ATLAS Trigger Study for Photon Jet Search
$\boldsymbol{X} \rightarrow aa \rightarrow 4\gamma$

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ATLAS Experiment

The Standard Model

Fermions (half-integer spin)	Quarks (come in three colors)			Leptons		
	I	II	III	I	II	III
	u Up	c Charm	t Top	e Electron	μ Muon	τ Tau
	+2/3 charge			-1 charge		
	d Down	s Strange	b Bottom	ν_e Neutrino	ν_μ Neutrino	ν_τ Neutrino
	-1/3 charge			0 charge		

Hadrons (Made of Quarks)	Baryons Fermionic Hadrons (Three Quarks)	Mesons Bosonic Hadrons (Quark & Anti-Quark)	Quark Color Charge	Red	Blue	Green
				Anti-Red	Anti-Blue	Anti-Green

Force	Electromagnetic	Strong	Weak		Gravity	Officially Gravity and the Graviton are not part of the Standard Model, but they are included here for completeness.
Vector Bosons (full-integer spin)	γ Photon	g Gluon (eight color combinations)	$W^{-/+}$ Boson	Z^0 Boson	Graviton (hypothetical)	

Scalar Boson (zero spin)	Higgs

Framework describing fundamental particles and their interactions

- Types of particles:
  - Fermions
  - Force carriers (gauge bosons)
  - Scalar boson (Higgs)
- Highly successful: predictive power confirmed by countless experiments (e.g., LHC)
- Still incomplete: doesn't explain dark matter, matter-antimatter asymmetry, excludes gravity

The Strong CP Problem

Charge Conjugation (C):

- Replaces all particles with their antiparticles (i.e., reverses charge)

Parity (P):

- Spatial inversion, similar to looking in a mirror (flips spatial coordinates)

CP Symmetry:

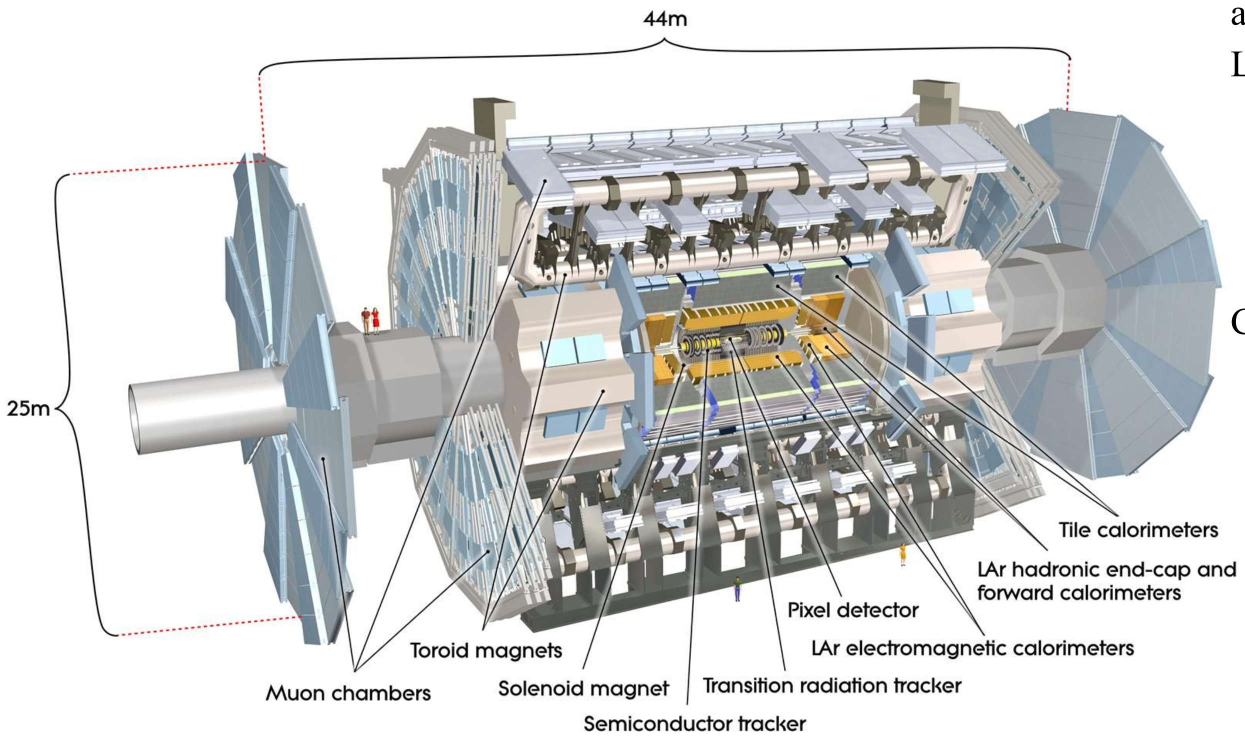
- Combines charge conjugation and parity transformations.

→ If CP is conserved, a mirrored universe made of antimatter behaves like ours.

The Strong CP Problem

- The weak force is known to violate C, P, and CP symmetry
- Also expected in Strong, but experiments have not spotted CP violations
- A natural question: Why is the QCD CP-violating term so small (or zero)?
- A possible solution are particles called axions, hypothesized to solve the strong CP problem
- Experiments thus are searching for axions or axion-like particles (ALPs)

ATLAS Detector



General-purpose particle detector at the Large Hadron Collider (LHC)

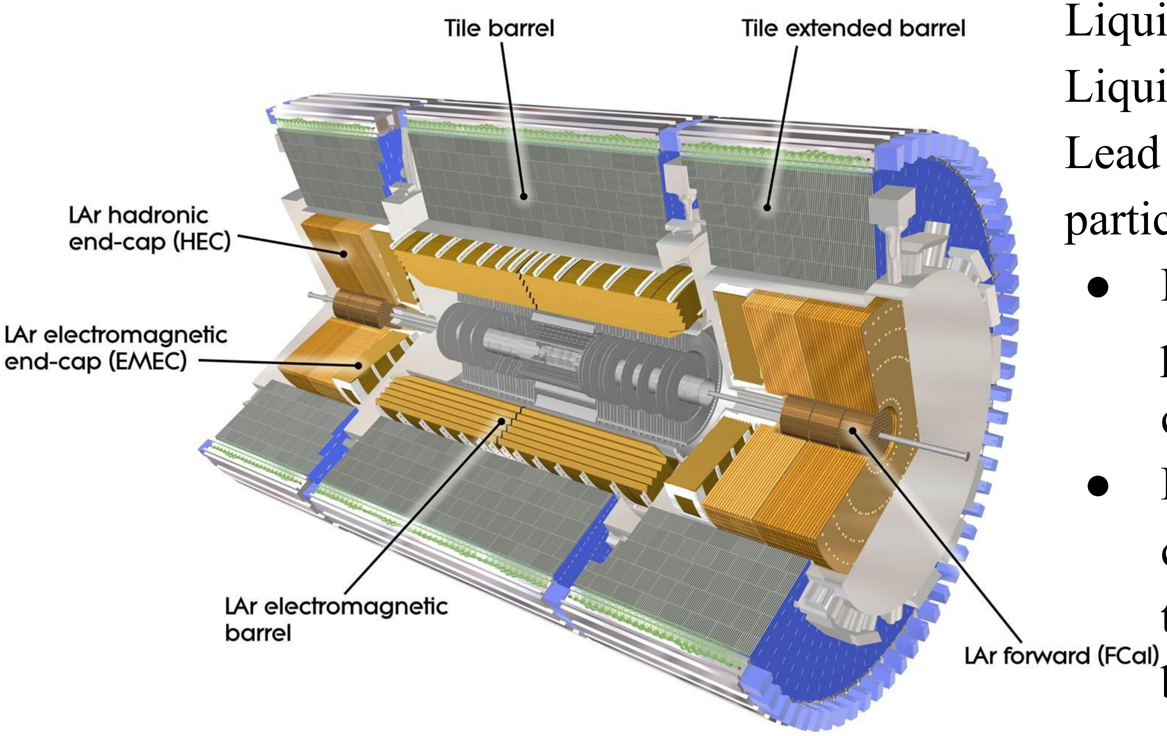
Layered structure:

- Inner Detector
- Electromagnetic Calorimeter
- Hadronic Calorimeter
- Muon Spectrometer

Coordinate system:

- η (eta): spatial coordinate describing the angle of a particle relative to the beam axis
- Φ (phi): the azimuthal angle, measures the angle in the transverse plane around the beam axis
- z: the beam axis

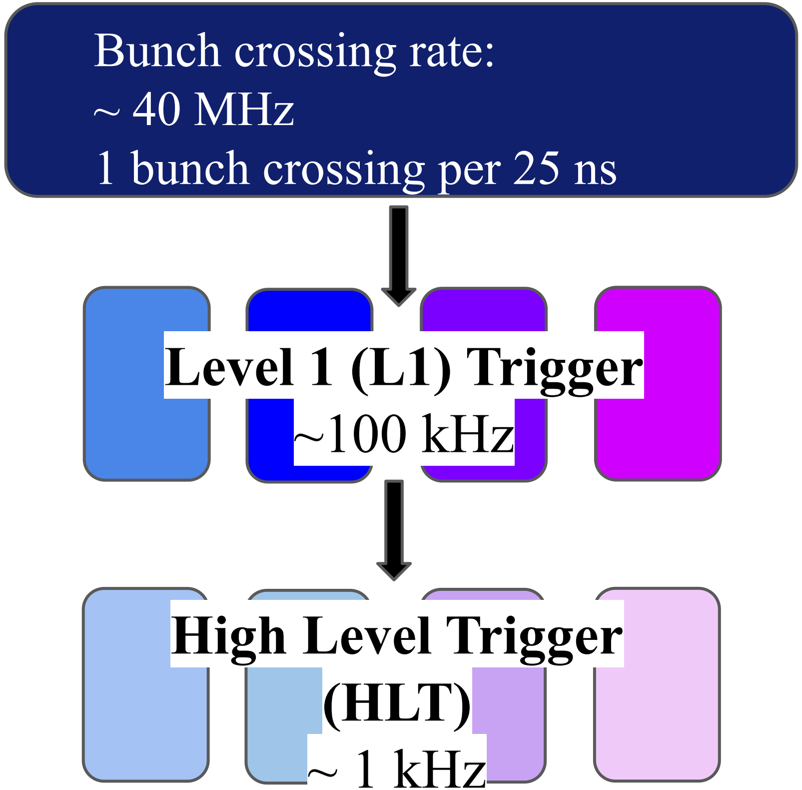
Liquid Argon Calorimeter



Liquid Argon (LAr) Calorimeter
Liquid argon → active medium
Lead plates → absorber material to initiate particle showers

- Measures the energy of incoming particles by collecting ionization current produced in LAr
- High granularity detector with 200K cells providing excellent energy and timing resolution, especially in the barrel and end cap regions

ATLAS Trigger System

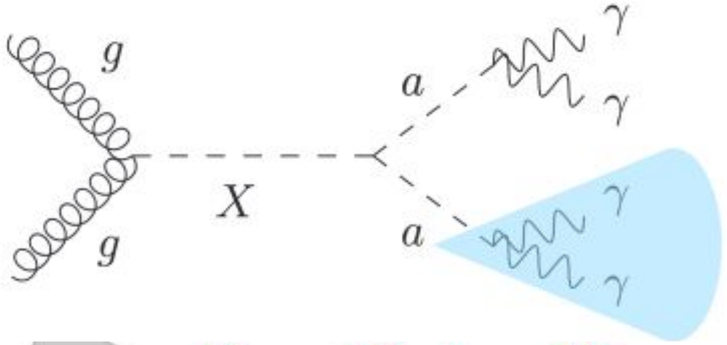


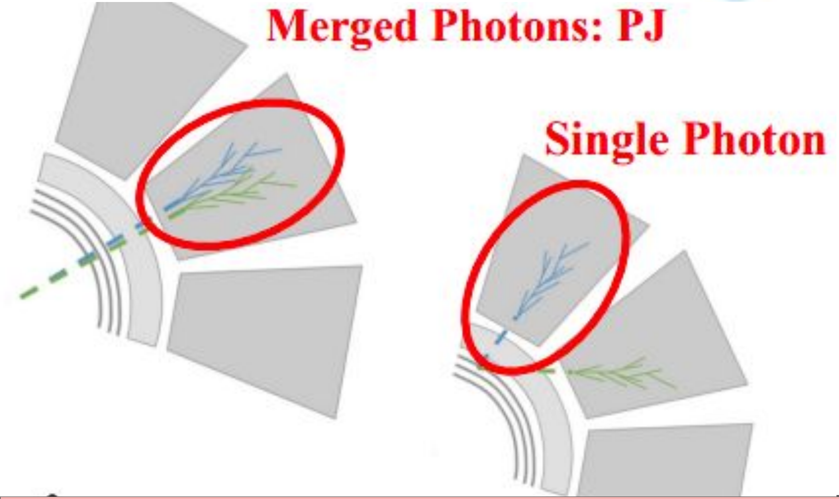
- Too many events, need something to filter data immediately → triggers

Works in two levels:

- Level-1 Trigger (L1):
  - Hardware-based, fast
  - Uses coarse detector information
- High-Level Trigger (HLT):
  - Software-based, more refined and slower
  - Applies full event reconstruction using entire detector

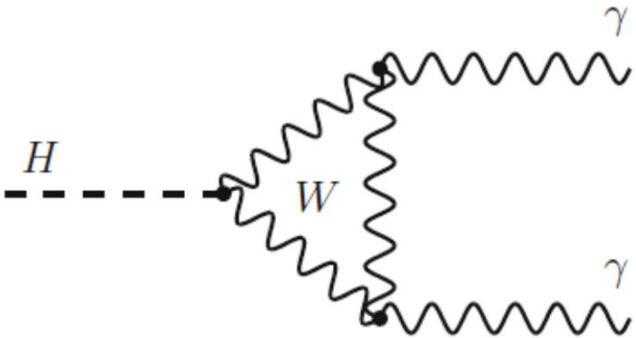
Photon Jet Search for Axion-like Particles

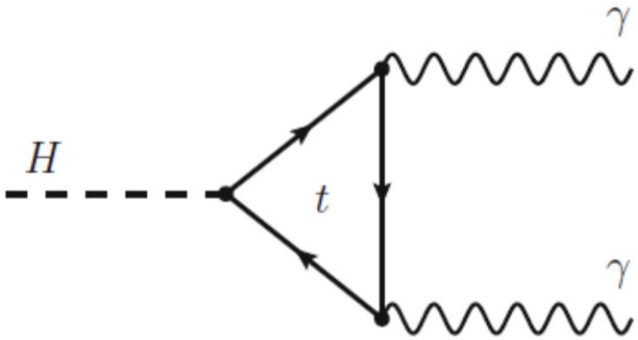




- Photon jet: two photons highly collimated together
- When the ALPs are light (with masses < 1 GeV) they have a large branching ratio to photons, which tend to overlap in the calorimeter → appear as one reconstructed object
- Potential machine-learning techniques want to distinguish photon jets from photons, but need to trigger on good data for training and analysis
- Studying trigger-level information to understand how merged photon candidates behave in the detector
- Aims to improve sensitivity to non-standard photon signatures potentially missed by conventional selections

Samples/Data Set



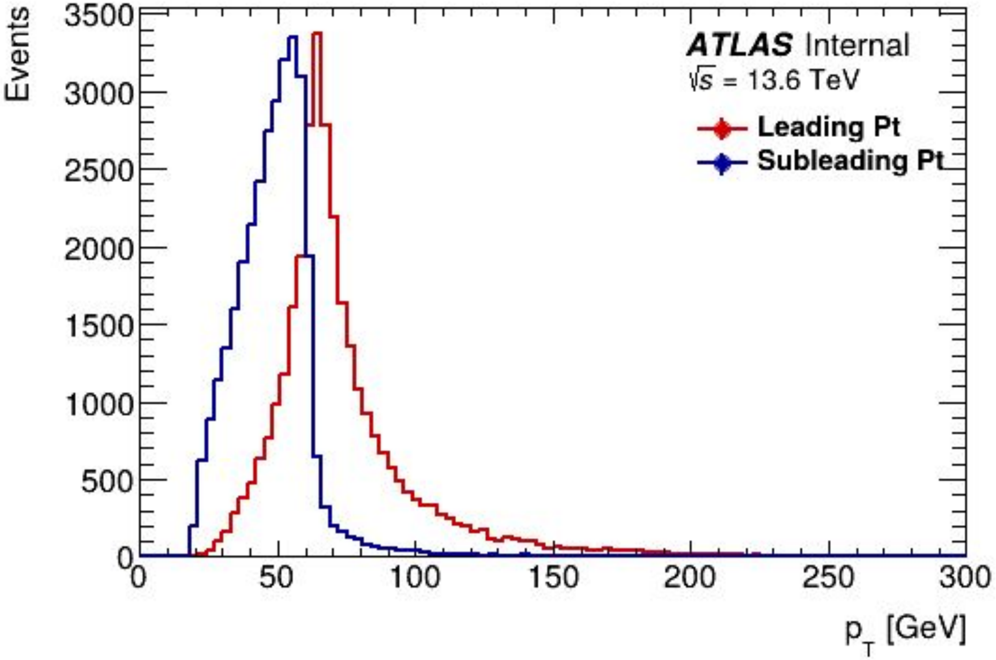


Samples:

- $H \rightarrow \gamma\gamma$ sample used do to similar decay to ALPs (two photon decay)
  - Similarly used scalar particle
- Four other signal samples used → varies Scalar and ALP mass
  - 125 GeV X →0.1 GeV ALP
  - 125 GeV X →0.5 GeV ALP
  - 800 GeV X → 1.0 GeV ALP
  - 800 GeV X → 2.5 GeV ALP

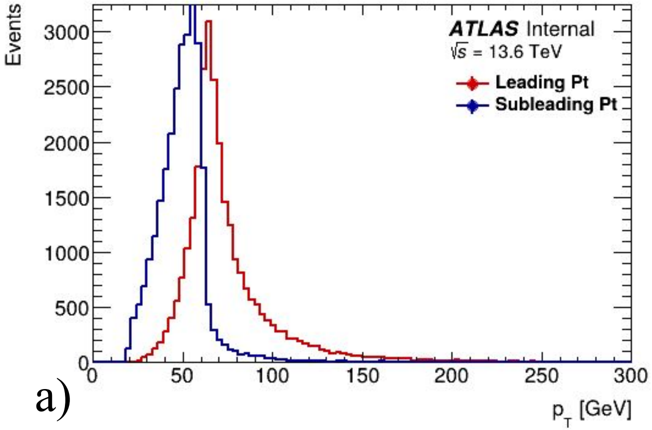
Kinematic Plots

$H \rightarrow \boldsymbol{\gamma\gamma}$ (background)

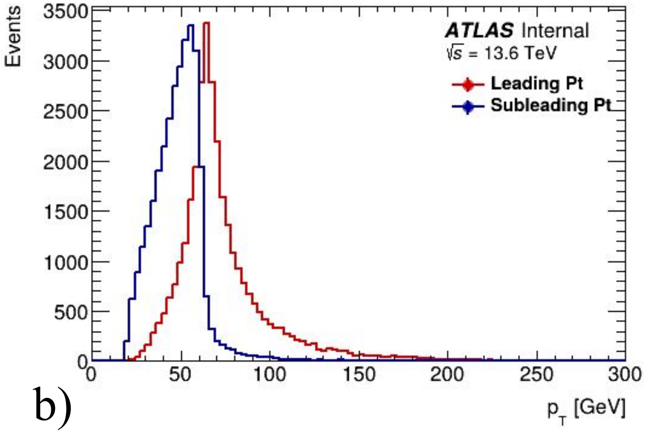


- Before studying triggers: need to see behavior of kinematics of the samples we use
- Should peak at ½ of higgs mass
- Key terms
  - p_T: Transverse momentum
  - Leading: the photon with the highest p_T in each event
  - Subleading: the photon with the second highest p_T in each event

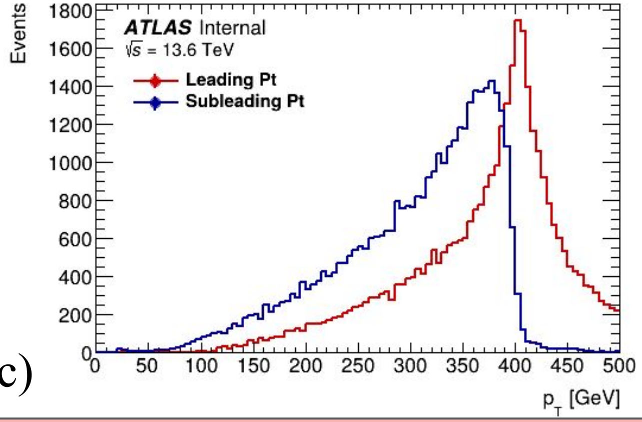
Kinematic Plots



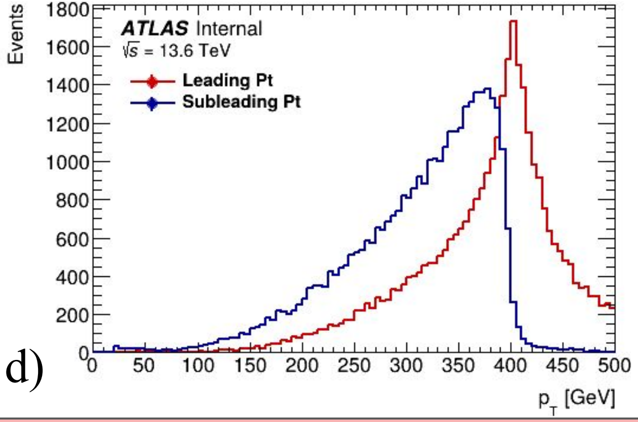
a)



b)



c)



d)

a) 125 GeV X →0.1 GeV ALP

b) 125 GeV X →0.5 GeV ALP

c) 800 GeV X → 1.0 GeV ALP

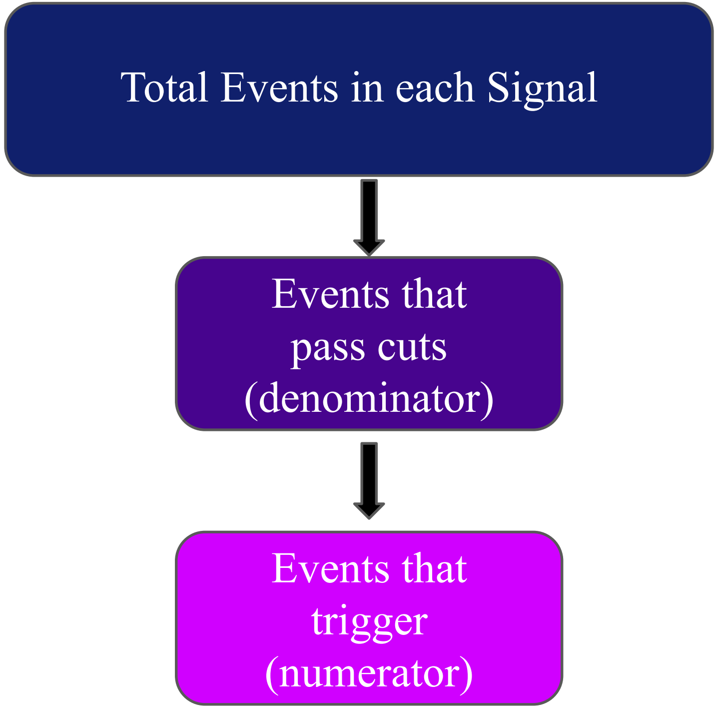
d) 800 GeV X → 2.5 GeV ALP

Data Cuts

- Key terms
  - Clean: standard quality criteria applied to photon candidates to exclude those associated with known problematic or noisy detector regions, ensuring reliable photon identification
  - ID: identifies the photons in each event with different quality requirement working points
  - Trigger Match: shows whether a particle activated that trigger

- Restricted data so that only:
  - Photon $p_T > 20$ GeV
  - Removed $1.37 < |\eta| < 1.52$
    - Due to degraded response from calorimeters in region between barrel and end cap
  - Photons that pass Loose ID
  - Events that pass cleaning
  - Events that pass trigger matching (for that specific trigger)

Trigger Efficiency Calculation

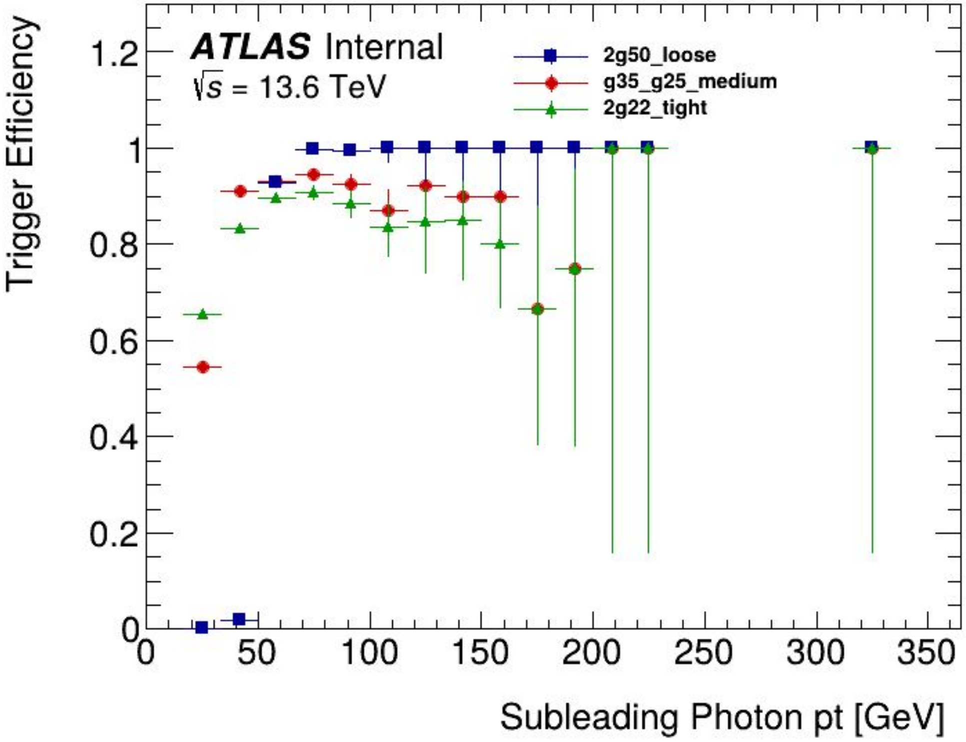


- Triggers have different thresholds and quality criteria, we are interested in seeing what fraction of our model passes each
- Efficiency is calculated with TEfficiency in ROOT:
  - N_trigger is the number of events satisfying both the offline selection and the trigger
  - N_total is the total number of events passing the offline selection.

$$\frac{N\_trigger}{N\_total}$$

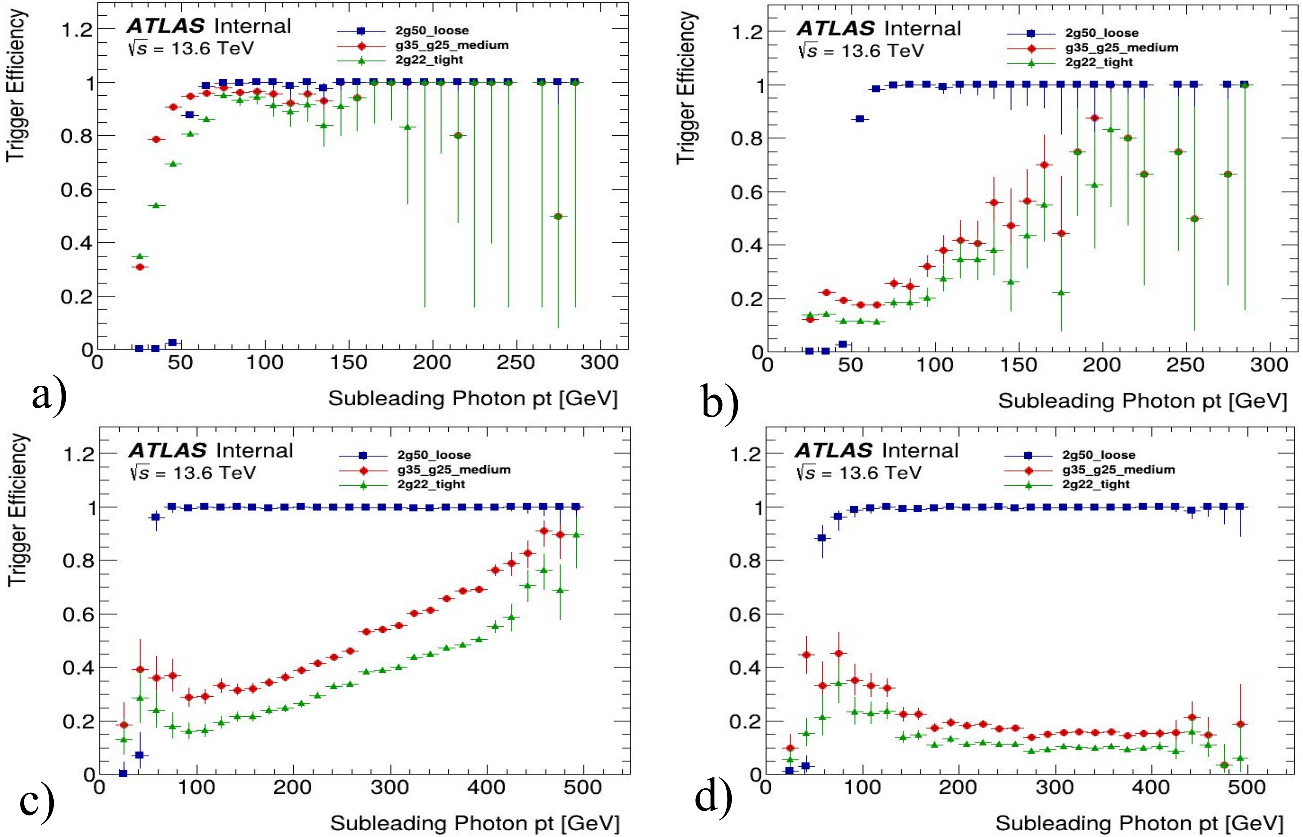
Trigger Efficiency as a Function of P_T ($H \rightarrow \gamma\gamma$)

$H \rightarrow \boldsymbol{\gamma\gamma}$ (background)



- 2g: diphoton trigger
- "Loose" "medium" and "tight" refer to strictness of criteria
- "50," "25," etc refer to the minimum value of p_T needed to pass
- Used $H \rightarrow \boldsymbol{\gamma\gamma}$ sample as an example of what trigger efficiency is supposed to be
- Used subleading photon for di-photon triggers because it dominates, fails the threshold more
- Fast "turn on curve" for loose, medium, and tight shown
- Graphed the efficiency of each trigger vs the binned P_T for each subleading photon

Trigger Efficiency as a Function of P_T



a) 125 GeV X →0.1 GeV ALP

b) 125 GeV X →0.5 GeV ALP

c) 800 GeV X → 1.0 GeV ALP

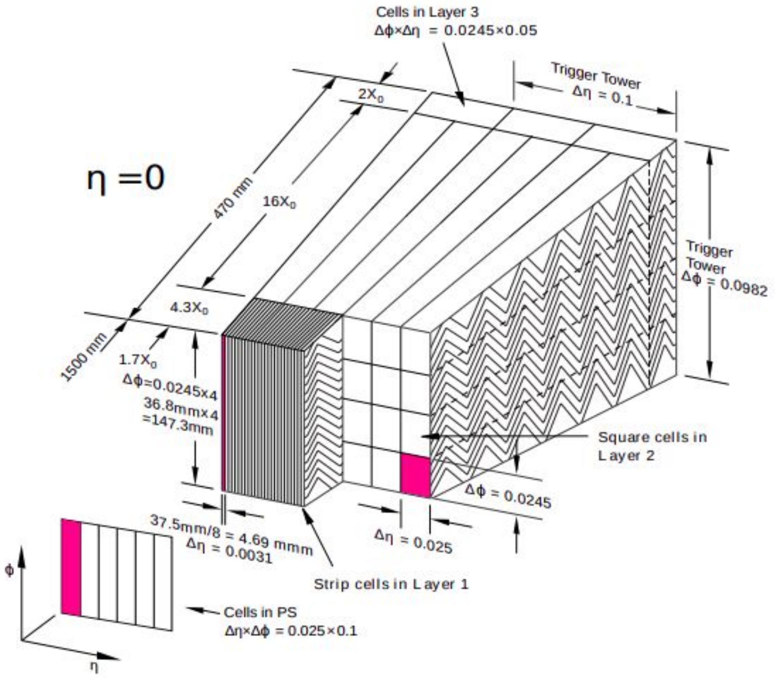
d) 800 GeV X → 2.5 GeV ALP

Overall Trigger Efficiency

signal	2g50_loose	g35_g25_ medium	g22_tight
$H \rightarrow \gamma\gamma$	45.04%	87.27%	83.90%
125 GeV *X*, 0.1 GeV *ALP*	43.08%	85.26%	69.80%
125 GeV *X*, 0.5 GeV *ALP*	46.80%	19.18%	12.79%
800 GeV *X*, 1.0 GeV *ALP*	99.51%	56.36%	40.50%
800 GeV *X*, 2.5 GeV *ALP*	99.26%	16.36%	10.56%

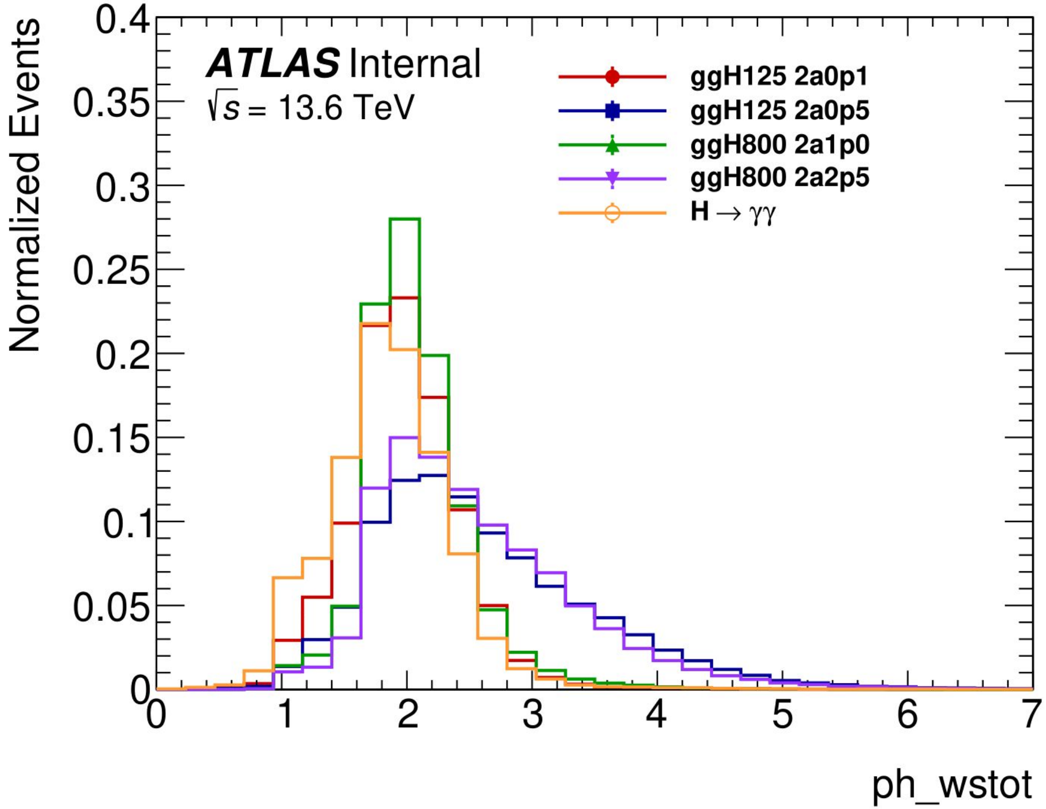
- More strict ID applies cuts on more variables, including “shower shape” variables (more later) that constrain the pattern of energy deposition in the LAr calorimeter

Electromagnetic Shower Shape Variables (SSV)



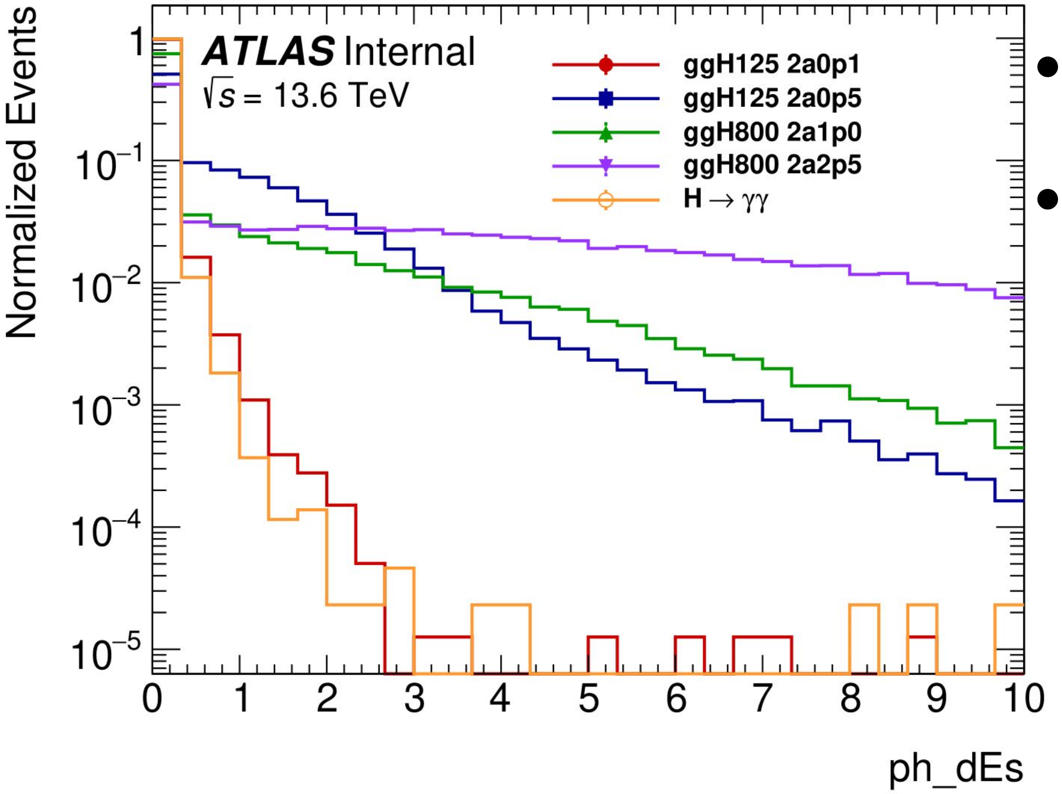
- The fine granularity of the LAr calorimeter can be used to characterize the "shape" of the EM shower resulting from photons or photon jets
- wstot → Width of the shower in the strip layer (first EM layer), computed over the full window (20 strips)
  - Helps resolve close-by energy peaks from overlapping photons
- ΔEs → The energy difference between the second-highest and lowest strip between the first two maxima
  - Sensitive to multi-peak showers
- E-ratio → Energy difference between the leading and subleading maxima in the strip layer
  - helps identify merged or asymmetric showers.

Shower Shape: WSTOT



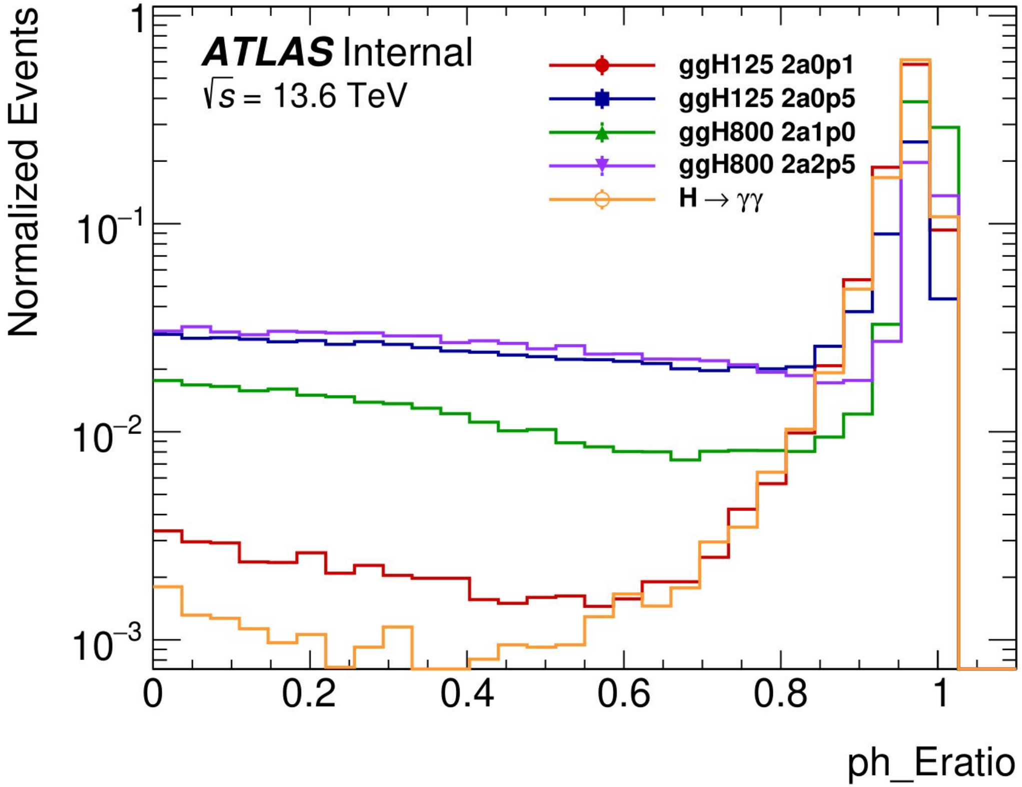
- wstot → Is used in tight trigger ID as a criteria that events must pass
- Mean should be around 2, however the events with higher ALP mass (125X→ 0.5 ALP, 800X → 1.0 ALP, 800X → 2.5 ALP) show a wider distribution
- Could be used to help distinguish photon jets from photons. However, causes a problem for the trigger, where the Tight trigger has low efficiency for ALPs

Shower Shape: ΔEs



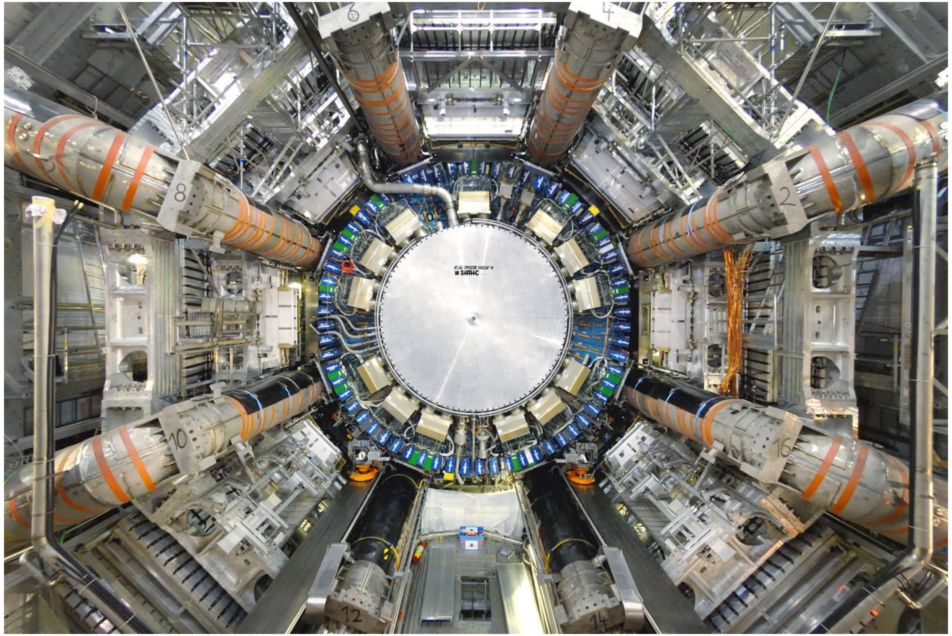
- ΔEs → Is also used in tight trigger ID as a criteria
- Semi-log scale
  - Again, higher mass ALPs show wider distribution

Shower Shape: E-Ratio



- E-ratio → Used in both medium and tight trigger ID as a criteria, could be the reason why medium efficiency drops off at higher masses
- Implies that medium and tight triggers drop off so dramatically due to the photons' non-collimation at higher masses

Conclusion



- Mass of ALPs changes distribution of the photons, and loose trigger is best for our studies
- Why? At higher ALP masses, the photons start to be less collimated, which causes them to fail the quality cuts on the shower shape variables we employ in both the medium and tight ID requirements
- In the signal models, we get these significant tails in the SSV distributions that kill the efficiency of medium and tight

THANK YOU

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Thank you for listening!

Any Questions?

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