Highlights of light hadron spectroscopy

Beijiang Liu

Celebration of the 500 Publications of BESIII, IHEP, 2023

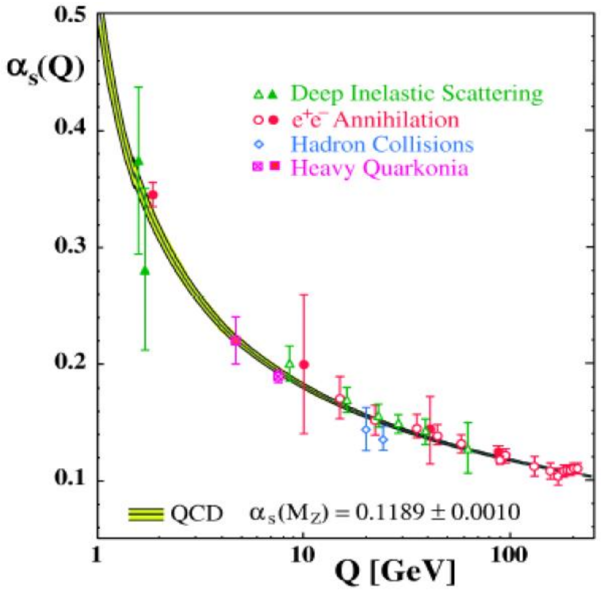
Introduction

- Hadrons, the complex building blocks of our world, emerge from interaction of quarks and gluons as described by QCD

- NPQCD: How does QCD give rise to hadrons?
  - What is the origin of confinement?
  - How is the mass generated in QCD?

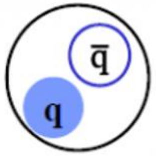
- Best discovery path : hadron spectroscopy

Asymptotic Freedom
PQCD

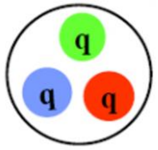


Confinement & NPQCD
“World of Hadrons”

Quark model

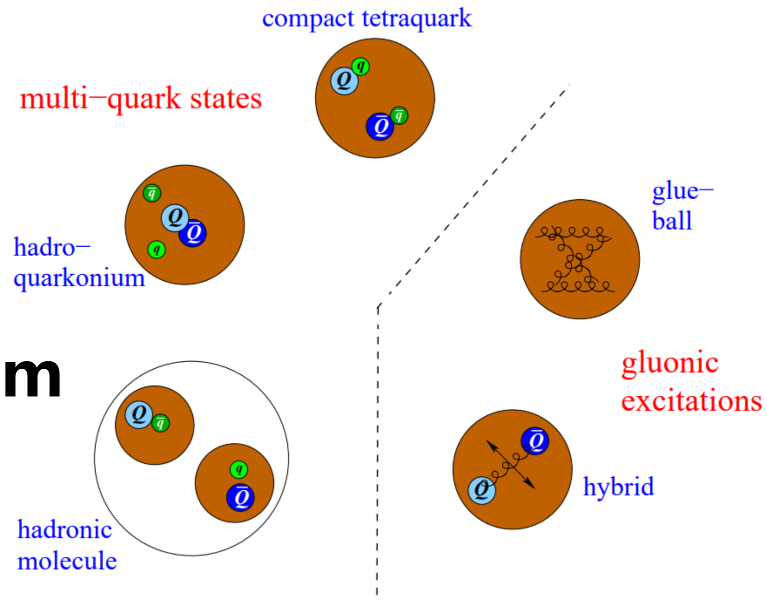


meson



baryons

configurations beyond QM



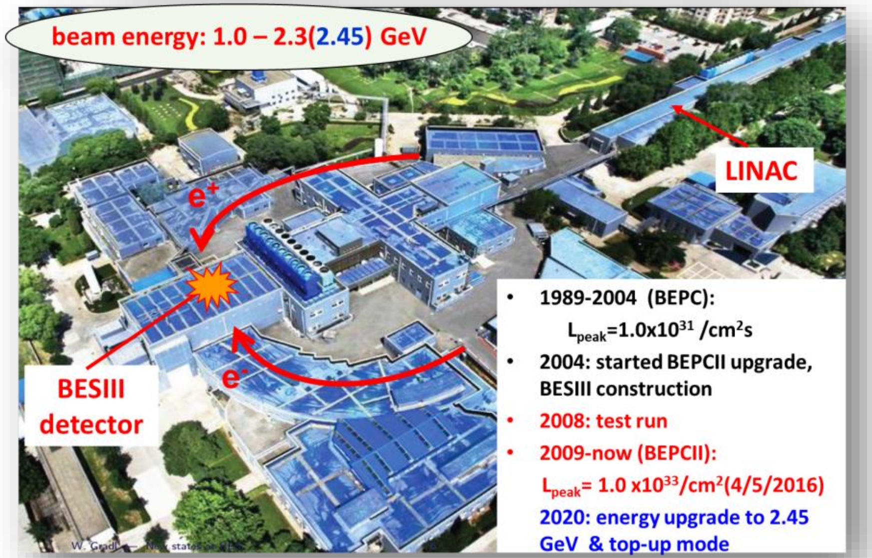
Light QCD exotics

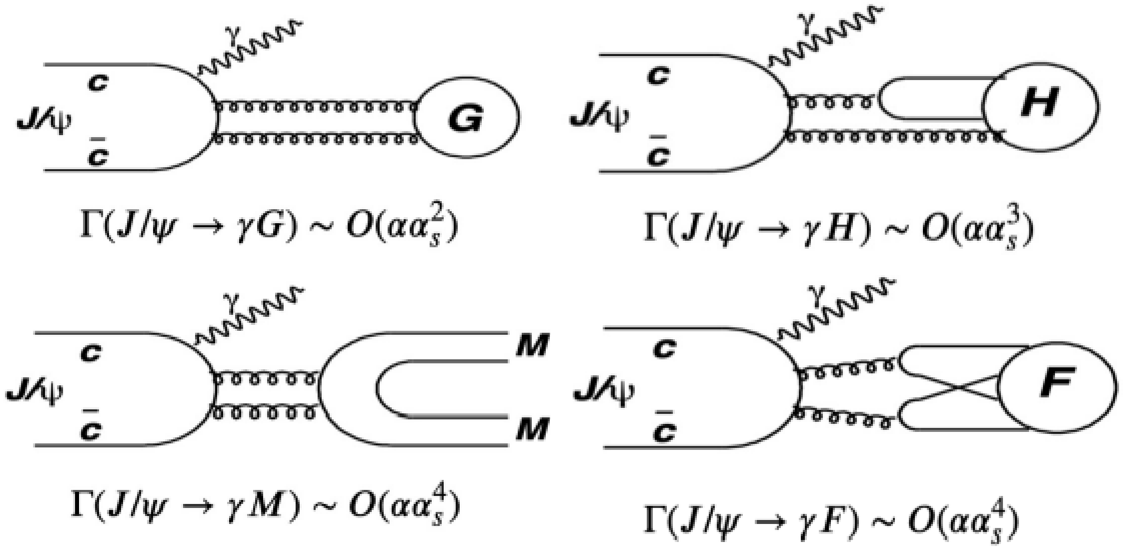
- **Quark model seems to work really well. Why?**
- **Key things to search for: additional degree of freedom**
  - Strong evidences for multi-quark in heavy quark sector
  - **Evidence for gluonic excitations remains sparse**
- **Role of gluons:**
  - Gluons mediate the strong force
  - **Hadron constituent: Mass? Quantum numbers? …**
  - Gluons' unique self-interacting property

    → **New form of matter: glueballs, hybrids**
  - **Gluonic Excitations provide measurements of the QCD potential**

Critical to confinement and mass dynamical generation

Beijing Electron Positron Collider (BEPCII)





Charmonium decays provide an ideal lab for light QCD exotics

- Clean high statistics data samples
  - High cross sections of $e^+e^- \to J/\psi,\ \psi'$
  - Low background
- Well defined initial and final states
  - Kinematic constraints
  - I(J^{PC}) filter
- "Gluon-rich" process

- Glueballs
- Spin-exotic states
- Threshold structures & multi-quark states

Focused on light QCD exotics in this talk.
Many other opportunities in light hadron spectroscopy at BESIII:

- Vector excitations in e^+e^- production
- Baryon spectroscopy

Glueballs

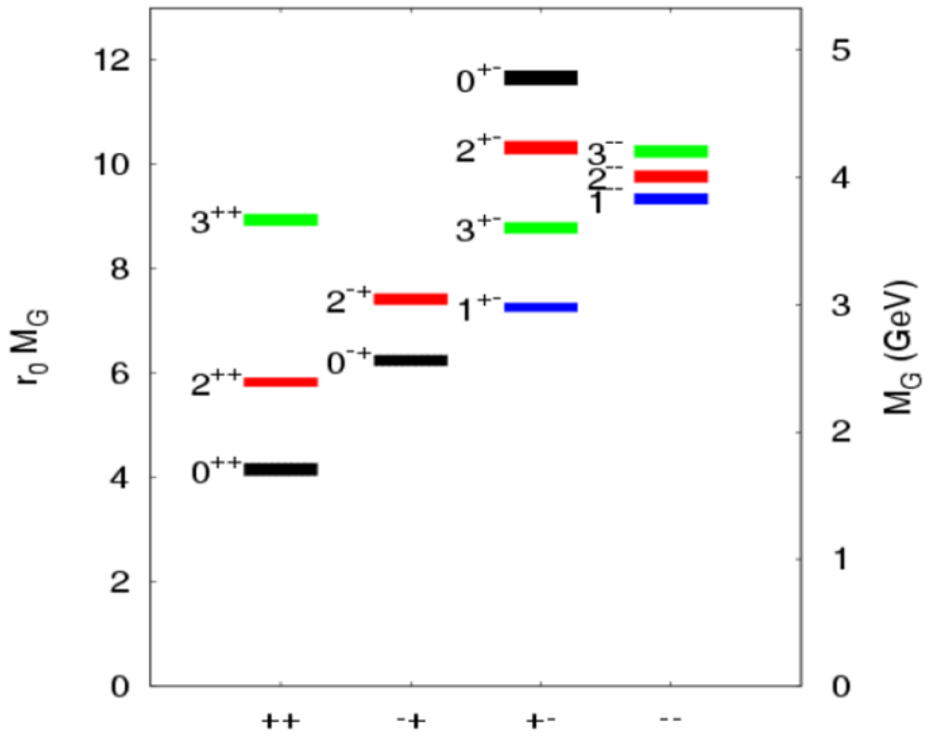
- **Low-lying glueballs with ordinary J^{PC}**

→ mixing with $q\bar{q}$ mesons

  - ~~**Observe a new peak**~~
  - Challenge: reveal the exotic admixture

- **Model-dependent predictions**
  - mass, width, partial width
- **Non-$q\bar{q}$ nature difficult to be established**
  - Supernumerary states
  - Unusual pattern of production and decay

'Cryptoexotic'



Glueballs from Lattice simulations in the pure gauge theory without quarks

What we have learned before

-- from MarkIII, BES, Crystal barrel, OBELIX, WA102, GAMS, E852, ...

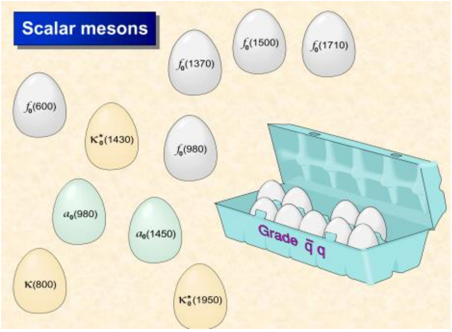
e^+e^- annihilation
$p\bar{p}$ annihilation
central exclusive production
charge-exchange reactions

Scalar: 1 nonet in quark model, f_0 & f_0'

Exp: overpopulation

LQCD : ground state 0^+ glueball ~1.7 GeV;

$$\Gamma(J/\psi \to \gamma G_{0+})/\Gamma_{total} = 3.8(9) \times 10^{-3}$$



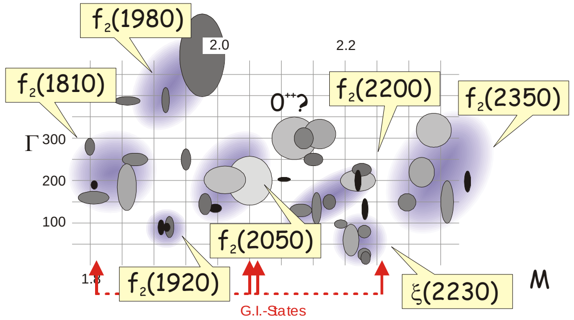
$f_0(1370)$, $f_0(1500)$, $f_0(1710)$

Tensor: 2 nonets($^3P_2$,$^3F_2$), complicated

Exp: large uncertainty

LQCD: 2^{++}(2.3~2.4 GeV);

$$\Gamma(J/\psi \to \gamma G_{2+})/\Gamma_{total} = 1.1(2) \times 10^{-2}$$

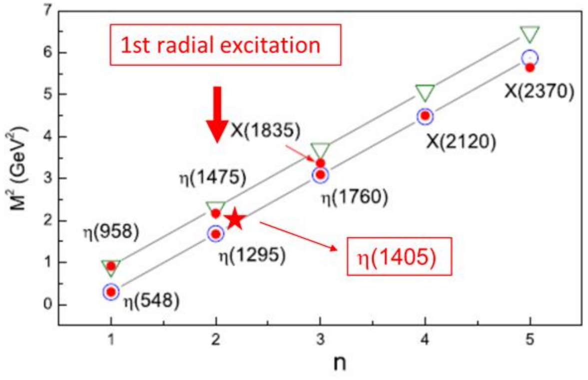


Pseudoscalar: η & η′ , "simple"

Exp: lacking of info. above 2 GeV; puzzles η(1295)? η(1405/1475)?

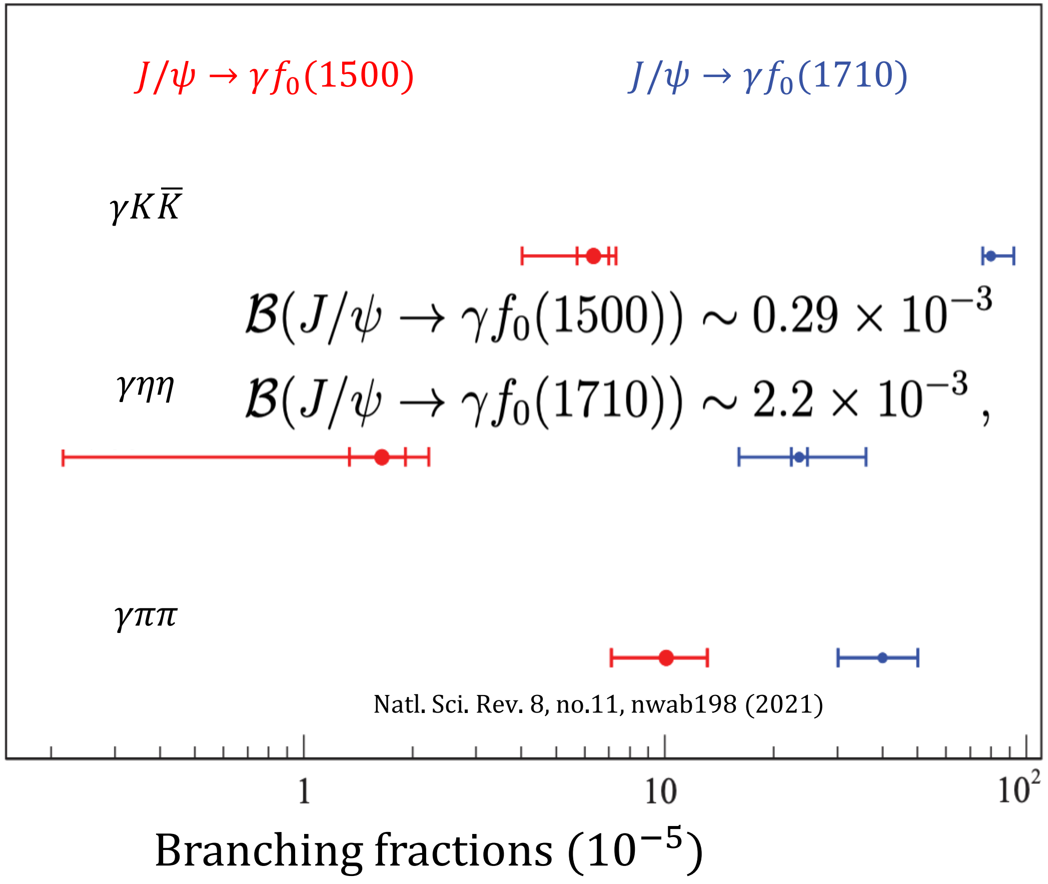
LQCD: 0^{-+}(2.3~2.6 GeV)

$$\Gamma(J/\psi \to \gamma G_{0-})/\Gamma_{total} = 2.31(80) \times 10^{-4}$$



Scalar glueball candidate: production properties

- **Scalar glueball is expected to have a large production in J/ψ radiative decays**:
  - LQCD: $\Gamma(J/\psi \to \gamma G_{0+})/\Gamma_{total} = 3.8(9) \times 10^{-3}$
  - Observed $B(J/\psi \to \gamma f_0(1710))$ is x10 larger than $f_0(1500)$
  - ➢ **BESIII: $f_0(1710)$ largely overlapped with scalar glueball**



BESIII PRD 87 092009 (2013)
BESIII PRD 92 052003 (2015)
BESIII PRD 98 072003 (2018)

Theoretical insights based on BESIII results

Scalar isoscalar mesons and the scalar glueball from radiative J/ψ decays

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Abstract

A coupled-channel analysis of BESIII data on radiative J/ψ decays into $\pi\pi$, $K\bar{K}$, $\eta\eta$ and $\omega\phi$ has been performed. The partial-wave amplitude is constrained by a large number of further data. The analysis finds ten isoscalar scalar mesons. Their masses, widths and decay modes are determined. The scalar mesons are interpreted as mainly SU(3)-singlet and mainly octet states. Octet isoscalar scalar states are observed with significant yields only in the 1500-2100 MeV mass region. Singlet scalar mesons are produced over a wide mass range but their yield peaks in the same mass region. The peak is interpreted as scalar glueball. Its mass and width are determined to $M = 1865 \pm 25^{+10}_{-30}$ MeV and $\Gamma = 370 \pm 50^{+30}_{-20}$ MeV, its yield in radiative J/ψ decays to $(5.8 \pm 1.0)\,10^{-3}$.

Phys.Lett.B 816, 136227 (2021)

Scalar and tensor resonances in J/ψ radiative decays

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[11]Center for Exploration of Energy and Matter, Indiana University, Bloomington, IN 47403, USA

We perform a systematic analysis of the $J/\psi \to \gamma\pi^0\pi^0$ and $\to \gamma K^0_S K^0_S$ partial waves measured by BESIII. We use a large set of amplitude parametrizations to reduce the model bias. We determine the physical properties of seven scalar and tensor resonances in the 1–2.5 GeV mass range. These include the well known $f_0(1500)$ and $f_0(1710)$, that are considered to be the primary glueball candidates. The hierarchy of resonance couplings determined from this analysis favors the latter as the one with the largest glueball component.

Eur.Phys.J.C 82, 80 (2022)

$f_0(1710)$ largely overlapped with scalar glueball

Tensor glueball candidate

$$\Gamma(J/\psi \to \gamma G_{2^+}) = 1.01(22)keV$$
$$\Gamma(J/\psi \to \gamma G_{2^+})/\Gamma_{tot} = 1.1 \times 10^{-2}$$

CLQCD, Phys. Rev. Lett. 111, 091601 (2013)

Experimental results

$$\mathbf{Br(J/\psi \to \gamma f_2(2340) \to \gamma\eta\eta) = \left(3.8^{+0.62+2.37}_{-0.65-2.07}\right) \times 10^{-5}}$$

BESIII PRD 87,092009 (2013)

$$\mathbf{Br(J/\psi \to \gamma f_2(2340) \to \gamma\phi\phi) = \left(1.91 \pm 0.14^{+0.72}_{-0.73}\right) \times 10^{-4}}$$

BESIII PRD 93, 112011 (2016)

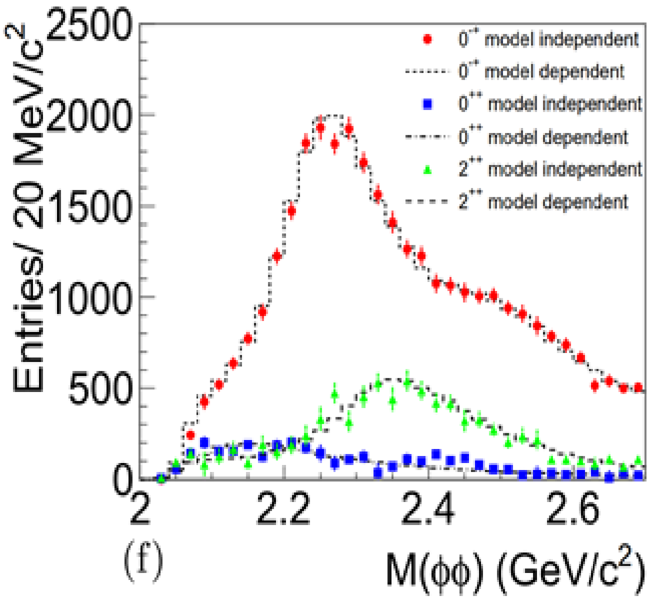
$$\mathbf{Br(J/\psi \to \gamma f_2(2340) \to \gamma K_s K_s) = \left(5.54^{+0.34+3.82}_{-0.40-1.49}\right) \times 10^{-5}}$$

BESIII PRD 98,072003 (2018)

$$\mathbf{Br(J/\psi \to \gamma f_2(2340) \to \gamma\eta'\eta') = \left(8.67 \pm 0.70^{+0.16}_{-1.67}\right) \times 10^{-6}}$$

BESIII PRD 105,072002 (2022)

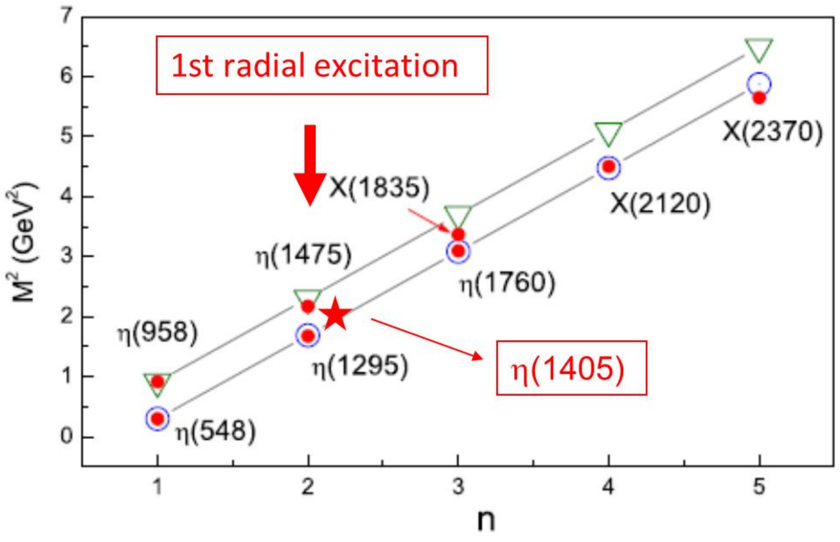
BESIII $J/\psi \to \gamma\phi\phi$ with 1.3B J/ψ

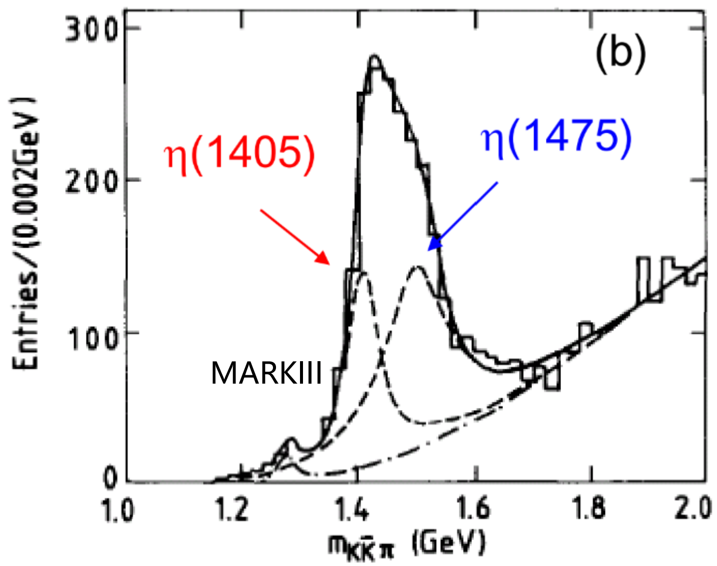


$f_2(2010)$, $f_2(2300)$ and $f_2(2340)$ stated in $\pi^- p$ reactions are observed with a strong production of $f_2(2340)$
Consist with WA102@CERN

It is desirable to search for more decay modes

Pseudoscalars





Where is the 0^{-+} glueball

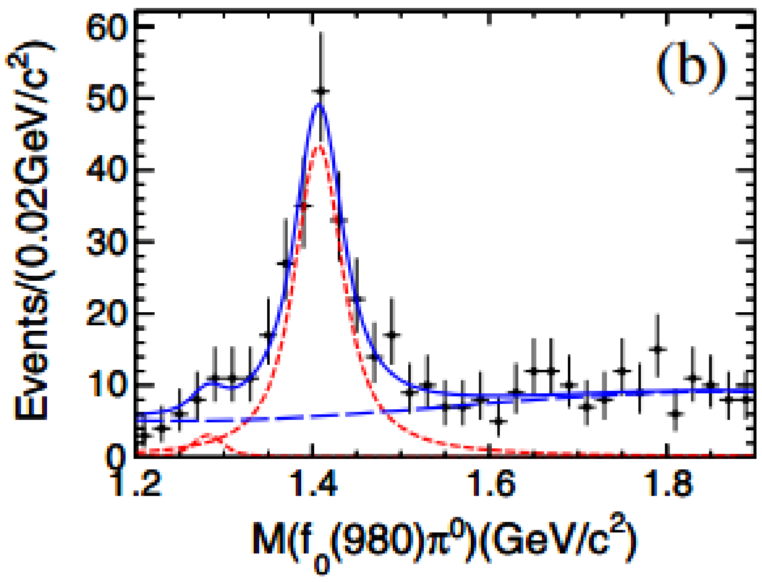
- LQCD： 0^{-+}(2.3~2.6 GeV)
- Does $\eta(1295)$ exist?
- What' s the nature of the outnumbered $\eta(1405)$?

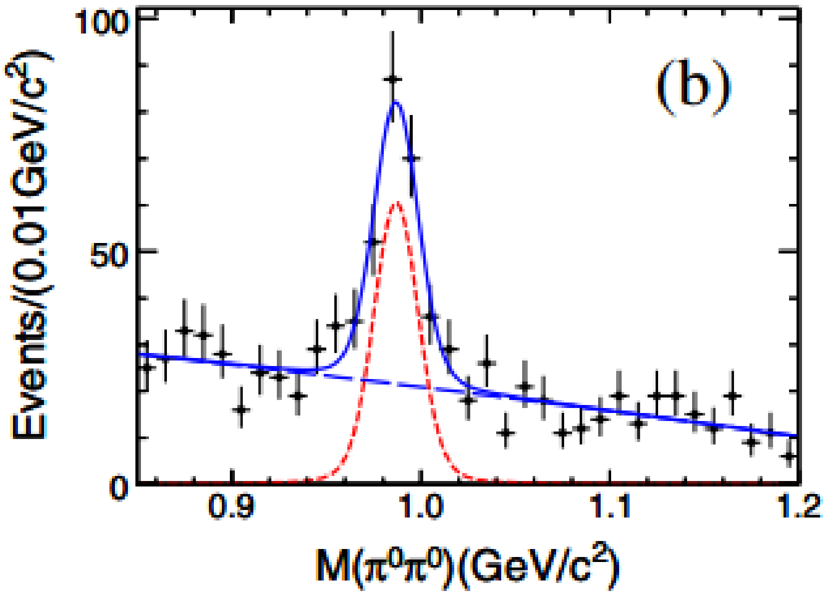
Long standing E-ι puzzle

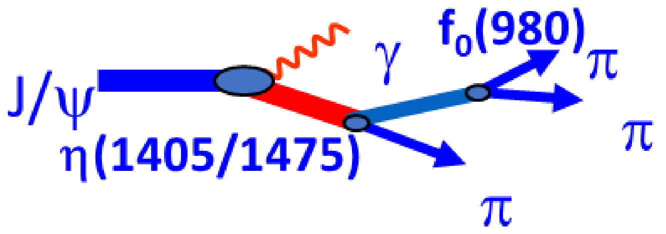
$$M = 1416 \pm 8^{+7}_{-5};\ \Gamma = 91^{+67}_{-31-38}{}^{+15}\ \mathrm{MeV}/c^2$$

$$M=1490^{+14+3}_{-8-6};\ \Gamma=54^{+37+13}_{-21-24}\ \mathrm{MeV}/c^2$$

Isospin-violating decay of $\eta(1405) \rightarrow f_0(980)\pi^0$







BESIII PRL 108 182001(2012)

f0(980) is extremely narrow: $\Gamma \cong 10$ MeV.

PDG: Γ(f0(980)) $\cong$ 40~100 MeV.

Anomalously large isospin violation:

$$\frac{Br(\eta(1405) \to f_0(980)\pi^0 \to \pi^+\pi^-\pi^0)}{Br(\eta(1405) \to a_0^0(980)\pi^0 \to \eta\pi^0\pi^0)} \cong (17.9 \pm 4.2)\%$$

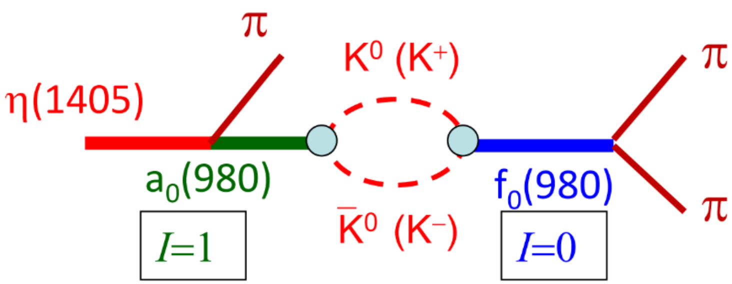
$$\xi_{af} = \frac{Br(\chi_{c1} \to f_0(980)\pi^0 \to \pi^+\pi^-\pi^0)}{Br(\chi_{c1} \to a_0(980)\pi^0 \to \eta\pi^0\pi^0)} < 1\%(90\%\ C.L.)$$

PRD, 83(2100)032003

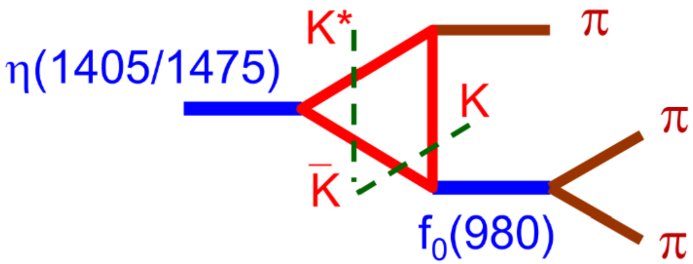
$\eta(1405)/\eta(1475)$ puzzle

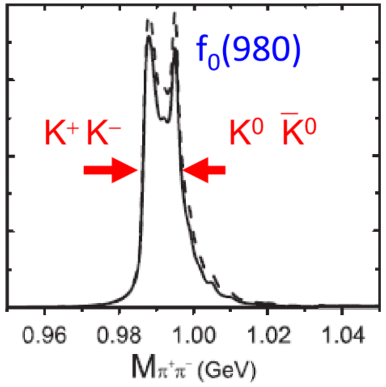
BESIII PRL 108 182001(2012)

Inspired by BESIII' s observation, the triangle singularity mechanism has been proposed



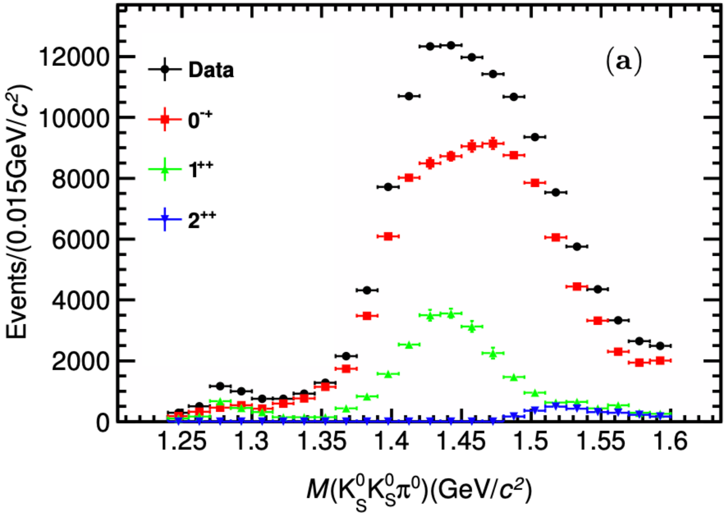
PRL 108 081803 (2012)



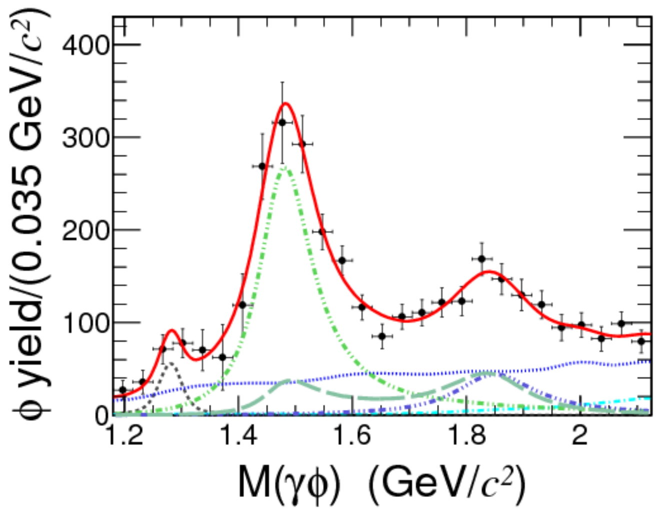


Further experimental information from

$J/\psi \to \gamma K_S K_S \pi^0$ **BESIII JHEP 03 121(2023)**



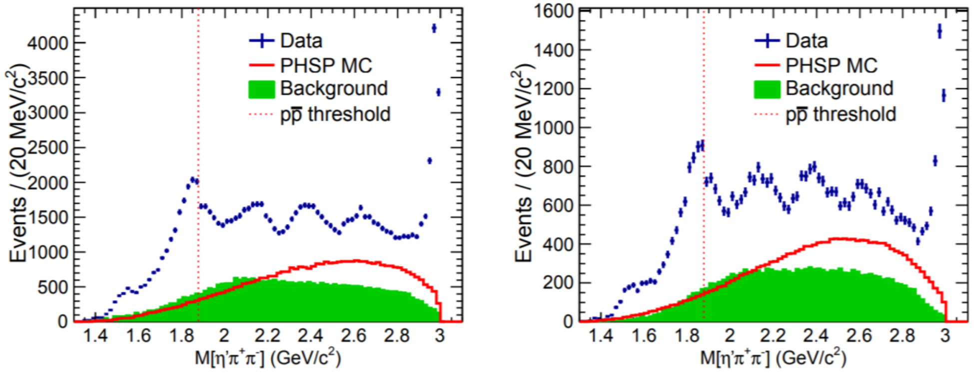
$J/\psi \to \gamma\gamma\phi$ **BESIII PRD97 051101(2018)**



X(2370)

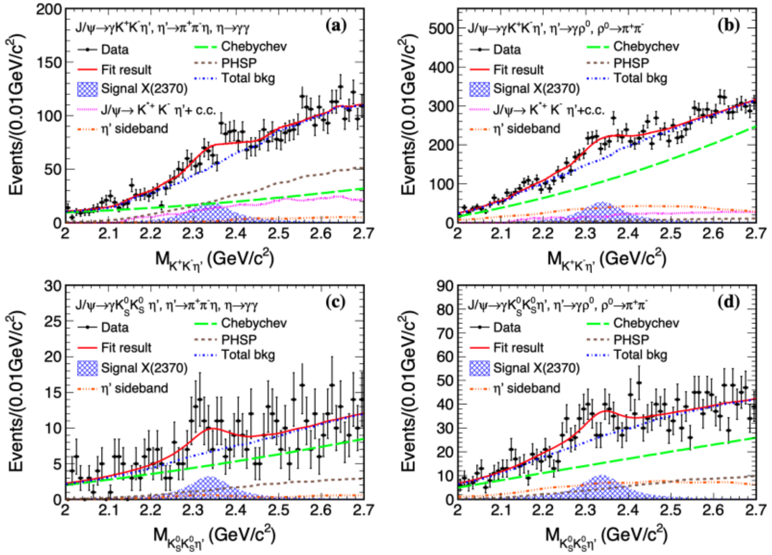
$J/\psi \to \gamma\eta'\pi^+\pi^-$

BESIII PRL 106, 072002, PRL 117, 042002



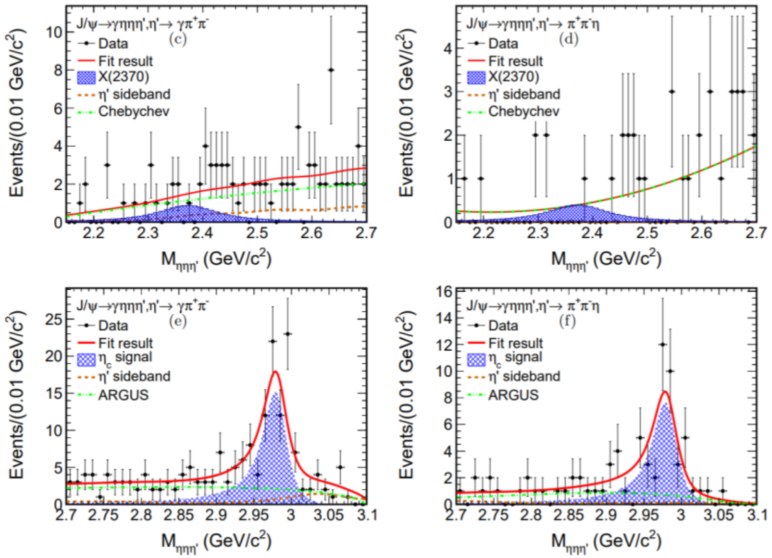
$J/\psi \to \gamma\eta' KK$

BESIII EPJC 80 746(2020)



$J/\psi \to \gamma\eta'\eta\eta$

BESIII PRD 103 012009 (2021)



Landscape of glueballs has been updated with BESIII’s inputs

Scalar: 1 nonet in quark model, f_0 & f_0'

Exp: overpopulation

LQCD : ground state 0^+ glueball ~1.7 GeV;

$$\Gamma(J/\psi \to \gamma G_{0+})/\Gamma_{total} = 3.8(9) \times 10^{-3}$$

- ✓**Large production rate of $f_0(1710)$ in J/ψ radiative decays**

Tensor: 2 nonets($^3P_2$,$^3F_2$), complicated

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- ✓**Large production rate of $f_2(2340)$ in J/ψ radiative decays**

Pseudoscalar: η & η' , “simple”

Exp: lacking of info. above 2 GeV; puzzles $\eta(1295)$? $\eta(1405/1475)$?

LQCD: 0^{-+}(2.3~2.6 GeV)

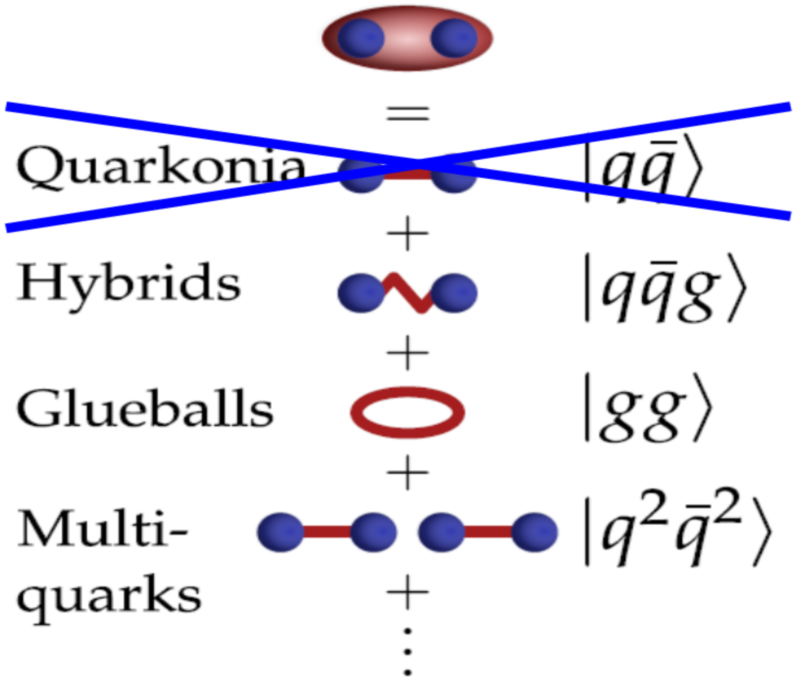
$$\Gamma(J/\psi \to \gamma G_{0-})/\Gamma_{total} = 2.31(80) \times 10^{-4}$$

- ✓**Non-observation of $\eta(1295)$**
- ✓**$\eta(1405/1475)$ one state?➔ manifestations of TS**
- ✓**$X(2370) \to$ various decay modes**

- Glueballs
- Spin-exotic states
- Threshold structures & multi-quark states

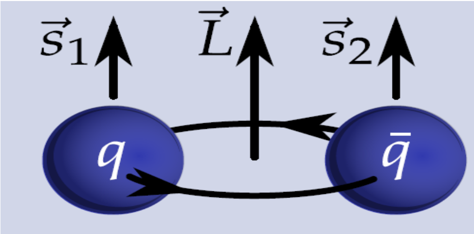
Light hadrons with exotic quantum numbers

- **Unambiguous signature for exotics**
  - Light Flavor-exotic hard to establish
  - **Efforts concentrate on Spin-exotic**
    - **Forbidden for $q\bar{q}$:**
      $J^{PC} = 0^{--}, \text{even}^{+-}, \text{odd}^{-+}$



Experiments:

- **Hadroproduction:** E852, VES, COMPASS, GAMS
- **$p\bar{p}$ annihilation:** Crystal Barrel, OBELIX, PANDA(under construction)
- **Photoproduction:** GlueX(2017-), CLAS

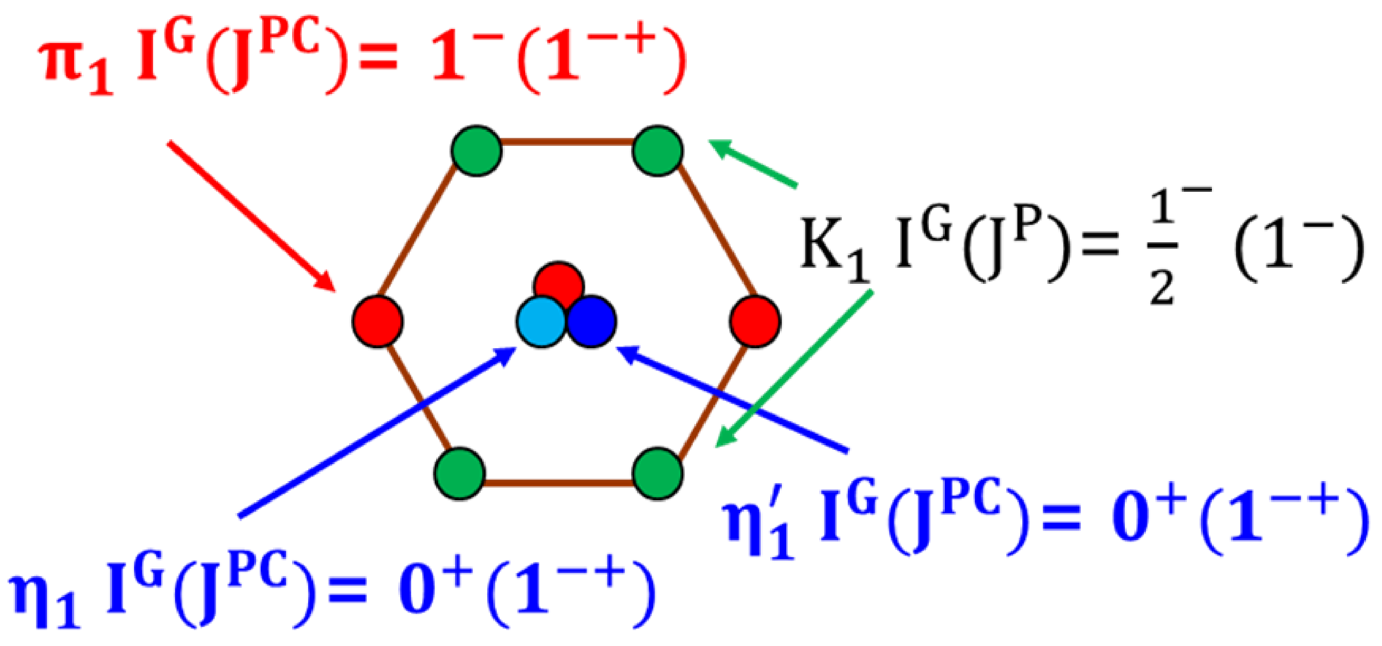


$\vec{J} = \vec{L} + \vec{S} \quad P = (-1)^{L+1} \quad C = (-1)^{L+S}$

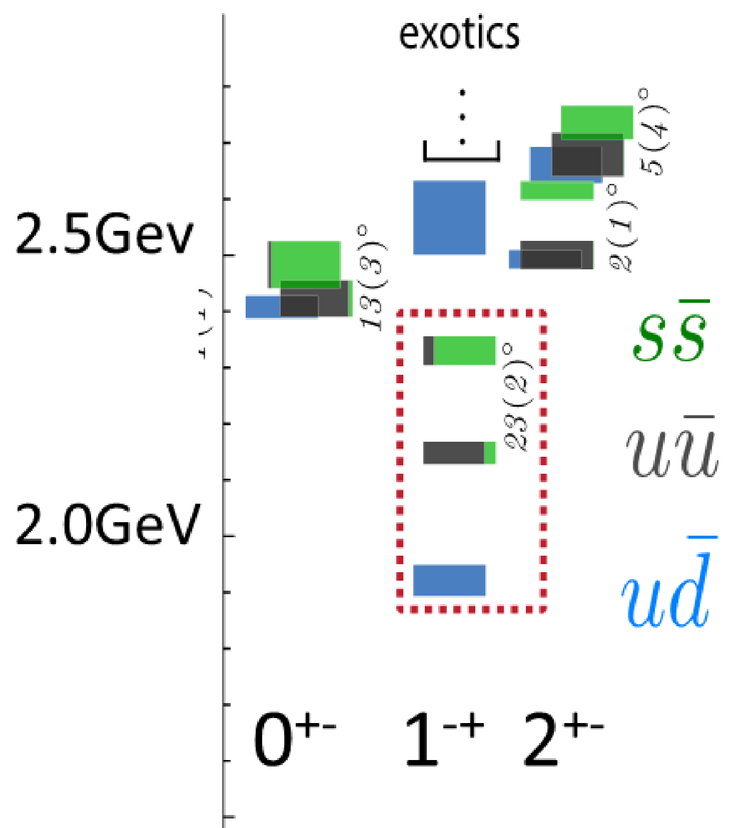
Allowed J^{PC}: $0^{-+}, 0^{++}, 1^{--}, 1^{+-}, 2^{++}, \ldots$

Spin-exotic mesons

- **Only 3 candidates so far: All 1^{-+} isovectors**
  - Experimental and interpretational issues
  - $\pi_1(1400)$ & $\pi_1(1600)$ can be explained as one pole
  - **Most popular interpretation: hybrid**



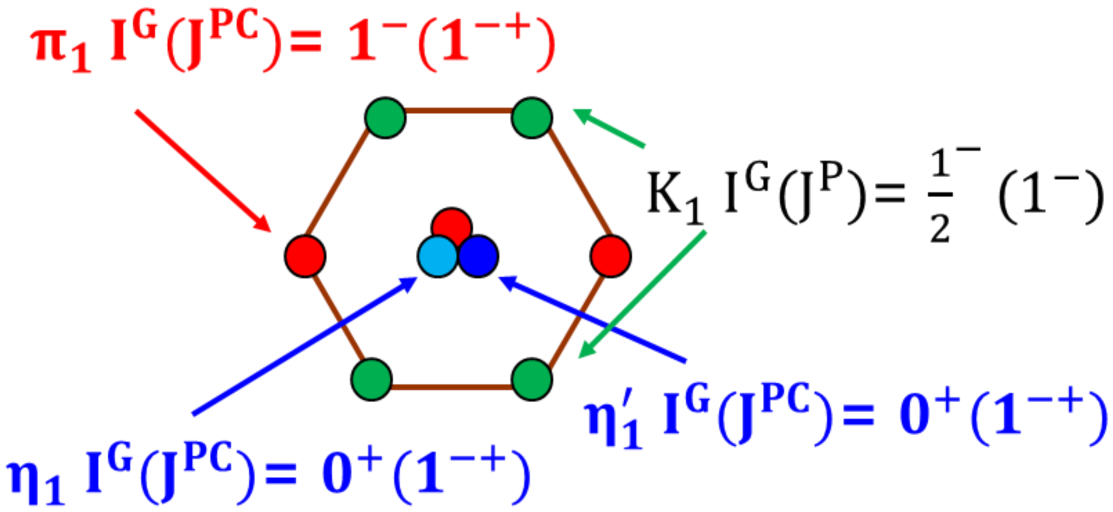
Lattice QCD Predictions:



PRD 83 111502 (2011)

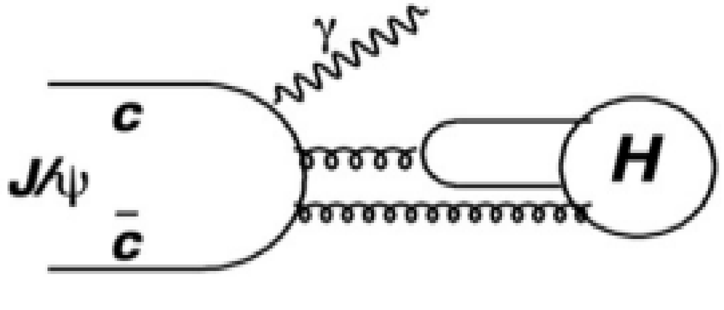
1^{-+} Hybrids

- **Isoscalar 1^{-+} is critical to establish the hybrid nonet**
  - **Can be produced in the gluon-rich charmonium decays**
  - **Can decay to $\eta\eta'$ in P-wave**



PRD 83,014021 (2011), PRD 83,014006 (2011), EPJ.P 135, 945(2020)

→ Search for η_1 (1^{-+}) in $J/\psi \to \gamma\eta\eta'$



$\Gamma(J/\psi \to \gamma H) \sim O(\alpha\alpha_s^3)$

Observation of **An Exotic 1^{-+} Isoscalar State $\eta_1(1855)$**

BESIII PRL 129 192002(2022) , PRD 106 072012(2022)

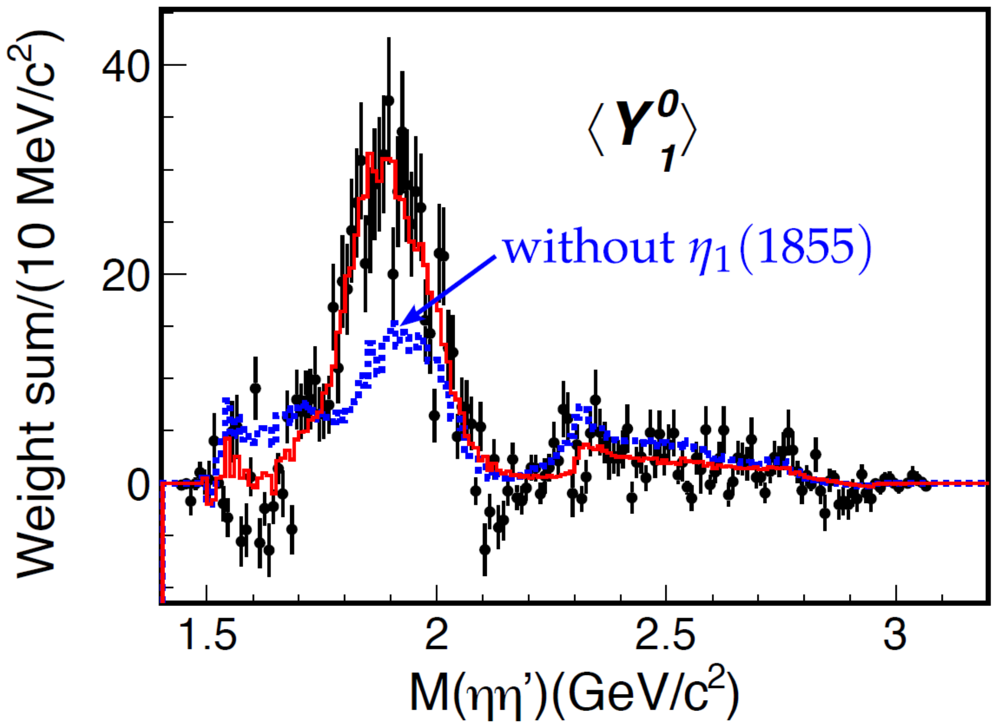
- **An isoscalar 1^{-+} , $\eta_1(1855)$, has been observed in $J/\psi \to \gamma\eta\eta'$ (>19σ)**

  $M = (1855 \pm 9^{+6}_{-1})\ \mathrm{MeV/c^2}$, $\Gamma = (188 \pm 18^{+3}_{-8})\ \mathrm{MeV/c^2}$

  $B(J/\psi \to \gamma\eta_1(1855) \to \gamma\eta\eta') = (2.70 \pm 0.41^{+0.16}_{-0.35}) \times 10^{-6}$

  - **Mass consistent with hybrid on LQCD**

- Suppression of $f_0(1710) \to \eta\eta'$ is observed
  - Consist with theoretical prediction in the decay property of glueball



An important step forward of light QCD exotics

Observation of An Exotic 1^{-+} Isoscalar State $\eta_1(1855)$

- **Opens a new direction to completing the picture of spin-exotics**
- **LQCD:** $B(J/\psi \to \gamma\eta_1(\text{hybrid})) \sim O(10^{-5})$[Phys.Rev.D 107 (2023) 5, 054511]
- **Inspired many interpretations: Hybrid/$K\bar{K}_1$Molecule/Tetraquark?**

Phys.Rev.D 107 (2023) 7, 074028;
Rept.Prog.Phys. 86 (2023) 026201;
Sci.China Phys.Mech.Astron. 65 (2022) 6, 261011;
CPC 46 , 051001(2022);
CPL 39, 051201 (2022);
PLB 834, 137478(2022);
PRD 106 , 074003(2022);
PRD 106, 036005(2022) ; …
& **Summary of Topical Group on Hadron Spectroscopy (RF07) of Snowmass 2021, 4 white papers as well**

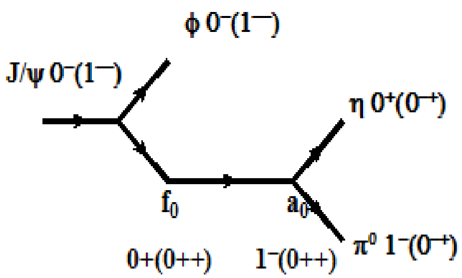
- Glueballs
- Spin-exotic states
- Threshold structures & multi-quark states

$a_0(980) - f_0(980)$ mixing

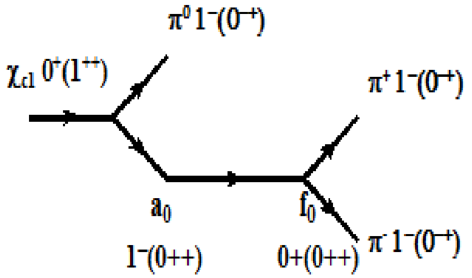
- The nature of ground state scalar $a_0(980)$ and $f_0(980)$ are controversial

  $q\bar{q}$, $K\bar{K}$ molecules, tetraquarks, hybrids,…?

- $a_0(980) - f_0(980)$ mixing is an important probe to the internal structure of $a_0(980)$ and $f_0(980)$

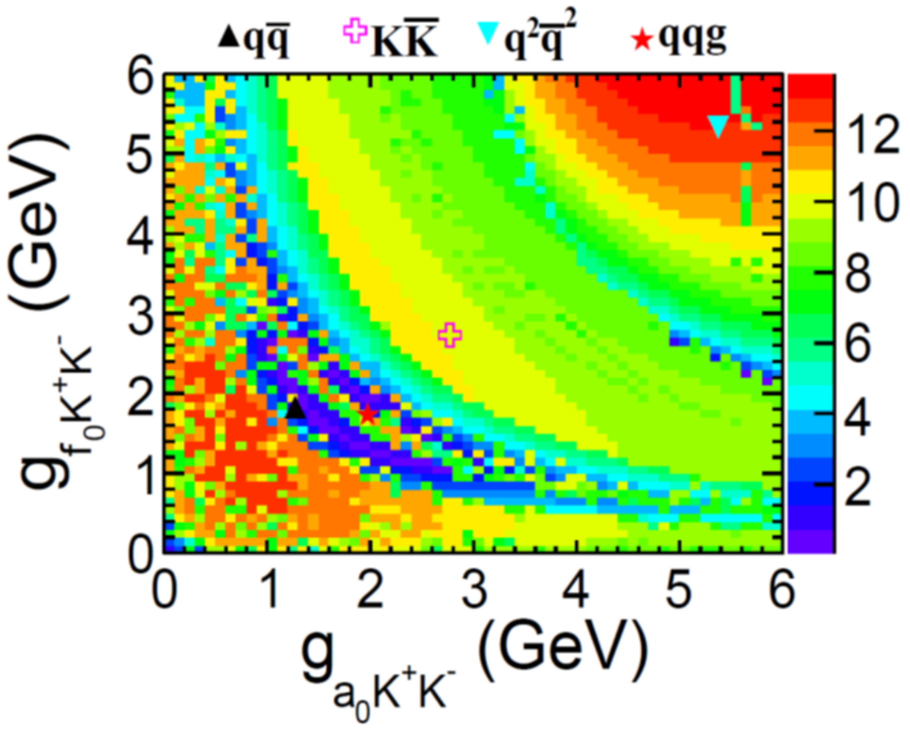


PR D75 114012, PR D76 074028



PR D78 074017

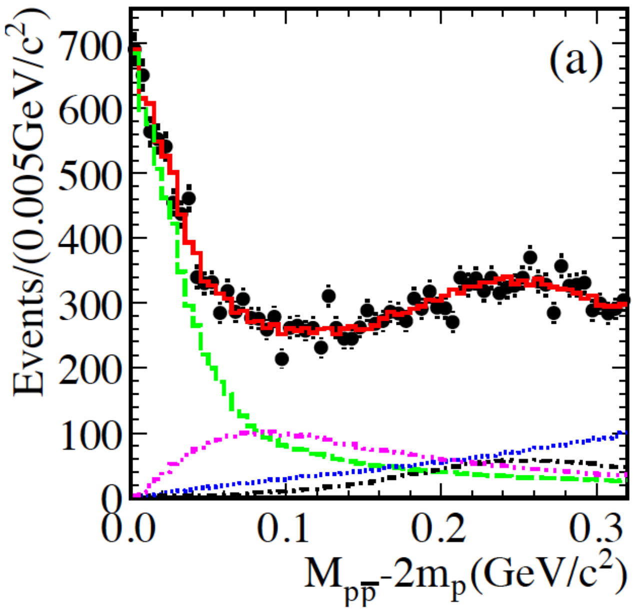
- First direct measurement with > 5σ



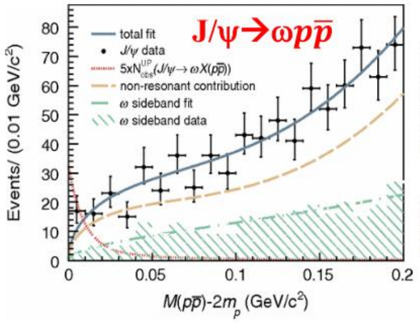
BESIII PRL 121 022001

$p\bar{p}$ threshold enhancement $X(p\bar{p})$

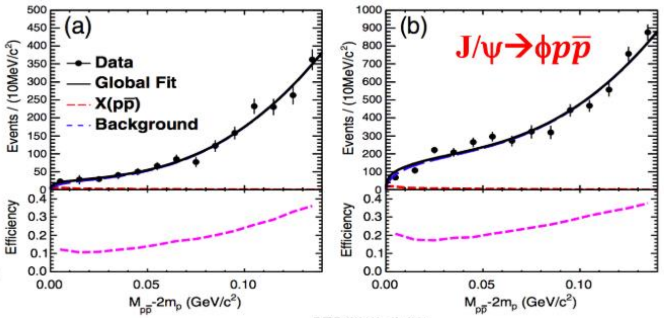
BESIII PRL 108 112003



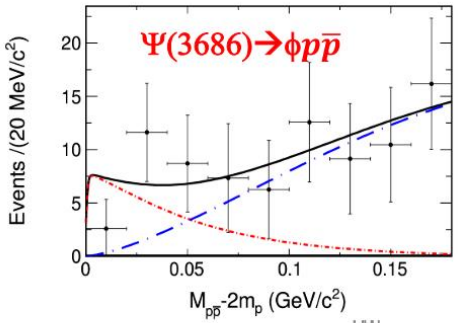
- First observed in $J/\psi \to \gamma p\bar{p}$ at BESII, confirmed by BESIII and CLEO-c
- PWA of $J/\psi \to \gamma p\bar{p}$: $J^{PC} = 0^{-+}$
- Non-observation in hadronic decays: not from pure FSI



BESIII PR D87 112014

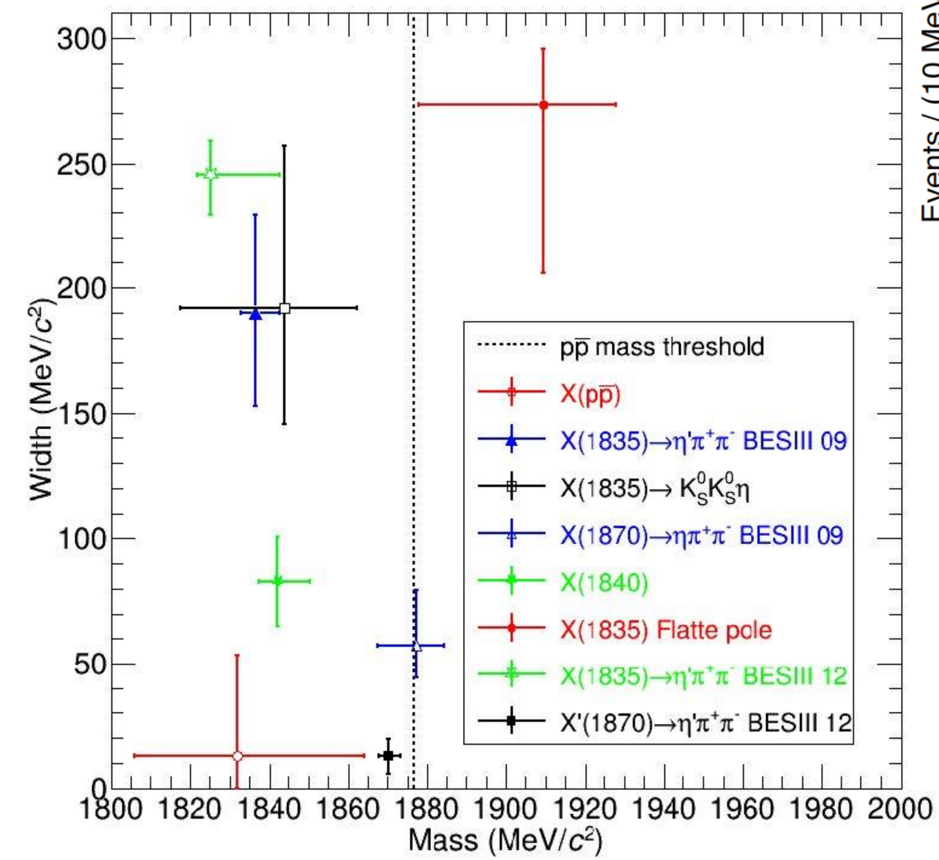


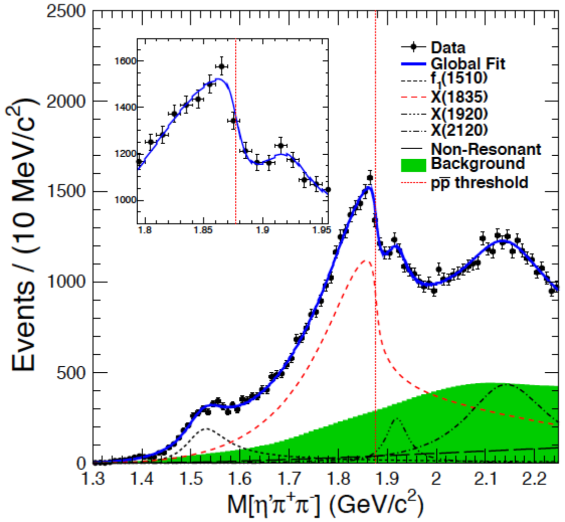
BESIII PR D93 052010



BESIII PR D99 112010

Structures around $p\bar{p}$ threshold

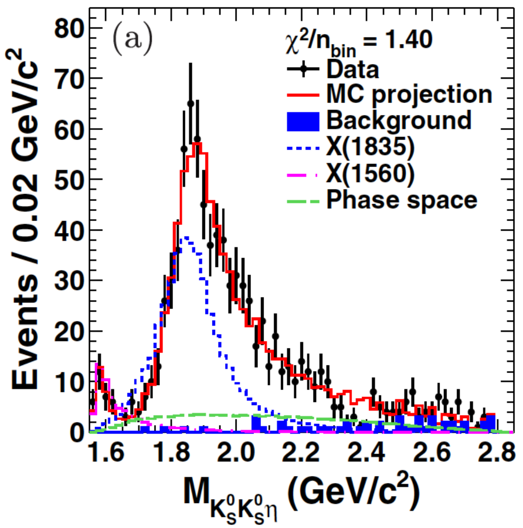




$J/\psi\to\gamma\eta'\pi^+\pi^-$

BESIII PRL 117, 042002 (2016)

Anomalous line shape near $p\bar{p}$ threshold:
connection between X(1835) and X($p\bar{p}$)



$J/\psi\to\gamma K_s K_s \eta$

BESIII PRL 115, 091803 (2015)

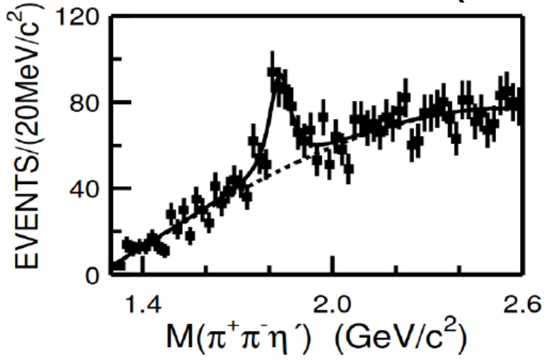
J^{PC} of X(1835) is determined to be 0^{-+}

Power of statistics

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

58 M J/ψ

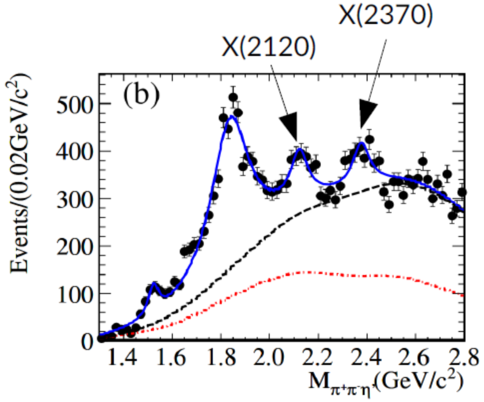
BESII PRL 95 262001(2005)



Observation of X(1835)

225M J/ψ

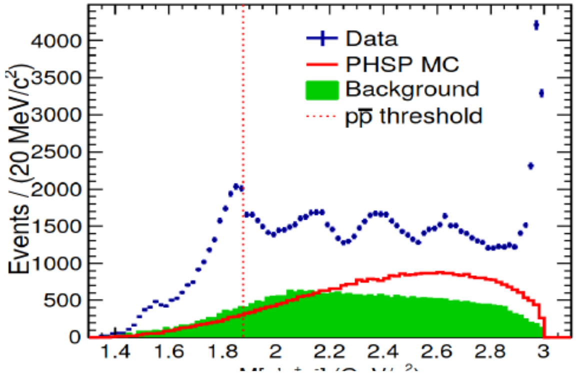
BESIII PRL 106 072002(2011)



Observation of X(2120), X(2370)

1.3B J/ψ

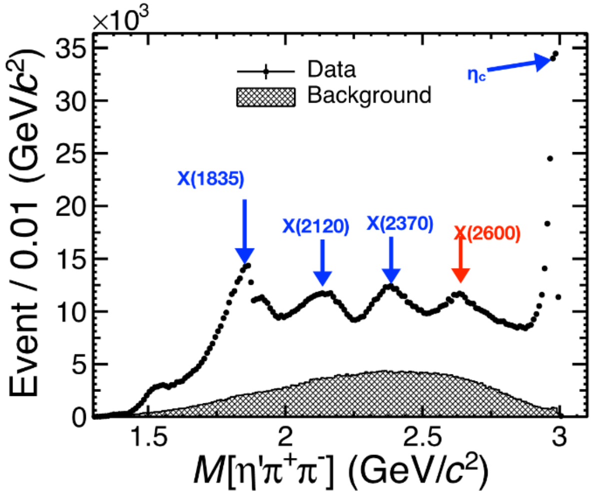
BESIII PRL 117 042002(2016)



Observation of anomalous line shape

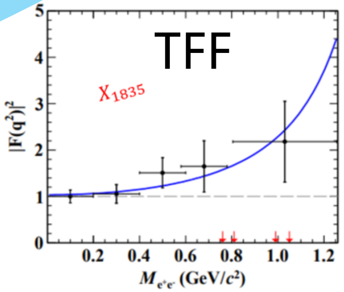
10B J/ψ

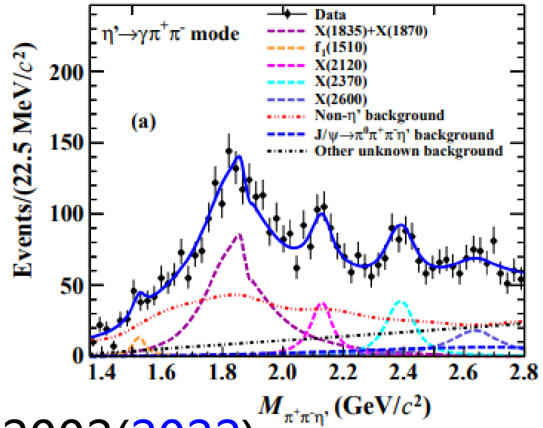
BESIII PRL 129, 042001 (2022)



Observation of X(2600)

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





BESIII PRL 129 022002(2022)

Prospects

- Data with unprecedented statistical accuracy from BESIII provides great opportunities to study light hadron spectroscopy
  - Further reveal the gluonic admixture in $f_0(1710)$, $f_2(2340)$, $X(2370)$ with more production and decay mechanisms
    - Coupled channel analyses; Two-photon process; Flavor filters; ......
  - Based on $\eta_1(1855)$, systematically explore the multiplet of spin-exotics
    - $\boldsymbol{\eta_1^{(\prime)}}$ and $\boldsymbol{\pi_1}$ in various J/ψ and χ_c decays
  - Clarify the nature of threshold structures, such as X($p\bar{p}$) and X(1835)
  - Search for more new baryon excitations

More interesting results are expected

Summary

- Understanding how hadron spectroscopy are generated from QCD remains a key question in fundamental physics, which requires
  - both heavy and light sectors; various probes
- BESIII has a crucial and unique role to play in the world-wide effort to explore the property of QCD in the non-perturbative regime
- Charmonium decays provide an ideal lab for light QCD exotics and produced many exciting results
  - **X(1835)/ X($p\bar{p}$) , X(2370), Spin-exotic $\eta_1(1855)$,……**

Thank you