Light Meson decay @ BESIII

Isabella Garzia, University of Ferrara and INFN
On behalf of the BESIII Collaboration

July 28 – August 6, 2020
PRAGUE, CZECH REPUBLIC
Light Meson Decay: Physics Highlight

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

### Decay mode

<table>
<thead>
<tr>
<th>Decay mode</th>
<th>Physics Highlight</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\eta \rightarrow \pi^+ \pi^- \pi^0, \pi^0 \pi^0 \pi^0$</td>
<td>$m_u - m_d$, CV (PRD92, 012014)</td>
</tr>
<tr>
<td>$\eta \rightarrow \gamma \gamma$, $\eta \rightarrow \pi^+ \pi^- \gamma$</td>
<td>Excl. BFs measurement</td>
</tr>
<tr>
<td>$\eta/\eta' \rightarrow \gamma \gamma \pi^0$</td>
<td>ChPT (PRD96, 012005)</td>
</tr>
<tr>
<td>$\eta' \rightarrow \gamma e^+ e^-$</td>
<td>Hadron structure (PRD83, 012002)</td>
</tr>
<tr>
<td>$\eta' \rightarrow \pi^+ \pi^- \pi^0, \pi^0 \pi^0 \pi^0$</td>
<td>$m_u - m_d$, CV (PRL118, 012001)</td>
</tr>
<tr>
<td>$\eta' \rightarrow \eta \pi^+ \pi^-, \eta \pi^0 \pi^0$</td>
<td>ChPT (PRD97, 012003)</td>
</tr>
<tr>
<td>$\eta' \rightarrow \mu^+ \mu^- \pi^+ \pi^-$</td>
<td>Box anomaly, CPV</td>
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<tr>
<td>$\mu^+ e^- \pi^+ \pi^-$</td>
<td></td>
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</tbody>
</table>

### Covered in this talk

<table>
<thead>
<tr>
<th>Physics Highlight</th>
<th>Reference paper</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\eta' \rightarrow \pi^0 \pi^0 \pi^0 \pi^0$</td>
<td><strong>PRD101</strong>, 032001 (2020)</td>
</tr>
<tr>
<td>$\eta' \rightarrow \eta \gamma \gamma$</td>
<td><strong>PRD100</strong>, 052015 (2019)</td>
</tr>
<tr>
<td>BFs $\eta'$ decays</td>
<td><strong>PRL122</strong>, 142002 (2019)</td>
</tr>
</tbody>
</table>

**Box anomaly, CPV**
2004: started BEPCII/BESIII construction
✓ Double rings
✓ Beam energy: 1-2.3 GeV
✓ Design luminosity: $1 \times 10^{33}$ cm$^{-2}$s$^{-1}$ @ $\psi(3770)$, achieved in 2016
2009 – today: BESIII physics runs

Beijing Electron Positron Collider II

http://english.ihep.cas.cn
2004: started BEPCII/BESIII construction
✓ Double rings
✓ Beam energy: 1-2.3 GeV
✓ Design luminosity: $1 \times 10^{33} \text{ cm}^{-2}\text{s}^{-1}$ @ $\psi(3770)$, achieved in 2016

2009 – today: BESIII physics runs

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\( \eta/\eta' \) and \( \omega \) from \( J/\psi \) decays

**2009/2012 J/\psi Data Set: 1310M**

NEW J/\psi Data Set available: 10 Billion

* used for future and ongoing analysis

- High production rate of light mesons in J/\psi decays
- Large data sample and unique opportunity to investigate light hadron decays

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

- No absolute BF measurements due to difficulty of tagging its inclusive decays
- $J/\psi \to \gamma \eta'$ with $\gamma$ conversions to $e^+e^-$ ($\times3$ for resolution of the radiative photon)

\[ B(\eta' \to X) = \frac{N_{\text{obs}}^{\eta' \to X} \frac{\varepsilon}{N_{\text{obs}}^{J/\psi \to \gamma \eta'}}}{\varepsilon_{\eta' \to X}} \]

- $\gamma$ detected by EMC

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

Results:

<table>
<thead>
<tr>
<th>Decay mode</th>
<th>$N_{\eta'\to X}^{\text{obs}}$</th>
<th>$\varepsilon_{\eta'\to X}$(%)</th>
<th>$B(\eta'\to X)$ (%)</th>
<th>$B/B(\eta'\to \eta\pi^+\pi^-)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\eta'\to\gamma\pi^+\pi^-$</td>
<td>913 106 ± 1052</td>
<td>44.11</td>
<td>29.90 ± 0.03 ± 0.55</td>
<td>28.9 ± 0.5</td>
</tr>
<tr>
<td>$\eta'\to\eta\pi^+\pi^-$</td>
<td>312 275 ± 570</td>
<td>27.75</td>
<td>41.24 ± 0.08 ± 1.24</td>
<td>42.6 ± 0.7</td>
</tr>
<tr>
<td>$\eta'\to\eta\pi^0\pi^0$</td>
<td>51 680 ± 238</td>
<td>9.08</td>
<td>21.36 ± 0.10 ± 0.92</td>
<td>22.8 ± 0.8</td>
</tr>
<tr>
<td>$\eta'\to\gamma\omega$</td>
<td>22 749 ± 163</td>
<td>14.98</td>
<td>2.489 ± 0.018 ± 0.074</td>
<td>2.62 ± 0.13</td>
</tr>
<tr>
<td>$\eta'\to\gamma\gamma$</td>
<td>70 669 ± 349</td>
<td>43.79</td>
<td>2.331 ± 0.012 ± 0.035</td>
<td>2.22 ± 0.08</td>
</tr>
</tbody>
</table>

- Signal yields obtained from the extended unbinned maximum likelihood fits to the invariant mass distributions
- **First direct measurement of absolute Branching Fractions for five $\eta'$ decay modes**
- $BF(J/\psi\to\gamma\eta') = (5.27\pm0.03\pm0.05)\times10^{-3}$ agrees with PDG
  - Significantly improved precision
- Agreement w.r.t. CLEO’s result within two standard deviation

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PRL 122,142002(2019)

[1] PRD98,030001
Search for $\eta' \rightarrow \pi^0 \pi^0 \pi^0 \pi^0$ rare decay

- Highly suppressed decay due to the S-wave CP violation
- Higher-order contributions involving D-wave pion loop or the production of two $f_2$ tensor mesons allow the decay without violate CP
  - $\text{BF} \sim 10^{-8}$ based on ChPT and VMD model

- At least 9 isolated photons and no charged tracks
- Energy-momentum conservation + mass-constraint for each $\pi^0$
  - $\chi^2_{8C} \leq 30$ for signal events
Search for $\eta' \rightarrow \pi^0 \pi^0 \pi^0 \pi^0$ rare decay

- No significant $\eta'$ signal
- Broad structure around 0.88 GeV/c$^2$ due to $J/\psi \rightarrow \gamma \eta'$, $\eta' \rightarrow \pi^0 \pi^0 \eta$

90% C.L. Upper Limit determined using a Bayesian approach:

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

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

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Search for $\eta' \to \gamma\gamma\eta (\gamma\gamma\pi^0)$ decay

- $\text{BF}(\eta' \to \gamma\gamma\pi^0) = (32.0\pm0.7\pm2.3)\times10^{-4}$ and $\text{BF}(\eta' \to \gamma\gamma\pi^0)\text{no-reso} = (6.16\pm0.64\pm0.67)\times10^{-4}$ measured by BESIII for the first time
- The $\eta' \to \gamma\gamma\eta$ decay has not be observed to date
  - GAMS-4π reported the upper limit of the BF $< 8 \times 10^{-4}$ at 90% C.L.
- **Prediction**: $2.0 \times 10^{-4}$ within the frameworks of the linear $\sigma$ model and VMD model

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

- Signal significance of $2.6\sigma$
Search for $\eta' \rightarrow \gamma \gamma \eta$ decay

- Bayesian method is used to obtain the signal upper limit at 90% C.L.

$$B(\eta' \rightarrow \gamma \gamma \eta) < 1.33 \times 10^{-4}$$

The obtained result is in tension with theoretical prediction
**ω → π⁺π⁻π⁰ Dalitz Plot Analysis**

- Provide further constraints to the calculation of EM form factor of \( ω → π^0γ^* \)
- Test prediction of DP distributions in the dispersive framework (PRD86,054013)
- Estimate crossed-channel effect

\[ J/ψ → ωη, \text{ with } η → γγ \text{ provide a clean sample of } ω \text{ events} \]

- **Dimensionless variables:**
  \[
  x = \frac{t - u}{\sqrt{3}R_ω}, \quad y = \frac{s - s_0}{R_ω} + \frac{2(m_{π^±} - m_{π^0})}{m_ω - 2m_{π^±} - m_{π^0}}
  \]
  \[
  R_ω = 2/3m_ω(m_ω - m_{π^+} - m_{π^-} - m_{π^0})
  \]
  \[
  s_0 = (s + t + u)/3
  \]

- **Polar coordinates (isospin conserving process)**
  \[
  z = |x + yi|^2, \quad φ = \arg(x + yi)
  \]

\[
|\mathcal{M}|^2 = \frac{|\vec{p}_+ \times \vec{p}_-|^2}{m_ω} \cdot |\mathcal{F}|^2.
\]

\[
|\mathcal{F}(z, φ)|^2 \propto 1 + 2αz + 2βz^{3/2} \sin 3φ + 2ζz^2 + 2δz^{5/2} \sin 3φ + \mathcal{O}(z^3),
\]

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\( \omega \rightarrow \pi^+ \pi^- \pi^0 \) Results

\[
|\mathcal{F}|^2 = 1 + 2\alpha z + 2\beta z^{3/2}\sin3\phi
\]
(additional terms consistent with zero)

- Dalitz plot distribution differs from a pure P-wave phase space (18.9\(\sigma\))

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

<table>
<thead>
<tr>
<th>Para. ( \times 10^3 )</th>
<th>Theoretical predictions</th>
<th>Experiment</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>w/o</td>
<td>w</td>
</tr>
<tr>
<td>Fit I ( \alpha )</td>
<td>136</td>
<td>94</td>
</tr>
<tr>
<td>Fit II ( \alpha )</td>
<td>125</td>
<td>84</td>
</tr>
<tr>
<td>( \beta )</td>
<td>30</td>
<td>28</td>
</tr>
</tbody>
</table>

Conclusions

[J/ψ decay provides an excellent laboratory to study light meson decays]

- η/η’ factory:
  - First precision measurement of absolute BFs for five η’ decay modes
  - Search for η’ → π⁰π⁰π⁰π⁰ rare decay
  - Study of doubly-radiative η’ → γγη decays: tension with theoretical prediction

- ω → π⁺π⁻π⁰ Dalitz plot analysis: deviation from a pure P-wave phase space
- … and many other interesting results not covered in this talk

- **10 billion of J/ψ data collected at BESIII**
  - This huge data sample allows to study light meson decays with unprecedent statistics
  - More interesting results are expected
Back-up slides
**The BESIII Detector**


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**Electromagnetic CsI(Tl) Calorimeter**

- $\sigma_{E/E} < 2.5\%$ @ 1 GeV (barrel)
- $\sigma_{E/E} < 5\%$ @ 1 GeV (end caps)
- $\sigma_{xy} \sim (6 \text{ mm})/E^{1/2}$ @ 1 GeV

**RPC Muon Detector**

- $\Delta\Omega/4\pi = 93\%$

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**Drift Chamber**

- $\sigma_{r\phi} \sim 130 \mu\text{m}$ (single wire)
- $\sigma_{pt}/p_t \sim 0.5\% @ 1 \text{ GeV}$

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**ToF**

- $\sigma_t \sim 90 \text{ ps}$ (barrel)
- $\sigma_t \sim 120 \text{ ps}$ (end caps)

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BESIII physics programme

**Light hadron physics**
- Meson and baryon spectroscopy
- Multiquark states
- Threshold effects
- Glueballs and hybrids
- Two-photon physics
- Form factors

**QCD and τ**
- Precision R measurement
- τ decay

**Charmonium physics**
- Precision spectroscopy
- Transitions and decays

**XYZ meson physics**
- Y(4260), Y(4360) properties
- Z_c(3900)^+, ...

**Charm physics**
- Semi-leptonic form factors
- Decay constants f_D and f_{D_s}
- CKM matrix: |V_{cd}| and |V_{cs}|
- D^0-\overline{D^0} mixing, CPV
- Strong phases

**Precision mass measurements**
- τ mass
- D, D^* mass

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<table>
<thead>
<tr>
<th>Decay modes</th>
<th>Reference</th>
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<tbody>
<tr>
<td>$\eta' \rightarrow \pi^+\pi^-\eta$</td>
<td>PRD 83,012003 (2011)</td>
</tr>
<tr>
<td>$\eta/\eta' \rightarrow \pi^+\pi^-, \pi^0\pi^0$</td>
<td>PRD 84, 032006(2011)</td>
</tr>
<tr>
<td>$\eta' \rightarrow \eta/\eta' \rightarrow \pi^+, \pi^0\pi^0\pi^0$</td>
<td>PRL 108, 182001(2012)</td>
</tr>
<tr>
<td>$\eta/\eta' \rightarrow \text{invisible}$</td>
<td>PRD 87, 012009(2013)</td>
</tr>
<tr>
<td>$\eta/\eta' \rightarrow \pi^+\text{ev}$</td>
<td>PRD 87, 032006(2013)</td>
</tr>
<tr>
<td>$\eta' \rightarrow 3(\pi^+\pi^-)$</td>
<td>PRD 88, 091502(2013)</td>
</tr>
<tr>
<td>$\eta' \rightarrow 2(\pi^+\pi^-), \pi^+\pi^-\pi^0\pi^0$</td>
<td>PRL 112, 251801(2014)</td>
</tr>
<tr>
<td>$\eta' \rightarrow \gamma \text{ e}^+\text{e}^-$</td>
<td>PRD 92, 012001(2015)</td>
</tr>
<tr>
<td>$\eta \rightarrow \pi^+\pi^-\pi^0, \eta/\eta' \rightarrow \pi^0\pi^0\pi^0$</td>
<td>PRD 92, 012014(2015)</td>
</tr>
<tr>
<td>$\eta \rightarrow \omega\text{ e}^+\text{e}^-$</td>
<td>PRD 92, 051101(2015)</td>
</tr>
<tr>
<td>$\eta' \rightarrow K\pi$</td>
<td>PRD 93, 072008(2016)</td>
</tr>
<tr>
<td>$\eta' \rightarrow \rho\pi$</td>
<td>PRL 118, 012001(2017)</td>
</tr>
<tr>
<td>$\eta' \rightarrow \gamma\gamma\pi^0$</td>
<td>PRD 96, 012005(2017)</td>
</tr>
<tr>
<td>$\eta' \rightarrow \gamma \pi^+\pi^-$</td>
<td>PRL 120, 242003(2018)</td>
</tr>
<tr>
<td>$\eta' \rightarrow \eta\pi^+\pi^-, \eta\pi^0\pi^0$</td>
<td>PRD 97, 012003(2018)</td>
</tr>
</tbody>
</table>
First observation of $\eta' \rightarrow \pi^+\pi^-\pi^+\pi^-, \pi^+\pi^-\pi^0\pi^0$

- $\eta' \rightarrow 4\pi$ suppressed by tiny phase space
- Only $\eta \rightarrow 4\pi^0$ is kinematically allowed
- ChPT: the amplitude goes to zero at leading order; non-zero contributions only at $O(p^6)$

ChPT+VMD:

$B(\eta' \rightarrow 2(\pi^+\pi^-)) = (1.0 \pm 0.3) \times 10^{-4}$,

$B(\eta' \rightarrow \pi^+\pi^-2\pi^0) = (2.4 \pm 0.7) \times 10^{-4}$.

PRL 112, 251801(2014): FIRST OBSERVATION

Using $1.3 \times 10^9$ $J/\psi$ events: $J/\psi \rightarrow \gamma \eta'$, $\eta' \rightarrow \pi^+\pi^-\pi^+\pi^-$
199$\pm$16 events for $\pi^+\pi^-\pi^+\pi^-$ and 84$\pm$16 events for $\pi^+\pi^-\pi^0\pi^0$

Background corrected $\eta'$ events vs. 38 $M_{\pi^+\pi^-}$ bins (4 entries per events)

ChPT+VDM provides a good description of data
First observation of $\eta' \rightarrow \pi^+\pi^-\pi^+\pi^-$, $\pi^+\pi^-\pi^0\pi^0$

- $\eta' \rightarrow 4\pi$ suppressed by tiny phase space
- Only $\eta \rightarrow 4\pi^0$ is kinematically allowed
- ChPT: the amplitude goes to zero at leading order; non-zero contributions only at $O(p^6)$

Good agreement between BESIII measurements and ChPT+VDM predictions

\[ B(\eta' \rightarrow 2(\pi^+\pi^-)) = (1.0 \pm 0.3) \times 10^{-4}, \]
\[ B(\eta' \rightarrow \pi^+\pi^-2\pi^0) = (2.4 \pm 0.7) \times 10^{-4}. \]

\[ B(\eta' \rightarrow \pi^+\pi^-\pi^+\pi^-) = (8.53 \pm 0.69 \pm 0.64) \times 10^{-5} \]
\[ B(\eta' \rightarrow \pi^+\pi^-\pi^0\pi^0) = (1.82 \pm 0.35 \pm 0.18) \times 10^{-4} \]
Matrix elements for the decay $\eta \rightarrow \pi^+\pi^-\pi^0$, $\eta/\eta' \rightarrow \pi^0\pi^0\pi^0$

$\eta/\eta' \rightarrow \pi\pi\pi$ is an isospin-violating process

- Electromagnetic contribution is strongly suppressed $\Rightarrow$ the decays are induced dominantly by strong interaction via explicit breaking of chiral symmetry by the u-d mass difference
  - Unique opportunity to investigate fundamental symmetries
  - Test chiral perturbation theory (ChPT) and other models
- Measurement of the matrix elements for $\eta/\eta'$ decays into $3\pi$ are fundamental
  - Two variables needed to describe a three-body decay: two of the pion energies in the $\eta/\eta'$ rest frame ($E_+, E_-, E_0$)

**Decay amplitude**

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

$X = \frac{\sqrt{3}}{Q} (E_{\pi^+} - E_{\pi^-}); \quad Y = 3 \frac{E_0 - m_0}{Q} - 1$

$\left| A(X, Y) \right|^2 = N (1 + a Y + b Y^2 + c X + e X Y + f Y^3 + ...)$

Odd power of $X$: charge conjugation violation

$\eta/\eta' \rightarrow \pi^0\pi^0\pi^0$

$Z = X^2 + Y^2 = \frac{2}{3} \sum_{i=1}^{3} \left( \frac{3T_i}{Q} - 1 \right)^2$

$\left| A(Z) \right|^2 = N (1 + 2aZ + ...)$

$\alpha \neq 0$: final state interaction
Matrix elements for $\eta \rightarrow \pi^+\pi^-\pi^0$  

$J/\psi \rightarrow \gamma \eta$, $\eta \rightarrow \pi^+\pi^-\pi^0$ and $\pi^0 \rightarrow \gamma\gamma$  

- Clear $\eta$ signal: 79625 events selected  
- Very small background: 0.2% from $\eta$ sidebands with no peaking bkg.

The Dalitz plot matrix elements of decay amplitude are obtained from unbinned maximum likelihood to data

$$P = \frac{\langle |A(X,Y)|^2 \otimes \sigma(X,Y) \rangle \epsilon(X,Y)}{\int_{DP} \langle |A(X,Y)|^2 \otimes \sigma(X,Y) \rangle \epsilon(X,Y) dX dY}$$

$$-\ln \mathcal{L} = - \sum_{i=1}^{N_{\text{event}}} \ln P(X_i, Y_i)$$

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Matrix elements for $\eta \rightarrow \pi^+\pi^-\pi^0$: RESULTS comparison

- $a = -1.128 \pm 0.015$,
- $b = 0.153 \pm 0.017$,
- $c = (0.047 \pm 0.851) \times 10^{-2}$,
- $d = 0.085 \pm 0.016$,
- $e = 0.017 \pm 0.019$,
- $f = 0.173 \pm 0.028$.

$c$ and $e$ parameters consistent with zero: no charge conjugation violation

- Good agreement with previous measurements within two standard deviations
- Parameters $a$, $b$, $d$, and $f$ almost are almost unchanged assuming or not charge parity violation in the decay
- Results consistent with dispersive approach and ChPT at NNLO
Matrix elements for $\eta/\eta' \rightarrow \pi^0\pi^0\pi^0$

\[ J/\psi \rightarrow \gamma\eta, \eta \rightarrow \pi^0\pi^0\pi^0 \text{ and } \pi^0 \rightarrow \gamma\gamma \]

- 33908 $\eta$ events selected
- $0<Z<0.7$ used to extract the slope parameter $\alpha$ (PHSP region in which $Z$ distribution is flat)
- Low bkg level < 1%

\[ J/\psi \rightarrow \gamma\eta', \eta' \rightarrow \pi^0\pi^0\pi^0 \text{ and } \pi^0 \rightarrow \gamma\gamma \]

- 1888 $\eta'$ events selected
- $0<Z<0.45$
- $\eta' \rightarrow \gamma\pi^0\pi^0$ bkg and $\eta'$ sidebands taken into account (11.2%)

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Matrix elements for $\eta/\eta' \rightarrow \pi^0\pi^0\pi^0$: RESULTS

$$\alpha_{\text{BESIII}}^{\eta \rightarrow \pi_0\pi_0\pi_0} = -0.055 \pm 0.014 \pm 0.004$$

$$\alpha_{\text{BESIII}}^{\eta' \rightarrow \pi_0\pi_0\pi_0} = -0.640 \pm 0.046 \pm 0.047$$

- Significant deviation from zero
  - This implies that the final-state interactions play an important role in the decay
- Few theoretical predictions for $\alpha_{\eta' \rightarrow \pi_0\pi_0\pi_0}$: agrees with prediction done in reference EPJA26, 383, in which a chiral unitary approach is used.
Amplitude analysis of $\eta' \rightarrow \pi^+\pi^-\pi^0$, $\pi^0\pi^0\pi^0$

- $\eta' \rightarrow \pi^+\pi^-\pi^0$
  - 8267 events selected
  - Two clusters corresponding to $\eta' \rightarrow \rho^\pm\pi^\mp$
  - Bkg from $\eta' \rightarrow \gamma\rho$ with $\rho \rightarrow \pi\pi/\gamma\pi\pi$, non-peaking process $J/\psi \rightarrow \pi^+\pi^-\pi^0\pi^0$

- $\eta' \rightarrow \pi^0\pi^0\pi^0$
  - 2237 events selected
  - Low bkg level from inclusive MC sample
  - Bkg from $J/\psi \rightarrow \gamma\eta'$ with $\eta' \rightarrow \eta\pi^0\pi^0$, non-peaking process $J/\psi \rightarrow \gamma\pi^0\pi^0\pi^0$

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PRL118, 012001(2017)
Amplitude analysis of $\eta' \rightarrow \pi^+\pi^-\pi^0, \pi^0\pi^0\pi^0$

Isobar model is used to perform a Dalitz plot analysis (PRD83, 074004)

- Unbinned maximum likelihood fit using both $\pi^+\pi^-\pi^0$ and $\pi^0\pi^0\pi^0$
- Data is well described by three components:
  1. P-wave ($\rho^\pm\pi^\mp$)
  2. Resonant S-wave ($\sigma\pi^0$)
  3. Phase space S-wave ($\pi\pi\pi$)
- Sensitivity only to the sum of the S-wave component: large interference between the two components which strongly depends on the $\sigma$ parameterization

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

<table>
<thead>
<tr>
<th>Decay mode</th>
<th>$\mathcal{B}$ ($10^{-4}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\pi^+\pi^-\pi^0$</td>
<td>35.91±0.54±1.74</td>
</tr>
<tr>
<td>$\pi^0\pi^0\pi^0$</td>
<td>35.22±0.82±2.54</td>
</tr>
<tr>
<td>$\rho^\pm\pi^\mp$</td>
<td>7.44±0.60±1.26±1.84</td>
</tr>
<tr>
<td>$(\pi^+\pi^-\pi^0)_S$</td>
<td>37.63±0.77±2.22±4.48</td>
</tr>
</tbody>
</table>

- Results in good agreement with previous BESIII results (PRL 108, 182001 (2012))
- $\mathcal{B}(\eta' \rightarrow \pi^0\pi^0\pi^0)/\mathcal{B}(\eta' \rightarrow \pi^+\pi^-\pi^0)_S = 0.94±0.03±0.13$
- $r_\pm = (8.77±1.19) \times 10^{-3}$ and $r_0 = (15.86±1.33) \times 10^{-3}$ ($r_0$ about two times larger than $r_\pm$)

Two times larger than GAMS measurements $(16.0±3.2) \times 10^{-4}$
(Z. Phys. C 36,603 (1987))
Doubly radiative $\eta'\rightarrow\gamma\gamma\pi^0$ decay

- $\eta'\rightarrow\gamma\gamma\pi^0$ studied in the Linear $\sigma$ Model (L$\sigma$M) and VMD framework
- **First measurements** (1.3x10$^9$ $J/\psi$ events: $J/\psi\rightarrow\gamma\eta'$, $\eta'\rightarrow\gamma\gamma\pi^0$)
  - Non-resonant $\eta'\rightarrow\gamma\gamma\pi^0$ simulated using VMD model with $\rho(1450)$- or $\omega(1650)$- exchange
  - A fit to the $\gamma\gamma\pi^0$ invariant mass distribution is performed to determined inclusive $\eta'\rightarrow\gamma\gamma\pi^0$ signal yield

Signal shape from MC
(incoherent mixture of $\rho$, $\omega$, and non-resonant components)

Class-I bkg: $J/\psi\rightarrow\gamma\eta'$ with $\eta'$ decaying into other final states other than the signal final state

Class-II bkg: $J/\psi$ decays without $\eta'$ ($J/\psi\rightarrow\gamma\pi^0\pi^0$ and $J/\psi\rightarrow\omega\eta$ with $\omega\rightarrow\gamma\pi^0$ and $\eta\rightarrow\gamma\gamma$)
**Doubly radiative $\eta' \rightarrow \gamma\gamma\pi^0$ decay**

The $\gamma\pi^0$ invariant mass spectra is fitted in order to extract the non-resonant contributions

- $|M_{\gamma\pi^0} - M_{\eta'}| < 25$ MeV/c$^2$

\[
pdf = f \cdot G(0, \sigma) \otimes [\epsilon(M_{\gamma\pi^0}) \times E_{\gamma\eta'}^3 \times E_{\gamma\omega(\rho)}^3 \times |\text{BW}_\omega(M_{\gamma\pi^0}) + \alpha e^{i\theta} \text{BW}_\rho(M_{\gamma\pi^0})|^2 \times B_{\eta'}^2 \times B_{\omega(\rho)}^2] + (1 - f) \cdot pdf_{comb-bkg} + N_{\text{non-reso}} \cdot pdf_{\text{non-reso}} + N_{bkg} \cdot pdf_{bkg}
\]

(b) C. Patrignani et al., Chin. Phys. C 40, 100001 (2016)
(c) D. Alde et al. (GAMS-2000), Z. Phys. C 36, 603 (1987)

<table>
<thead>
<tr>
<th>Decay mode</th>
<th>$\mathcal{B}_{\text{BESIII}} \left(10^{-4}\right)$</th>
<th>$\mathcal{B}_{\text{PDG}} \left(10^{-4}\right)$</th>
<th>$\mathcal{B}_{\text{th}} \left(10^{-4}\right)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$(\eta' \rightarrow \gamma\gamma\pi^0)_{\text{incl.}}$</td>
<td>$32.0 \pm 0.7 \pm 2.3$</td>
<td>-</td>
<td>57–65 (LσM+VMD)</td>
</tr>
<tr>
<td>$\eta' \rightarrow \gamma\omega \rightarrow \gamma\gamma\pi^0$</td>
<td>$23.7 \pm 0.7 \pm 1.8$</td>
<td>$21.7 \pm 1.3$</td>
<td></td>
</tr>
<tr>
<td>$(\eta' \rightarrow \gamma\gamma\pi^0)_{\text{non-reso}}$</td>
<td>$6.16 \pm 0.64 \pm 0.67$</td>
<td>$&lt; 80 \text{ @ 90% C.L.}$</td>
<td></td>
</tr>
</tbody>
</table>

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

- $a_0(980)$ - $f_0(980)$ still controversial explanation about their nature
- Direct measure of the $f_0(980)$ - $a_0(980)$ mixing in the process proposed in 1979 [PLB88,367]

$J/\psi \rightarrow \phi f_0(980) \rightarrow \phi a^0_0(980) \rightarrow \phi \eta \pi^0$ and $\chi_{c1} \rightarrow \pi^0 a^0_0(980) \rightarrow \pi^0 f_0(980) \rightarrow \pi^0 \pi^+\pi^-$ (isospin violating decays)

Constructive interference

Destructive interference

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Mixing intensities:

\[
\xi_{fa} = \frac{B[J/\psi \to \phi f_0(980) \to \phi a_0^0(980) \to \phi \eta \pi^0]}{B[J/\psi \to \phi f_0(980) \to \phi \pi \pi]},
\]

\[
\xi_{af} = \frac{B[\chi_{c1} \to \pi^0 a_0^0(980) \to \pi^0 f_0(980) \to \pi^0 \pi^+ \pi^-]}{B[\chi_{c1} \to \pi^0 a_0^0(980) \to \pi^0 \pi^0 \eta]}.
\]

<table>
<thead>
<tr>
<th>Channel</th>
<th>Solution I</th>
<th>Solution II</th>
<th>$a_0^0(980) \to f_0(980)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B$ (mixing) ($10^{-6}$)</td>
<td>$3.18 \pm 0.51 \pm 0.38 \pm 0.28$</td>
<td>$1.31 \pm 0.41 \pm 0.39 \pm 0.43$</td>
<td>$0.35 \pm 0.06 \pm 0.03 \pm 0.06$</td>
</tr>
<tr>
<td>$B$ (EM) ($10^{-6}$)</td>
<td>$3.25 \pm 1.08 \pm 1.08 \pm 1.12$</td>
<td>$2.62 \pm 1.02 \pm 1.13 \pm 0.48$</td>
<td>$\cdots$</td>
</tr>
<tr>
<td>$B$ (total) ($10^{-6}$)</td>
<td>$4.93 \pm 1.01 \pm 0.96 \pm 1.09$</td>
<td>$4.37 \pm 0.97 \pm 0.94 \pm 0.06$</td>
<td>$\cdots$</td>
</tr>
<tr>
<td>$\xi$ (%)</td>
<td>$0.99 \pm 0.16 \pm 0.30 \pm 0.09$</td>
<td>$0.41 \pm 0.13 \pm 0.17 \pm 0.13$</td>
<td>$0.40 \pm 0.07 \pm 0.14 \pm 0.07$</td>
</tr>
</tbody>
</table>

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