中国物理学会高能物理分会第十四届全国粒子物理学术会议（2024）

$f_0(980)$ meson photoproduction in the $\pi^0\pi^0$ decay mode

何庆华 南京航空航天大学 @青岛

HE Qinghua, Nanjing University of Aeronautics and Astronautics

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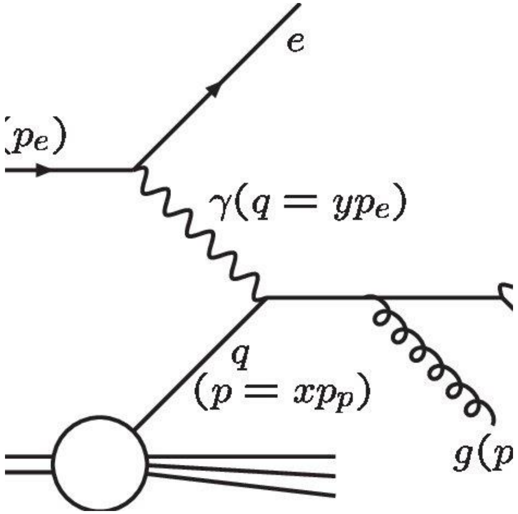
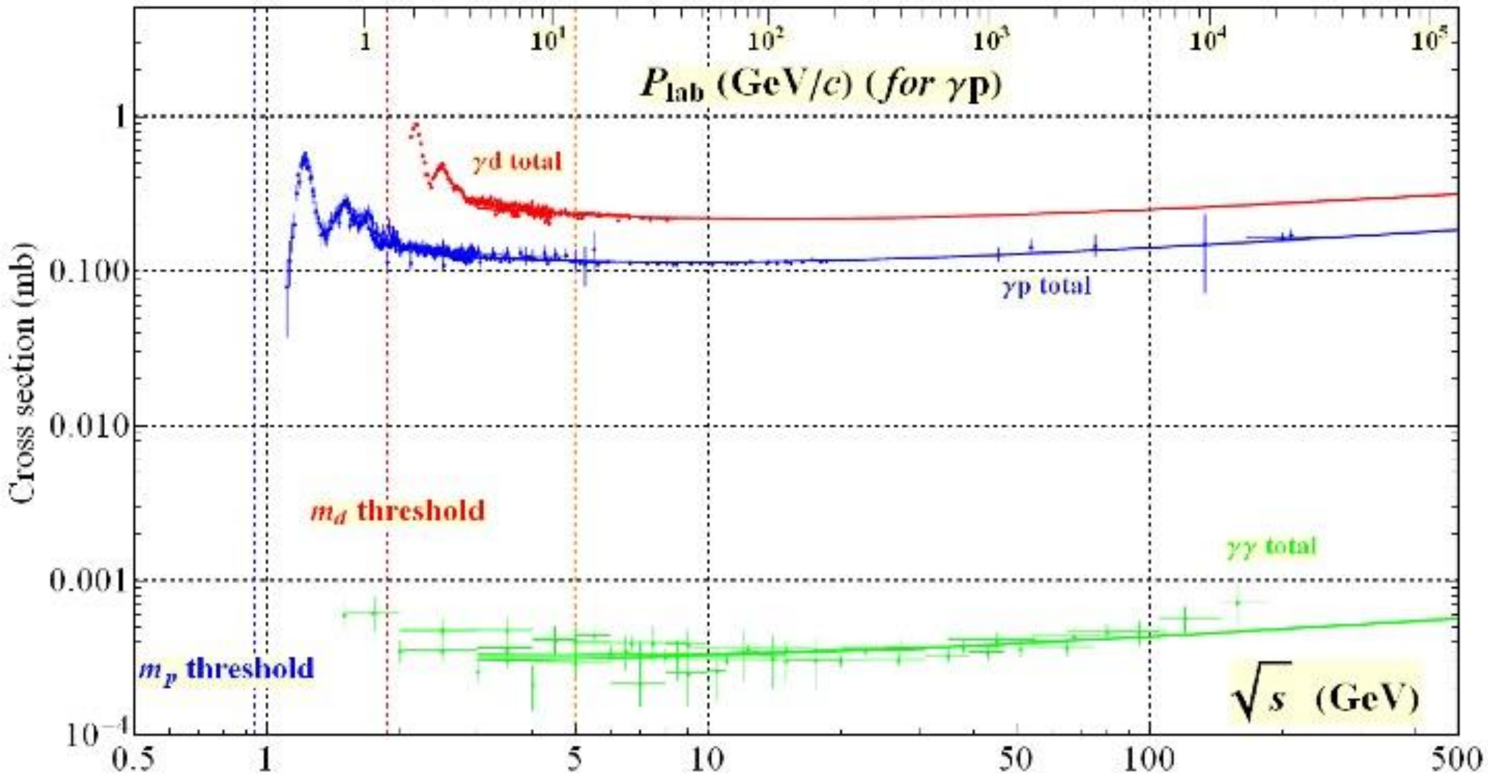
Motivation

QCD非微扰能区强相互作用机制

主要实验数据来自于电子、$\pi^{\pm}$介子等带电粒子探针引起的核反应，实验观测到的共振态依然远少于理论预测的数量

采用GeV光子探针激发核子（光生反应）研究重子共振态被给予厚望



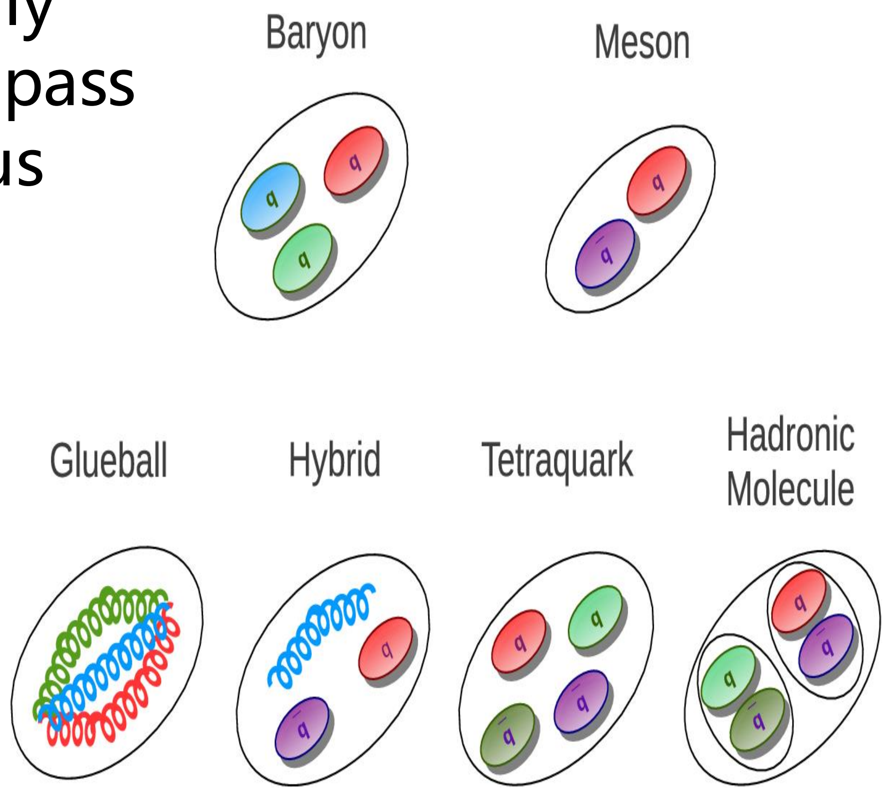


Motivation

- The light-quark non strange scalar mesons $a_0(980)$, $f_0(980)$, $f_0(1370)$, $a_0(1450)$, $f_0(1500)$, and $f_0(1710)$ are of great interest because there is no generally accepted view of their structure that can encompass $qq\bar{q}\bar{q}$, molecular, $q\bar{q}$, and glueball states in various combinations.

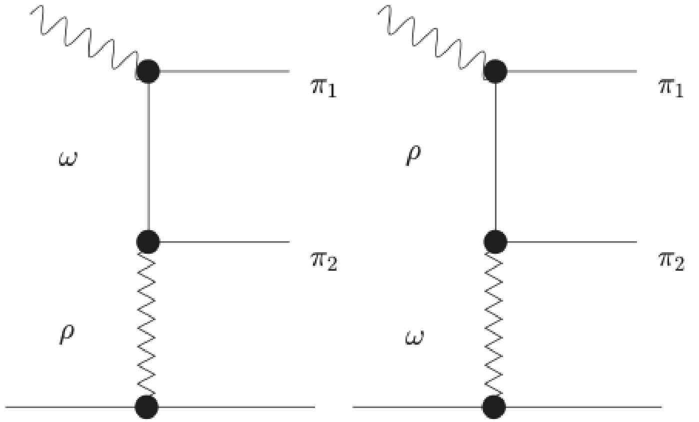
- The scalar meson $f_0(980)$ has been attracting as a possible candidate of exotic non-$q\bar{q}$ states such as a $K\bar{K}$ molecule and a tetraquark.

- The measurement of differential cross sections and photon beam asymmetries in $f_0(980)$ photoproduction is considered as one of useful ways to understand its nature.



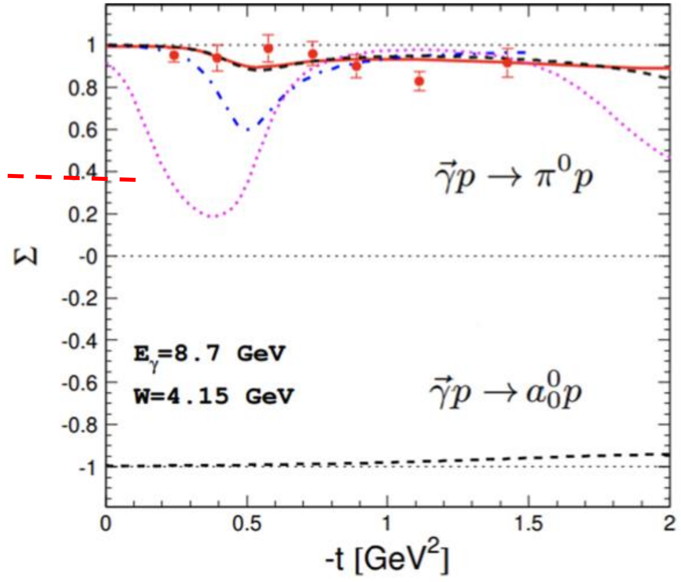
Motivation

1. A Regge model calculation with ρ and ω exchange suggests that the differential cross section is sensitive to the strength of $q\bar{q}$ and a quasi-bound state of $K\bar{K}$ pair in the $f_0(980)$ meson.



[1] A. Donnachie and Yu. S. Kalashnikova, Phys.Rev.C 93, 025203 (2016).
[2] A. Donnachie and Yu. S. Kalashnikova, Phys.Rev.C 78, 064603 (2008).

2. The t-channel vector meson (natural parity) exchange gives the photon beam asymmetry Σ of −1 in the scalar meson photoproduction, and its magnitude decreases by the mixture of unnatural parity which arises from axial-vector meson exchange and re-scattering diagrams, providing additional information about the $f_0(980)$ nature.



[3] I.I. Strakovsky et al., Phys. Rev. C. 107 (2023) 15203.

BGOegg experiment

A large acceptance electromagnetic (EM) calorimeter BGOegg (Fig.1) was constructed at ELPH, Tohoku University. This calorimeter system has been transferred to the new laser Compton scattering beamline LEPS2 at SPring-8, where a 1.3-2.9 GeV photon beam with high linear polarization is available. The phase-1 experiments have started from 2014 April with the EM calorimeter BGOegg and the additional detectors for charged particles. We are now upgrading the experimental setup by covering most of the solid angles with EM calorimeters to start new data collection in the phase-2 experiments.

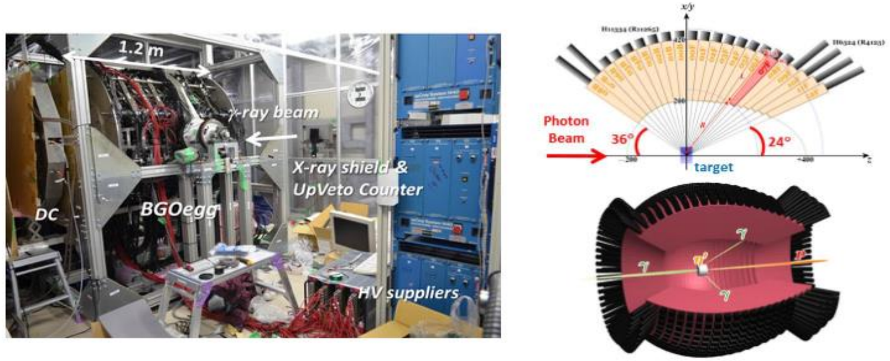


Fig.1 A picture of BGOegg inside the thermostatic booth (Left) and the drawings of BGOegg (Right).

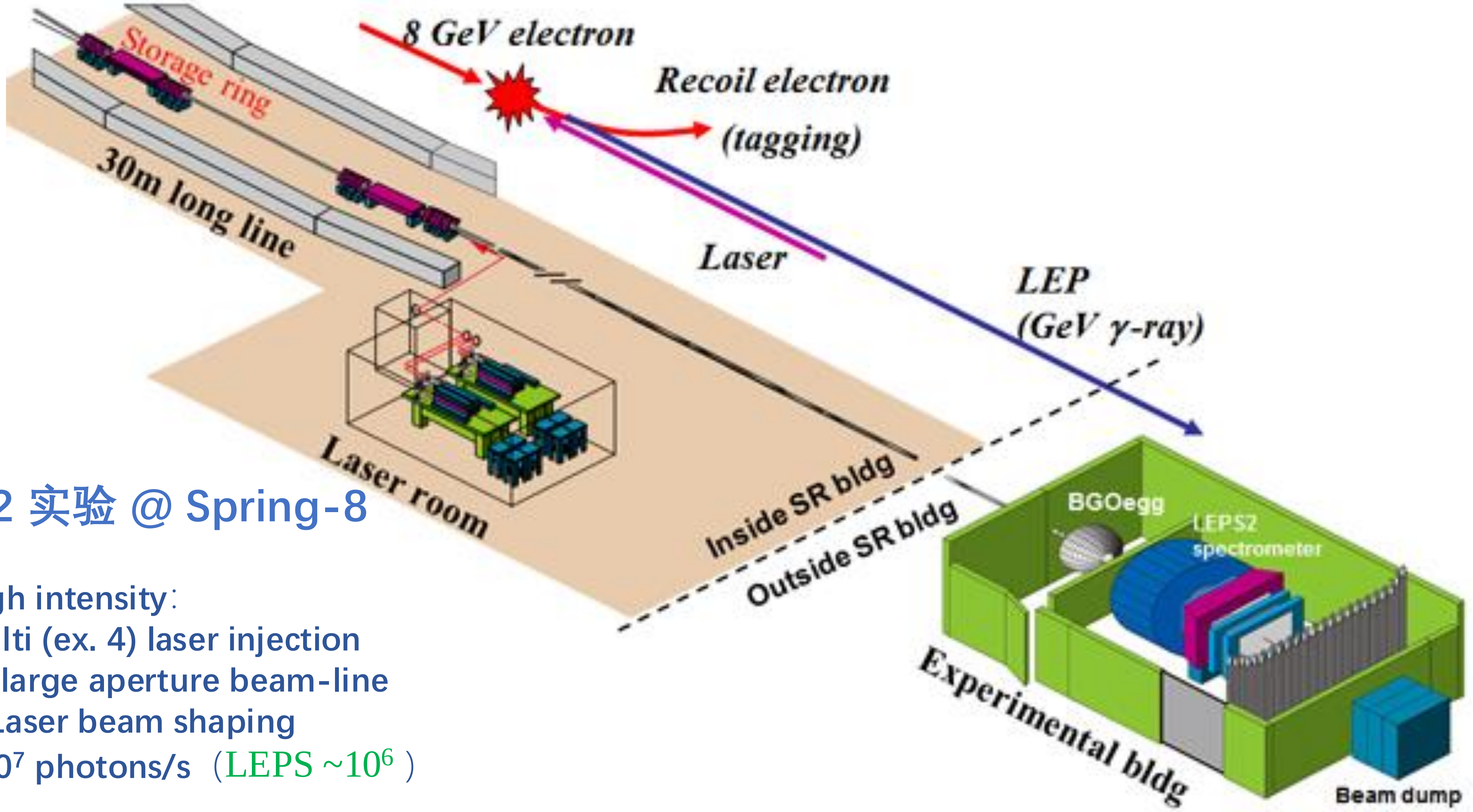
Physics

experiments, we are planning to upgrade the detector setup as shown in Fig.3. Instead of using DC and RPC, the forward acceptance hole of the BGOegg calorimeter will be covered by additional EM calorimeters. We install the "Forward Gamma" detector, which consists of 252 PWO crystals, in the polar angle range of 3 to 16 degrees. We are also considering to cover the gap region between the BGOegg calorimeter and the Forward Gamma detector. This configuration will significantly reduce backgrounds in the direct measurement of η'-mass spectral shape using a nuleus target.

Status

The LEPS2/BGOegg experiments are carried out under the collaboration of ELPH (Tohoku University), RCNP (Osaka University), Nanjing University of Aeronautics and Astronautics, Kyoto University, KEK, RIKEN, JASRI (SPring-8), and many other institutes in the world. ELPH and RCNP cooperate the LEPS2 facility.

BGOegg experiment

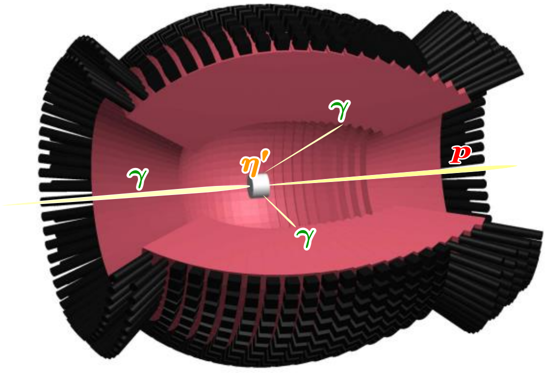


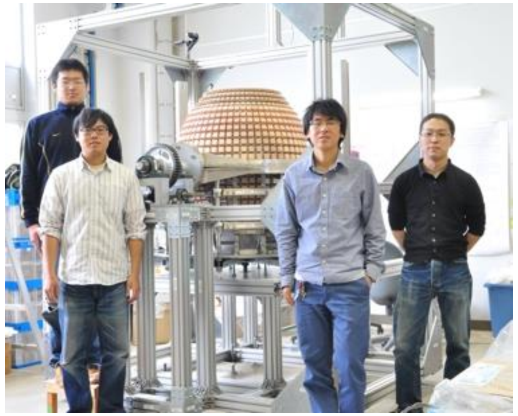
LEPS2 实验 @ Spring-8

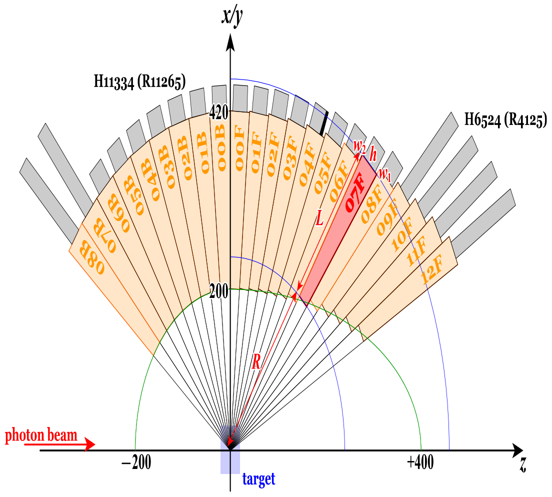
High intensity:
Multi (ex. 4) laser injection
w/ large aperture beam-line
& Laser beam shaping
~10^7 photons/s（LEPS ~10^6 ）

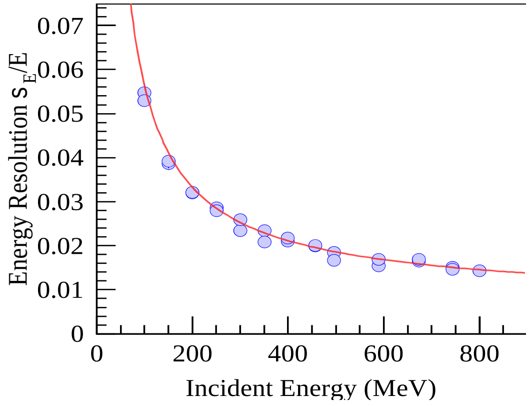
BGOegg experiment

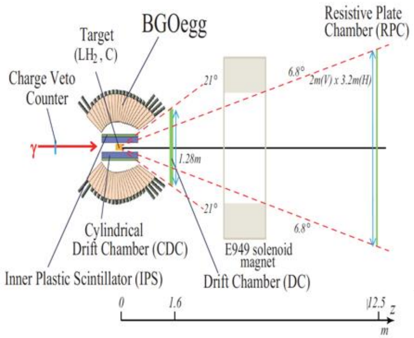
全立体角电磁量能器BGOegg能量分辨率世界领先



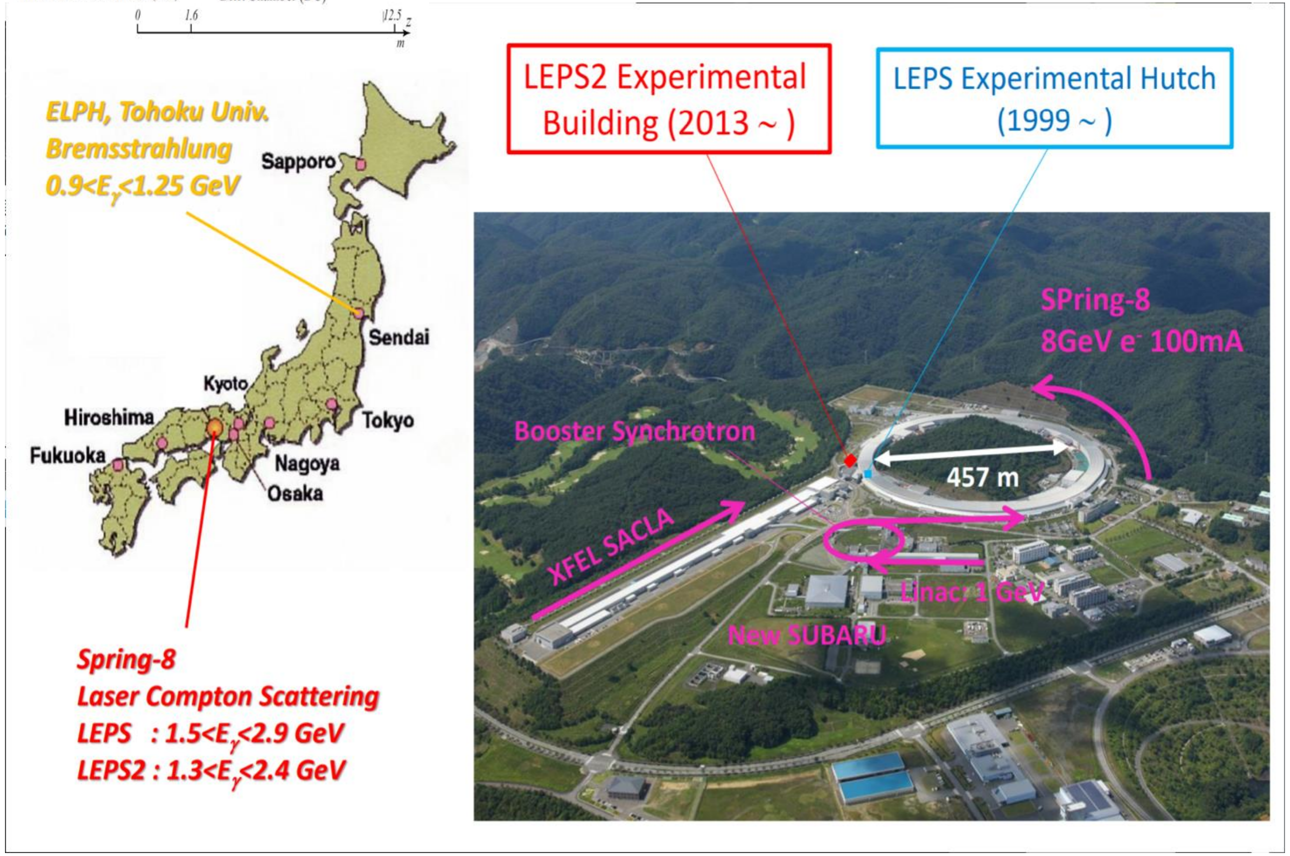




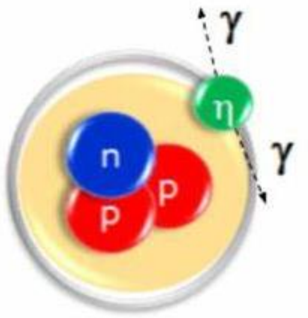




全立体角探测器BGOegg光输出均匀性研究、在线能量、时间标定等



BGOegg experiment



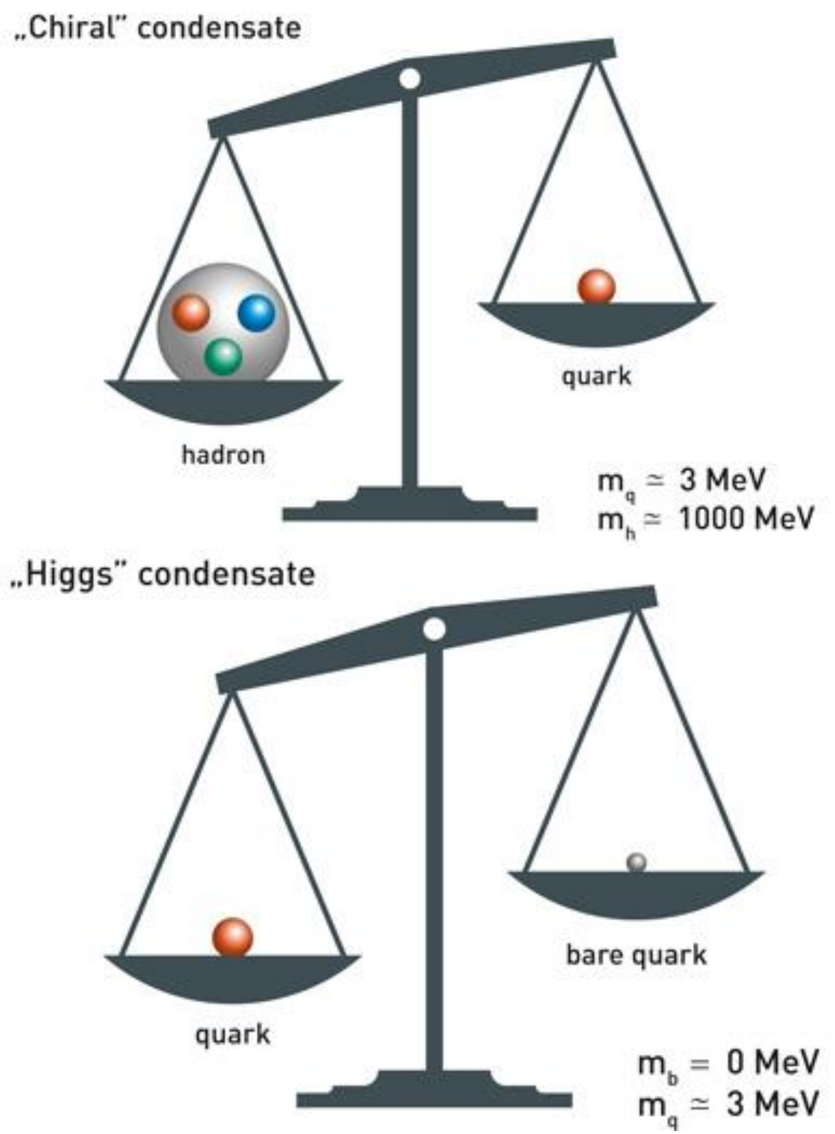
³He-η bound state

Physics

- **Search for η' mesic nuclei**
  - mass reduction of 80-150 MeV at nuclear density (partial restoration of chiral symmetry inside high-density condition)
  - bound η' mesic nuclei in the C(γ,p)X reaction.
- **Differential cross-section and beam asymmetry of the neutral mesons**

  The production of mesons from liquid hydrogen targets is suitable for investigating the excitation states of nucleons.
- **In-medium effect of the spectral shape of η'**
  - The width of η' may change
  - Aaccurately measuring the spectrum of η'

强子质量起源研究



汤川耦合与黑格斯粒子解释了基本费米子如夸克和轻子的质量来源，然而强子质量的绝大部分（也是目前世界可观测到的部分）是因为量子色动力学中的强相互作用产生的。

手征对称性破缺在解释轻强子质量谱方面扮演了重要角色

$U_A(1)$对称性的破缺 → $\eta'(985)$ 介子具有异常大的质量
η'和η的质量差异常大

↓

测量η'在一个原子核中的质量（手征对称性会部分恢复并因此削弱异常效应）

Nambu-Jona-Lasinio and linear sigma models containing an $U_A(1)$ symmetry breaking term —预测→ 150 and 80 MeV 质量下降

强子质量起源研究

- The mass reduction is described as an attractive potential for an η' meson in a nucleus
- **η'-nucleus bound states** can be formed.
- To search for η' -nucleus bound states, we used missing-mass spectroscopy of the ${}^{12}C(\gamma,p)$ reaction detecting decay products in coincidence.

$$E_{\rm ex} - E_0^{\eta'} = MM[{}^{12}\mathrm{C}(\gamma, p_f)] - M_{^{11}\mathrm{B}} - M_{\eta'}$$

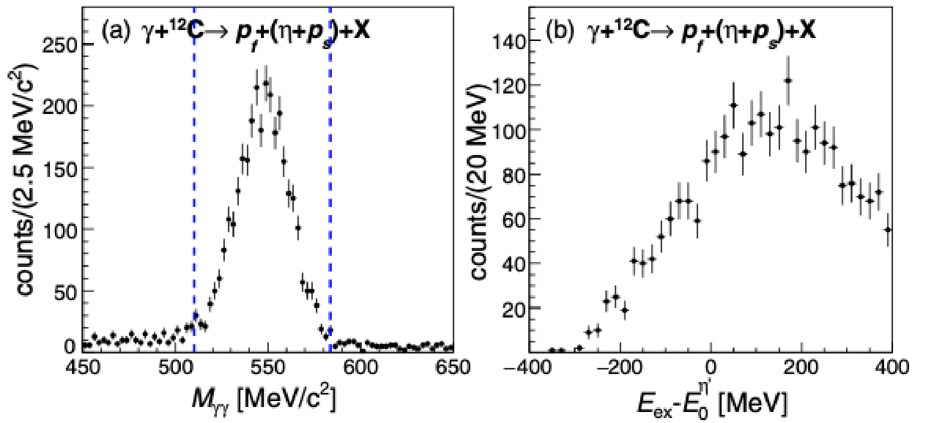


FIG. 1. (a) The 2γ invariant mass distribution around the η mass and (b) the excitation function of the $(\eta + p_s)$ coincidence data. The region in $\pm 2.5\sigma$ from the invariant mass peak is indicated by the blue-dashed lin

We measured missing mass spectrum of the ${}^{12}\mathrm{C}(\gamma, p)$ reaction for the first time in coincidence with potential decay products from η' bound nuclei. We tagged an $(\eta + p)$ pair associated with the $\eta' N \to \eta N$ process in a nucleus. After applying kinematical selections to reduce backgrounds, no signal events were observed in the bound-state region. An upper limit of the signal cross section in the opening angle $\cos\theta^{\eta p}_{\rm lab} < -0.9$ was obtained to be 2.2 nb/sr at the 90% confidence level. It is compared with theoretical cross sections, whose normalization ambiguity is suppressed by measuring a quasifree η' production rate. Our results indicate a small branching fraction of the $\eta' N \to \eta N$ process and/or a shallow η'-nucleus potential.

DOI: 10.1103/PhysRevLett.124.202501

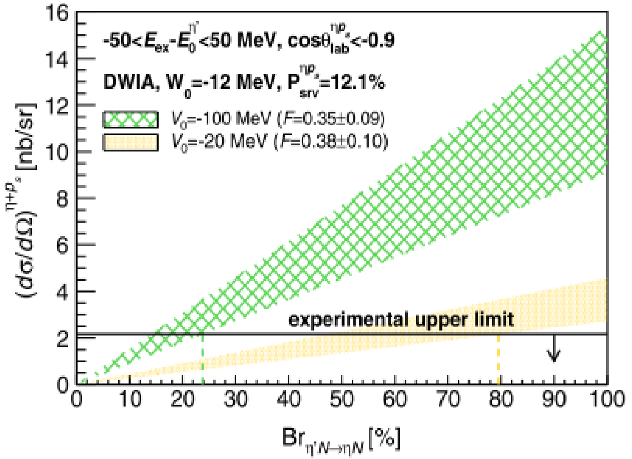


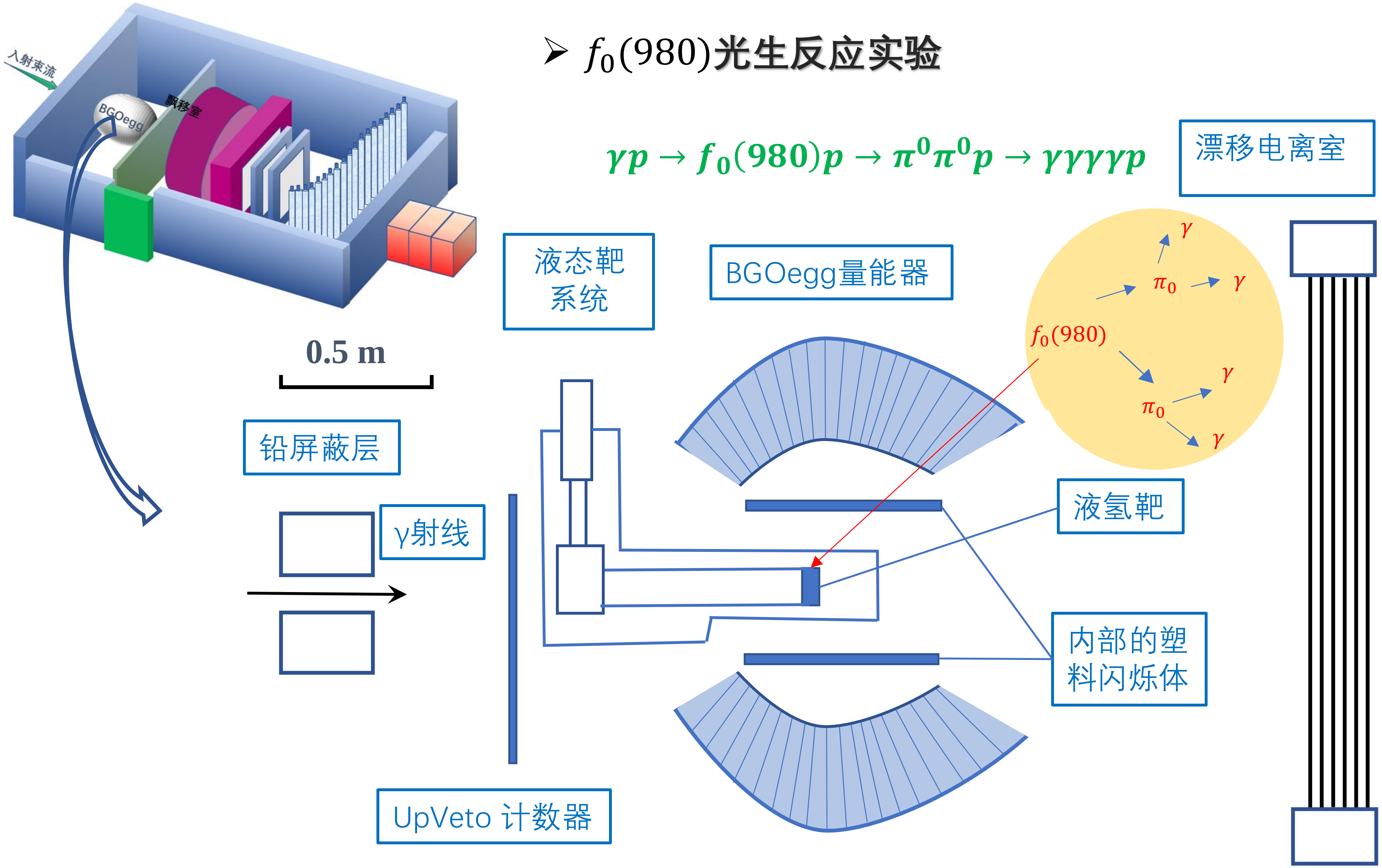
FIG. 4. The experimental upper limit of $(d\sigma/d\Omega)^{\eta+p_s}_{\rm exp}$ at the 90% confidence level, and $(d\sigma/d\Omega)^{\eta+p_s}_{\rm theory}$ as a function of $\mathrm{Br}_{\eta' N\to\eta N}$.

BGOegg/LEPS2 collaboration, Phys. Rev. Lett. **124**, 202501 (2020).

$f_0(980)$光生反应束流极化度分析

➢ $f_0(980)$光生反应实验

$$\gamma p \to f_0(980)p \to \pi^0\pi^0 p \to \gamma\gamma\gamma\gamma p$$



BGOegg

- 1320 BGOcrystals
- Polar coverage: 24°-144°
- EM cluster energy threshold: 30 MeV
- 2 hits $\Delta t < 2$ ns

Planner drift chamber

Polar coverage: $\theta < 21^\circ$

Tagged beam photons

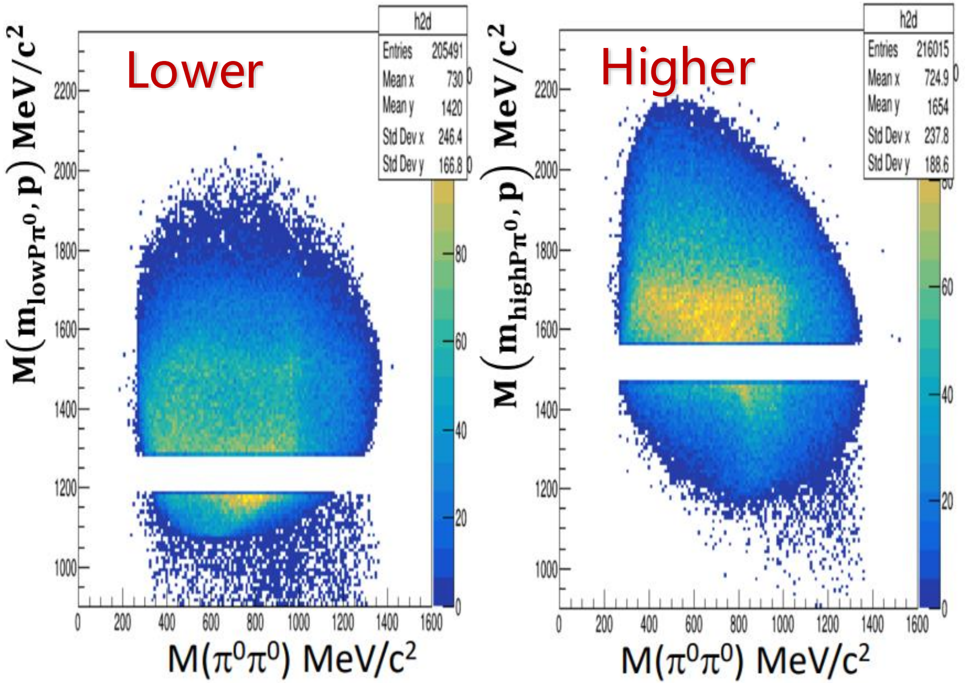
reaches 3.320×10^{12} with the correction for dead times.

4 neutral clusters
1 charged particle hit

$f_0(980)$光生反应束流极化度分析

➢ $f_0(980)$光生反应事件选择　$\gamma p \to f_0(980)p \to \pi^0\pi^0 p$

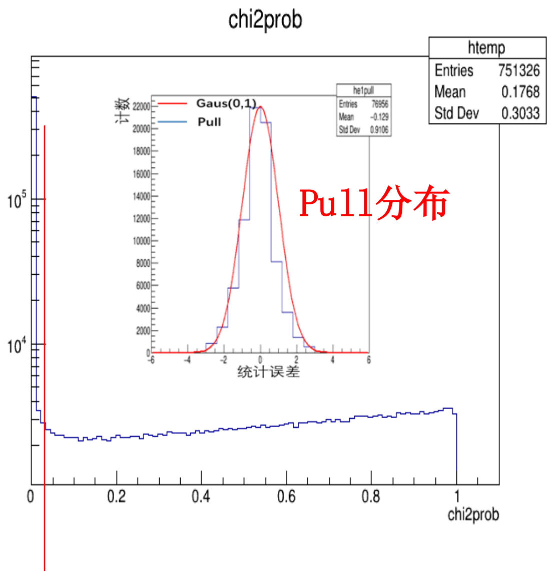
干扰共振态本底事件去除



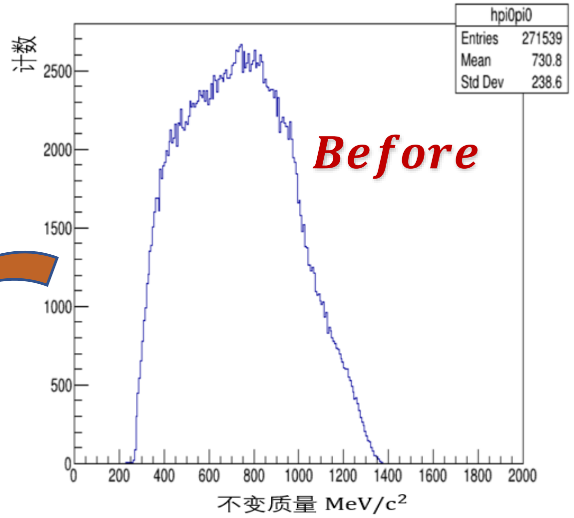
Δ *Cut*　　$N*$（1520）*Cut*

运动学拟合

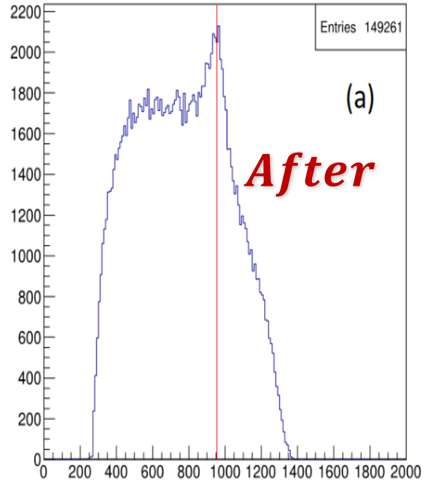
➢ 6 constraints KF
➢ $P(\chi^2) > 2\%$

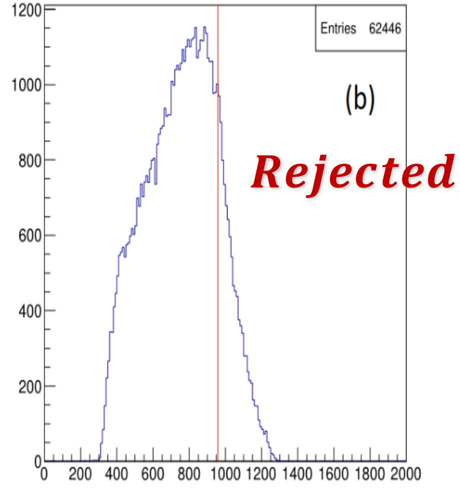


$P(\chi^2) > 2\%$



$E_\gamma > 1.45\ GeV \&\& CL > 0.1 \&\& \Delta\ Cut$





$f_0(980)$光生反应束流极化度分析

$f_0(980)$信号提取

➢ $f_0(980)$束流不对称性分析

Voigt方程拟合$\pi^0\pi^0$不变质量分布提取$f_0(980)$产额

为了提高信噪比，使用cut：upper-side 1σ Δ cut：（M(π^0p)−1232 > 50 MeV)，（低动量π0与质量子的不变质量)，最后约有 133, 000 事件用于最后分析.

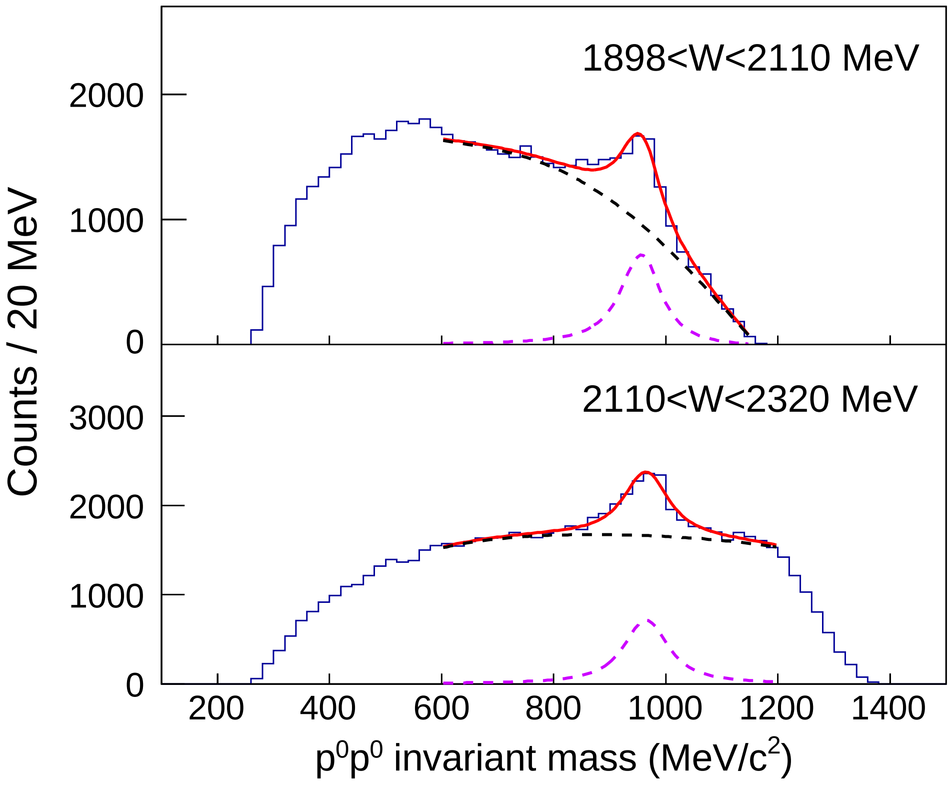


Fig. 1 Invariant mass spectra of $\pi^0\pi^0$ in two energy bins. Voigt functions are fitted with polynomial background functions to extract $f_0(980)$ signals.

两个公式的卷积得到的：

$$g(x) = \frac{1}{\sqrt{2\pi\sigma}} e^{\frac{x^2}{2\sigma^2}}$$

$$l(x) = \frac{\frac{1}{\pi}\frac{lg}{2}}{x^2 + \frac{lg^2}{4}}$$

其中，$g(x)$为高斯公式，$l(x)$为洛伦兹公式。

[1] Q. H. He, N. Muramatsu, First measurement of $f(980)$ meson photoproduction in the $\pi^0\pi^0$ decay mode, SPring-8/SACLA Research Frontiers 2023 (2024)

$f_0(980)$光生反应束流极化度分析

- $f_0(980)$微分截面测量($d\sigma/dt$)

$\gamma p \to f_0(980)p \to \pi^0\pi^0 p$ BGOegg Exp.

$@E_\gamma = 1.3\sim2.4$ GeV

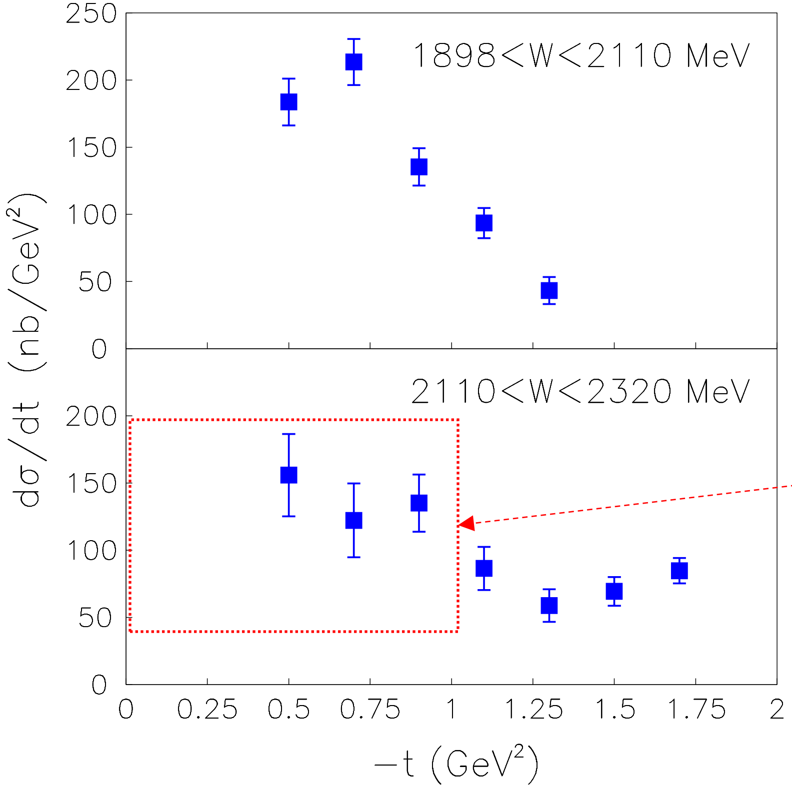


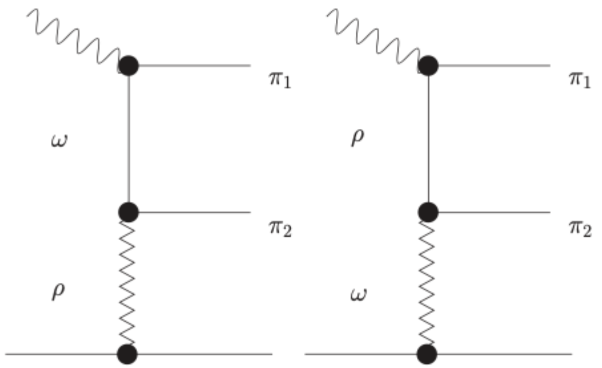
Fig. 2 Differential cross sections $d\sigma/dt$ of $\gamma p \to f_0(980)p \to \pi^0\pi^0 p$

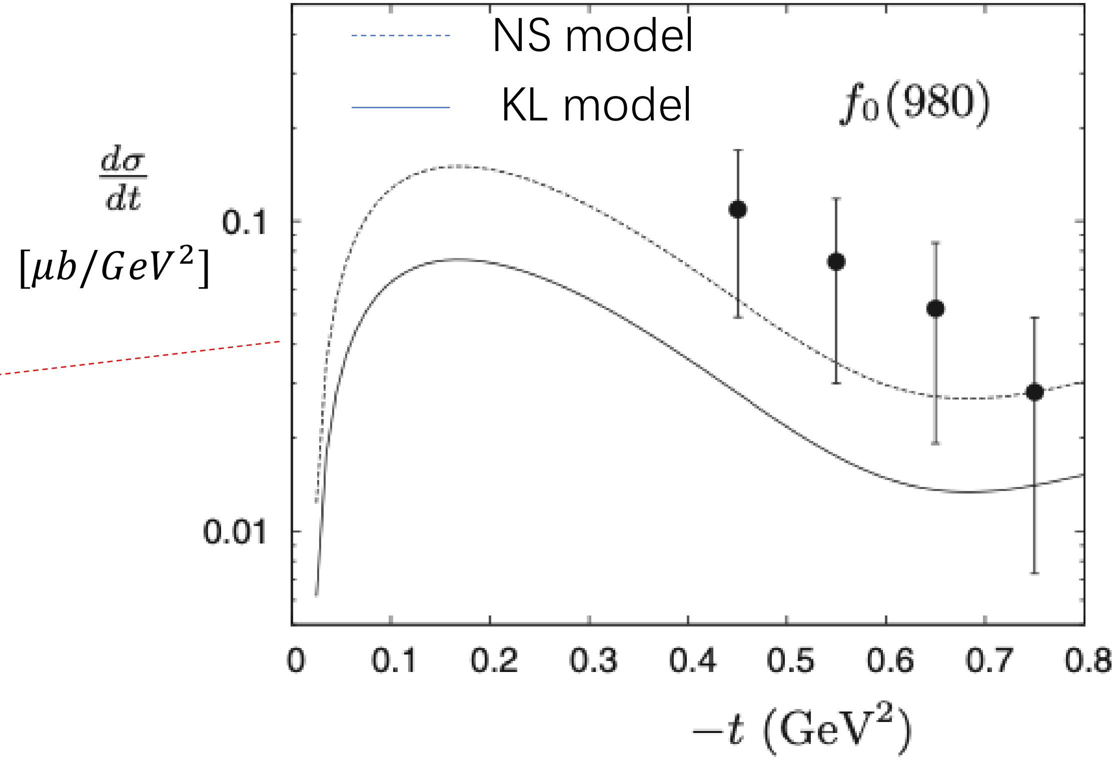
[1] SPring-8/SACLA Research Frontiers 2023 (2024)

Theoretical calculation

Reggeized model

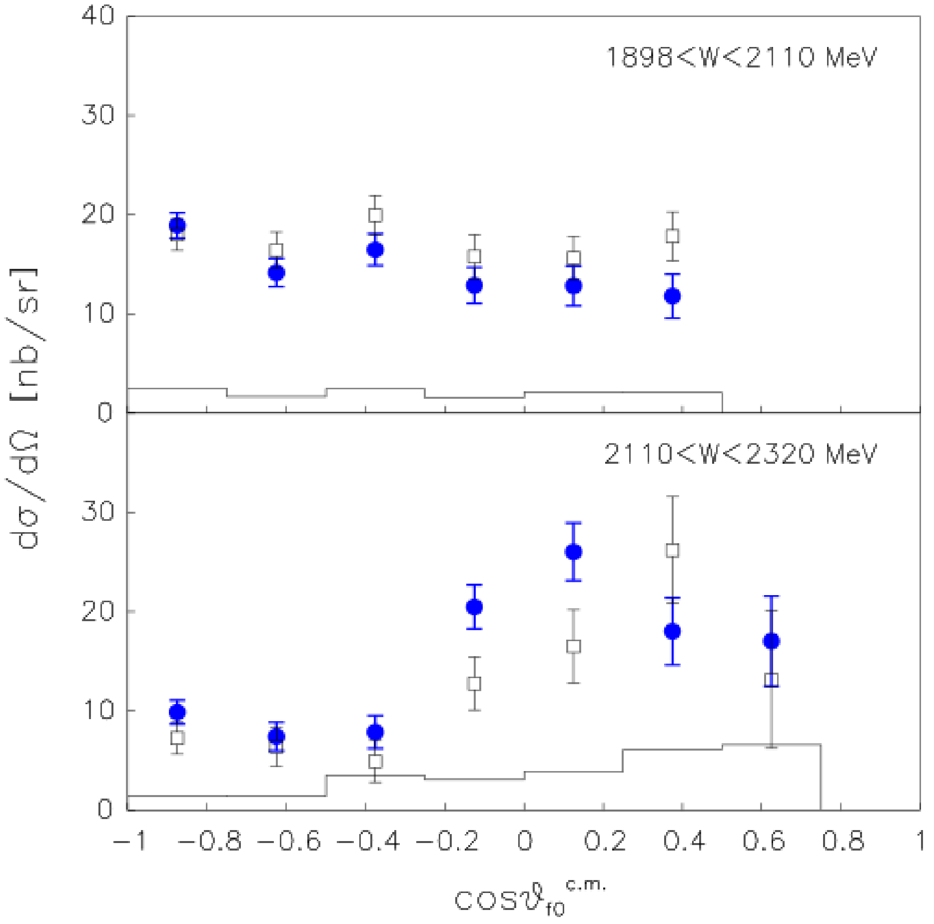
$@E_\gamma = 3.5$ GeV





[2] A. Donnachie and Yu. S. Kalashnikova, Phys.Rev.C 93, 025203 (2016).

➢ $f_0(980)$微分截面$d\sigma/d\Omega$测量



BGOegg data

$$\gamma p \to f_0(980)p \to \pi^0\pi^0 p$$

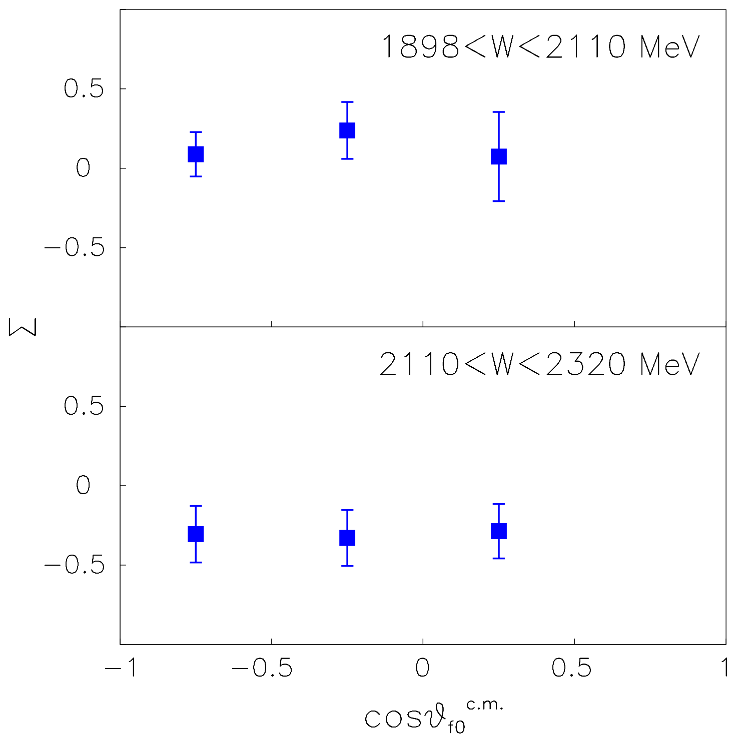
$$@E_\gamma = 1.3\sim2.4\ \mathrm{GeV}$$

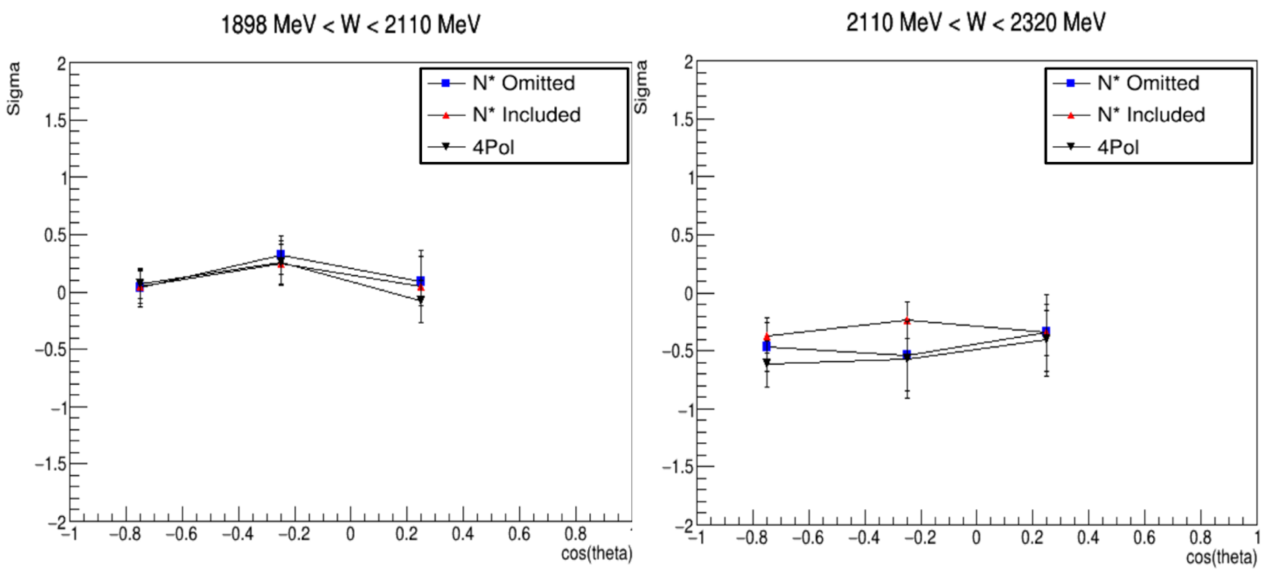
FIG. 2. Differential cross sections $d\sigma/d\Omega$ of the reaction $\gamma p \to f_0(980)p \to \pi^0\pi^0 p$ for the two event-selection conditions without (closed circles) and with (open squares) requirement of the N^* cuts. The vertical bars show statistical uncertainties. The histograms represent the magnitudes of systematic uncertainties for the case without the N^* cuts.

[1] **Phys. Rev. C 107, L042201 (2023)**

$f_0(980)$光生反应束流极化度分析

➢ $f_0(980)$束流不对称性测量





$$P_\gamma \Sigma / f_{int} = (N_{perp} - N_{para})/(N_{perp} + N_{para})$$

$$N_{perp} = \int_{\pi/4}^{3/4\pi} \frac{d\sigma_0}{d\Omega}(1 - P_\gamma \Sigma \cos 2\Phi) d\Phi + \int_{5/4\pi}^{7/4\pi} \frac{d\sigma_0}{d\Omega}(1 - P_\gamma \Sigma \cos 2\Phi) d\Phi$$

$$N_{para} = \int_{-\pi/4}^{\pi/4} \frac{d\sigma_0}{d\Omega}(1 - P_\gamma \Sigma \cos 2\Phi) d\Phi + \int_{3/4\pi}^{5/4\pi} \frac{d\sigma_0}{d\Omega}(1 - P_\gamma \Sigma \cos 2\Phi) d\Phi,$$

在较高能区，Σ 是负值，代表了矢量介子交换。

$f_{int} = \pi/2$: correction factor for the integration over $\pi/2$ azimuthal angle ranges

[1] SPring-8/SACLA Research Frontiers 2023 (2024)

Summary

- Photon beam asymmetries and differential cross sections of $\boldsymbol{\gamma p \rightarrow f_0(980)p \rightarrow \pi^0\pi^0 p}$ were measured.
- The asymmetries Σs in the lower W bin are close to zero or slightly positive, while in the higher bin are negative values around -0.3, indicating the contribution of t-channel vector meson (natural parity) exchange in $f_0(980)$ photoproduction.
- At the higher energies, the deviation from $\Sigma = -1$ is seen possibly because of the unnatural parity contribution of axial-vector exchange [e.g., $b_1(1235)$] and re-scattering diagrams with two Reggeon exchange in addition to the contamination of s- and u-channel diagrams.
- The differential cross section $\boldsymbol{d\sigma/dt}$ measured in a smaller $|-t|$ region is comparable to the theoretical prediction assuming a $q\bar{q}$ component in $\boldsymbol{f_0(980)}$.
- The coupling of the $f_0(980)$ meson with the re-scattering diagrams may be particularly interesting to explore its structure in future theoretical works.

Future Plan (1)

(1) Statistics of $\gamma p \rightarrow f_0(980)p \rightarrow \pi^0\pi^0 p$ data will be doubled

(2) Theoretical calculation at $E_\gamma = 1.3 \sim 2.4$ GeV and higher $|-t|$ is highly welcomed

BGOegg data $@E_\gamma = 1.3\sim2.4$ GeV

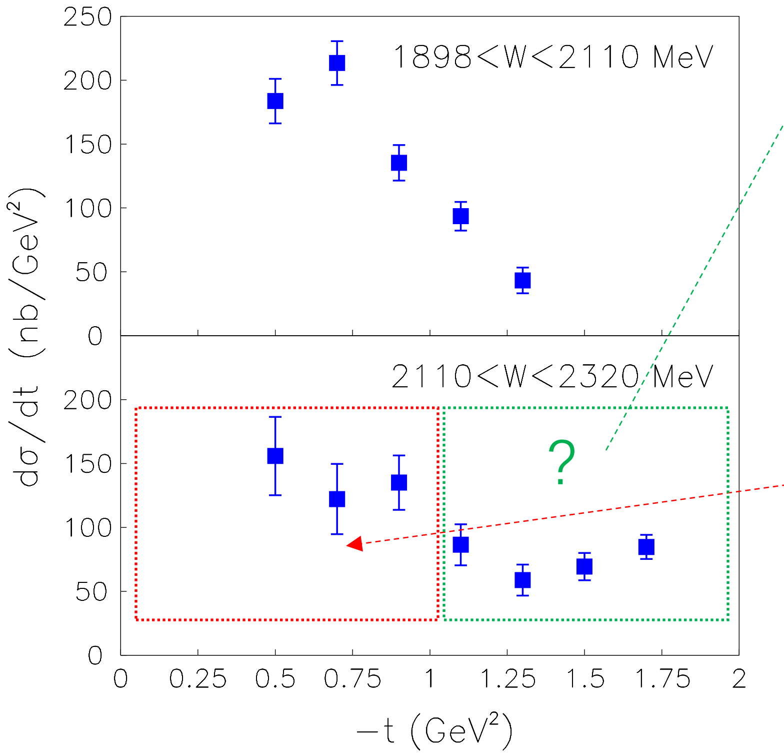
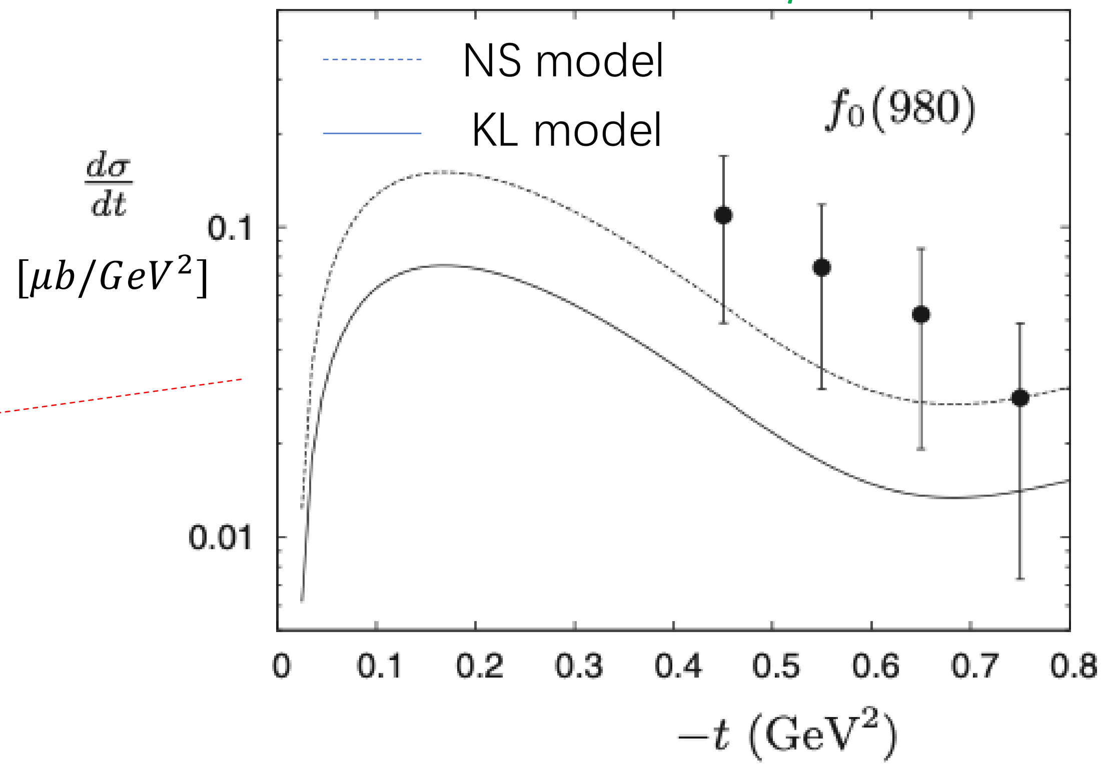


Fig. 2 Differential cross sections $d\sigma/dt$ of $\gamma p \rightarrow f_0(980)p \rightarrow \pi^0\pi^0 p$

[1] Q. H. He, N. Muramatsu, SPring-8/SACLA Research Frontiers 2023 (2024)

Theoretical calculation

Reggeized model $@E_\gamma = 3.5$ GeV

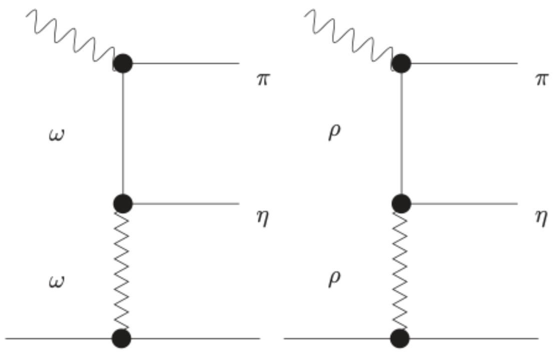


[2] A. Donnachie and Yu. S. Kalashnikova, Phys.Rev.C 93, 025203 (2016).

Future Plan (2)

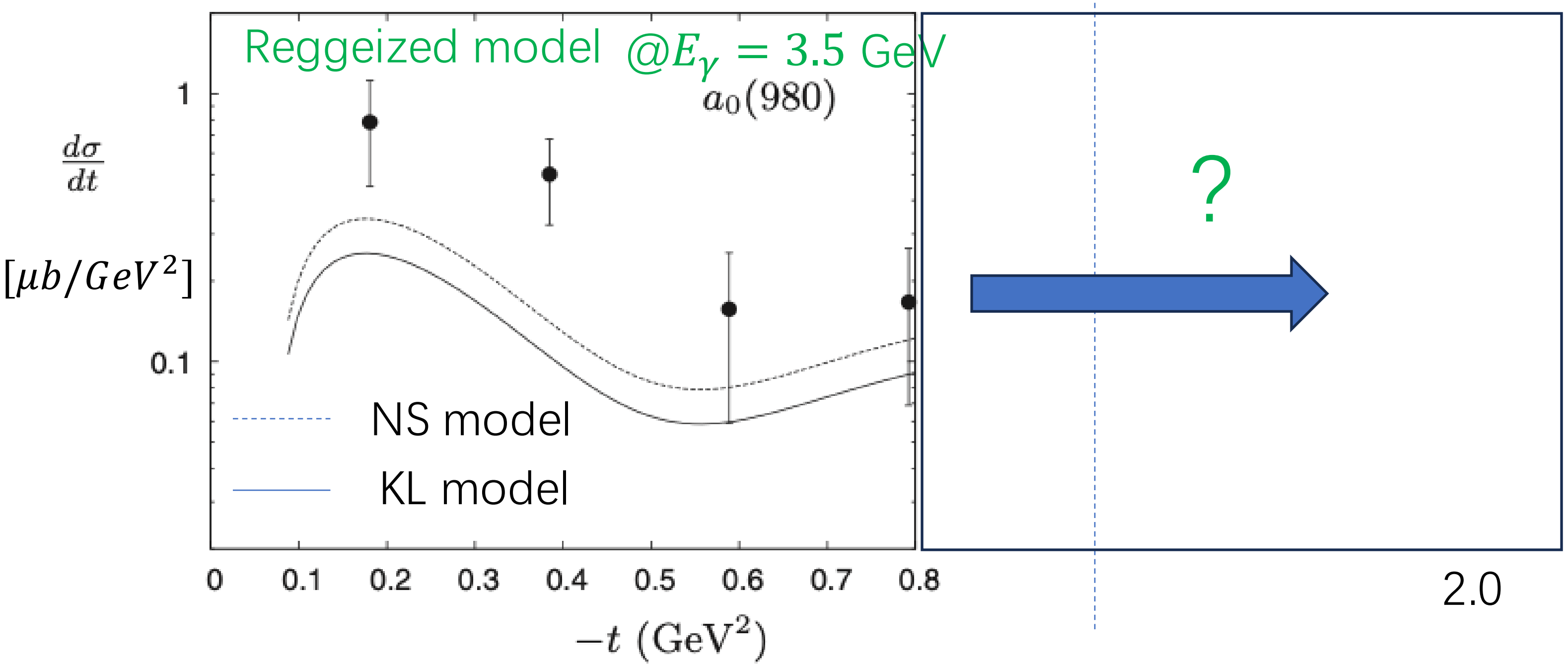
(1) Beam asymmetry analysis of $\gamma p \to a_0(980) p \to \pi^0 \pi^0 p$ data is on the way

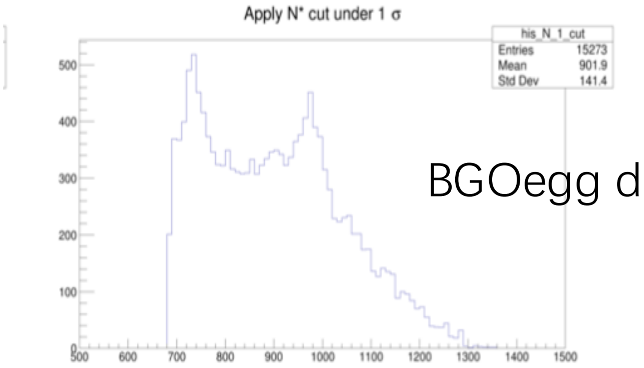
(2) Theoretical calculation at $E_\gamma = 1.3 \sim 2.4$ GeV and higher $|-t|$ is highly welcomed

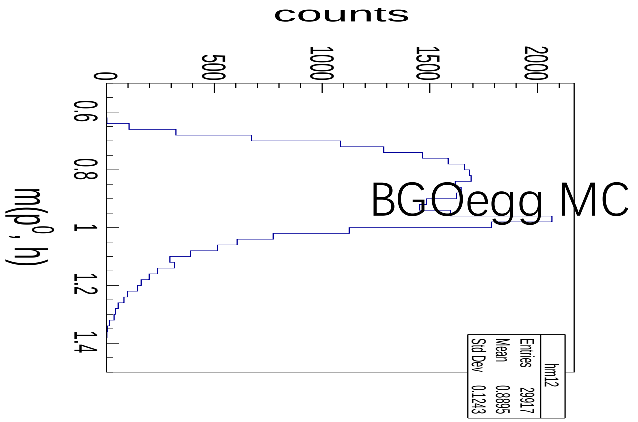


Theoretical calculation

BGOegg data $@E_\gamma = 1.3 \sim 2.4$ GeV







[2] A. Donnachie and Yu. S. Kalashnikova, Phys.Rev.C 93, 025203 (2016).

Acknowledgements

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- **Norihito Muramatsu, Tohoku University**
- **Shengkai WANG, NUAA**
- **Tianzhu MO, NUAA**

Thank you!

backup

pseudovector

$b_1(1235)$

$I^G(J^{PC}) = 1^+(1^{+-})$

Mass $m = 1229.5 \pm 3.2$ MeV (S = 1.6)
Full width $\Gamma = 142 \pm 9$ MeV (S = 1.2)

$b_1(1235)$ DECAY MODES	Fraction (Γ_i/Γ)		Confidence level	p (MeV/c)
$\omega\pi$	seen			348
[D/S amplitude ratio = 0.277 ± 0.027]				
$\pi^\pm\gamma$	$(1.6\pm0.4) \times 10^{-3}$			607
$\eta\rho$	seen			†
$\pi^+\pi^+\pi^-\pi^0$	< 50	%	84%	535
$K^*(892)^\pm K^\mp$	seen			†
$(K\overline{K})^\pm\pi^0$	< 8	%	90%	248
$K^0_S K^0_L \pi^\pm$	< 6	%	90%	235
$K^0_S K^0_S \pi^\pm$	< 2	%	90%	235
$\phi\pi$	< 1.5	%	84%	147

Lepton Family number (*LF*) violating modes

$e^\pm\mu^\mp$	*LF*	< 2	$\times 10^{-6}$	CL=90%	504

$h_1(1170)$

$I^G(J^{PC}) = 0^-(1^{+-})$

Mass $m = 1166 \pm 6$ MeV
Full width $\Gamma = 375 \pm 35$ MeV

$h_1(1170)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$\rho\pi$	seen	305

$$\gamma + {}^{12}\mathrm{C} \rightarrow p_f + \eta' \otimes {}^{11}\mathrm{B} \qquad (1a)$$

$$\hookrightarrow \eta' + p \rightarrow \eta + p_s. \qquad (1b)$$

The forward-going proton, p_f, is used for the missing-mass spectroscopy. The side-going proton, p_s, is emitted in the η‘N → ηN reaction, which is one of the most promising absorption processes for an η’ meson bound to a nucleus