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BERKELEY LAB

Parnassus

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

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ML4Jets 2024

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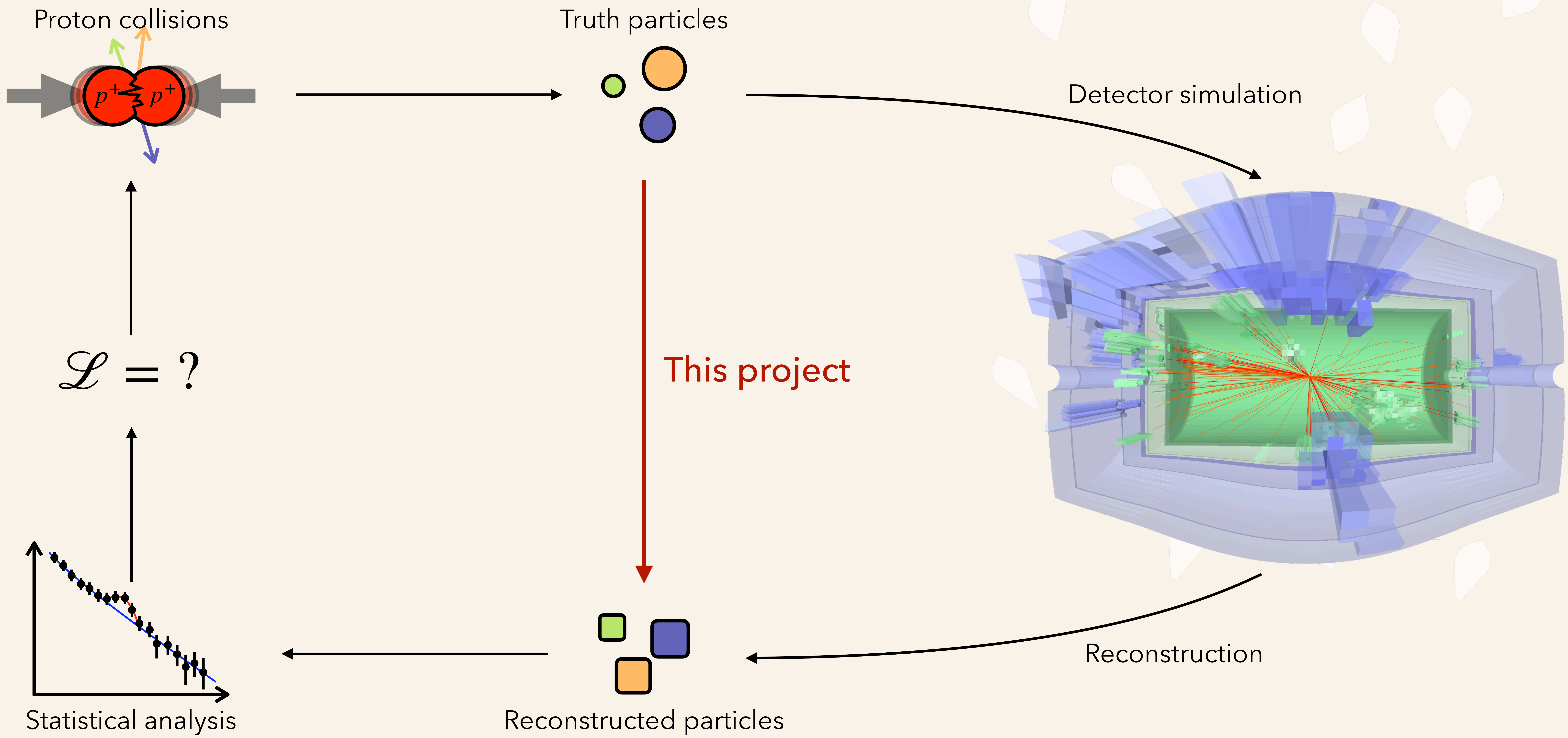
Motivation



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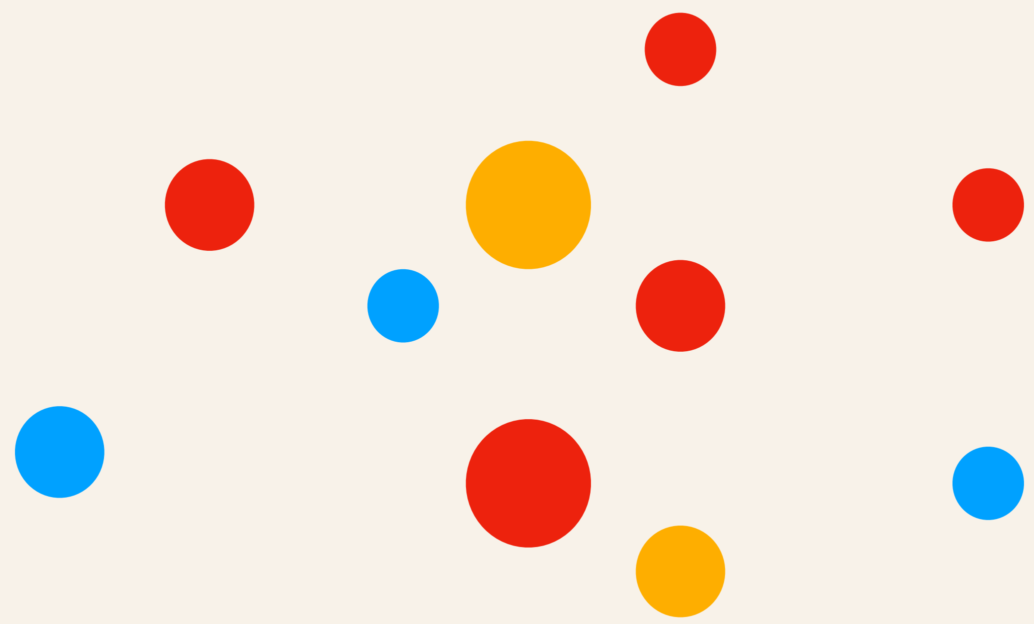
Problem to solve

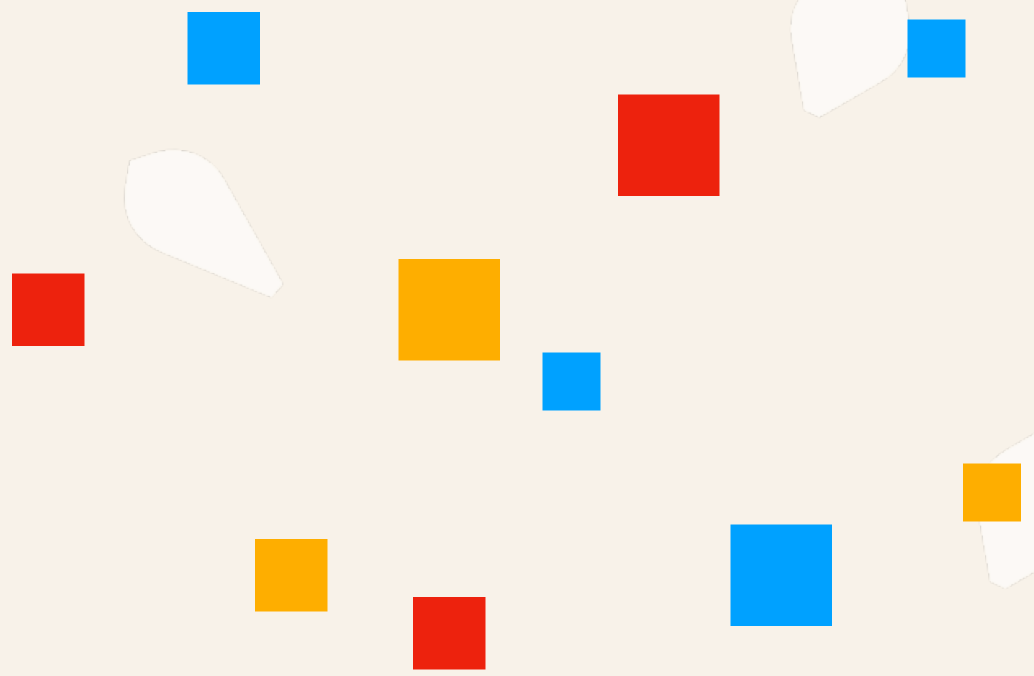
Final state truth particles



Set to Set

?

Reconstructed objects



Amount of objects

+

Their properties

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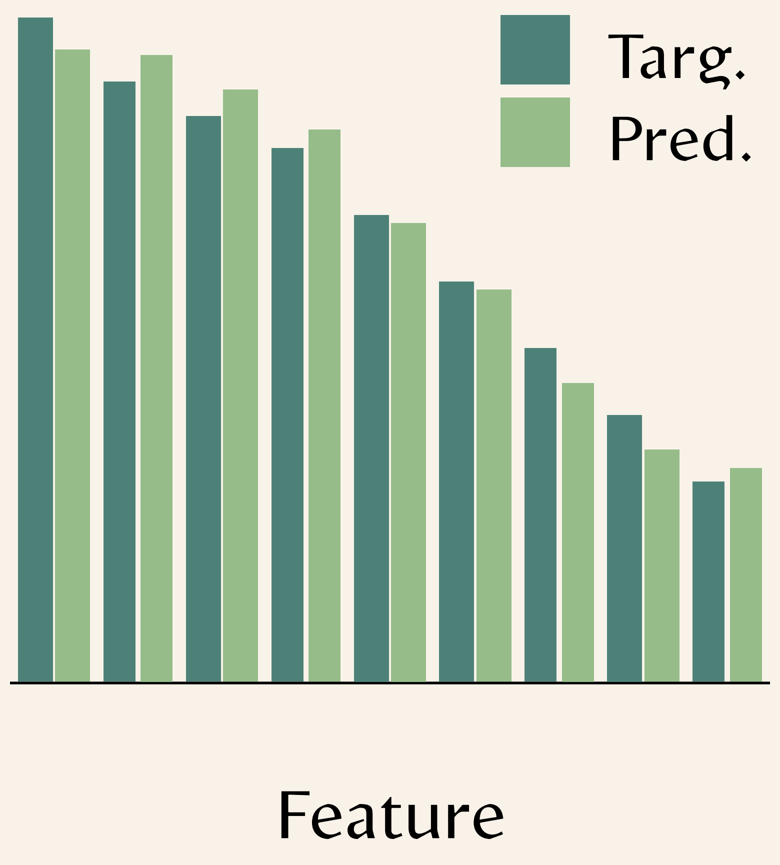
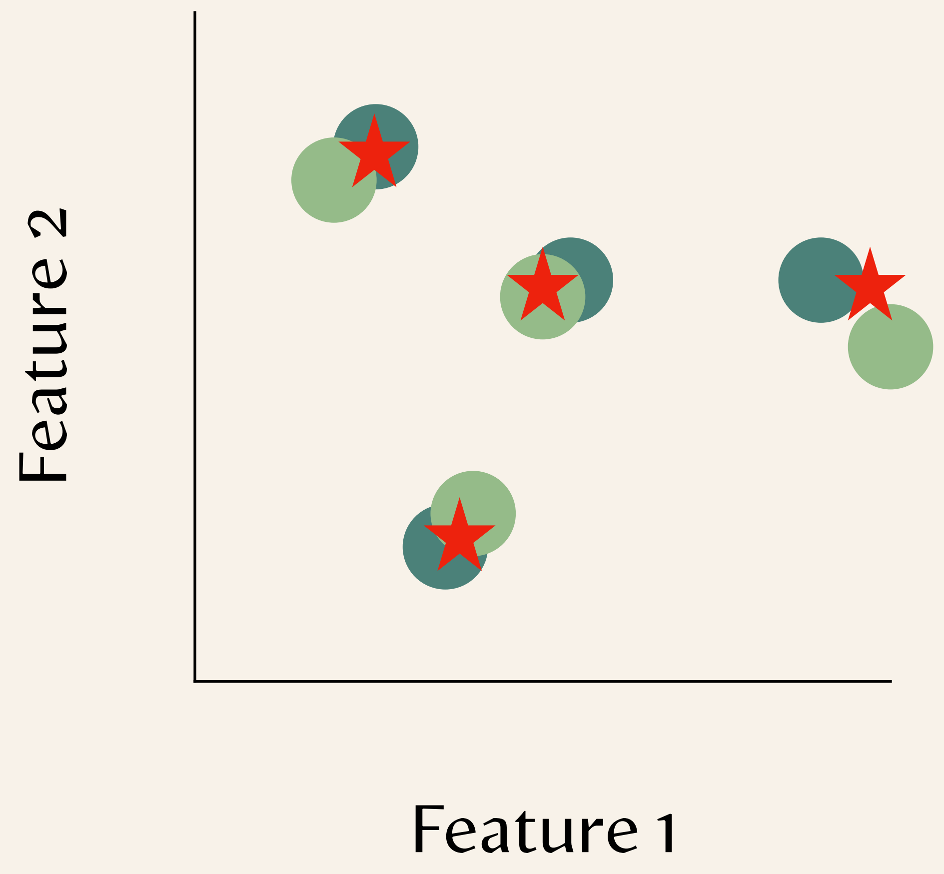
Goals

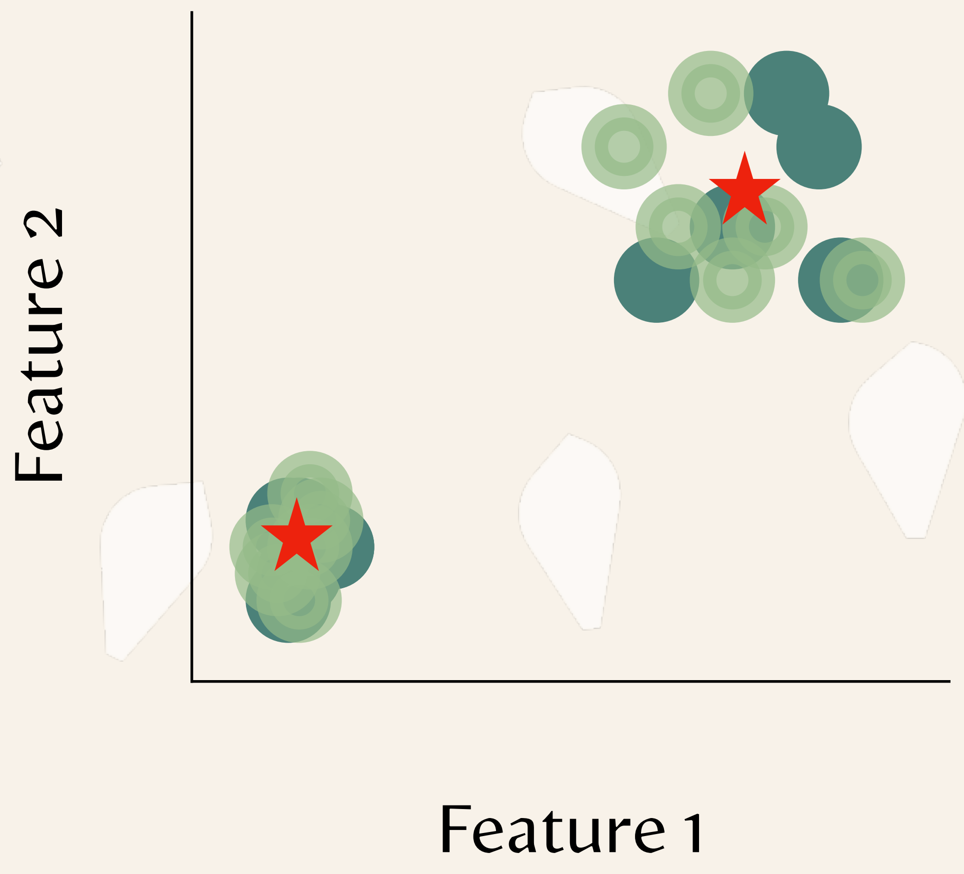
Marginal distributions

Reconstruct constituents

Resolution

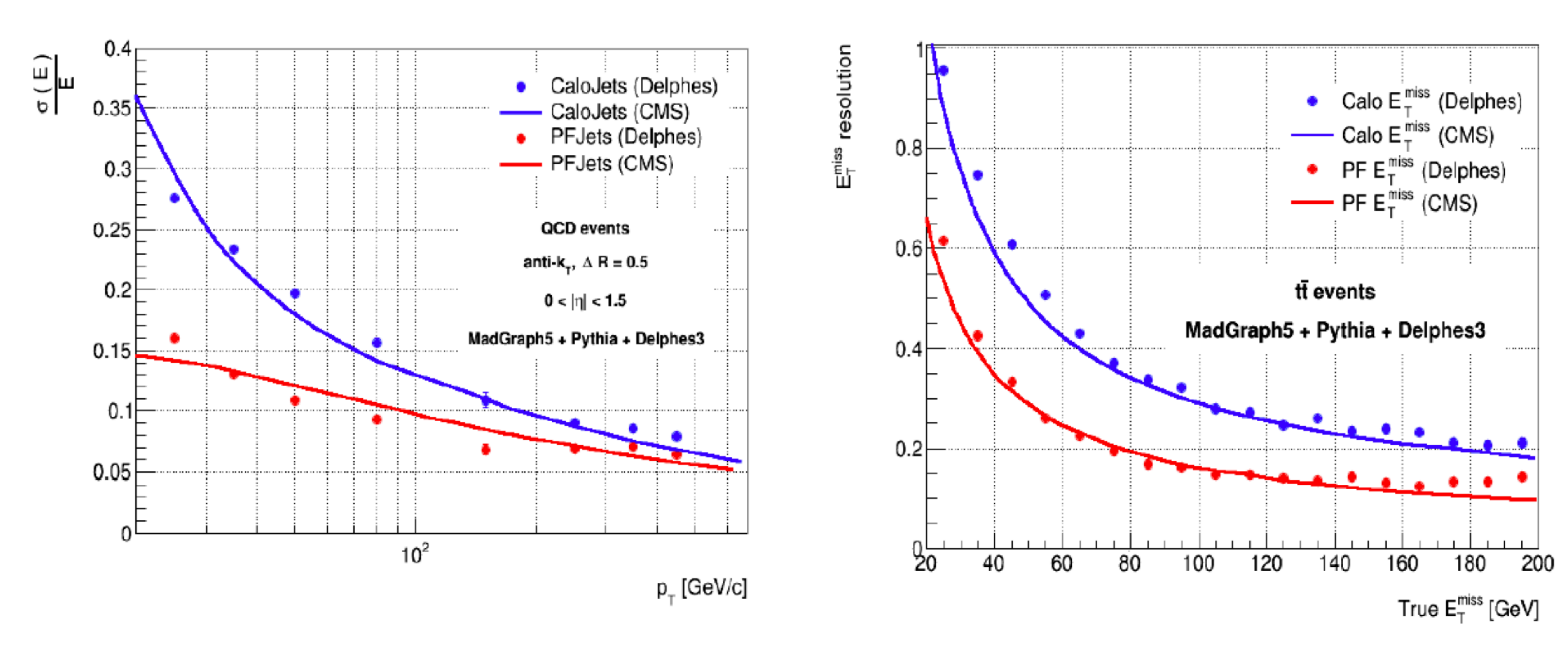






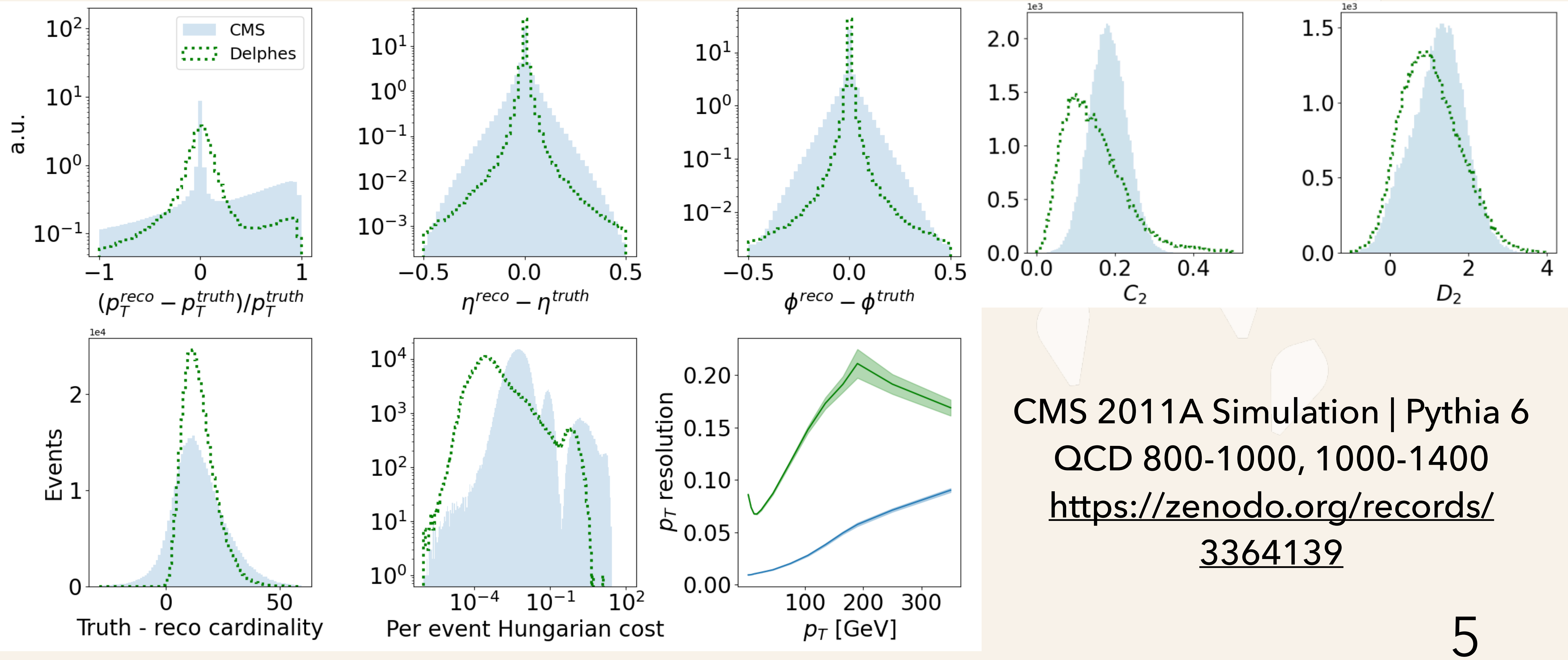
Existing approach: Delphes 3

- Public parametrized simulation
- Commonly used for research
- Very fast
- Shows good agreement of jet kinematics and resolution
- Not used by ATLAS/CMS
- Not very suitable for substructure and individual particle properties



Delphes 3

http://arxiv.org/abs/1307.6346



CMS 2011A Simulation | Pythia 6
QCD 800-1000, 1000-1400
https://zenodo.org/records/3364139

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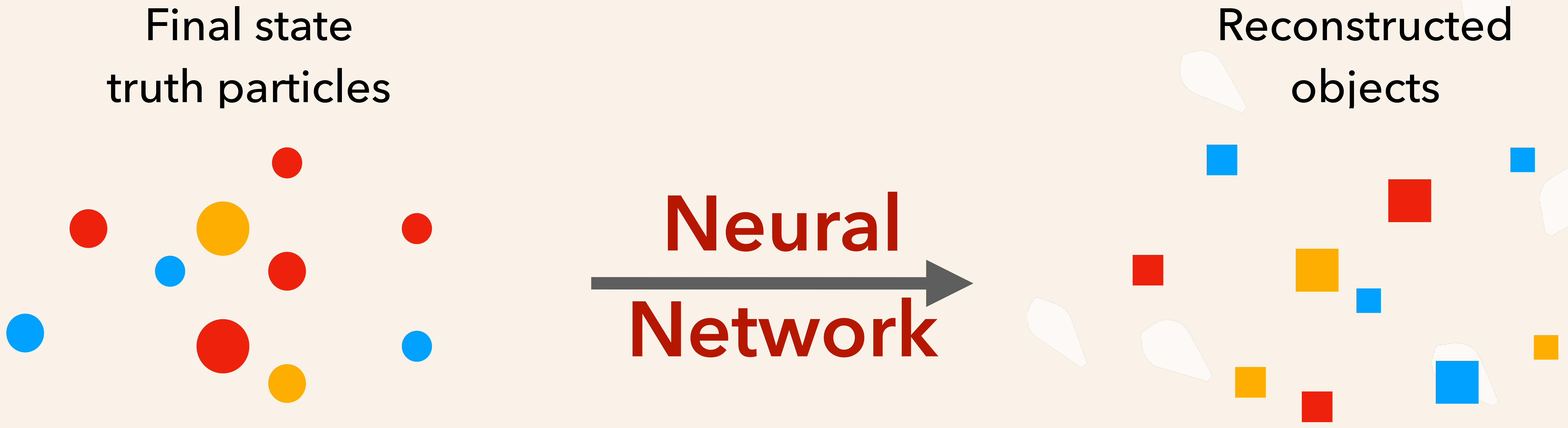
ML-based approach



ML-based approach: Our journey

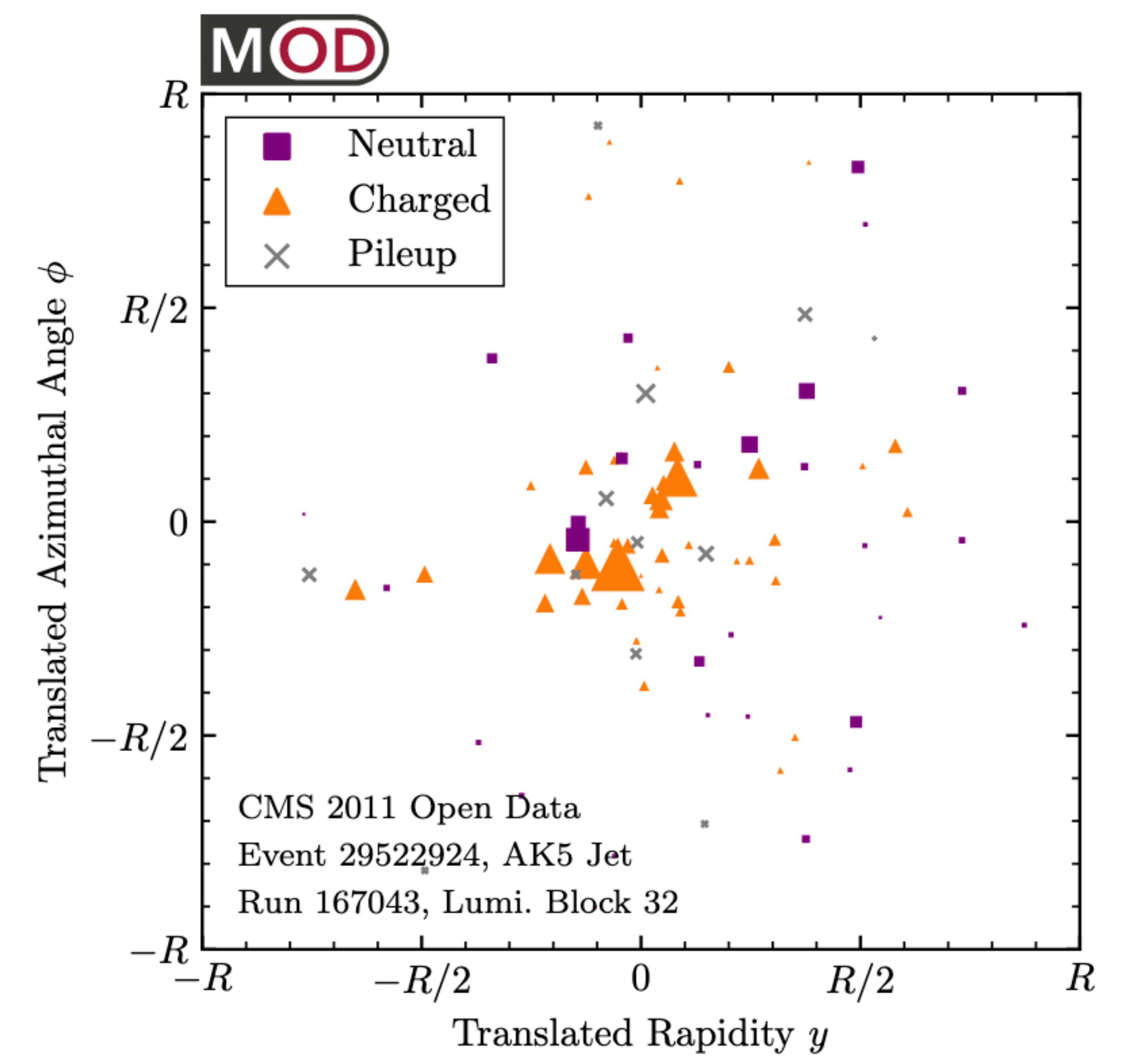
Toy model: emulated tracks	Full GEANT4 reconstruction and simulation	CMS 2011A Simulation QCD, Single jets	CMS 2011A Simulation QCD, TTbar, H4lep **Full event**
Only charged particles	Charged + Neutral	Charged + Neutral	Charged + Neutral
p_T, η, ϕ	p_T, η, ϕ, q	p_T, η, ϕ	$p_T, \eta, \phi, \vec{v}$, PID
GNN with Slot-Attention	Diffusion and Flow matching models	Flow matching	Flow matching
arXiv:2211.06406 Published in MLST	arXiv:2405.10106 Accepted in PRD	arXiv:2406.01620 Accepted in PRL	

This talk

Single-Jet (arXiv:2406.01620)

- CMS 2011A Simulation dataset
- Full CMS simulation
- QCD dijets events, jets clustered with anti-kt 0.5 $p_T > 375, |\eta| < 1.9$
- 200 particles max

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



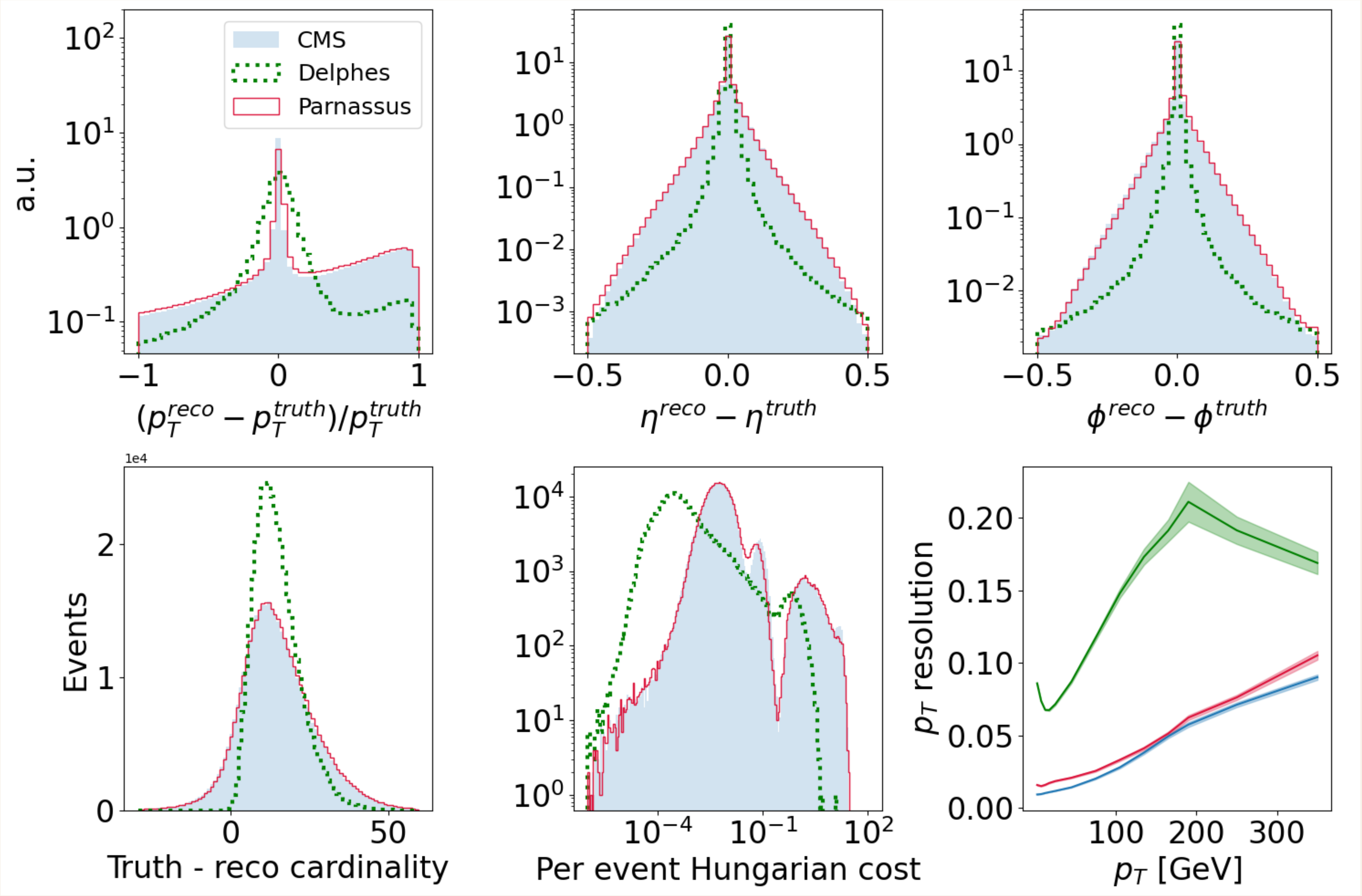
Example QCD jet (http://arxiv.org/abs/1908.08542)

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

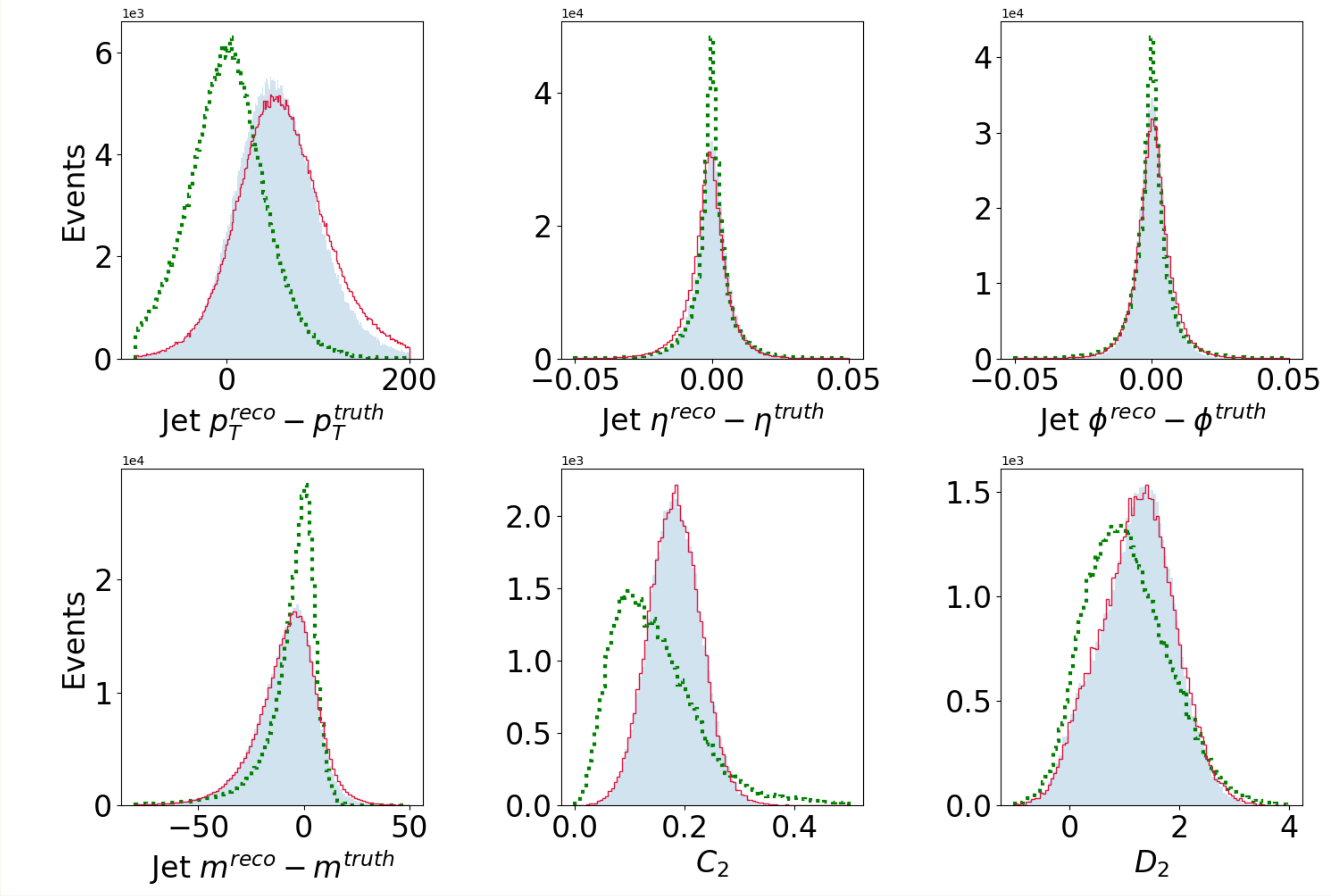
Results: Single Jets

Very good agreement with CMS Pflow

Outperform Delphes everywhere



Particle features

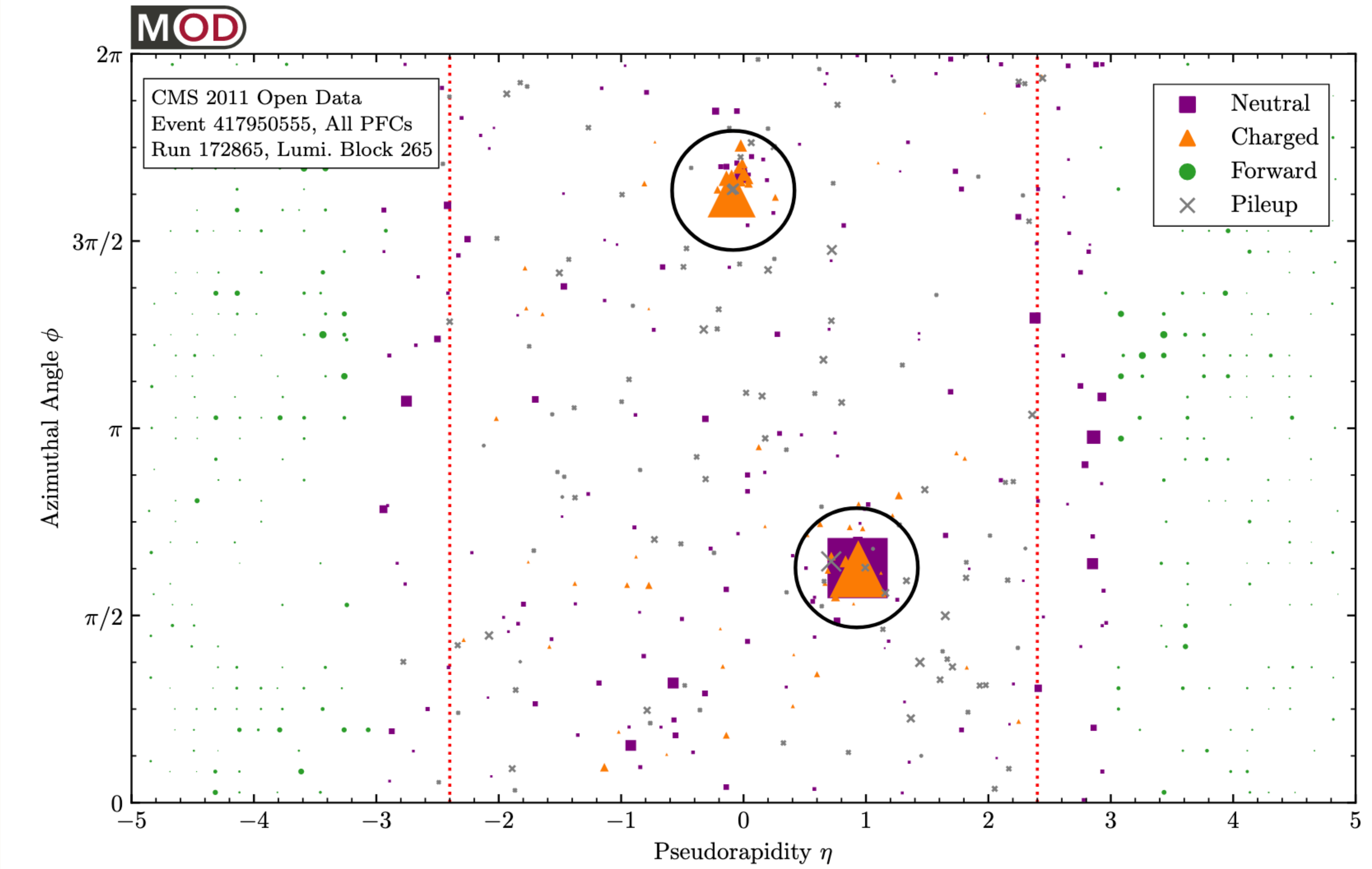


Jet features

Full event

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

Dataset	Training	Testing
QCD 470-600 GeV	✓	✓
TTbar	✓	✓
Higgs → 4 leptons		✓
QCD 1000-1400 GeV		✓



Example QCD event (http://arxiv.org/abs/1908.08542)

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

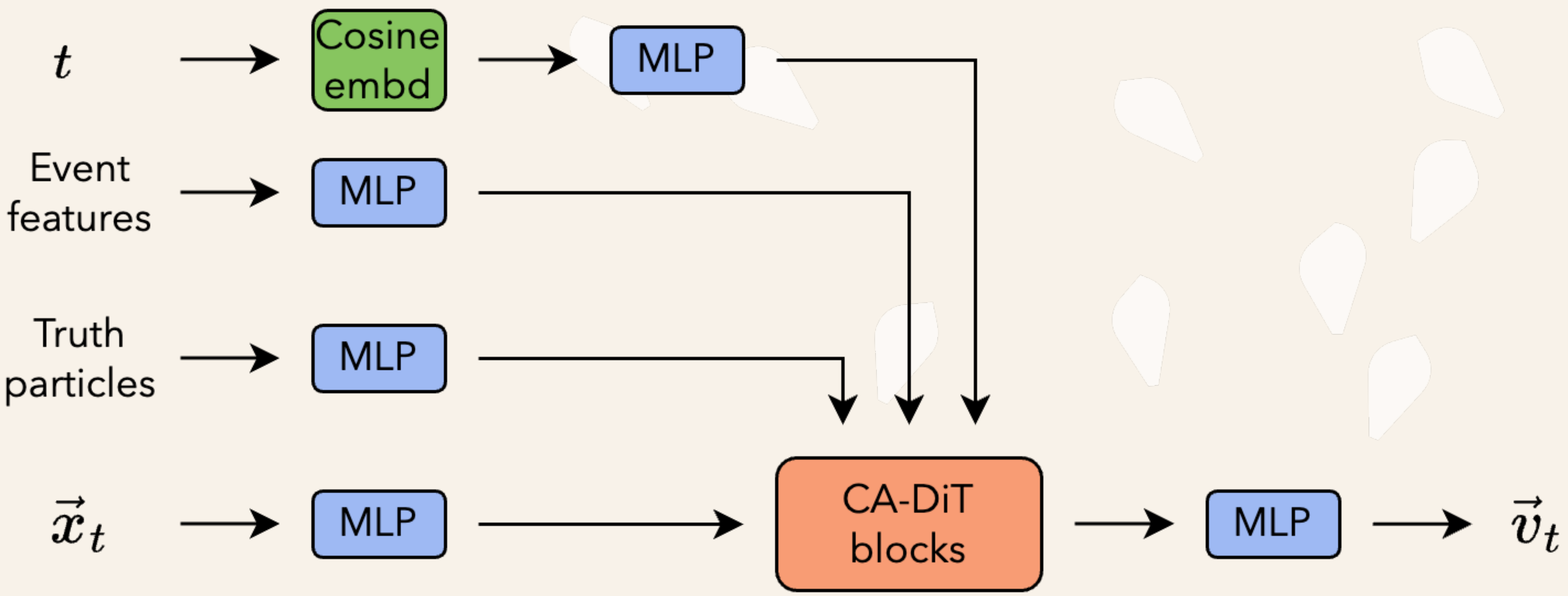
Full event: model description

- 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
- $p_T, \eta, \phi, \vec{v}$, PID prediction

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

$$u_t(x|z) = \frac{x_1 - (1-\sigma)x}{1 - (1-\sigma)t}$$

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



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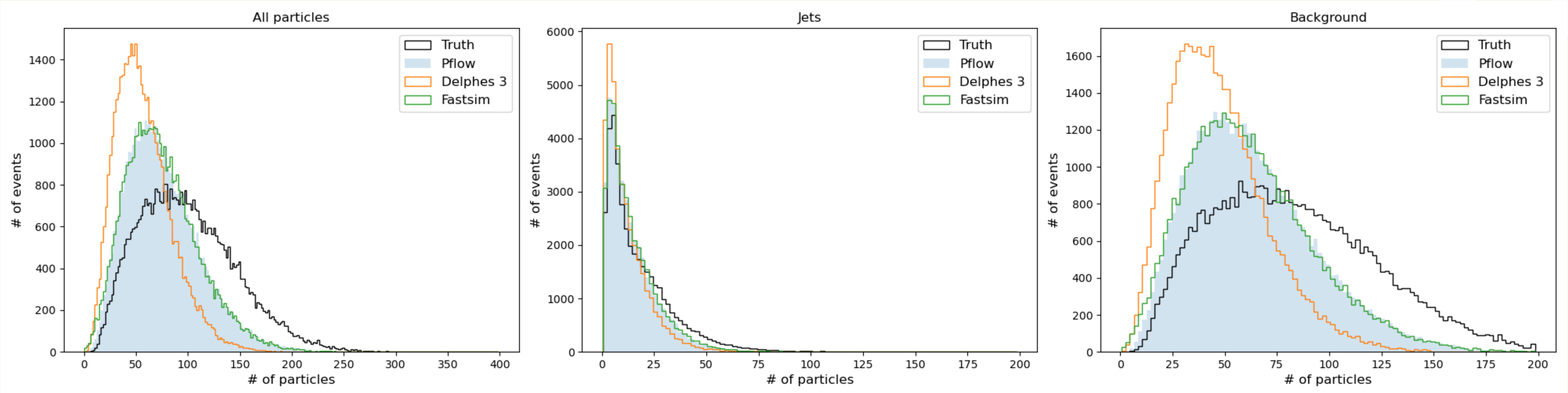
Results: Higgs → 4 leptons

Cardinality



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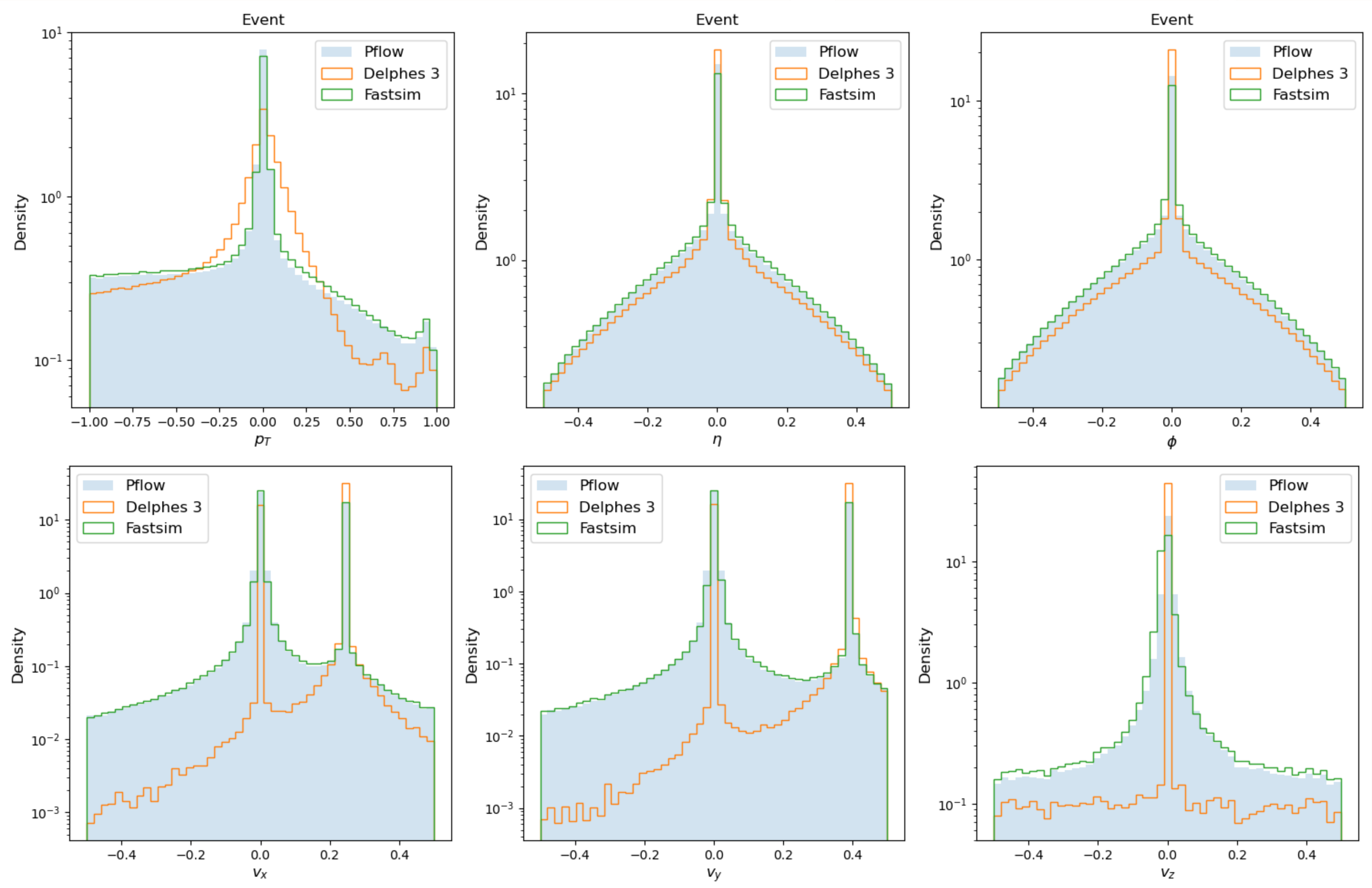
Results: Higgs → 4 leptons

Residuals

- Based on Hungarian Matching between PFOs and Truth particles with ΔR metric
- Neutral PFOs are set to zero vertex



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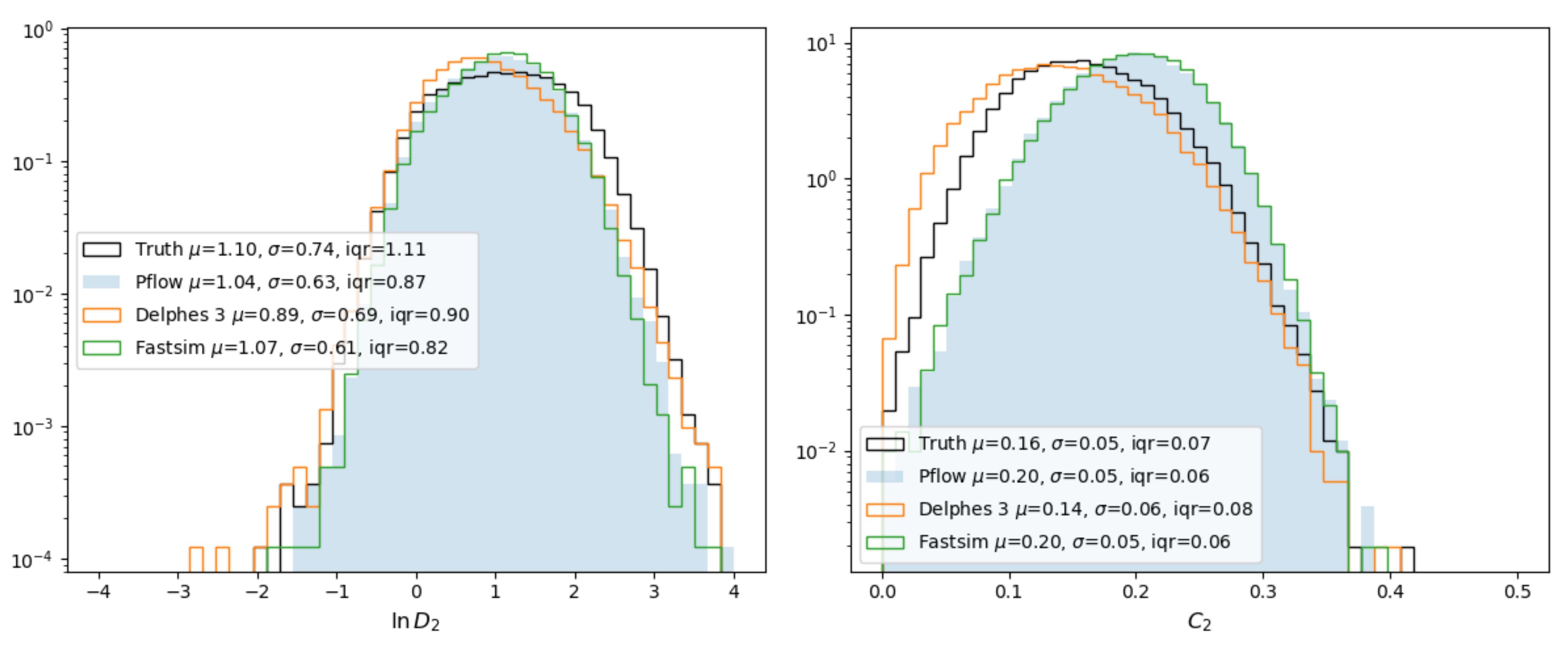
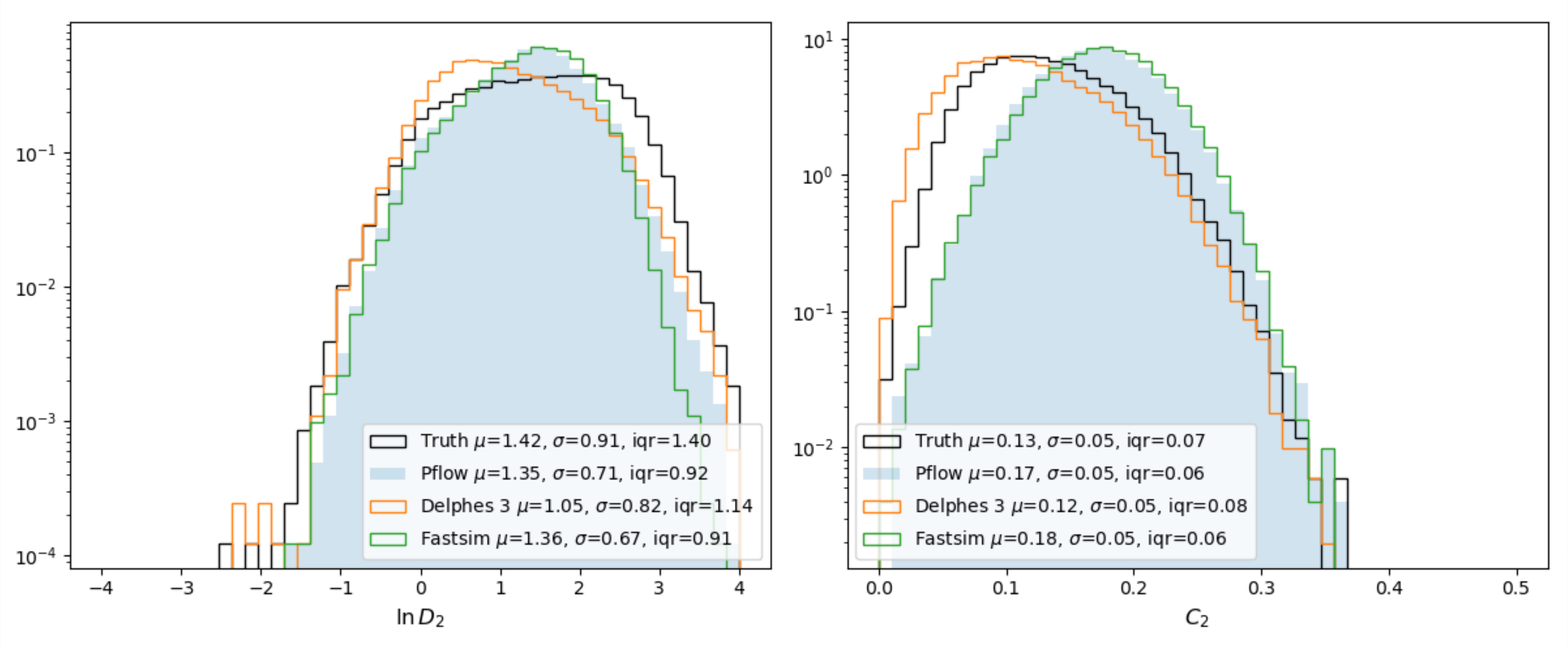
Results: Higgs → 4 leptons, TTbar, QCD

Jet substructure

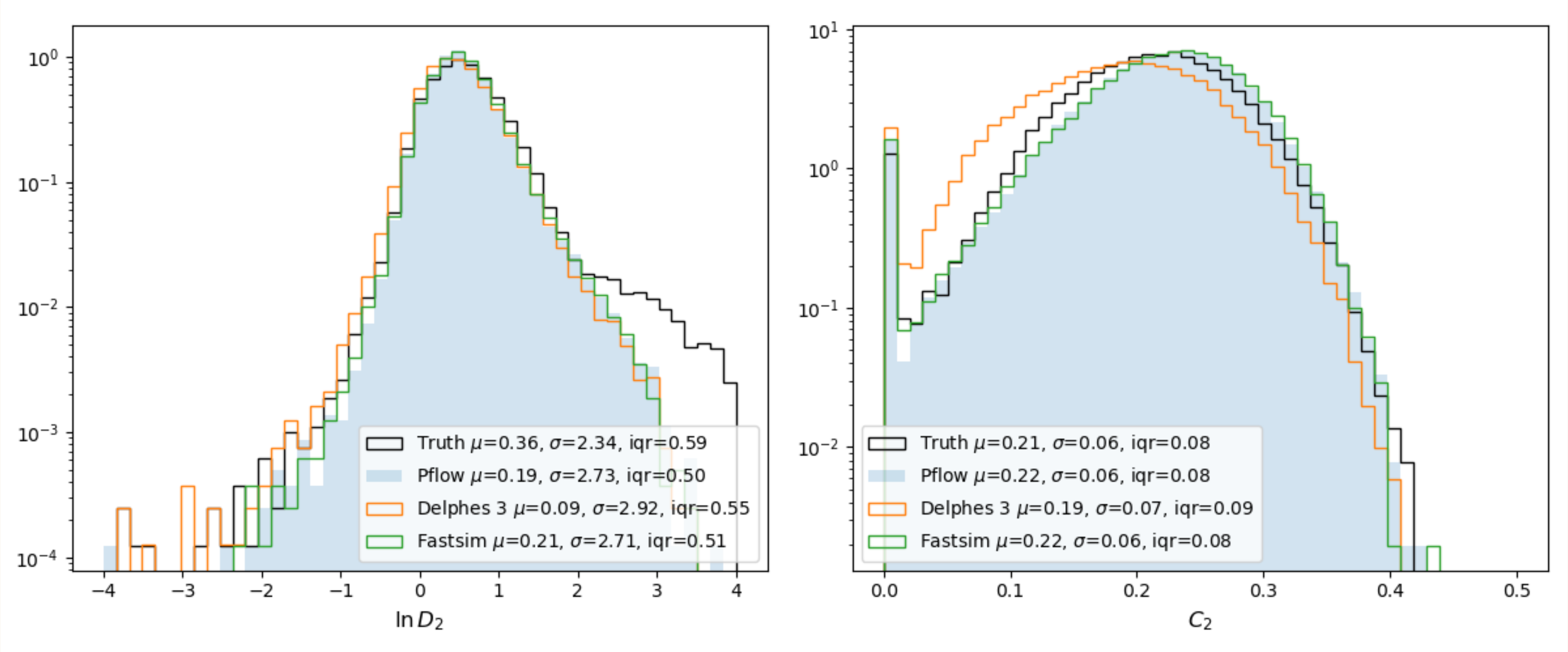
QCD 470-600 GeV



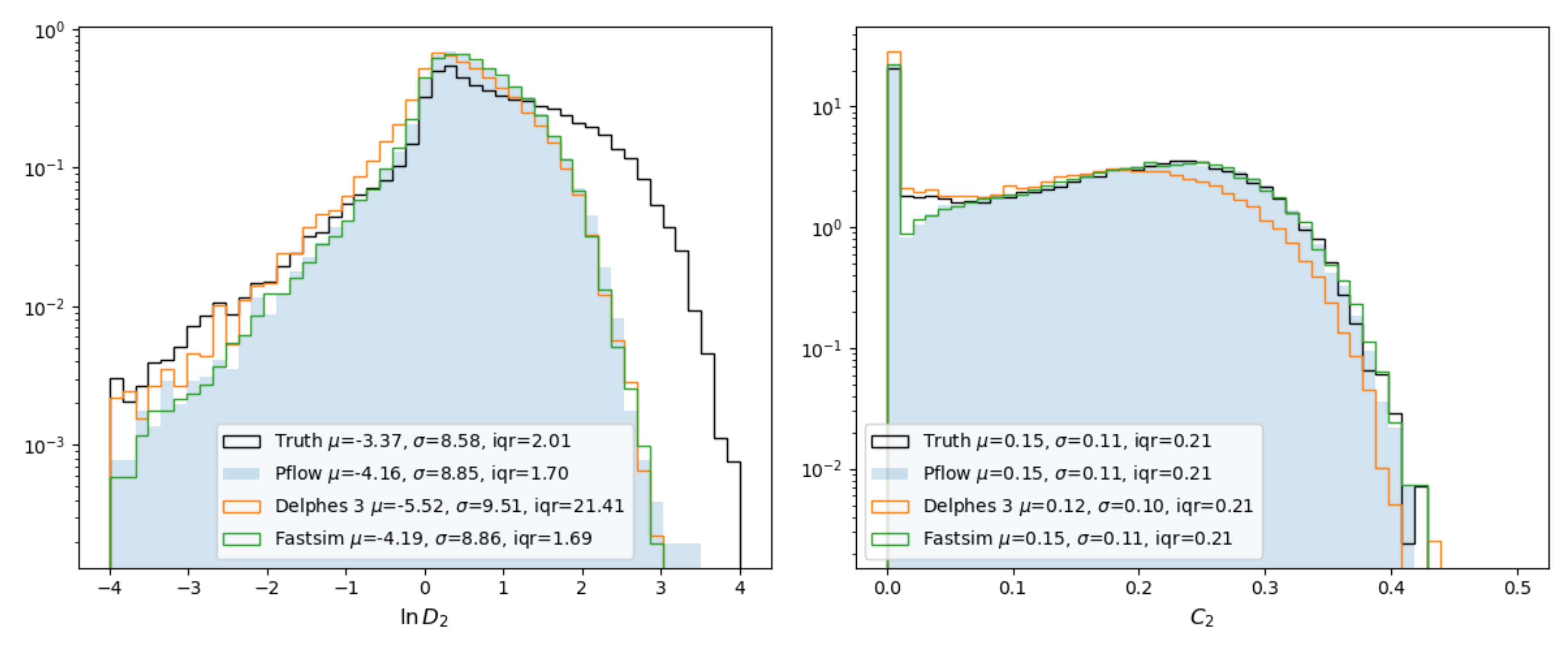
QCD 1000-1400 GeV



TTbar



Higgs → 4 leptons



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Summary

Conclusions

- 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
- Facilitate the sharing of such models to the broad physics community

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

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Backup