BESIII上轻介子衰变的研究进展

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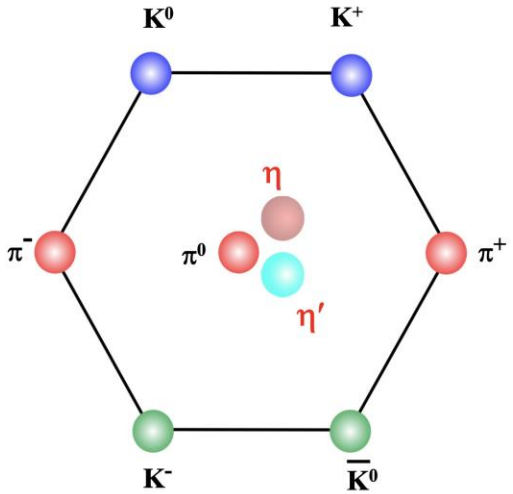

$I^G(J^{PC}) = 0^+(0^{-+})$

2025年轻强子专题研讨会

河南 安阳

5月8日-12日

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

η' Physics

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- C, CP violations
- P, CP violations
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BSM Physics in Dark Sector:
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- 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
$\eta' \to \pi^+\pi^-e^+e^-$	$2.4\left(^{+1.3}_{-1.0}\right) \times 10^{-3}$	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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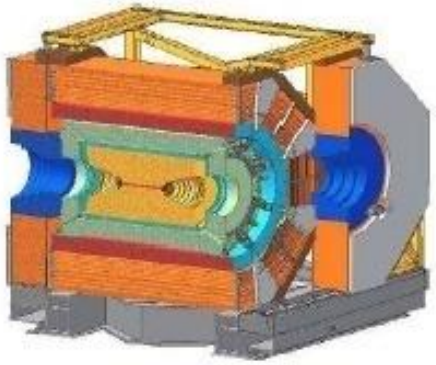
Source of η/η' events

New Proposals

e^+e^- Collider

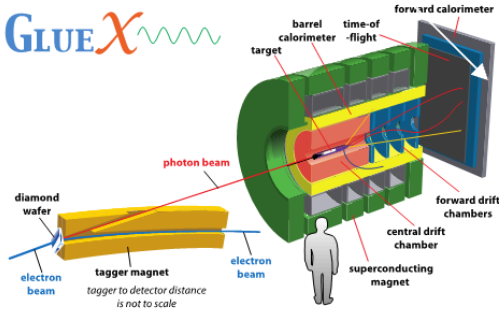
BESIII at BEPCII



KLOE-2

Fixed-target

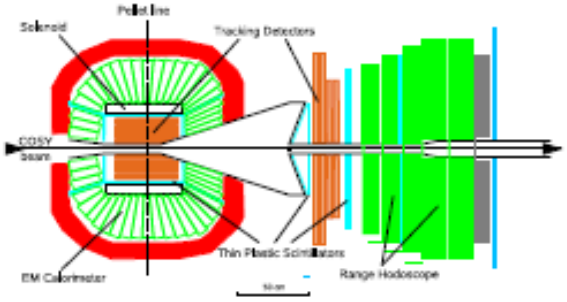
JEF at JLab



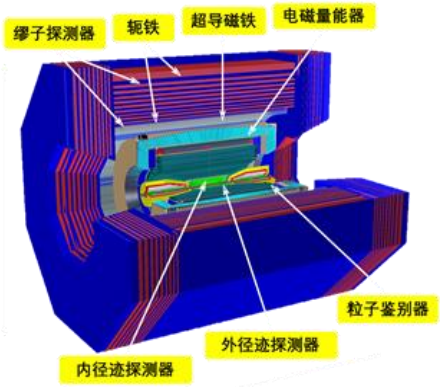
CLAS(12)

Crystal Ball

WASA at COSY

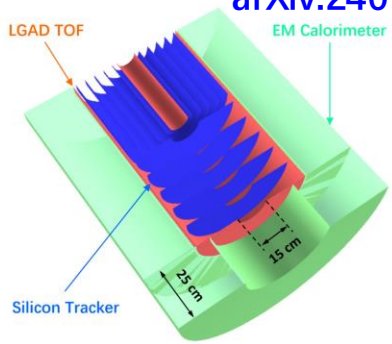


STCF

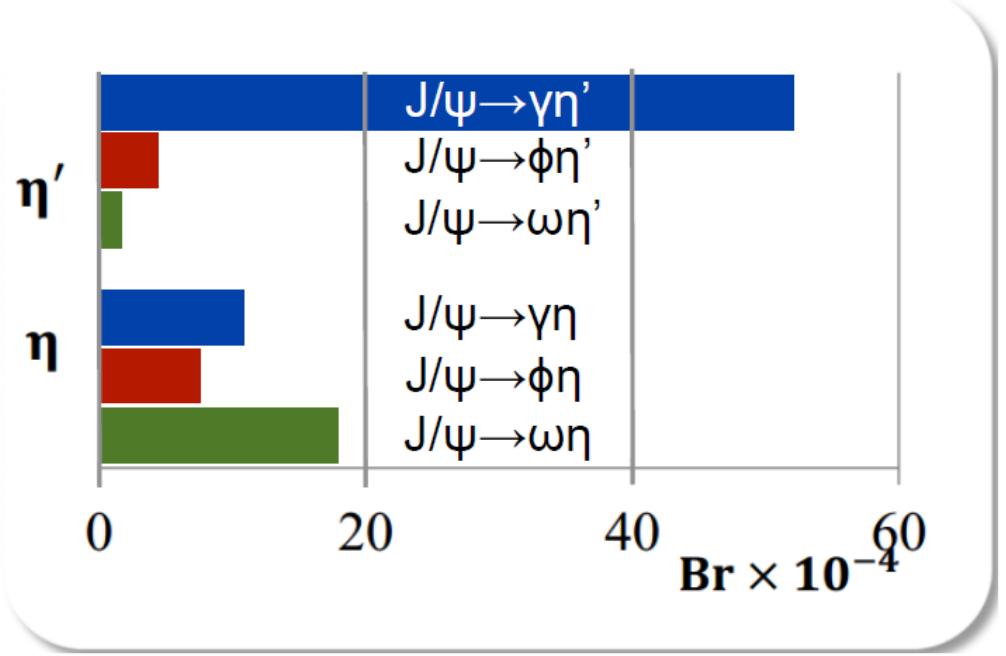


η factory at HIAF

arXiv:2407.00874



η/η′ sample from J/ψ decays at BESIII



- 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
- Unique opportunity to investigate the decays of η/η′

$\eta' \to \pi^+\pi^-\eta \to 2.2\times10^7\ \eta$

BESIII: an important role in η/η′ decays

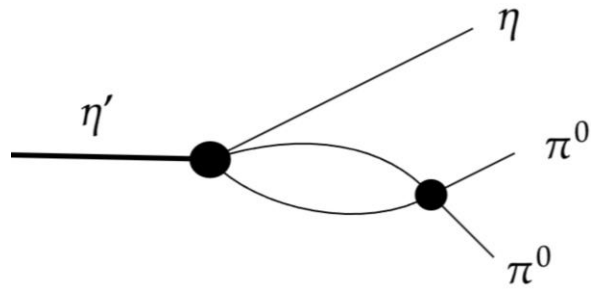
Decay channel	Physics	Publication
$\eta\to\pi^+\pi^-\pi^0$, $\eta/\eta'\to\pi^0\pi^0\pi^0$	Matrix elements, m_u-m_d, C-inv	PRD92, 012014(2015)
$\eta'\to\omega e^+e^-$	First observation, BR	PRD92, 051101(2015)
$\eta'\to K\pi$	Weak decay, UL	PRD93, 072008 (2016)
$\eta'\to\rho\pi$	First observation, BR	PRL118, 012001(2017)
$\eta'\to\gamma\gamma\pi^0$	BR, B boson	PRD96, 012005(2017)
$\eta'\to\gamma\pi^+\pi^-$	BR, decay dynamic (box anomaly)	PRL120, 242003(2018)
$\eta'\to\pi^+\pi^-\eta$, $\eta'\to\pi^0\pi^0\eta$	Matrix elements, cusp effect	PRD97, 012003(2018)
$\omega\to\pi^+\pi^-\pi^0$	Dalitz plot analysis	PRD98, 112007(2018)
$P\to\gamma\gamma$	BRs, chiral anomaly	PRD97, 072014(2018)
$\eta'\to\gamma\gamma\eta$	UL	PRD100, 052015(2019)
Absolute BF of η′ decays	BRs	PRL122, 142002(2019)
$\eta'\to\pi^0\pi^0\pi^0\pi^0$	CP-Vio, UL	PRD101, 032001(2020)
$\eta'\to\pi^+\pi^-e^+e^-$	BR, CP-viol assymm	PRD103, 092005(2021)
$\eta'\to\pi^+\pi^-u^+u^-$	BR, decay dynamic	PRD103, 072006(2021)
Absolute BF of η decays	BRs	PRD104, 092004(2021)
$\eta'\to e^+e^-e^+e^-$	BR, TFF	PRD105, 112010(2022)
$\eta'\to\eta\pi^0\pi^0$	Cusp effect	PRL130, 081901(2023)
$\eta\to\pi^+\pi^-\pi^0$, $\pi^0\pi^0\pi^0$	Matrix elements, cusp effect	PRD107,092007(2023)
$\eta'\to2(\pi^+\pi^-)$,$\pi^+\pi^-\pi^0\pi^0$, $2(\pi^0\pi^0)$	VMD, CP-Vio	PRD 109, 032006 (2024)
$\eta'\to\pi^+\pi^-e^+e^-$, $\pi^+\pi^-u^+u^-$	BR, decay dynamic, CP-Vio	JHEP07, 135 (2024), arXiv:2501.10130v1
$\eta/\eta'\to\gamma e^+e^-$	TFF	PRD109, 072001 (2024)
$\eta/\eta'\to l^+l^-l^+l^-$	BR, TFF	PRD111,052002 (2025)

Recent highlights of eta/eta' at BESIII

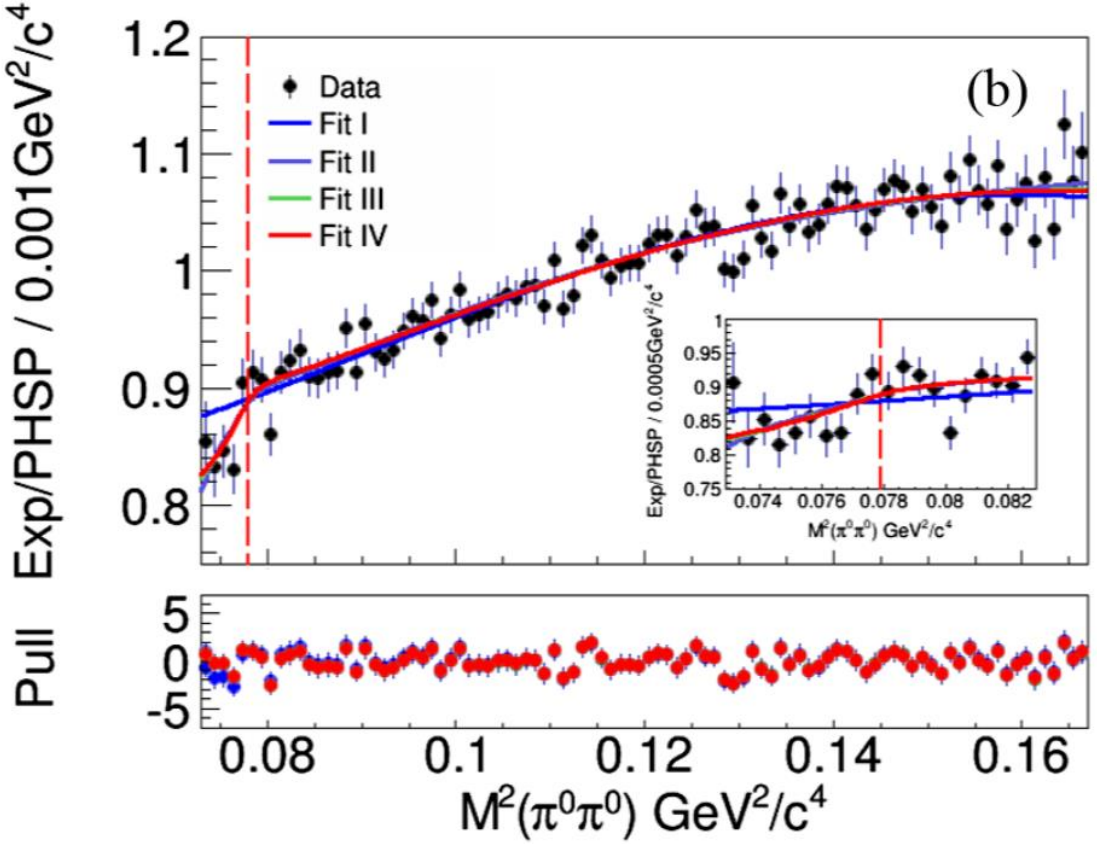
- Decay dynamics
- Transition Form Factors
- Dark force

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

BESIII: PRL130, 081901(2023)



- Investigation on ππ and πη final interactions
- The cusp effect ($\pi^+\pi^- \to \pi^0\pi^0 \to \pi^+\pi^-$) is sizable in this decay



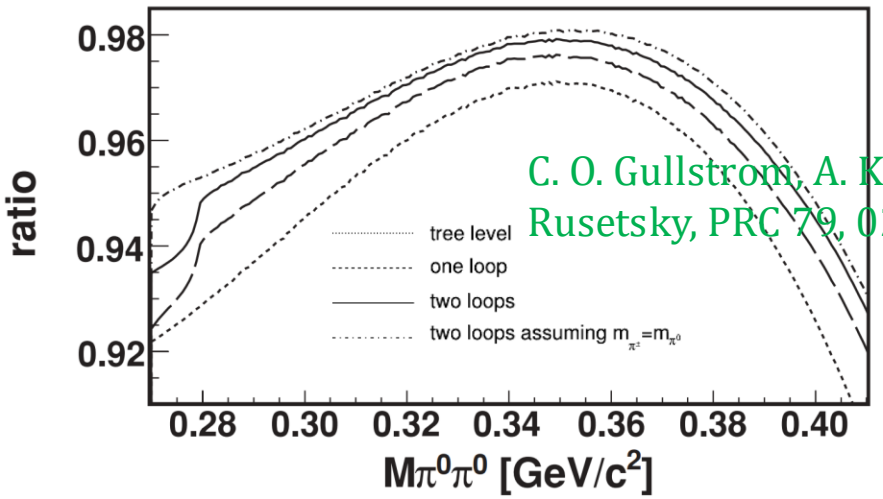
B. Kubis, S. P. Schneider, EPJC 62, 511 (2009)

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

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

- Fits at different cases
- Cusp effect with ~3.5 σ!

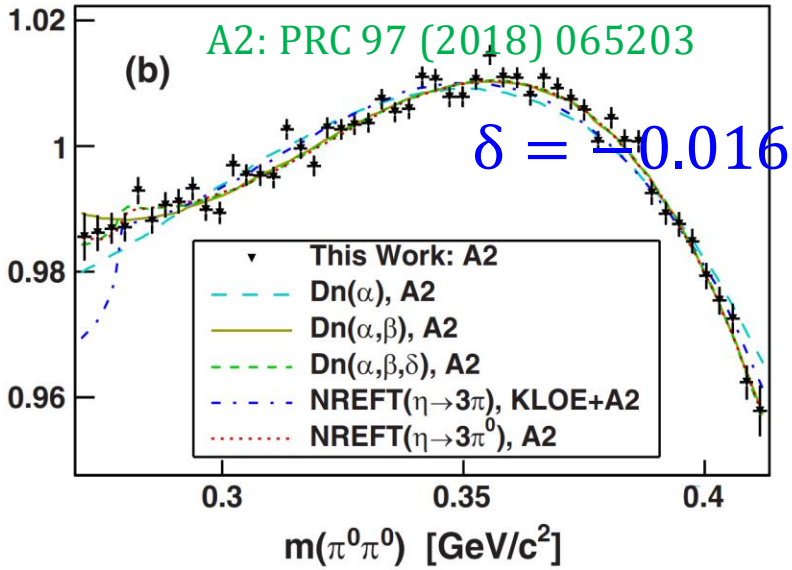
Cusp structure in $\eta \to \pi^0\pi^0\pi^0$



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

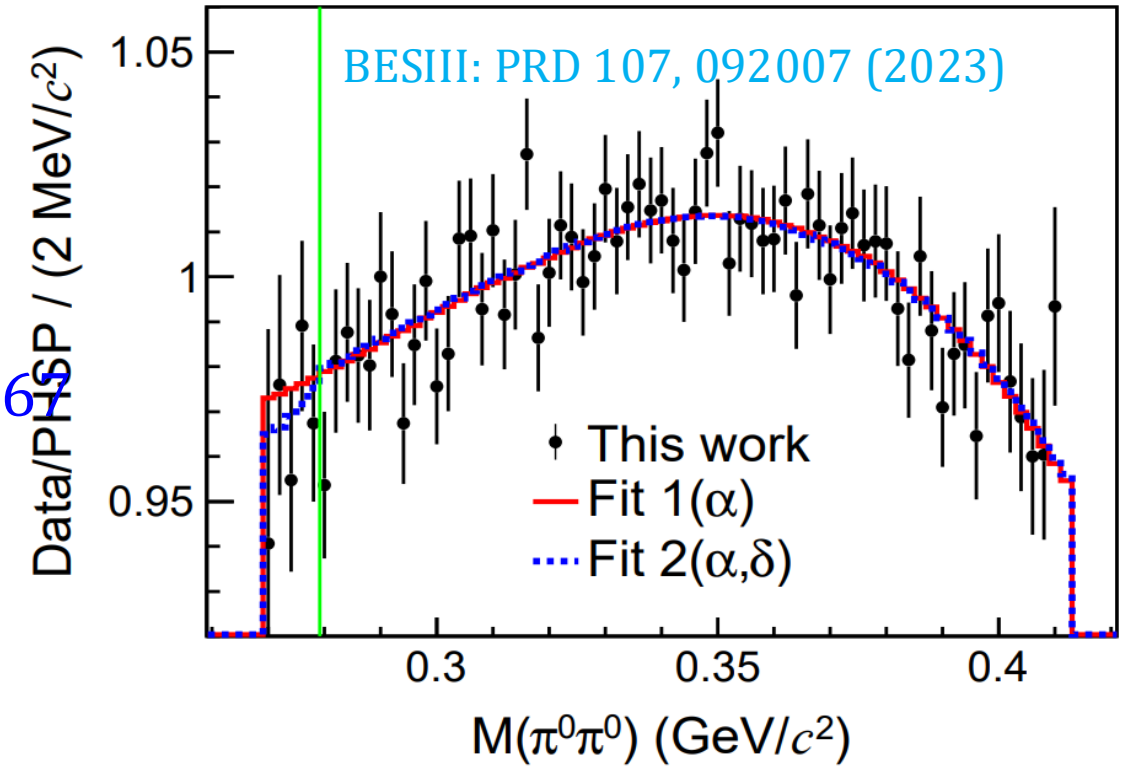
$$|A(X,Y)|^2 \propto 1 + 2\alpha Z + 2\delta \sum_{i=1}^{3} \Re\sqrt{1 - s_i/4m^2_{\pi^\pm}}$$

$\delta = -0.018 \pm 0.022_{stat.}$



A2: PRC 97 (2018) 065203

$\delta = -0.0169 \pm 0.0066$



BESIII: PRD 107, 092007 (2023)

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

BESIII: PRD 107, 092007 (2023)

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

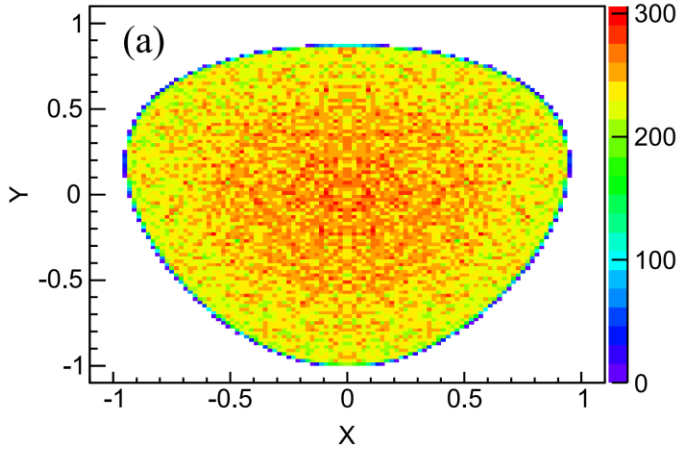
$$|A(X,Y)|^2 \propto 1 + 2\alpha Z + 2\beta(3X^2Y - Y^3) + 2\gamma Z^2 + \cdot$$

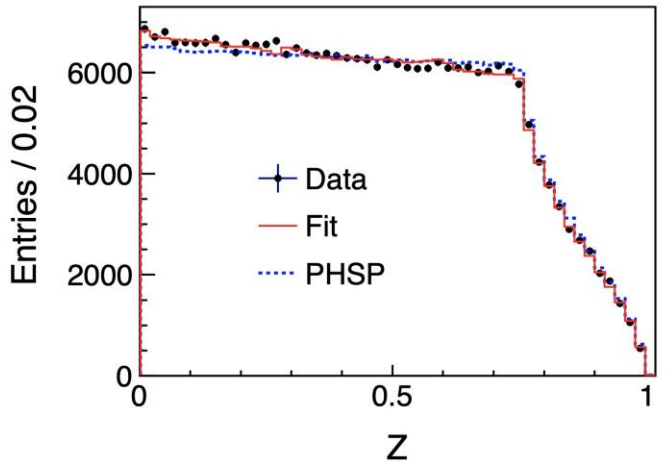
$$Z = X^2 + Y^2 = \frac{2}{3}\sum_{i=1}^{3}\left(\frac{3T_i}{Q} - 1\right)^2$$

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

$$\beta = 0.0038 \pm 0.0033_{stat.}$$

$$\gamma = -0.018 \pm 0.014_{stat.}$$

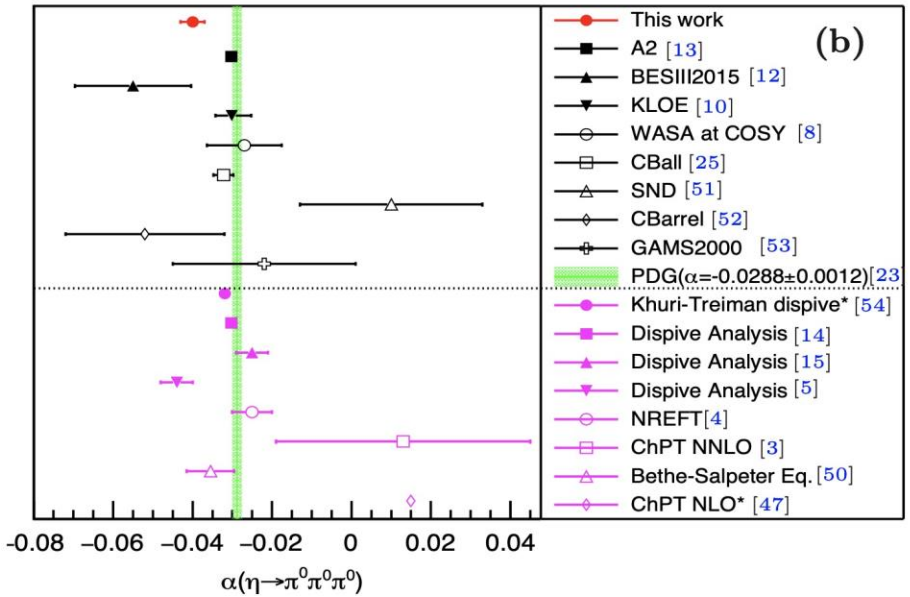




α is consistent with A2 ($-0.0302 \pm 0.0008_{stat.}$) in 2.8σ

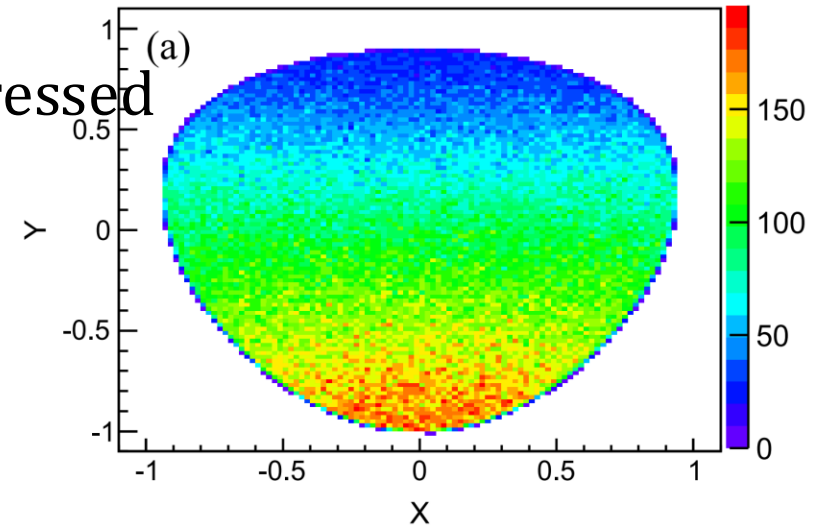
$$\beta(A_2) = -0.0070 \pm 0.0010_{stat.}$$

$$\gamma(A_2) = -0.0023 \pm 0.0040_{stat.}$$



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

BESIII: PRD 107, 092007 (2023)



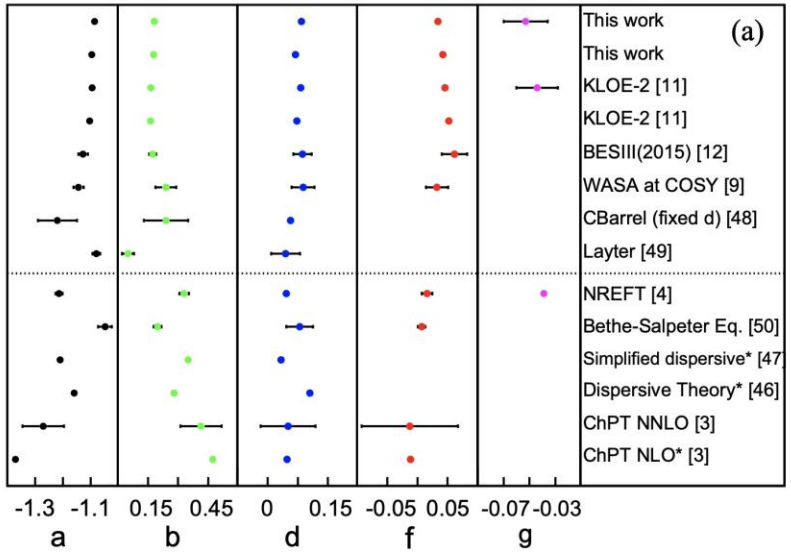
➢SM: Isospin violating process, C conserved, EM effects suppressed

⇒ ideal process to extract $m_u - m_d$

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

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

$$\begin{aligned} a &= -1.086 \pm 0.006 \pm 0.001, \\ b &= 0.162 \pm 0.006 \pm 0.003, \\ d &= 0.083 \pm 0.007 \pm 0.001, \\ f &= 0.118 \pm 0.011 \pm 0.003, \\ g &= -0.053 \pm 0.017 \pm 0.003. \end{aligned}$$



$c = (-0.086 \pm 2.986) \times 10^{-3}$, $e = -0.001 \pm 0.007$

⇒ no C symmetry breaking

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

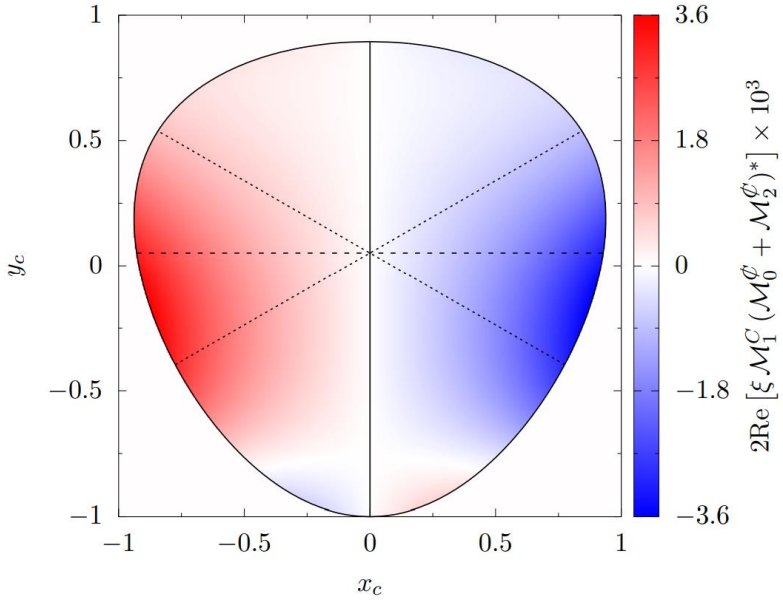
BESIII: PRD 107, 092007 (2023)

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

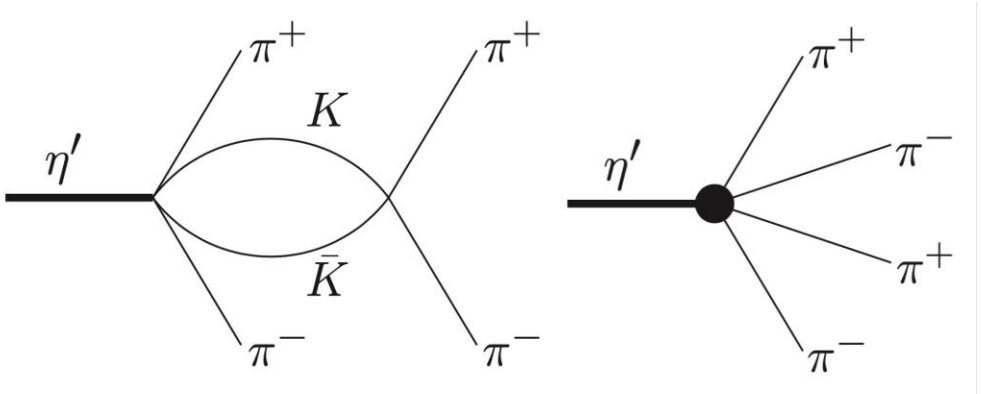


overall C/CP-violation | ΔI = 2 | ΔI = 0

Experiment	$A_{LR}(\%)$	$A_Q(\%)$	$A_S(\%)$
This work	$0.114 \pm 0.131 \pm 0.001$	$-0.035 \pm 0.131 \pm 0.011$	$-0.070 \pm 0.131 \pm 0.009$
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

Amplitude analysis for $\eta' \to 4\pi$

BESIII: PRD 109, 032006 (2024)



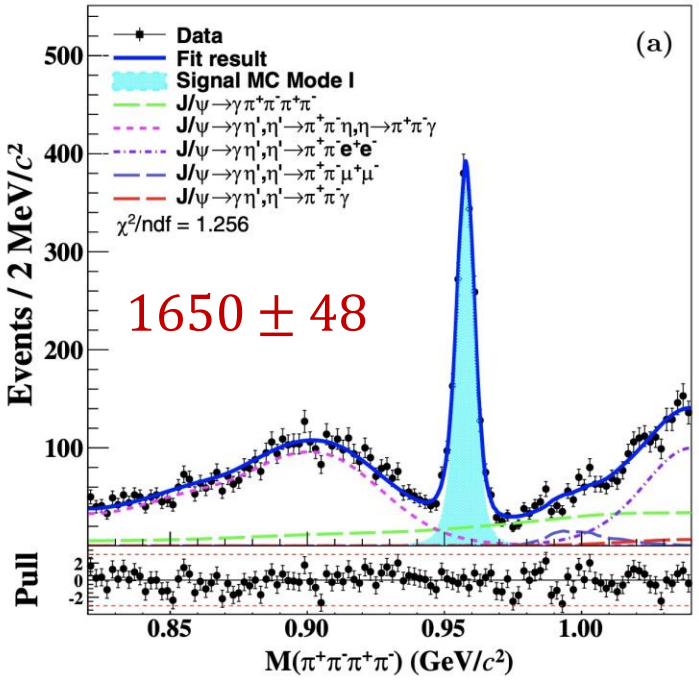
Loop and counter term at O(p^6)

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

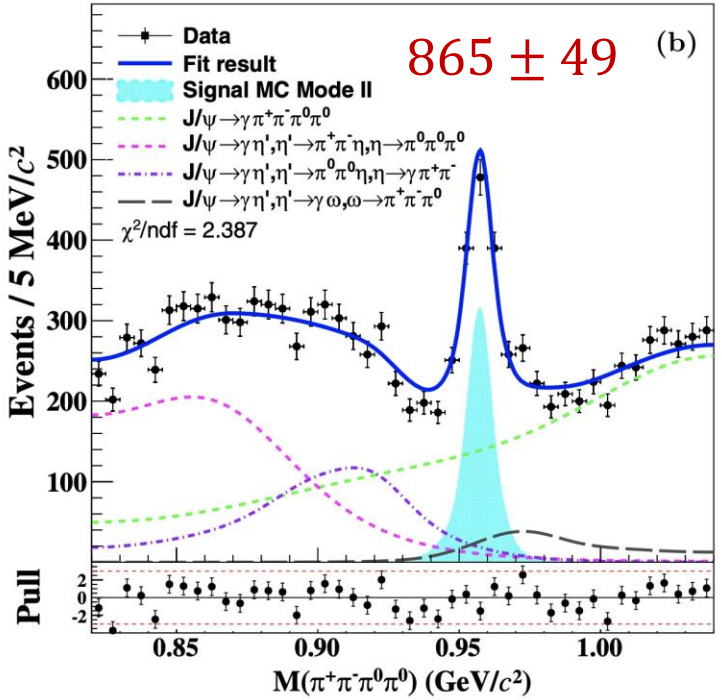
$Br(\eta' \to 2(\pi^+\pi^-)) = (1.0 \pm 0.3) \times 10^{-4}$

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

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



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



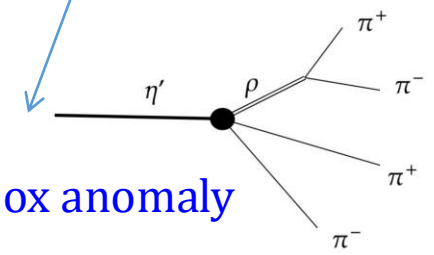
$Br(\eta' \to \pi^+\pi^-\pi^+\pi^-) = (8.56 \pm 0.25 \pm 0.23) \times 10^{-5}$

$Br(\eta' \to \pi^+\pi^-\pi^0\pi^0) = (2.12 \pm 0.12 \pm 0.10) \times 10^{-4}$

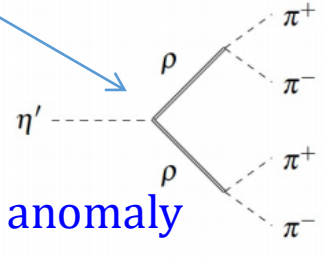
Amplitude analysis results for $\eta' \to 2(\pi^+\pi^-)$ BESIII: PRD 109, 032006 (2024)

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

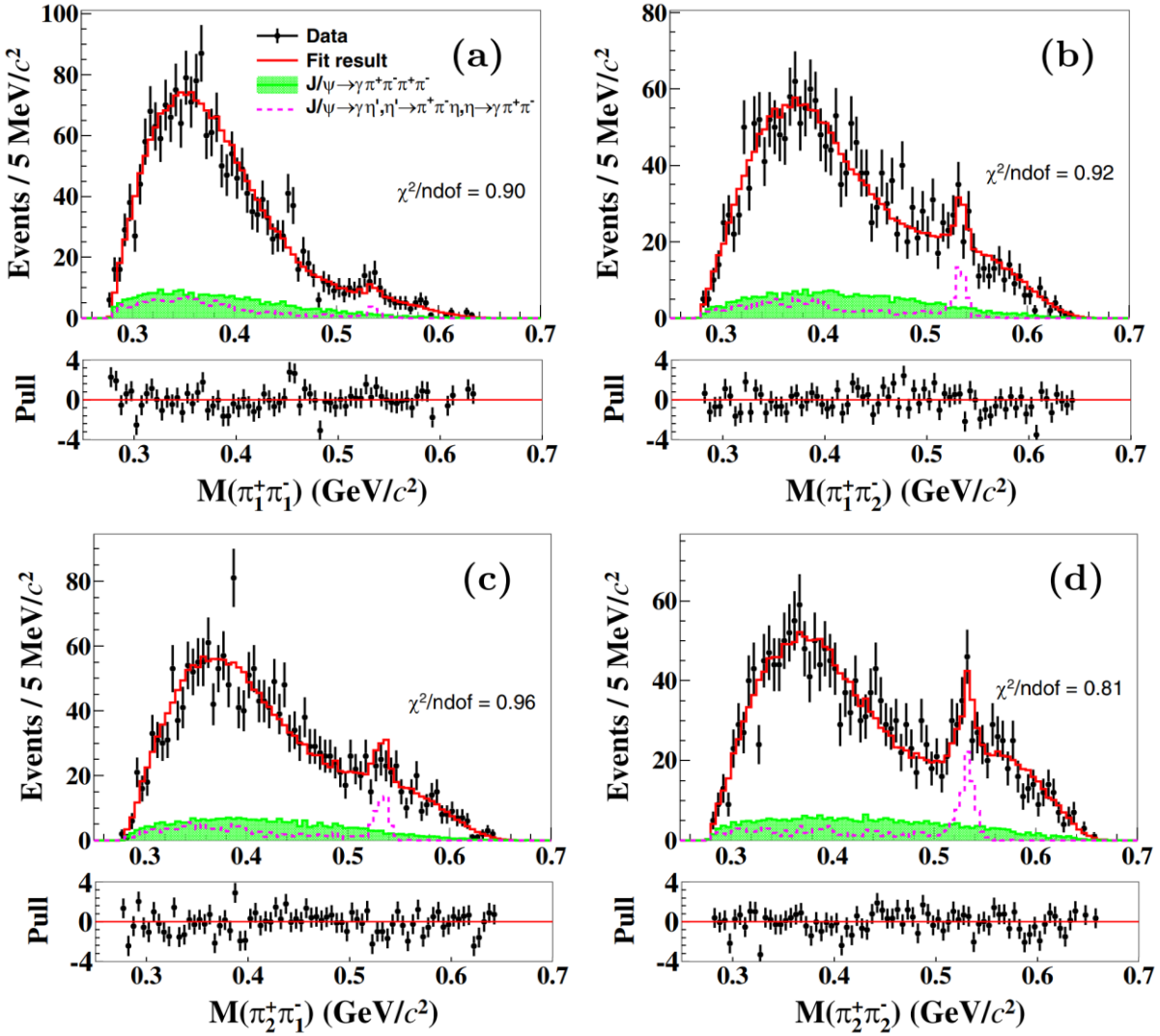


Triangle anomaly

- First measurement of the doubly virtual isovector form factor

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

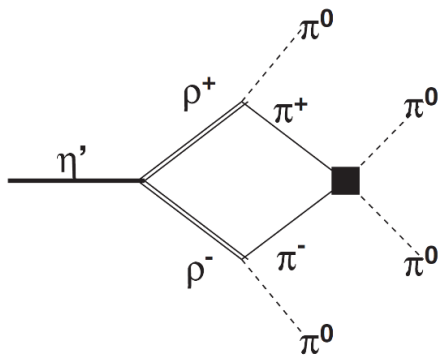
If $\alpha \simeq 1$, triangle anomaly would be dominated



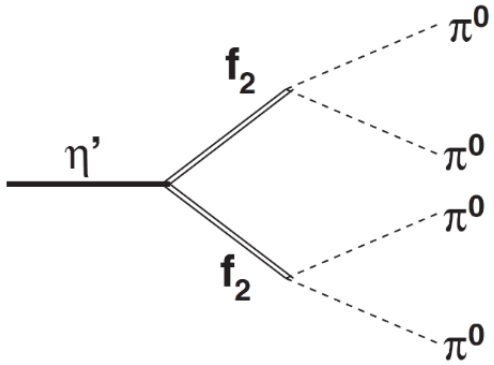
Search for rare decay $\eta' \to \pi^0\pi^0\pi^0\pi^0$

BESIII: PRD 109, 032006 (2024)

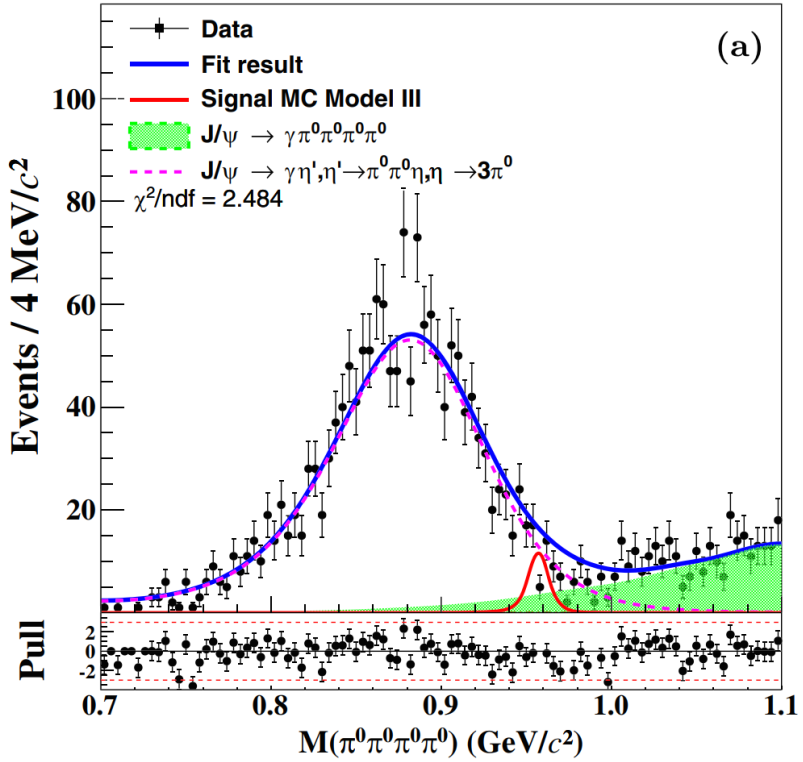
- CP-violation S-wave, induced by the QCD Lagrangian θ-term ⇒ Br~10^{-23}
- CP-conserving higher order ⇒ Br~10^{-8} F. K. Guo, B. Kubis, A. Wirzba, PRD 85,014014 (2012)



D-wave pion loop

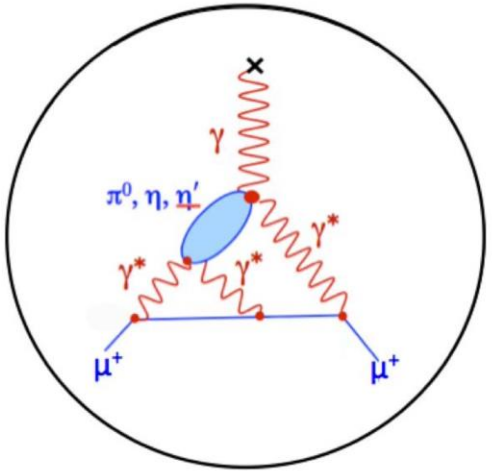


Small contribution from two f_2 tensor mesons



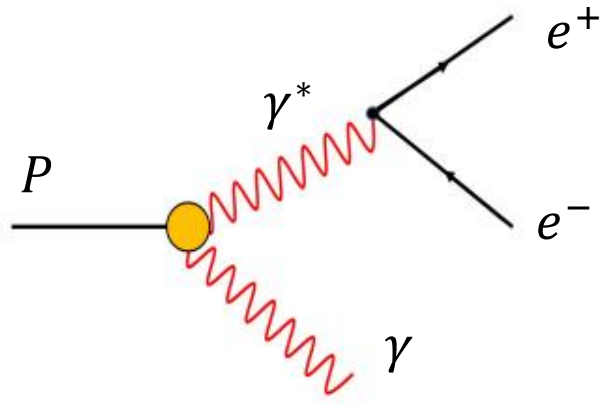
- With 10 billion J/ψ, the UL at 90% CL is set as 1.24×10^{-5}

Transition form factor of η/η'

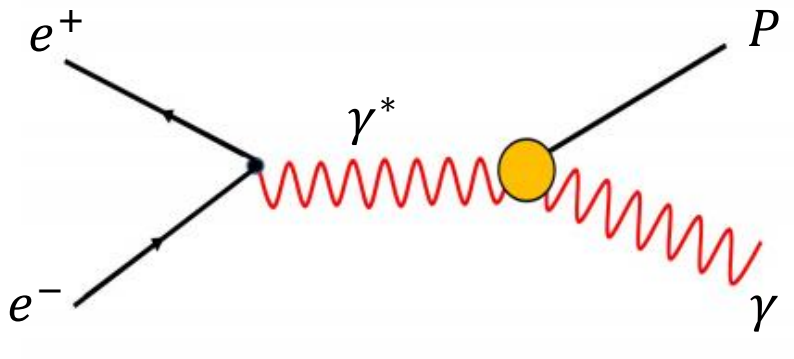


- Important input for HLbL contributions

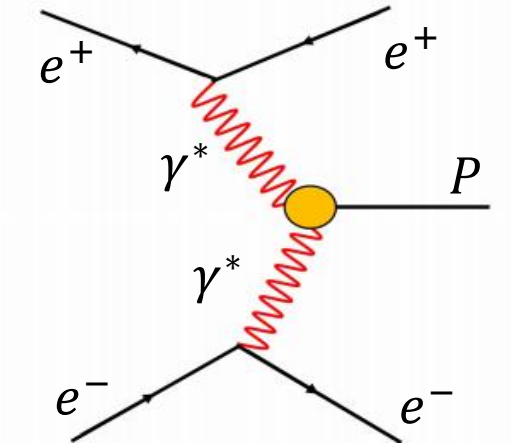
Pseudoscalar TFFs are experimentally accessible in three different processes



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



Annihilation process $q^2>M^2$

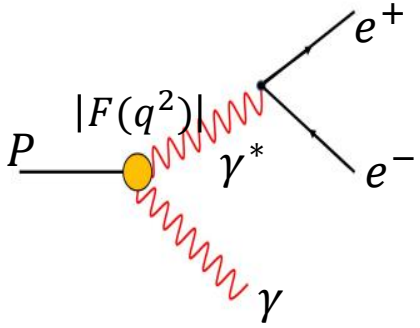


Two photon process

Transition form factor of $\eta/\eta' \to \gamma e^+e^-$

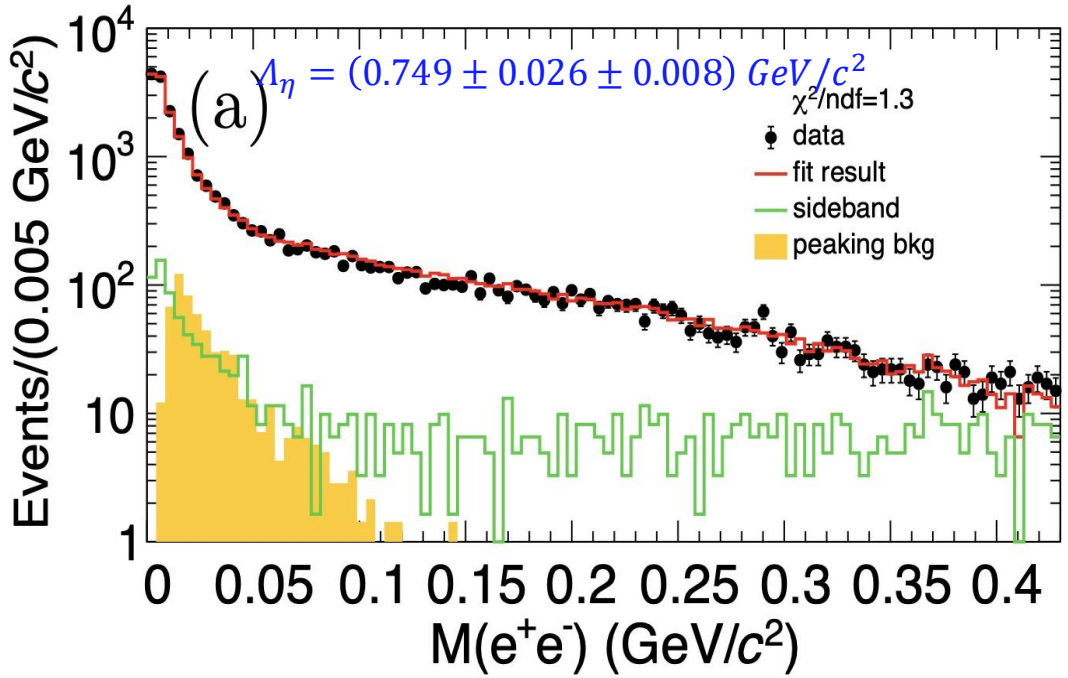
BESIII: PRD 109, 072001 (2024)

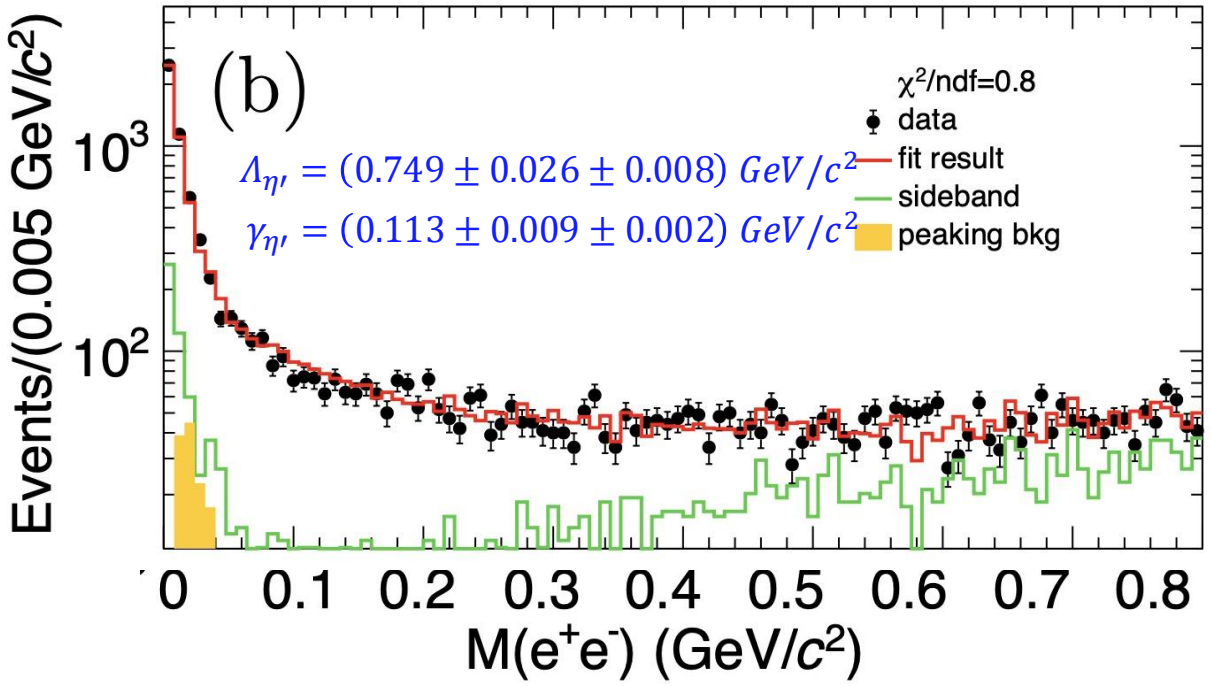
$$\frac{d\Gamma(P \to \gamma l^+ l^-)}{dq^2 \Gamma_{\gamma\gamma}} = \frac{2\alpha}{3\pi}\frac{1}{q^2}\sqrt{1-\frac{4m_l^2}{q^2}}\left(1+\frac{2m_l^2}{q^2}\right)\left(1-\frac{q^2}{M_P^2}\right)^3 |F_P(q^2,0)|^2$$



❖ $\eta \to \gamma e^+e^-$, single-pole model: $F(q^2) = \frac{1}{1-q^2/\Lambda^2}$

❖ $\eta' \to \gamma e^+e^-$, Multi-pole model: $|F(q^2)|^2 = \frac{\Lambda^2(\Lambda^2+\gamma^2)}{(\Lambda^2-q^2)^2+\Lambda^2\gamma^2}$

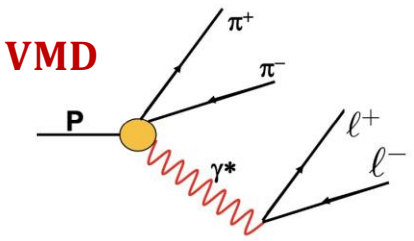




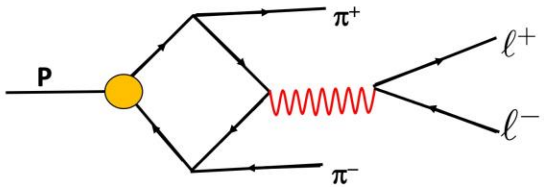
Amplitude analysis result of $\eta' \to \pi^+\pi^- l^+ l^-$ BESIII: JHEP 07, 135 (2024)

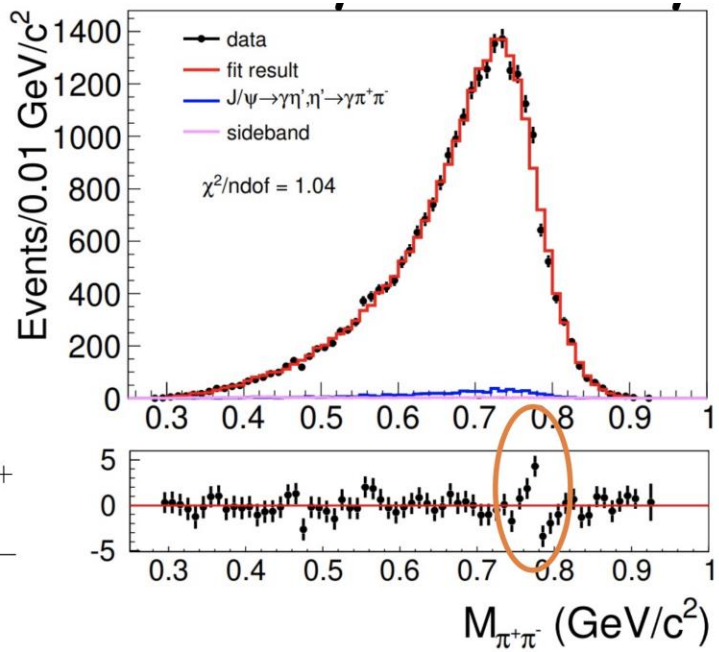
- ρ^0, box-anomaly and ω to describe data

VMD



Box-anomaly

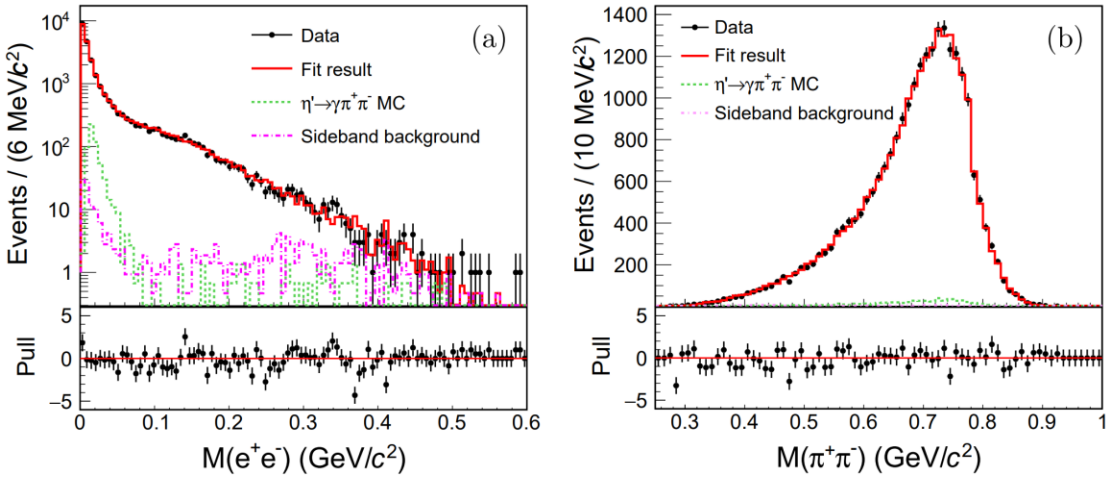




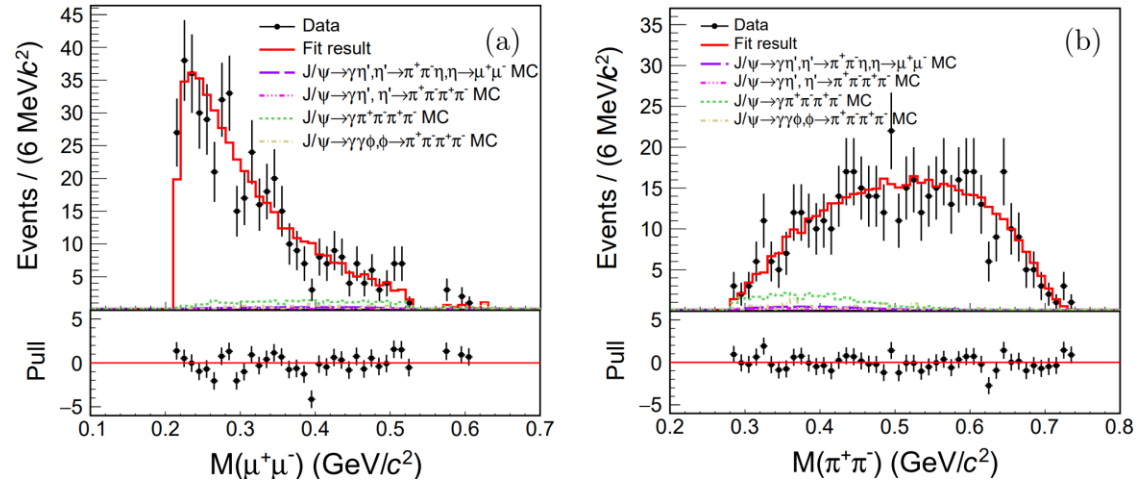
✓ First assess to FFs with $\eta' \to \pi^+\pi^- l^+ l^-$

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

$\pi^+\pi^- e^+ e^-$



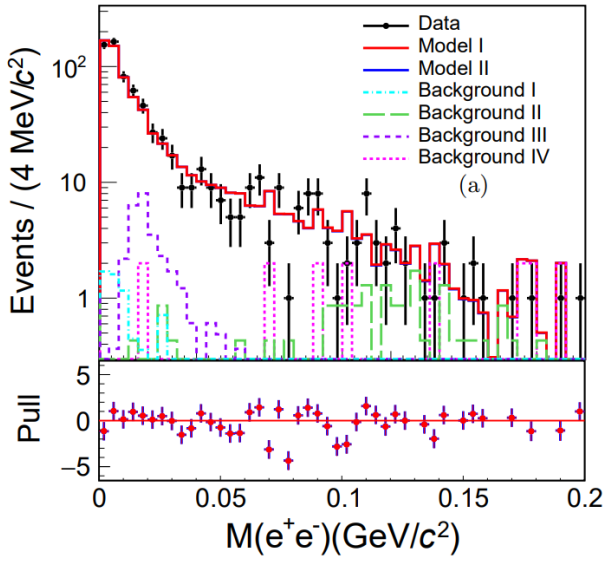
$\pi^+\pi^- \mu^+ \mu^-$

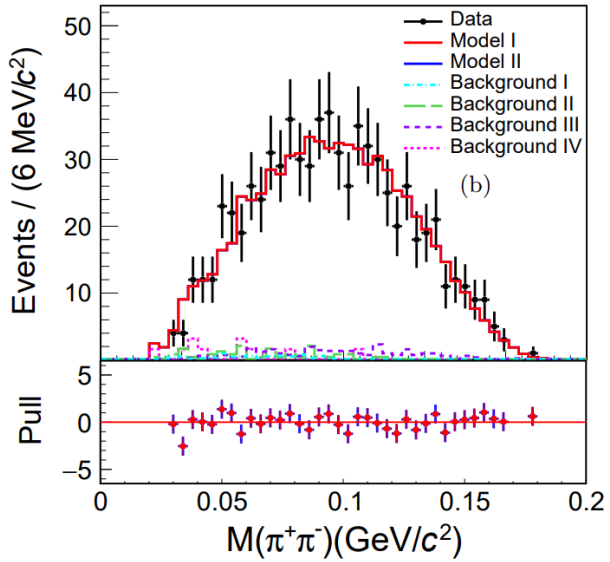


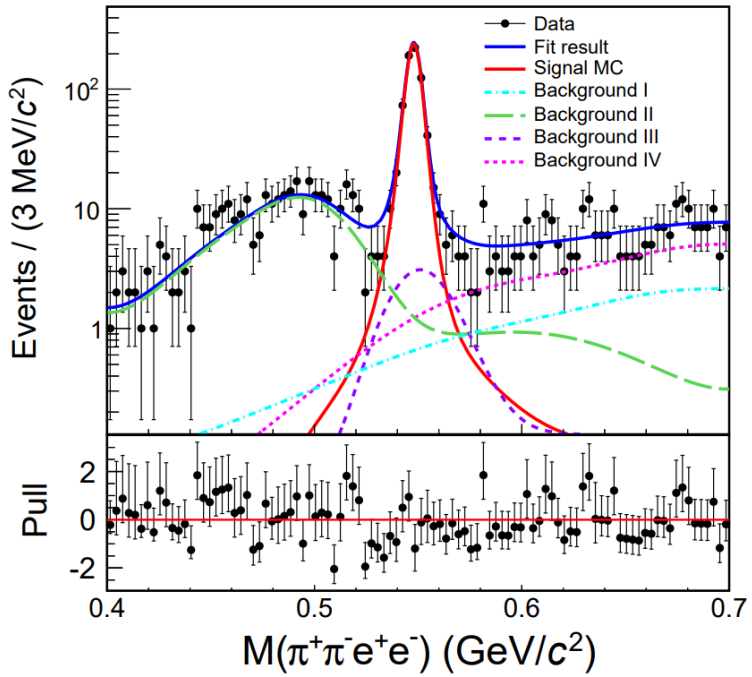
Study of $\eta \to \pi^+\pi^- l^+ l^-$

arXiv:2501.10130v1 [hep-ex] Accepted by PRD

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







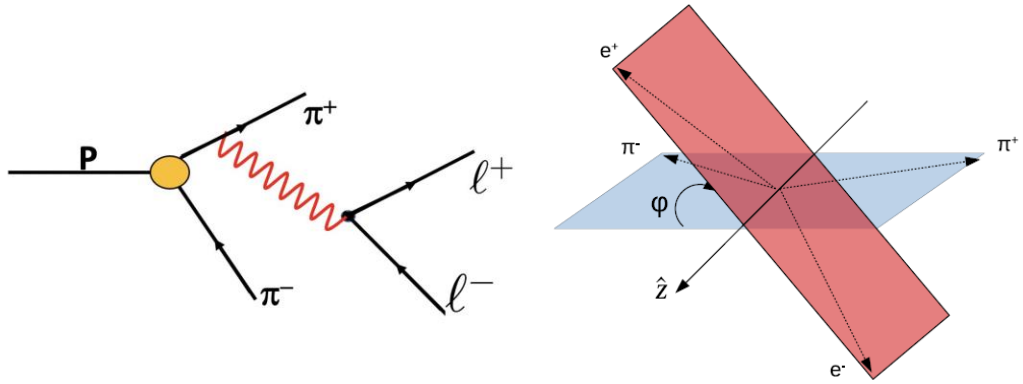
$$Br(\eta \to \pi^+\pi^- e^+ e^-) = (3.07 \pm 0.12 \pm 0.19) \times 10^{-4}$$

- Allow to access the decay dynamic but with limited statistics
- No event left in for $\pi^+\pi^-\mu^+\mu^-$ hypothesis in η signal region and the UL is set as 4.0×10^{-7} at the 90% CL.

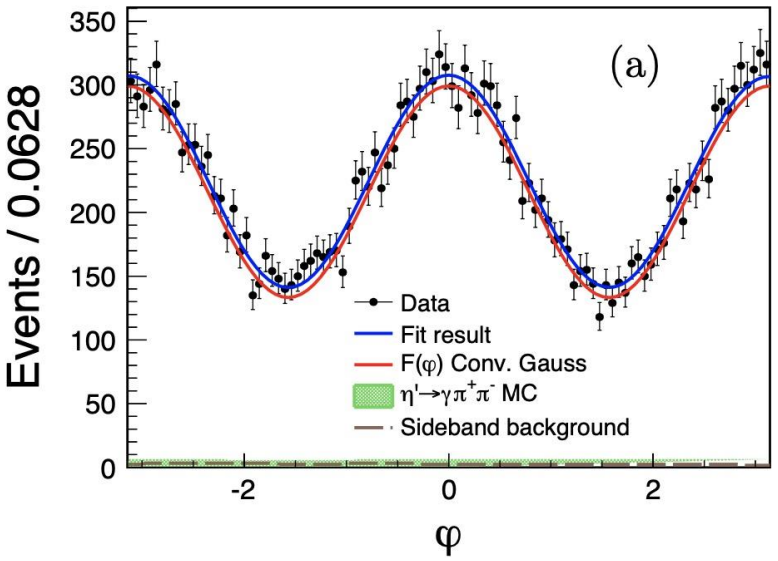
CP Asymmetry in $\eta/\eta' \to \pi^+\pi^- l^+ l^-$

JHEP 07, 135 (2024), arXiv:2501.10130v1

- A new sources of CP violation beyond the CKM phase and outside flavor-changing processes

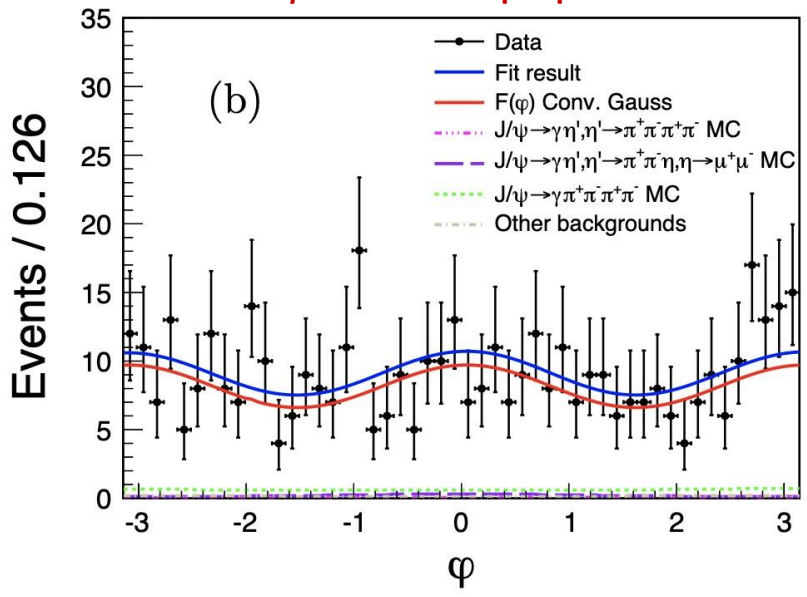


$\eta' \to \pi^+\pi^- e^+ e^-$



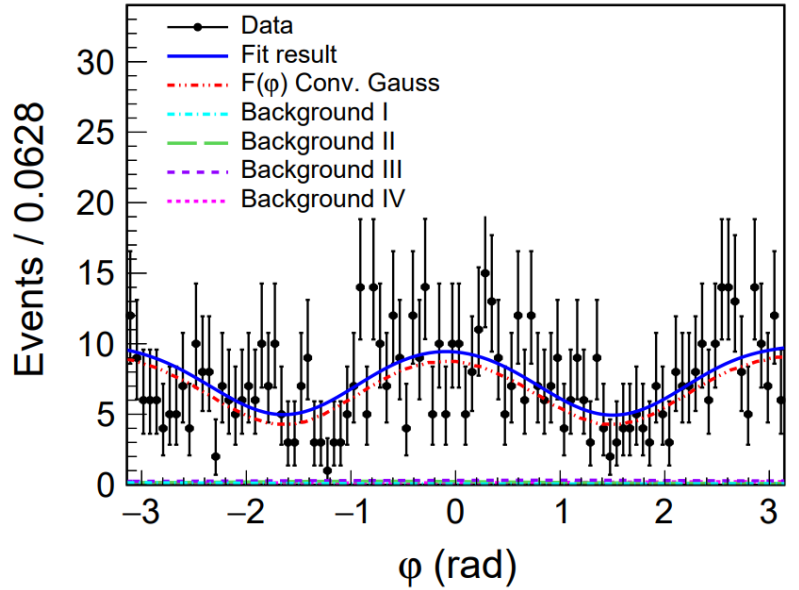
$A_{CP} = (-0.21 \pm 0.73 \pm 0.01)\%$

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



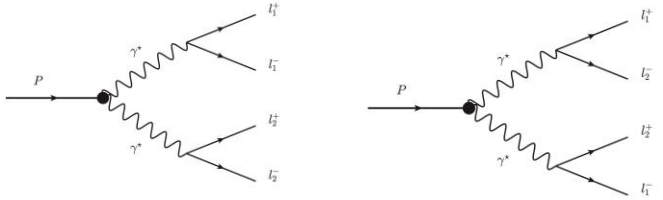
$A_{CP} = (0.62 \pm 4.71 \pm 0.08)\%$

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

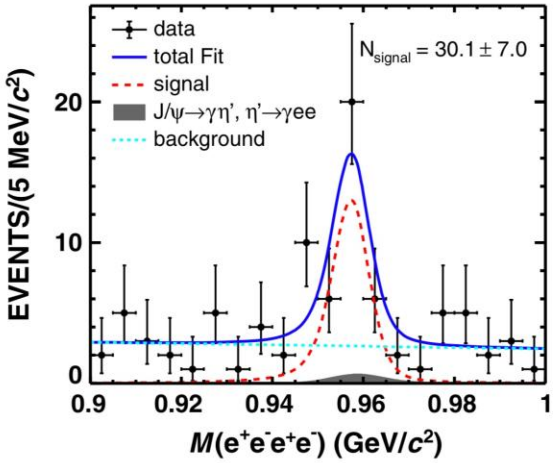


$A_{CP} = (-4.04 \pm 4.69 \pm 0.14)\%$

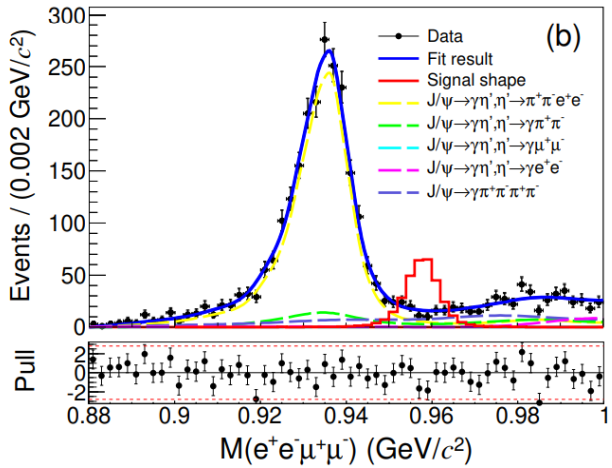
Double Dalitz decays $\eta/\eta' \to l^+l^-l^+l^-$



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

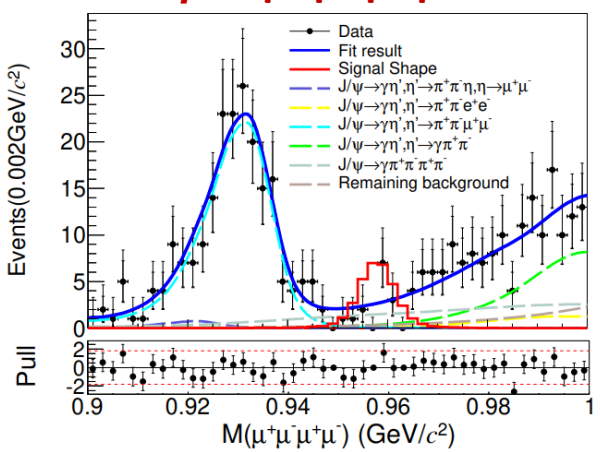


$\eta' \to e^+e^-\mu^+\mu^-$

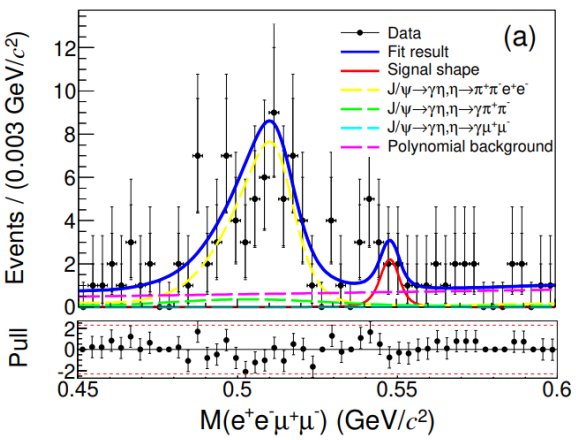


BESIII: PRD105,112010 (2022)

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



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



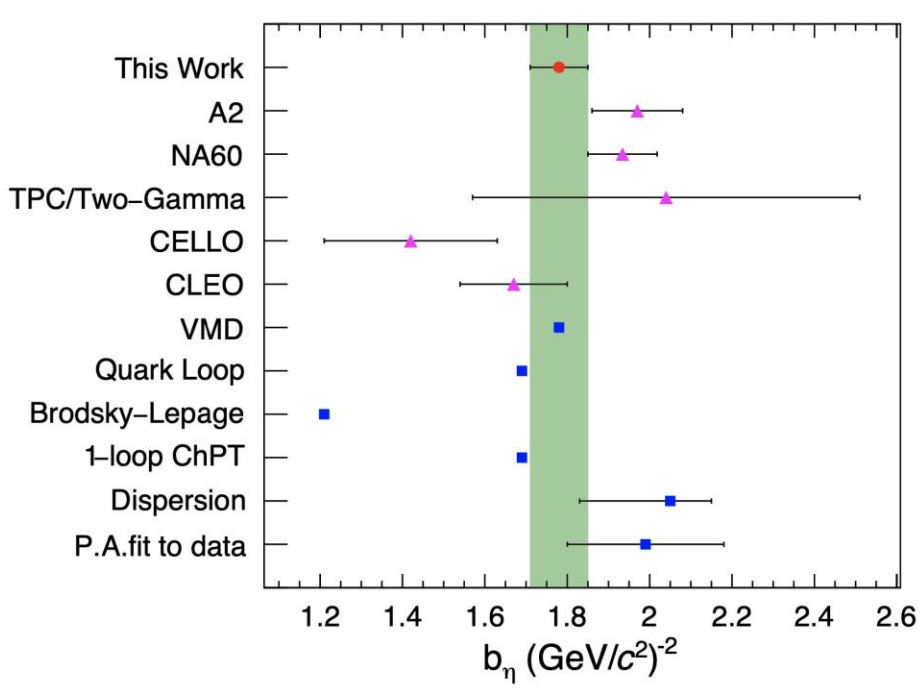
BESIII: PRD111,052002 (2025)

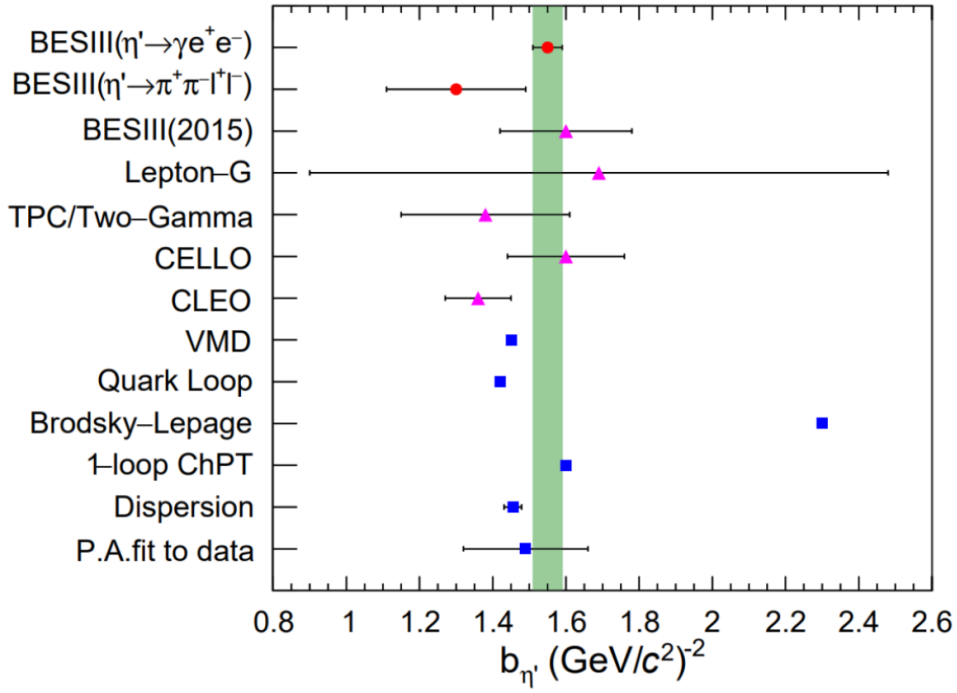
Decay	Hidden gauge [9]	Modified VMD [9]	Data driven approach [10]	Experimental result	
$\eta \to e^+e^-e^+e^-$	$2.680(13) \times 10^{-5}$	$2.668(13) \times 10^{-5}$	$2.17(2) \times 10^{-5}$	$2.40(22) \times 10^{-5}$ [11]	KLOE
$\eta' \to e^+e^-e^+e^-$	$2.384(4) \times 10^{-6}$	$2.317(4) \times 10^{-6}$	$2.10(45) \times 10^{-6}$	$4.5(1) \times 10^{-6}$ [12]	BESIII 2022
$\eta \to \mu^+\mu^-\mu^+\mu^-$	$3.992(27) \times 10^{-9}$	$3.797(26) \times 10^{-9}$	$3.98(15) \times 10^{-9}$	$5.0(8) \times 10^{-9}$ [13]	CMS
$\eta' \to \mu^+\mu^-\mu^+\mu^-$	$2.360(12) \times 10^{-8}$	$2.185(10) \times 10^{-8}$	$1.69(36) \times 10^{-8}$	-	$< 5.28 \times 10^{-7}$
$\eta \to e^+e^-\mu^+\mu^-$	$2.213(26) \times 10^{-6}$	$2.154(22) \times 10^{-6}$	$2.39(7) \times 10^{-6}$	$< 1.6 \times 10^{-4}$ [15]	$< 6.88 \times 10^{-6}$
$\eta' \to e^+e^-\mu^+\mu^-$	$8.626(33) \times 10^{-7}$	$7.968(31) \times 10^{-7}$	$6.39(91) \times 10^{-7}$	-	$< 1.75 \times 10^{-6}$

T. Petri, arXiv:1010.2378

CPC 42 (2018) 023109

Slope parameter: $b_{\eta/\eta'} = \frac{\mathrm{d}|F(q^2)|}{dq^2}\Big|_{q^2=0}$





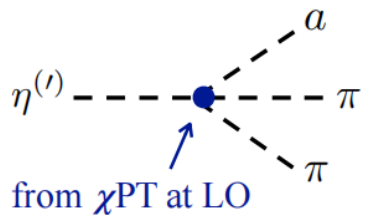
$b_\eta = 1.781 \pm 0.123 \pm 0.033\ (\mathrm{GeV/c^2})^{-2}$

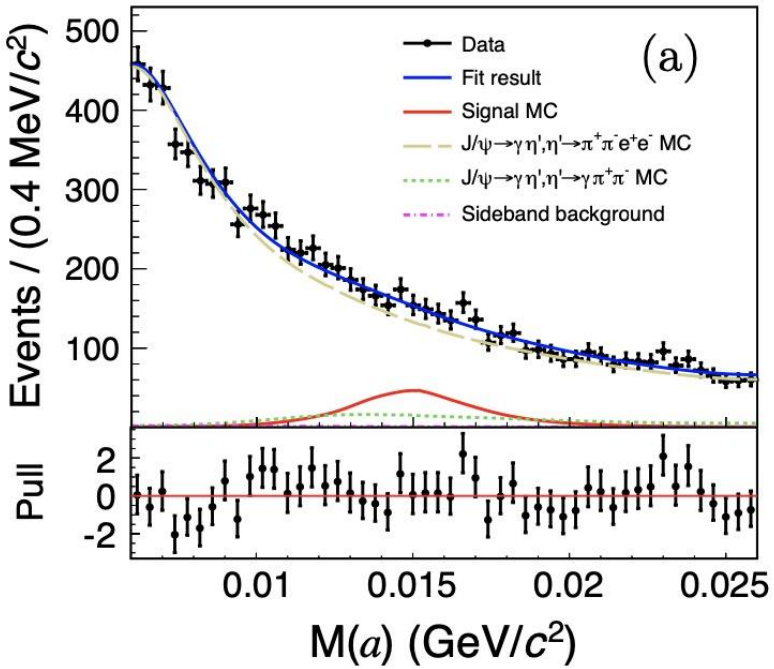
$b_{\eta'} = 1.574 \pm 0.048 \pm 0.016\ (\mathrm{GeV/c^2})^{-2}$

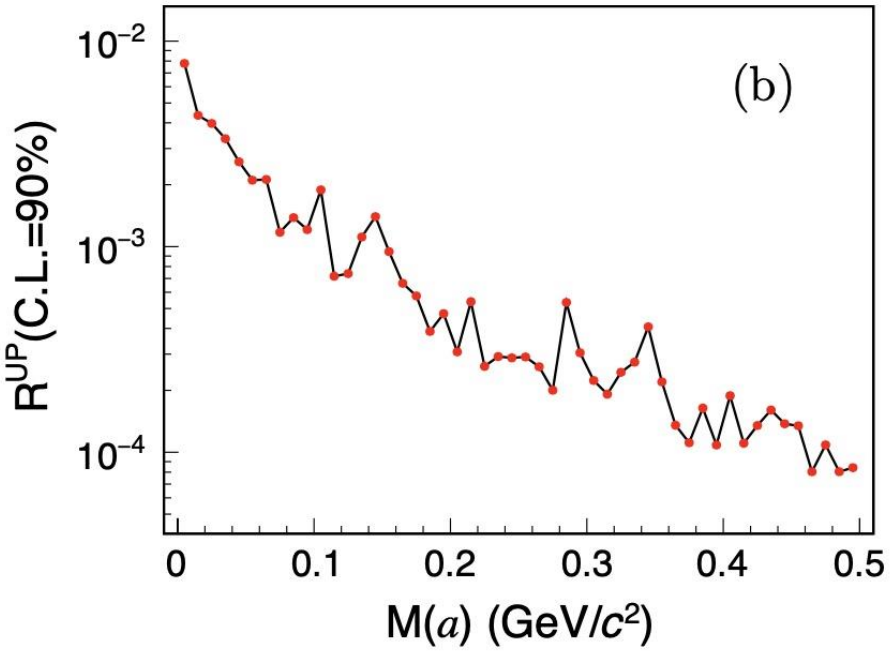
BSM Physics in Dark Sector

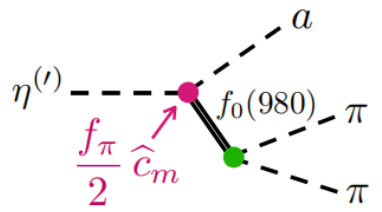
JHEP 07 (2024) 135

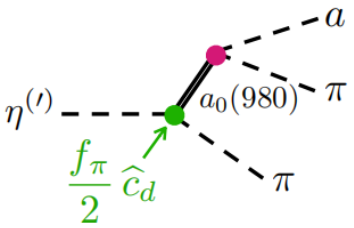
- Axion-like particle in $\eta' \to \pi^+\pi^- a,\ a \to e^+e^-$







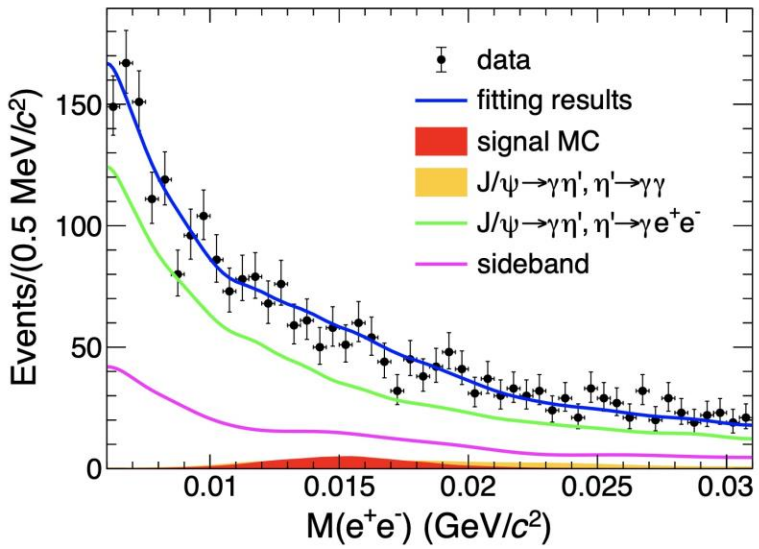




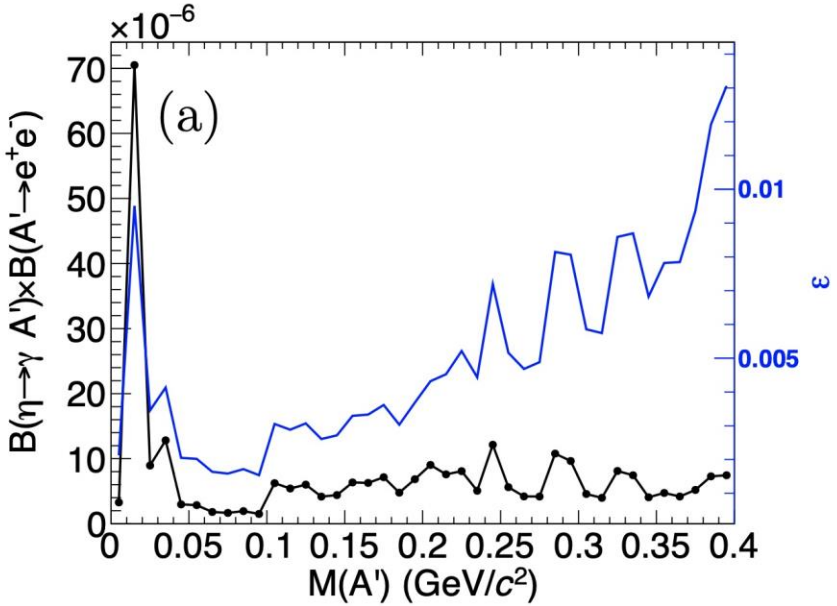
BSM Physics in Dark Sector

PRD 109 (2024) 072001

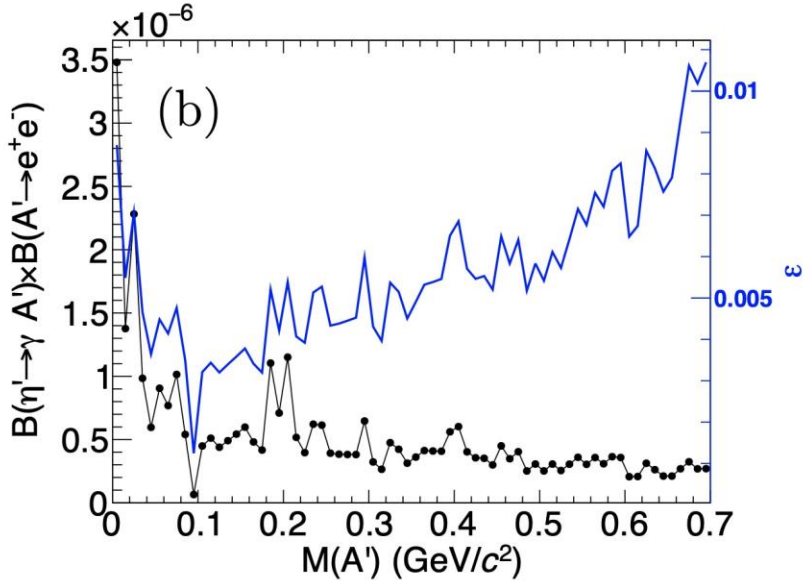
- Dark photon in $\eta/\eta' \to \gamma A', A' \to e^+e^-$



$\eta \to \gamma A', A' \to e^+e^-$



$\eta' \to \gamma A', A' \to e^+e^-$



Summary

- η/η': an important tool for particle physics
- BESIII: an unique place for light mesons
  - Significant progresses achieved on decay mechanisms, TFFs … with unprecedented statistics
- Together with other experiments, the light meson physics will be into a precision era

Thanks for your attention!!!

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

$$\overline{\left|\mathcal{A}_{\eta'\to\pi^+\pi^- l^+ l^-}\right|}^2(s_{\pi\pi}, s_{ll}, \theta_\pi, \theta_1, \phi) = \frac{e^2}{8k^2}|M(s_{\pi\pi}, s_{ll})|^2 \times \lambda\left(m_{\eta'}^2, s_{\pi\pi}, s_{ll}\right) \times \left[1 - \beta_1^2 \sin^2\theta_1 \sin^2\phi\right] s_{\pi\pi}\beta_\pi^2 \sin^2\theta_\pi$$

A. Faessler, C. Fuchs, M. I. Krivoruchenko, PRC 61, 035206 (2000)
B. Borasoy, R. Nissler, EPJA 33, 95 (2007)
T. Petri, arXiv:1010.2378

$$M(s_{\pi\pi}, s_{ll}) = M_{mix} \times VMD(s_{\pi\pi}, s_{ll})$$

contains the information of the decaying particle and the form factor

$$VMD(s_{\pi\pi}, s_{ll}) = \underbrace{1 - \frac{3}{4}(c_1 - c_2 + c_3)}_{\text{Box anomaly}} + \underbrace{\frac{3}{4}(c_1 - c_2 - c_3)\frac{m_V^2}{m_V^2 - s_{ll} - i m_V \Gamma(s_{ll})}}_{\text{VMD contribution}} + \underbrace{\frac{3}{2}c_3 \frac{m_V^2}{m_V^2 - s_{ll} - i m_V \Gamma(s_{ll})} \frac{m_{V,\pi}^2}{m_{V,\pi}^2 - s_{\pi\pi} - i m_{V,\pi}\Gamma(s_{\pi\pi})}}_{\text{VMD contribution}}$$