



Parnassus An Automated Approach to Accurate, Precise, and Fast Detector Simulation and Reconstruction

Etienne Dreyer, Eilam Gross, <u>Dmitrii Kobylianskii</u>, Vinicius Mikuni, Benjamin Nachman

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Proton collisions





































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truth particles













Goals

Marginal distributions



Feature





Goals

Marginal distributions



Feature 2



Feature



4



Goals

Marginal distributions



Feature 2



Feature





Existing approach: Delphes 3

Public parametrized simulation

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- Commonly used for research
- Very fast

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- Shows good agreement of jet kinematics and resolution
- Not used by ATLAS/CMS
- Not very suitable for substructure and individual particle properties































Toy model: emulated tracks

Only charged particles

 p_T, η, ϕ

GNN with Slot-Attention

arXiv:2211.06406 Published in MLST







Published in MLST

Full GEANT4 reconstruction and simulation

Charged + Neutral

$$p_T, \eta, \phi, q$$

Diffusion and Flow matching models





Accepted in PRD

Published in MLST

CMS 2011A Simulation QCD, Single jets

Charged + Neutral

 p_T, η, ϕ

Flow matching

arXiv:2406.01620 Accepted in PRL

<u>Accepted in PRD</u>

Published in MLST

CMS 2011A Simulation QCD, Single jets

Charged + Neutral

 p_T, η, ϕ

Flow matching

arXiv:2406.01620 Accepted in PRL CMS 2011A Simulation QCD, TTbar, H4lep **Full event**

Charged + Neutral

 $p_T, \eta, \phi, \vec{v}, \mathsf{PID}$

Diffusion and Flow matching models

arXiv:2503.19981 Submitted to PRD

Single-Jet (<u>arXiv:2406.01620</u>)

- CMS 2011A Simulation dataset
- Full CMS simulation

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 QCD dijets events, jets clustered with anti-kt 0.5

 $p_T > 375, |\eta| < 1.9$

- 200 particles max
- Flow matching model

p_T^{\min} - p_T^{\max} [GeV]	Type	Training	Testing
470 - 600	Out-of-distribution		\checkmark
600 - 800	Out-of-distribution		\checkmark
800 - 1000	In-distribution	\checkmark	\checkmark
1000 - 1400	In-distribution	\checkmark	\checkmark
1400 - 1800	Out-of-distribution		\checkmark
1800 - ∞	$Out\-of\-distribution$		\checkmark

Delphes dataset for comparison was simulated by us with addition of CMS PileUp Minimum bias events.

Results: Single Jets

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Very good agreement with CMS Pflow

Jet features

Full event

- CMS Open Data, Simulation Datasets 2011
- Full event dataset
- $p_T > 1$ GeV, $|\eta| < 2.7$ cut on PFOs and truth particles
- 3M events for training

Dataset	Training	Testing			
QCD 470-600 GeV	\checkmark	\checkmark			
TTbar	\checkmark	\checkmark			
<u>Higgs → 4 leptons</u>		\checkmark			
QCD 1000-1400 GeV		\checkmark			

Example QCD event

Image is for illustrative purposes, datasets were extracted by us from CMS Open Data.

Full event: model description

- Conditional Flow Matching model
- Separate ResNet CFM network for (cardinality, E_x^{miss} , E_y^{miss} , H_T) prediction
- Cross-Attention Diffusion
 Transformer architecture for particle properties

- Maximum 400 particles
- p_T, η, ϕ, \vec{v} , PID prediction

t

Event features

Truth particles

 \vec{x}_t

$$p_t(x \mid z) = \mathcal{N} \left(x \mid tx_1, (t\sigma - t + 1)^2 \right)$$
$$u_t(x \mid z) = \frac{x_1 - (1 - \sigma)x}{1 - (1 - \sigma)t}$$

$$\mathscr{L}(\theta) = \mathbb{E}_{t,q(x_1),p_t(x|x_1)} \| v_{\theta}(x,t) - u_t(x|x_1) \|^2$$

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Results: Event level quantities

Results: Jet level quantities

Results: Particle level quantities Delphes Delphes Parnassus (F)CMS Pflow CMS Pflow Parnassus (F)Delphes CMS Pflow Parnassus (F)-0.35 10^{-1} -0.30 - 0.25 600 600 10^{-2} -0.20 QCD QCD -0.15 10^{-3} -0.10 Tolation . - 0.05 -10^{-4} -0.00 -2.0-1.5-0.5 0.5 1.0 1.5 -1.00.0 125 150 175 200 -2 25 100 50 75 2 -10 p_T , GeV V_X η

Summary plots

H_T residual

 C_2 residual

Particle class distribution

Summary

<u>Conclusions</u>

- CFM is a very powerful tool for PFOs generation
- Model is able to generalize to different processes and phase space regions
- Due to lack of truth pile-up particles model learned it implicitly
- Parnassus outperforms Delphes and is very close to CMS PFOs, especially in substructure and per-particle features

Future work directions

- Implement configurable and user-friendly interface with documentation
- Work with experiments (ATLAS, CMS) to produce and validate specific models: Work in ATLAS started
- Facilitate the sharing of such models to the broad physics community

https://github.com/parnassus-hep/cms-flow-evt

Jet residuals

Particle residuals

Class plots

								(CMS P	flow] Parn	assus (F)		Parna	assus (I	D)		Delph	ies					
CMS Pflow Parnassus (F)											Parnassus (D) Delph									Delphes						
	Ch. ha).73	0.01	0.01	0.16	0.10	0.72	0.01	0.01	0.17	0.10	0.72	0.01	0.01	0.17	0.10	0.76	0.00	0.00	0.05	0.19			- 0.6		
	0 - o ⁺).23	0.62	0.00	0.06	0.09	0.23	0.59	0.00	0.07	0.11	0.22	0.60	0.00	0.06	0.13	0.09	0.75	0.00	0.01	0.15			- 0.5		
→ 4/	+_ 0).17	0.00	0.74	0.05	0.03	0.17	0.00	0.73	0.06	0.03	0.18	0.00	0.73	0.05	0.03	0.08	0.00	0.85	0.01	0.06		·i	- 0.4 		
Н	had).55	0.01	0.01	0.26	0.18	0.56	0.01	0.01	0.25	0.18	0.68	0.01	0.01	0.19	0.12	0.45	0.01	0.01	0.18	0.36			- 0.3 \log		
	Nu.		0.01	0.01	0.10	0.20	0.50	0.01	0.01	0.10	0.00	0.50	0.01	0.01	0.10	0.00	0.00	0.01	0.00	0.04				- 0.1		
).50	0.01	0.01	0.19	0.29	0.50	0.01	0.01	0.19	0.29	0.52	0.01	0.01	0.18	0.28	0.30	0.01	0.00	0.04	0.65			0.0		
	h. hac).76	0.00	0.00	0.12	0.11	0.76	0.00	0.00	0.12	0.11	0.75	0.00	0.00	0.13	0.12	0.84	0.00	0.00	0.04	0.11			- 0.6		
	0 - G ⁺	0.43	0.34	0.00	0.08	0.15	0.43	0.33	0.00	0.08	0.16	0.42	0.33	0.00	0.08	0.18	0.11	0.75	0.00	0.03	0.12			- 0.5		
tt	+, 0).31	0.00	0.55	0.06	0.08	0.31	0.00	0.54	0.07	0.08	0.32	0.00	0.54	0.06	0.08	0.08	0.00	0.85	0.02	0.05		[]	- 0.4		
1	had µ		0.00	0.00	0.92	0.97	0 50	0.00	0.00	0.92	0.96	0.64	0.00	0.00	0.16	0.10	0.20	0.00	0.00	0.95	0.42			-0.3 ದೆ		
	Nu.	J.5U	0.00	0.00	0.23	0.27	0.00	0.00	0.00	0.23	0.20	0.04	0.00	0.00	0.10	0.19	0.32	0.00	0.00	0.20	0.43			- 0.2		
	- √	0.43	0.01	0.00	0.15	0.41	0.44	0.01	0.00	0.15	0.40	0.45	0.01	0.00	0.14	0.40	0.19	0.00	0.00	0.04	0.77		ⁱ	0.0		
	n. had).76	0.00	0.00	0.11	0.13	0.75	0.00	0.00	0.12	0.13	0.74	0.00	0.00	0.12	0.14	0.85	0.00	0.00	0.04	0.11			- 0.6		
	6 ⁺ C).68	0.05	0.00	0.09	0.19	0.67	0.04	0.00	0.10	0.20	0.66	0.04	0.00	0.09	0.21	0.13	0.70	0.00	0.04	0.13			- 0.5		
) 470	+. 0) 51	0.00	0.30	0 09	0.11	0.51	0.00	0.28	0.08	0.12	0.52	0.00	0.27	0.09	0.12	0.11	0.00	0 77	0.03	0.09		·3	- 0.4		
QCL	had μ		0.00	0.00	0.00	0.11	0.01	0.00	0.20	0.00	0.12		0.00	0.21	0.00	0.12	0.11	0.00		0.00	0.00			- _{0.3} ದ		
	Nu.]).53	0.00	0.00	0.20	0.27	0.55	0.00	0.00	0.19	0.27	0.66	0.00	0.00	0.14	0.19	0.32	0.00	0.00	0.22	0.47			- 0.2		
	ר∽ 0	0.49	0.00	0.00	0.13	0.38	0.50	0.00	0.00	0.13	0.36	0.50	0.00	0.00	0.13	0.37	0.18	0.00	0.00	0.04	0.78		i	0.0		
	n. had).76	0.00	0.00	0.11	0.13	0.74	0.00	0.00	0.12	0.14	0.74	0.00	0.00	0.12	0.14	0.85	0.00	0.00	0.04	0.11			- 0.6		
	Ch ⁺ Ch).68	0.04	0.00	0.09	0.19	0.68	0.03	0.00	0.09	0.20	0.66	0.03	0.00	0.09	0.22	0.12	0.71	0.00	0.04	0.13			- 0.5		
600			0.00	0.00	0.00	0.10	0.50	0.00	0.00	0.00	0.10	0.50	0.00	0.05	0.00	0.10	0.10	0.00	0.00	0.001	0.00		·	0.4		
QCD	ad μ^{-1}	J.52	0.00	-0.29	0.08	0.12	0.52	0.00	-0.26	0.09	0.13	0.52	0.00	-0.27	0.08	0.12	0.10	0.00	-0.79	0.02	0.09			a.1 1.0 1.0		
	Nu. h).54	0.00	0.00	0.19	0.27	0.55	0.00	0.00	0.18	0.26	0.66	0.00	0.00	0.14	0.19	0.32	0.00	0.00	0.21	0.47			- 0.2		
	ס -≺).49	0.00	0.00	0.13	0.37	0.51	0.00	0.00	0.13	0.35	0.51	0.00	0.00	0.13	0.36	0.18	0.00	0.00	0.04	0.78			- 0.1		
	Ch	n. had	e^{\pm}	μ^{\pm}	Nu. had	1γ	Ch. had	e [±]	μ^{\pm}	Nu. had	$ert \gamma$	Ch. had	e^{\pm}	μ^{\pm}	Nu. had	γ	Ch. had	e^{\pm}	μ^{\pm}	Nu. had	1γ	Ch. had	e^{\pm} μ^{\pm} Nu. had γ	<u> </u>		

