Новости физики легких адронов

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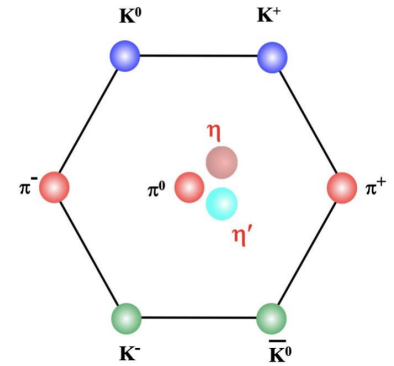
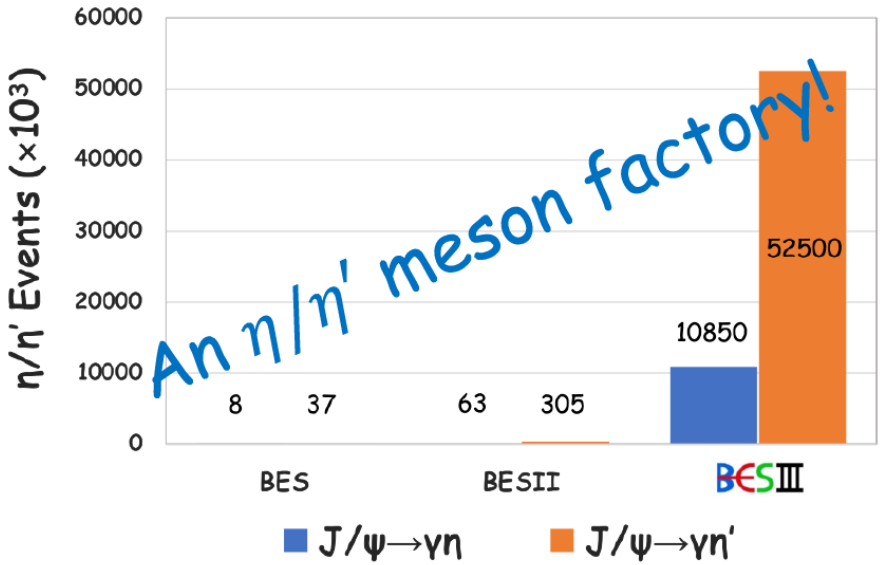
РАЗЛИВ

План доклада

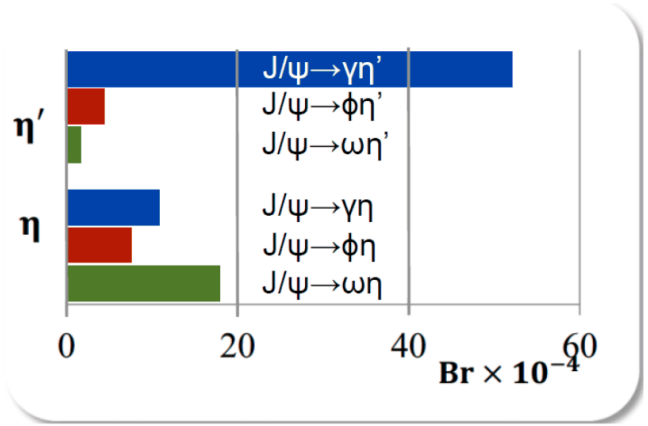
- BESIII как фабрика η и η′ мезонов
  - Изучение различных свойств
  - Изучение переходных формфакторов η и η′
- Легкая экзотика на BESIII



Collected 10 billion J/ψ Events!



- High production rate of η/η' in J/ψ decays
  - ✓ Radiative decays: 5.2×10^7 η', 1.1×10^7 η
  - ✓ Hadronic decays: 6.5×10^6 η', 2.5×10^7 η



- $J/\psi \to \gamma\eta \quad \Longrightarrow 1 \times 10^7\ \eta$
- $J/\psi \to \gamma\eta', \eta' \to \pi^+\pi^-\eta \quad \Longrightarrow 2.2 \times 10^7\ \eta$

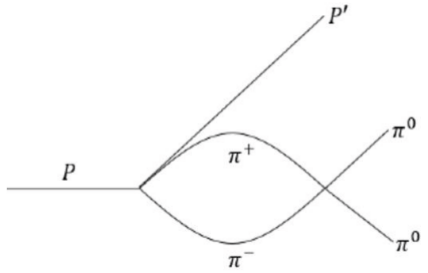
Evidence of Cusp Effect in $\eta' \to \pi^0\pi^0\eta$

PRL 130, 081901 (2023)

Эффект каспа (cusp effect) — это резкий излом в спектре инвариантных масс $\pi^0\pi^0$ возникающий вблизи порога рождения пары $\pi^+\pi^-$ из-за сильного взаимодействия в конечной состоянии.

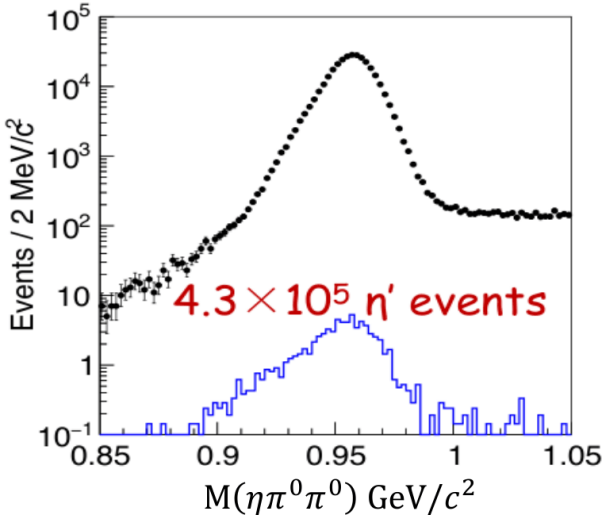
- In $\pi\pi$ interaction, one of the prominent features is the loop contribution to the ππ scattering: The S-wave charge exchange rescattering $\pi^+\pi^- \to \pi^0\pi^0$ causes a prominent cusp at the center of mass energy corresponding to the summed mass of two charged pions.

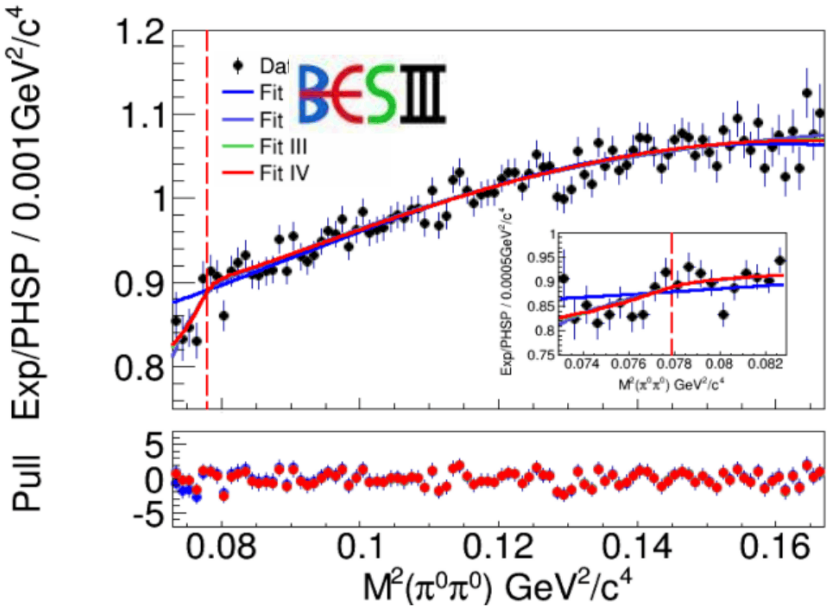
- By determining the strength of the S-wave $\pi\pi$ interaction to study the fundamental properties of QCD at low energies.



high term of $\pi\pi$ rescattering

EPJC 62, 511 (2009)





$$M = M_{tree} + M_{one-loop} + M_{two-loop}$$

Fit	Notes
I	Only the tree level contribution
II	Consider the loop level contribution
III	Fix some parameters based on Fit II to reduce the correlations
IV	Ignore the non-cusp terms from the loop contributions

- Non-relativistic effective field theory
- Evidence of the cusp effect around 3.5σ.

Dalitz Plot Analysis of $\eta \to \pi^+\pi^-\pi^0$

Phys. Rev. D 107, 092007 (2023)

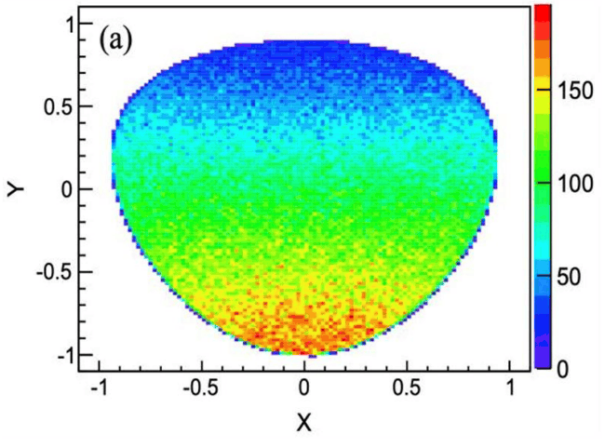
- The Dalitz plot is generally described as:

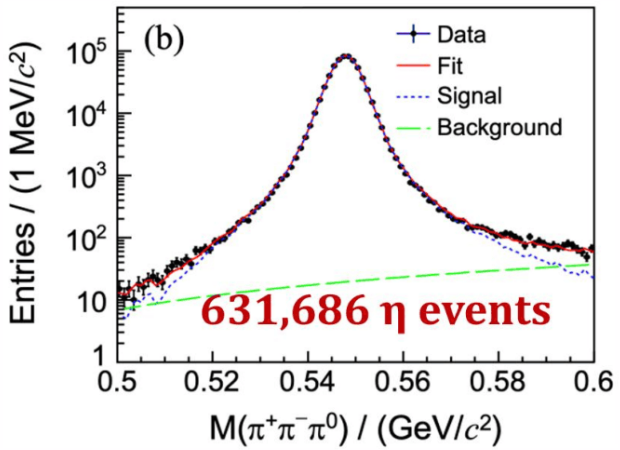
$$X = \frac{\sqrt{3}}{Q_\eta}(T_{\pi^+} - T_{\pi^-}), Y = \frac{3T_{\pi^0}}{Q_\eta} - 1$$

- The squared amplitude can be expanded as:

$$|A(X,Y)|^2 \propto 1 + aY + bY^2 + cX + dX^2 + eXY + fY^3 + gX^2\mathrm{Y} + ..$$

  - a, b, c, d, e, f, g are the Dalitz plot matrix elements.
  - c and e are related to charge conjugation violation.



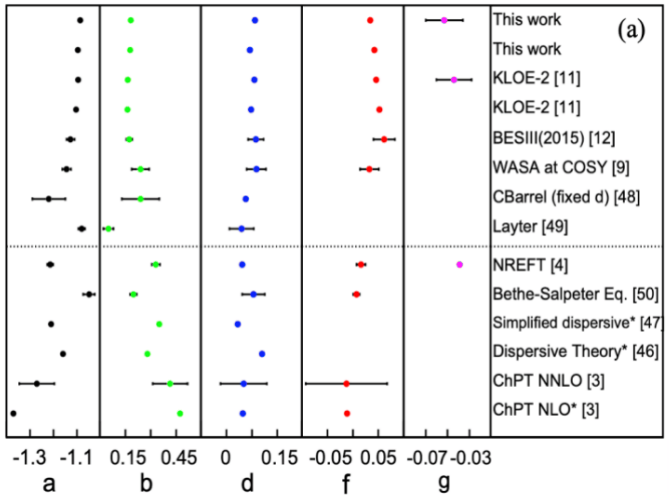


- Ignoring the high-order term

$a = -1.097 \pm 0.005 \pm 0.001$
$b = 0.158 \pm 0.006 \pm 0.003$
$d = 0.070 \pm 0.006 \pm 0.001$
$f = 0.134 \pm 0.010 \pm 0.003$

- Included the cubic term

$a = -1.086 \pm 0.006 \pm 0.001$
$b = 0.162 \pm 0.006 \pm 0.003$
$d = 0.083 \pm 0.007 \pm 0.001$
$f = 0.118 \pm 0.011 \pm 0.003$
$g = -0.053 \pm 0.017 \pm 0.003$



➡ All parameters related with C symmetry breaking are consistent with zero

Dalitz Plot Analysis of $\eta \to \pi^0\pi^0\pi^0$

Phys. Rev. D 107, 092007 (2023)

- The density distribution of the Dalitz plot has threefold symmetry due to the three identical π^0s in the final state.

$$Z = X^2 + Y^2 = \frac{2}{3}\sum_{i=1}^{3}\left(\frac{3T_i}{Q_\eta} - 1\right)^2$$

$$|A(X,Y)|^2 \propto 1 + 2\alpha Z$$

- KLOE: $\sim 420\ \mathrm{pb}^{-1}$ ($\simeq 1.4 \cdot 10^9\ \phi$) data

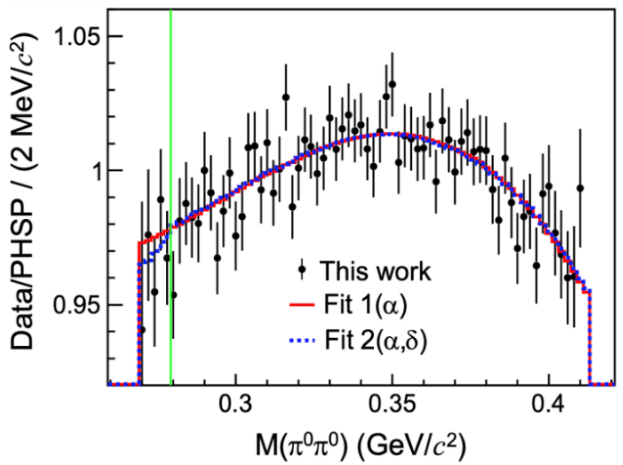
$$\alpha = -0.0301 \pm 0.0035_{stat}\ ^{+0.0022}_{-0.0035}\ _{syst}$$

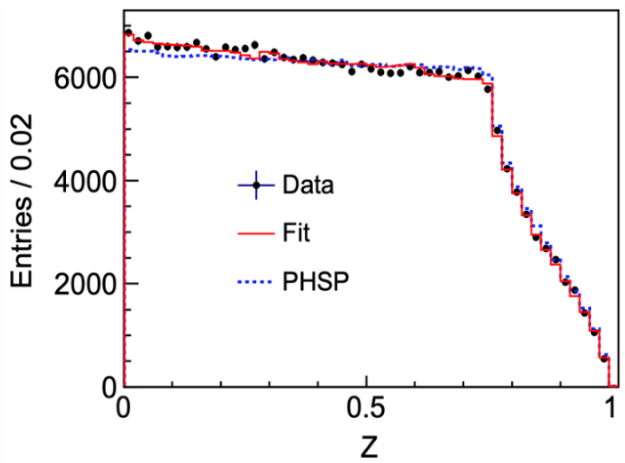
- BESIII: 10 billion J/ψ radiative decays

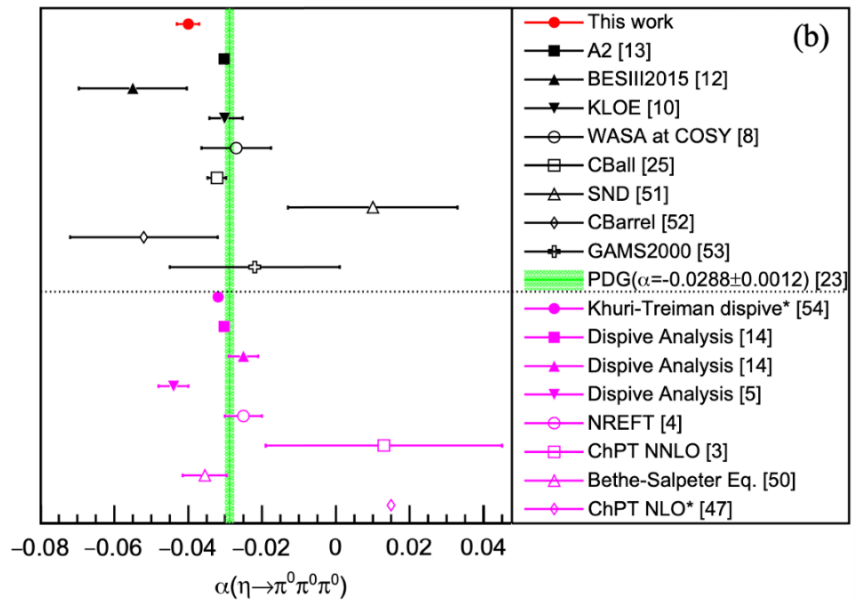
$$\alpha = -0.0406 \pm 0.0035 \pm 0.0008$$

- α is consistent with A2 and KLOE measurement within 2.8σ

- The cusp effect is investigated, but no obvious contribution is found.







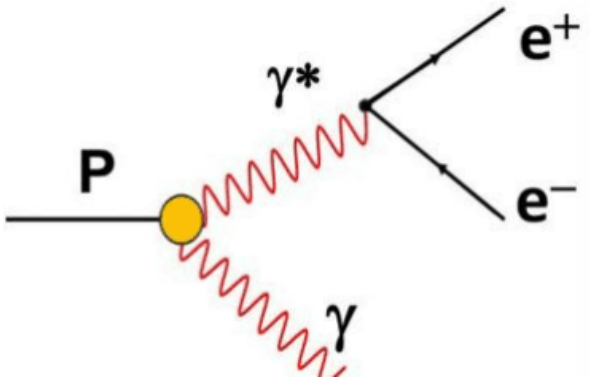
Transition Form Factor of $\eta/\eta' \to \gamma e^+ e^-$

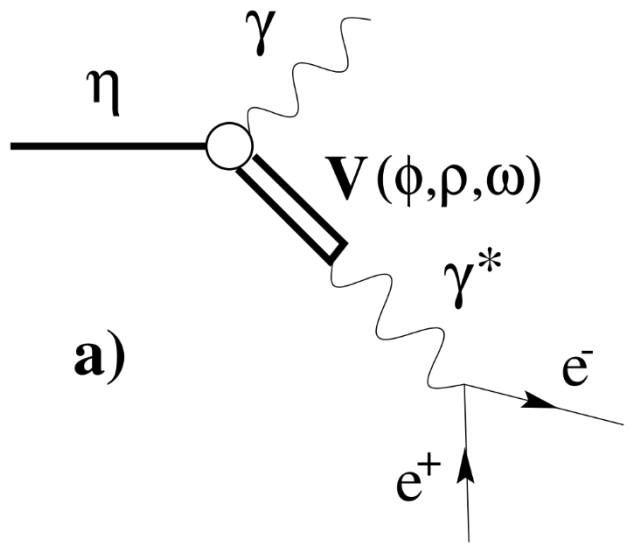
- Performed an unbinned fit based on the amplitude formula.

$$\frac{d\Gamma(P \to \gamma l^+ l^-)}{dq^2 \Gamma_{\gamma\gamma}} = \frac{2\alpha}{3\pi}\frac{1}{q^2}\sqrt{1-\frac{4m_l^2}{q^2}}\left(1+\frac{2m_l^2}{q^2}\right)\left(1-\frac{q^2}{M_P^2}\right)|F(q^2)|^2$$

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

- Multi-pole: $|F(q^2)|^2 = \frac{\Lambda^2(\Lambda^2+\gamma^2)}{(\Lambda^2-q^2)^2+\Lambda^2\gamma^2}$





VDM:

$b_\eta \approx 1.8\ \text{GeV}^{-2}$

$b_{\eta'} \approx 1.45\ \text{GeV}^{-2}$

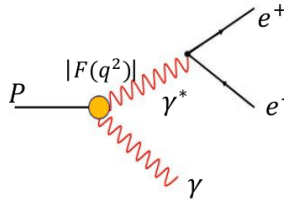
- Using the transition form factor predicted by the VMD mode
  - Single-pole: $F(q^2) = \frac{1}{1-q^2/\Lambda^2}$
  - Slope parameter: $b_p = \left.\frac{d|F(q^2)|}{dq^2}\right|_{q^2=0} = \Lambda^{-2}$

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

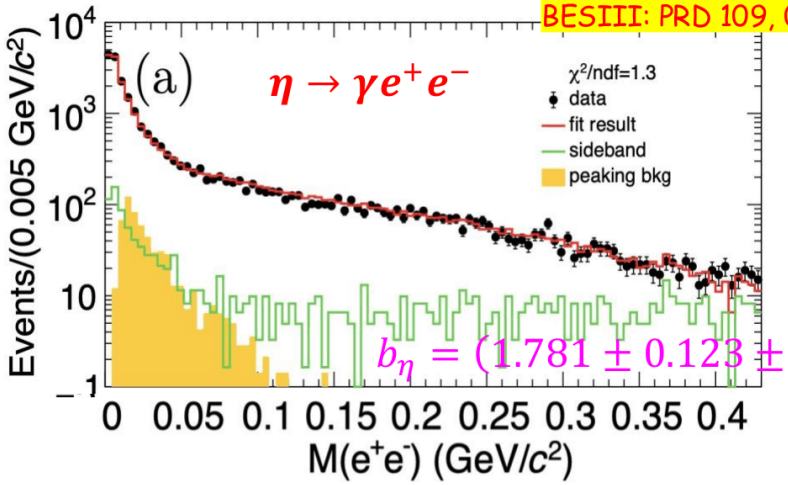
$\Lambda_\eta = (0.749 \pm 0.026 \pm 0.008)\ \mathrm{GeV}/c^2$

$\Lambda_{\eta'} = (0.802 \pm 0.007 \pm 0.008)\ \mathrm{GeV}/c^2$

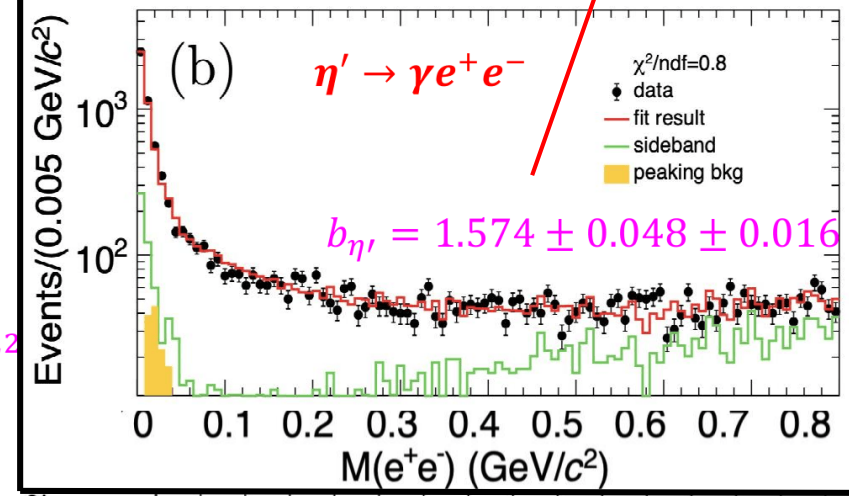
$\gamma_{\eta'} = (0.113 \pm 0.009 \pm 0.002)\ \mathrm{GeV}/c^2$



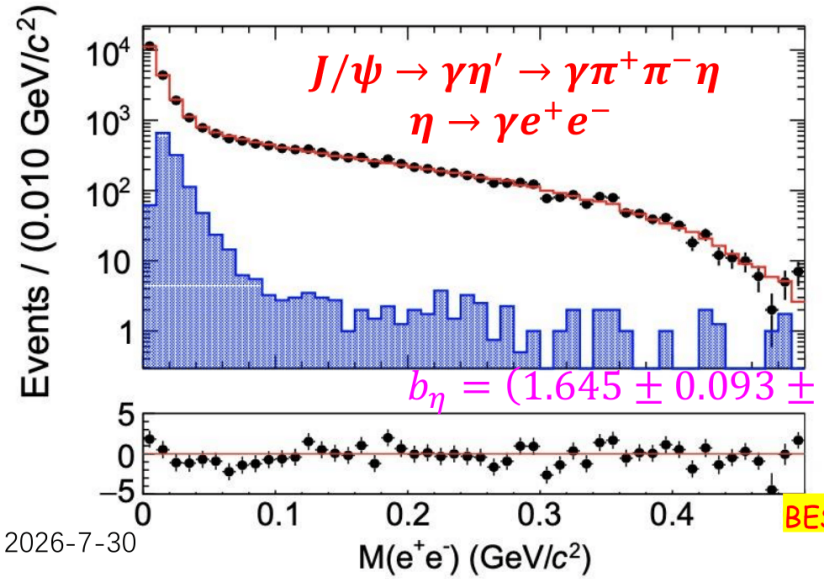
BESIII: PRD 109, 072001 (2024)



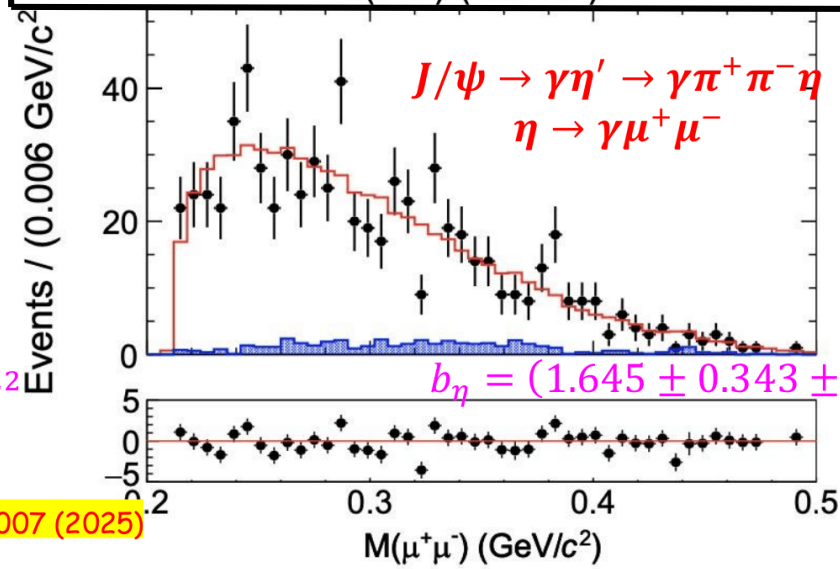
$b_\eta = (1.781 \pm 0.123 \pm 0.033)\ GeV/c^2$



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



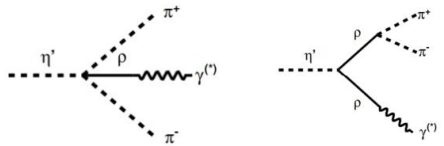
$b_\eta = (1.645 \pm 0.093 \pm 0.024)\ GeV/c^2$



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

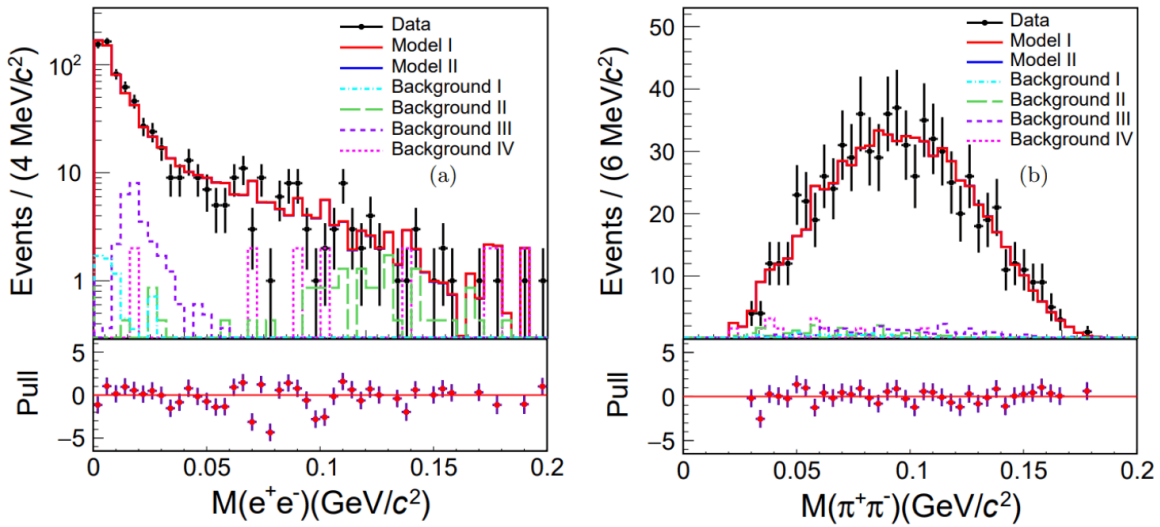
BESIII: PRD112, 052007 (2025)

Study of $\eta \to \pi^+\pi^- l^+ l^-$



BESIII: PRD 111 (2025) 072008 (arXiv:2501.10130)

- BESIII: 10 billion J/ψ radiative decays $Br(\eta \to \pi^+\pi^- e^+ e^-) = (3.07 \pm 0.12 \pm 0.19) \times 10^{-4}$
  - Allow to access dynamic but with limited statistics $m_V = (749 \pm 54 \pm 14)\ MeV/c$



	$\mathcal{B}(\eta \to \pi^+\pi^- e^+ e^-)$ (10^{-4})	$\mathcal{B}(\eta \to \pi^+\pi^- \mu^+ \mu^-)$ (10^{-9})
Unitary χPT [1]	$2.99^{+0.06}_{-0.09}$	$7.50^{+1.80}_{-0.70}$
Hidden gauge [2]	3.14 ± 0.17	8.65 ± 0.39
VMD [2]	3.02 ± 0.12	8.64 ± 0.25
CMD-2 [4]	$3.7^{+2.5}_{-1.8} \pm 3.0$	...
WASA [5]	$4.3^{+0.2}_{-1.6} \pm 0.4$	$< 3.6 \times 10^5$
KLOE [6]	$2.68 \pm 0.09 \pm 0.07$	...

- No event left for $\eta \to \pi^+\pi^- \mu^+ \mu^-$ hypothesis $Br(\eta \to \pi^+\pi^- \mu^+ \mu^-) < 4.0 \times 10^{-4}$ at 90% CL.
- No CP-Violation found

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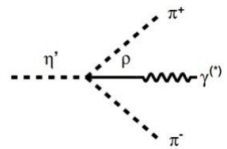
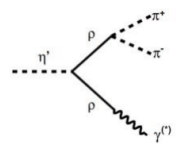
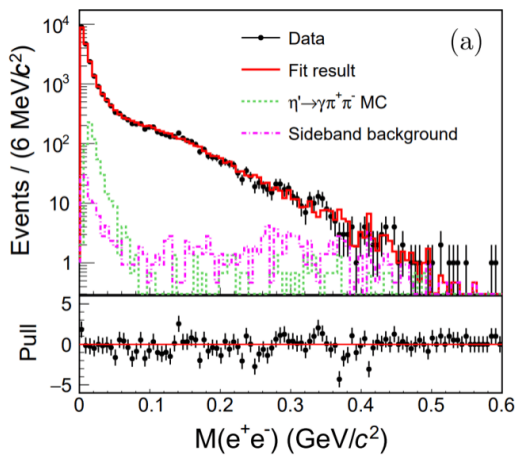
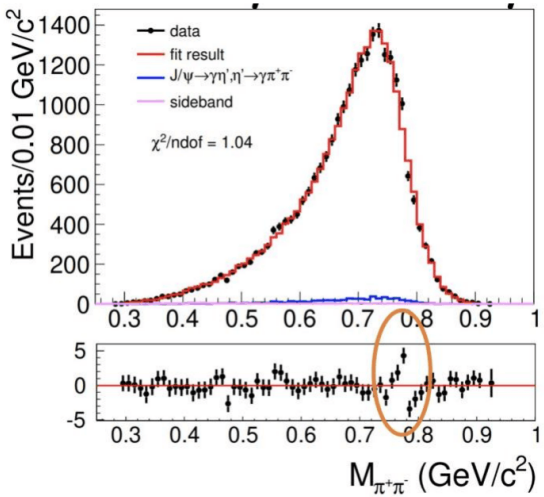
TFF of $\eta' \to \pi^+\pi^- l^+ l^-$

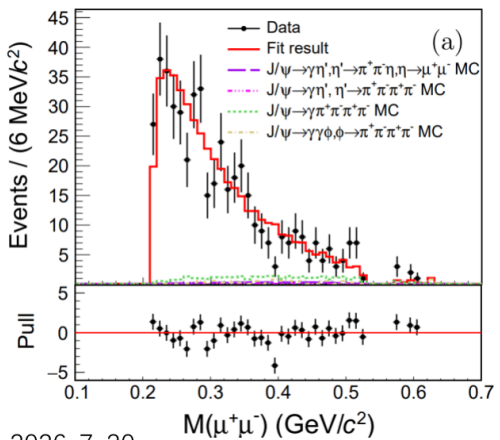


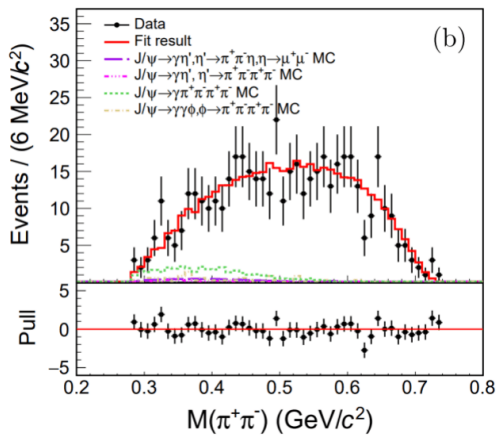


BESIII: JHEP 07, 135 (2024)



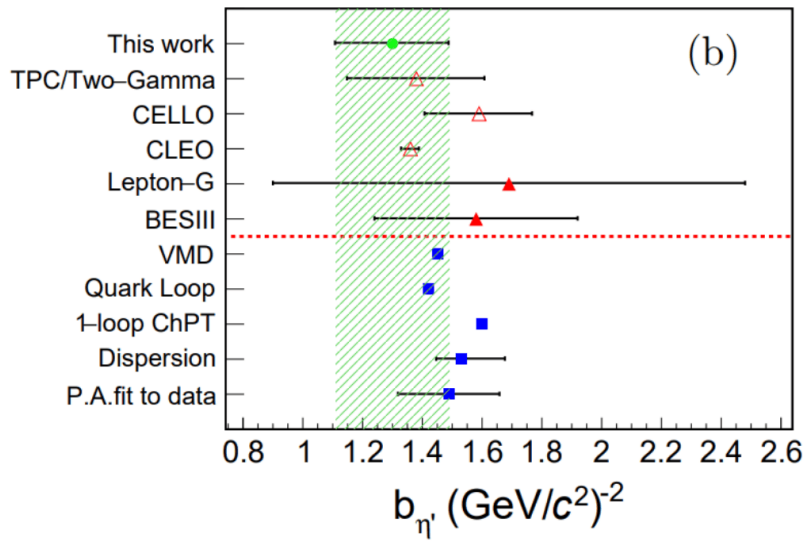






- **Box-anomaly** is needed to describe data
- **$\omega \to \pi^+\pi^-$ is also necessary**
- First time to assess the form factors with $\eta' \to \pi^+\pi^- l^+ l^-$ within VMD

$$b_{\eta'} = 1.30 \pm 0.19\ (\mathrm{GeV}/c^2)^{-2}$$



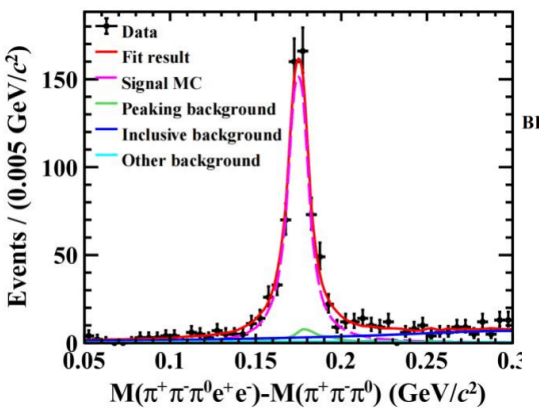
$\omega \to \pi^+\pi^-\pi^0$

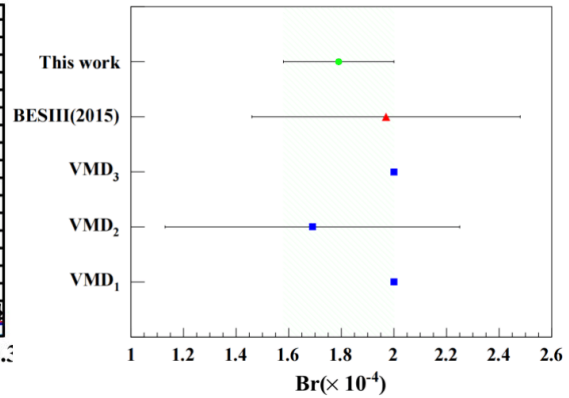
TFF of $\eta' \to \omega e^+ e^-$

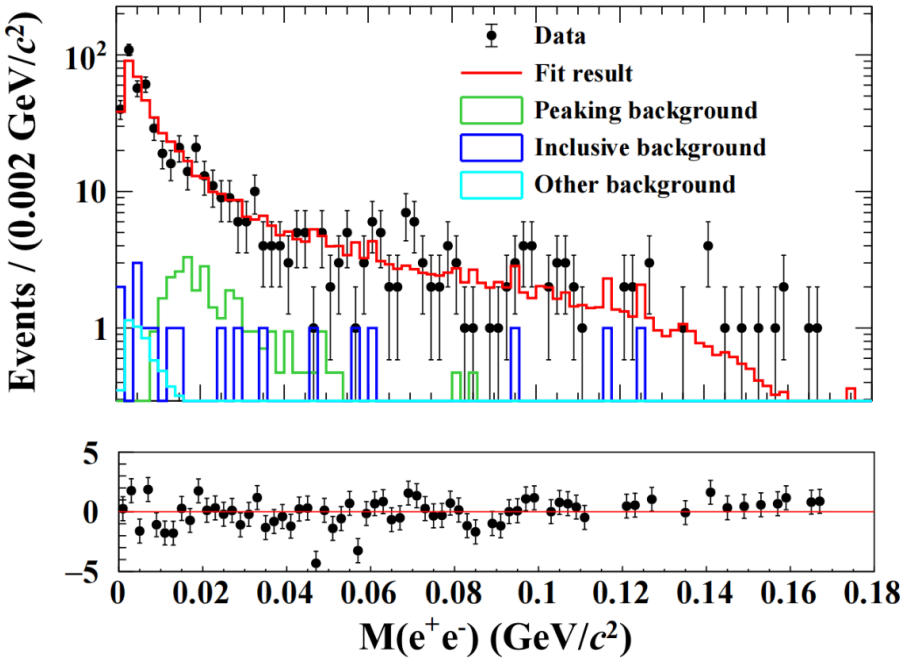
BESIII arXiv:2603.08120

- With 10 billion J/ψ events, 609.1 ± 27.7 $\eta' \to \omega e^+ e^-$ signal events are observed

$$\mathrm{Br}(\eta' \to \omega e^+ e^-) = (1.79 \pm 0.09 \pm 0.12) \times 10^{-4}$$







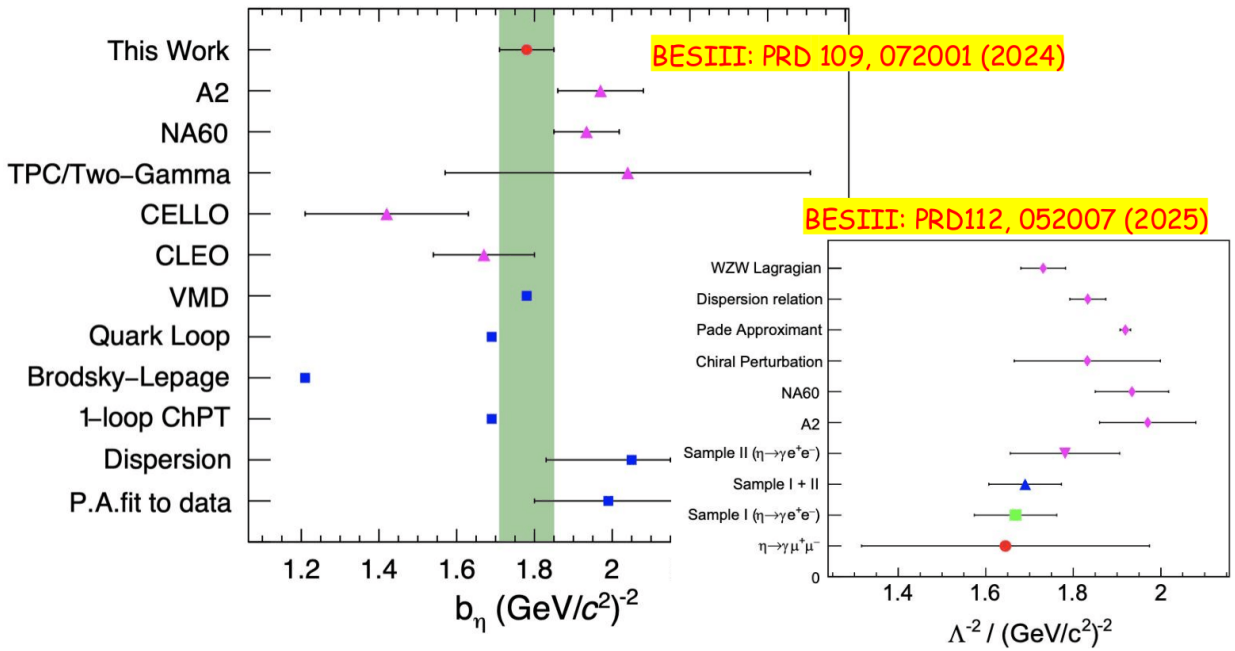
$$|\mathcal{A}_{\eta' \to e^+e^-\omega}|^2 = \frac{2^6\pi^2 M_{\eta'}^3 \alpha \Gamma_{\eta' \to \gamma\omega}}{(M_{\eta'}^2 - M_\omega^2)^3} |F(q^2)|^2 \cdot \frac{(M_{\eta'}^2 - q^2 - M_\omega^2)^2 - 4M_\omega^2 q^2}{q^2} (2 - \beta^2 \sin^2\theta)$$

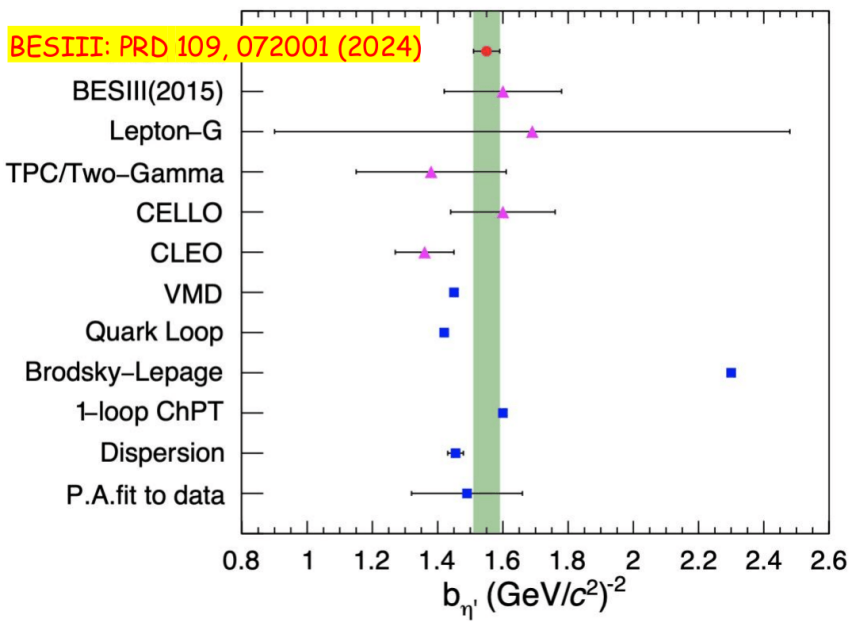
$$\text{slope} \equiv \left.\frac{dF}{dq^2}\right|_{q^2=0} = \frac{1}{\Lambda^2}$$

TFF is measured for the first time: $\Lambda^{-1} = (2.92 \pm 0.83 \pm 0.15)\ GeV^{-1}$

Transition Form Factor of $\eta/\eta' \to \gamma e^+e^-$

Summary of the TFF for η/η'





Combined the two $\eta \to \gamma e^+e^-$ samples:

$$b_\eta = (1.707 \pm 0.076 \pm 0.029)\ GeV/c^2$$

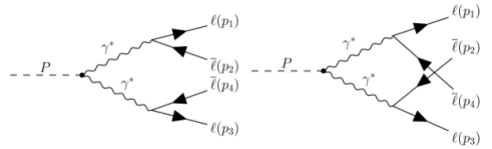
$\boldsymbol{\eta \to \gamma\mu^+\mu^-}$: $b_\eta = (1.645 \pm 0.343 \pm 0.017)\ GeV/c^2$

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

$\eta' \to \pi^+\pi^-e^+e^-$: $b_{\eta'} = 1.30 \pm 0.19\ (\mathrm{GeV/c^2})^{-2}$

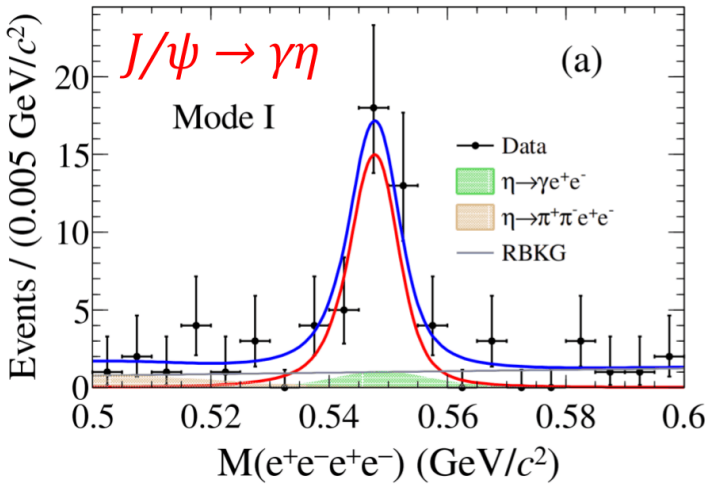
$\eta' \to \omega e^+e^-$: $\Lambda^{-1} = (2.92 \pm 0.83 \pm 0.15)\ GeV^{-1}$

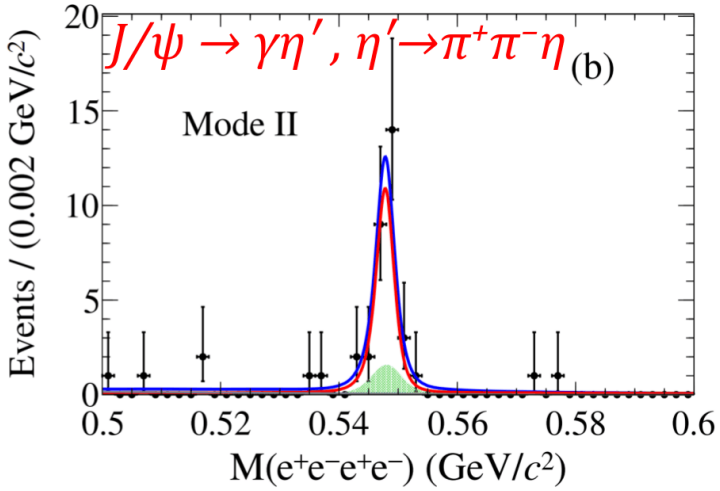
Double Dalitz decays $\eta \to e^+e^-e^+e^-$

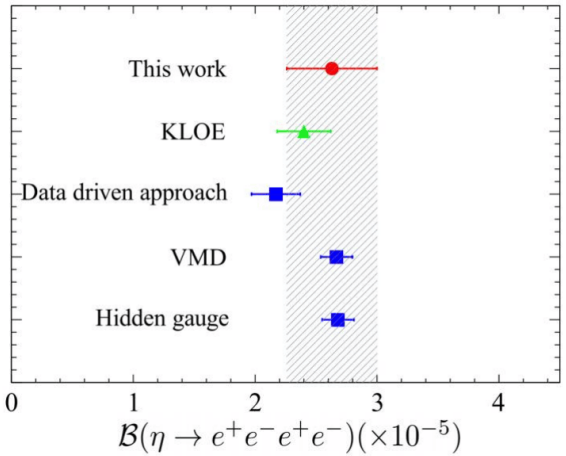


➢Expected to proceed through two virtual photons, TFF

BESIII: arXiv:2605.04898v1







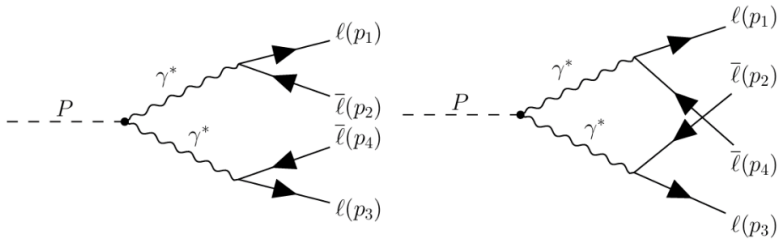
Mode	$N^{\rm obs}$	ϵ (%)	$\mathcal{B}$ ($\times 10^{-5}$)
I	35.9 ± 6.7	13.1	2.51 ± 0.47
II	29.5 ± 6.1	4.7	2.80 ± 0.58

Source	$\eta \to e^+e^-e^+e^-$ ($\times 10^{-5}$)	
Hidden gauge [11]	2.68 ± 0.13	T. Petri, arXiv:1010.2378
Modified VMD [11]	2.67 ± 0.13	
Data driven approach [12]	2.17 ± 0.20	CPC 42 (2018) 023109
KLOE [13]	2.40 ± 0.22	
BESIII [14]	$(2.63 \pm 0.34 \pm 0.16) \times 10^{-5}$	Combined result

Study of $\eta/\eta' \to l^+l^-l^+l^-$

Phys. Rev. D 105,112010 (2022)
Phys. Rev. D 111, 052002 (2025)
arXiv: 2605.04898 (Submit to PRD)

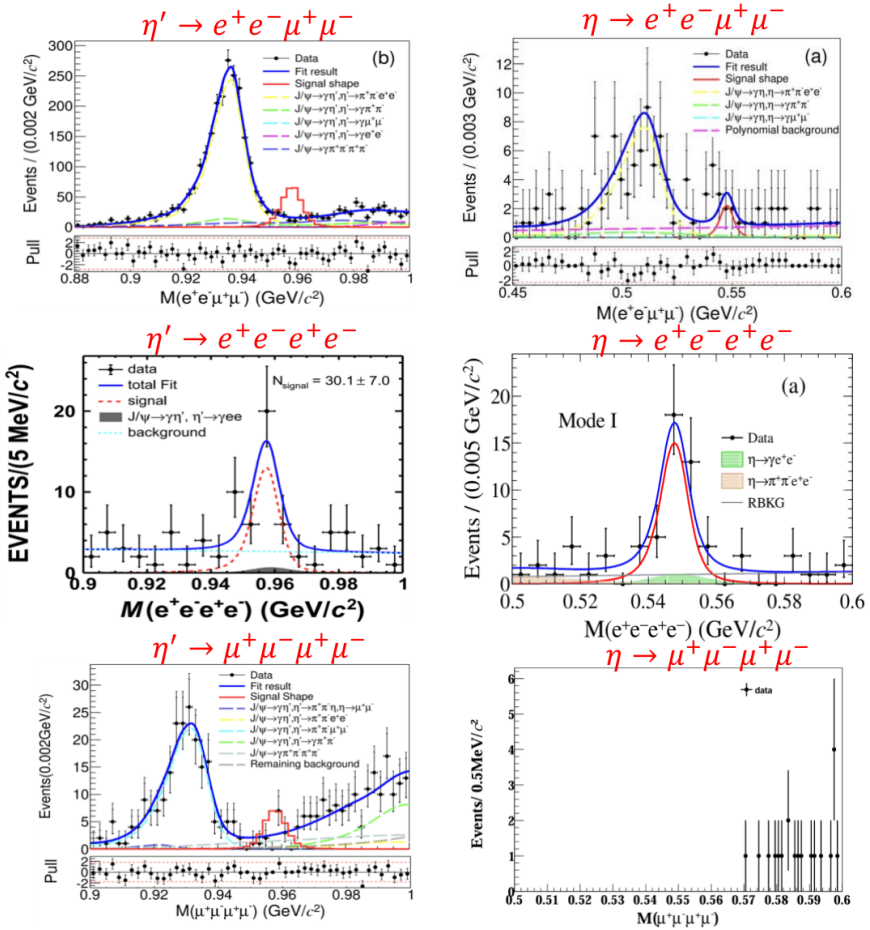
✧ The double Dalitz decays through two virtual photons intermediate with internal photon conversion to l^+l^- pairs.



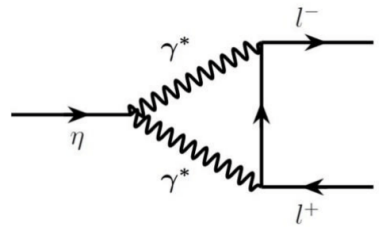
✧ The branching fraction:

Decay mode	Theoretical predictions		Experiment
	VMD	Data driven approach	BESIII
$\eta \to e^+e^-e^+e^-$	$2.67(13) \times 10^{-5}$	$2.71(2) \times 10^{-5}$	$(2.6 \pm 0.3 \pm 0.2) \times 10^{-5}$
$\eta' \to e^+e^-e^+e^-$	$2.32(4) \times 10^{-6}$	$2.10(45) \times 10^{-6}$	$(4.5 \pm 1.0 \pm 0.5) \times 10^{-5}$
$\eta \to e^+e^-\mu^+\mu^-$	$2.15(22) \times 10^{-6}$	$2.39(7) \times 10^{-6}$	$< 6.88 \times 10^{-6}$
$\eta' \to e^+e^-\mu^+\mu^-$	$7.97(31) \times 10^{-7}$	$6.39(9) \times 10^{-7}$	$< 1.75 \times 10^{-6}$
$\eta \to \mu^+\mu^-\mu^+\mu^-$	$3.80(26) \times 10^{-9}$	$3.98(15) \times 10^{-9}$	$< 3.59 \times 10^{-7}$
$\eta' \to \mu^+\mu^-\mu^+\mu^-$	$2.19(10) \times 10^{-8}$	$1.69(36) \times 10^{-8}$	$< 5.28 \times 10^{-7}$

➡ The ULs are quite close to the SM predictions.



Study of $\eta \to e^+e^-$ and $\mu^+\mu^-$



➢SM: $\eta \to l^+l^-$ proceeds via fourth-order electromagnetic transition, dominated by a two-photon intermediate state

➢$\eta \to e^+e^-$: Suppressed, helicity factor is proportional to m_e^2

➢Dispersive prediction:

$$Br(\eta \to e^+e^-) = (5.37 \pm 0.04 \pm 0.02) \times 10^{-9}$$
$$Br(\eta \to \mu^+\mu^-) = (4.54 \pm 0.04 \pm 0.02) \times 10^{-6}$$

N. Messerli, M. Hoferichter, B.-L. Hoid, S. Holz, and B. Kubis, arXiv:2512.13776

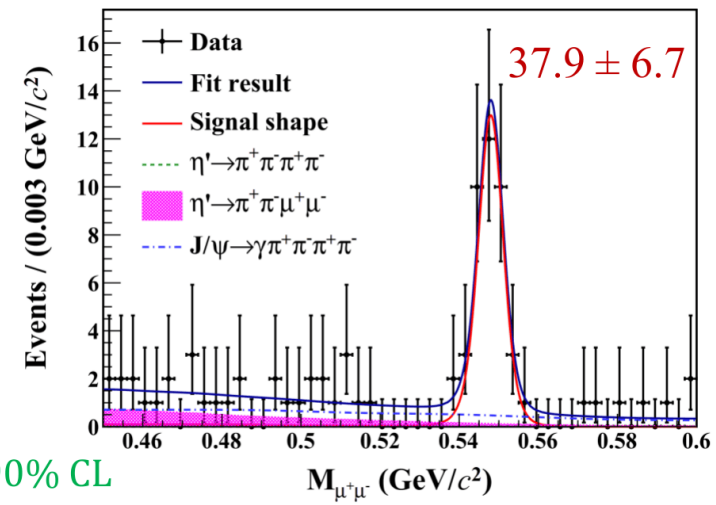
BESIII: arXiv:2512.07144v2

- With η sample from $J/\psi \to \gamma\eta', \eta' \to \pi^+\pi^-\eta, J/\psi \to \gamma l^+l^-$ background is highly reduced compared with $J/\psi \to \gamma\eta$

$$Br(\eta \to \mu^+\mu^-) = (5.8 \pm 1.0 \pm 0.2) \times 10^{-6}$$

- No event left for $\eta \to e^+e^-$ hypothesis

$$Br(\eta \to e^+e^-) < 2.2 \times 10^{-7}\ at\ 90\%\ CL$$



PDG: $Br(\eta \to \mu^+\mu^-) = (5.7 \pm 0.8) \times 10^{-6}$ && $Br(\eta \to e^+e^-) < 7 \times 10^{-7}\ at\ 90\%\ CL$

Легкая экзотика на BESIII

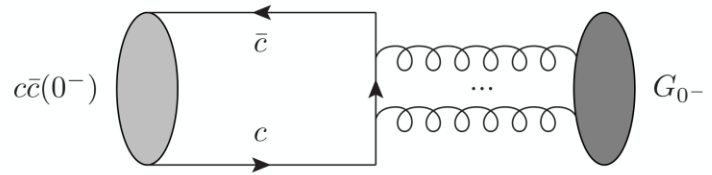
- Lightest 0-+ Glueball as Dominant Constituent of X(2370)
- Exotic 1^{-+} states: $\eta_1(1855)$ and $\pi(1600)$

Glue Почему именно в рад. распадах J/ψ ay

◈ **Gluon rich environment in J/ψ radiative decay**

◈ **LQCD prediction on high glueball production**

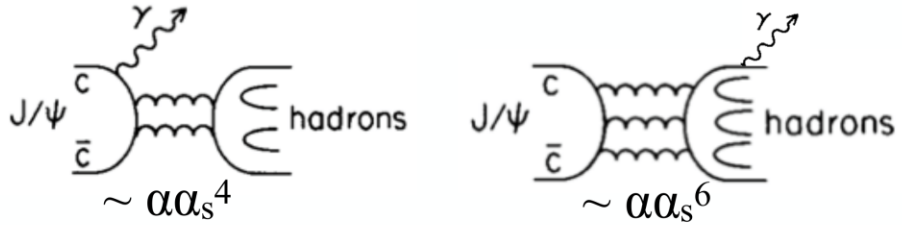
✦ Lightest 0^{-+} glueball: $(2.31 \pm 0.80) \times 10^{-4}$ PRD 100 (2019) 054511



PLB 827 (2022) 136960, arXiv: 2605.01757, arXiv:2607.17294

✦ Mixing mechanism between 0^{-+} $c\bar{c}$ and 0^{-+} glueball: $(2 \sim 20) \times 10^{-3}$ even with tiny mixing angle (2^o ~ 5^o)

◈ **Well isolate glueball signal experimentally**



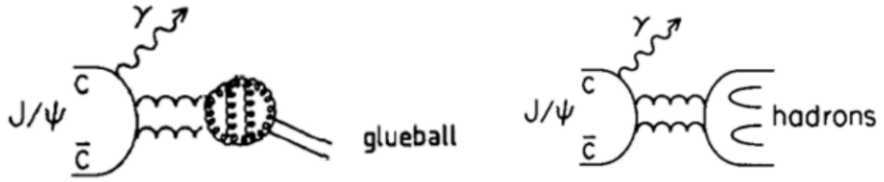
✦ **Isospin filter:** final states dominated by **I=0** processes

✦ **Spin-parity filter: C parity must be + (** $J^{pc}=0^{-+}$, 0^{++}...)

✦ **Clean environment in e^+e^- collision:** very different from **p-p collision**

◈ **Distinctive property vs. normal hadrons :**

✦ **Higher glueball production rate**



➡ **J/ψ Radiative decay is an ideal place to search for glueballs**

6

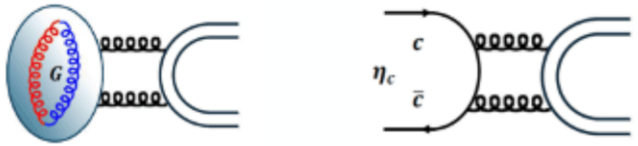
Как должен «выглядеть» кандидат в glueball

Glueball Decays

No rigorous predictions on decay patterns and their branching ratios

Clear physics picture for experimental identification of Glueball

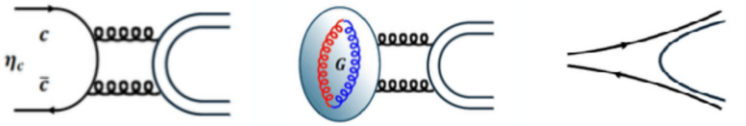
- **Flavor-singlet state:** due to generalized G-parity conservation, $K^*\bar{K}$ mode is forbidden for 0^{-+} glueball
- **Decay pattern similarities to charmonium decays: they all decay via gluons** (PLB 106 (1981) 114, PLB 109 (1982) 326, Phys. Rep. 454 (2007) 1)
- **Narrow partial decay width: ~ a few MeV** (no dominant decay modes, $\sqrt{OZI}$ rule) VS **>100MeV** (dominant OZI allowed decay for most mesons)
- **Suppression of $G \to \gamma\omega, \gamma\phi$: no quark component and no direct interaction with photon** VS $\gamma\omega, \gamma\phi$ **as flavor filters for** $s\bar{s}/u\bar{u} + d\bar{d}$ **content**



Decay pattern similarities between 0^{-+} glueball and η_c

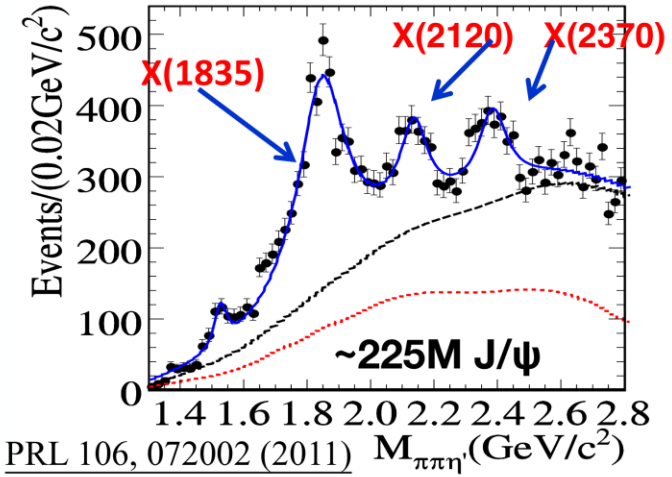
5 major η_c decay modes (from PDG)
— 5 "Golden" modes in 0^{-+} glueball traditional searches

	Decays involving hadronic resonances	
Γ_1	$\eta'(958)\pi\pi$	(1.87±0.26) %
Γ_2	$\eta'(958)K\bar{K}$	(1.61±0.25) %
	Decays into stable hadrons	
Γ_{34}	$K\bar{K}\pi$	(7.0 ±0.4) %
Γ_{35}	$K\bar{K}\eta$	(1.32±0.15) %
Γ_{36}	$\eta\pi^+\pi^-$	(1.7 ±0.5) %

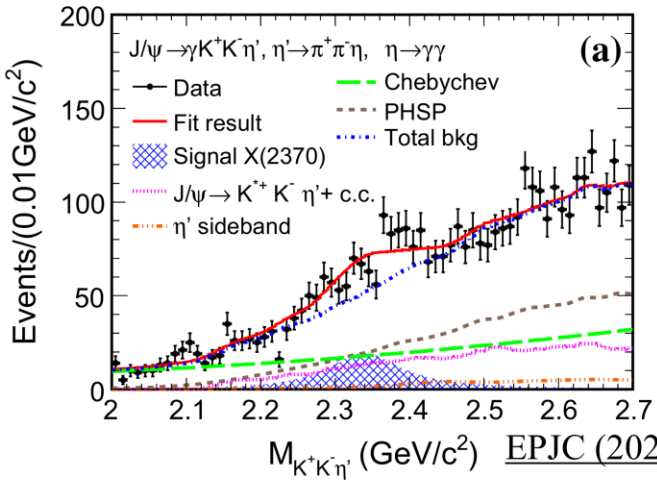


7

Discovery of the X(2370)



PRL 106, 072002 (2011)



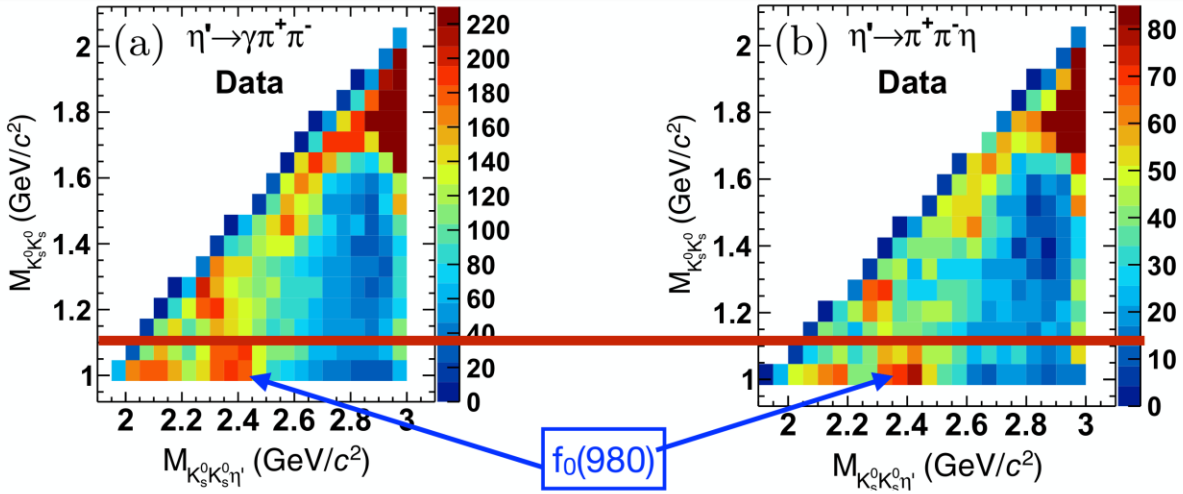
EPJC (2020) 80:746

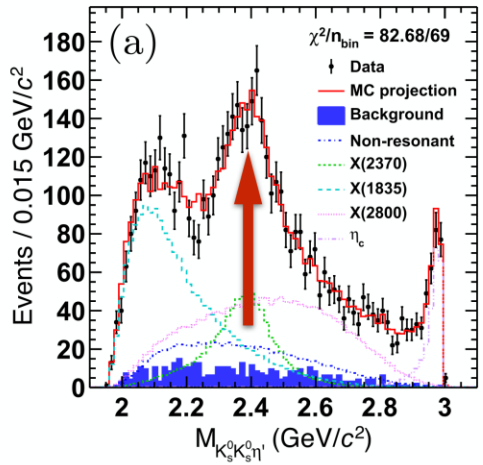
- Discovered (6.4σ) by BESIII in $J/\psi \to \gamma\pi^+\pi^-\eta'$ in 2011
  - Produced in the gluon-rich J/ψ radiative decays
  - Its mass is consistent with LQCD prediction on the 0^{-+} glueball
- Observed in flavor symmetric decay modes of $\pi^+\pi^-\eta'$ and $K\bar{K}\eta'$ (8.3σ) — favorite decay modes of 0^{-+} glueball

Видят в следующих модах:

- **Decay modes of X(2370)** $\to \pi\pi\eta', K\bar{K}\eta', K\bar{K}\pi, \pi\pi\eta, K\bar{K}\eta, a(980)\pi$ **observed**

Spin-Parity determination of the X(2370): $J^{pc} = 0^{-+}$





- **Analysis advantage of $J/\psi\to\gamma K^0_sK^0_s\eta'$:**
  - Almost background free channel (exchange symmetry and C-parity conservation)
  - 10billion J/ψ data
  - Very good BESIII detector performance
- **Clear signal of X(1835),X(2370),η_c with $f_0(980)$ selection**
- **Best PWA fit can well describe the data**

X(2370) measurements (agree with 0^{-+} predictions):

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

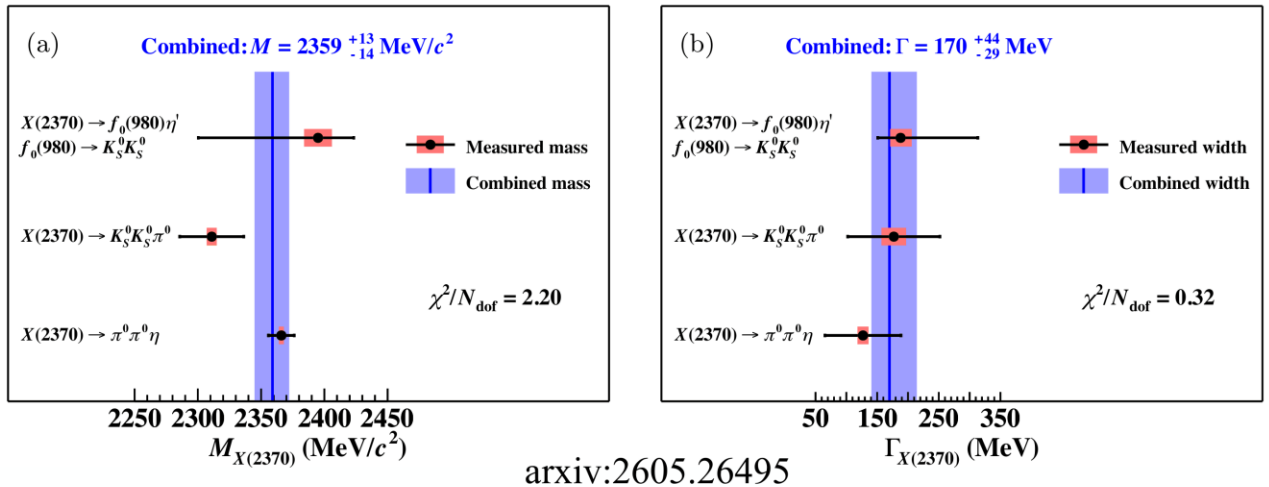
$M = 2395 \pm 11^{+26}_{-94}$ MeV

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

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

For the first time, the spin-parity of the X(2370) is determined to be 0^{-+}: provide a crucial foundation for the comparison between measurements and 0^{-+} Glueball predictions

Mass, Width, High Production Rate and Narrow Partial Decay Width



arxiv:2605.26495

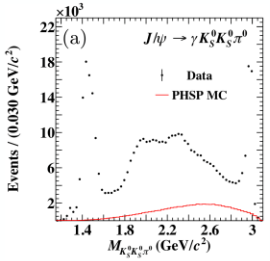
Decay channel arxiv:2607.20366	$\mathcal{B}$ $(\times 10^{-4})$
$J/\psi \to \gamma X(2370) \to \gamma K\bar{K}\pi$	$3.25 \pm 0.25^{+0.73}_{-0.75}$
$J/\psi \to \gamma X(2370) \to \gamma\pi\pi\eta$	$3.2 \pm 0.1^{+0.9}_{-1.0}$
$J/\psi \to \gamma X(2370) \to \gamma\pi\pi\eta'$	$1.94 \pm 0.04^{+0.33}_{-0.88}$
$J/\psi \to \gamma X(2370) \to \gamma K\bar{K}\eta'$	$0.39 \pm 0.05 \pm 0.10$

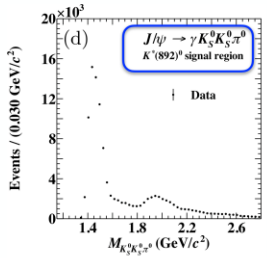
$K\bar{K}\eta'$: $f_0(980)\eta'$ …
$\pi\pi\eta'$: $f_0(980)\eta', f_0(500)\eta'$ …
$\pi\pi\eta$: $a_0(980)\pi^0 f_0(500)\eta, f_0(1500)\eta f_0(1710)\eta$ …
$K\bar{K}\pi$: $K_0^*(1430)\bar{K}$, $K_0^*(800)\bar{K}, a_0(980)\pi^0$ …

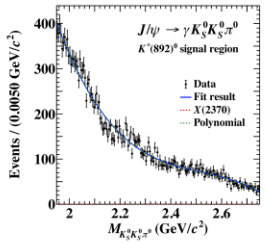
Combined results (consistent with lightest 0^{-+} glueball predictions)

- **Mass:** $M_{X(2370)} = 2359^{+13}_{-14} MeV/c^2$
- **Width:** $\Gamma_{X(2370)} = 170^{+44}_{-29} MeV$
- **Based on BR measurements in 4 channels + accounting for missing decay modes:**
  - **Reasonable to have the high production rate:** $B(J/\psi \to \gamma X(2370)) > 1 \times 10^{-3}$
  - **Narrow partial decay width: S-wave two-body decay with 1~10% →partial width ~ a few MeV**

Flavor-singlet property measurement for the X(2370)





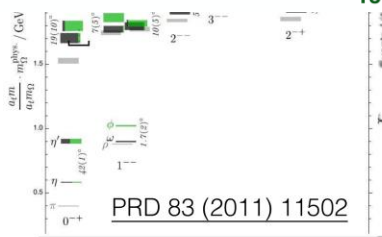


- No evidence of the decay of $X(2370) \to K^*(892)\bar{K}^0$ (significance is only 0.1σ)
  - Branching fraction ratio in $K_S^0 K_S^0 \pi^0$ mode:

$$R = \frac{B[X(2370) \to K^*(892)^0 \bar{K}^0] + c.c. \to K_S^0 K_S^0 \pi^0}{X(2370) \to K_S^0 K_S^0 \pi^0} < 0.081 @ 90\% C.L.$$

  - Branching fraction ratio w.r.t. total X(2370) production: $B[X(2370) \to K^*(892)\bar{K}] < 1.6\% @ 90\% C.L.$
- Suppression of $X(2370) \to K^*(892)\bar{K}^0$ mode indicates the X(2370) to be a flavor-singlet state
  - First flavor-singlet hadron state observed above 1GeV

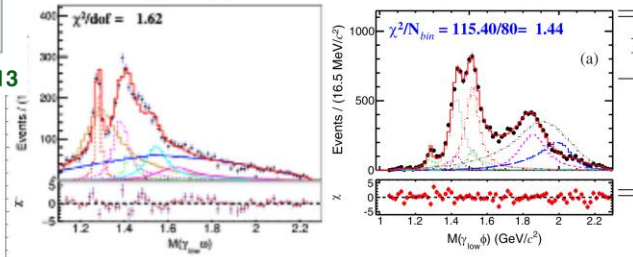
arxiv:2607.20366



PRD 83 (2011) 11502

Suppression of $q\bar{q}$ contents

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



PRD 111(2025) 052011

Resonance R	$J/\psi \to \gamma R \to \gamma\gamma\omega$ $(\times 10^{-6})$ [29]	$J/\psi \to \gamma R \to \gamma\gamma\phi$ $(\times 10^{-6})$ [30]
$\eta(1405)$	$3.54 \pm 0.20^{+0.65}_{-0.24}$	$3.57 \pm 0.18^{+0.59}_{-0.61}$
$X(1835)$	< 0.11	$3.37 \pm 0.19^{+0.78}_{-1.10}$
$X(2370)$	< 0.04	< 0.11

$$B(J/\psi \to \gamma X(2370)) > 1 \times 10^{-3}$$

- LQCD prediction: no flavor singlet formed via $s\bar{s}/u\bar{u} + d\bar{d}$ mixing above 1GeV (supported by PDG data)
- Study in $J/\psi \to \gamma\gamma\omega$ and $J/\psi \to \gamma\gamma\phi$
  - Strong suppression of $X(2370) \to \gamma\omega, \gamma\phi$: disfavor $s\bar{s}/u\bar{u} + d\bar{d}$ content
  - Significantly lower than the decay rates of $\eta(1405)$ and X(1835): disfavor η/η' excitation
- Narrow partial decay widths ~a few MeV: disfavor $q\bar{q}$, multi-quark or hybrid states (typical OZI decay width ~100MeV)
- Flavor-singlet property $B[X(2370) \to K^*(892)\bar{K}] < 1.6\%$ (decay width <2MeV): disfavor η/η' excitation (expected 15-200MeV)

$s\bar{s}/u\bar{u} + d\bar{d}$ content should be strongly suppressed in X(2370)

Lightest 0^{-+} Glueball as Dominant Constituent of X(2370)

◈ **Properties of the X(2370)**

- ✦ High production rate in J/ψ radiative decays
- ✦ Decay pattern similarities to η_c
- ✦ Flavor-singlet state
- ✦ Narrow partial decay widths
- ✦ Strong suppressions of $\gamma\omega$,$\gamma\phi$ decays

} **The combination of these signatures enable us to identify whether a particle is a glueball or not**

◈ **These properties are fully consistent with the expected signatures of glueball**

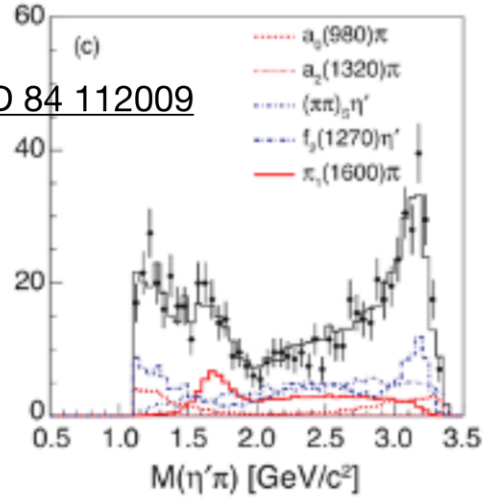
- ✦ Other interpretations can hardly explain all of them simultaneously

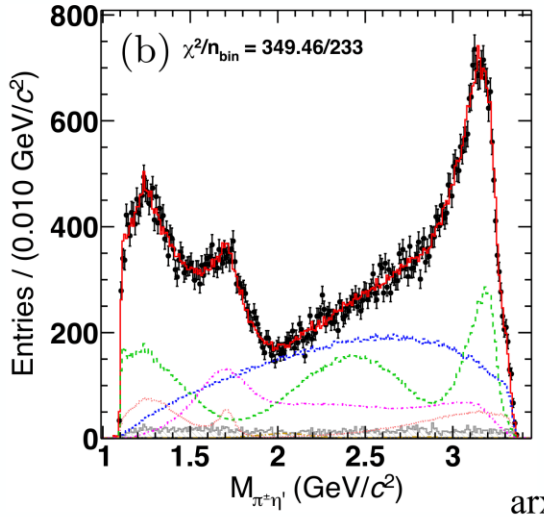
◈ **The lightest 0^{-+} glueball is needed for a natural and complete explanation of the X(2370) properties**

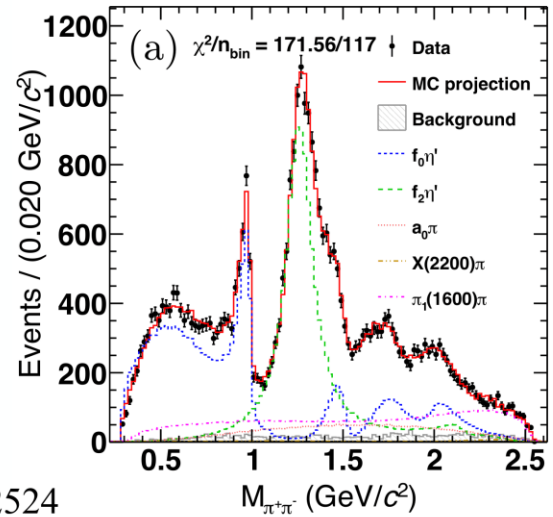
The lightest 0^{-+} glueball is the dominant constituent of the X(2370)

Observation of Exotic 1^{-+} Isovector state $\pi(1600)$

PRD 84 112009







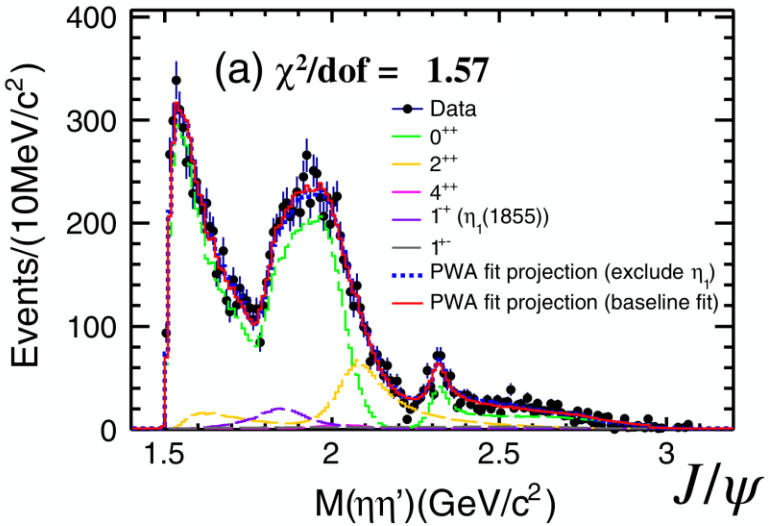
arxiv:2604.12524

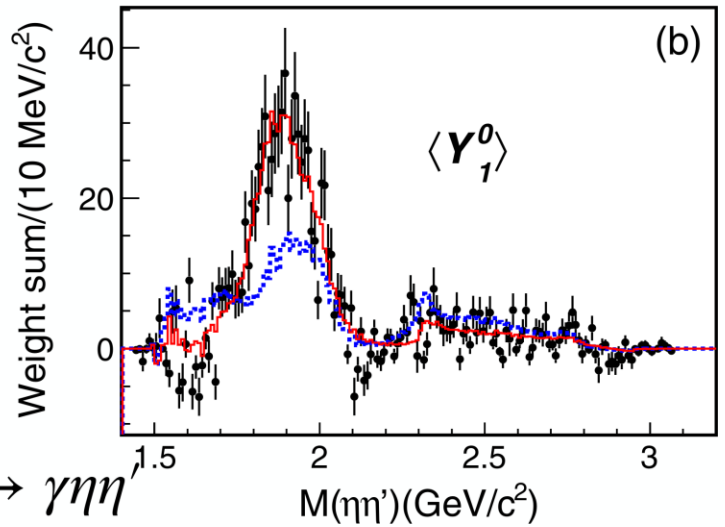
- CLEO-c results: evidence of an exotic P-wave $\eta'\pi$ amplitude with 4σ and but no significant phase motion
- PWA in $\psi' \to \gamma\chi_{c1}(\chi_{c1} \to \pi^+\pi^-\eta')$ with higher ψ' data sample @ BESIII:
  - **First observation of Exotic 1^{-+} Isovector state $\pi(1600)$ with a significance >21σ**
  - **The significance of phase motion is also greater than 11σ**
  - **Difference mass shape descriptions achieve the consistent pole position:**

$$(1690 \pm 16^{+36}_{-44}) - i(217 \pm 5^{+7}_{-19})\ \textbf{MeV}$$

$$B[\chi_{c1} \to \pi_1(1600)^{\pm}\pi^{\mp}] \times B[\pi_1(1600)^{\pm} \to \pi^{\pm}\eta'] = (4.30 \pm 0.14^{+1.04}_{-1.03}) \times 10^{-4}$$

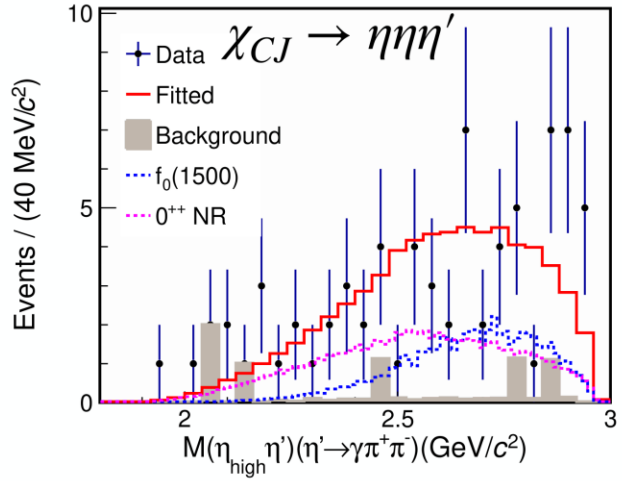
Observation of Exotic 1^{-+} Isoscalar $\eta_1(1855)$



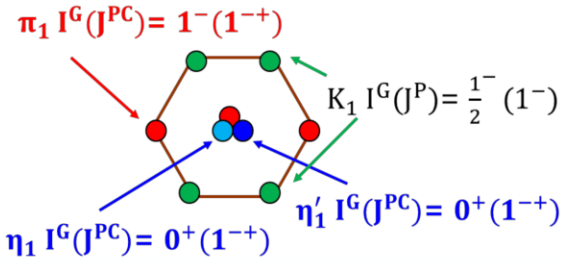


$J/\psi \to \gamma\eta\eta'$

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



CPC 49 (2025) 123001



- **$J/\psi \to \gamma\eta\eta'$ is a good channel for $\eta_1(1^{-+})$ search**
- **Observation of an isoscalar 1^{-+} $\eta_1(1855)$ in $J/\psi \to \gamma\eta\eta'$ (>19σ)**
  - M= $1855 \pm 9^{+6}_{-1}$ MeV, $\Gamma = 188 \pm 18^{+3}_{-8}$ MeV, $B(J/\psi \to \gamma\eta_1(1855) \to \gamma\eta\eta') = (2.70 \pm 0.41^{+0.16}_{-0.35}) \times 10^{-6}$
- No significant $\eta_1(1855)$ is observed in $\chi_{c1} \to \eta\eta\eta'$:
  $B(\chi_{c1} \to \eta_1(1855)\eta)B(\eta_1(1855) \to \eta\eta') < 9.79 \times 10^{-5}$
- **Mass consistent with LQCD on hybrid, and more interpretations** (KK Molecule/Tetraquark)

BACKUP SLIDEs

Decay list of light meson in BESIII

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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Decay list of light meson in BESIII

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
$\eta' \to \eta\pi^+\pi^-$	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)% (*)	$m_u - m_d$
$\eta' \to \mu^+\mu^-\gamma$	$1.09(27) \times 10^{-4}$	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
$\eta' \to \pi^+\pi^-e^+e^-$	$2.4\binom{+1.3}{-1.0} \times 10^{-3}$	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
$\eta' \to \pi^0\pi^0$	$<1.8 \times 10^{-5}$	P/CP violation
$\eta' \to 2\pi^0$	$<4 \times 10^{-4}$	P/CP violation

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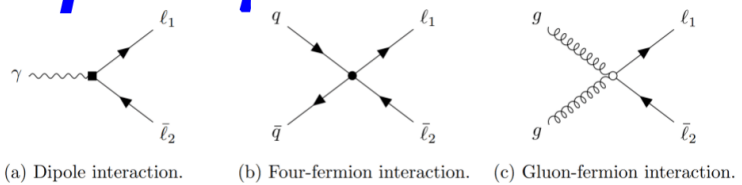
Search for CLFV process $\eta' \to e\mu$ and $\eta \to e\mu$



(a) Dipole interaction. (b) Four-fermion interaction. (c) Gluon-fermion interaction.

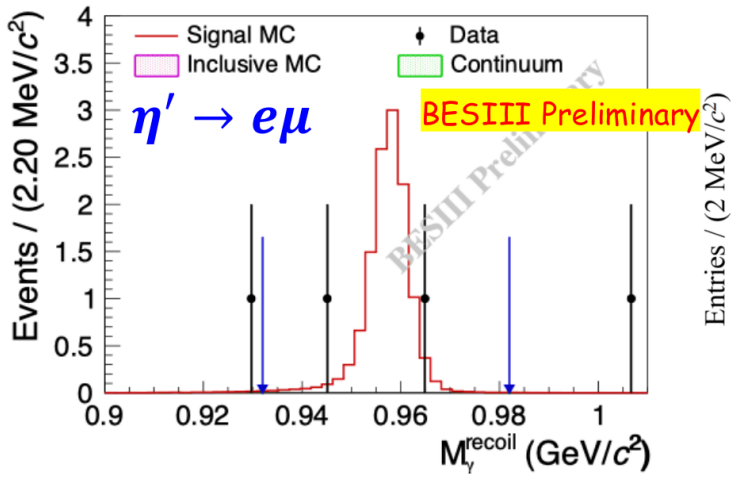
- Highly suppressed in SM $\propto \left(\Delta m_{ij}^2/M_W^2\right)^2 \sim 10^{-50}$
- Many New Physics models introduce Charge Lepton Flavor Violation (CLFV) processes
- Latest result $\mathcal{B}(\eta \to e\mu) < 6.0\times10^{-6}$ from CLEO in 2000 and $\mathcal{B}(\eta' \to e\mu) < 4.7 \times 10^{-4}$ from SPES2 in 1996

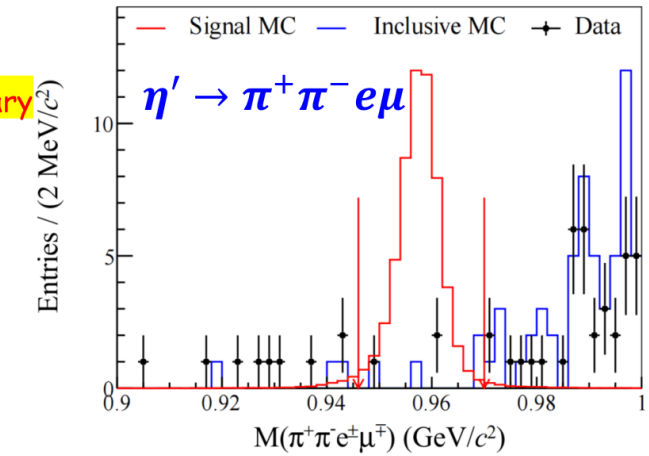
- For $\eta' \to e\mu$ with $J/\psi \to \gamma\eta'$ process is used.
- While for $\eta \to e\mu, J/\psi \to \gamma\eta' \to \gamma\pi^+\pi^-\eta$ is used to suppress continuum backgrounds

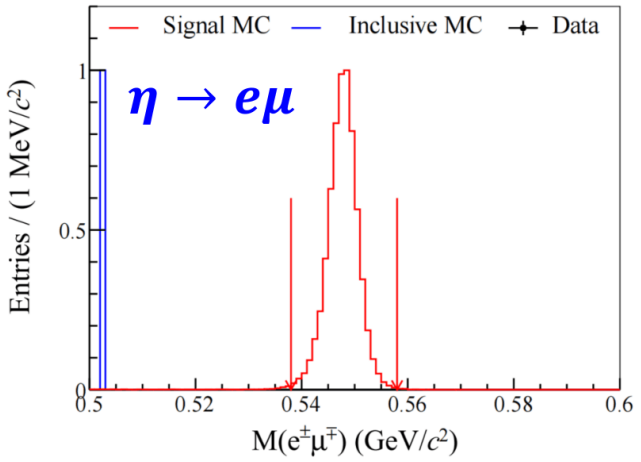
$\mathrm{B}(\eta' \to e\mu) < 6.3\times10^{-7}$

$\mathrm{B}(\eta \to e\mu) < 6.8\times10^{-7}$

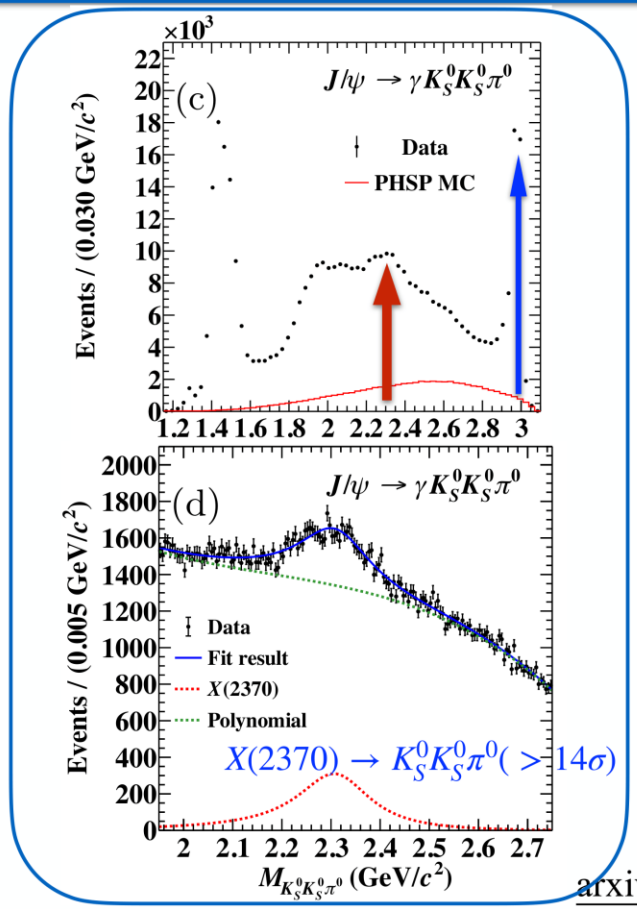
BESIII: arXiv:2606.22373

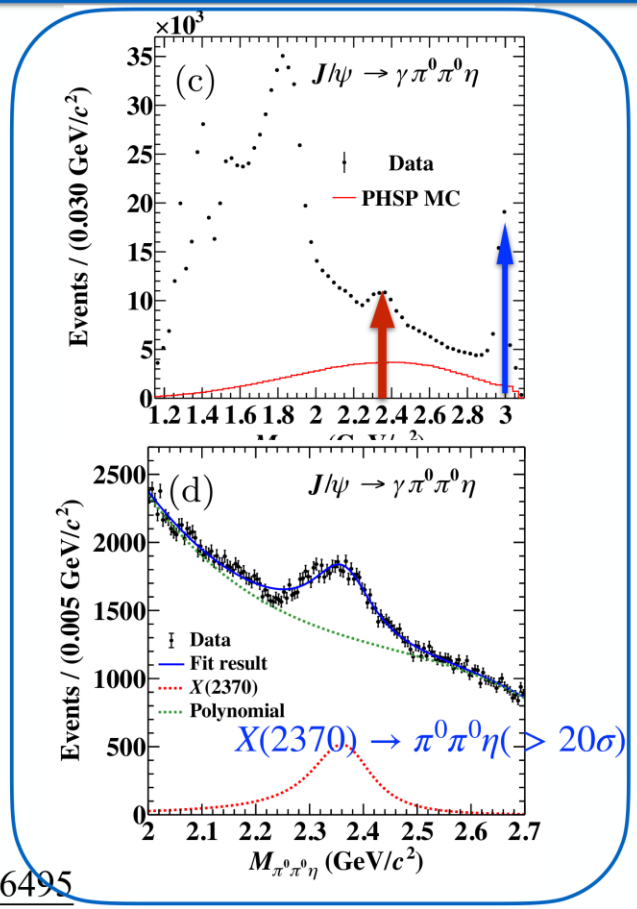


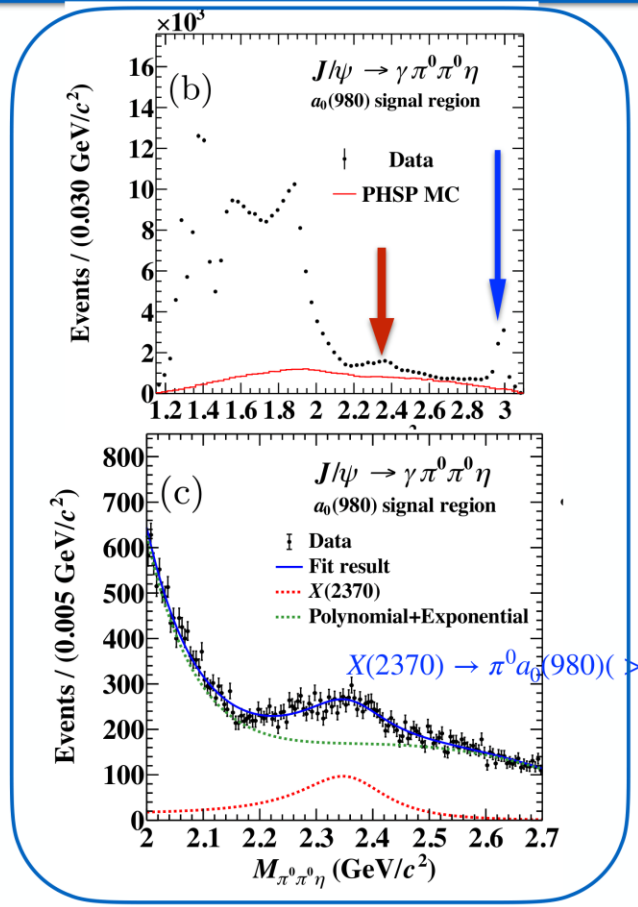




Observation of the X(2370) in $K_S^0K_S^0\pi^0$ and $\pi^0\pi^0\eta$







arxiv:2605.26495

- **Decay modes of X(2370)→$\pi\pi\eta'$,$K\bar{K}\eta'$,$K\bar{K}\pi$,$\pi\pi\eta$, $K\bar{K}\eta$, $a(980)\pi$ observed**
- **Such high decay pattern similarity between the X(2370) and η_c strongly supports the glueball interpretation of the X(2370)**

◈ **Decay modes of X(2370)→$\pi\pi\eta'$,$K\bar{K}\eta'$,$K\bar{K}\pi$,$\pi\pi\eta$, $K\bar{K}\eta$, $a(980)\pi$ observed**