Light Meson Decays at BESIII

(On behalf of the BESIII Collaboration)
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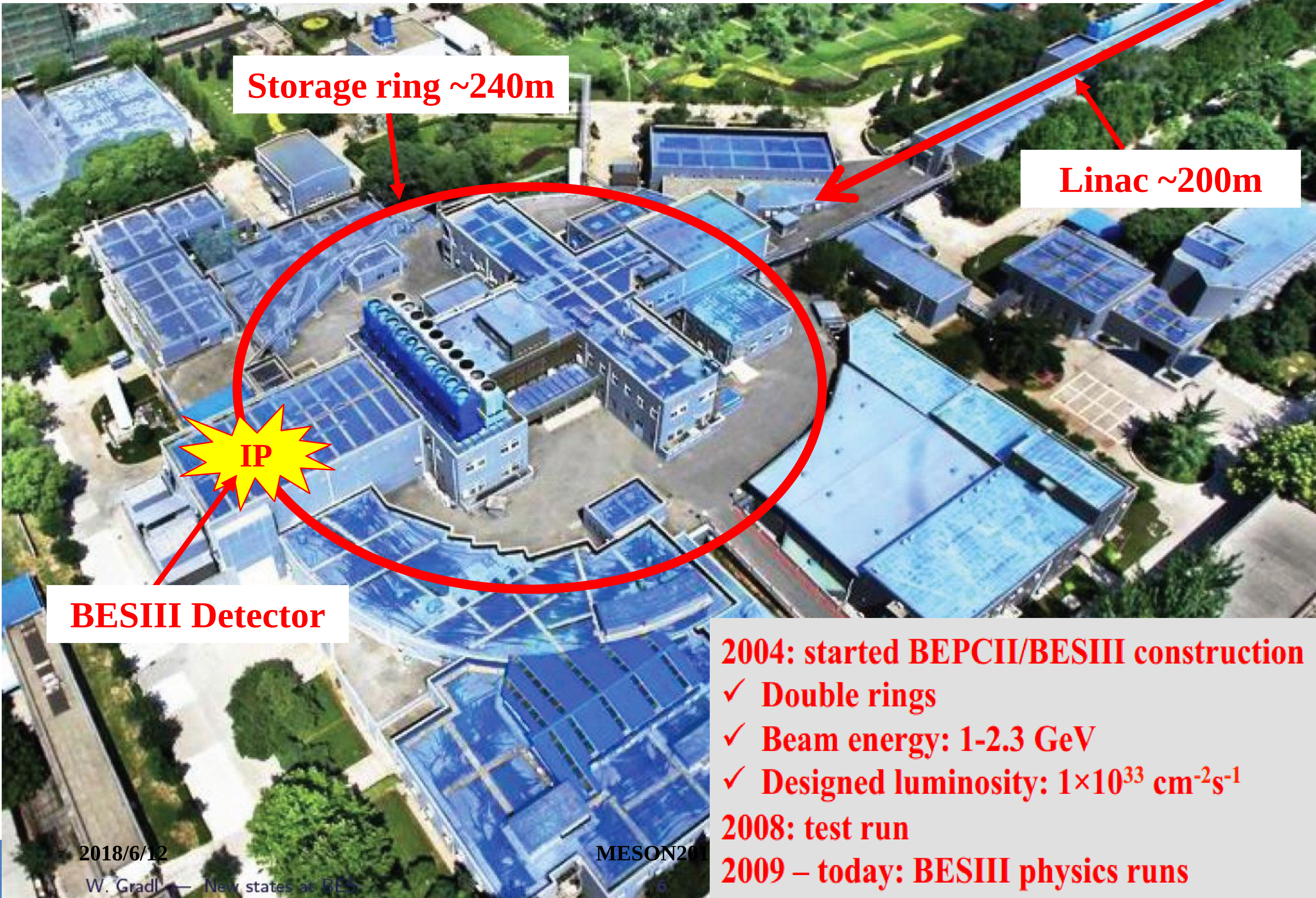
OUTLINE

- **Introduction**
- **η' meson decays**
  - **Hadonic decays:** $\eta' \to \pi^{+(0)}\pi^{-(0)}\pi^0$, $\eta' \to \pi^{+(0)}\pi^{-(0)}\eta$
  - **Radiative decays:** $\eta' \to \gamma\pi^+\pi^-$, $\eta' \to \gamma\gamma\pi^0$
- **$a_0^0(980)$-$f_0(980)$ mixing**
  - $a_0^0(980) \to f_0(980)$: $J/\psi \to \phi a_0(980) \to \phi\eta\pi^0$
  - $f_0(980) \to a_0^0(980)$: $\chi_{c1} \to \pi^0 f_0(980) \to \pi^0\pi^+\pi^-$
- **Summary**

Beijing Electron Positron Collider II (BEPC II)



2004: started BEPCII/BESIII construction

- ✓ Double rings
- ✓ Beam energy: 1-2.3 GeV
- ✓ Designed luminosity: 1×10^{33} cm^{-2}s^{-1}

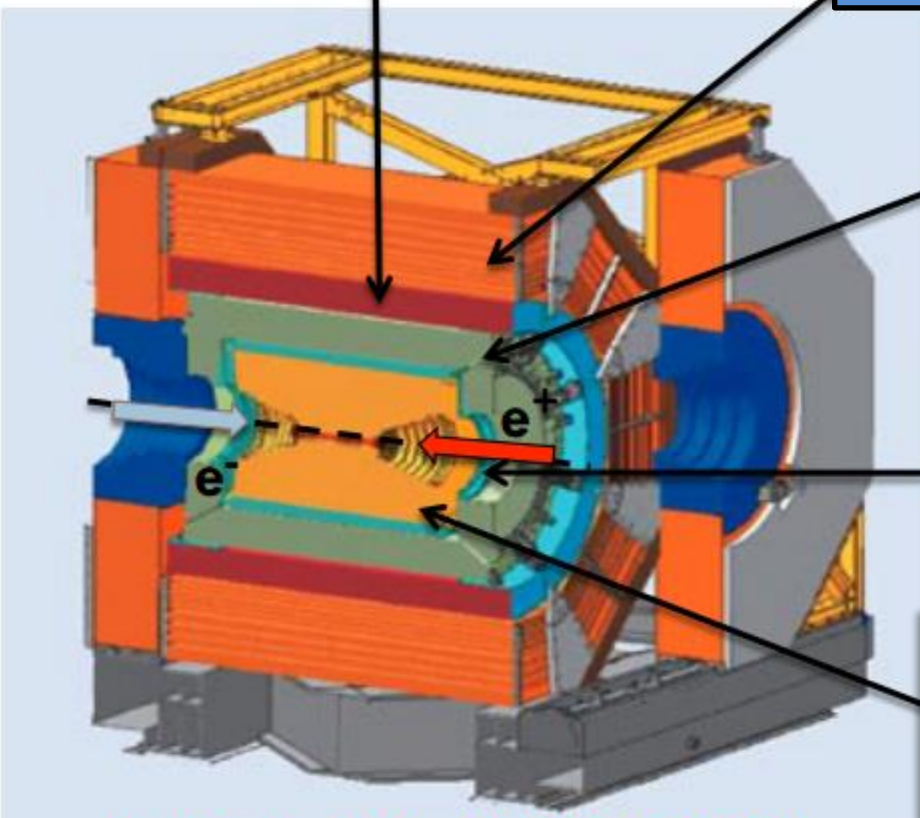
2008: test run

2009 – today: BESIII physics runs

BESIII Detector

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

Superconducting solenoid (1T)



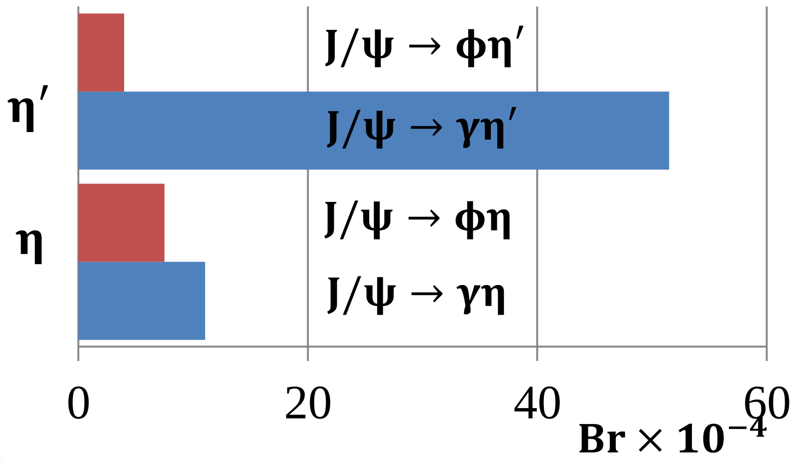
Nucl. Instr. Meth. A614, 345 (2010)

Electromagnetic CsI(Tl) Calorimeter
$\sigma_E/E < 2.5\%$ @ 1 GeV (barrel)
$\sigma_E/E < 5\%$ @ 1 GeV (end caps)
$\sigma_{xy} = (6\ \mathrm{mm})/E^{1/2}$ @ 1 GeV

Time of Flight
$\sigma_t = 90$ ps (barrel)
$\sigma_t = 120$ ps (end caps)

Drift Chamber
$\sigma_{r\phi} = 130\ \mu m$ (single wire)
$\sigma_{pt}/p_t = 0.5\ \%$ @ 1 GeV

η, η' from J/ψ decays



- **High production rate of light mesons in J/ψ decays**
- **BESIII: τ –charm factory**
- **Also a factory for light mesons ($\eta/\eta'/\omega$)**
- **η/η' from J/ψ radiative decays**

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

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

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

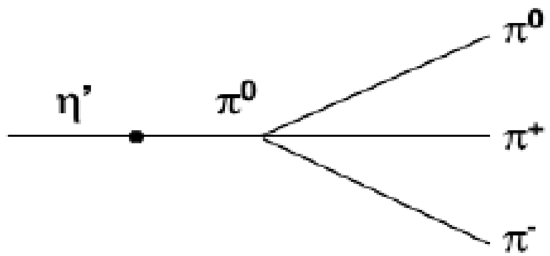
Amplitude Analysis of $\eta' \to \pi^{+(0)}\pi^{-(0)}\pi^0$

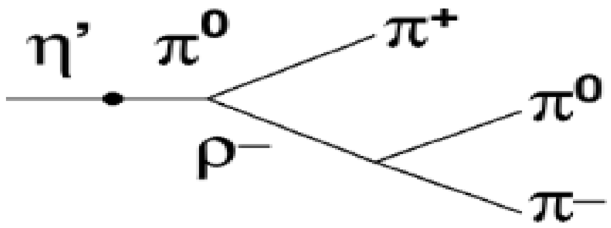
- $\eta' \to \pi\pi\pi$ are isospin-violating processes , dominated by strong interaction [Nucl. Phys. B460, 127(1996)]
- light quark mass difference $(m_d - m_u)/m_s$ can be extracted

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

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

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





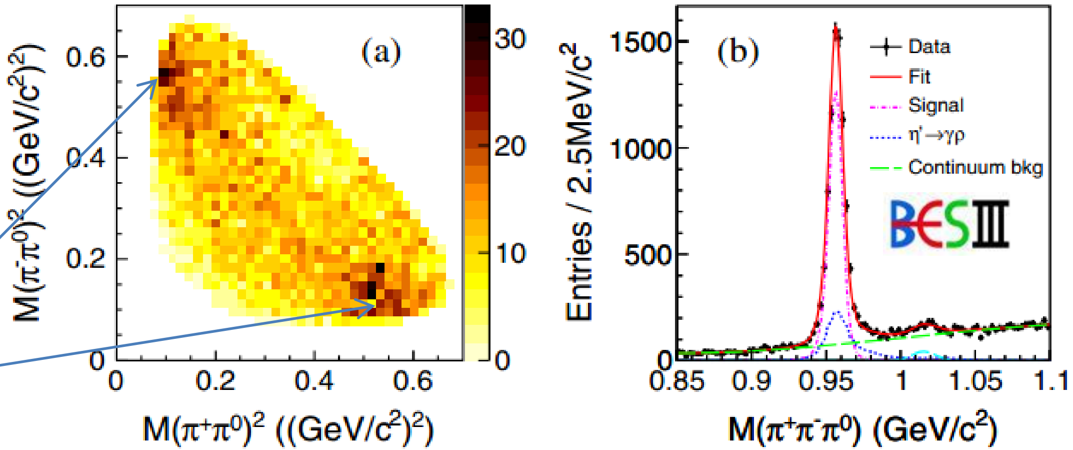
Amplitude Analysis of $\eta' \to \pi^{+(0)}\pi^{-(0)}\pi^0$

PRL 118, 012001 (2017)

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

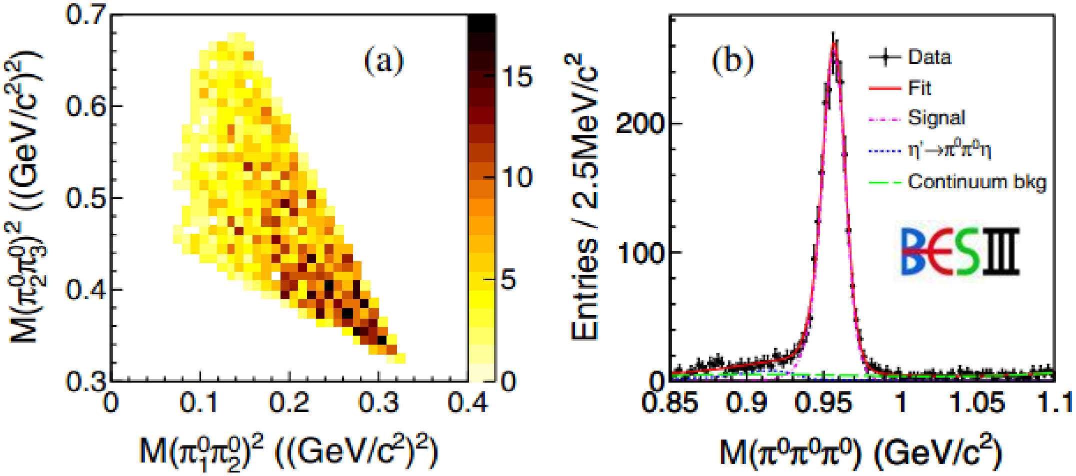
8267 events

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



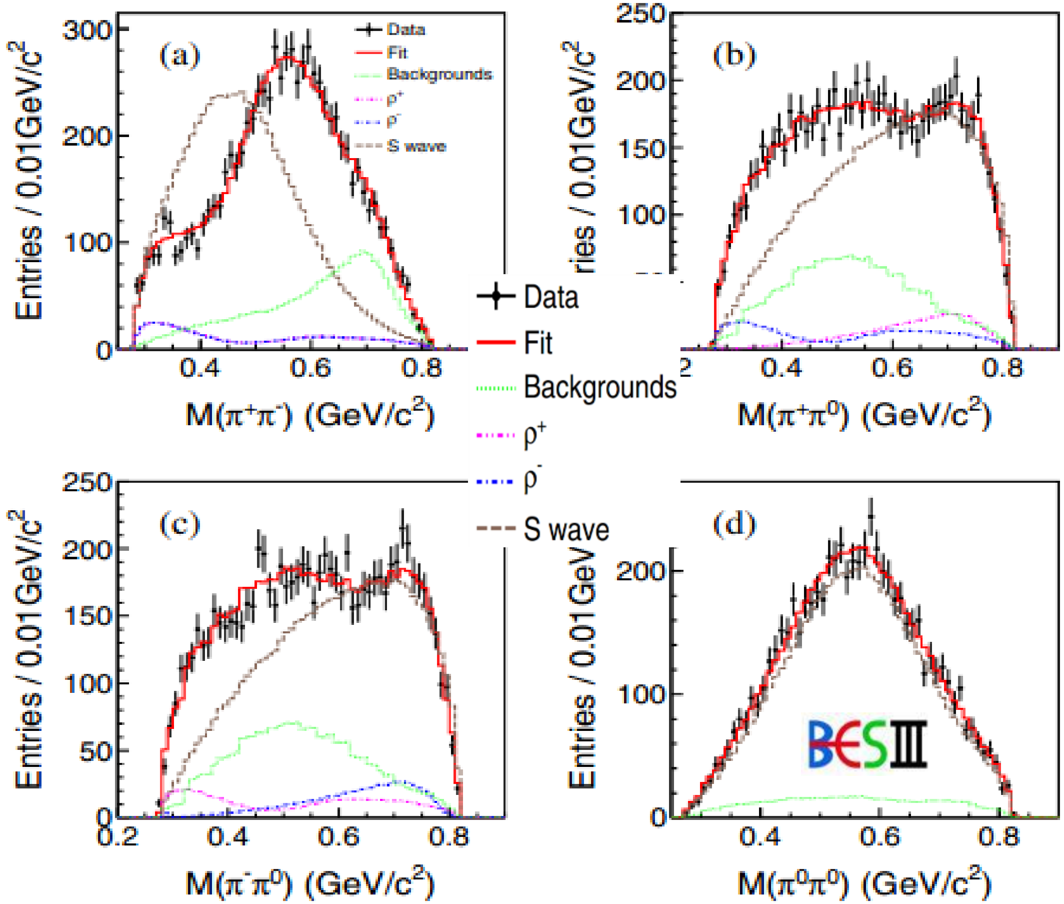
$\eta' \to \pi^0\pi^0\pi^0$

2237 events



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

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 $> 24\sigma$**

$B(\eta' \to \pi^+\pi^-\pi^0)$
$= (35.91 \pm 0.54 \pm 1.74) \times 10^{-4}$
$B(\eta' \to \pi^0\pi^0\pi^0)$
$= (35.22 \pm 0.82 \pm 2.54) \times 10^{-4}$
$B(\eta' \to \rho^{\pm}\pi^{\mp})$
$= (7.44 \pm 0.06 \pm 1.26 \pm 1.84) \times 10^{-4}$
$B(\eta' \to \pi^+\pi^-\pi^0)_S$
$= (37.63 \pm 0.77 \pm 2.22 \pm 4.48) \times 10^{-4}$

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

- **Remains a subject of effective ChPT**
- **explored by CLEO, VES, GAMS Collaboration but with limited statistics**
- **$\eta' \to \pi^+\pi^-\eta$ is studied based on 225M J/ψ at BESIII [PRD83,012003(2011)]**
- **A cusp due to $\pi^+\pi^-$ mass threshold for the Dalitz plot of $\eta' \to \pi^0\pi^0\eta$**
- **For the charged decay mode**

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

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**

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

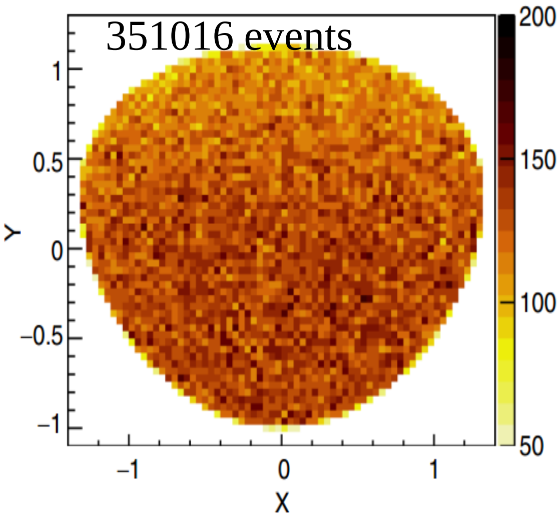
- **linear representation**

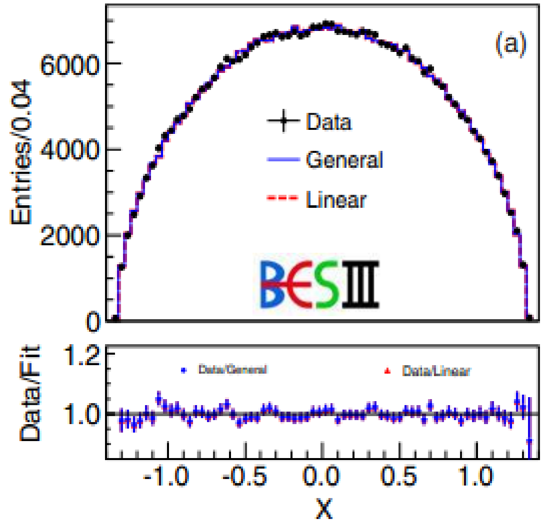
$$|M(X,Y)|^2 = N(|1 + \alpha Y|^2 + cX + dX^2 + \cdots),$$

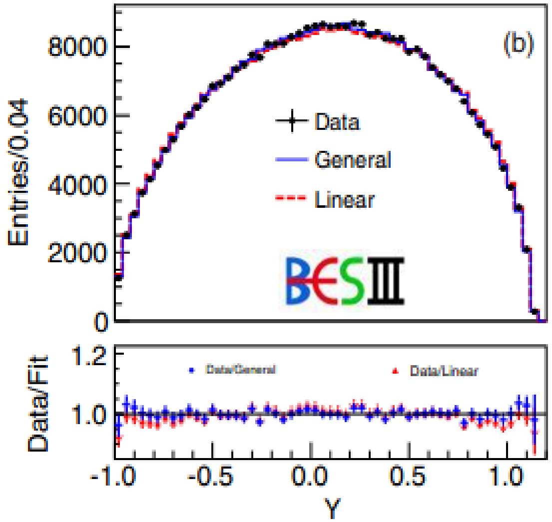
Here, a, b, c, d are free parameters
α is a complex number, a=2Re(α),
b=Re(α)^2 +Im(α)^2

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

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)

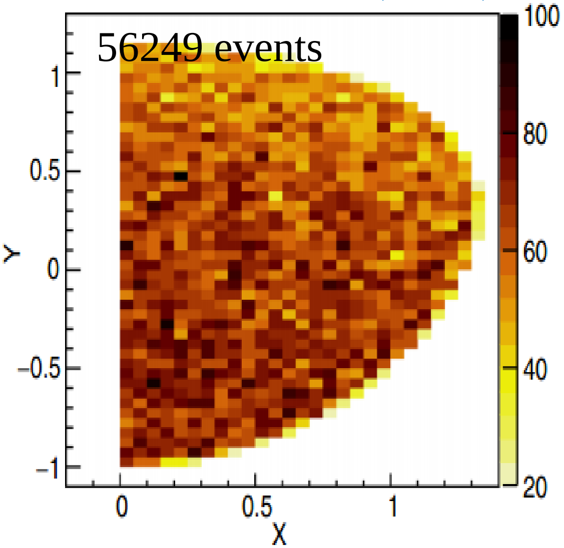
[5]Eur. Phys. J. A 26, 383(2005)

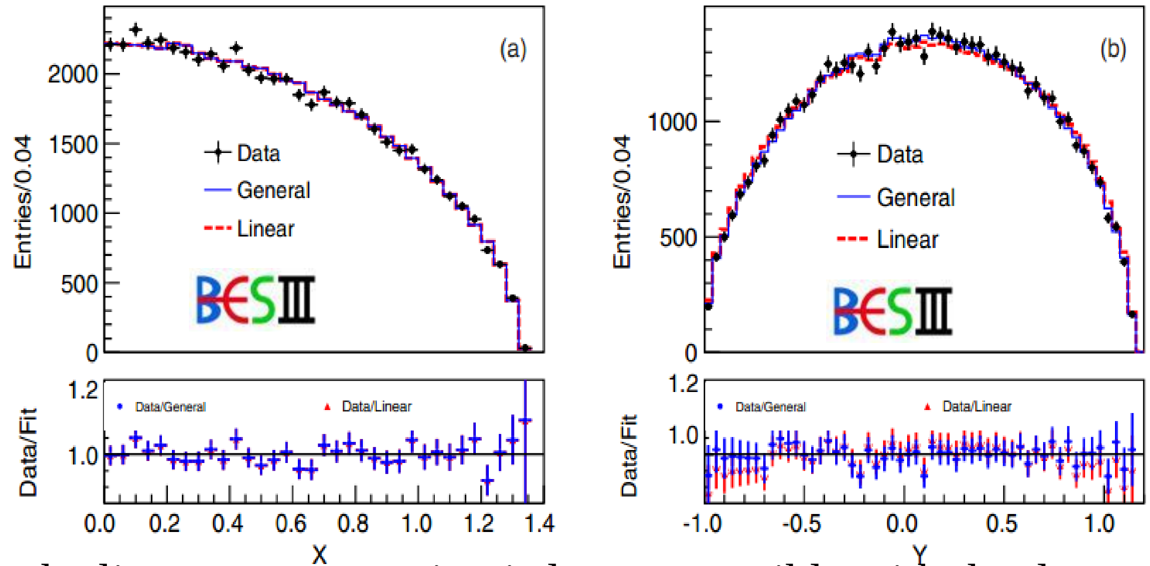
[7] JHEP 05 ,094(2011)

[10] Phys. Lett. B 651, 22 (2007)

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

PRD 97,012003(2018)





the linear representation is less compatible with the data

	$\eta' \to \eta\pi^0\pi^0$		
Parameter	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	···	$-0.054(19)$	$-0.061(9)(5)$

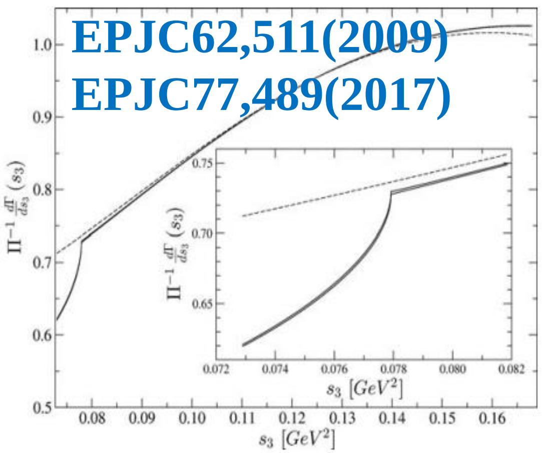
[5]Eur. Phys. J. A 26, 383(2005)
[12] Phys. At. Nucl.72, 231 (2009)

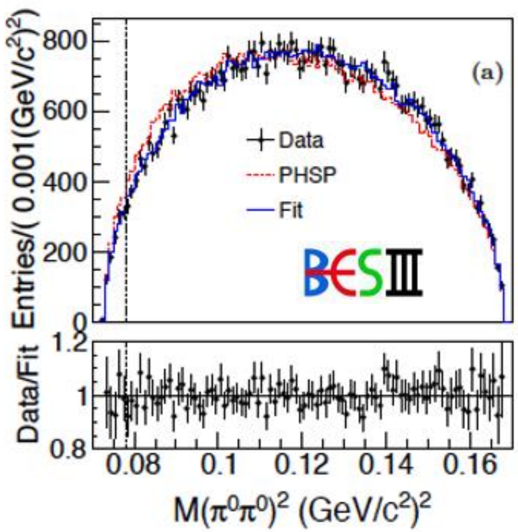
Matrix Elements for $\eta' \to \pi^0\pi^0\eta$

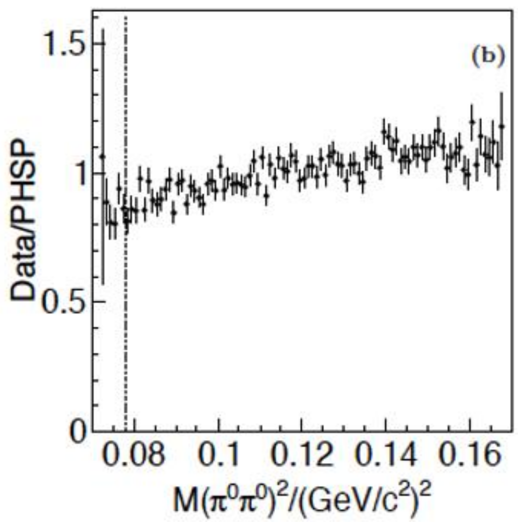
Search for cusp effect

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

EPJC62,511(2009)
EPJC77,489(2017)



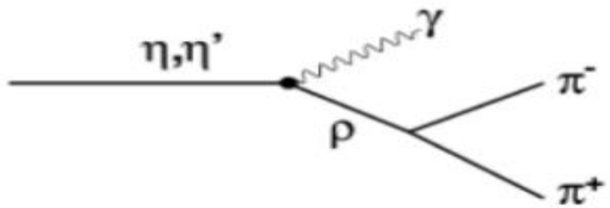


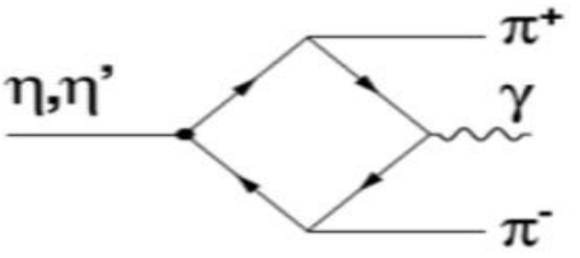


- **No evidence of a cusp effect with current statistics**

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

- In VMD model, this process is dominated by $\eta' \to \gamma\rho(770)$
- Studied by several experiments , a peak shift 20MeV was observed
- 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)]





The dipion mass dependent differential rate :

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

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

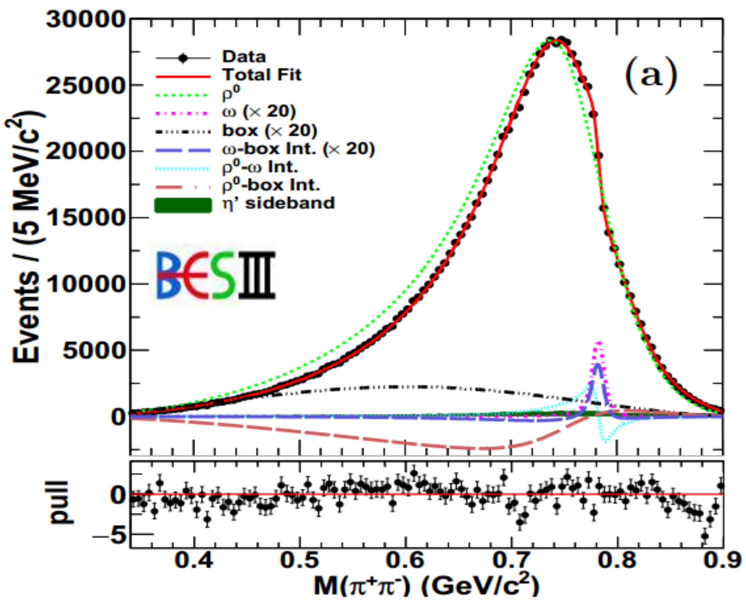
$q_\pi(s) = \sqrt{s - 4m_\pi^2}/2$

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

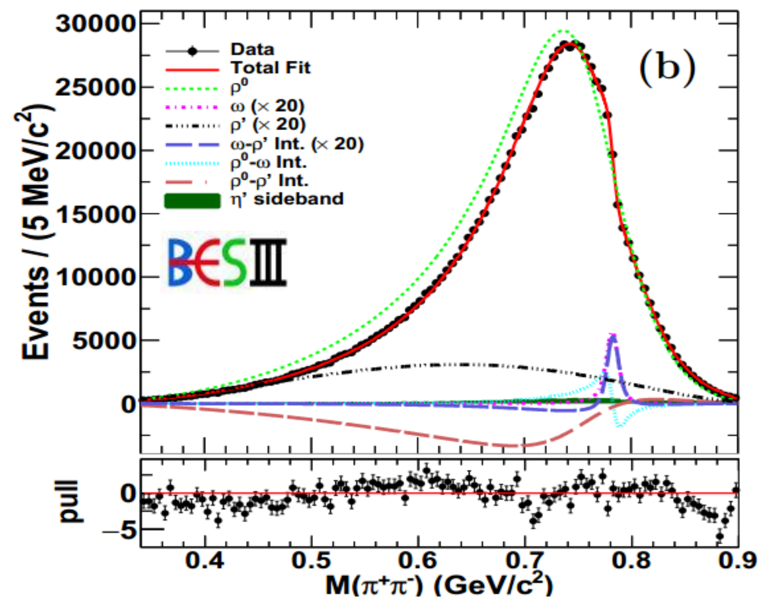
Model dependent fit

arXiv:1712.01525v2

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



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



- Besides the ρ^0, the ω contribution is needed
- Fits with only ρ^0 and only $\rho^0 - \omega$ interference are insufficient
- Extra contribution of box-anomaly or $\rho(1450)$, or both of them is necessary

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

Model independent fit

◆ $A = N \cdot P(s) \cdot F_V(s)$

$P(s) = 1 + k \cdot s + \lambda \cdot s^2 + \xi \cdot BW_\omega$

N is a normalization factor ,$F_V(s)$ is the pion vector form factor, obtained by $e^+e^- \to \pi^+\pi^-$.

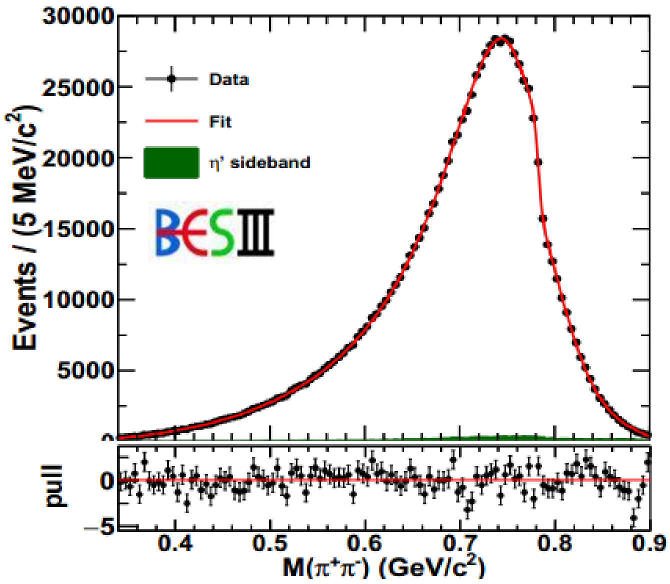
◆ **Fit results:**

$k = (0.992 \pm 0.039 \pm 0.067 \pm 0.16)\mathrm{GeV}^{-2}$

$\lambda = (-0.523 \pm 0.039 \pm 0.066 \pm 0.181)\mathrm{GeV}^{-2}$

$\xi = (0.199 \pm 0.006 \pm 0.011 \pm 0.007)\mathrm{GeV}^{-2}$

arXiv:1712.01525v2

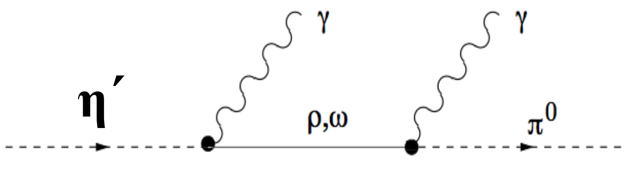


◆ **the ω contribution and quadratic term are significant (34σ and 13σ)**

◆ **A fit without ω contribution is insufficient**

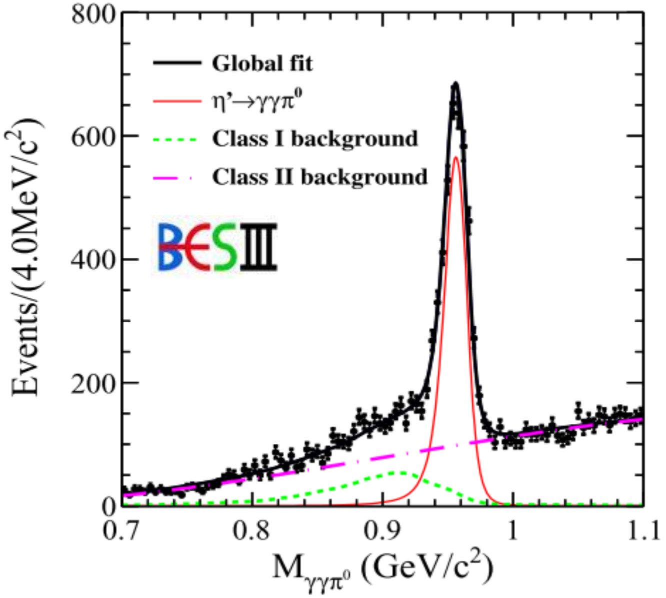
Doubly radiative decay $\eta' \to \gamma\gamma\pi^0$

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



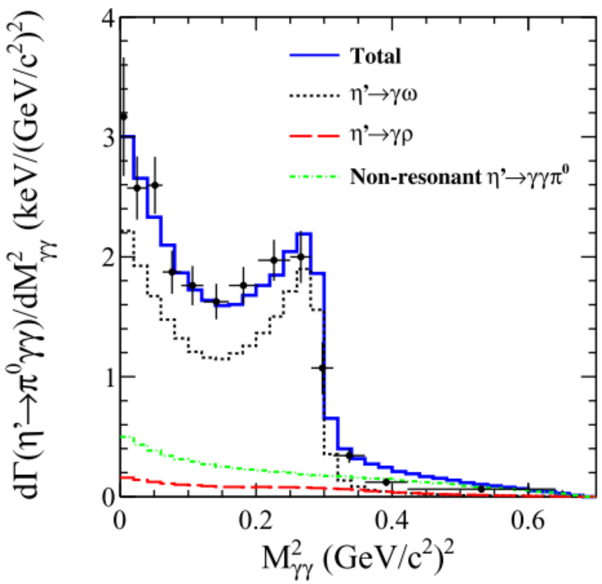
- In experiment, only an upper limit of $B(\eta' \to \gamma\gamma\pi^0) < 8 \times 10^{-4}$ at 90% C.L.

PRD.96.012005(2017)



- The inclusive $\eta' \to \gamma\gamma\pi^0$ includes the vector mesons ρ /ω and the nonresonant contribution

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



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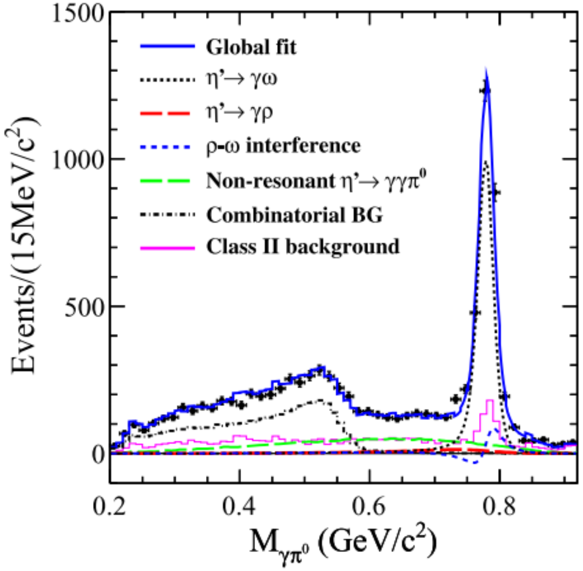


This measurement:

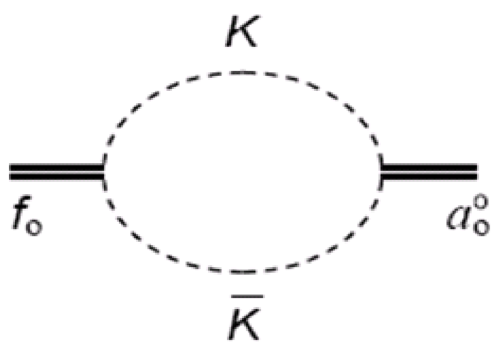
$B(\eta' \to \gamma\gamma\pi^0)_{inc} = (3.20 \pm 0.07 \pm 0.23) \times 10^{-3}$
$B(\eta' \to \gamma\omega) = (23.7 \pm 1.4 \pm 1.8) \times 10^{-4}$
$B(\eta' \to \gamma\gamma\pi^0)_{NR} = (6.16 \pm 0.64 \pm 0.67) \times 10^{-4}$

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

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

$a_0^0(980)$-$f_0(980)$ 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	$\pi\pi, KK$



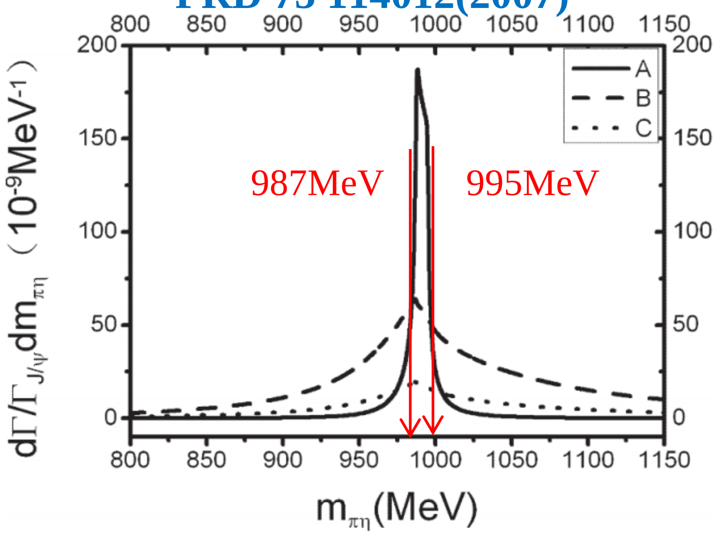
- **In theory, $a_0^0(980)$ and $f_0(980)$ are explained as $q\bar{q}$ mesons, tetraquarks, $K\bar{K}$ molecules, $q\bar{q}g$ hybrids**

- **In 1970s, the mixing mechanism was firstly proposed [PLB 88, 367 (1979)]**

$$m(K^+K^-) \approx 987\text{MeV} \quad m(K^0\overline{K^0}) \approx 995\text{MeV}$$
$$m(K^0\overline{K^0}) - m(K^+K^-) \approx 8\text{MeV}$$

- **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 $J/\psi \to \phi f_0(980) \to \phi a_0^0(980) \to \phi\eta\pi^0$ and $\chi_{c1} \to \pi^0 a_0^0(980) \to \pi^0 f_0(980) \to \pi^0\pi^+\pi^-$ [Wu, Zhao, Zou, PRD 75 114012(2007), PRD 78 074017(2008)]**

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

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

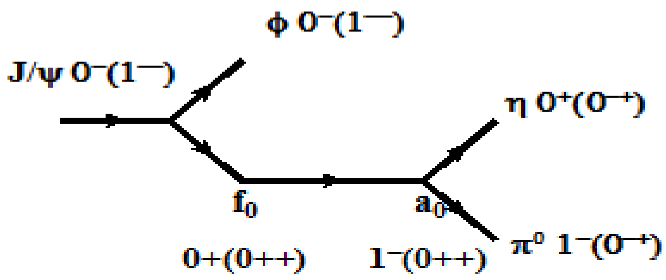
- **Mixing intensity is sensitive to couplings of $g_{a_0K^+K^-}$ and $g_{f_0K^+K^-}$**
- **Measured at BESIII based on 225M J/ψ and 108M ψ' [PRD83.032003(2011)]**

  significance <5σ

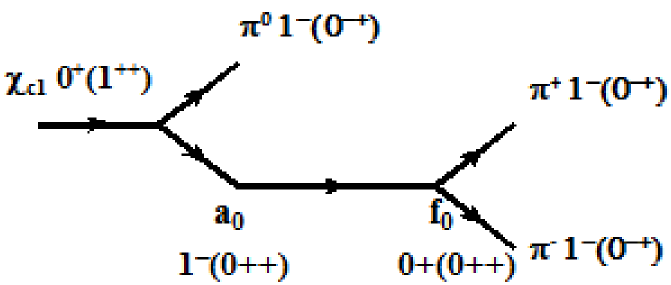
  $\xi_{af} < 1.0\%@90\%\text{C. L.}$

  $\xi_{fa} < 1.1\%@90\%\text{C. L.}$

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



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

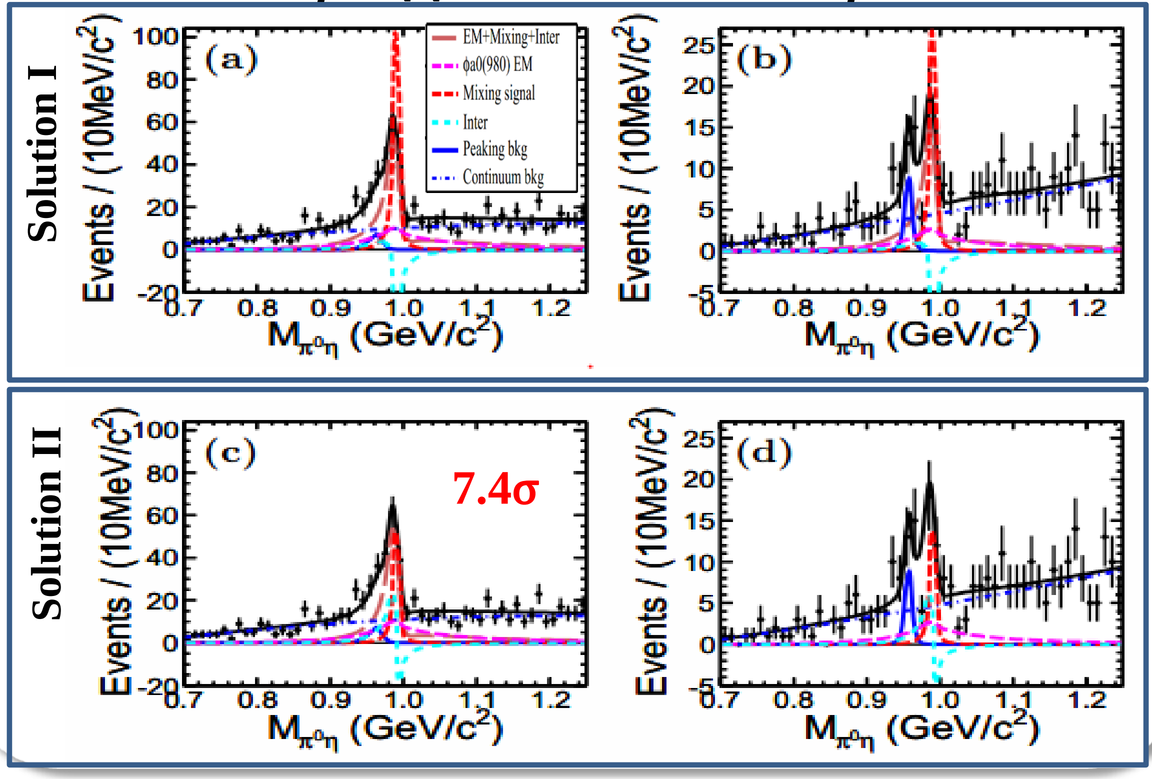


$f_0(980) \to a_0^0(980)$ mixing

arXiv:1802.00583v3

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

$\eta \to \gamma\gamma$ $\eta \to 3\pi$

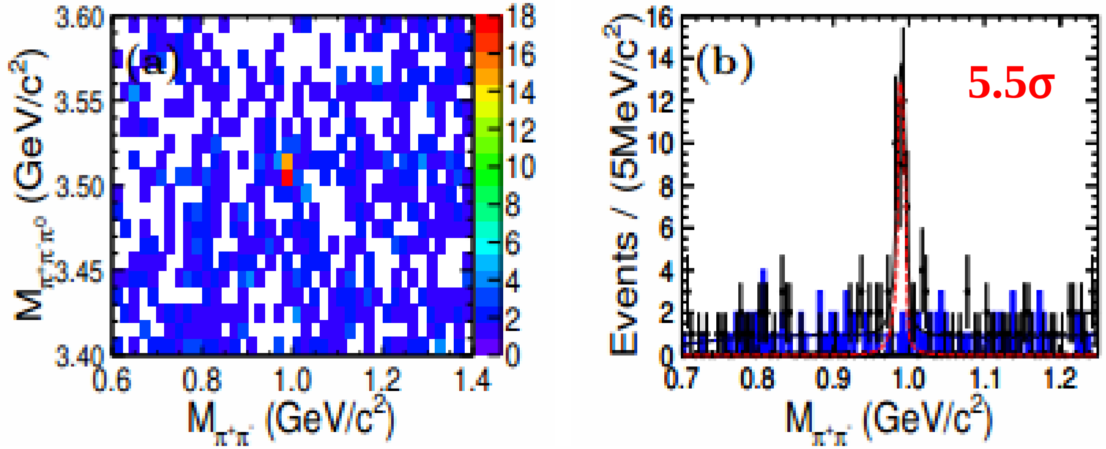


Channel	$f_0(980) \to a_0^0(980)$ Solution I	Solution II
$\mathcal{B}$(mixing) (10^{-6})	$3.18 \pm 0.51 \pm 0.38 \pm 0.28$	$1.31 \pm 0.41 \pm 0.39 \pm 0.43$
$\mathcal{B}$(EM) (10^{-6})	$3.25 \pm 1.08 \pm 1.08 \pm 1.12$	$2.62 \pm 1.02 \pm 1.13 \pm 0.48$
$\mathcal{B}$(total) (10^{-6})	$4.93 \pm 1.01 \pm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

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

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

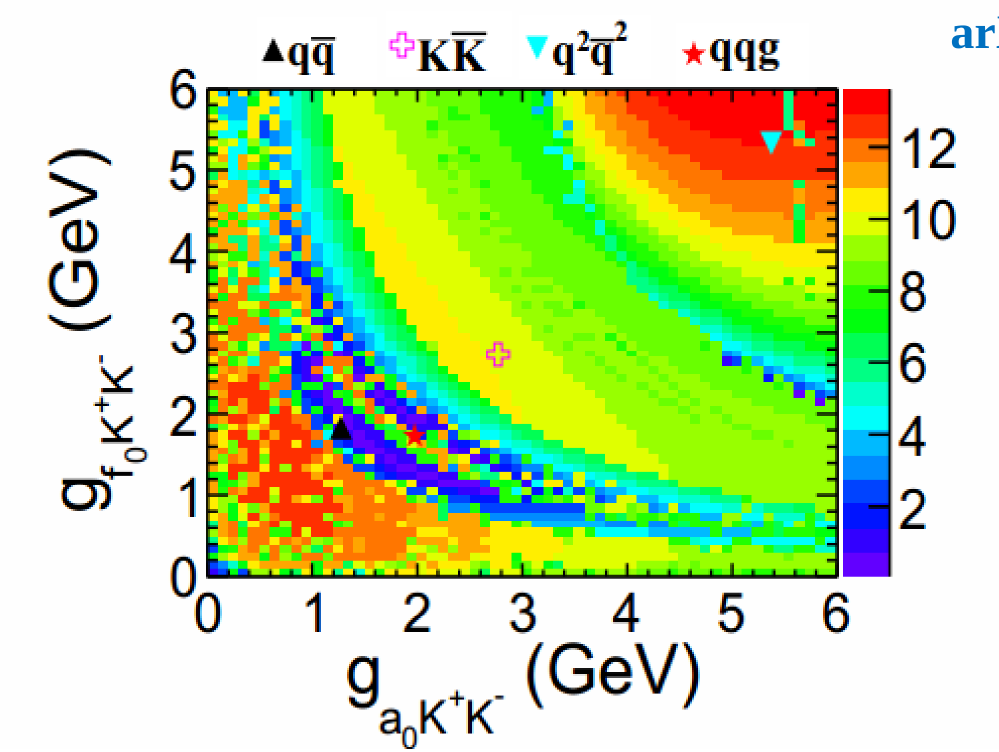
arXiv:1802.00583v3



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

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

arXiv:1802.00583v3



- Z-axis represents the statistical significance of the mixing signal
- The regions with higher significance indicate the larger probability
- difficult to directly discriminate different theoretical models due to large uncertainties of these models

Summary(I)

- **Four η' meson decays and $a_0^0(980)$-$f_0(980)$ mixing are reviewed**
  - **Amplitude analysis of $\eta' \to \pi^{+(0)}\pi^{-(0)}\pi^0$**

    Significant p-wave $\eta' \to \rho^{\pm}\pi^{\mp}$ is observed for the first time

  - **Dalitz plot analysis of $\eta' \to \pi^{+(0)}\pi^{-(0)}\eta$**

    The linear representation does not describe the data well

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

    Both model-dependent and -independent approaches, contributions of ω and the ρ(770)−ω interference are observed for the first time

  - **First observation of $\eta' \to \gamma\gamma\pi^0$**

    Branching fraction of the inclusive $\eta' \to \gamma\gamma\pi^0$ and $M_{\gamma\gamma}^2$ dependent partial widths are measured for the first time

Summary(II)

- **First observation of $a_0^0(980)$-$f_0(980)$ mixing**

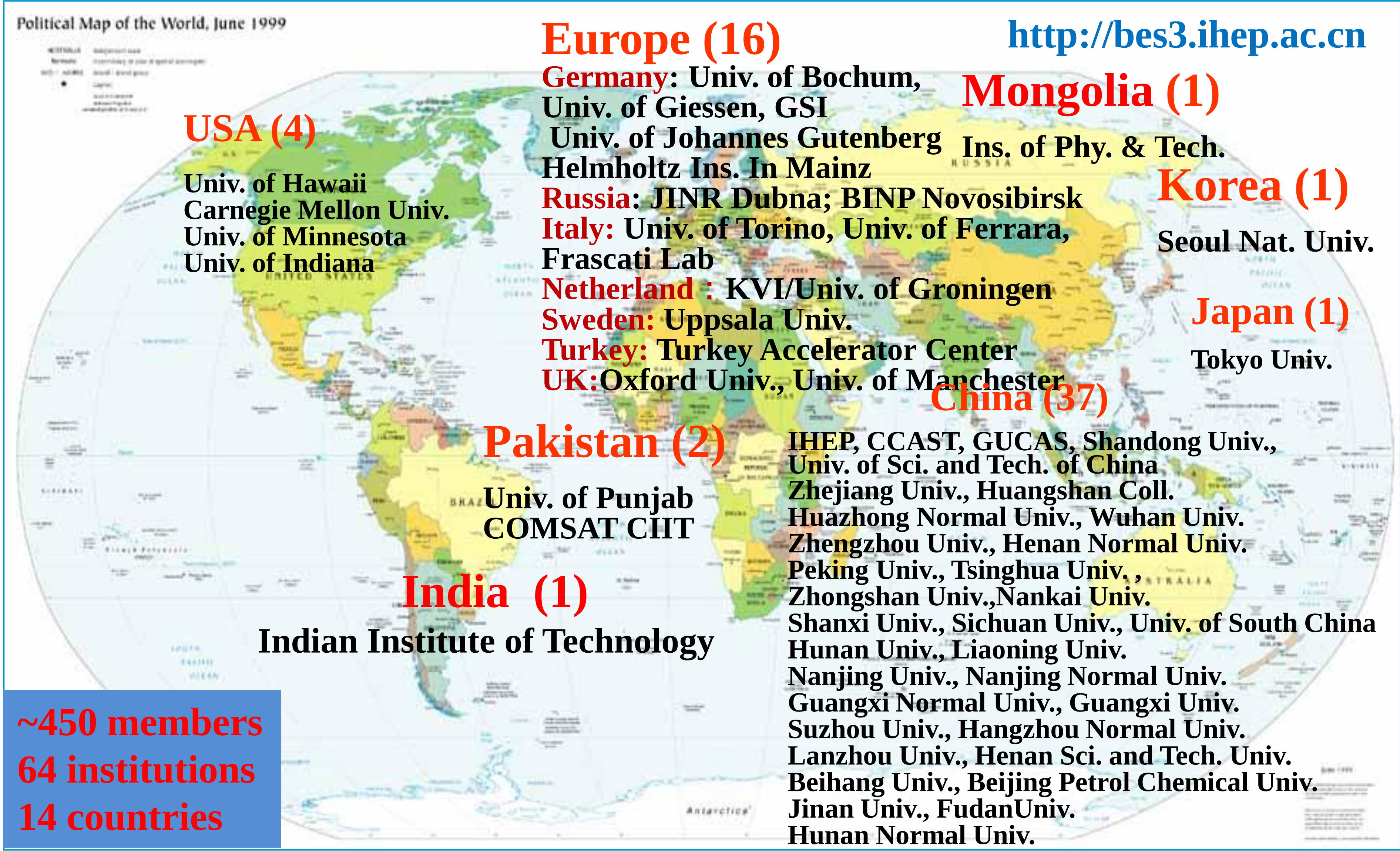
The mixing signal with 7.4σ and 5.5σ for the first time, the constraint regions on $g_{a_0K^+K^-}$ and $g_{f_0K^+K^-}$ are roughly obtained by the significance test

- **J/ψ(ψ') decay is a unique place to study light mesons**
- **BESIII: 1.3 billion + 3.7 billion J/ψ events**
  - **A sample of 3.7 billion J/ψ events will be taken in ~2018**
  - **So large data sample allows us to study light mesons with the unprecedented statistics**
  - **More interesting results are expected**

Thank you for your attention!

Backup

BESIII Collaboration



http://bes3.ihep.ac.cn

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BESIII publications on η/η' decays

- $\eta' \to \pi^+\pi^-\eta$ PRD83, 012003(2011)
- $\eta/\eta' \to \pi^+\pi^-, \pi^0\pi^0$ PRD83, 032006(2011)
- $\eta' \to \pi^+\pi^-\pi^0, \pi^0\pi^0\pi^0$ PRL108, 182001(2012)
- $\eta/\eta' \to$ invisible PRD87,012009(2013)
- $\eta/\eta' \to \pi^+ e\nu$ PRD87,032006(2013)
- $\eta' \to 3(\pi^+\pi^-)$ PRD88,091502(2013)
- $\eta' \to 2(\pi^+\pi^-), \pi^+\pi^-\pi^0\pi^0$ PRL112,251801(2014)
- $\eta' \to \gamma e^+e^-$ PRD92,012001(2015)
- $\eta \to \pi^+\pi^-\pi^0, \eta/\eta' \to \pi^0\pi^0\pi^0$ PRD92,012014(2015)
- $\eta' \to \omega e^+e^-$ PRD92,051101(2015)
- $\eta' \to K\pi$ PRD93, 072008 (2016)
- $\eta' \to \rho\pi$ PRL118,012001(2017)
- PRD96,012005(2017)
- $\eta' \to \gamma\pi^+\pi^-$ arXiv:1712.01525, accepted by PRL
- $\eta' \to \pi^+\pi^-\eta, \eta' \to \pi^0\pi^0\eta$ PRD97, 012003 (2018)

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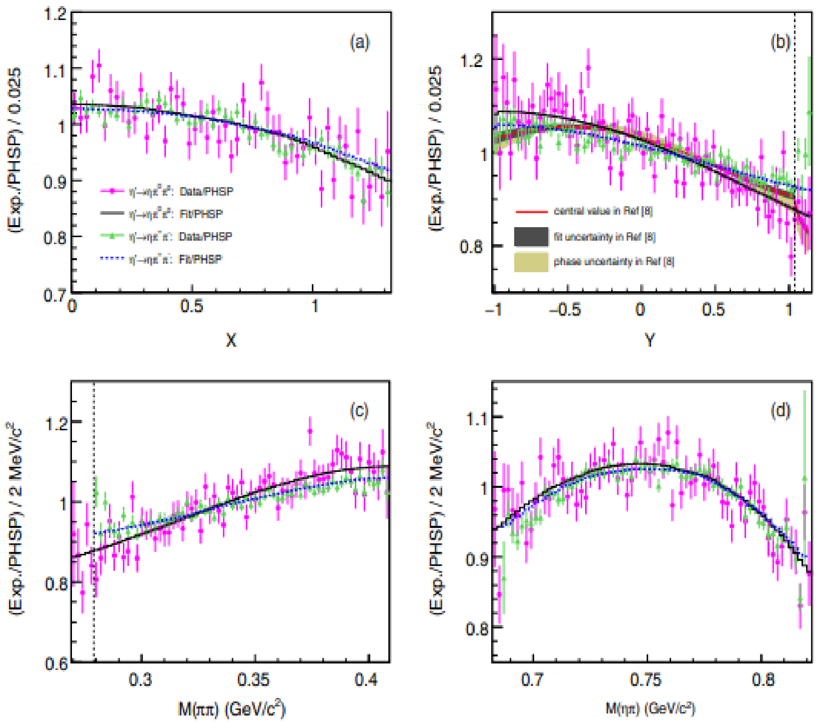

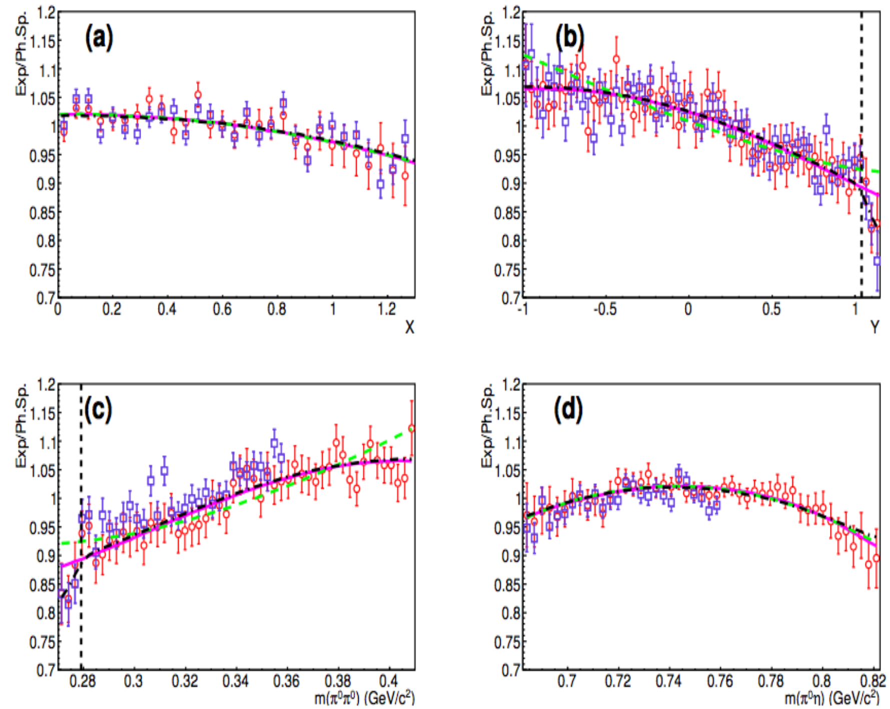

PRD 97, 012003 (2018)

hep-ex/1709.0423