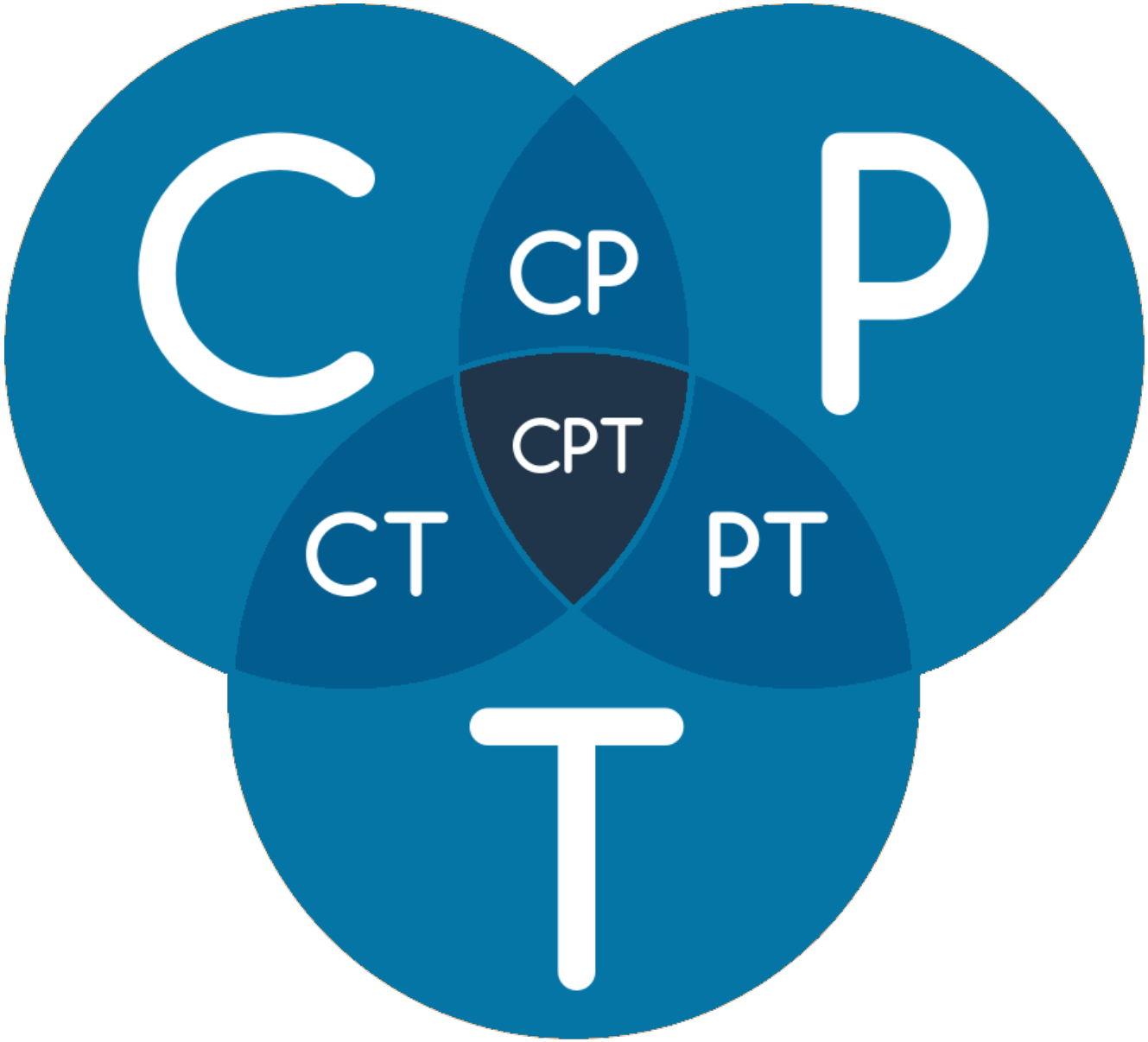
Search for symmetry violating η decays

Cristina Collicott

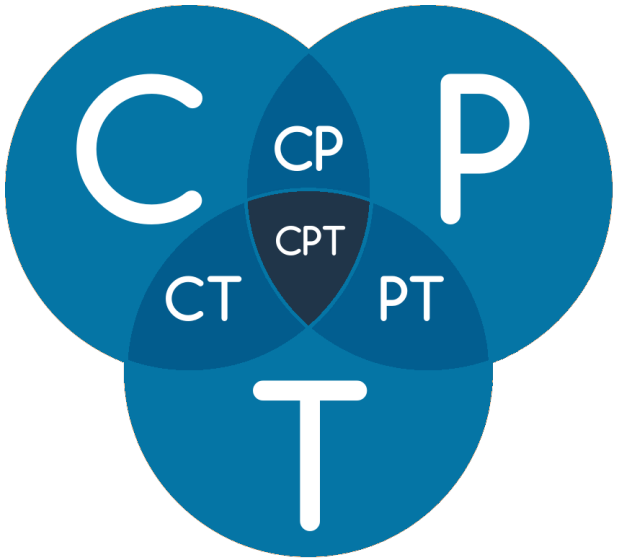
MESON 2018

Fundamental Symmetries



Current state of affairs

- Violation of C, P, and T in weak interactions



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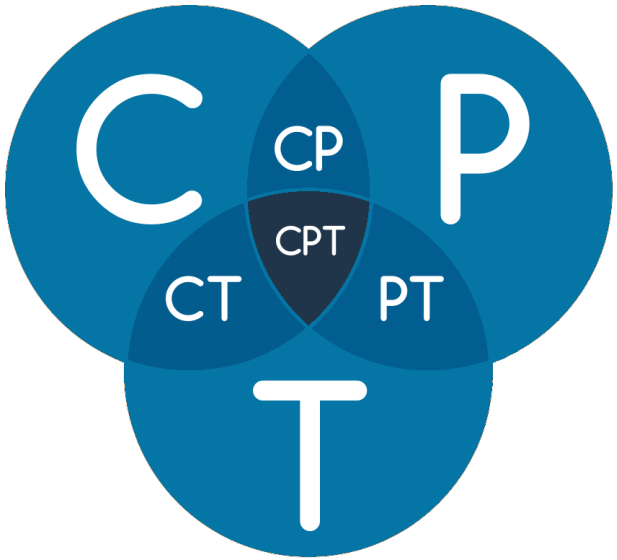

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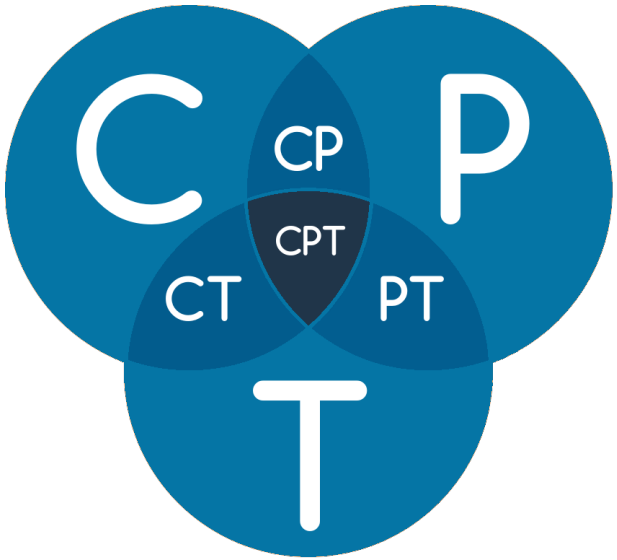

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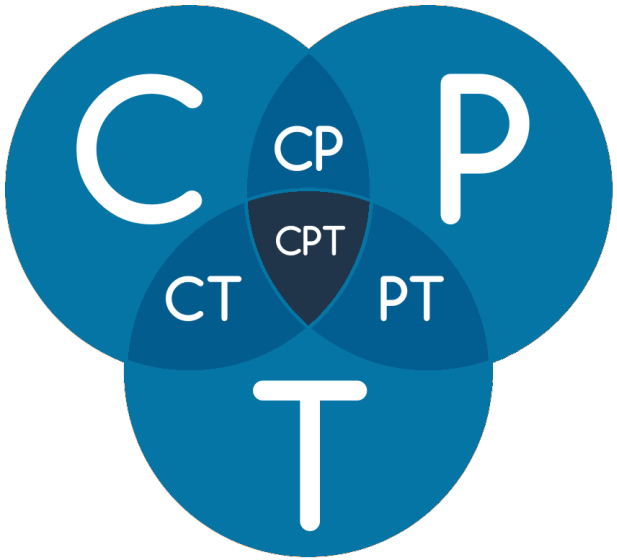

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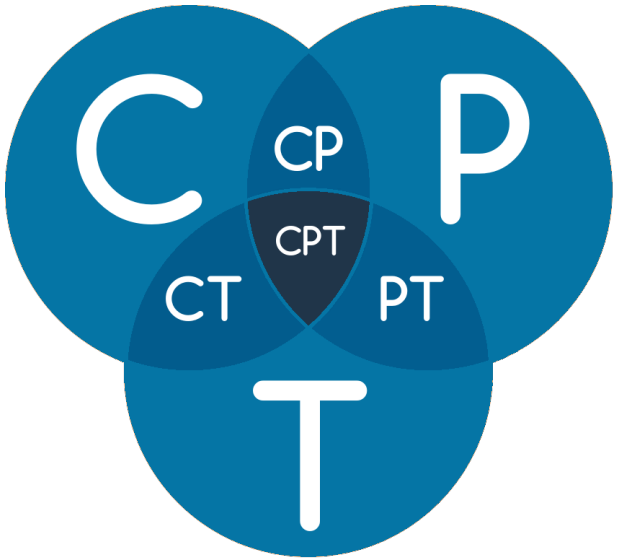
- Strong/EM/Gravity seem to be C/P/T invariant
- all CPT-violation tests are consistent with zero
- KM mechanism provides an elegant inclusion of CP violation into the SM (three mixing angles and one CP-violating complex phase)
- All measured CP violation has been explained with this mechanism



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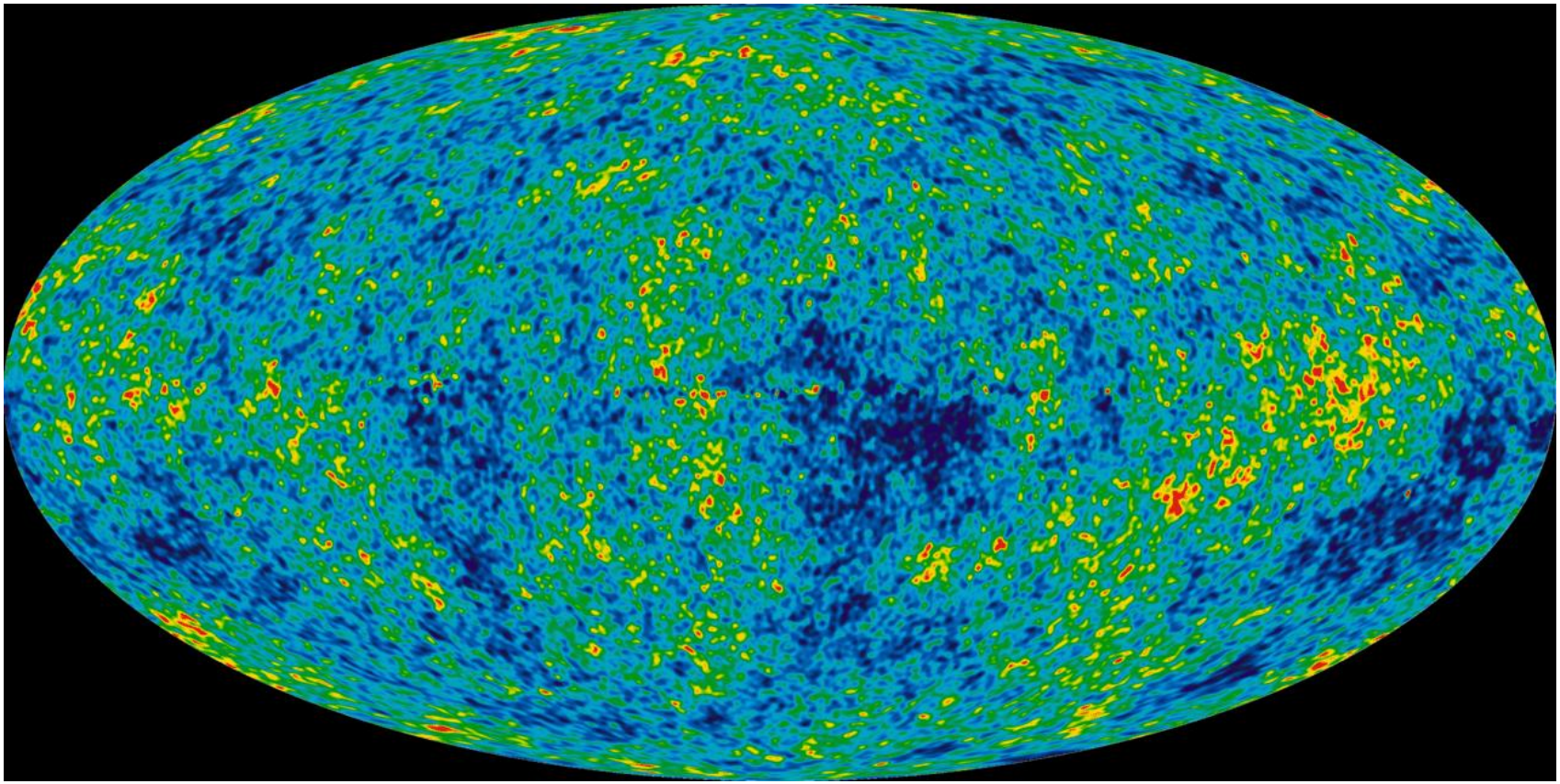

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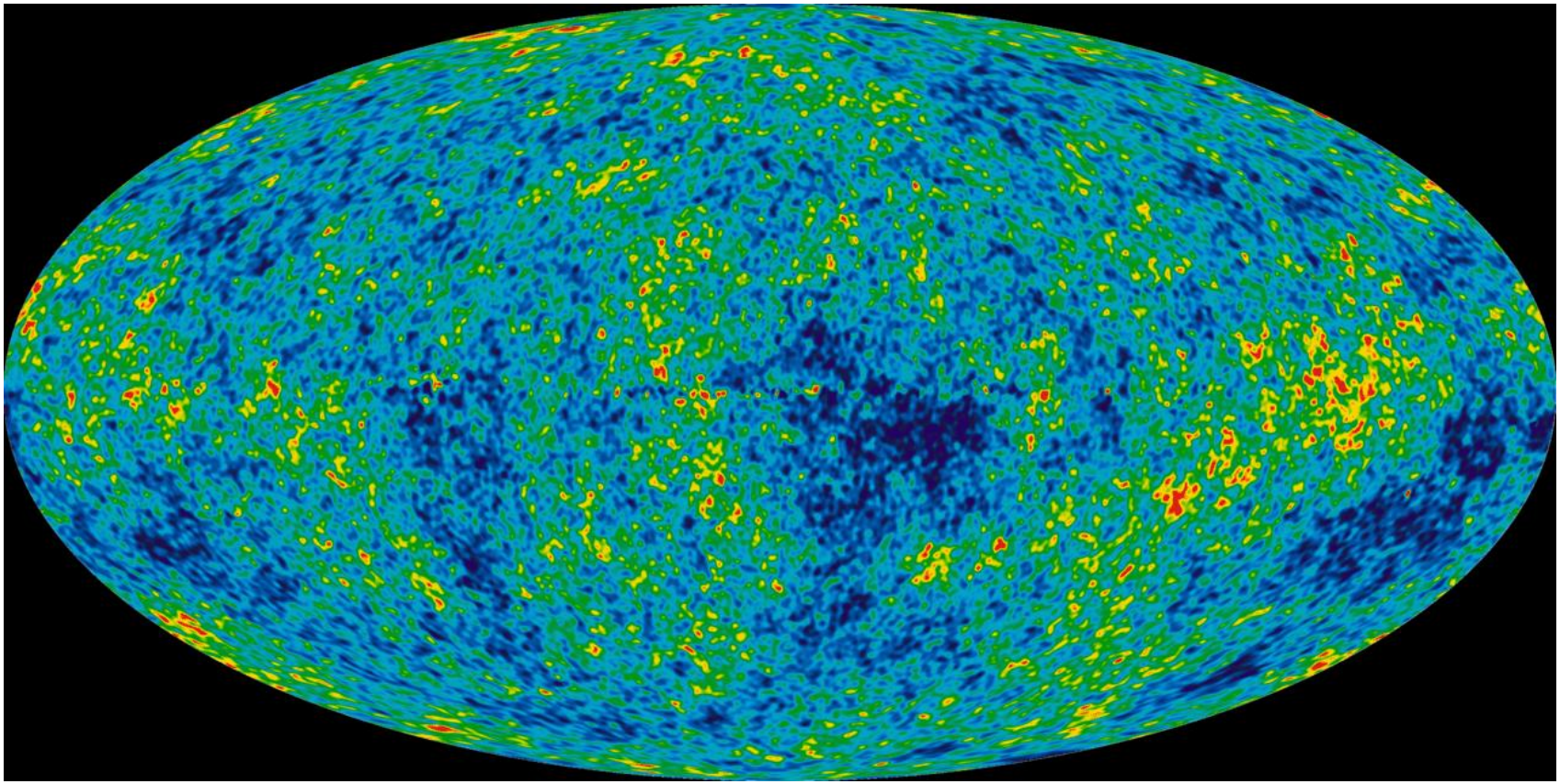

The (observable) Universe is matter dominated...

SM prediction for matter/antimatter is too small

Proposed search for new symmetry violating modes

There are **many** ongoing searches (B^0 mesons, Kaons, ...) for symmetry violating modes at facilities world wide (BaBar/Belle/...)

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- $\eta \to 3\gamma$ – C violating

with the Crystal Ball at MAMI

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We propose to search for the decays:

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- $\eta \to \pi^0\gamma$ – C violating
- $\eta \to 4\pi^0$ – CP violating

with the Crystal Ball at MAMI

Existing Upper Limits (UL)

Crystal Ball at AGS

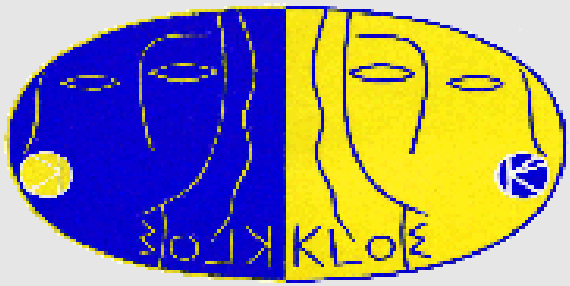
$(\eta \to 3\gamma) \quad < 4 \times 10^{-5}$
$(\eta \to \pi^0\gamma) < \mathbf{9 \times 10^{-5}}$
$(\eta \to \mathbf{4\pi^0}) < \mathbf{6.9 \times 10^{-7}}$

BROOKHAVEN NATIONAL LABORATORY

Determined from 3×10^7 η
Produced via $(\pi^- p \to \eta n)$

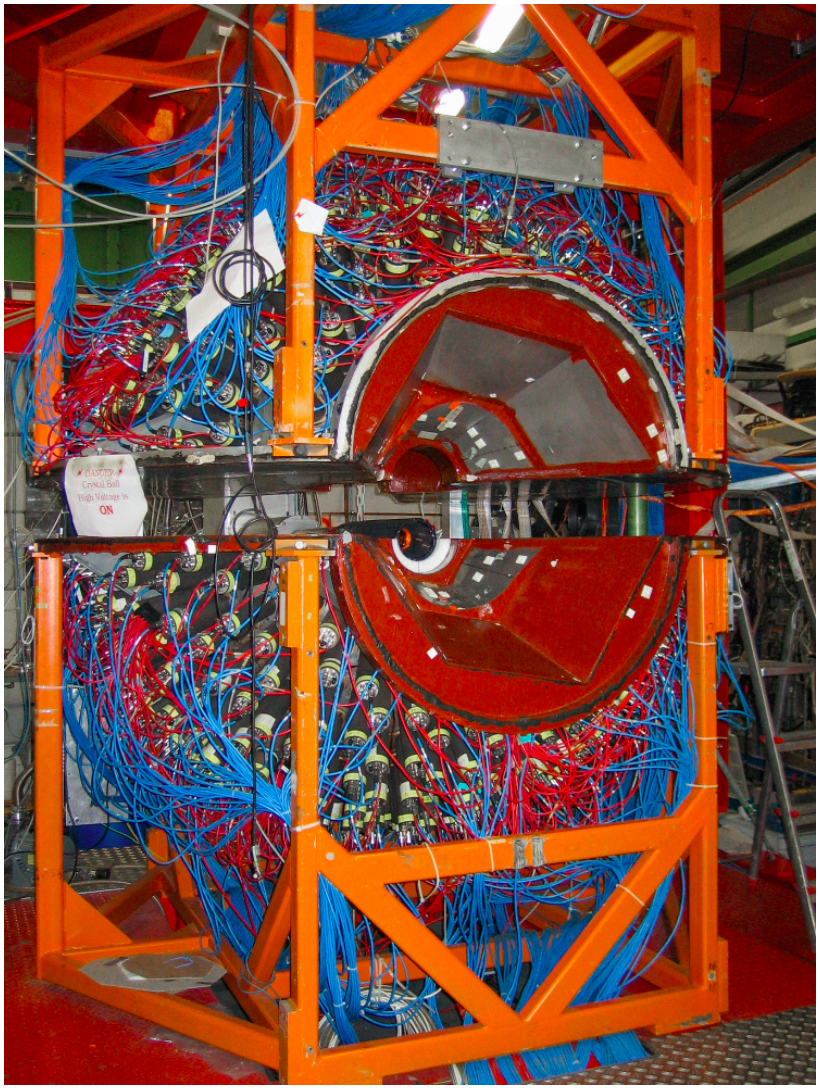
KLOE at DAFNE

$(\eta \to \mathbf{3\gamma}) < \mathbf{1.6 \times 10^{-5}}$



Determined from 1.8×10^7 η
Produced via $(\phi \to \eta\gamma)$

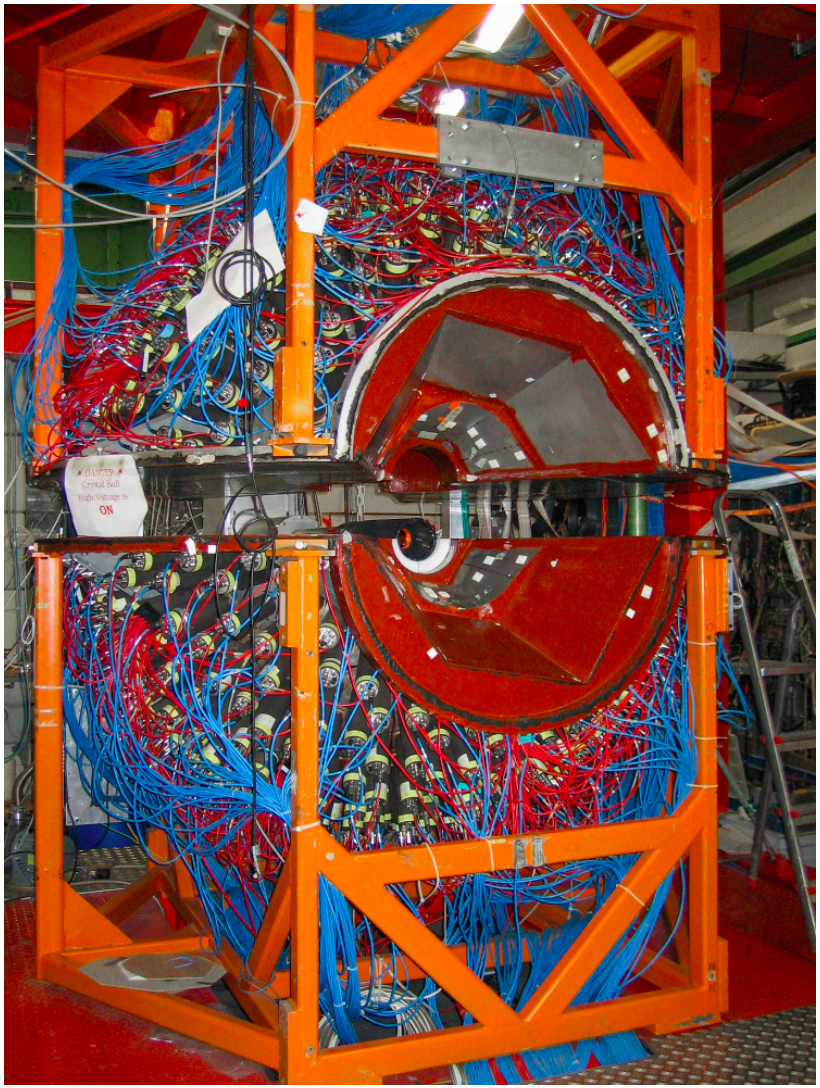
Crystal Ball at MAMI



Overview:

- MAMI: 1.6 GeV e^- accelerator

Crystal Ball at MAMI



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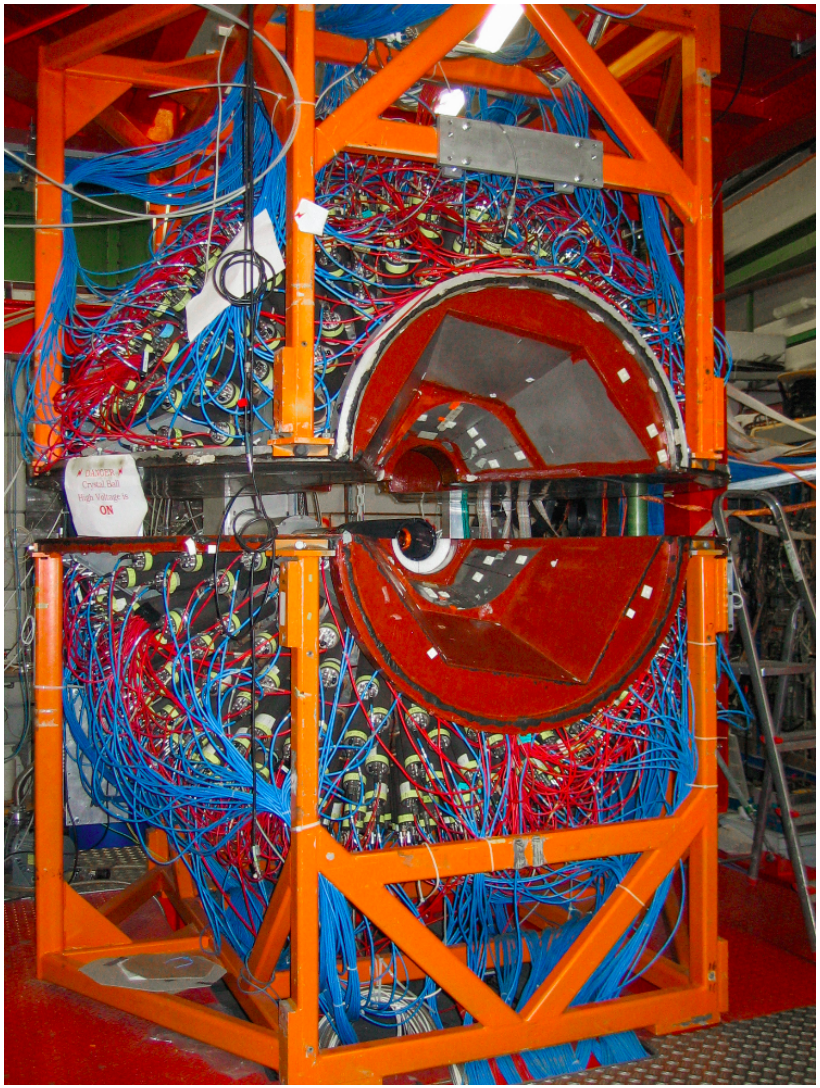

Overview:

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  η produced: $\gamma p \rightarrow \eta p$

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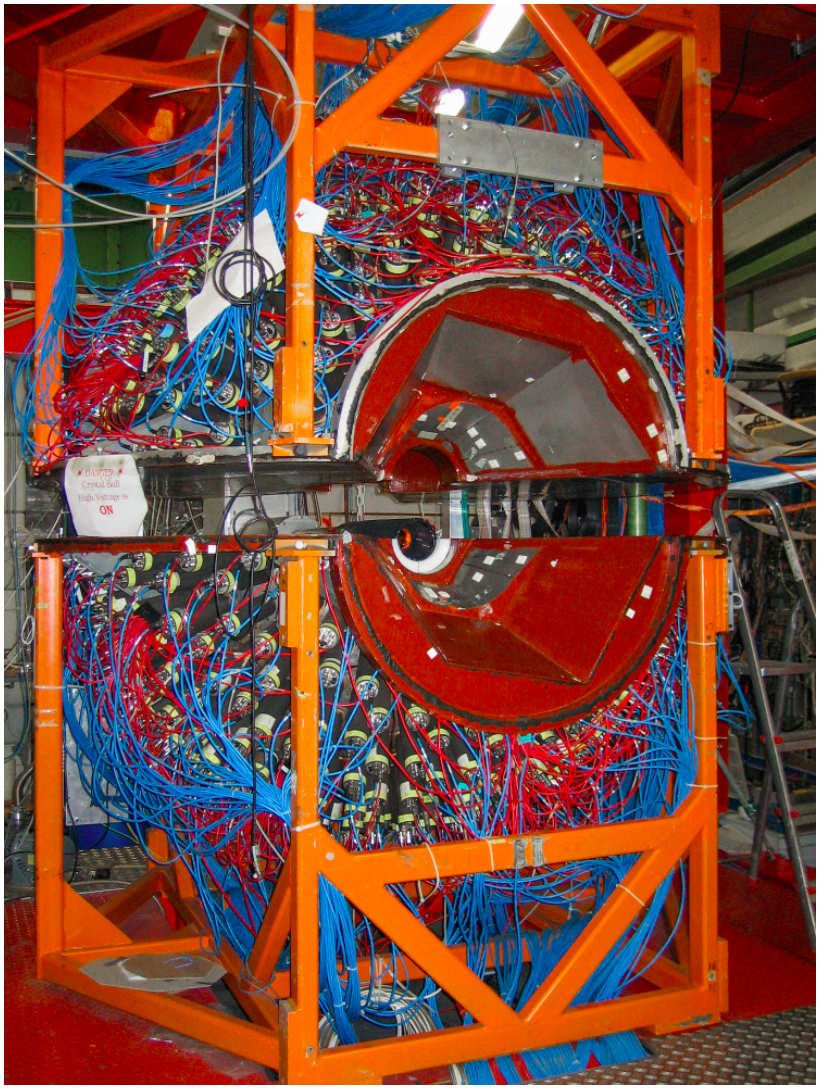

Overview:

- MAMI: 1.6 GeV e^- accelerator
- γ beam via Bremsstrahlung
- 10 cm liquid H_2 target
  η produced: $\gamma p \rightarrow \eta p$
- Crystal Ball and TAPS
  - excellent γ reconstruction!
  - large angular coverage
  (ideal for high multiplicity final states, $\eta \rightarrow 4\pi^0$)

η beamtimes in A2

Two beamtimes in 2007/2009

Run I - 2007

- E-MAMI = 1508 MeV
- 5 cm LH_2 target

Run II - 2009

- E-MAMI = 1557 MeV
- 10 cm LH_2 target

Total combined η mesons produced via $(\gamma p \rightarrow \eta p)$

$$\eta = (6.23 \pm 0.10) \times 10^7$$

*$\#\eta$ determined from an average between $\eta \rightarrow 3\pi^0$ and $\eta \rightarrow 2\gamma$

Analysis Approach

Event selection

- Final state # of photons (3/8)
- Kinematic fit (cut on decay, anti-cut on background)
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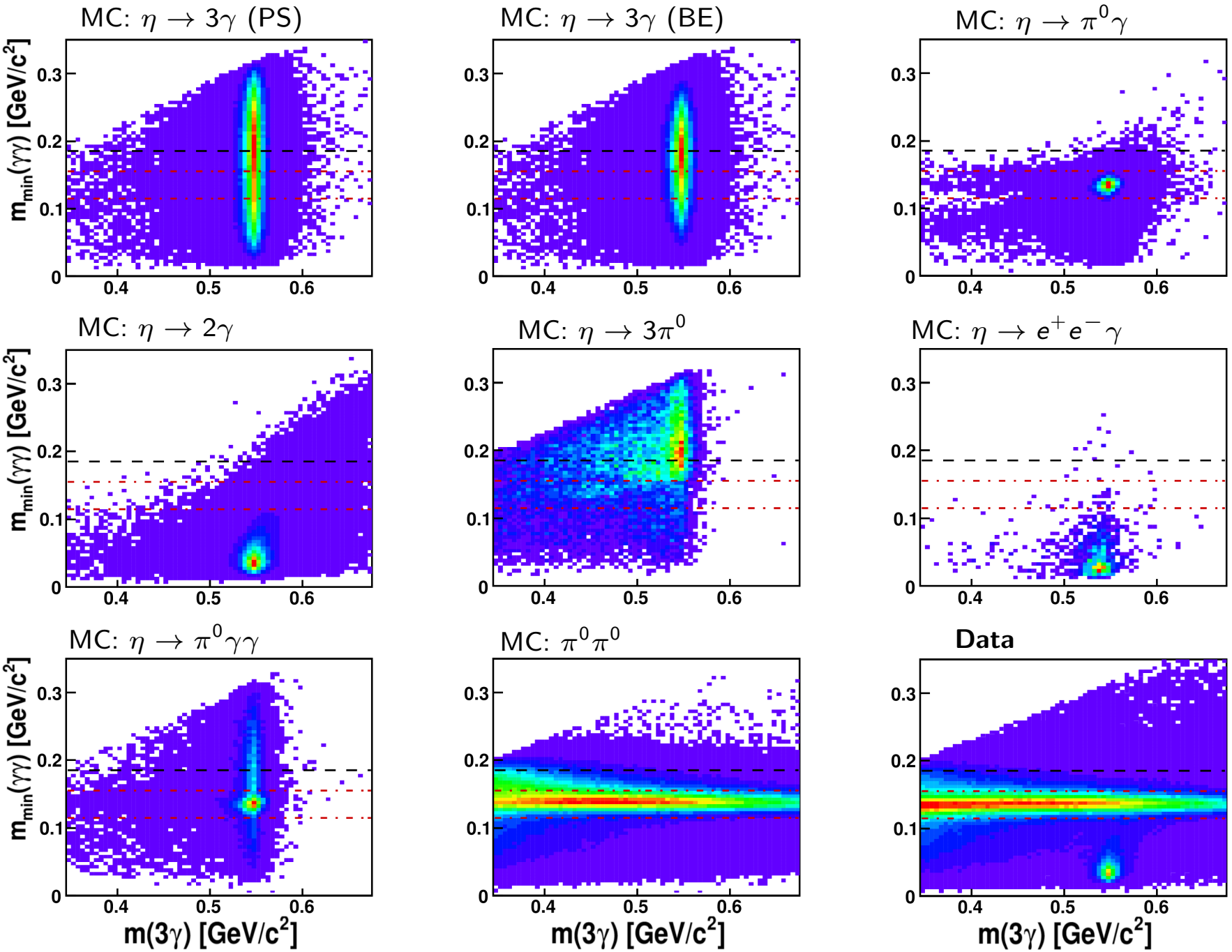
Correct number of signal events by det-eff, ϵ

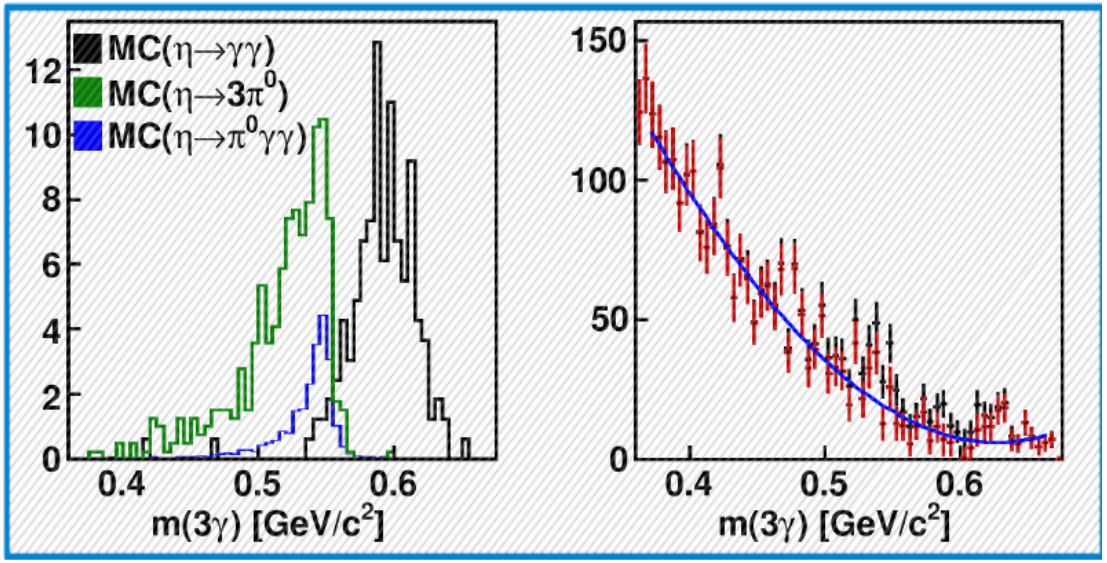
Smooth bkgs are parameterized

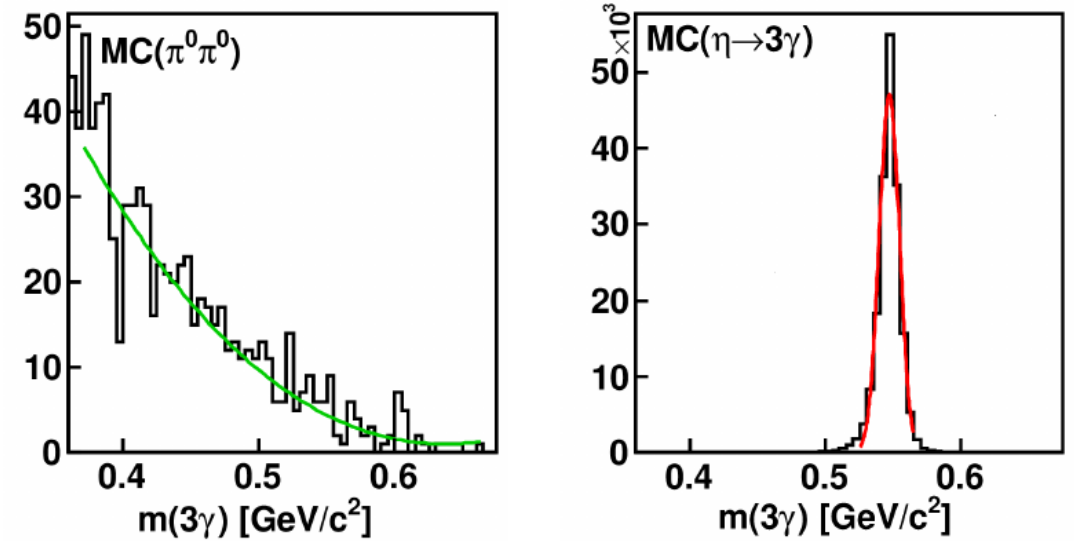
Extract the number of signal events

Calculate BR from signal events and total η


MC: $\eta \to 3\gamma$ (PS)
MC: $\eta \to 3\gamma$ (BE)
MC: $\eta \to \pi^0\gamma$
MC: $\eta \to 2\gamma$
MC: $\eta \to 3\pi^0$
MC: $\eta \to e^+e^-\gamma$
MC: $\eta \to \pi^0\gamma\gamma$
MC: $\pi^0\pi^0$
Data
$m_{min}(\gamma\gamma)$ [GeV/c^2]
m(3γ) [GeV/c^2]
0
0.1
0.2
0.3
0.4
0.5
0.6

Fitting example, $\eta \to 3\gamma$





- Subtract peaking bkgs

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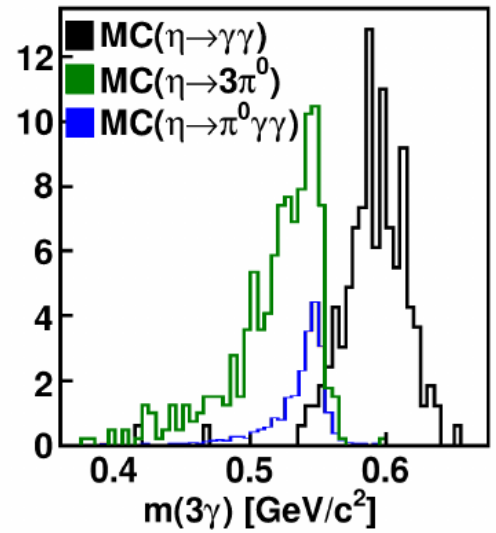

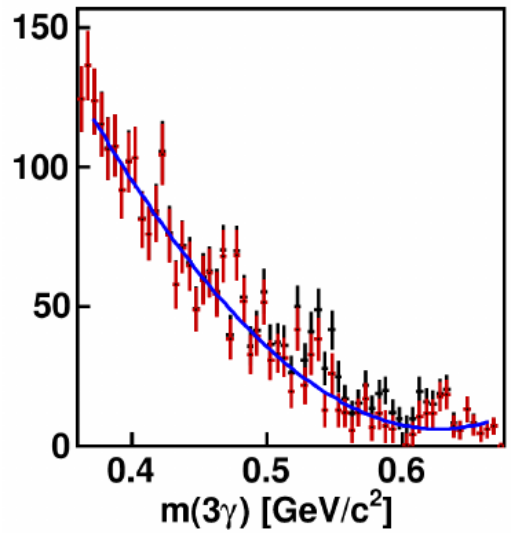

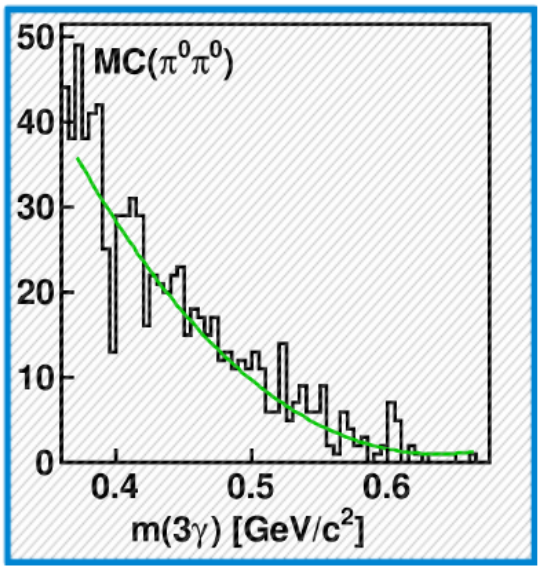

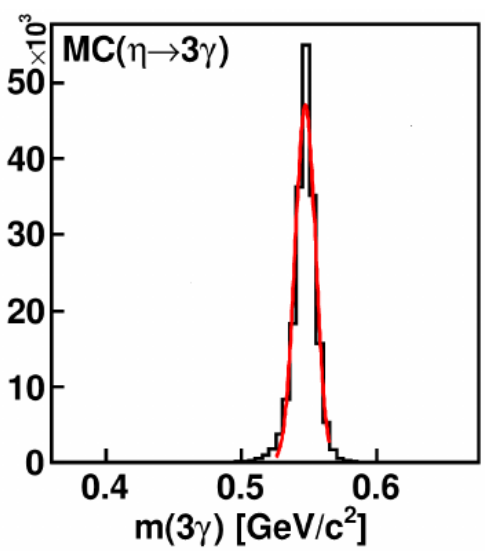

- Subtract peaking bkgs
- Parametrize smooth bkgs

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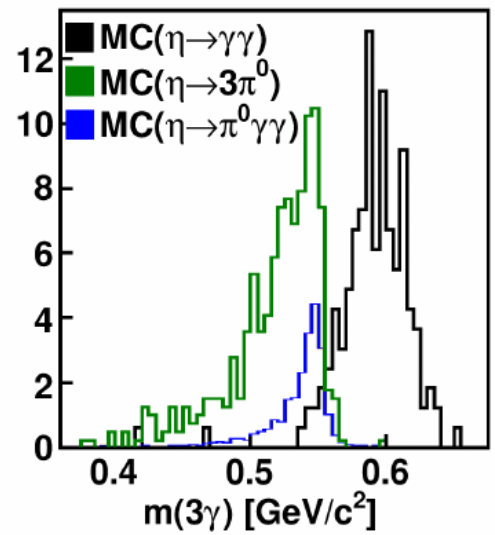

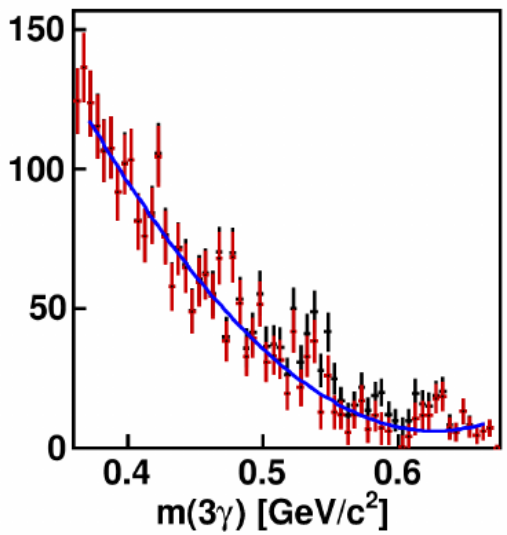

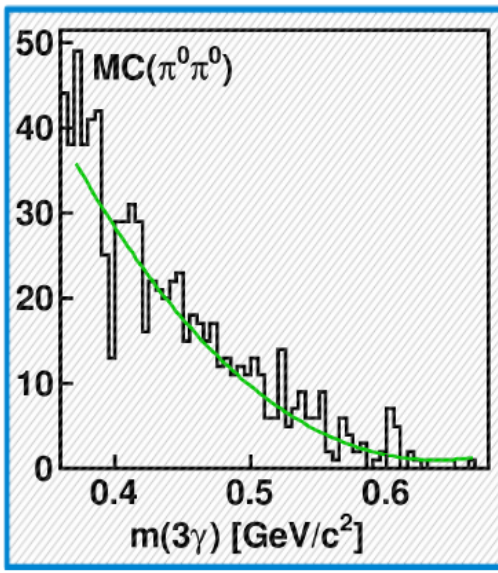

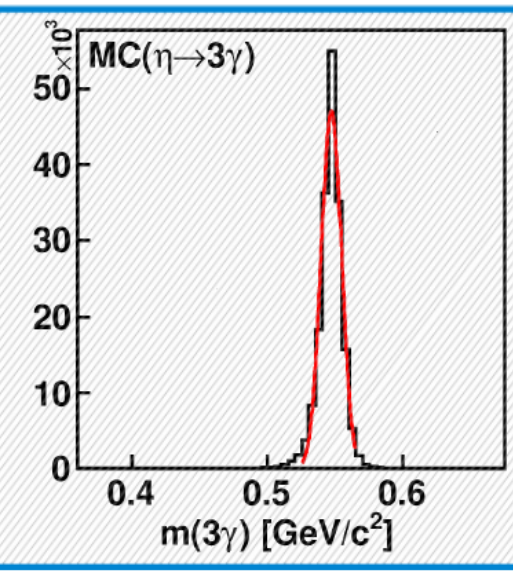

- Subtract peaking bkgs
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- Smooth bkg + MC of signal form fitting function

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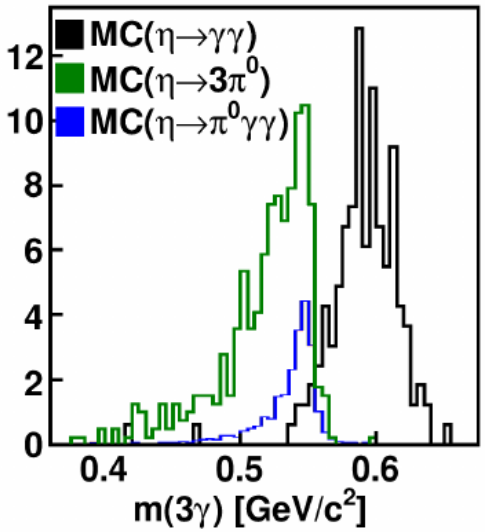

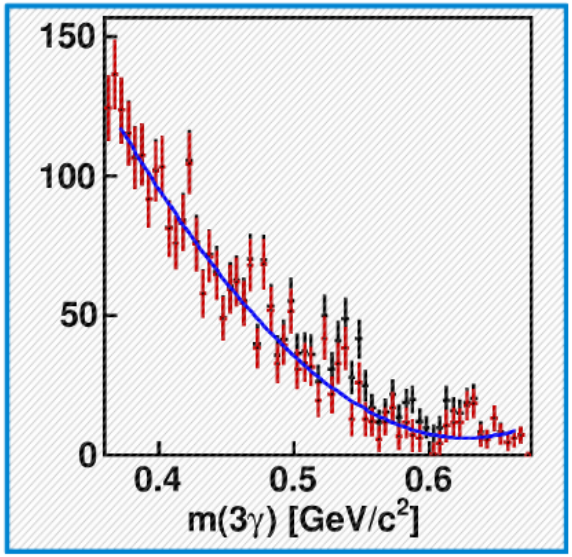

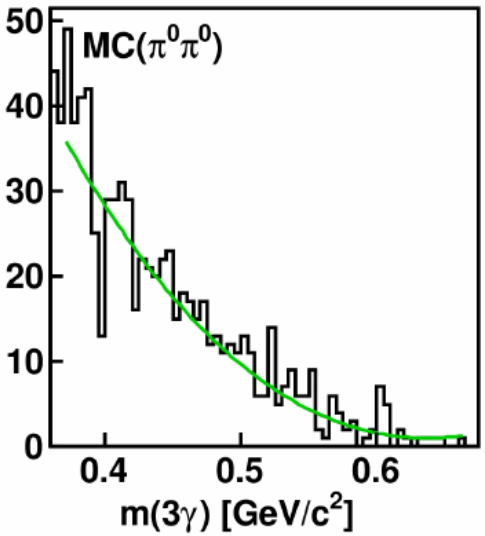

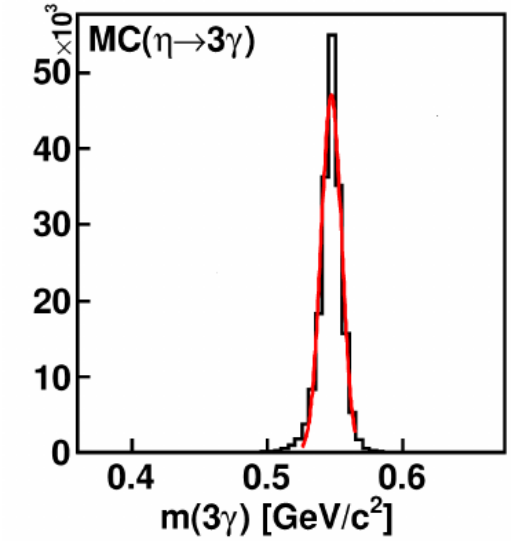

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- Apply fit to (MC subtracted) experimental data

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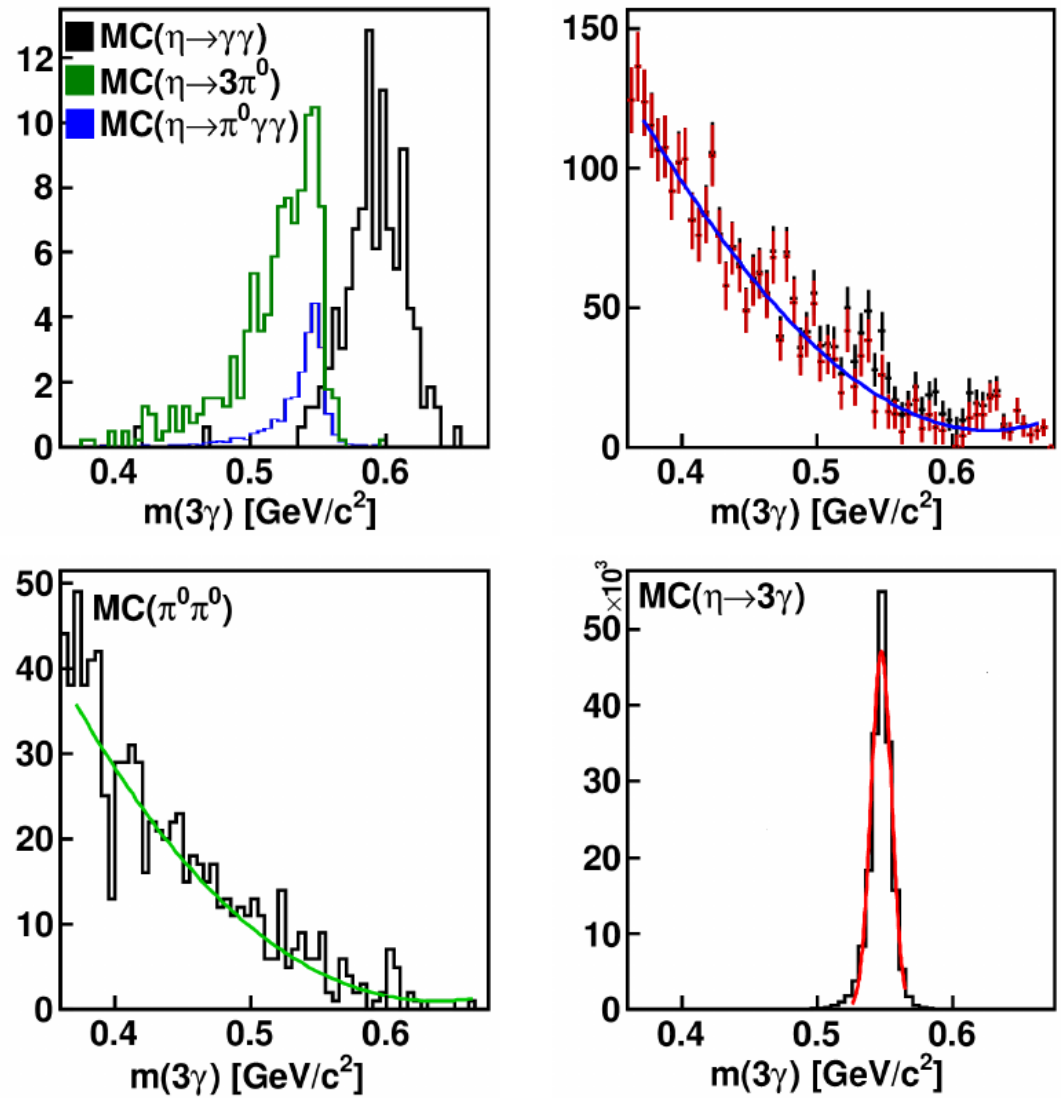

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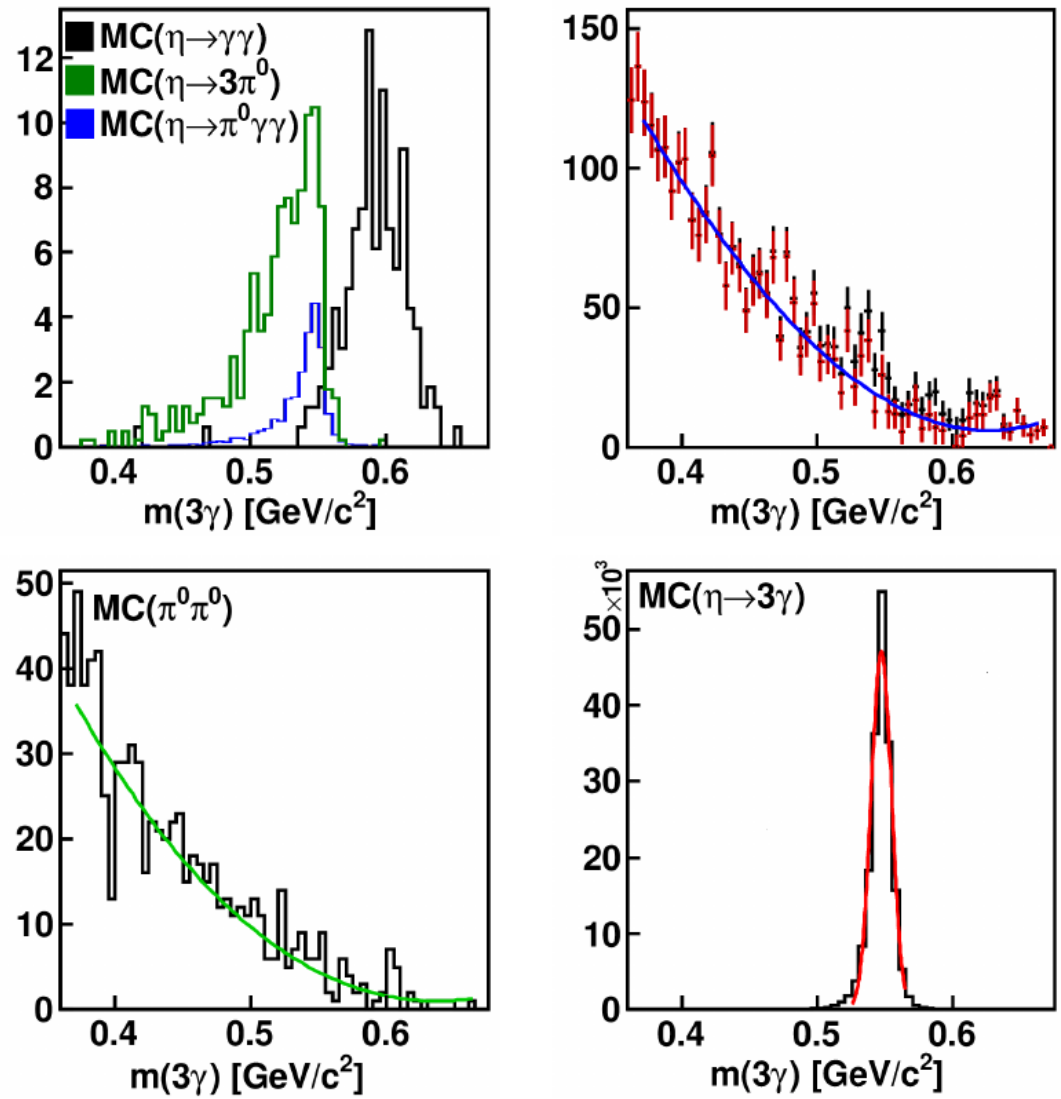

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  total $<$ 424 decays (90% CL)

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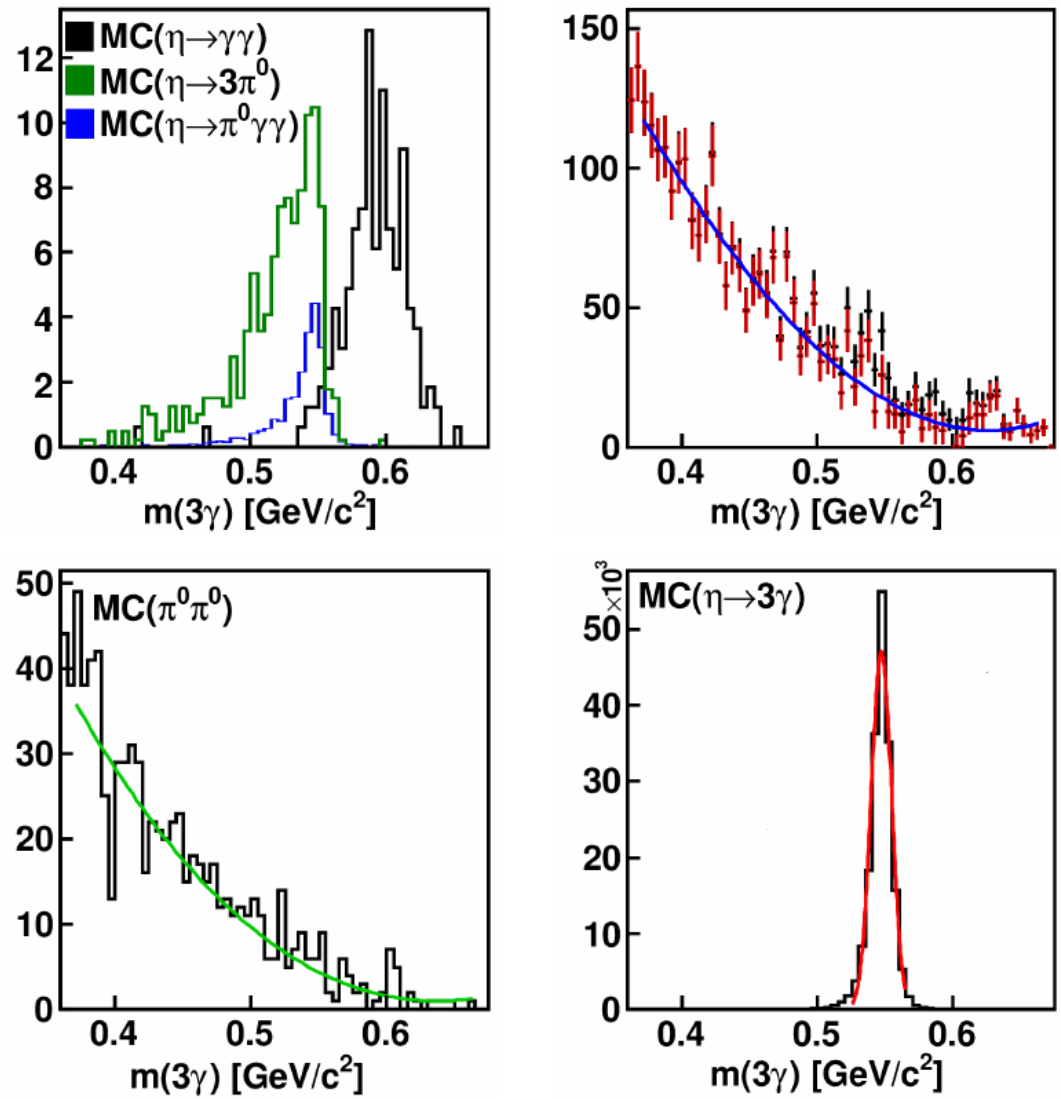

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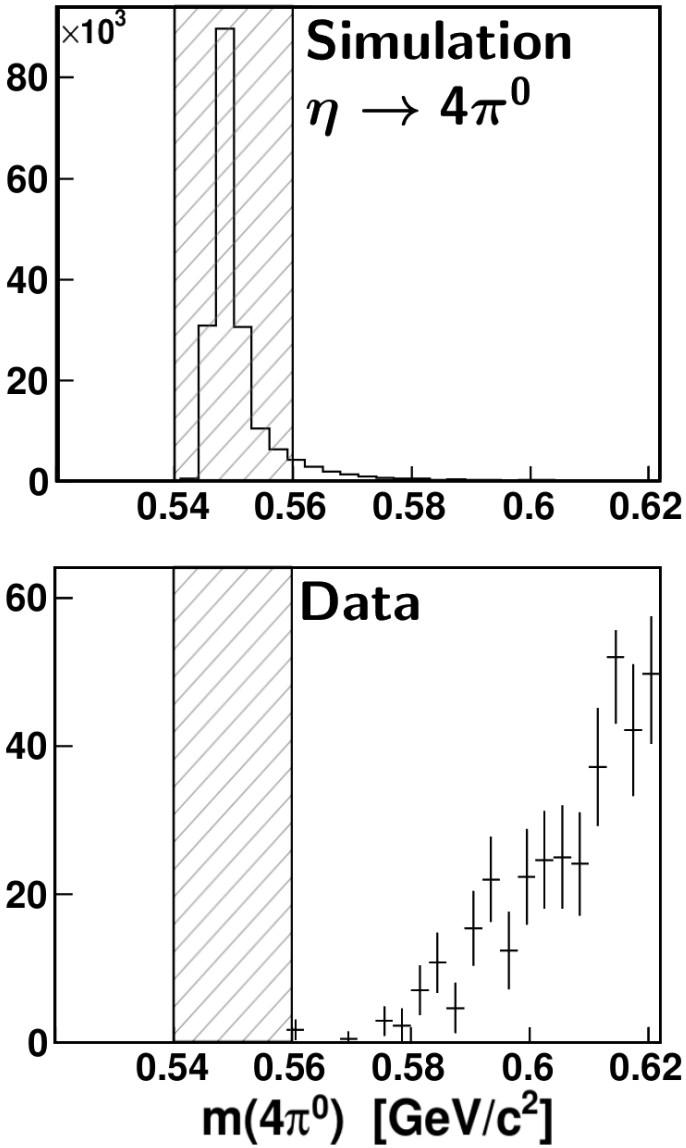
  total $<$ 424 decays (90% CL)
- Extract branching ratio
  BR $< 6.8 \times 10^{-6}$ (90% CL)

Fitting example, $\eta \longrightarrow 4\pi^0$



- Detection efficiency, ϵ
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  (Run II) $\epsilon = 21.8\%$

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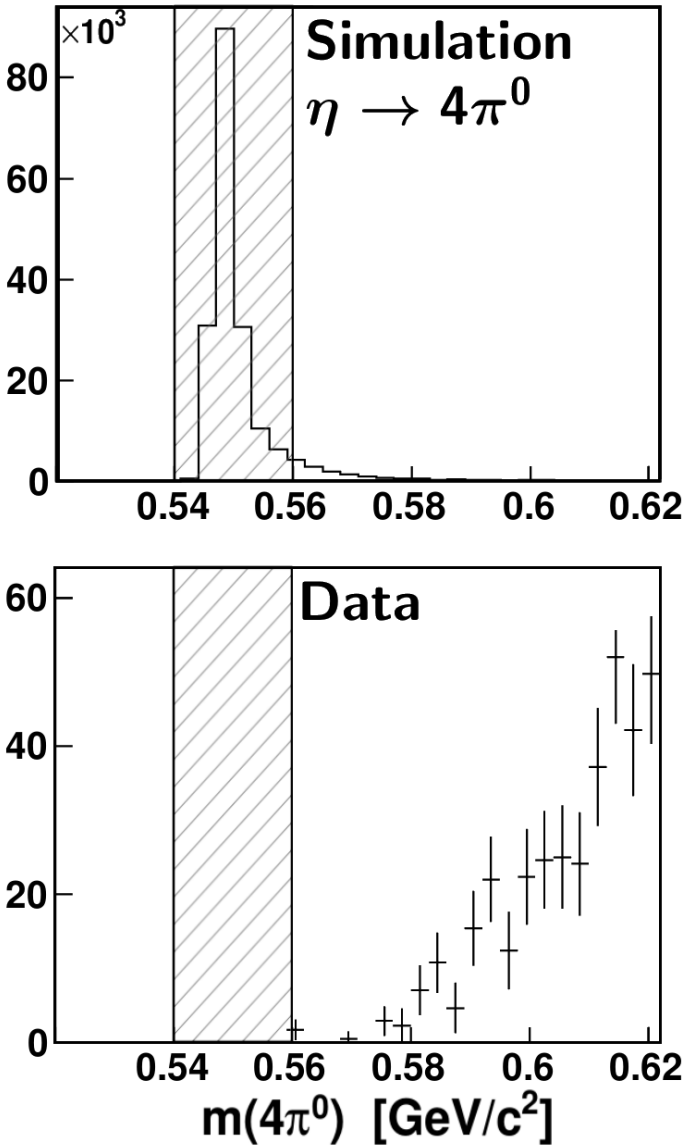

- Detection efficiency, ϵ
  (Run I) $\epsilon = 22.6\%$
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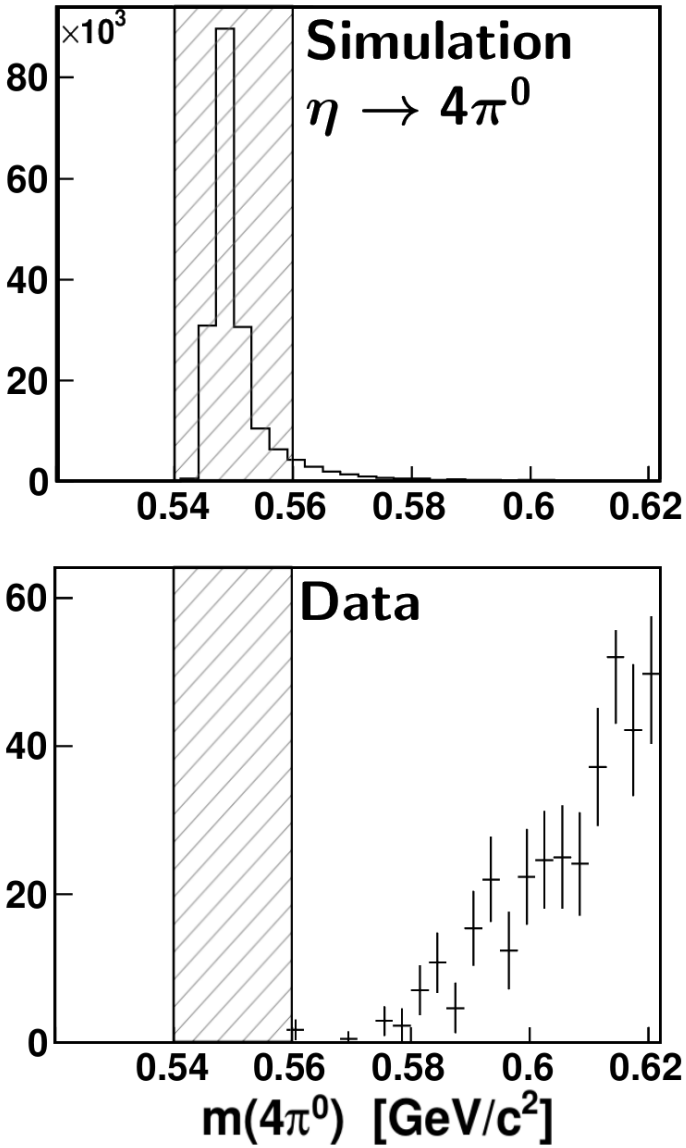
- Extract # of signal events
  total < 2.44 (90% CL)

Fitting example, $\eta \longrightarrow 4\pi^0$



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  BR $< 1.8 \times 10^{-7}$ (90% CL)

Summary of new upper limits on η

New measurements of symmetry violating η decays for:

$$\eta \to 3\gamma$$

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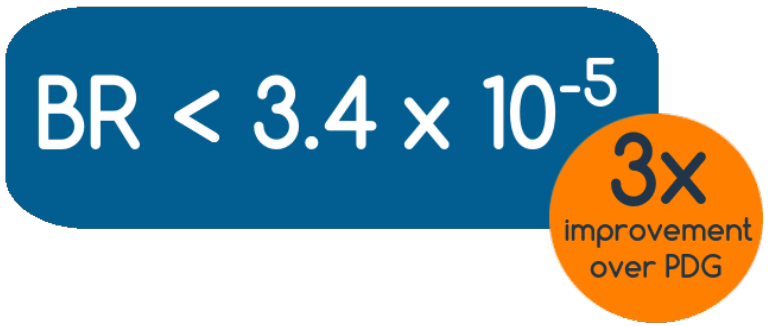
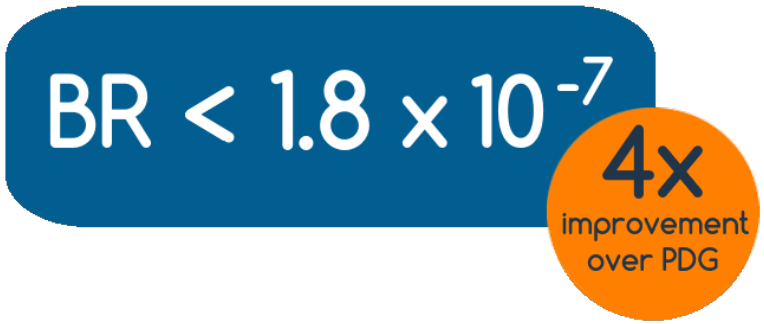


$$\eta \to \pi^0\gamma$$



$$\eta \to 4\pi^0$$

All BR cited for (90% CL)

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Symmetry violation studies allow for new physics searches (BSM)

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The Crystal Ball experiment at MAMI can help contribute to these searches in the light meson sector

We've performed a new search on the neutral decays of the η

- $\eta \to 3\gamma$ – C violating
- $\eta \to \pi^0\gamma$ – C violating
- $\eta \to 4\pi^0$ – CP violating

2-4$\times$ Improvement on the existing BR-UL

Future experiments

Ongoing experiment in A2 will produce high statistics π^0 data set, produced via $(\gamma p \to \pi^0 p)$.

Projected $(\gamma p \to \pi^0 p)$ on tape about 5×10^9

Interesting to investigate:

- $\pi^0 \to 3\gamma$ – C violating
- $\pi^0 \to 4\gamma$ – rare

SM - η

SM

D.A. Dicus/JEF proposal, *Estimate of the rate of the decay* $\eta \to 3\gamma$

$$\frac{\Gamma(\eta \to 3\gamma)}{\Gamma(\eta \to 2\gamma)} = 10^{-24}.$$

SM

A. Kupsc and A. Wirzba, *Tests of fundamental symmetries in* η *mesons*, 2011

$$\Gamma(\eta \to 4\pi^0) \leq 10^{-10}.$$

$$\Gamma(\eta' \to 4\pi^0) \leq 10^{-8}.$$

SM and BSM theories - π^0

SM: Charge conjugation violation $\rightarrow$ strong interactions

F.A. Berends, *The T violating decay of* $\pi^0 \rightarrow 3\gamma$, 1965

$$\frac{\Gamma(\pi^0 \rightarrow 3\gamma)}{\Gamma(\pi^0 \rightarrow 2\gamma)} = 10^{-6}.$$

SM: Charge conjugation violation $\rightarrow$ weak interactions

D.A. Dicus, *Estimate of the rate of the rare decay* $\pi^0 \rightarrow 3\gamma$, 1975

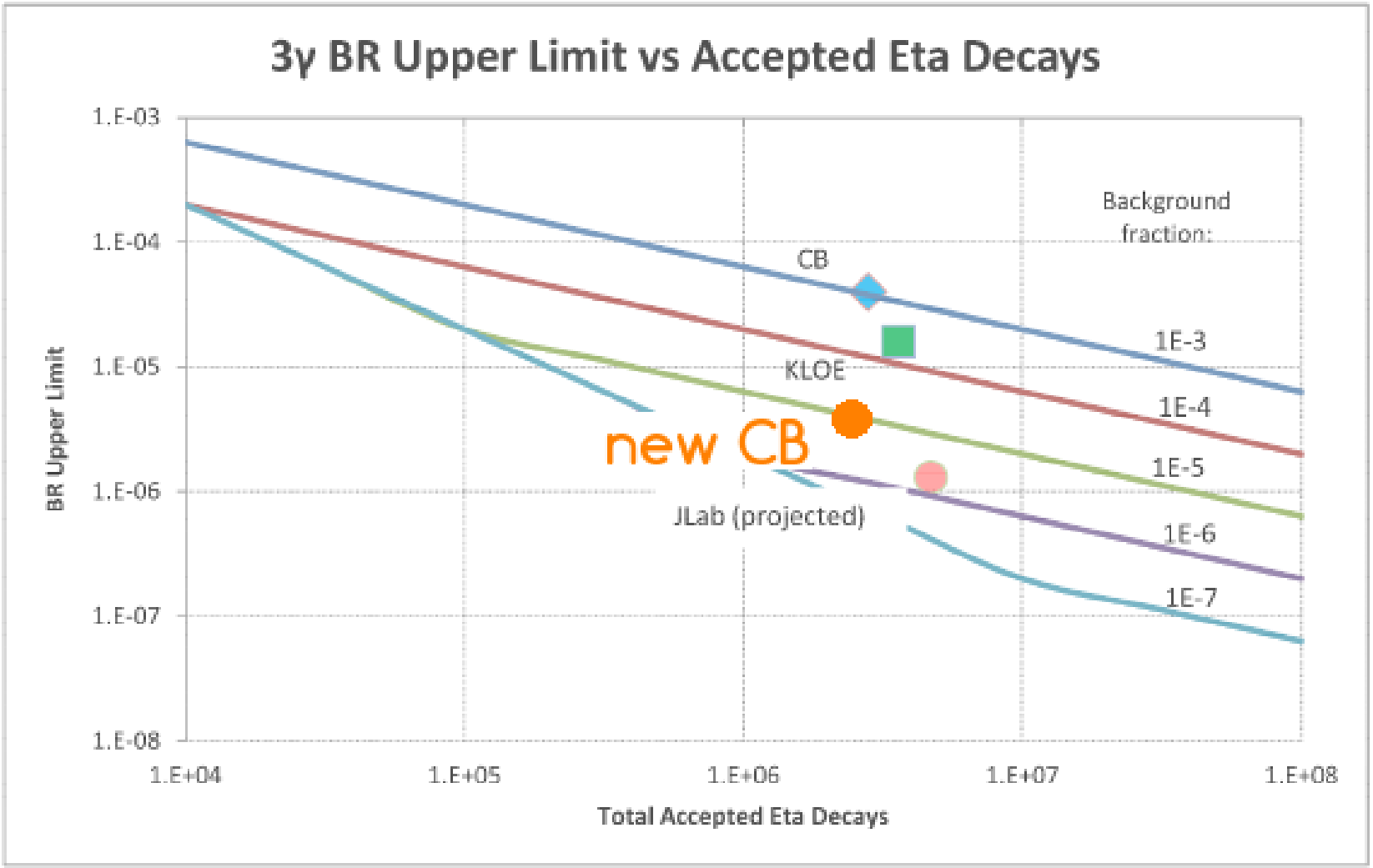
$$\frac{\Gamma(\pi^0 \rightarrow 3\gamma)}{\Gamma(\pi^0 \rightarrow 2\gamma)} = 10^{-31\pm6}.$$

BSM: non-commutative quantum electrodynamics (NCQED)

Grosse and Liao, *Anomalous C-violating Three Photon Decay of the Neutral Pion in Non-commutative Quantum Electrodynamics*, 2001

$$\frac{\Gamma(\pi^0 \rightarrow 3\gamma)}{\Gamma(\pi^0 \rightarrow 2\gamma)} = 10^{-21}.$$

For the JLab folks...



Analysis: $\eta \to 3\gamma$ and $\eta \to \pi^0\gamma$

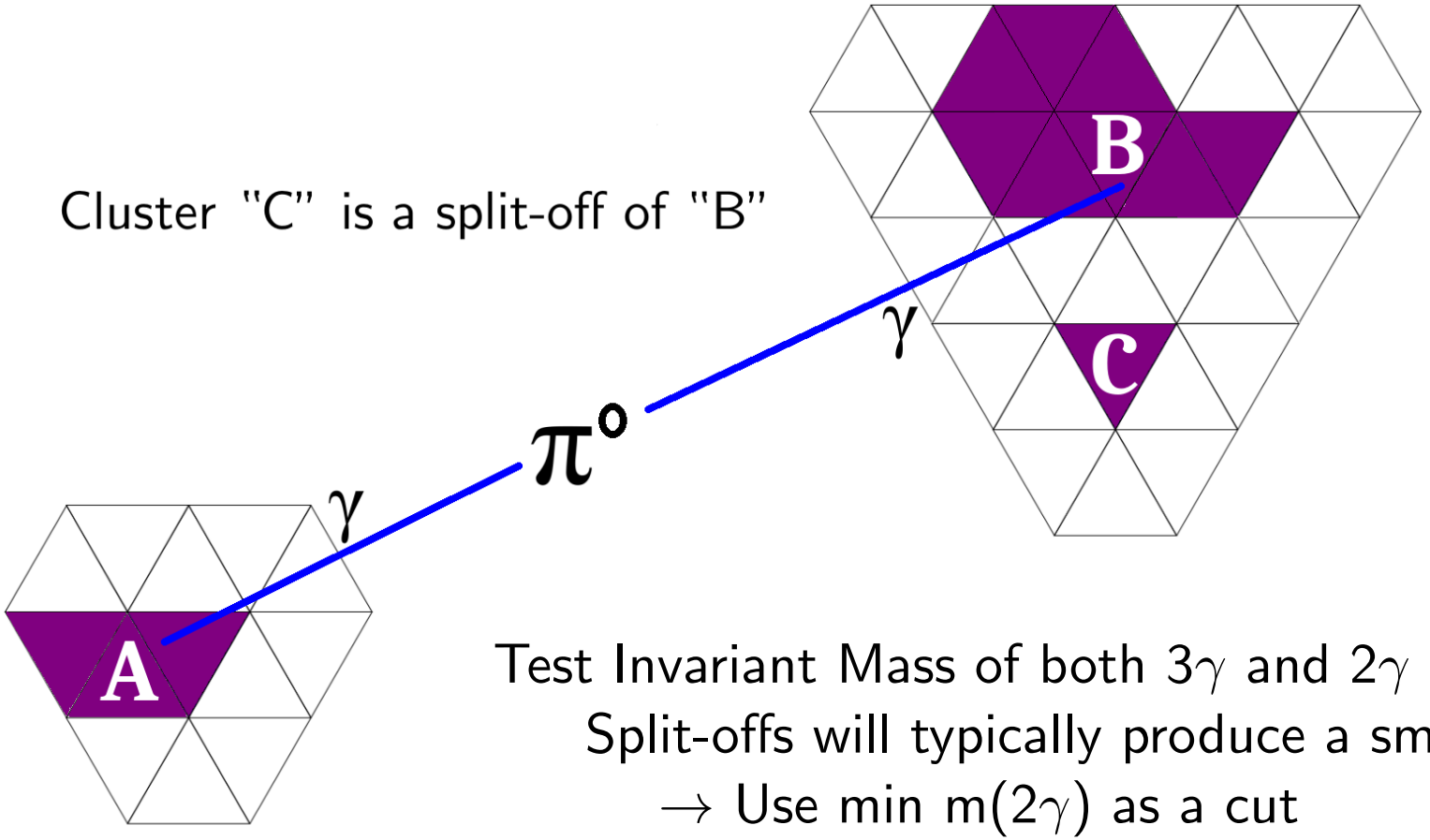
Difficult analysis!
Low BR for forbidden decays ... Many backgrounds to consider

Some initial considerations

- 3 cluster, or 4 cluster (with recoil) final state
- γs only in CB (better charged mode suppression: $\eta \to e^+e^-\gamma$)
- backgrounds from split-offs ($\eta \to 2\gamma$ + split-off)
- backgrounds from missed γ ($\gamma p \to 2\pi^0 p$ + missed γ)
- backgrounds from overlaps ($\eta \to 3\pi^0$ + overlaps)

Analysis: Split-offs

Cluster "C" is a split-off of "B"

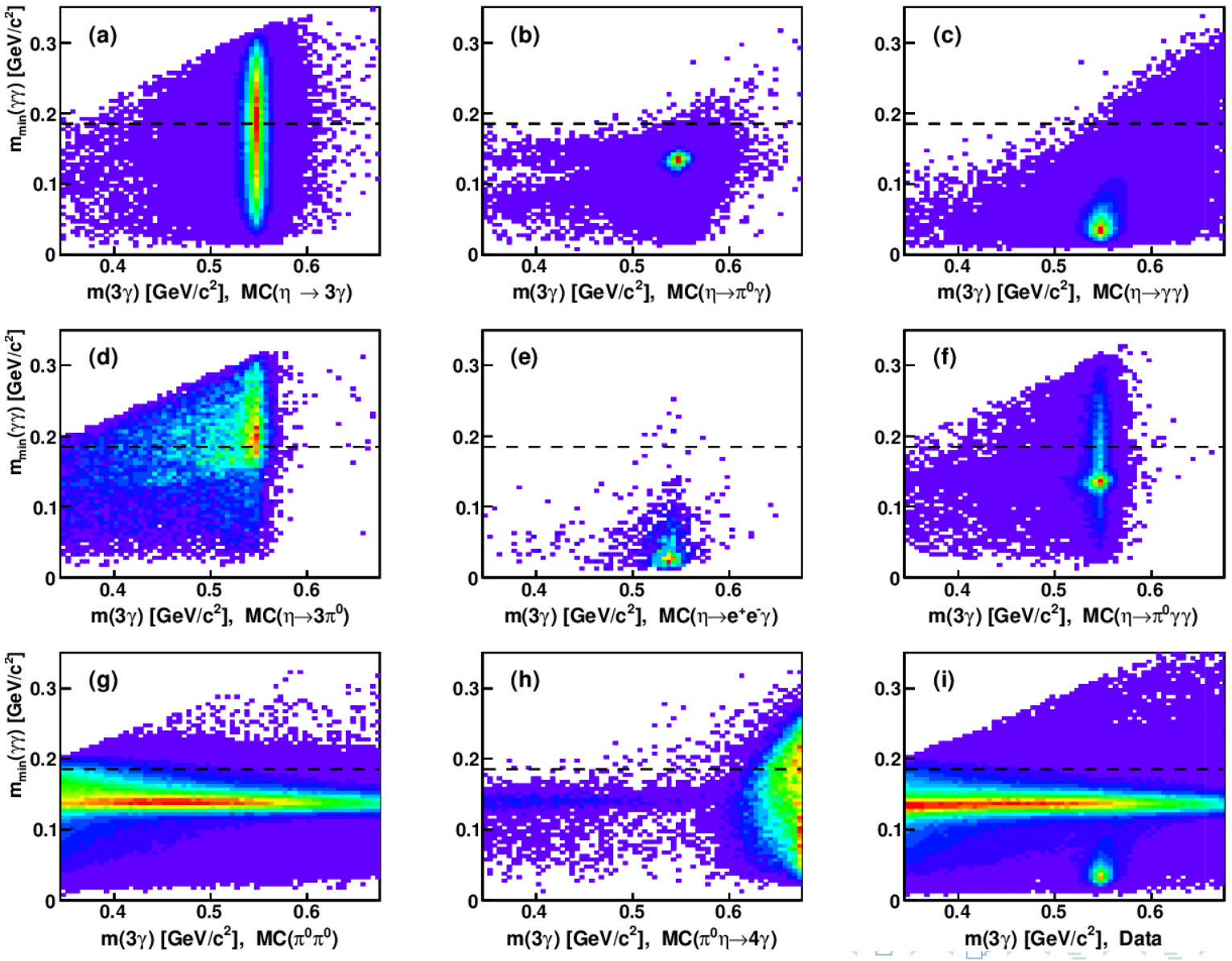


Test Invariant Mass of both 3γ and 2γ combos

Split-offs will typically produce a small IM

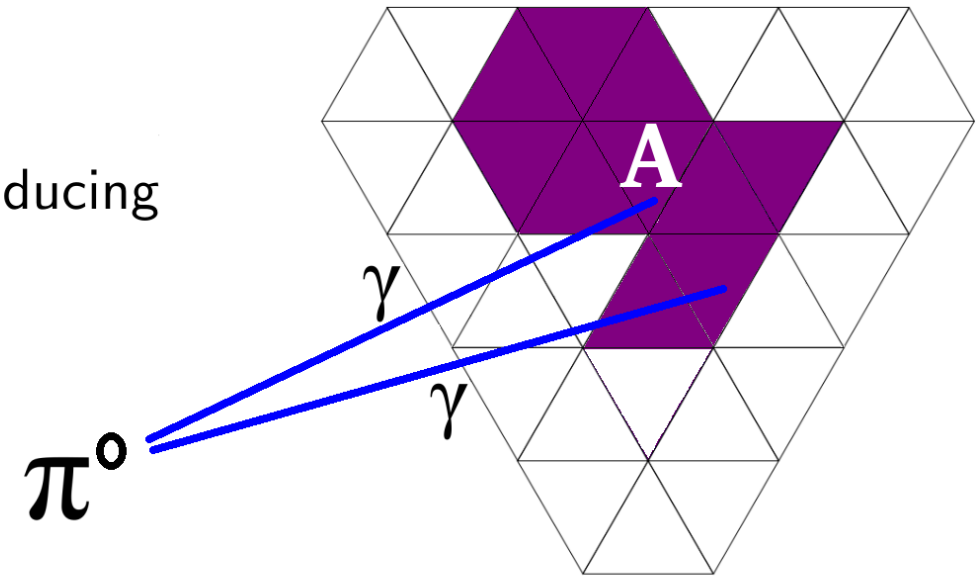
$\rightarrow$ Use min m(2γ) as a cut

Analysis: m(2γ) v. m(3γ)



Analysis: Overlaps

Clusters overlap, producing only 1 cluster



$$R = \sqrt{\frac{\Sigma_i^k E_i (\Delta r_i)^2}{\Sigma_i^k E_i}}$$

Test the cluster size of all photons

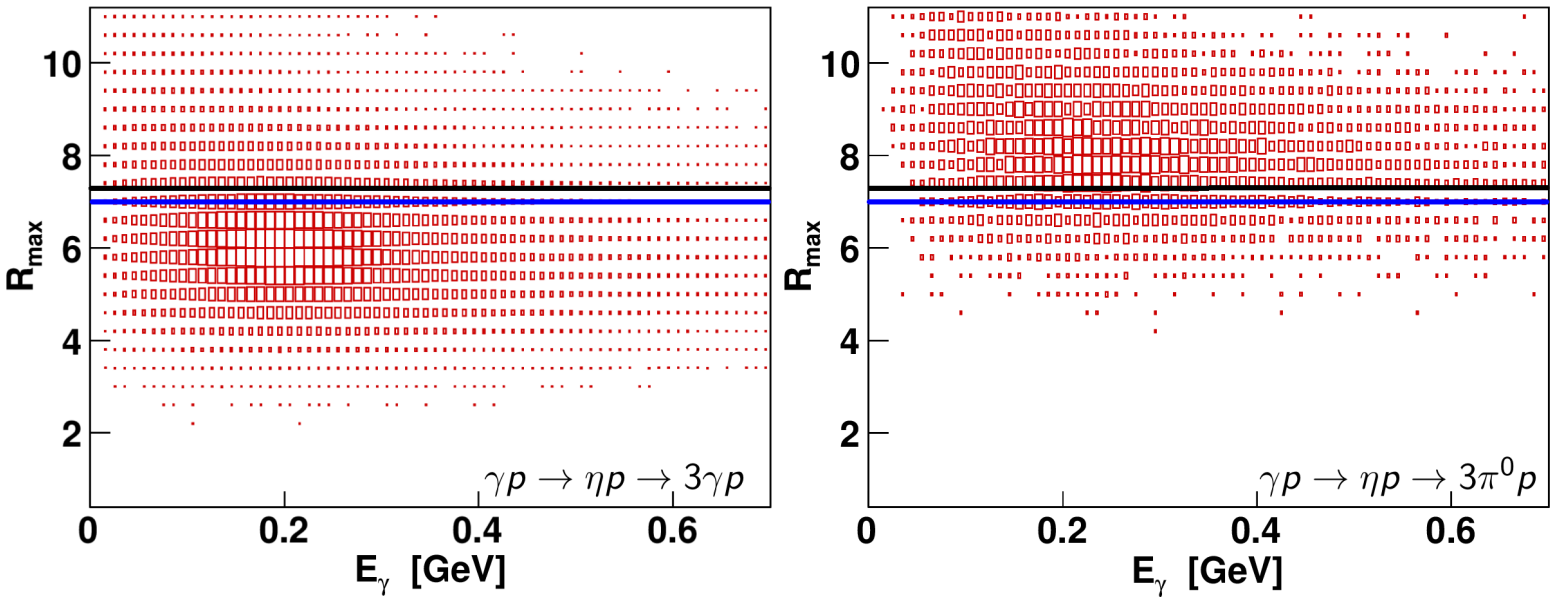
Overlaps will have larger effective radii

$\rightarrow$ Use max R as a cut

*Δr_i is the opening angle between the cluster direction and the crystal axis

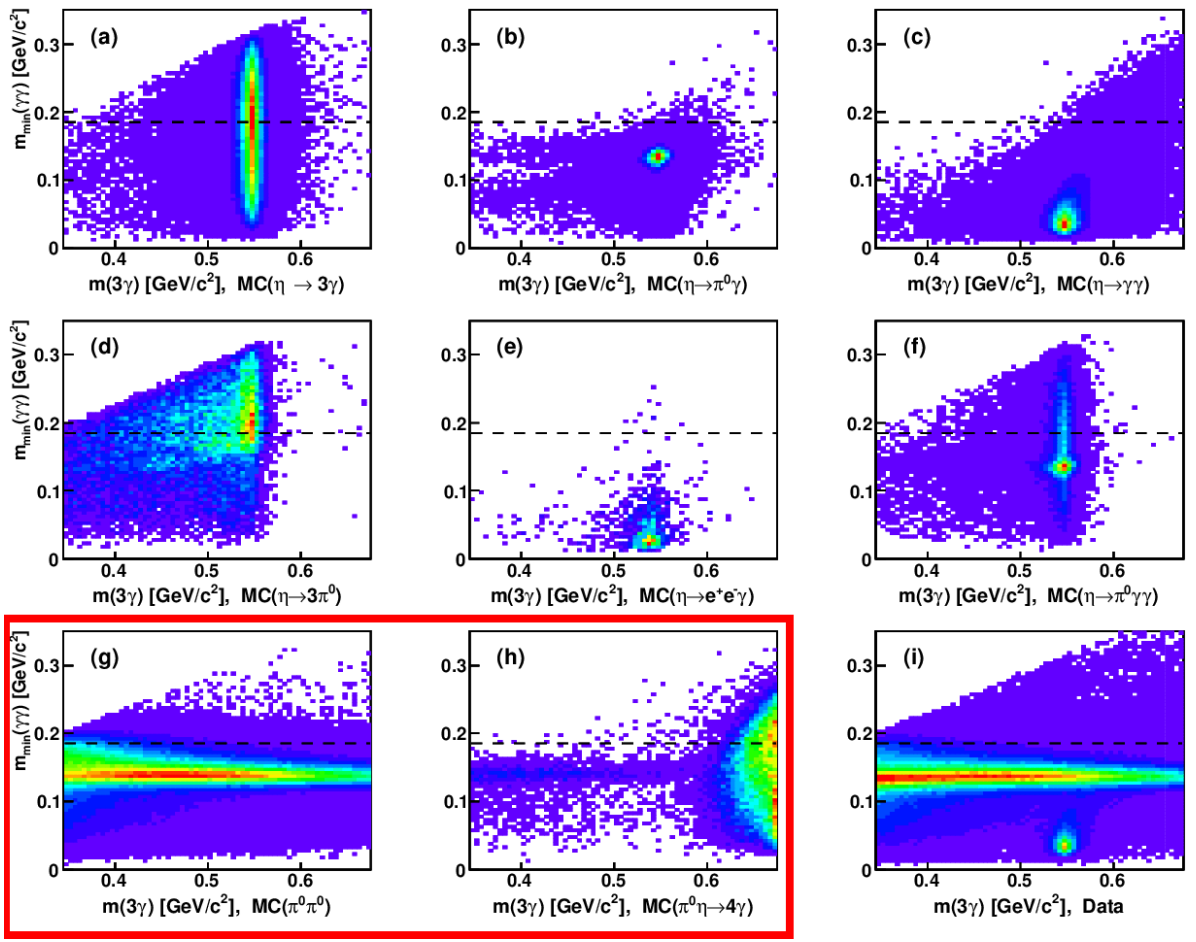
Analysis: Effective radius, R

Demonstrated previously* that a cut on R can be an effective tool for suppressing $\eta \to 3\pi^0$ background



*B.M.K Nefkens et al., Phys. Rev. C 72 035212 (2005)

Analysis: Parametrization of backgrounds



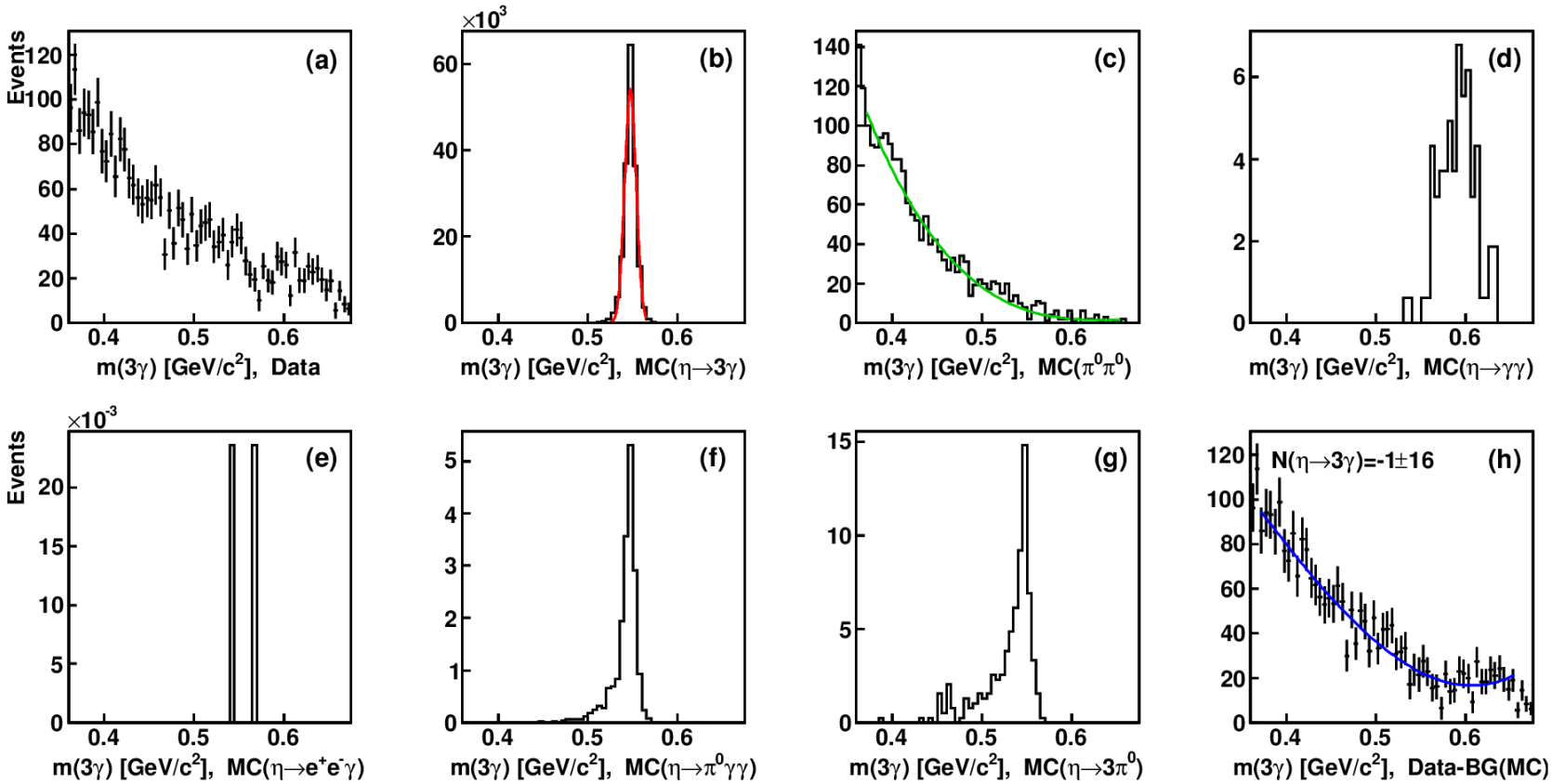
$\gamma p \to \pi^0 \eta \to 4\gamma p$ has a very steep shape (makes parametrization difficult)

$\to$Place cut at threshold

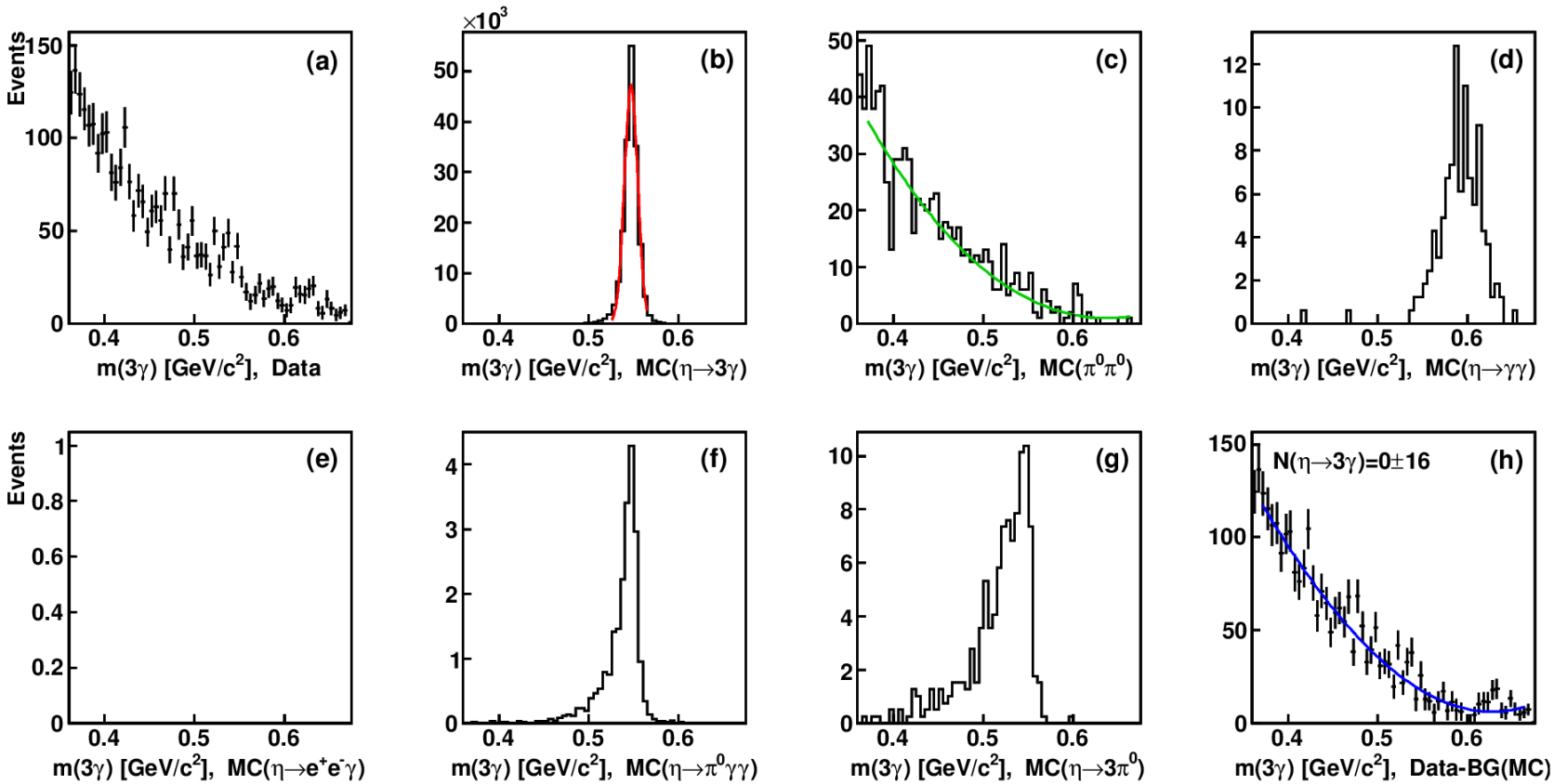
Analysis: Summary of cuts, $\eta \to 3\gamma$

Decay	**Kinematic fitting cuts**
$\eta \to 3\gamma$	$CL(\gamma p \to \eta p \to 3\gamma p) > 0.1$
	$CL(\gamma p \to \pi^0 p \to 2\gamma p) < 10^{-5}$
	$CL(\ \gamma p \to \eta p \to 2\gamma p\ ) < 10^{-5}$
	$CL(\gamma p \to \pi^0\pi^0 p \to 4\gamma p) < 10^{-5}$
	$CL(\ \gamma p \to \pi^0\eta p \to 4\gamma p\ ) < 10^{-5}$
	Additional cuts
	All γ clusters in CB, no PID hits
	$m_{min}(\gamma\gamma) > 0.185$ GeV/c^2
	Maximum cluster effective radius, R < 7.0
	$E_\gamma < 940$ MeV

Results: m(3γ) $\eta \to 3\gamma$ selection criteria (Run I)



Results: m(3γ) $\eta \to 3\gamma$ selection criteria (Run II)



Results: BR($\eta \to 3\gamma$)

Run I: $N(\eta \to 3\gamma) = -1 \pm 16$ $\epsilon = 0.0867$

Run II: $N(\eta \to 3\gamma) = 0 \pm 16$ $\epsilon = 0.0879$

The number of $\eta \to 3\gamma$ decays produced in Run I and Run II is less than 424 at the 90% CL.

Total number of η produced was 6.23×10^7, giving a new UL:

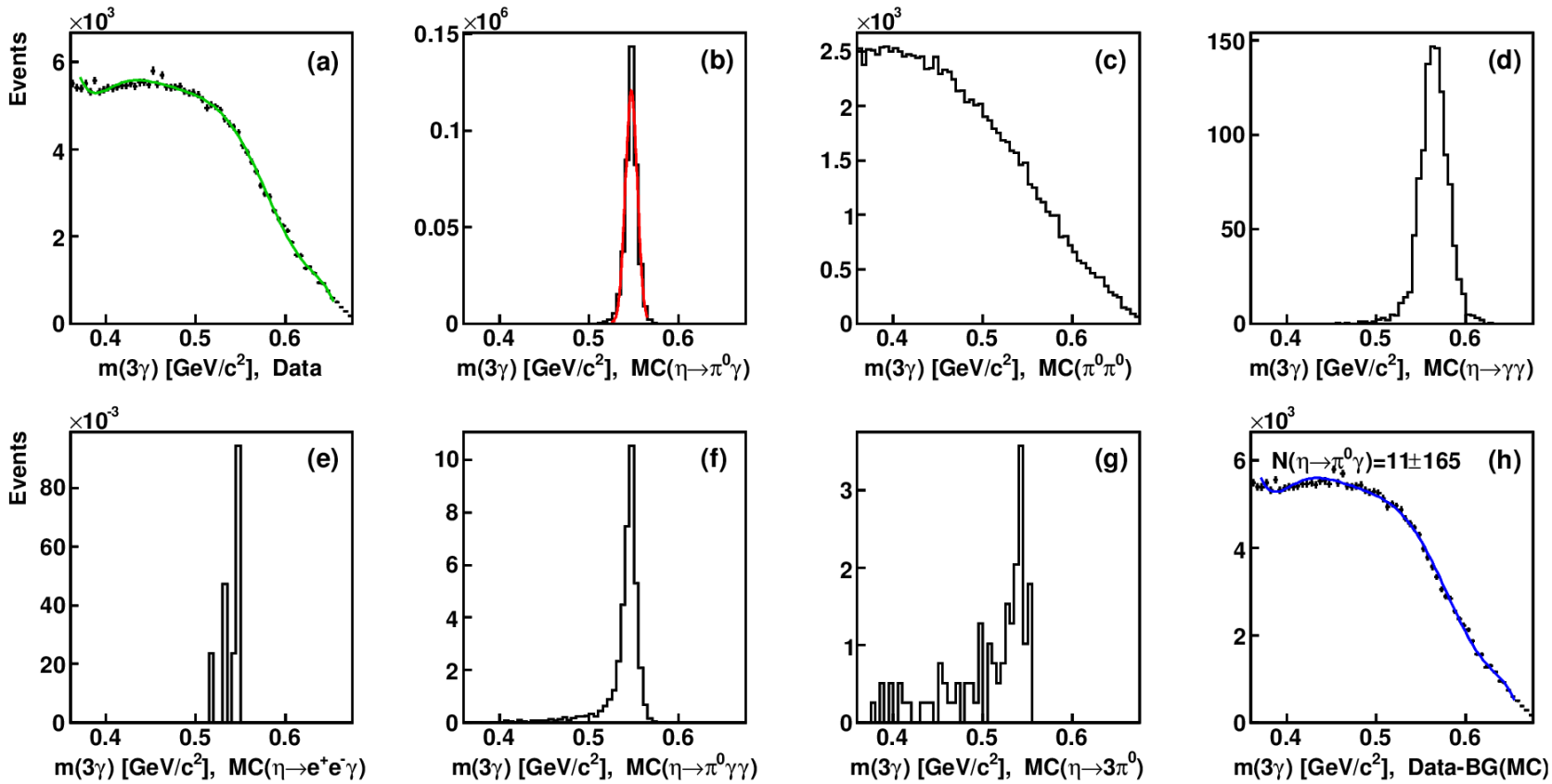
$$BR(\eta \to 3\gamma) \leq 6.8 \times 10^{-6} \text{ at the } 90\% \text{ CL},$$

improving the current PDG value, 1.6×10^{-7}, by a factor >2.

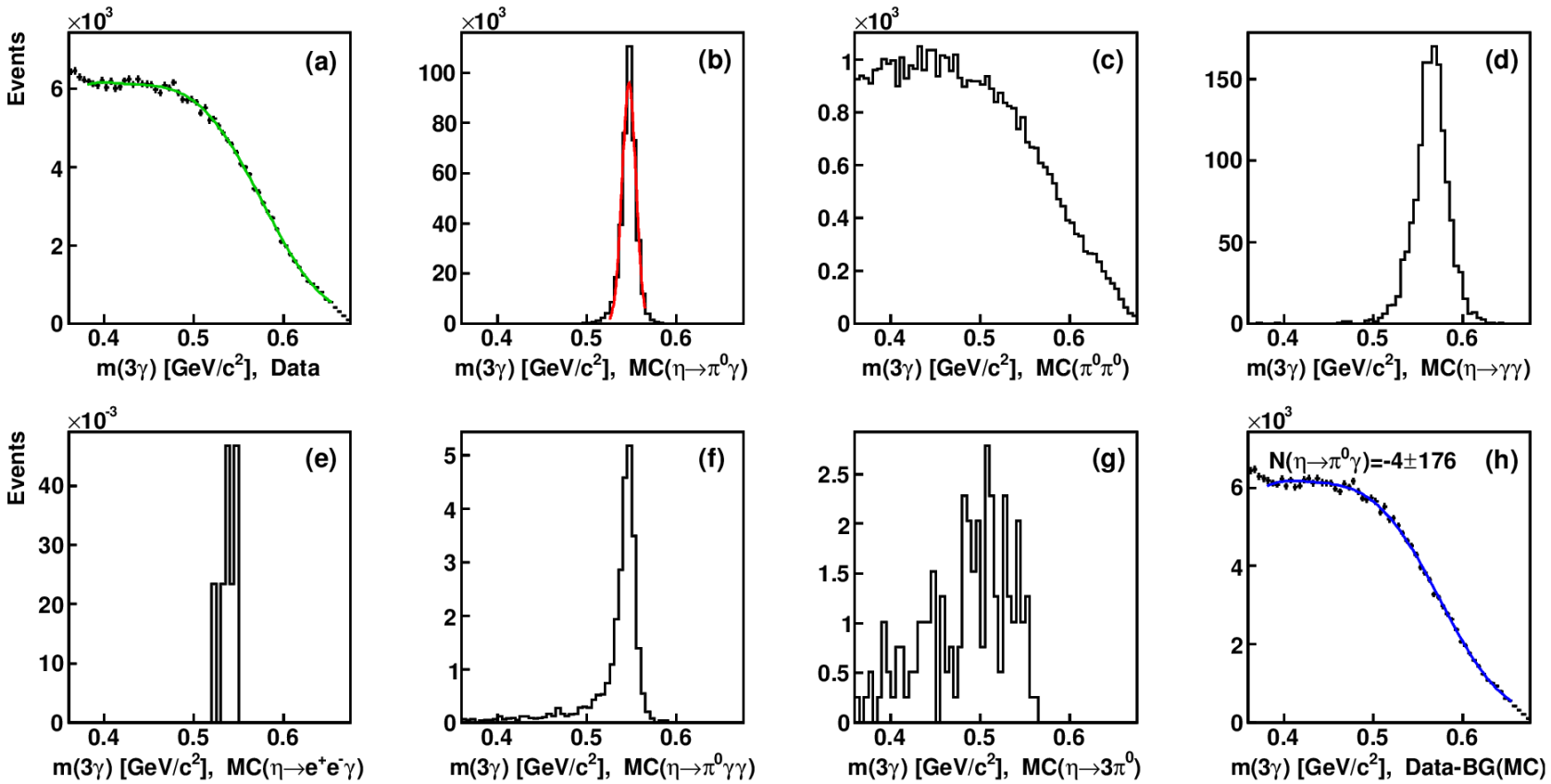
Analysis: Summary of cuts, $\eta \to \pi^0\gamma$

Decay	**Kinematic fitting cuts**
$\eta \to \pi^0\gamma$	$CL(\gamma p \to \eta p \to 3\gamma p) > 0.15$
	$CL(\gamma p \to \pi^0 p \to 2\gamma p) < 10^{-5}$
	$CL(\ \gamma p \to \eta p \to 2\gamma p\ ) < 10^{-5}$
	$CL(\gamma p \to \pi^0\pi^0 p \to 4\gamma p) < 10^{-5}$
	$CL(\ \gamma p \to \pi^0\eta p \to 4\gamma p\ ) < 10^{-5}$
	Additional cuts
	All γ clusters in CB, no PID hits
	$0.115 < m_{min}(\gamma\gamma) > 0.155$ GeV/c^2
	Maximum cluster effective radius, $R < 7.3$
	$E_\gamma < 940$ MeV

Results: m(3γ) $\eta \to \pi^0\gamma$ selection criteria (Run I)



Results: m(3γ) $\eta \to \pi^0\gamma$ selection criteria (Run II)



Results: BR($\eta \to \pi^0\gamma$)

Run I: N($\eta \to \pi^0\gamma$) = 11 $\pm$ 165
ϵ = 0.200

Run II: N($\eta \to \pi^0\gamma$) = -4 $\pm$ 176
ϵ = 0.185

The number of $\eta \to \pi^0\gamma$ decays produced in Run I and Run II is less than 2125 at the 90% CL.

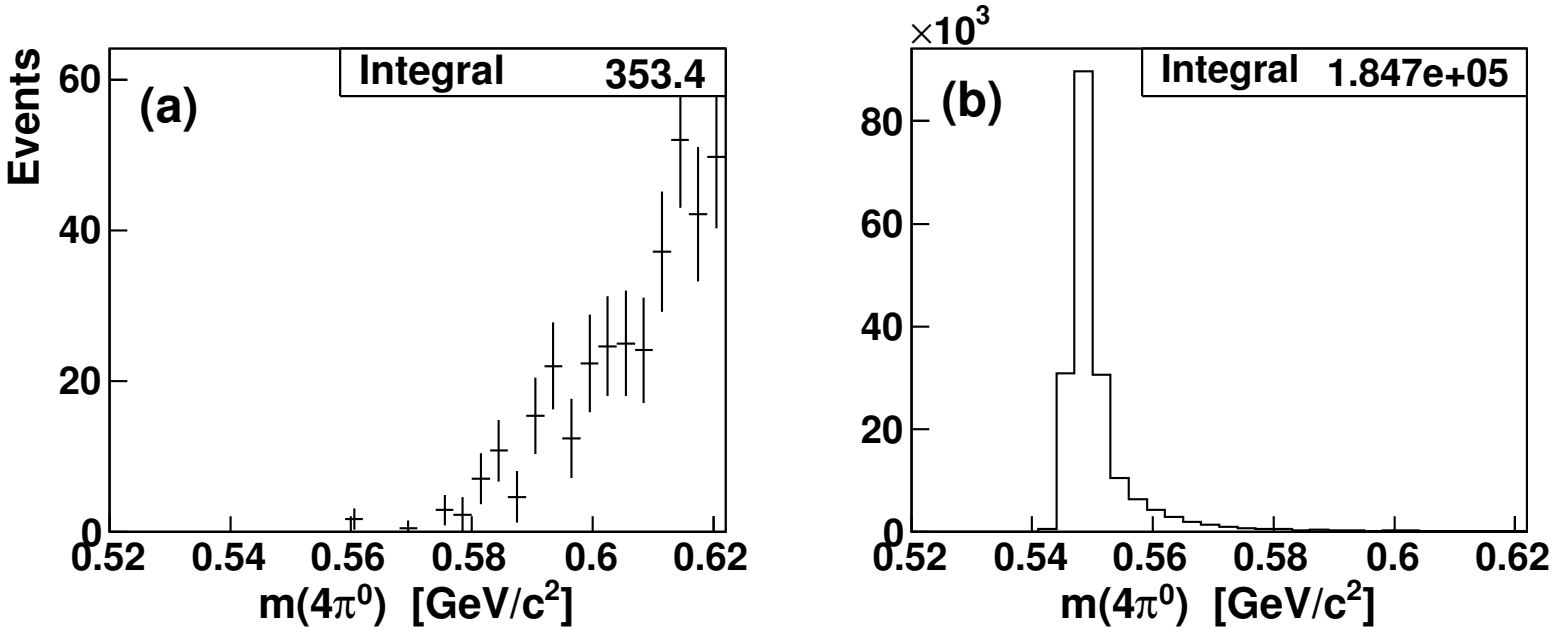
Total number of η produced was 6.23×10^7, giving a new UL:

$$BR(\eta \to \pi^0\gamma) \leq 3.4 \times 10^{-5} \text{ at the } 90\% \text{ CL},$$

improving the current PDG value, 9×10^{-5}, by a factor roughly 3.

Analysis: $\eta \to 4\pi^0$

Select CL($\gamma p \to \eta p \to 4\pi^0 p \to 8\gamma p$) > 0.0001



The number of $\eta \to 4\pi^0$ decays produced in Run I ($\epsilon = 0.226$) and Run II ($\epsilon = 0.218$) is less than 2.44 at the 90% CL.

$$BR(\eta \to 4\pi^0) \leq 1.8 \times 10^{-7} \text{ at the 90\% CL},$$

improving the current PDG value, 6.9×10^{-7}, by a factor of 4.

Summary

New measurements of symmetry violating η decays for:

$BR(\eta \to 3\gamma) \leq 6.8 \times 10^{-6}$ at the 90% CL,
improving the current PDG value, 1.6×10^{-7}, by a factor >2.

$BR(\eta \to \pi^0\gamma) \leq 3.4 \times 10^{-5}$ at the 90% CL,
improving the current PDG value, 9×10^{-5}, by a factor roughly 3.

$BR(\eta \to 4\pi^0) \leq 1.8 \times 10^{-7}$ at the 90% CL,
improving the current PDG value, 6.9×10^{-7}, by a factor of 4.

Paper in prep

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