h(125)→aa→γγγγ

Hgg Working Group Meeting

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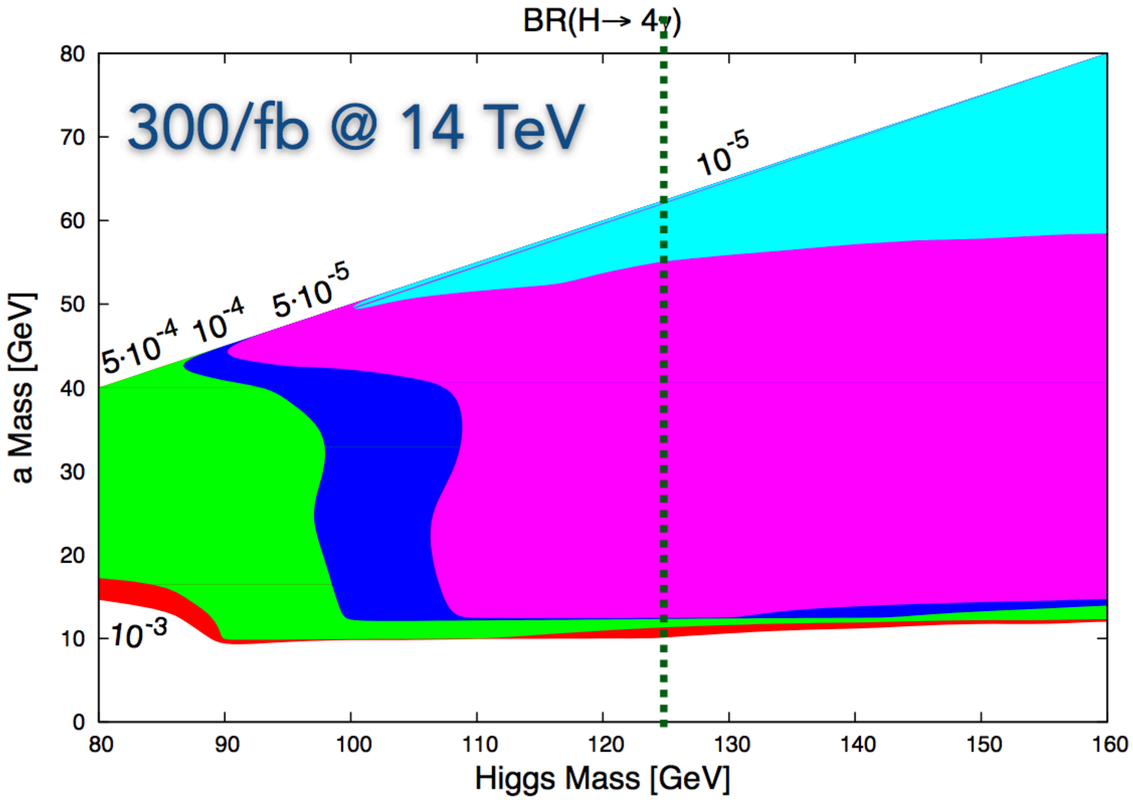
H→aa→γγγγ : Motivation

The possibility of light scalars is a very well established scenario

- The usual suspects {(N)MSSM, SM+Singlet, etc} typically have very sub-dominant BR (a→γγ), but
  - Non-trivial SM extensions can change that picture by suppressing a→fermions
  - Also, 4γ final state is basically SM background free and we can take advantage of the high γ online/ offline reconstruction and identification efficiency

Existing studies show sensitivity for discovery down to Br(h→aa→4γ) ~10^{-5} for 300/fb @ 14 TeV

hep-ph/0608331



Overview of the updates

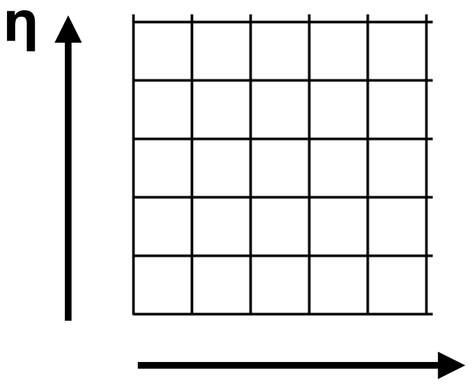
- Since we are probing m(a) from 100 MeV to 60 GeV, it is important to look at the topology of the final state
  - Higher is m(a), lower is the boost of the "a" boson and larger are the values of ΔR (calculated between two photons from the same "a")

- Depending on m(a), we can design different categories:
  - **4 resolved photons**
  - **2 resolved + 1 merged photon**
  - **2 pairs of merged photons**

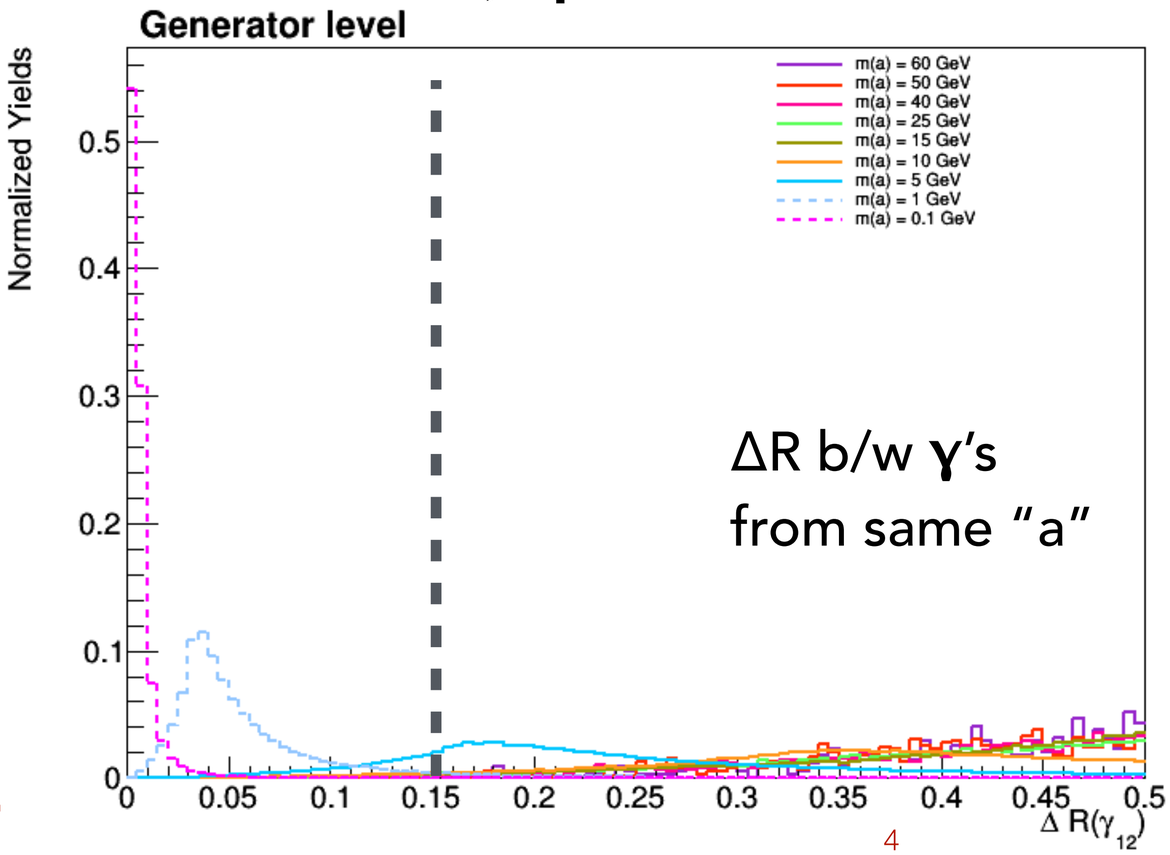
- Today's updates aim to design these categories using the Gen- and Reco- level photons

Motivation to perform a Generator level study

- Fundamental question: can we reconstruct our signal as resolved photons?
- In ECAL, a cluster of 5x5 crystals refers to **ΔR ~ 0.123**
- Since there are always 4 **γ**'s at Gen level, we can see what ΔR looks like b/w **γ**'s coming from the same "a"
- If we choose a cut-off at **ΔR = 0.15** , i.e consider the **γ**'s to be merged if ΔR < 0.15, then
  - For m(a) < 5 GeV, most **γ**'s (coming from the same "a") are merged, i.e cannot be reconstructed as two separate photons



Array of 5x5 crystals



ΔR b/w **γ**'s from same "a"

Generator level study

- Begin by calculating ΔR b/w each of the 6 photon pairs

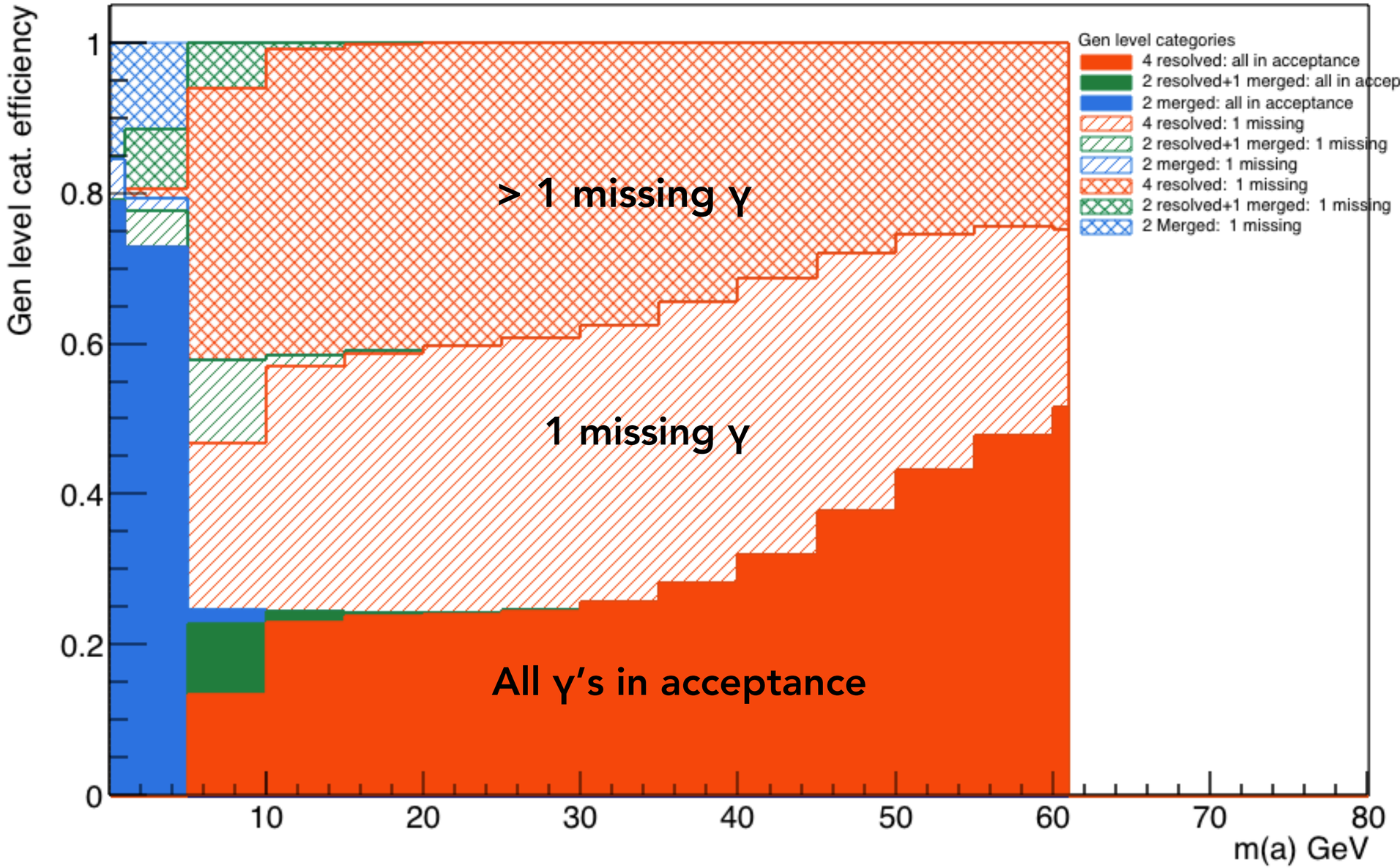
If no pairs found with ΔR < 0.15	1 pair with ΔR < 0.15	2 pairs with ΔR < 0.15
• **4 resolved γ's case**	• **2 resolved + 1 merged γ's case**	• **2 pairs of merged γ's case**

- Also need to apply detector acceptance requirements
  - Leading and sub-leading **γ** should have P_T > 30 GeV and > 18 GeV, respectively (motivated by selections in the online Di-photon HLT paths)
  - 3rd and 4th **γ** should have P_T > 10 GeV
  - All 4 **γ**'s should have |**η**| < 2.5
- Based on this criteria, events can be divided into the following categories:

4 resolved γ's:	**2 resolved + 1 merged γ's:**	**2 pairs of merged γ's:**
• **All in acceptance**	• **All in acceptance**	• **All in acceptance**
• **1 missing γ**	• **1 missing γ**	• **1 missing γ**
• **> 1 missing γ**	• **>1 missing γ**	• **> 1 missing γ**

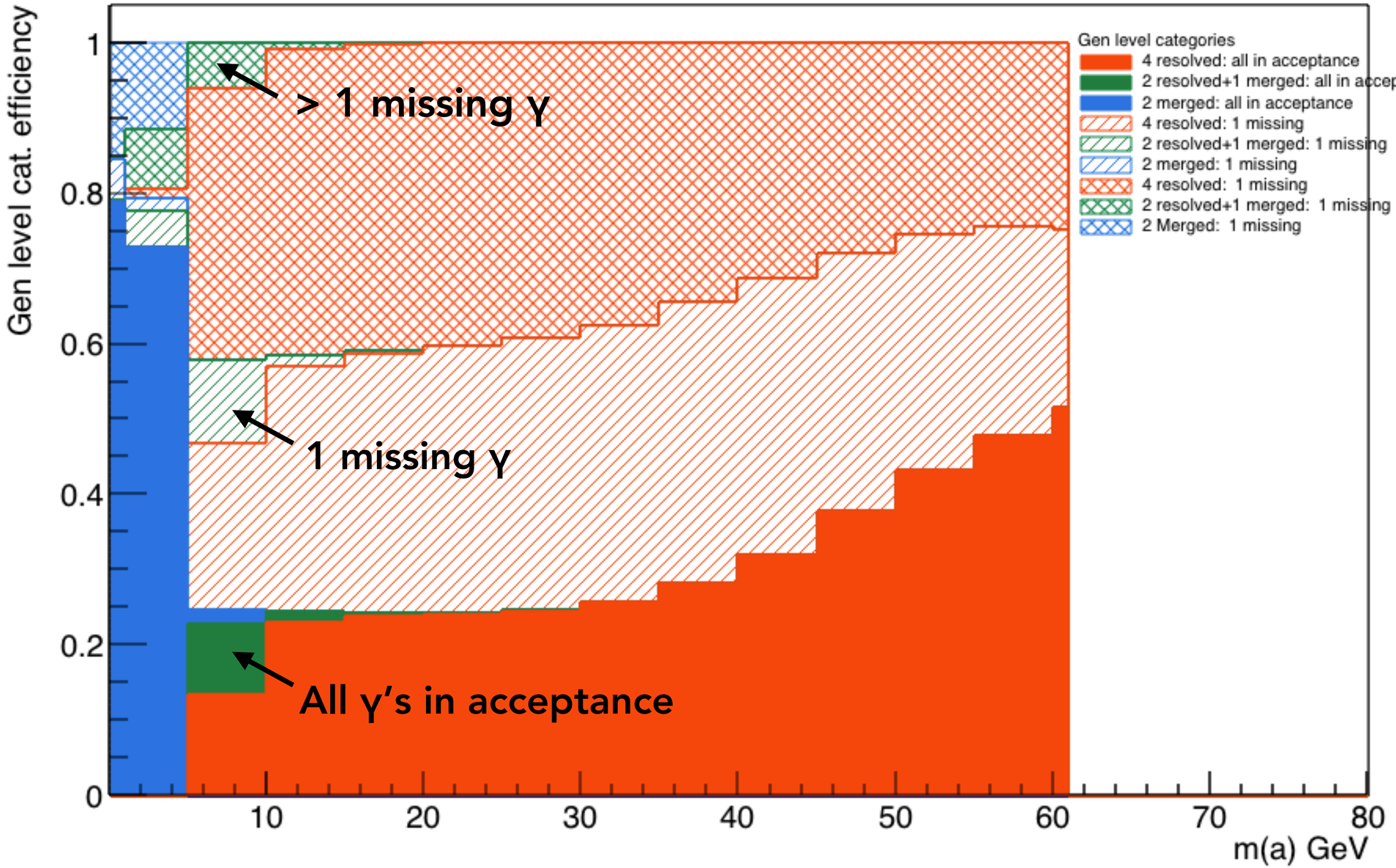
Generator level study

In red are the events with **4 resolved photons (no pairs found with ΔR < 0.15)**



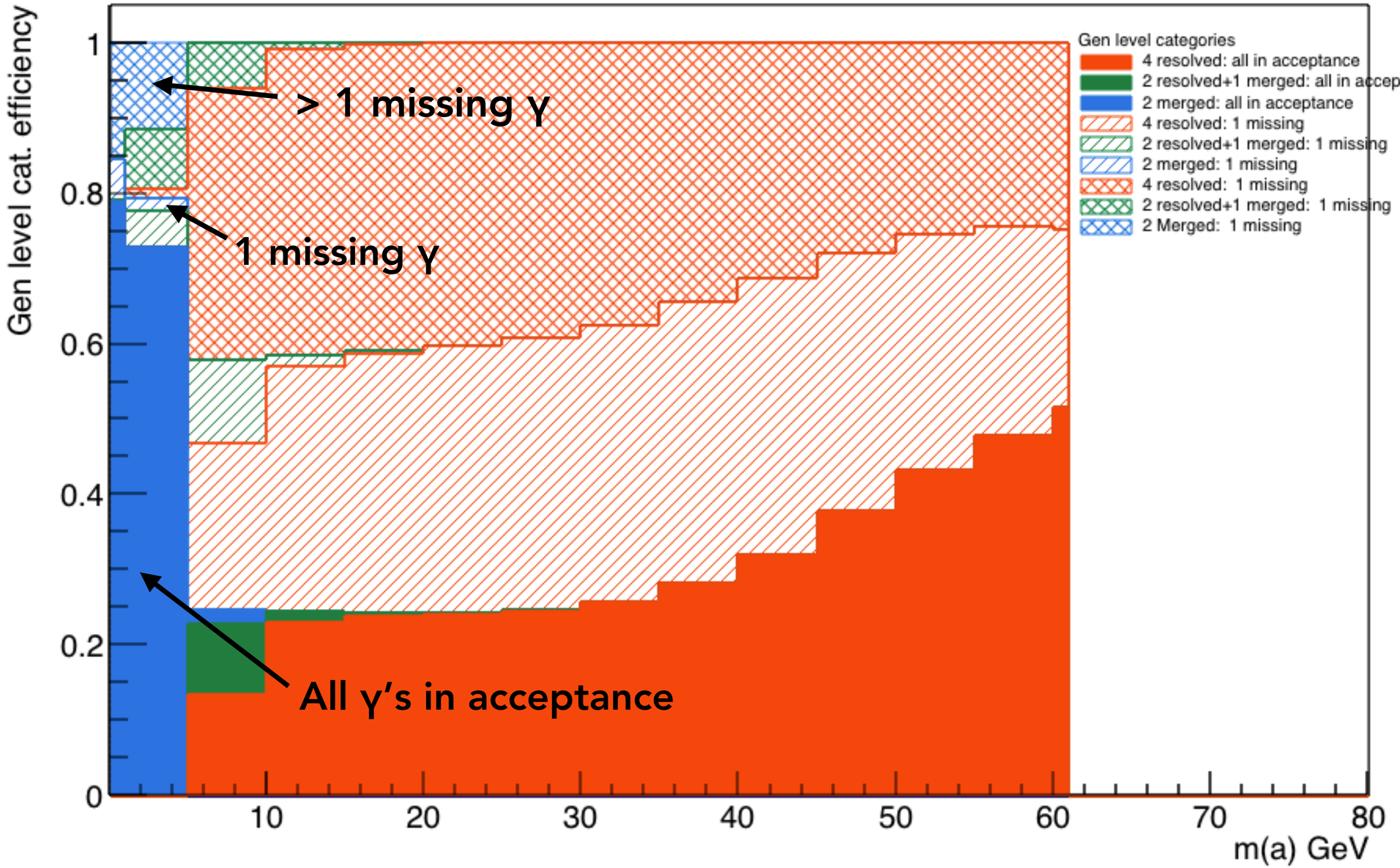
Generator level study

In green are the events with **2 resolved + 1merged photons (1 pair found with ΔR < 0.15)**



Generator level study

In blue are the events with
2 pairs of merged photons
(2 pairs found with ΔR < 0.15)



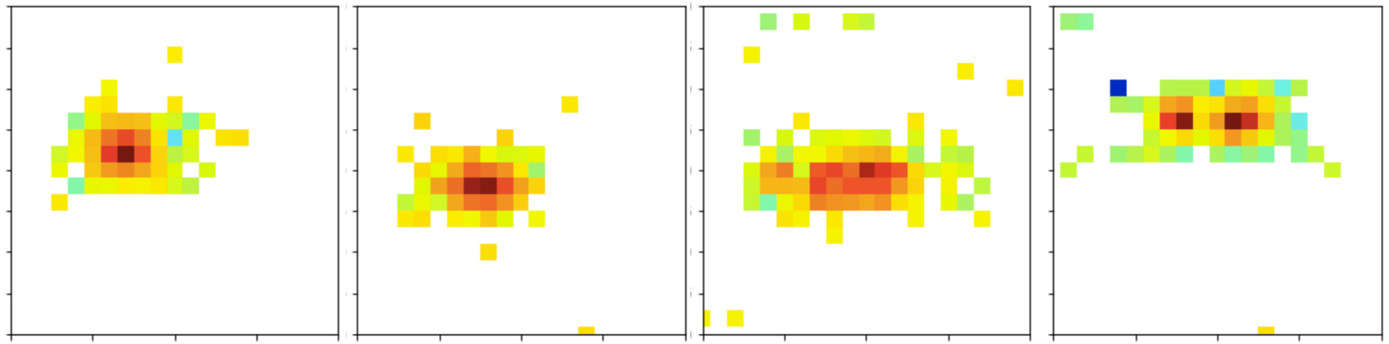
Comments on generator level study

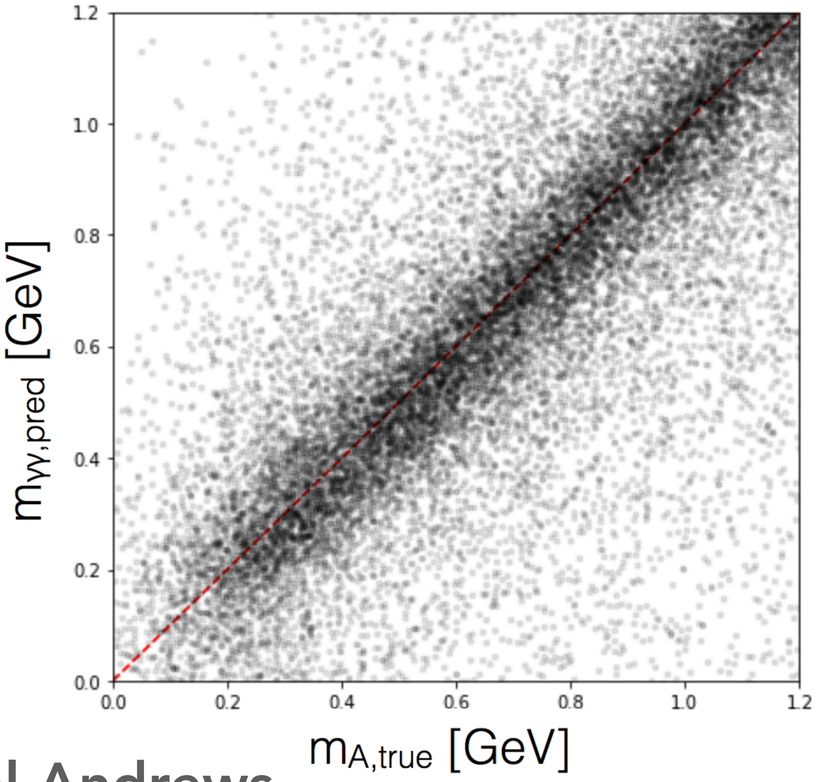
- For **m(a) > 10 GeV**, the **fully resolved** topology is the dominant one
- The fraction of events falling under the 4 resolved **γ**'s (all **γ**'s within detector acceptance) ranges from **23% for m(a) = 10 GeV** to **51% for m(a) = 60 GeV**
- Fraction of events under **4 resolved γ's (1 missing γ)** is also significant (from 32% for 10 GeV to 23% for 60 GeV); but, cannot reconstruct the 4**γ** invariant mass here (The 4th **γ** can be recovered if the P_T threshold is lowered, but this may require some fine-tuning since those objects may not be supported)
- The events with **4 resolved γ's (> 1 missing γ) are unrecoverable**
- For **m(a) = 5 GeV and 10 GeV, only 9% and 1% of events fall under the 2 resolved + 1 merged γ's (all in acceptance)**, respectively — **Less important than the 4 resolved γ's and 2 pairs of merged γ's case, but could still be worth studying later down the line**

Comments on generator level study

- For **m(a) = 100 MeV and 1 GeV**, the dominant category is **2 pairs of merged γ's (all γ's in acceptance)**
  - However, for this mass regime a separate analysis has to be developed since the **standard photon identification MVA will cease to work**
  - New classification would be needed in this case; In contact with Michael Andrews (from CMU) (working on developing mass regression on merged photon clusters) Link to Michael's presentation

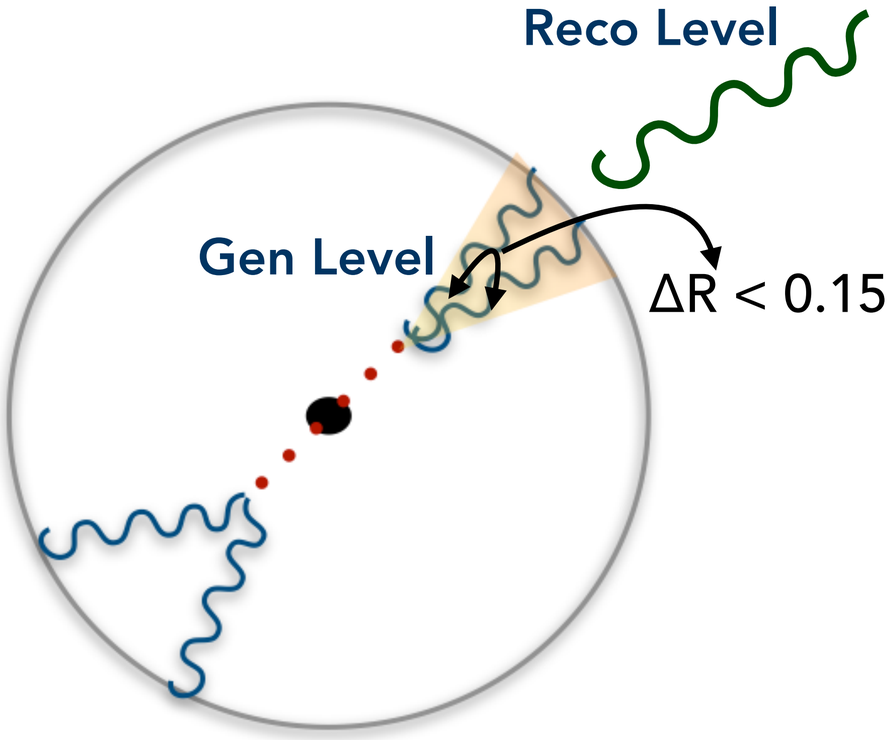
- **Mass regression on merged photon clusters:**
  For exotic light scalar decays, A→γγ, try to perform mass regression on the merged photon cluster





From Michael Andrews

Gen-Reco Matching



- Start by identifying a merged photon at Gen level (if $\Delta R < 0.15$)
- Loop over the collection of Reco photons and look for one which is close to the Gen-level merged photon within a cone of $\Delta R = 0.15$
- If more than one such Reco photons are found, then the one with the least ΔR is flagged as a merged photon at the Reco-level
- By doing this, we can flag each photon at the Reco level as “resolved” or “merged”
- Next step is to mimic the categories @ Reco level

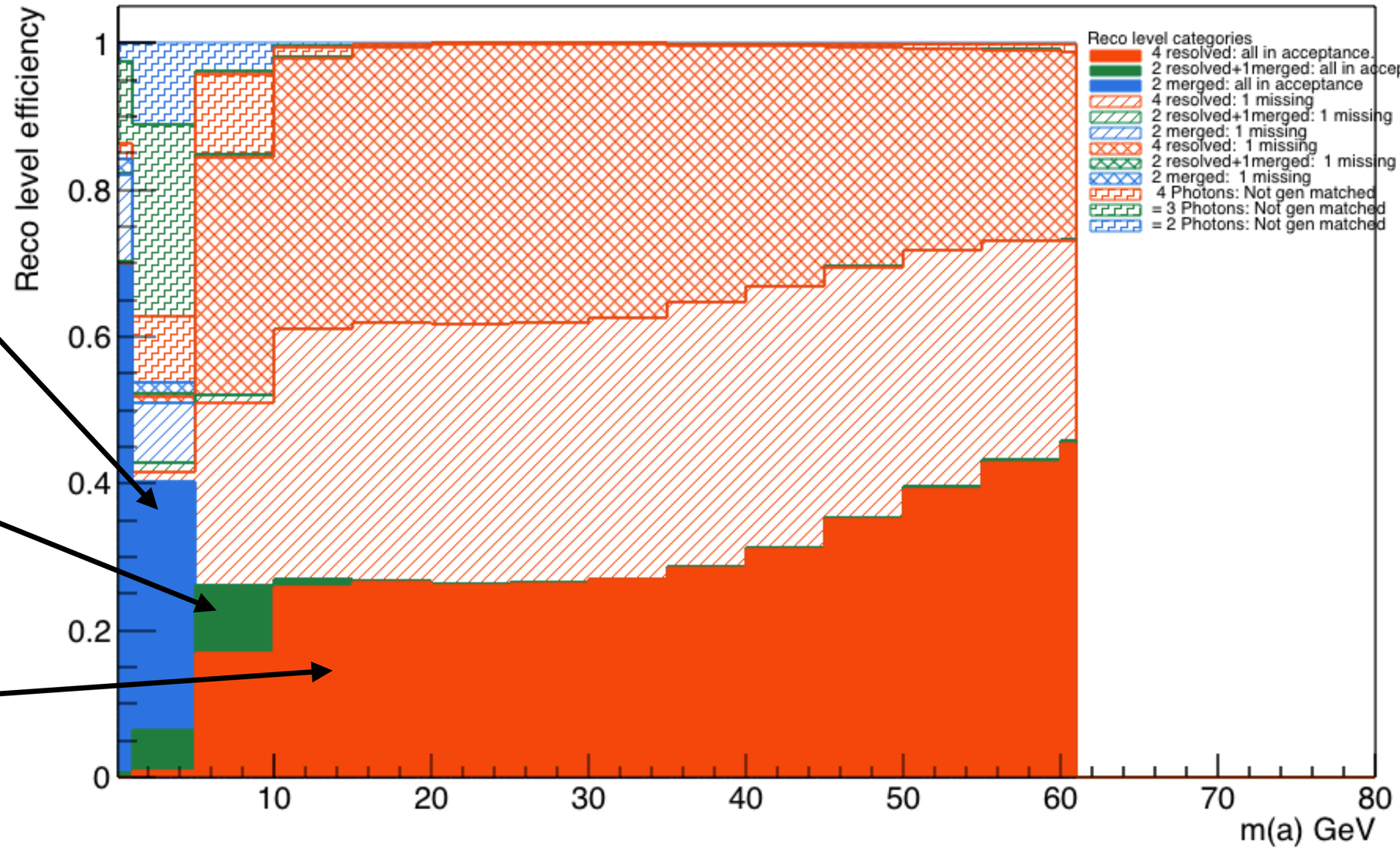
Reco level categorization

Possible to reconstruct the 4γ invariant mass in these categories

2 pairs of merged reconstructed γ's

2 resolved + 1merged reconstructed γ's

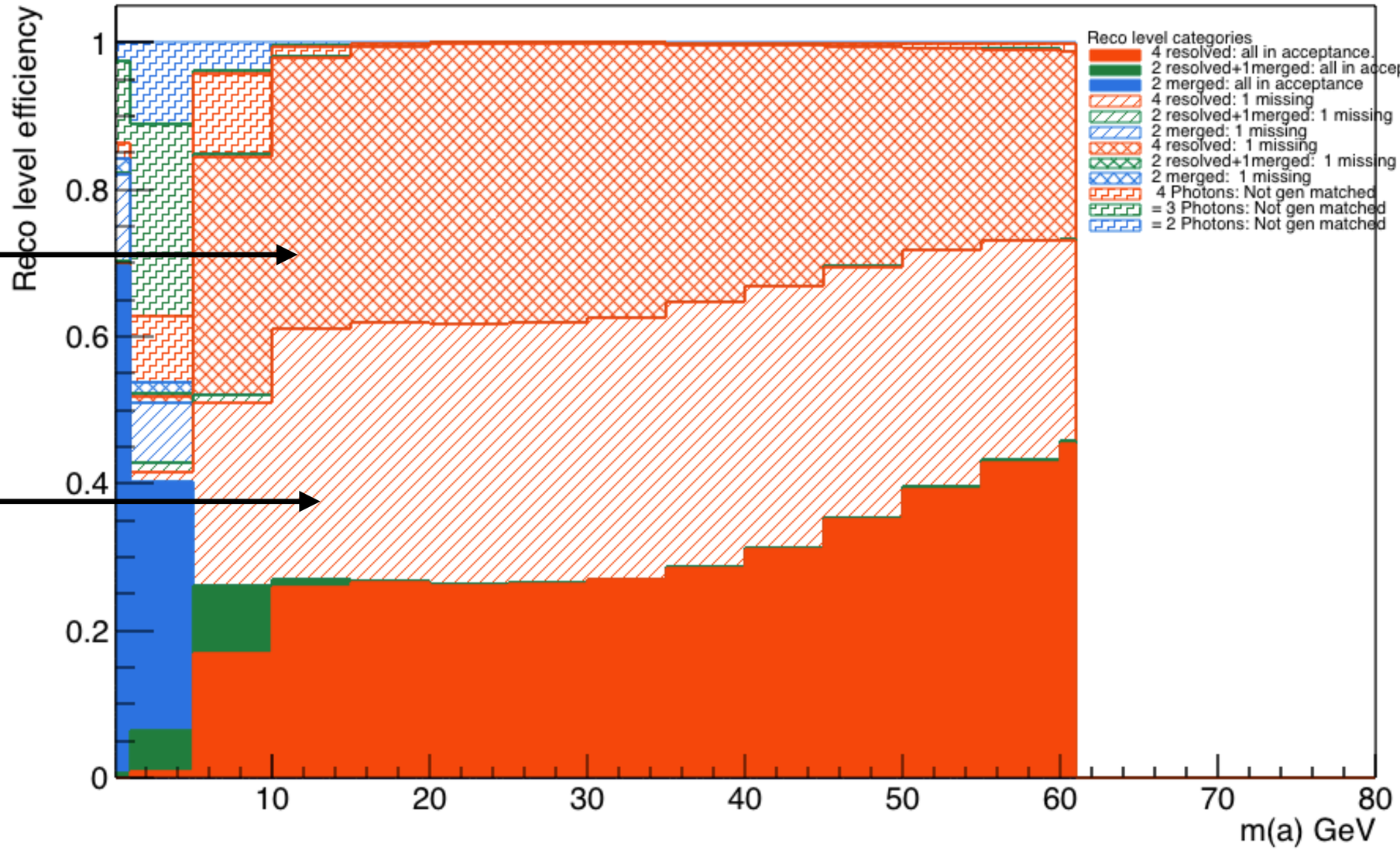
4 reconstructed resolved γ's



Reco level categorization

2 reconstructed resolved γ's

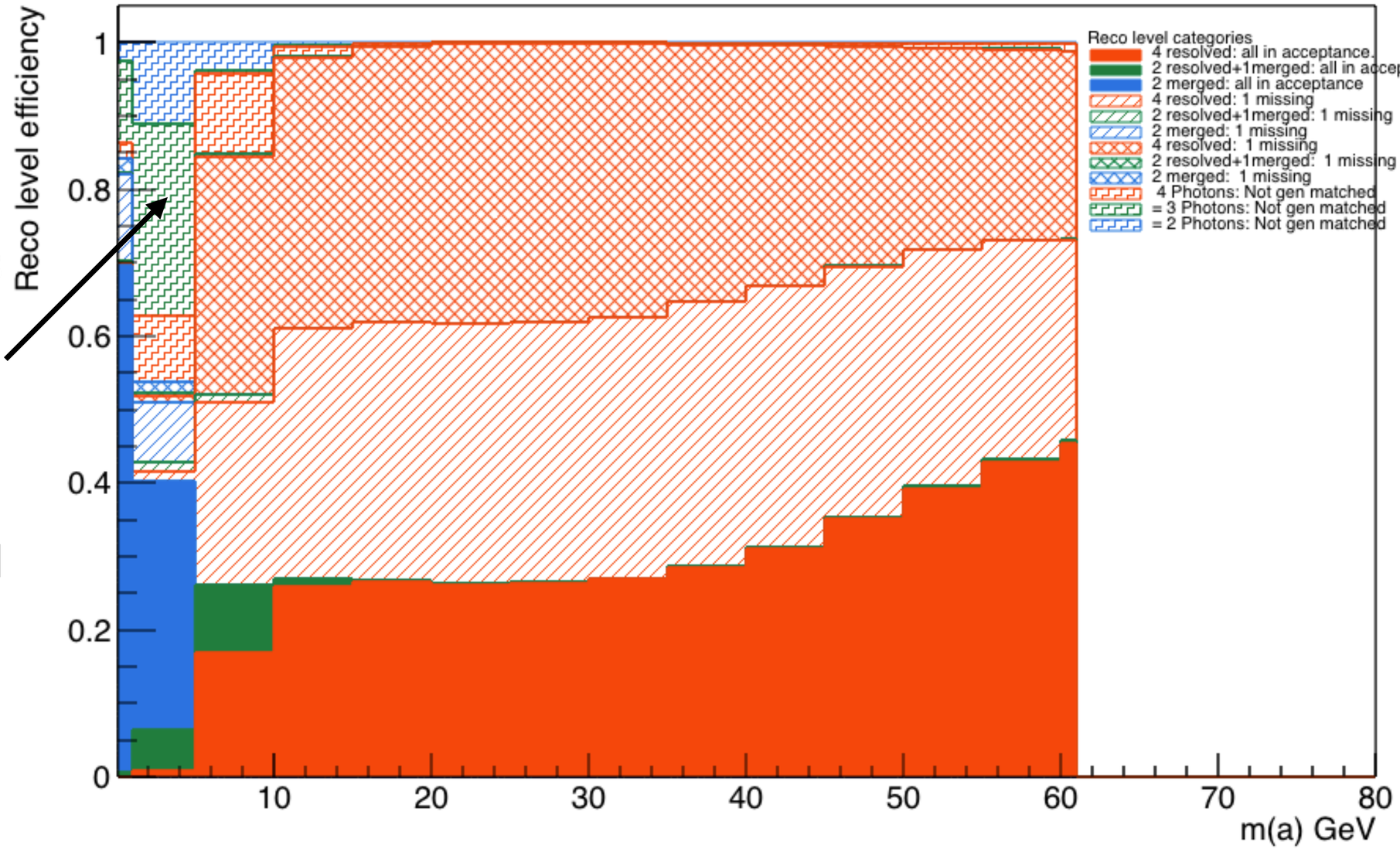
3 reconstructed resolved γ's



Reco level categorization

Mix of events; we have 3 reconstructed γ's, but using Gen-level information they have been identified as:

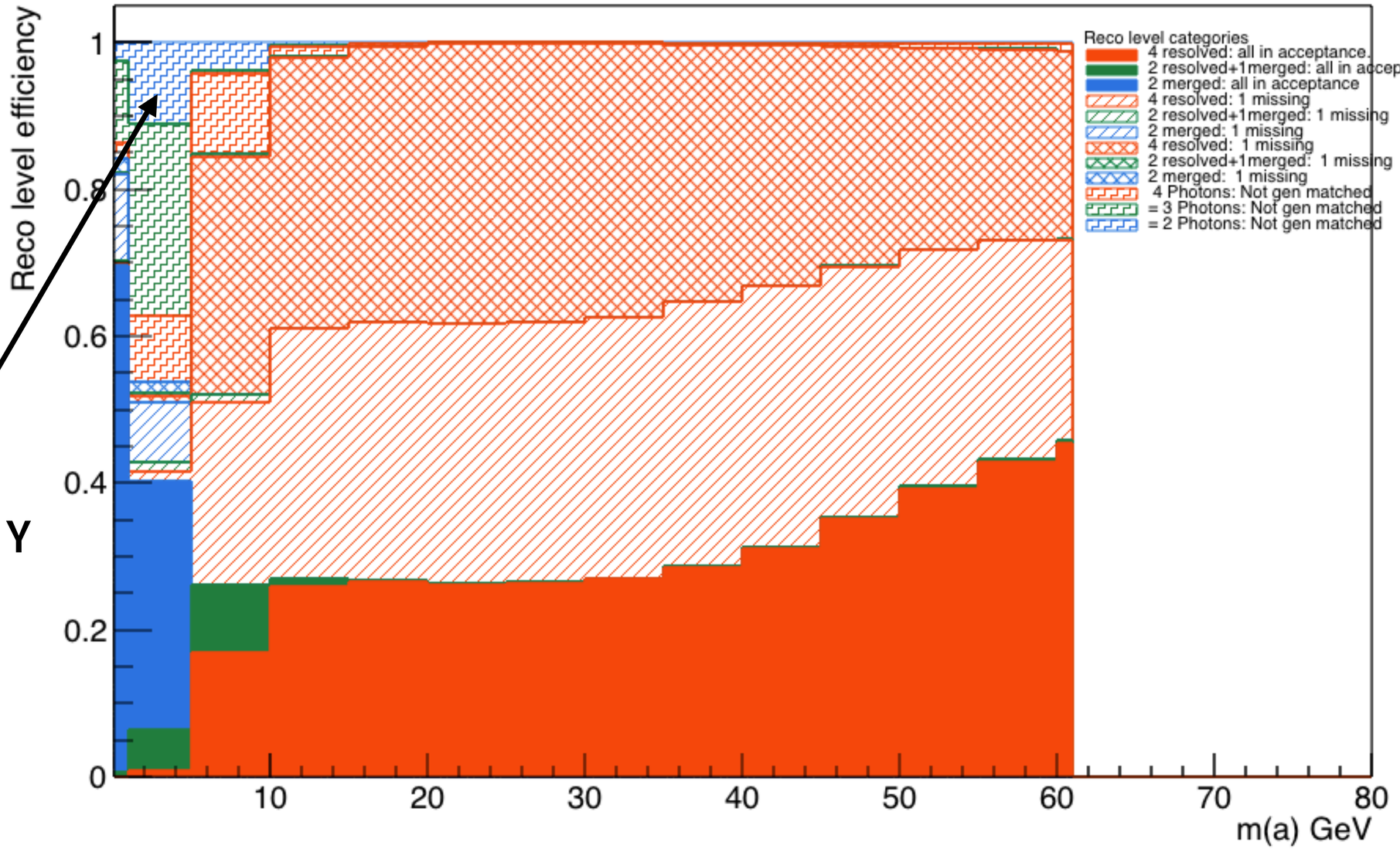
- 2 merged + 1 resolved γ's
- 3 merged γ's



Reco level categorization

We have 2 reconstructed γ's, but using Gen-level information they have been identified as:

- 1 merged + 1 resolved γ



Comments on reco level study

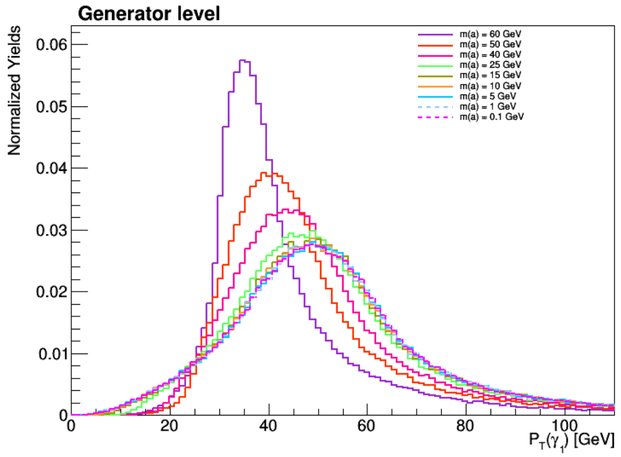
- Used the Gen level information to perform categorization @ Reco level
- There is slight mismatch b/w this plot & the one shown for Gen level
  - This is where the machine learning techniques can help!
- Indicative of the fact that Gen-Reco matching could be re-tuned (5 crystal separation could be too conservative)
- For **m(a) > 10 GeV** the **fully resolved** topology is the dominant one (**26% for m(a) = 10 GeV** to **46% for m(a) = 60 GeV**)

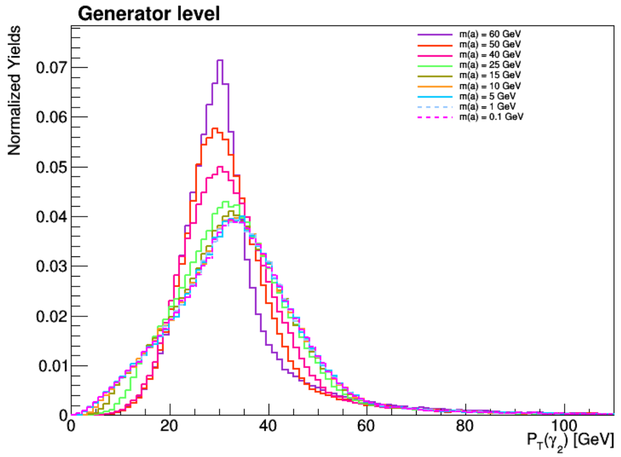
Conclusions

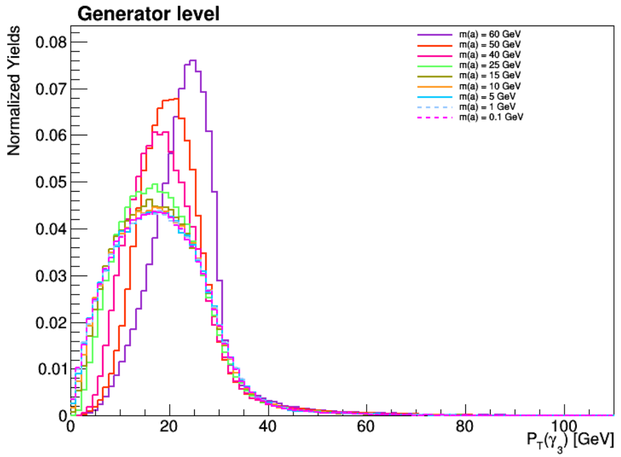
- There are 3 main categories: **4 resolved γ's, 2 resolved + 1 merged γ's, 2 pairs of merged γ's**

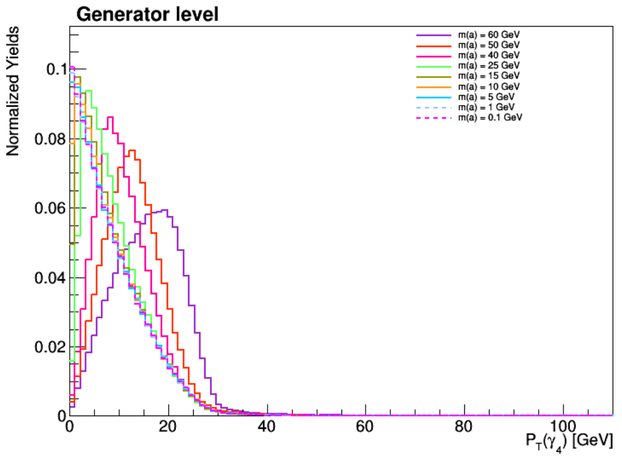
- Both, Gen and Reco level studies show that for m(a) > 10 GeV, efforts should be concentrated on the 4 Resolved **γ**'s category
  - Main backgrounds for this final state:
    - 4 Jets
    - **γ** + 3 Jets
    - **γ γ** + 2 Jets
    - **γ γ γ** + Jet (Need to request for these samples)
    - DY + 2 Jets
  - Next time, present background study of these backgrounds + trigger studies

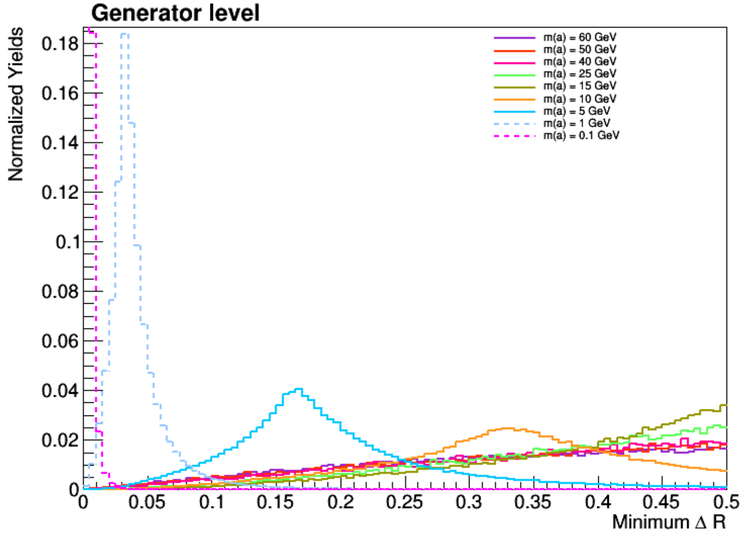
Backup


Generator level
Normalized Yields
m(a) = 60 GeV
m(a) = 50 GeV
m(a) = 40 GeV
m(a) = 25 GeV
m(a) = 15 GeV
m(a) = 10 GeV
m(a) = 5 GeV
m(a) = 1 GeV
m(a) = 0.1 GeV
$P_T(\gamma_1)$ [GeV]


Generator level
Normalized Yields
m(a) = 60 GeV
m(a) = 50 GeV
m(a) = 40 GeV
m(a) = 25 GeV
m(a) = 15 GeV
m(a) = 10 GeV
m(a) = 5 GeV
m(a) = 1 GeV
m(a) = 0.1 GeV
$P_T(\gamma_2)$ [GeV]

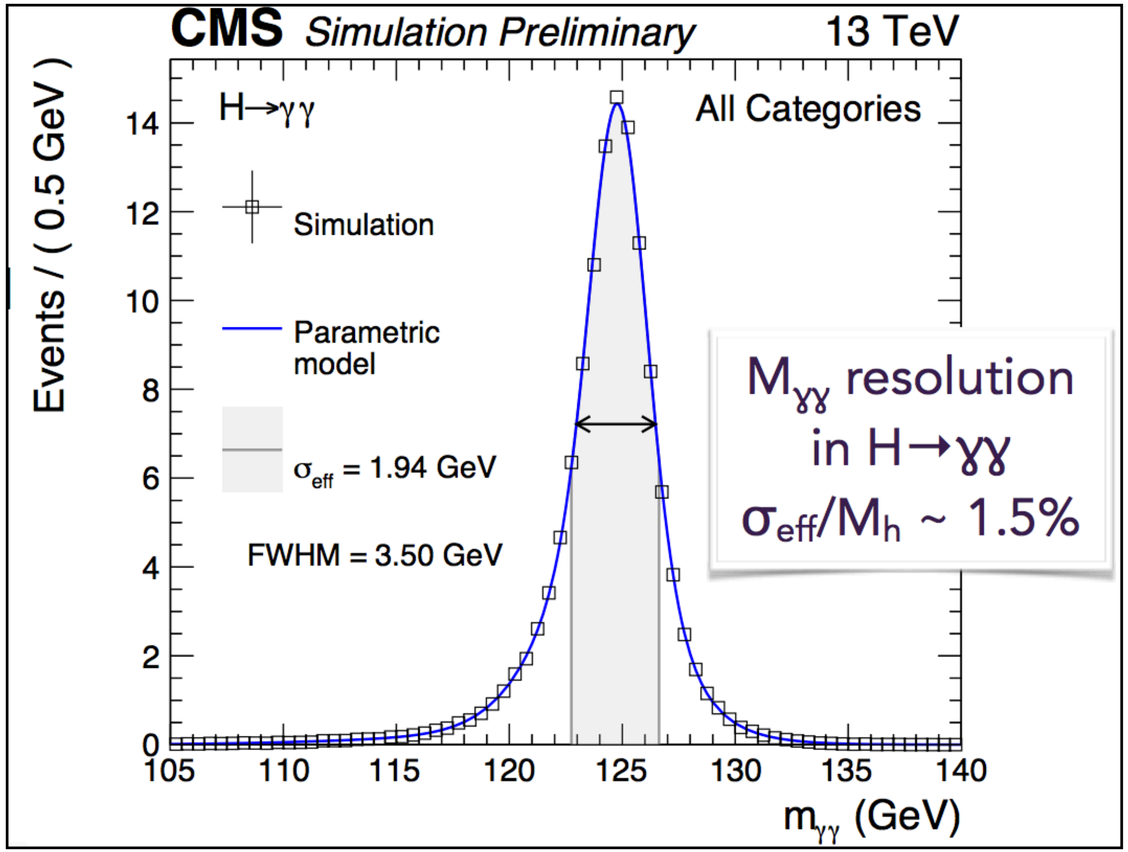

Generator level
Normalized Yields
m(a) = 60 GeV
m(a) = 50 GeV
m(a) = 40 GeV
m(a) = 25 GeV
m(a) = 15 GeV
m(a) = 10 GeV
m(a) = 5 GeV
m(a) = 1 GeV
m(a) = 0.1 GeV
$P_T(\gamma_3)$ [GeV]


Generator level
Normalized Yields
m(a) = 60 GeV
m(a) = 50 GeV
m(a) = 40 GeV
m(a) = 25 GeV
m(a) = 15 GeV
m(a) = 10 GeV
m(a) = 5 GeV
m(a) = 1 GeV
m(a) = 0.1 GeV
$P_T(\gamma_4)$ [GeV]


Generator level
Normalized Yields
m(a) = 60 GeV
m(a) = 50 GeV
m(a) = 40 GeV
m(a) = 25 GeV
m(a) = 15 GeV
m(a) = 10 GeV
m(a) = 5 GeV
m(a) = 1 GeV
m(a) = 0.1 GeV
Minimum Δ R

Higgs Exotic decays : Why study them?

- But how standard is the Higgs Boson?
  - Extremely narrow width (Γ_h ~ 4.07 MeV ; Γ_h/m_h ~ 3.3 x10^{-5})
  - Small coupling to another light state can open up additional sizable decay modes
  - Good reasons to suspect that new physics couples preferentially to the Higgs boson (it provides one of only a few "portals" that allow SM matter to interact w/ hidden-sector matter)



Catalogue of exotic decays: arxiv:1312.4992

Higgs Exotic decays : Why study them?

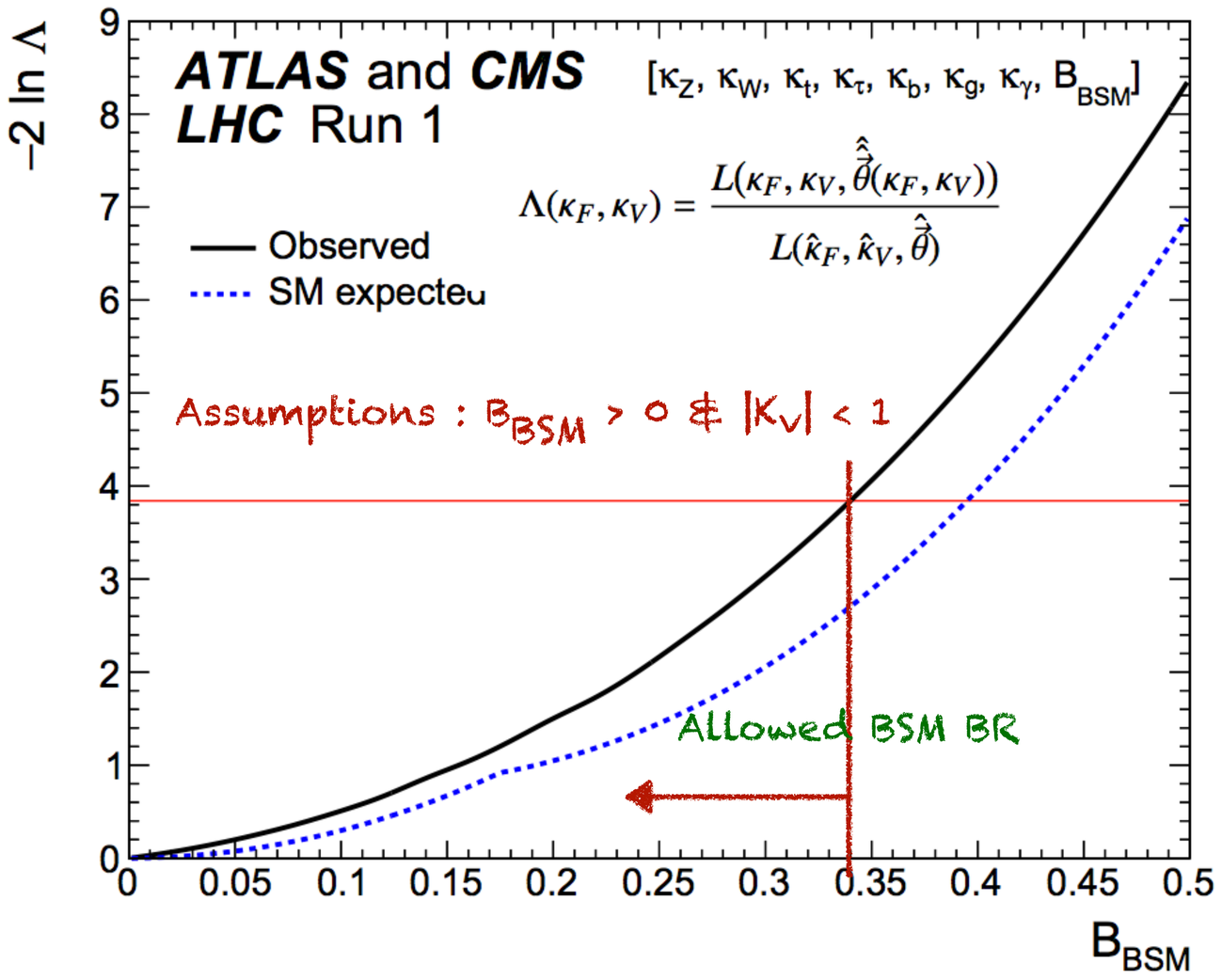
- Negative log-likelihood scan of B_{BSM} (branching ratio into BSM particles) when allowing additional BSM contributions to the Higgs boson width.

- Upper limit of $B_{BSM} = 0.34$ at 95% CL was obtained.

- **What can we do experimentally?**

1. Constrain B_{BSM} indirectly by means of precision Higgs physics

2. Directly look for exotic decays of the Higgs boson

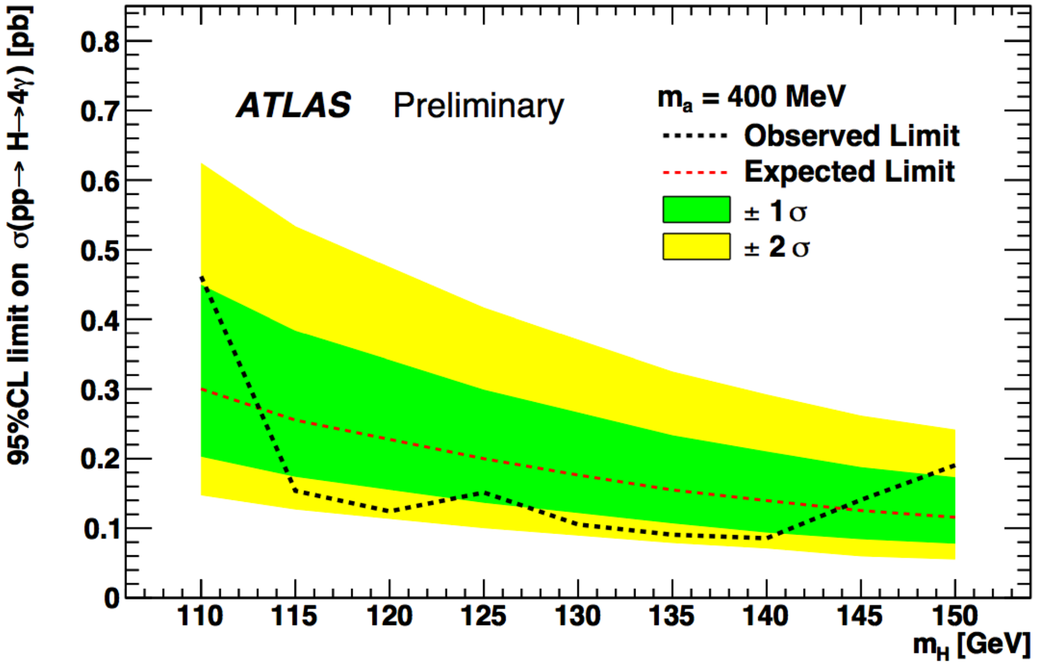


From arXiv:1606.02266

H→aa→γγγγ : Existing studies

- **ATLAS collaboration** has performed a search for "a Higgs boson decaying to four photons through light CP-odd scalar coupling" using 4.9 fb^{-1} of 7 TeV pp collision data
  ATLAS-CONF-2012-079

- The search explores the mass range m(a) ∈ [100,400] MeV
  - Highly boosted regime
  - Study of the fraction of H→aa→γγγγ events that would contribute to an effective H→γγ signal
  - 95% confidence-level exclusion limits provided on Higgs boson production cross-section times H→aa→γγγγ branching fraction in the range 110 GeV < m_h < 150 GeV



(c) m_a = 400 MeV

This search is new to CMS!

- Check for gen-reco matching

$$\frac{P_T \text{ of Reco } \gamma \text{ (that has been matched to a merged } \gamma \text{ @ Gen level)}}{P_T \text{ of that Gen level Merged } \gamma}$$

For m(a) = 100 MeV

(This is the mass point with the most merged photons)