北京谱仪III实验上轻介子衰变的研究

康晓琳

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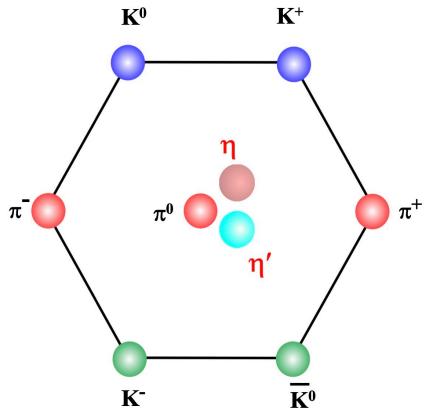

第三届惠州大装置高精度核物理研讨

2025年4月19日至23日

中科院近代物理所 惠州研究部

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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η' Physics

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

Channel	Expt. branching ratio	Discussion
$\eta' \to \eta\pi^+\pi^-$	42.6(7)%	Large-N_c χPT, light Higgs scalars
$\eta' \to \pi^+\pi^-\gamma$	28.9(5)%	Chiral anomaly, theory input for singly-virtual TFF and $(g-2)_\mu$, P/CP violation
$\eta' \to \eta\pi^0\pi^0$	22.8(8)%	Large-N_c χPT
$\eta' \to \omega\gamma$	2.489(76)% [58]	Theory input for singly-virtual TFF and $(g-2)_\mu$
$\eta' \to \omega e^+e^-$	$2.0(4) \times 10^{-4}$	Theory input for doubly-virtual TFF and $(g-2)_\mu$
$\eta' \to 2\gamma$	2.331(37)% [58]	Chiral anomaly, η–η' mixing
$\eta' \to 3\pi^0$	2.54(18)% (⋆)	$m_u - m_d$
$\eta' \to \mu^+\mu^-\gamma$	$1.09(27) \times 10^{-4}$	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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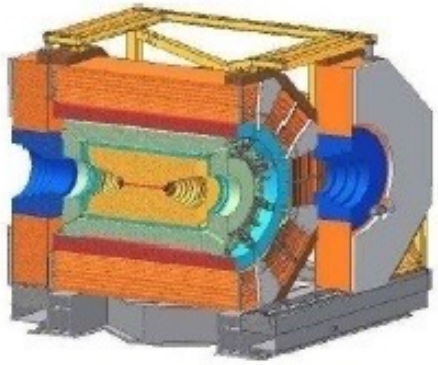
Source of η/η' events

New Proposals

e^+e^- Collider

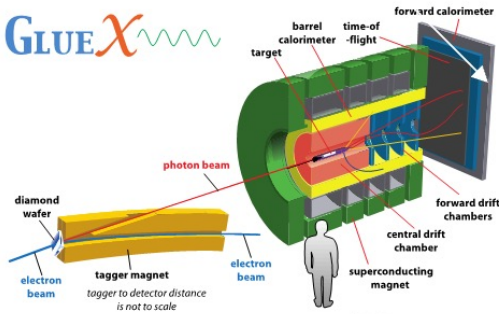
BESIII at BEPCII



KLOE-2

Fixed-target

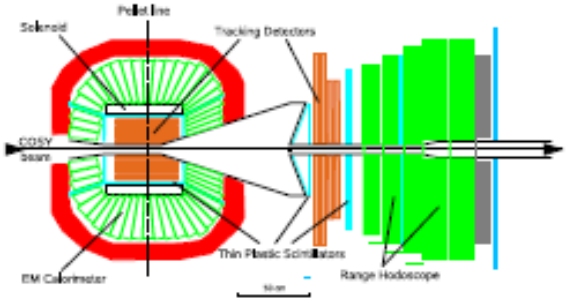
JEF at JLab



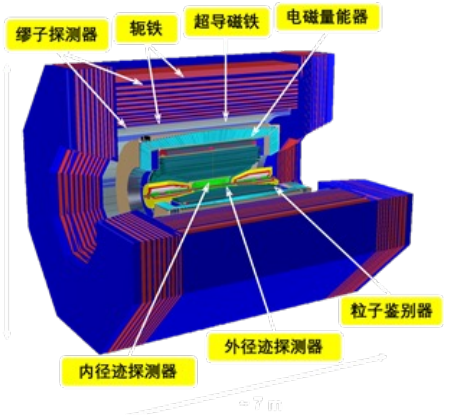
CLAS(12)

Crystal Ball

WASA at COSY

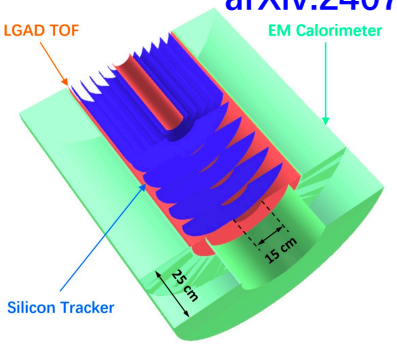


STCF

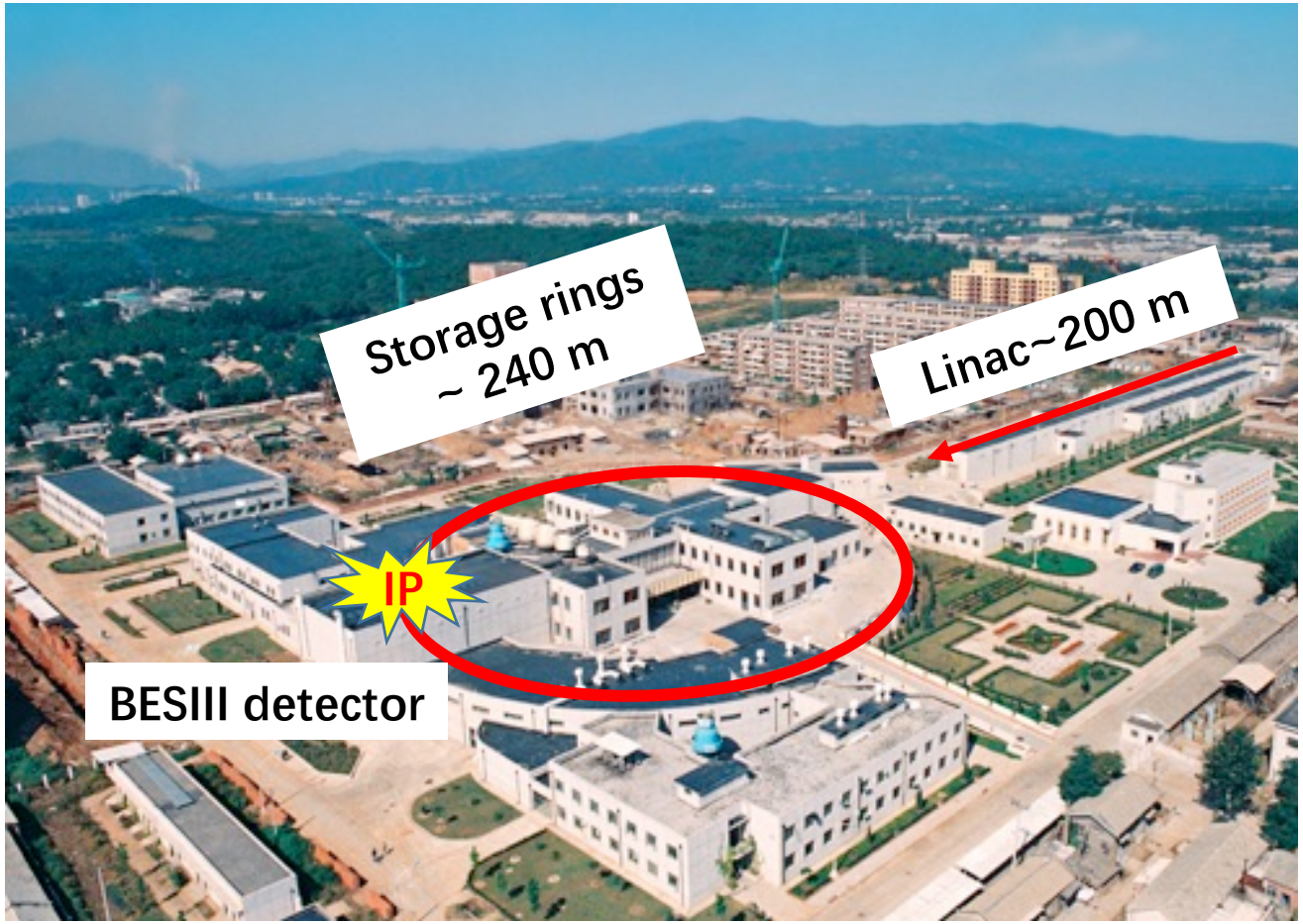


η factory at HIAF

arXiv:2407.00874

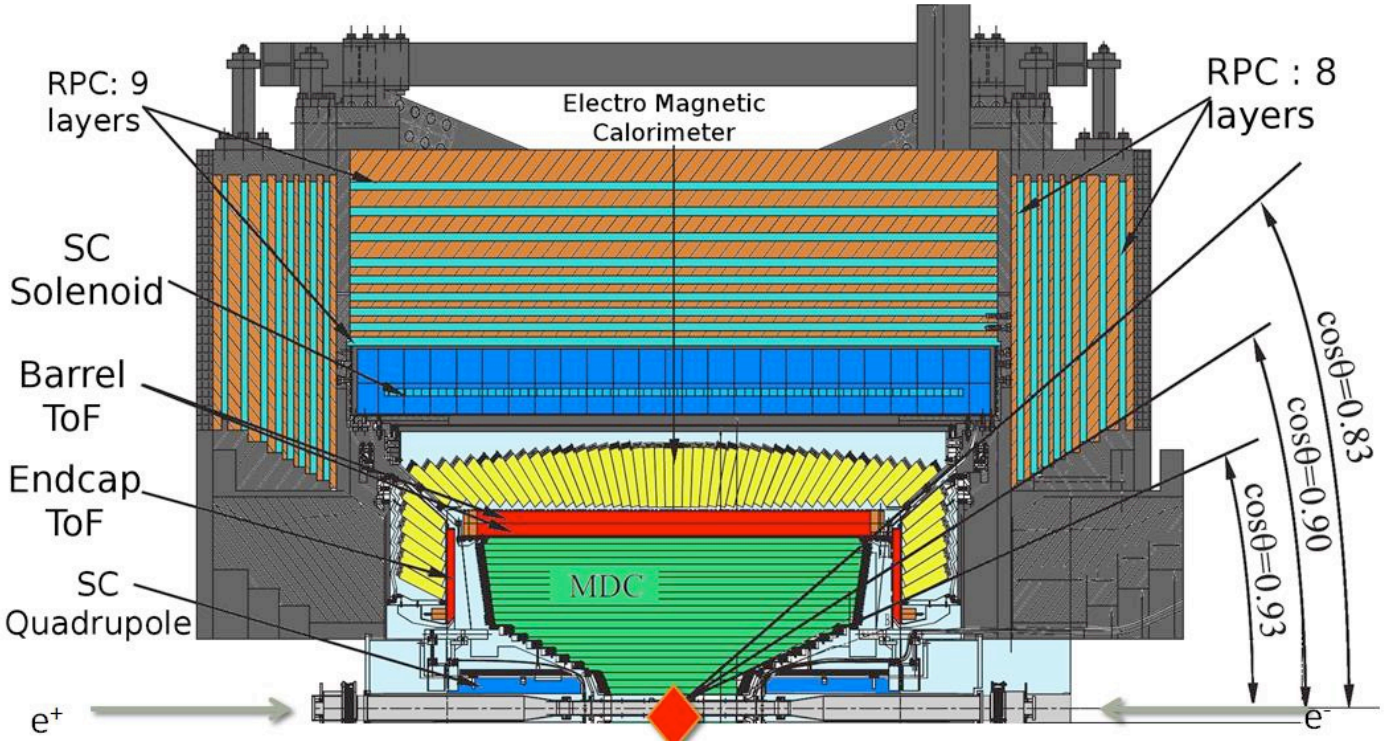


Beijing Electron and Positron Collider(BEPCII)



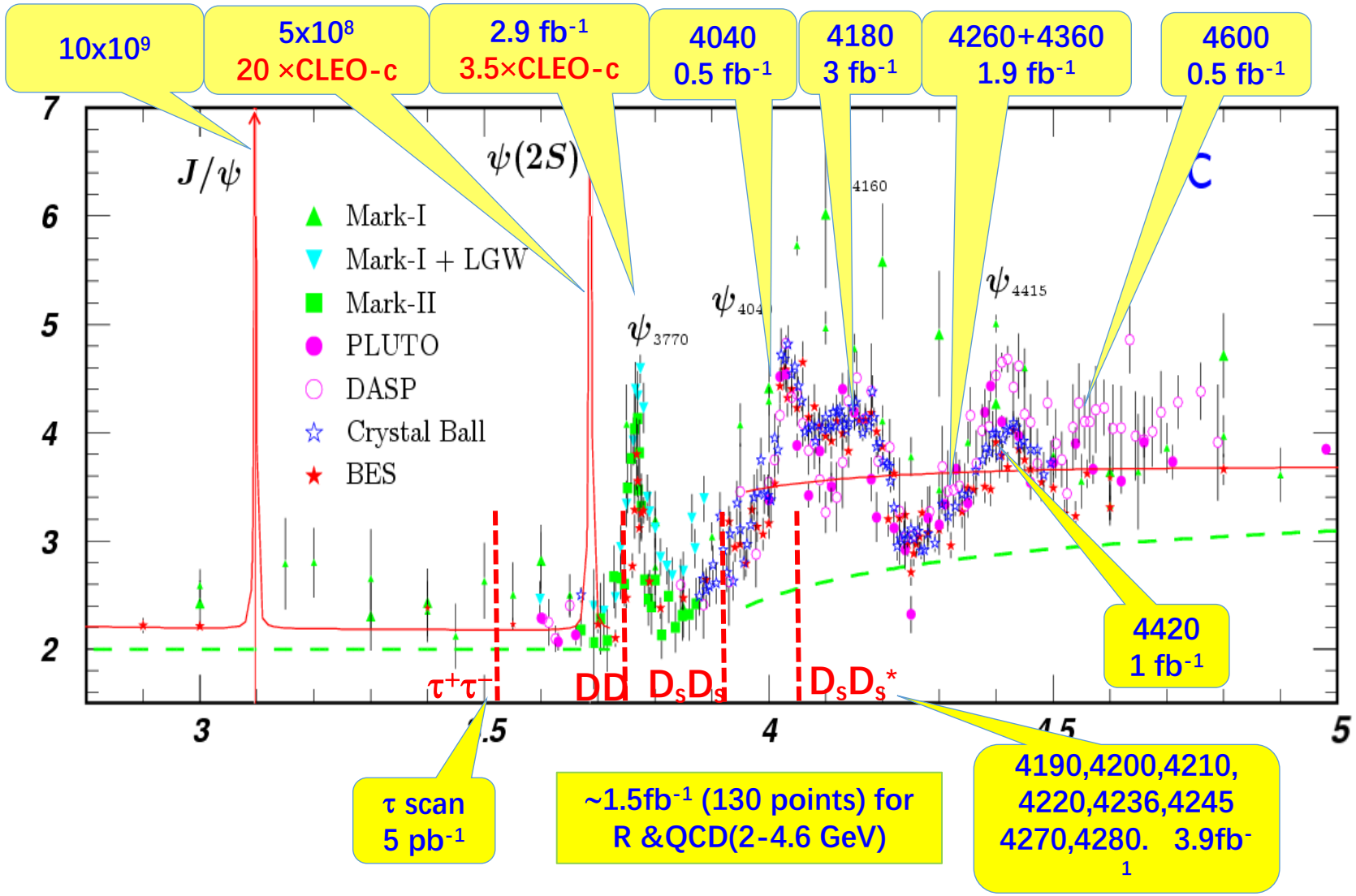
- Symmetric, double rings e^+e^- collider @ $\sqrt{s}$=2-4.9GeV
- Peak luminosity $\approx 10^{33}cm^{-2}s^{-1}$ at $\sqrt{s}$=3.770GeV
- Crab-Waist interaction scheme with the crossing angle of 11 mrad
- Top-up operation since 2018

BESIII detector



- **Acceptance: 93% of 4π**
- **Main Drift Chamber**: small cell & gas
  - ✓ σ_{xy}=130 μm, σ_P/P=0.5%@1 GeV
  - ✓ $\sigma_{dE/dx}$=6%
- **Time of Flight (TOF)**
  - ✓ σ_T=70 ps for barrel layers
  - ✓ σ_T=110 ps (65 ps with updated MRPC) for endcaps
- **Super Conducting Solenoid**: 1.0T (0.9T for 2012)
- **Electromagnetic Calorimeter**: CsI Crystals
  - ✓ σ_E/E=2.5%@1 GeV
  - ✓ Position resolution 6mm@1GeV
- **RPC Muon ID**: 9 layer

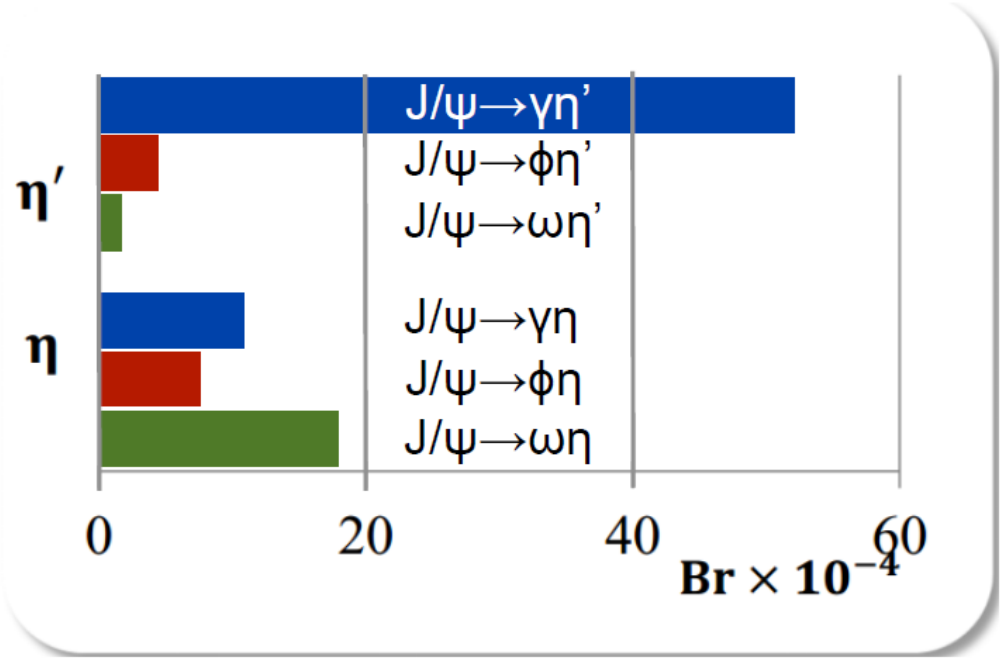
Data set and Physics at BESIII



- Wide topics @ √s=2-5 GeV
- Light hadron Physics
- Charmonium physics
- XYZ particles
- Discrete symmetries breaking
- Charm physics
- Physics with tau lepton
- R-value measurement
- …

Chin. Phys. C 44, 040001 (2020)

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

PDG2024

η REFERENCES

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HAYRAPETY...	23A	PRL 131 091903	A. Hayrapetyan *et al.*	(CMS Collab.)
ABLIKIM	21AM	PR D104 092004	M. Ablikim *et al.*	(BESIII Collab.)
BABUSCI	20A	JHEP 2010 047	D. Babusci *et al.*	(KLOE-2 Collab.)
ZHEVLAKOV	19	PR D99 031703	A.S. Zhevlakov *et al.*	(TMSK, MAINZ, TUBIN+)
ACHASOV	18B	PR D98 052007	M.N. Achasov *et al.*	(SND Collab.)
ADLARSON	18C	PL B784 378	P. Adlarson *et al.*	(WASA-at-COSY Collab.)
PRAKHOV	18	PR C97 065203	S. Prakhov *et al.*	(A2 Collab. at MAMI)
AAIJ	17D	PL B764 233	R. Aaij *et al.*	(LHCb Collab.)
ADLARSON	17B	PR C95 035208	P. Adlarson *et al.*	(A2 Collab. at MAMI)
ANASTASI	16A	JHEP 1605 019	A. Anastasi *et al.*	(KLOE-2 Collab.)
ARNALDI	16	PL B757 437	R. Arnaldi *et al.*	(NA60 Collab.)
ABLIKIM	15G	PR D92 012014	M. Ablikim *et al.*	(BESIII Collab.)
ADLARSON	14A	PR C90 045207	P. Adlarson *et al.*	(WASA-at-COSY Collab.)
AGAKISHIEV	14	PL B731 265	G. Agakishiev *et al.*	(HADES Collab.)
NEFKENS	14	PR C90 025206	B.M.K. Nefkens *et al.*	(A2 Collab. at MAMI)
NIKOLAEV	14	EPJ A50 58	A. Nikolaev *et al.*	(MAMI-B, MAINZ, BONN)
ABLIKIM	13	PR D87 012009	M. Ablikim *et al.*	(BESIII Collab.)
ABLIKIM	13G	PR D87 032006	M. Ablikim *et al.*	(BESIII Collab.)
BABUSCI	13	PL B718 910	D. Babusci *et al.*	(KLOE/KLOE-2 Collab.)
BABUSCI	13A	JHEP 1301 119	D. Babusci *et al.*	(KLOE-2 Collab.)
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ABLIKIM	21J	PR D103 092005	M. Ablikim *et al.*	(BESIII Collab.)
ABLIKIM	20E	PR D101 032001	M. Ablikim *et al.*	(BESIII Collab.)
ABLIKIM	19AW	PR D100 052015	M. Ablikim *et al.*	(BESIII Collab.)
ABLIKIM	19T	PRL 122 142002	M. Ablikim *et al.*	(BESIII Collab.)
ABLIKIM	18	PR D97 012003	M. Ablikim *et al.*	(BESIII Collab.)
ABLIKIM	18C	PRL 120 242003	M. Ablikim *et al.*	(BESIII Collab.)
ADLARSON	18A	PR D98 012001	P. Adlarson *et al.*	(A2 Collab. at MAMI)
GONZALEZ-S...	18A	EPJ C78 758	S. Gonzalez-Solis, E. Passemar	(BEIJ, IND+)
AAIJ	17D	PL B764 233	R. Aaij *et al.*	(LHCb Collab.)
ABLIKIM	17	PRL 118 012001	M. Ablikim *et al.*	(BESIII Collab.)
ABLIKIM	17T	PR D96 012005	M. Ablikim *et al.*	(BESIII Collab.)
ABLIKIM	16M	PR D93 072008	M. Ablikim *et al.*	(BESIII Collab.)
ABLIKIM	15AD	PR D92 051101	M. Ablikim *et al.*	(BESIII Collab.)
ABLIKIM	15G	PR D92 012014	M. Ablikim *et al.*	(BESIII Collab.)
ABLIKIM	15O	PR D92 012001	M. Ablikim *et al.*	(BESIII Collab.)
ABLIKIM	15P	PR D92 012007	M. Ablikim *et al.*	(BESIII Collab.)
ACHASOV	15	PR D91 092010	M.N. Achasov *et al.*	(SND Collab.)
AKHMETSHIN	15	PL B740 273	R.R. Akhmetshin *et al.*	(CMD-3 Collab.)
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ABLIKIM	13G	PR D87 032006	M. Ablikim *et al.*	(BESIII Collab.)
ABLIKIM	13O	PR D87 092011	M. Ablikim *et al.*	(BESIII Collab.)
ABLIKIM	13U	PR D88 091502	M. Ablikim *et al.*	(BESIII Collab.)
ABLIKIM	12E	PRL 108 182001	M. Ablikim *et al.*	(BESIII Collab.)
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ABLIKIM	11G	PR D84 032006	M. Ablikim *et al.*	(BESIII Collab.)

New approach to investigate η decays with $\eta' \to \pi^+\pi^-\eta$

X. L. Kang, Y. Y. Ji. B. H. Xiang, S. S. Fang, PRD 108, 014038 (2023)

PDG2024

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ABLIKIM	11G	PR D84 032006	M. Ablikim *et al.*	(BESIII Collab.)

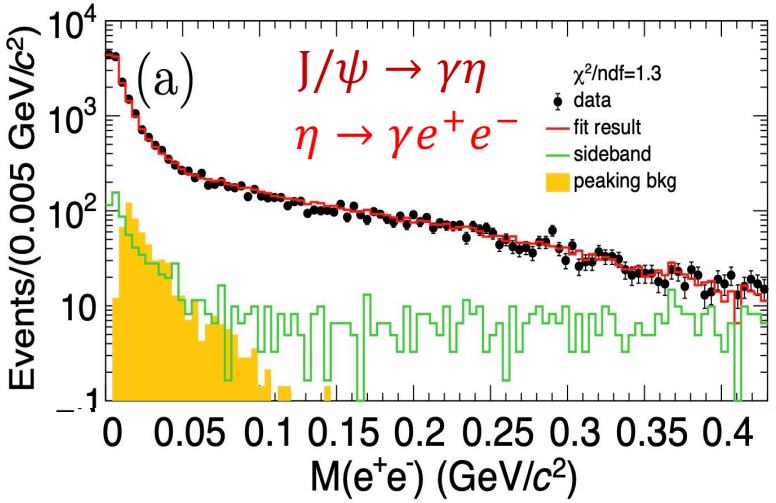
- $J/\psi \to \gamma\eta \to 1.1\times10^7\ \eta$
- $J/\psi \to \gamma\eta',\ \eta' \to \pi^+\pi^-\eta \to 2.2\times10^7\ \eta$

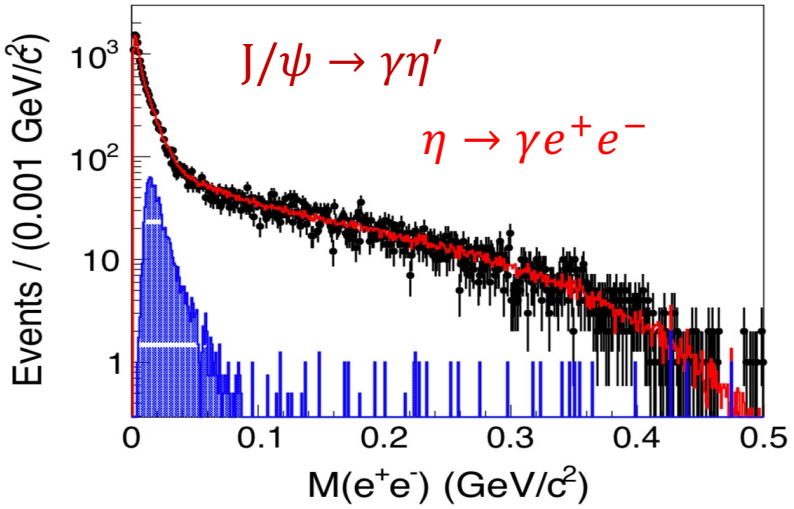
- η' constraint to suppress backgrounds from QED and J/ψ decays!
- Help distinguish muons from pions

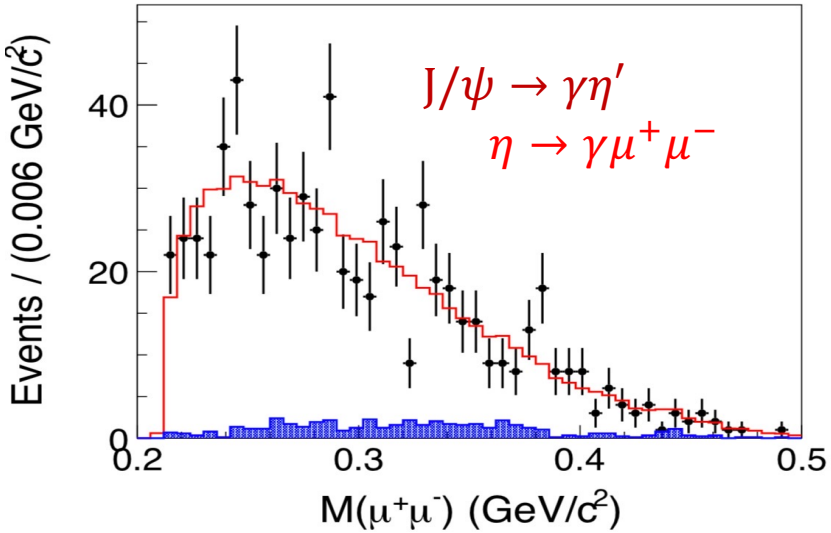
"Few results" on η decays at BESIII

Feasibility study of $J/\psi \to \gamma\eta', \eta' \to \pi^+\pi^-\eta$

X. L. Kang, Y. Y. Ji. B. H. Xiang, S. S. Fang, PRD 108, 014038 (2023)







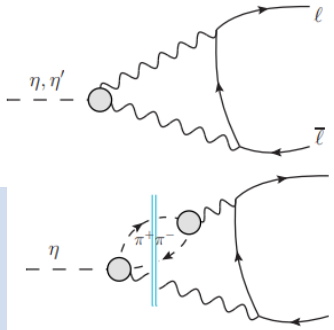
- Background level is low
- Help distinguish muons from pions

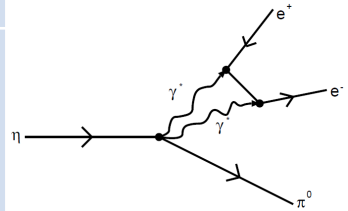
Feasibility study of $J/\psi \to \gamma\eta', \eta' \to \pi^+\pi^-\eta$ at STCF

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

- With 1 trillion J/ψ hypothesis at STCF
- 5.2×10^9 η' inclusive decays (2.2×10^9 η events) are simulated at STCF

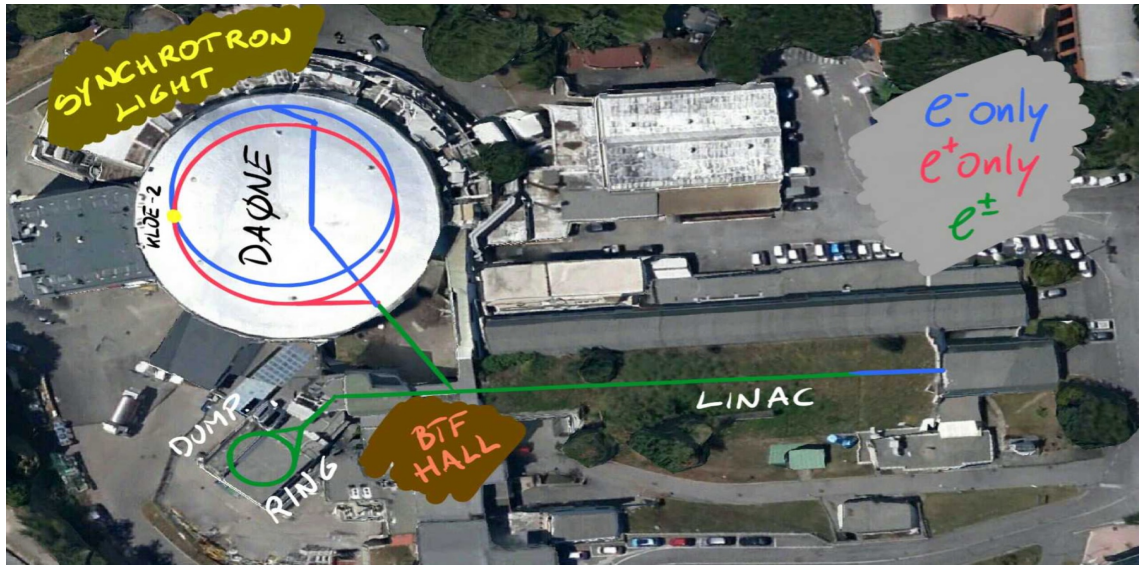
	SM Prediction	PDG	STCF Estimation	Comment
$\eta \to e^+e^-$	$10^{-9}\sim10^{-10}$	$< 7\times10^{-7}$ (SND)	$< 10^{-9}$	• Fourth-order EM transition • Dominant by $\eta \to \gamma^*\gamma^* \to l^+l^-$ and intermediate hadronic states • Leptoquarks
$\eta \to \mu^+\mu^-$	$10^{-6}\sim10^{-7}$	$(5.8 \pm 0.8)\times10^{-6}$ SPECII	$(5.88 \pm 0.09)\times10^{-6}$	
$\eta \to \pi^+\pi^-$	$\sim10^{-16}$	$< 4.4\times10^{-6}$ KLOE-2	$< 7.8\times10^{-8}$	• P and CP violating decays • contribute to neutron EDM
$\eta \to \pi^0\pi^0$		$< 3.5\times10^{-4}$ GAM4	$< 6.9\times10^{-7}$	
$\eta \to \pi^0e^+e^-$	$10^{-11}\sim10^{-8}$	$< 7.5\times10^{-6}$ WASA	$< 2\times10^{-7}$	• $\eta \to \pi^0\gamma^* \to \pi^0l^+l^-$ is C-violated process • Dominant by C-conserving process $\eta \to \pi^0\gamma^*\gamma^* \to \pi^0l^+l^-$
$\eta \to \pi^0\mu^+\mu^-$		$< 5\times10^{-6}$ SPEC	$< 8.5\times10^{-8}$	





KLOE/KLOE-2 @ DAΦNE

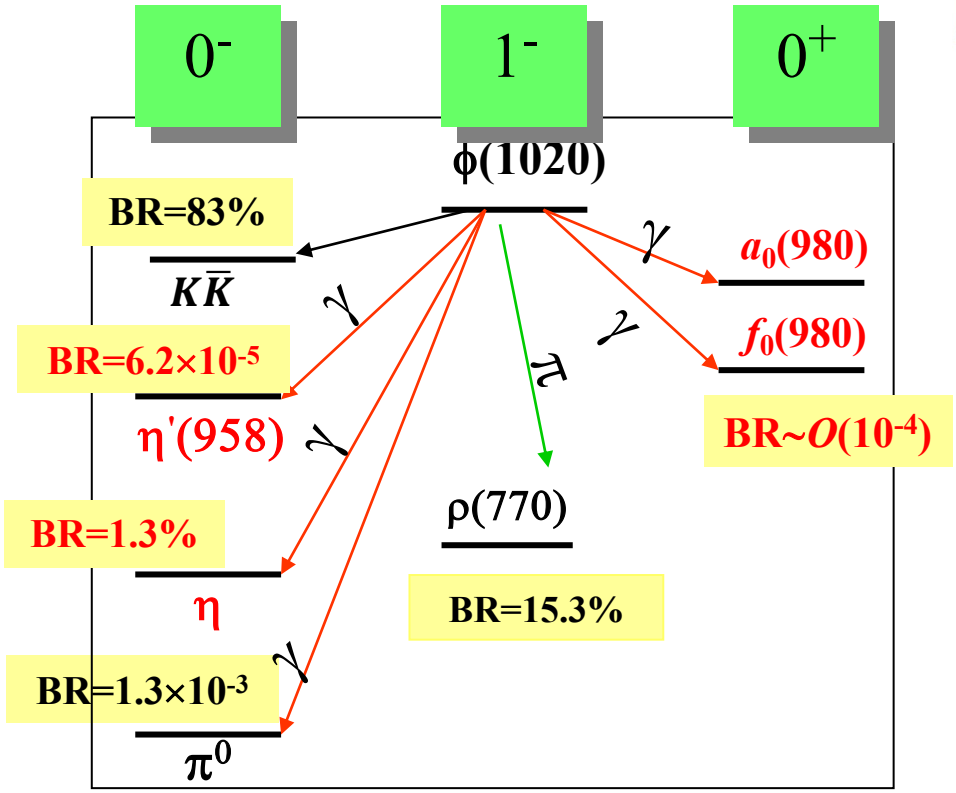
- DAΦNE: Double rings e^+e^- collider @ $\sqrt{s}=M_\phi=1019.4$ MeV; $\sigma_{peak} \approx 3.1$ μb
- 2001-2005 KLOE collected ~2.5 fb^{-1} @ ϕ peak and 250 pb^{-1} off-peak @ $\sqrt{s}=1000$ MeV
- Updated DAΦNE (2008), crabbed waist interaction scheme + large beam crossing
- 2014-2018 KLOE-2 collected ~5.5 fb^{-1} @ ϕ peak



KLOE+KLOE-2 data sample: ~ 8 fb^{-1}
~2.4×10^{10} ϕ mesons, the largest sample collected at ϕ
Unique sample for typology and statistical relevance

Physics @ KLOE-2

- **Kaon physics: 8.2×10^9 Ks and K_L events**
  - CKM unitarity test, CPT and QM tests with kaon interferometry, Direct tests of T and CPT using entanglement, Ks rare decays…
- **Light hadronic physics**
  - **3.1×10^8 η events**
  - **1.5×10^8 η' events**
- **γγ physics: $e^+e^-\to e^+e^-\gamma^*\gamma^*\to e^+e^-X$**
  - X=$\pi^0/\eta \Rightarrow \Gamma(\pi^0\to\gamma\gamma)$, space-like TFF



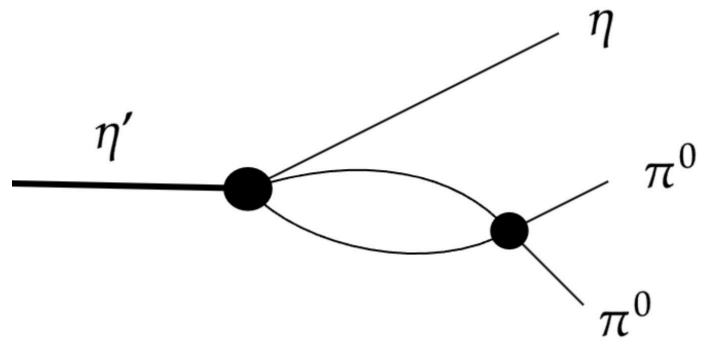
- Hadronic cross section via ISR [$e^+e^-\to\gamma(2\pi, 3\pi, 4\pi)$]: hadronic corrections to $(g-2)_\mu$
- **Dark force searches:**
  - $e^+e^-\to U\gamma\to\pi\pi\gamma$, $\mu\mu\gamma$
  - Leptophobic B boson search: $\phi\to\eta B$ ($B\to\pi^0\gamma$), $\eta\to B\gamma$ ($B\to\pi^0\gamma$)
  - Higgsstrahlung: $e^+e^-\to Uh'\to\mu^+\mu^-$ + miss. Energy

KLOE-2 Coll., EPJC68(2010)619, EPJ WoC 166 (2018)

Recent experimental results on η/η' decays

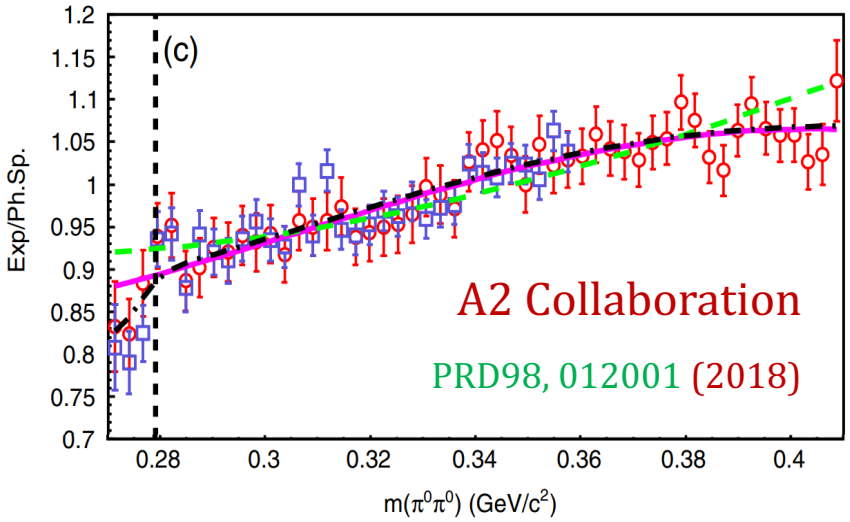
Evidence of cusp effect in $\eta' \to \pi^0\pi^0\eta$

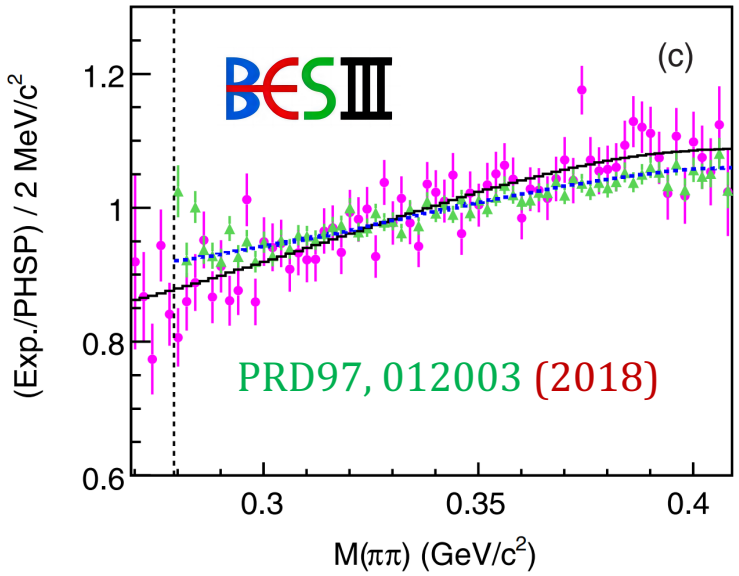
- Investigation on ππ and πη final interactions
- S-wave charge-exchange rescattering: $\pi^+\pi^- \to \pi^0\pi^0 \to \pi^+\pi^-$
- The size of cusp effect is predicted to be about 6% in $\eta' \to \pi^0\pi^0\eta$ within NREFT

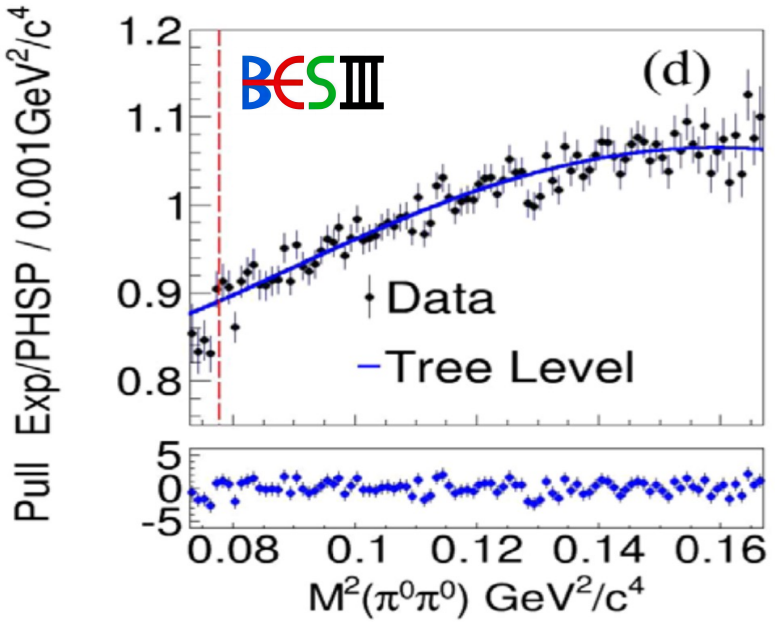


B. Kubis and S. P. Schneider, EPJC 62, 511 (2009)

BESIII: PRL130, 081901(2023)







BESIII: PRL130, 081901(2023)

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

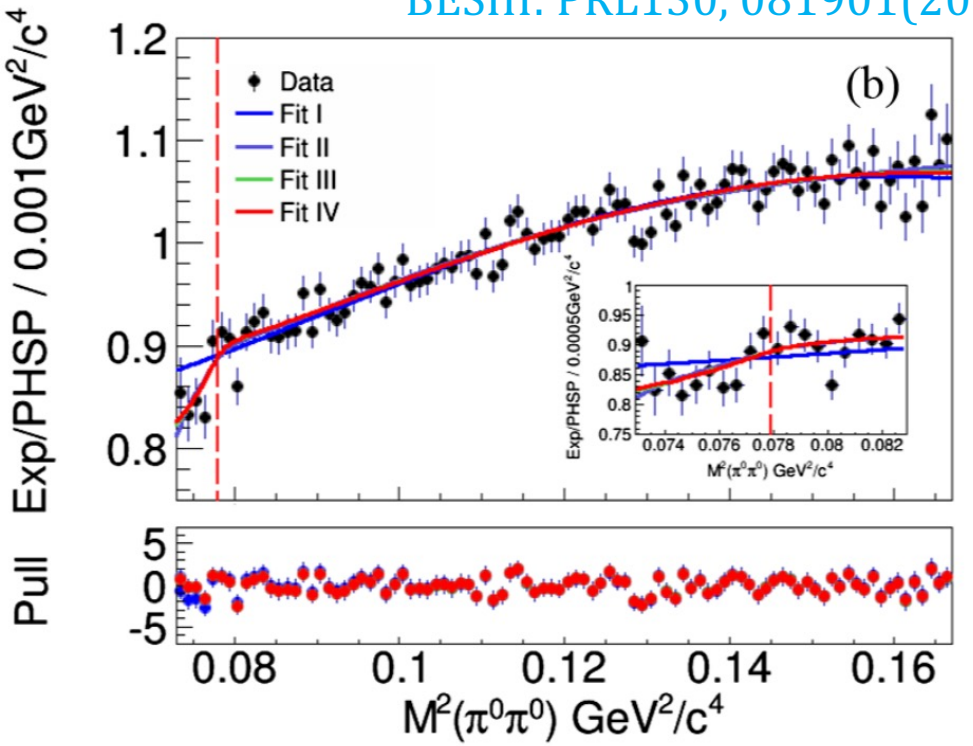
B. Kubis, S. P. Schneider, EPJC 62, 511 (2009)

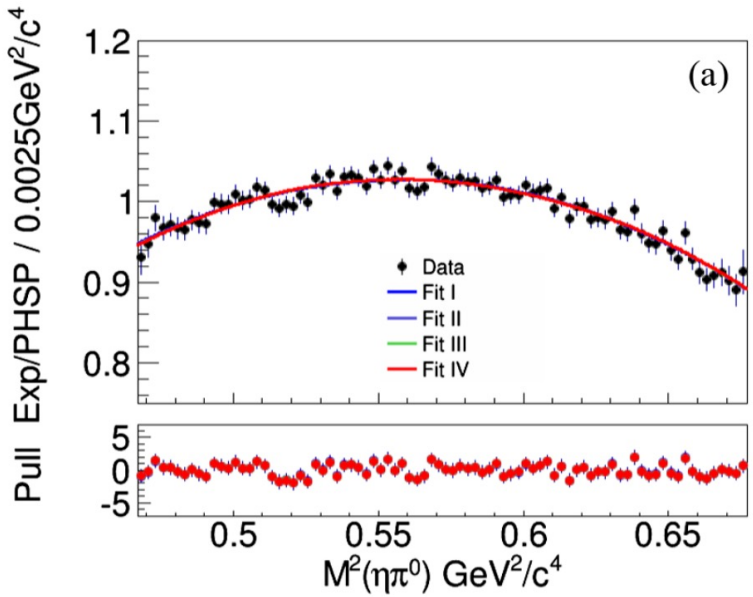
$$\mathcal{M}_{\eta' \to \eta\pi^0\pi^0} = \mathcal{M}_N^{tree} + \mathcal{M}_N^{one-loop} + \mathcal{M}_N^{two-loop} + \cdots$$

- 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

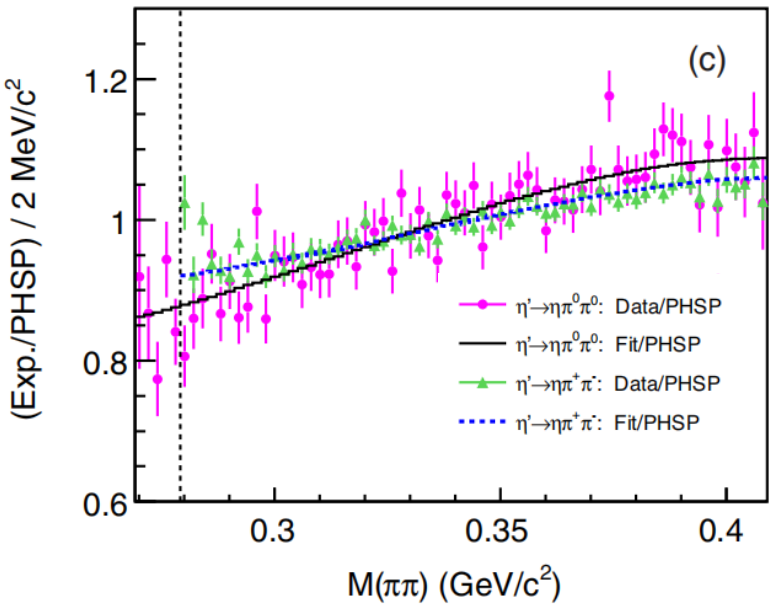
π–π scattering pars

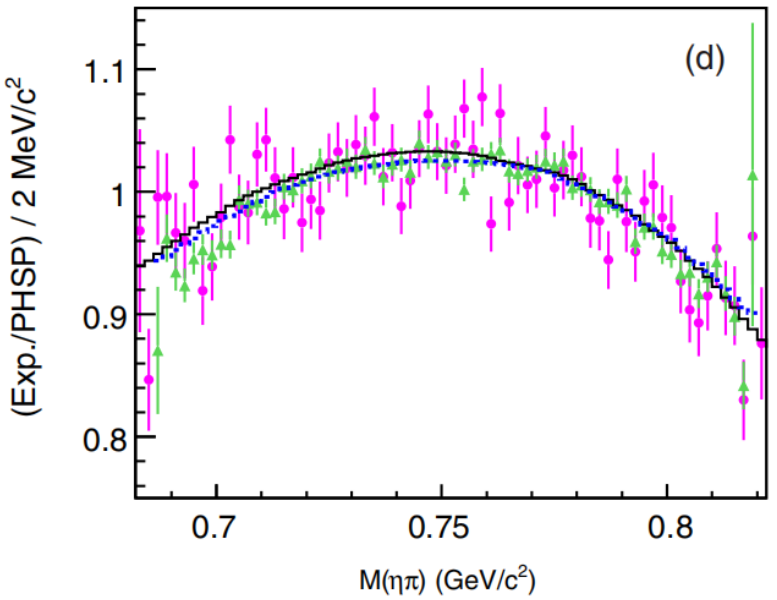
Matrix elements for $\eta' \to \pi^+\pi^-\eta$

BESIII: PRD 97 (2018) 012003

- Based on 1.3 billion, the matrix elements in tree level fo $\eta' \to \pi^+\pi^-\eta$ are measured

Para-	$\eta' \to \eta\pi^+\pi^-$				
meter	EFT [5]	Large N_C [7]	RChT [7]	VES [10]	This work
a	$-0.116(11)$	$-0.098(48)$ (fixed)		$-0.127(18)$	$-0.056(4)(2)$
b	$-0.042(34)$	$-0.050(1)$	$-0.033(1)$	$-0.106(32)$	$-0.049(6)(6)$
c	...	...	...	$+0.015(18)$	$0.0027(24)(18)$
d	$+0.010(19)$	$-0.092(8)$	$-0.072(1)$	$-0.082(19)$	$-0.063(4)(3)$



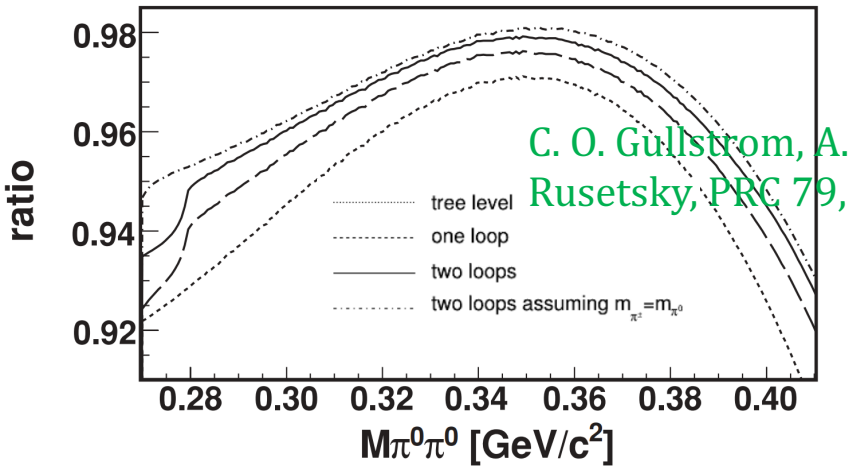


➢ Amplitude analysis of $\eta' \to \pi^+\pi^-\eta$ within NREFT is ongoing, sizeble contribution from final state interactions

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

➢ The difference on DP between $\eta' \to \pi^+\pi^-\eta$ and $\eta' \to \pi^0\pi^0\eta$ can be used to extract the u-d quark mass difference

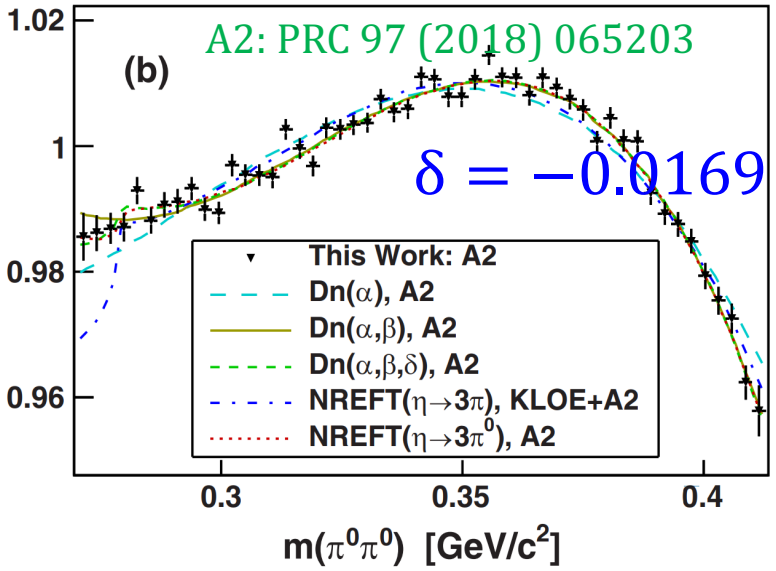
Cusp structure in $\eta \to \pi^0\pi^0\pi^0$



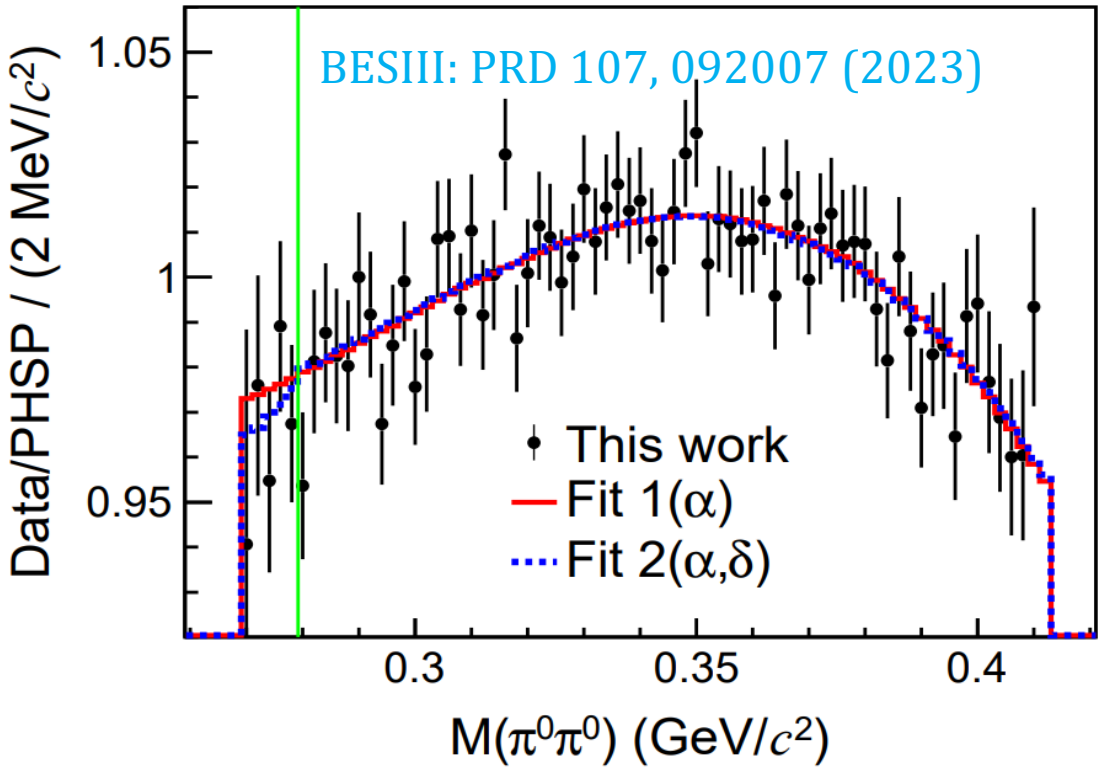
C. O. Gullstrom, A. Kupsc, A. Rusetsky, PRC 79, 028201 (2009)

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

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



$\delta = -0.0169 \pm 0.0067$

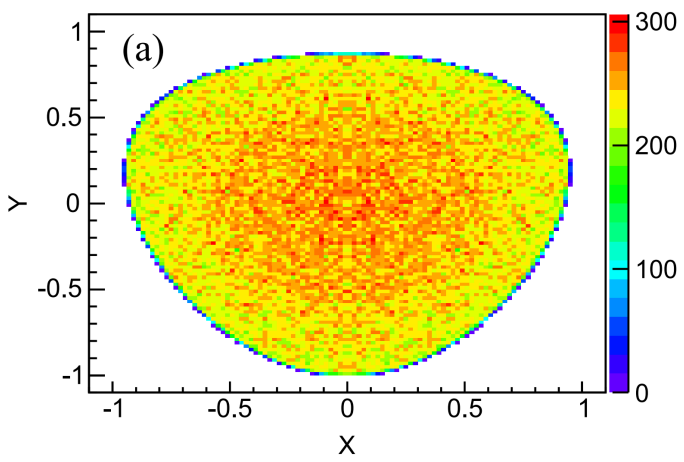


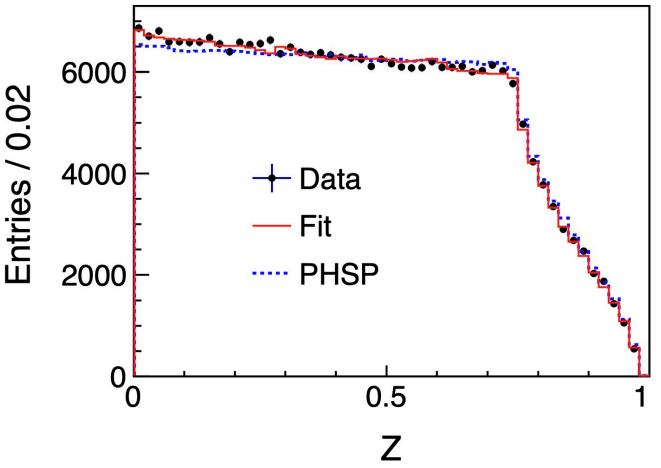
Matrix elements for $\eta \to \pi^0\pi^0\pi^0$

BESIII: PRD 107, 092007 (2023)
https://www.hepdata.net/record/141642

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

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



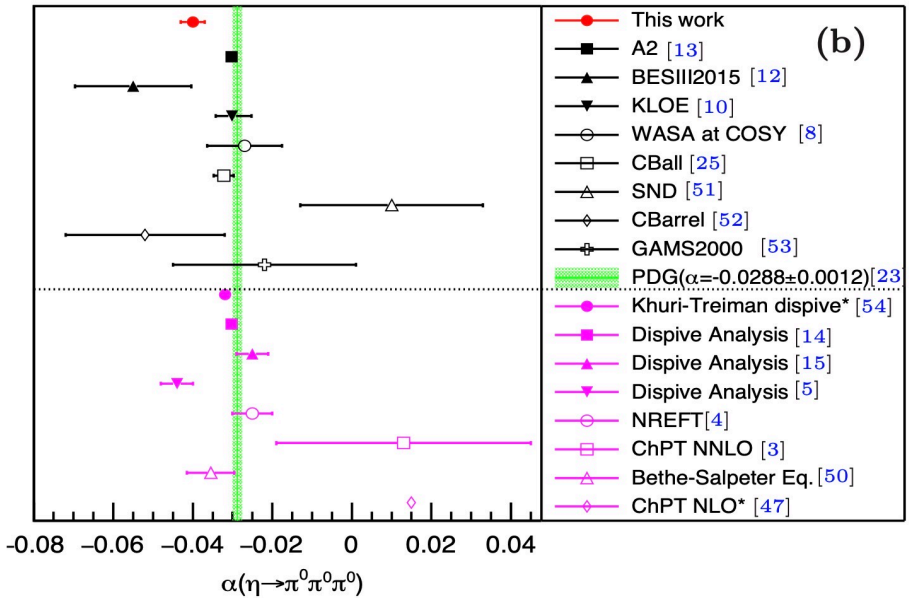


$$\alpha = -0.0406 \pm 0.0035 \pm 0.0008$$

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

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

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



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

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

Precision study of $\eta \to \pi^+\pi^-\pi^0$

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

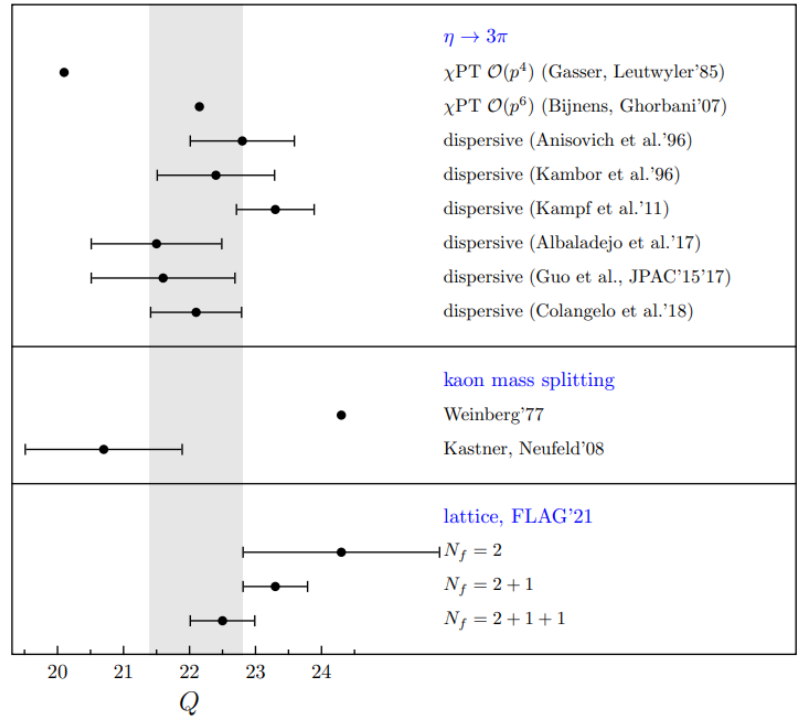
⇒ ideal process to extract $m_u - m_d$

$$\Gamma(\eta \to \pi^+\pi^-\pi^0) = \frac{1}{Q^4}\frac{M_K^4(M_K^2 - M_\pi^2)^2}{6912\pi^3 M_\eta^3 M_\pi^4 F_\pi^4}\int_{s_{\min}}^{s_{\max}} ds \int_{u_-(s)}^{u_+(s)} du\, |M(s,t,u)|^2$$

$$Q^2 = \frac{m_s^2 - \hat{m}^2}{m_d^2 - m_u^2} = \begin{matrix} 22.0 \pm 0.7 \\ 21.6 \pm 1.1 \end{matrix}$$

G. Colangelo, S. Lanz, H. Leutwyler, E. Passemar, PRL 118, 022001 (2017)

P. Guo, I. V. Danilkin, C. Fernández-Ramírez, V. Mathieu, A. P. Szczepaniak, PLB 771, 497 (2017)



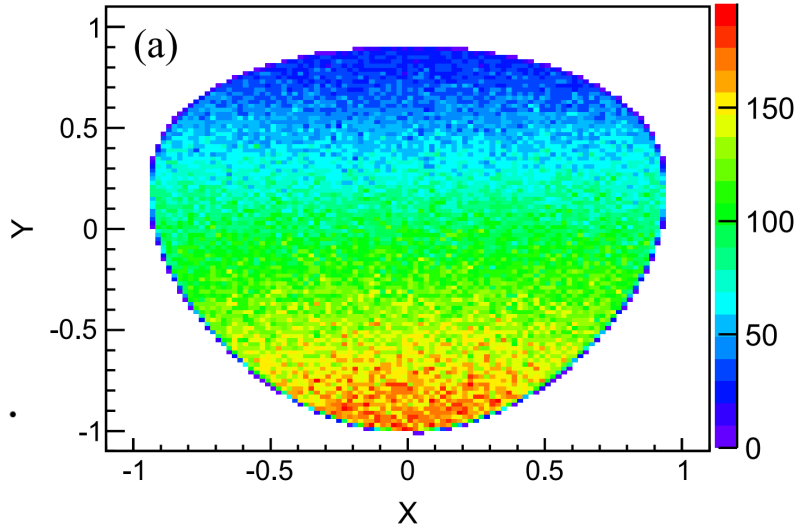
Matrix elements for $\eta \to \pi^+\pi^-\pi^0$

BESIII: PRD 107, 092007 (2023)

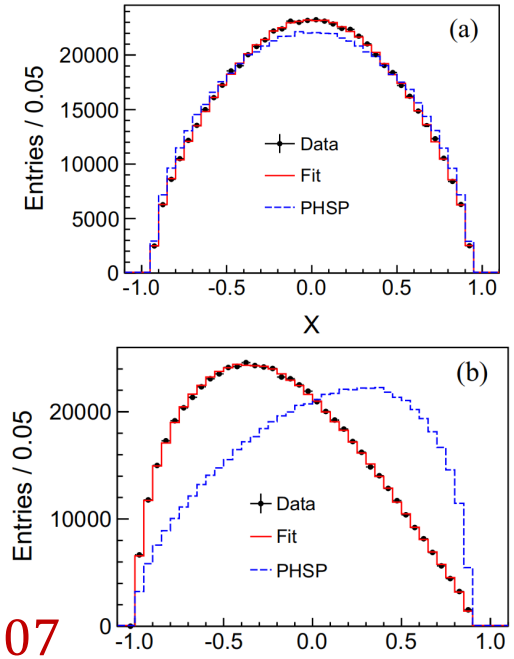
https://www.hepdata.net/record/141642

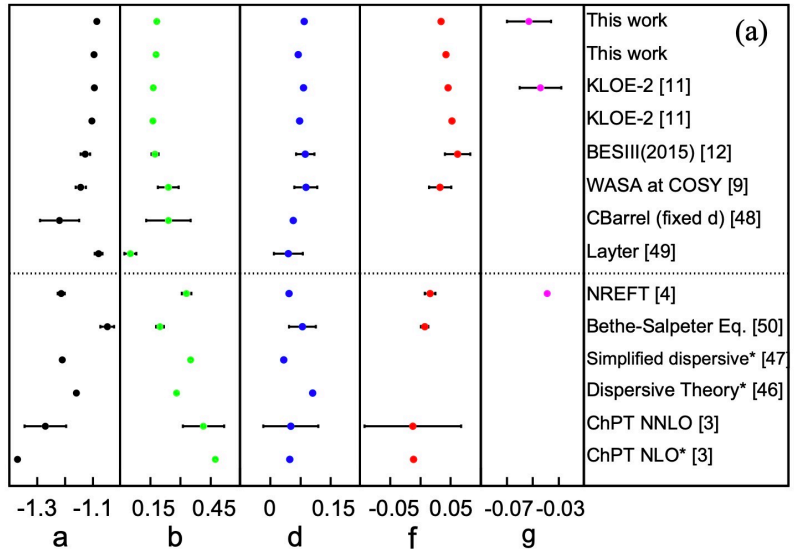
$$X = \frac{\sqrt{3}}{Q}(T_{\pi^+} - T_{\pi^-}), Y = \frac{3T_{\pi^0}}{Q} - 1,$$

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



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





Odd power of X is related with C symmery

$c = (-0.086 \pm 2.986)\times10^{-3}$, 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

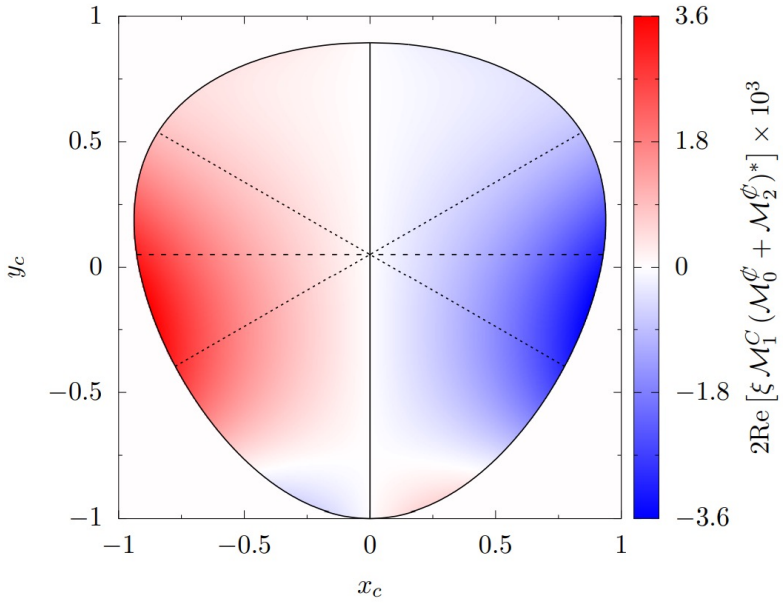
H. Akdag, T. Isken, B. Kubis, JHEP 02 (2022)137

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

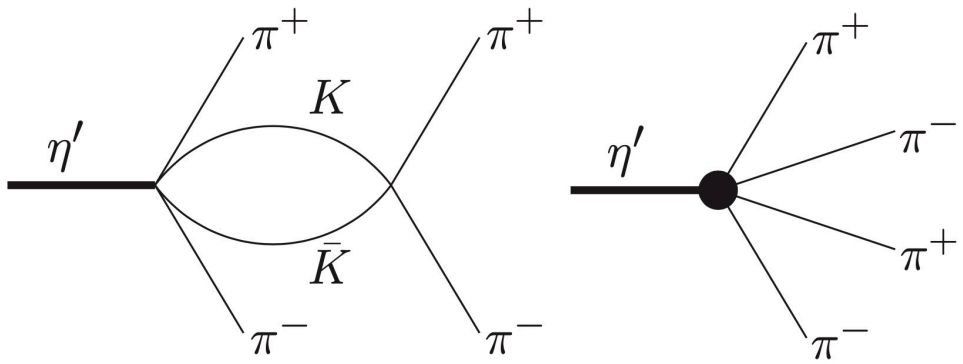


overall C/CP-violation | ΔI = 2 | ΔI = 0

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)

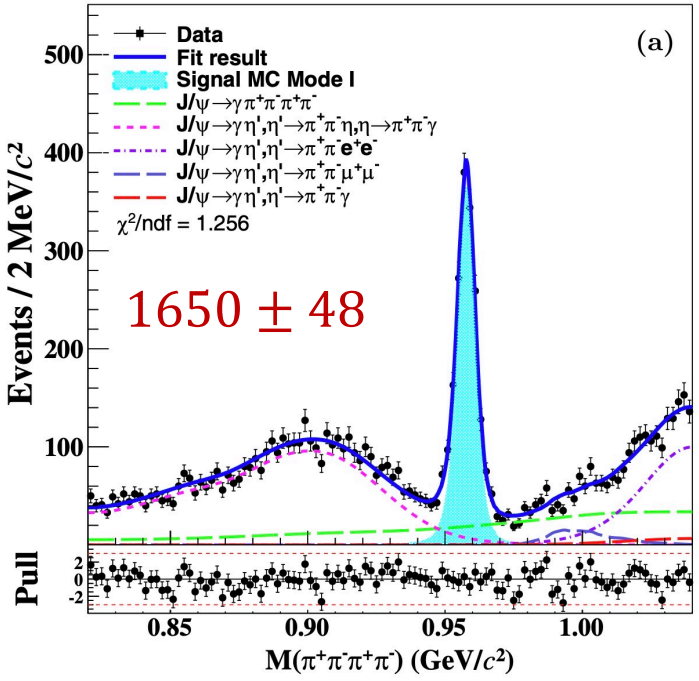
F. K. Guo, B. Kubis, A. Wirzba, PRD 85,014014 (2012)

$Br(\eta' \to 2(\pi^+\pi^-)) = (1.0 \pm 0.3)\times10^{-4}$

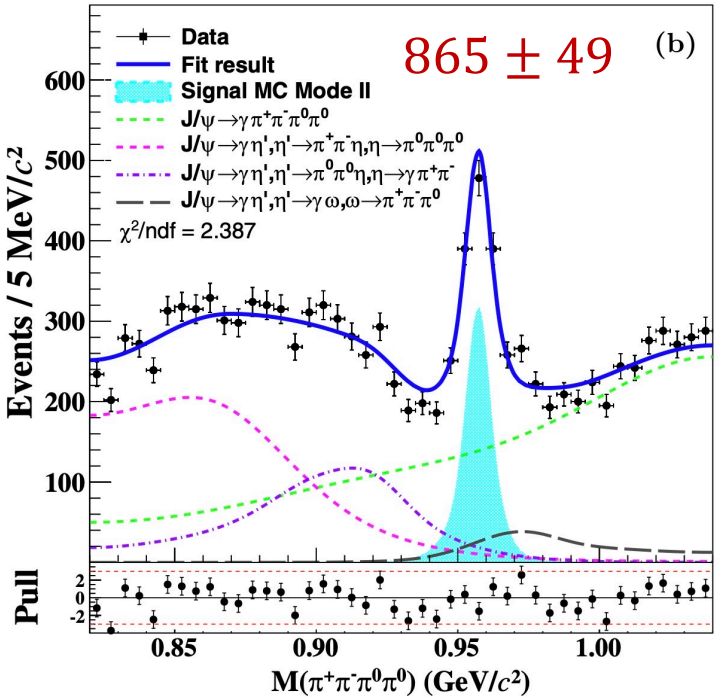
$Br(\eta' \to \pi^+\pi^-2\pi^0) = (2.4 \pm 0.7)\times10^{-4}$

Theoretical Calculation

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



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



$Br(\eta' \to \pi^+\pi^-\pi^+\pi^-) = (8.56 \pm 0.25 \pm 0.23)\times10^{-5}$

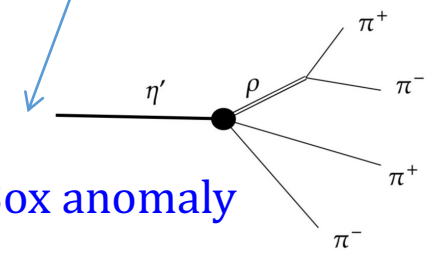
$Br(\eta' \to \pi^+\pi^-\pi^0\pi^0) = (2.12 \pm 0.12 \pm 0.10)\times10^{-4}$

BESIII Results

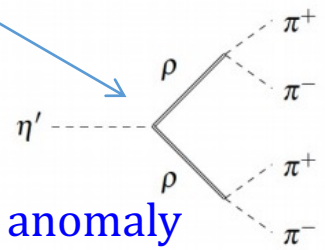
Amplitude analysis results for $\eta' \to 2(\pi^+\pi^-)$ BESIII: PRD 109, 032006 (2024)

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

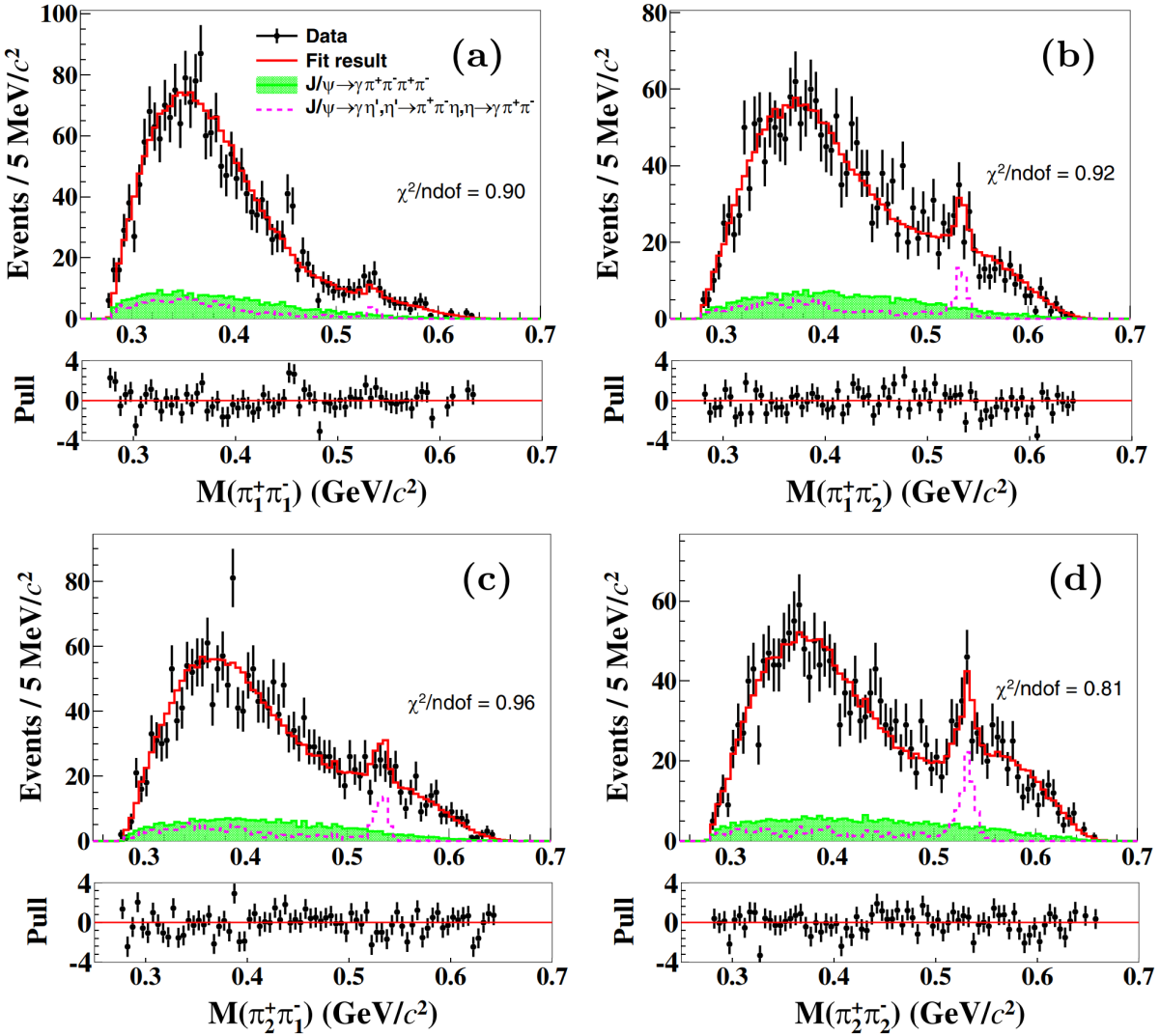


Triangle anomaly

- First measurement of the doubly virtual isovector form factor

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

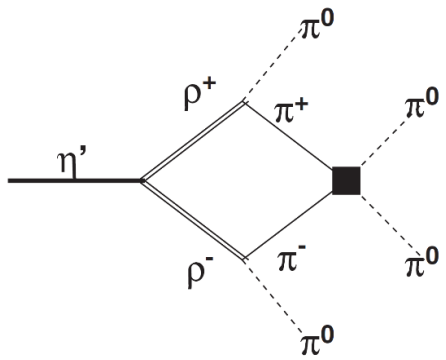
If $\alpha \simeq 1$, triangle anomaly would be dominated



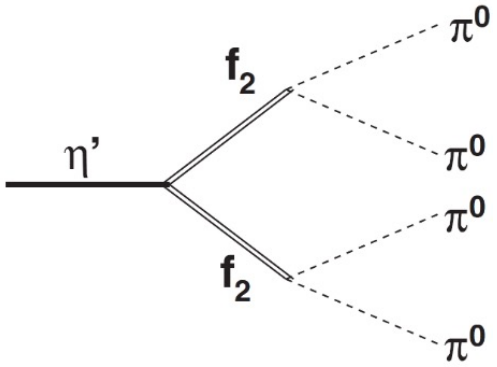
Search for rare decay $\eta' \to \pi^0\pi^0\pi^0\pi^0$

BESIII: PRD 109, 032006 (2024)

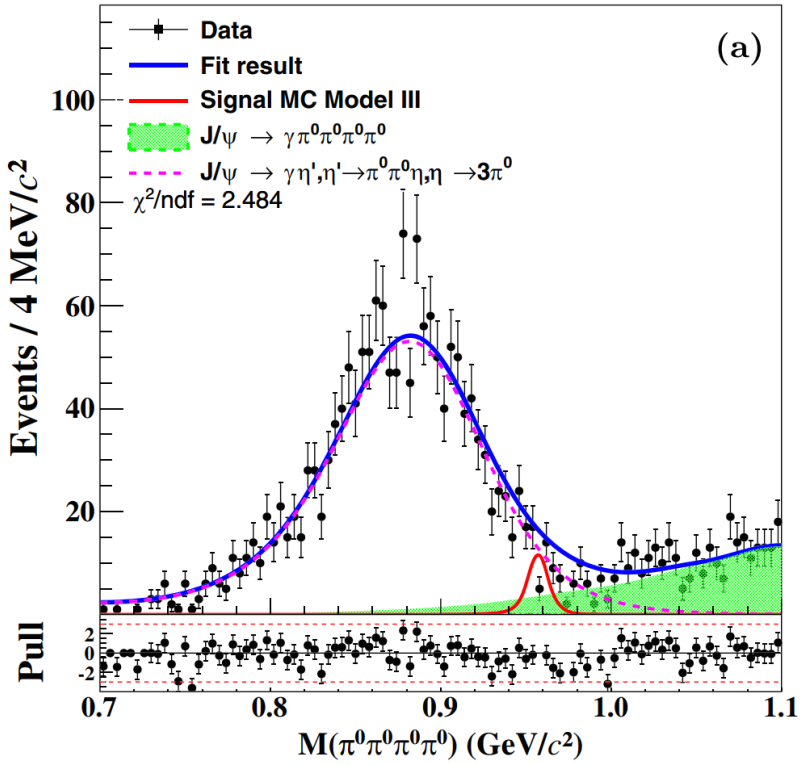
- CP-violation S-wave, induced by the QCD Lagrangian θ-term ⇒ Br~10^{-23}
- CP-conserving higher order ⇒ Br~10^{-8} F. K. Guo, B. Kubis, A. Wirzba, PRD 85,014014 (2012)



D-wave pion loop

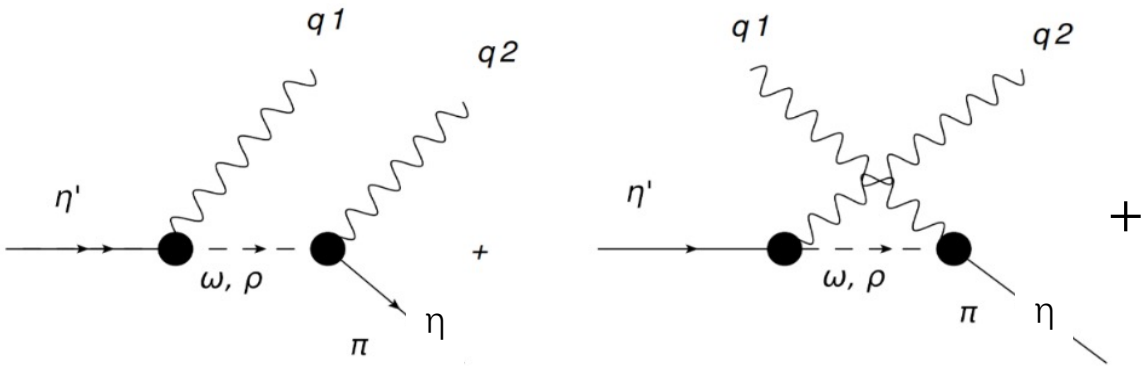


Small contribution from two f_2 tensor mesons



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

Double radiative decays $\eta' \to \gamma\gamma\pi^0/\eta$



R. Escribano, S. Gonzalez-Solis, R. Jora, E. Royo, PRD 102 (2020) 034026

+ $a_0(980)$, $\sigma(600)$ and $f_0(980)$ contributions

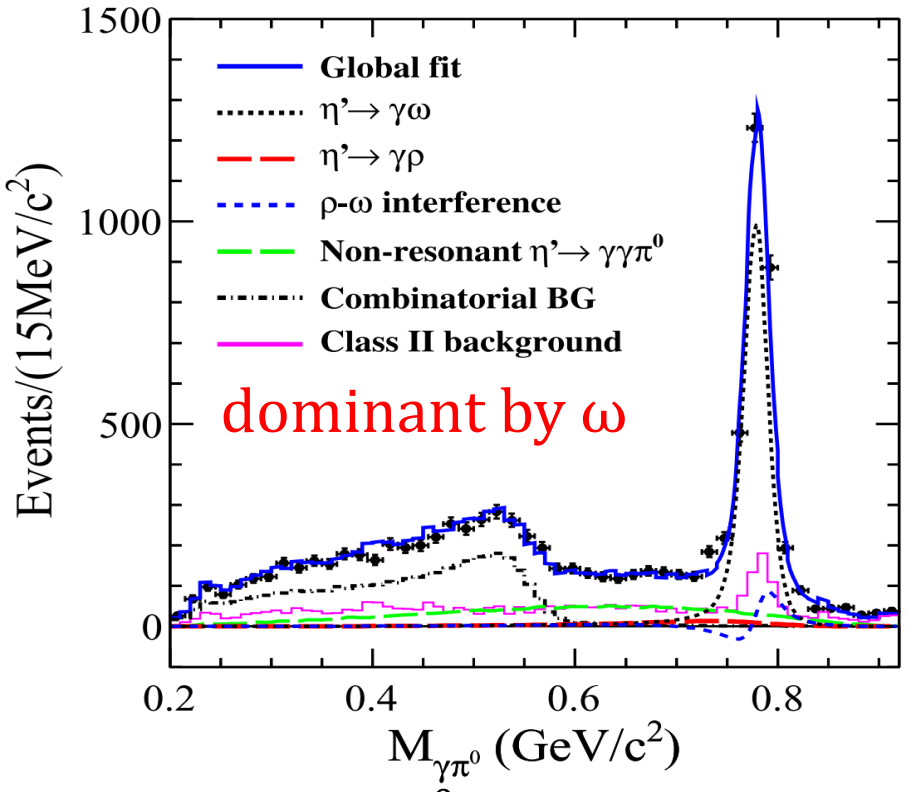
- Within the frameworks of the linear σ model (LsM) and VMD model

$$\mathcal{A}^{VMD}_{P\to\gamma\gamma P'} = \sum_{V=\rho^0,\omega,\phi} g_{VP\gamma} g_{VP'\gamma} \left[\frac{(P\cdot q_2 - m_P^2)\{a\} - \{b\}}{m_V^2 - t - i m_V \Gamma_V} + \left\{ \begin{array}{c} q_1 \leftrightarrow q_2 \\ t \leftrightarrow u \end{array} \right\} \right]$$

- ✓ BF($\eta' \to \gamma\gamma\pi^0$)=2.91(21)×$10^{-3}$
- ✓ BF ($\eta' \to \gamma\gamma\eta$)=1.17(8)×$10^{-4}$
- ✓ Br($\eta \to \pi^0\gamma\gamma$) = (1.30±0.08)×$10^{-4}$

Double radiative decays $\eta' \to \gamma\gamma\pi^0/\eta$

BESIII: PRD 96, 012005 (2017)

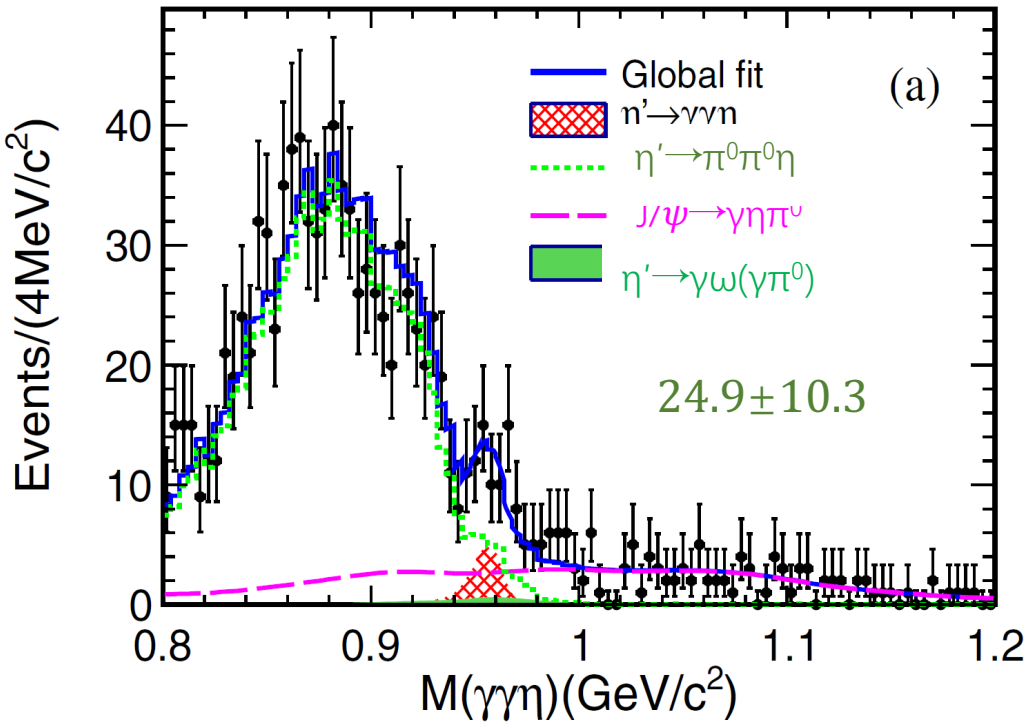


$$\mathrm{Br}(\eta' \to \gamma\gamma\pi^0) = (32.0 \pm 0.7 \pm 2.3)\times10^{-4}$$

$$\mathrm{Br}(\eta' \to \gamma\omega \to \gamma\gamma\pi^0) = (23.7 \pm 1.4 \pm 1.8)\times10^{-4}$$

$$\mathrm{Br}(\eta' \to \gamma\gamma\pi^0)(\mathrm{NR}) = (6.16 \pm 0.64 \pm 0.67)\times10^{-4}$$

BESIII: PRD 100, 052015 (2019)



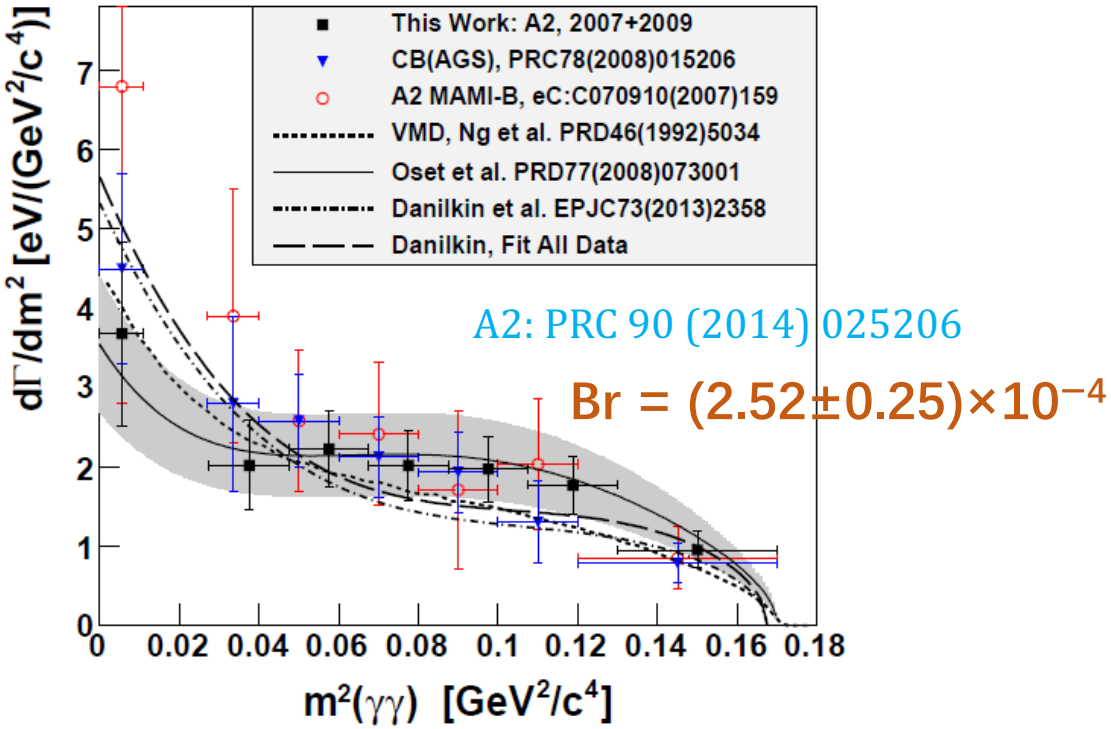
$$B(\eta' \to \gamma\gamma\eta) = (8.25 \pm 3.41 \pm 0.72) \times 10^{-5}$$

With 10 Billion J/ψ, the study is ongoing

Doubly radiative decay $\eta\to\gamma\gamma\pi^0$

- ChPT "golden mode": $O(p^2)$ null, $O(p^4)$ suppressed, $O(p^6)$ dominates [PLB 276(1) (1984) 185]
- Discrepancy between experimental and theoretical results

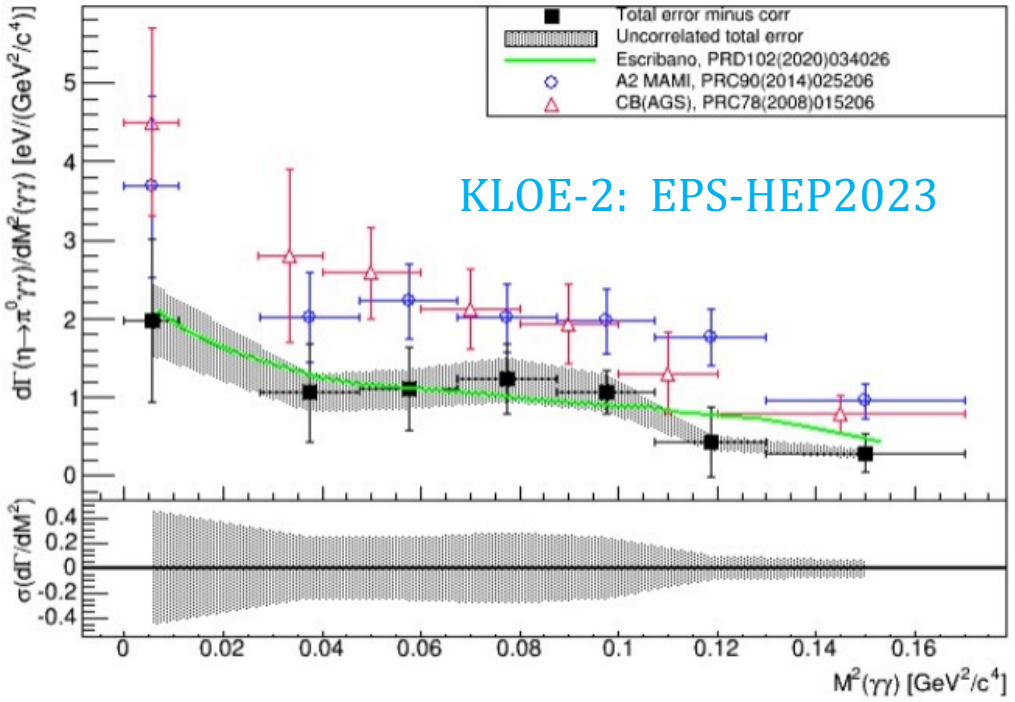
$Br(\eta\to\pi^0\gamma\gamma) = (1.30\pm0.08)\times10^{-4}$ LσM+VMD



A2: PRC 90 (2014) 025206

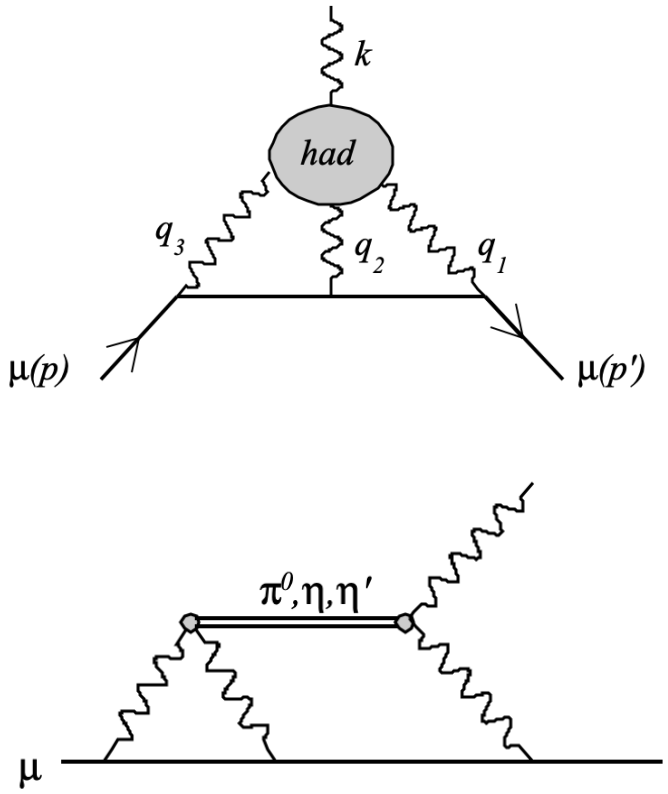
$Br = (2.52\pm0.25)\times10^{-4}$

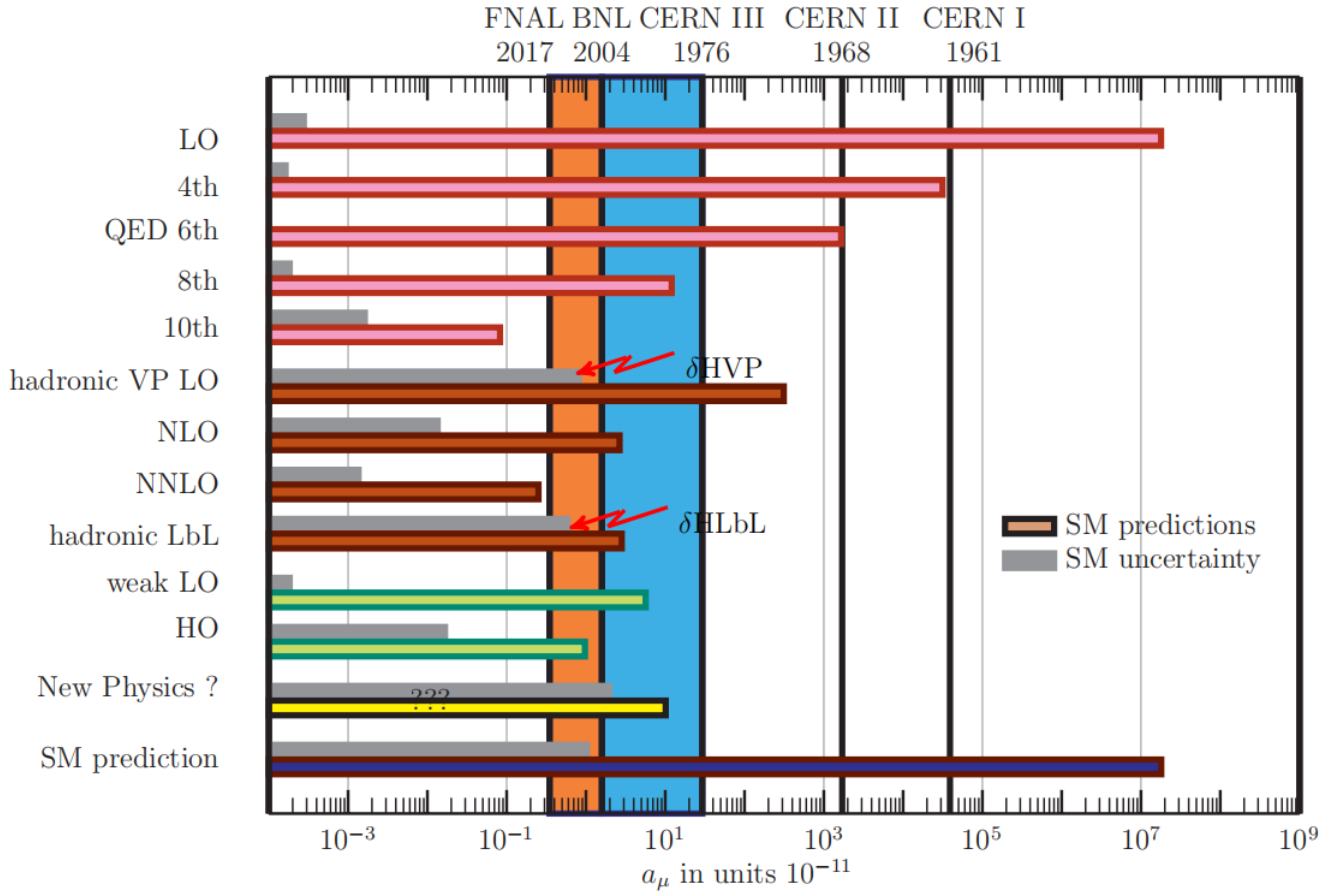
$Br= (0.99\pm 0.11\pm 0.24)\times10^{-4}$



Transition form factor of η/η'

Important input for HLbL of g-2

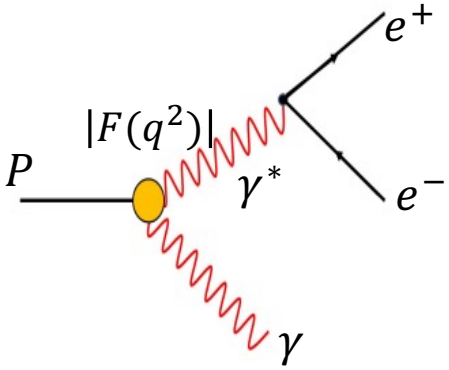




Transition form factor of $\eta/\eta' \to \gamma e^+e^-$

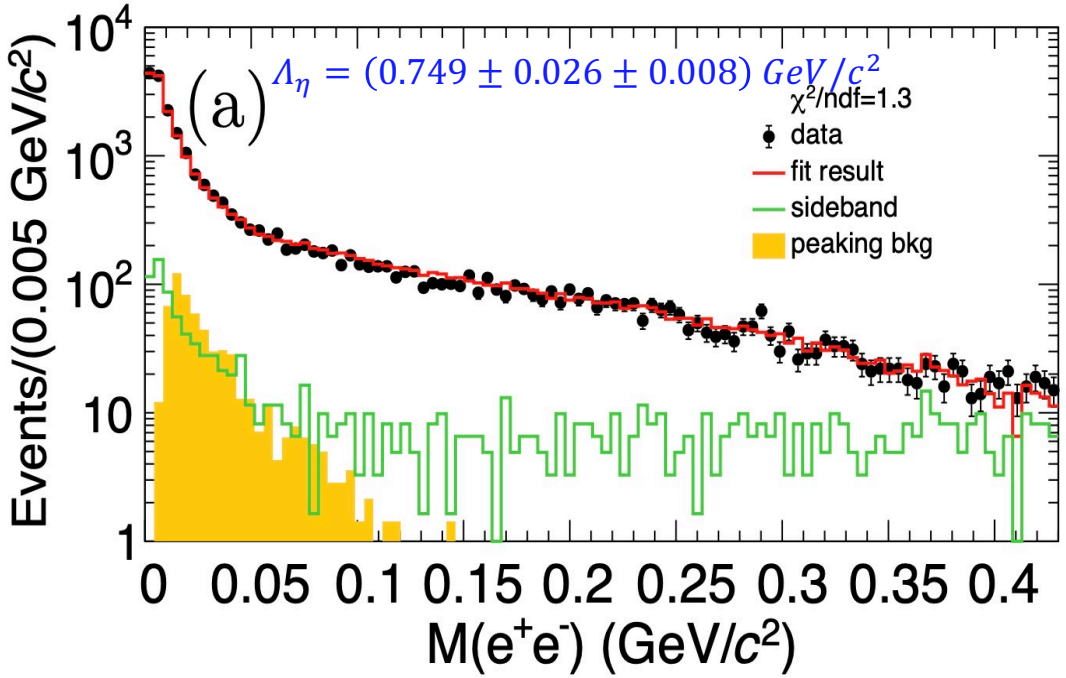
BESIII: PRD 109, 072001 (2024)

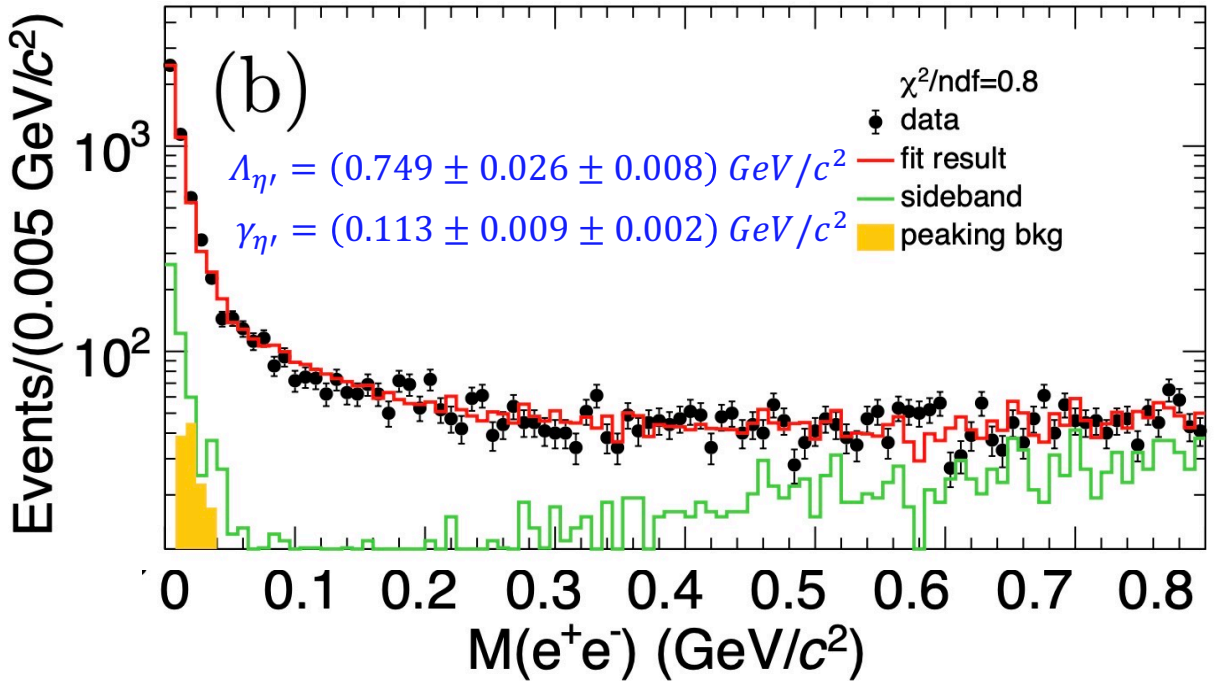
$$\frac{d\Gamma(P \to \gamma l^+ l^-)}{dq^2 \Gamma_{\gamma\gamma}} = \frac{2\alpha}{3\pi}\frac{1}{q^2}\sqrt{1-\frac{4m_l^2}{q^2}}\left(1+\frac{2m_l^2}{q^2}\right)\left(1-\frac{q^2}{M_P^2}\right)^3 |F_P(q^2,0)|^2$$



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

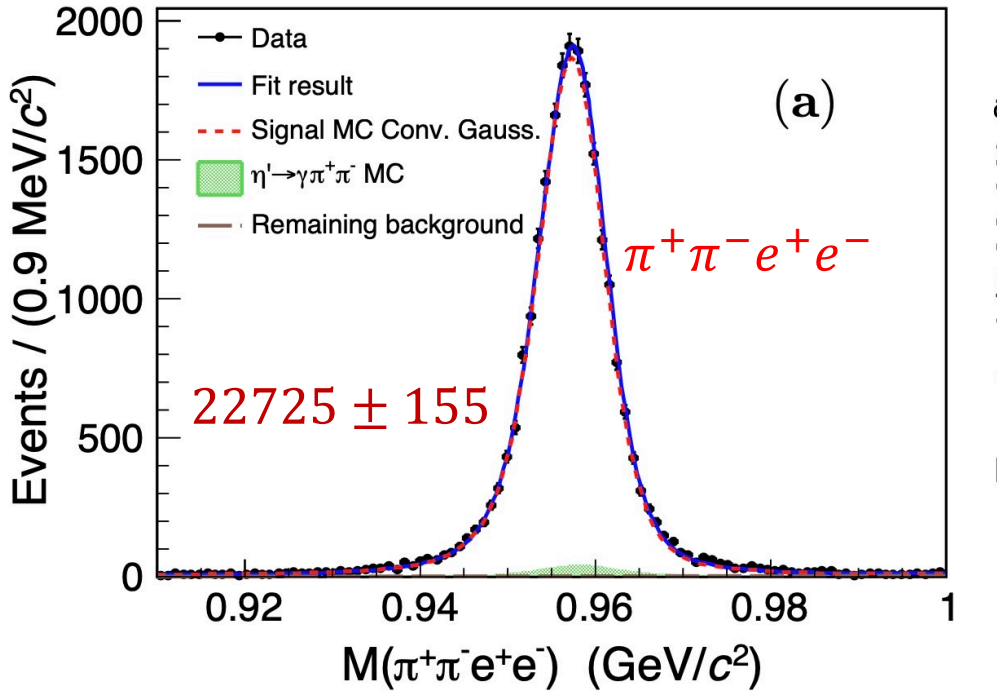
❖ For $\eta' \to \gamma e^+e^-$, Multi-pole model: $|F(q^2)|^2 = \frac{\Lambda^2(\Lambda^2+\gamma^2)}{(\Lambda^2-q^2)^2+\Lambda^2\gamma^2}$

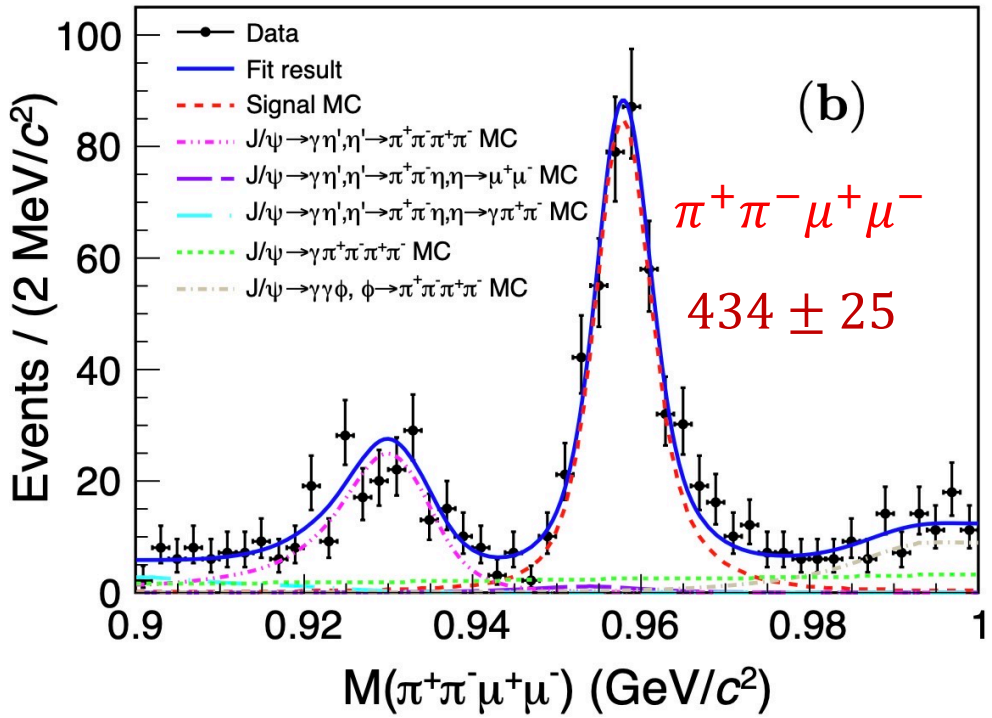




Precision study of $\eta' \to \pi^+\pi^- l^+ l^-$

BESIII: JHEP 07, 135 (2024)





BESIII 2024

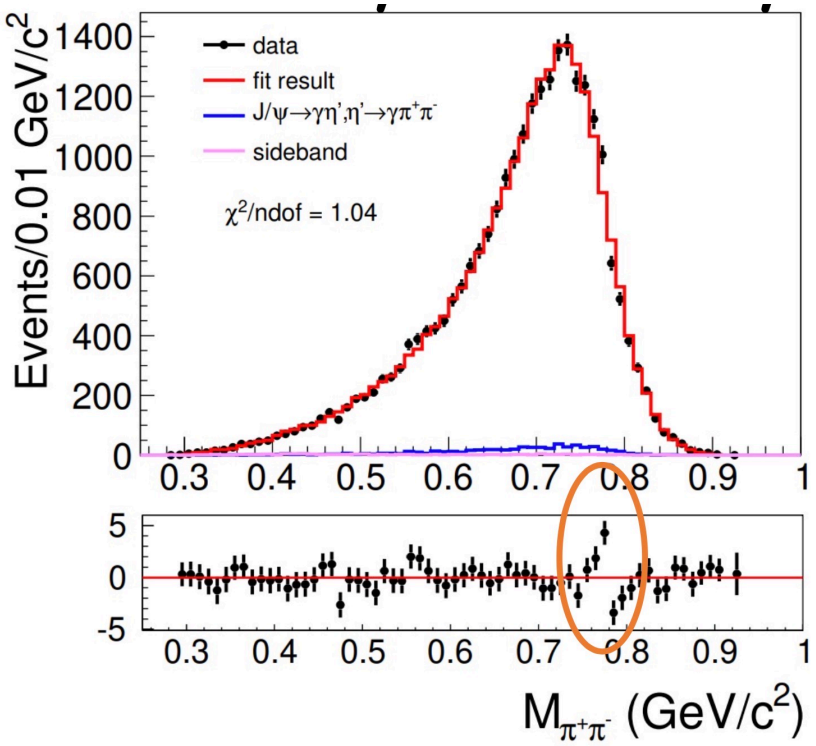
$$Br(\eta' \to \pi^+\pi^- e^+ e^-) = (2.45 \pm 0.02 \pm 0.08)\times 10^{-3}$$

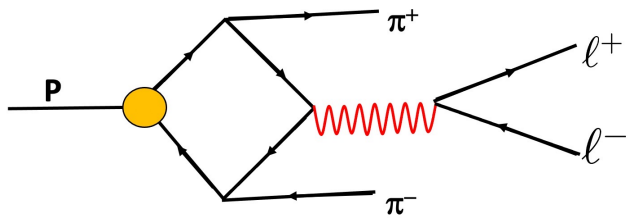
$$Br(\eta' \to \pi^+\pi^- \mu^+ \mu^-) = (2.16 \pm 0.12 \pm 0.06)\times 10^{-5}$$

	$\mathcal{B}(\eta' \to \pi^+\pi^- e^+ e^-)$ (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)$^\diamond$	$2.11 \pm 0.12 \pm 0.15$	< 2.9
BESIII (2021)$^\diamond$	$2.42 \pm 0.05 \pm 0.08$	$1.97 \pm 0.33 \pm 0.19$
CLEO$^\diamond$	$2.50^{+1.2}_{-0.9} \pm 0.5$	< 24

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

BESIII: JHEP 07, 135 (2024)

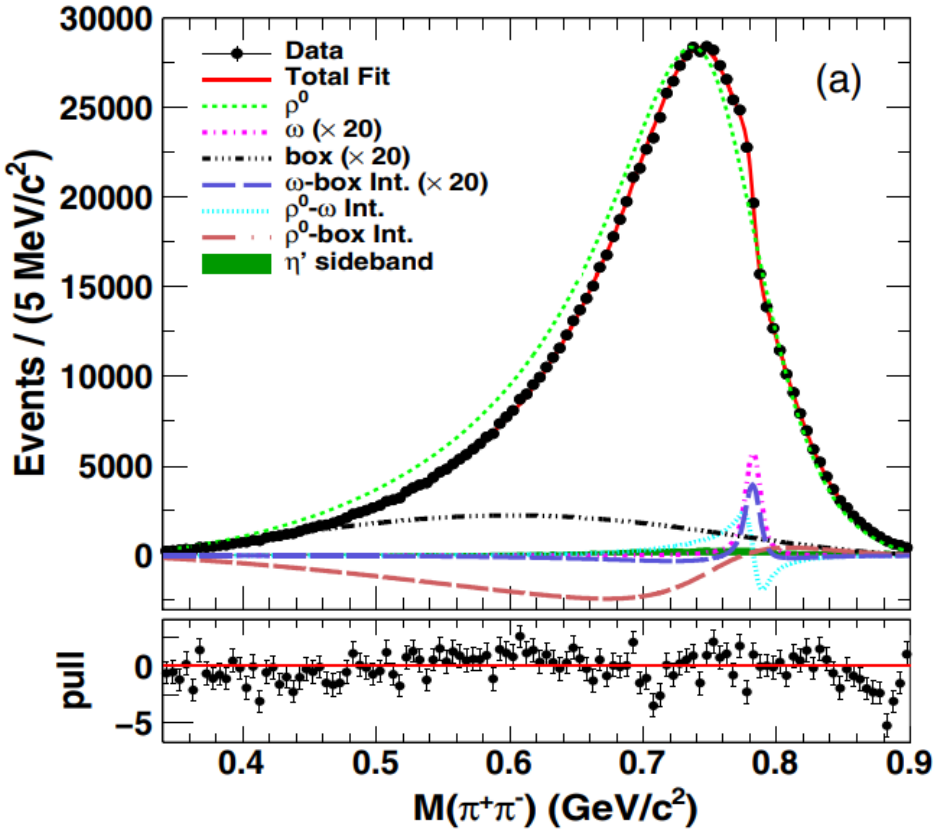




- **Box-anomaly** is needed to describe data
  - ✓ Similar as $\eta' \to \gamma\pi^+\pi^-$, replacing γ with an off-shell one
- $\omega \to \pi^+\pi^-$ is also necessary

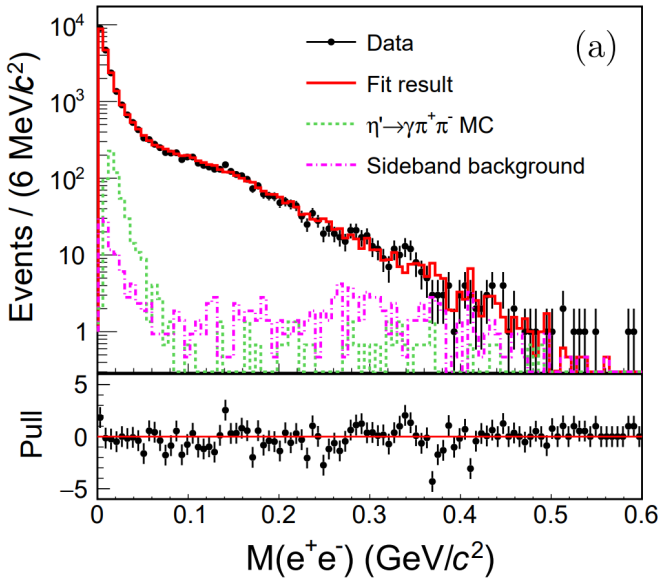
$\eta' \to \gamma\pi^+\pi^-$

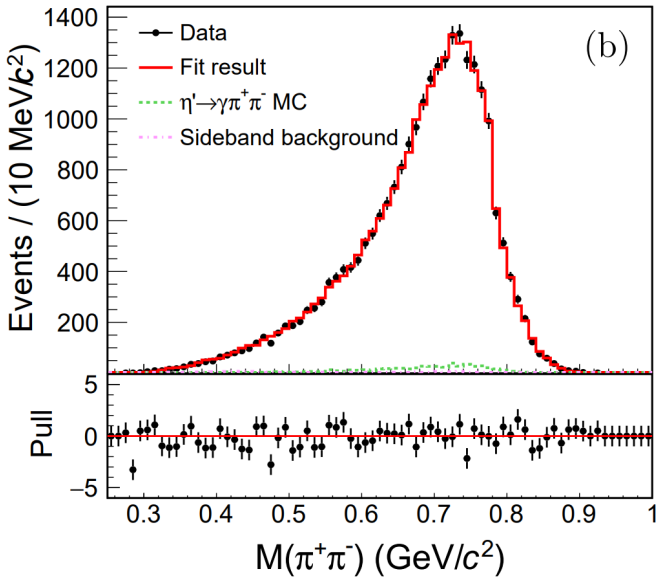
BESIII: PRL 120 (2018) 242003

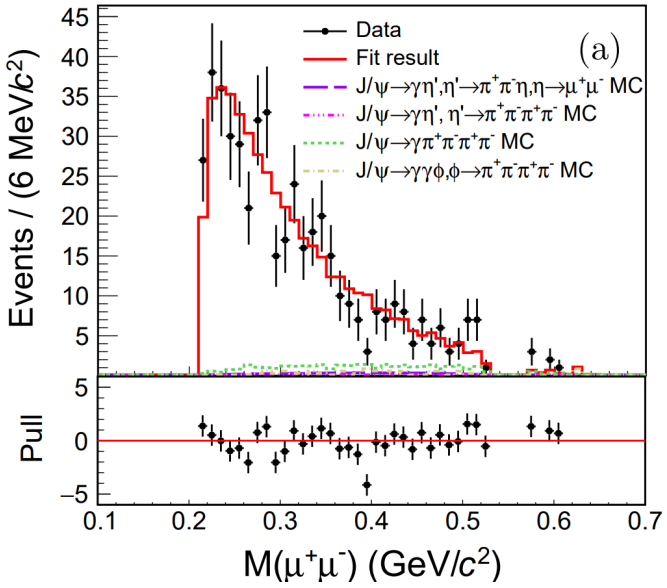


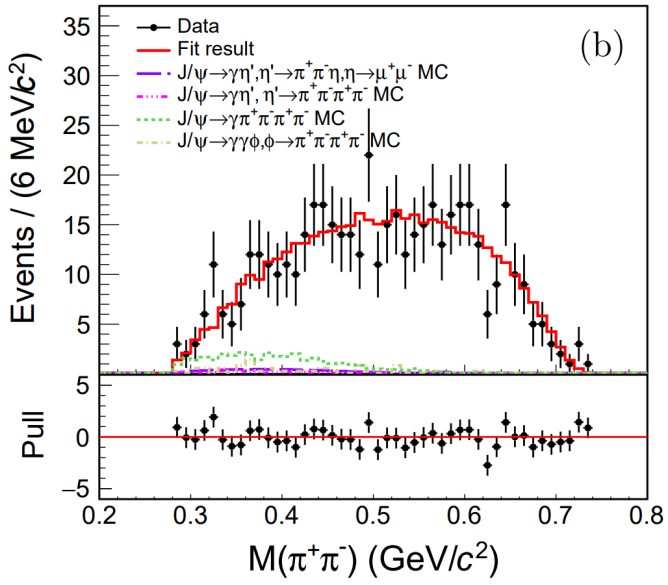
ρ(770)-ω-box anomaly

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





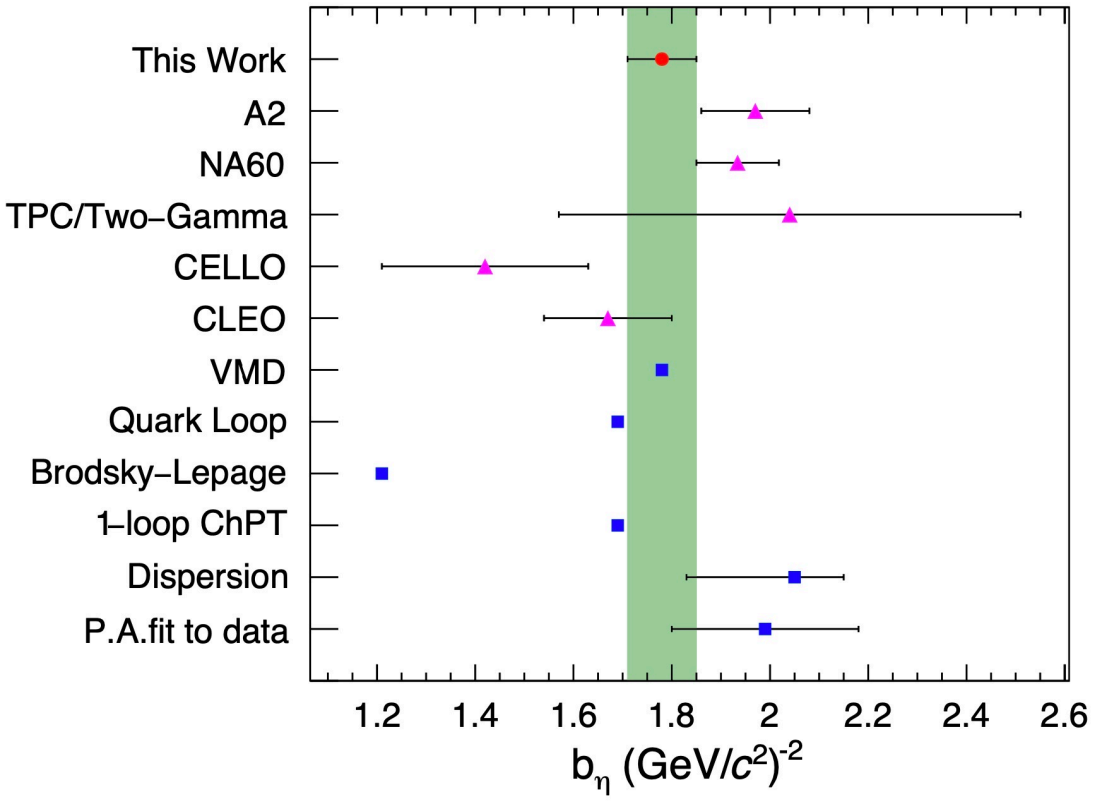




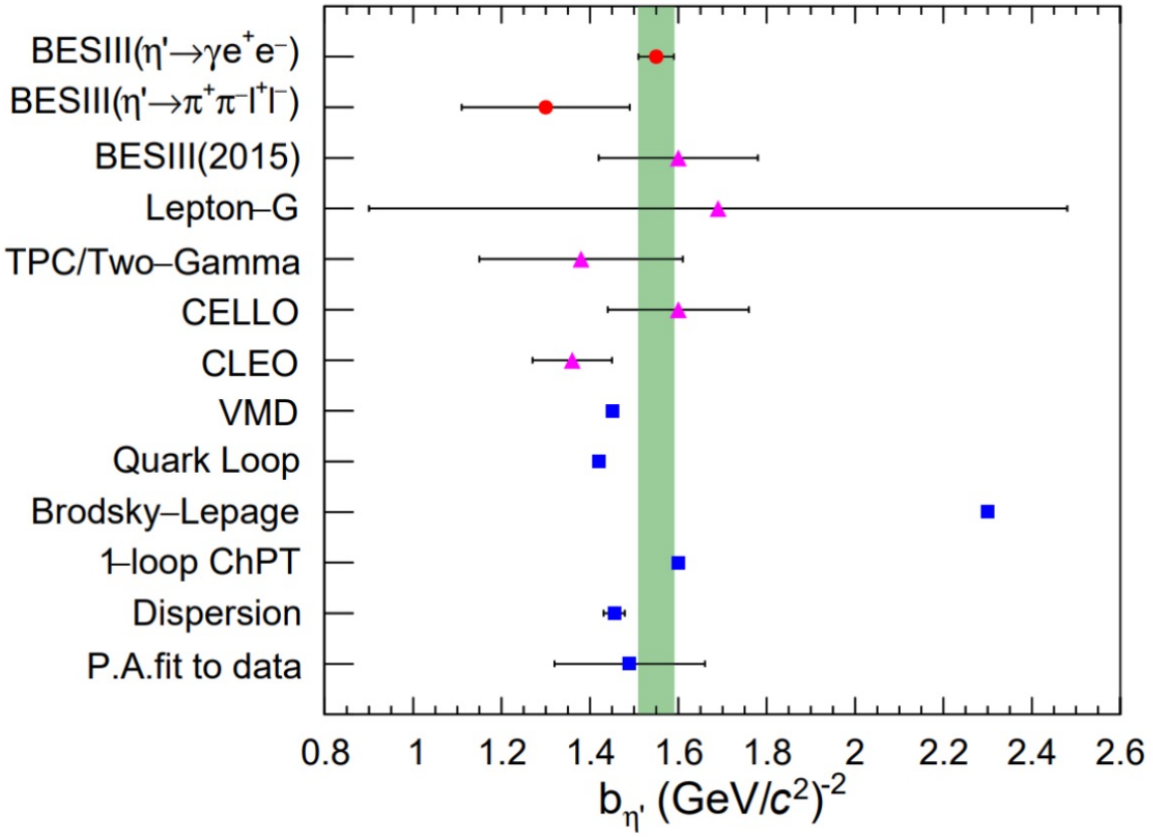
✓ First time to assess the form factors with $\eta' \to \pi^+\pi^- l^+ l^-$ within VMD

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

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



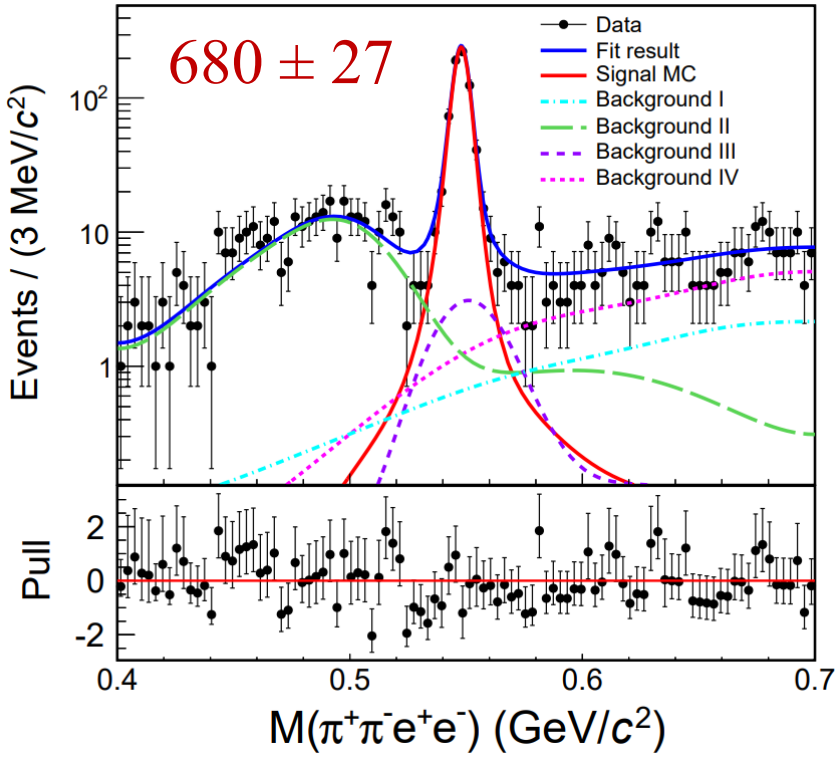
$$b_\eta = 1.781 \pm 0.123 \pm 0.033\ (\mathrm{GeV/c^2})^{-2}$$



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

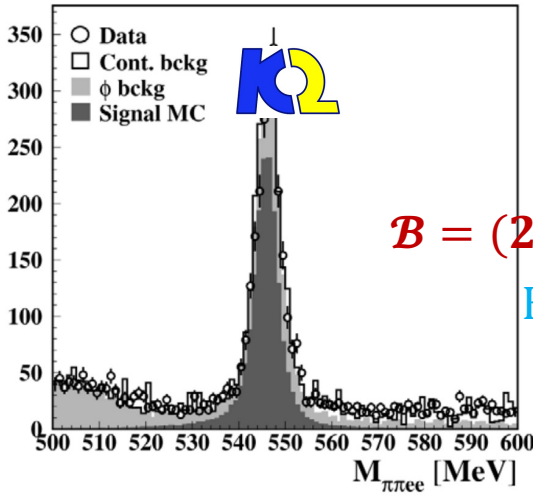
Study of $\eta \to \pi^+\pi^- l^+ l^-$

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



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

- No event left for $\eta \to \pi^+\pi^-\mu^+\mu^-$
- The UL is set as 4.0×10^{-7} at the 90% CL



$Nsig = 1555 \pm 52$

$\mathcal{B} = (2.68 \pm 0.05 \pm 0.07)\times 10^{-4}$

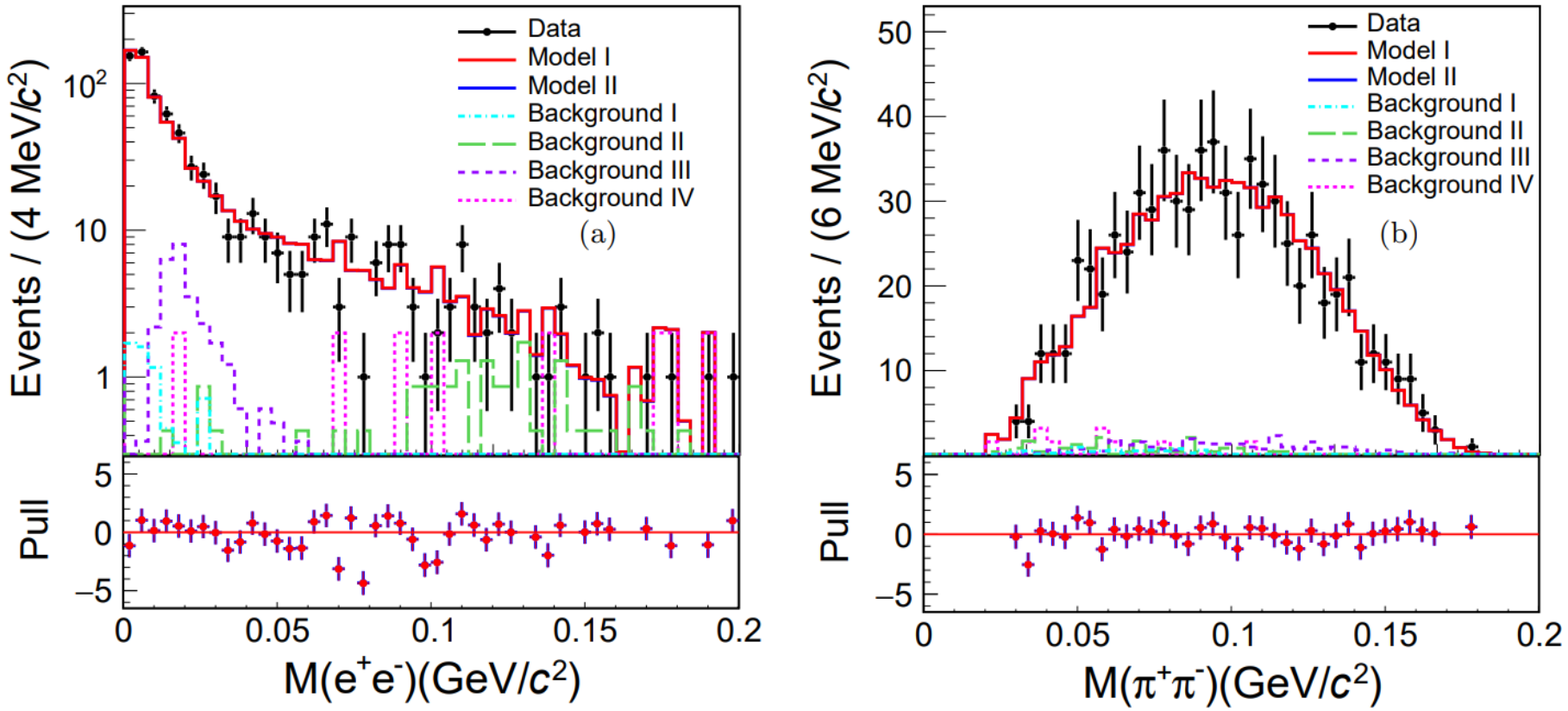
KLOE: PLB 675 (2009) 283

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

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

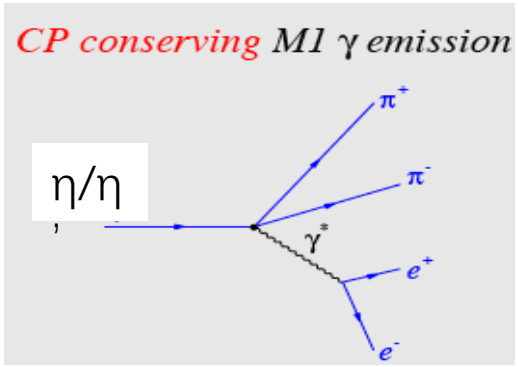
arXiv:2501.10130v1 [hep-ex] Accepted by PRD

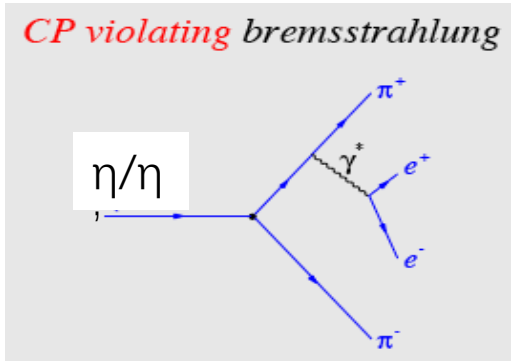
Allow to access the decay dynamic but with limited statistics

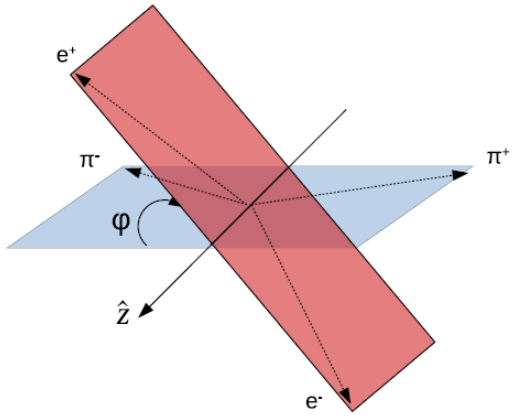


Asymmetry in $\eta/\eta' \to \pi^+\pi^- l^+ l^-$

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







[Dao-Neng Gao, Mod.Phys.Lett.A17 (2002) 1583]

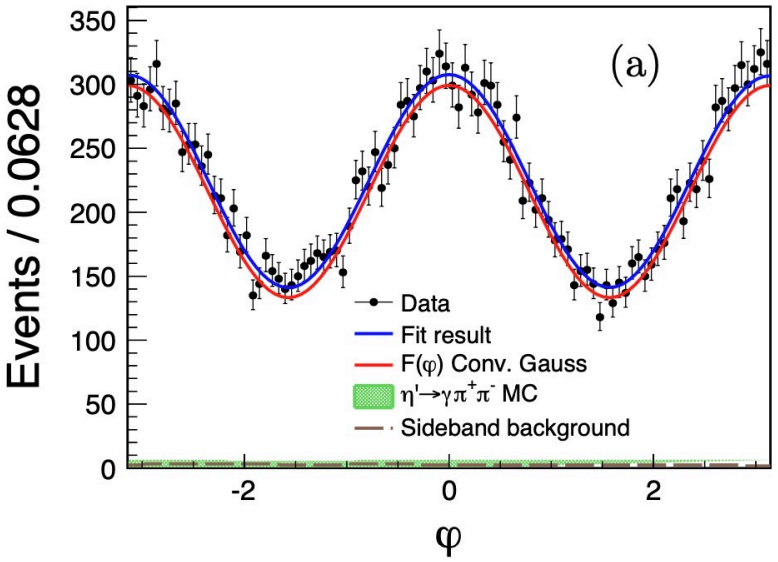
The interference term can be extracted by the asymmetry of sin2φ distribution

$$\mathcal{A}_\varphi = \frac{N(\sin 2\varphi > 0) - N(\sin 2\varphi < 0)}{N(\sin 2\varphi > 0) + N(\sin 2\varphi < 0)}$$

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

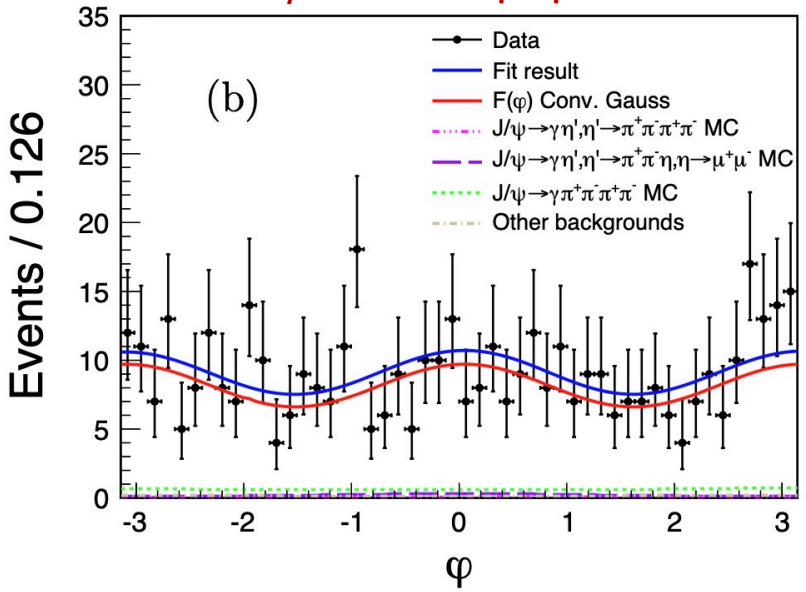
BESIII: JHEP 07, 135 (2024)

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



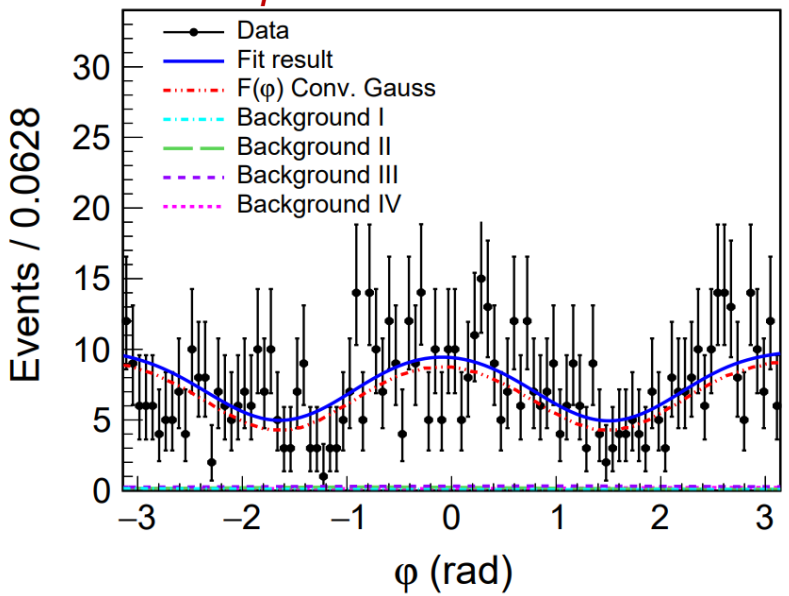
$A_{CP} = (-0.21 \pm 0.73 \pm 0.01)\%$

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



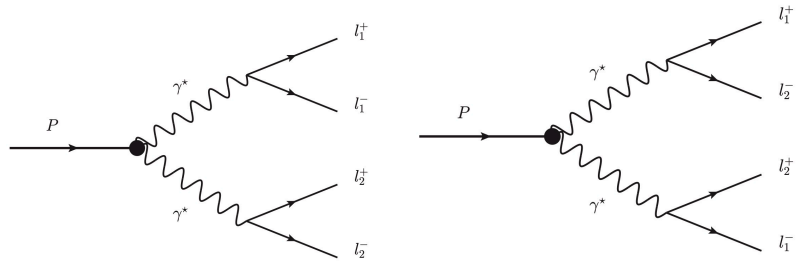
$A_{CP} = (0.62 \pm 4.71 \pm 0.08)\%$

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

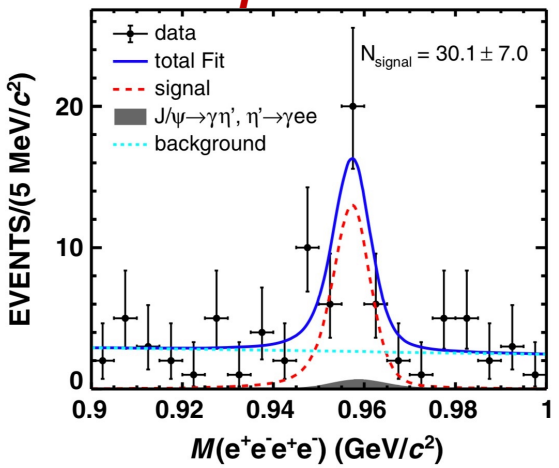


$A_{CP} = (-4.04 \pm 4.69 \pm 0.14)\%$

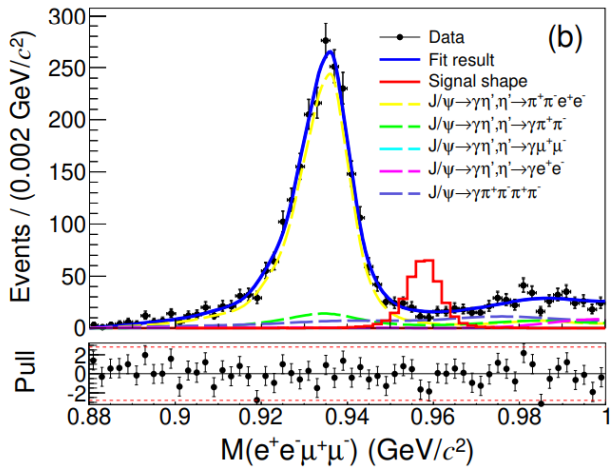
Double Dalitz decays $\eta^{(\prime)} \to l^+l^-l^+l^-$



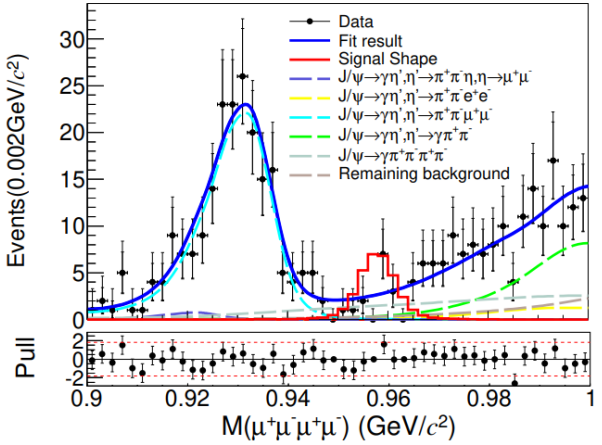
$\eta' \to e^+e^-e^+e^-$



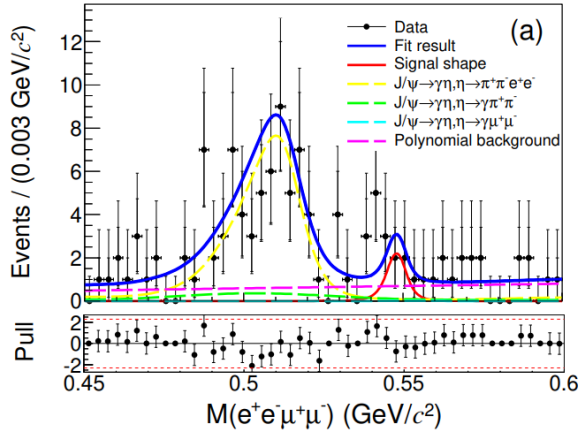
$\eta' \to e^+e^-\mu^+\mu^-$



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



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



BESIII: PRD105,112010

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]
$\eta' \to e^+e^-e^+e^-$	$2.384(4) \times 10^{-6}$	$2.317(4) \times 10^{-6}$	$2.10(45) \times 10^{-6}$	$4.5(1) \times 10^{-6}$ [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]
$\eta' \to \mu^+\mu^-\mu^+\mu^-$	$2.360(12) \times 10^{-8}$	$2.185(10) \times 10^{-8}$	$1.69(36) \times 10^{-8}$	-
$\eta \to e^+e^-\mu^+\mu^-$	$2.213(26) \times 10^{-6}$	$2.154(22) \times 10^{-6}$	$2.39(7) \times 10^{-6}$	$< 1.6 \times 10^{-4}$ [15]
$\eta' \to e^+e^-\mu^+\mu^-$	$8.626(33) \times 10^{-7}$	$7.968(31) \times 10^{-7}$	$6.39(91) \times 10^{-7}$	-

KLOE

BESIII 2022

CMS

$< 5.28 \times 10^{-7}$

$< 6.88 \times 10^{-6}$

$< 1.75 \times 10^{-6}$

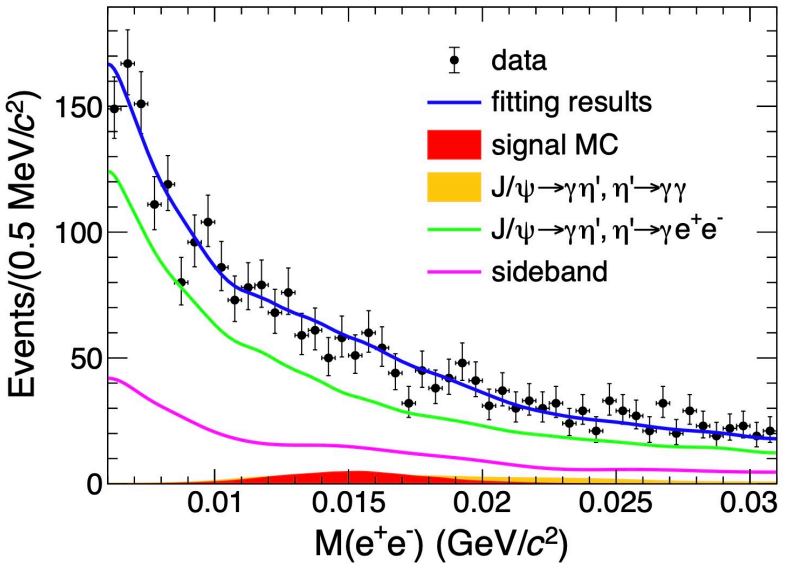
T. Petri, arXiv:1010.2378

CPC 42 (2018) 023109

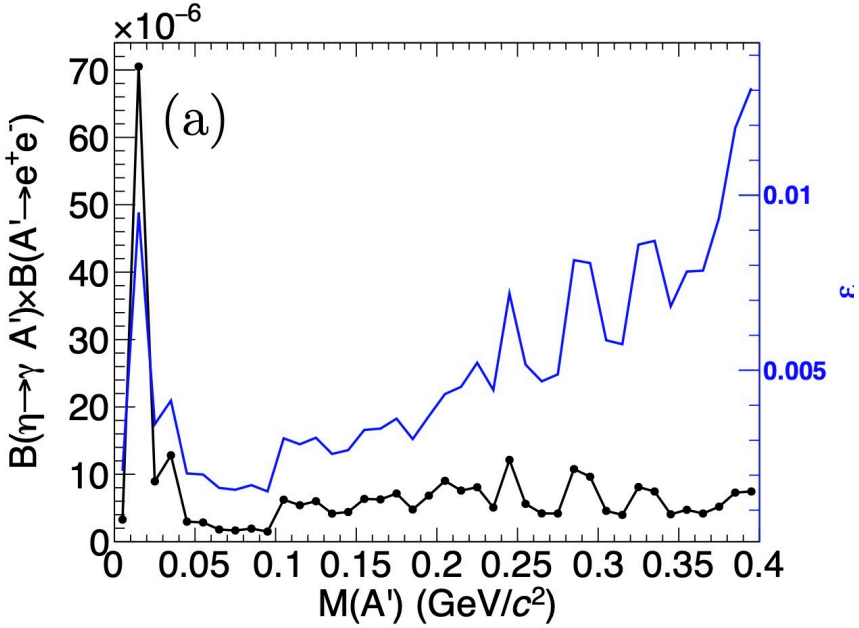
BSM Physics in Dark Sector

BESIII: PRD 109 (2024) 072001

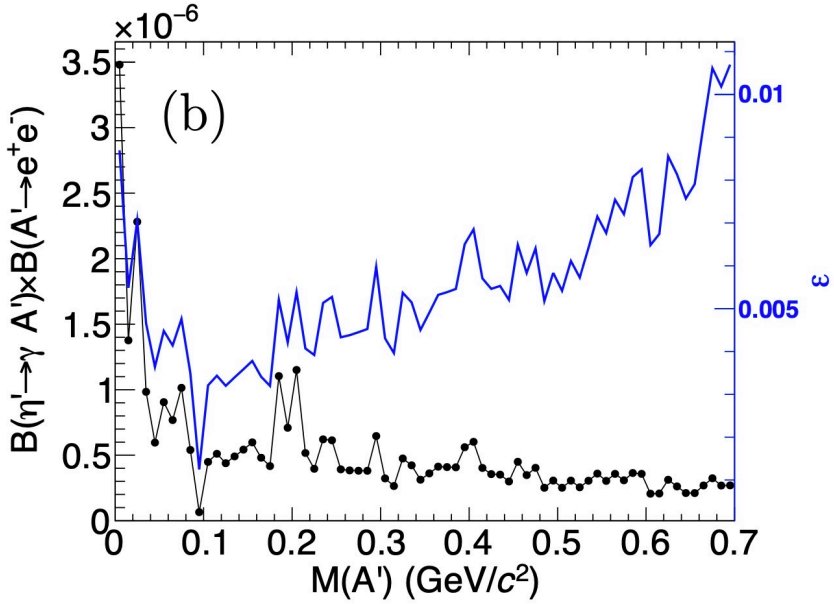
- Dark photon in $\eta/\eta' \to \gamma A', A' \to e^+e^-$



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



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



BSM Physics in Dark Sector

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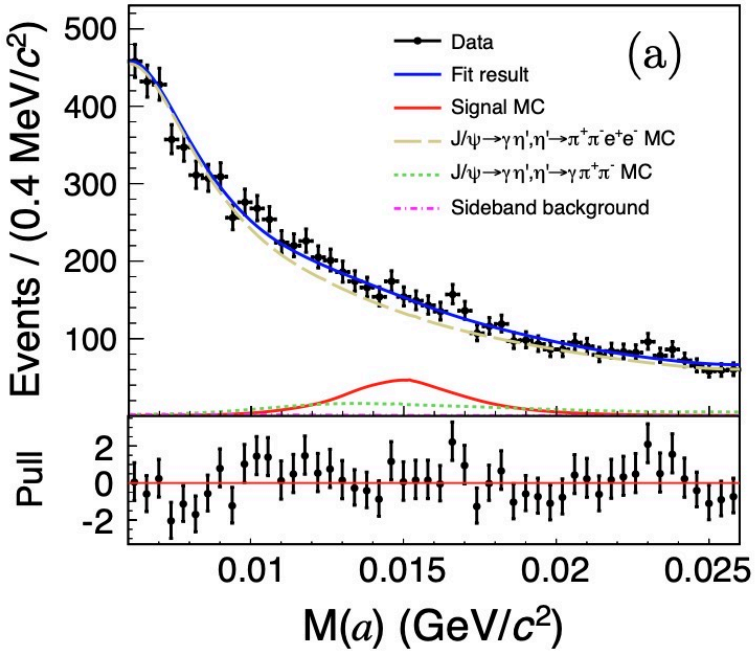
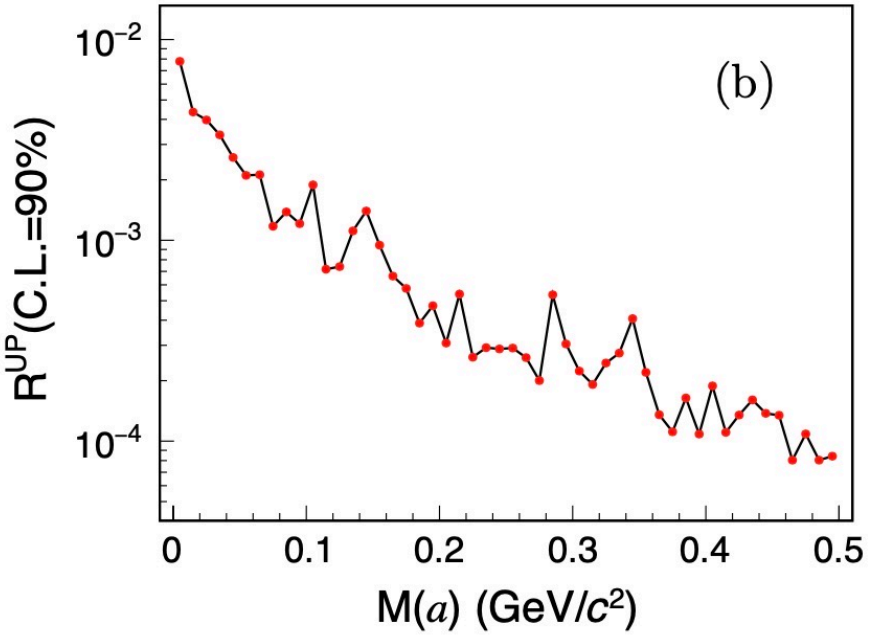
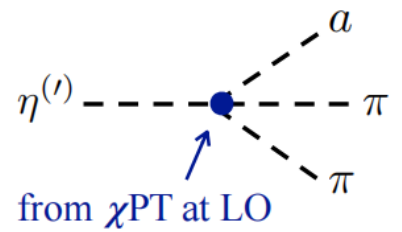
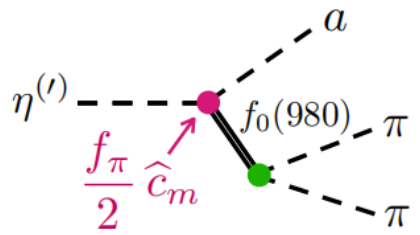
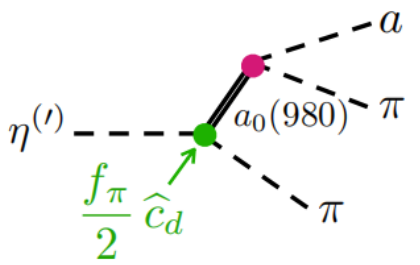
- Axion-like particle in $\eta' \to \pi^+\pi^- a,\ a \to e^+e^-$











Summary

- η/η': an important tool for particle physics: SM and BSM
- Significant progresses achieved on decay mechanisms, TFFs …
- But still far away for fully exploit the physics potential on η/η'
- We are looking forward for more experimental statistics

Thanks for your attention!!!