BESIII Results and Overview

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On behalf of the BESIII Collaboration

Outline

- Introduction to BEPCII and BESIII
- Light hadron spectroscopy
- η and η' physics
- XYZ states
- Summary

The Discovery of J/ψ

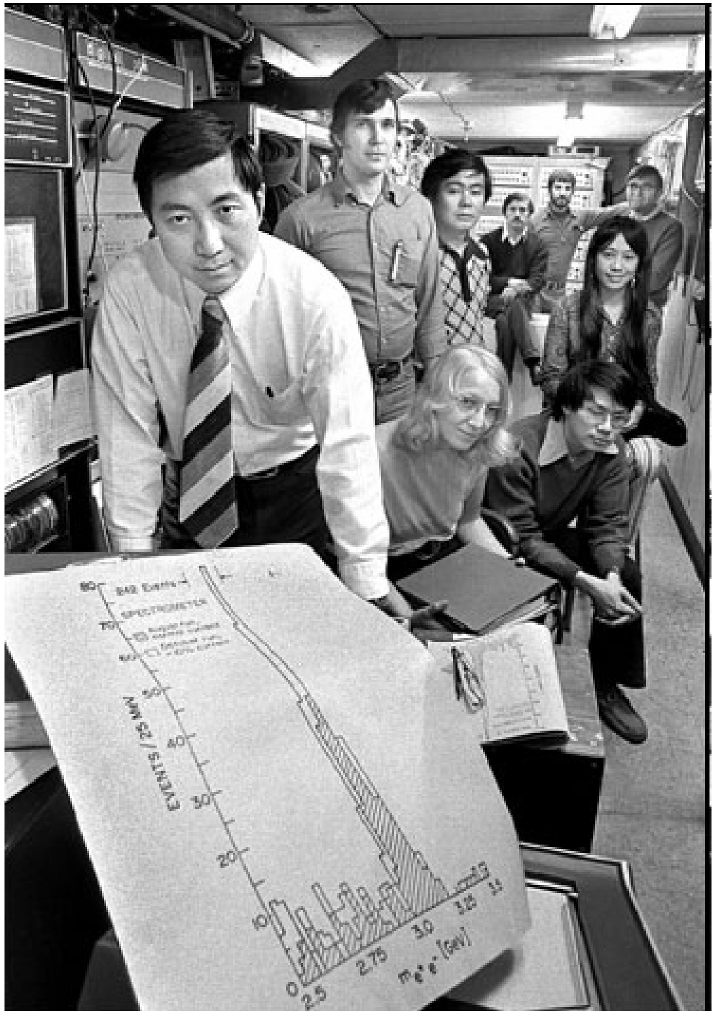
•On Nov. 11, 1974, Burt Richter (SLAC) announced the discovery of the ψ and Sam Ting (Brookhaven) announced the discovery of the J.

•The J/ψ with a mass of 3.096 GeV was soon interpreted as being made up of a c and a c-bar quark.

•The existence of the charmed quark had been predicted by Glashow, Iliopoulos, and Maiani to explain the absence of strangeness changing neutral currents.

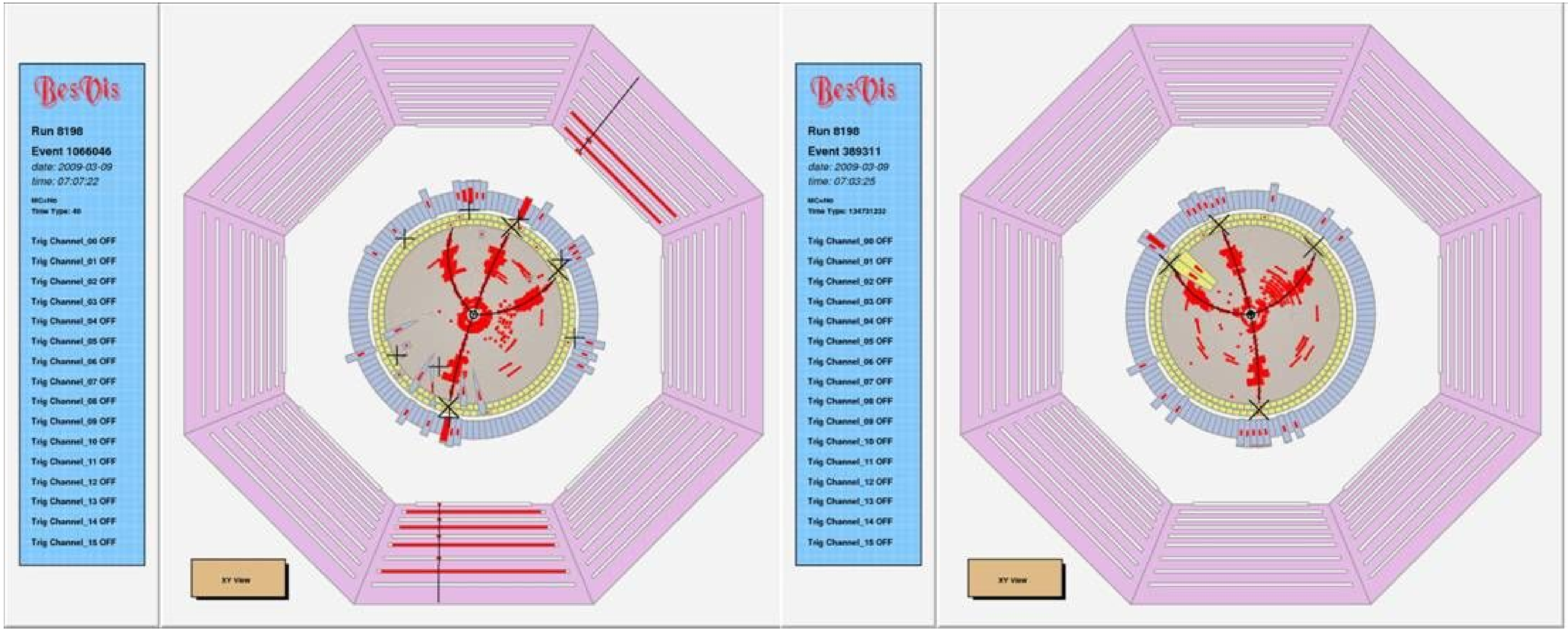
•The discovery led physicists to finally take quarks seriously.

• They received the Nobel Prize in 1976 for their discovery.



Sam Ting with hundred J/Ψs

Illustration

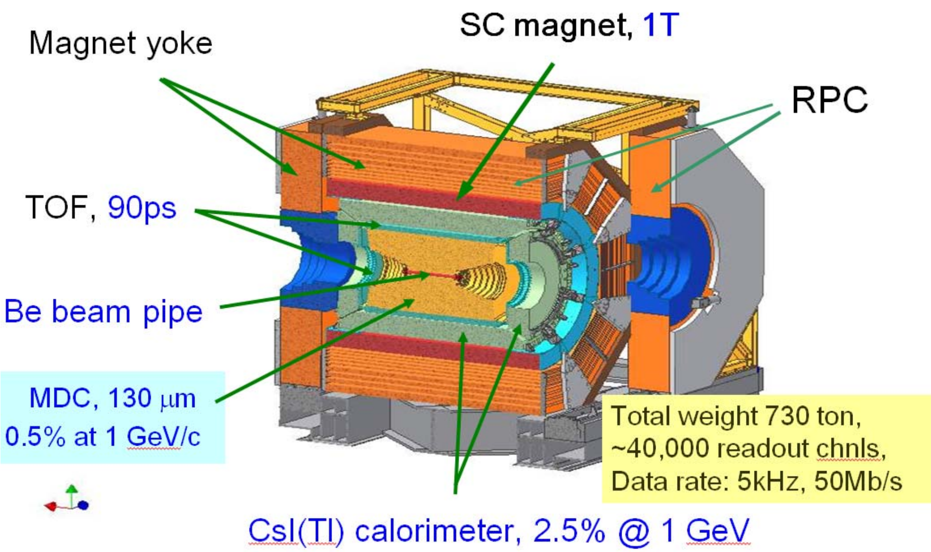


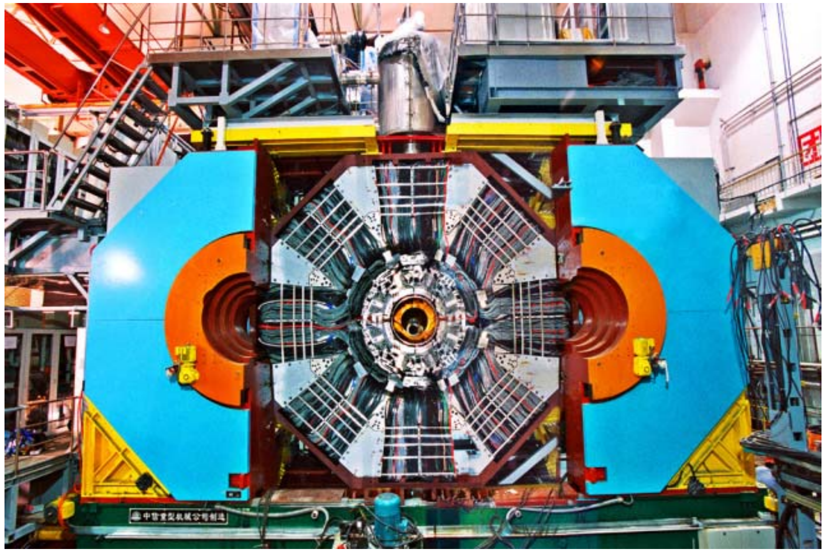
$$\psi(2s) \to \pi^+\pi^- J/\psi$$
$$J/\psi \to \mu^+\mu^-$$

$$\psi(2s) \to \pi^+\pi^- J/\psi$$
$$J/\psi \to e^+e^-$$

Beijing Electron Positron Collider II

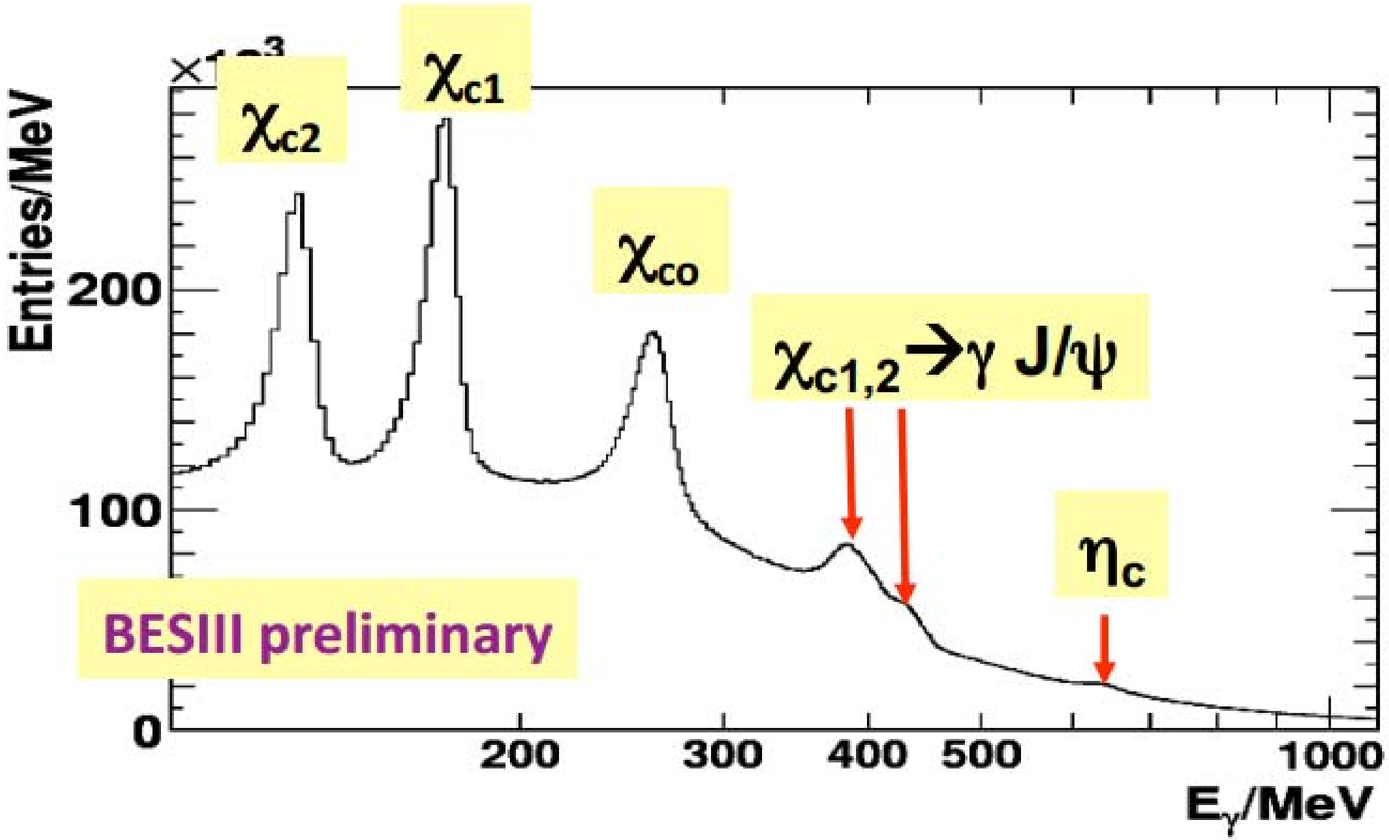
BESIII Detectors





Sub-detectors			Performance
MDC	Momentum resolution		0.5%@1GeV
	dE/dx resolution		6%
EMC	Energy resolution		2.5%@1GeV
	Spatial resolution		6 mm
TOF	Time resolution	Barrel	80 ps (Bhabha)
		Endcap	110 ps (Di-muon)
MUC	9 layers RPC, 8 layers for endcap		

Spectrum of Ψ(2s) Inclusive Decays

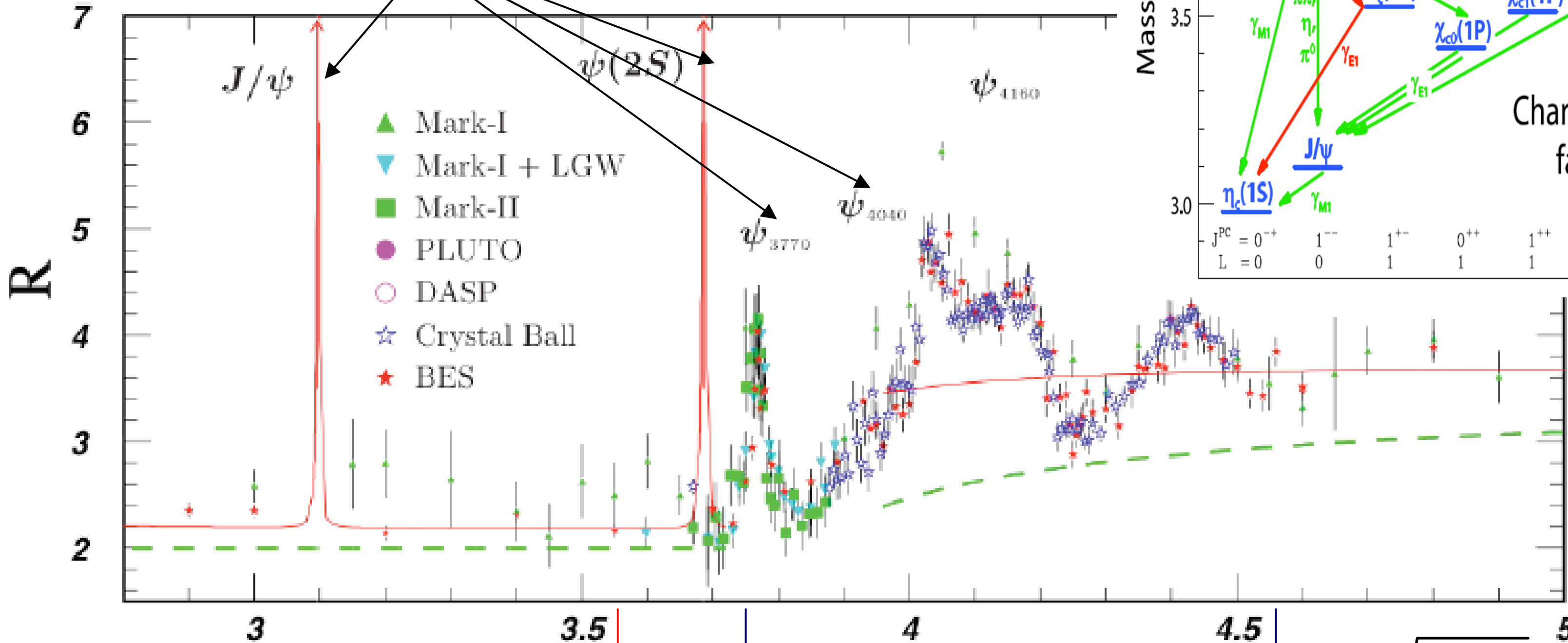


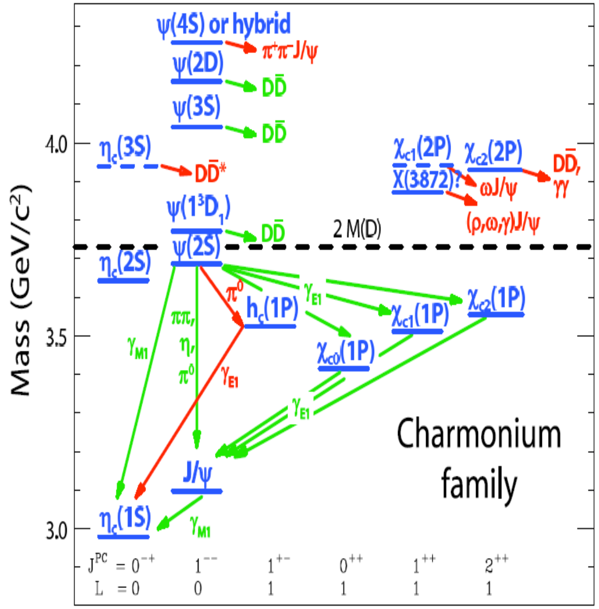
photons from ψ(2S) decays

- EMC has an excellent energy resolution.

The Energy Region

Charmonium: $c\bar{c}$





Open charm

$\sqrt{s_{e^+e^-}}$ GeV

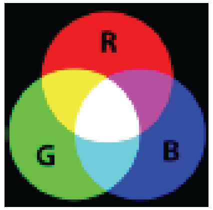
$$R = \frac{\sigma_{e^+e^- \to hadrons}}{\sigma_{e^+e^- \to \mu^+\mu^-}}$$

Threshold for tau-pairs

Rich and interesting physics region

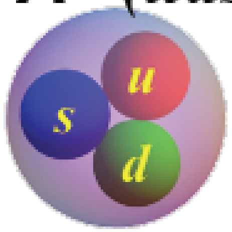
Quantum Chromodynamics (QCD)

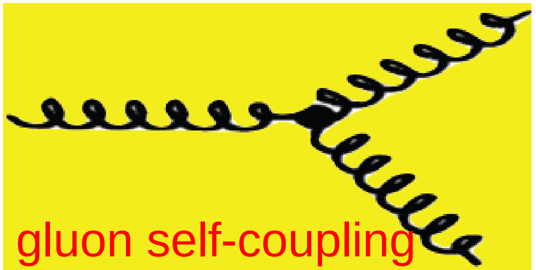
3 primary colors ➔ white



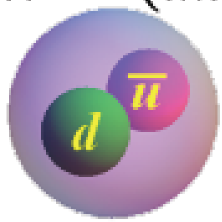
color + complementary color ➔ white

$\Lambda = (uds)$





$\pi^- = (d\bar{u})$



Baryons are red-blue-green triplets

Mesons are color-anticolorpairs

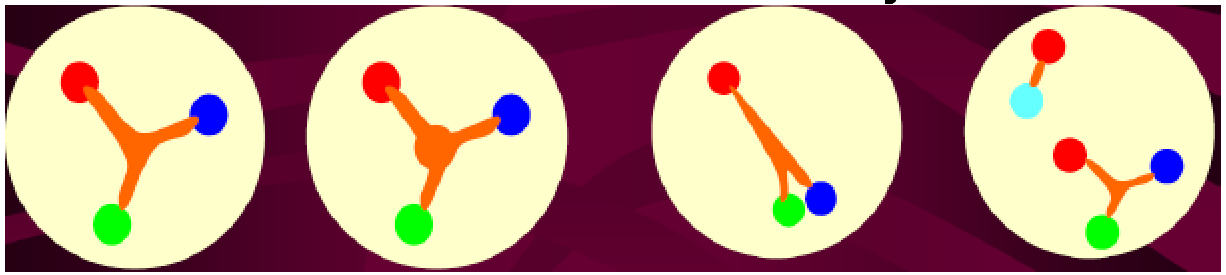
- Carriers of the strong interaction are gluons with two color. This is different from the carriers of EM, which don't carry any electric charge.
- QCD predicts all particles are color-singlet.

Where is the “missing baryons”?

(1) Does the quark model completely describe the nature of baryons?

The baryon model links number of baryons. In theory: N4>N2>N1>N3, however, in experiment: $N_{observed} << N1$.

Quark models predict many more baryons than have been observed



1, 3 quarks

2, quarks and flux tubes

3, quark-diquark

4, multi quarks

…

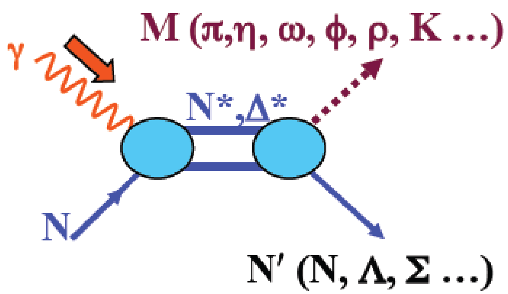
(2) Do the resonances simply escape from detection?

Almost all existing data results come from πN experiments.

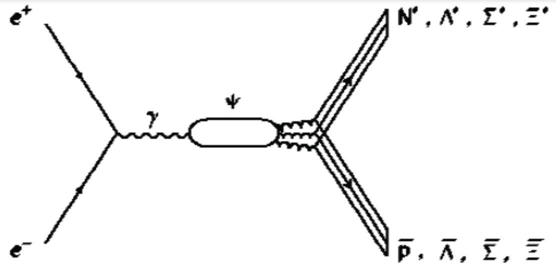
Charmonium decays at the BESIII experiment, give novel insights into baryons and provide complementary information to πN experiments.

Why Charmonium at BESIII?

JLab, ELSA, MAMI, ESRF, Spring-8, ….



$J/\psi(\psi') \rightarrow \overline{B}BM \Rightarrow N^*, \Lambda^*, \Sigma^*, \Xi^*$



	Previous Data	BESIII now	Goal
J/ψ	BESII 58 M	1.2 B (20x BESII)	10 B
ψ (3686)	CLEO: 28M	0.5 B (20x CLEO)	3 B
ψ (3770)	CLEO: 0.8/fb	2.9/fb (3.5x CLEO)	20/fb
Above open charm threshold	CLEO: 0.6/fb@4160	0.4/fb @4040, 2/fb@4260, 0.5/fb @4360, Data for lineshape	5-10/fb
R scan & τ	BESII	R @2.23,2.4,2.8,3.4, 25/pb tau	

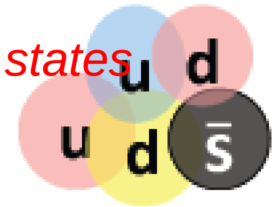
Interference between N and N*bar could be studied
Not only N*, but also Λ*, Σ*, Ξ*
High statistics of charmonium@ BESIII

Quantum States Allowed within the QCD

Pentaquark:

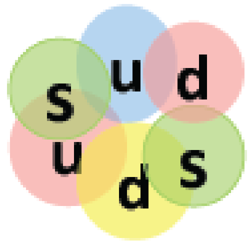
Exotic states

S=+1 Baryon



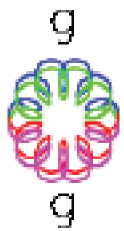
H-diBaryon

tightly bound
6-quark state



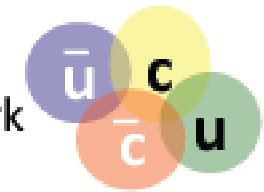
Glueball

Color-singlet multi-
gluon bound state

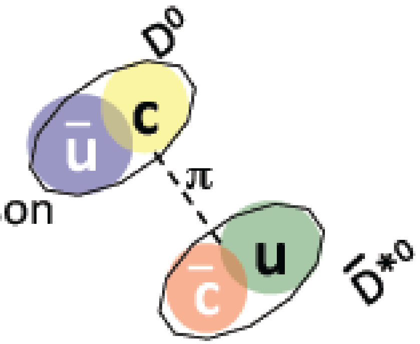


Tetraquark mesons

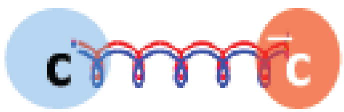
tightly bound
diquark-diantiquark



loosely bound
meson-antimeson
"molecule"



$q\bar{q}$-gluon hybrid mesons



Partial Wave Analysis

PWA, a powerful analysis strategy aims to find more states and determine their properties.

The probability to observe the event characterized by the measurement ξ is

$$P_i(\xi) = \frac{\omega(\xi)\varepsilon(\xi)}{\int d\xi \omega(\xi)\varepsilon(\xi)}$$

$$\omega(\xi) \equiv \frac{d\sigma}{d\phi} = \left|\sum_j c_j A_j\right|^2 = \left|\sum_j c_j R_j B(p,q)\Theta_j\right|^2$$

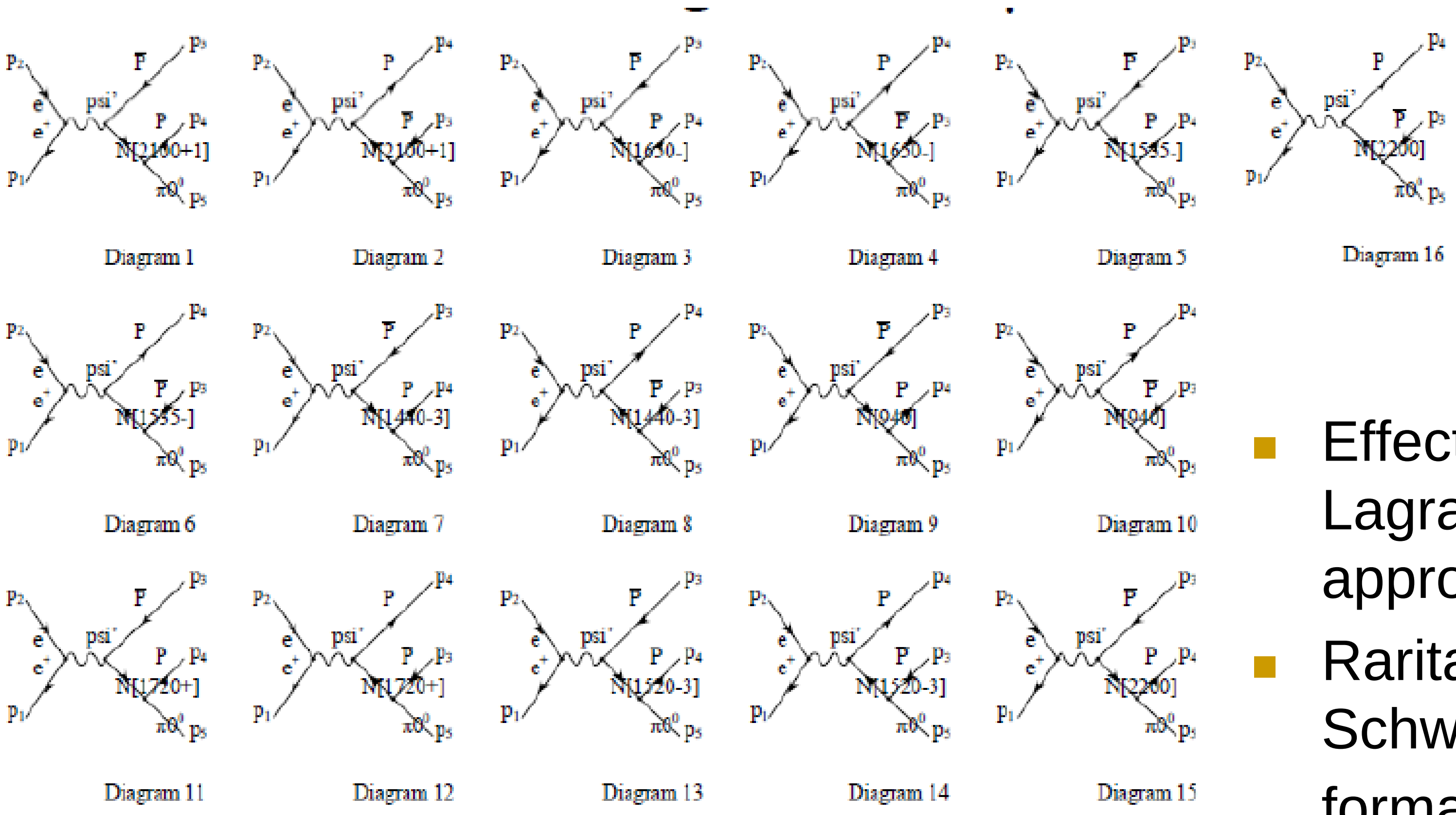
where $\varrho(\xi)$ is the detection efficiency and $\omega(\xi) \equiv d\sigma/d\Phi$ is the differential cross section,and $d\Phi$ is the standard element of phase space. A_j is the partial wave amplitude with coupling strength determined by a complex coefficient c_j.

The likelihood for a particular model is

$$L = \prod_{i=1}^{N_{events}} P_i(\xi)$$

A series of likelihood fits are performed for parameter estimation and model evaluation.

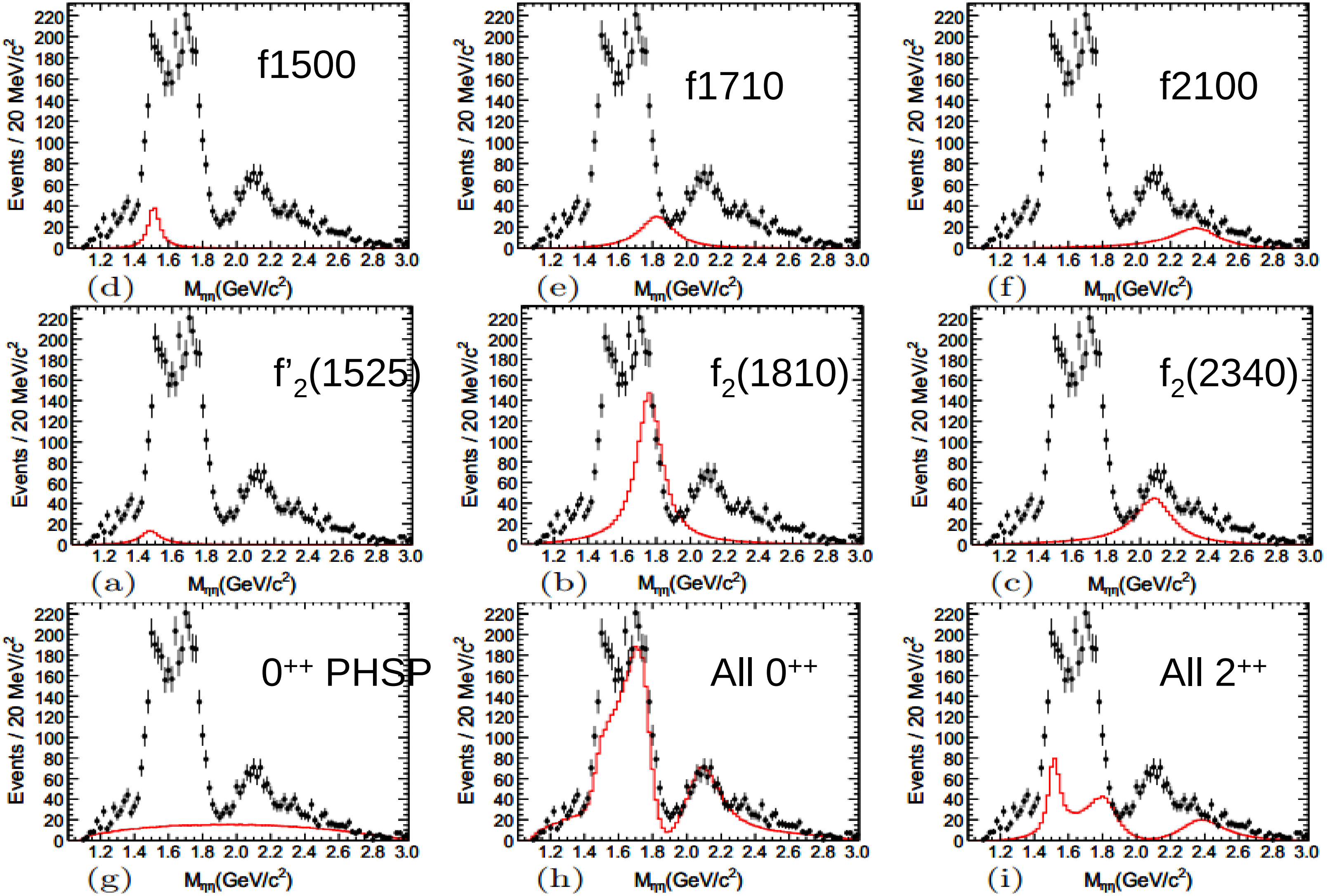
Feynman Diagram Calculation



- Effective Lagrangian approach
- Rarita-Schwinger formalism

FDC Project by J.X Wang, Nucl.Instrum.Meth. A534 (2004) 241

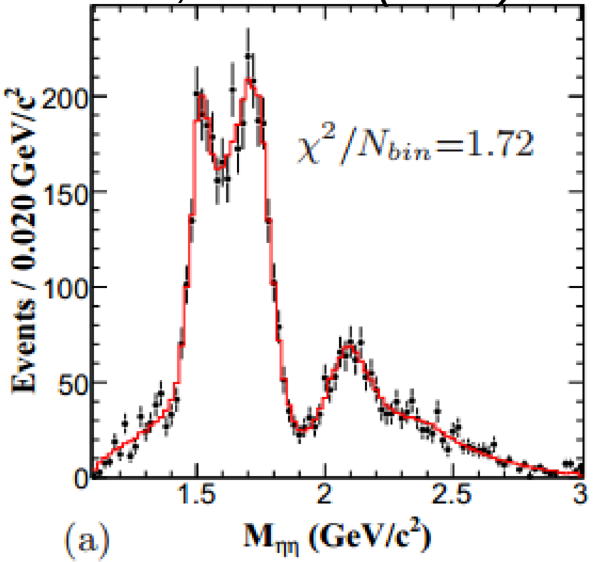
PWA of J/ ψ →γηη


f1500
f1710
f2100
f'2(1525)
f2(1810)
f2(2340)
0++ PHSP
All 0++
All 2++
(d)
(e)
(f)
(a)
(b)
(c)
(g)
(h)
(i)
Mηη(GeV/c2)
Events / 20 MeV/c2

PWA of J/ ψ →γηη

PRL 48, 458 (1982), Crystal Ball.
PRD 87, 092009 (2013)

An indirect way to search for glueball candidates.



$\gamma f(1710) \to \gamma KK$ $(8.5^{+1.2}_{-0.9}) \times 10^{-4}$

$\gamma f(1710) \to \gamma\pi\pi$ $(4.0 \pm 1.0) \times 10^{-4}$

$\gamma f(1710) \to \gamma\omega\omega$ $(3.1 \pm 1.0) \times 10^{-4}$

$\gamma f(1710) \to \gamma\eta\eta$ $(2.35^{+0.13+1.24}_{-0.11-0.74}) \times 10^{-4}$

PRL 110(2013) 021601, Long-cheng Gui et al. calculates by LQCD,

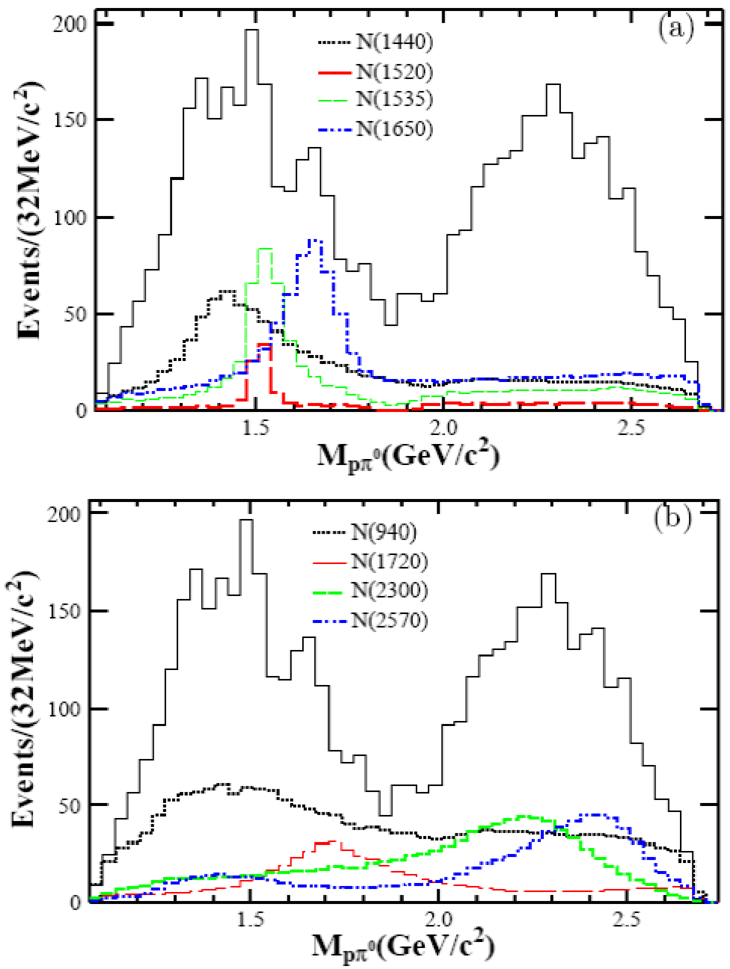
$$Br(J/\psi \to \gamma G(0^{++})) = 3.8(9) \times 10^{-3}$$

Need more experimental effort.

Resonance	Mass(MeV/c^2)	Width(MeV/c^2)	$\mathcal{B}(J/\psi \to \gamma X \to \gamma\eta\eta)$	Significance
$f_0(1500)$	1468^{+14+20}_{-15-74}	$136^{+41+8}_{-26-100}$	$(1.61^{+0.29+0.41}_{-0.32-1.28}) \times 10^{-5}$	8.2 σ
$f_0(1710)$	1759^{+6+14}_{-6-25}	172^{+10+31}_{-10-15}	$(2.35^{+0.07+1.23}_{-0.07-0.72}) \times 10^{-4}$	25.0 σ
$f_0(2100)$	2081^{+13+23}_{-13-34}	273^{+27+65}_{-24-18}	$(9.99^{+0.57+5.52}_{-0.52-2.21}) \times 10^{-5}$	13.9 σ
$f_2'(1525)$	1513^{+5+3}_{-5-10}	75^{+12+15}_{-10-9}	$(3.41^{+0.43+1.22}_{-0.50-1.23}) \times 10^{-5}$	11.0 σ
$f_2(1810)$	1822^{+29+61}_{-24-54}	$229^{+52+64}_{-42-152}$	$(5.38^{+0.60+3.31}_{-0.67-2.24}) \times 10^{-5}$	6.4 σ
$f_2(2340)$	$2362^{+31+139}_{-30-59}$	$334^{+62+164}_{-54-99}$	$(5.58^{+0.61+1.93}_{-0.65-1.81}) \times 10^{-5}$	7.6 σ

PWA of ψ(2s)→$p\bar{p}\pi^0$

PRL 110, 022001(2013)



Resonance	N	ϵ(%)	B.F.($\times 10^{-5}$)
$N(940)$	$1870^{+90+487}_{-90-327}$	27.5 ± 0.4	$6.42^{+0.20+1.78}_{-0.20-1.28}$
$N(1440)$	$1060^{+90+459}_{-90-227}$	27.9 ± 0.4	$3.58^{+0.25+1.59}_{-0.25-0.84}$
$N(1520)$	190^{+14+64}_{-14-48}	28.0 ± 0.4	$0.64^{+0.05+0.22}_{-0.05-0.17}$
$N(1535)$	$673^{+45+263}_{-45-256}$	25.8 ± 0.4	$2.47^{+0.28+0.99}_{-0.28-0.97}$
$N(1650)$	$1080^{+77+382}_{-77-467}$	27.2 ± 0.4	$3.76^{+0.28+1.37}_{-0.28-1.66}$
$N(1720)$	$510^{+27+50}_{-27-197}$	26.9 ± 0.4	$1.79^{+0.10+0.24}_{-0.10-0.71}$
$N(2300)$	$948^{+68+394}_{-68-213}$	34.2 ± 0.4	$2.62^{+0.28+1.12}_{-0.28-0.64}$
$N(2570)$	$795^{+45+127}_{-45-83}$	35.3 ± 0.4	$2.13^{+0.08+0.40}_{-0.08-0.30}$
Total	4515±93	25.8 ± 0.4	$16.5 \pm 0.3 \pm 1.5$

Two new baryonic excited states are observed in PWA analysis. N(2300)$[1/2]^+$, N(2570) $[5/2]^-$.

See more results about baryons study:

$J/\psi \to \eta p\bar{p}$ *PRD 88, 032010 (2013)*

$J/\psi \to \Lambda \bar{\Sigma}^0 + c.c$ *PRD 87, 012007 (2013)*

$\psi' \to \bar{p}K\Sigma^0, \Sigma^0 \to \gamma\Lambda$ *PRD 86, 032008 (2012)*

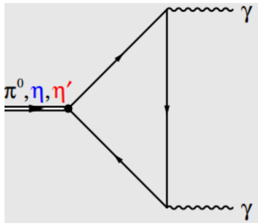
$\chi_{c0} \to p\bar{n}\pi^-(p\bar{n}\pi^-\pi^0)$ *PRD 86, 052011 (2012)*

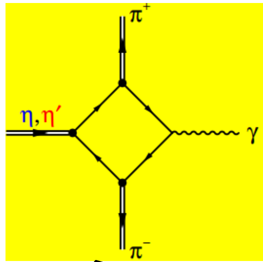
η and η ' Physics at BESIII

KLOE, WASA-at-COSY, CB at MAINZ, CLAS, GlueX, *PRD 19, 2188(1979).*

- Rich physics field:

$\eta/\eta' \to 2\gamma$	**chiral anomaly**
$\eta/\eta' \to \pi^+\pi^-\pi^0$	***quark mass***
$\eta' \to \gamma\pi^+\pi^-$	**box anomaly**
$\eta/\eta' \to \pi\pi$	**CP violation**
$\eta/\eta' \to \mu^+\mu^-\pi^0, e^+e^-\pi^0$	**C violation**
$\eta/\eta' \to \mu\, e$	**LF violation**





- Huge samples of prompt η/η' with 1.2 billion J/psi decays.
  - J/psi→$\gamma\eta$ (η'), J/psi→$\phi\eta$ (η')

B(J/ψ $\to\gamma\eta$)~1.1$\times$10^{-3} → 1.32$\times$10^{6} η events
B(J/ψ $\to\gamma\eta'$)~5.2$\times$10^{-3} → 6.24$\times$10^{6} η' events
B(J/ψ $\to\phi\,\eta$)~7.5$\times$10^{-4} → 9.0$\times$10^{5} η events
B(J/ψ $\to\phi\,\eta'$)~4.0$\times$10^{-4} → 4.8$\times$10^{5} η' events

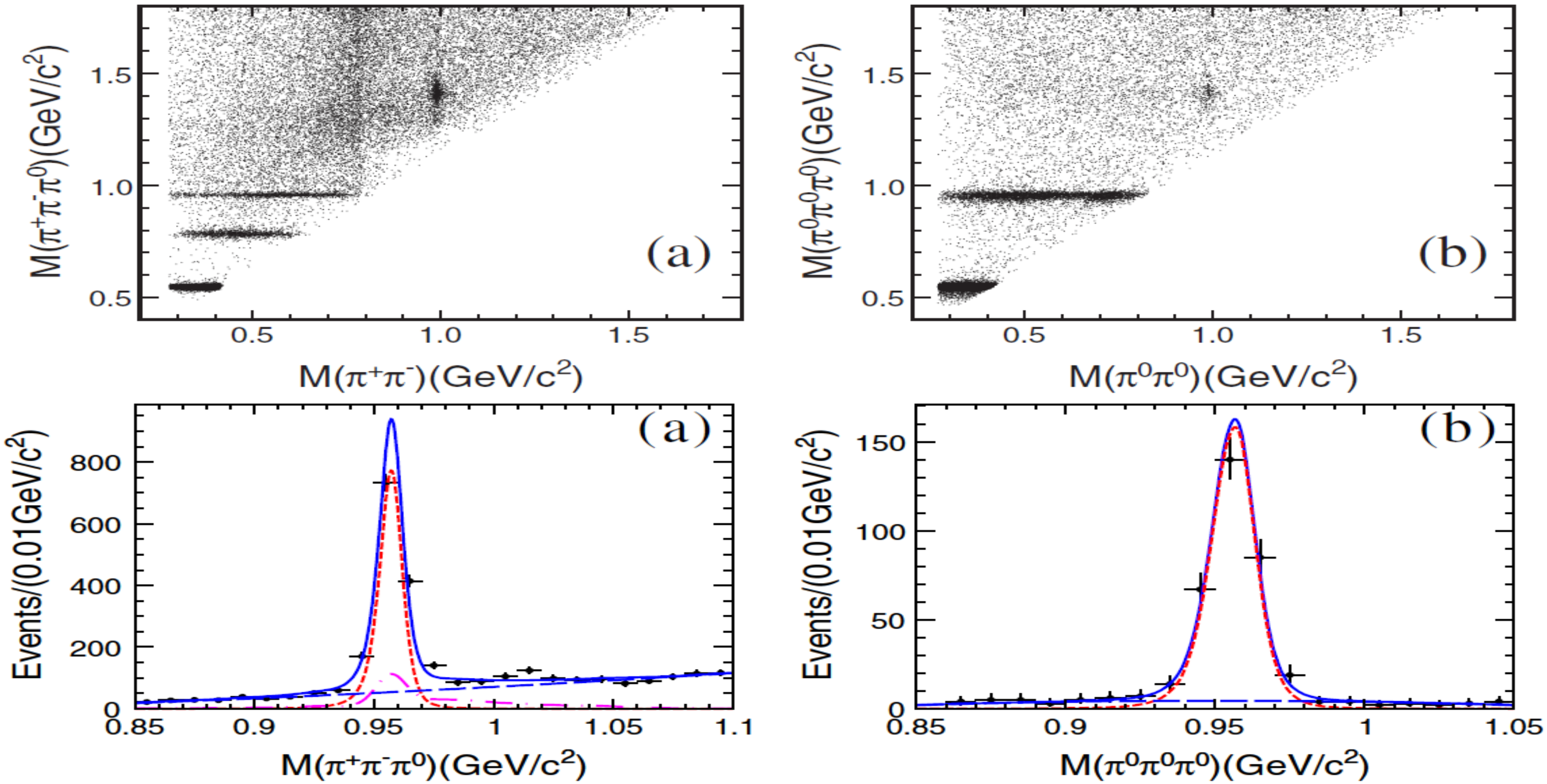
$\eta' \rightarrow \pi\pi\pi$ in $J/\psi \rightarrow \gamma\eta'$

PRL 108, 182001(2012)

$$\chi_{4c}(\gamma\gamma\gamma\pi^+\pi^-) > \chi_{4c}(\gamma\gamma\gamma\gamma\pi^+\pi^-)$$

$$\chi_{4c}(\gamma\gamma\gamma\pi^+\pi^-) > \chi_{4c}(\gamma\gamma\pi^+\pi^-)$$

$$\chi_{7c}(\gamma 3\pi^0) < 60$$



π^0- η Mixing

Phys. Rev.D19 (1979) 2188

$$|\pi^0\rangle = \cos\theta_{\pi\eta}|\tilde{\pi}^0\rangle + \sin\theta_{\pi\eta}|\tilde{\eta}\rangle$$

$$|\eta\rangle = -\sin\theta_{\pi\eta}|\tilde{\pi}^0\rangle + \cos\theta_{\pi\eta}|\tilde{\eta}\rangle$$

$\eta' \to \pi\pi\pi$, *forbidden*

$\eta' \to \eta\pi\pi$, *allowed*

by isospin conservation

$$R = \frac{\Gamma(\eta' \to \pi\pi\pi)}{\Gamma(\eta' \to \eta\pi\pi)} = c_1 \sin^2\theta_{\pi\eta}(+\ldots) \propto \Delta m^2(+\ldots)$$

$$\sin\theta_{\pi\eta} = \frac{\sqrt{3}(m_d - m_u)}{4(m_s - \hat{m})}, \hat{m} = (m_d + m_u)/2$$

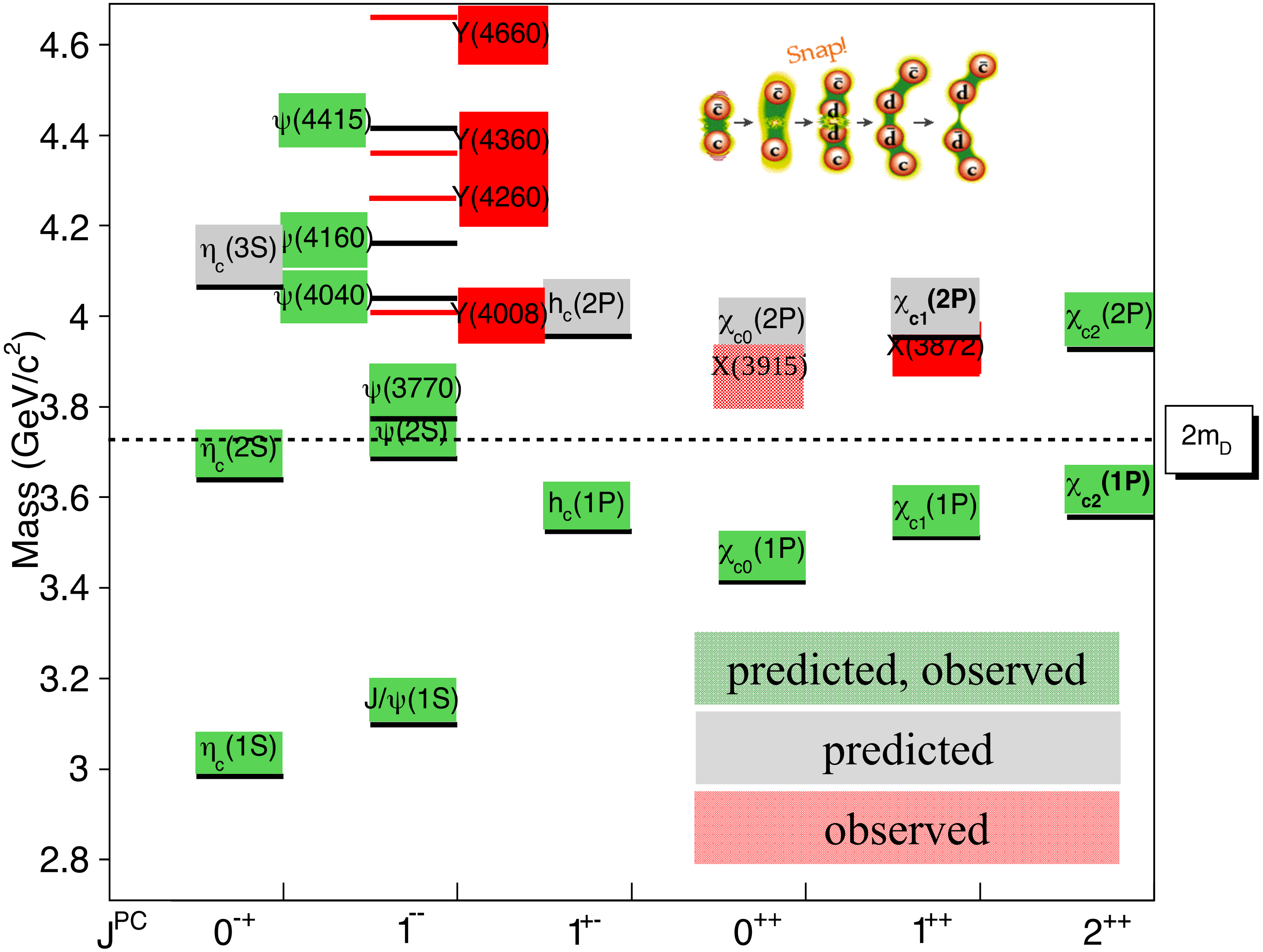
$Br(\eta' \to \pi^+\pi^-\pi^0) = (3.83 \pm 0.15 \pm 0.39) \times 10^{-3}$ (PDG2010: $(3.6^{+1.1}_{-0.93}) \times 10^{-3}$) *agreement*

For $\eta' \to 3\pi^0$, the branching ration is two times larger than the world average value.

$Br(\eta' \to 3\pi^0) = (3.56 \pm 0.22 \pm 0.34) \times 10^{-3}$ $[PDG2010 = (1.68 \pm 0.22) \times 10^{-3}]$

$$\frac{Br(\eta' \to 3\pi^0)}{Br(\eta' \to 2\pi^0\eta)} \approx 1.6\%, \frac{Br(\eta' \to \pi^+\pi^-\pi^0)}{Br(\eta' \to \pi^+\pi^-\eta)} \approx 0.9\%$$

Charmonium Spectroscopy



Z(4430)
Z(4050)
Z(4250)
Z(4200)
$Z_c(3900)$
$Z_c(3885)$
$Z_c(4020)$
$Z_c(4025)$

X(3940)
Z(3930)

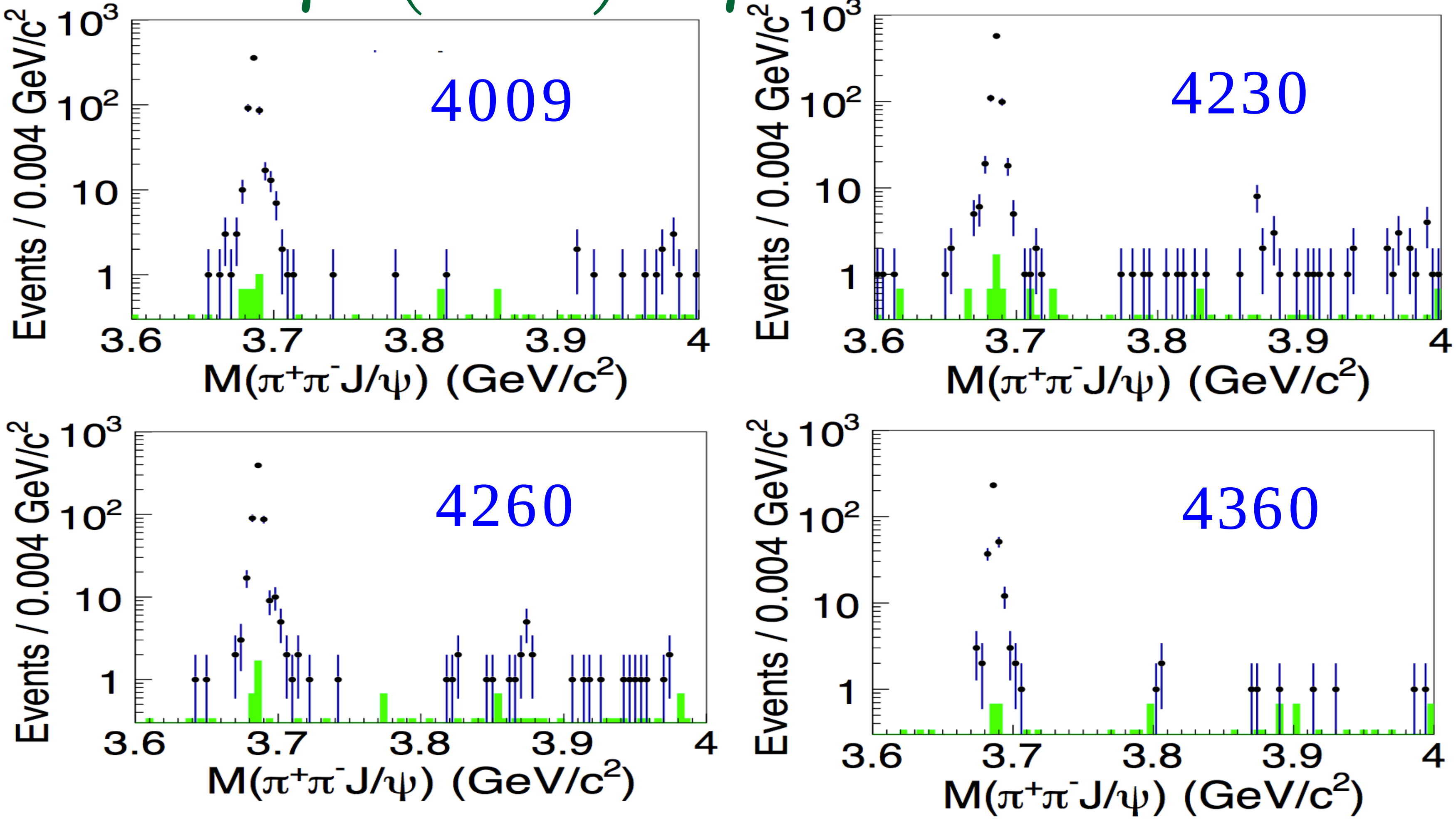
Y(3940)
Y(4140)
X(4350)

X(3872)

- Observed by Belle in $B^{\pm} \to K^{\pm}\pi^{+}\pi^{-}J/\psi$ [PRL91,262001(2003)]
- Close to $D^0\bar{D}^{*0}$ mass threshold, narrow peak
- $J^{PC}=1^{++}$ [CDF (PRL98,132002) $1^{++}/2^{-+}$; LHCb (EPJC72,1972) 1^{++}]
- Nature unclear:
  - D^0D^{*0} bound state?
  - Mixture of $\chi_{c1}(2P)$ and $D^0\bar{D}^{*0}$ bound state?
  - Conventional charmonium $\chi_{c1}(2P)$? tetraquark? hybrid?...
- Production
  - pp collison; B decays;
  - $Y(4260) \to \gamma X(3872)$ [BESIII, PRL112, 092001 (2014)]
- Decay: $\pi^+\pi^-J/\psi$, $\pi^+\pi^-\pi^0 J/\psi$, $D^0\bar{D}^0\pi^0$, $D^0\bar{D}^{*0}$, $\gamma J/\psi$, $\gamma\psi'$

Observation of [PRL112, 092001 (2014)]

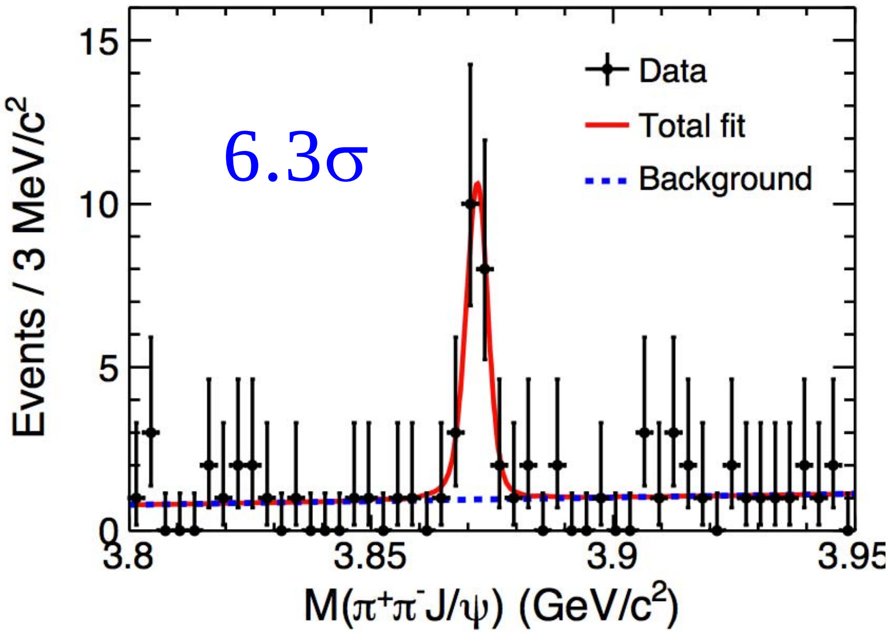
$e^+e^- \rightarrow \gamma X(3872) \rightarrow \gamma\pi^+\pi^- J/\psi$

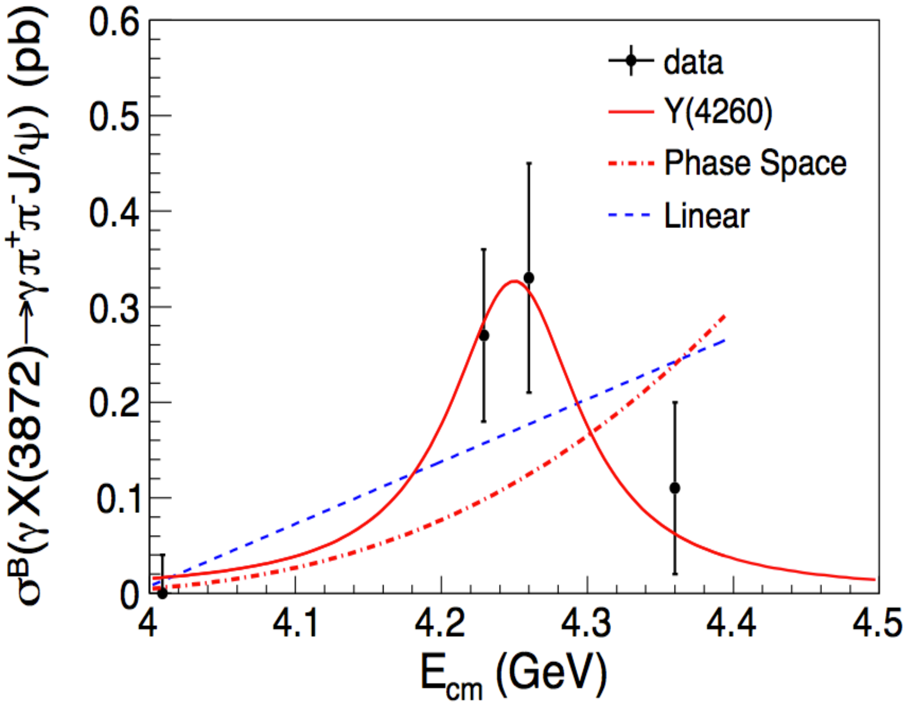


Clear ISR ψ' signal for data validation; X(3872) signal at around 4.23-4.26 GeV

observation of X(3872)

[PRL112, 092001 (2014)]





Obvious X(3872) signal through radiative decay

N =20.1±4.5;

M = 3871.9±0.7±0.2 MeV

[PDG = 3871.68 ±0.17 MeV]

- Seems from Y(4260) decays
- $\sigma(e^+e^- \rightarrow \pi^+\pi^- J/\psi)$ = (62.9 ± 1.9 ± 3.7) pb; $B(X(3872) \rightarrow \pi^+\pi^- J/\psi)$ = 5%

$$\frac{\sigma(e^+e^- \rightarrow \gamma X(3872))}{\sigma(e^+e^- \rightarrow \pi^+\pi^- J/\psi)} \quad \sim 11\%$$

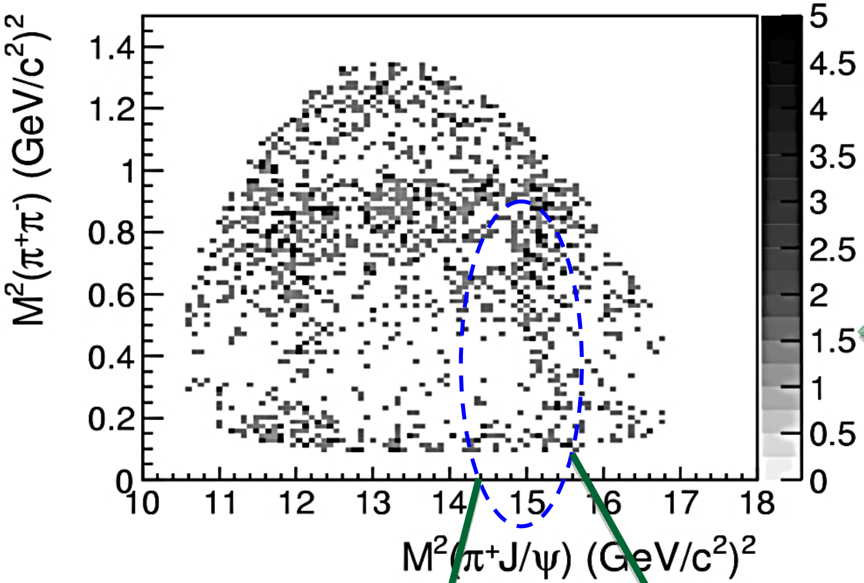
X(3872) Radiative Decays

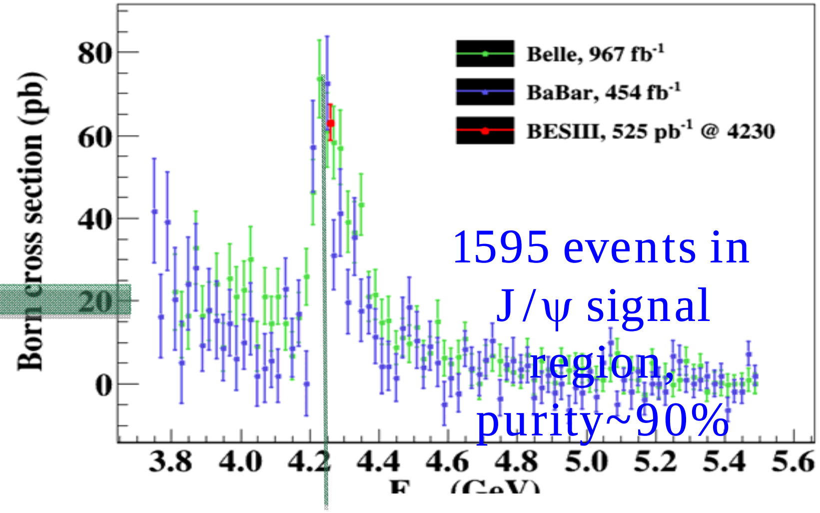
- Radiative decays of X(3872) help to understand its nature
  - X(3872)→$\gamma J/\psi$ determines its C-parity
  - Ratio (R) of X(3872)→$\gamma\psi'$ to $\gamma J/\psi$:
  - Theoretical predictions:
    - $D\bar{D}^*$ molecule: (3-4)$\times 10^{-3}$
    - Charmonium: 1.2-15
    - Mixture: 0.5-5
  - Experimental measurements:
    - BaBar: 3.4$\pm$1.4, 3.5σ [PRL102, 132001 (2009)]
    - Belle: <2.1 @ 90% C.L [PRL107, 091803 (2011)]
    - LHCb: 2.46$\pm$0.64$\pm$0.29, 4.4σ arXiv:1404.0275

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

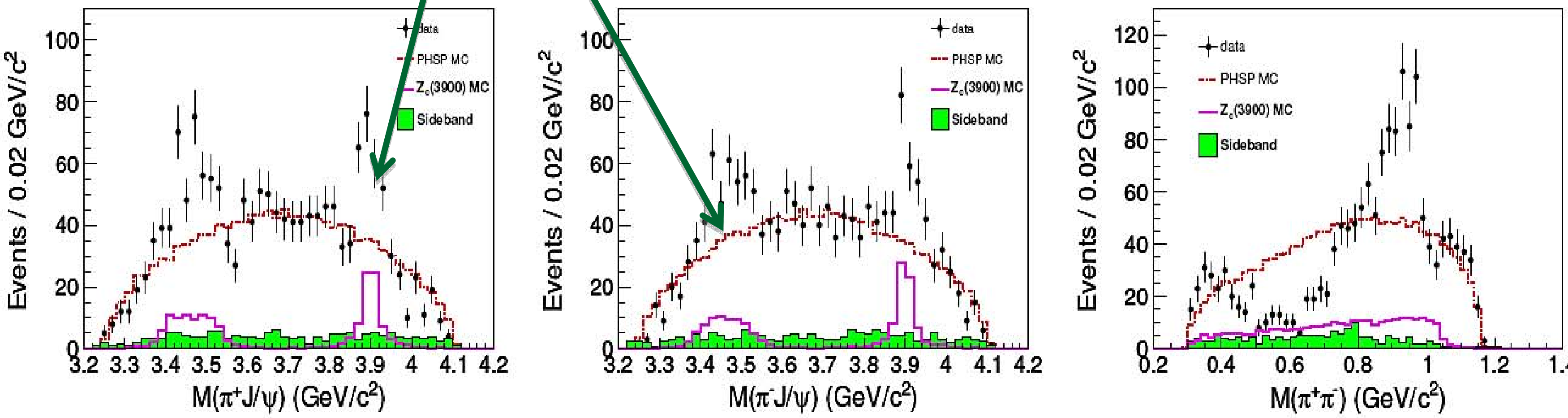
[PRL110, 252001(2013)]

525 pb^{-1} data at 4.260 GeV

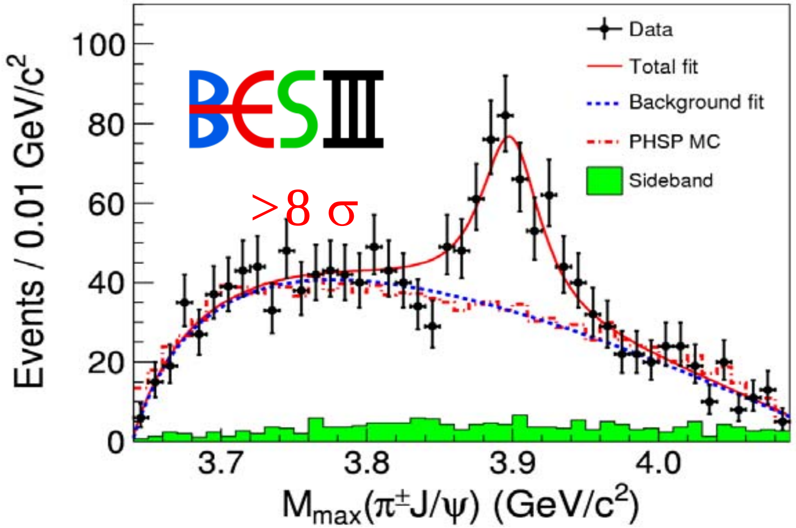




1595 events in J/ψ signal region, purity~90%



Observation of $Z_c(3900)$

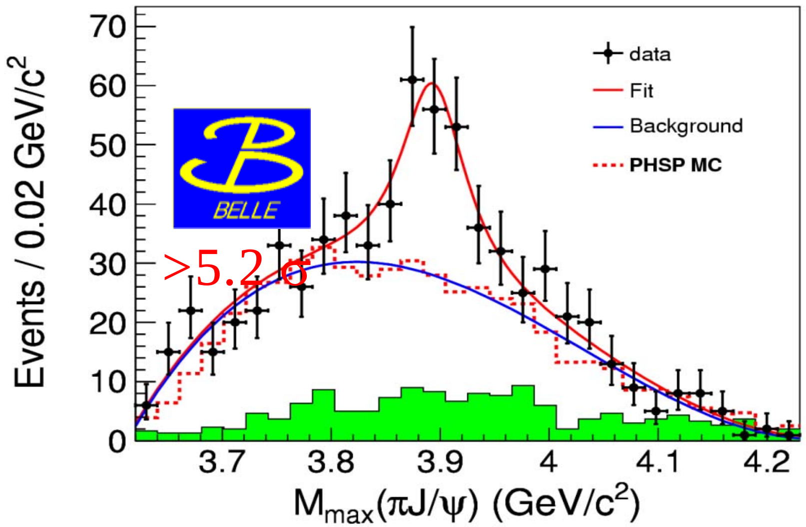


BESIII: [PRL110, 252001(2013)]

M = 3899.0±3.6±4.9 MeV

Γ = 46±10±20 MeV

307 ± 48 events



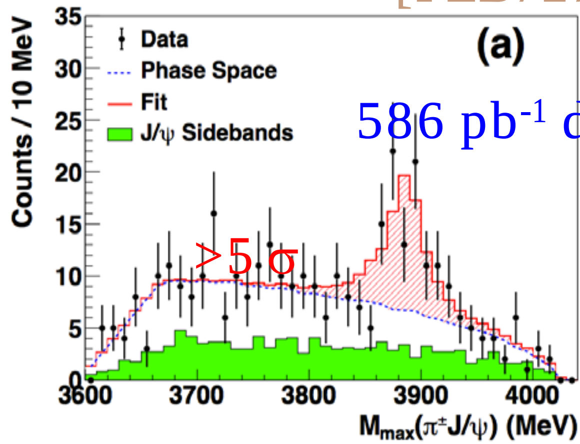
BELLE: [PRL110, 252002 (2013)]

M = 3894.5±6.6±4.5 MeV

Γ = 63±24±26 MeV

159 ± 49 events

[PLB727, 366-370(2013)]



CLEOc data

586 pb^{-1} data at 4.170 GeV

M = 3886±4±2 MeV

Γ = 37±4±8 MeV

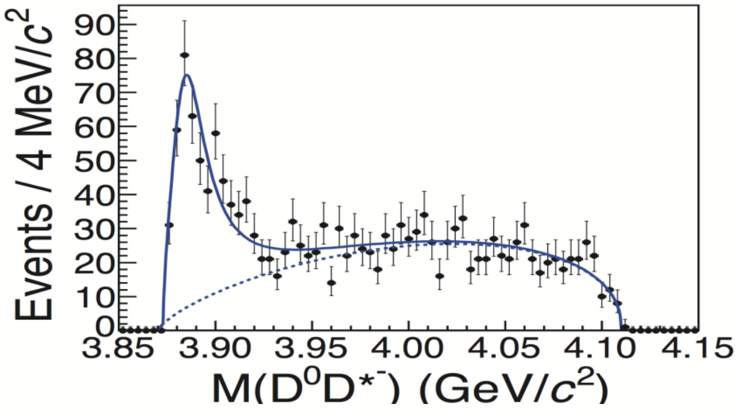
81 ± 16 events

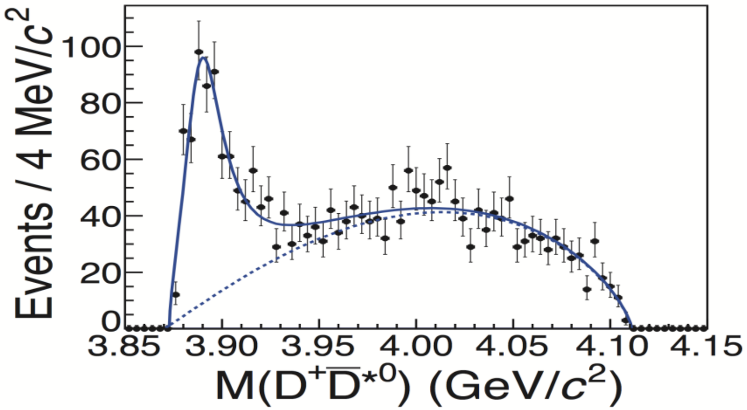
$e^+e^- \rightarrow \pi^- (D^*\bar{D})^+ + c.c.$

525 pb^{-1} data at 4.260 GeV

[PRL112, 022001 (2014)]

- Strategy:
  - reconstruct $D^0 \rightarrow K^-\pi^+ / D^+ \rightarrow K^-\pi^+\pi^+$; reconstruct "bachelor" π; require D* in the missing mass using kinematic fit; look at the recoil side of π





M = 3883.9±1.5±4.2 MeV

Γ = 24.8±3.3±11.0 MeV

σ×B 85.3±6.6±22.0 pb

Assuming $Z_c(3885)$ is $Z_c(3900)$

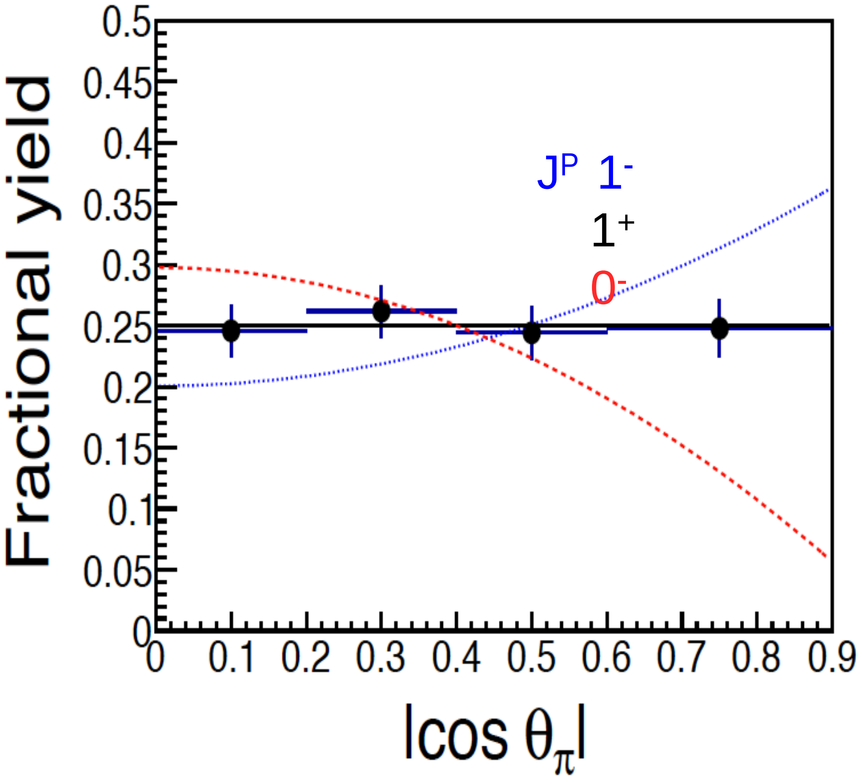
$$\frac{\Gamma(Z_c(3885) \to D\bar{D}^*)}{\Gamma(Z_c(3900) \to \pi J/\psi)} = 6.2 \pm 1.1 \pm 2.7$$

Large non-$D\bar{D}$ coupling

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

[PRL112, 022001 (2014)]

- $\cos\theta_\pi$:
  - bachelor pion's pole angle (relative to beam direction) in the CMS



- 0^-: P-wave, with $J_Z=\pm1$ → $\sin^2\theta_\pi$
- ~~0^+: parity conservation~~
- 1^-: P-wave, $1+\cos^2\theta_\pi$
- 1^+: S-wave/D-wave, D-wave small contribution → flat distribution

fits favor 1^+ assumption

Summary

- Fruitful results come from the BESIII experiment.
- New highlight in light hadron, XYZ physics.
- Looking forward to new results, since more data is still being taken under energy range 4. ~ 4.6 GeV.