AllShowers: One model for all calorimeter showers

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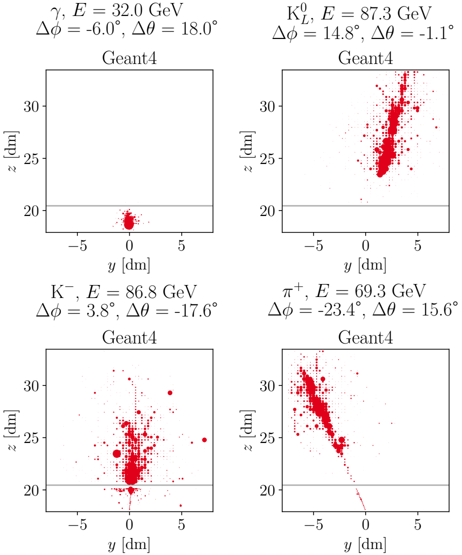
Motivation

Goal:

- previous models for specific particle types
  - CaloClouds[1]: photons
  - CaloHadronic[2]: positively charged pions
- one model for all particle types
  - reduce memory footprint and complexity
  - leverage shared knowledge between different particle showers

Dataset:

- 12 particle types
- simulated with Geant4 and DD4hep
- ECAL + HCAL of International Large Detector (ILD)

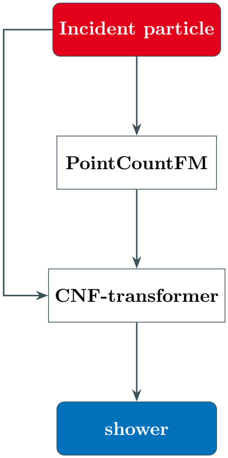


[1] Erik Buhmann et al. CaloClouds: fast geometry-independent highly-granular calorimeter simulation. 2023. arXiv: 2305.04847

[2] Thorsten Buss et al. CaloHadronic: a diffusion model for the generation of hadronic showers. 2025. arXiv: 2506.21720

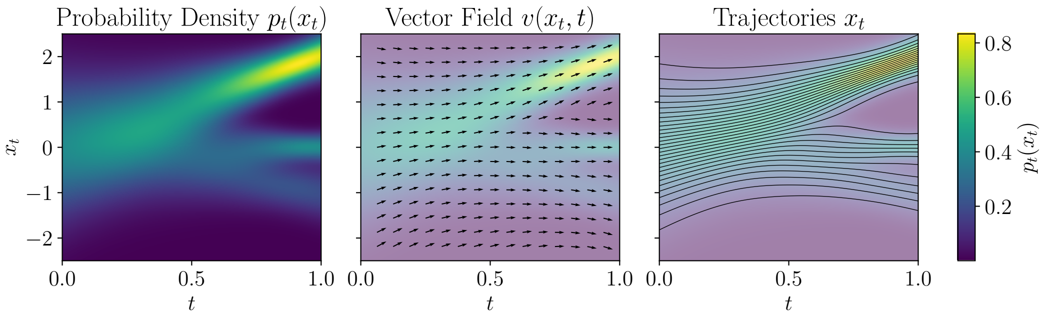
AllShowers Model Overview

- continuous normalizing flow[3]
- based on point clouds
- attention mechanism for point interactions[4]
- conditioning on incident particle properties
  - particle type
  - energy
  - direction (normalized 3-momentum)
- PointCountFM generates the number of points per layer
- CNF-Transformer generates the point positions and energies
  - layer index given as a condition
  - one embedding vector per calorimeter layer
  - one embedding vector per particle type



[3] Yaron Lipman et al. Flow Matching for Generative Modeling. 2023. arXiv: 2210.02747
[4] Ashish Vaswani et al. Attention Is All You Need. 2017. arXiv: 1706.03762

Continuous Normalizing Flow



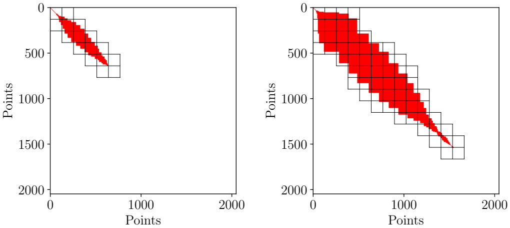
$$\partial_t \mathbf{x}_t = v(\mathbf{x}_t, t) \qquad \mathbf{x}_0 \sim p_0$$

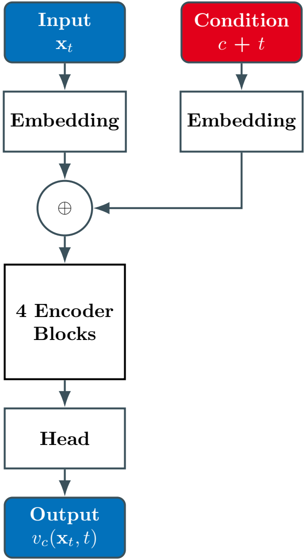
$$\log p_1(\mathbf{x}_1) = \log p_0(\mathbf{x}_0) - \int_0^1 \mathrm{Tr}\left(\frac{\partial v}{\partial \mathbf{x}_t}\right) dt$$

- regressing $v(\mathbf{x}_t, t)$ with a network
  - training with flow matching
- sampling
  - sample noise from prior distribution
  - solve the ODE given by the network

CNF-Transformer

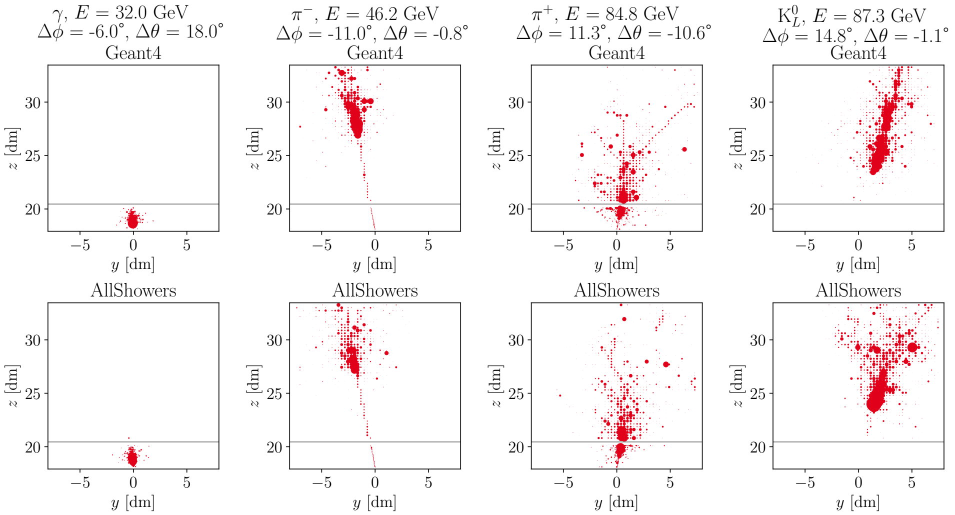
- model learns $v_c(\mathbf{x}_t, t)$
- transformer encoder blocks with self-attention
- using flex-attention[5]
- only points up to two calorimeter layers apart can interact



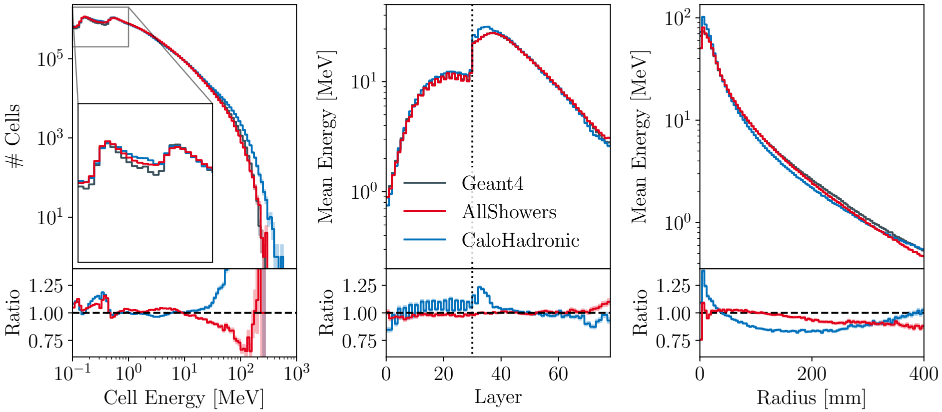


[5] Juechu Dong et al. Flex Attention: A Programming Model for Generating Optimized Attention Kernels. 2024. arXiv: 2412.05496

Individual Showers

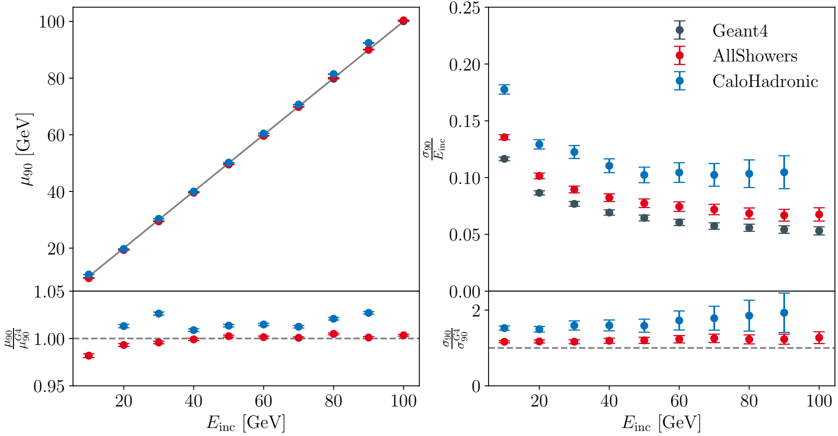


Comparison to CaloHadronic (Pions)



- hit energy, layer energy and radius distributions for π^+ showers
- comparison between AllShowers, CaloHadronic and Geant4

Linearity and Resolution (Pions)



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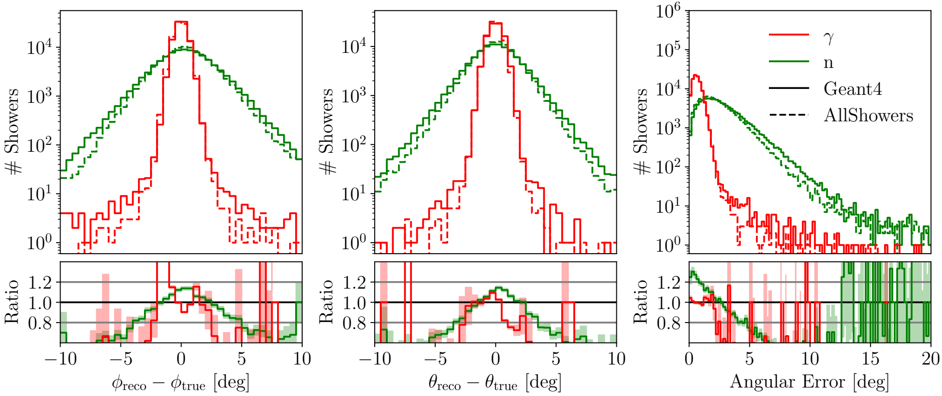
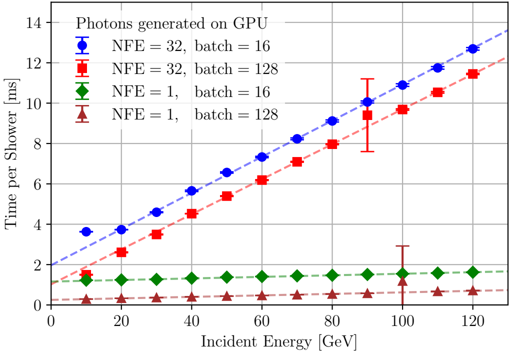
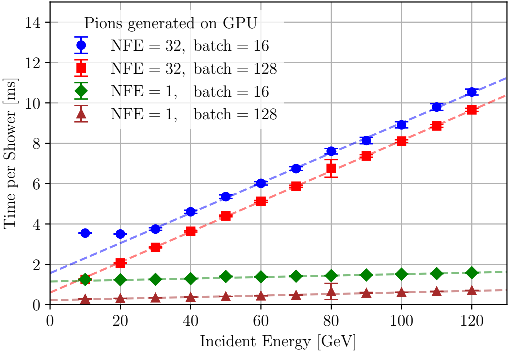
Internal Angle



- PCA-based angular reconstruction
- overall good agreement with Geant4
- hadrons harder to reconstruct
- some larger deviations in the tails

Inference Time





- generation time on an NVIDIA A100
- linear scaling with incident energy
- slightly faster generation for pions
- constant offset independent of energy

Summary

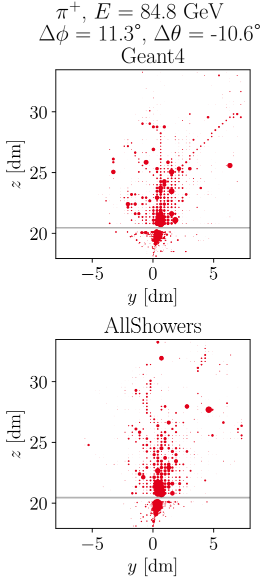
- AllShowers is a generative model for calorimeter showers
- unifying generation of 12 particle types in one model
- conditioned on incident particle properties:
  - particle type
  - energy
  - direction (normalized 3-momentum)
- well reproduces sample-wise and distribution-wise features
- higher fidelity than shower-type-specific models for hadronic showers

Paper on arXiv

2601.11716

Code on GitHub

FLC-QU-hep/
AllShowers

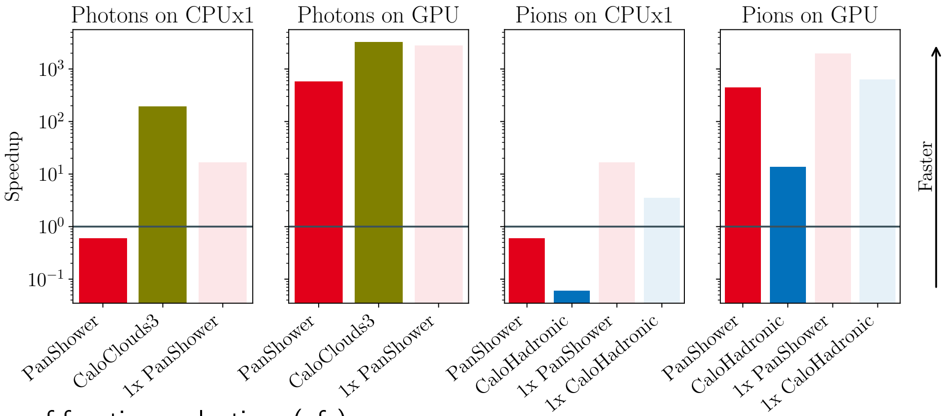


Model Size

Model	Layer-level model	Point-level model	Total
AllShowers	351,822	263,491	615,313
CaloClouds3	6,026,520	69,640	6,096,160
CaloHadronic	349,905	1,784,724	2,134,629

- Number of trainable parameters for AllShowers, CaloClouds3 and CaloHadronic
- AllShowers is significantly smaller than previous models

Inference Time

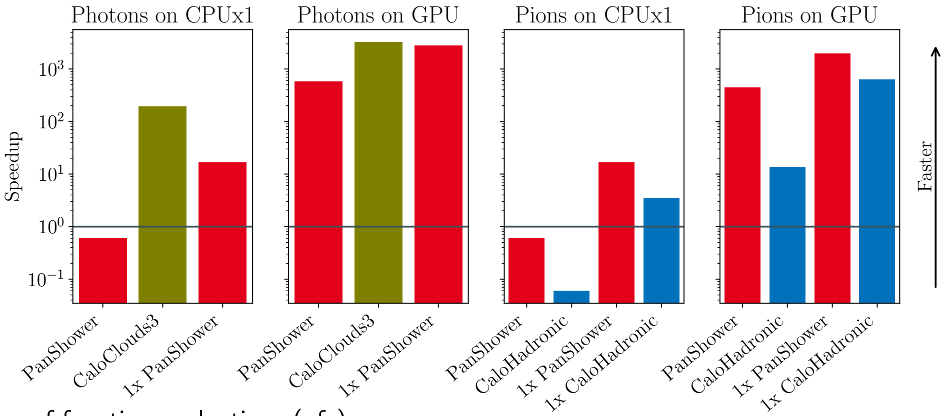


Number of function evaluations (nfe):

CaloClouds3	1		
AllShowers	32	1x AllShowers	1
CaloHadronic	59	1x CaloHadronic	1

	Hardware	batch size
CPU	AMD EPYC 7402	1
GPU	NVIDIA A100	16

Inference Time



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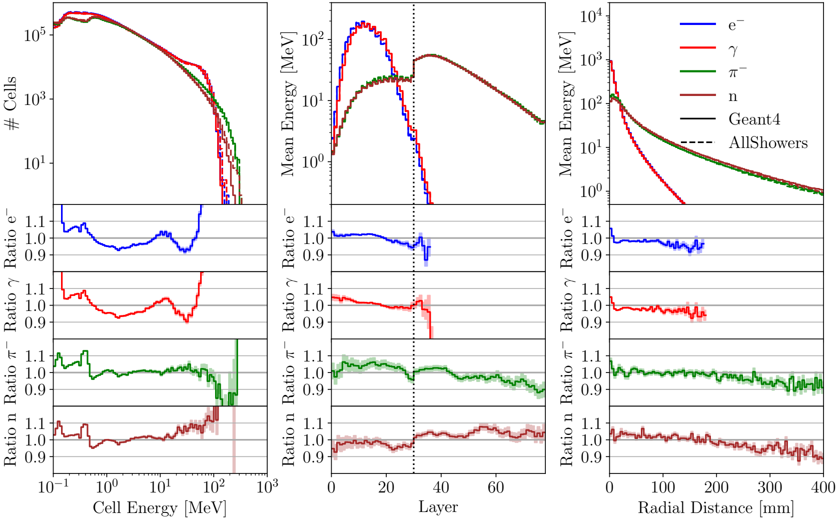
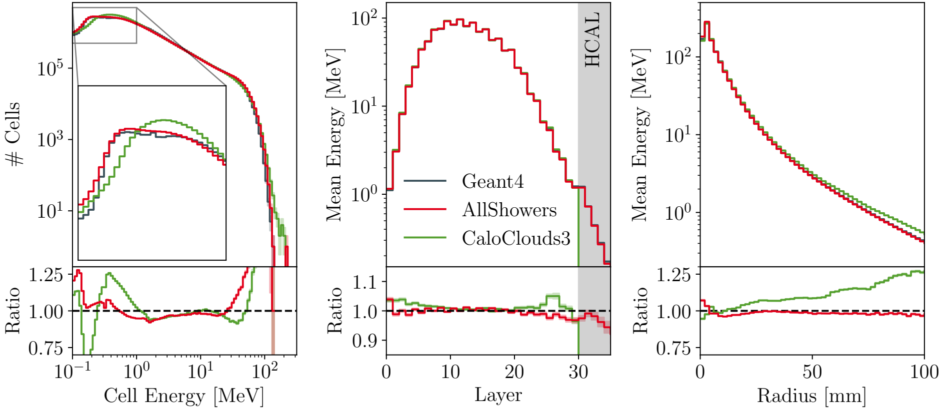
Distribution Level Comparison



Comparison to CaloClouds3 (Photons)



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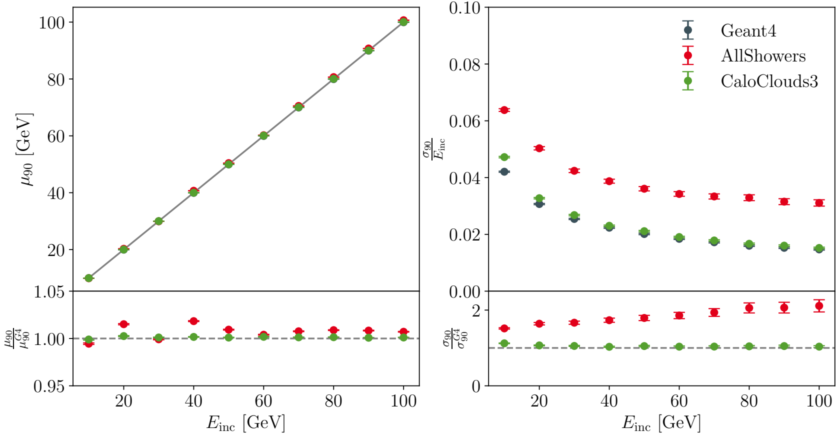
Linearity and Resolution (Photons)



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