Light Meson Decays at BESIII

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(On behalf of the BESIII Collaboration)

Outline

- **BEPCII and BESIII**

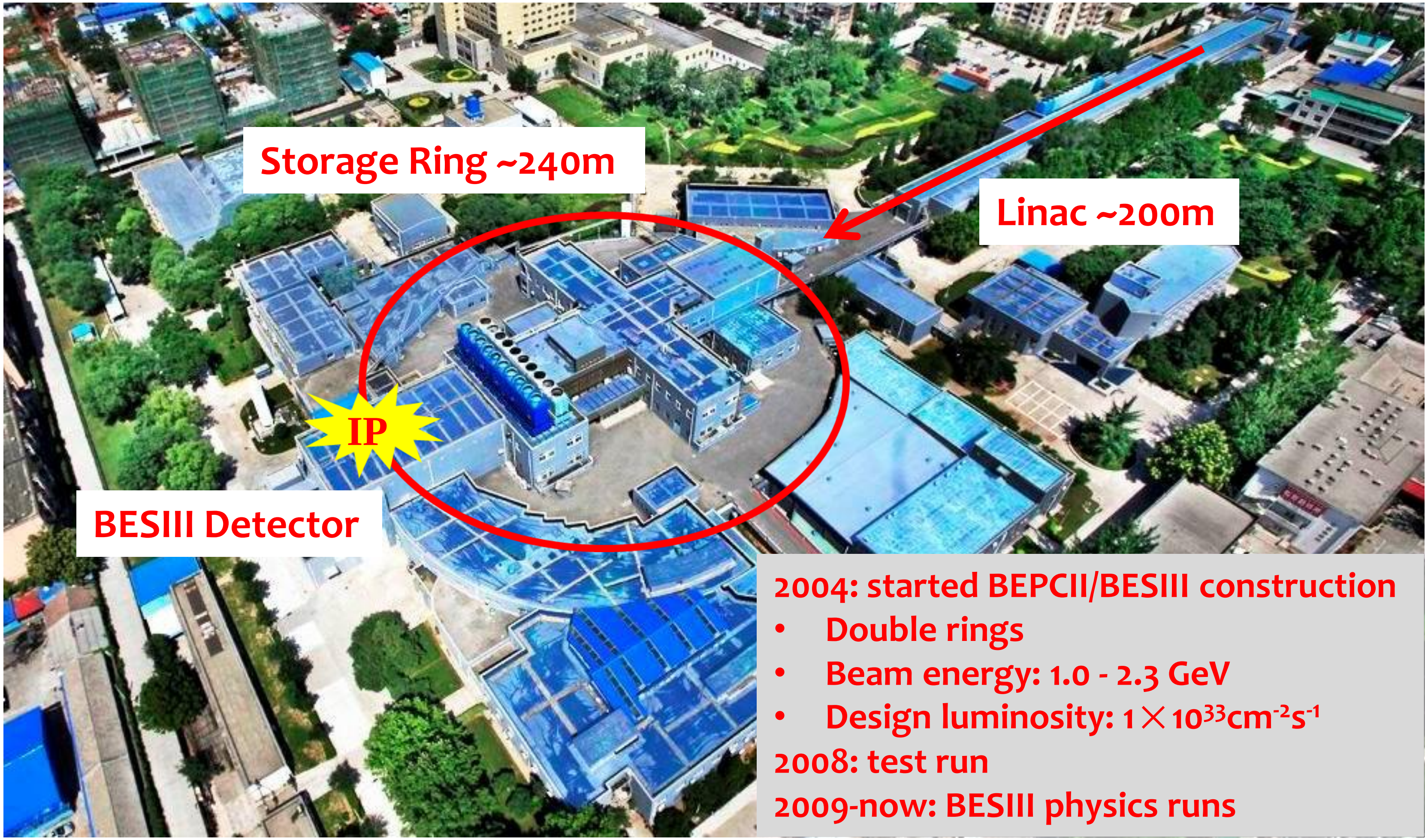
- **η´ Meson Decays**
  - $\eta' \rightarrow \eta\pi^+\pi^-$, $\eta\pi^0\pi^0$
  - $\eta' \rightarrow \gamma\pi^+\pi^-$
  - η´ branching fractions
  - $\eta' \rightarrow \gamma\gamma\eta$
  - $\eta' \rightarrow \pi^0\pi^0\pi^0\pi^0$

- **ω Meson Decay**
  - $\omega \rightarrow \pi^+\pi^-\pi^0$

- **$a_0^0(980)$-$f_0(980)$ Mixing**

- **Summary**

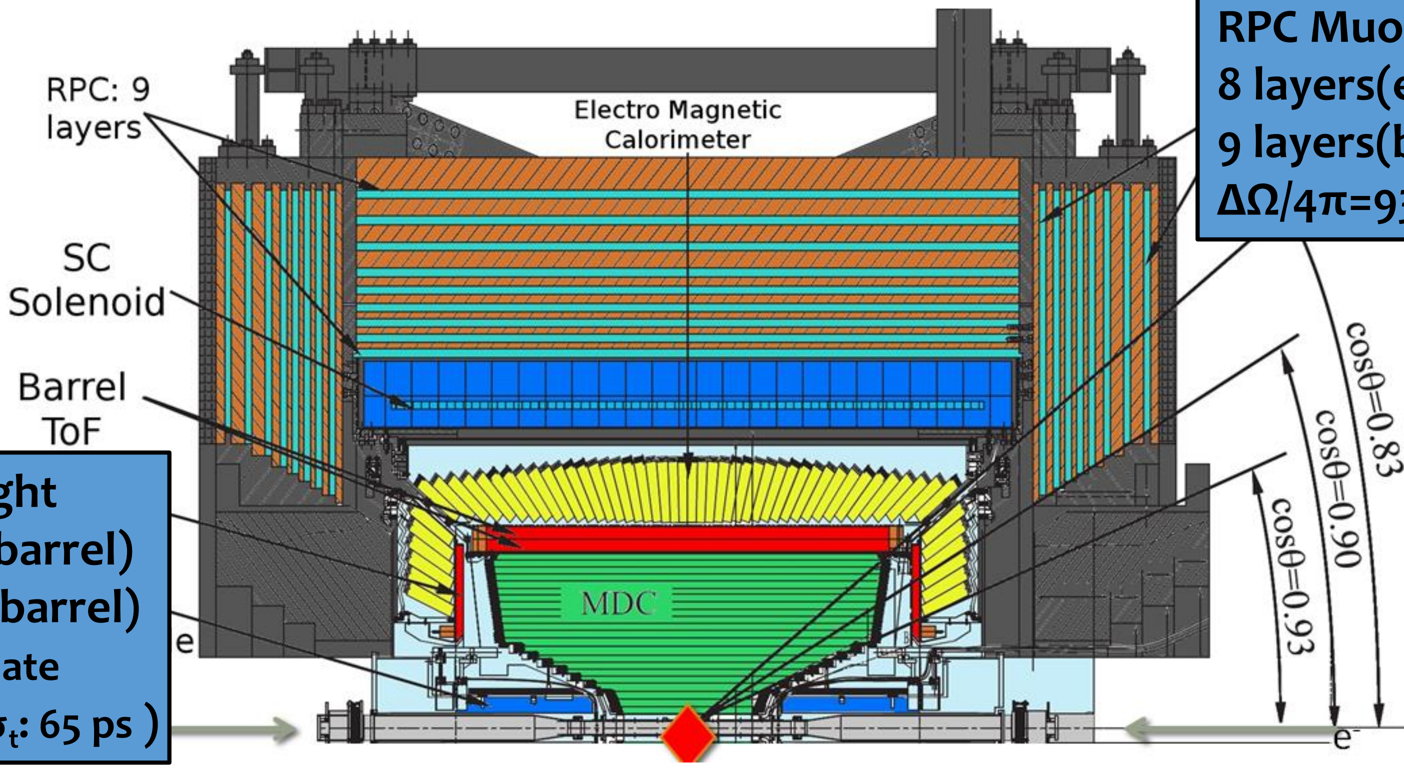
Beijing Electron Positron Collider II (BEPC II)



2004: started BEPCII/BESIII construction
- Double rings
- Beam energy: 1.0 - 2.3 GeV
- Design luminosity: $1 \times 10^{33} cm^{-2} s^{-1}$

2008: test run
2009-now: BESIII physics runs

BESIII Detector



RPC Muon Detector
8 layers(endcaps)+
9 layers(barrel)
$\Delta\Omega/4\pi=93\%$

Time of Flight
σ_t = 90 ps (barrel)
σ_t = 110 ps (barrel)
(endcap update
with MRPC σ_t: 65 ps)

Main Drift Chamber
σ_{xy} = 130 μm, dE/dx~6%
σ_p/p = 0.5% @ 1 GeV

Electromagnetic Calorimeter
Barrel : $\sigma_E/E<2.5\%$, @ 1 GeV
Endcap : $\sigma_E/E<5.0\%$, @ 1 GeV
σ_{xy} = (6 mm)/$E^{1/2}$@ 1 GeV

η' Meson Decays

η/η' Physics

- **Test the predictions of ChPT.**
- **Study transition form factors.**
- **Test fundamental symmetries.**
- **Probe physics beyond the SM.**

η decay mode	Physics highlights	η' decay mode	Physics highlights
$\eta \to \gamma\gamma\pi^0$	ChPT	$\eta' \to \pi\pi$	CPV
$\eta \to \gamma B$	Leptopbobic dark boson	$\eta' \to \gamma\gamma$	Chiral anomaly
$\eta \to \pi^0\pi^0\pi^0$	m_u-m_d	$\eta' \to \gamma\pi\pi$	Box anomaly
$\eta \to \pi^+\pi^-\pi^0$	m_u-m_d, CV	$\eta' \to \pi^+\pi^-\pi^0$	m_u-m_d, CV
$\eta \to \gamma\gamma\gamma$	CPV	$\eta' \to l^+l^-\pi^0$	CV

η/η' from J/ψ Decays

- 1.3×10^9 J/ψ events (2009+2012)
- High production rate of light mesons in J/ψ decays

- η/η' from J/ψ radiative decays
  - 7.2×10^6 η'
  - 2.4×10^6 η
- η/η' from J/ψ hadronic decays (e.g. $J/\psi \to \phi\eta$)
  - 3×10^5 η'
  - 5×10^5 η
- Large data samples and unique opportunity to investigate the decays of η/η'.

Dalitz plot analysis of $\eta' \to \eta\pi^+\pi^-, \eta\pi^0\pi^0$

- **Remains a subject of effective ChPT.**
- **Explored by CLEO, VES, GAMS Collaboration but with limited statistics.**
- **$\eta' \to \eta\pi^+\pi^-$ is studied based on 225M J/ψ at BESIII** [PRD 83,012003(2011)].
- **A cusp due to $\pi^+\pi^-$ mass threshold for the Dalitz plot of $\eta' \to \eta\pi^0\pi^0$.**

- For the charged decay mode

$$X = \frac{\sqrt{3}(T_{\pi^+} - T_{\pi^-})}{Q}, Y = \frac{m_\eta + 2m_\pi}{m_\pi}\frac{T_\eta}{Q} - 1$$

T_π and T_η denote the kinetic energies of π and η in the η' rest frame, $Q = m_{\eta'} - m_\eta - 2m_\pi$.

- For the neutral decay mode

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

- general representation

$$|M(X,Y)|^2 = N(1 + aY + bY^2 + cX + dX^2 + \cdots)$$

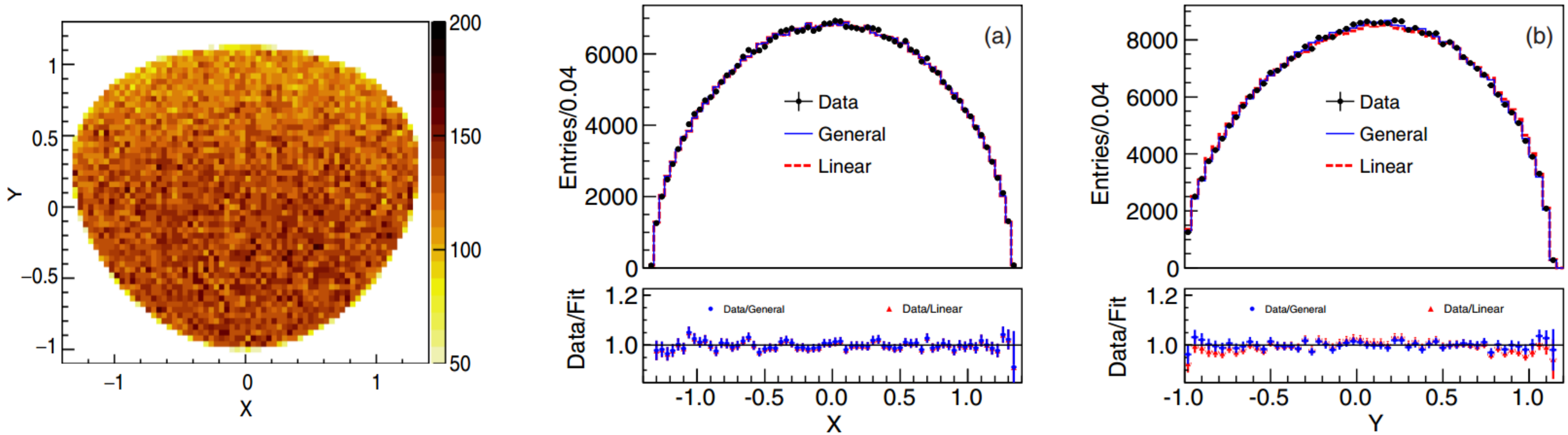
- linear representation

$$|M(X,Y)|^2 = N\left(|1 + \alpha Y|^2 + cX + dX^2 + \cdots\right)$$

Here, a,b,c,d are free parameters, α is a complex number, a = 2Re(α), b = Re(α)²+ Im(α)².

Dalitz plot analysis of η′ → ηπ⁺π⁻

PRD 97,012003(2018)

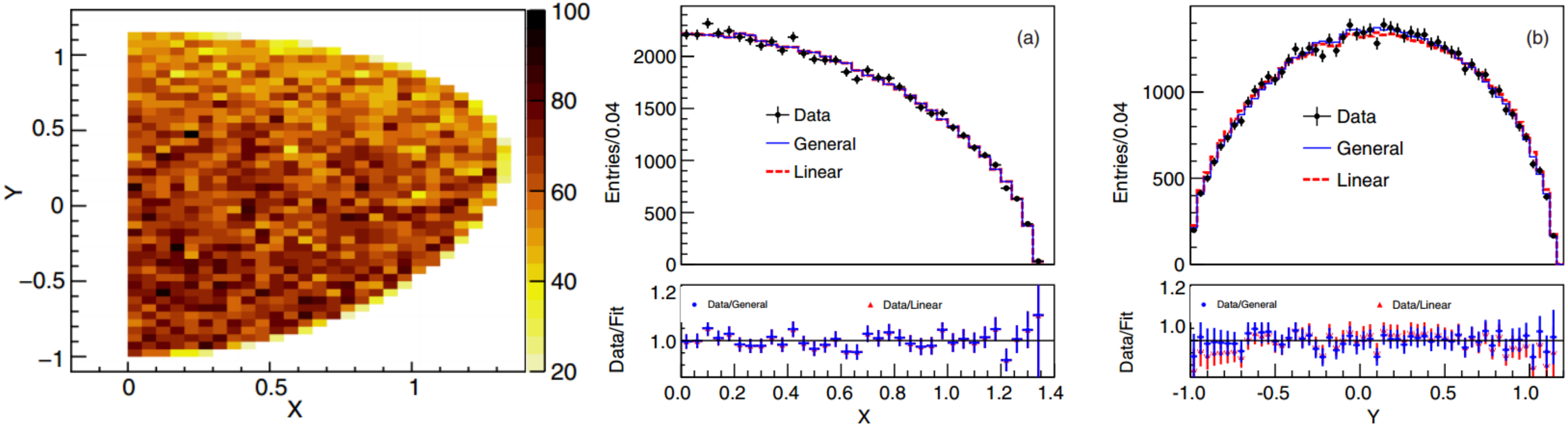


- **The linear representation is less compatible with the data.**

	$\eta' \to \eta\pi^+\pi^-$				
Parameter	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)
$\Re(\alpha)$	...	...	...	−0.072(14)	−0.034(2)(2)
$\Im(\alpha)$	...	...	...	0.000(100)	0.000(19)(1)
c	...	...	...	+0.020(19)	0.0027(24)(15)
d	...	...	...	−0.066(34)	−0.053(4)(4)

Dalitz plot analysis of $\eta' \to \eta\pi^0\pi^0$

PRD 97,012003(2018)



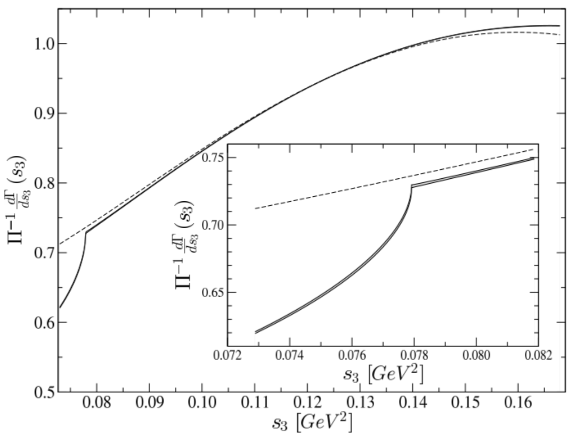
- **The linear representation is less compatible with the data.**

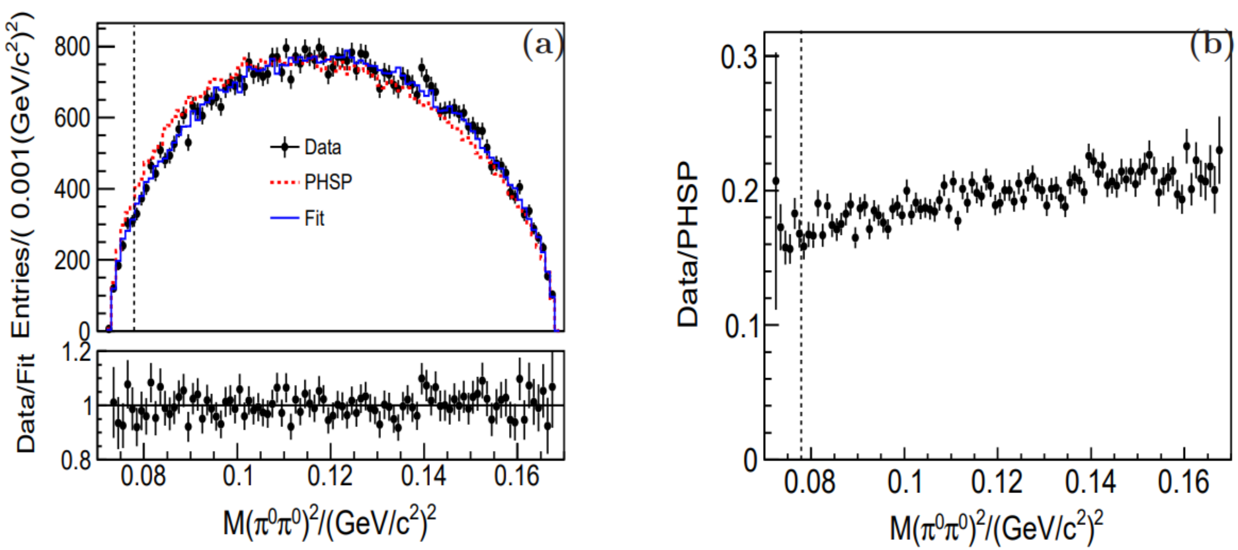
Parameter	$\eta' \to \eta\pi^0\pi^0$ EFT [5]	GAMS-4π [12]	This work
a	$-0.127(9)$	$-0.067(16)$	$-0.087(9)(6)$
b	$-0.049(36)$	$-0.064(29)$	$-0.073(14)(5)$
c	...	...	...
d	$+0.011(21)$	$-0.067(20)$	$-0.074(9)(4)$
$\Re(\alpha)$	...	$-0.042(8)$	$-0.054(4)(1)$
$\Im(\alpha)$	...	$0.000(70)$	$0.000(38)(2)$
c	...	...	...
d	...	$-0.054(19)$	$-0.061(9)(5)$

Dalitz plot analysis of $\eta' \to \eta\pi^0\pi^0$

- **Search for cusp effect**:

FSI: A cusp effect (more than 8%) on $\pi^0\pi^0$ mass spectrum below the $\pi^+\pi^-$ mass threshold [EPJC62, 511 (2009)].

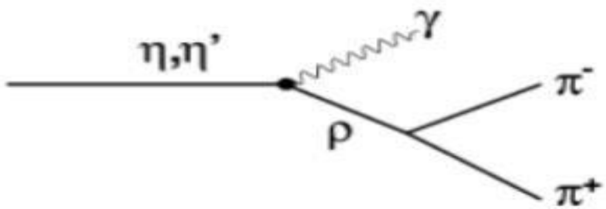


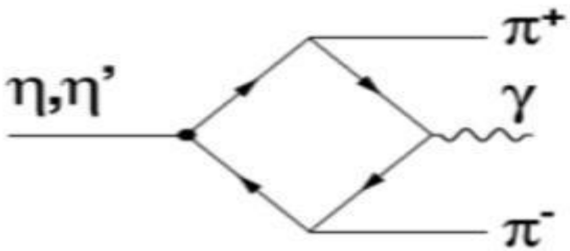


No evidence of a cusp effect with current statistics.

Study of $\eta' \to \gamma\pi^+\pi^-$ decay dynamics

- **In VMD model, this process is dominated by $\eta' \to \gamma\rho$**
- **The discrepancy attributed to the Wess-Zumino-Witten anomaly in the ChPT, known as the box anomaly.**[PLB37, 95 (1971), NPB223, 422 (1983)]
- **Recently a model-independent approach based on ChPT was proposed.**[PLB 707, 184 (2012)]
- **Studied by several experiments, but no consistent picture due to limited statistics**
  - **ρ mass shift or not ?**
  - **box anomaly or not ?**





The dipion mass dependent differential rate :

$$[d\Gamma/dM(\pi^+\pi^-)] = [k_\gamma^3 q_\pi^3(s)/48\pi^3]|\mathcal{A}|^2,$$

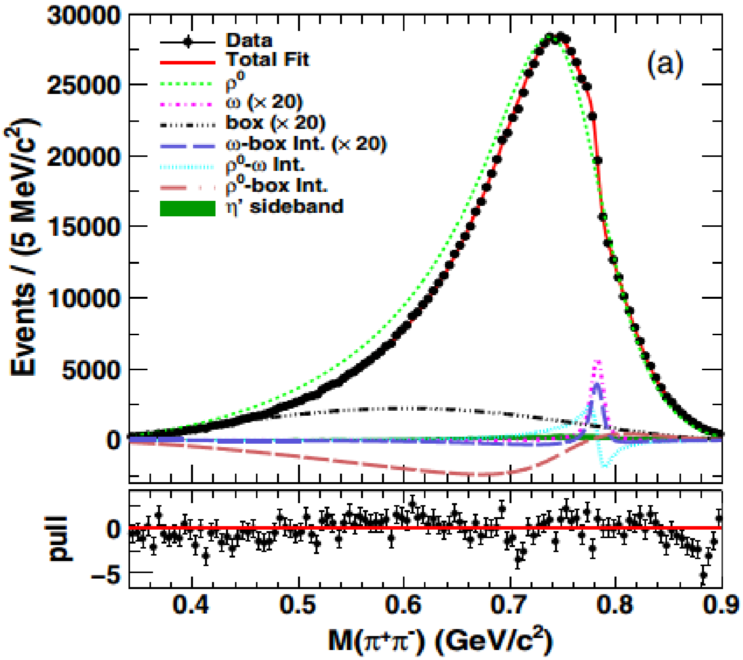
$$k_\gamma = (m_{\eta'}^2 - s)/(2m_{\eta'}), \; q_\pi(s) = \sqrt{s - 4m_\pi^2}/2$$

Study of $\eta' \to \gamma\pi^+\pi^-$ decay dynamics

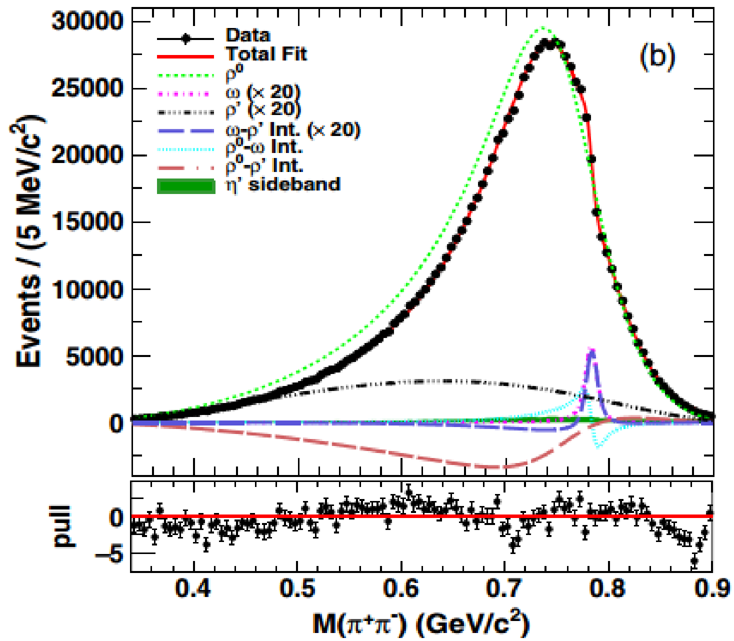
Model dependent fit

PRL 120, 242003 (2018)

Fit with $\rho(770)$–ω–box anomaly



Fit with $\rho(770)$–ω– $\rho(1450)$



- Besides the $\rho(770)$, the ω contribution is needed.
- $\rho(770)$ - ω cannot describe data well.
- Extra contribution of box-anomaly or $\rho(1450)$, or both of them is necessary.

Measurement of the BFs of η´ decays

- There are only the relative measurements of BFs of η´ decays from experiments.
- Difficult to tag the inclusive decays in J/ψ → γη´ because of the poor energy resolution of radiative photon.

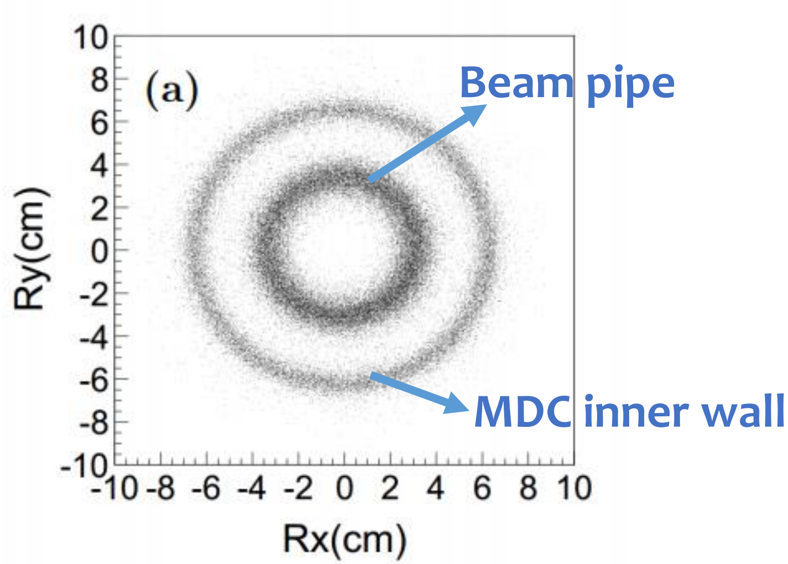
- BF for each η′ exclusive decay is obtained with

Using photon conversions

$$\mathcal{B}(\eta' \to X) = \boxed{\frac{N^{\rm obs}_{\eta'\to X}}{\varepsilon_{\eta'\to X}}} \cdot \boxed{\frac{\varepsilon}{N^{\rm obs}_{J/\psi\to\gamma\eta'}}} \cdot f,$$

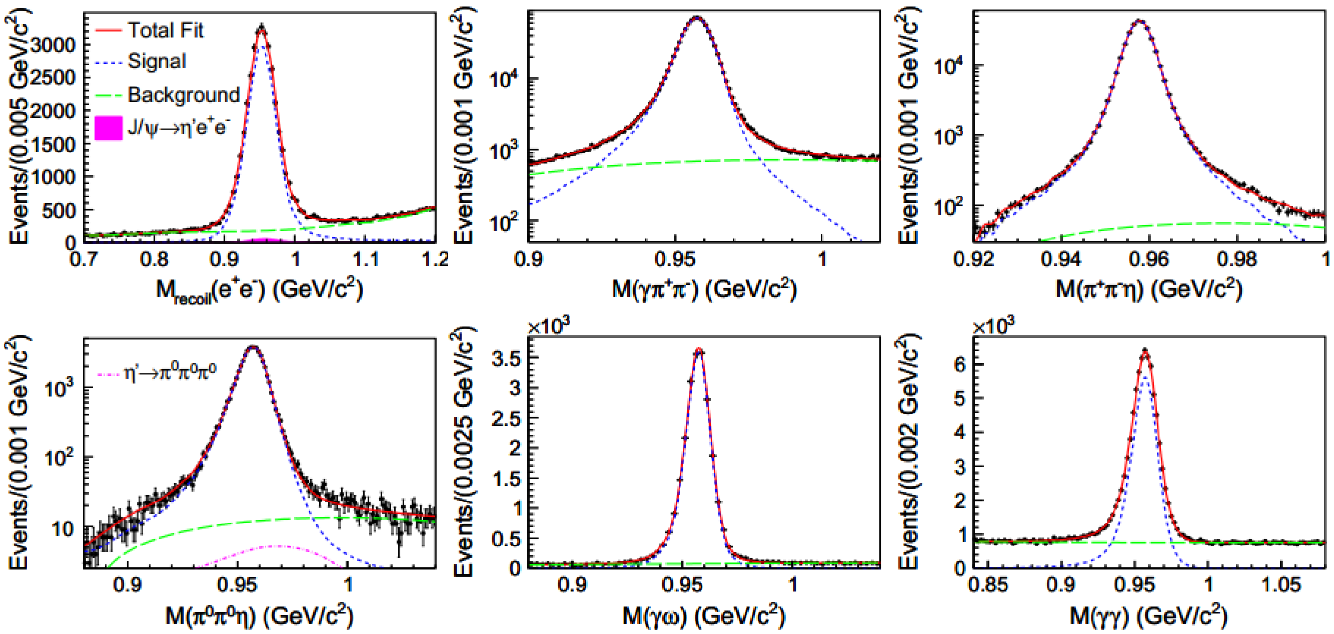
γ directly detected by EMC

- Developed a mothed to reconstruct radiative photon using photon conversions to e⁺e⁻ pairs.
- Resolution of the radiative photon could be improved by a factor of 3.



Measurement of the BFs of η´ decays

PRL 122, 142002 (2019)



Decay Mode	$N^{\mathrm{obs}}_{\eta'\to X}$	$\varepsilon_{\eta'\to X}(\%)$	$\mathcal{B}(\eta' \to X)(\%)$ This measurement	PDG
$\eta' \to \gamma\pi^+\pi^-$	913106±1052	44.11	29.90±0.03±0.55	28.9±0.5
$\eta' \to \eta\pi^+\pi^-$	312275±570	27.75	41.24±0.08±1.24	42.6±0.7
$\eta' \to \eta\pi^0\pi^0$	51680±238	9.08	21.36±0.10±0.92	22.8±0.8
$\eta' \to \gamma\omega$	22749±163	14.98	2.489±0.018±0.074	2.62±0.13
$\eta' \to \gamma\gamma$	70669±349	43.79	2.331±0.012±0.035	2.22±0.08

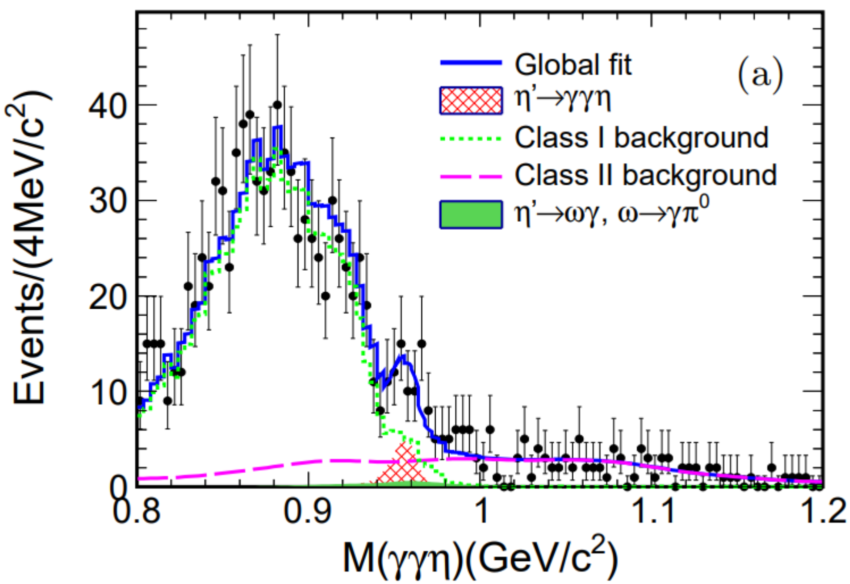
First direct measurement of absolute BFs for five η´ modes.

Search for $\eta' \to \gamma\gamma\eta$

arXiv:1906.10346

- **Within the frame work of the linear σ model and the VMD model, the BF of $\eta' \to \gamma\gamma\eta$ is predicted to be 2.0×10^{-4}.** [arXiv:1812.08454]
- **GAMS-4π reported the upper limit of the BF $<8 \times 10^{-4}$ at the 90% C.L.** [Phys. Atom. Nucl. 78, 1043 (2015)]

Search for $\eta' \to \gamma\gamma\eta$ in the J/ψ radiative decay.



Significance: 2.6 σ

BF: $(8.25 \pm 3.41 \pm 0.72) \times 10^{-5}$

Upper limit of BF:

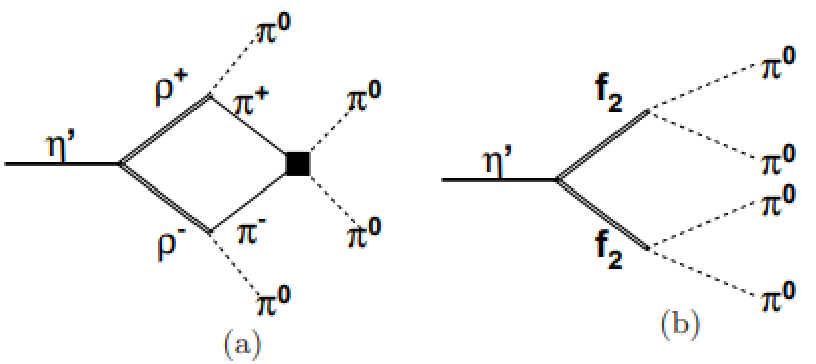
$<1.33 \times 10^{-4}$ at the 90% C.L.

The obtained result is in tension with theoretical prediction.

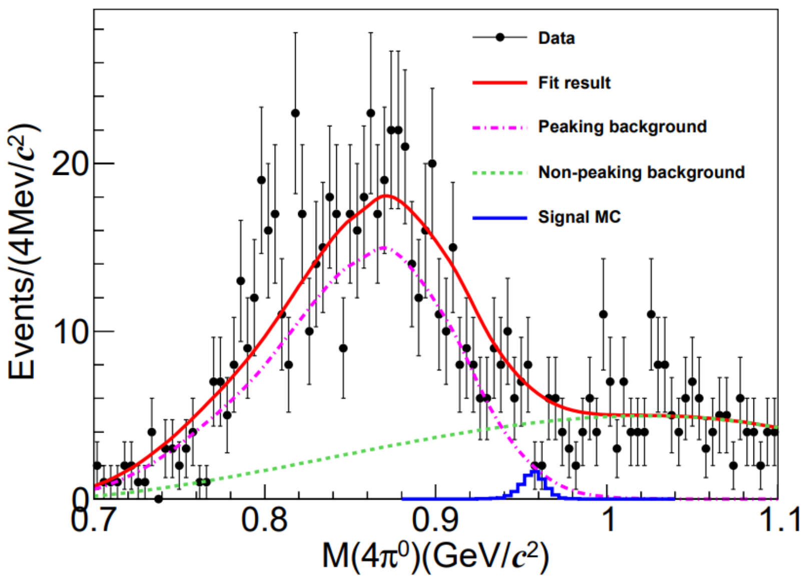
Search for rare decay $\eta' \to \pi^0\pi^0\pi^0\pi^0$

arXiv:1908.01988

- **Highly suppressed decay because of the S-wave CP-violation.**
- **Higher-order contributions, involving a D-wave pion loop or the production of two f2 tensor mesons provide a CP-conserving route through which the decay can occur.** [PRD 85, 014014 (2012)]



Search for $\eta' \to \pi^0\pi^0\pi^0\pi^0$ in the J/ψ radiative decay.



No evidence for the rare decay.

Upper limit:

$B(\eta' \to 4\pi^0) < 4.94 \times 10^{-5}$ at the 90% C.L.

This limit is approximately a factor of six smaller than the previous most stringent result. [Mod. Phys. Lett. A 29, 1450213 (2014)]

ω Meson Decay

Dalitz plot analysis of $\omega \to \pi^+\pi^-\pi^0$

- **Provide further constraints to the calculation of the electromagnetic transition form factors of $\omega \to \pi^0\gamma^*$**[PRD 86, 054013 (2012)]
- **Test prediction of Dalitz plot distribution in the dispersive framework.** [PRD 86, 054013 (2012). EPJC 72, 2014 (2012)]
- **Verify the crossed-channel effect.**

- The density of the Dalitz plot

$$|\mathcal{M}|^2 = \frac{|\vec{p}_+ \times \vec{p}_-|^2}{m_\omega} \cdot |\mathcal{F}|^2,$$

$$|\mathcal{F}(z,\phi)|^2 \propto 1 + 2\alpha z + 2\beta z^{3/2} \sin 3\phi + 2\zeta z^2 + 2\delta z^{5/2} \sin 3\phi + \mathcal{O}(z^3),$$

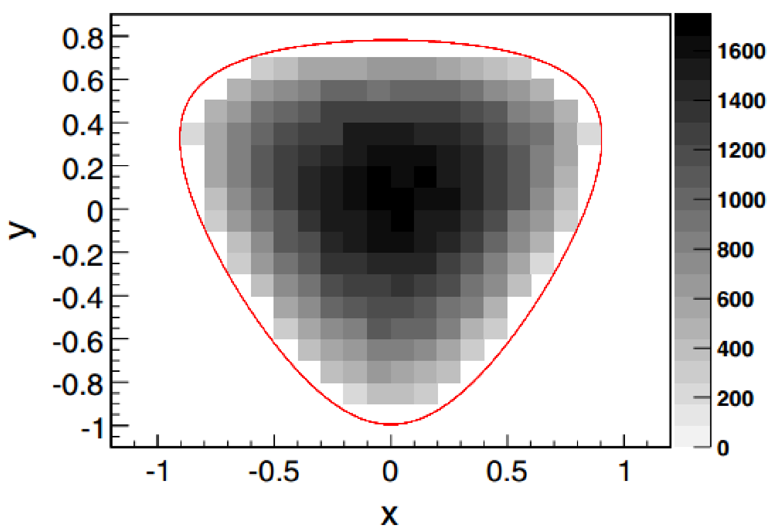
- Dimensionless variables

$$x = \frac{t-u}{\sqrt{3}R_\omega}, \qquad y = \frac{s-s_0}{R_\omega} + \frac{2(m_{\pi^\pm} - m_{\pi^0})}{m_\omega - 2m_{\pi^\pm} - m_{\pi^0}},$$

$$s_0 = (s+t+u)/3, \; R_\omega = \tfrac{2}{3} m_\omega (m_\omega - m_{\pi^+} - m_{\pi^-} - m_{\pi^0}).$$

- Related polar variables

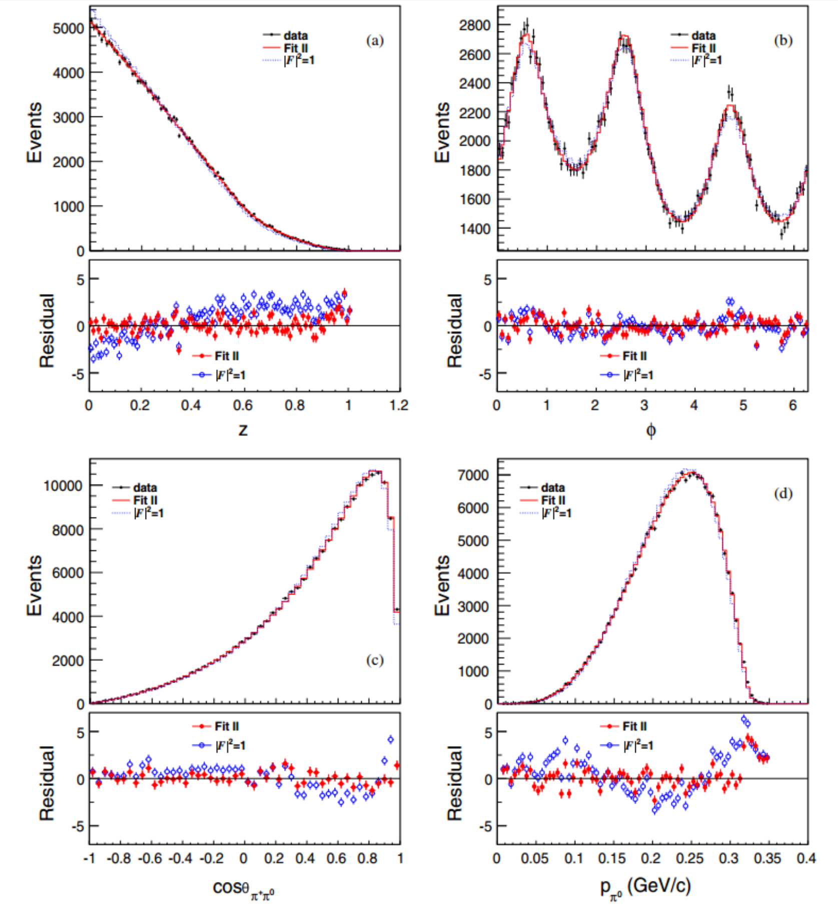
$$z = |x + yi|^2, \qquad \phi = \arg(x + yi).$$



Dalitz plot analysis of $\omega \to \pi^+\pi^-\pi^0$

PRD 98, 112007 (2018)

- **Dalitz plot distribution deviates from the P-wave phase space (significance: 18.9σ)**
- **The fitted parameter values are consistent with the theoretical predictions without incorporatin crossed-channel effects.**



		Theoretical predictions					Experiment
		Ref. [4]		Ref. [5]			
	Para. $\times 10^3$	w/o	w	w/o	w	Ref. [19]	BESIII
Fit I	α	136	94	(137,148)	(84,96)	202	$132.1 \pm 6.7 \pm 4.6$
Fit II	α	125	84	(125,135)	(74,84)	190	$120.2 \pm 7.1 \pm 3.8$
	β	30	28	(29,33)	(24,28)	54	$29.5 \pm 8.0 \pm 5.3$

$a_0^0(980)$- $f_0(980)$ Mixing

$a_0^0(980)$- $f_0(980)$ Mixing

- **$a_0^0(980)$- $f_0(980)$ still controversial explanation about their nature.**
- **In 1970s, the mixing mechanism was firstly proposed.** [PLB 88, 367 (1979)]
- **Theorist proposed to directly measure $a_0^0(980)$- $f_0(980)$ mixing via:**

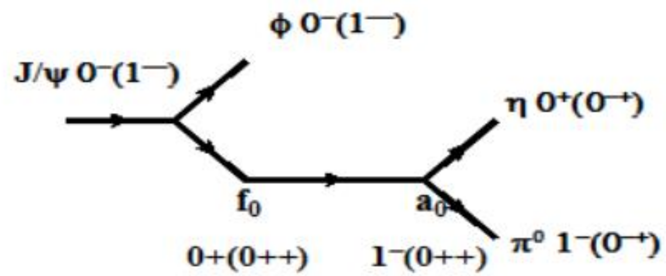
  J/ψ→$\phi a_0^0(980) \rightarrow \phi\eta\pi^0$,

  $\chi_{c1} \rightarrow \pi^0 f_0(980) \rightarrow \pi^0 \pi^+ \pi^-$.

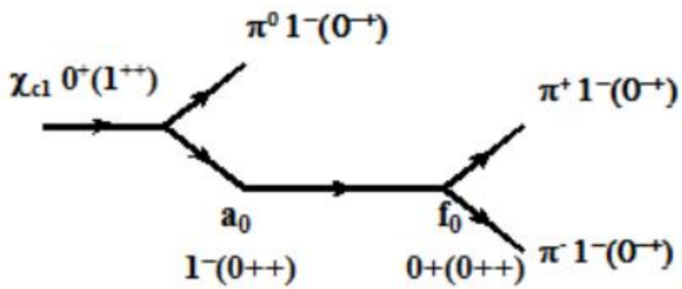
[Wu, Zhao, Zou, PRD 75 114012(2007), PRD 78 074017(2008)]

- **Measured at BESIII based on 225M J/ψ and 108M ψ(2S), significance < 5σ.** [PRD83.032003(2011)]

- $f_0(980) \rightarrow a_0^0(980)$ Mixing



- $a_0^0(980) \rightarrow f_0(980)$Mixing

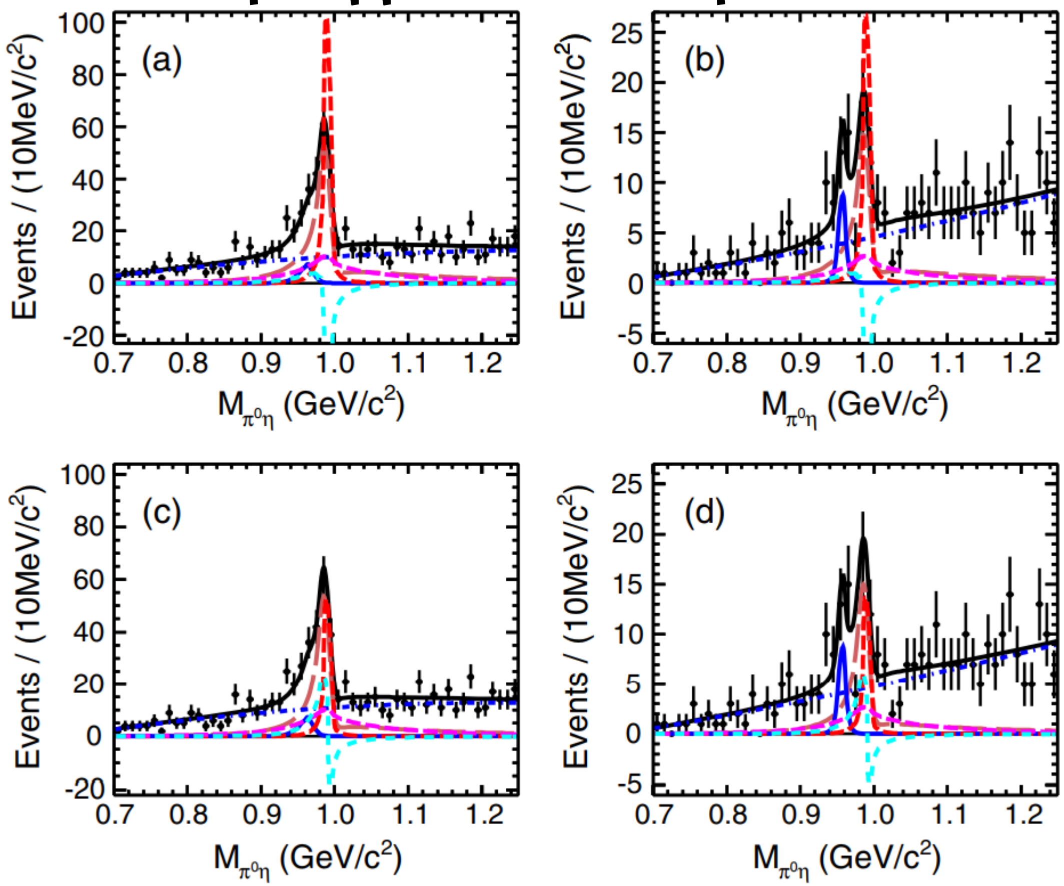


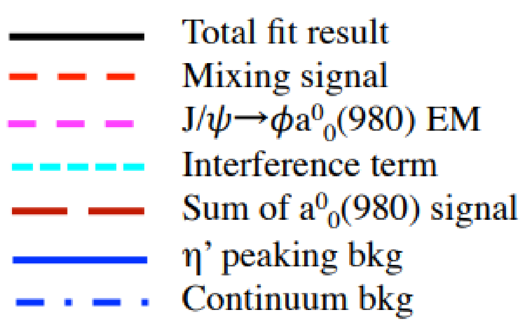
$a_0^0(980)$- $f_0(980)$ Mixing

PRL 121, 022001(2018)

- Constructed by $\eta \rightarrow \gamma\gamma$ and $\eta \rightarrow \pi^+\pi^-\pi^0$
- Interference between EM and mixing signal
- Two solutions are found, significance of $f_0(980) \rightarrow a_0^0(980)$ is **7.4σ**

$\eta \rightarrow \gamma\gamma$ | $\eta \rightarrow \pi^+\pi^-\pi^0$

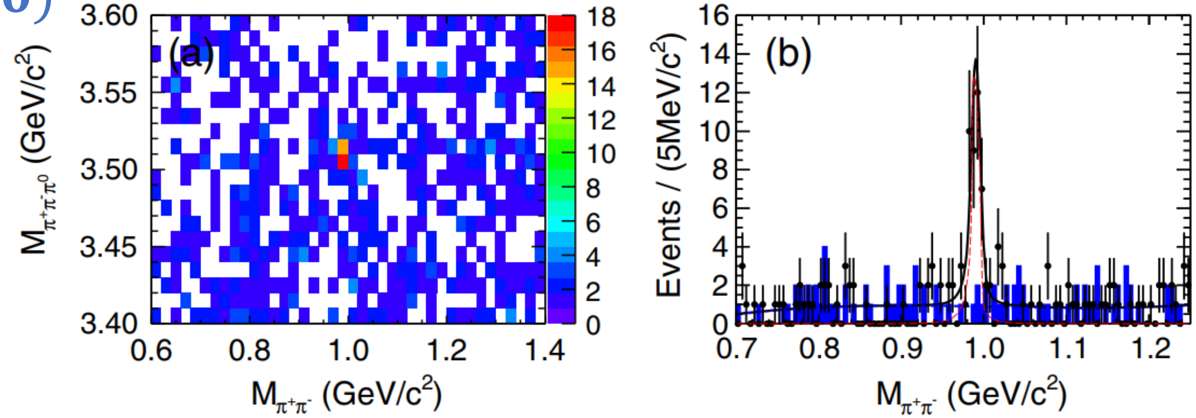




$a_0^0(980)$- $f_0(980)$ Mixing

PRL 121, 022001(2018)

- **Very narrow peak of $f_0(980)$**
- **EM contribution too weak ,can be negligible**
- **Interference is negligible**
- **Significance of $a_0^0(980)\rightarrow f_0(980)$is 5.5σ**



The mixing intensities:

$$\xi_{fa} = \frac{\mathcal{B}[J/\psi \to \phi f_0(980) \to \phi a_0^0(980) \to \phi\eta\pi^0]}{\mathcal{B}[J/\psi \to \phi f_0(980) \to \phi\pi\pi]},$$

$$\xi_{af} = \frac{\mathcal{B}[\chi_{c1} \to \pi^0 a_0^0(980) \to \pi^0 f_0(980) \to \pi^0\pi^+\pi^-]}{\mathcal{B}[\chi_{c1} \to \pi^0 a_0^0(980) \to \pi^0\pi^0\eta]}.$$

	$f_0(980) \to a_0^0(980)$		
Channel	Solution I	Solution II	$a_0^0(980) \to f_0(980)$
$\mathcal{B}$ (mixing) (10^{-6})	$3.18 \pm 0.51 \pm 0.38 \pm 0.28$	$1.31 \pm 0.41 \pm 0.39 \pm 0.43$	$0.35 \pm 0.06 \pm 0.03 \pm 0.06$
$\mathcal{B}$ (EM) (10^{-6})	$3.25 \pm 1.08 \pm 1.08 \pm 1.12$	$2.62 \pm 1.02 \pm 1.13 \pm 0.48$	$\cdots$
$\mathcal{B}$ (total) (10^{-6})	$4.93 \pm 1.01 \pm 0.96 \pm 1.09$	$4.37 \pm 0.97 \pm 0.94 \pm 0.06$	$\cdots$
ξ (%)	$0.99 \pm 0.16 \pm 0.30 \pm 0.09$	$0.41 \pm 0.13 \pm 0.17 \pm 0.13$	$0.40 \pm 0.07 \pm 0.14 \pm 0.07$

Summary

- **J/ψ decay provides an excellent laboratory to study light meson decays.**
- As η′ factory
  - Dalitz plot analysis of $\eta' \rightarrow \eta\pi\pi$: the linear representation is less compatible with the data.
  - Precision study of the decay dynamics of $\gamma\pi^+\pi^-$: need extra contribution besides ρ(770) – ω.
  - First direct measurement of absolute BFs for five η′ modes.
  - Search for $\eta' \rightarrow \gamma\gamma\eta$: the result is in tension with theoretical prediction.
  - Search for $\eta' \rightarrow \pi^0\pi^0\pi^0\pi^0$: the most stringent upper limit.
- Dalitz plot analysis of $\omega \rightarrow \pi^+\pi^-\pi^0$: deviates from the P-wave PHSP.
- First observation of $a_0^0(980)$- $f_0(980)$ mixing.

- **BESIII: 1.3 billion + 8.7 billion (10 billion in total) J/ψ events**
  - **The large data sample allows to study light mesons with the unprecedented statistics;**
  - **More interesting results are expected.**

Thanks for your attention.

Backup

BESIII publications on η/η' decays

- $\eta' \to \pi^+\pi^-\eta$ Phys. Rev. D 83, 012003 (2011)
- $\eta/\eta' \to \pi^+\pi^-, \pi^0\pi^0$ Phys. Rev. D 84, 032006 (2011)
- $\eta' \to \pi^+\pi^-\pi^0, \pi^0\pi^0\pi^0$ Phys. Rev. Lett. 108, 182001(2012)
- $\eta/\eta' \to$ invisible Phys. Rev. D 87, 012009 (2013)
- $\eta/\eta' \to \pi^+ e\nu$ Phys. Rev. D 87, 032006 (2013)
- $\eta' \to 3(\pi^+\pi^-)$ Phys. Rev. D 88, 091502 (2013)
- $\eta' \to 2(\pi^+\pi^-), \pi^+\pi^-\pi^0\pi^0$ Phys. Rev. Lett. 112, 251801 (2014)
- $\eta' \to \gamma e^+e^-$ Phys. Rev. D 92, 012001 (2015)
- $\eta \to \pi^+\pi^-\pi^0, \eta/\eta' \to \pi^0\pi^0\pi^0$ Phys. Rev. D 92, 012014 (2015)
- $\eta' \to \omega e^+e^-$ Phys. Rev. D 92, 051101 (2015)
- $\eta' \to K\pi$ Phys. Rev. D 93, 072008 (2016)
- $\eta' \to \rho\pi$ Phys. Rev. Lett. 118, 012001(2017)
- $\eta' \to \gamma\gamma\pi^0$ Phys. Rev. D 96, 012005 (2017)
- $\eta' \to \gamma\pi^+\pi^-$ Phys. Rev. Lett. 120, 242003 (2018)
- $\eta' \to \eta\pi^+\pi^-, \eta\pi^0\pi^0$ Phys. Rev. D 97, 012003 (2018)
- η' branching fractions Phys. Rev. Lett. 122, 142002 (2019)
- $\eta' \to \gamma\gamma\eta$ arXiv:1906.10346
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