

# Light meson decays at BESIII

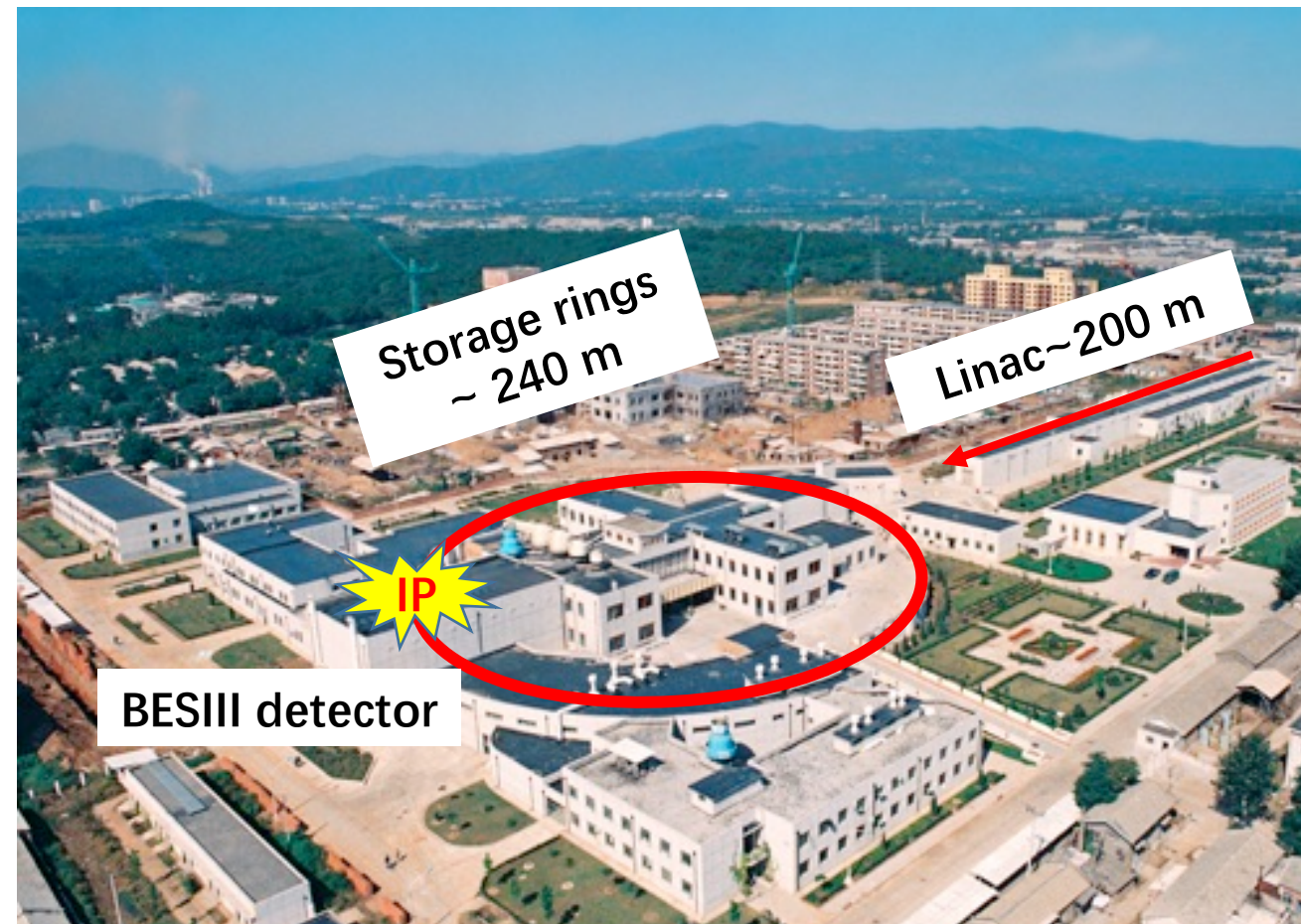
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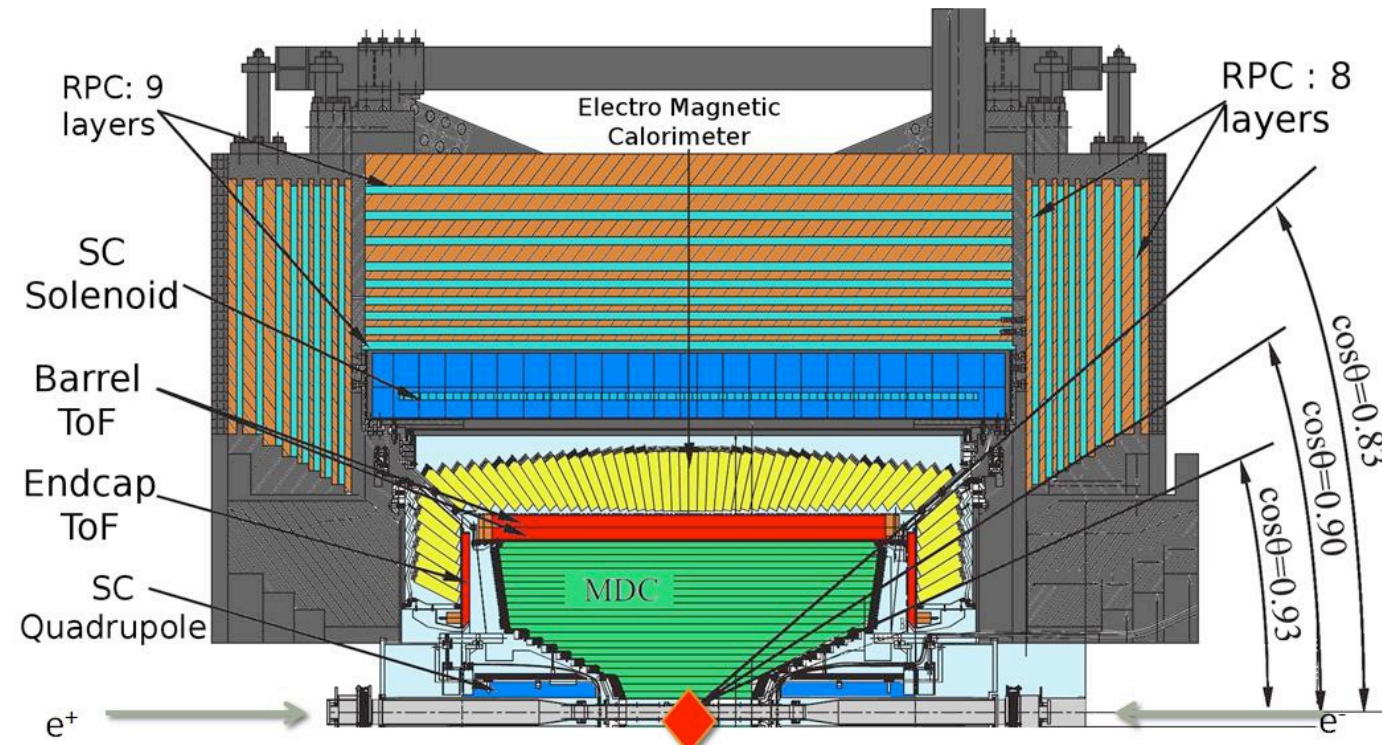
50<sup>th</sup> International Symposium on Multiparticle Dynamics (ISMD2021)

# Beijing Electron and Positron Collider(BEPCII)



- Symmetric, double rings  $e^+e^-$  collider @  $\sqrt{s}=2-4.9\text{GeV}$
- Peak luminosity  $\approx 10^{33}\text{cm}^{-2}\text{s}^{-1}$  at  $\sqrt{s}=3.770\text{GeV}$
- Crab-Waist interaction scheme with the crossing angle of 11 mrad
- Top-up operation since 2018

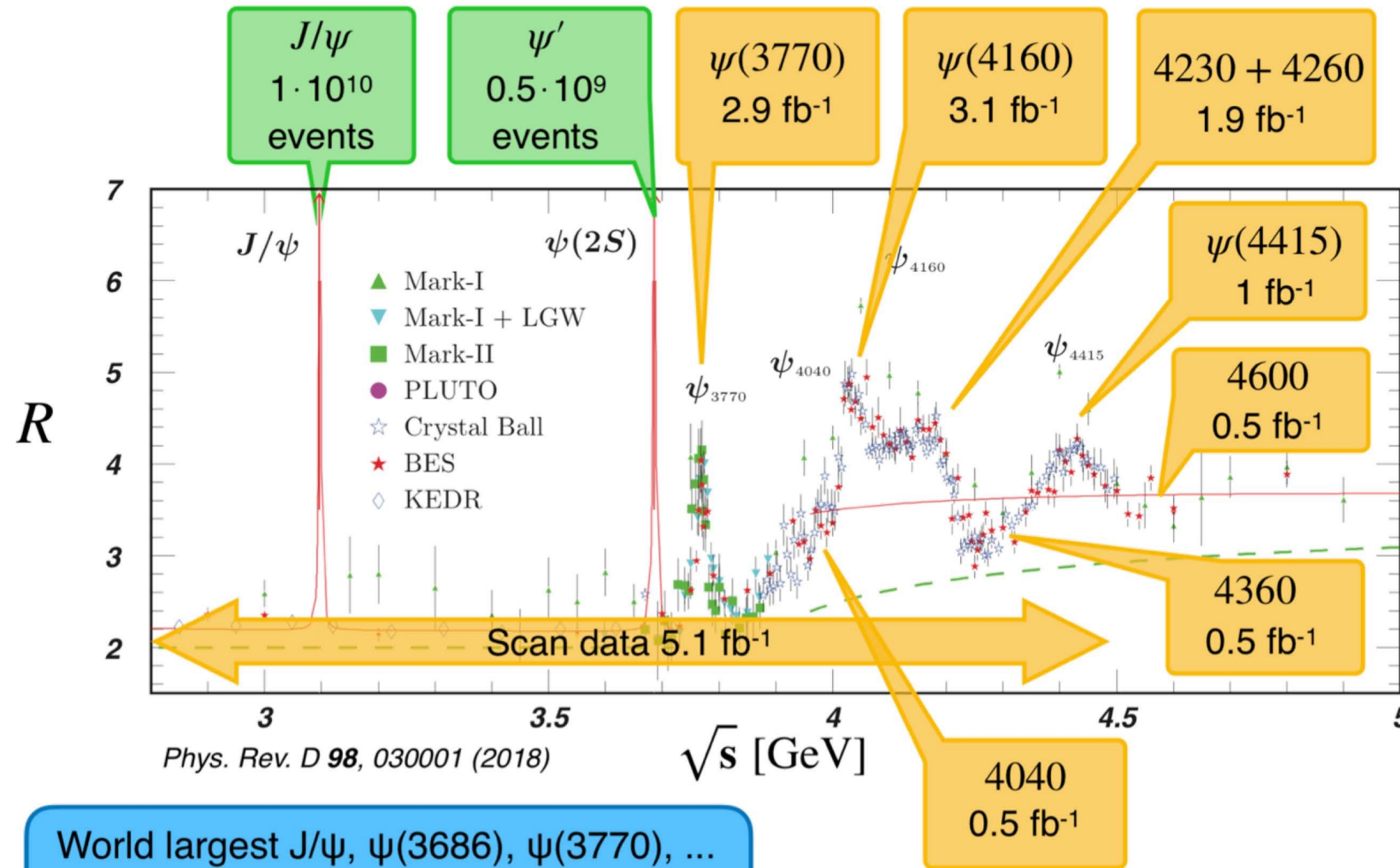
# BESIII detector



- **Acceptance: 93% of  $4\pi$**
- **Main Drift Chamber:** small cell & gas
  - ✓  $\sigma_{xy}=130\text{ }\mu\text{m}$ ,  $\sigma_p/P=0.5\% @ 1\text{ GeV}$
  - ✓  $\sigma_{dE/dx}=6\%$
- **Time of Flight (TOF)**
  - ✓  $\sigma_T=70\text{ ps}$  for barrel layers
  - ✓  $\sigma_T=110\text{ ps}$  (65 ps with updated MRPC) for endcaps
- **Super Conducting Solenoid:** 1.0T (0.9T for 2012)
- **Electromagnetic Calorimeter:** CsI Crystals
  - ✓  $\sigma_E/E=2.5\% @ 1\text{ GeV}$
  - ✓ Position resolution 6mm@1GeV
- **RPC Muon ID:** 9 layer



# Data set and Physics at BESIII



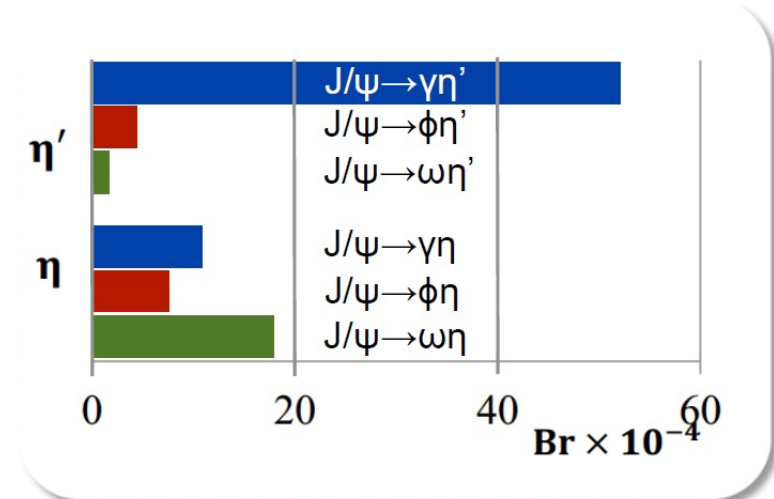
- Wide physics topics @  $\sqrt{s}=2-4.9\text{GeV}$
- Light hadron Physics
- Charmonium physics
- XYZ particles
- Discrete symmetries breaking
- Charm physics
- Physics with tau lepton
- R-value measurement
- ...

[Chin. Phys. C 44, 040001 \(2020\)](#)

# $\eta/\eta'$ sample from $J/\psi$ decays at BESIII

- Understand the low energy QCD
- Test the predictions of ChPT
- Probe the u-d quark mass difference
- Search for discrete symmetries violation (CV, CPV) and test fundamental symmetries
- Probe physics beyond the SM

Why  $\eta/\eta'$  ???



- High production rate of  $\eta/\eta'$  in  $J/\psi$  decays
  - radiative decays:  $5.2 \times 10^7 \eta'$ ,  $1.1 \times 10^7 \eta$
  - hadronic decays:  $6.5 \times 10^6 \eta'$ ,  $2.5 \times 10^7 \eta$
- Unique opportunity to investigate the decays of  $\eta/\eta'$

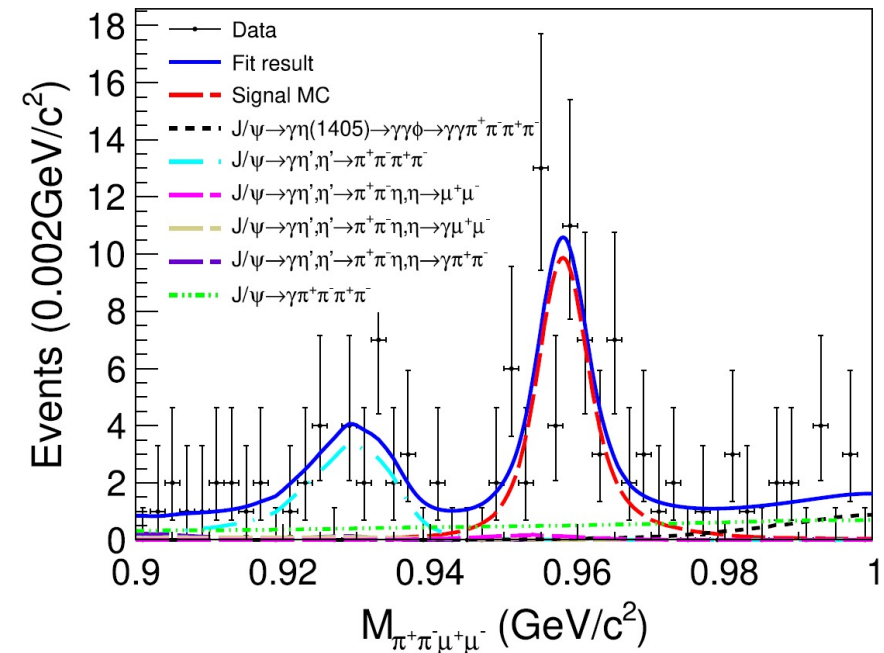
# Observation of $\eta' \rightarrow \pi^+ \pi^- \mu^+ \mu^-$

PRD 103,072006 (2021)

- The process is expected to proceed through an intermediate virtual photon  $\eta' \rightarrow \pi^+ \pi^- \gamma^* \rightarrow \pi^+ \pi^- \mu^+ \mu^-$ , may involve the box anomaly contribution
- Due to the low phase space, the predictions for the branching fraction of  $\eta' \rightarrow \pi^+ \pi^- \mu^+ \mu^-$  are in the range of  $(1.5-2.5) \times 10^{-5}$
- Most stringent UL ( $2.9 \times 10^{-5}$  @90% CL.) is from BESIII with 225 M  $J/\psi$  PRD87, 092011 (2013)

- $1.31 \times 10^9$   $J/\psi$  are used to search for this decay via  $J/\psi \rightarrow \gamma \eta' (\pi^+ \pi^- \mu^+ \mu^-)$
- PID and 4 constraint Kinematic fit
- Main backgrounds are from  $J/\psi \rightarrow \gamma \pi^+ \pi^- \pi^+ \pi^-$
- $53 \pm 9$  signal events are observed

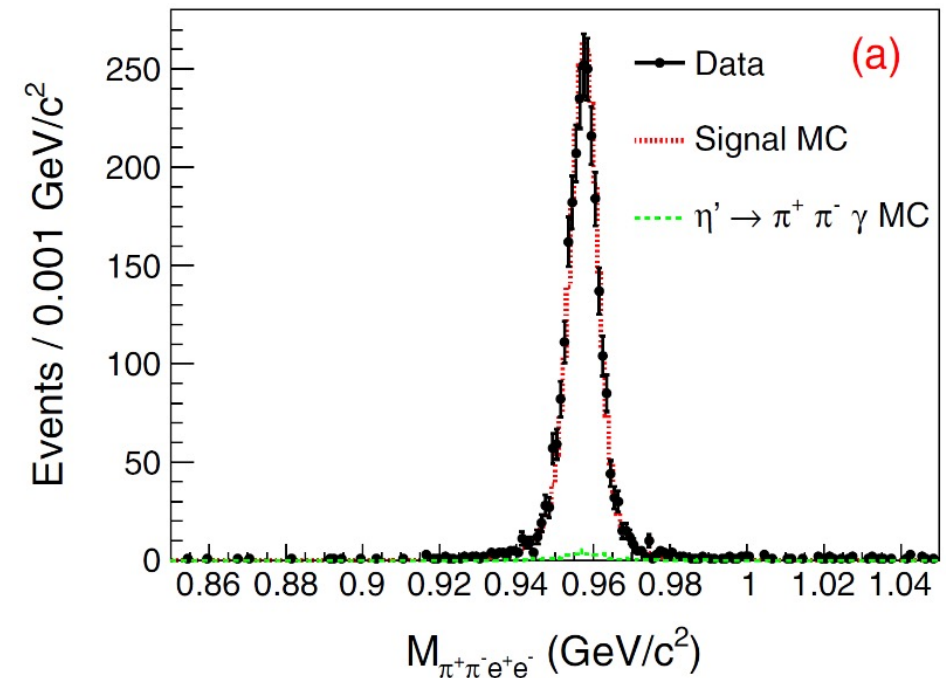
$$\mathcal{B}(\eta' \rightarrow \pi^+ \pi^- \mu^+ \mu^-) = (1.97 \pm 0.33(\text{stat}) \pm 0.19(\text{syst})) \times 10^{-5}$$



# The study of $\eta' \rightarrow \pi^+ \pi^- e^+ e^-$ PRD 103,092005 (2021)

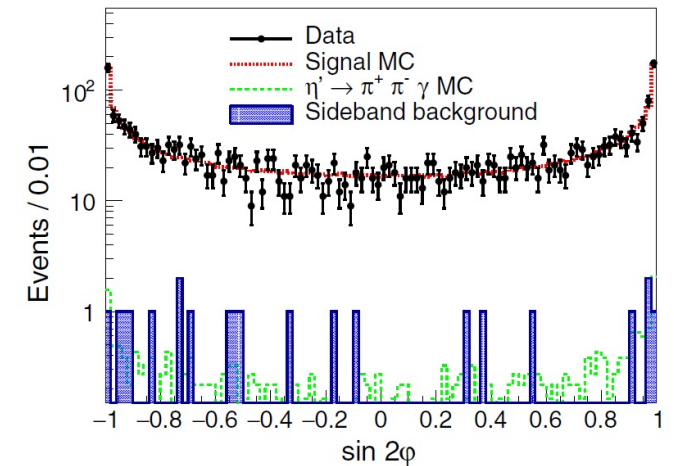
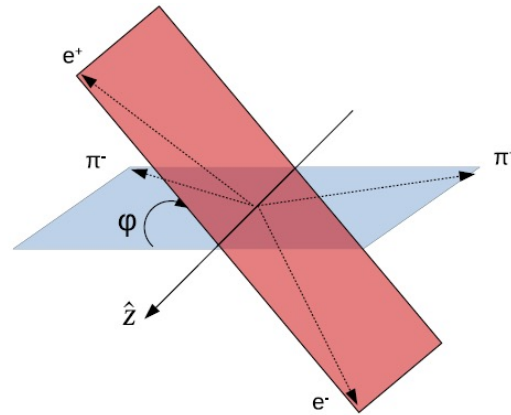
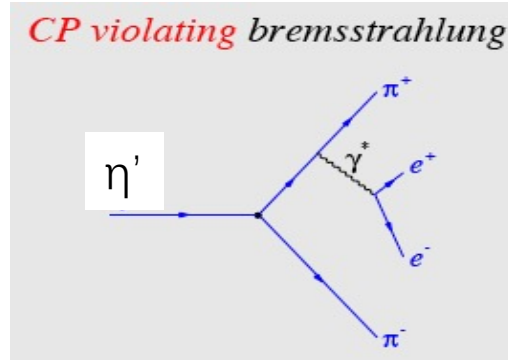
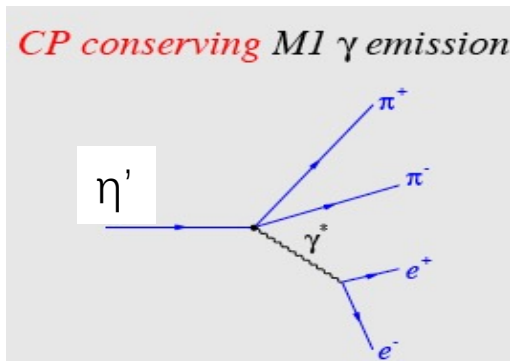
- The process is expected to proceed through an intermediate virtual photon  $\eta' \rightarrow \pi^+ \pi^- \gamma^* \rightarrow \pi^+ \pi^- e^+ e^-$ , exhibit a contribution from the box anomaly
- Two VMD models predict the BF to be  $(2.17 \pm 0.21) \times 10^{-3}$  and  $(2.27 \pm 0.13) \times 10^{-3}$  ([arXiv: 1010.2378](#))
- $\text{Br}(\eta' \rightarrow \pi^+ \pi^- e^+ e^-) = (2.13^{+0.17}_{-0.31}) \times 10^{-3}$  from ChPT model ([EPJA 33\(2007\) 95](#))
- With 225 M  $J/\psi$ , BESIII measured the  $\text{Br} = (2.11 \pm 0.12_{\text{stat}} \pm 0.15_{\text{syst.}}) \times 10^{-3}$  ([PRD 87 \(2013\) 092011](#))
- $1.31 \times 10^9 J/\psi$  are used to update this analysis via  $J/\psi \rightarrow \gamma \eta' (\pi^+ \pi^- e^+ e^-)$
- Photon conversion on beam pipe is rejected
- 2% of contamination from  $\eta' \rightarrow \pi^+ \pi^- \gamma$

$$\begin{aligned}
 \mathcal{B}(\eta' \rightarrow \pi^+ \pi^- e^+ e^-) &= \frac{N_{\eta' \rightarrow \pi^+ \pi^- e^+ e^-} \times \epsilon_{\eta' \rightarrow \pi^+ \pi^- \gamma} \times \mathcal{B}(\eta' \rightarrow \pi^+ \pi^- \gamma)}{N_{\eta' \rightarrow \pi^+ \pi^- \gamma} \times \epsilon_{\eta' \rightarrow \pi^+ \pi^- e^+ e^-}} \\
 &= (2.42 \pm 0.05_{\text{stat}} \pm 0.08_{\text{syst}}) \times 10^{-3}
 \end{aligned}$$



# Search for CP violation in $\eta' \rightarrow \pi^+ \pi^- e^+ e^-$ PRD 103,092005 (2021)

- Test of a new sources of CP violation beyond the CKM phase and outside flavor-changing processes
- CP asymmetry arises from the interference between the CP conserving magnetic and CP-violating electric transition [\[Dao-Neng Gao, Mod.Phys.Lett.A17 \(2002\) 1583\]](#)



The interference term can be extracted by the asymmetry of  $\sin 2\phi$  distribution

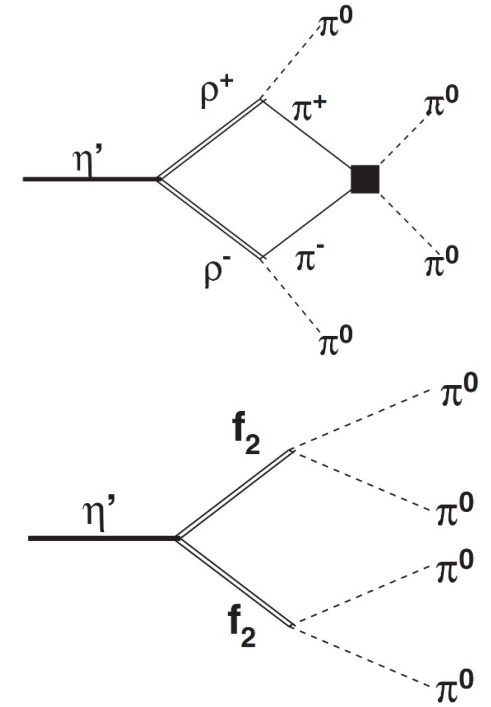
$$\mathcal{A}_\phi = \frac{N(\sin 2\phi > 0) - N(\sin 2\phi < 0)}{N(\sin 2\phi > 0) + N(\sin 2\phi < 0)} = (2.9 \pm 3.7_{\text{stat}} \pm 1.1_{\text{syst}})\%$$

Consistent with 0 within uncertainties, no CP-violation.



# The rare decay of $\eta' \rightarrow \pi^0 \pi^0 \pi^0 \pi^0$ PRD 101,032001(2020)

- $\eta' \rightarrow \pi^0 \pi^0 \pi^0 \pi^0$  is highly suppressed
  - S-wave is CP-violation process, induced by the QCD Lagrangian  $\theta$ -term  $\Rightarrow \text{Br} \sim 10^{-23}$
  - CP-conserving higher order PRD 85, 014014 (2012)
    - ✓ D-wave pion loop  $\Rightarrow$  ChPT and VMD model ( $\cdots$ but not strictly based on EFT) predict the Br to be at the level of  $10^{-8}$
    - ✓ Two  $f_2$  tensor mesons  $\rightarrow$  contribution is expected very small

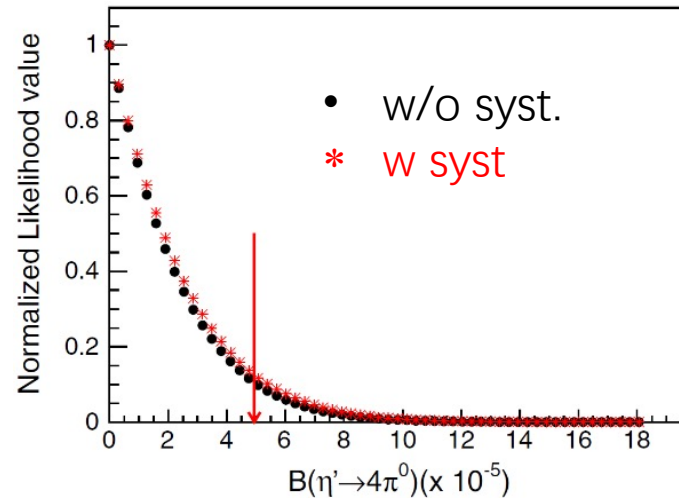
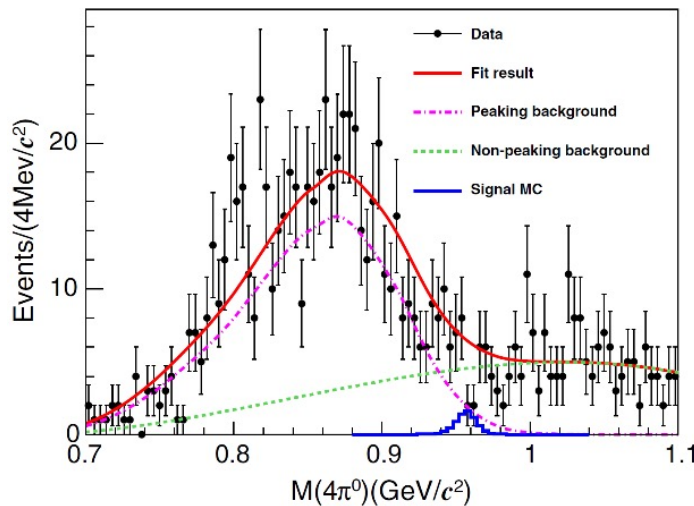


- GAMS-4 $\pi$  Collaboration presented the UL on  $\text{Br} < 3.2 \times 10^{-4}$  at 90% C.L. Mod. Phys. Lett. A 29, 1450213 (2014)
- $1.31 \times 10^9$   $J/\psi$  are used to search for this decay via  $J/\psi \rightarrow \gamma \eta' (\pi^0 \pi^0 \pi^0 \pi^0)$

# The rare decay of $\eta' \rightarrow \pi^0 \pi^0 \pi^0 \pi^0$ (cont)

PRD 101,032001(2020)

- At least 9 isolated photons and no charged tracks
- Energy-momentum conservation + mass-constraint kinematic fits are performed to reconstruct and select  $\pi^0$ s
- No significant  $\eta'$  signal
- Main backgrounds are from  $J/\psi \rightarrow \gamma \eta'$ ,  $\eta' \rightarrow \pi^0 \pi^0 \eta (\pi^0 \pi^0 \pi^0)$



With a Bayesian approach, the UL at 90% CL is set as:

$$\mathcal{B}(\eta' \rightarrow 4\pi^0) < 4.94 \times 10^{-5}$$

A factor 6 smaller than the previous most stringent result ([Mod.Phys.Lett.A29,1450213](#))

# Search for the rare decay of $\eta' \rightarrow \gamma\gamma\eta$

PRD 100, 052015 (2019)

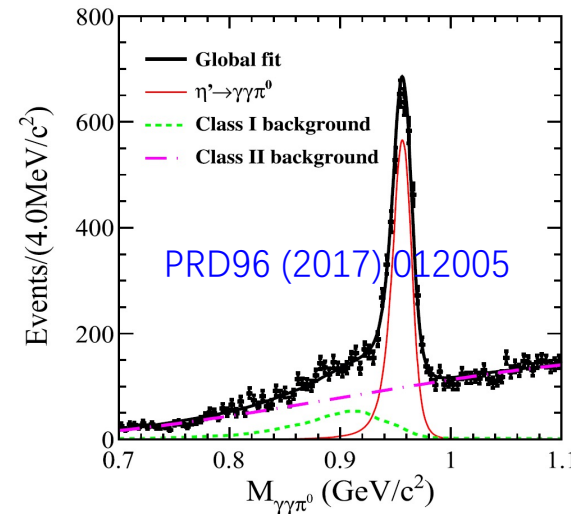
- Within the frameworks of the linear  $\sigma$  model ( $L\sigma M$ ) and VMD model [PRD 102, 034026 \(2020\)](#)

✓  $BF(\eta' \rightarrow \gamma\gamma\pi^0) = 3.8 \times 10^{-3}$  and  $BF(\eta' \rightarrow \gamma\gamma\eta) = 2.0 \times 10^{-4}$

- ✓ With  $1.31 \times 10^9$   $J/\psi$ , BESIII reported the first observation of  $\eta' \rightarrow \gamma\gamma\pi^0$

$$BF(\eta' \rightarrow \gamma\gamma\pi^0) = (3.20 \pm 0.07 \pm 0.23) \times 10^{-4}$$

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



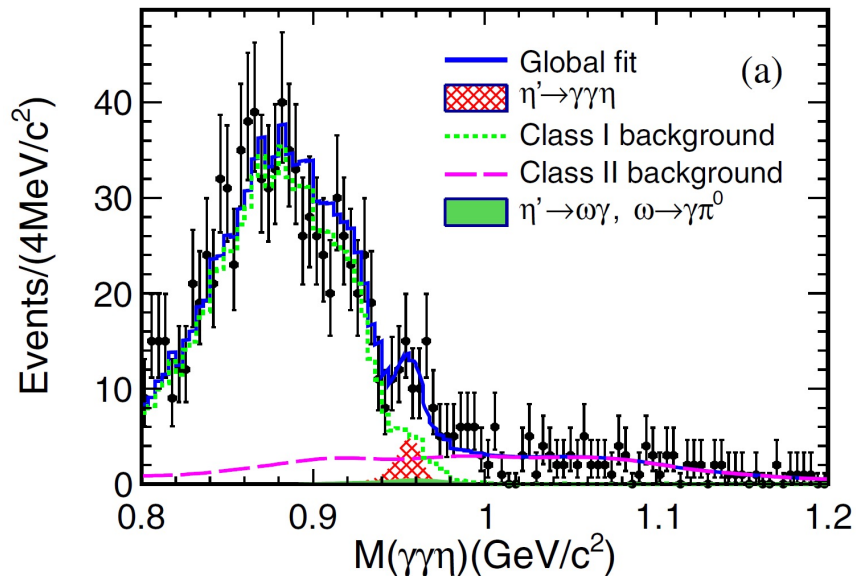
- GAMS-4 $\pi$  reported the most stringent UL  $BF(\eta' \rightarrow \gamma\gamma\eta) < 8 \times 10^{-3}$  at the 90% CL [\[Phys. Atom. Nucl. 78, 1043 \(2015\)\]](#)
- Search for this decay via  $J/\psi \rightarrow \gamma\eta'(\gamma\gamma\eta)$  with  $\eta \rightarrow \gamma\gamma$  with  $1.31 \times 10^9$   $J/\psi$  sample

# Search for the rare decay of $\eta' \rightarrow \gamma\gamma\eta$

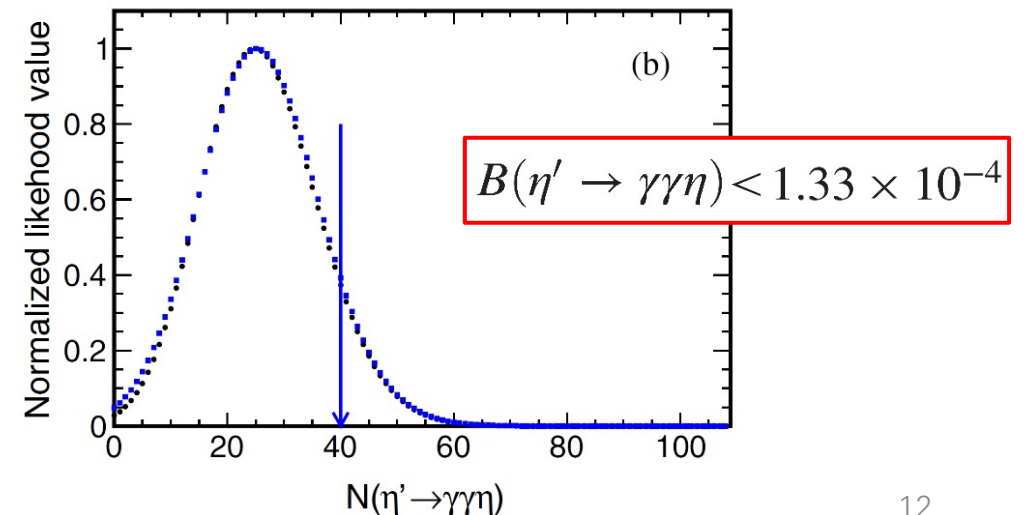
PRD 100, 052015 (2019)

- at least 5 isolated photons and no charged tracks
- $\delta_{\eta'/\eta}^2 = \left(\frac{M(\gamma\gamma\eta) - m(\eta')}{\sigma_1}\right)^2 + \left(\frac{M(\gamma\gamma) - m(\eta)}{\sigma_2}\right)^2$  and kinematic fits are used to construct signal events
- Main backgrounds are from  $J/\psi \rightarrow \gamma\eta'(\pi^0\pi^0\eta)$ ,  $J/\psi \rightarrow \gamma\eta'(\gamma\omega \rightarrow \gamma\pi^0)$  and  $J/\psi \rightarrow \gamma\eta\pi^0$
- A global fit yields  $24.9 \pm 10.3$   $\eta' \rightarrow \gamma\gamma\eta$  signal events with a statistical significance of  $2.6\sigma$

$$B(\eta' \rightarrow \gamma\gamma\eta) = (8.25 \pm 3.41 \pm 0.72) \times 10^{-5}$$



An UL at 90% CL is also set by Bayesian approach:

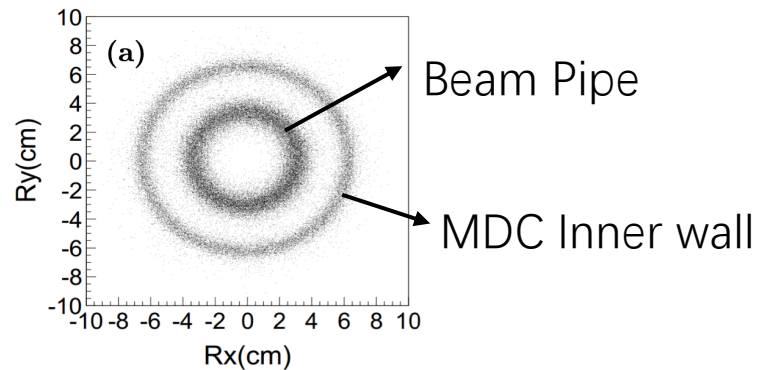




# Precision measurement of the BFs of $\eta'$ decays

PRL122, 142002 (2019)

- No absolute BF measurements due to difficulty of tagging its inclusive decays
- $J/\psi \rightarrow \gamma \eta'$  with  $\gamma$  conversions to  $e^+e^-$  ( $\times 3$  for resolution of the radiative photon)

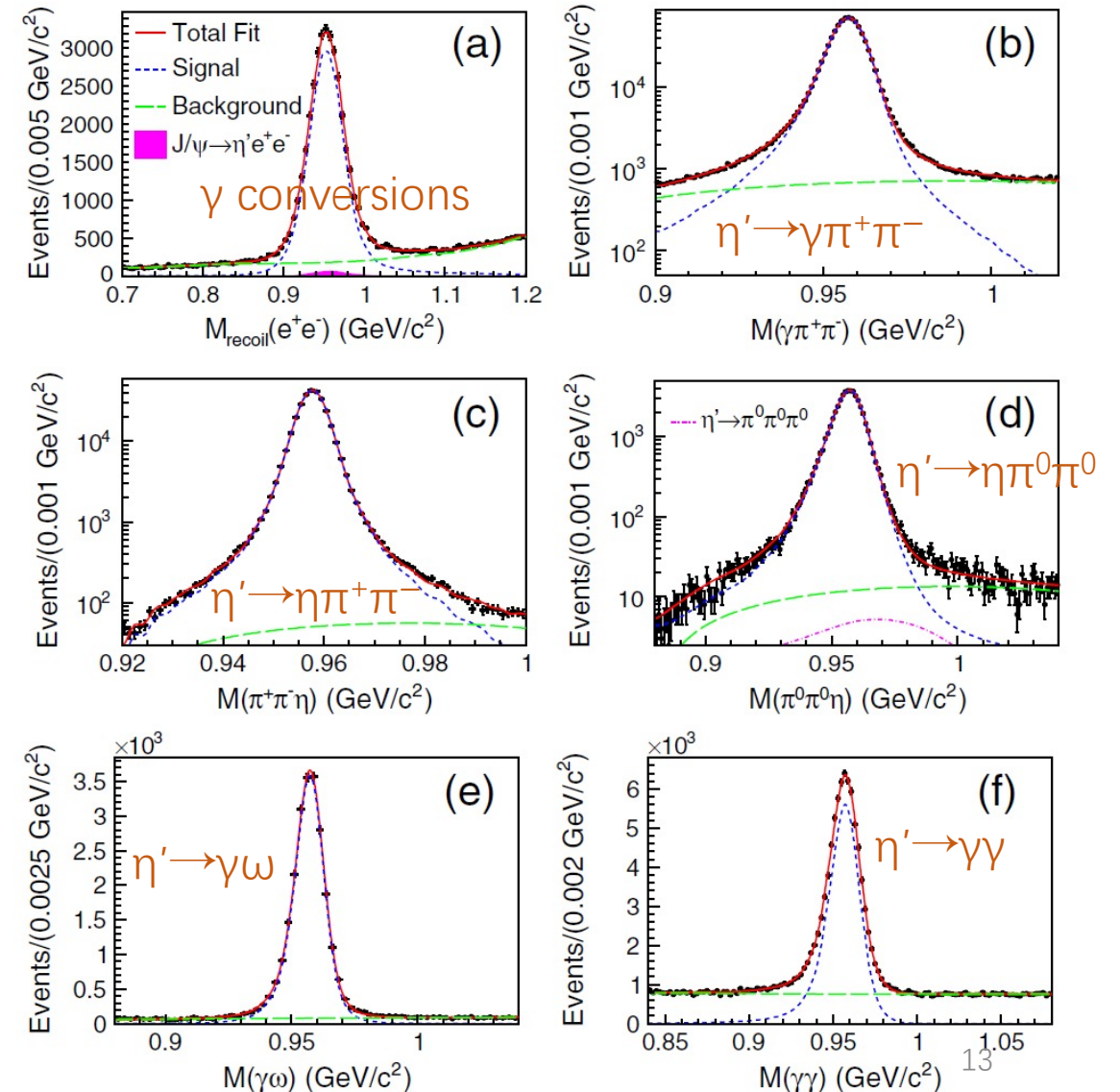


- Precision measurements of  $\eta' \rightarrow \gamma \pi^+ \pi^-$ ,  $\eta \pi^+ \pi^-$ ,  $\eta \pi^0 \pi^0$ ,  $\gamma \omega$ , and  $\gamma \gamma$ , using  $J/\psi \rightarrow \gamma \eta'$ , but with the radiative photon detected by calorimeter EMC

$$\mathcal{B}(\eta' \rightarrow X) = \frac{N_{\eta' \rightarrow X}^{\text{obs}}}{\mathcal{E}_{\eta' \rightarrow X}} \frac{\epsilon}{N_{J/\psi \rightarrow \gamma \eta'}^{\text{obs}}} f$$

$\gamma$  directly detected by EMC

using  $\gamma$  conversions



# Precision measurement of the BFs of $\eta'$ decays

PRL122, 142002 (2019)

Decay mode	$N_{\eta' \rightarrow X}^{\text{obs}}$	$\varepsilon_{\eta' \rightarrow X}(\%)$	$\mathcal{B}(\eta' \rightarrow X)(\%)$		$\mathcal{B}/\mathcal{B}(\eta' \rightarrow \eta\pi^+\pi^-)$	
			This measurement	PDG [7]	This measurement	CLEO [9]
$\eta' \rightarrow \gamma\pi^+\pi^-$	$913\,106 \pm 1052$	44.11	$29.90 \pm 0.03 \pm 0.55$	$28.9 \pm 0.5$	$0.725 \pm 0.002 \pm 0.010$	$0.677 \pm 0.024 \pm 0.011$
$\eta' \rightarrow \eta\pi^+\pi^-$	$312\,275 \pm 570$	27.75	$41.24 \pm 0.08 \pm 1.24$	$42.6 \pm 0.7$	...	...
$\eta' \rightarrow \eta\pi^0\pi^0$	$51\,680 \pm 238$	9.08	$21.36 \pm 0.10 \pm 0.92$	$22.8 \pm 0.8$	$0.518 \pm 0.003 \pm 0.021$	$0.555 \pm 0.043 \pm 0.013$
$\eta' \rightarrow \gamma\omega$	$22\,749 \pm 163$	14.98	$2.489 \pm 0.018 \pm 0.074$	$2.62 \pm 0.13$	$0.0604 \pm 0.0005 \pm 0.0012$	$0.055 \pm 0.007 \pm 0.001$
$\eta' \rightarrow \gamma\gamma$	$70\,669 \pm 349$	43.79	$2.331 \pm 0.012 \pm 0.035$	$2.22 \pm 0.08$	$0.0565 \pm 0.0003 \pm 0.0015$	$0.053 \pm 0.004 \pm 0.001$

- Signal yields obtained by unbinned maximum likelihood fits to the invariant mass distributions
- $\text{BF}(J/\psi \rightarrow \gamma\eta') = (5.27 \pm 0.03 \pm 0.05) \times 10^{-3}$  agrees with PDG value, with a significantly improved precision
- First direct measurement of absolute BFs for five  $\eta'$  decay modes
- The relative BFs are in agreement w.r.t. CLEO's result within two standard deviation

# Conclusion

- $J/\psi$  decay provides a unique laboratory to study light meson decays
- With 2009+2012  $J/\psi$  data (1.3 Billion), BESIII Collaboration produced fruitful results related light meson decays
  - Observation of  $\eta' \rightarrow \pi^+ \pi^- \mu^+ \mu^-$
  - Search for CP violation in  $\eta' \rightarrow \pi^+ \pi^- e^+ e^-$
  - Search for the rare decay of  $\eta' \rightarrow \pi^0 \pi^0 \pi^0 \pi^0$  and of  $\eta' \rightarrow \gamma \gamma \eta$
  - Precision measurement of the BF's of  $\eta'$  decays
  - ... and many other interesting results not covered in this talk
- And now to 10 Billion  $J/\psi$  events collected at BESIII
  - a unique worldwide sample, allows to study light mesons with the unprecedented statistics
  - More interesting results are foreseen

Thanks for your attention!!!

Backup slides



# Dalitz Plot Analysis of $\omega \rightarrow \pi^+ \pi^- \pi^0$

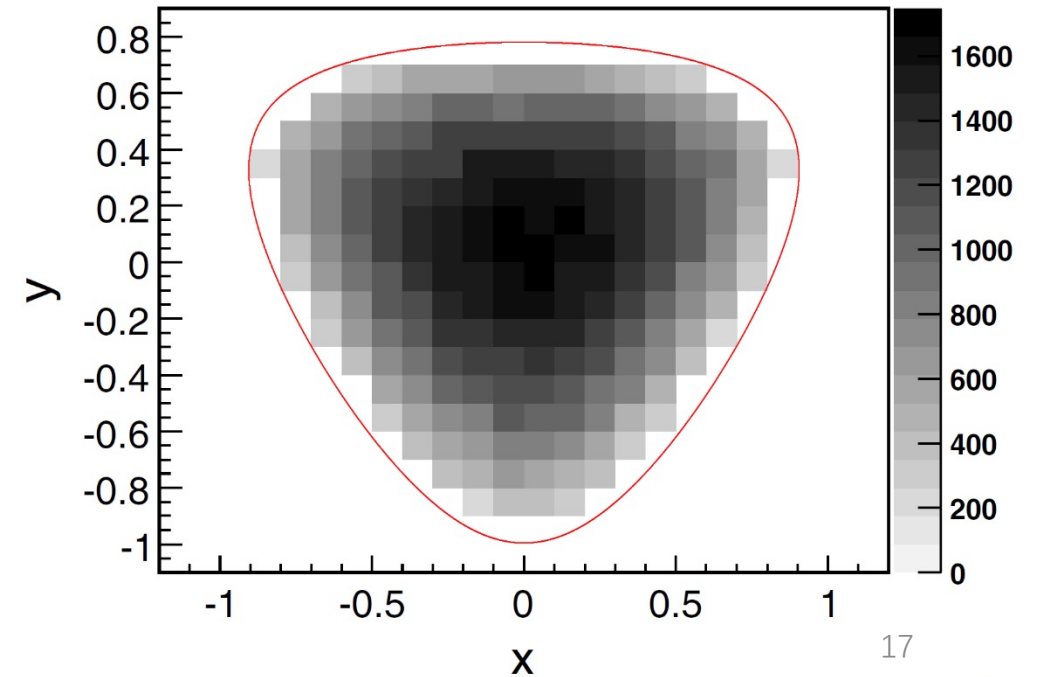
PRD98, 112007 (2018)

- Provide further constraints to the calculation of EM transition form factor of  $\omega \rightarrow \pi^0 \gamma^*$
- Test prediction of DP distributions in the dispersive framework ([PRD86,054013\(2012\)](#))
- In the isobar model,  $\omega \rightarrow \pi^+ \pi^- \pi^0$  decay can be described via intermediate  $\rho\pi$  state. While the third pion can interact with the decay products of the  $\rho$  resonance (crossed-channel effect)

$J/\psi \rightarrow \omega \eta$ , with  $\eta \rightarrow \gamma\gamma$  provide a clean sample of  $\omega$  events

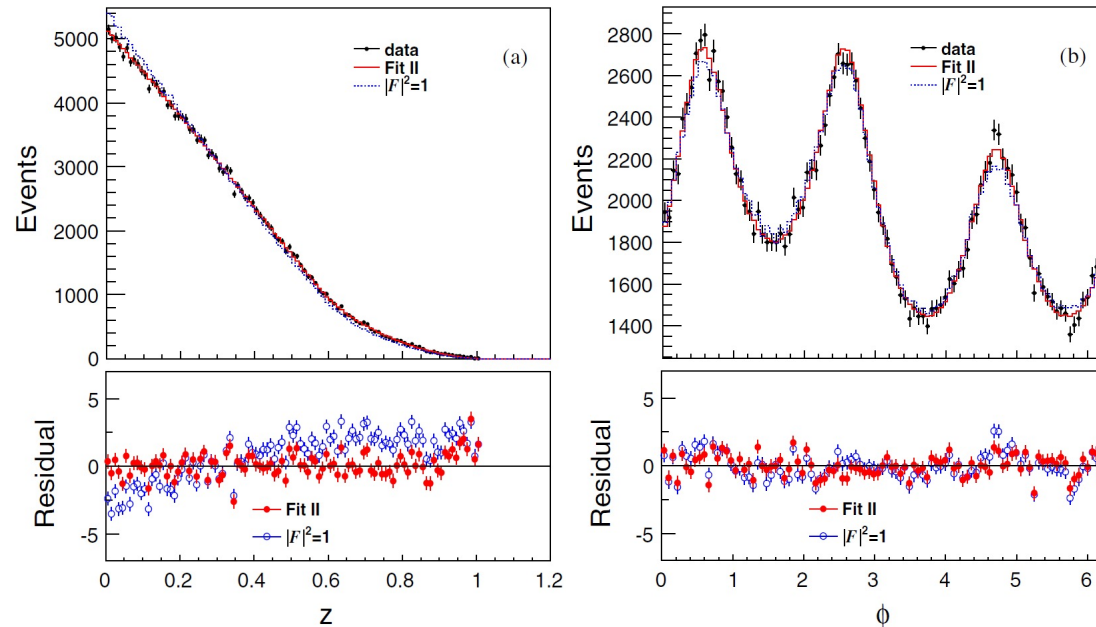
$$x = \frac{t - u}{\sqrt{3}R_\omega}, \quad y = \frac{s - s_0}{R_\omega} + \frac{2(m_{\pi^\pm} - m_{\pi^0})}{m_\omega - 2m_{\pi^\pm} - m_{\pi^0}},$$

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



# Dalitz Plot Analysis of $\omega \rightarrow \pi^+ \pi^- \pi^0$

PRD98, 112007 (2018)



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

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

pure P-wave PHSP:  $|F|^2 = 1$

$$|F|^2 = 1 + 2\alpha z + 2\beta z^{3/2} \sin 3\phi$$

		[4] PRD 91,094029				Theoretical predictions		Experiment
		Ref. [4]		Ref. [5] [5] EPJC 72,2014		[19] EPJA 49,116		
		w/o	w	w/o	w	Ref. [19]	BESIII	
Fit I	$\alpha$	136	94	(137,148)	(84,96)	202	$132.1 \pm 6.7 \pm 4.6$	
Fit II	$\alpha$	125	84	(125,135)	(74,84)	190	$120.2 \pm 7.1 \pm 3.8$	
	$\beta$	30	28	(29,33)	(24,28)	54	$29.5 \pm 8.0 \pm 5.3$	

The fitted parameters are consistent with the predictions without incorporating crossed channel effects