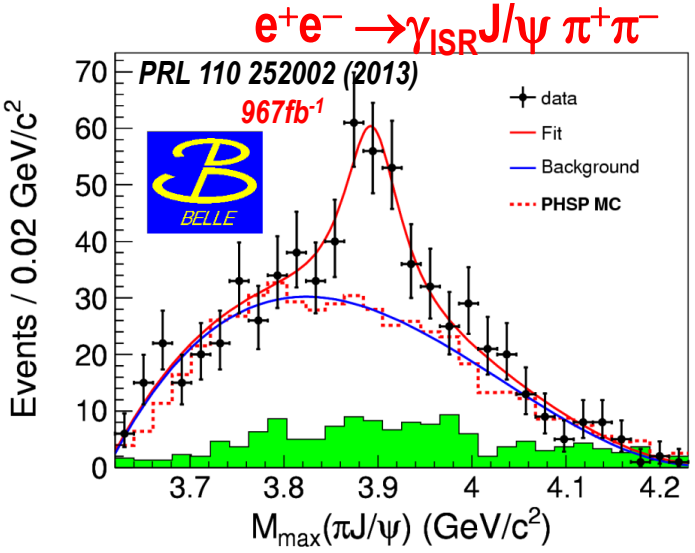


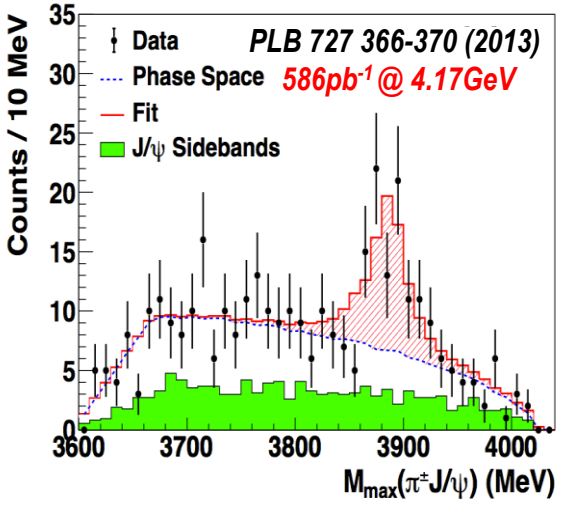
- Observed in final states :
  - $\pi^{\pm}J/\psi$, $\pi^{\pm}\psi(2S)$, $\pi^{\pm}h_c$, $\pi^{\pm}\chi_{cJ}$, $(D^{(*)}\bar{D}^{(*)})^{\pm}$,…
- Experimental search:
  - BESIII/CLEO-c : $e^+e^- \to \pi^{\pm}$ +Exotics, ….
  - Belle/BaBar : $e^+e^- \to (\gamma_{ISR})\pi^{\pm}$+Exotics, ….
  - Belle/BaBar/LHCb: $B \to K^{\pm}$+Exotics, …

Observation of $Z_c(3900)^{\pm}$









BESIIII

M = 3899.0±3.6±4.9 MeV

Γ = 46±10±20 MeV

307 ± 48 events, >8σ

BELLE

M = 3894.5±6.6±4.5 MeV

Γ = 63±24±26 MeV

159 ± 49 events, >5.2σ

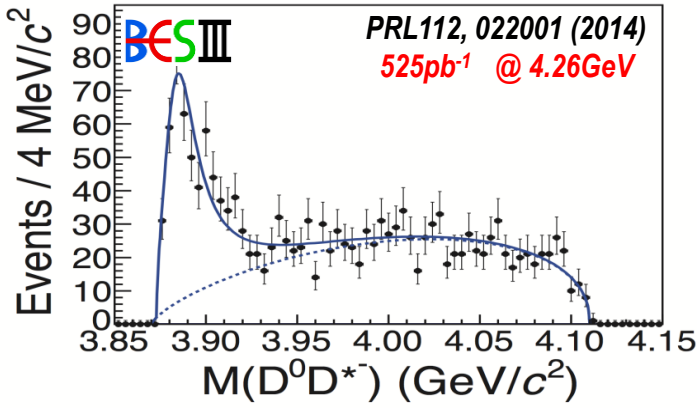
CLEO-c Data

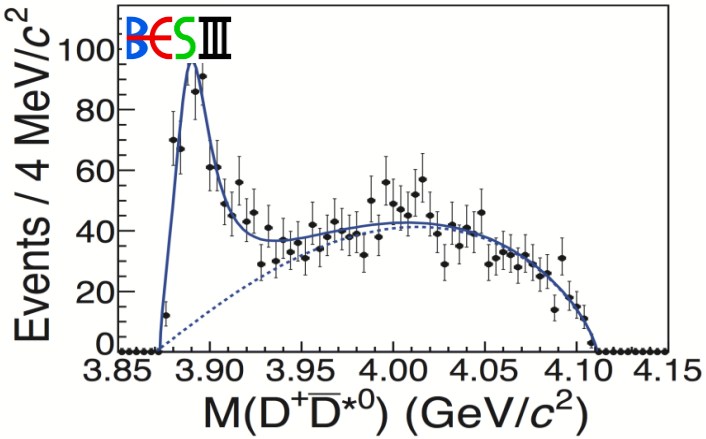
M = 3886±4±2 MeV

Γ = 37±4±8 MeV

81 ± 16 events, >5σ

$e^+e^- \to \pi^\pm (D\bar{D}^*)^\mp$ @4.26GeV





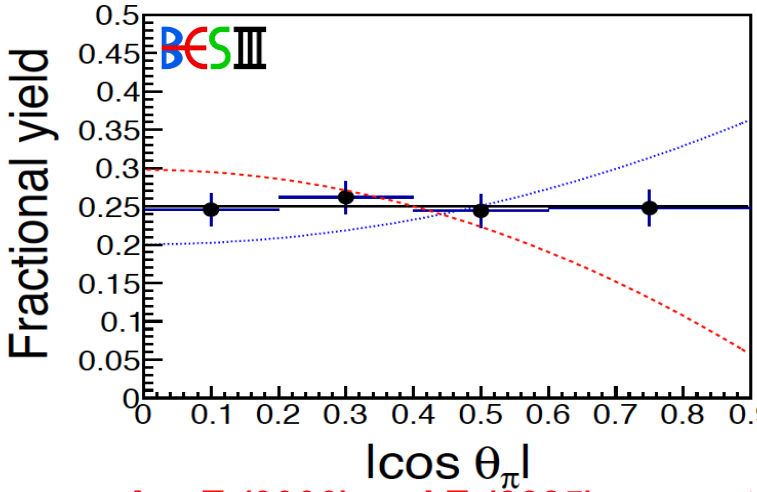
M[Z_c(3885)] = 3883.9±1.5±4.2MeV

Γ[Z_c(3885)] = 24.8±3.3±11.0MeV

2σ/1σ below those of Z_c(3900)

- Bachelor π angular distribution :

favors a $J^P=1^+$ assignment



Are Z_c(3900) and Z_c(3885) same states?

- If Z_c(3885) is Z_c(3900):

$$\frac{\Gamma(Z_c(3900) \to D\bar{D}^*)}{\Gamma(Z_c(3900) \to \pi J/\psi)} = 6.2 \pm 2.9$$

Large non-DDbar coupling

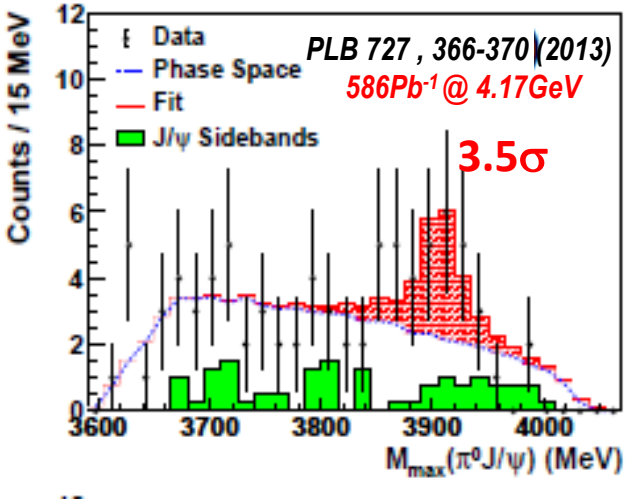
Typical values : ψ(3770)~500, ψ(4040)~200

Very different dynamics in the Y(4260)–Z_c(3900) system?

$Z_c(3900)^0$ @$e^+e^- \to \pi^0\pi^0 J/\psi$

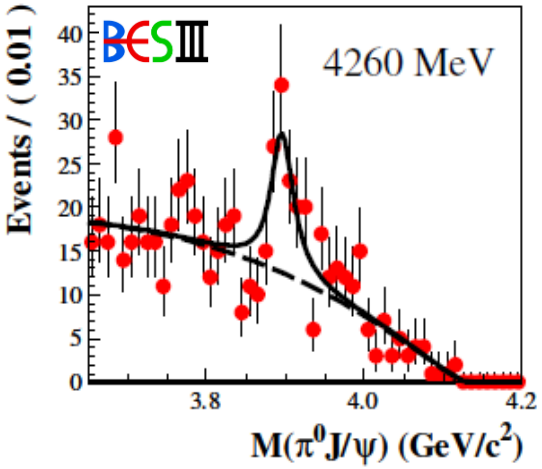
Has an isospin partner, $Z_c(3900)^0$?

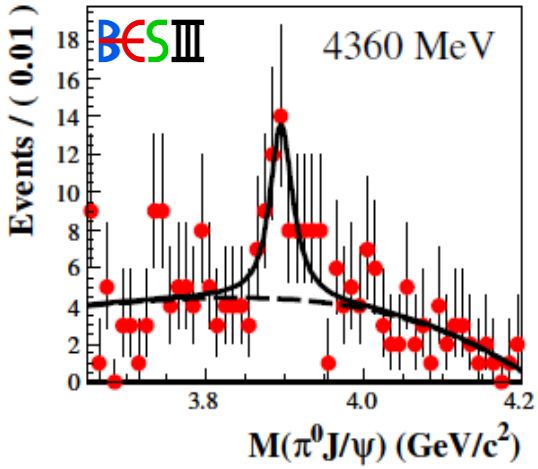
BESIII Preliminary

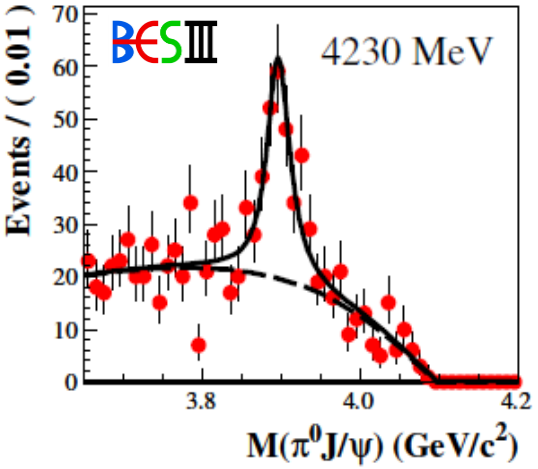


- 2.8fb^{-1} data at 10 energy points from 4230~4420 MeV
- $Z_c(3900)^0$ is observed clearly at E_{cm}=4230, 4260, 4360MeV
- BESIII preliminary results :
  - M= 3894.8$\pm$2.3 MeV, Γ = 29.6$\pm$8.2 MeV
  - Significance = 10.4 σ

Neutral isospin partner, $Z_c(3900)^0$ observed

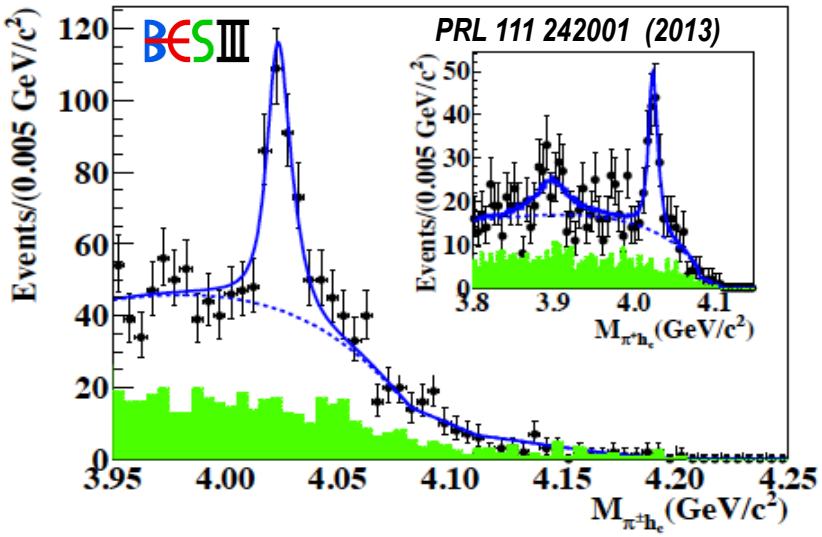






Observation of $Z_c(4020)^{\pm}$

$e^+e^- \to \pi^+\pi^- h_c$

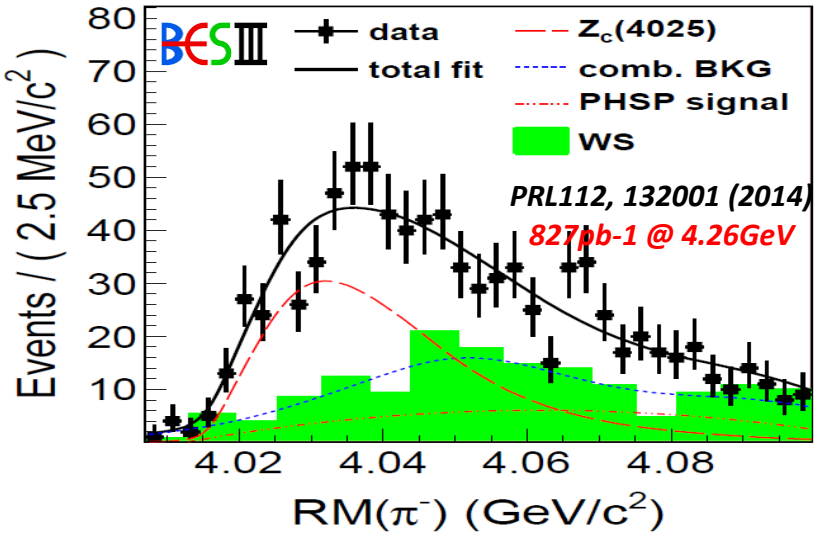


- Narrow $\pi^{\pm}h_c$ structure observed
  - M = 4022.9±0.8±2.7 MeV;
  - Γ= 7.9±2.7±2.6 MeV
  - Significance : 8.9σ
- No significant evidence for $Z_c(3900) \to \pi^{\pm}h_c$
  - Significance 2.1σ
  - @ Ecm = 4260 MeV

$$\sigma(e^+e^- \to \pi^{\pm}Z_c(3900)^{\mp} \to \pi^+\pi^- h_c) < 11 \text{ pb}$$

$$\sigma(e^+e^- \to \pi^{\pm}Z_c(3900)^{\mp} \to \pi^+\pi^- J/\psi) = 13 \pm 5 \text{ pb}$$

$e^+e^- \to \pi^{\pm}(D^*D^*)^{\mp}$



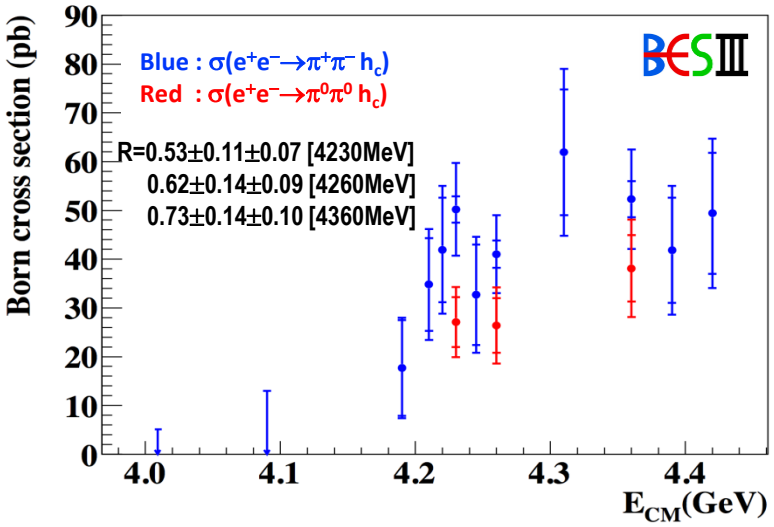
- Deviation from phase space decay
  - M = 4026.3±2.6±3.7 MeV
  - Γ = 24.8±5.6±7.7 MeV
  - Significance : 10σ

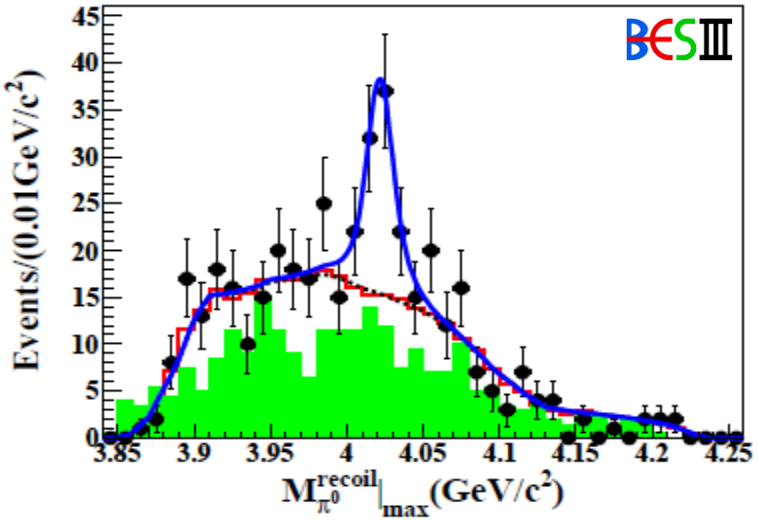
Are $Z_c(4020)$ and $Z_c(4025)$ same particle?

- If $Z_c(4025)$ is the $Z_c(4020)$

$$\frac{\Gamma(Z_c(4020) \to D^*\bar{D}^*)}{\Gamma(Z_c(4020) \to \pi h_c)} = 12 \pm 5$$

$Z_c(4020)^0$ @ $e^+e^- \to \pi^0\pi^0 h_c$





BESIII Preliminary

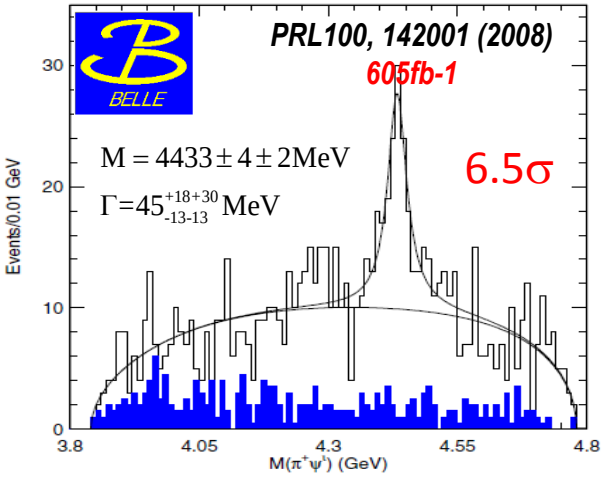
- Study $e^+e^- \to \pi^0\pi^0 h_c$ at E_{cm} = 4230, 4260, 4360 MeV
- X-sec. is about half of that charged process, agree with the expectation of isospin symmetry
- Observe $Z_c(4020)^0$ structure in $\pi_0 h_c$ mass distribution
- BESIII preliminary Result :
  - $M[Z_c(4020)^0] = 4023.6 \pm 2.2 \pm 3.9$ MeV

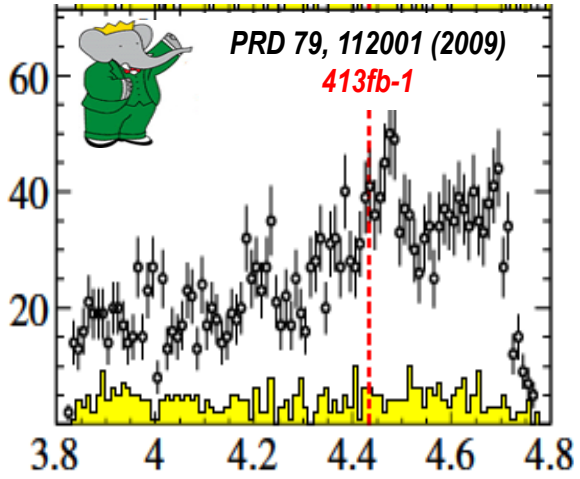
    $[M[Z_c(4020)^\pm] = 4022.9 \pm 0.8 \pm 2.7$ MeV$]$
  - Width fixed to charged $Z_c(4020)$
  - Significance : $>5\sigma$

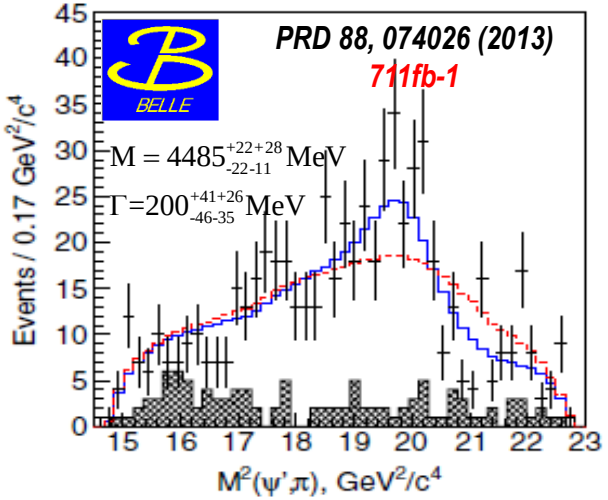
Neutral partner of charge $Z_c(4020)$ observed!

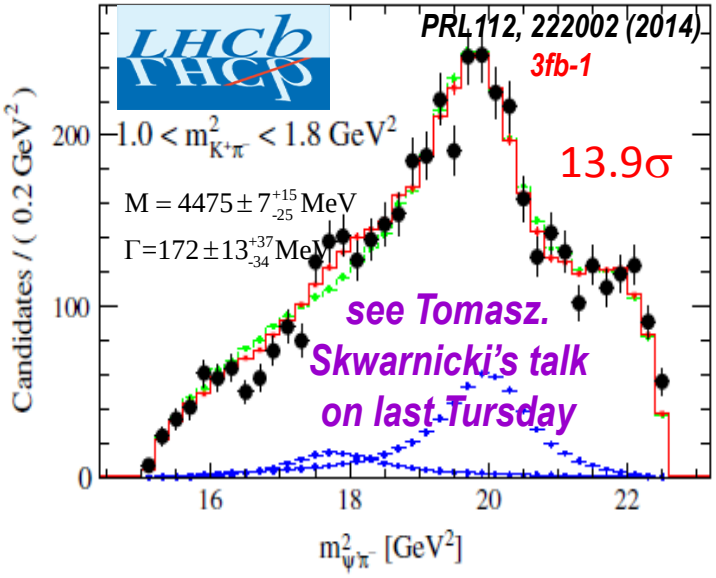
Observation of neutral $Z_c(3900)$ and $Z_c(4020)$ → Isovector nature of Z_c states established

$Z_c(4430)$ in $B^0 \to \psi(2S)K\pi$





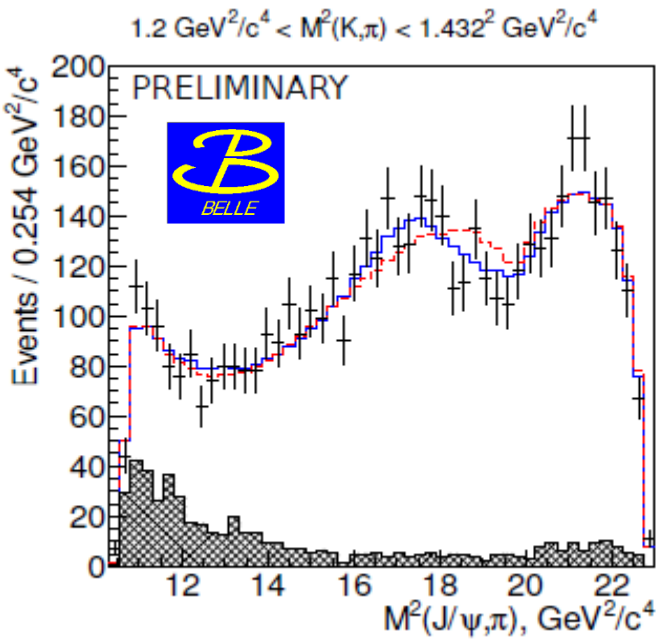


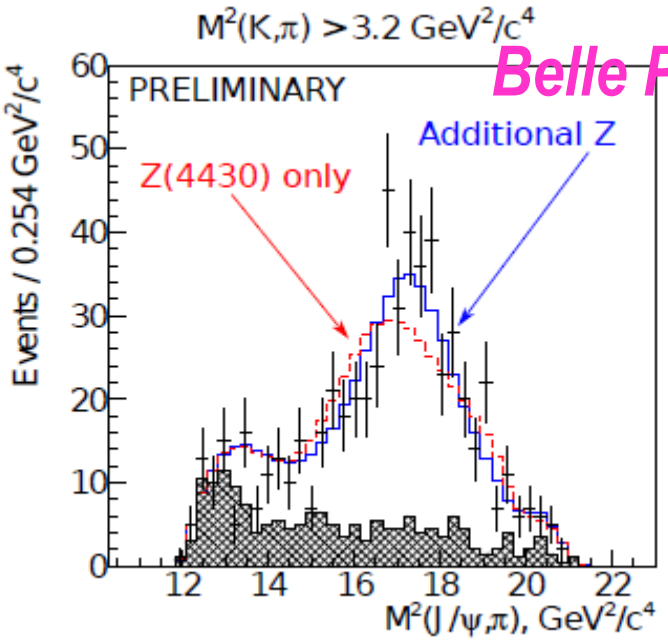


- First charged charmonium-like particle, reported by Belle
- Babar : the reflections of K*states, but not contradict to Belle
- LHCb established its existence, $J^p=1^+$ unambiguously
  [4D model-independent approach, Argand diagram]
- Belle's updated results confirmed its existence, J^p favored 1^+
- Mass and width are higher than that of previous Belle results

Second Z_c observed by two experiments,
The existence of $Z_c(4430)$ or $Z_c(4480)$ established !

$B^0 \to J/\psi k\pi$ @ Belle





Belle Preliminary

- 4D amplitude analysis
- New Z_c (4200) is found ($J^P = 1^+$) with 7.2σ:

$$M = 4196^{+31+17}_{-29-6}\ \mathrm{MeV}/c^2,\ \Gamma = 370^{+70+70}_{-70-85}\ \mathrm{MeV}.$$

- Exclusion levels ($J^p=0^-, 1^-, 2^-, 2^+$) : 6.7σ , 7.7σ, 5.2σ, 7.6σ
- $Z_c(4430)$ is also found (4σ) , $\dfrac{\mathcal{B}(Z_c(4430)^+ \to \psi(2S)\pi^+)}{\mathcal{B}(Z_c(4430)^+ \to J/\psi\pi^+)} \sim 10$

A new charged charmonium-like particle, $Z_c(4200)$?

A new $Z_c(4430)$ decay mode?

Need confirmation!

see Pavel Krokovny's talk on last Tursday

Z_c States

Three established charged charmonium-like structure $Z_c^{\pm}$

$Z_c(3900)^{\pm}$

- Narrow charged structure above $(DD^*)^{\pm}$ mass threshold
- Observed in $\pi^{\pm}J/\psi$ final state
- Decay to $(D\bar{D}^*)^{\pm}$ and $\pi^{\pm}J/\psi$ in ratio of $6\pm3:1$
- Neutral isospin partner $Z_c(3900)^0$
- $J^P=1^+$
- Production seems correlated with Y(4260) decay

$Z_c(4020)^{\pm}$

- Narrow charged structure above $(D^*D^*)^{\pm}$ mass threshold
- Observed in $\pi^{\pm}h_c$ final state
- Decay to $(D^*\bar{D}^*)^{\pm}$ and $\pi^{\pm}h_c$ in ratio of $12\pm5:1$
- Neutral isospin partner $Z_c(4020)^0$
- unknown
- Production correlated with Y(4260) or Y(4360) is unclear

$Z_c(4430)^{\pm}$/ $Z_c(4480)^{\pm}$

- Charged structure above $(D_1D^*)^{\pm}$ mass threshold
- Observed in $\pi^{\pm}\psi(2S)$, evidence decay to $\pi^{\pm}J/\psi$
- Unknown
- Unknown
- $J^P=1^+$
- Production in B decay

Three $Z_c^{\pm}$ need further confirmation

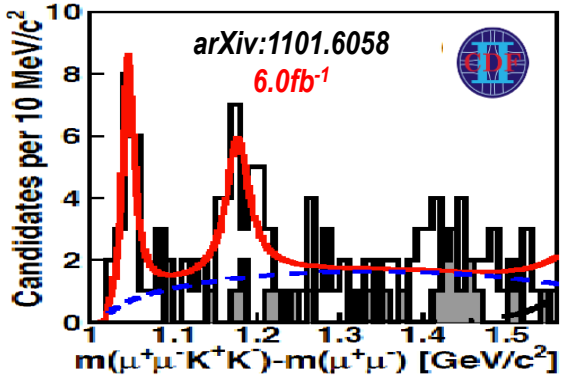
- $Z_c(4200)$ observed in $B\to J/\psi K\pi$ decay
- $Z_c(4050)$, $Z_c(4250)$ observed in $B^0\to K^-\pi^+\chi_{c1}$

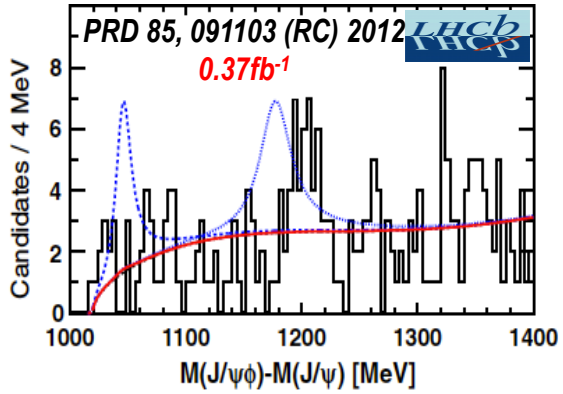
PRD 78, 072004 (2008)

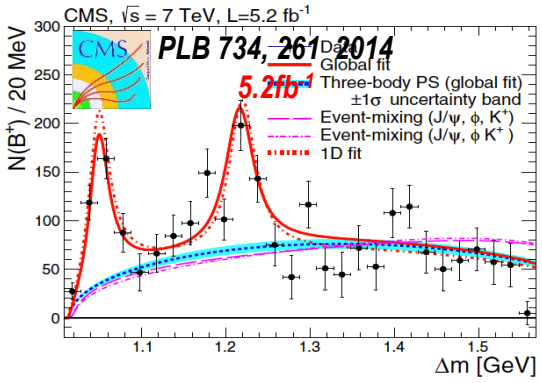
Nature is unclear

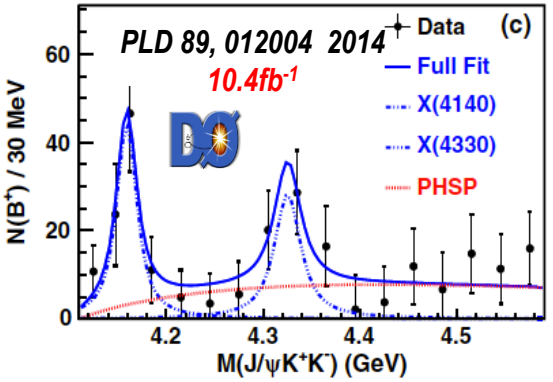
- New type of QCD state or dynamically generated structure?
- One certainty : not conventional charmonium

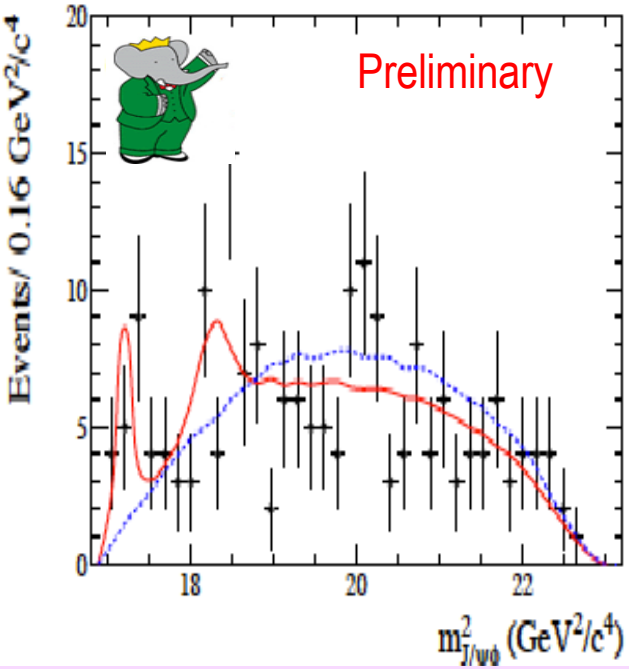
Controversy on B→K(J/ψϕ)











f(4140)=(7.3±2.5±3.8)%, UL @ 90% C.L. =12.1 %
f(4270)=(7.7±3.7±5.2)%, UL @ 90% C.L. =16.4 %

- Y(4140) and Y(4274) was first observed by CDF in $B^+ \to J/\psi\phi K^+$
- LHCb did not observed the two resonances
- CMS confirmed the results
- D0 showed hints for the two Y resonances

Can not access the present of resonance behavior

Higher statistics and a full Dalitz plot analysis is need

See Valentina Santoro's talks on last Thursday

Summary & Perspectives

- In light hadron, a lot of puzzles and controversies remain to be solved
- In charmonium-like (bottomnium-like), a lot of new observations in last decade
  - X(3872) :
    - Well established, but nature is unclear
    - Observed in Y(4260) radiative decay : any correlation with Y(4260) and $Z_c(3900)$?
  - Y states :
    - The existence Y(4008) need confirmed
    - Inconsistent line shape from $e^+e^- \to \pi\pi h_c$, $\omega\chi_{c0}$: fine structure exist around 4230MeV?
  - Z_c states :
    - Three ($Z_c(3900)$, $Z_c(4020)$, $Z_c(4430)$) established, $Z_c(4050)$, $Z_c(4250)$, $Z_c(4200)$ need confirmation
    - Spin-parity measured to be 1^+, isovector nature established, origin is unclear

    Nature are unclear, but not conventional charmonium
  - What may help:
    - Measure and understand transitions between states, explore all possible decay modes
    - More data at a variety of E_{cm} may shed light in the study.
    - Strong similarities between charmonium and bottomonium system

Summary & Perspectives

➢ Experimental challenges

- **High precision measurements : High statistics, high precision data, advance analysis tools etc**
- **Global view : different experiments, different production and decay mechanisms**

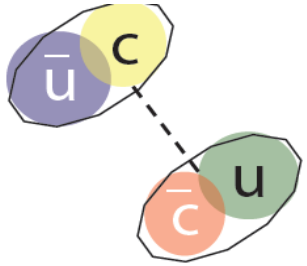
➢ Experimental opportunities

- **Belle, Babar, BESIII@BEPCII, ….**
  - **Have remarkable success and made significant contributions on charmonium (-like) study**
  - **Can immediately add our understanding the meson spectrum above the open charm threshold**
- **Coming Belle II, Panda, and updated LHC and others experiments: CLAS12, GlueX ….**
  - **Promise to have much more fruitful results on spectroscopy.**

Thank You!

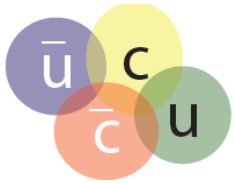
Backup Slide

Exotic Meson (Charmonium-Like)



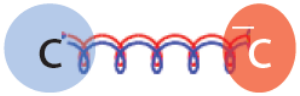
Molecular states :

- Loosely bound states of a pair of mesons,
- bound by the long-range color-singlet pion exchange,
- weakly bound, mesons tend to decay as if they were free.



Tetraquarks :

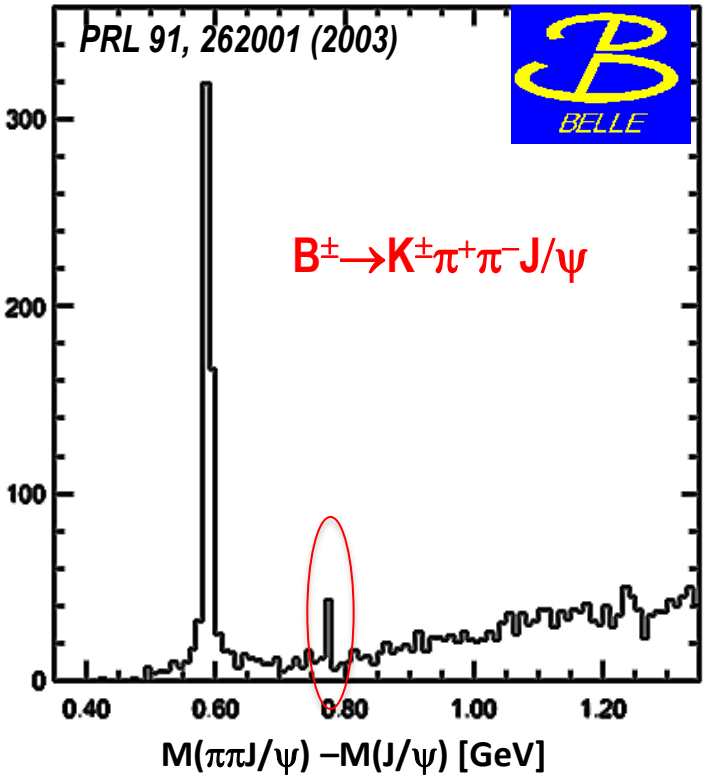
- bound states of four quarks,
- bound by colored-force between quarks,
- decay through rearrangement,
- many states with the same multiplet, some are with non-zero charge, or strangeness



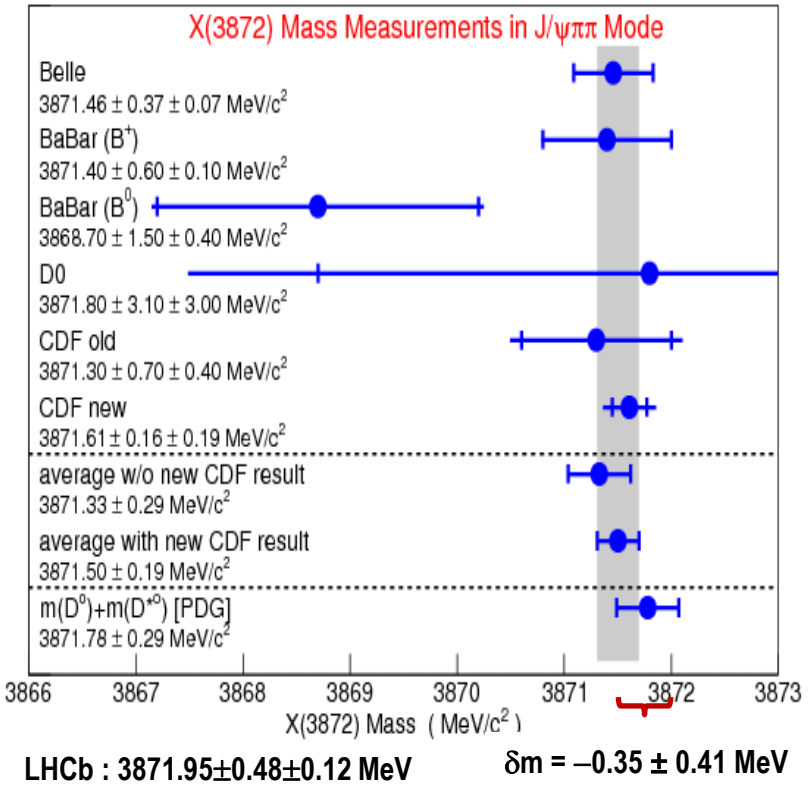
Hybrid :

- bound states with a pair of quarks and one excited gluon
- Lattice and model predictions for lowest lying charmonium hybrid m~4200MeV

Observation of X(3872)



The X(3872) was first observed by Belle, soon confirmed by several experiments



LHCb : 3871.95±0.48±0.12 MeV **δm = –0.35 ± 0.41 MeV**

Well-established neutral state

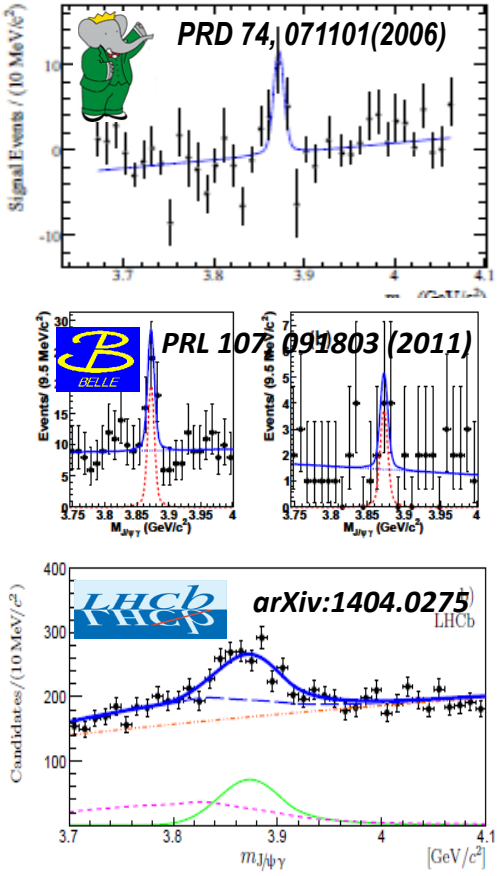
Mass : Very close to $\bar{D}^0D^{*0}$ threshold

Width : Very narrow, < 1.2 MeV

Stimulated special interest in its nature !

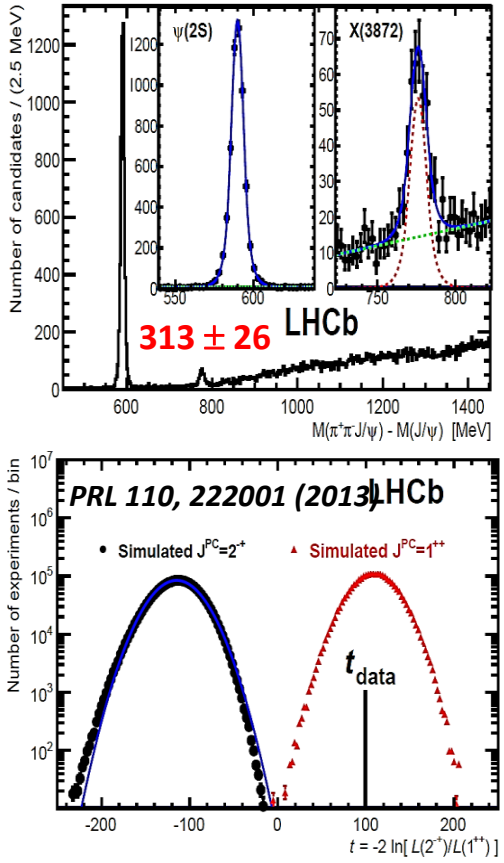
J^{PC} of the X(3872) is 1^{++}

X(3872)→γJ/ψ

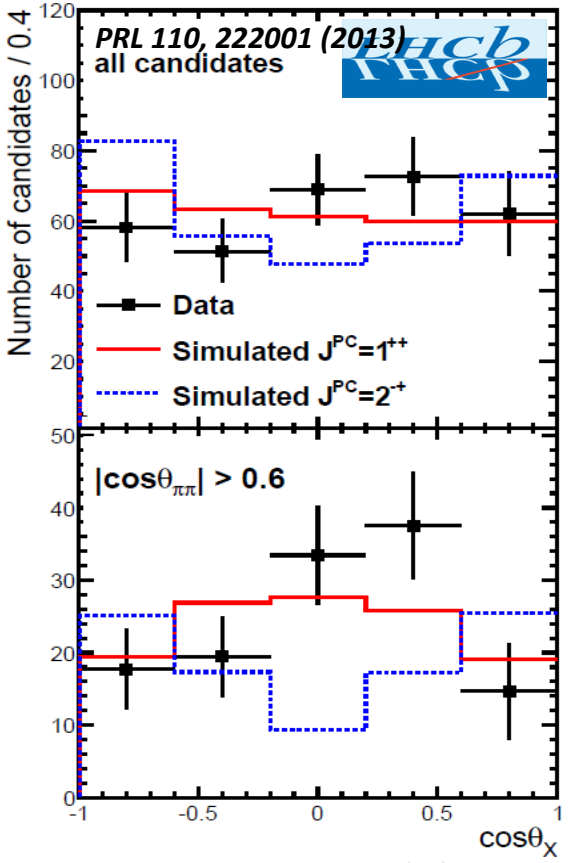


C-even state!

X(3872)→$\pi^+\pi^-$ J/ψ



Absent in two-photon interaction
=> limit for $J^{PC}=2^{-+}$

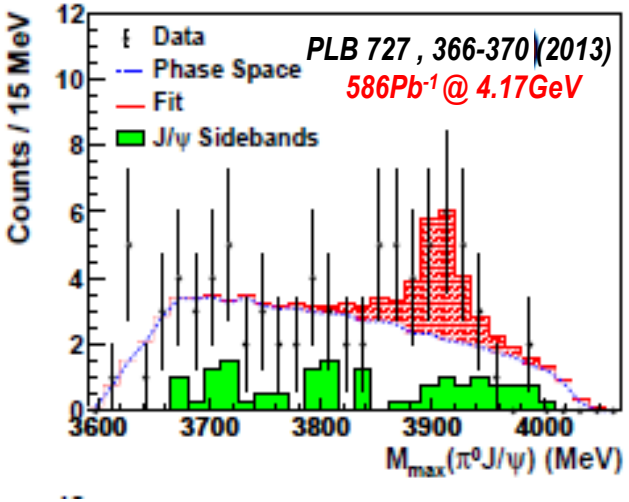


LHCb:
$J^{PC}=2^{-+}$ rejected at 8.2σ!

$Z_c(3900)^0$ @$e^+e^- \to \pi^0\pi^0 J/\psi$

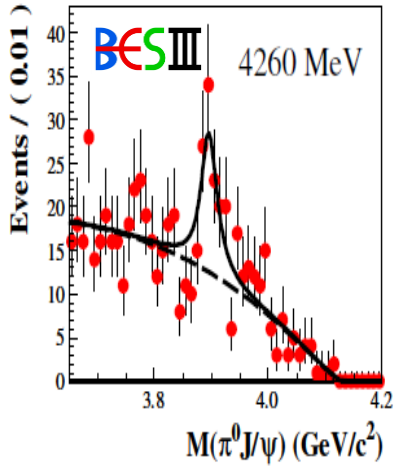
Has an isospin partner, $Z_c(3900)^0$?

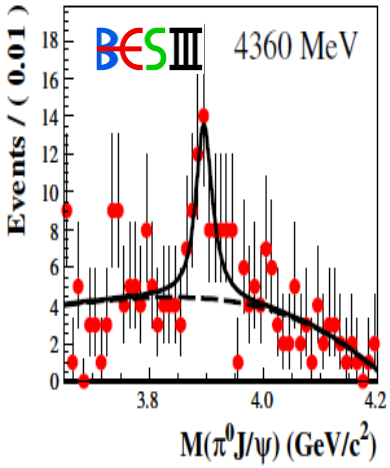
BESIII Preliminary

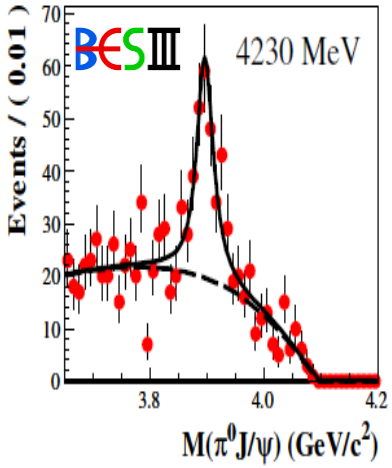


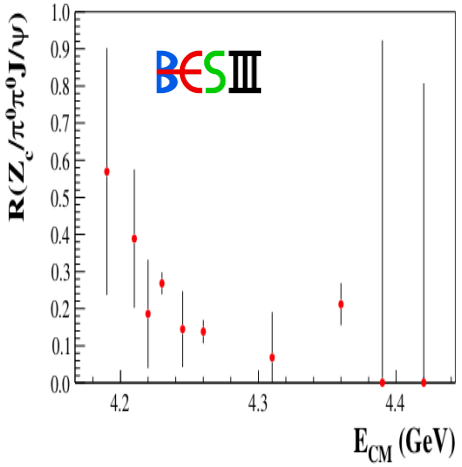
- 2.8fb^{-1} data at 10 energy points from 4260~4420 MeV
- $Z_c(3900)^0$ is observed clearly at E_{cm}=4230, 4260, 4360MeV
- BESIII preliminary results :
  - M= 3894.8$\pm$2.3 MeV, Γ = 29.6$\pm$8.2 MeV
  - Significance = 10.4 σ
- $R(Z_c^0/\pi^0\pi^0 J/\psi)=N(Z_c^0(3900))/N(\pi^0\pi^0 J/\psi)$, E_{cm} dependence

Neutral isospin partner, $Z_c(3900)^0$ observed



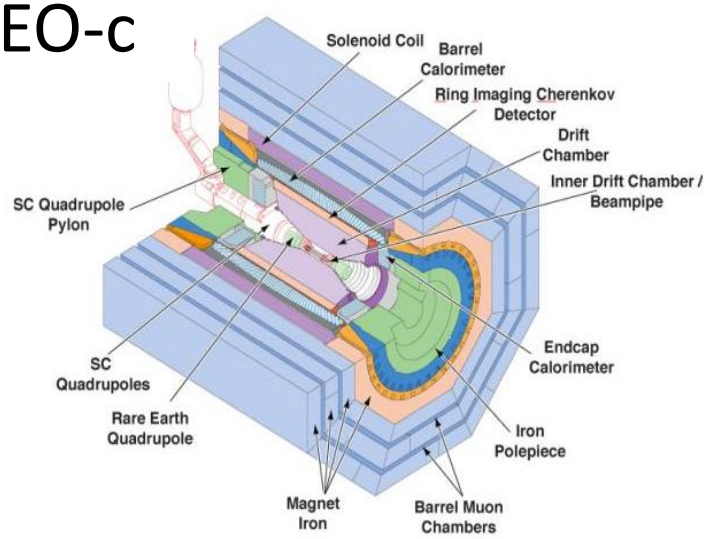


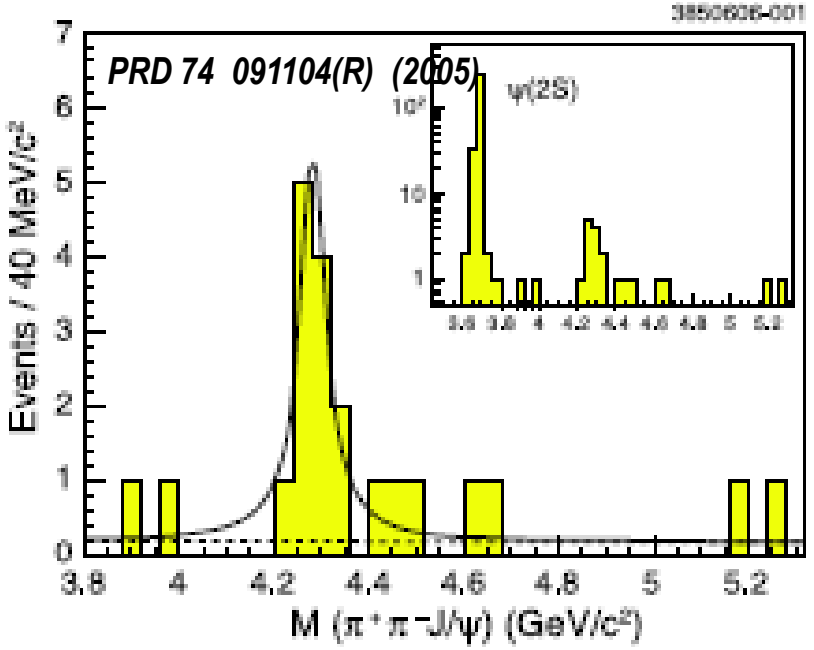




$e^+e^- \to \gamma_{ISR}\, J/\psi\, \pi^+\pi^-$

CLEO-c





$$M(Y(4260)) = (4284^{+17}_{-16}(\text{stat}) \pm 4(\text{syst}))\ \text{MeV}/c^2,$$

$$\Gamma(Y(4260)) = (73^{+39}_{-25}(\text{stat}) \pm 5(\text{syst}))\ \text{MeV}/c^2.$$

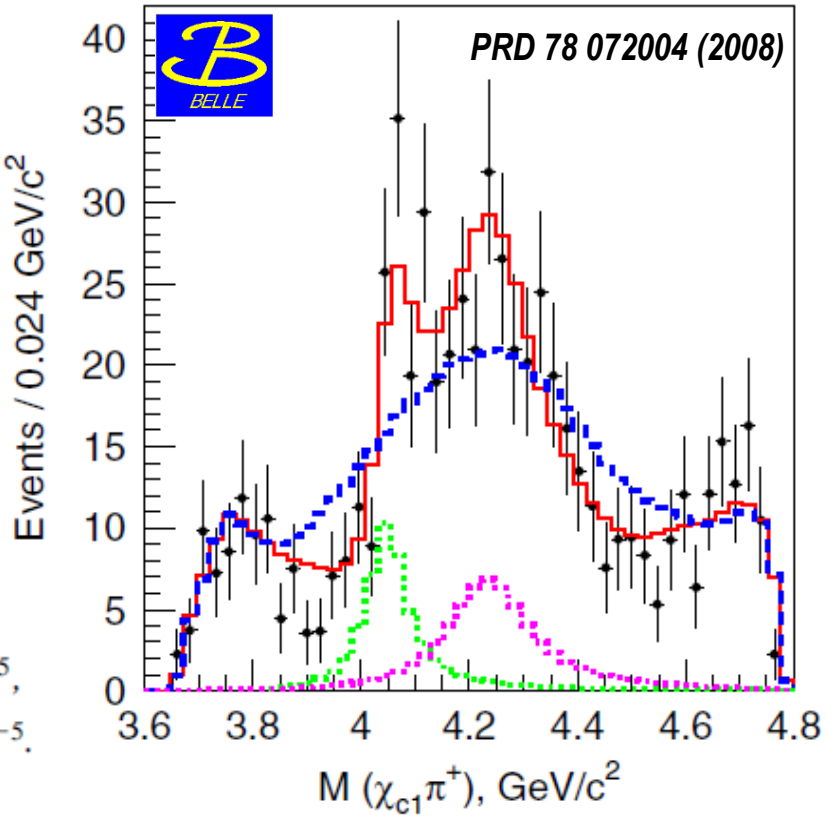
$Z_c(4050)$, $Z_c(4250)$

$B^0 \to K^- \pi^+ \chi_{c1}$

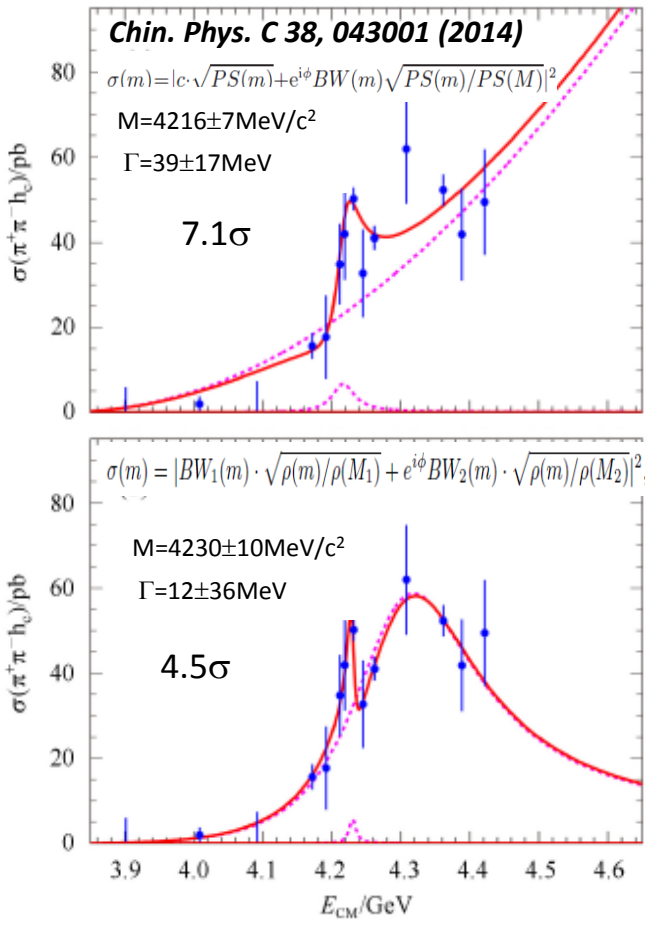
Dalitz plot analysis :

$$M_1 = (4051 \pm 14^{+20}_{-41})\ \mathrm{MeV}/c^2,$$
$$\Gamma_1 = (82^{+21+47}_{-17-22})\ \mathrm{MeV},$$
$$M_2 = (4248^{+44+180}_{-29-35})\ \mathrm{MeV}/c^2,$$
$$\Gamma_2 = (177^{+54+316}_{-39-61})\ \mathrm{MeV},$$

$$\mathcal{B}(\bar{B}^0 \to K^- Z_1^+) \times \mathcal{B}(Z_1^+ \to \pi^+ \chi_{c1}) = (3.0^{+1.5+3.7}_{-0.8-1.6}) \times 10^{-5},$$
$$\mathcal{B}(\bar{B}^0 \to K^- Z_2^+) \times \mathcal{B}(Z_2^+ \to \pi^+ \chi_{c1}) = (4.0^{+2.3+19.7}_{-0.9-0.5}) \times 10^{-5}.$$



$e^+e^- \to \pi^+\pi^- h_c$ Interpretation



- Fit with two different scenarios :
  - Three body PHSP + a narrow resonance
  - Two resonances

  Very likely a narrow structure around 4.23GeV
- Others possible interpretation
  - A relative S-wave $D\bar{D}_1$ molecular Y(4260) and a non-resonant background term [arXiv:1310.2190]
  - Y(4260) and Y(4360) are mixture of two hadro - charmonium states [Mod. Phys. Lett. A 29, 1450060].
  - ……..
- Various QCD calculate indicate :
  - Charmonium-hybrid lies in mass region of two Y states.
  - $c\bar{c}$ tend to be in a spin-singlet state
  - Couple strong to a spin-singlet charmonium state h_c

More high precision measurement at above 4.42GeV and around 4.22GeV are desired to better understand the structure.

Summary & Perspectives

1. In light hadron, a lot of puzzles and controversies remain to be solved
2. In charmonium-like (bottomnium-like), a lot of new observations in last decade

- X(3872) :
  - Well established : mass, width, spin-parity, close to $D^0\bar{D}^{*0}$ mass threshold
  - Nature is unclear : large ratio of $X(3872)\to\gamma\psi(2S)$ to $X(3872)\to\gamma J/\psi$, isospin violation
  - Observed in Y(4260) radiative decay : any correlation with Y(4260) or $Z_c(3900)$?
- Y states :
  - All produced in e^+e^- collisions, narrow structure above charm threshold, Y(4008) need confirmed
  - Only one established decay model, strongly couple to charmonium, no evidence in open-charm process and R-value scan
  - Inconsistent line shape of $e^+e^-\to\pi\pi h_c$, $\omega\chi_{c0}$ make the situation more complicate
  - Nature unclear : Hybrid, Molecule, Threshold effect, Triangle singularity…..?
- Z_c states :
  - Three ($Z_c(3900)$, $Z_c(4020)$, $Z_c(4430)$) established, $Z_c(4050)$, $Z_c(4250)$, $Z_c(4200)$ need confirmed
  - Narrow charge structure above $D^{(*)}\bar{D}^{(*)}$ threshold, large non-$D\bar{D}$ decay ratio
  - Isospin triplet partner observed, spin-parity measured to be 1^+
  - Origin is unclear
  - Nature unclear : New type QCD states or dynamically generated structure? But not conventional charmonium
- What will help:
  - Measure and understand transitions between states is essential, explore all possible decay modes of new state
  - More data at a variety of E_{cm} may shed light in the study.
  - Strong similarities between charmonium and bottomonium system.

Summary & Perspectives

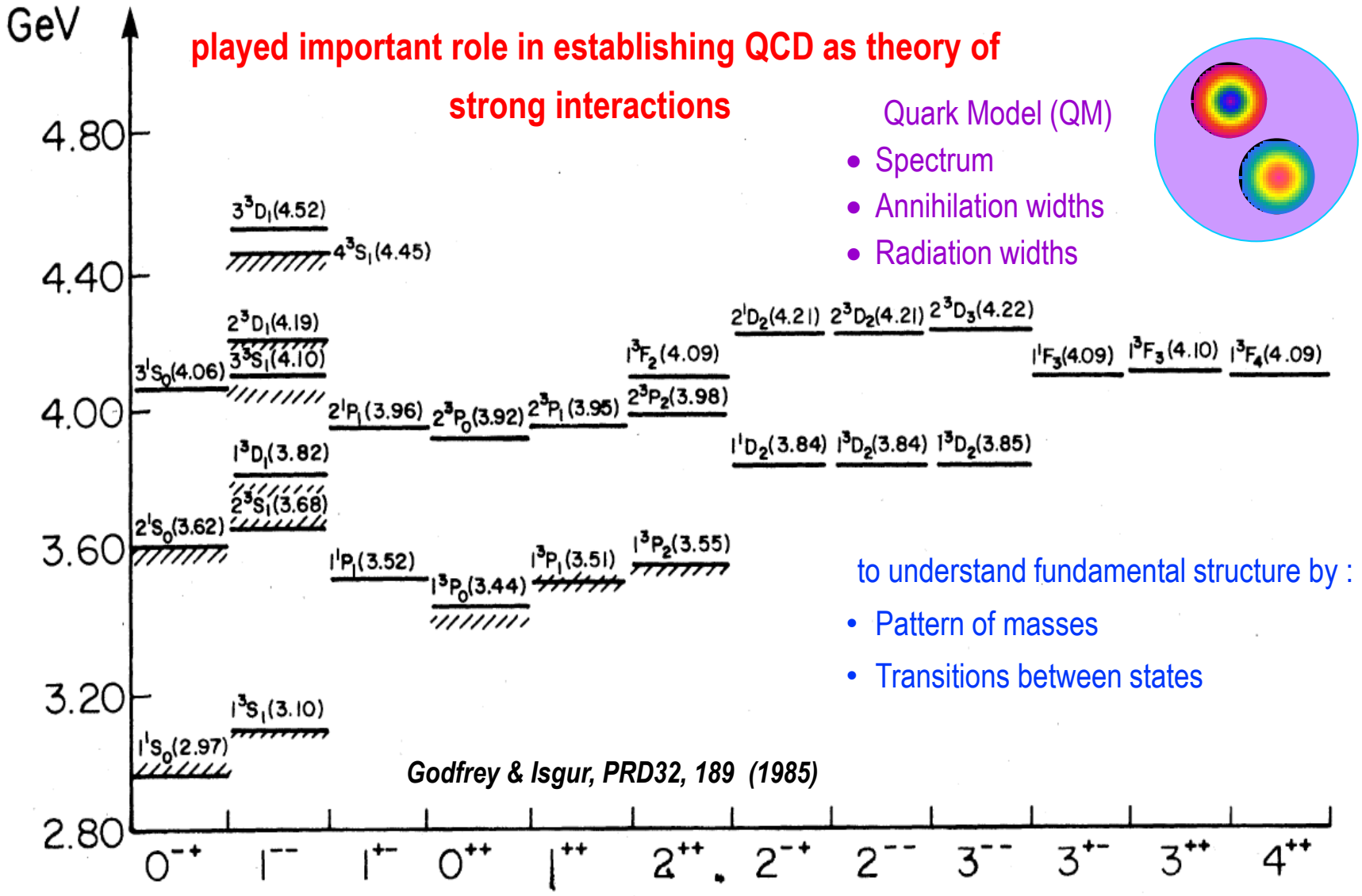
3. Experimental challenges

- High precision measurements : High statistics & precision data, advance analysis tools etc
- Global view : different experiments, different production and decay mechanisms

4. Experimental opportunities

- BESIII@BEPCII
  - Is the only experiment currently taking data using e^+e^- collisions,
  - Already made significant contributions to charmonium (-like) in region above the open-charm threshold
  - Can immediate add to our understanding the $c\bar{c}$ meson spectrum above the open-charm threshold
- Belle, Babar and Belle II
  - Belle and Babar have remarkable success in quarkonium spectroscopy,
  - No doubt for further success for Belle II with the upgraded detector and a factor of fifty increased luminosities
- LHC
  - LHCb had made great measurement improved the results from B-Factory : a definitive determination J^{pc} of X(3872) etc.
  - ALTAS and CMS have proved to have capabilities working on spectroscopy : Confirmed Y(4140) in $J/\psi\phi$ [CMS] , discovered χ_{bJ} (3P) [ATLAS]
  - Promise to be even more fruitful sources after a two-year shutdown for an upgrade
- PANDA @ FAIR
  - Designed to study the charmonium (-like) states, expected to begin data taking around 2019
  - Can produce all J^{pc} states directly, as long as have large branching fractions to $p\bar{p}$
  - Have stronger coupling to tetraquark charmonium than that of conventional charmonium?

Charmonium Spectroscopy



Godfrey & Isgur, PRD32, 189 (1985)

played important role in establishing QCD as theory of strong interactions

Quark Model (QM)

- Spectrum
- Annihilation widths
- Radiation widths

to understand fundamental structure by :

- Pattern of masses
- Transitions between states