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EXPLAINABLE AI FOR ML JET TAGGERS

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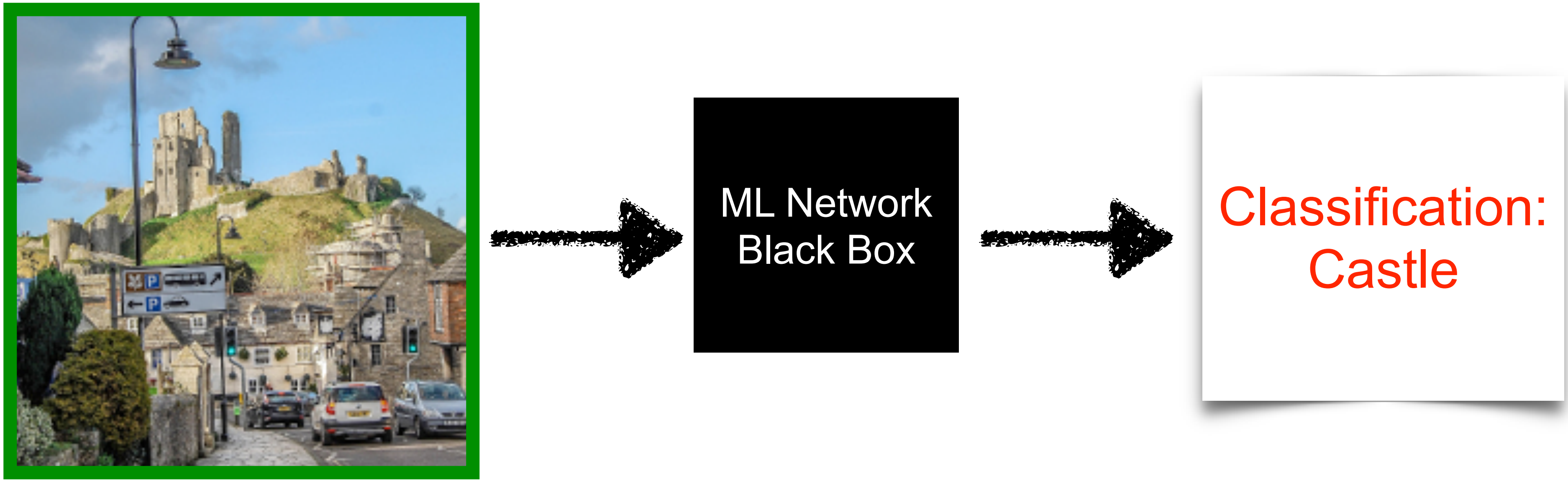
Motivation



https://doi.org/10.1007/978-3-030-28954-6_10

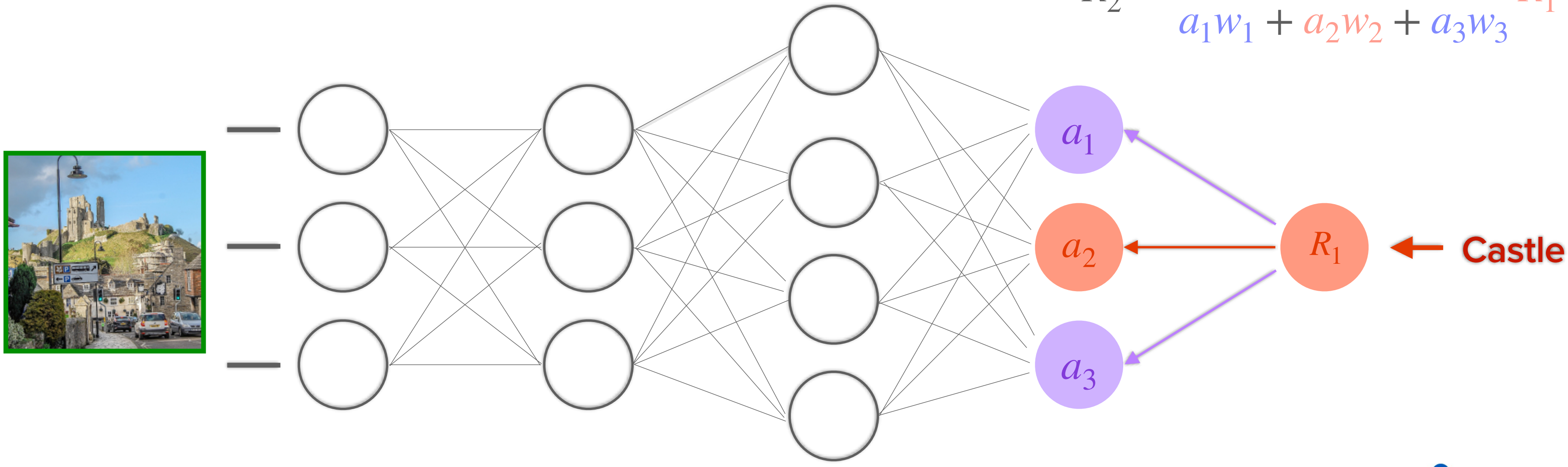
How do we understand the network's decision-making process?

ML explainability with LRP

LRP (layer-wise relevance propagation) propagates a prediction backwards through the network, assigning a relevance to each input

$$R_j = \sum_k \frac{a_j w_{jk}}{\sum_{0,j} a_j w_{jk}} R_k$$

$$R_2 = \frac{a_2 w_2}{a_1 w_1 + a_2 w_2 + a_3 w_3} R_1$$



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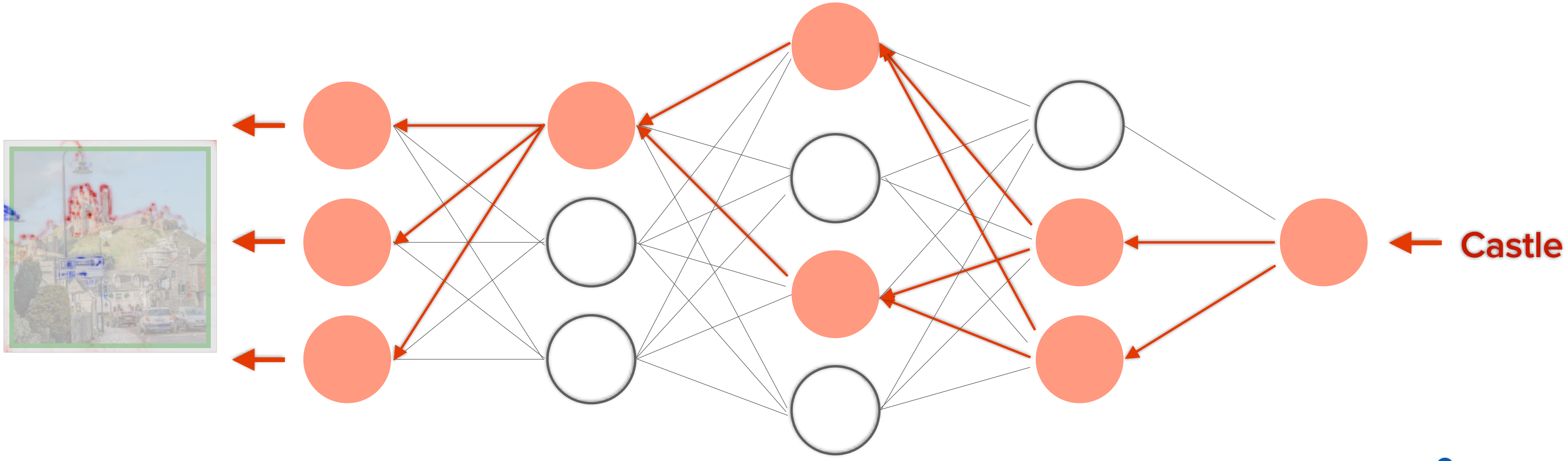
ML explainability with LRP

- **Relevance is conserved -** the prediction is not changed
- **LRP attributes the entirety of the network's decision to the inputs**
  - Visualized as a heat map, in the case of images



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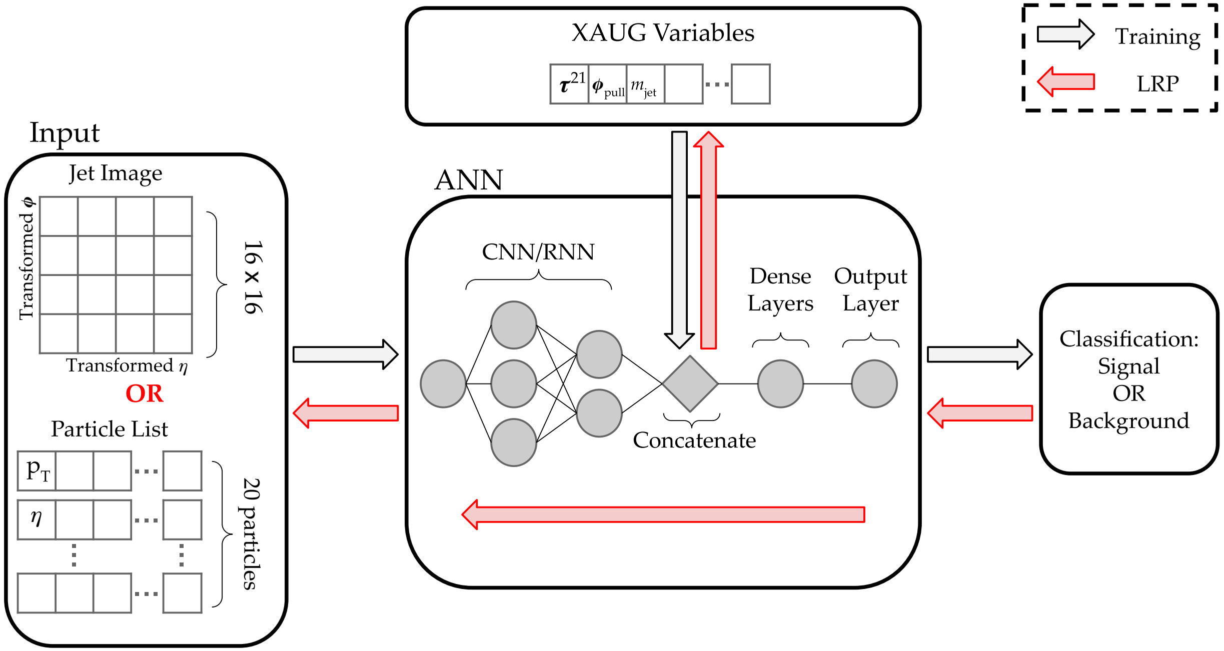
ML explainability with XAUG Variables

- **Goal:** explain decisions of ML jet classifiers using expert augmented (XAUG) variables

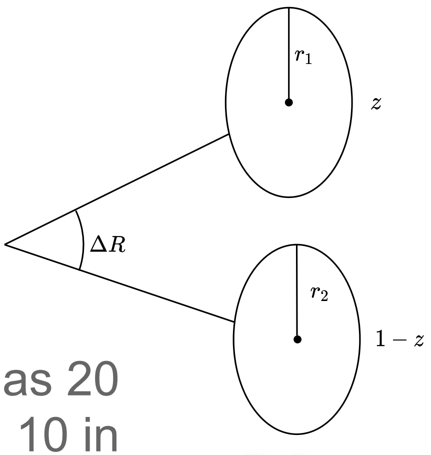
- **Method:** Input XAUGs into jet tagger, analyze network decision with LRP, and compare to network without XAUGs



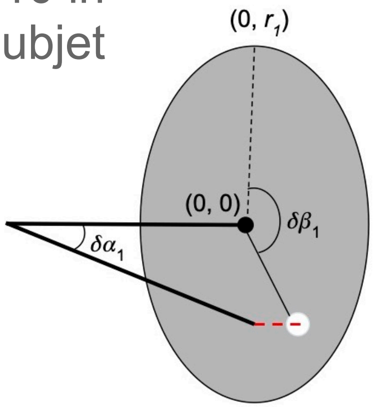
TOY MODEL

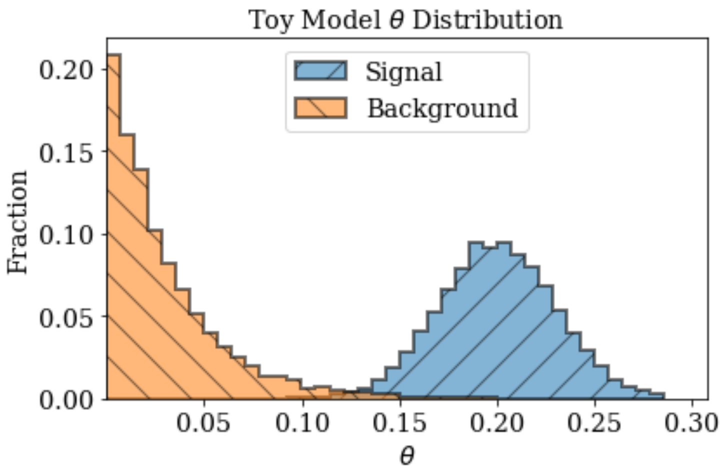
Toy Model

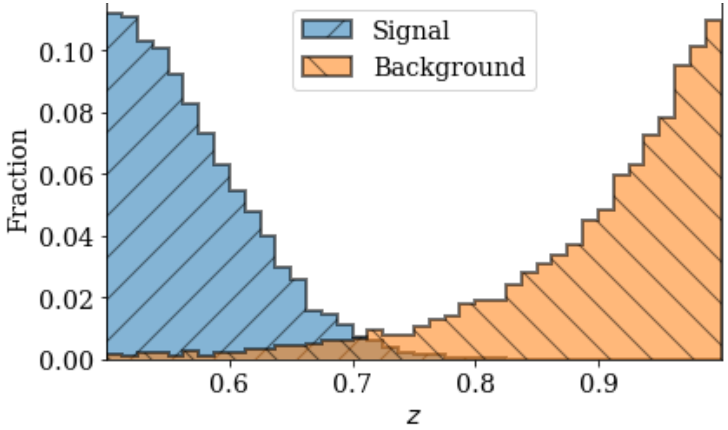
- **Toy events simulated to mimic particle-level events**
- **Goal: capture all event information with a few variables**



Each “jet” has 20 particles, 10 in each subjet

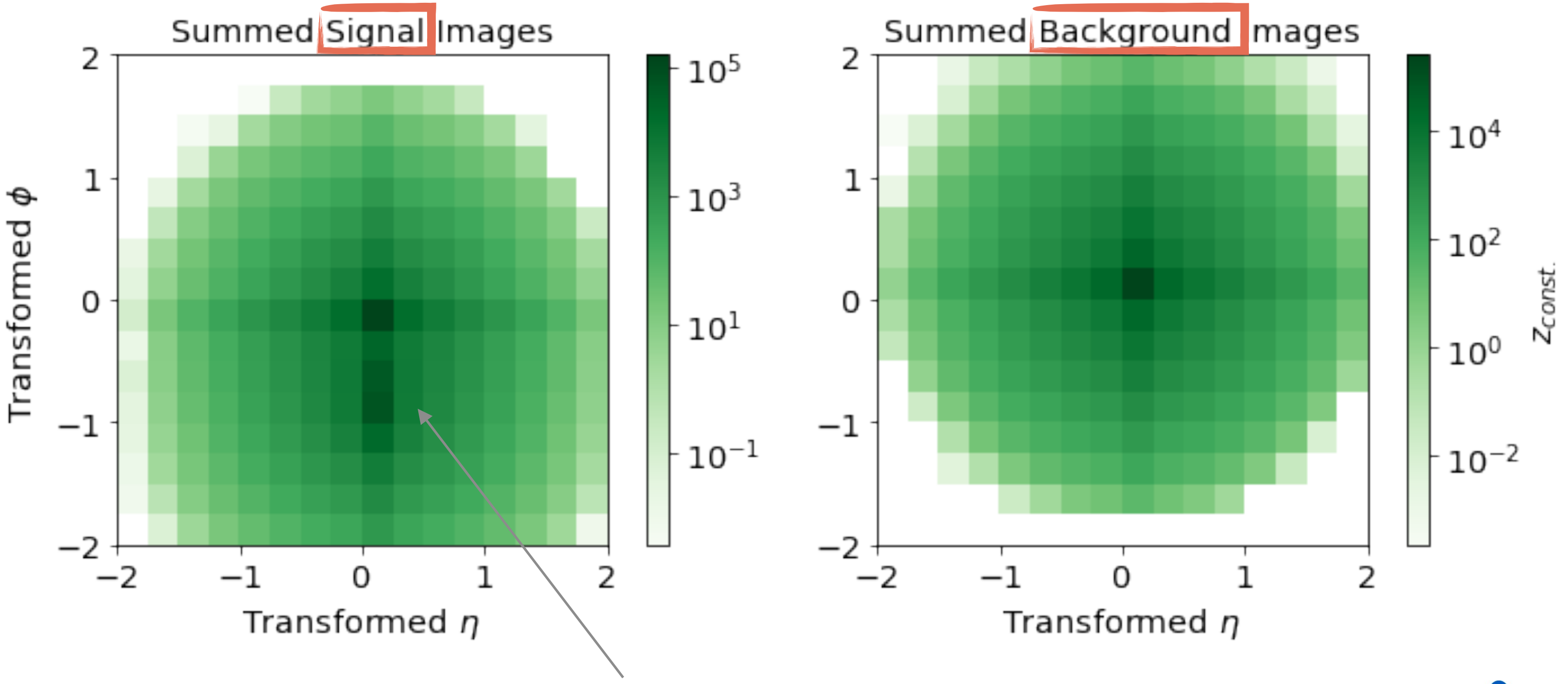






Toy Model

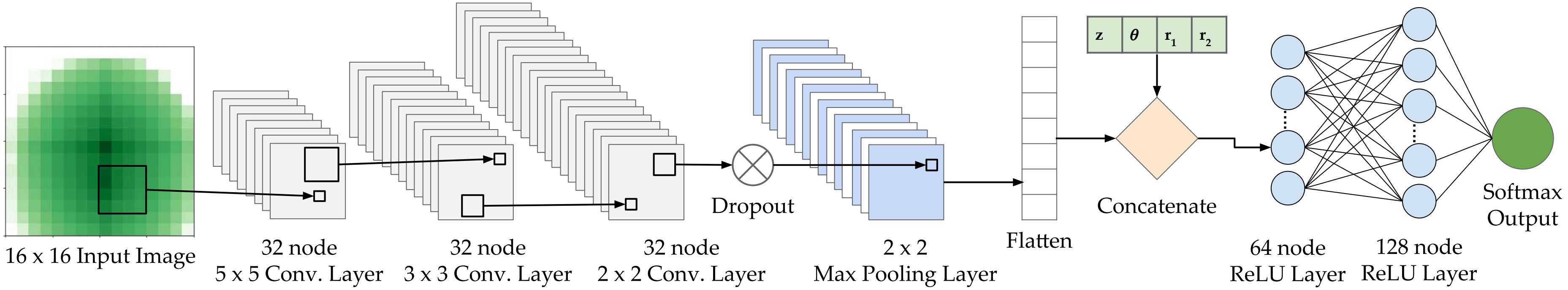
- **Image pre-processing**
  - Leading-p_T subjet at (0,0), sub-leading at (0,-1)
  - Parity flip



Much more pronounced second subjet

2DCNN

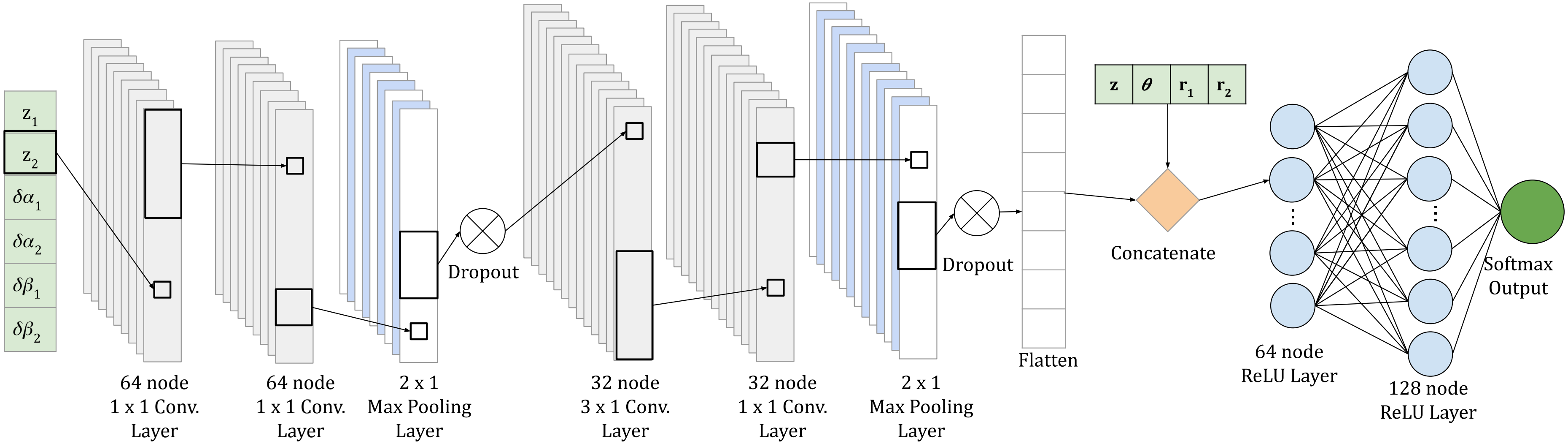
Architecture based on ImageTop network



10.1088/1748-0221/15/06/P06005

1DCNN

Architecture based on DeepAK8 jet classifier



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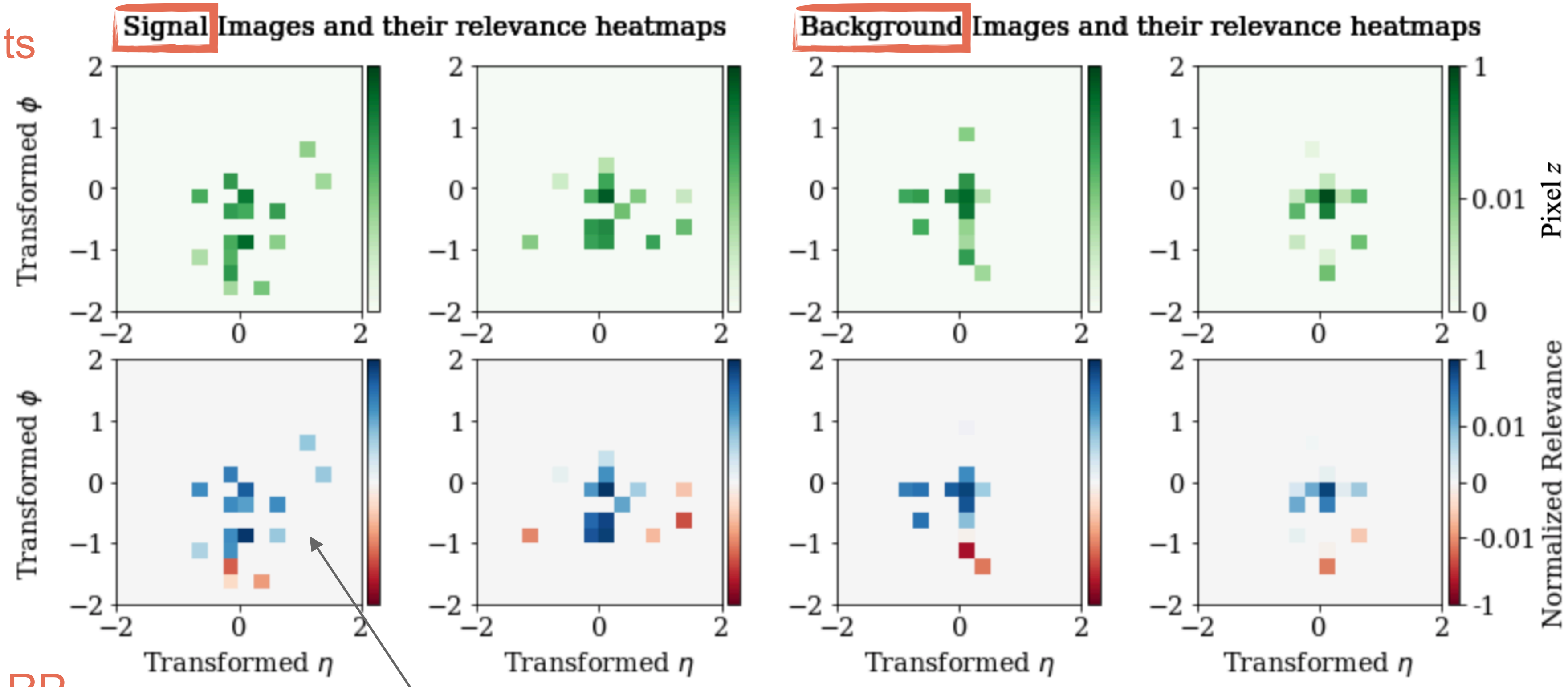
Toy 2DCNN LRP Heatmaps

Inputs

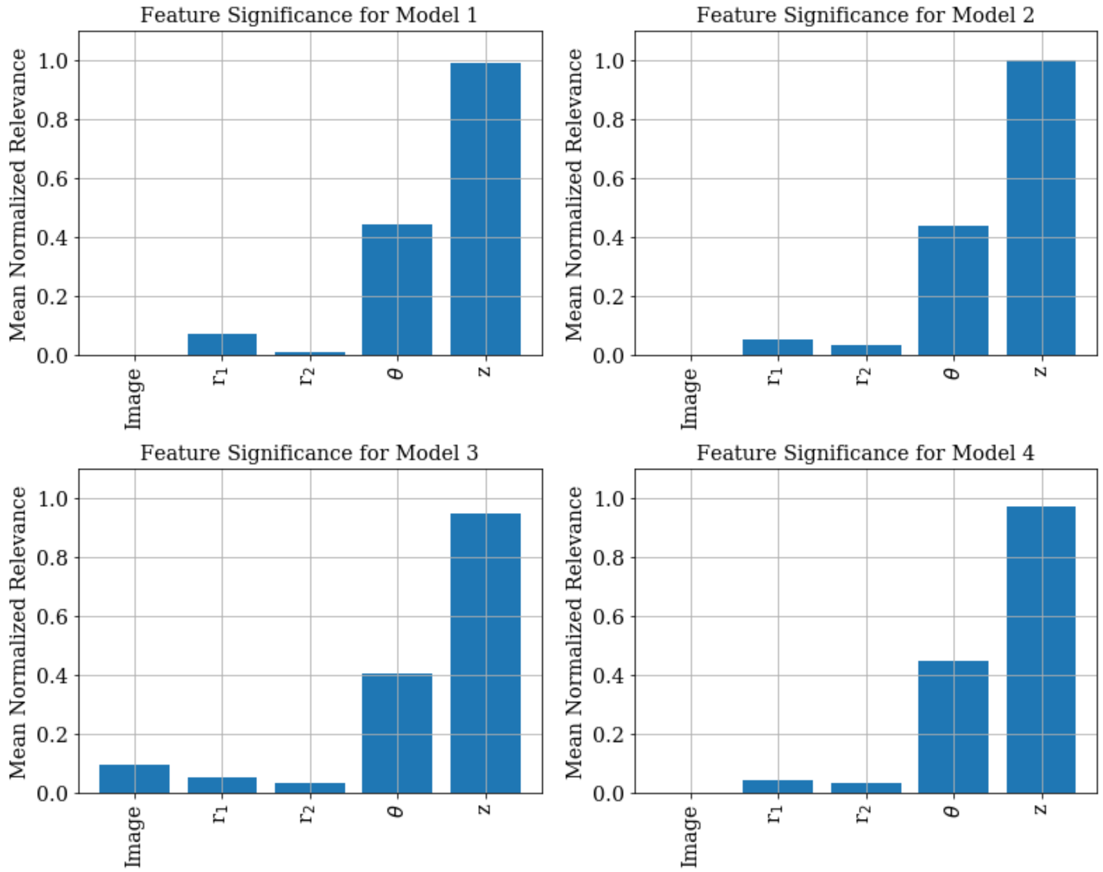


LRP Results

Signal: more relevance along ϕ axis

Toy 2DCNN Results

- **Mean normalized relevance**
  - **For each event:** find feature with max absolute LRP score, divide all scores by this max value
    - **For each image:** sum absolute value of normalized pixels to get a single image LRP score
  - **For each feature:** average normalized relevance scores across all events



Feature Significance for Model 1

Feature Significance for Model 2

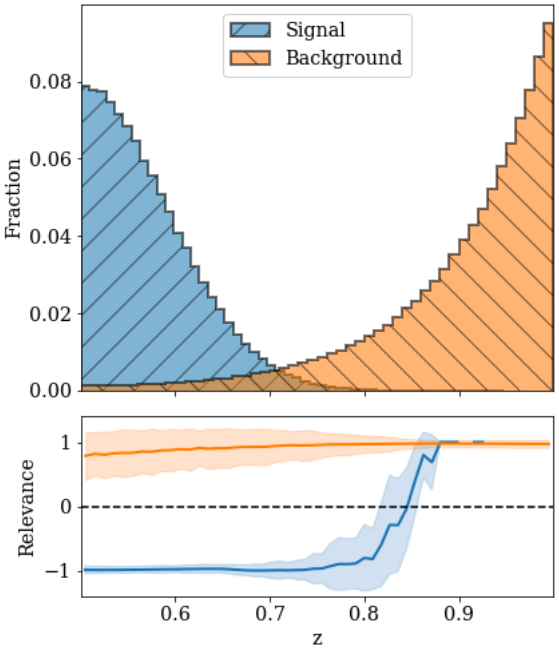
Feature Significance for Model 3

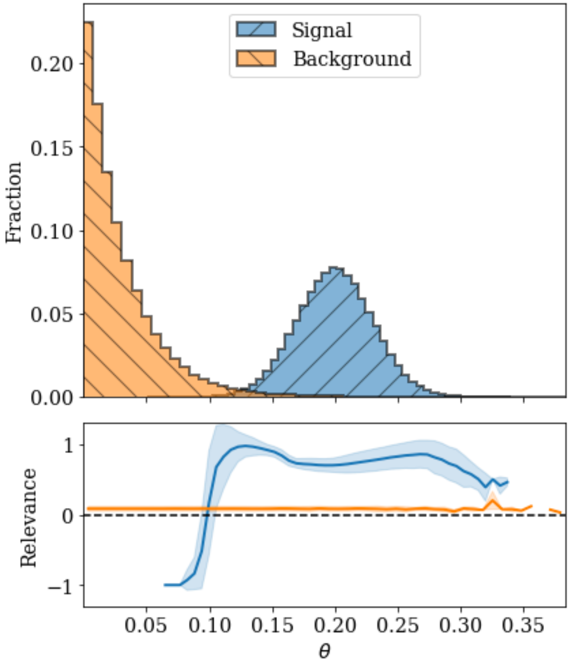
Feature Significance for Model 4

Some variation between trainings

Toy 2DCNN Results

- **Profile plots:** relevance vs corresponding input variable
- For some profiles relevance appears to reflect input distribution, but other don’t - **networks’ decision boundaries live in a higher dimensional space**

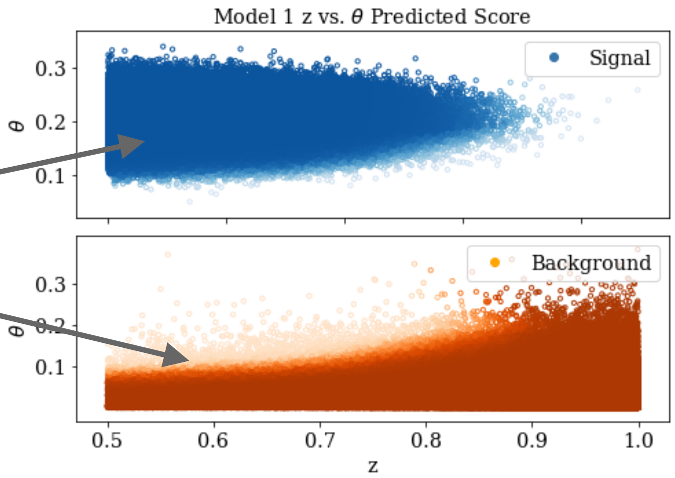


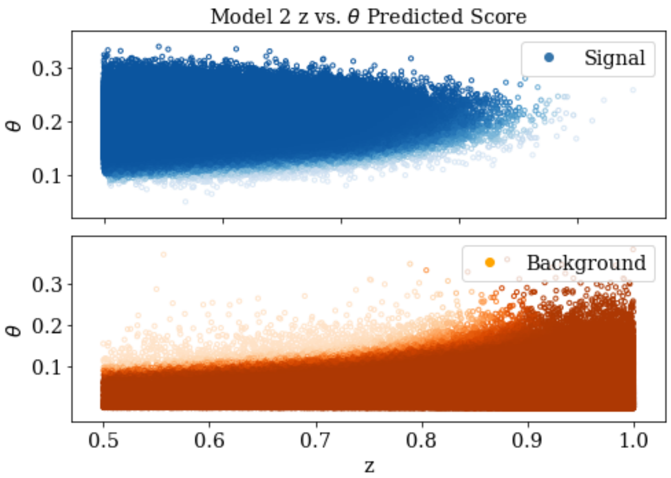


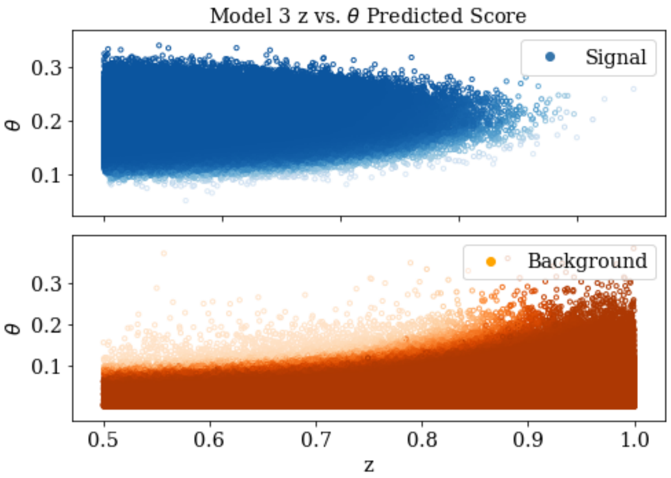
Toy 2DCNN Results

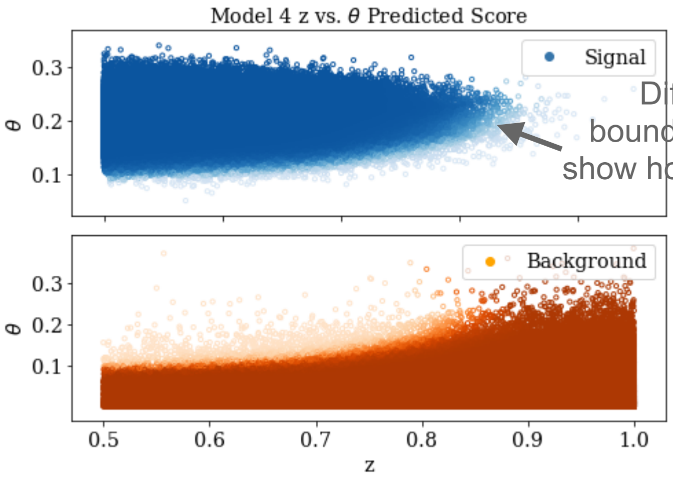
Darker markers corresponds to higher relevance scores.

Sharp gradient shows decision boundary for these variables


Model 1 z vs. θ Predicted Score


Model 2 z vs. θ Predicted Score

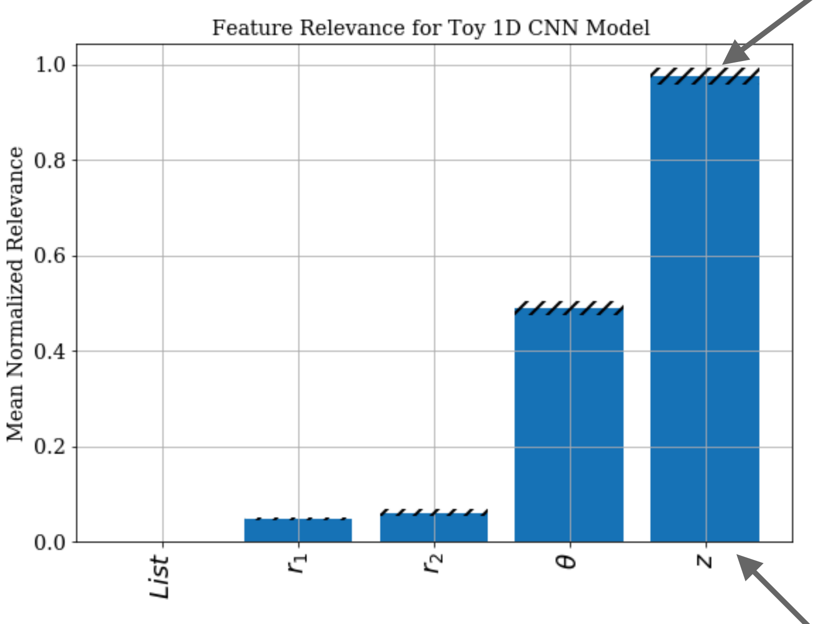

Model 3 z vs. θ Predicted Score

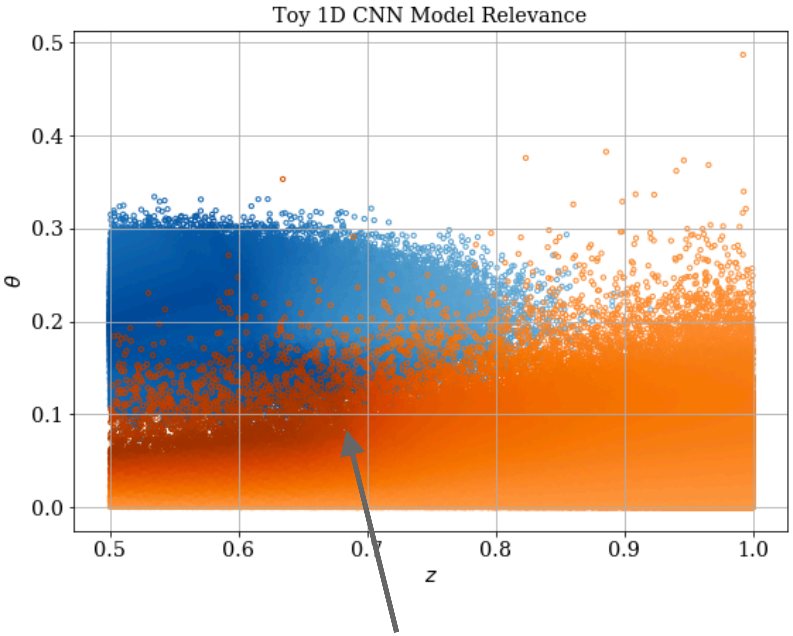

Model 4 z vs. θ Predicted Score

Differences in boundary shapes show how trainings vary

Toy 1DCNN Results

Error bars show standard deviation of relevance after multiple trainings.





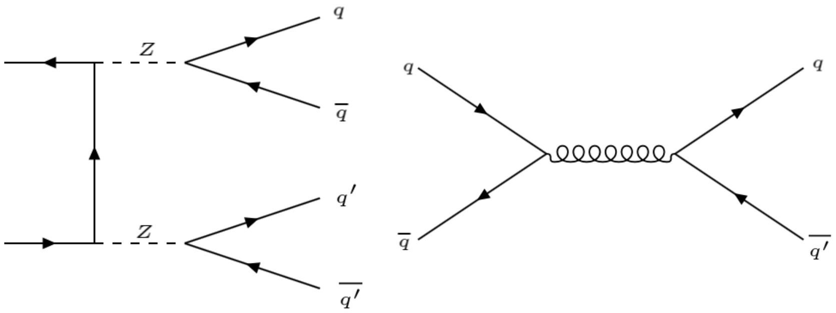
Most relevant features are same as 2DCNN.

More robust “substructure” within relevance of the top two variables.

PYTHIA MODEL

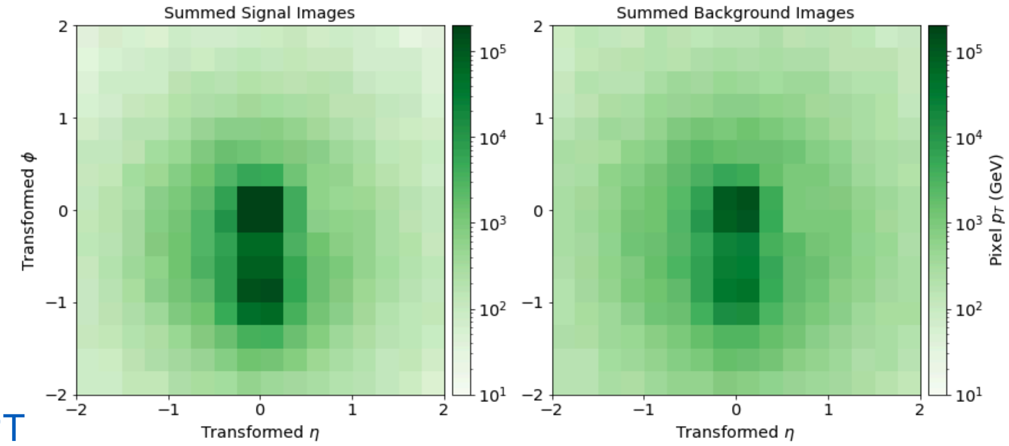
Pythia Model

- **Simulated with Pythia8**
  - Signal: SM $ZZ, Z \rightarrow b\bar{b}$
  - QCD



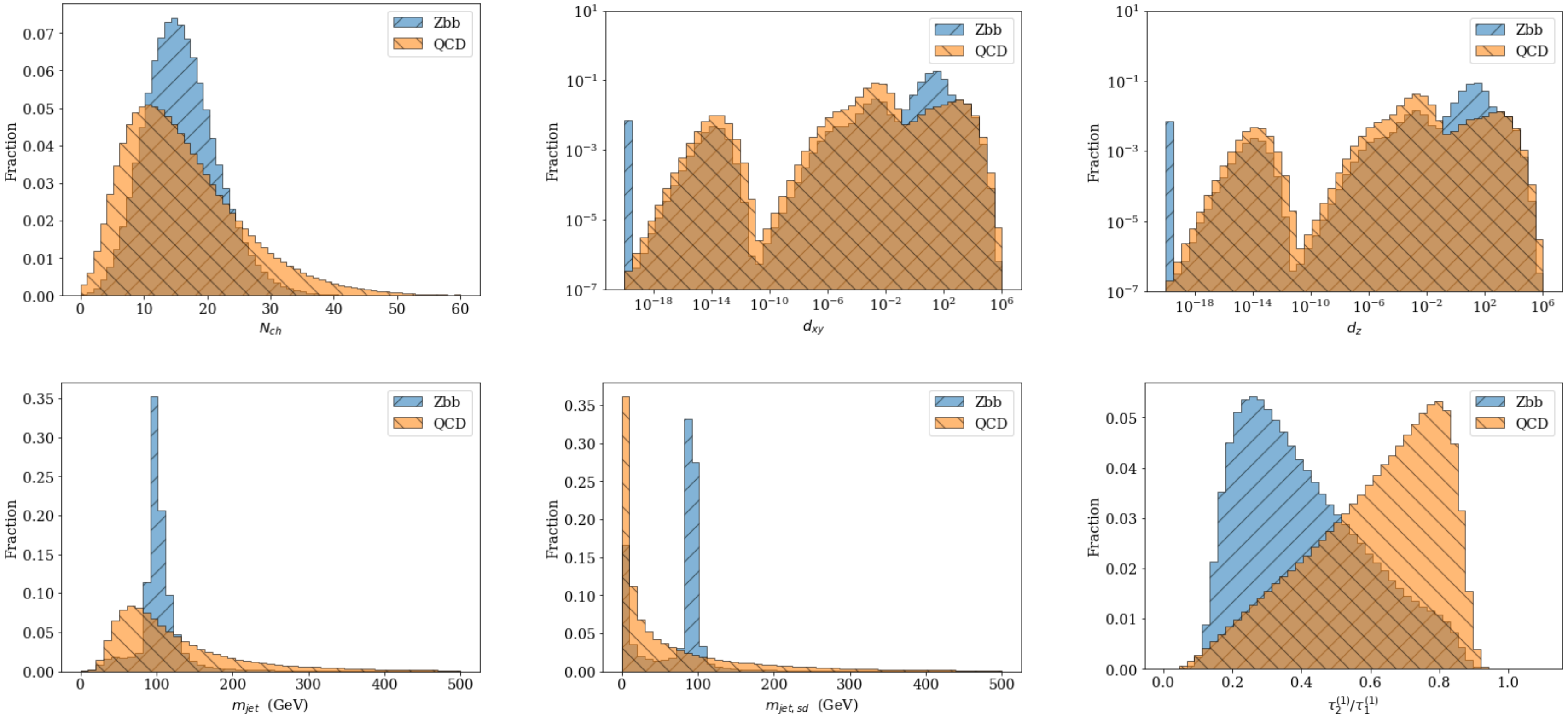
- **Jets**
  - Consider leading AK8 jet
  - p_T > 200 GeV
  - mMDT: $z_{cut} = 0.1, \beta = 0$

- **Preprocessing**
  - Normalize inputs wrt to jet p_T
  - Same as toy model



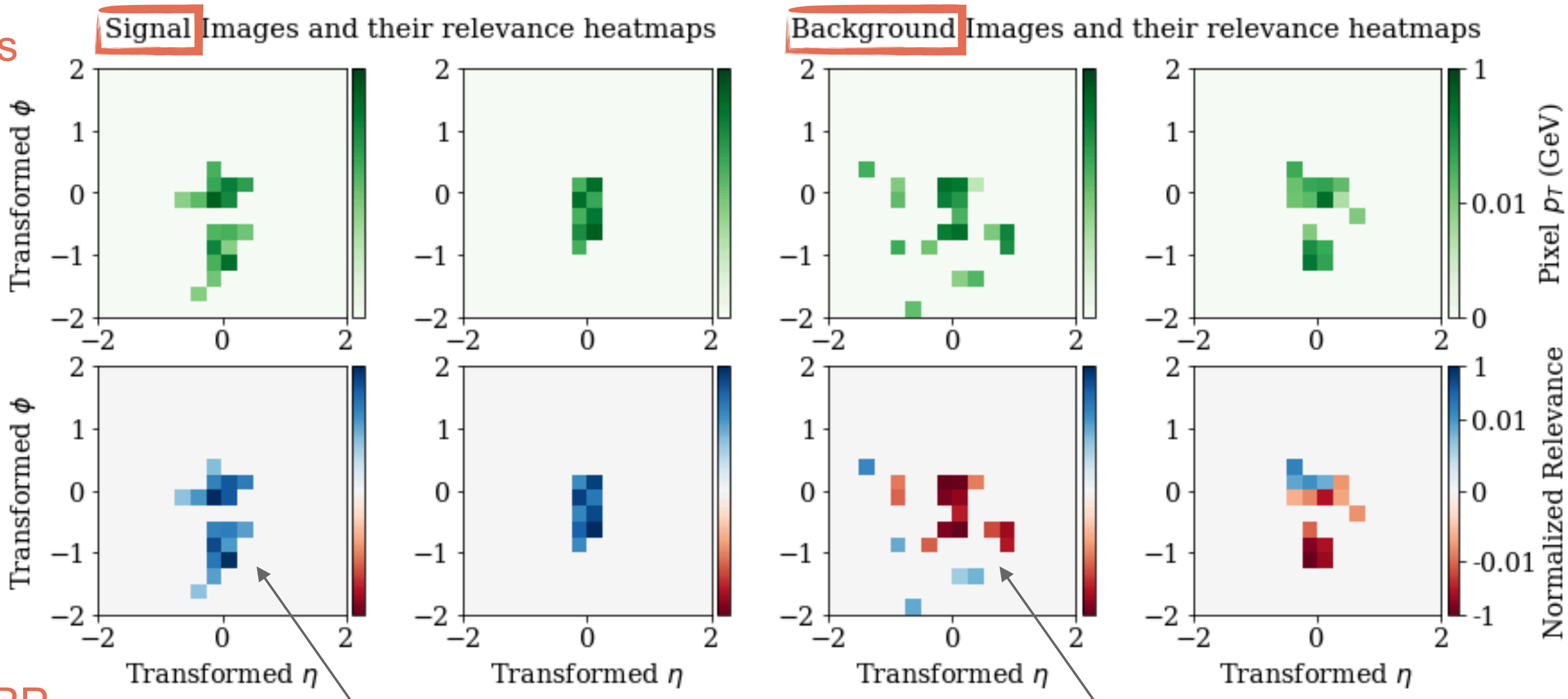
Pythia Model

Use same network structure as toy model; replace particle-level inputs



Pythia LRP Heatmaps

Inputs



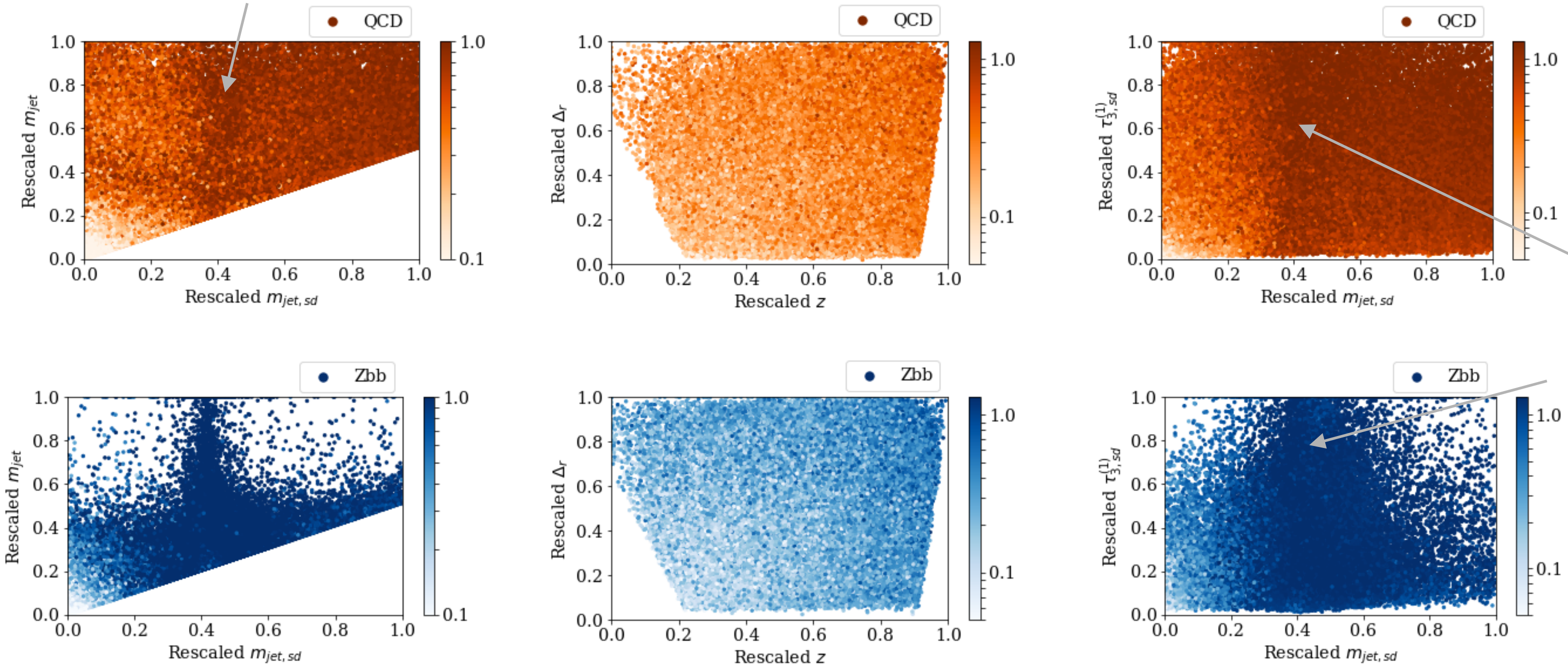
LRP Results

Signal: mostly positive relevance, primarily along ϕ axis

Background: mostly negative relevance, more diffuse

Pythia 1DCNN Results

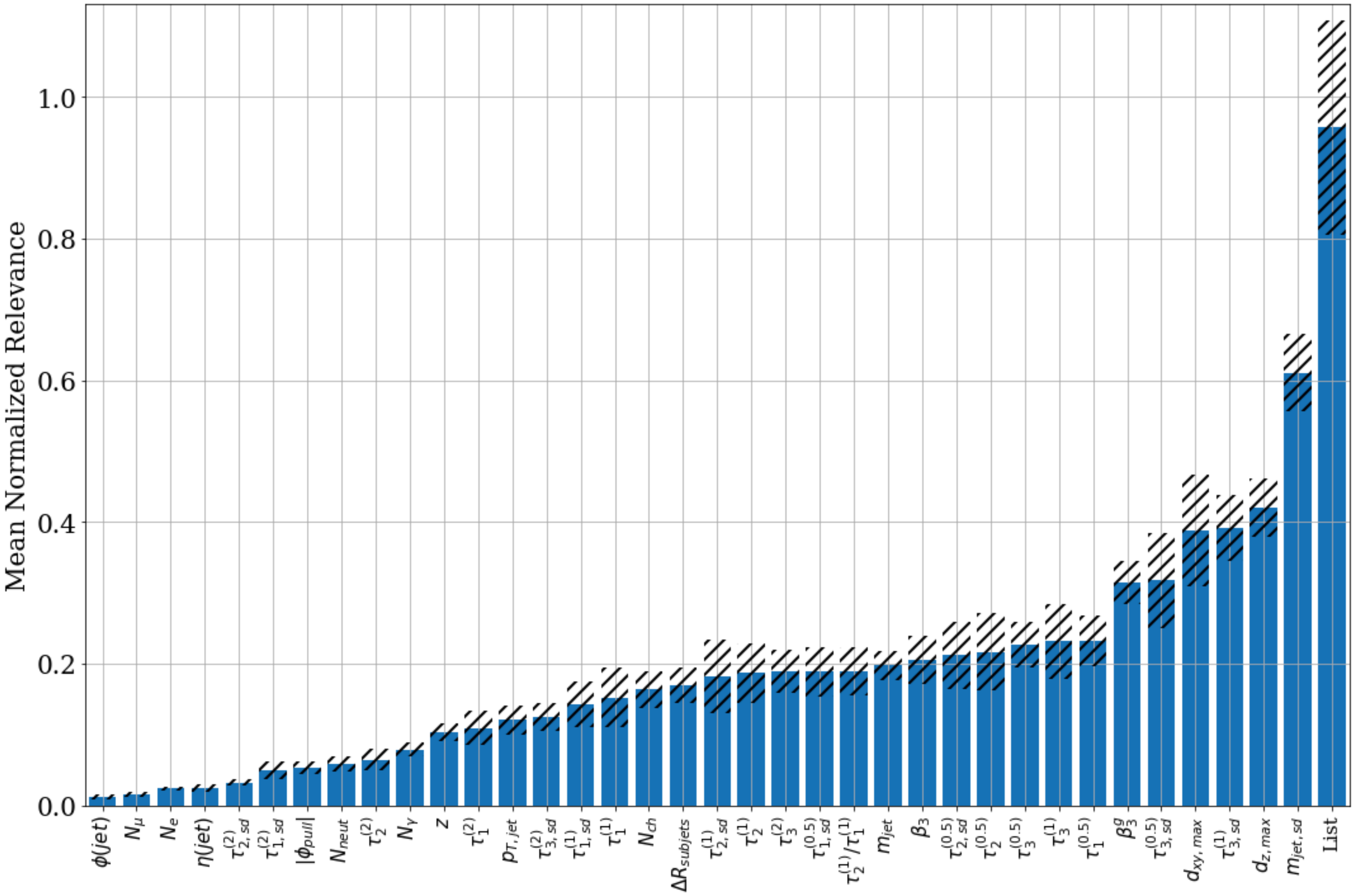
Darker markers: higher absolute relevance score



Decision boundaries: not as clear as for toy model

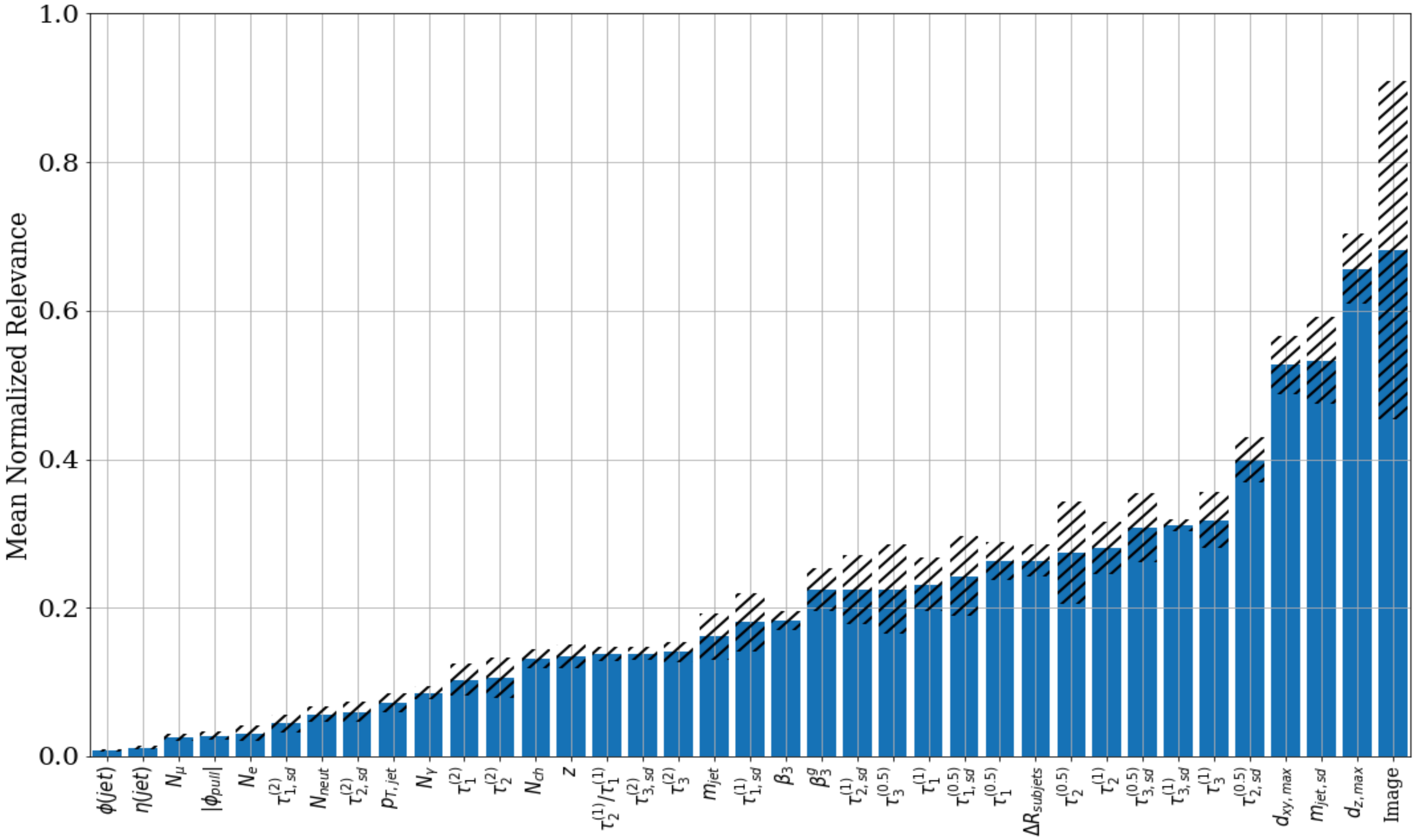
Pythia 1DCNN Results

Particle list: highest relevance for all models



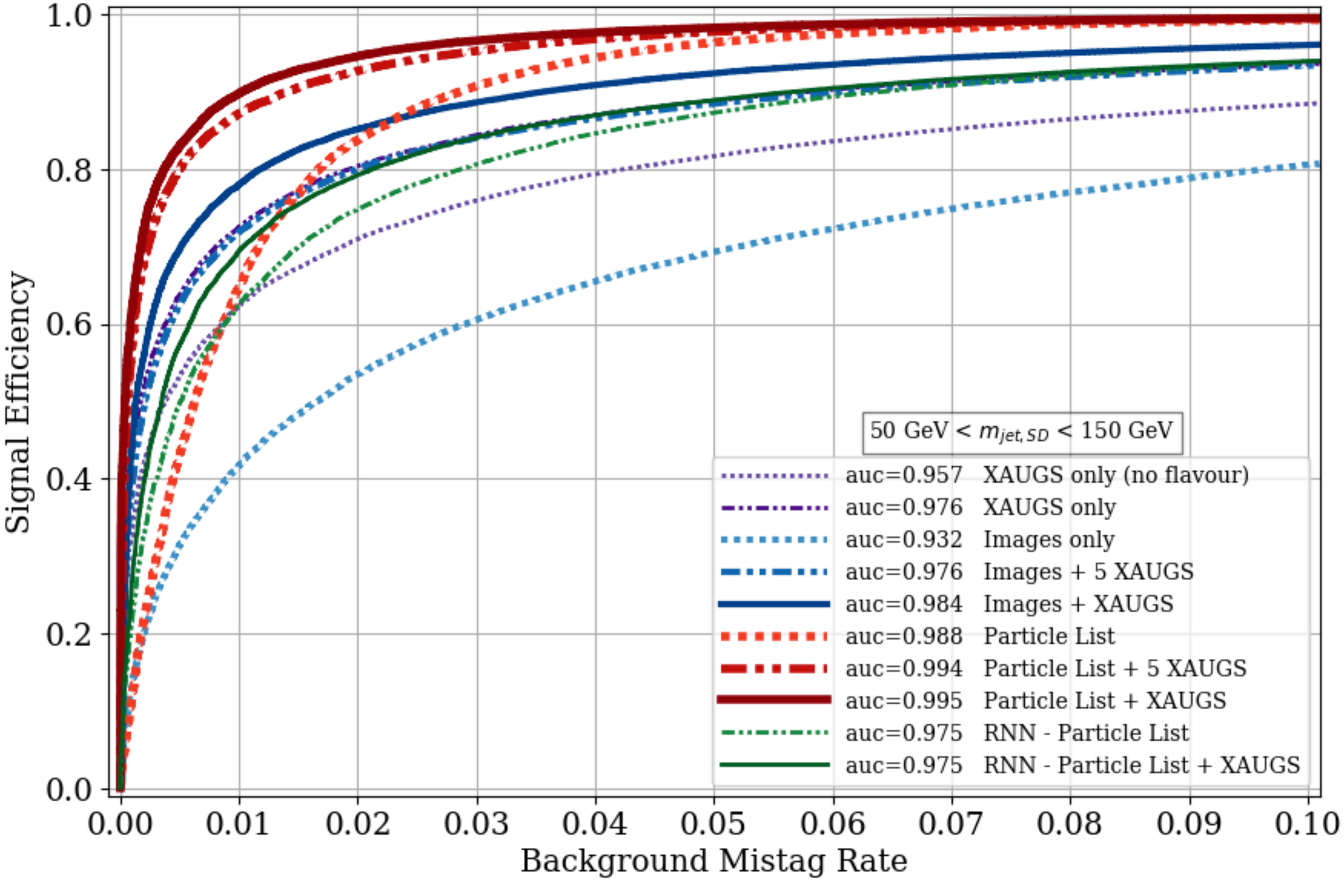
Pythia 2DCNN Results

Image and $\mathbf{d_{z,max}}$: highest relevance, depending on the model



Pythia Results: Model Comparisons

- **Images only does worst**
- **Particle List + XAUGs does best**
  - Particle list + 5 XAUGS comparable



Conclusions

- **Introduced novel method for ML tagger explainability:** LRP + expert augmented variables
    - Help explain network decisions, and relevant subspaces

- **XAUGs**
    - Can boost classification performance
    - Can entirely capture relevant information of lower-level networks

- **XAUGs + LRP**
    - Can be used to reduce list of network inputs
    - Can be used to quantify numerical uncertainty in DNN training

ADDITIONAL MATERIAL

LRP Propagation Rules

- **LRP-z**
  - Redistributes the relevance in proportion to the contributions to the neuron activation.
  - Gradient X Input → Noisy

$$R_j = \sum_k \frac{a_j w_{jk}}{\sum_{0,j} a_j w_{jk}} R_k$$

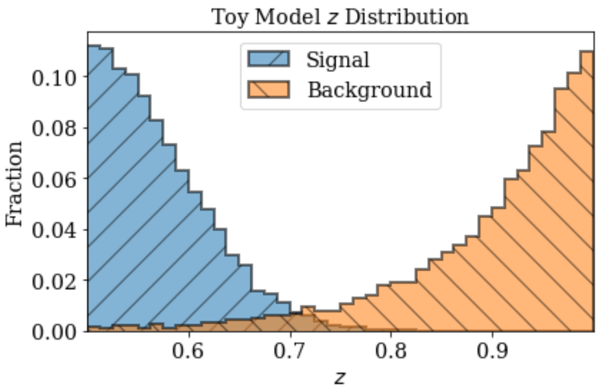
- **LRP-ϵ**
  - ϵ absorbs some relevance for weak and/or contradictory contributions.
  - For large ϵ only salient explanation factors survive the absorption → Less Noisy
  - **Used in our networks' dense layers**

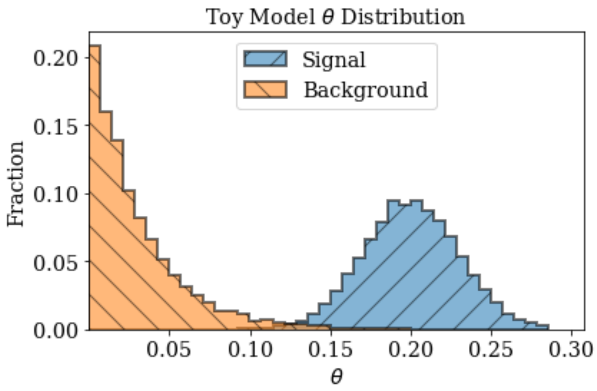
$$R_j = \sum_k \frac{a_j w_{jk}}{\epsilon + \sum_{0,j} a_j w_{jk}} R_k$$

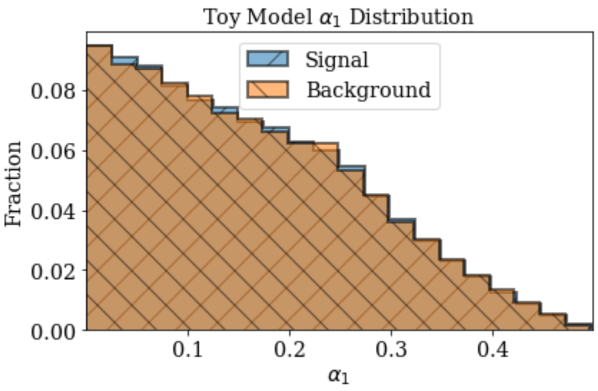
- **LRP-$\alpha_1 \beta_0$**
  - Limiting effect on how large positive and negative relevance can grow → Stable Explanations
  - **Used in our networks' convolution layers**

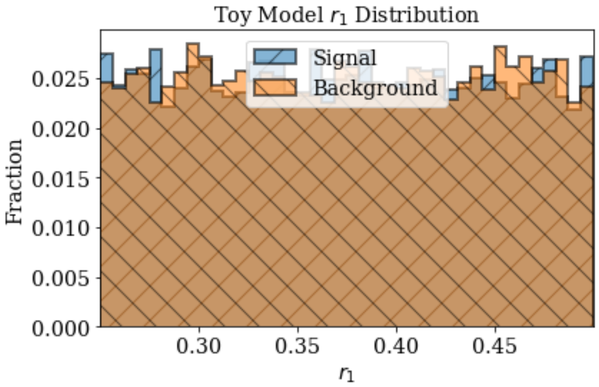
$$R_j = \sum_k \left(\alpha \frac{(a_j w_{jk})^+}{\sum_{0,j} (a_j w_{jk})^+} - \beta \frac{(a_j w_{jk})^-}{\sum_{0,j} (a_j w_{jk})^-} \right) R_k$$

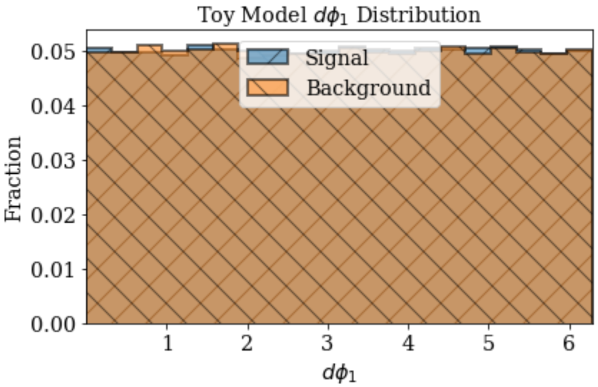
Toy Model Inputs

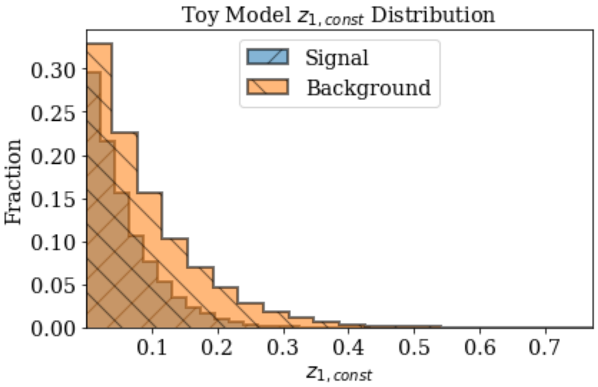


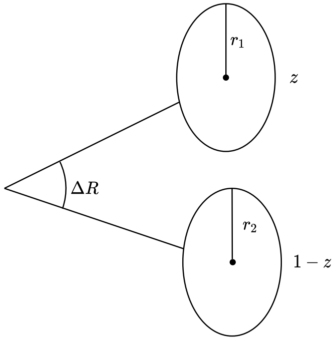


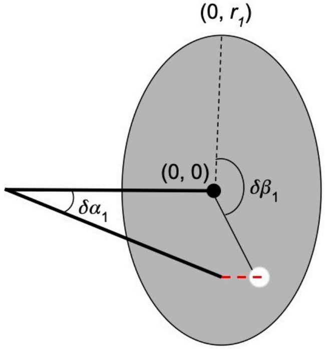




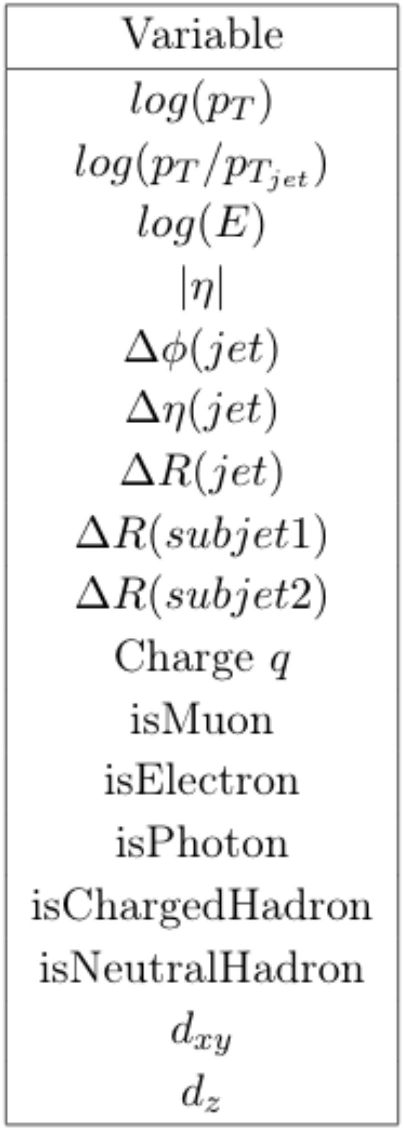








Particle List Inputs



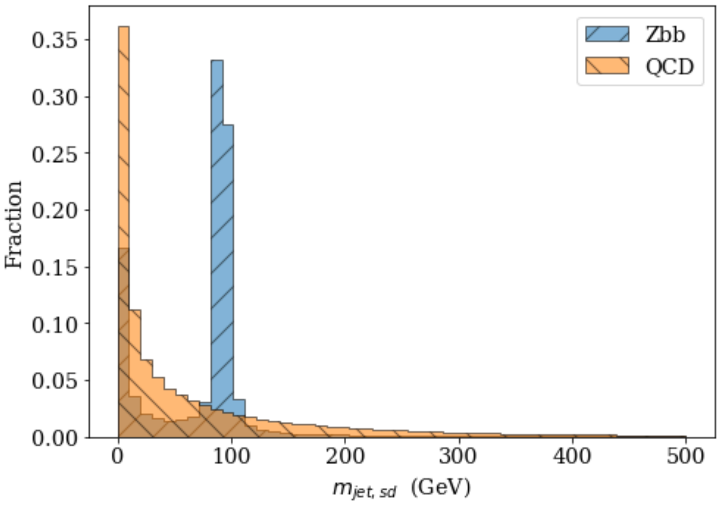
Variable
$log(p_T)$
$log(p_T/p_{T_{jet}})$
$log(E)$
$\|\eta\|$
$\Delta\phi(jet)$
$\Delta\eta(jet)$
$\Delta R(jet)$
$\Delta R(subjet1)$
$\Delta R(subjet2)$
Charge q
isMuon
isElectron
isPhoton
isChargedHadron
isNeutralHadron
d_{xy}
d_z

Pythia Model Preprocessing

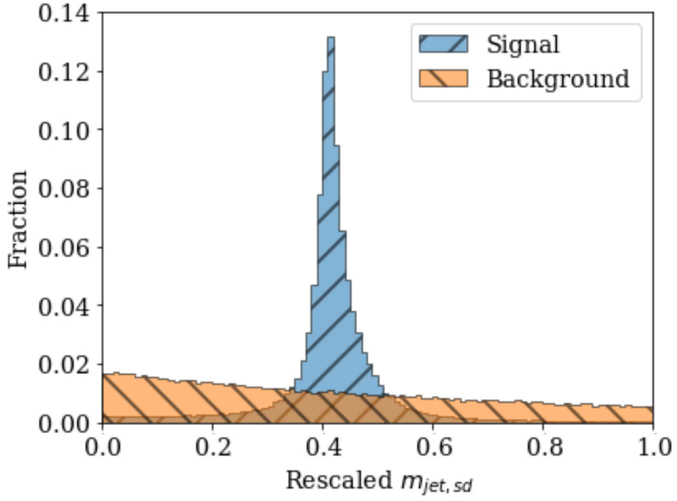
1. Cut on softdrop mass: keep jets with m_{SD} 50-150 GeV

2. Numerical rescaling

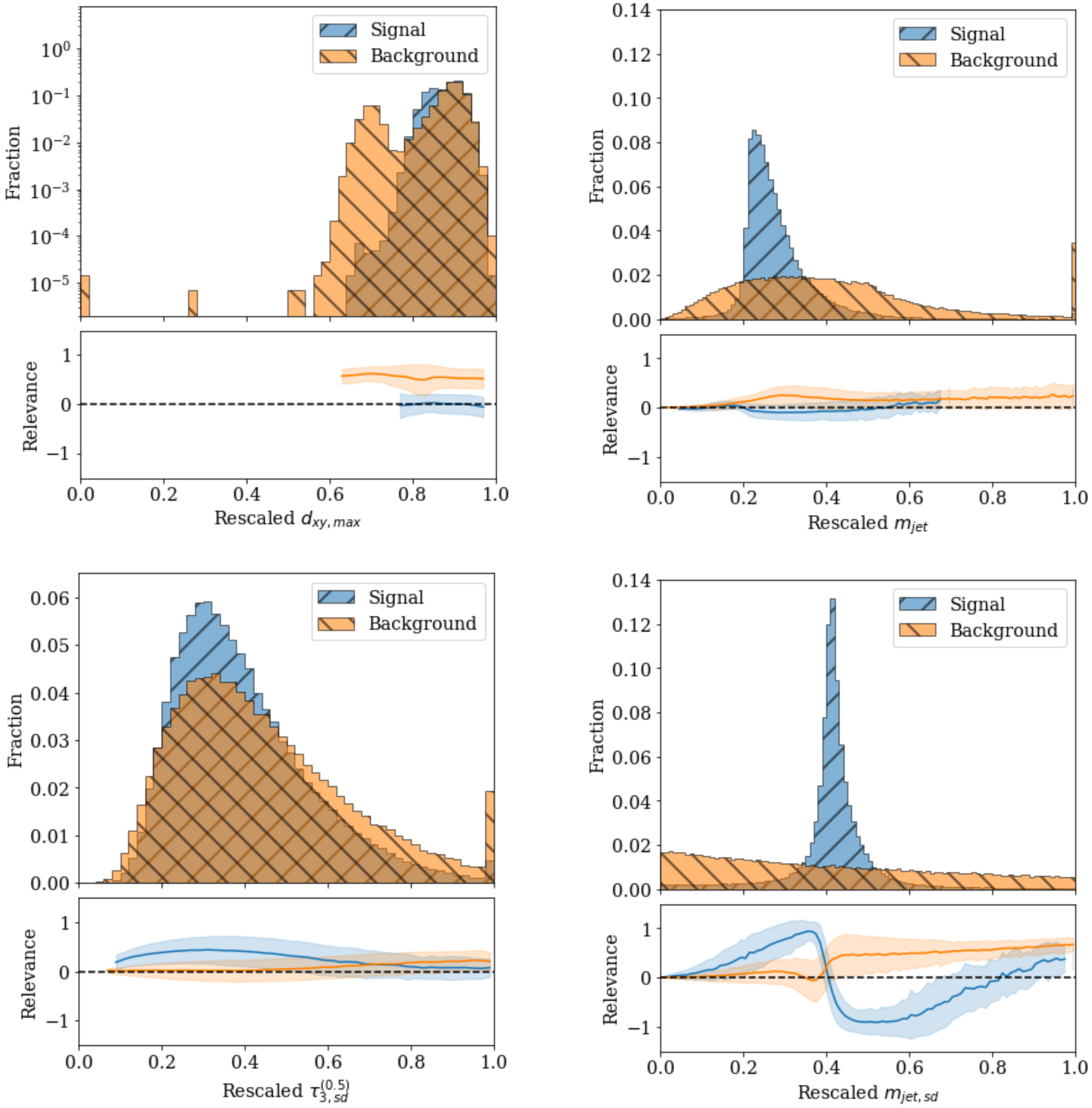
1. Rebin outliers to *mean + 3(std)* and *mean - 3(std)*
2. Input distributions are then rescaled from 0 to 1: $\frac{x - x_{min}}{x_{min} - x_{max}}$



Mass cut + rescaling



Pythia Model 1D LRP Plots



Profiles don’t show clear decision boundary - need higher dimensional plots