A Search for Light Axion-Like Particles: Using Z->ee to Validate Transformer-Based Identification of Boosted Diphotons

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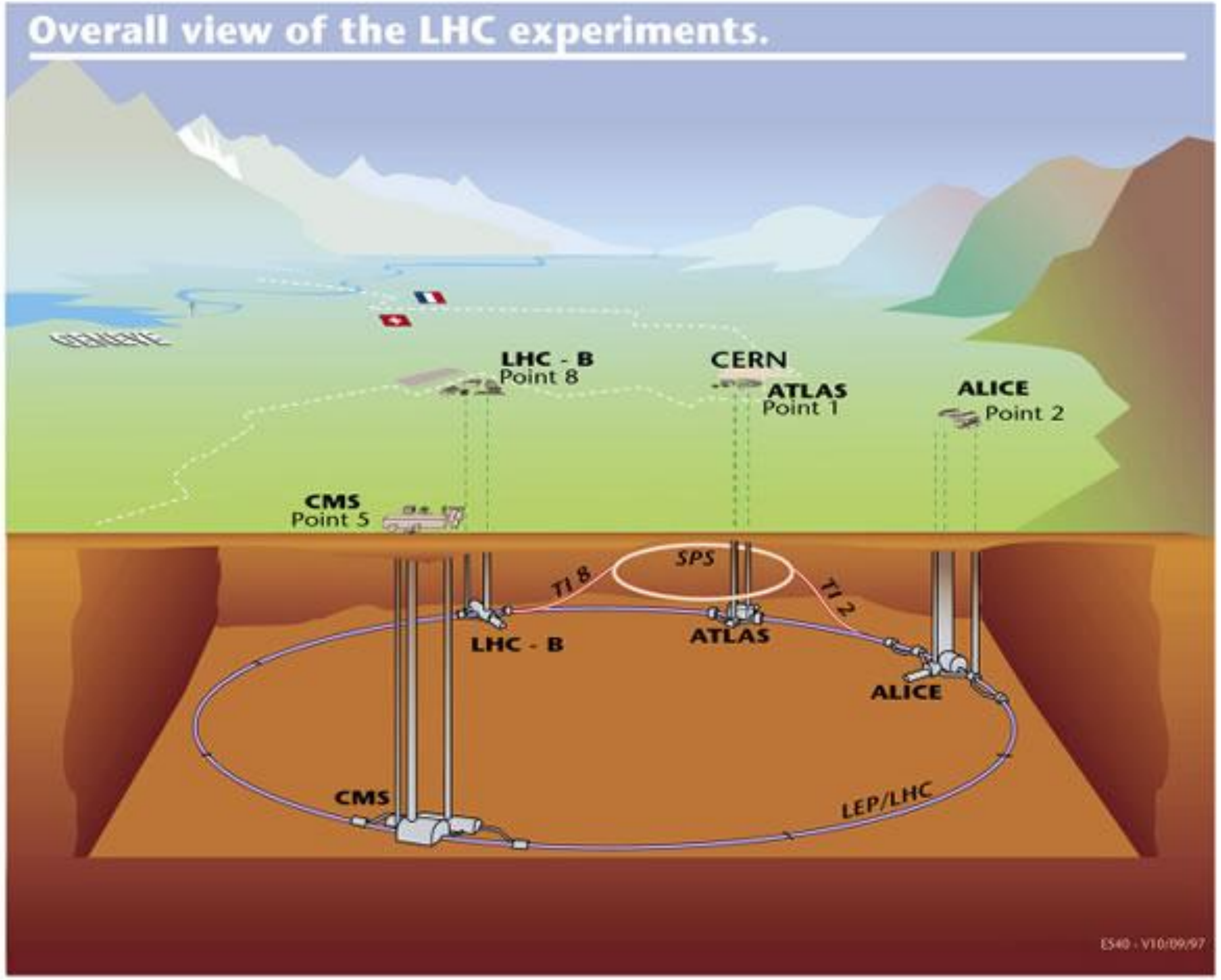
Nevis Laboratories
Columbia University

ATLAS
Experiment

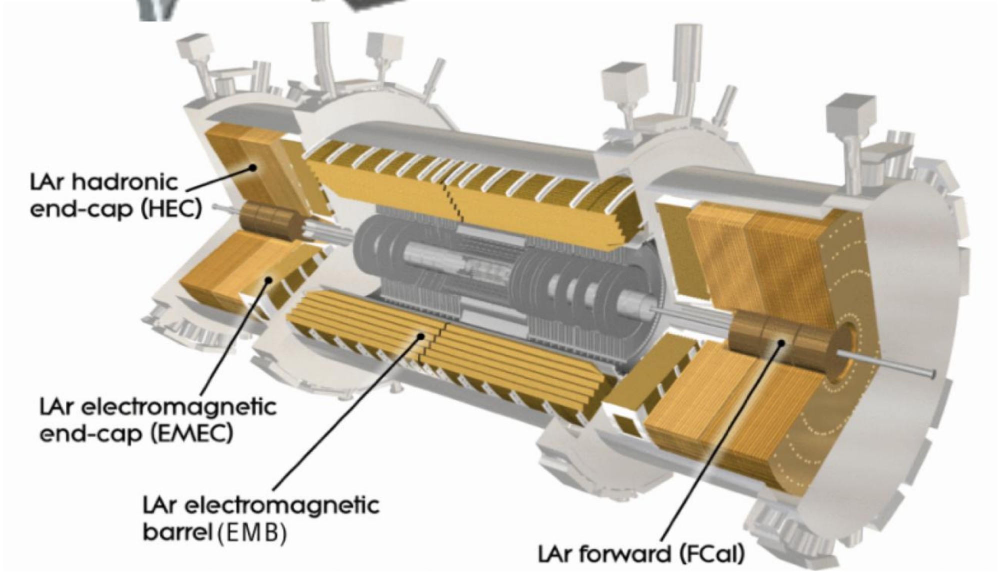
The Large Hadron Collider

- Large Hadron Collider (LHC): The most powerful particle accelerator in the world
- Particle collisions at energies of $\sqrt{s} = 14$ TeV
- Four major collision points: ATLAS, CMS, ALICE, LHCb



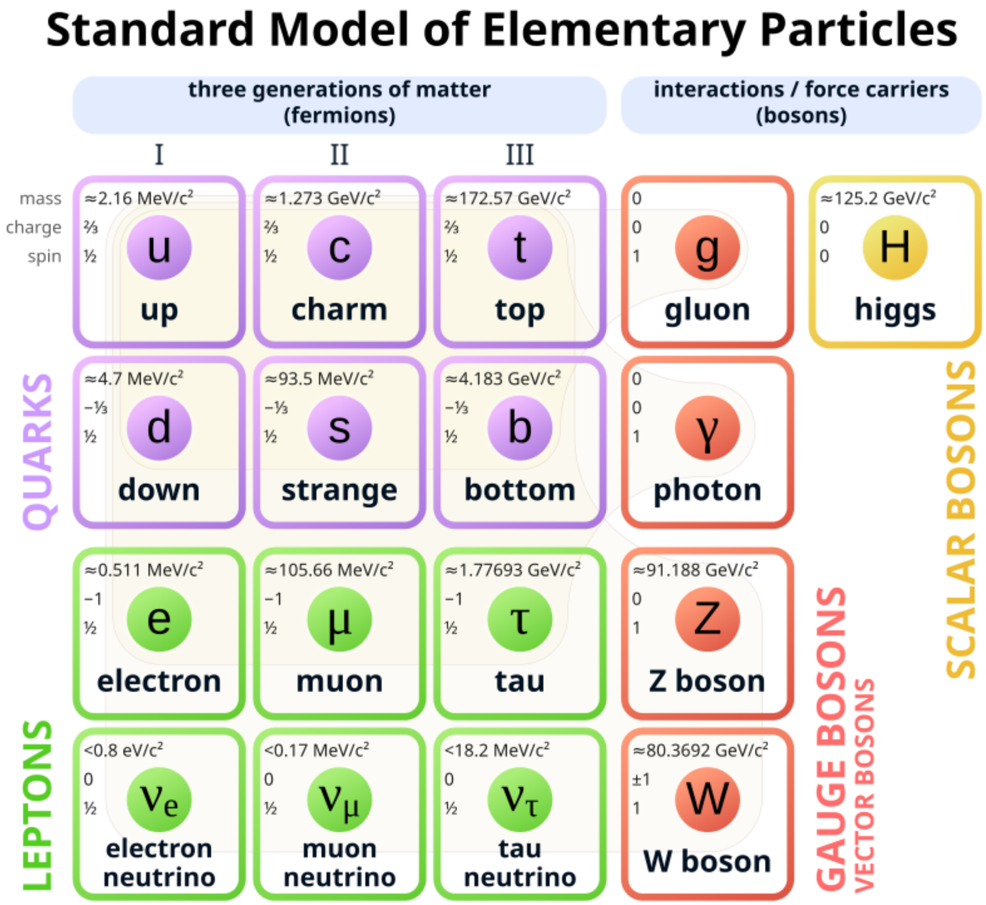
The ATLAS Detector

- A Toroidal LHC ApparatuS (ATLAS): the largest detector at the LHC
- 3 Concentric Cylindrical Layers:
  - Inner Detector
  - Calorimeters (EM and hadronic)
  - Muon spectrometer



Addressing the CP Problem: Axion-Like Particles (ALPs)

- A conflict in the Standard Model: The strong force does not break CP symmetry
- Theoretical axions offer a solution to the CP problem
- ALPs share properties with axions and are candidates for dark matter
- Columbia's search for ALPs: $X \rightarrow aa \rightarrow 4\gamma$



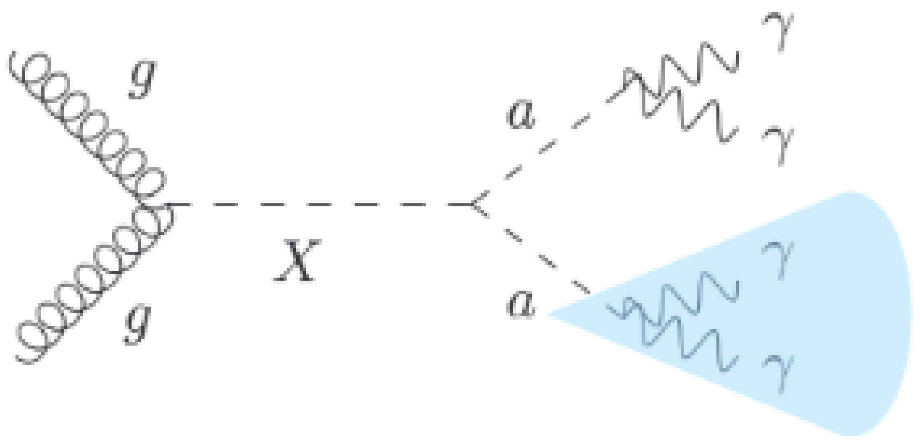
Machine Learning-Based Photon Classification

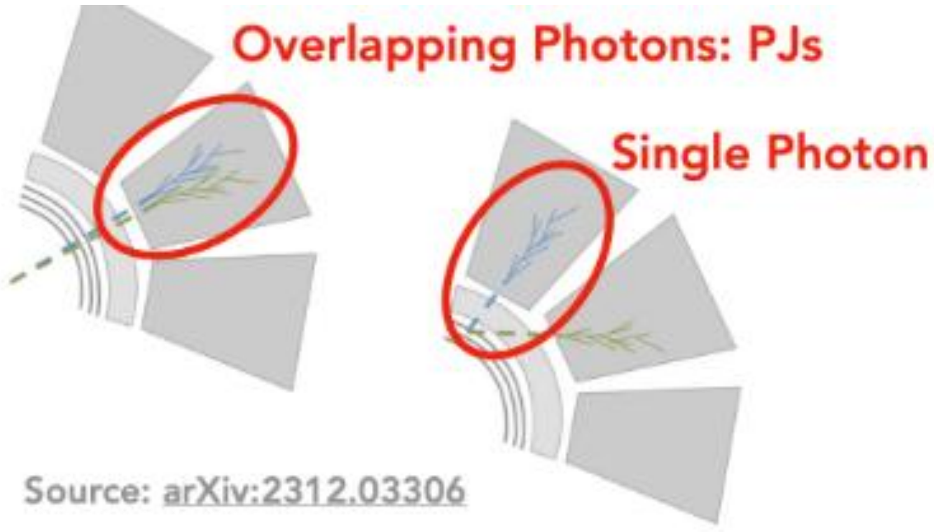
- The signal $X \to aa \to 4\gamma$ decay produces boosted photon pairs that hit the detector very close together

- Merged photon pairs (signal) and single photons (background) are nearly identical in the detector

- The Columbia analysis uses a **transformer** trained to distinguish merged photon pairs from single photons

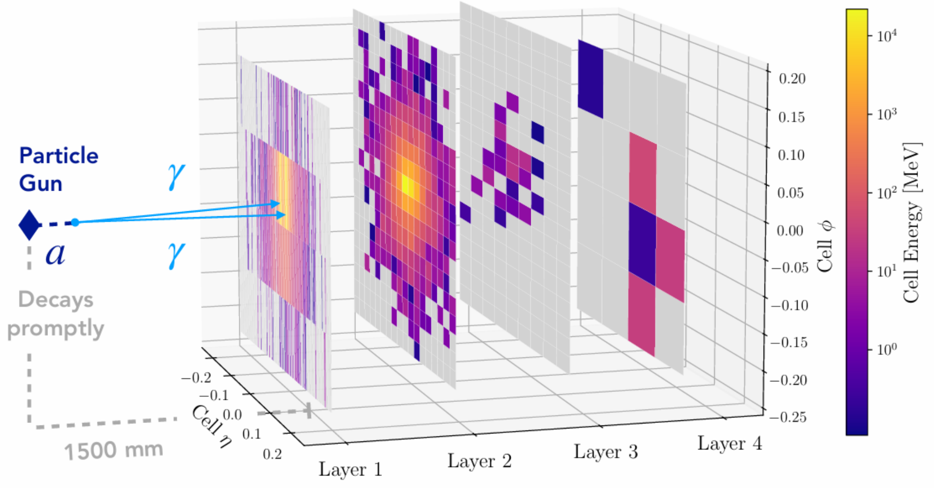
Transformer: arXiv:2607.08175 [hep-ph]





Cell-Level Information Optimizes Model Performance

- The ATLAS calorimeter is composed of small cells that measure particle energy
- Shower shape variables (SSVs) characterize many-cell regions using a few variables
- Using **full cell-level information** to train the transformer **improves performance** over previous SSV-trained classifiers



Model	Overall AUC	Background Rejection ($1/\epsilon_{bkg}$) 90% ϵ_{sig}	95% ϵ_{sig}	99% ϵ_{sig}
		SSV-Level		
BDT	0.92	3.2	1.8	1.2
DNN	0.92	3.1	1.8	1.2
		Cell-Level		
CNN	0.95	6.4	2.6	1.3
PFN	0.97	62 ± 7	5.4 ± 0.2	1.48 ± 0.01
Transformer	**0.98**	$\mathbf{472 \pm 60}$	$\mathbf{9.0 \pm 0.4}$	$\mathbf{1.64 \pm 0.01}$
MLP Mixer	**0.93**	**4.3**	**2.1**	**1.2**

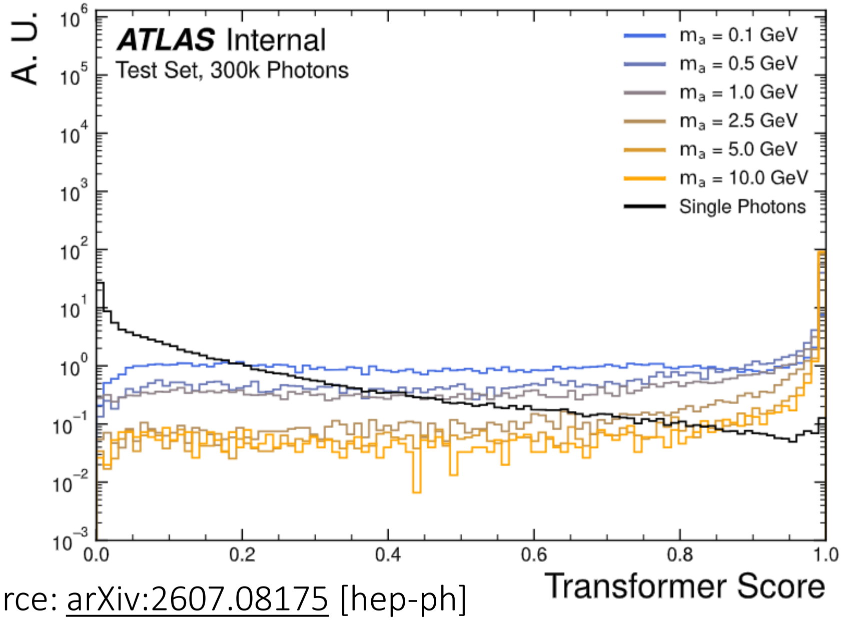
Source: arXiv:2607.08175 [hep-ph]

Validating the Transformer with Data

- Initial training with undiscovered particles can only be evaluated on simulated samples

- To compare the model's performances on simulation and on data, the transformer can be evaluated with background samples

- $Z \rightarrow e^{+}e^{-}$ decay produces electrons, which look very similar to single photons in the calorimeter



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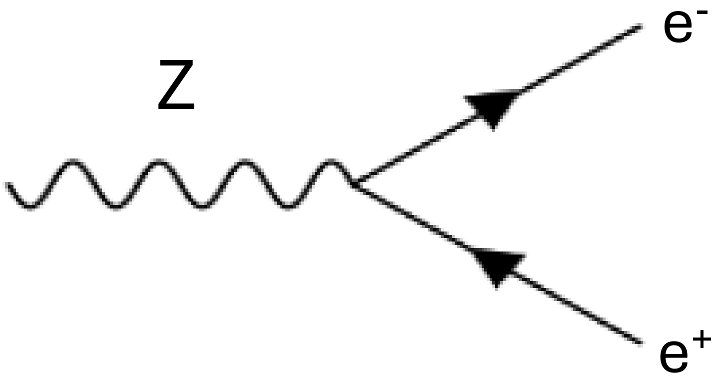


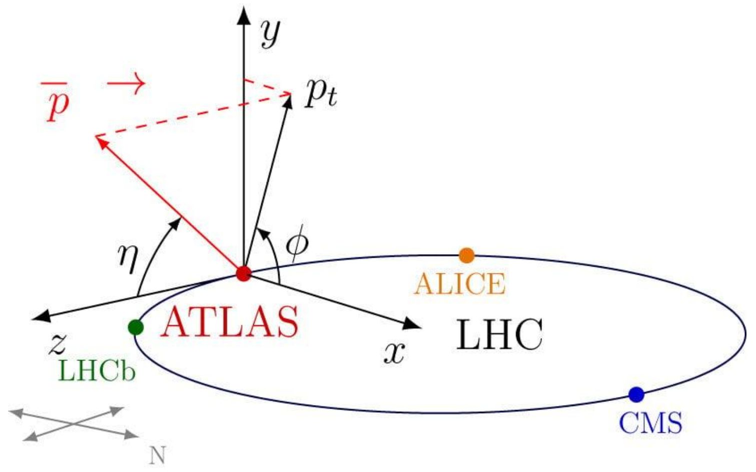
$\mathrm{Z} \rightarrow e^{+}\mathrm{e}^{-}$ Sample Composition

Z-->e^{+}e^{-} Sample from 2022 (Run 3)

Data: 19,478,724 events

Simulation: 37,320,526 events

- The simulation aims to perfectly mimic the data
- Ideally, the transformer should perform equally on simulation and data samples



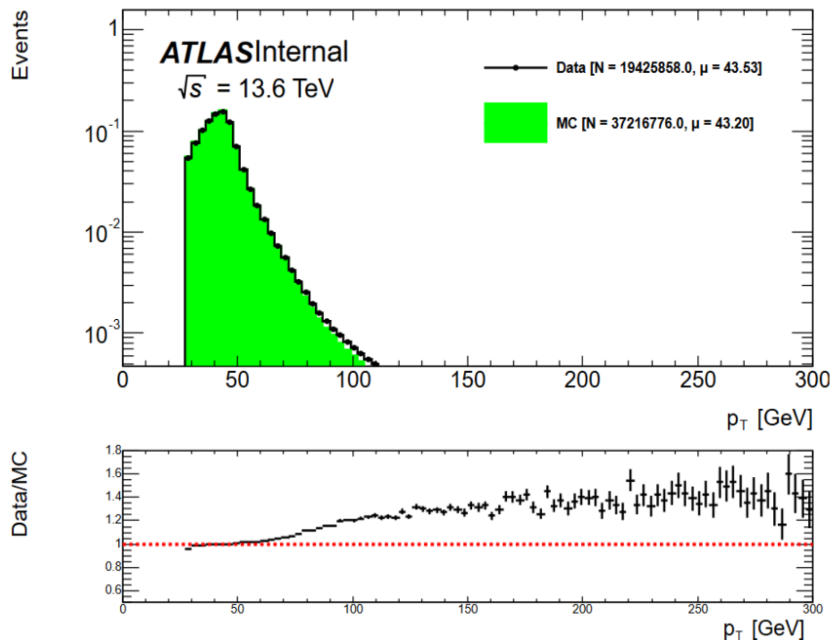
Cuts Applied to $\mathrm{Z} \rightarrow e^{+}\mathrm{e}^{-}$ Background Sample

Value	Cut
Transverse Momentum (p_T)	$p_T > 20$ GeV
Z Boson Mass (m_{ee})	80 GeV < m_{ee} < 100 GeV
Pseudorapidity (η)	|n| < 1.37, 1.52 < |η| < 2.5
Net Electron Pair Charge	Net Charge = 0

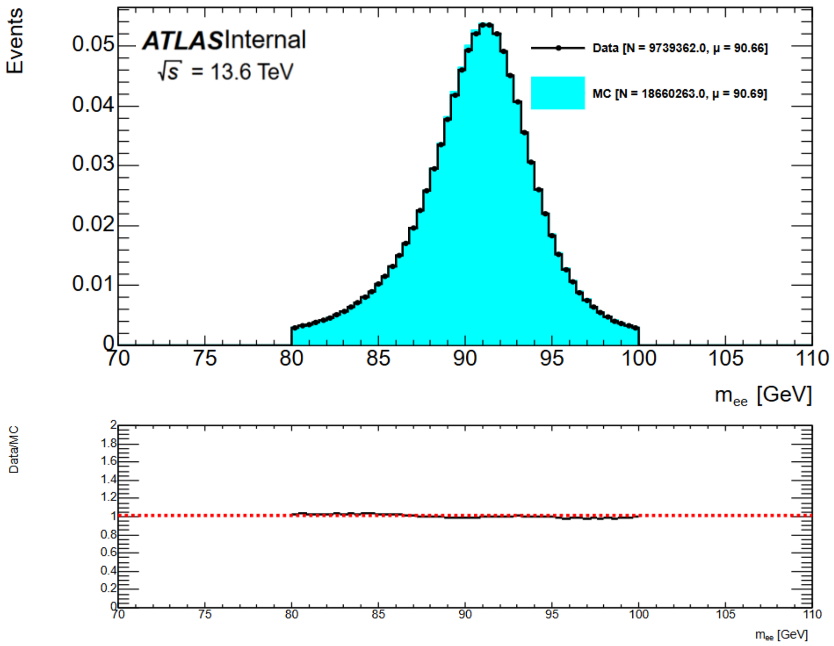
p_T and Z Boson Mass in the Sample

- Good agreement between simulation and data in both p_T and m_{ee}
- Z boson mass averages to ~90.6 GeV for data and simulation (compare to 91.2 GeV)

Transverse Momentum (p_T)



Z Boson Mass (m_{ee})

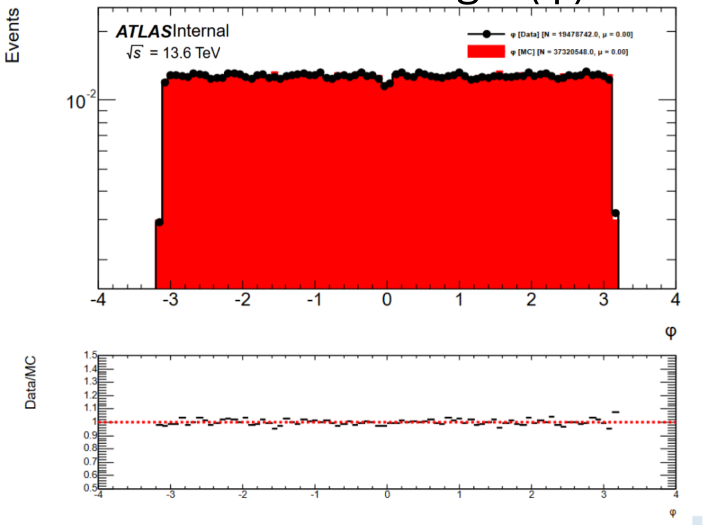


Spatial Distribution of Events in the Detector

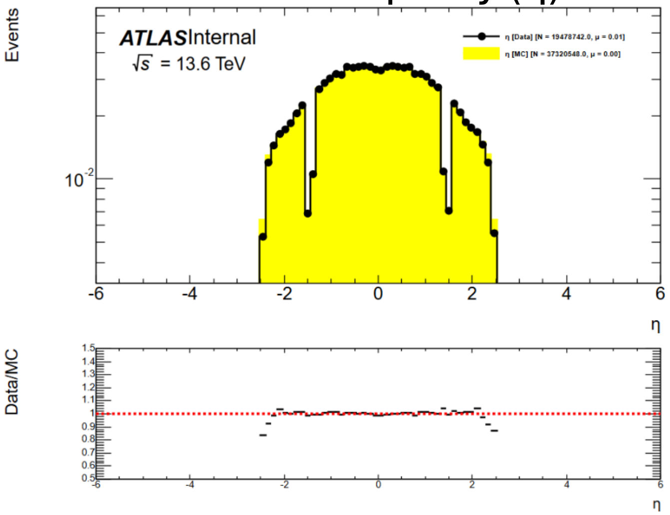
- Good agreement between simulation and data in both η and ϕ

- Unrolling the inner surface of the detector around ϕ creates an η-ϕ plane

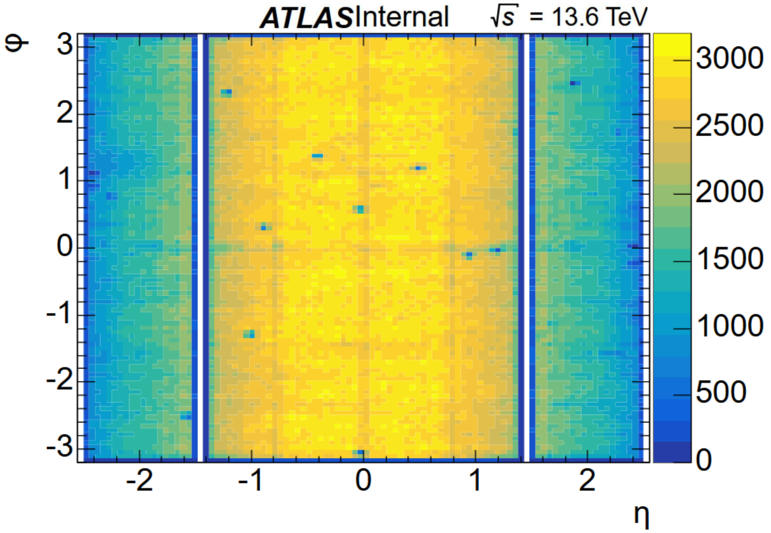
Azimuthal Angle (ϕ)



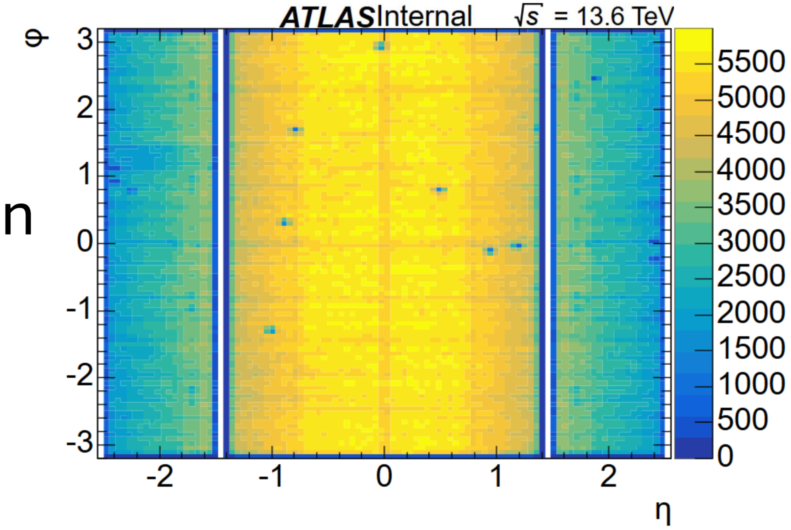
Pseudorapidity (η)



Data



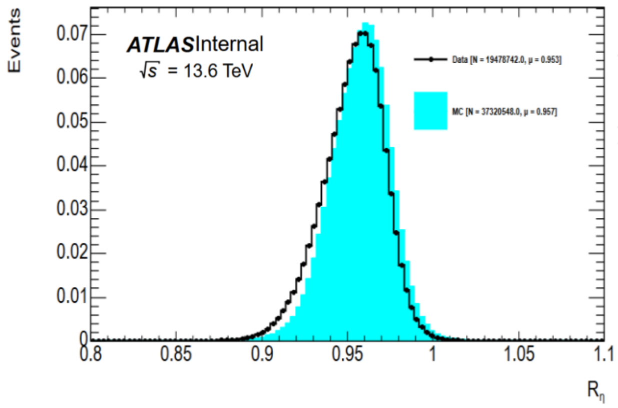
Simulation

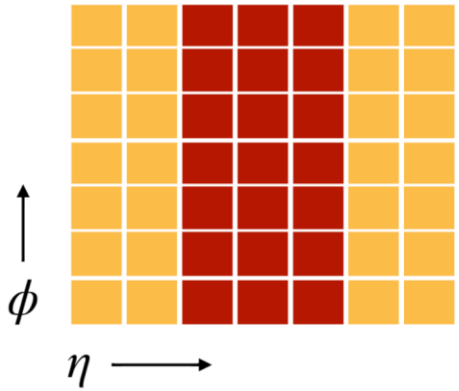


Shower Shape Variable Agreement Between Data and Simulation

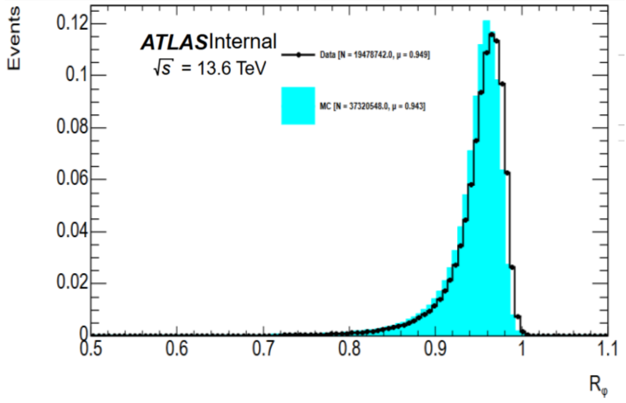
Data and simulation show reasonable agreement across shower shape variables

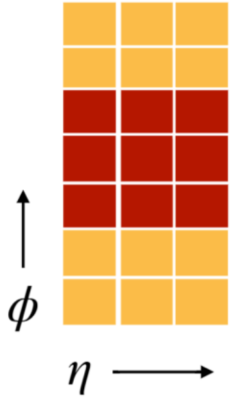
η Energy Ratio (R_η)



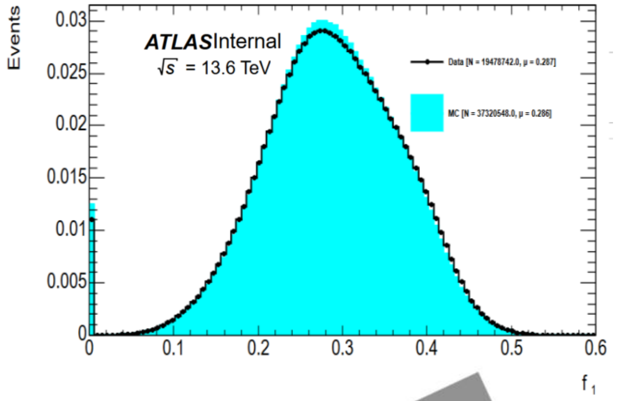


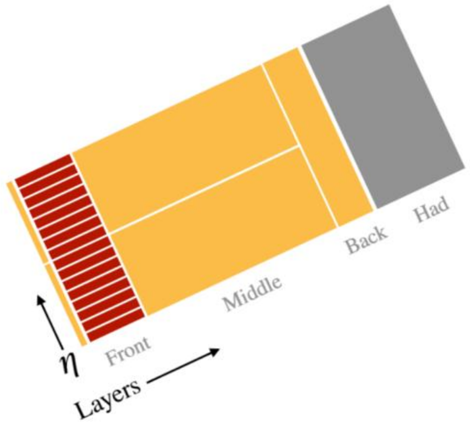
ϕ Energy Ratio (R_ϕ)



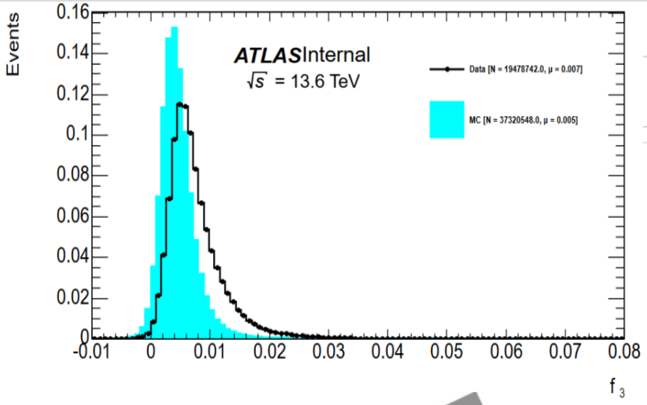


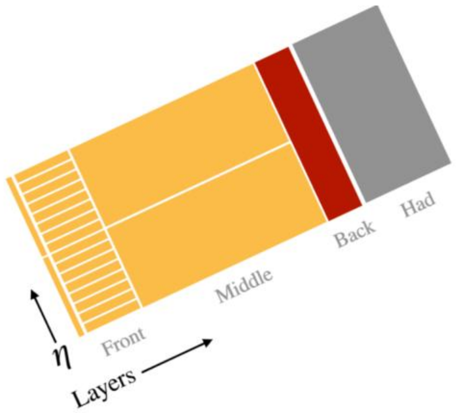
Energy Fraction (f_1)





Energy Fraction (f_3)



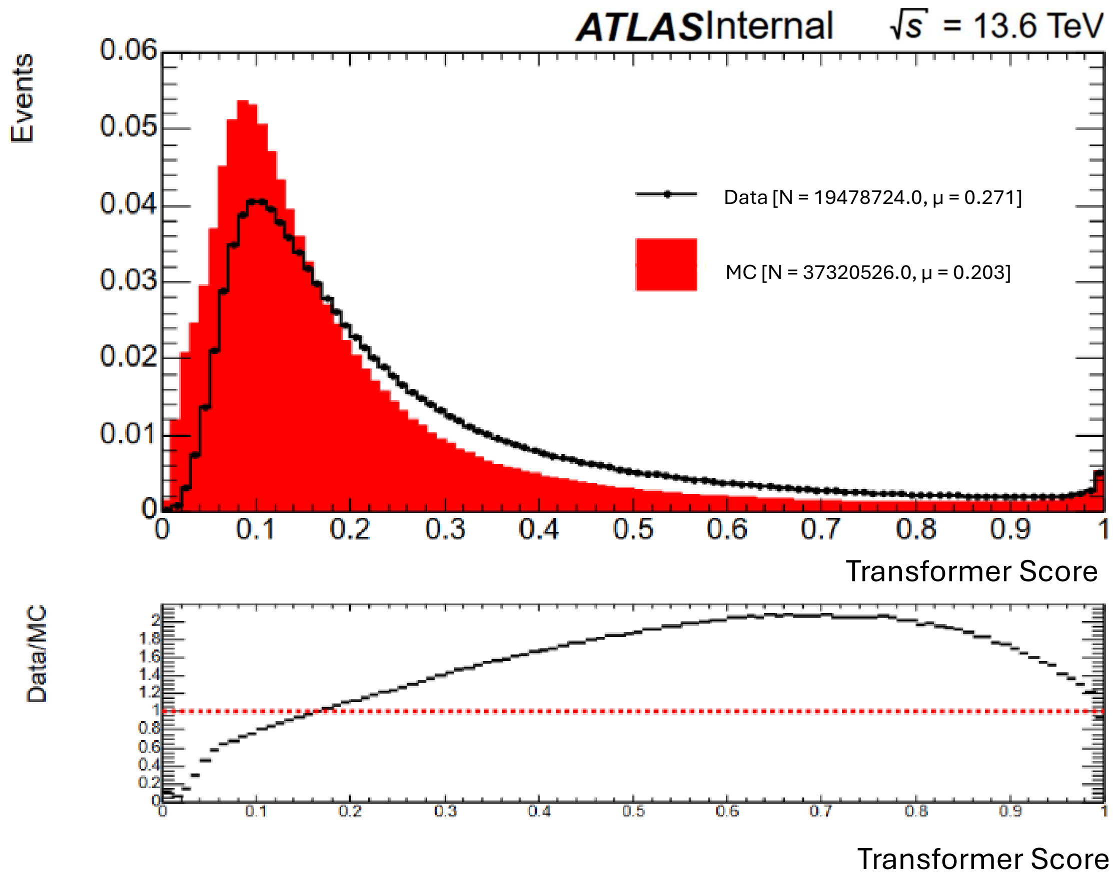


Data-Simulation Disagreement in the Transformer

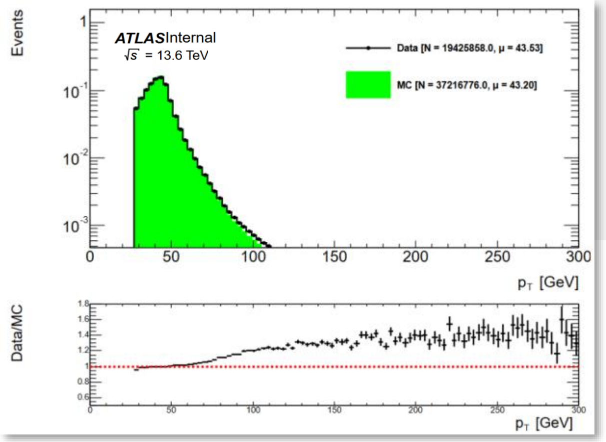
Unexpectedly, the transformer performance on electrons is not the same in data and simulation

- As expected, the transformer categorizes the **electrons as background-like**
- Can **correlations with physical values** like kinematics or shower shape variables **reveal an underlying pattern** behind the transformer's inconsistency?

Transformer Score for $Z \rightarrow e^+e^-$ Sample

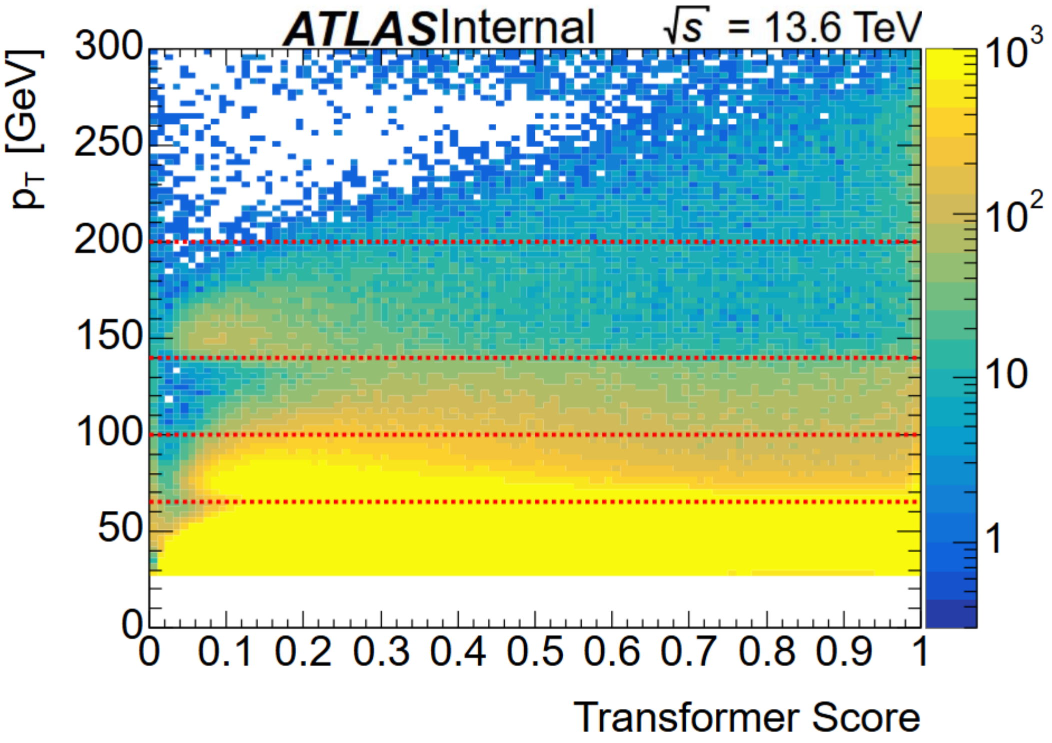


p_T Bins According to Transformer Score Distribution



- There is noticeable variation in transformer score across p_T

Data



Bins [GeV]

[200, 300)

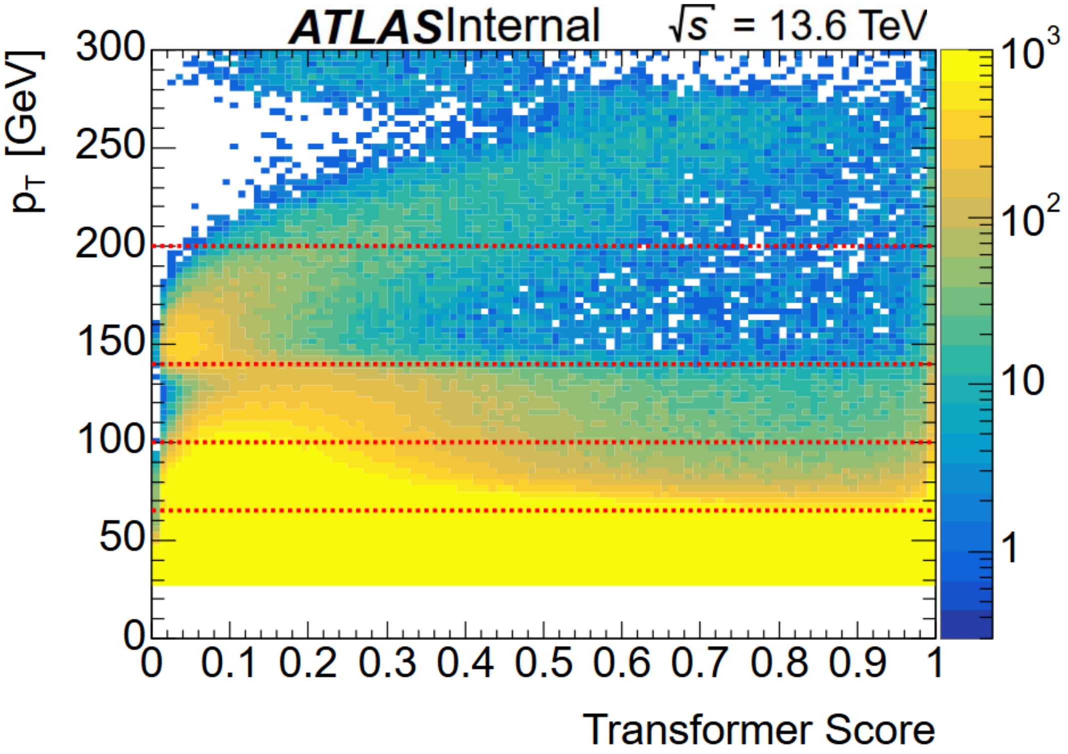
[140, 200)

[100, 140)

[65, 100)

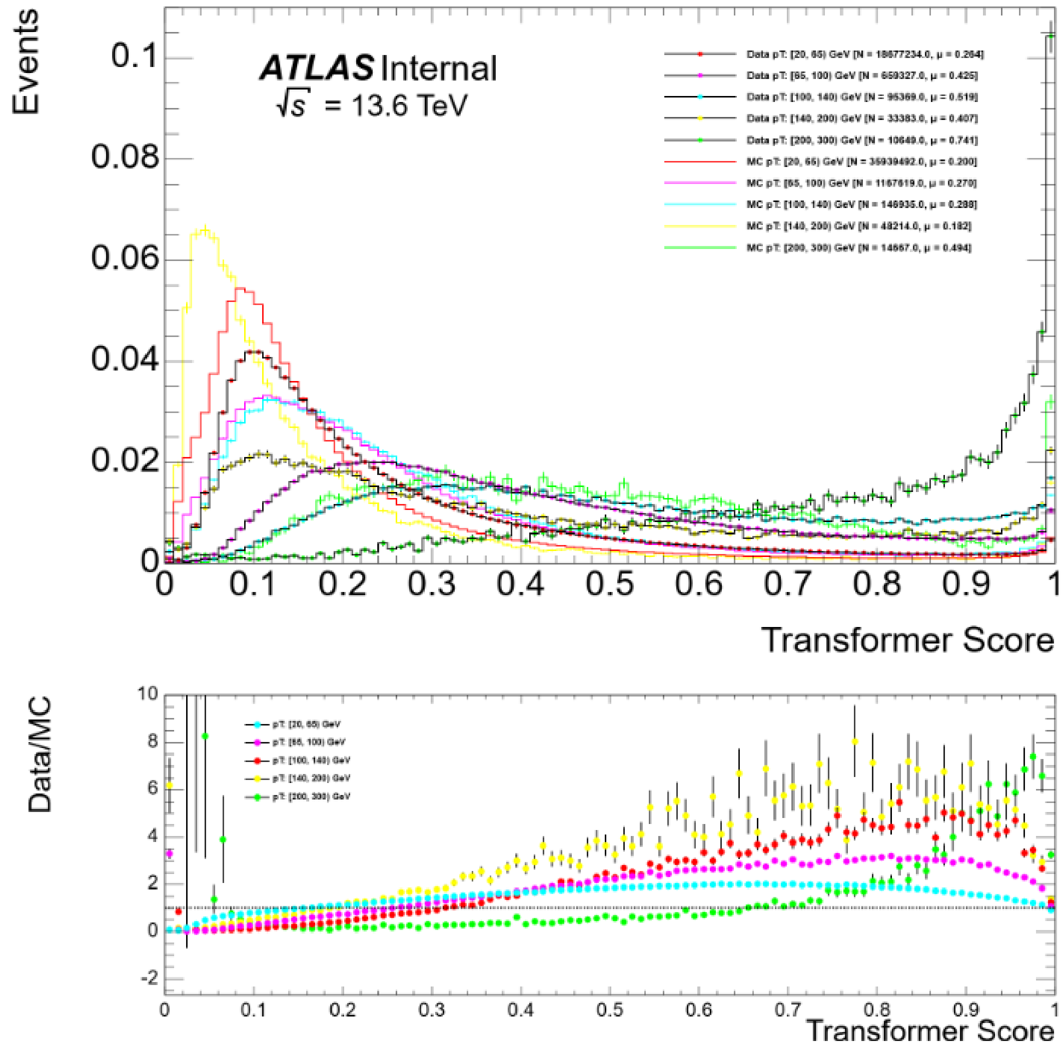
[20, 65)

Simulation



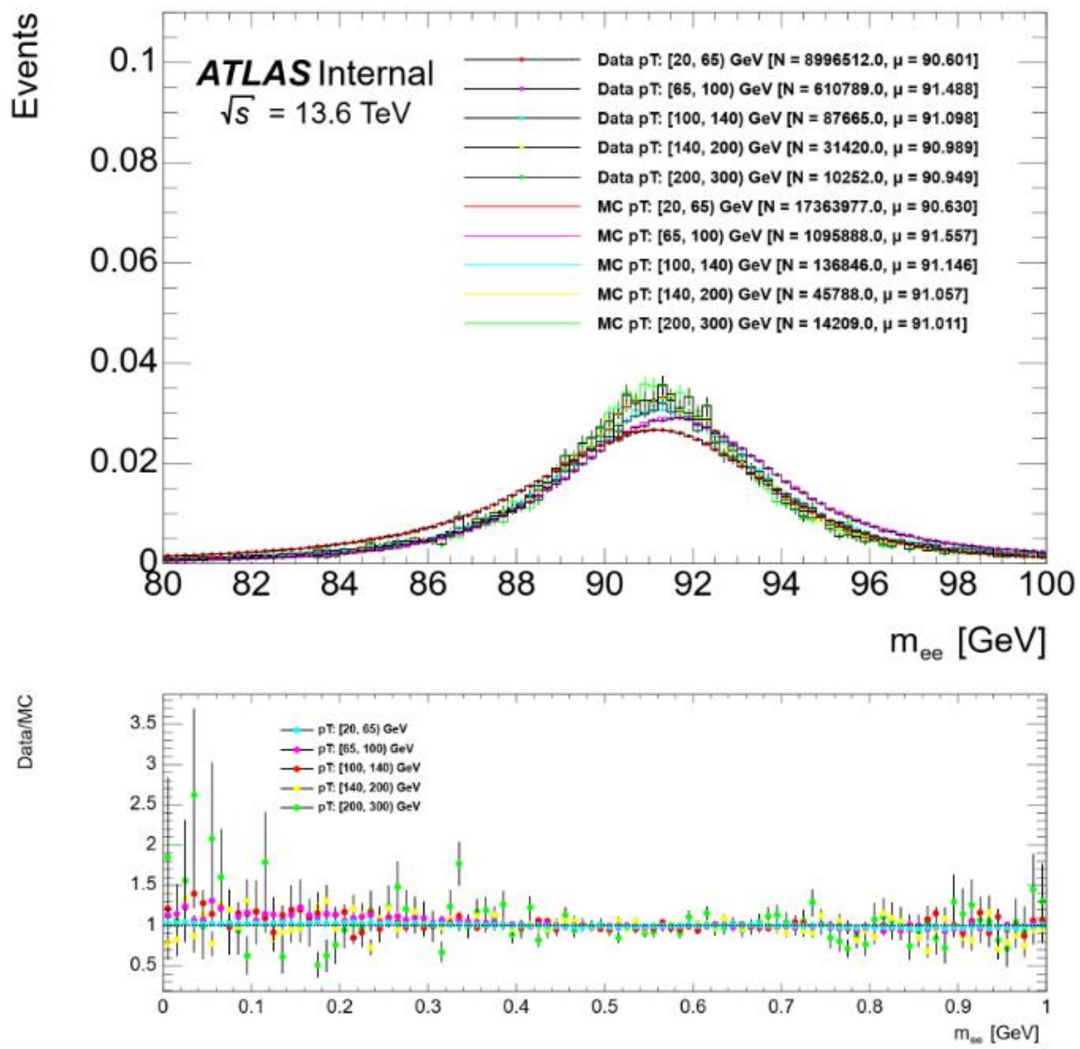
p_T-Binned Transformer Score

- p_T Bins (GeV): [20, 65), [65, 100), [100, 140), [140, 200), [200, 300)
- There is a strong disagreement between data and simulation in the highest p_T bin
- Highest p_T bin ≈ 0.1% of overall sample



Sample Purity Across p_T Bins

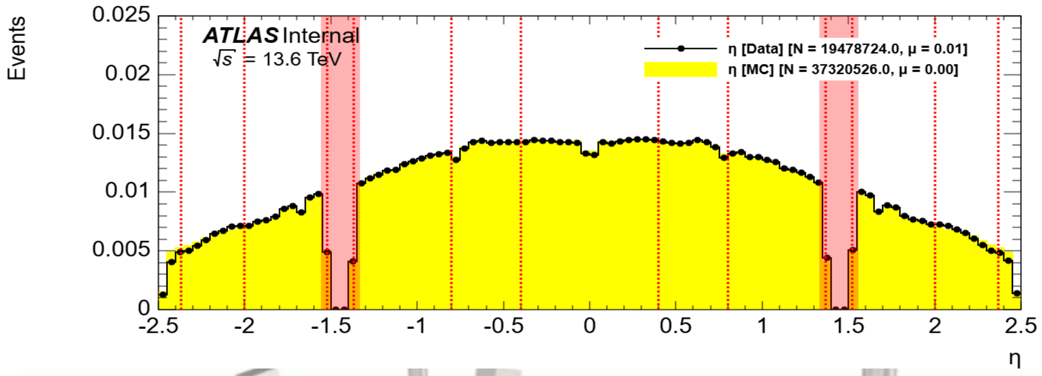
- Electron parent mass shows no significant variation across p_T bins
- All bins average between 90.60 GeV and 91.55 GeV (Z boson: 91.2 GeV)
- The data-simulation disagreement is not due to lack of sample purity at high p_T

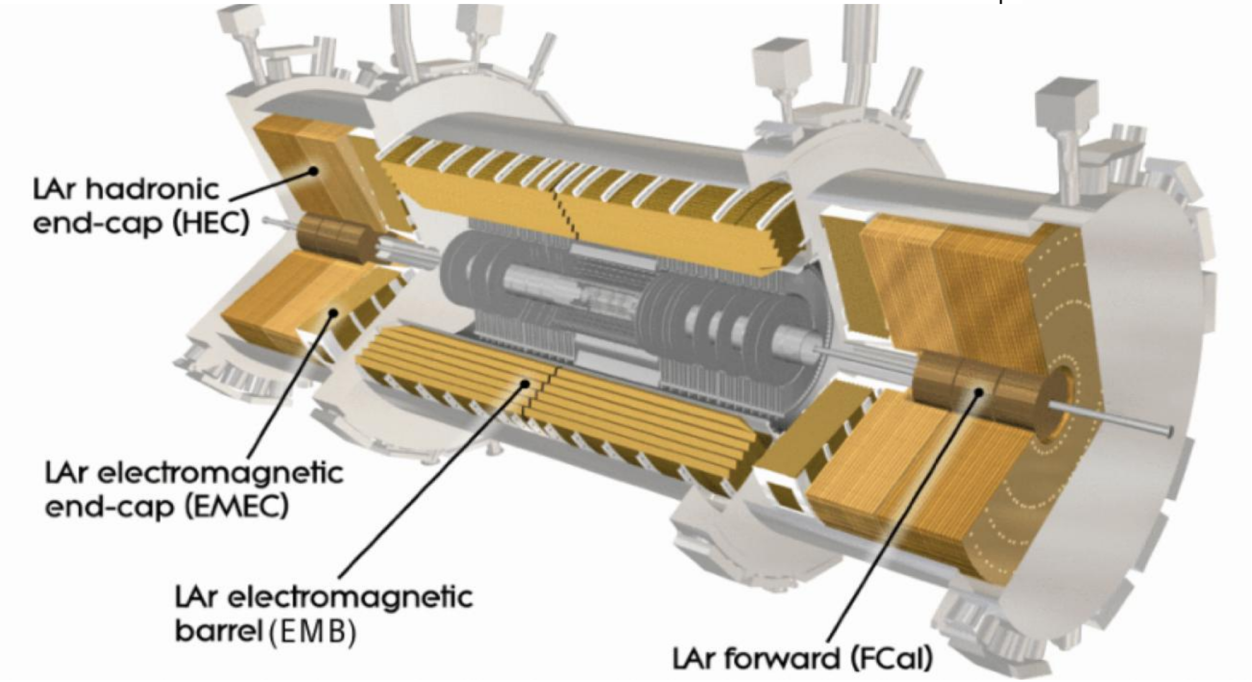


η Bins According to Detector Geometry

Different regions of the calorimeter correspond to different values of |η|

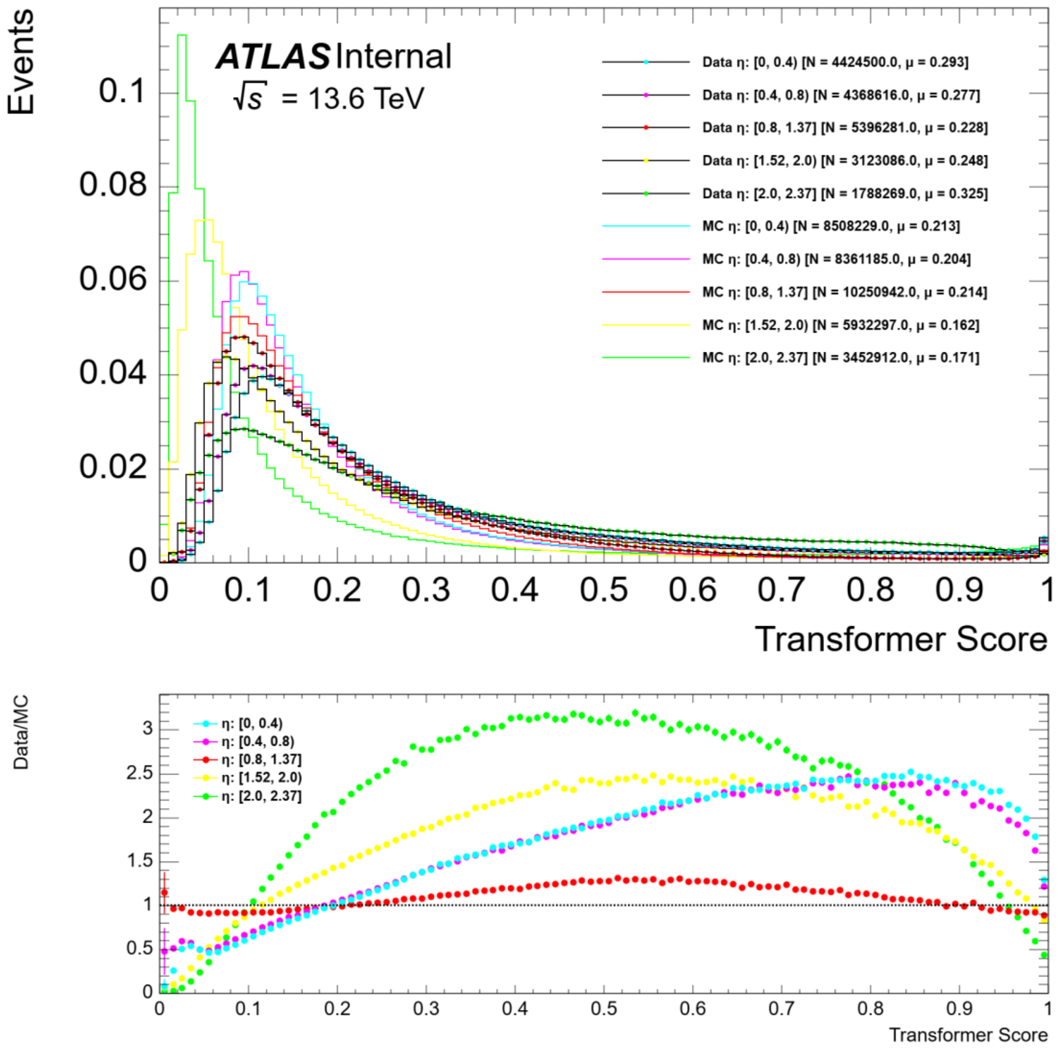
- Inner Barrel: [0, 0.4), [0.4, 0.8)
- Outer Barrel: [0.8, 1.37)
- Endcap: [1.52, 2.0), [2.0, 2.37)





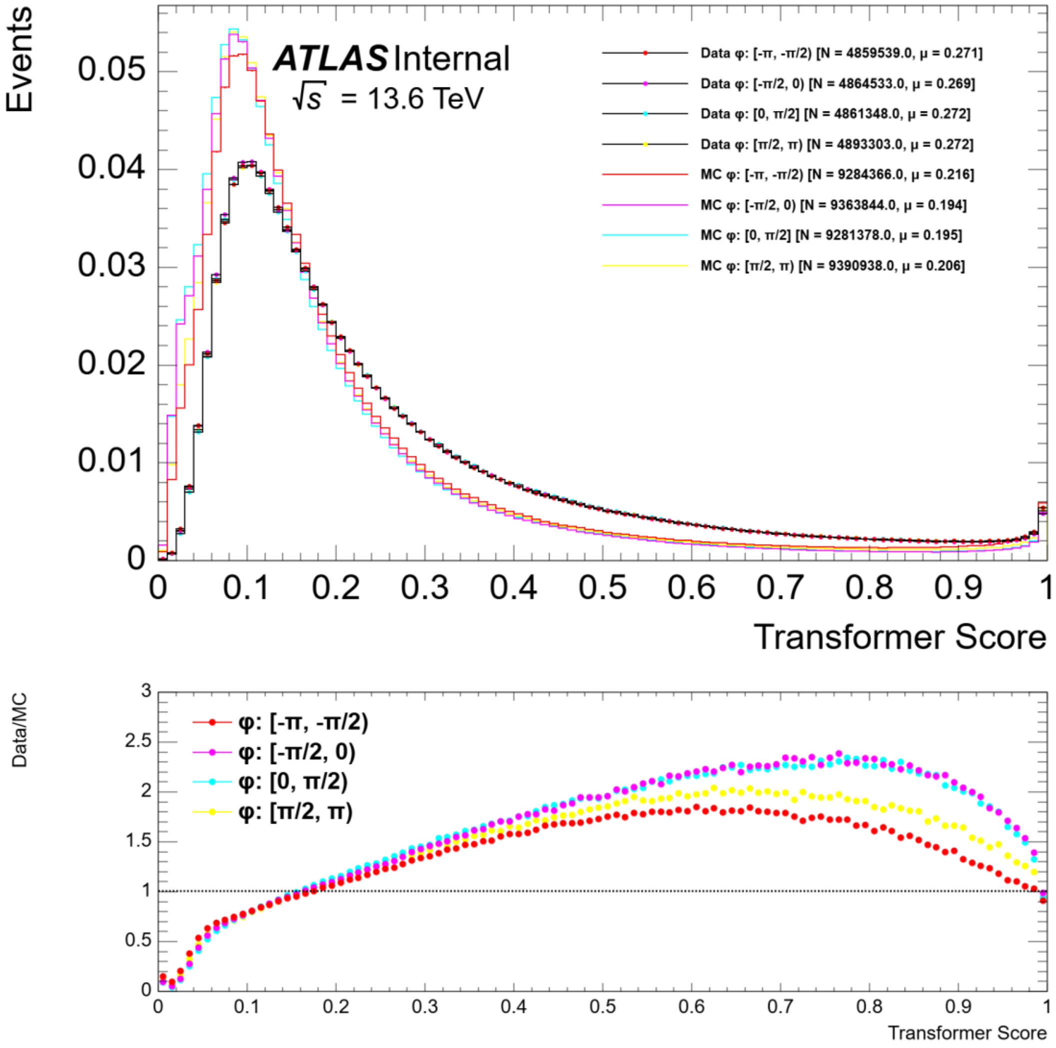
η-Binned Transformer Score

- η Bins: [0, 0.4), [0.4, 0.8), [0.8, 1.37), [1.52, 2.0), [2.0, 2.37)
- There is a significantly stronger agreement between data and simulation in the [0.8, 1.37) bin

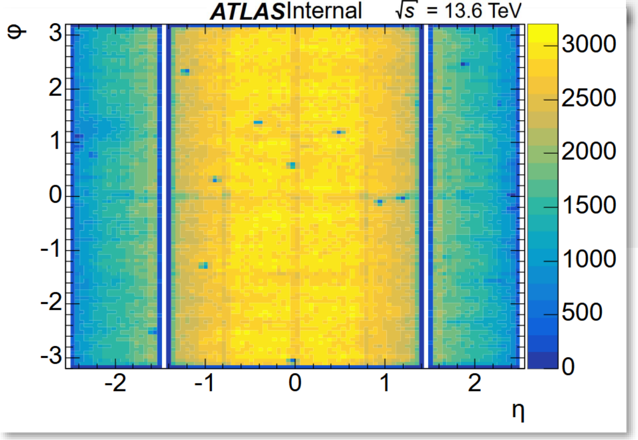


Φ-Binned Transformer Score

- Φ Bins: [-π, - π/2), [- π/2, 0), [0, π/2), [π/2, π)
- Data and simulation show individual consistency across bins
- The disagreement between data and simulation remains in all bins

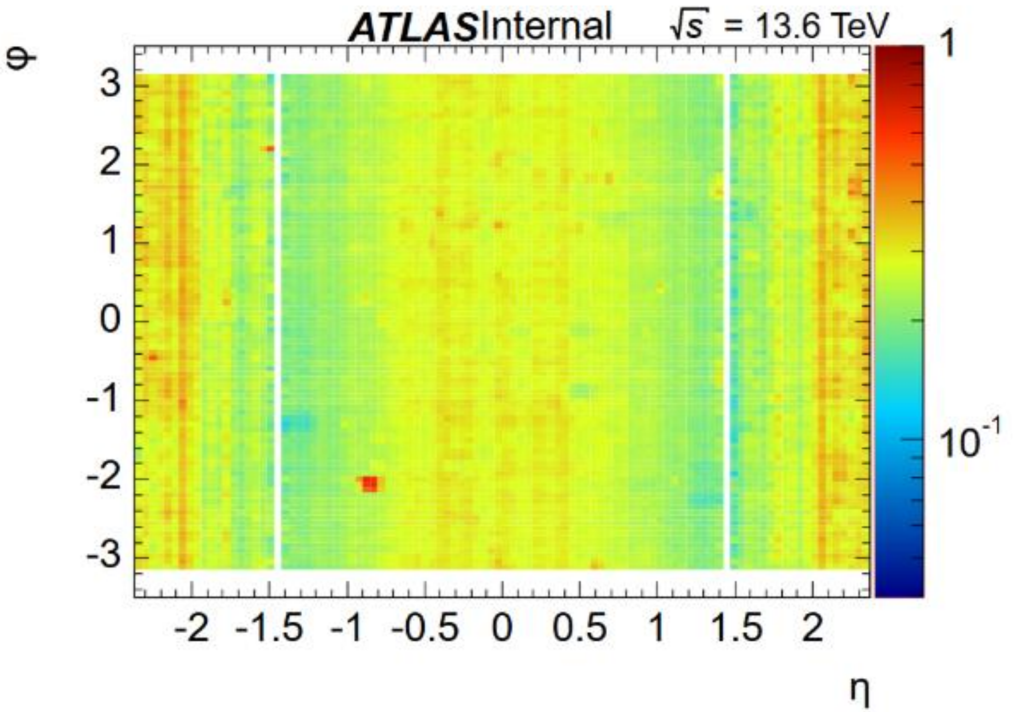


A Spatial Representation of Transformer Score

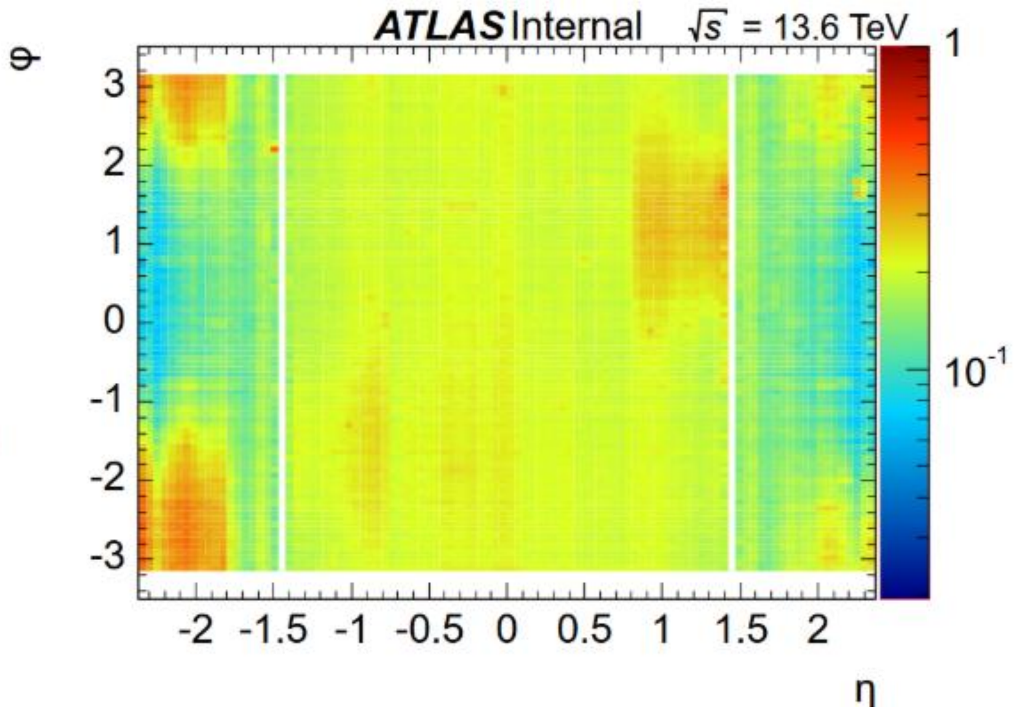


- There is spatially-correlated disagreement between data and simulation transformer scores

Data

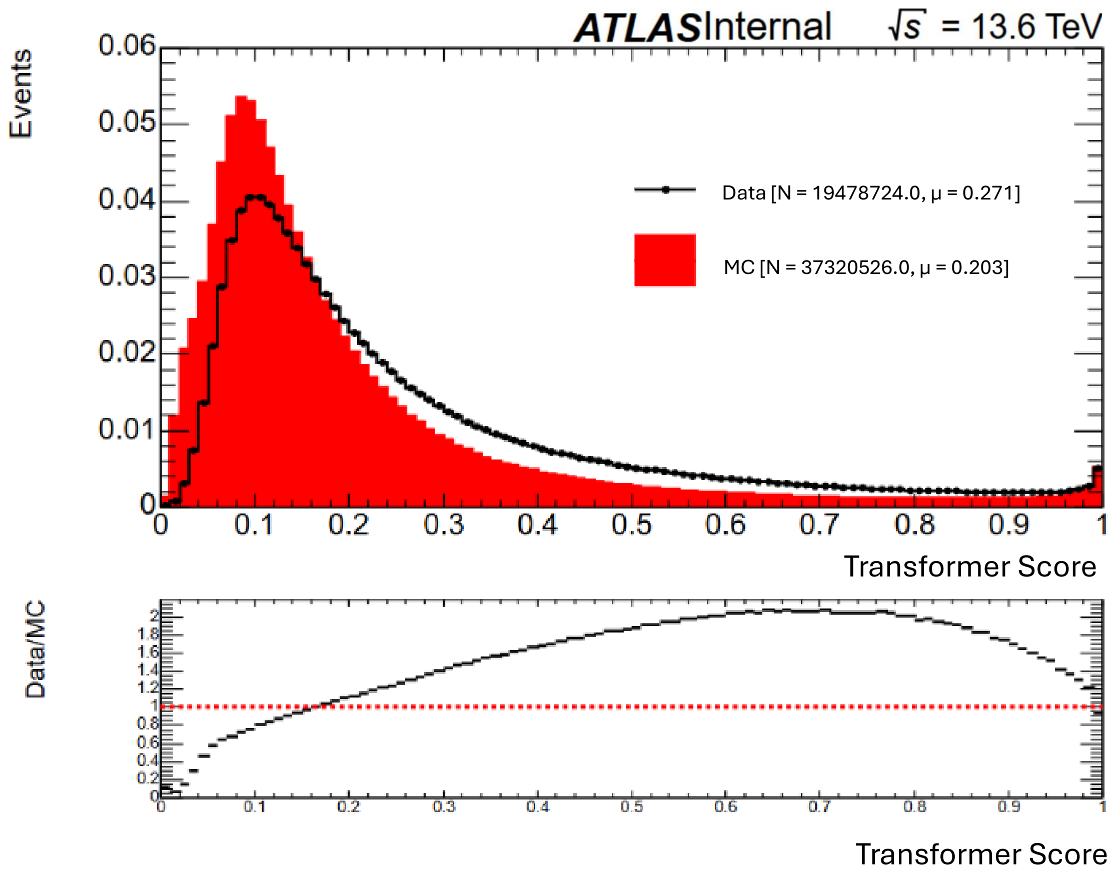


Simulation



Conclusions

Transformer Score for $Z \to e^+e^-$ Sample



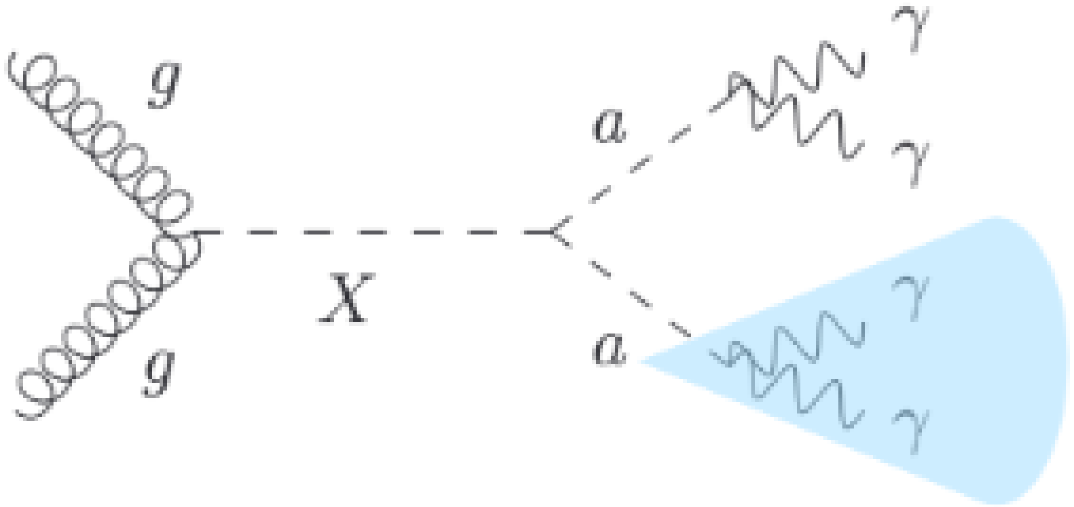
Despite good agreement between data and simulation events in kinematics and SSVs, we see:

- An unexpected magnitude of **disagreement** between data and simulation scores **at high p_T**

- Spatially-localized regions of transformer score disagreements between data and simulation

Future Work

- Re-sample along p_T and η in the training samples to match signal and background distributions
- Re-train the transformer on new samples to improve on the initial round of training
- Re-examine the improved transformer's performance on background samples



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- Professor Georgia Karagiorgi, Professor Reshmi Mukherjee, and Amy Garwood for all of the hard work that made this REU possible
- My fellow REUs and everyone at Nevis for making this summer so much fun
- The NSF for funding this research

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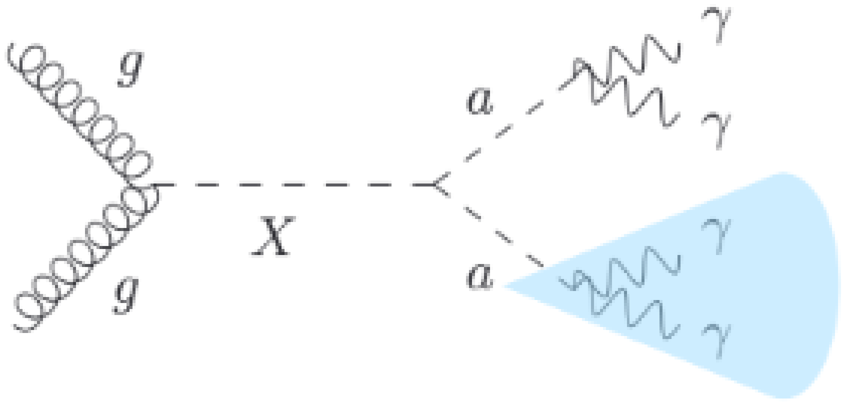
Questions?



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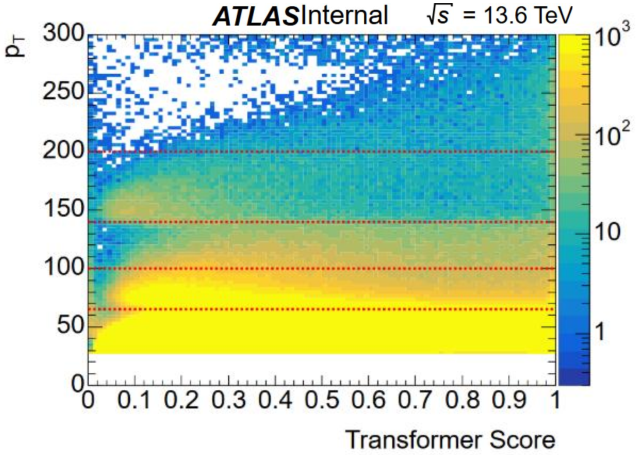
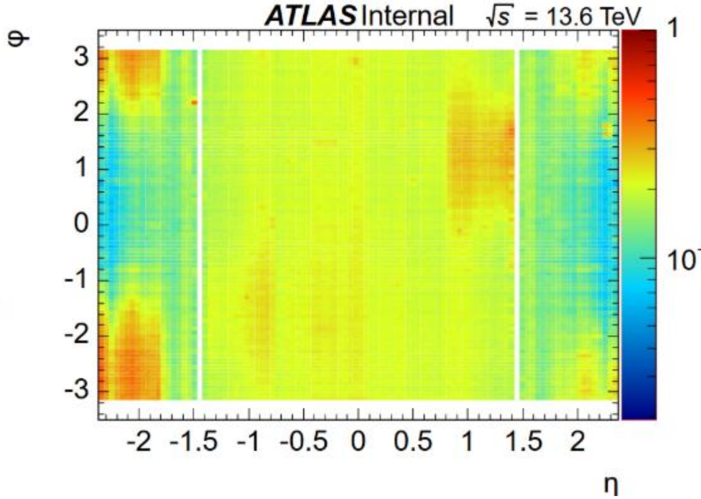
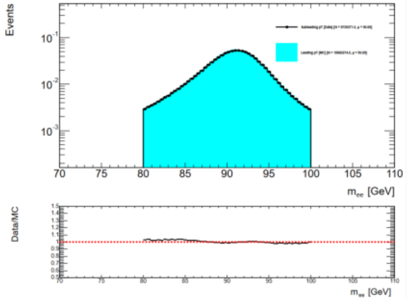


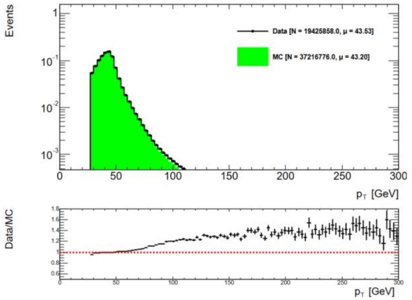
ATLAS Internal
$\sqrt{s}$ = 13.6 TeV
p_T
Transformer Score



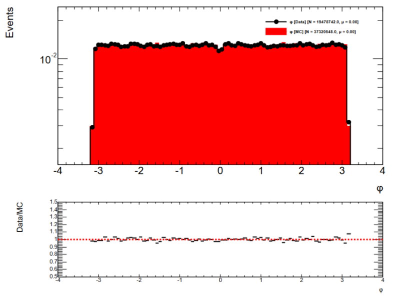
ATLAS Internal
$\sqrt{s}$ = 13.6 TeV
φ
η



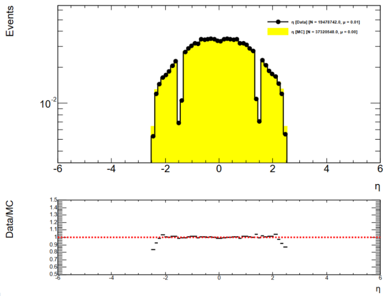
Events
Data/MC
m_{ee} [GeV]



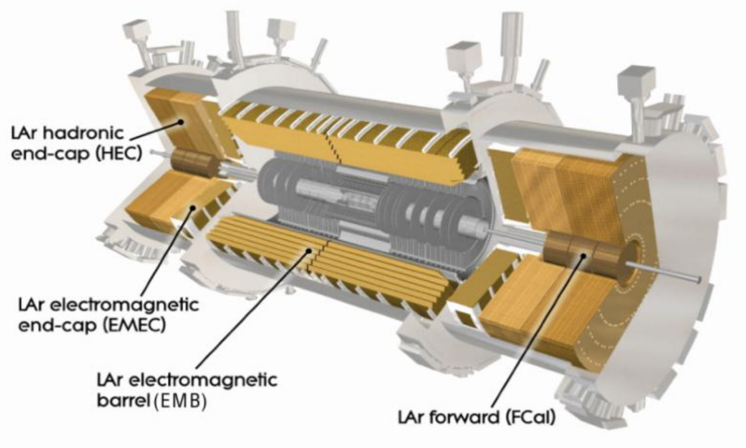
Events
Data [N = 19425858.0, μ = 43.53]
MC [N = 37216776.0, μ = 43.20]
Data/MC
p_T [GeV]



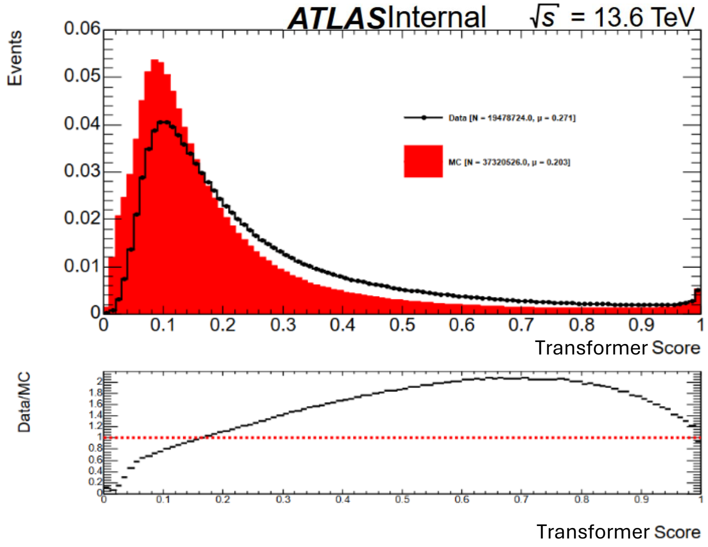
Events
Data/MC
φ



Events
Data/MC
η



LAr hadronic end-cap (HEC)
LAr electromagnetic end-cap (EMEC)
LAr electromagnetic barrel (EMB)
LAr forward (FCal)

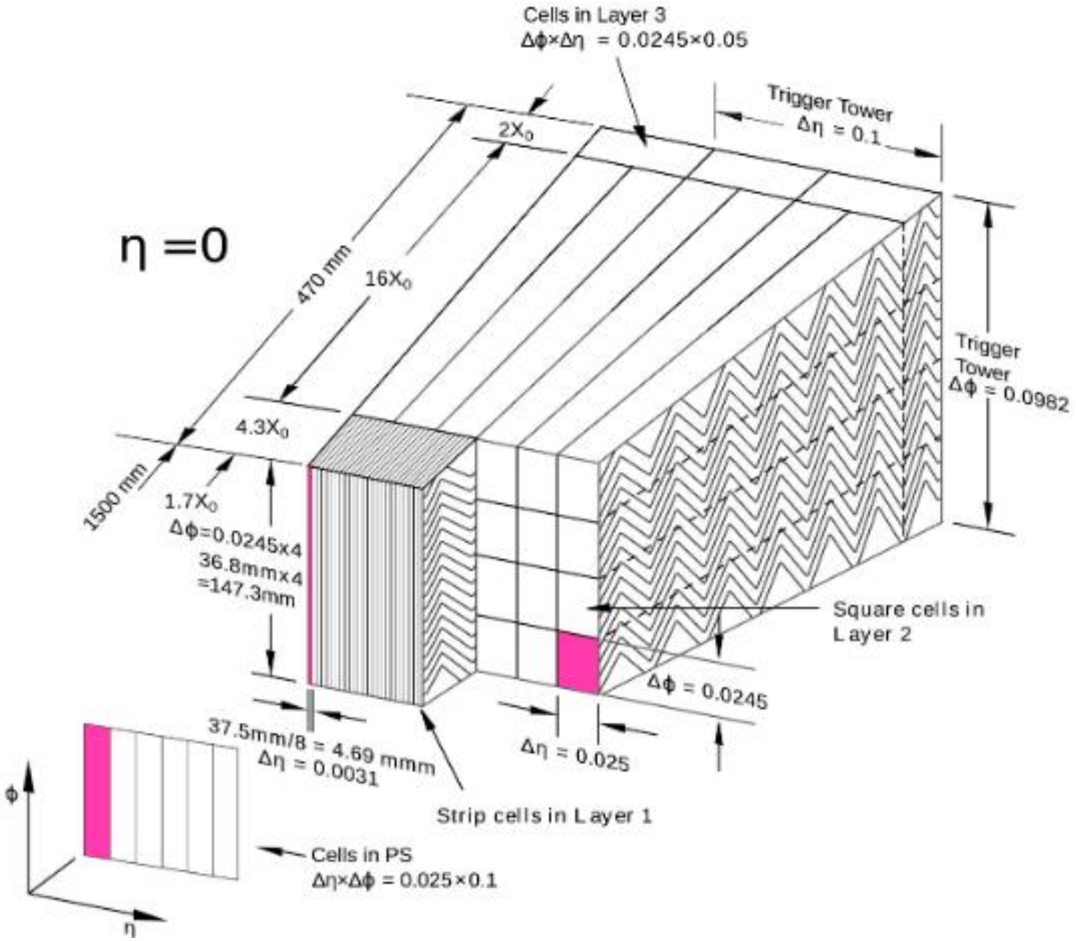


ATLAS Internal
$\sqrt{s}$ = 13.6 TeV
Events
Data [N = 19478724.0, μ = 0.271]
MC [N = 37320526.0, μ = 0.203]
Transformer Score
Data/MC
Transformer Score

Backup

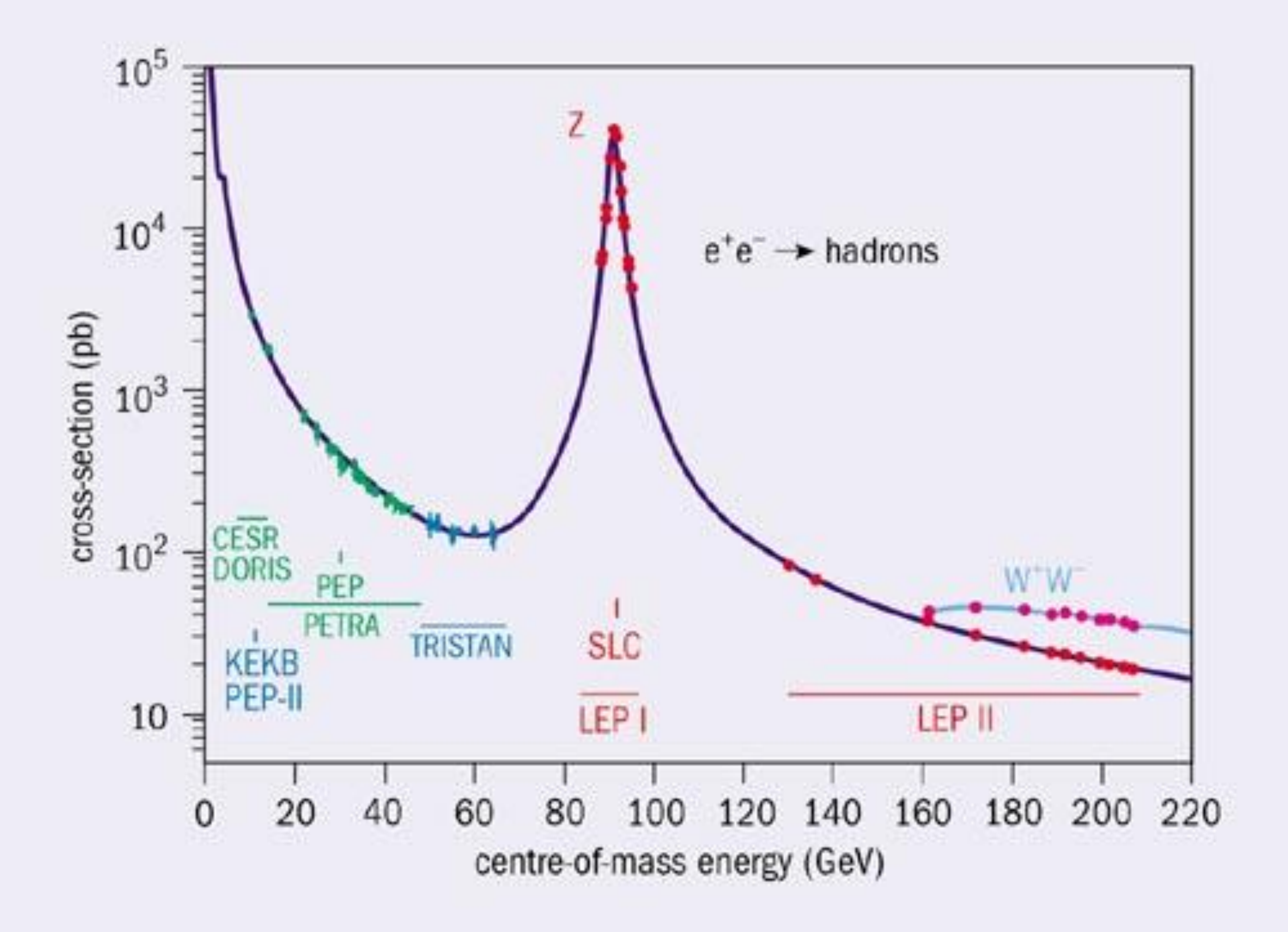
The Liquid Argon Calorimeter

- Measures energies of EM particles
- 3 Layers:
  1. Fine Granularity Strips
  2. Majority of Energy Collection
  3. High Energy Shower Correction



Z Boson Data

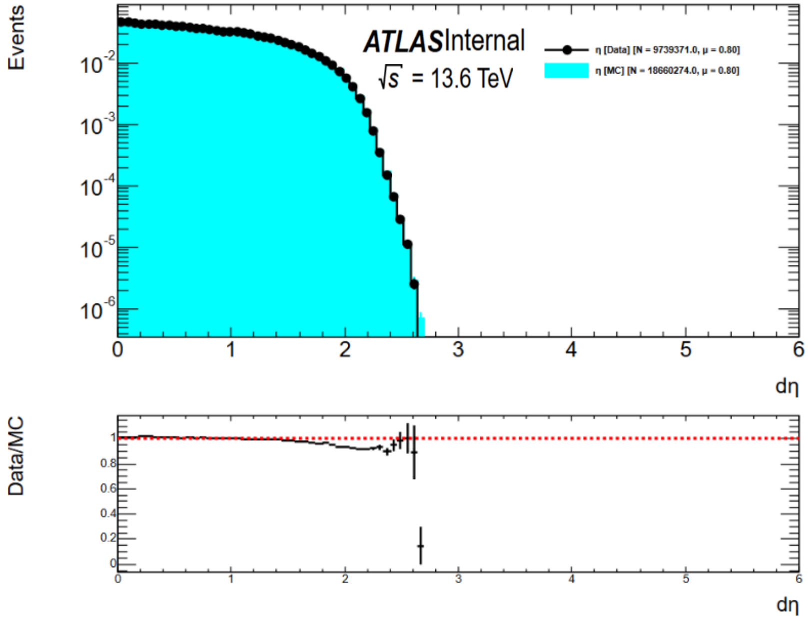
- In data, the Z boson occurs far more frequently than the noise around it
- Strongest peak: 80-100 GeV
- Allows for good assurance when using data as background validation



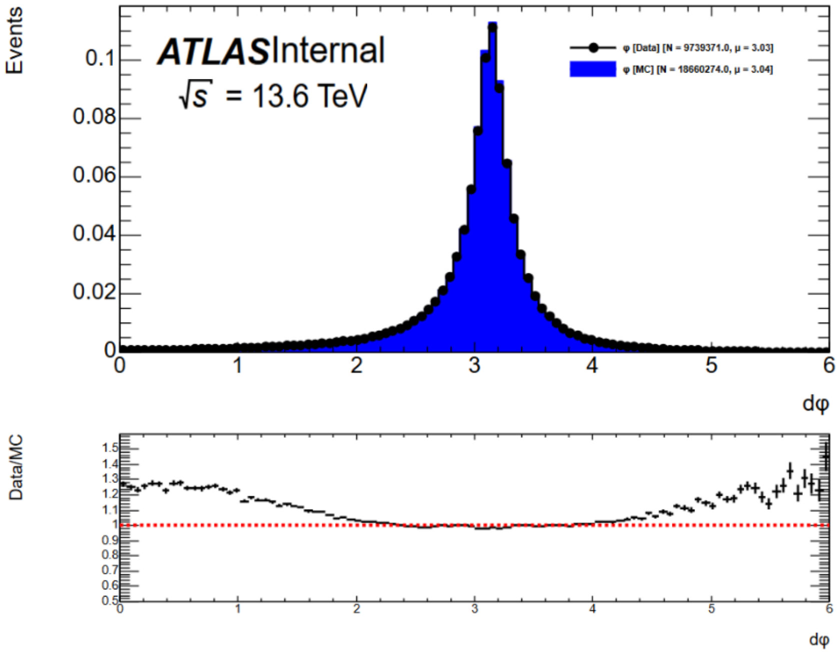
CERN Courier, 2004

Further Kinematic Plots

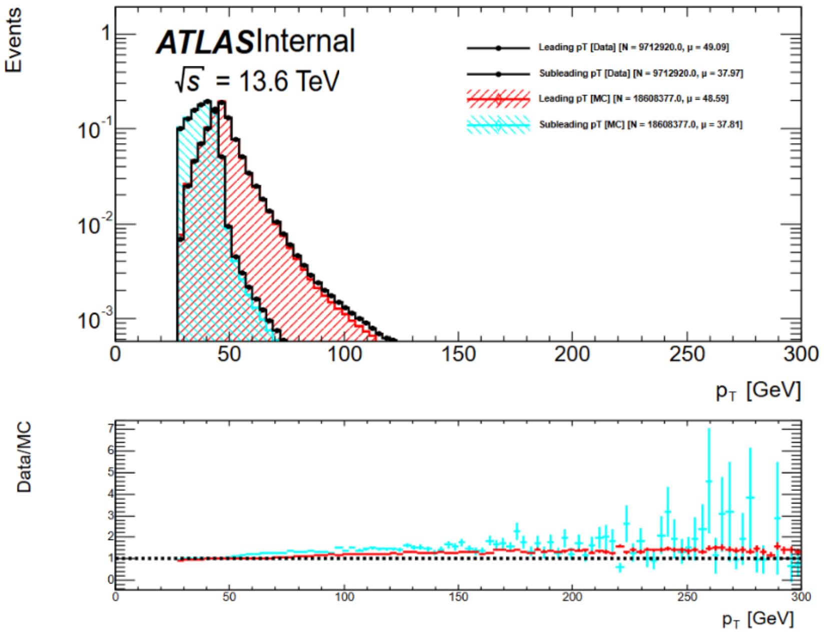
Pseudorapidity e⁻ Separation (dη)



Azimuthal e⁻ Separation (dΦ)

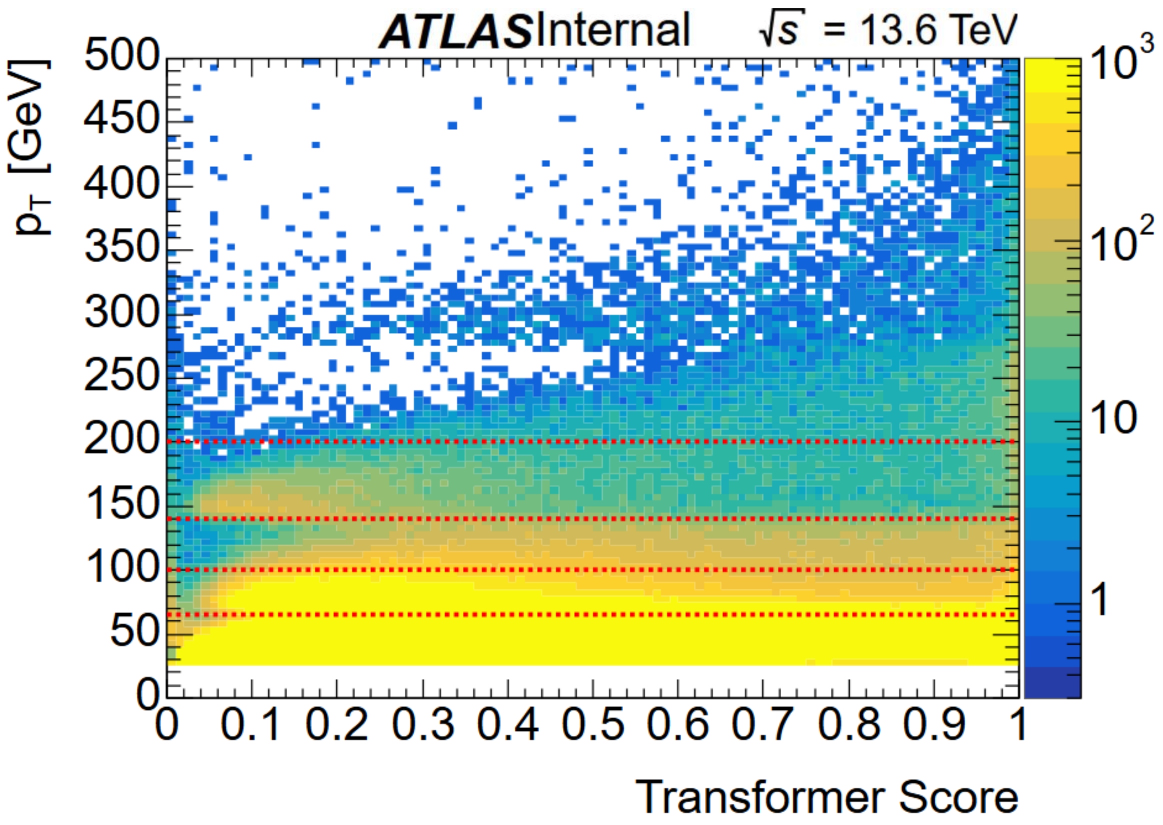


Leading and Sub-leading p_T

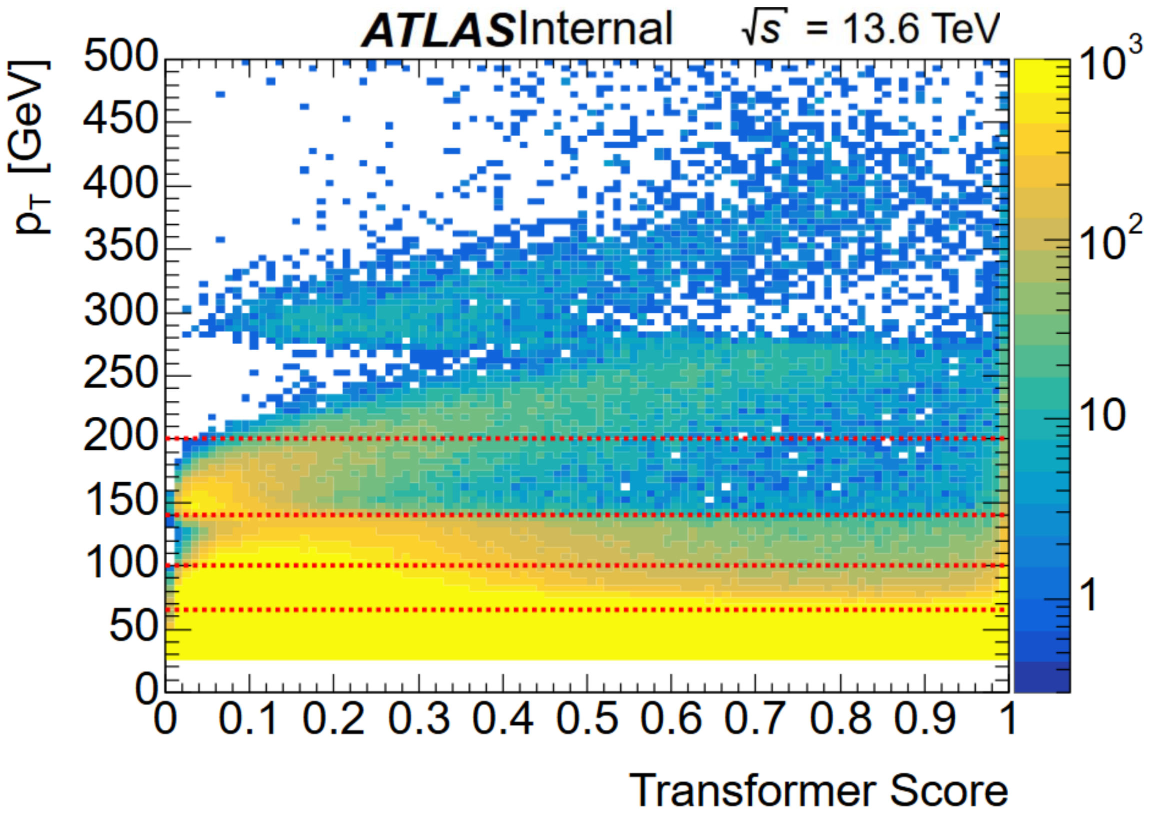


Extended p_T-Score Distribution

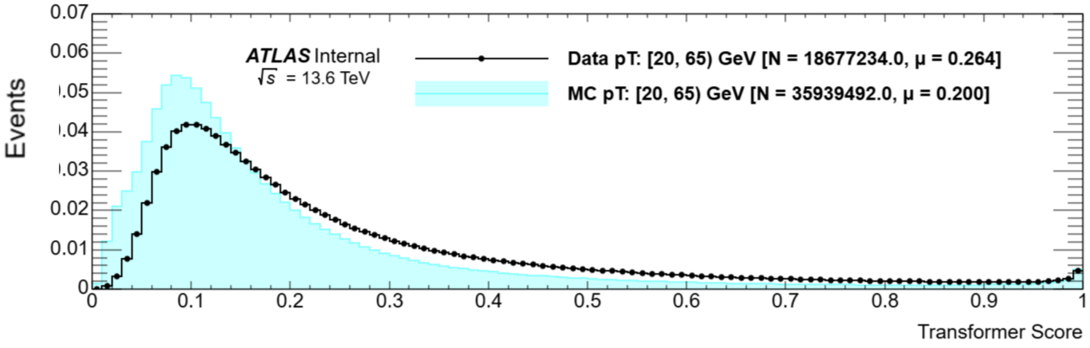
Data

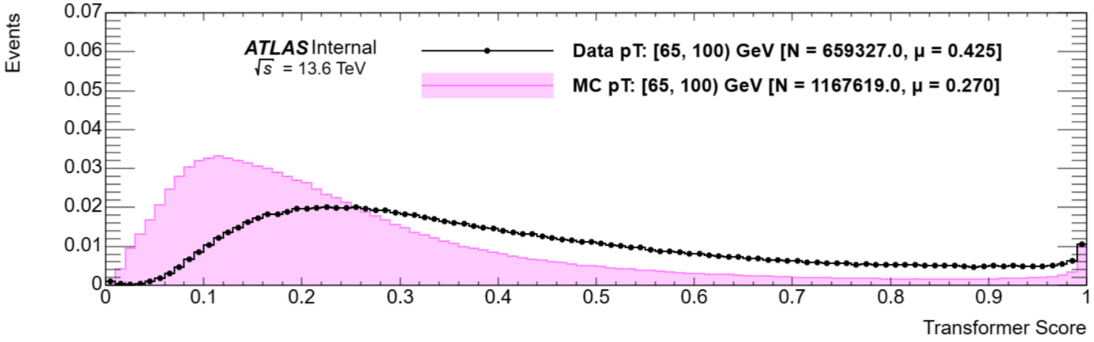


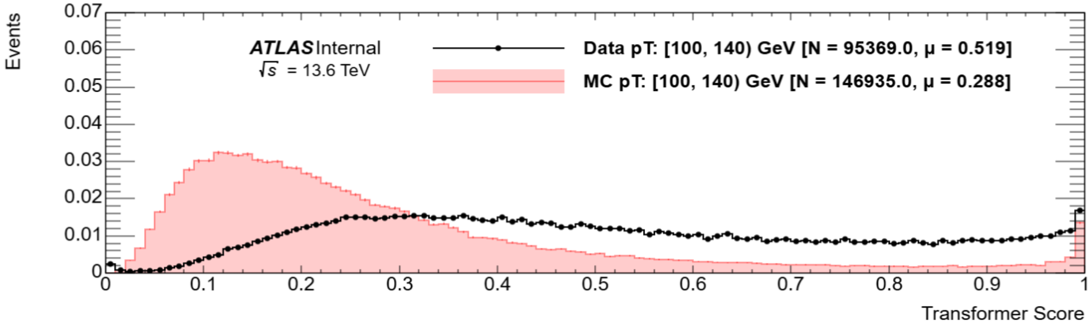
Simulation

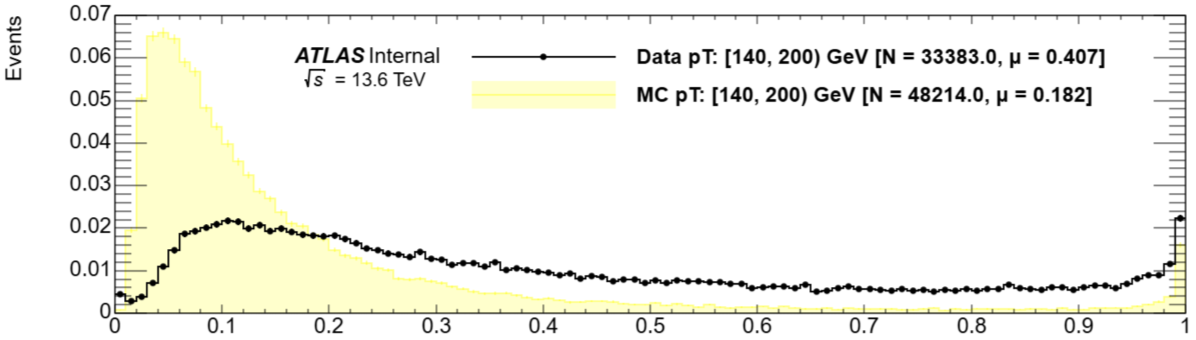


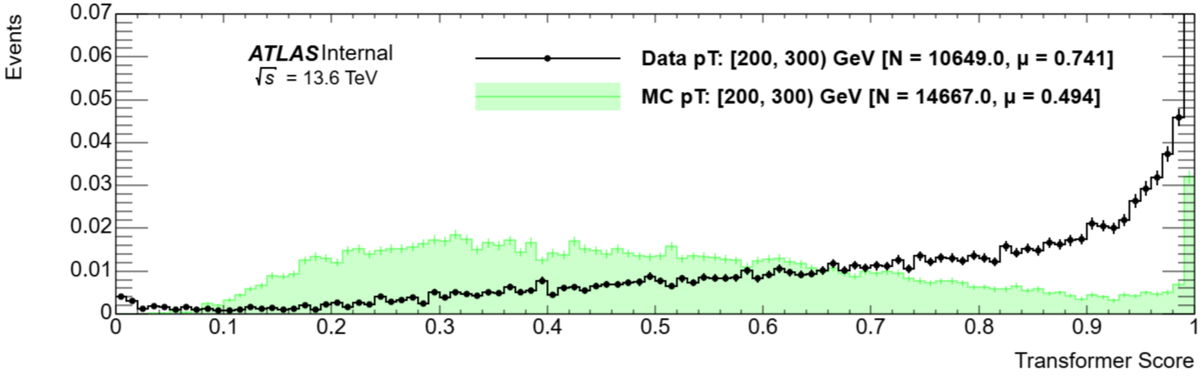
Transformer Score - Stratified p_T Binning



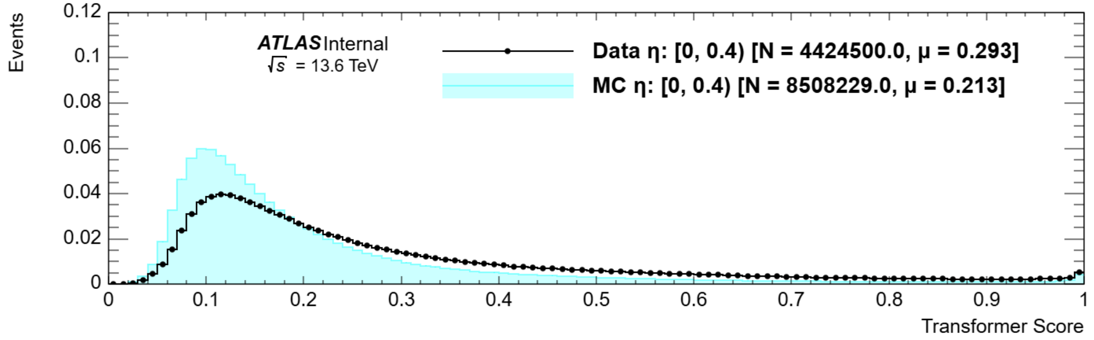


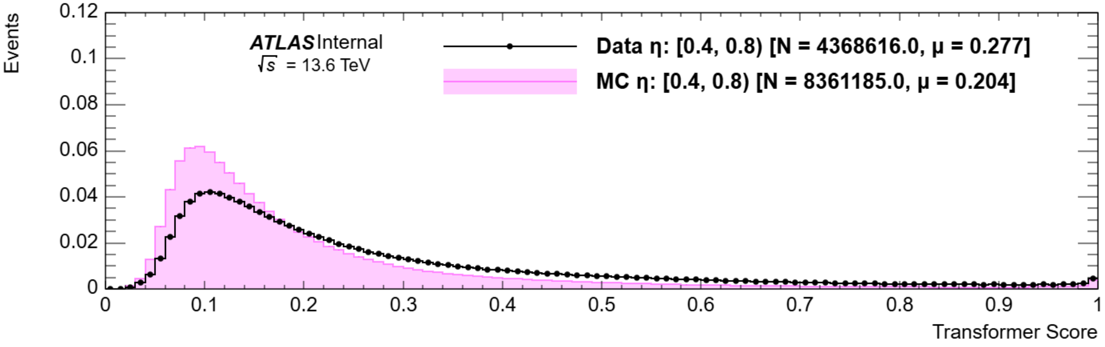


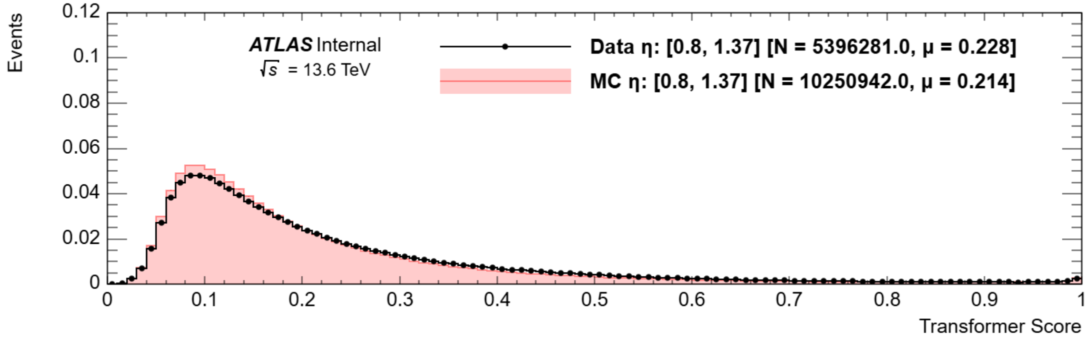


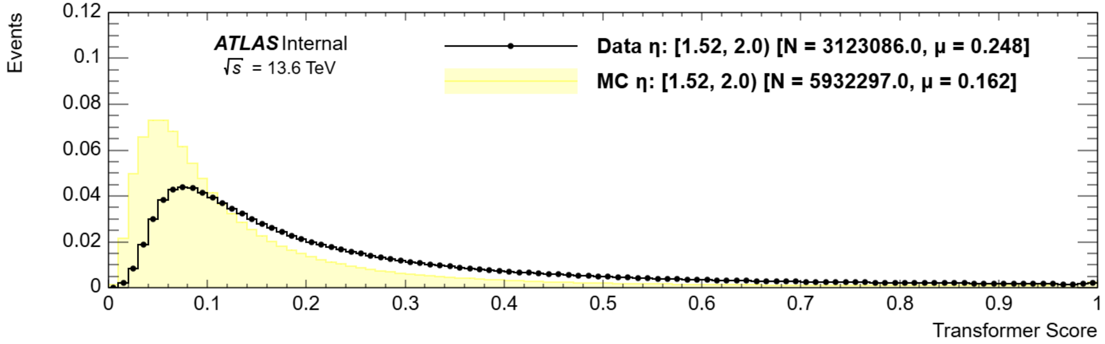


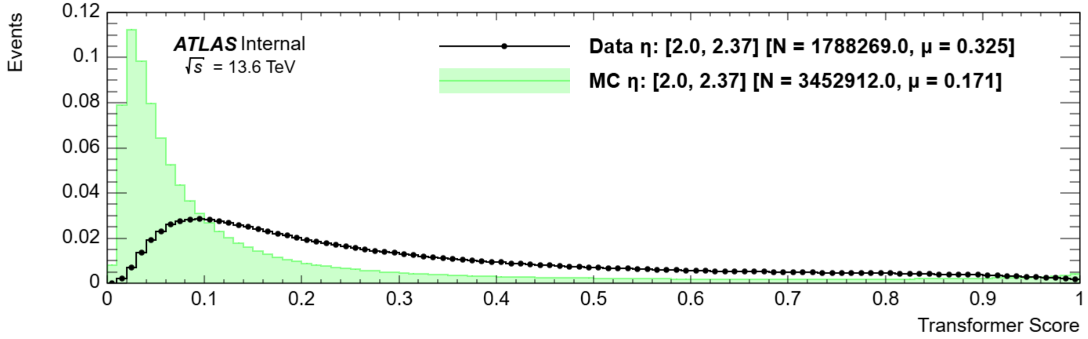
Transformer Score - Stratified η Binning





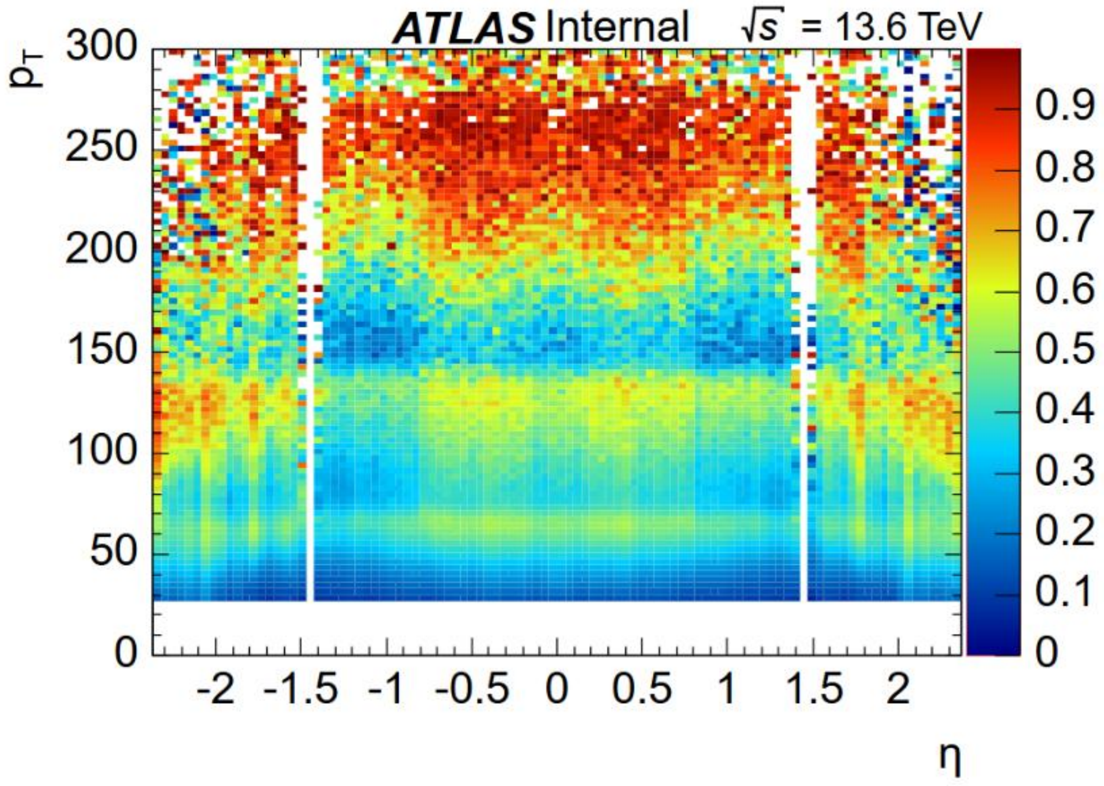




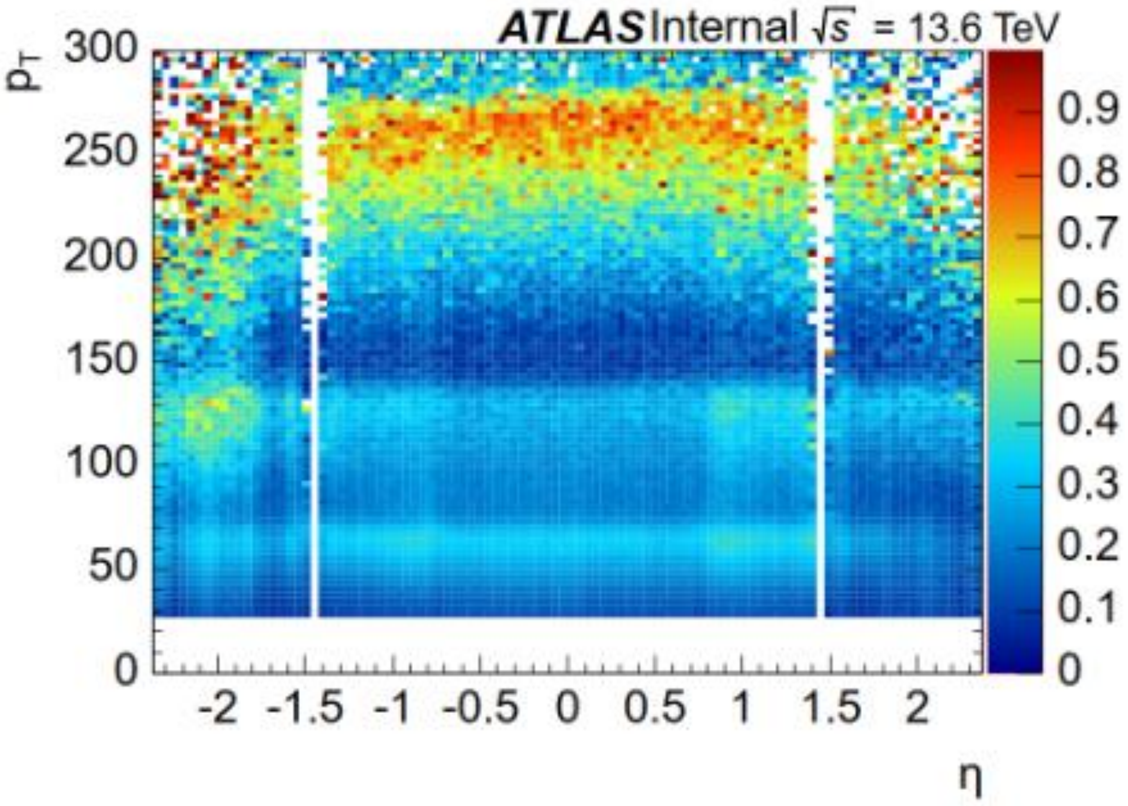


2-Variable Kinematic Score Correlations – p_T vs η

Data

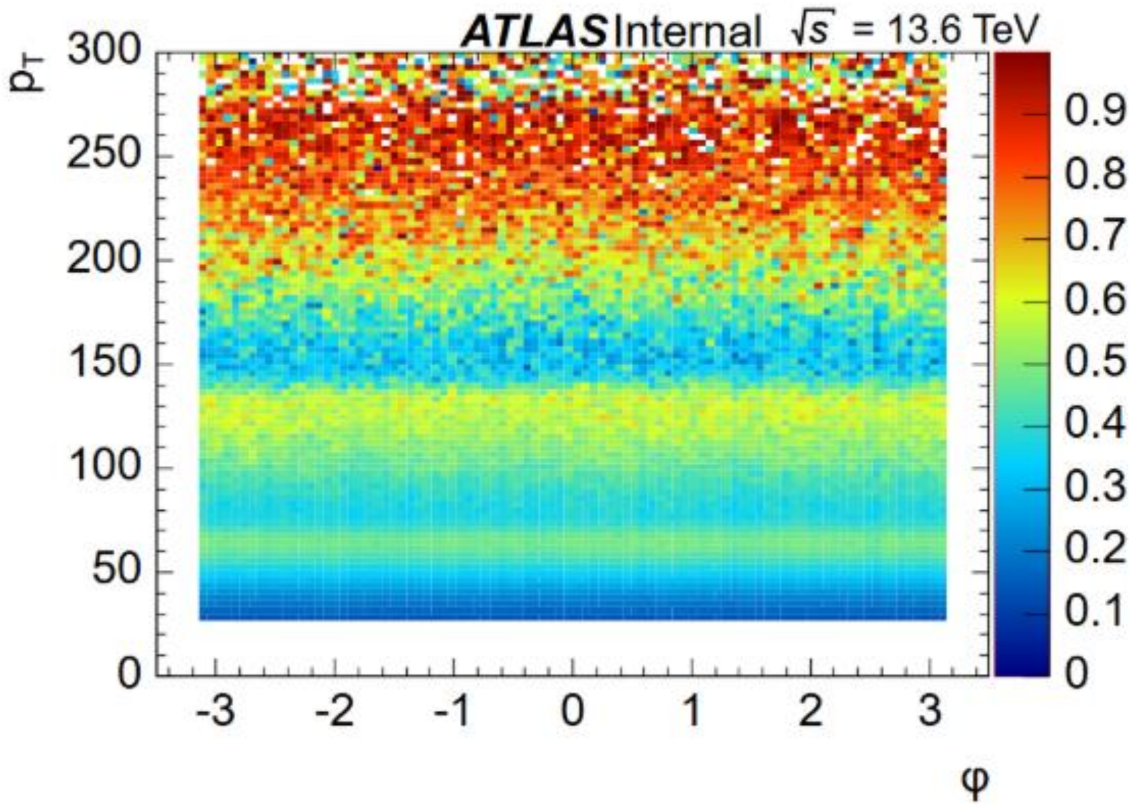


Simulation



2-Variable Kinematic Score Correlations – p_T vs Φ

Data



Simulation