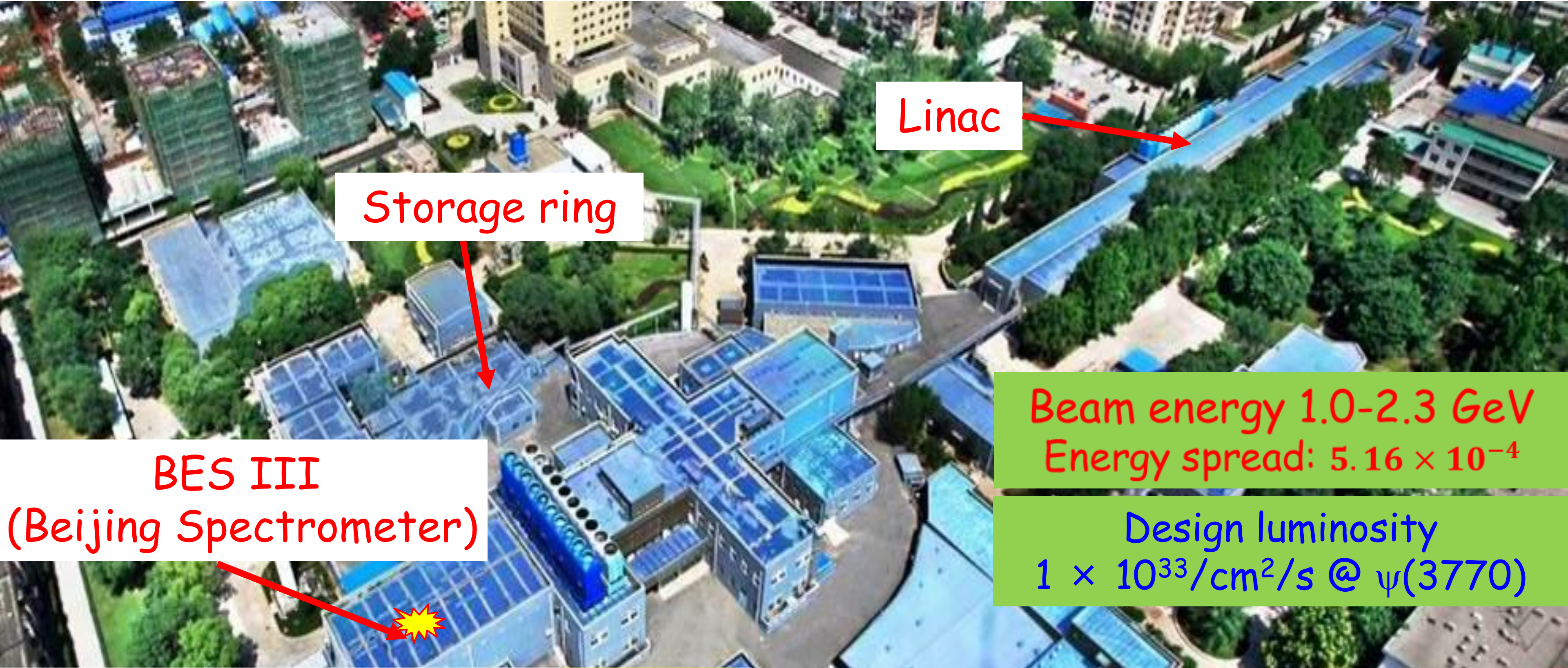
PWA at BESIII

LIU Beijiang (IHEP, CAS)
For BESIII collaboration

ATHOS 2013, 21-24 May 2013, Kloster Seeon

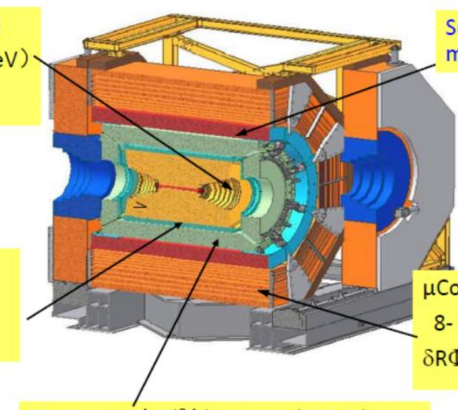


Beam energy 1.0-2.3 GeV
Energy spread: 5.16×10^{-4}

Design luminosity
$1 \times 10^{33}/cm^2/s$ @ $\psi(3770)$

NIM A614, 345 (2010)

The BESIII Detector



BEPC II
(Beijing Electron-positron collider)
2004: started BEPCII upgrade,
BESIII construction
2008: test run
2009-now: BESIII physics run

Physics of τ-charm region

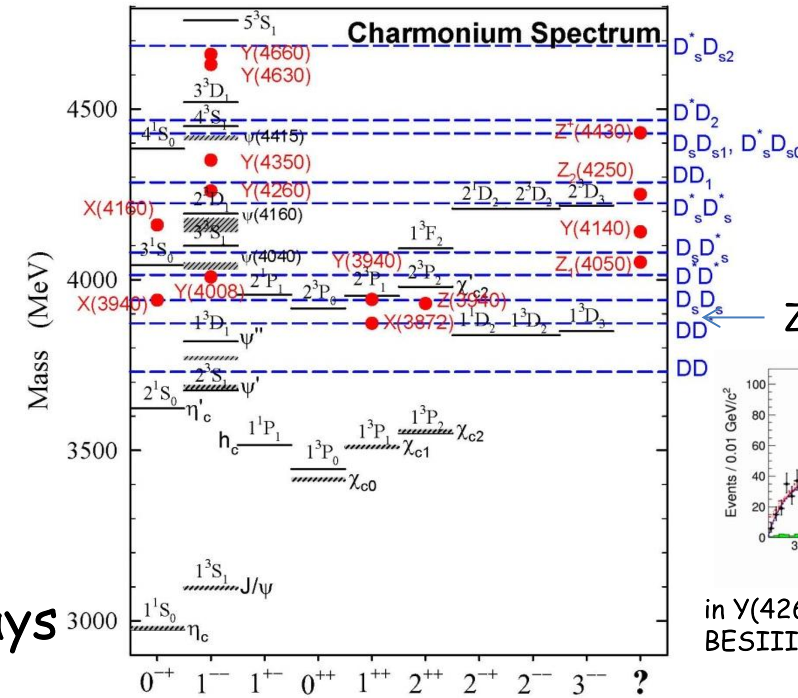
Charmonium physics:
- Spectroscopy
- transitions and decays

Light hadron physics:
- meson & baryon spectroscopy
- glueball & hybrid
- two-photon physics
- e.m. form factors of nucleon

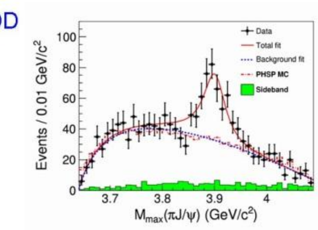
Open Charm physics:
- (semi)leptonic + hadronic decays
- decay constant, form factors
- CKM matrix: Vcd, Vcs
- D^0-D^0bar mixing and CP violation
- rare/forbidden decays

Tau physics:
- tau decays near threshold
- tau mass scan

…and many more.



Zc(3900)

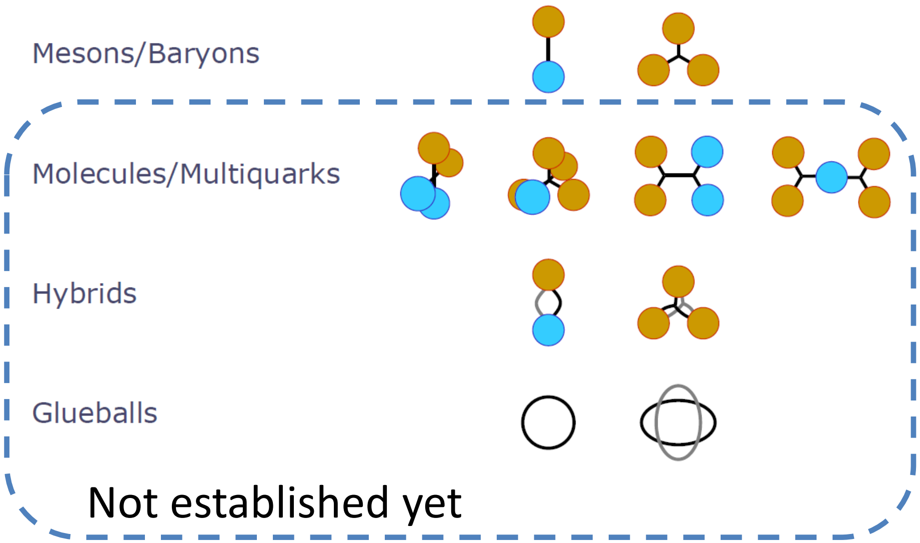


in Y(4260) decays
BESIII arxiv:1303.5949

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

World's largest samples

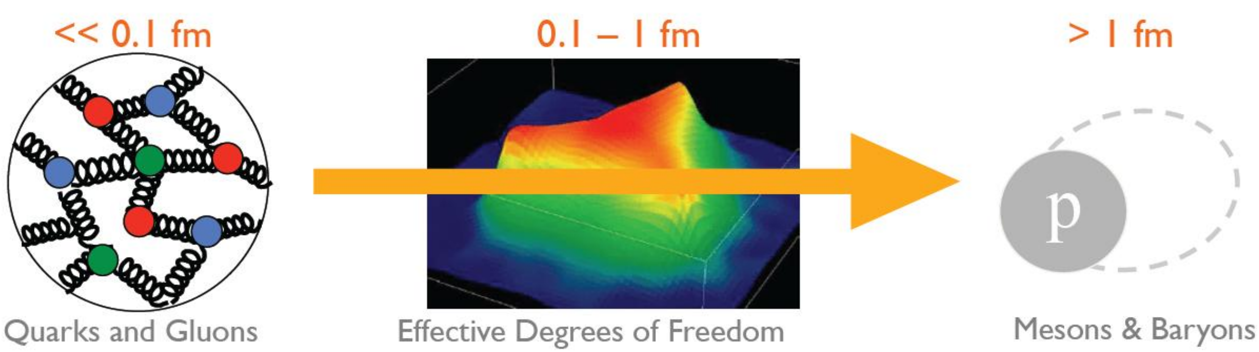
Hadron spectrum



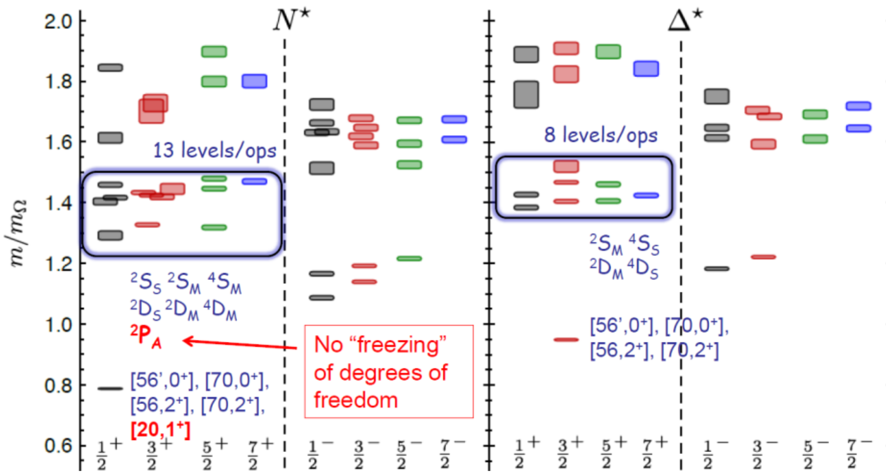
Continuous efforts in experiment and theory

- Hadron spectroscopy is a key tool to investigate QCD

  - testing QCD in the confinement regime
  - providing insights into the fundamental degrees of freedom

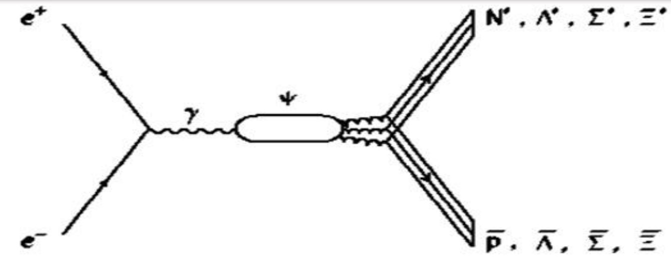


Where are the "missing" baryons?



LQCD results, PR D84 074508 (2011)

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



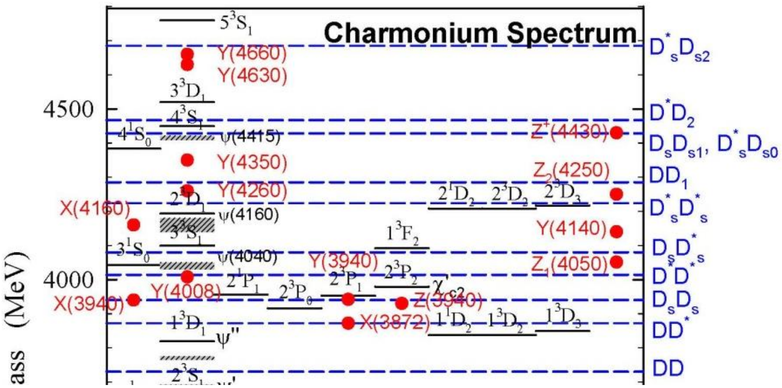
- ✓ Pure isospin 1/2 filter: $\psi \rightarrow N\bar{N}\pi$, $\psi \rightarrow N\bar{N}\pi\pi$
- ✓ Missing N* with small couplings to πN & γN , but large coupling to gggN : $\psi \rightarrow N\bar{N}\pi/\eta/\eta'/\omega/\phi$, $\bar{p}\Sigma\pi$, $\bar{p}\Lambda K$ …
- ✓ Interference between N* and N*bar bands in $\psi \rightarrow N\bar{N}\pi$ Dalitz plots may help to distinguish some ambiguities in PWA of πN
- ✓ Not only N*, but also Λ^*, Σ^*, Ξ^*
- ✓ High statistics of charmonium @ BES III

	****	***	**	*
N Spectrum	11	3	6	2
Δ Spectrum	7	3	6	6

➜ Particle Data Group (J. Phys. G **37**, 075021 (2010))

➜ little known (many open questions left)

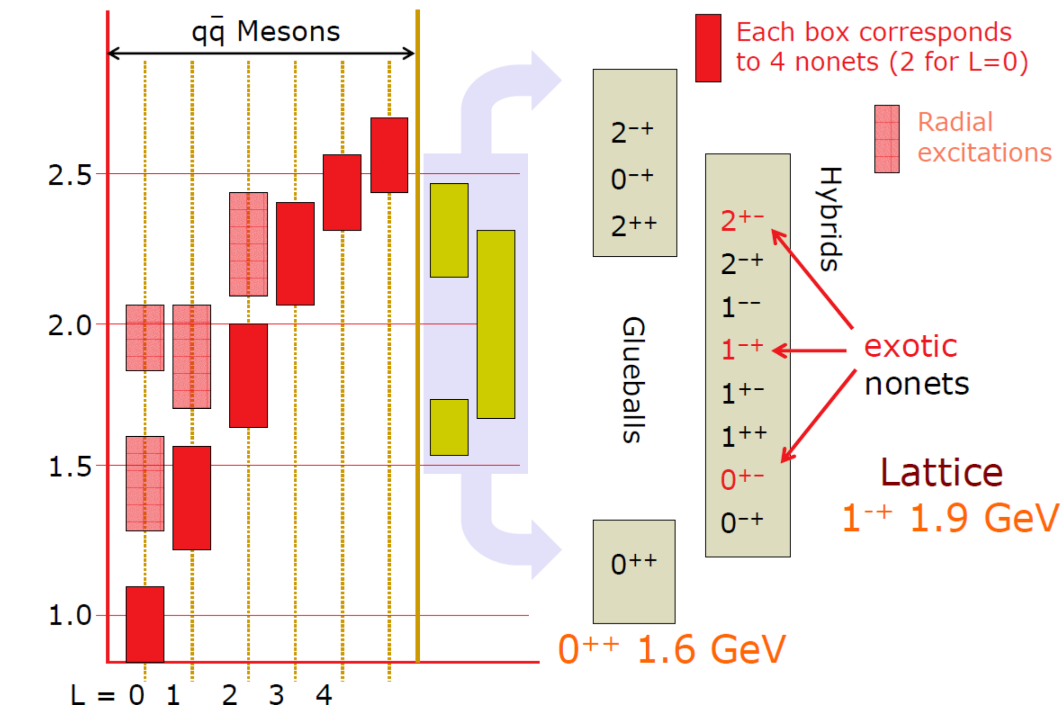
Where are the QCD exotics

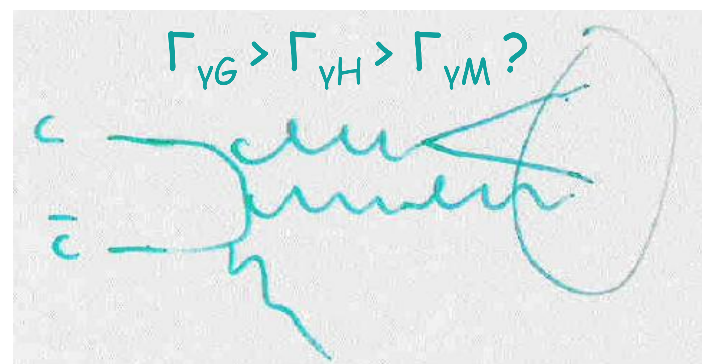


hybrids
molecules
hadrocharmonium
tetraquarks
threshold effects

Produce Y's directly
e+e- @4260/4360/…

BES provides some ideal hunting grounds *Power of high statistics*

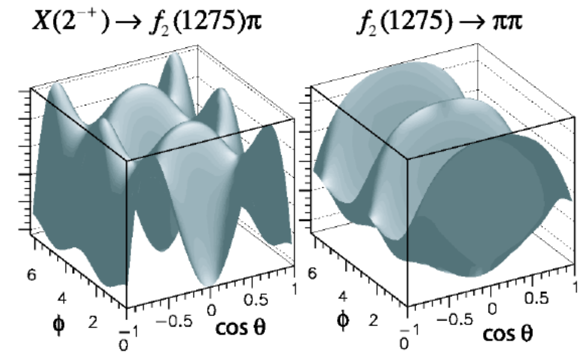




"gluon-rich"

Partial wave analysis

"Holography"



Tasks:

- ☐ **Map out the resonances**
- ☐ **Systematic determination of resonance properties:**
  spin-parity,
  resonance parameters,
  production properties,
  decay properties, …
  - ◆ resonances tend to be broad and plentiful, leading to intricate interference patterns, or buried under a background in the same and in other waves.

Event-wise ML fit to all observables simultaneously

$$\omega(\xi) \equiv \frac{d\sigma}{d\Phi} = \left|\sum_i c_i \underbrace{R_i B(p,q)}_{\text{dynamic}} \underbrace{Z(L)}_{\text{angular}}\right|^2$$

Event-wise efficiency correction

$$P(\xi) = \frac{\omega(\xi)\epsilon(\xi)}{\int \omega(\xi)\epsilon(\xi)}$$

Tools: PWA

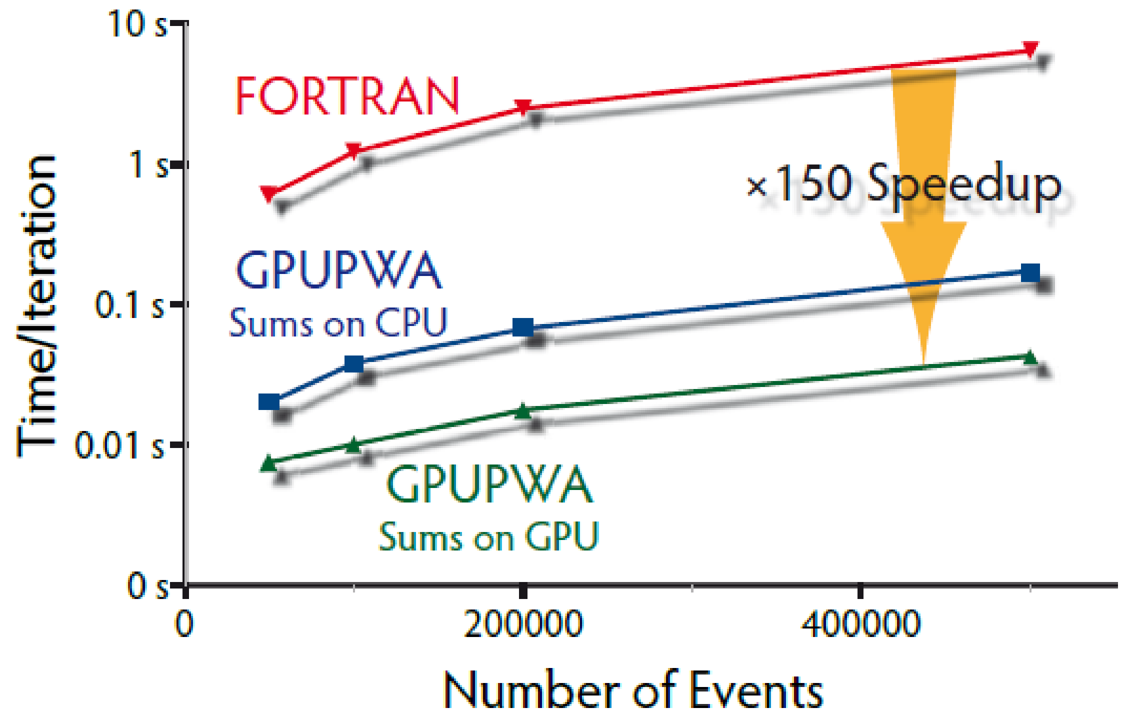
- ✓ **Decompose to partial wave amplitudes**
- ✓ **Make full use of data**
- ✓ **Handle the interference**
- ✓ **Extract resonance properties with high sensitivity and accuracy**

GPUPWA

N. Berger, B.J. Liu and J.K. Wang, J.Phys.Conf.Ser., 219, 042031 (2010)

http://gpupwa.sourceforge.net

OpenCL



Data parallelism in event-wise likelihood PWA fit

- Selected results of PWA at BESIII
  - $\psi' \to \pi^0 p\bar{p}$
  - $J/\psi, \psi' \to \gamma p\bar{p}$
  - $J/\psi \to \gamma\eta\eta$
  - $J/\psi \to \gamma\omega\phi$

Covariant tensor amplitudes generated by FDC-PWA
NIM. A534 241
http://v-www.ihep.ac.cn/~wjx/

Covariant tensor amplitudes, EPJ A26 125

Covariant tensor amplitudes, EPJ A16 537

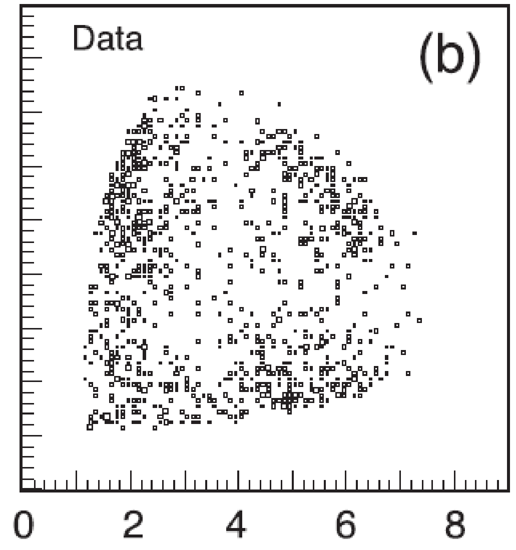
All these analyses using 2009 data sets
($225 * 10^6\ J/\psi, 106 * 10^6\ \psi'$)

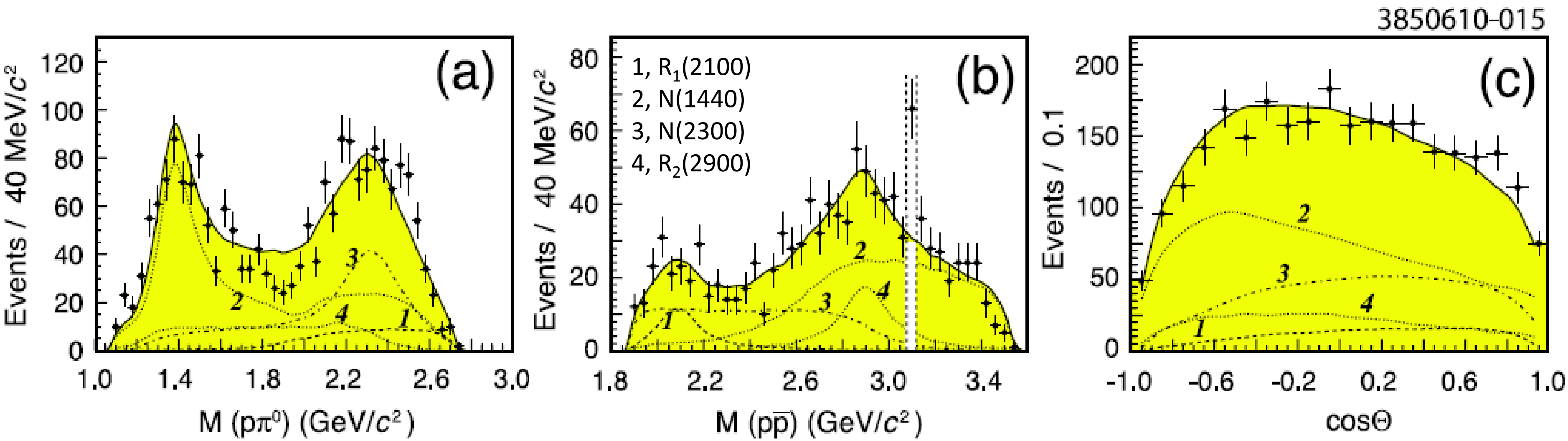
* Accelerated by GPUPWA

$$\psi' \to \pi^0 p\bar{p}$$

CLEO-c: PRD 82 092002 (2010)

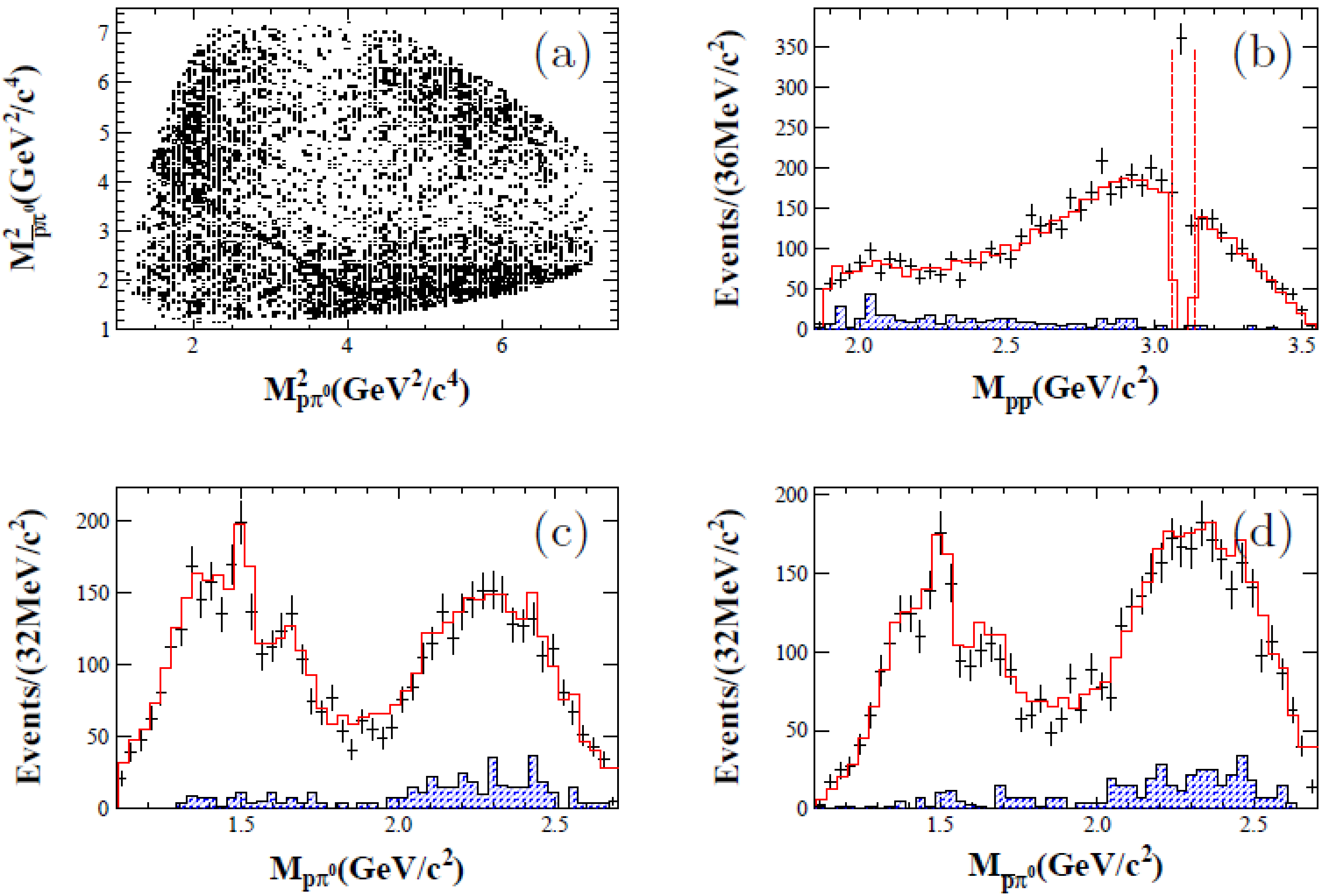
Interference is NOT considered





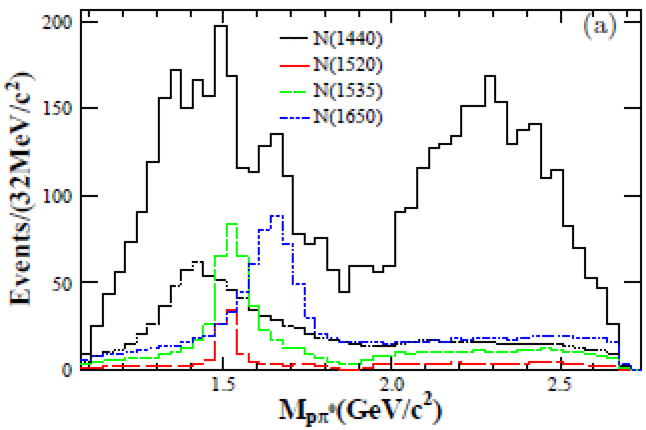
PWA of $\psi' \to \pi^0 p\bar{p}$ at BESIII

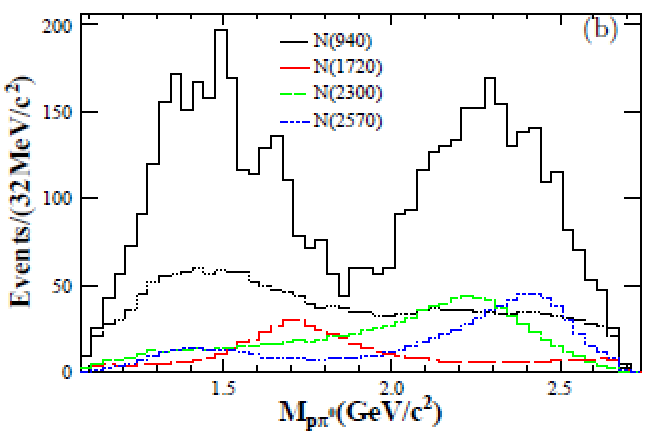
Phys.Rev.Lett. 110 (2013) 022001



PWA of $\psi' \to \pi^0 p\bar{p}, \pi^0 \to \gamma\gamma$ at BESIII

Phys.Rev.Lett. 110 (2013) 022001



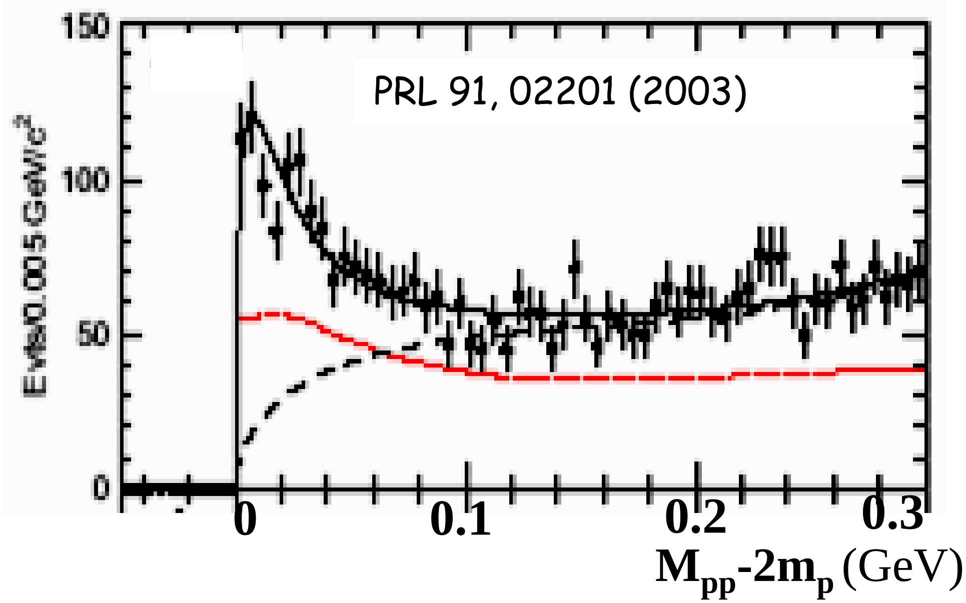


Resonance	M(MeV/c^2)	Γ(MeV/c^2)	ΔS	ΔN_{dof}	Sig.
$N(1440)$	1390^{+11+21}_{-21-30}	$340^{+46+70}_{-40-156}$	72.5	4	11.5σ
$N(1520)$	1510^{+3+11}_{-7-9}	115^{+20+0}_{-15-40}	19.8	6	5.0σ
$N(1535)$	1535^{+9+15}_{-8-22}	120^{+20+0}_{-20-42}	49.4	4	9.3σ
$N(1650)$	1650^{+5+11}_{-5-30}	150^{+21+14}_{-22-50}	82.1	4	12.2σ
$N(1720)$	1700^{+30+32}_{-28-35}	$450^{+109+149}_{-94-44}$	55.6	6	9.6σ
$N(2300)$	$2300^{+40+109}_{-30-0}$	$340^{+30+110}_{-30-58}$	120.7	4	15.0σ
$N(2570)$	2570^{+19+34}_{-10-10}	250^{+14+69}_{-24-21}	78.9	6	11.7σ

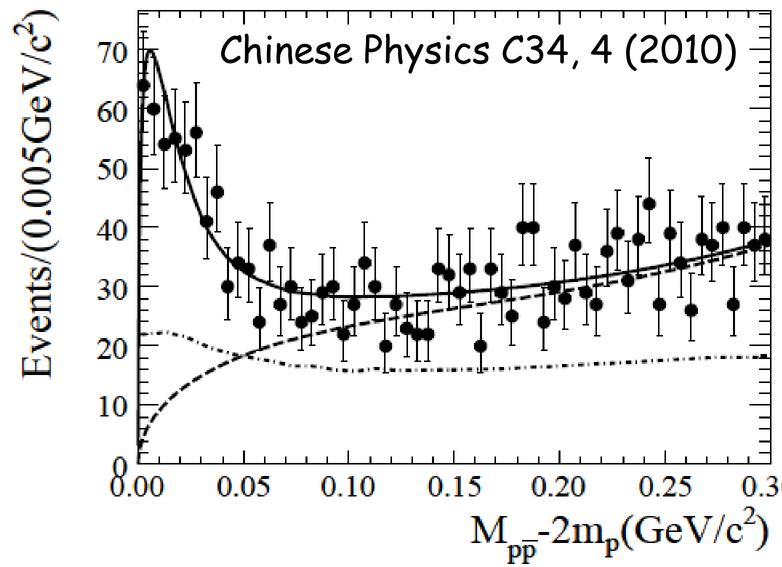
2 New N* are found:
N(2300) 1/2+ and
N(2570) 5/2-

Enhancement at $M_{p\bar{p}}$ threshold in $J/\psi \to \gamma p\bar{p}$

$J/\psi \to \gamma p\bar{p}$



$\psi' \to \pi^+\pi^- J/\psi, J/\psi \to \gamma p\bar{p}$



Observed at BES2

Agree with spin zero expectation

$M = 1859^{+3}_{-10}{}^{+5}_{-25}\ MeV/c^2, \Gamma < 30\ MeV/c^2\ (90\%\ CL)$

Confirmed at BES3

$M = 1861^{+6}_{-13}{}^{+7}_{-26}\ MeV/c^2, \Gamma < 38\ MeV/c^2\ (90\%\ CL)$

Many possibilities:

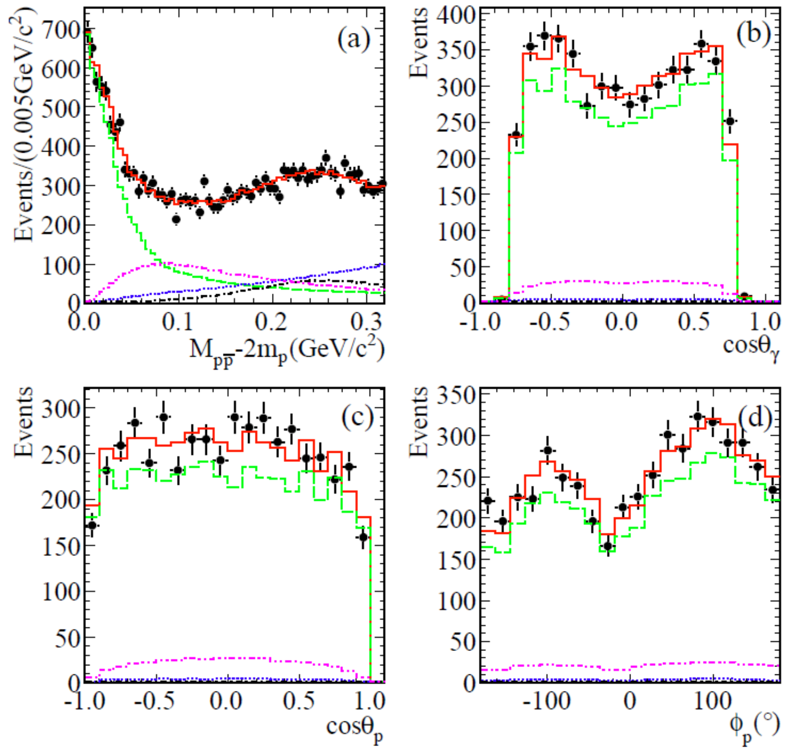
ordinary meson/$p\bar{p}$ bound state/multiquark/glueball/final state interaction (FSI)

Spin-parity analysis

is essential for determining place in the spectrum and possible nature

PWA of $J/\psi \to \gamma p\bar{p}$

- PWA of $J/\psi \to \gamma p\bar{p}$ was first performed
- The fit with a BW and S-wave FSI (I=0) factor can well describe $p\bar{p}$ mass threshold structure.
- It is much better than that without FSI effect ($\Delta 2\ln L = 5,\ \ 7.1\sigma$)
- Different FSI models → Model dependent uncertainty



Phys. Rev. Lett. 108, 112003 (2012)

Spin parity, mass, width and branching ratio:

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

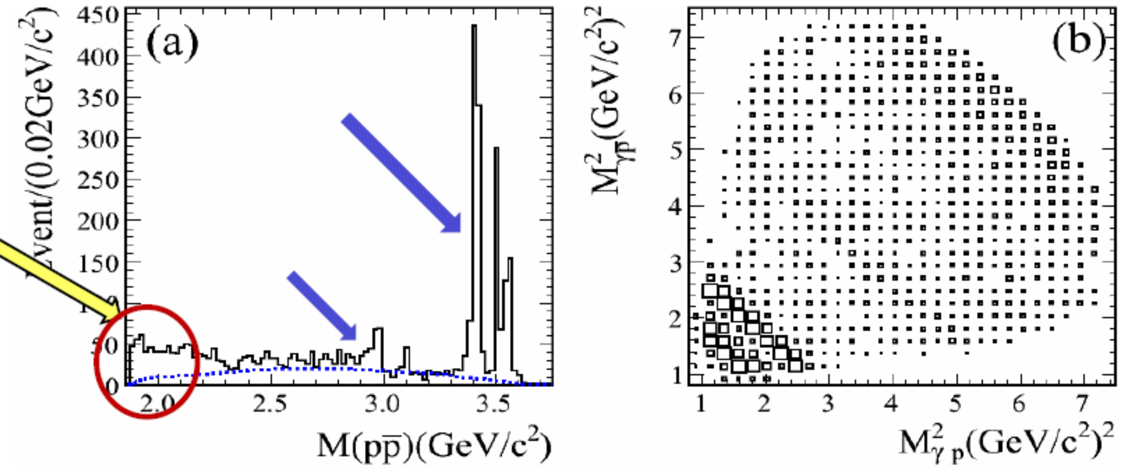
$M = 1832^{+19}_{-5}(stat)^{+18}_{-17}(sys) \pm 19(model) MeV/c^2,$

$\Gamma = 13 \pm 39(stat)^{+10}_{-13}(sys) \pm 4(model) MeV/c^2,\ \ \Gamma < 76\ MeV/c^2\ (90\%\ CL),$

$B(J/\psi \to \gamma X) B(X \to p\bar{p}) = \left(9.0^{+0.4}_{-1.1}(stat)^{+1.5}_{-5.0}(sys) \pm 2.3(model)\right) * 10^{-5}$

$M_{p\bar{p}}$ threshold structure in $\psi' \to \gamma p\bar{p}$

Obviously different line shape of ppbar mass spectrum near threshold from that in J/ψ decays



PWA results:

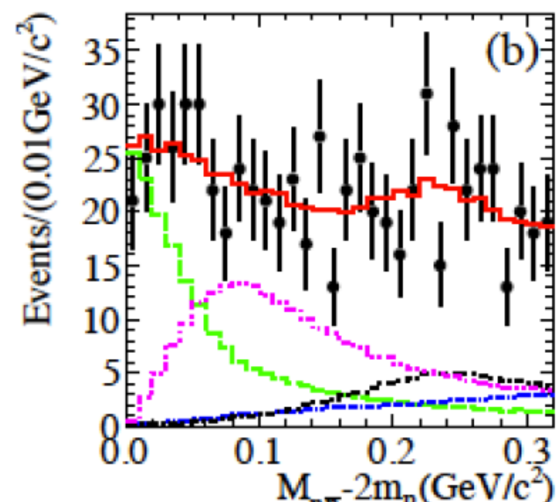
- Significance of X(ppbar) is > 6.9 σ .
- The production ratio R: **first measurement**

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

$$= (5.08^{+0.71}_{-0.45}(\text{stat})^{+0.67}_{-3.58}(\text{syst}) \pm 0.12(\text{mod}))\%$$

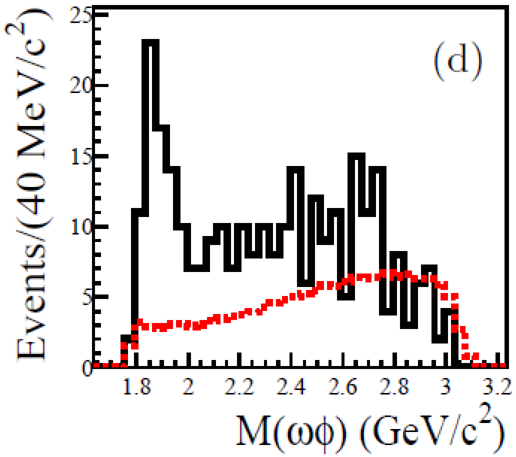
- It is suppressed compared with “12% rule”.

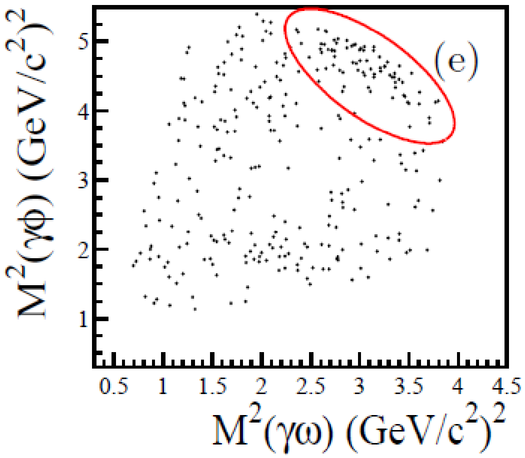
PWA Projection:



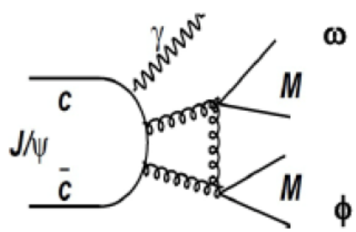
PRL 108,112003(2012)

$M_{\omega\phi}$ threshold structure in $J/\psi \to \gamma\omega\phi$





BESII PRL 96(2006) 162002



$J/\psi \to \gamma\omega\phi$ **(DOZI)**

For X(1810):

$$M = 1812^{+19}_{-26} \pm 18\ \mathrm{MeV/c^2}$$

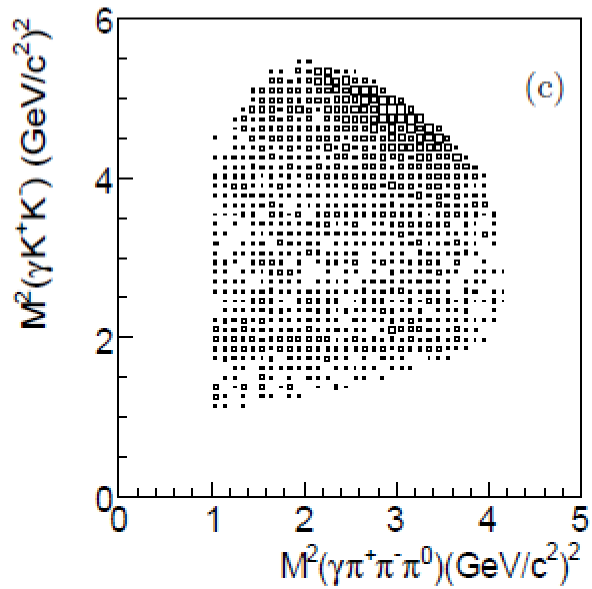
$$\Gamma = 105 \pm 20 \pm 28\ \mathrm{MeV/c^2}$$

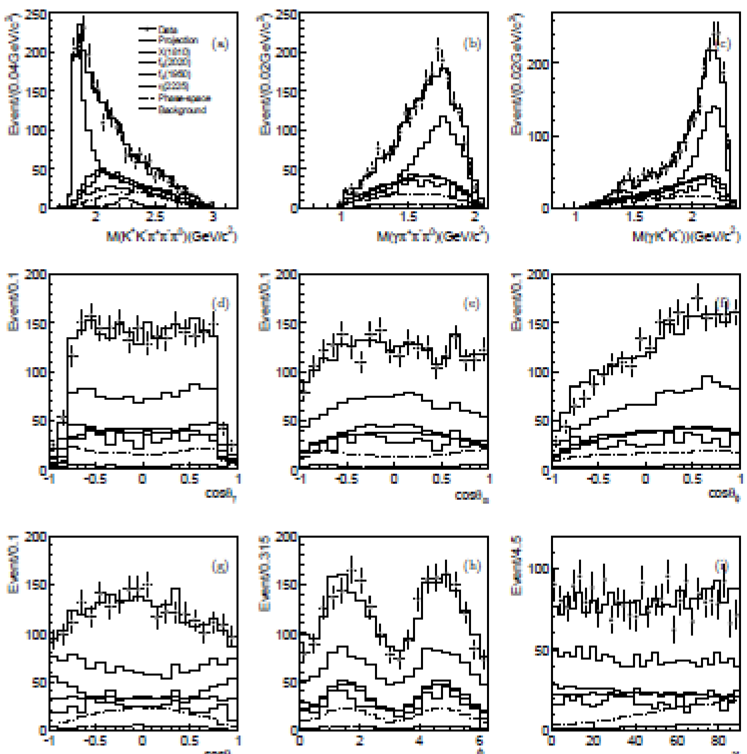
J^{PC} favors 0^{++} over 0^{-+} and 2^{++}

PWA of $J/\psi \to \gamma\omega\phi$ at BESIII

Phys.Rev. D87 (2013) 032008

Resonance	J^{PC}	M(MeV/c^2)	Γ(MeV/c^2)	Events	ΔS	Δndf	Significance
$X(1810)$	0^{++}	1795 ± 7	95 ± 10	1319 ± 52	783	4	$> 30\sigma$
$f_2(1950)$	2^{++}	1944	472	665 ± 40	211	2	20.4σ
$f_0(2020)$	0^{++}	1992	442	715 ± 45	100	2	13.9σ
$\eta(2225)$	0^{-+}	2226	185	70 ± 30	23	2	6.4σ
phase space	0^{-+}	—	—	319 ± 24	45	2	9.1σ





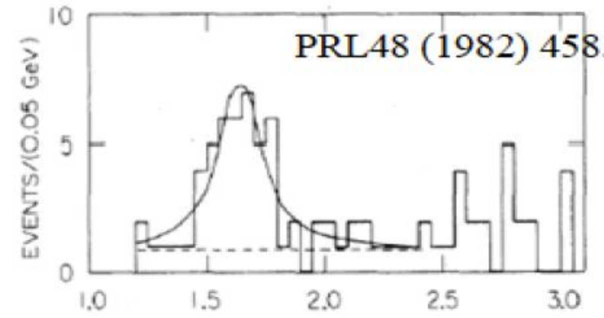
X(1810) is confirmed with 0+

Is X(1810) the $f_0(1710)/f_0(1790)$ or new state?

Study of ηη system

- $f_0(1710)$ was first observed in J/ψ radiative decays to ηη by Crystal Ball.
- LQCD predicts

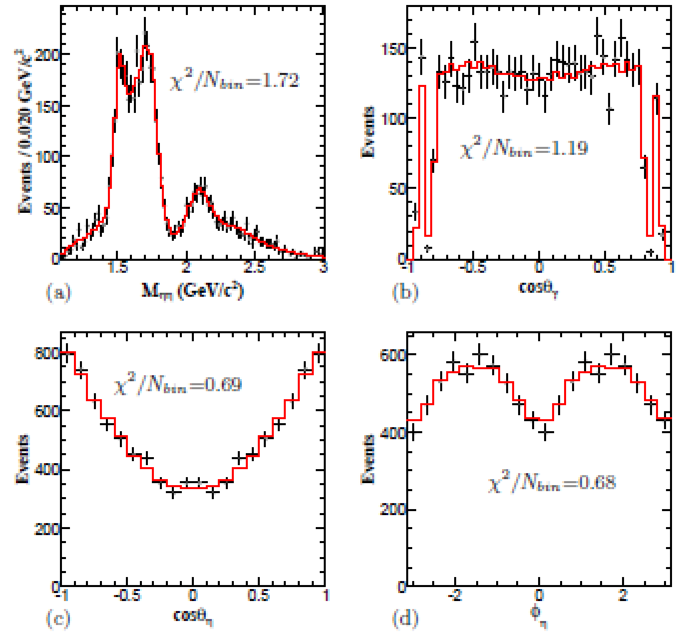
$$\boxed{0^{++} : 1710 \pm 50 \pm 80}$$

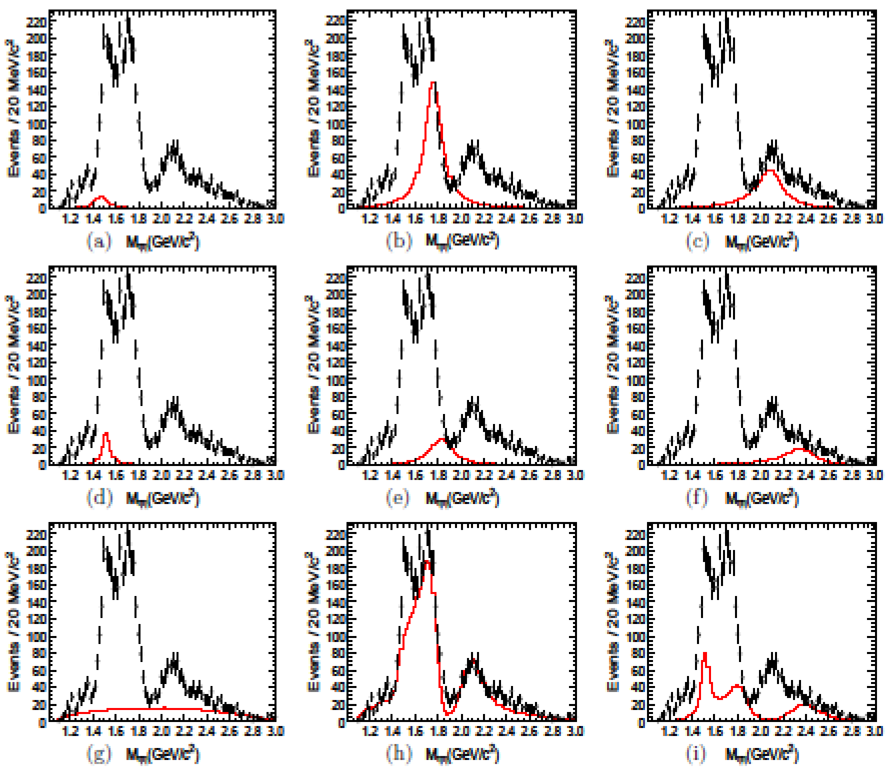


- Crystal Barrel Collaboration (2002) analyzed the three final states $\pi^0\pi^0\pi^0$, $\eta\pi^0\pi^0$ and $\pi^0\eta\eta$ with K-matrix formalism. Found a 2^{++}(~1870MeV), but no $f_0(1710)$.
- E835 (2006): ppbar→$\pi^0\eta\eta$, found $f_0(1500)$ and $f_0(1710)$.
- WA102 and GAMS all identified $f_0(1710)$ in ηη.

PWA of $J/\psi \rightarrow \gamma\eta\eta$ @BESIII
(arXiv:1301.0053, to appear in PRD)

Resonance	Mass(MeV/c^2)	Width(MeV/c^2)	$\mathcal{B}(J/\psi \rightarrow \gamma X \rightarrow \gamma\eta\eta)$	Significance
$f_0(1500)$	1468^{+14+23}_{-15-74}	$136^{+41+28}_{-26-100}$	$(1.65^{+0.26+0.51}_{-0.31-1.40}) \times 10^{-5}$	8.2 σ
$f_0(1710)$	$1759 \pm 6^{+14}_{-25}$	$172 \pm 10^{+32}_{-16}$	$(2.35^{+0.13+1.24}_{-0.11-0.74}) \times 10^{-4}$	25.0 σ
$f_0(2100)$	$2081 \pm 13^{+24}_{-36}$	273^{+27+70}_{-24-23}	$(1.13^{+0.09+0.64}_{-0.10-0.28}) \times 10^{-4}$	13.9 σ
$f_2'(1525)$	$1513 \pm 5^{+4}_{-10}$	75^{+12+16}_{-10-8}	$(3.42^{+0.43+1.37}_{-0.51-1.30}) \times 10^{-5}$	11.0 σ
$f_2(1810)$	1822^{+29+66}_{-24-57}	$229^{+52+88}_{-42-155}$	$(5.40^{+0.60+3.42}_{-0.67-2.35}) \times 10^{-5}$	6.4 σ
$f_2(2340)$	$2362^{+31+140}_{-30-63}$	$334^{+62+165}_{-54-100}$	$(5.60^{+0.62+2.37}_{-0.65-2.07}) \times 10^{-5}$	7.6 σ





- **$f_0(1710)$ and $f_0(2100)$ are dominant scalars.**
- **$f_0(1500)$ exists (8.2σ).**
- **Br of $f_0(1710)$ and $f_0(2100)$ are ~10x larger than that of $f_0(1500)$**
- **$f_2'(1525)$ is the dominant tensor.**

PWA of $J/\psi \to \gamma\eta\eta$ @BESIII: a case study
Efficiency, background treatment

$$P(\xi:\alpha) = \frac{\omega(\xi,\alpha)\epsilon(\xi)}{\int d\xi\omega(\xi,\alpha)\epsilon(\xi)}$$

The probability to observe the event characterized by the measurement ξ

$$\omega(\xi,\alpha) = \frac{d\sigma}{d\Phi} = (\sum_i A_i)^2$$

Differential cross section

$$P(\xi_1,\xi_2,\dots,\xi_n:\alpha) = \prod_{i=1}^{N} P(\xi:\alpha) = \prod_{i=1}^{N} \frac{\omega(\xi_i,\alpha)\epsilon(\xi_i)}{\int d\xi\omega(\xi,\alpha)\epsilon(\xi)} = L$$

Standard likelihood

$$\ln L = \sum_{i=1}^{N} \ln\left(\frac{\omega(\xi_i,\alpha)}{\int d\xi\omega(\xi,\alpha)\epsilon(\xi)}\right) + \cancel{\sum_{i=1}^{N} \epsilon(\xi_i)}$$

The efficiency is included in the normalization.
The second term is dropped in the fit.

$$\sigma' = \int d\xi\omega(\xi,\alpha)\epsilon(\xi) \cong \frac{1}{N_{gen}} \sum_{i=1}^{N_{acc}} \omega(\xi_i,\alpha)$$

Observed total cross section

$$\ln L = \sum_{i=1}^{N} \ln\left(\frac{\omega(\xi_i,\alpha)}{\int d\xi\omega(\xi,\alpha)\epsilon(\xi)}\right) = \sum_{i=1}^{N} \ln\left(\frac{\omega(\xi_i,\alpha)}{\sigma'}\right)$$

$$L_S(data) = \prod_{i}^{N_{data}} P_S(\xi_i)$$

Likelihood is defined with signal PDF

$$L_S(signal) = \frac{L_S(data)}{L_S(background)}$$

Background subtraction
-- using η sidebands

PWA of $J/\psi \to \gamma\eta\eta$ @BESIII: a case study
Selection of partial wave components

Step 1: have a starting point, according to
1, Previous studies;
2, PDG list;
3, Some educated guess from the distributions;

- the component of largest contribution should be chosen as the reference for the relative magnitude and relative phase.

We tested the following mesons listed in PDG 2012: $f_2(1270)$, $f_0(1370)$, $f_2(1430)$, $f_0(1500)$, $f_2^{'}(1525)$, $f_2(1565)$, $f_2(1640)$, $f_0(1710)$, $f_2(1810)$, $f_2(1910)$, $f_2(1950)$, $f_2(2010)$, $f_0(2020)$, $f_4(2050)$, $f_0(2100)$, $f_2(2150)$, $f_0(2200)$, $f_J(2220)$, $f_2(2300)$, $f_4(2300)$, $f_0(2330)$, $f_2(2340)$.

Step 2: add more components
1, Add one additional component out of the pool of candidates;
2, Optimize the parameters. Check the significance for each component;
3, Repeat 1 and 2. Keep the most significant one in your solution;
Repeat 1,2,3, until there's no more significant component to add;

→ all the components in the baseline fit are > 5 sigma
→ all the possible extra components are < 5 sigma

PWA of $J/\psi \to \gamma\eta\eta$ @BESIII: a case study
Systematic uncertainties in PWA

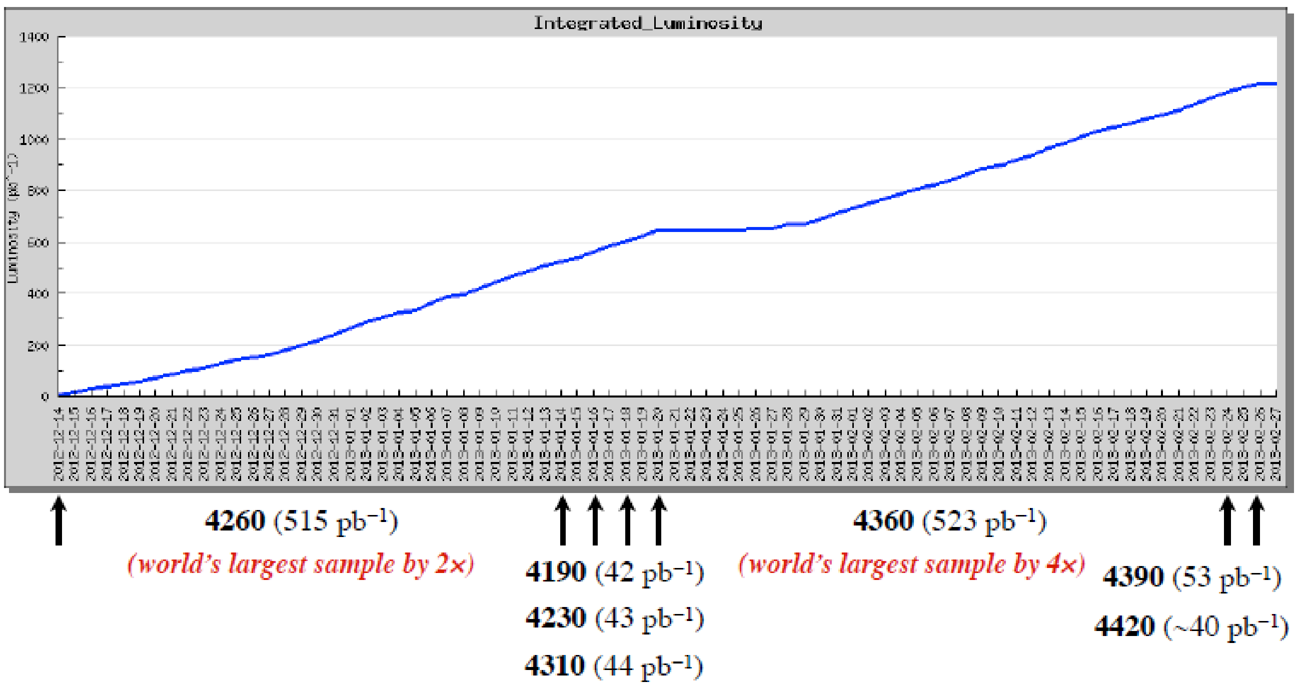
Resonance	Mass(MeV/c^2)	Width(MeV/c^2)	$\mathcal{B}(J/\psi \to \gamma X \to \gamma\eta\eta)$	Significance
$f_0(1500)$	1468^{+14+23}_{-15-74}	$136^{+41+28}_{-26-100}$	$(1.65^{+0.26+0.51}_{-0.31-1.40}) \times 10^{-5}$	$8.2\ \sigma$
$f_0(1710)$	$1759 \pm 6^{+14}_{-25}$	$172 \pm 10^{+32}_{-16}$	$(2.35^{+0.13+1.24}_{-0.11-0.74}) \times 10^{-4}$	$25.0\ \sigma$
$f_0(2100)$	$2081 \pm 13^{+24}_{-36}$	273^{+27+70}_{-24-23}	$(1.13^{+0.09+0.64}_{-0.10-0.28}) \times 10^{-4}$	$13.9\ \sigma$
$f_2'(1525)$	$1513 \pm 5^{+4}_{-10}$	75^{+12+16}_{-10-8}	$(3.42^{+0.43+1.37}_{-0.51-1.30}) \times 10^{-5}$	$11.0\ \sigma$
$f_2(1810)$	1822^{+29+66}_{-24-57}	$229^{+52+88}_{-42-155}$	$(5.40^{+0.60+3.42}_{-0.67-2.35}) \times 10^{-5}$	$6.4\ \sigma$
$f_2(2340)$	$2362^{+31+140}_{-30-63}$	$334^{+62+165}_{-54-100}$	$(5.60^{+0.62+2.37}_{-0.65-2.07}) \times 10^{-5}$	$7.6\ \sigma$

- Extra components [the major contribution to sys.err]
  - The interference caused by the small component can be large
  - For new observations, we quote the most conservative significance from the alternative fits
- Non-resonant contribution
- Dynamical functions (in this analysis, BW forms)
- Background treatment

Summary

- A lot of interesting results on hadron spectroscopy have been obtained at BESIII.
- BESIII took 1.2 billion J/ψ events and 0.5 billion ψ' events.

BESIII Data-taking



Look forward to many new results from BESIII!

And we are right now collecting 3× more Y(4260) decays...

Thank you