

# Search for the dark scalar, $S$ , in rare $\eta$ -meson decay

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for the **GlueX Collaboration**

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# Table of contents

- 1 Introduction
- 2 Selection criteria
  - FCAL2, “JEF”, selection criteria
  - FCAL, “GlueX”, selection criteria
- 3 Signal PDF
- 4 Detection efficiency and irreducible background
- 5 Limit calculation
- 6 Conclusion

# Introduction

Boosted  $\eta^{(\prime)}$ -mesons can be produced through  $\gamma p \rightarrow \eta^{(\prime)} p$  process and measured at photon-beam facilities.

- Here, we are searching for the dark scalar,  $S$ , produced in  $\eta \rightarrow \pi^0 S$  with  $S \rightarrow \gamma\gamma$   
=> Simulated with genEtaRegge, 20M events for 12 different masses, between few MeV/c<sup>2</sup> and  $\sim 410$  MeV/c<sup>2</sup>
- Expected background sources:
  - ▶  $\eta \rightarrow \pi^0 \gamma\gamma$  with Branching Ratio (BR), BR = 0.00027 (“irreducible” and main background)  
=> Simulated with genEtaRegge
  - ▶  $\eta \rightarrow \pi^0 \pi^0 \pi^0$  with BR = 0.3257 (reducible and non-negligible background)  
=> Simulated with genEtaRegge and evtgen using the Belle (II) eta decay card (in a future iteration we will use Jon optimized and up-to-date card)
  - ▶ Other hadronic decays, (reducible and negligible(?) background)  
=> Not yet taken into account but expecting to use bggn

Reaction filter and DSelector are used with standard PID selection criteria

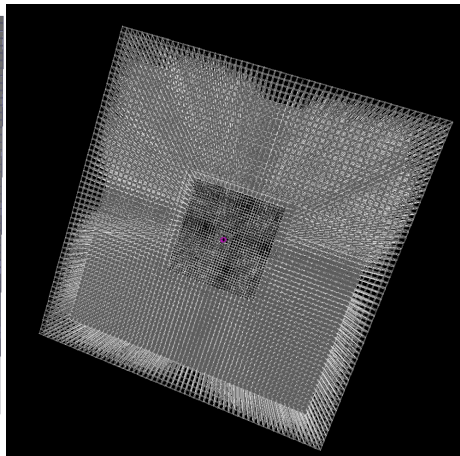
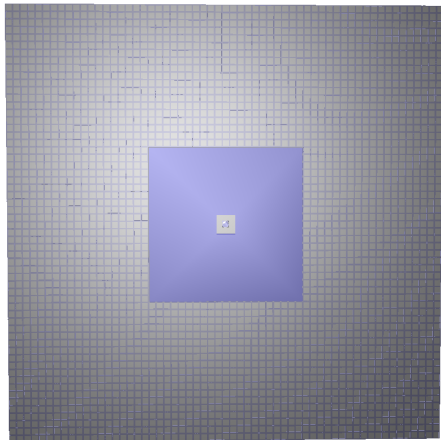
- Reaction: 1\_14\_17\_14, and Decay: 17\_7\_1\_1
- In the simulation results presented today, individual  $PbW0_2$  energy threshold set to the default unrealistic value of 50 MeV, we are expecting to run with 5 MeV energy threshold

All simulation are done for FCAL and FCAL2

# FCAL2

JEF "software" is on the master branch thanks to Simon

- **VARIATION=mc\_JEF** must be used with run number not yet allocated
- ROOT-OpenGL
- ROOT-x3d



Preliminary coarse geometry is implemented

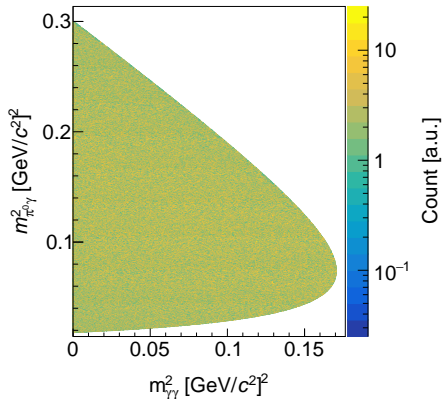
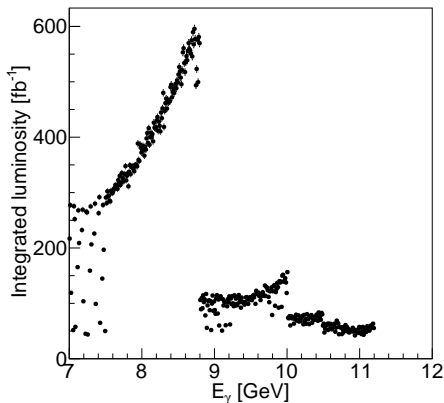
# $\gamma p \rightarrow \eta(\rightarrow \pi^0 \gamma \gamma) p$

- Simulate 1M events with MCwrapper and genEtaRegge

- $N_{\text{thrown}}(E_\gamma) = \sigma(E_\gamma) \cdot \text{BR}(\eta \rightarrow \pi^0 \gamma \gamma) \cdot \mathcal{L}(E_\gamma)$

- Luminosity simulated

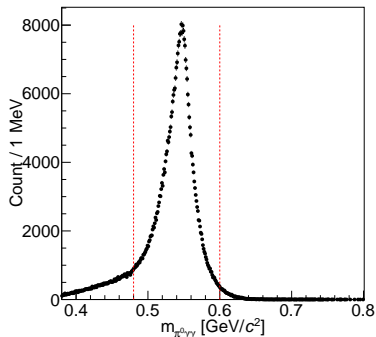
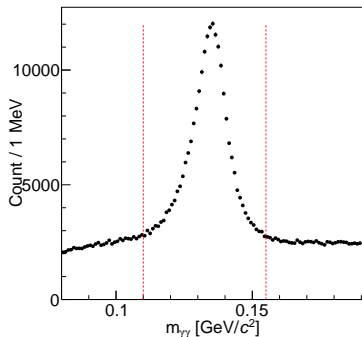
- Phase-space  $\eta$  decay



- Also, 1M events with MCwrapper and genEtaRegge w/  $3\pi^0$  and evtgen each

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

- Decay channel  $\eta \rightarrow \pi^0 \gamma \gamma$
- Select events with 4 “good” neutral hits in BCAL/FCAL2/CAL
  - ▶ BCAL & FCAL2 default GlueX cluster energy threshold
  - ▶ CCAL default PRIMEX-D cluster energy threshold
- Invariant mass of photon pair cut on  $\pi^0$  mass
- Select best combination of  $4\gamma$  to  $\pi^0 \gamma \gamma$
- Use  $\pi^0$  mass as constrain, construct  $\pi^0 \gamma \gamma$  invariant mass
- No fiducial cuts
  
- $\pi^0$  candidates
- $\eta$  candidates



# Selection criteria

10 possible variables identified (so far)

- $\chi^2$
- Coplanarity between  $\eta$  and  $p$
- Mass conservation
- Extra energy
- Unused tracks
- $\pi^0\gamma\gamma$  invariant mass
- Cluster number below  $4.5^\circ$
- Vertex  $z$  and  $r$
- Proton momentum

Optimized by the Figure-Of-Merit (FOM),  $N_{\text{sig}}(m)/\sqrt{N_{\text{sig}}(m) + N_{\text{nkg}}(m)}$

- Signal, sig:  $\eta \rightarrow \pi^0\gamma\gamma$ , BR = 0.00027
  - ▶ genEtaRegge, 1M events thrown
  - ▶  $N_{\text{sig}}(m) = N_{\text{rec}}(m) \times BR(\eta \rightarrow \pi^0\gamma\gamma)/BR(\eta \rightarrow \pi^0\pi^0\pi^0)$
- Background, bkg:  $\eta \rightarrow \pi^0\pi^0\pi^0$ , BR = 0.3257
  - ▶ genEtaRegge, 1M events thrown
  - ▶  $N_{\text{sig}}(m) = N'_{\text{rec}}(m)$
- FOM for each  $m_{\gamma\gamma}$
- $N_{\text{rec}}(m) = \text{integral}(m - 3\sigma(m), m + 3\sigma(m))$   
where  $m$  is the mass and  $\sigma$  is the dark scalar weighted width ( $\sigma(m) = \sqrt{A \cdot w_1^2(m) + (A - 1) \cdot w_2^2(m)}$ )
- $N'_{\text{rec}}(m) = \text{integral}(m - 3\sigma(m), m + 3\sigma(m))$

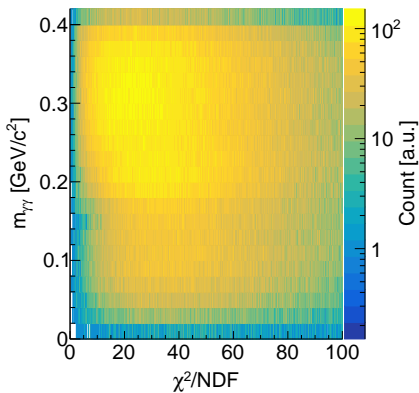
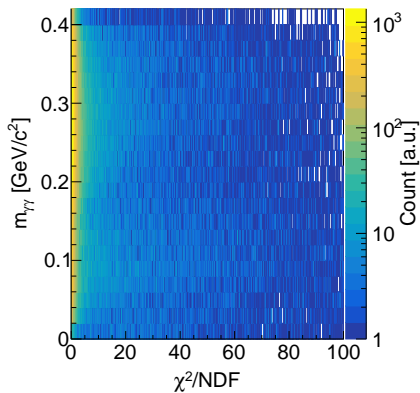
The optimization is very preliminary

# FCAL2, Kinfit $\chi^2$

$m_{\gamma\gamma}$  vs. vs. kinfit  $\chi^2$  for:

● Signal

● Background





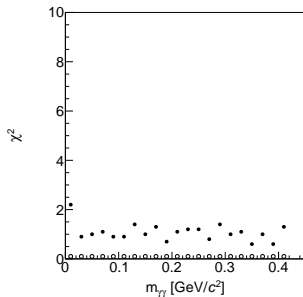
# FCAL2, Kinfit $\chi^2$

FOM vs. kinfit  $\chi^2$ :

- $m_{\gamma\gamma} = 110 \text{ MeV}/c^2$

- $m_{\gamma\gamma} = 310 \text{ MeV}/c^2$

- Selection criteria vs.  $m_{\gamma\gamma}$



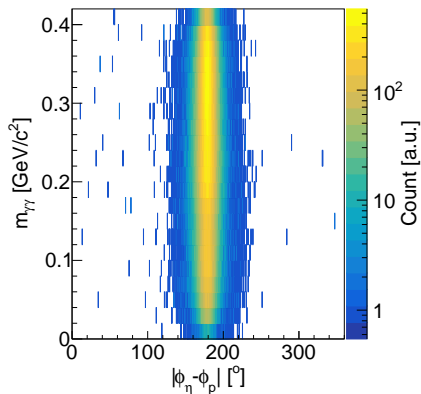
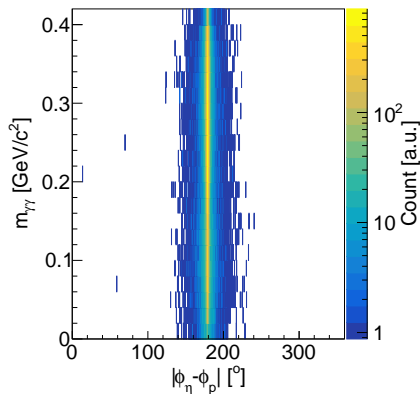
- Find lower value
- Find upper value

# FCAL2, coplanarity between $\eta$ and $p$

$m_{\gamma\gamma}$  vs. coplanarity between  $\eta$ -candidate and  $p$  for:

● Signal

● Background



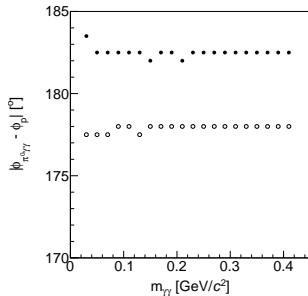
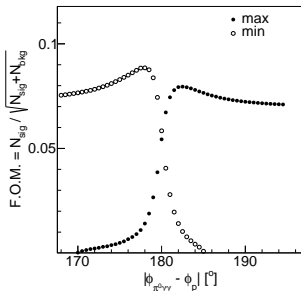
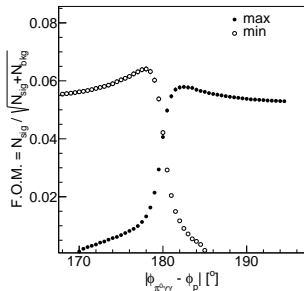
# FCAL2, coplanarity between $\eta$ and $p$

FOM vs. coplanarity between  $\eta$ -candidate and  $p$  for:

●  $m_{\gamma\gamma} = 110 \text{ MeV}/c^2$

●  $m_{\gamma\gamma} = 310 \text{ MeV}/c^2$

● Selection criteria vs.  $m_{\gamma\gamma}$

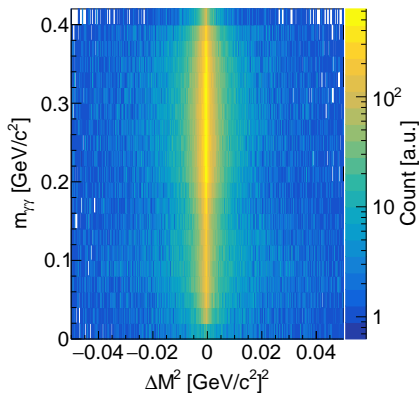


- Find lower value
- Find upper value

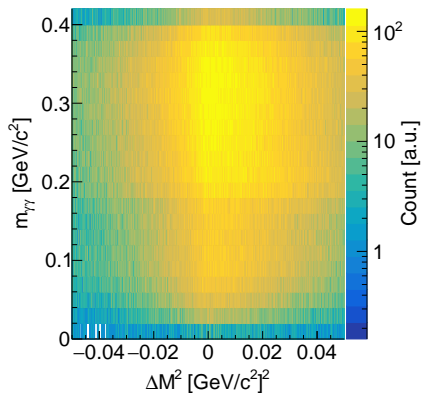
# FCAL2, mass conservation

$m_{\gamma\gamma}$  vs. mass conservation,  $\Delta M^2$ , for:

● Signal



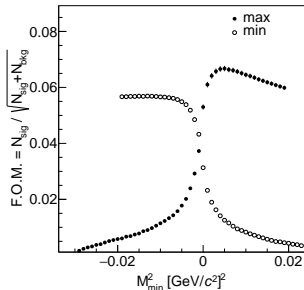
● Background



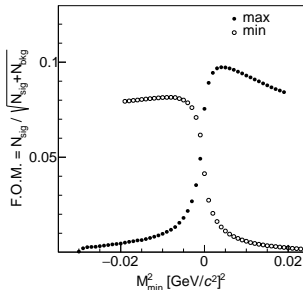
# FCAL2, mass conservation

FOM vs. mass conservation for:

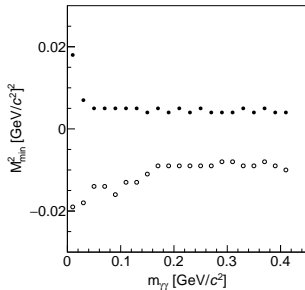
●  $m_{\gamma\gamma} = 110 \text{ MeV}/c^2$



●  $m_{\gamma\gamma} = 310 \text{ MeV}/c^2$



● Selection criteria vs.  $m_{\gamma\gamma}$



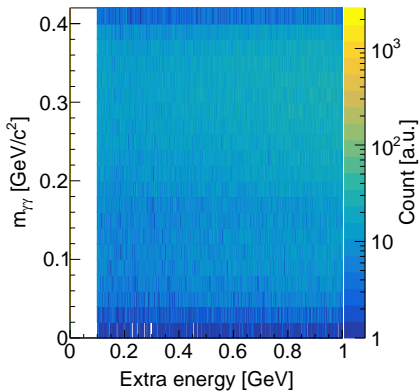
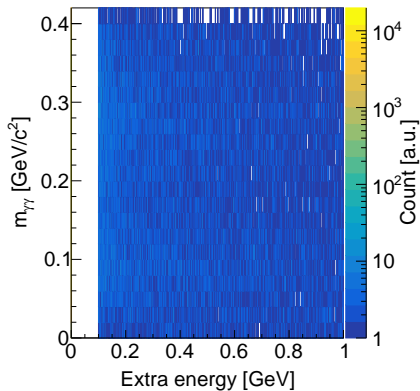
- Find lower value
- Find upper value

# FCAL2, extra energy

$m_{\gamma\gamma}$  vs. extra energy for:

● Signal

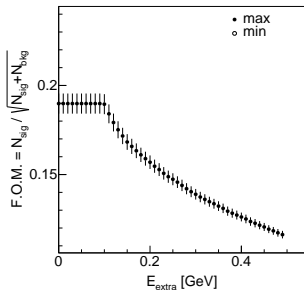
● Background



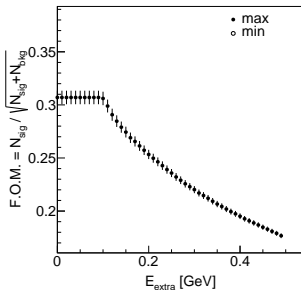
# FCAL2, extra energy

FOM vs. extra energy for:

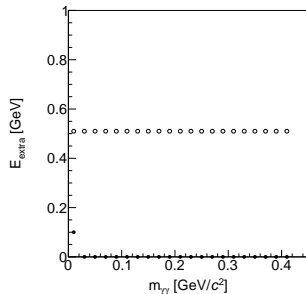
•  $m_{\gamma\gamma} = 110 \text{ MeV}/c^2$



•  $m_{\gamma\gamma} = 310 \text{ MeV}/c^2$



• Selection criteria vs.  $m_{\gamma\gamma}$



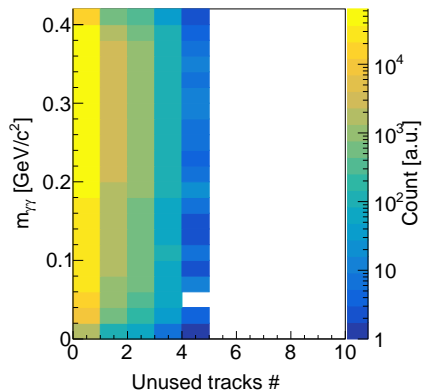
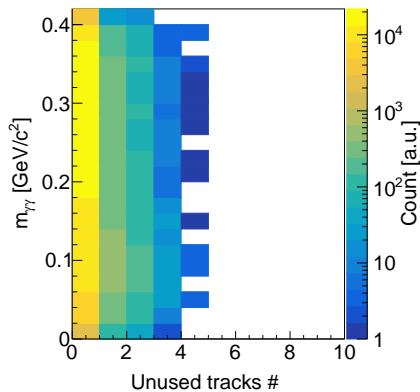
• Find value

# FCAL2, unused track number

$m_{\gamma\gamma}$  vs. unused track number for:

● Signal

● Background





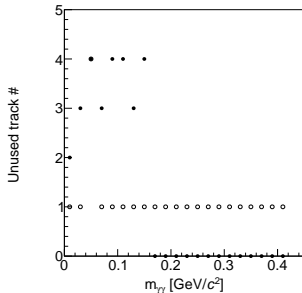
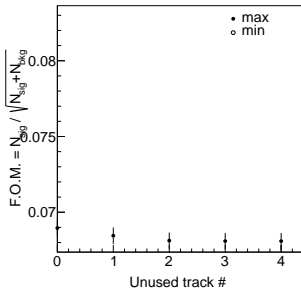
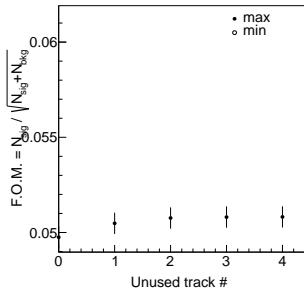
# FCAL2, unused track number

FOM vs. unused track number for:

●  $m_{\gamma\gamma} = 110 \text{ MeV}/c^2$

●  $m_{\gamma\gamma} = 310 \text{ MeV}/c^2$

● Selection criteria vs.  $m_{\gamma\gamma}$



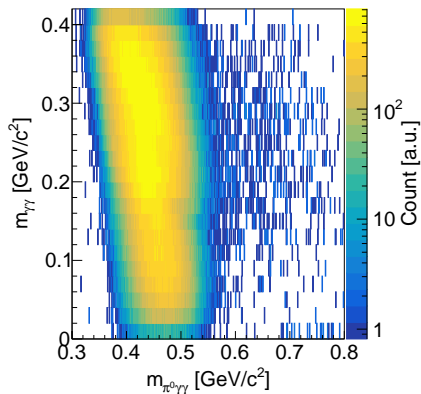
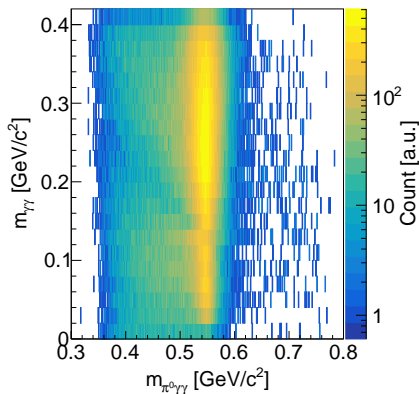
● Find value

# FCAL2, $\pi^0\gamma\gamma$ invariant mass

$m_{\gamma\gamma}$  vs.  $\pi^0\gamma\gamma$  invariant mass for:

● Signal

● Background



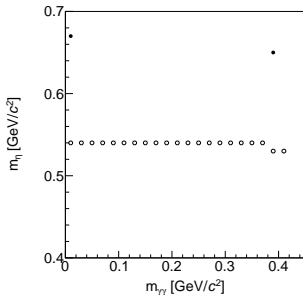
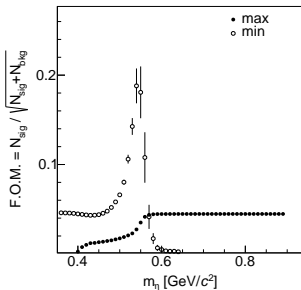
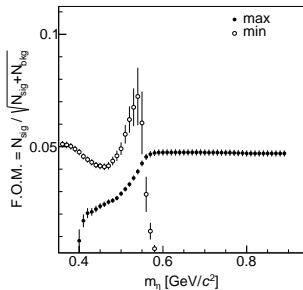
# FCAL2, $\pi^0\gamma\gamma$ invariant mass

FOM vs.  $\pi^0\gamma\gamma$  invariant mass for:

●  $m_{\gamma\gamma} = 110 \text{ MeV}/c^2$

●  $m_{\gamma\gamma} = 310 \text{ MeV}/c^2$

● Selection criteria vs.  $m_{\gamma\gamma}$



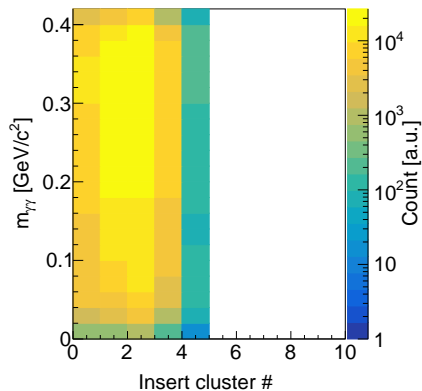
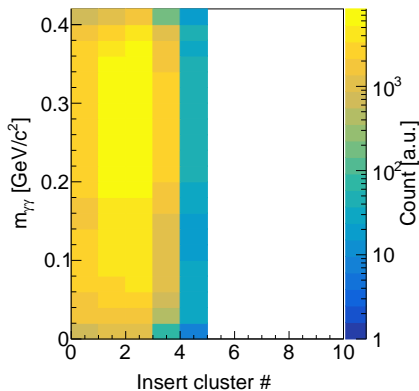
- Find lower value
- Find upper value

# FCAL2, cluster number below $4.5^\circ$

$m_{\gamma\gamma}$  vs. cluster number below  $4.5^\circ$  for:

● Signal

● Background



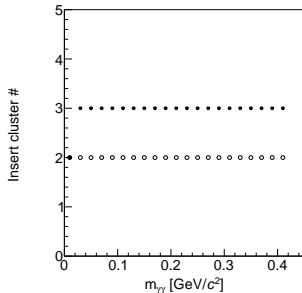
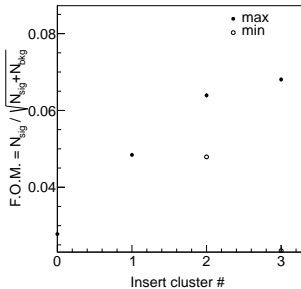
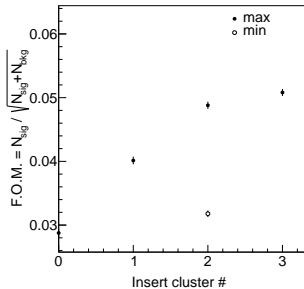
# FCAL2, cluster number below $4.5^\circ$

FOM vs. cluster number below  $4.5^\circ$  for:

●  $m_{\gamma\gamma} = 110 \text{ MeV}/c^2$

●  $m_{\gamma\gamma} = 310 \text{ MeV}/c^2$

● Selection criteria vs.  $m_{\gamma\gamma}$



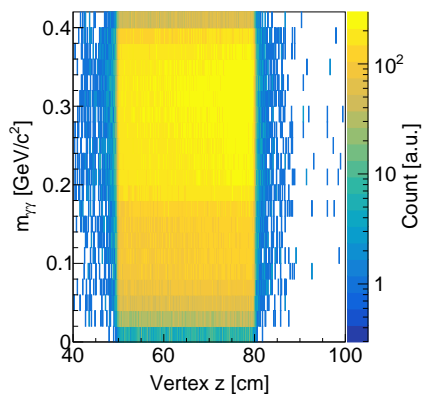
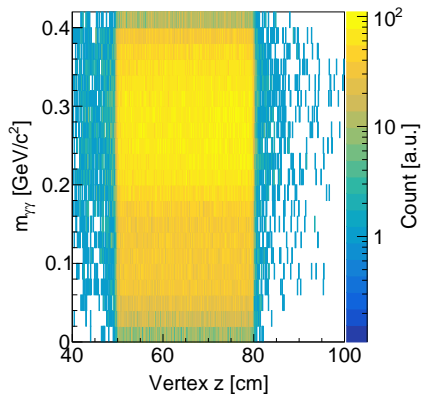
- Find lower value
- Find upper value

# FCAL2, vertex production z

$m_{\gamma\gamma}$  vs. vertex production z for:

● Signal

● Background



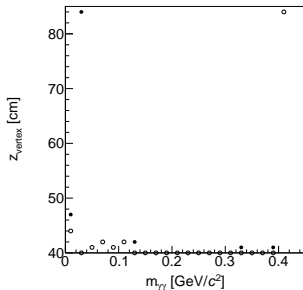
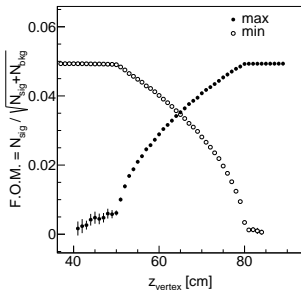
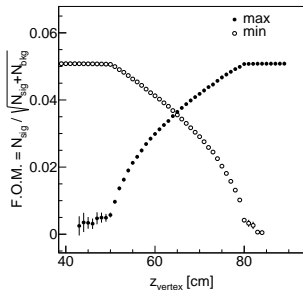
# FCAL2, vertex production z

FOM vs. vertex production z for:

●  $m_{\gamma\gamma} = 110 \text{ MeV}/c^2$

●  $m_{\gamma\gamma} = 310 \text{ MeV}/c^2$

● Selection criteria vs.  $m_{\gamma\gamma}$



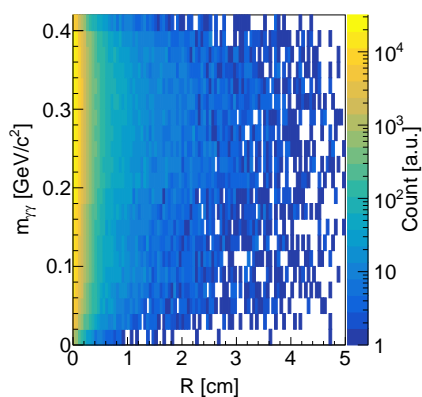
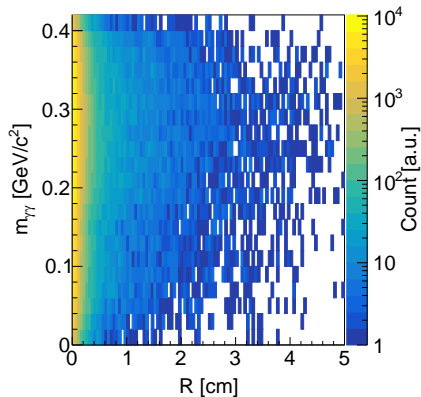
- Find lower value
- Find upper value

# FCAL2, vertex production $r$

$m_{\gamma\gamma}$  vs. vertex production  $r$  for:

● Signal

● Background





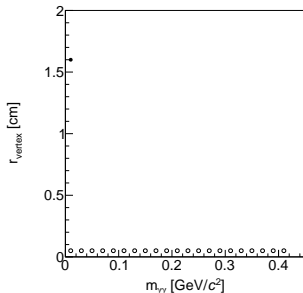
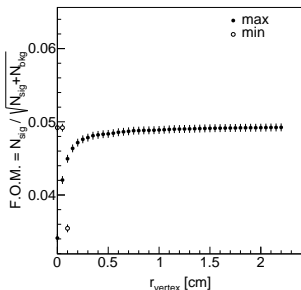
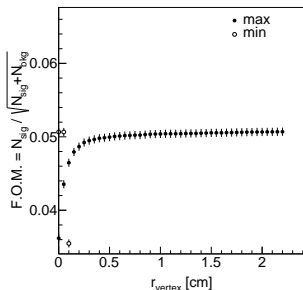
# FCAL2, vertex production r

FOM vs. vertex production r for:

●  $m_{\gamma\gamma} = 110 \text{ MeV}/c^2$

●  $m_{\gamma\gamma} = 310 \text{ MeV}/c^2$

● Selection criteria vs.  $m_{\gamma\gamma}$



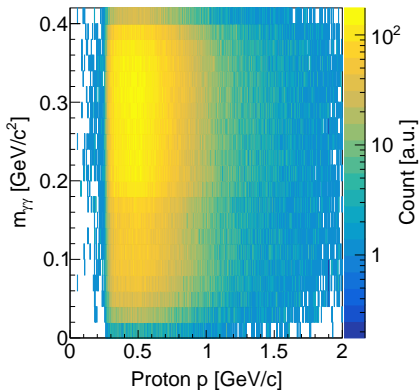
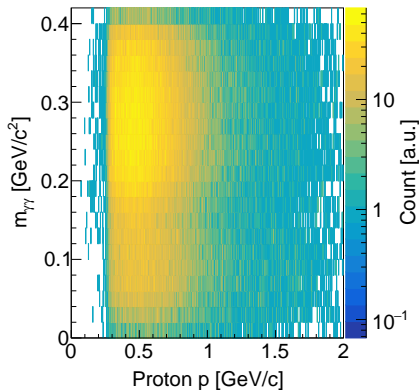
- Find lower value
- Find upper value

# FCAL2, proton momentum

$m_{\gamma\gamma}$  vs. proton momentum for:

● Signal

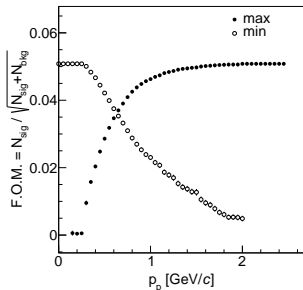
● Background



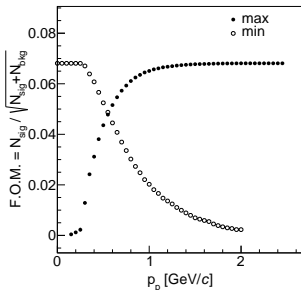
# FCAL2, proton momentum

FOM vs. proton momentum for:

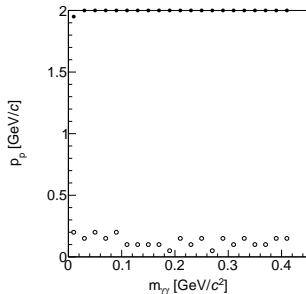
●  $m_{\gamma\gamma} = 110 \text{ MeV}/c^2$



●  $m_{\gamma\gamma} = 310 \text{ MeV}/c^2$



● Selection criteria vs.  $m_{\gamma\gamma}$



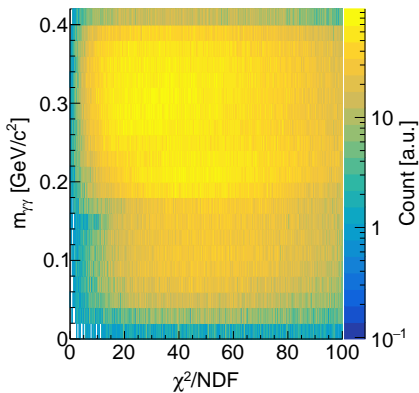
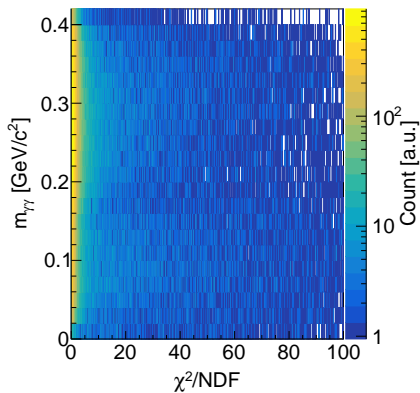
- Find lower value
- Find upper value

# FCAL, Kinfitt $\chi^2$

$m_{\gamma\gamma}$  vs. vs. kinfitt  $\chi^2$  for:

● Signal

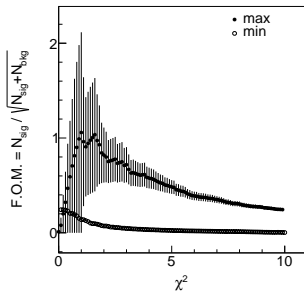
● Background



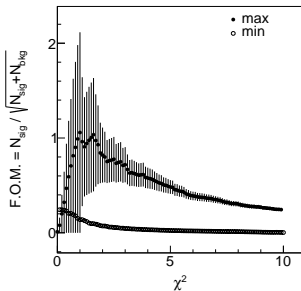
# FCAL, Kinfitt $\chi^2$

FOM vs. kinfitt  $\chi^2$ :

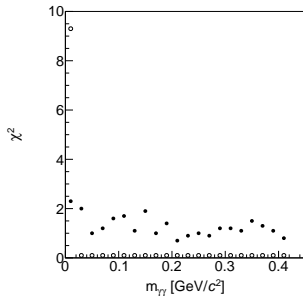
•  $m_{\gamma\gamma} = 110 \text{ MeV}/c^2$



•  $m_{\gamma\gamma} = 310 \text{ MeV}/c^2$



• Selection criteria vs.  $m_{\gamma\gamma}$



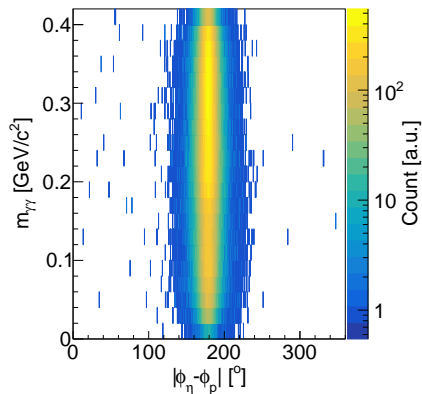
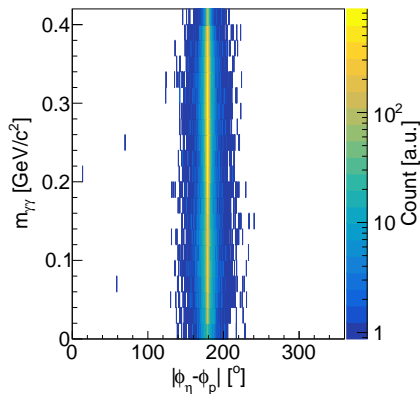
- Find lower value
- Find upper value

# FCAL, Coplanarity between $\eta$ and $p$

$m_{\gamma\gamma}$  vs. coplanarity between  $\eta$ -candidate and  $p$  for:

● Signal

● Background



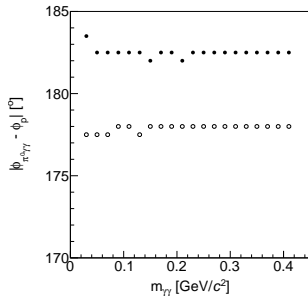
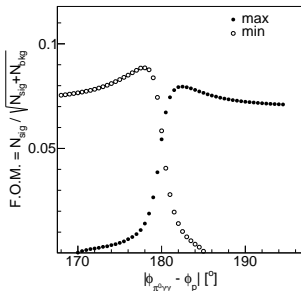
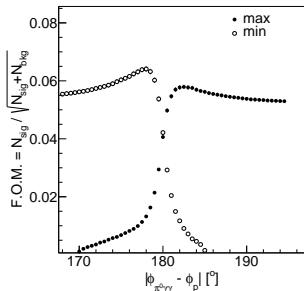
# FCAL, coplanarity between $\eta$ and $p$

FOM vs. coplanarity between  $\eta$ -candidate and  $p$  for:

●  $m_{\gamma\gamma} = 110 \text{ MeV}/c^2$

●  $m_{\gamma\gamma} = 310 \text{ MeV}/c^2$

● Selection criteria vs.  $m_{\gamma\gamma}$

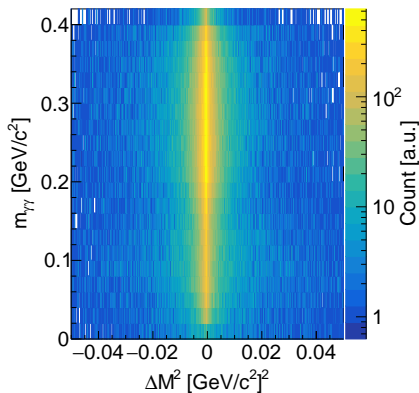


- Find lower value
- Find upper value

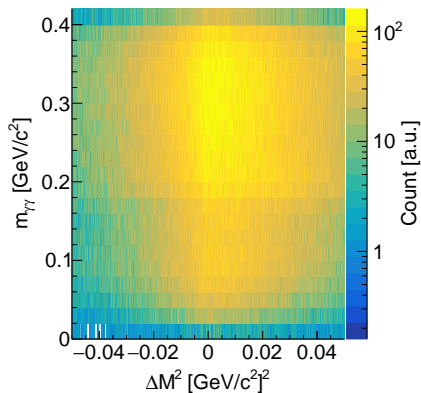
# FCAL, mass conservation

$m_{\gamma\gamma}$  vs. mass conservation,  $\Delta M^2$ , for:

● Signal



● Background

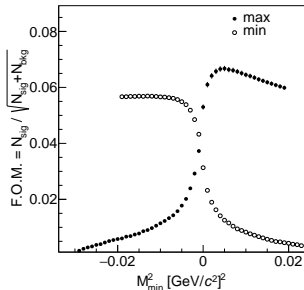




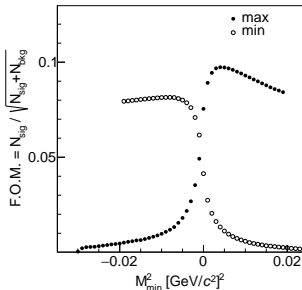
# FCAL, mass conservation

FOM vs. mass conservation for:

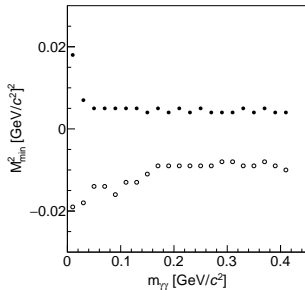
●  $m_{\gamma\gamma} = 110 \text{ MeV}/c^2$



●  $m_{\gamma\gamma} = 310 \text{ MeV}/c^2$



● Selection criteria vs.  $m_{\gamma\gamma}$



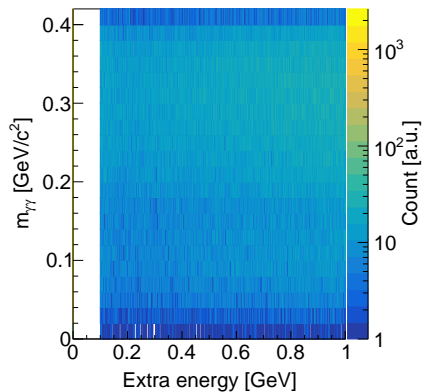
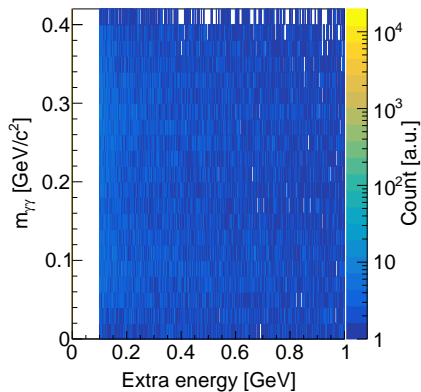
- Find lower value
- Find upper value

# FCAL, extra energy

$m_{\gamma\gamma}$  vs. extra energy for:

● Signal

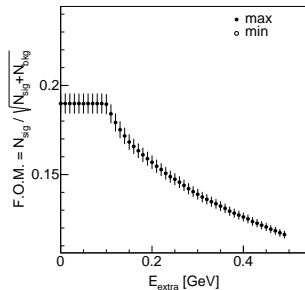
● Background



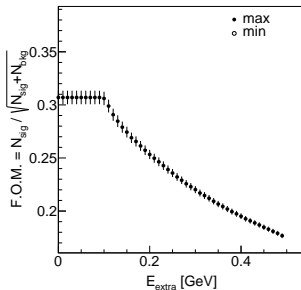
# FCAL, extra energy

FOM vs. extra energy for:

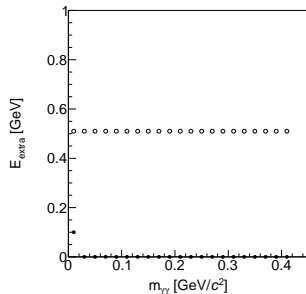
•  $m_{\gamma\gamma} = 110 \text{ MeV}/c^2$



•  $m_{\gamma\gamma} = 310 \text{ MeV}/c^2$



• Selection criteria vs.  $m_{\gamma\gamma}$



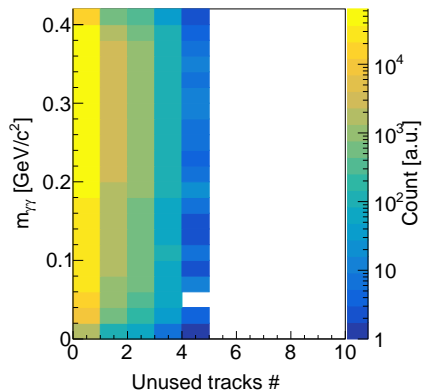
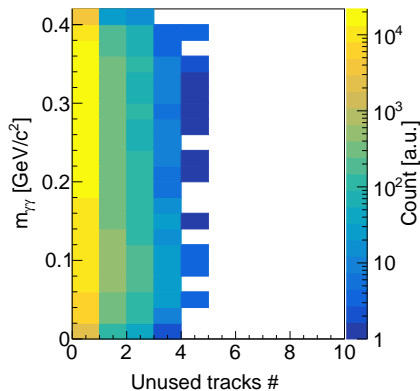
• Find value

# FCAL, unused track number

$m_{\gamma\gamma}$  vs. unused track number for:

● Signal

● Background



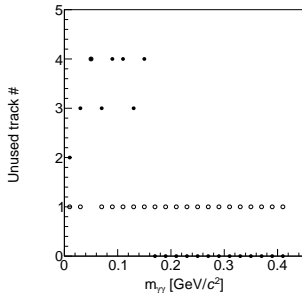
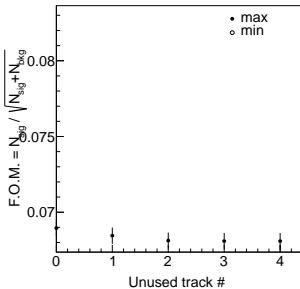
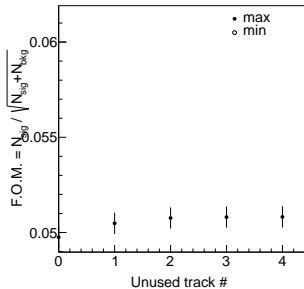
# FCAL, unused track number

FOM vs. unused track number for:

●  $m_{\gamma\gamma} = 110 \text{ MeV}/c^2$

●  $m_{\gamma\gamma} = 310 \text{ MeV}/c^2$

● Selection criteria vs.  $m_{\gamma\gamma}$



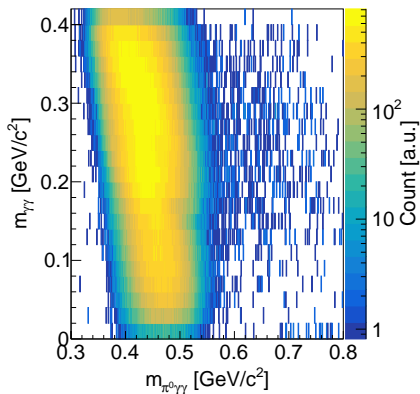
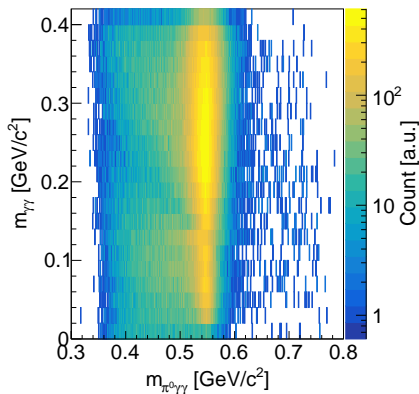
● Find value

# FCAL, $\pi^0\gamma\gamma$ invariant mass

$m_{\gamma\gamma}$  vs.  $\pi^0\gamma\gamma$  invariant mass for:

● Signal

● Background



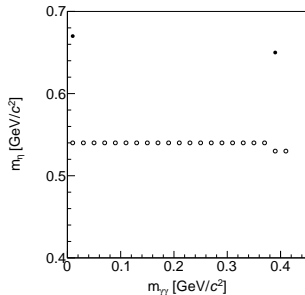
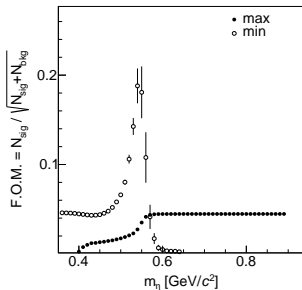
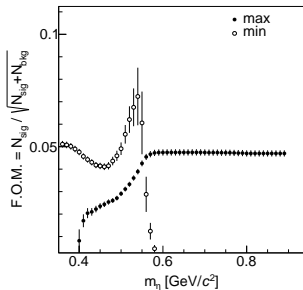
# FCAL, $\pi^0\gamma\gamma$ invariant mass

FOM vs.  $\pi^0\gamma\gamma$  invariant mass for:

●  $m_{\gamma\gamma} = 110 \text{ MeV}/c^2$

●  $m_{\gamma\gamma} = 310 \text{ MeV}/c^2$

● Selection criteria vs.  $m_{\gamma\gamma}$



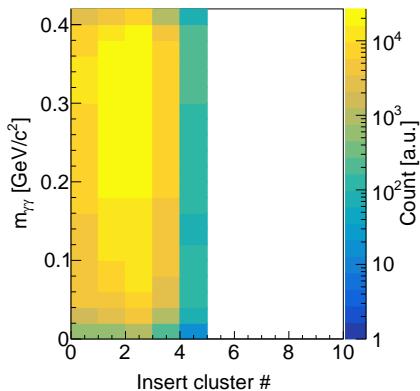
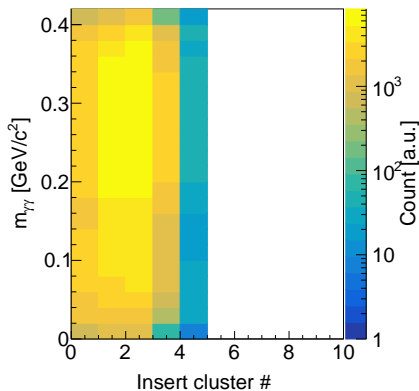
- Find lower value
- Find upper value

# FCAL, cluster number below $4.5^\circ$

$m_{\gamma\gamma}$  vs. cluster number below  $4.5^\circ$  for:

● Signal

● Background





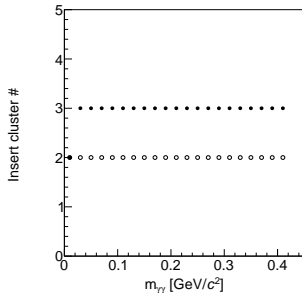
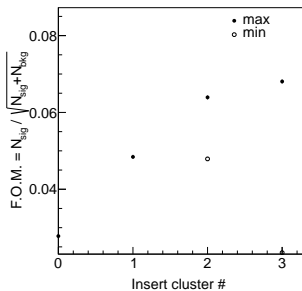
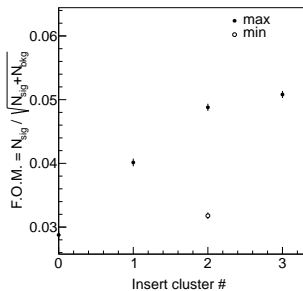
# FCAL, cluster number below $4.5^\circ$

FOM vs. cluster number below  $4.5^\circ$  for:

●  $m_{\gamma\gamma} = 110 \text{ MeV}/c^2$

●  $m_{\gamma\gamma} = 310 \text{ MeV}/c^2$

● Selection criteria vs.  $m_{\gamma\gamma}$



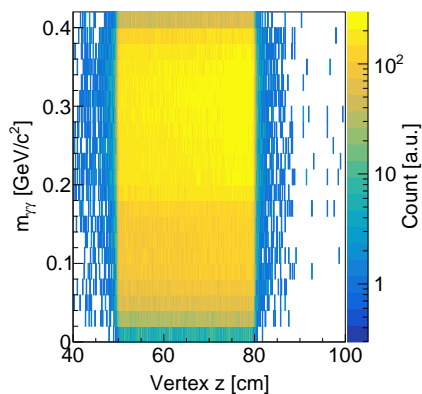
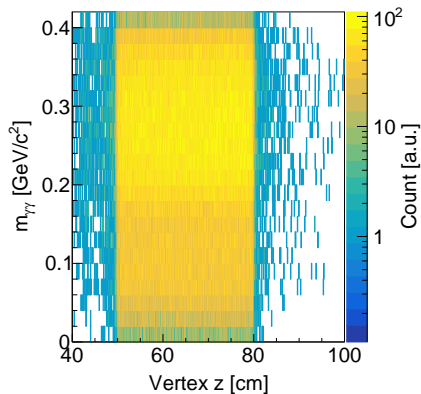
- Find lower value
- Find upper value

# FCAL, vertex production z

$m_{\gamma\gamma}$  vs. vertex production z for:

● Signal

● Background



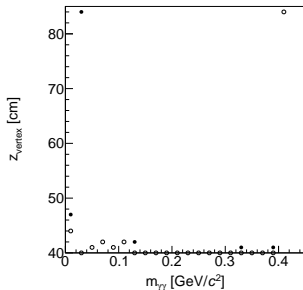
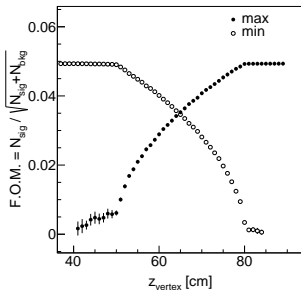
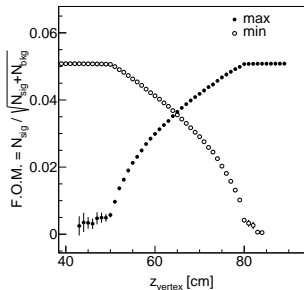
# FCAL, vertex production z

FOM vs. vertex production z for:

●  $m_{\gamma\gamma} = 110 \text{ MeV}/c^2$

●  $m_{\gamma\gamma} = 310 \text{ MeV}/c^2$

● Selection criteria vs.  $m_{\gamma\gamma}$



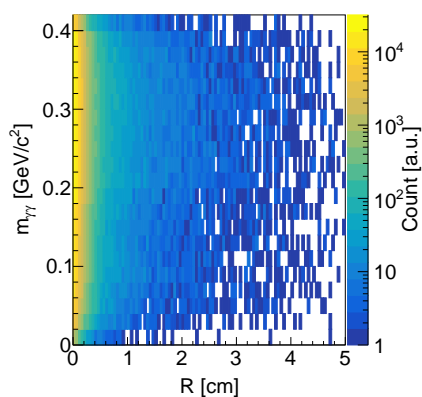
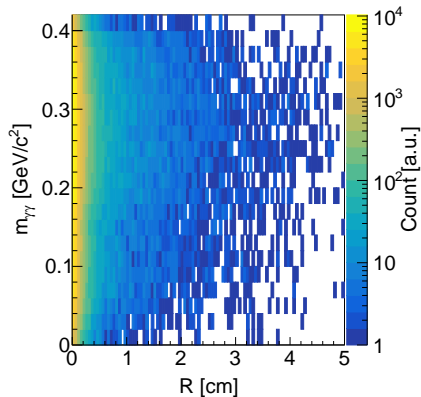
- Find lower value
- Find upper value

# FCAL, vertex production $r$

$m_{\gamma\gamma}$  vs. vertex production  $r$  for:

● Signal

● Background



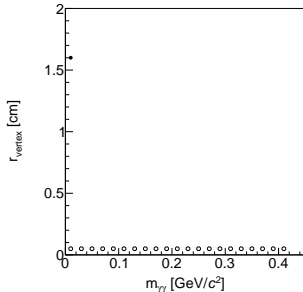
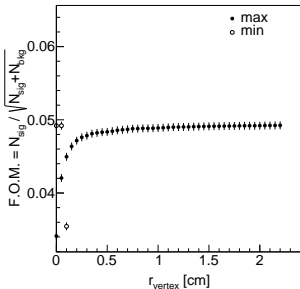
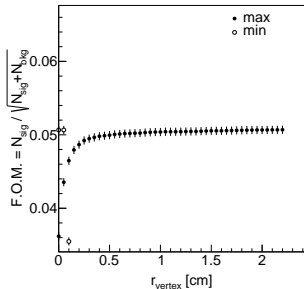
# FCAL, vertex production $r$

FOM vs. vertex production  $r$  for:

●  $m_{\gamma\gamma} = 110 \text{ MeV}/c^2$

●  $m_{\gamma\gamma} = 310 \text{ MeV}/c^2$

● Selection criteria vs.  $m_{\gamma\gamma}$



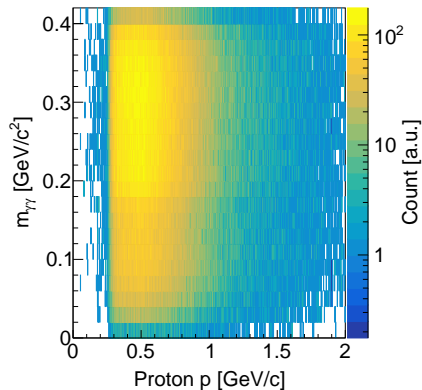
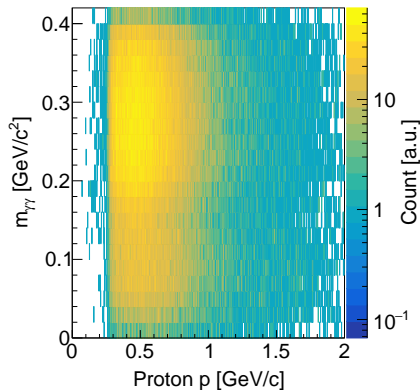
- Find lower value
- Find upper value

# FCAL, proton momentum

$m_{\gamma\gamma}$  vs. proton momentum for:

● Signal

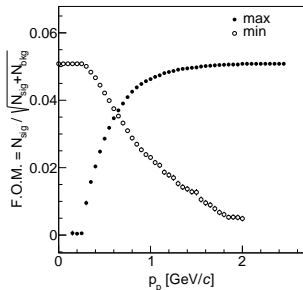
● Background



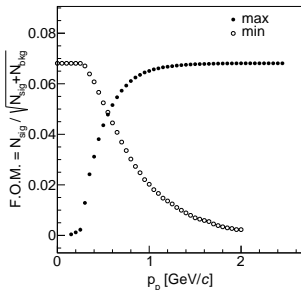
# FCAL, proton momentum

FOM vs. proton momentum for:

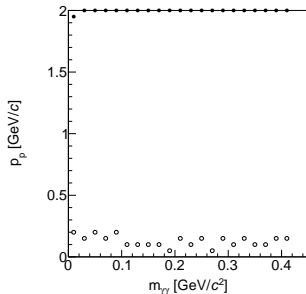
●  $m_{\gamma\gamma} = 110 \text{ MeV}/c^2$



●  $m_{\gamma\gamma} = 310 \text{ MeV}/c^2$



● Selection criteria vs.  $m_{\gamma\gamma}$



- Find lower value
- Find upper value

# Selection criteria individual effect

Each selection is applied individually

- Percentage of surviving events relative to the number of events passing the PID selection criteria i.e.  $4\gamma$ 's + proton
- FCAL2 ("JEF")

Selection criteria	$\pi^0\gamma\gamma$	$\pi^0\pi^0\pi^0$	0.01	0.05	0.1	0.2	0.3	0.4
$\chi^2$	37.2939	0.0125739	42.912	49.6509	46.5465	49.3675	45.0621	40.9101
$\eta$ mass	57.7636	0.29415	54.3901	61.6631	53.247	56.3289	54.349	57.0939
Extra energy	87.0665	3.50772	81.4739	87.2083	83.636	86.3082	86.2306	85.8524
Insert cluster #	13.4118	13.0171	7.26749	10.6096	10.319	12.7841	13.0609	7.22132
Coplanarity	77.079	27.290	73.8225	81.1225	77.2915	78.6463	76.7438	76.89078
Unused tracks	97.3437	94.1531	94.8914	97.6763	97.1152	97.5583	97.5463	97.6232
Vertex R	98.4515	99.1361	98.5727	98.5609	98.4881	98.4807	98.4593	98.3794
Vertex z	98.985	99.4657	99.0886	98.9905	99.0046	98.9819	98.9754	98.9266

- FCAL ("GlueX")

Selection criteria	$\pi^0\gamma\gamma$	$\pi^0\pi^0\pi^0$	0.01	0.05	0.1	0.2	0.3	0.4
$\chi^2$	43.672	0.0112184	37.2339	40.8227	38.847	41.2701	36.9526	31.8757
$\eta$ mass	52.823	0.225907	59.969	65.3512	56.3317	59.335	58.5022	60.3857
Extra energy	84.7308	3.78774	86.5824	89.2825	85.5537	87.7503	87.9114	87.6146
Insert Cluster #	10.9807	12.0343	9.03417	12.6199	12.0863	13.7393	14.2095	8.9927
Coplanarity	76.832	27.6318	76.4711	81.2351	77.5681	78.5437	76.8432	76.5972
Unused tracks	97.1863	93.9026	94.4392	97.6277	97.0667	97.5946	97.4696	97.5548
Vertex z	98.4894	98.9763	99.0886	98.9905	99.0046	98.9819	98.9754	98.9266
Vertex R	98.6571	99.3196	98.5727	98.5609	98.4881	98.4807	98.4593	98.3794

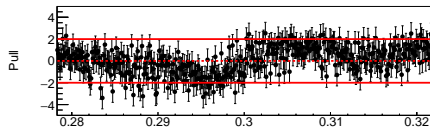
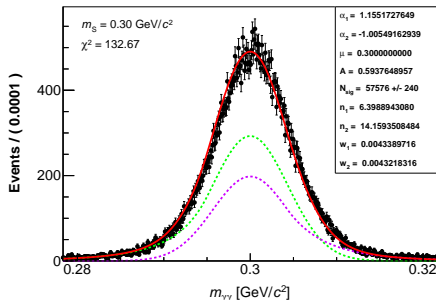
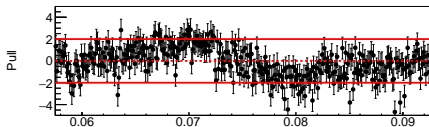
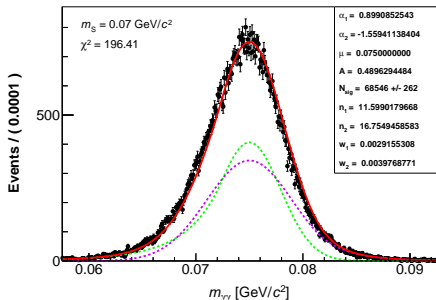
Kinfit  $\chi^2$  and  $\eta$  mass are the most selective criteria



# Signal PDF

Determined by Jared <https://hallweb.jlab.org/wiki/images/c/c9/Jared1.pdf>

- 2 Crystal Balls with common mean and two different widths
- Set of python macros that iterate until each parameter has a smooth behavior vs. mass

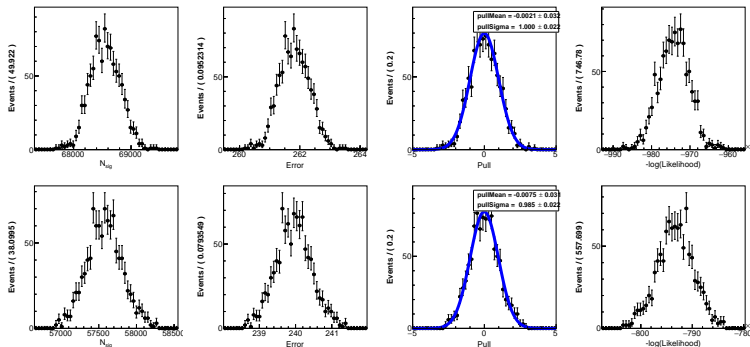


After 6th iteration, the behavior starts to be smooth

# Signal PDF, quality check

Determined by Jared <https://hallweb.jlab.org/wiki/images/c/c9/Jared1.pdf>

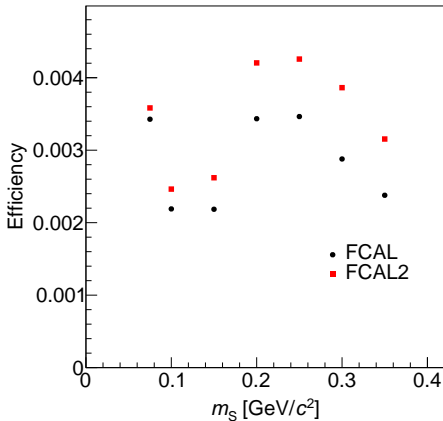
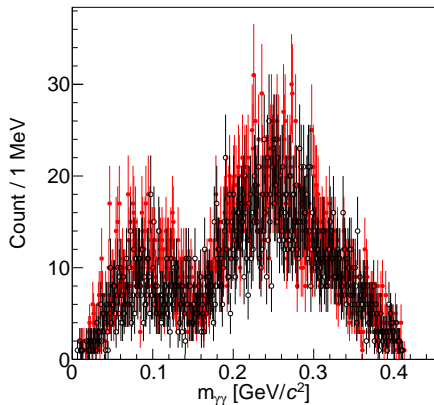
- RooFit build-in toy mc study to check fit quality
- Parametrization is working well between 75 and 350 MeV/ $2^2$
- At each edges, the PDF not yet determined



Good PDF, but Jared will also find a more simple PDF: Gauss + Crystal Ball or 2/3 Gauss

# Detection efficiency and irreducible background

After all selection criteria are applied:

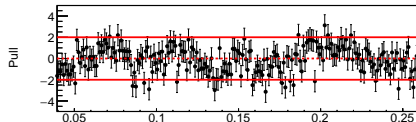
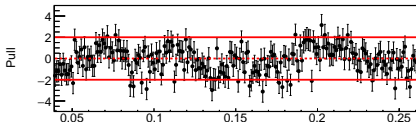
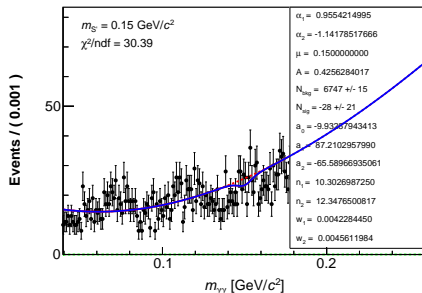
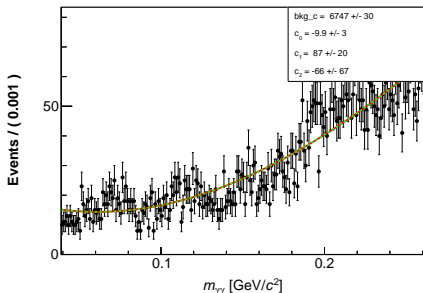


Background un-smooth behavior is still not understood

# Limit calculation

With ROOFIT and ROOSTAT build-in calculator

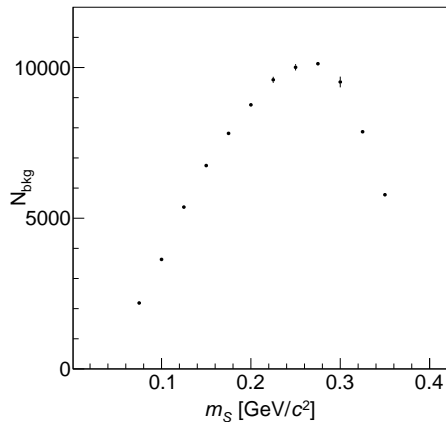
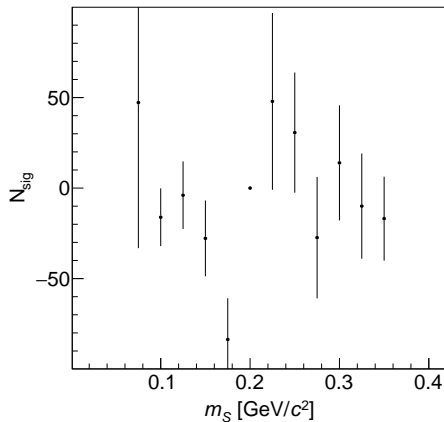
- Background PDF, 3rd polynomial
- 25 MeV/ $c^2$  step scan
- Fit range  $\pm 25 \cdot \sigma_{\text{weighted}}$  around the mass scanned



Model:  $N_{sig} \times \text{signal PDF} + N_{bkg} \times \text{background PDF}$

# Limit calculation

Measured  $N_{sig}$  and  $N_{bkg}$  vs mass

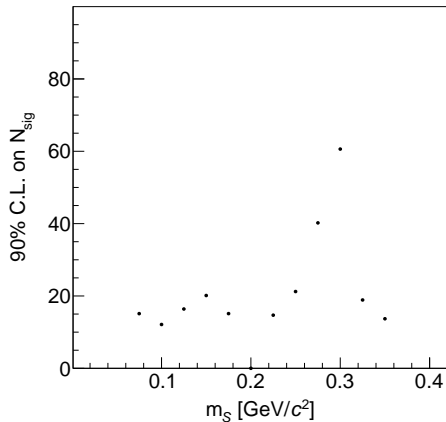
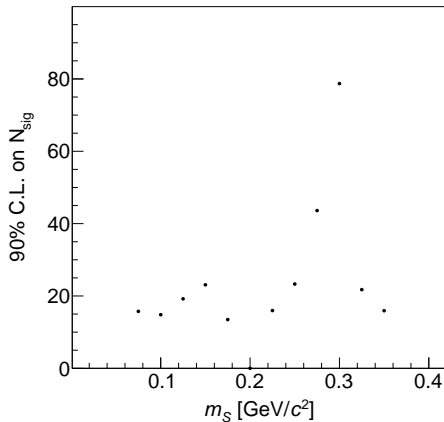


Shape and  $N_{sig}$  are transferred to the limit calculator

# Limit calculation

Two calculators used:

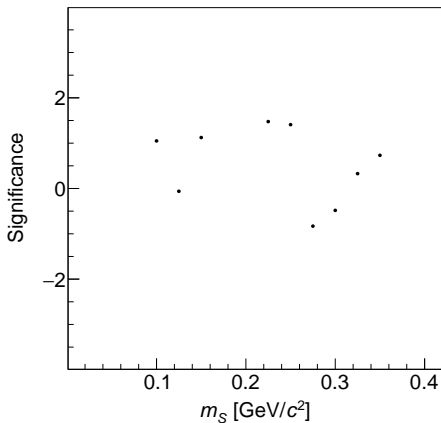
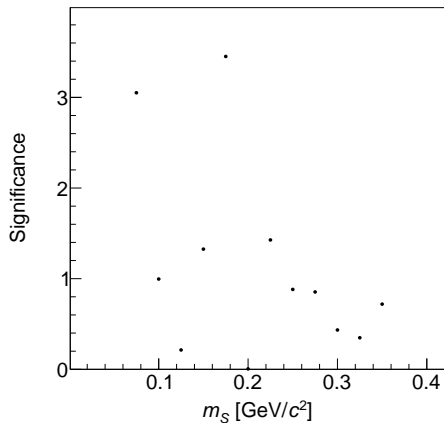
- ProfileLikelihoodCalculator
- BayesianCalculator



90% upper limit on the number of signal measured

# Limit calculation

Significance



As expected the background simulation as no signal but only large local fluctuations

# Baryonic fine structure constant

$\alpha_S$  using the equation for the partial width ratio  $\Gamma(\eta \rightarrow S\pi^0)/\Gamma(\eta \rightarrow \gamma\gamma)$  from B case and S. Tulin, PRD **89**, 114008 (2014) as:

$$\begin{aligned}\alpha_S &= \left[ \frac{\alpha}{2} \left( 1 - \frac{m_S^2}{m_\eta^2} \right)^{-3} \left| \mathcal{F}(m_S^2) \right|^{-2} \frac{1}{\mathcal{B}(S \rightarrow \gamma\gamma)} \right] \\ &\times \left[ \frac{\Gamma(\eta \rightarrow \gamma\pi^0\gamma)}{\Gamma(\eta \rightarrow \gamma\gamma)} \right] \\ &\times \left[ \frac{\Gamma(\eta \rightarrow S\pi^0 \rightarrow \gamma\pi^0\gamma)}{\Gamma(\eta \rightarrow \pi^0\gamma\gamma)} \right],\end{aligned}\tag{1}$$

where  $\alpha$  is the electromagnetic fine structure constant. The first factor in Eq. (1), which is purely theoretical, contains the phase space, the form factor  $\mathcal{F}(m_S^2)$ , and the branching fraction of  $S \rightarrow \gamma\gamma$  decay. The branching fraction provided in arXiv:1812.05103v1. The second factor is obtained from the latest measurements PDG. The third factor is determined from the  $\eta$  and  $S$  yields and reconstruction efficiencies ( $N_S/\varepsilon(\eta \rightarrow S\pi^0 \rightarrow \pi^0\gamma\gamma)/\alpha_S/(N_\eta/\varepsilon(\eta \rightarrow \pi^0\gamma\gamma))$ ). **Not** sure if  $\mathcal{F}(m_S^2)$  should be the same than for B case



# Conclusion

Preliminary selection criteria:

- Hand-made guided by FOM
- MVA (to do list)

Preliminary PDF for:

- Signal
- (Background, we will start once the non-smooth distribution is understood)  
=> Considered at the moment as a crude 3rd order Polynomial

Preliminary expected 90% upper limit on the number of signal measured