

Light Meson Decays at BESIII



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IHEP

(On behalf of the BESIII Collaboration)



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OUTLINE

➤ Introduction

➤ η' meson decays

◆ Hadronic decays: $\eta' \rightarrow \pi^{+(0)}\pi^{-(0)}\pi^0$, $\eta' \rightarrow \pi^{+(0)}\pi^{-(0)}\eta$

◆ Radiative decays: $\eta' \rightarrow \gamma\pi^+\pi^-$, $\eta' \rightarrow \gamma\gamma\pi^0$

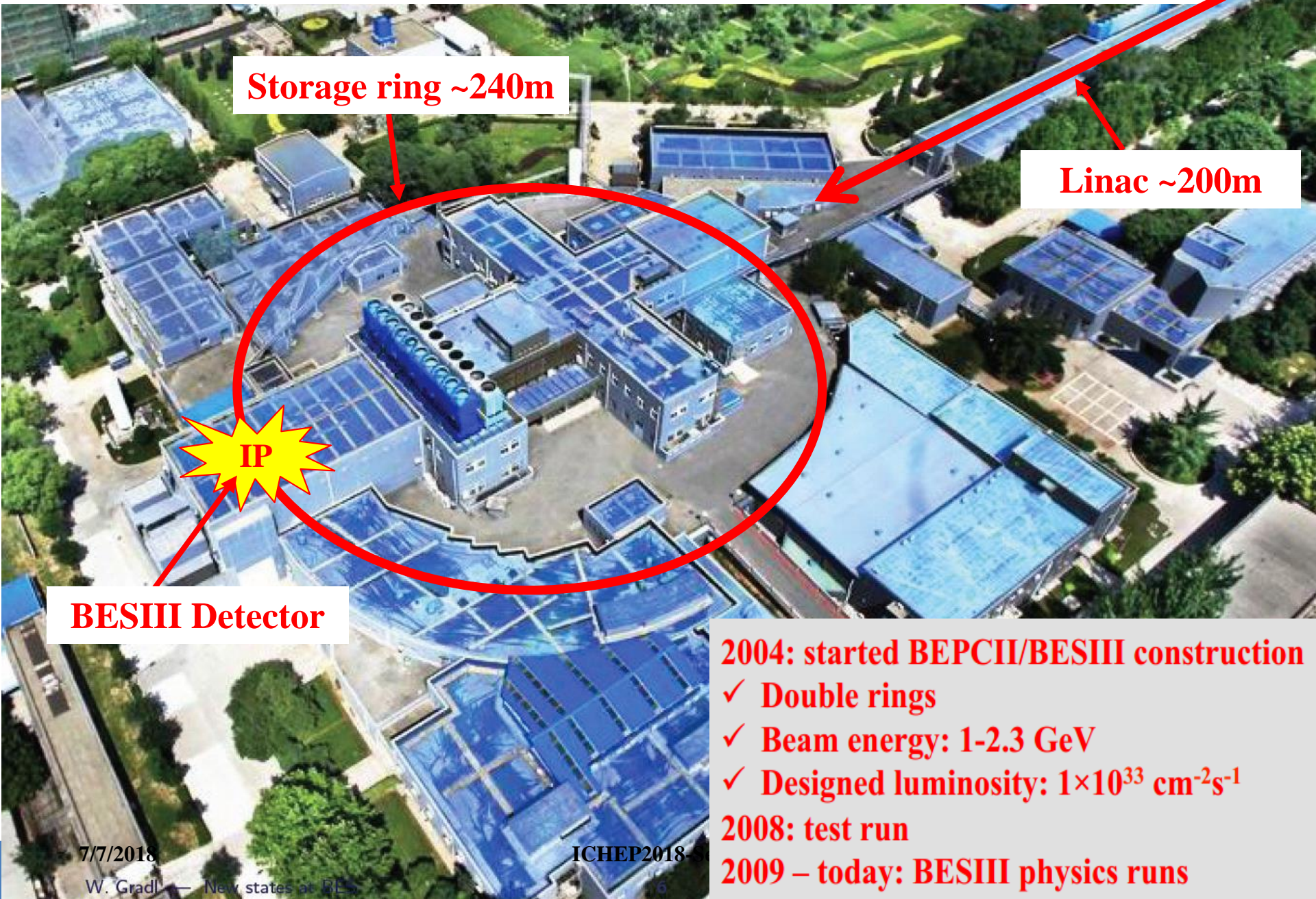
➤ $a_0^0(980)$ - $f_0(980)$ mixing

◆ $a_0^0(980) \rightarrow f_0(980)$: $J/\psi \rightarrow \phi a_0(980) \rightarrow \phi \eta \pi^0$

◆ $f_0(980) \rightarrow a_0^0(980)$: $\chi_{c1} \rightarrow \pi^0 f_0(980) \rightarrow \pi^0 \pi^+ \pi^-$

➤ Summary

Beijing Electron Positron Collider II (BEPC II)



Storage ring ~240m

Linac ~200m

IP

BESIII Detector

2004: started BEPCII/BESIII construction

✓ Double rings

✓ Beam energy: 1-2.3 GeV

✓ Designed luminosity: $1 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$

2008: test run

2009 – today: BESIII physics runs

BESIII Detector

Superconducting solenoid (1T)

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

Electromagnetic CsI(Tl) Calorimeter

$\sigma_E/E < 2.5\%$ @ 1 GeV (barrel)

$\sigma_E/E < 5\%$ @ 1 GeV (end caps)

$\sigma_{xy} = (6 \text{ mm})/E^{1/2}$ @ 1 GeV

Time of Flight

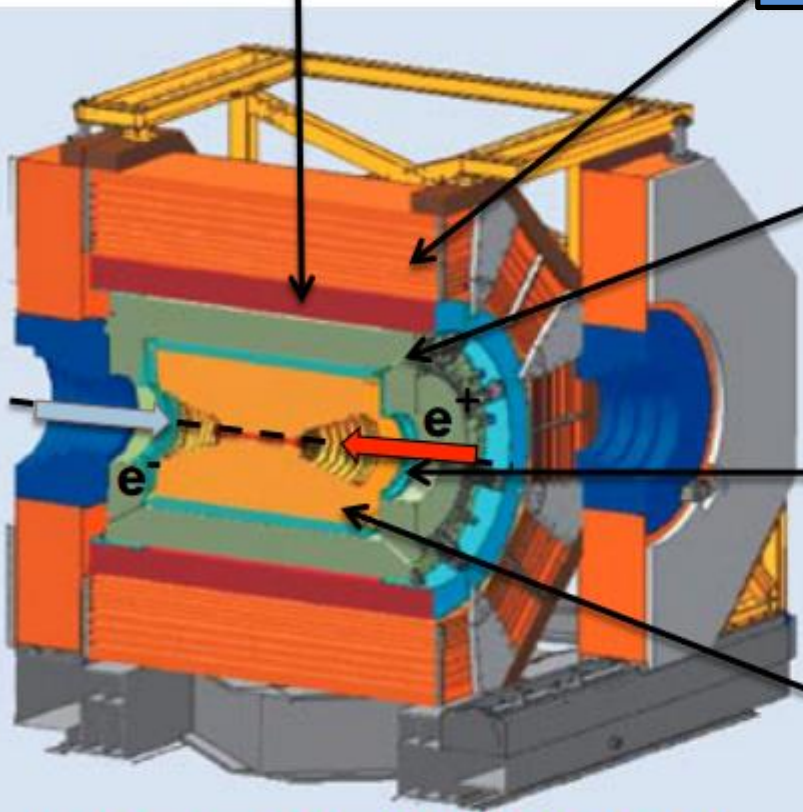
$\sigma_t = 90 \text{ ps}$ (barrel)

$\sigma_t = 120 \text{ ps}$ (end caps)

Drift Chamber

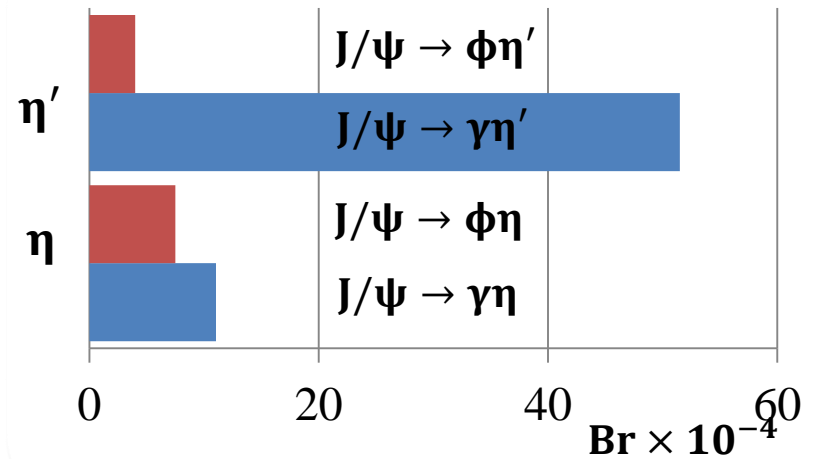
$\sigma_{r\phi} = 130 \mu\text{m}$ (single wire)

$\sigma_{pt}/p_t = 0.5\%$ @ 1 GeV



Nucl. Instr. Meth. A614, 345 (2010)

η, η' from J/ψ decays



◆ High production rate of light mesons in J/ψ decays

◆ η/η' from J/ψ radiative decays

$$\rightarrow 7.2 \times 10^6 \eta'$$

$$\rightarrow 2.4 \times 10^6 \eta$$

◆ η/η' from J/ψ hadronic decays (e.g. $J/\psi \rightarrow \phi \eta$)

$$\rightarrow 3 \times 10^5 \eta'$$

$$\rightarrow 5 \times 10^5 \eta$$

η, η' : a rich physics field

- ◆ test the predictions of ChPT
- ◆ study transition form factors
- ◆ test fundamental symmetries
- ◆ probe physics beyond the SM

η decay mode	physics highlight	η' mode	physics highlight
$\eta \rightarrow \pi^0 2\gamma$	ChPT	$\eta' \rightarrow \pi\pi$	CPV
$\eta \rightarrow \gamma B$	leptophobic dark boson	$\eta' \rightarrow 2\gamma$	chiral anomaly
$\eta \rightarrow 3\pi^0$	$m_u - m_d$	$\eta' \rightarrow \gamma\pi\pi$	box anomaly, form factor
$\eta \rightarrow \pi^+\pi^-\pi^0$	$m_u - m_d, CV$	$\eta' \rightarrow \pi^+\pi^-\pi^0$	$m_u - m_d, CV$
$\eta \rightarrow 3\gamma$	CPV	$\eta' \rightarrow \mu^+\mu^-\pi^0, e^+e^-\pi^0$	CV

Recent results on η/η' decays at BESIII

◆ Hadronic decays

- $\eta' \rightarrow \pi^+\pi^-\pi^0, \pi^0\pi^0\pi^0$
- $\eta' \rightarrow \pi^+\pi^-\eta, \pi^0\pi^0\eta$

◆ Radiative decays

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

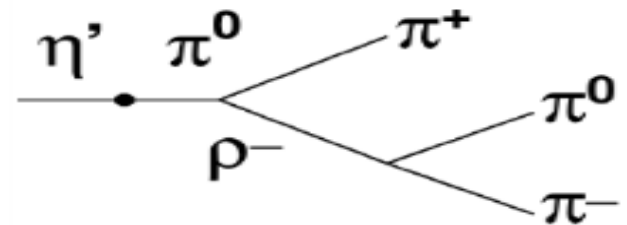
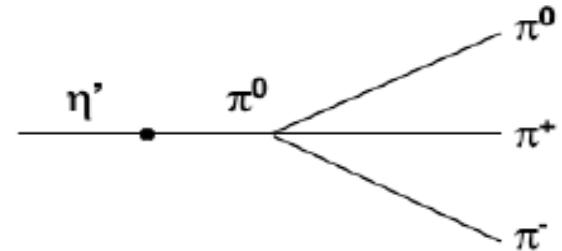
Amplitude Analysis of $\eta' \rightarrow \pi^{+(0)}\pi^{-(0)}\pi^0$

- ◆ $\eta' \rightarrow \pi\pi\pi$ are isospin-violating processes, dominated by strong interaction [Nucl. Phys. B460, 127(1996)]
- ◆ light quark mass difference $(m_d - m_u)/m_s$ can be extracted [PRD 19, 2188(1979)]

$$r_{\pm} = \frac{B(\eta' \rightarrow \pi^+ \pi^- \pi^0)}{B(\eta' \rightarrow \pi^+ \pi^- \eta)}$$

$$r_0 = \frac{B(\eta' \rightarrow \pi^0 \pi^0 \pi^0)}{B(\eta' \rightarrow \pi^0 \pi^0 \eta)}$$

- ◆ Using ChPT, large P-wave contribution of $\eta' \rightarrow \rho^{\pm} \pi^{\mp}$ is predicted [Eur. Phys. J. A 26, 383(2005)]

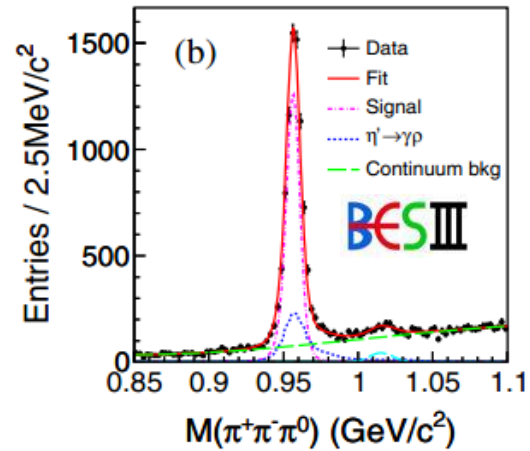
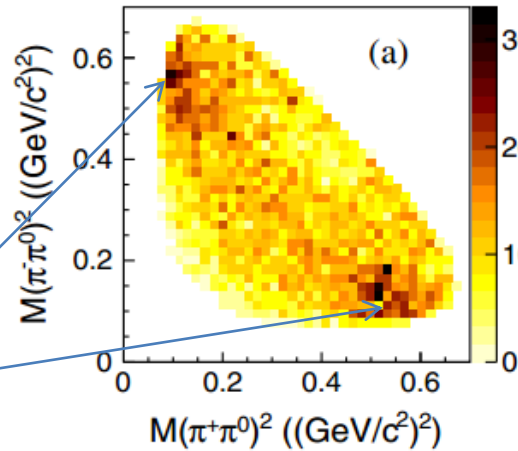


Amplitude Analysis of $\eta' \rightarrow \pi^{+(0)}\pi^{-(0)}\pi^0$

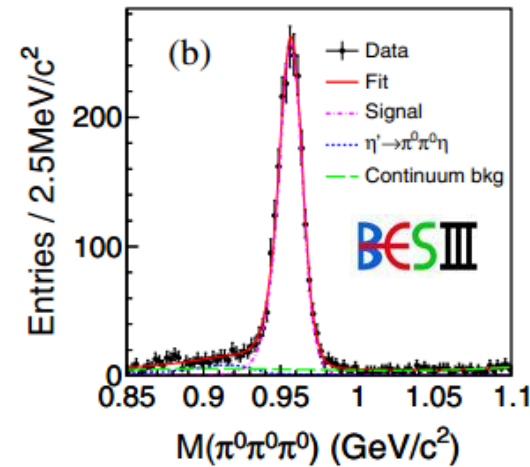
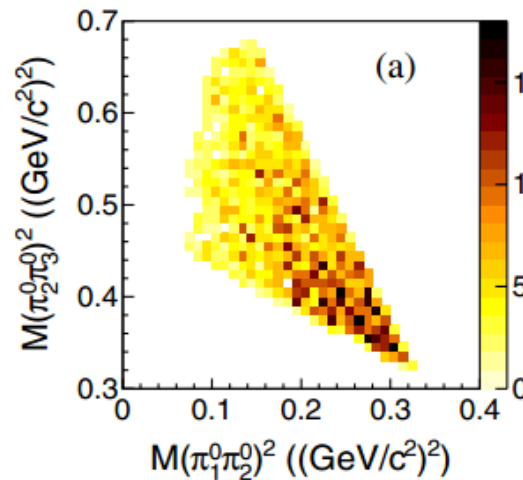
PRL 118, 012001 (2017)

$\eta' \rightarrow \pi^+\pi^-\pi^0$
8267 events

$\eta' \rightarrow \rho^\pm\pi^\mp$

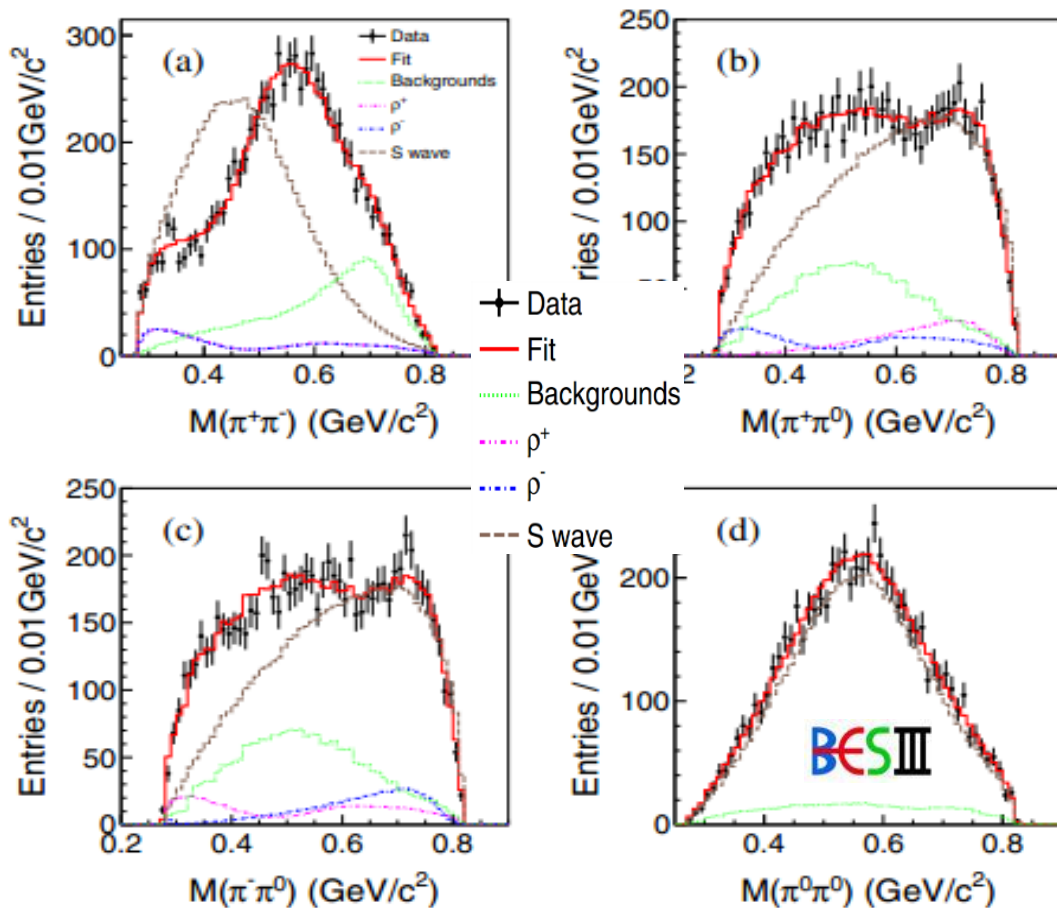


$\eta' \rightarrow \pi^0\pi^0\pi^0$
2237 events



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

PRL 118, 012001 (2017)



- ◆ Described by **three components**: P wave ($\rho^\pm\pi^\mp$), resonant S wave ($\sigma\pi^0$), phase-space S wave ($\pi\pi\pi$)
- ◆ Each component $> 24\sigma$

$$B(\eta' \rightarrow \pi^+\pi^-\pi^0) = (35.91 \pm 0.54 \pm 1.74) \times 10^{-4}$$

$$B(\eta' \rightarrow \pi^0\pi^0\pi^0) = (35.22 \pm 0.82 \pm 2.54) \times 10^{-4}$$

$$B(\eta' \rightarrow \rho^\pm\pi^\mp) = (7.44 \pm 0.06 \pm 1.26 \pm 1.84) \times 10^{-4}$$

$$B(\eta' \rightarrow \pi^+\pi^-\pi^0)_S = (37.63 \pm 0.77 \pm 2.22 \pm 4.48) \times 10^{-4}$$

- ◆ Obtained decay width ratios:
 $r_\pm = (8.77 \pm 1.19) \times 10^{-3}$
 $r_0 = (15.86 \pm 1.33) \times 10^{-3}$

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

◆ Remains a subject of effective ChPT

◆ explored by CLEO, VES, GAMS Collaboration but with limited statistics

◆ A cusp due to $\pi^+\pi^-$ mass threshold for the Dalitz plot of $\eta' \rightarrow \pi^0\pi^0\eta$

◆ For the charged decay mode

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

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

◆ For the neutral decay mode

$$X = \frac{\sqrt{3}|T_{\pi_1^0} - T_{\pi_2^0}|}{Q}.$$

◆ general representation

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

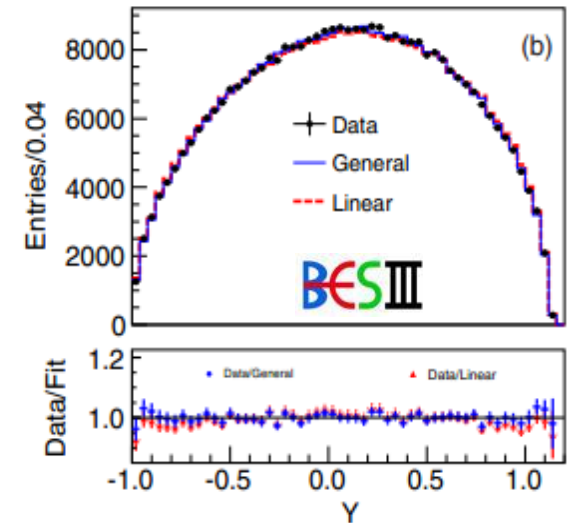
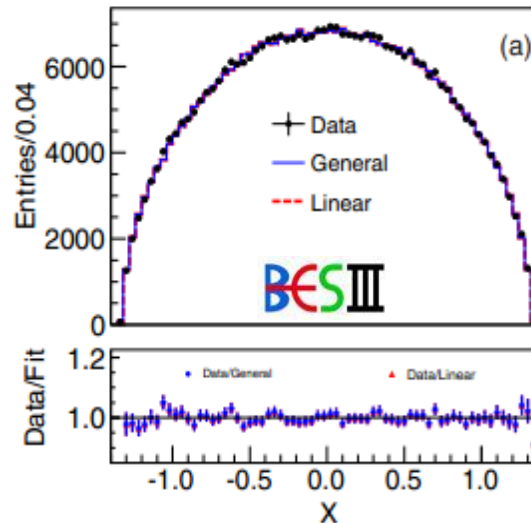
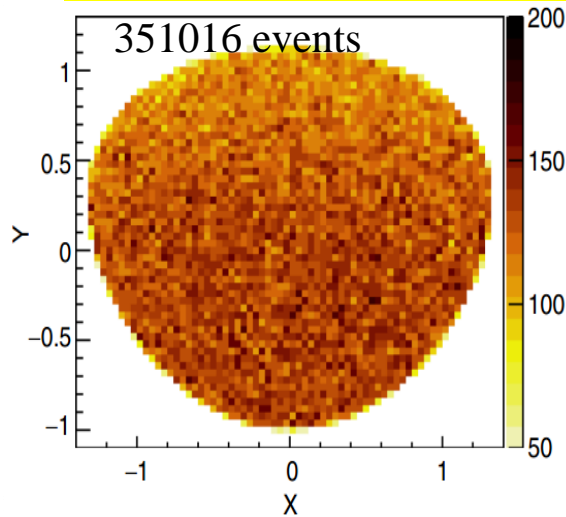
◆ linear representation

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

Here, a, b, c, d are free parameters
 α is a complex number, $a=2\text{Re}(\alpha)$,
 $b=\text{Re}(\alpha)^2 + \text{Im}(\alpha)^2$

Matrix Elements for $\eta' \rightarrow \pi^+ \pi^- \eta$

PRD 97,012003(2018)

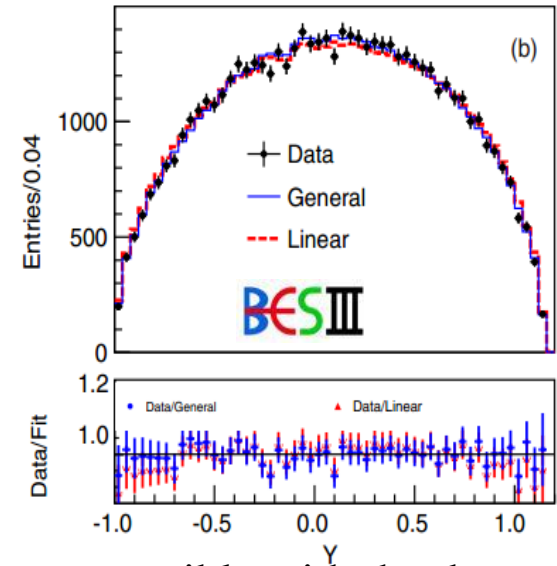
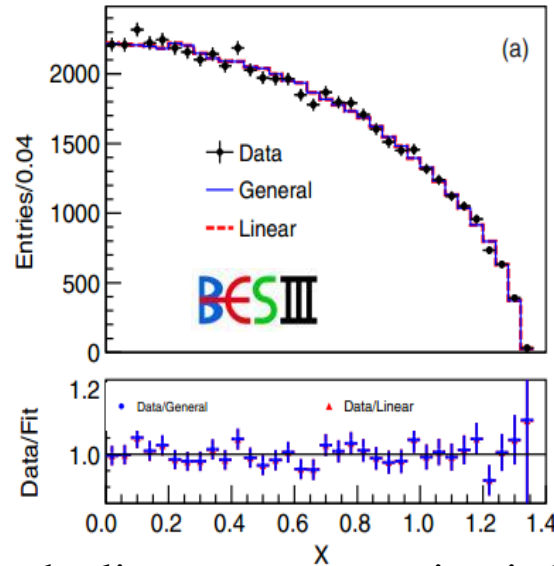
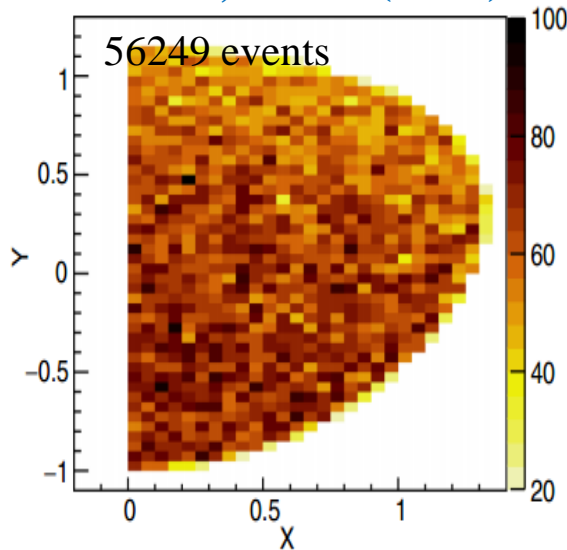


the linear representation is less compatible with the data

Parameter	$\eta' \rightarrow \eta \pi^+ \pi^-$				This work
	EFT [5]	Large N_C [7]	RChT [7]	VES [10]	
a	-0.116(11)	-0.098(48) (fixed)	-0.127(18)	-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)
$\Re(\alpha)$	[5] Eur. Phys. J. A 26, 383(2005)	...	...	-0.072(14)	-0.034(2)(2)
$\Im(\alpha)$	[7] JHEP 05, 094(2011)	...	...	0.000(100)	0.000(19)(1)
c	[10] Phys. Lett. B 651, 22 (2007)	...	...	+0.020(19)	0.0027(24)(15)
d				-0.066(34)	-0.053(4)(4)

Matrix Elements for $\eta' \rightarrow \pi^0 \pi^0 \eta$

PRD 97,012003(2018)



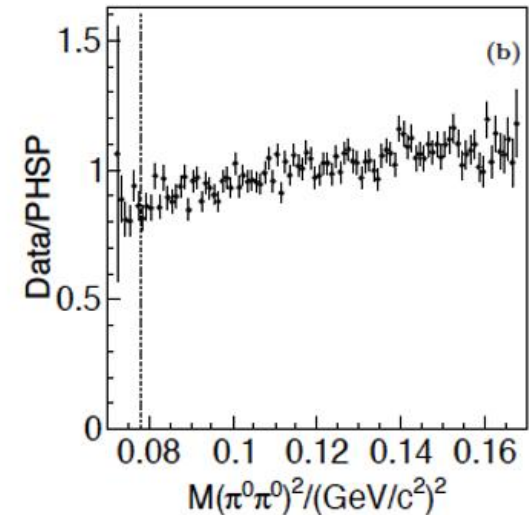
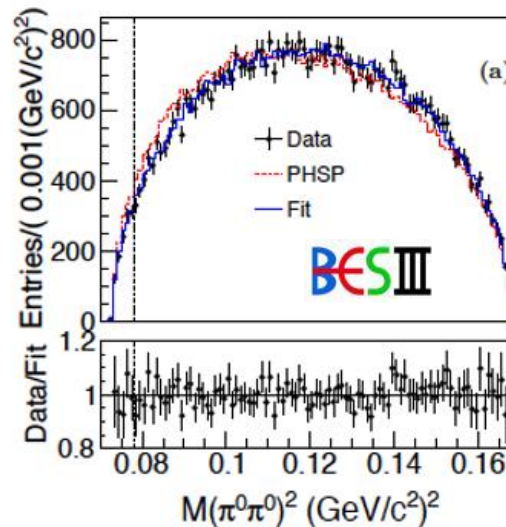
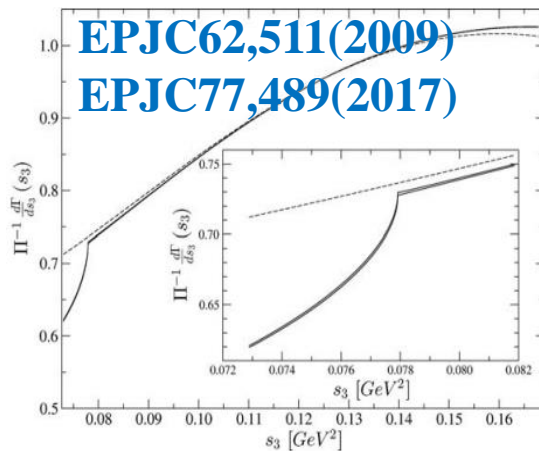
the linear representation is less compatible with the data

Parameter	$\eta' \rightarrow \eta \pi^0 \pi^0$		
	EFT [5]	GAMS-4 π [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)
$\Re(\alpha)$	[5]Eur. Phys. J. A 26, 383(2005)	-0.042(8)	-0.054(4)(1)
$\Im(\alpha)$	[12] Phys. At. Nucl. 72, 231 (2009)	0.000(70)	0.000(38)(2)
c	...	...	...
d	...	-0.054(19)	-0.061(9)(5)

Matrix Elements for $\eta' \rightarrow \pi^0 \pi^0 \eta$

Search for cusp effect

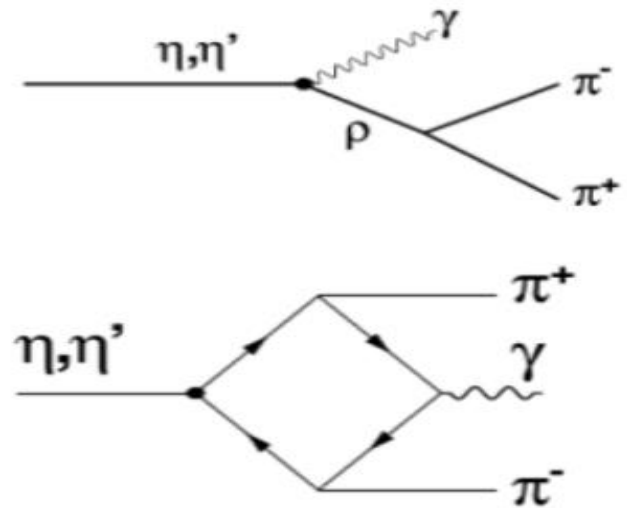
- ◆ FSI: A cusp effect (more than 8%) on $\pi^0 \pi^0$ mass spectrum below the $\pi^+ \pi^-$ mass threshold [EPJC62, 511 (2009)]



- ◆ No evidence of a cusp effect with current statistics

Study of $\eta' \rightarrow \gamma\pi^+\pi^-$ Decay Dynamics

- ◆ In VMD model, this process is dominated by $\eta' \rightarrow \gamma\rho(770)$
- ◆ 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 are proposed: $A \propto P(s) \cdot F_V(s)$ [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 :

$$\frac{d\Gamma}{dM(\pi^+\pi^-)} = \frac{k_\gamma^3 q_\pi^3(s)}{48\pi^3} |A|^2$$

$$k_\gamma^3 = (m_{\eta'}^2 - s)/2m_{\eta'}$$

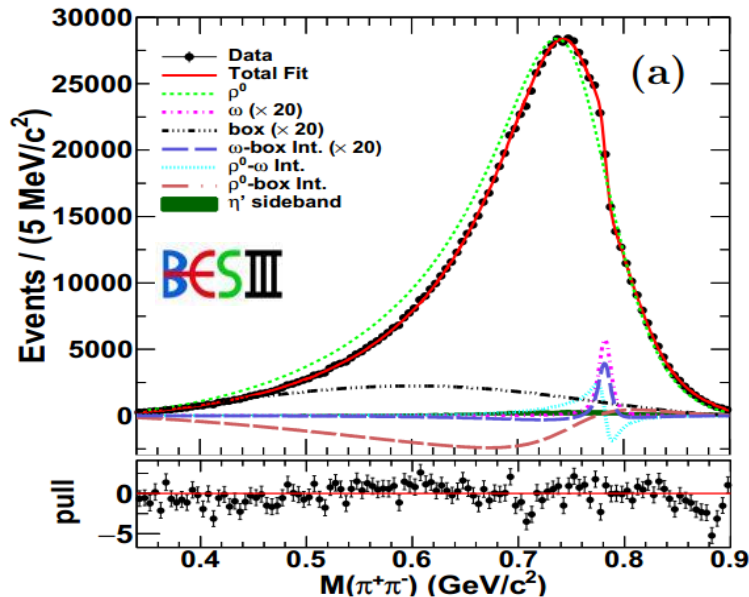
$$q_\pi(s) = \sqrt{s - 4m_\pi^2}/2$$

Study of $\eta' \rightarrow \gamma\pi^+\pi^-$ Decay Dynamics

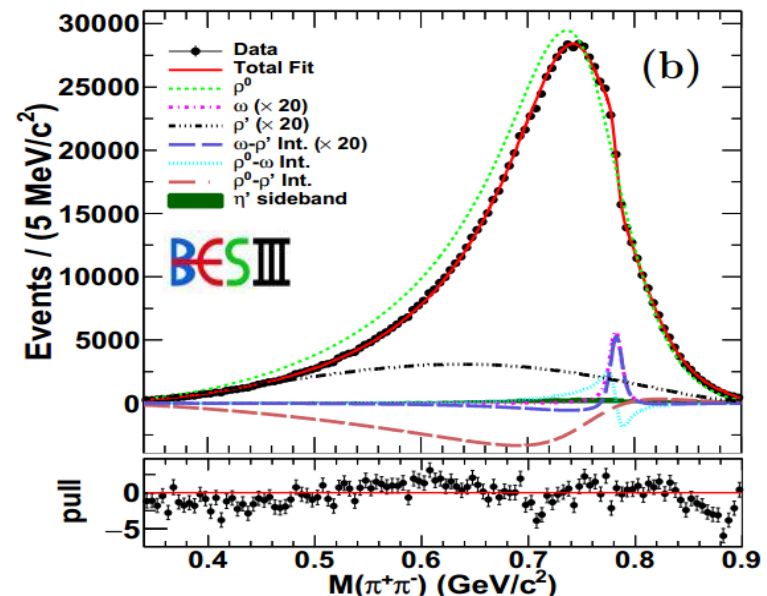
Model dependent fit

PRL 120, 242003 (2018)

Fit with $\rho(770) - \omega$ - box anomaly



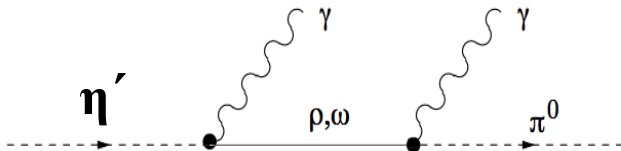
Fit with $\rho(770) - \omega - \rho(1450)$



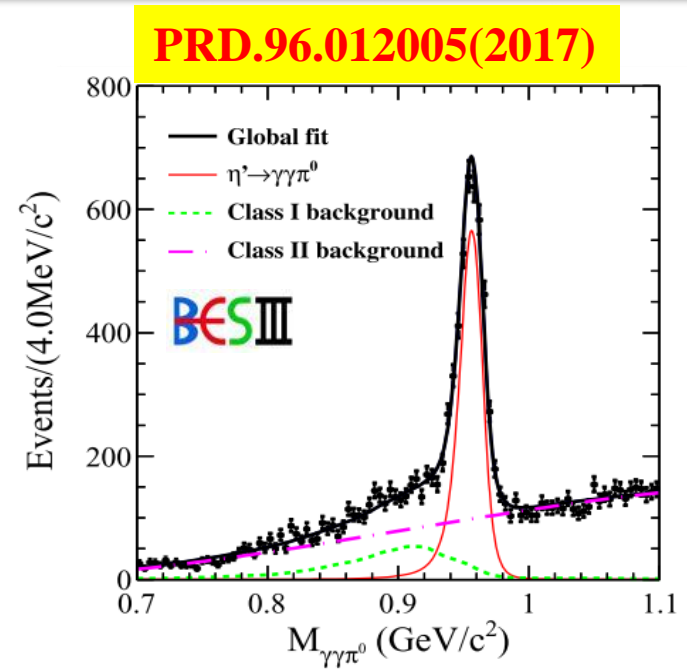
- ◆ Besides the $\rho(770)$, the ω contribution is needed
- ◆ $\rho(770)$ - ω cannot describe data well
- ◆ Extra contribution of box-anomaly or $\rho(1450)$, or both of them is necessary

Doubly radiative decay $\eta' \rightarrow \gamma\gamma\pi^0$

- ◆ Test QCD calculations on the transition form factor
- ◆ Test the high order of ChPT
- ◆ VMD contribution is dominant



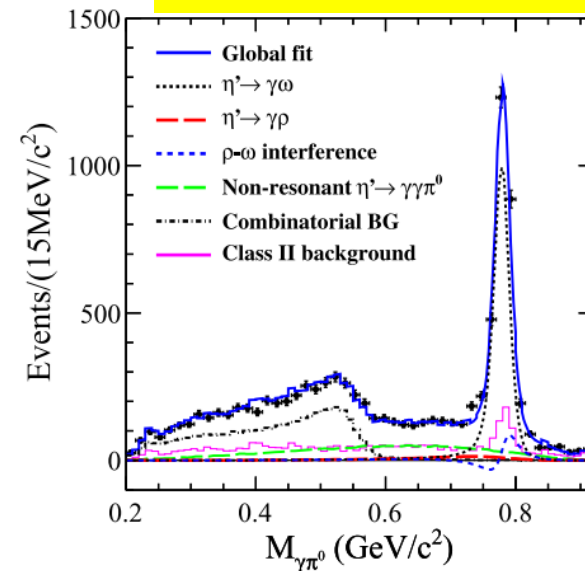
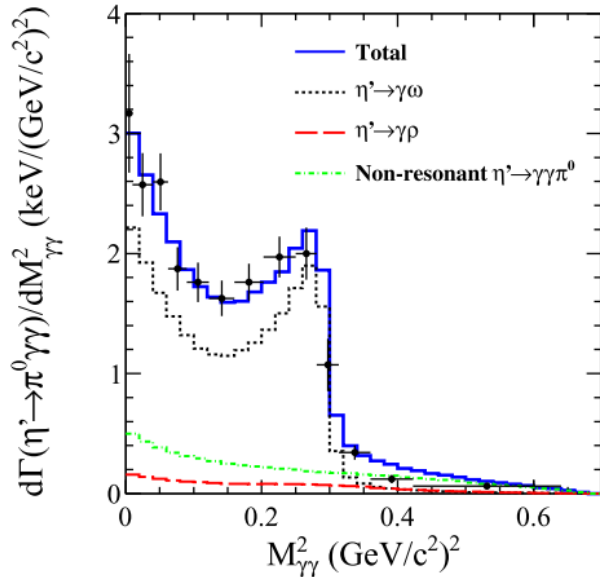
- ◆ In experiment, only an upper limit of $B(\eta' \rightarrow \gamma\gamma\pi^0) < 8 \times 10^{-4}$ at 90% C.L.



- ◆ The inclusive $\eta' \rightarrow \gamma\gamma\pi^0$ includes the vector mesons ρ / ω and the non-resonant contribution

Doubly radiative decay $\eta' \rightarrow \gamma\gamma\pi^0$

PRD.96.012005(2017)



This measurement:

$$B(\eta' \rightarrow \gamma\gamma\pi^0)_{inc} = (3.20 \pm 0.07 \pm 0.23) \times 10^{-3}$$

$$B(\eta' \rightarrow \gamma\omega) = (23.7 \pm 1.4 \pm 1.8) \times 10^{-4}$$

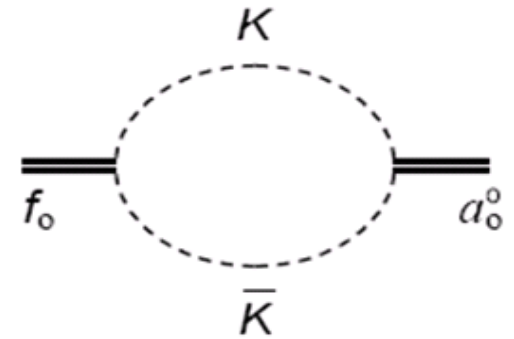
$$B(\eta' \rightarrow \gamma\gamma\pi^0)_{NR} = (6.16 \pm 0.64 \pm 0.67) \times 10^{-4}$$

$$\text{PDG: } B(\eta' \rightarrow \gamma\gamma\pi^0) < 8.0 \times 10^{-4}$$

$$\text{Linear } \sigma \text{ model and VMD: } B(\eta' \rightarrow \gamma\gamma\pi^0) \sim 6.0 \times 10^{-3}$$

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

Meson	$I^G(J^{PC})$	Mass(MeV)	Width(MeV)	Decay
$a_0(980)$	$1^-(0^{++})$	980 ± 20	50~100	$\eta\pi, KK$
$f_0(980)$	$0^+(0^{++})$	990 ± 10	10~100	$\pi\pi, KK$

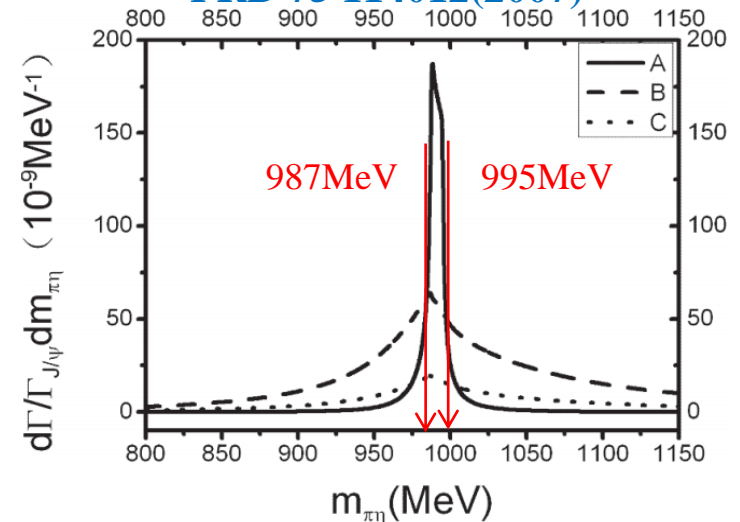


◆ In theory, $a_0^0(980)$ and $f_0(980)$ are explained as $q\bar{q}$ mesons, $K\bar{K}$ molecules, tetraquarks, $q\bar{q}g$ hybrids

◆ In 1970s, the mixing mechanism was firstly proposed [PLB 88, 367 (1979)]
 $m(K^+K^-) \approx 987\text{MeV}$ $m(K^0\bar{K}^0) \approx 995\text{MeV}$
 $m(K^0\bar{K}^0) - m(K^+K^-) \approx 8\text{MeV}$

◆ A narrow peak of about 8MeV is predicted

PRD 75 114012(2007)



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

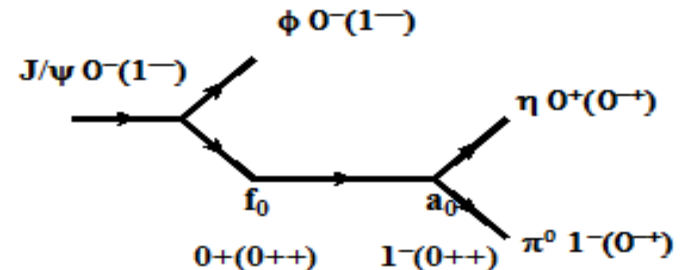
- ◆ Theorist proposed to directly measure $f_0(980) \leftrightarrow a_0^0(980)$ mixing via $J/\psi \rightarrow \phi f_0(980) \rightarrow \phi a_0^0(980) \rightarrow \phi \eta \pi^0$ and $\chi_{c1} \rightarrow \pi^0 a_0^0(980) \rightarrow \pi^0 f_0(980) \rightarrow \pi^0 \pi^+ \pi^-$ [Wu, Zhao, Zou, PRD 75 114012(2007), PRD 78 074017(2008)]

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

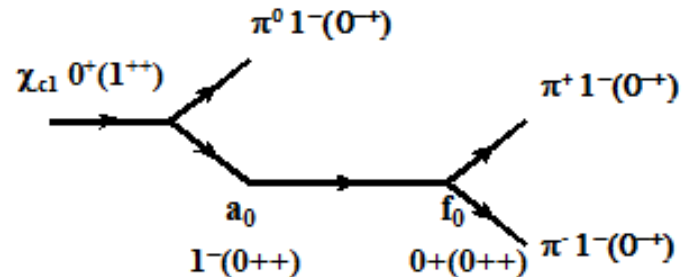
$$\xi_{af} = \frac{\mathcal{B}(\chi_{c1} \rightarrow \pi^0 a_0^0(980) \rightarrow \pi^0 f_0(980) \rightarrow \pi^0 \pi^+ \pi^-)}{\mathcal{B}(\chi_{c1} \rightarrow \pi^0 a_0^0(980) \rightarrow \pi^0 \pi^0 \eta)}$$

- ◆ Mixing intensity is sensitive to couplings of $g_{a_0 K^+ K^-}$ and $g_{f_0 K^+ K^-}$
- ◆ Measured at BESIII based on 225M J/ψ and 108M ψ' [PRD83.032003(2011)]
significance $< 5\sigma$
 $\xi_{af} < 1.0\% @ 90\% \text{C. L.}$
 $\xi_{fa} < 1.1\% @ 90\% \text{C. L.}$

$f_0(980) \rightarrow a_0^0(980)$ mixing:



$a_0^0(980) \rightarrow f_0(980)$ mixing:



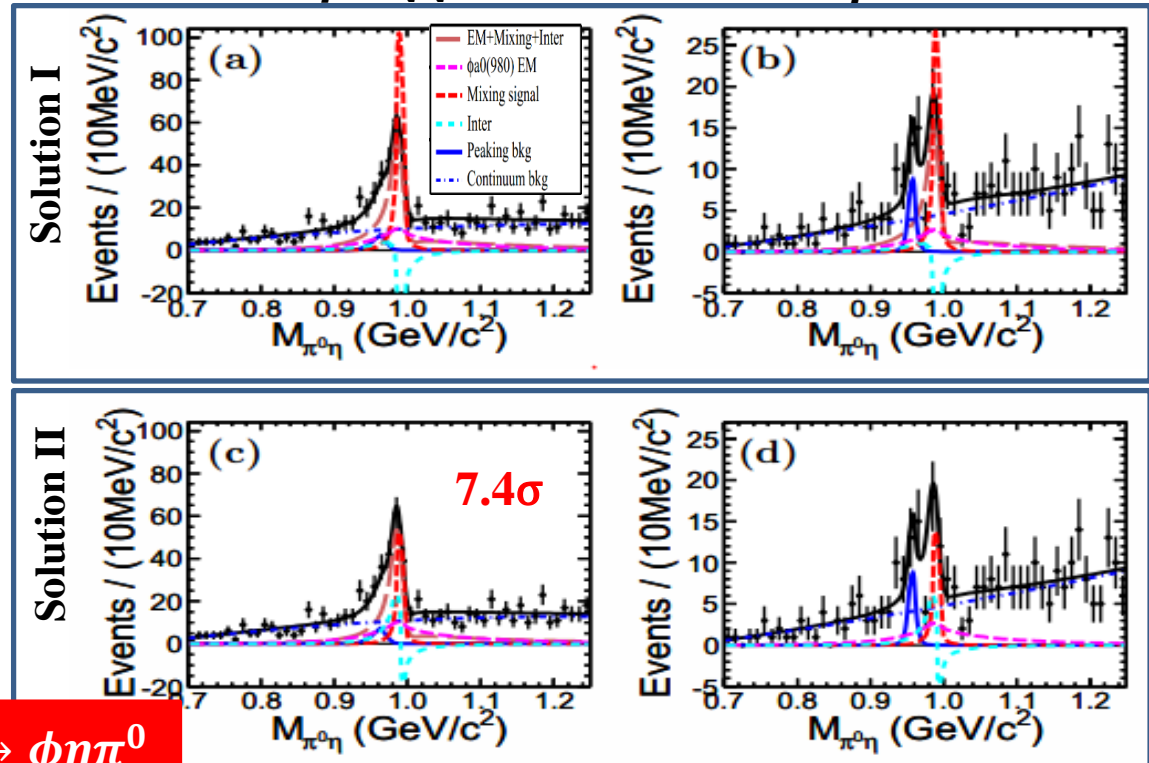
$f_0(980) \rightarrow a_0^0(980)$ mixing

arXiv:1802.00583v3 (accepted by PRL)

- ◆ Constructed by $\eta \rightarrow \gamma\gamma$ and $\eta \rightarrow 3\pi$
- ◆ Interference between EM and mixing signal
- ◆ Two solutions are found
- ◆ Significance of $f_0(980) \rightarrow a_0^0(980)$ is 7.4σ

$\eta \rightarrow \gamma\gamma$

$\eta \rightarrow 3\pi$



$J/\psi \rightarrow \phi f_0(980) \rightarrow \phi a_0^0(980) \rightarrow \phi \eta \pi^0$

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

Channel

Solution I

Solution II

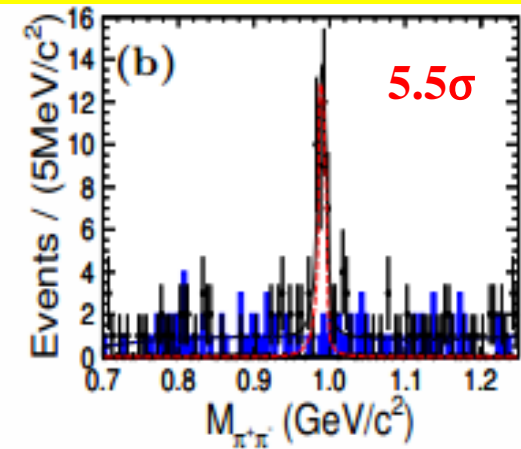
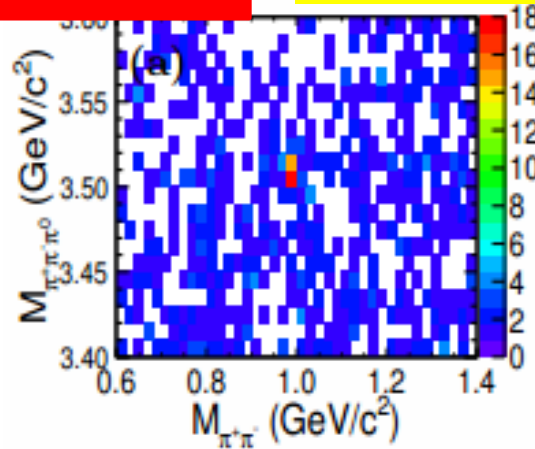
$\mathcal{B}(\text{mixing}) (10^{-6})$	$3.18 \pm 0.51 \pm 0.38 \pm 0.28$	$1.31 \pm 0.41 \pm 0.39 \pm 0.43$
$\mathcal{B}(\text{EM}) (10^{-6})$	$3.25 \pm 1.08 \pm 1.08 \pm 1.12$	$2.62 \pm 1.02 \pm 1.13 \pm 0.48$
$\mathcal{B}(\text{total}) (10^{-6})$	$4.93 \pm 1.01 \pm 0.96 \pm 1.09$	$4.37 \pm 0.97 \pm 0.94 \pm 0.06$
$\xi (\%)$	$0.99 \pm 0.16 \pm 0.30 \pm 0.09$	$0.41 \pm 0.13 \pm 0.17 \pm 0.13$

$a_0^0(980) \rightarrow f_0(980)$ mixing

$\chi_{c1} \rightarrow \pi^0 a_0^0(980) \rightarrow \pi^0 f_0(980) \rightarrow \pi^0 \pi^+ \pi^-$

arXiv:1802.00583v3 (accepted by PRL)

- ◆ 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



Channel	$a_0^0(980) \rightarrow f_0(980)$
$\mathcal{B}(\text{mixing}) (10^{-6})$	$0.35 \pm 0.06 \pm 0.03 \pm 0.06$
$\mathcal{B}(\text{EM}) (10^{-6})$	—
$\mathcal{B}(\text{total}) (10^{-6})$	—
$\xi (\%)$	$0.40 \pm 0.07 \pm 0.14 \pm 0.07$

Summary

- $J/\psi(\psi')$ decay is a unique place to study light mesons
- BESIII: 1.3 billion + **4.6 billion** J/ψ events
 - ◆ A sample of 4.6 billion J/ψ events **was taken in 2018**
 - ◆ So large data sample allows to study light mesons with the unprecedented statistics
 - ◆ More interesting results are expected

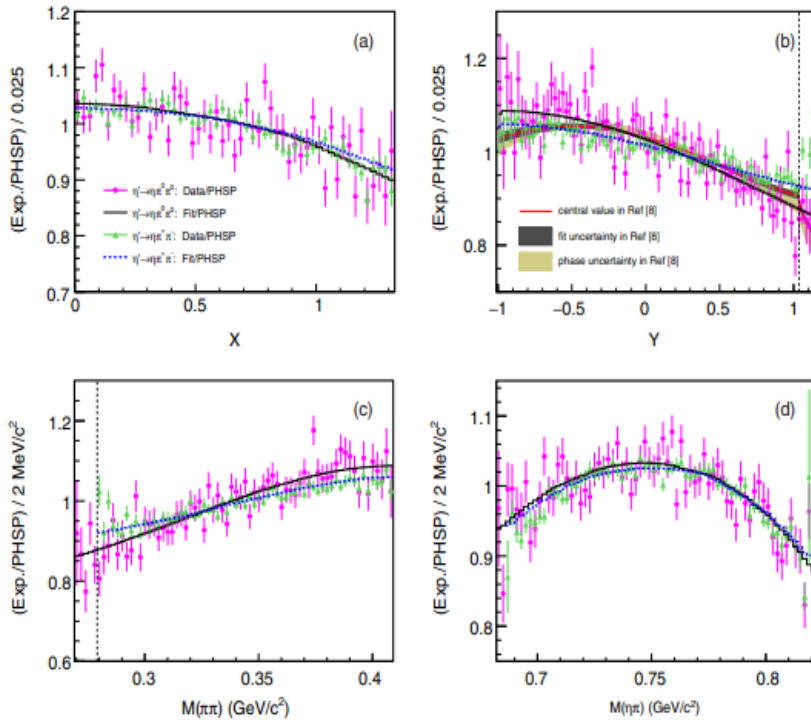
Thanks

Backup

BESIII publications on η/η' decays

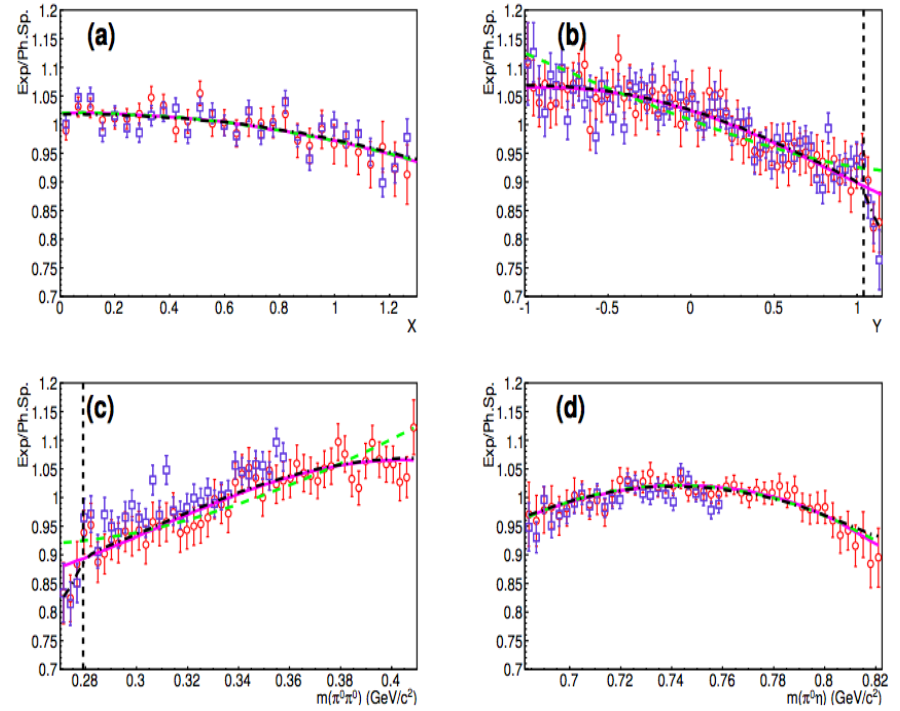
- $\eta' \rightarrow \pi^+\pi^-\eta$ PRD83, 012003(2011)
- $\eta/\eta' \rightarrow \pi^+\pi^-, \pi^0\pi^0$ PRD83, 032006(2011)
- $\eta' \rightarrow \pi^+\pi^-\pi^0, \pi^0\pi^0\pi^0$ PRL108, 182001(2012)
- $\eta/\eta' \rightarrow \text{invisible}$ PRD87,012009(2013)
- $\eta/\eta' \rightarrow \pi^+e\nu$ PRD87,032006(2013)
- $\eta' \rightarrow 3(\pi^+\pi^-)$ PRD88,091502(2013)
- $\eta' \rightarrow 2(\pi^+\pi^-), \pi^+\pi^-\pi^0\pi^0$ PRL112,251801(2014)
- $\eta' \rightarrow \gamma e^+e^-$ PRD92,012001(2015)
- $\eta \rightarrow \pi^+\pi^-\pi^0, \eta/\eta' \rightarrow \pi^0\pi^0\pi^0$ PRD92,012014(2015)
- $\eta' \rightarrow \omega e^+e^-$ PRD92,051101(2015)
- $\eta' \rightarrow K\pi$ PRD93, 072008 (2016)
- $\eta' \rightarrow \rho\pi$ PRL118,012001(2017)
- $\eta' \rightarrow \gamma\gamma\pi^0$ PRD96,012005(2017)
- $\eta' \rightarrow \gamma\pi^+\pi^-$ PRL 120, 242003 (2018)
- $\eta' \rightarrow \pi^+\pi^-\eta, \eta' \rightarrow \pi^0\pi^0\eta$ PRD97, 012003 (2018)

BESIII Collaboration



PRD 97, 012003 (2018)

A2 Collaboration



hep-ex/1709.0423