# Measurement of the branching ratio of a rare decay $\eta \rightarrow \pi^0\gamma\gamma$ with WASA-at-COSY

**Kavita Lalwani**
**for WASA-at-COSY collaboration**
**I.I.T Bombay, INDIA**

# Outline

- Physics Motivation
- WASA-at-COSY setup
- Simulation
- Data Analysis
- Results
- Summary and outlook

# Understanding QCD at low energy through a rare decay $\eta \rightarrow \pi^0 \gamma\gamma$

## Two peculiar properties of QCD

**Asymptotic Freedom :** At high momentum transfers (short distances)
Coupling small → quark inside hadron behaves as a free particle.
Perturbative QCD explains experimental observations well .

**Confinement :** At small momentum transfers (large distances)
Coupling large → confinement of quarks and gluons inside hadrons.
Perturbative QCD fails → Effective field theory

# QCD at low energy

**Most successful Effective field Theory → Chiral Perturbation Theory**

Lagrangian in terms of increasing powers of momentum in $\chi$PTh

- $O(p^2)$ is absent, because no direct coupling of photon with $\pi^0$ and $\eta$.
- $O(p^4)$ very small, because hadronic loops are suppressed.
- $O(p^6)$ first sizable contribution.

The reaction $\eta \to \pi^0\gamma\gamma$ is a gold plated test of higher order $\chi$PTh.

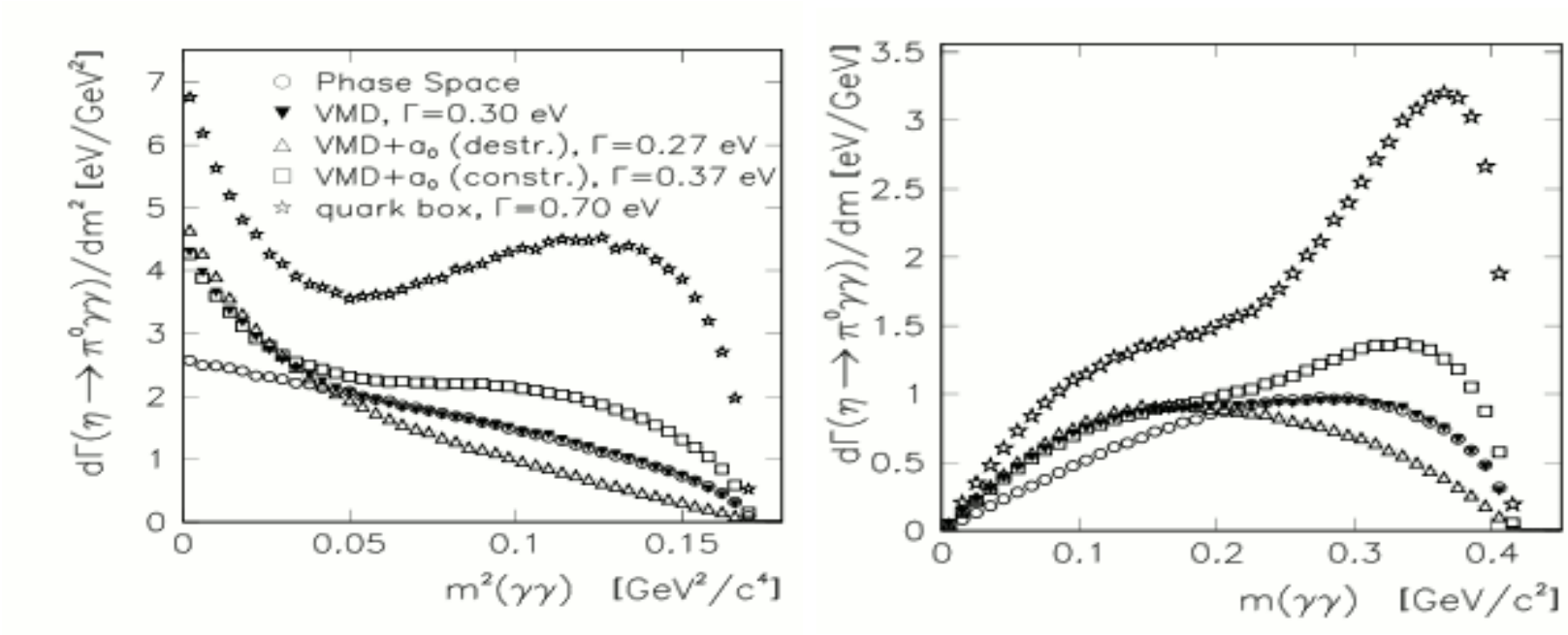
| Theory | $\Gamma(\eta \to \pi^0\gamma\gamma)$ |
|---|---|
| $\chi$PTh, $O(p^2)$ | 0 |
| $\chi$PTh, …+ $O(p^4)$ | 0.004 |
| $\chi$PTh,…+ $O(p^6)$ | $0.42 \pm 0.20$ |
| $\chi$PTh,…+ $O(p^6)$ | 0.47 |
| $\chi$PTh,ENJL…+$O(p^6)$ | $0.58 \pm 0.30$ |
| VMD | $0.30 \pm 0.15$ |
| Q box | 0.70 |
| $\chi$PTh,…+ $O(p^6)$ | $0.44 \pm 0.09$ |
| Unitarized $\chi$PTh | $0.47 \pm 0.10$ |

Theoretical predictions for $\eta \to \pi^0\gamma\gamma$

Ref : Phys. Rev. D 67,073013 (2003)

# QCD at low energy

- Another stringent test of the theory would be the shape of the invariant mass of two photons not forming a pion.
- Earlier studies have been hampered by the lack of statistics.
- We have $3\times10^7$ total eta produced in 2008 and 2009.




Ref : J. N. Ng and D. J. Peters, Phys. Rev. D 46, 5034 (1992)
Ref : J. N. Ng and D. J. Peters, Phys. Rev. D 47, 4939 (1993)

# Previous Measurements

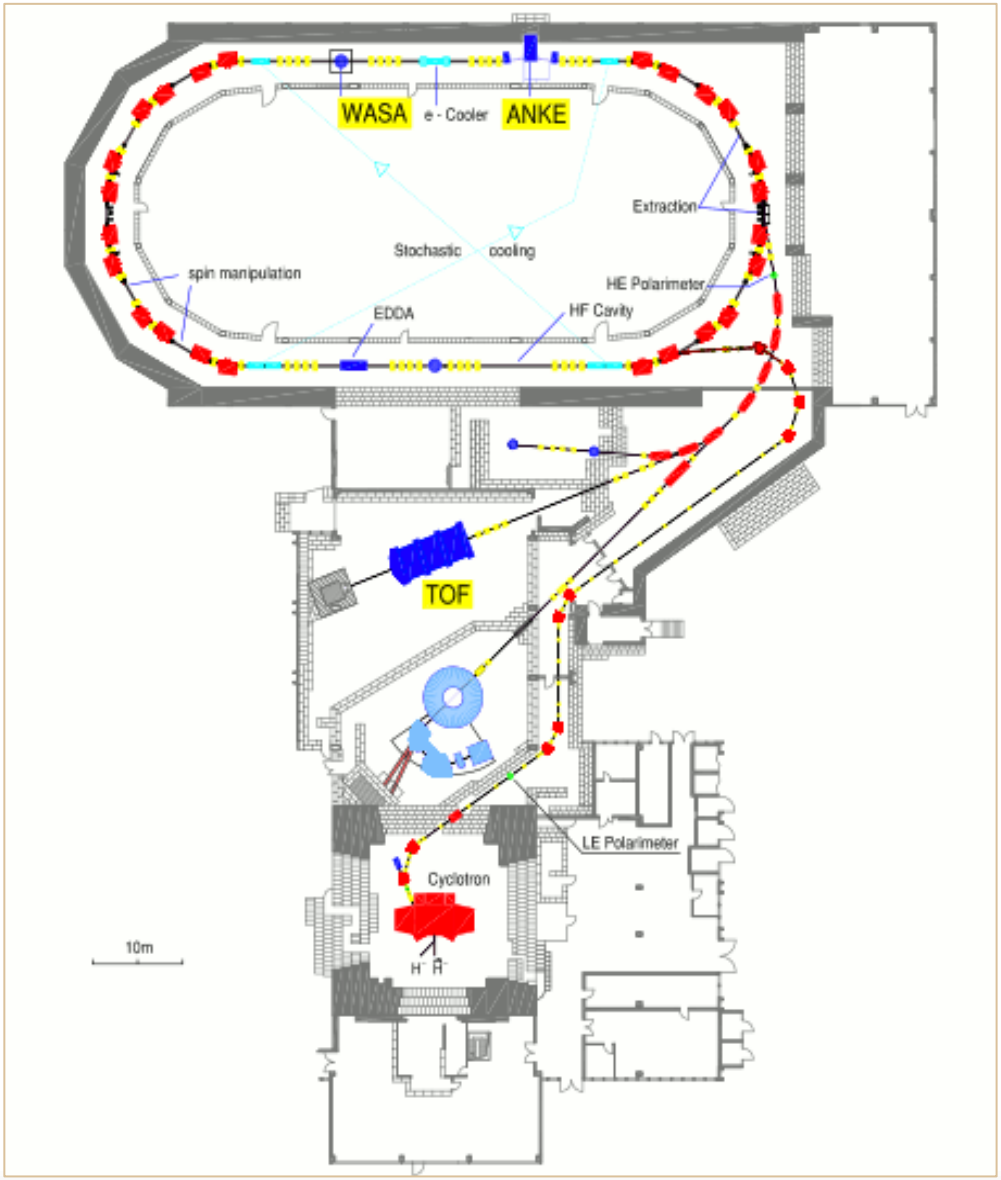
| Experiments | $BR(\eta\rightarrow\pi^0\gamma\gamma)$ |
|---|---|
| GAMS | $(7.1 \pm 1.4)\times10^{-4}$ [3] |
| Crystal Ball | $(2.21 \pm 0.24_{stat} \pm 0.38_{sys}) \times10^{-4}$[1] |
| KLOE | $( 8.4 \pm 2.7_{stat} \pm 1.4_{sys}) \times10^{-5}$ [2] |

- The existing experimental results of $BR(\eta\rightarrow\pi^0\gamma\gamma)$ and theoretical calculations for $\Gamma(\eta\rightarrow\pi^0\gamma\gamma)$ vary a lot .
- Motivated us to measure the branching ratio of $\eta\rightarrow\pi^0\gamma\gamma$ with WASA-at-COSY.

[1] S. Prakhov et al., Phys. Rev. C 78, 015206 (2008).
[2] B. Di Micco et. al., Acta Phys. Slov. 56, 403 (2006).
[3] D .Alde, et al. Z. Phys.C 25, 225(1984).

# WASA-at-COSY setup

## COSY (Cooler SYnchrotron)




Operated at the Institute For Nuclear Physics (IKP), Forschunszentrum, Juelich in Germany.

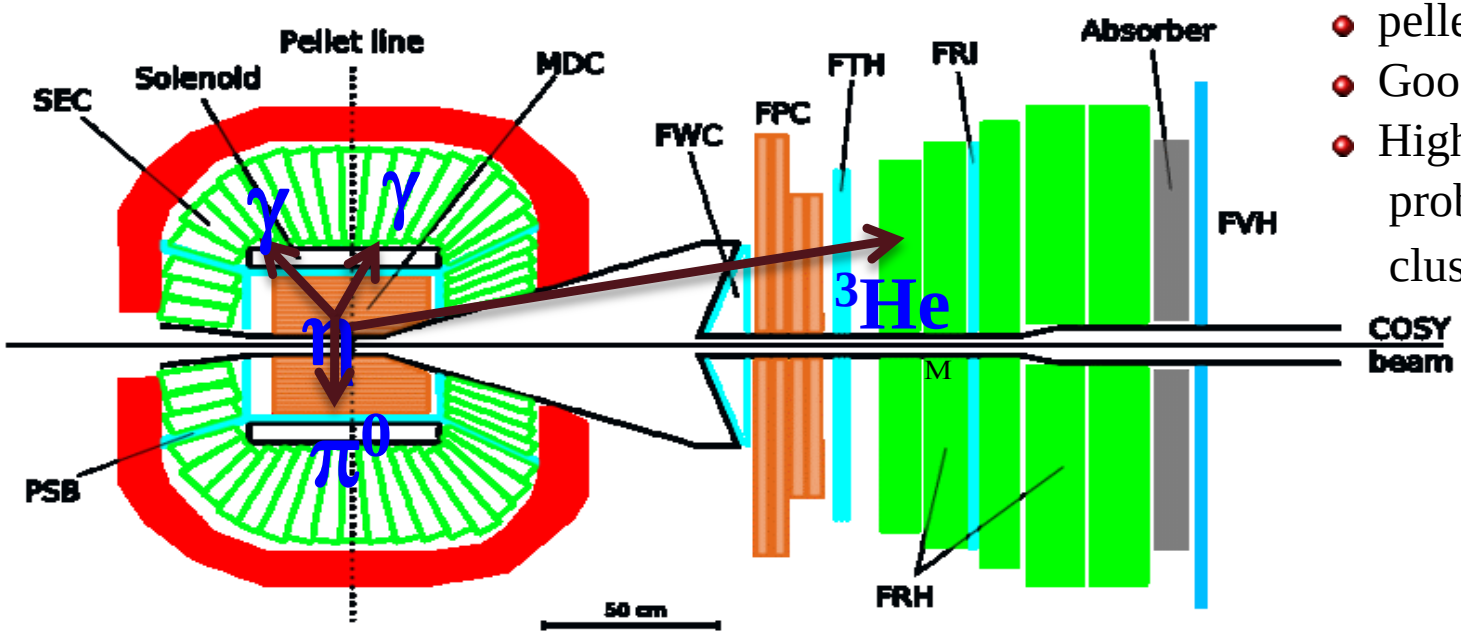
### Salient features:

- Circumferences : 184 cm
- Delivers polarized and unpolarized proton and deuteron beams in the momentum range 0.3 to 3.7 GeV/c

# WASA-at-COSY setup

## WASA (Wide Angle Shower Apparatus)

Reaction: $p + d \rightarrow {}^3He\ \eta \rightarrow {}^3He\ \pi^0\gamma\gamma$




Salient features of WASA

- $4\pi$ setup.
- pellet target (35μm)
- Good mass resolution in FD
- High Granularity → Less probability of merging cluster in CD

Invariant mass of η

Missing mass of $^3He$

Sum of the decay products of η meson ($\pi^0$, γ, γ)

$$M^2_{missing} = E^2_{missing} - p^2_{missing}$$
$$= (E_{beam} - E_{^3He})^2 - (p_{beam} - p_{^3He})^2$$

# Data Analysis

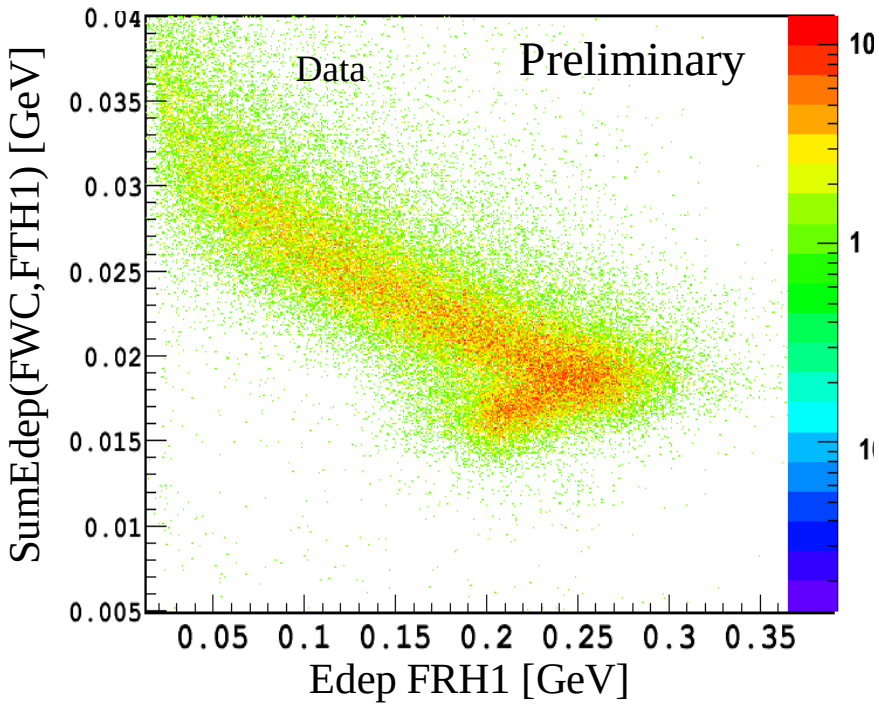
@ beam kinetic energy 1.0 GeV

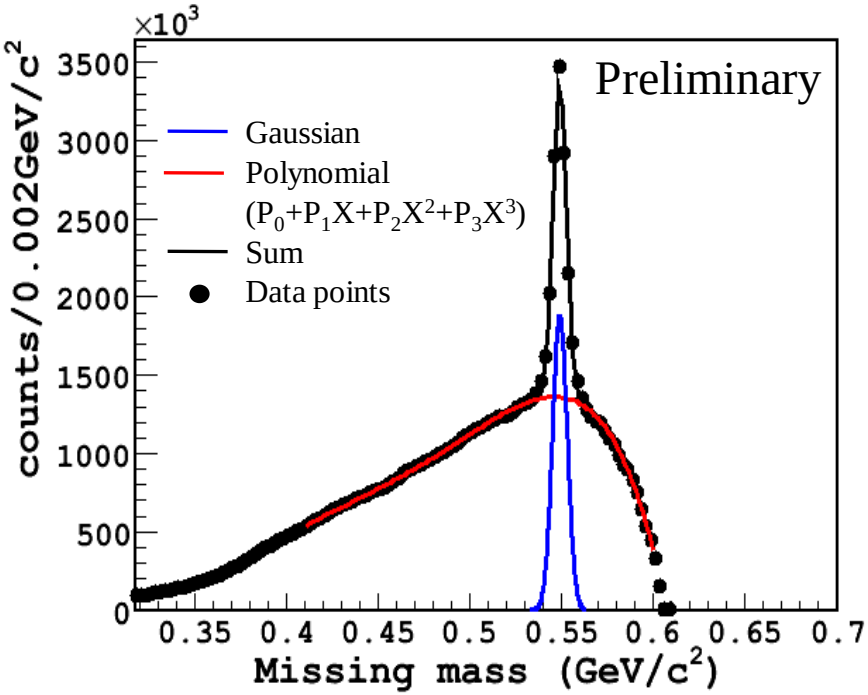
- $pd \rightarrow {}^3He\ \eta$
- $pd \rightarrow {}^3He\ \eta \rightarrow {}^3He\ \pi^0\gamma\gamma$
- $pd \rightarrow {}^3He\ \eta \rightarrow {}^3He\ 3\pi^0$

# Analysis of pd→$^3$He η

- Production run : September – November 2008.

## Identification of $^3$He




Measured : 8.014×10$^6$ η events from missing mass of $^3$He analysis

Reconstruction efficiency : 77%

⇒ Total eta produced : 1.03×10$^7$

# Analysis of $pd \rightarrow {}^3He\ \eta(\rightarrow \pi^0\gamma\gamma)$

- As the branching ratio of the channel is very small ($\sim 10^{-4}$), detailed simulations are required
- On the basis of simulations the following channels contribute as the background

| Background Channel | | Cross section |
|---|---|---|
| $pd \rightarrow {}^3He\ 2\pi^0$ | Four photons in the final state | 1.5 μb |
| $pd \rightarrow {}^3He\ 3\pi^0$ | Overlapping of two photon cluster or | 0.10 μb |
| $\eta \rightarrow 3\pi^0$ | missing of two photons | 0.12μb |

η Production cross section : 0.4 μb

# Event Selection Criteria

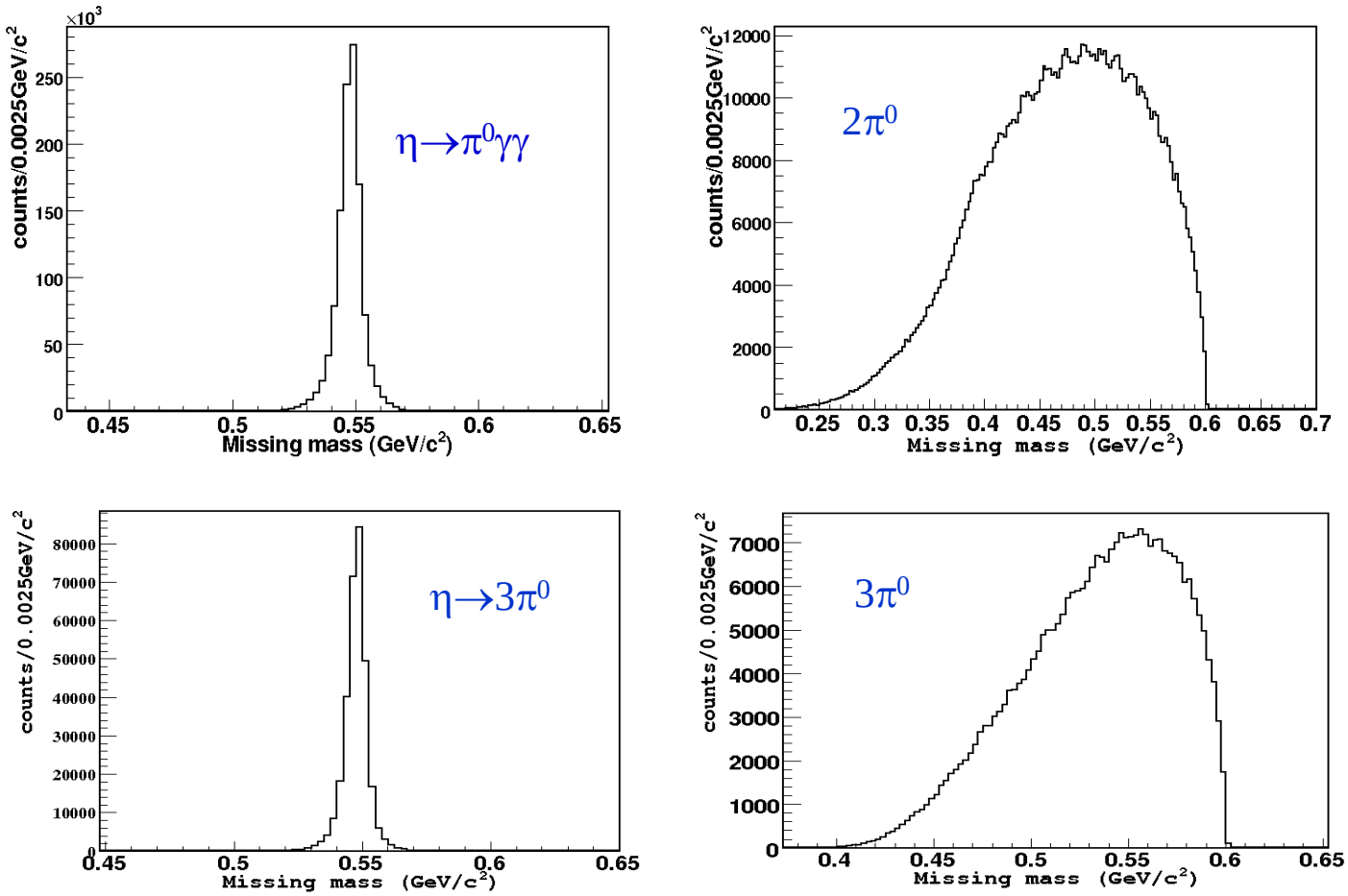
## Basic Conditions

- One charged track in the Forward Detector
- Four neutral clusters in the Central Detector with $E_{dep}$ > 20 MeV
- No charged track in the Mini Drift Chamber (MDC)

# Simulations

## Missing mass of $^3$He for signal and contributing channels

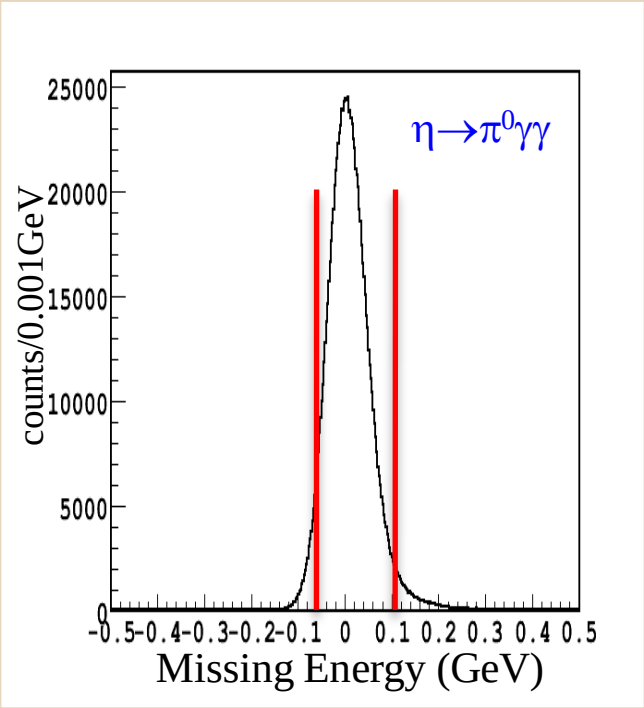
$3\times10^6$ events generated using event generator PLUTO @ $T_{beam}$ 1.0 GeV.

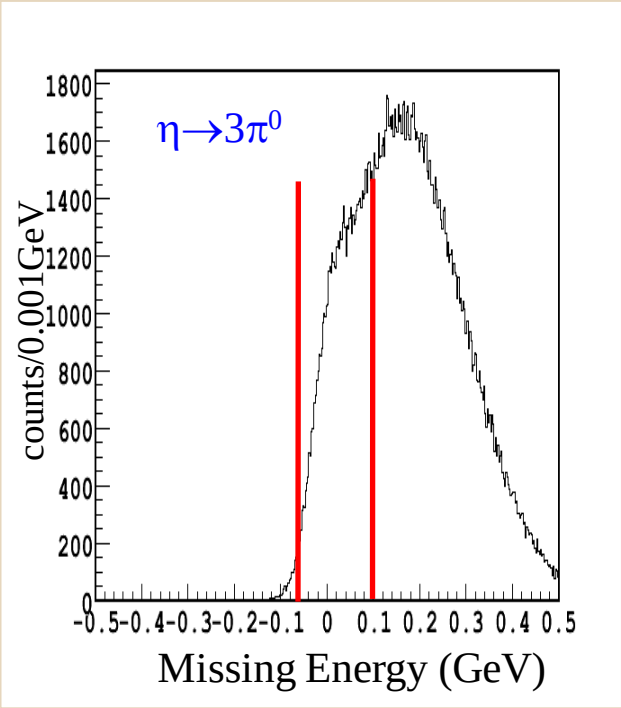


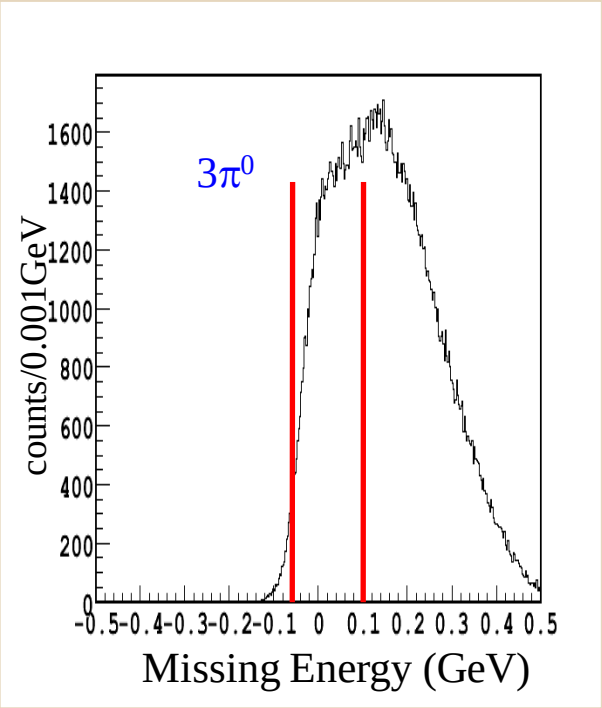
# Further Selection Criteria

Simulations $\eta \rightarrow 3\pi^0$ , pd $\rightarrow {}^3$He $3\pi^0$

-0.1 < Missing energy of full event < 0.1 GeV




- Energy deficit in the final state because of the two photon missing in the forward direction

# Simulations $2\pi^0$

## Kinematic fitting

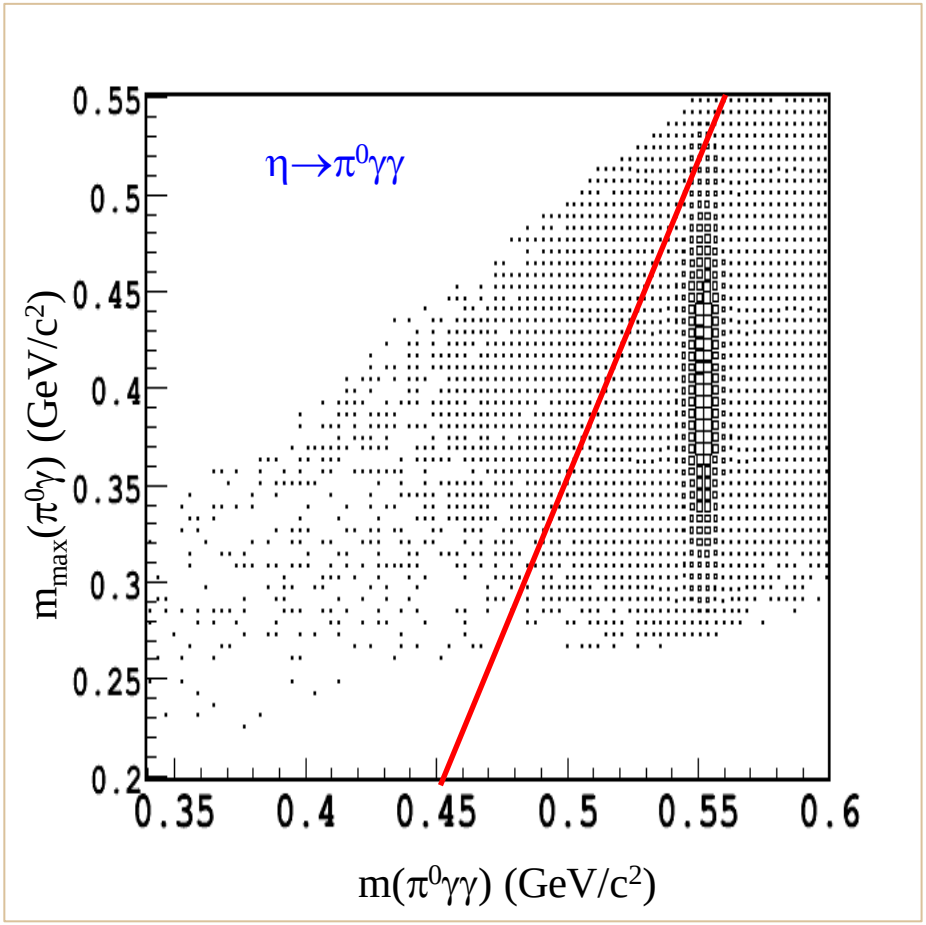
- Four photons in the final state → Kinematically subset of the signal events $\eta \rightarrow \pi^0\gamma\gamma$
- Two hypothesis have been simultaneously confirmed for each event

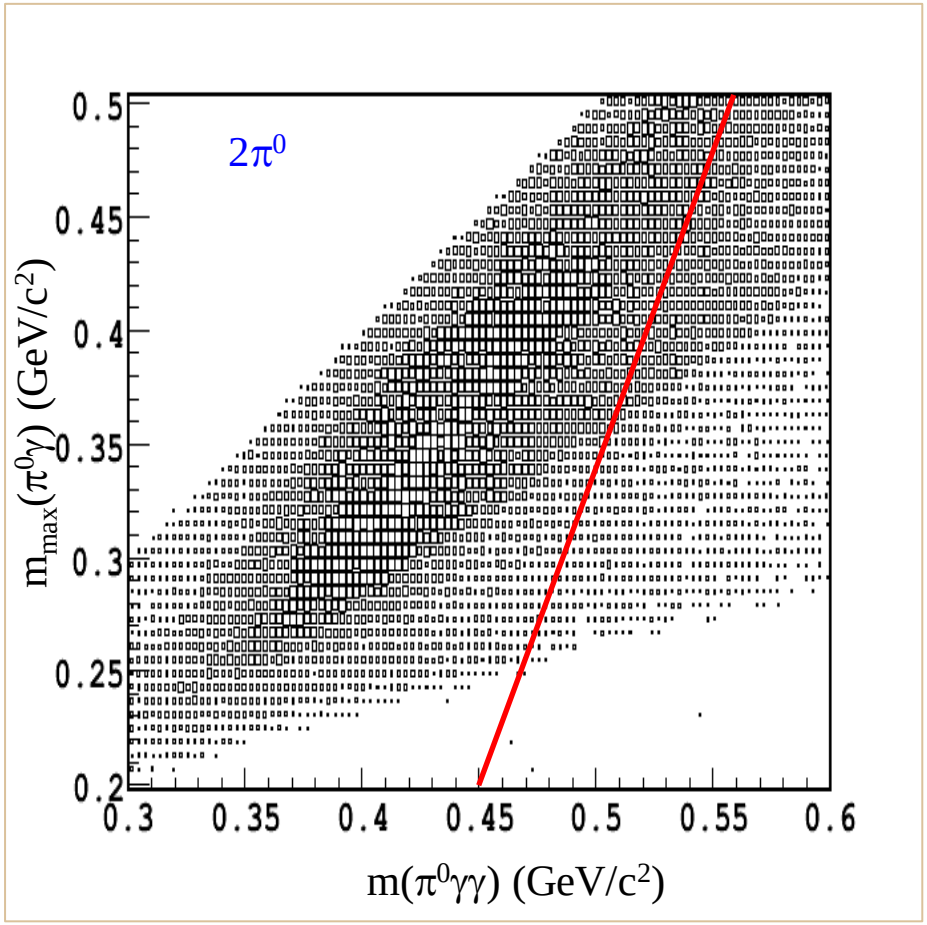
$$pd \rightarrow {}^3He\ \pi^0\pi^0$$
$$pd \rightarrow {}^3He\ \pi^0\gamma\gamma$$

- Selecting $2\pi^0$ confidence level less than 0.01% , throws away most of the $2\pi^0$ background.
- Selecting $\pi^0\ \gamma\gamma$ confidence level greater than 0.1, accepts good $\pi^0\gamma\gamma$ events.

# Simulations $2\pi^0$

Discarding all events for which $m_{max}(\pi^0\gamma)$ lies above the line

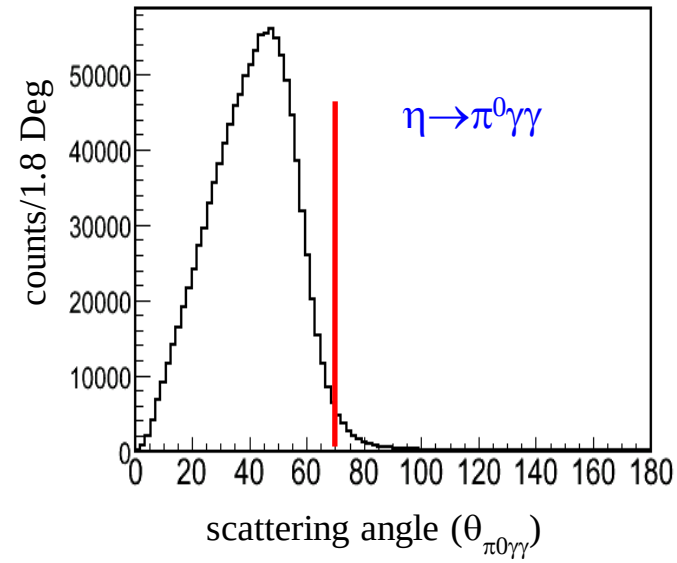


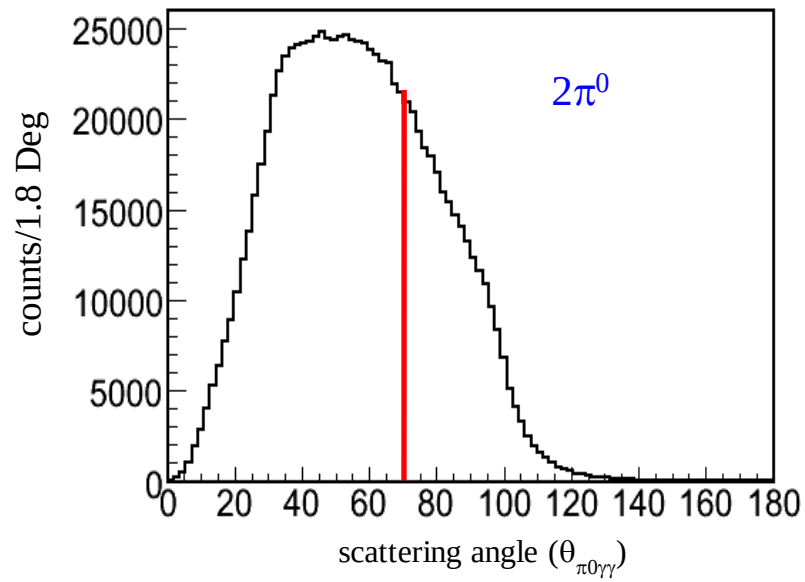



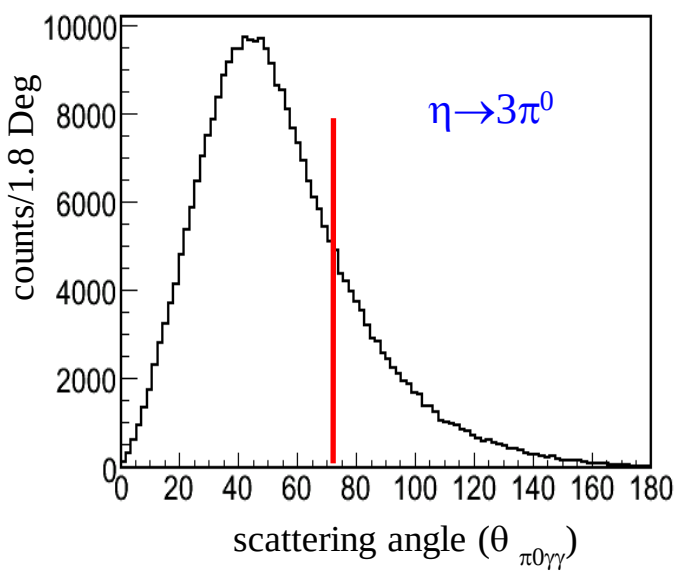

$m_{max}(\pi^0\gamma) = 4.062\times m(\pi^0\gamma\gamma) - 1.627$

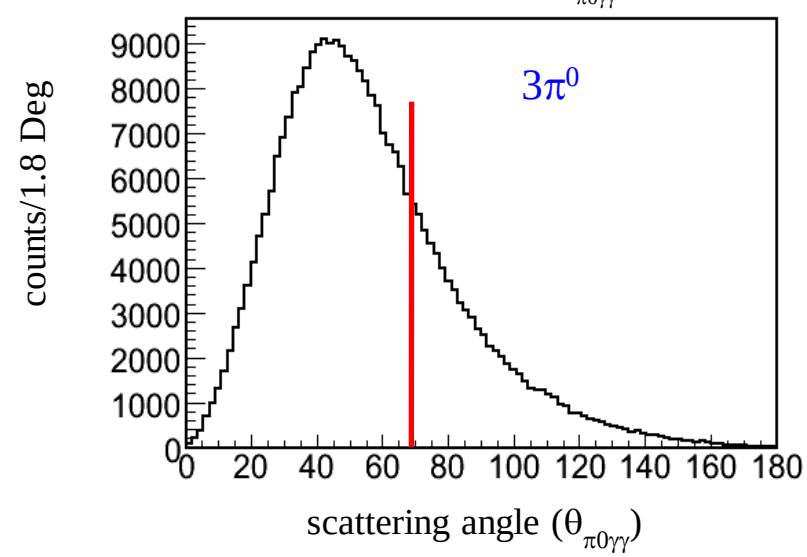
# Simulations

## Scattering angle ($\theta_{\pi^0\gamma\gamma}$) < $70^0$



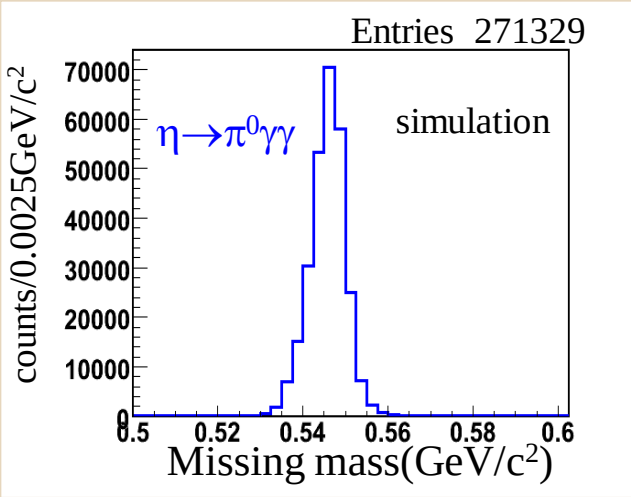
# Event Selection Criteria

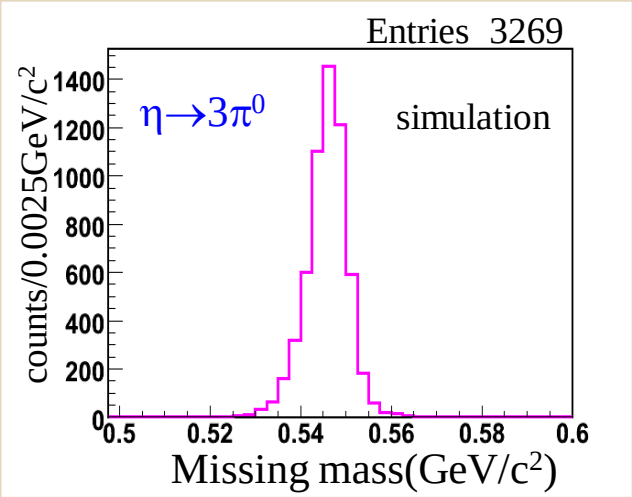
## Reconstruction Efficiency (%)

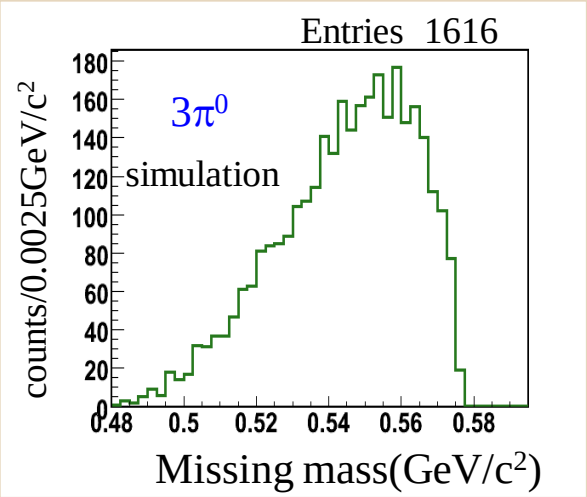
| **Condition** | **$\varepsilon(\eta\rightarrow\pi^0\gamma\gamma)$** | **$\varepsilon(\eta\rightarrow3\pi^0)$** | **$\varepsilon(2\pi^0)$** | **$\varepsilon(3\pi^0)$** |
|---|---|---|---|---|
| Preliminary cuts | 42.5 | 4.97 | 3.88 | 1.61 |
| -0.1 <MEsys < 0.1, $IM_\eta > 0.529$ GeV/$c^2$ | 26.36 | 0.81 | 2.37 | 0.23 |
| $CL(2\pi^0) < 0.01$ % | 18.48 | 0.71 | 0.043 | 0.202 |
| Cut on 2d ($m_{max}(\pi^0\gamma)$, $m(\pi^0\gamma\gamma)$) | 18.3 | 0.71 | 0.023 | 0.102 |
| $CL(\pi^0\gamma\gamma) > 0.1$ | 13.90 | 0.304 | 0.0023 | 0.085 |
| $\theta_\eta < 70^0$ | 13.84 | 0.30 | 0.001 | 0.083 |
| $IM_{2\gamma} > 0.179$ | 12.28 | 0.20 | 0.0006 | 0.080 |
| $35^0$ < Opening angle($^3$He and $\pi^0\gamma\gamma$) < $70^0$ | 9.04 | 0.10 | 0.0003 | 0.053 |

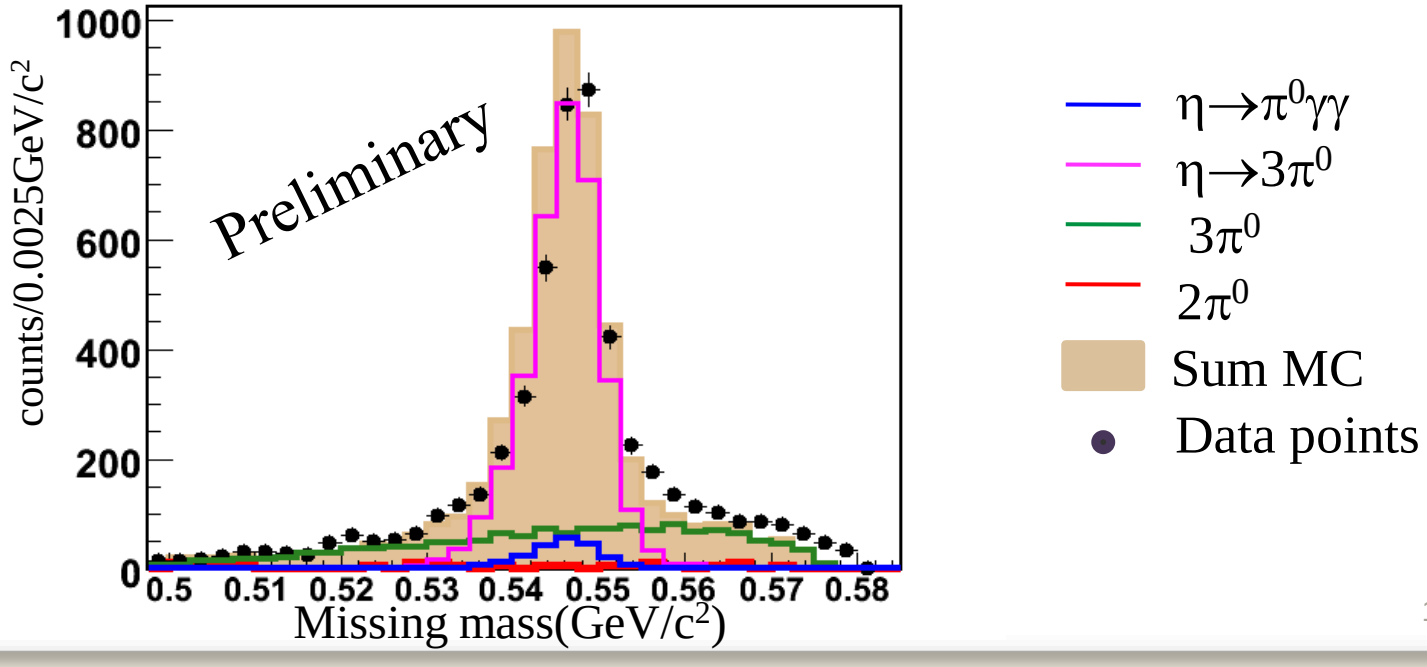
# Results

## Missing mass of $^3$He



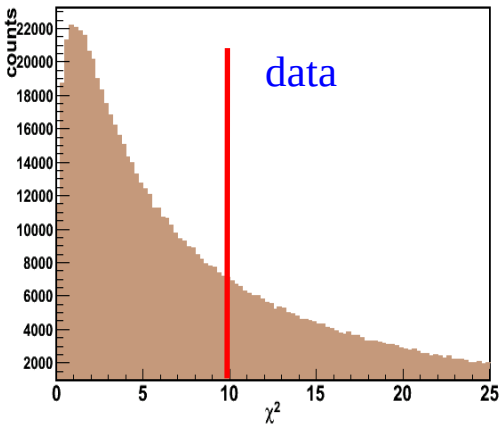



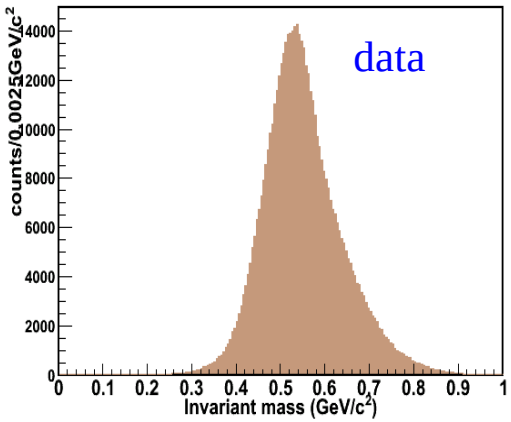
To find out $\eta \rightarrow 3\pi^0$ events in the same data set

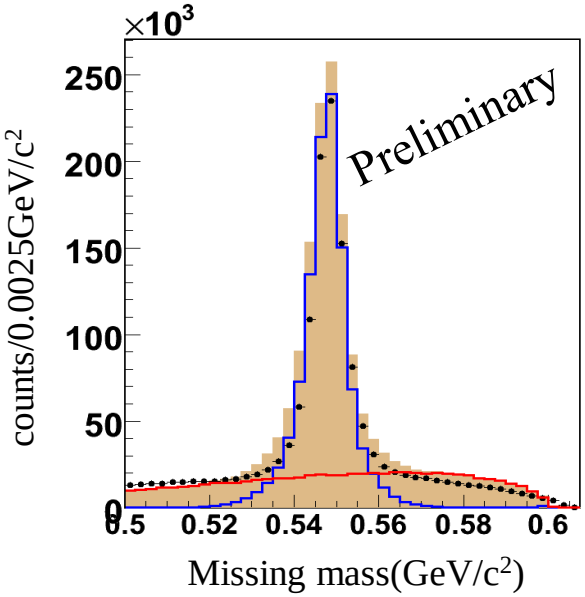
# Results

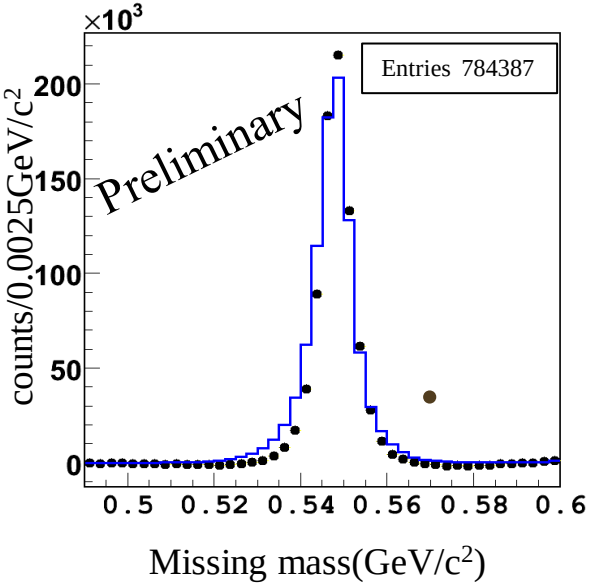
## Missing mass of $^3$He

Analysis of $\eta \rightarrow 3\pi^0 \rightarrow 6\gamma$ as signal

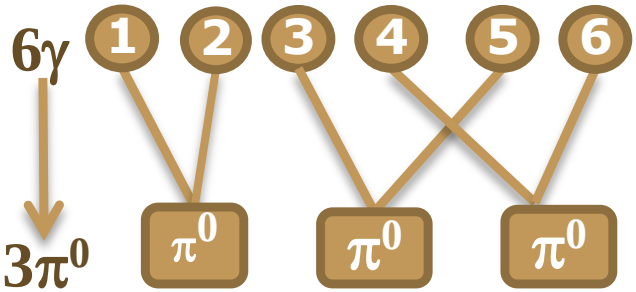



15 possible combinations




$$\chi^2 = \sum_{i=1,3} \frac{(IM_{\gamma\gamma_i} - m_{\pi^0})^2}{\sigma^2_{det}}$$

$\eta \rightarrow 3\pi^0$

$3\pi^0$

Sum MC

Data points

Total $\eta \rightarrow 3\pi^0$ produced $2.9 \times 10^6$

# Results

- Reconstruction efficiency of $\eta \rightarrow \pi^0\gamma\gamma$ is 9.04% and the reconstruction efficiency of $\eta \rightarrow 3\pi^0$ is 0.10% as background.

- After subtracting remaining contributions of background, we have measured $300 \pm 54$ $\eta \rightarrow \pi^0\gamma\gamma$ events.

- Statistical error on the branching ratio of $\eta \rightarrow \pi^0\gamma\gamma = 0.7 \times 10^{-4}$

# Summary

- Monte Carlo describes the experimental data.
- Measured 300±54 $\eta \rightarrow \pi^0 \gamma\gamma$ events and statistical error on branching ratio of $\eta \rightarrow \pi^0 \gamma\gamma$ : $0.7 \times 10^{-4}$

# Outlook

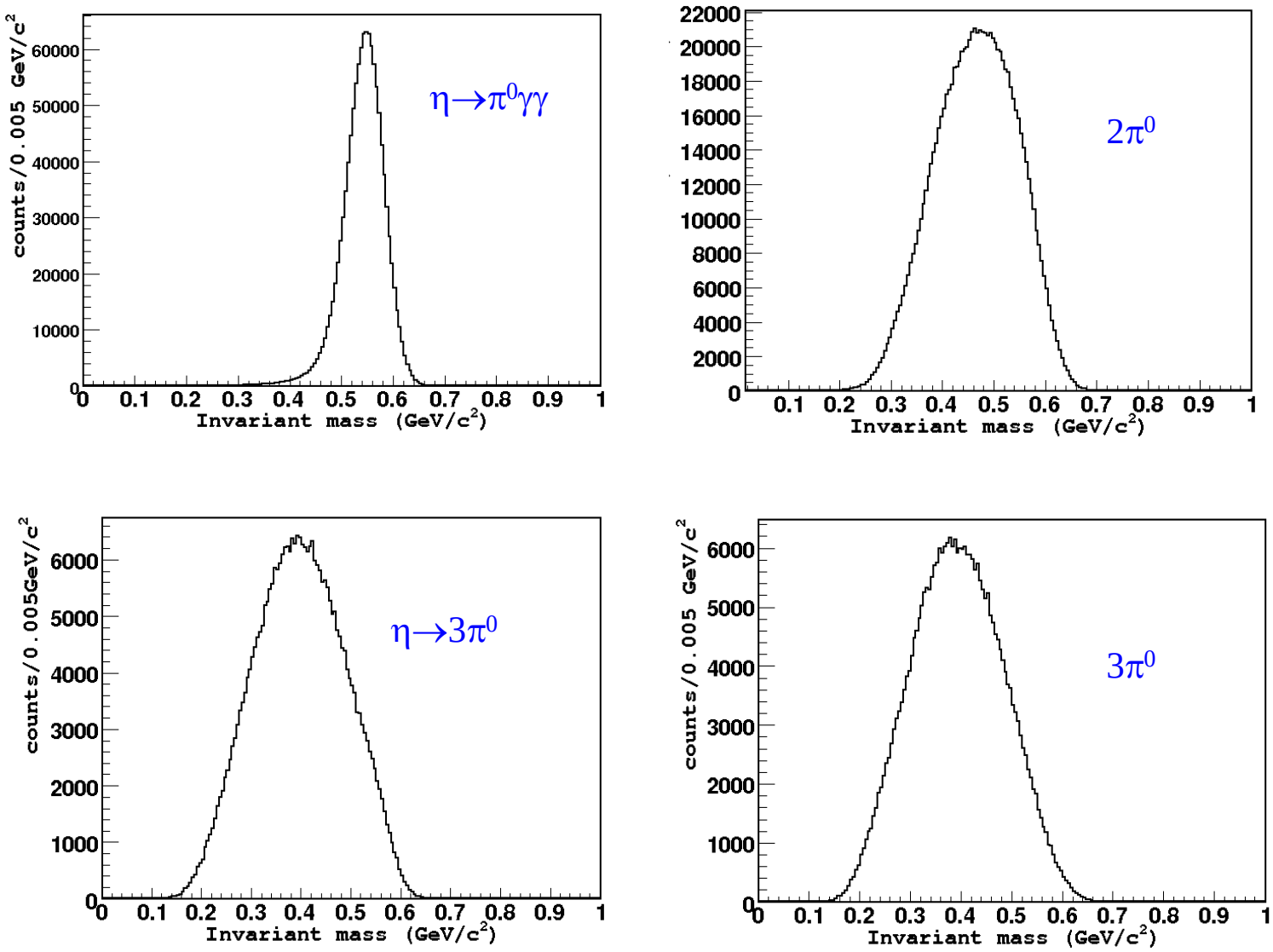
- Can investigate whether additional condition of z vertex would increase the signal to background ratio.
- Understand $\eta \rightarrow 3\pi^0$ background and estimate other systematical errors.
- Extract the spectrum of invariant mass of $2\gamma$ with more statistics in 2009.

# WASA-at-COSY collaboration


# Thanks

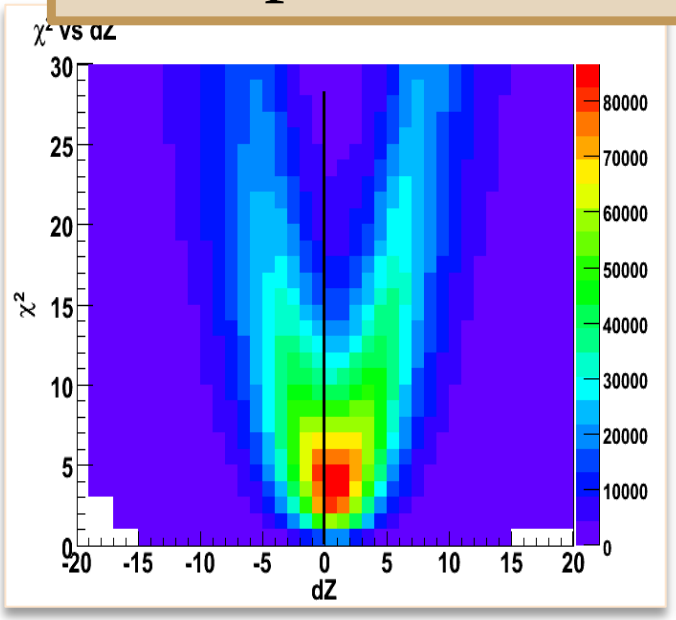
# Simulations

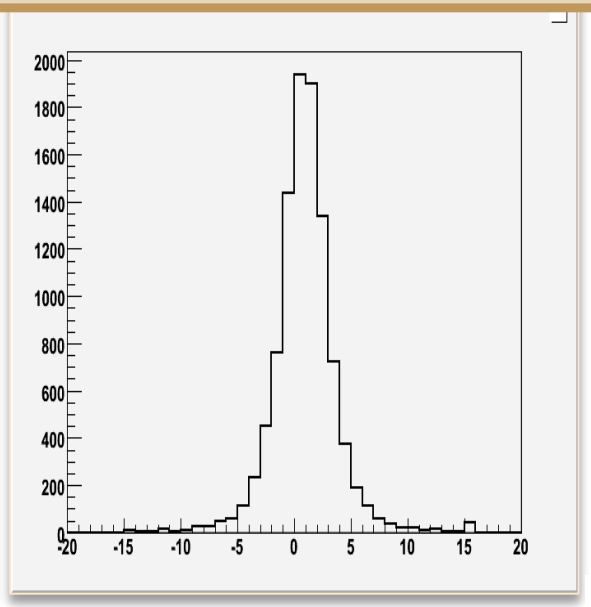
## Invariant mass of η (→$\pi^0\gamma\gamma$) for signal and contributing channels



# Back up slides

## To improve S/B ratio  Implemented z vertex fitting

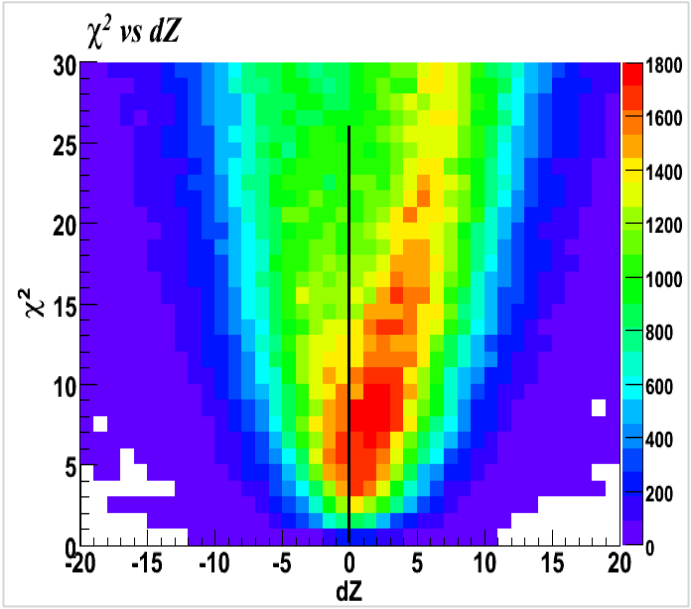


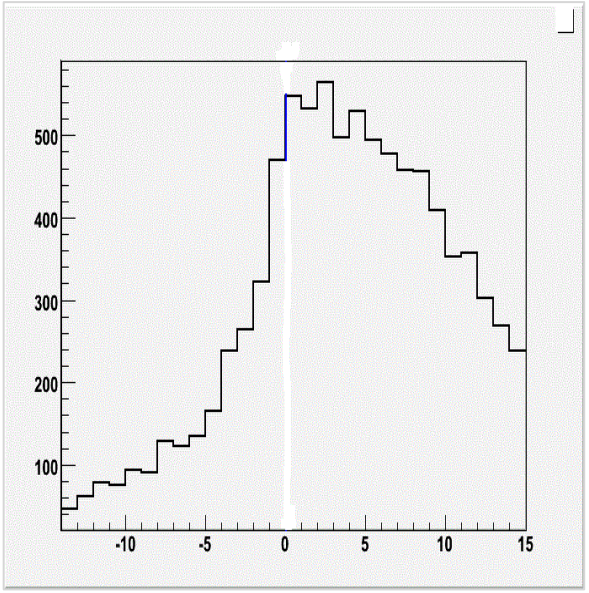



$\eta \rightarrow \pi^0\gamma\gamma$

Z of the cluster is changed from -15 to 15mm in step of 1mm

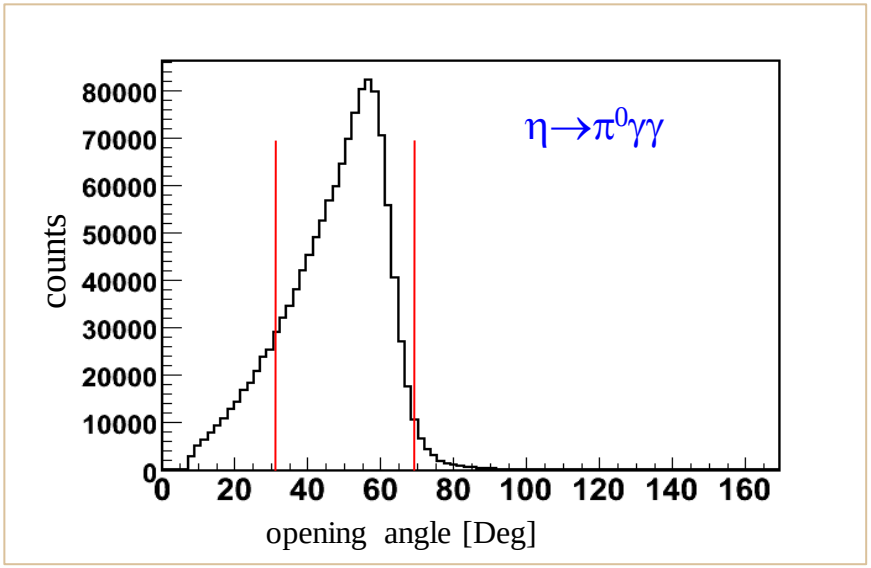
$\eta \rightarrow 3\pi^0$ **(background)**

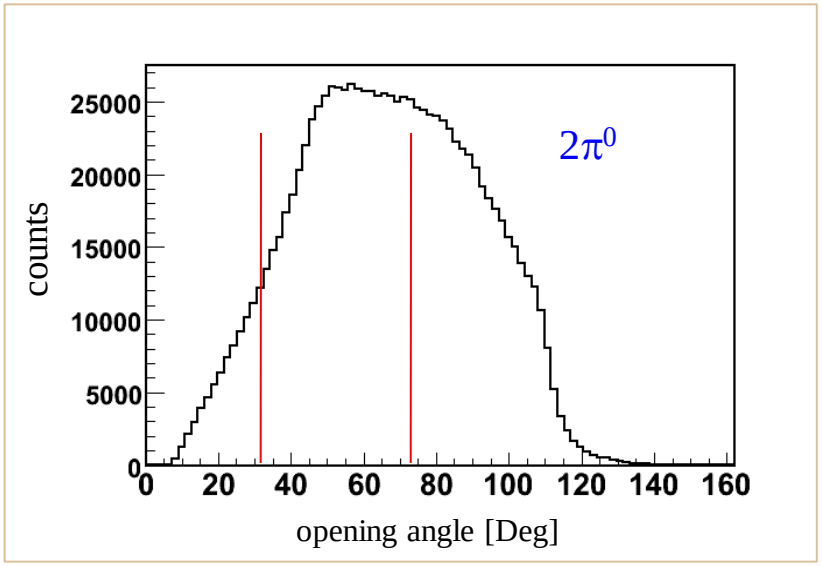


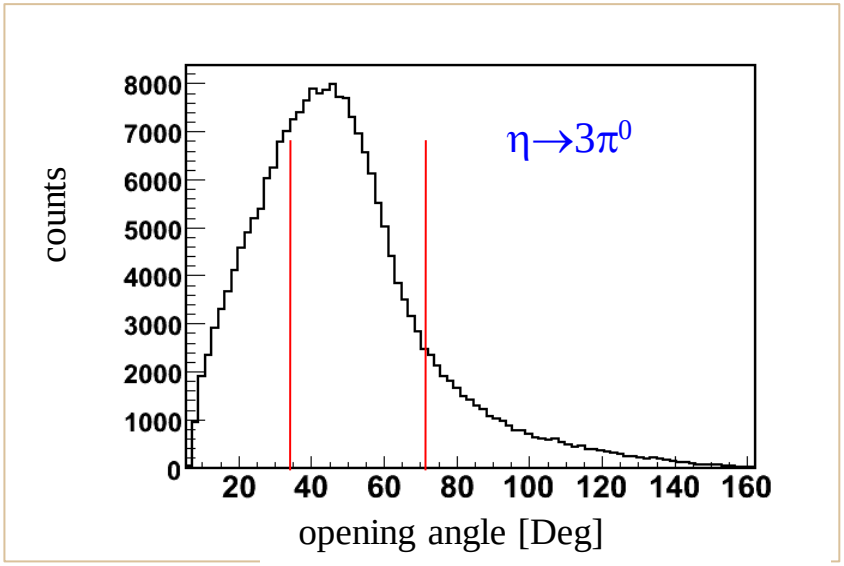



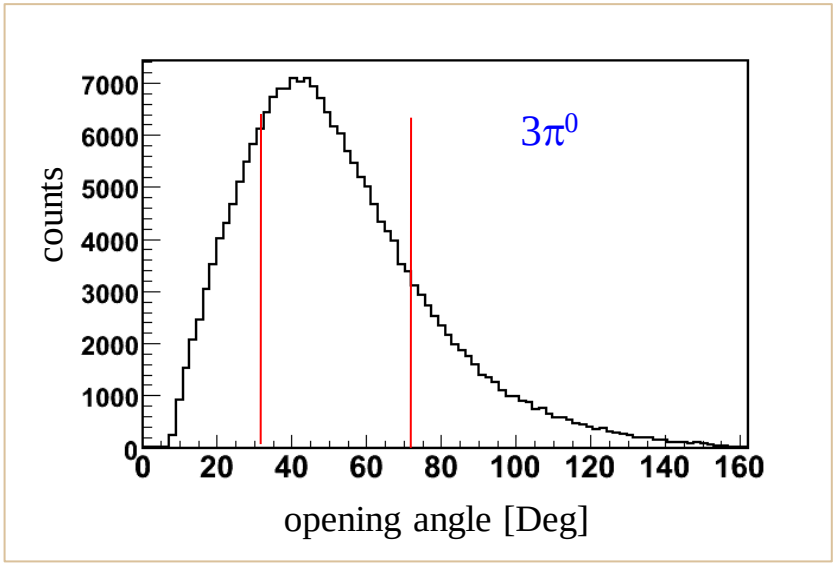
# Simulations

## $35^0$ < Opening angle ($^3$He, $\pi^0\gamma\gamma$) < $70^0$



# Calculation of the branching ratio of $\eta \to \pi^0\gamma\gamma$

$$BR(\eta \to \pi^0\gamma\gamma) = B_1 \times (BR(\eta \to 3\pi^0))$$

$$B_1 = \frac{n(\eta \to \pi^0\gamma\gamma)}{n(\eta \to 3\pi^0)}$$

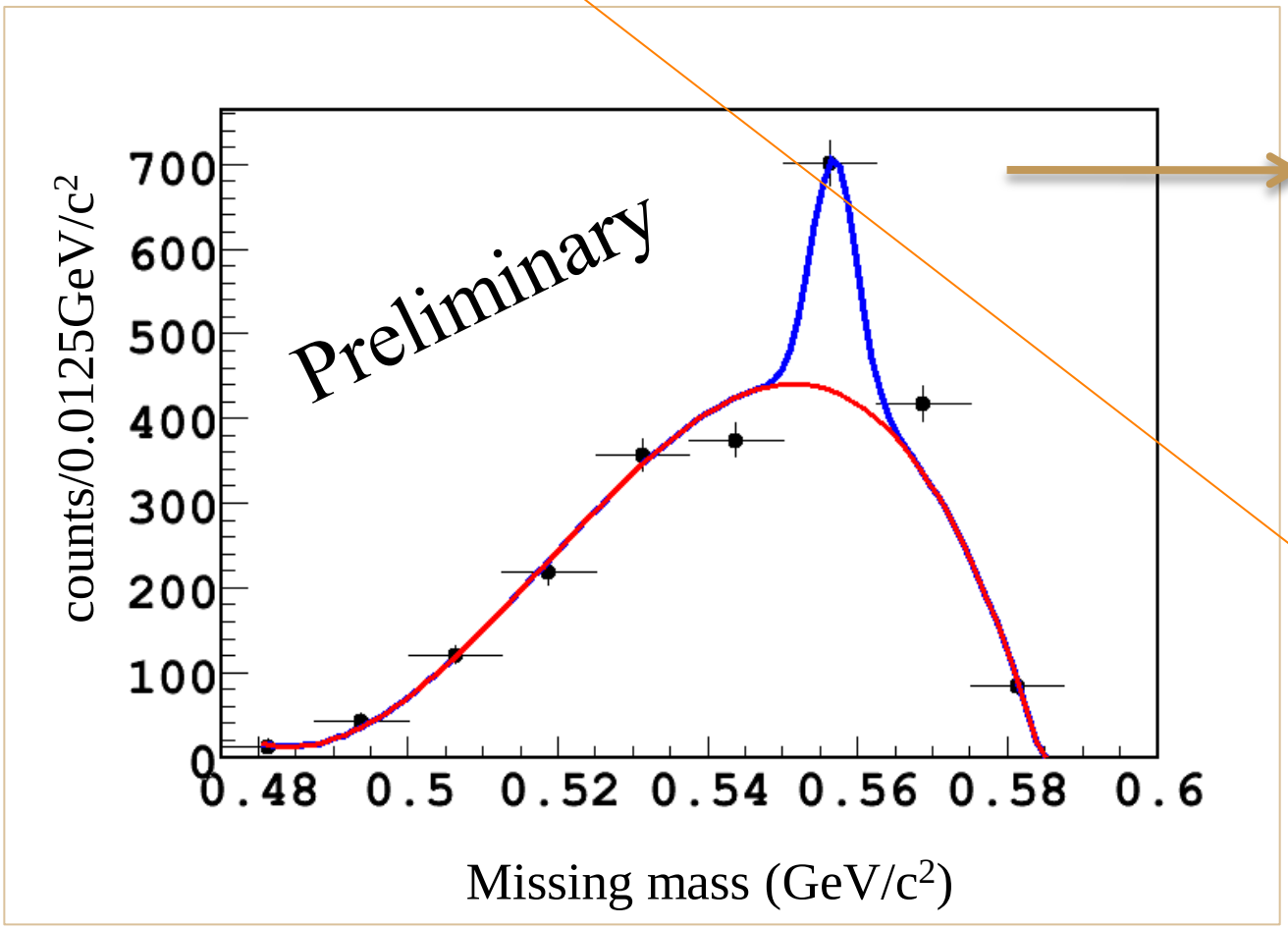
$$n = N / \varepsilon$$

Here $N(\eta \to \pi^0\gamma\gamma) = 289$ $\quad$ $N(\eta \to 3\pi^0) = 7.84 \times 10^5$

$\varepsilon = 9.04\%$ $\quad$ $\varepsilon = 27\%$

$BR(\eta \to 3\pi^0) = 32\%$ (PDG value)

**$BR(\eta \to \pi^0\gamma\gamma) = (3.48 \pm 0.67_{stat}) \times 10^{-4}$**




289 $\eta\rightarrow\pi^0\gamma\gamma$ events in $3\sigma$ range of eta peak

# Results

- We have measured 300 $\eta \rightarrow \pi^0\gamma\gamma$ events.
- Reconstruction efficiency from Monte Carlo is 9.04% and the reconstruction efficiency of $\eta \rightarrow 3\pi^0$ 0.10% as background.
- Statistical error on the branching ratio of $\eta \rightarrow \pi^0\gamma\gamma$ = $0.7\times10^{-4}$

After subtracting $\eta \rightarrow 3\pi^0$ background