ESI-Fastlight: a Conditional Normalizing Flow for Fast pfRICH Hitmap Generation

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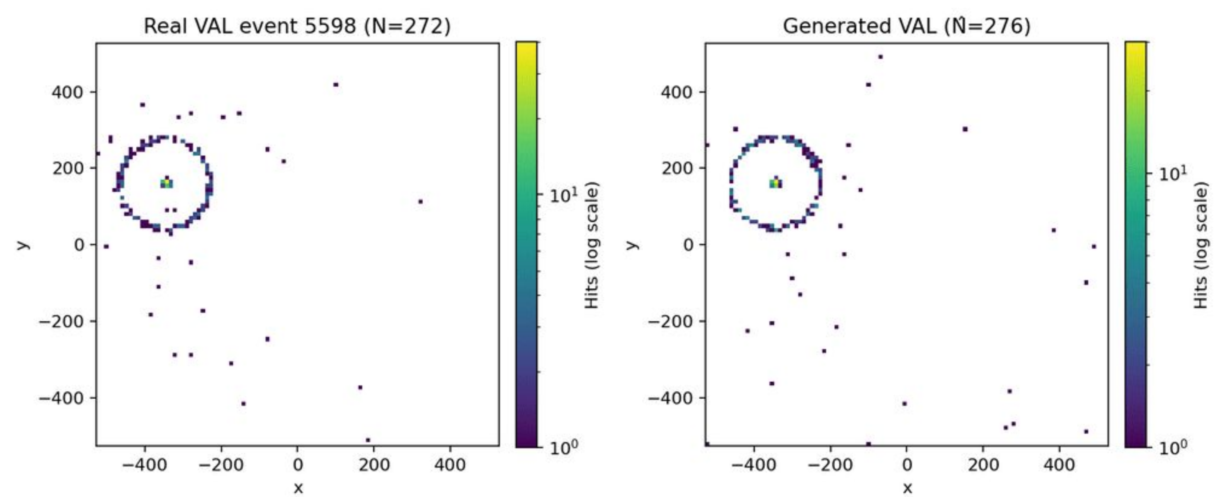
ESI-Fastlight[1]

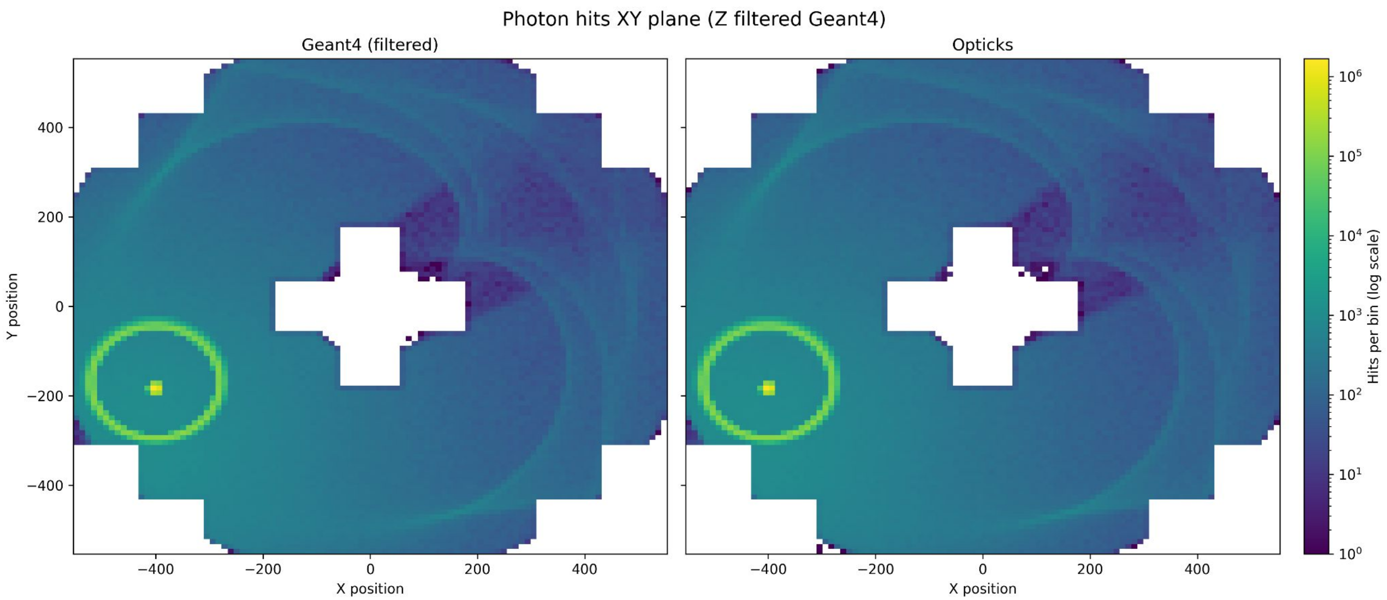
- The work is part of a BNL Physics Dept. exploratory R&D project on approaches to improving EIC ePIC simulation
- Goal: realistic pfRICH hitmaps without running Geant4 end-to-end simulation – Utilize ML
  - Input for training: primary momentum, position, hit maps
  - Output of the trained model: realistic hit maps for specified condition (primary params)
- Approach: MLP (multilayer perceptron) + CNF (conditional normalizing flow) with physics-aware priors
- To build the training dataset we used a GPU simulation[2] to speed up Geant4

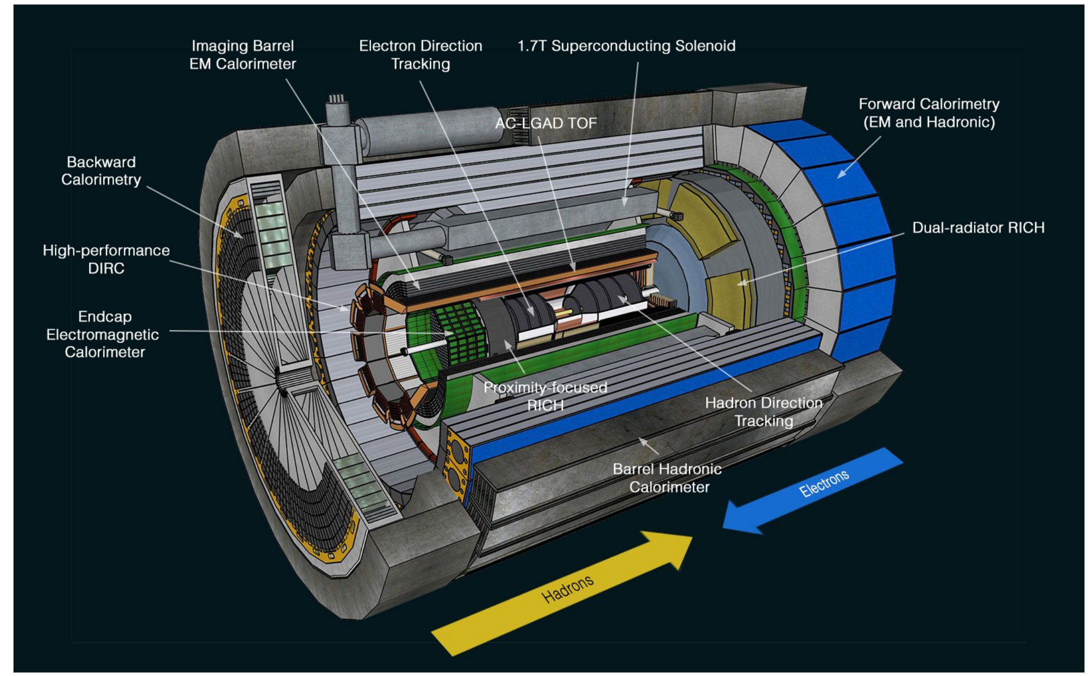


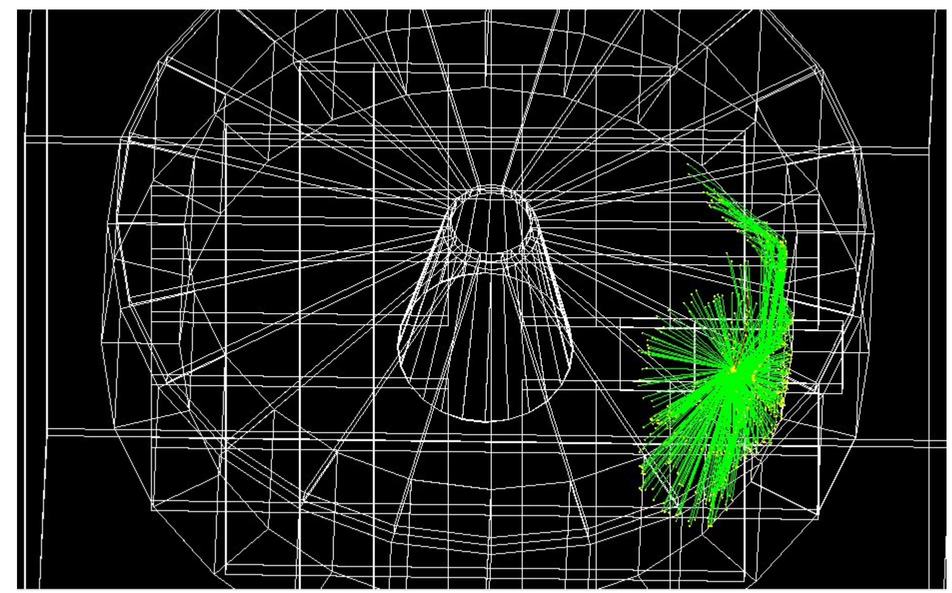
[1]https://github.com/BNLNPPS/esi-fastlight
[2]https://github.com/BNLNPPS/eic-opticks

EIC-Opticks with pfRICH geometry

- EIC-Opticks is able to simulate Cherenkov and scintillation photons
- 50k 5 MeV/c e^- → ~ 50M photons
  - Single thread G4 CPU vs EIC-Opticks 148±9x speedup
  - 20 threads MT G4 CPU vs EIC-Opticks 9.3±0.5x speedup

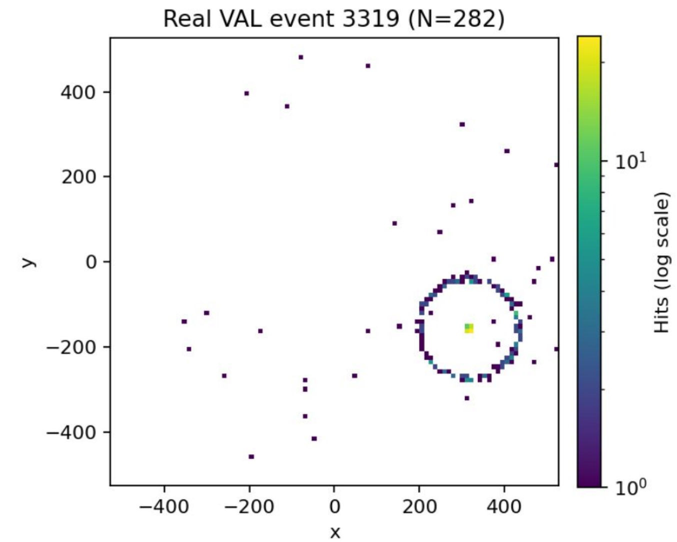






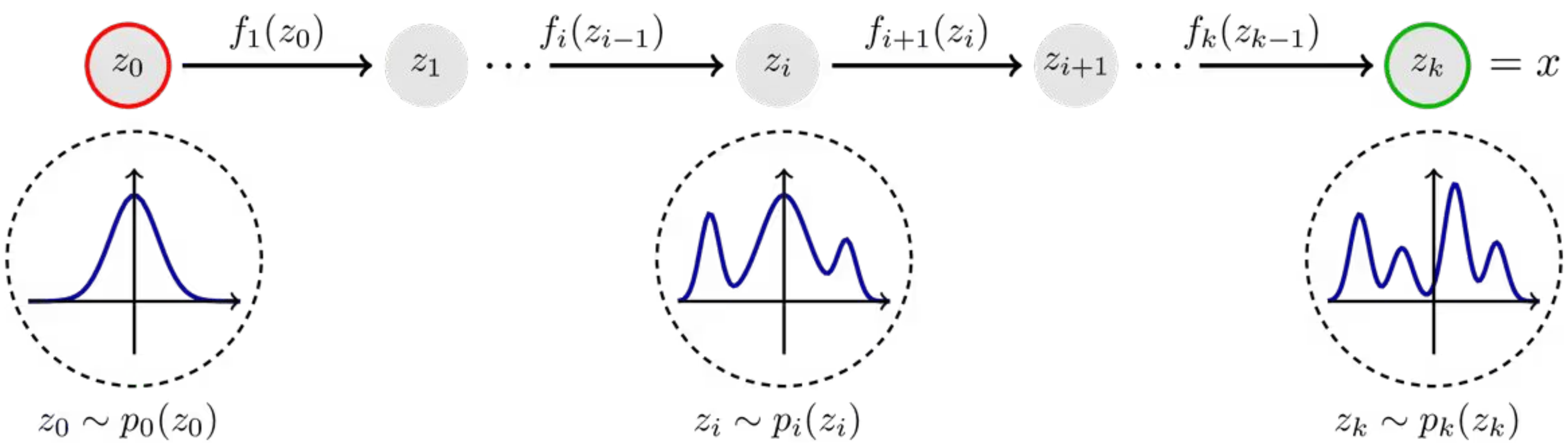
The input data and preprocessing

- Inputs:
  - Hit map, containing a few hundred coordinates (2D)
  - Information on the primary particle (7 conditioners):
    - Kinetic energy
    - Origin
    - Momentum vector
- Preprocessing:
  - Kinetic energy is translated to scale of Cherenkov ring
  - Center prediction: a small MLP predicts the ring center
    - Hits are “shifted” so the ring would be in center
    - Translation handling: the CNF’s vector field sees centered hits, so the flow learns shape



Conditional Normalizing Flow explanation

- Normalizing Flow Idea: “Construct complex distributions from simple ones via a flow of successive invertible transformations”
    - 1. Define an underlying PDF (probability density function) in latent space
    - 2. Find the transformation/flow that describes the measured datasets by transforming the defined PDF
    - 3. Likelihood maximization is used to fit the transformation/flow parameters
    - 4. Invert the transformation flow -> Can create realistic samples
- An example of set of transformations that map Gaussian to complex PDF:



CNF explanation

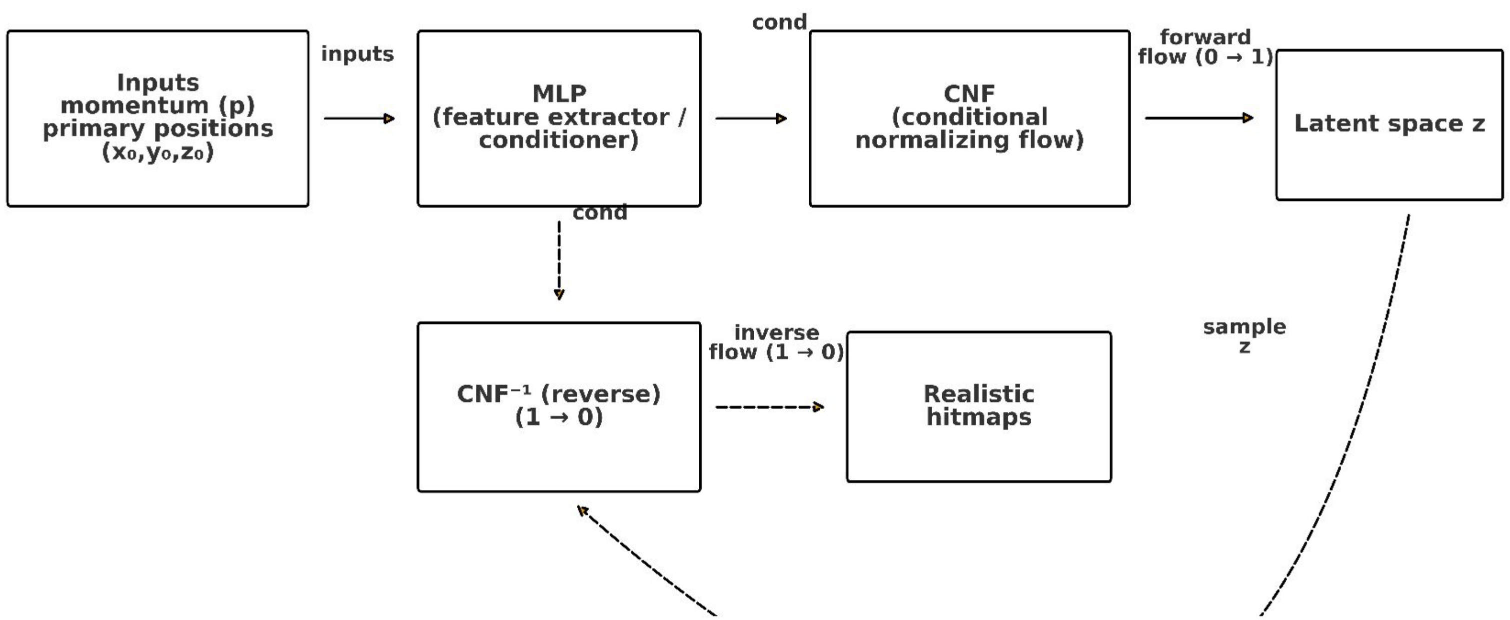
- Our prior:
  - Ring
  - Tight Gaussian
  - Very wide Gaussian
- The weights are learned on the conditions
- Loss main terms:
  - Hit NLL (negative log likelihood): fit observed hits
  - Mixture prior: regularizer against degeneracy
  - Count NLL: Total hits per event N

$$p(z \mid c) = w_{\text{ring}}(c) \underbrace{\frac{1}{\sqrt{2\pi}\, S(c)\, \|z-\mu(c)\|} \exp\left[-\frac{\left(\|z-\mu(c)\| - R(c)\right)^2}{2\, S(c)^2}\right]}_{p_{\text{ring}}(z \mid c)} + w_{\text{center}}(c) \underbrace{\frac{1}{2\pi\, \sigma(c)^2} \exp\left[-\frac{\|z-\mu(c)\|^2}{2\, \sigma(c)^2}\right]}_{p_{\text{center}}(z \mid c)} + w_{\text{noise}}(c) \underbrace{\frac{1}{2\pi\, \tau^2} \exp\left[-\frac{\|z\|^2}{2\, \tau^2}\right]}_{p_{\text{noise}}(z)}$$

$$\mathcal{L} = \underbrace{\left[-\log p_0(z_0) + \int_0^1 \text{Tr}(\partial f_\theta / \partial z_t)\, dt\right]}_{\text{Hit NLL}} + \lambda_m \mathcal{L}_{\text{mix}} + \lambda_N \mathcal{L}_{\text{count}}$$

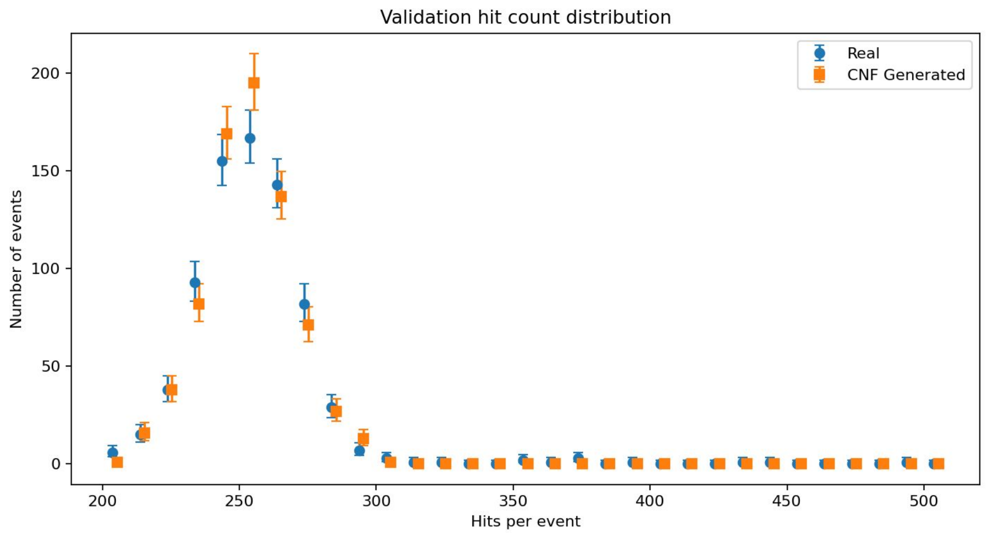
Architecture

- ~10k trainable parameters
- 6 MLP heads to determine:
  - Center position, center width, ring radius, ring thickness
  - Prior mixture weights
  - Poisson count head
- Core MLP:
  - Vector field that maps hits between data and latent space
  - Used to determine PDF for a given set of conditioners



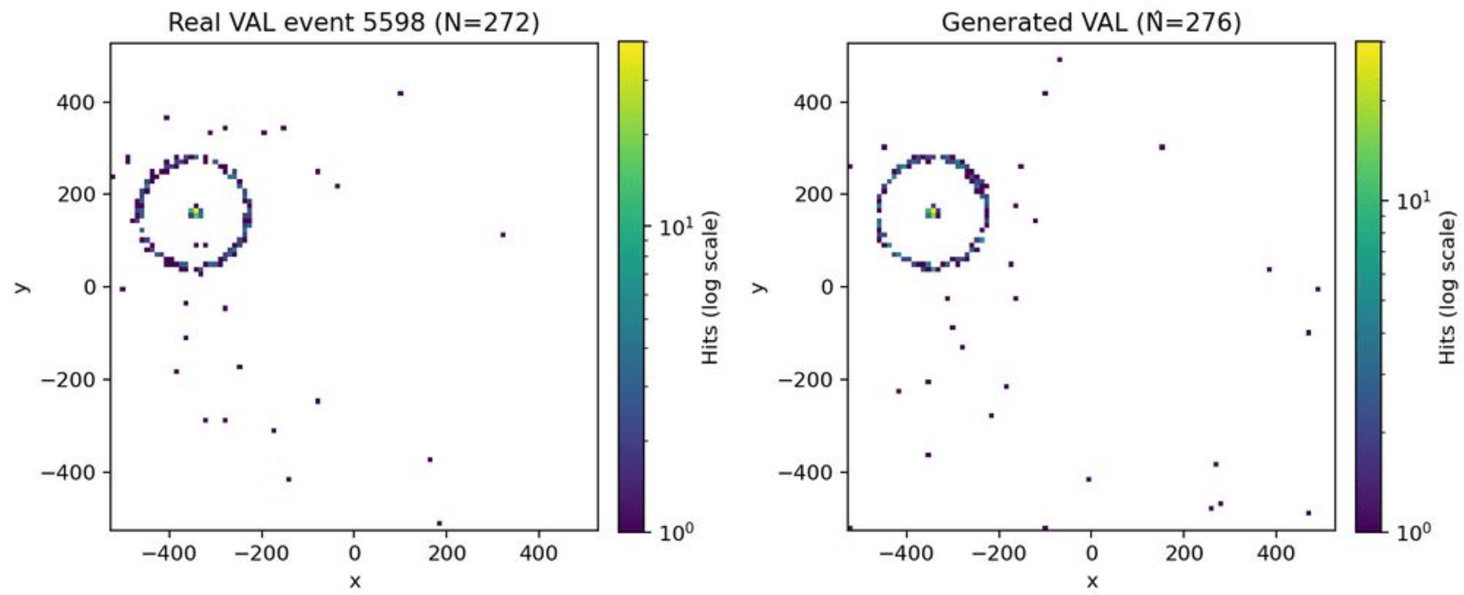
Results and outlook

- Network is currently capable of generating events with one ring
  - Model is ~100kB saved



Detailed Monte Carlo

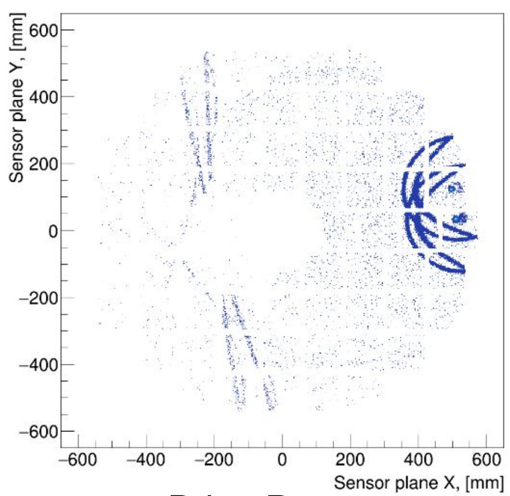
CNF surrogate with same input parameters



Brookhaven National Laboratory

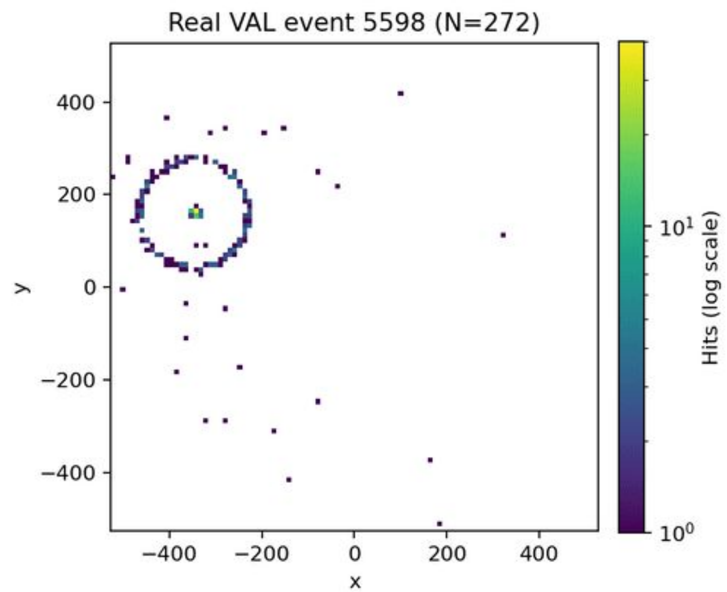
Results and outlook

- Network is currently capable of generating events with one ring
  - Model is ~100kB saved
  - Need to allow multiple rings
  - Train for pions, kaons and protons
- Investigate reconstruction?
- Investigate folded rings edge case
- PID? Reconstruction?



Brian Page
2023 Electron-Ion Collider User Group meeting

Detailed Monte Carlo



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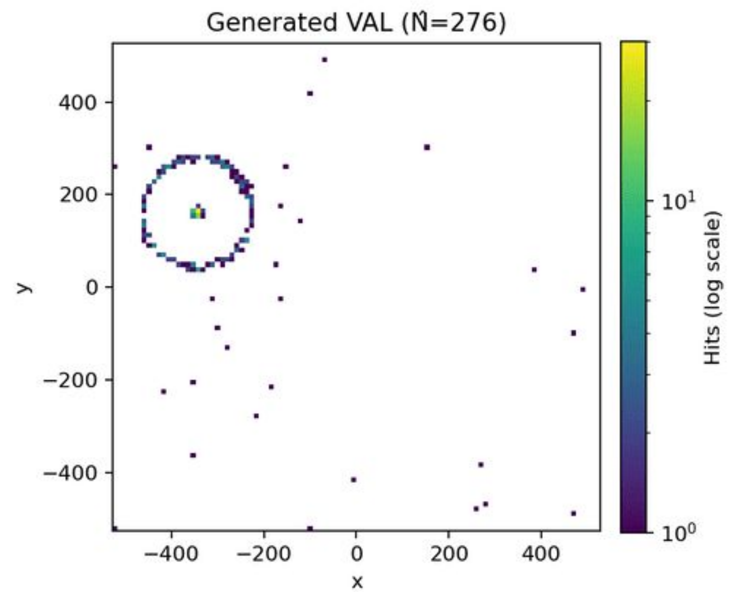

Thank you for your attention!