Highlights on Light Meson Physics

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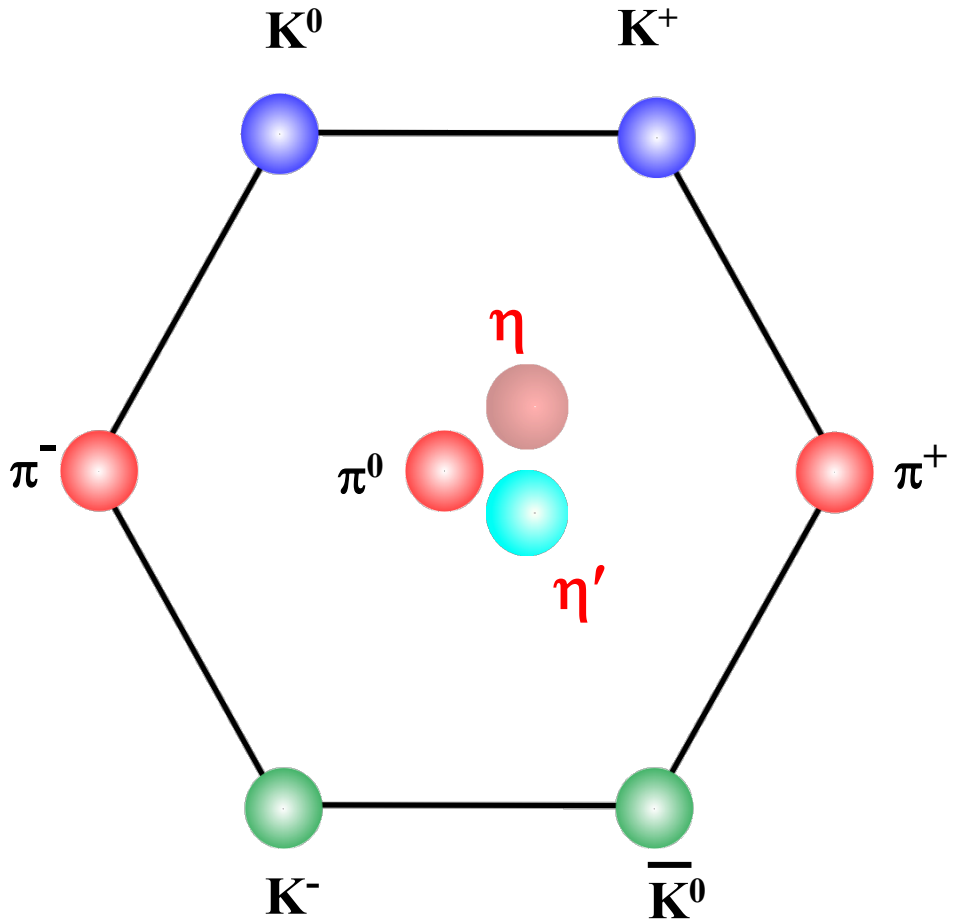
OUTLINE

- Light meson physics
- BESIII: a light meson factory
- What is "NEW" at BESIII ?
- Summary

Light Meson Physics

- **Light mesons**
  - Important roles in particle physics, e.g. strong interactions, Quark Model, CP violation …
- **Rich physics**
  - Test ChPT predictions
  - EM Form factors
  - Test fundamental symmetries
  - Probe new physics beyond the SM



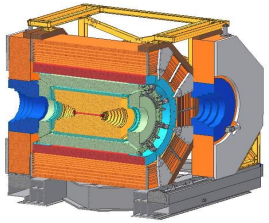
Source of η/η′ events

CLAS(12)

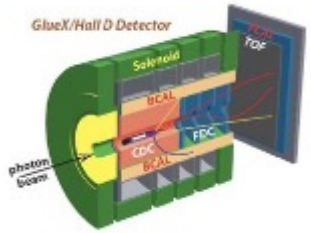
Crystal Ball

WASA-at-COSY

KLOE-2



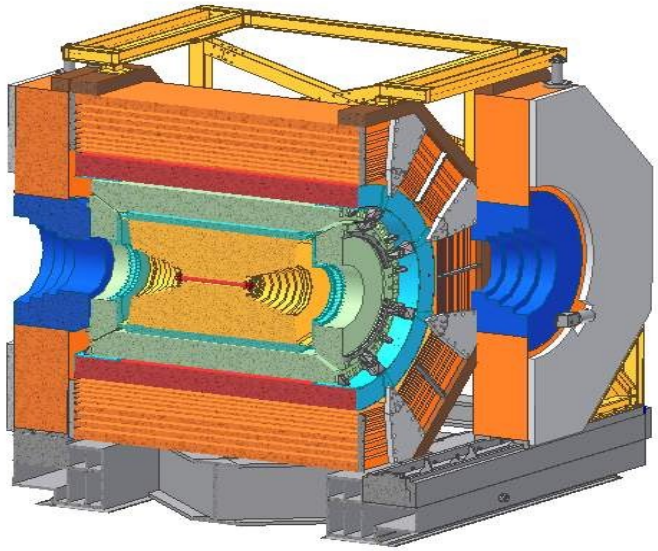
BESIII



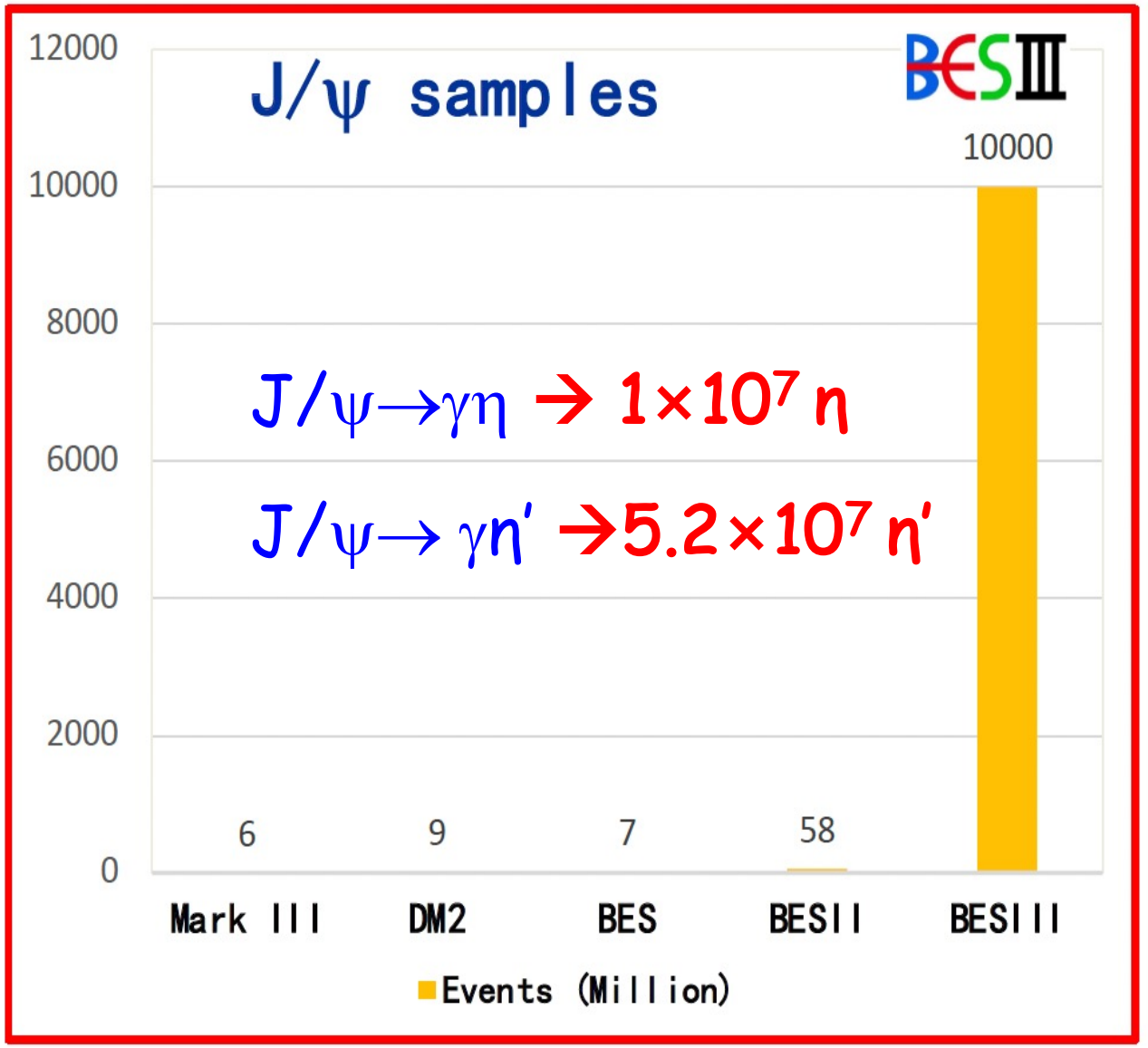
GlueX

New proposals: REDTOP, eta factory at HIAF……

η/η′ events at BESIII



A light meson factory !



BESIII: an important role in η/η′ decays

η REFERENCES

ABLIKIM	23AN	PR D107 092007	M. Ablikim *et al.*	(BESIII Collab.)
HAYRAPETY...	23A	PRL 131 091903	A. Hayrapetyan *et al.*	(CMS Collab.)
ABLIKIM	21AM	PR D104 092004	M. Ablikim *et al.*	(BESIII Collab.)
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ACHASOV	18B	PR D98 052007	M.N. Achasov *et al.*	(SND Collab.)
ADLARSON	18C	PL B784 378	P. Adlarson *et al.*	(WASA-at-COSY Collab.)
PRAKHOV	18	PR C97 065203	S. Prakhov *et al.*	(A2 Collab. at MAMI)
AAIJ	17D	PL B764 233	R. Aaij *et al.*	(LHCb Collab.)
ADLARSON	17B	PR C95 035208	P. Adlarson *et al.*	(A2 Collab. at MAMI)
ANASTASI	16A	JHEP 1605 019	A. Anastasi *et al.*	(KLOE-2 Collab.)
ARNALDI	16	PL B757 437	R. Arnaldi *et al.*	(NA60 Collab.)
ABLIKIM	15G	PR D92 012014	M. Ablikim *et al.*	(BESIII Collab.)
ADLARSON	14A	PR C90 045207	P. Adlarson *et al.*	(WASA-at-COSY Collab.)
AGAKISHIEV	14	PL B731 265	G. Agakishiev *et al.*	(HADES Collab.)
NEFKENS	14	PR C90 025206	B.M.K. Nefkens *et al.*	(A2 Collab. at MAMI)
NIKOLAEV	14	EPJ A50 58	A. Nikolaev *et al.*	(MAMI-B, MAINZ, BONN)
ABLIKIM	13	PR D87 012009	M. Ablikim *et al.*	(BESIII Collab.)
ABLIKIM	13G	PR D87 032006	M. Ablikim *et al.*	(BESIII Collab.)
BABUSCI	13	PL B718 910	D. Babusci *et al.*	(KLOE/KLOE-2 Collab.)
BABUSCI	13A	JHEP 1301 119	D. Babusci *et al.*	(KLOE-2 Collab.)
AGAKISHIEV	12A	EPJ A48 64	G. Agakishiev *et al.*	(HADES Collab.)
GOSLAWSKI	12	PR D85 112011	P. Goslawski *et al.*	(COSY-ANKE Collab.)
ABLIKIM	11G	PR D84 032006	M. Ablikim *et al.*	(BESIII Collab.)

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η′(958) REFERENCES

ABLIKIM	23AH	PRL 130 081901	M. Ablikim *et al.*	(BESIII Collab.)
ABLIKIM	22E	PR D105 112010	M. Ablikim *et al.*	(BESIII Collab.)
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ABLIKIM	15P	PR D92 012007	M. Ablikim *et al.*	(BESIII Collab.)
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AKHMETSHIN	15	PL B740 273	R.R. Akhmetshin *et al.*	(CMD-3 Collab.)
PDG	15	RPP 2015 at pdg.lbl.gov		(PDG Collab.)
ABLIKIM	14M	PRL 112 251801	M. Ablikim *et al.*	(BESIII Collab.)
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BESIII: an important role in η/η′ decays

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What is "NEW" at BESIII ?

- New decays
- New decay mechanisms
- New approaches
- New tests for fundamental symmetries

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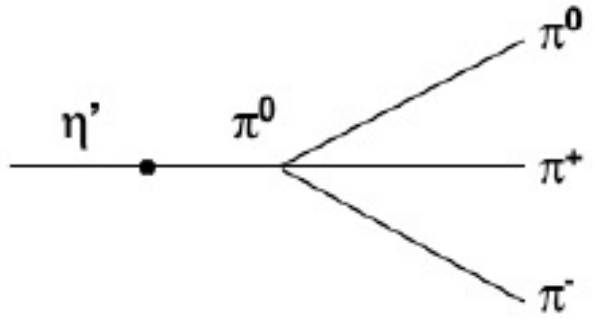
New decays

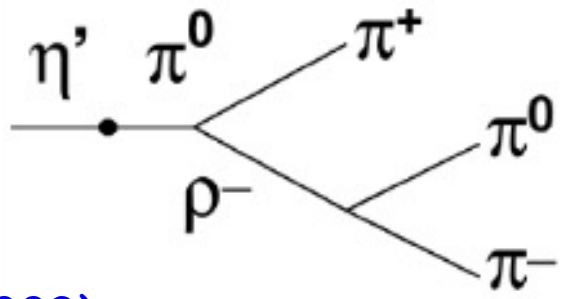
$\eta' \to 2(\pi^+\pi^-)$, $\pi^+\pi^-\pi^0\pi^0$	PRL112, 251801(2014)
$\eta' \to \gamma e^+e^-$	PRD92, 012001(2015)
$\eta' \to \omega e^+e^-$	PRD92, 051101(2015)
$\eta' \to \rho\pi$	PRL118, 012001(2017)
$\eta' \to \gamma\gamma\pi^0$	PRD96, 012005(2017)
$\eta' \to \pi^+\pi^- u^+u^-$	PRD103, 072006(2021)
$\eta' \to e+e-e+e-$	PRD105,112010(2022)

Observation of $\eta' \to \rho^+\pi^-$

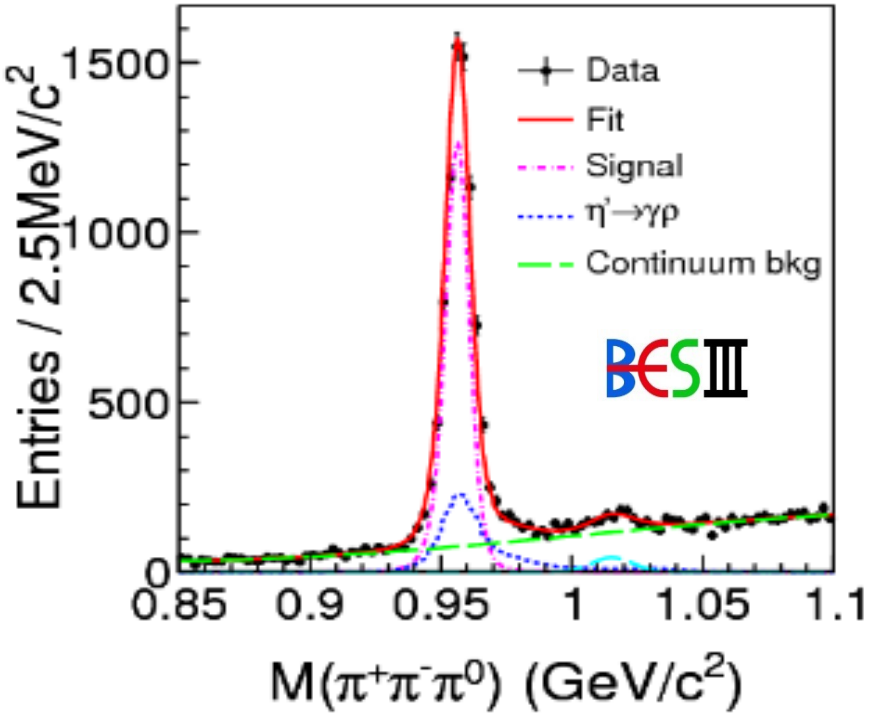


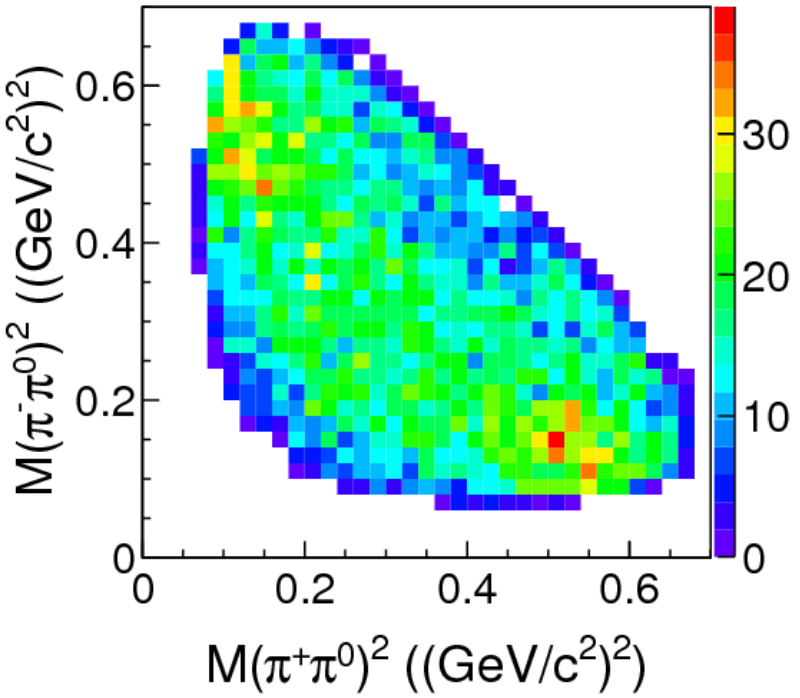
D. Gross et al., PRD19,2188(1979)

$$r = \frac{\Gamma_{\eta' \to \pi^+\pi^-\pi^0}}{\Gamma_{\eta' \to \eta\pi^+\pi^-}} \approx (16.8)\frac{3}{16}\left(\frac{m_d - m_u}{m_s}\right)^2$$



N. Beisert et al., Nucl. Phys. A716,186(2003)

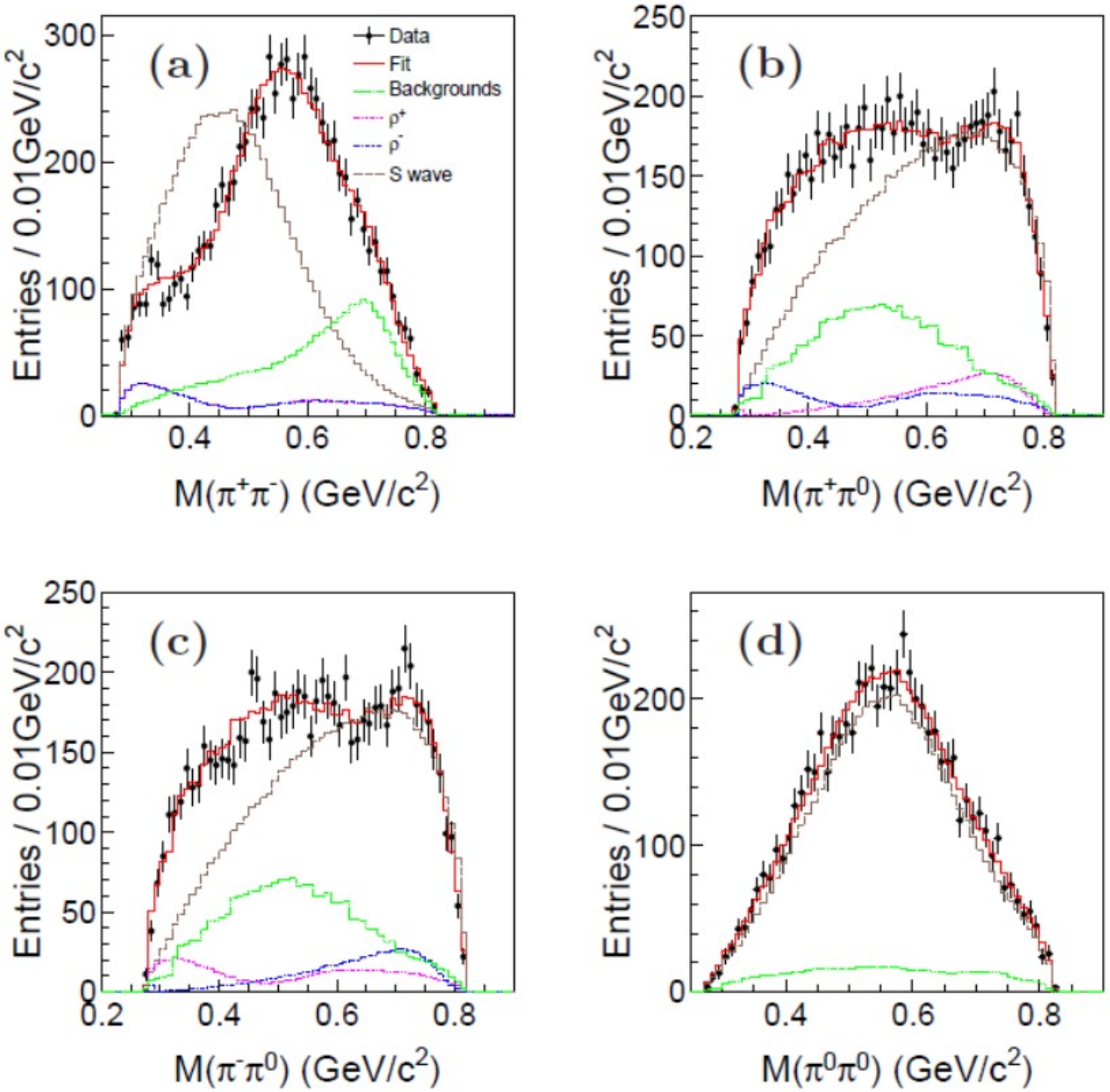




$\eta' \to \pi^+\pi^-\pi^0$

PRL118, 012001(2017)

Amplitude analysis of $\eta' \to \rho^+\pi^-$

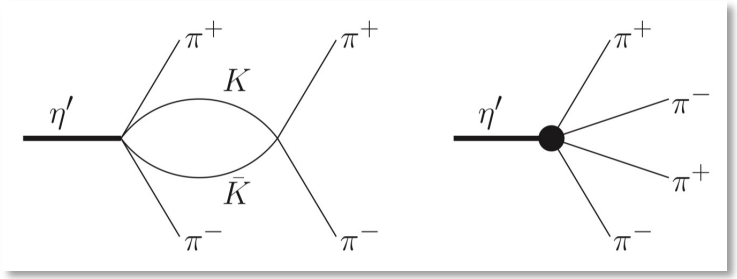


PRL118, 012001(2017)

Decay Mode	$\mathcal{B}$ $(\times 10^{-4})$
$\pi^+\pi^-\pi^0$	$35.91 \pm 0.54 \pm 1.74$
$\pi^0\pi^0\pi^0$	$35.22 \pm 0.82 \pm 2.60$
$\rho^+\pi^-$	$3.72 \pm 0.30 \pm 0.63 \pm 0.92$
$\rho^-\pi^+$	$3.72 \pm 0.30 \pm 0.63 \pm 0.92$
$(\pi^+\pi^-\pi^0)_S$	$37.63 \pm 0.77 \pm 2.22 \pm 4.48$

Analysis with 10 billion J/ψ is in progress !

Observation of $\eta' \to \pi^+\pi^-\pi^+\pi^-, \pi^+\pi^-\pi^0\pi^0$

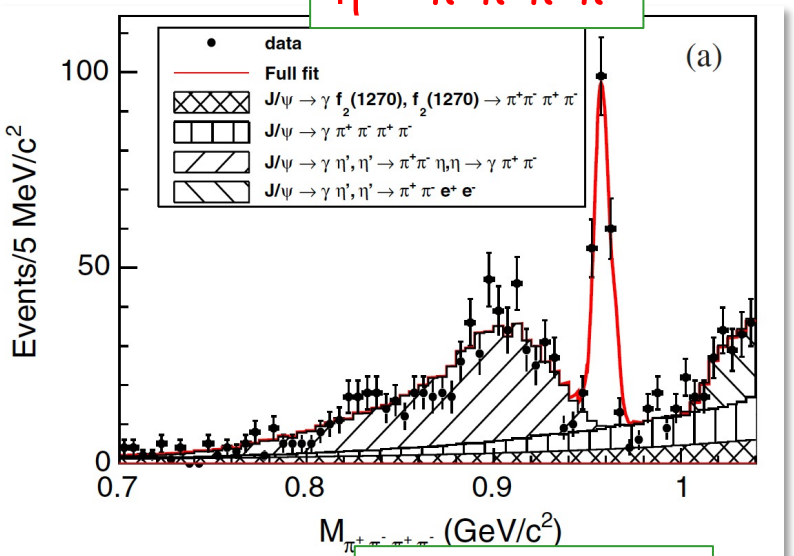


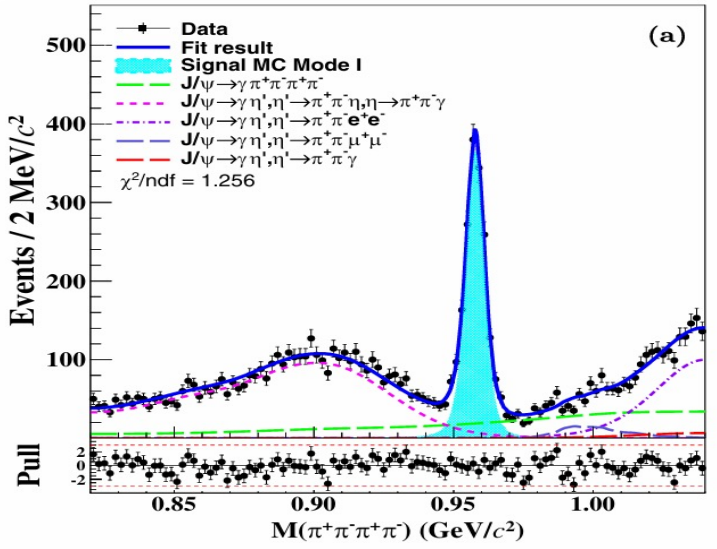
ChPT+VMD:
only occur at $O(p^6)$

$B(\eta' \to \pi^+\pi^-\pi^+\pi^-) = (1.0 \pm 0.3) \times 10^{-4}$
$B(\eta' \to \pi^+\pi^-\pi^0\pi^0) = (2.4 \pm 0.7) \times 10^{-4}$

F.K. Guo et al ,PRD 85,014014 (2012)

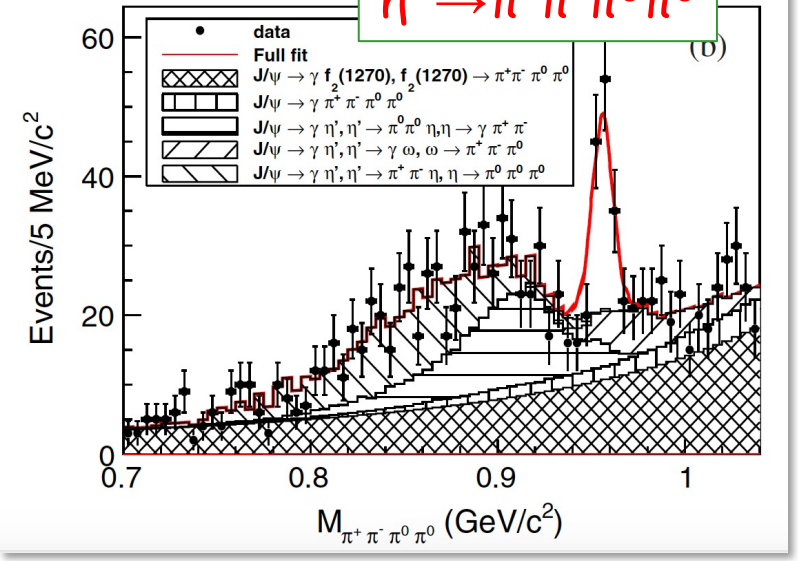
$\eta' \to \pi^+\pi^-\pi^+\pi^-$

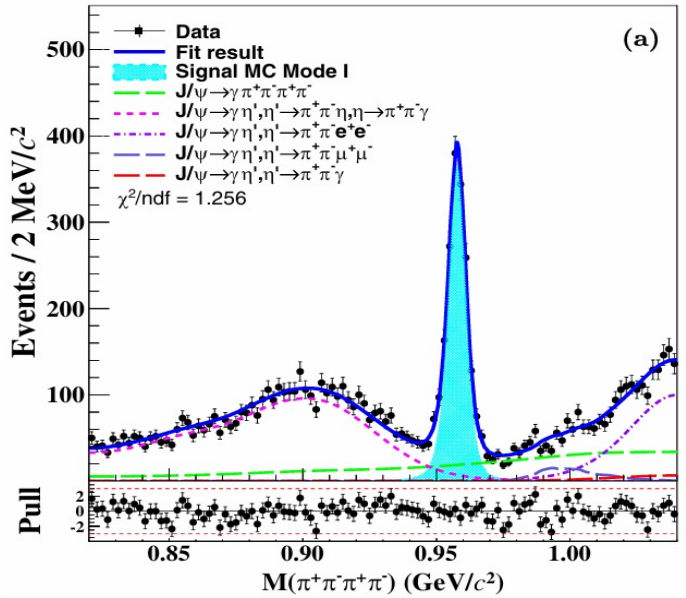




PRL112,251801(2014)

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



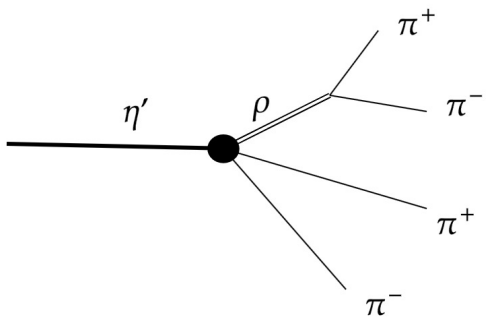


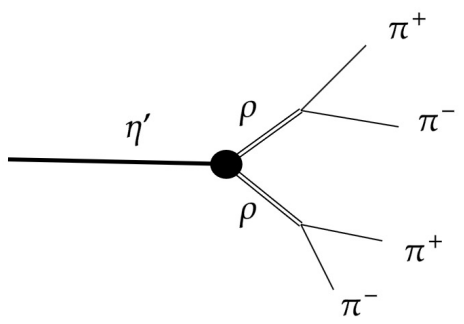
PRD 109, 032006 (2024)

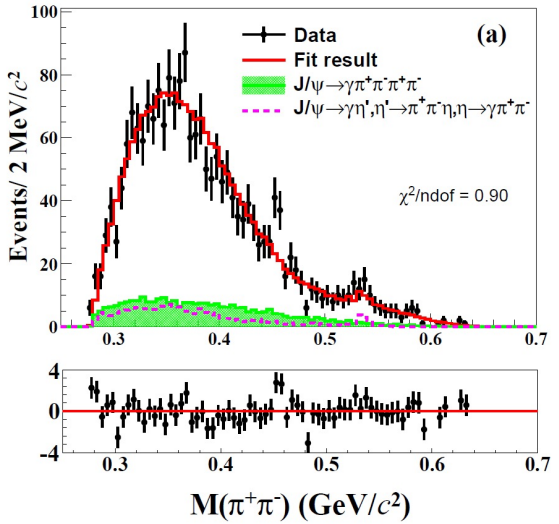
Amplitude analysis results

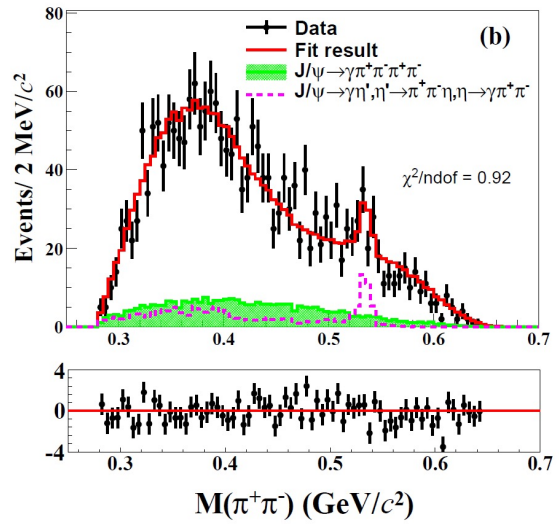
- **The decay amplitude based on the ChPT and VMD model**

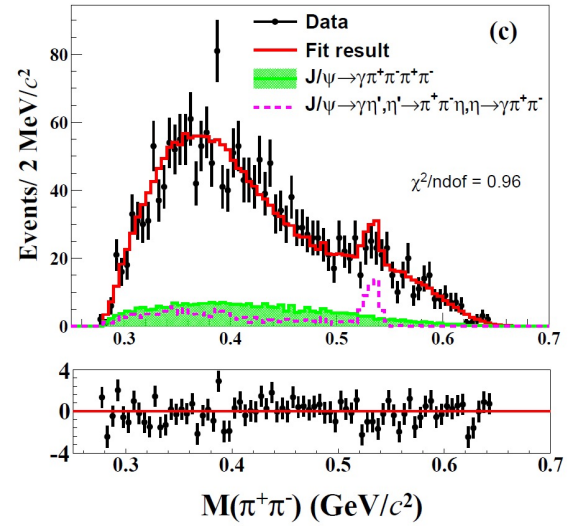
$$\mathcal{A}(\eta' \to \pi^+\pi^-\pi^+\pi^-) = \epsilon_{\mu\nu\alpha\beta} p_1^\mu p_2^\nu p_3^\alpha p_4^\beta \times \left\{ \left[\frac{s_{12}}{D_\rho(s_{12})} + \frac{s_{34}}{D_\rho(s_{34})} - \frac{s_{14}}{D_\rho(s_{14})} - \frac{s_{23}}{D_\rho(s_{23})} \right] + \alpha \left[\frac{M_\rho^2(s_{12}+s_{34})}{D_\rho(s_{12})D_\rho(s_{34})} - \frac{M_\rho^2(s_{14}+s_{23})}{D_\rho(s_{14})D_\rho(s_{23})} \right] \right\}$$

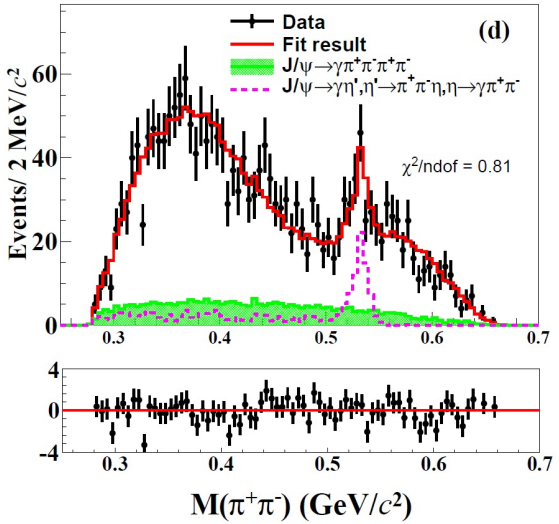






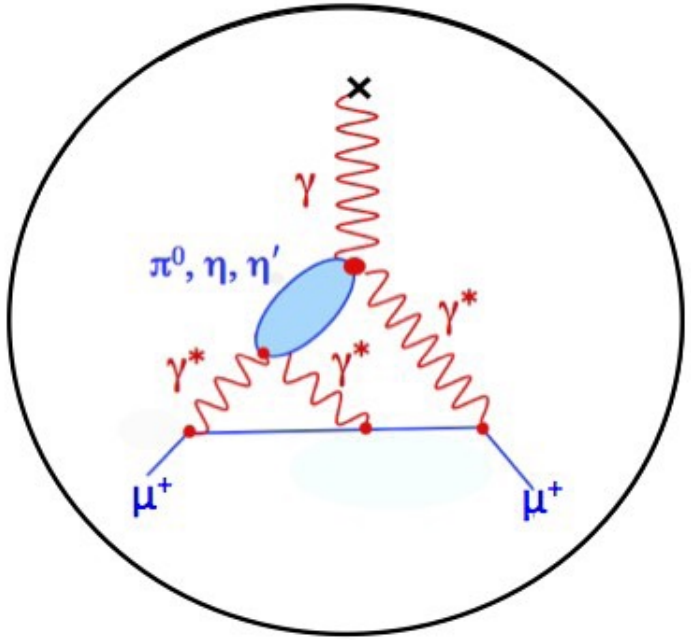






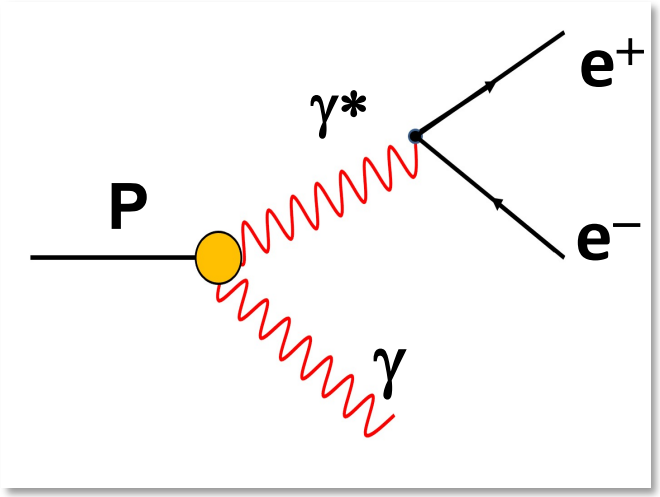
$\alpha = 1.22 \pm 0.33 \pm 0.04$, **consistent with the theoretical expectation**

TFFs as experimental input @ BESIII

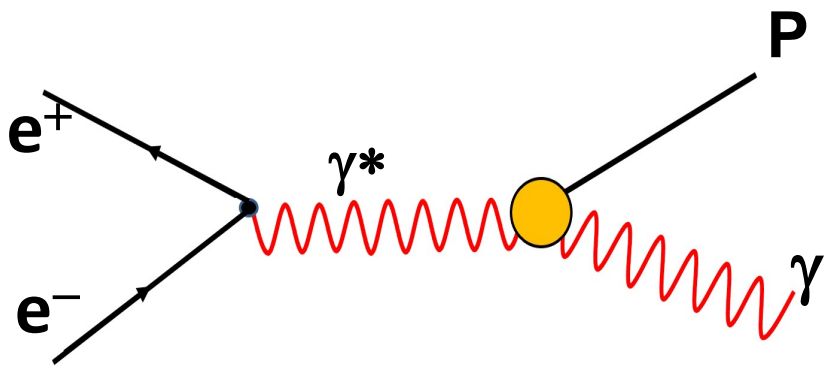


HLbL contributions

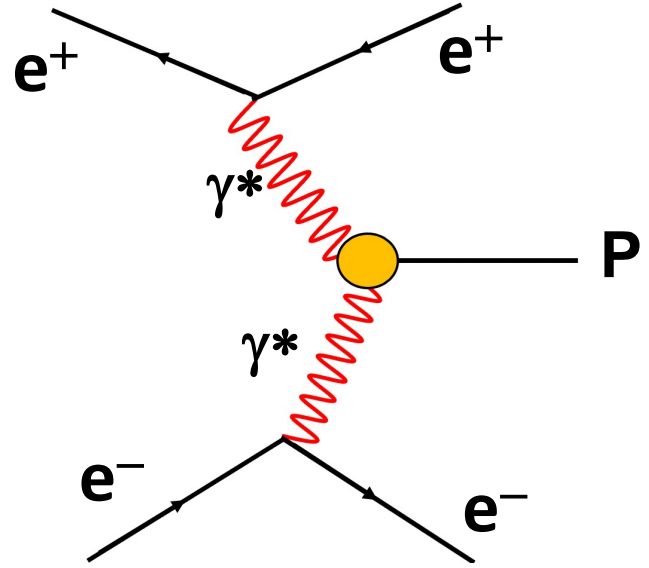
Pseudoscalar TFFs are experimentally accessible in three different processes



Dalitz decays $0 < q^2 < M^2$



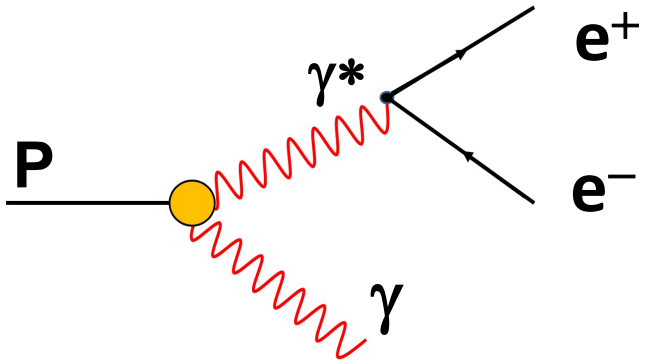
Annihilation process $q^2 = s > M^2$

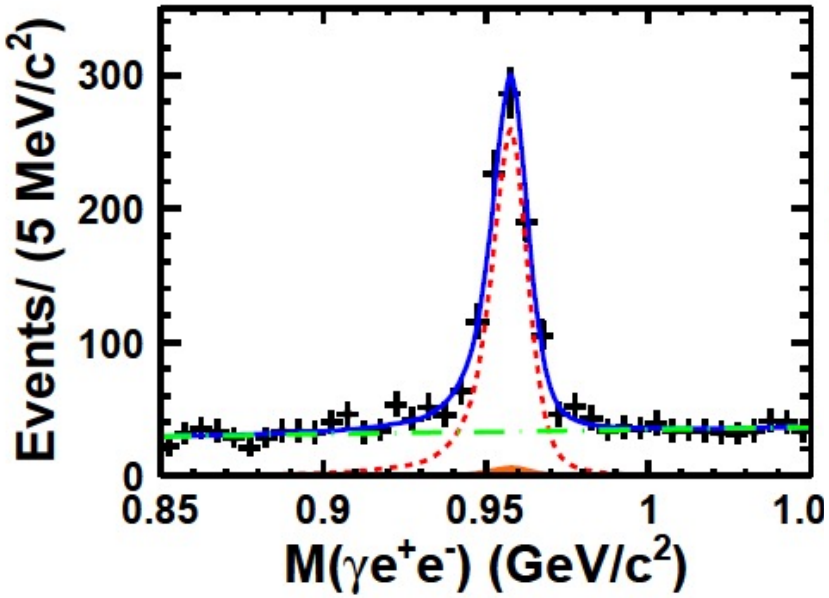


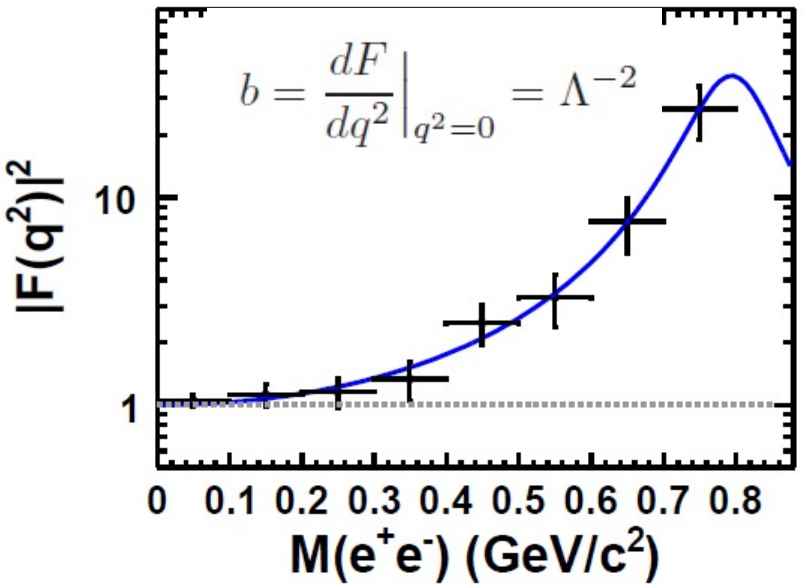
Two photon process

Observation of $\eta' \to \gamma e^+e^-$

PRD 92, 012001 (2015)







$B(\eta' \to \gamma e^+e^-) = (4.69 \pm 0.20 \pm 0.23) \times 10^{-4}$

4.2×10^{-4} EMT, PRC61,035206

$b_{\eta'} = 1.60 \pm 0.17 \pm 0.08$ GeV $^{-2}$

Theoretical predictions:

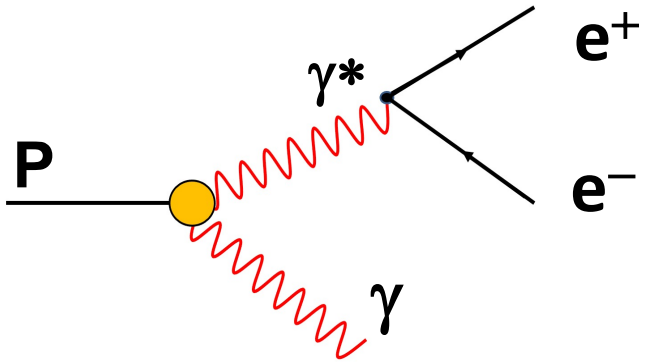
$b_{\eta'} = 1.45$ GeV^{-2} VMD

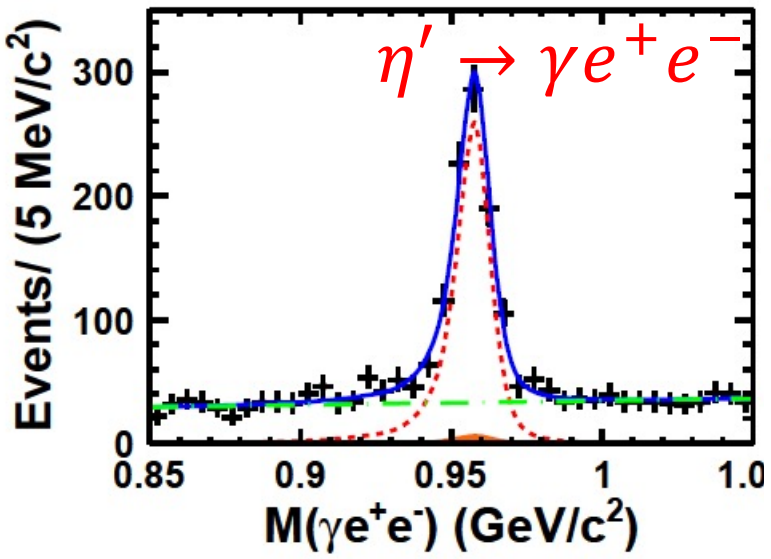
$b_{\eta'} = 1.60$ GeV^{-2} ChPT

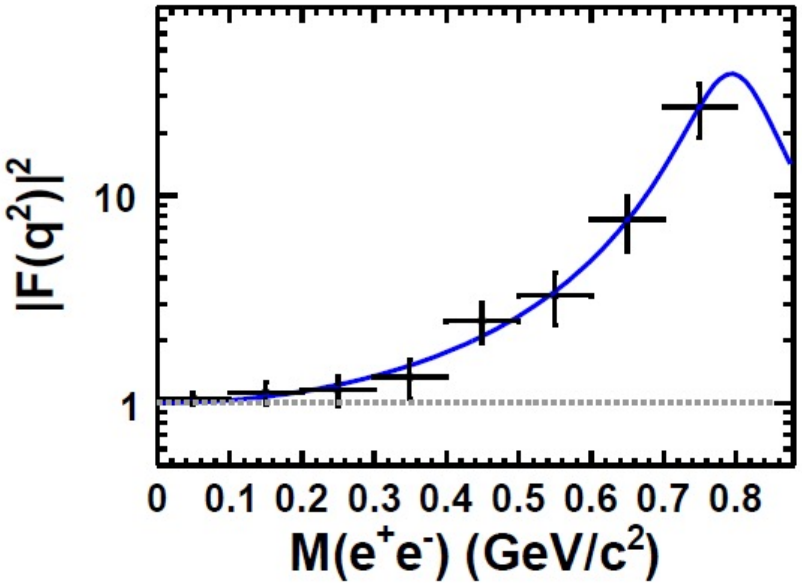
$b_{\eta'} = 1.53^{+0.15}_{-0.08}$ GeV^{-2} Dispersion

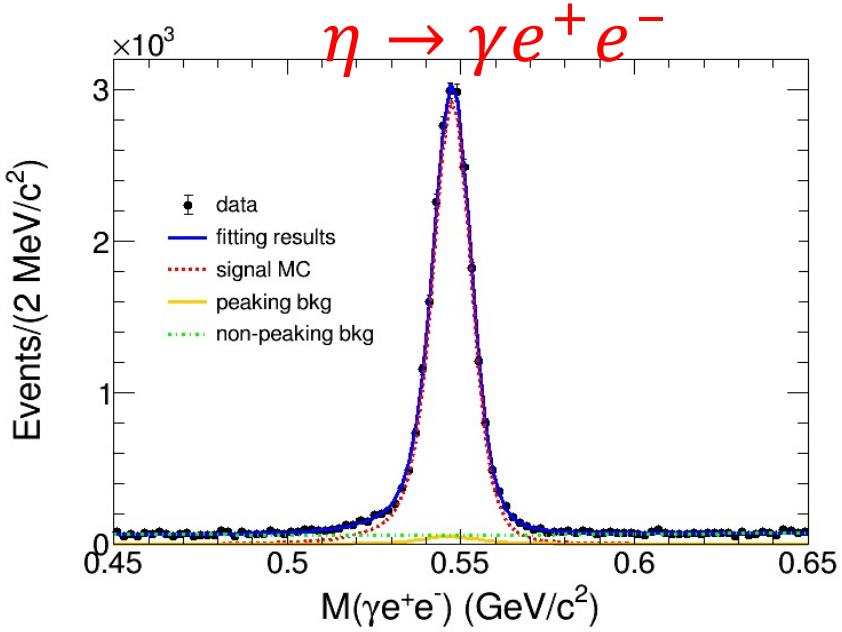
Observation of $\eta' \to \gamma e^+ e^-$

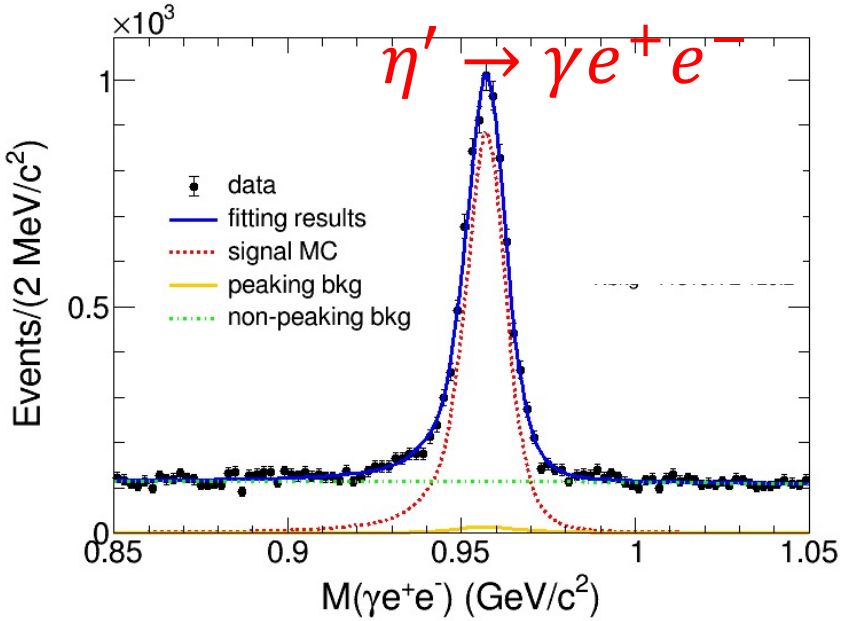
PRD 92, 012001 (2015)





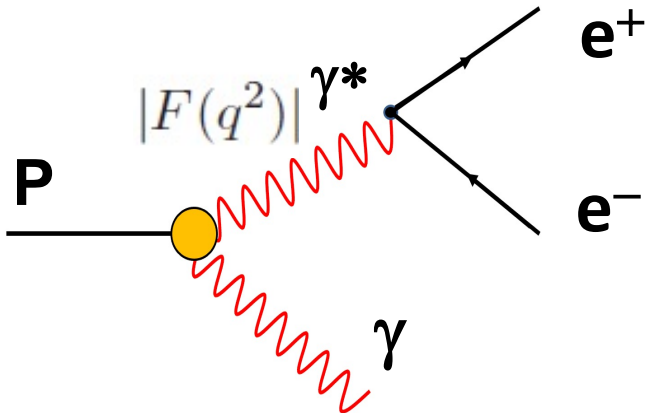






PRD 109, 072001 (2024)

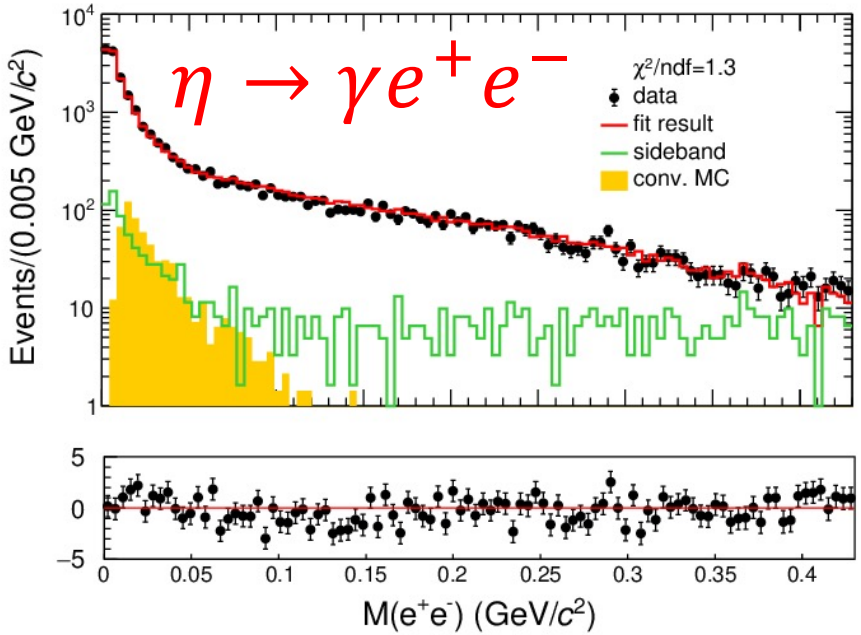
Transition Form Factors in $\eta/\eta' \to \gamma e^+e^-$

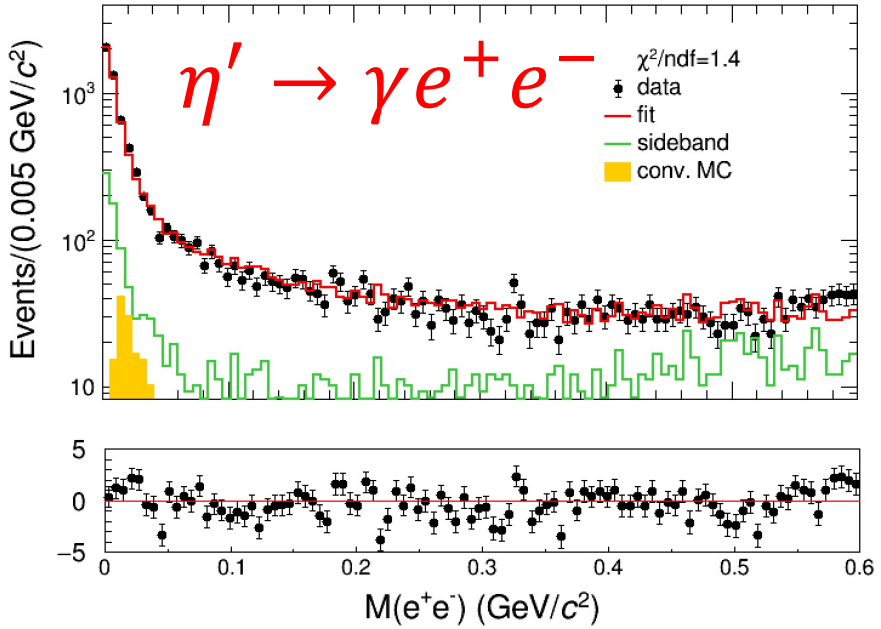


$$\frac{d\Gamma(P \to \ell^+\ell^-\gamma)}{dq^2\Gamma_{\gamma\gamma}} = \frac{2\alpha}{3\pi}\frac{1}{q^2}\sqrt{1-\frac{4m_\ell^2}{q^2}}\left(1+\frac{2m_\ell^2}{q^2}\right)\left(1-\frac{q^2}{M_P^2}\right)^3 |F_P(q^2,0)|^2$$

Single-pole: $F(q^2) = \frac{1}{1-q^2/\Lambda^2}$

$$b_P = \left.\frac{d\ln|F_P(q^2)|}{dq^2}\right|_{q^2=0}$$

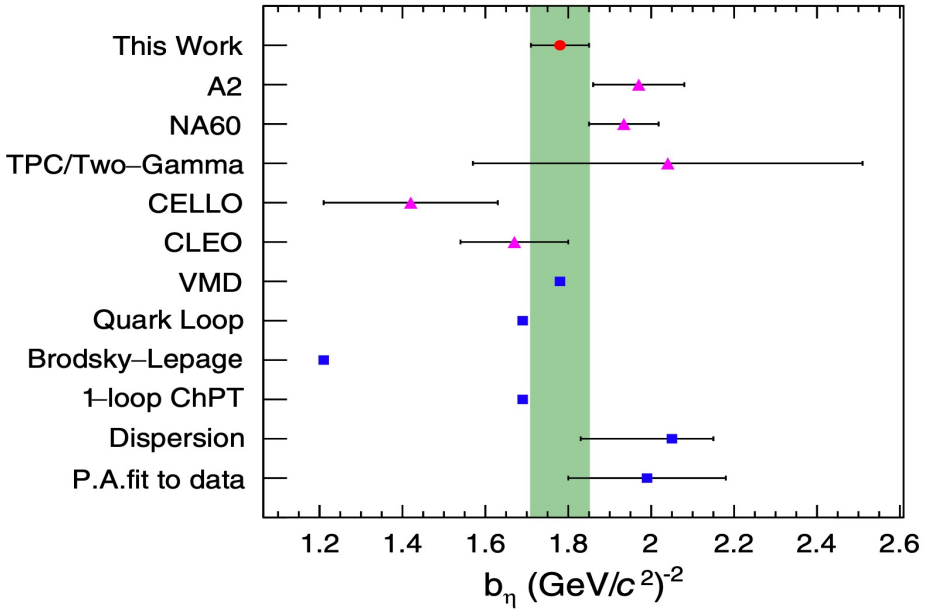


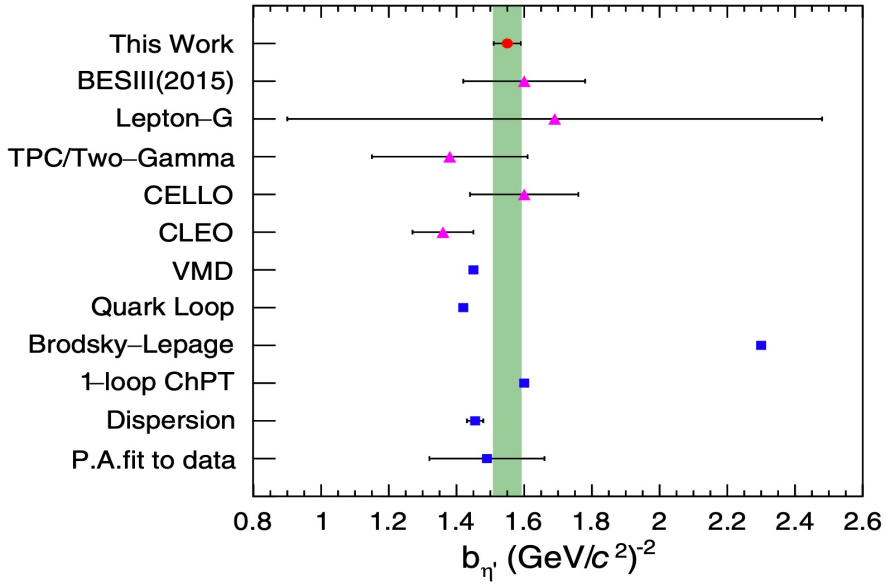


$b_\eta = (1.78 \pm 0.12(stat))\ (\mathrm{GeV}/c^2)^{-2}$

$b_{\eta'} = (1.57 \pm 0.05(stat))\ (\mathrm{GeV}/c^2)^{-2}$

Comparisons

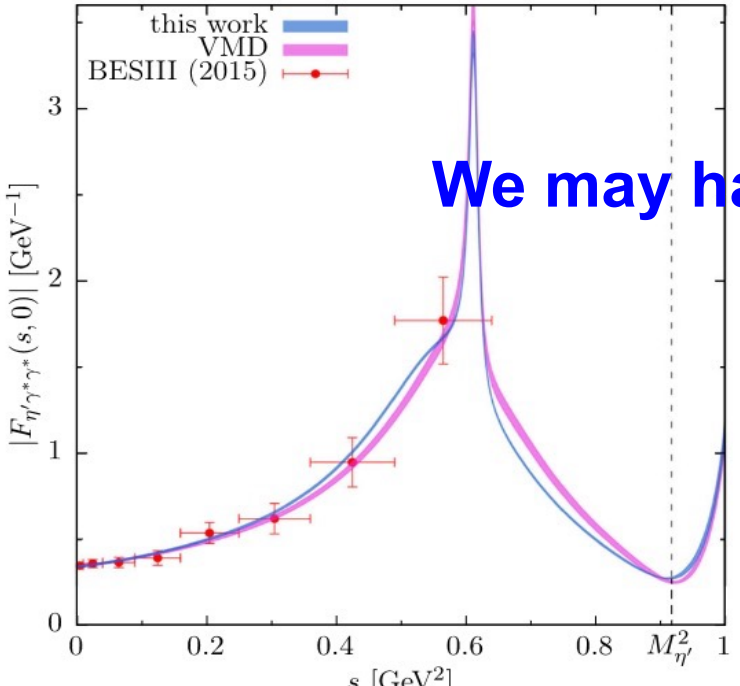




New parameterization ?

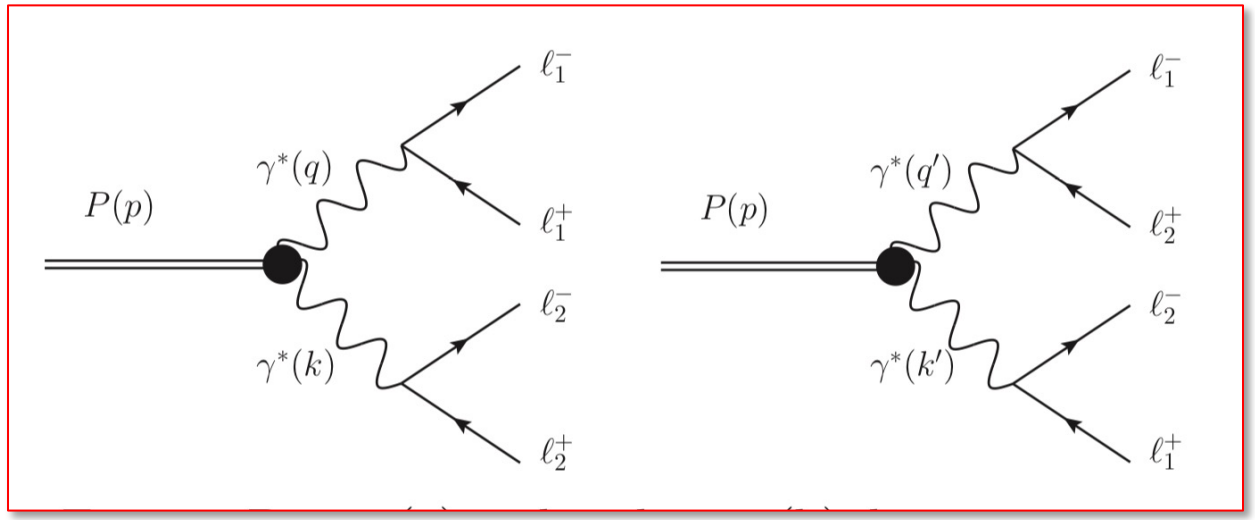
$$F_{P\gamma^*\gamma^*}(s,0) = F_{P\gamma\gamma}\left[1+\frac{\epsilon_{\rho\omega}s}{M_\omega^2 - s - iM_\omega\Gamma_\omega}\right] \times \frac{s}{48\pi^2}\int_{4M_\pi^2}^{\infty} ds' \frac{\sigma_\pi^3(s')P(s')|F_\pi^V(s')|^2}{s'-s-i\epsilon} + \frac{F_{P\gamma\gamma}w_{P\omega\gamma}s}{M_\omega^2 - s - iM_\omega\Gamma_\omega}\left[1+\frac{\epsilon_{\rho\omega}s}{48\pi^2 g_{\omega\gamma}^2} \times \int_{4M_\pi^2}^{\infty} ds' \frac{\sigma_\pi^3(s')|F_\pi^V(s')|^2}{s'(s'-s-i\epsilon)}\right] + \frac{F_{P\gamma\gamma}w_{P\phi\gamma}s}{M_\phi^2 - s - iM_\phi\Gamma_\phi},$$

EPJC 82,434)2022)



We may have a fit to data soon

Observation of $\eta' \to e^+e^-e^+e^-$



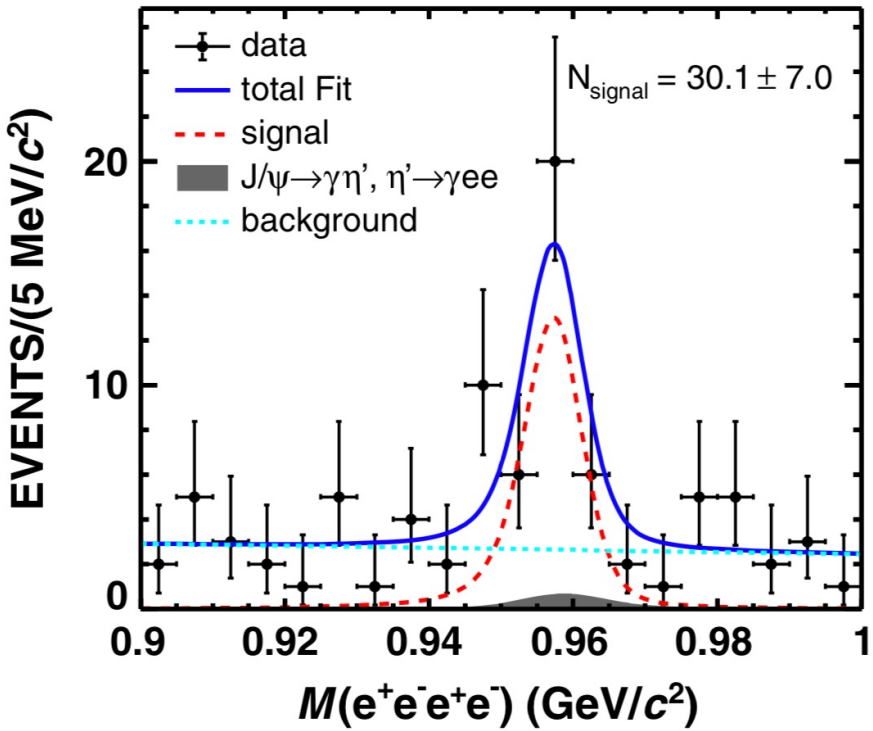
- Test the theoretical models
- Form factors→ $(g-2)_\mu$
- No experimental evidence yet!

$B(\eta' \to e^+e^-e^+e^-) = (4.5 \pm 1.0 \pm 0.5) \times 10^{-6}$

PRD 105, 112010 (2022)

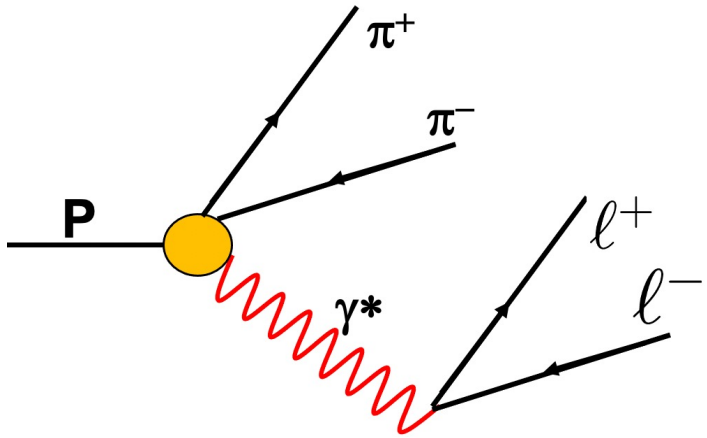
Chinese Physics C42 (2018) 023109

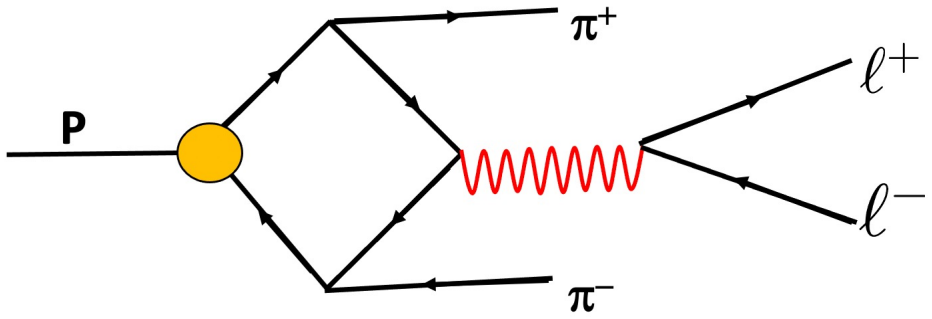
$\eta' \to e^+e^-e^+e^-$	$2.10(45) \times 10^{-6}$
$\eta' \to \mu^+\mu^-\mu^+\mu^-$	$1.69(36) \times 10^{-8}$
$\eta' \to e^+e^-\mu^+\mu^-$	$6.39(91) \times 10^{-7}$

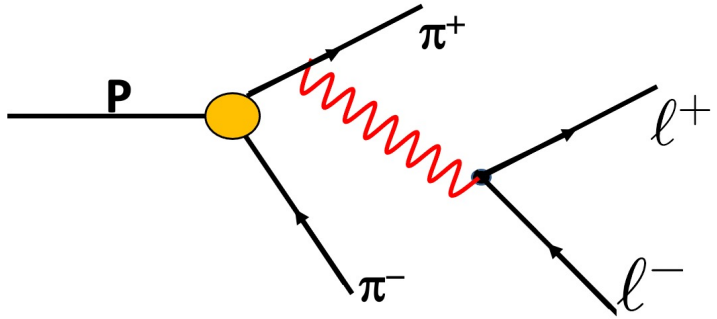


Observation of $\eta' \to \pi^+\pi^- l^+ l^-$

JHEP07(2024)135







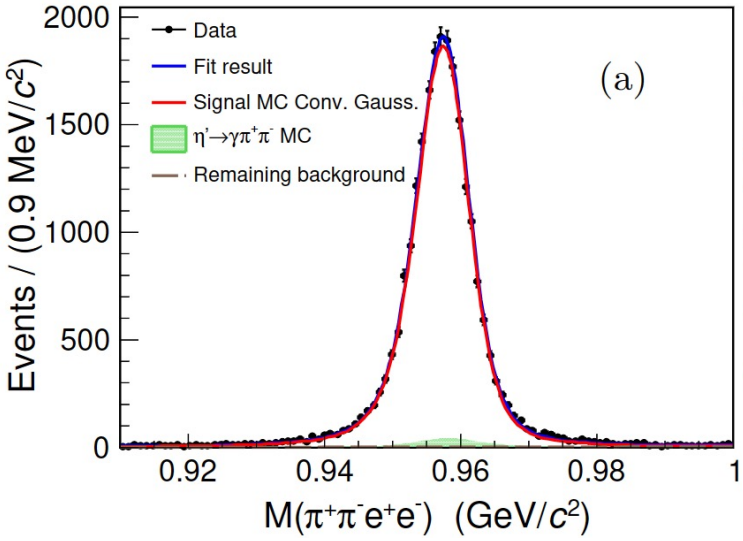
VMD

Box-anomaly

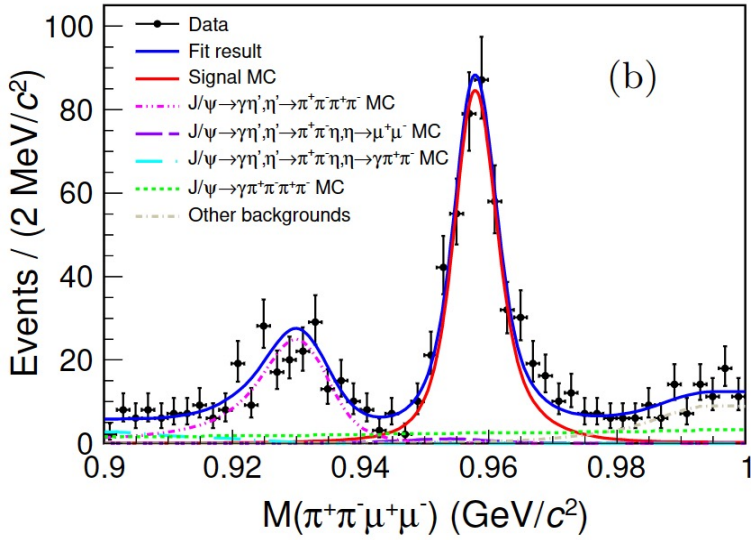
CP violation

	$\mathcal{B}(\eta' \to \pi^+\pi^- e^+e^-)$ (10^{-3})	$\mathcal{B}(\eta' \to \pi^+\pi^- \mu^+\mu^-)$ (10^{-5})
Hidden gauge*	2.17 ± 0.21	2.20 ± 0.30
Unitary χPT*	$2.13^{+0.17}_{-0.31}$	$1.57^{+0.96}_{-0.75}$
VMD*	2.27 ± 0.13	2.41 ± 0.25
BESIII (2013)$^\diamond$	$2.11 \pm 0.12 \pm 0.15$	< 2.9
BESIII (2021)$^\diamond$	$2.42 \pm 0.05 \pm 0.08$	$1.97 \pm 0.33 \pm 0.19$
CLEO$^\diamond$	$2.50^{+1.2}_{-0.9} \pm 0.5$	< 24

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

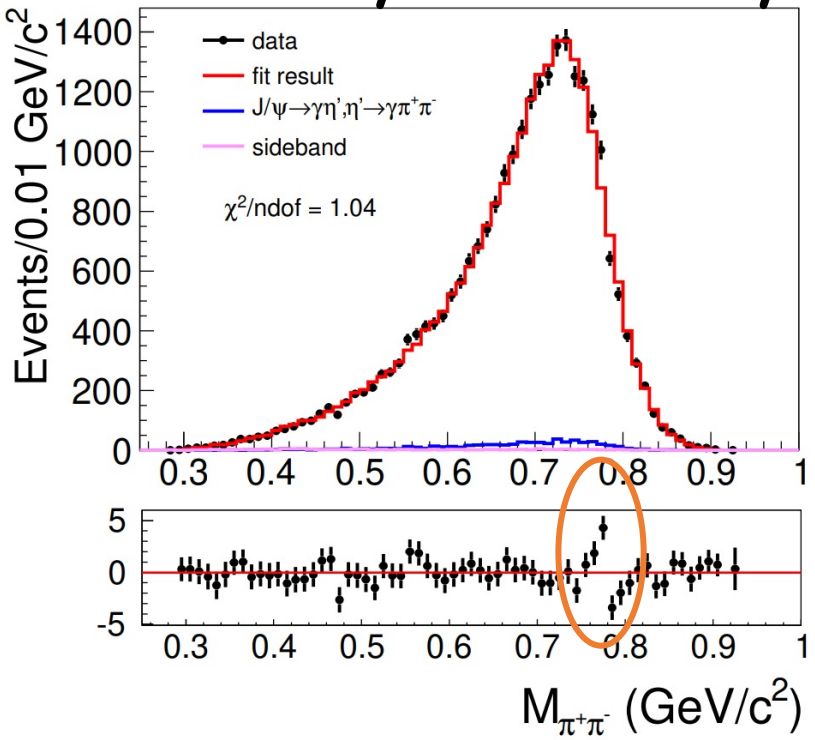


$\eta' \to \pi^+\pi^- \mu^+\mu^-$

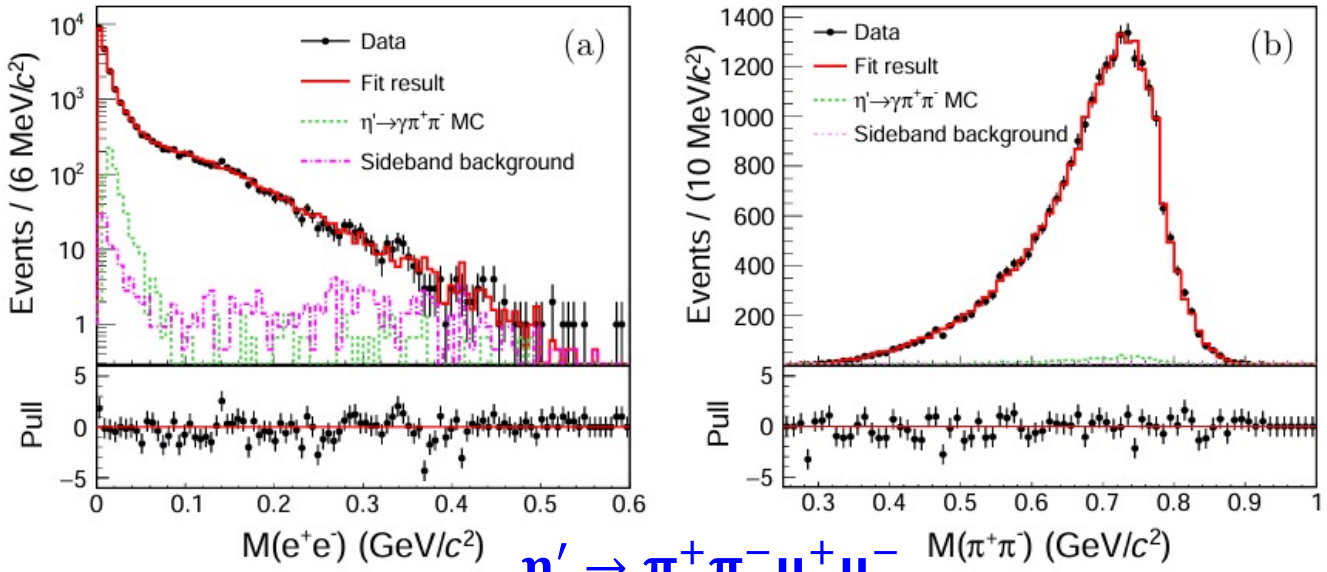


Amplitude analysis results

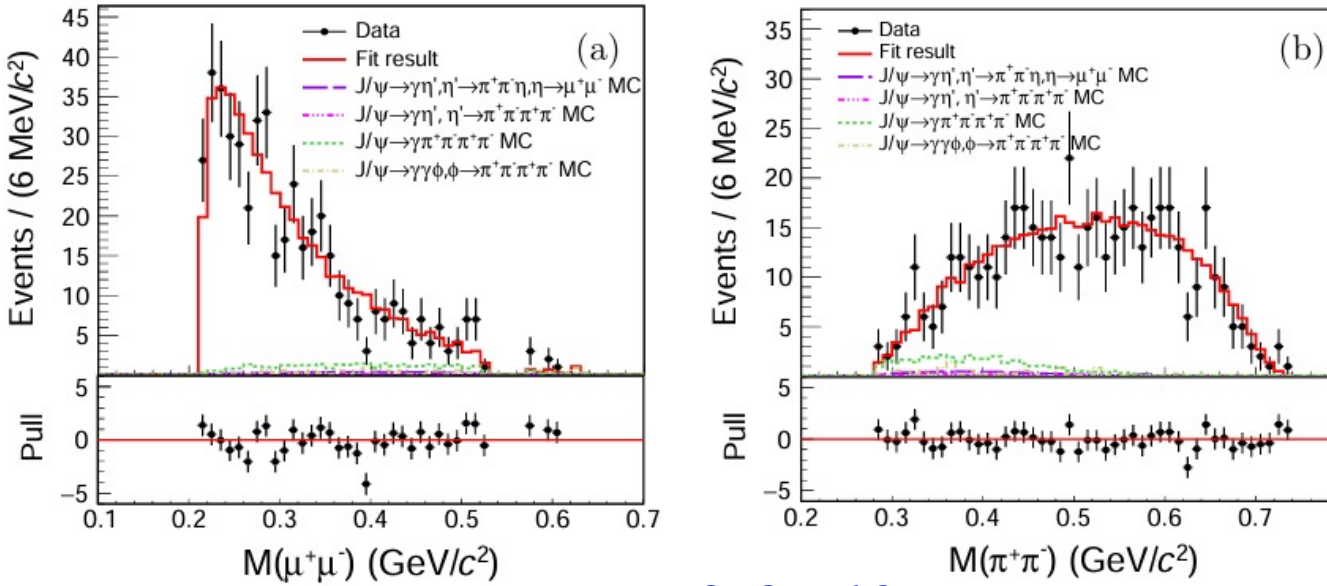
- ✓ ρ^0 only can not describe data
- ✓ $\omega \to \pi^+\pi^-$ decay is necessary !



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



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



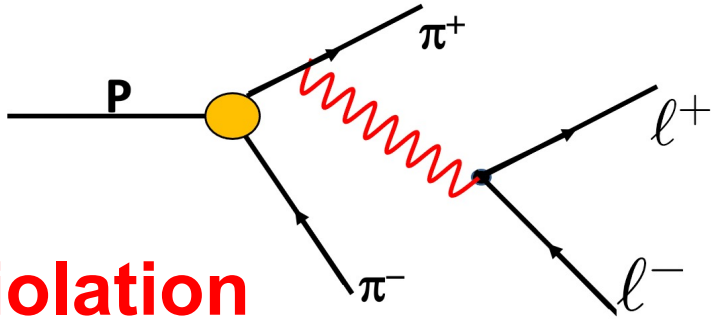
- **First time to measure form factors wtih** $\eta' \to \pi^+\pi^- l^+ l^-$

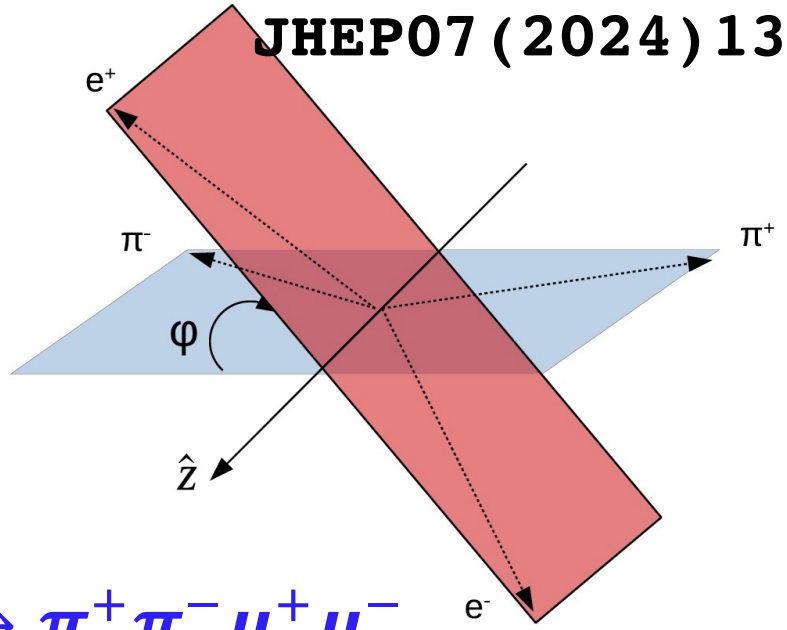
$$b_{\eta'} = 1.30 \pm 0.19\ \left(\mathrm{GeV}/c^2\right)^{-2}$$

JHEP07(2024)135

Search for *CP* Asymmetry

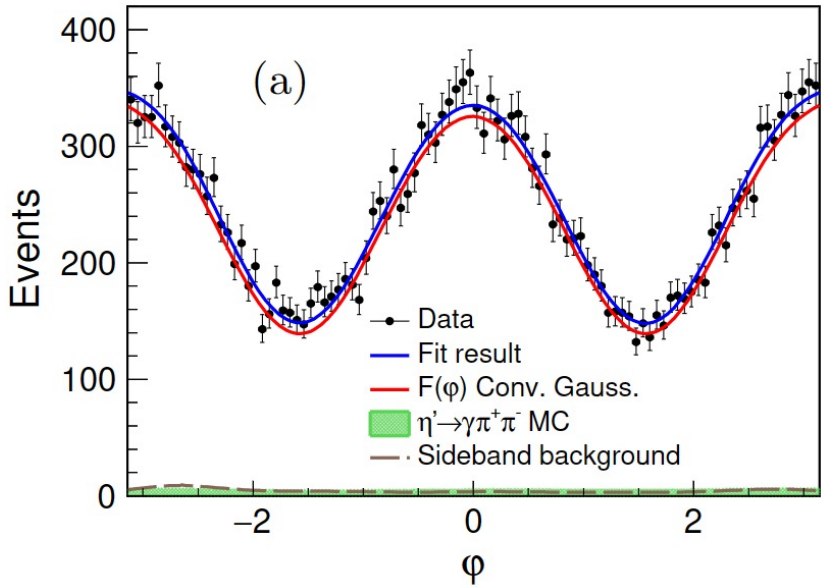
JHEP07(2024)135





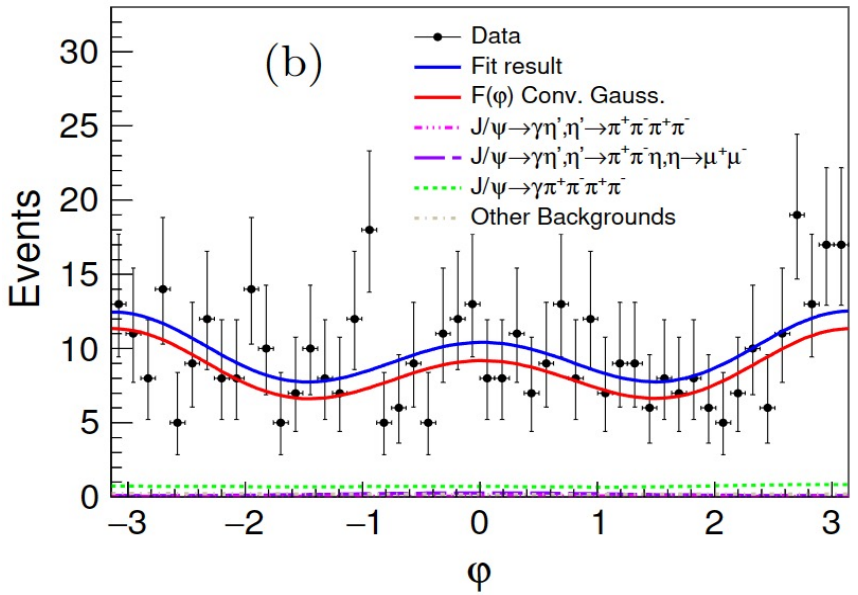
CP violation

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



$\mathcal{A}_{CP} = \quad (-0.21 \pm 0.73(stat))\%.$

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

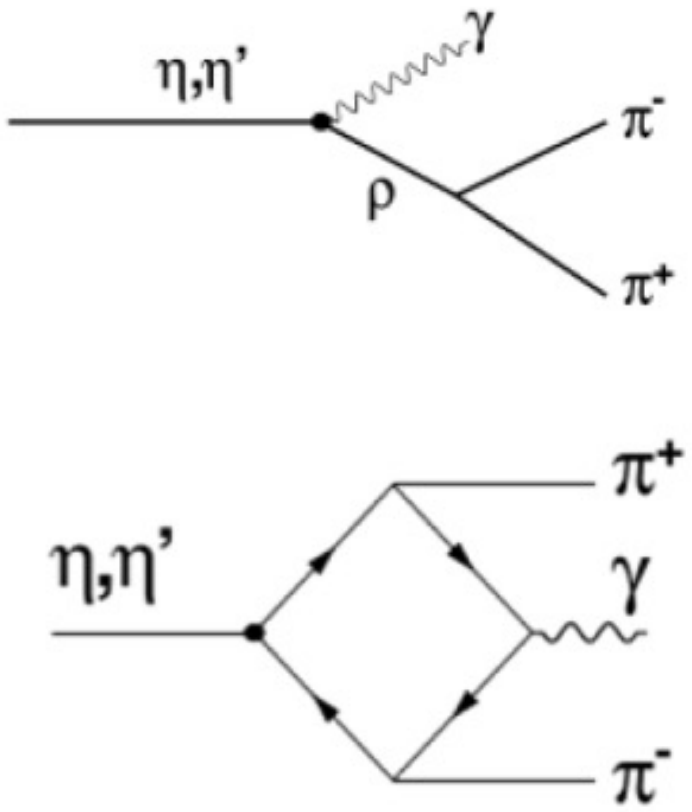


$(0.62 \pm 4.71(stat))\%$

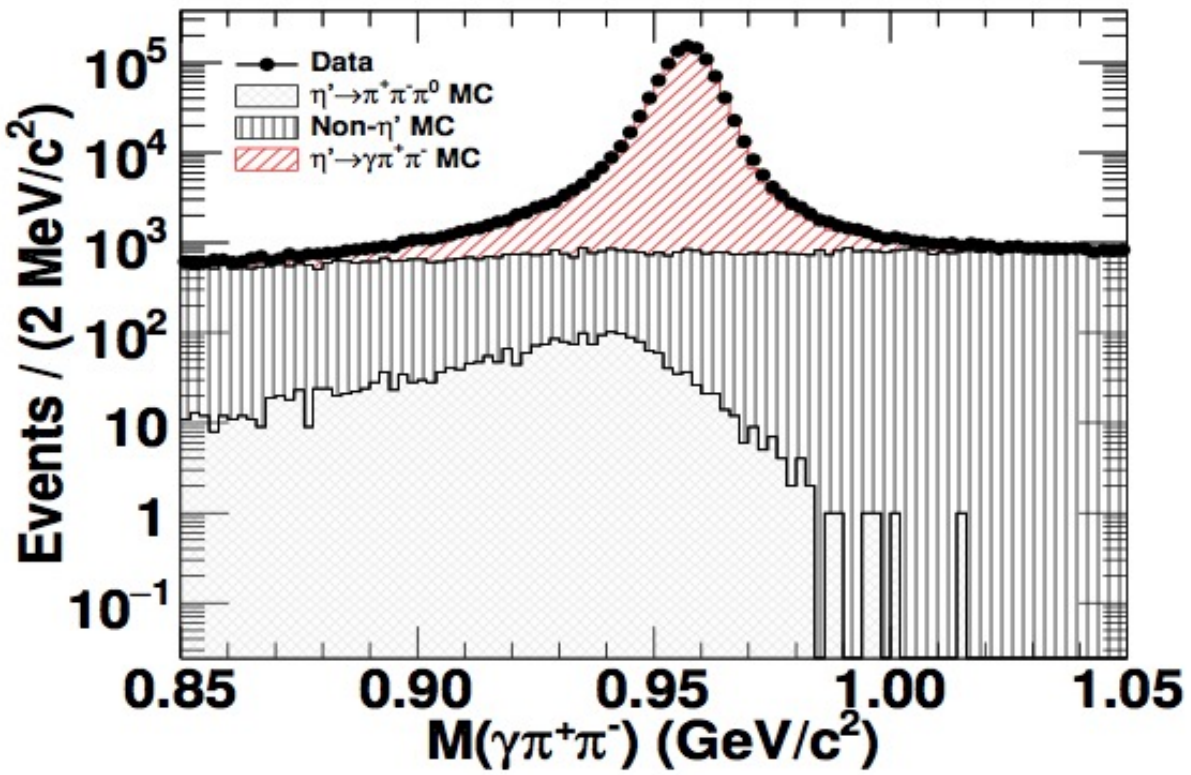
New decay mechanisms

Precision study of $\eta' \to \gamma\pi^+\pi^-$	PRL120, 242003(2018)
Cusp effect in $\eta' \to \pi^0\pi^0\eta$	PRL130, 081901(2023)

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



~0.9M events



high term of ChPT→ box anomaly

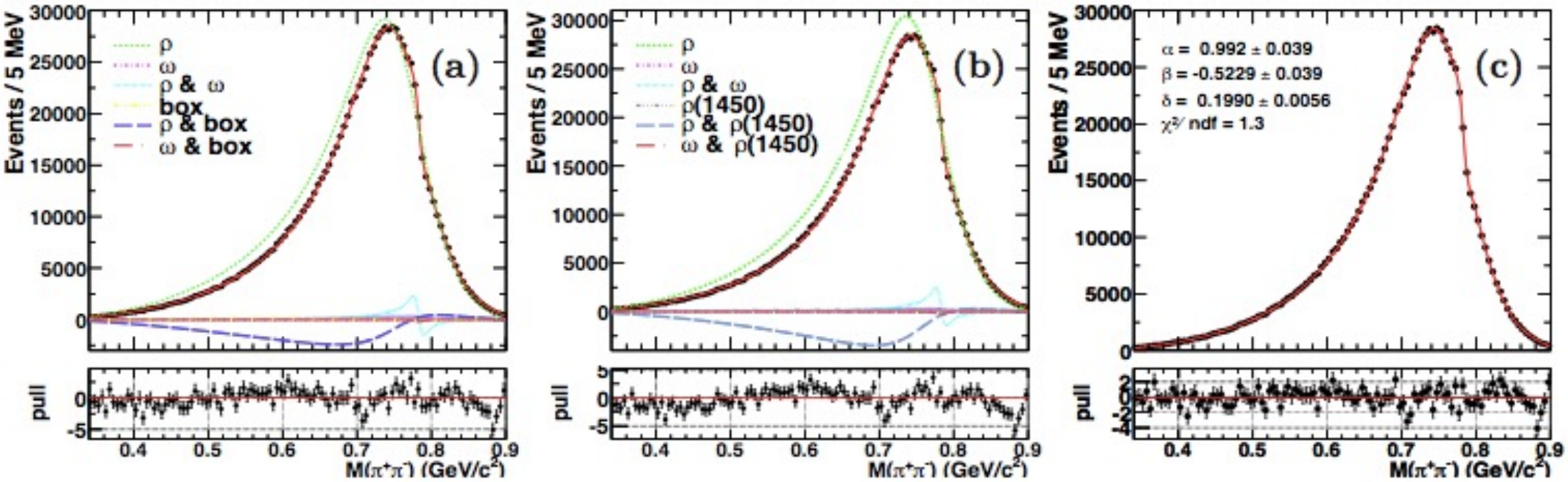
PRL120,242003(2018)

Model-(in)dependent fit

fit with ρ(770)-ω-box anomaly

fit with ρ(770)-ω-ρ(1450)

$P(s_{\pi\pi}) = 1 + \alpha\, s_{\pi\pi} + \beta\, O(s^2_{\pi\pi}) + \delta\, BW_\omega$



✓ ρ(770)-ω cannot describe data well

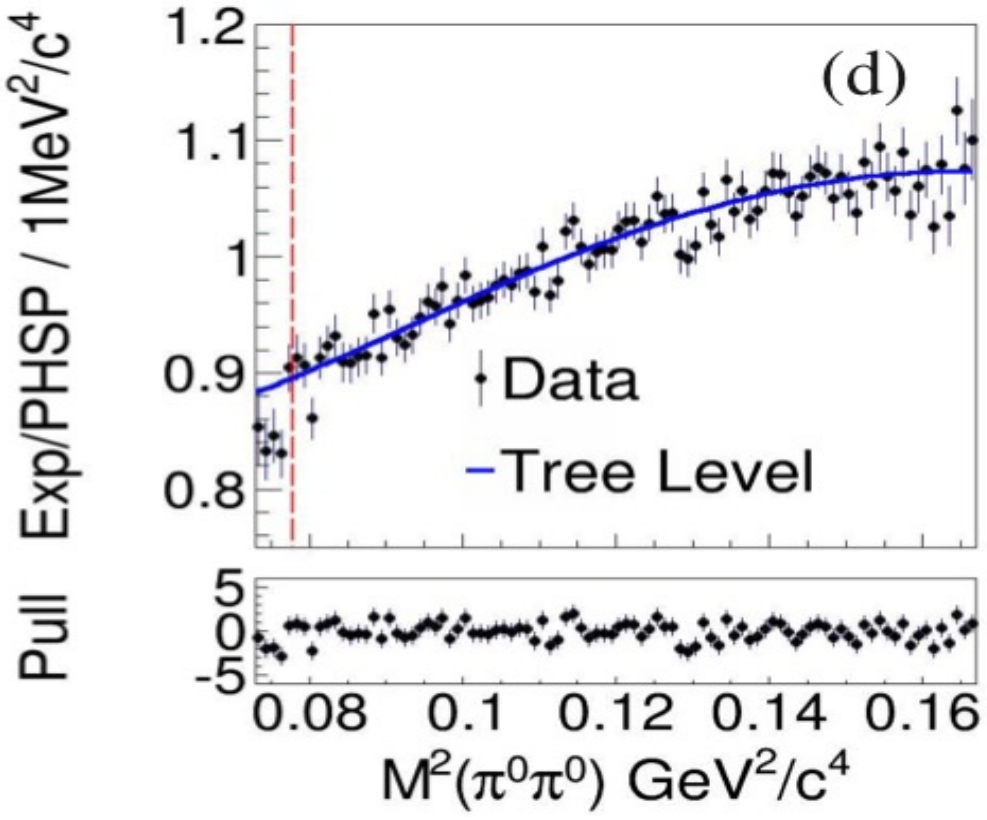
✓ Extra contribution (maybe ρ(1450) or box-anomaly) is also necessary

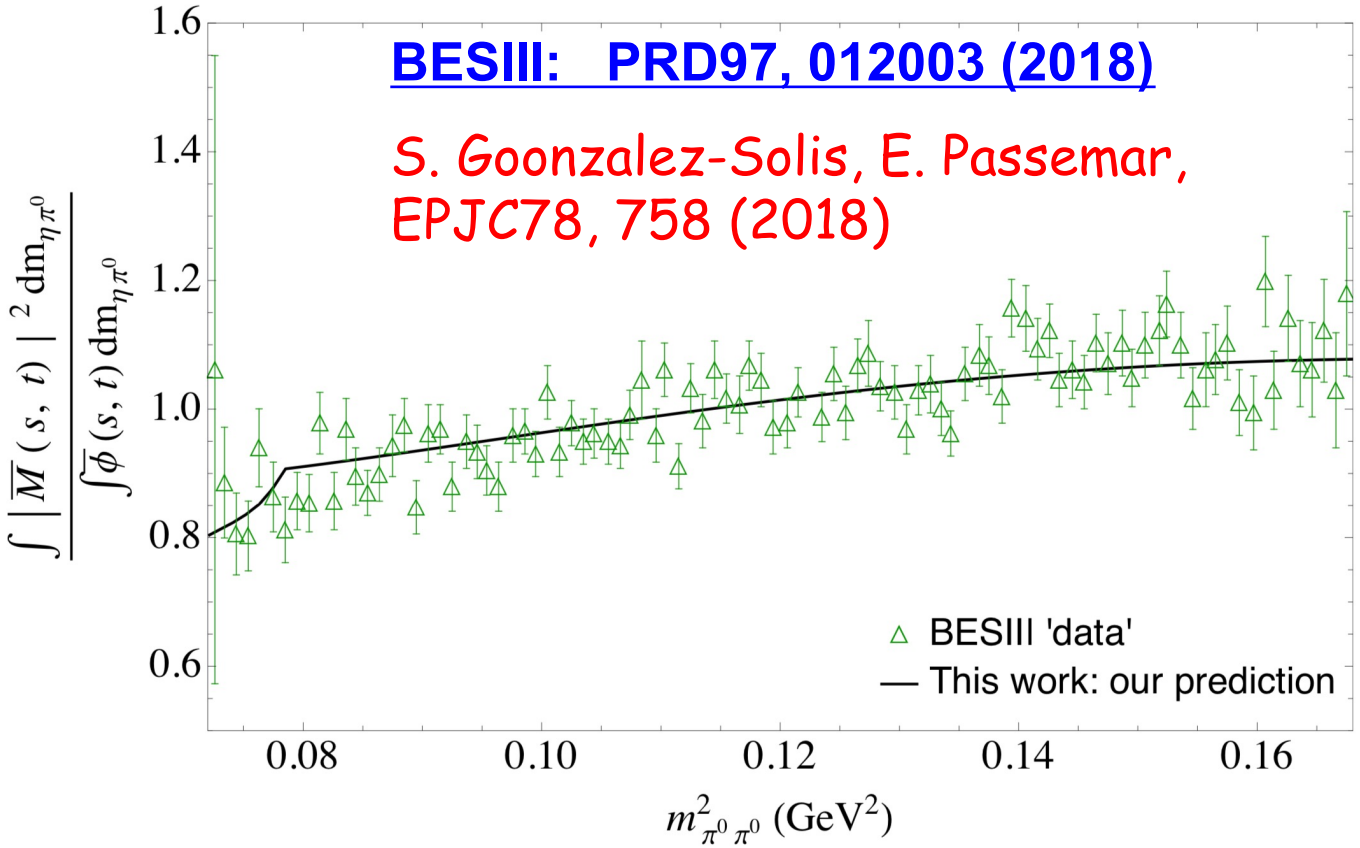
Analysis with 10 billion J/ψ is in progress !

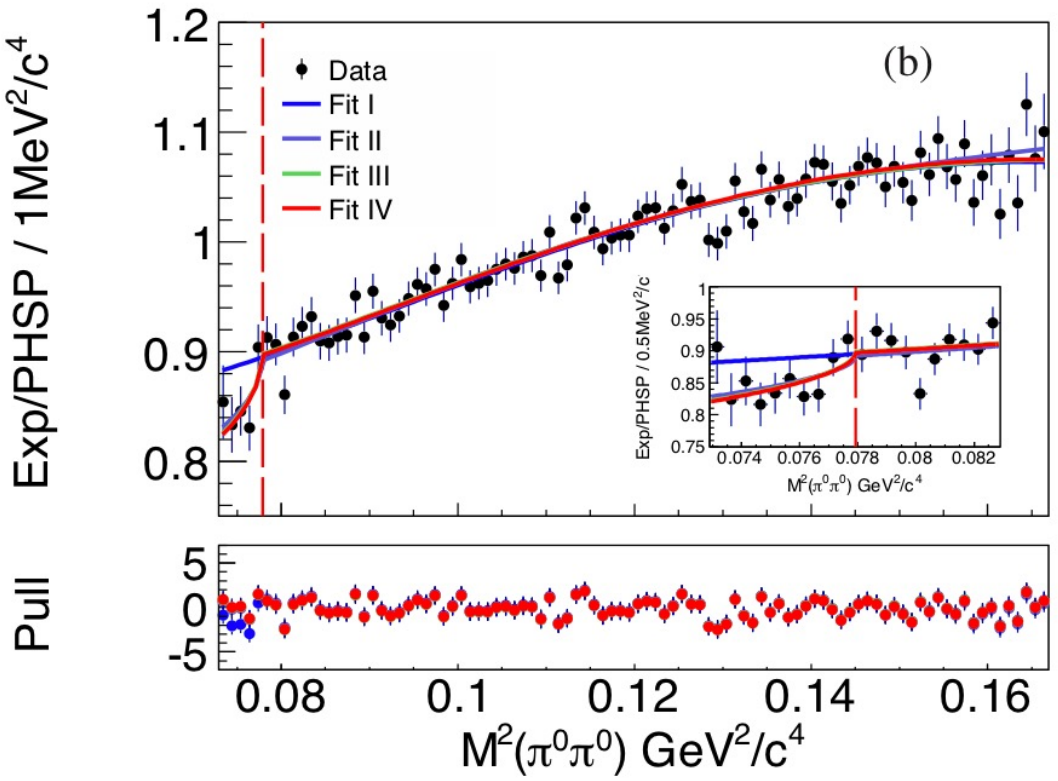
Evidence of the cusp effect in $\eta' \to \pi^0\pi^0\eta$

PRL130,081901(2023)

- Investigation on ππ and πη final interactions
- The cusp effect is sizeable in this decay







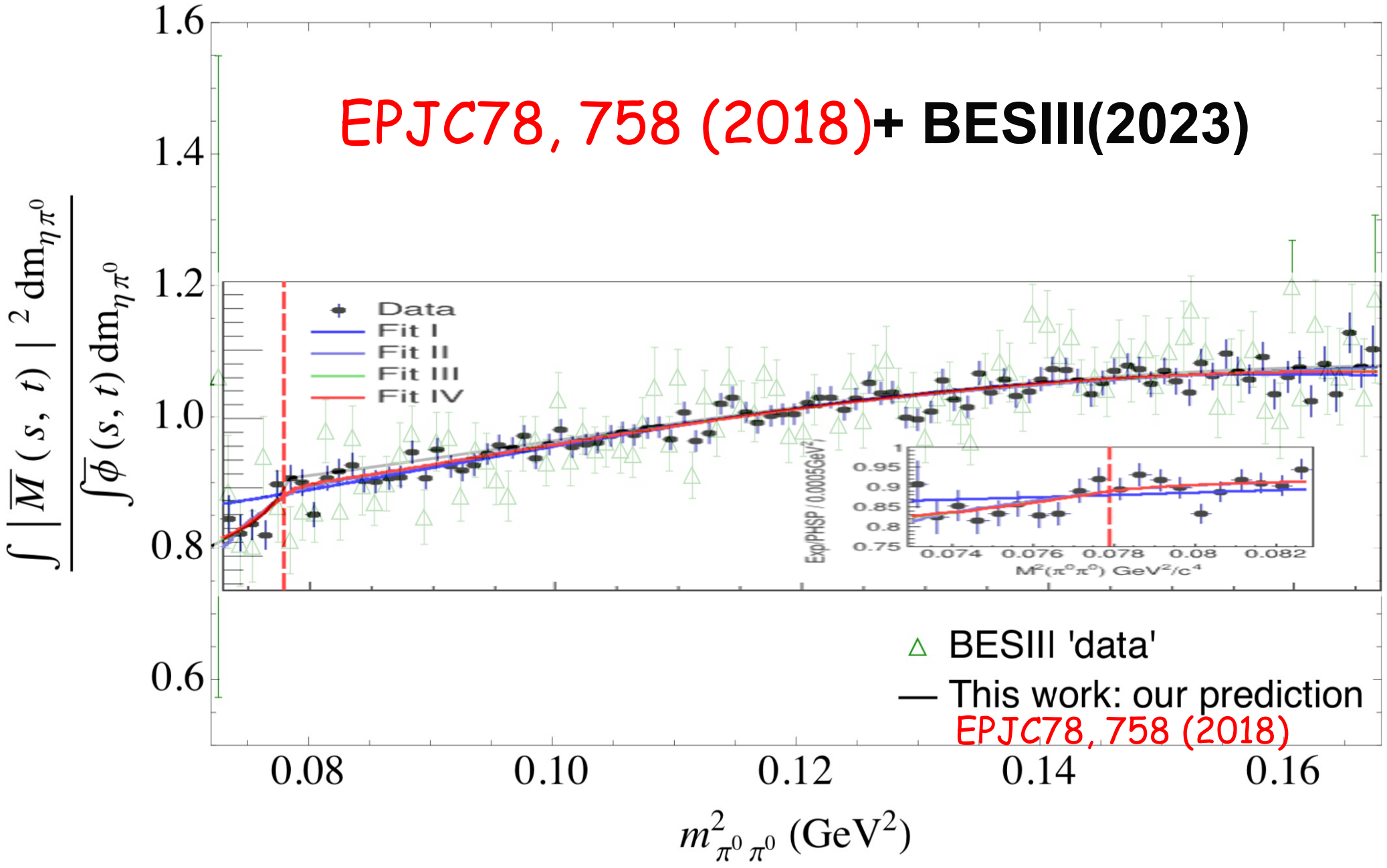
- Non-relativistic effective field theory

  B. Kubis and S. P. Schneider, EPJC 62, 511 (2009)

- Fits at different cases

- Evidence of the cusp effect @ 3.5σ !

Parameters	Fit I	Fit II	Fit III	Fit IV
a	$-0.075 \pm 0.003 \pm 0.001$	-0.207 ± 0.013	-0.143 ± 0.010	$-0.077 \pm 0.003 \pm 0.001$
b	$-0.073 \pm 0.005 \pm 0.001$	-0.051 ± 0.014	-0.038 ± 0.006	$-0.066 \pm 0.006 \pm 0.001$
d	$-0.066 \pm 0.003 \pm 0.001$	-0.068 ± 0.004	-0.067 ± 0.003	$-0.068 \pm 0.004 \pm 0.001$
$a_0 - a_2$	-	0.174 ± 0.066	0.225 ± 0.062	$0.226 \pm 0.060 \pm 0.012$
a_0	-	0.497 ± 0.094	-	-
a_2	-	0.322 ± 0.129	-	-
Statistical Significance	-	3.4σ	3.7σ	3.6σ

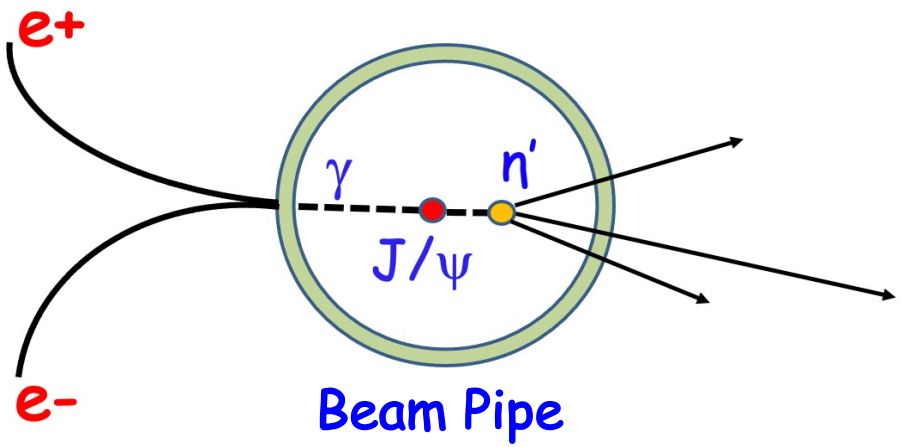

EPJC78, 758 (2018)+ BESIII(2023)
$\int \left| \overline{M}(s,t) \right|^2 \mathrm{d}m_{\eta\pi^0} \Big/ \int \overline{\phi}(s,t)\,\mathrm{d}m_{\eta\pi^0}$
1.6
1.4
1.2
1.0
0.8
0.6
0.08
0.10
0.12
0.14
0.16
$m^2_{\pi^0\pi^0}$ (GeV^2)
Data
Fit I
Fit II
Fit III
Fit IV
Exp/PHSP / 0.0005GeV^2
M^2($\pi^0\pi^0$) GeV^2/c^4
△ BESIII 'data'
— This work: our prediction
EPJC78, 758 (2018)

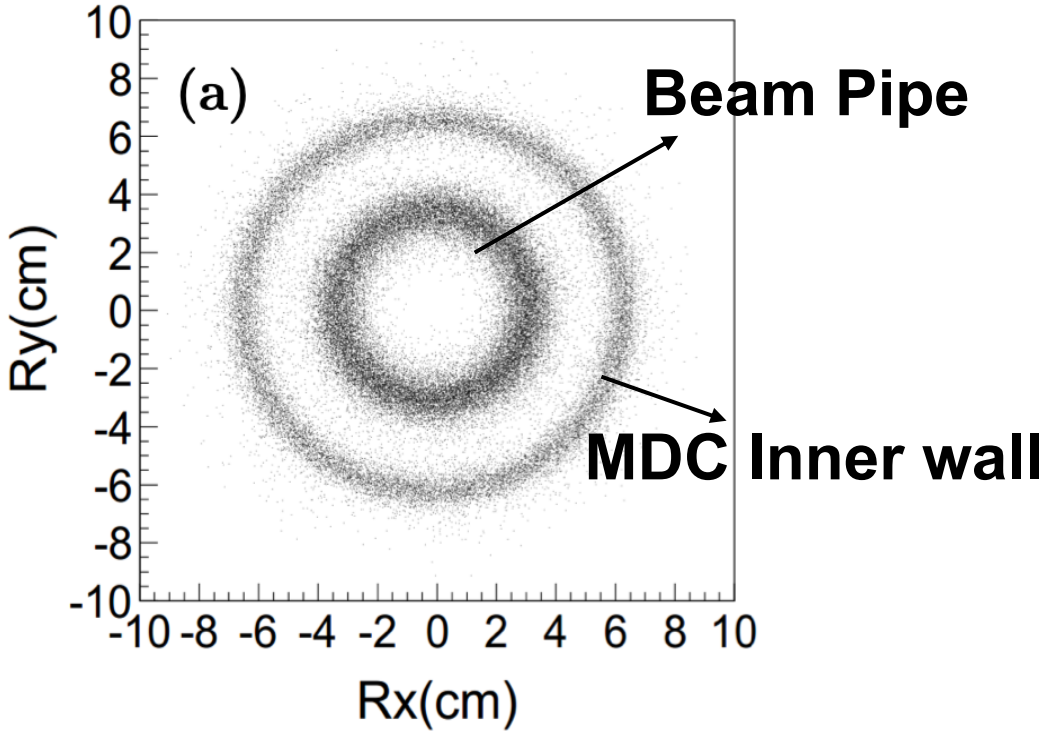
New approaches

Absolute Measurement of BFs of η’ decay modes	PRL122, 142002(2019)
Novel approach to investigate η decays	PRD108,014038(2023)

γ conversion: η/η′ inclusive decays

- A novel way to measure the absolute BFs of η/η′ decays
- Excellent momentum resolution for electrons @MDC

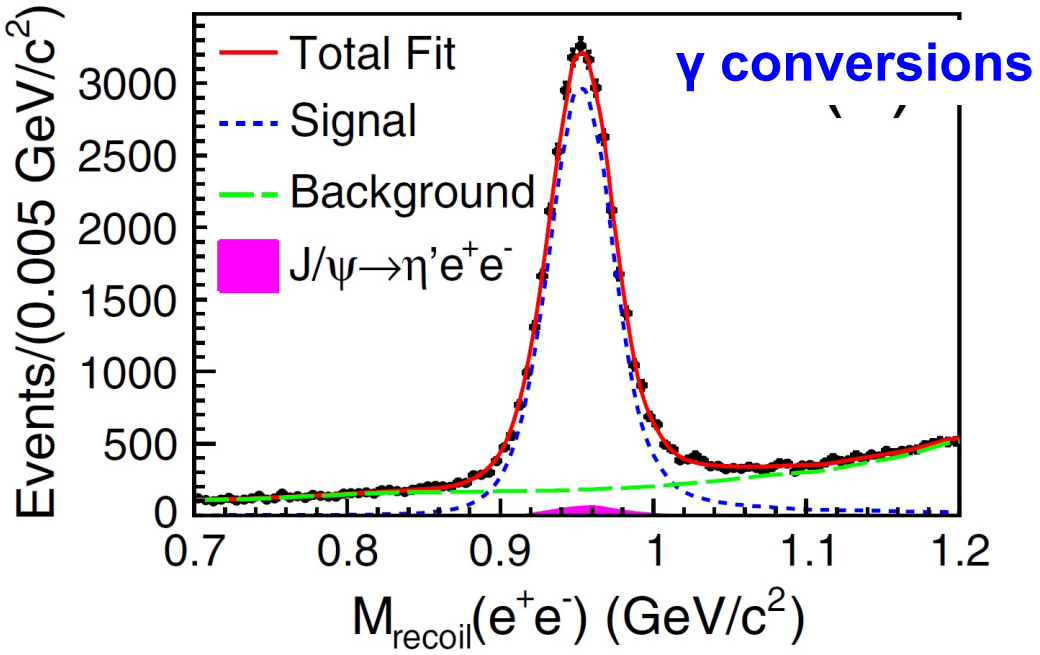




$$\mathcal{B}(\eta' \to X) = \frac{N^{obs}_{\eta' \to X}}{\varepsilon_{\eta' \to X}} \Big/ \frac{\varepsilon}{N^{obs}_{J/\psi \to \gamma\eta'}}$$

First Measurement of Absolute BFs of η′ /η decays

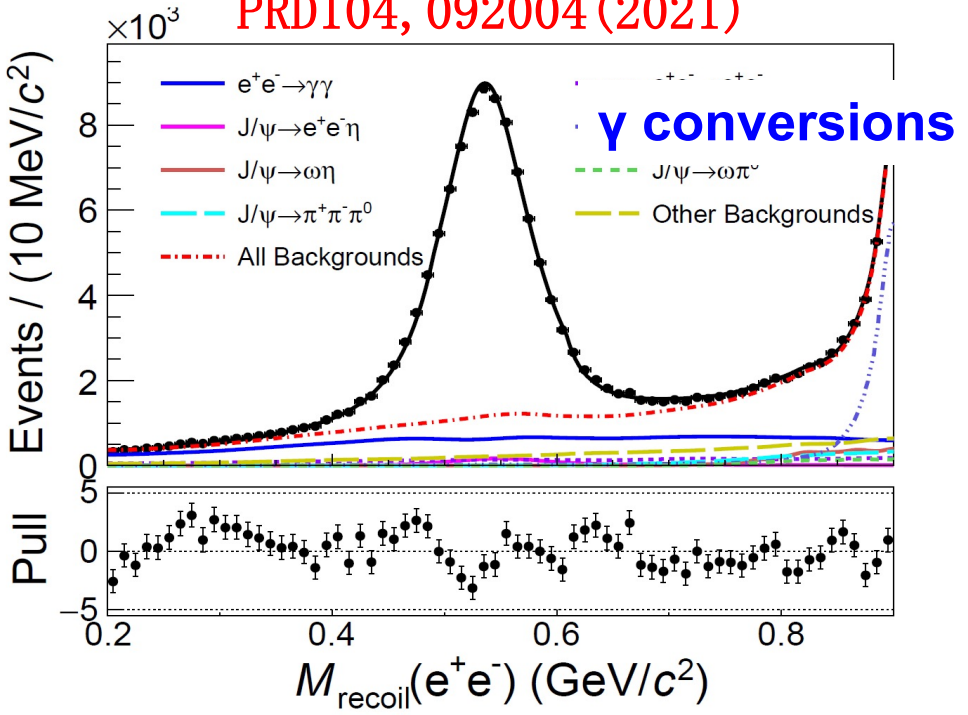
PRL122, 142002(2019)



Decay mode	$\mathcal{B}(\eta' \to X)(\%)$ This measurement	PDG [7]
$\eta' \to \gamma\pi^+\pi^-$	$29.90 \pm 0.03 \pm 0.55$	28.9 ± 0.5
$\eta' \to \eta\pi^+\pi^-$	$41.24 \pm 0.08 \pm 1.24$	42.6 ± 0.7
$\eta' \to \eta\pi^0\pi^0$	$21.36 \pm 0.10 \pm 0.92$	22.8 ± 0.8
$\eta' \to \gamma\omega$	$2.489 \pm 0.018 \pm 0.074$	2.62 ± 0.13
$\eta' \to \gamma\gamma$	$2.331 \pm 0.012 \pm 0.035$	2.22 ± 0.08

B(J/ψ→γη′) = (5.27±0.03±0.05)×10⁻³

PRD104, 092004(2021)



X	This work	PDG
$\gamma\gamma$	$39.86 \pm 0.04 \pm 0.99$	39.41 ± 0.20
$\pi^0\pi^0\pi^0$	$31.96 \pm 0.07 \pm 0.84$	32.68 ± 0.23
$\pi^+\pi^-\pi^0$	$23.04 \pm 0.03 \pm 0.54$	22.92 ± 0.28
$\pi^+\pi^-\gamma$	$4.38 \pm 0.02 \pm 0.10$	4.22 ± 0.08

B(J/ψ→γη) = (1.067±0.005±0.023)×10⁻³

New approach to investigate η decays with $\eta' \to \pi^+\pi^-\eta$

Xiao-lin Kang, Yuyao Ji et al, PRD 108, 014038 (2023)

η REFERENCES PDG2022

ABLIKIM	23AN	PR D107 092007	M. Ablikim *et al.*	(BESIII Collab.)
HAYRAPETY...	23A	PRL 131 091903	A. Hayrapetyan *et al.*	(CMS Collab.)
ABLIKIM	21AM	PR D104 092004	M. Ablikim *et al.*	(BESIII Collab.)
BABUSCI	20A	JHEP 2010 047	D. Babusci *et al.*	(KLOE-2 Collab.)
ZHEVLAKOV	19	PR D99 031703	A.S. Zhevlakov *et al.*	(TMSK, MAINZ, TUBIN+)
ACHASOV	18B	PR D98 052007	M.N. Achasov *et al.*	(SND Collab.)
ADLARSON	18C	PL B784 378	P. Adlarson *et al.*	(WASA-at-COSY Collab.)
PRAKHOV	18	PR C97 065203	S. Prakhov *et al.*	(A2 Collab. at MAMI)
AAIJ	17D	PL B764 233	R. Aaij *et al.*	(LHCb Collab.)
ADLARSON	17B	PR C95 035208	P. Adlarson *et al.*	(A2 Collab. at MAMI)
ANASTASI	16A	JHEP 1605 019	A. Anastasi *et al.*	(KLOE-2 Collab.)
ARNALDI	16	PL B757 437	R. Arnaldi *et al.*	(NA60 Collab.)
ABLIKIM	15G	PR D92 012014	M. Ablikim *et al.*	(BESIII Collab.)
ADLARSON	14A	PR C90 045207	P. Adlarson *et al.*	(WASA-at-COSY Collab.)
AGAKISHIEV	14	PL B731 265	G. Agakishiev *et al.*	(HADES Collab.)
NEFKENS	14	PR C90 025206	B.M.K. Nefkens *et al.*	(A2 Collab. at MAMI)
NIKOLAEV	14	EPJ A50 58	A. Nikolaev *et al.*	(MAMI-B, MAINZ, BONN)
ABLIKIM	13	PR D87 012009	M. Ablikim *et al.*	(BESIII Collab.)
ABLIKIM	13G	PR D87 032006	M. Ablikim *et al.*	(BESIII Collab.)
BABUSCI	13	PL B718 910	D. Babusci *et al.*	(KLOE/KLOE-2 Collab.)
BABUSCI	13A	JHEP 1301 119	D. Babusci *et al.*	(KLOE-2 Collab.)
AGAKISHIEV	12A	EPJ A48 64	G. Agakishiev *et al.*	(HADES Collab.)
GOSLAWSKI	12	PR D85 112011	P. Goslawski *et al.*	(COSY-ANKE Collab.)
ABLIKIM	11G	PR D84 032006	M. Ablikim *et al.*	(BESIII Collab.)

- Production rate lower than η′
- Background from QED and J/ψ decays

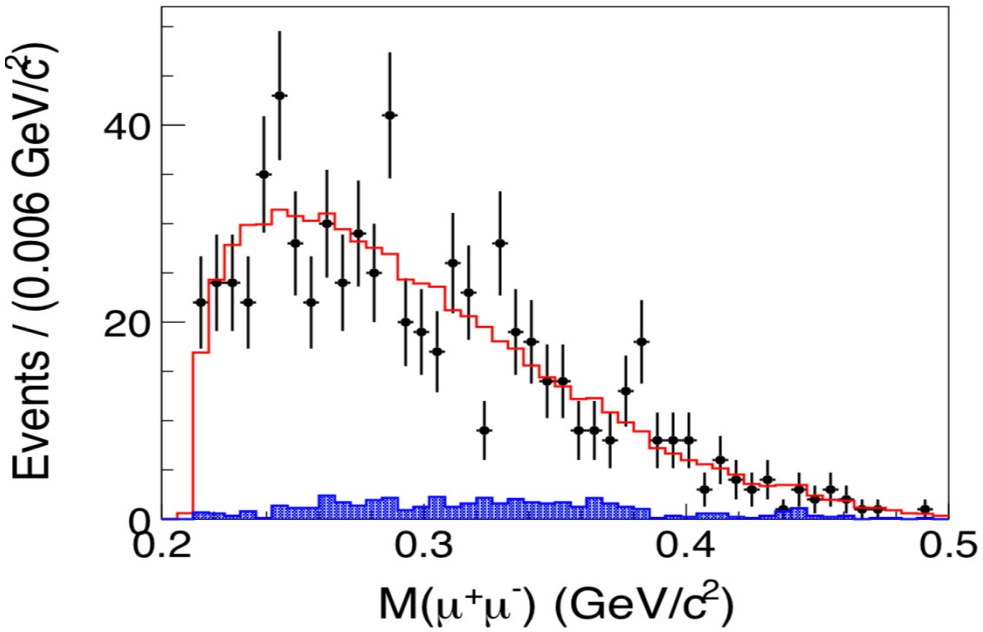
$J/\psi \to \gamma\eta \to 1\times10^7\ \eta$

$J/\psi \to \gamma\eta',\ \eta' \to \pi^+\pi^-\eta \to 2.2\times10^7\ \eta$

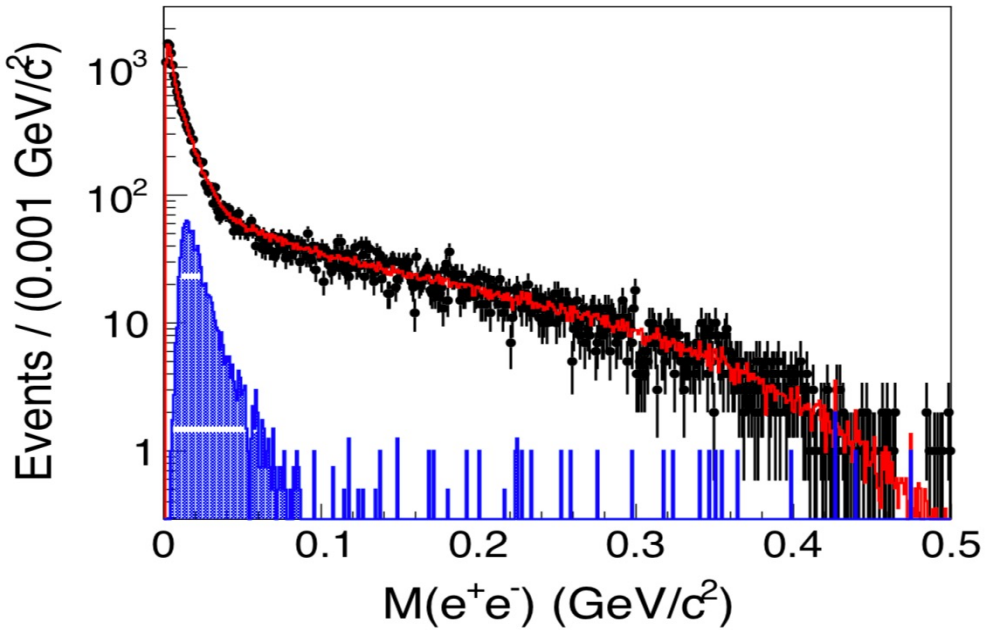
One more η′ constraint to suppress the background events !

Feasibility study $J/\psi \to \gamma\eta'$, $\eta' \to \pi^+\pi^-\eta$

$\eta \to \gamma\mu^+\mu^-$



$\eta \to \gamma e^+ e^-$



- Help distinguish muons from pions
- Background level is low

Xiao-lin Kang, Yuyao Ji et al, PRD 108, 014038 (2023)

Summary

- BESIII: a light meson factory
  - a unique place for light mesons
  - Allow to study light meson decays with high precision
- Significant progresses achieved on η/η′ decays
  - η/η′ : hadronic, radiative and rare decays
- More results are expected to come soon !
- Together with other experiments, the light meson physics will be into a precision era