Light hadron physics@ BESIII

刘北江

BESIII实验物理研讨会 2026.2.6-9

Hadrons

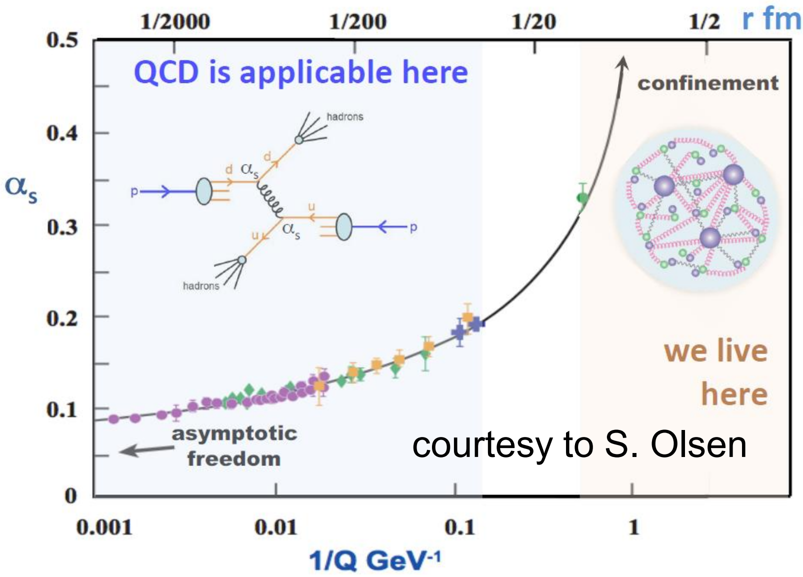
- **Dominant part of visible matter in the universe**
- **To fully understand the strong interaction**
  - **Understanding the rich and complex features of its bound states, hadrons**

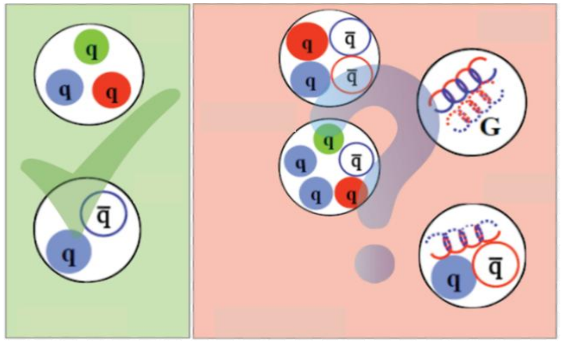
➢How are hadrons formed from quarks and gluons?

➢What is the origin of confinement?

➢How is the mass of hadron generated in QCD?

➢What is the dynamics of effective DoF in hadrons?





Structure

Spectroscopy

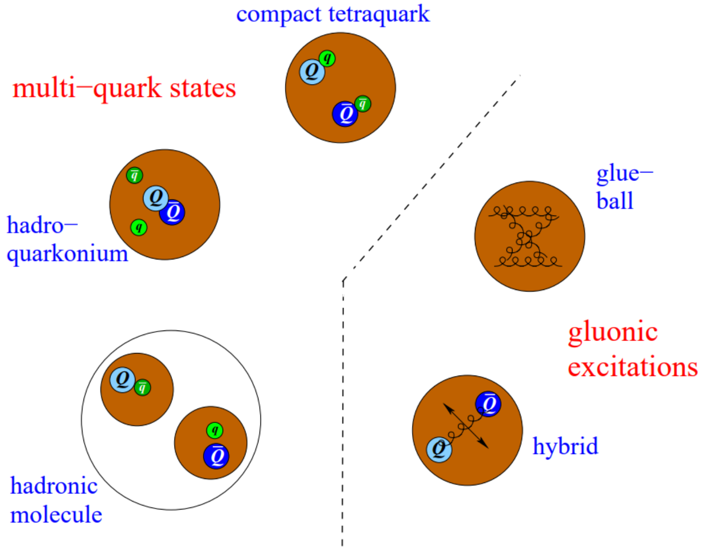
Interactions

Light hadrons

Precision tests & rare phenomena

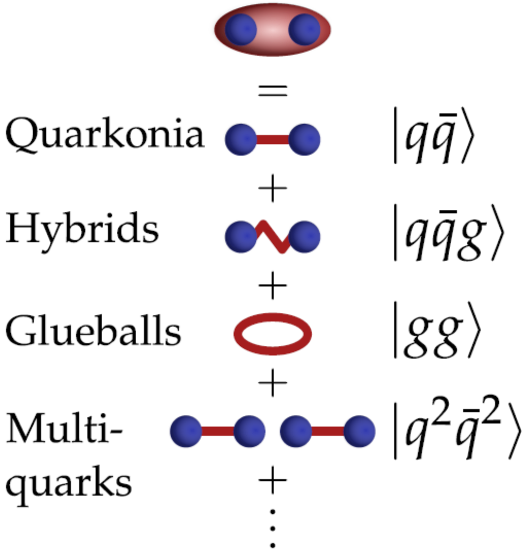
Hadron spectroscopy

QCD exotics



Phys.Rept. 873 (2020) 1

- **Key to access the effective degree of freedom of QCD**
  - Strong evidences for multi-quark in heavy quark sector
    https://qwg.ph.nat.tum.de/exoticshub/
  - **Evidence for gluonic excitations remains sparse**
    - **Crucial info for strong force and QCD vacuum**



Physical meson

A linear superposition of all allowed color-singlet configurations

Identification of exotics is challenging

Manifestly exotic: with forbidden QN

Flavor exotic: $Z_c, T_{cc}, T_{\psi\psi}$ … …

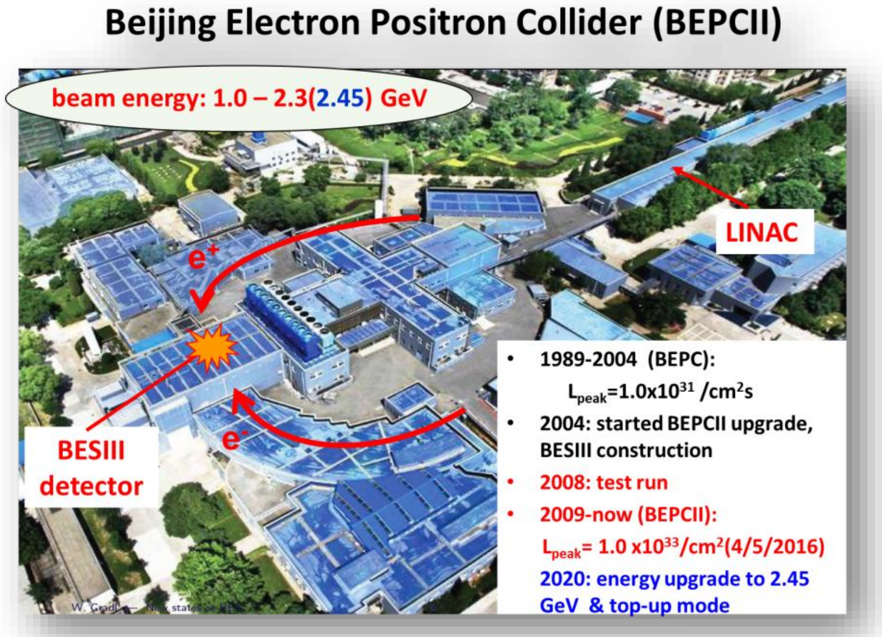
Spin exotic: $\mathbf{J^{PC} = 0^{--}, even^{+-}, odd^{-+}}$

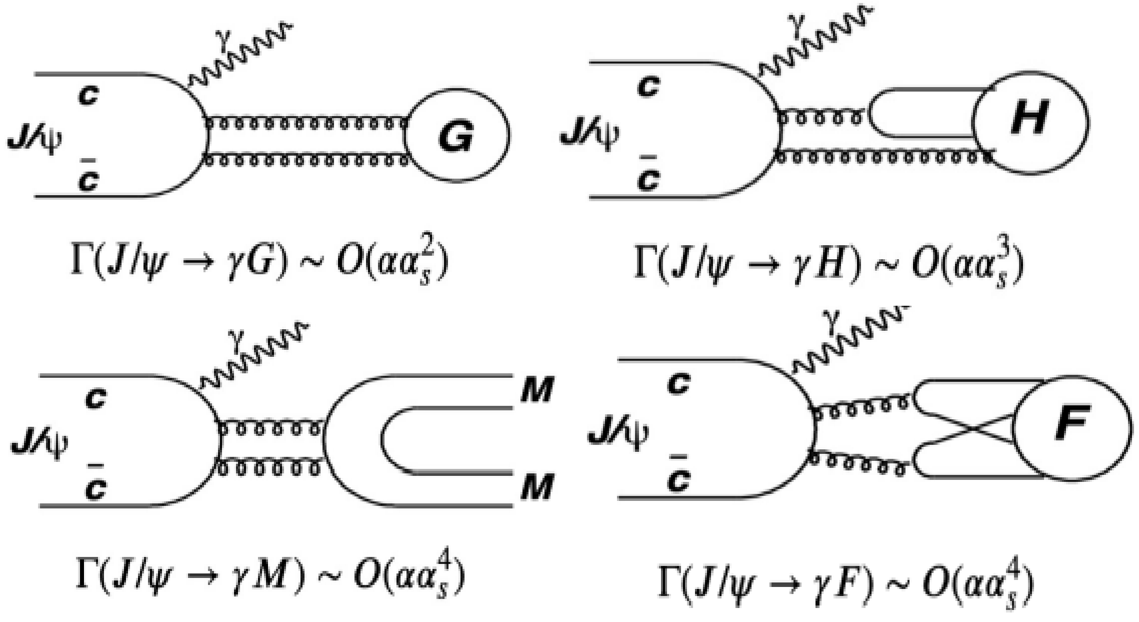
Crypto exotic: with QN as $q\bar{q}$

Supernumerary states - -> **glueball**

Abnormal properties

+ Kinematic effects



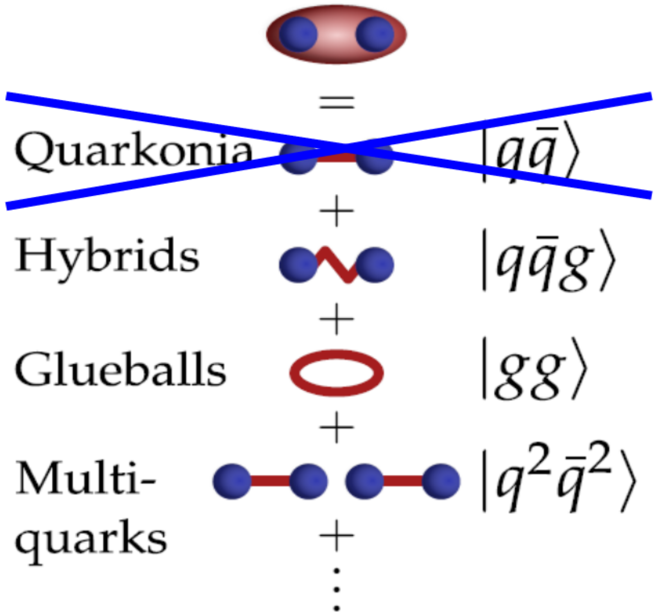


Charmonium decays provide an ideal lab for Gluonic Excitations

- Gluon-rich process
- Well defined initial and final states
  - Kinematic constraints
  - Isospin and J^{PC} filters
- Clean high statistics data samples: 10×10^9 J/ψ and 2.7×10^9 ψ' @ BESIII
  - High cross sections of $e^+e^- \to J/\psi,\ \psi'$
  - Low background

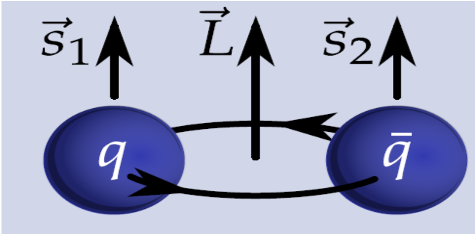
Light hadrons with exotic quantum numbers

- **Finding unambiguous signature for exotics**
  - **Efforts concentrate on Spin-exotic**
    - **Forbidden for $q\bar{q}$:**
      $\mathbf{J^{PC} = 0^{--}, even^{+-}, odd^{-+}}$



Experiments:

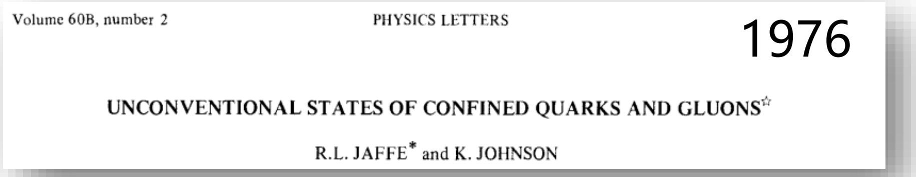
- **Hadroproduction:** GAMS, VES, E852, COMPASS, AMBER
- **$p\bar{p}$ annihilation:** Crystal Barrel, OBELIX, PANDA
- **Photoproduction:** GlueX, CLAS



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

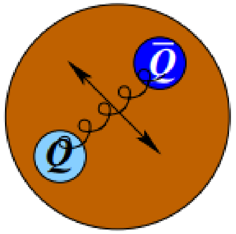
Allowed J^{PC}: $0^{-+}, 0^{++}, 1^{--}, 1^{+-}, 2^{++}, \ldots$

Predictions

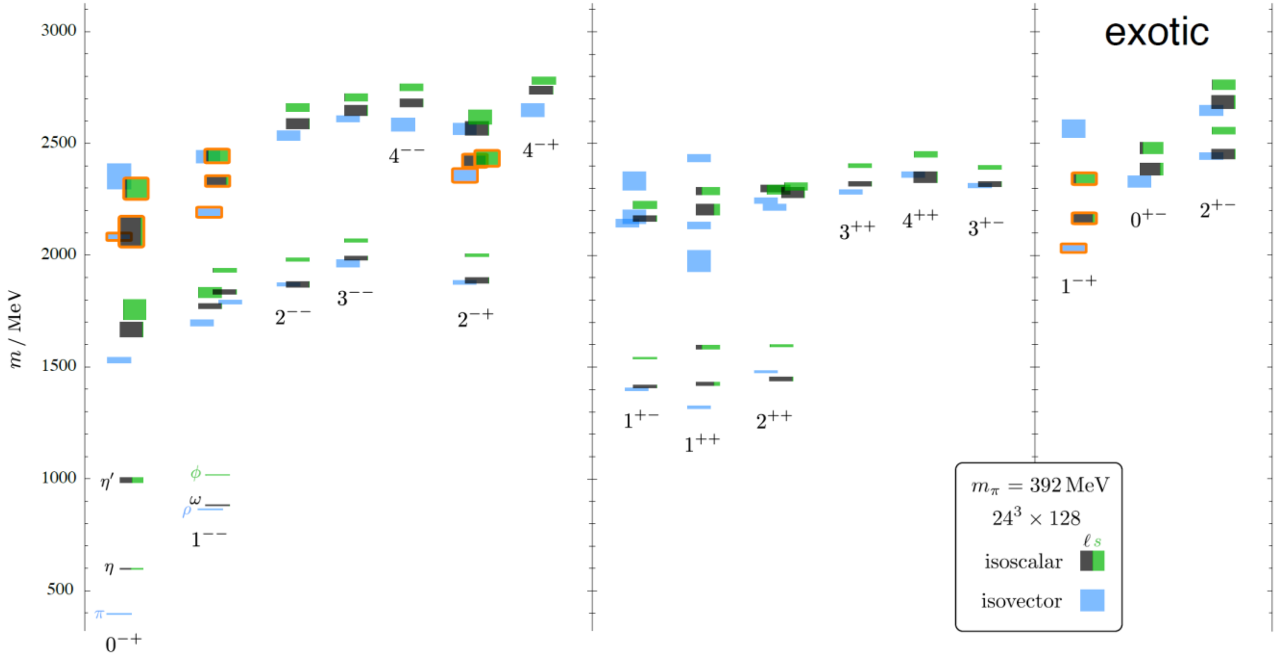

Volume 60B, number 2 PHYSICS LETTERS 1976

UNCONVENTIONAL STATES OF CONFINED QUARKS AND GLUONS☆

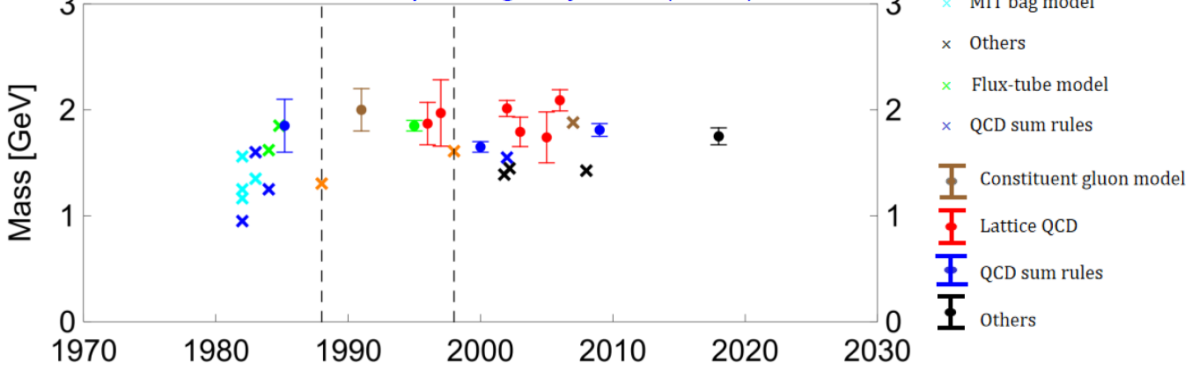
R.L. JAFFE* and K. JOHNSON



PRD 88 094505(2013)

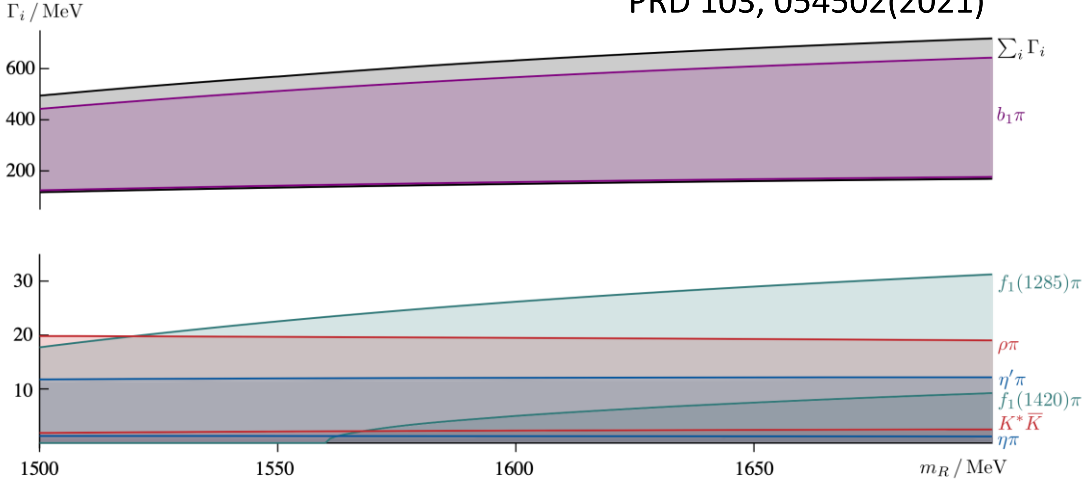


[Rept.Prog.Phys. 86 (2023) 026201]



Mass of $\mathbf{1^{-+}}$ hybrid

PRD 103, 054502(2021)

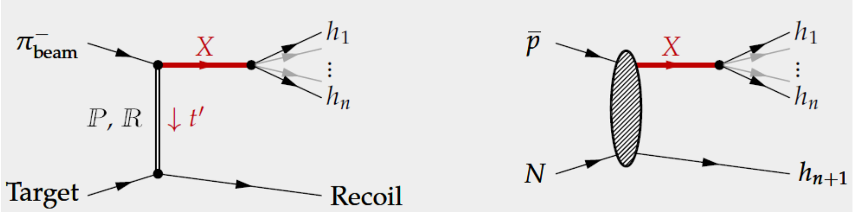


Decay width of $\mathbf{1^{-+}}$ hybrid π_1

On lattice,

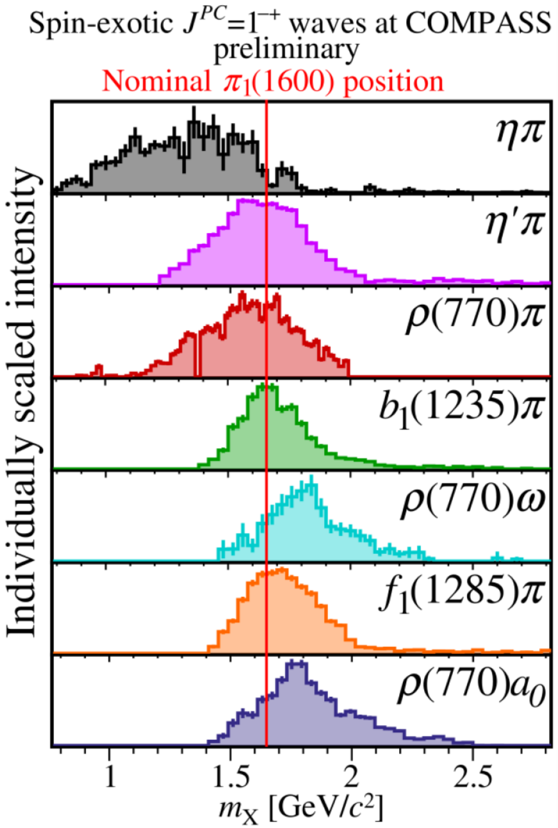
- Meson excitations similar to quark model
- Hybrid supermultiplet: $\mathbf{0^{-+}}$, $\mathbf{1^{--}}$, $\mathbf{2^{-+}}$, $\mathbf{1^{-+}}$
- Lightest spin-exotic state in LQCD: $\mathbf{1^{-+}}$ hybrid

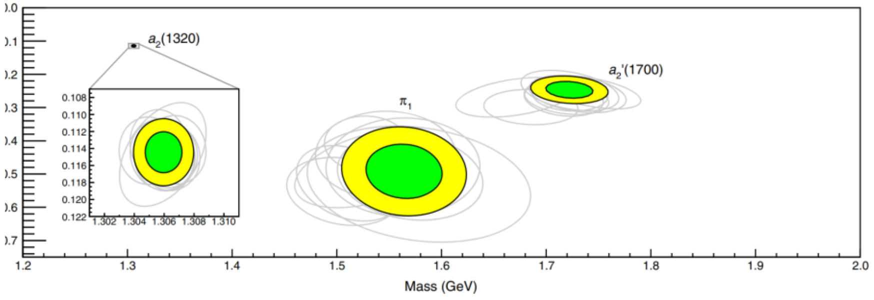
Spin-exotic mesons



Review: PRC 82, 025208 (2010), PPNP 82, 21 (2015), EPJC 83 (2023) 1125

- Candidates over 3 decades
  - $\pi_1(1400)$, $\pi_1(1600)$, $\pi_1(2015)$ (needs confirmation), all isovetors



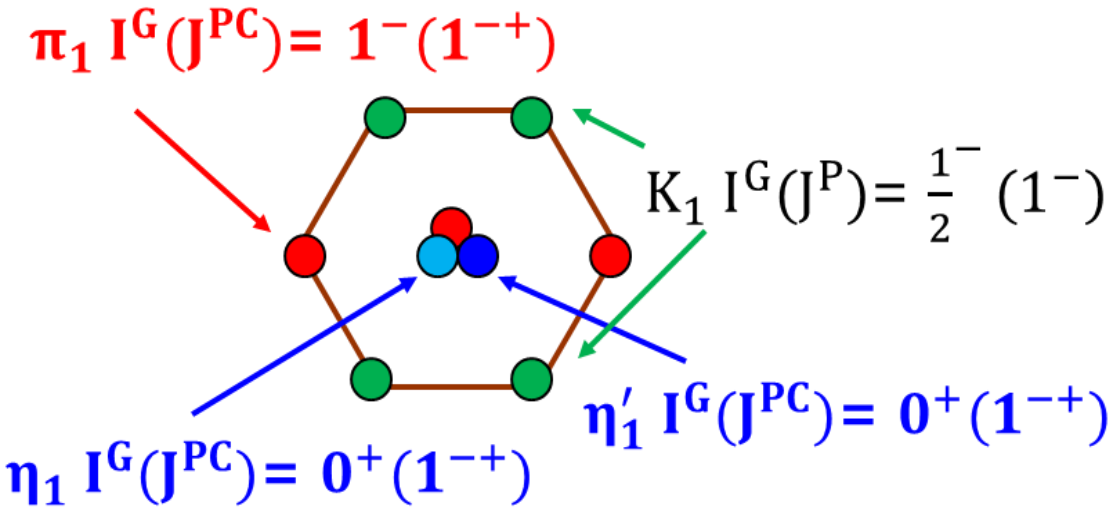


[PRL 122, 042002 (2019), EPJ C 81, 1056 (2021)]

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

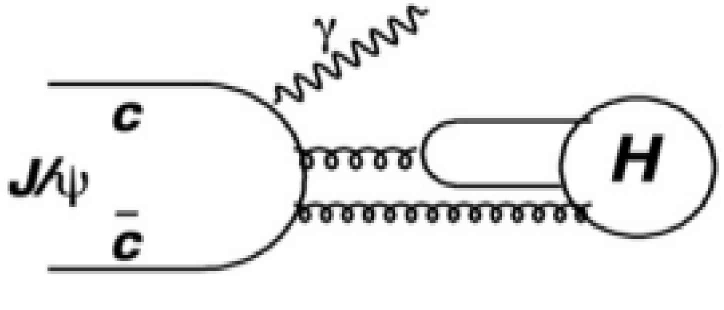
1^{-+} Hybrids

- **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 P135, 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 $\eta_1(1855)$

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

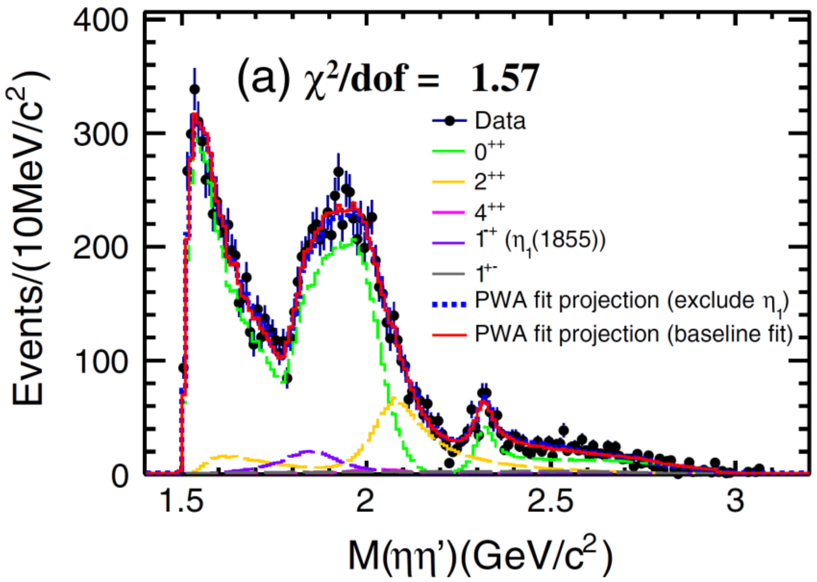
- **An isoscalar 1^{-+}, $\eta_1(1855)$, has been observed in $J/\psi \to \gamma\eta\eta'$ (>19σ)**

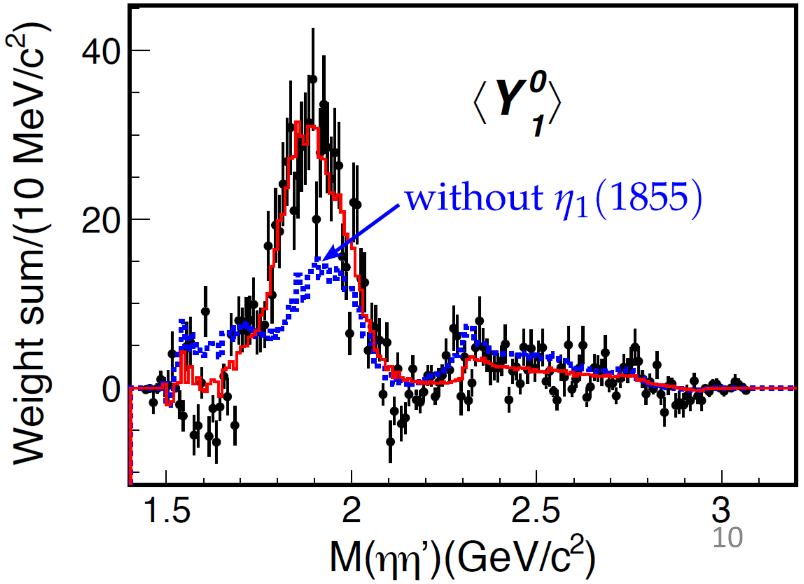
  $M = (1855 \pm 9^{+6}_{-1})\ \mathrm{MeV}/c^2,\ \Gamma = (188 \pm 18^{+3}_{-8})\ \mathrm{MeV}/c^2$

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

  - **Mass consistent with hybrid on LQCD**

- **$\eta\eta'$ in P-waves uniquely indicates 1^{-+} exotic quantum numbers**





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

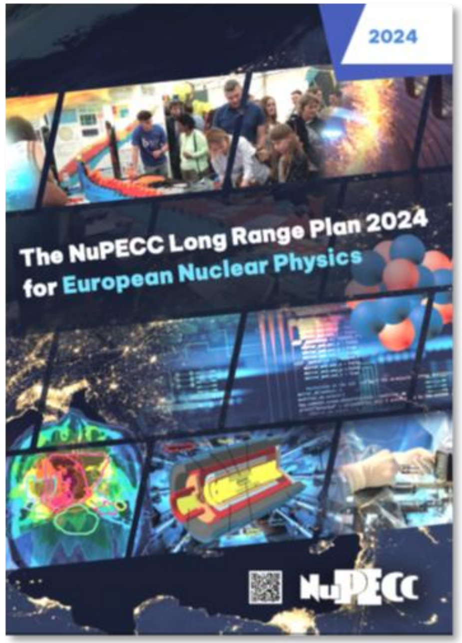
PRL 129 192002(2022) , PRD 106 072012(2022)

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

  NPA 1047 122874(2024); Rept.Prog.Phys. 86 (2023) 026201; PRD 107 (2023) 7, 074028; SCPMA 65 (2022) 6, 261011; CPC 46 , 051001(2022); CPL 39, 051201 (2022); PLB 834, 137478(2022); PRD 106 , 074003(2022); PRD 106, 036005(2022) ;...

- **Opens a new direction to completing the picture of spin-exotics**
  - **As a "recent achievements and highlights" and a "future directions" in hadron spectroscopy in the NuPECC LRP**
  - **50 years of QCD: Exotic mesons, "observation of an $\eta_1(1855)$ state could be a breakthrough"**

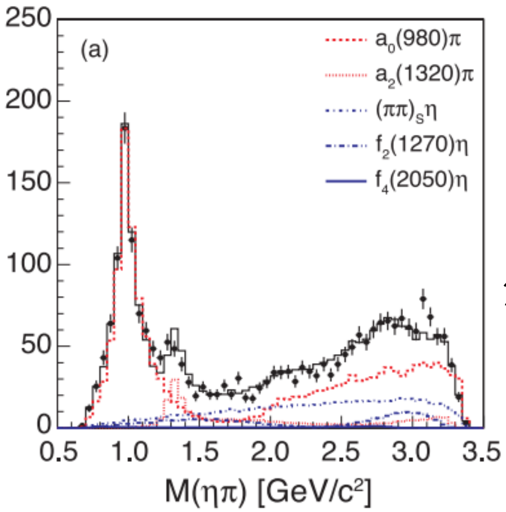
    [EPJ.C 83 (2023) 1125]



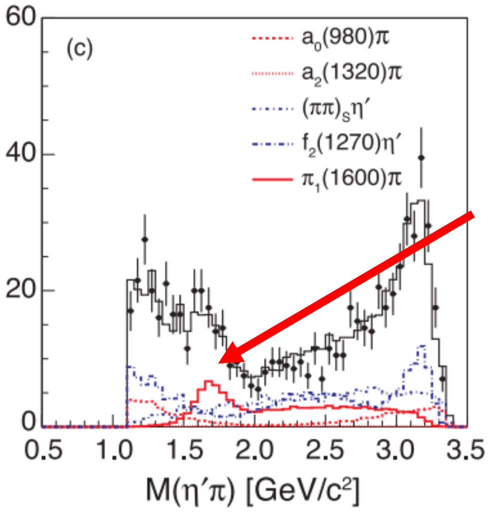
Studies of π_1 in $\chi_{c1} \to \pi^+\pi^-\eta^{(\prime)}$

PR D84 112009 (2011)

$\mathbf{2.6 \times 10^7}$ $\psi(3686)$@CLEO − c



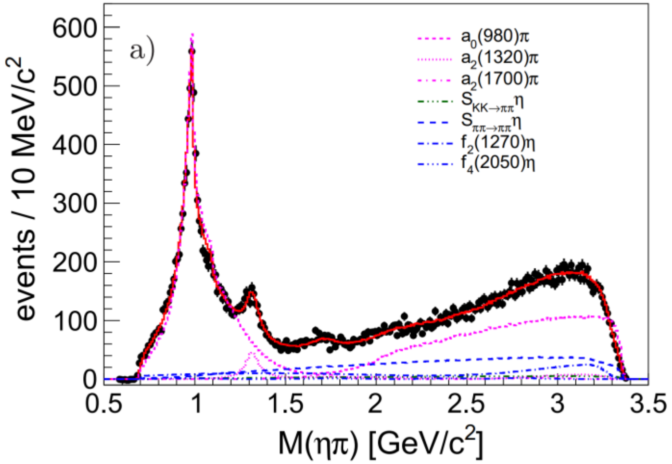
No evidence of $\pi_1 \to \eta\pi$



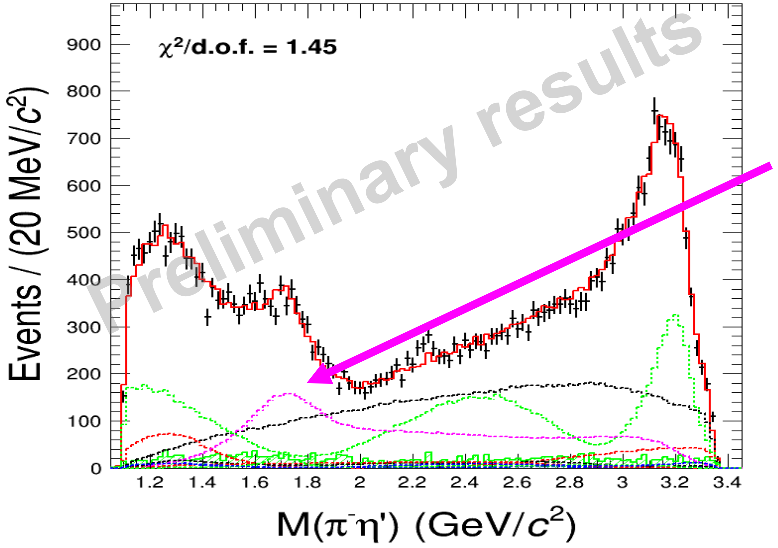
Evidence of $\pi_1 \to \eta'\pi$ (without significant BW phase motion)

PR D95 032002(2017)

44.8×10^7 $\psi(3686)$@BESIII



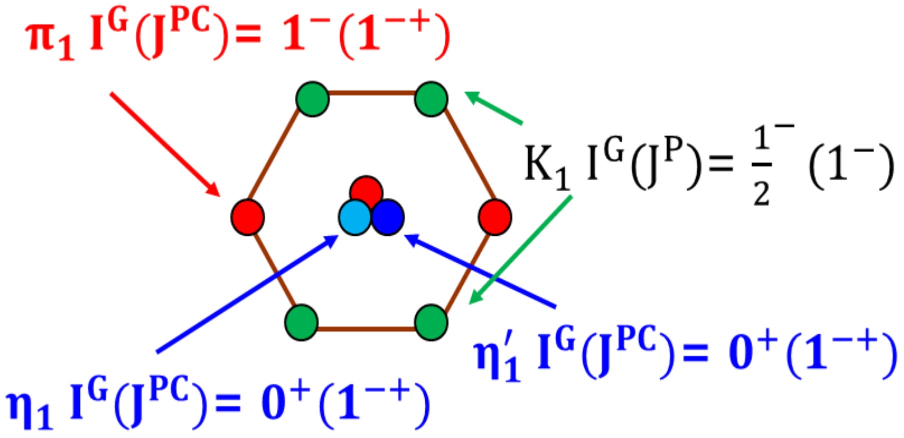
$\mathbf{2.7 \times 10^9}$ $\psi(3686)$@BESIII [New]

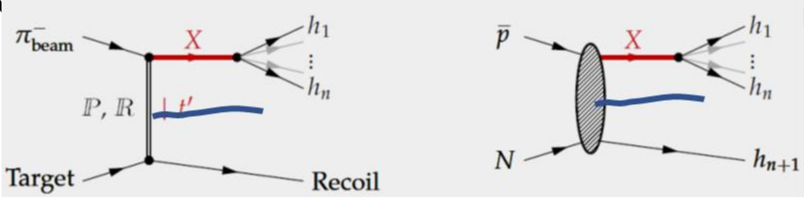


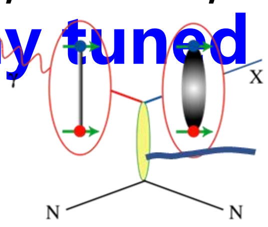
- $\pi_1(1600)$ observed>10σ
- **with a significant BW phase motion**
- $\mathbf{J^{PC}}$= $\mathbf{1^{-+}}$, **better than other assignments well over 10σ**

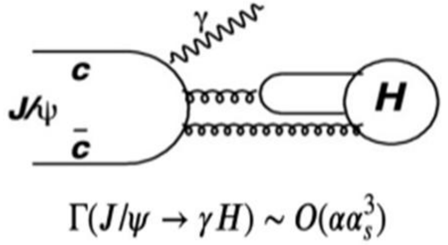
1^{-+} Hybrids

- What are the nature of $\pi_1(1600)$ and $\eta_1(1855)$?
  - Decay: e.g. for η_1, $J/\psi \to \gamma + \eta f_1, K_1\bar{K}$
  - Production: e.g. for η_1, $J/\psi \to \omega\eta\eta'$, $\phi\eta\eta'$
- Where is the $\eta_1^{(\prime)}$?
- Does K_1 exist and how to identify it?
- Where are the other $J^{PC} = (0^{--},)\text{even}^{+-}, \text{odd}^{-+}$ states?
- New results from COMPASS, AMBER, BESIII, Glu… and PAN… Stay tuned





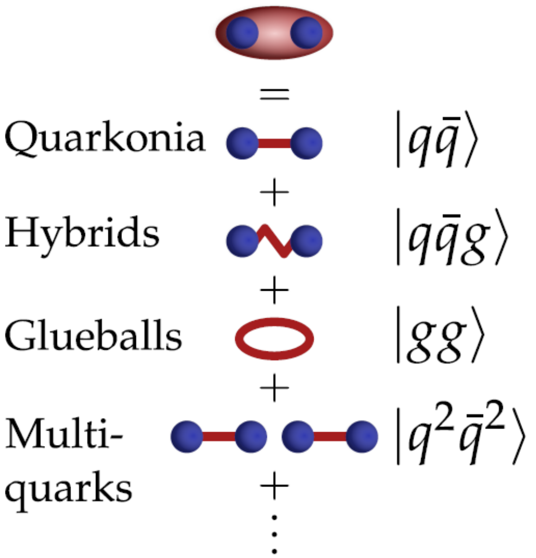




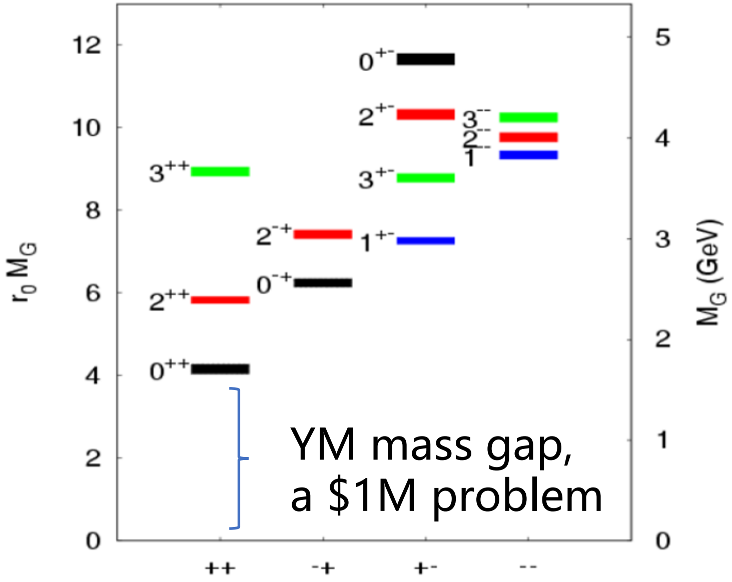
Glueballs

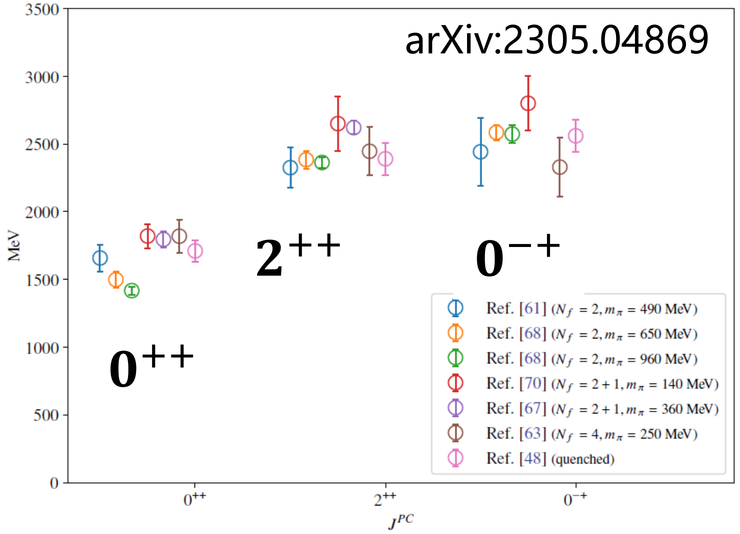
- Glueballs are the most direct prediction of QCD
  - Color singlets as a consequence of the gluon self-interactions
- Essential for understanding of confinement and mass dynamical generation
- Theoretical predictions from lattice QCD and QCD-inspired models mostly consistent
  - Light-mass glueballs: $J^{PC} = 0^{++}, 2^{++},\ 0^{-+}$

non-$\mathbf{q\bar{q}}$ nature with ordinary quantum numbers is difficult to establish



PRD 73 014516 (2006)





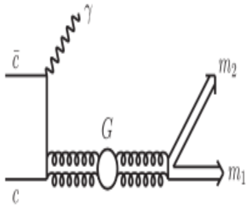
Yang-Mills glueballs on lattice (quenched and unquenched)

Glueball hunting for over 40 years

- **Supernumerary states** w.r.t. quark model
  - A priori, mixed with nearby $\mathbf{q\bar{q}}$
  - Assignment of some $q\bar{q}$ multiplets is difficult
- Detailed and accurate information about couplings to production and decay channels is required
- Strongly produced in **gluon-rich processes**
- Decay: **gluon is flavor-blind**
  - $SU(3)_{\text{flavor}}$ symmetry expected, but differing quark masses leads exceptions
  - No rigorous predictions on decay patterns
  - Could be analogy to **OZI suppressed** decays of charmonium, as they all decay via gluons [PLB 380 189(1996), Commu. Theor. Phys. 24.373(1995)]

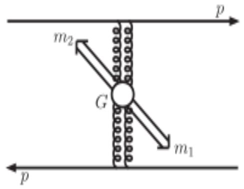
gluon-rich processes

[Phys. Rept. 454 1]



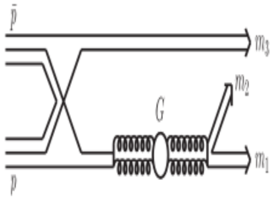
Charmonium decays:

BESIII, MRKIII…



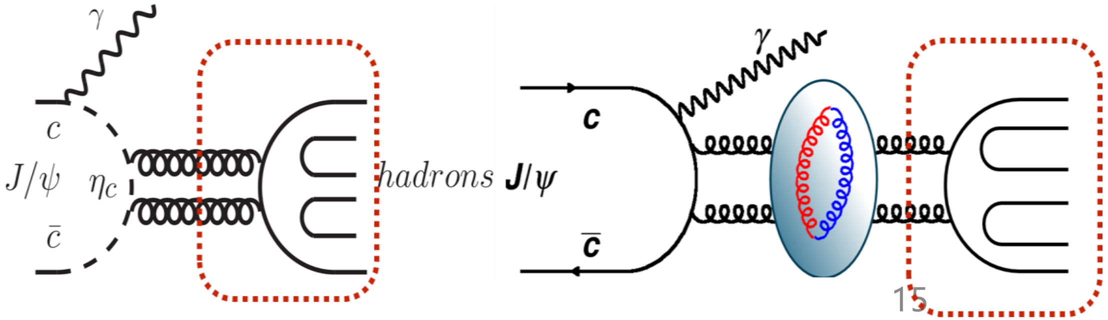
pp double-Pomeron exchange:

WA102, GAMS…



$\mathbf{p\bar{p}}$ annihilation:

Crystal barrel, OBELIX…



Scalar glueball candidate

- **Supernumerary scalars** suggest additional degrees of freedom
  - However, mixing scenarios are controversial
- Measured $\mathrm{B}(J/\psi \to \gamma f_0(1710))$ is **x10 larger** than $f_0(1500)$

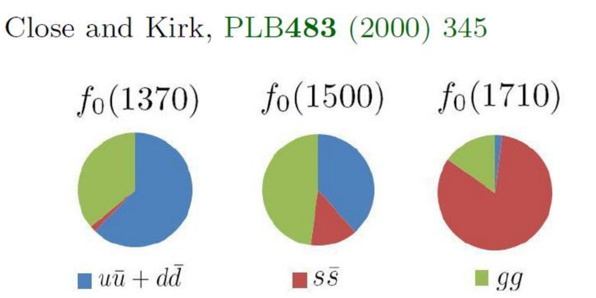
  BESIII [PRD 87 092009, PRD 92 052003, PRD 98 072003]

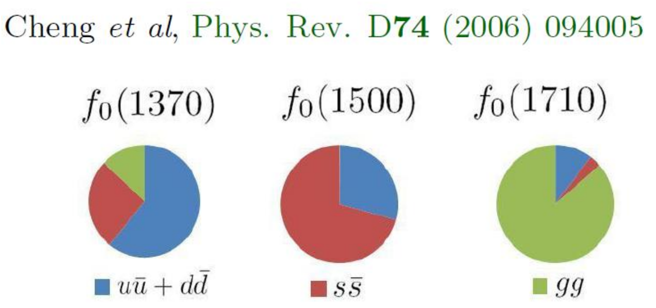
  - LQCD: $\Gamma(J/\psi \to \gamma G_{0+})/\Gamma_{total} = 3.8(9) \times 10^{-3}$ [PRL 110, 091601(2013)]

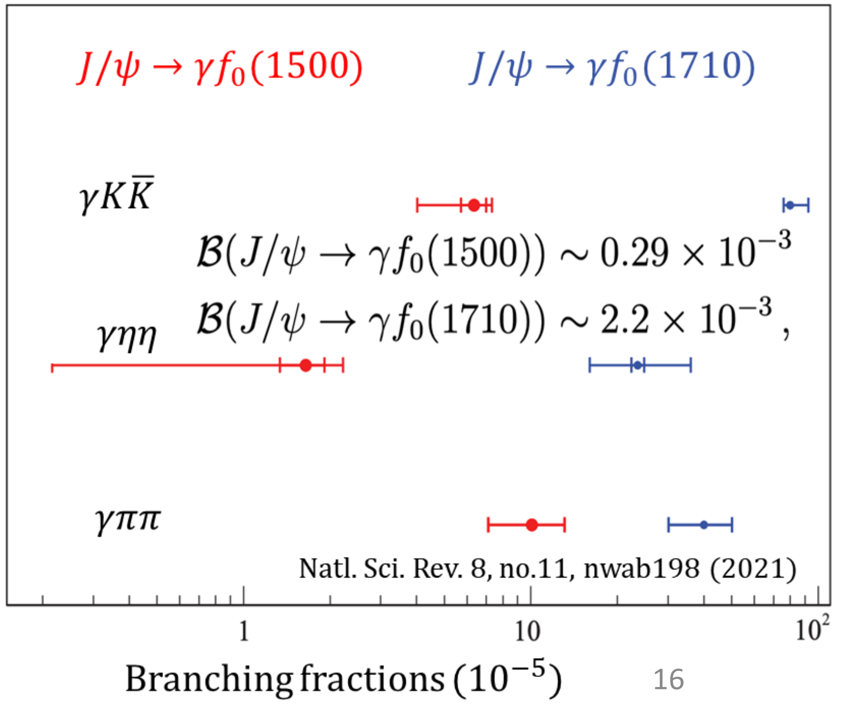
  ➢ **BESIII: $f_0(1710)$ largely overlays with the scalar glueball**

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

BESIII [PRD 106 072012(2022)]







Identification of scalar glueball with coupled-channel analyses based on BESIII data

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

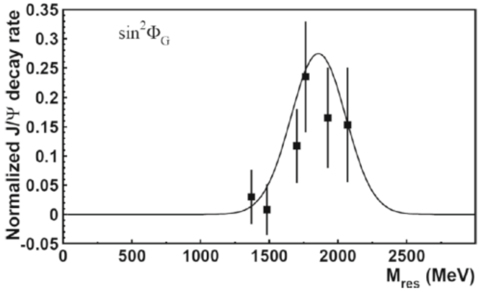
A.V. Sarantsev[a,b], I. Denisenko[c], U. Thoma[a], and E. Klempt[a]

[a]Helmholtz–Institut für Strahlen– und Kernphysik, Universität Bonn, Germany
[b]NRC "Kurchatov Institute", PNPI, Gatchina 188300, Russia
[c]Joint Institute for Nuclear Research, Joliot-Curie 6, 141980 Dubna, Moscow region, Russia

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 $M = 1865\pm25^{+10}_{-30}$ MeV and $\Gamma = 370\pm50^{+30}_{-20}$ MeV, its yield in radiative J/ψ decays to $(5.8 \pm 1.0)\,10^{-3}$.

Phys.Lett.B 816, 136227 (2021)
Eur.Phys.J.C 83 1125(2023)



Production rate: $5.8(1) \times 10^{-3}$

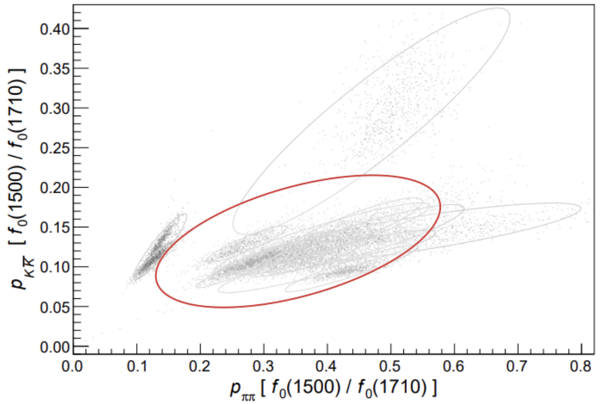
Scalar and tensor resonances in J/ψ radiative decays

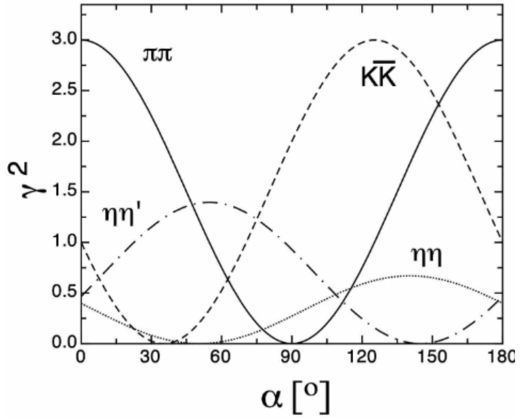
A. Rodas,[1,2,*] A. Pilloni,[3,4,5,†] M. Albaladejo,[6] C. Fernández-Ramírez,[7] V. Mathieu,[8,9] and A. P. Szczepaniak[2,10,11]
(Joint Physics Analysis Center)

[1]Department of Physics, College of William and Mary, Williamsburg, VA 23187, USA
[2]Theory Center, Thomas Jefferson National Accelerator Facility, Newport News, VA 23606, USA
[3]INFN Sezione di Roma, I-00185 Roma, Italy
[4]Dipartimento di Scienze Matematiche e Informatiche, Scienze Fisiche e Scienze della Terra, Università degli Studi di Messina, I-98166 Messina, Italy
[5]INFN Sezione di Catania, I-95123 Catania, Italy
[6]Instituto de Física Corpuscular (IFIC), Centro Mixto CSIC-Universidad de Valencia, Institutos de Investigación de Paterna, Aptd. 22085, E-46071 Valencia, Spain
[7]Instituto de Ciencias Nucleares, Universidad Nacional Autónoma de México, Ciudad de México 04510, Mexico
[8]Departament de Física Quàntica i Astrofísica and Institut de Ciències del Cosmos, Universitat de Barcelona, E08028, Spain
[9]Departamento de Física Teórica, Universidad Complutense de Madrid and IPARCOS, E-28040 Madrid, Spain
[10]Physics Department, Indiana University, Bloomington, IN 47405, USA
[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

Indications of tensor glueball

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

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)

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

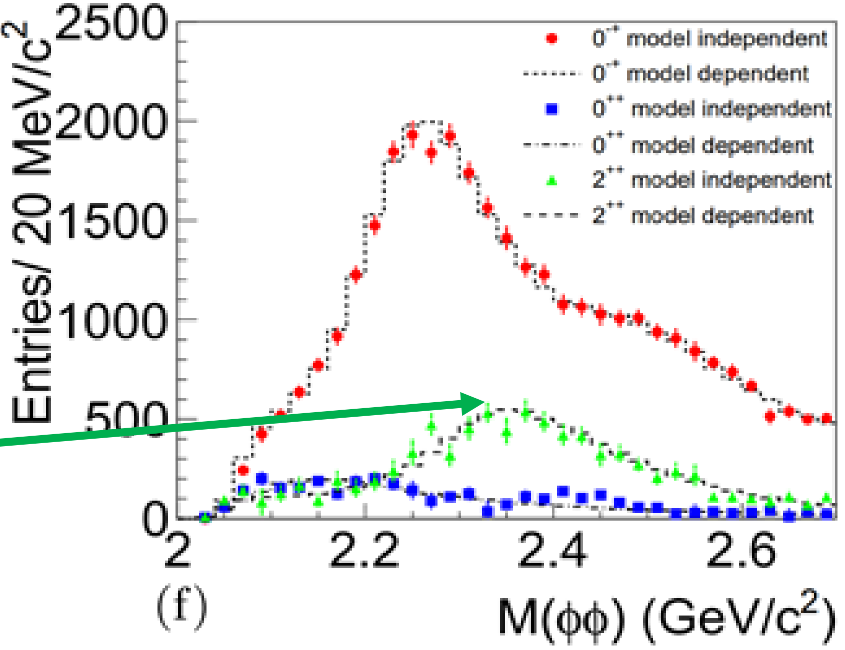
BESIII PRD 98,072003 (2018)

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

BESIII PRD 105,072002 (2022)

still desired to study more decay modes

BESIII $J/\psi \to \gamma\phi\phi$ [PRD 93, 112011 (2016)]

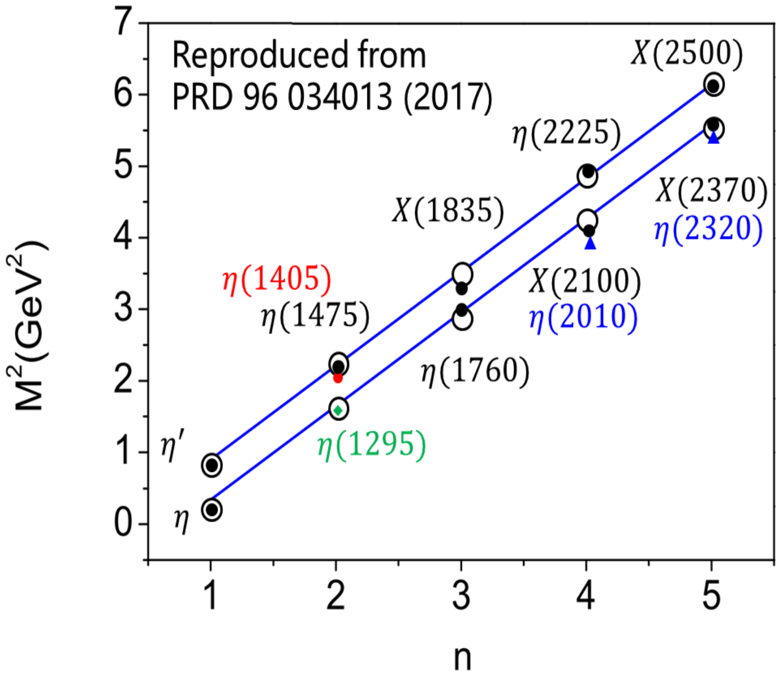


- $f_2(2010)$, $f_2(2300)$ and $f_2(2340)$ in πp reactions are all observed in $J/\psi \to \gamma\phi\phi$ with a **strong production of $f_2(2340)$**
- Consistent with **double-Pomeron exchange** from WA102@CERN

More complicated due to the large number of tensor states

Where is the 0^{-+} glueball

- Pseudoscalar sector, a promising window
  - [Future Physics Programme of BESIII(2020)， CPC 44, 040001]
  - Only η, η′ (& radial excitations) from quark model
- Mass
  - LQCD： 0^{-+} glueball (2.3~2.6 GeV)
  - Puzzles remain in low mass region
- Production
  - LQCD: $\Gamma(J/\psi \to \gamma G_{0-})/\Gamma_{\text{total}} = 2.31(80) \times 10^{-4}$, at the same level as 0^{-+} mesons [PRD.100.054511(2019)]
- **Decays**
  - **Possible guidance: OZI suppressed decays of η_c**
  - **$0^{-+} \to 3\mathrm{P}$ is a good place to look for**
    - $0^{-+} \to 2\mathrm{P}$ is forbidden
    - $0^{-+} \to 3\mathrm{P}$ can via S-wave, while 0^{+} or 2^{+} is suppressed



$\eta_c \to 3\,\mathrm{P}$ in PDG

Decays involving hadronic resonances

Γ_1	$\eta'(958)\pi\pi$	(1.87±0.26) %
Γ_2	$\eta'(958)K\overline{K}$	(1.61±0.25) %

Decays into stable hadrons

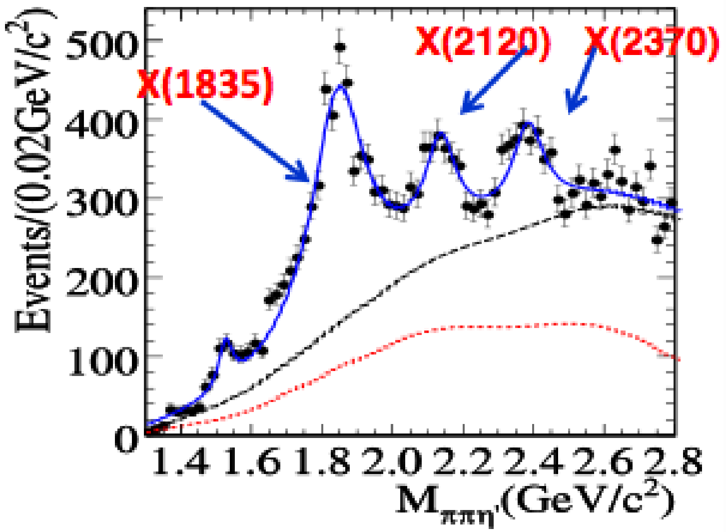
Γ_{34}	$K\overline{K}\pi$	(7.0 ±0.4) %
Γ_{35}	$K\overline{K}\eta$	(1.32±0.15) %
Γ_{36}	$\eta\pi^+\pi^-$	(1.7 ±0.5) %

- No dominant decay
- Flavor symmetric

A glueball-like state $X(2370)$

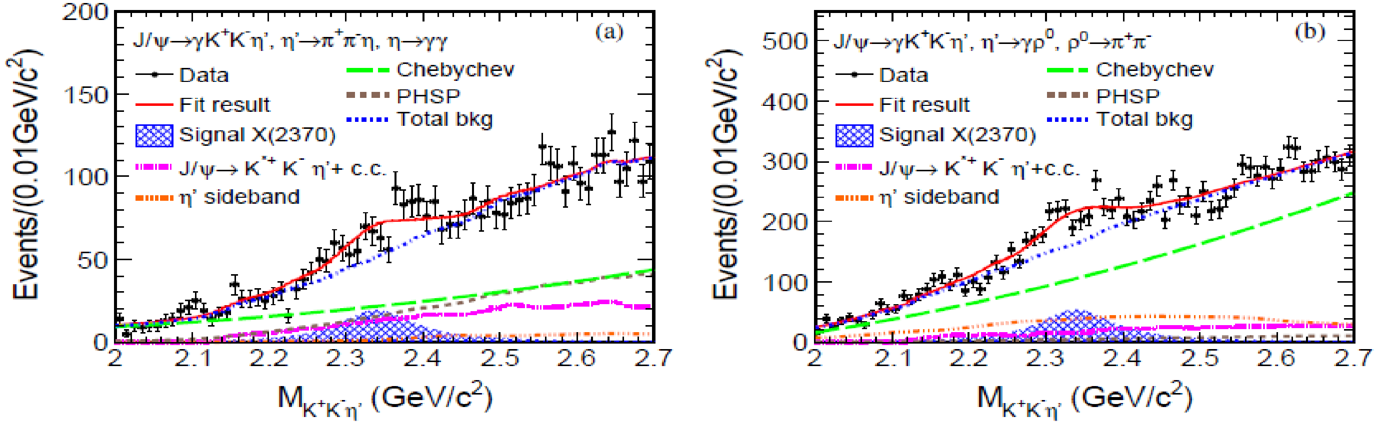
- **Discovered by BESIII in $J/\psi \to \gamma\eta'\pi\pi$ in 2011**
- Confirmed by BESIII in $J/\psi \to \gamma\eta'\pi\pi$, $\boldsymbol{\gamma\eta'KK}$ **(new mode)**
  - Not seen in $J/\psi \to \gamma\eta'\eta\eta$ [BESIII PRD 103 012009 (2021)], $J/\psi \to \gamma\gamma\phi$ [BESIII PRD.111.052011(2025)]. Upper limits of BF are well consistent with predictions of 0^{-+}glueball
- **Mass consistent with LQCD prediction for 0^{-+} glueball**

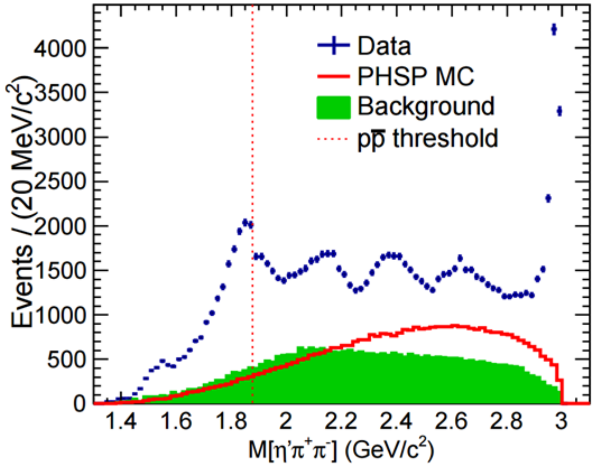
$J/\psi \to \gamma\eta'\pi\pi$



BESIII PRL 106, 072002(2011)

$J/\psi \to \gamma\eta'KK$ BESIII EPJC 80 746(2020)





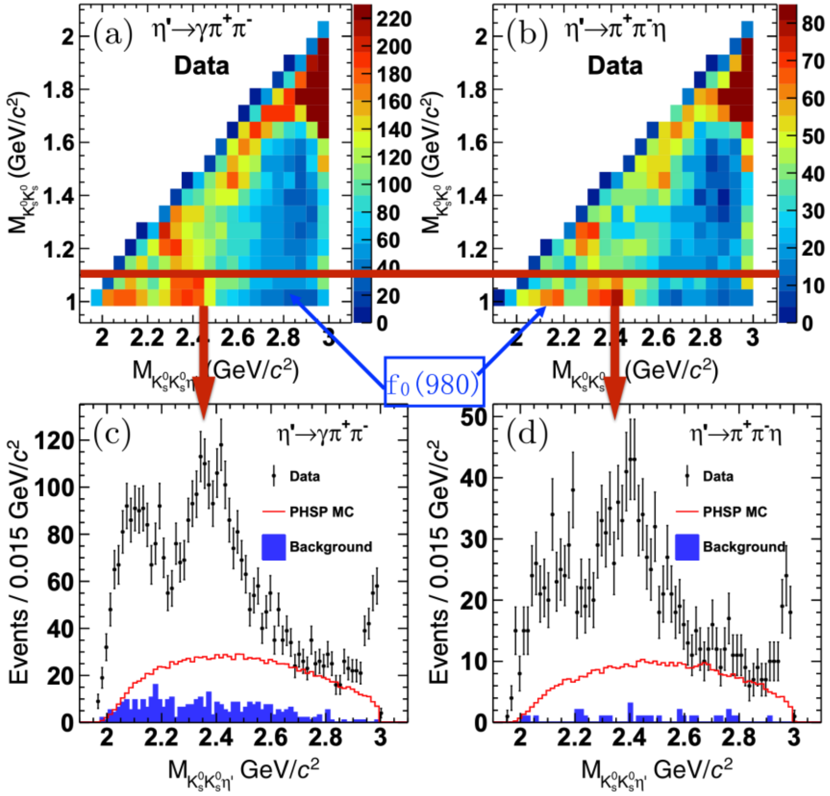
BESIII PRL 117, 042002 (2016)

A glueball-like state $X(2370)$

- **Spin-parity determined to be 0^{-+}** → As promised

$J/\psi \to \gamma\eta' K_S^0 K_S^0$ BESIII PRL 132, 181901(2024)

[BESIII whitepaper(2020)， CPC 44, 040001]



From simulation studies, the detection efficiency of a typical decay mode of a pseudoscalar glueball is estimated to be a few percent. Recently, a new decay mode of $X(2370)$ was observed in the spectrum of $\eta' K\bar{K}$ of $J/\psi \to \gamma\eta' K\bar{K}$. We performed a feasibility study to determine the spin-parity of $X(2370)$. The neutral channel $J/\psi \to \gamma\eta' K_S^0 K_S^0$ provides a clean environment for amplitude analysis as it does not suffer from significant backgrounds such as $J/\psi \to \pi^0\eta' K_S^0 K_S^0$, which are present in the charged channel $J/\psi \to \pi^0\eta' K^+K^-$. MC samples with statistics equivalent to the current data and 10 billion J/ψ were generated with a certain set of amplitude parameters. Amplitude analysis was performed of the MC samples with various hypothesis. Table 2.4 shows that the spin-parity of $X(2370)$ can be unambiguously determined with higher statistics of data. BESIII accumulated 10 billion J/ψ

$J^{PC} = 0^{-+}$ with significance >9.8σ

$M = 2395 \pm 11^{+26}_{-94}$ MeV

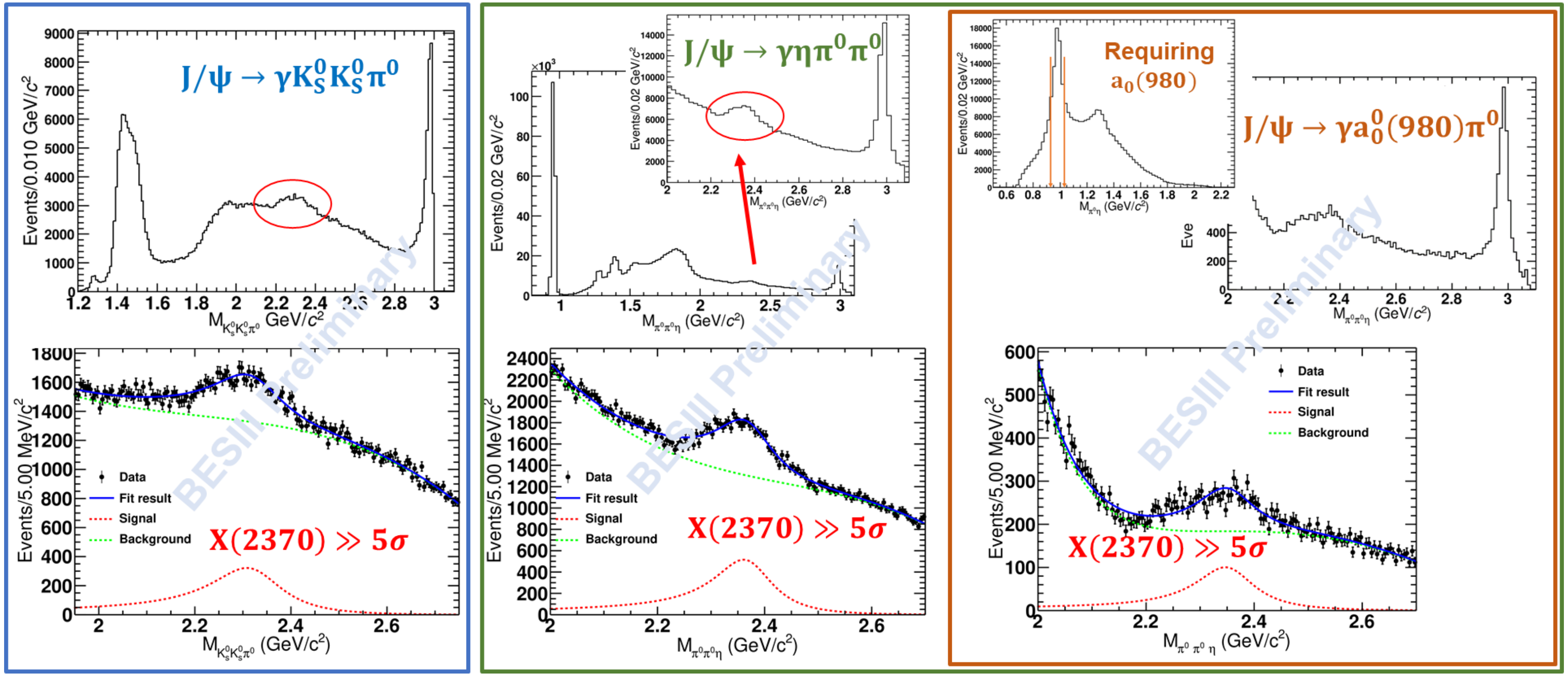
$\Gamma = 188^{+18}_{-17}{}^{+124}_{-33}$ MeV

$B(J/\psi\to\gamma X(2370))B(X(2370)\to f_0(980)\eta')B(f_0(980)\to K^0_S K^0_S)$
$= 1.31 \pm 0.22^{+2.85}_{-0.84} \times 10^{-5}$

Highlights of ICHEP2024

ichep2024.org

PRL 2024 COLLECTION



*$\eta(2320) \to \eta\eta\eta, \eta\pi\pi$ [PL B496 145(2000)] could be the same state

$\mathbf{X(2370)}$ observed in the gluon-rich $\mathbf{J/\psi}$ radiative decays

- **A first-time determination of $\mathbf{J^{PC}=0^{-+}}$**
- **Mass and production rate consistent with LQCD**
- **Decay modes $\mathbf{X(2370) \to \eta'\pi\pi, \eta' KK, K_S^0K_S^0\eta, K_S^0K_S^0\pi^0, \eta\pi^0\pi^0, a_0^0(980)\pi^0}$, in analog to $\mathbf{\eta_c}$ with OZI-suppressed style**

Qualitatively consistent with $\mathbf{0^{-+}}$ glueball

"Discovering" glueball 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)

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

✓ **$B(J/\psi \to \gamma f_0(1710))$ is x10 larger than $f_0(1500)$; suppression of $f_0(1710) \to \eta\eta'$**

➔ **Large gluonic component**

BESIII [PRD 87 092009, PRD 92 052003, PRD 98 072003, PRD 106 072012]

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

BESIII [PRD 87,092009, PRD 93, 112011, PRD 98,072003, PRD 105,072002]

✓ **$X(2370)$: a good candidate with analogy decay pattern as η_c**

BESIII [PRL 106, 072002, PRL 117, 042002, EPJC 80 746, PRL 132, 181901, PoS ICHEP2024 490]

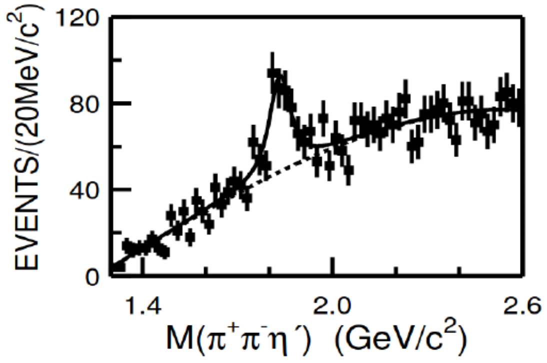
definitively manifest the gluonic degrees of freedom yet?

Threshold structures

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

58 M J/ψ

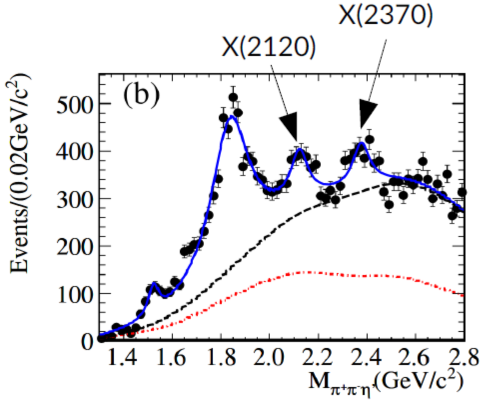
PRL 95 262001(2005)



Observation of X(1835)

225M J/ψ

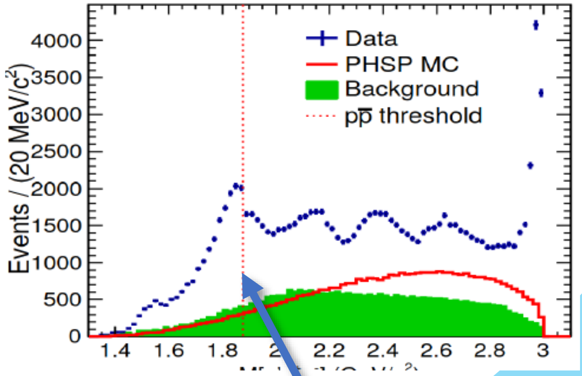
PRL 106 072002(2011)



Observation of X(2120), X(2370)

1.3B J/ψ

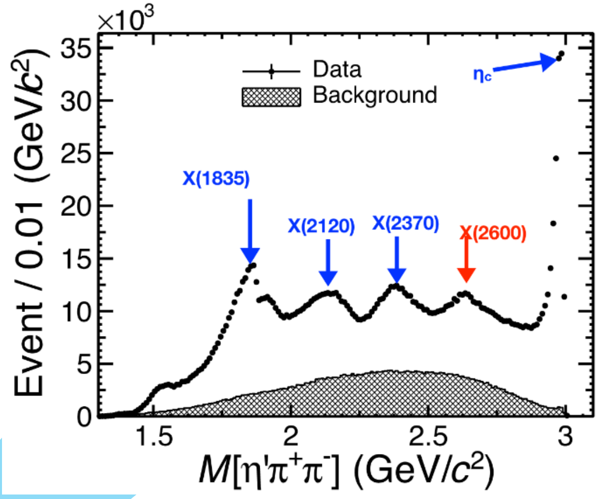
PRL 117 042002(2016)



Observation of anomalous line shape

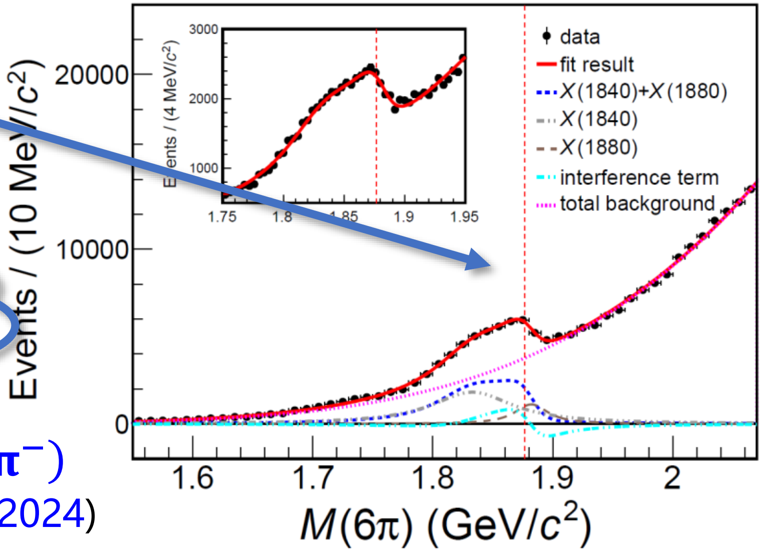
10B J/ψ

PRL 129, 042001 (2022)



Observation of X(2600)

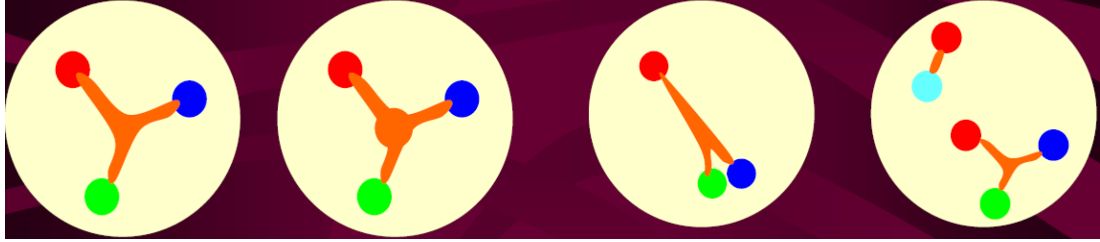
Indicating a ppbar bound state



$J/\psi \to \gamma 3(\pi^+\pi^-)$

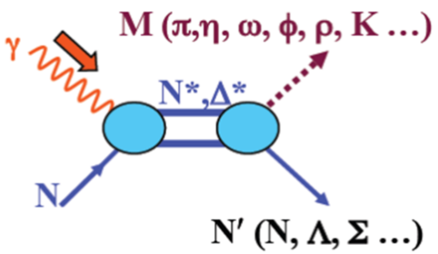
PRL 132,151904 (2024)

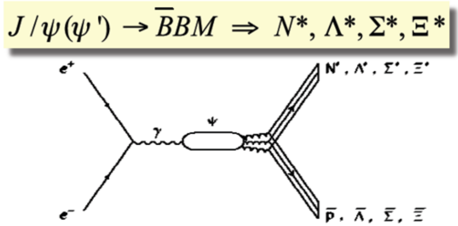
Baryon spectroscopy

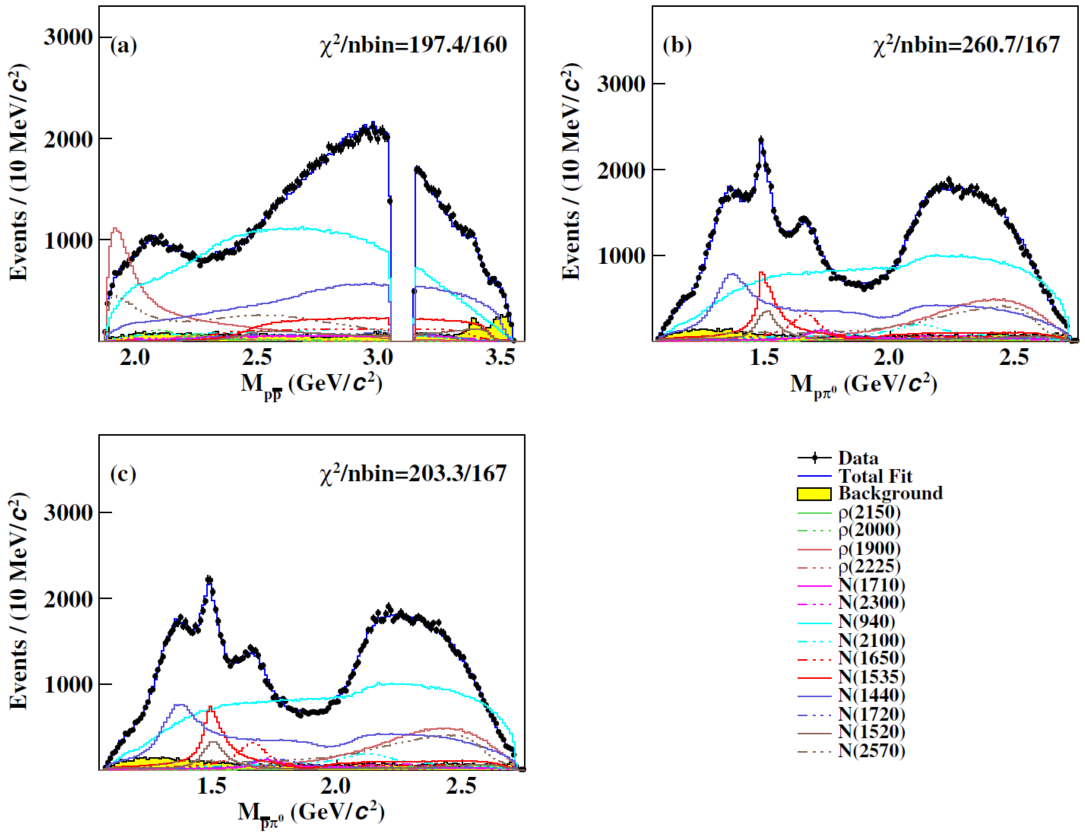


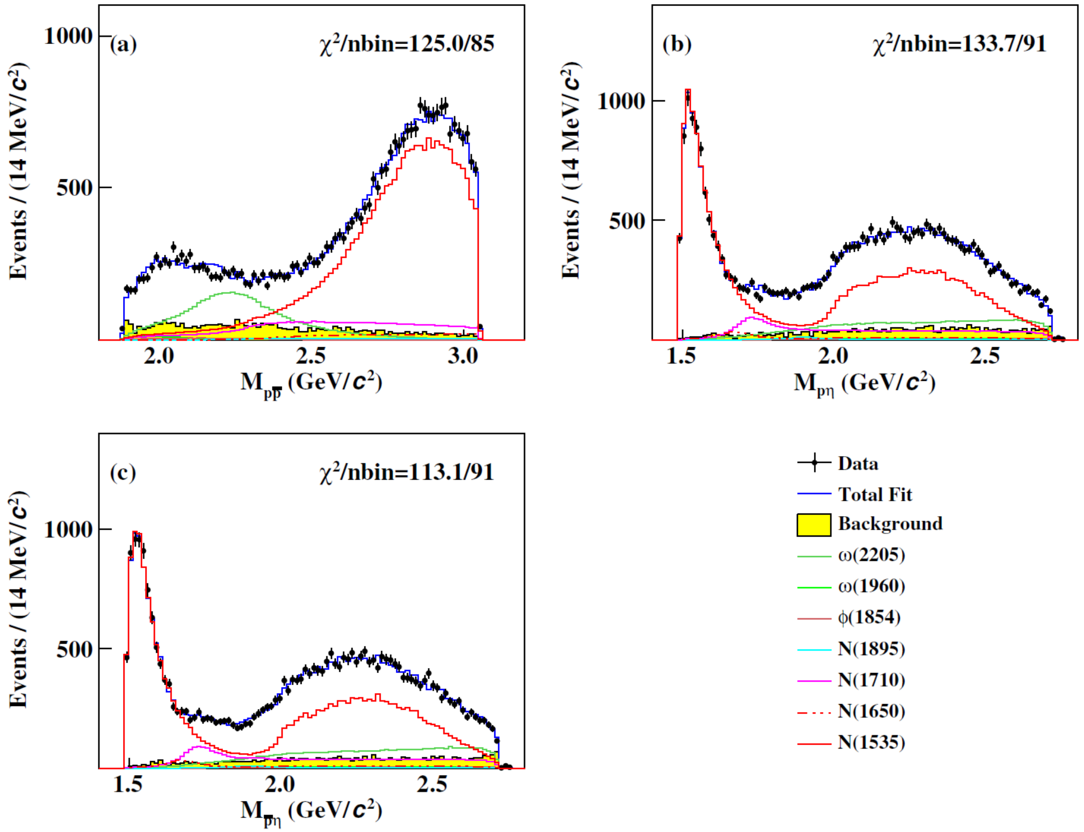
$\psi(2S) \to \bar{p}p\pi^0/\eta$

Phys.Rev.D 111 (2025) 3, 032011









Structure

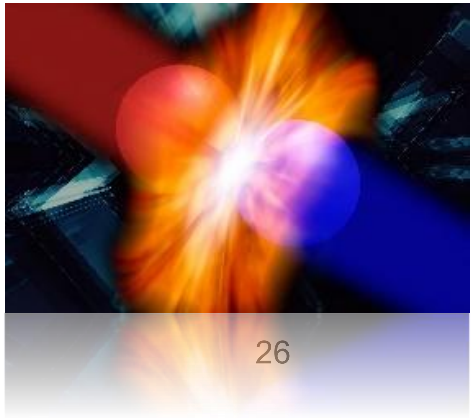
Spectroscopy

Interactions

Light hadrons

Precision tests
& rare phenomena

See Hongfei Shen and Tao Luo's talks



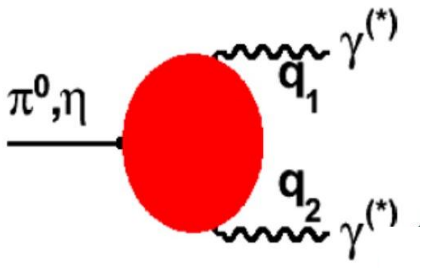
BESIII as an η/η' factory

BESIII	η events	η' events
$J/\psi \to \gamma\eta/\eta'$	1.1×10^7	5.2×10^7
$J/\psi \to \gamma\eta'(\pi^+\pi^-\eta)$	$2.2{\times}10^7$	
$J/\psi \to \phi/\omega\eta/\eta'$	2.5×10^7	6.5×10^6

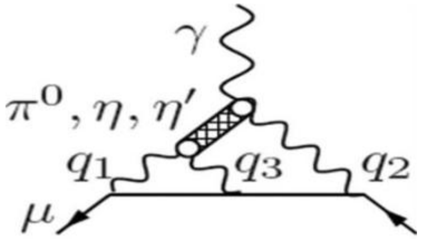
Low Background:

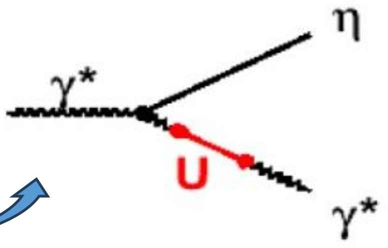
- Many strong and electromagnetic decays are forbidden at leading order due to P, C, CP, G-parity, or angular momentum conservation
- Symmetry-violating η, η′ decays in SM, sourced by the weak interaction, are negligible

Meson transition form factors

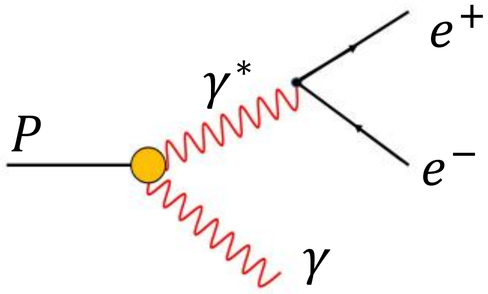


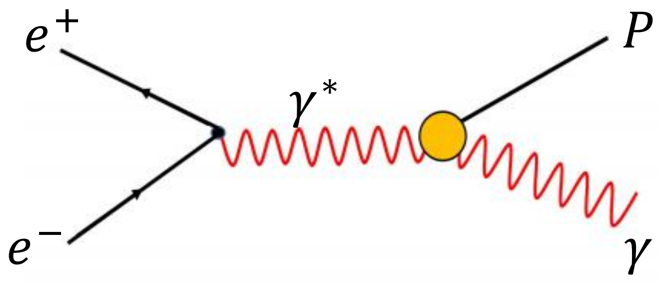
- Low energy QCD:
  - Enters in th. description of QCD processes
  - Evolution with Q^2 predicted by pQCD: models can be tested using data on Q^2 dependance
- Light-by-light contribution to a_μ
- Search for light dark force mediator

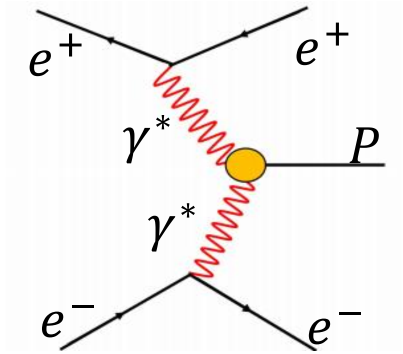




Experimentally

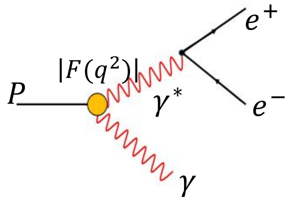




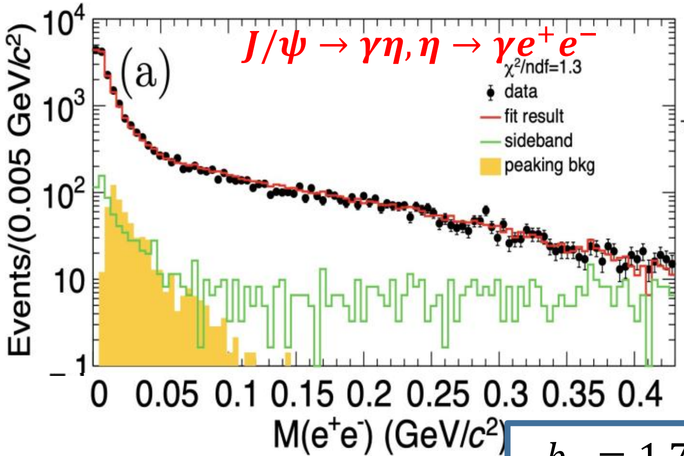


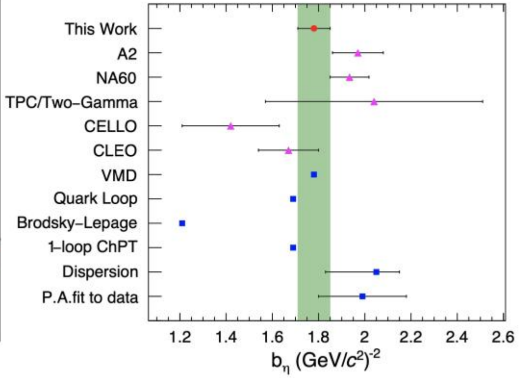
Dalitz decays $0<q^2<M^2$ **Annihilation process $q^2>M^2$** **Two photon process $q^2<0$**

TFF of $\eta/\eta' \to \gamma e^+e^-$

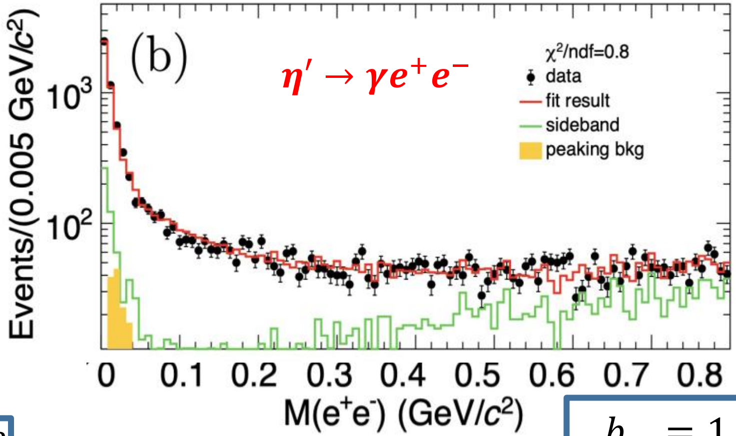


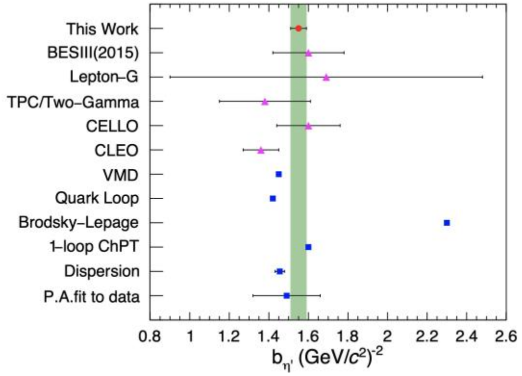
BESIII: PRD 109, 072001 (2024)





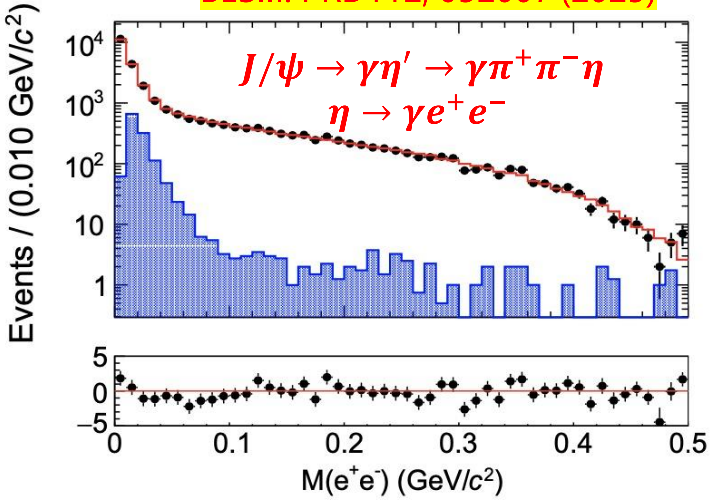
$b_\eta = 1.781 \pm 0.123 \pm 0.033\ (\mathrm{GeV/c^2})^{-2}$

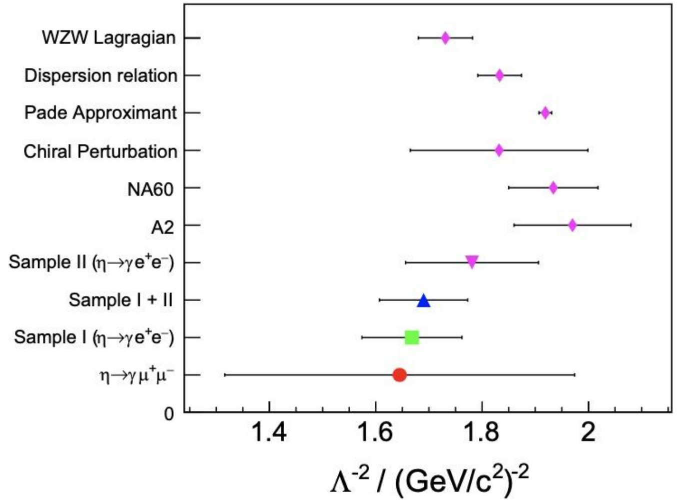


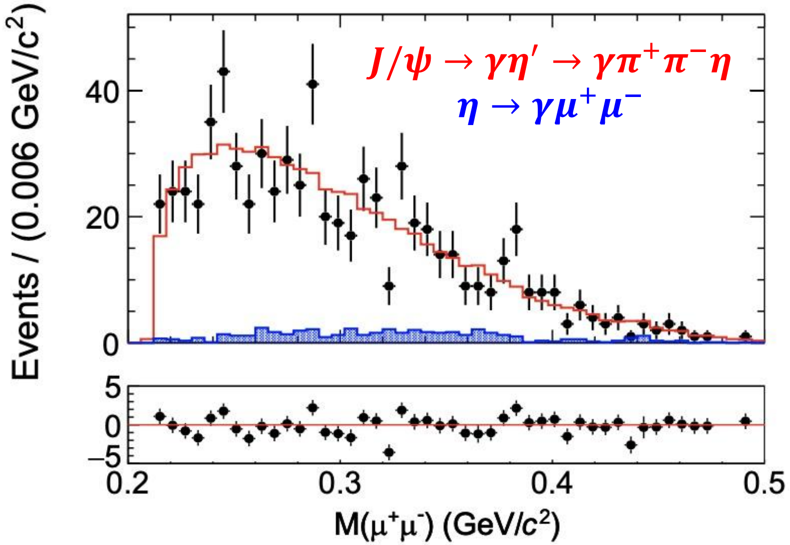


$b_{\eta'} = 1.574 \pm 0.048 \pm 0.016\ (\mathrm{GeV/c^2})^{-2}$

BESIII: PRD112, 052007 (2025)







Combined the two $\eta \to \gamma e^+e^-$: $b_\eta = (1.707 \pm 0.076 \pm 0.029)\ GeV/c^2$

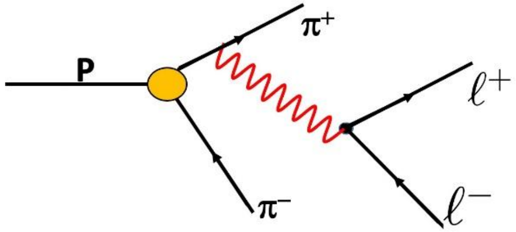
$b_\eta = (1.645 \pm 0.343 \pm 0.017)\ GeV/c^2$

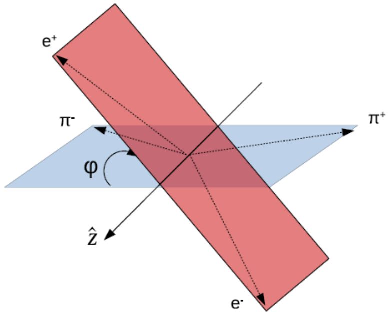
*A simplified single-pole model in VMD

Asymmetry in $\eta^{(\prime)} \to \pi^+\pi^- l^+ l^-$

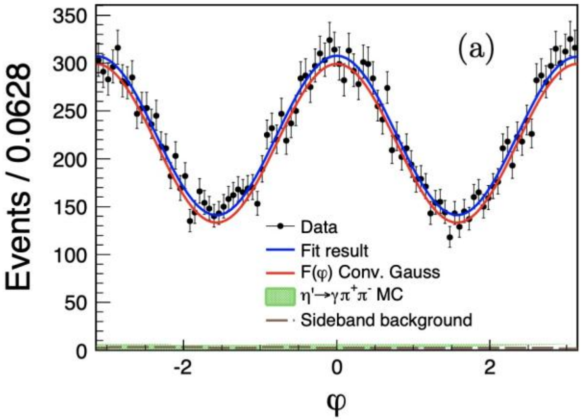
D. N. Gao, Mod Phys Lett A17 (2002) 1583
M. Zillinger, B. Kubis, P. Sánchez-Puertas, JHEP 12 (2022) 001

- Test of non-CKM CP Violation:
- Arises from interference between CP conserving magnetic and CP violating electric transition



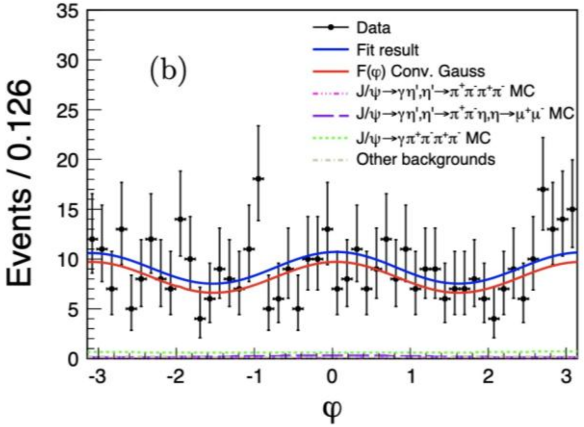


$\eta' \to \pi^+\pi^- e^+ e^-$



$A_{CP} = (-0.21 \pm 0.73 \pm 0.01)\%$

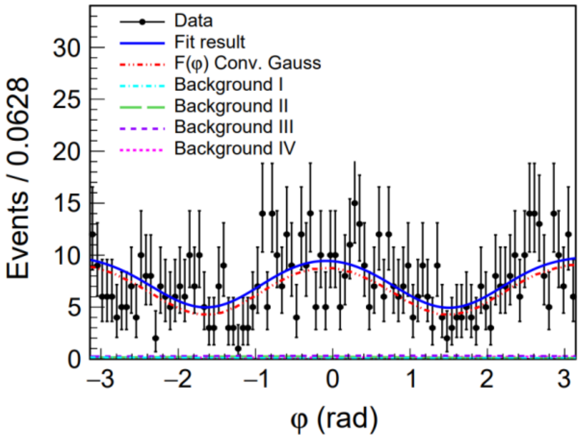
$\eta' \to \pi^+\pi^- \mu^+ \mu^-$



$A_{CP} = (0.62 \pm 4.71 \pm 0.08)\%$

BESIII: JHEP 07, 135 (2024)

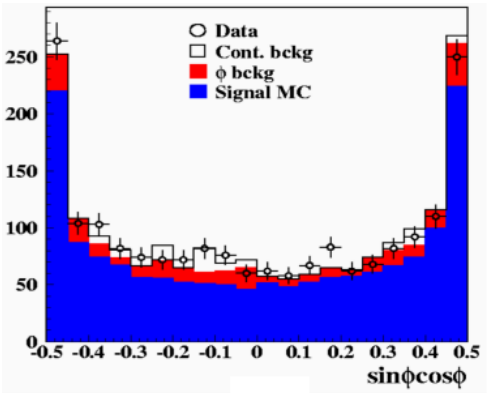
$\eta \to \pi^+\pi^- e^+ e^-$



$A_{CP} = (-4.04 \pm 4.69 \pm 0.14)\%$

BESIII: arXiv:2501.10130v1

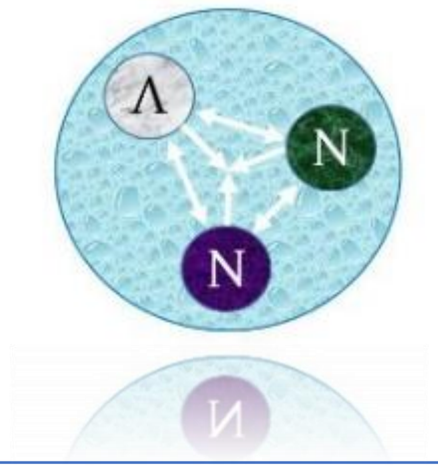
$\eta \to \pi^+\pi^- e^+ e^-$



$A_{CP} = (-0.6 \pm 2.5 \pm 1.8)\%$

KLOE: PLB 675 (2009) 283

All asymmetries consistent with zero at 10^{-3} level



Structure

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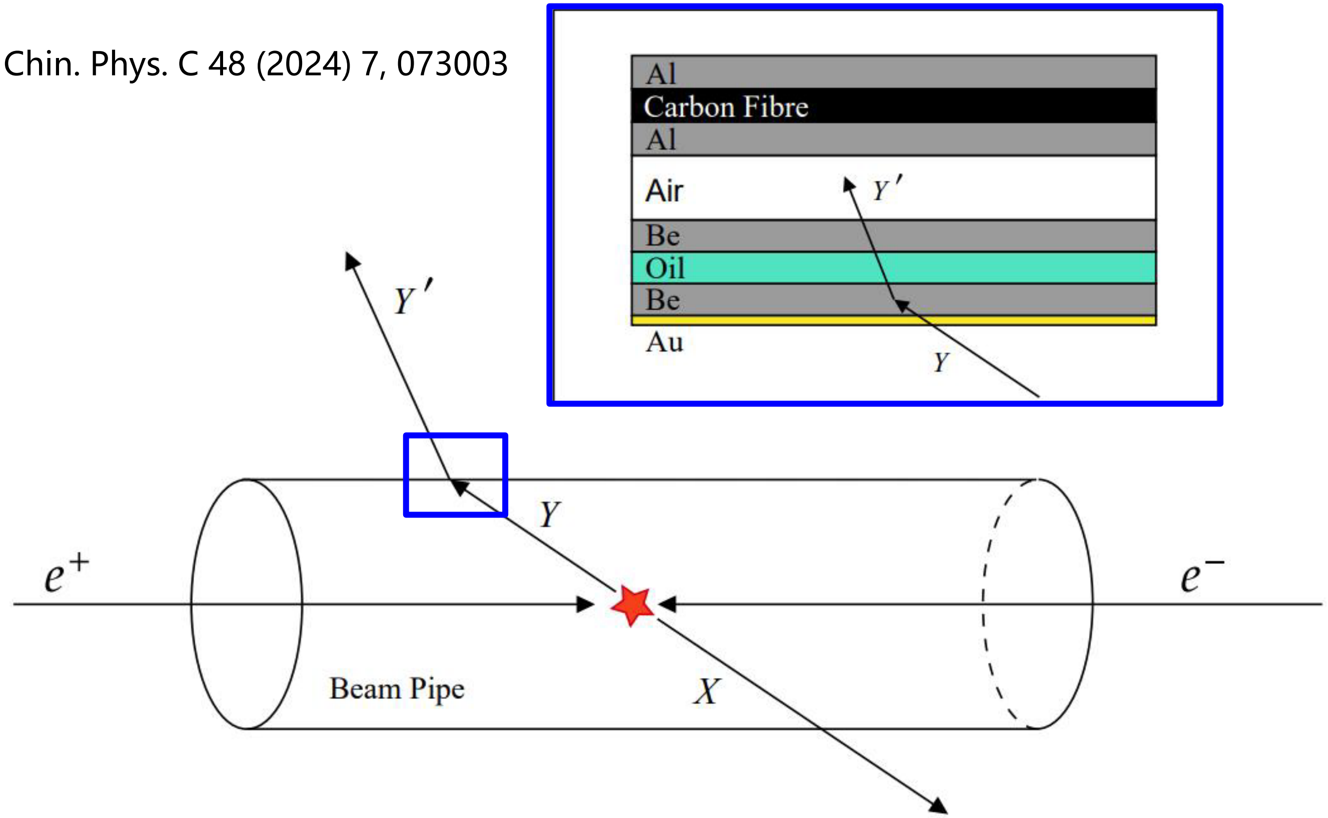
Interactions

Light hadrons

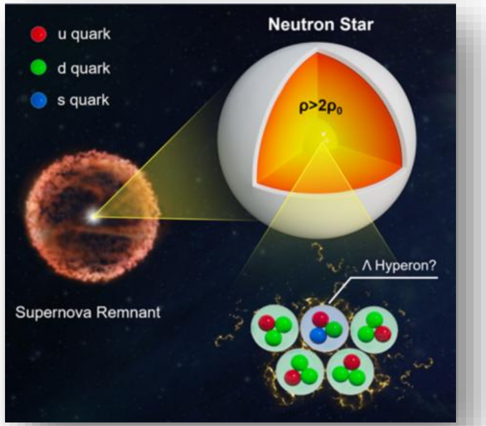
Precision tests & rare phenomena

Image from Chin. Phys. C 48 (2024) 7, 073003



Hadron (YN) interactions with BESIII

- Crucial component to predict hypernuclei properties
- Key to understand the hyperon puzzle of neutron stars



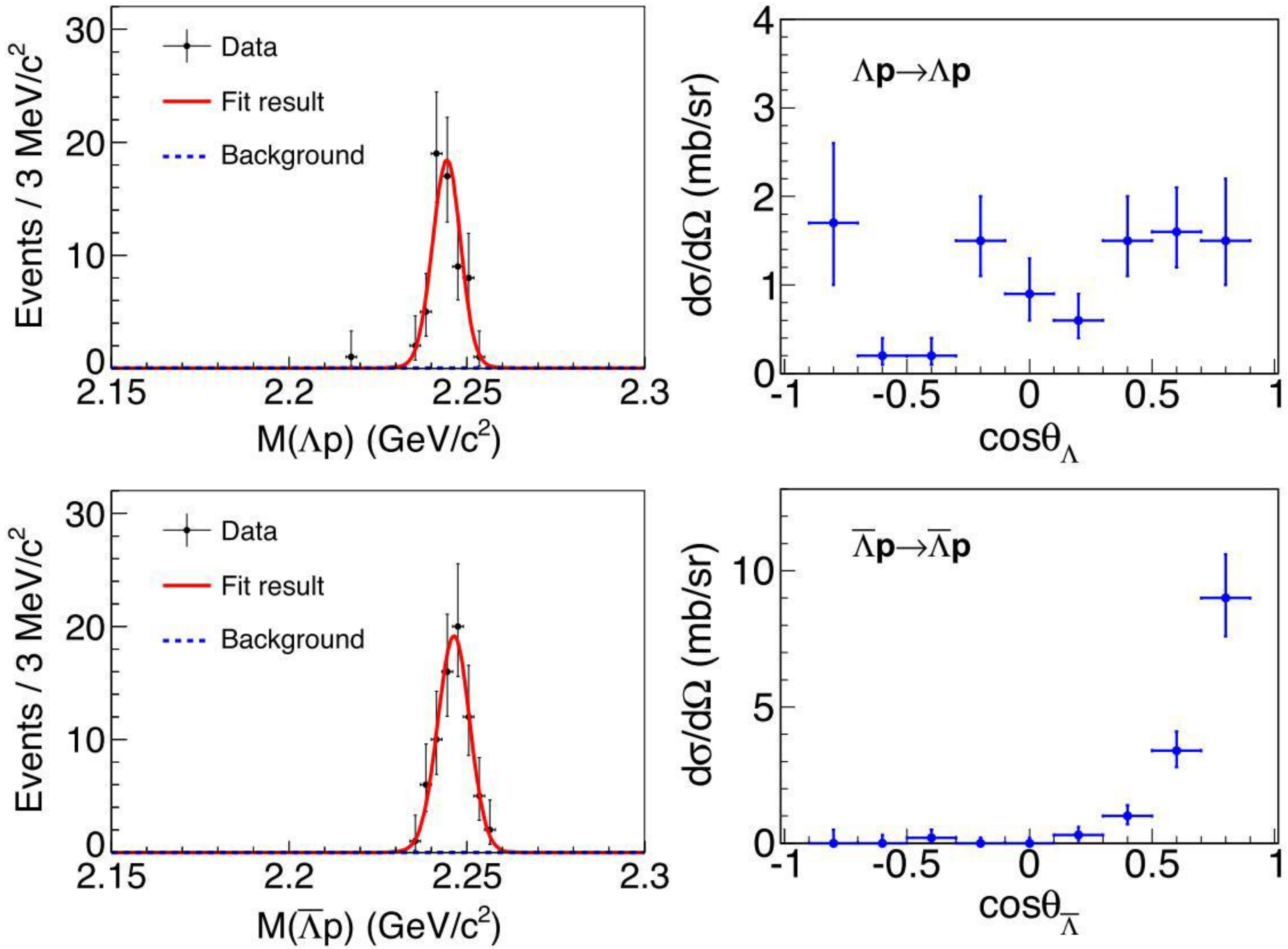
First study of antihyperon-nucleon scattering

BESIII PRL 132, 231902 (2024)

Beam: $\Lambda/\bar{\Lambda}$ from $J/\psi \rightarrow \Lambda\bar{\Lambda}$, using 10B J/ψ

$p_{\Lambda} = 1.074 \pm 0.017\ \mathrm{GeV/c^2}$, $|\cos\theta_{\Lambda(\bar{\Lambda})}| < 0.9$

Target: proton, the hydrogen nuclei in the cooling oil of the beam pipe

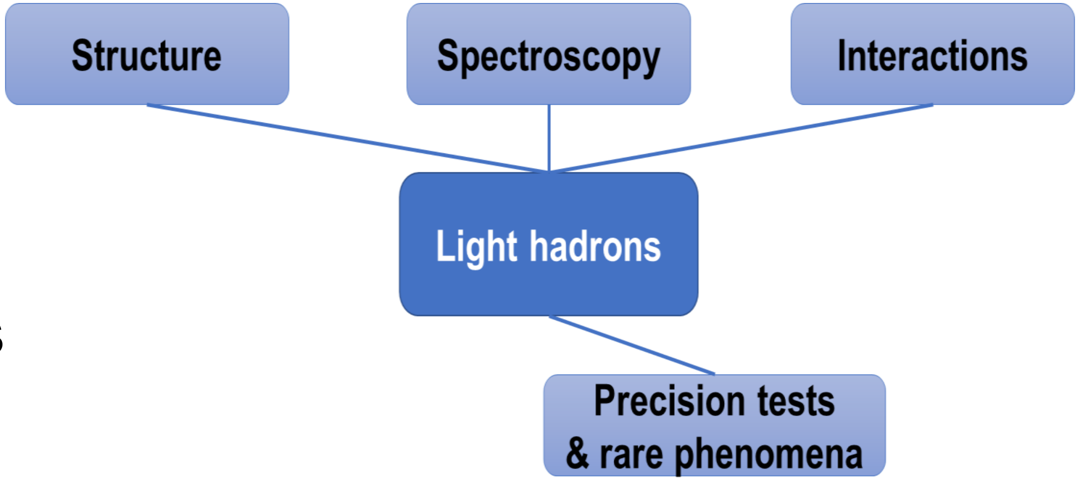


$\sigma(\Lambda p \rightarrow \Lambda p) = (12.2 \pm 1.6(\mathrm{stat.}) \pm 1.1(\mathrm{syst.}))$ mb

$\sigma(\bar{\Lambda} p \rightarrow \bar{\Lambda} p) = (17.5 \pm 2.1(\mathrm{stat.}) \pm 1.6(\mathrm{syst.}))$ mb

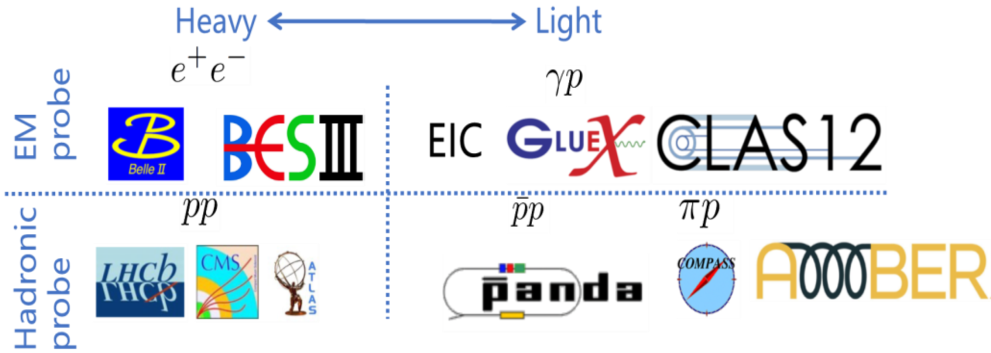
- **Slight tendency of forward scattering for $\Lambda p \rightarrow \Lambda p$**
- **Strong forward peak for $\bar{\Lambda} p \rightarrow \bar{\Lambda} p$**

Outlook



- Light hadron is central to study hadron physics

- Global efforts with various probes in running and planned experiments



BESIII plays a leading role in the studies of glueballs and hybrids

- Leveraging the high precision of current and future data requires
  - Advanced analysis techniques (See AI talks tomorrow)
  - Close theory-experiment collaboration

Rich η/η' Physics

Standard Model Tests:
- Chiral symmetry and anomalies
- Extract $\eta-\eta'$ mixing angle and quark mass ratio
- Theory inputs to HLbL for $(g-2)_\mu$
- QCD scalar dynamics

Fundamental Symmetry Tests:
- C, CP violations
- P, CP violations
- Lepton flavor violations

BSM Physics in Dark Sector:
- Vector bosons (B boson, dark photon and X boson)
- Dark scalars
- Pseudoscalars (ALPs)
- BSM weak decays

Channel	Expt. branching ratio	Discussion
$\eta\to 2\gamma$	39.41(20)%	Chiral anomaly, η–η' mixing
$\eta\to 3\pi^0$	32.68(23)%	m_u-m_d
$\eta\to\pi^0\gamma\gamma$	$2.56(22)\times 10^{-4}$	χPT at $\mathcal{O}(p^6)$, leptophobic B boson, light Higgs scalars
$\eta\to\pi^0\pi^0\gamma\gamma$	$<1.2\times 10^{-3}$	χPT, axion-like particles (ALPs)
$\eta\to 4\gamma$	$<2.8\times 10^{-4}$	$<10^{-11}$[55]
$\eta\to\pi^+\pi^-\pi^0$	22.92(28)%	m_u-m_d, C/CP violation, light Higgs scalars
$\eta\to\pi^+\pi^-\gamma$	4.22(8)%	Chiral anomaly, theory input for singly-virtual TFF and $(g-2)_\mu$, P/CP violation
$\eta\to\pi^+\pi^-\gamma\gamma$	$<2.1\times 10^{-3}$	χPT, ALPs
$\eta\to e^+e^-\gamma$	$6.9(4)\times 10^{-3}$	Theory input for $(g-2)_\mu$, dark photon, protophobic X boson
$\eta\to\mu^+\mu^-\gamma$	$3.1(4)\times 10^{-4}$	Theory input for $(g-2)_\mu$, dark photon
$\eta\to e^+e^-$	$<7\times 10^{-7}$	Theory input for $(g-2)_\mu$, BSM weak decays
$\eta\to\mu^+\mu^-$	$5.8(8)\times 10^{-6}$	Theory input for $(g-2)_\mu$, BSM weak decays, P/CP violation
$\eta\to\pi^0\pi^0\ell^+\ell^-$		C/CP violation, ALPs
$\eta\to\pi^+\pi^-e^+e^-$	$2.68(11)\times 10^{-4}$	Theory input for doubly-virtual TFF and $(g-2)_\mu$, P/CP violation, ALPs
$\eta\to\pi^+\pi^-\mu^+\mu^-$	$<3.6\times 10^{-4}$	Theory input for doubly-virtual TFF and $(g-2)_\mu$, P/CP violation, ALPs
$\eta\to e^+e^-e^+e^-$	$2.40(22)\times 10^{-5}$	Theory input for $(g-2)_\mu$
$\eta\to e^+e^-\mu^+\mu^-$	$<1.6\times 10^{-4}$	Theory input for $(g-2)_\mu$
$\eta\to\mu^+\mu^-\mu^+\mu^-$	$<3.6\times 10^{-4}$	Theory input for $(g-2)_\mu$
$\eta\to\pi^+\pi^-\pi^0\gamma$	$<5\times 10^{-4}$	Direct emission only
$\eta\to\pi^\pm e^\mp\nu_e$	$<1.7\times 10^{-4}$	Second-class current
$\eta\to\pi^+\pi^-$	$<4.4\times 10^{-6}$ [56]	P/CP violation
$\eta\to 2\pi^0$	$<3.5\times 10^{-4}$	P/CP violation
$\eta\to 4\pi^0$	$<6.9\times 10^{-7}$	P/CP violation

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Fundamental Symmetry Tests:
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BSM Physics in Dark Sector:
- Vector bosons (B boson, dark photon and X boson)
- Dark scalars
- Pseudoscalars (ALPs)
- BSM weak decays

Channel	Expt. branching ratio	Discussion
$\eta' \to \eta\pi^+\pi^-$	42.6(7)%	Large-N_c χPT, light Higgs scalars
$\eta' \to \pi^+\pi^-\gamma$	28.9(5)%	Chiral anomaly, theory input for singly-virtual TFF and $(g-2)_\mu$, P/CP violation
$\eta' \to \eta\pi^0\pi^0$	22.8(8)%	Large-N_c χPT
$\eta' \to \omega\gamma$	2.489(76)% [58]	Theory input for singly-virtual TFF and $(g-2)_\mu$
$\eta' \to \omega e^+e^-$	$2.0(4) \times 10^{-4}$	Theory input for doubly-virtual TFF and $(g-2)_\mu$
$\eta' \to 2\gamma$	2.331(37)% [58]	Chiral anomaly, η–η' mixing
$\eta' \to 3\pi^0$	2.54(18)% $^{(\star)}$	$m_u - m_d$
$\eta' \to \mu^+\mu^-\gamma$	$1.09(27) \times 10^{-4}$	Theory input for $(g-2)_\mu$, dark photon
$\eta' \to e^+e^-\gamma$	$4.73(30) \times 10^{-4}$	Theory input for $(g-2)_\mu$, dark photon
$\eta' \to \pi^+\pi^-\mu^+\mu^-$	$<2.9 \times 10^{-5}$	Theory input for doubly-virtual TFF and $(g-2)_\mu$, P/CP violation, dark photon, ALPs
$\eta' \to \pi^+\pi^-e^+e^-$	$2.4(^{+1.3}_{-1.0}) \times 10^{-3}$	Theory input for doubly-virtual TFF and $(g-2)_\mu$, P/CP violation, dark photon, ALPs
$\eta' \to \pi^0\pi^0\ell^+\ell^-$		C/CP violation, ALPs
$\eta' \to \pi^+\pi^-\pi^0$	$3.61(17) \times 10^{-3}$	$m_u - m_d$, C/CP violation, light Higgs scalars
$\eta' \to 2(\pi^+\pi^-)$	$8.4(9) \times 10^{-5}$	Theory input for doubly-virtual TFF and $(g-2)_\mu$
$\eta' \to \pi^+\pi^-2\pi^0$	$1.8(4) \times 10^{-4}$	
$\eta' \to 2(\pi^+\pi^-)\pi^0$	$<1.8 \times 10^{-3}$	ALPs
$\eta' \to K^\pm\pi^\mp$	$<4 \times 10^{-5}$	Weak interactions
$\eta' \to \pi^\pm e^\mp\nu_e$	$<2.1 \times 10^{-4}$	Second-class current
$\eta' \to \pi^0\gamma\gamma$	$3.20(24) \times 10^{-3}$	Vector and scalar dynamics, B boson, light Higgs scalars
$\eta' \to \eta\gamma\gamma$	$8.3(3.5) \times 10^{-5}$ [59]	Vector and scalar dynamics, B boson, light Higgs scalars
$\eta' \to 4\pi^0$	$<4.94 \times 10^{-5}$ [60]	(S-wave) P/CP violation
$\eta' \to e^+e^-$	$<5.6 \times 10^{-9}$	Theory input for $(g-2)_\mu$, BSM weak decays
$\eta' \to \mu^+\mu^-$		Theory input for $(g-2)_\mu$, BSM weak decays
$\eta' \to \ell^+\ell^-\ell^+\ell^-$		Theory input for $(g-2)_\mu$
$\eta' \to \pi^+\pi^-\pi^0\gamma$		B boson
$\eta' \to \pi^+\pi^-$	$<1.8 \times 10^{-5}$	P/CP violation
$\eta' \to 2\pi^0$	$<4 \times 10^{-4}$	P/CP violation

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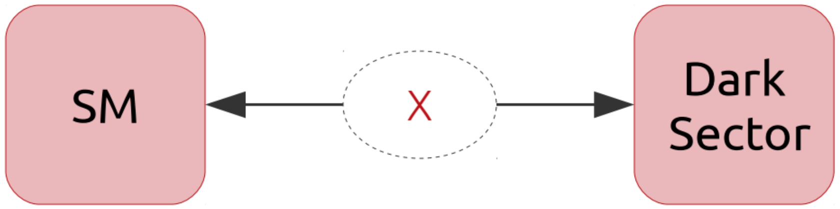
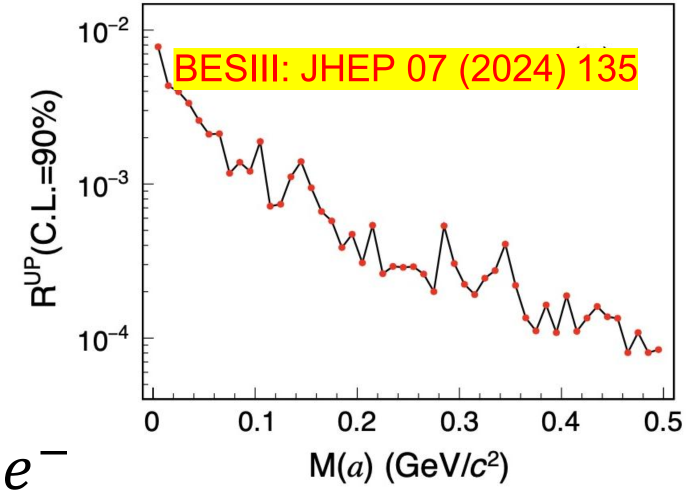
BSM Physics in Dark Sector

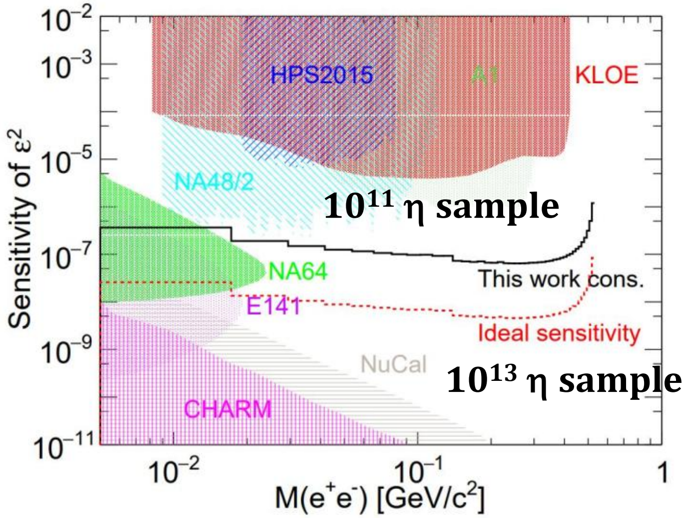


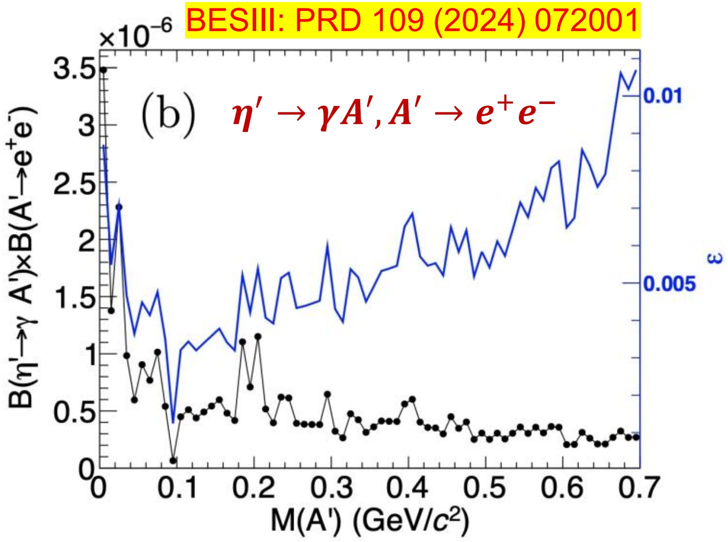
- ALPs in $\eta' \to \pi^+\pi^- a,\ a \to e^+e^-$
- Dark photon in $\eta/\eta' \to \gamma A', A' \to e^+e^-$

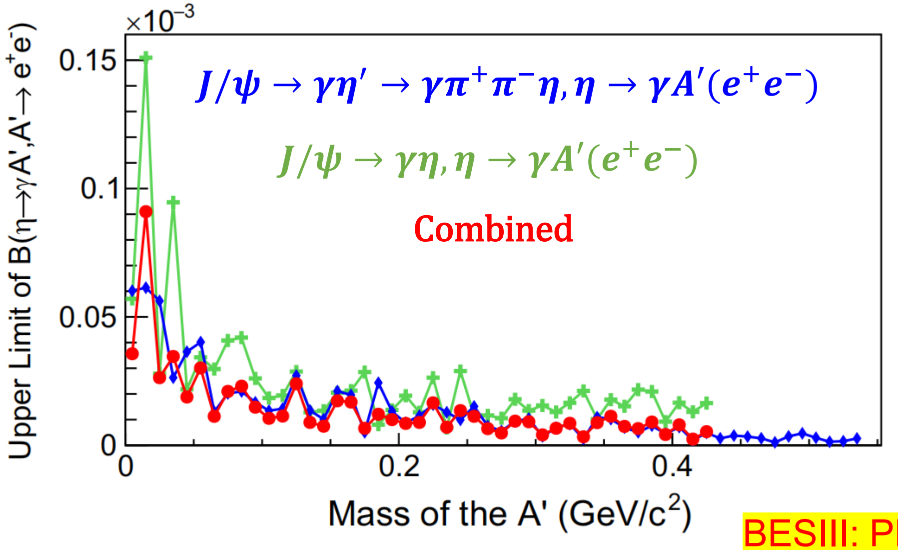
$\eta' \to \pi^+\pi^- a, a \to e^+e^-$

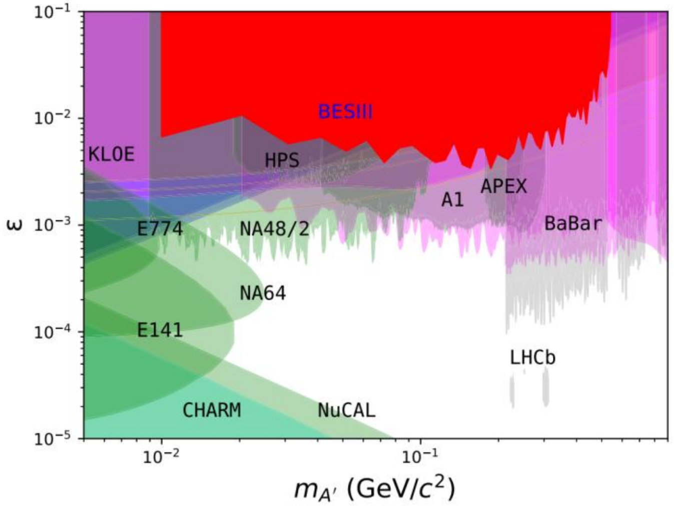


Sensitive study of dark photon in $\eta \to \gamma e^+e^-$ at HHaS arXiv:2506.11733





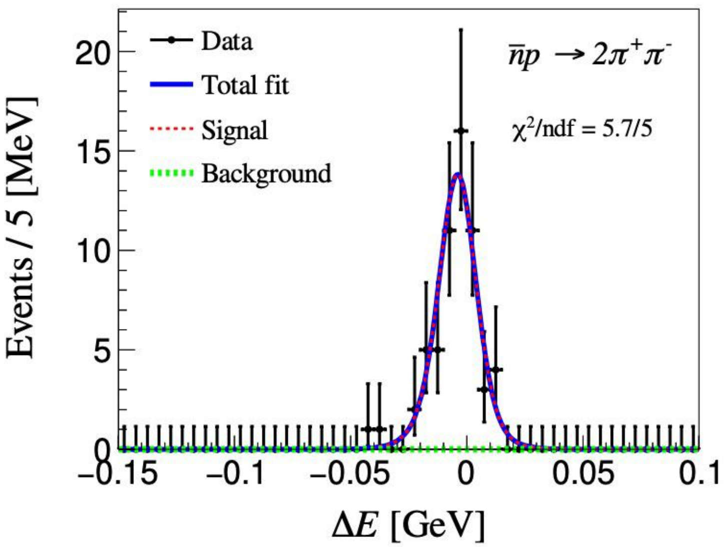


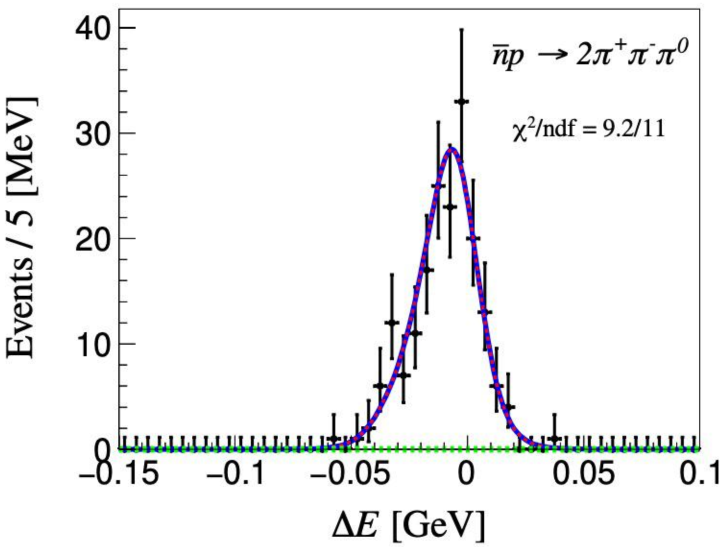


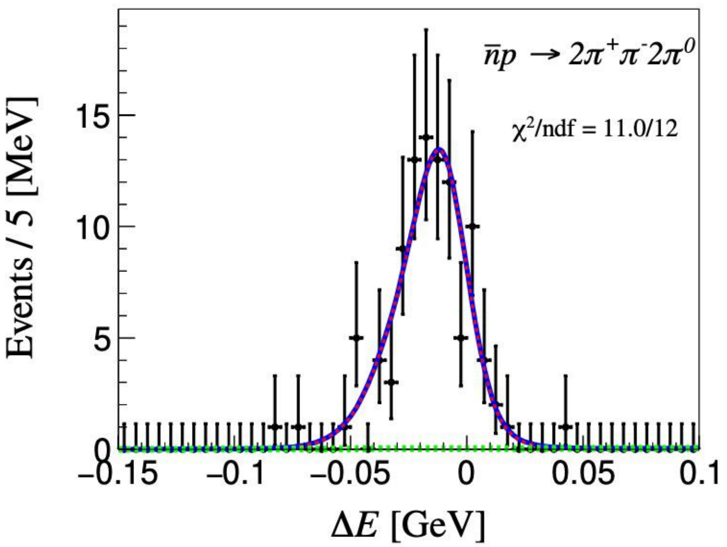
BESIII: PRD112, 052007 (2025)

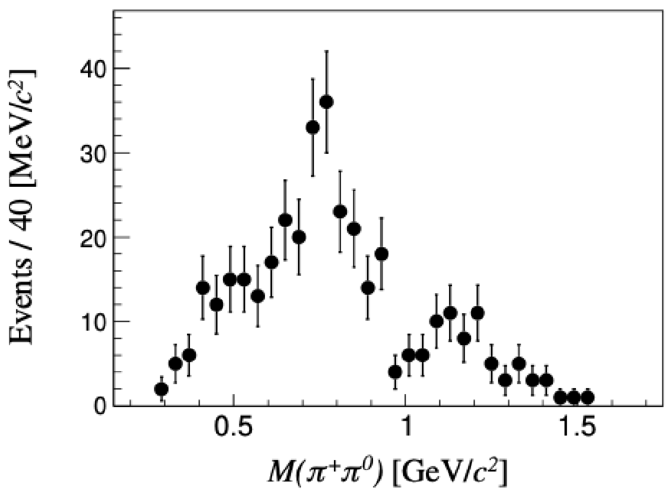
$\bar{n}p \to 2\pi^+\pi^-, 2\pi^+\pi^-\pi^0, 2\pi^+\pi^-2\pi^0$

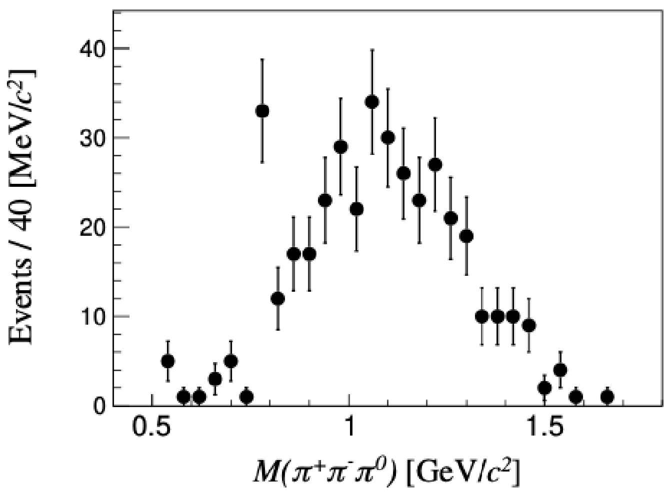
arXiv:2511.21462











- The absence of Coulomb corrections and the purity of the I = 1 state of $\bar{n}p$
- The first experimental investigation of the $\bar{n}p$ interaction above 800 MeV
- Clear signals from ρ/ω, indicating significant contributions from vector intermediate states