Converted Photons in the Search for Photon-Jets from Light Axion-Like Particles

Nevis Laboratories REU

Lyra Bornholdt-Collins, Tufts University

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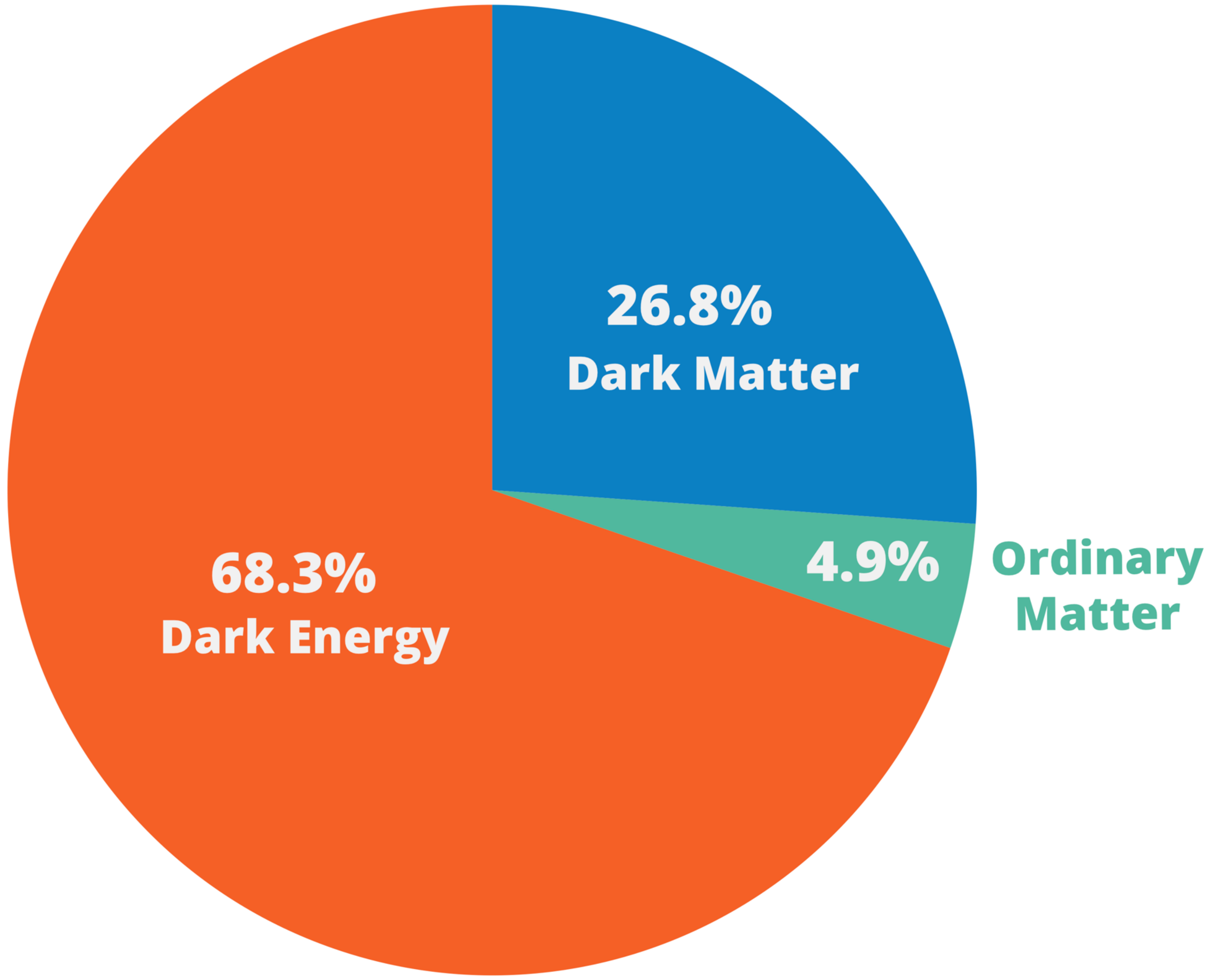
Nevis Laboratories
Columbia University

ATLAS
EXPERIMENT

Introduction and Motivations

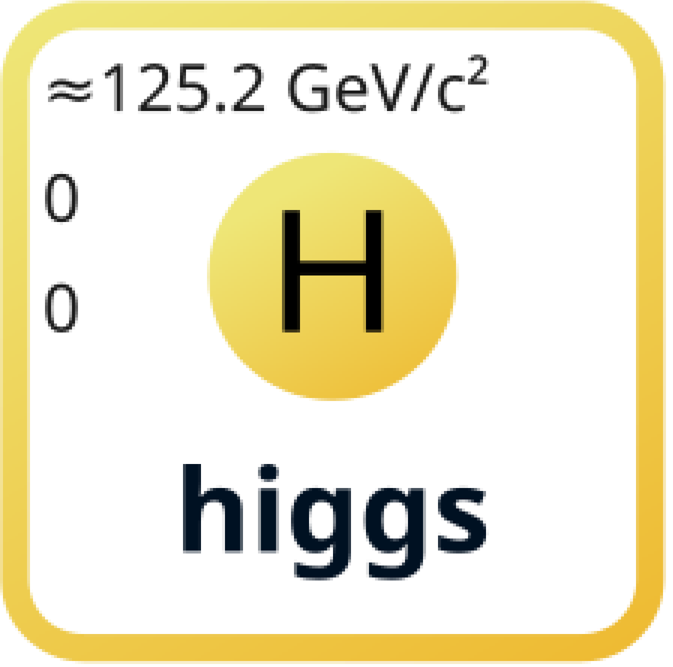
Axions and Axion-Like Particles

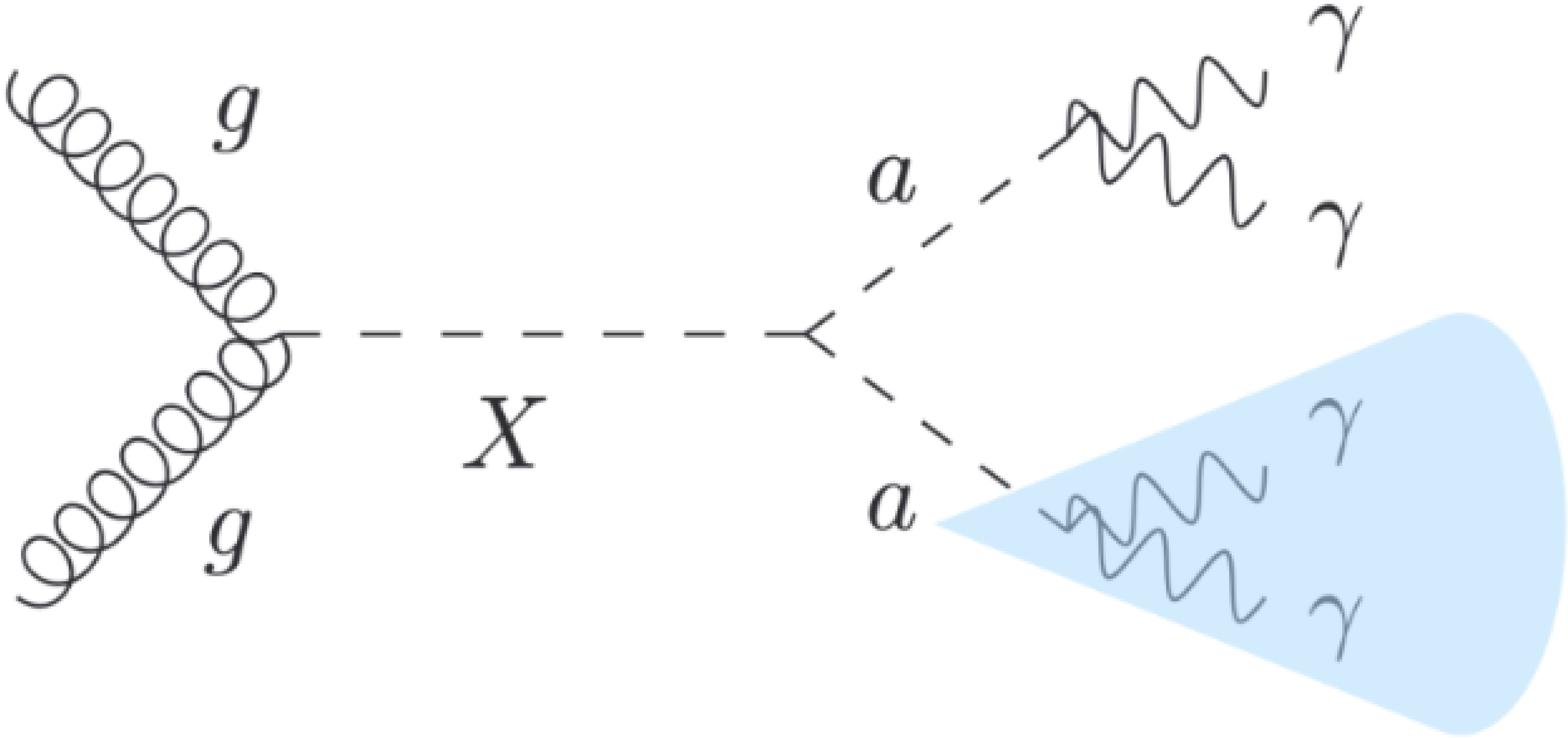
- The axion was proposed in 1970s as a solution to the **strong Charge-Parity (CP) problem**
  - The strong force should theoretically violate matter-antimatter symmetry (experimentally does not)
- Now searching for Axion-*Like* Particles (ALPs),
- ALPs are also candidates for dark matter



Light ALPs

- Theoretically light ALPs have diphoton decay signature – which we can detect!
- Parent mass particle “X”
  - Could be the Higgs boson
- ALPs here denoted as “a”
- Photons are highly collimated

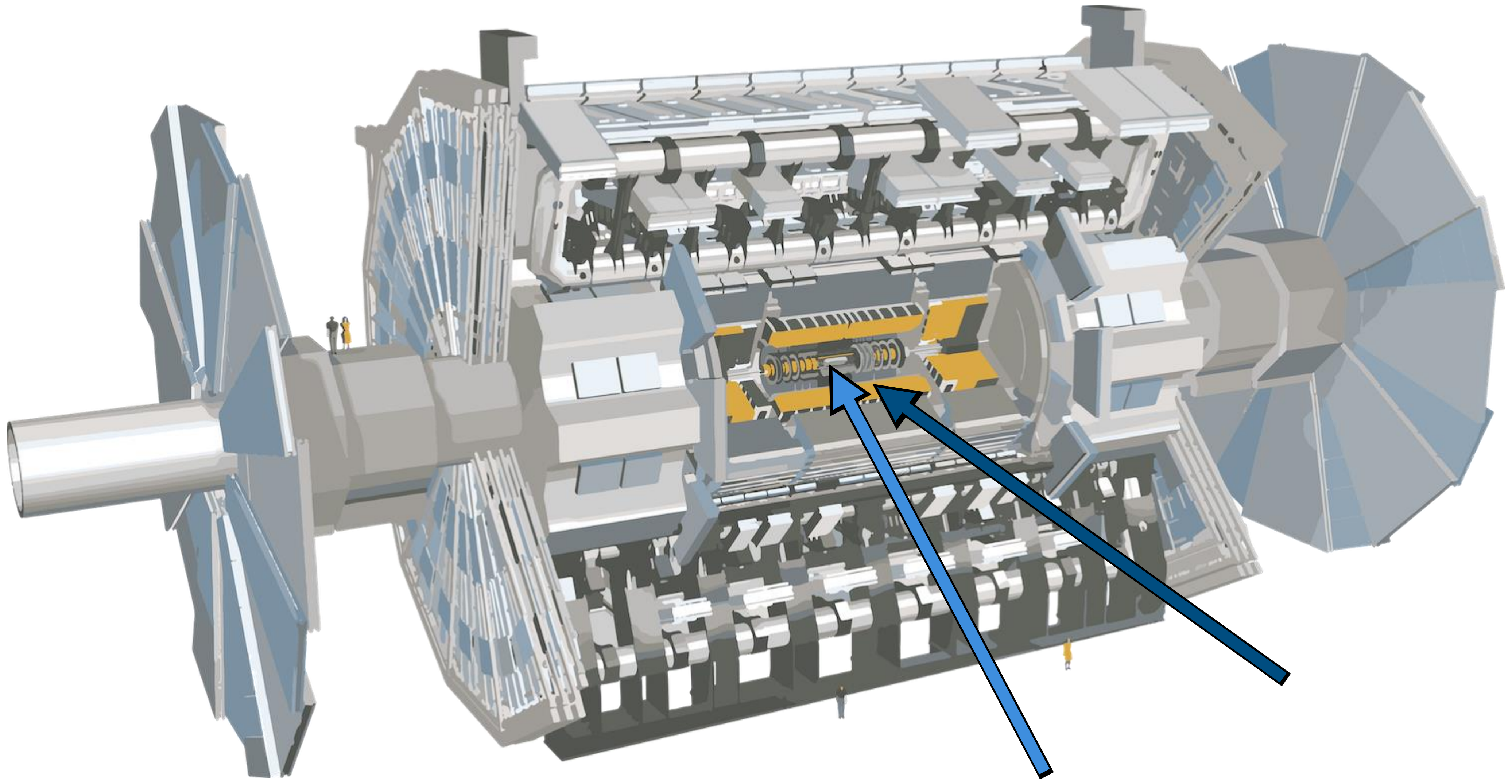


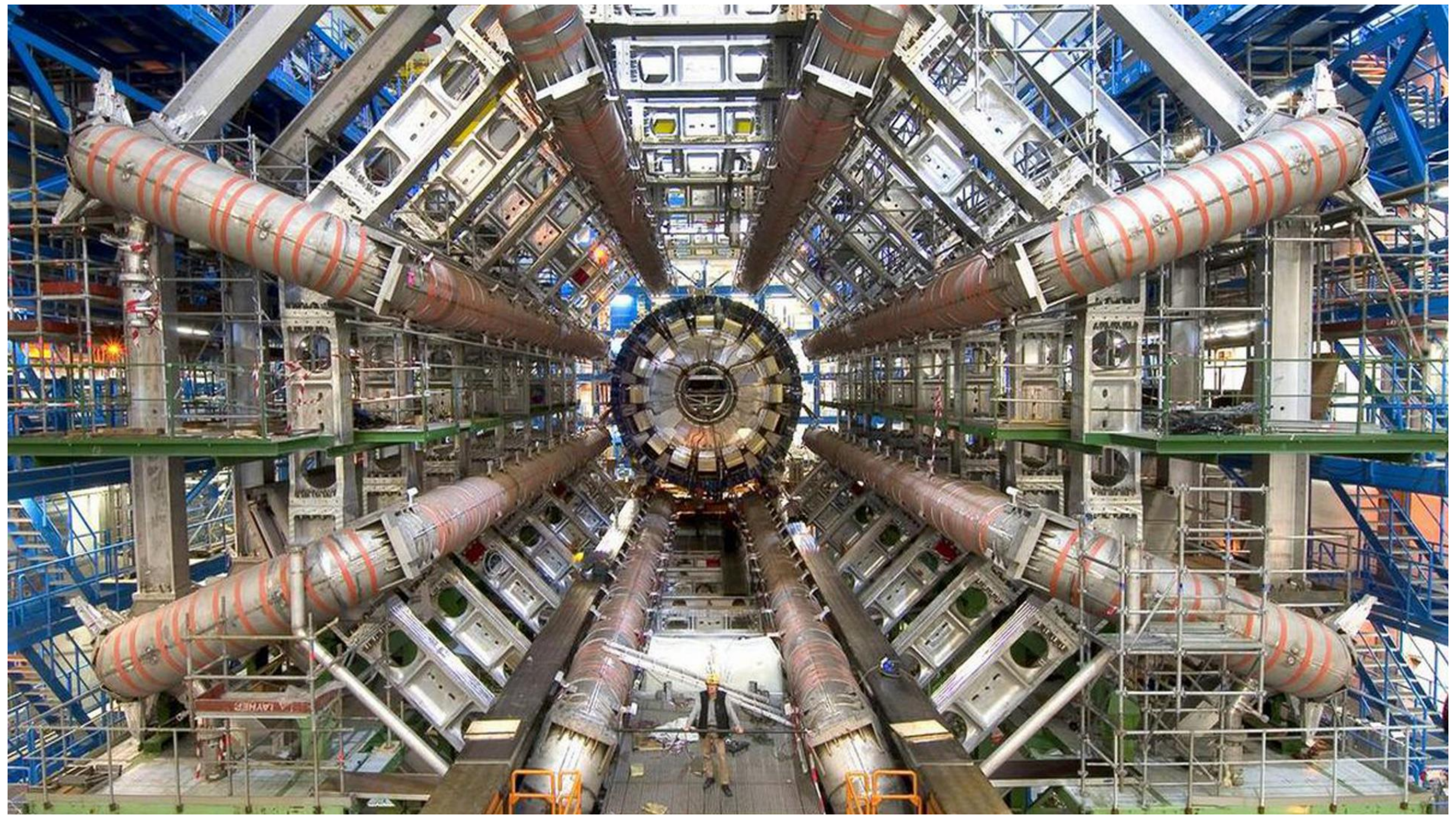


The Large Hadron Collider (LHC)

- Located at CERN near Geneva, Switzerland
- Largest, highest-energy particle accelerator in the world (27 km circumference)
- Accelerates protons near the speed of light and then collides them together ($\sqrt{s} = 13.6\ \mathrm{TeV}$)
- 4 main collision points around the ring: ATLAS, CMS, Alice and LHCb

The ATLAS Detector

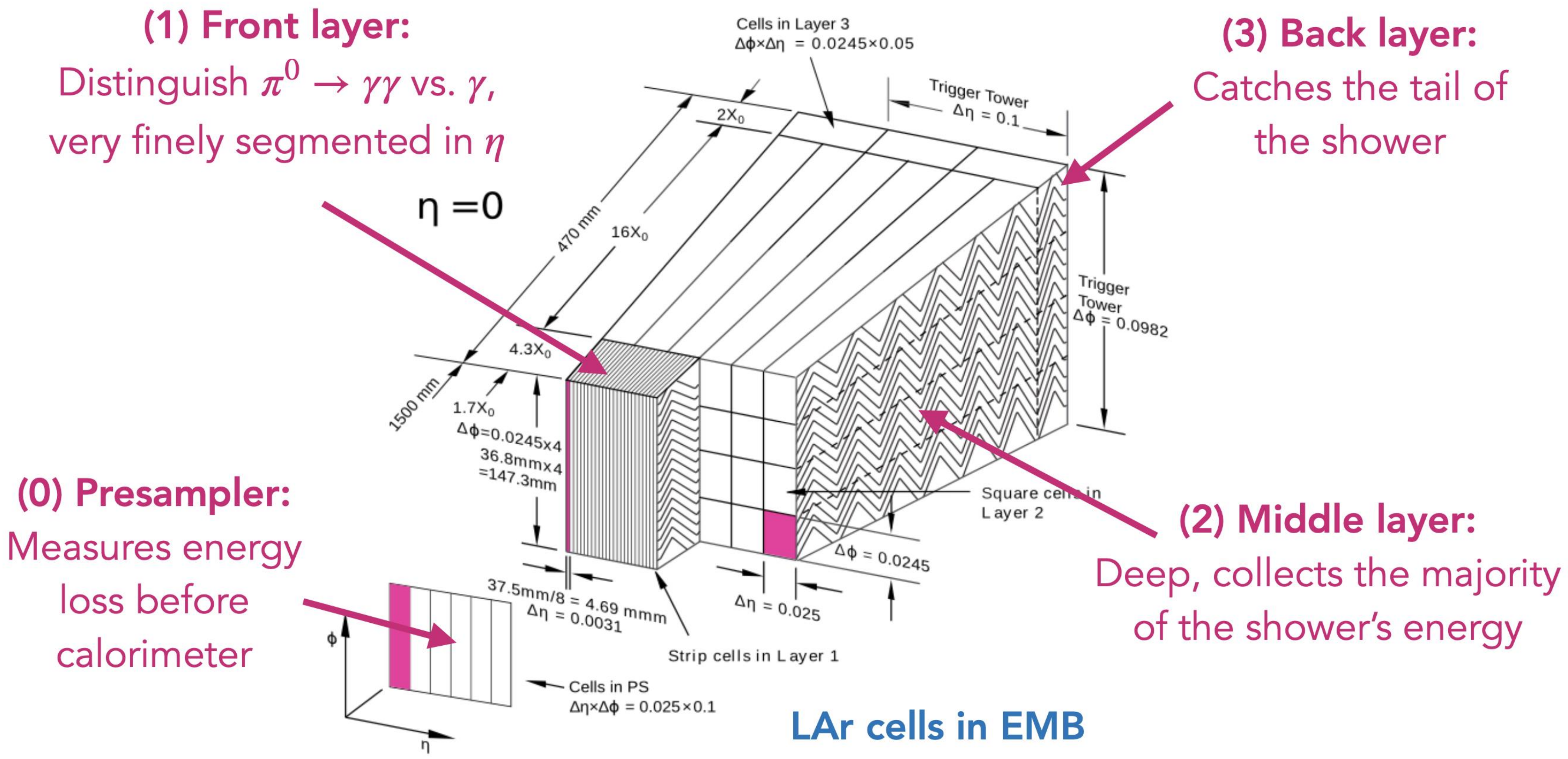


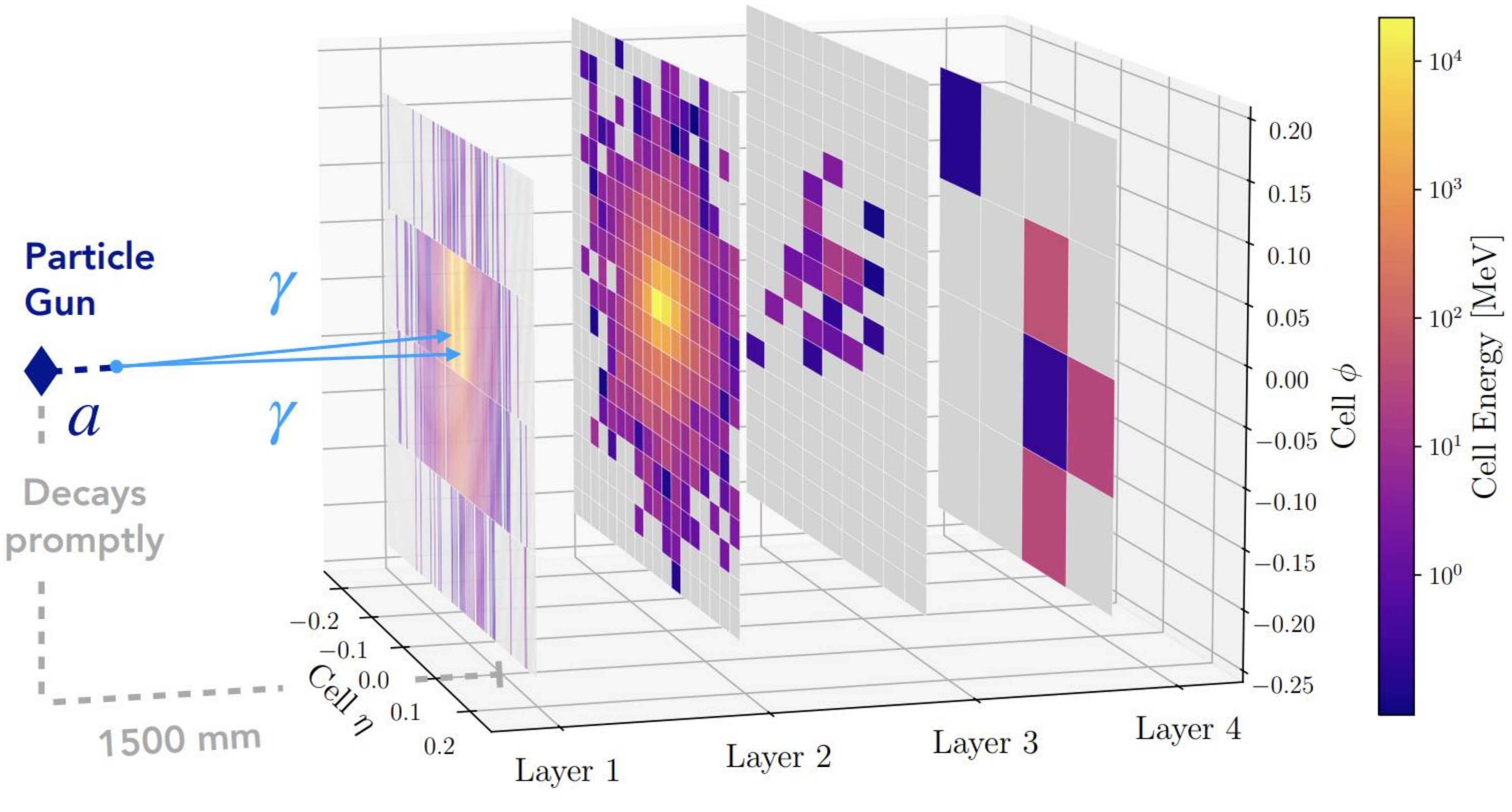


- The largest and one of two general-purpose detectors at the LHC (25m diameter, 46m long)
- Located 100m underground and weighs 7,000 tons
- Detects over 1 billion collisions per second
- Components include the inner detector and the liquid argon (LAr) electromagnetic calorimeter

LAr Electromagnetic Calorimeter

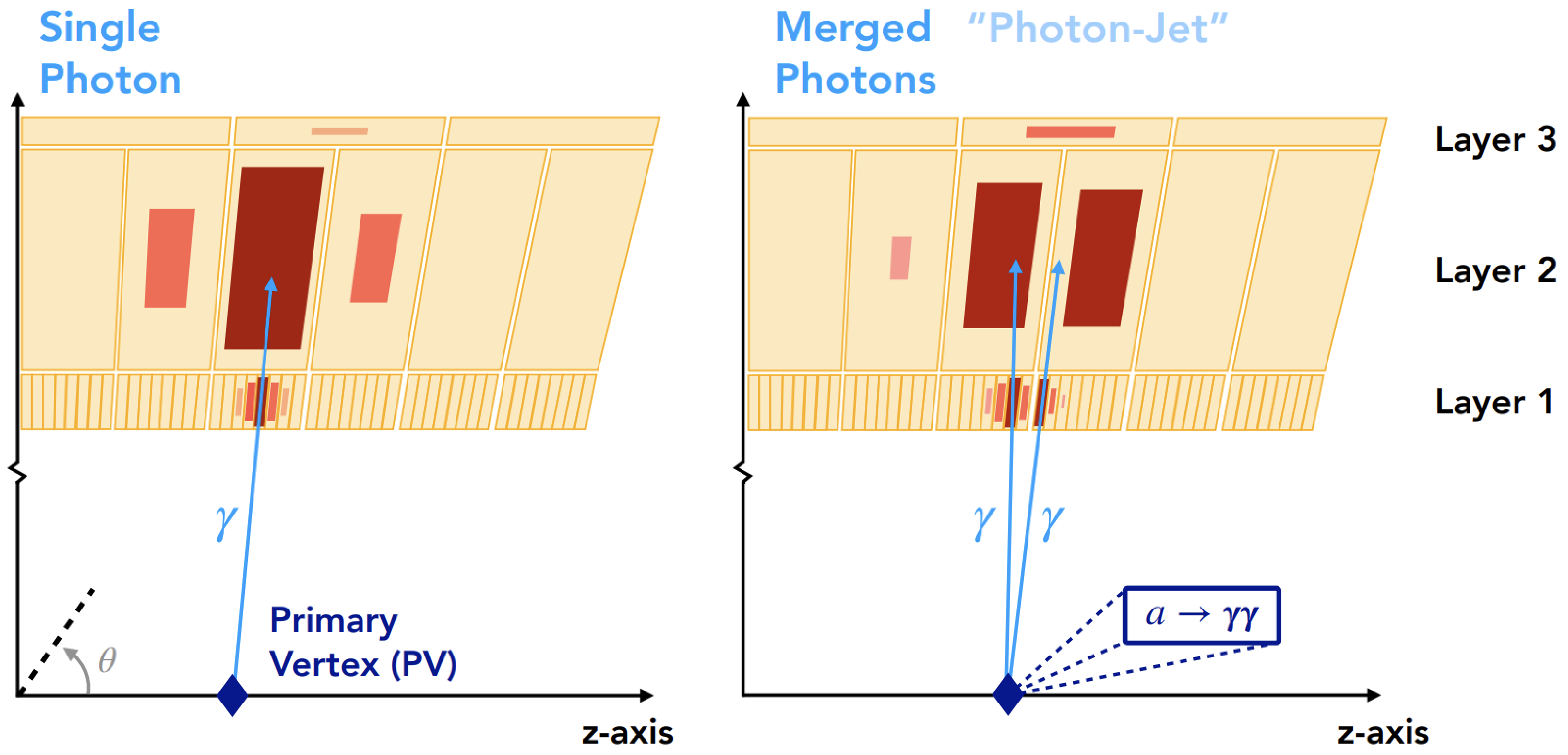
- The EM Calorimeter surrounds the inner detector
- 3 layers, just under 200,000 cells
- Measures energy of electrons and photons in each cell

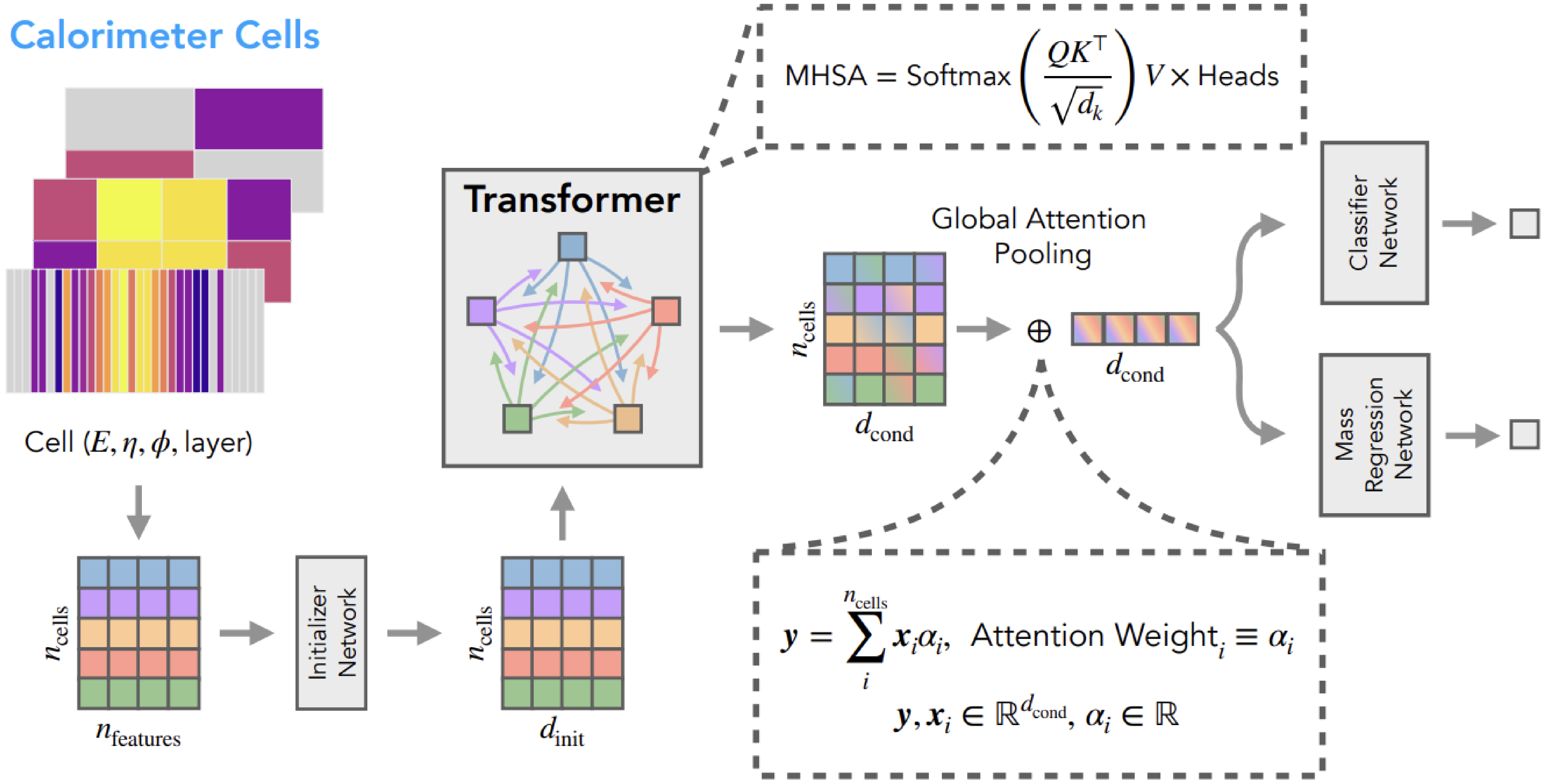




The Transformer

- Diphoton decay is highly collimated, so is difficult to distinguish from a single photon
- Created a machine learning (ML) model – a Transformer – to determine whether an object looks like ALP signal or not
- Takes cell level input and assigns events a score from 0 (background-like) to 1 (signal-like)





arXiv:2607.08175 [hep-ph]

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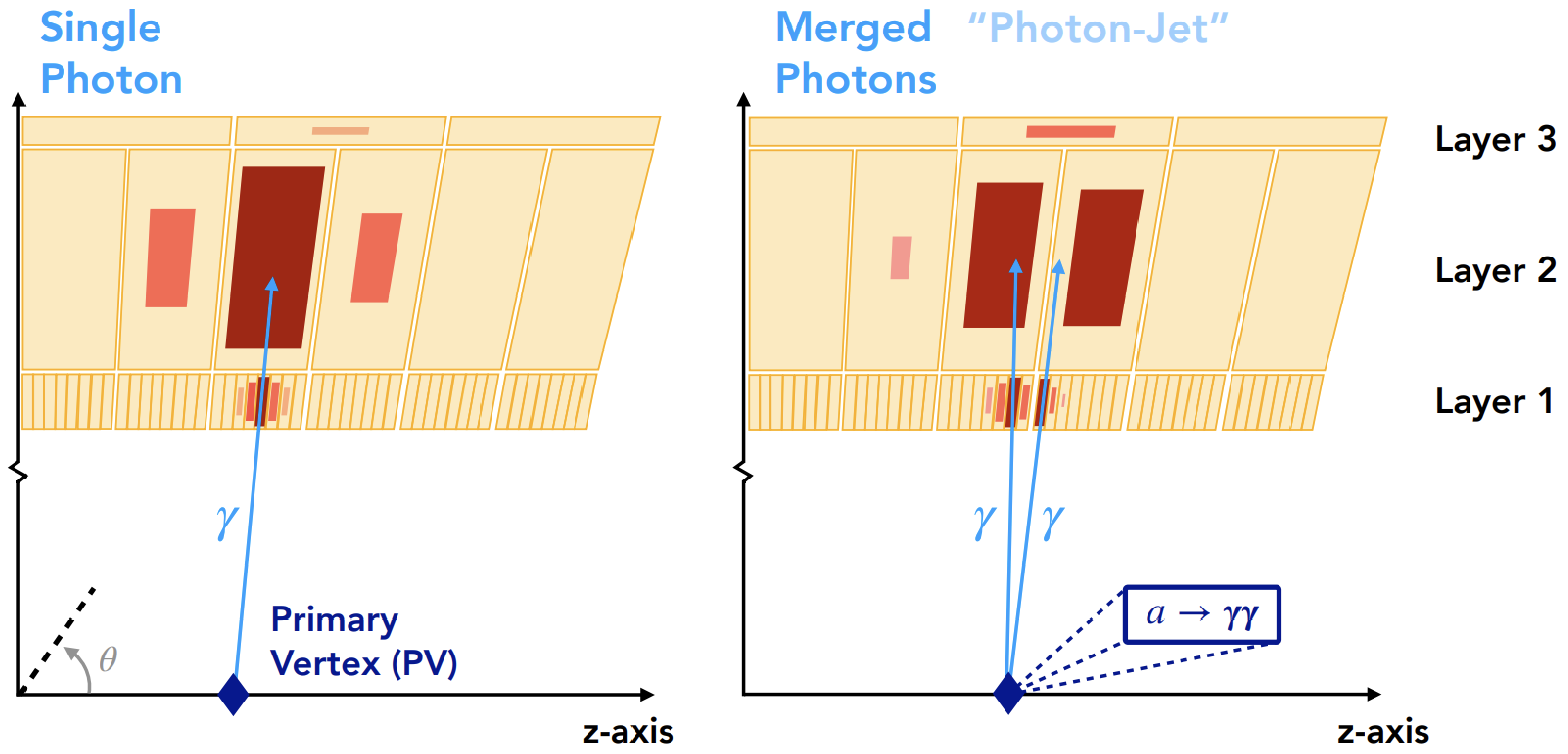

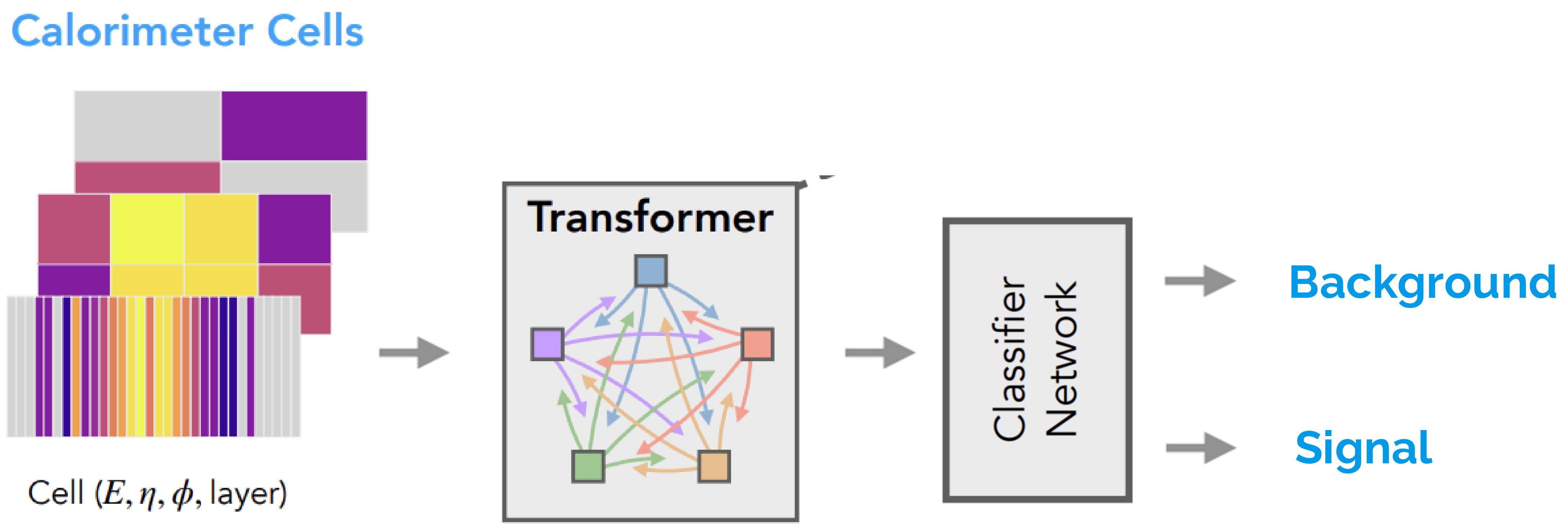

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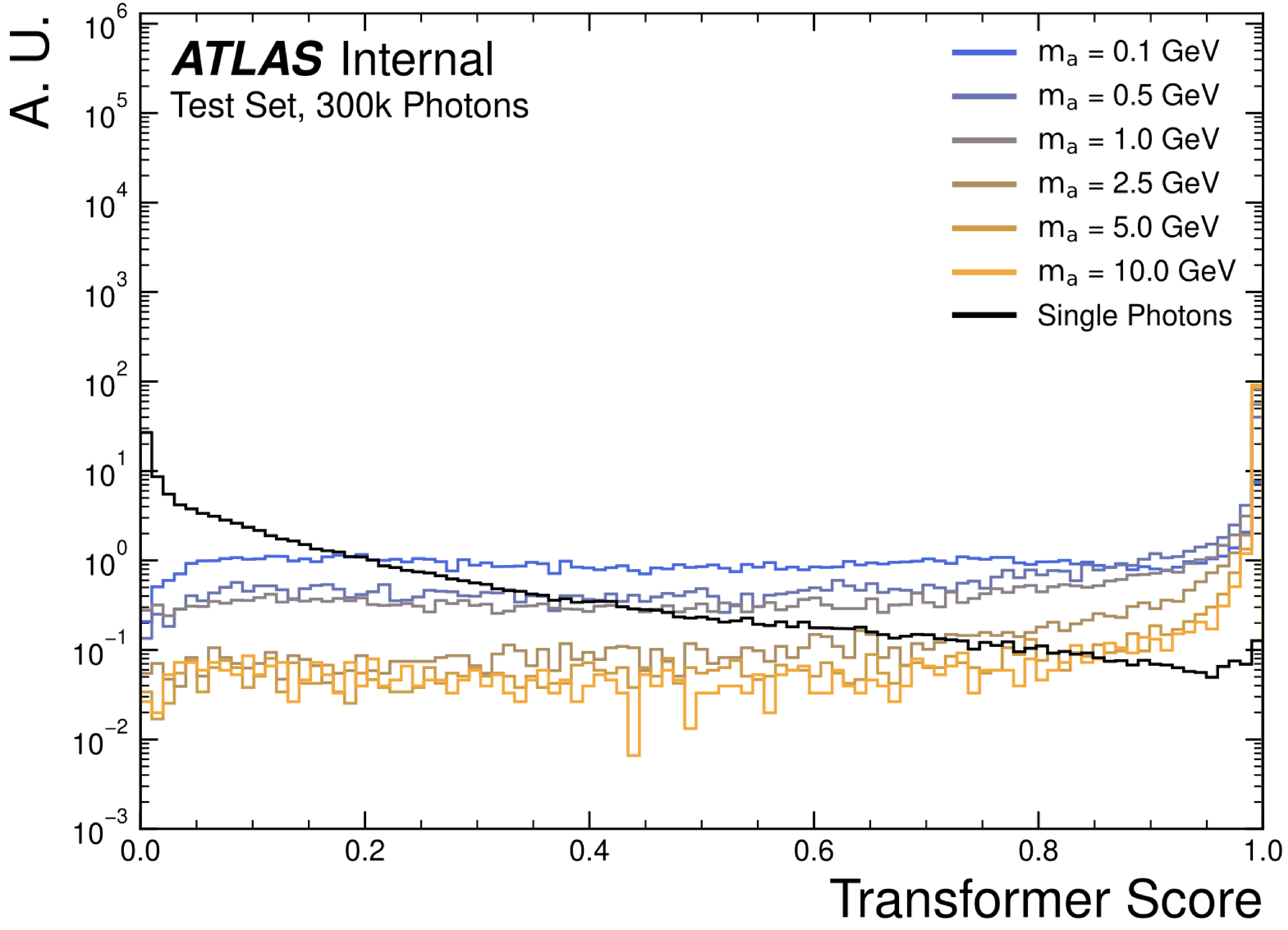
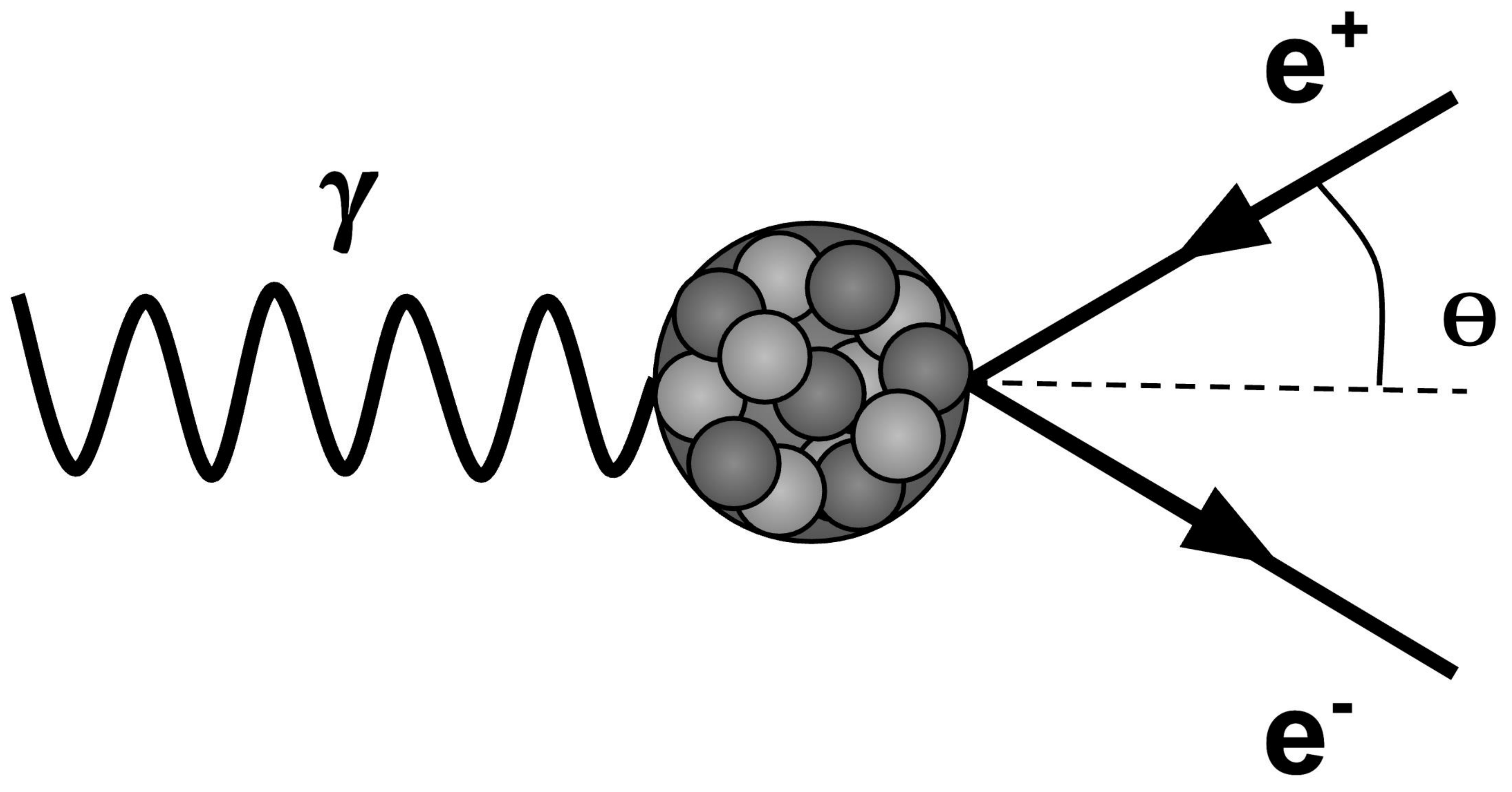
Transformer Scores from Training

- Black line is single photons – this is background
- Blue through yellow lines indicate different ALP masses from Monte Carlo (simulated data) – this is signal
- Can see that the sample ALP masses peak more at 1 and less at 0, where the background single photons peak more at 0.



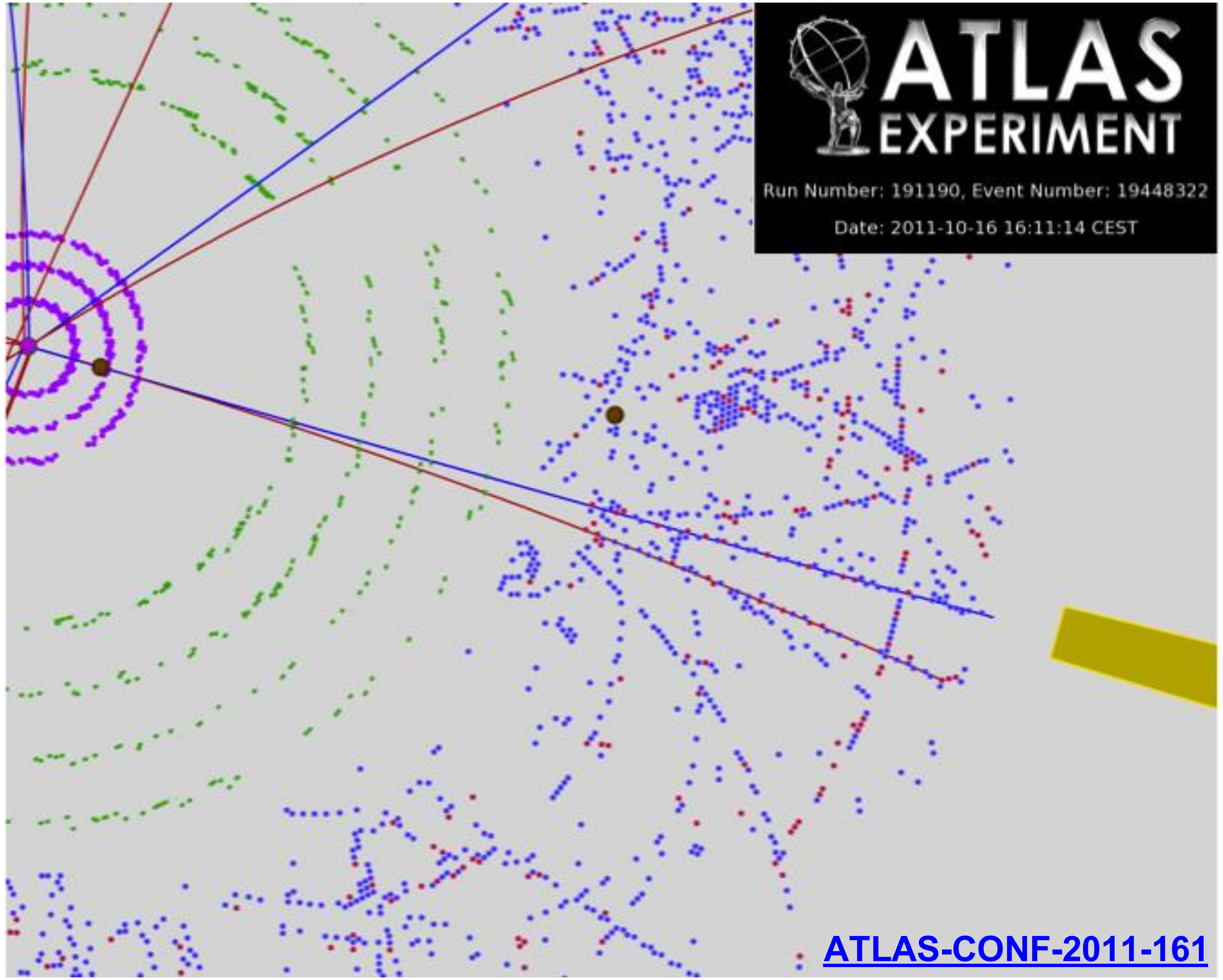
Converted Photons

- Working to validate the transformer in data by looking at converted photons as background
- When photon contacts material in detector can convert into electron-positron pair
- Only happens in presence of material (must preserve conservation of energy and momentum)
- Photon conversion looks like diphoton ALP decay signal (highly collimated), can check how transformer treats these events
- Using Run 3 data from 2022
  - Requiring **exactly one photon** to avoid signal-like events and preserve blindness



Converted Photons ATLAS Event Displays

- Shows path of the two tracks through the inner detector
  - The track of the electron is in blue, the track of the positron is in red
- Brown dot indicates vertex of conversion



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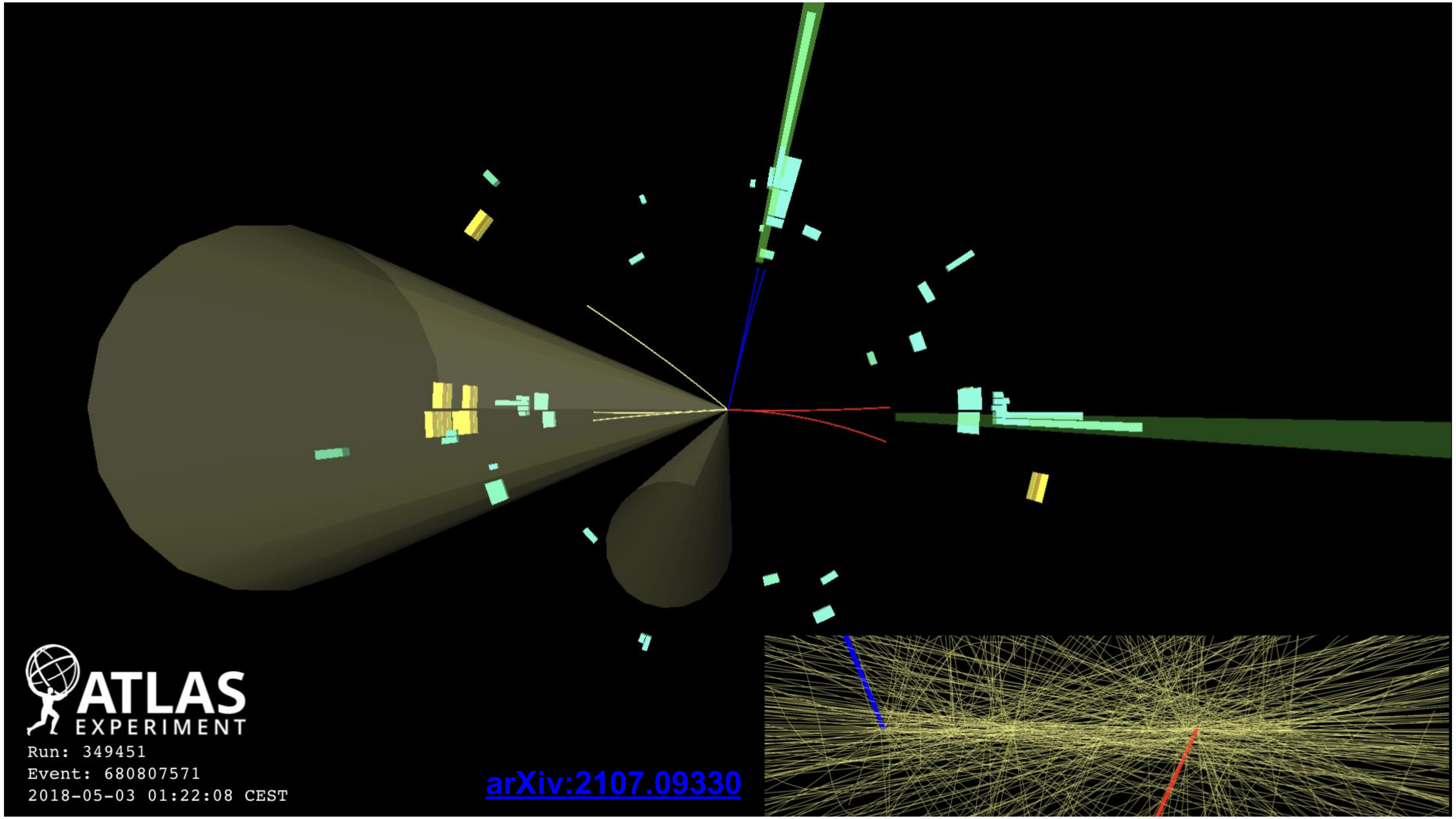
Converted Photons ATLAS Event Displays

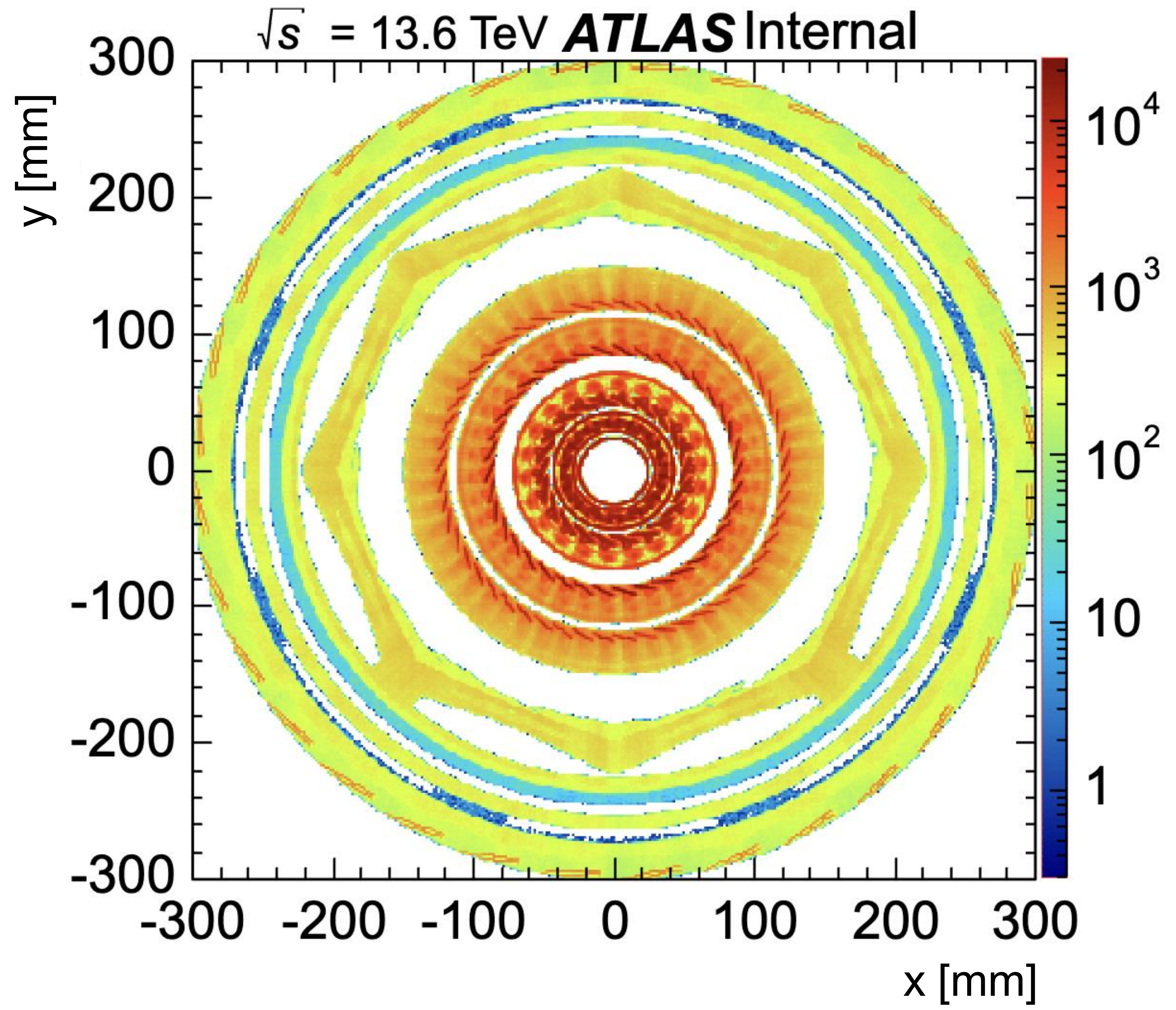
- 2 converted photons pictured
- The photons indicated by the transparent green bands
- Both photons converted in the SCT

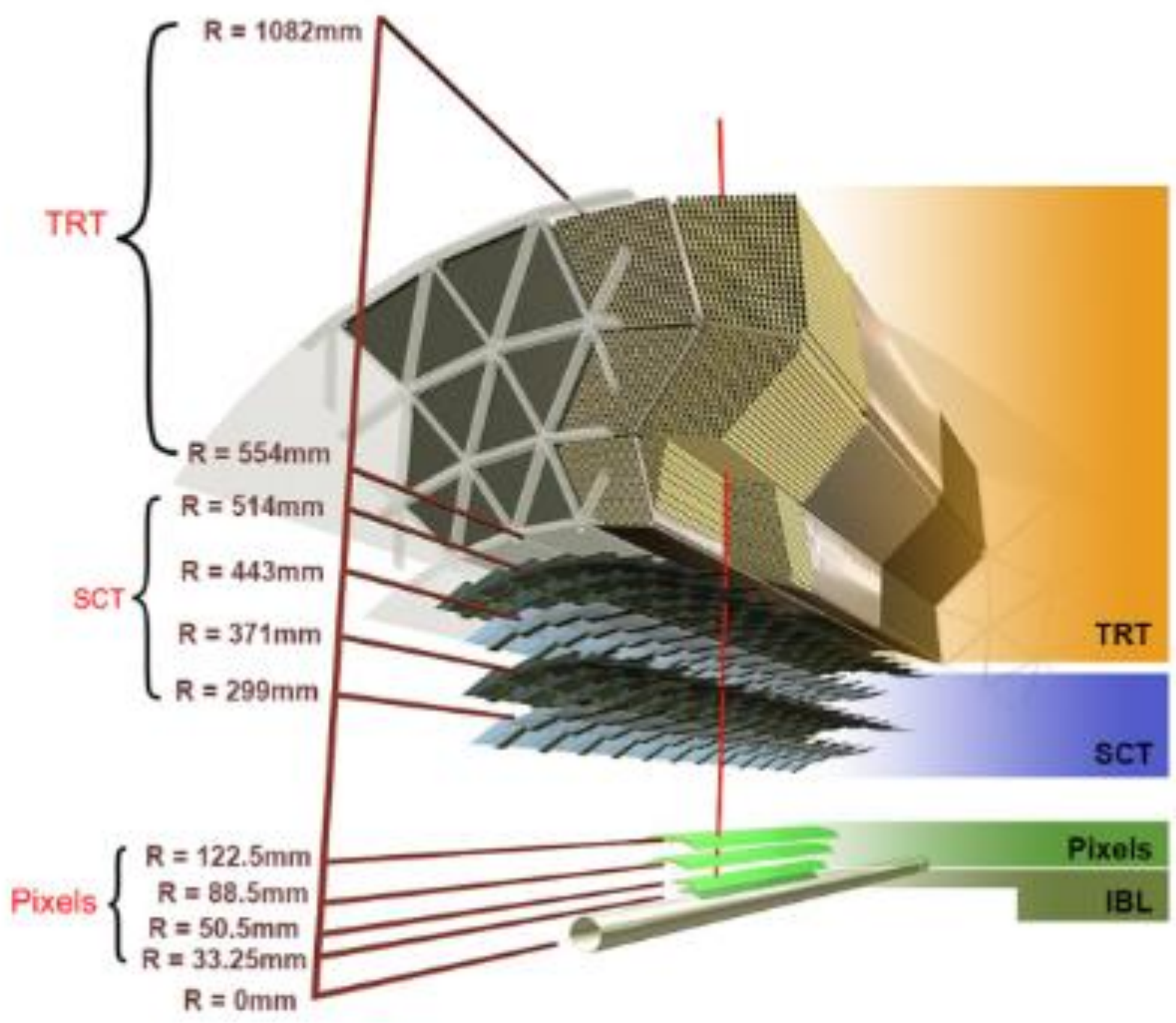


Study on Converted Photons as Background to ALP Signal

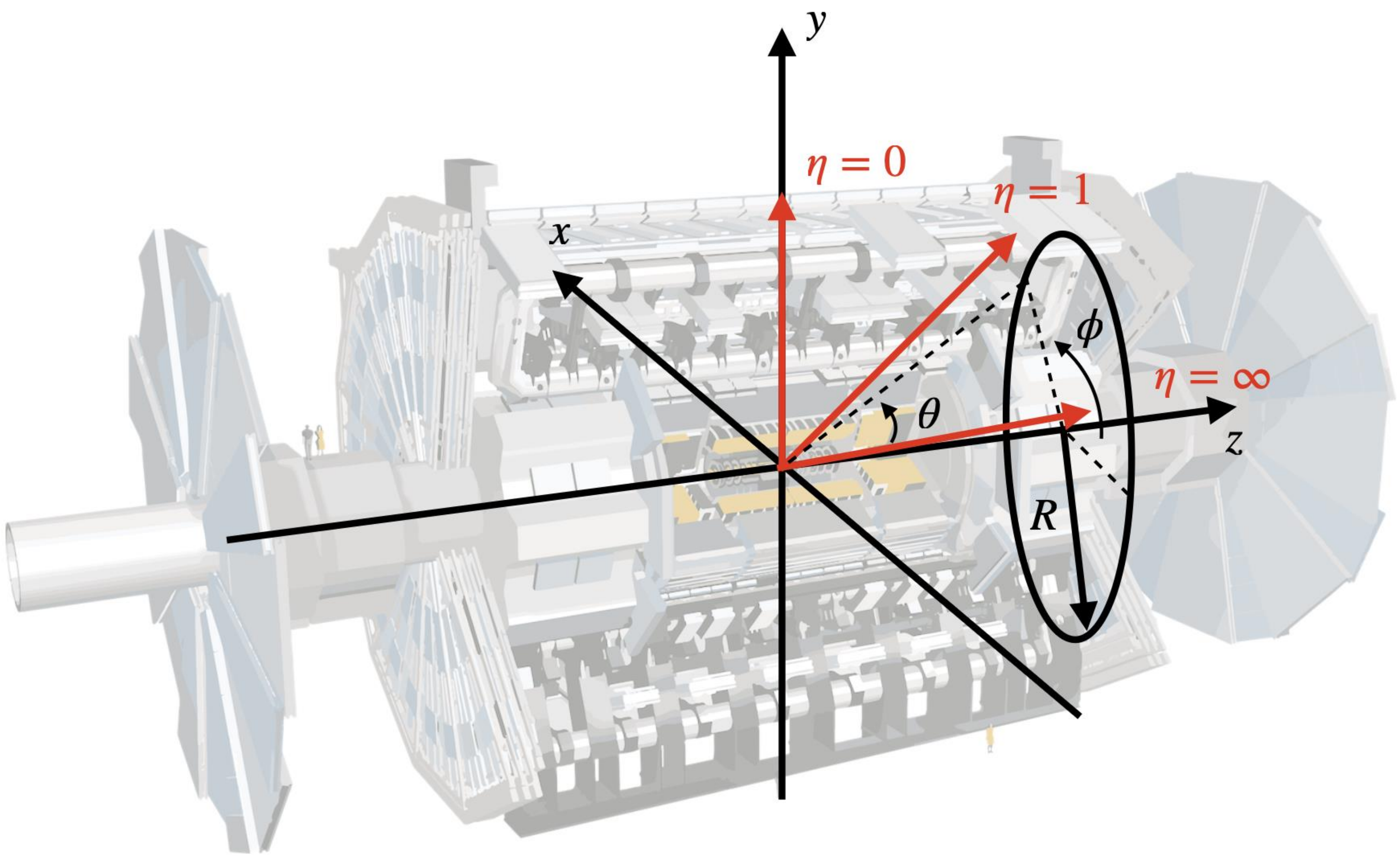
Mapping Conversion Vertices

- By mapping the vertices of these events, we can verify these are converted photons because we essentially see a map of the inner detector!





Kinematic Variables

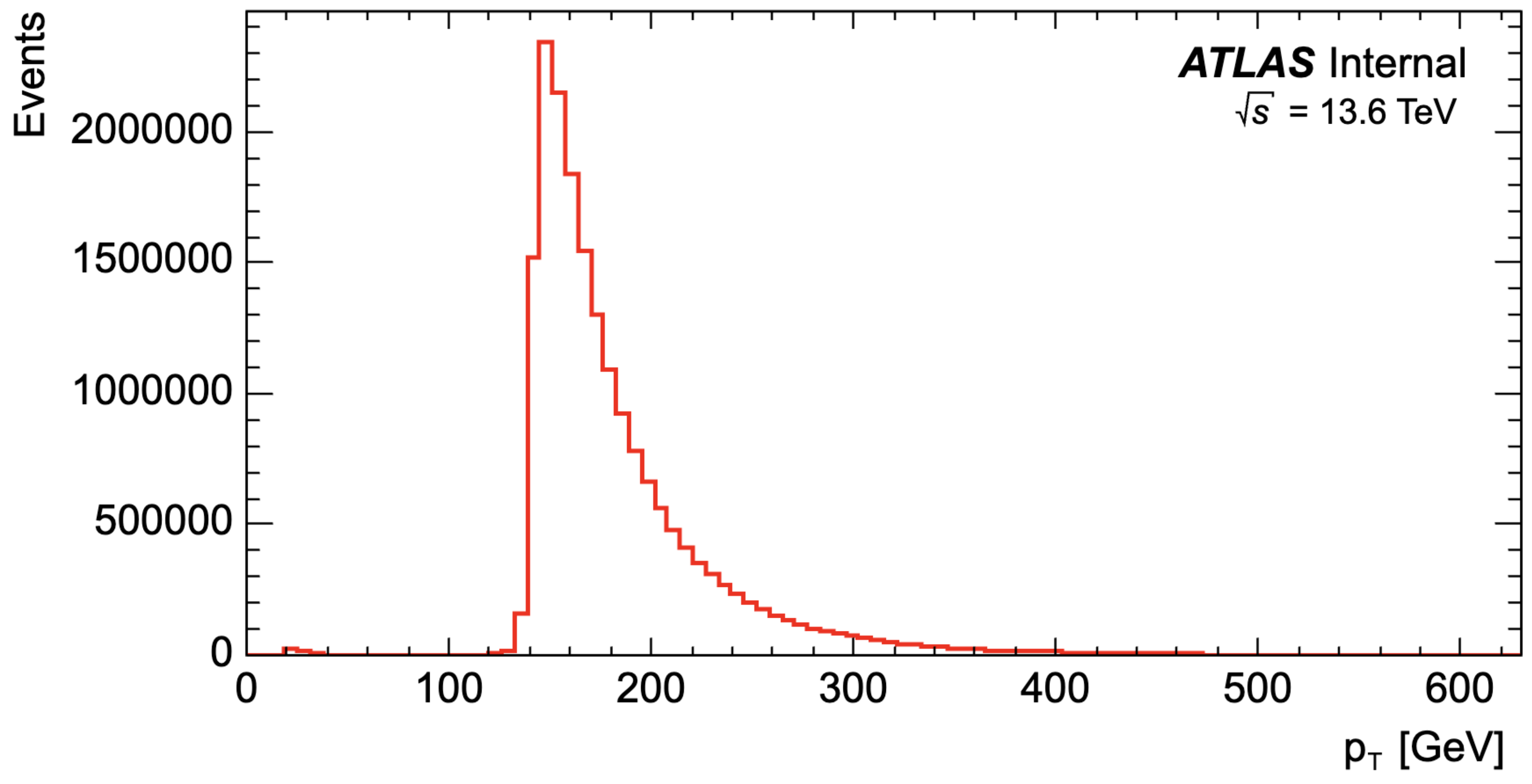


- p_T: transverse momentum
- η (pseudorapidity): tilt from the x-y plane
  $\eta \equiv -\ln\left(\tan\left(\frac{\theta}{2}\right)\right)$
- ϕ: azimuthal angle

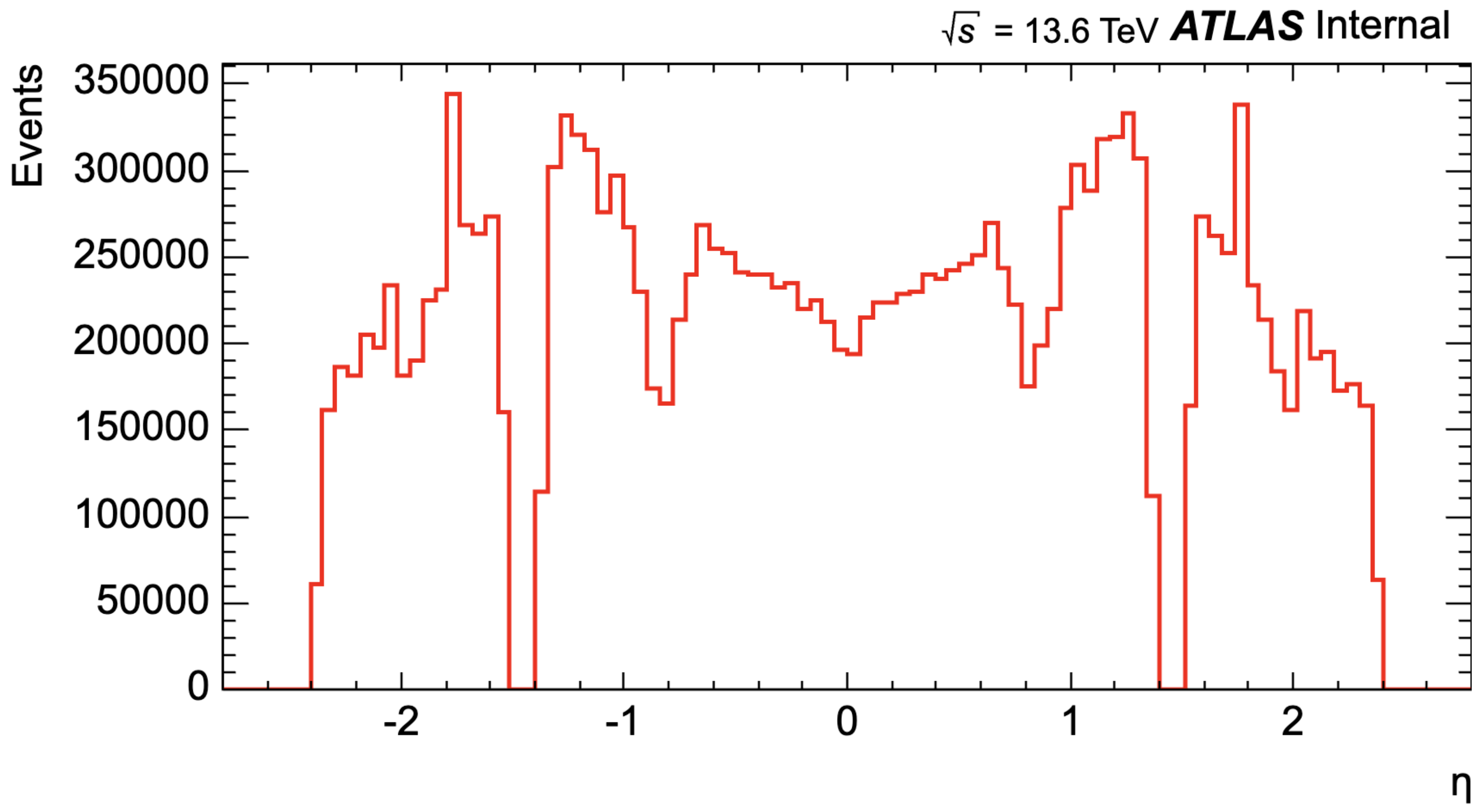
Kinematic Distributions of Events

- Kinematic plots for p_T, η and ϕ
- For single converted photons only from data collected in 2022
- Trigger matched to the g_140_loose trigger
- Only isolated events

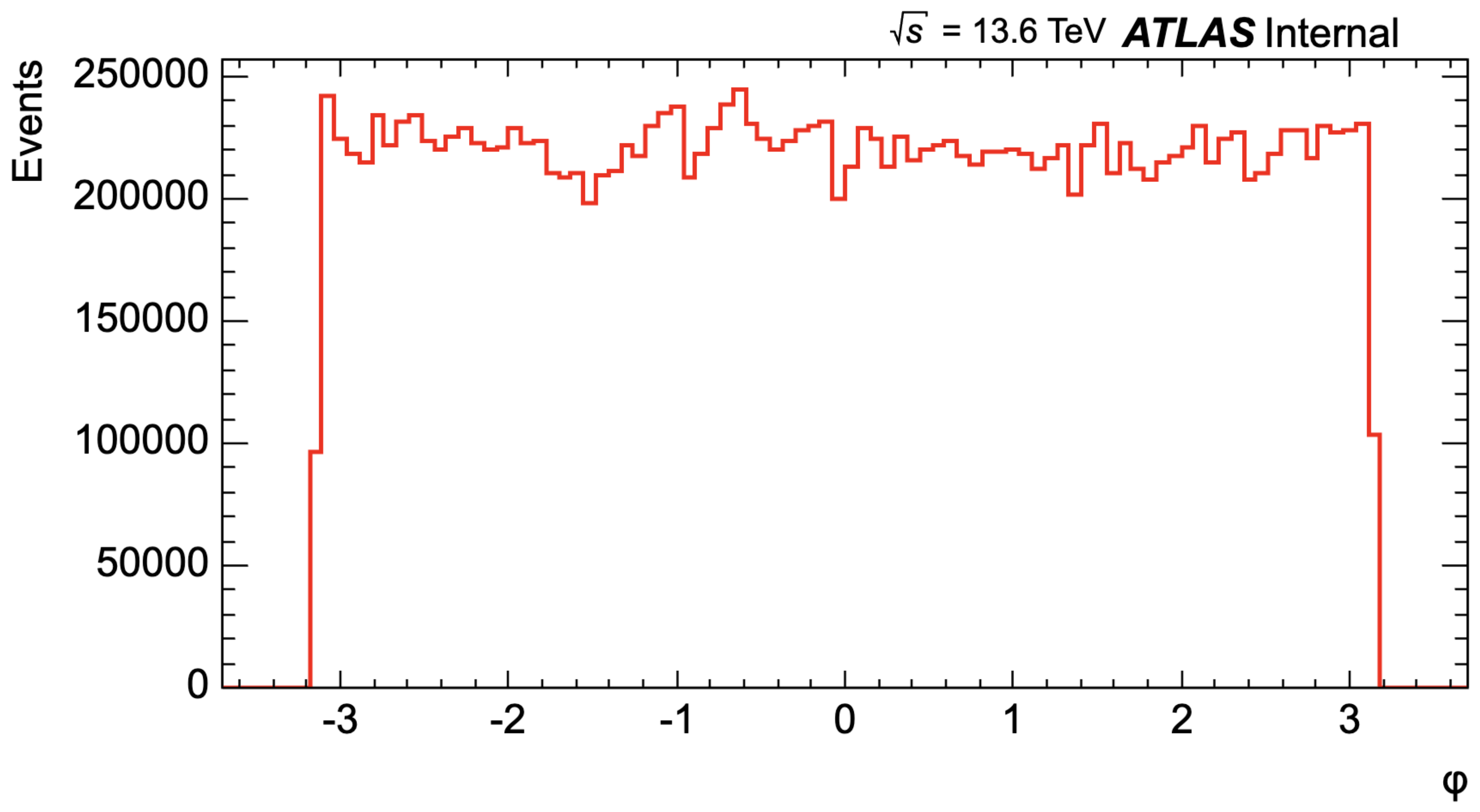
Converted Photons p_T



Converted Photons η

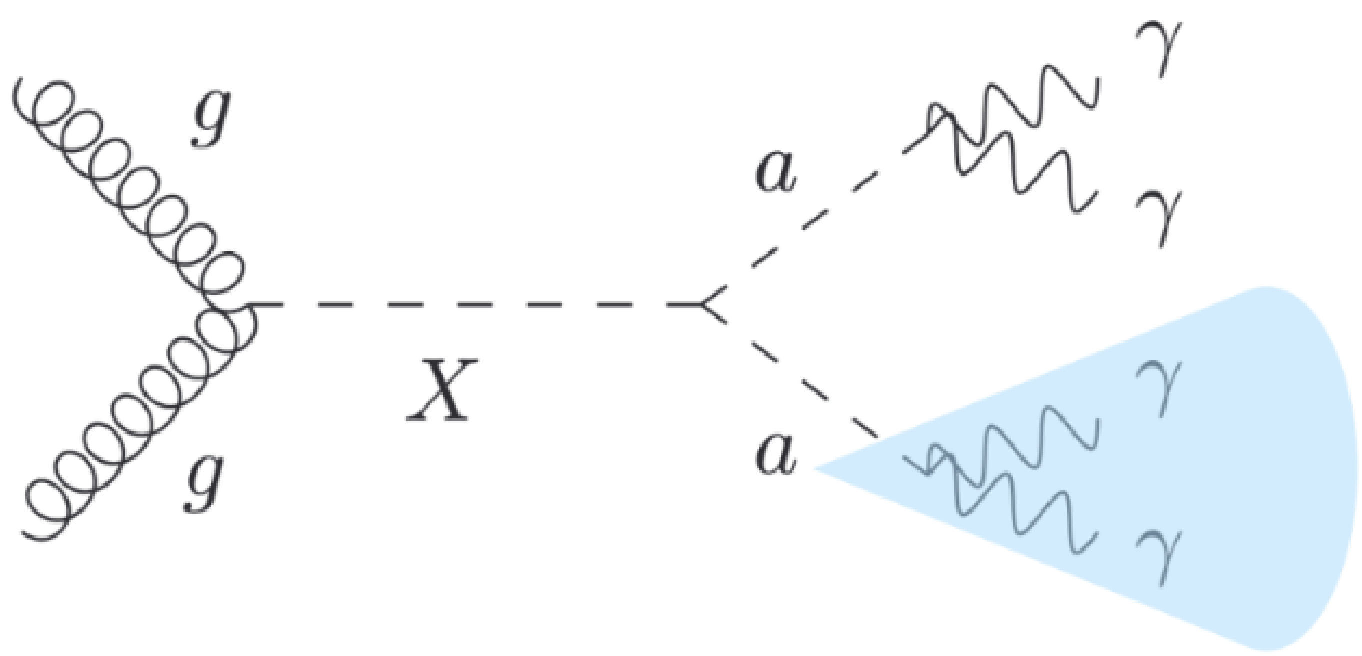


Converted Photons ϕ

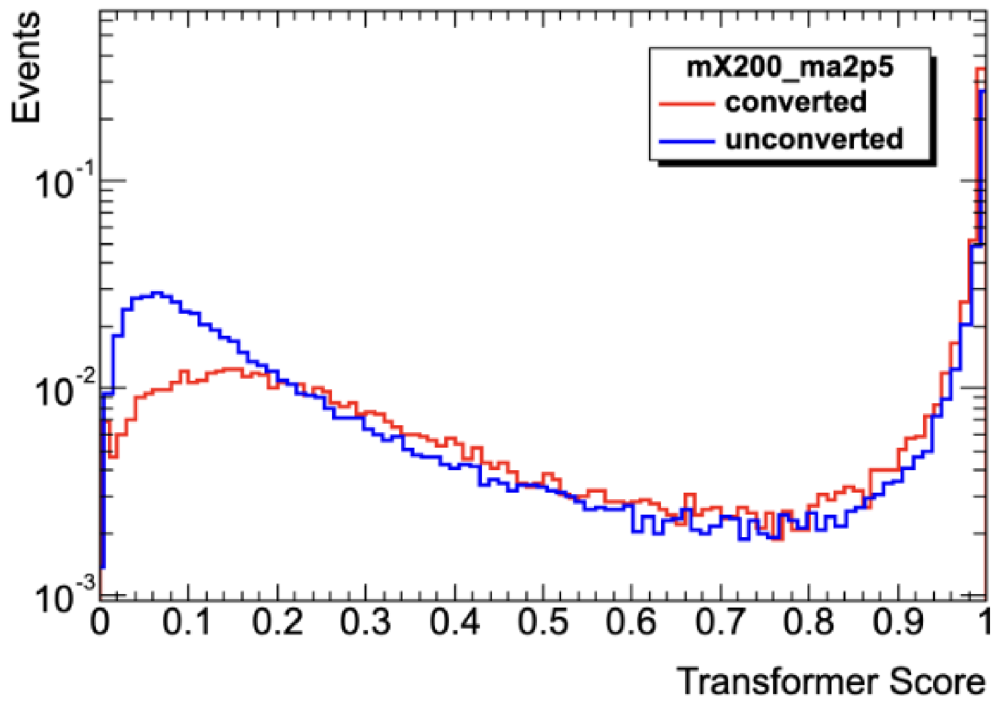


Transformer Scores – MC Signal Sample

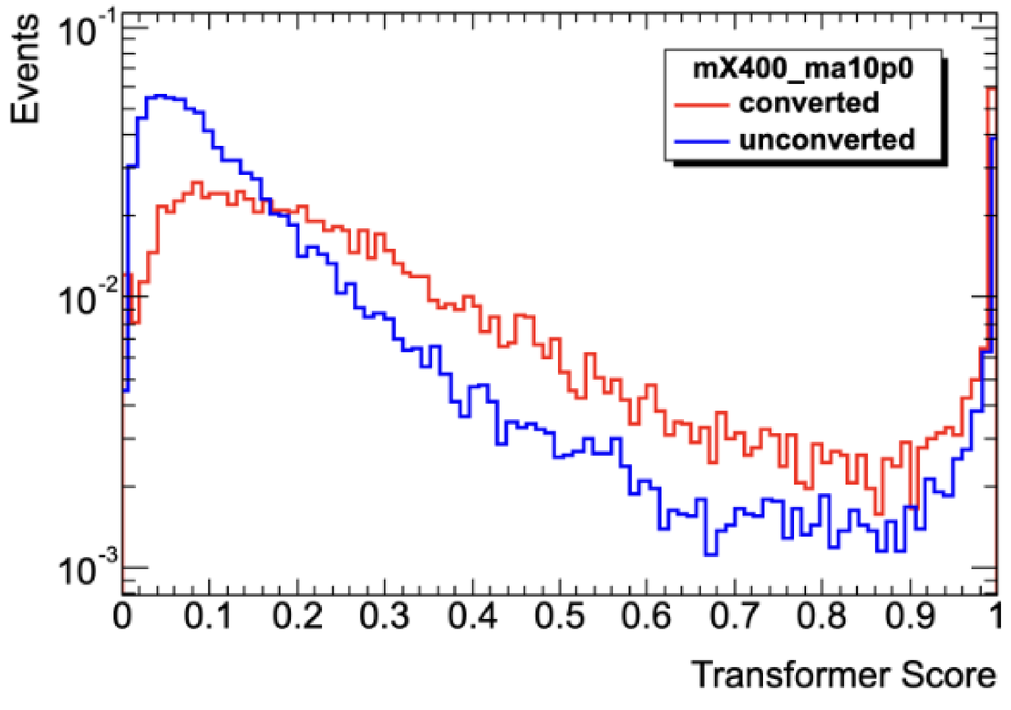
- Transformer scores for the converted and unconverted photons of different Monte Carlo signal sample – different possible mass pairings
    - From pair of collimated photons produced by a scalar parent particle
- Generally, converted photons look more signal like than unconverted photons (as expected theoretically)



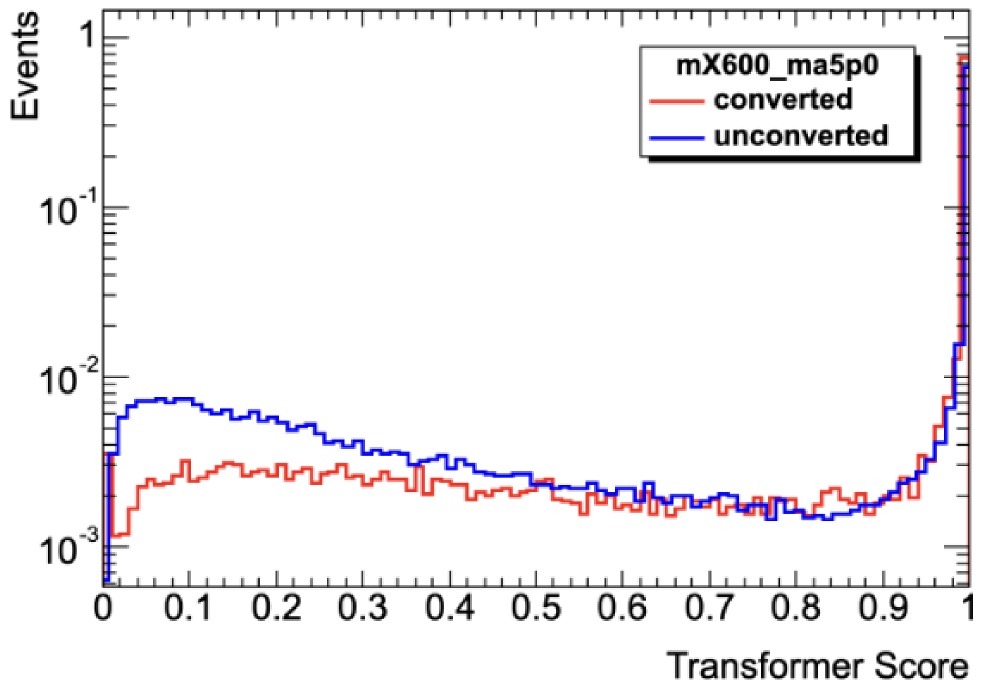
X: 200 GeV, a: 2.5 GeV



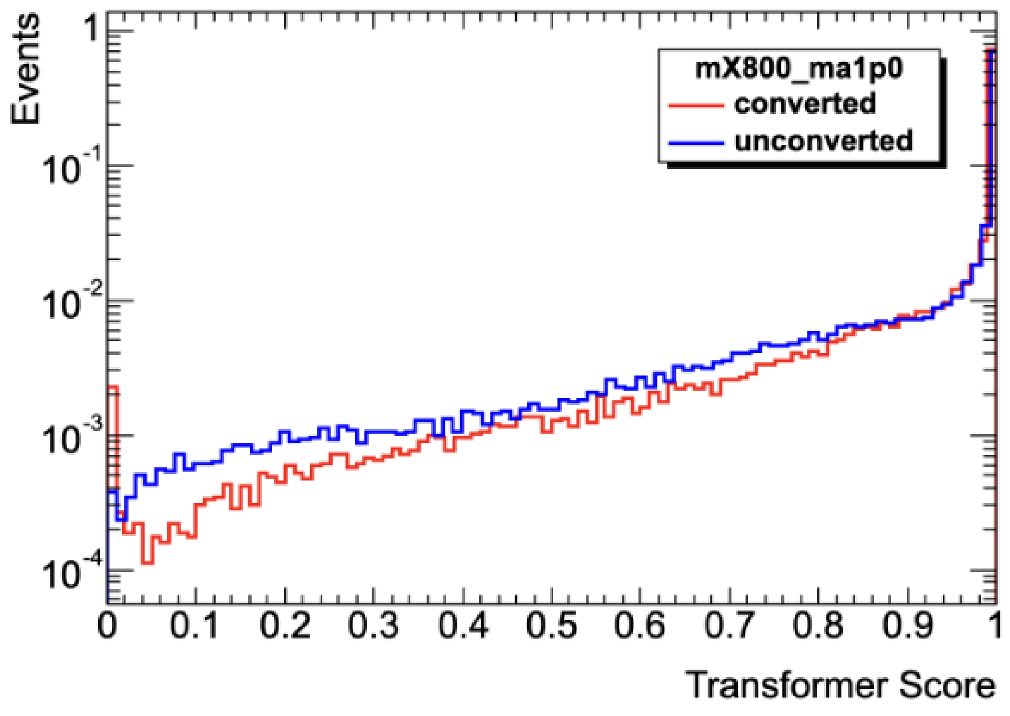
X: 400 GeV, a: 10.0 GeV



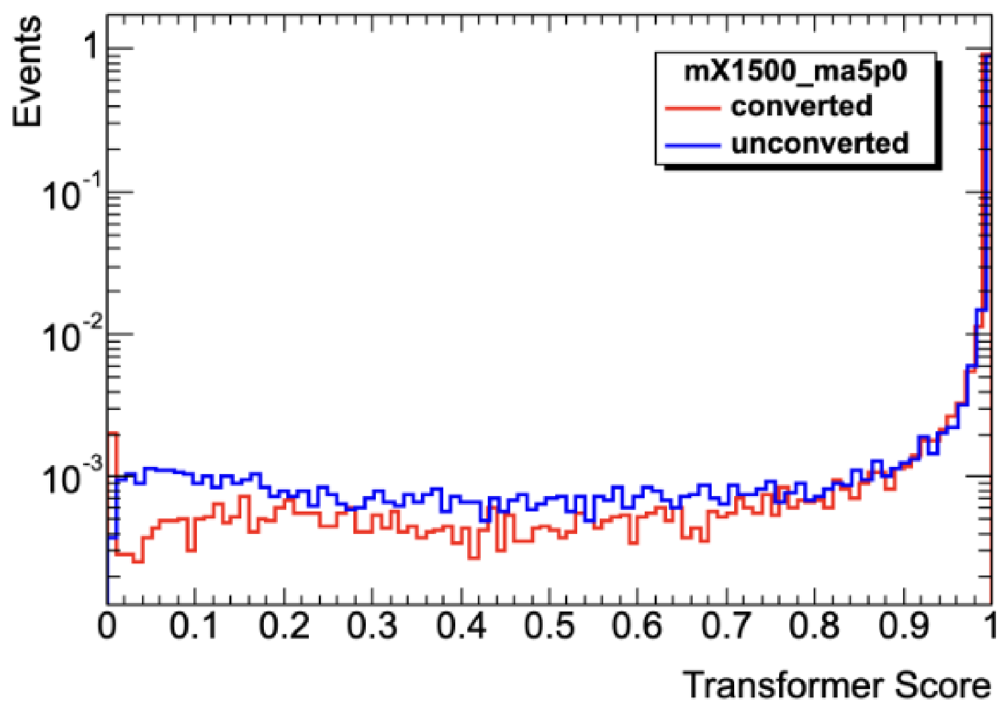
X: 600 GeV, a: 5.0 GeV



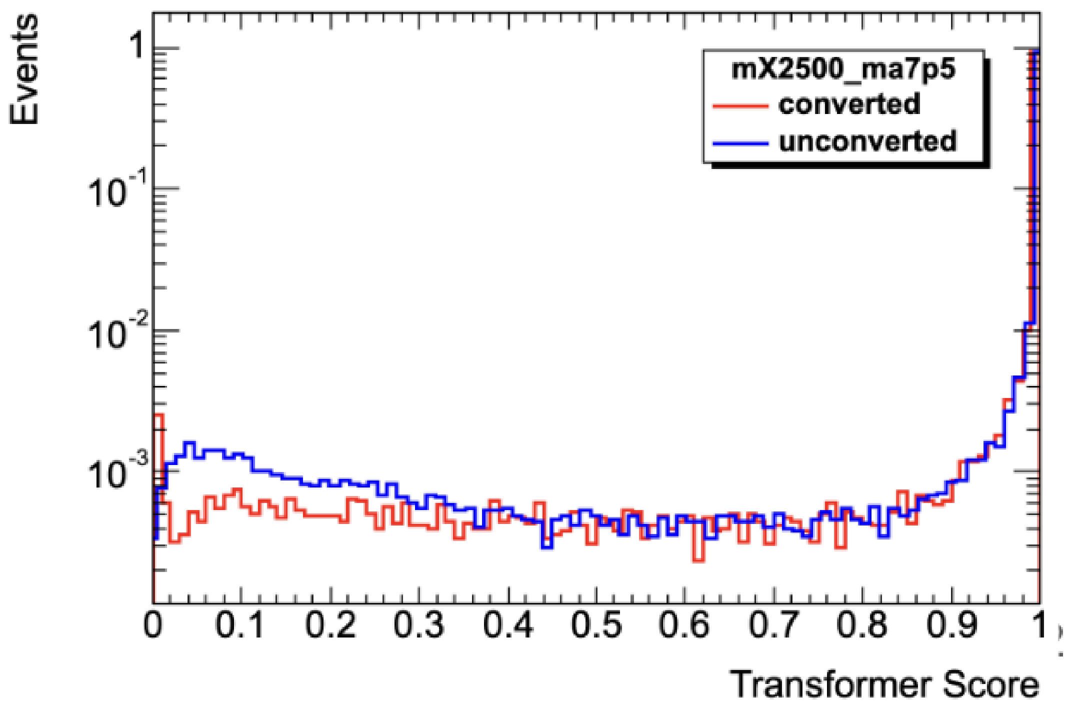
X: 800 GeV, a: 1.0 GeV



X: 1500 GeV, a: 5.0 GeV



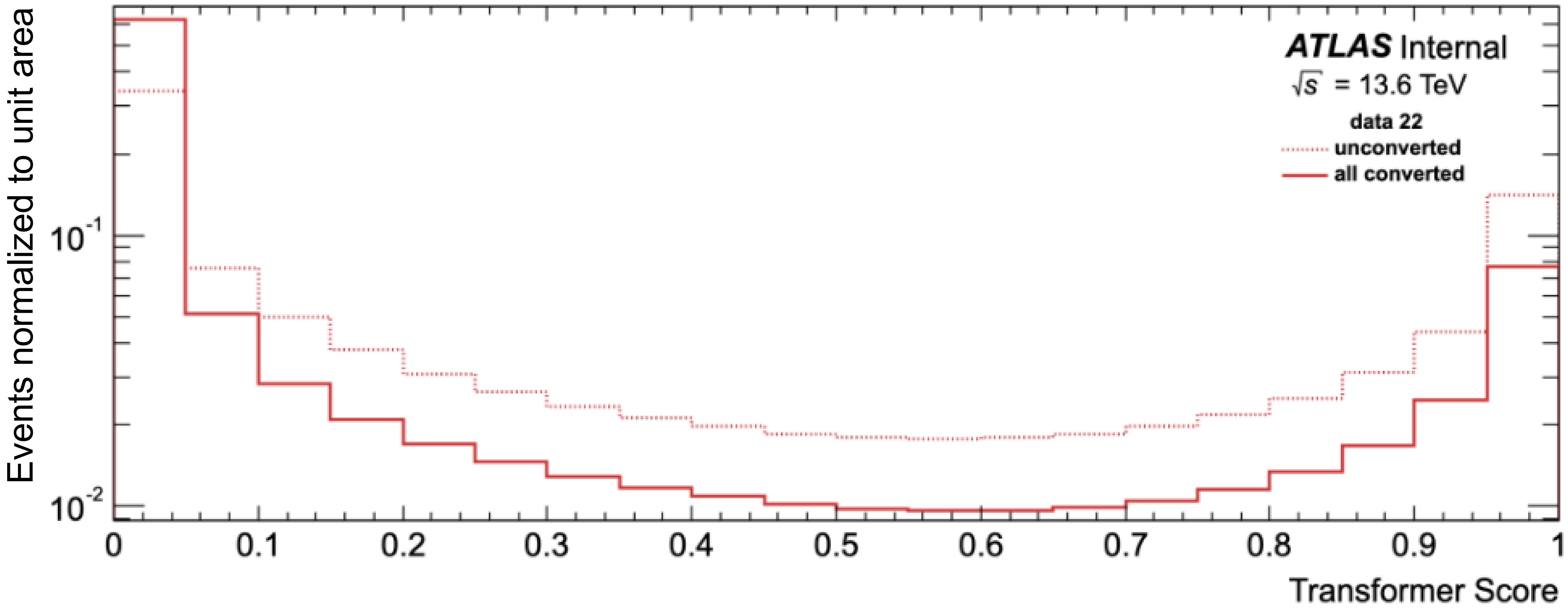
X: 2500 GeV, a: 7.5 GeV



Transformer Scores – Converted and Unconverted

- Transformer scores for unconverted and converted photons from data from 2022
  - With cuts so that the photon is isolated, trigger matched, and there is only one photon
  - Also cuts on η such that |η| < 2.37 and p_T at 20 GeV

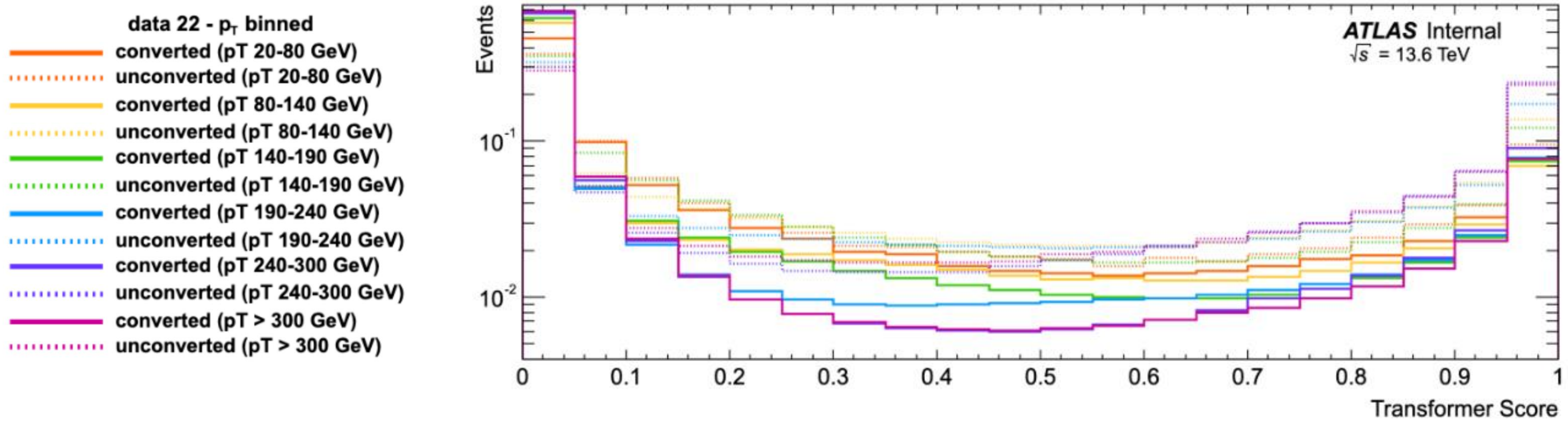
- We see the converted photons look a lot more like background than the unconverted photons – not what we had expected from the transformer!



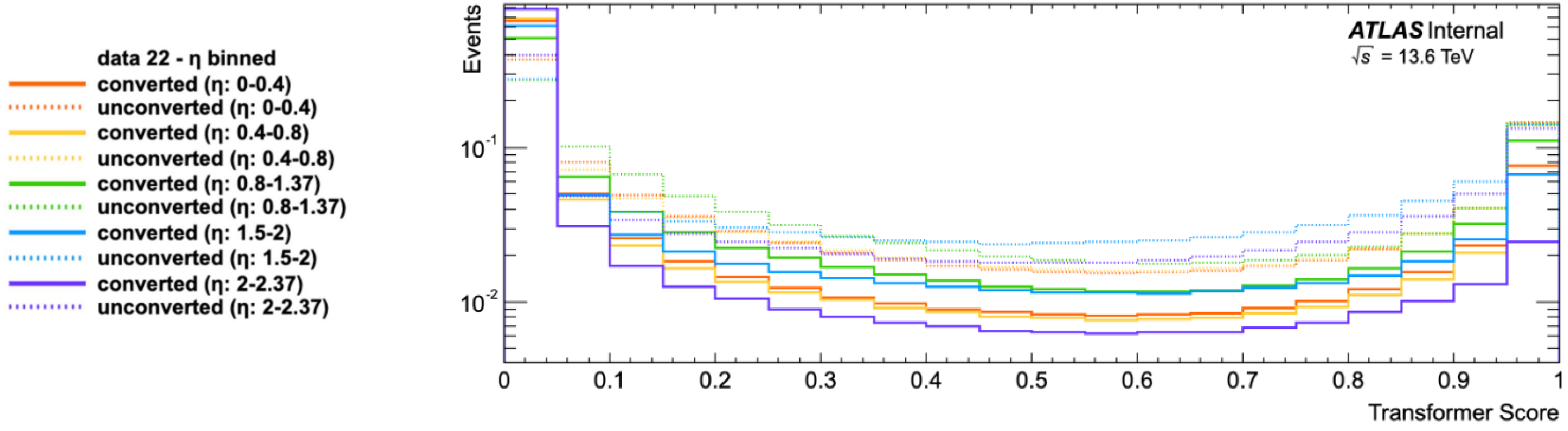
Binning by Kinematic Variables

- To the right are transformer scores from data binned by p_T, η and ϕ
- "Binned" meaning events are grouped into slices of each variable, which shows if there is some variation based on that variable
- The ϕ binning has no variation across bins (expected), but the p_T and η variation is significant

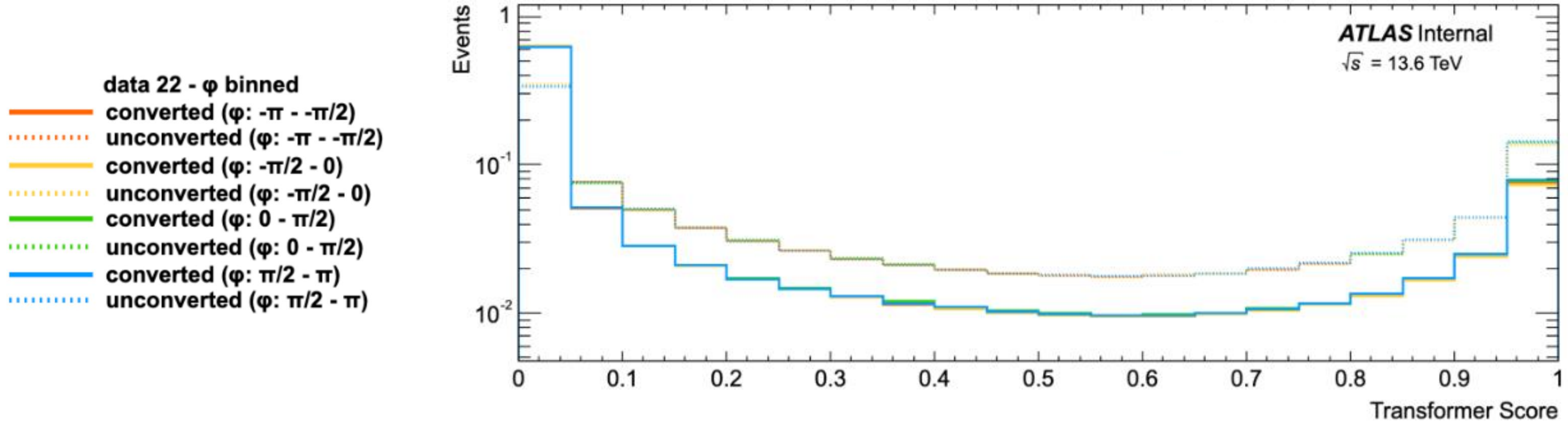
p_T binned Transformer Scores



η binned Transformer Scores

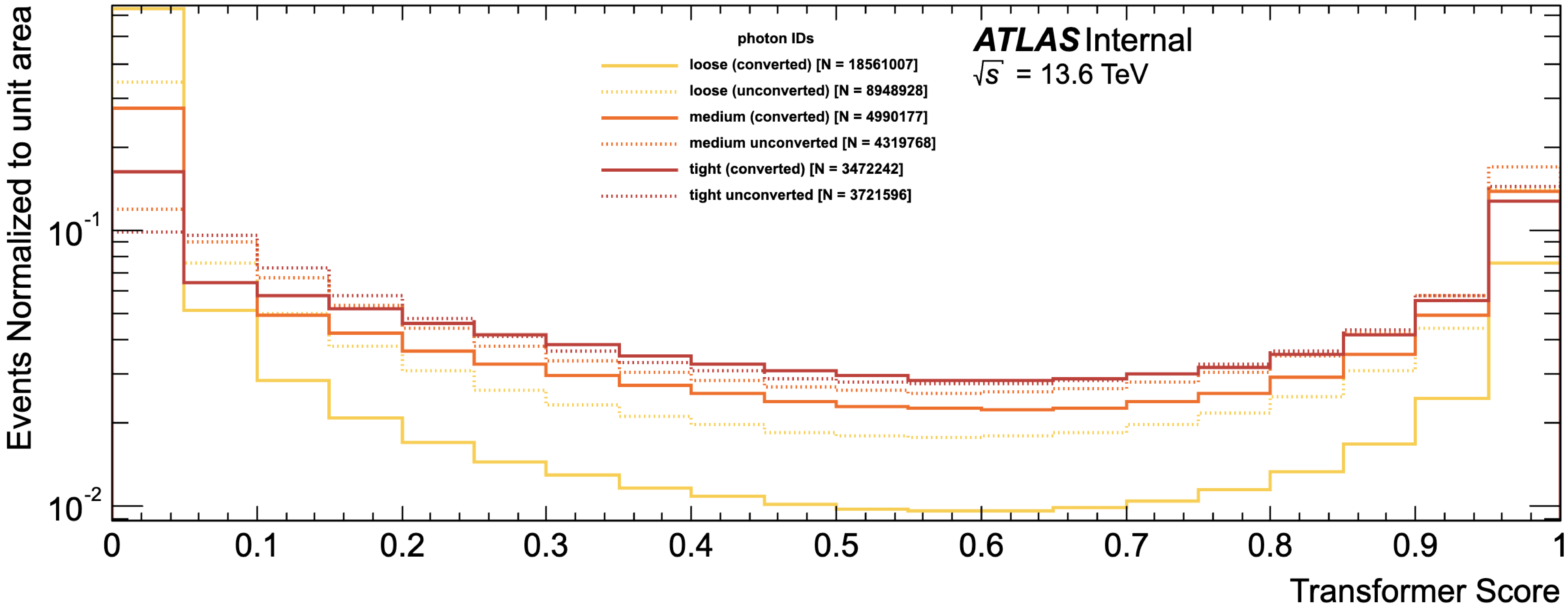


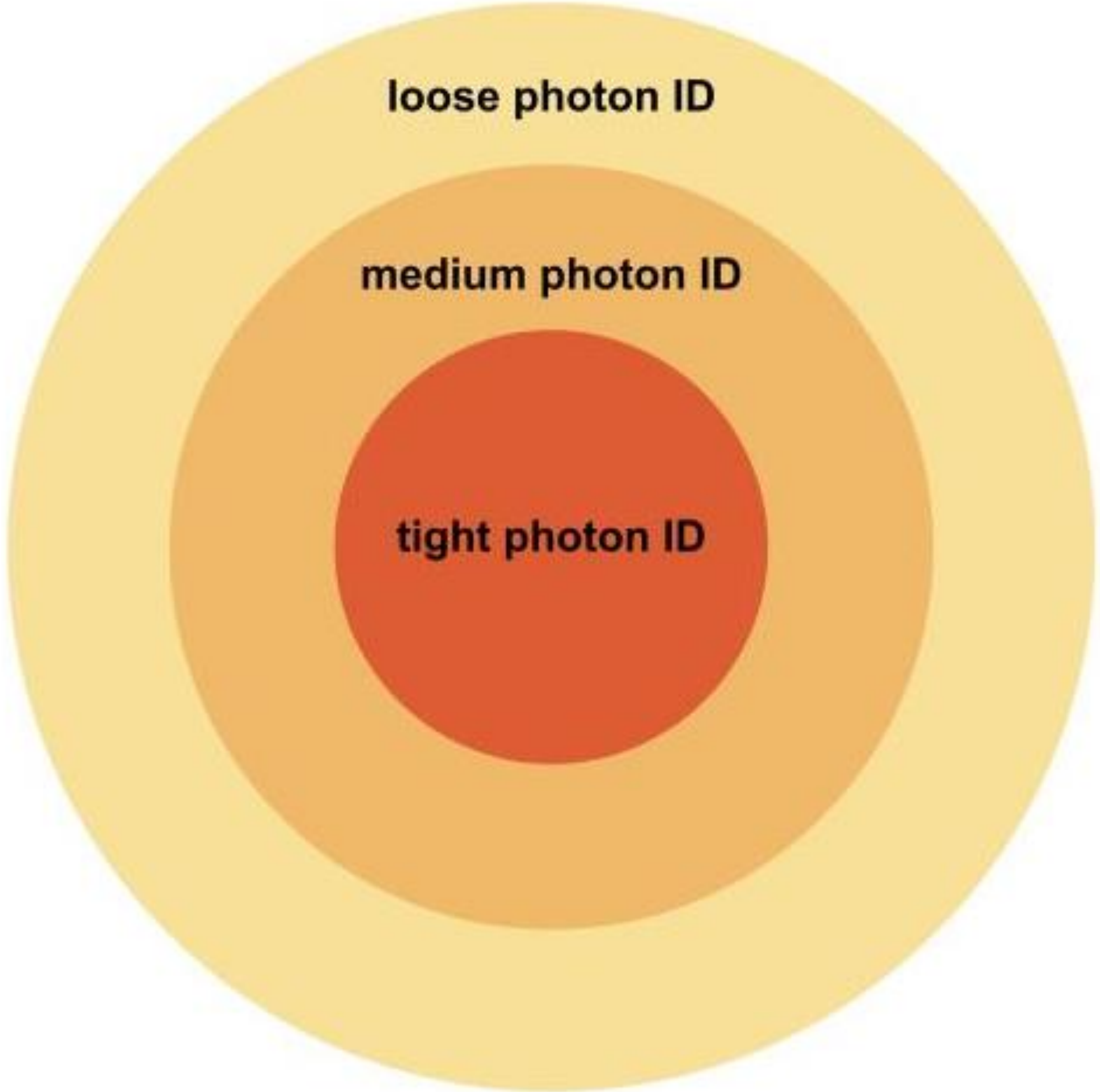
ϕ binned Transformer Scores



Transformer Scores – Photon Identifications

- Also able to apply photon IDs: Loose is least strict, tight is most strict
- But, what we see here is that actually with these medium and tight flags, the photons are looking *more* like signal and less like background.





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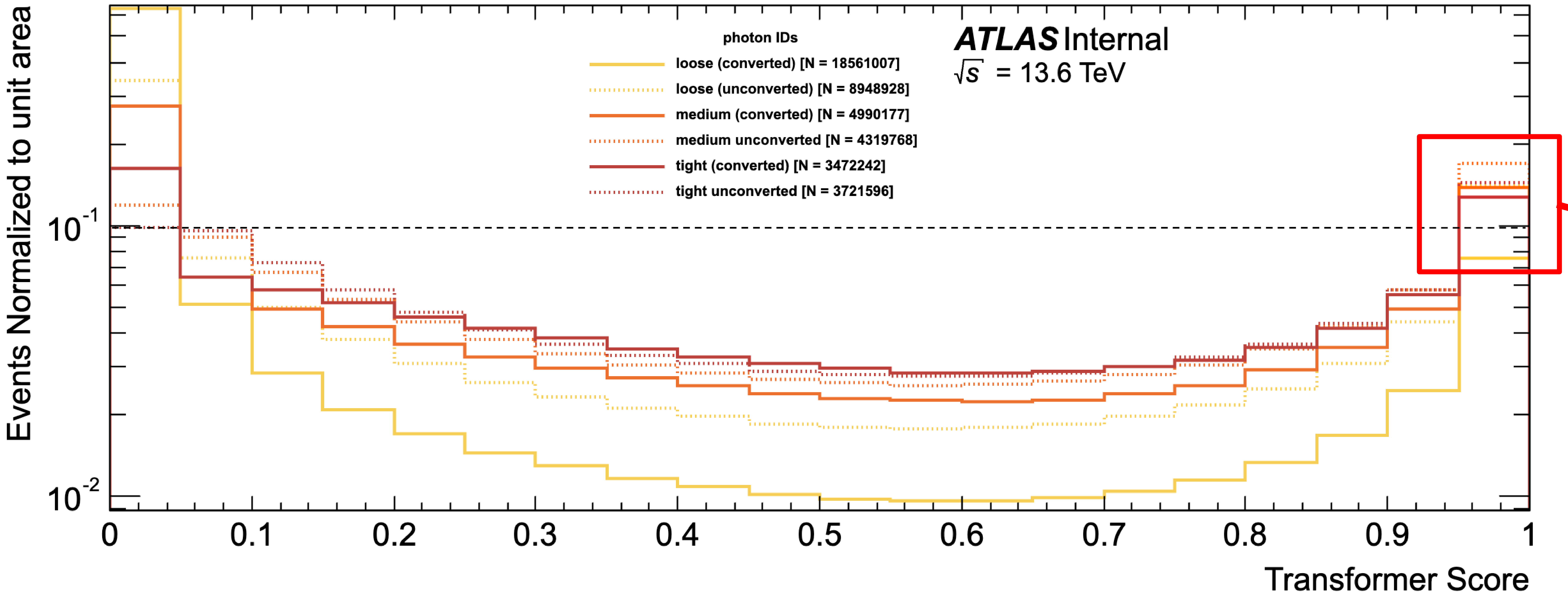
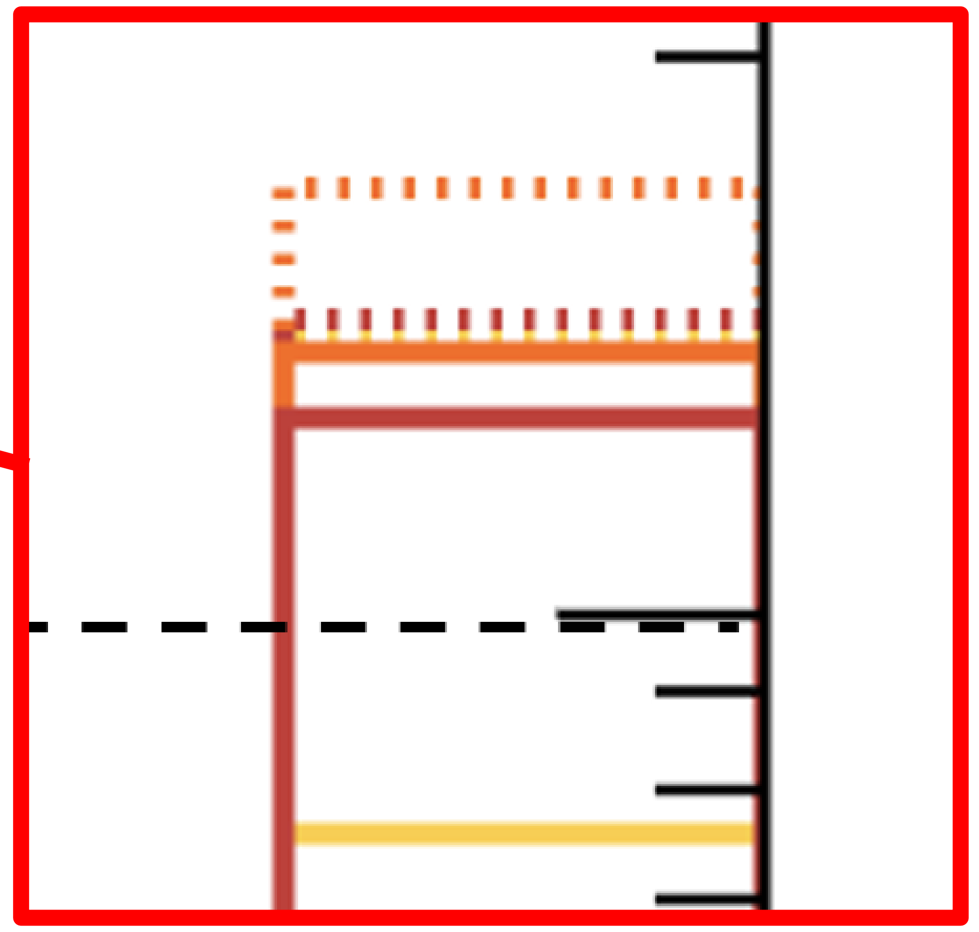
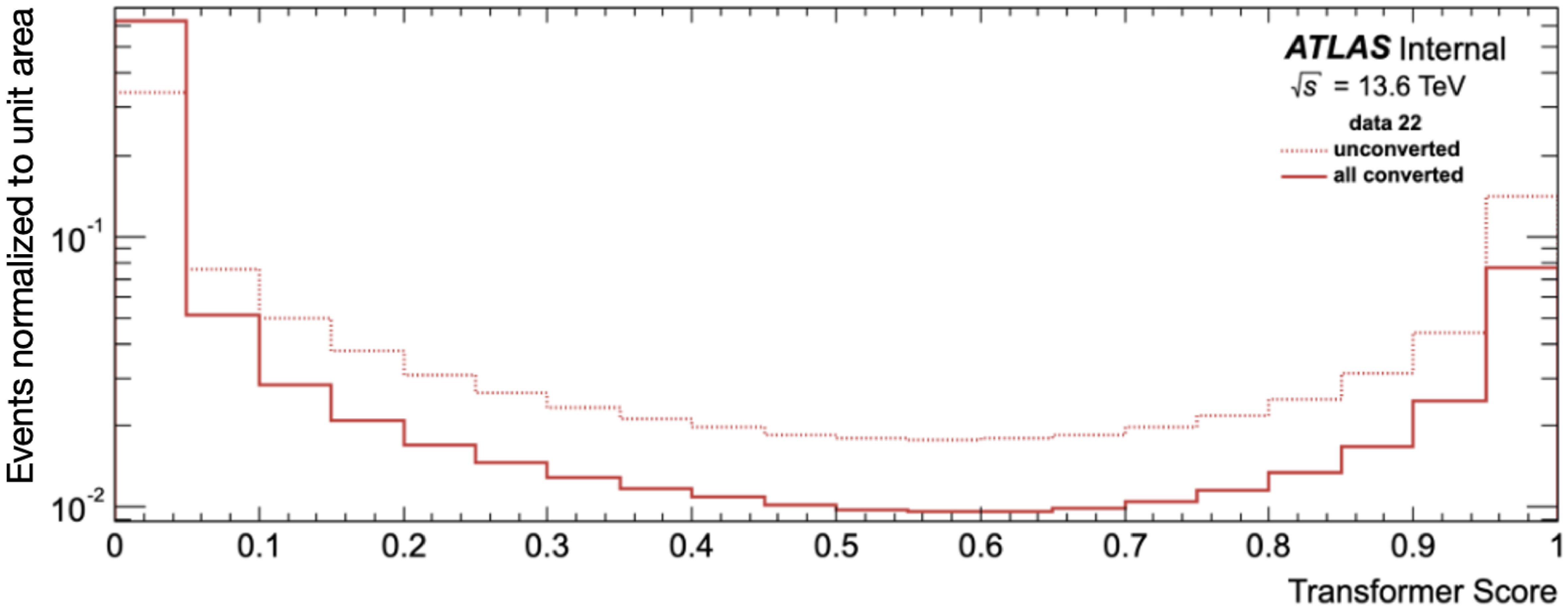
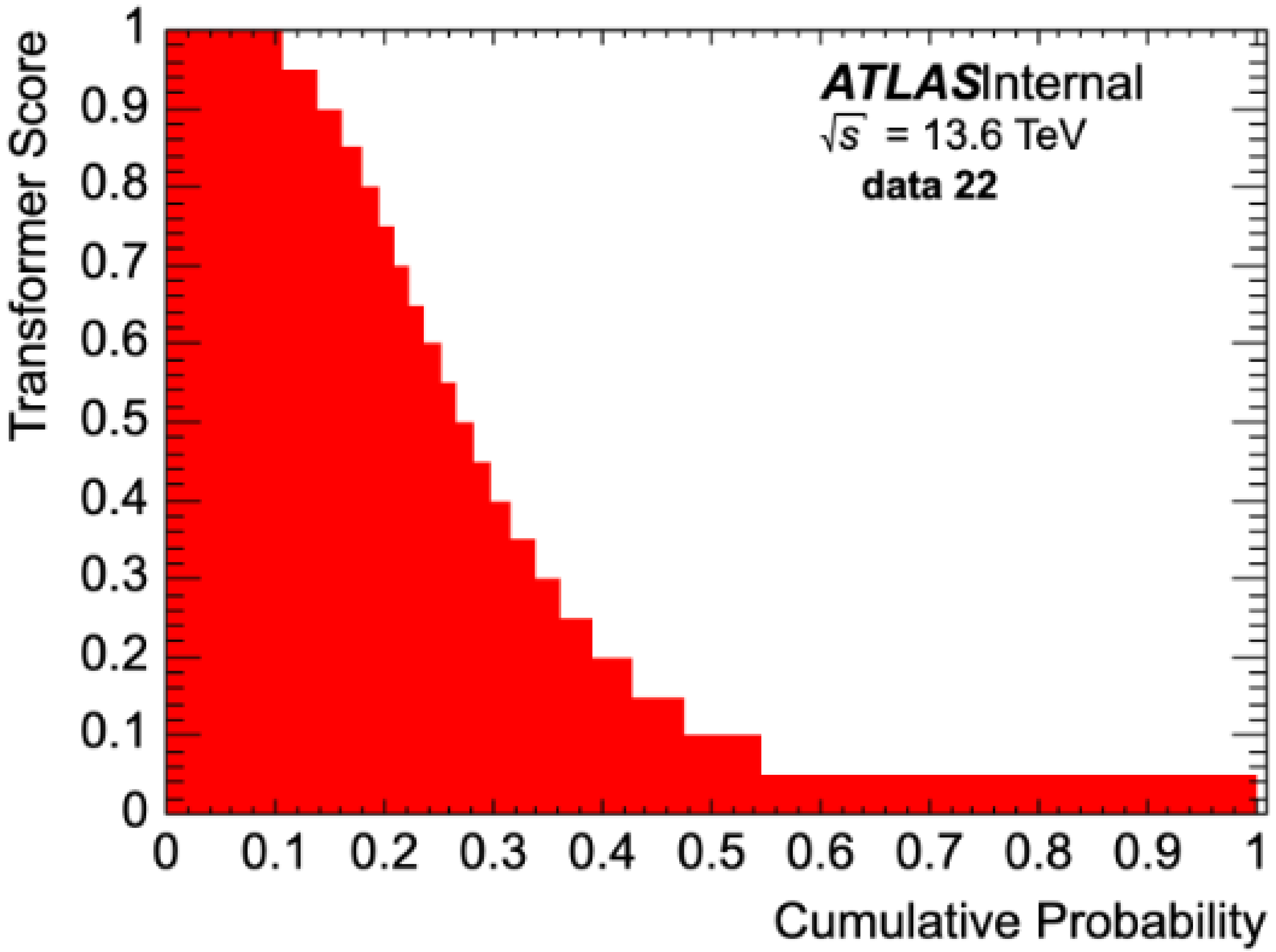




Background Efficiency of Transformer Scores

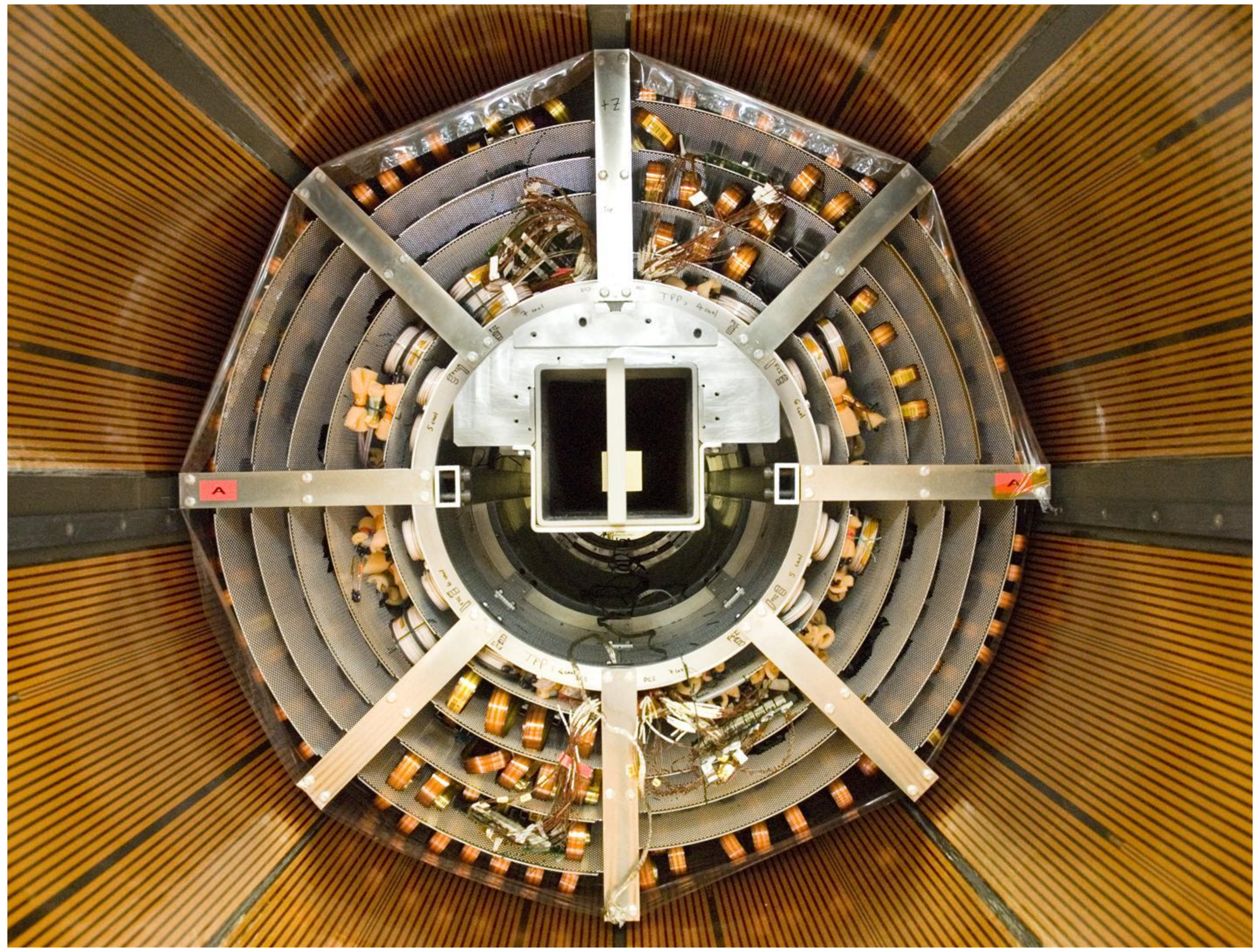
- Eventually, when the transformer is implemented, we will make a cut to distinguish signal-like versus background-like objects
- This plot shows us what percentage of data we are preserving when we make any particular cut
- For example, a cut at a transformer score of 0.6 would mean we keep just under 30% of the total events





Next Steps

- Ultimately, the kinematic binning did not provide concrete answers for why the transformer is treating converted photons more like background than the unconverted photons
  - Raises more questions about the nature of the pT and η variation
- More questions raised by the tight photon behavior in the transformer
  - Possible paths include looking deeper into photon isolation
- These findings necessitate revisiting the training of the transformer



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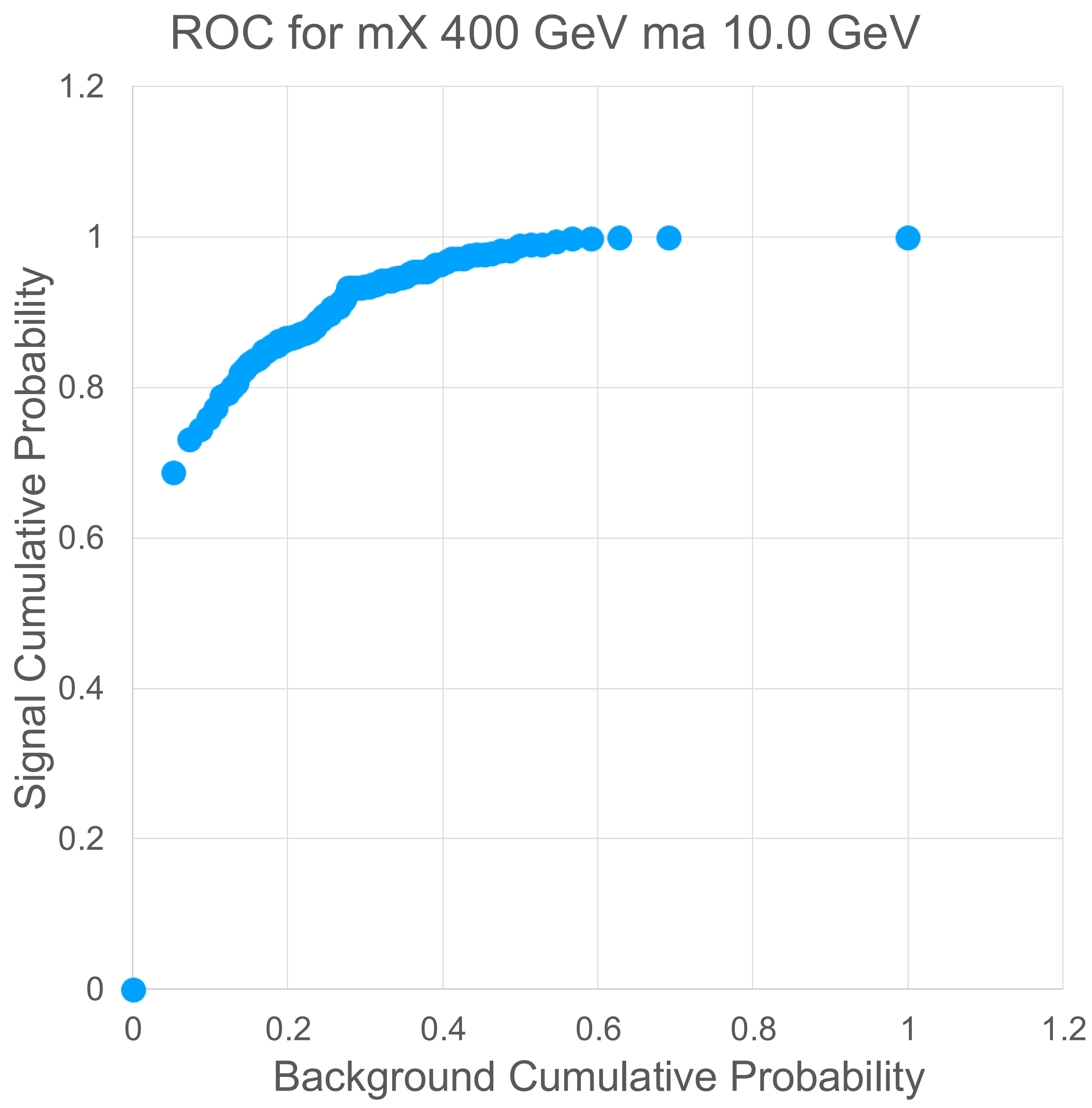
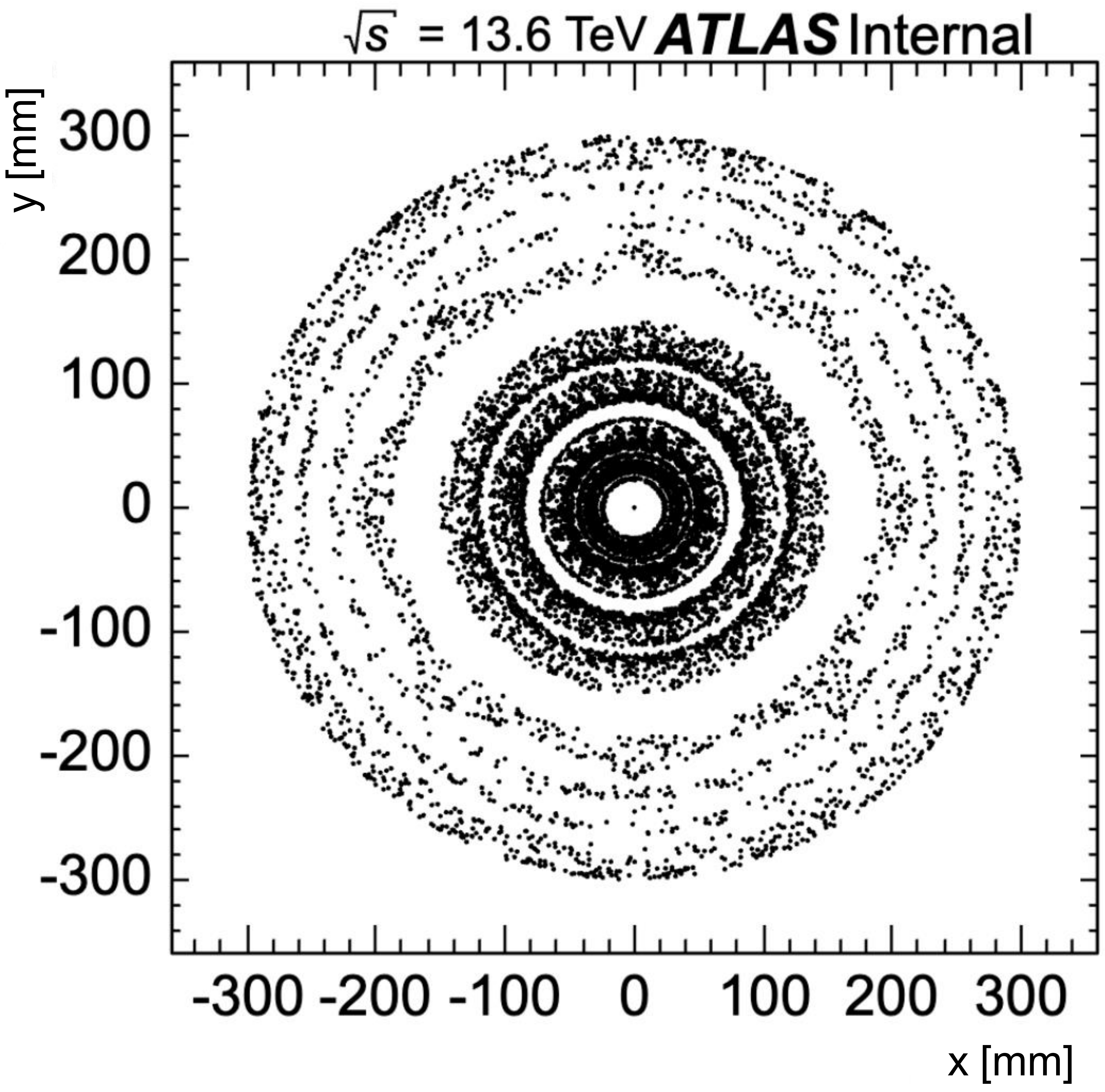
Backup

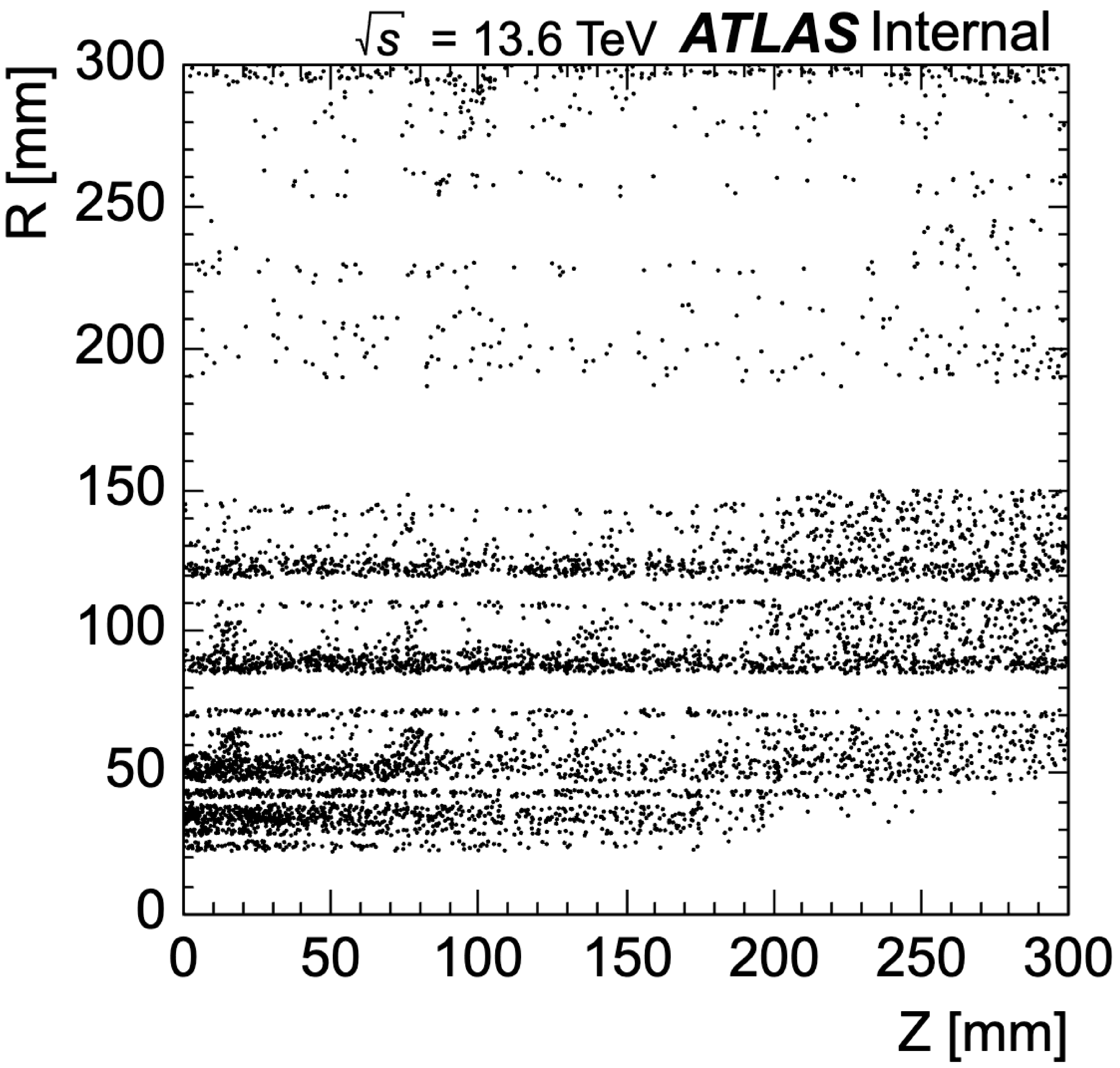
ROC Curve

- Background cumulative probability is converted photon background from data
- Signal cumulative probability is from MC simulated data for mX 400 GeV and ma 10.0 GeV
- Perfect ROC curve would follow x = y
- Can see background probability drops almost immediately and signal drops off much later



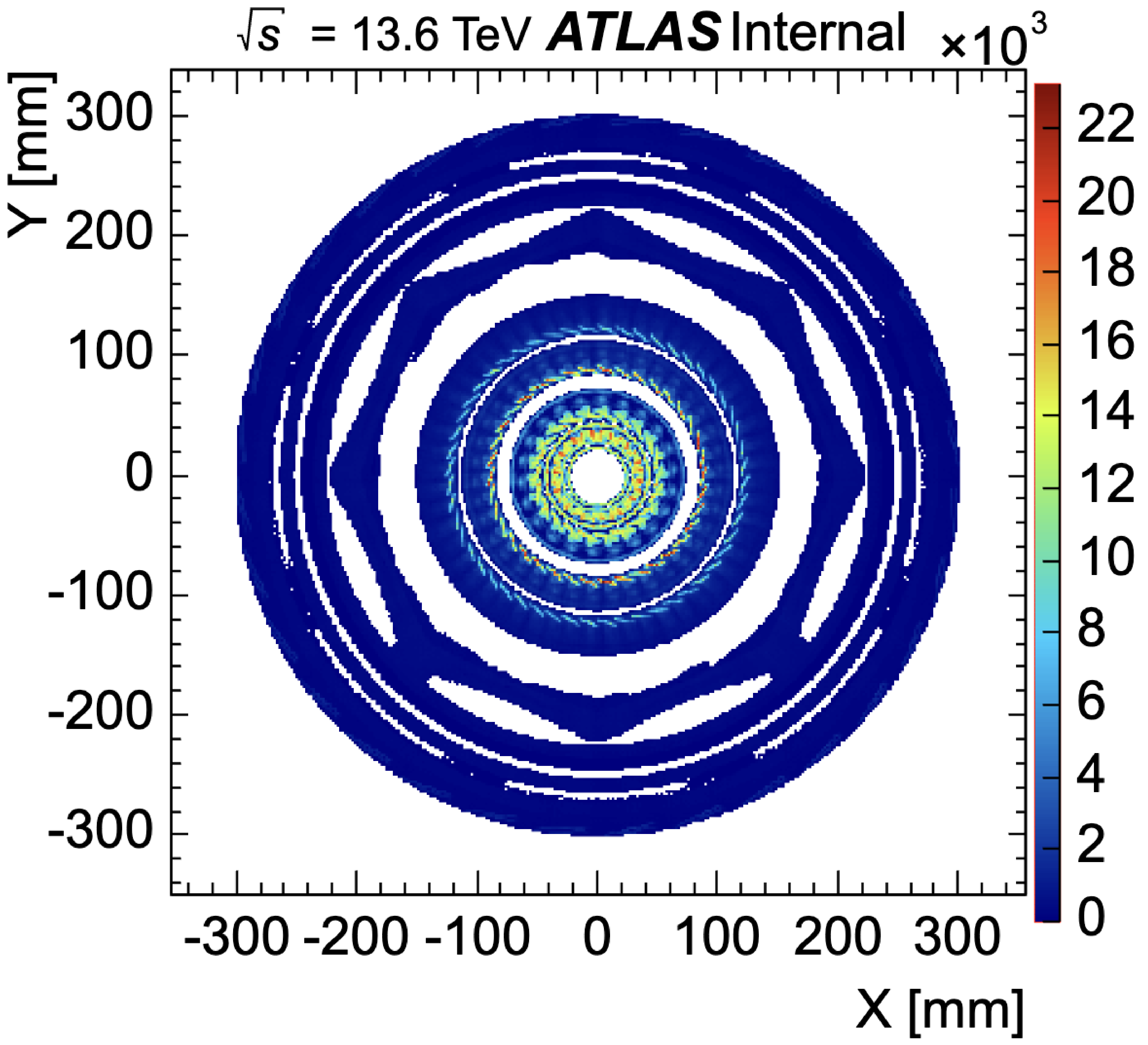
Scatter Plots for Material Mapping x-y and r-z



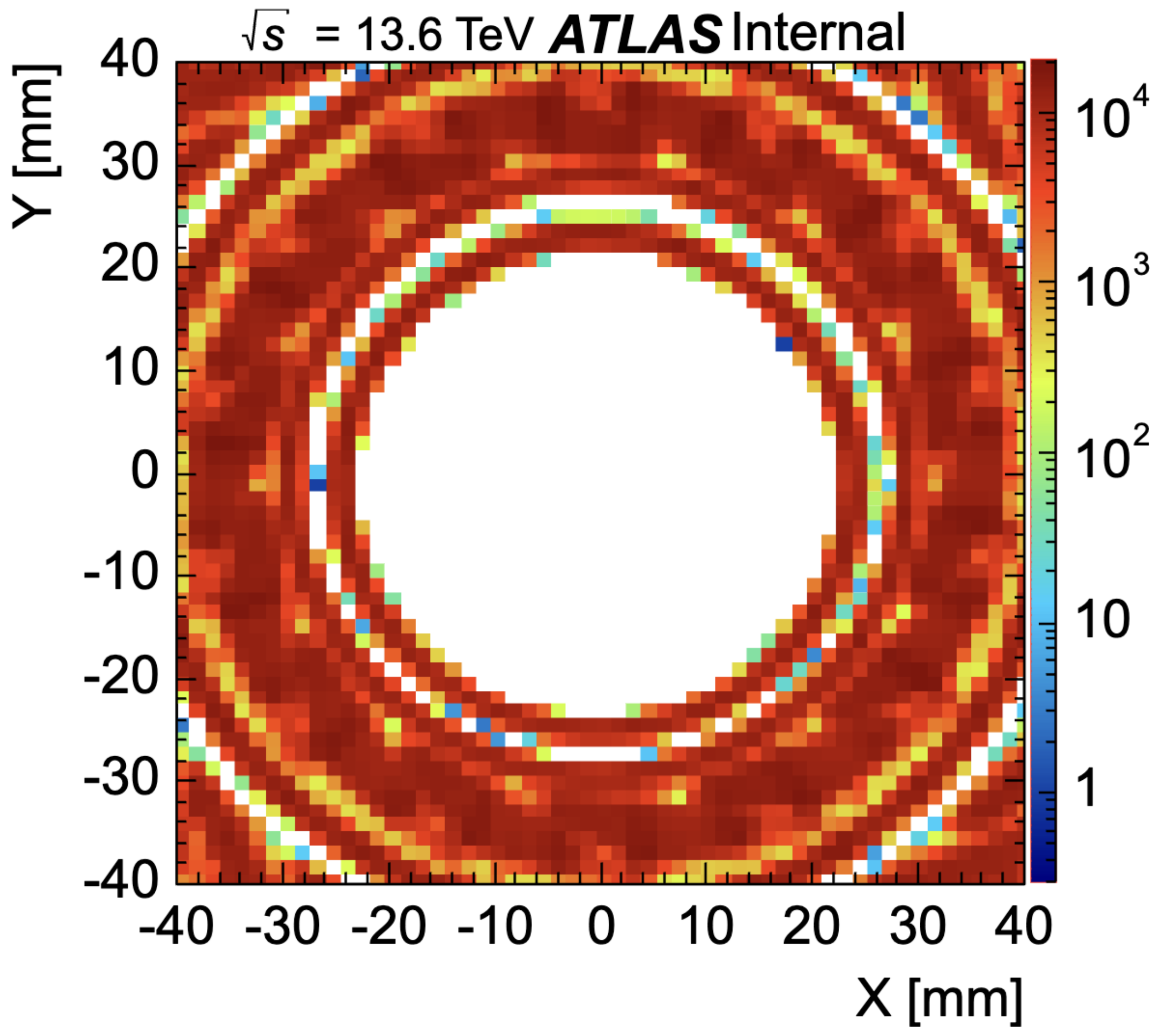


Linear Material Mapping and 40mm Zoom

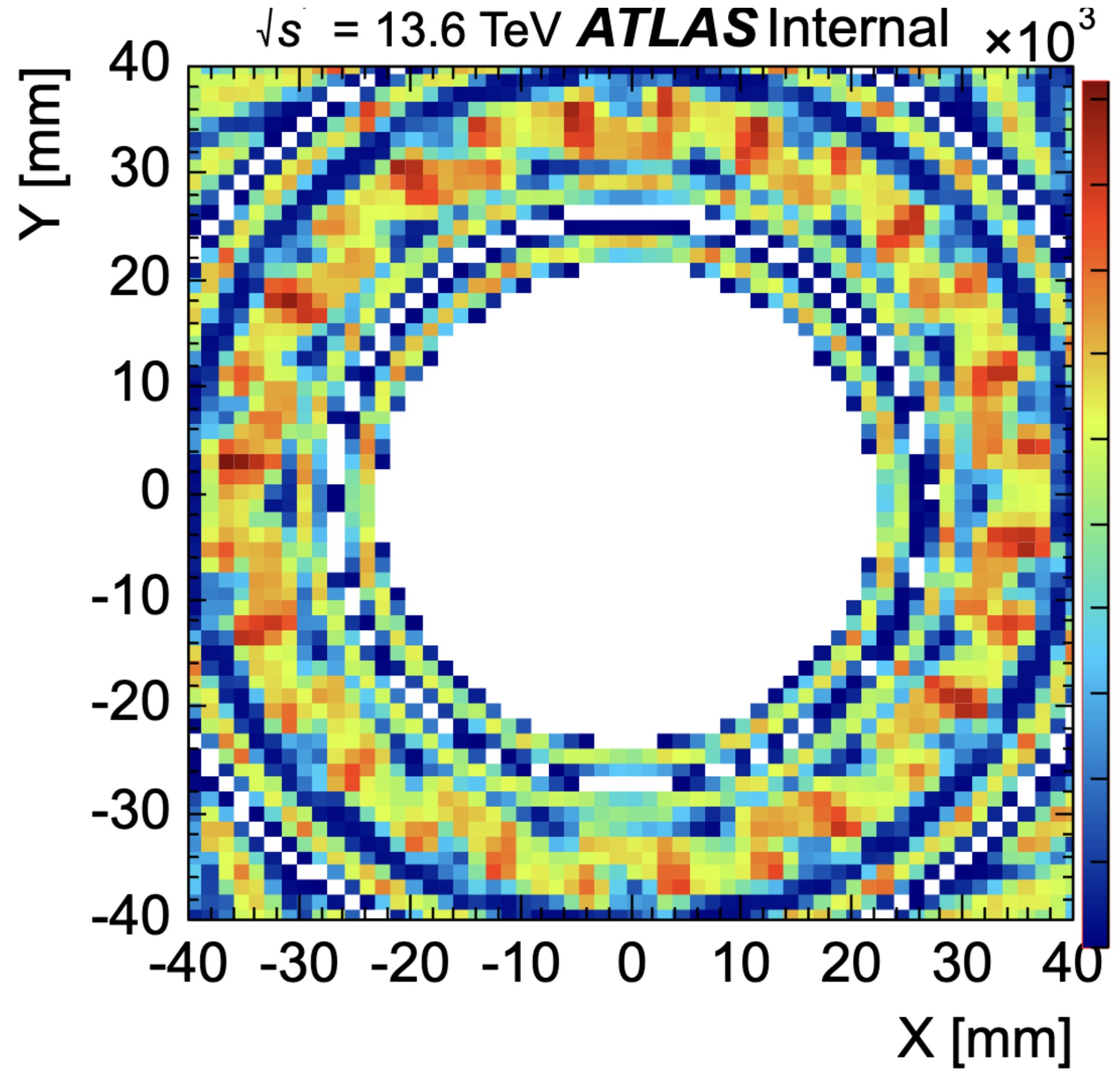
Linear Material Mapping in x-y plane



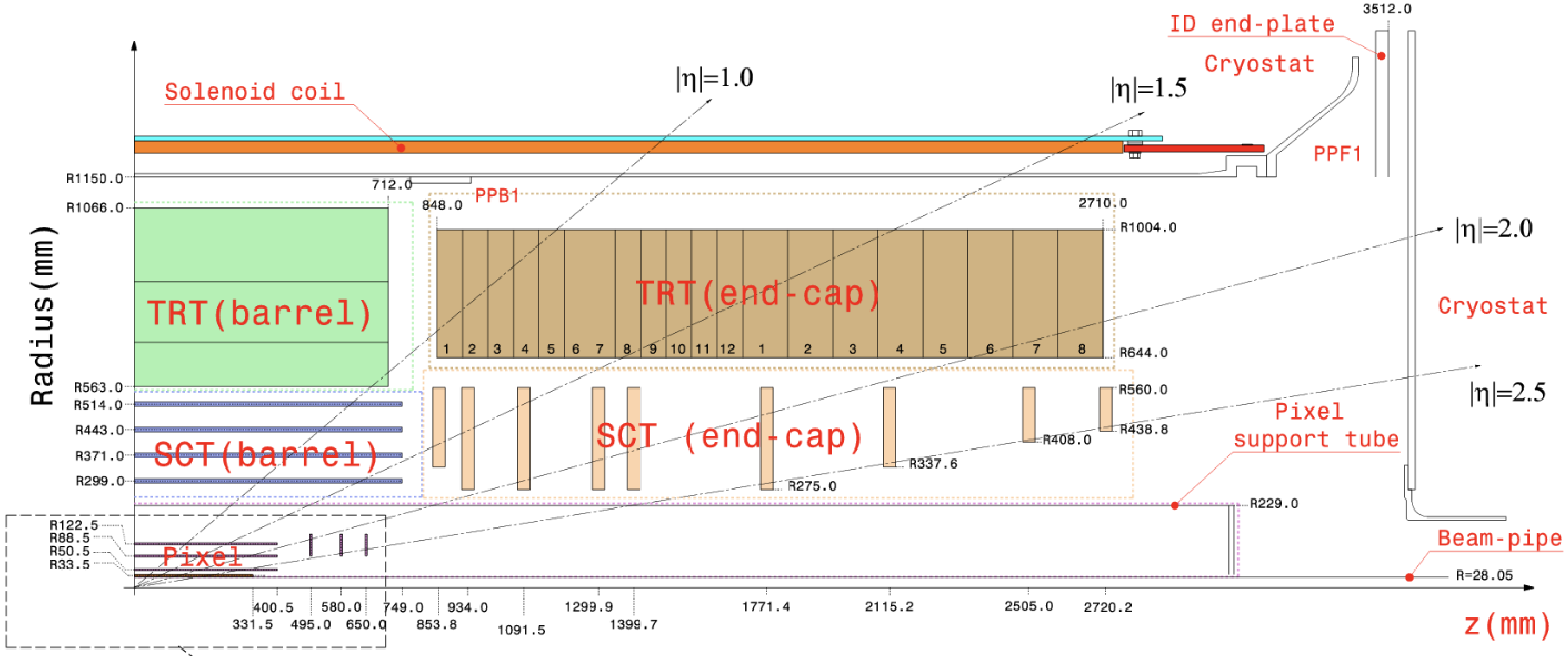
Zoom to 40mm (log scaled)

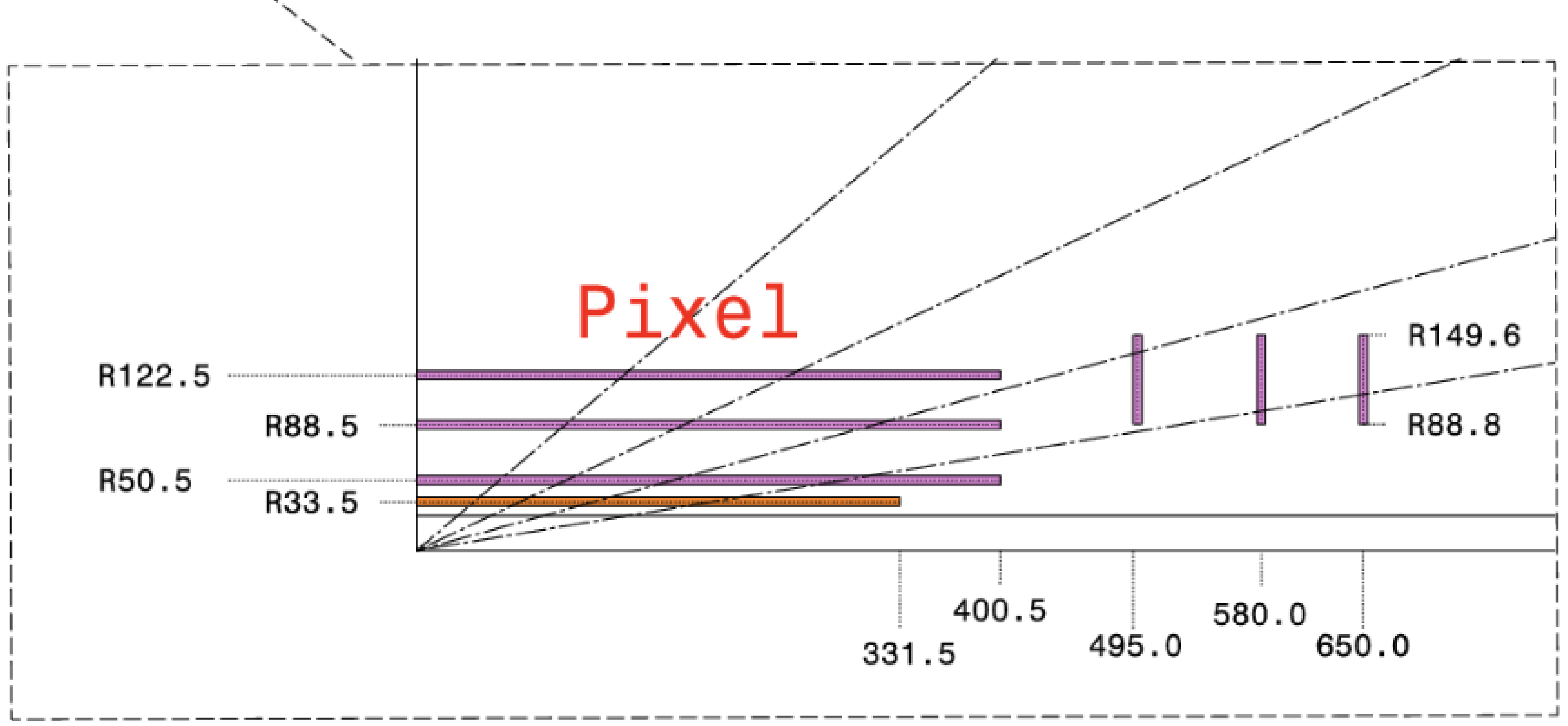


Zoom to 40mm (linear)



R and Z Geometry Visualization

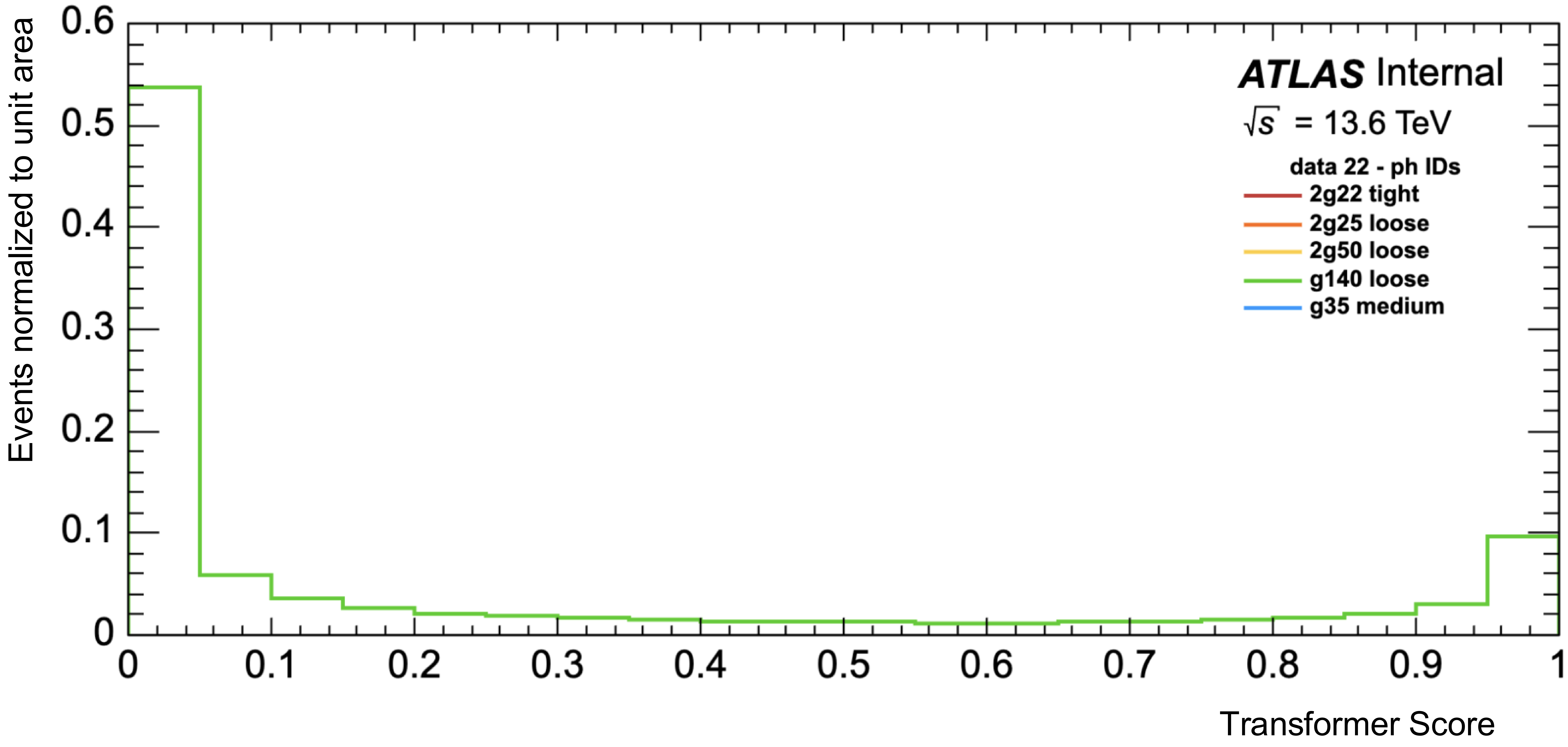




Envelopes

Pixel		31<R<242 (mm)
SCT barrel		255<R<549 (mm)
SCT end-cap		251<R<610 (mm)
TRT barrel		554<R<1082 (mm)
TRT end-cap		617<R<1106 (mm)

Trigger Matching for Data 22 Transformer Scores



2g22tight: 0

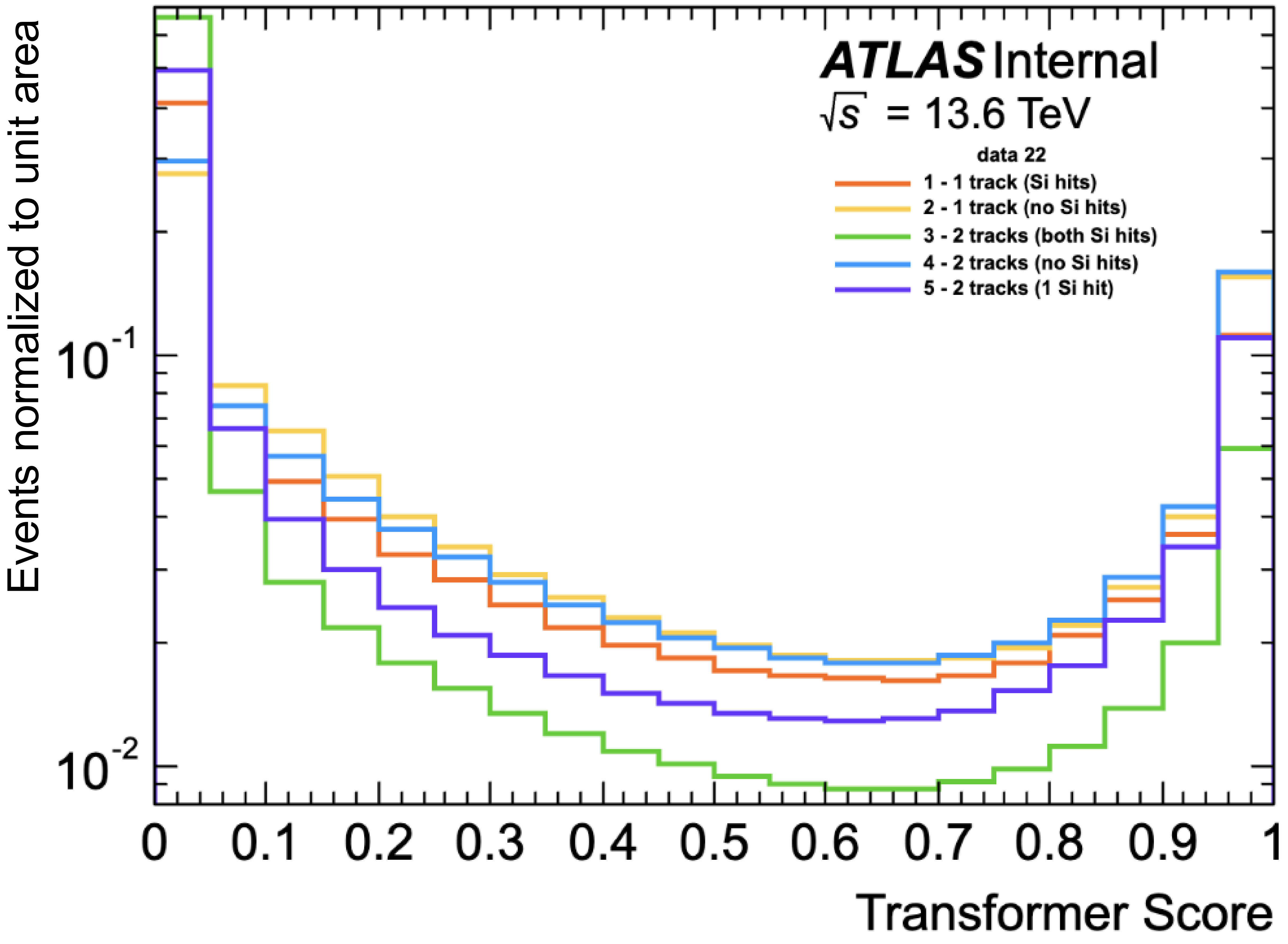
2g25loose: 0

2g50loose: 0

g140loose: 27509935

g35_g25med:0

Converted Photons Transformer Scores Separated by Conversion Type



0: unconverted photon

1: one track only, with Si hits

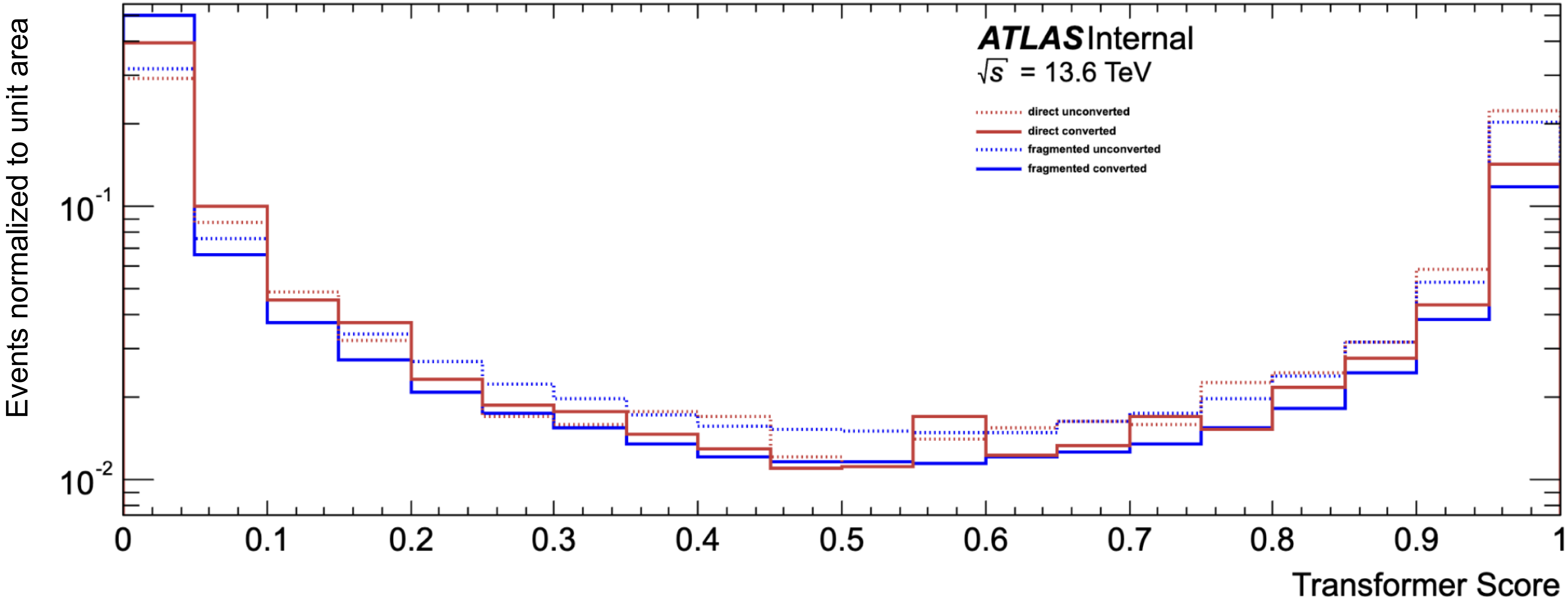
2: one track only, no Si hits (TRT only)

3: two tracks, both with Si hits

4: two tracks, none with Si hits (TRT only)

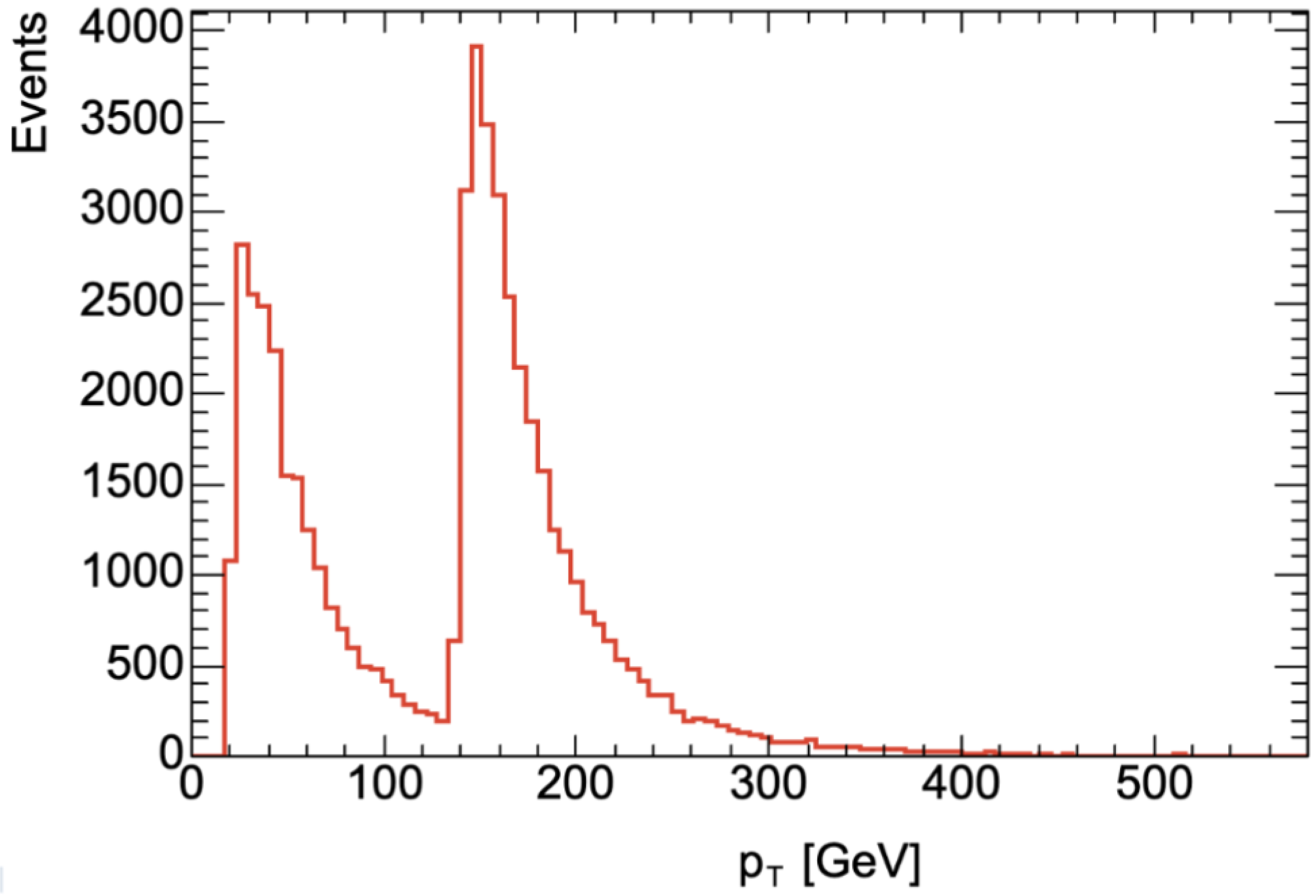
5: two tracks, only one with Si hits

Transformer Scores for γ+ Jets

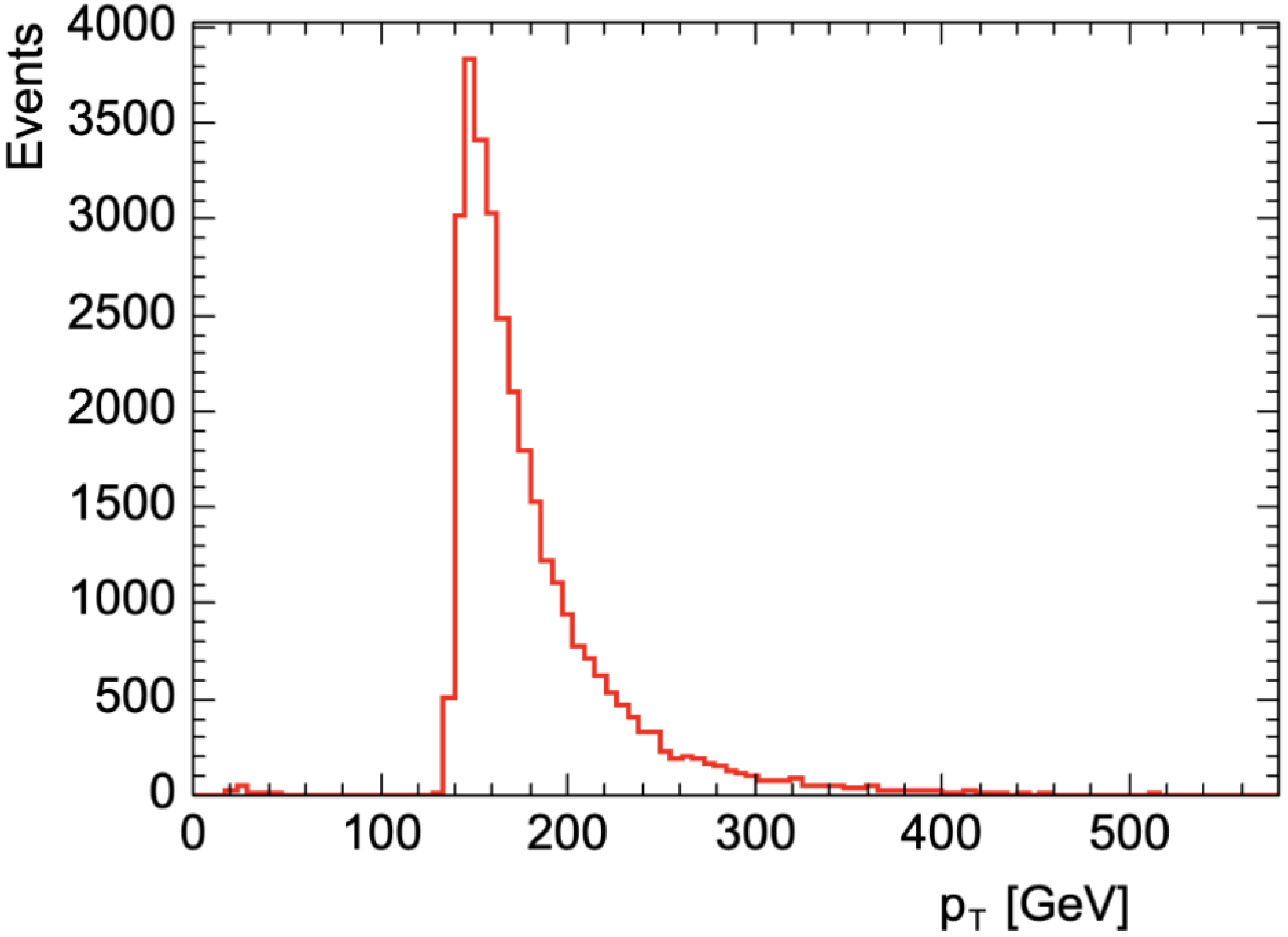


Background pT plots

No trigger matching



Trigger matched to g140_loose



Efficiencies for Signal Sample