Precision Study of η/η' decays (Experiment)

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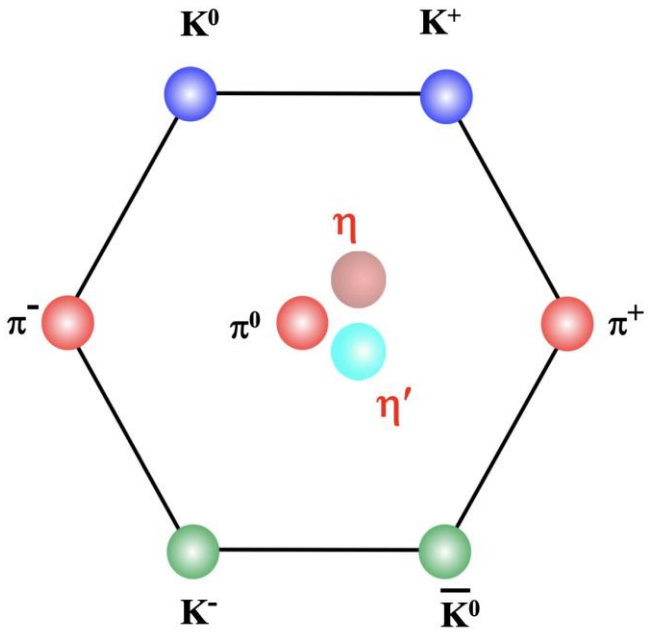
The 7th International Workshop on Future Tau Charm Facilities

Nov 23 - 27, 2025 Huangshan

Outline

- η/η' Physics
- η/η' samples
- Recent highlights
- Prospects and Conclusion



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

Phys. Rept. 945 (2022) 1-105

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- 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
$\eta' \to \pi^+\pi^-e^+e^-$	$2.4\left(^{+1.3}_{-1.0}\right) \times 10^{-3}$	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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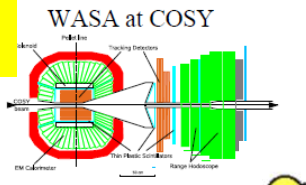
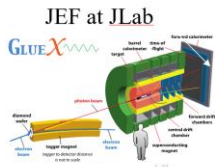
Experimental η/η' samples

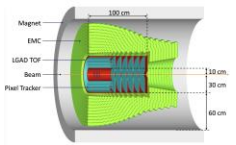
e^+e^- Collider

Fixed-target





Proposed RedTop and HHaS@HIAF

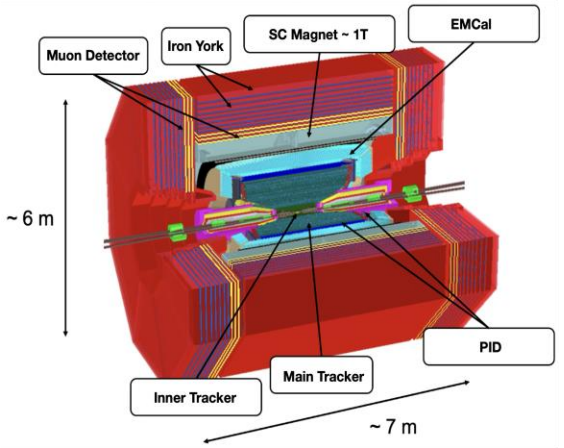


Experiment	η events	η' events
BESIII $J/\psi \to \gamma\eta/\eta'$	1.1×10^7	5.2×10^7
$J/\psi \to \gamma\eta'(\pi^+\pi^-\eta)$	2.2×10^7	
$J/\psi \to \phi/\omega\eta/\eta'$	2.5×10^7	6.5×10^6
KLOE-2 $\phi \to \gamma\eta/\eta'$	3×10^8	1.5×10^6
WASA@COSY $pp \to \eta X$	$\sim 3 \times 10^7$	
A2@MAMI $\gamma p \to \eta/\eta' X$	$\sim 6 \times 10^7$	$\sim 3 \times 10^6$
HADES $pp \to \eta X$	$\sim 4.5 \times 10^8$	
JEF@JLAB $\gamma p \to \eta X$	$\sim 10^7$	
REDTOP, HIAF $pLi \to \eta X$	$\sim 10^{13}$/yr	

Proposed STCF:
η/η' factory

340 times BESIII statistics:

$\Rightarrow \sim 10^{10}\ \eta$ and $10^{10}\eta'$

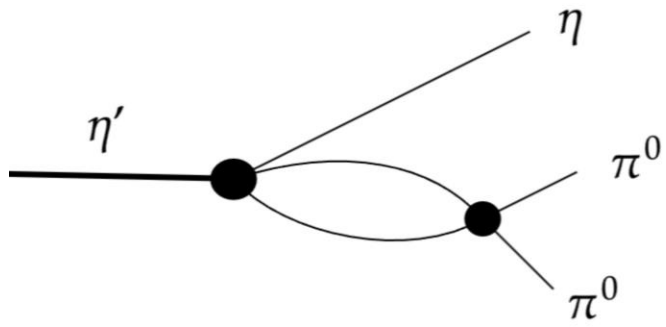


Recent highlights

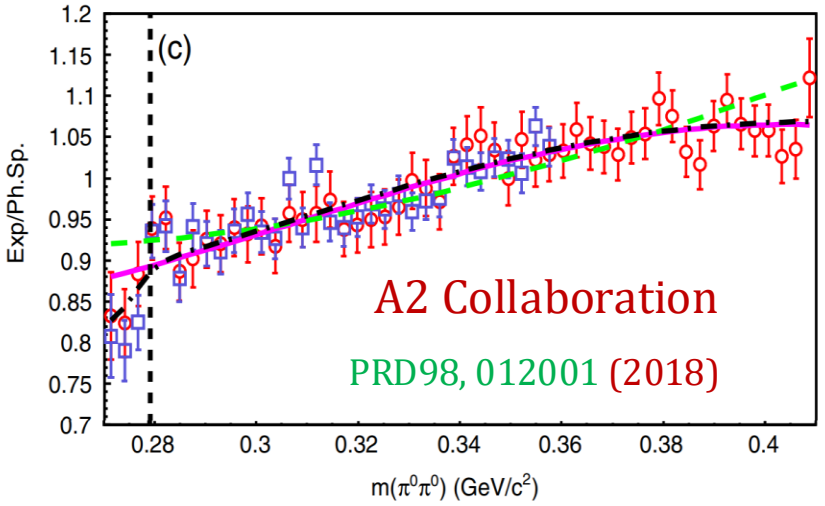
Evidence of cusp effect in $\eta' \to \pi^0\pi^0\eta$

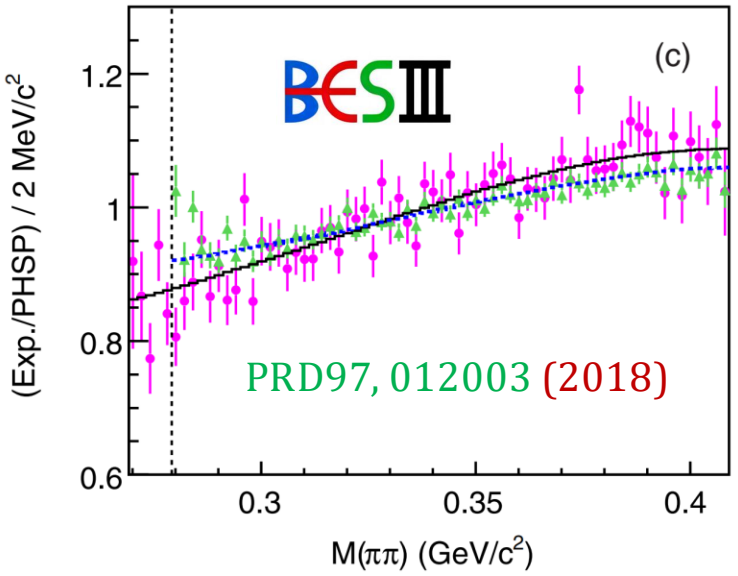
BESIII: PRL130, 081901(2023)

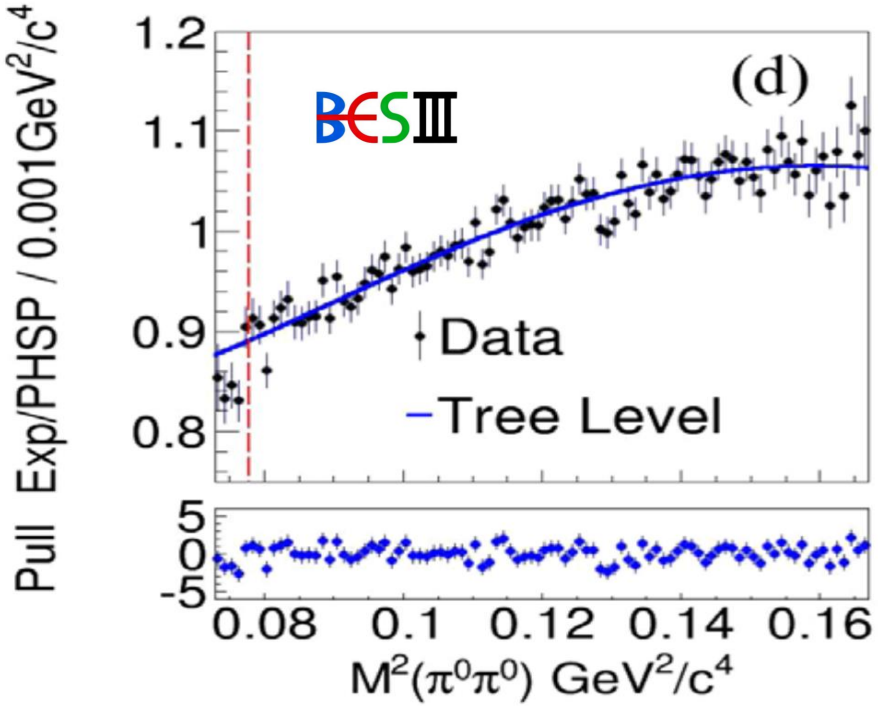
- Investigation on ππ and πη final interactions
- S-wave charge-exchange rescattering: $\pi^+\pi^- \to \pi^0\pi^0 \to \pi^+\pi^-$
- The size of cusp effect is predicted to be about 6% in $\eta' \to \pi^0\pi^0\eta$ within NREFT



B. Kubis and S. P. Schneider, EPJC 62, 511 (2009)







BESIII: PRL130, 081901(2023)

- One and two-loop level contributions based on NREFT are introduced

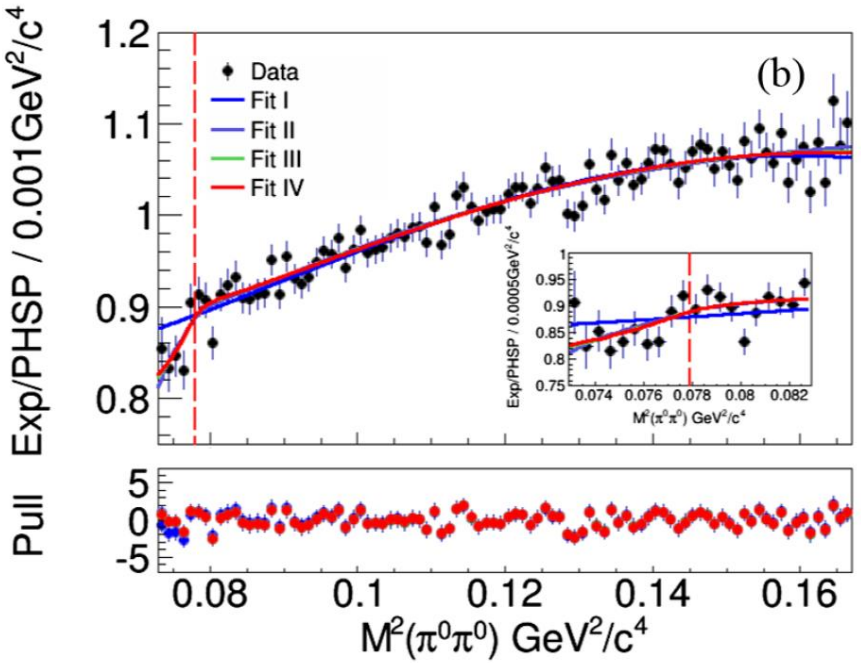
B. Kubis, S. P. Schneider, EPJC 62, 511 (2009)

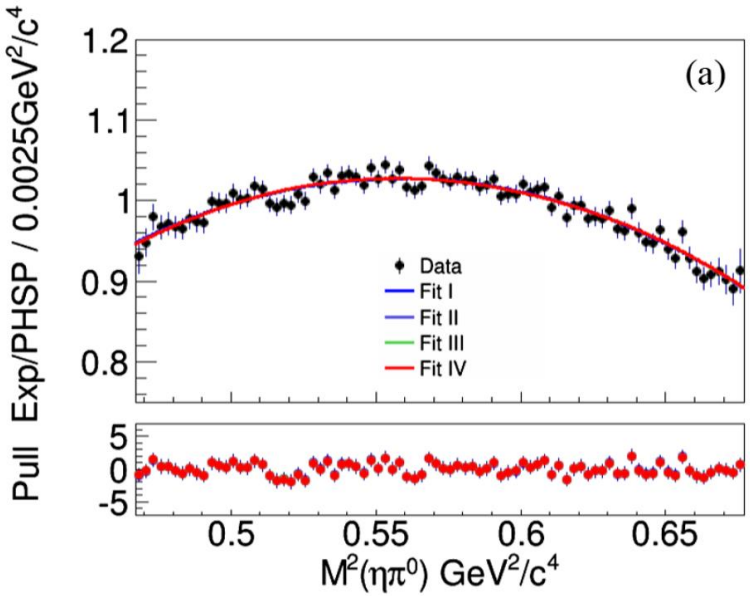
$$\mathcal{M}_{\eta' \to \eta\pi^0\pi^0} = \mathcal{M}_N^{tree} + \mathcal{M}_N^{one-loop} + \mathcal{M}_N^{two-loop} + \cdots$$

- Tree level amplitude is equivalent to general presentation

$$X = \frac{\sqrt{3}}{Q}(T_{\pi^+} - T_{\pi^-}), Y = \frac{m_\eta + 2m_\pi}{m_\pi}\frac{T_\eta}{Q} - 1$$

$$|M(X,Y)|^2 = N(1 + aY + bY^2 + cX + dX^2 + \ldots)$$





Cusp effect with ~3.5 σ!

With cusp effect

Parameters	Fit I	Fit II	Fit III	Fit IV
a	$-0.075 \pm 0.003 \pm 0.001$	-0.207 ± 0.013	-0.143 ± 0.010	$-0.077 \pm 0.003 \pm 0.001$
b	$-0.073 \pm 0.005 \pm 0.001$	-0.051 ± 0.014	-0.038 ± 0.006	$-0.066 \pm 0.006 \pm 0.001$
d	$-0.066 \pm 0.003 \pm 0.001$	-0.068 ± 0.004	-0.067 ± 0.003	$-0.068 \pm 0.004 \pm 0.001$
$a_0 - a_2$	-	0.174 ± 0.066	0.225 ± 0.062	$0.226 \pm 0.060 \pm 0.012$
a_0		0.497 ± 0.094	-	-
a_2	-	0.322 ± 0.129	-	-
Statistical Significance	-	3.4σ	3.7σ	3.6σ

π–π scattering pars

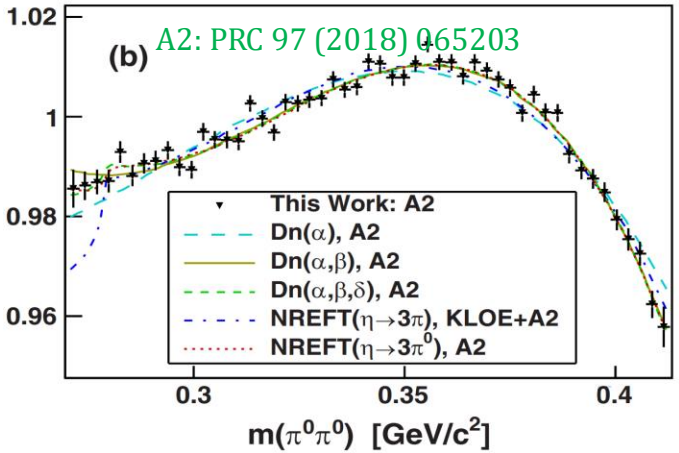
Cusp and slope parameter for $\eta \to \pi^0\pi^0\pi^0$

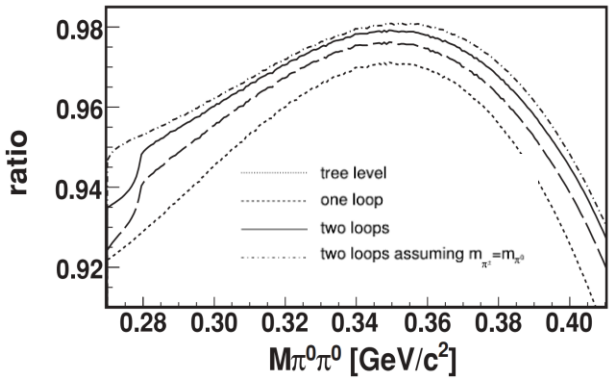
BESIII: PRD 107, 092007 (2023)

KLOE: PLB 694 (2011) 16

$$|A(X,Y)|^2 \propto 1 + 2\alpha Z + 2\beta(3X^2Y - Y^3) + 2\gamma Z^2 + \cdots + 2\delta \sum_{i=1}^{3} \Re\sqrt{1 - s_i/4m_{\pi^\pm}^2}$$

C. O. Gullstrom, A. Kupsc, A. Rusetsky, PRC 79, 028201 (2009)





- KLOE: ~420 pb^{-1} ($\simeq 1.4 \cdot 10^9$ ϕ) data

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

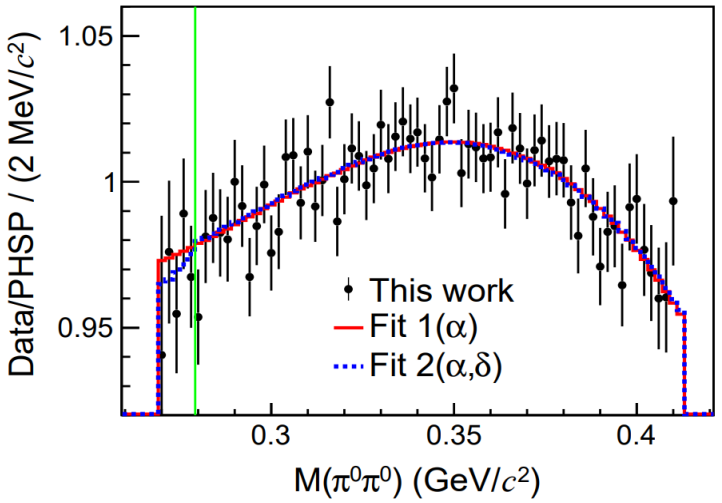
- BESIII: 10 billion J/ψ radiative decays

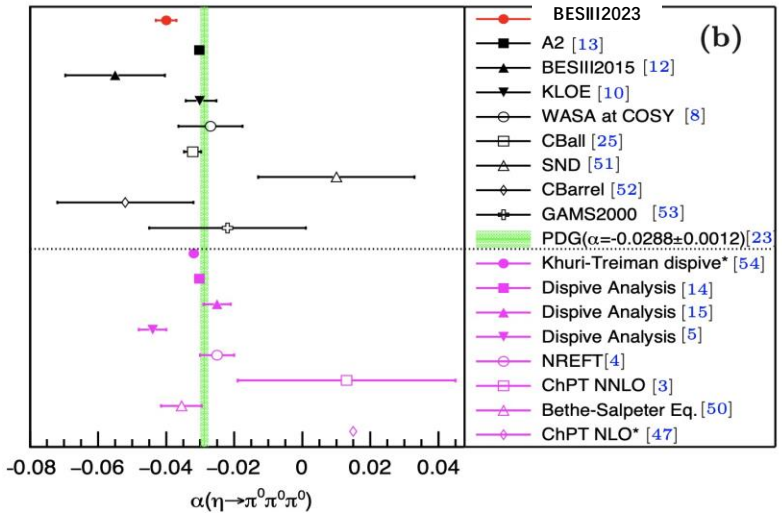
$$\alpha = -0.0406 \pm 0.0035 \pm 0.0008$$
$$\beta = 0.0038 \pm 0.0033_{stat.}$$
$$\gamma = -0.018 \pm 0.014_{stat.}$$
$$\delta = -0.018 \pm 0.022_{stat.}$$

$\Rightarrow \alpha$ is consistent with A2 and KLOE results in 2.8σ

A2: Higher order contributions and hint of cusp A2: PRC 97 (2018) 6, 065203

$$\alpha(A_2) = -0.0302 \pm 0.0008_{stat.}$$
$$\beta(A_2) = -0.0070 \pm 0.0010_{stat.}$$
$$\gamma(A_2) = -0.0023 \pm 0.0040_{stat.}$$
$$\delta(A_2) = -0.0169 \pm 0.0067$$





Matrix elements for $\eta \to \pi^+\pi^-\pi^0$

BESIII: PRD 107, 092007 (2023)

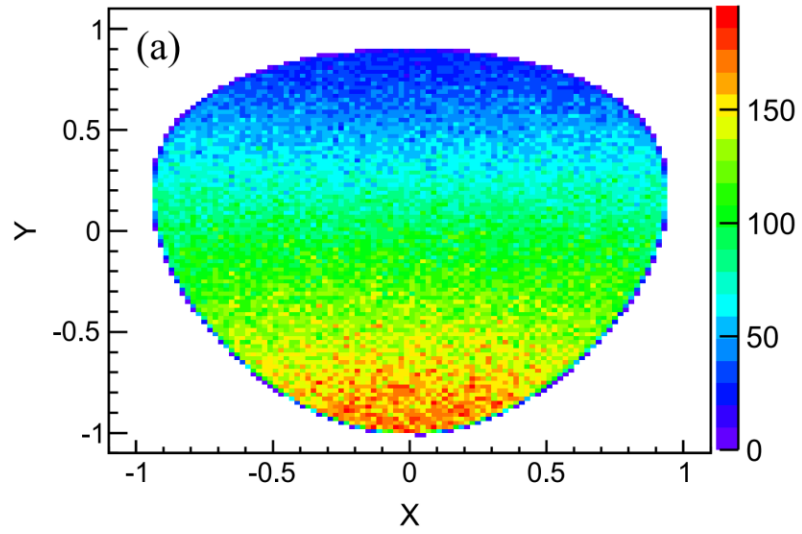
https://www.hepdata.net/record/141642

➢ SM: Isospin violating process, C conserved, EM effects suppressed

⇒ ideal process to extract $m_u - m_d$

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

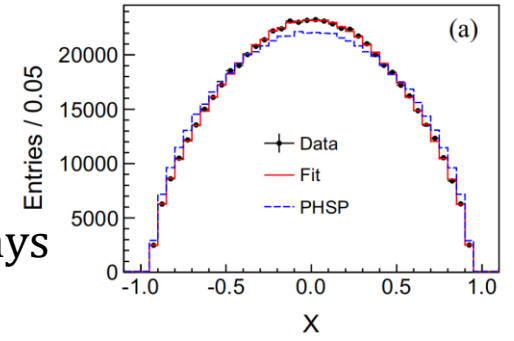
$$|A(X,Y)|^2 \propto 1 + aY + bY^2 + cX + dX^2 + eXY + fY^3 + gX^2Y + \cdots$$

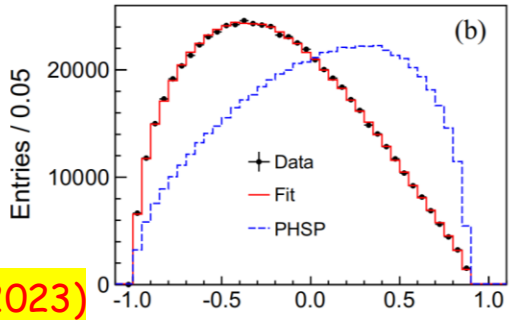


✓ KLOE-2: 1.6 fb^{-1} data

✓ First observation of non-zero g-term

✓ Confirmed by BESIII~10 billion J/ψ radiative decays



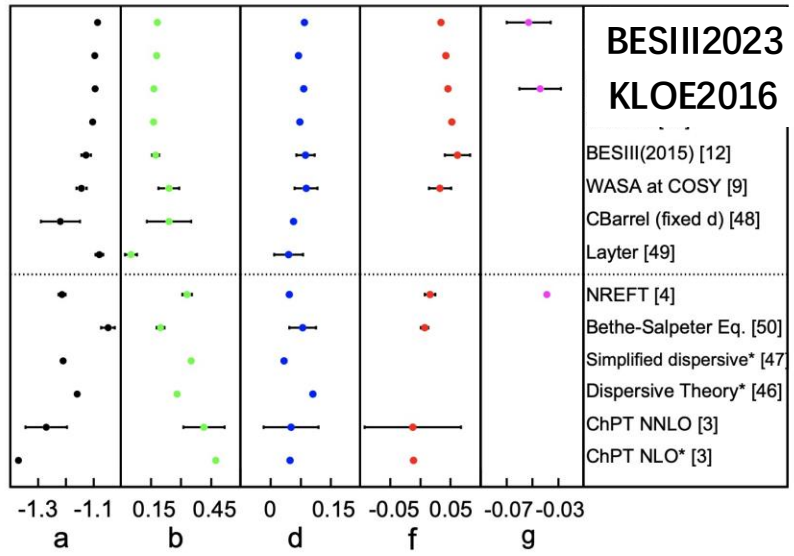


$$a = -1.095 \pm 0.003^{+0.003}_{-0.002}$$
$$b = +0.145 \pm 0.003 \pm 0.005$$
$$d = +0.081 \pm 0.003^{+0.006}_{-0.005}$$
$$f = +0.141 \pm 0.007^{+0.007}_{-0.008}$$
$$g = -0.044 \pm 0.009^{+0.012}_{-0.013}$$

KLOE-2: JHEP 1605 (2016) 019

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

BESIII: PRD 107, 092007 (2023)



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

Dalitz plot Asymmetries in $\eta \to \pi^+\pi^-\pi^0$

BESIII: PRD 107, 092007 (2023)

KLOE: JHEP 1605 (2016) 019

S. Gardner, J. Shi, PRD 101 (2020) 115038

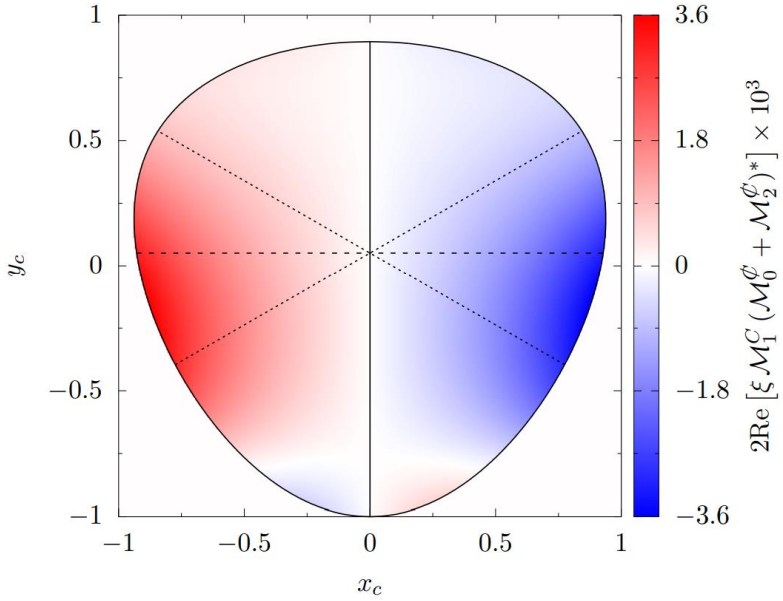
H. Akdag, T. Isken, B. Kubis, JHEP 02 (2022)137

J. Shi, J. Liang, S. Gardner PR 110 (2024) 055039

➢ BSM: C broken, isospin either conserved or broken

$$\mathcal{M}(s,t,u) = \mathcal{M}_1^C(s,t,u) + \mathcal{M}_0^{\not C}(s,t,u) + \mathcal{M}_2^{\not C}(s,t,u)$$

➢ The interferences give rise to mirror symmetry breaking (permille level) in the Dalitz plot



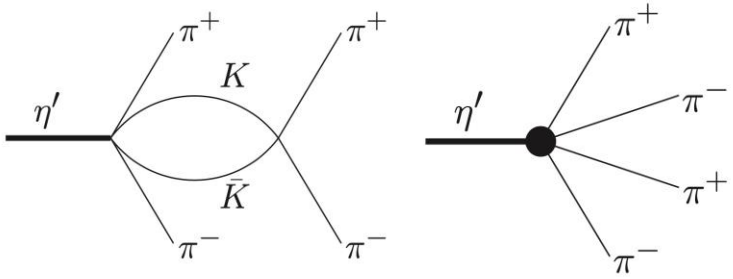
overall C/CP-violation | ΔI = 2 | ΔI = 0

Experiment	$A_{LR}(\%)$	$A_Q(\%)$	$A_S(\%)$
BESIII	$0.114 \pm 0.131 \pm 0.001$	$-0.035 \pm 0.131 \pm 0.011$	$-0.070 \pm 0.131 \pm 0.009$
KLOE-2 [11]	$-0.050 \pm 0.045^{+0.050}_{-0.110}$	$0.018 \pm 0.045^{+0.048}_{-0.023}$	$0.004 \pm 0.045^{+0.031}_{-0.035}$
Jane [40]	0.28 ± 0.26	-0.30 ± 0.25	0.20 ± 0.25
Layter [24]	-0.05 ± 0.22	-0.07 ± 0.22	0.10 ± 0.22
Gormley [41]	1.5 ± 0.5	-	0.5 ± 0.5

All asymmetries consistent with zero at 10^{-4} level

Study of $\eta' \to 4\pi$

BESIII: PRD 109, 032006 (2024)

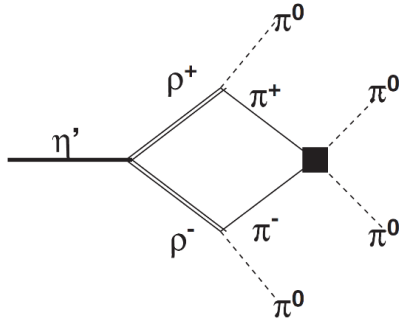


Loop and counter term at $O(p^6)\Rightarrow$

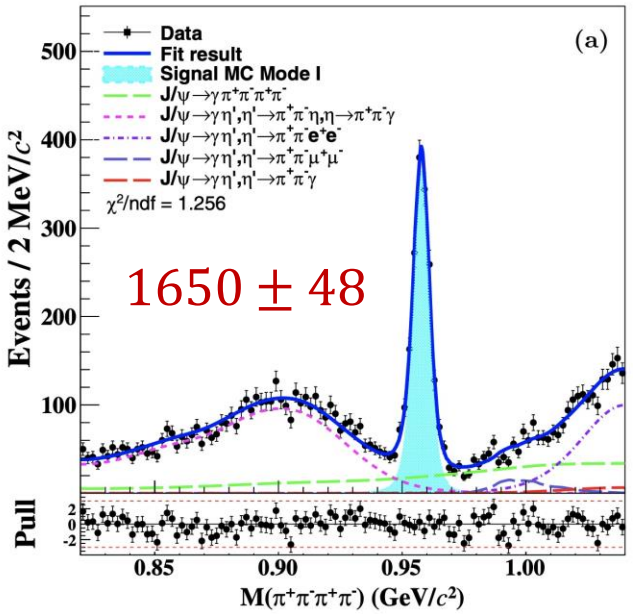
$Br(\eta' \to 2(\pi^+\pi^-)) = (1.0 \pm 0.3) \times 10^{-4}$

$Br(\eta' \to \pi^+\pi^- 2\pi^0) = (2.4 \pm 0.7) \times 10^{-4}$

F. K. Guo, B. Kubis, A. Wirzba, PRD 85,014014 (2012)

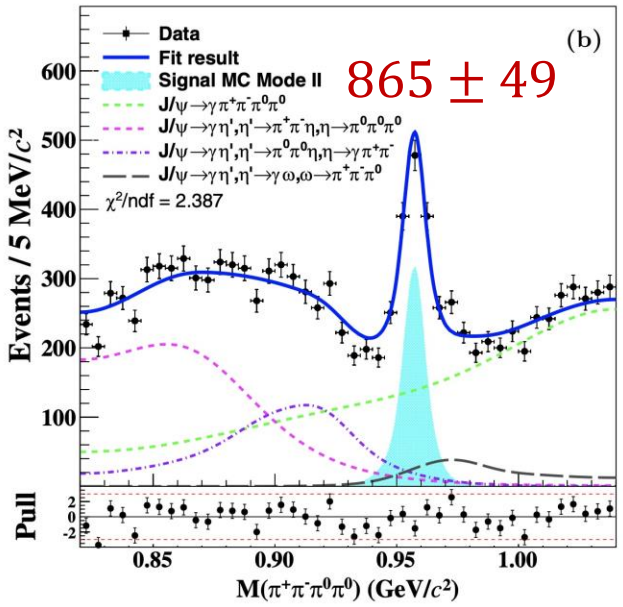


D-wave pion loop
$\Rightarrow$ Br~10^{-8}



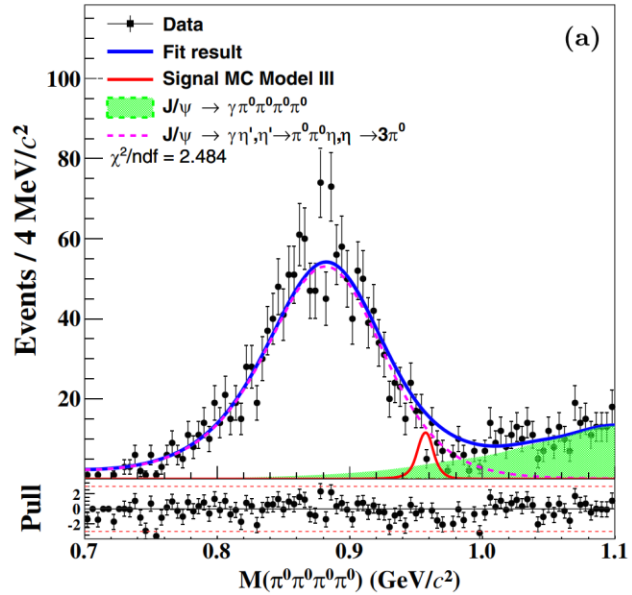
$\eta' \to \pi^+\pi^-\pi^+\pi^-$

$Br = (8.56 \pm 0.25 \pm 0.23) \times 10^{-5}$



$\eta' \to \pi^+\pi^-\pi^0\pi^0$

$Br = (2.12 \pm 0.12 \pm 0.10) \times 10^{-4}$



$\eta' \to \pi^0\pi^0\pi^0\pi^0$

the UL at 90% CL: 1.24×10^{-5}

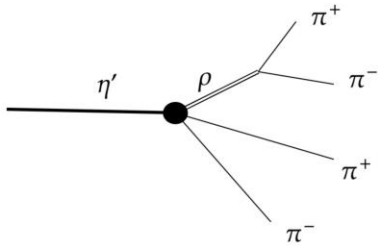
Decay dynamic of $\eta' \to 2(\pi^+\pi^-)$

BESIII: PRD 109, 032006 (2024)

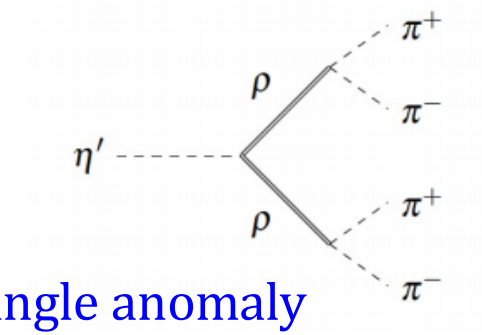
Based on the combination of ChPT and VMD model:

PRD85, 014014 (2012)

$$\mathcal{A}(\eta' \to \pi^+\pi^-\pi^+\pi^-) = \epsilon_{\mu\nu\alpha\beta} p_1^\mu p_2^\nu p_3^\alpha p_4^\beta \times \left\{ \left[\frac{s_{12}}{D_\rho(s_{12})} + \frac{s_{34}}{D_\rho(s_{34})} - \frac{s_{14}}{D_\rho(s_{14})} - \frac{s_{23}}{D_\rho(s_{23})} \right] + \alpha \left[\frac{M_\rho^2(s_{12}+s_{34})}{D_\rho(s_{12})D_\rho(s_{34})} - \frac{M_\rho^2(s_{14}+s_{23})}{D_\rho(s_{14})D_\rho(s_{23})} \right] \right\},$$



Box anomaly

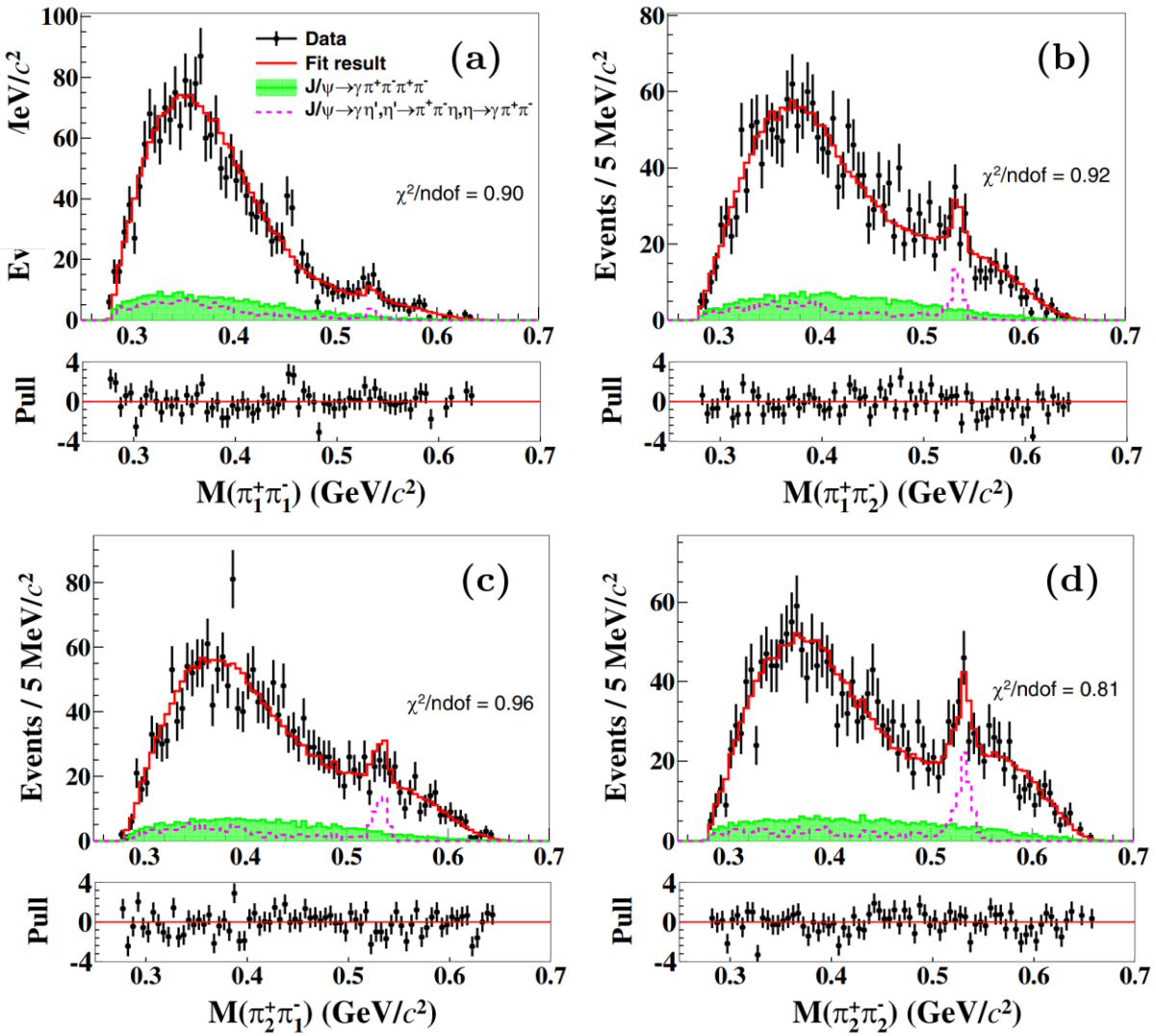


Triangle anomaly

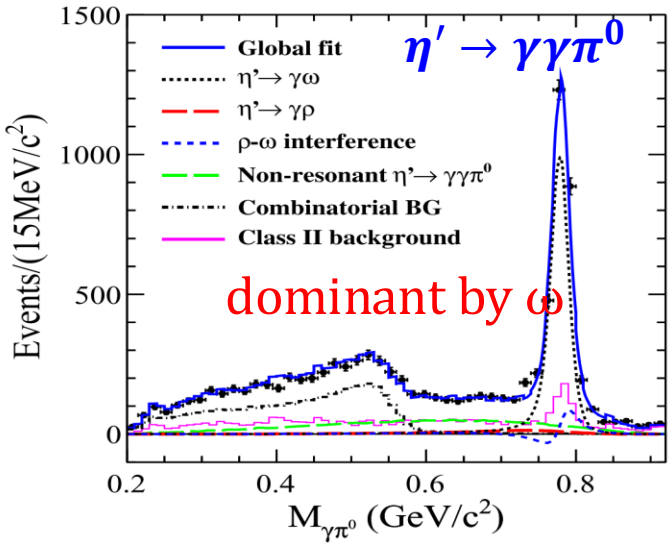
- First measurement of the doubly virtual isovector form factor

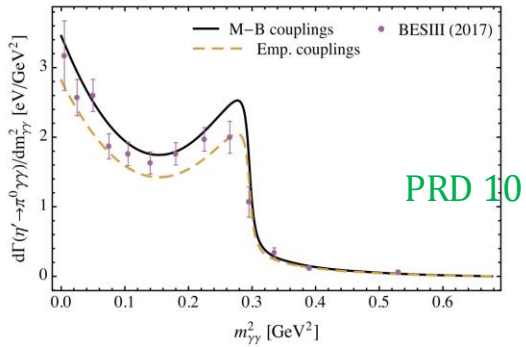
$$\alpha = \frac{c_3}{c_1 - c_2} = 1.22 \pm 0.33 \pm 0.04$$

If $\alpha \simeq 1$, triangle anomaly would be dominated



Double radiative decays $\eta^{(\prime)} \to \gamma\gamma\pi^0/\eta$





PRD 102 (2020) 034026

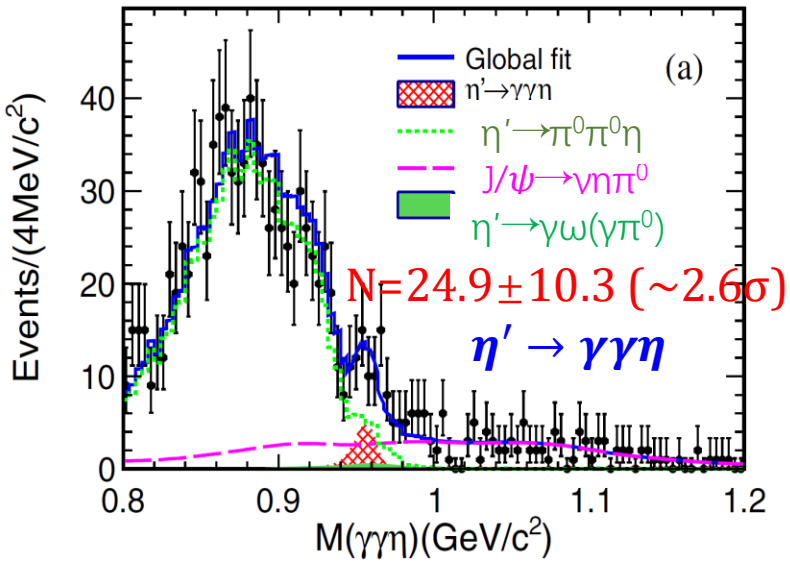
$\mathrm{Br}(\eta' \to \gamma\gamma\pi^0) = (32.0 \pm 0.7 \pm 2.3) \times 10^{-4}$

$\mathrm{Br}(\eta' \to \gamma\omega \to \gamma\gamma\pi^0) = (23.7 \pm 1.4 \pm 1.8) \times 10^{-4}$

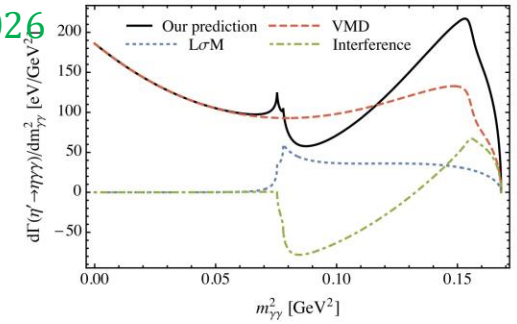
$\mathrm{Br}(\eta' \to \gamma\gamma\pi^0)(\mathrm{NR}) = (6.16 \pm 0.64 \pm 0.67) \times 10^{-4}$

BESIII: PRD 96, 012005 (2017)

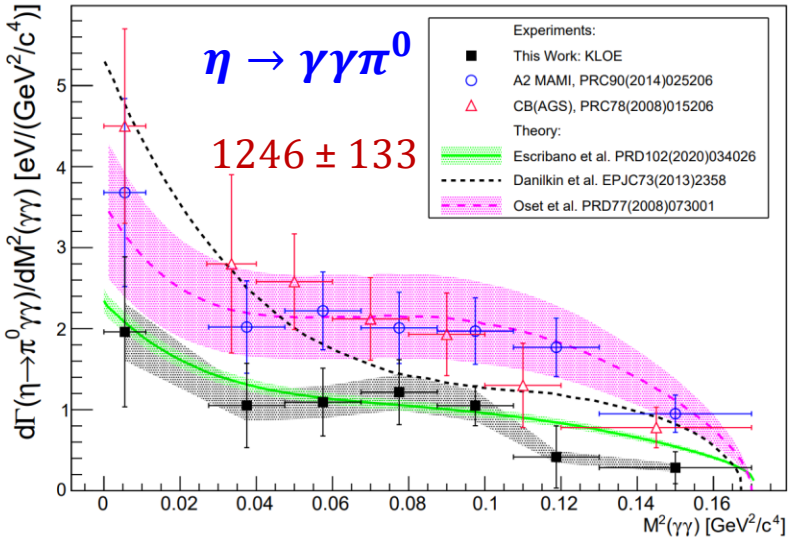
BESIII: PRD 100, 052015 (2019)



$\mathrm{B}(\eta' \to \gamma\gamma\eta) = (8.25 \pm 3.41 \pm 0.72) \times 10^{-5}$



KLOE-2:arXiv:2505.09285 Lint ~ 1.7 fb^{-1}



$\mathrm{Br}(\eta \to \pi^0\gamma\gamma) = (0.99 \pm 0.11 \pm 0.24) \times 10^{-4}$

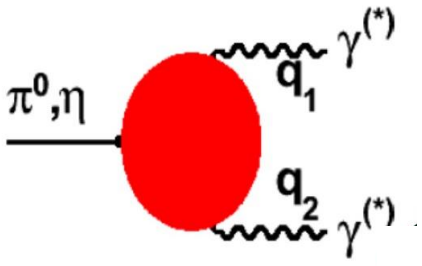
$\mathrm{Br}_{(A2)} = (2.52 \pm 0.25) \times 10^{-4}$

A2: PRC 90 (2014) 025206

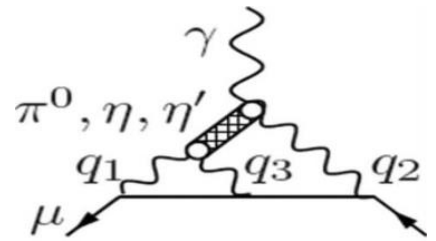
$\mathrm{Br}(\eta \to \pi^0\gamma\gamma) = (1.30 \pm 0.08) \times 10^{-4}$ LσM+VMD

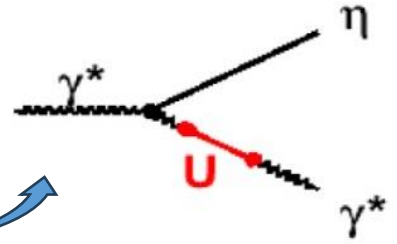
Also can be used to search leptophobic B boson $\eta^{(\prime)} \to \gamma B \to \gamma\gamma\pi^0/\eta$.

Meson transition form factors

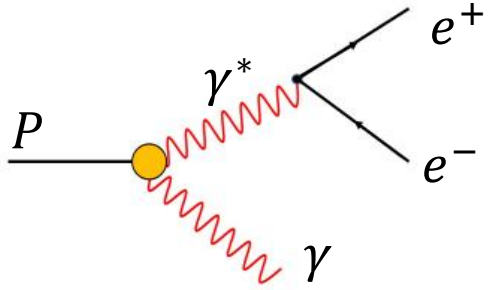


- Low energy QCD:
  - Enters in th. description of QCD processes
  - Evolution with Q^2 predicted by pQCD: models can be tested using data on Q^2 dependance
- Light-by-light contribution to a_μ
- Search for light dark force mediator

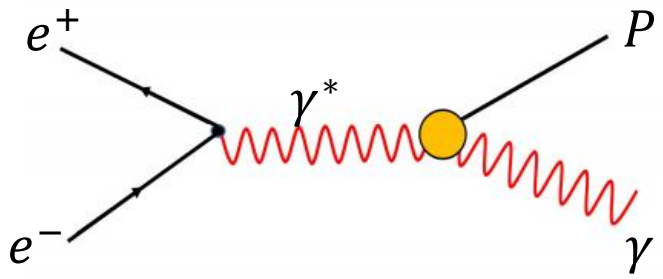




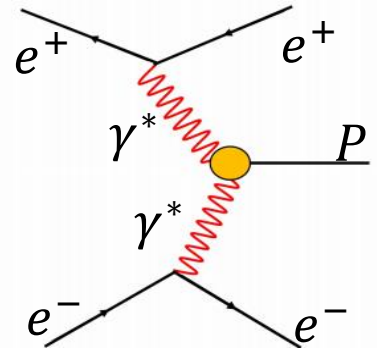
Experimentally



Dalitz decays $0<q^2<M^2$

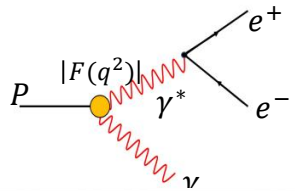


Annihilation process $q^2>M^2$

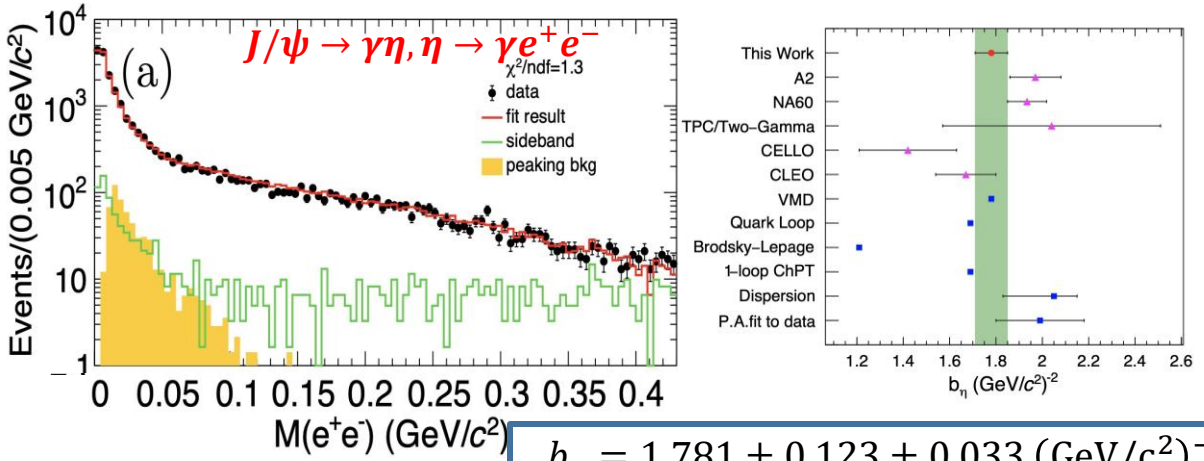


Two photon process $q^2<0$

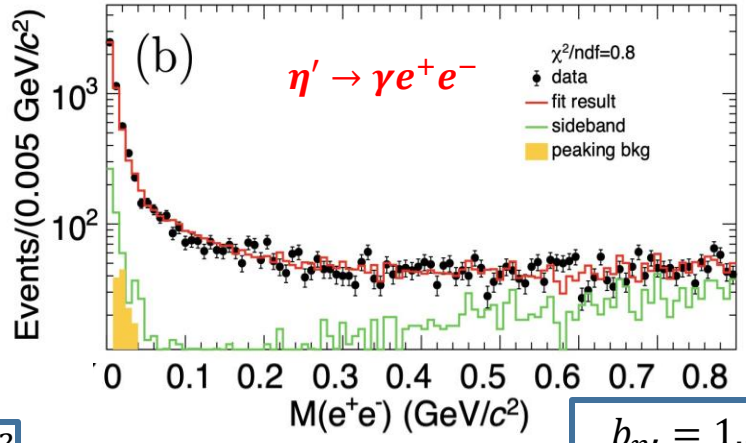
TFF of $\eta/\eta' \to \gamma e^+e^-$

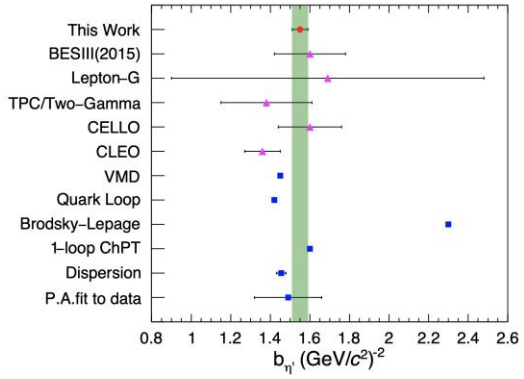


BESIII: PRD 109, 072001 (2024)



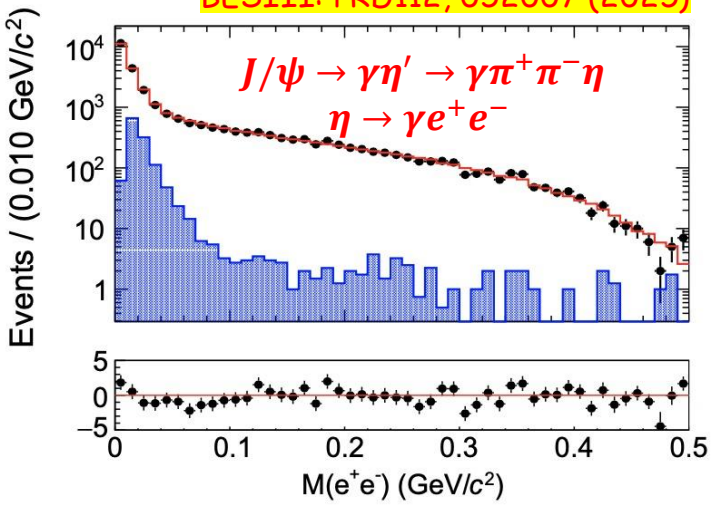
$b_\eta = 1.781 \pm 0.123 \pm 0.033\ (\mathrm{GeV/c^2})^{-2}$

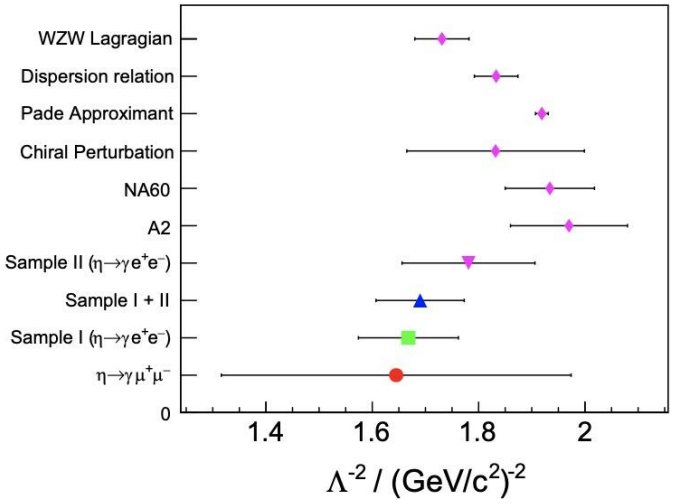


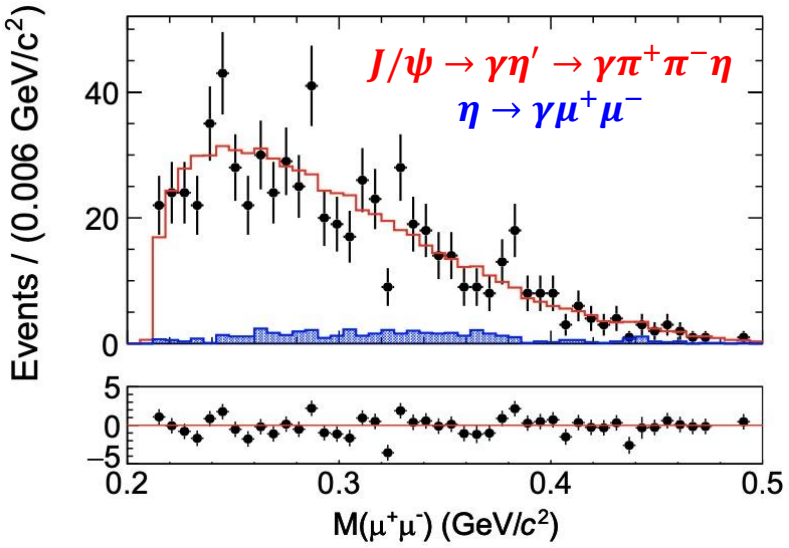


$b_{\eta'} = 1.574 \pm 0.048 \pm 0.016\ (\mathrm{GeV/c^2})^{-2}$

BESIII: PRD112, 052007 (2025)





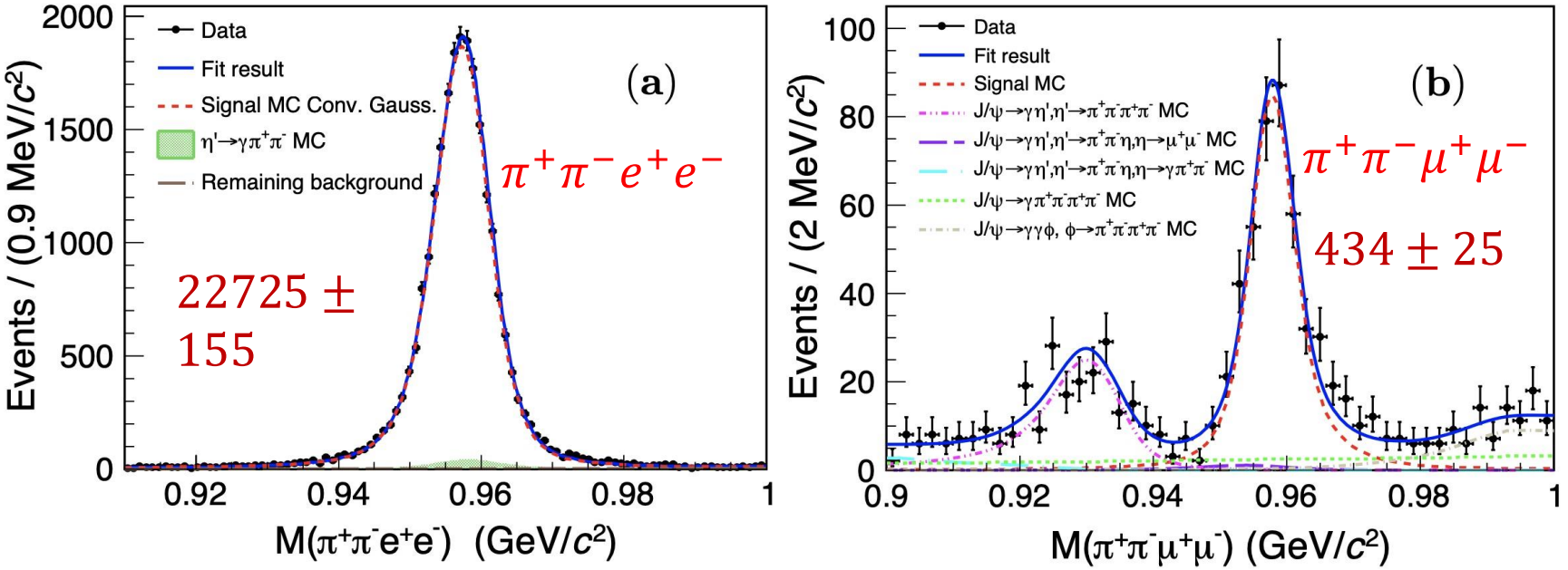


Combined the two $\eta \to \gamma e^+e^-$: $b_\eta = (1.707 \pm 0.076 \pm 0.029)\ GeV/c^2$

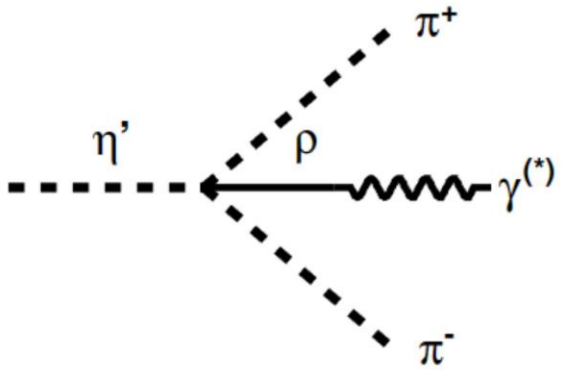
$b_\eta = (1.645 \pm 0.343 \pm 0.017)\ GeV/c^2$

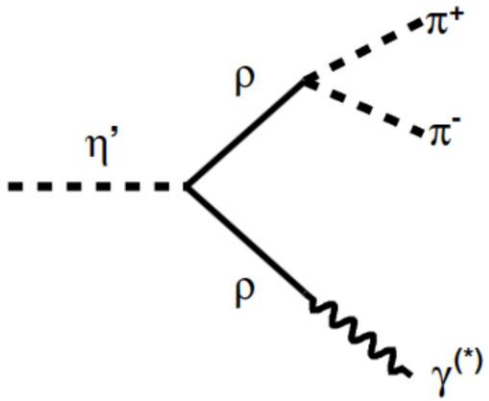
Precision study of $\eta' \to \pi^+\pi^- l^+ l^-$

BESIII: JHEP 07, 135 (2024)



VMD Contribution





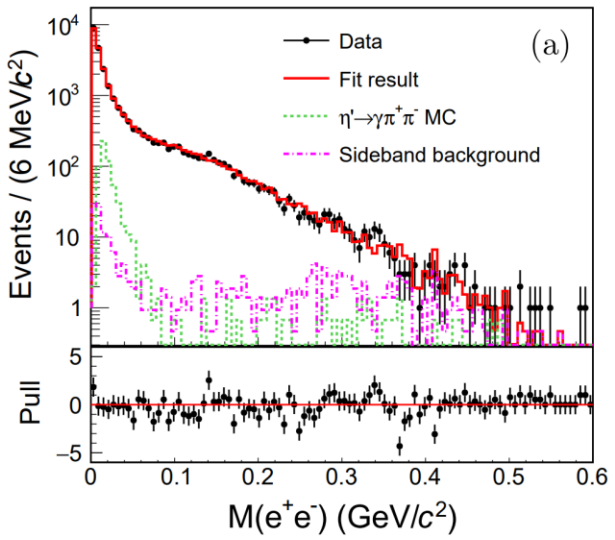
BESIII 2024

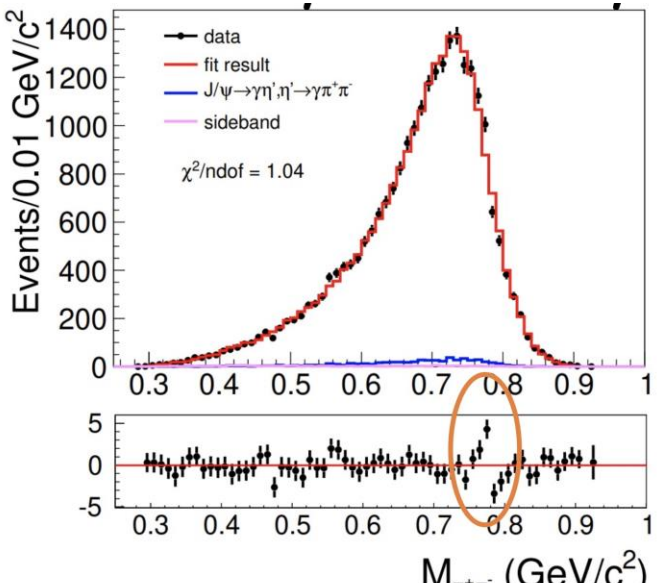
$2.45 \pm 0.02 \pm 0.08$ $\quad$ $2.16 \pm 0.12 \pm 0.06$

	$\mathcal{B}(\eta' \to \pi^+\pi^- e^+ e^-)$ (10^{-3})	$\mathcal{B}(\eta' \to \pi^+\pi^- \mu^+ \mu^-)$ (10^{-5})
Hidden gauge*	2.17 ± 0.21	2.20 ± 0.30
Unitary χPT*	$2.13^{+0.17}_{-0.31}$	$1.57^{+0.96}_{-0.75}$
VMD*	2.27 ± 0.13	2.41 ± 0.25
BESIII (2013)◇	$2.11 \pm 0.12 \pm 0.15$	< 2.9
BESIII (2021)◇	$2.42 \pm 0.05 \pm 0.08$	$1.97 \pm 0.33 \pm 0.19$
CLEO◇	$2.50^{+1.2}_{-0.9} \pm 0.5$	< 24

Amplitude analysis result of $\eta' \to \pi^+\pi^- l^+ l^-$

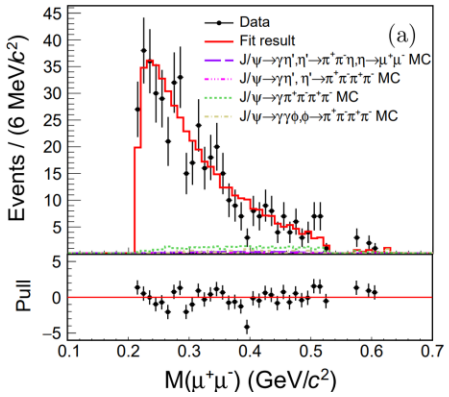
BESIII: JHEP 07, 135 (2024)

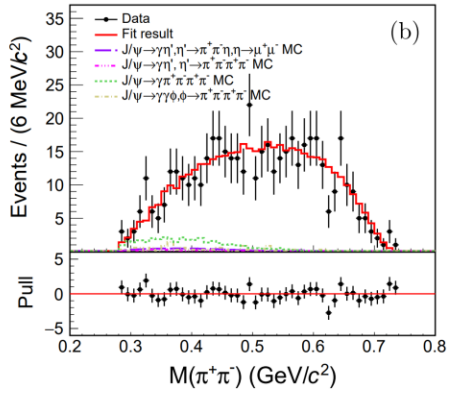


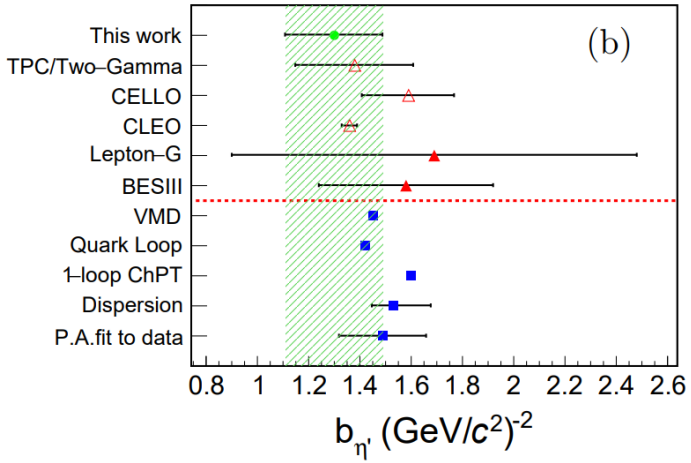


- **Box-anomaly** is needed to describe data
- $\omega \to \pi^+\pi^-$ is also necessary
- First time to assess the form factors with $\eta' \to \pi^+\pi^- l^+ l^-$ within VMD

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



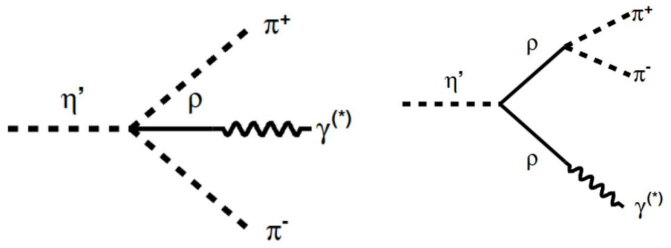




$\eta' \to \pi^+\pi^- e^+ e^-$	Model I	Model II	Model III
	$c_1 - c_2 = c_3 = 1$	$c_1 - c_2 = 1/3, c_3 = 1$	$c_1 - c_2 \neq c_3$
$m_V (\mathrm{MeV}/c^2)$	$954.3 \pm 87.8 \pm 36.4$	857.4 ± 76.5	787.5 ± 173.9
$m_{V,\pi} (\mathrm{MeV}/c^2)$	$765.3 \pm 1.2 \pm 20.2$	765.4 ± 1.2	764.8 ± 1.3
$m_\omega (\mathrm{MeV}/c^2)$	$778.7 \pm 1.3 \pm 17.3$	778.7 ± 1.3	778.7 ± 1.4
$\beta (10^{-3})$	$8.5 \pm 1.4 \pm 0.7$	8.5 ± 1.4	8.1 ± 1.5
θ	$1.4 \pm 0.3 \pm 0.1$	1.4 ± 0.3	1.4 ± 0.3
$c_1 - c_2$	1	1/3	-0.03 ± 1.09
c_3	1	1	1.03 ± 0.03
$\chi^2/ndof(e^+e^-, \pi^+\pi^-)$	77.9/82.0, 47.8/65.0	78.7/82.0, 47.6/65.0	79.4/82.0, 45.1/65.0
$b_{\eta'} (\mathrm{GeV}/c^2)^{-2}$	$1.10 \pm 0.20 \pm 0.07$	1.36 ± 0.24	1.61 ± 0.71
	Hidden gauge	Full VMD	Modified VMD

$\eta' \to \pi^+\pi^- \mu^+ \mu^-$	Model I	Model II	Model III
	$c_1 - c_2 = c_3 = 1$	$c_1 - c_2 = 1/3, c_3 = 1$	$c_1 - c_2 \neq c_3$
$m_V (\mathrm{MeV}/c^2)$	$649.4 \pm 55.9 \pm 35.6$	601.6 ± 25.7	589.6 ± 25.9
$m_{V,\pi} (\mathrm{MeV}/c^2)$	$757.3 \pm 24.1 \pm 18.0$	765.4 ± 18.8	774.4 ± 43.5
$c_1 - c_2$	1	1/3	0.01 ± 0.45
c_3	1	1	0.98 ± 0.40
$\chi^2/ndof(\mu^+\mu^-, \pi^+\pi^-)$	48.1/34.0, 32.9/46.0	48.3/34.0, 32.9/46.0	49.7/35.0, 32.4/46.0
$b_{\eta'} (\mathrm{GeV}/c^2)^{-2}$	$2.37 \pm 0.41 \pm 0.27$	2.76 ± 0.24	2.88 ± 0.25

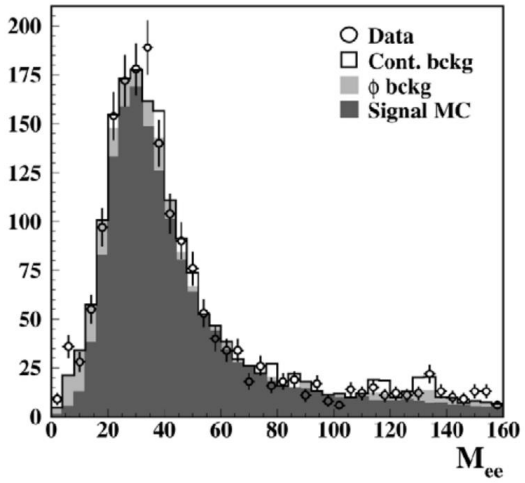
Study of $\eta \to \pi^+\pi^- l^+ l^-$

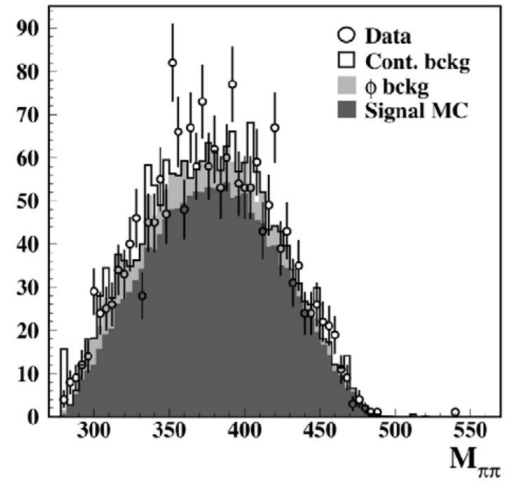


KLOE: PLB 675 (2009) 283

- KLOE: $L_{int} \sim 1.7\ fb^{-1}$ @ $\sqrt{s} = M\phi$

	$\mathcal{B}(\eta \to \pi^+\pi^- e^+ e^-)$ (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]	$2.68 \pm 0.09 \pm 0.07$	...



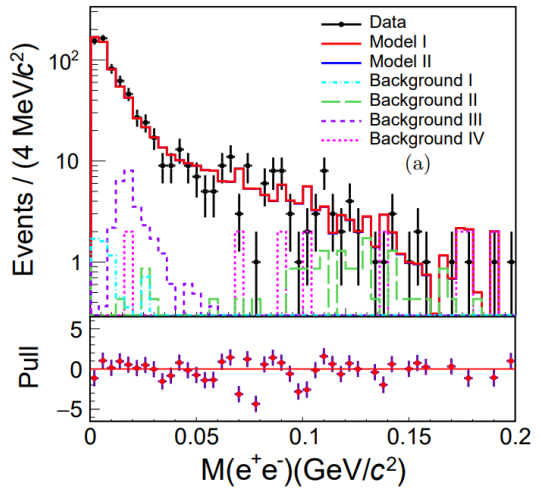


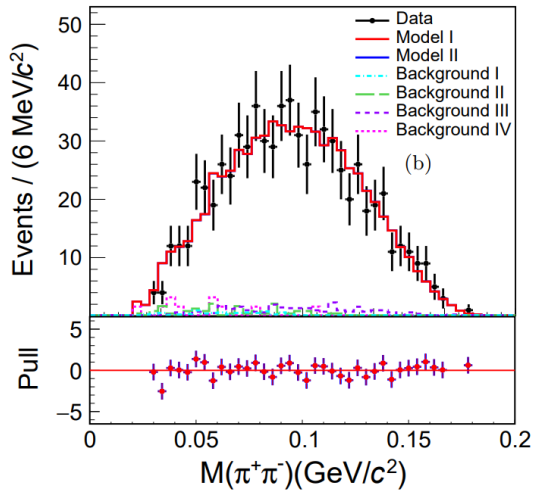
- BESIII: 10 billion J/ψ radiative decays

$$Br(\eta \to \pi^+\pi^- e^+ e^-) = (3.07 \pm 0.12 \pm 0.19) \times 10^{-4}$$

- Allow to access decay dynamic but with limited statistics
- No event left in for $\pi^+\pi^-\mu^+\mu^-$ hypothesis in η region

$$Br(\eta \to \pi^+\pi^- \mu^+ \mu^-) < 4.0 \times 10^{-4} \text{ at } 90\% \text{ CL.}$$



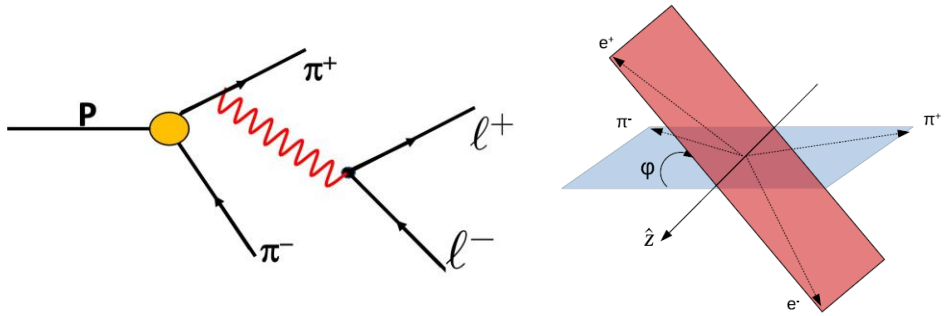


BESIII: arXiv:2501.10130v1

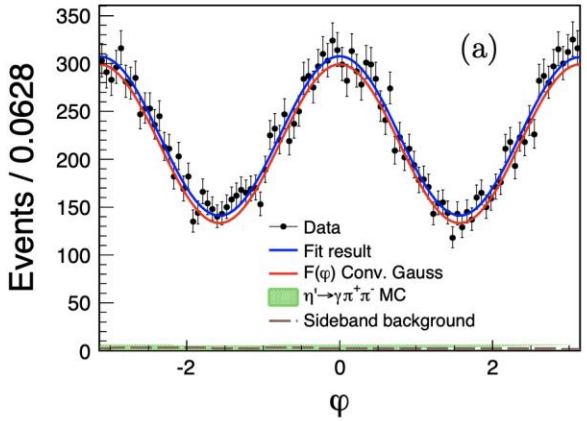
Asymmetry in $\eta^{(\prime)} \to \pi^+\pi^- l^+ l^-$

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

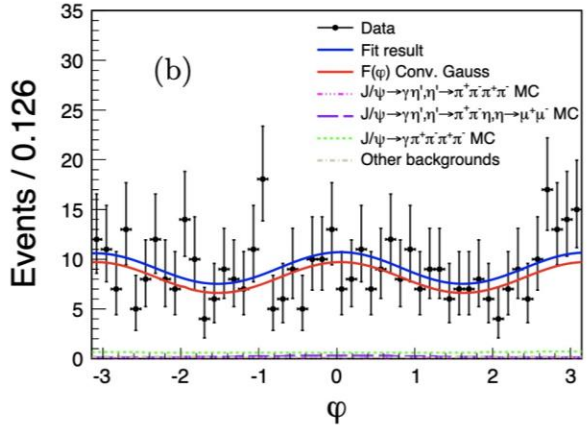


$\eta' \to \pi^+\pi^- e^+ e^-$



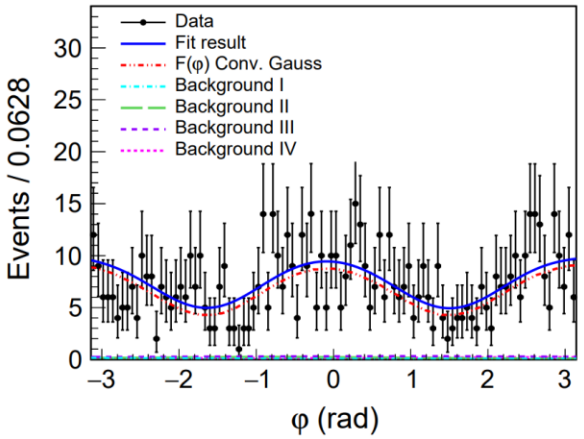
$A_{CP} = (-0.21 \pm 0.73 \pm 0.01)\%$

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



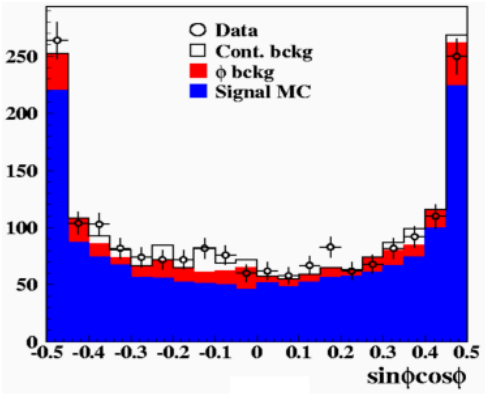
$A_{CP} = (0.62 \pm 4.71 \pm 0.08)\%$

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



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

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



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

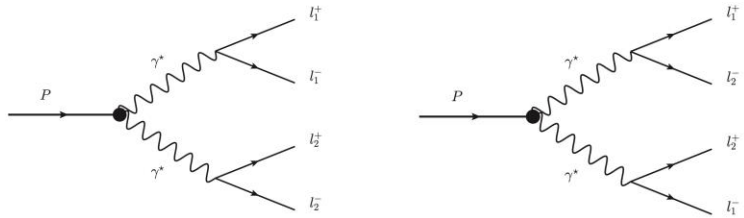
BESIII: JHEP 07, 135 (2024)

BESIII: arXiv:2501.10130v1

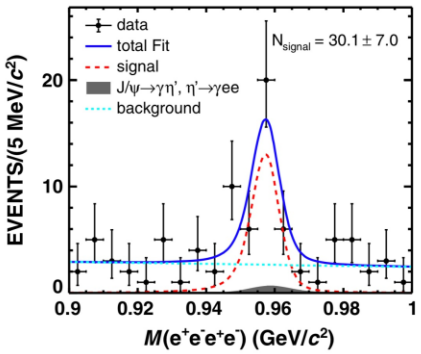
KLOE: PLB 675 (2009) 283

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

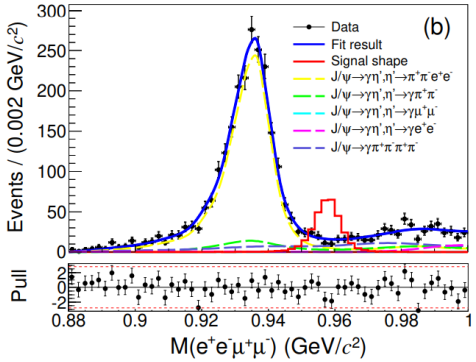
Double Dalitz decays $\eta/\eta' \to l^+l^-l^+l^-$



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

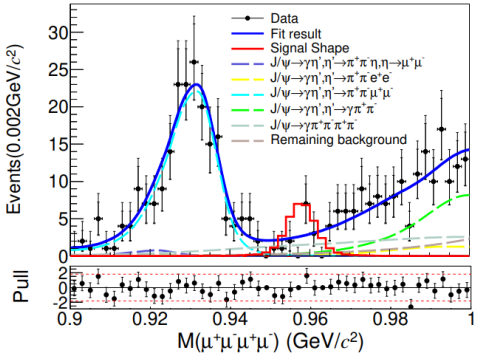


$\eta' \to e^+e^-\mu^+\mu^-$



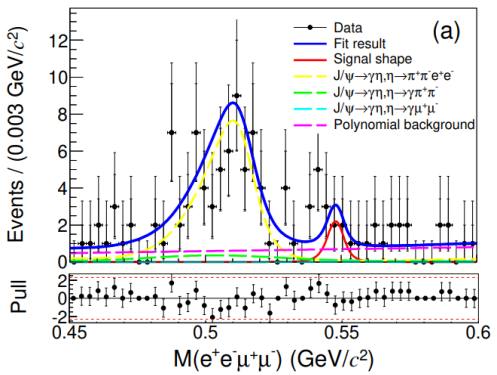
BESIII: PRD105,112010 (2022)

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

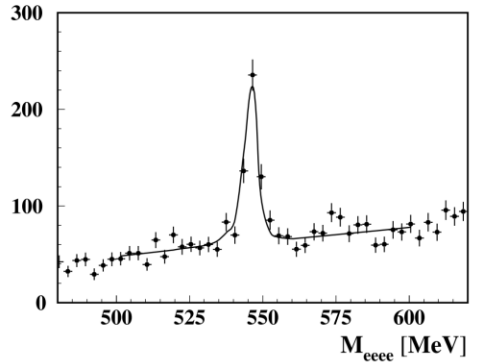


BESIII: PRD111,052002 (2025)

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



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



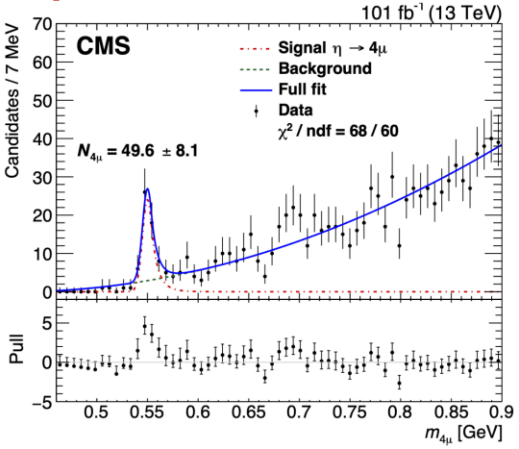
KLOE: PLB 702 (2011) 324

- Statistics limited !

Decay	Hidden gauge [9]	Modified VMD [9]	Data driven approach [10]	Experimental result
$\eta \to e^+e^-e^+e^-$	$2.680(13) \times 10^{-5}$	$2.668(13) \times 10^{-5}$	$2.17(2) \times 10^{-5}$	$2.40(22) \times 10^{-5}$ [11]
$\eta' \to e^+e^-e^+e^-$	$2.384(4) \times 10^{-6}$	$2.317(4) \times 10^{-6}$	$2.10(45) \times 10^{-6}$	$4.5(1) \times 10^{-6}$ [12]
$\eta \to \mu^+\mu^-\mu^+\mu^-$	$3.992(27) \times 10^{-9}$	$3.797(26) \times 10^{-9}$	$3.98(15) \times 10^{-9}$	$5.0(8) \times 10^{-9}$ [13]
$\eta' \to \mu^+\mu^-\mu^+\mu^-$	$2.360(12) \times 10^{-8}$	$2.185(10) \times 10^{-8}$	$1.69(36) \times 10^{-8}$	$< 5.28 \times 10^{-7}$
$\eta \to e^+e^-\mu^+\mu^-$	$2.213(26) \times 10^{-6}$	$2.154(22) \times 10^{-6}$	$2.39(7) \times 10^{-6}$	$< 6.88 \times 10^{-6}$
$\eta' \to e^+e^-\mu^+\mu^-$	$8.626(33) \times 10^{-7}$	$7.968(31) \times 10^{-7}$	$6.39(91) \times 10^{-7}$	$< 1.75 \times 10^{-6}$

T. Petri, arXiv:1010.2378 CPC 42 (2018) 023109

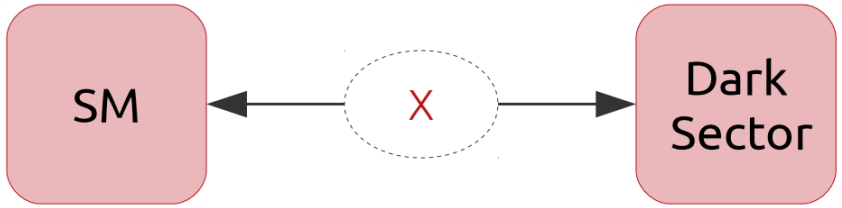
$\eta \to \mu^+\mu^-\mu^+\mu^-$



CMS: PRL 131 (2023) 091903

The ULs are quite close to the SM predictions.

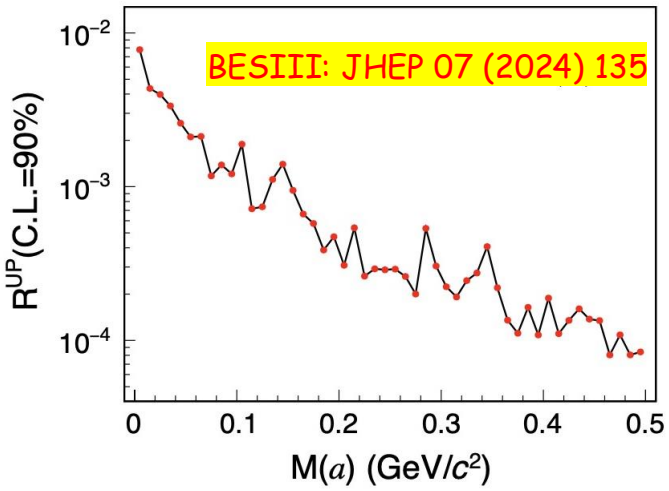
BSM Physics in Dark Sector

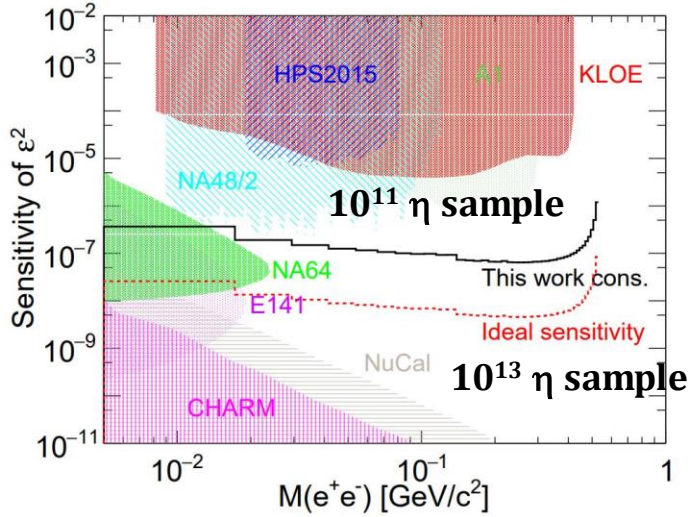


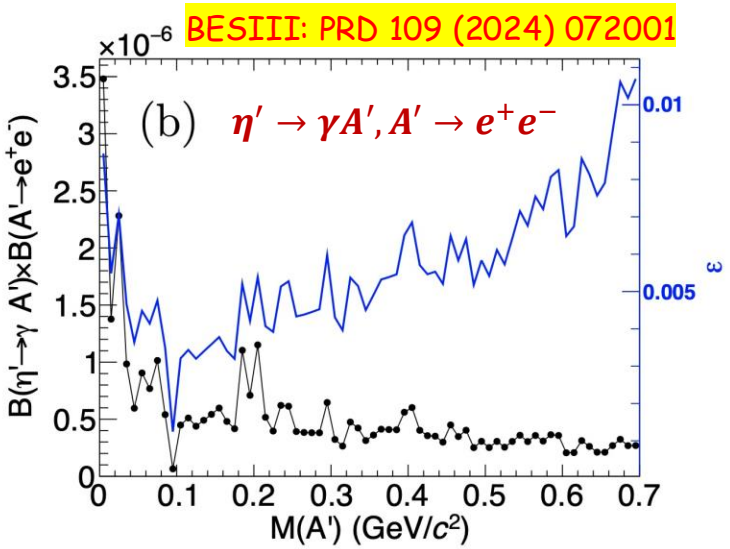
- ALPs in $\eta' \to \pi^+\pi^- a,\ a \to e^+e^-$
- Dark photon in $\eta/\eta' \to \gamma A', A' \to e^+e^-$

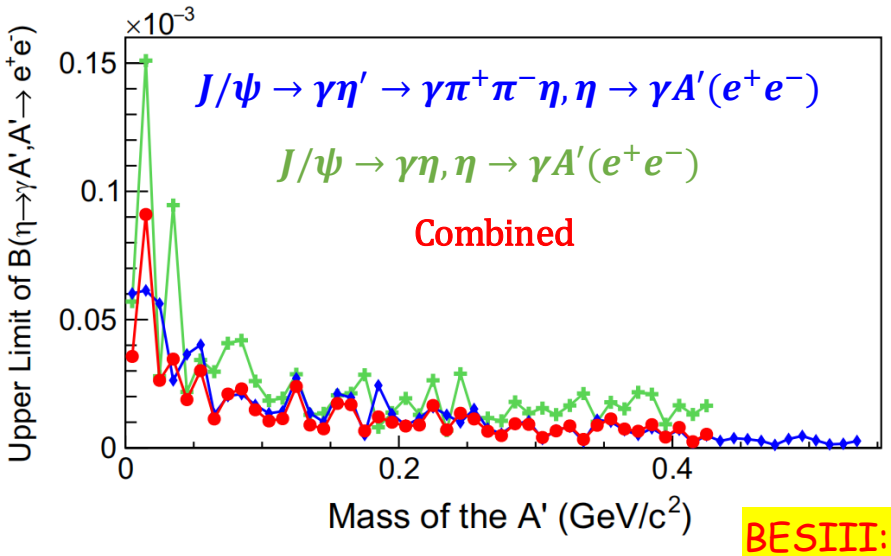
Sensitive study of dark photon in $\eta \to \gamma e^+e^-$ at HHaS arXiv:2506.11733

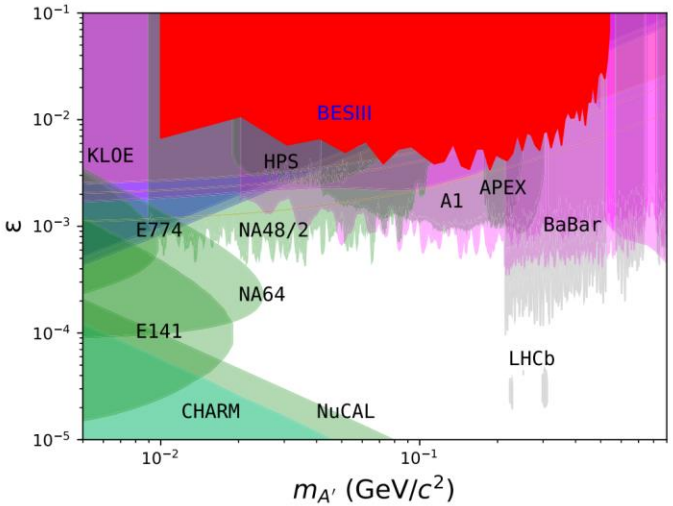
$\eta' \to \pi^+\pi^- a, a \to e^+e^-$











BESIII: PRD112, 052007 (2025)

X17 in $\eta \to \pi^+\pi^-e^+e^-$

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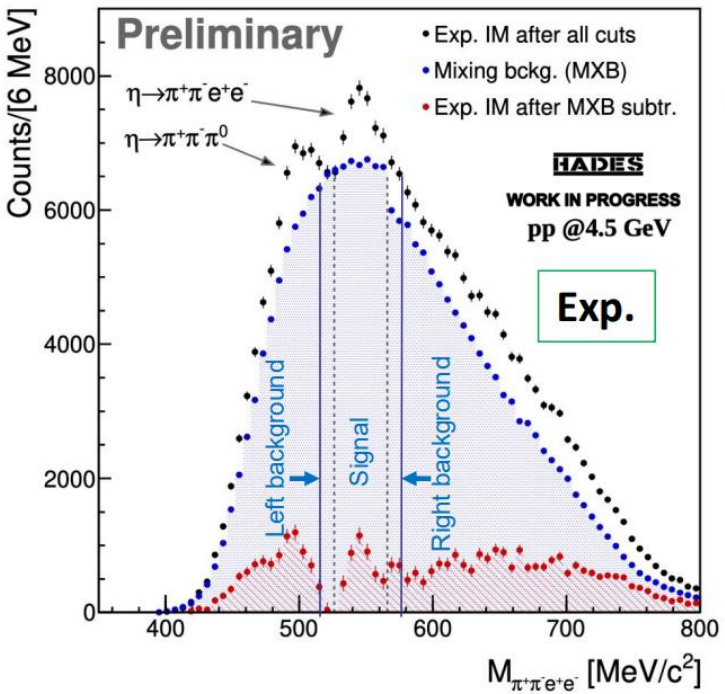
Extraction of $\eta \to \pi^+ \pi^- e^+ e^-$ signal



Estimated numer of signal events	2758
η peak mean (MeV)	548.40
η peak sigma (MeV)	32.59

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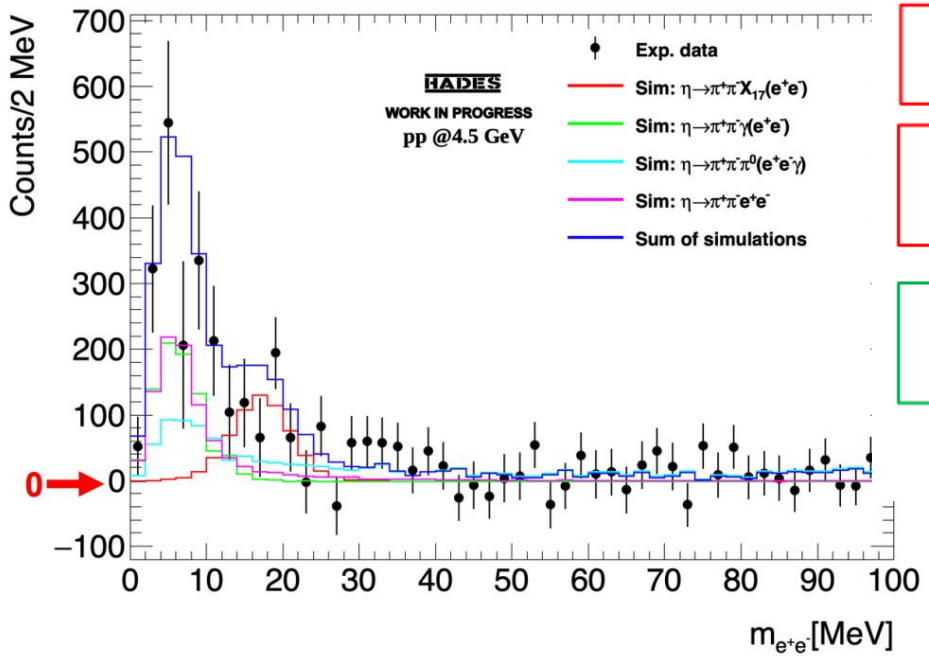
Results

- Final distribution of e^+e^- invariant mass after background subtraction
- Estimated total efficiency and acceptance factor: $1.1 \cdot 10^{-3}$



$N^{UL}_{X17} = 255$ (CL=90%)

$BR_{\eta->\pi+\pi-X17} < 2.58 \cdot 10^{-5}$

$BR^{theory}_{\eta->\pi+\pi-a} < 4 \cdot 10^{-6}$

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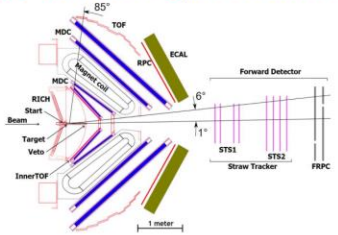
HADES - High Acceptance Di-Electron Spectrometer



February 2022 measurement:

- **proton – proton** collisions at energy of **T = 4.5 GeV** using LH_2 target
- **28 days** of measurement
- estimated total integrated luminosity **~ 5.6 [pb^{-1}]**

- **START** – T0 reaction for ToF
- **RICH** – Cherenkov detector (di-electron e^+e^-)
- **MDC and STS** – track reconstruction
- **Magnet Coil** – generates magnetic field
- **ToF & RPC** – Time-of-Flight META detectors
- **ECAL** – electromagnetic calorimeter (photons)
- **Trigger logic based on InnerToF and Meta**

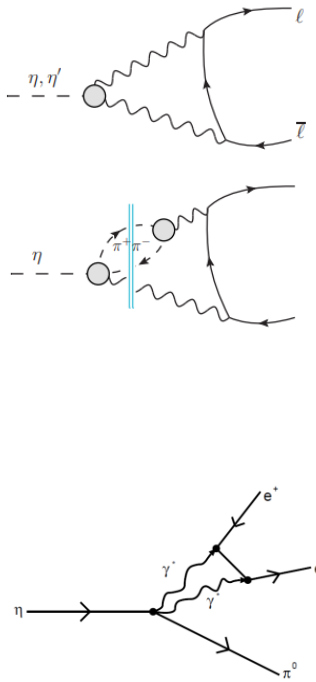
Marcin Zieliński's talk in Baryon2025

Sensitivity study of η rare decays at STCF

X. L. Kang, Y. Y. Ji, X. Q. Yuan, B. H. Xiang, et al, PRD 108 (2023) 014038

- 1 trillion J/ψ events, $\mathbf{J/\psi \to \gamma\eta', \eta' \to \pi^+\pi^-\eta}$ is used
- 5.2 billion η' inclusive decays (Pseudo-data) are simulated ~2.2x10^9 η

	SM	PDG	STCF Estimation	Comment
$\eta \to e^+e^-$	10^{-9}~10^{-10}	$< 7 \times 10^{-7}$ (SND)	$< 10^{-9}$	• Dominant by $\eta \to \gamma^*\gamma^* \to l^+l^-$ and intermediate hadronic states • fourth-order EM transition
$\eta \to \mu^+\mu^-$	10^{-6}~10^{-7}	$(5.8 \pm 0.8) \times 10^{-6}$ SPECII	$(5.88 \pm 0.09) \times 10^{-6}$	
$\eta \to \pi^+\pi^-$	~10^{-16}	$< 4.4 \times 10^{-6}$ KLOE-2	$< 7.8 \times 10^{-8}$	• P and CP violation • contribute to neutron EDM
$\eta \to \pi^0\pi^0$		$< 3.5 \times 10^{-4}$ GAMS4	$< 6.9 \times 10^{-7}$	
$\eta \to \pi^0e^+e^-$	10^{-11}~10^{-8}	$< 7.5 \times 10^{-6}$ WASA	$< 2 \times 10^{-7}$	• $\eta \to \pi^0\gamma^* \to \pi^0l^+l^-$ C-violated • $\eta \to \pi^0\gamma^*\gamma^* \to \pi^0l^+l^-$ C-conserved
$\eta \to \pi^0\mu^+\mu^-$		$< 5 \times 10^{-6}$ SPEC	$< 8.5 \times 10^{-8}$	



Conclusions

- η/η' serves as a perfect lab for SM precision test, fundamental symmetries, and probe new physics beyond SM
- Important results: decay dynamics, rare/forbidden decays, transition form factors, discrete symmetries …
- With the proposed facilities, the light meson physics will be into a precision era
- … far from enough η/η' samples

Thanks for your attention!!!