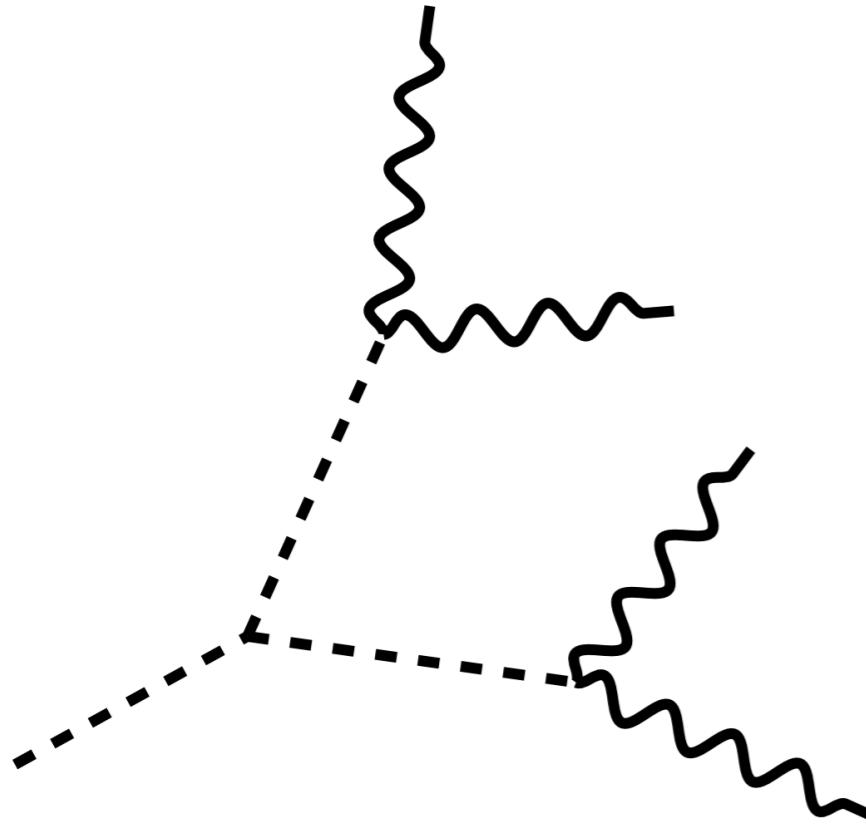




# $h(125) \rightarrow aa \rightarrow \gamma\gamma\gamma\gamma$



## Higgs to 4 Gamma Update

Tanvi Wamorkar<sup>1</sup>  
Toyoko Oriomo<sup>1</sup>  
Andrea Massironi<sup>2</sup>

<sup>1</sup>Northeastern University

<sup>2</sup>INFN Milano-Bicocca

6th March 2018  
NEU Meeting



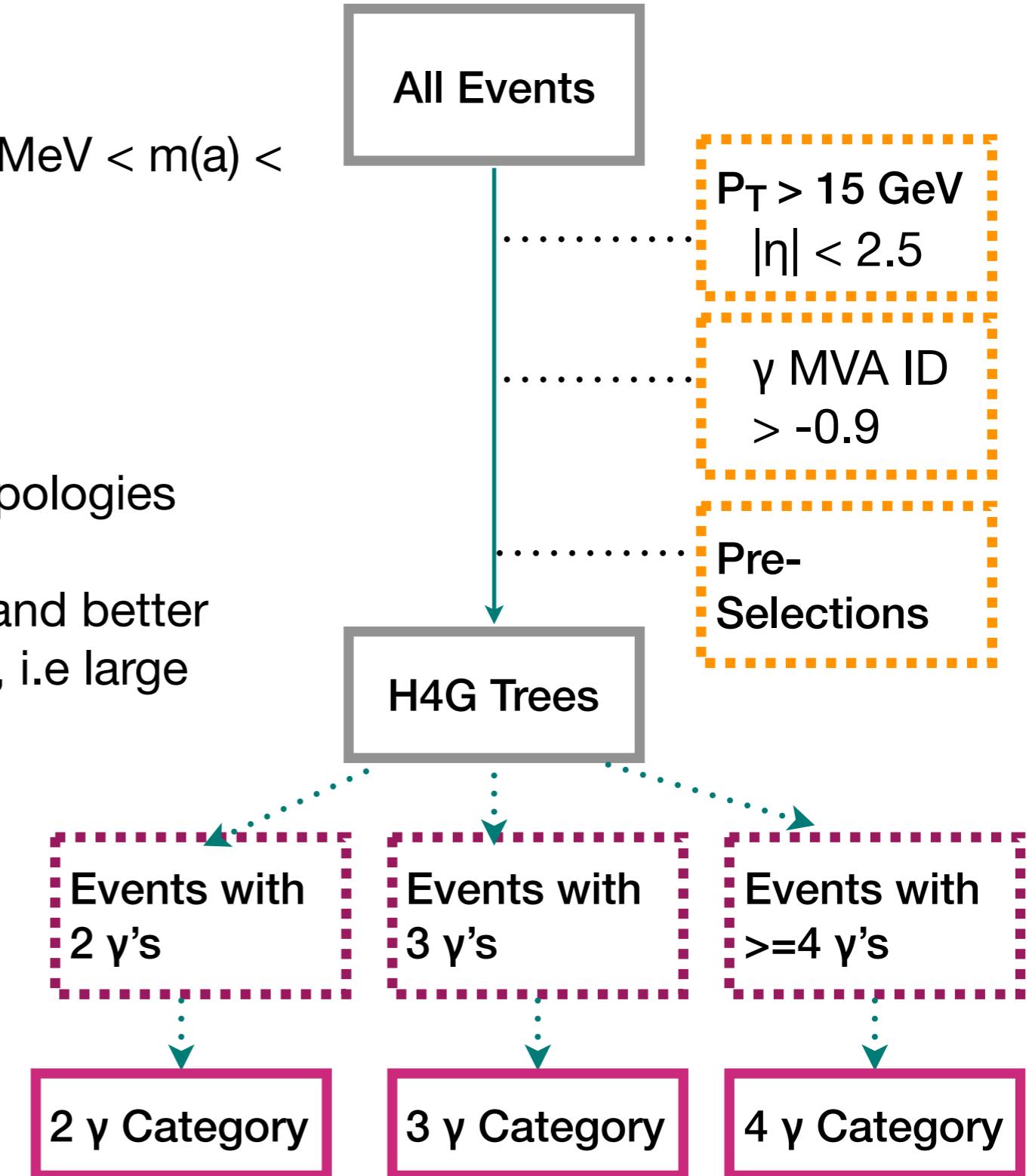
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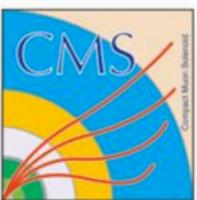
This talk:

- Update on changes since last time
- Changed Pre-selection cuts
- Efficiency study of pre-selection cuts
- Presented the changes at Hgg meeting yesterday [Link here](#)

# ANALYSIS STRATEGY

- $h(125) \rightarrow aa \rightarrow \gamma\gamma\gamma\gamma$
- Probing mass region ranging from  $100 \text{ MeV} < m(a) < 60 \text{ GeV}$
- Highly boosted “a’s”
  - Collimated products of “a” decays
- Depending on  $m(a)$  we have different topologies
- Higher the  $m(a)$ , lower the boost of “a” and better isolated are the decay product photons, i.e large values of  $\Delta R$





# TRIGGER & PRESELECTION

- Online selection identical to low mass  $h \rightarrow \gamma\gamma$  search
- Passing the OR of the two Low mass HLT paths

- **OR Path**

HLT\_Diphoton30EB\_18EB\_R9Id\_OR\_IsoCaloId\_AND\_HE\_R9Id\_DoublePixelVeto\_Mass55

- **AND Path**

HLT\_Diphoton30PV\_18PV\_R9Id\_AND\_IsoCaloId\_AND\_HE\_R9Id\_DoublePixelVeto\_Mass55

- **Pre-Selection**

- Loose Photon ID  $> -0.9$

- Trigger strategy on MC based on offline selection similar to online

**NEW**

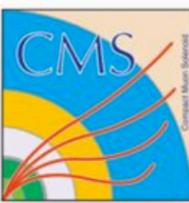
Cut on EE

Cut on EB

Offline Trigger like requirements

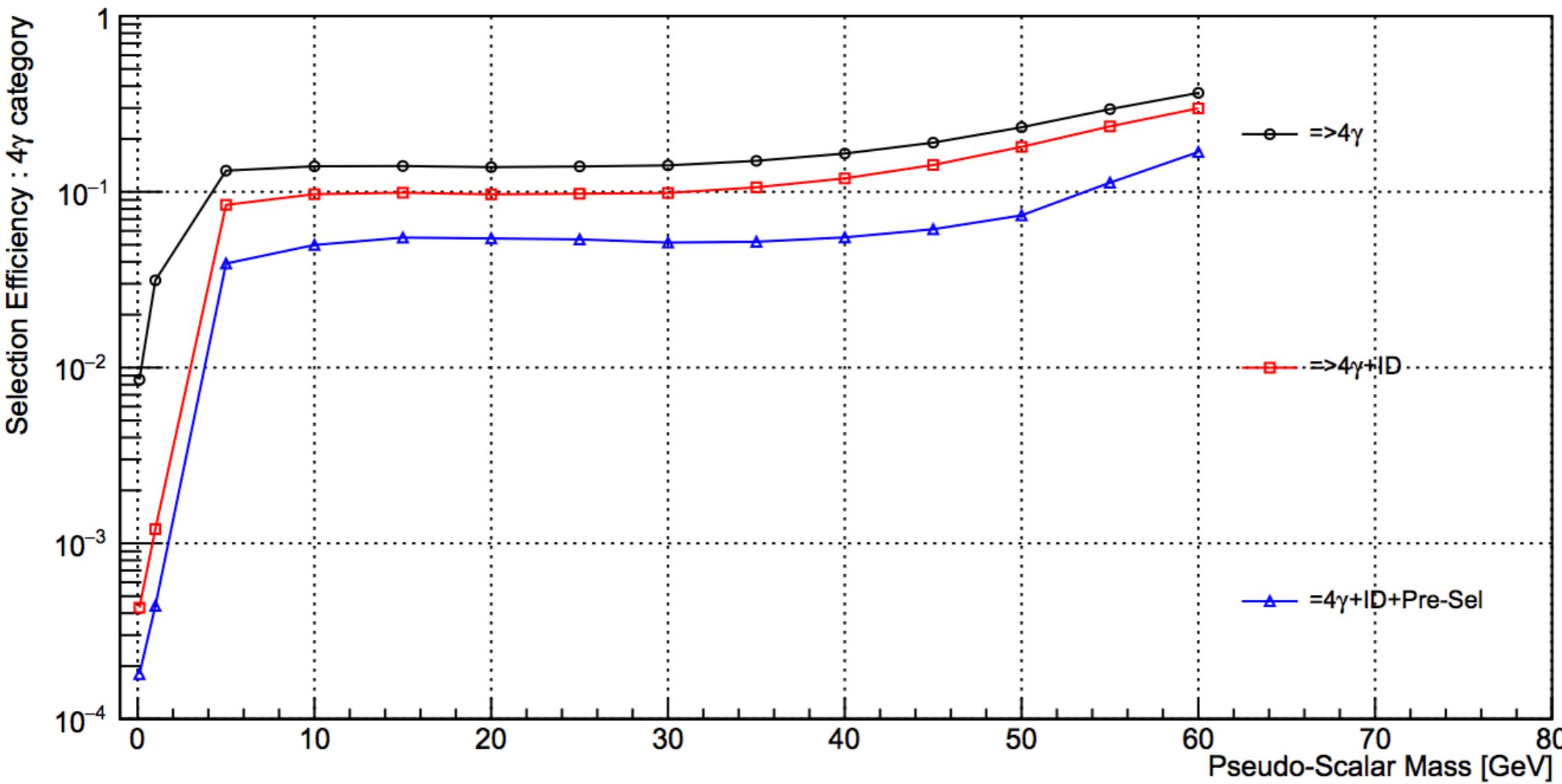
Category		R9	Trigger path	H/E	$\sigma_{inj}$	Pho Iso	Trk Iso
Both photons in EB		$> 0.85$ $> 0.85$	OR	$< 0.08$ $< 0.08$	-	-	-
		$> 0.85$ $> 0.85$	AND	$< 0.08$ $< 0.08$	$< 0.015$ $< 0.015$	$< 6 + 0.012 * Pt$ $< 6 + 0.012 * Pt$	$< 6 + 0.002 * Pt$ $< 6 + 0.002 * Pt$
		$> 0.5 \& & < 0.85$ $> 0.5 \& & < 0.85$	OR	$< 0.08$ $< 0.08$	$< 0.015$ $< 0.015$	$< 6 + 0.012 * Pt$ $< 6 + 0.012 * Pt$	$< 6 + 0.002 * Pt$ $< 6 + 0.002 * Pt$
At least one Photon in EE	Second photon in EB	$> 0.9$ $> 0.85$	AND	$< 0.08$ $< 0.08$	$< 0.035$ $< 0.015$	$< 6 + 0.012 * Pt$ $< 6 + 0.012 * Pt$	$< 6 + 0.002 * Pt$ $< 6 + 0.002 * Pt$
	Second Photon in EE	$> 0.9$ $> 0.9$	AND	$< 0.08$ $< 0.08$	$< 0.035$ $< 0.035$	$< 6 + 0.012 * Pt$ $< 6 + 0.012 * Pt$	$< 6 + 0.002 * Pt$ $< 6 + 0.002 * Pt$

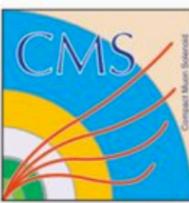
- $m_{\gamma\gamma} > 55 \text{ GeV}$ ,  $P_T$  lead  $\gamma > 30 \text{ GeV}$ ,  $P_T$  sub-lead  $\gamma > 18 \text{ GeV}$ , Pixel Veto applied



# SIGNAL EFFICIENCIES : $4\gamma$ CATEGORY

- Events w/ at least 4  $\gamma$ 's all of which have  $P_T > 15 \text{ GeV}$  &  $|\eta| < 2.5$
- Events w/ at least 4  $\gamma$ 's all of which have  $P_T > 15 \text{ GeV}$  &  $|\eta| < 2.5$  + photon MVA ID  $> -0.9$
- Events w/ at least 4  $\gamma$ 's all of which have  $P_T > 15 \text{ GeV}$  &  $|\eta| < 2.5$  + photon MVA ID  $> -0.9$  +passed pre-selections

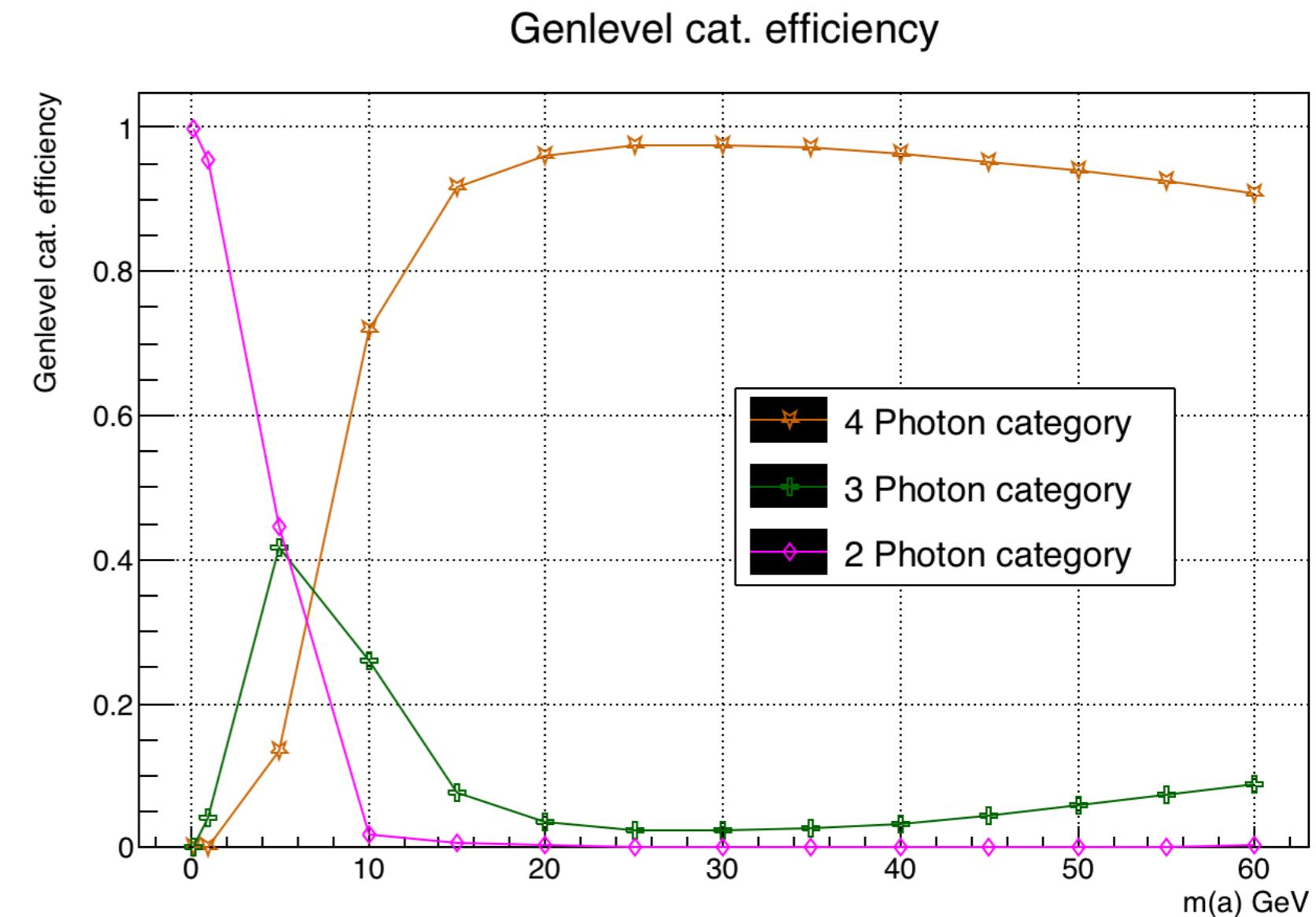


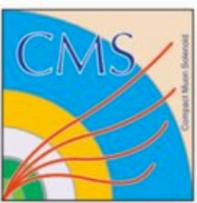


# GEN LEVEL CATEGORIZATION

- Since @ Gen level there are always 4 $\gamma$ 's , we look at delta R between each of the 6 photon pairs
- Define 3 categories:
  - No pairs found with  $\text{deltaR} < 0.3 \rightarrow$  4 Photon Category (all isolated photons)
  - 1 pair found with  $\text{deltaR} < 0.3 \rightarrow$  3 Photon Category(1 Fat Photon + 2 Isolated Photons)
  - 2 pairs found with  $\text{deltaR} < 0.3 \rightarrow$  2 Photon Category ( 2 Fat Photons)

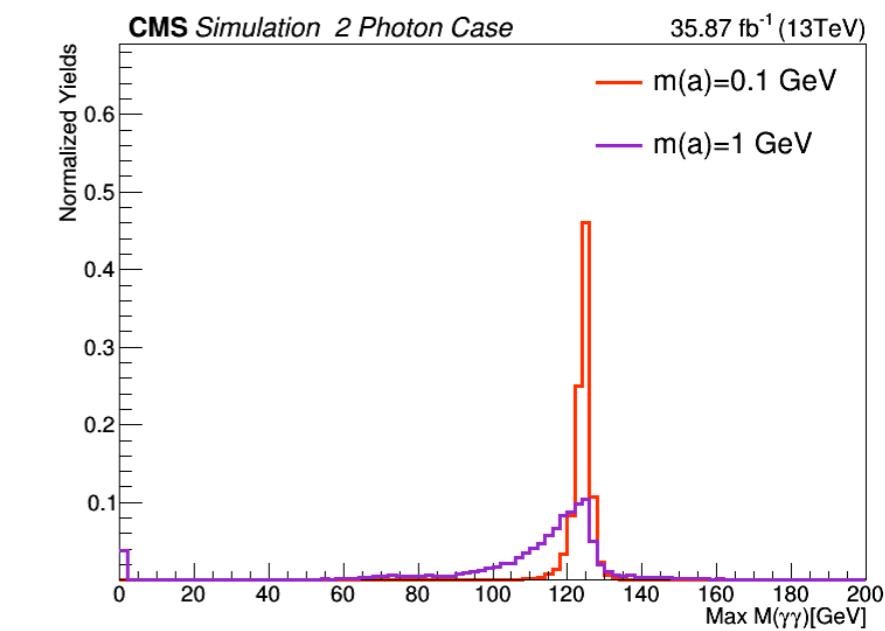
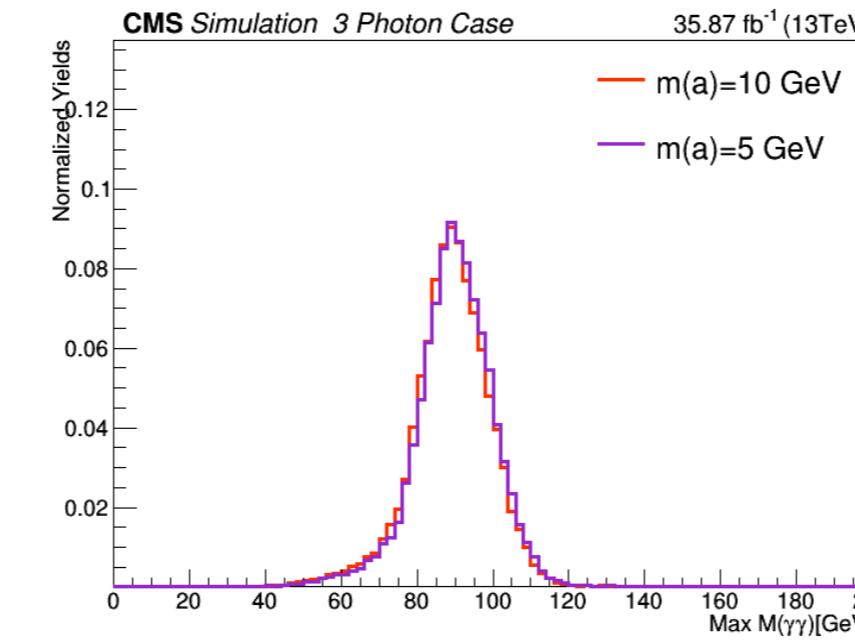
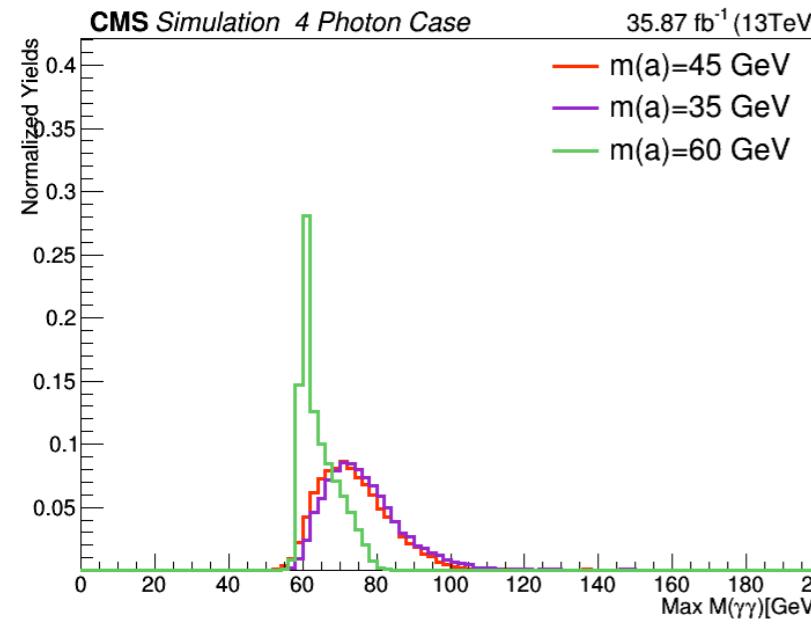
- Plot on the right shows fraction of events falling into the 3 categories for different mass points





# $m_{\gamma\gamma} > 55 \text{ GeV CUT}$

- Due to combinatorics, there is always one photon pair that passes the  $m_{\gamma\gamma} > 55 \text{ GeV}$  cut
- In the **4 photon category**
  - 6 possible photon pairs
- In the **3 photon category**
  - 3 possible photon pairs
- In the **2 photon category**
  - 1 photon pair
- Shown below is the distribution(reco-level) of the maximum diphoton mass out of all possible combinations for each of the 3 categories

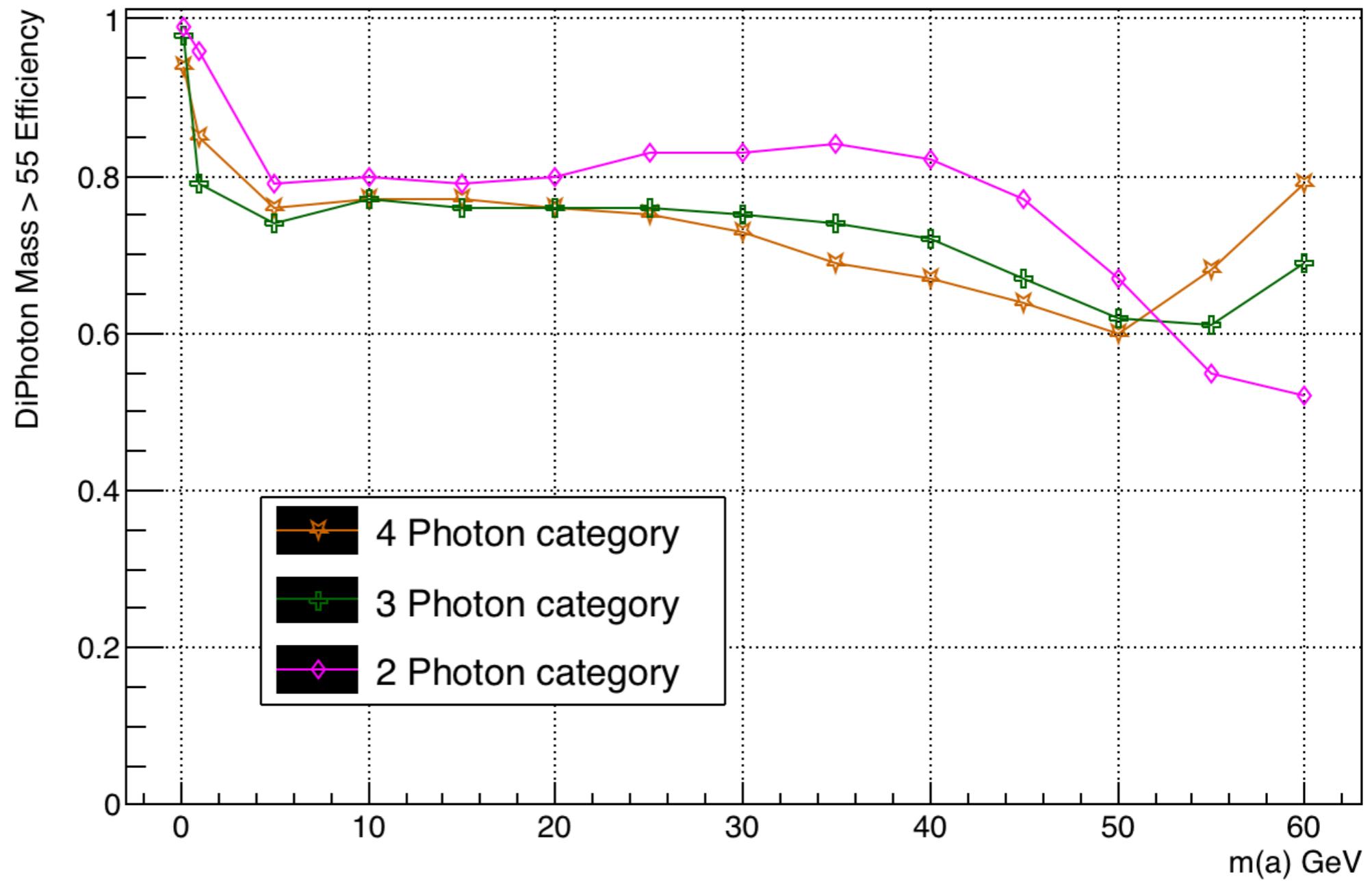




# $m_{\gamma\gamma} > 55$ GeV CUT

DiPhoton Mass  $> 55$  Efficiency

- Efficiency of the  $m_{\gamma\gamma} > 55$  GeV cut

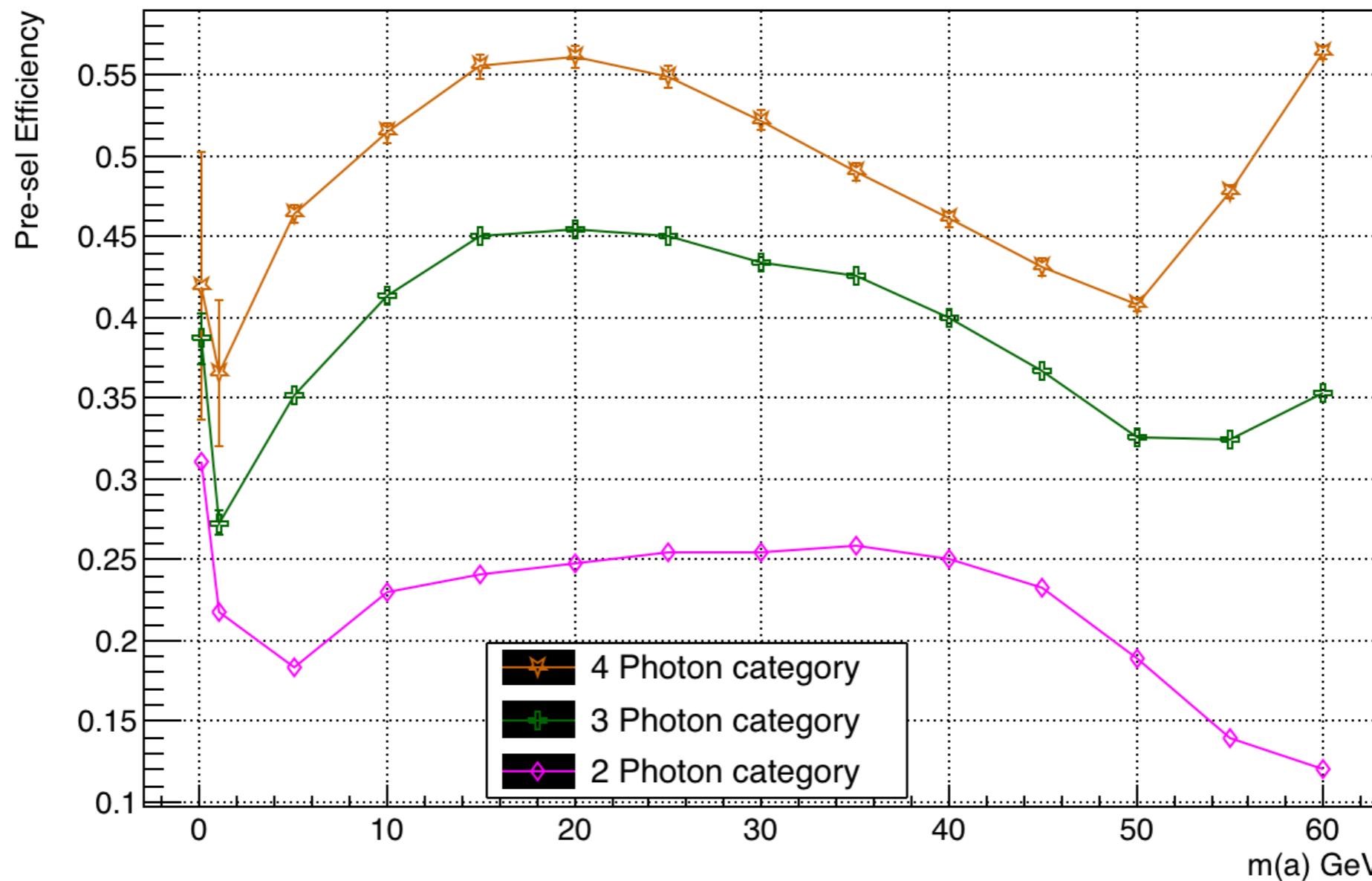


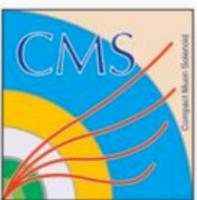


# PRE-SELECTION EFFICIENCY

- Efficiency of the pre-selection cuts for each of the 3 categories
- Efficiency =  $\frac{\# \text{ of events that pass acceptance cuts + Photon MVA + Pre-selections}}{\# \text{ of events that pass acceptance cuts + Photon MVA}}$

Pre-selection Efficiency

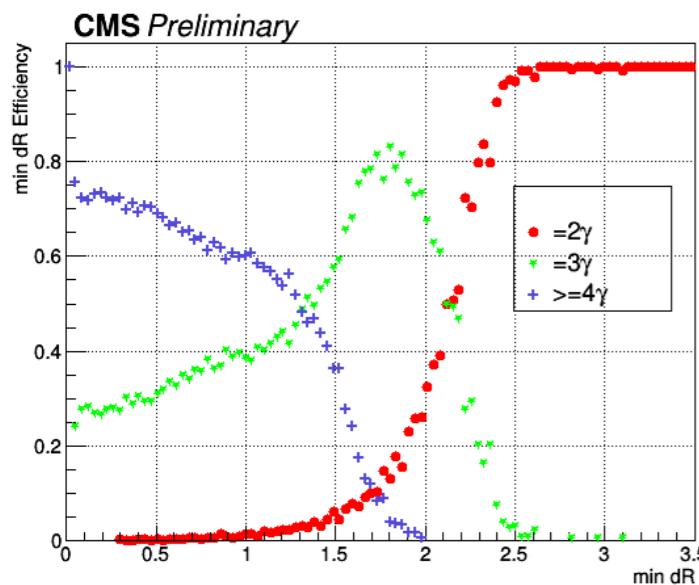




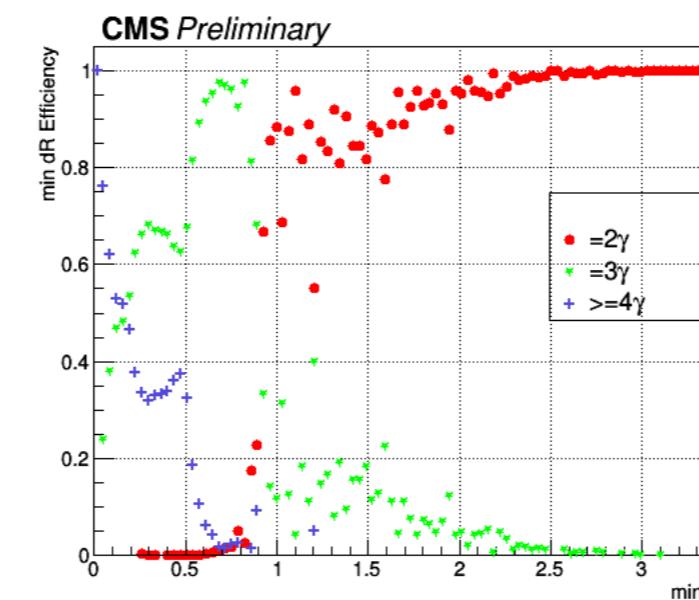
# MIN. dR EFFICIENCY

- Efficiency of the 3 categories as a function of min dR (minimum of the delta R calculated between different photon pairs)

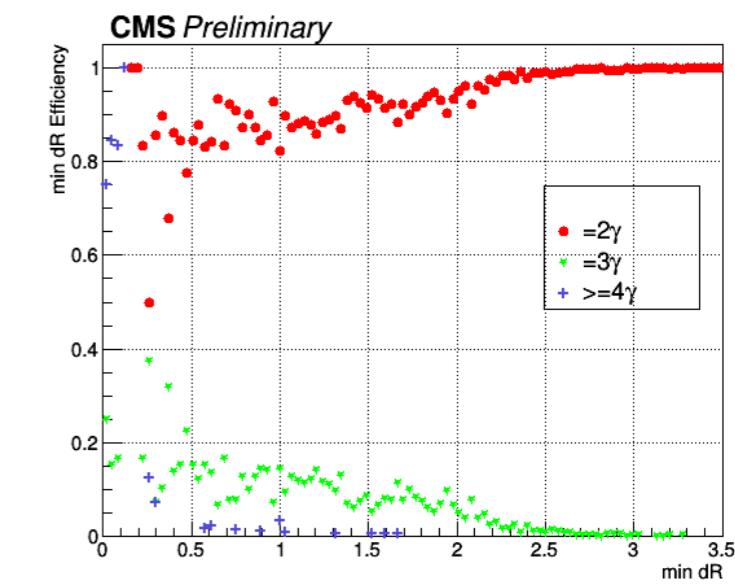
**$m(a) = 60 \text{ GeV}$**



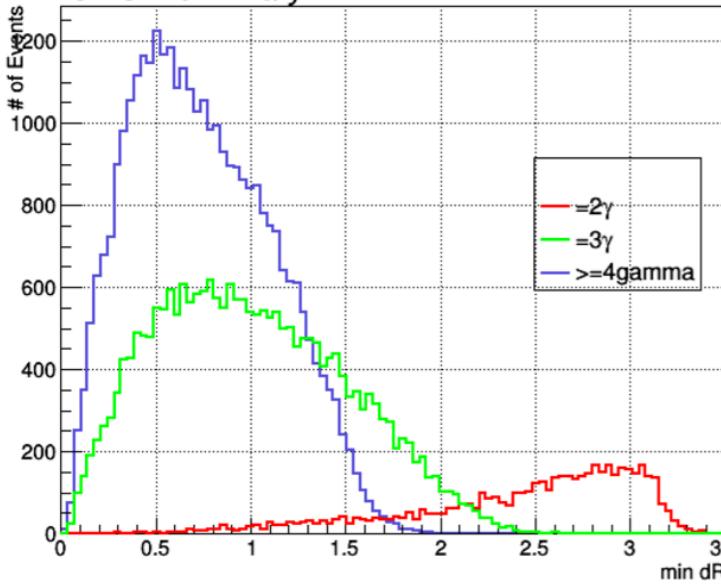
**$m(a) = 15 \text{ GeV}$**



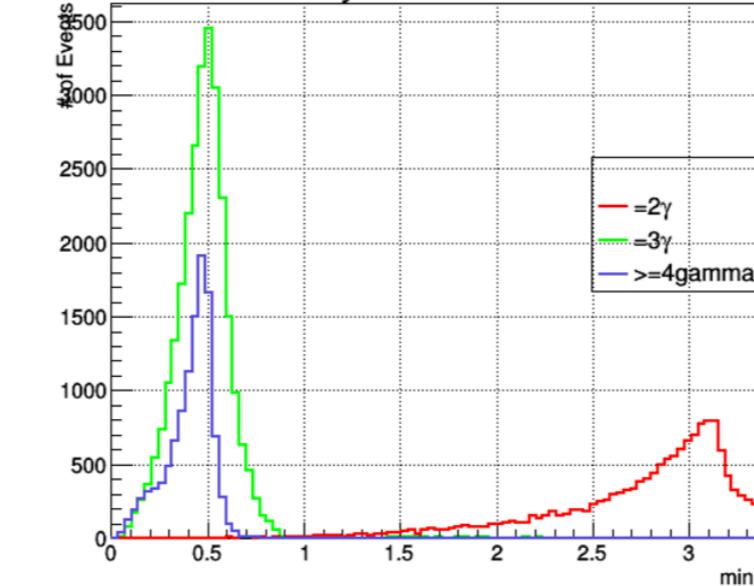
**$m(a) = 0.1 \text{ GeV}$**



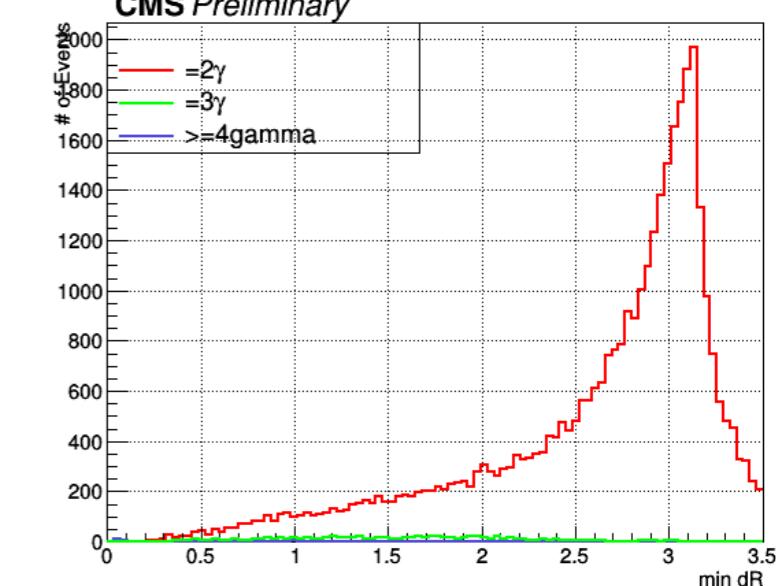
**CMS Preliminary**

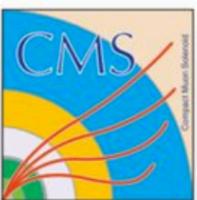


**CMS Preliminary**



**CMS Preliminary**

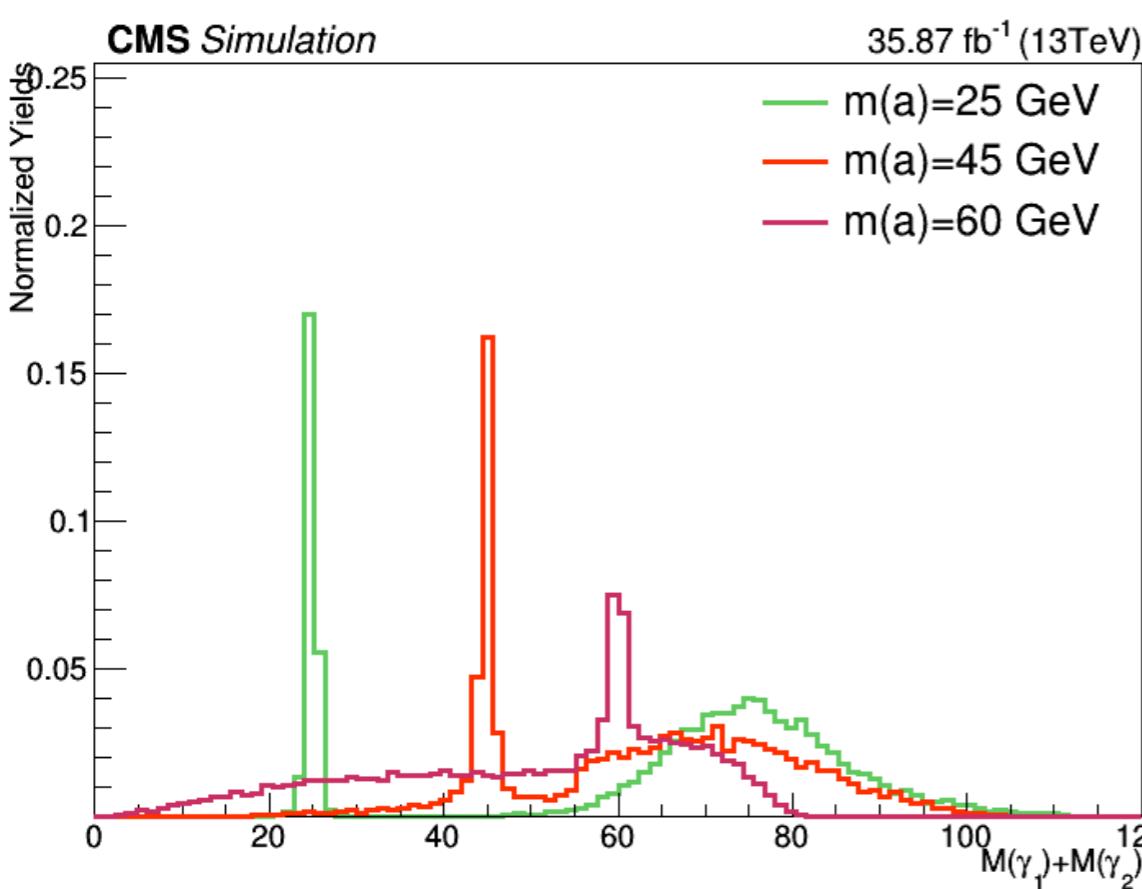




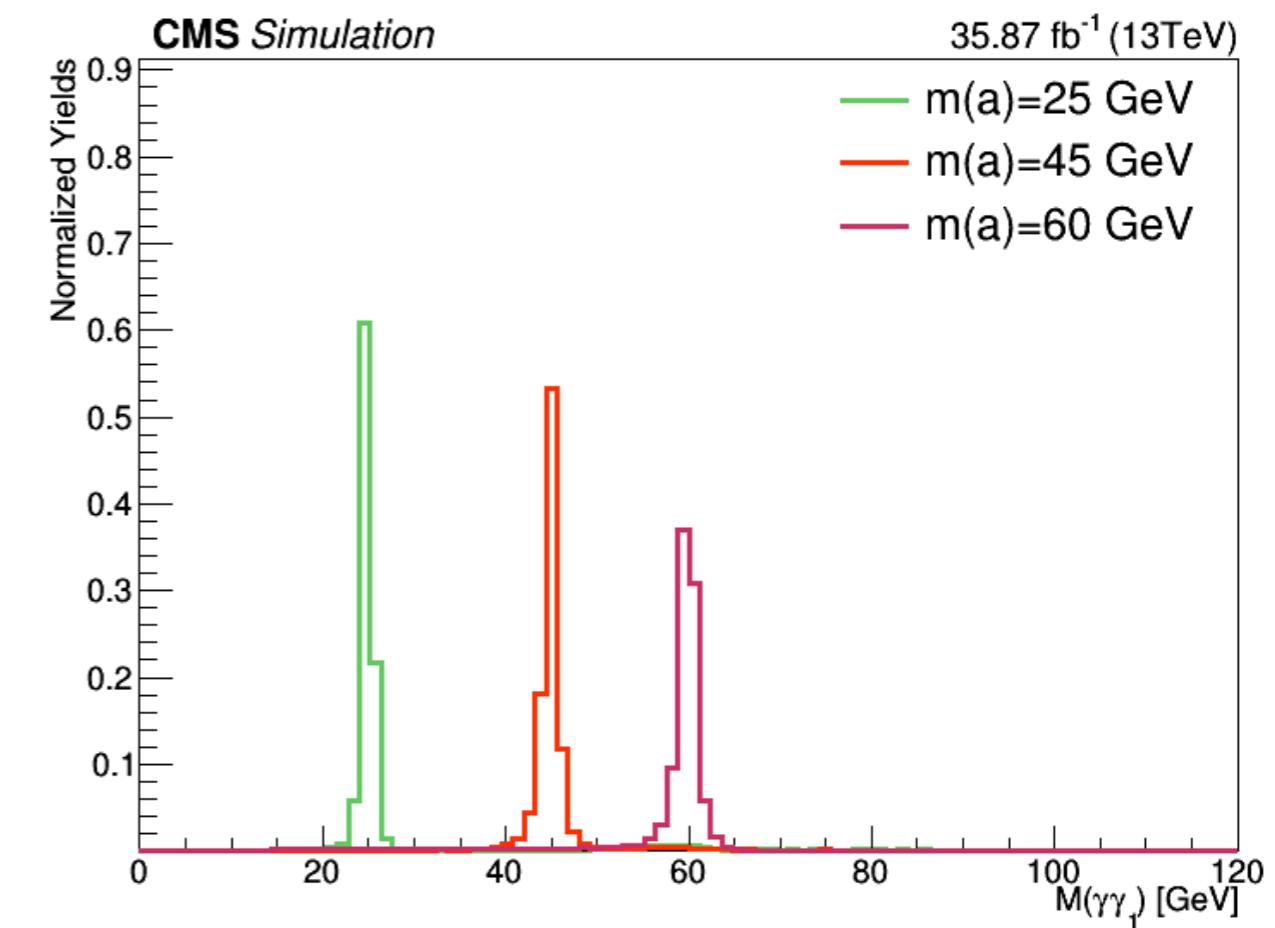
# DIPHOTON PAIRING

- We can get information about  $a \rightarrow \gamma\gamma$  in the event by correctly pairing the photons
- From the 4 final photons, we select pairs that make diphotons with most similar masses
  - Performs better than pairing the leading and subleading photon

**Unpaired**



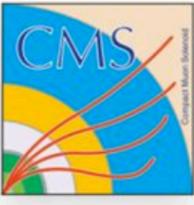
**Paired**



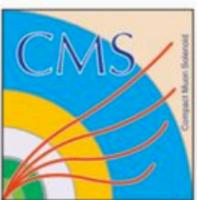


# SUMMARY & OUTLOOK

- Updates/changes in the analysis strategy were presented
- To Do Next
  - Trigger and pre-selection scale factors for the  $4\gamma$  category to have this category of the analysis completed



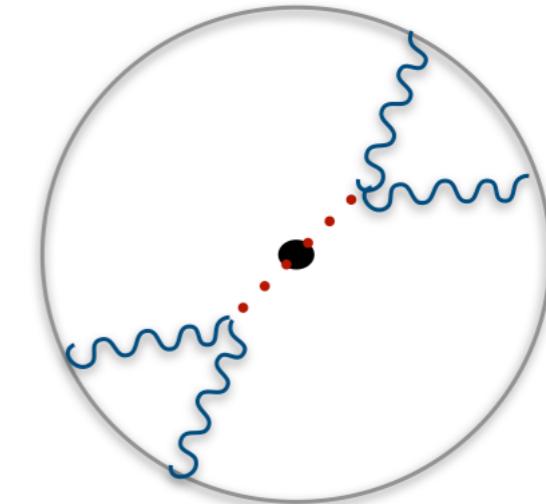
# BACKUP



# CATEGORIES

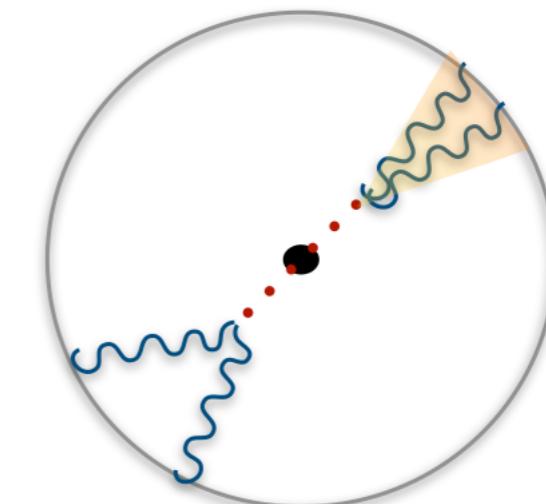
## 4 Isolated Photons

- “a” is not boosted, the decay products are well isolated
- Select events with at least 4  $\gamma$ 's and then select the 4 highest  $P_T$   $\gamma$ 's



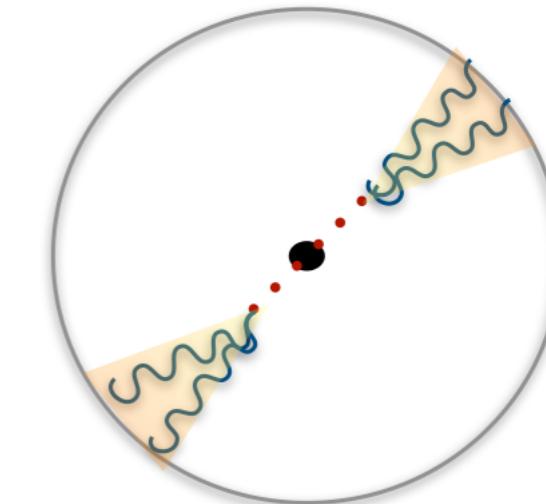
## 2 Isolated Photons + 2 Merged Photons

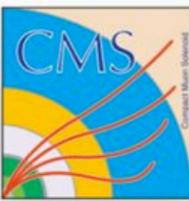
- Boosted “a” case
- Select events with exactly 3  $\gamma$ 's
- Can be further split into 2 sub-categories
  - 2 Isolated + 2 merged  $\gamma$ 's
  - 3 Isolated  $\gamma$ 's + 1 missing  $\gamma$  (due to  $P_T$  or  $\eta$  cut)



## 2 Pairs of Merged Photons

- Highly boosted “a” scenario
- Select events with exactly 2  $\gamma$ 's
- Heavily polluted by  $H \rightarrow \gamma\gamma$  events
- Need to develop a custom MVA ID





## The Low-Mass HLT DiPhoton Trigger

### "OR" PATH\*

#### L1 SEEDED LEG

- $E_T > 10^9$  GeV (EE)
- $E_T > 30$  GeV (EB)
- $R_g > 0.5(0.8)$  in EB(EE)
- $H/E < 0.10(0.1)$  in EB(EE)



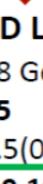
SEEDED LEG

$R_g > 0.85(0.9)$  in EB(EE)



OR

$\sigma_{in\eta} < 0.015(0.035)$  in EB(EE)  
ECAL isolation  $< 6.0 + 0.012E_T$



OR

#### UNSEEDED LEG ( $N \geq 2$ )

- $E_T > 18$  GeV
- $\eta < 1.5$
- $R_g > 0.5(0.8)$  in EB(EE)

#### UNSEEDED LEG

$H/E < 0.10(0.1)$  in EB(EE)

PIXEL VETO



$R_g > 0.85(0.9)$  in EB(EE)

$\sigma_{in\eta} < 0.015(0.035)$  in EB(EE)

ECAL isolation  $< 6.0 + 0.012E_T$

Track isolation  $< 6.0 + 0.002E_T$

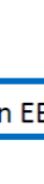
$M_{\gamma\gamma} > 55$  GeV

## The Low-Mass HLT DiPhoton Trigger

### "AND" PATH\*

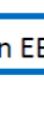
#### L1 SEEDED LEG

- $E_T > 30$  GeV (EE)
- $E_T > 30$  GeV (EB)
- $R_g > 0.5(0.8)$  in EB(EE)
- $H/E < 0.10(0.1)$  in EB(EE)



SEEDED LEG

$R_g > 0.85(0.9)$  in EB(EE)



AND

$\sigma_{in\eta} < 0.015(0.035)$  in EB(EE)  
ECAL isolation  $< 6.0 + 0.012E_T$



AND

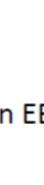
#### UNSEEDED LEG ( $N \geq 2$ )

- $E_T > 18$  GeV
- $\eta < 2.5$
- $R_g > 0.5(0.8)$  in EB(EE)

#### UNSEEDED LEG

$H/E < 0.10(0.1)$  in EB(EE)

PIXEL VETO



$R_g > 0.85(0.9)$  in EB(EE)

$\sigma_{in\eta} < 0.015(0.035)$  in EB(EE)

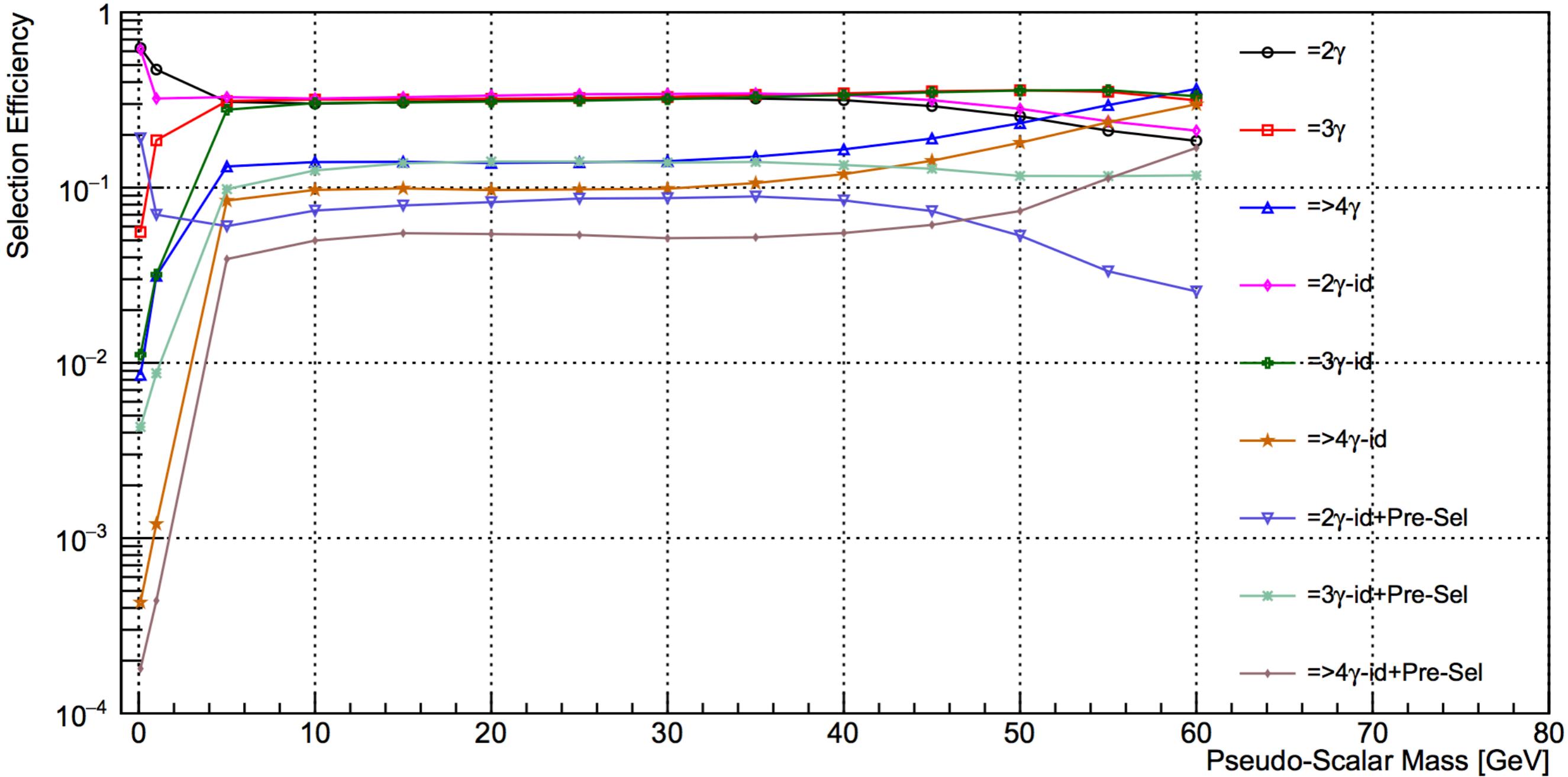
ECAL isolation  $< 6.0 + 0.012E_T$

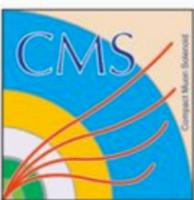
Track isolation  $< 6.0 + 0.002E_T$

$M_{\gamma\gamma} > 55$  GeV



# SIGNAL EFFICIENCIES

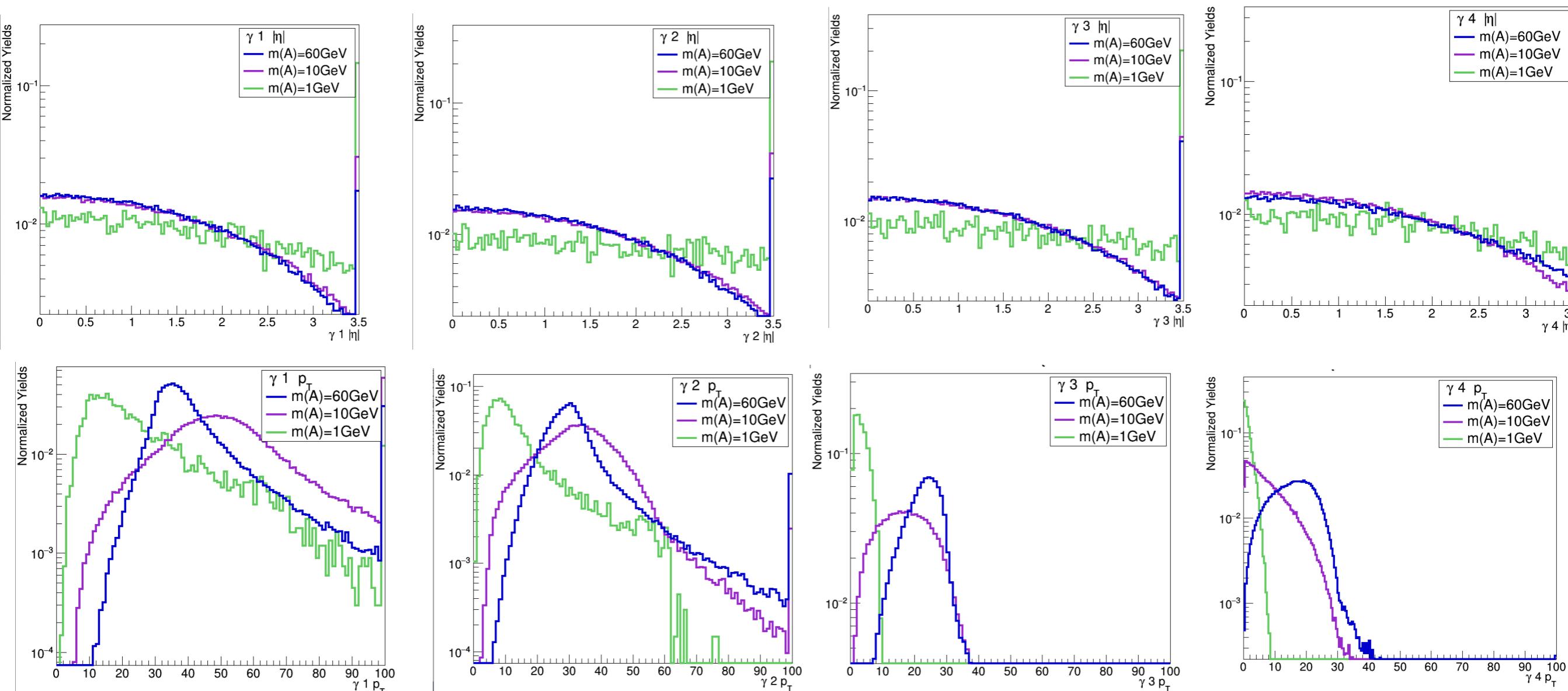


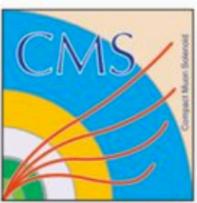


# GEN LEVEL DISTRIBUTIONS

- Shown in the following slides are the distributions for 60 GeV, 10 GeV and 1 GeV
- All plots are normalized to 1
- Overflow bin is also shown

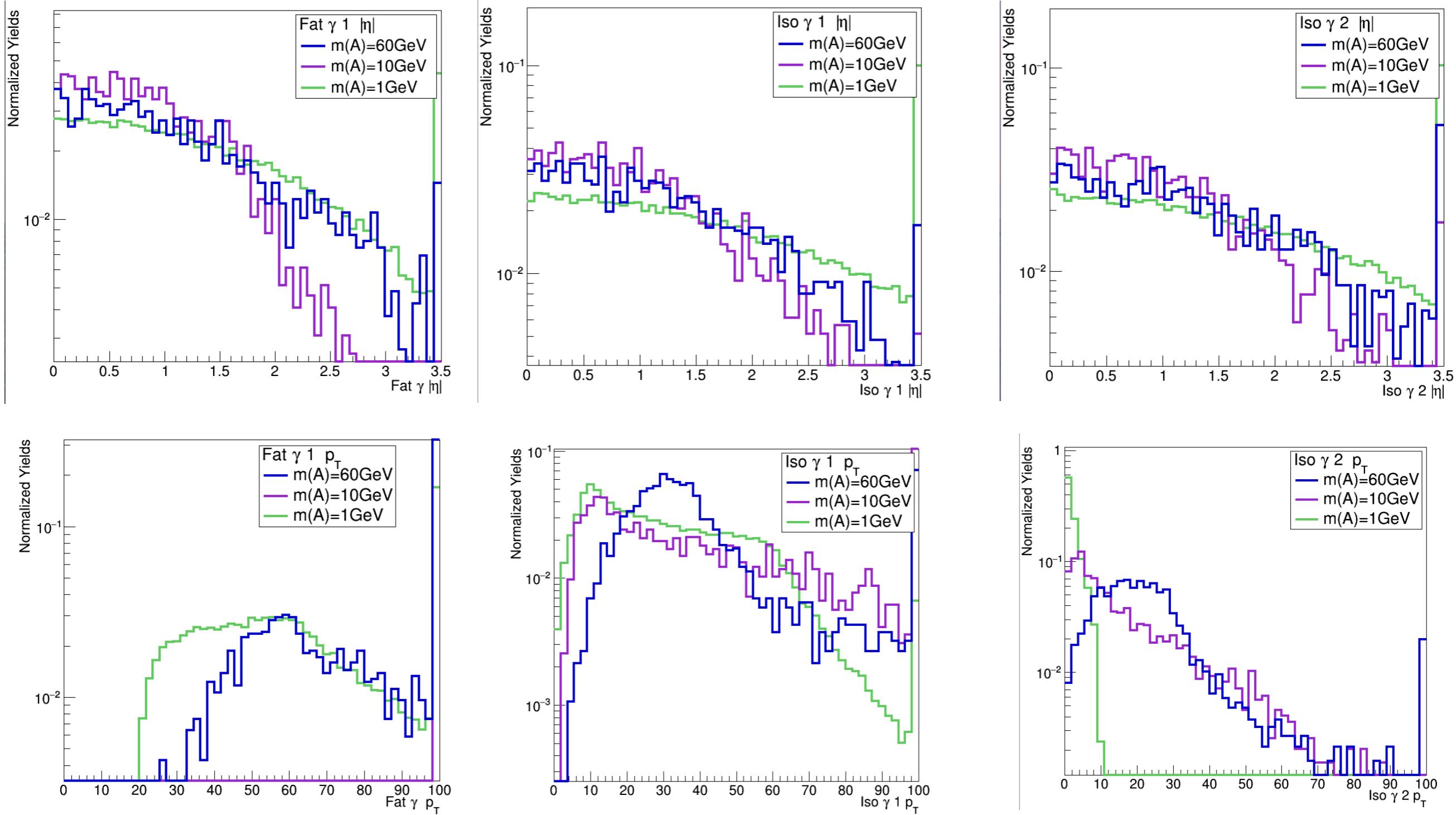
## 4 Gamma Category : 4 Isolated photon case:

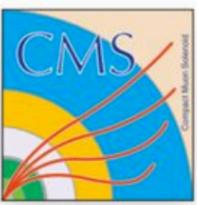




# GEN LEVEL DISTRIBUTIONS

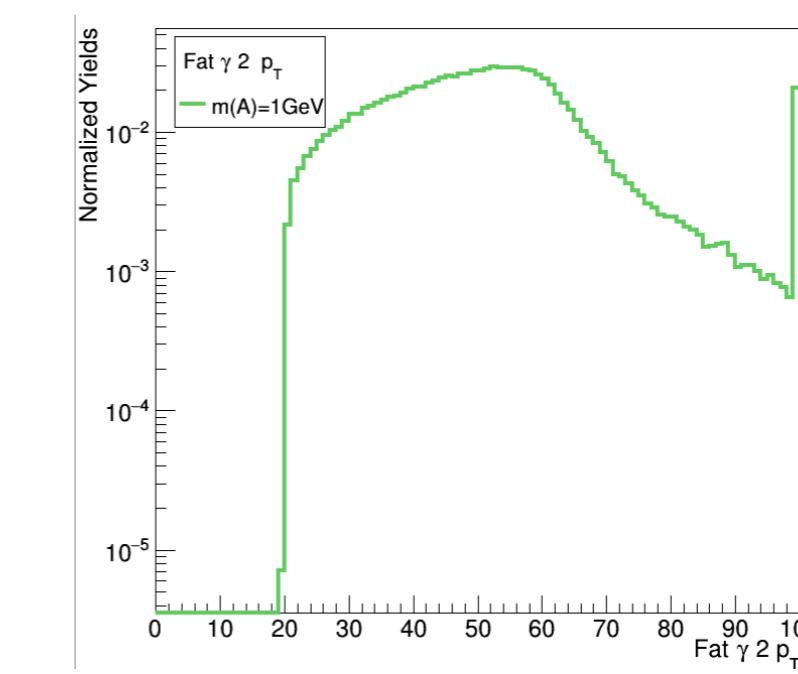
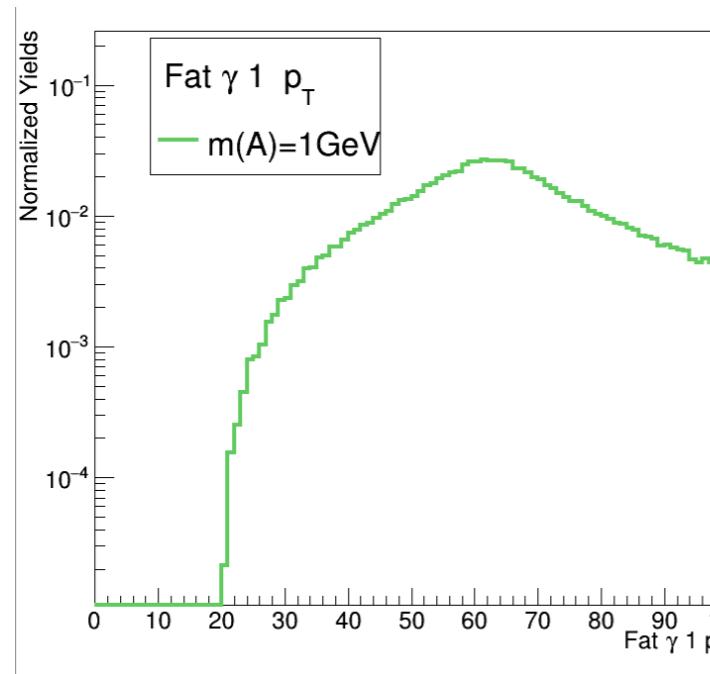
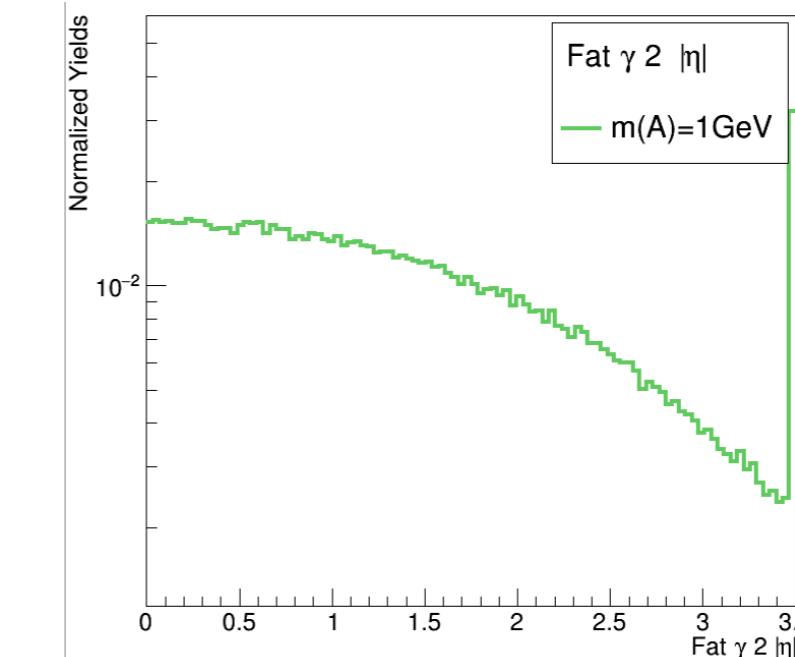
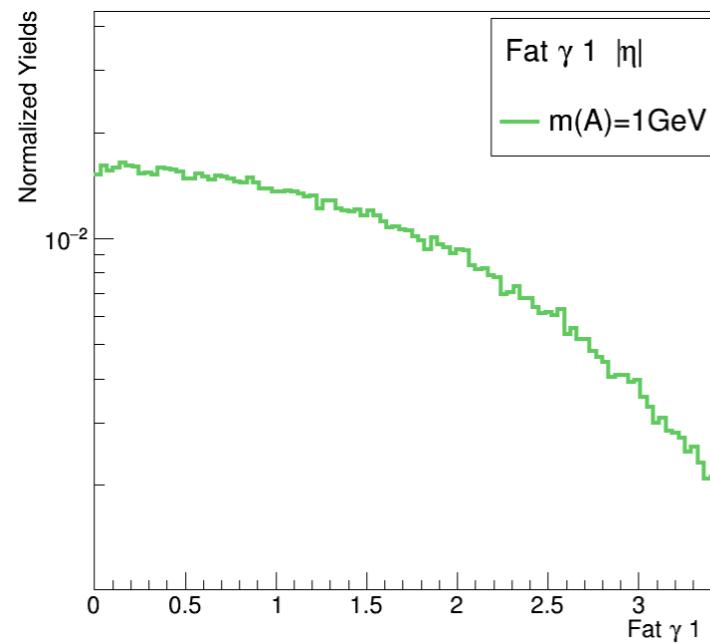
3 Gamma Category : 2 Isolated photons + 2 merged photons case:

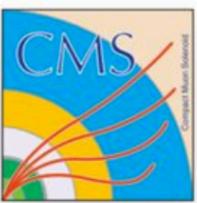




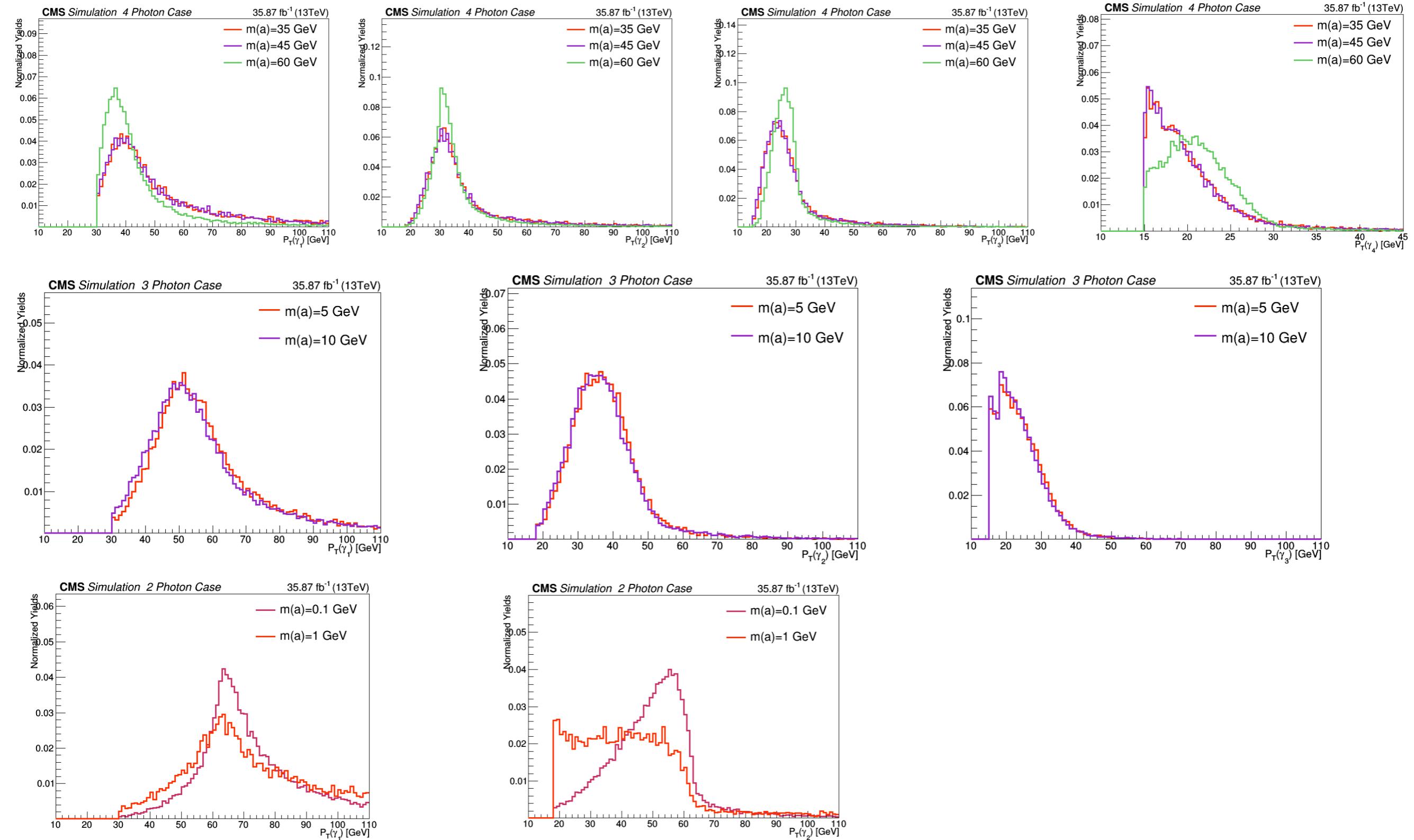
# GEN LEVEL DISTRIBUTIONS

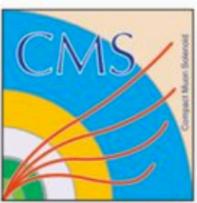
2 Gamma Category : 2 pairs of merged photons case





# RECO LEVEL DISTRIBUTIONS





# TRIGGER & PRESELECTION

- Online selection identical to low mass  $h \rightarrow \gamma\gamma$  search
- Passing the OR of the two Low mass HLT paths
  - **OR Path**  
HLT\_Diphoton30EB\_18EB\_R9Id\_OR\_IsoCaloId\_AND\_HE\_R9Id\_DoublePixelVeto\_Mass55
  - **AND Path**  
HLT\_Diphoton30PV\_18PV\_R9Id\_AND\_IsoCaloId\_AND\_HE\_R9Id\_DoublePixelVeto\_Mass55
- **Pre-Selection**
  - Loose Photon ID  $> -0.9$
  - Trigger strategy on MC based on offline selection similar to online
  - Different kind of photon pairs being considered according to their  $\eta$  and R9 values

**OLD**

Offline Trigger like requirements

Category		R9	H/E	$\sigma_{\eta\eta}$	Pho Iso	Trk Iso
Both photons in EB		$> 0.5$	$< 0.07$	$< 0.0105$	$< 4 \text{ GeV}$	$< 6 \text{ GeV}$
At least one Photon in EE	Second photon in EB	$> 0.85$	$< 0.07$	$< 0.0105$	$< 4 \text{ GeV}$	$< 6 \text{ GeV}$
At least one Photon in EE	Second photon in EE	$> 0.9$	$< 0.035$	$< 0.0275$	$< 4 \text{ GeV}$	$< 6 \text{ GeV}$

- $m_{\gamma\gamma} > 55 \text{ GeV}$ ,  $P_T$  lead  $\gamma > 30 \text{ GeV}$ ,  $P_T$  sub-lead  $\gamma > 18 \text{ GeV}$ , Pixel Veto applied