Light Meson decays at BESIII

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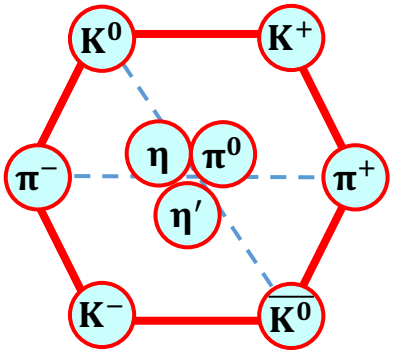
Outline

- Light meson physics
- BESIII: a light meson factory
- η/η′ Decays at BESIII
- Summary

Light Meson Physics

- Light Meson
  - ✧ Important roles in particle physics
  - ✧ Understanding the low energy QCD



- Light Meson Decays
  - ✧ Standard Model

    VMD, ChPT(Chiral perturbation theory), NREFT(The non-relativistic effective field theory) *etc.*

    ππ scattering

    transition form factor (theory input for (g-2)μ) ...
  - ✧ New physics beyond the Standard Model

    axion-like particles (ALPs)

    dark photons

    new sources of P-/C- and CP-violation ...

Source of η/η′ Events

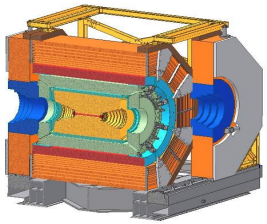
- η/η′ : Light masses, narrow widths and simple decay final-state topologies.
- A hot topic of theoretical discussions and an important research subject for many experimental collaborations.

CLAS(12)

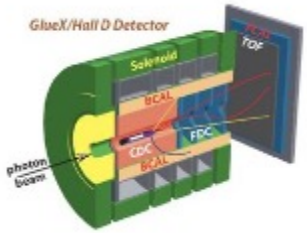
Crystal Ball

WASA-at-COSY

KLOE-2



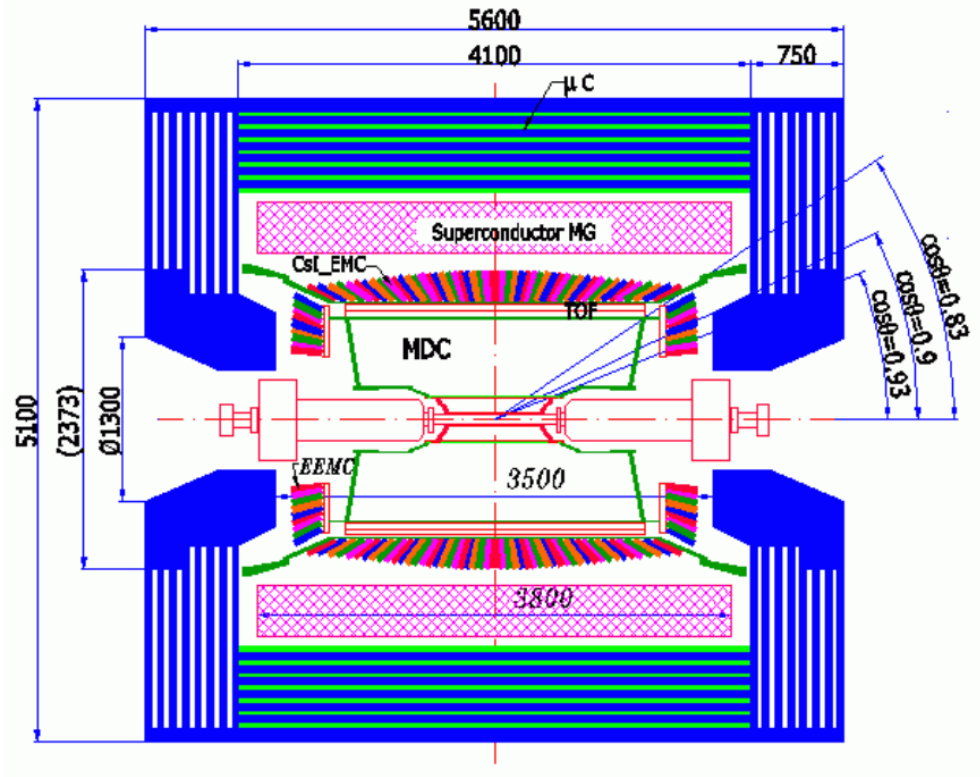
BESIII



GlueX

The BESIII Detector

Chin. Phys.C 44 (2020) 4, 040001

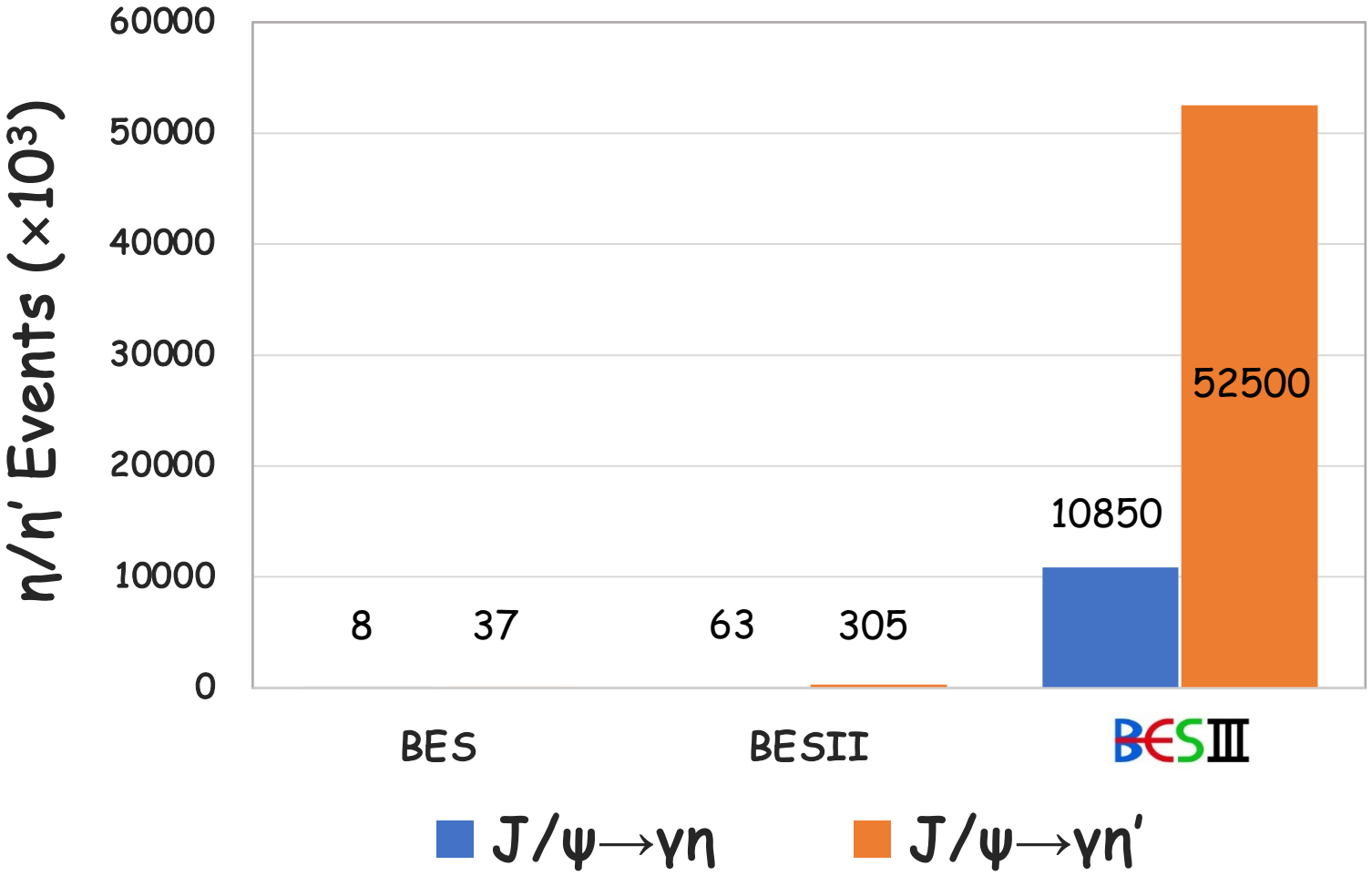


An overview of the BESIII detector.

- The BESIII detector records symmetric e^+e^- collisions provided by the BEPCII storage ring.
- Design luminosity: 1×10^{33} $cm^{-2}s^{-1}$
- Center-of-mass (cms) energies ranging from 2.0 to 4.95 GeV.
- From the inside out: Main drift chamber(MDC), Time-of-flight (TOF), Electromagnetic calorimeter (EMC), Superconducting magnet (SMG), and Muon detector (MUC).
- The facility is used for studies of hadron physics and τ -charm physics.

10 billion J/ψ Events available !

η/η' Events at BESIII



A light meson factory !

η/η′ Decays at BESIII

Decay channel	Physics	Publication
$\eta'\to 2(\pi^+\pi^-)$, $\pi^+\pi^-\pi^0\pi^0$	First Observation - BR	PRL112, 251801 (2014)
$\eta'\to\gamma e^+e^-$	First Observation - BR - TFF	PRD92, 012001 (2015)
$\eta'\to\omega e^+e^-$	First Observation - BR	PRD92, 051101 (2015)
$\eta'\to K\pi$	Weak Decay - UL	PRD93, 072008 (2016)
$\eta'\to\rho\pi$	First Observation - BR	PRL118, 012001 (2017)
$\eta'\to\gamma\gamma\pi^0$	BR - B Boson	PRD96, 012005 (2017)
$\eta'\to\gamma\pi^+\pi^-$	BR - Box anomaly	PRL120, 242003 (2018)
$\eta'\to\pi^+\pi^-\eta$, $\eta'\to\pi^0\pi^0\eta$	Matrix elemts - Cusp Effect	PRD97, 012003 (2018)
$\omega\to\pi^+\pi^-\pi^0$	Dalitz plot analysis	PRD98, 112007 (2018)
$P\to\gamma\gamma$	BRs - Chiral anomaly	PRD97, 072014 (2018)
$\eta'\to\gamma\gamma\eta$	UL	PRD100, 052015 (2019)
Absolute BR of η′ decays	BRs	PRL122, 142002 (2019)
$\eta'\to\pi^0\pi^0\pi^0\pi^0$	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)
$\eta'\to\pi^0\pi^0\eta$	Cusp effect	PRL130, 081901 (2023)
$\eta\to\pi^+\pi^-\pi^0$, $\eta\to\pi^0\pi^0\pi^0$	Matrix Elements - m_u-m_d	PRD107, 092007 (2023)

Hadronic decays

Radiative decays

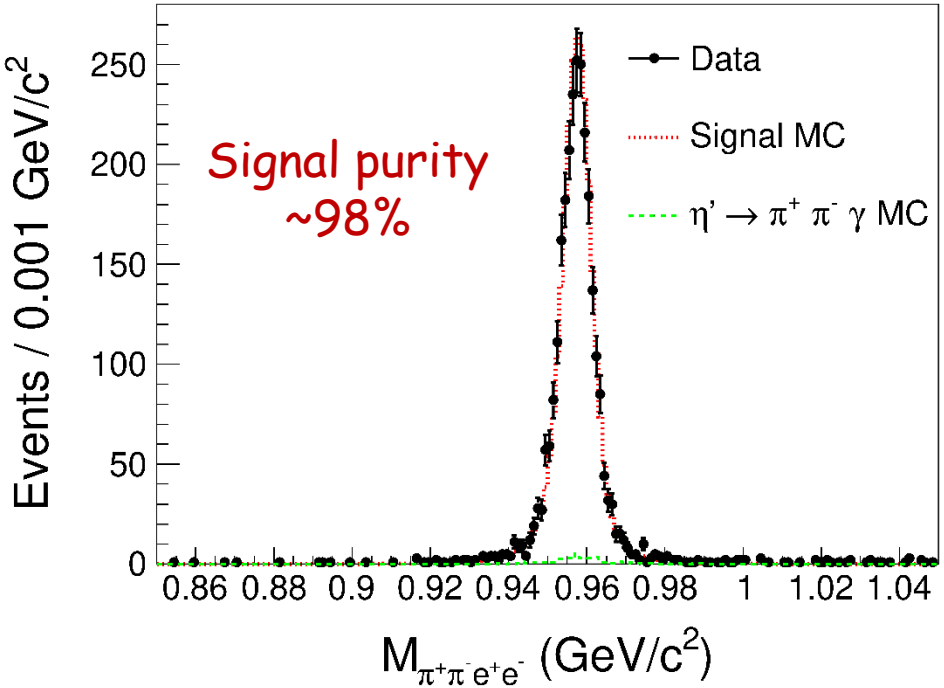
Rare/forbidden decays

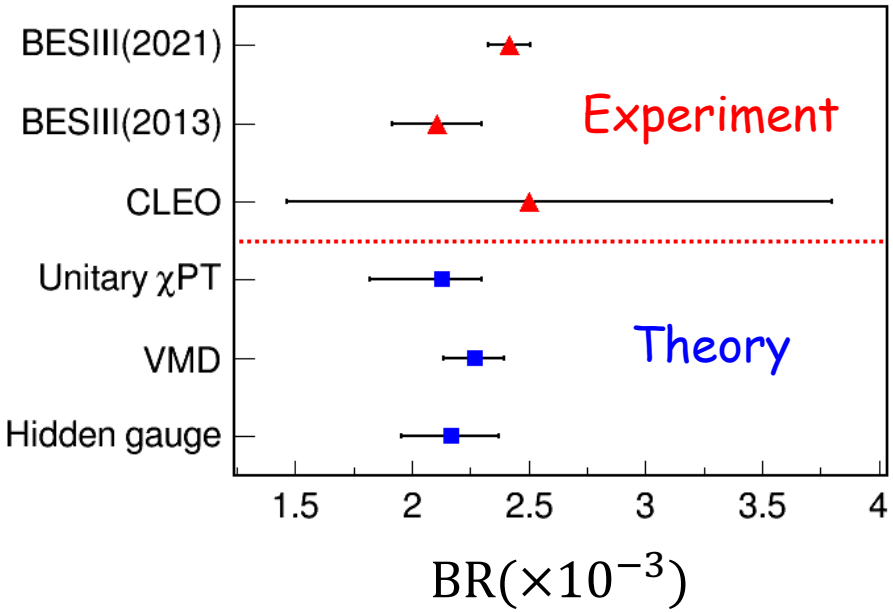
Experimental results

Theoretical verification

Measurement of the Branching Fraction of $\eta' \to \pi^+\pi^-e^+e^-$

PRD103, 092005 (2021)

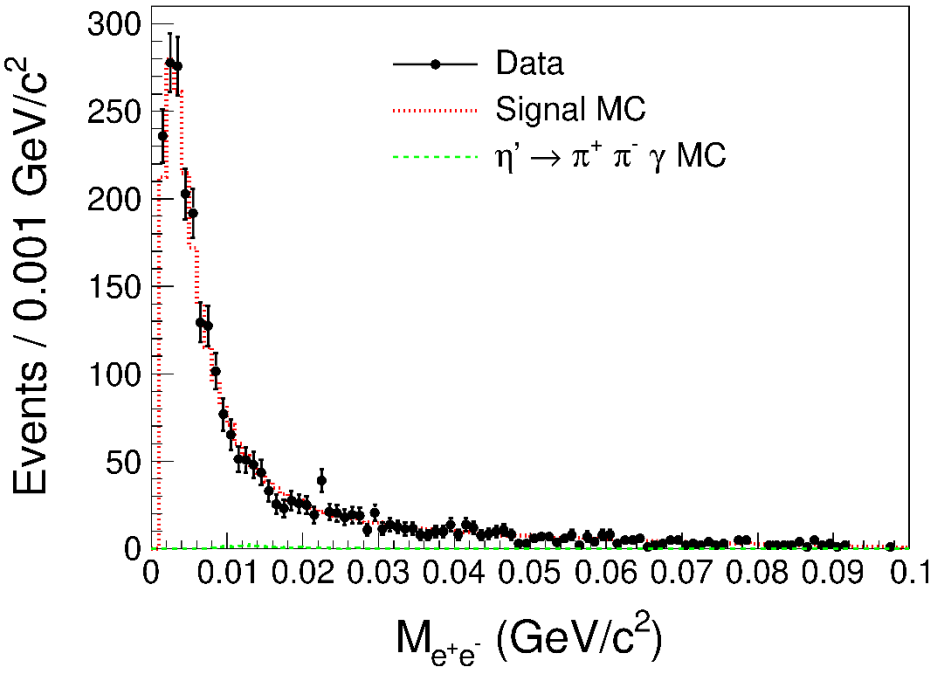


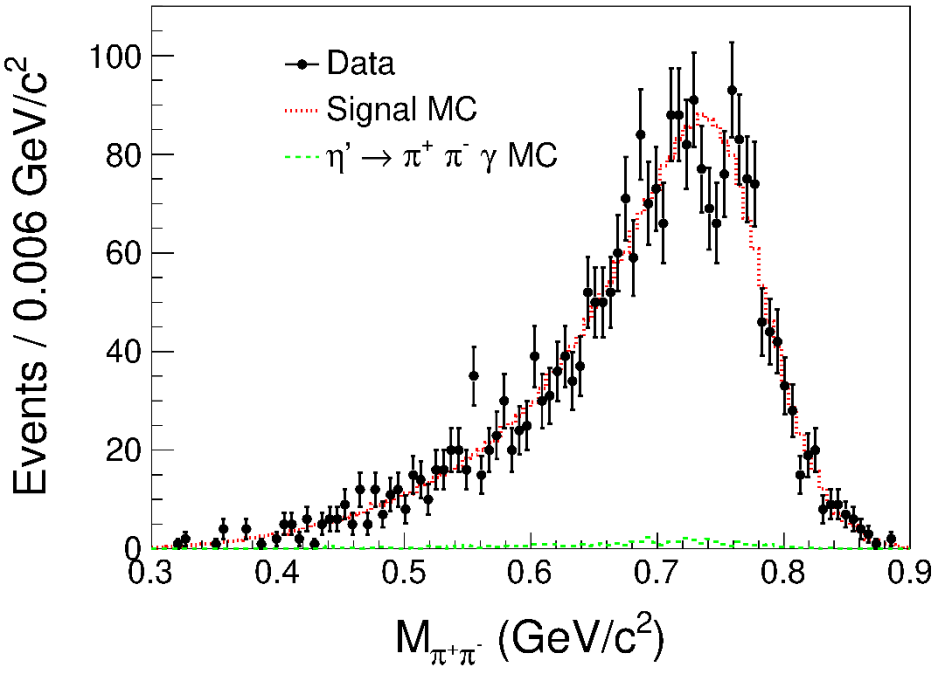


$$\mathrm{BR}(\eta' \to \pi^+\pi^-e^+e^-) = \left(2.42 \pm 0.05_{\mathrm{stat.}} \pm 0.08_{\mathrm{syst.}}\right)\times 10^{-3}$$

Measurement of the Branching Fraction of $\eta' \to \pi^+\pi^-e^+e^-$

PRD103, 092005 (2021)



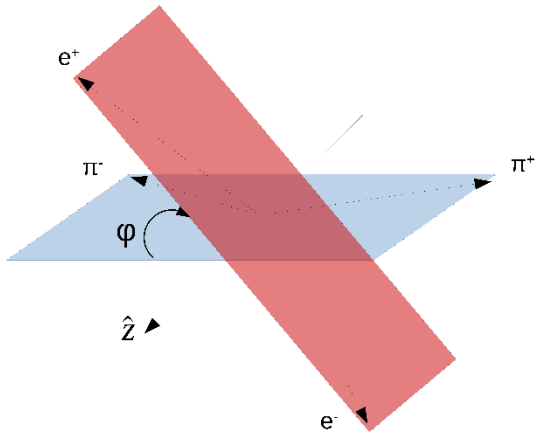


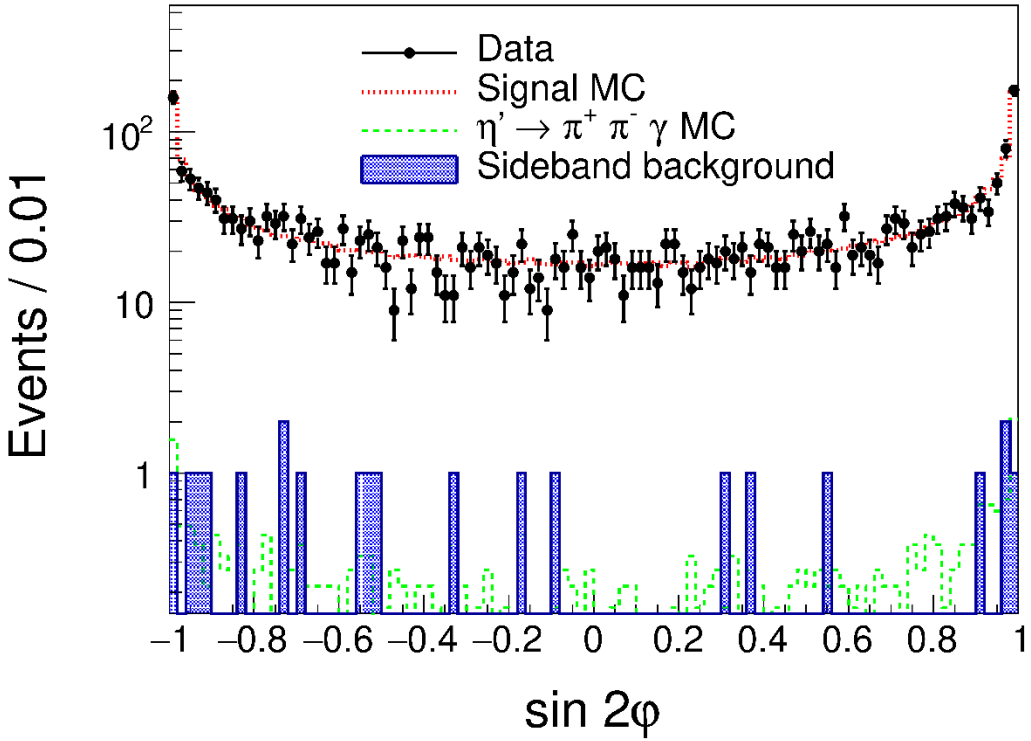
With high statistics of 10 bllion J/ψ events, the $\eta^{(\prime)}$ transition form factor study is in progress!

Search for a CP-Violating Asymmetry in $\eta' \to \pi^+\pi^-e^+e^-$

PRD103, 092005 (2021)

- Manifested as asymmetry in angle φ



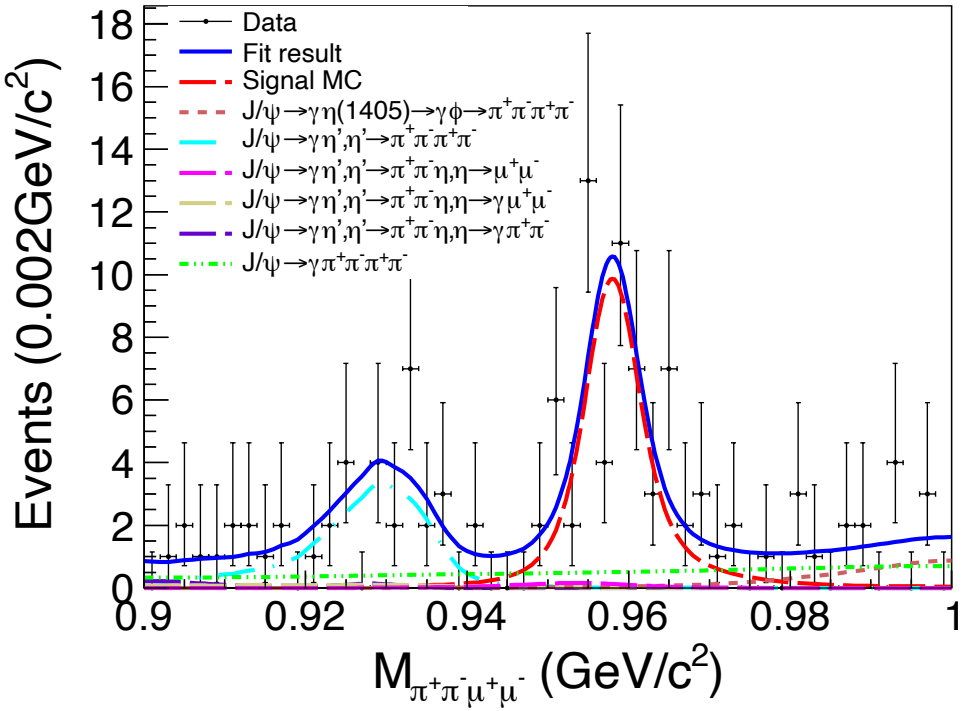


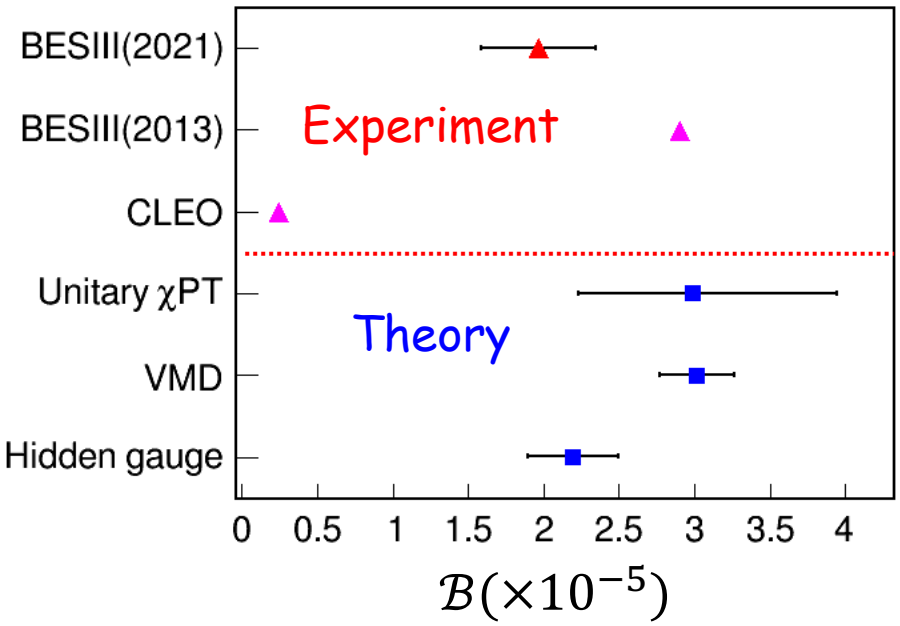
$$\mathcal{A}_\varphi = \frac{1}{\Gamma}\int_0^{2\pi} \frac{d\Gamma}{d\varphi}\,\mathrm{sign}(\sin 2\varphi)\,d\varphi = \frac{N(\sin 2\varphi > 0) - N(\sin 2\varphi < 0)}{N(\sin 2\varphi > 0) + N(\sin 2\varphi < 0)} = (2.9 \pm 3.7_{\mathrm{stat.}} \pm 1.1_{\mathrm{syst.}})\%$$

Consistent with the standard model expectation of no CP-violation !

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

PRD103, 072006 (2021)



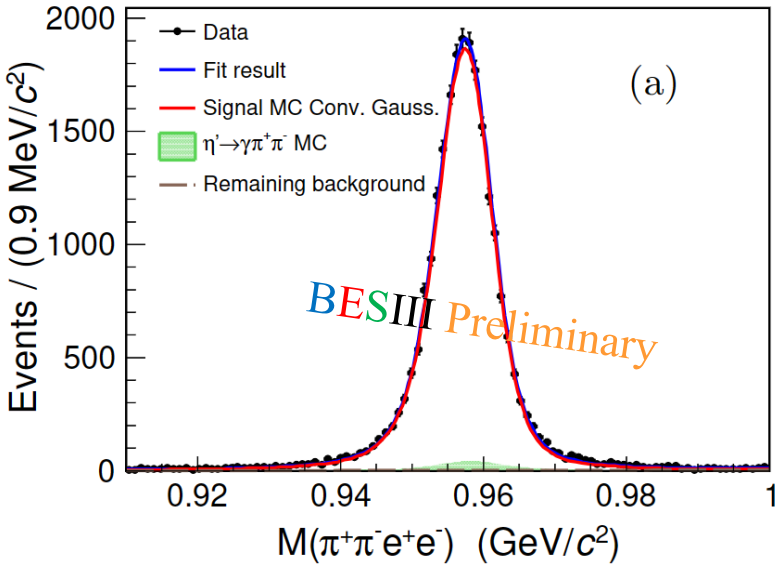


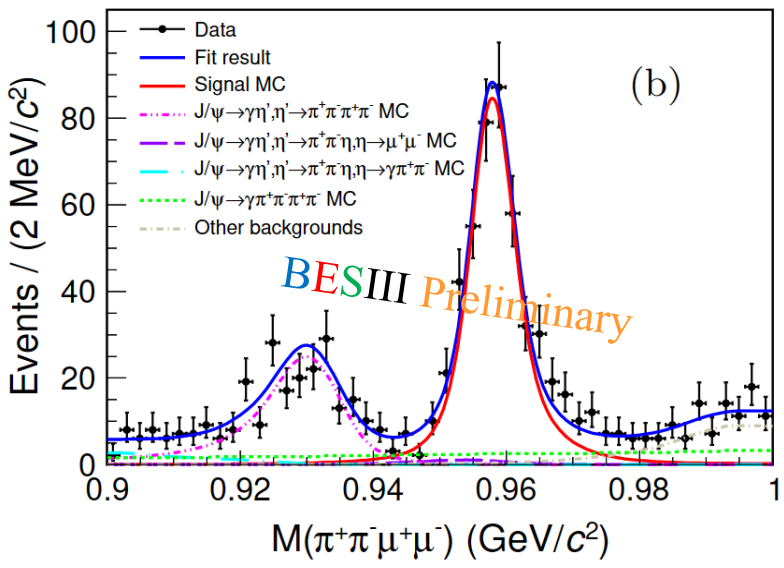
$$\mathrm{BR}\,(\eta' \to \pi^+\pi^-\mu^+\mu^-) = \left(1.97 \pm 0.33_{\mathrm{stat.}} \pm 0.19_{\mathrm{syst.}}\right)\times 10^{-5}$$

First observation with 8σ statistical significance !

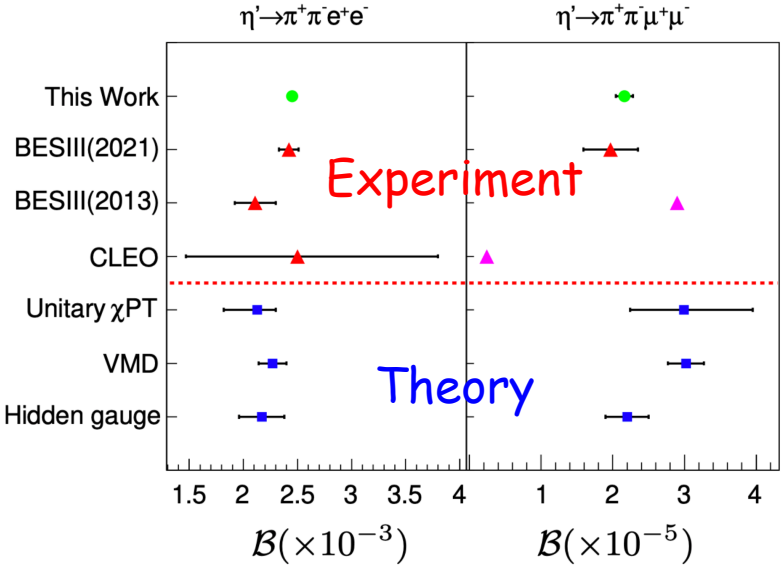
Preliminary results of $\eta' \to \pi^+\pi^- l^+ l^-$ in BESIII

- BFs study of $\eta' \to \pi^+\pi^- l^+ l^-$ with 10 bllion J/ψ events





Decay channel	BR
$\eta' \to \pi^+\pi^- e^+ e^- (10^{-3})$	$2.45 \pm 0.02_{\text{stat.}}$
$\eta' \to \pi^+\pi^- \mu^+ \mu^- (10^{-5})$	$2.16 \pm 0.12_{\text{stat.}}$



Preliminary results of $\eta' \to \pi^+\pi^- l^+ l^-$ in BESIII

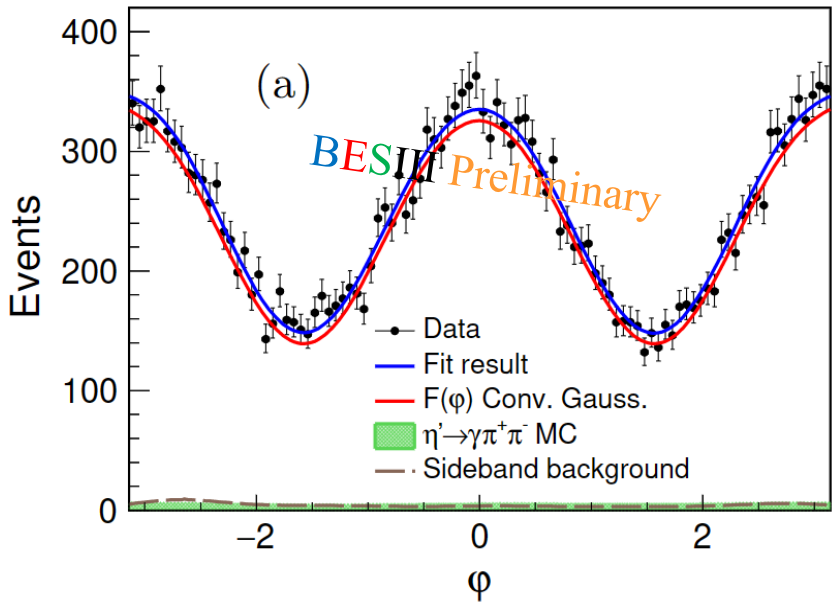
- **Results of CP Asymmetry**

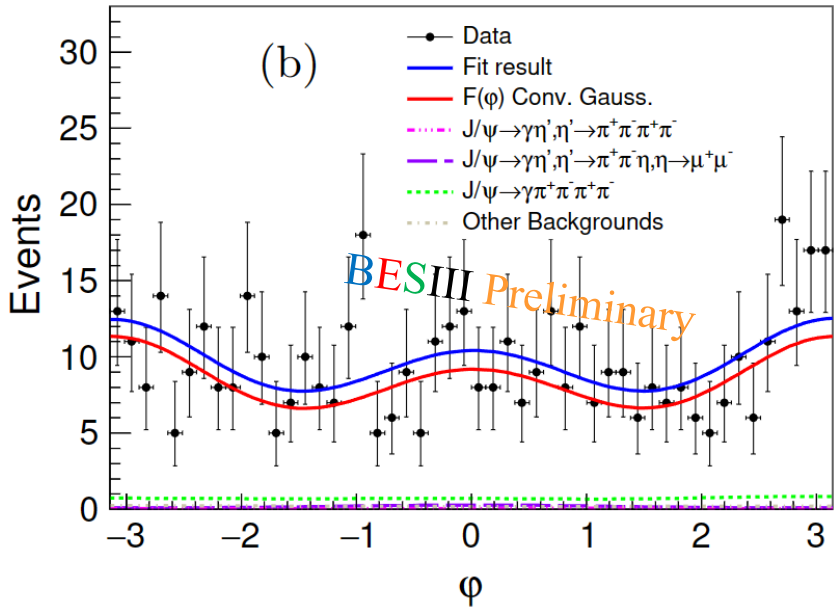
✧ The asymmetry parameter is defined as

$$\mathcal{A}_\varphi = \frac{\int_{-\pi}^{\pi} F(\varphi) sign(\sin 2\varphi) d\varphi}{\int_{-\pi}^{\pi} F(\varphi) d\varphi} = \frac{4b}{(2+a)\pi}$$

$F(\varphi) = 1 + a\cdot\sin^2\varphi + b\cdot\sin 2\varphi$ → the mixed term (the CP-violating term)

↓ the dominant term





$\mathcal{A}_\varphi(\eta' \to \pi^+\pi^- e^+ e^-) = (-0.21 \pm 0.73_{\text{stat.}})\%$ $\mathcal{A}_\varphi(\eta' \to \pi^+\pi^- \mu^+ \mu^-) = (0.62 \pm 4.71_{\text{stat.}})\%$

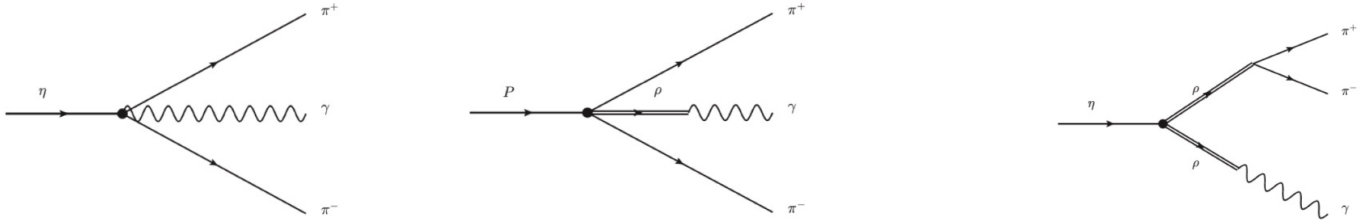
No CP asymmetry evidence is found at the present statistics !

Preliminary results of $\eta' \to \pi^+\pi^- l^+ l^-$ in BESIII

- **Electromagnetic Transition Form Factor**

✧ Within the VMD model, it can be factorized into three separate parts

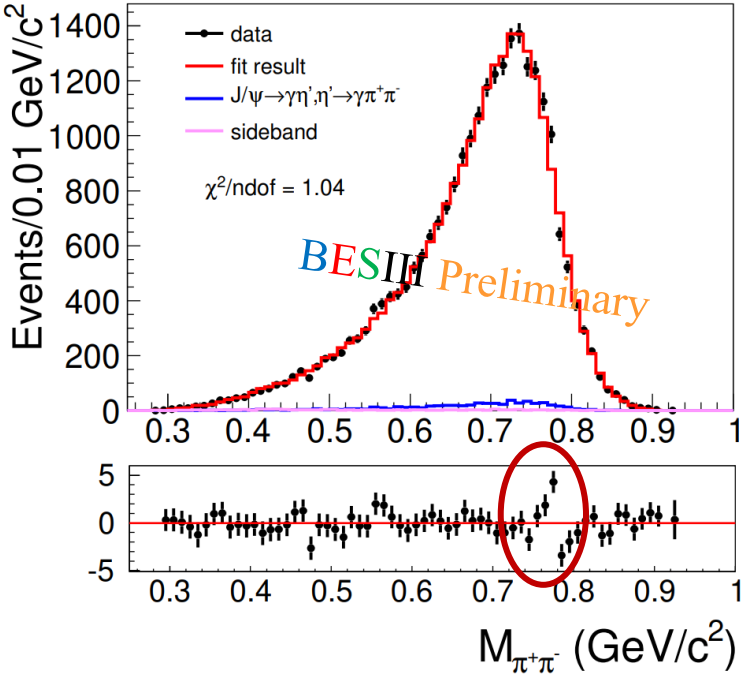
$$VMD(s_{\pi\pi}, s_{ll}) = 1 - \frac{3}{4}(c_1 - c_2 + c_3) + \frac{3}{4}(c_1 - c_2 - c_3)\frac{m_V^2}{m_V^2 - s_{ll} - im_V\Gamma(s_{ll})} + \frac{3}{2}c_3\frac{m_V^2}{m_V^2 - s_{ll} - im_V\Gamma(s_{ll})}\frac{m_{V,\pi}^2}{m_{V,\pi}^2 - s_{\pi\pi} - im_{V,\pi}\Gamma(s_{\pi\pi})}$$



✧ For $\eta' \to \pi^+\pi^- e^+ e^-$ decay mode, only the ρ^0 contribution is insufficient to describe the $\pi^+\pi^-$ mass spectrum of data and extra contributions from ω is necessary.

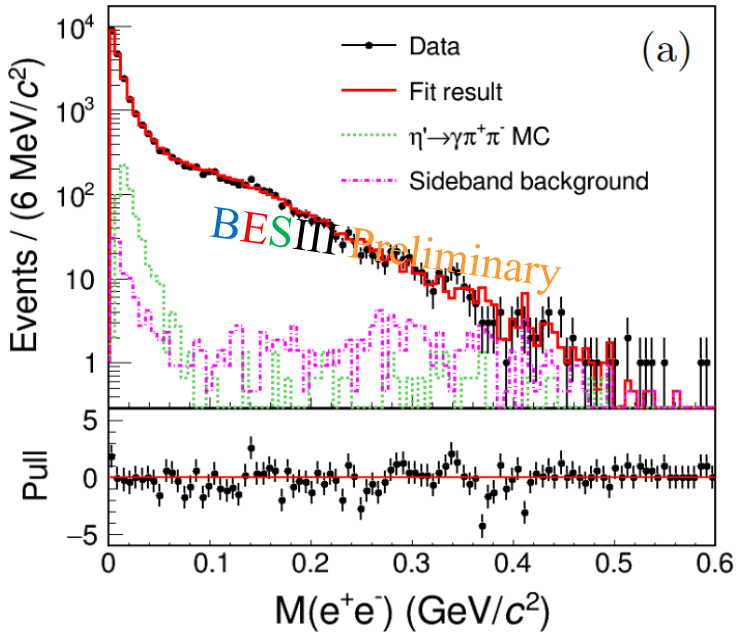
$$\frac{m_{V,\pi}^2}{m_{V,\pi}^2 - s_{\pi\pi} - im_{V,\pi}\Gamma(s_{\pi\pi})}$$

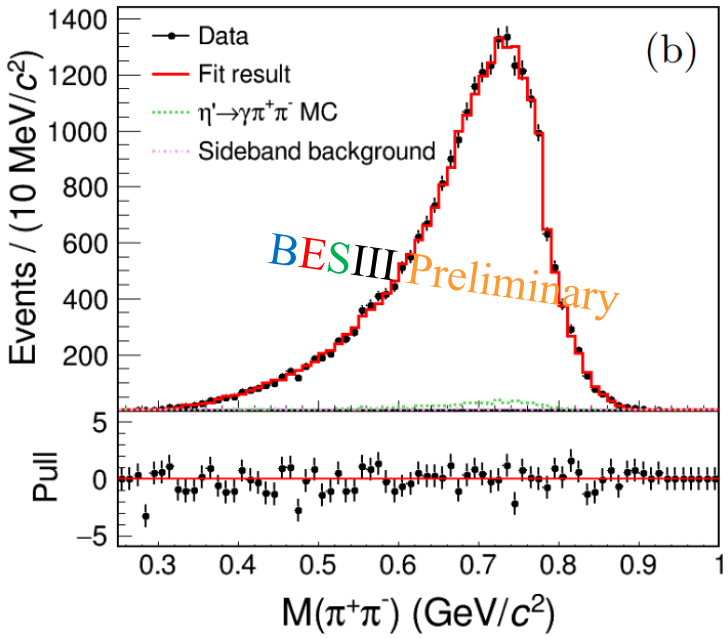
$$\frac{m_{V,\pi}^2}{m_{V,\pi}^2 - s_{\pi\pi} - im_{V,\pi}\Gamma(s_{\pi\pi})} + \beta e^{i\theta}\frac{m_\omega^2}{m_\omega^2 - s_{\pi\pi} - im_\omega\Gamma_\omega}$$



Preliminary results of $\eta' \to \pi^+\pi^- l^+ l^-$ in BESIII

- TFF Results of $\eta' \to \pi^+\pi^- e^+ e^-$



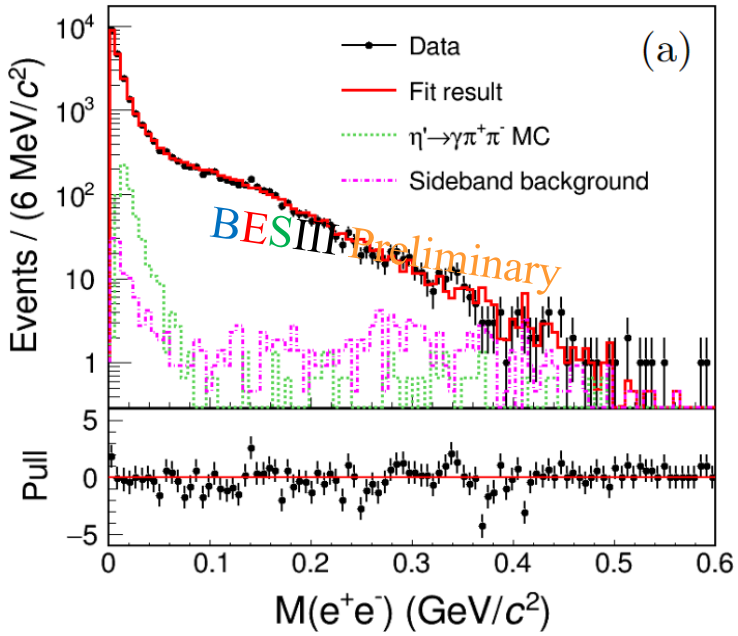


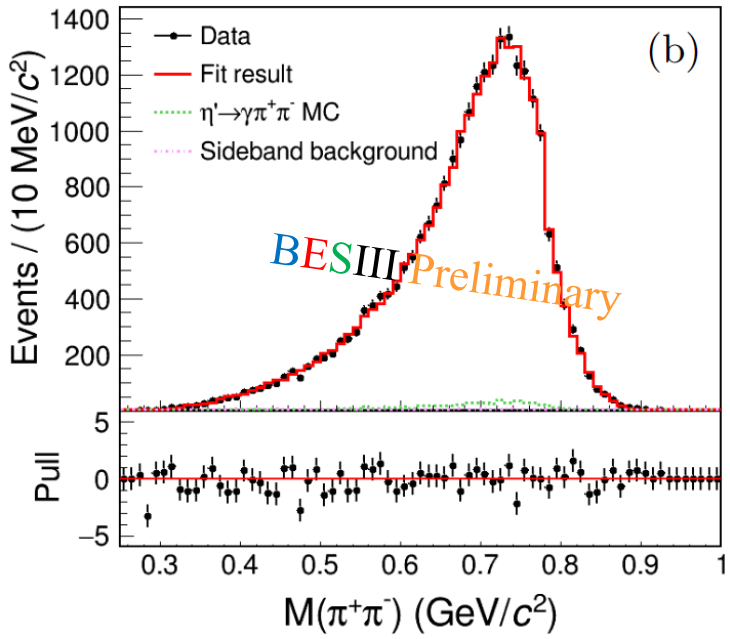
Parameter	Fit Results
c_1-c_2, c_3	1, 1
m_V (MeV/c^2)	954.26±82.53
$m_{V,\pi}$ (MeV/c^2)	765.32±1.12
$b_{\eta'} \approx 1/m^2_V$ (MeV/c^2)$^{-2}$	1.10±0.19

- Limited statistics at the high e^+e^- mass region lead to the large statistical uncertainty of m_V.
- A greater η' data sample is needed to make a more precise measurement.
- A test with $c_1 - c_2 = c_3$ gives $c_1 - c_2 = c_3 = 1.03 \pm 0.02$.

Preliminary results of $\eta' \to \pi^+\pi^- l^+ l^-$ in BESIII

- TFF Results of $\eta' \to \pi^+\pi^- e^+ e^-$





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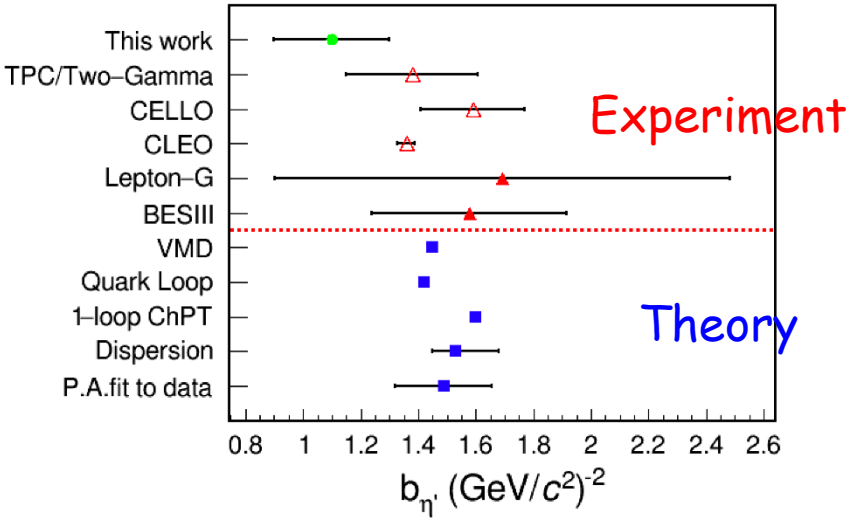
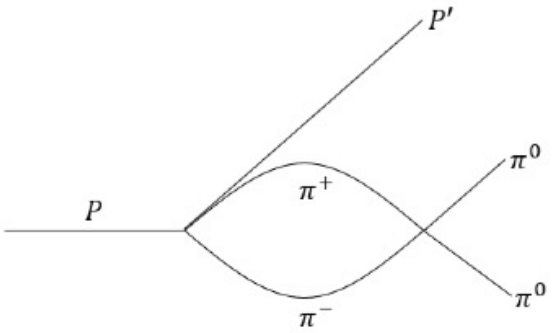
Electromagnetic interaction radius



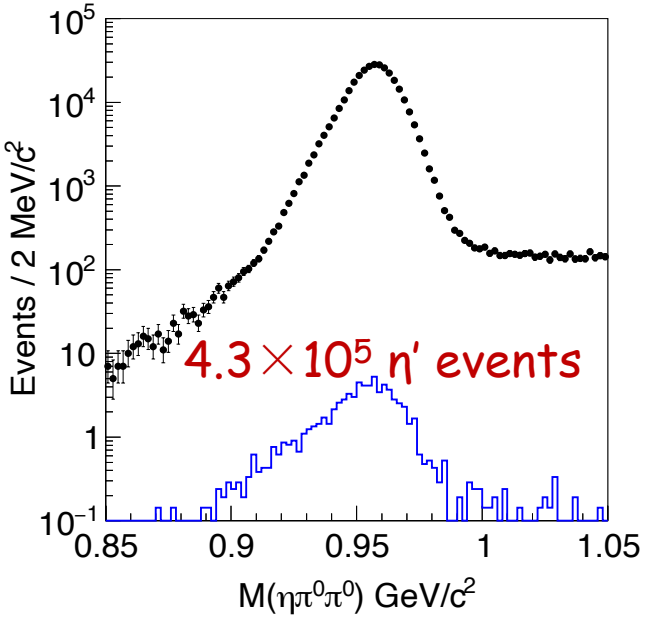
Evidence of the cusp effect in $\eta' \to \pi^0\pi^0\eta$

PRL130,081901(2023)

- Test ChPT and NREFT model
- In $\pi\pi$ interaction, one of the prominent features is the loop contribution to the $\pi\pi$ 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 $\pi\pi$ interaction to study the fundamental properties of QCD at low energies.



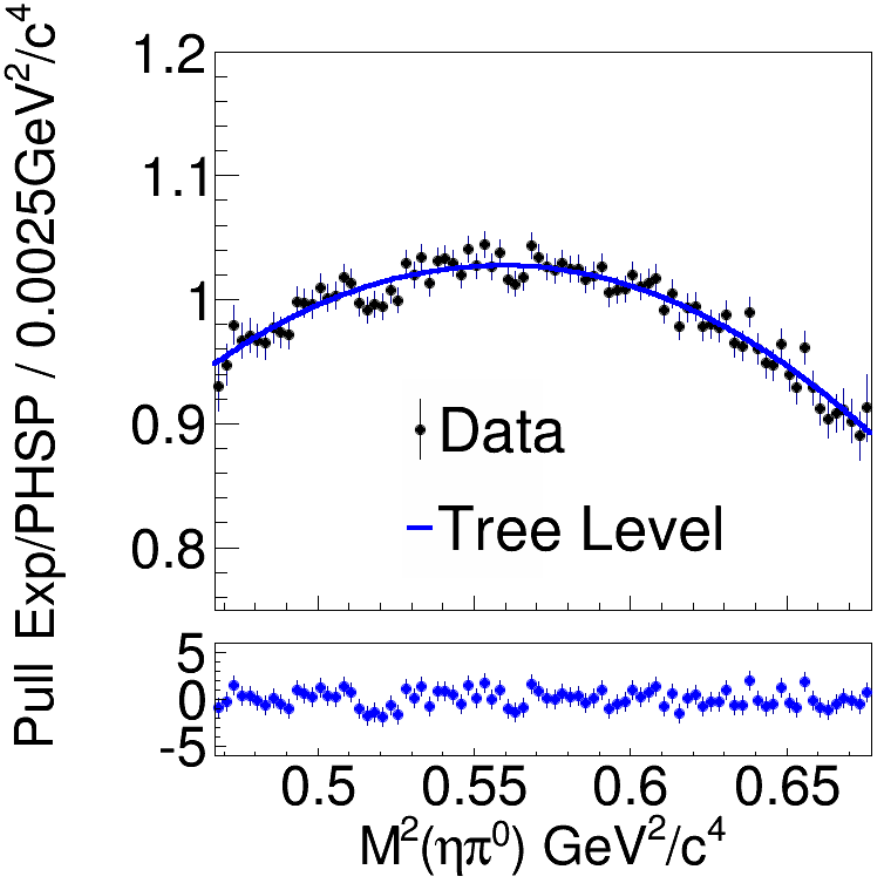
One-loop contribution in $P \to P'\pi^0\pi^0$ decay, where P and P' denote pseudoscalar particles in initial and final states, respectively.
Different behaviors below and above the charged pion mass threshold cause the cusp effect.

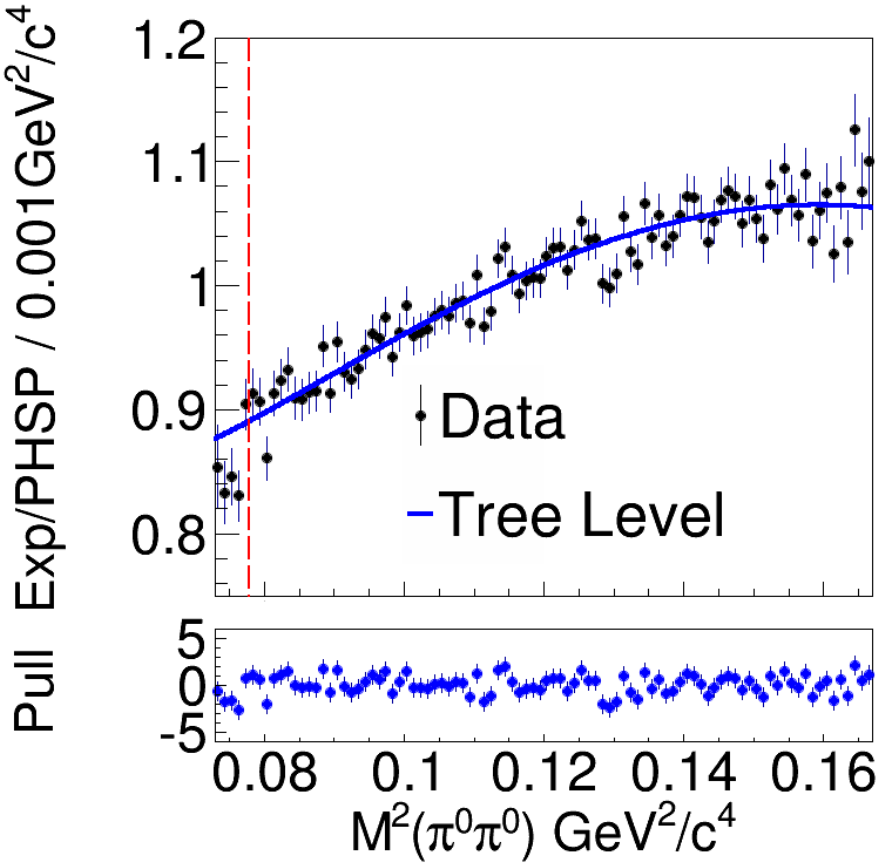


Evidence of the cusp effect in $\eta' \to \pi^0\pi^0\eta$

PRL130,081901(2023)

- Fit I: Only the tree level contribution

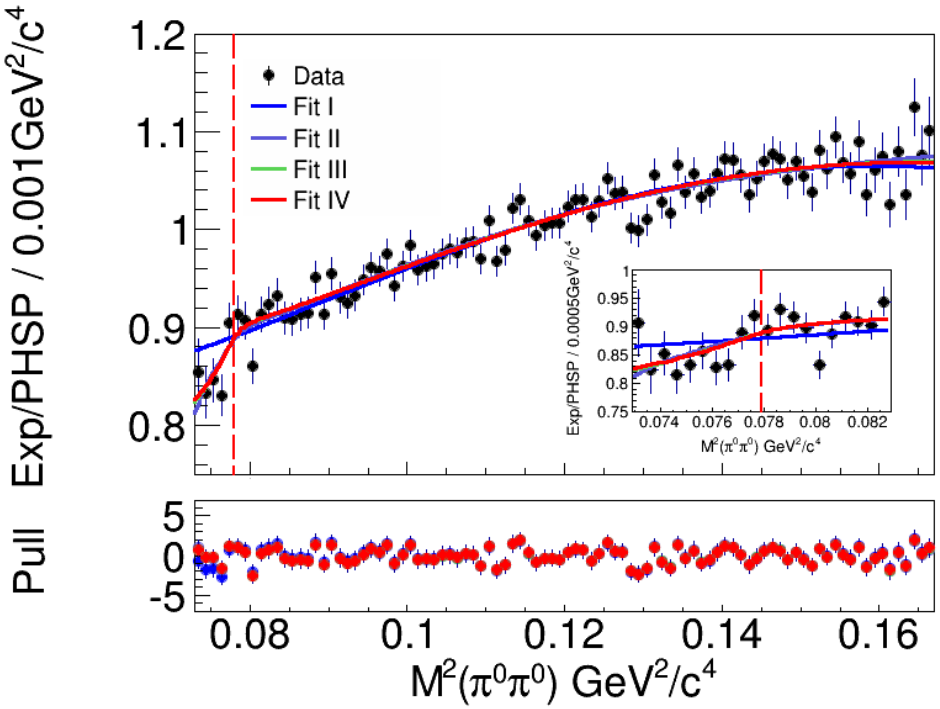




The cusp effect is sizeable in this decay.

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

PRL130,081901(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 some parameters 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:

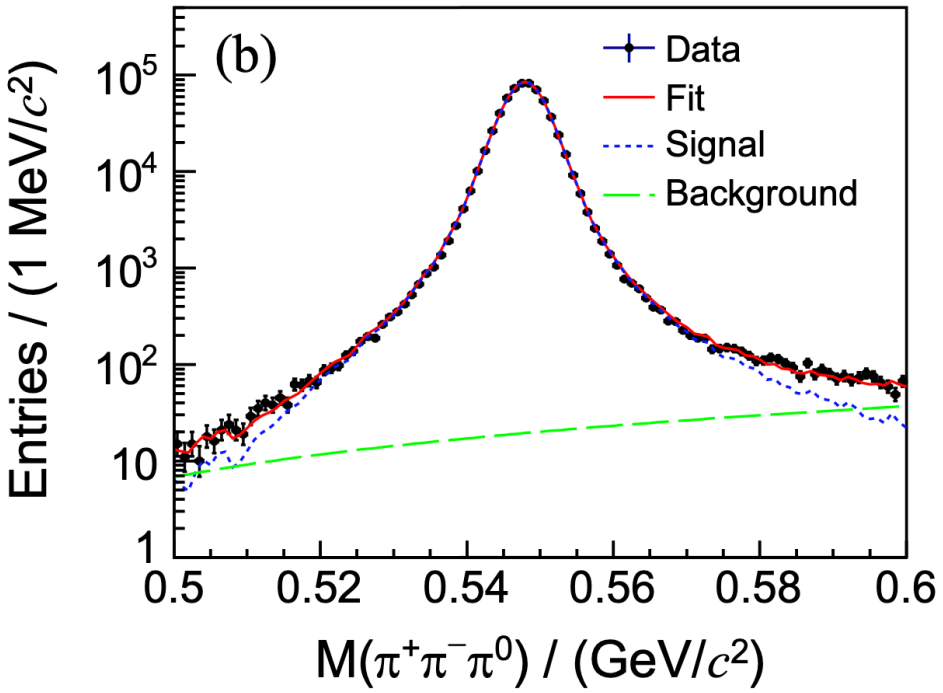
$$a_0 - a_2 = 0.226 \pm 0.060 \pm 0.012$$

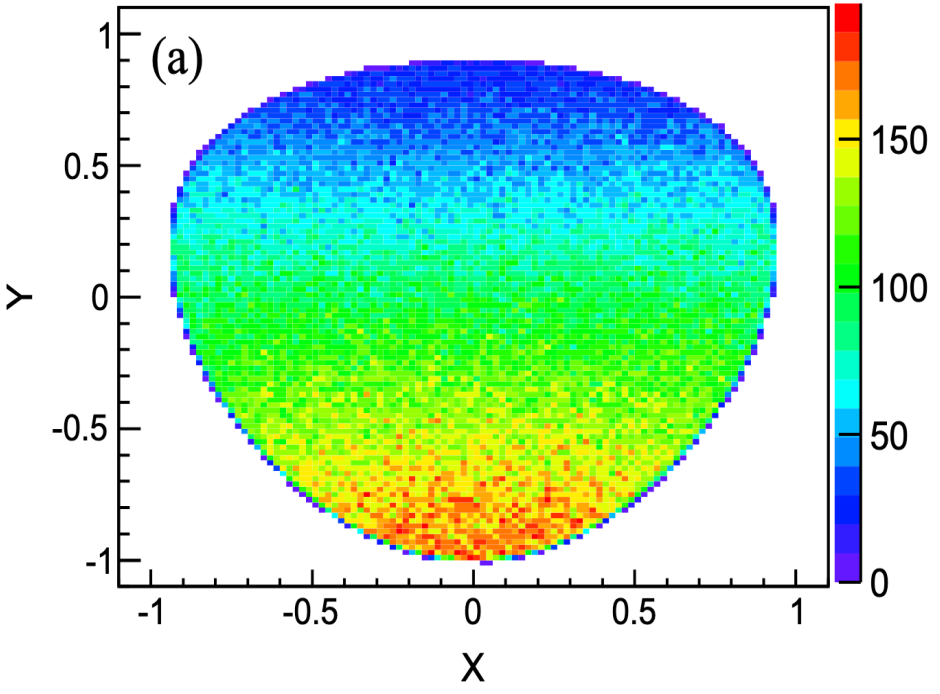
Precision measurement of the matrix elements for $\eta\to\pi^+\pi^-\pi^0$ and $\eta\to\pi^0\pi^0\pi^0$ decays

PRD107,092007(2023)

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

631,686 $\eta\to\pi^+\pi^-\pi^0$ events





- The Dalitz plot is generally described by the following two variables

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

Precision measurement of the matrix elements for $\eta\to\pi^+\pi^-\pi^0$ and $\eta\to\pi^0\pi^0\pi^0$ decays

- **$\eta\to\pi^+\pi^-\pi^0$** ***PRD107,092007(2023)***

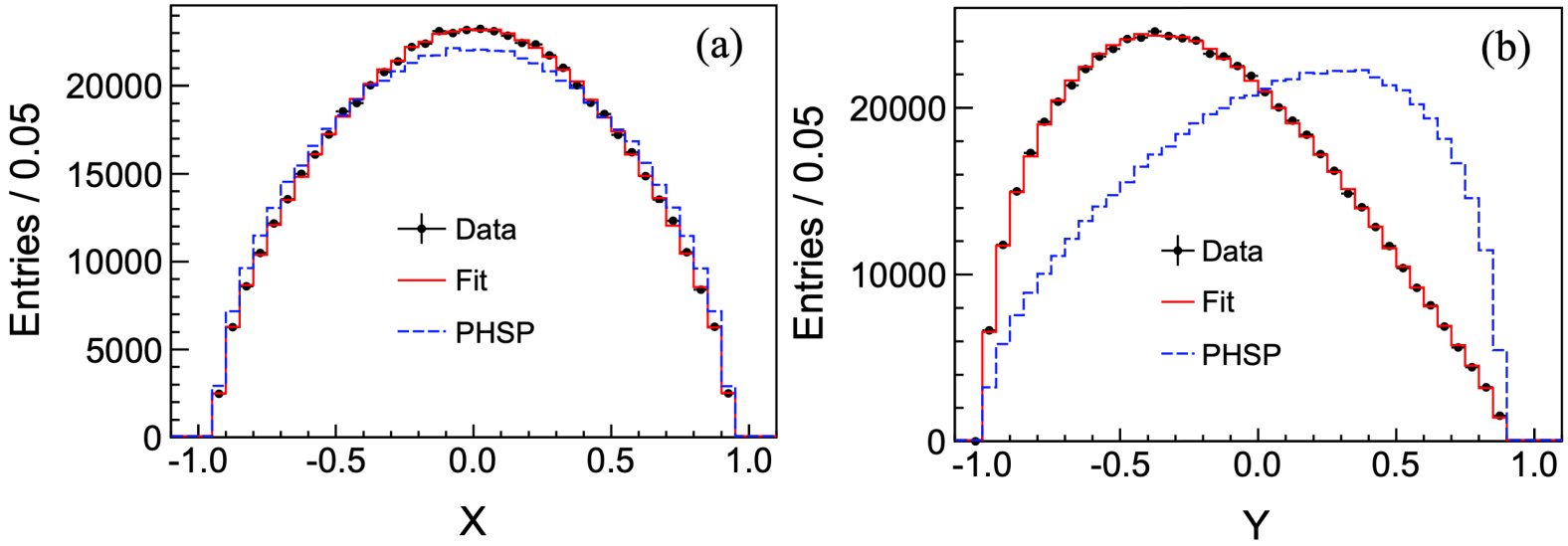
✧ The phase space can not describe the data well indicating the presence of interactions between the final-state particles.

✧ 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.



The projection of the Dalizt distribution.

Precision measurement of the matrix elements for $\eta\to\pi^+\pi^-\pi^0$ and $\eta\to\pi^0\pi^0\pi^0$ decays

PRD107,092007(2023)

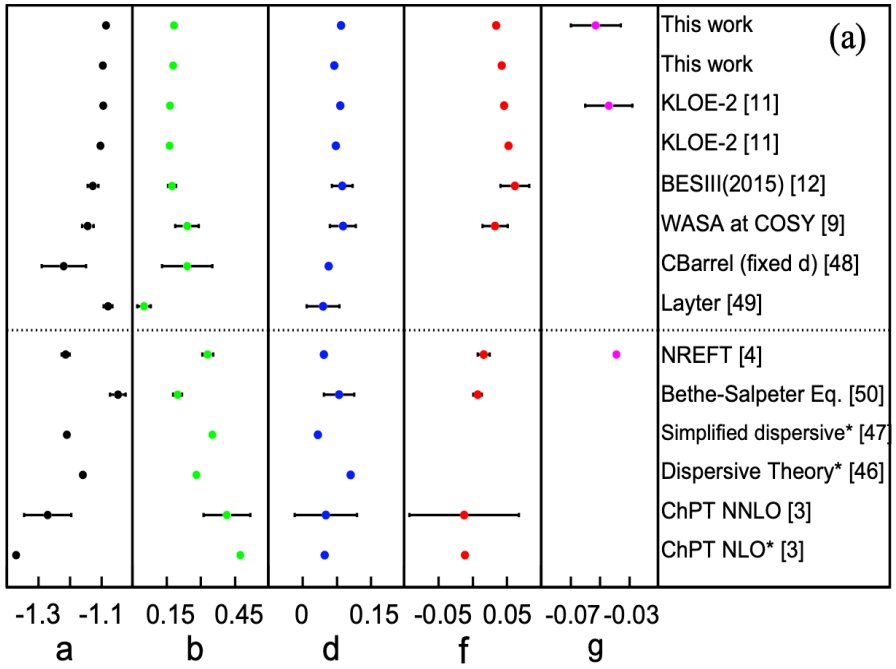
- $\eta\to\pi^+\pi^-\pi^0$

✧ Ignoring the high-order term gX^2Y

$$a = -1.097 \pm 0.005 \pm 0.001$$
$$b = 0.158 \pm 0.006 \pm 0.003$$
$$d = 0.070 \pm 0.006 \pm 0.001$$
$$f = 0.134 \pm 0.010 \pm 0.003$$

✧ Included the cubic term gX^2Y

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



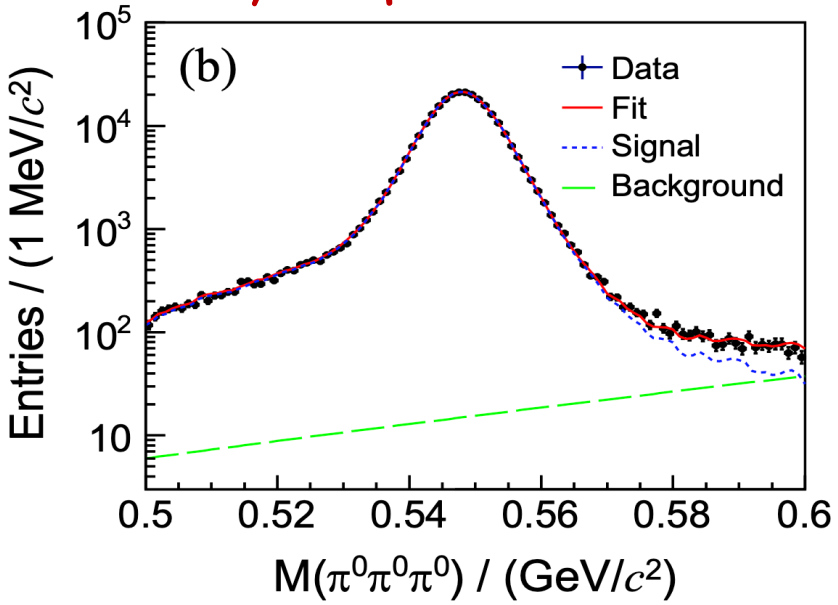
The results are consistent with recent experimental results, and are in reasonable agreement with the theoretical calculation based on the dispersive approach and ChPT at next-to-next-to-leading order (NNLO) level.

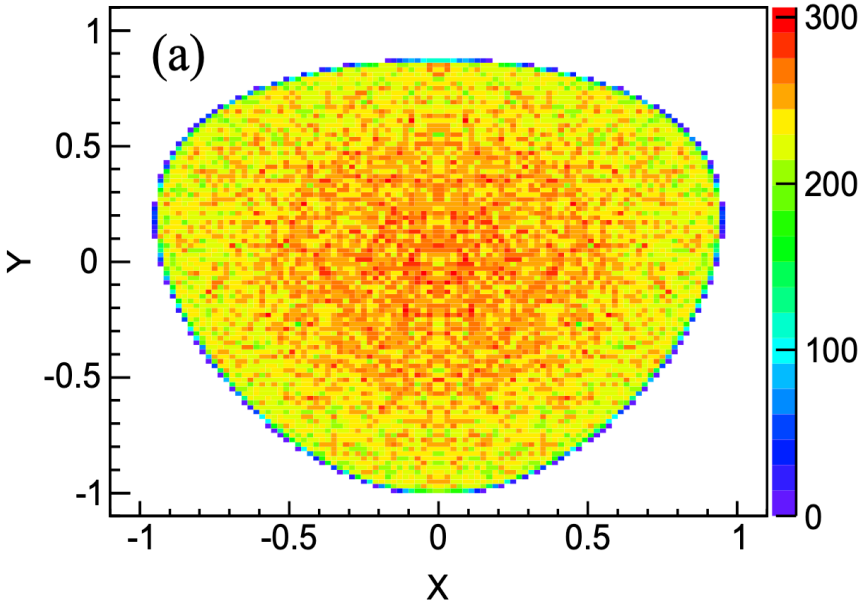
Precision measurement of the matrix elements for $\eta\to\pi^+\pi^-\pi^0$ and $\eta\to\pi^0\pi^0\pi^0$ decays

PRD107,092007(2023)

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

272,322 $\eta\to\pi^0\pi^0\pi^0$ events





- The density distribution of the Dalitz plot has threefold symmetry due to the three identical π^0s in the final state. Hence, the density distribution can be parametrized using a polar variable

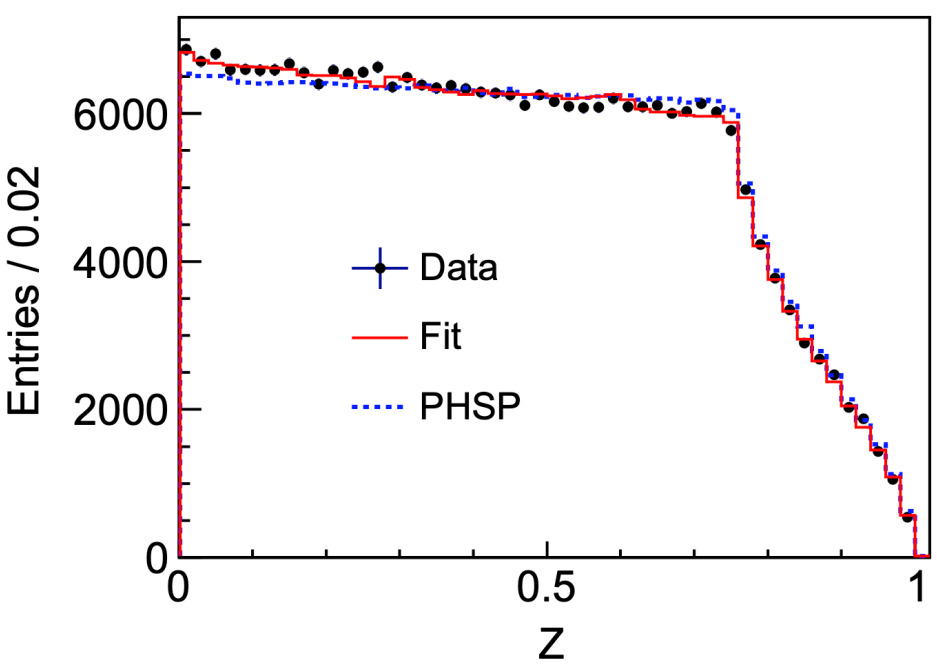
$$Z = X^2 + Y^2 = \frac{2}{3}\sum_{i=1}^{3}\left(\frac{3T_i}{Q_\eta} - 1\right)^2$$

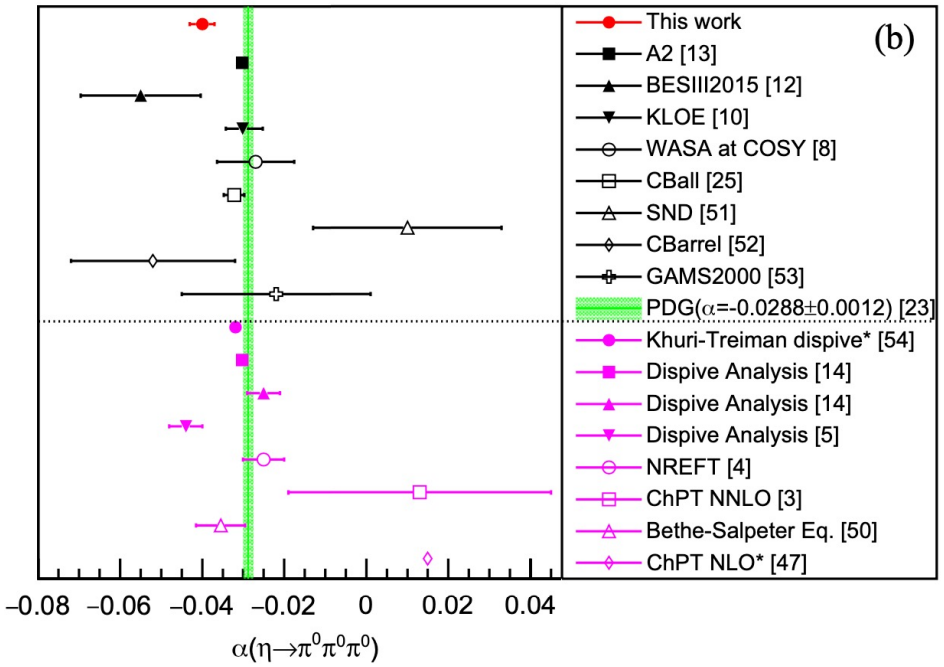
Precision measurement of the matrix elements for $\eta\to\pi^+\pi^-\pi^0$ and $\eta\to\pi^0\pi^0\pi^0$ decays

PRD107,092007(2023)

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

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



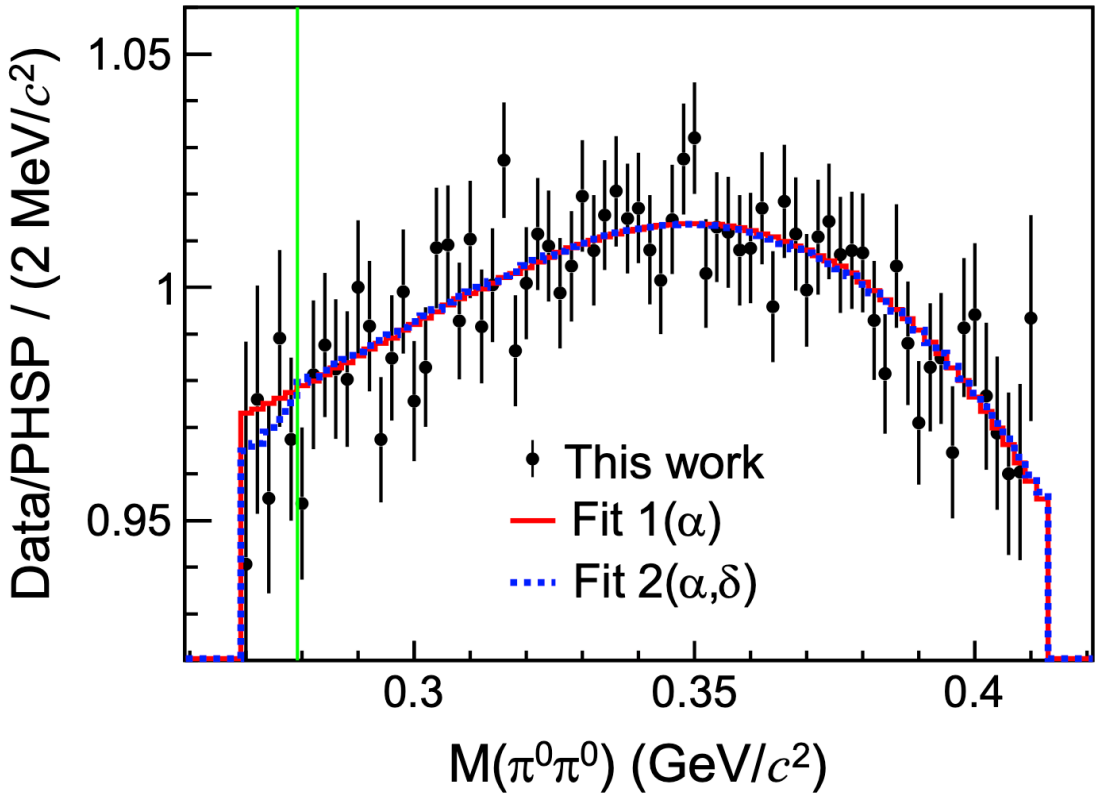


- slope parameter $\alpha = -0.0406 \pm 0.0035 \pm 0.0008$, which is consistent with the A2 measurement within 2.8σ.
- No significant higher-order contribution is found at the current level of precision.

Precision measurement of the matrix elements for $\eta\to\pi^+\pi^-\pi^0$ and $\eta\to\pi^0\pi^0\pi^0$ decays

PRD107,092007(2023)

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



The cusp effect is investigated, but no obvious contribution is found.

Summary

- BESIII: 10 billion J/ψ events (collected in 2009~2019)
  - ✧ Light Meson Factory !
- Recent results on Light Meson decays are presented
  - ✧ $\eta' \to \pi^+\pi^- e^+ e^-$: Branching Fraction, CP-Violation
  - ✧ $\eta' \to \pi^+\pi^- \mu^+ \mu^-$: Branching Fraction
  - ✧ $\eta' \to \pi^0\pi^0\eta$: Cusp effect, $\pi\pi$ scattering length
  - ✧ $\eta \to \pi^+\pi^-\pi^0$, $\eta \to \pi^0\pi^0\pi^0$: Matrix Elements, Cusp effect
- More results are expected to come soon
  - ✧ Dalitz analysis of η/η′ decays
  - ✧ Rare and forbidden decays
  - ✧ Transition Form Factors
  - ...

THANKS