Axion searches in rare Higgs decays at ATLAS

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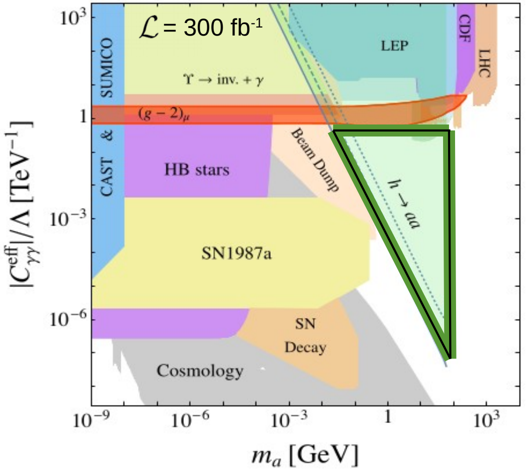
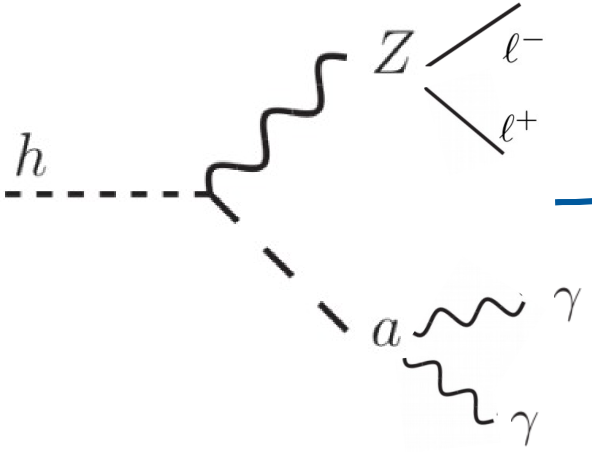
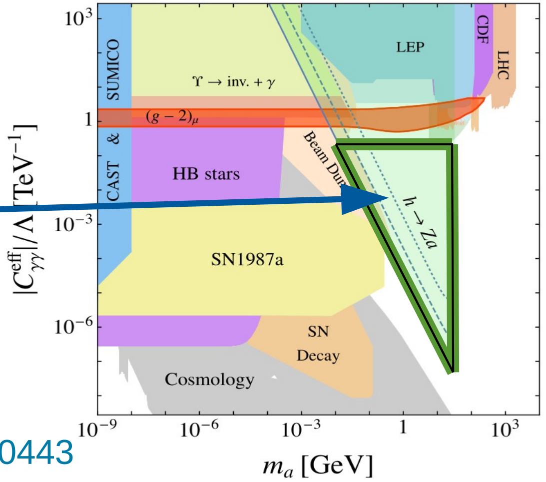
Theoretical background & Motivation

- Standard Model allows CP violation in strong interaction however no CP violation has been observed experimentally – <u>the strong CP problem</u>
- Axion or axion-like particles (ALPs) could solve the strong CP problem.
- Possible ALPs could couple to the Higgs boson in new parameter spaces.







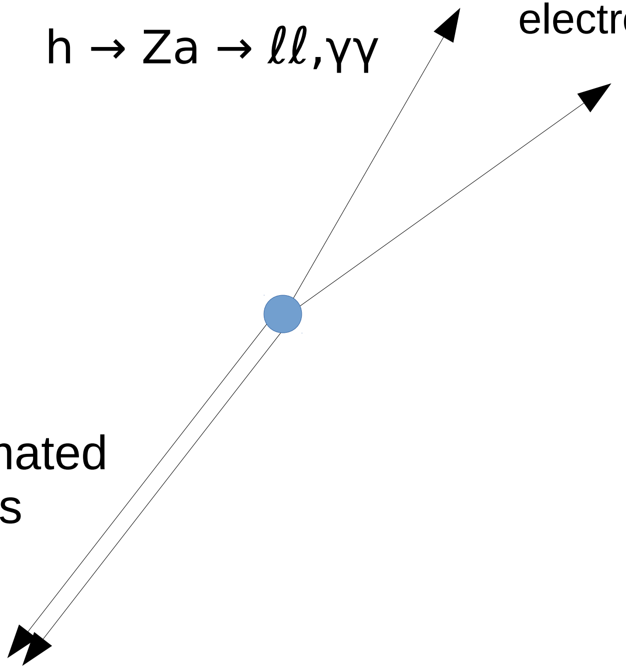
arXiv:1708.00443

Signature

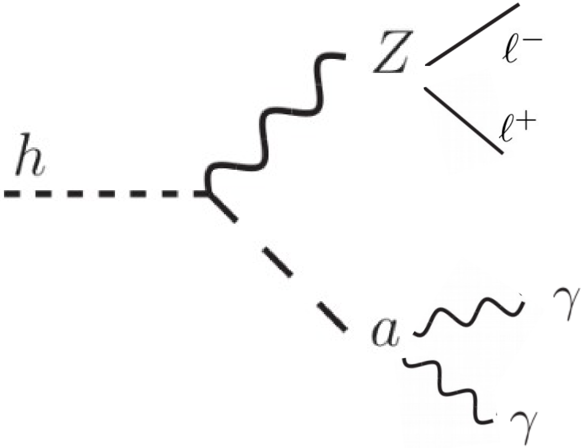
- Signature: 2 leptons + 2 collimated photons

h → Za → ℓℓ,γγ

2 leptons:
electrons or muons to trigger

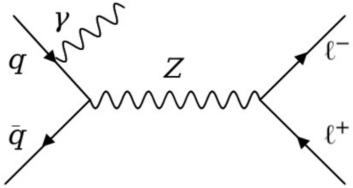


2 collimated photons

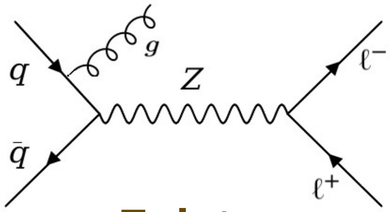


- ALP may be long-lived, focus on prompt decays for now

Main backgrounds Z+jets & Z+γ

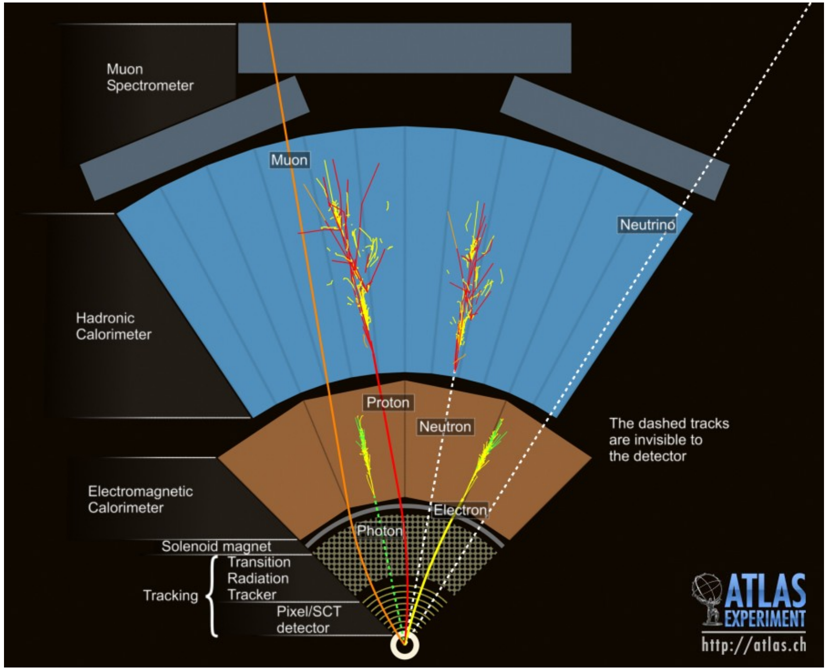


Zγ

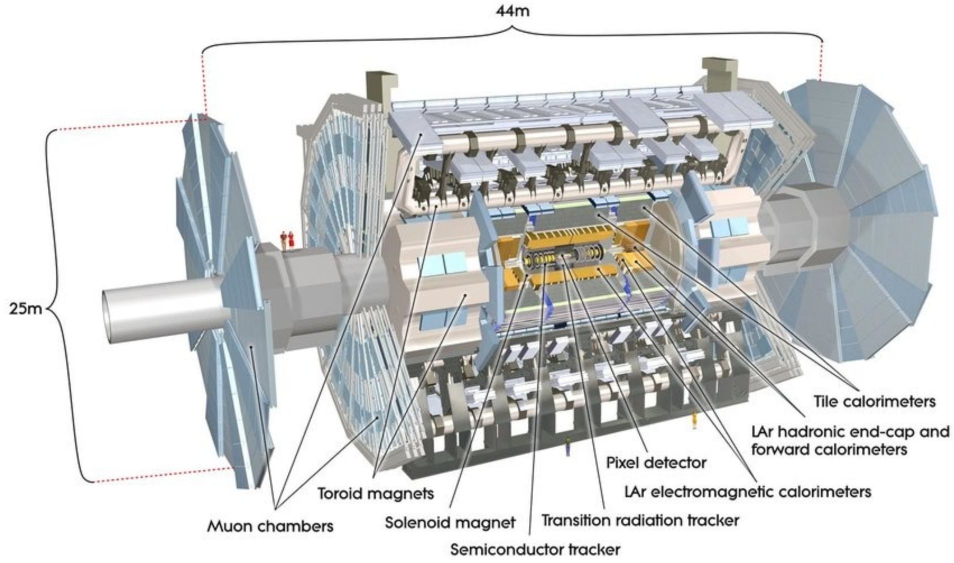


Z+jets

ATLAS detector

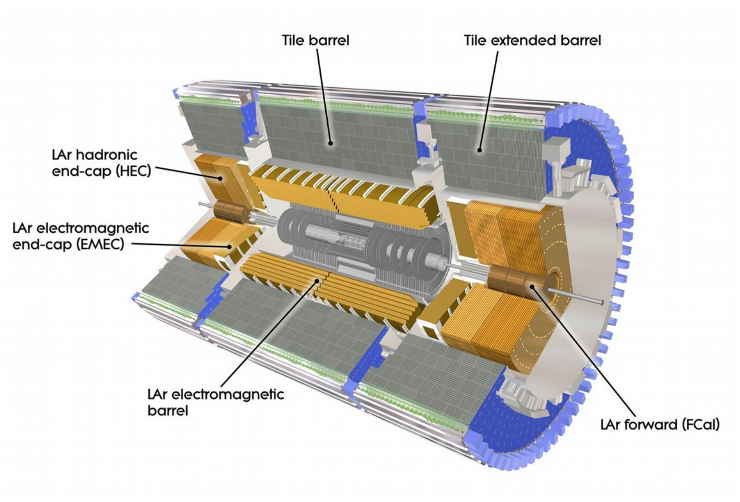


ATLAS Public pages



- The detector is made up of several large subsystems:
  - Inner detector (ID)
  - Electromagnetic (ECAL) and Hadronic calorimeters (HCAL)
  - Muon spectrometer

Photon Reconstruction & Identification



Reconstruction: Matching energy clusters of neighbouring EM calorimeter cells to inner detector tracks.

Photon **Isolation** & **Identification (ID)** criteria applied to reduce effects from background photons, such as from pile-up.

Isolation: cuts on transverse energy in a cone, ΔR.

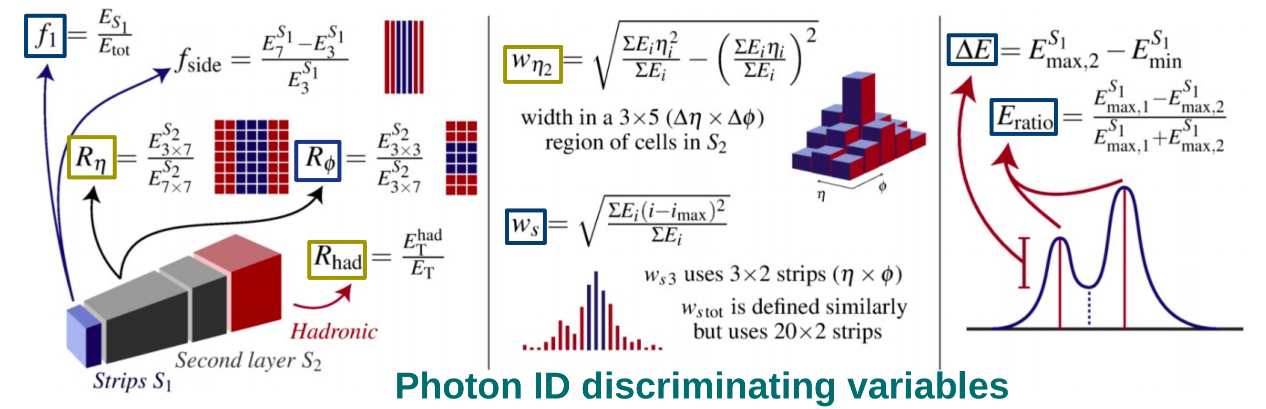
ID: rectangular cuts on calorimetric variables for separation from fake signatures.

- **Loose ID**: Middle layer + hadronic leakage variables.
- **Tight ID**: + Strip layer variables.

$$E_T^{\mathrm{iso}}\Big|_{\Delta R<0.2} < 0.065 \cdot E_T$$

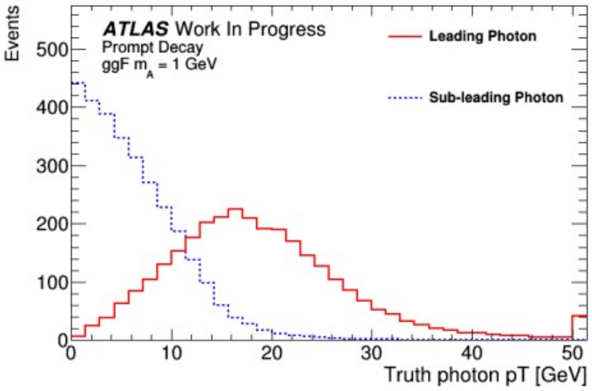
$$p_T^{\mathrm{iso}}\Big|_{\Delta R<0.2} < 0.05 \cdot E_T\,;$$

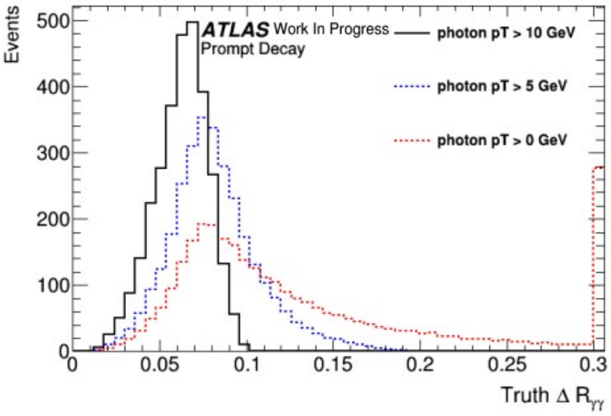
Loose Isolation criteria



Photon ID discriminating variables

Truth level



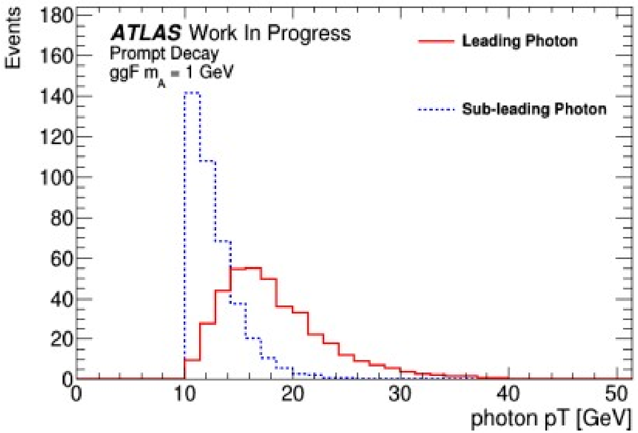


Plots for Gluon-fusion mA = 1 GeV

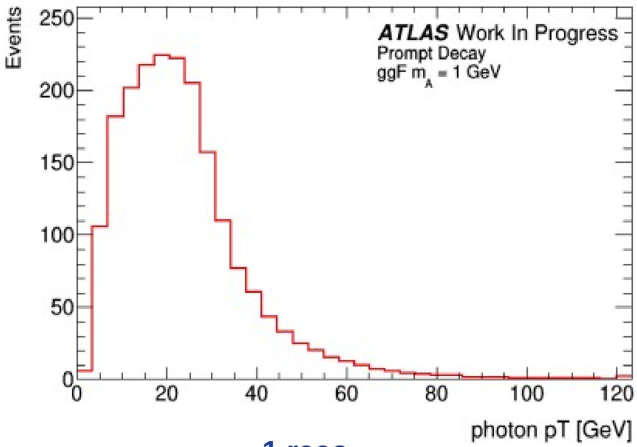
At low photon pT, **many signal di-photon pairs are merged together**

- Events asymmetric in photon pT
- Low truth level separation, ΔR

Reco level



2 reco photons



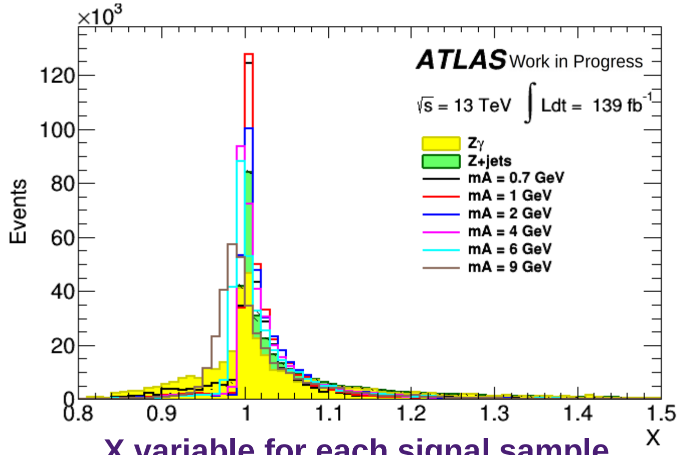
1 reco photon

Event Categorisation

$$X = \Delta R_{\gamma\gamma} \frac{p_{T\gamma\gamma}}{2m_{\gamma\gamma}}$$

From kinematics, define variable X.

A common property of each signal sample for selection



X variable for each signal sample
Normalised to same integrals

Categorisation

Resolved Category: Events for which the <u>di-photon pair</u> with X closest to 1 satisfies $0.96 < X < 1.2$. Both photons $pT > 10$ GeV and satisfying $\Delta R_{\gamma\gamma} < 1.5$

Merged Category: The event fails Resolved category and it includes <u>a photon</u> with $pT > 20$ GeV.

Isolation cuts and Photon ID are not used during categorisation but are included afterwards with all photons required to pass loose isolation cuts and Loose PID.

Photon Selection

Photons must pass loose isolation cuts & Loose PID.

Efficiency x Acceptance

Resolved
Low mass points: 0.3% – 5%
High mass points: 28% - 43%

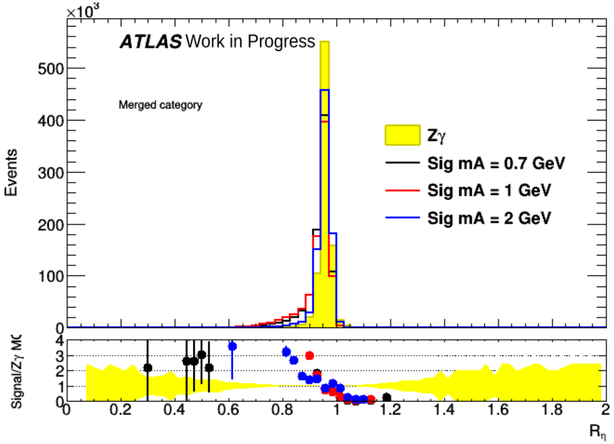
Merged
Low mass points: 40% – 57%

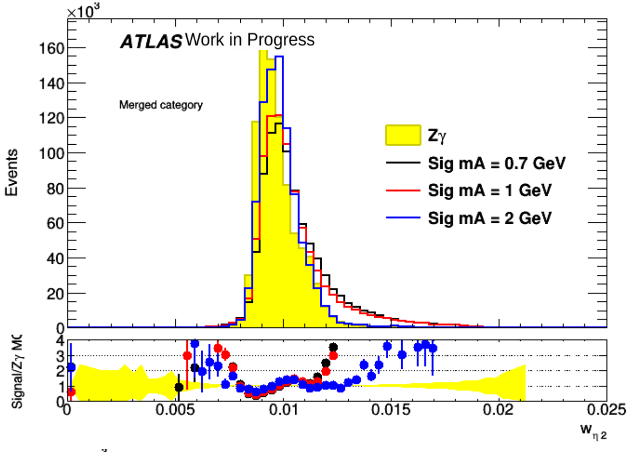
Low mass points:
mA = 0.7 GeV, 1 GeV or 2 GeV

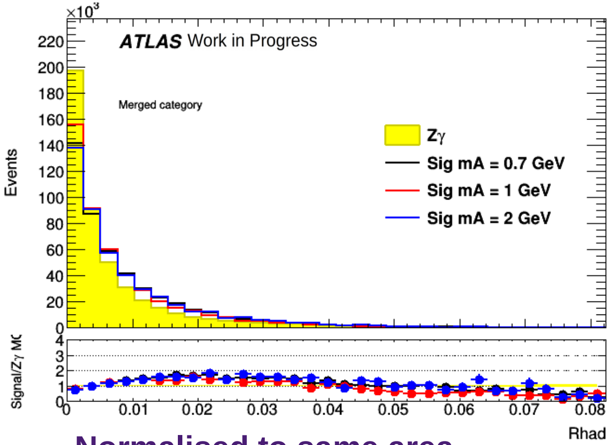
High mass points:
mA = 4 GeV, 6 GeV, 9 GeV

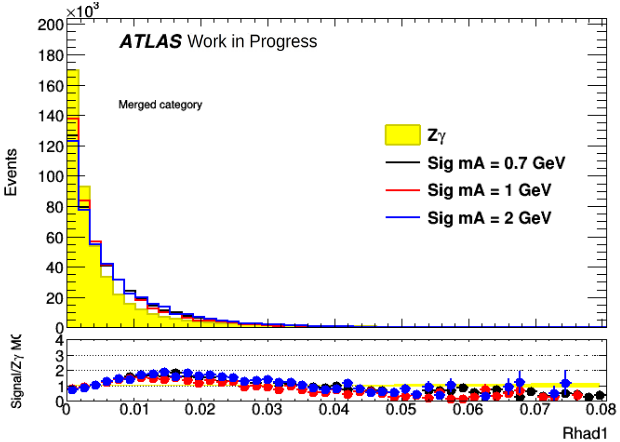
Split categories so **Resolved for high mass** and **Merged for low mass**

Merged category: Photon ID Loose PID variables









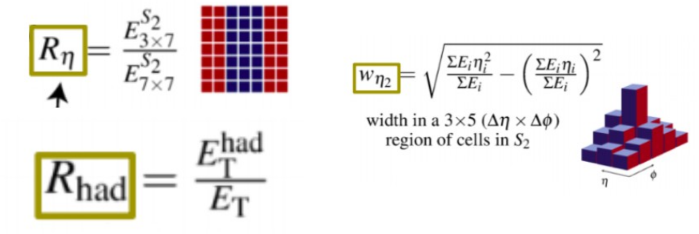
Normalised to same area

Two photons reconstructed as one

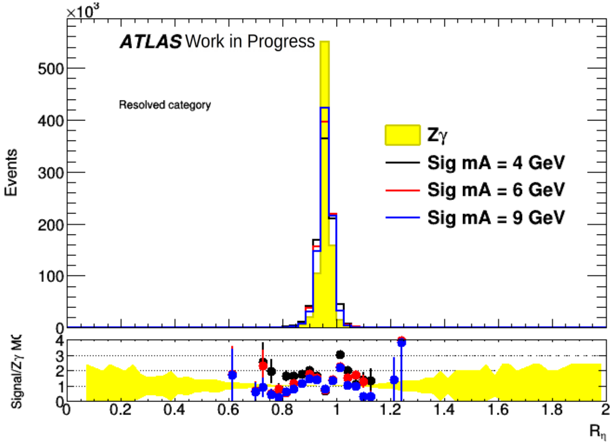
Isolation already applied.

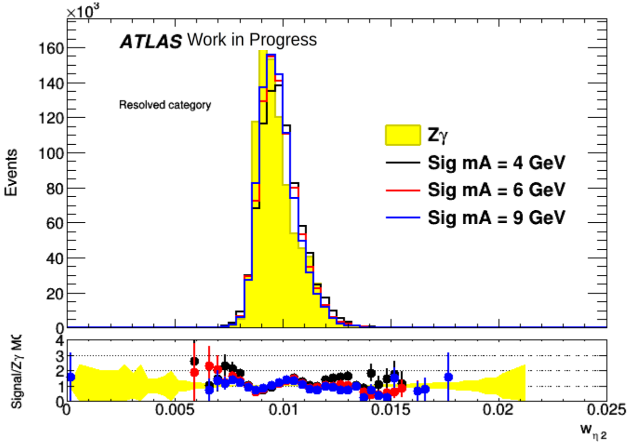
Main differences seen in variables **R_η and $w_{\eta 2}$**

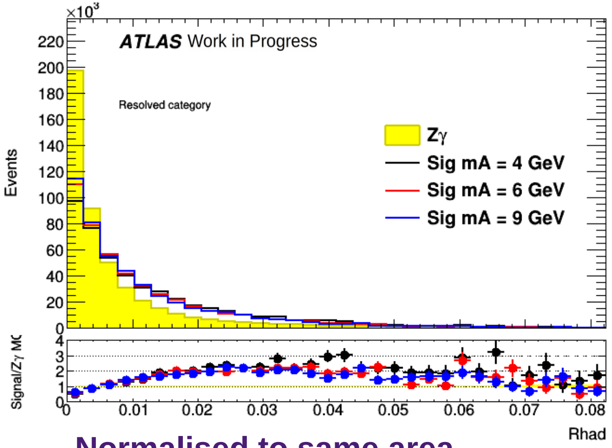
Signal has longer tail: explaining relative drop in efficiency.

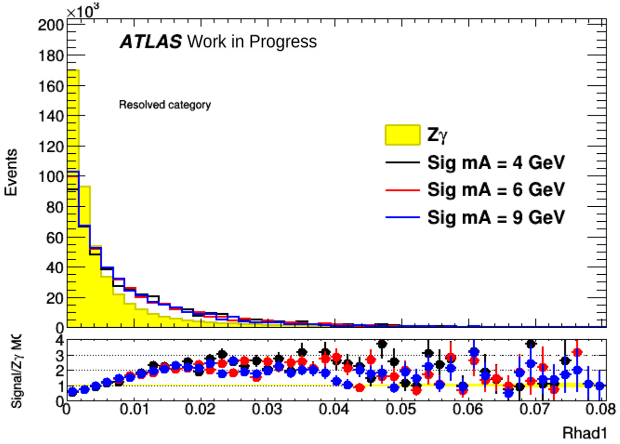


Resolved category: Photon ID Loose PID variables









Normalised to same area

Both photons reconstructed separately

Isolation already applied.

Smaller discrepancies.

Shapes more comparable to Zγ distributions.

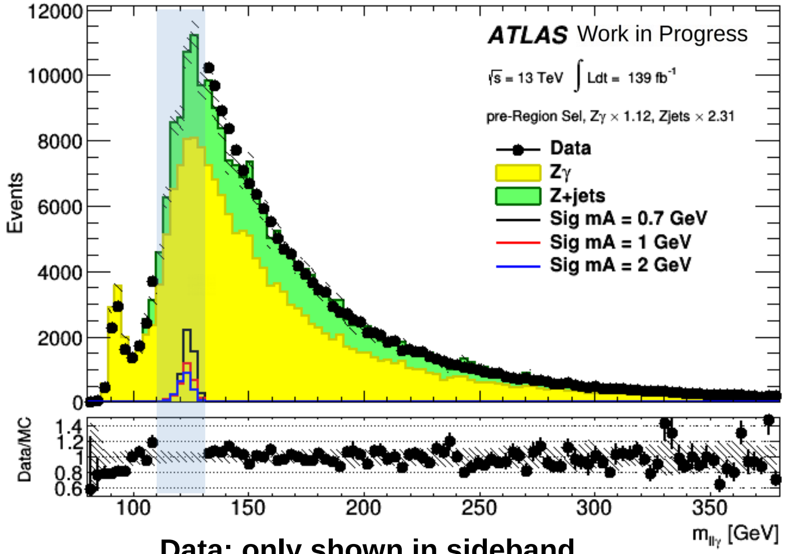
All signal BR=0.1

Merged Category

axion-particle candidate reconstructed as one photon

Signal region: 110 GeV < $m_{ll\gamma}$ < 130 GeV,

Eratio used in sideband to fix normalisation of Z+jets & Zγ backgrounds

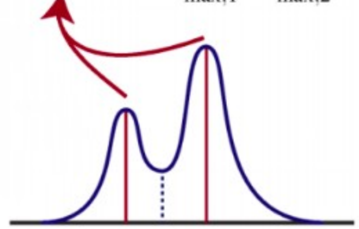


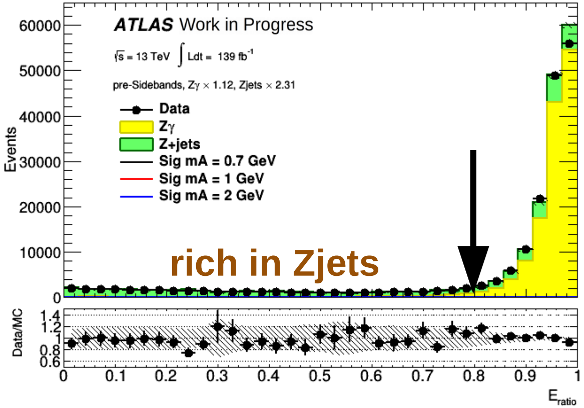
Data: only shown in sideband

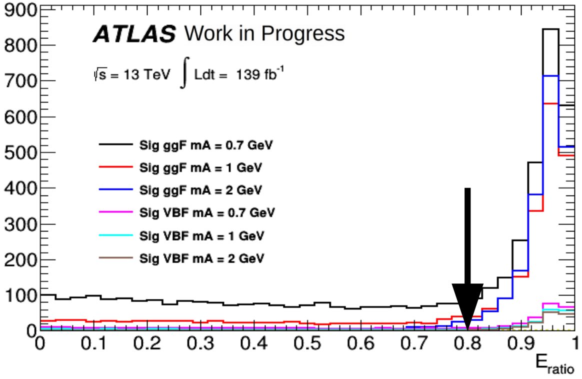
Region	Selection
pre-SR	$m_{\ell\ell\gamma}$ window
pre-SB	$m_{\ell\ell\gamma}$ sideband
SR	pre-SR, $E_{ratio} > 0.8$
SB	pre-SB, $E_{ratio} > 0.8$

Eratio: Ratio of largest and second largest energy deposit over sum of total.

$$\boxed{E_{\text{ratio}}} = \frac{E^{S1}_{\text{max},1} - E^{S1}_{\text{max},2}}{E^{S1}_{\text{max},1} + E^{S1}_{\text{max},2}}$$







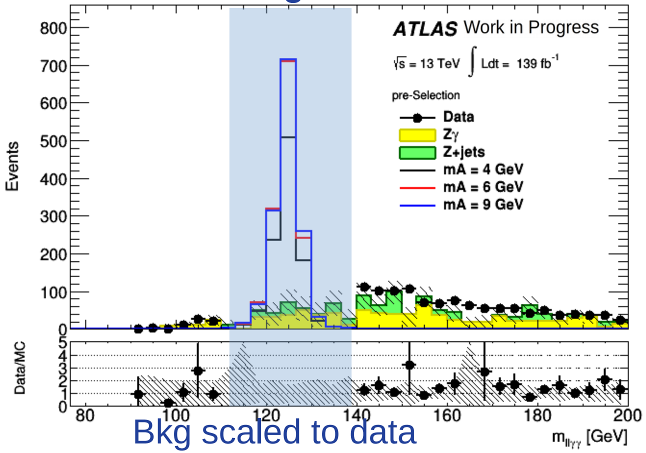
Resolved category

Two reconstructed photons from a→γγ decay.

Strategy Overview

- Use m(llγγ) to define signal (SR) and sideband (SB) regions
- Fit the m(γγ) distribution to extract signal

All signal BR=0.1



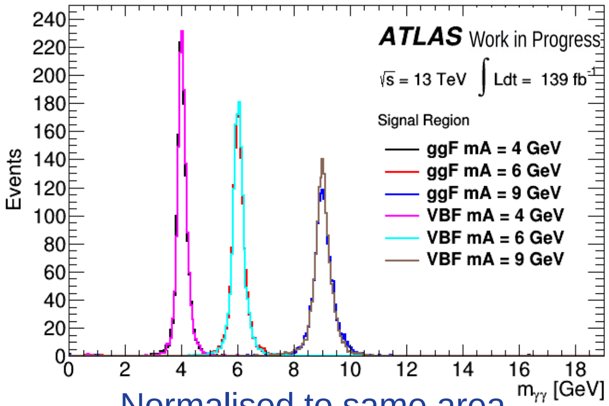
Bkg scaled to data

SR: 110 GeV < $m_{ll\gamma\gamma}$ < 140 GeV

But

- Cannot extrapolate from SB to SR because the kinematics are different
- Suffer from MC statistics

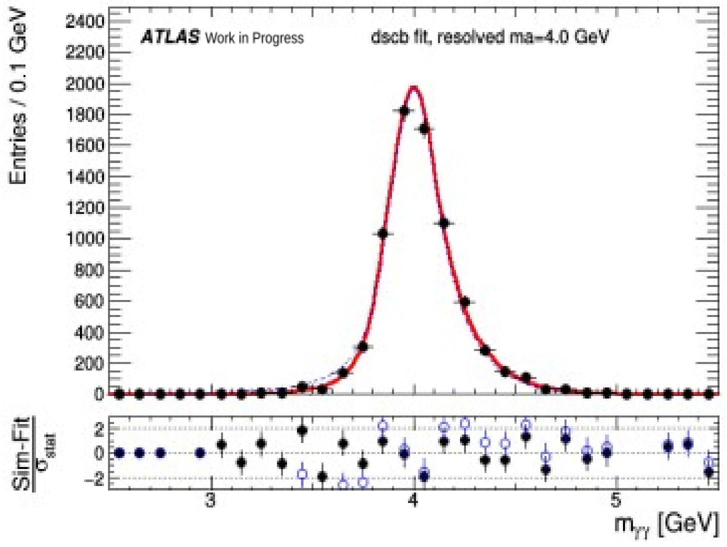
  → Try a data driven approach instead.

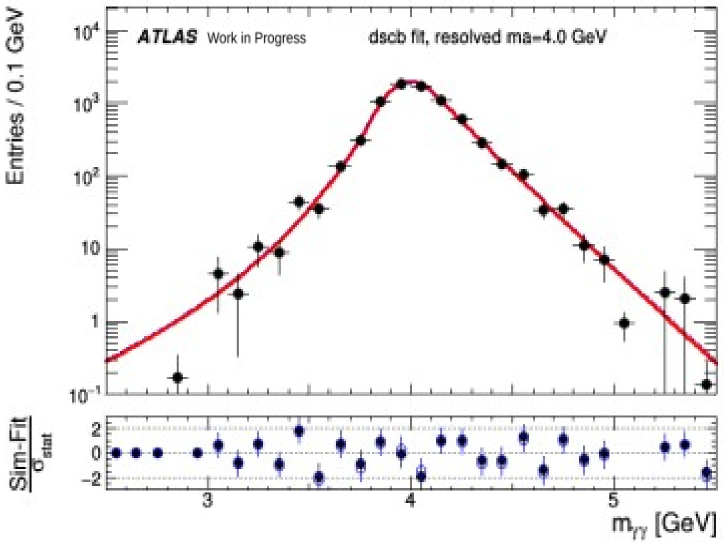


Normalised to same area

No background MC scale factors in plots

Resolved category: Signal Parameterization





Black points = Monte Carlo simulated signal for mA = 4 GeV

Double Sided Crystal Ball used to model signal mass point distributions that are not simulated (**red**) and interpolated using fits between simulated mass points (**blue**).

Conclusion

- Axion searches in Higgs decay $h \rightarrow Za \rightarrow \ell\ell,\gamma\gamma$ at the ATLAS detector.

- Merged signal photons is a real challenge, especially at low axion mass, and requires splitting search into two categories; called Merged & Resolved.

- Work still on-going. Several options for improvements but right now prioritizing robustness.

Thank you

Back-up

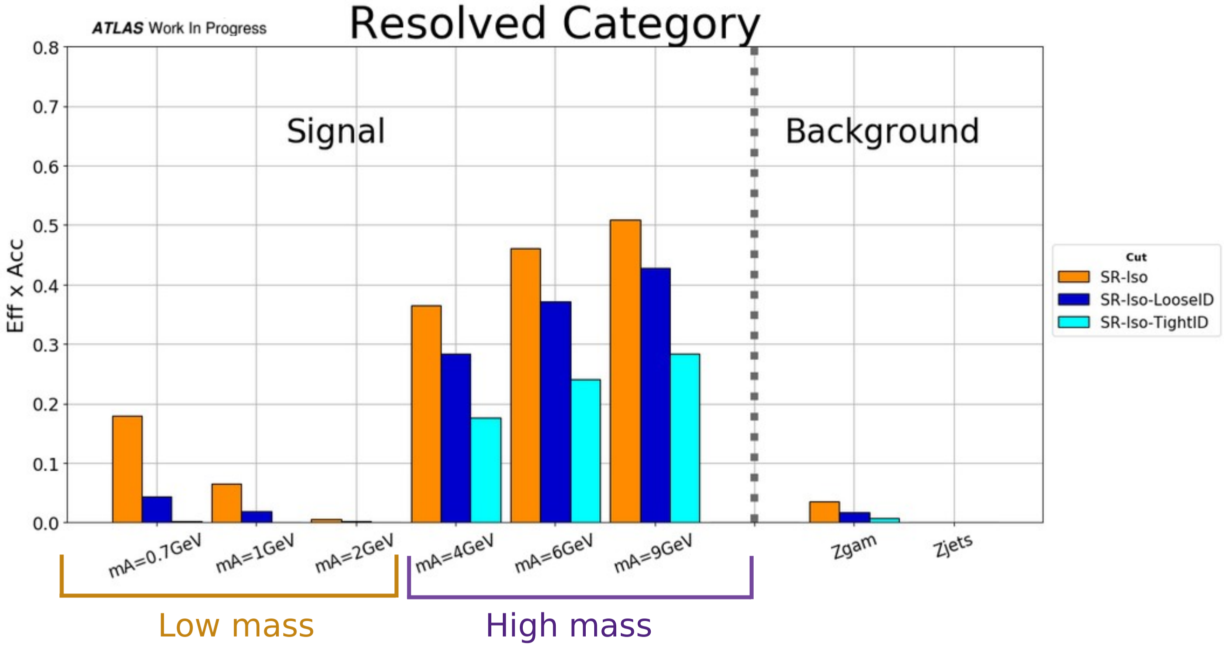
Photon Selection: Resolved Category

Photons must pass at least FCLoose isolation and Loose PID.

Low mass points:
mA = 0.7 GeV, 1 GeV or 2 GeV

High mass points:
mA = 4 GeV, 6 GeV, 9 GeV

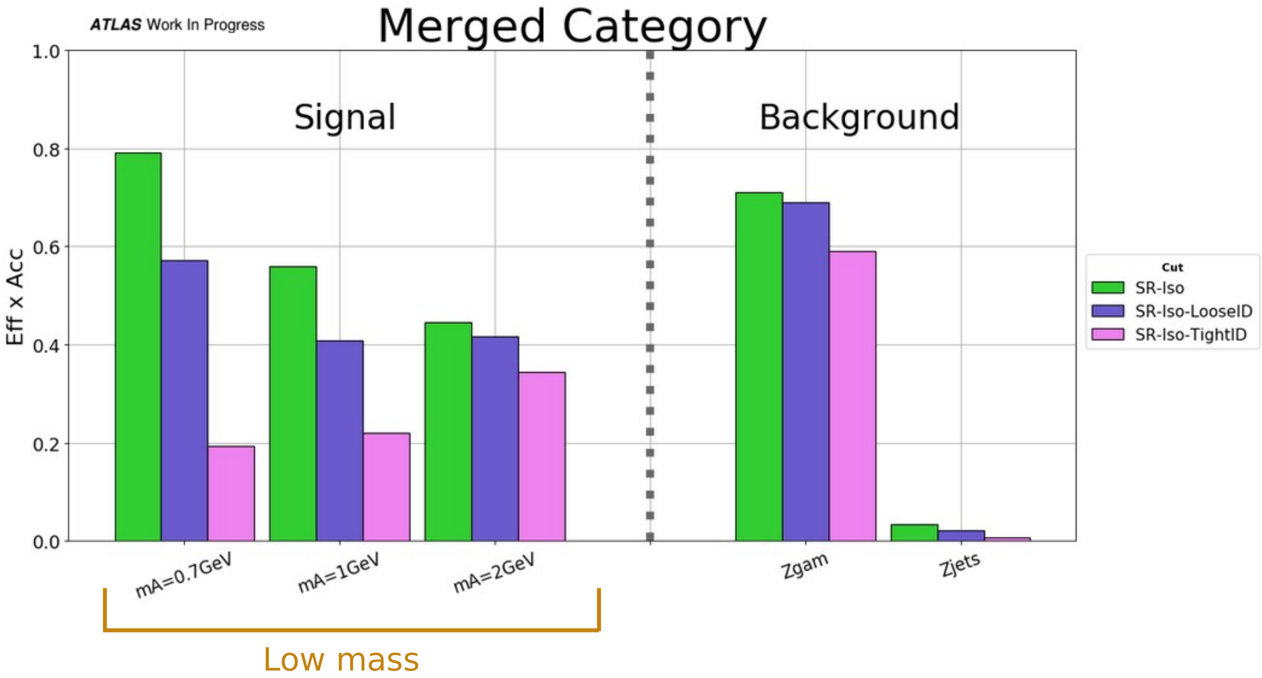
Background efficiencies < 2%



Passes Loose ID (**blue bar**) for final selection

Photon Selection: Merged Category

For merged category, **Low mass points** passing Loose ID have efficiencies ranging 40-60%.



Photon Selection: Resolved Category, isolation

Isolation variable distributions of high mass points match real photons better than in low mass.

FCLoose includes a topocone20/pT cut < 0.065.

Low mass values peak higher than high mass points.

2 GeV affected the most, explaining why Isolation cut efficiency is lowest.

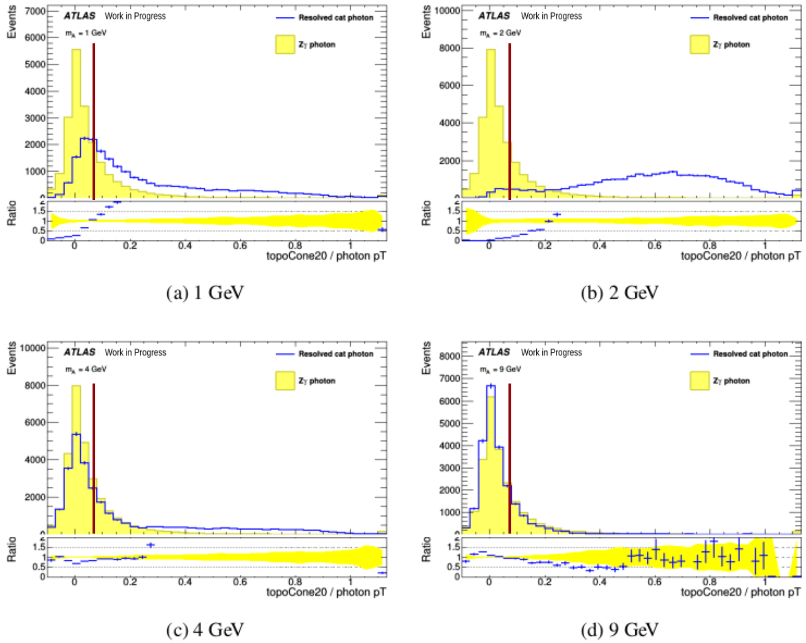
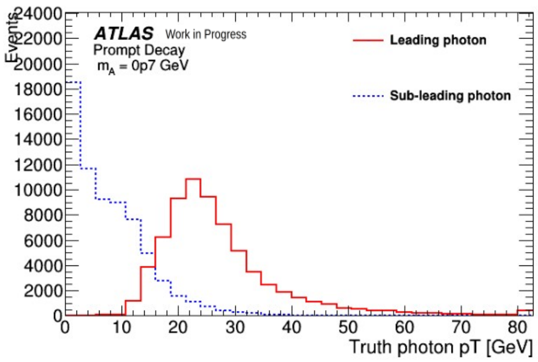
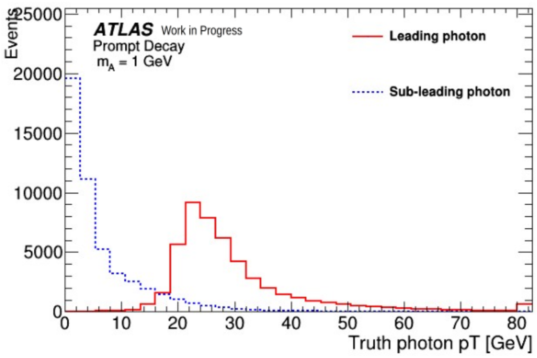


Figure 16: Resolved category signal leading photon distribution (line) comparison with photon from $Z\gamma$ (shaded) for calorimeter isolation topocone with ΔR cone 0.2 divided by photon p_{T}, for different signal mass points. No isolation cuts applied and photon $p_{\mathrm{T}} > 10$ GeV. Photons are truth matched. All shapes normalised to same integral and the last bin includes also the histogram overflow.

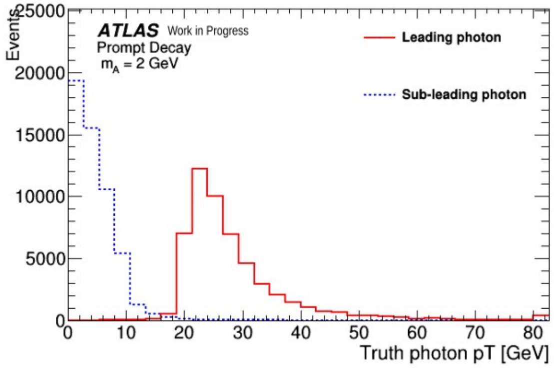
Merged category: Truth Photon pT



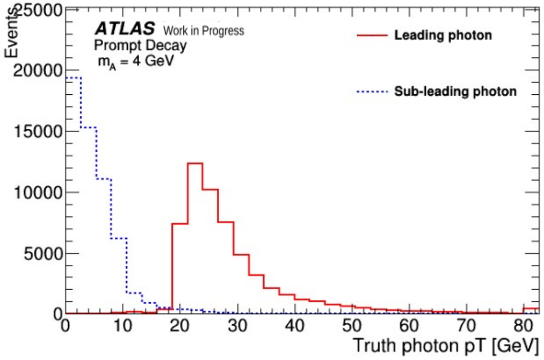
(a) 0.7 GeV



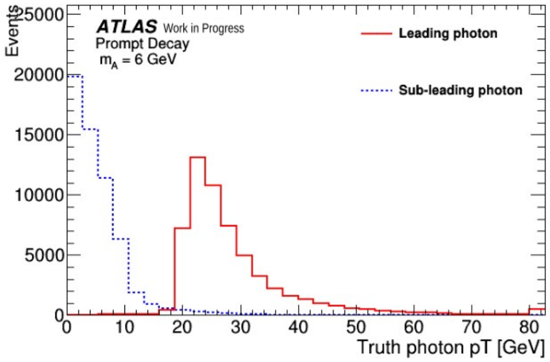
(b) 1 GeV



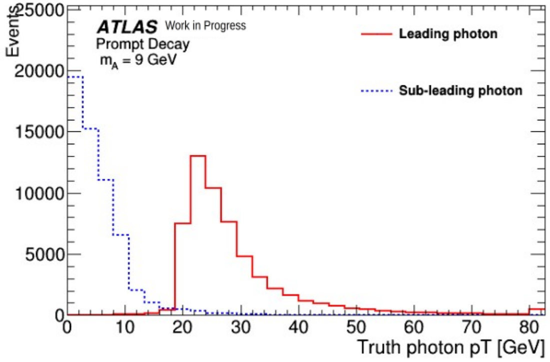
(c) 2 GeV



(d) 4 GeV

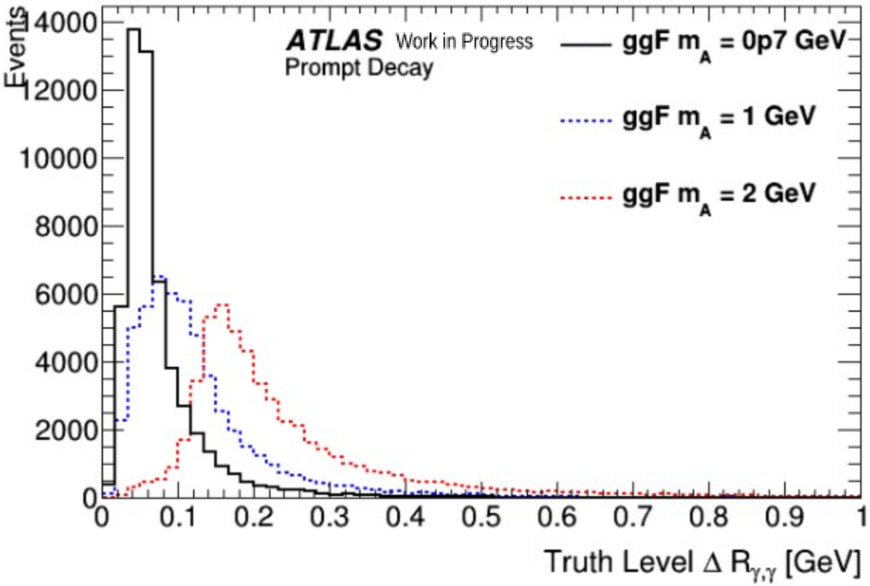


(e) 6 GeV

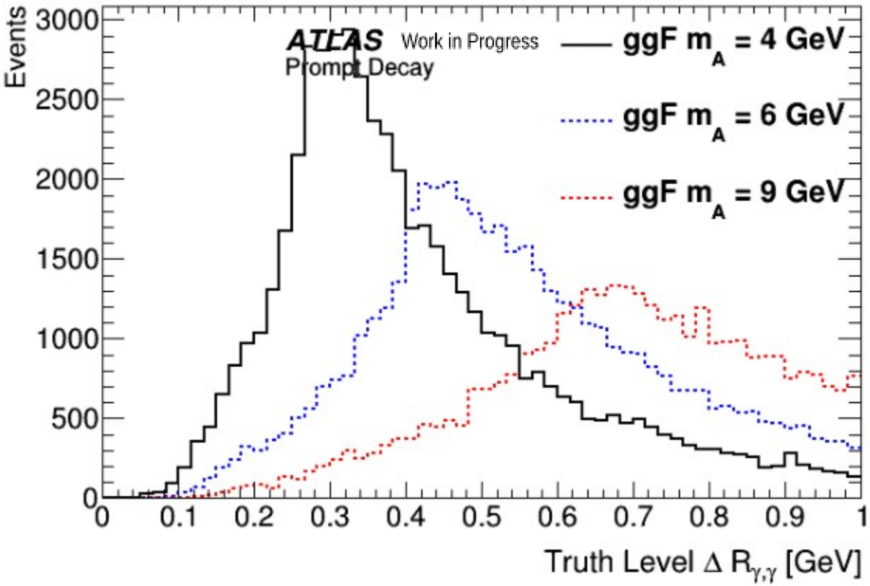


(f) 9 GeV

Merged category: Truth Photon $\Delta R_{\gamma\gamma}$

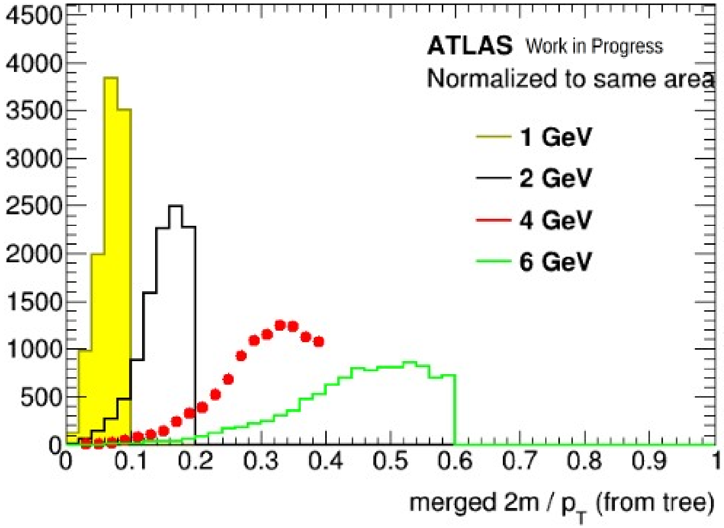


(a) 0.7 – 2 GeV



(b) 4 – 9 GeV

Merged category: Isolation discussion

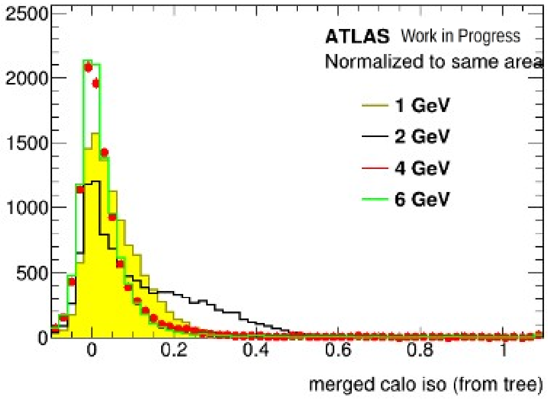


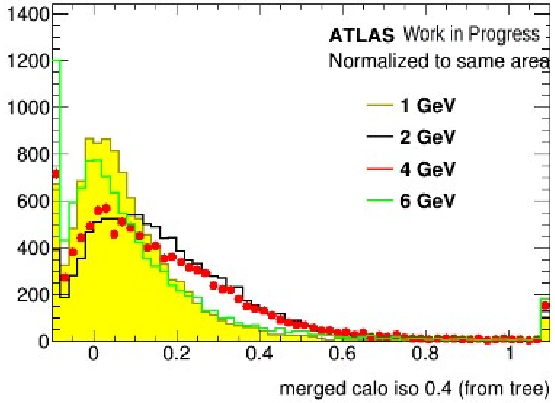
Quantity approx equal to DR between the 2 photons from the axion

Isolation cone ~ 0.1 – 0.2
- it should be 1 GeV, 4 and 6 GeV similar

Isolation cone ~ 0.1 – 0.4
- it should be 1, 6 similar, and 2, 4 similar

This is what we observe!





Photon ID variables

Strip Layer

Category	Description	Symbol	*loose*	*tight*
EM Strip layer	$w_{s3} = \sqrt{\frac{\sum E_i(i-i_{\max})^2}{\sum E_i}}$ Shower width in η for EM 1$^{\text{st}}$ layer using three strip cells centered on the largest energy deposit. E_i is the energy of strip cell i and $i_{\max}$ the cell ID value with the largest energy.	w_{s3}		✓
	Similar to w_{s3} but for all cells in a window $\eta \times \phi = 20 \times 2$ in cell units.	w_{stot}		✓
	$F_{side} = \frac{E(\pm 3)-E(\pm 1)}{E(\pm 1)}$ Lateral containment of the shower along the η direction. $E(\pm n)$ is the energy $\pm n$ strip cells around cell with largest energy.	F_{side}		✓
	$\Delta E = [E^{S1}_{2^{\text{nd}}\max} - E^{S1}_{\min}]$ The difference between the energy of the strip with the second largest energy, $E^{S1}_{2^{\text{nd}}\max}$, and the energy in the strip cell with the lowest energy between the largest and second largest energy, $E^{S1}_{\min}$. Equal to 0 when there is no second maxima.	ΔE		✓
	$\Delta E = \frac{E^{S1}_{1^{\text{st}}\max} - E^{S1}_{2^{\text{nd}}\max}}{E^{S1}_{1^{\text{st}}\max} + E^{S1}_{2^{\text{nd}}\max}}$ Relative difference between energy strip cell with largest energy, $E^{S1}_{1^{\text{st}}\max}$, and strip cell with second largest energy, $E^{S1}_{2^{\text{nd}}\max}$. Equal to 1 when there is no second maxima.	E_{ratio}		✓

Photon ID variables

Middle Layer

Category	Description	Symbol	*loose*	*tight*
EM Middle layer	$R_\eta = \frac{E^{S2}_{3\times7}}{E^{S2}_{7\times7}}$ The ratio of the sum $E_{3\times7}$ of the energies in the second layer cells of the EM calorimeter contained in a 3×7 rectangle in $eta \times phi$ space of cell unit 0.025×0.0245 to sum of energies $E_{7\times7}$ in a 7×7 cell rectangle, centered around the photon cluster.	R_η	✓	✓
	$w_{\eta2} = \sqrt{\frac{\sum E_i\eta_i^2}{\sum E_i} - \left(\frac{\sum E_i\eta_i^2}{\sum E_i}\right)^2}$ E_i is the energy deposit and η_i the position of cell i. Shower lateral width in the EM middle layer, using all cells in a window $\eta\times\phi = 3\times5$ in cell units	$w_{\eta2}$	✓	✓
	$R_\eta = \frac{E^{S2}_{3\times3}}{E^{S2}_{3\times7}}$ Like R_η but in ϕ direction. Behaves differently for unconverted and converted photons since for converted the electrons and positrons bend in ϕ when immersed within a magnetic field.	R_ϕ		✓

Photon ID variables

Hadronic Leakage

Category	Description	Symbol	*loose*	*tight*
Acceptance	$\|\eta\| < 2.37$ with $1.37 < \|\eta\| < 1.52$ excluded	-	✓	✓
Hadronic leakage	$R_{\mathrm{had}} = \frac{E_{\mathrm{T}}^{\mathrm{had}}}{E_{\mathrm{T}}}$ The transverse energy $E_{\mathrm{T}}^{\mathrm{had}}$ deposited in the all cells of hadronic calorimeter whose center is in a window $\Delta\eta \times \Delta\phi = 0.24 \times 0.24$ behind the photon cluster, ratio to the total transverse energy E_{T} of the photon candidate. Used for $\|\eta\|$ region between 0.8 and 1.37	R_{had}	✓	✓
	$R_{\mathrm{had1}} = \frac{E_{\mathrm{T}}^{\mathrm{had,1}}}{E_{\mathrm{T}}}$ The transverse energy $E_{\mathrm{T}}^{\mathrm{had,1}}$ deposited in the cells of hadronic calorimeter first layer whose center is in a window $\Delta\eta \times \Delta\phi = 0.24 \times 0.24$ behind the photon cluster, ratio to the total transverse energy E_{T} of the photon candidate. Used for $\|\eta\|$ region that R_{had} does not.	R_{had1}	✓	✓