Light Meson decays at BESIII

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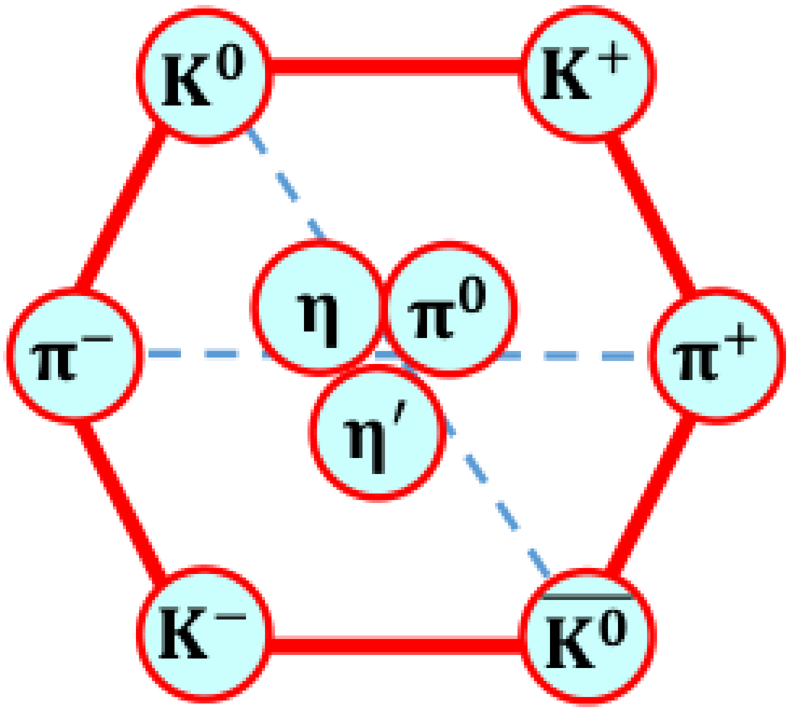
Outline

- Light meson physics
- BESIII: a light meson factory
- η/η' decays at BESIII
  - Decay mechanisms
  - Form factors
- Summary

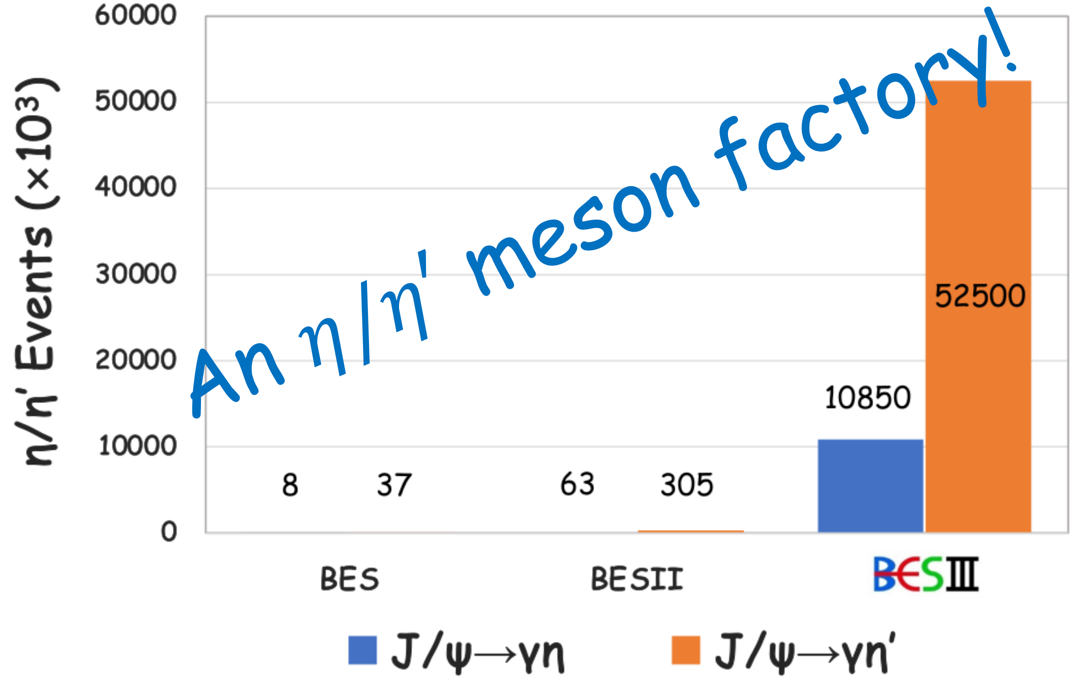
Light Meson Physics

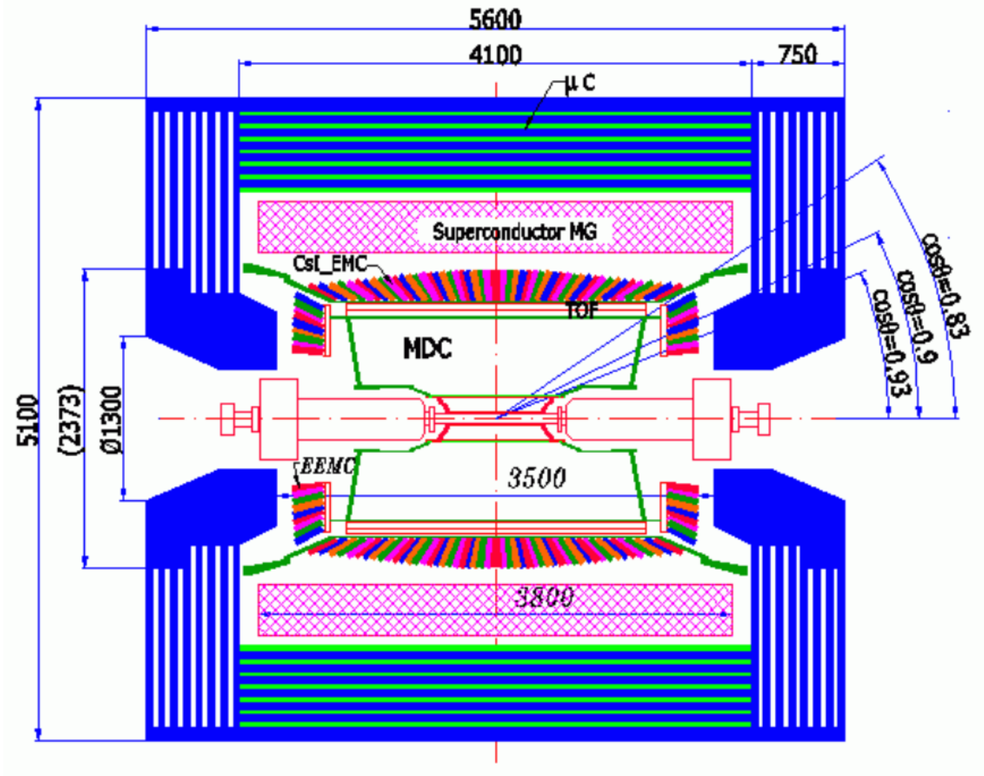
- Light mesons
  - ✓ Important roles in particle physics, e.g. strong interactions, Quark Model, CP violation …
- Rich physics
  - ✓ Test ChPT predictions
  - ✓ EM Form factors
  - ✓ Test fundamental symmetries
  - ✓ Probe new physics beyond the SM



BESIII Detector

- The BESIII detector records symmetric e^+e^- collisions provided by the BEPCII storage ring.
- The facility is used for studies of τ-charm physics.
- Collected 10 billion J/ψ Events!
  - ✓ $J/\psi \to \gamma P, VP, \ldots$





Decay list of light meson in BESIII

Decay channel	Physics	Publication
$\eta' \to \rho\pi$	First Observation, BR	PRL118, 012001 (2017)
$\eta' \to \gamma\gamma\pi^0$	BR, B Boson	PRD96, 012005 (2017)
$\eta' \to \gamma\pi^+\pi^-$	BR, Box anomaly	PRL120, 242003 (2018)
$\eta' \to \pi^+\pi^-\eta, \eta' \to \pi^0\pi^0\eta$	Matrix elements, Cusp effect	PRD97, 012003 (2018)
$P \to \gamma\gamma$	BRs, Chiral anomaly	PRD97, 072014 (2018)
$\eta' \to \gamma\gamma\eta$	UL	PRD100, 052015 (2019)
Absolute BR of η' decays	BRs	PRL122, 142002 (2019)
$\eta' \to 4\pi^0$	CP violation, UL	PRD101, 032001 (2020)
Absolute BR of η decays	BRs	PRD104, 092004 (2021)
$\eta' \to \pi^+\pi^-e^+e^-$	BR, CP violation asymmetry	PRD103, 092005 (2021)
$\eta \to \pi^+\pi^-\mu^+\mu^-$	BR, Decay dynamics	PRD103, 072006 (2021)
$\eta' \to e^+e^-e^+e^-$	BR	PRD.105.112010(2022)
$\eta' \to \pi^0\pi^0\eta$	Cusp effect	PRL130, 081901 (2023)
$\eta \to \pi^+\pi^-\pi^0, 3\pi^0$	Matrix elements, $m_u - m_d$	PRD107, 092007 (2023)
$\eta' \to 4\pi$	Amplitude analysis	PRD109, 032006 (2024)
$\eta/\eta' \to \gamma e^+e^-$	Form factor	PRD109, 072001 (2024)
$\eta' \to \pi^+\pi^-l^+l^-$	Form factor, CP violation	JHEP07, 135(2024)

BESIII: an important role in η/η' decays

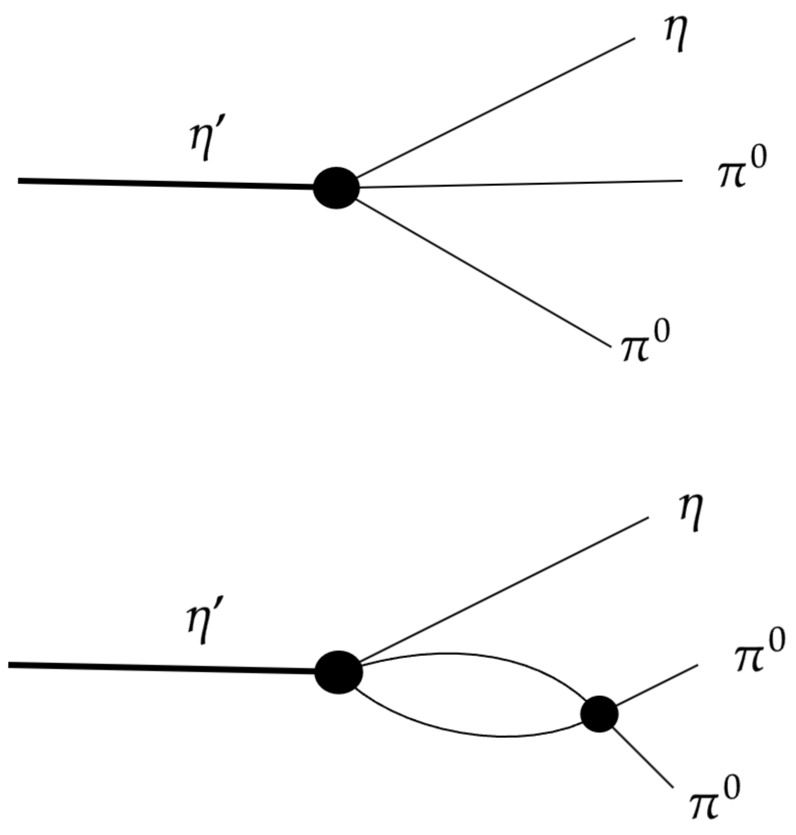
- Decay mechanisms
- Form factors

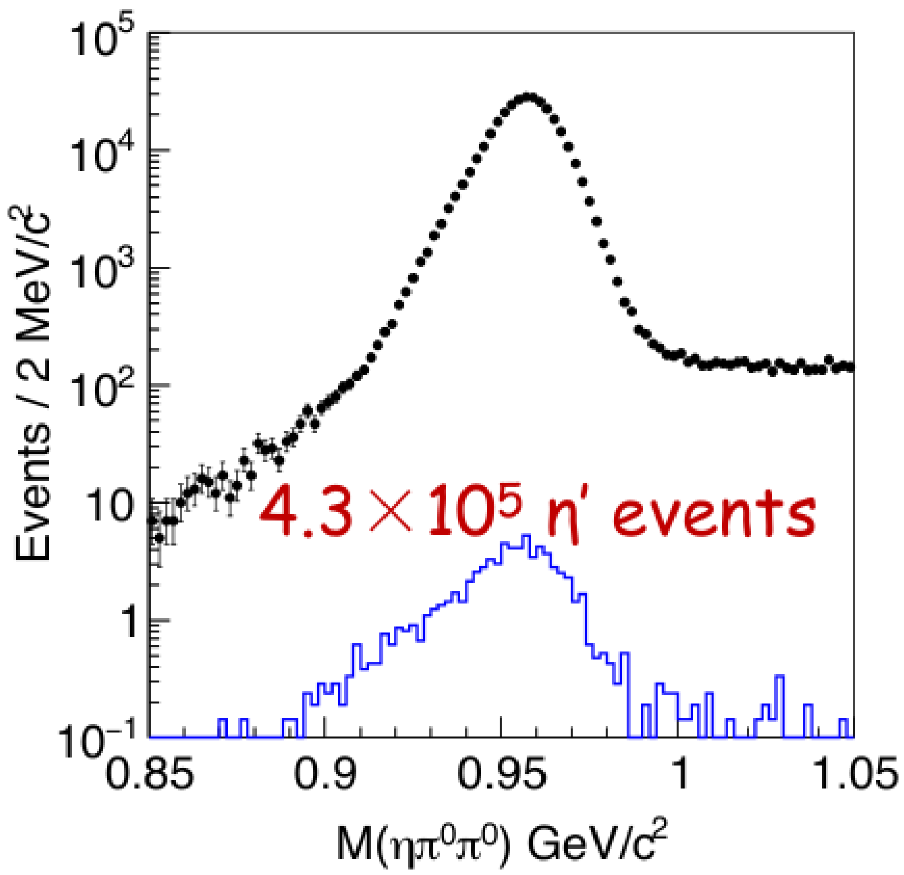
Decay mechanisms

- Evidence of the cusp effect in $\eta' \to \pi^0\pi^0\eta$ — $\mathrm{PRL130, 081901\ (2023)}$
- Improved measurement of the decays $\eta' \to \pi^+\pi^-\pi^{+(0)}\pi^{-(0)}$ and search for the rare decay $\eta' \to 4\pi^0$ — $\mathrm{PRD109, 032006\ (2024)}$

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

PRL 130, 081901 (2023)

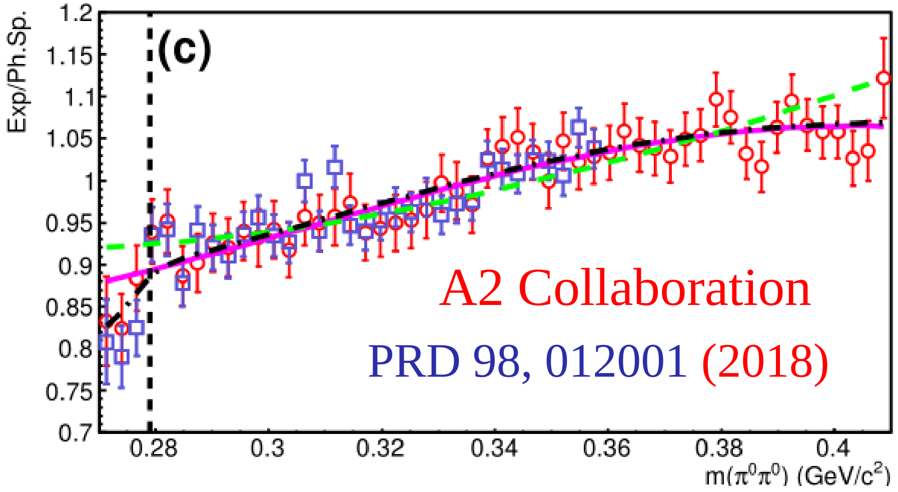


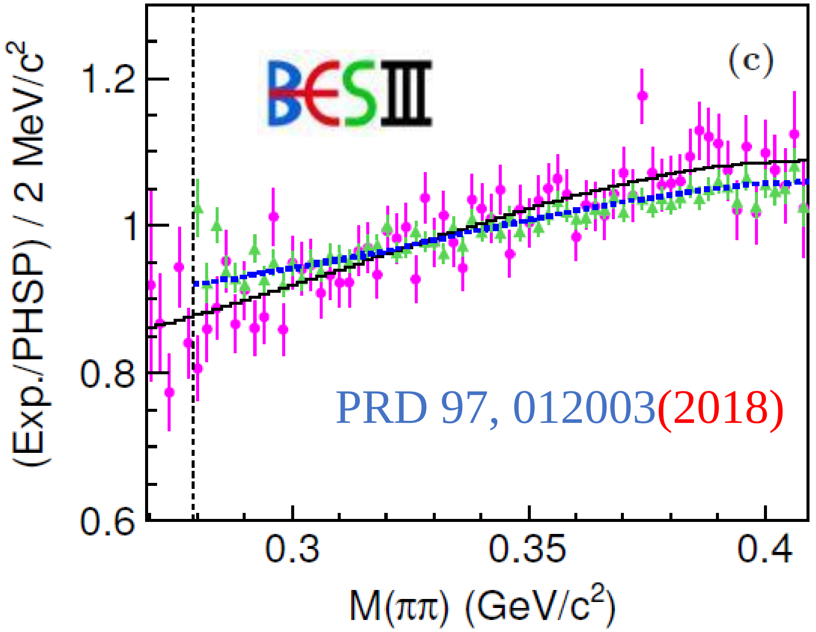


high term of $\pi\pi$ rescattering

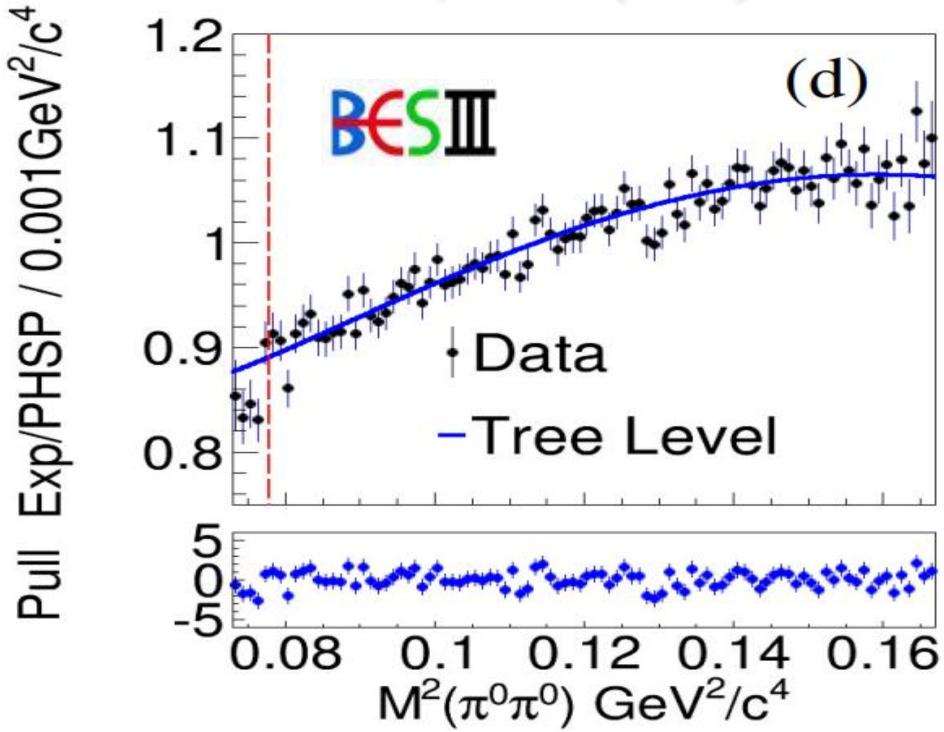
EPJC 62, 511 (2009)

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



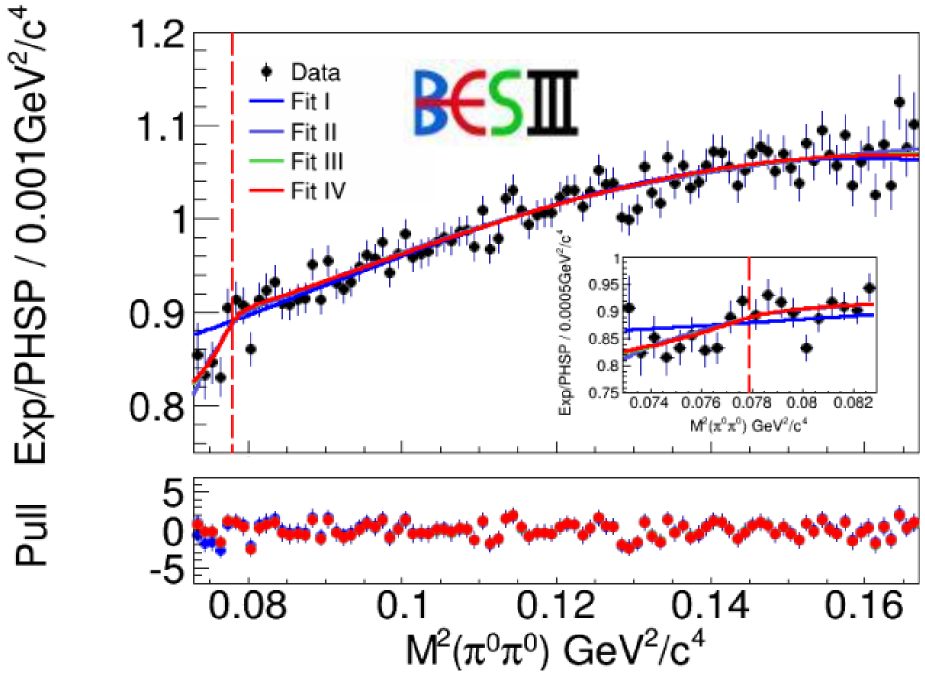


PRL130,081901(2023)



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

PRL 130, 081901 (2023)



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

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

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

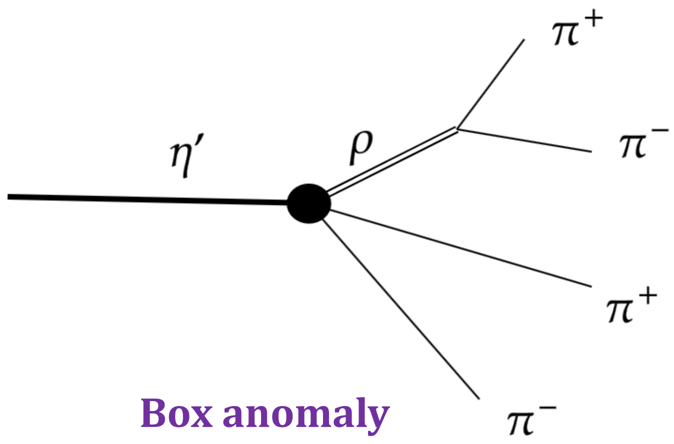
PRD 109, 032006 (2024)

- Chiral anomaly: triangle anomaly, box anomaly, pentagon anomaly

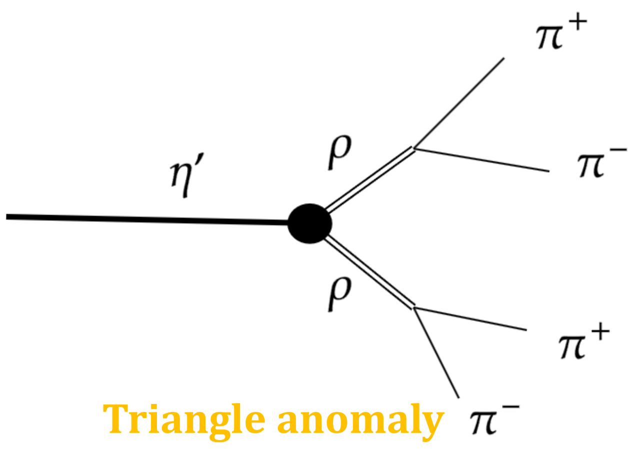
$$\pi^0 \to \gamma\gamma \qquad \eta' \to \gamma\pi^+\pi^- \qquad K^+K^- \to \pi^+\pi^-\pi^0$$

- Combination of ChPT and VMD model: (PRD85, 014014 (2012))

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



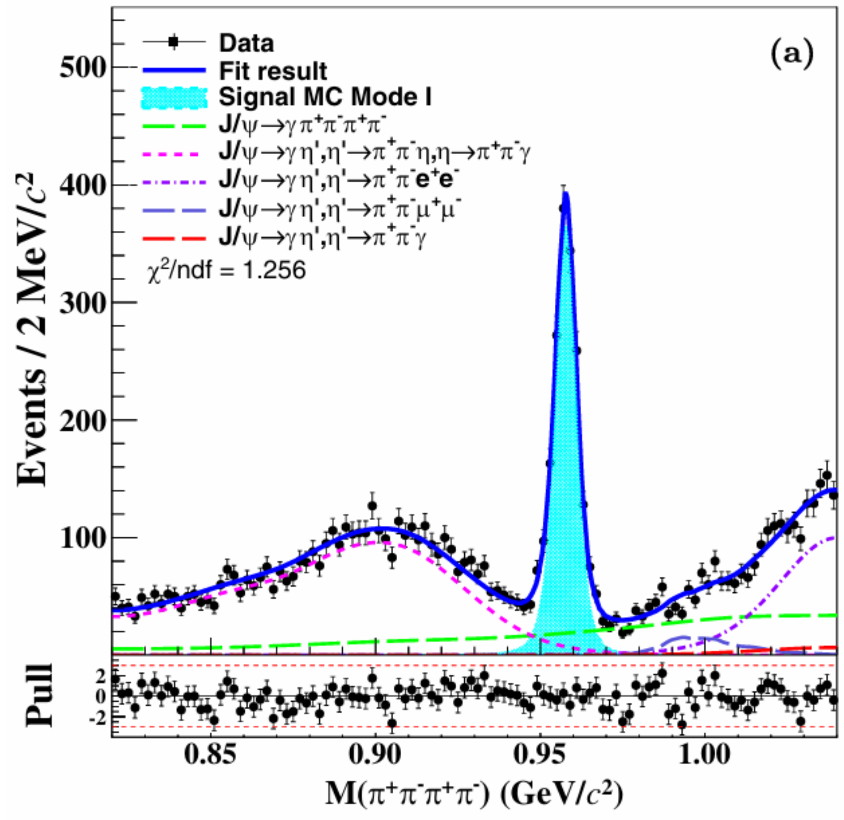
Box anomaly

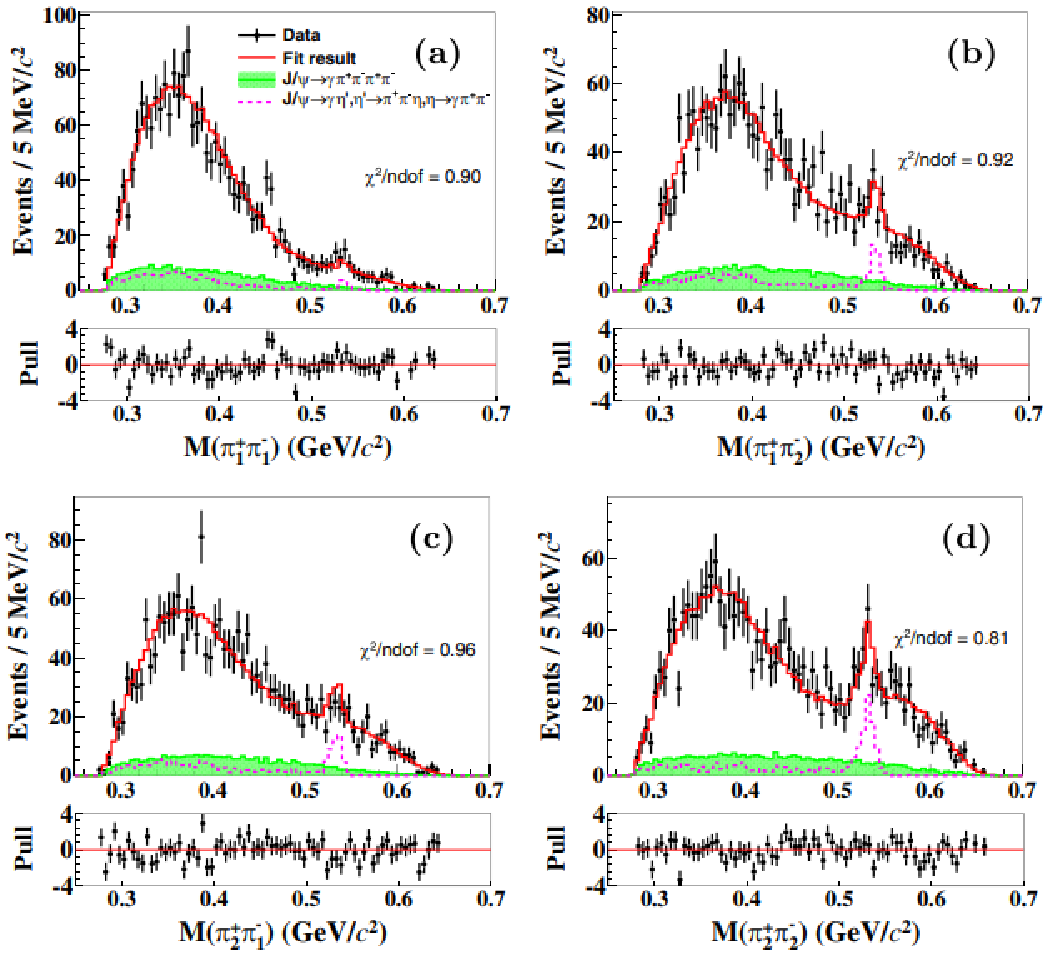


Triangle anomaly

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

PRD 109, 032006 (2024)





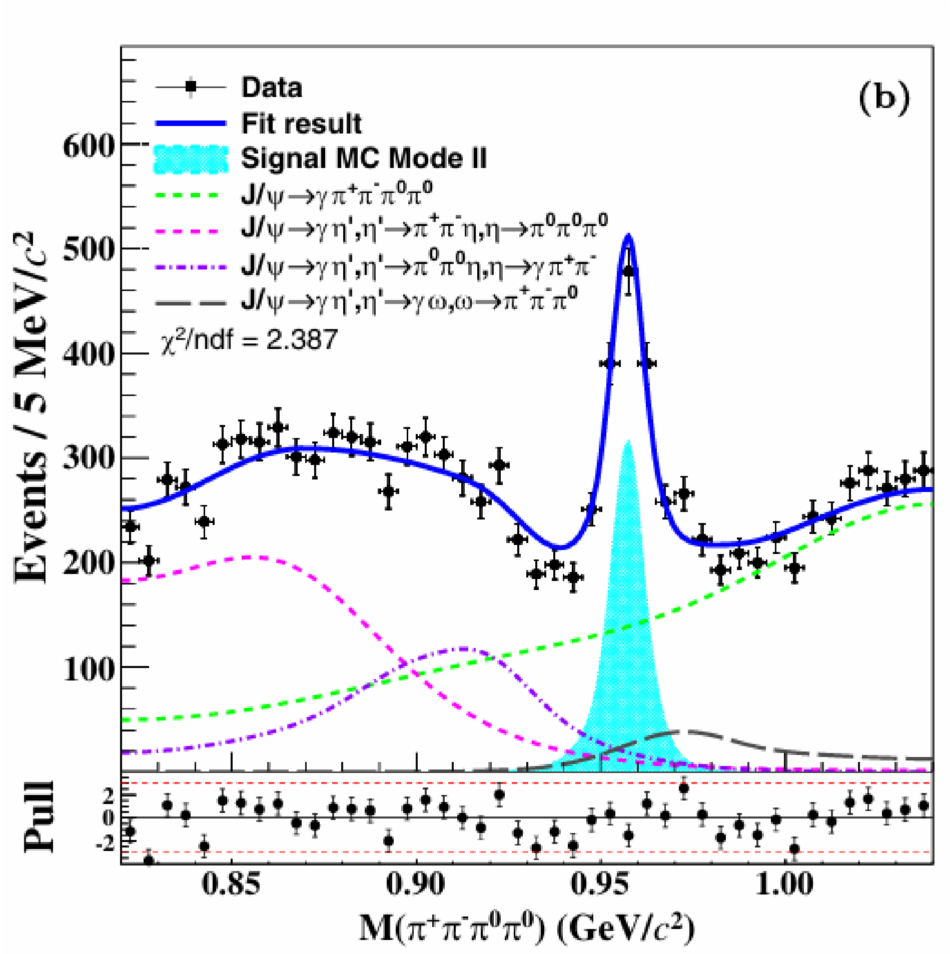
First measurement:

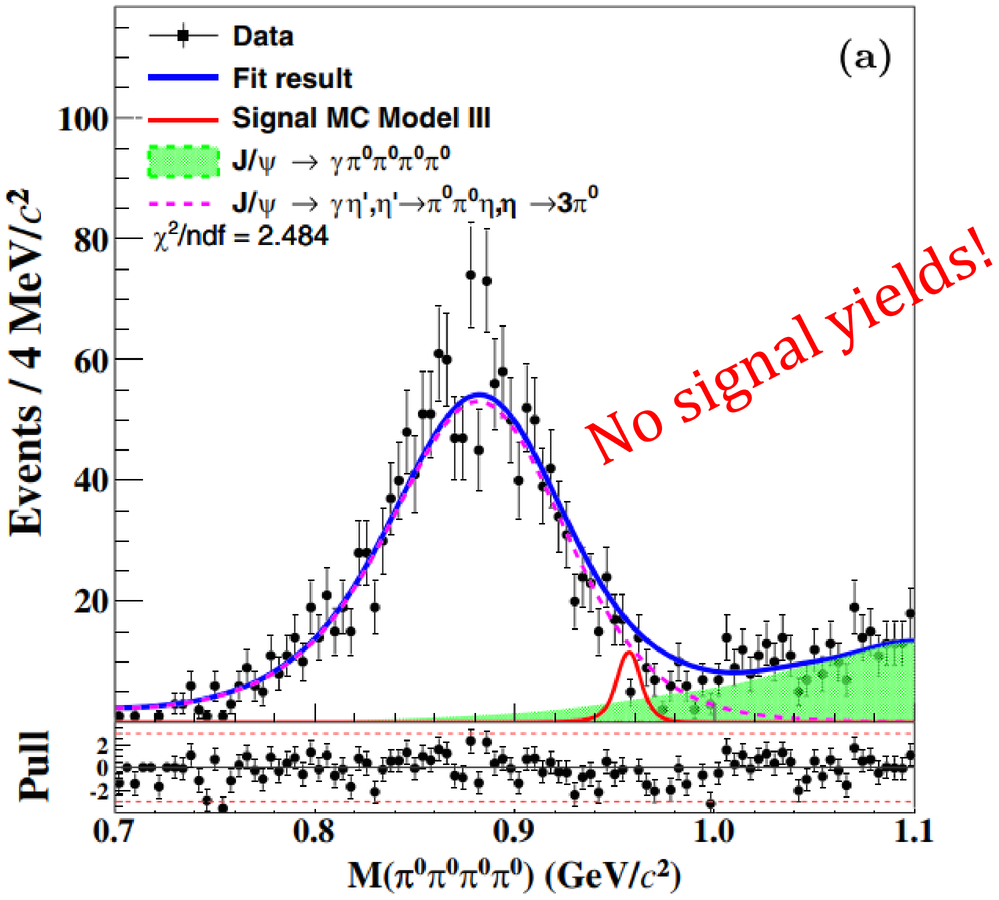
$\alpha = 1.22 \pm 0.33 \pm 0.04$

If $\alpha = 1$, triangle anomaly would be dominated.

$\eta' \rightarrow \pi^{+(0)}\pi^{-(0)}\pi^0\pi^0$

PRD 109, 032006 (2024)





$B\left(\eta' \rightarrow \pi^+\pi^-\pi^0\pi^0\right) = (2.12 \pm 012 \pm 0.1) \times 10^{-4}$

$B\left(\eta' \rightarrow \pi^0\pi^0\pi^0\pi^0\right) < 1.24 \times 10^{-5}$

Form factors

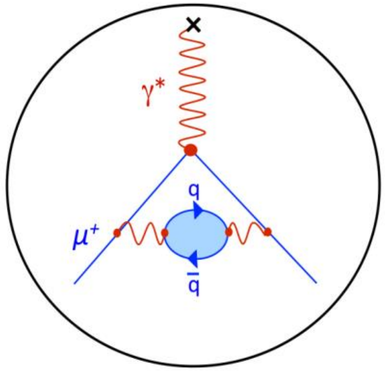
- Improved measurements of the Dalitz decays $\eta/\eta' \rightarrow \gamma e^+ e^-$ PRD109, 072001 (2024)
- Measurement of the Electromagnetic Transition Form Factors in the decays $\eta' \rightarrow \pi^+\pi^- l^+ l^-$ JHEP07, 135(2024)

Form Factor Physics

- ✓ Describe the complex internal structure or intermediate processes
- ✓ It determines the size of hadronic quantum corrections in the calculation of the $(g-2)_\mu$

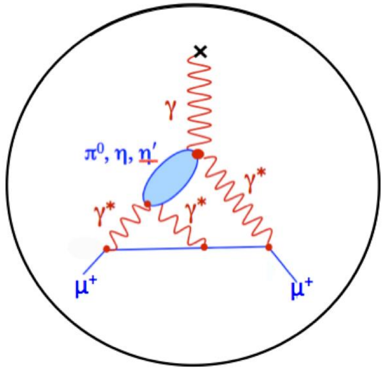
$$a_\mu = \frac{1}{2}(g-2)_\mu$$

$$a_\mu^{SM} = a_\mu^{QED} + a_\mu^{EW} + a_\mu^{hadron},\ a_\mu^{hadron} = a_\mu^{HVP} + a_\mu^{HLbL}$$



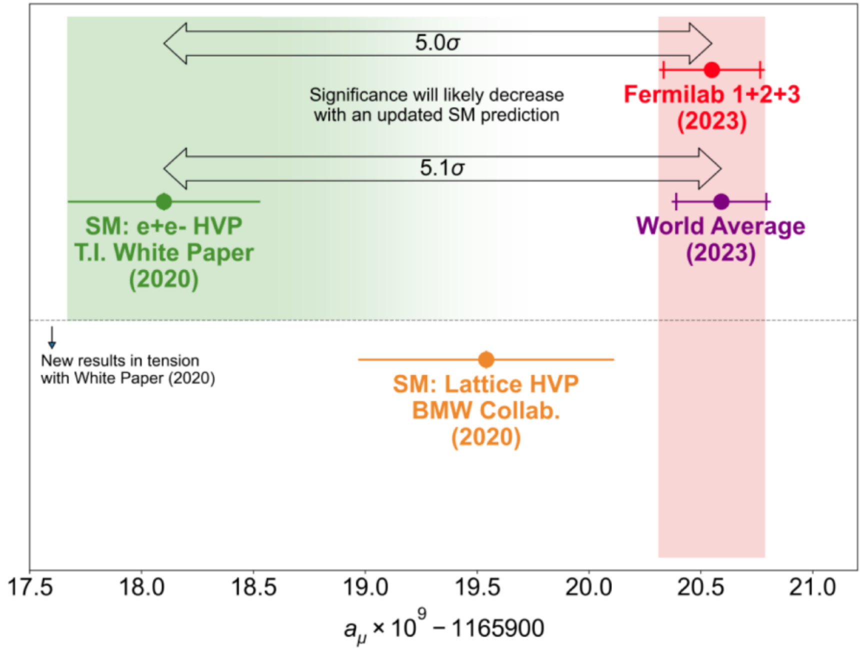
$a_\mu^{HVP} = 6845(40) \times 10^{-11}$

Hadronic Vacuum Polarization(LO)



$a_\mu^{HLbL} = 92(18) \times 10^{-11}$

Hadronic Light-by-Light

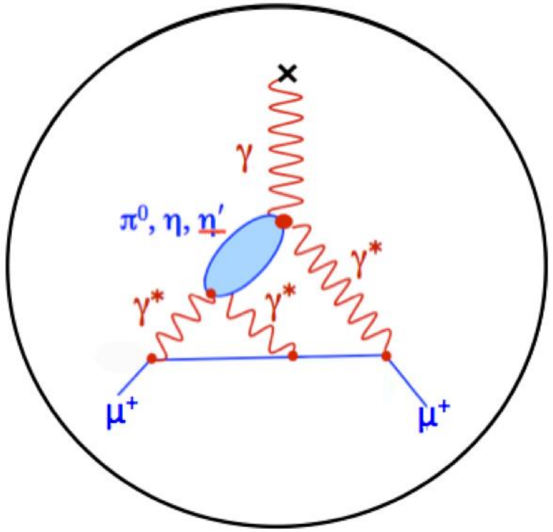


- ✓ Experimental input is needed to improve the precision of predictions!

Form Factor Physics

- ✓ The coupling of π^0, η, and η' with photon in HLbL can be described using transition form factor (TFF).

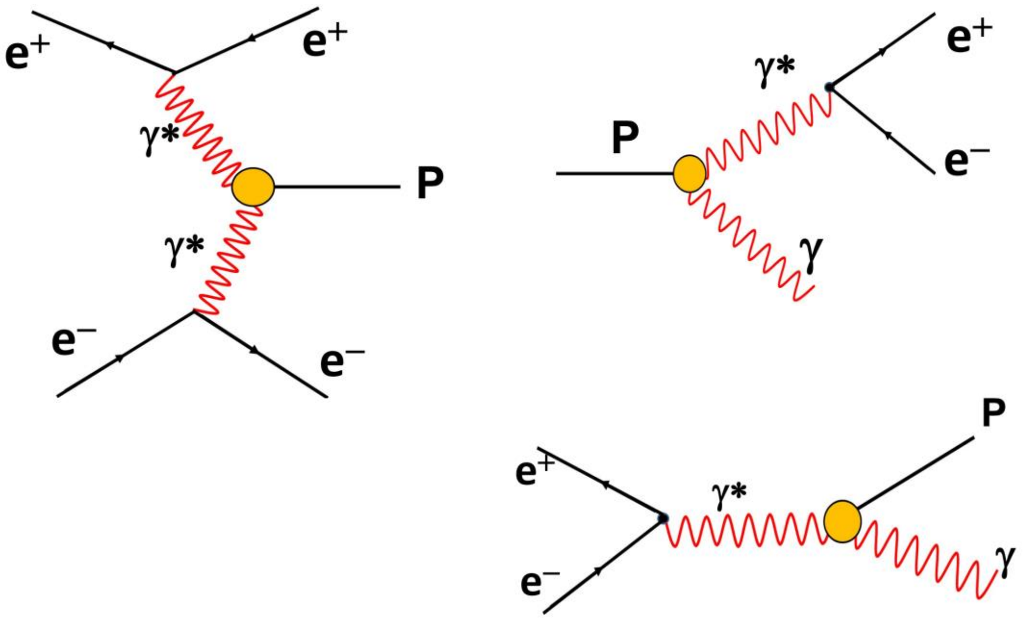
TFFs as experimental input!



- ✓ TFFs are experimentally accessible in three different processes

Space-like

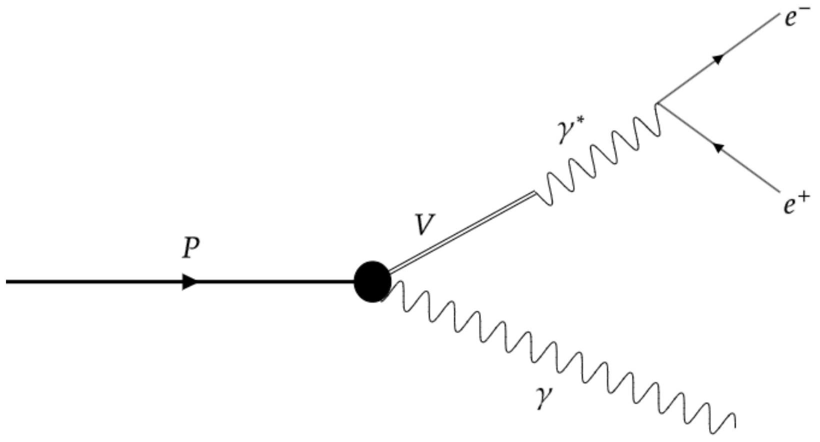
Time-like



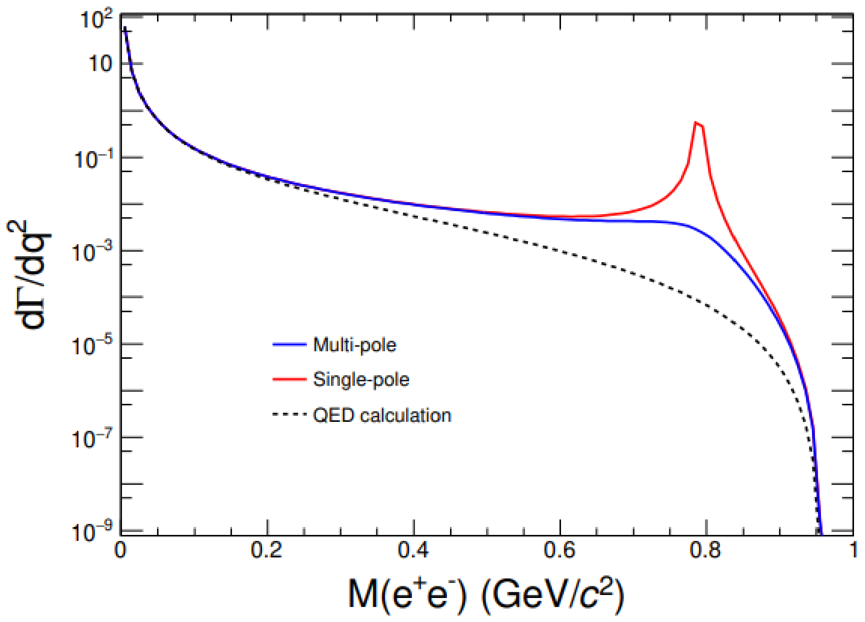
$\eta/\eta' \to \gamma e^+ e^-$

- The decay rate

$$\frac{d\Gamma(P \to \gamma l^+ l^-)}{dq^2 \Gamma(P \to \gamma\gamma)} = \frac{2\alpha}{3\pi}\frac{1}{q^2}\sqrt{1-\frac{4m_l^2}{q^2}}\left(1+\frac{2m_l^2}{q^2}\right)\left(1-\frac{q^2}{m_P^2}\right)^3 |F(q^2)|^2$$
$$= [\mathrm{QED}(q^2)] \times |F(q^2)|^2$$



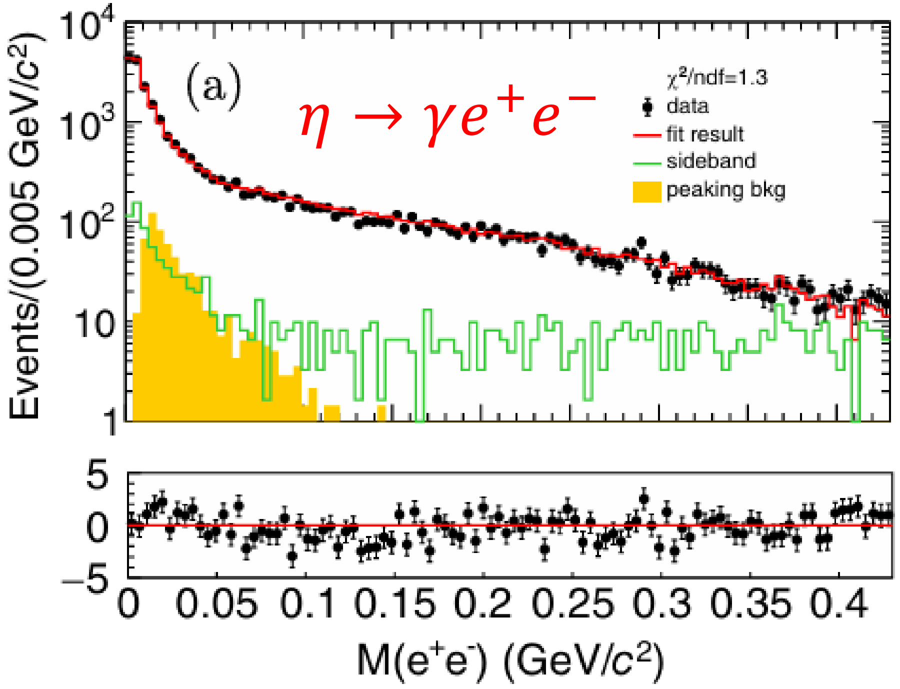
- Single-pole: $F(q^2) = \frac{1}{1-q^2/\Lambda^2}$
- Multi-pole: $|F(q^2)|^2 = \frac{\Lambda^2(\Lambda^2+\gamma^2)}{(\Lambda^2-q^2)^2+\Lambda^2\gamma^2}$
- Slope parameter: $b_{\eta'} = \frac{d|F(q^2)|}{dq^2}|_{q^2=0}$

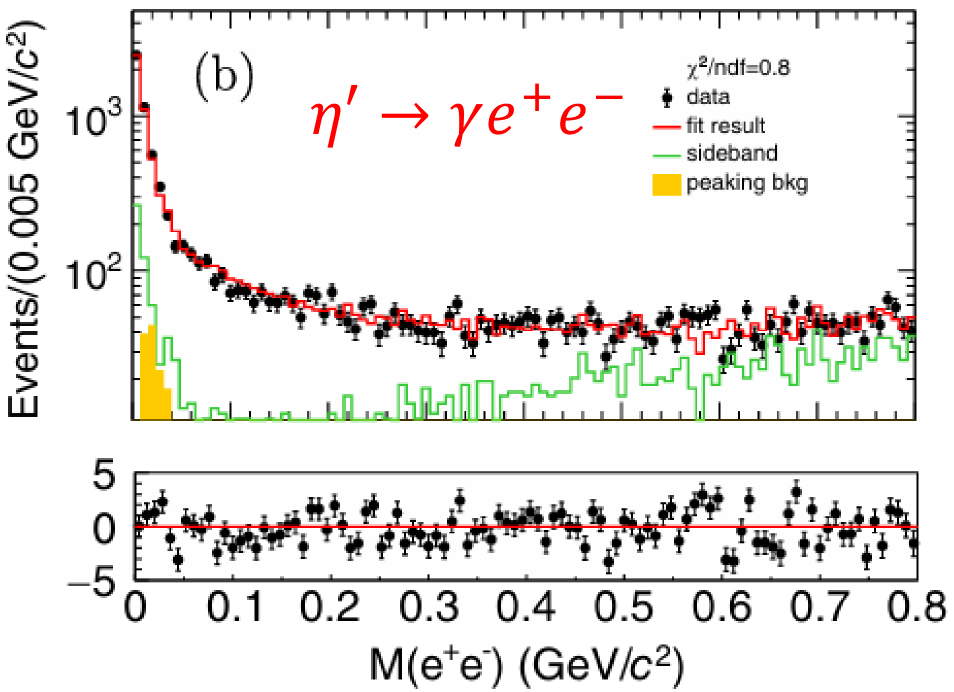


$\eta/\eta' \to \gamma e^+ e^-$

PRD 109, 072001 (2024)

- Unbinned maximum likelihood fit with $M(e^+e^-)$
  - ✓ less systematic uncertainties
  - ✓ better consideration of resolution





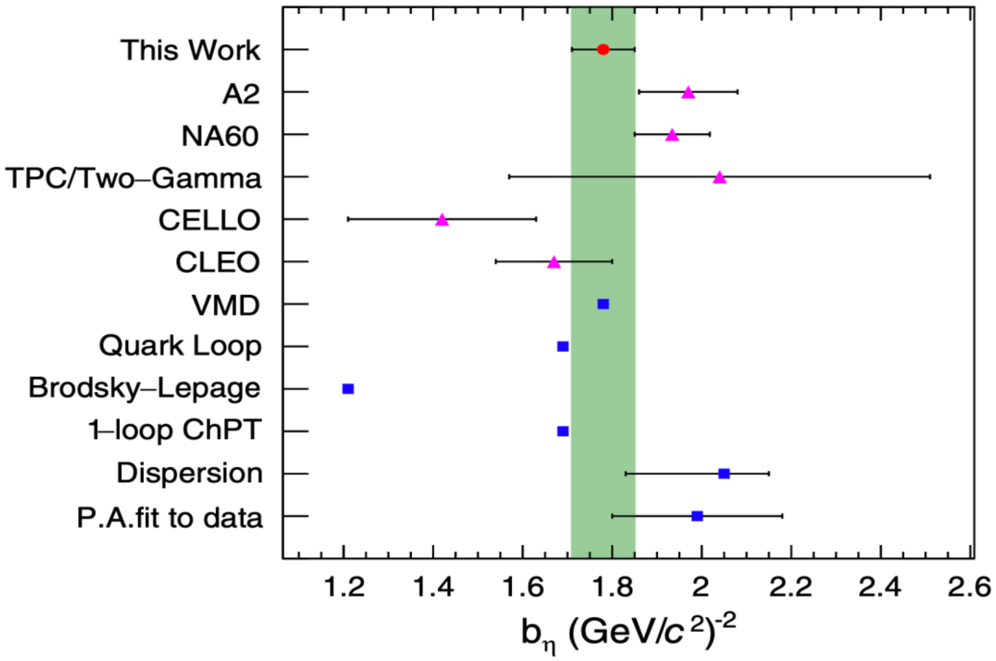
$\eta/\eta' \to \gamma e^+ e^-$

PRD 109, 072001 (2024)

✧ Single-pole formula is sufficient for η

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

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

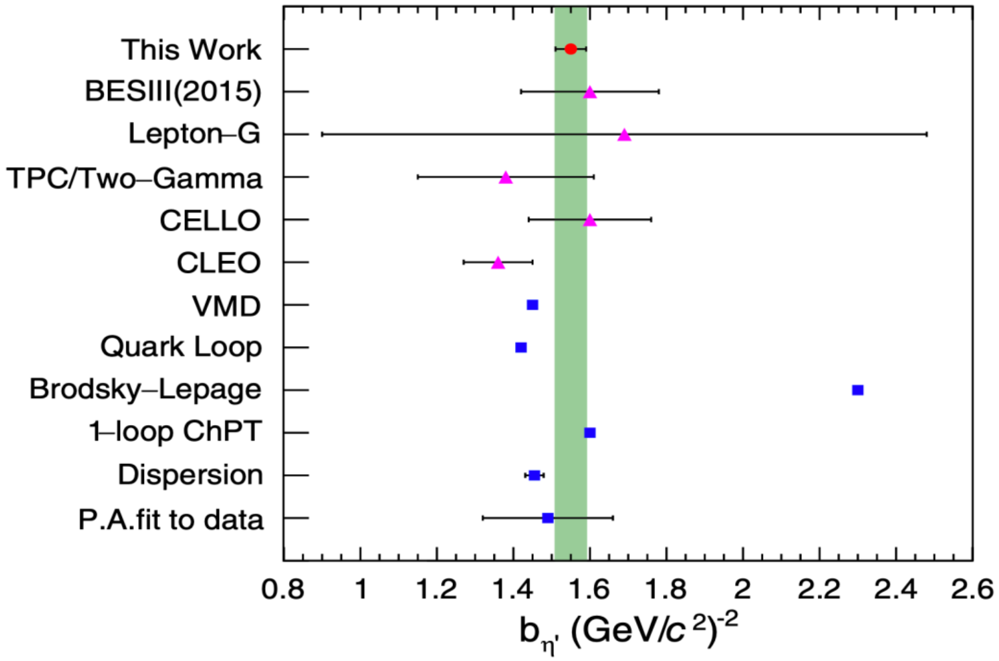


✧ Multi-pole formula for η'

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

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

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



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

JHEP07, 135(2024)

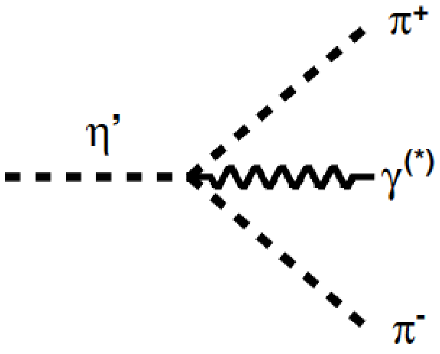
✧ Decay amplitude

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

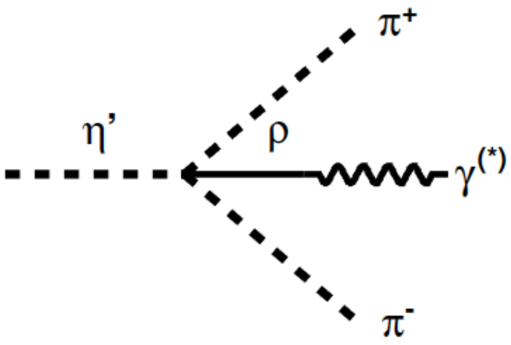
✧ $M(s_{\pi\pi}, s_{ll}) = \mathcal{M}_{mix} \times VMD(s_{\pi\pi}, s_{ll})$ contains the information of the decaying particle and the form factor.

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

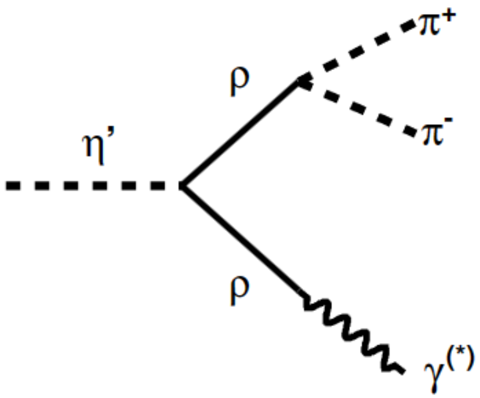
$$VMD(s_{\pi\pi}, s_{ll}) = 1 - \frac{3}{4}(c_1 - c_2 + c_3) + \frac{3}{4}(c_1 - c_2 - c_3)\frac{m_V^2}{m_V^2 - s_{ll} - i m_V \Gamma(s_{ll})} + \frac{3}{2}c_3 \frac{m_V^2}{m_V^2 - s_{ll} - i m_V \Gamma(s_{ll})}\frac{m_{V,\pi}^2}{m_{V,\pi}^2 - s_{\pi\pi} - i m_{V,\pi}\Gamma(s_{\pi\pi})}$$



Axial anomaly



VMD contribution

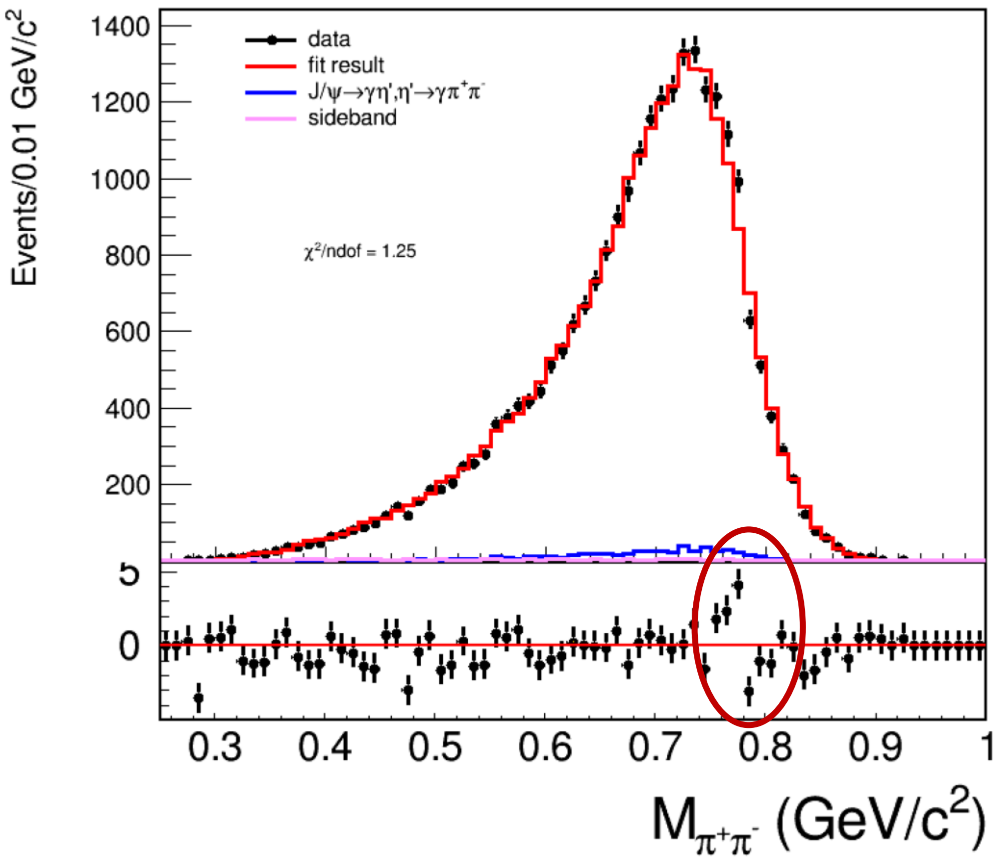


VMD contribution

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

JHEP07, 135(2024)

- By adjusting the values of the c_i-parameters, we can switch between the various VMD models.
  I. Hidden gauge model: $c_1 - c_2 = c_3 = 1$
  II. Full VMD model: $c_1 - c_2 = \frac{1}{3}, c_3 = 1$
  III. Modified VMD: $c_1 - c_2 \neq c_3$



- For $\eta' \to \pi^+\pi^- e^+ e^-$ decay
  - ✓ ρ^0 only can not describe data well.
  - ✓ $\omega \to \pi^+\pi^-$ decay is necessary!

$$\frac{m_{V,\pi}^2}{m_{V,\pi}^2 - s_{\pi\pi} - i m_{V,\pi}\Gamma(s_{\pi\pi})} + \beta e^{i\theta} \frac{m_\omega^2}{m_\omega^2 - s_{\pi\pi} - i m_\omega \Gamma(s_{\pi\pi})}$$

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

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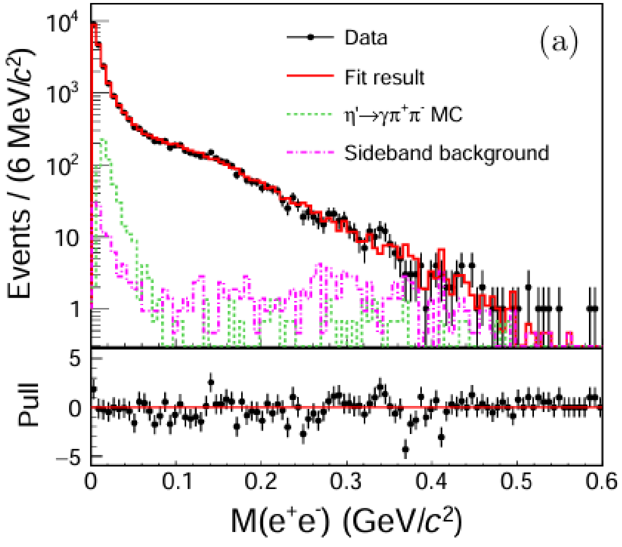
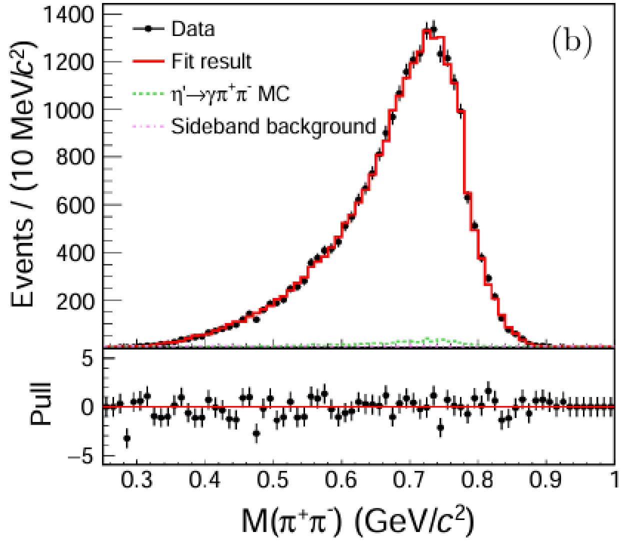
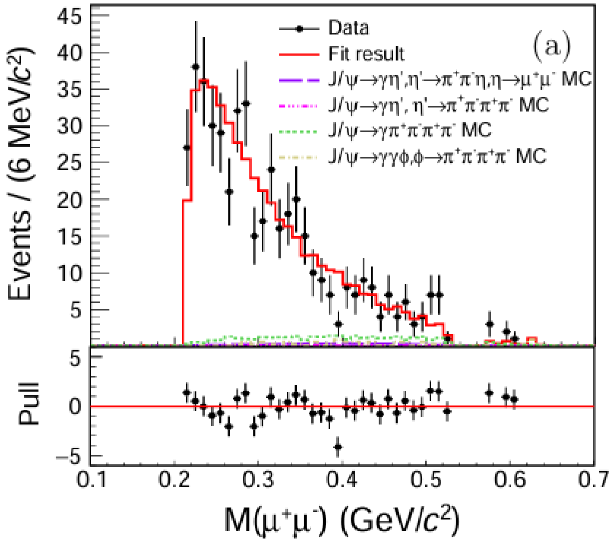
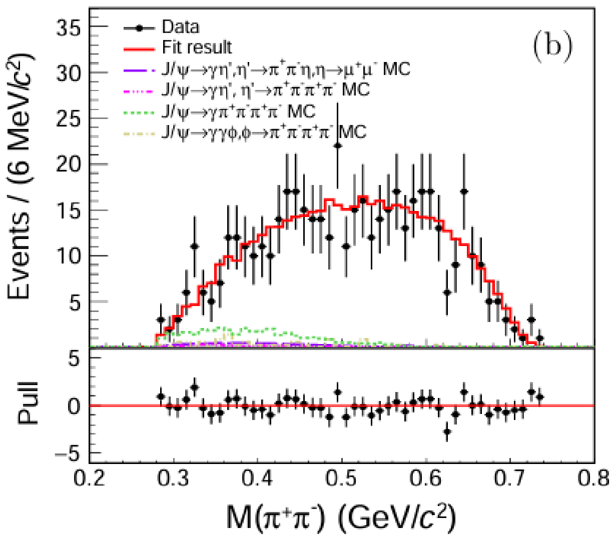


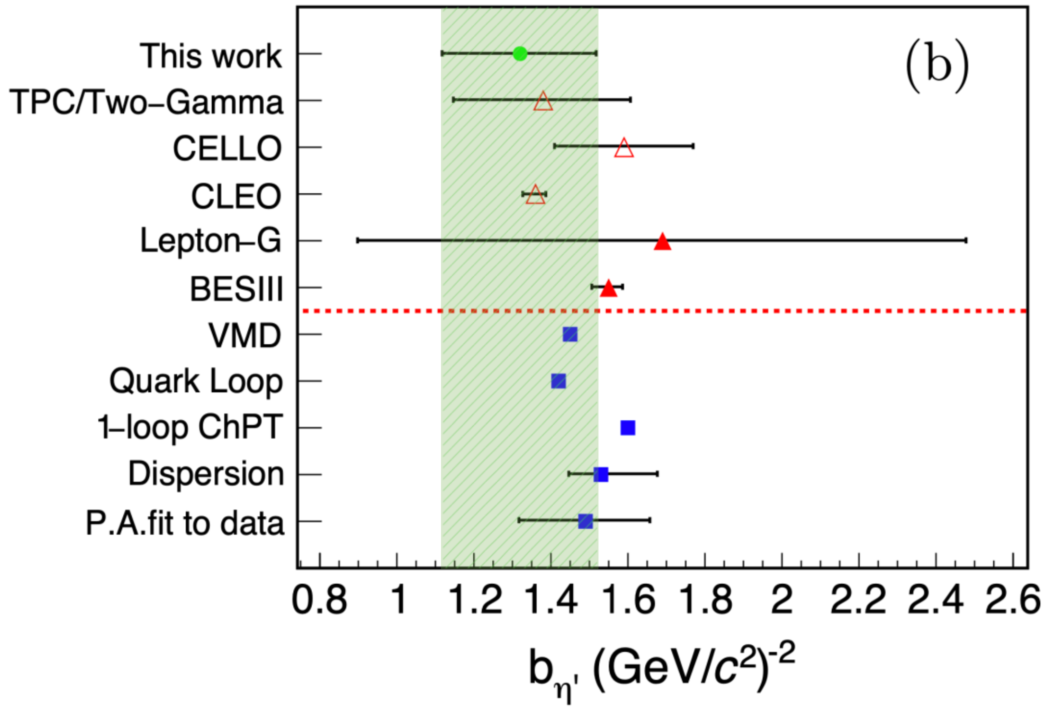






- First time to study form factors with $\eta' \to \pi^+\pi^-l^+l^-$:

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



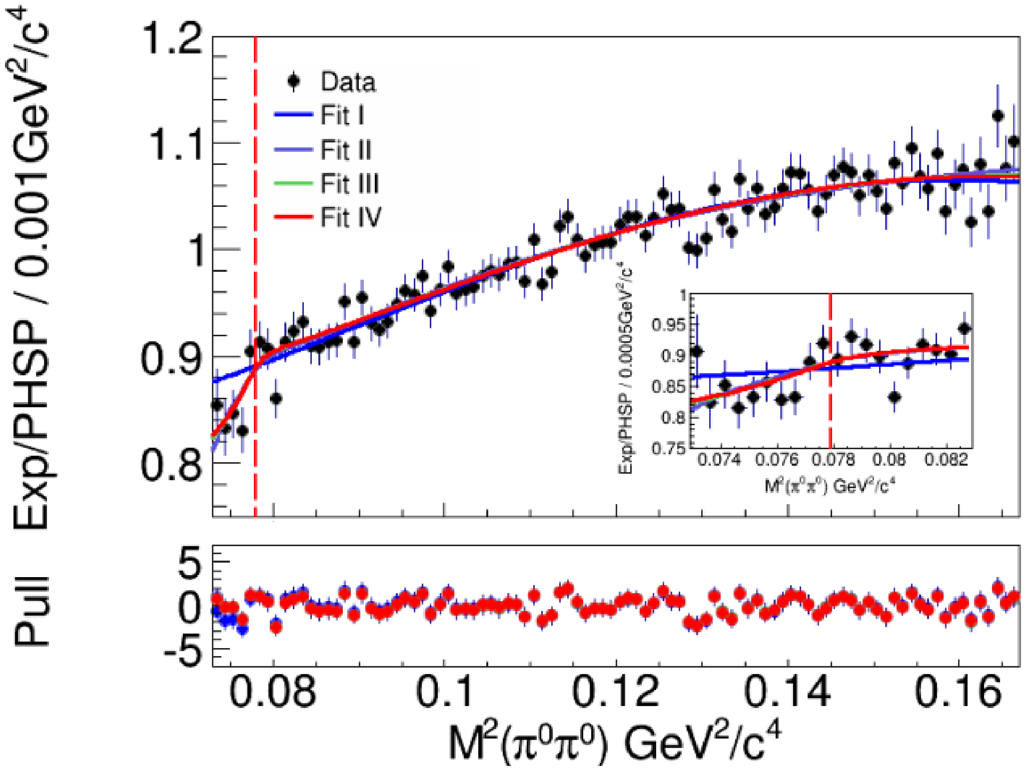
Summary

- ✧BESIII: a Light Meson Factory!
  - ✓ A unique place for light mesons
  - ✓ Allow to study light meson decays with high precision
- ✧Significant progresses achieved on η/η' decays
  - ✓ η/η': Decay mechanisms, Form factors…
- ✧More results are expected to come soon!
  - ✓ $\eta' \to \pi^+\pi^-\eta, \eta' \to e^+e^-\omega$, ...
  - ✓ Rare decays

THANKS

Backup

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



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

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

- Non-relativistic effective field theory

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

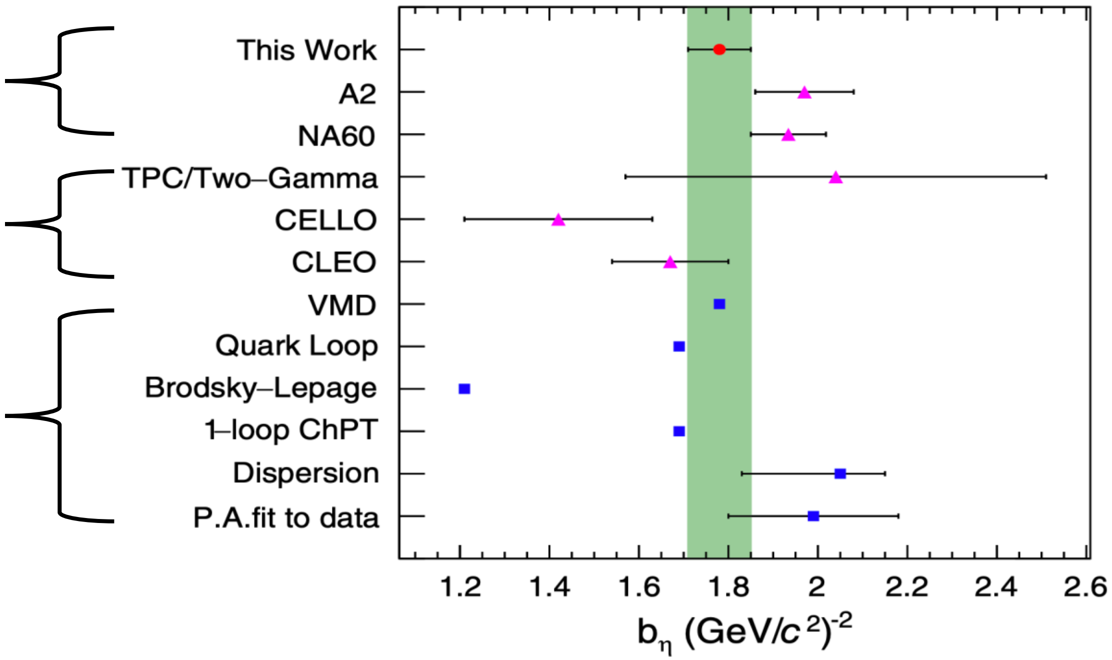
- The statistical significance is found to be around 3.5σ.

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

Time-like: $\eta' \to \gamma l^+ l^-$

Space like: $e^+e^- \to e^+e^-\eta'$

Theory



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

TFF Results

$\eta' \to \pi^+\pi^-e^+e^-$	Model I	Model II	Model III
	$c_1 - c_2 = c_3 = 1$	$c_1 - c_2 = 1/3, c_3 = 1$	$c_1 - c_2 \neq c_3$
$m_V(\mathrm{MeV}/c^2)$	$954.3 \pm 82.5 \pm 36.4$	857.4 ± 74.3	787.5 ± 137.9
$m_{V,\pi}(\mathrm{MeV}/c^2)$	$765.3 \pm 1.1 \pm 20.2$	765.4 ± 1.1	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 ± 1.4
θ	$1.4 \pm 0.3 \pm 0.1$	1.4 ± 0.3	1.4 ± 0.4
$c_1 - c_2$	1	1/3	-0.03 ± 0.87
c_3	1	1	1.03 ± 0.02
$\chi^2/ndof(e^+e^-, \pi^+\pi^-)$	65.3/82.0, 44.5/65.0	66.1/82.0, 44.3/65.0	66.8/82.0, 42.2/65.0
$b_{\eta'}(\mathrm{GeV}/c^2)^{-2}$	$1.10 \pm 0.19 \pm 0.07$	1.36 ± 0.24	1.61 ± 0.56

$\eta' \to \pi^+\pi^-\mu^+\mu^-$	Model I	Model II	Model III
	$c_1 - c_2 = c_3 = 1$	$c_1 - c_2 = 1/3, c_3 = 1$	$c_1 - c_2 \neq c_3$
$m_V(\mathrm{MeV}/c^2)$	$649.4 \pm 52.3 \pm 35.6$	601.6 ± 24.0	589.6 ± 24.2
$m_{V,\pi}(\mathrm{MeV}/c^2)$	$757.3 \pm 22.6 \pm 18.0$	765.4 ± 17.6	774.4 ± 40.7
$c_1 - c_2$	1	1/3	0.01 ± 0.42
c_3	1	1	0.98 ± 0.38
$\chi^2/ndof(\mu^+\mu^-, \pi^+\pi^-)$	36.1/34.0, 30.4/46.0	36.1/34.0, 30.4/46.0	37.4/35.0, 29.9/46.0
$b_{\eta'}(\mathrm{GeV}/c^2)^{-2}$	$2.37 \pm 0.38 \pm 0.27$	2.76 ± 0.22	2.88 ± 0.24

→ **Large statistical uncertainty of m_V and $c_1 - c_2$**

- A test with $c_1 - c_2 = c_3$ gives

$$c_1 - c_2 = c_3 = 1.03 \pm 0.02$$

- Provide a weighted average of the slope parameter for $\eta' \to \pi^+\pi^-e^+e^-$ and $\eta' \to \pi^+\pi^-\mu^+\mu^-$ based on Model I.

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