ABSTRACT

3D instance segmentation remains a challenging problem in computer vision. Particle tracking at colliders like the LHC can be framed as an instance segmentation task: beginning from a point cloud of hits in a particle detector, an algorithm must identify which hits belong to individual particle trajectories and extract track properties. Graph Neural Networks (GNNs) have shown promising performance on standard instance segmentation tasks. In this work we demonstrate the applicability of instance segmentation GNN architectures to particle tracking; moreover, we re-imagine the traditional Cartesian space approach to track-finding and instead work in a conformal geometry that allows the GNN to identify tracks and extract parameters in a single shot.

BOUNDING ELLIPSES

Ellipse Parameterization
- 5 degrees of freedom: \( B = (\eta, \phi, a, b, \theta) \)
- First and second principle components of each track’s hit cluster used to estimate ellipse parameters

Ellipse Encoding
- Ellipses encoded with coordinates of each node for training labels
- \( \delta_x = (\eta_x - \eta_t), \delta_y = (\phi_x - \phi_t), \delta_z = \log \frac{a}{a_t}, \delta_b = \log \frac{b}{b_t}, \delta_{\theta} = \theta - \theta_t \)

GNN ARCHITECTURE

Overview: PointGNN
- This model is based on the PointGNN, an instance segmentation network designed to localize and classify objects in a graph
- Key components: graph re-embedding, localization/classification, bounding box merging

(1) Graph Re-embedding Modules
- Nodes re-embedded with \( T \) separate graph modules:

\[
s_{t}^{j+1} = g^t(\rho(x_j - x_i + \Delta p_{i,j}, s_j^t}, s_i^t)\)

(2a) Localization Branch
- MLP to predict encoded bounding ellipses for each node
- Huber Loss: \( l_i = \frac{1}{n_{hits}} \sum_{j=1}^{n_{hits}} \min_{\phi, \eta} |y_i - x_j| / (4 - \delta^p)\)

(2b) Classification
- MLP to predict the class of a hit: noise (0) or track hit (1)
- BCE Loss: \( l_c = -\frac{1}{n_{hits}} \sum_{j=1}^{n_{hits}} y_j \log y_i + (1 - y_j) \log (1 - y_i)\)

(3) Box Merging
- Modified NMS strategy to build hit clusters

(4) Conformal Tracking
- Predict transverse track parameters in conformal space
- MSE Loss: \( l_e = \frac{1}{n_{clusters}} \sum_{i=1}^{n_{clusters}} \min_{\phi, \eta} \left( \frac{p_x^2}{\sigma_{p_x}^2} + \frac{p_y^2}{\sigma_{p_y}^2} + \frac{\epsilon_{\phi}^2}{\sigma_{\phi}^2} + \frac{\epsilon_{\eta}^2}{\sigma_{\eta}^2} \right)\)

(5) Total Loss:
- Scaled to balance the terms: \( l_{total} = \alpha_l + \beta_{loc} + \gamma_l\)

REFERENCES
