A few highlights of light QCD exotics

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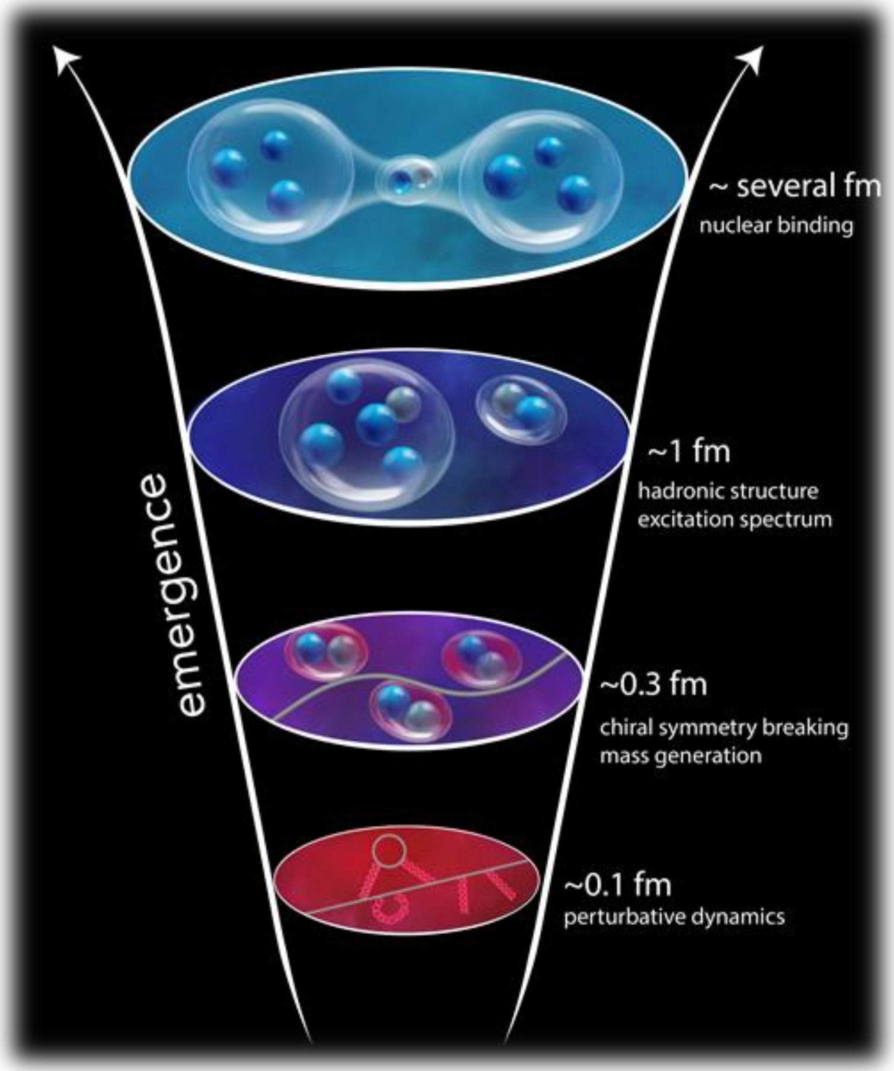
第六届强子谱和强子结构研讨会, 北京

Hadrons

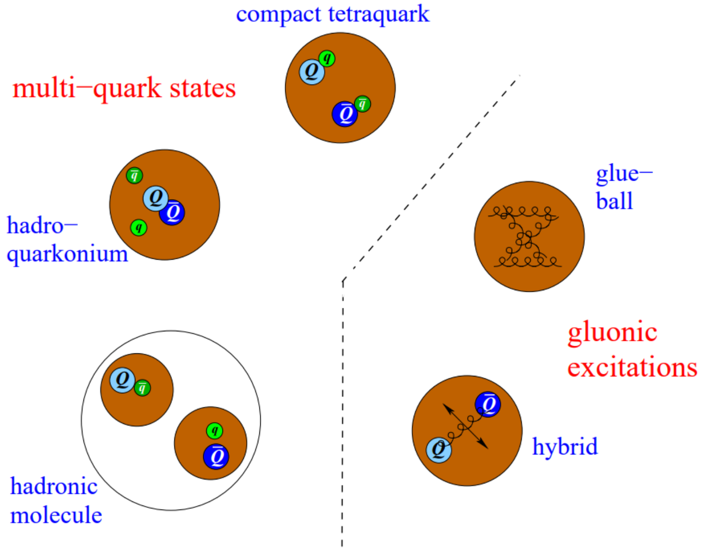
- Hadrons: complex building block of the visible universe
- Emergence of hadron structure
  - How are hadrons formed from quarks?
  - What is the origin of confinement?
  - How is the mass of hadron generated in QCD?
  - What is the dynamics of effective DoF in hadrons?

→ **spectroscopy**



arXiv:2306.09360

Hadron spectroscopy



Phys.Rept. 873 (2020) 1

- **How does QCD give rise to hadrons?**
  - **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
    https://qwg.ph.nat.tum.de/exoticshub/
  - **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

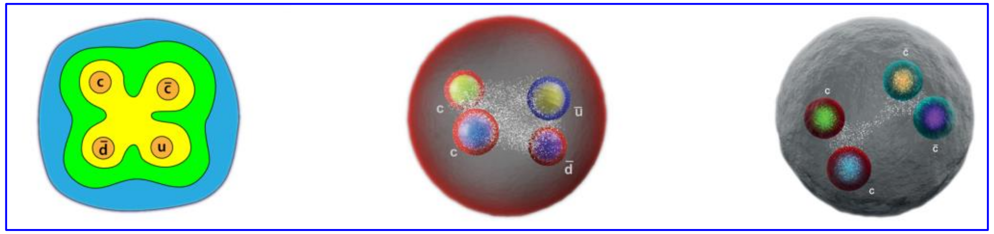
Light QCD exotics

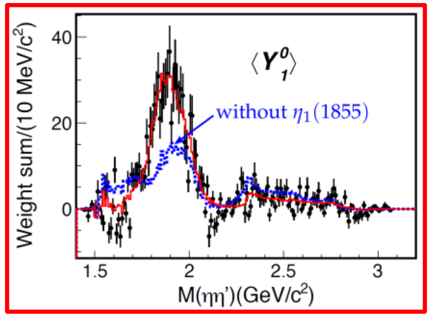
QCD exotics

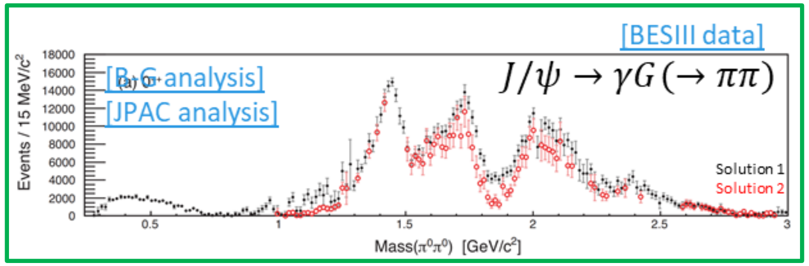
How to identify:

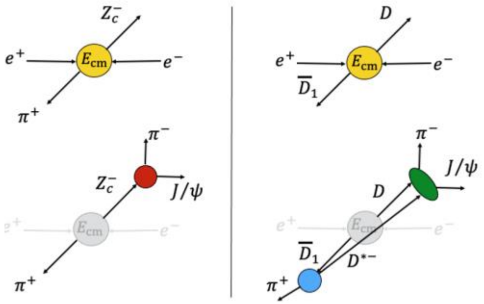
- Manifestly exotic
  - Flavor exotic
  - Spin exotic: $\mathbf{J^{PC} = 0^{--}, even^{+-}, odd^{-+}}$
- Crypto exotic
  - Supernumerary states
  - Abnormal properties

\+ kinematics









Synergies in new era of precision spectroscopy

- From serendipitous discoveries of new states to the systematic study of spectral properties and patterns
- High statistics → emergence of new properties/phenomena
- Test QCD with various probes

Heavy ⟷ Light

EM probe

e^+e^-

Belle II BESIII

γp

EIC GlueX CLAS12

Hadronic probe

pp

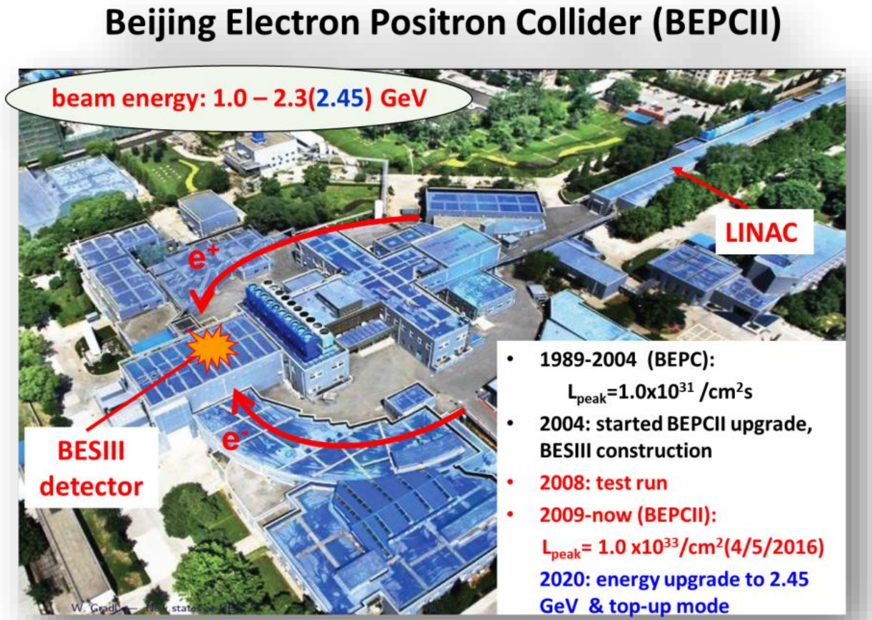
LHCb CMS ATLAS

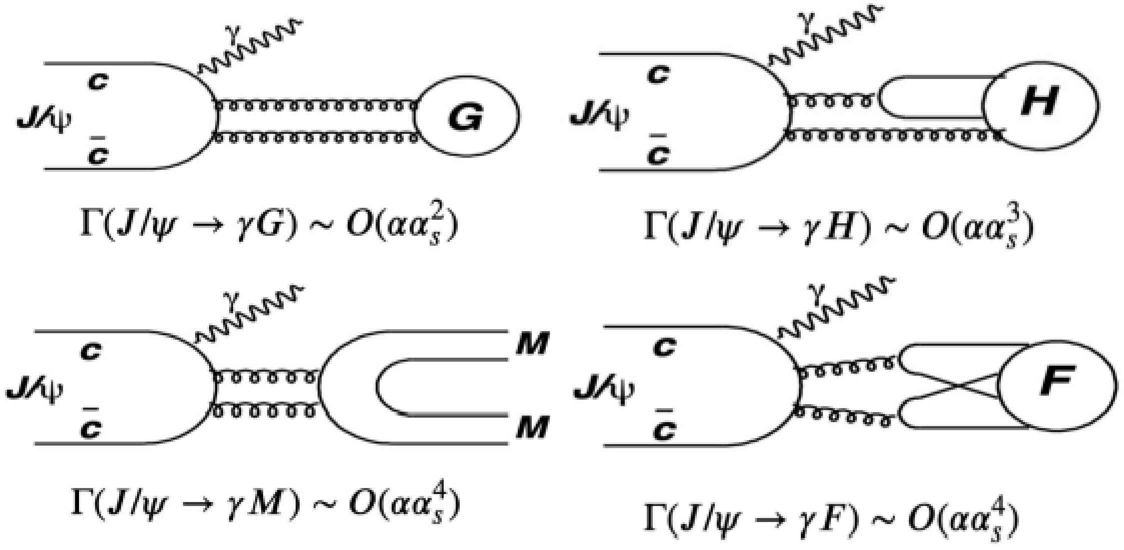
$\bar{p}p$

panda

πp

COMPASS AMBER





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

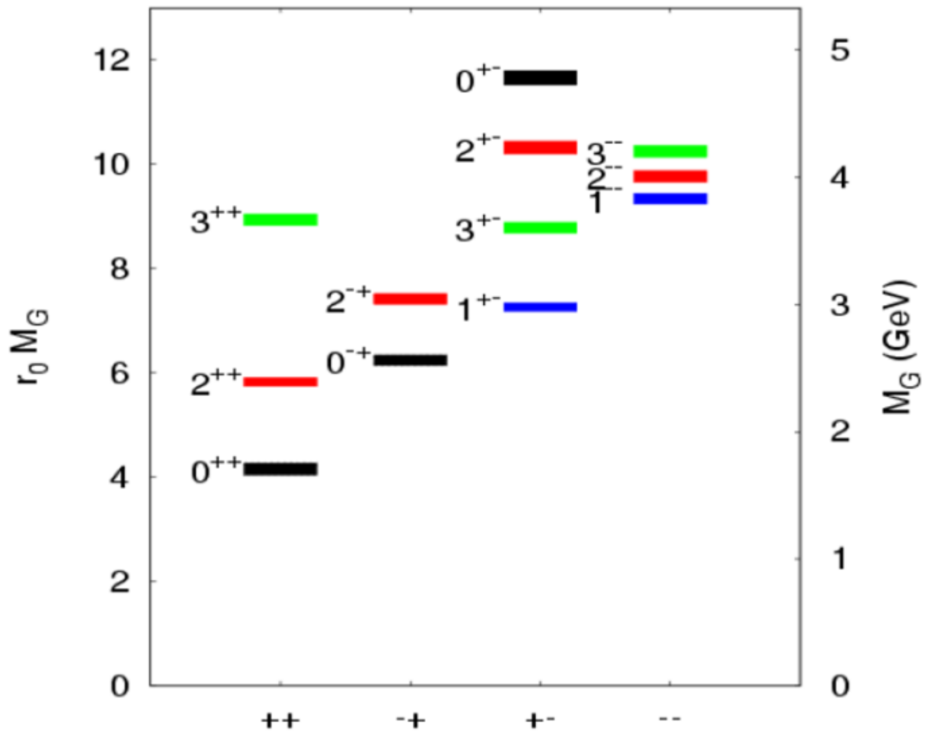
- **Low-lying glueballs with ordinary J^{PC}**

→ 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

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

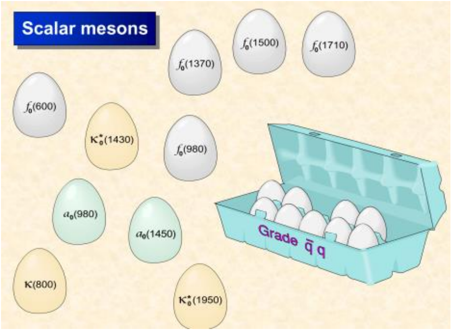
-- from MarkIII, BES, Crystal barrel, OBELIX, WA102, GAMS, E852, ...

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

Exp: overpopulation

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

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



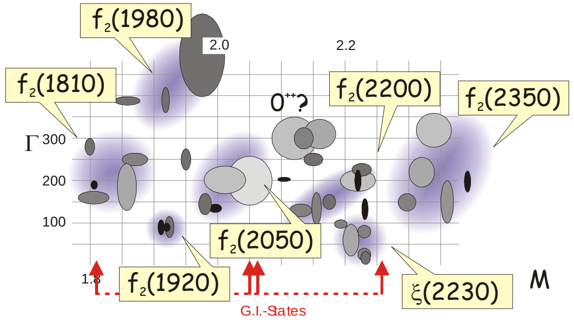
$f_0(1370)$, $f_0(1500)$, $f_0(1710)$

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

Exp: large uncertainty

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

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

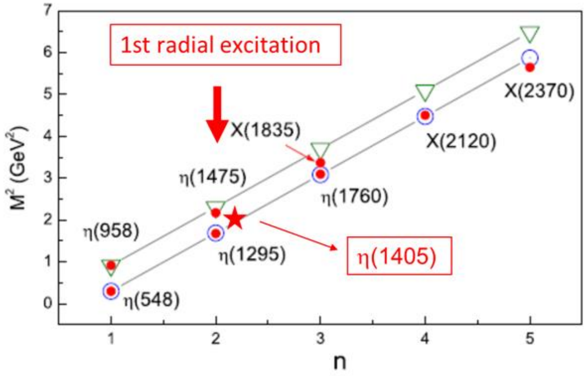


Pseudoscalar: η & η′ , "simple"

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

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

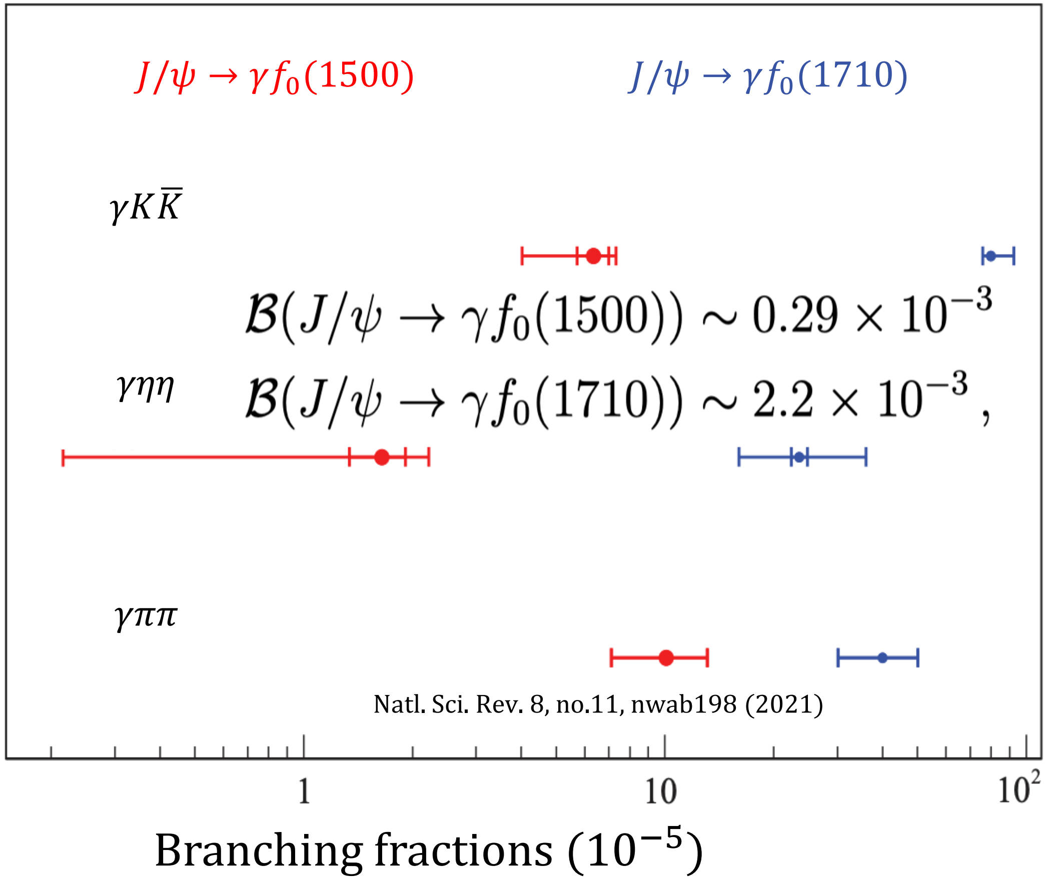
$$\Gamma(J/\psi \to \gamma G_{0-})/\Gamma_{total} = 2.31(80) \times 10^{-4}$$



Scalar glueball candidate: production properties

- **Scalar glueball is expected to have a large production in $\mathbf{J/\psi}$ 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)

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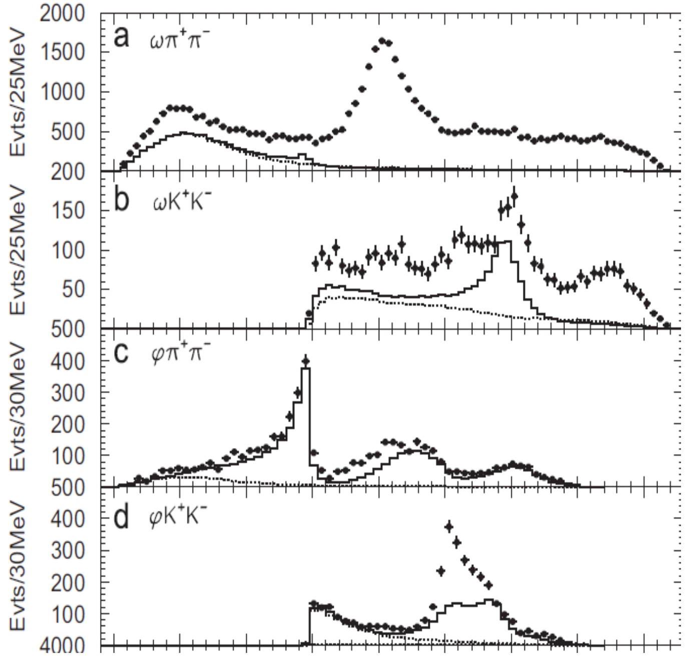
We perform a systematic analysis of the $J/\psi \to \gamma\pi^0\pi^0$ and $\to \gamma K^0_S K^0_S$ partial waves measured by BESIII. We use a large set of amplitude parametrizations to reduce the model bias. We determine the physical properties of seven scalar and tensor resonances in the 1–2.5 GeV mass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

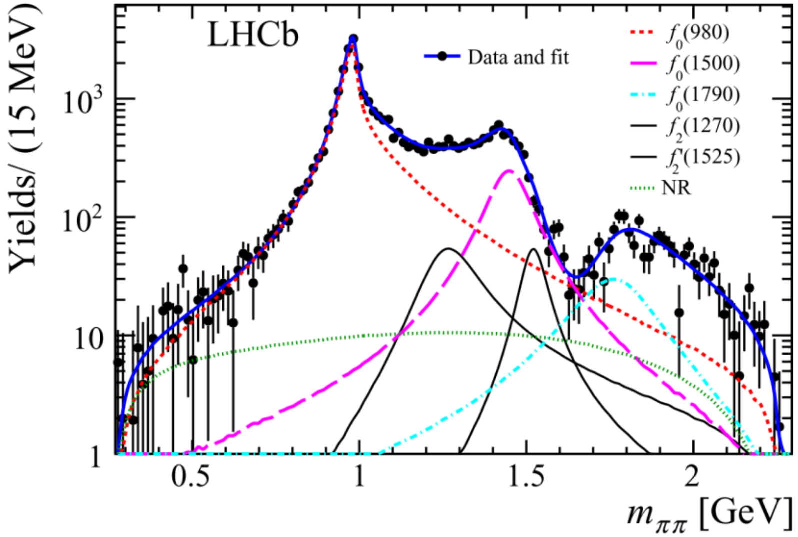
$\phi\pi^+\pi^-$ ➔ Enhancement at 1790 MeV/c^2

ϕK^+K^- ➔ No peak around 1700 MeV/c^2

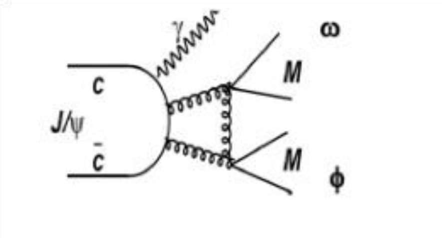
$f_0(1800)$

$B_s \to J/\psi f_0$ is selective for $s\bar{s}$

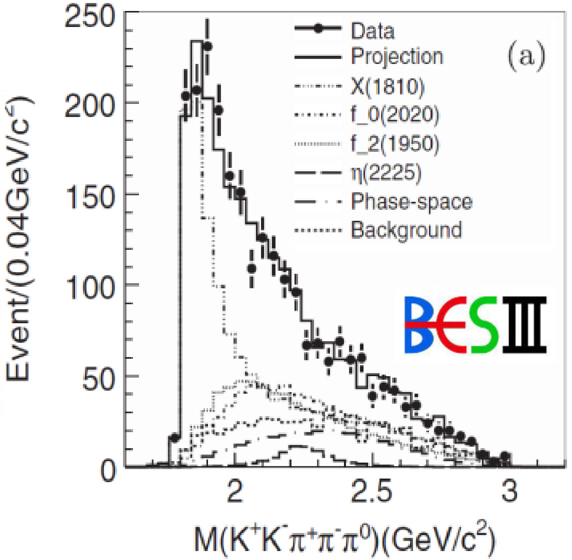
PLB 797 (2019) 134789



PRD 87, 032008(2013)



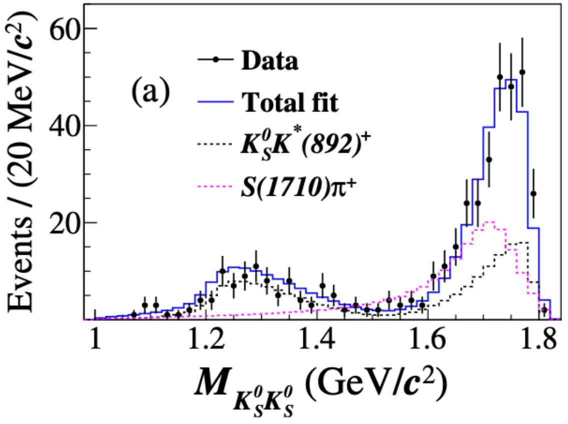
$J/\psi \to \gamma\omega\phi$ (DOZI)



$a_0(1817)$

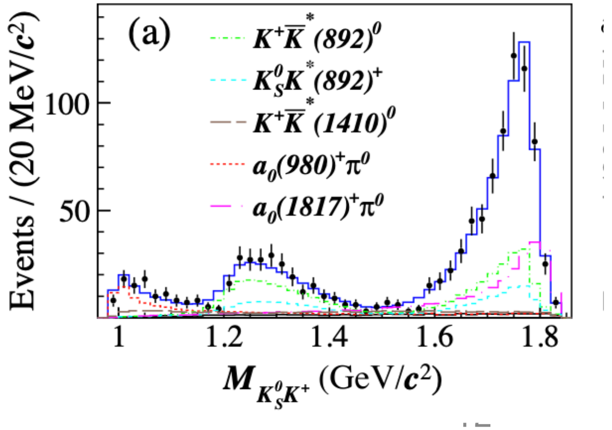
PRD105, L051103 (2022)

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



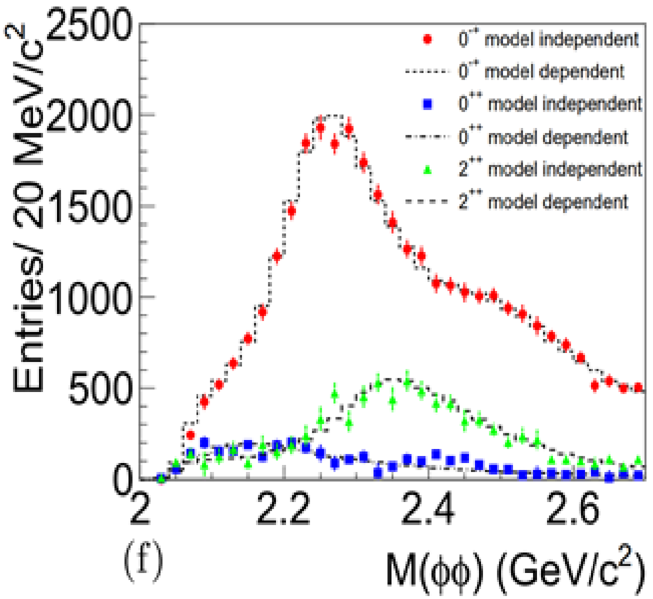
PRL129, 182001 (2022)

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



Tensor glueball candidate

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



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

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)

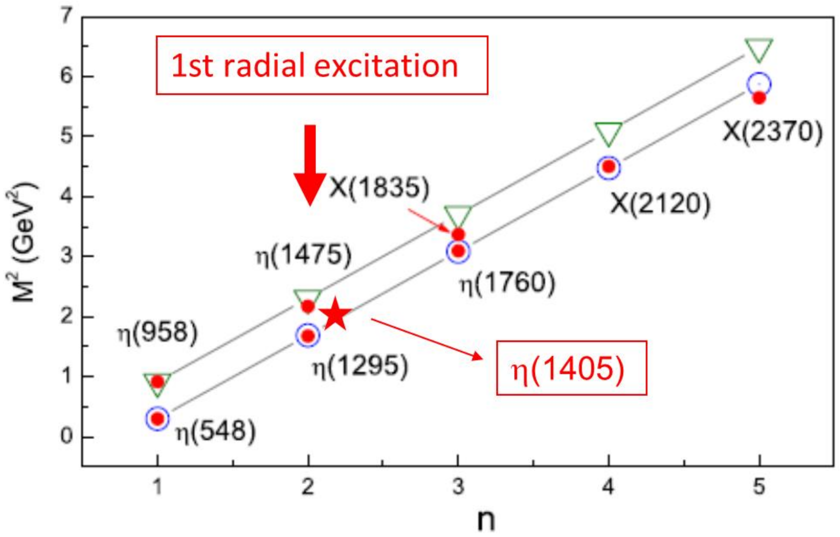
$$\mathbf{Br(J/\psi \to \gamma f_2(2340) \to \gamma\eta'\eta') = \left(8.67 \pm 0.70^{+0.16}_{-1.67}\right) \times 10^{-6}}$$

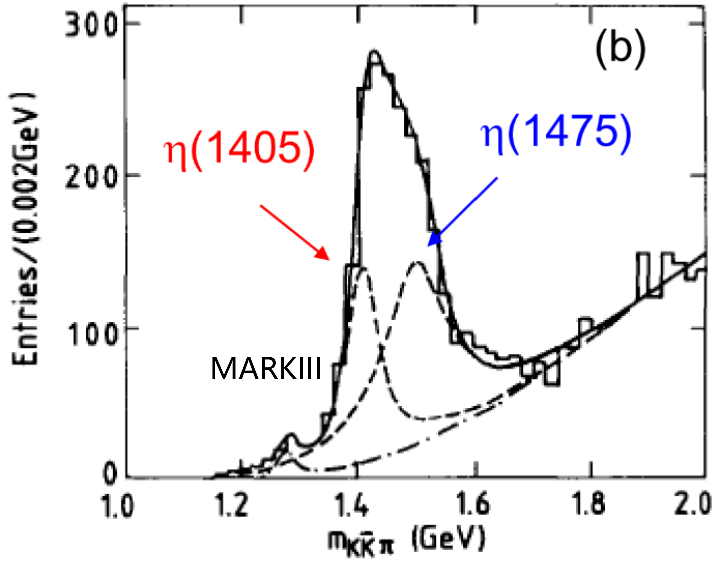
BESIII PRD 105,072002 (2022)

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

It is desirable to search for more decay modes

Pseudoscalars





Where is the 0^{-+} glueball

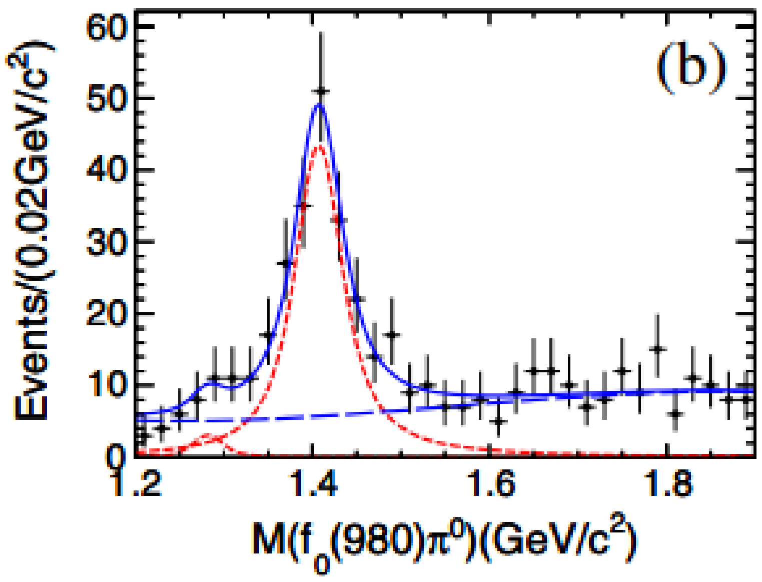
- LQCD： 0^{-+}(2.3~2.6 GeV)
- Does $\eta(1295)$ exist?
- What' s the nature of the outnumbered $\eta(1405)$?

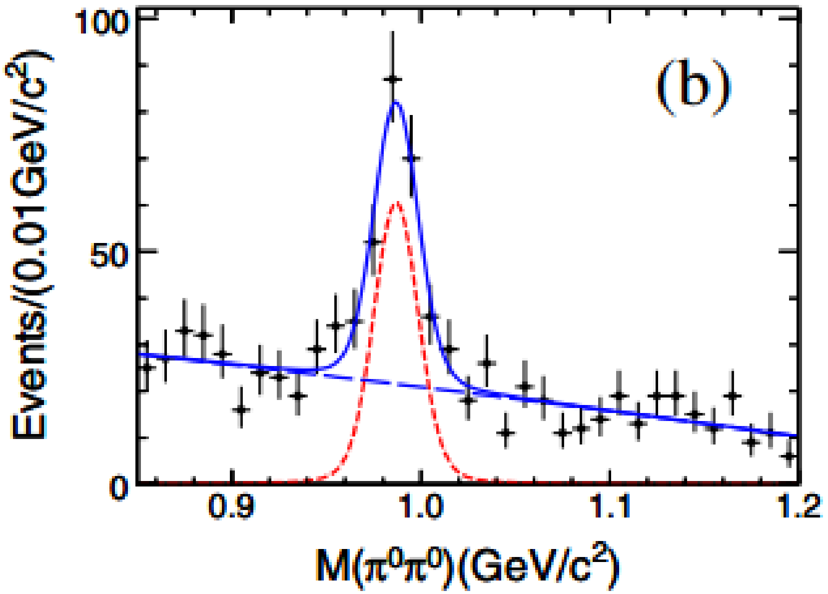
Long standing E-ι puzzle

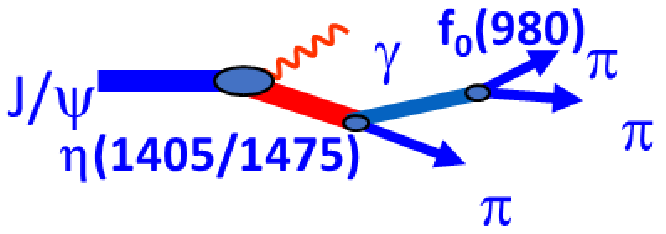
$$M = 1416 \pm 8^{+7}_{-5};\ \Gamma = 91^{+67}_{-31-38}{}^{+15}\ \mathrm{MeV}/c^2$$

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

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







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:

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

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

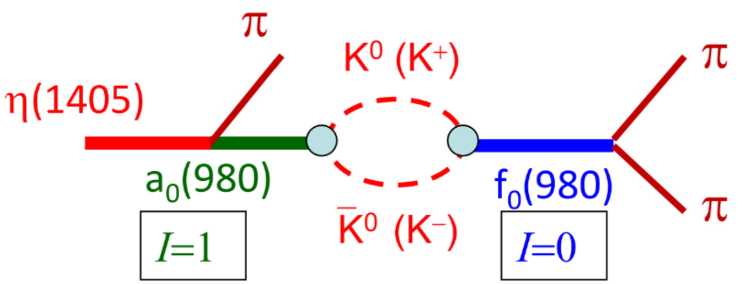
PRD, 83(2100)032003

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

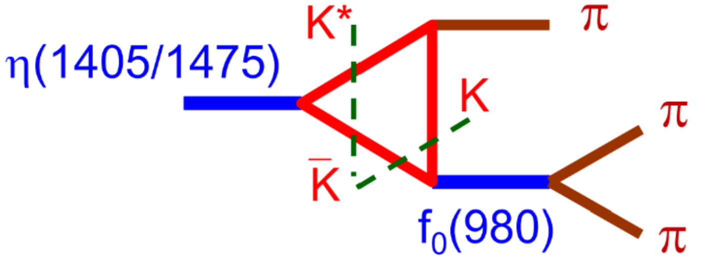
BESIII PRL 108 182001(2012)

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

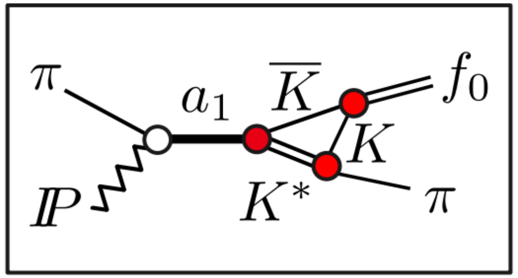
- Manifested in many near-threshold structures



PRL 108 081803 (2012)



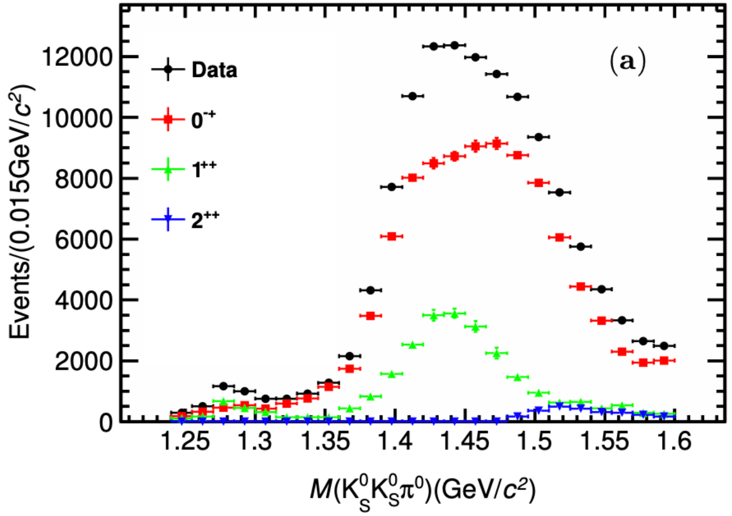
a₁(1420) COMPASS@CERN



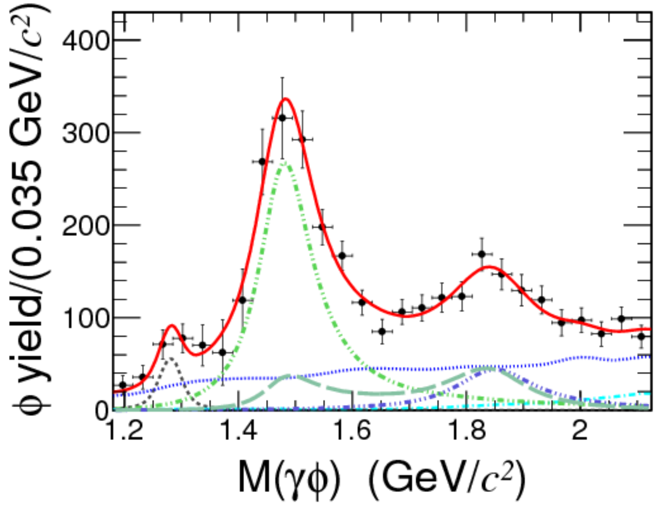
PRL 127 082501 (2021)

Further experimental information

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



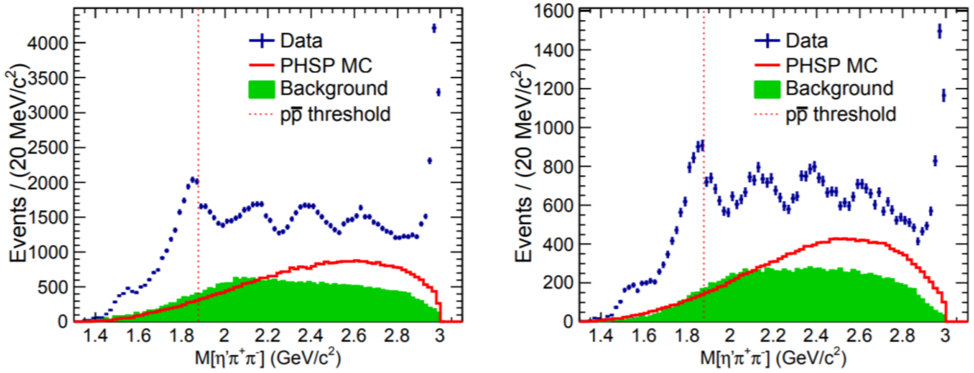
$J/\psi \to \gamma\gamma\phi$ BESIII PRD97 051101(2018)



X(2370)

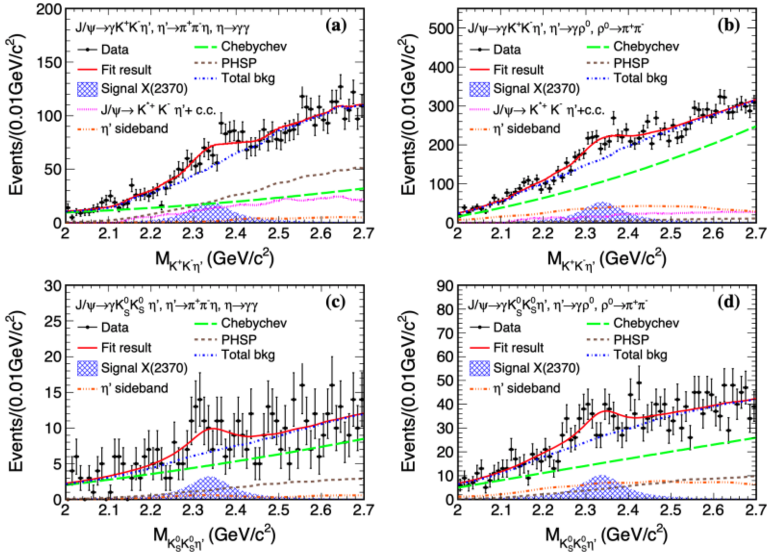
$J/\psi \to \gamma\eta'\pi^+\pi^-$

BESIII PRL 106, 072002, PRL 117, 042002



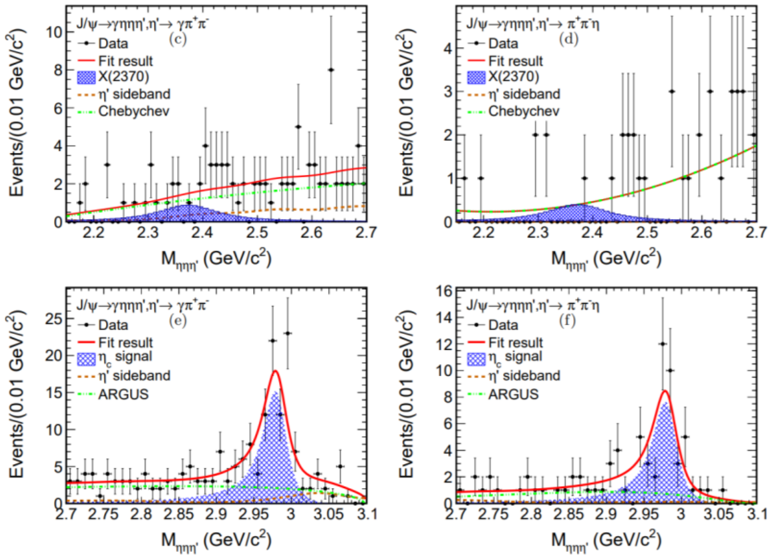
$J/\psi \to \gamma\eta' KK$

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)

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

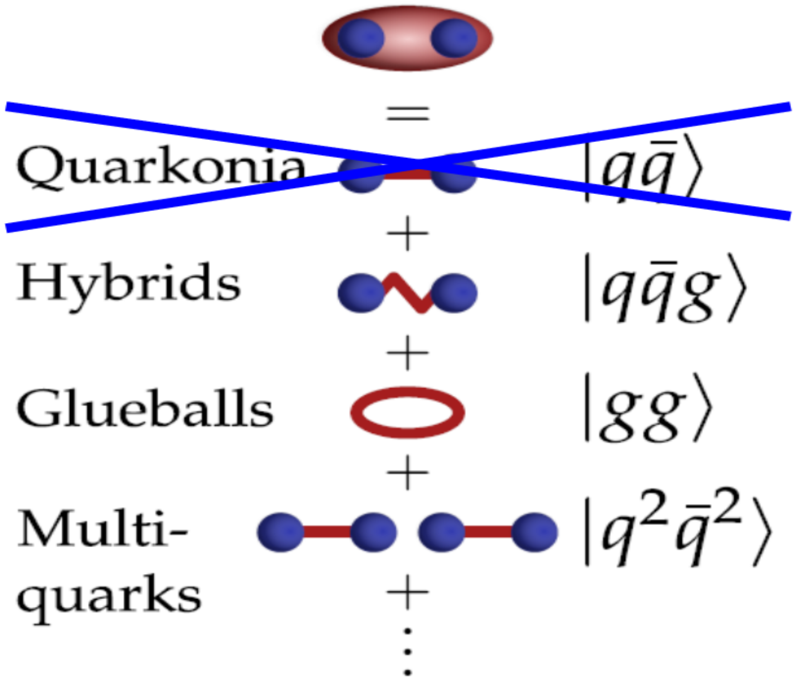
- ✓**Large production rate of $f_0(1710)$ in J/ψ radiative decays**
- ✓**Large production rate of $f_2(2340)$ in J/ψ radiative decays**
- ✓**Non-observation of $\eta(1295)$**
- ✓**$\eta(1405/1475)$ one state?➔ manifestations of TS**
- ✓**$X(2370) \to$ various decay modes**

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

Light hadrons with exotic quantum numbers

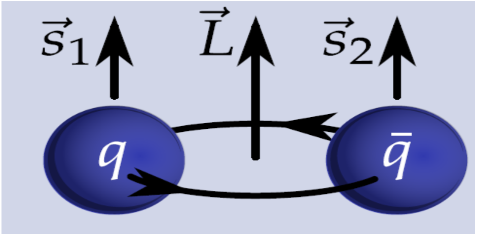
- **Unambiguous signature for exotics**
  - Light Flavor-exotic hard to establish
  - **Efforts concentrate on Spin-exotic**
    - **Forbidden for $\mathbf{q\bar{q}}$:**

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



Experiments:

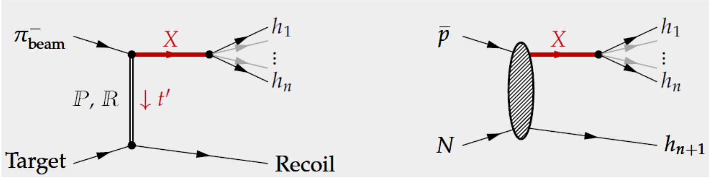
- **Hadroproduction:** E852, VES, COMPASS, GAMS
- **$\mathbf{p\bar{p}}$ annihilation:** Crystal Barrel, OBELIX, PANDA(under construction)
- **Photoproduction:** GlueX(2017-), CLAS



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

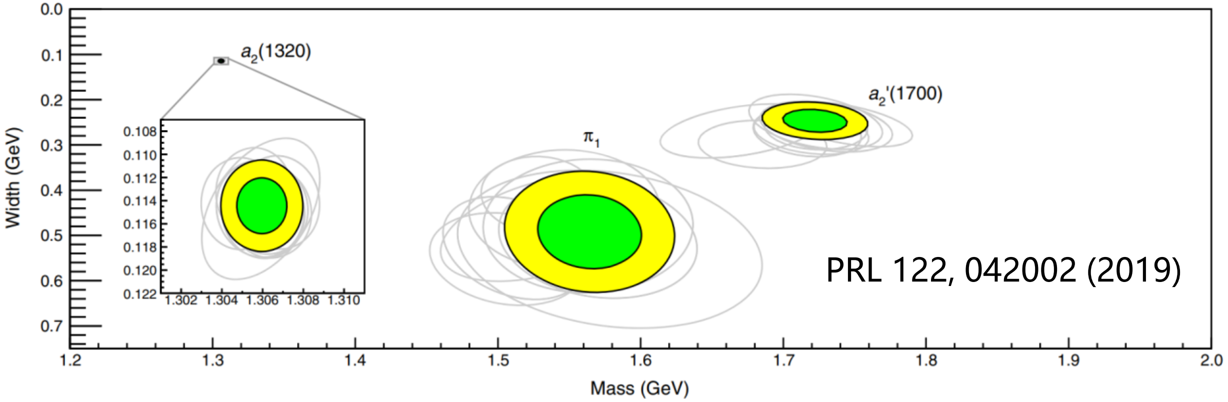
Allowed J^{PC}: $0^{-+}, 0^{++}, 1^{--}, 1^{+-}, 2^{++}, \ldots$

Detailed reviews: PRC 82, 025208 (2010)， PPNP 82, 21 (2015)



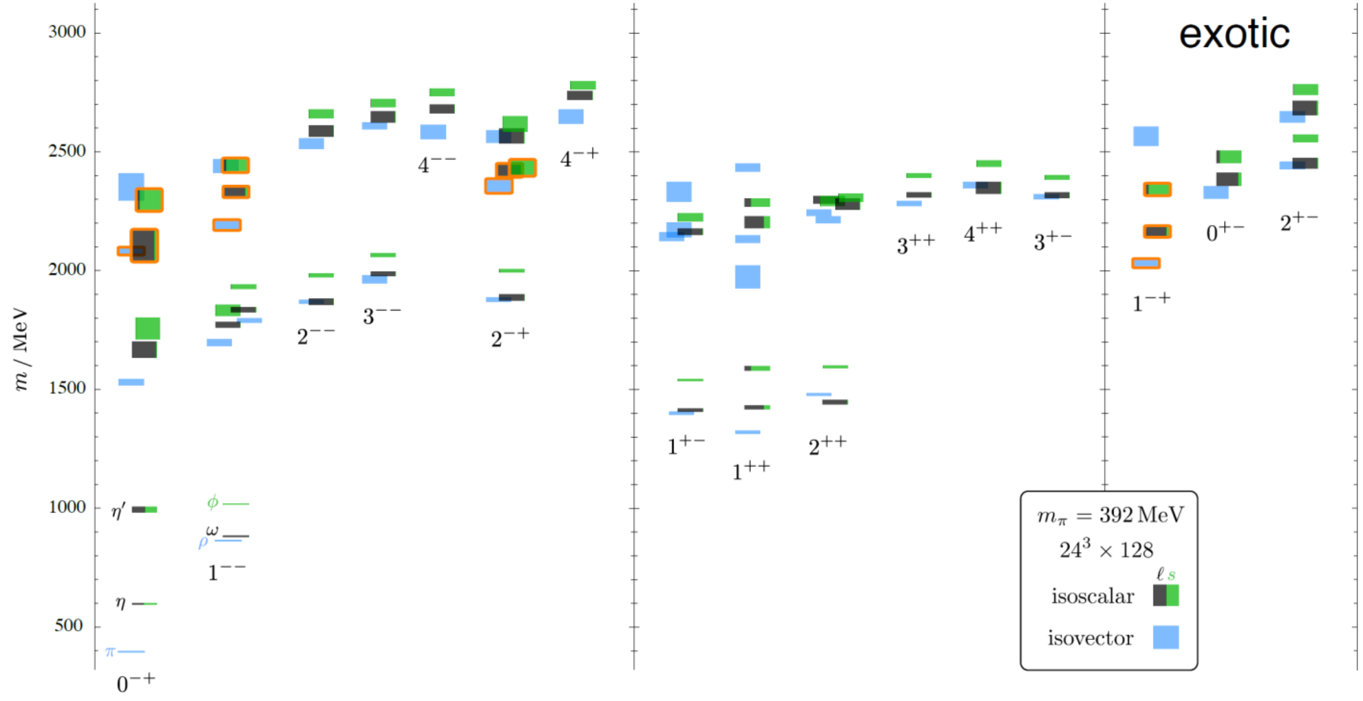
Spin-exotic mesons

- **Only 3 candidates so far: All 1^{-+} isovectors**
  - $\pi_1(1400)$: seen in $\eta\pi$
  - $\pi_1(1600)$: seen in $\rho\pi$, $\eta'\pi$, $b_1\pi$, $f_1\pi$
  - $\pi_1(2015)$ (needs confirmation): seen in $b_1\pi$, and $f_1\pi$
- Some claims are controversial
- $\pi_1(1400)$ & $\pi_1(1600)$ can be explained as one pole

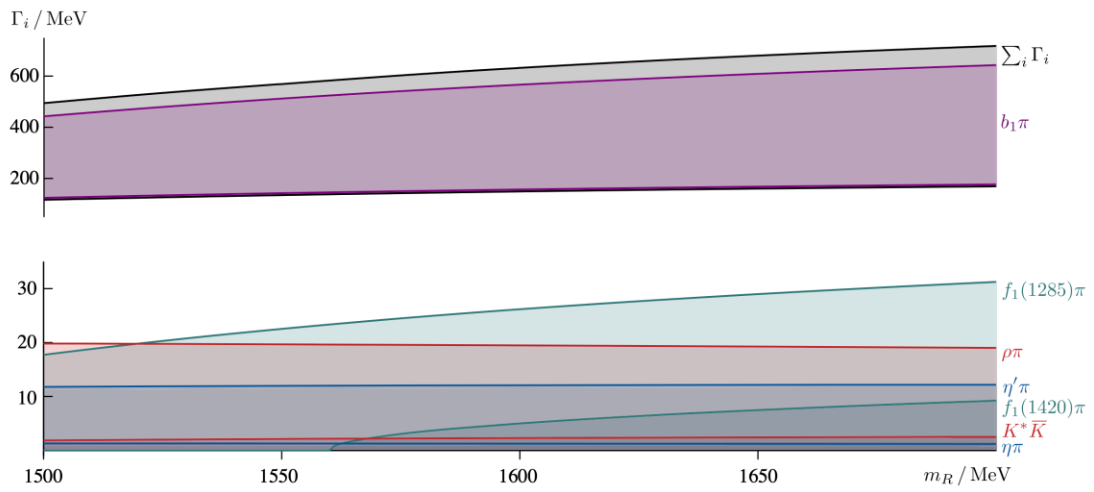


	Decay mode	Reaction	Experiment
$\pi_1(1400)$	$\eta\pi$	$\pi^- p \to \pi^- \eta p$	GAMS
		$\pi^- p \to \pi^0 \eta n$	KEK
		$\pi^- p \to \pi^- \eta p$	E852
		$\pi^- p \to \pi^0 \eta n$	E852
		$\bar{p} n \to \pi^- \pi^0 \eta$	CBAR
		$\bar{p} p \to \pi^0 \pi^0 \eta$	CBAR
	$\rho\pi$	$\bar{p} p \to 2\pi^+ 2\pi^-$	Obelix
$\pi_1(1600)$	$\eta'\pi$	$\pi^- Be \to \eta' \pi^- \pi^0 Be$	VES
		$\pi^- p \to \pi^- \eta' p$	E852
	$b_1\pi$	$\pi^- Be \to \omega \pi^- \pi^0 Be$	VES
		$\bar{p} p \to \omega \pi^+ \pi^- \pi^0$	CBAR
		$\pi^- p \to \omega \pi^- \pi^0 p$	E582
	$\rho\pi$	$\pi^- Pb \to \pi^+ \pi^- \pi^- X$	COMPASS
		$\pi^- p \to \pi^+ \pi^- \pi^- p$	E582
	$f_1\pi$	$\pi^- p \to p \eta \pi^+ \pi^- \pi^-$	E582
		$\pi^- A \to \eta \pi^+ \pi^- \pi^- A$	VES
$\pi_1(2015)$	$f_1\pi$	$\pi^- p \to \omega \pi^- \pi^0 p$	E582
	$b_1\pi$	$\pi^- p \to p \eta \pi^+ \pi^- \pi^-$	

Hybrid from LQCD



PRD 88 094505(2013)



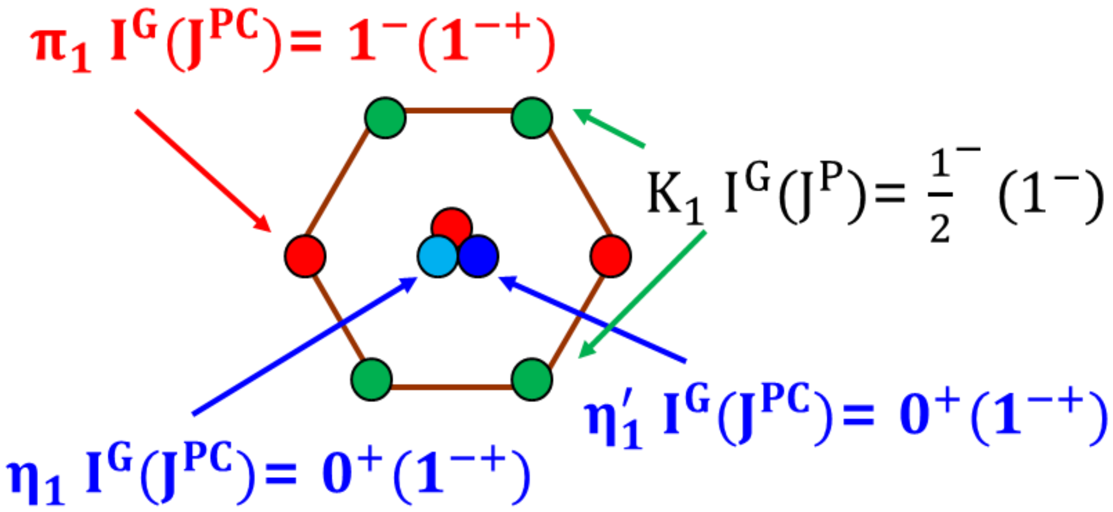
PRD 103, 054502(2021)

Lightest spin-exotic state: $\mathbf{1^{-+}}$

Decay width of $\mathbf{1^{-+}}$ hybrid

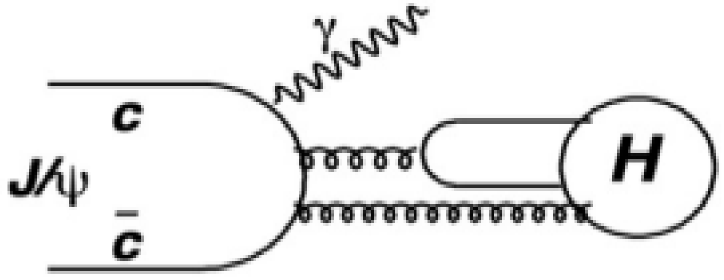
1^{-+} Hybrids

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



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

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

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

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

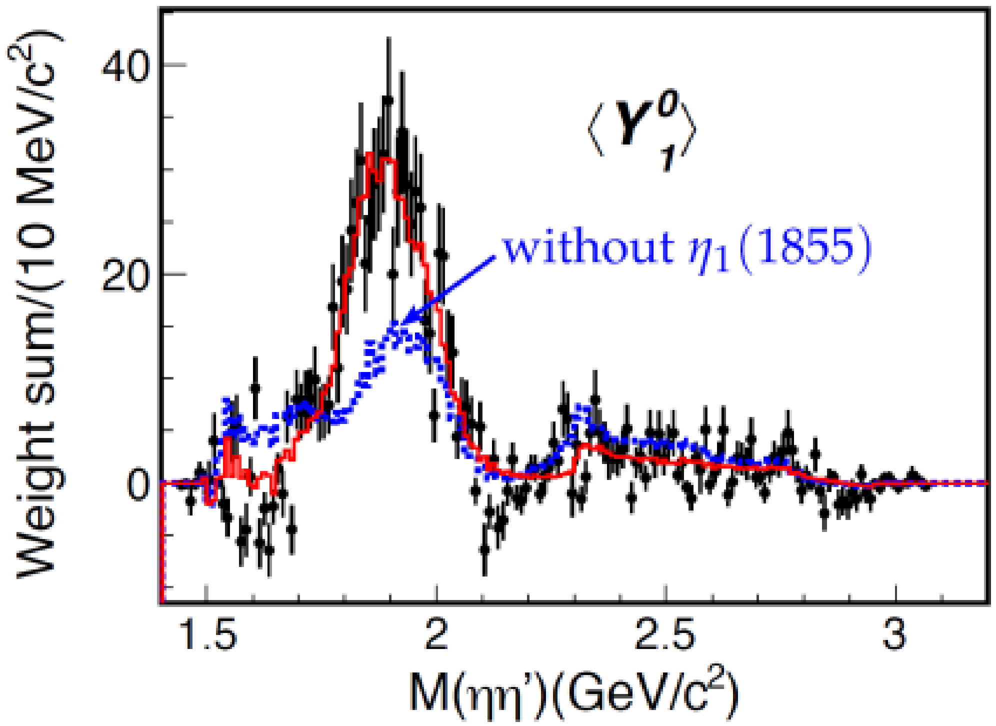
  $M = \left(1855 \pm 9^{+6}_{-1}\right)\,\mathrm{MeV/c^2}, \Gamma = \left(188 \pm 18^{+3}_{-8}\right)\,\mathrm{MeV/c^2}$

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

  - **Mass consistent with hybrid on LQCD**

- **Inspired many interpretations: Hybrid/$\mathbf{K\bar{K}_1}$Molecule/Tetraquark?**

- Further more, suppression of $f_0(1710) \to \eta\eta'$ supports it has a large overlap with glueball

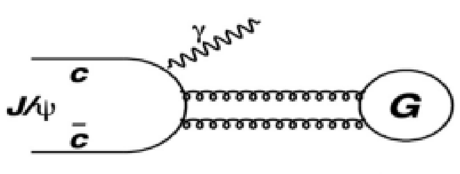


Opens a new direction to completing the picture of spin-exotics

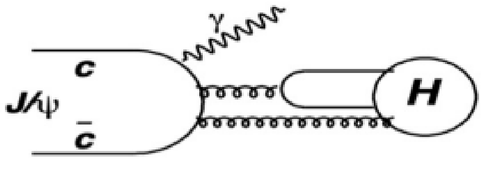
Observation of **An Exotic 1^{-+} Isoscalar State $\eta_1(1855)$**

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

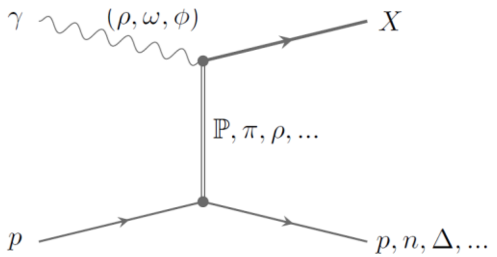
- **Uniqueness, enrichment and complementary**
  - **High statistics gluon-rich environment: 10 B J/ψ, 2.7 B ψ', a lot of χ_{cJ}**
  - **BESIII is not only a good lab for glueball, but also for light spin-exotics**
    - **π_1, $\eta_1^{(\prime)}$, and other partners**



$\Gamma(J/\psi \to \gamma G) \sim O(\alpha\alpha_s^2)$

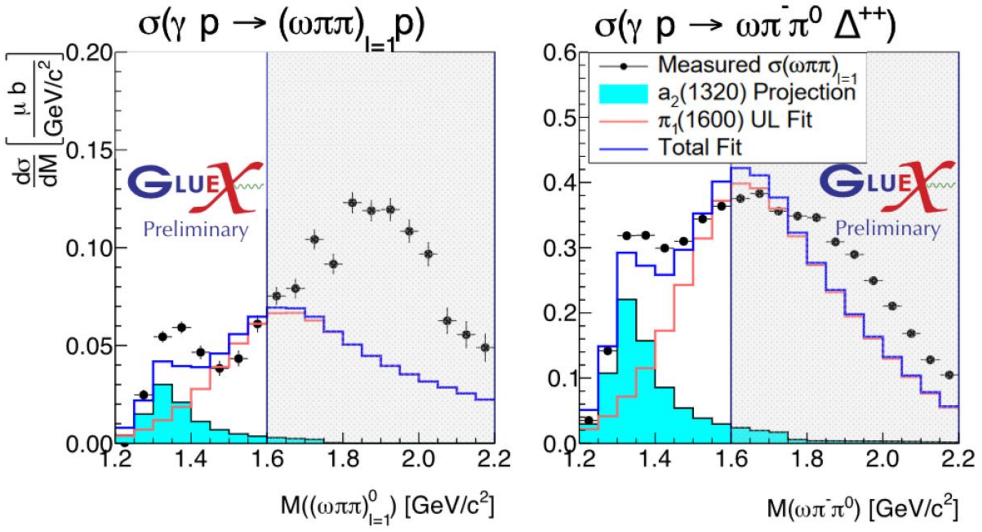


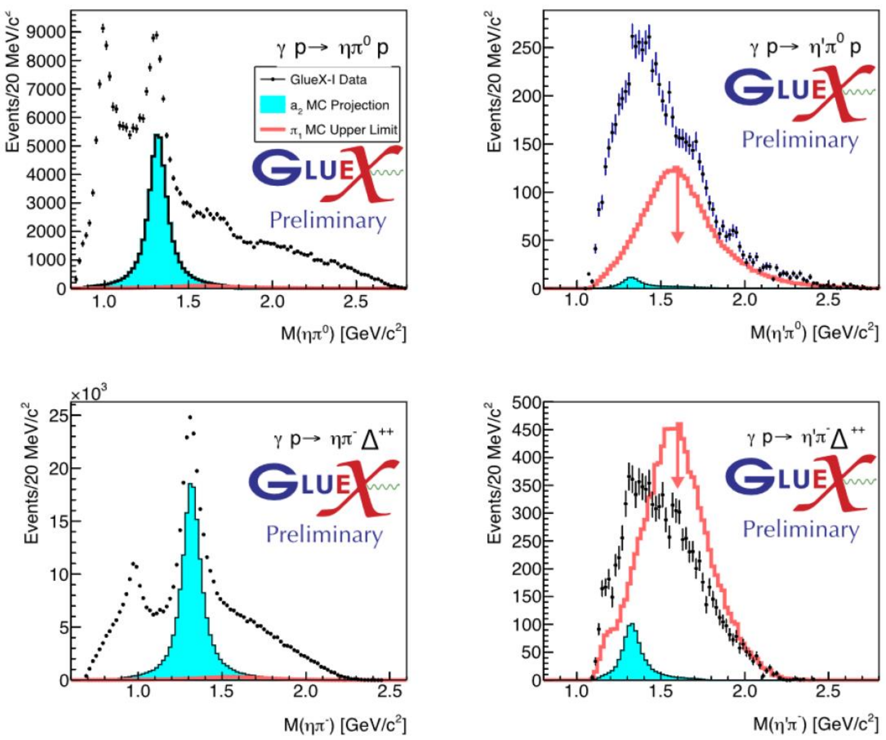
$\Gamma(J/\psi \to \gamma H) \sim O(\alpha\alpha_s^3)$



$\pi_1(1600)$ upper limits and projections to $\pi\eta$, $\pi\eta'$

- Upper limits for $\pi_1(1600)$ branching fractions from LQCD
- Saturate measured $\omega\pi\pi$ cross section ($I = 1$)





- Projections combine LQCD with measured $a_2(1320)$ and (iso-vector) $b_1\pi$ cross sections
- Expect small signal in $\eta\pi$, but signal could saturate $\eta'\pi$ channels $\to$ **enforced effort**

A. Austregesilo, Hadron2023

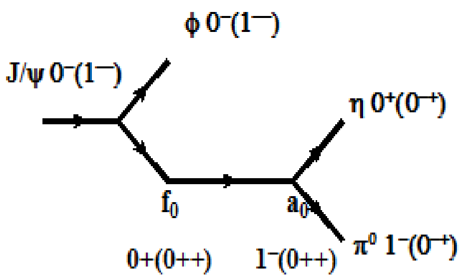
- Glueballs
- Spin-exotic states
- Threshold structures & multi-quark states

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

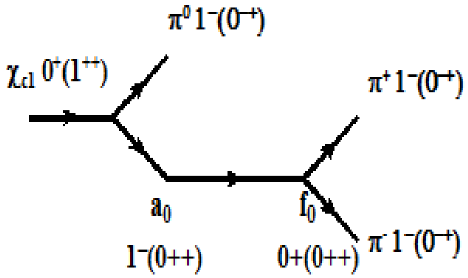
- The nature of ground state scalar $a_0(980)$ and $f_0(980)$ are controversial

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

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

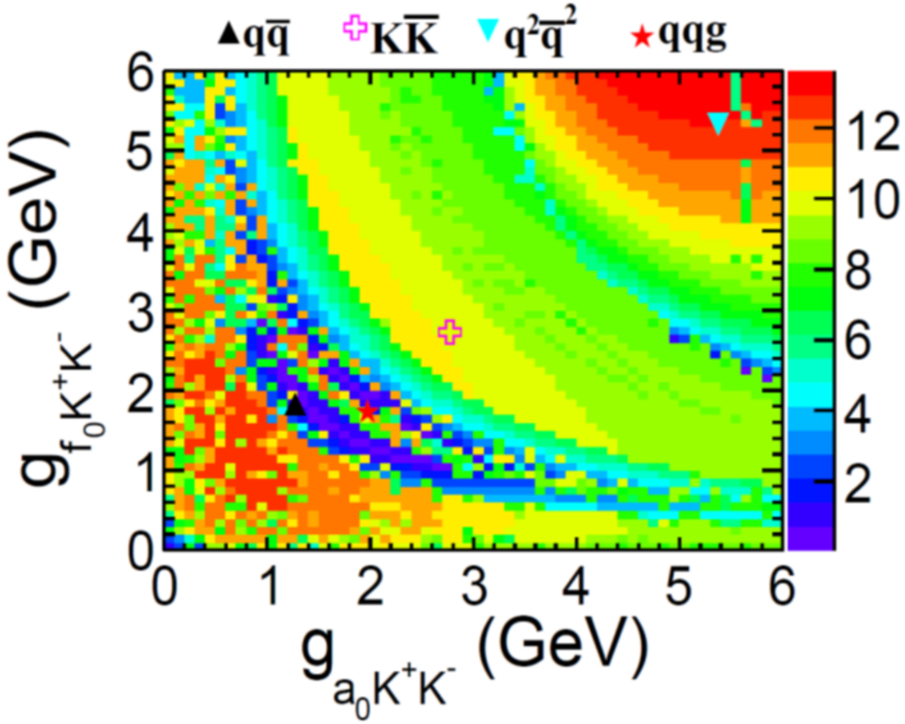


PR D75 114012, PR D76 074028



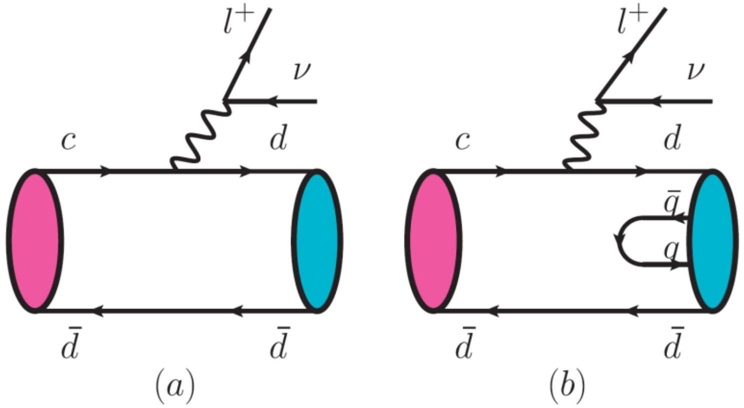
PR D78 074017

- First direct measurement with > 5σ



BESIII PRL 121 022001

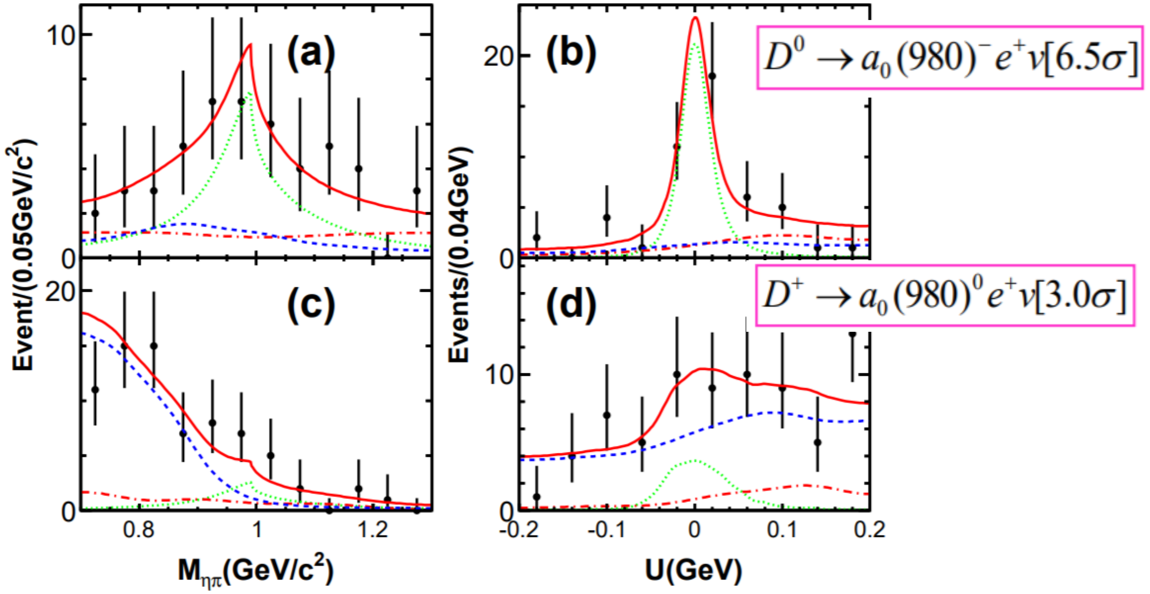
Explore light hadrons with charmed meson decays



In the SU(3) symmetry limit,

PR D82, 034016 (2010)

$$R = \frac{\mathcal{B}(D^+ \to f_0(980)l^+\nu) + \mathcal{B}(D^+ \to f_0(600)l^+\nu)}{\mathcal{B}(D^+ \to a_0^0(980)l^+\nu)} = \begin{cases} 1 & \text{two quark} \\ 3 & \text{tetra-quark} \end{cases}.$$

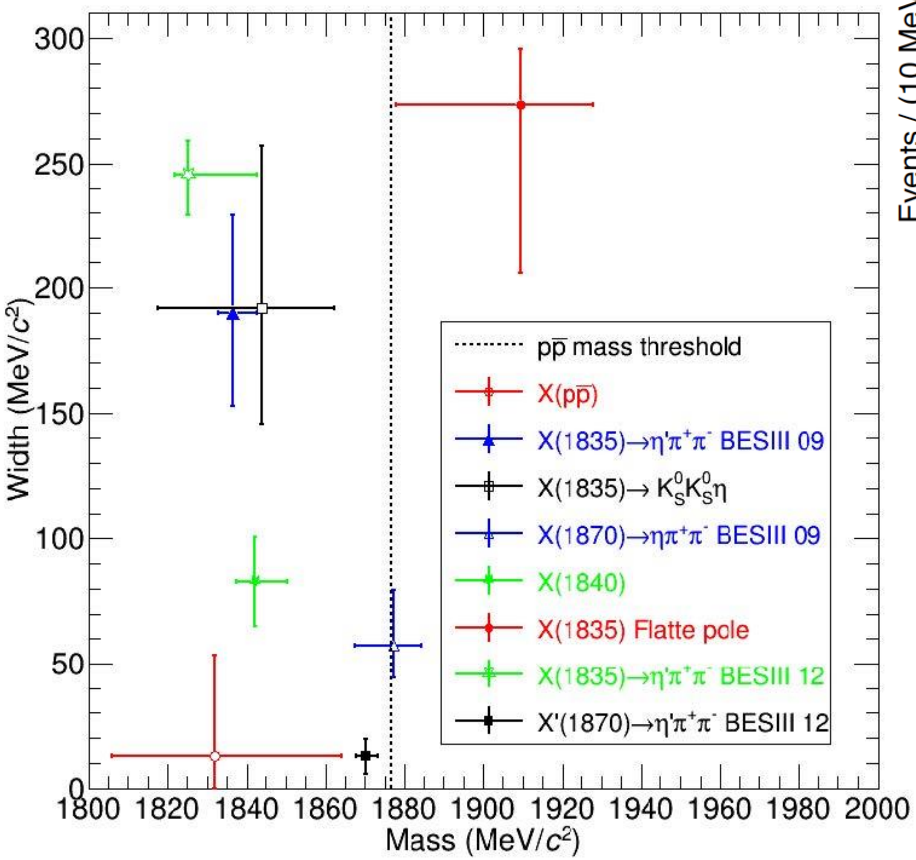


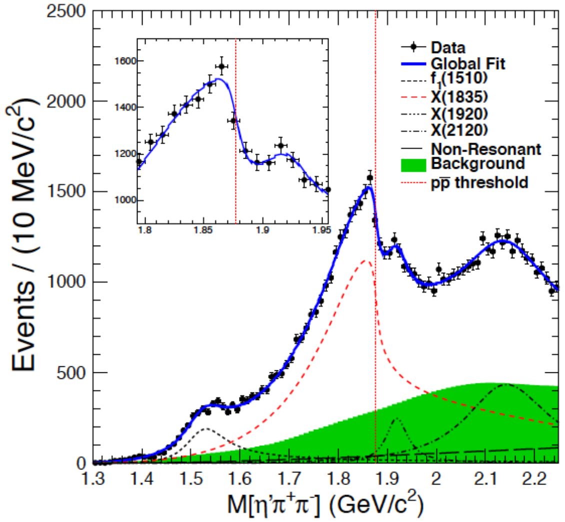
BESIII measurements:

PRL 121, 081802 (2018)
PRL 122, 062001 (2019)

$R_{BESIII} > 2.7$ @ 90% C.L.

Structures around $p\bar{p}$ threshold

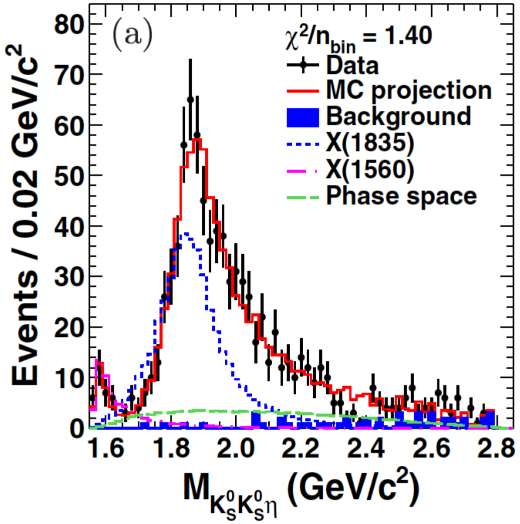




$J/\psi \to \gamma\eta'\pi^+\pi^-$

BESIII PRL 117, 042002 (2016)

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



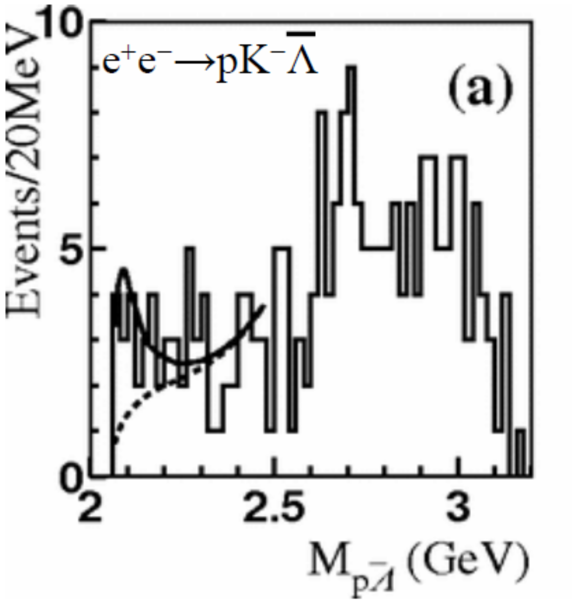
$J/\psi \to \gamma K_s K_s \eta$

BESIII PRL 115, 091803 (2015)

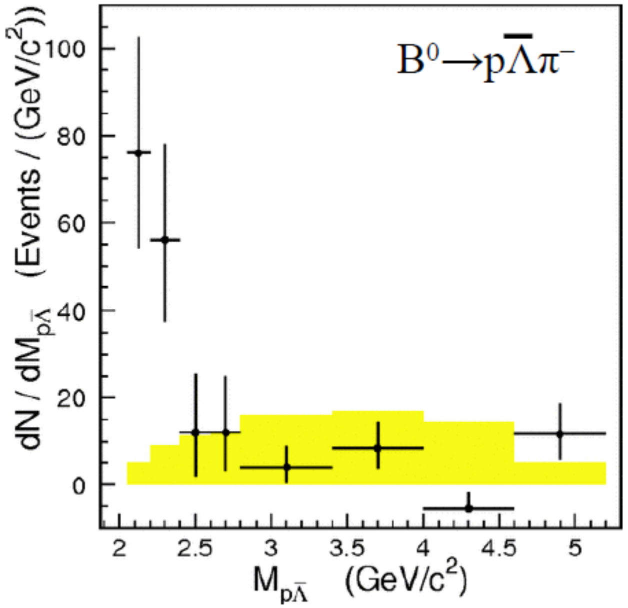
J^{PC} of X(1835) is determined to be 0^{-+}

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

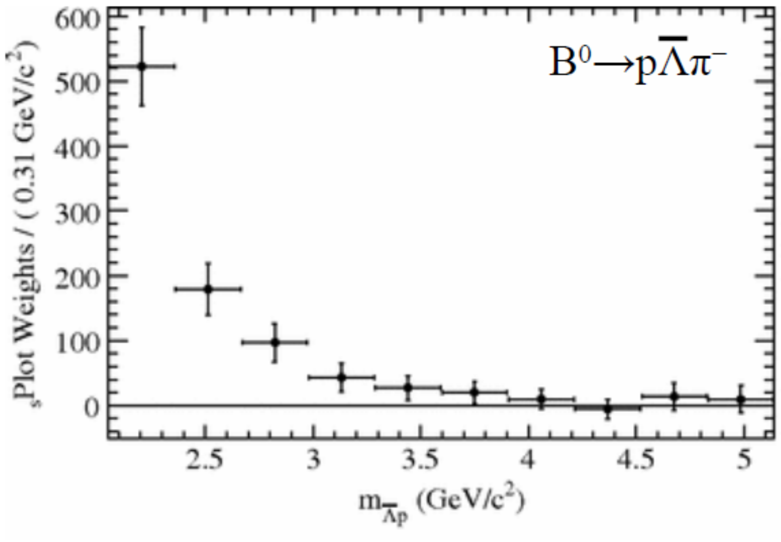
BES, PRL93, 112002 (2004)



BELLE, PRL90, 201802 (2003)



BaBar, PRD79, 112009 (2009)

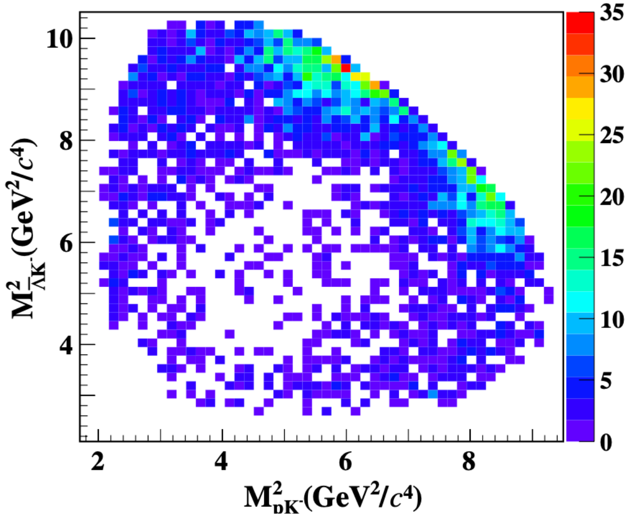


- Different scenarios investigated: baryonium state [PRD74,014029], baryon-antibaryon SU(3) nonets [PLB626,95], final state interaction [IJMPA22,5401], ...

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

arXiv:2303.01989

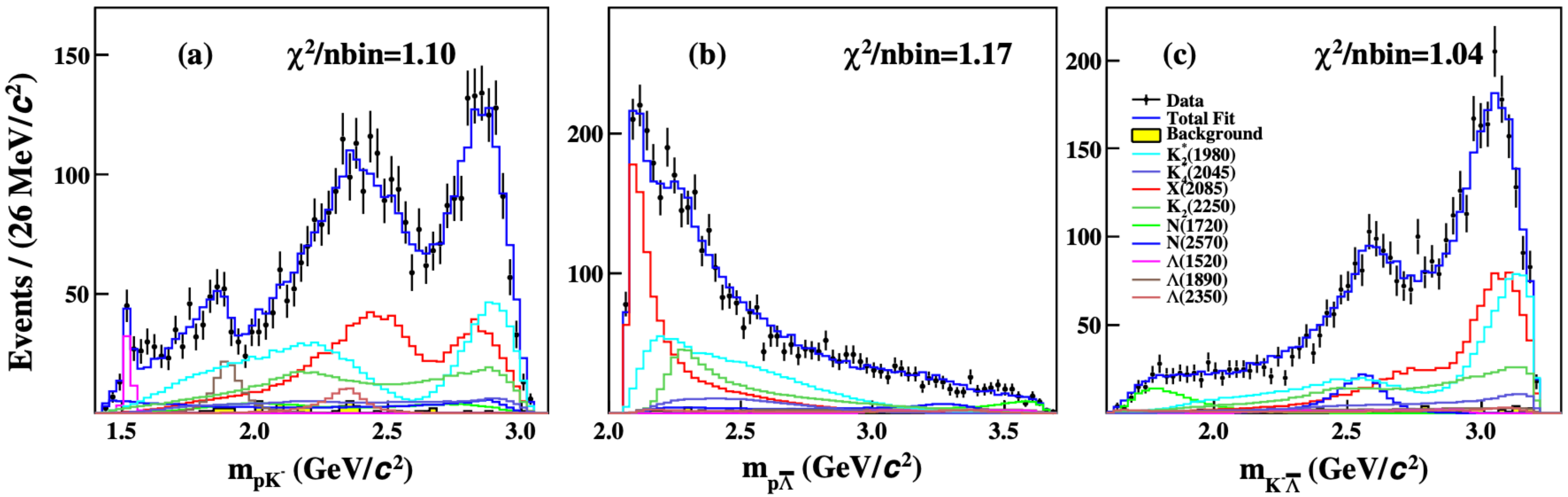
6 different center of mass energies between 4.008 GeV to 4.682 GeV



- 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

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

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



Summary

- Understanding how hadron spectroscopy are emerged from QCD remains a key question in fundamental physics, which requires
  - both heavy and light sectors
  - Complementary experimental information
- Critical collaboration with theory
  - Reaction models
  - Theoretical constraints

Thank you for your attention