Light Meson Decays at BESIII

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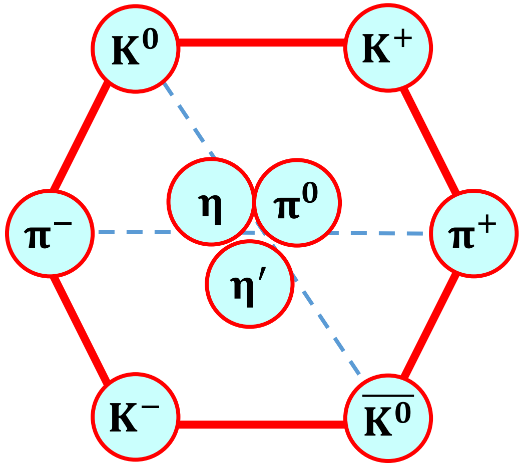
Contents

Light Meson Physics

✓ **Light Meson**

✧ **Important roles in particle physics**

✧ **Understanding the low energy QCD**



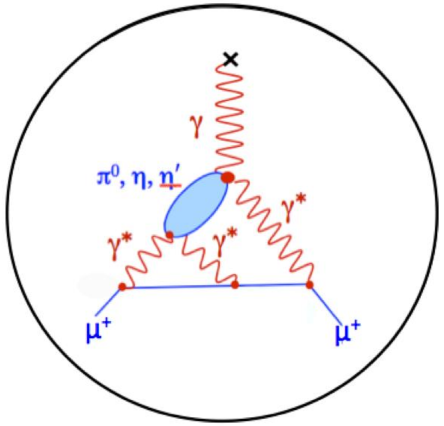
✓ **Light Meson Decays: Rich Physics**

✧ **Test theoretical model**

- Vector Meson Dominance (VMD), Chiral Perturbation Theory (ChPT), Non-Relativistic Effective Field Theory (NREFT) …

✧ **Transition form factor**

- Important input for HLbL contributions



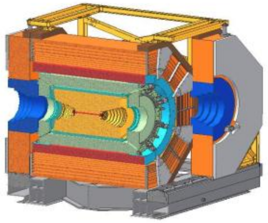
✧ **Test fundamental symmetries**

✧ **New physics beyond the Standard Model**

- ALPs, dark photons, new sources of P/C/CP-violation …

Source of η/η'

- ✓ **η/η' :** Light masses, narrow widths and simple decay final-state topologies.
- ✓ A hot topic of **theoretical discussions** and **an important research subject** for many experimental collaborations.



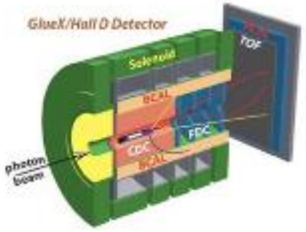
BESIII

Crystal Ball

WASA-at-COSY

KLOE-2

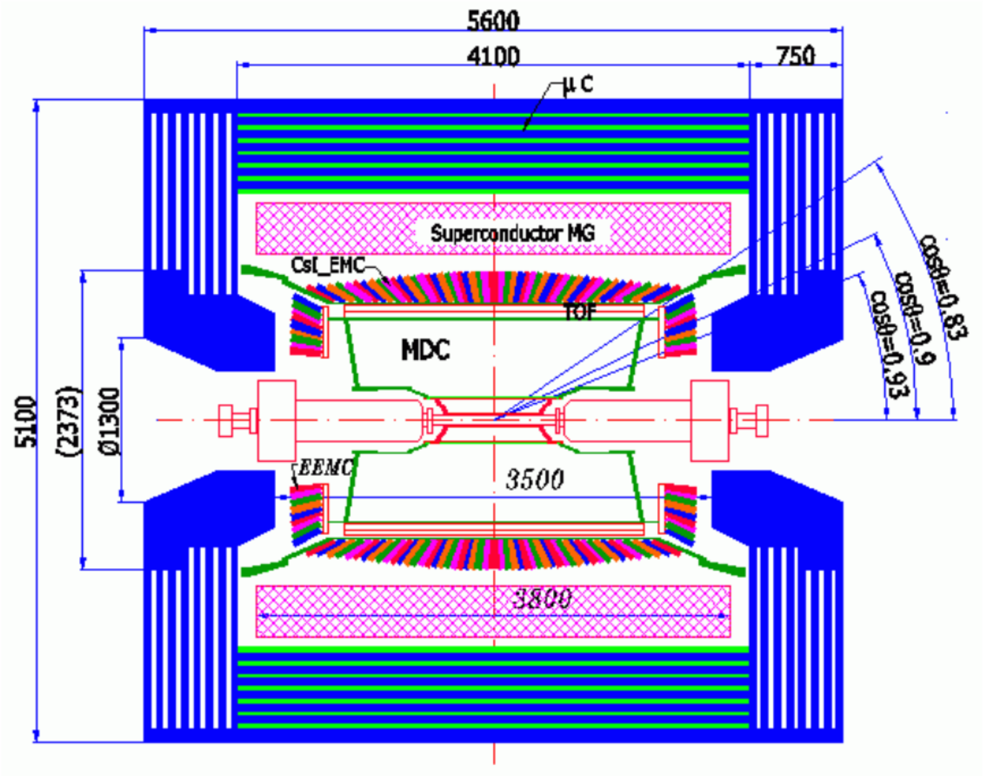
CLAS(12)



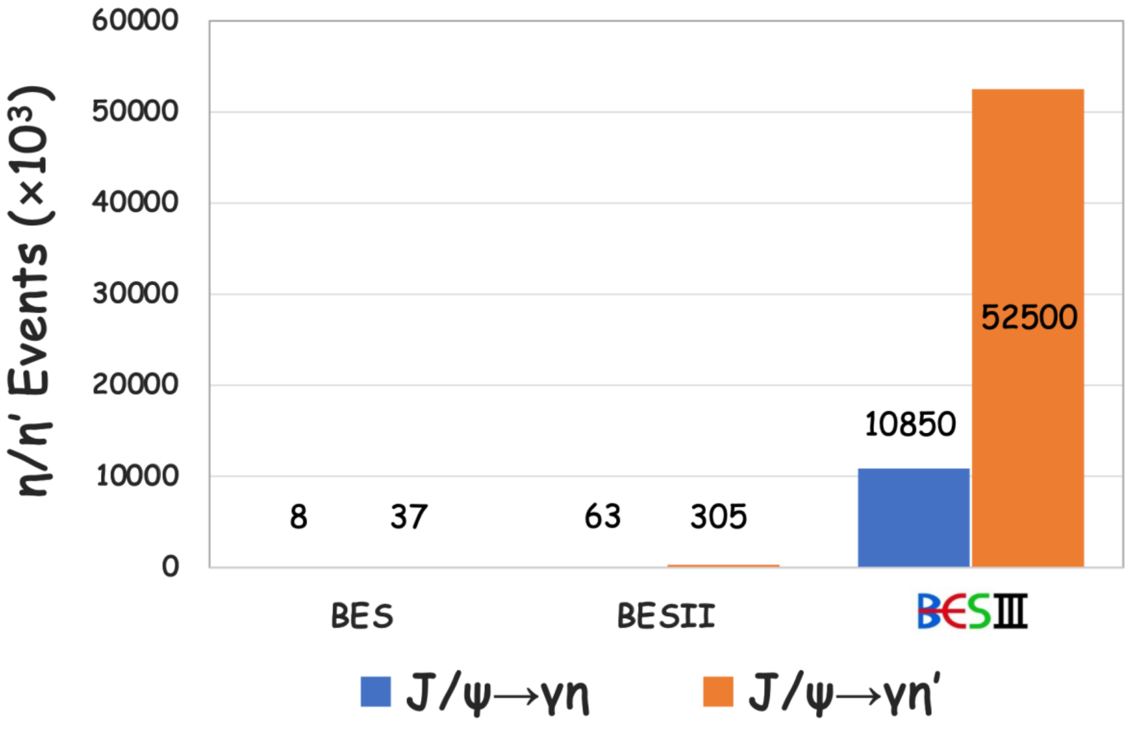
GlueX

BESIII Detector

- ✓ The BESIII detector records symmetric e^+e^- collisions provided by the BEPCII storage ring.
- ✓ The facility is used for studies of hadron physics and τ-charm physics.
- ✓ Collected 10 billion J/ψ Events!



An overview of the BESIII detector.

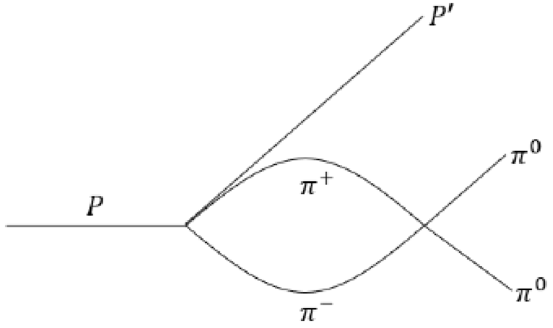


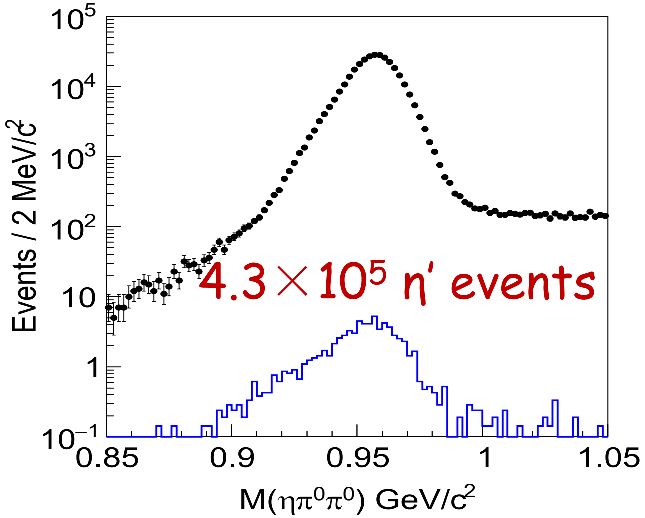
A light meson factory!

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

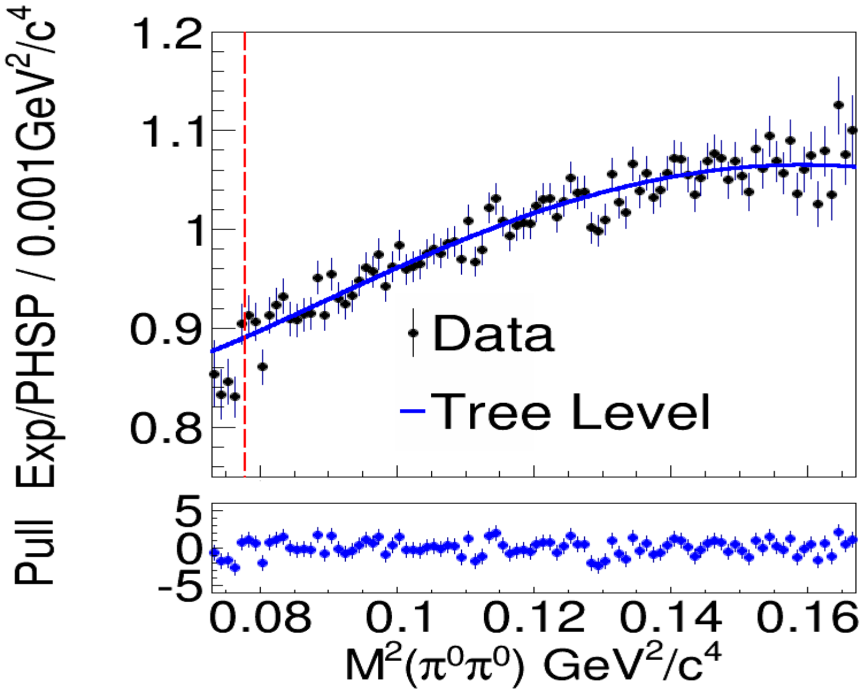
Phys. Rev. L 130, 081901 (2023)

- Test **ChPT** and **NREFT** model
- In ππ interaction, one of the prominent features is the loop contribution to the ππ scattering: **The S-wave charge-exchange rescattering $\pi^+\pi^- \to \pi^0\pi^0$ causes a prominent cusp at the center of mass energy corresponding to the summed mass of two charged pions.**
- By determining the strength of the S-wave ππ interaction to study the fundamental properties of QCD at low energies.





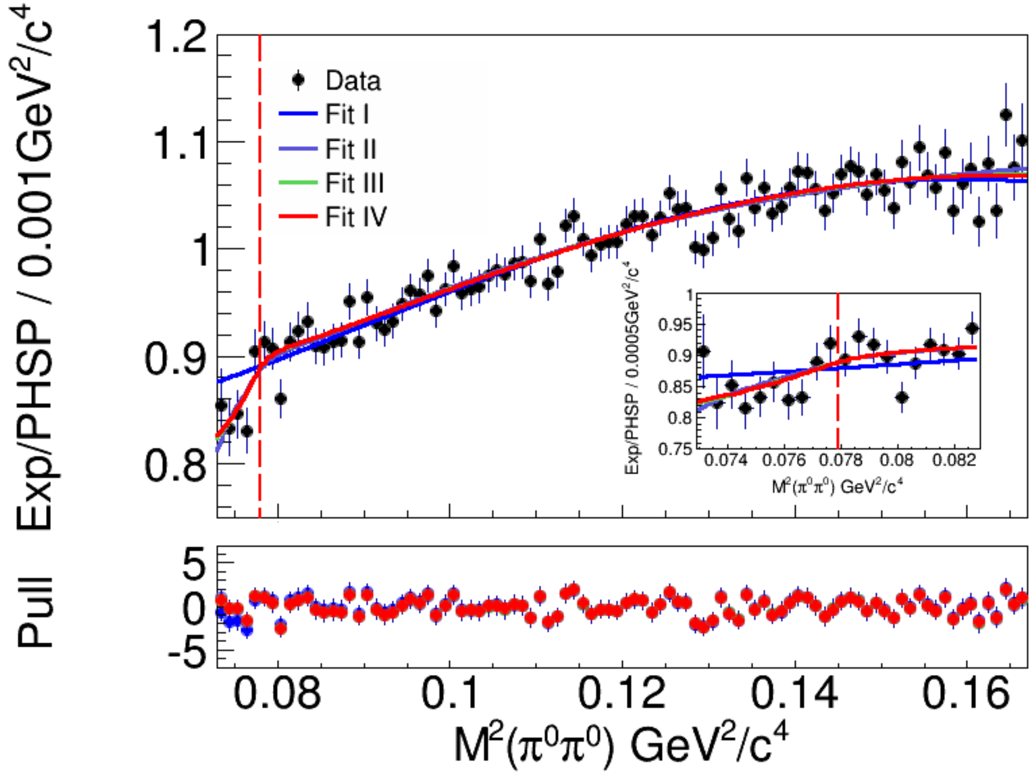
- **Fit I: Only the tree level contribution**



The cusp effect is sizeable in this decay.

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

Phys. Rev. L 130, 081901 (2023)



$$\mathcal{M} = \mathcal{M}^{tree} + \mathcal{M}^{one-loop} + \mathcal{M}^{two-loop}$$

Fit	Notes
I	Only the tree level contribution
II	Consider the loop level contribution
III	Fix noncusp term based on Fit II to reduce the correlations
IV	Ignore the noncusp terms from the loop contributions

- For each case of Fit II, III or IV, the amplitude provides a good description of the structure around the charged pion mass threshold.
- The statistical significance is found to be around 3.5σ.
- Based on Fit IV, The ππ scattering length combination:

$$a_0 - a_2 = 0.226 \pm 0.060 \pm 0.012$$

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

Phys. Rev. D 107, 092007 (2023)

✧ The Dalitz plot is generally described by kinematic variable

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

✧ The squared amplitude can be expanded as:

$$|A(X,Y)|^2\propto 1+aY+bY2+cX+dX^2+eXY+fY^3+gX^2Y+\cdots$$

- a, b, c, d, e, f, g are the Dalitz plot matrix elements.
- c and e are related to charge conjugation violation.
- In strong interactions, c and e are fixed to 0.

✓ **Ignoring** gX^2Y

$a=-1.097\pm0.005\pm0.001$

$b=0.158\pm0.006\pm0.003$

$d=0.070\pm0.006\pm0.001$

$f=0.134\pm0.010\pm0.003$

✓ **Included** gX^2Y

$a=-1.086\pm0.006\pm0.001$

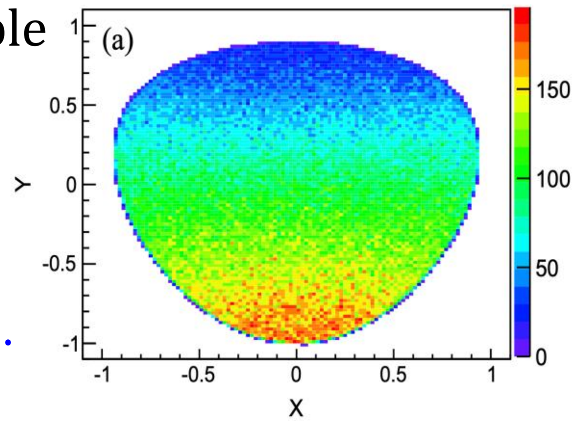
$b=0.162\pm0.006\pm0.003$

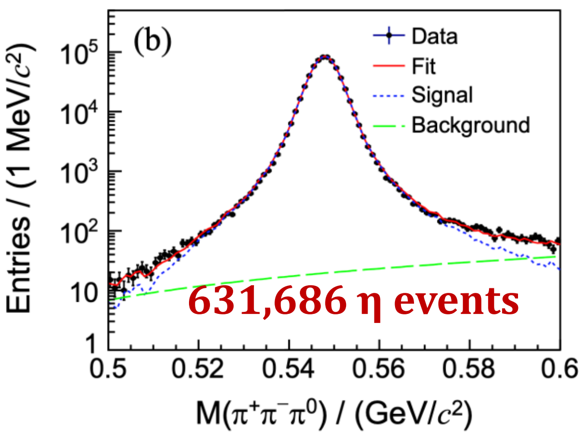
$d=0.083\pm0.007\pm0.001$

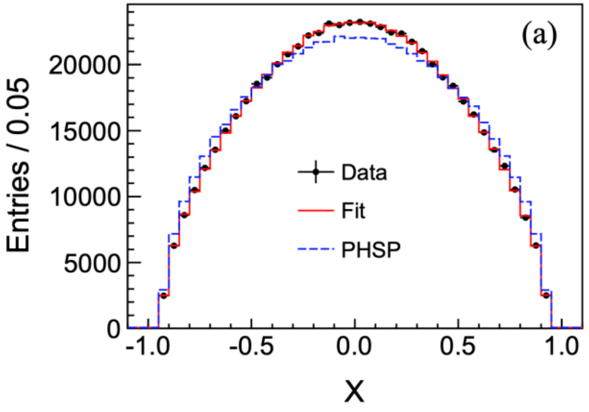
$f=0.118\pm0.011\pm0.003$

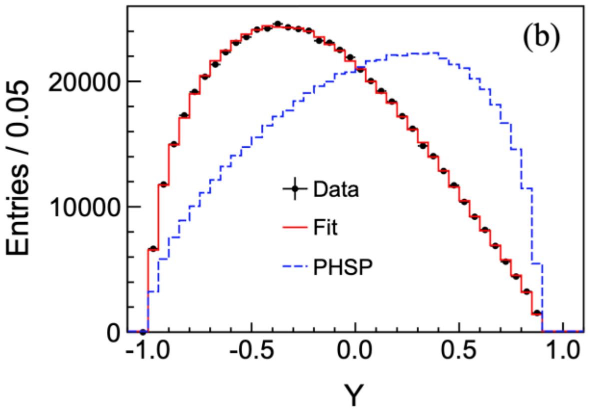
$g=-0.053\pm0.017\pm0.003$

Low background









The presence of interactions between the final-state particles.

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

Phys. Rev. D 107, 092007 (2023)

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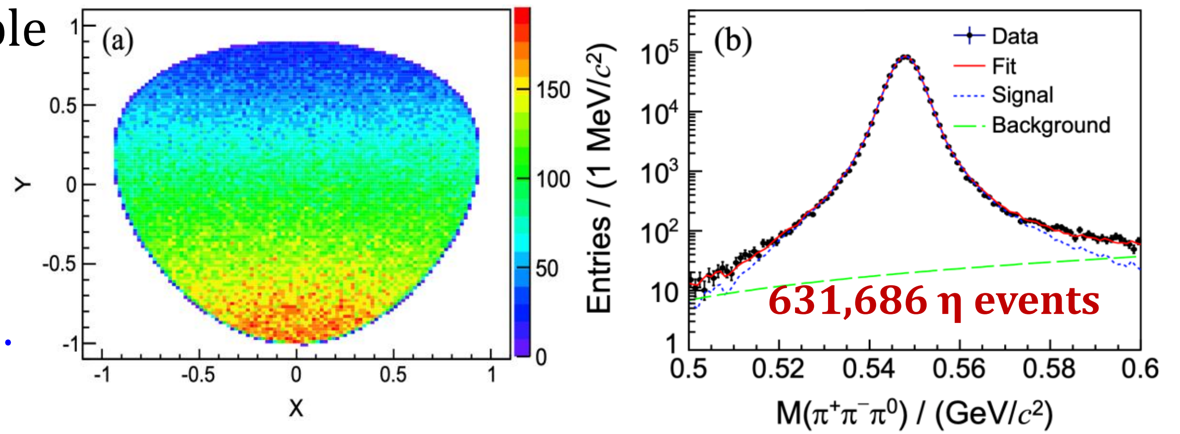

631,686 η events

✓ **Ignoring** gX^2Y

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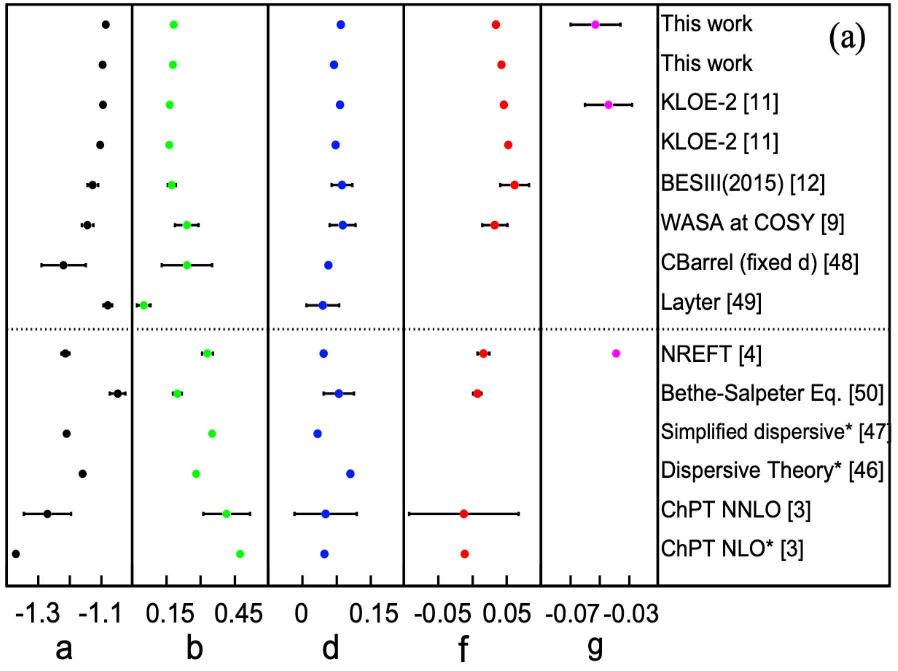


Dalitz Plot Analysis of $\eta \to \pi^0\pi^0\pi^0$

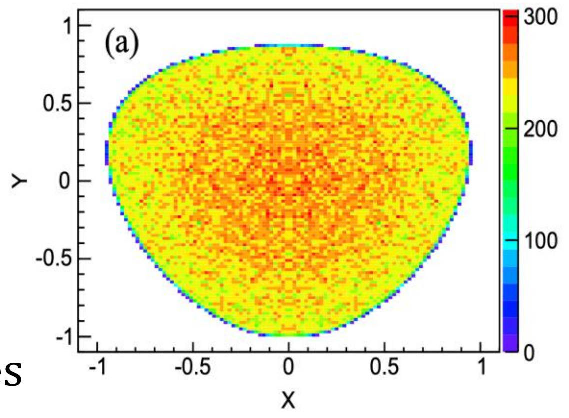
Phys. Rev. D 107, 092007 (2023)

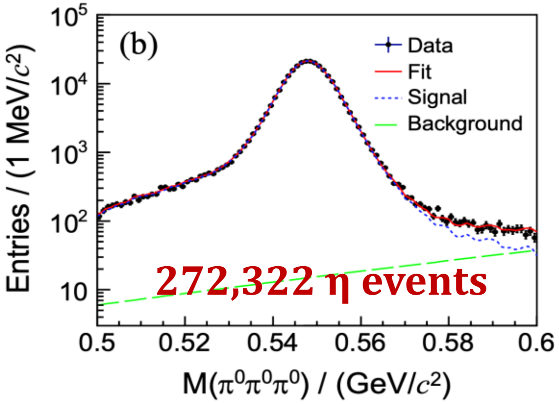
- ✧ The density distribution of the Dalitz plot has threefold symmetry due to the three identical π^0s in the final state.

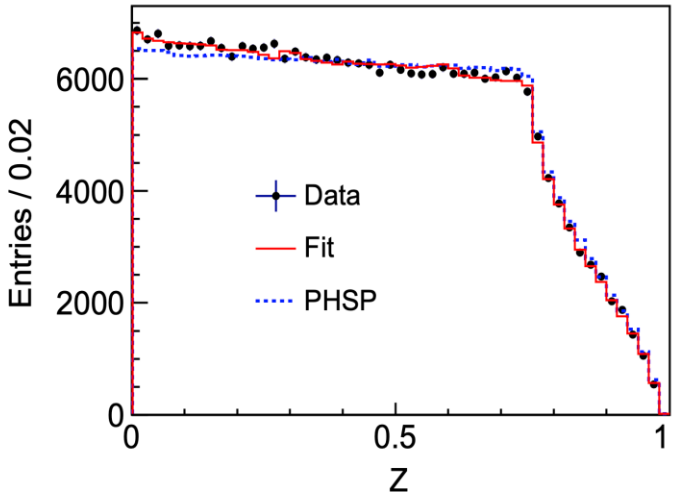
$$Z = X^2 + Y^2 = \frac{2}{3}\sum_{i=1}^{3}\left(\frac{3T_i}{Q_\eta} - 1\right)^2$$

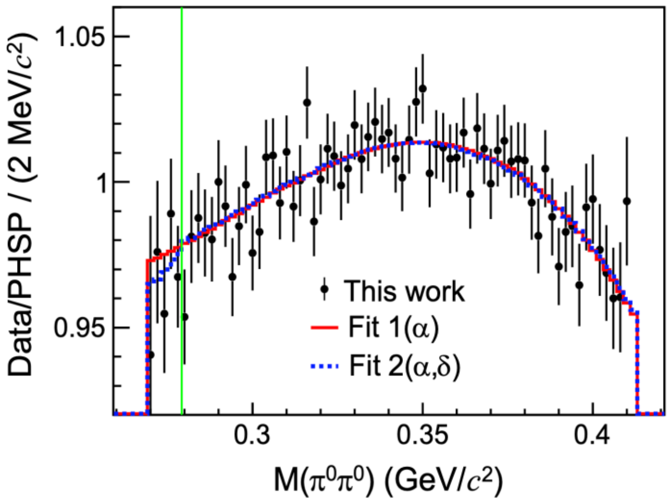
$$|A(X,Y)|^2 \propto 1 + 2\alpha Z$$

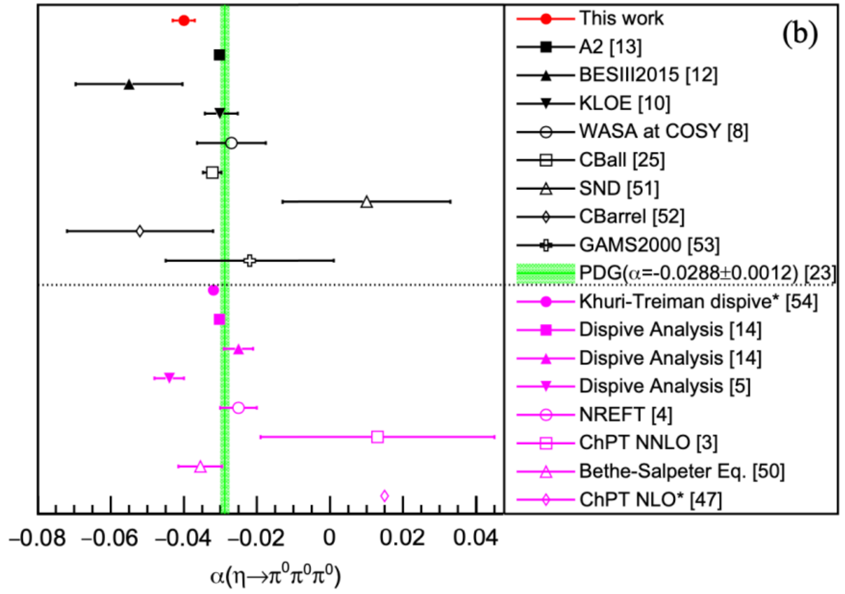
- ✧ $\alpha = -0.0406 \pm 0.0035 \pm 0.0008$
  - The result of the interaction between the final-state particles
  - Consistent with A2 measurement within **2.8σ**.
- ✧ No significant higher-order contribution is found at the current level of precision.
- ✧ **The cusp effect is investigated, but no obvious contribution is found.**











Amplitude Analysis for $\eta' \to \pi^+\pi^-\pi^+\pi^-$

Phys. Rev. D 109, 032006 (2024)

- Decay mode: $J/\psi \to \gamma\eta', \eta' \to \pi^+\pi^-\pi^+\pi^-$
- To investigate the doubly virtual isovector contribution.
- Decay amplitude is constructed with the combination of the **ChPT** and **VMD model**.

$$F(s_{12}, s_{34}) = \left[\frac{s_{12}}{D_\rho(s_{12})} + \frac{s_{34}}{D_\rho(s_{34})} - \frac{s_{14}}{D_\rho(s_{14})} - \frac{s_{23}}{D_\rho(s_{23})}\right]$$

$$+ \frac{c_3}{c_1 - c_2}\left[\frac{m_\rho^2(s_{12} - s_{34})}{D_\rho(s_{12})D_\rho(s_{34})} - \frac{m_\rho^2(s_{14} - s_{23})}{D_\rho(s_{14})D_\rho(s_{23})}\right]$$

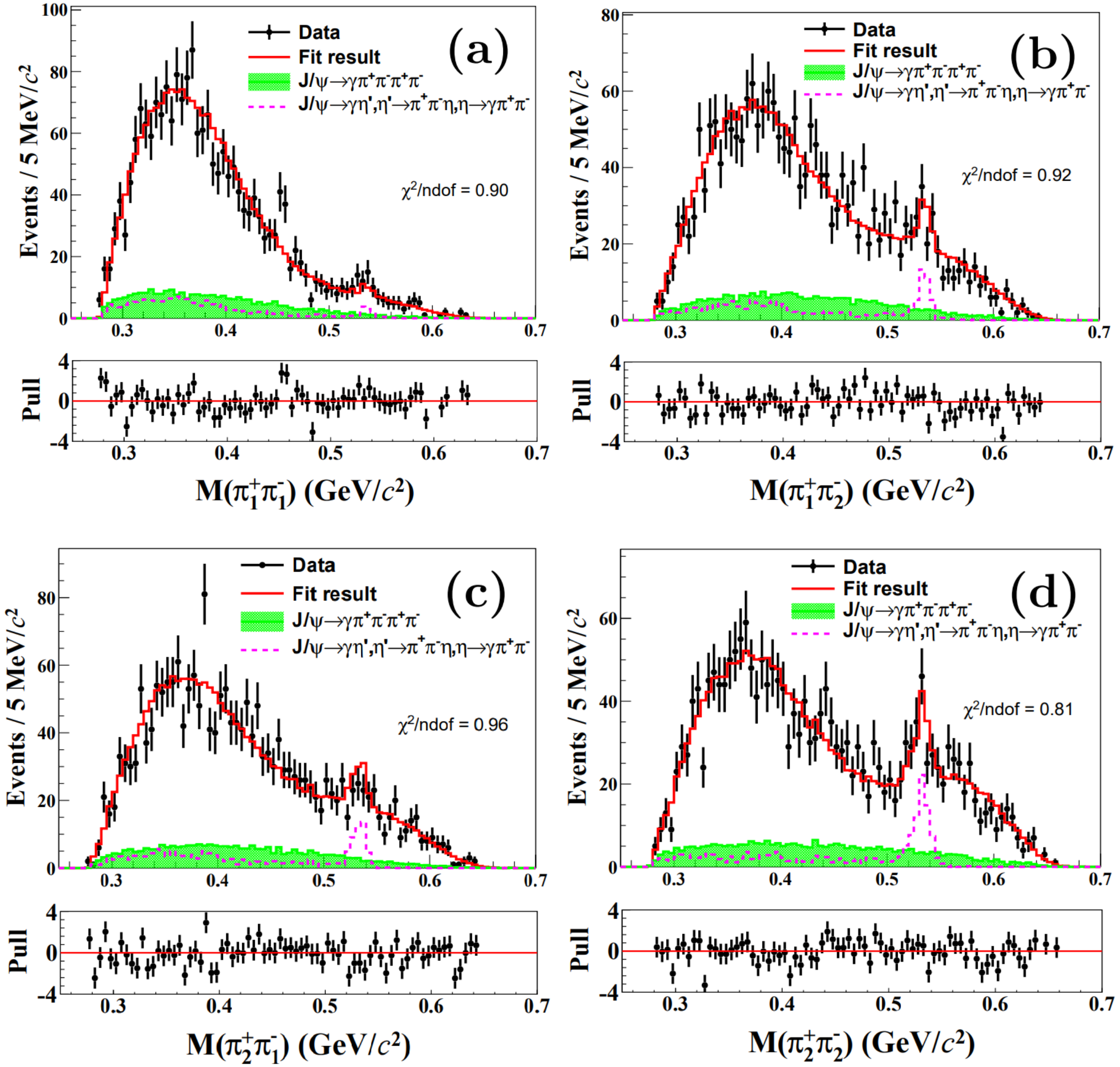
$$D_\rho(s) = M_\rho^2 - s - iM_\rho\Gamma_\rho(s)$$ ➡ The inverse ρ propagator

$$\Gamma_\rho(s) = \frac{M_\rho}{\sqrt{s}}\left(\frac{s - 4M_\pi^2}{M_\rho^2 - 4M_\pi^2}\right)^{\frac{3}{2}}\Gamma_\rho$$

- To simplify the model for validation, we assuming $c_1 - c_2 = 1$, the fit yields

$$c_3 = 1.22 \pm 0.29 \pm 0.04,$$

which is consistent with the theoretical expectation of $c_3 = 1$



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

Phys. Rev. D 109, 072001 (2024)

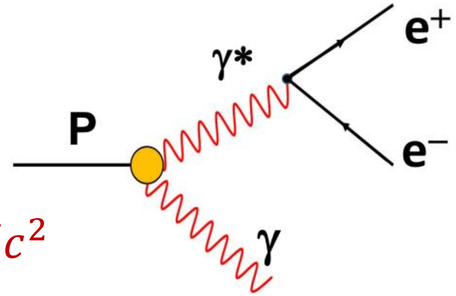
- Performed an unbinned fit based on the amplitude formula.
  - Reduce the systematic uncertainties from resolution and QED contribution subtraction.
  - Make full use of the observed data to test theoretical model.

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

- For $\eta \to \gamma e^+e^-$, Single-pole formula

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

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

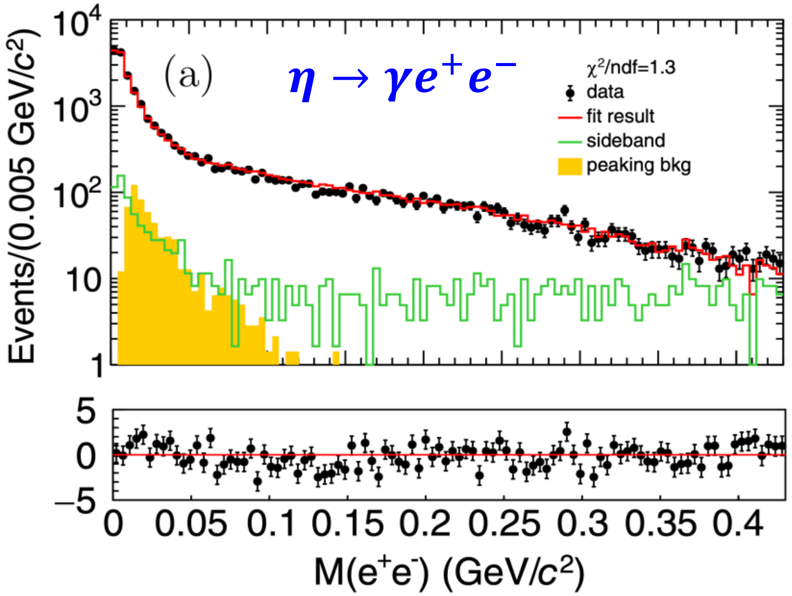


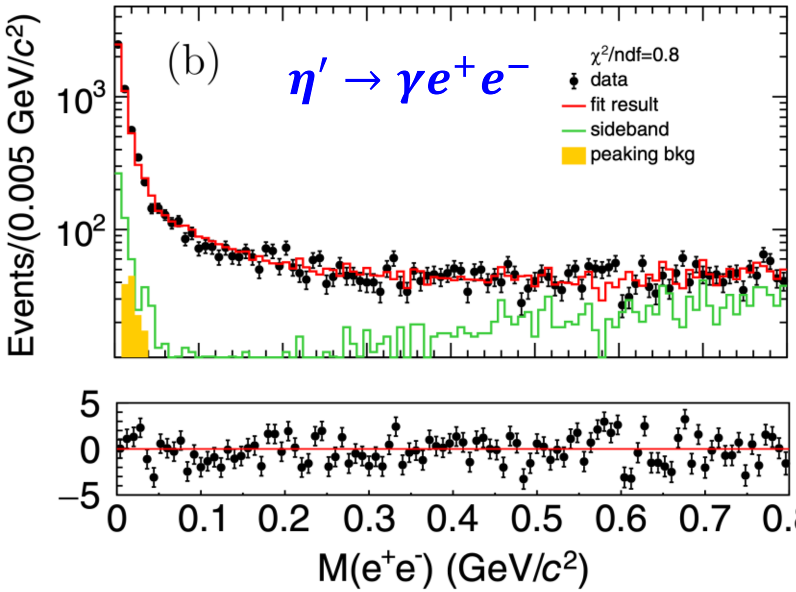
- For $\eta' \to \gamma e^+e^-$, Multi-pole formula

$$\left|F(q^2)\right|^2 = \frac{\Lambda^2(\Lambda^2+\gamma^2)}{(\Lambda^2-q^2)^2+\Lambda^2\gamma^2}$$

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

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





Transition Form Factor of η′→π⁺π⁻l⁺l⁻

JHEP 07, 135 (2024)

- First time to measure the form factors with $\eta' \to \pi^+\pi^- l^+ l^-$
- Decay amplitude

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

  - $M(s_{\pi\pi}, s_{ll}) = \mathcal{M}_{mix} \times VMD(s_{\pi\pi}, s_{ll})$
    contains the information of the decaying particle and the VMD input.

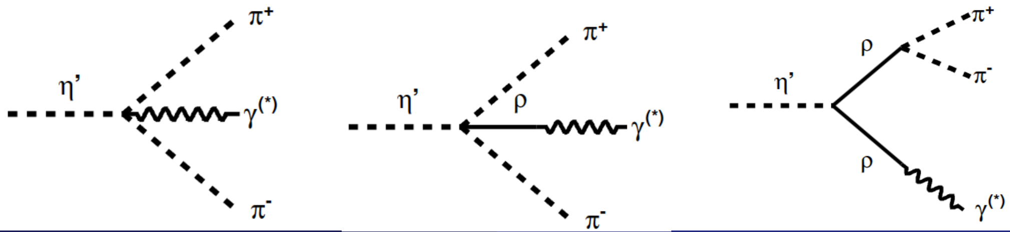
- Within the VMD model, TFF can be parameterized into three separate parts

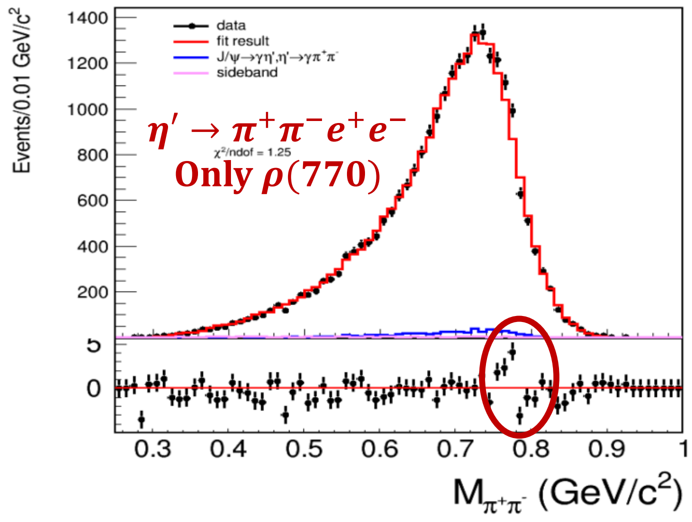
$$VMD(s_{\pi\pi}, s_{ll}) = \boxed{1 - \frac{3}{4}(c_1 - c_2 + c_3)}$$

→ Axial anomaly

$$\boxed{+\frac{3}{4}(c_1 - c_2 - c_3)\frac{m_V^2}{m_V^2 - s_{ll} - i m_V \Gamma(s_{ll})} + \frac{3}{2}c_3 \frac{m_V^2}{m_V^2 - s_{ll} - i m_V \Gamma(s_{ll})}\frac{m_{V,\pi}^2}{m_{V,\pi}^2 - s_{\pi\pi} - i m_{V,\pi}\Gamma(s_{\pi\pi})}}$$

→ VMD contribution





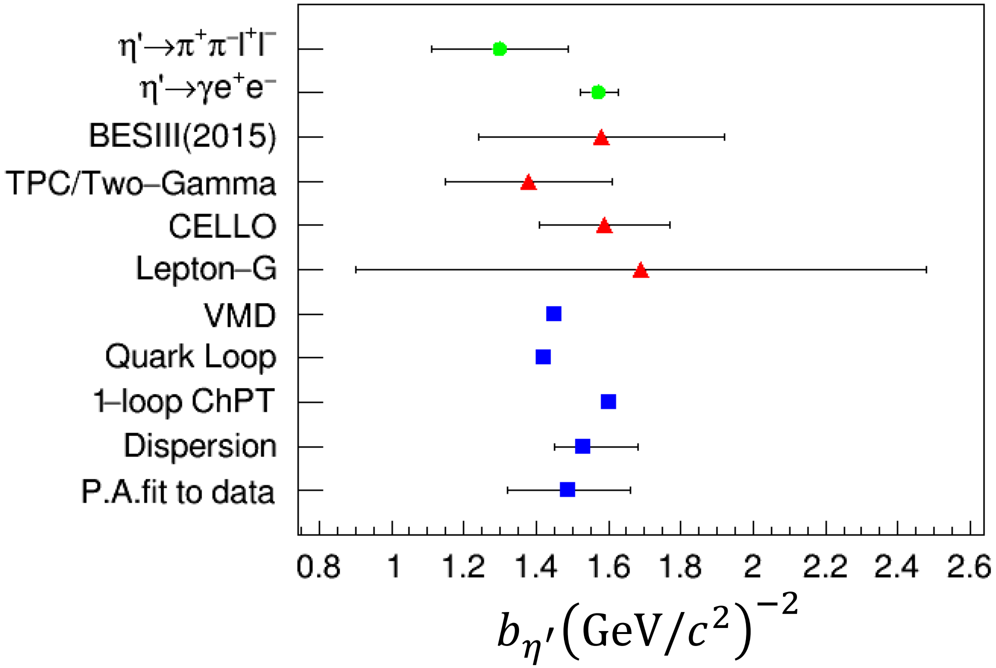
$\omega \to \pi^+\pi^-$ decay is necessary!

Transition Form Factor of $\eta' \to \pi^+\pi^- l^+ l^-$

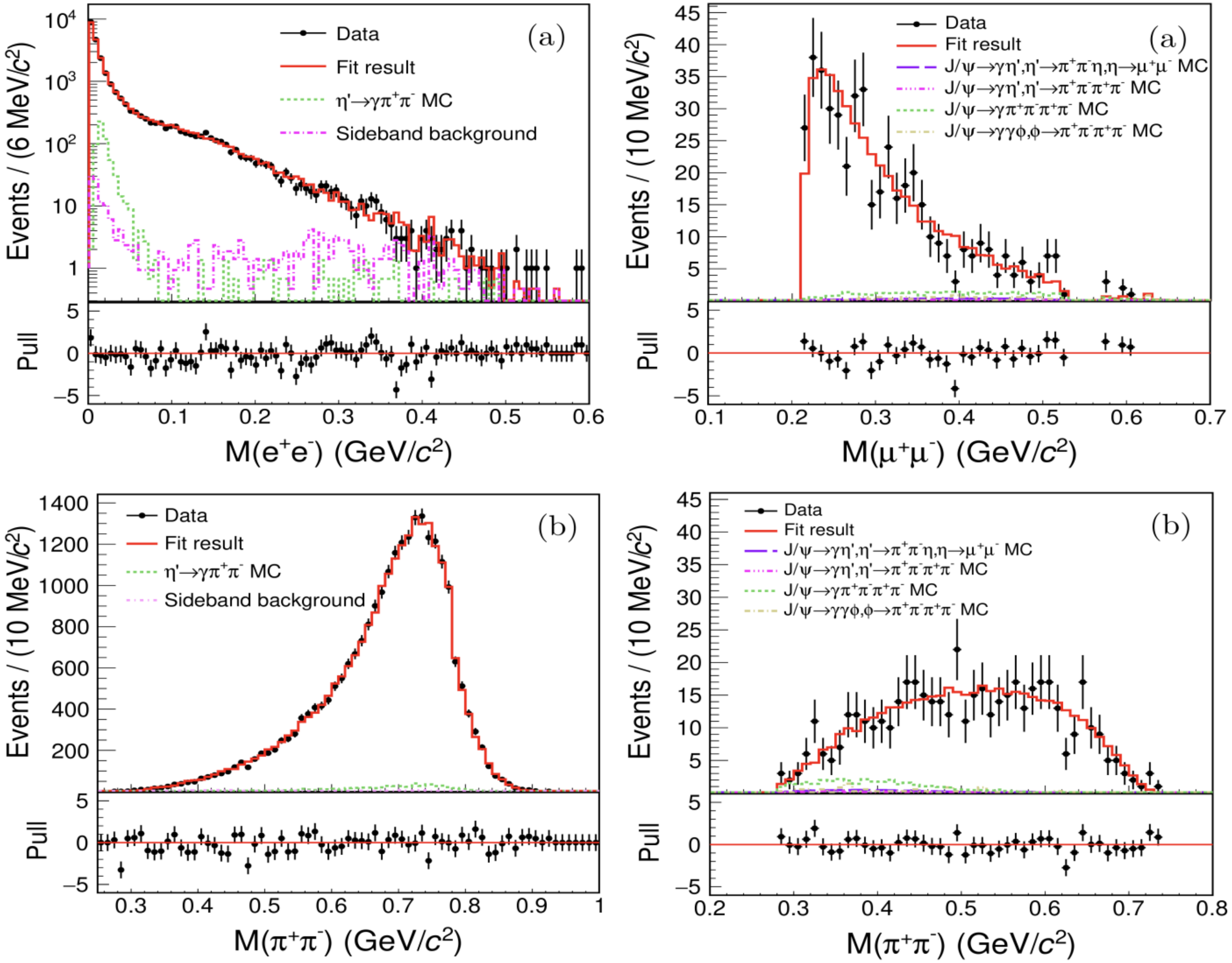
JHEP 07, 135 (2024)

- Perform unbinned fits
- Slope parameter: $b_P = \left.\frac{d|F(q^2)|}{dq^2}\right|_{q^2=0}$
- Combine $\eta' \to \pi^+\pi^- e^+e^-$ and $\eta' \to \pi^+\pi^-\mu^+\mu^-$

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



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



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

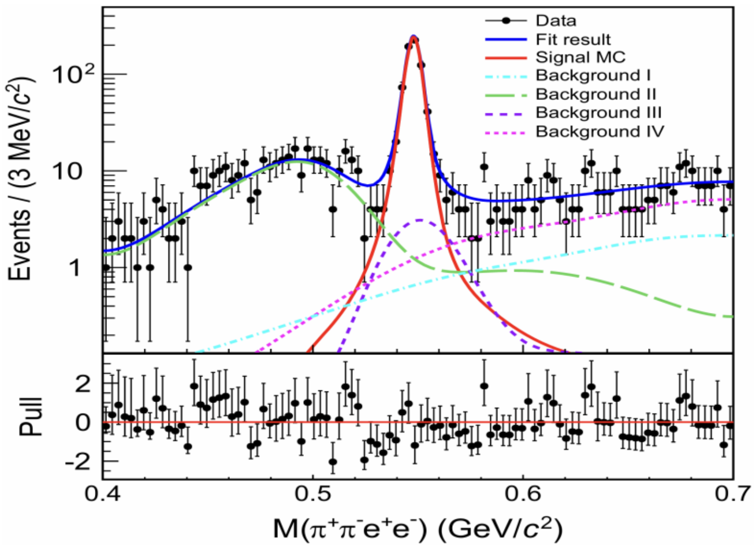
Phys. Rev. D 111, 072008 (2025)

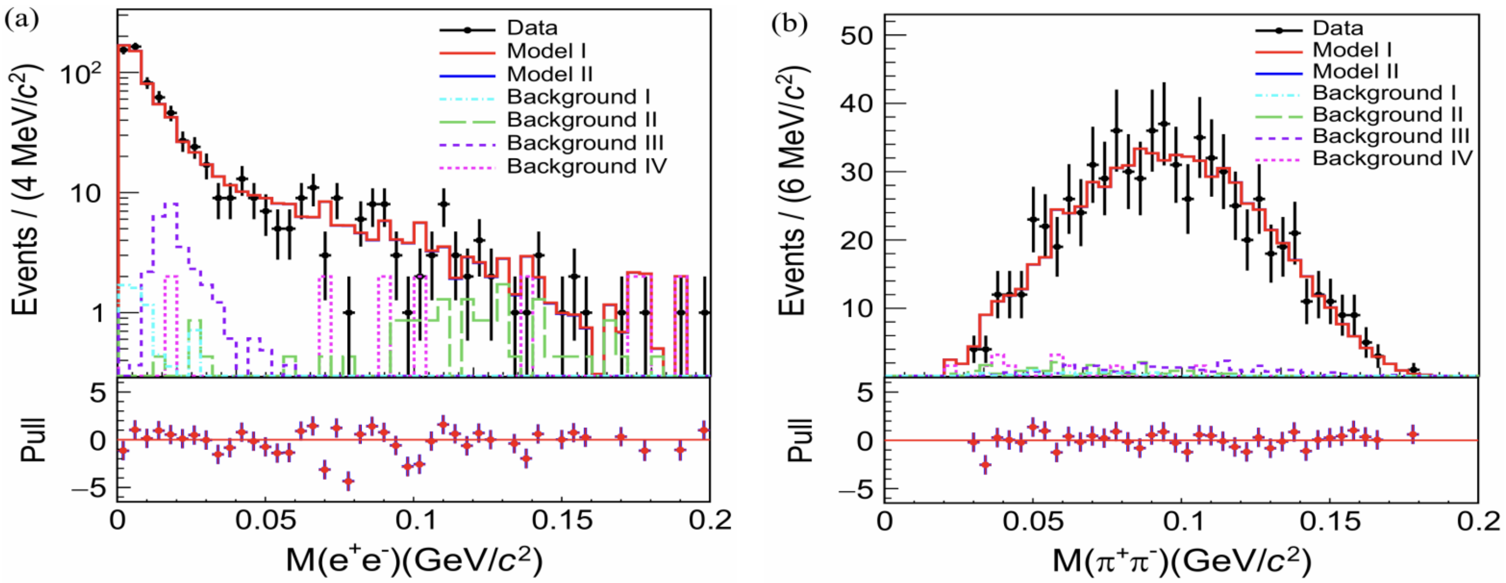
- The branching fraction

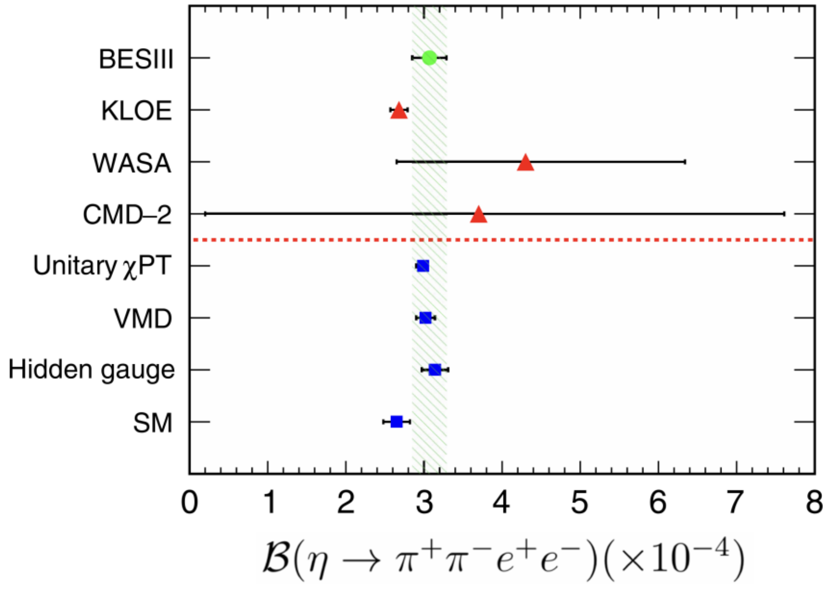
$$\mathcal{B}(\eta \to \pi^+\pi^- e^+e^-) = (3.07 \pm 0.12 \pm 0.19) \times 10^{-4}$$

- No event are left for $\pi^+\pi^-\mu^+\mu^-$ hypothesis in η signal region and the UL is set as 4.0×10^{-7} at the 90% CL
- For $\eta \to \pi^+\pi^- e^+e^-$, perform the amplitude analysis.
  - The amplitude formula is similar to that of $\eta' \to \pi^+\pi^- e^+e^-$.

$$m_V = (748.62 \pm 53.54 \pm 25.90)\ \mathrm{MeV}/c^2$$



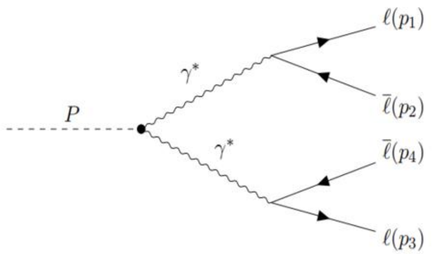


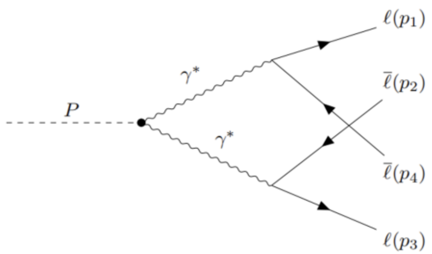


Double Dalitz decays $\eta/\eta' \to l^+l^-l^+l^-$

Phys. Rev. D 105, 112010 (2022)
Phys. Rev. D 111, 052002 (2025)

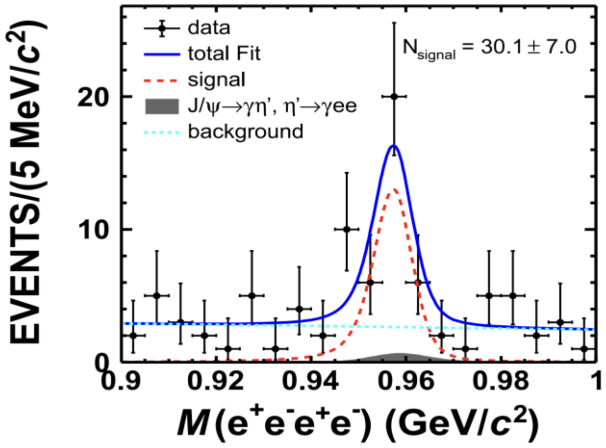
- The double Dalitz decays through two virtual photons intermediate with internal photon conversion to l^+l^- pairs, which understand the pseudoscalar transition form factor.



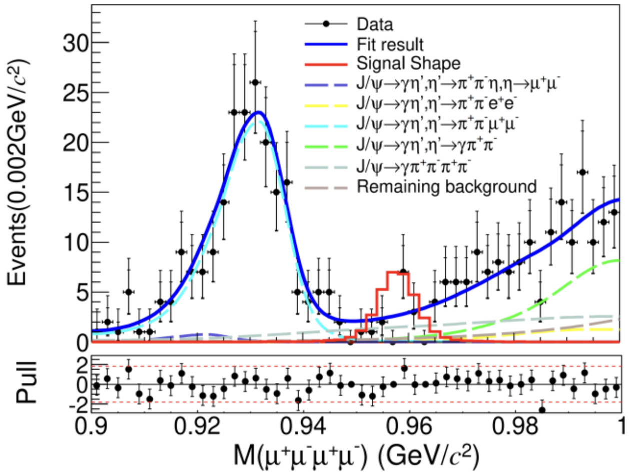


Decay mode	$\mathcal{B}$
$\eta' \to e^+e^-e^+e^-$	$(4.5 \pm 1.0 \pm 0.5) \times 10^{-6}$
$\eta' \to \mu^+\mu^-\mu^+\mu^-$	$< 5.28 \times 10^{-7}$ (90% C. L.)
$\eta' \to e^+e^-\mu^+\mu^-$	$< 1.75 \times 10^{-6}$ (90% C. L.)
$\eta \to e^+e^-\mu^+\mu^-$	$< 6.88 \times 10^{-6}$ (90% C. L.)

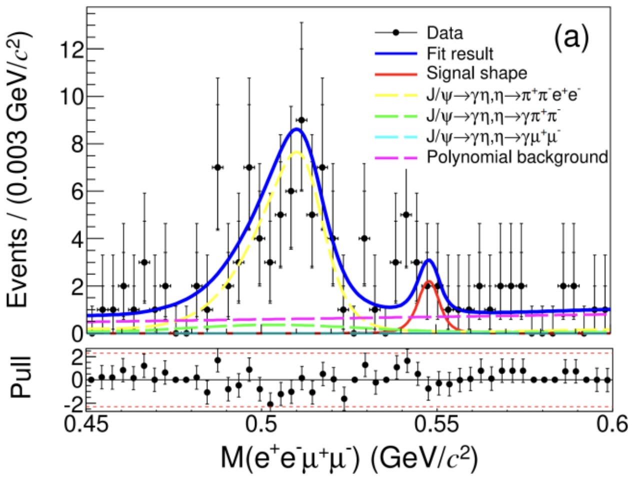
$\eta' \to e^+e^-e^+e^-$



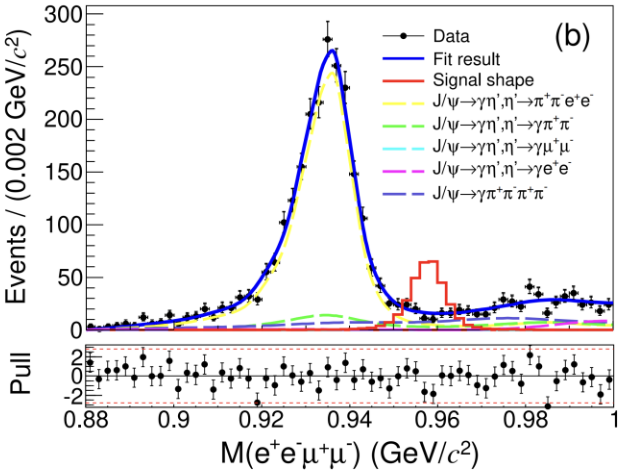
$\eta' \to \mu^+\mu^-\mu^+\mu^-$



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



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



Transition Form Factor of η’→π⁺π⁻η, η→γl⁺l⁻

arXiv: 2506. 08576 (Submit to PRD)

- The background of the $\eta \to \gamma l^+ l^-$ decays derived from $\eta' \to \pi^+\pi^-\eta$ is **lower** than that of the decay directly obtained via $J/\psi \to \gamma\eta$.
- The transition form factor predicted by VMD
  - Single pole: $F(q^2) = \frac{1}{1-q^2/\Lambda^2}$
  - Slope parameter: $b_P = \frac{d|F(q^2)|}{dq^2}\Big|_{q^2=0} = \Lambda^{-2}$
- For $\eta \to \gamma\mu^+\mu^-$ decay

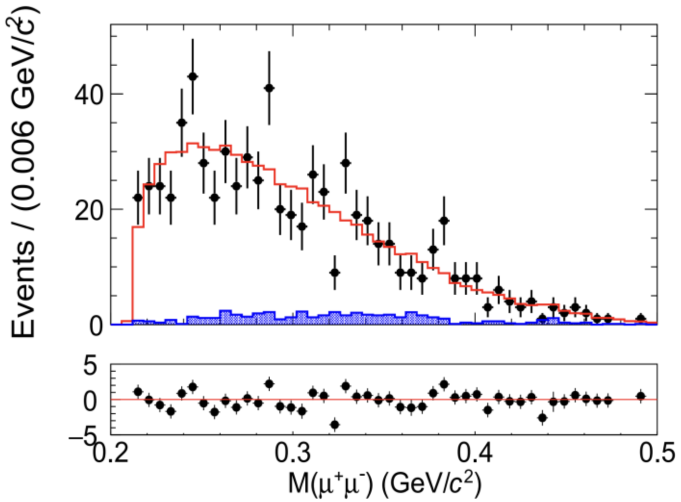
$$\boldsymbol{\Lambda^{-2} = 1.645 \pm 0.343 \pm 0.017\ (\mathrm{GeV}/c^2)^{-2}}$$

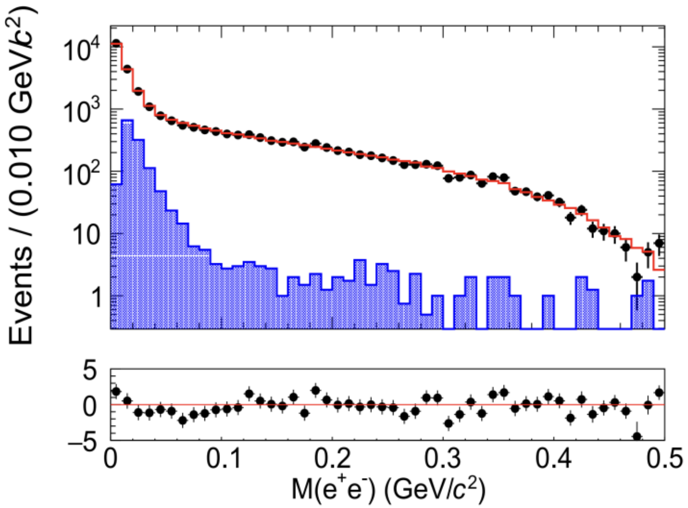
- For $\eta \to \gamma e^+ e^-$ decay

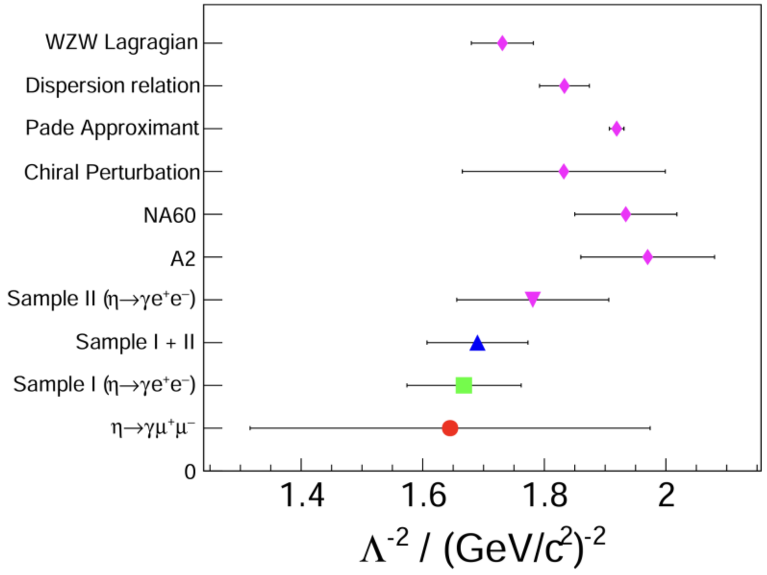
$$\boldsymbol{\Lambda^{-2} = 1.668 \pm 0.093 \pm 0.024\ (\mathrm{GeV}/c^2)^{-2}}$$

- By combining with the results based on the $J/\psi \to \gamma\eta, \eta \to \gamma e^+ e^-$ events from the previous BESIII measurement

$$\boldsymbol{\Lambda^{-2} = 1.707 \pm 0.076 \pm 0.029\ (\mathrm{GeV}/c^2)^{-2}}$$







Summary

- The BESIII detector has collected 10 billion J/ψ events , which provide excellent conditions for the study of η/η' decays.
- The BESIII collaboration has published several measurement results related to η/η' decays recently.

Decay mode	Physics	Publication
$\eta' \to \pi^0\pi^0\eta$	Cusp effect	PRL130, 081901 (2023)
$\eta \to \pi^+\pi^-\pi^0/\pi^0\pi^0\pi^0$	Matrix Elements - $m_u - m_d$	PRD107, 092007 (2023)
$\eta' \to \pi^+\pi^-\pi^+\pi^-$	BR, Amplitude analysis	Phys. Rev. D 109, 032006 (2024)
$\eta/\eta' \to \gamma e^+e^-$	BR, TFF, Dark photon	Phys. Rev. D 109, 072001 (2024)
$\eta/\eta' \to \pi^+\pi^- l^+l^-$	BR, CP violation, TFF, ALPs	JHEP 07, 135 (2024) Phys. Rev. D 111, 072008 (2025)
$\eta/\eta' \to l^+l^-l^+l^-$	BR, Double Dalitz decays	Phys. Rev. D 105, 112010 (2022) Phys. Rev. D 111, 052002 (2025)
$\eta' \to \pi^+\pi^-\eta, \eta \to \gamma l^+l^-$	BR, TFF, Dark photon	arXiv: 2506. 08576 (Submit to PRD)

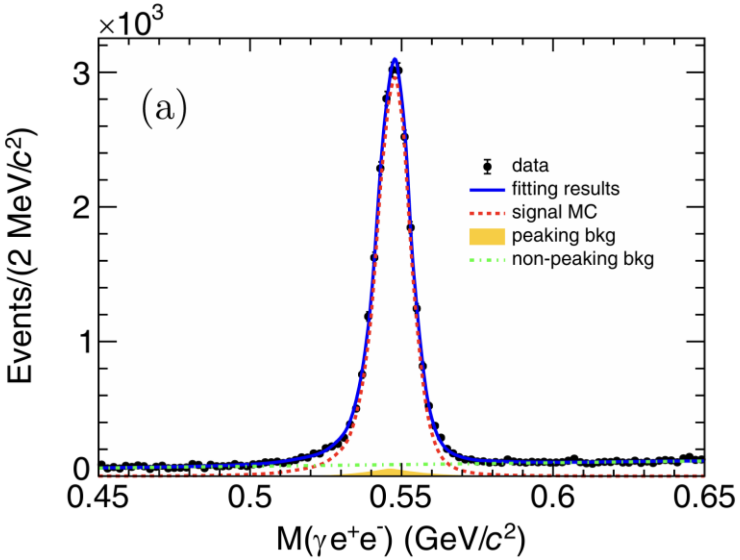
- Further analysis is currently in progress, and more results are expected to come soon!
  - $\eta' \to \pi^+\pi^-\pi^0$
  - $\eta/\eta' \to \gamma\pi^+\pi^-$
  - $\eta' \to l^+l^-\pi^0\pi^0$
  - $\eta \to e^+e^-e^+e^-$
  - $\eta \to \mu^+\mu^-$
  - ……

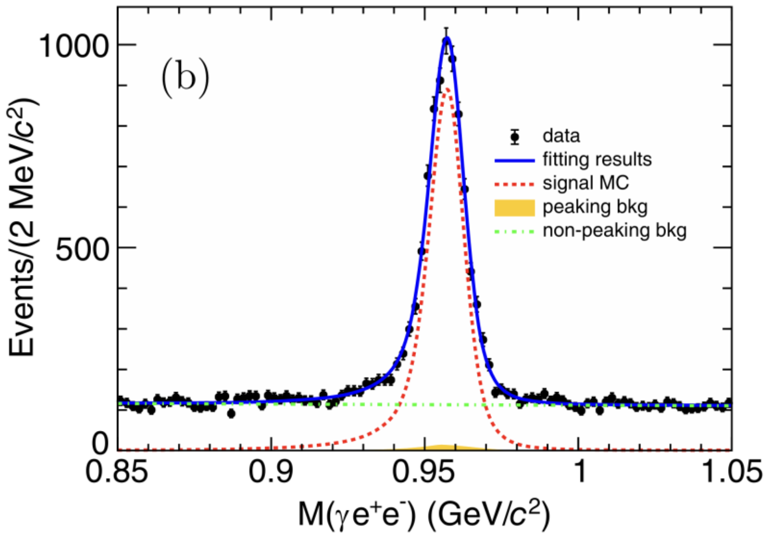
Thank You !

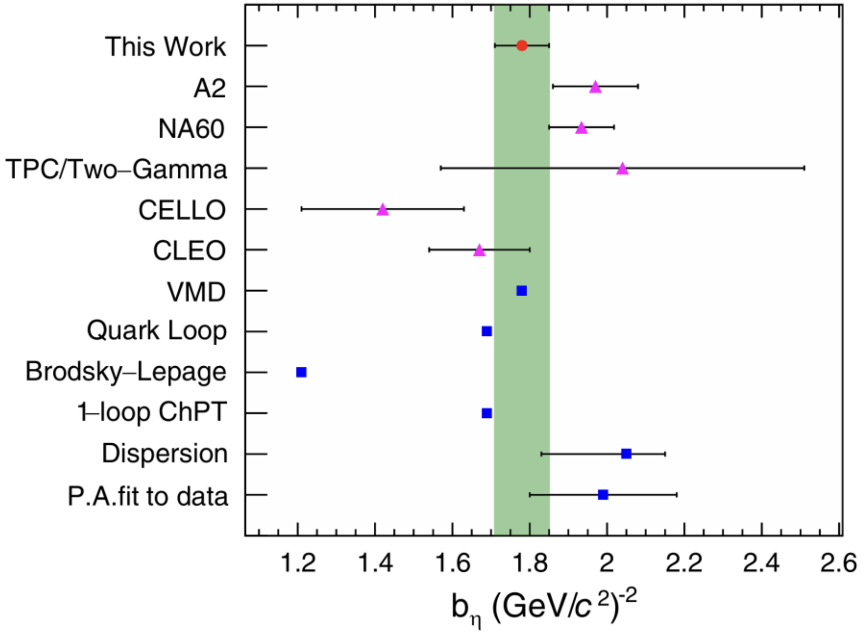
Back Up

Back up

- $\eta/\eta' \to \gamma e^+e^-$
  - ✓ Branching fraction
  - ✓ η TFF





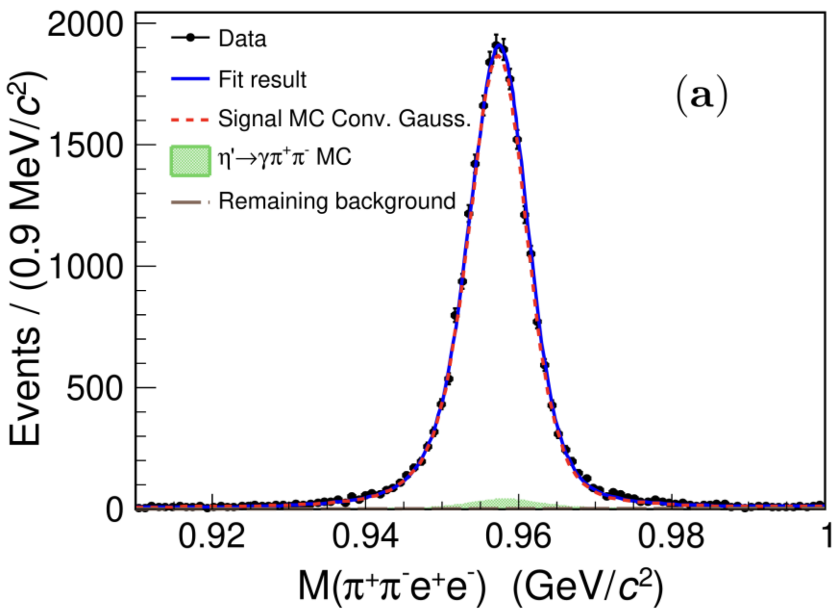


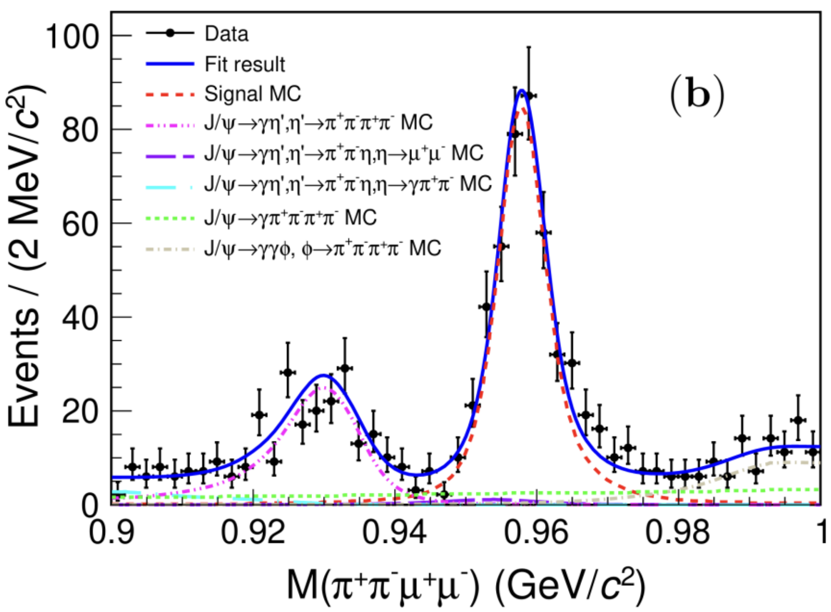
$$\text{(a) } \mathcal{B}(\eta \to \gamma e^+e^-) = (7.07 \pm 0.05 \pm 0.23) \times 10^{-3}$$

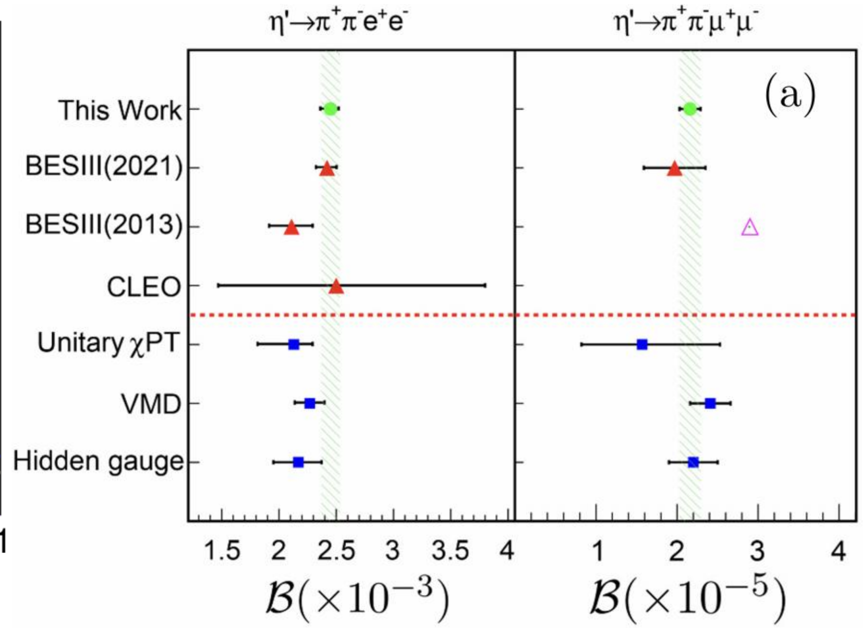
$$\text{(b) } \mathcal{B}(\eta' \to \gamma e^+e^-) = (4.83 \pm 0.07 \pm 0.14) \times 10^{-4}$$

Back up

- $\eta' \to \pi^+\pi^- l^+ l^-$
  - ✓ Branching fraction





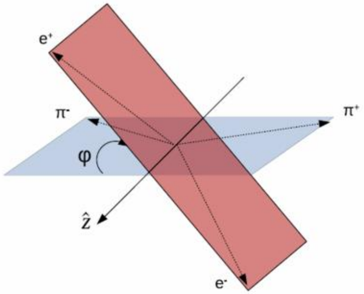


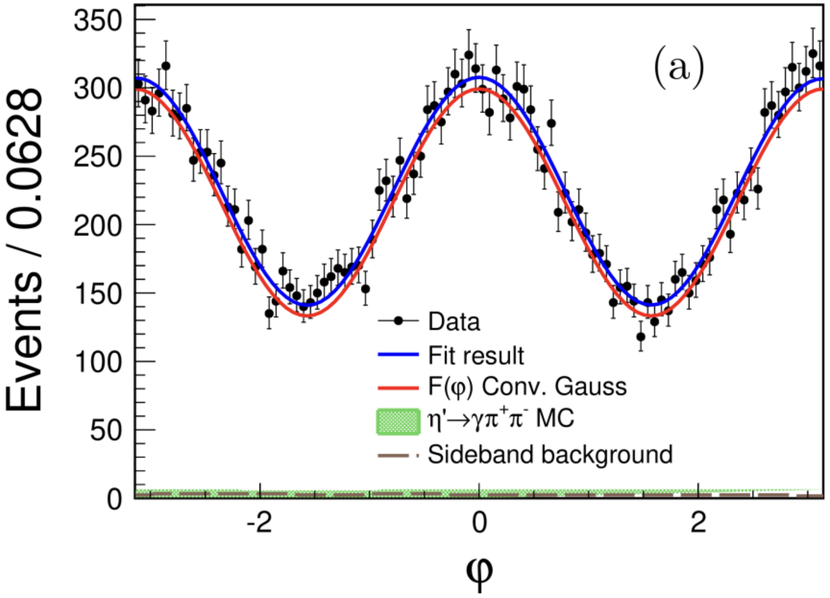
$$\mathcal{B}(\eta' \to \pi^+\pi^- e^+ e^-) = (2.45 \pm 0.02 \pm 0.08) \times 10^{-3}$$

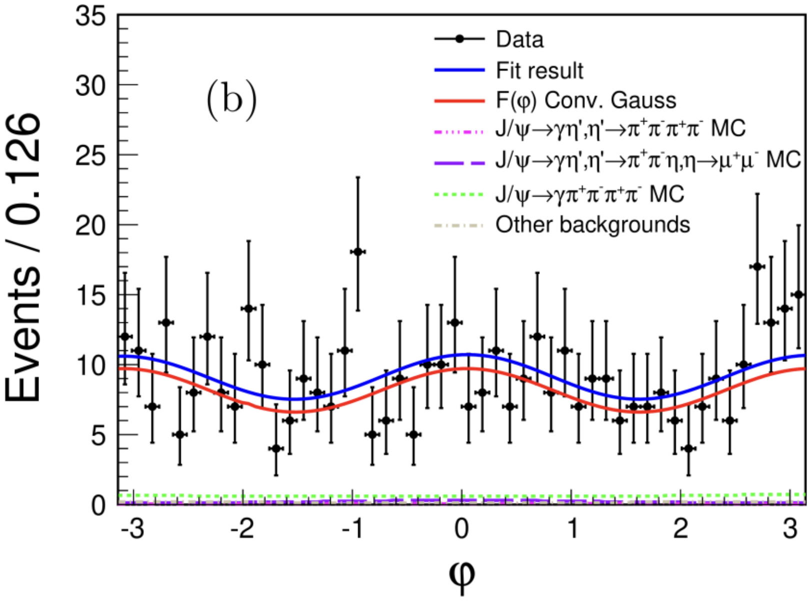
$$\mathcal{B}(\eta' \to \pi^+\pi^- \mu^+ \mu^-) = (2.16 \pm 0.12 \pm 0.06) \times 10^{-5}$$

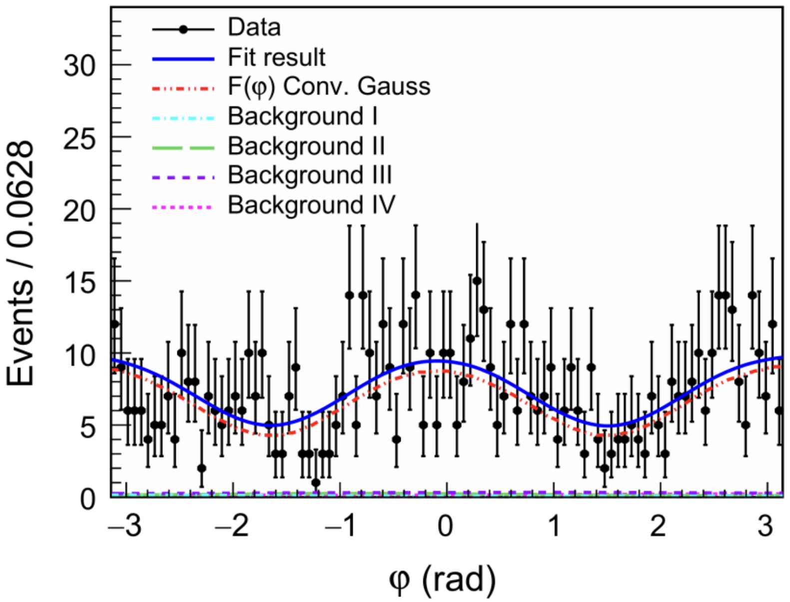
Back up

- $\eta/\eta' \to \pi^+\pi^- l^+ l^-$
  - ✓ CP-violating asymmetry









$$\mathcal{A}(\eta' \to \pi^+\pi^- e^+ e^-) = (-0.21 \pm 0.73 \pm 0.01)\%$$

$$\mathcal{A}(\eta' \to \pi^+\pi^- \mu^+ \mu^-) = (0.62 \pm 4.71 \pm 0.08)\%$$

$$\mathcal{A}(\eta \to \pi^+\pi^- e^+ e^-) = (-4.04 \pm 4.69 \pm 0.14)\%$$

Back up

- $\eta' \to \pi^+\pi^- l^+ l^-$
  - ✓ Transition form factor

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

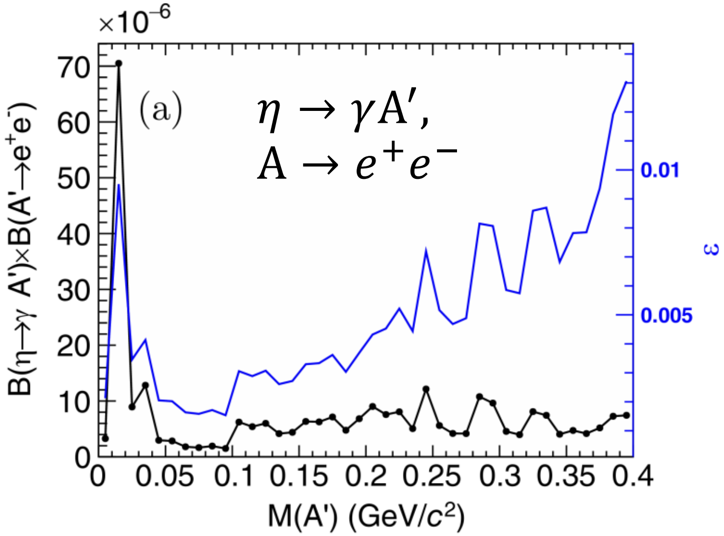
Table 4. The TFF fit results of the $\eta' \to \pi^+\pi^- e^+ e^-$ decay.

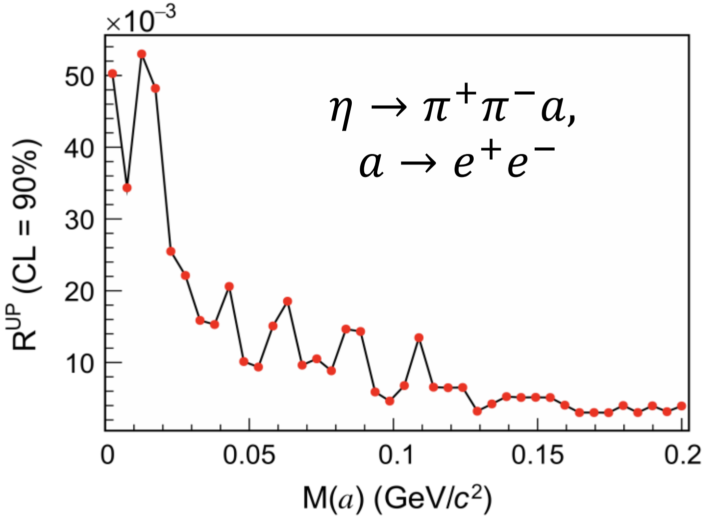
$\eta' \to \pi^+\pi^- \mu^+ \mu^-$	Model I	Model II	Model III
	$c_1 - c_2 = c_3 = 1$	$c_1 - c_2 = 1/3, c_3 = 1$	$c_1 - c_2 \neq c_3$
$m_V\,(\mathrm{MeV}/c^2)$	$649.4 \pm 55.9 \pm 35.6$	601.6 ± 25.7	589.6 ± 25.9
$m_{V,\pi}\,(\mathrm{MeV}/c^2)$	$757.3 \pm 24.1 \pm 18.0$	765.4 ± 18.8	774.4 ± 43.5
$c_1 - c_2$	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

Table 5. The TFF fit results of the $\eta' \to \pi^+\pi^- \mu^+ \mu^-$ decay.

Back up

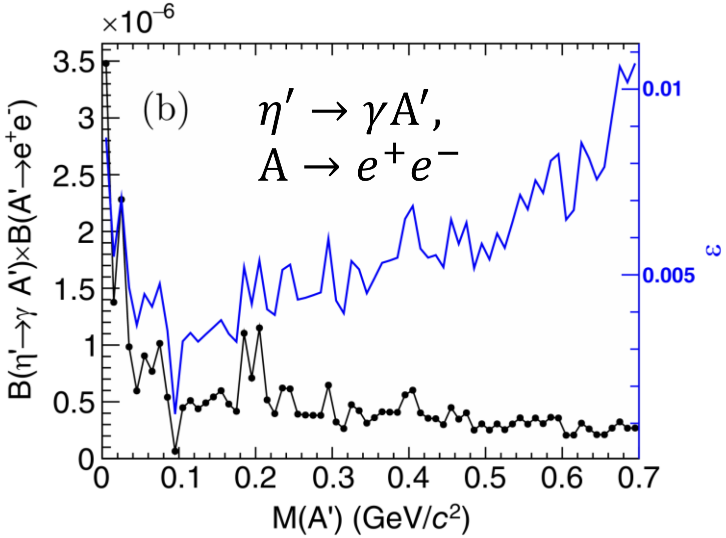
- Search for dark photon/ALPs of $\eta/\eta' \to \gamma e^+e^-$ and $\eta/\eta' \to \pi^+\pi^-e^+e^-$

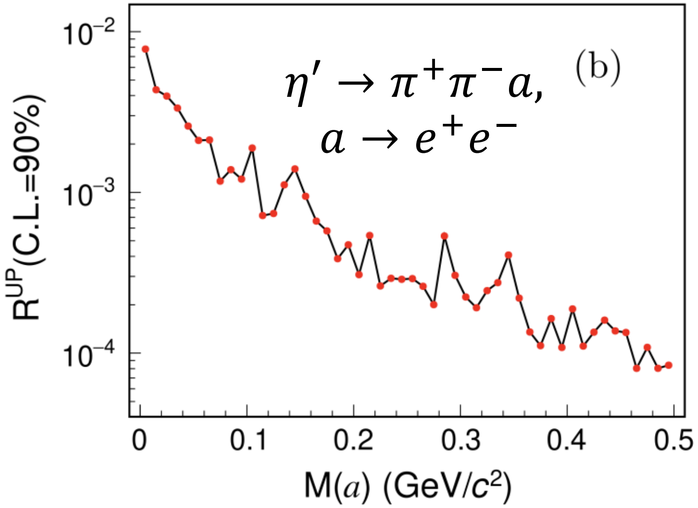




$$\mathcal{B}(P \to \gamma A') = 2\varepsilon^2\left(1-\frac{m_{A'}^2}{m_P^2}\right)^3 \mathcal{B}(P \to \gamma\gamma),$$

- ε is the coupling strength





$$R^{UP} = \frac{\mathcal{B}(\eta/\eta' \to \pi^+\pi^-a)\cdot\mathcal{B}(a \to e^+e^-)}{\mathcal{B}(\eta/\eta' \to \pi^+\pi^-e^+e^-)}$$