Light QCD exotics at BESIII

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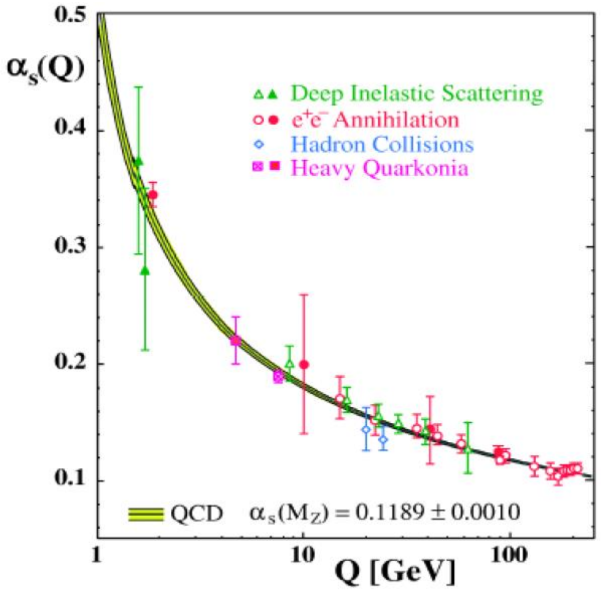
Introduction

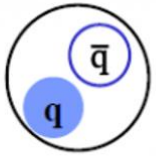
- Hadrons, the complex building blocks of our world, emerge from interaction of quarks and gluons as described by QCD
- NPQCD: How does QCD give rise to hadrons?
  - What is the origin of confinement?
  - How is the mass generated in QCD?
- Best discovery path : hadron spectroscopy

Asymptotic Freedom
PQCD

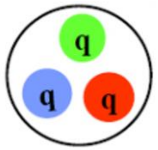


Confinement & NPQCD
"World of Hadrons"

Quark model



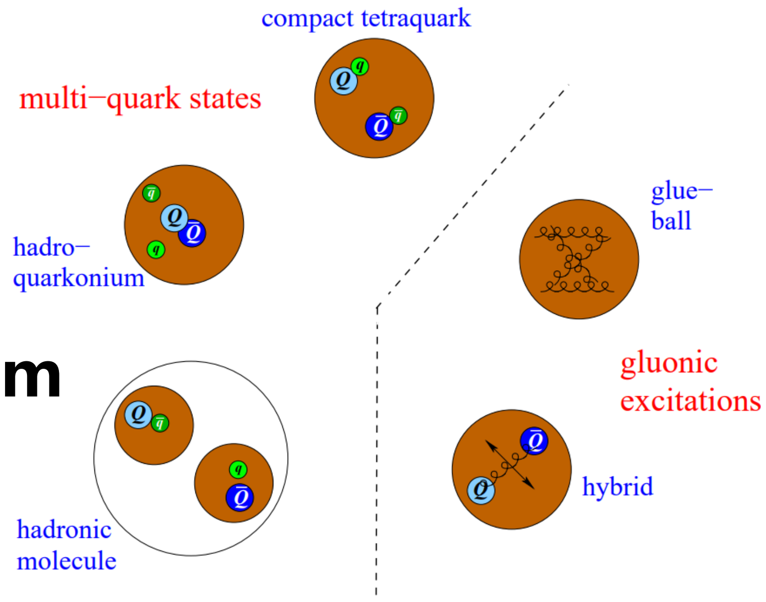
meson



baryons

Light QCD exotics

configurations beyond QM

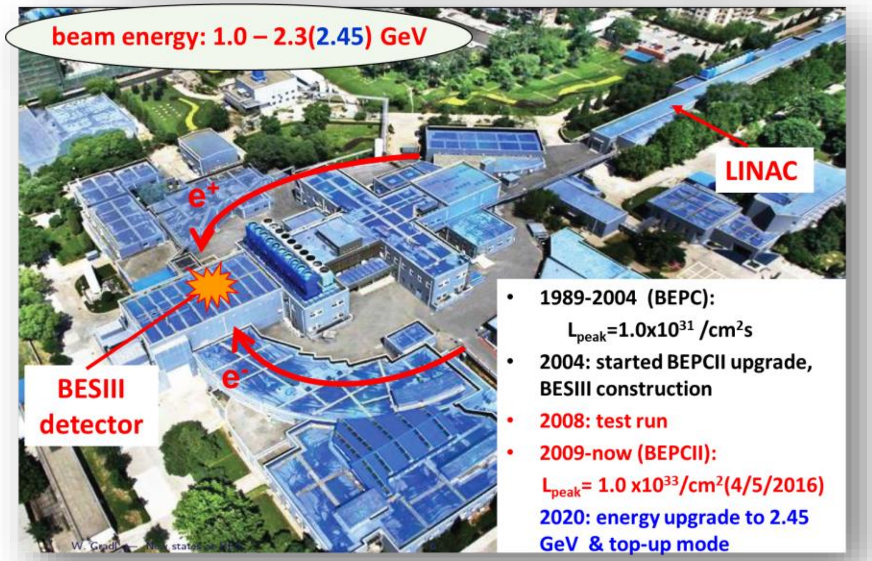


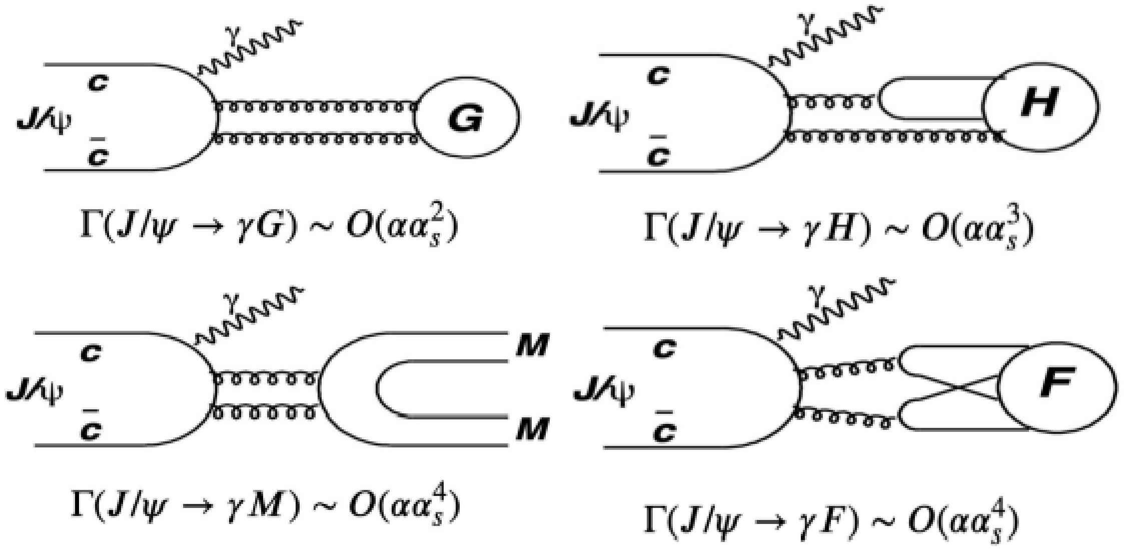
- **Quark model seems to work really well. Why?**
- **Key things to search for: additional degree of freedom**
  - Strong evidences for multi-quark in heavy quark sector
  - **Evidence for gluonic excitations remains sparse**
- **Role of gluons:**
  - Gluons mediate the strong force
  - **Hadron constituent: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

Glueballs

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

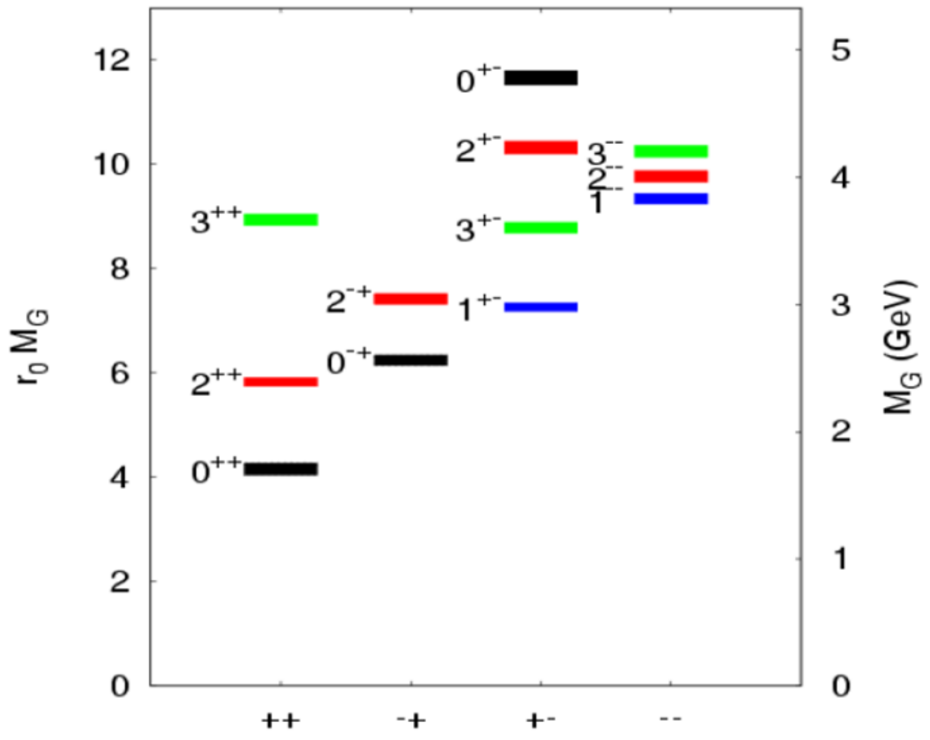
→ mixing with $q\bar{q}$ mesons

  - ➢ ~~**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, ...

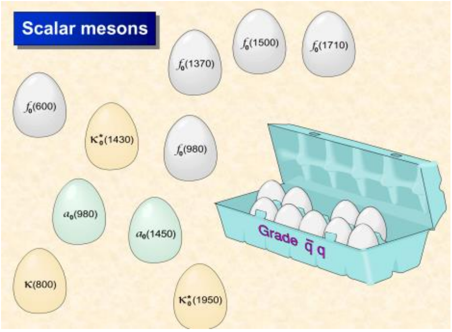
e^+e^- annihilation
$p\bar{p}$ annihilation
central exclusive production
charge-exchange reactions

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

Exp: overpopulation

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

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



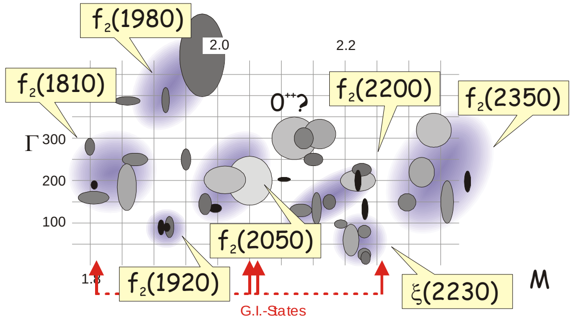
$f_0(1370)$, $f_0(1500)$, $f_0(1710)$

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

Exp: large uncertainty

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

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

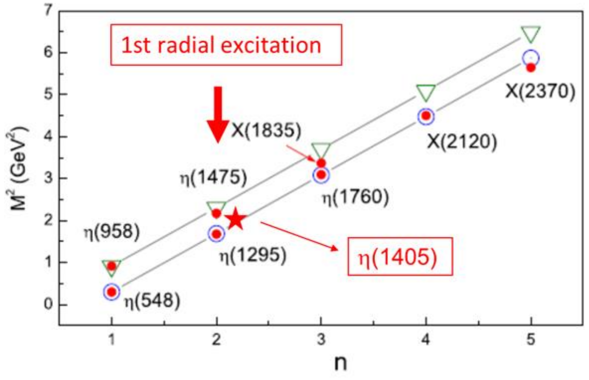


Pseudoscalar: η & η′ , "simple"

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

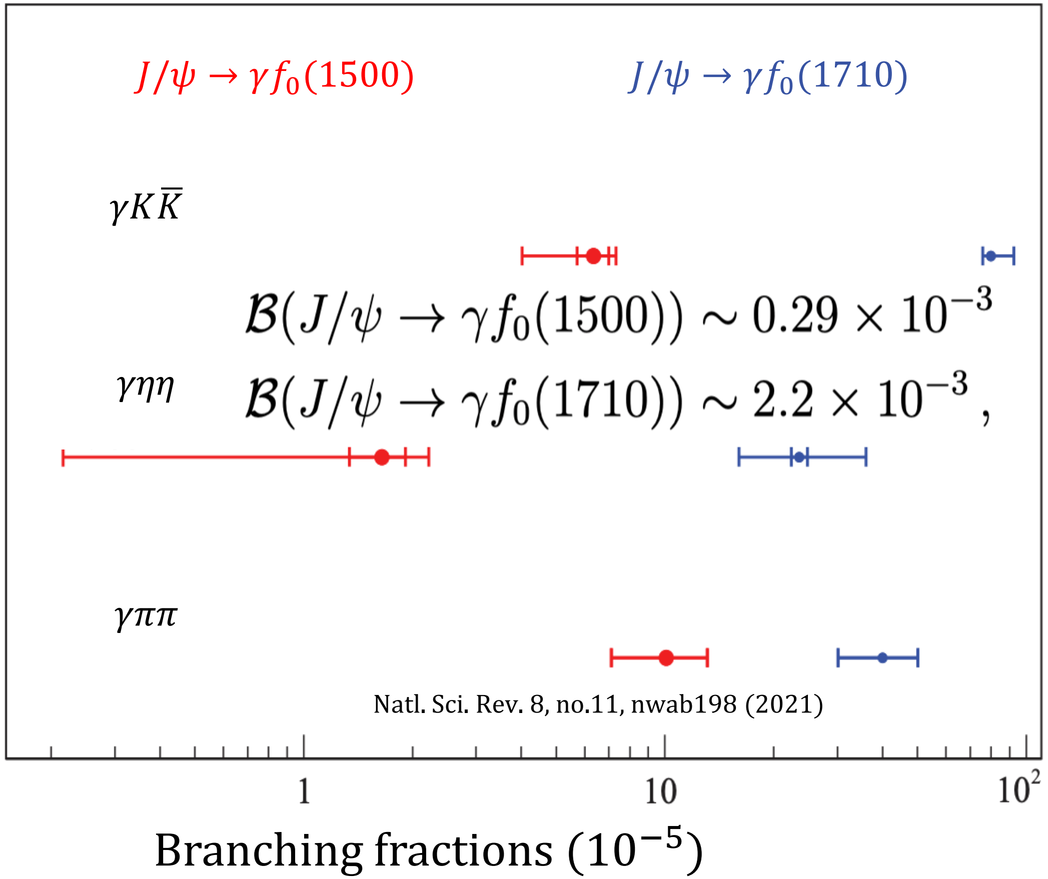
LQCD: 0^{-+}(2.3~2.6 GeV)

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



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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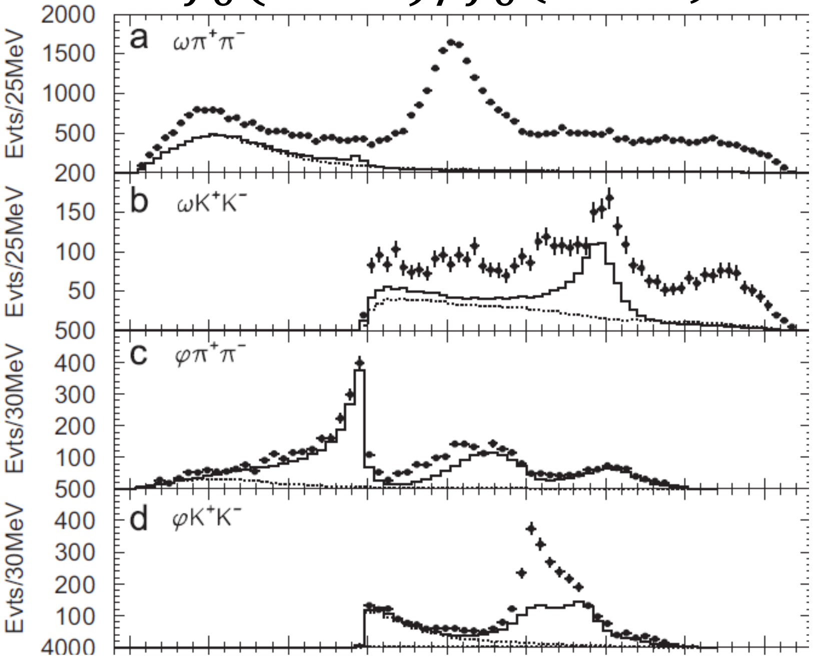
We perform a systematic analysis of the $J/\psi \to \gamma\pi^0\pi^0$ and $\to \gamma K^0_S K^0_S$ partial waves measured by BESIII. We use a large set of amplitude parametrizations to reduce the model bias. We determine the physical properties of seven scalar and tensor resonances in the 1–2.5 GeV mass 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

More scalars

$f_0(1710)/f_0(1790)$?



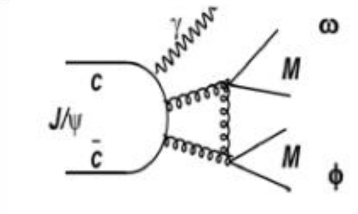
ωK^+K^- ➜ Peak around 1700 MeV/c^2 (OZI rule: $n\bar{n}$ structure)

$\phi\pi^+\pi^-$ ➜ Enhancement at 1790 MeV/c^2

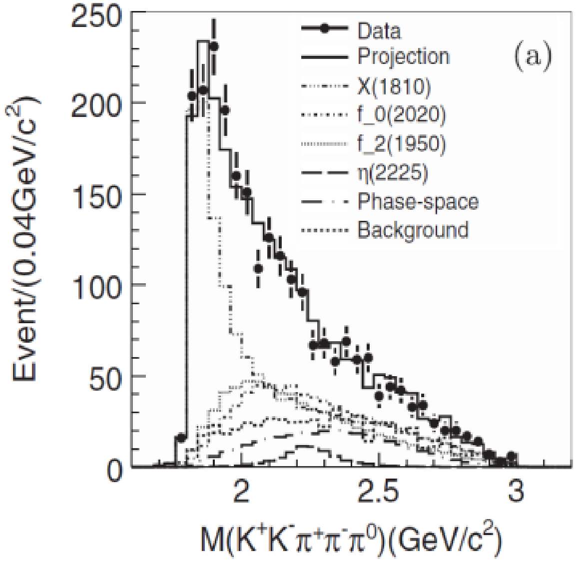
ϕK^+K^- ➜ No peak around 1700 MeV/c^2

$f_0(1800)$

PRD 87, 032008(2013)



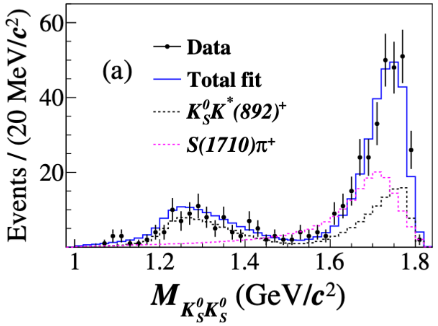
$J/\psi \to \gamma\omega\phi$ **(DOZI)**



$a_0(1710)/a_0(1817)$?

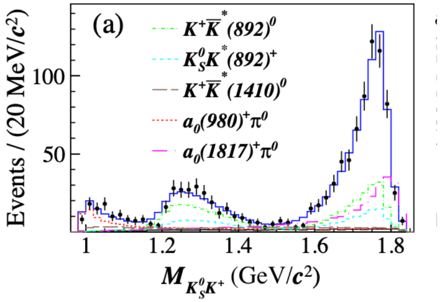
PRD105, L051103 (2022)

$D_s^+ \to K_S^0 K_S^0 \pi^+$



PRL129, 182001 (2022)

$D_s^+ \to K^0_S K^+ \pi^0$



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)

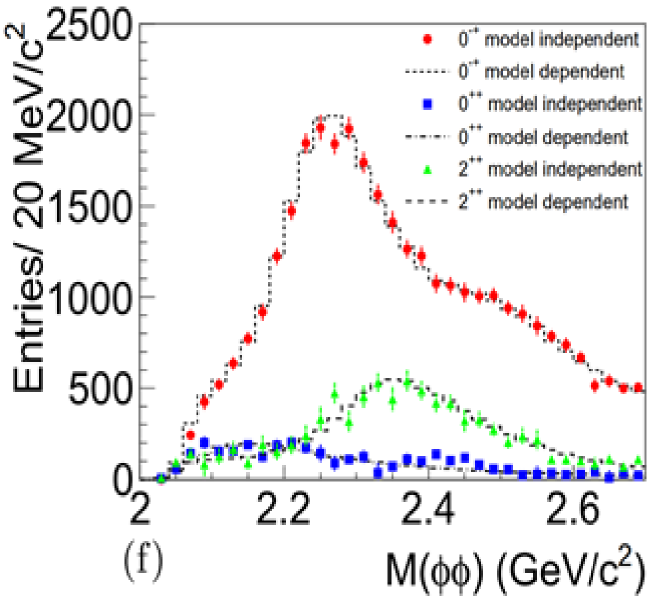
$$\mathbf{Br}(J/\psi \to \gamma f_2(2340) \to \gamma K_s K_s) = \left(5.54^{+0.34+3.82}_{-0.40-1.49}\right) \times 10^{-5}$$

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)

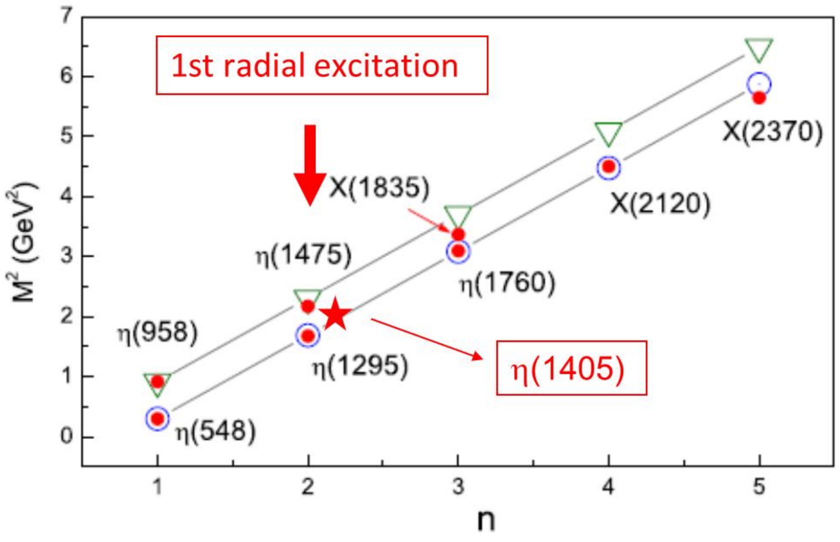
BESIII $J/\psi \to \gamma\phi\phi$ with 1.3B J/ψ

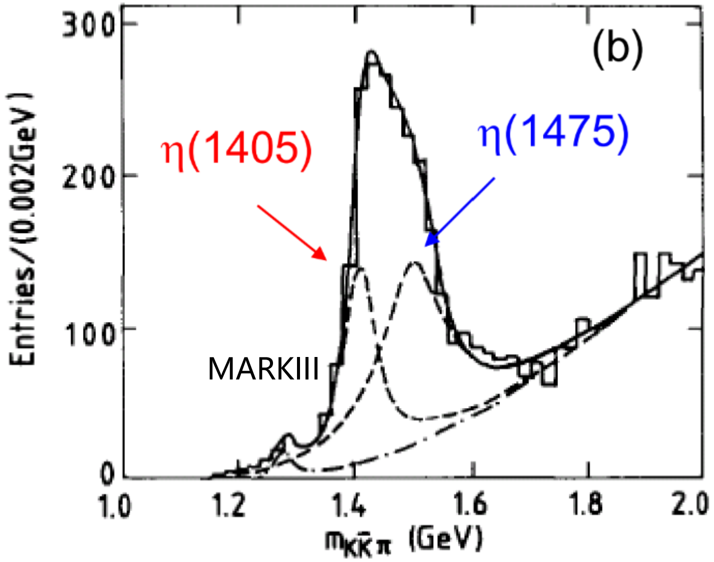


$f_2(2010)$, $f_2(2300)$ and $f_2(2340)$ stated in $\pi^- p$ reactions are observed with a strong production of $f_2(2340)$
Consist with WA102@CERN

It is desirable to search for more decay modes

Pseudoscalars





Where is the 0^{-+} glueball

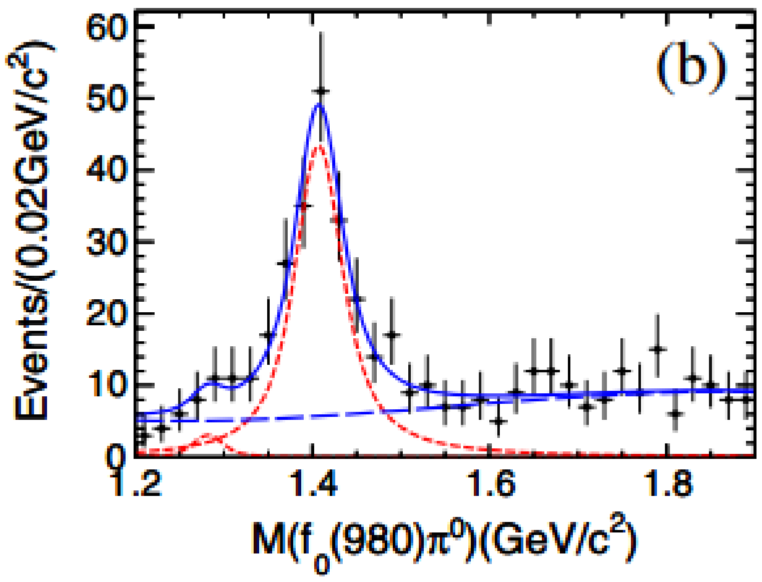
- LQCD: 0^{-+}(2.3~2.6 GeV)
- Does $\eta(1295)$ exist?
- What' s the nature of the outnumbered $\eta(1405)$?

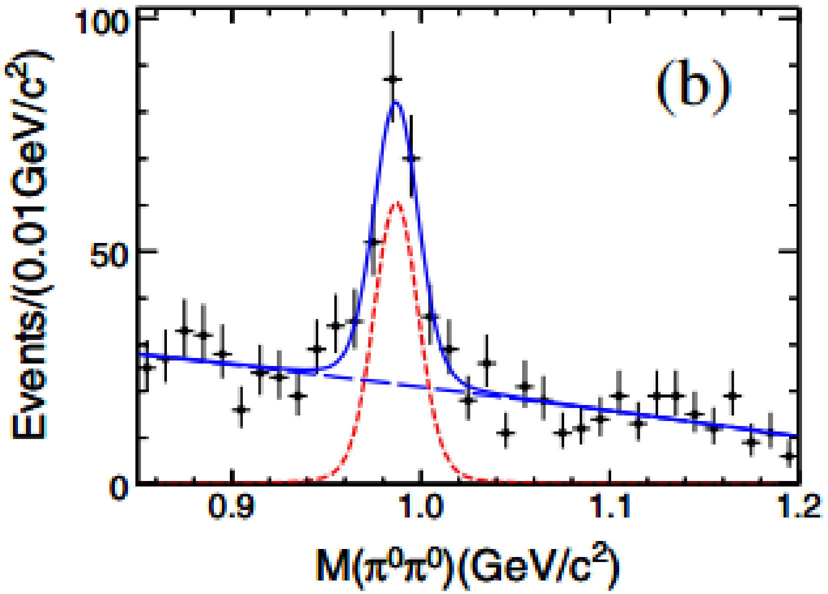
Long standing E-ι puzzle

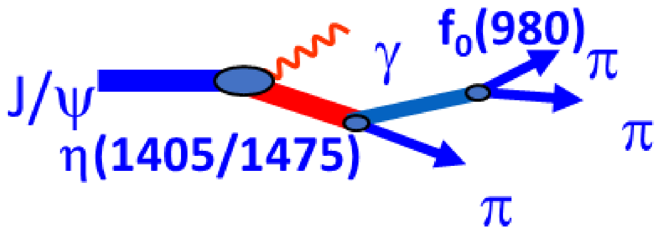
$$M = 1416 \pm 8^{+7}_{-5};\ \Gamma = 91^{+67}_{-31-38}{}^{+15}\ \mathrm{MeV}/c^2$$

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

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:

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

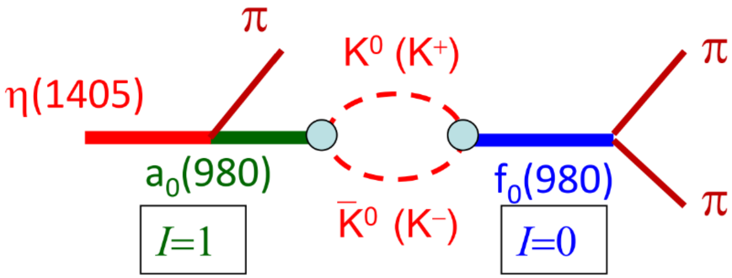
$$\xi_{af} = \frac{Br(\chi_{c1} \rightarrow f_0(980)\pi^0 \rightarrow \pi^+\pi^-\pi^0)}{Br(\chi_{c1} \rightarrow a_0(980)\pi^0 \rightarrow \eta\pi^0\pi^0)} < 1\%(90\%\ C.L.)$$

PRD, 83(2100)032003

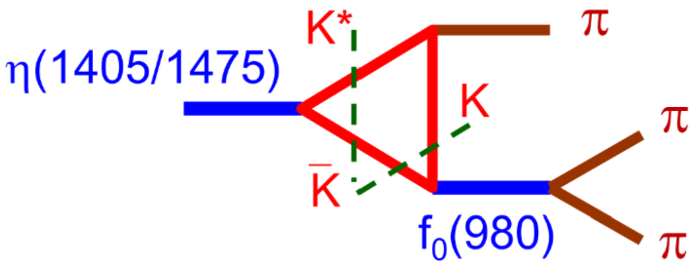
$\eta(1405)/\eta(1475)$ puzzle

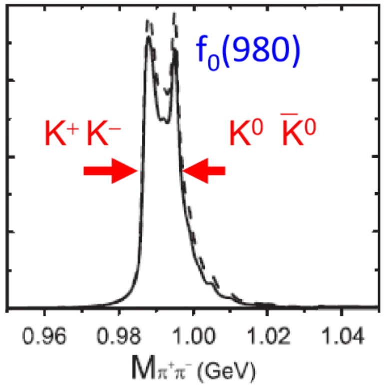
BESIII PRL 108 182001(2012)

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



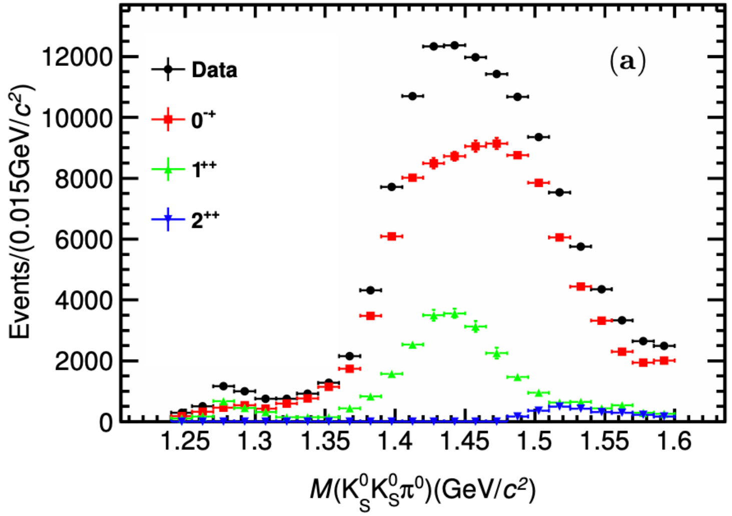
PRL 108 081803 (2012)





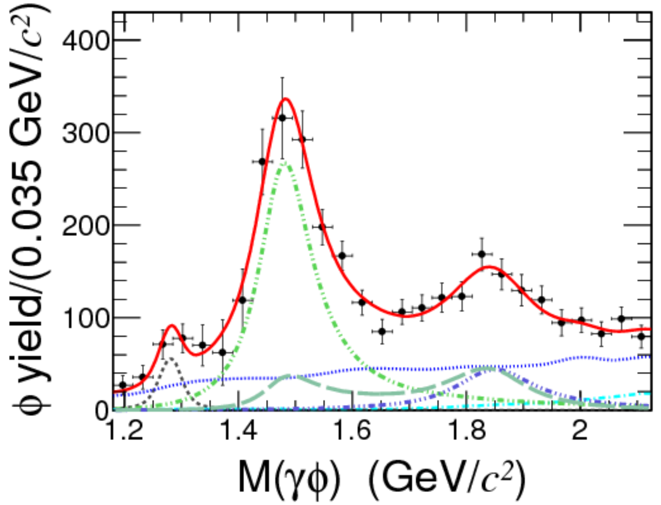
Further experimental information from

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



$J/\psi \to \gamma\gamma\phi$

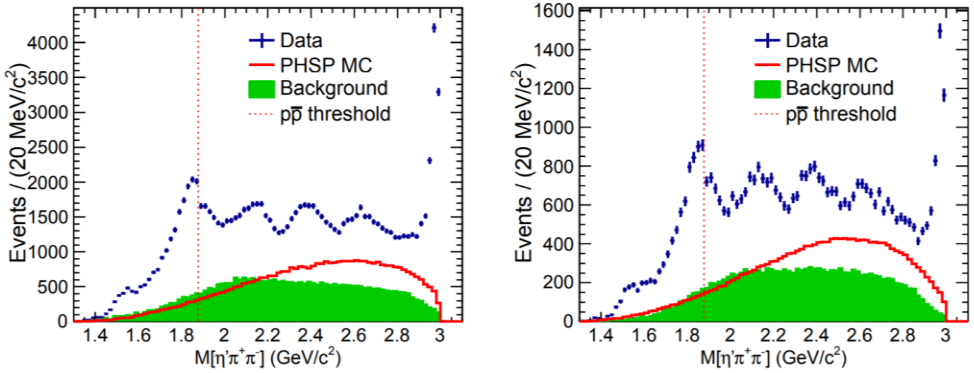
BESIII PRD97 051101(2018)



X(2370)

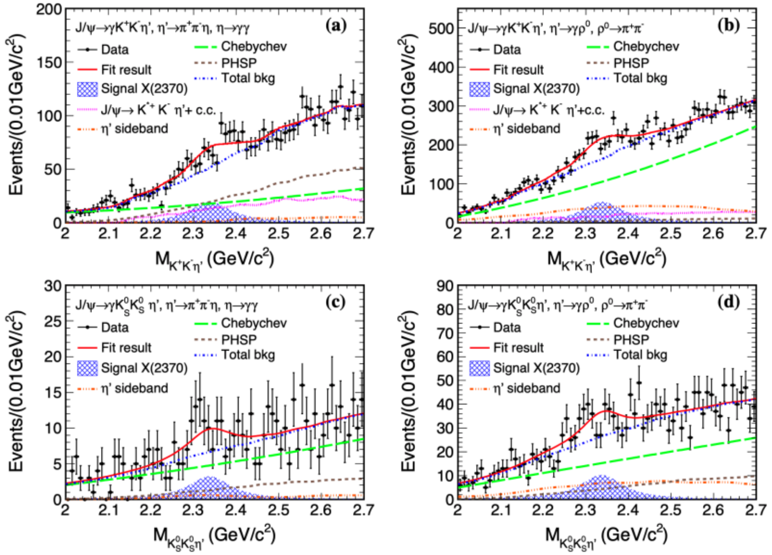
$J/\psi \to \gamma\eta'\pi^+\pi^-$

BESIII PRL 106, 072002, PRL 117, 042002



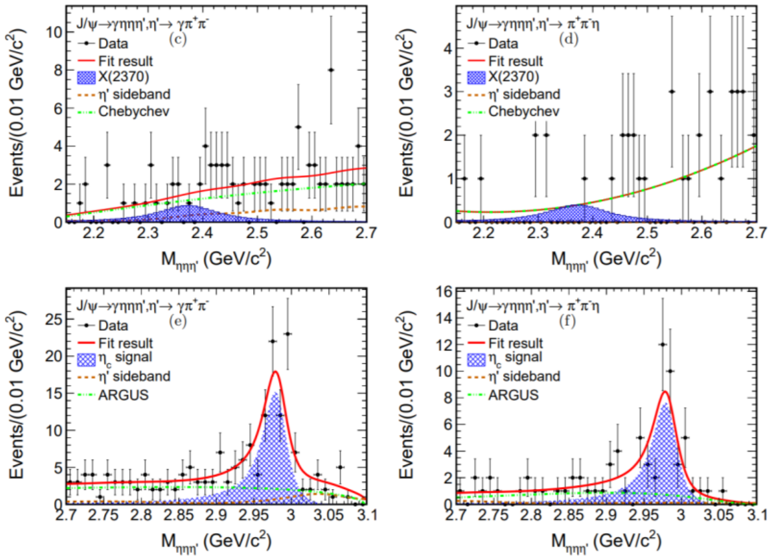
$J/\psi \to \gamma\eta' KK$

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;

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

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 $\eta(1295)$? $\eta(1405/1475)$?

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

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

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

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

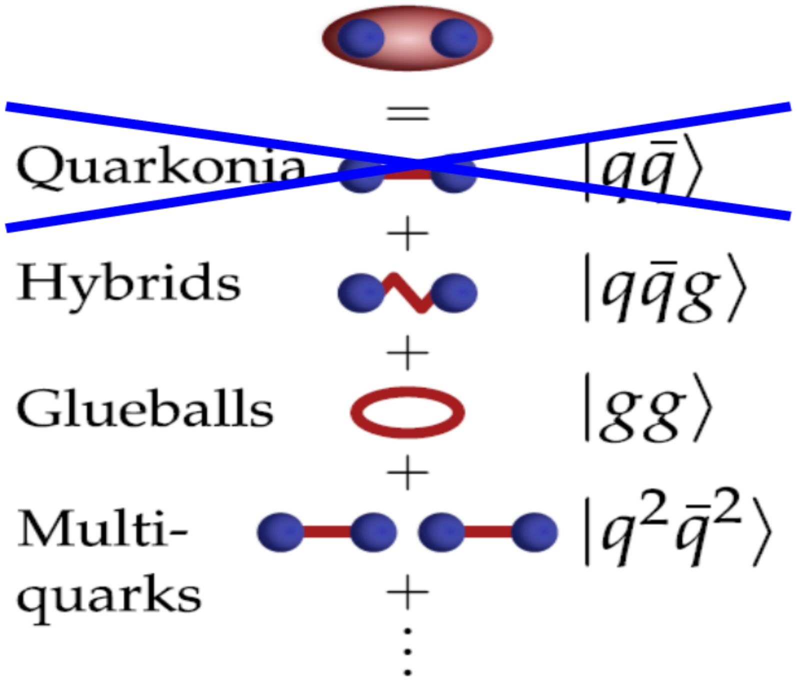
- ✓**Non-observation of $\eta(1295)$**
- ✓**$\eta(1405/1475)$ one state?➔ manifestations of TS**
- ✓**$X(2370) \to$ various decay modes**

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

Light hadrons with exotic quantum numbers

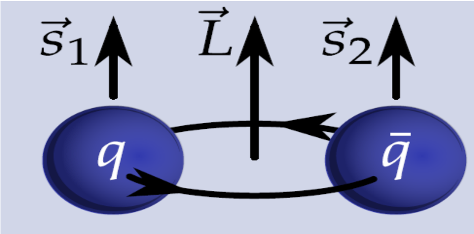
- **Unambiguous signature for exotics**
  - Light Flavor-exotic hard to establish
  - **Efforts concentrate on Spin-exotic**
    - **Forbidden for $q\bar{q}$:**

      $\mathbf{J^{PC} = 0^{--}, even^{+-}, odd^{-+}}$



Experiments:

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

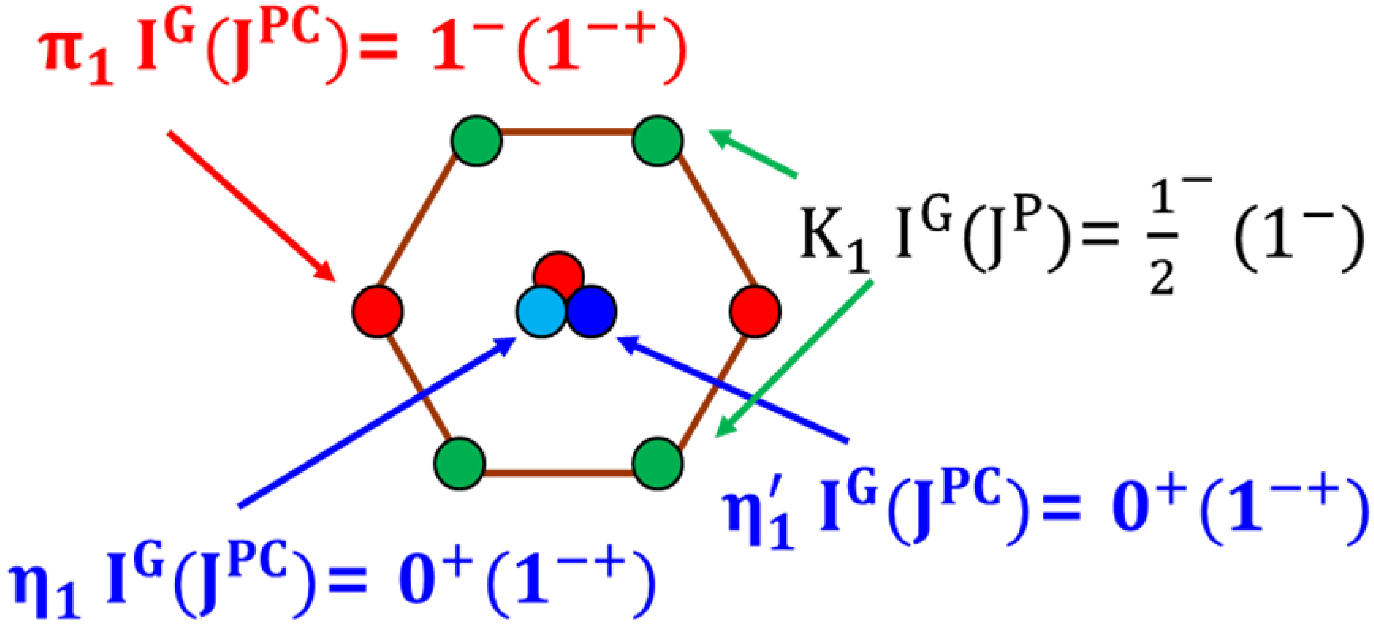


$\vec{J} = \vec{L} + \vec{S} \quad P = (-1)^{L+1} \quad C = (-1)^{L+S}$

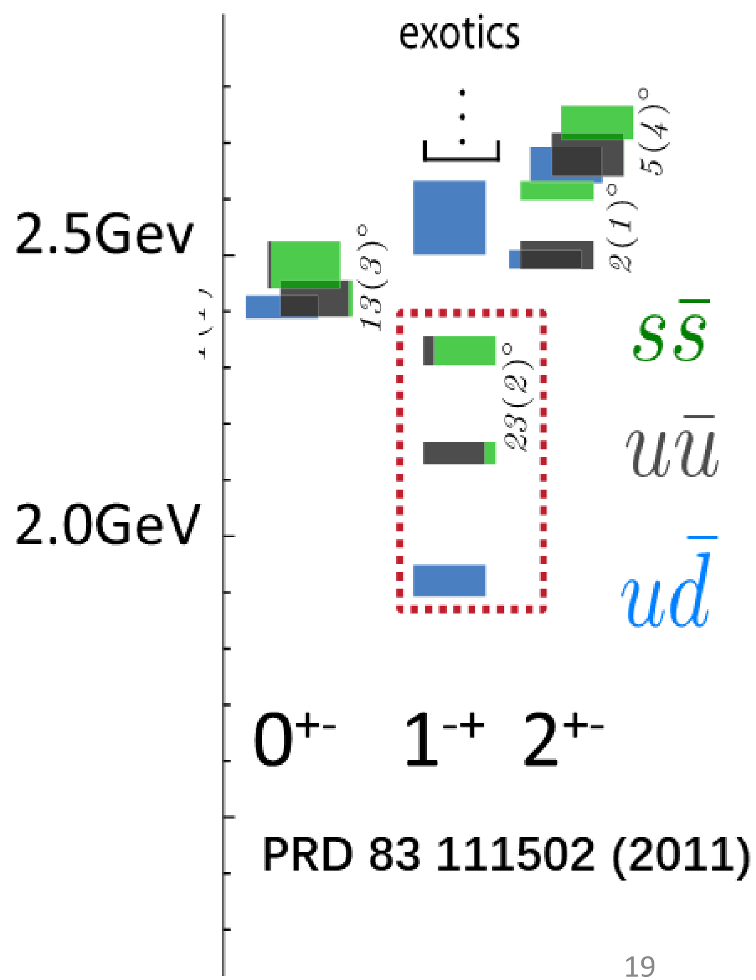
Allowed $\mathbf{J^{PC}: 0^{-+}, 0^{++}, 1^{--}, 1^{+-}, 2^{++}, \ldots}$

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**

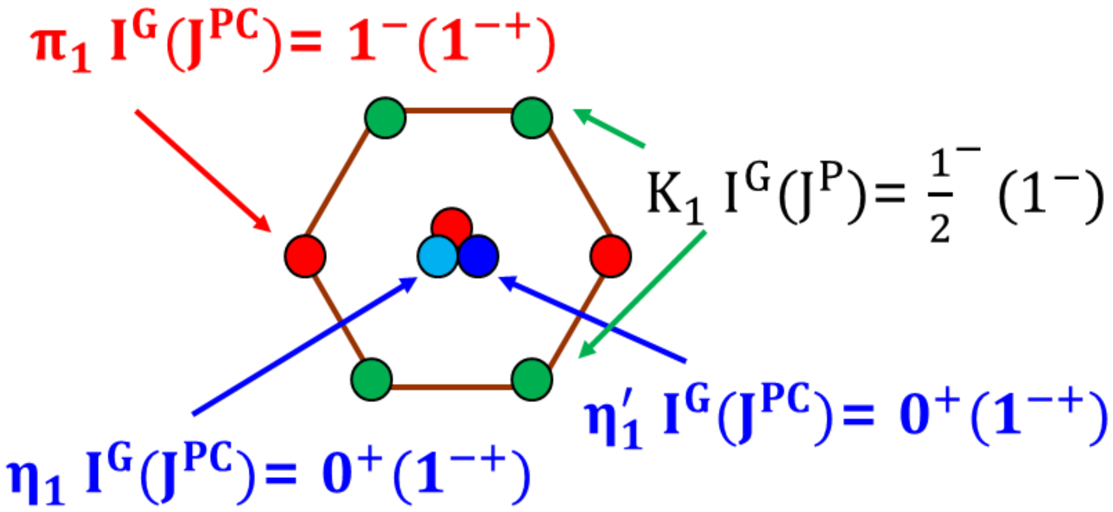


Lattice QCD Predictions:



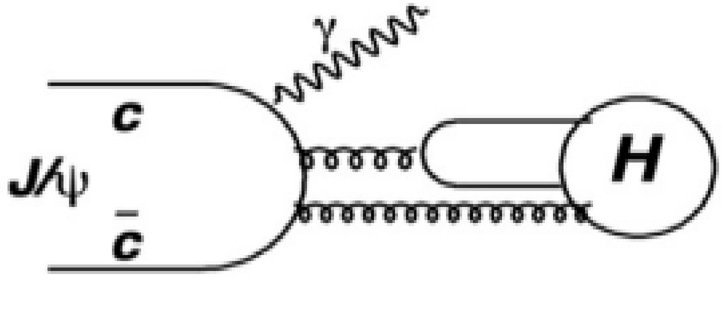
1^{-+} Hybrids

- **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), EP.J.P 135, 945(2020)

→ Search for $\eta_1\ (1^{-+})$ in $J/\psi \to \gamma\eta\eta'$



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

Observation of An Exotic Isoscalar State $\eta_1(1855)$ (1^{-+}) in $J/\psi \to \gamma\eta\eta'$

Phys. Rev. Lett. 129, 192002 (2022), Phys. Rev. D 106, 072012 (2022)

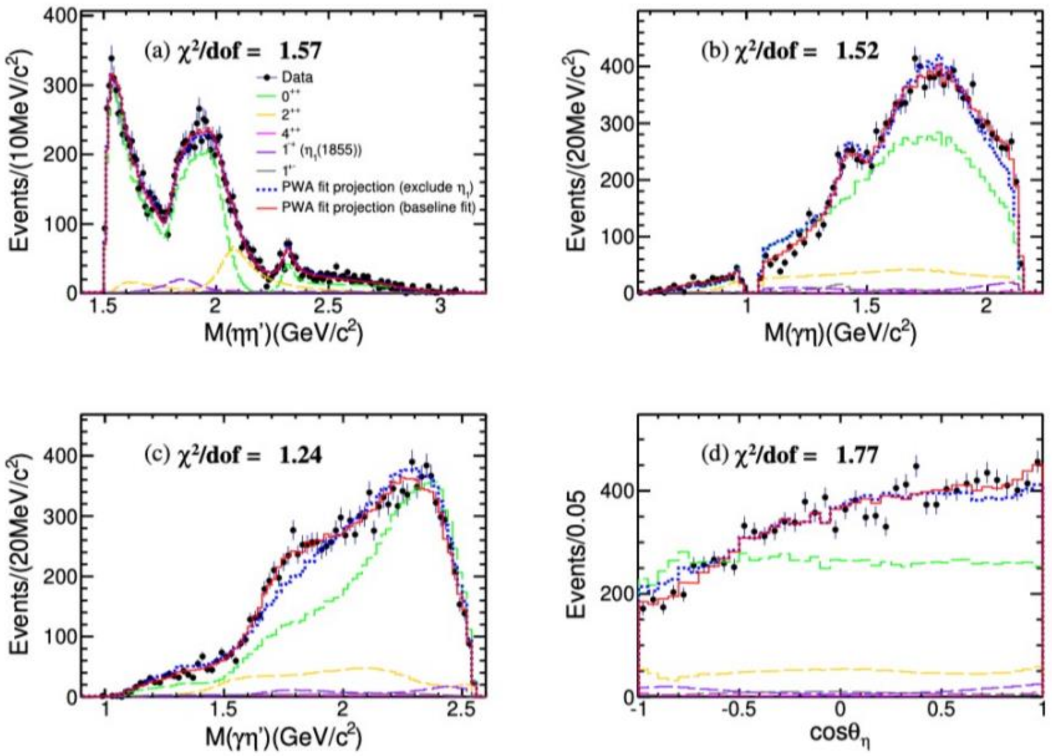
- The η' is reconstructed from $\gamma\pi^+\pi^-$ & $\eta\pi^+\pi^-$, η from $\gamma\gamma$
- Partial wave analysis of $J/\psi \to \gamma\eta\eta'$
  - Quasi two-body decay amplitudes in the sequential decay processes $J/\psi \to \gamma X, X \to \eta\eta'$ and $J/\psi \to \eta X, X \to \gamma\eta'$ and $J/\psi \to \eta' X, X \to \gamma\eta$ are constructed using the covariant tensor formalism and GPUPWA*

**World's first PWA framework with GPU acceleration*

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

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

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



- **Mass is consistent with LQCD calculation for the 1^{-+} hybrid $(1.7\sim2.1\ \mathrm{GeV}/c^2)$**
  - **Hybrid? Molecule? Tetraquark?**

Further Checks on the 1^{-+} State $\eta_1(1855)$

- Angular distribution as a function of $M(\eta\eta')$ expressed **model-independently**

$$\langle Y_l^0\rangle \equiv \sum_{i=1}^{N_k} W_i Y_l^0(cos\theta_\eta^i)$$

- Related to the spin-0(S), spin-1(P), spin-2(D) amplitudes in $\eta\eta'$ by:

$$\sqrt{4\pi}\langle Y_0^0\rangle = S_0^2 + P_0^2 + P_1^2 + D_0^2 + D_1^2 + D_2^2,$$

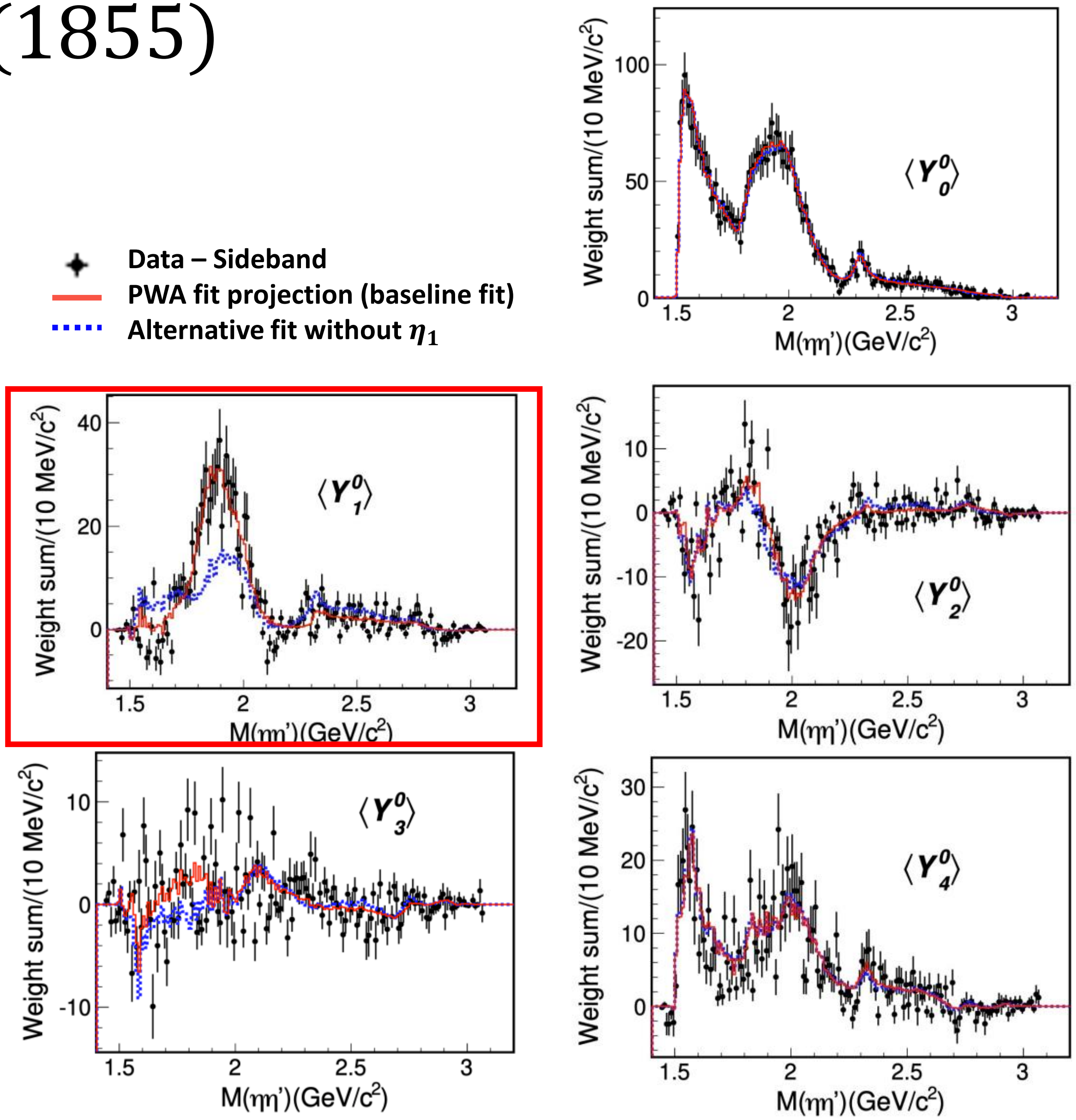
$$\sqrt{4\pi}\langle Y_1^0\rangle = 2S_0P_0\cos\phi_{P_0} + \frac{2}{\sqrt{5}}(2P_0D_0\cos(\phi_{P_0}-\phi_{D_0}) + \sqrt{3}P_1D_1\cos(\phi_{P_1}-\phi_{D_1})),$$

$$\sqrt{4\pi}\langle Y_2^0\rangle = \frac{1}{7\sqrt{5}}(14P_0^2 - 7P_1^2 + 10D_0^2 + 5D_1^2 - 10D_2^2) + 2S_0D_0\cos\phi_{D_0},$$

$$\sqrt{4\pi}\langle Y_3^0\rangle = \frac{6}{\sqrt{35}}(\sqrt{3}P_0D_0\cos(\phi_{P_0}-\phi_{D_0}) - P_1D_1\cos(\phi_{P_1}-\phi_{D_1})),$$

$$\sqrt{4\pi}\langle Y_4^0\rangle = \frac{1}{7}(6D_0^2 - 4D_1^2 + D_2^2).$$

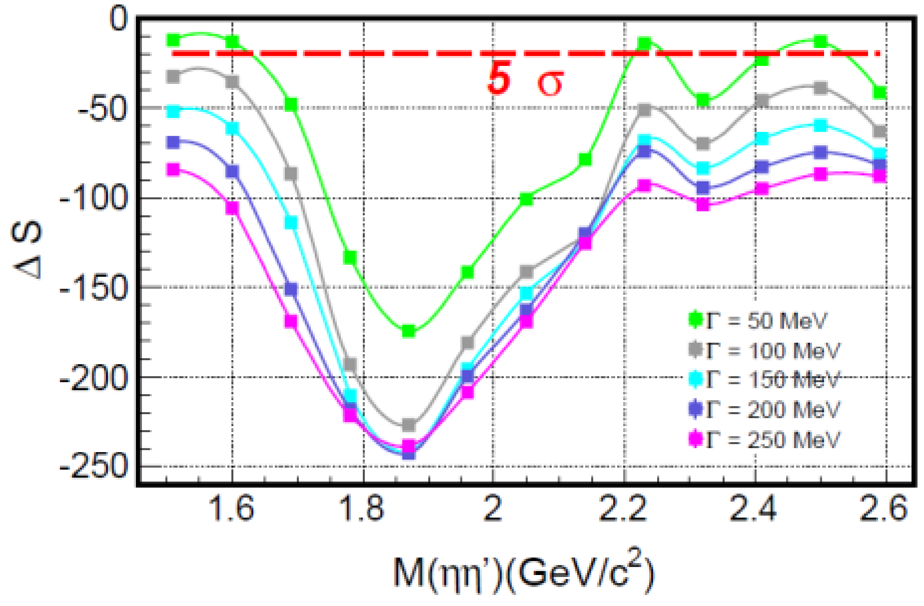
- **Narrow structure** in $\langle Y_1^0\rangle$
  - ➢**Cannot be described by resonances in $\gamma\eta(\eta')$**
  - **$\eta_1(1855)\to\eta\eta'$ needed**



Further Checks on the 1^{-+} State $\eta_1(1855)$

- Change $\mathbf{J^{PC}}$ of $\eta_1(1855)$: log-likelihood ↓235
  - ➢ **$\mathbf{J^{PC}}$ prefer $\mathbf{1^{-+}}$**
- Remove BW phase motion of $\eta_1(1855)$: log-likelihood ↓43
  - ➢ Resonance structure needed
- Assuming $\eta_1(1855)$ as additional resonance, evaluate its significance with various masses and widths
  - ➢ Significant 1^{-+} contribution around $1.8\ \mathrm{GeV/c^2}$ needed
- Systematic uncertainties are studied, and significance of $\eta_1(1855)$ **remains larger than $\mathbf{19\sigma}$** in all cases

significance of $\eta_1(1855)$ with various masses and widths



Discussions about $f_0(1500)$ & $f_0(1710)$

- Significant $f_0(1500)$

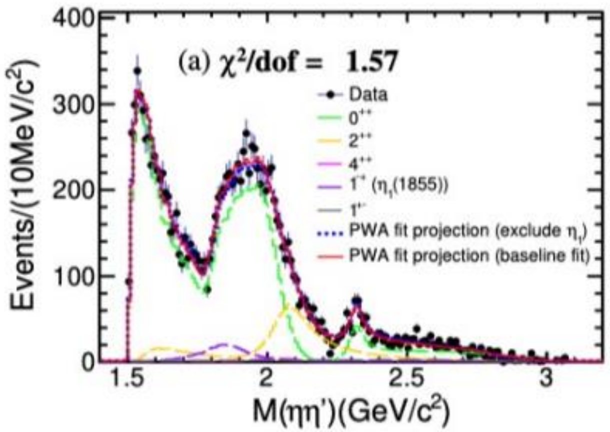
$$\frac{B(f_0(1500) \to \eta\eta')}{B(f_0(1500) \to \pi\pi)} = (1.66^{+0.42}_{-0.40}) \times 10^{-1}$$

consistent with PDG

- **Absence of $f_0(1710)$**

$$\frac{B(f_0(1710) \to \eta\eta')}{B(f_0(1710) \to \pi\pi)} < 2.87 \times 10^{-3} \text{ @90\% C.L.}$$

➢ Supports to the hypothesis that $f_0(1710)$ overlaps with the ground state scalar glueball
  - Scalar glueball expected to be suppressed $B(G \to \eta\eta')/B(G \to \pi\pi) < 0.04$



Decay mode	Resonance	M (MeV/c^2)	Γ (MeV)	$M_{\rm PDG}$ (MeV/c^2)	$\Gamma_{\rm PDG}$ (MeV)	B.F. ($\times 10^{-5}$)	Sig.
$J/\psi \to \gamma X \to \gamma\eta\eta'$	$f_0(1500)$	1506	112	1506	112	$1.81\pm0.11^{+0.19}_{-0.13}$	$\gg 30\sigma$
	$f_0(1810)$	1795	95	1795	95	$0.11\pm0.01^{+0.04}_{-0.03}$	11.1σ
	$f_0(2020)$	$2010\pm6^{+6}_{-4}$	$203\pm9^{+13}_{-11}$	1992	442	$2.28\pm0.12^{+0.29}_{-0.20}$	24.6σ
	$f_0(2330)$	$2312\pm7^{+7}_{-3}$	$65\pm10^{+3}_{-12}$	2314	144	$0.10\pm0.02^{+0.01}_{-0.02}$	13.2σ
	$\eta_1(1855)$	$1855\pm9^{+6}_{-1}$	$188\pm18^{+3}_{-8}$	-	-	$0.27\pm0.04^{+0.02}_{-0.04}$	21.4σ
	$f_2(1565)$	1542	122	1542	122	$0.32\pm0.05^{+0.12}_{-0.02}$	8.7σ
	$f_2(2010)$	$2062\pm6^{+10}_{-7}$	$165\pm17^{+10}_{-5}$	2011	202	$0.71\pm0.06^{+0.10}_{-0.06}$	13.4σ
	$f_4(2050)$	2018	237	2018	237	$0.06\pm0.01^{+0.03}_{-0.01}$	4.6σ
	0^{++} PHSP	-	-	-	-	$1.44\pm0.15^{+0.10}_{-0.20}$	15.7σ
$J/\psi \to \eta' X \to \gamma\eta\eta'$	$h_1(1415)$	1416	90	1416	90	$0.08\pm0.01^{+0.01}_{-0.02}$	10.2σ
	$h_1(1595)$	1584	384	1584	384	$0.16\pm0.02^{+0.03}_{-0.01}$	9.9σ

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**

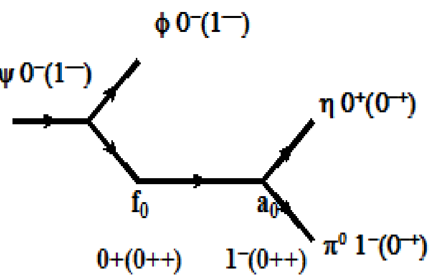
- Glueballs
- Spin-exotic states
- Threshold structures & multi-quark states

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

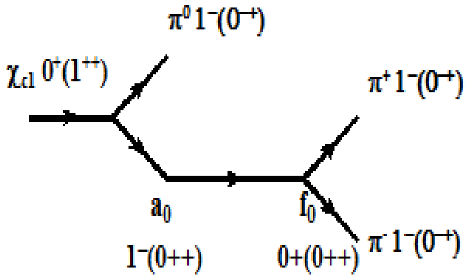
- The nature of ground state scalar $a_0(980)$ and $f_0(980)$ are controversial

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

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

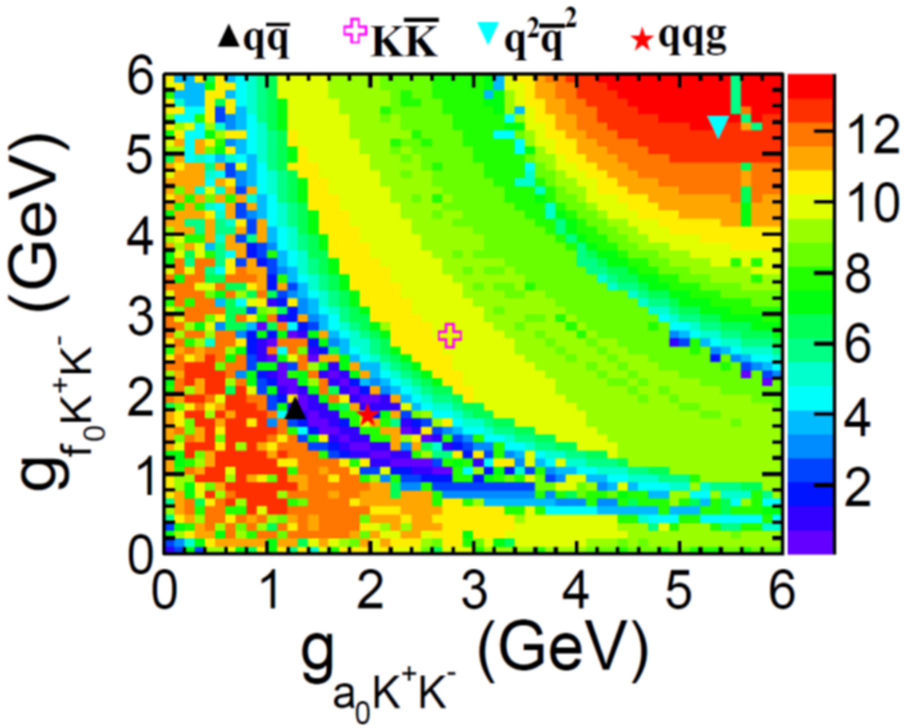


PR D75 114012, PR D76 074028



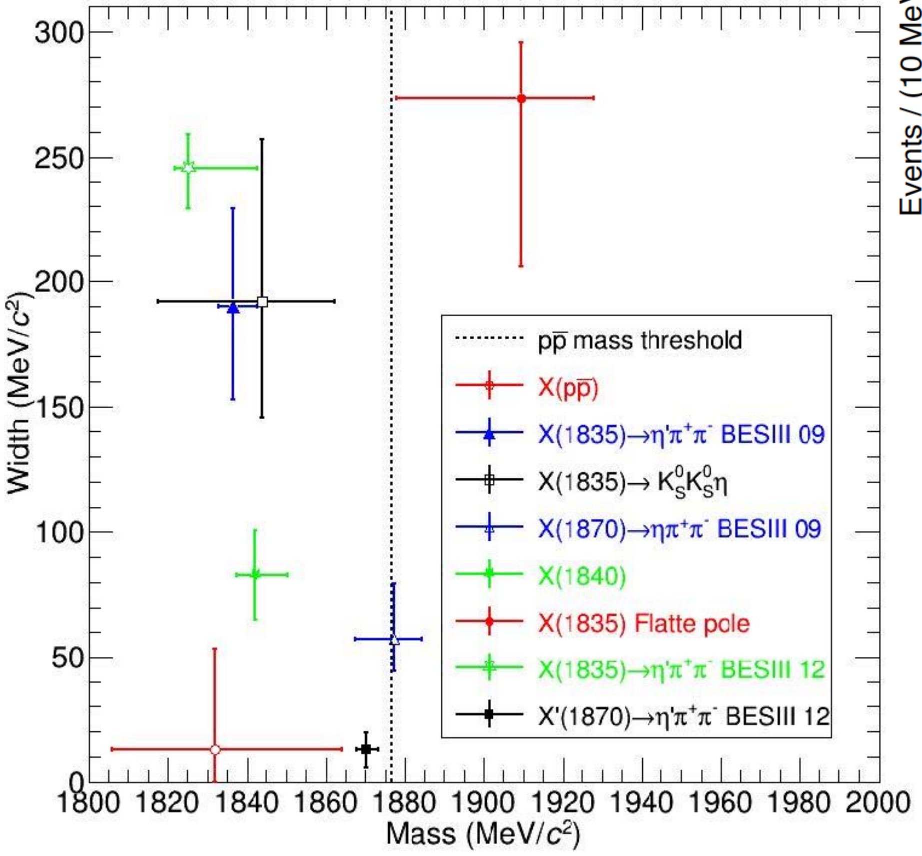
PR D78 074017

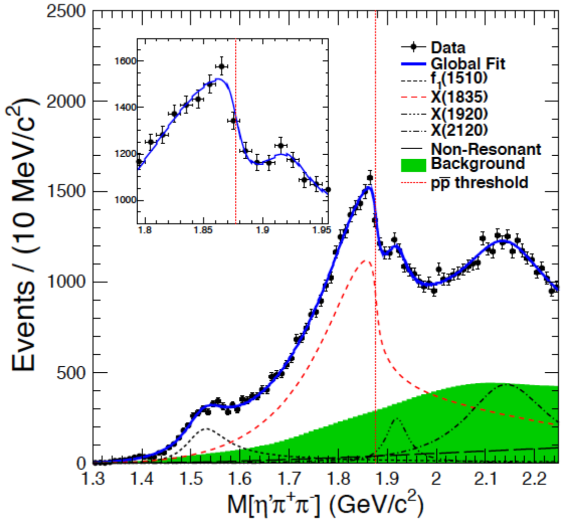
- First direct measurement with > 5σ



BESIII PRL 121 022001

Structures around $p\bar{p}$ threshold

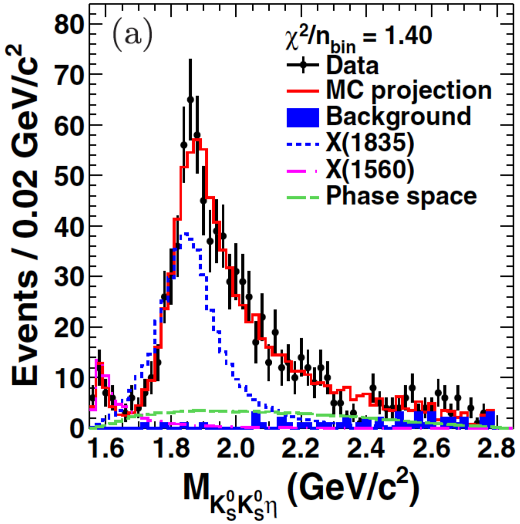




$J/\psi \to \gamma \eta' \pi^+ \pi^-$

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)

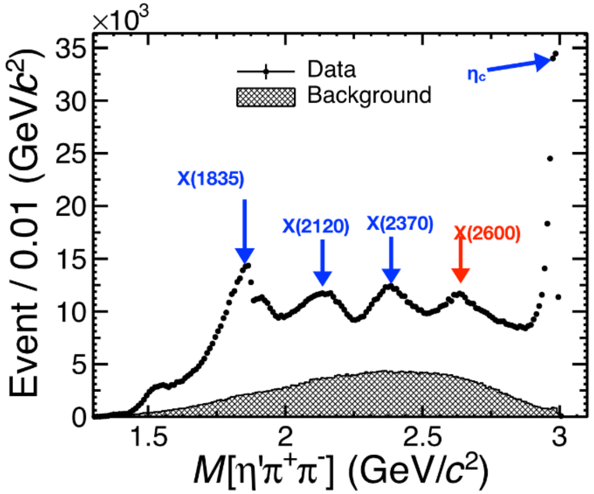
J^{PC} of X(1835) is determined to be 0^{-+}

Power of statistics

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

10B J/ψ

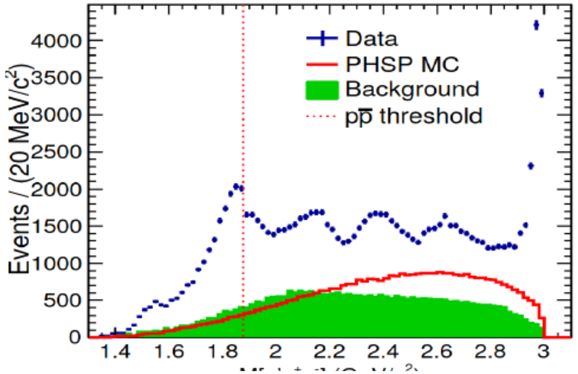
BESIII PRL 129, 042001 (2022)



Observation of X(2600)

1.3B J/ψ

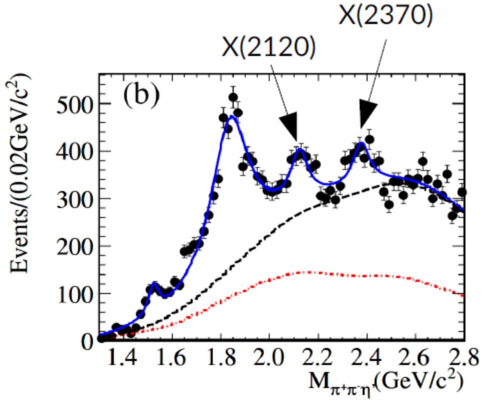
BESIII PRL 117 042002(2016)



Observation of anomalous line shape

225M J/ψ

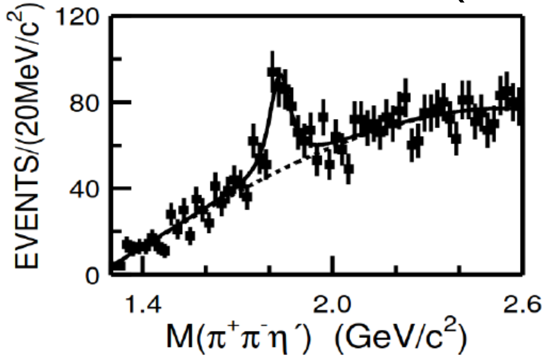
BESIII PRL 106 072002(2011)



Observation of X(2120), X(2370)

58 M J/ψ

BESII PRL 95 262001(2005)

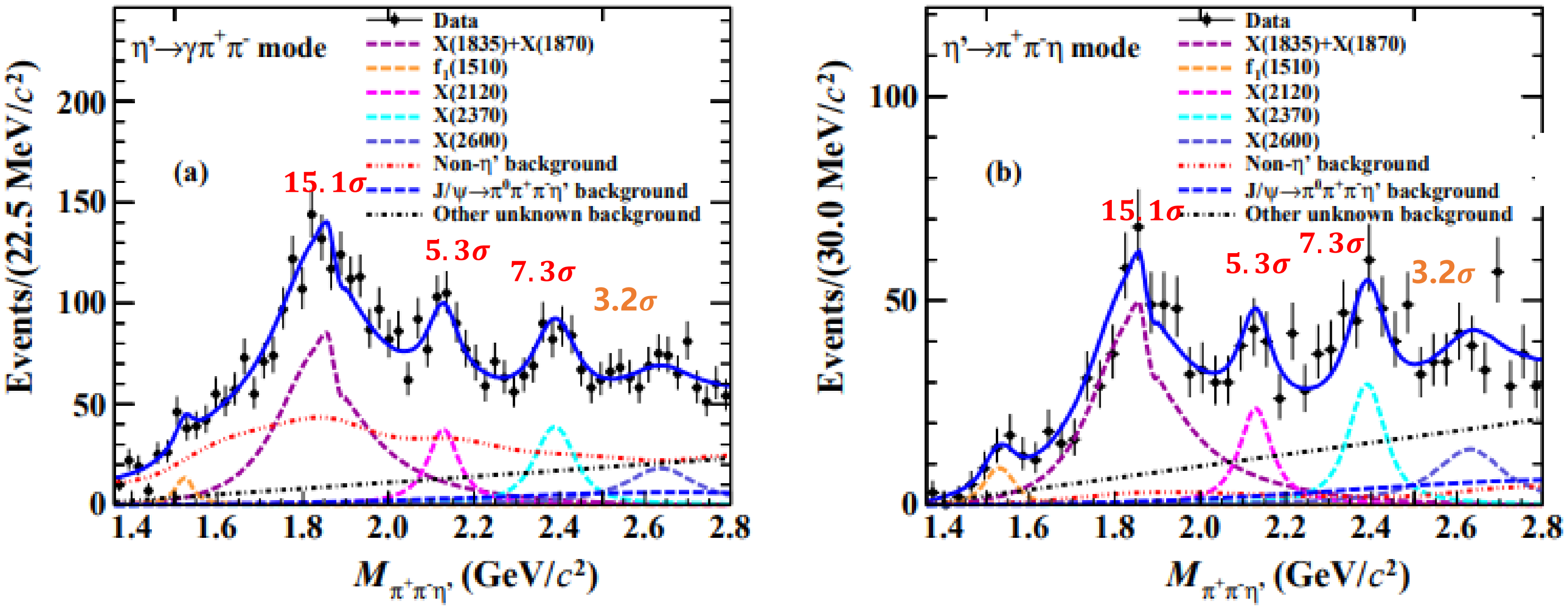


Observation of X(1835)

Observation of X(1835), X(2120) and X(2370) in J/ψ EM Dalitz Decays

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

- **Confirmation** of $\mathbf{X(1835)}, \mathbf{X(2120)}, \mathbf{X(2370)}$ previously observed in $J/\psi \to \gamma\pi^+\pi^-\eta'$



PRL 129 (2022) 2, 022002

reconstruct η' from $\gamma\pi^+\pi^-$(left) & $\eta(\to\gamma\gamma)\pi^+\pi^-$ (right)

Observation of X(1835), X(2120) and X(2370) in J/ψ EM Dalitz Decays

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

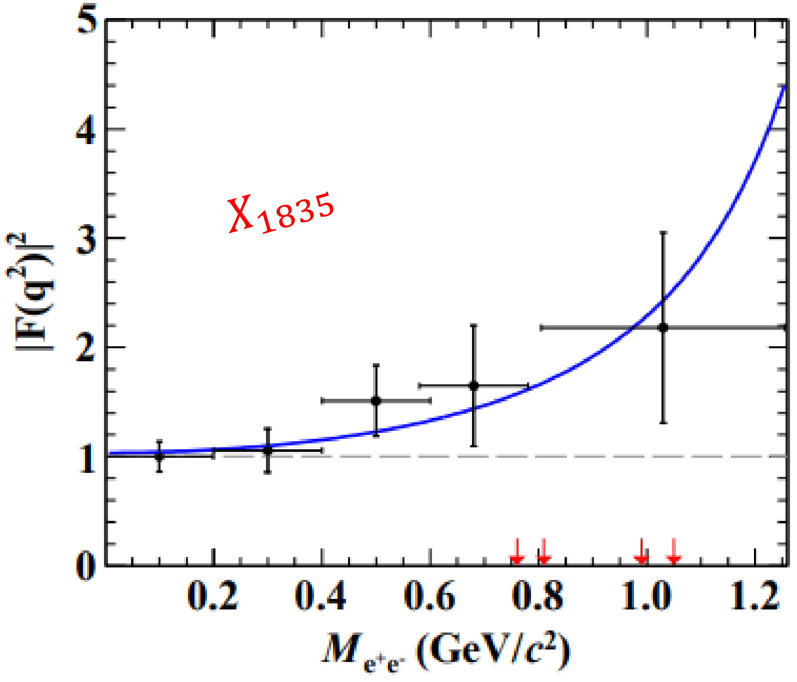
- Measurement of the **Transition Form Factor** of $J/\psi \to e^+e^-X(1835)$
  - the structure-dependent partial width can be modified by transition form factor, which provides information of the EM structure

PRL 129 (2022) 2, 022002

$$\frac{d\Gamma(J/\psi \to X(1835)e^+e^-)}{dq^2\Gamma(J/\psi \to X(1835)\gamma)} = \left|F(q^2)\right|^2 \times [QED(q^2)]$$

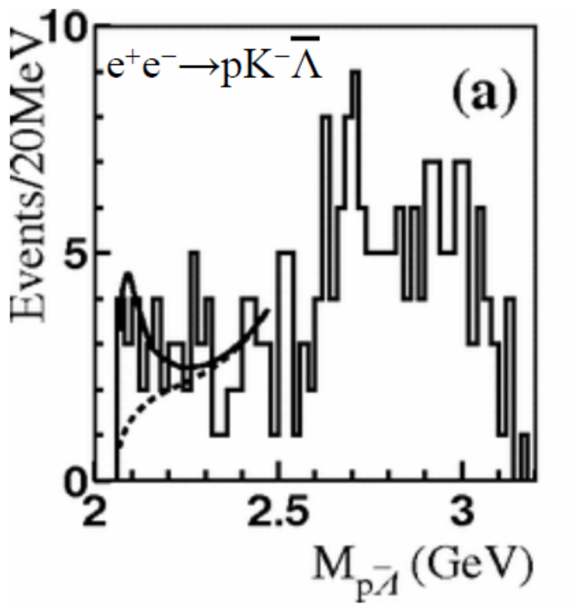
$$F(q^2) = \frac{1}{1 - q^2/\Lambda^2}$$

$$\Lambda = 1.75 \pm 0.29 \pm 0.05\ GeV/c^2$$

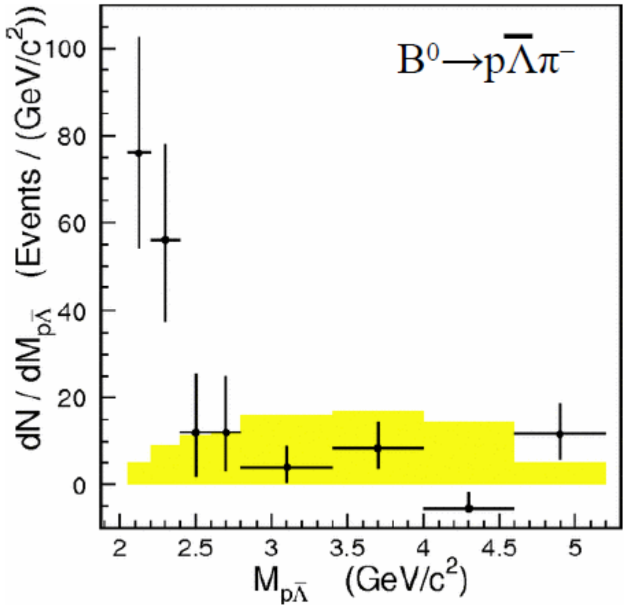


Narrow structure in $p\bar{\Lambda}$

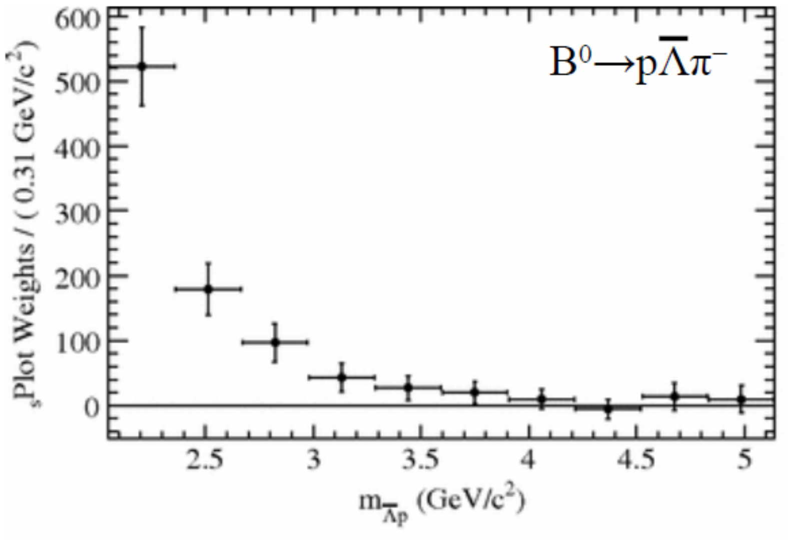
BES, PRL93, 112002 (2004)



BELLE, PRL90, 201802 (2003)



BaBar, PRD79, 112009 (2009)

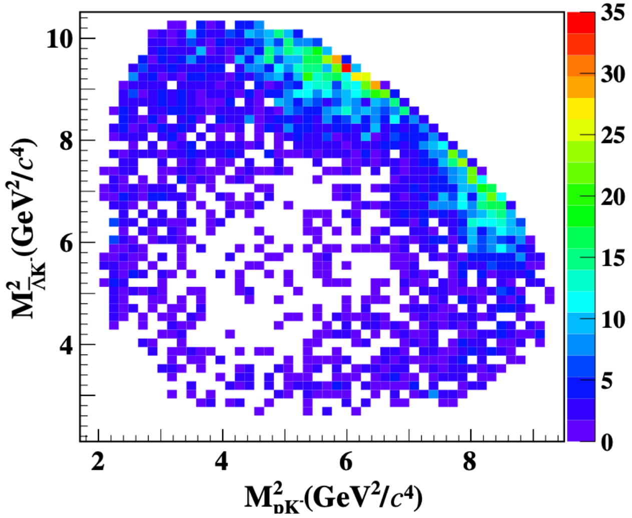


- Different scenarios investigated: baryonium state [PRD74,014029], baryon-antibaryon SU(3) nonets [PLB626,95], final state interaction [IJMPA22,5401], …

$e^+e^- \to pK^-\bar{\Lambda}$

arXiv:2303.01989

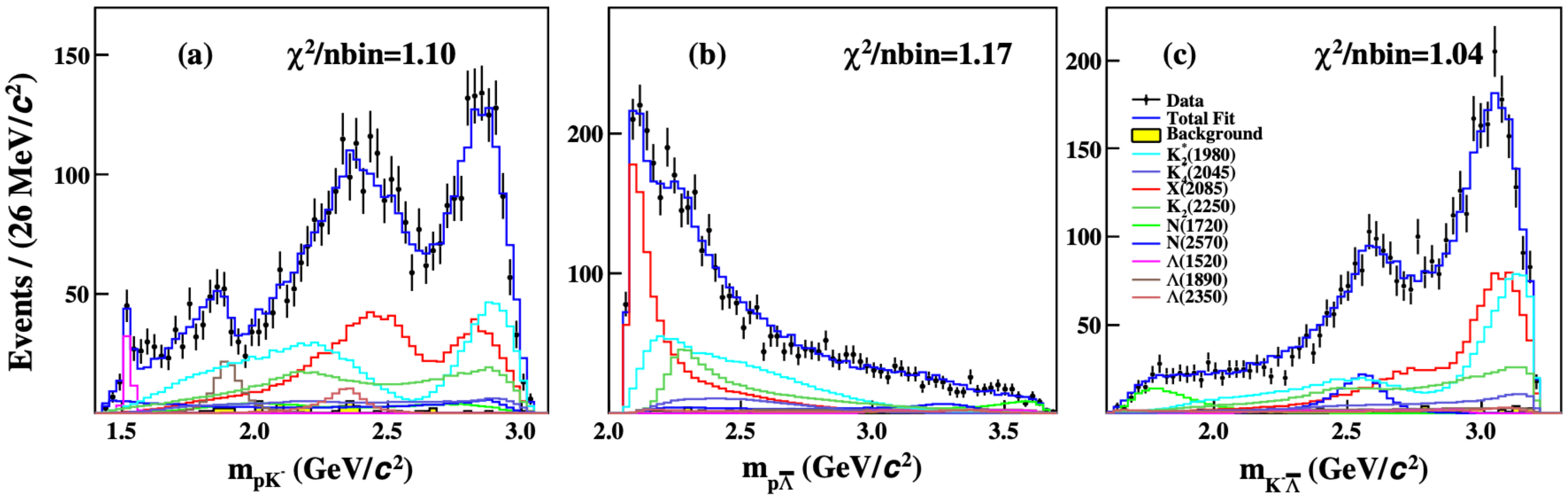
6 different center of mass energies between 4.008 GeV to 4.682 GeV



- Significant near threshold enhancement in the $p\bar{\Lambda}$
- X(2085):
  - observed with statistical significance > 20σ
  - $J^P = 1^+$ with statistical significance > 5σ over other quantum numbers

$$M_{pole} = (2086 \pm 4 \pm 6)\,\text{MeV} \quad \Gamma_{\text{pole}} = (56 \pm 5 \pm 16)\,\text{MeV}$$

- No matching with any state predicted by the potential model + narrow width ➔exotic properties of X(2085)
- Same structure as in PRL93, 112002 ?



Prospects

- Data with unprecedented statistical accuracy from BESIII provides great opportunities to study light hadron spectroscopy
  - Further reveal the gluonic admixture in $\mathrm{f_0(1710)}$, $\mathrm{f_2(2340)}$, $\mathrm{X(2370)}$ 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($\mathrm{p\bar{p}}$) 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 $\eta_1(1855)$,……**
- Critical collaboration with theory

Thank you