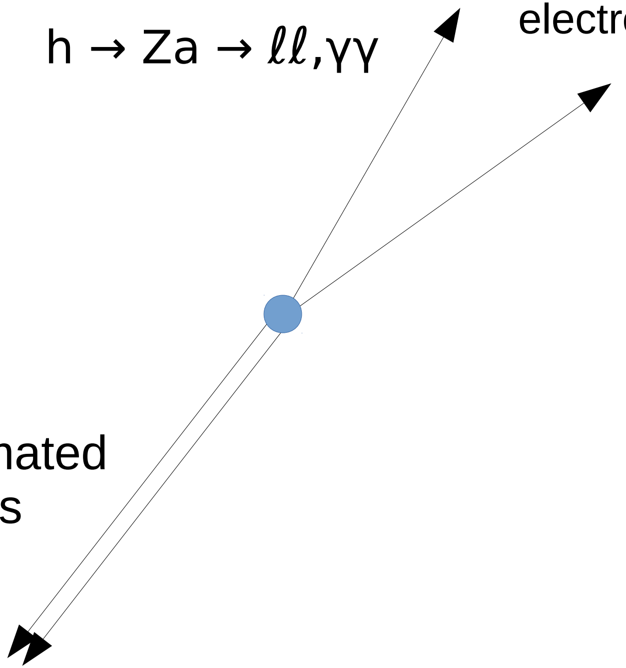
Axion searches in rare Higgs decays at ATLAS

Adam Ruby , Cristiano Sebastiani
Nikolaos Rompotis, Sergey Burdin

Signature

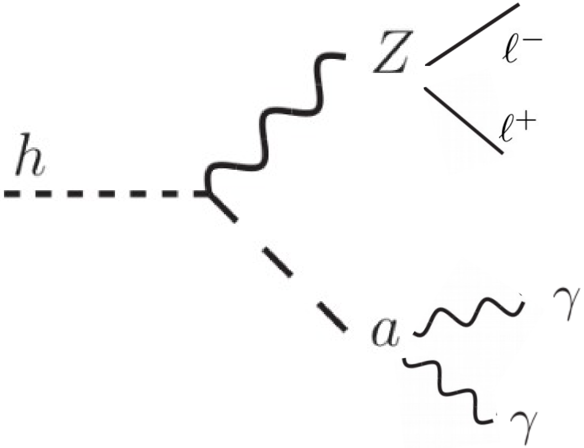
- Signature: 2 leptons + 2 collimated photons

$h \rightarrow Za \rightarrow \ell\ell, \gamma\gamma$



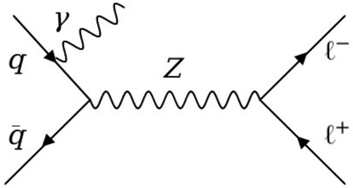
2 leptons:
electrons or muons to trigger

2 collimated photons

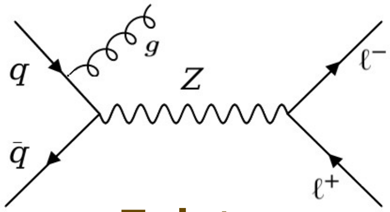


- ALP may be long-lived, focus on prompt decays for now

Main backgrounds Z+jets & Z+γ

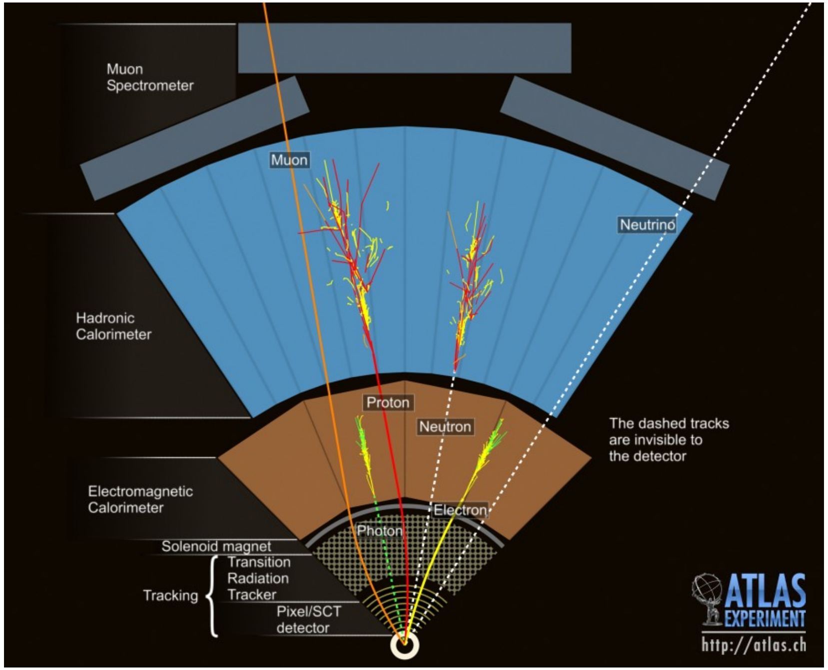


Zγ

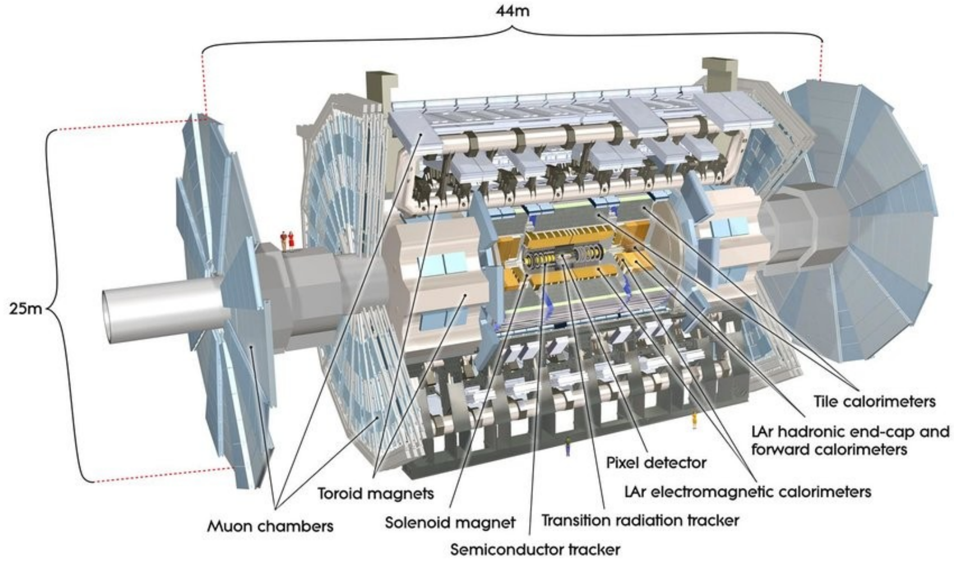


Z+jets

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

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

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

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

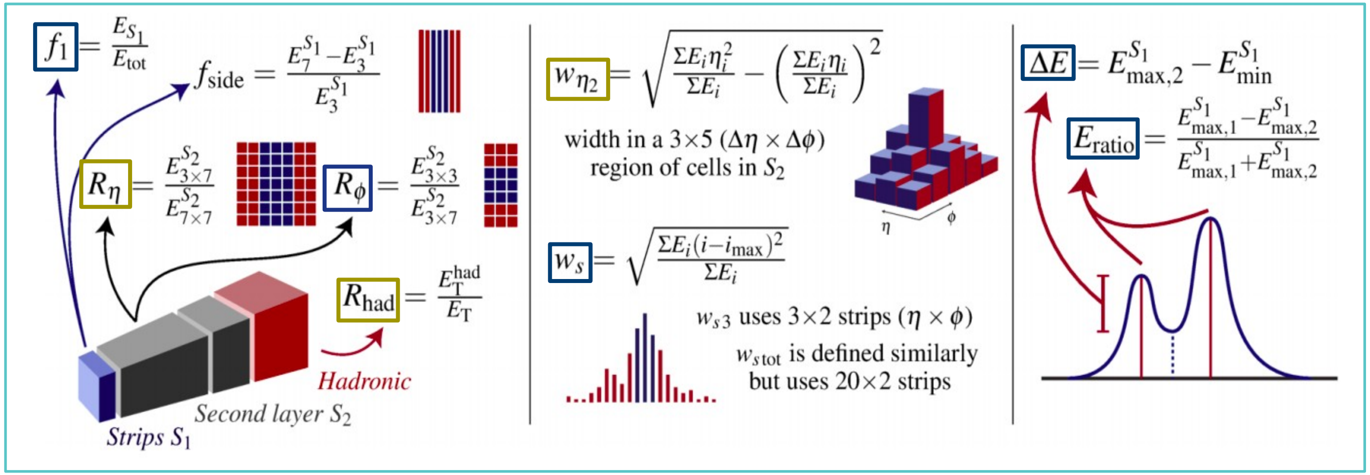
Loose ID: Middle layer + hadronic leakage variables.

Tight ID: + Strip layer variables.

$$E_{\mathrm{T}}^{\mathrm{iso}}\big|_{\Delta R<0.2} < 0.065 \cdot E_{\mathrm{T}}$$

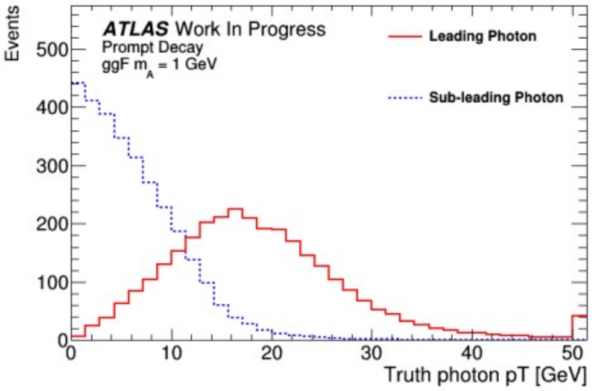
$$p_{\mathrm{T}}^{\mathrm{iso}}\big|_{\Delta R<0.2} < 0.05 \cdot E_{\mathrm{T}}\ ;$$

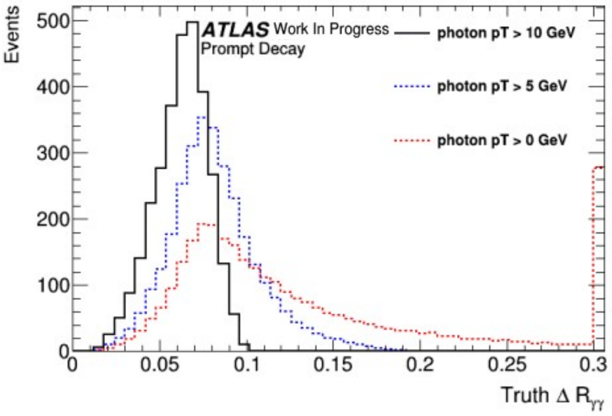
Loose Isolation criteria



Photon ID discriminating variables

Truth level



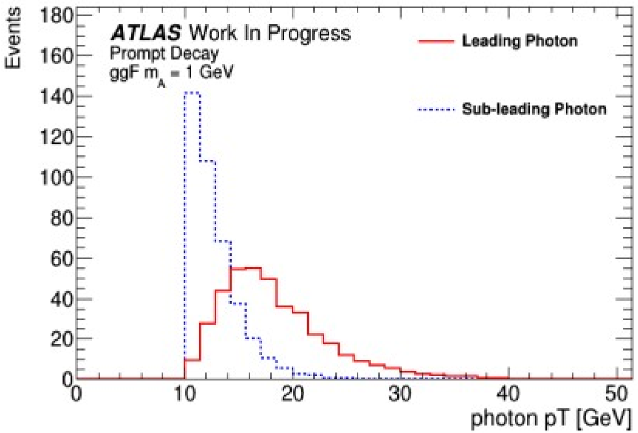


Plots for Gluon-fusion mA = 1 GeV

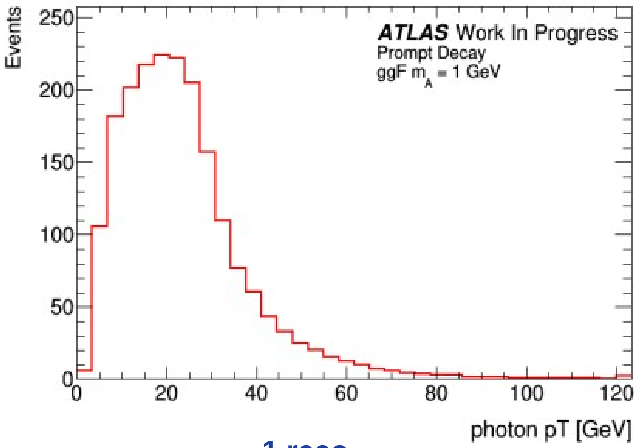
At low photon pT, **many signal di-photon pairs are merged together**

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

Reco level



2 reco photons



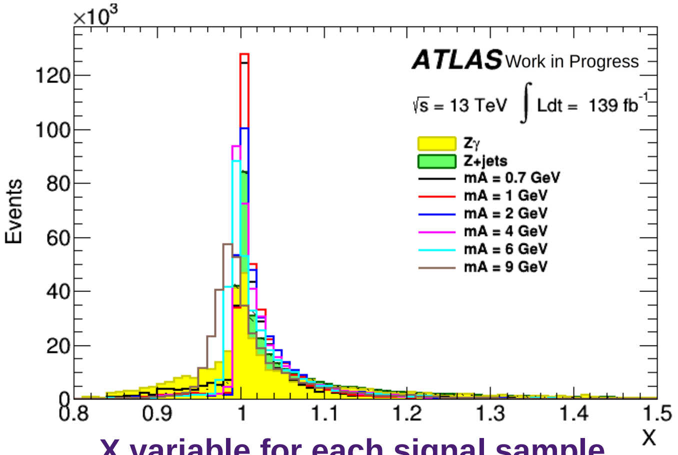
1 reco photon

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

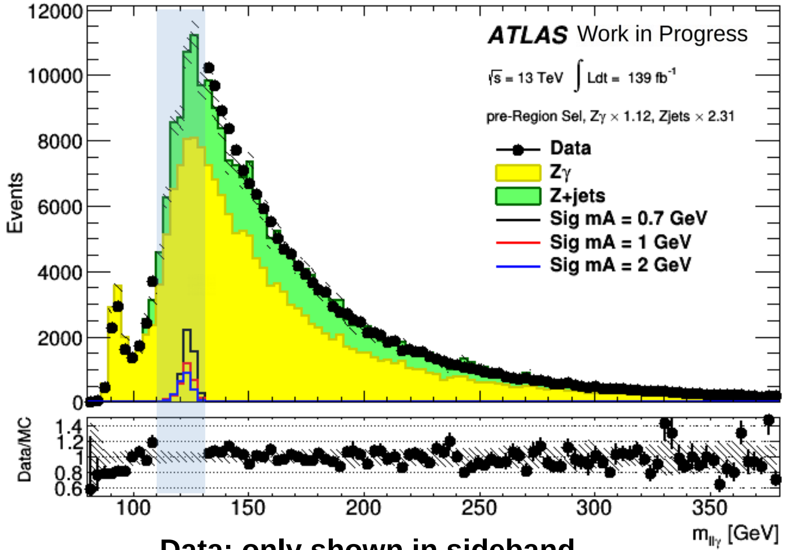
Resolved Category: Events for which the <u>di-photon pair</u> with X closest to 1 satisfies $0.96 < X < 1.2$. Both photons pT > 10 GeV and satisfying $\Delta R_{\gamma\gamma} < 1.5$

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.

Merged Category

axion-particle candidate reconstructed as one photon

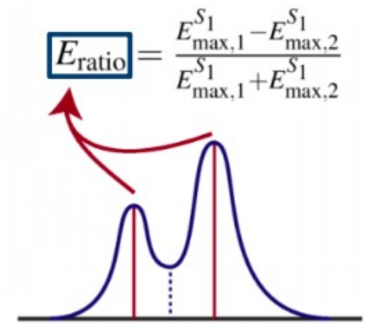


Data: only shown in sideband

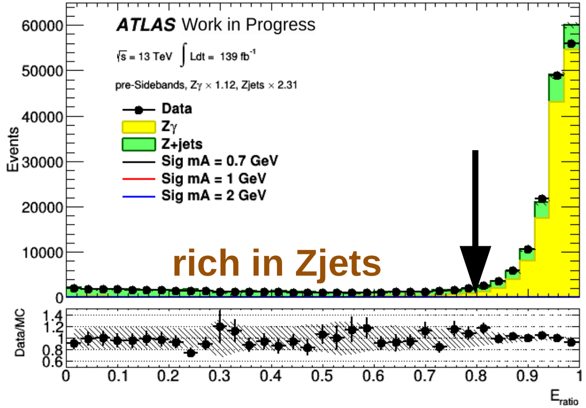
Region	Selection
pre-SR	$m_{\ell\ell\gamma}$ window
pre-SB	$m_{\ell\ell\gamma}$ sideband
SR	pre-SR, $E_{ratio} > 0.8$
SB	pre-SB, $E_{ratio} > 0.8$

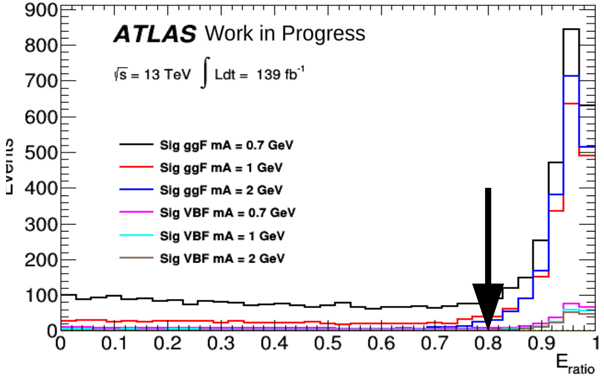
Signal region: 110 GeV < $m_{ll\gamma}$ < 130 GeV,

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



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





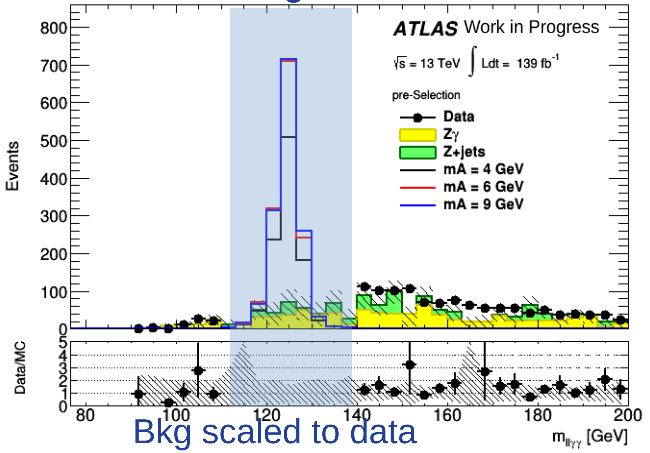
Resolved category

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



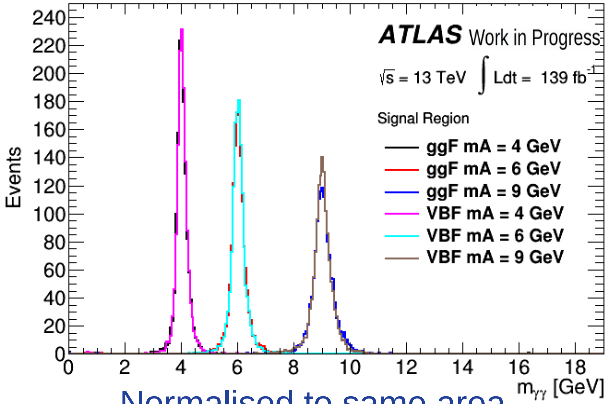
Bkg scaled to data

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

Conclusion

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

- Merged signal photons is a 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

Photons must pass loose isolation cuts & Loose PID.

Efficiency x Acceptance

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

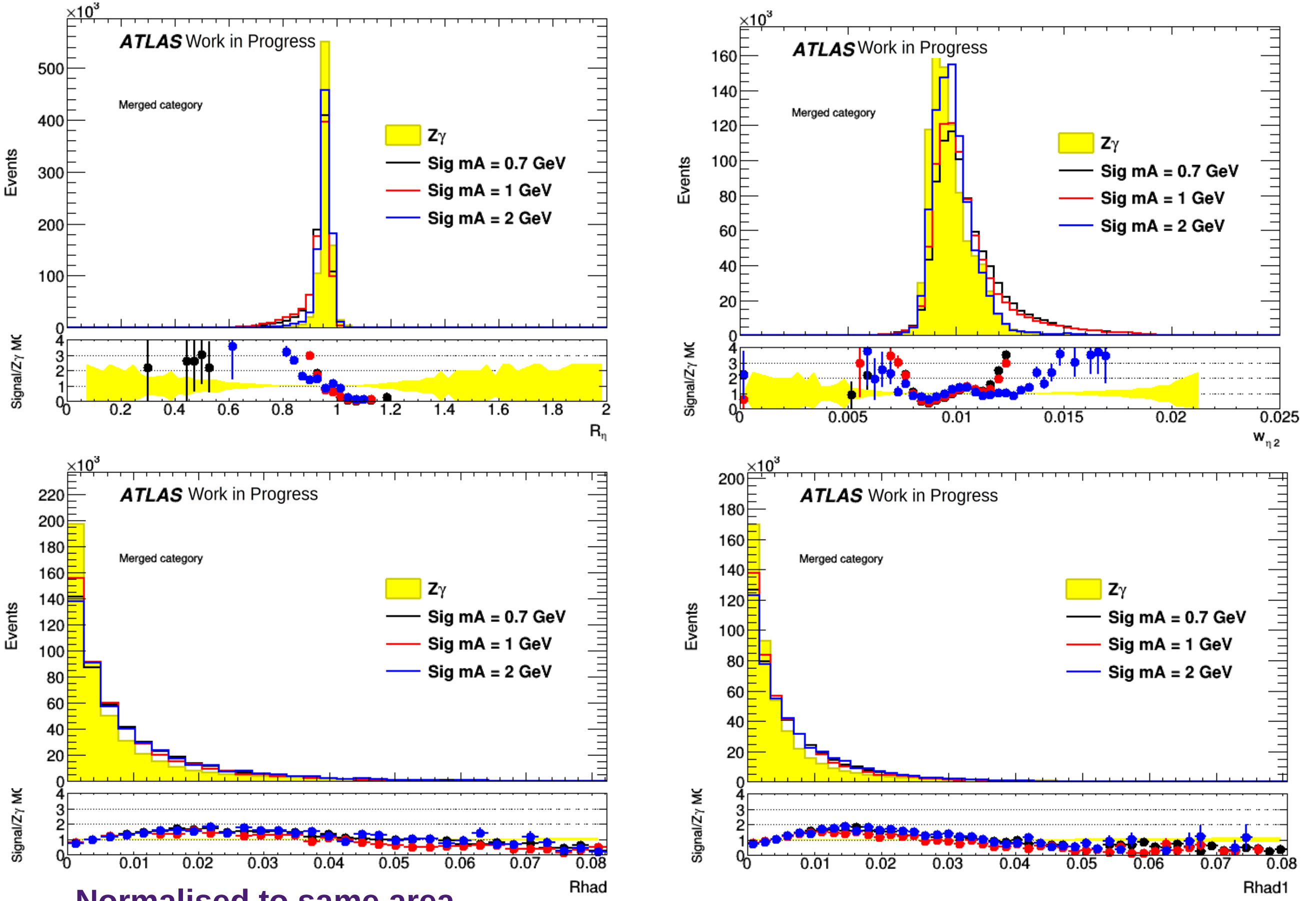
Merged
Low mass points: 40% – 57%

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



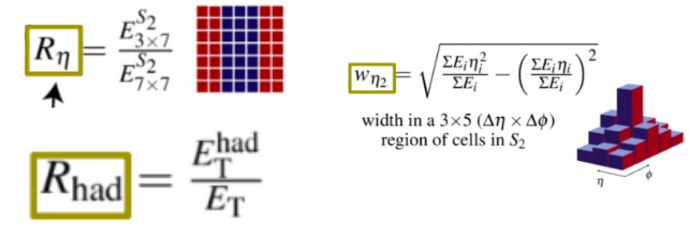
Normalised to same area

Two photons reconstructed as one

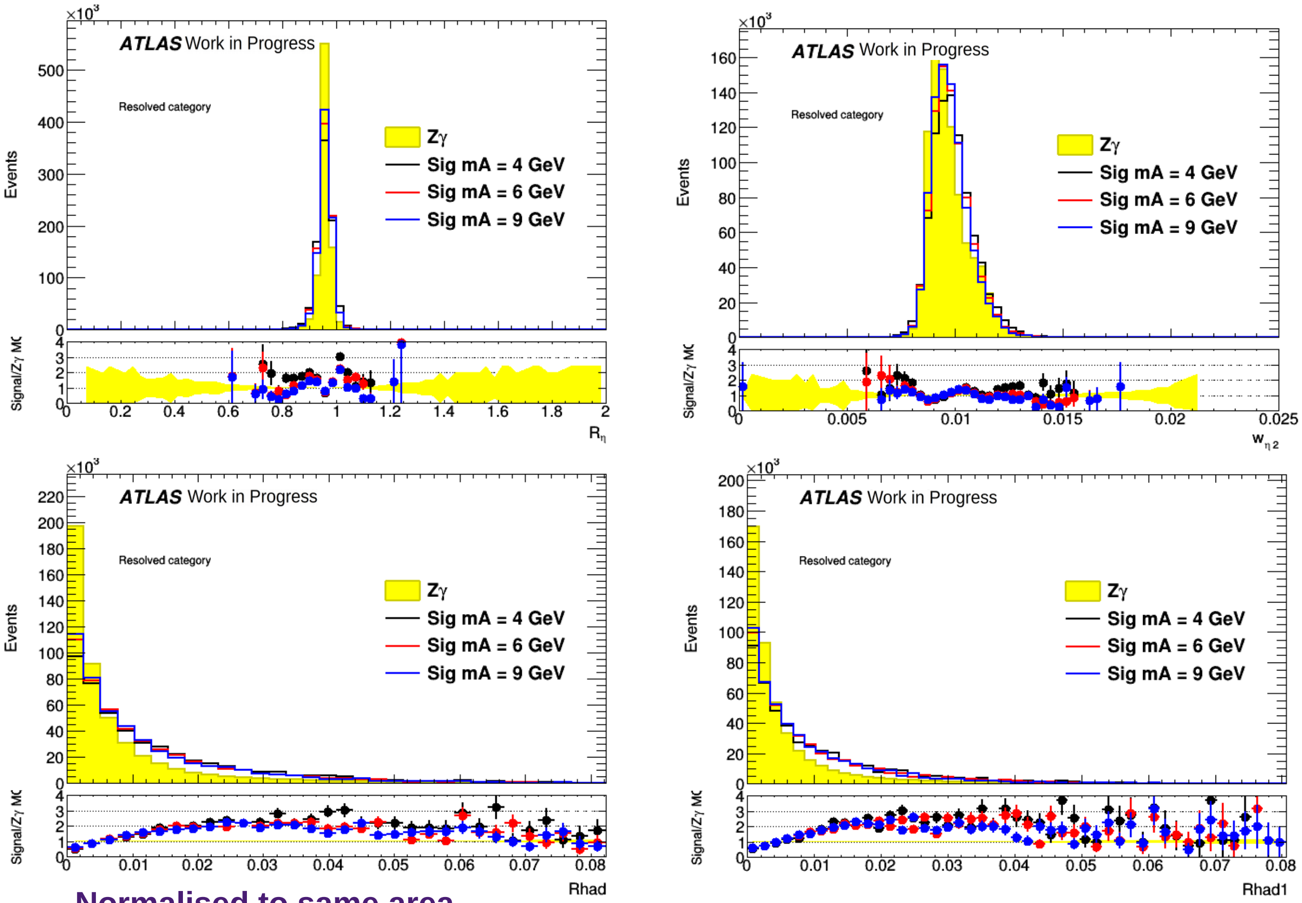
Isolation already applied.

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

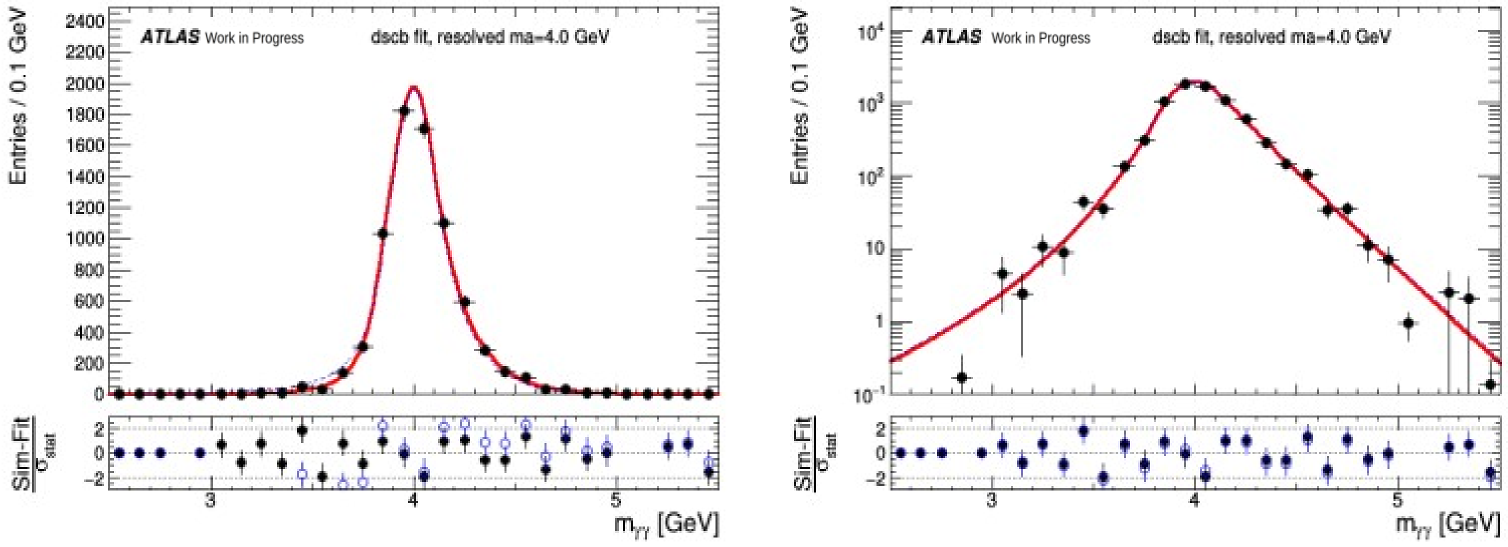
Both photons reconstructed separately

Isolation already applied.

Smaller discrepancies.

Shapes more comparable to Zγ distributions.

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**).

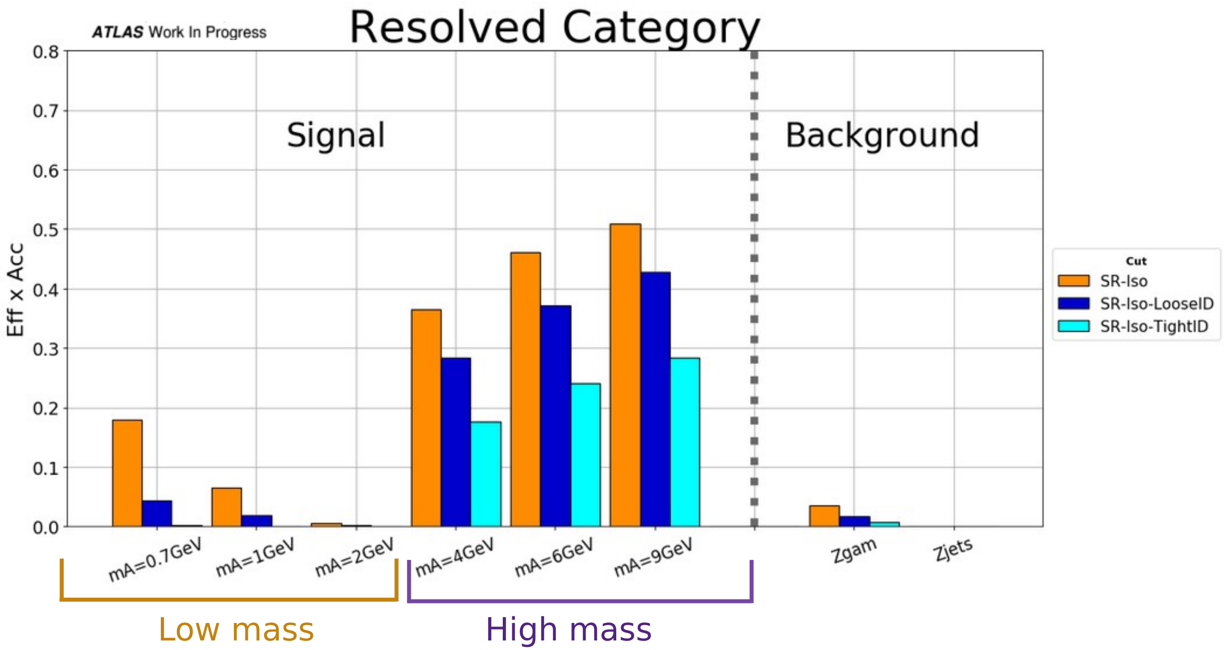
Photon Selection: Resolved Category

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

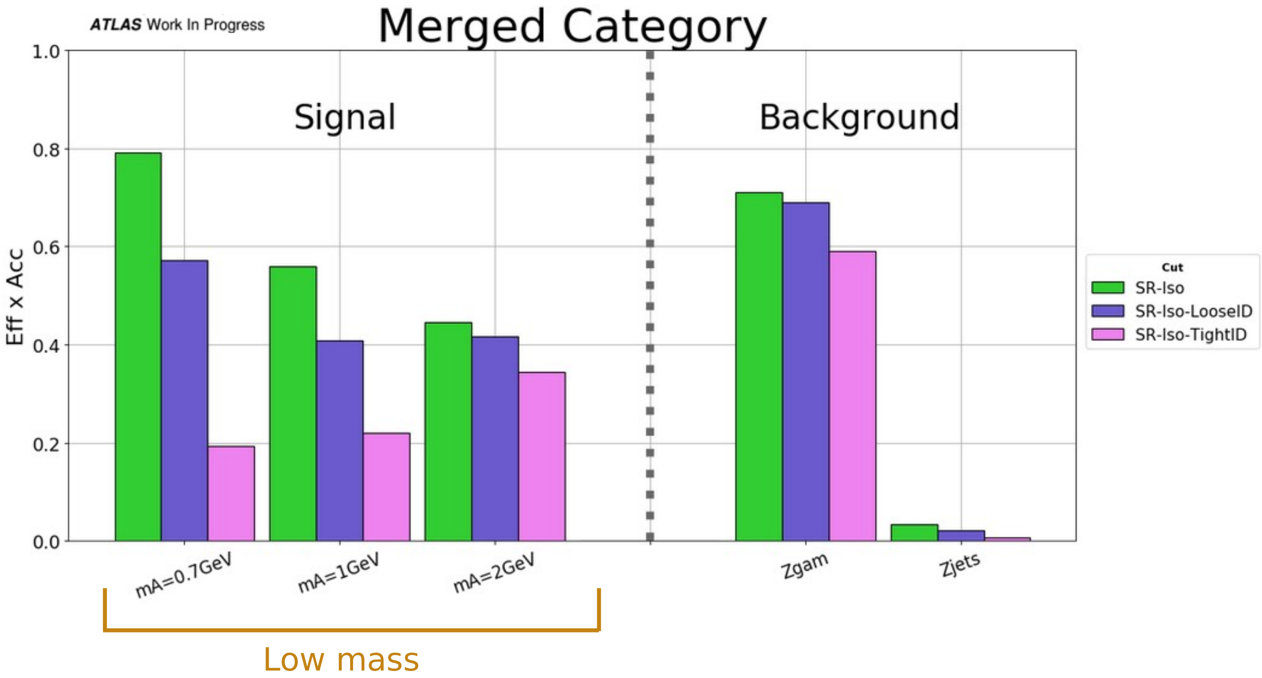
Background efficiencies < 2%



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%.



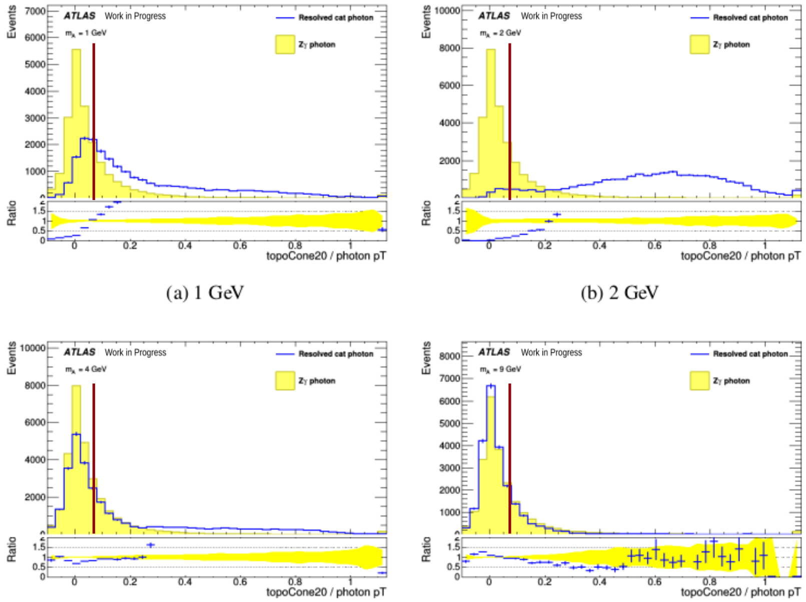
Photon Selection: Resolved Category, isolation

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.

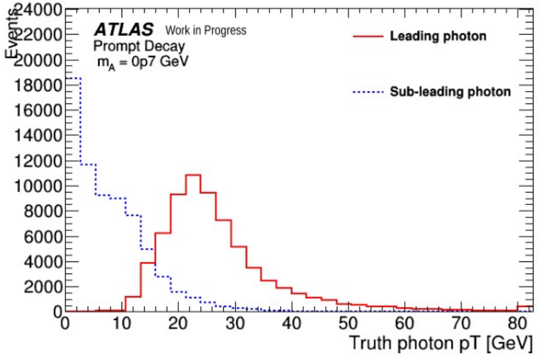


(a) 1 GeV (b) 2 GeV

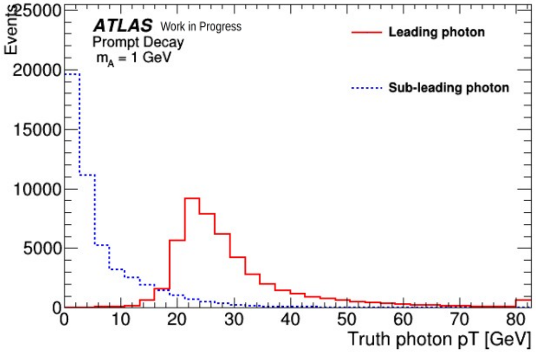
(c) 4 GeV (d) 9 GeV

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 $p_T > 10$ GeV. Photons are truth matched. All shapes normalised to same integral and the last bin includes also the histogram overflow.

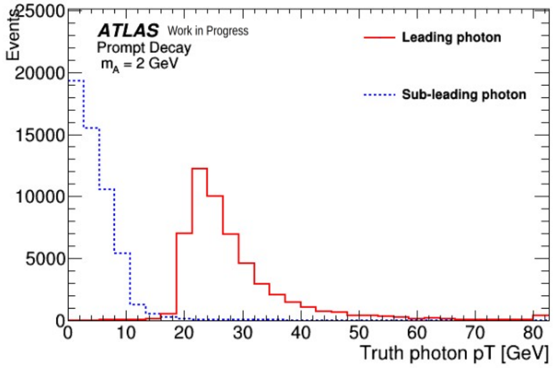
Merged category: Truth Photon pT



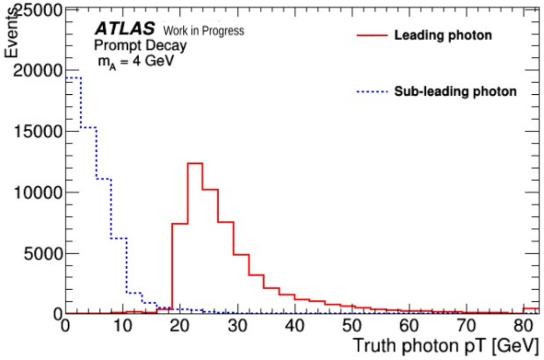
(a) 0.7 GeV



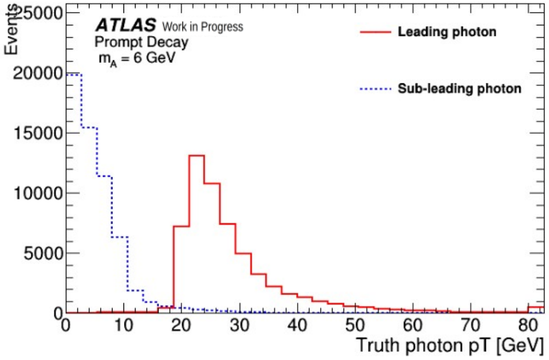
(b) 1 GeV



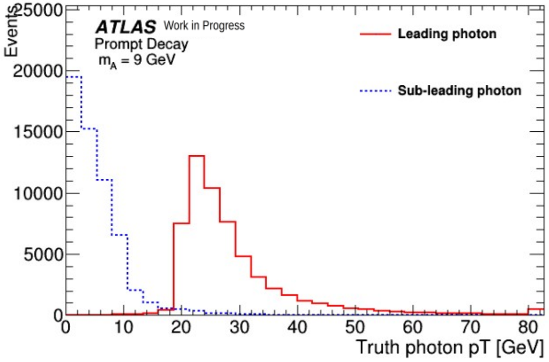
(c) 2 GeV



(d) 4 GeV

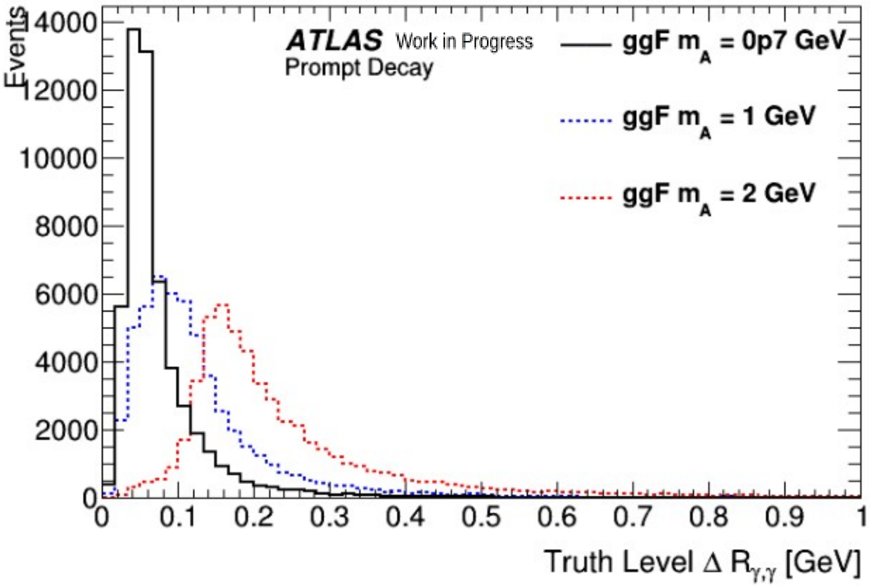


(e) 6 GeV

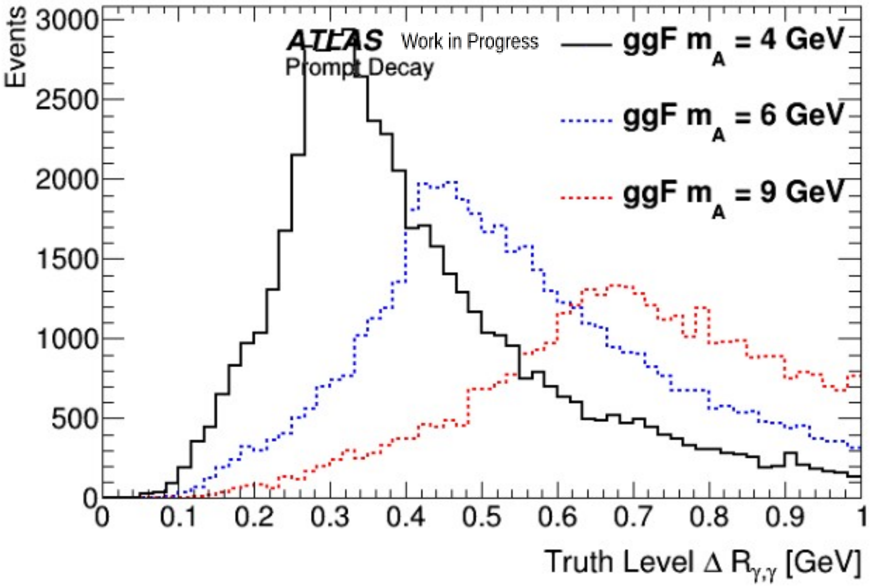


(f) 9 GeV

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

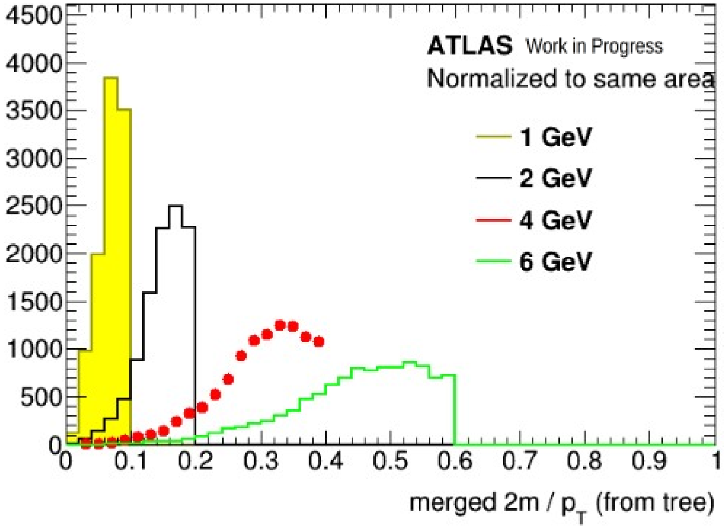


(a) 0.7 – 2 GeV



(b) 4 – 9 GeV

Merged category: Isolation discussion

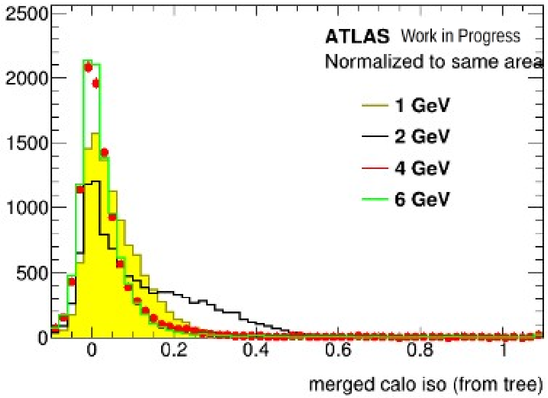


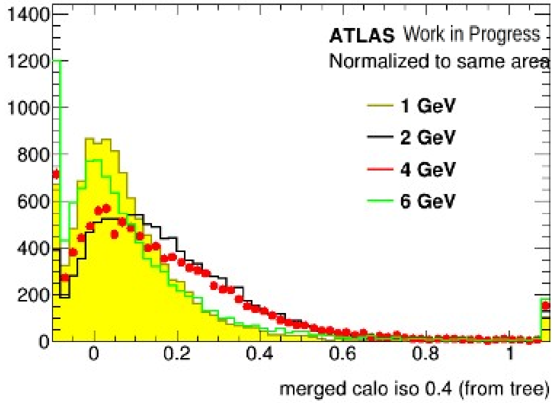
Quantity approx equal to DR between the 2 photons from the axion

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 1st 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 $\eta \times \phi = 3 \times 5$ 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	$R_{\text{had}} = \frac{E_{\text{T}}^{\text{had}}}{E_{\text{T}}}$ The transverse energy $E_{\text{T}}^{\text{had}}$ 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}	✓	✓
	$R_{\text{had1}} = \frac{E_{\text{T}}^{\text{had,1}}}{E_{\text{T}}}$ The transverse energy $E_{\text{T}}^{\text{had,1}}$ 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}	✓	✓