Updates on $\eta \to \gamma\gamma\pi^0$

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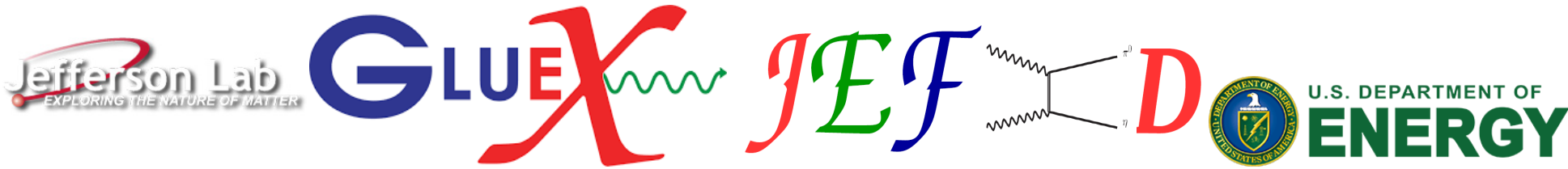

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Electromagnetic decays of light mesons - L.G. Lansberg

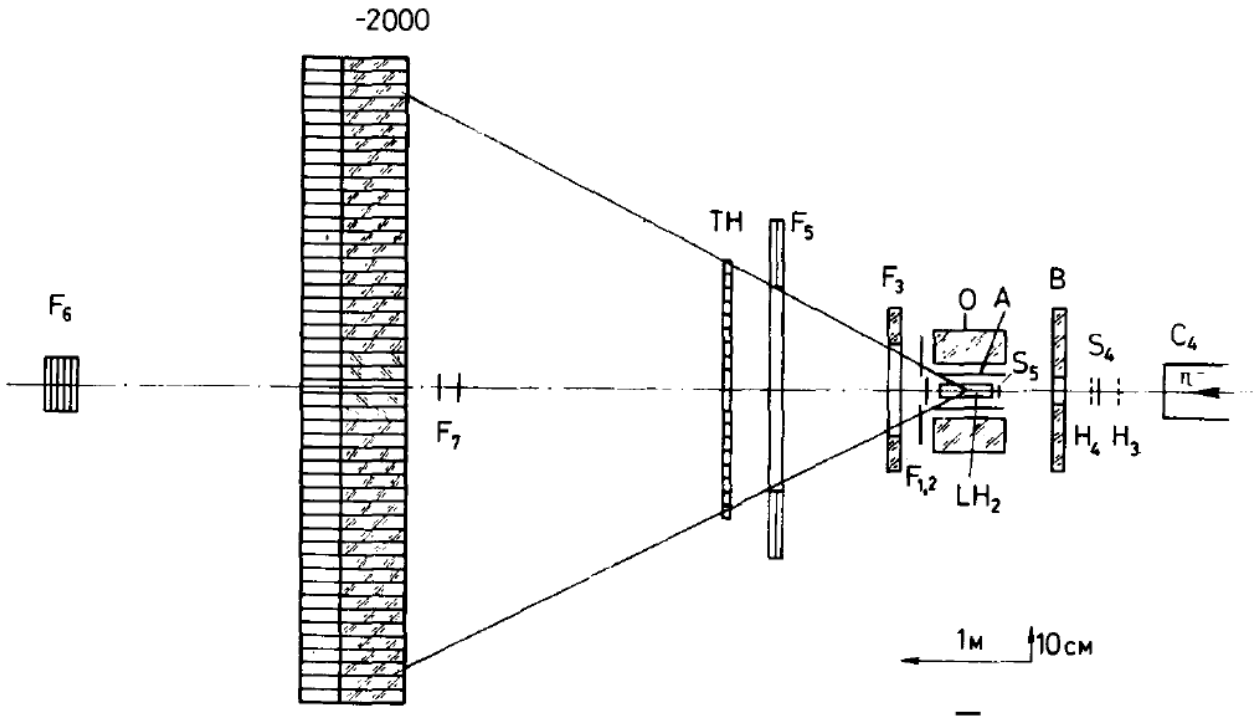


Fig. 6. The layout of GAMS-2000. The main unit of this apparatus is the hodoscope Čerenkov γ-spectrometer, 48×32 matrix of total absorption lead-glass counters. S_4, S_5, H_3, H_4 – scintillation counters and hodoscopes of the π^--beam; LH_2 – liquid hydrogen target; A, O, F_{1-5}, B – guard counters; $F_{6,7}$ – beam-killing system; TH hodoscope was not used in the $\eta \to \pi^0\gamma\gamma$ search.

- 30 GeV π^- beam, $\sim 3 \times 10^{11} \pi^-$ on target
- $\pi^- p \to \eta^{(\prime)} n$, $6 \times 10^5 \eta$ produced via this process

GAMS-2000 results

Electromagnetic decays of light mesons - L.G. Lansberg

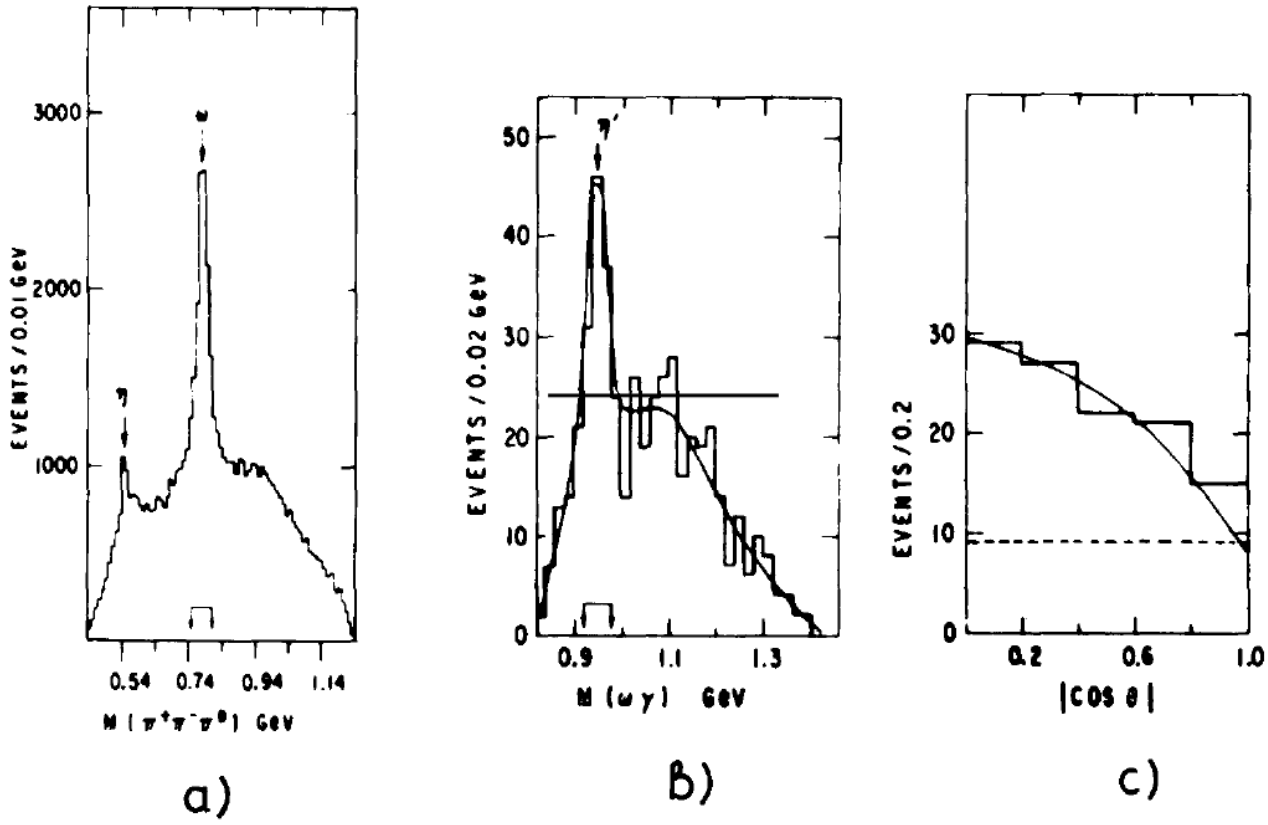


Fig. 5. (a) $\pi^+\pi^-\pi^0$ effective mass spectrum (68962 events), showing the 750–810 MeV ω-mass cut. (b) $\omega\gamma$ effective mass distribution (478 events). The curve is the result of a two-parameter fit: (the η' peak is parametrized by a Gaussian of central mass 955 MeV and an instrumental width of 50 MeV) + (background represented by Monte-Carlo generated, acceptance corrected $\omega\pi^0$ phase space events from which one γ out of the four was randomly detected). (c) Distribution in $|\cos\vartheta|$ (corrected for acceptance) for 114 events between the arrows in (b). The solid line represents the best fit by the form: $a + b\,(1-\cos^2\vartheta)$. The dotted line represents the background subtraction of 45 events obtained from the fit on (b).

- GAMS-2000 $\mathcal{B}(\eta' \to \omega\gamma) = 2.8 \pm 0.5\%$
- PDG-2022 $\mathcal{B}(\eta' \to \omega\gamma) = 2.52 \pm 0.07\%$

GAMS-2000 results

Electromagnetic decays of light mesons - L.G. Lansberg

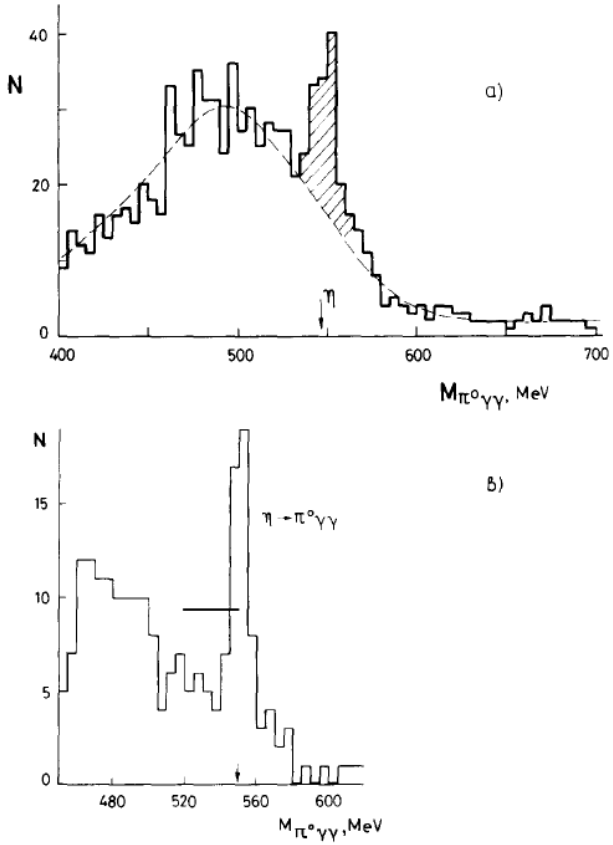


Fig. 7. (a) Mass spectrum of the $\pi^0\gamma\gamma$ system measured in the reaction $\pi^-p \to \pi^0\gamma\gamma n$. The arrow points at the η mass. The background part of the spectrum (dashed curve) is largely due to the $\eta \to 3\pi^0 \to 6\gamma$ (2.6) decay, with two "missed photons". (b) The same data, but analyzed with a new program for shower reconstruction. As a result the background from (2.6) with "missed photons" is greatly reduced.

- GAMS-2000 $\mathcal{B}(\eta \to \gamma\gamma\pi^0) = 0.07 \pm 0.016\%$
- PDG-2022 $\mathcal{B}(\eta \to \gamma\gamma\pi^0) = 0.0255 \pm 0.022\%$

No $\omega \to \gamma\pi^0$ And no $\eta' \to \gamma\omega$ with $\omega \to \gamma\pi^0$ are shown, $\mathrm{m}_{\gamma\pi^0}$ cut applied?

$\eta^{'} \to \gamma\omega$

Is a good reference channel candidate

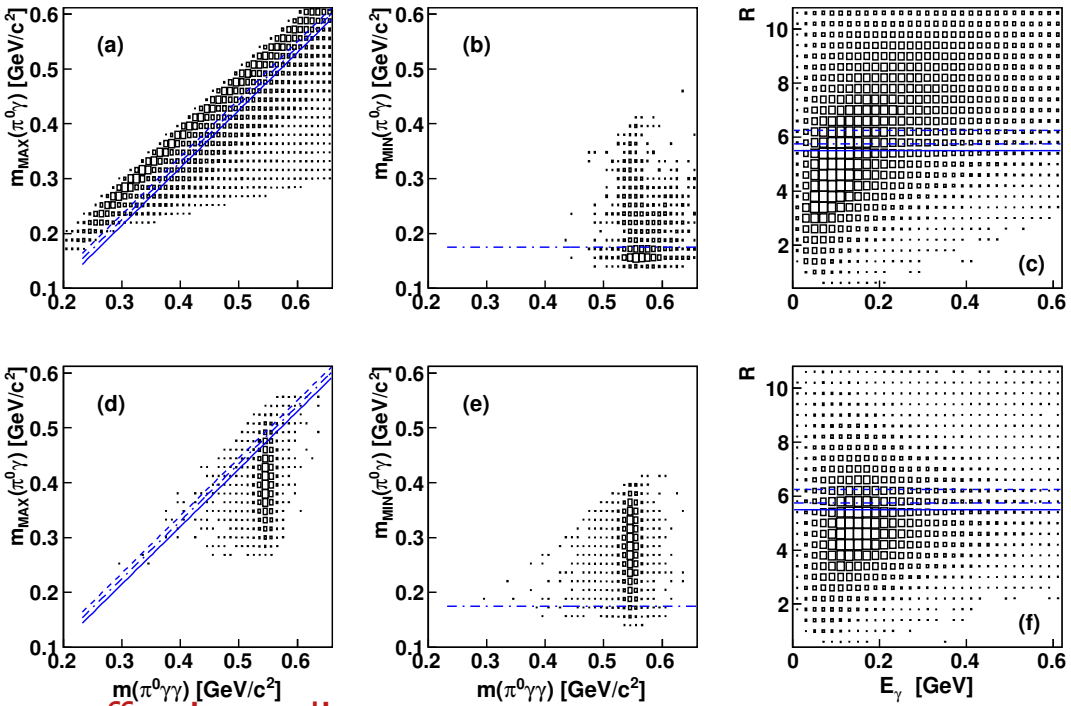
- $\mathcal{B}(\eta^{'} \to \omega\gamma) = 2.52\%$
  - $\mathcal{B}(\omega \to \pi^0\pi^+\pi^-) = 89.2\%$
  - $\mathcal{B}(\omega \to \gamma\pi^0) = 8.28\%$
  - $\mathcal{B}(\pi^0 \to \gamma\gamma) = 98.823\%$
- $\mathcal{B}(\eta' \to \omega\gamma) = \mathcal{B}(\eta' \to \omega\gamma) \times \mathcal{B}(\omega \to \pi^0\pi^+\pi^-) \times \mathcal{B}(\pi^0 \to \gamma\gamma) = 2.247\%$
- $\mathcal{B}(\eta' \to \omega\gamma) = \mathcal{B}(\eta' \to \omega\gamma) \times \mathcal{B}(\omega \to \gamma\pi^0) \times \mathcal{B}(\pi^0 \to \gamma\gamma) = 0.204\%$
- Two decays can be reconstructed
- If $\epsilon(\eta^{'} \to \gamma\omega[\to \gamma\pi^0]) = \epsilon(\eta \to \gamma\gamma\pi^0)$, $\frac{N(\eta^{'} \to \gamma\omega[\to \gamma\pi 0])}{N((\eta \to \gamma\gamma\pi^0)} \sim 10$

In general, every rare decay studied should/must have a reference channel to validate the analysis

A2 experiment

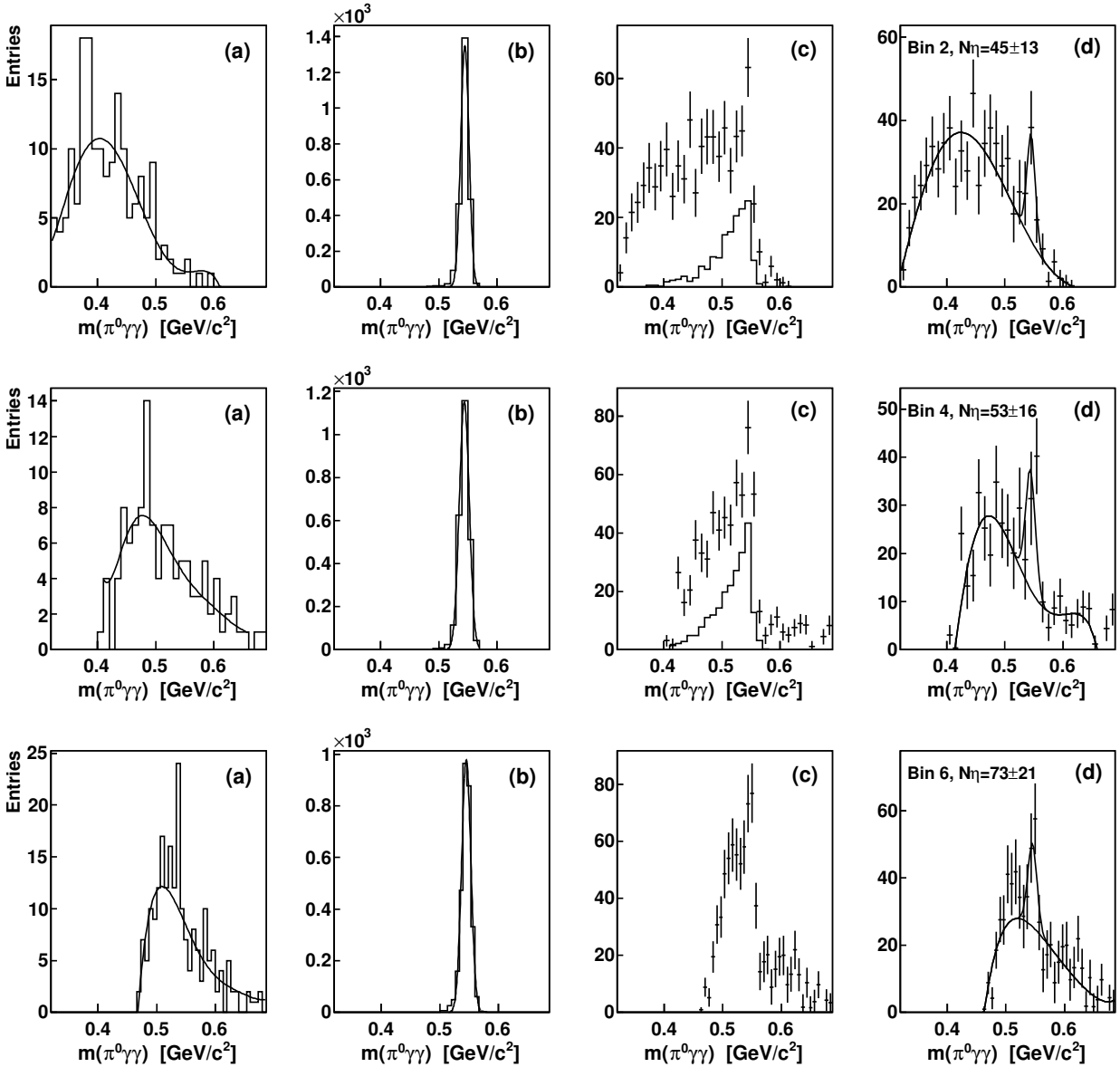
Key numbers and facts: S. Prakhov et al. PRC 90, 025206 (2014)

- $6 \times 10^7 \eta$ produced in $\gamma p \to \eta p$ between threshold and 800 MeV
- 1200 $\eta \to \gamma\gamma\pi^0$ observed
- $\epsilon(\eta \to \gamma\gamma\pi^0)$ varies between 7 and 14 %
- $\frac{S}{B}$ varies between 30 and 50%
- Main backgrounds:
  - (a) $\gamma p \to \pi^0\pi^0 p$, $\pi^0\pi^0$ veto applied, cut applied similar to cuting π^0-peak in $m_{\gamma\gamma}$
  - (b) $\eta \to \gamma\gamma$, peaking background produced mostly by shower splitting, elimated by a $m(\gamma\pi^0)$ cut
  - (c) $\eta \to \pi^0\pi^0\pi^0$, peaking background produced mostly by shower merging, strongly reduced by a cut on the shower effective radius



Currently testing shower effective radius cut

A2 yield extraction

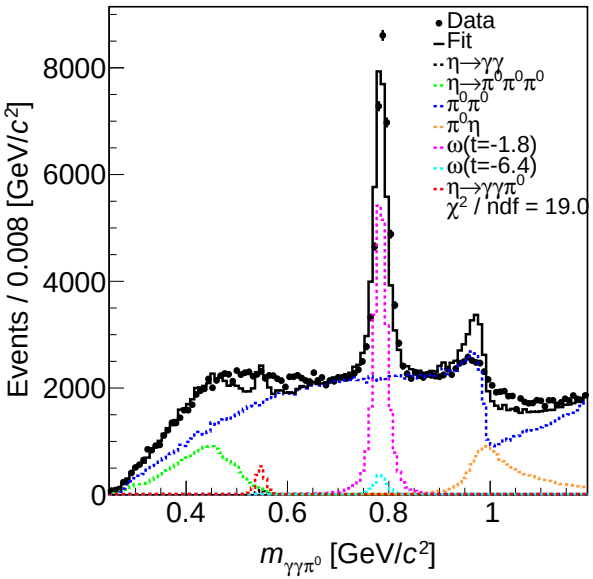


Best analysis on the market so far!

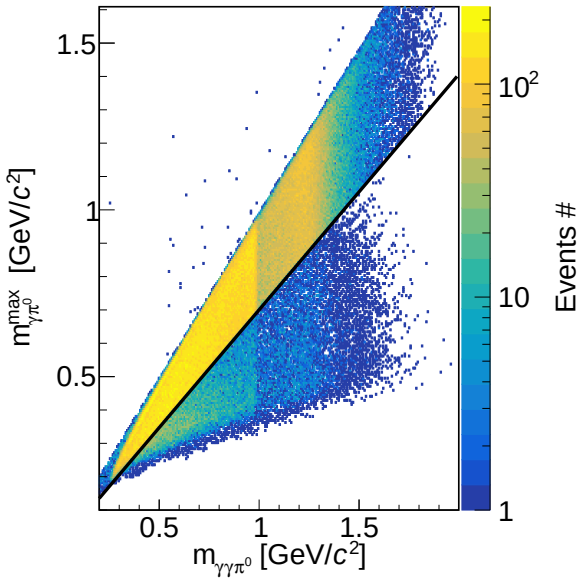
GlueX/JEF Basic Selection Criteria

- 4 "photon" hypotheses DNeutral_Shower with
  - $|t_{\gamma}^{\mathrm{CAL}} - t_{\mathrm{RF}}| \leq 2$ ns
  - $\mathrm{E}_{\mathrm{cluster}} \geq 250$ MeV
- χ^2_{test} to select best $\gamma\gamma\pi^0$ combination and discriminate other possible final states ($\pi^0\pi^0$, $\pi^0\eta$, $\eta\eta$, $\pi^0\eta'$, $\eta\eta'$, $\eta'\eta'$)
- χ^2_{test} to select best track coplanar to $\gamma\gamma\pi^0$
- BCAL veto: allow only one "hadronic" shower and zero neutral shower both with $|t_{\mathrm{shower}}^{\mathrm{BCAL}} - t_{\mathrm{RF}}| \leq 6$ ns
- $\mathrm{E}_{\gamma} \geq 8.3$ GeV

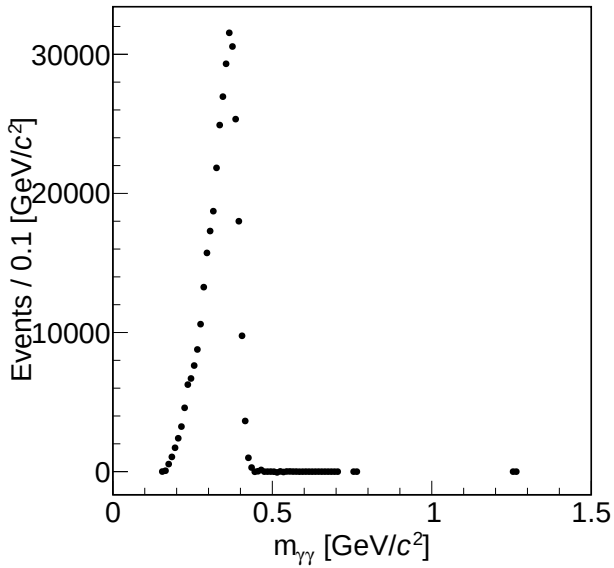
- As is



- MC simu $\pi^0\pi^0$ background



- After A2-$\pi^0\pi^0$-veto for $\eta \to \gamma\gamma\pi^0$ MC signal



A2 veto not applicable as is

GlueX/JEF Basic Selection Criteria

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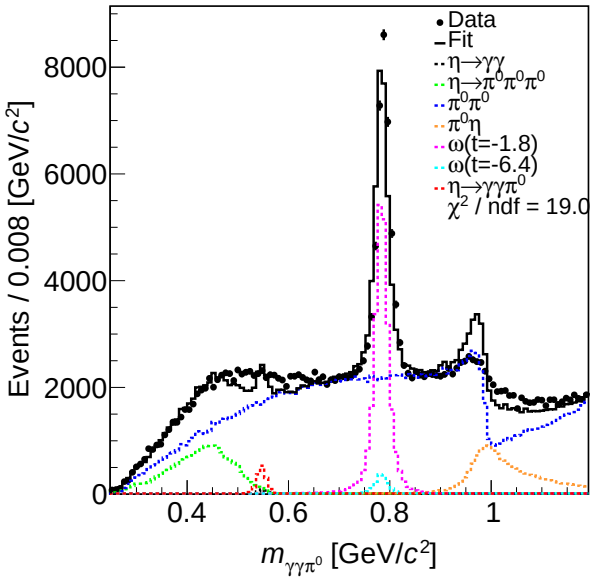
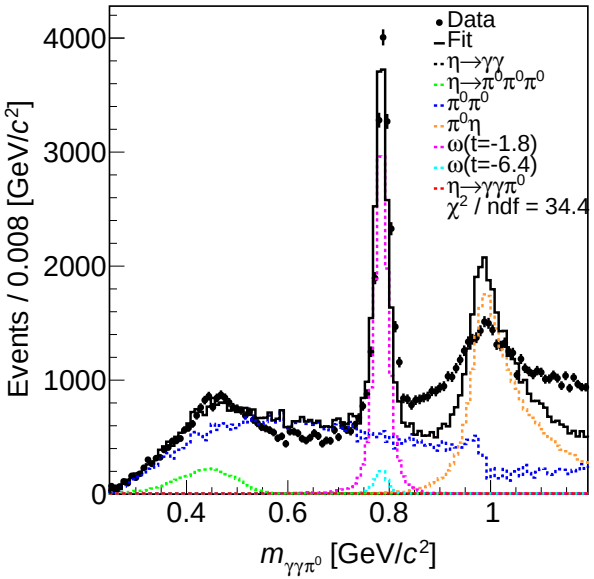
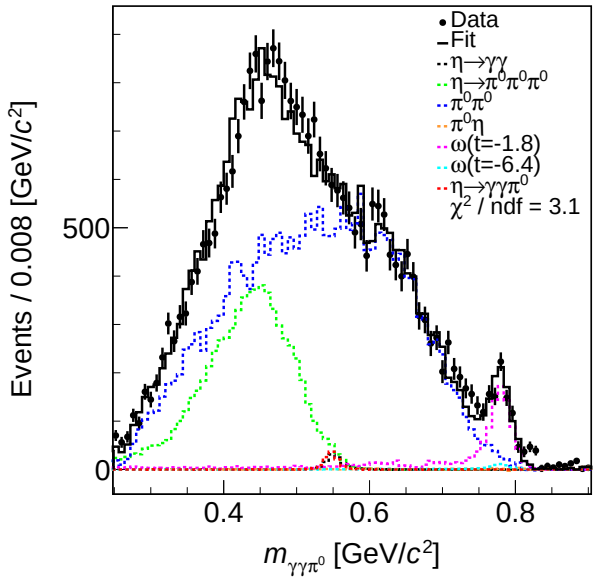
- As is



- $\pi^0\pi^0$-veto ie $!(110 \leq \mathrm{m}_{\gamma\gamma} \leq 160\ \mathrm{MeV}/c^2)$



- $\pi^0\pi^0$- and $\omega \to \gamma\pi^0$-vetos ie $\mathrm{m}_{\gamma\pi^0} \leq 600\ \mathrm{MeV}/c^2$



Compare to A2 does the boost really decreases the background? B >> S!

$\eta \to \gamma\gamma$ background

Two sources:

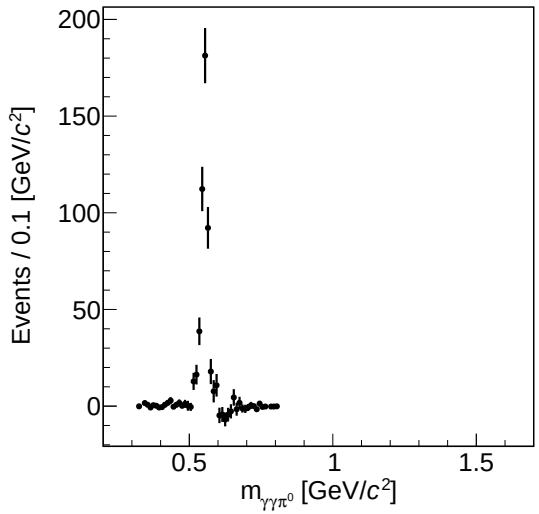
- γ conversion mostly removed by TOF veto
- Shower splitting, latest Island Algorithm strongly reduced the splitting compared to Default Algorithm

TOF veto removed for 2017-01 run period MC simulation:

- $\sim$ 50% of the $\eta \to \gamma\gamma$ background
- $\sim$ 30% of the $\eta \to \gamma\gamma\pi^0$ signal

Splitting:

- Default Algorithm: $\sim$ 0.04 % chance of splitting resulting to half of the peaking $\eta \to \gamma\gamma$ background
- Island Algorithm: ? % chance of splitting resulting to ? of the peaking $\eta \to \gamma\gamma$ background



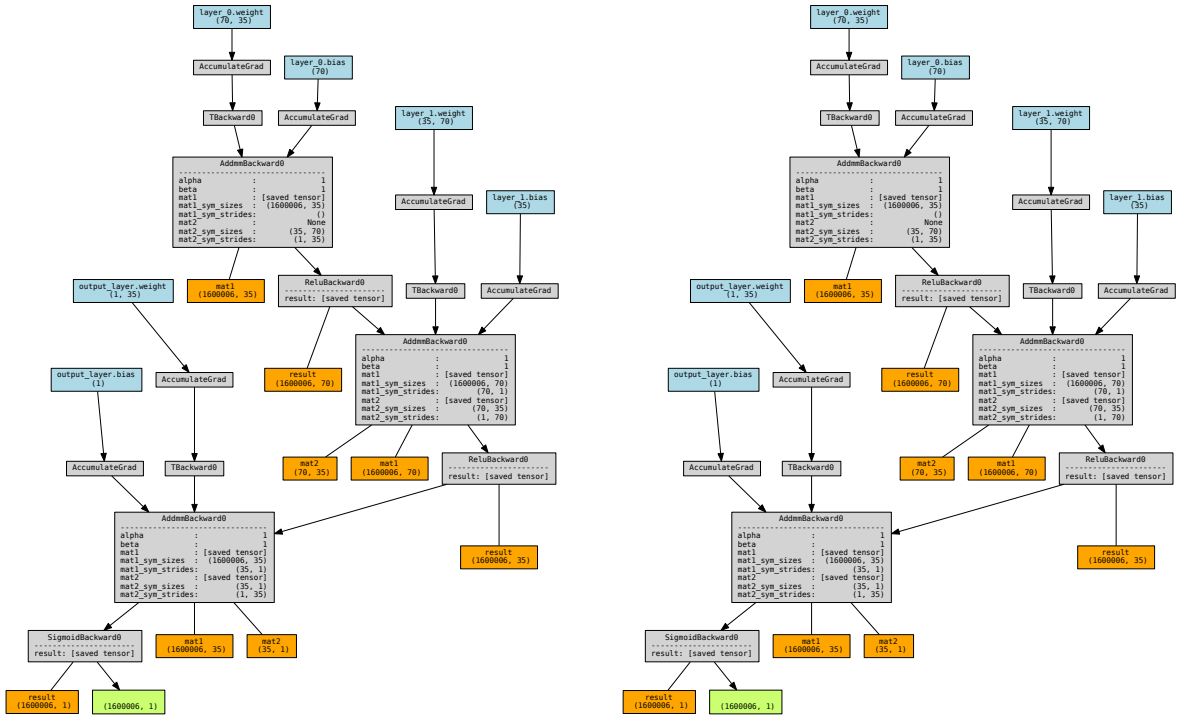
Kinematic fit is making the mass peak

Physics-Informed Neural Network (PINN)

Based on P. Feichtinger et al. EPJC 82 (2022) 2, 121 and D. Lersch et al.

35 features or inputs:

- Process thrust, E_γ, $\mathrm{m}_{\gamma\gamma\gamma\gamma}$, and
- For each FCAL showers: SumV, SumU, E1E9, E5E29, cluster size in block number unit

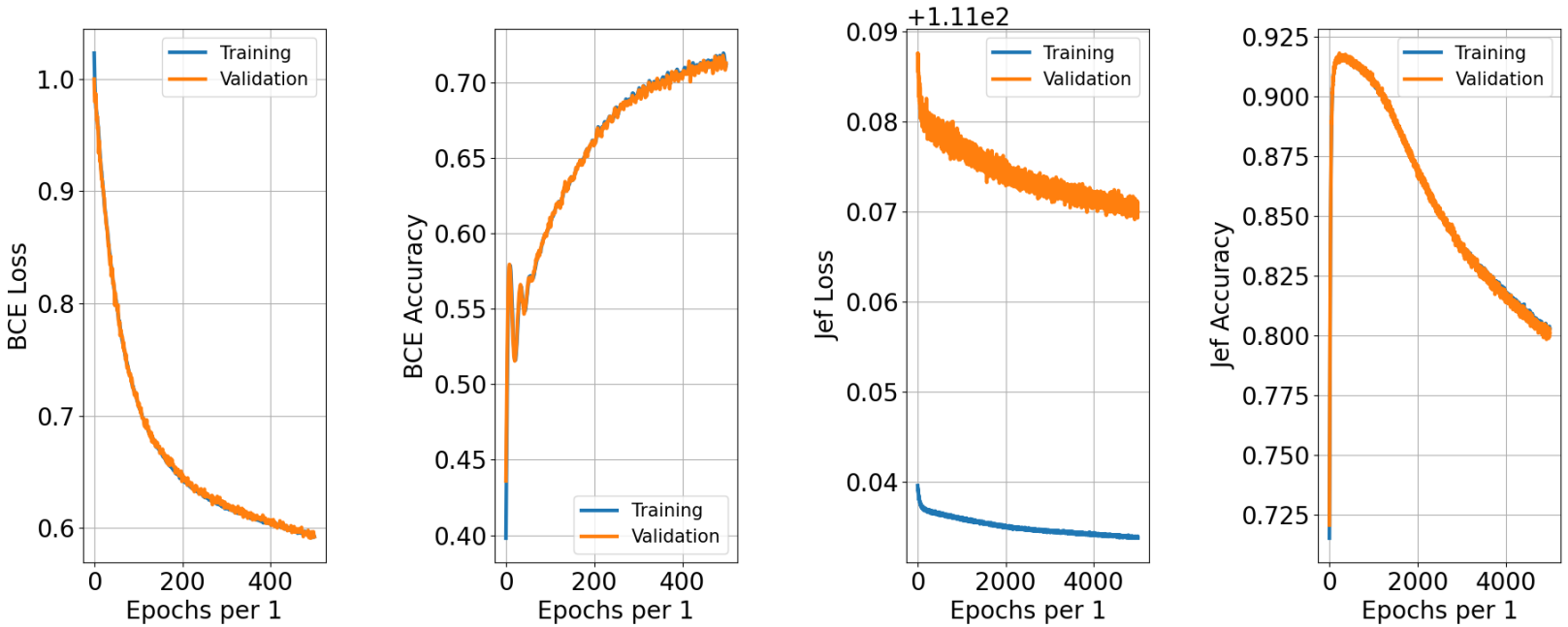


- 2 hidden layers with 70 and 35 neurons, respectively activated by RELU
- 1 sigmaoid output

Training done into two steps: pre-training with BCE & final training with PINN per $\mathrm{m}^{\mathrm{i}}_{\gamma\gamma}$-slice and with a customized loss function

Loss and accuracy

Customized loss function compares signal with overall statistical uncertainty in short $\frac{\sqrt{S+B}}{S}$



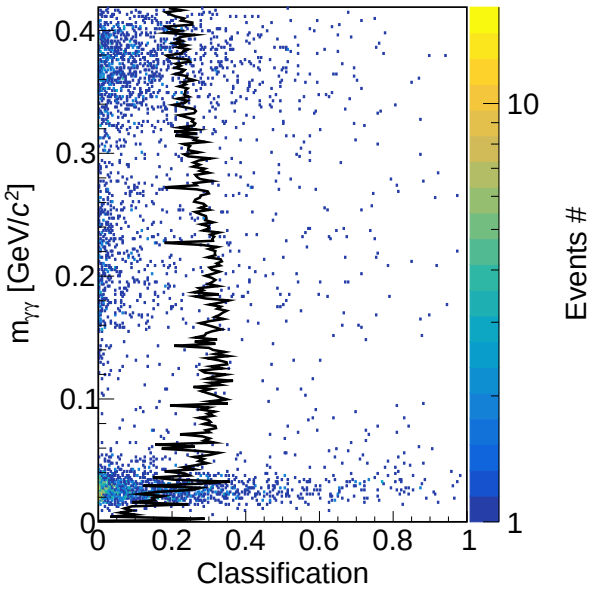
- Slice size, $2\sigma - \mathrm{m}^{\mathrm{i}}_{\gamma\gamma} \leq \mathrm{m}^{\mathrm{i}}_{\gamma\gamma} \leq 2\sigma + \mathrm{m}^{\mathrm{i}}_{\gamma\gamma}$
- Trainings for every other slices, 5σ step
- Net architecture, activation function, loss rate, and number of epoch not tune yet via the HyPerparameter Optimization technique
- Loss function is also not optimized yet, different class of Figure-Of-Merit can be tested

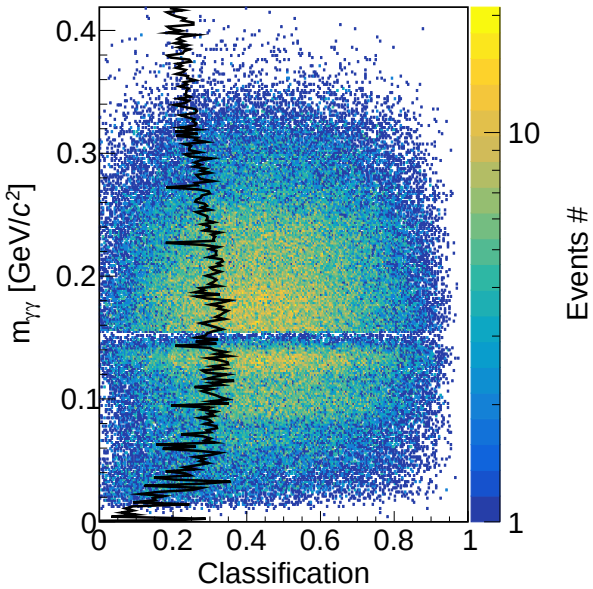
Goal find set of cuts to get the smallest $\frac{\sqrt{S+B}}{S}$ value or highest sensitivity

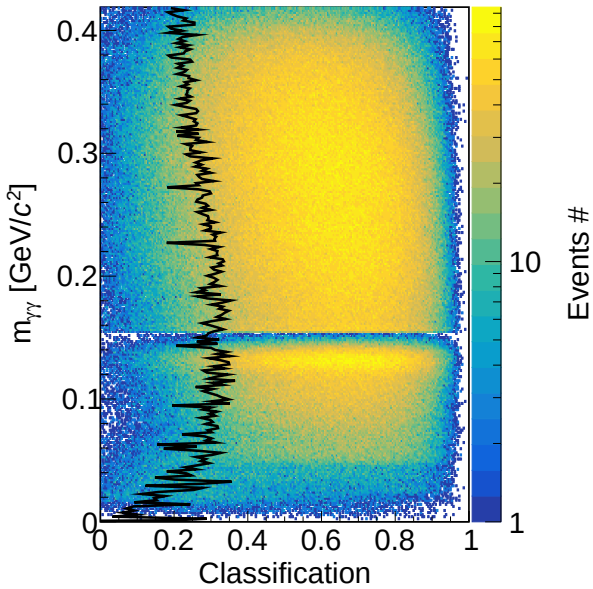
Pre-training BCE

Results after the BCE pre-training

- 39.31M $\gamma p \to \eta p$ with $\eta \to \gamma\gamma$, labeled as background
- 32.57M $\gamma p \to \eta p$ with $\eta \to \pi^0\pi^0\pi^0$, labeled as background
- 10M $\gamma p \to \eta p$ with $\eta \to \gamma\gamma\pi^0$, labeled as signal







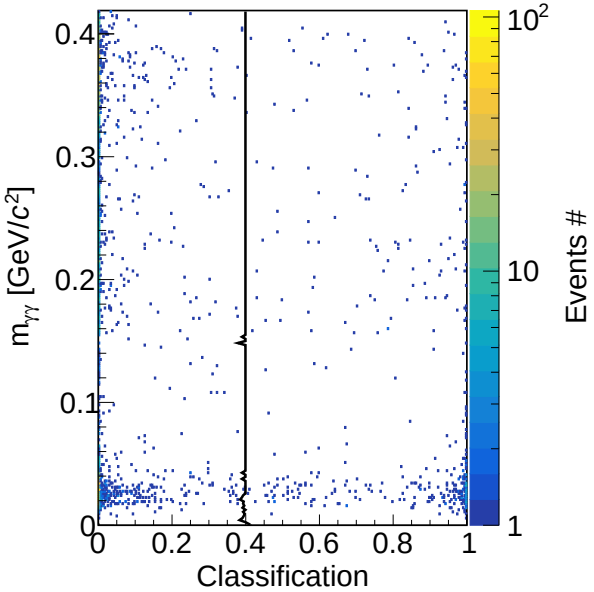
- Black line is the optimal threshold or smallest $\frac{\sqrt{S+B}}{S}$ value
- BCE net output is in average 0.25 ± 0.1

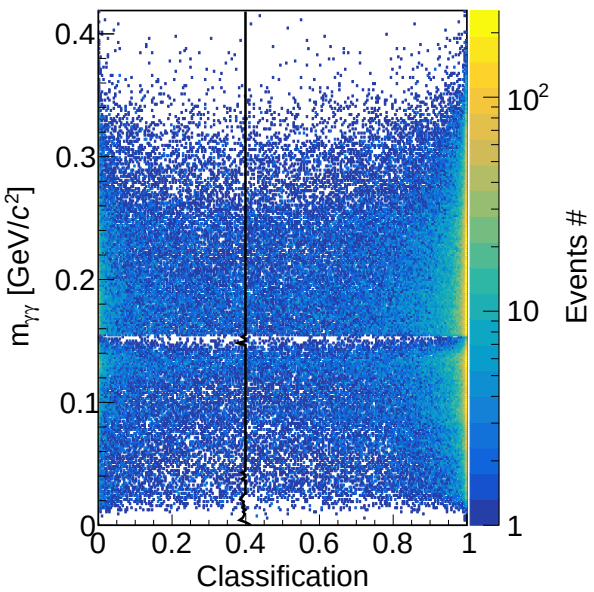
BCE model used as starting point for PINN training

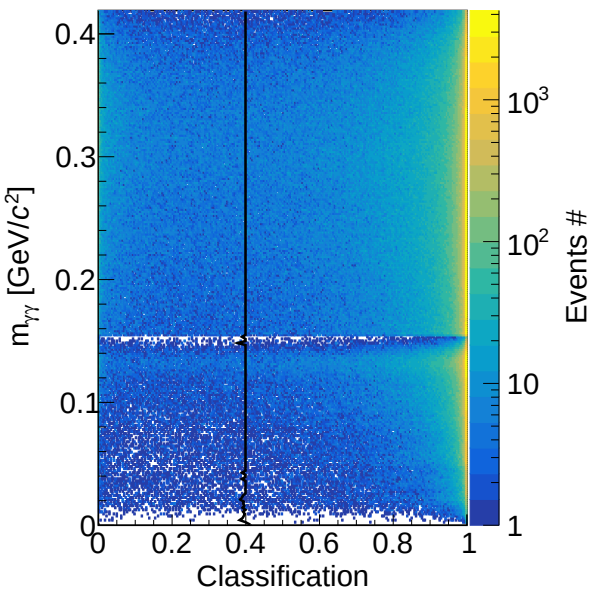
PINN

Results after the PINN training

- 39.31M $\gamma p \to \eta p$ with $\eta \to \gamma\gamma$, labeled as background
- 32.57M $\gamma p \to \eta p$ with $\eta \to \pi^0\pi^0\pi^0$, labeled as background
- 10M $\gamma p \to \eta p$ with $\eta \to \gamma\gamma\pi^0$, labeled as signal





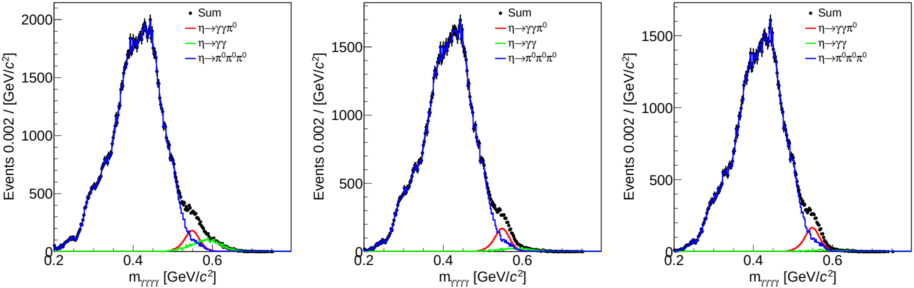


- Black line is the optimal threshold or smallest $\frac{\sqrt{S+B}}{S}$ value
- PINN output is 0.4 ± 0.01

Use one value for all masses

Testing samples

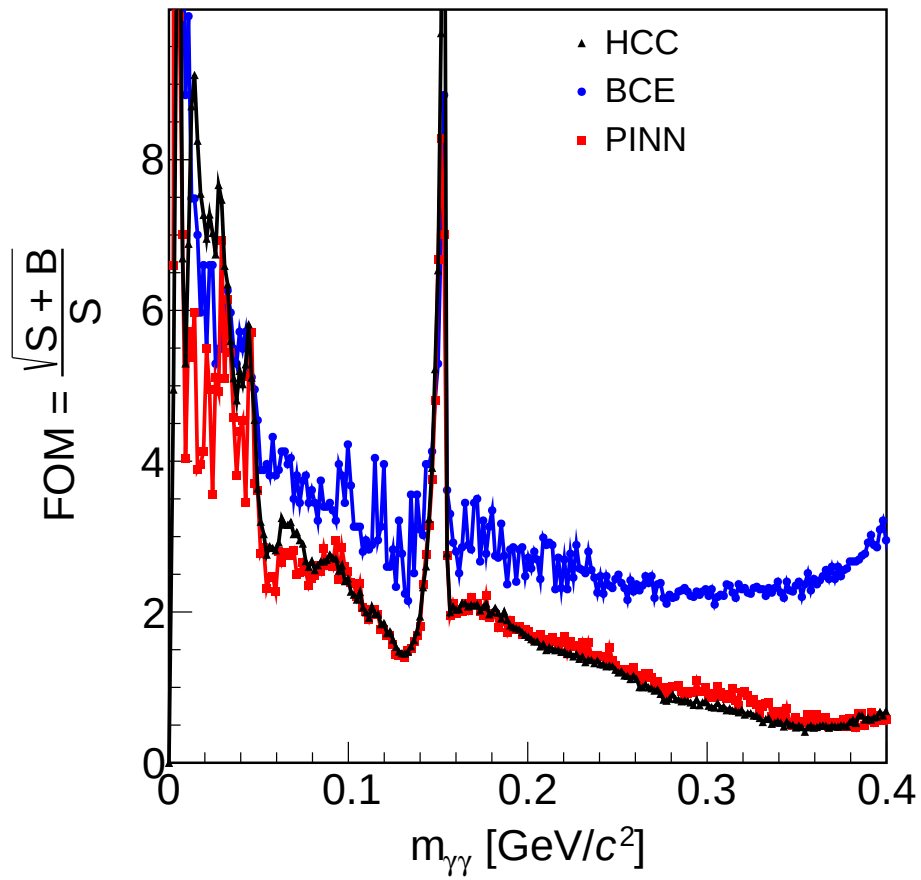
- Hand Crafted Cut (HCC)
- BCE
- PINN



- PINN starts after the basic selection criteria discribed in slide 9
- Use reconstructed variables
- No TOF veto used, $\eta \to \gamma\gamma$ background suppress by an order of magnitude w/o any cuts on $m_{\gamma\gamma}$
- Working on including $\pi^0\pi^0$ and ω backgrounds

FOM comparison

Between the HCC, BCE, and PINN:



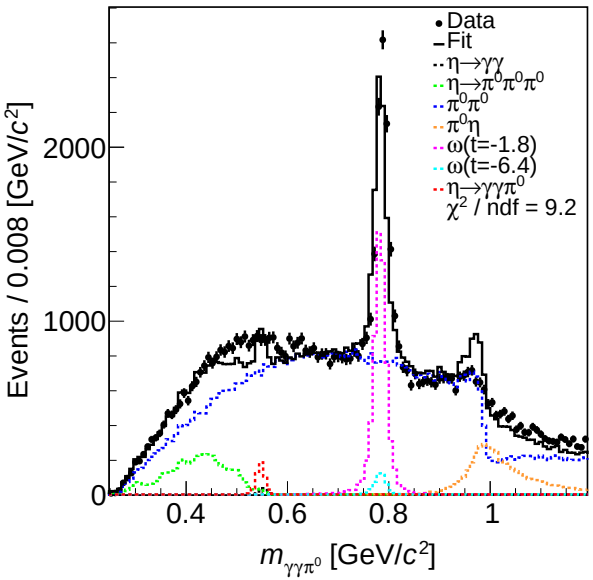
Ideally, PINN significance >> HCC significance and PINN systematic error (not calculated yet) $\sim$ HCC systemtatic error (also not calculated yet). But, it is not always the case.

GlueX/JEF Advance Selection Criteria

Basic selection criteria applied

- TOF-veto applied
- Only 4 FCAL clusters
- CL $> 0.01\%$
- One photon in the insert

- As is



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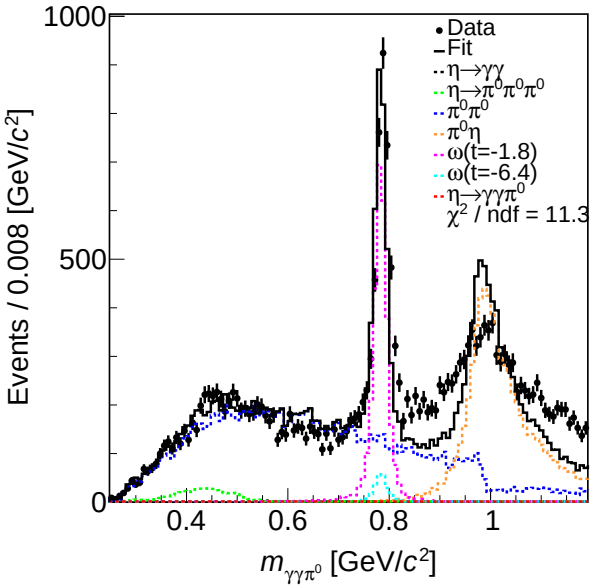

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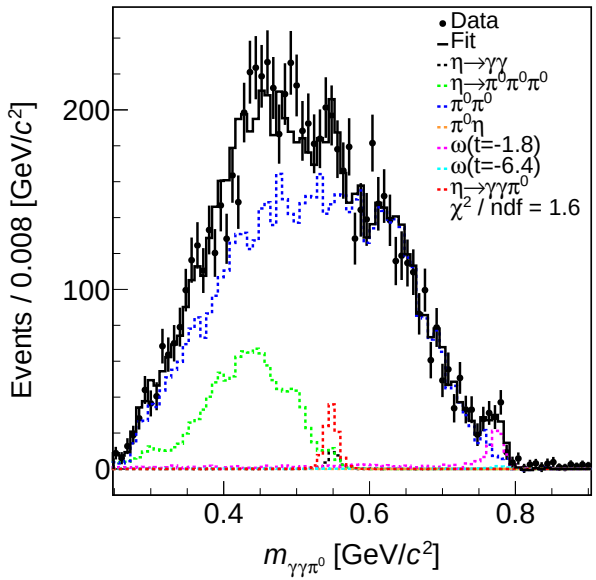

- $\mathrm{N}^{\mathrm{expected}}_{\eta\to\gamma\gamma\pi^0}$ $\sim$550 for 53 pb^{-1}
- $\mathrm{N}^{\mathrm{fit}}_{\eta\to\gamma\gamma\pi^0}$ $\sim$100 for 53 pb^{-1}
- If true, $\mathcal{B} \sim 2.7 \times 10^{-4}/5$

Conclusion

Reviewed GAMS-2000 and A2 results

- GAMS-2000 results on $\eta \to \gamma\gamma\pi^0$ are completly off from the world average
- A2 results are the best on the market but so far were not reproduced

GlueX/JEF status

- A2-cuts are not working as is
- With HCC, GlueX/JEF S/B much worse than A2!
- As is we are leading toward an UL

PINN with customized loss function

- Require to understand fairly well the backgrounds
- Works fairly well on reduced background test samples, reduced $\eta \to \gamma\gamma$ peaking background by an order of magnitude
- Start with a minimum set of HCC, this miminum has not been determined yet
- Significance and systematic errors must be competitive compared to HCC to be usuable
- Less complicate model will also be explored