Light Meson Decays at BESIII

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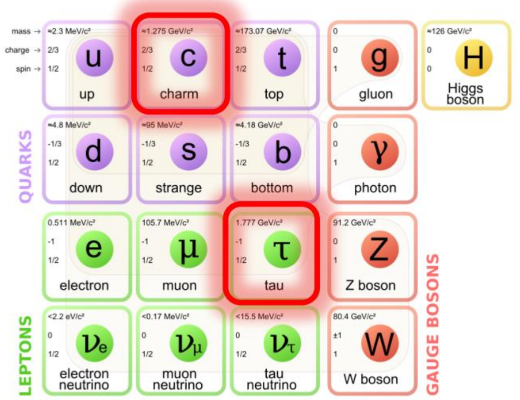
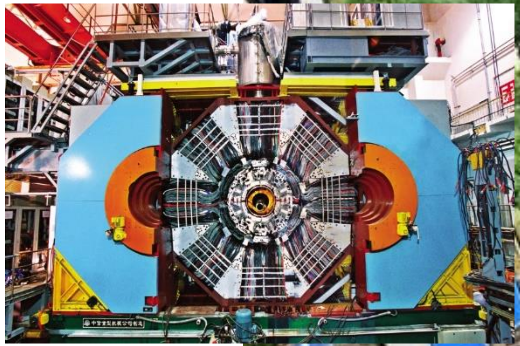
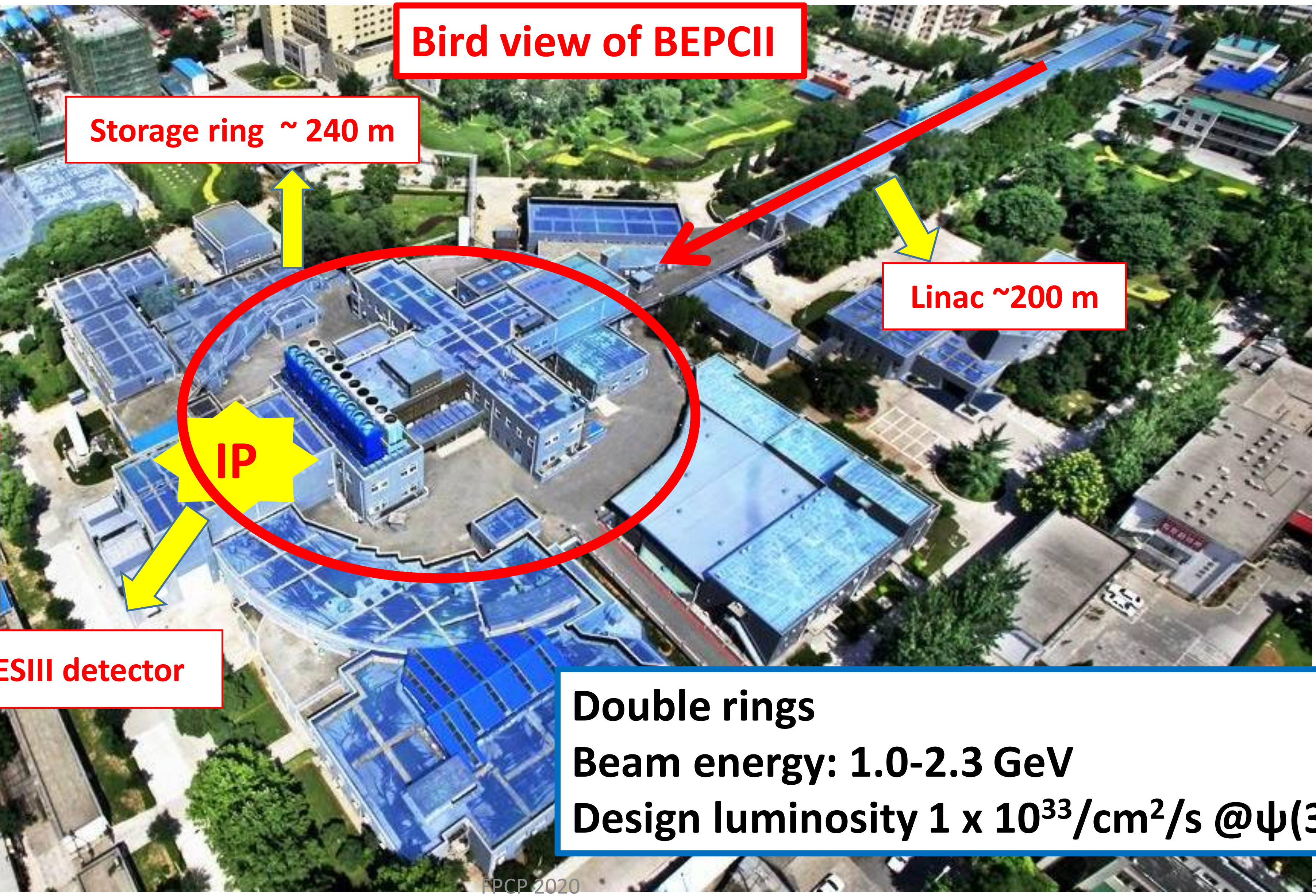
Outline

- Introduction
- η' Meson Decays
  - ✓ Hadronic decays: $\eta' \to \pi^{+(0)}\pi^{-(0)}\eta$, $\eta' \to \pi^{+(0)}\pi^{-(0)}\pi^0$, $\eta' \to \pi^0\pi^0\pi^0\pi^0$
  - ✓ Radiative decays: $\eta' \to \gamma\pi^+\pi^-$, $\eta' \to \gamma\gamma\eta$
  - ✓ η' branching fractions
- $a_0^0(980) - f_0(980)$ Mixing
- Summary

Beijing Electron Positron Collider II (BEPCII)

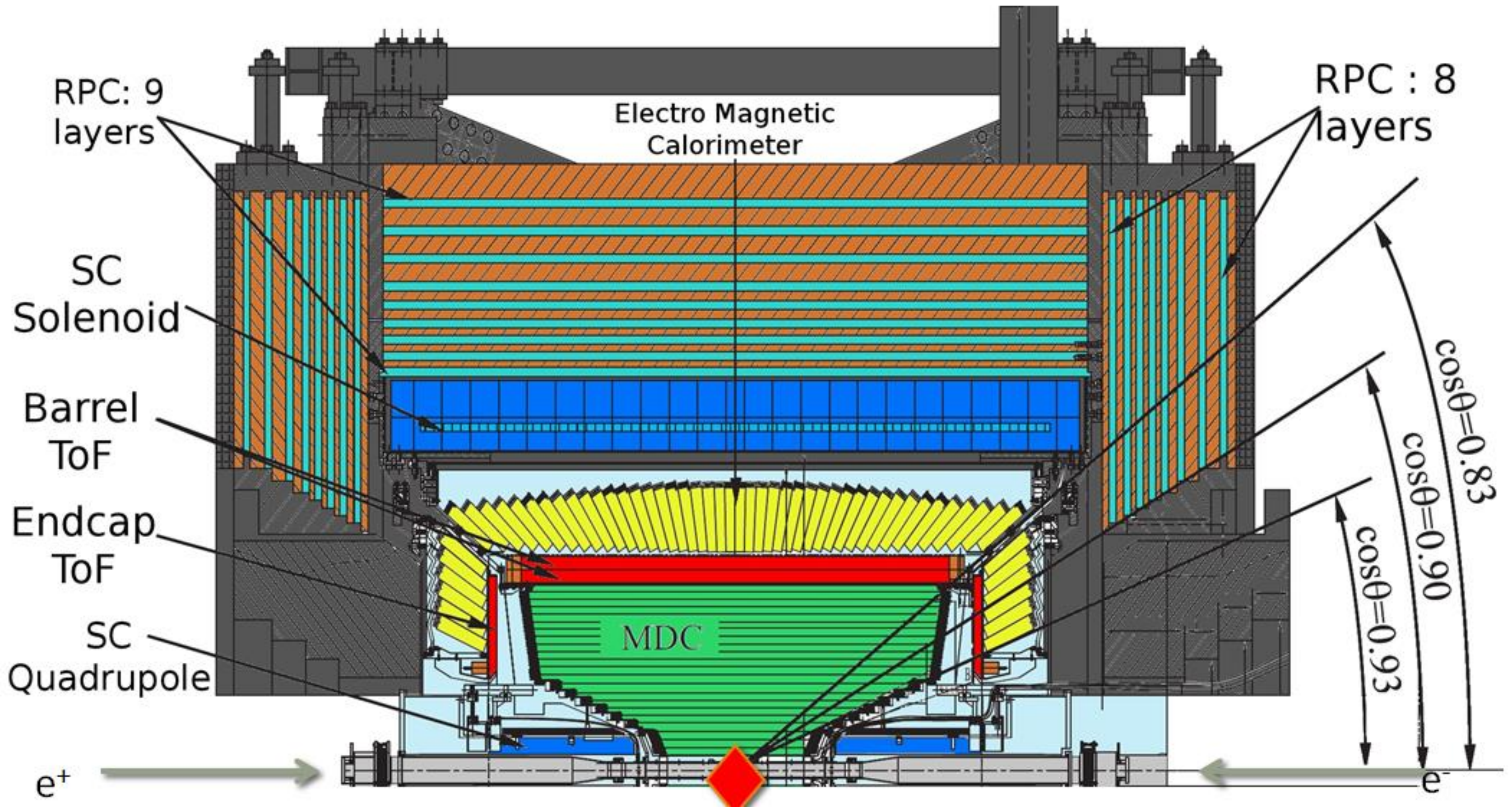






Double rings
Beam energy: 1.0-2.3 GeV
Design luminosity 1 x 10^{33}/cm^2/s @ψ(3770)

BESIII detector



Main Drift Chamber
σ_P/P = 0.5% @ 1 GeV
$\sigma_{dE/dx}$ = 6%

Time of Flight
σ_T = 70 ps (barrel two layers)
110(60) ps (endcap)

Super Conducting Solenoid
1.0 T (2009)
0.9 T (2012)

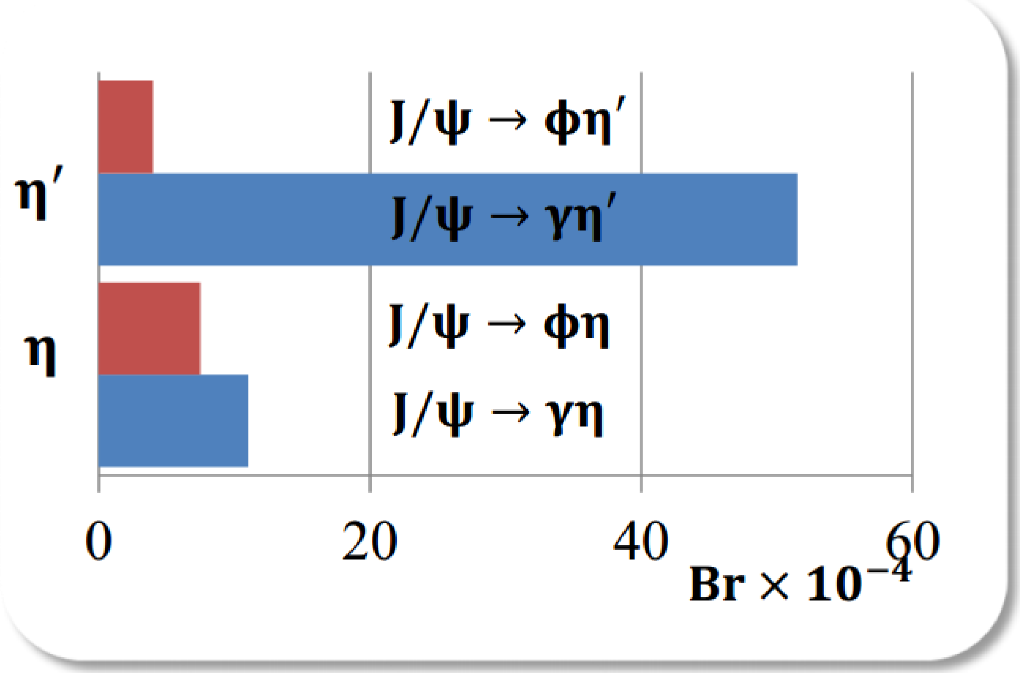
Electromagnetic Calorimeter
$\sigma_E/\sqrt{E}$ = 2.5% @ 1 GeV

η/η' : a rich physics field

- test the predictions of CHPT
- study transition form factor
- 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



- High production rate of light mesons in J/ψ decays
- η/η' from J/ψ radiative decays
  - ✓ $7.2 \times 10^6\ \eta'$
  - ✓ $2.4 \times 10^6\ \eta$
- η/η' from J/ψ hadronic decays (e.g. $J/\psi \to \phi\eta$)
  - ✓ $5 \times 10^5\ \eta'$
  - ✓ $3 \times 10^5\ \eta$
- 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

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

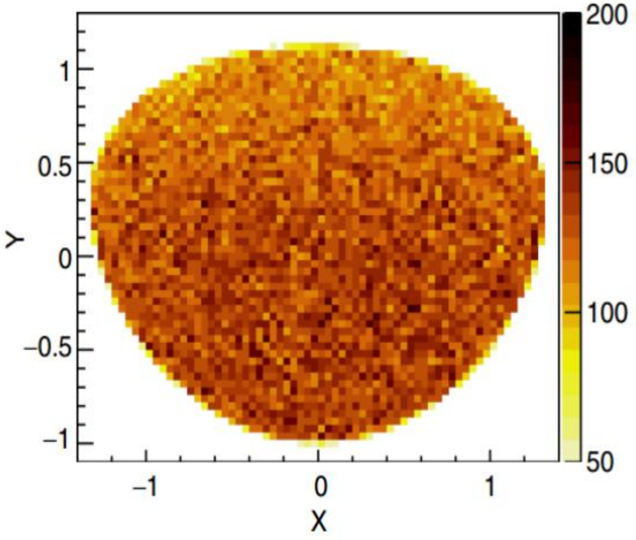
- linear representation

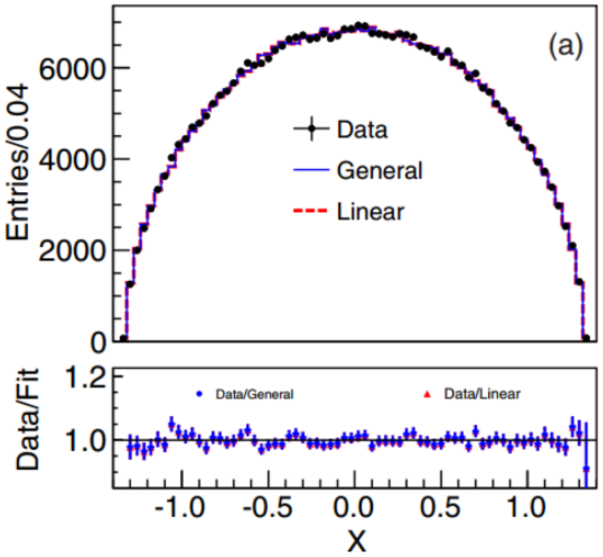
$$|M(X,Y)|^2 = N\left(|1 + \alpha Y|^2 + cX + dX^2 + \cdots\right)$$

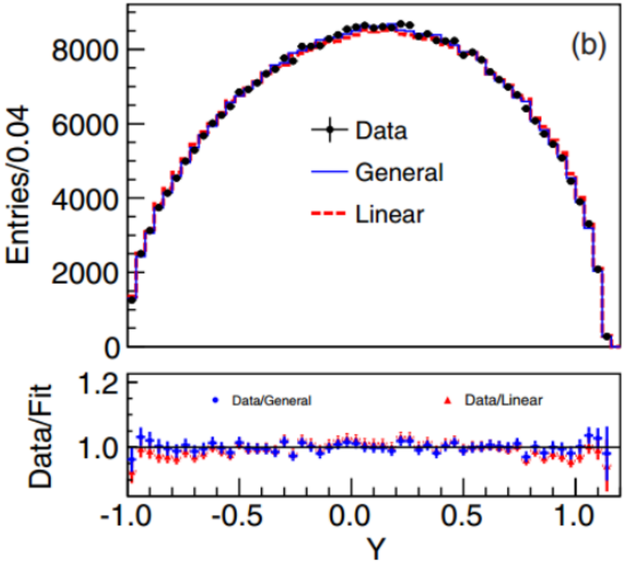
Here, a,b,c,d are free parameters, α is a complex number, a = 2Re(α), b = Re(α)²+ Im(α)².

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

PRD 97, 012003 (2018)





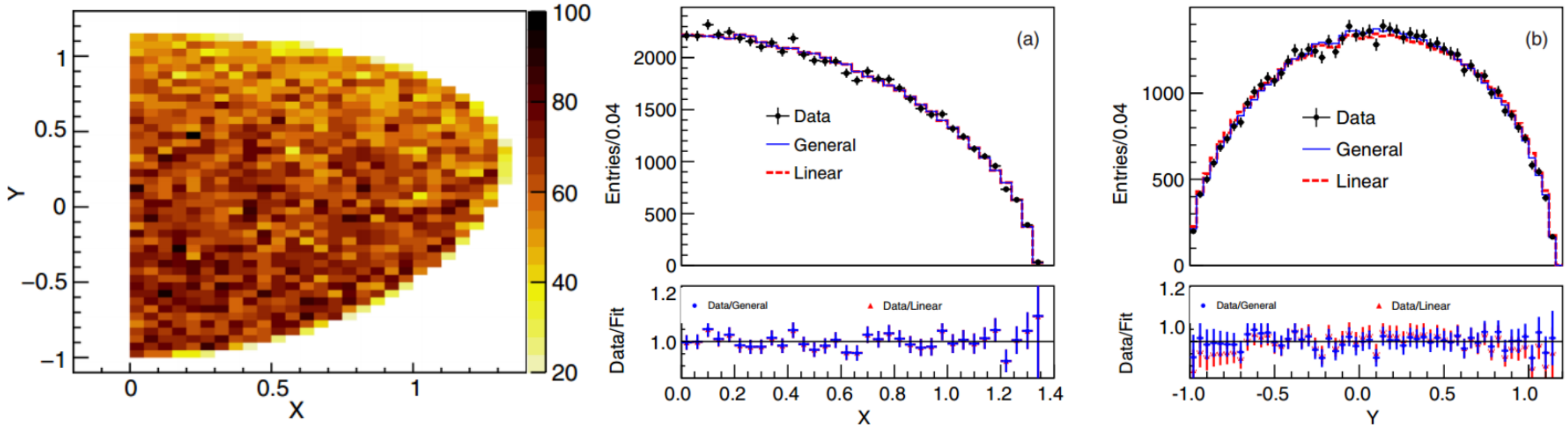


- The linear representation is less compatible with the data.

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



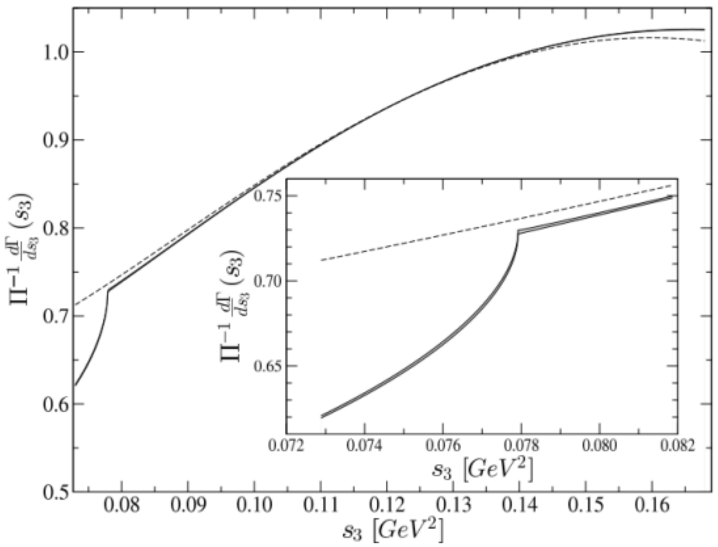
- The linear representation is less compatible with the data.

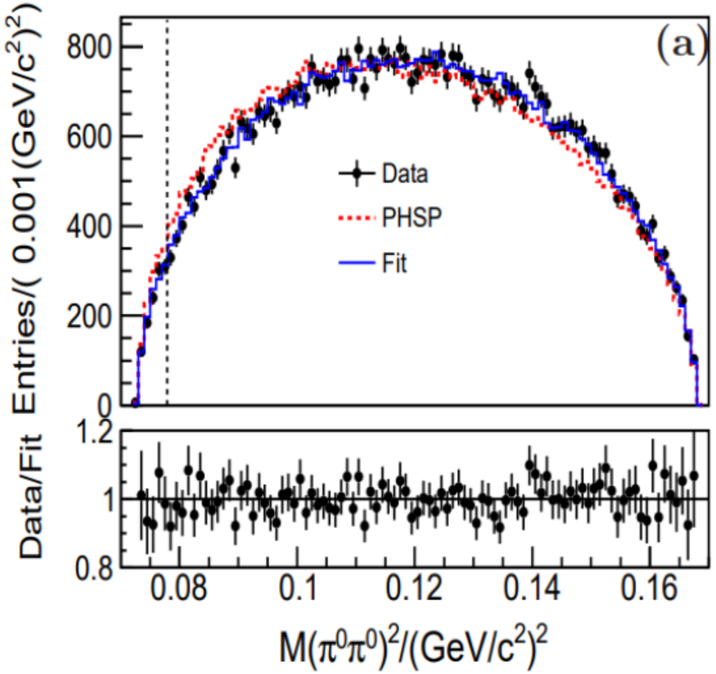
	$\eta' \to \eta\pi^0\pi^0$		
Parameter	EFT [5]	GAMS-4π [12]	This work
a	$-0.127(9)$	$-0.067(16)$	$-0.087(9)(6)$
b	$-0.049(36)$	$-0.064(29)$	$-0.073(14)(5)$
c	...	...	...
d	$+0.011(21)$	$-0.067(20)$	$-0.074(9)(4)$
$\Re(\alpha)$	...	$-0.042(8)$	$-0.054(4)(1)$
$\Im(\alpha)$	...	$0.000(70)$	$0.000(38)(2)$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

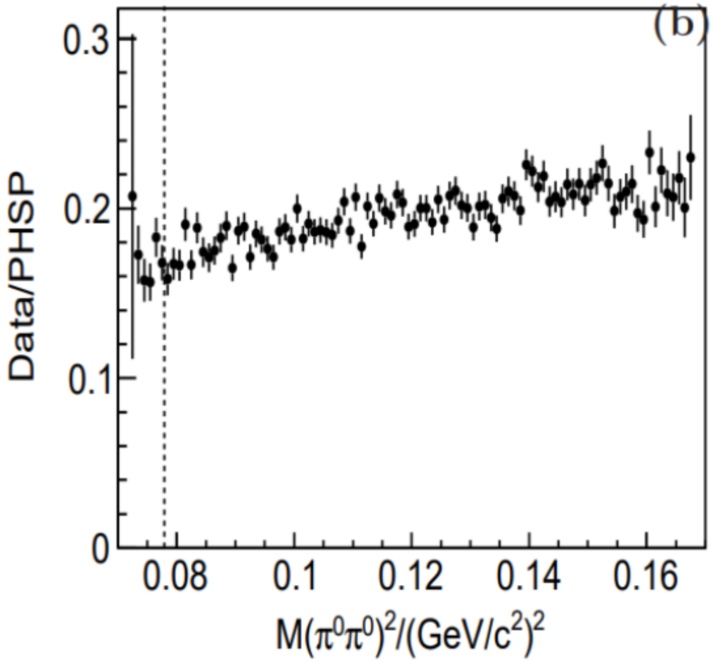
Dalitz plot analysis of $\eta' \to \eta\pi^0\pi^0$

- **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.

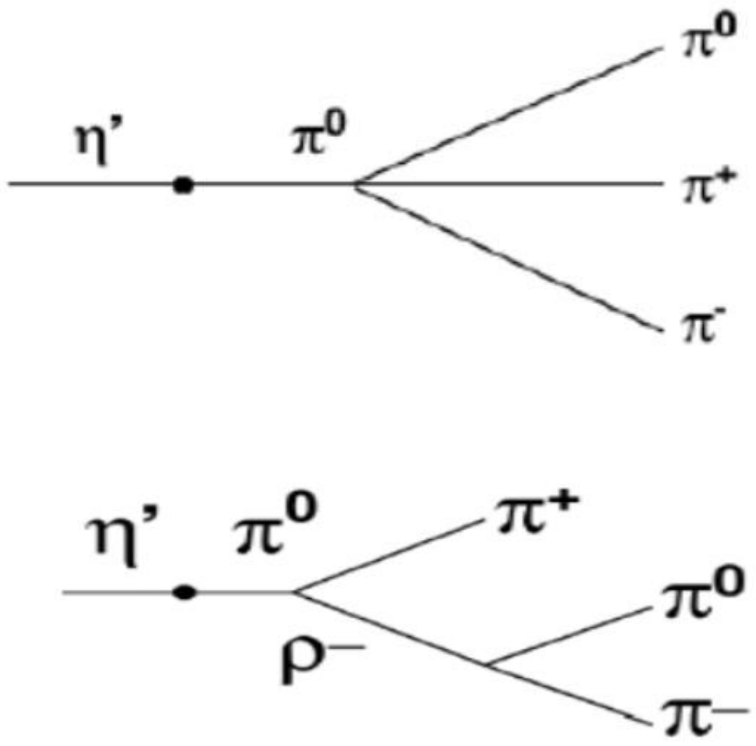
Amplitude analysis of $\eta' \to \pi^{+(0)}\pi^{-(0)}\pi^0$

- $\eta' \to \pi\pi\pi$ are isospin-violating process, 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)]

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

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

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



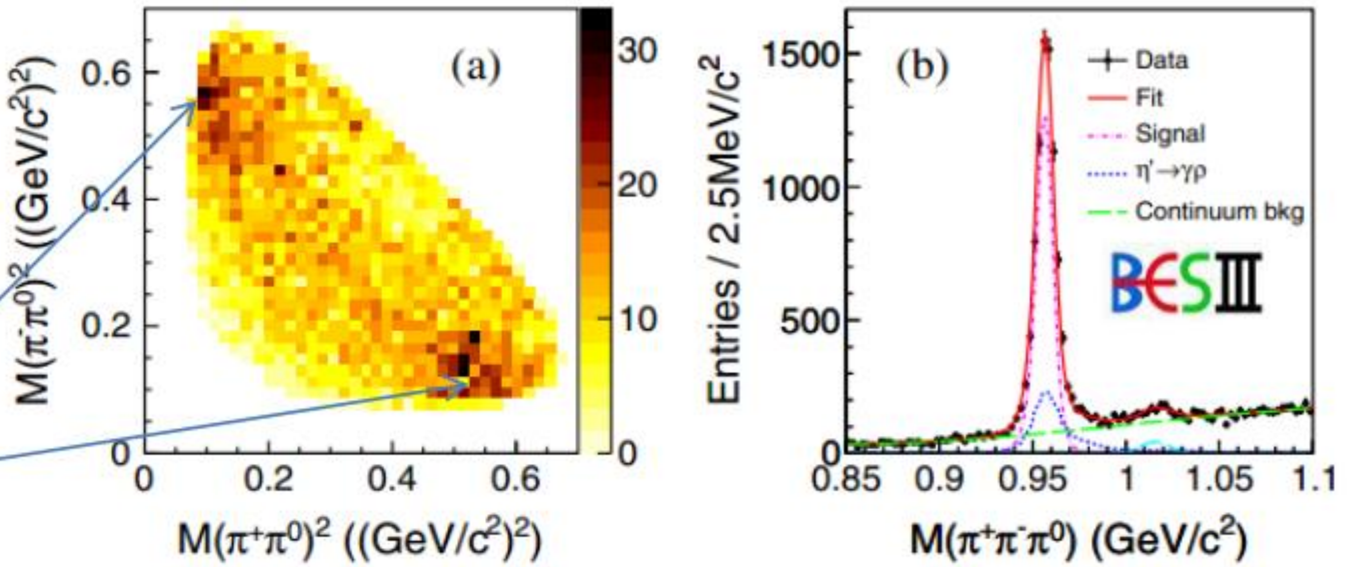
Amplitude analysis of $\eta' \to \pi^{+(0)}\pi^{-(0)}\pi^0$

PRL 118, 012001 (2017)

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

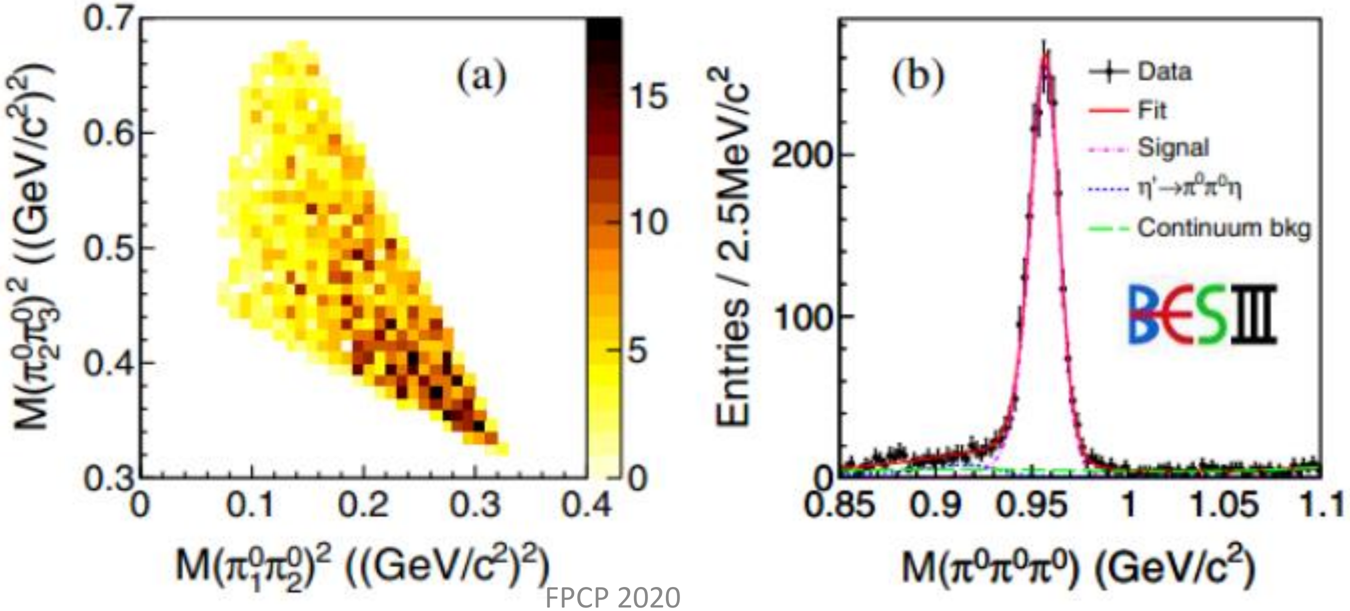
8267 events

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



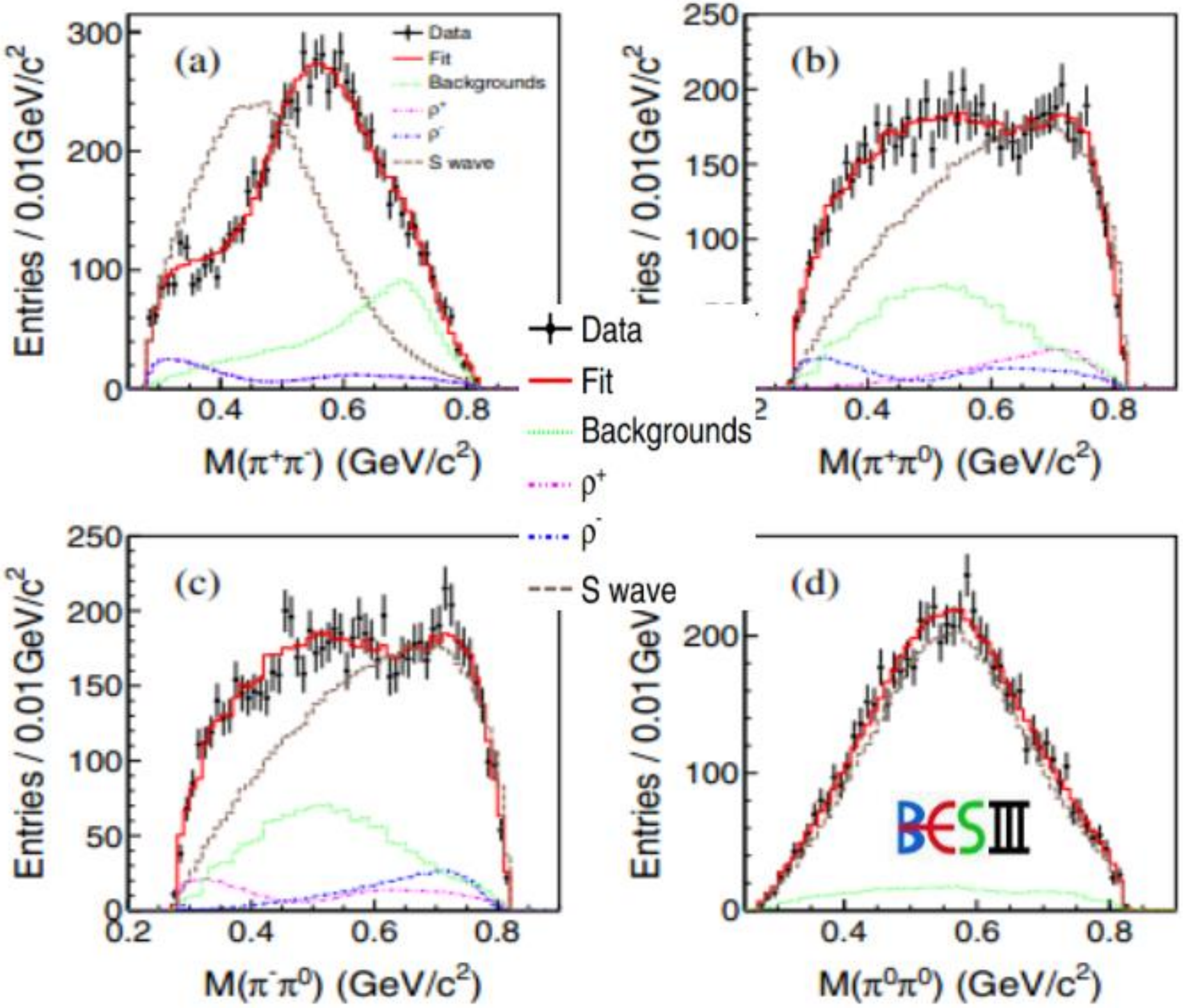
$\eta' \to \pi^0\pi^0\pi^0$

2237 events



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

PRL 118, 012001 (2017)



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

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

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

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

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

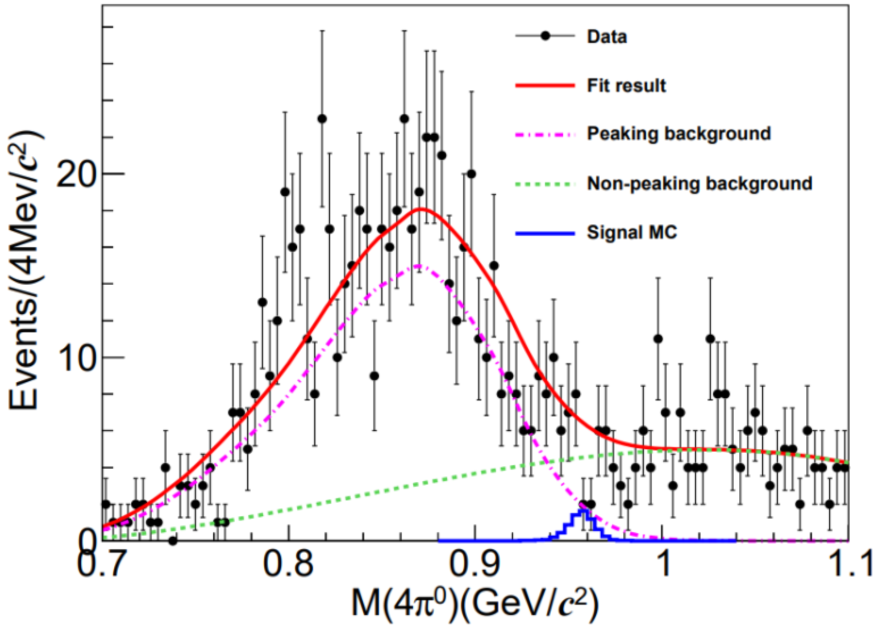
- Obtained decay width ratios:

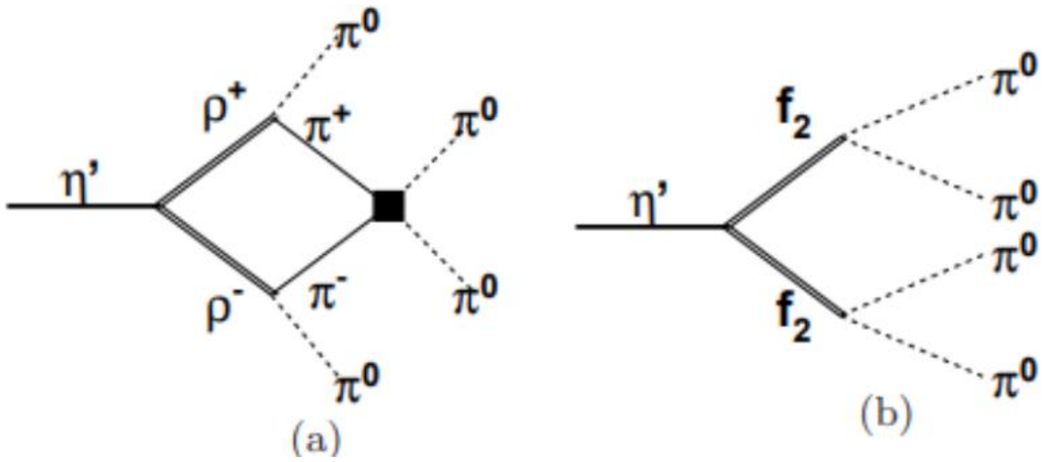
$$r_{\pm} = (8.77 \pm 1.19) \times 10^{-3}$$
$$r_0 = (15.86 \pm 1.33) \times 10^{-3}$$

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

PRD 101, 032001 (2020)

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





No evidence for the rare decay.

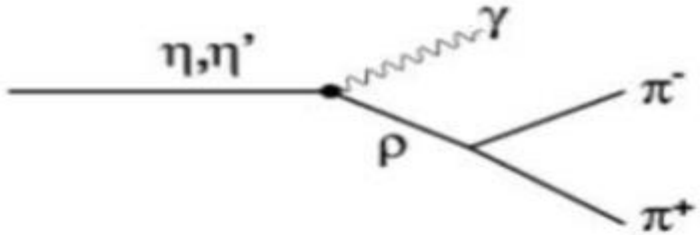
Upper limit:

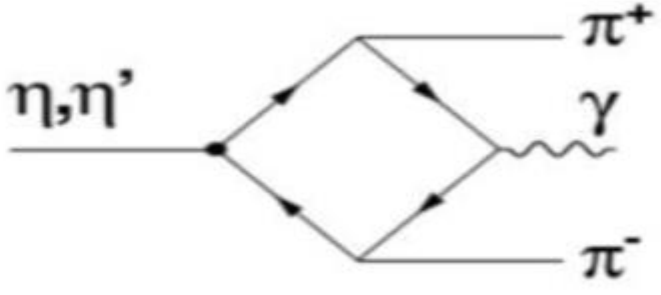
$B(\eta' \to 4\pi^0) < 4.94 \times 10^{-5}$ at the 90% C.L.

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

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 [PLB 37, 95 (1971), NPB223, 422 (1983)]**
- **Recently a model-independent approach based on ChPT are 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 :

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

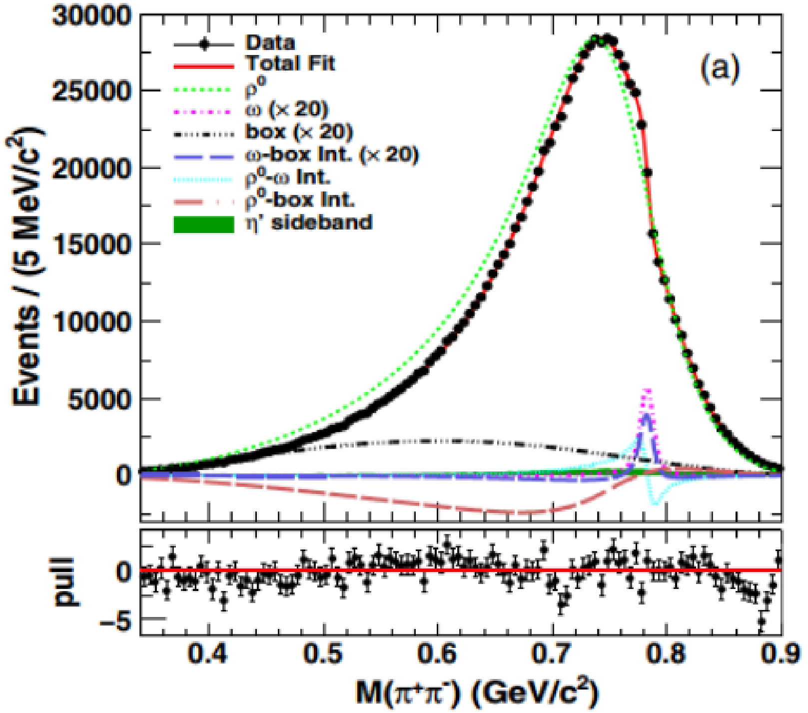
$$k_\gamma = (m_{\eta'}^2 - s)/(2m_{\eta'}),\ q_\pi(s) = \sqrt{s-4m_\pi^2}/2$$

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

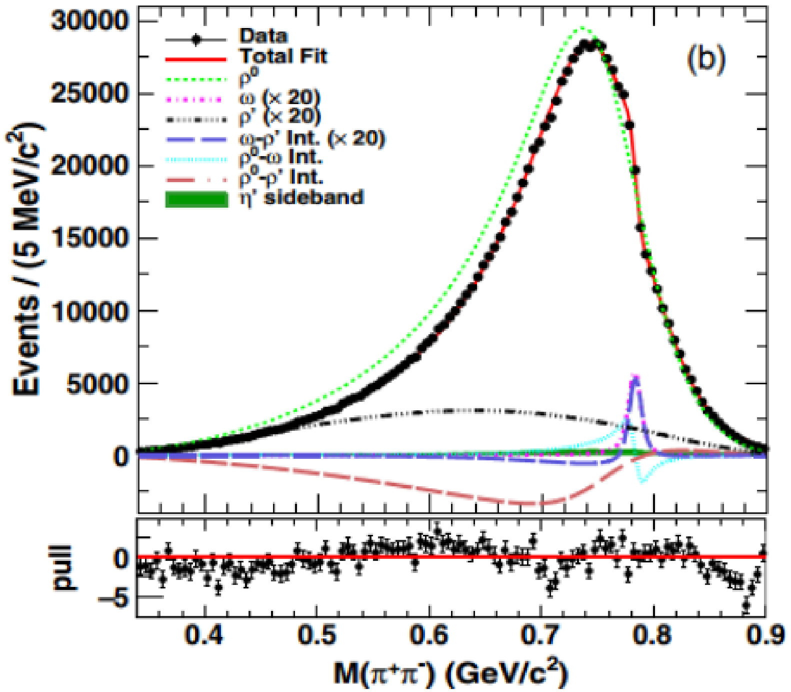
PRL 120, 242003 (2018)

Model dependent fit

Fit with ρ(770)–ω–box anomaly



Fit with ρ(770)–ω– ρ(1450)



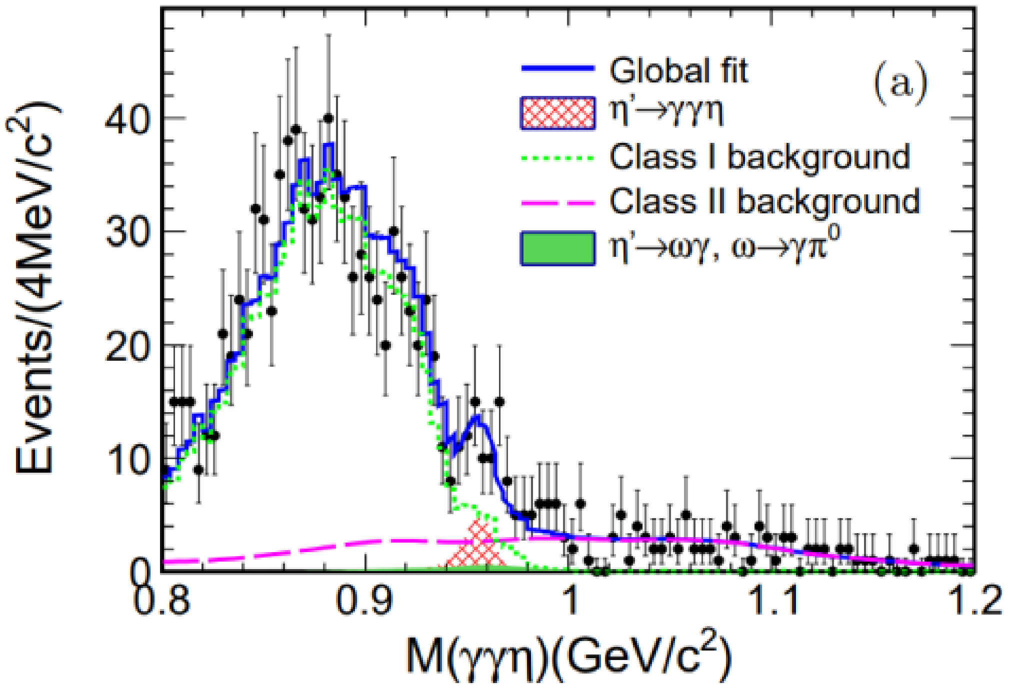
- Besides the ρ(770), the ω contribution is needed.
- ρ(770) - ω cannot describe data well.
- Extra contribution of box-anomaly or ρ(1450), or both of them is necessary.

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

PRD 100, 052015 (2019)

- 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}.
- GAMS-4π reported the upper limit of the BF $< 8.0 \times 10^{-4}$ 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.

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 $J/\psi \to \gamma\eta'$ because of the poor energy resolution of radiative photon

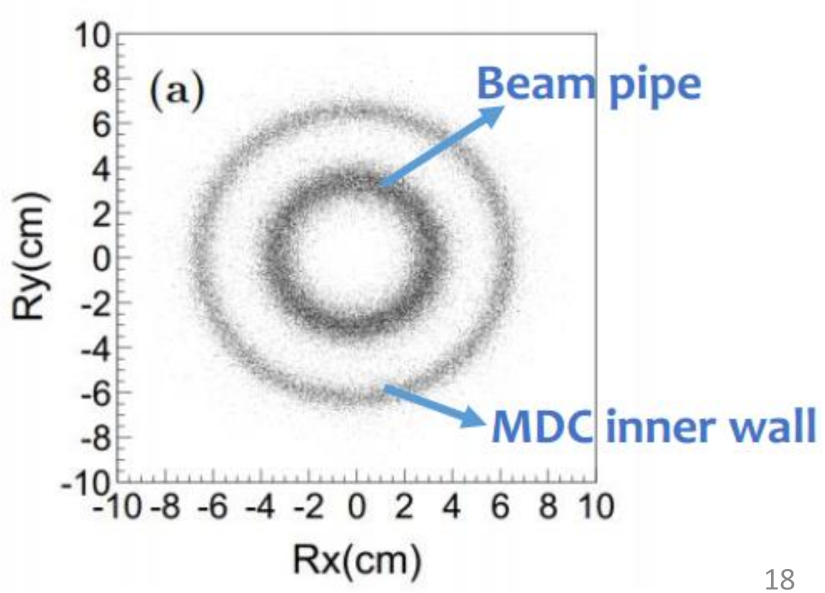
- Developed a method to reconstruct radiative photon using photon conversions to e^+e^- pairs.
- Resolution of the radiative photon could be improved by a factor of 3.

- BF for each η′ exclusive decay is obtained with

Using photon conversions

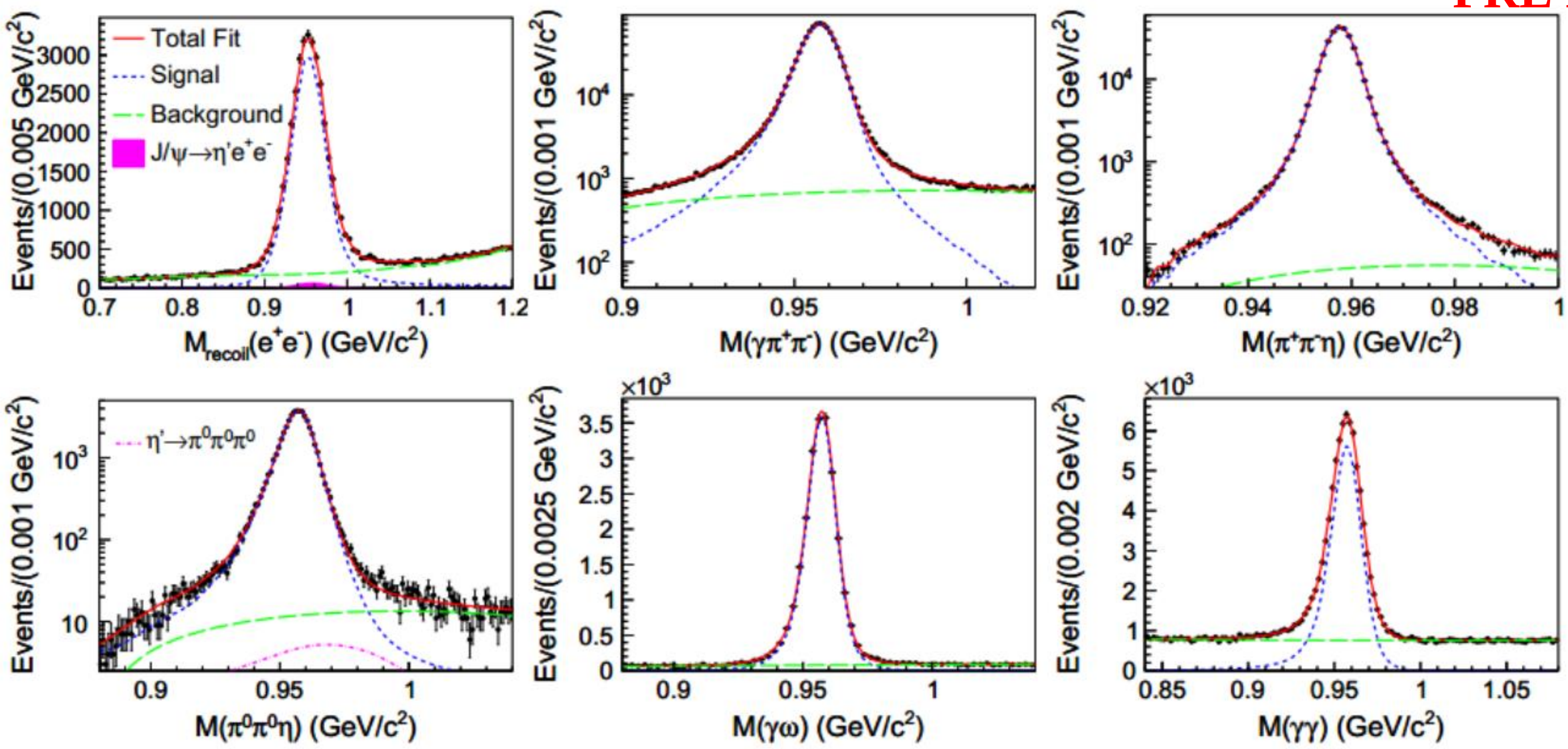
$$\mathcal{B}(\eta' \to X) = \boxed{\frac{N^{\mathrm{obs}}_{\eta'\to X}}{\varepsilon_{\eta'\to X}}} \cdot \boxed{\frac{\varepsilon}{N^{\mathrm{obs}}_{J/\psi\to\gamma\eta'}}} \cdot f,$$

γ directly detected by EMC



Measurement of the BFs of η' decays

PRL 122, 142002 (2019)



Decay Mode	$N^{\rm obs}_{\eta'\to X}$	$\varepsilon_{\eta'\to X}(\%)$	$\mathcal{B}(\eta'\to X)(\%)$	
			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 measure of absolute BFs for five η' modes.

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

- $a_0^0(980) - f_0(980)$ still controversial 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:

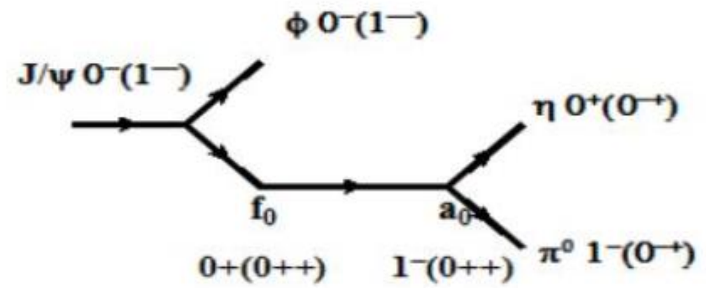
$$J/\psi \to \phi a_0^0(980) \to \phi\eta\pi^0$$

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

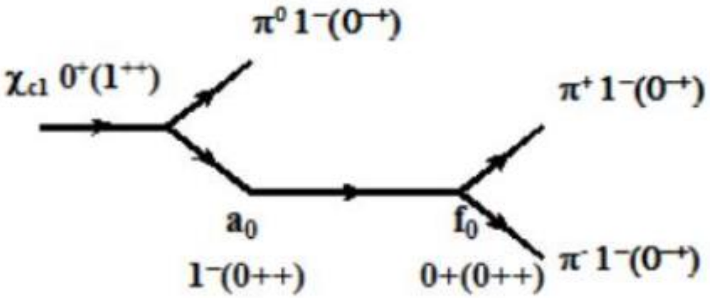
[Wu, Zhao, Zou, PRD 75, 114012 (2007), PRD 78, 074017 (2008)]

- Measured at BESIII based on 225M J/ψ and 108M $\psi(2S)$, significance $< 5\sigma$. [PRD 83, 032003 (2011)]

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



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

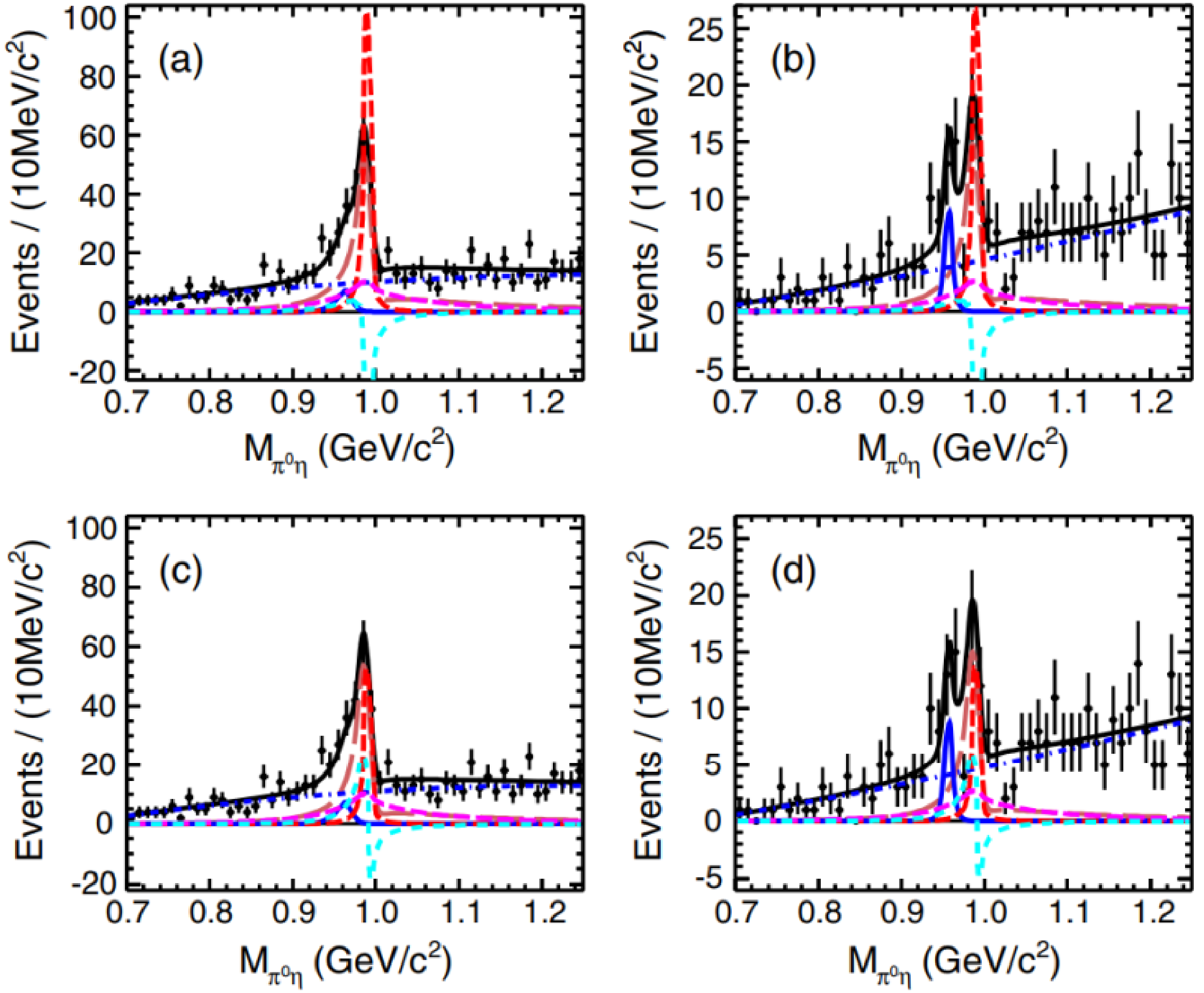


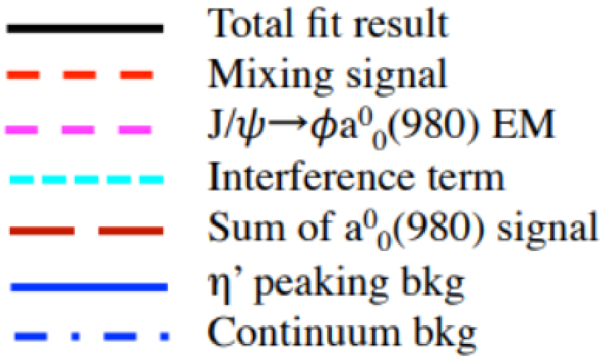
$f_0(980) \to a_0^0(980)$ Mixing

PRL 121, 022001 (2018)

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

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

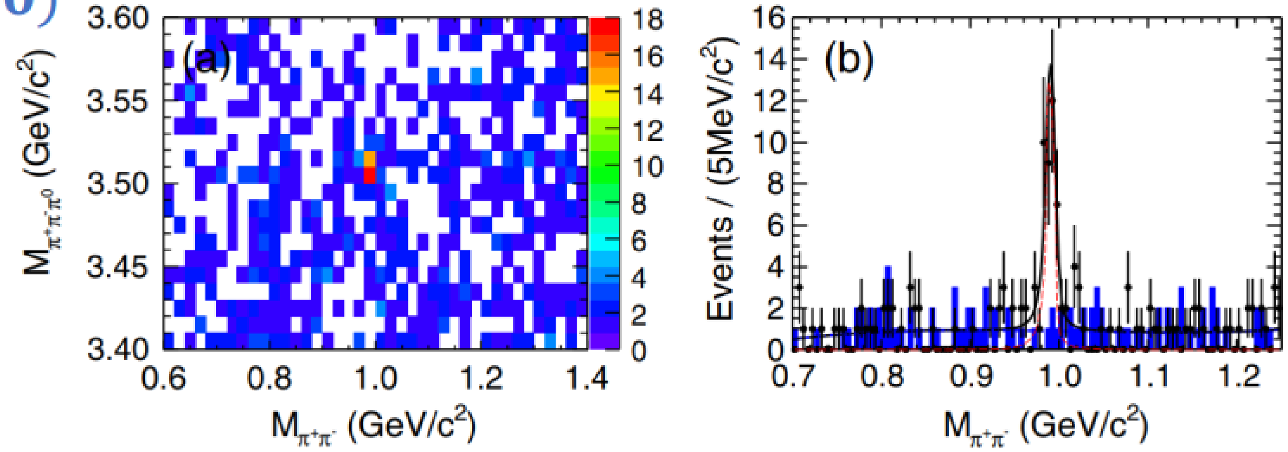




$a_0^0(980) \to f_0(980)$ Mixing

PRL 121, 022001 (2018)

- Very narrow peak of $f_0(980)$
- EM contribution too weak ,can be negligible
- Interference is negligible
- Significance of $a_0^0(980) \to f_0(980)$ 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})	$3.25 \pm 1.08 \pm 1.08 \pm 1.12$	$2.62 \pm 1.02 \pm 1.13 \pm 0.48$	...
$\mathcal{B}$ (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 (%)	$0.99 \pm 0.16 \pm 0.30 \pm 0.09$	$0.41 \pm 0.13 \pm 0.17 \pm 0.13$	$0.40 \pm 0.07 \pm 0.14 \pm 0.07$

Summary (I)

- η' meson decays, ω meson decay and $a_0^0(980)-f_0(980)$ mixing are reviewed

- **Dalitz plot analysis of $\eta' \to \eta\pi^+\pi^-$, $\eta\pi^0\pi^0$: the linear representation is less compatible with the data.**
- **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.**
- **Search for $\eta' \to \pi^0\pi^0\pi^0\pi^0$: the most stringent upper limit.**
- **Precision study of the decay dynamics of $\gamma\pi^+\pi^-$: need extra contribution besides $\rho(770)-\omega$.**
- **Search for $\eta' \to \gamma\gamma\eta$: the result is in tension with theoretical prediction.**
- **First direct measurement of absolute BFs for η' five modes.**

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 decay is an unique place to study light meson decays.
- 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

Back up

- $\eta' \to \pi^+\pi^-\eta$ — 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)
- $\eta' \to \gamma\gamma\eta$ — Phys.Rev.D 100, 052015 (2019)
- $\eta' \to \pi^0\pi^0\pi^0\pi^0$ — Phys.Rev.D 101, 032001 (2020)

BESIII Collaboration