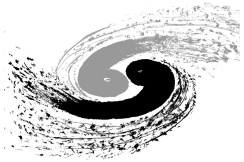

Light Meson Studies at BESIII

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(On behalf of the BESIII Collaboration)

14-25 March 2022, Mainz (Remotely)
Hadron Spectroscopy: The Next Big Steps

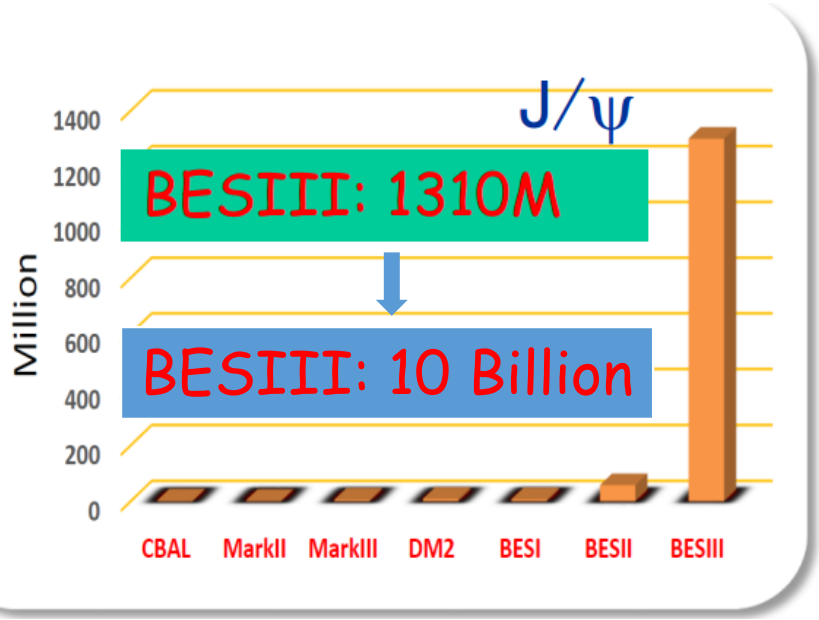
Outline:

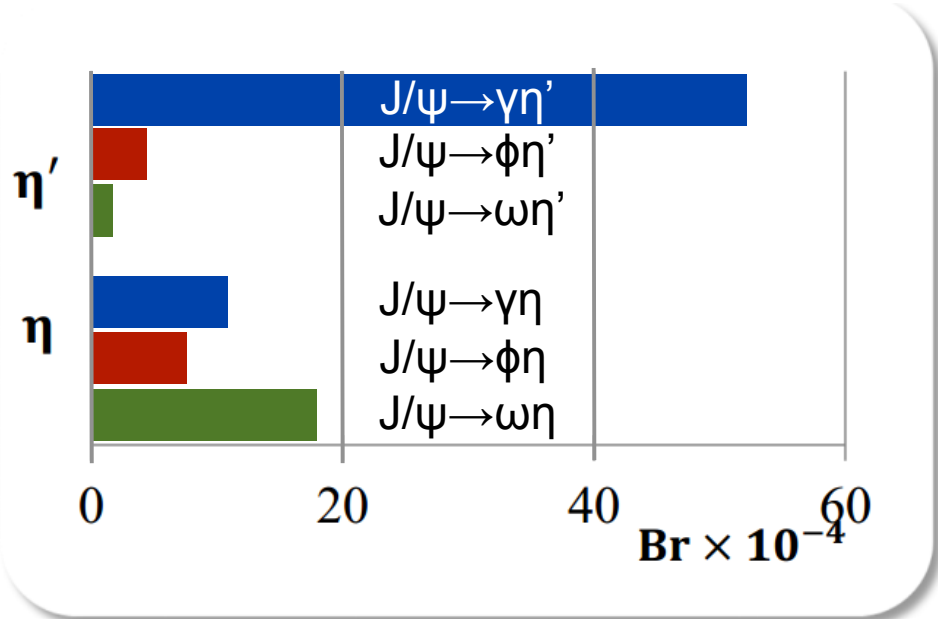
η/η' Physics

- Both η and η' play an important role in understanding the low energy quantum chromodynamics (QCD).
- Decays of the η/η' probe a wide variety of physics issues, such as π^0-η mixing, light quark masses and pion-pion scattering.
- In particular the η' meson, much heavier than the Goldstone bosons of broken chiral symmetry, plays a special role as the predominant singlet state arising from the strong axial U(1) anomaly.
- In addition, the decays of both η and η' mesons are used to search for processes beyond the Standard Model (SM) and to test fundamental discrete symmetries.

η Decays	Physics Highlights	η' Decays	Physics Highlights
$\eta \to \gamma\gamma\pi^0$	ChPT	$\eta' \to \pi\pi$	CPV
$\eta \to \gamma B$	Leptophobic 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	$\eta' \to \pi^0\pi^0\eta$	cusp effect

η/η' from J/ψ Decays at BESIII





- 1.3 billion J/ψ events (collected in 2009 and 2012)
  - η/η' from J/ψ radiative decays: $6.8 \times 10^6 \eta'$, $1.4 \times 10^6 \eta$
  - η/η' from J/ψ hadronic decays: $8.5 \times 10^5 \eta'$, $3.3 \times 10^6 \eta$
- More data collected since 2018, 10 billion J/ψ events in total now
- Unique opportunity to investigate the decays of η/η'.

Recent Works on η/η' Meson Studies at BESIII

Based on 1.3 billion J/ψ events:

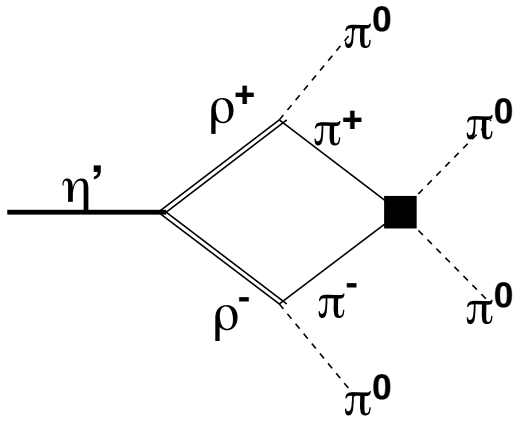
- $\eta' \to \pi^0\pi^0\pi^0\pi^0$
- $\eta' \to \gamma\gamma\eta$
- $\eta' \to \pi^+\pi^- e^+ e^-$
- $\eta' \to \pi^+\pi^-\mu^+\mu^-$

Based on 10 billion J/ψ events:

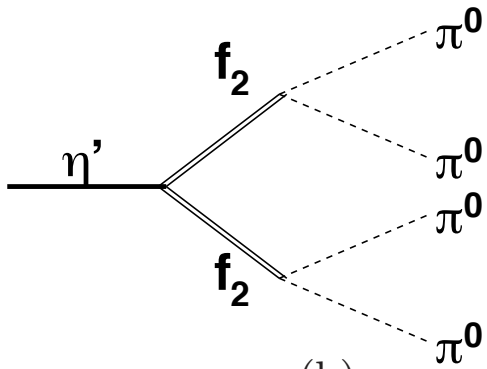
- Absolute branching fractions of η decay modes

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

- Suppressed due to S-wave CP-violation.
- CP-conserving higher-order contributions:
  - D-wave pion loop
  - Production of two f_2 tensor mesons
- D-wave contribution[1]:
  - At the level of 10^{-8}
  - Based on ChPT and VMD models
- Upper limits obtained by GAMS-4π[2]:
  - 3.2×10^{-4} at the 90% C.L.



(a)



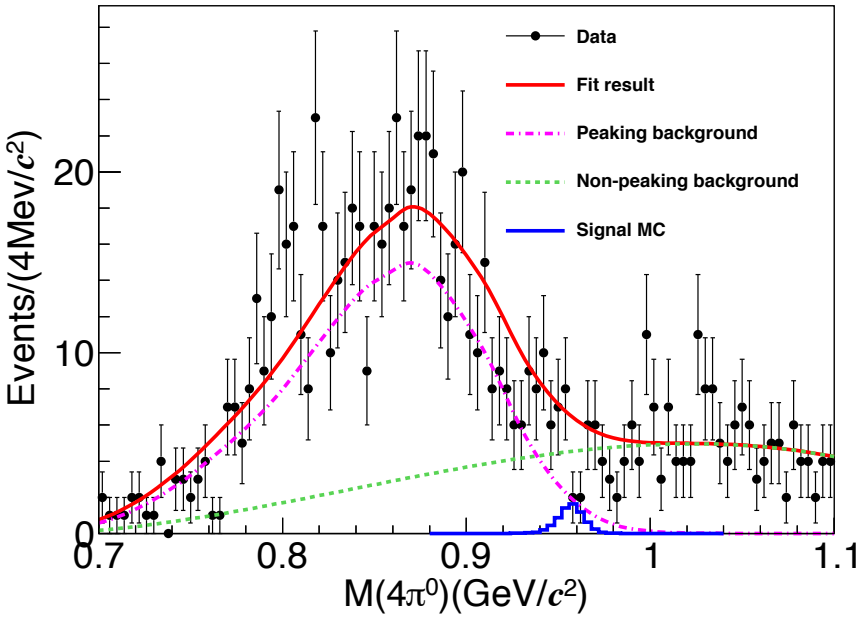
(b)

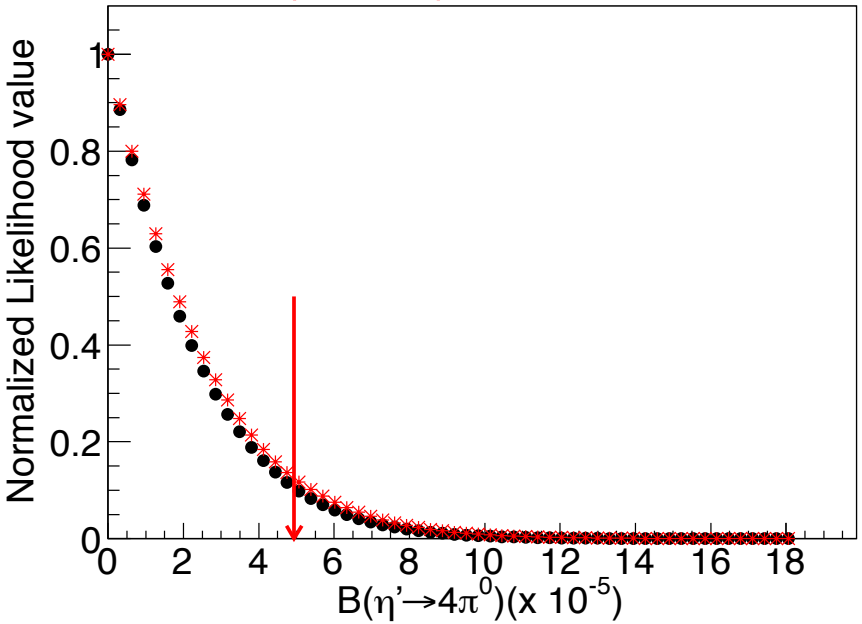
[1] Feng-Kun Guo, Bastian Kubis, and Andreas Wirzba, Phys. Rev. D **85**, 014014 (2012).

[2] S. V. Donskov *et al.*, Mod. Phys. Lett. A **29**, 1450213 (2014).

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

Phys. Rev. D 101, 032001 (2020)

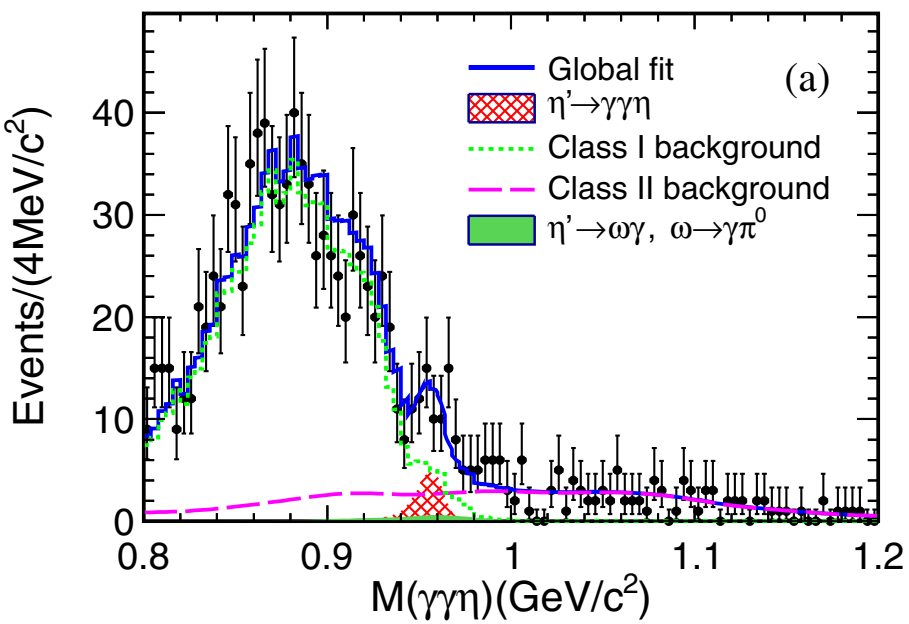




- $J\psi \to \gamma\eta',\ \eta' \to 4\pi^0$
- Signal contribution negligible.
- Upper limit: 4.94×10^{-5} at the 90% C.L.
- Approximately a factor of six smaller than the previous most stringent result.

$\eta' \to \gamma\gamma\eta$

- Branching fraction of $\eta' \to \gamma\gamma\eta$ is predicted to be 2.0×10^{-4} within the frameworks of linear σ model and the VMD model[3, 4].
- Upper limit reported by GAMS-4π[5]: 8×10^{-4} at the 90% C.L.



Phys. Rev. D 100, 052015 (2019)

- $J/\psi \to \gamma\eta',\ \eta' \to \gamma\gamma\eta,\ \eta \to \gamma\gamma$
- $\mathcal{B}(\eta' \to \gamma\gamma\eta)$: $(8.25 \pm 3.41 \pm 0.72) \times 10^{-5}$
- Statistical significance: 2.6 σ.
- Upper limit: 1.33×10^{-4} at the 90% C.L., in tension with the theoretical prediction

[3] R. Jora, Nucl. Phys. Proc. Suppl. **207**, 224 (2010).
[4] R. Escribano *et al.*, Phys. Rev. D **102**, 034026 (2020).
[5] S.V. Donskov *et al.*, Phys. Atom. Nucl. **78**, 1043 (2015)

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

Branching fraction of $\eta' \to \pi^+\pi^- e^+ e^-$:

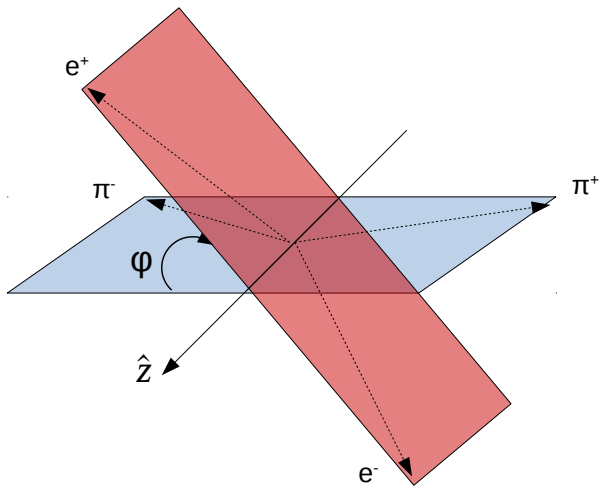
- Theoretical predictions:
  - Two different VMD models[6]: $(2.17 \pm 0.21) \times 10^{-3}$ and $(2.27 \pm 0.13) \times 10^{-3}$
  - ChPT model[7]: $(2.13^{+0.17}_{-0.31}) \times 10^{-3}$
- Most precise measurement before[8]: $(2.11 \pm 0.12_{stat.} \pm 0.15_{syst.}) \times 10^{-3}$

Possible CP-violating contribution[9−11]:

- An electric dipole type transition
- Manifest itself as an asymmetry of $\sin 2\varphi$:

$$\mathcal{A}_\varphi = \frac{N(\sin 2\varphi > 0) - N(\sin 2\varphi < 0)}{N(\sin 2\varphi > 0) + N(\sin 2\varphi < 0)} \qquad (1)$$

- Previous measurement of $\mathcal{A}_\varphi$: consistent with zero



[6] T. Petri, PhD thesis, Forschungszentrum Julich, (2010), arXiv:1010.2378[nucl-th].
[7] B. Borasoy and R. Nissler, Eur. Phys. J. A 33, 95 (2007).
[8] M. Ablikim *et al.*, (BESIII Collaboration), Phys. Rev. D 87, 092011 (2013).
[9] C. Q. Geng, J. N. Ng, and T. H. Wu, Mod. Phys. Lett. A 17, 1489 (2002).
[10] D.-N. Gao, Mod. Phys. Lett. A 17, 1583 (2002).
[11] L. Gan, B. Kubis, E. Passemar, and S. Tulin, (2020), arXiv:2007.00664hep-ph.

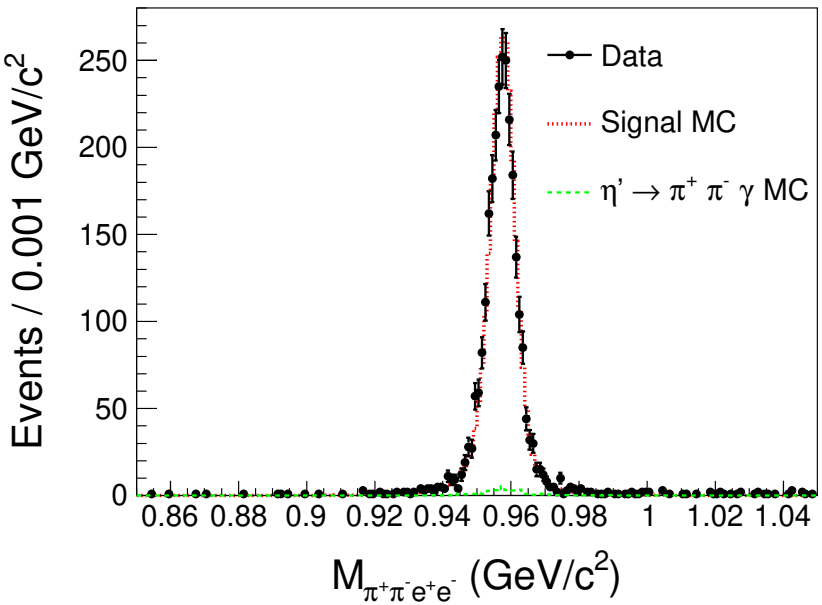
$\eta' \to \pi^+\pi^- e^+ e^-$

Measurement of branching fraction:

- To minimize the uncertainty of the number of J/ψ, the tracking efficiency, and the particle identification efficiency, the branching fraction is calculated according to

$$\mathcal{B}(\eta' \to \pi^+\pi^- e^+ e^-) = \mathcal{B}(\eta' \to \pi^+\pi^-\gamma) \cdot \frac{N_{\eta' \to \pi^+\pi^- e^+ e^-} \cdot \varepsilon_{\eta' \to \pi^+\pi^-\gamma}}{N_{\eta' \to \pi^+\pi^-\gamma} \cdot \varepsilon_{\eta' \to \pi^+\pi^- e^+ e^-}} \quad (2)$$

- The $\mathcal{B}(\eta' \to \pi^+\pi^-\gamma)$ is referred from PDG, N_i is the event yield in channel i, ε_i is the corresponding efficiency.



Phys. Rev. D 103, 092005 (2021)

- Signal region:
  $|M_{\pi^+\pi^- e^+ e^-} - m_{\eta'}| < 0.02\,\mathrm{GeV}/c^2$
- Signal purity: 98%
  based on MC simulations of $\eta' \to \pi^+\pi^-\gamma$
- $\mathcal{B}(\eta' \to \pi^+\pi^- e^+ e^-)$:
  $(2.42 \pm 0.05_{stat.} \pm 0.08_{syst.}) \times 10^{-3}$
  consistent with the predictions

. **Measurement of $\mathcal{A}_\varphi$:**

$$\mathcal{A}_\varphi = \frac{N(\sin 2\varphi > 0) - N(\sin 2\varphi < 0)}{N(\sin 2\varphi > 0) + N(\sin 2\varphi < 0)}$$

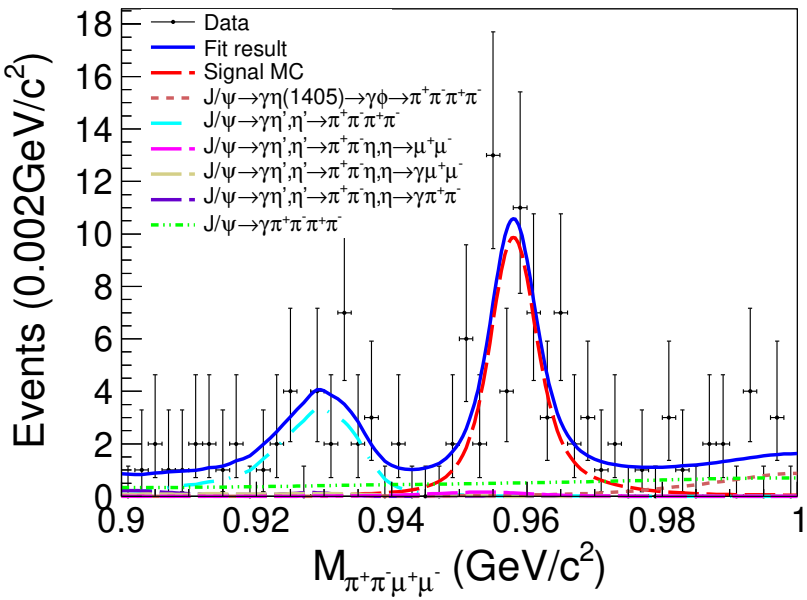
- Due to the limited momentum resolution, some events with a true value $\sin 2\varphi < 0$ are reconstructed with a value $\sin 2\varphi > 0$. The fraction of such events, α is estimated with signal MC sample.
- Corrected $\mathcal{A}_\varphi$:

$$\mathcal{A}_{\varphi,\,\text{corr.}} = \frac{\mathcal{A}_{\varphi,\,\text{rec.}}}{1 - 2\alpha} \tag{3}$$

- Result: $\mathcal{A}_\varphi = (2.9 \pm 3.7_{stat.} \pm 1.1_{syst.})\,\%$, consistent with zero.

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

- Predictions on $\mathcal{B}(\eta' \to \pi^+\pi^-\mu^+\mu^-)$[6,12,13]:
  - in the range of $(1.5 - 2.5) \times 10^{-5}$.
- No significant signal has been observed before this work.
- Most stringent upper limit measured before[13]:
  - $\mathcal{B}(\eta' \to \pi^+\pi^-\mu^+\mu^-) < 2.9 \times 10^{-5}$ at the 90% C.L.



Phys. Rev. D 103, 072006 (2021)

- $\mathcal{B}(\eta' \to \pi^+\pi^-\mu^+\mu^-)$: $(1.97 \pm 0.33_{stat.} \pm 0.18_{syst.}) \times 10^{-5}$
- Statistical significance: 8σ
- In good agreement with theoretical predictions

[12] A. Faessler, C. Fuchs and M. I. Krivoruchenko, Phys. Rev. C **61**, 035206 (2000).
[13] B. Borasoy and R. Nissler, Eur. Phys. J. A **33**, 95 (2007).

Absolute Branching Fractions of η Decay Modes

- Decays of η meson are sensitive to a wide variety of physics issues.
- No **absolute branching fractions**(BFs) of η decays have been measured due to difficulty of tagging its inclusive decays.
- A method for **tagging inclusive decays** of η is developed.

$$J/\psi \to \gamma\eta,\ \eta \to \textit{anything},\ \gamma \to e^+e^-(\gamma \text{ conversion process})$$

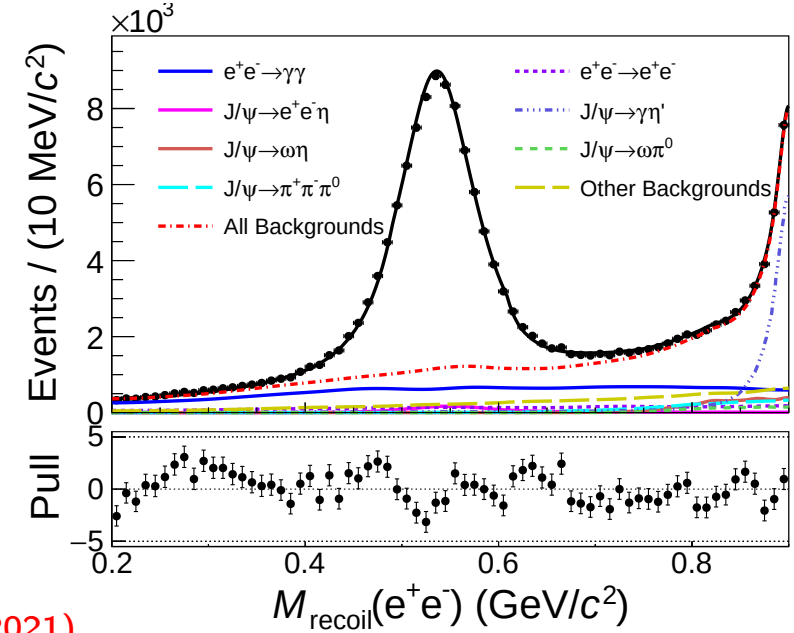
- γ **conversion**: a photon with energy greater than twice the mass of electron convert to e^+e^- when passing near the nucleus of an atom.
- Energy resolution of the radiative photon could be improved by a factor of 2.
- Number of η can be extracted from **recoil mass spectrum** of γ

Absolute Branching Fractions of η Decay Modes

- Step 1: Inclusive decays

$$B(J/\psi \to \gamma\eta) = \frac{N^{obs}_{J/\psi\to\gamma\eta}}{N_{J/\psi}\cdot\varepsilon f} \tag{4}$$

$N^{obs}_{J/\psi\to\gamma\eta}$ and $N_{J/\psi}$: observed η yield and number of J/ψ events.
ε: detection efficiency obtained from MC simulation
f: correct the difference in γ conversion efficiencies between data and MC



Phys. Rev. D 104, 092004 (2021)

$$B(J/\psi \to \gamma\eta) = (1.067 \pm 0.005_{stat.} \pm 0.023_{syst.}) \times 10^{-3}$$

PDG: $(1.108 \pm 0.027) \times 10^{-3}$ (before this work)

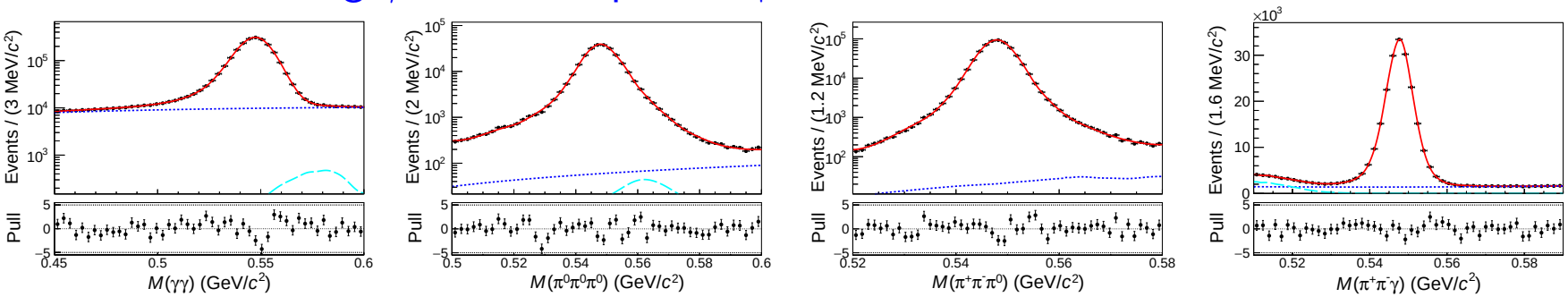
Absolute Branching Fractions of η Decay Modes

- Step 2: Exclusive decays

↓ Directly detected by detector

$$B(\eta \to X) = \frac{B(J/\psi \to \boxed{\gamma}\eta, \eta \to X)}{B(J/\psi \to \boxed{\gamma}\eta)} = \frac{N^{obs}_{\eta\to X}}{\varepsilon_{\eta\to X}} \cdot \frac{\varepsilon f}{N^{obs}_{J/\psi\to\gamma\eta}} \quad (5)$$

Using γ conversion process ↑



Phys. Rev. D 104, 092004 (2021)

X	$\mathcal{B}(\eta \to X)/\mathcal{B}(\eta \to \gamma\gamma)$	
	This Work	CLEO
$\pi^0\pi^0\pi^0$	$0.802 \pm 0.002 \pm 0.014$	$0.884 \pm 0.022 \pm 0.019$
$\pi^+\pi^-\pi^0$	$0.578 \pm 0.001 \pm 0.008$	$0.587 \pm 0.011 \pm 0.009$
$\pi^+\pi^-\gamma$	$0.110 \pm 0.001 \pm 0.002$	$0.103 \pm 0.004 \pm 0.004$

X	$\mathcal{B}(\eta \to X)$ (%)		
	This Work	CLEO	PDG
$\gamma\gamma$	$39.86 \pm 0.04 \pm 0.99$	$38.45 \pm 0.40 \pm 0.36$	39.41 ± 0.20
$\pi^0\pi^0\pi^0$	$31.96 \pm 0.07 \pm 0.84$	$34.03 \pm 0.56 \pm 0.49$	32.68 ± 0.23
$\pi^+\pi^-\pi^0$	$23.04 \pm 0.03 \pm 0.54$	$22.60 \pm 0.35 \pm 0.29$	22.92 ± 0.28
$\pi^+\pi^-\gamma$	$4.38 \pm 0.02 \pm 0.10$	$3.96 \pm 0.14 \pm 0.14$	4.22 ± 0.08

Summary and Outlook

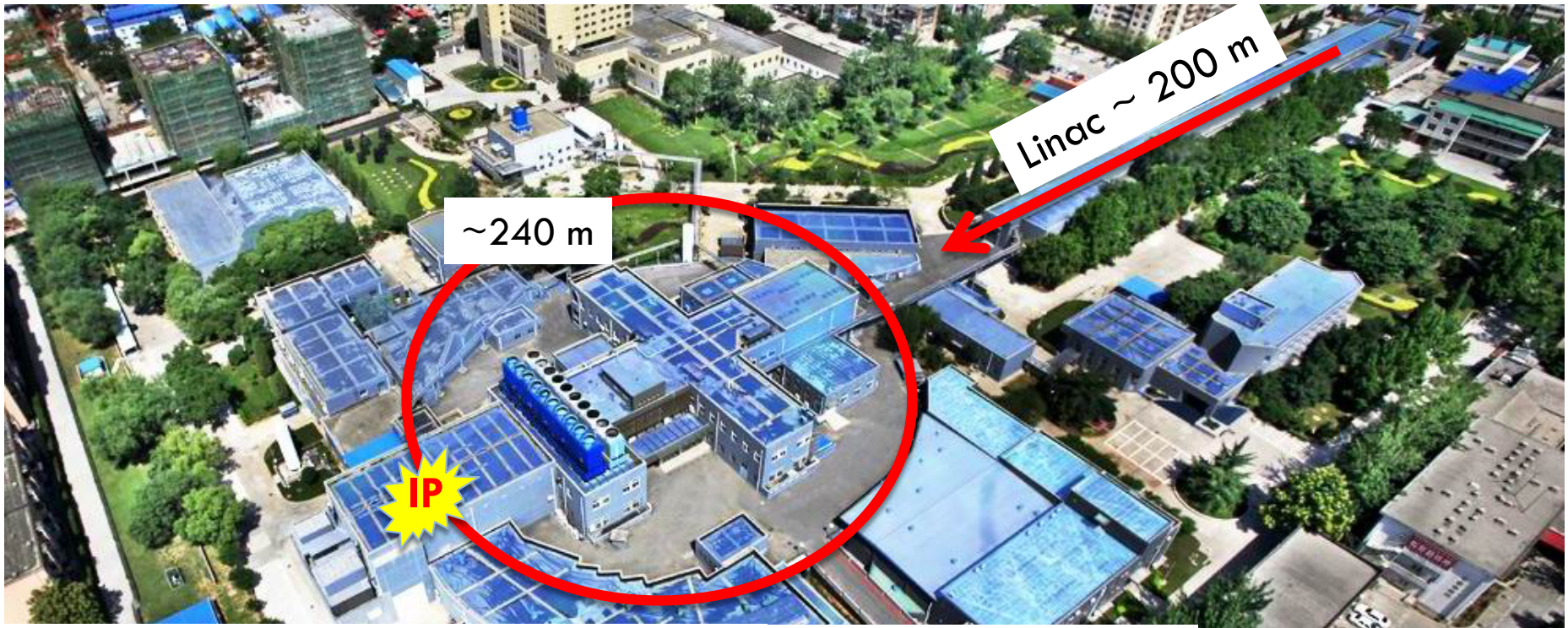
- Large J/ψ decay sample at BESIII provides an excellent laboratory to study light meson decays.
- η/η' studies:
  - Search for $\eta' \to \pi^0\pi^0\pi^0\pi^0$
    - Upper limit: 4.94×10^{-5} at the 90% C.L.
  - Search for $\eta' \to \gamma\gamma\eta$
    - $\mathcal{B}(\eta' \to \gamma\gamma\eta)=(8.25 \pm 3.41_{stat.} \pm 0.72_{syst.}) \times 10^{-5}$ (Statistical significance: 2.6 σ)
    - Upper limit: 1.33×10^{-4} at the 90% C.L.
  - Search for $\eta' \to \pi^+\pi^- e^+ e^-$
    - $\mathcal{B}(\eta' \to \pi^+\pi^- e^+ e^-)=(2.42 \pm 0.05_{stat.} \pm 0.08_{syst.}) \times 10^{-3}$
    - $\mathcal{A}_\varphi = (2.9 \pm 3.7_{stat.} \pm 1.1_{syst.})$ %
  - Search for $\eta' \to \pi^+\pi^-\mu^+\mu^-$
    - $\mathcal{B}(\eta' \to \pi^+\pi^-\mu^+\mu^-)=(1.97 \pm 0.33_{stat.} \pm 0.18_{syst.}) \times 10^{-5}$ (Statistical significance: 8σ)
  - Absolute branching fractions of η decay modes
    - $\mathcal{B}(J/psi \to \gamma\eta)=(1.067 \pm 0.005_{stat.} \pm 0.023_{syst.}) \times 10^{-3}$
    - $\mathcal{B}(\eta \to \gamma\gamma)=(39.86 \pm 0.04_{stat.} \pm 0.99_{syst.})$%, $\mathcal{B}(\eta \to \pi^0\pi^0\pi^0)=(31.96 \pm 0.07_{stat.} \pm 0.84_{syst.})$%
    - $\mathcal{B}(\eta \to \pi^+\pi^-\pi^0)=(23.04 \pm 0.03_{stat.} \pm 0.54_{syst.})$%, $\mathcal{B}(\eta \to \pi^+\pi^-\gamma)=(4.38 \pm 0.02_{stat.} \pm 0.10_{syst.})$%

Summary and Outlook

- With the 10 billion J/ψ decay sample available now, more interesting results can be expected:
  - Standard Model precision tests
    - $(g-2)_\mu$, η/η' transition form factor, ...
  - Discrete symmetry tests
    - C and CP-voilation, ...
  - Search for η/η' rare decays
  - Search for light BSM particles
  - ... ...

Backup

Beijing Electron Positron Collider II (BEPC II)



2004: BEPCII/BESIII construction
Double-ring e^+e^- collider running in tau-charm energy region
Beam energy: 1-2.3 GeV(1-2.45 GeV since 2019)
Design luminosity: $1 \times 10^{33} cm^{-2} s^{-1}$
2009-today: BESIII physics runs

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)

BESIII Publications on η/η' Decays (continue)

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)
$\eta' \to \pi^+\pi^-\mu^+\mu^-$	Phys. Rev. D 103, 072006 (2021)
$\eta' \to \pi^+\pi^- e^+ e^-$	Phys. Rev. D 103, 092005 (2021)
η branching fractions	Phys. Rev. D 104, 092004 (2021)