Improved measurement of $\eta' \to 4\pi$

Zihan Zhao[1], Qin Chang[1] and Shuangshi Fang[2]

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HFP Group Meeting

2022.10.08

What's new?(I)

BAM-00622: new Referee Committee formed

Forum: BAM-00622: Improved measurement of etap to 4pions, by Zihan Zhao et al.
Date: Jul 26, 10:00
From: Dayong Wang <*Dayong Wang*>

Dear all,

We are pleased to announce that a new referee committee is formed for the analysis.
"BAM-00622: Improved measurement of etap to 4pions", by Zihan Zhao et al.

Three referees are :
Yingchun Zhu, <yingchun@ustc.edu.cn>, USTC (Chair)
Liqing Qin, <qinlq@mailbox.gxnu.edu.cn>, GXNU
Liangchen Liu, <liulc@ihep.ac.cn>, HAUT

Many thanks for the three referees' kind help.

According to the BESIII publication rule, referees are required to respond to any communications in an interval of no longer than 2 weeks.

The Link of HyperNews forum :
http://hnbes3.ihep.ac.cn/HyperNews/get/paper622.html
The memo in docDB :
https://docbes3.ihep.ac.cn/DocDB/0011/001120/004/Memo_V1.6.pdf
The talk in P&S meeting in Indico :
https://indico.ihep.ac.cn/event/17229

BESIII

Memo version 2.1

BESIII Analysis Memo

BAM-622

September 7, 2022

Improved measurement of $\eta' \to 4\pi$

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Internal Referee Committee

Yingchun Zhu (Chair)[c], Liqing Qin[d], and Liangchen Liu[e]

[c] *USTC*
[d] *GXNU*
[e] *HAUT*

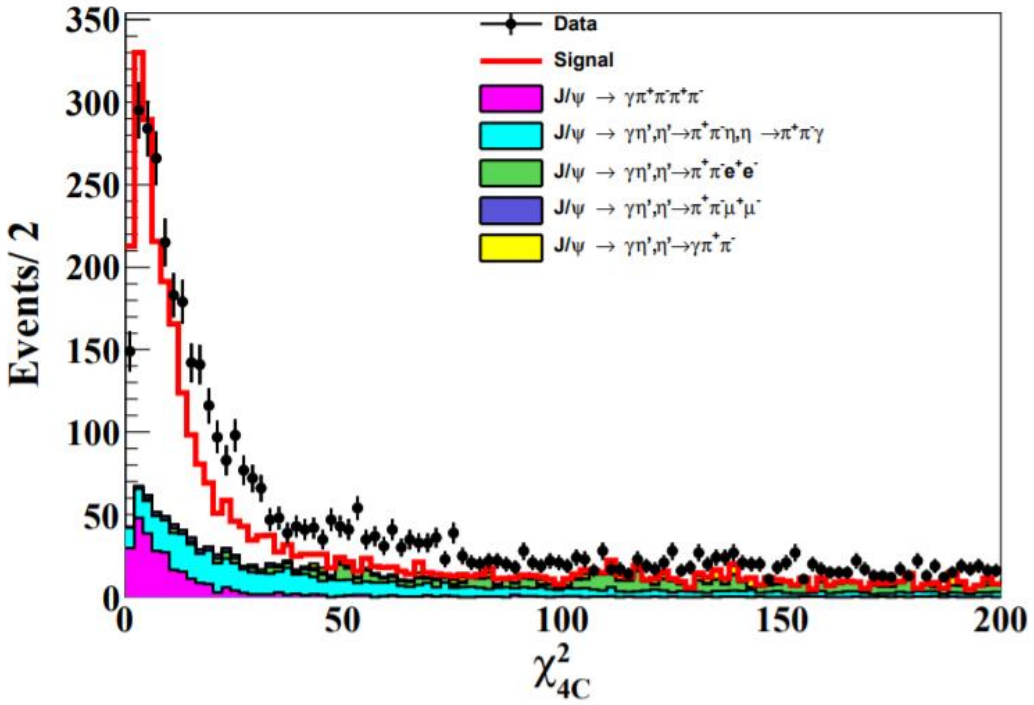
HN : http://hnbes3.ihep.ac.cn/HyperNews/get/paper622.html

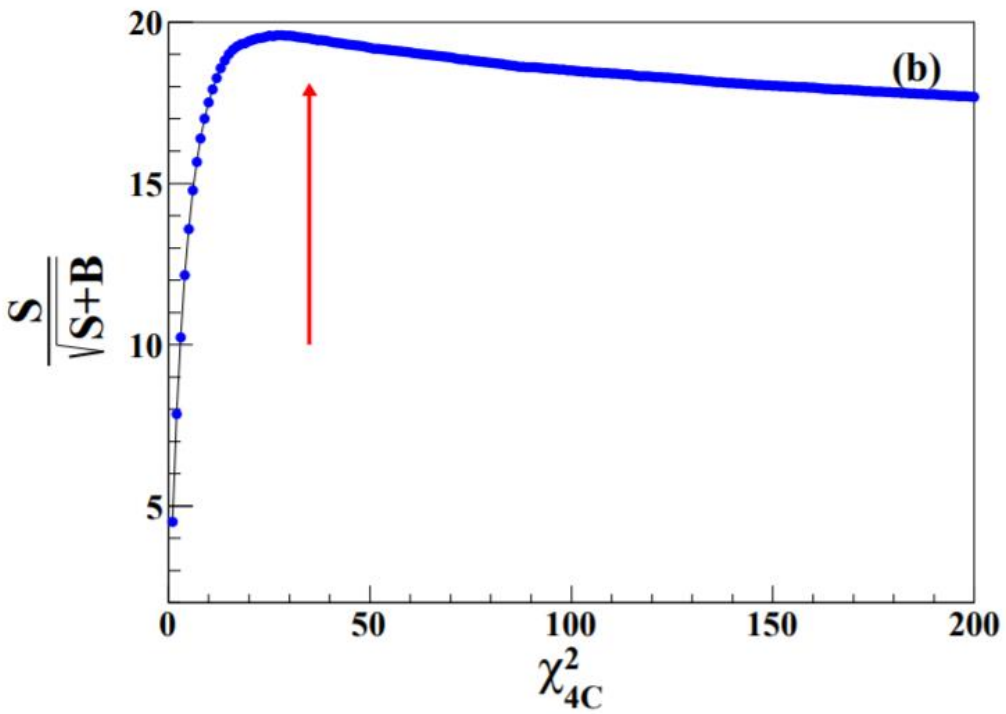
Abstract

Using a sample of $(10087\pm44)\times10^6$ J/ψ events collected with the BESIII detector, the decays $\eta' \to \pi^+\pi^-\pi^+\pi^-$, $\eta' \to \pi^+\pi^-\pi^0\pi^0$, and $\eta' \to 4\pi^0$ are studied via $J/\psi \to \gamma\eta'$. A clear η' peak is observed in the $\pi^+\pi^-\pi^+\pi^-$ and $\pi^+\pi^-\pi^0\pi^0$ mass spectra, respectively. The branching fractions of $\eta' \to \pi^+\pi^-\pi^+\pi^-$ and $\eta' \to \pi^+\pi^-\pi^0$ π^0 are measured to be $(8.53 \pm 0.25(stat.) \pm 0.23(sys.)) \times 10^{-5}$ and $(2.18 \pm 0.12(stat.) \pm 0.10(sys.)) \times 10^{-4}$. No significant η' signal is observed in the $4\pi^0$ invariant mass spectrum. With a Bayesian approach, the upper limit on the branching fraction is determined to be $\mathcal{B}(\eta' \to 4\pi^0) < 1.28 \times 10^{-5}$ at the 90% confidence level. With improved precision, the results are consistent with the previous measurements.

What's new?(II)

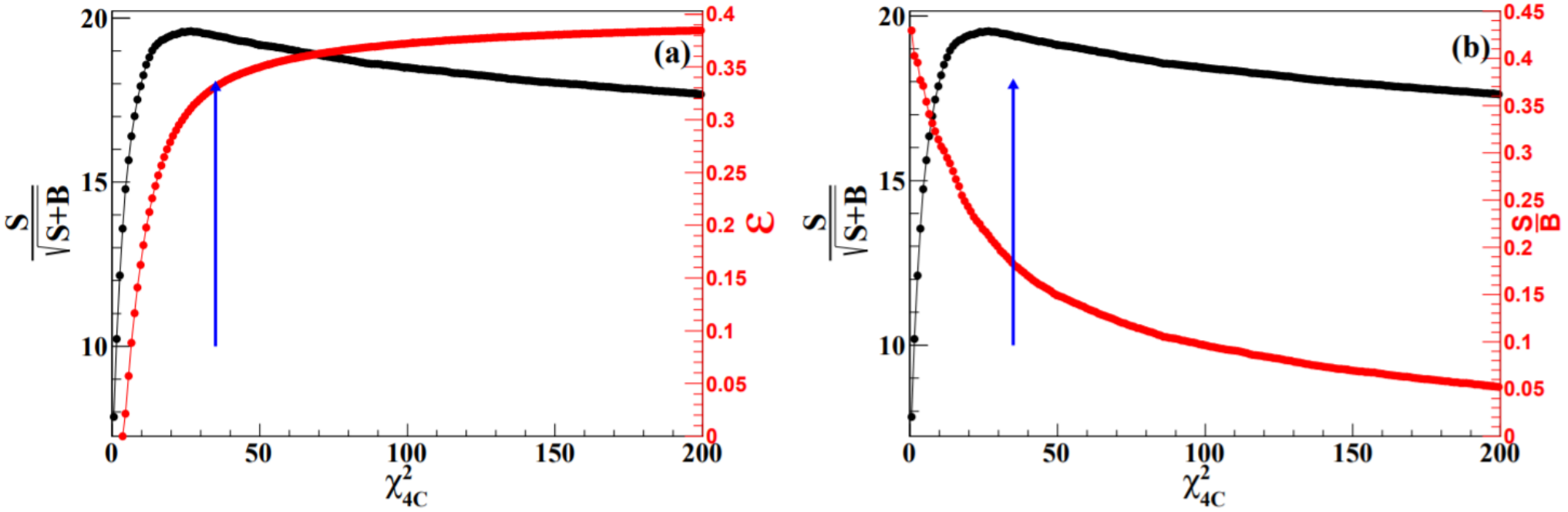
Updated result of $\eta' \to \pi^+\pi^-\pi^+\pi^-$





- $\chi^2_{4C} < 35$

Optimization result

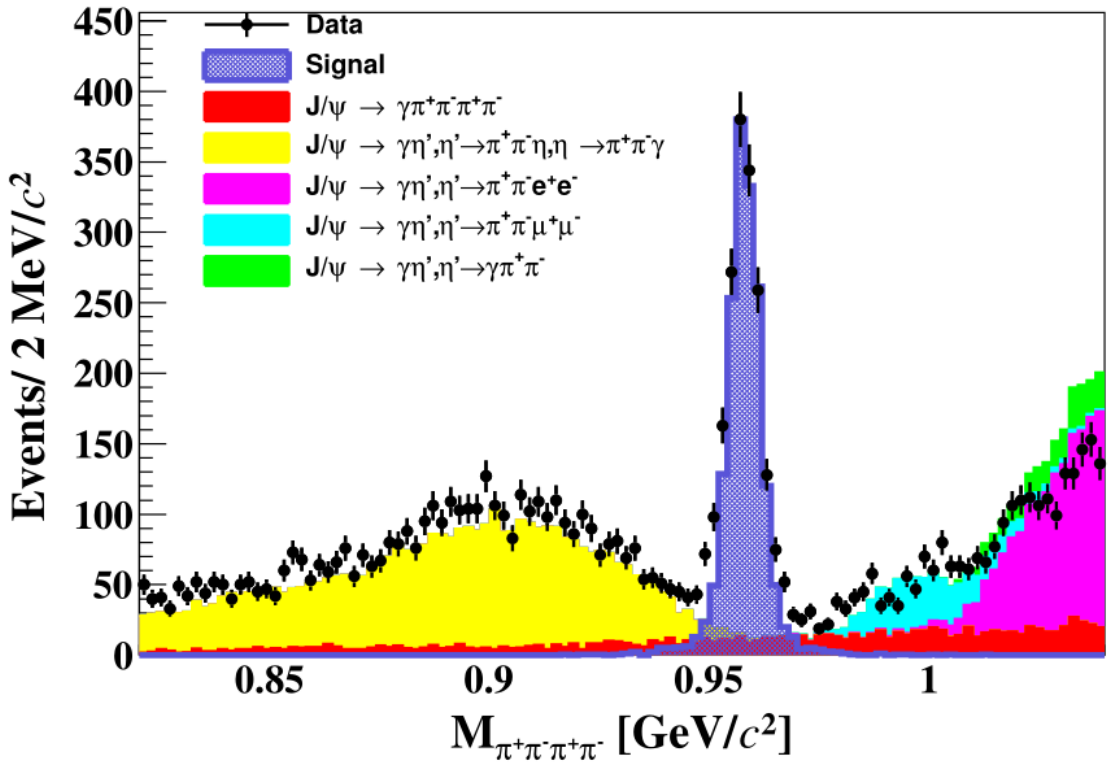


- (a) The red line represents the detection efficiency. (b) The red line shows the value of S/B.

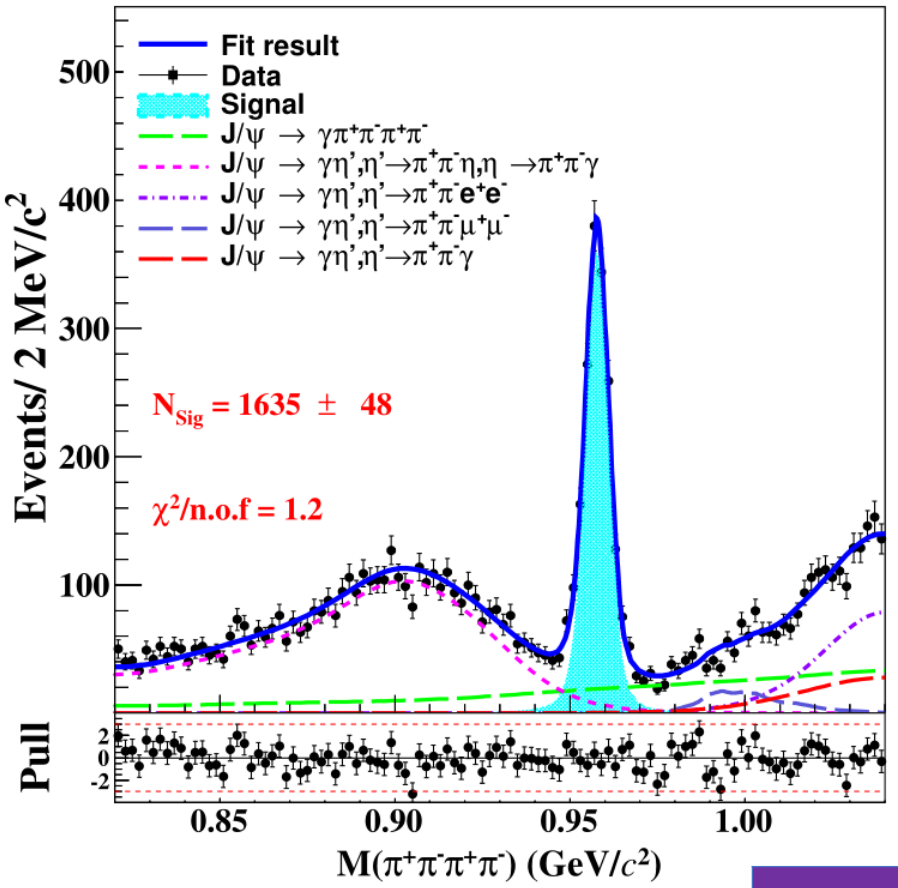
Background Study

Q3. Table 4: the N_{norm} of the first channel is more than the second channel. But in Fig.3, I see the red is less than yellow. Please explain that.

Re: Sorry for the typo. For the decay channel of $J/\psi \to \gamma\pi^+\pi^-\pi^+\pi^-$, the number of N_{norm} is 1903 ± 44. In order to reduce the influence of statistical uncertainty, We then generated the 12×10^6 exclusive MC samples for this background process. And the fitting result and systematic uncertainty of $\eta' \to \pi^+\pi^-\pi^-\pi^-$ have been updated in our updated MEMO.



Fitting result of $M(\pi^+\pi^-\pi^+\pi^-)$



- Signal: PDF shape
- Background :

  PDF shape of continuous background($J/\psi \to \gamma\pi^+\pi^-\pi^+\pi^-$),

  PDF shape of peak background($J/\psi \to \gamma\eta', \eta' \to \pi^+\pi^-\eta, \eta \to \pi^+\pi^-\gamma$),

  PDF shape of peak background($J/\psi \to \gamma\eta'$, $\eta' \to \pi^+\pi^-e^+e^-$),

  PDF shape of peak background($J/\psi \to \gamma\eta'$, $\eta' \to \pi^+\pi^-\mu^+\mu^-$),

  PDF shape of peak background($J/\psi \to \gamma\eta'$, $\eta' \to \gamma\pi^+\pi^-$).

- $\mathcal{B}(\eta' \to \pi^+\pi^-\pi^+\pi^-) = \frac{N_{sig}}{N_{J/\psi}\cdot B(J/\psi\to\gamma\eta\prime)\cdot\varepsilon}$

Mode	N_{sig}	ε(%)	$\mathcal{B}(\times10^{-5})$
$\eta' \to \pi^+\pi^-\pi^+\pi^-$	**1635±48**	**36.2**	**8.53±0.25**$(stat)$

What's new?(III)

Updated result of $\eta' \to \pi^+\pi^-\pi^0\pi^0$

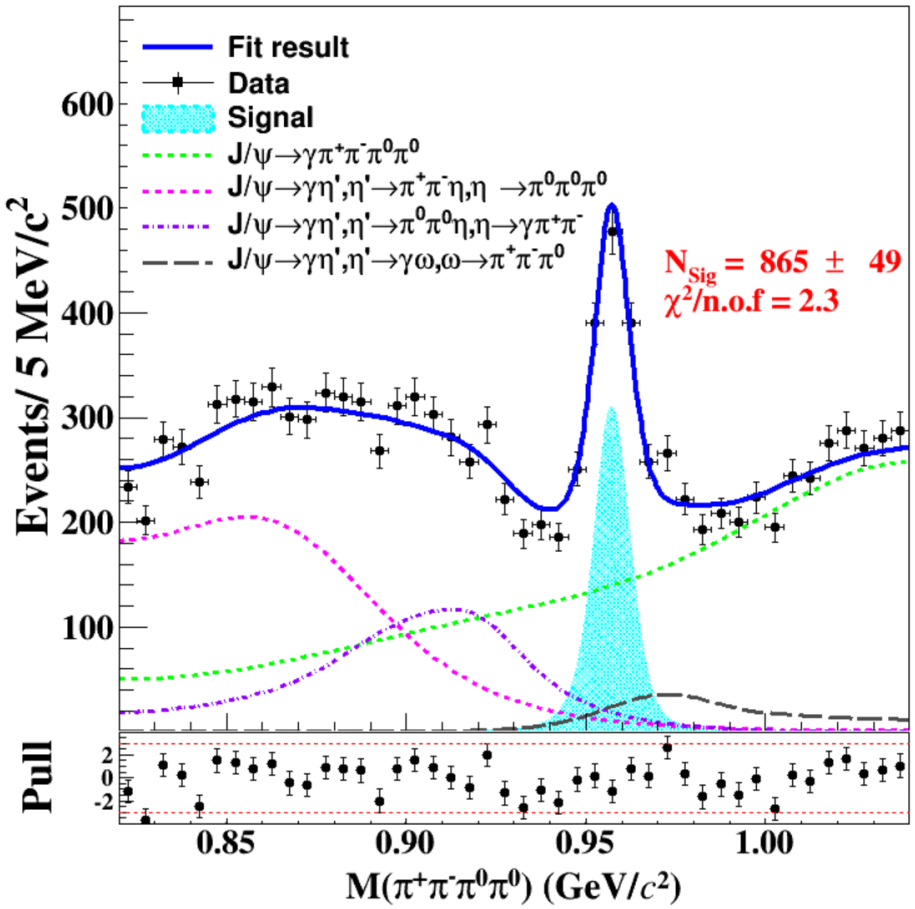
Q4. Table 3 and Table 4: maybe I misunderstand something here, so correct me if I am wrong: N_{sel} is the number of events surviving that background MC, N_{norm} is the size of that same background MC once your fit scaled it to the appropriate size. Is that right? I am confused, because sometimes $N_{sel} > N_{norm}$, and sometimes $N_{sel} < N_{norm}$. If you use the MC in your fit, I believe you want the scaling factor on that MC (your fit constant) to be $<<1$ ideally (so that you can safely ignore the error bars on the MC lineshape).

Re: Yes, for those events who did not contributed to the η' mass region, I did not generate such a large sample to reduce the statistical uncertainty. Take $J/\psi \to \gamma\eta'(\eta' \to \pi^+\pi^-\eta(\eta \to 3\pi^0))$ for example, most of these background events contributed to the low mass region below 0.9 GeV. Now I am generating another sample to reduce the statistical uncertainty, but I believed that its impact on the results is small.

Table 4: The residual events of the exclusive MC samples for the background channels. N_{gen} is for the number of generated MC events, N_{sel} is for the selected events with the same criteria as the data, N_{norm} is the number of normalized events.

Decay mode	$N_{gen}(10^4)$	N_{sel}	N_{norm}
$J/\psi \to \gamma\pi^+\pi^-\pi^0\pi^0$	8022	6373±80	6352±80
$J/\psi \to \gamma\eta', \eta' \to \pi^+\pi^-\eta, \eta \to \pi^0\pi^0\pi^0$	945	3093±56	2284±48
$J/\psi \to \gamma\eta', \eta' \to \pi^0\pi^0\eta, \eta \to \gamma\pi^+\pi^-$	560	26728±163	2298±48
$J/\psi \to \gamma\eta', \eta' \to \gamma\omega, \omega \to \pi^+\pi^-\pi^0$	400	2488±50	726±27

Fitting result of $M(\pi^+\pi^-\pi^0\pi^0)$



- Signal: PDF shape
- Background :

  PDF shape of continuous background($J/\psi \to \gamma\pi^+\pi^-\pi^0\pi^0$),

  PDF shape of peak background($J/\psi \to \gamma\eta', \eta' \to \pi^+\pi^-\eta, \eta \to \pi^0\pi^0\pi^0$),

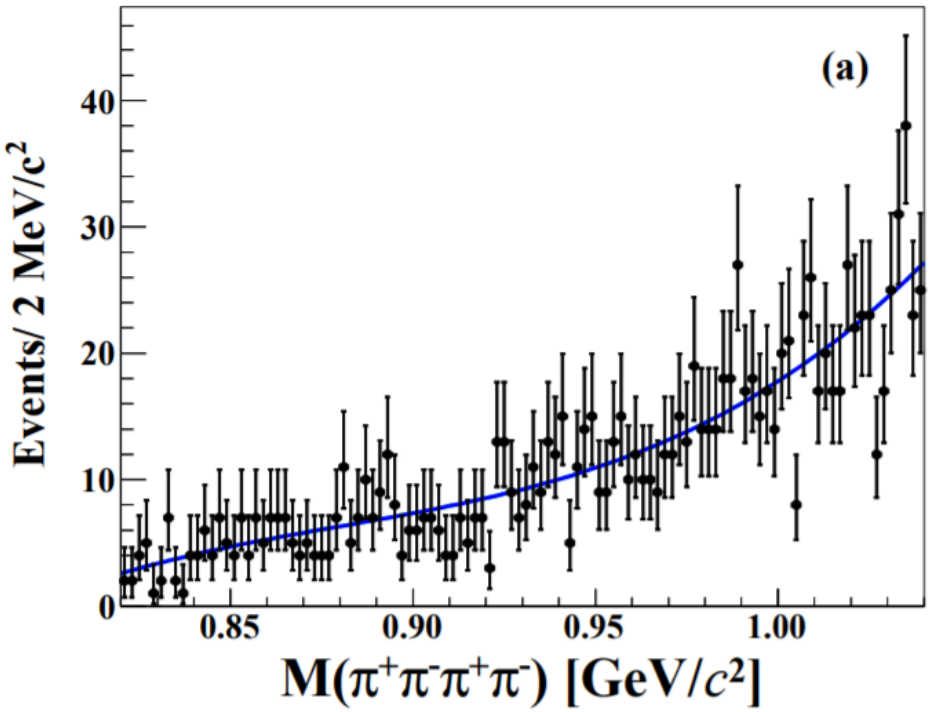
  PDF shape of peak background($J/\psi \to \gamma\eta', \eta' \to \pi^0\pi^0\eta, \eta \to \pi^+\pi^-\gamma$),

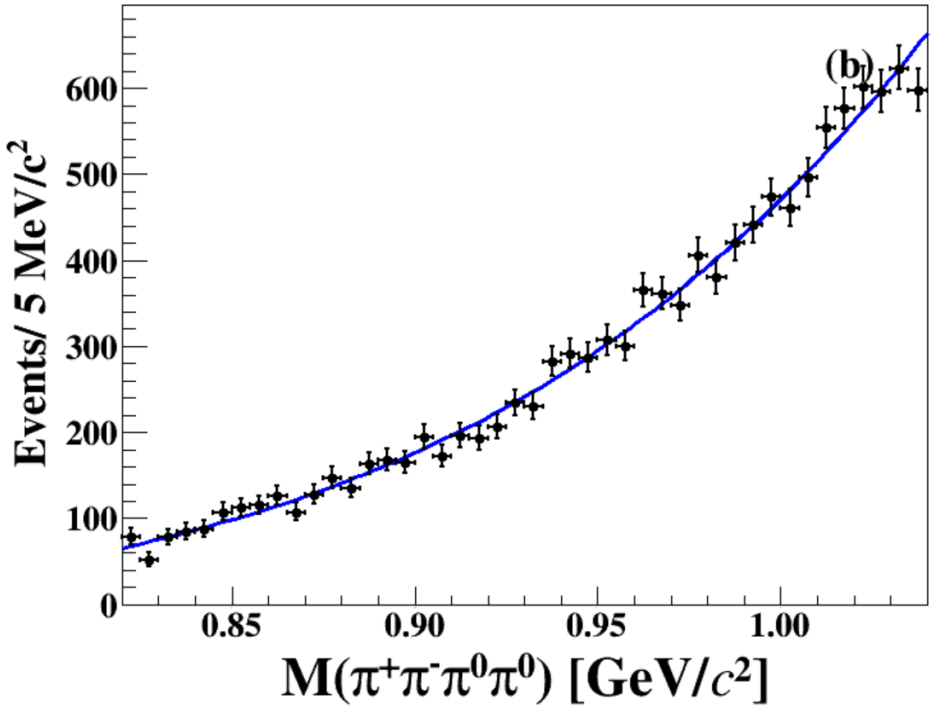
  PDF shape of peak background($J/\psi \to \gamma\eta', \eta' \to \gamma\omega, \omega \to \pi^+\pi^-\pi^0$).

- $\mathcal{B}(\eta' \to \pi^+\pi^-\pi^0\pi^0) = \dfrac{N_{sig}}{N_{J/\psi}\cdot\mathcal{B}(J/\psi\to\gamma\eta')\cdot\varepsilon\cdot\mathcal{B}(\pi^0\to\gamma\gamma)\mathcal{B}(\pi^0\to\gamma\gamma)}$

Mode	N_{sig}	ε(%)	$\mathcal{B}(\times10^{-4})$
$\eta' \to \pi^+\pi^-\pi^0\pi^0$	865±49	7.8	2.18±0.12($stat$)

Systematic uncertainty from continuous background shape





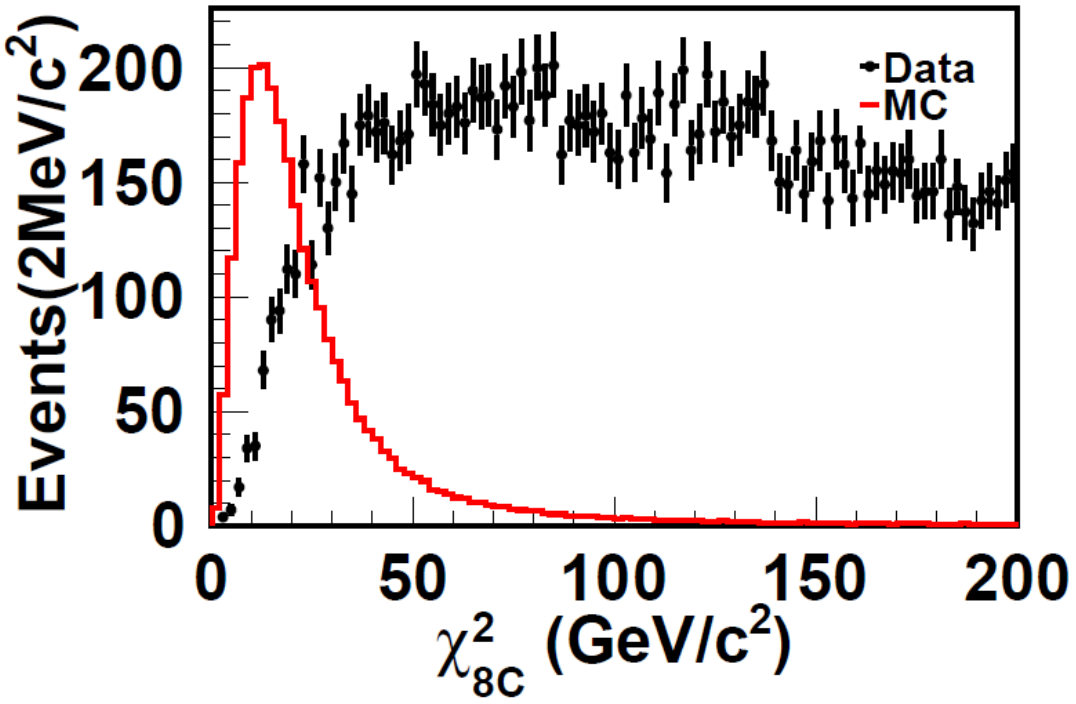
- Fit of $J/\psi \to \gamma\pi^+\pi^-\pi^+\pi^-$ and $J/\psi \to \gamma\pi^+\pi^-\pi^0\pi^0$ PHSP MC. The solid blue line is the best fit result with a third-order Chebychev polynomial function.

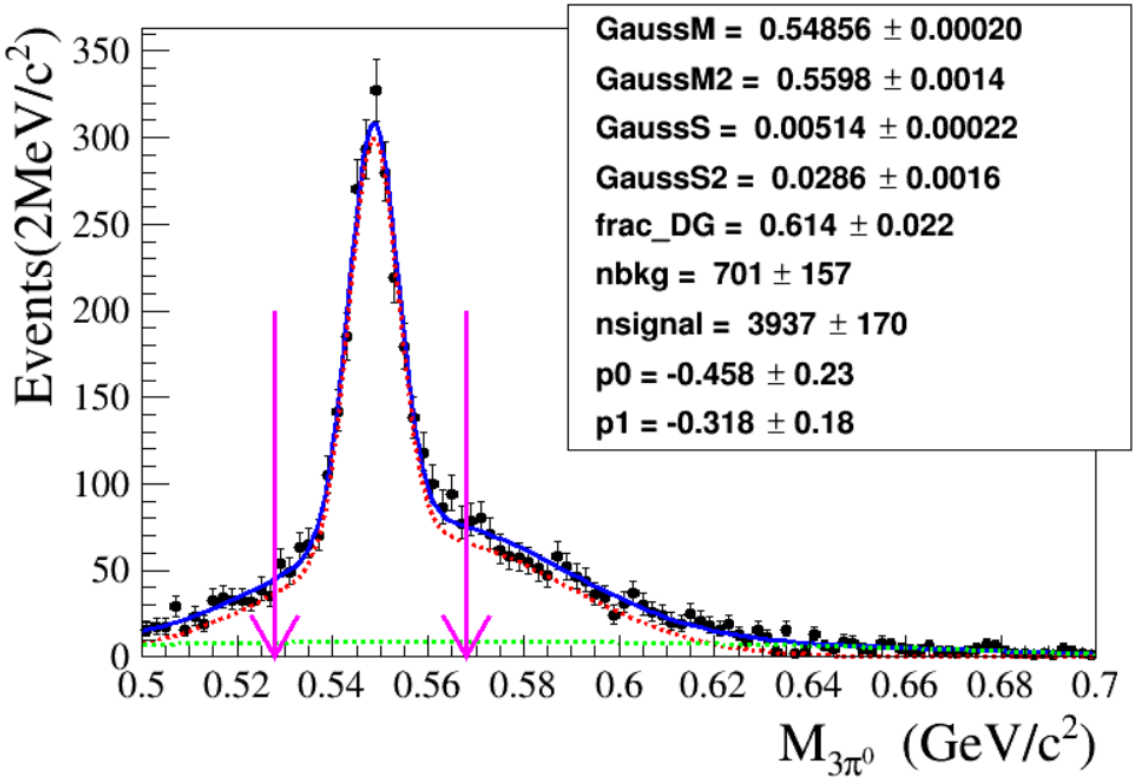
Total Systematic Uncertainty

Sources	$\eta' \to \pi^+\pi^-\pi^+\pi^-$(%)	$\eta' \to \pi^+\pi^-\pi^0\pi^0$(%)
MDC tracking	2	1
Photon detection efficiency	0.5	2.5
Kinematic fit	0.6	0.2
Peak background shape	0.4	0.09
Continuous background shape	0.2	1.4
Veto $\eta(\omega)$ signal	-	2.8
$\mathcal{B}(J/\psi \to \gamma\eta')$	1.3	1.3
$\mathcal{B}(\pi^0 \to \gamma\gamma)$	-	0.06
Number of J/ψ events	0.44	0.44
Generator Model	0.6	0.8
Total	2.7	4.4

What's new?(IV)

Updated result of $\eta' \to \pi^0\pi^0\pi^0\pi^0$





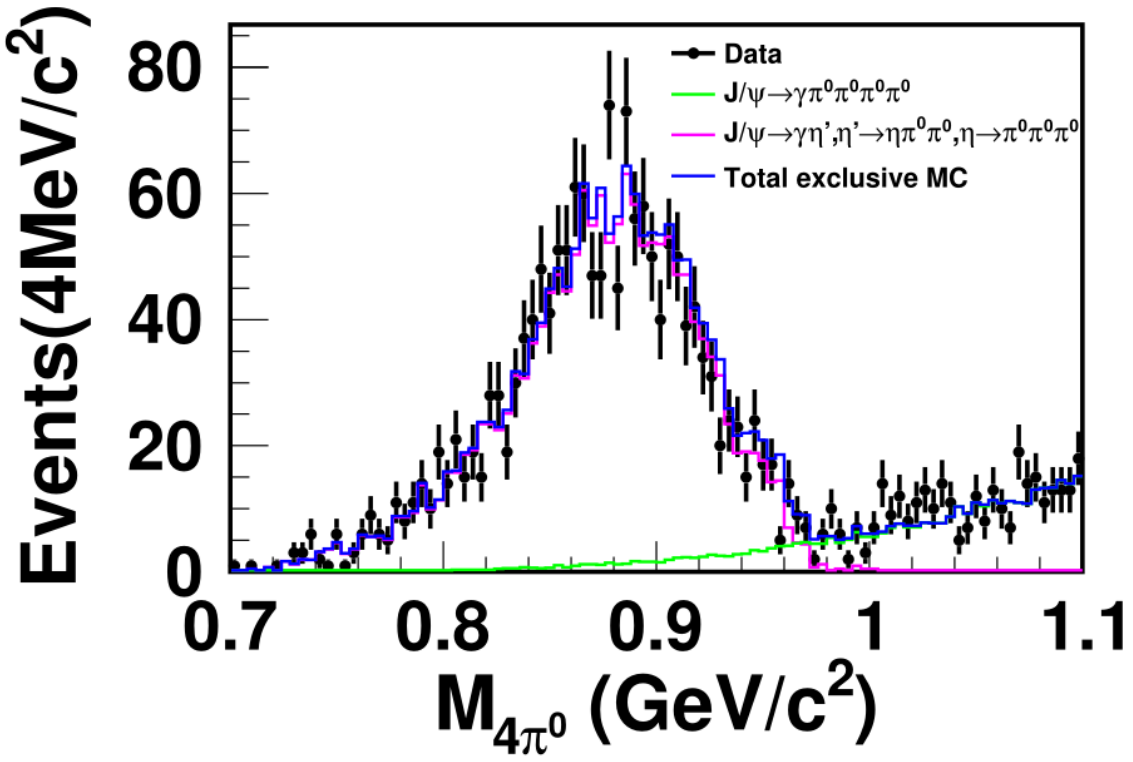
- $\chi^2_{8C} < 40$
- $\chi^2_{4C}(\gamma\pi^0\pi^0\pi^0\pi^0) < \chi^2_{4C}(\gamma\gamma\pi^0\pi^0\pi^0\pi^0)$
- $\chi^2_{4C}(\gamma\pi^0\pi^0\pi^0\pi^0) < \chi^2_{4C}(\gamma\gamma\gamma\pi^0\pi^0\pi^0\pi^0)$

- Veto $\eta \to \pi^0\pi^0\pi^0$:

$$\left|M_{3\pi_i^0} - M_\eta^{PDG}\right| > 0.02\,GeV/c^2 \ (i = 1,2,3,4)$$

Background study

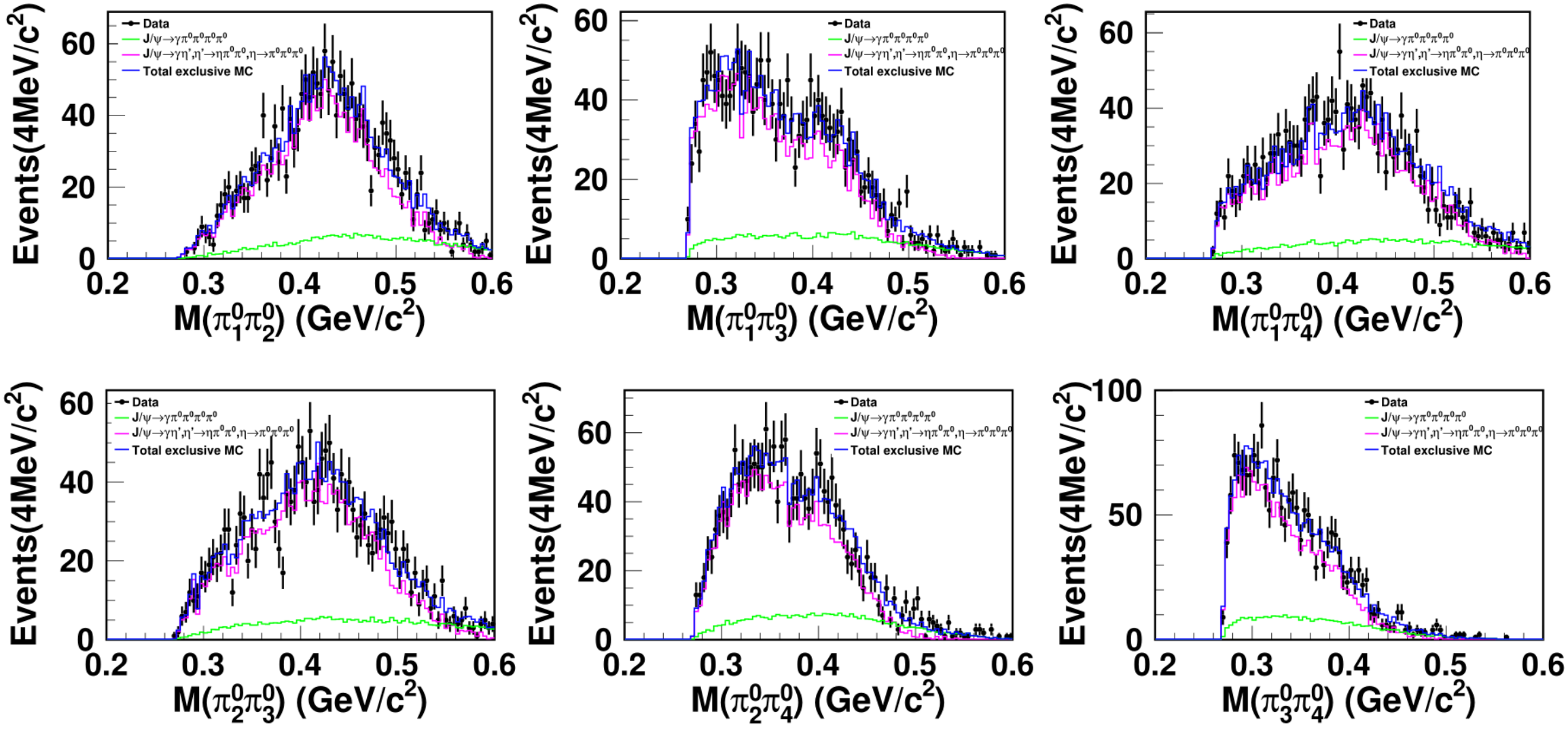
- **The distribution of $4\pi^0$ mass spectrum for the main background channels:**



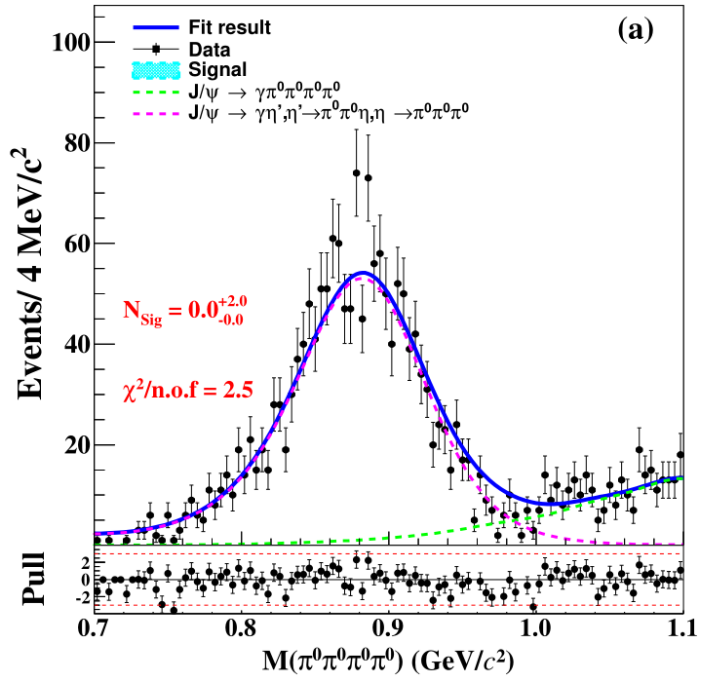
- The **peaking** background events is from:
  $J/\psi \to \gamma\eta',\eta' \to \pi^0\pi^0\eta,\eta \to \pi^0\pi^0\pi^0$

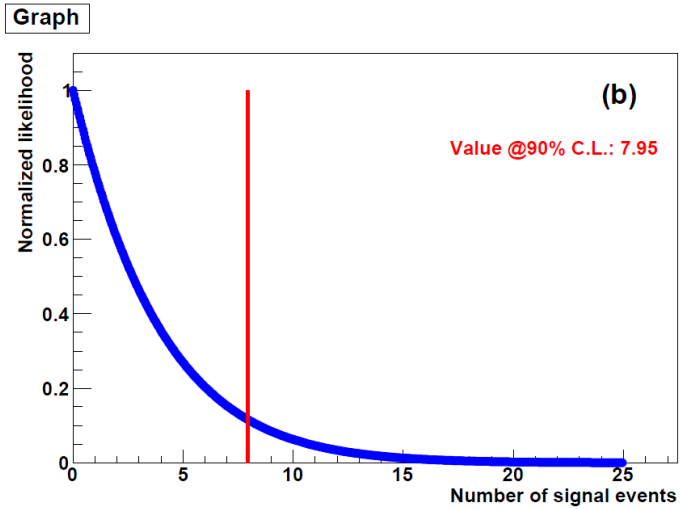
- The **continuous** background events mainly comes from:
  $J/\psi \to \gamma\pi^0\pi^0\pi^0\pi^0$

MC and Data Comparison



Fitting result of $M(\pi^0\pi^0\pi^0\pi^0)$





- Fit Model:
  - Signal: PDF shape
  - Background :

    PDF shape of continuous background($J/\psi \to \gamma\pi^0\pi^0\pi^0\pi^0$),

    PDF shape of peak background($J/\psi \to \gamma\eta', \eta' \to \pi^0\pi^0\eta, \eta \to \pi^0\pi^0\pi^0$).

- Upper Limit:
  - We use a **Bayesian** method to calculate the Upper limits of the signal yields at the 90% confidence level in different hypotheses.
  - The maximum one, $N_{UL} = 7.95$, is used to evaluate the upper limit on the branching fraction.

Total Systematic Uncertainty

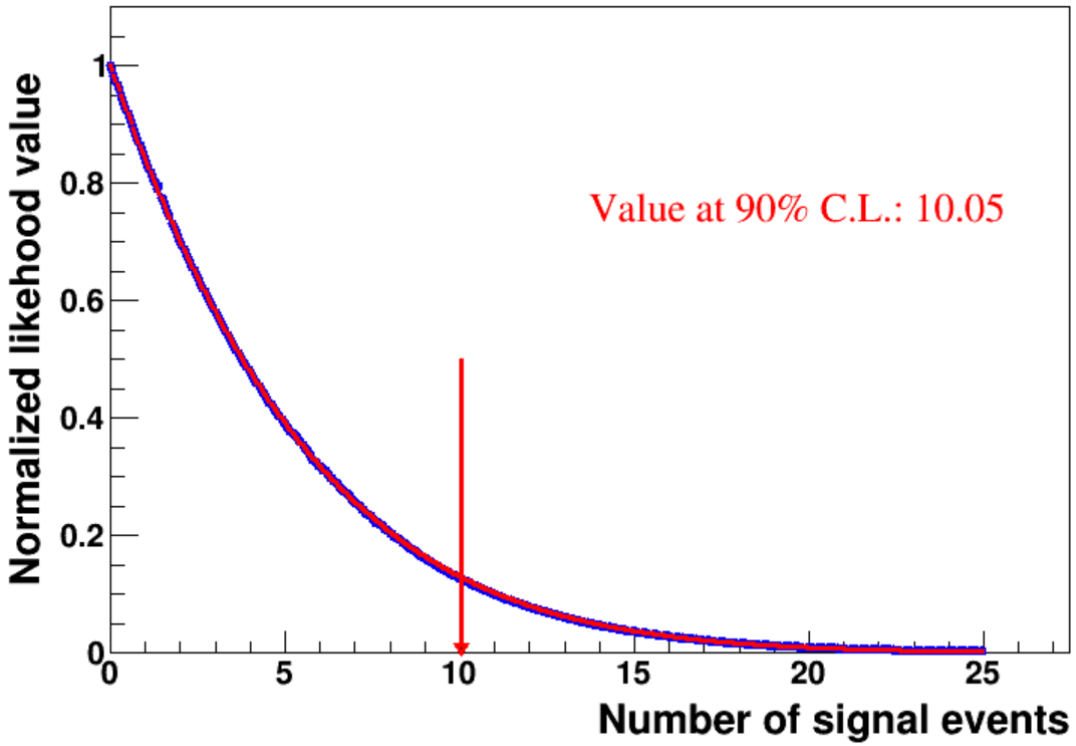
➢ Additive Systematic Uncertainties

Sources		$B^{UL} \times 10^{-5}$
Fit range	[0.7 , 1.095]GeV/c^2	1.01
	[0.7 , 1.105] GeV/c^2	1.12
	[0.705 , 1.1] GeV/c^2	1.01
	[0.705 , 1.095] GeV/c^2	1.01
	[0.705 , 1.105] GeV/c^2	1.02
Signal shape	MC shape convolution Gaussian	1.02
Continuous background shape	2_{nd} order polynomial	1.0
Peaking background shape	MC shape convolution Gaussian	1.26
The number of peaking background events	1465	1.15

➢ Multiplicative Systematic Uncertainties

Sources	$\eta' \to 4\pi^0$ (%)
Photon detection efficiency	4.5
Kinematic fit	5.6
Veto $\eta \to \pi^0\pi^0\pi^0$	3.0
$\mathcal{B}(J/\psi \to \gamma\eta')$	1.3
$\mathcal{B}(\pi^0 \to \gamma\gamma)$	0.12
Number of J/ψ events	0.44
Generator Model	0.1
Total	8.0

Upper Limit of $\eta' \to 4\pi^0$



- To conservatively estimate the upper limit of branching fraction, the systematic uncertainties are considered by convolving a **Gaussian** function into the normalized likelihood.

$$L'(N) = \int_0^1 L\left(\frac{S}{\hat{S}}N\right) exp\left[-\frac{(S-\hat{S})}{2\sigma_S^2}\right] dS$$

$$\mathcal{B}^{UL} = \frac{N_{UL}}{N_{J/\psi} \cdot \mathcal{B}(J/\psi \to \gamma\eta') \cdot \varepsilon \cdot (\mathcal{B}(\pi^0 \to \gamma\gamma))^4}$$

- **Upper Limit:** $\mathcal{B}(\eta' \to \pi^0\pi^0\pi^0\pi^0) < \mathbf{1.28 \times 10^{-5}}$

*Normalized likelihood distribution before (**blue** dots) and after (**red** dots) convolution.

Summary & Next to do

Using a sample of 10087M J/ψ events collected with the BESIII :

Mode	N_{sig}	$\varepsilon(\%)$	$Br(\eta' \to X)$(this work)	$Br(\eta' \to X)$[1][2](pre.result)
$\eta' \to \pi^+\pi^-\pi^+\pi^-$	1635±48	36.2	$(8.53\pm0.25(stat.)\pm0.23(sys.))\times 10^{-5}$	$(8.53\pm0.69(stat.)\pm0.64(sys.))\times 10^{-5}$
$\eta' \to \pi^+\pi^-\pi^0\pi^0$	865±49	7.8	$(2.18\pm0.12(stat.)\pm0.10(sys.))\times 10^{-4}$	$(1.82\pm0.35(stat.)\pm0.18(sys.))\times 10^{-4}$
$\eta' \to \pi^0\pi^0\pi^0\pi^0$	< 10.05	1.6	$< 1.28\times 10^{-5}$	$< 4.94\times 10^{-5}$

- ✓ The results of $\mathcal{B}(\eta' \to \pi^+\pi^-\pi^+\pi^-)$ 、 $\mathcal{B}(\eta' \to \pi^+\pi^-\pi^0\pi^0)$ and $\mathcal{B}(\eta' \to 4\pi^0)$ have been updated.
- ✓ With improved precision, the results are also consistent with the previous measurements.
- ✓ The first round questions from the two referees have been answered.

Next to do

- ➢ Measurement of Form Factor in $\eta' \to \pi^+\pi^-\pi^+\pi^-$.
- ➢ Draft is in preparation.

THANKS!☺

[1] Phys. Rev. Lett. 113, 039903 (2014).
[2] M.Ablikim et al.(BESIII Collaboration),Phys,Rev.D 101,032001(2020)