Review of Light Hadron Spectroscopy

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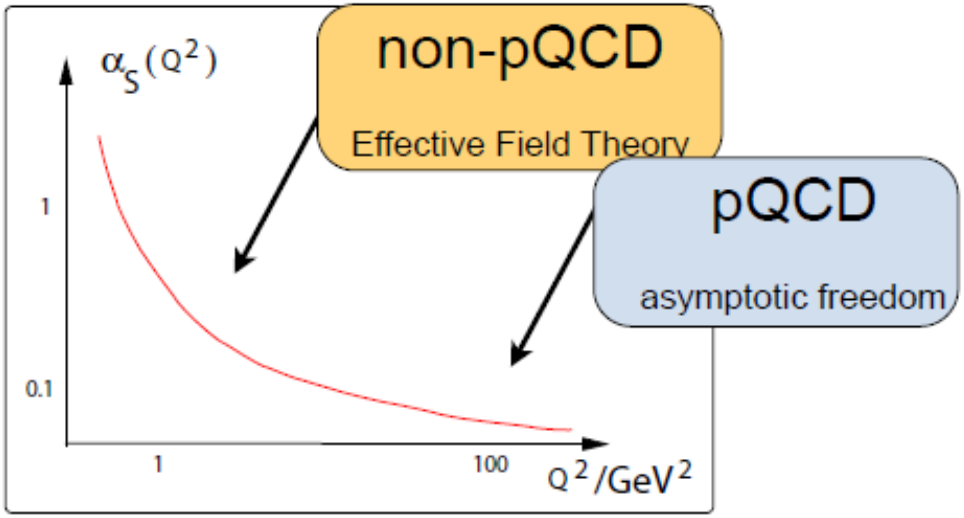
Workshop on Physics at Future High Intensity Collider@2-7 GeV in China
Jan. 14-16, 2015, Hefei

OUTLINE

- Why light hadron physics
- Current status and forefront issues
  - Meson spectroscopy
  - Exotics
  - Baryon spectroscopy
- Summary & Perspective

Why light hadron physics ?

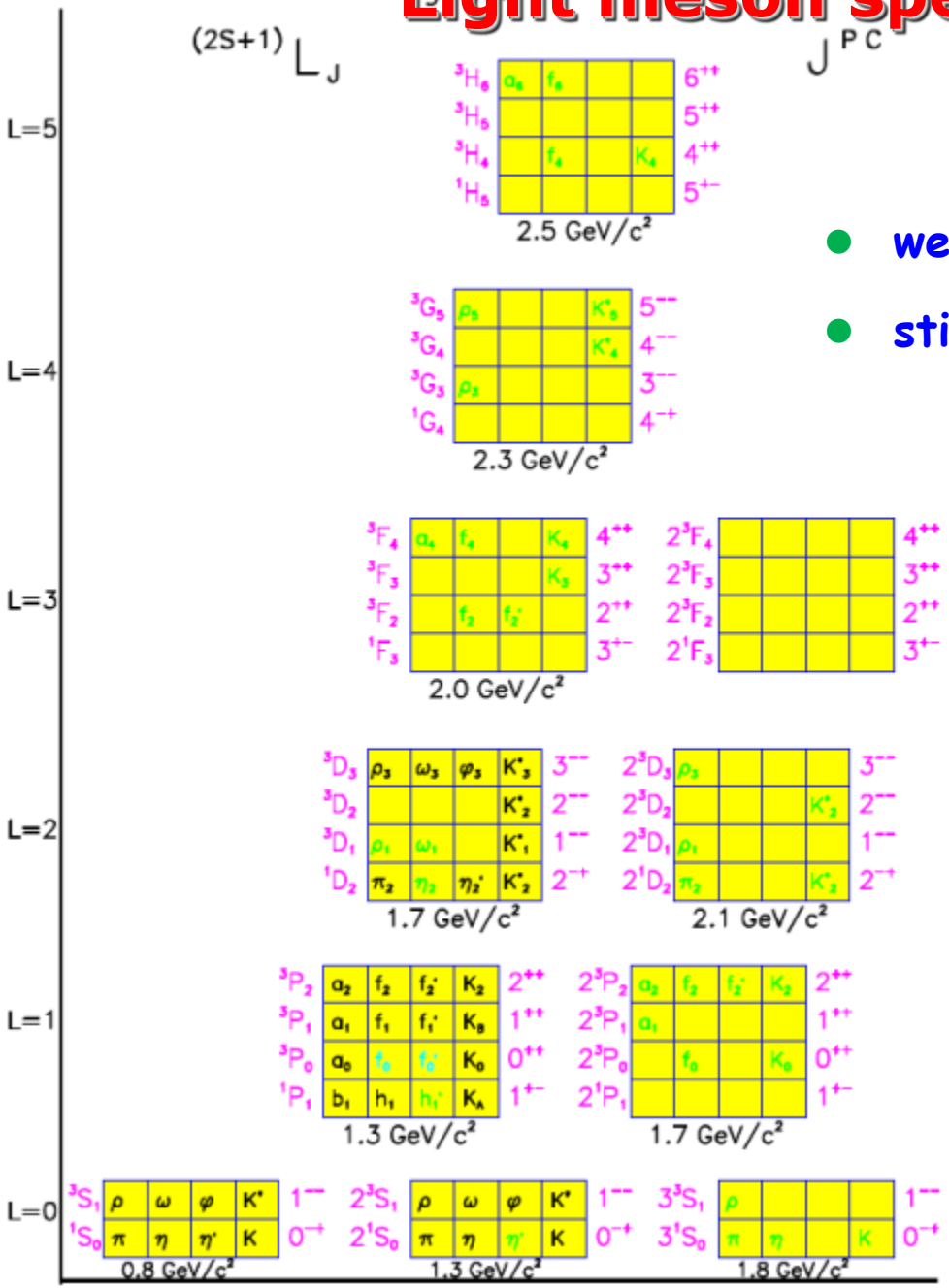


"That [intermediate distance] scale is the richest phenomenologically, and is certainly the crux region to understand...what QCD is really about. And at the heart of the subject is the hadron spectrum, in particular the spectrum built from light quarks. (...) **Without question, there is a great need... for a new round of experiments,...**"

James D. Bjorken (2000)

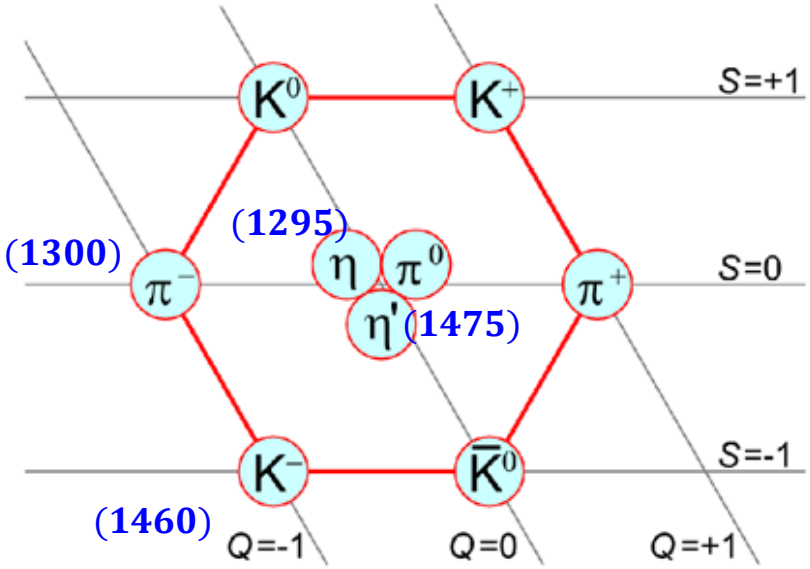
- ✓ QCD degrees of freedom at low energy
- ✓ Understanding of the quark and gluon confinement
- ✓ Particles beyond the QM

Light meson spectra from QM



- well established for several nonets
- still far from complete

Pseudoscalar nonets



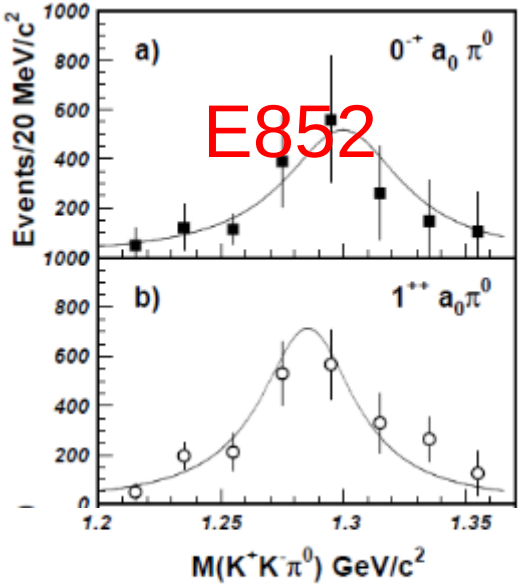
- Ground states: well described by QM
- Radial excited states (2^1S_0)
  - η(1295) and f_1(1285) ?
  - η(1475) and η(1405) , η(1760) ?

η(1295) & $f_1(1285)$

- η(1295)
  - only observed in πp interactions
  - its existence is questionable
  - Due to interference between $f_1(1285)$ and $\eta(\pi\pi)_{S\text{-wave}}$

E. Klempt and A. Zaitsev Phys. Reports 454,1(2007)

Resonance	M (MeV/c^2)	Γ (MeV/c^2)
$f_1(1285)$	$1288 \pm 4 \pm 5$	$45 \pm 9 \pm 7$
$\eta(1295)$	$1302 \pm 9 \pm 8$	$57 \pm 23 \pm 21$

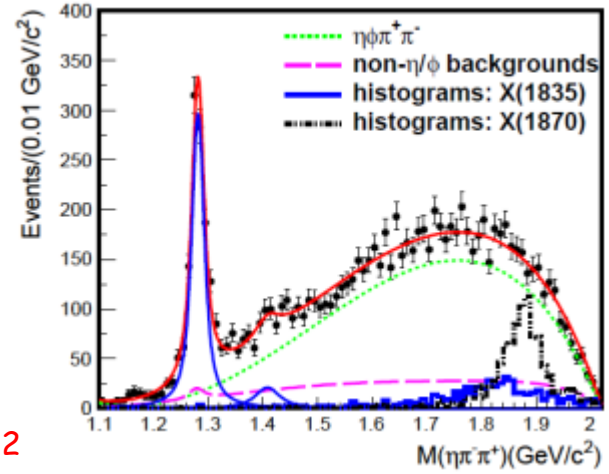


E852, PLB516,264(2001)

- More decays, e.g.,

J/ψ →{ω,ρ, γ}X

may shed light on η(1295)

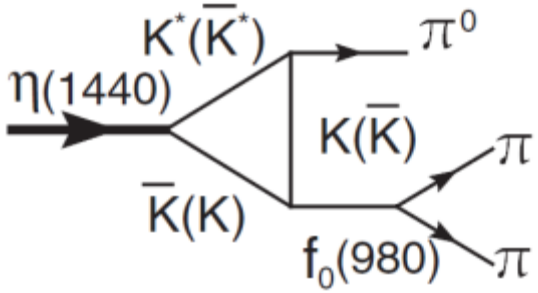


Γ =21.0±1.7 MeV
M=1281.7±0.6 MeV/c^2

BESIII, arXiv:1412.5258

η(1405) & η(1475)

- η(1440)
  - η(1405)→$a_0\pi$
  - η(1475)→K* $\bar{K}$
- One or two resonances?



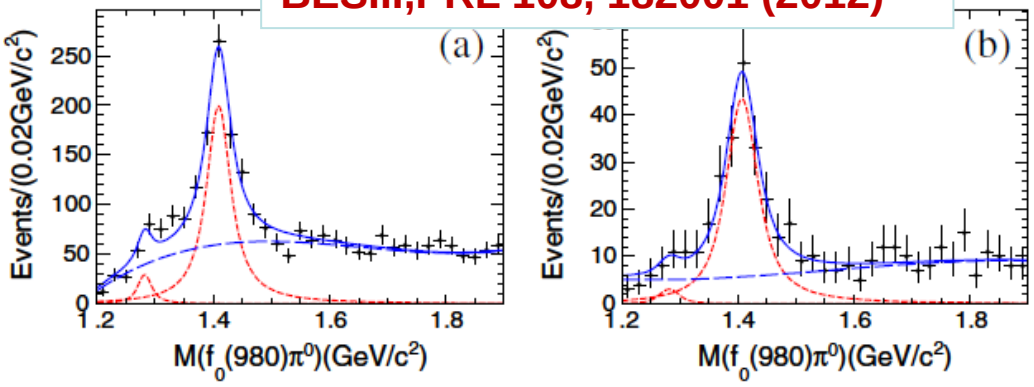
Triangle Singularity (TS)

one η(1440) is enough to describe the experimental data !

J.J.Wu et al, PRL 108, 081803(2012)

First observed: η(1405)→$f_0(980)\pi^0$

BESIII,PRL 108, 182001 (2012)



Resonance	$M(\mathrm{MeV}/c^2)$	$\Gamma(\mathrm{MeV}/c^2)$
$\eta(1405)(\pi^+\pi^-\pi^0)$	1409.0 ± 1.7	48.3 ± 5.2
$\eta(1405)(\pi^0\pi^0\pi^0)$	1407.0 ± 3.5	55.0 ± 11.0

$$\frac{BR(\eta(1405) \to f_0(980)\pi^0)}{BR(\eta(1405) \to a_0(980)\pi)} \approx 25\%$$

Large isospin breaking!

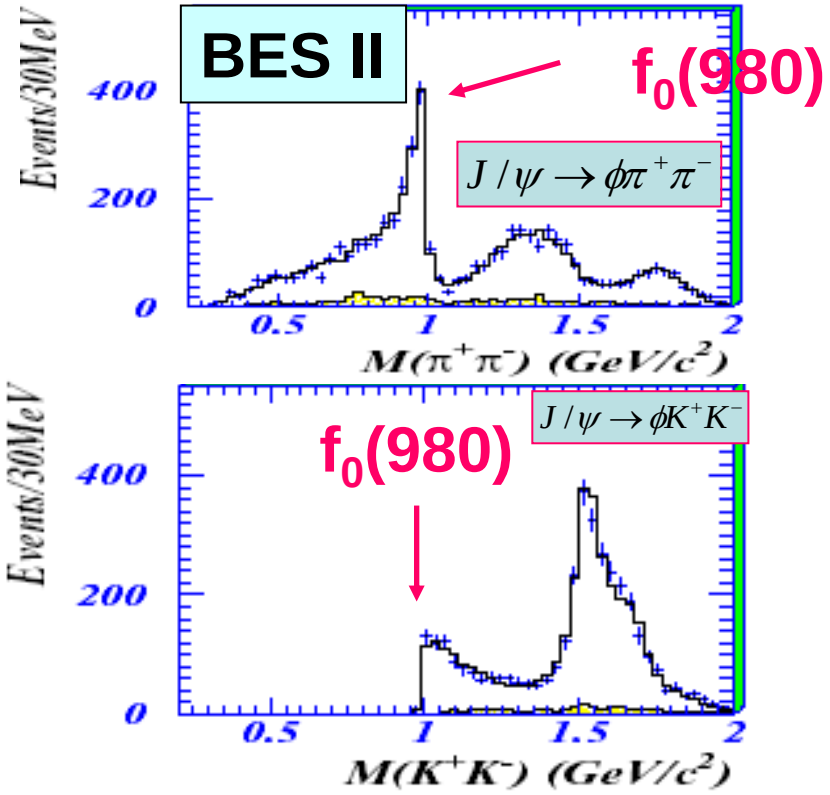
Light scalar meson

- Why light scalar mesons are interesting?
  - There have been hot debates on **the existence of σ and κ**
  - **σ, κ and $f_0(980)$ are also possible mutiquark states. They are all near threshold.**
  - Lattice QCD predicts the 0^{++} **scalar glueball mass ~ 1.6 GeV.** **$f_0(1500)$** and **$f_0(1710)$** are good candidates.

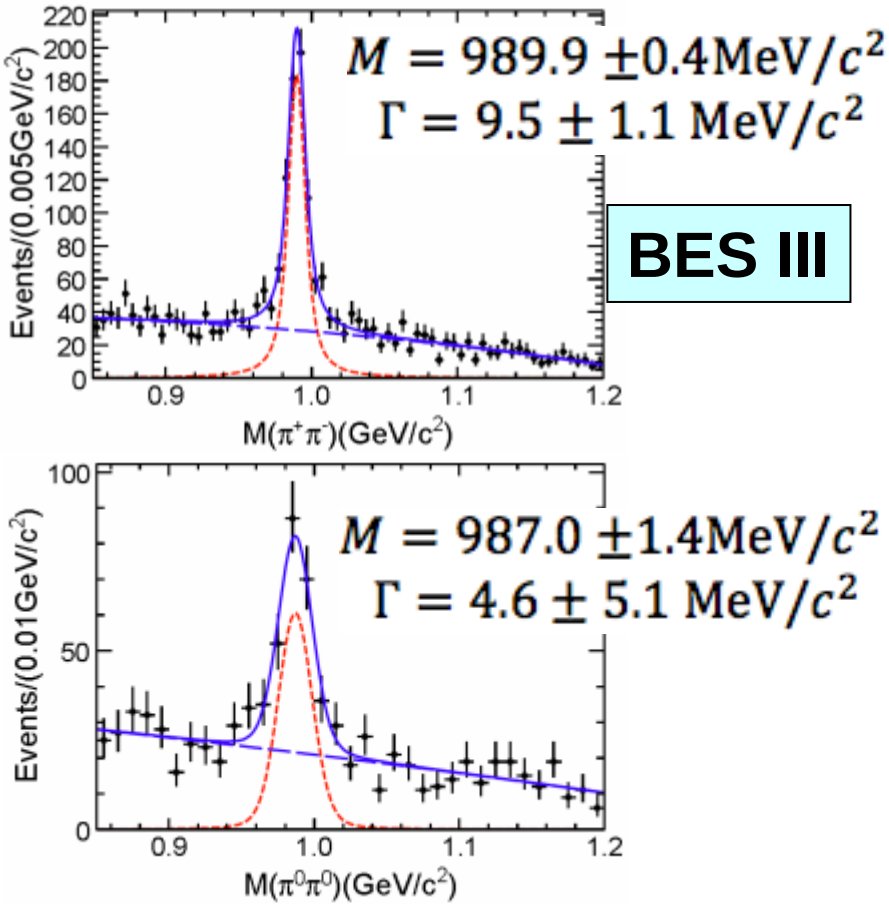
Name	Mass [MeV/c^2]	Width [MeV/c^2]	Decays
$f_0(600)$ *	$400-1200$	$600-1000$	$\pi\pi$, $\gamma\gamma$
$f_0(980)$ *	980 ± 10	$40-100$	$\pi\pi$, $K\bar{K}$, $\gamma\gamma$
$f_0(1370)$ *	$1200-1500$	$200-500$	$\pi\pi$, $\rho\rho$, $\sigma\sigma$, $\pi(1300)\pi$, $a_1\pi$, $\eta\eta$, $K\bar{K}$
$f_0(1500)$ *	1507 ± 5	109 ± 7	$\pi\pi$, $\sigma\sigma$, $\rho\rho$, $\pi(1300)\pi$, $a_1\pi$, $\eta\eta$, $\eta\eta'$ $K\bar{K}$, $\gamma\gamma$
$f_0(1710)$ *	1718 ± 6	137 ± 8	$\pi\pi$, $K\bar{K}$, $\eta\eta$, $\omega\omega$, $\gamma\gamma$
$f_0(1790)$			
$f_0(2020)$	1992 ± 16	442 ± 60	$\rho\pi\pi$, $\pi\pi$, $\rho\rho$, $\omega\omega$, $\eta\eta$
$f_0(2100)$	2103 ± 7	206 ± 15	$\eta\pi\pi$, $\pi\pi$, $\pi\pi\pi\pi$, $\eta\eta$, $\eta\eta'$
$f_0(2200)$	2189 ± 13	238 ± 50	$\pi\pi$, $K\bar{K}$, $\eta\eta$

$f_0(980)$

$\eta(1405) \to f_0(980)\pi$



PL B607 (2005) 243



- Large coupling with KK indicates big $s\bar{s}$ component in $f_0(980)$

$$M = 965 \pm 8 \pm 6 \ MeV$$
$$g_{\pi\pi} = 165 \pm 10 \pm 15 \ MeV$$
$$\frac{g_{KK}}{g_{\pi\pi}} = 4.21 \pm 0.25 \pm 0.21$$

Surprising result: very narrow width!

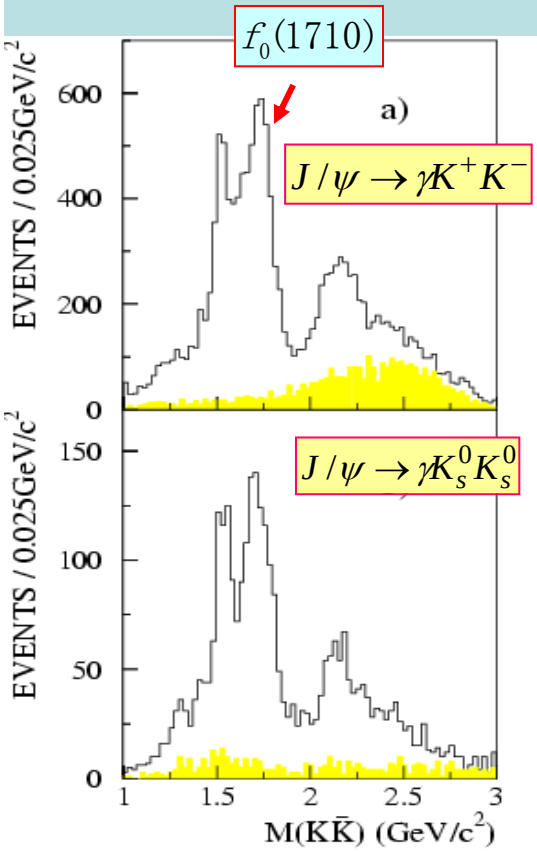
PRL 108, 182001 (2012)

Unusual properties of $f_0(1370)$, $f_0(1710)$ and $f_0(1790)$

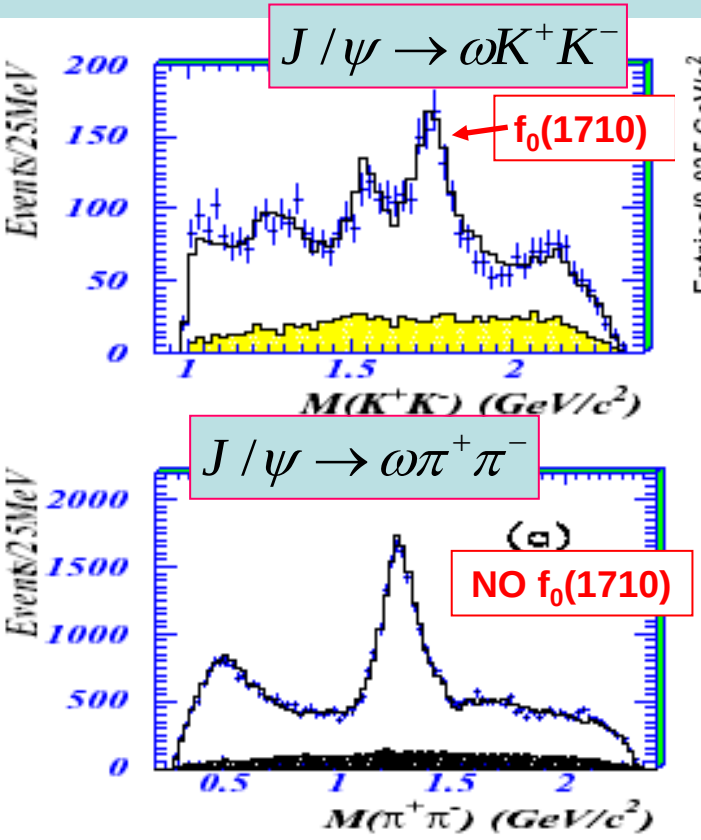
- **$f_0(1710)$:**
  - It dominantly decays to KK (not to $\pi\pi$) → $s\bar{s}$
  - It is mainly produced together with ω (not ϕ) → $u\bar{u} + d\bar{d}$
  - What is it ?
- **$f_0(1370)$ and $f_0(1790)$**
  - They dominantly decays to $\pi\pi$ (not to KK) → $s\bar{s}$
  - It is mainly produced together with ϕ (not ω) → $u\bar{u} + d\bar{d}$
  - What are they ?

→ Scalar Puzzle

$f_0(1710)$ at BESII

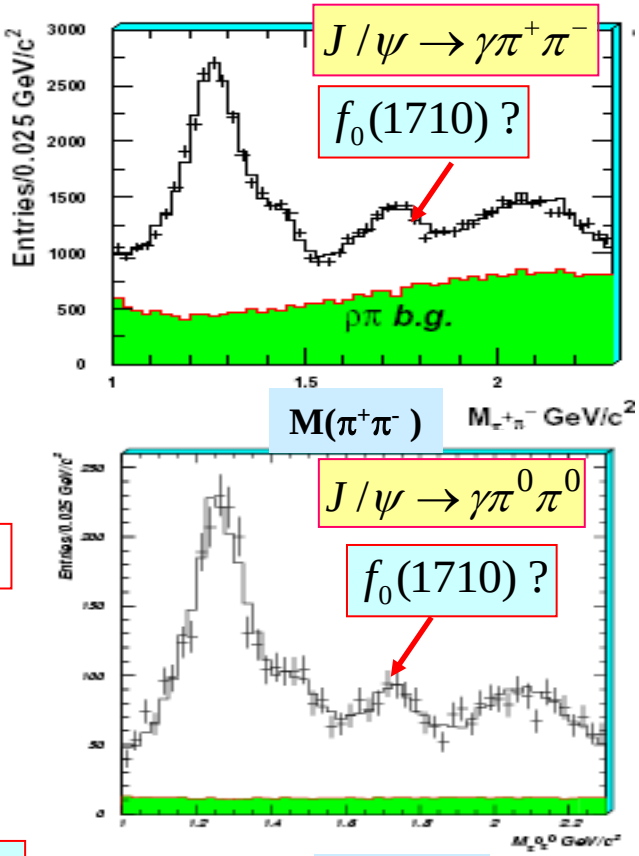


PRD 68 (2003) 052003



$$\frac{B(f_0(1710) \to \pi\pi)}{B(f_0(1710) \to K\bar{K})} < 0.13 \quad @\ 95\%CL$$

PL B603 (2004) 138



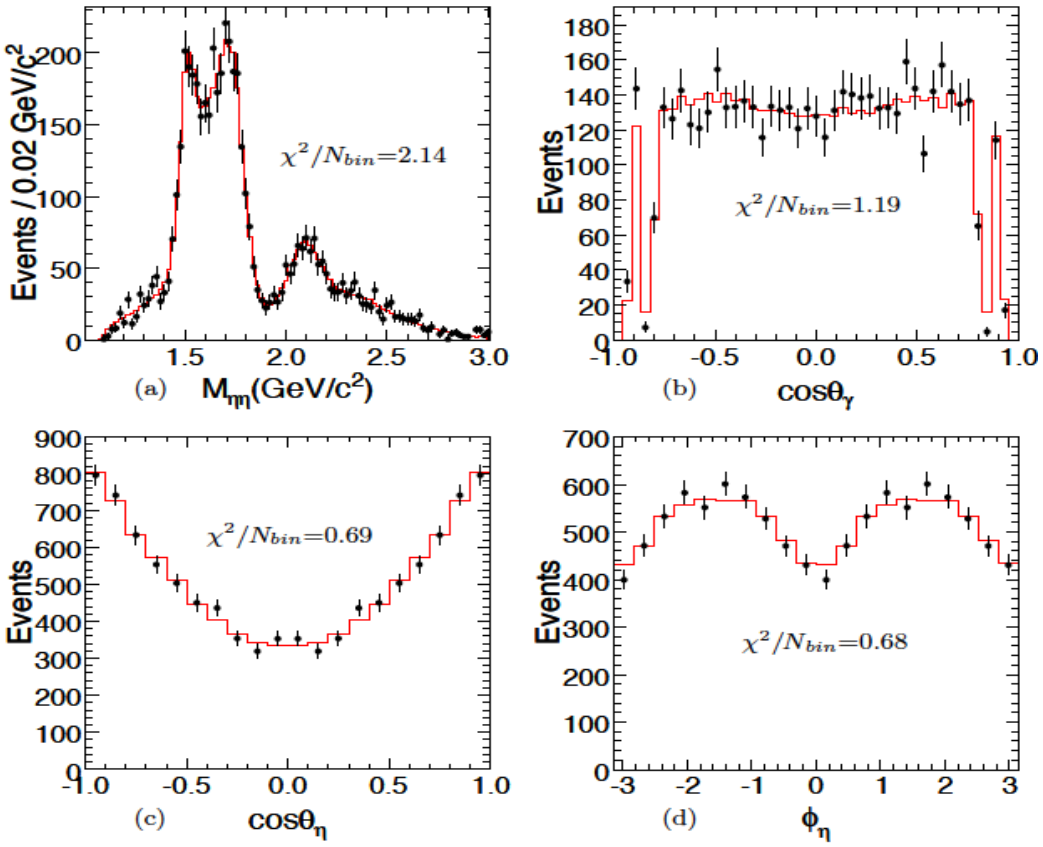
M($\pi^+\pi^-$)

M($\pi^0\pi^0$)

PL B642 (2006) 441

PWA of $J/\psi \to \gamma\eta\eta$

Phys. Rev. D. 87, 092009 (2013)

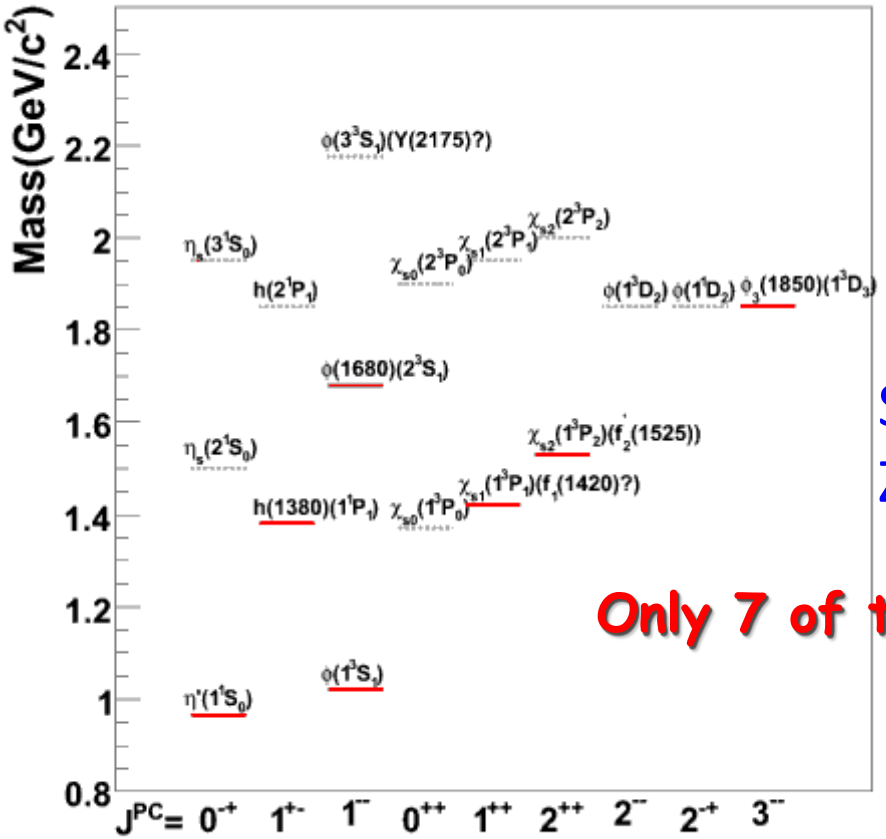


- $f_0(1710)$ and $f_0(2100)$ are dominant scalars
- $f_0(1500)$ exists (8.2σ)
- $f_2'(1525)$ is the dominant tensor
- $f_2(1810)$ and $f_2(2340)$ exist (6.4 and 7.6σ)
- No evidence for $f_J(2220)$

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

Strangeonia spectrum

- Like charmonia, a similar pattern for the strangeonia is expected
- Much less well understood, most of them have not been observed yet
- Strangeonia serve as a bridge between short and large distance behavior of QCD confinement potential



identified

not identified

S $\bar{S}$ System – what do we know?

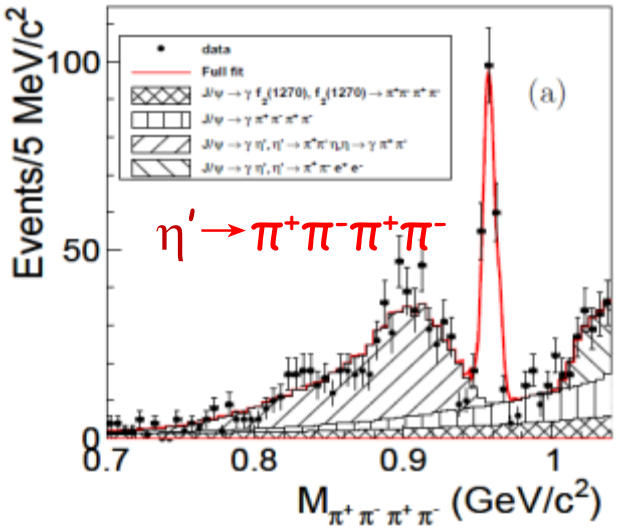
Zs states?

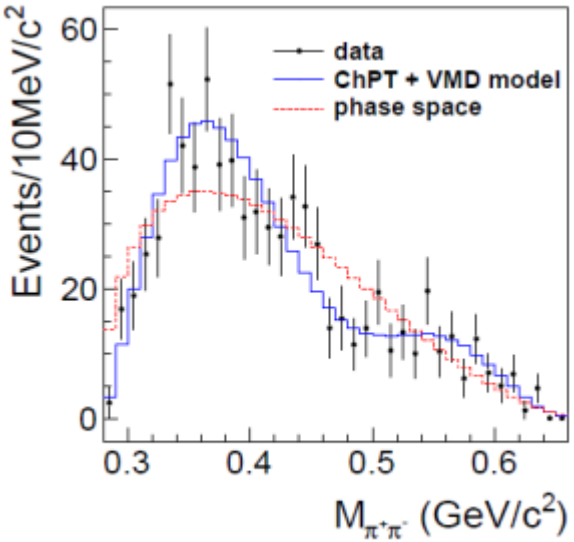
Only 7 of them have been identified !

Also listed in JLAB physics program

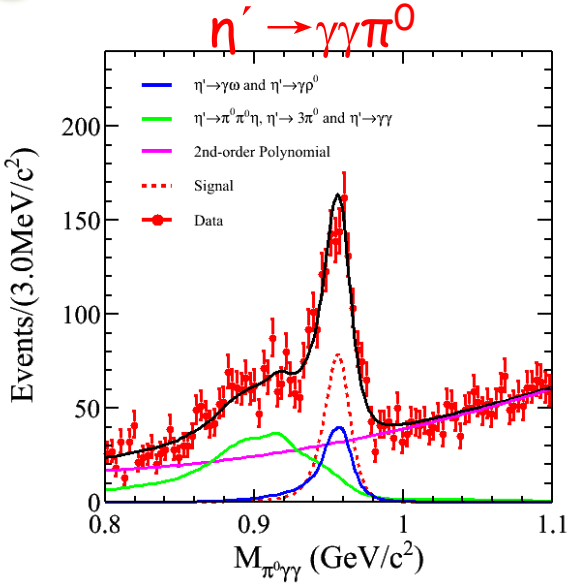
η and η′ physics

PRL112,251801(2014)

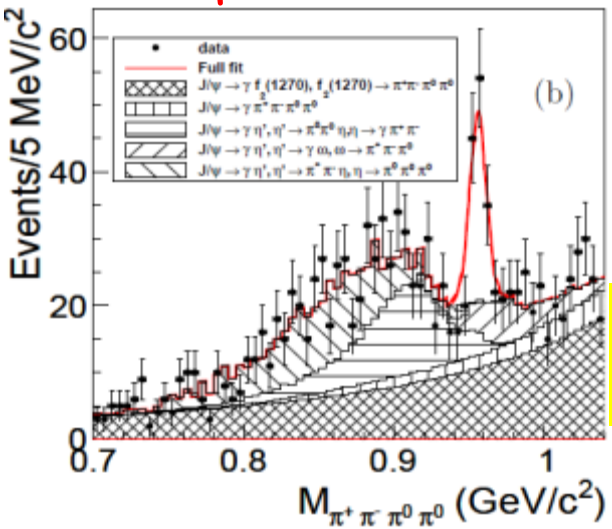




η′→γγπ⁰



η′→π⁺π⁻π⁰π⁰



B(η′→π⁺π⁻π⁺π⁻)=(8.63±0.69±0.64) ×10⁻⁵
B(η′→π⁺π⁻π⁰π⁰)=(1.82±0.35±0.18) ×10⁻⁴

B(η′→π⁺π⁻π⁺π⁻)=(1.0±0.3) ×10⁻⁴
B(η′→π⁺π⁻π⁰π⁰)=(2.4±0.7) ×10⁻⁴

ChPT+VMD

Phys. Rev. D 85,014014 (2012)

B(η′→γγπ⁰)=[6.91±0.51±0.54±0.20(PDG)] ×10⁻⁴ (preliminary)

B(η′→γγπ⁰): ~6×10⁻⁴

Nucl. Phys. Proc. Suppl. 207-208, 224 (2010)
R. Escribano, PoS QNP 2012, 079 (2012)

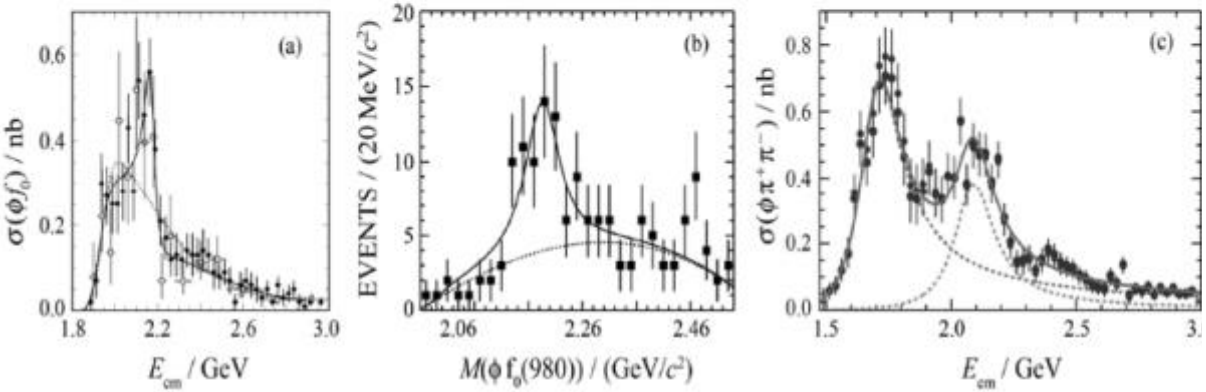
Y(2175)/ϕ(2170)

first observed by Babar
confirmed by Belle and BESII

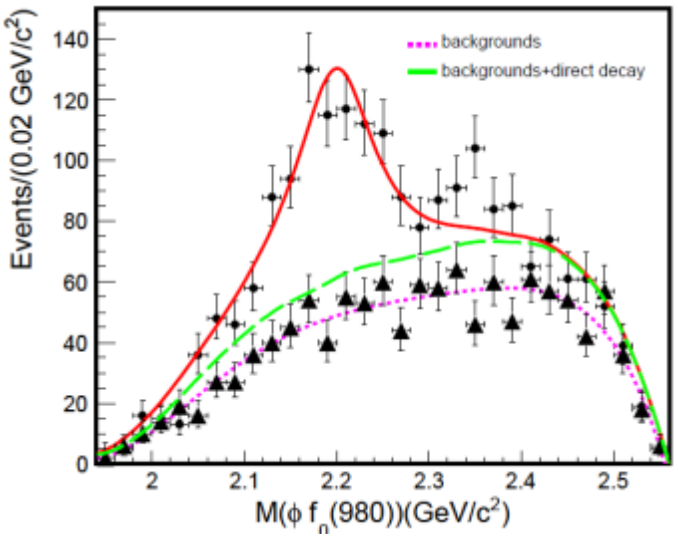
Phys Rev, D74 : 091103(2006)

Phys Rev, 2009, D80 : 031101

Phys. Rev Let t ,100:102003(2008)



BESIII, arXiv:1412.5258



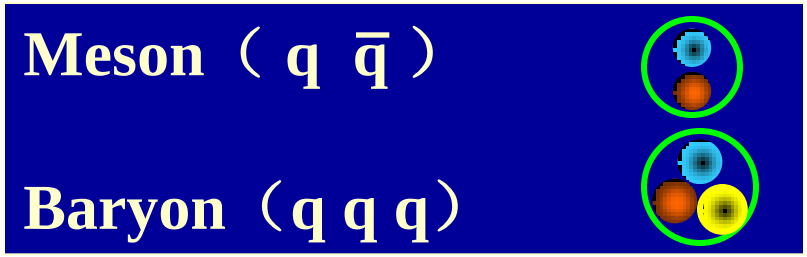
Collaboration	Process	M (MeV/c^2)	Γ (MeV)
BABAR [2]	$e^+e^- \to \phi f_0$ (ISR)	$2175 \pm 10 \pm 15$	$58 \pm 16 \pm 20$
BESII [3]	$J/\psi \to \eta\phi f_0(980)$	$2186 \pm 10 \pm 6$	$65 \pm 23 \pm 17$
BELLE [4]	$e^+e^- \to \phi f_0$ (ISR)	$2079 \pm 13^{+79}_{-28}$	$192 \pm 23^{+25}_{-61}$
BABAR(updated) [5]	$e^+e^- \to \phi f_0$ (ISR)	$2172 \pm 10 \pm 8$	$96 \pm 19 \pm 12$
BESIII	$J/\psi \to \eta\phi f_0(980)$	$2200 \pm 6 \pm 5$	$104 \pm 15 \pm 15$

- hybrids or strangeonium ?

New forms of hadrons

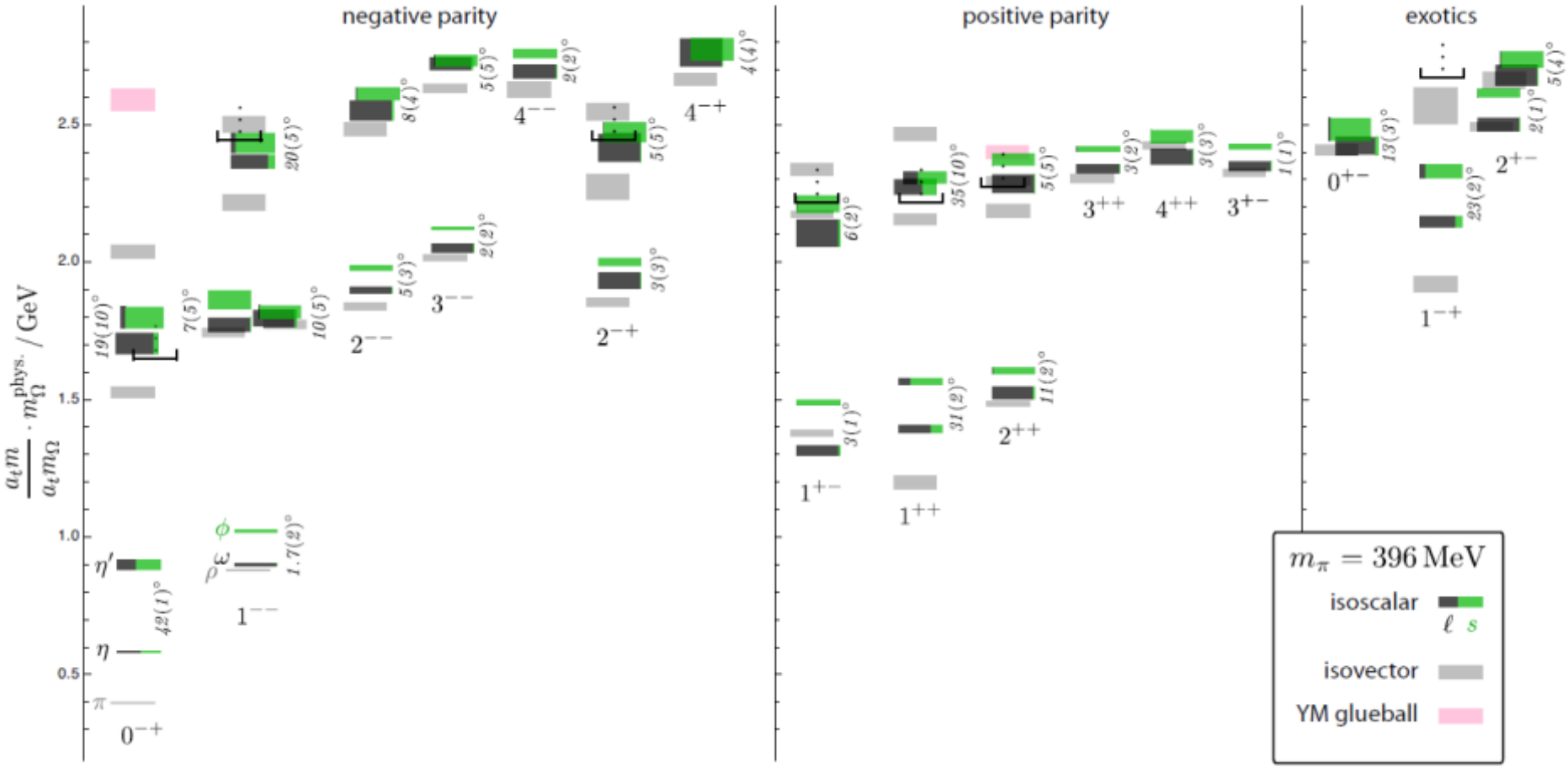
- Hadrons consist of 2 or 3 quarks:

Naive Quark Model:



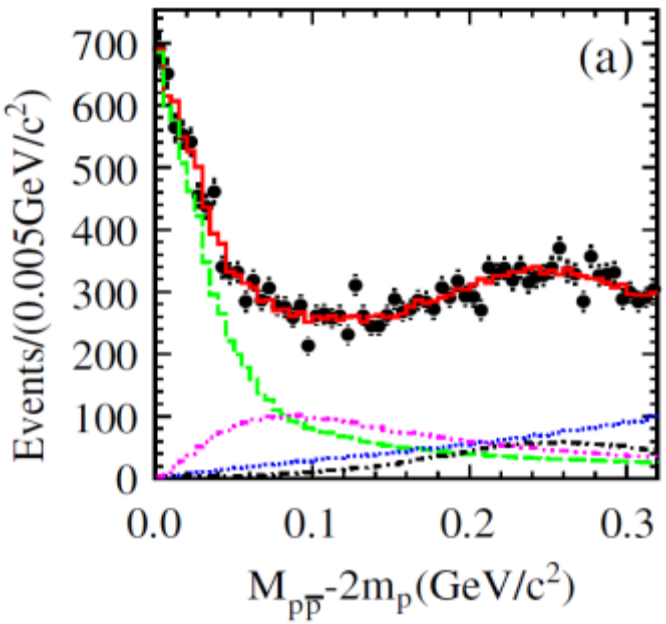
- QCD predicts the new forms of hadrons:
  - Multi-quark states : Number of quarks >= 4
  - Hybrids : $q\bar{q}g$, $qqqg$ …
  - Glueballs : gg, ggg …
  - Exotics: ($J^{PC}=0^{--},0^{+-},1^{-+},2^{+-},3^{-+},\ldots$)

Meson spectroscopy in LQCD



PWA of J/ψ→γp $\bar{p}$

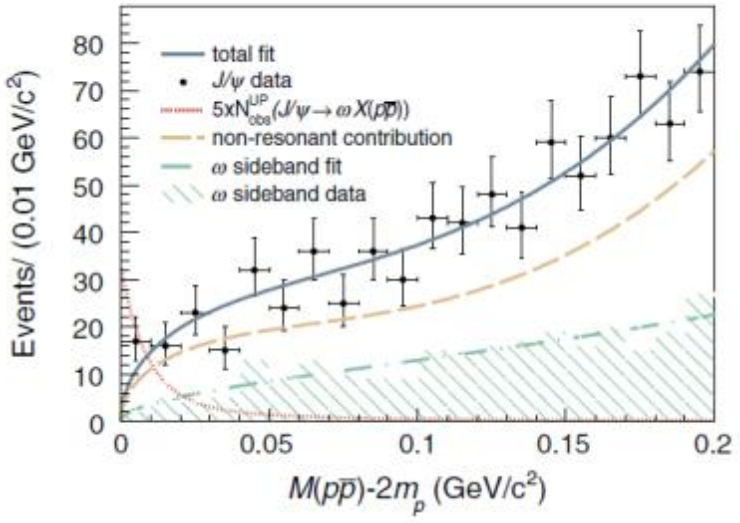
- PWA of J/ψ→γp $\bar{p}$ was first performed
- The fit with a BW and S-wave FSI(I=0) factor can well describe p $\bar{p}$ mass threshold structure.
- It is much better than that without FSI effect, and Δ2lnL=51 (7.1σ)



PRL 108,112003(2012)

- **Spin-parity of X(ppbar): $J^{PC}=0^{-+}$**

>6.8σ better than other J^{pc} assignments

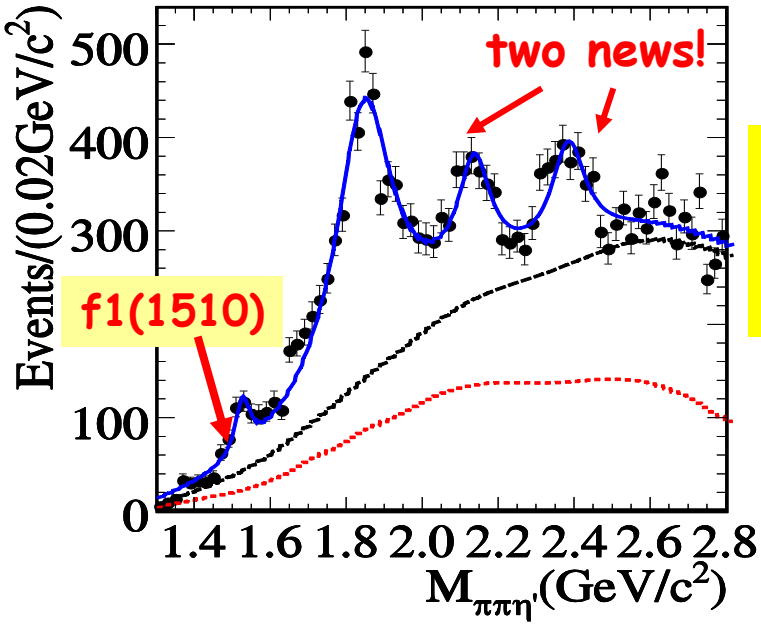


No similar structure was observed in J/ψ→ωp $\bar{p}$

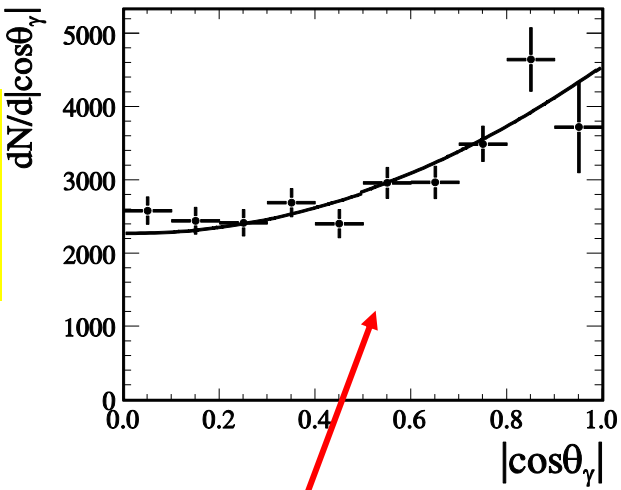
PRD 87, 112004(2013)

Confirmation of X(1835) and two new structures

PRL 106, 072002(2011)



$J/\psi \to \gamma\eta'\pi^+\pi^-$
$\eta' \to \eta\pi^+\pi^-$
$\eta' \to \gamma\rho$



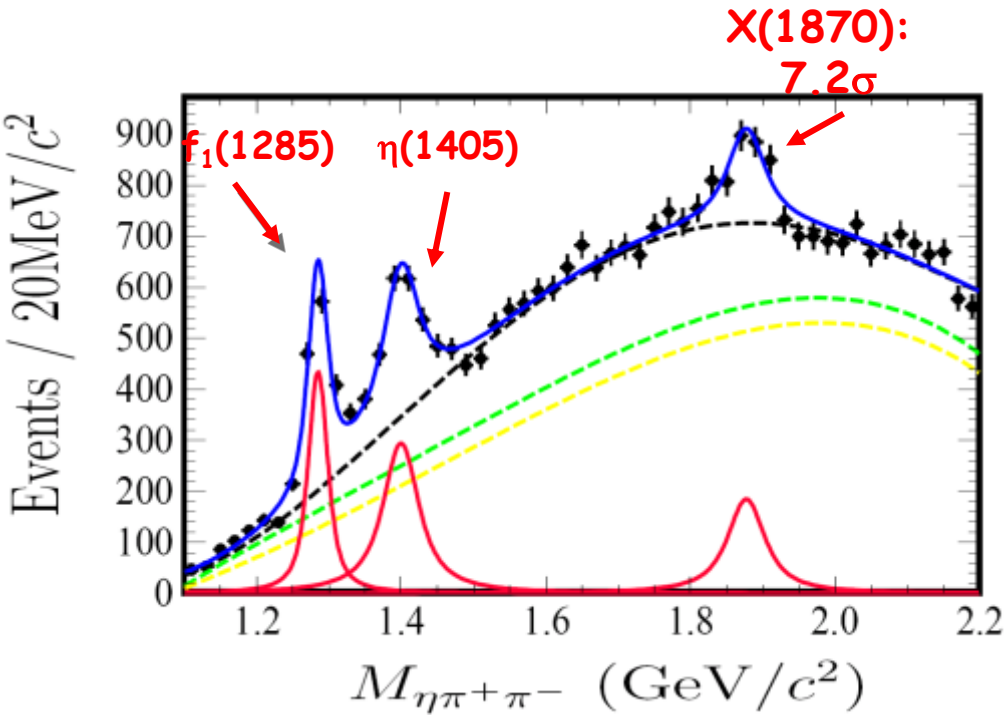
X(1835) consistent with 0^-

BESIII fit results:

Resonance	M(MeV/c^2)	Γ(MeV/c^2)	Stat.Sig.
X(1835)	$1836.5 \pm 3.0^{+5.6}_{-2.1}$	$190.1 \pm 9.0^{+38}_{-36}$	>20σ
X(2120)	$2122.4 \pm 6.7^{+4.7}_{-2.7}$	$83 \pm 16^{+31}_{-11}$	7.2σ
X(2370)	$2376.3 \pm 8.7^{+3.2}_{-4.3}$	$83 \pm 17^{+44}_{-6}$	6.4σ

✓Nature of X(2120)/X(2370): pseudoscalar glueball ? η/η' excited states?

X(1870) in $J/\psi \to \omega\eta\pi^+\pi^-$

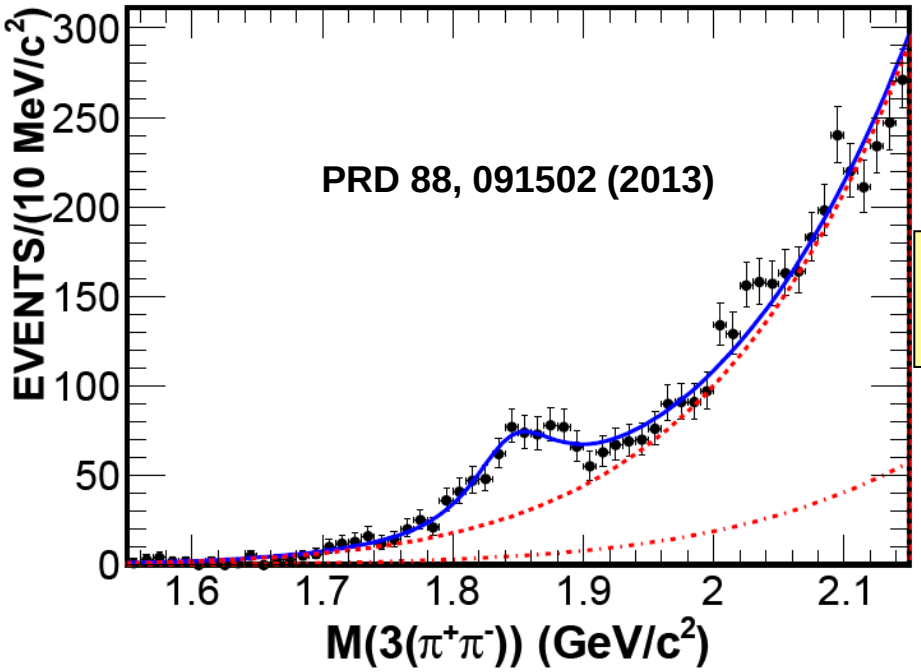


PRL 107, 182001(2011)

Identification of X(1870): 0^{-+}(?)
It is X(1835)?

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

Observation of X(1840) in $J/\psi \to \gamma 3(\pi^+\pi^-)$

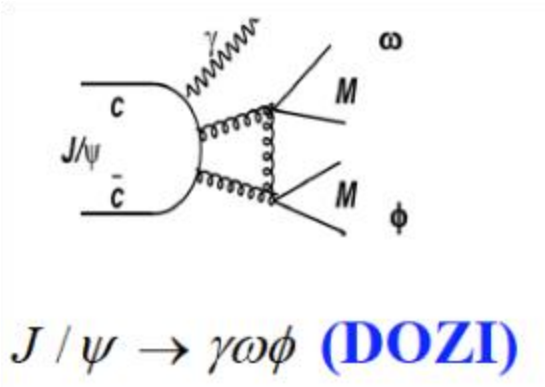


$M=1842.2\pm4.2\ ^{+7.1}_{-2.6}\ MeV/c^2$
$\Gamma = 83\pm14\pm11 MeV$

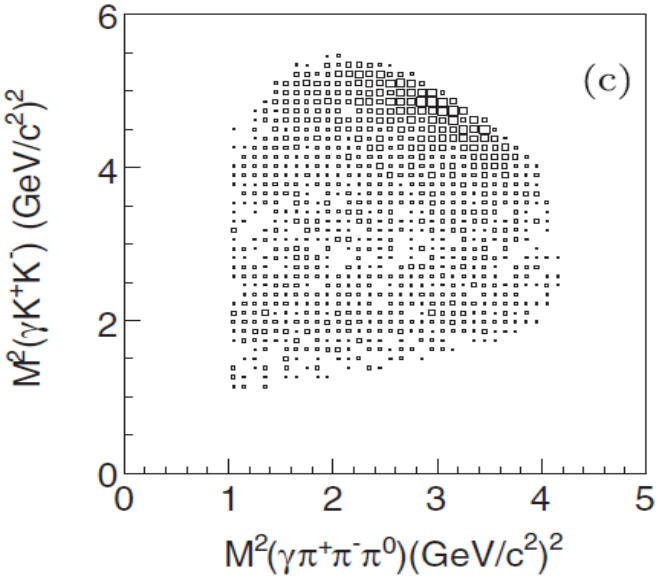
- Mass is consistent with that of X(1835), but the width is much smaller than $\Gamma_{x(1835)} = 190.1\pm9.0^{+38}_{-36}$ MeV
- A new decay modes of X(1835)?

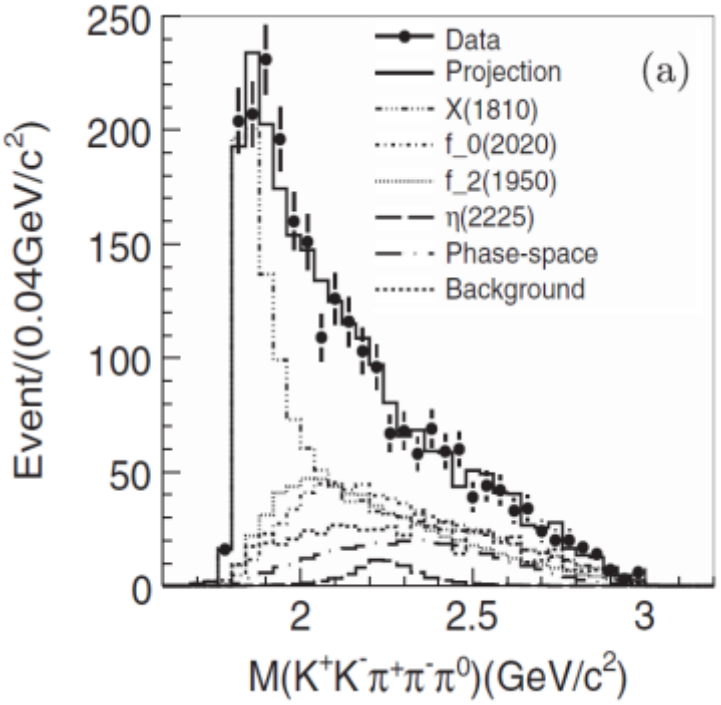
PWA of J/ψ→γωϕ

PRD 87, 032008(2013)



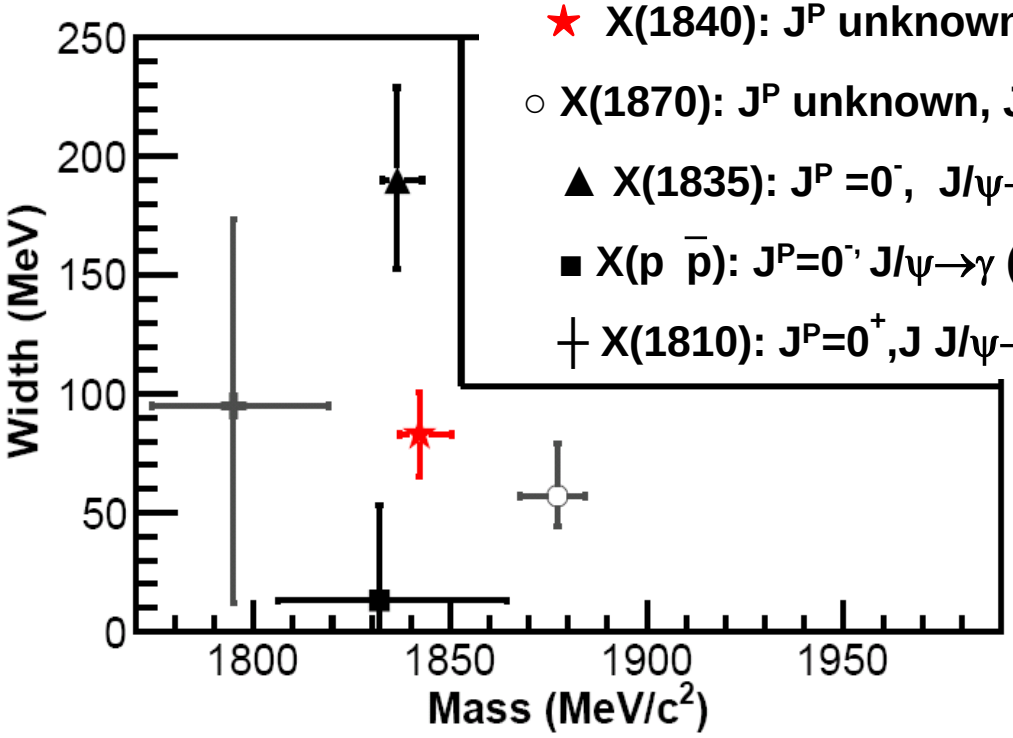
$J/\psi \to \gamma\omega\phi$ (DOZI)





- **Confirmed the enhancement observed at BESII**
- **M= $1795 \pm 7^{+13}_{-5} \pm 19$(model) MeV/c2,**
  Γ =$95 \pm 10^{+21}_{-34} \pm 75$(model) MeV
- **Spin-parity is determined to be 0^+**
- **the same as $f_0(1710)/f_0(1790)$, or a new state ?**

Comparisons of the observations at BES



★ X(1840): J^P unknown,J/ψ→γ 3(π+ π-) PRD88,091502

○ X(1870): J^P unknown, J/ψ→ ω (ηππ) PRL107, 182001

▲ X(1835): $J^P = 0^-$, J/ψ→γ (η'ππ) PRL106, 072002

■ X(p $\bar{p}$): $J^P = 0^-$, J/ψ→γ (p $\bar{p}$) PRL108,112003

┼ X(1810): $J^P = 0^+$,J J/ψ→γ (ωϕ) PRD 87, 032008

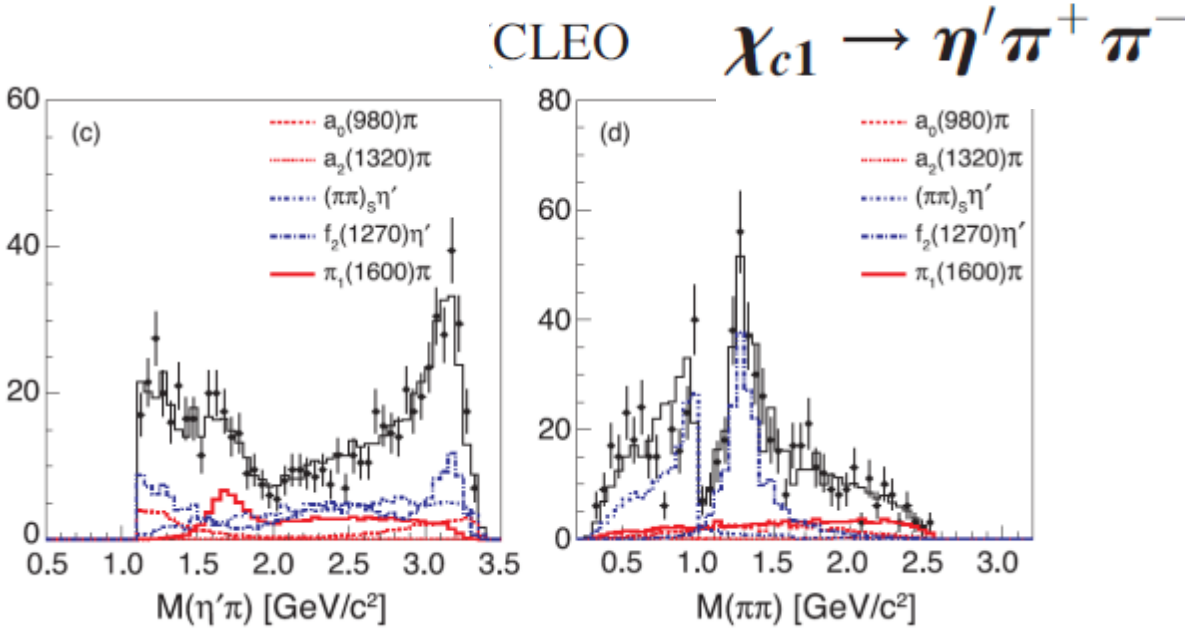
X(18??) near the threshold position of proton-antiproton

Are they the same particle? It is crucial to identify these observations.

Exotics ($J^{PC}=0^{--},0^{+-},1^{-+},2^{+-},3^{-+},\ldots$)

- J^{PC} exotic particles: beyond the naive quark model
- easily to distinguish from others due to the exotic J^{PC}
- production rate and dynamics are not well understood
- candidates?

  - $\pi_1(1400)$
  - $\pi_1(1600)$



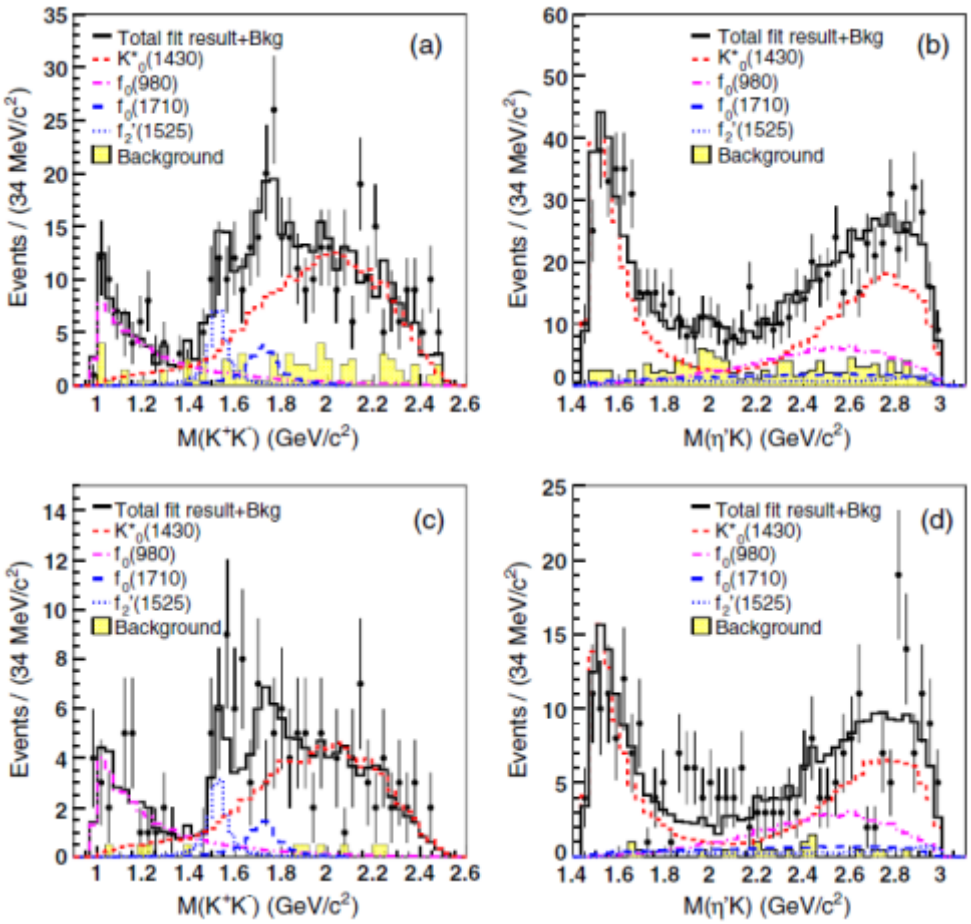
PRD84 (2011) 112009

Evidence of an exotic η′π amplitude [$\pi_1(1600)$?] was seen

χ_{cJ}: an important source for light hadron physics!

$\chi_{c1} \to K^+K^-\eta'$

106M Ψ'

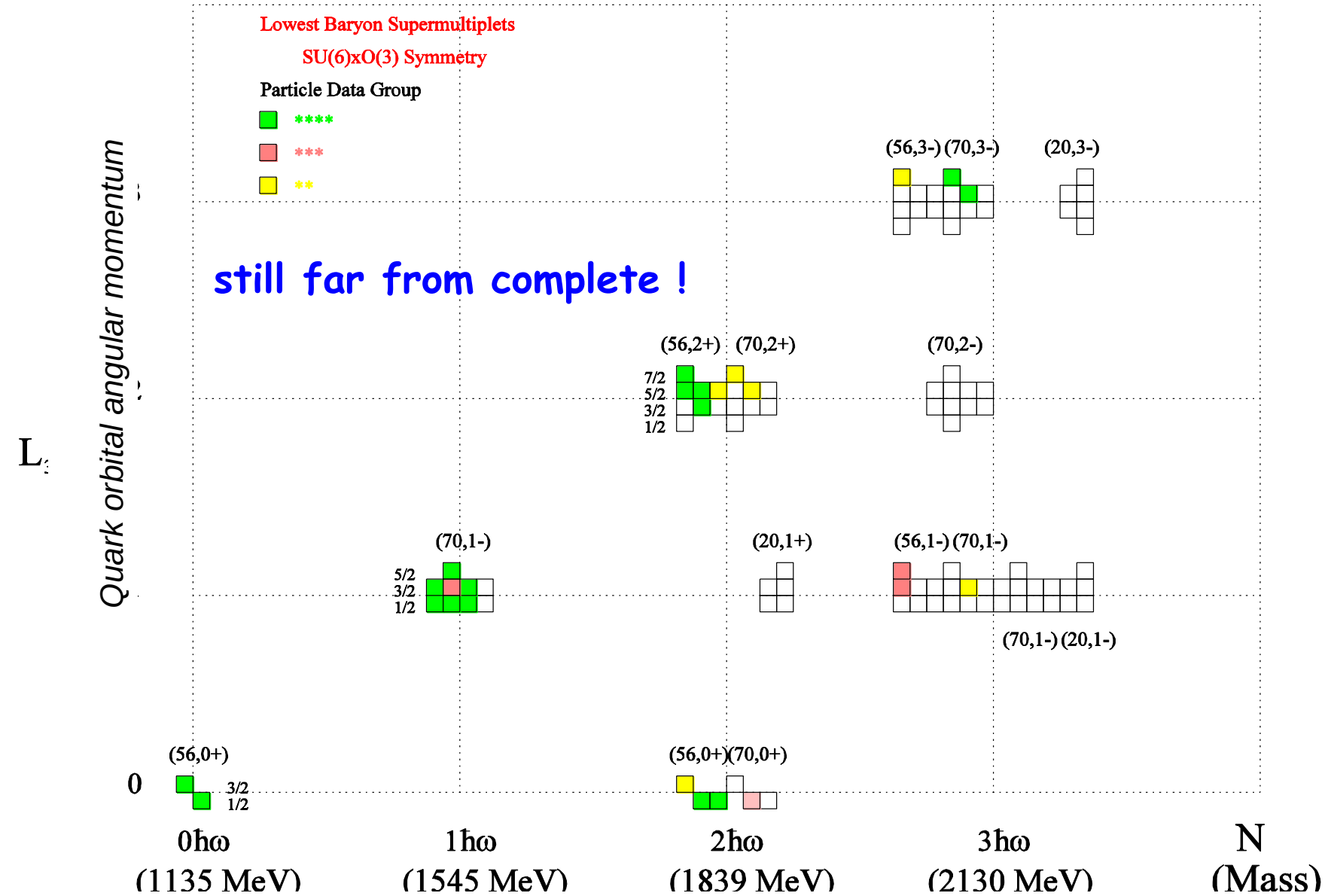


BESIII: Phys. Rev. D89,074030(2014)

Baryon spectroscopy

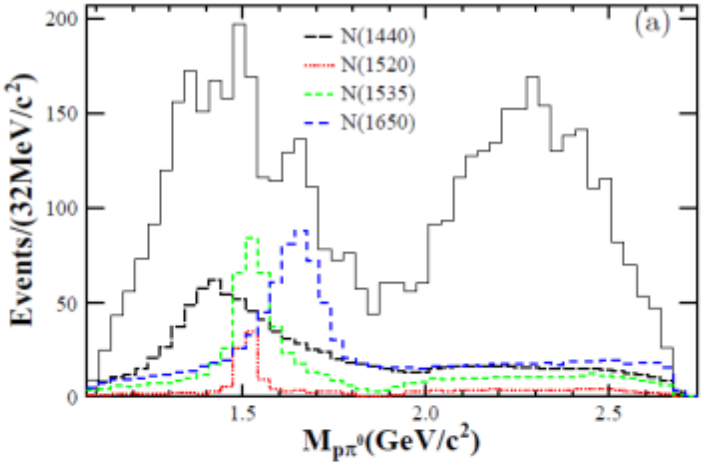
- **The established baryons are described to 3-quark (qqq) configurations**
- Non-relativistic quark model is successful in interpreting of the excited baryons
- **Also provides an explicit classification for light baryons in terms of group symmetry**
- Predicts more excited stated ("missing resonance problem")

SU(6)xO(3) Classification of Baryons



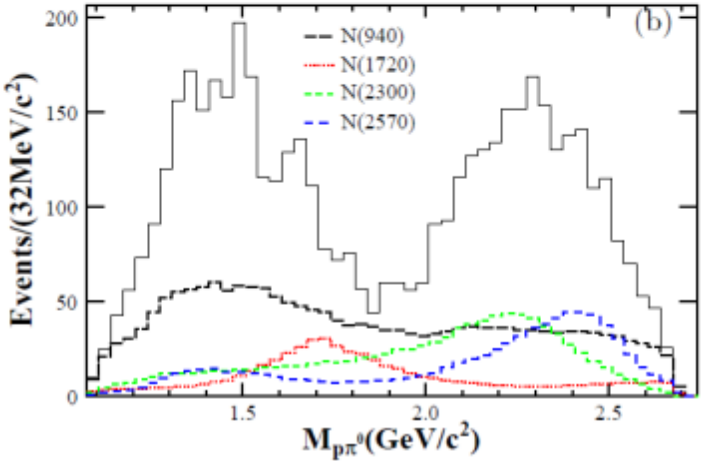
PWA results on N* baryons in $\psi' \to \pi^0 p \bar{p}$

Phys.Rev.Lett. 110 (2013) 022001



- 2-body decay:
  $\psi(2S) \to X\pi^0, X \to p\bar{p}$
  $\psi(2S) \to p\bar{N}^*, \bar{N}^* \to \bar{p}\pi^0$ + c.c.
- isospin conservation:
  Δ suppressed

Two new baryonic excited states are observed !

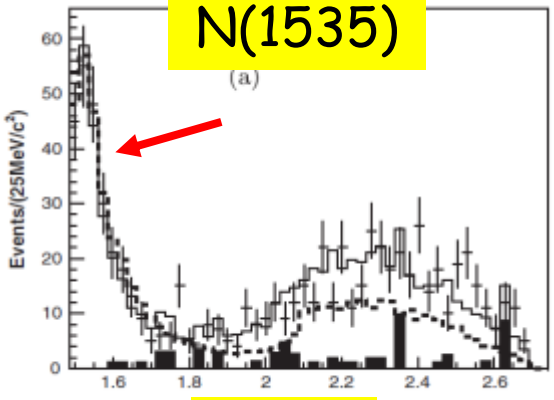


Resonance	M(MeV/c^2)	Γ(MeV/c^2)	ΔS	ΔN_{dof}	C.L.
$N(1440)$	1390^{+11+21}_{-21-30}	$340^{+46+70}_{-40-156}$	72.5	4	11.5σ
$N(1520)$	1510^{+3+11}_{-7-9}	115^{+20+0}_{-15-40}	19.8	6	5.0σ
$N(1535)$	1535^{+9+15}_{-8-22}	120^{+20+0}_{-20-42}	49.4	4	9.3σ
$N(1650)$	1650^{+5+11}_{-5-30}	150^{+21+14}_{-22-50}	82.1	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

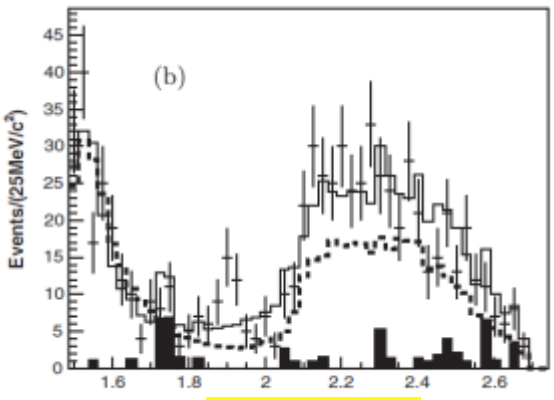
N(1535) in $\psi' \to \eta p \bar{p}$

PRD 88, 032010(2013)

N(1535)



M(pη)



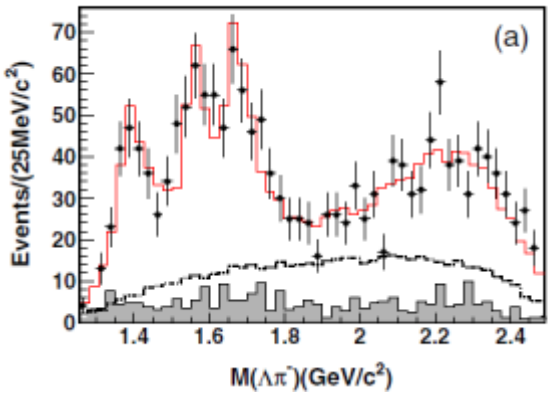
M($\bar{p}\eta$)

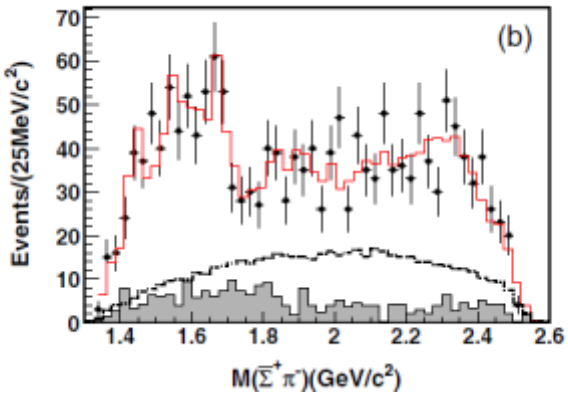
Mass: $1524 \pm 5^{+10}_{-4}$ MeV/c^2

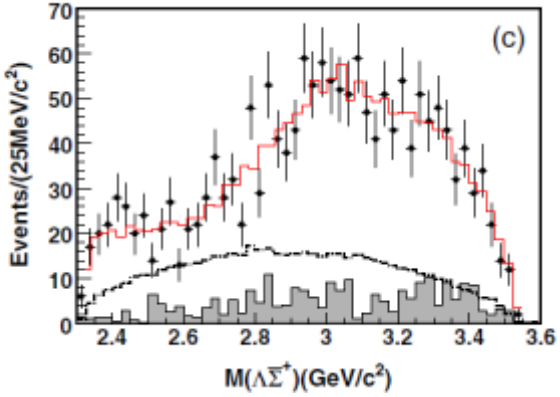
Width: 130^{+27+57}_{-24-10} MeV/c^2

PRD 88, 112007 (2013)

$$\psi(3686) \to \Lambda \bar{\Sigma}^+ \pi^-$$

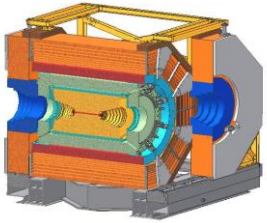




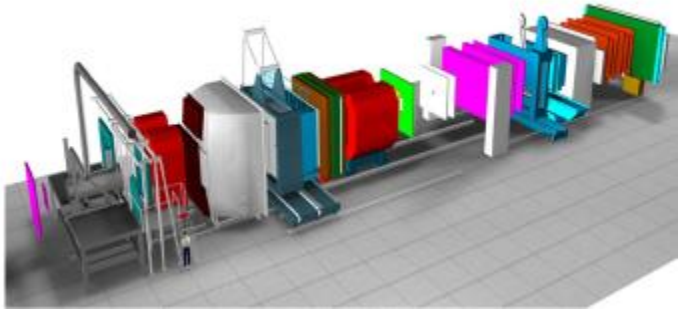


- **Clear structures were observed**

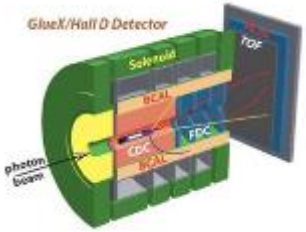
Current facilities



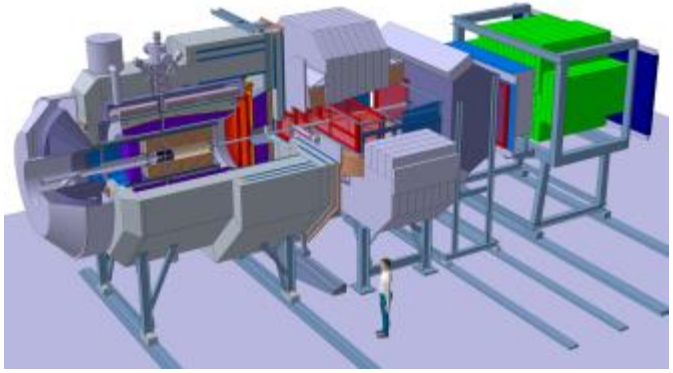
BESIII



COMPASS



GlueX

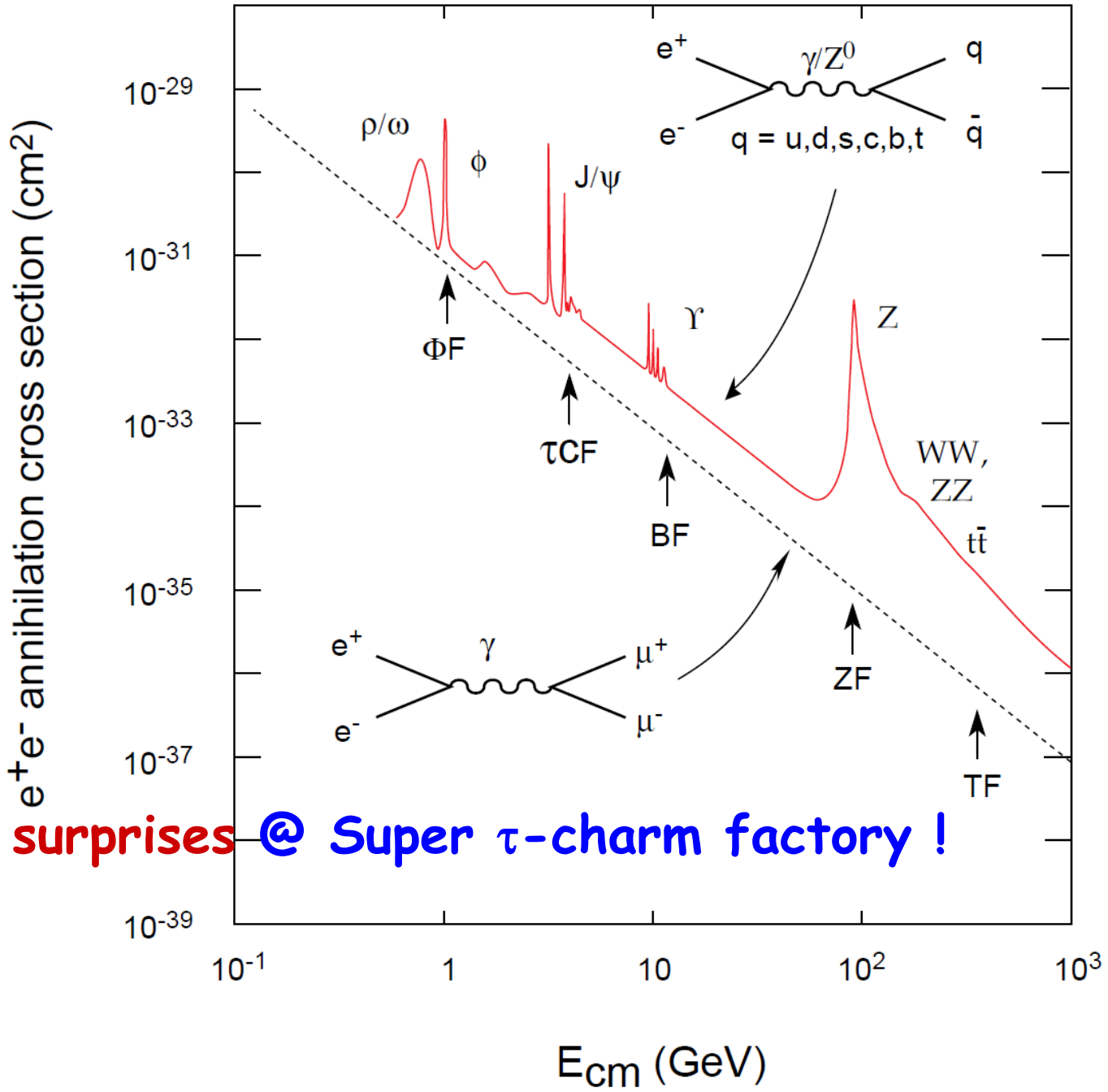


PANDA

Summary

- Rich physics in light hadrons
  - search for exotics → QCD
  - study of strangeonia → Quark model
  - light meson decays → test of ChPT
  - Search for missing baryons→ QCD, Quark model

  ……
- Mapping out the light hadron spectroscopy is crucial
- 1.3 billion J/Ψ and 0.5 billion Ψ' @ BESIII
- BESIII plays an important role in light hadron physics



More surprises @ Super τ-charm factory !

Thank you !