Light Meson Decays at BESIII

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On behalf of the BESIII collaboration

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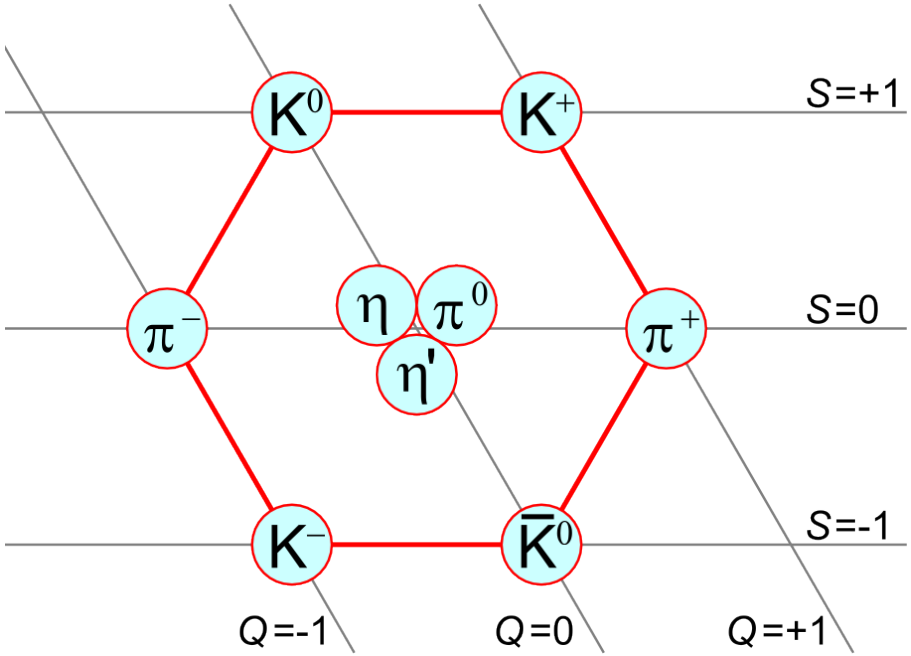
Why η/η'?

- Probe low energy QCD
  → Test predictions of ChPT, VMD, e.t.c.
- Light quark mass difference
- C, P, CP, G eigenstates
  → Test discrete symmetries
- EM and strong decays forbidden at lowest order
  → Very narrow, easy to reconstruct
  → New physics contributions enhanced



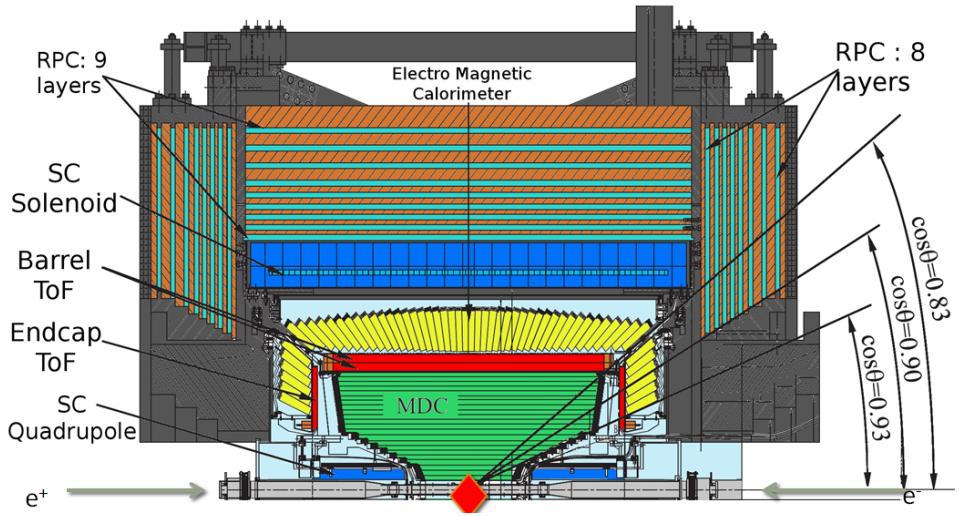
BESIII at BEPCII

Beijing Electron-Positron Collider (BEPCII)

- CMS Energy from 2 to 4.95 GeV/c^2
- Design luminosity 10^{33} cm^{-2}s^{-1}

Beijing Spectrometer (BESIII)

- Near 4π coverage
- Helium-gas drift chamber
- CsI(Tl) crystal calorimeter
- MRPC TOF-system
- 1 T super-conducting solenoid
- RPC-based muon chamber
- World's largest datasets at:
  - J/ψ: 10B events
    (here results from 1.3B)



Mode	$\mathcal{B}$ $[\times 10^{-4}]$	N
$J/\psi \to$		
$\gamma\eta'$	52.5 ± 0.7	5.25×10^7
$\gamma\eta$	11.08 ± 0.27	1.08×10^7

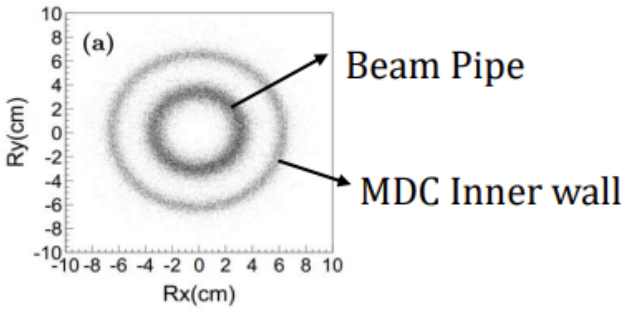
Since PANIC 2017

Many interesting BESIII results since the last PANIC:

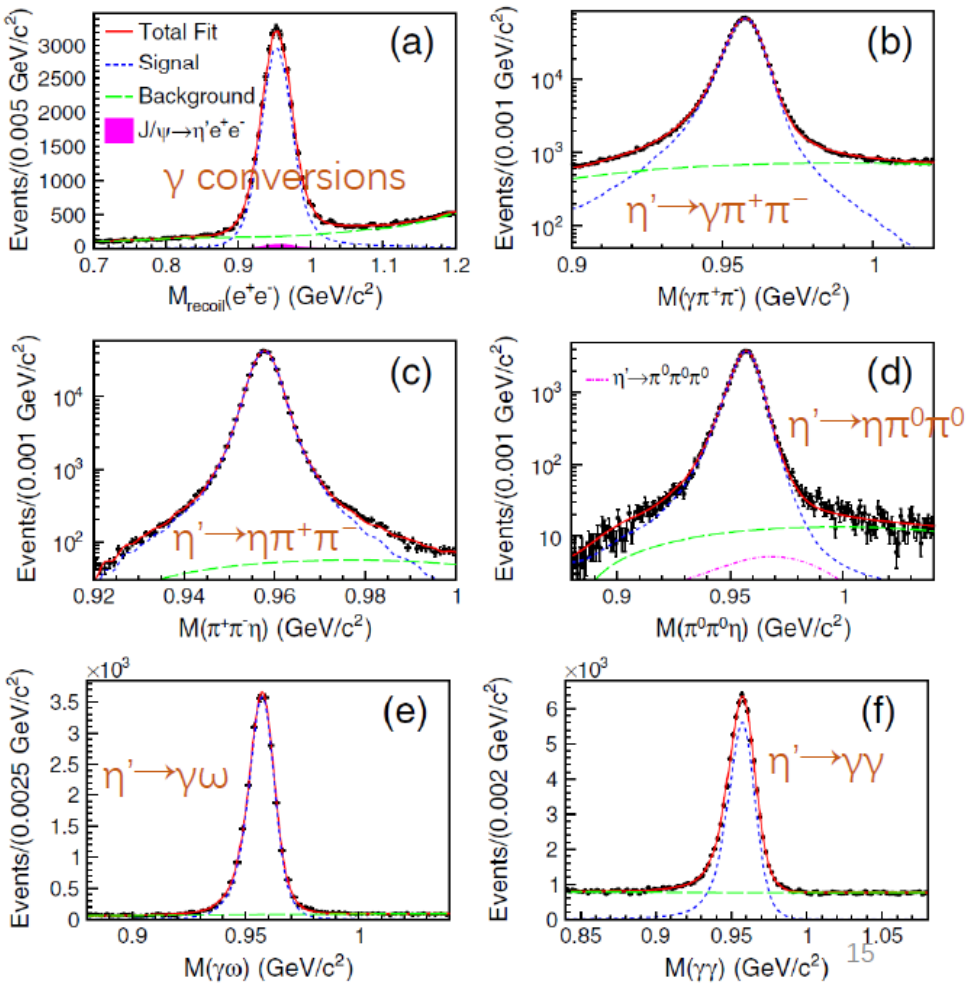
- Precision Study of $\eta' \to \gamma\pi^+\pi^-$ Decay Dynamics PRL 120,242003 (2018)
- Measurement of the matrix elements for the decays $\eta' \to \eta\pi^+\pi^-\eta$ and $\eta' \to \eta\pi^0\pi^0\eta$ PRD 97, 012003 (2018)
- Dalitz plot analysis of the decay $\omega \to \pi^+\pi^-\pi^0$ PRD 98, 112007 (2018)
- Observation of $a_0^0(980) - f_0(980)$ Mixing PRL 121, 022001(2018)
- Precision Measurement of the Branching Fractions of η' Decays PRL 122, 142002(2019)
- Search for the decay $\eta' \to \gamma\gamma\eta$ PRD 100, 052015(2019)
- Search for the rare decay $\eta' \to \pi^0\pi^0\pi^0\pi^0$ PRD 101, 032001(2020)
- Observation of $\eta' \to \pi^+\pi^-e^+e^-$ PRD 103, 072006(2021)
- Measurement of the branching fraction of and search for a CP-violating asymmetry in $\eta' \to \pi^+\pi^-e^+e^-$ PRD 103, 092005(2021)

Absolute Branching Fractions of η' Decays

- Important e.g. as normalization for the study of rare decays.
- Prerequisite for measuring invisible decays
- **Challenge:** Tagging inclusive decays
- **Solution:** Tag $J/\psi \to \gamma\eta'$ through conversion of radiative photon!
  $\to$ Better energy resolution than EMC.



$$\mathcal{B}(\eta' \to X) = \underbrace{\frac{N_{\eta' \to X}}{\epsilon_{\eta' \to X}}}_{\text{Using EMC}} \underbrace{\frac{\epsilon}{N_{J/\psi \to \gamma\eta'}} f}_{\text{Using conversion}}$$



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PRL 122, 142002(2019)

Absolute Branching Fractions of η' Decays

Mode	N	$\mathcal{B}(\%)$ (this work)	$\mathcal{B}(\%)$ (PDG previous)
$\eta' \to \gamma\pi^+\pi^-$	913106 ± 1052	$29.90 \pm 0.03 \pm 0.55$	28.9 ± 0.5
$\eta' \to \eta\pi^+\pi^-$	312275 ± 570	$41.24 \pm 0.08 \pm 1.24$	42.6 ± 0.7
$\eta' \to \eta\pi^0\pi^0$	51680 ± 238	$21.36 \pm 0.10 \pm 0.92$	22.8 ± 0.8
$\eta' \to \gamma\omega$	22749 ± 163	$2.489 \pm 0.018 \pm 0.074$	2.62 ± 0.013
$\eta' \to \gamma\gamma$	70669 ± 349	$2.331 \pm 0.012 \pm 0.035$	2.22 ± 0.08
$J/\psi \to \gamma\eta'$	35980 ± 234	$0.527 \pm 0.003 \pm 0.005$	0.513 ± 0.017

Relative BFs in good agreement with results from CLEO

PRD 79, 111101(R)(2009)

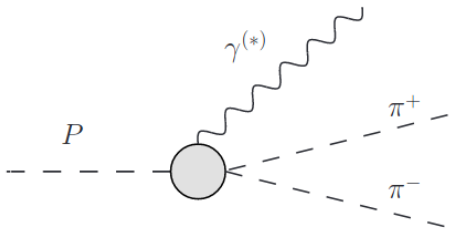
PRL 122, 142002(2019)

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

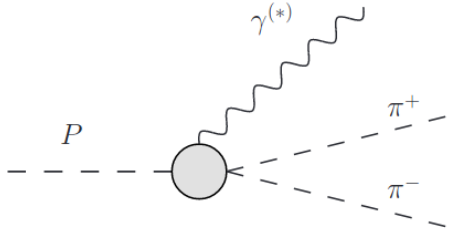
- Proceeds via intermediate virtual photon $\eta' \to \pi^+\pi^-\gamma^* \to \pi^+\pi^-e^+e^-$.
- Contribution from WZW box anomaly.
  Phys. Lett. B 37: 95-97 (1971), Nucl. Phys. B; 223: 422-432 (1983)
- Possible BSM contribution from CP-violating electric dipole transition
  - Interference term prop. to $\sin 2\varphi$

$$\mathcal{A}_{CP} =< \mathrm{sgn}(\sin 2\varphi) >= \frac{1}{\Gamma}\int_0^{2\pi} \frac{d\Gamma}{d\varphi}\,\mathrm{sgn}(\sin 2\varphi)\,d\varphi$$

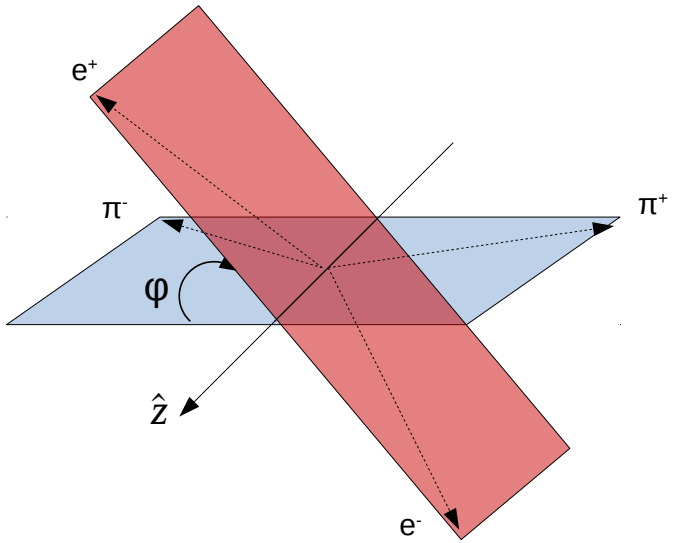
Mod. Phys. Lett.A17, 1489 (2002), Mod. Phys. Lett. A17, 1583 (2002)



M_1 (*CP conserving*)



E_1 (*CP violating*)

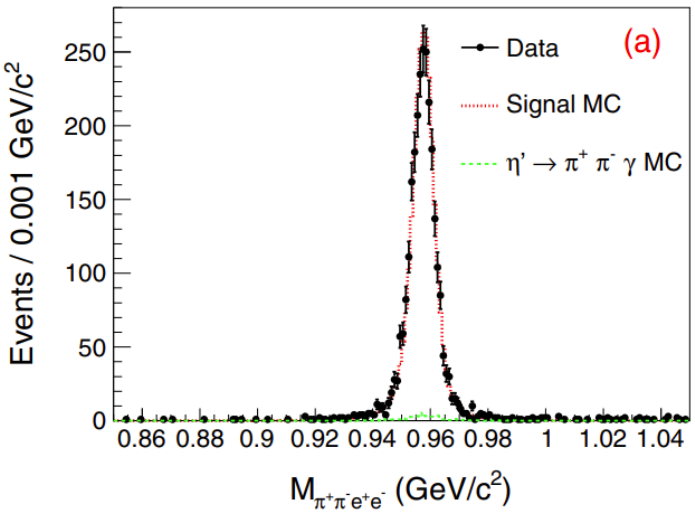


Branching Fraction of $\eta' \to \pi^+\pi^-e^+e^-$

With 225M J/ψ BESIII measured:
$\mathcal{B}(\eta' \to \pi^+\pi^-e^+e^-) = (2.11 \pm 0.12_{stat.} \pm 0.15_{syst.}) \times 10^{-3}$ (PRD 87 (2013) 092011)

Predictions:

Model	$\mathcal{B}$ (10^{-3})	Ref.
Hidden gauge (VMD)	2.17 ± 0.21	arXiv:1010.2378
Modified VMD	2.27 ± 0.13	arXiv:1010.2378
ChPT	$2.13^{+0.17}_{-0.31}$	EPJ. A33,95(2007)



New BESIII analysis based on 1.31B J/ψ

- 2584 ± 52 signal events
- $\sim 2\%$ background from $\eta' \to \pi^+\pi^-\gamma$ via photon conversion
- $\eta' \to \pi^+\pi^-\gamma$ measured for normalization

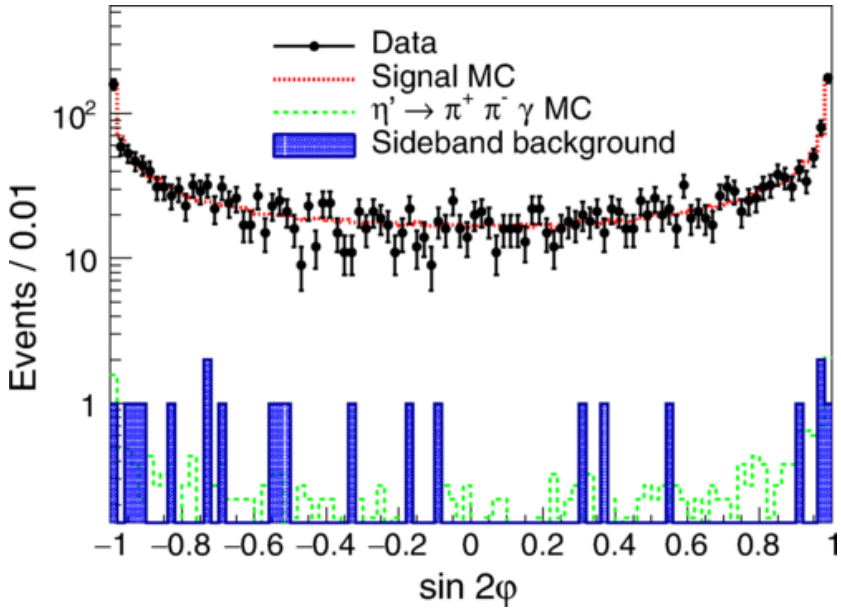
$$\mathcal{B}(\eta' \to \pi^+\pi^-e^+e^-) = (2.42 \pm 0.05_{stat.} \pm 0.08_{syst.}) \times 10^{-3}$$

PRD 103, 092005(2021)

CP-Violation in $\eta' \to \pi^+\pi^-e^+e^-$

- First measurement of asymmetry in $\eta' \to \pi^+\pi^-e^+e^-$.
- Comparable precision to measurement of CP-asymmetry in $K_L \to \pi^+\pi^-e^+e^-$ PRL. 84, 408 (2000)

Region	ε[%]	Yield
$\sin 2\varphi > 0$	15.95 ± 0.02	1331 ± 40
$\sin 2\varphi < 0$	15.93 ± 0.02	1287 ± 37



$$\mathcal{A}_{CP} = \frac{N(\sin 2\varphi>0) - N(\sin 2\varphi<0)}{N(\sin 2\varphi>0) + N(\sin 2\varphi<0)} = (2.9 \pm 3.7_{\text{stat.}} \pm 1.1_{\text{syst.}}) \times 10^{-2}$$

Consistent with zero with 0.04 precision. No CP-violation observed.

PRD 103, 092005(2021)

First observation of $\eta' \to \pi^+\pi^-\mu^+\mu^-$

Predictions:

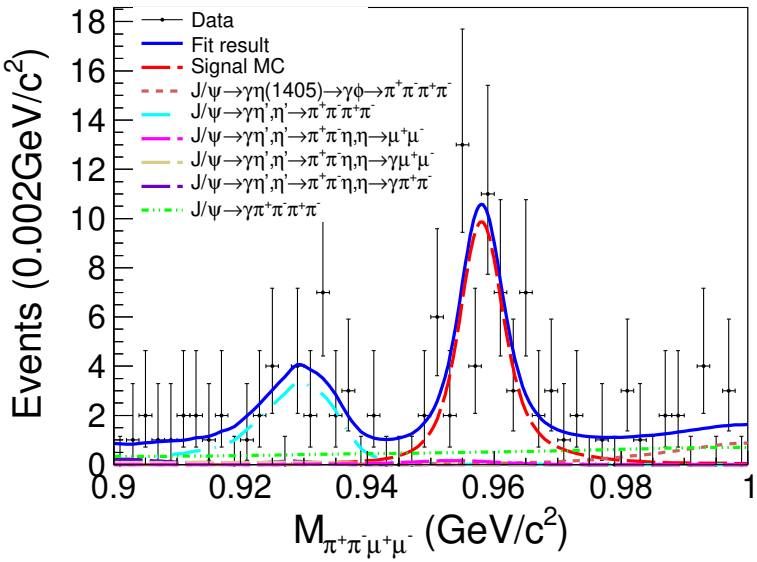
Model	$\mathcal{B}$ (10^{-5})	Ref.
Hidden gauge (VMD)	2.20 ± 0.30	arXiv:1010.2378
Modified VMD	2.41 ± 0.25	arXiv:1010.2378
ChPT	$1.57^{+0.96}_{-0.75}$	EPJ. A33, 95(2007)

Previous UL from BESIII with 225M J/ψ events:
$\mathcal{B}(\eta' \to \pi^+\pi^-\mu^+\mu^-) < 2.9 \times 10^{-5}$. (PRD87, 092011 (2013))

New BESIII analysis with 1.31×10^9 J/ψ

- 53 ± 9 signal events observed
- 8σ significance
- Good agreement with predictions

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



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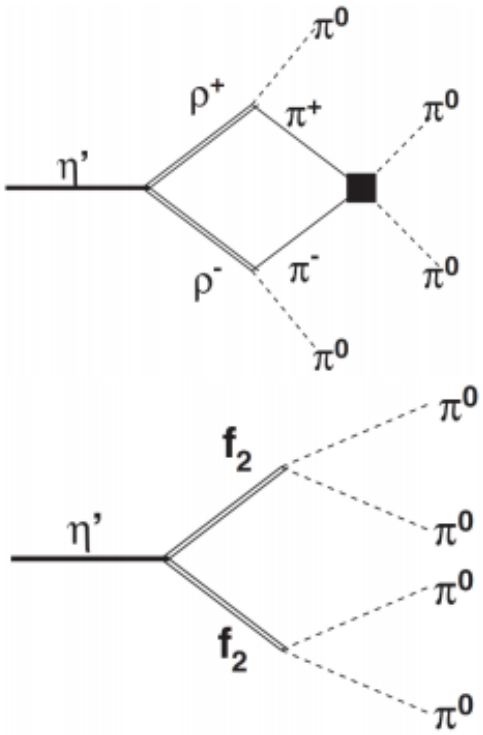
PRD 103, 072006(2021)

Search for $\eta' \to 4\pi^0$

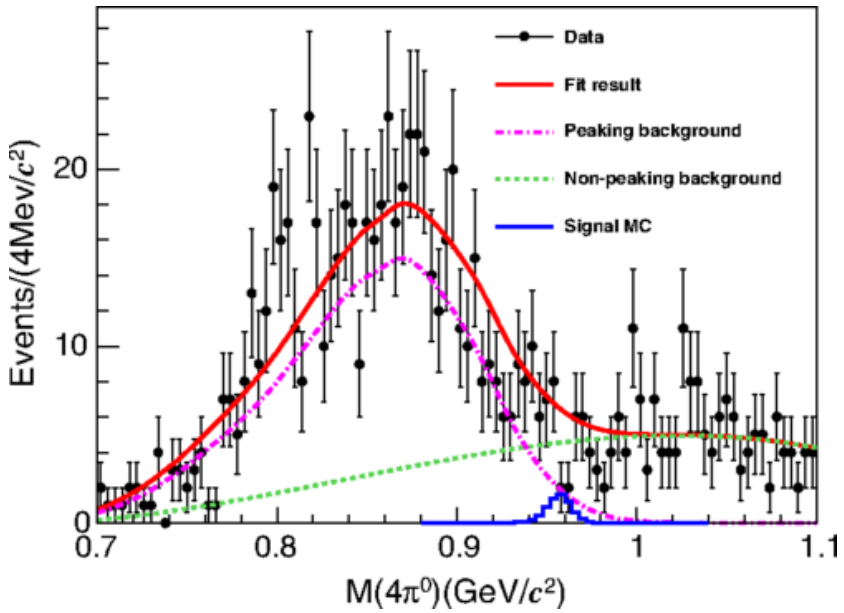
- S-wave contribution violates CP.
  $\to$ Constrained by strong CP θ
  $\mathcal{B} \sim 10^{-23}$
- CP conserved at higher orders

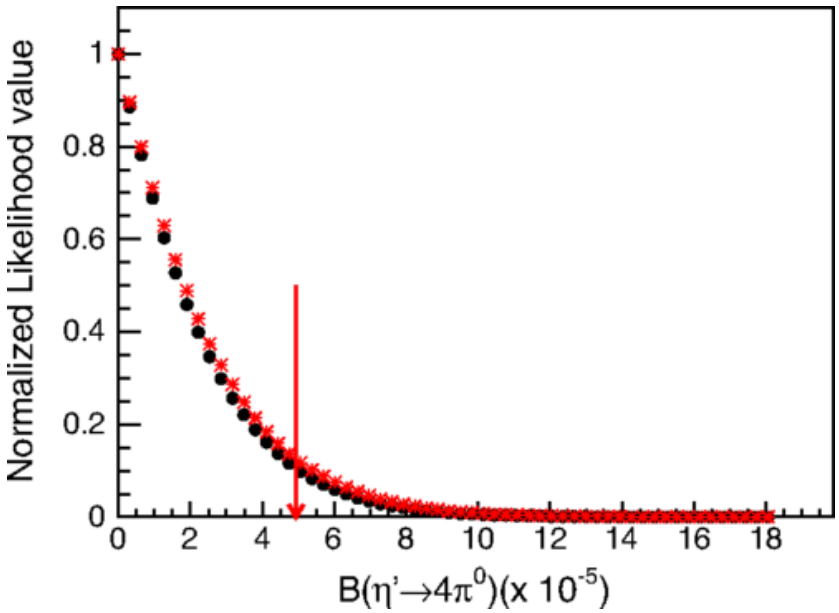
  PRD 85, 014014 (2012)
  - Pion-loop contribution
    $\mathcal{B} \sim 4 \times 10^{-8}$
  - f_2 contribution possible but comparatively negligible.
- Previous upper limit from GAMS-4π
  $\mathcal{B}(\eta' \to 4\pi^0) < 3.2 \times 10^{-4}$
  Mod. Phys. Lett. A 29, 1450213 (2014)



Search for $\eta' \to 4\pi^0$

Based on 1.31×10^9 J/ψ events
Main background from $J/\psi \to \gamma\eta'$, $\eta' \to \pi^0\pi^0\eta$, $\eta \to \pi^0\pi^0\pi^0$
No significant signal observed





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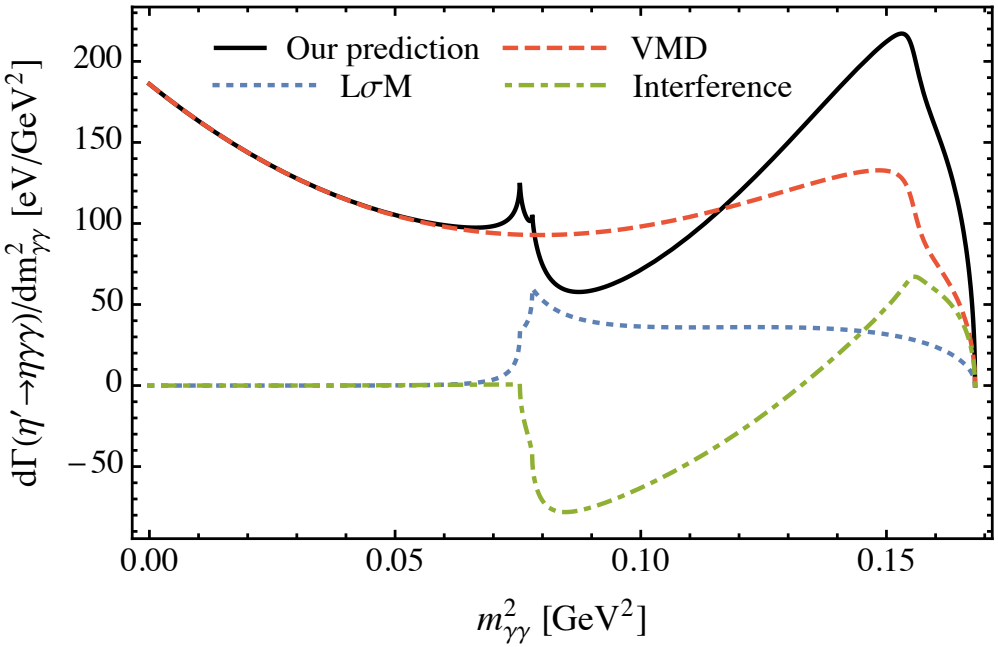
$\mathcal{B}(\eta' \to 4\pi^0) < 4.94 \times 10^{-5}$ at 90 % C.L.
$\sim$ Six times smaller than previous best limit

PRD 101, 032001(2020)

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

- Probes higher-order ChPT
- Contributions from intermediate vector and scalar mesons
- LσM+VMD prediction $\mathcal{B}(\eta' \to \gamma\gamma\eta) = 2.0 \times 10^{-4}$
  PRD 102, 034026 (2020)



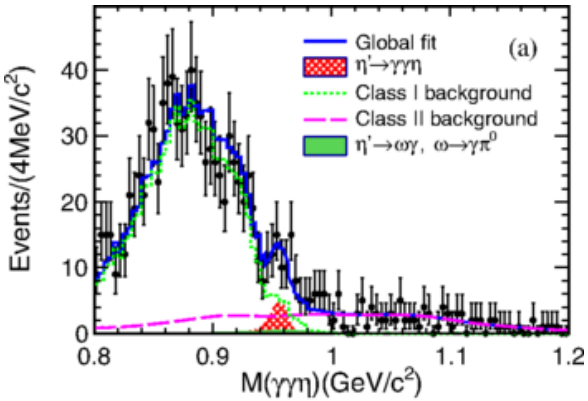
- Previous limit from GAMS-4π $\mathcal{B}(\eta' \to \gamma\gamma\eta) < 8 \times 10^{-3}$ at 90% CL
  Phys. Atom. Nucl. 78, 1043 (2015)

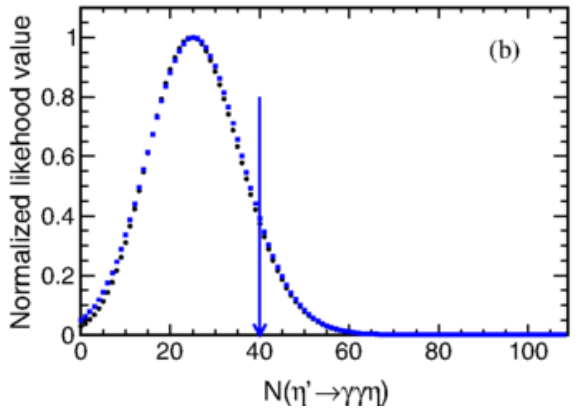
Search for $\eta' \to \gamma\gamma\eta$

- Based on $1.31 \times 10^9 J/\psi$
- Main background from
  $J/\psi \to \gamma\eta'$, $\eta' \to \pi^0\pi^0\eta$
  $J/\psi \to \gamma\eta', \eta' \to \gamma\omega$, $\omega \to \gamma\pi^0$,
  $J/\psi \to \gamma\eta\pi^0$
- Fit yields 25 ± 10 signal events.
- 2.6σ stat. significance.

Upper limit:

$$\mathcal{B}(\eta' \to \gamma\gamma\eta) < 1.33 \times 10^{-4} \text{ at } 90\ \%\ \text{C.L.}$$





BESIII

PRD 100, 052015(2019)

Summary & Outlook

Recent progress in η' decays:

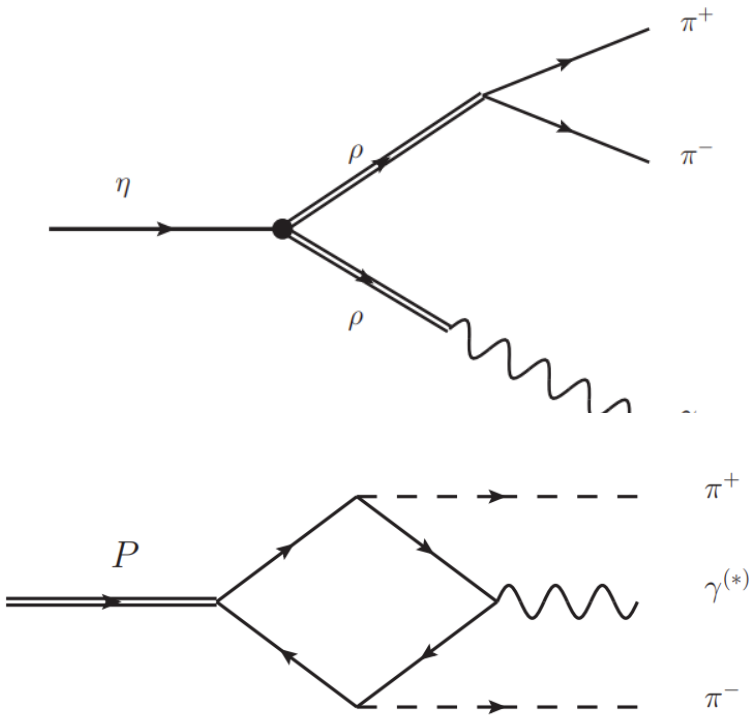
- First measurement of absolute BFs of five most common decay modes
- First observation of $\eta' \to \pi^+\pi^-\mu^+\mu^-$
- First measurement of CP asymmetry in $\eta' \to \pi^+\pi^-e^+e^-$ and improved precision on $\mathcal{B}(\eta' \to \pi^+\pi^-e^+e^-)$
- Improved upper limits for rare decays $\eta' \to 4\pi^0$, $\eta' \to \gamma\gamma\eta$

With 10B J/ψ, many exciting results foreseen on *e.g.*:

- Rare decays
- Dynamics/Transition form factors
- Searches for QCD axion, dark photon

Backup: Decay dynamics of $\eta' \to \pi^+\pi^-\gamma$

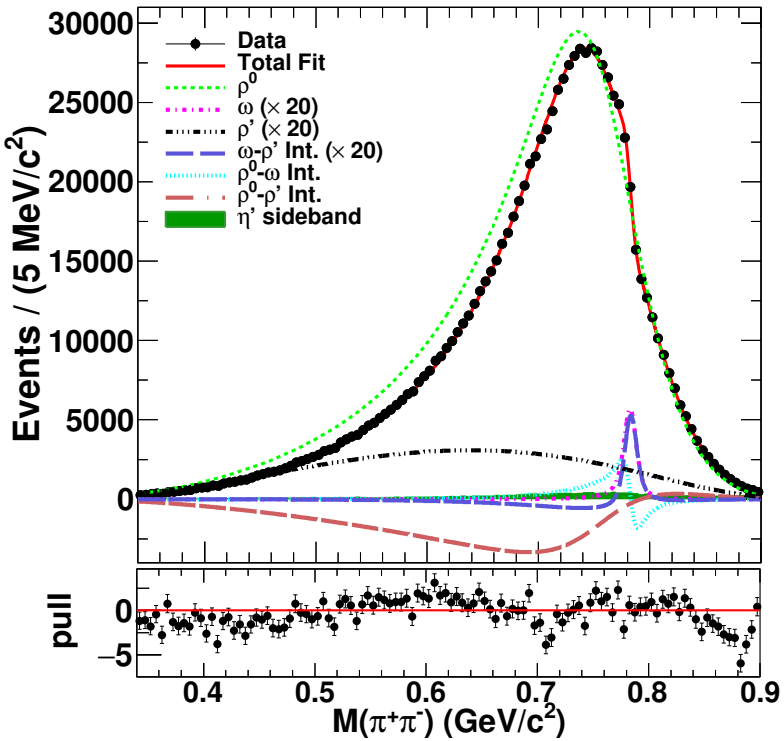
- Dominated by $\eta' \to \gamma\rho^0$
- $+20$ MeV$/c^2$ peak shift in $\pi\pi$ invariant mass spectrum observed by many experiments
  e.g. (JADE Collaboration), PLB 113, 190 (1982), (CELLO Collaboration), PLB 114, 378 (1982); PLB 125, 518E (1983)
- Discrepancy attributed to WZW box anomaly
- Model-independent approach has also been proposed
  PLB 707:184-190 (2012)



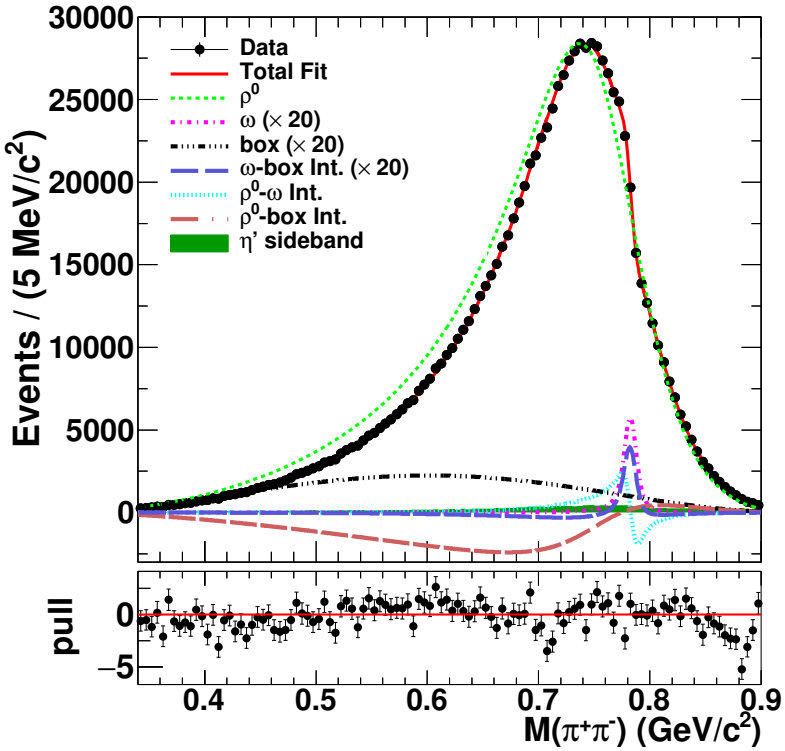
Backup: Decay dynamics of $\eta' \to \pi^+\pi^-\gamma$

Model-dependent fits to 9.7×10^5 signal events

$\rho - \omega - \rho'$



$\rho - \omega -$box anomaly



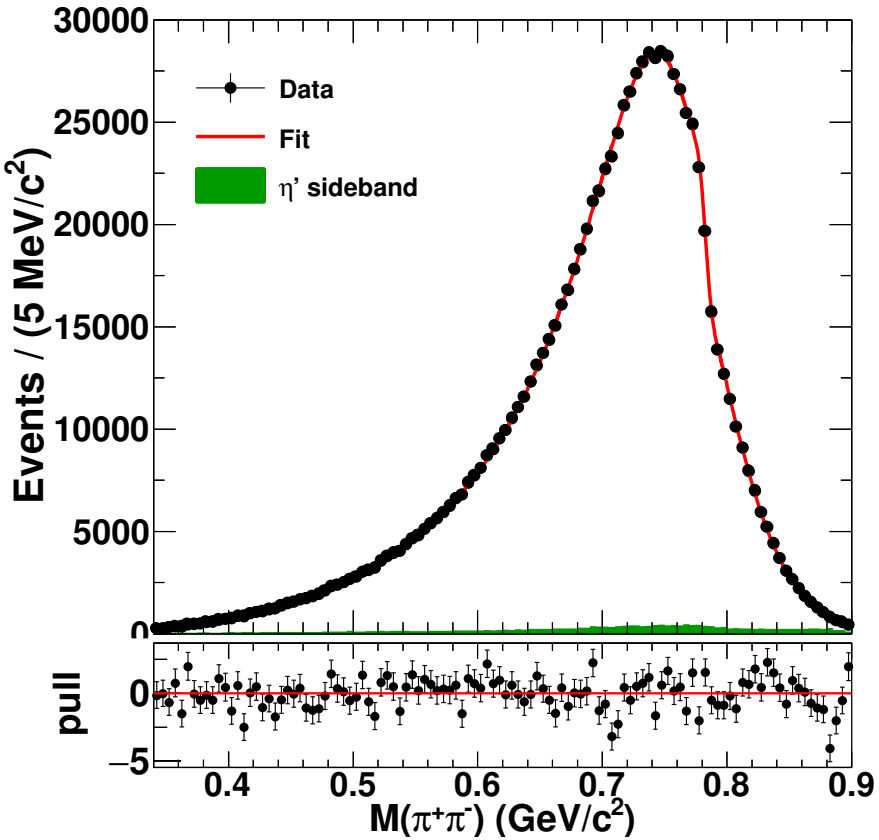
- Contributions from ω and $\rho(770) - \omega$-interference observed
- Additional contribution from box anomaly or $\rho(1450)$ necessary

PRL 120,242003 (2018)

Backup: Decay dynamics of $\eta' \to \pi^+\pi^-\gamma$

Model-independent fit

Following PLB 707, 184 (2012)



- Contributions from ω and $\rho(770) - \omega$-interference observed
- Process-specific part of amplitude determined

PRL 120,242003 (2018)