

BESIII轻介子研究进展

房双世（高能所）

BESIII轻强子物理研讨会

2021年10月23日

OUTLINE

- Physics with light meson decays
- Brief review on n/n' physics
- Recent progresses
- Summary and Prospects

Physics with light meson decays

- Rich physics
 - test ChPT predictions
 - Form factors
 - Precision test fundamental symmetries
 - Probe new physics beyond the SM
- Excited states (strange, strangeonium . .)

Source of light mesons



CLAS2



Crystal Ball

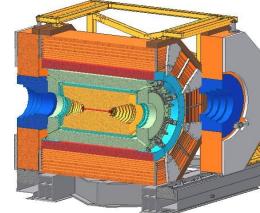


WASA-at-COSY

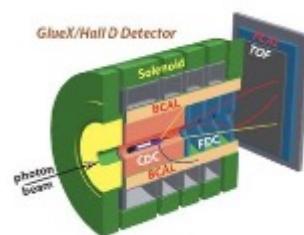


KLOE-2

1×10^{10} J/ψ events



BESIII



GlueX

BESIII: a factory of light mesons

- n/n' from $J/\psi \rightarrow \gamma\eta/\eta' \rightarrow 1 \times 10^7 n, 5.2 \times 10^7 n'$
- n/n' from $J/\psi \rightarrow \phi\eta/\eta' \rightarrow 4 \times 10^6 n, 2.5 \times 10^6 n'$

- Hadronic decays
 - $\eta' \rightarrow \pi^+\pi^-\eta, \pi^0\pi^0\eta$
 - $\eta' \rightarrow \pi^+\pi^-\pi^+\pi^-, \pi^+\pi^-\pi^0\pi^0$
 - $n/n' \rightarrow \pi^+\pi^-\pi^0, n/n' \rightarrow \pi^0\pi^0\pi^0$
- Radiative decays
 - $n/n' \rightarrow \gamma e^+e^-$
 - $n/n' \rightarrow \gamma\gamma\pi^0$
 - $n/n' \rightarrow \gamma\pi^+\pi^-$
- Rare/forbidden decays
 - $n/n' \rightarrow$ invisible decays
 - $n/n' \rightarrow \pi e\nu$
 -

Achievements with 1.3 billion J/ ψ events

- $\eta' \rightarrow 2(\pi^+\pi^-)$, $\pi^+\pi^-\pi^0\pi^0$ PRL112,251801(2014)
- $\eta' \rightarrow \gamma e^+e^-$ PRD92,012001(2015)
- $\eta \rightarrow \pi^+\pi^-\pi^0$, $\eta/\eta' \rightarrow \pi^0\pi^0\pi^0$ PRD92,012014(2015)
- $\eta' \rightarrow \omega e^+e^-$ PRD92,051101(2015)
- $\eta' \rightarrow K\pi$ PRD93, 072008 (2016)
- $\eta' \rightarrow \rho\pi$ PRL118,012001(2017)
- $\eta' \rightarrow \gamma\gamma\pi^0$ PRD96,012005(2017) (康晓琳, 2018年晨光杯二等奖)
- $\eta' \rightarrow \gamma\pi^+\pi^-$ PRL120,242003(2018) (秦丽清, 2021年晨光杯一等奖)
- $\eta' \rightarrow \pi^+\pi^-\eta$, $\eta' \rightarrow \pi^0\pi^0\eta$ PRD97, 012003(2018)
- $\omega \rightarrow \pi^+\pi^-\pi^0$ PRD98, 112007(2018)
- two photon decays of P. PRD97,072014(2018)
- $\eta' \rightarrow \gamma\gamma\eta$ PRD100, 052015(2019)
- Absolute BF of η' decays PRL122,142002(2019)
- $\eta' \rightarrow \pi^0\pi^0\pi^0\pi^0$ PRD101, 032001(2020)
- $\eta' \rightarrow \pi^+\pi^-e^+e^-$ PRD103,092005(2021)
- $\eta' \rightarrow \pi^+\pi^-u+u^-$ PRD103,072006(2021)

η/η' hadronic decays

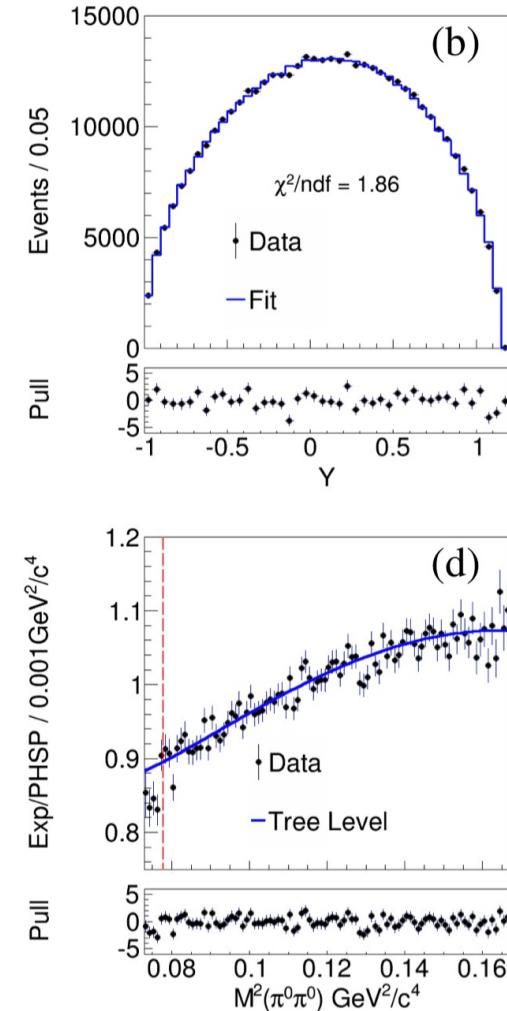
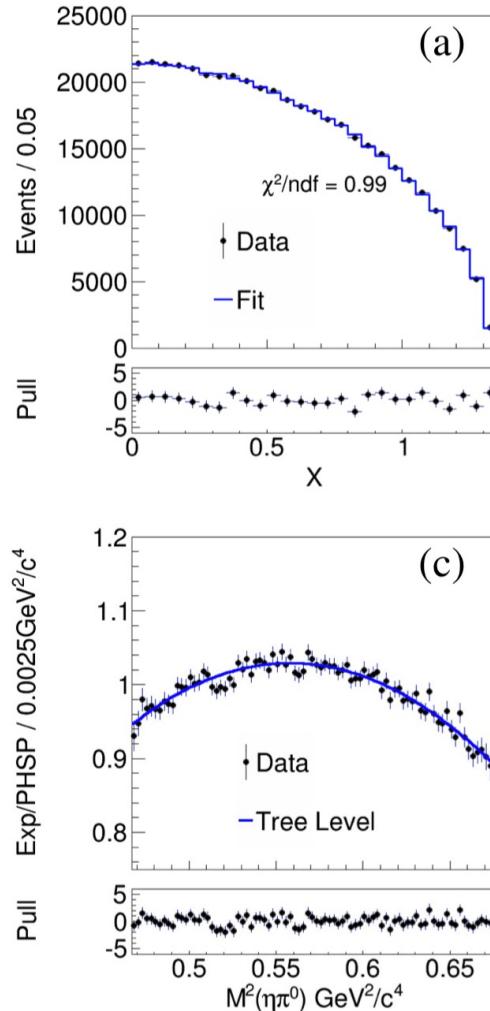
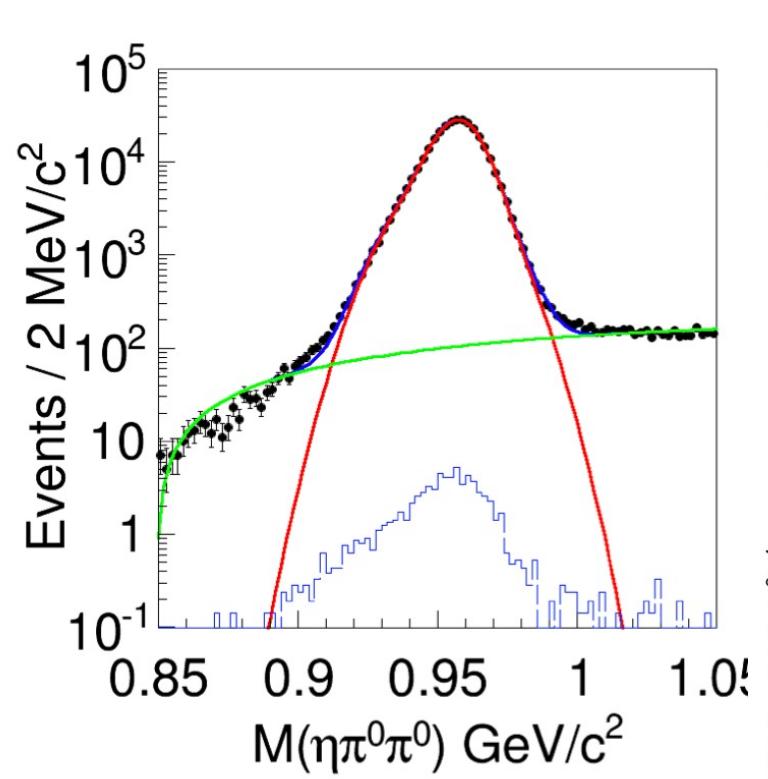
- $\eta' \rightarrow \pi^+ \pi^- \eta / \pi^0 \pi^0 \eta$
- $\eta/\eta' \rightarrow 3\pi$
- $\eta' \rightarrow 4\pi$

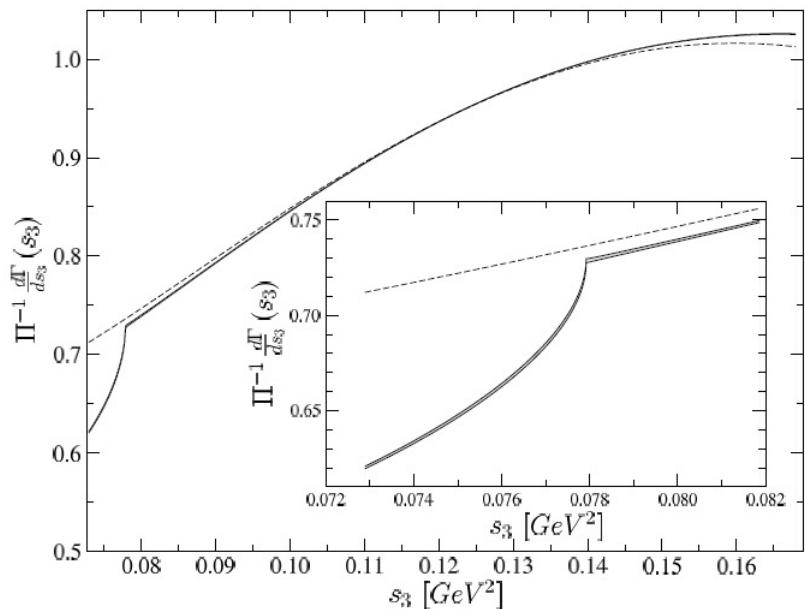
Dalitz plot of $\eta' \rightarrow \pi^+\pi^-\eta, \pi^0\pi^0\eta$

(师荣盛: bam-00443: draft)

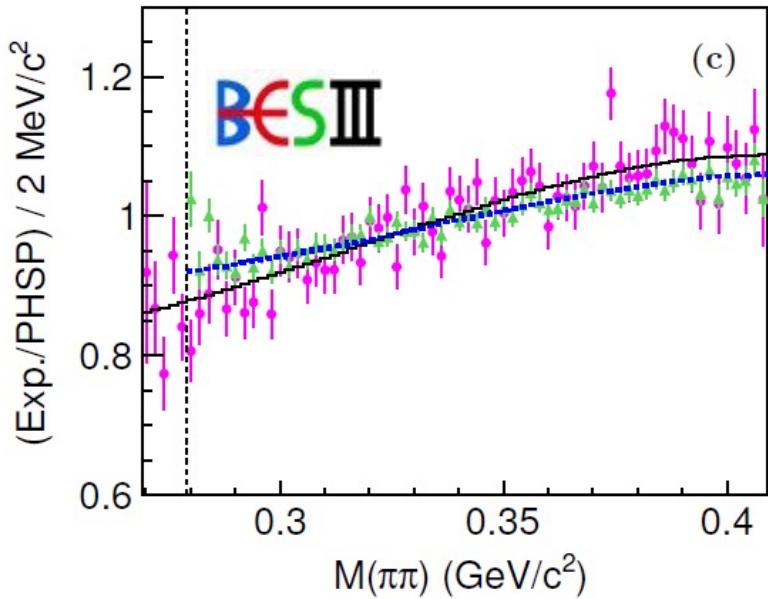
$$X = \frac{\sqrt{3}}{Q} (T_{\pi^+} - T_{\pi^-}),$$

$$Y = \frac{m_\eta + 2m_\pi}{m_\pi} \frac{T_\eta}{Q} - 1$$

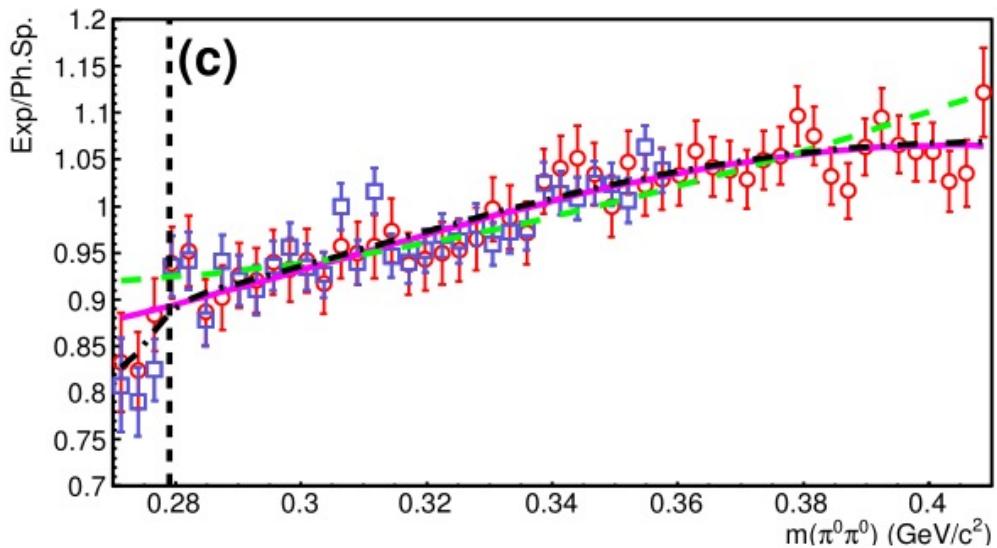




Eur.Phys.J.C62:511-523,2009

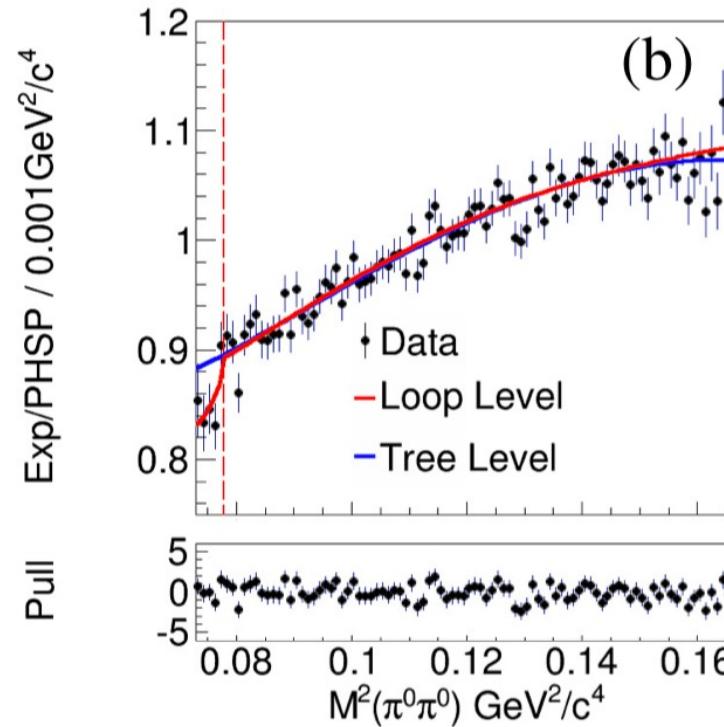
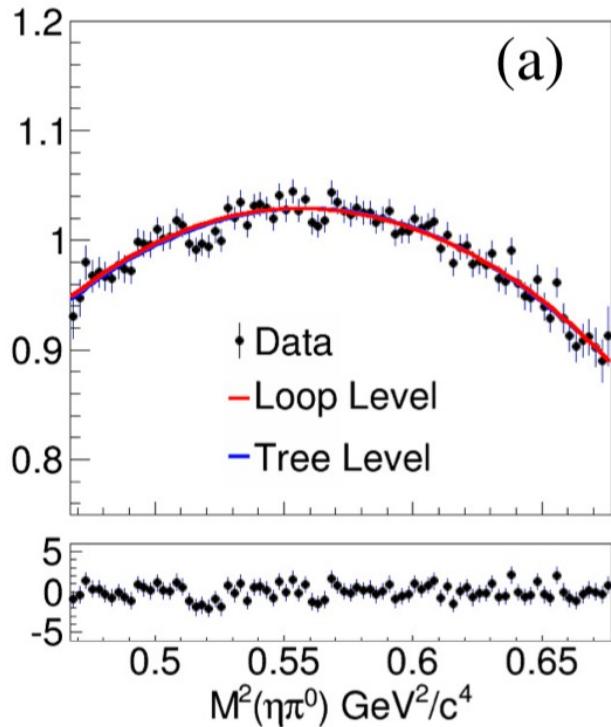


Phys. Rev. D 97, 012003 (2018)



Phys. Rev. D 98, 012001 (2018)
A2 Collaboration

Evidence of the cusp effect!



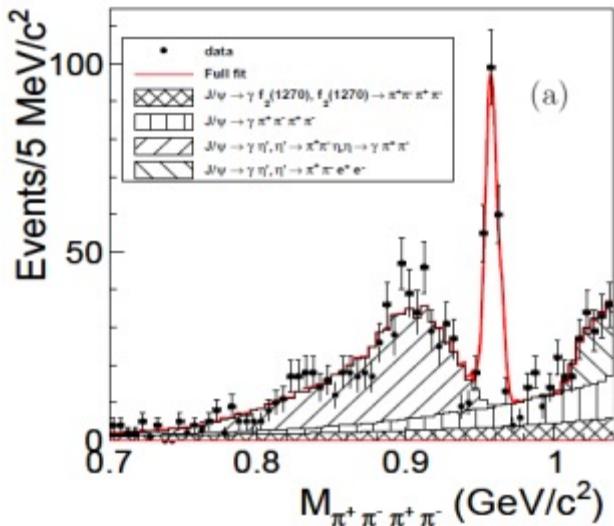
Parameters	Fit I	Fit II	Fit III	Fit IV
a	$-0.075 \pm 0.003 \pm 0.001$	-0.207 ± 0.013	-0.143 ± 0.010	$-0.077 \pm 0.003 \pm 0.001$
b	$-0.073 \pm 0.005 \pm 0.001$	-0.051 ± 0.014	-0.038 ± 0.006	$-0.066 \pm 0.006 \pm 0.001$
d	$-0.066 \pm 0.003 \pm 0.001$	-0.068 ± 0.004	-0.067 ± 0.003	$-0.068 \pm 0.004 \pm 0.001$
$a_0 - a_2$	-	0.174 ± 0.066	0.225 ± 0.062	$0.226 \pm 0.060 \pm 0.024$
a_0	-	0.497 ± 0.094		
a_2	-	0.322 ± 0.129		
Statistical Significance		3.4σ	3.7σ	3.6σ

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

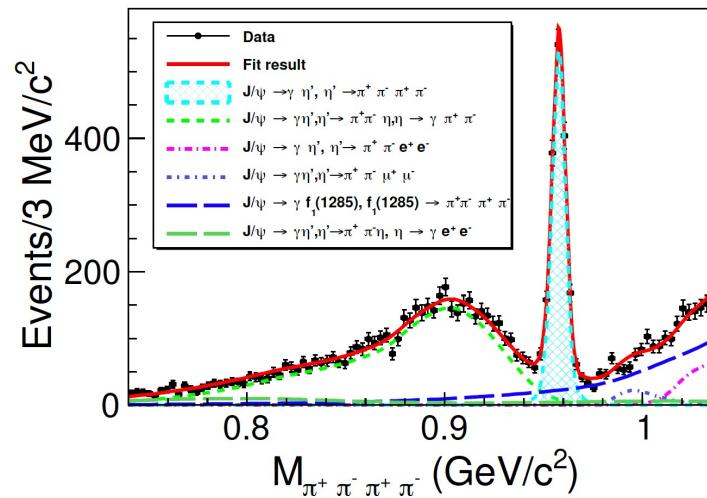
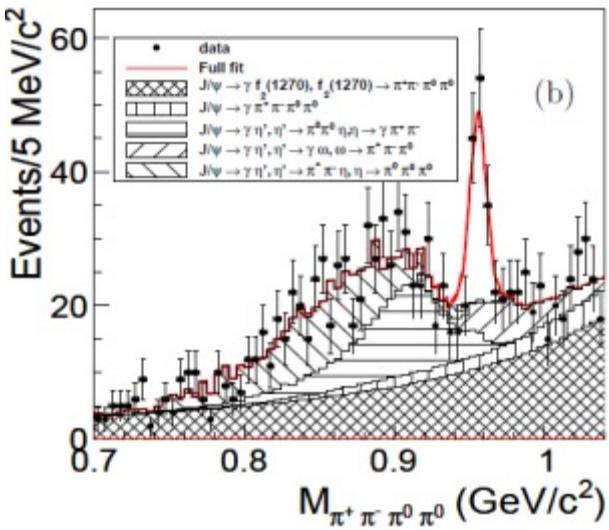
常万玲 (毕业), 赵子涵 (in progress)

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

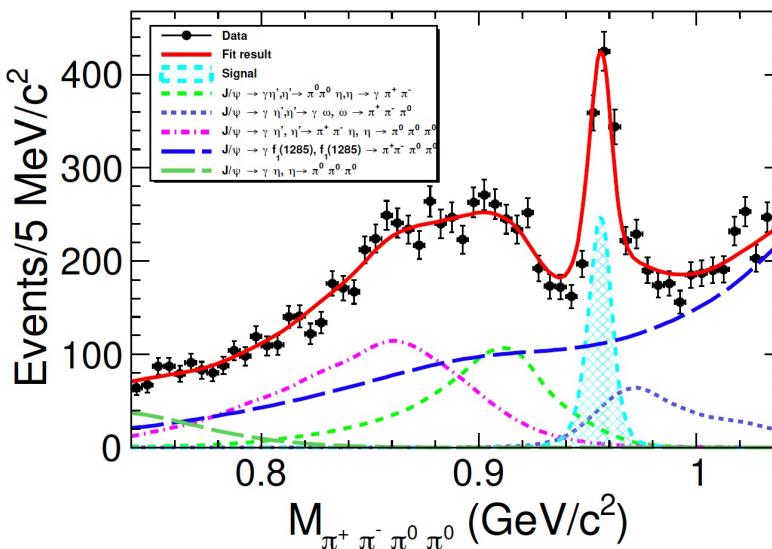
F.K. Guo, B. Kubis, A. Wirzba, Phys. Rev. D 85, 014014 (2012)



PRL112, 251801(2014)



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



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

$$\eta \rightarrow \pi^+ \pi^- \pi^0, \eta \rightarrow 3\pi^0 \quad (\text{康晓琳: BAM--00543})$$

Dalitz variables:

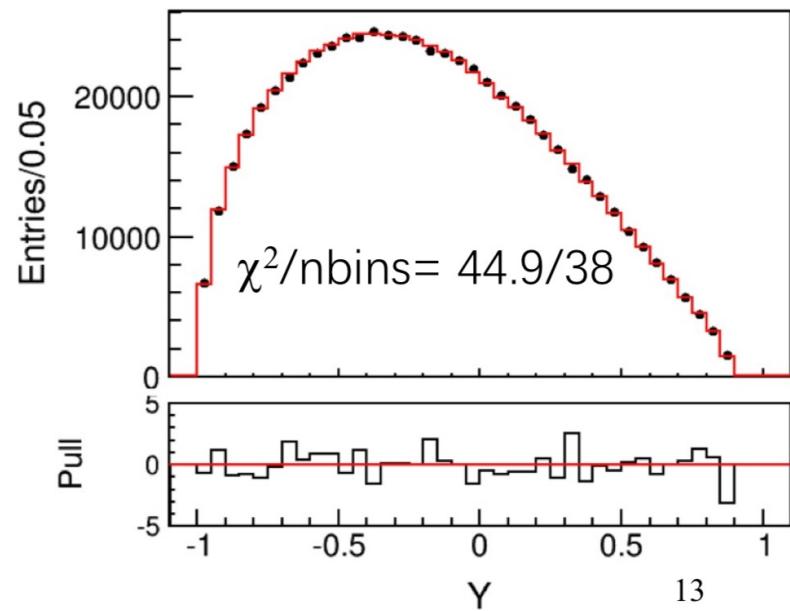
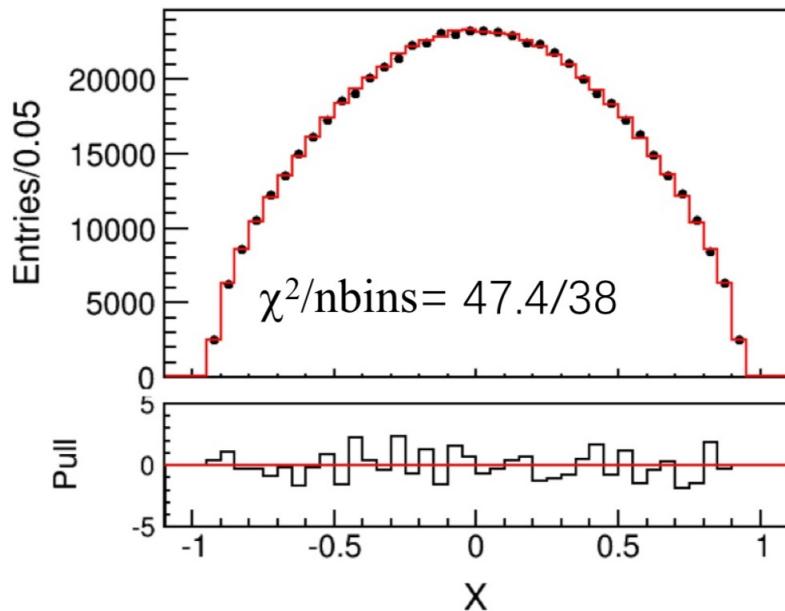
$$Y = \frac{3T_{\pi^0}}{Q} - 1, \quad X = \frac{\sqrt{3}}{Q}(T_{\pi^+} - T_{\pi^-})$$

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

$$|A(X, Y)|^2 = N(1 + aY + bY^2 + cX + dX^2 + eXY + fY^3 + \dots),$$

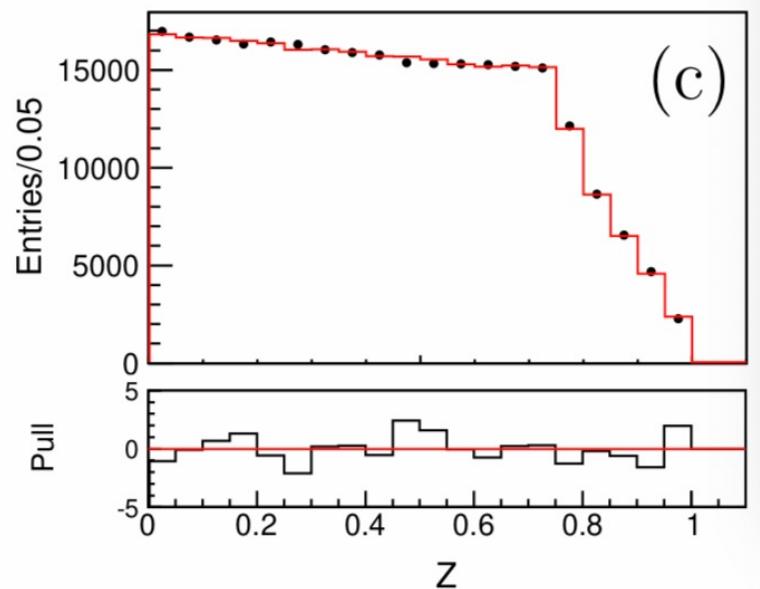
Parameterizations for $\eta \rightarrow 3\pi^0$

$$|A|^2 \propto 1 + 2\alpha Z + 2\beta(3X^2Y - Y^3) + 2\gamma Z^2 + \dots + 2\delta \sum_{i=1}^3 \rho(s_i),$$



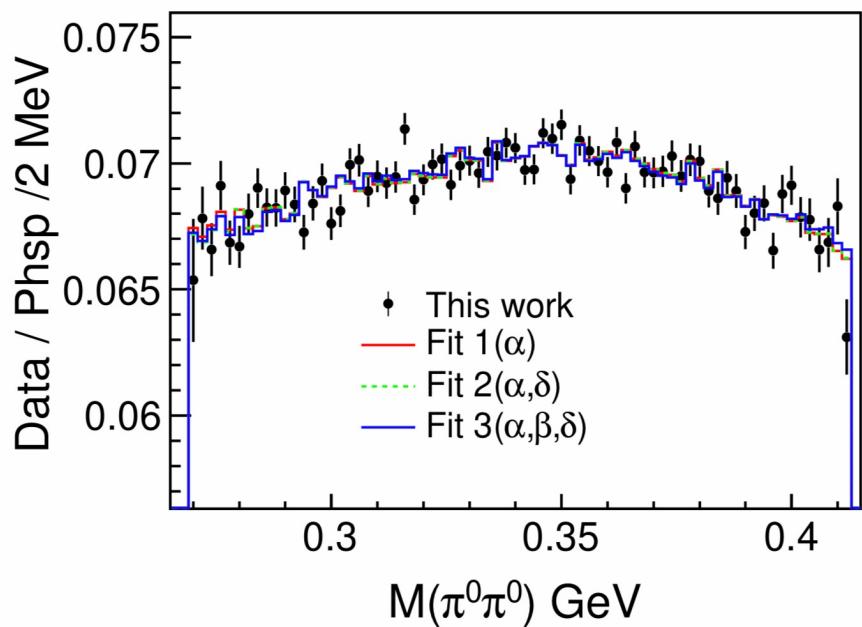
χ^2/nbins	a	b	c	d	e	f
BESIII-2015	$-1.128 \pm 0.015 \pm 0.008$	$0.153 \pm 0.017 \pm 0.004$	0(fixed)	$0.085 \pm 0.016 \pm 0.009$	0(fixed)	$0.173 \pm 0.028 \pm 0.021$
KLOE-2	$-1.104 \pm 0.003 \pm 0.002$	$0.142 \pm 0.003 \pm 0.005$	0(fixed)	$0.073 \pm 0.003 \pm 0.004$	0(fixed)	$0.154 \pm 0.006 \pm 0.005$

- Consistent with BESIII previous results
- No evident C-parity violation



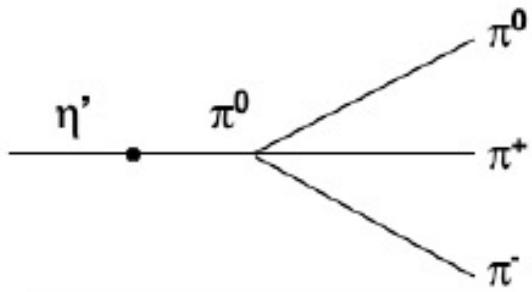
$$\alpha = -0.043 \pm 0.003 \pm 0.001$$

Consistent with previous results



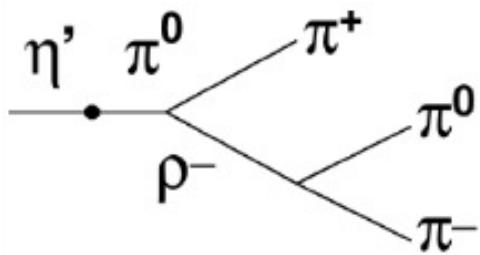
No evident cusp effect !

$$\eta' \rightarrow \rho^+ \pi^- + C.C.$$



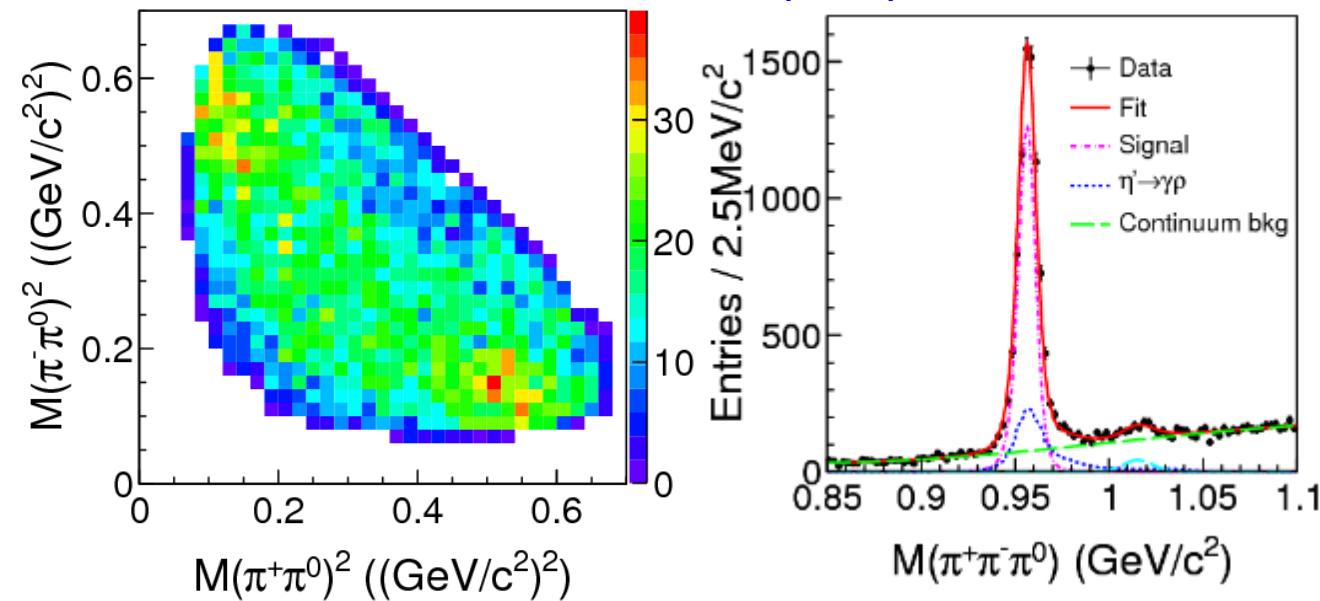
D. Gross et al., PRD19, 2188(1979)

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



N. Beisert, B. Borasoy, Nucl. Phys. A716, 186(2003)

PRL, 118, 012001(2017)



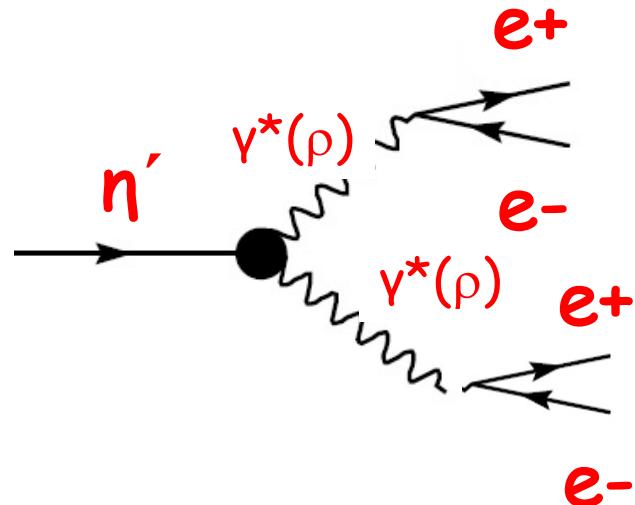
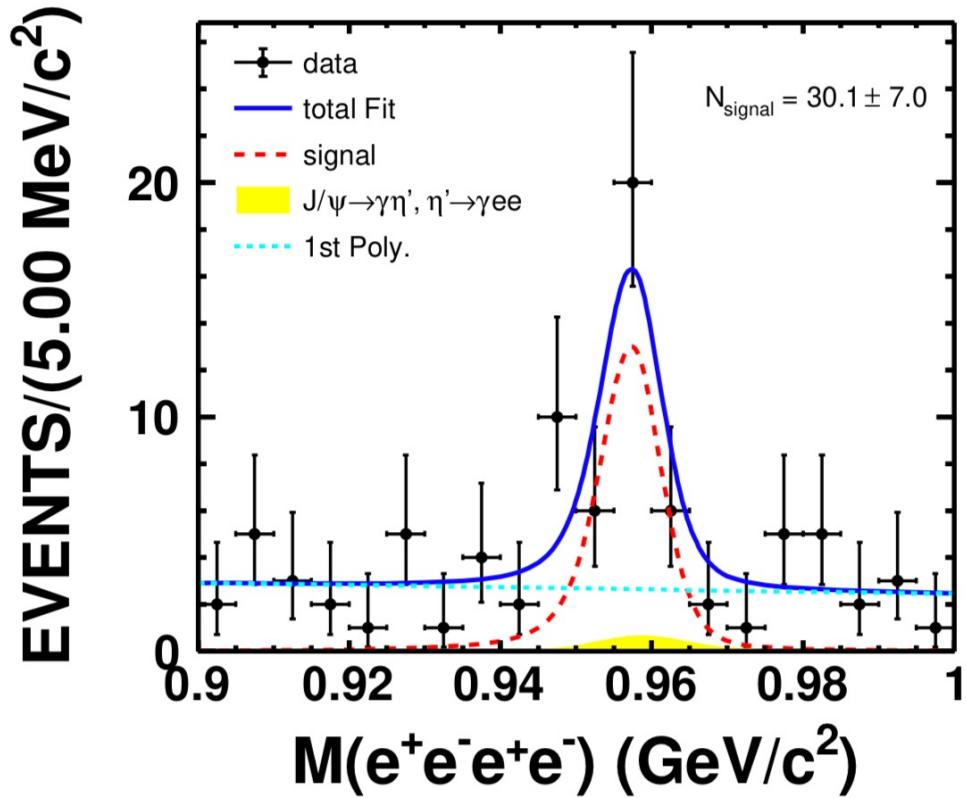
$\eta' \rightarrow \pi^+ \pi^- \pi^0$
~8000 events

康晓琳: in progress

η/η' radiative decays

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

$\eta' \rightarrow e^+e^- e^+e^-$
 (王梦真, BAM-00501)

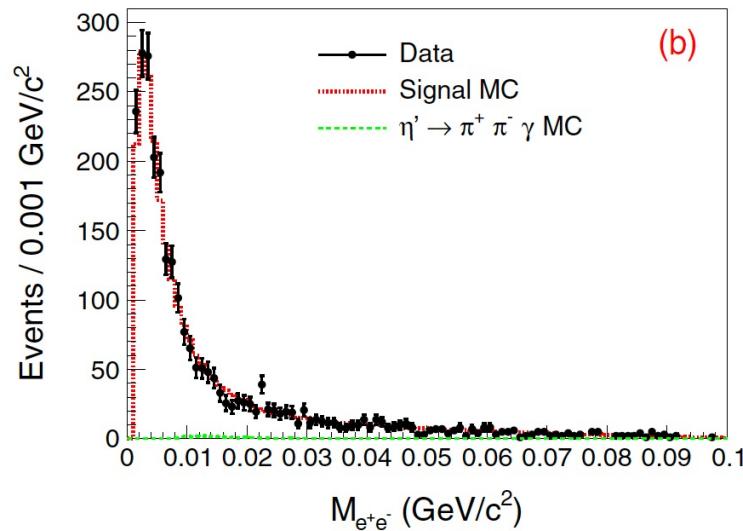


$$\mathcal{B}(\eta' \rightarrow e^+e^- e^+e^-) = (4.5 \pm 1.0(\text{stat.}) \pm 0.5(\text{sys.})) \times 10^{-6}$$

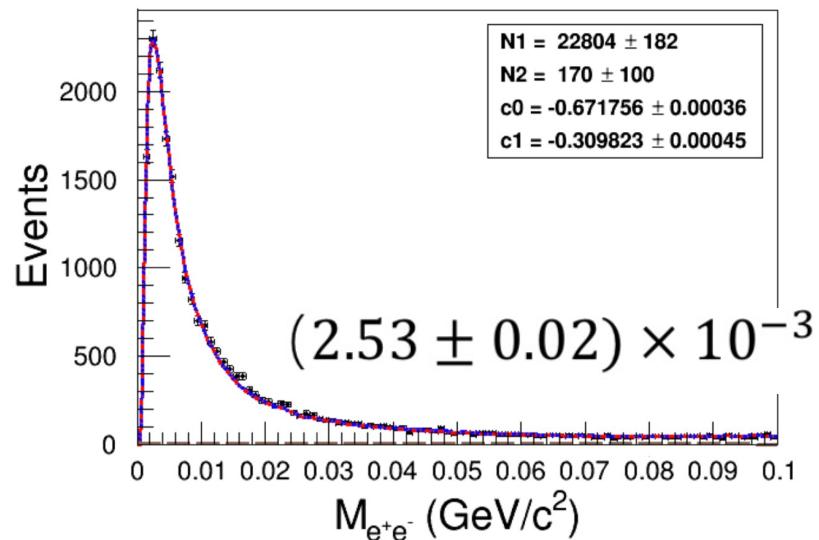
Theoretical prediction: $\sim 2.2 \times 10^{-6}$

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

PRD103,092005(2021) [09+12 data]

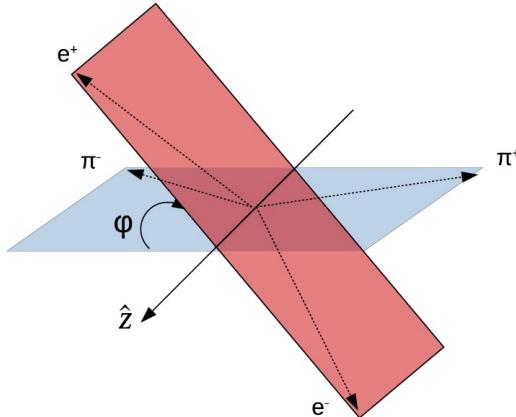


(吉钰瑶, in progress)



$$B(\eta' \rightarrow \pi^+ \pi^- e^+ e^-) = (2.42 \pm 0.05 \pm 0.08) \times 10^{-3}, \text{ EMT: } 1.8 \times 10^{-3}$$

PRC 61,0305206(2000)

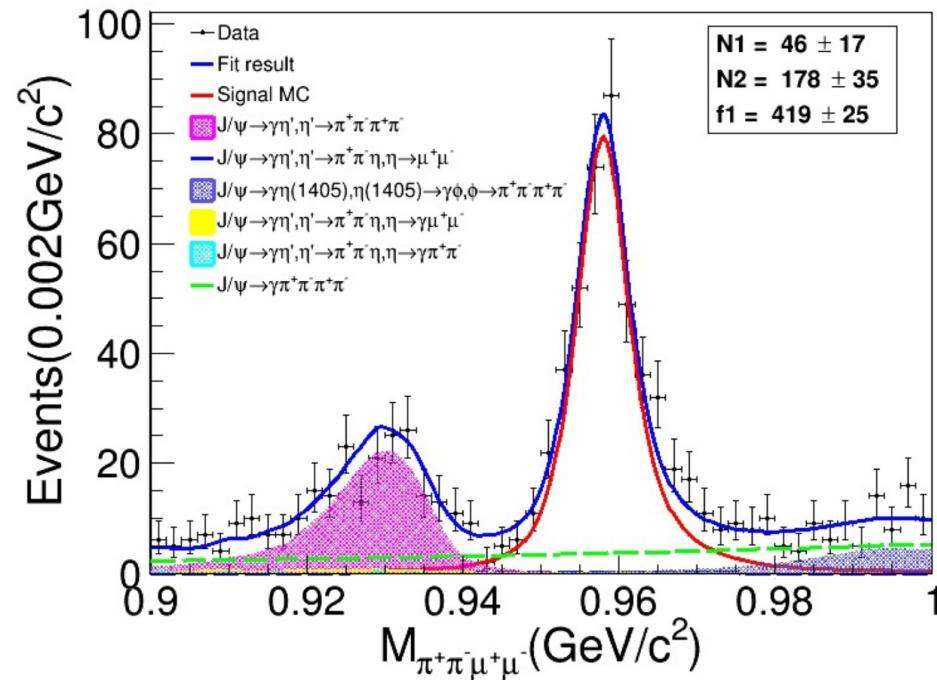
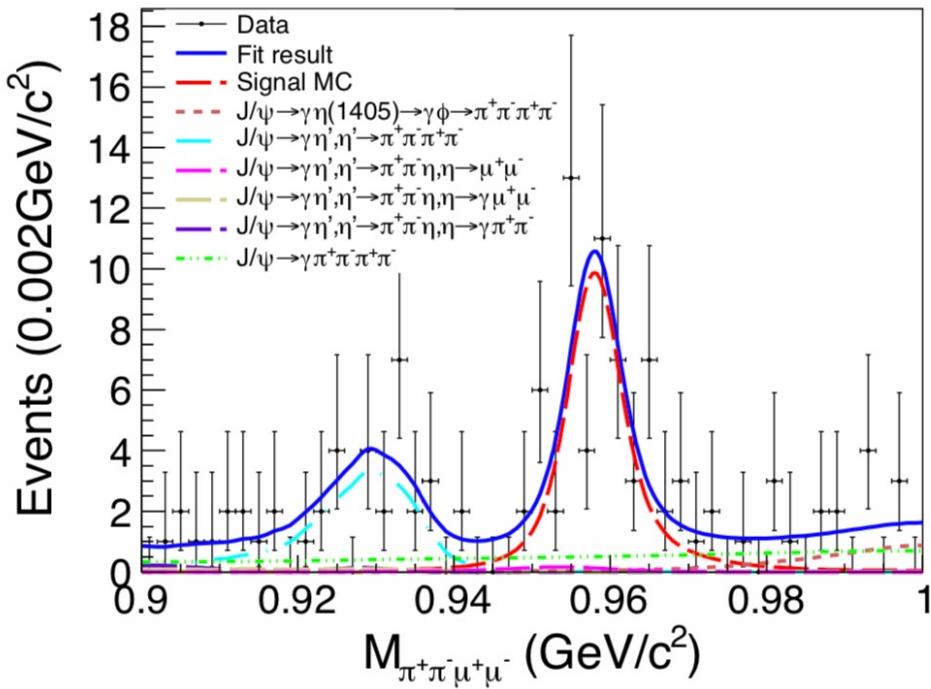


$$\mathcal{A}_\varphi = \frac{N(\sin\varphi \cos\varphi > 0) - N(\sin\varphi \cos\varphi < 0)}{N(\sin\varphi \cos\varphi > 0) + N(\sin\varphi \cos\varphi < 0)} = (1.6 \pm 2.0_{stat.} \pm 0.6_{syst.}) \%$$

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

PRD103,072006(2021) [09+12 data]

(吉钰瑶, in progress)

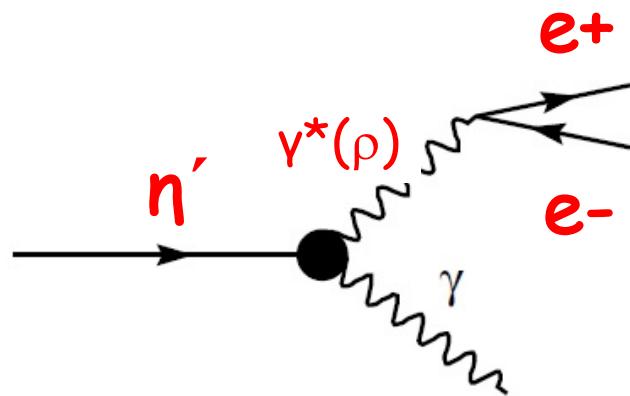


$$B(\eta' \rightarrow \pi^+ \pi^- \mu^+ \mu^-) = (1.97 \pm 0.33 \pm 0.18) \times 10^{-5}, EMT \sim 2.5 \times 10^{-5}$$

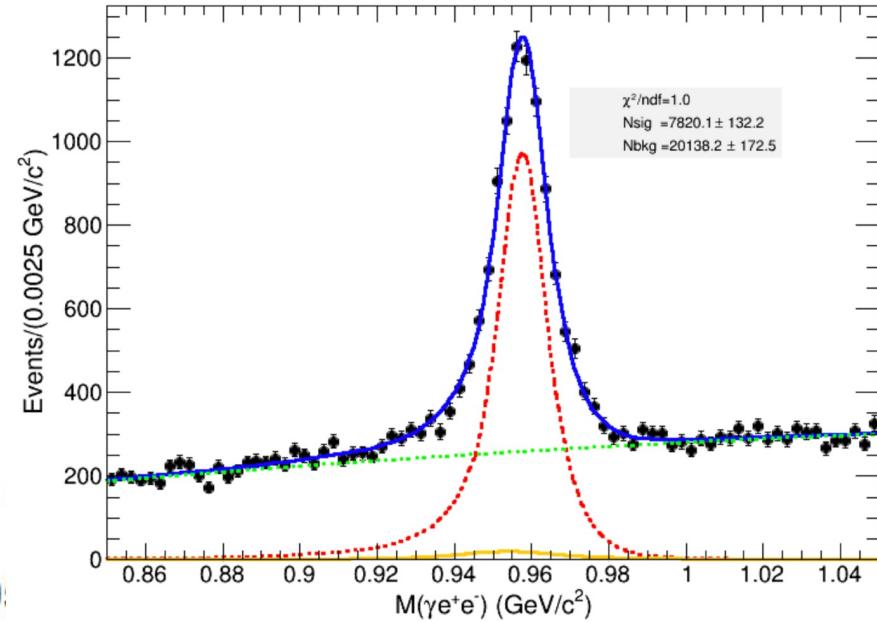
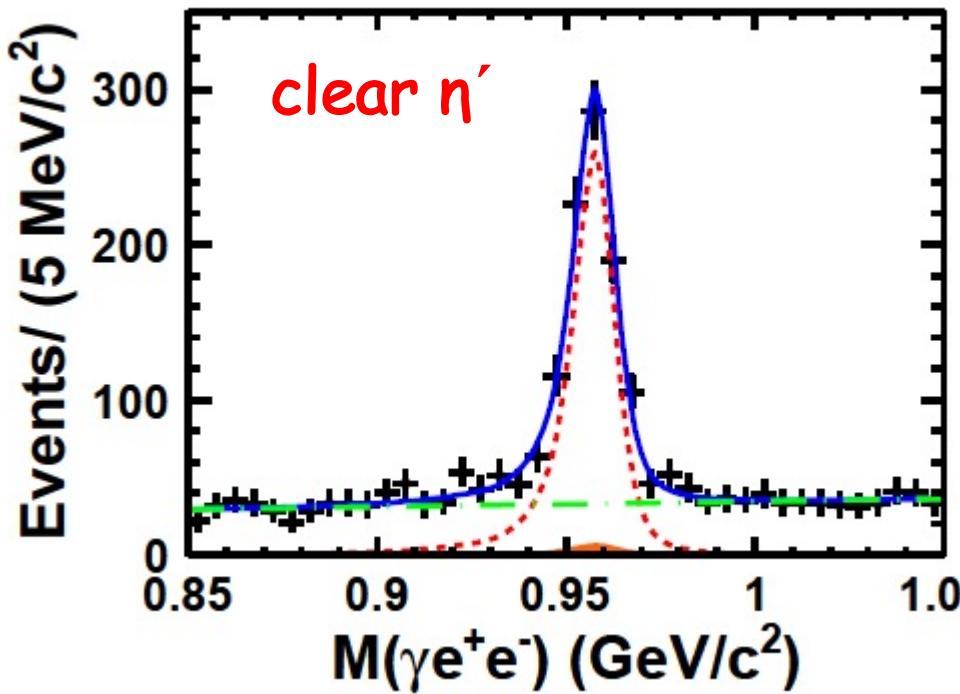
A. Faessler et al, Phys. Rev. C 61, 035206(2000)

$\eta' \rightarrow \gamma e^+ e^-$
 (向本后, 物理软件会)

- Investigate the inner structure of the meson
- Transition form factor



$$\begin{aligned}
 & \frac{d\Gamma(\eta' \rightarrow \gamma l^+ l^-)}{dq^2 \Gamma(\eta' \rightarrow \gamma\gamma)} \\
 &= \frac{2\alpha}{3\pi} \frac{1}{q^2} \sqrt{1 - \frac{4m_l^2}{q^2}} \left(1 + \frac{2m_l^2}{q^2}\right) \left(1 - \frac{q^2}{m_{\eta'}^2}\right)^3 |F(q^2)|^2 \\
 &= [\text{QED}(q^2)] \times |F(q^2)|^2,
 \end{aligned}$$

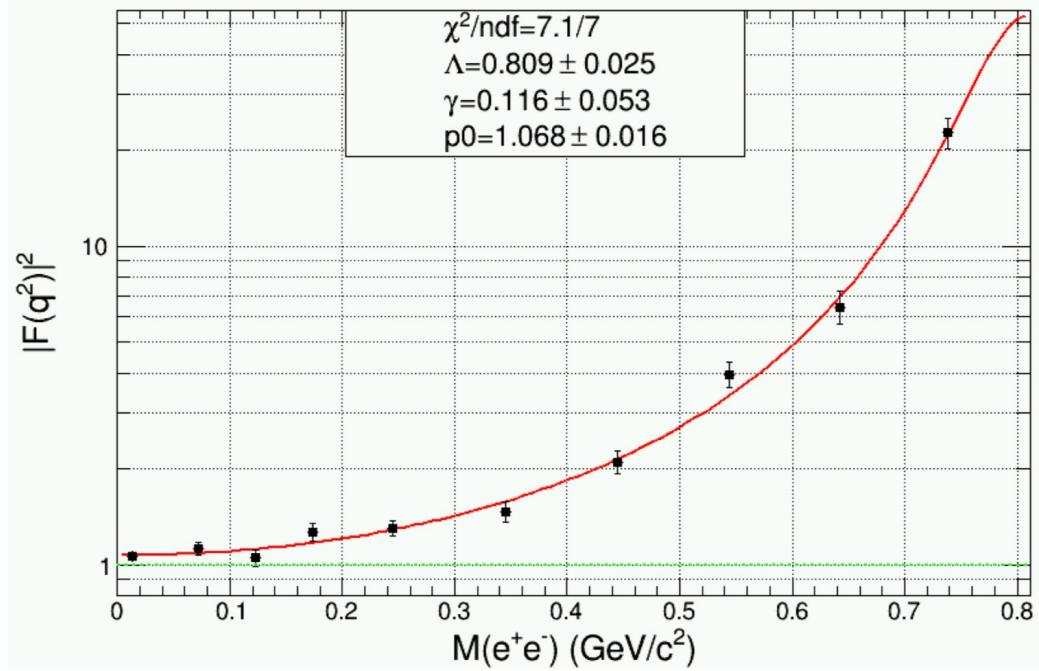


$$Br(\eta' \rightarrow \gamma e^+ e^-) = (4.92 \pm 0.13(stat.)) \times 10^{-4}$$

PDG:

$$Br(\eta' \rightarrow \gamma e^+ e^-) = (4.91 \pm 0.27) \times 10^{-4}$$

4.2 × 10⁻⁴ effective meson theory, PRC61,035206



$$|F(q^2)|^2 = p_0 \frac{\Lambda^2(\Lambda^2 + \gamma^2)}{(\Lambda^2 - q^2)^2 + \Lambda^2\gamma^2}$$

$$b = \left. \frac{dF}{dq^2} \right|_{q^2=0} = \Lambda^{-2}$$

- $\Lambda_{\eta'} = (0.809 \pm 0.025(\text{stat.})) \text{ GeV}$
- $\gamma_{\eta'} = (0.116 \pm 0.053(\text{stat.})) \text{ GeV}$

- In agreement with the results of $\eta' \rightarrow \gamma\mu+\mu-$ from CELLO

$$b_{\eta'} = (1.7 \pm 0.4) \text{ GeV}^{-2}$$

- Theoretical predictions:

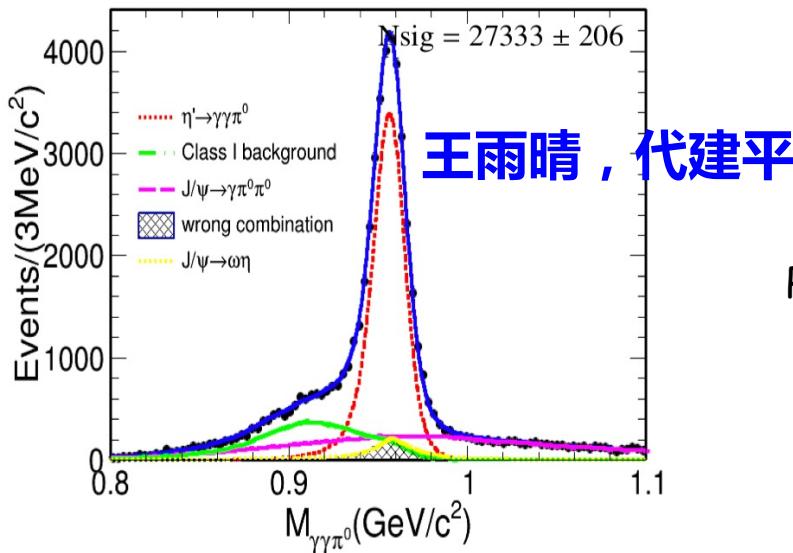
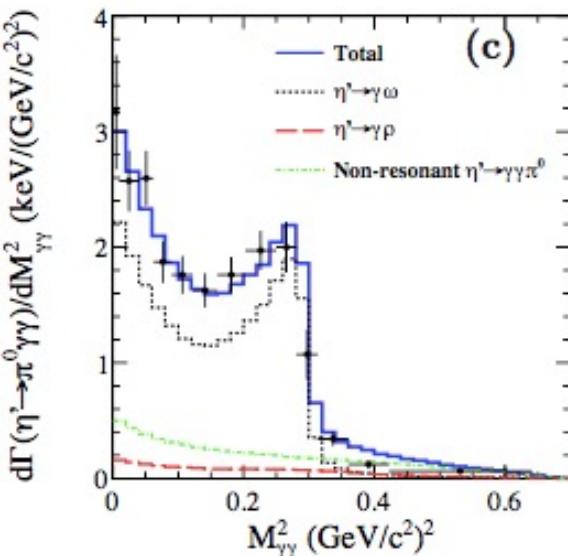
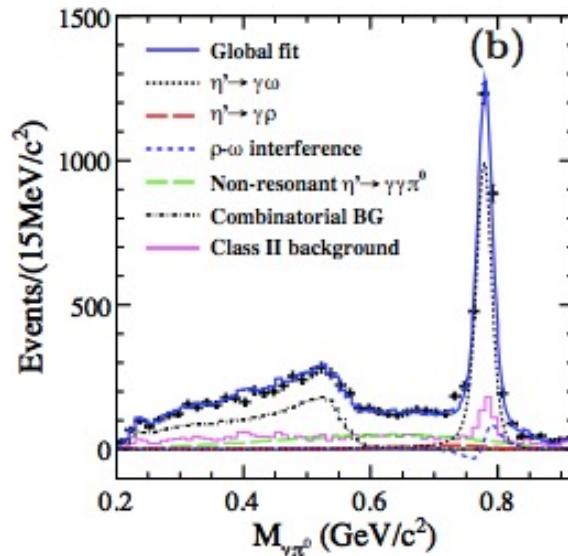
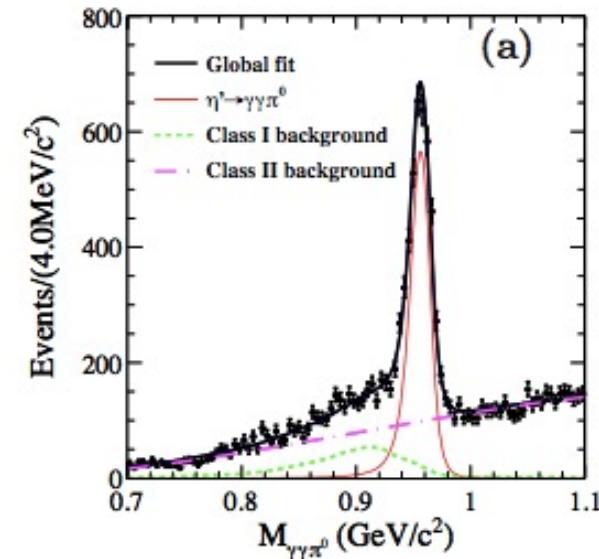
$$b_{\eta'} = 1.45 \text{ GeV}^{-2}$$

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

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

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

[Phys. Rev. D 96, 012005 \(2017\)](#)

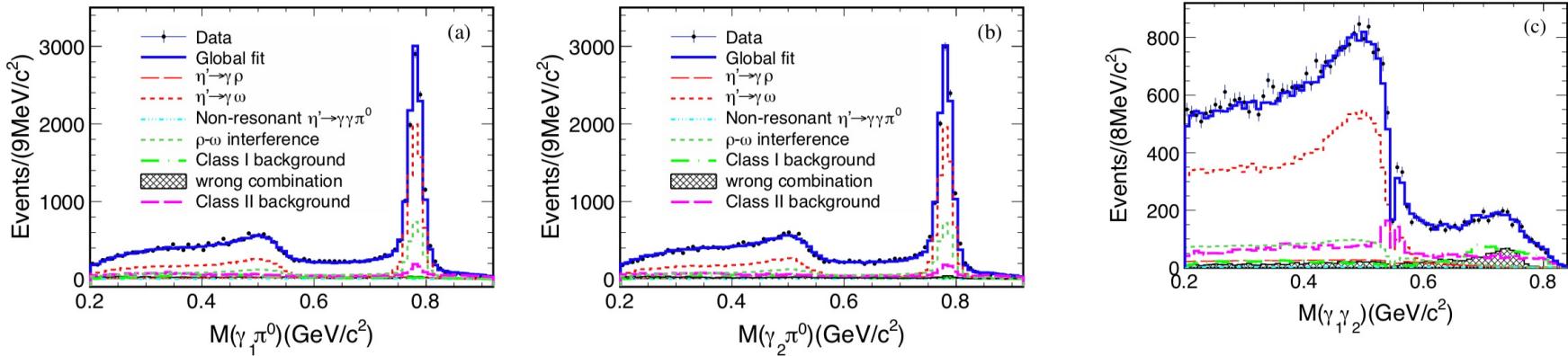


$$B(\eta' \rightarrow \gamma\gamma\pi^0)_{\text{NR}} = [6.16 \pm 0.64 \pm 0.67] \times 10^{-4}$$

Linear σ model & VMD

P. Jora, Nucl. Phys. Proc. Suppl. 207-208, 224 (2010)
R. Escribano, PoS QNP 2012, 079 (2012)

Amplitude analysis of $\eta' \rightarrow \gamma\gamma\pi^0$



$$B(\eta' \rightarrow \gamma\gamma\pi^0)_{NR} = [1.8 \pm 0.5 \pm 0.7] \times 10^{-5}$$

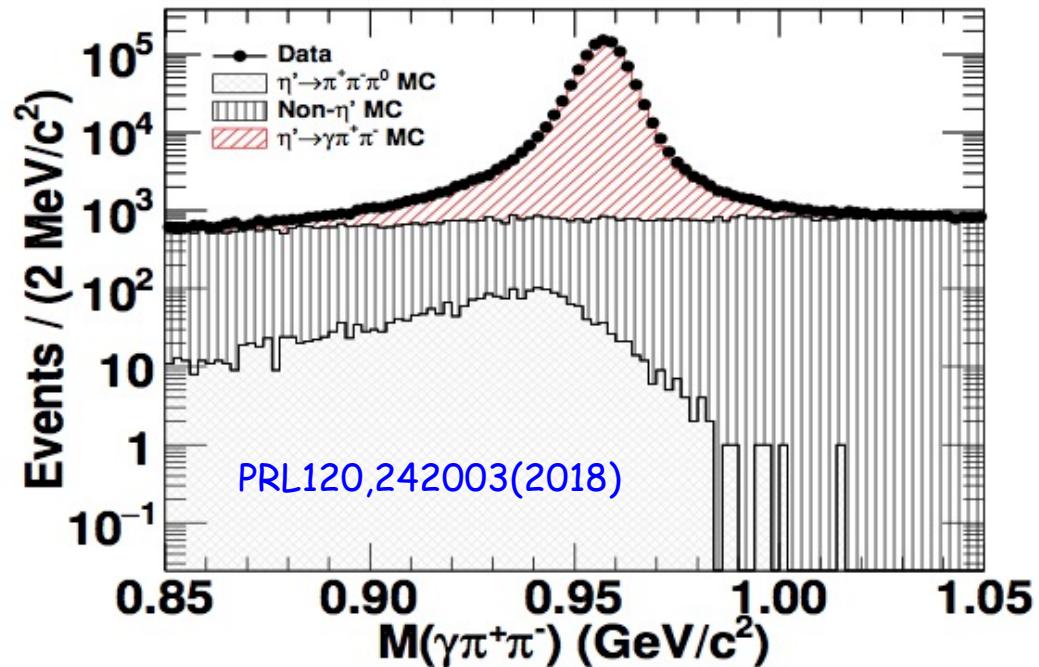
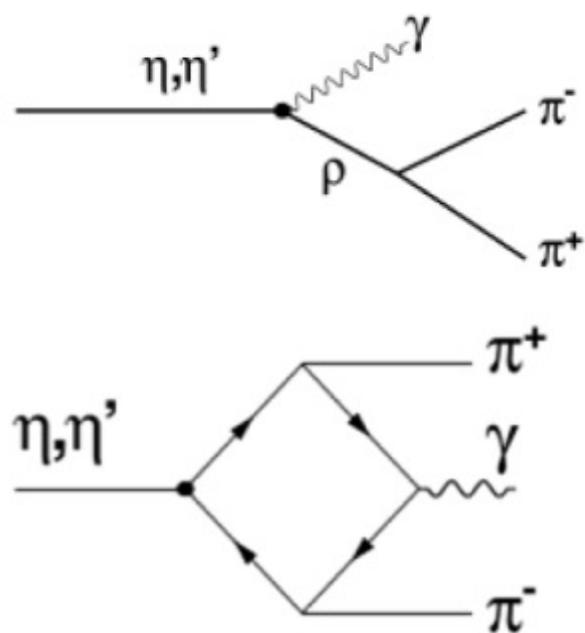
Lots of checks performed

- Dominated by ρ, ω
- Non-resonant contribution ($>5\sigma$)
- With non-resonant contribution: $B(\eta' \rightarrow \gamma\rho \rightarrow \gamma\pi^0) = 30+3\%$
- Without non-resonant contribution: $B(\eta' \rightarrow \gamma\rho \rightarrow \gamma\pi^0) = 51+4.3\%$
- Non-resonant contribution necessary

$\eta' \rightarrow \gamma\pi^+\pi^-$ decay dynamics (秦丽清)

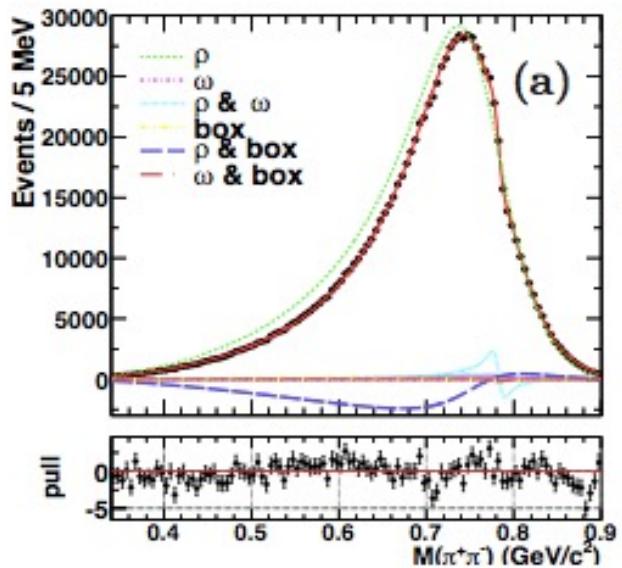
- high term of WZW ChPT \rightarrow box anomaly
- studied by many experiments (CB, L3 ...)
- no consistent picture due to limited statistics
 - ρ mass shift or not ?
 - box anomaly or not ?

~0.9M events

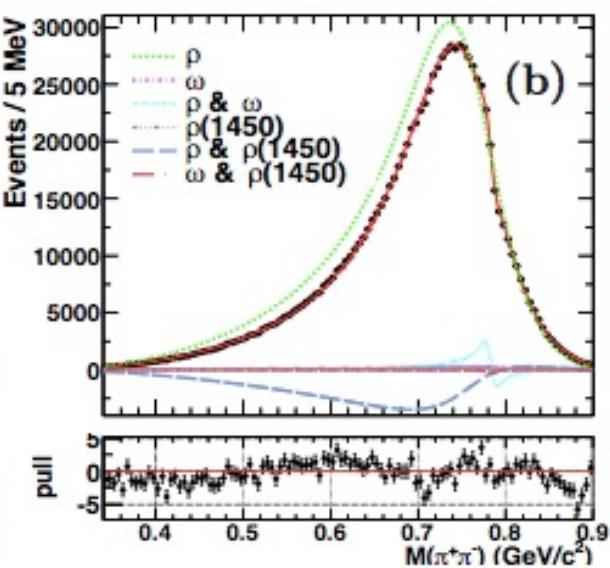


Model-(in)dependent fit

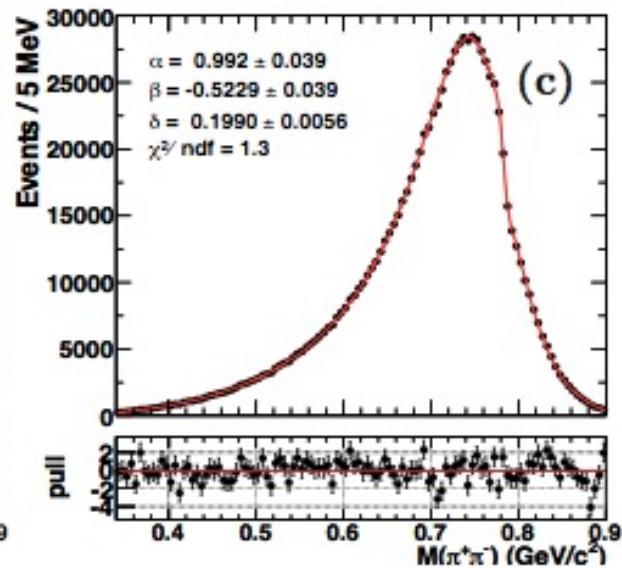
fit with $\rho(770)$ - ω -box anomaly



fit with $\rho(770)$ - ω - $\rho(1450)$



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



- ✓ $\rho(770)$ - ω cannot describe data well
- ✓ Extra contribution (maybe $\rho(1450)$ or box-anomaly) is also necessary

Crystal barrel: $\alpha = (1.80 \pm 0.49 \pm 0.04) \text{GeV}^{-2}$

$\beta = (0.04 \pm 0.36 \pm 0.03) \text{GeV}^{-4}$

GAMS-2000: $\alpha = (2.7 \pm 1.0) \text{GeV}^{-2}$

η/η' rare decays

- $\eta/\eta' \rightarrow \pi\pi$
- η/η' invisible decays
- η/η' weak decays
-

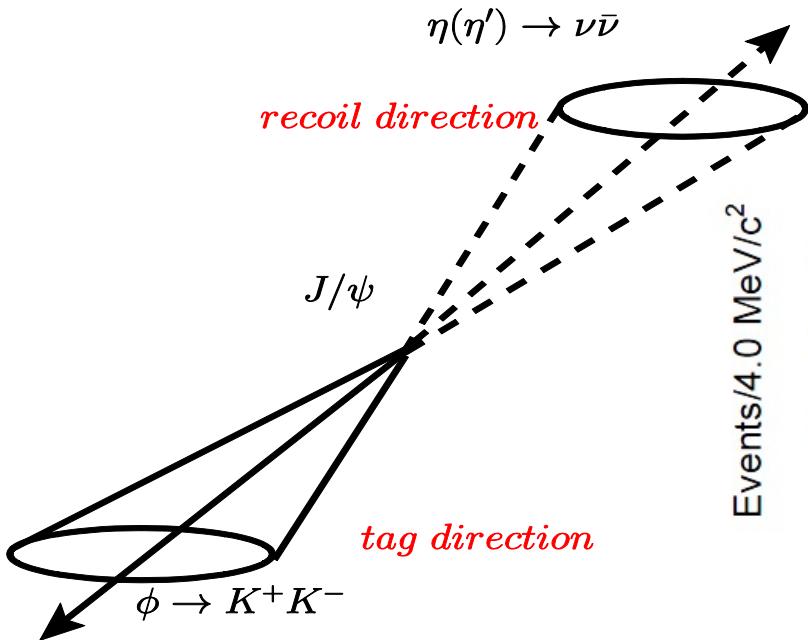
相关工作进展较少

Charge conjugation (C), Parity (P),
Lepton family number (LF) violating modes

Γ_{24}	$\pi^+ \pi^-$	P, CP	< 6	$\times 10^{-5}$	90%
Γ_{25}	$\pi^0 \pi^0$	P, CP	< 4	$\times 10^{-4}$	90%
Γ_{26}	$\pi^0 e^+ e^-$	C	[a] < 1.4	$\times 10^{-3}$	90%
Γ_{27}	$\eta e^+ e^-$	C	[a] < 2.4	$\times 10^{-3}$	90%
Γ_{28}	3γ	C	< 1.0	$\times 10^{-4}$	90%
Γ_{29}	$\mu^+ \mu^- \pi^0$	C	[a] < 6.0	$\times 10^{-5}$	90%
Γ_{30}	$\mu^+ \mu^- \eta$	C	[a] < 1.5	$\times 10^{-5}$	90%
Γ_{31}	$e \mu$	LF	< 4.7	$\times 10^{-4}$	90%

η'

$\eta/\eta' \rightarrow \text{invisible}$ in $J/\psi \rightarrow \phi\eta/\eta'$

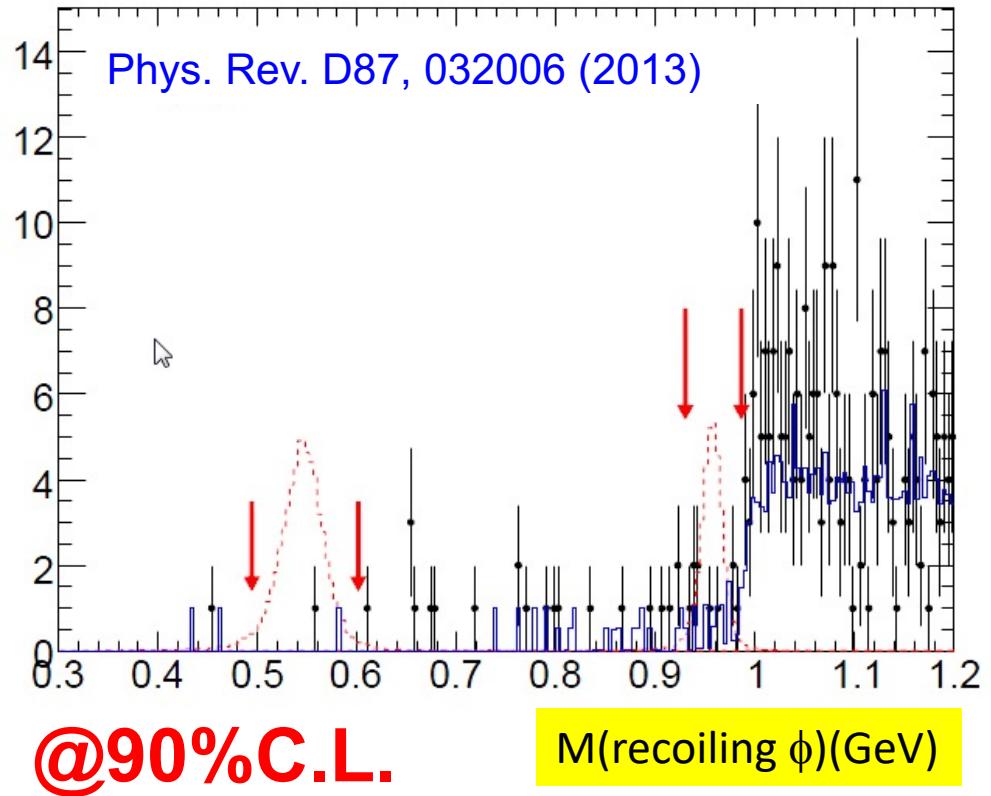


225 million J/ψ events

$B(\eta \rightarrow \text{invisible}) < 1.0 \times 10^{-4}$

$B(\eta' \rightarrow \text{invisible}) < 5.3 \times 10^{-4}$

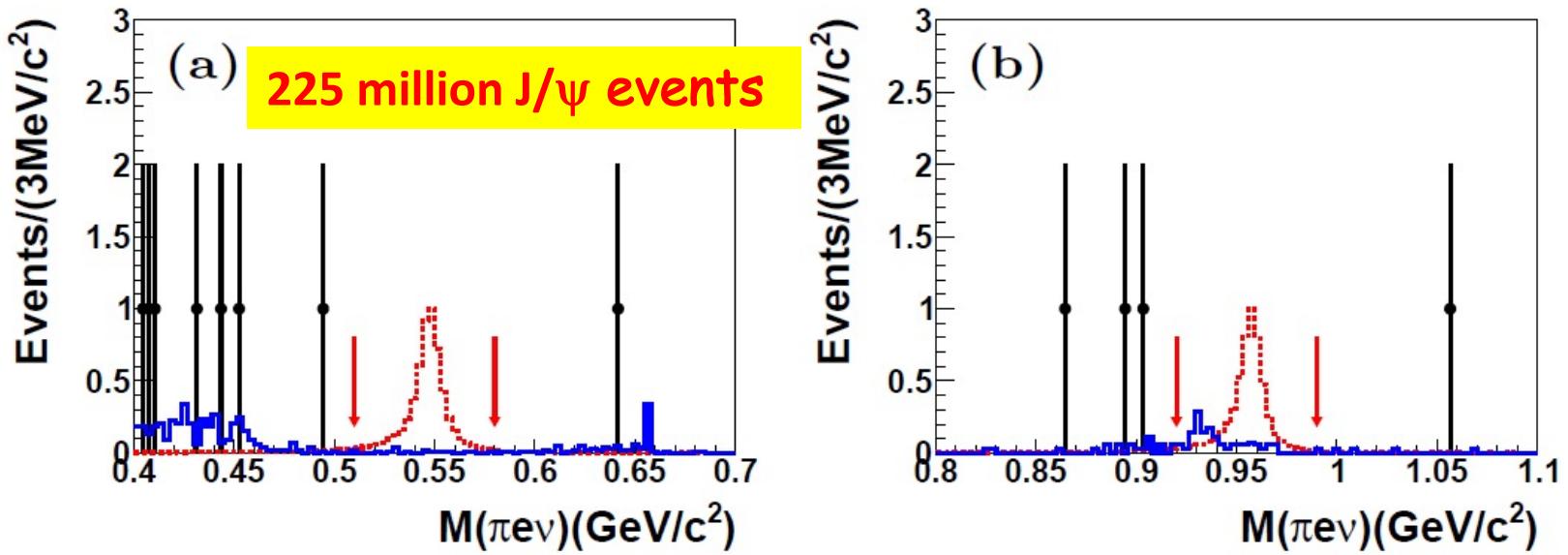
Reconstructing $\phi \rightarrow K^+K^-$ and looking at recoiling mass of ϕ



Search for weak decays of η/η'

Phys. Rev. D87, 032006 (2013)

- within SM : $B(\eta \rightarrow \pi^- e^+ \nu + c.c.) \sim 2 \times 10^{-13}$
H. Neufeld and H. Rupertsberger, Z. Phys. C 68, 91 (1995)
- by considering scalar or vector type interactions:
 $B(\eta \rightarrow \pi^- e^+ \nu + c.c.) \sim 10^{-8} - 10^{-9}$ P. Herczeg, Prog. Part. Nucl. Phys. 46, 413 (2001)

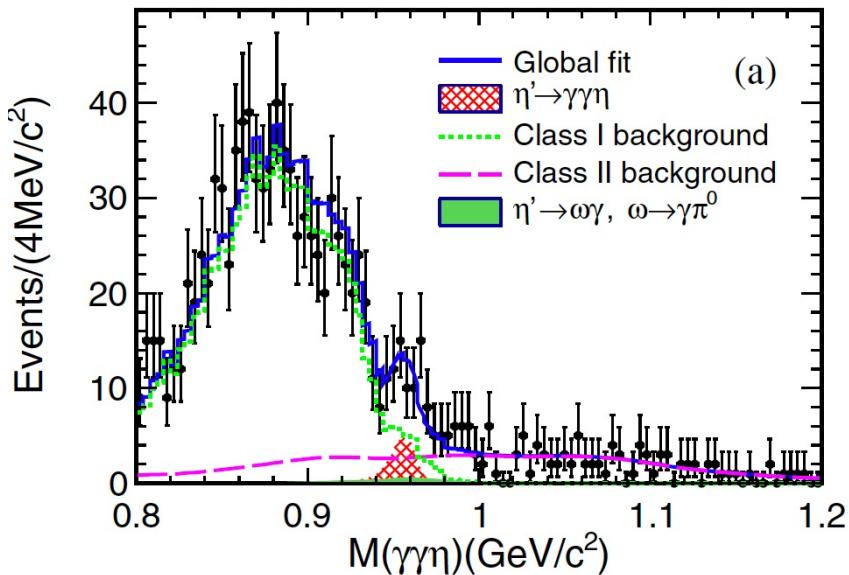


$$B(\eta \rightarrow \pi^- e^+ \nu + c.c.) < 1.7 \times 10^{-4}$$
$$B(\eta' \rightarrow \pi^- e^+ \nu + c.c.) < 2.2 \times 10^{-4}$$

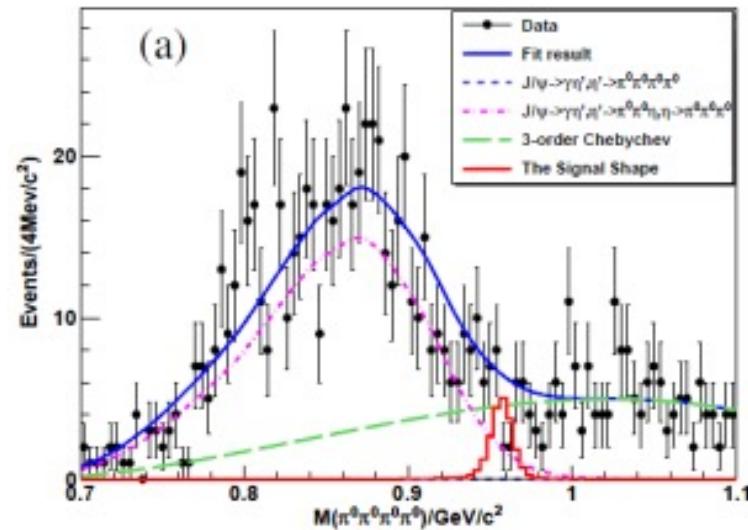
@90% C.L.

Search for $\eta' \rightarrow \gamma\gamma\eta$, $\eta' \rightarrow \pi^0\pi^0\pi^0\pi^0$

Phys. Rev. D100, 052015(2019)



Phys. Rev. D101, 032001(2020)



$$B(\eta' \rightarrow \gamma\gamma\eta) < 1.33 \times 10^{-4} \text{ @ 90% CL}$$

$$B(\eta' \rightarrow \pi^0\pi^0\pi^0\pi^0) < 1.5 \times 10^{-5} \text{ @ 90% CL}$$

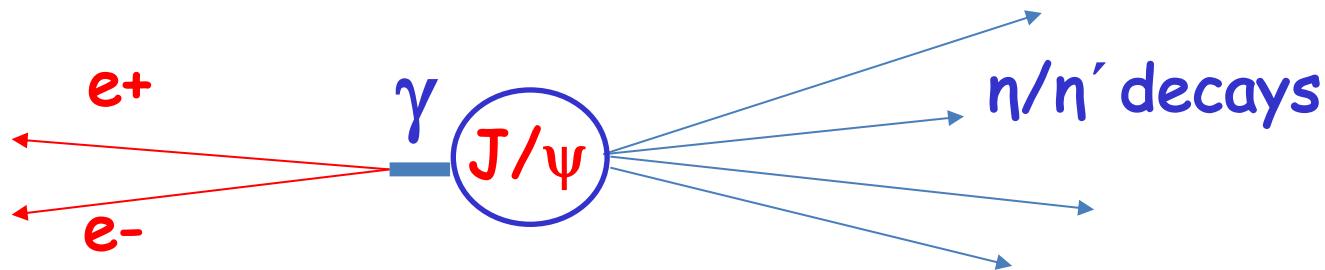
$$B(\eta' \rightarrow \gamma\gamma\eta) : \sim 2.6 \times 10^{-4}$$

$$B(\eta' \rightarrow \pi^0\pi^0\pi^0\pi^0) \sim 4 \times 10^{-8}$$

F.K. Guo, B. Kubis, A. Wirzba, Phys. Rev. D 85, 014014 (2012)

P. Jora, Nucl. Phys. Proc. Suppl. 207-208, 224 (2010)
 R. Escribano, PoS QNP 2012, 079 (2012)

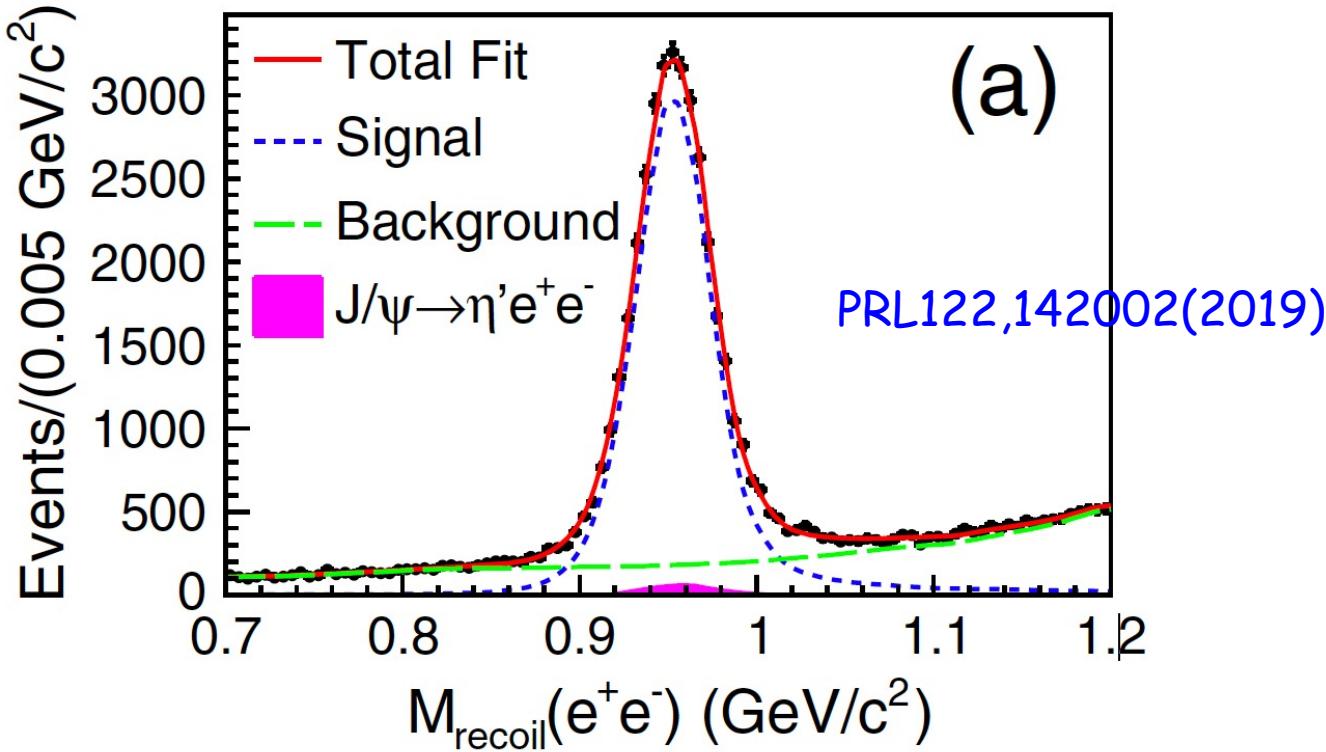
γ conversion: η/η' inclusive decays



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

- Absolute BF of η' decays
- Absolute BF of η decays

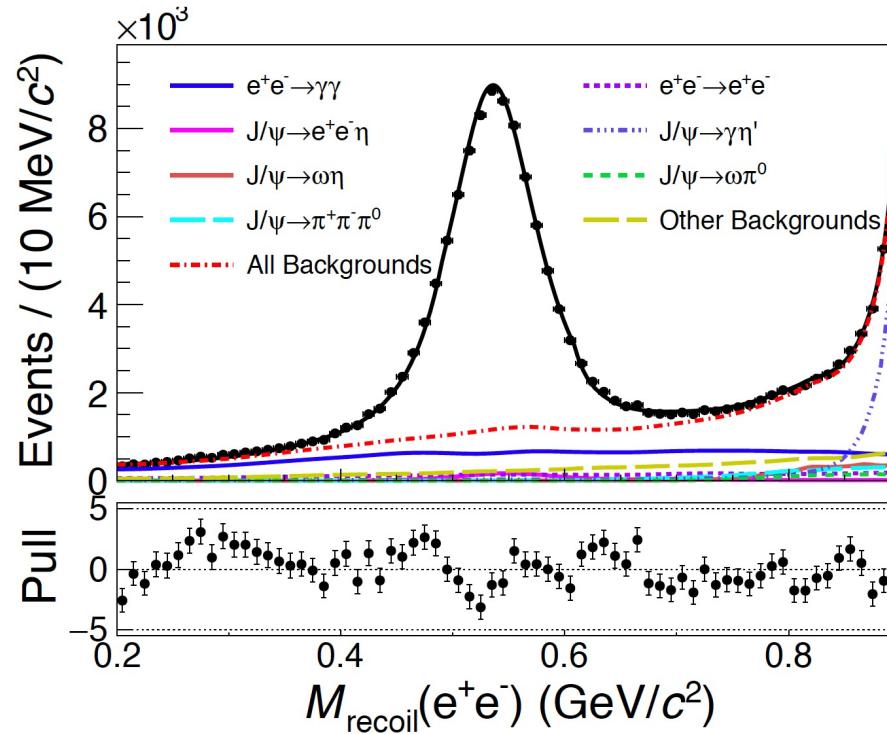
Absolute BF of η' decays



Decay mode	$N_{\eta' \rightarrow X}^{\text{obs}}$	$\epsilon_{\eta' \rightarrow X} (\%)$	$\mathcal{B}(\eta' \rightarrow X) (\%)$	
			This measurement	PDG [7]
$\eta' \rightarrow \gamma \pi^+ \pi^-$	$913\ 106 \pm 1052$	44.11	$29.90 \pm 0.03 \pm 0.55$	28.9 ± 0.5
$\eta' \rightarrow \eta \pi^+ \pi^-$	$312\ 275 \pm 570$	27.75	$41.24 \pm 0.08 \pm 1.24$	42.6 ± 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 ± 0.8
$\eta' \rightarrow \gamma \omega$	$22\ 749 \pm 163$	14.98	$2.489 \pm 0.018 \pm 0.074$	2.62 ± 0.13
$\eta' \rightarrow \gamma \gamma$	$70\ 669 \pm 349$	43.79	$2.331 \pm 0.012 \pm 0.035$	2.22 ± 0.08

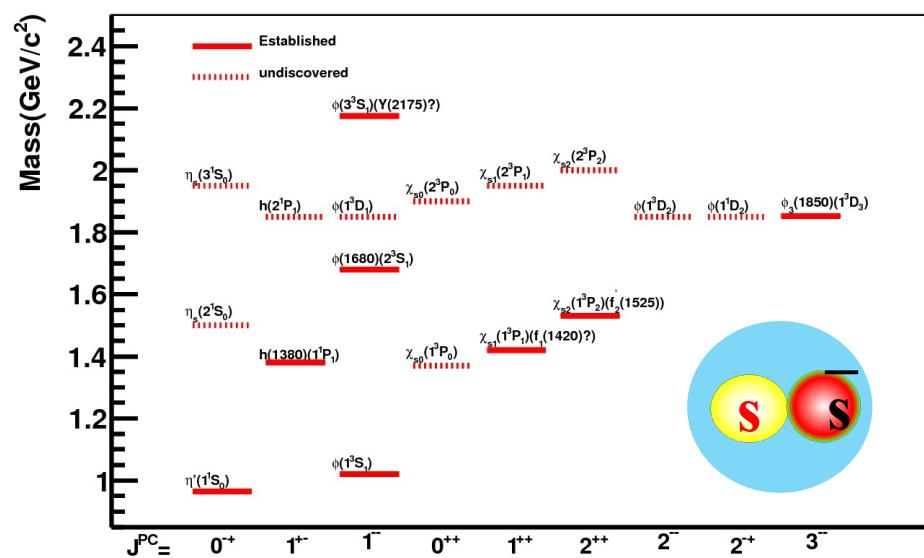
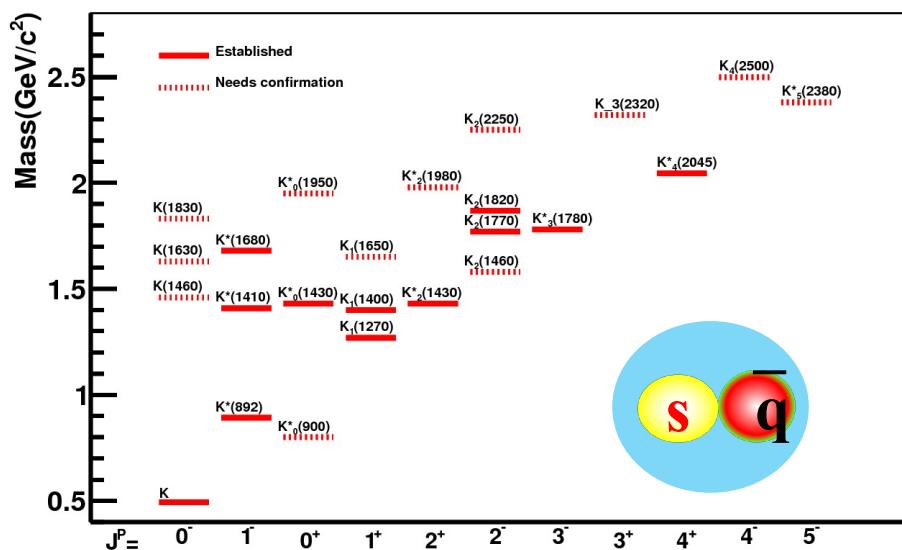
Absolute BFs of η decays

arXiv:2109.12812 (accepted by PRD)



X	$\mathcal{B}(\eta \rightarrow X) (\%)$		
	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

Strange and strangeonium mesons

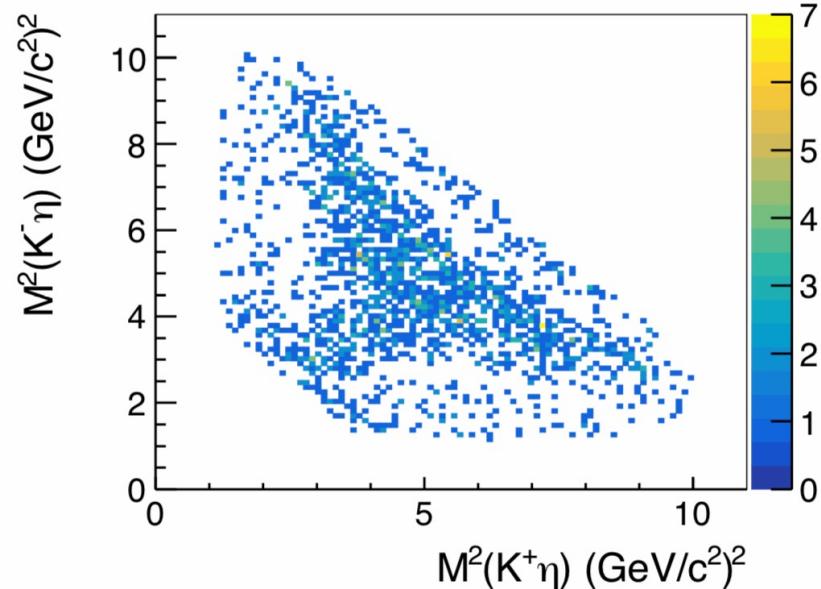
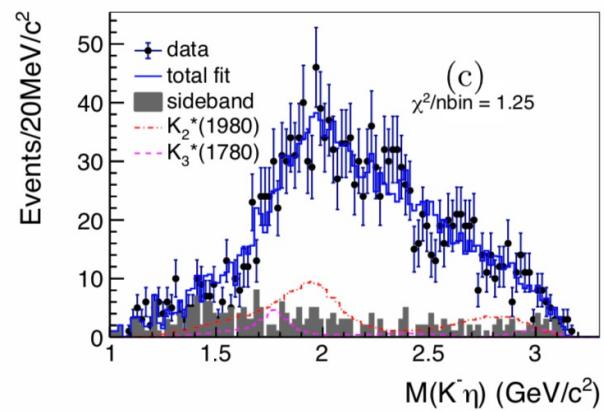
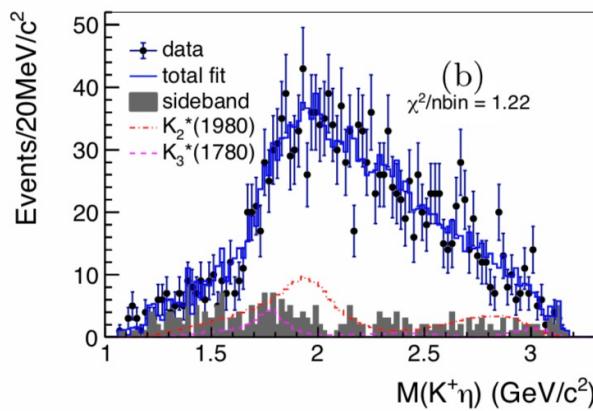
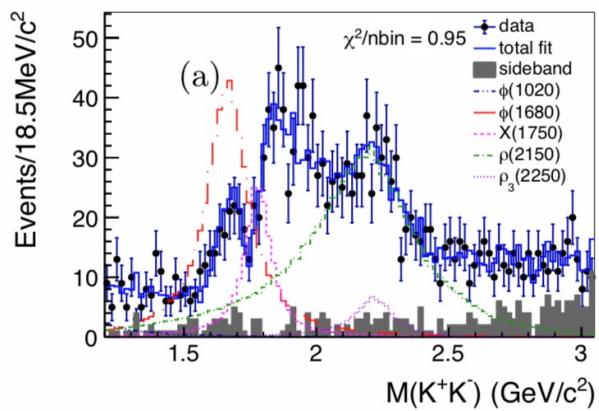


奇异介子: $J/\psi[\psi(3686)] \rightarrow K+K-\pi^0, KKs\pi \dots$

奇异夸克偶素: $J/\psi[\psi(3686)] \rightarrow K+K-\eta, K+K-\eta', KK^*\eta \dots$

PWA of $\psi(3686) \rightarrow K^+K^-\eta$

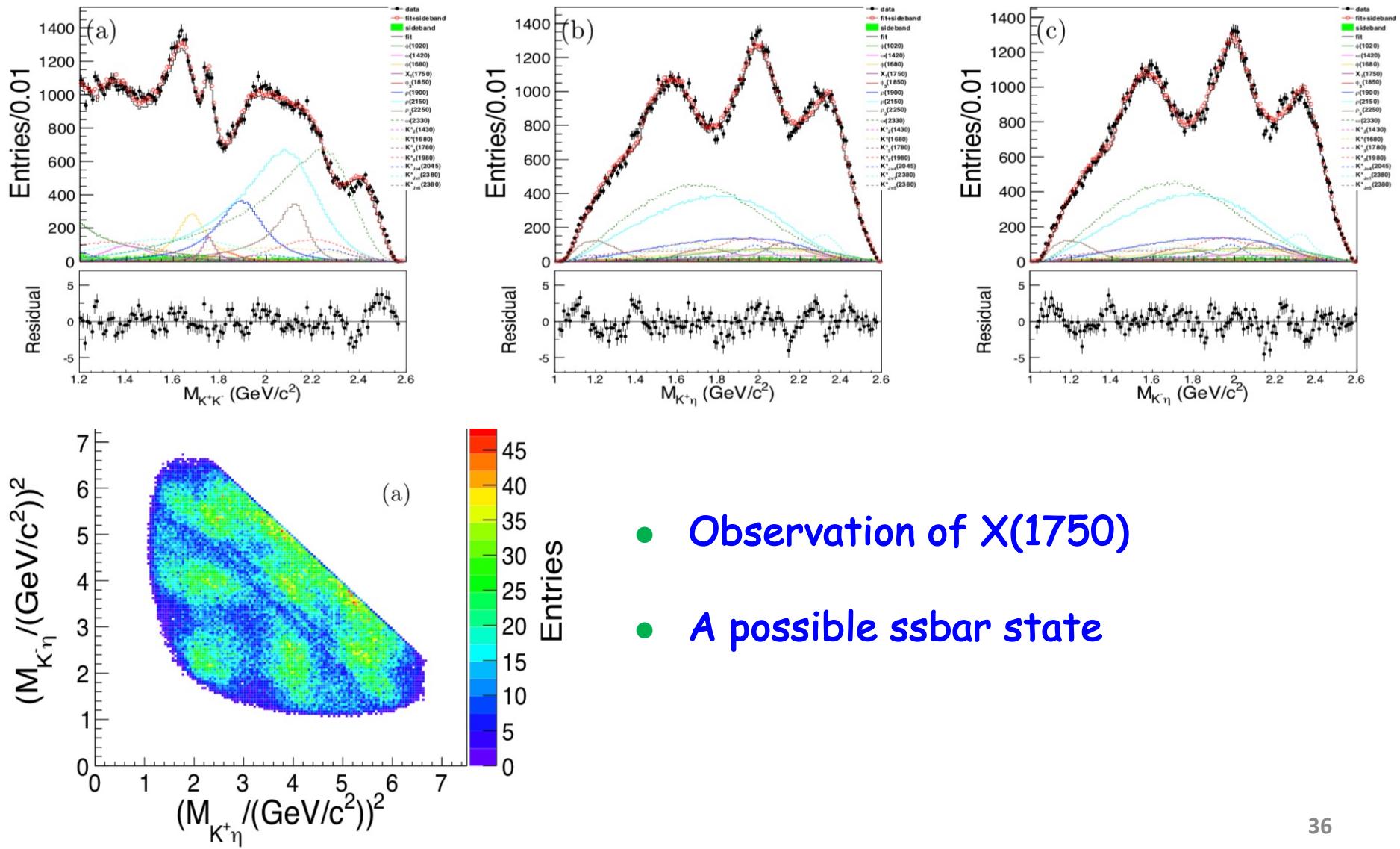
Phys. Rev. D101, 032008(2020)



Resonance	M (MeV/c^2)	Γ (MeV)
$\phi(1680)$	1680^{+12+21}_{-13-21}	185^{+30+25}_{-26-47}
$X(1750)$	1784^{+12+0}_{-12-27}	106^{+22+8}_{-19-36}
$\rho(2150)$	2255^{+17+50}_{-18-41}	$460^{+54+160}_{-48-90}$
$\rho_3(2250)$	2248^{+17+59}_{-17-5}	$185^{+31+17}_{-26-103}$
$K_2^*(1980)$	2046^{+17+67}_{-16-15}	408^{+38+72}_{-34-44}
$K_3^*(1780)$	1813^{+15+65}_{-15-16}	191^{+43+3}_{-37-81}

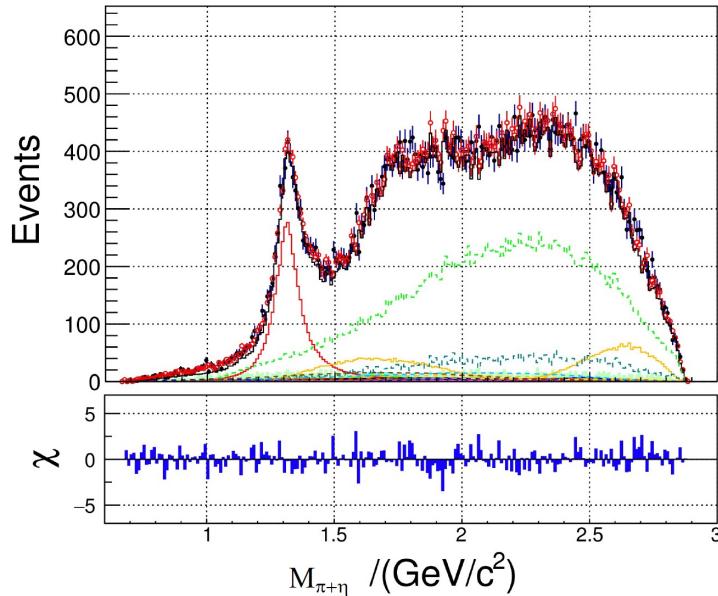
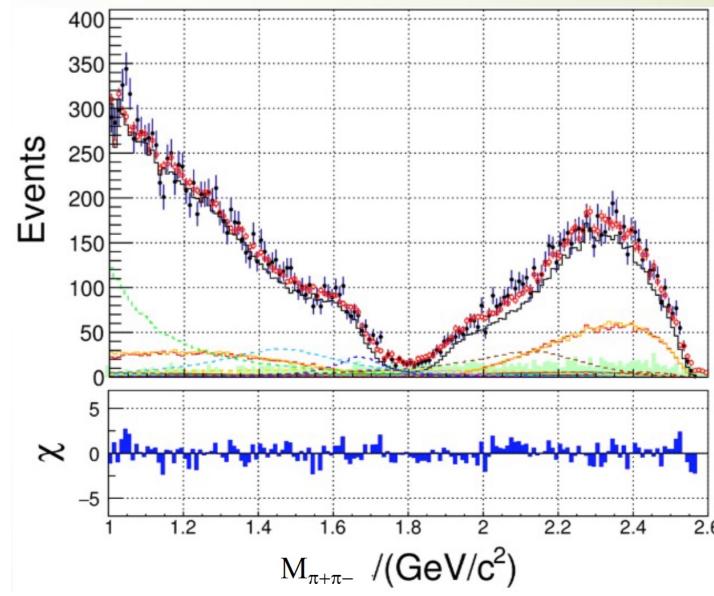
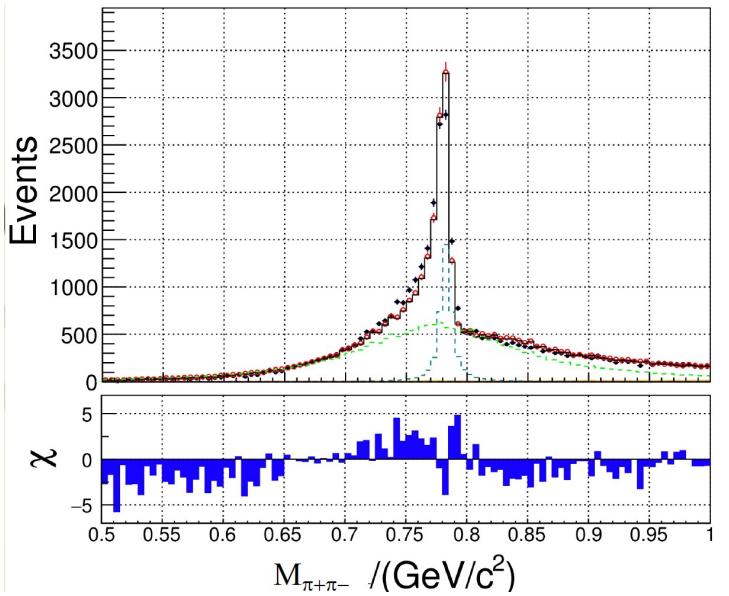
PWA of $J/\psi \rightarrow K^+K^-\eta$

(Bam-00405, 刘欢欢)



PWA of $J/\psi \rightarrow \pi^+ \pi^- \eta$

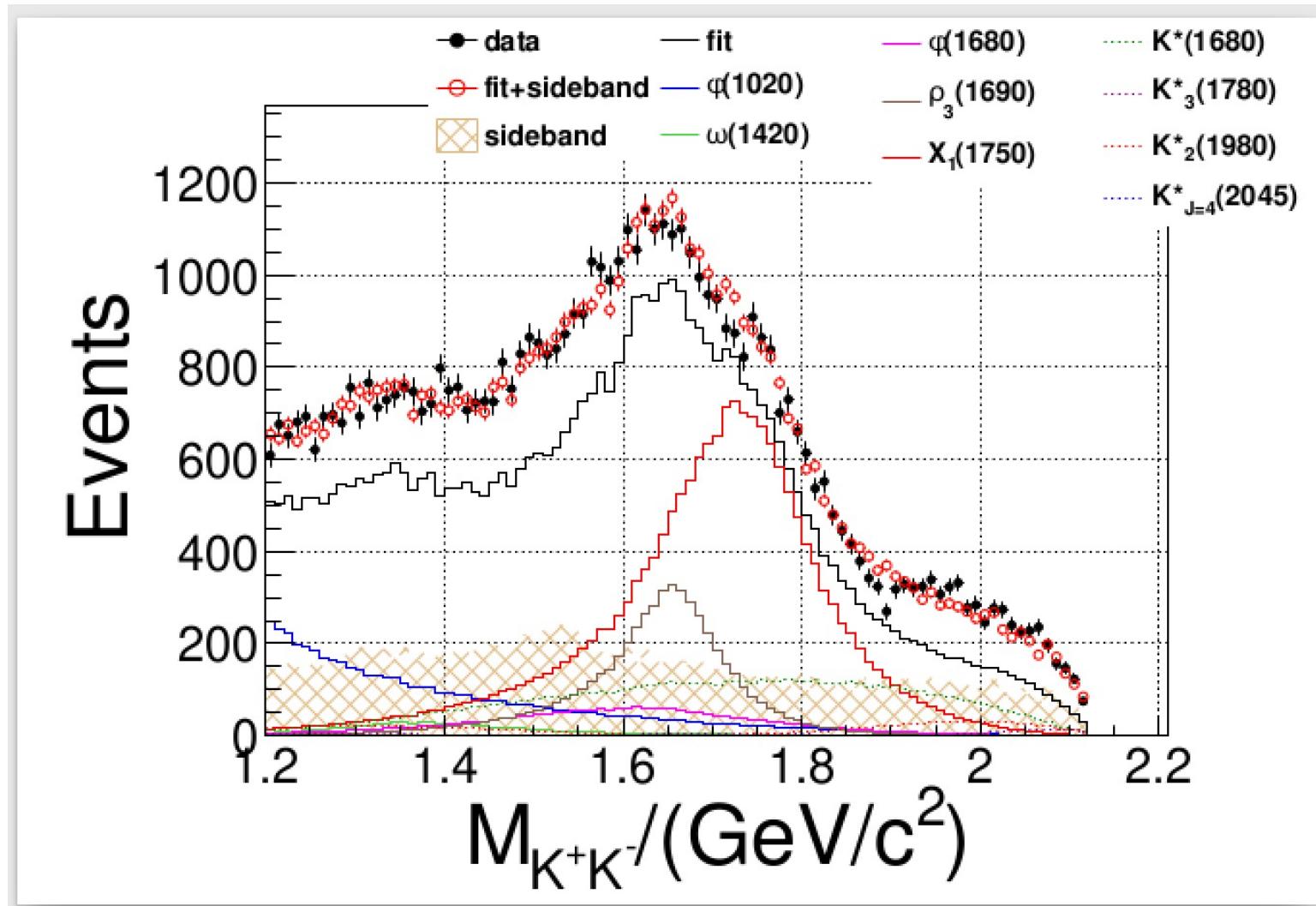
(秦丽清, 刘欢欢, in progress)



- Low production rate of $X(1750)$
- A possible $s\bar{s}$ state

PWA of $J/\psi \rightarrow K^+K^-\eta'$

(龚丽, in progress)



Summary

- BESIII : also a factory of light meson decays
- Precision test of fundamental physics
- Recent progresses

- $\eta' \rightarrow \pi^+ \pi^- e^+ e^-$ PRD103,092005(2021)
- $\eta' \rightarrow \pi^+ \pi^- u^+ u^-$ PRD103,072006(2021)
- Absolute BF of η decays arXiv:2109.12812 (accepted by PRD)
- Many analyses are in progress

- 10 billion J/ψ events are available at BESIII
 - update η/η' decays
 - search for rare decays
 - other light mesons, ρ , ω , ϕ , excited states

谢谢！