

Data-Driven Generation & Inference of LArTPC Images Using Conditional Latent Diffusion Models

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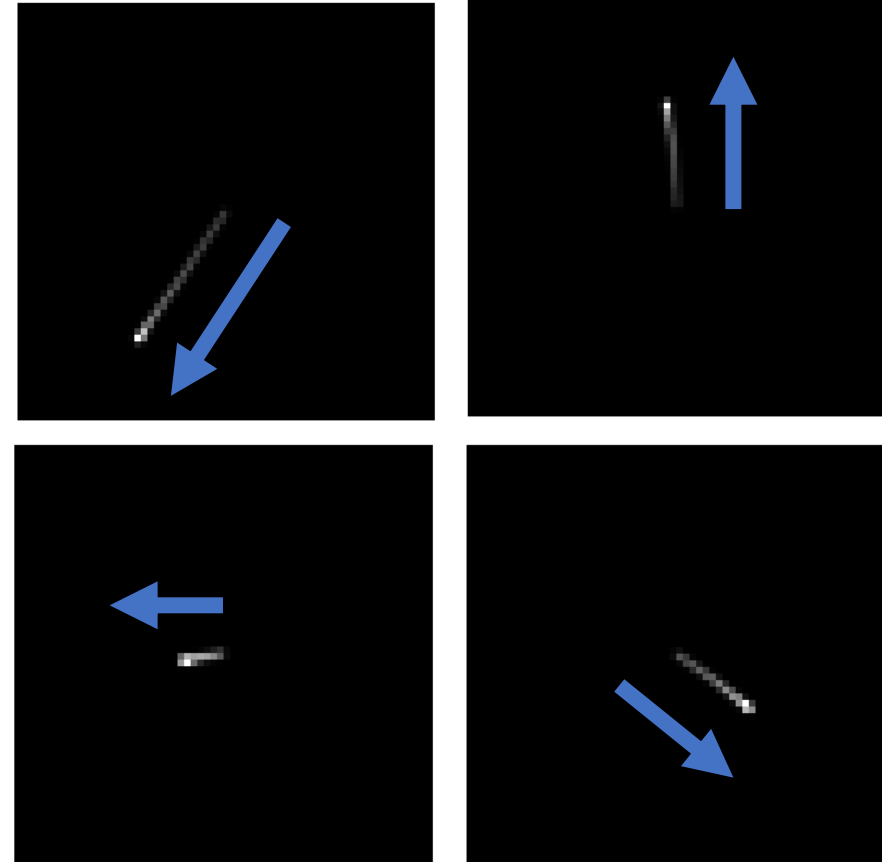


The NSF Institute for
Artificial Intelligence and
Fundamental Interactions



LArTPC Images

- Protons 50 – 100 MeV
- Geant4 simulation
- 2D projections of 3D events



Diffusion Model

Training (data \rightarrow noise)



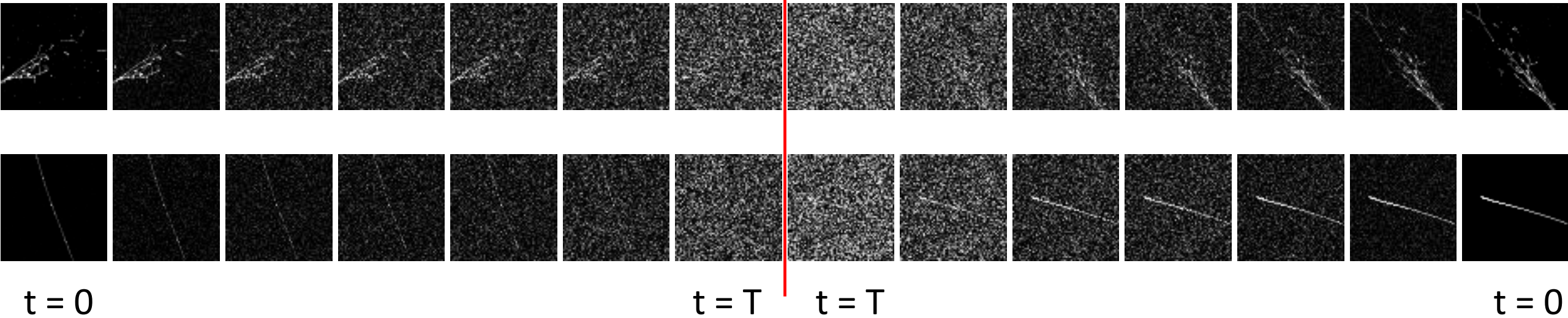
$t = 0$

$t = T$

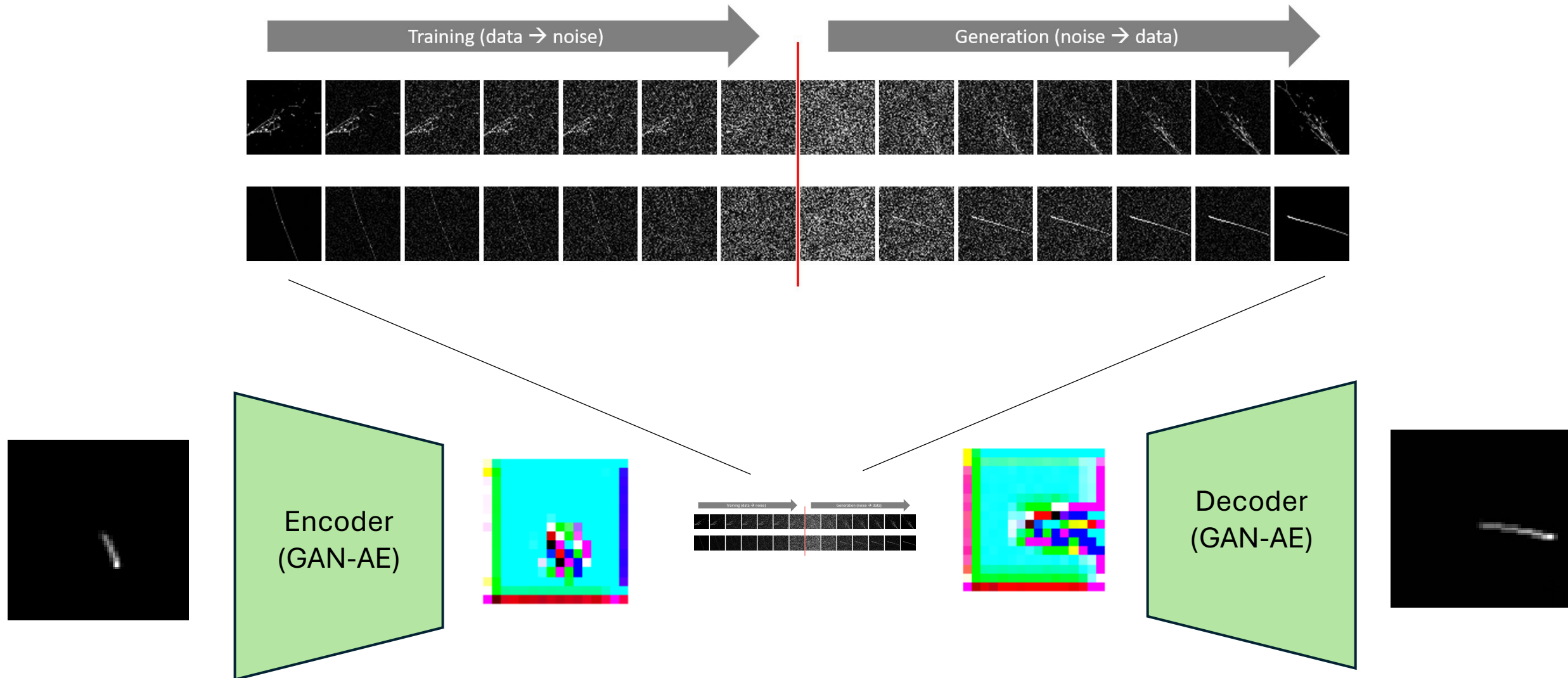
Diffusion Model

Training (data \rightarrow noise)

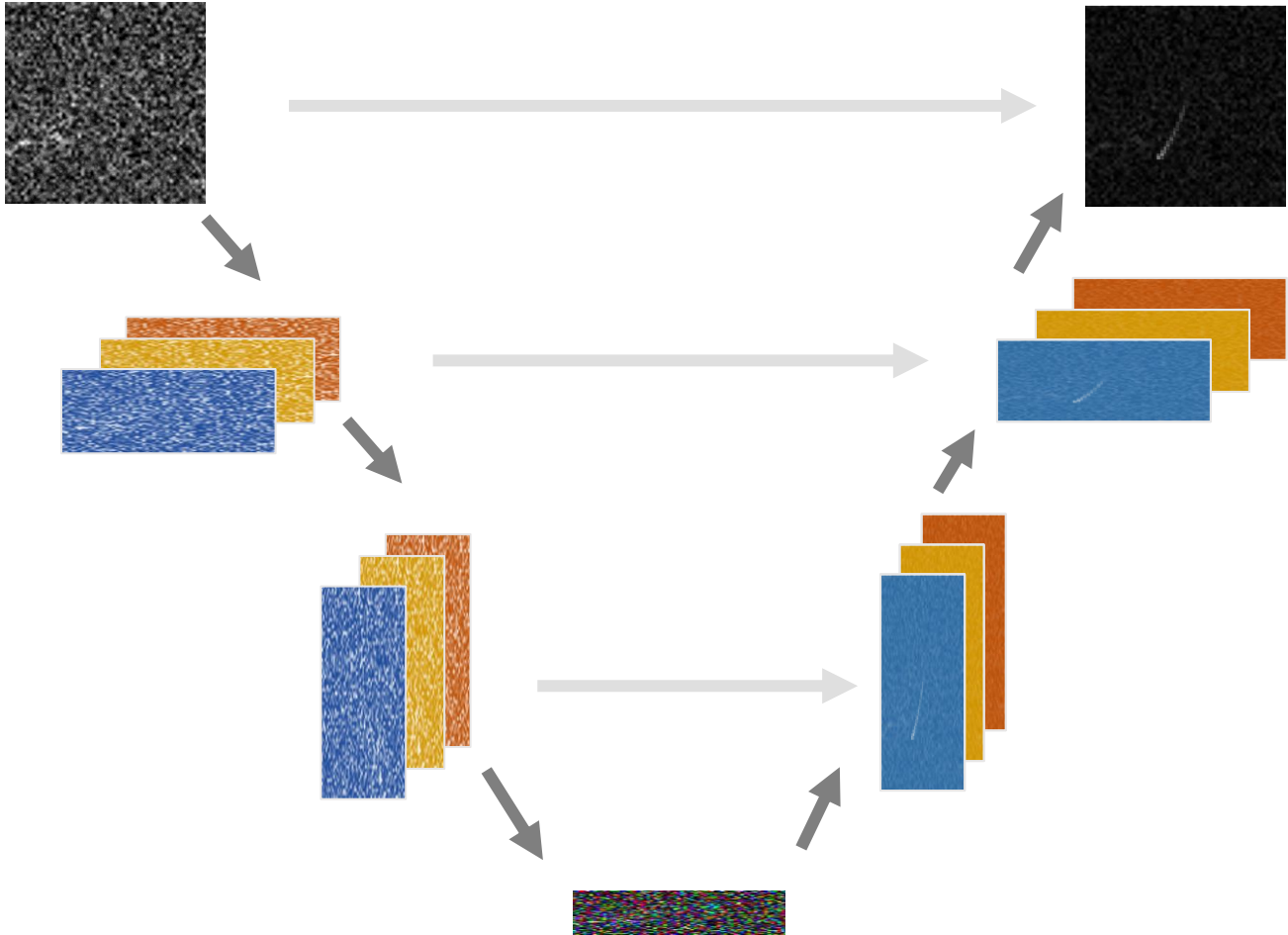
Generation (noise \rightarrow data)



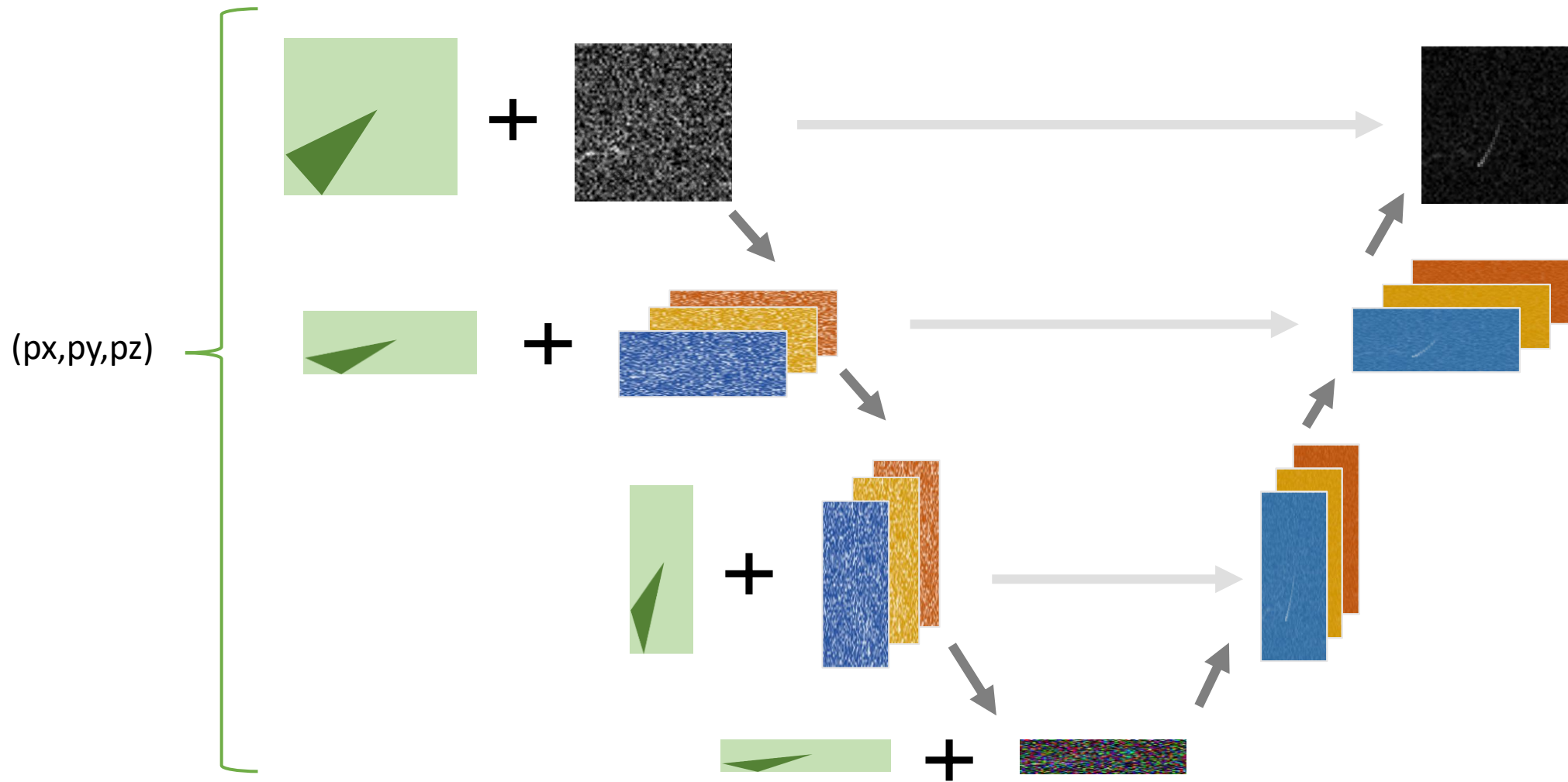
Latent Diffusion Model (LDM)



Conditional Latent Diffusion Model



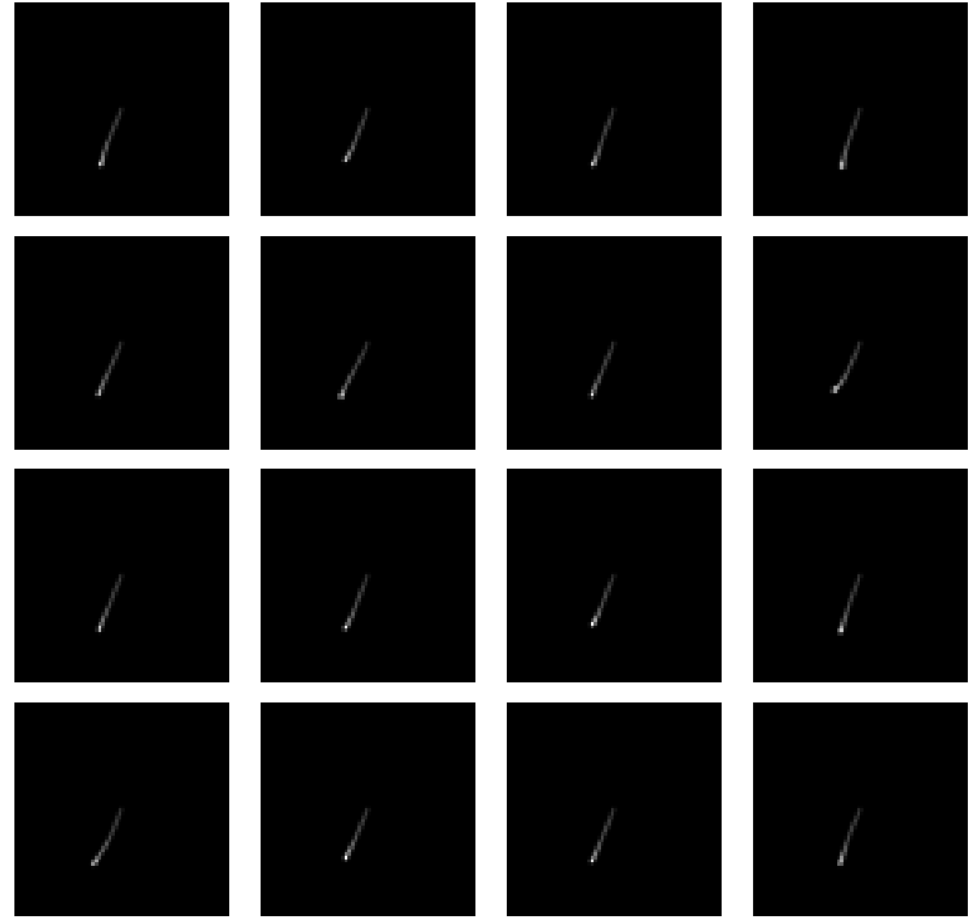
Conditional Latent Diffusion Model



Data-Driven Generation

One proton with momentum \mathbf{p}

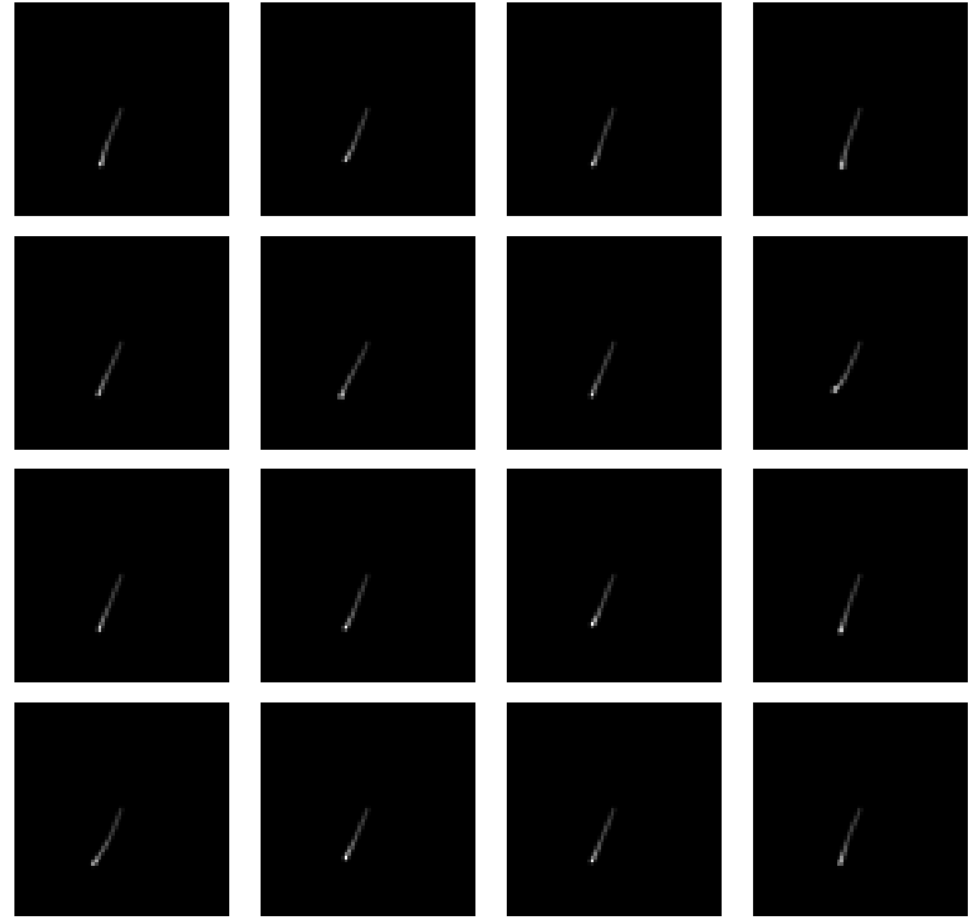
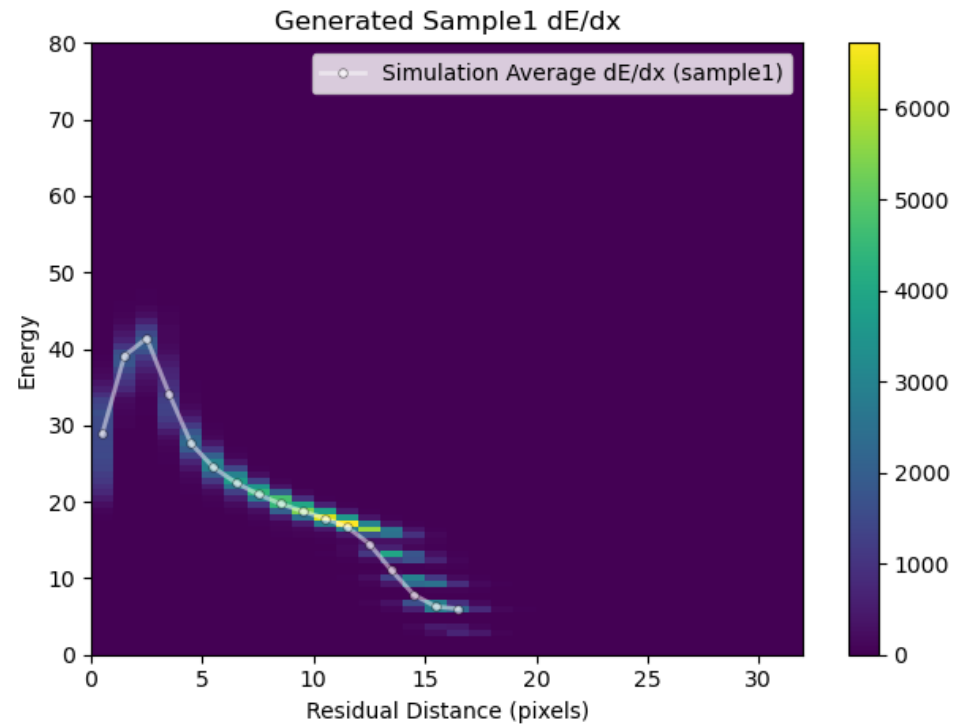
Cond LDM



- No underlying physics simulation

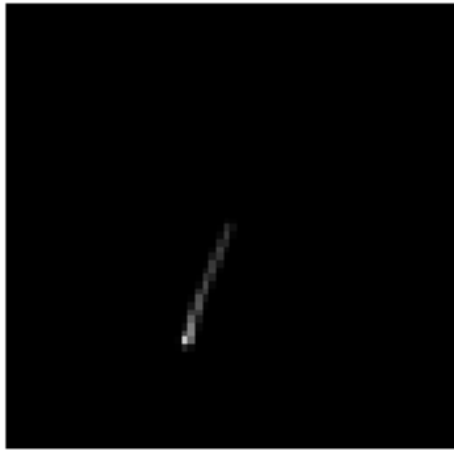
Data-Driven Generation

- Realistic physics (Bragg peak etc.)



Inference Problem

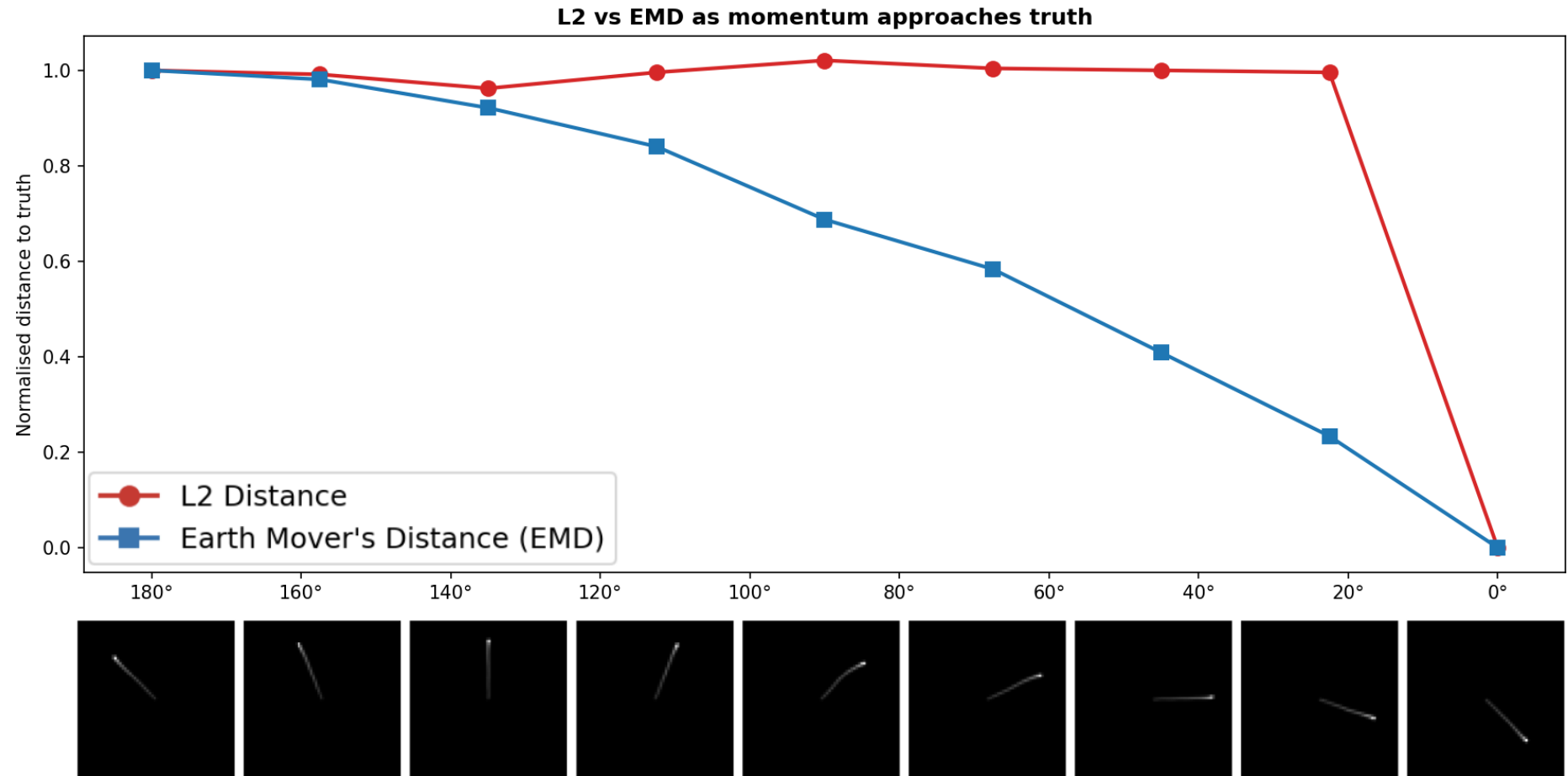
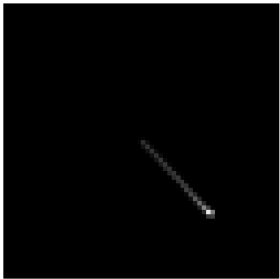
- Infer particle properties from image
- Need a loss function to compare images



One proton with momentum \mathbf{p}

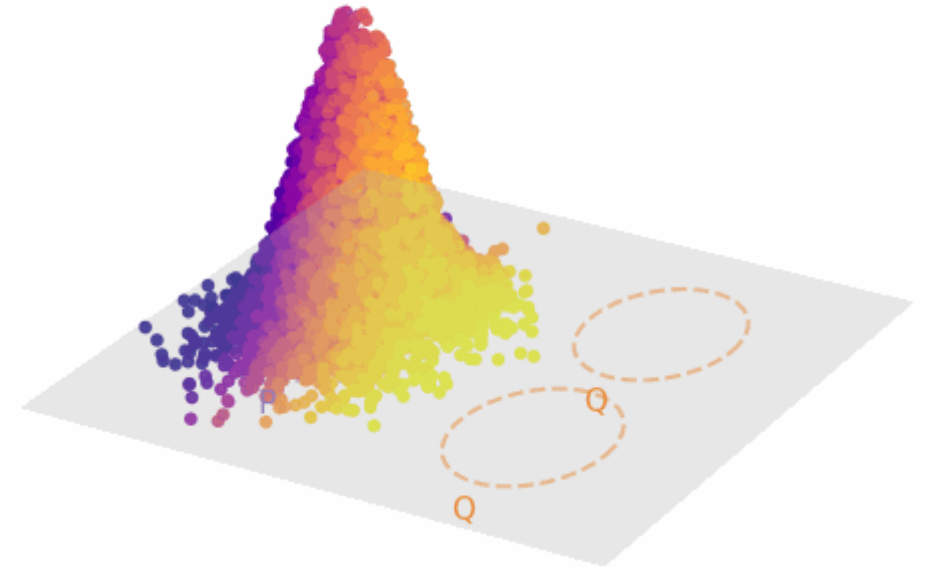
Image Distance Metrics

Truth Event



Earth Mover's Distance (EMD)

- a.k.a Wasserstein-1 distance
- Optimal transport plan for distributions
- Minimize the work needed to move mass



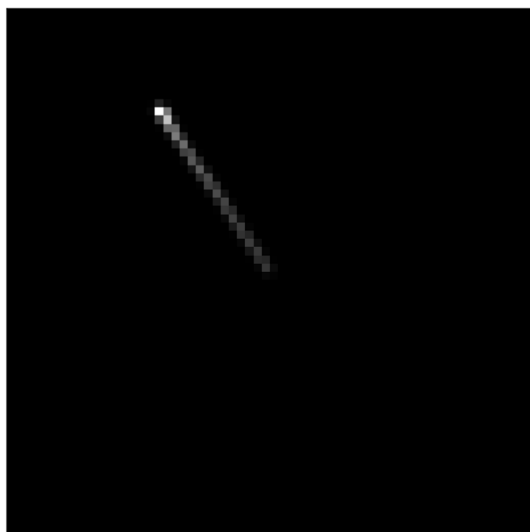
Inference Using Gradient Descent

- Loss = $\text{EMD}(\text{input image}, \text{condLDM}(\mathbf{p}))$
- Backpropagate to momentum condition \mathbf{p}
- Traverse loss surface via stochastic gradient descent

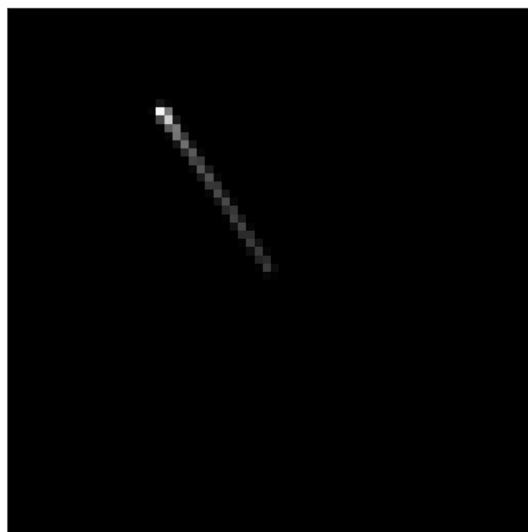
$$\text{EMD}(\text{input image}, \text{generator}(\mathbf{p}))$$


Track Inference

Unknown \mathbf{p} image

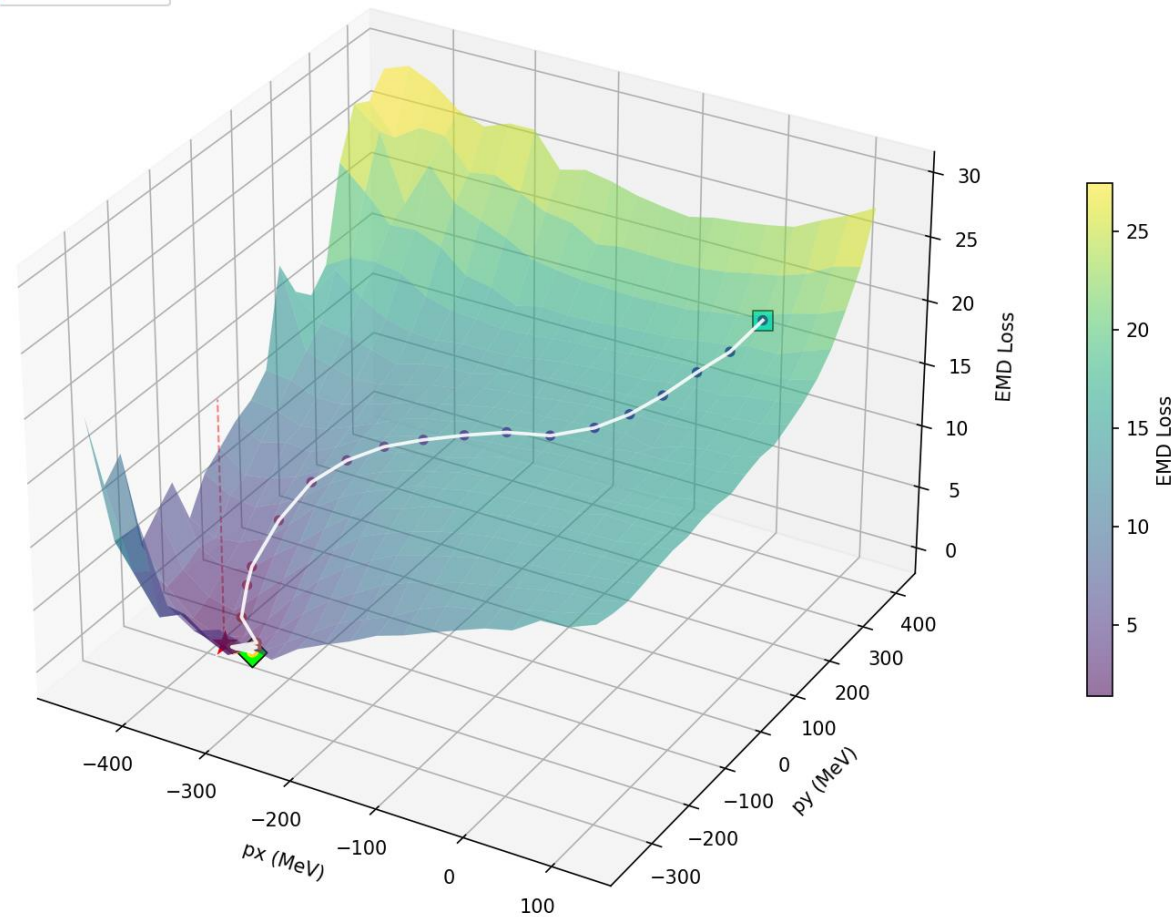


Generated from inferred \mathbf{p}



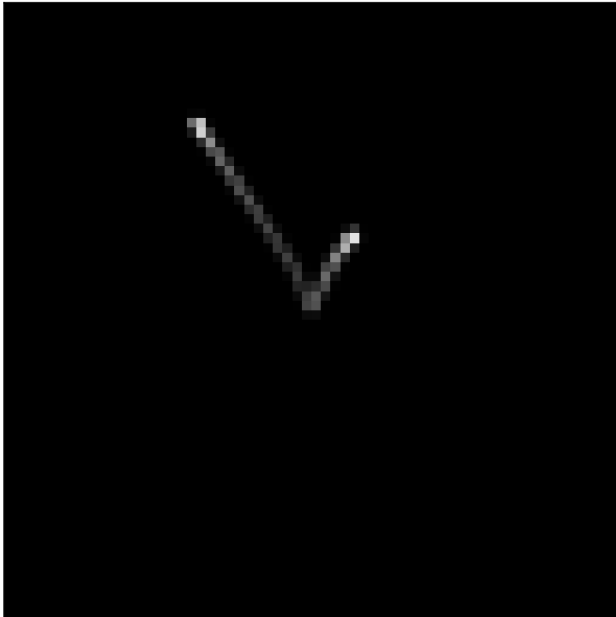
Loss Surface & SGD Trajectory ($p_z = 40$ MeV fixed)

Start EMD=20.162
End EMD=0.019
Truth (-356, -245)



Number of Tracks

Target two track

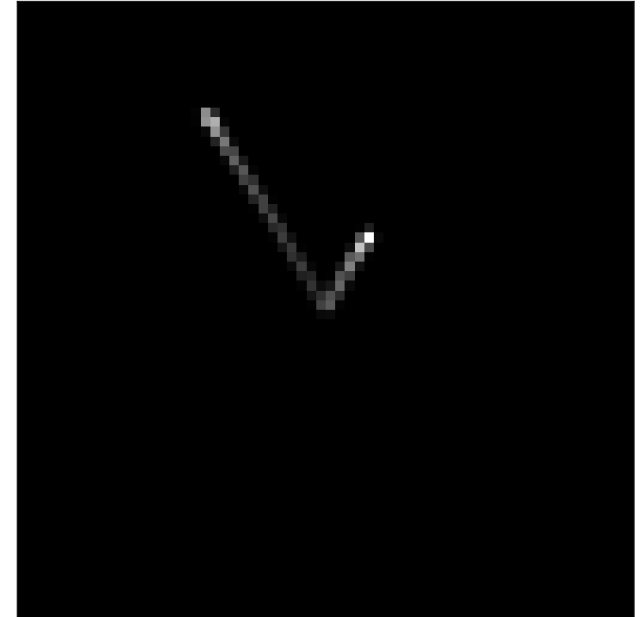


One track hypothesis



EMD = 3.01

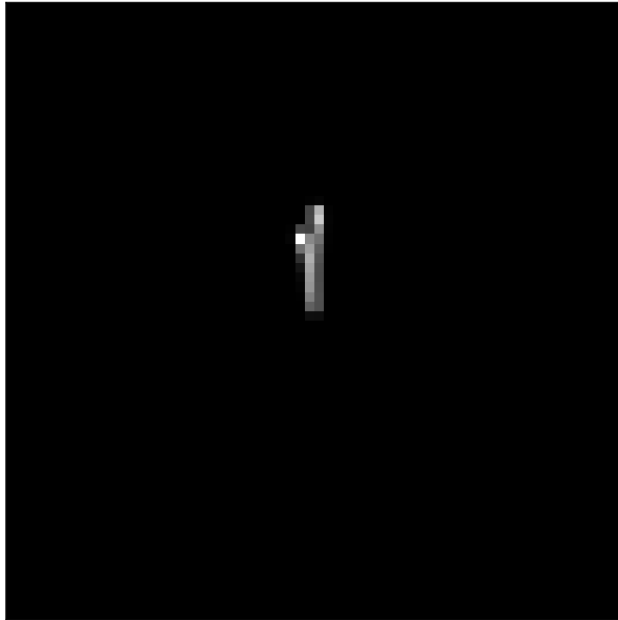
Two track hypothesis



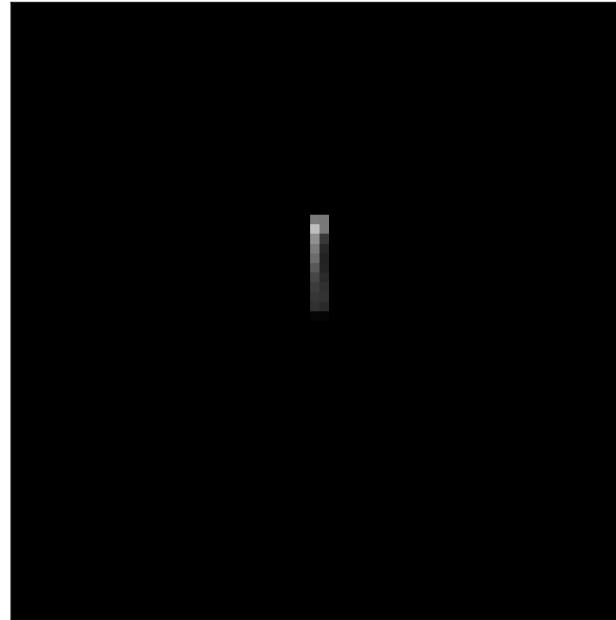
EMD = 0.15

Co-linear Tracks

Target two track

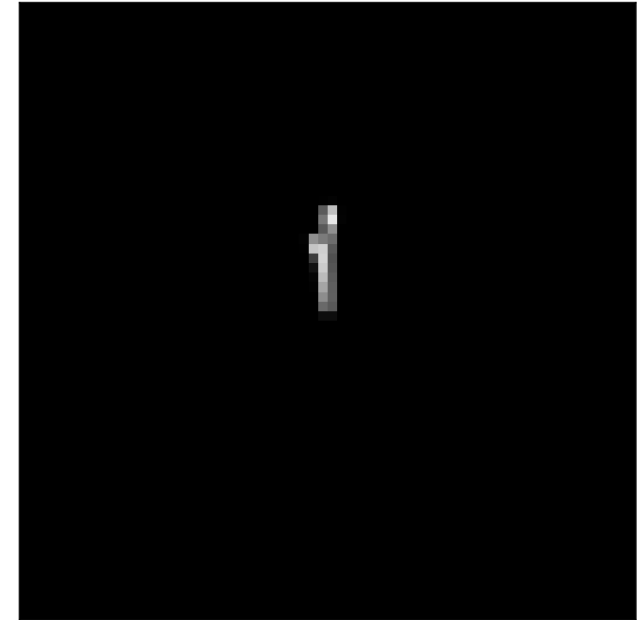


One track hypothesis



EMD = 0.28

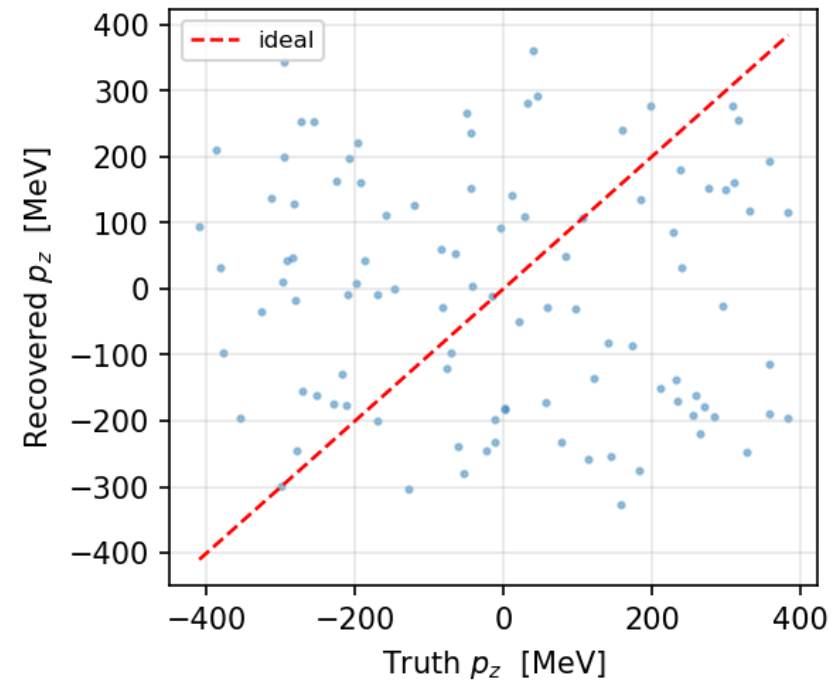
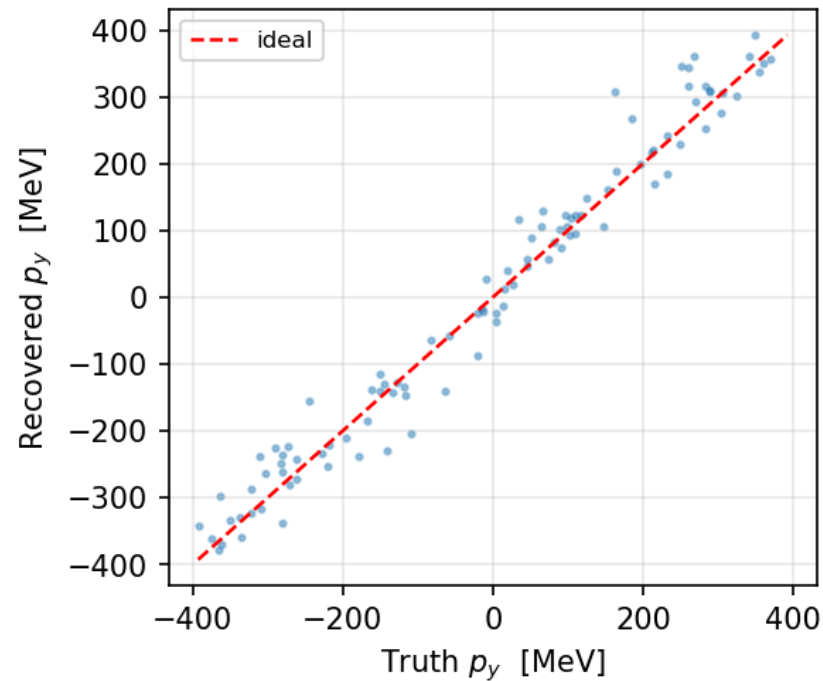
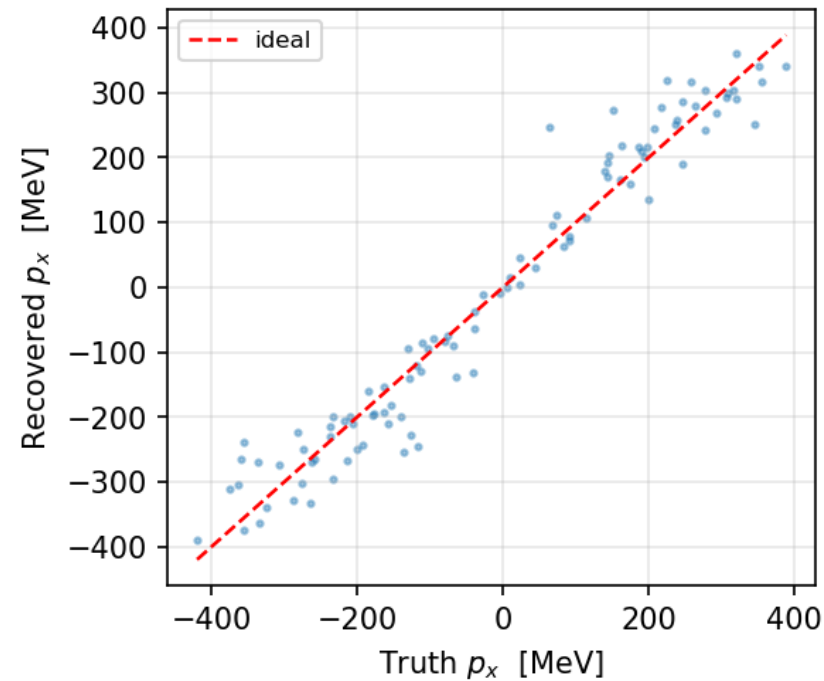
Two track hypothesis



EMD = 0.04

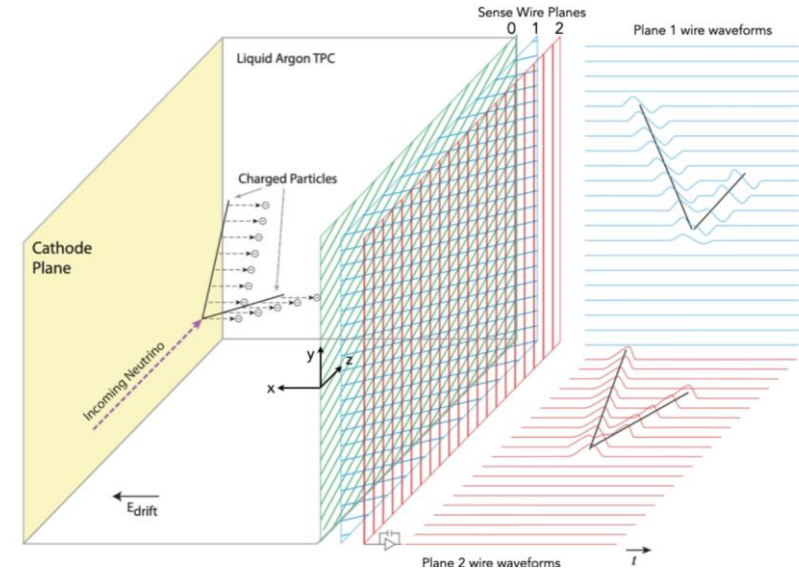
2D Images with 3D Momentums

- Inferred momentum good for p_x and p_y , but bad for p_z

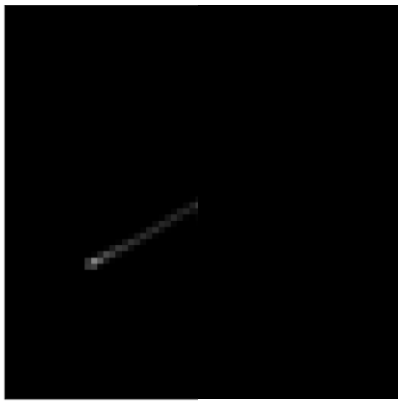


Projection Trick

- 3D events \rightarrow 2D projection images

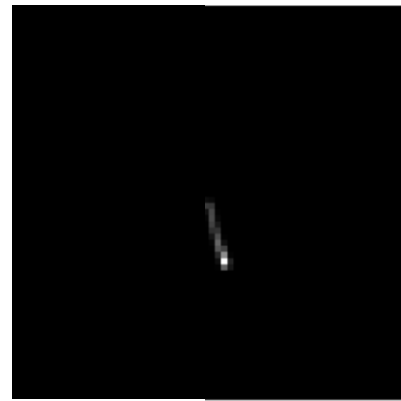


xy projection



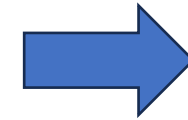
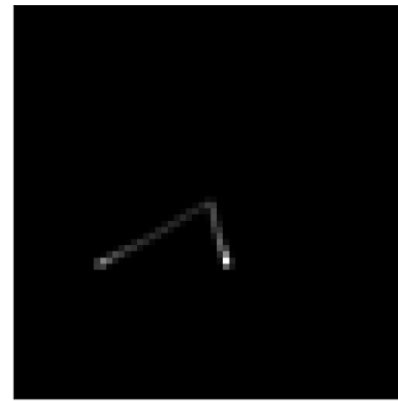
+

xz projection

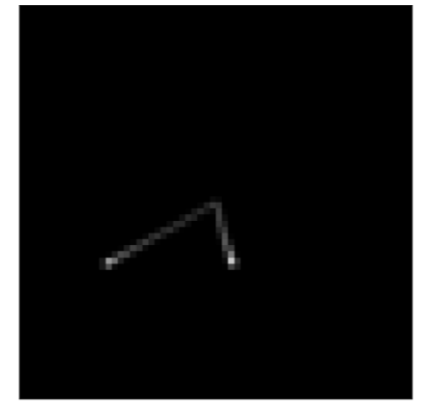


=

xy + xz projection

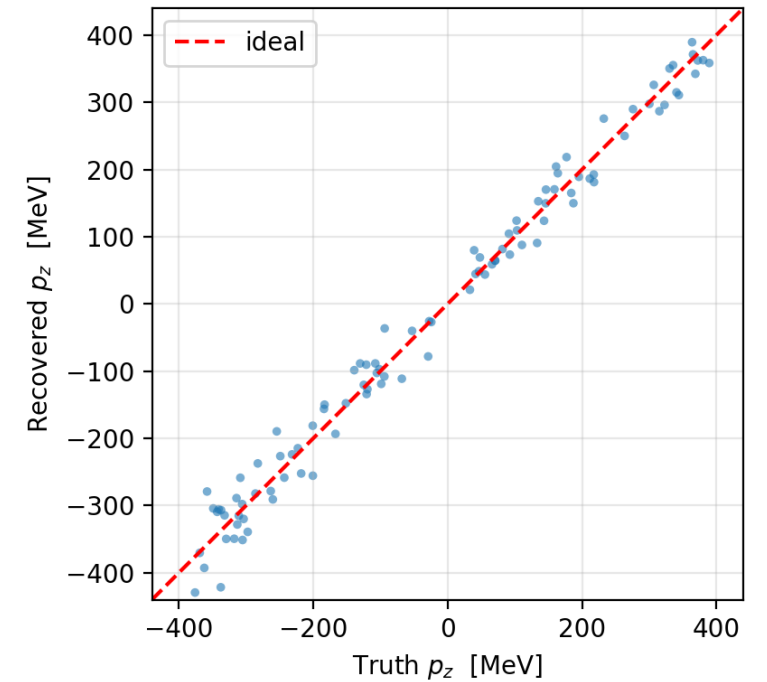
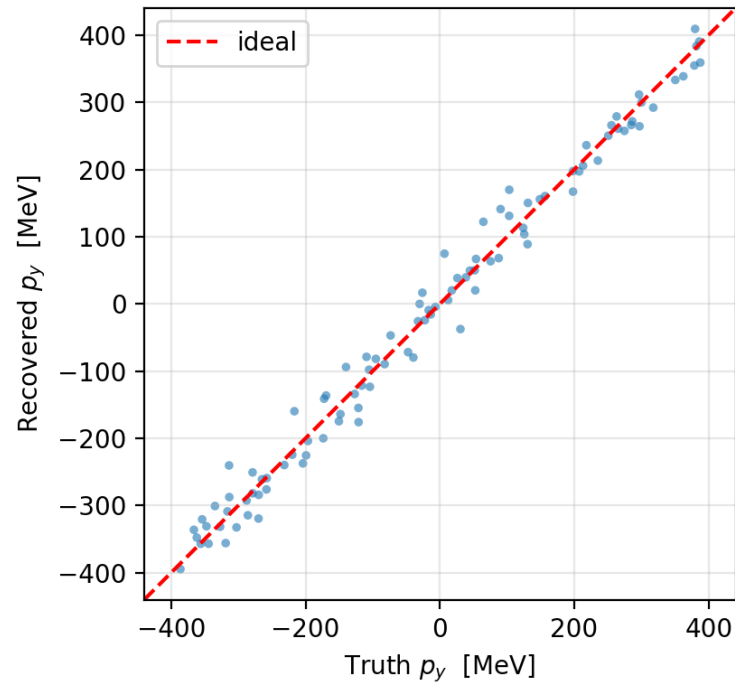
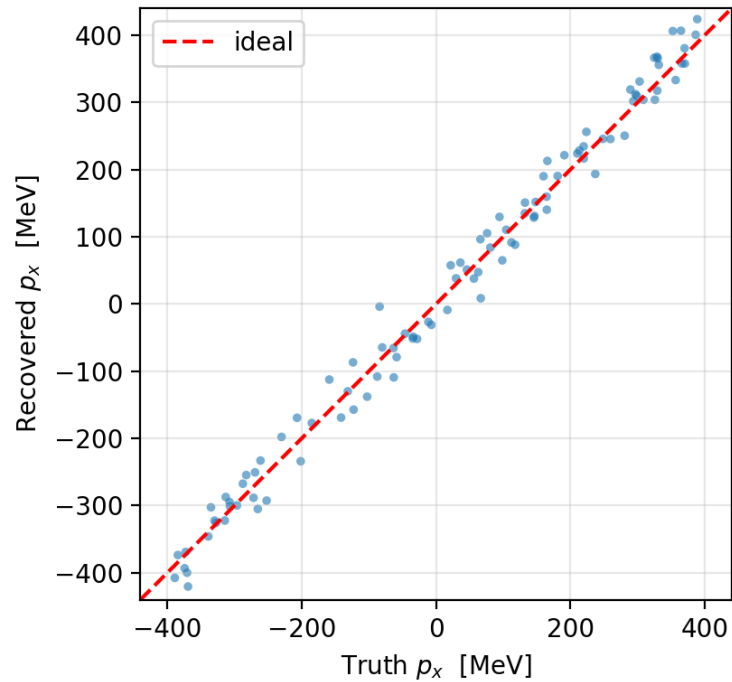


Inferred



Projection Trick

- Inferred 3D momentums



Conclusions

- Conditional latent diffusion model allows for event generation without underlying physics simulation (i.e. data-driven approach)
- Inference of event properties without traditional reconstruction methods using EMD loss and gradient descent
- Demonstrated with LArTPC protons. Goal of applying to regimes that traditional event generators struggle (neutrino-nucleus interactions)