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BERKELEY LAB

Parnassus

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

Etienne Dreyer, Eilam Gross, Dmitrii Kobylianskii, Vinicius Mikuni, Benjamin Nachman

EPS-HEP 2025

Motivation

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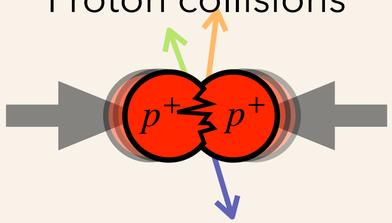
Motivation

Proton collisions



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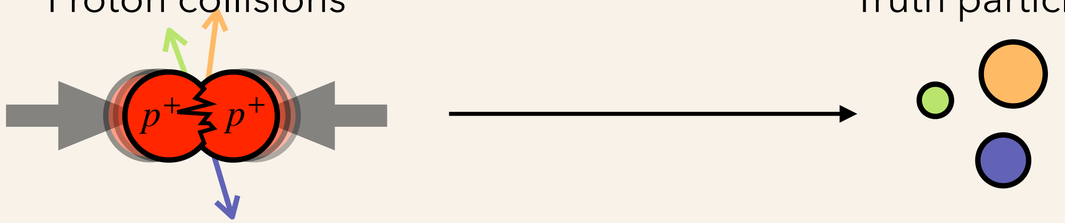

Truth particles

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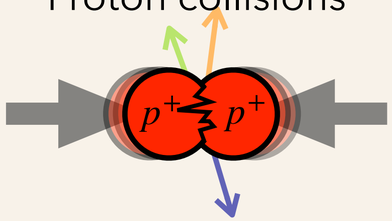

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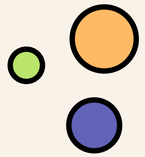
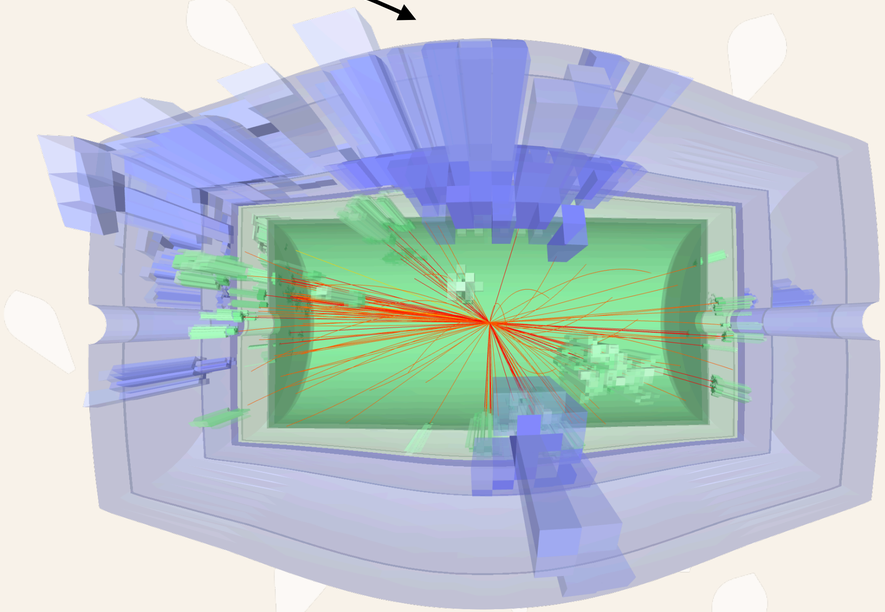


Detector simulation



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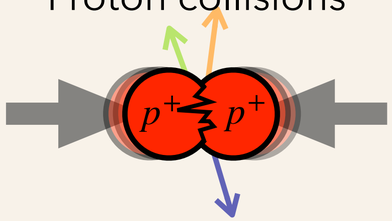

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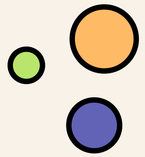

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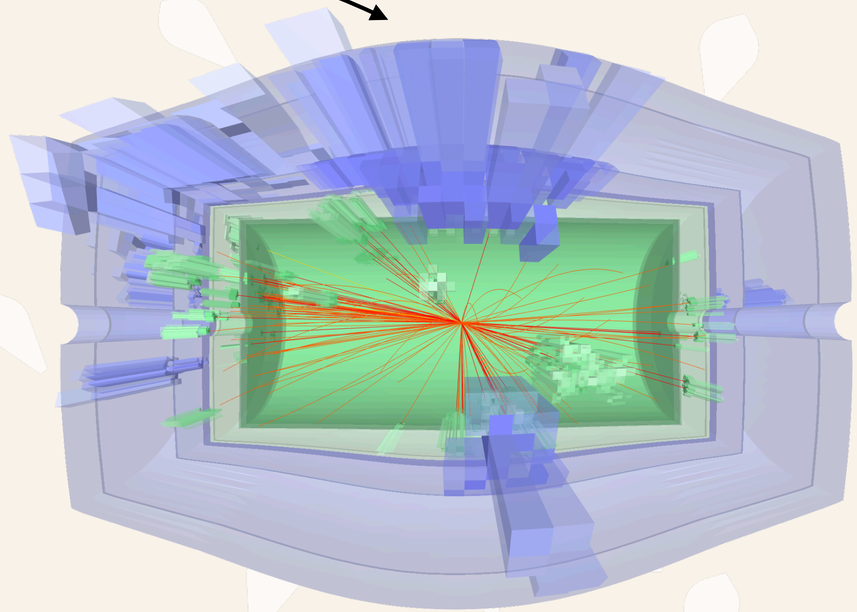
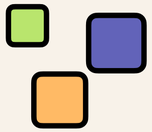


Reconstruction



Reconstructed particles

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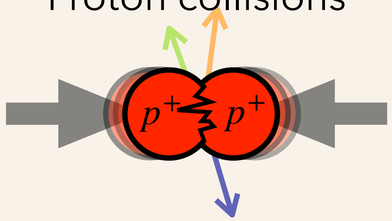
Motivation

Proton collisions



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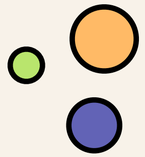
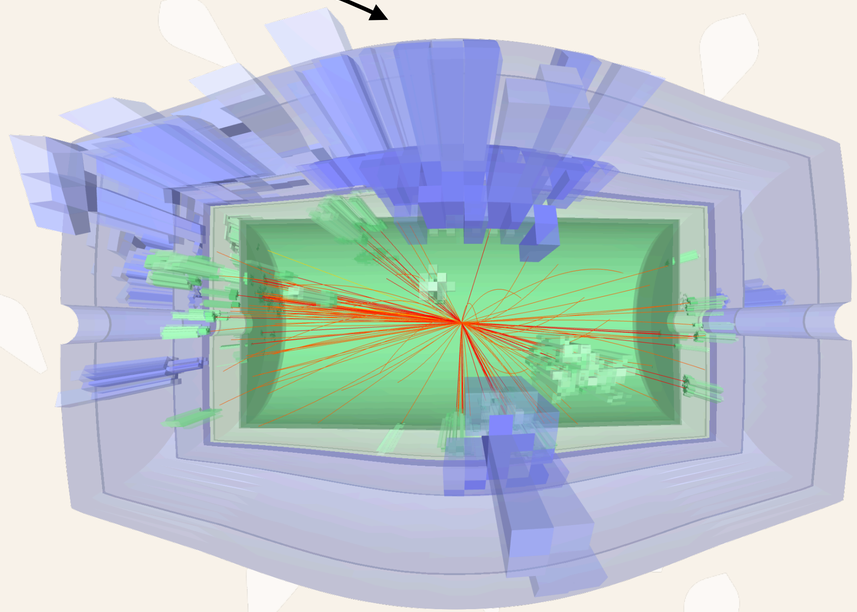


Detector simulation



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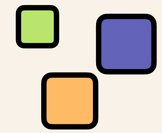

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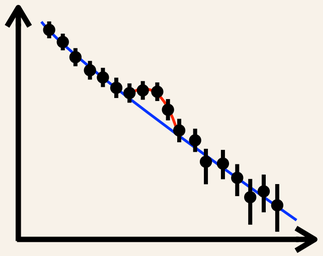

Statistical analysis

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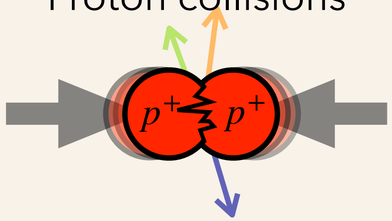
Motivation

Proton collisions



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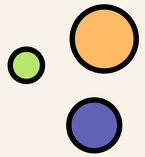

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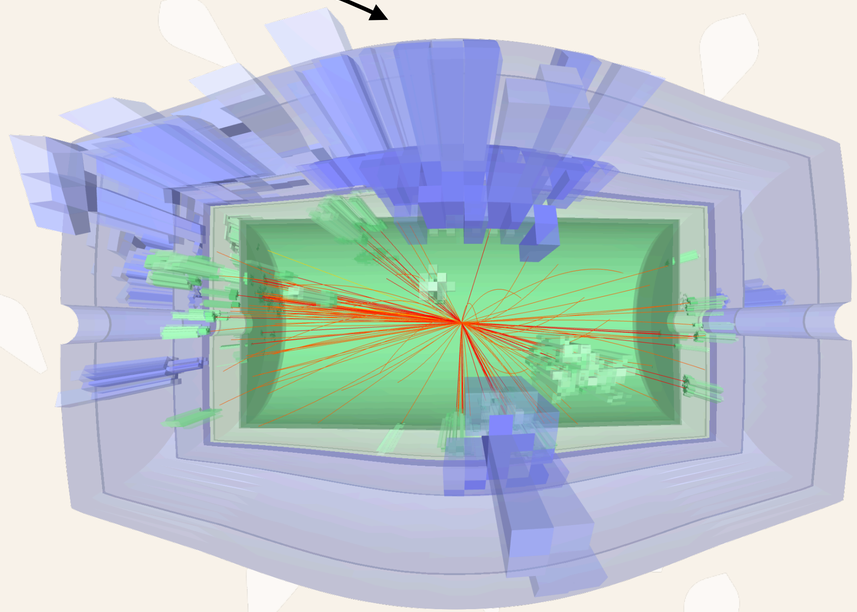
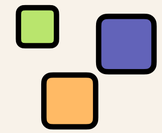
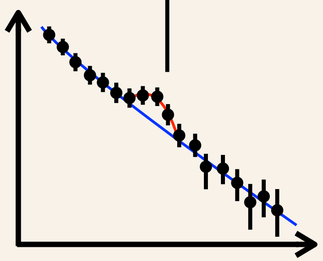


Reconstruction



Reconstructed particles



Statistical analysis

$$\mathscr{L} = ?$$

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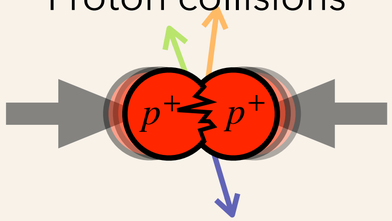
Motivation

Proton collisions



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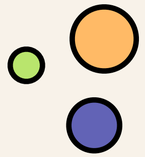

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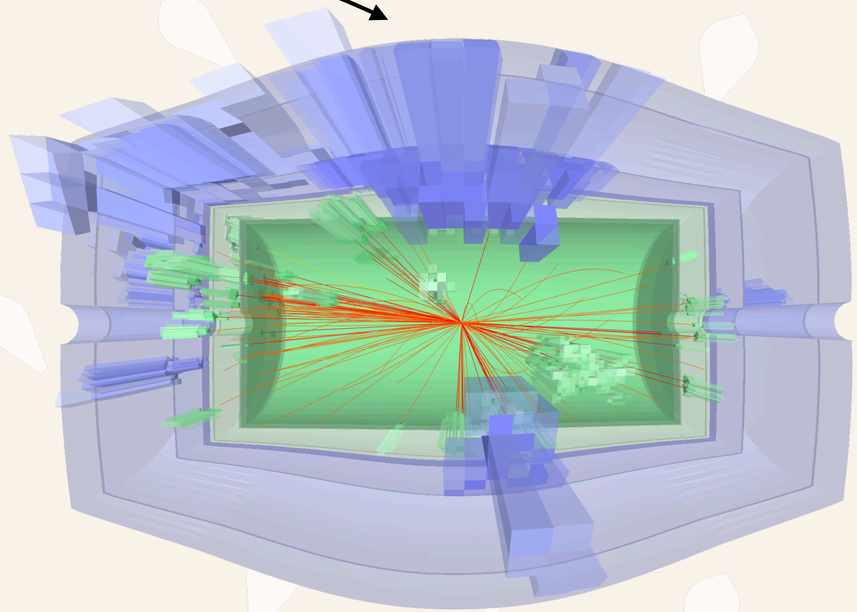
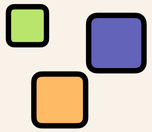
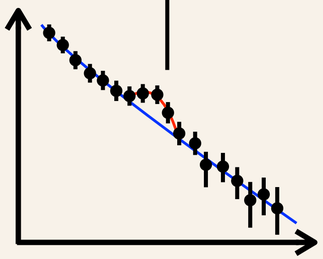


Reconstruction



Reconstructed particles

This project



Statistical analysis

$\mathscr{L} = ?$

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Problem to solve

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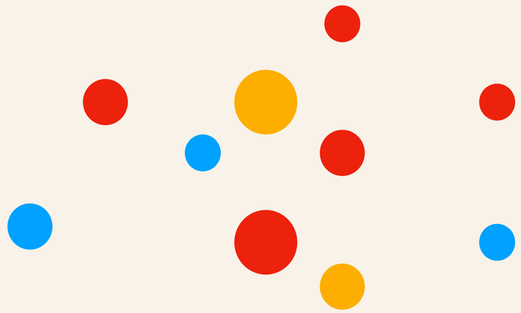
Problem to solve

Final state
truth particles



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Problem to solve

Final state
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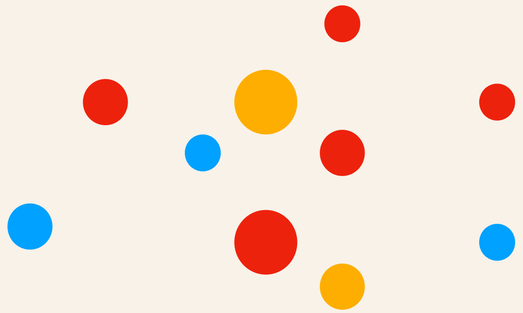
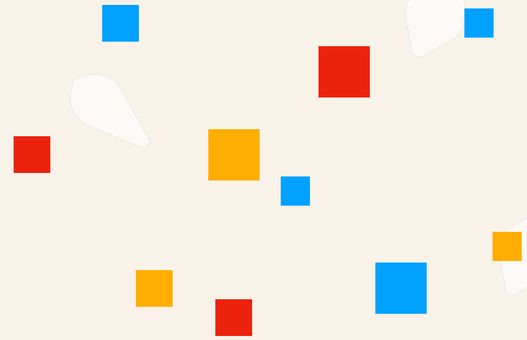


Reconstructed
objects



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Problem to solve

Final state
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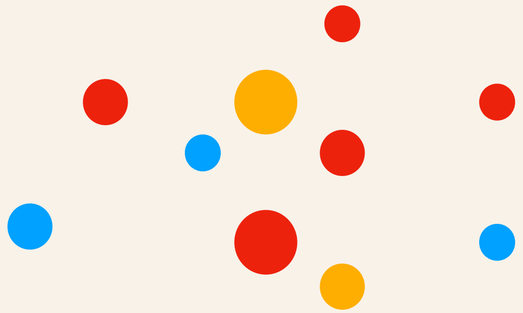

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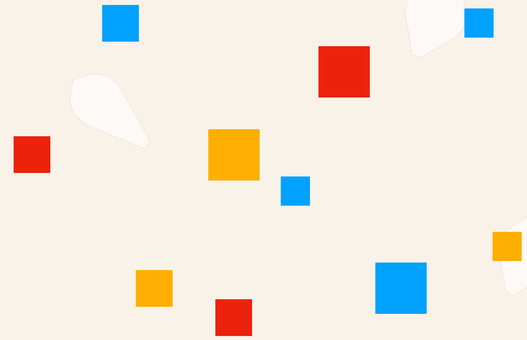


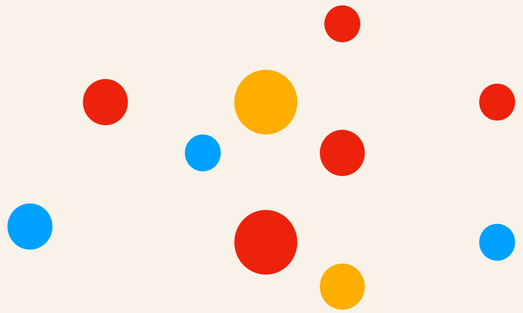
Amount of objects

+

Their properties

Problem to solve

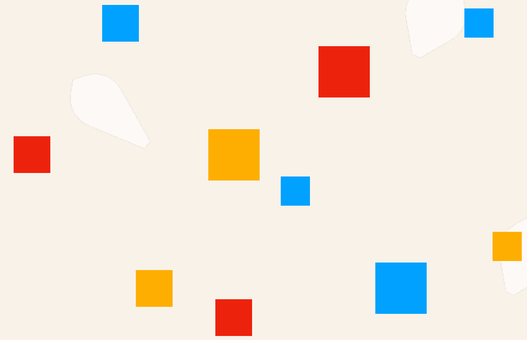
Final state
truth particles



Set to Set

?

Reconstructed
objects



Amount of objects
+
Their properties

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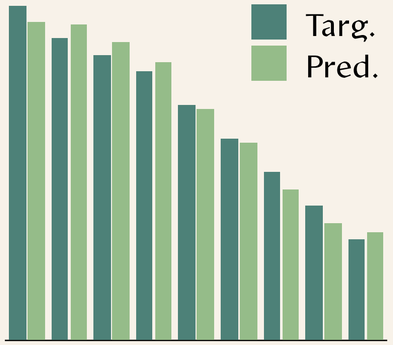
Goals

Goals

Marginal distributions

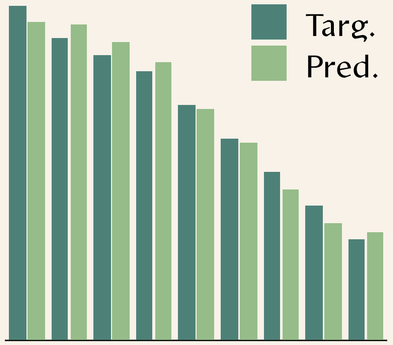


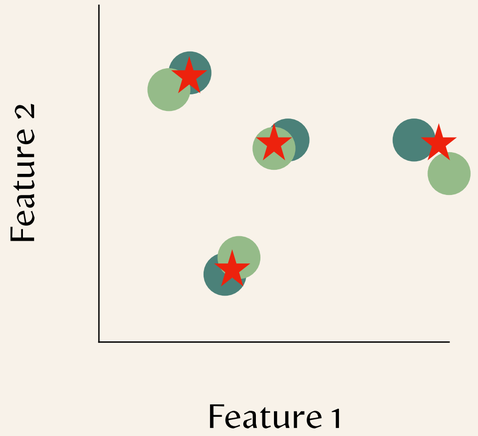
Feature

Goals

Marginal distributions

Reconstruct constituents



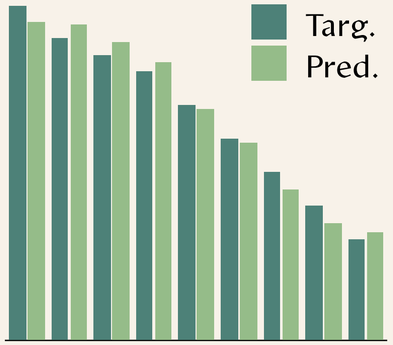


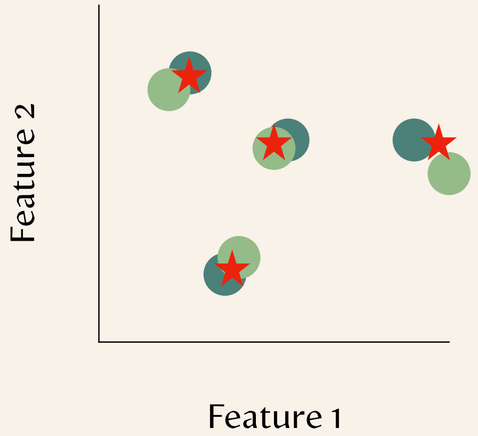
Goals

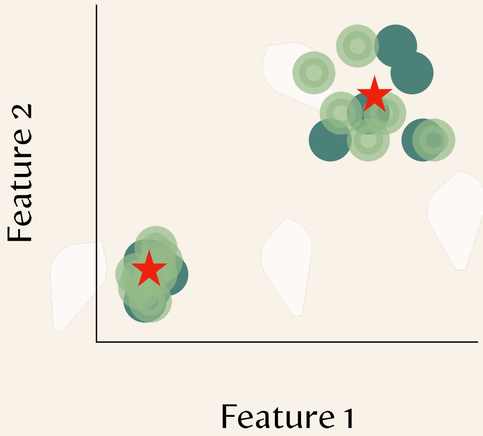
Marginal distributions

Reconstruct constituents

Resolution

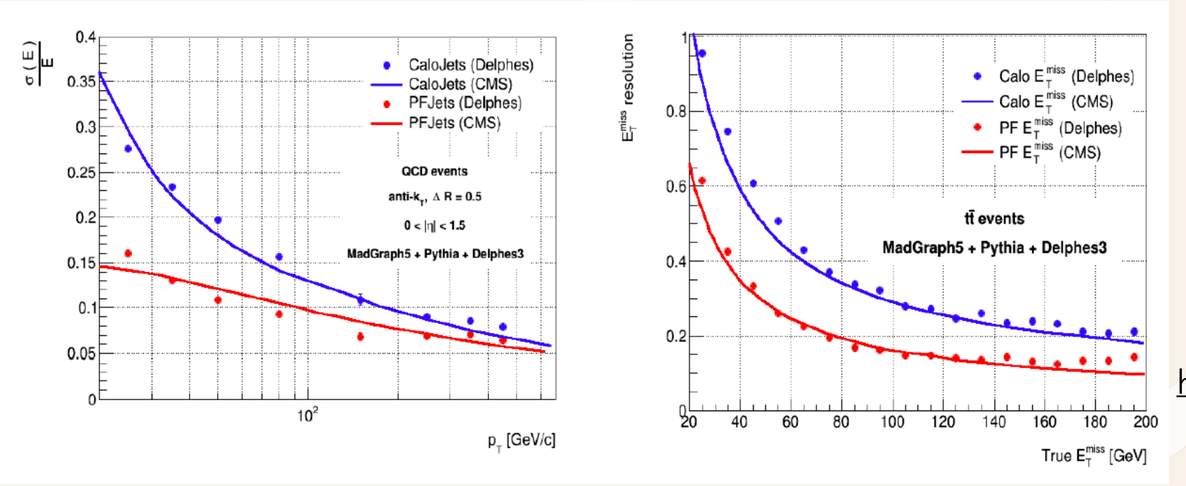






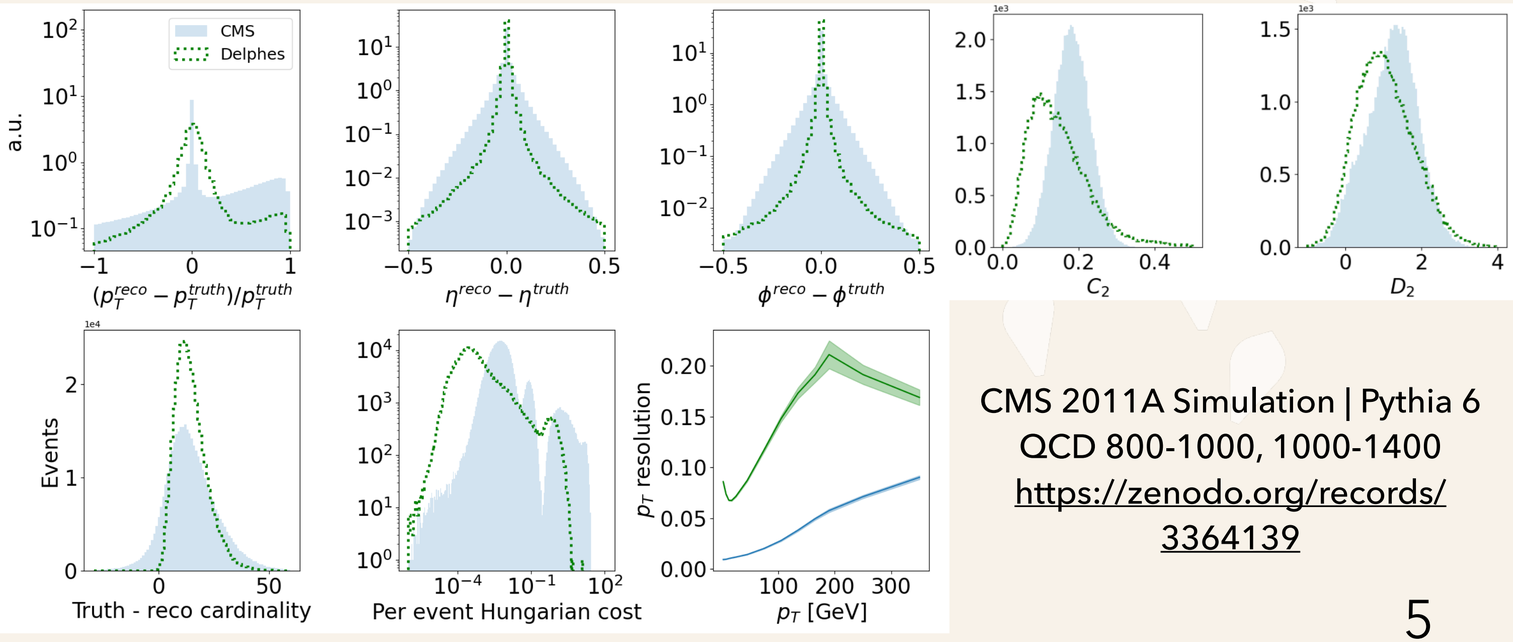
Existing approach: Delphes 3

- 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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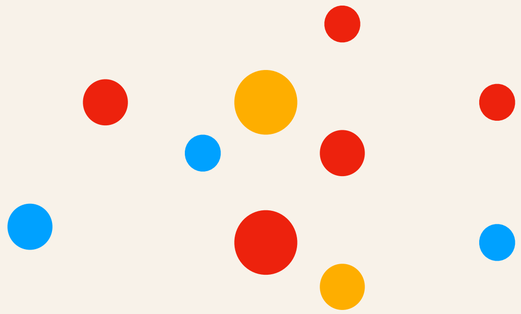
ML-based approach

ML-based approach

Final state
truth particles



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ML-based approach

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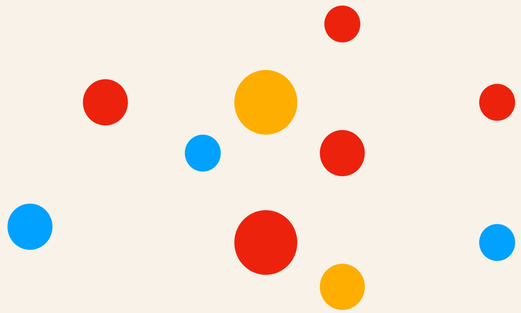

Neural Network

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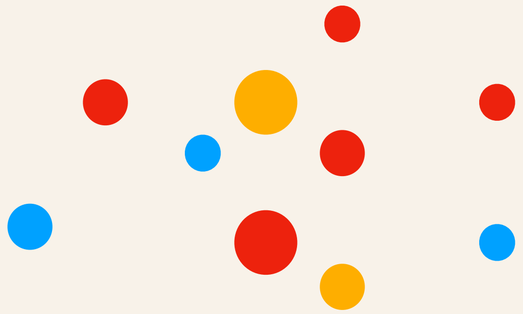
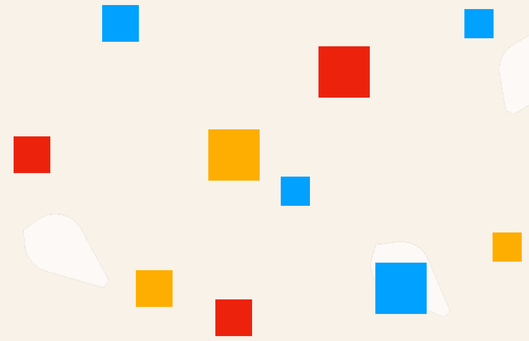
ML-based approach

Final state
truth particles



Neural Network

Reconstructed
objects



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ML-based approach: Our journey

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ML-based approach: Our journey

Toy model: emulated tracks

Only charged particles

p_T, η, ϕ

GNN with Slot-Attention

arXiv:2211.06406

Published in MLST

ML-based approach: Our journey

Toy model: emulated tracks

Only charged particles

p_T, η, ϕ

GNN with Slot-Attention

Full GEANT4 reconstruction and simulation

Charged + Neutral

p_T, η, ϕ, q

Diffusion and Flow matching models

arXiv:2211.06406
Published in MLST

arXiv:2405.10106
Accepted in PRD

ML-based approach: Our journey

Toy model: emulated tracks	Full GEANT4 reconstruction and simulation	CMS 2011A Simulation QCD, Single jets
Only charged particles	Charged + Neutral	Charged + Neutral
p_T, η, ϕ	p_T, η, ϕ, q	p_T, η, ϕ
GNN with Slot-Attention	Diffusion and Flow matching models	Flow matching
arXiv:2211.06406 Published in MLST	arXiv:2405.10106 Accepted in PRD	arXiv:2406.01620 Accepted in PRL

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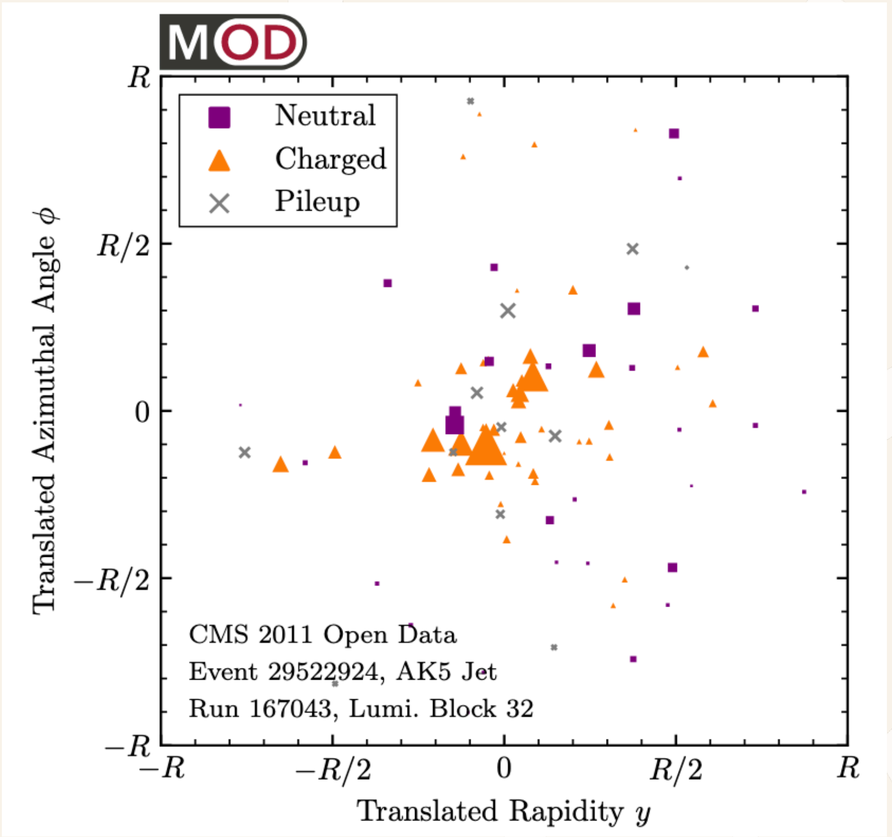
ML-based approach: Our journey

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	Diffusion and Flow matching models
arXiv:2211.06406 Published in MLST	arXiv:2405.10106 Accepted in PRD	arXiv:2406.01620 Accepted in PRL	arXiv:2503.19981 Submitted to PRD

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
- Flow matching model

$p_T^{\min}$ - $p_T^{\max}$ [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		✓



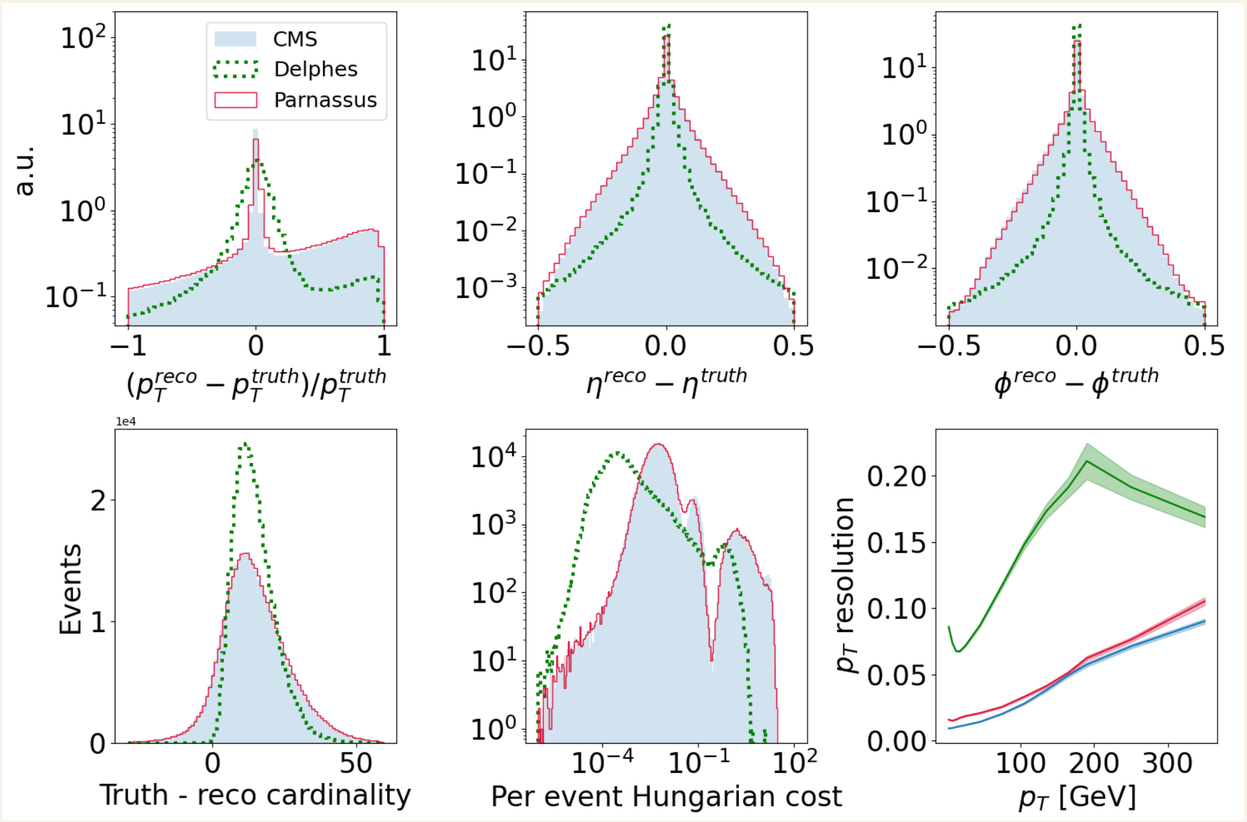
Example QCD jet
(http://arxiv.org/abs/1908.08542)

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

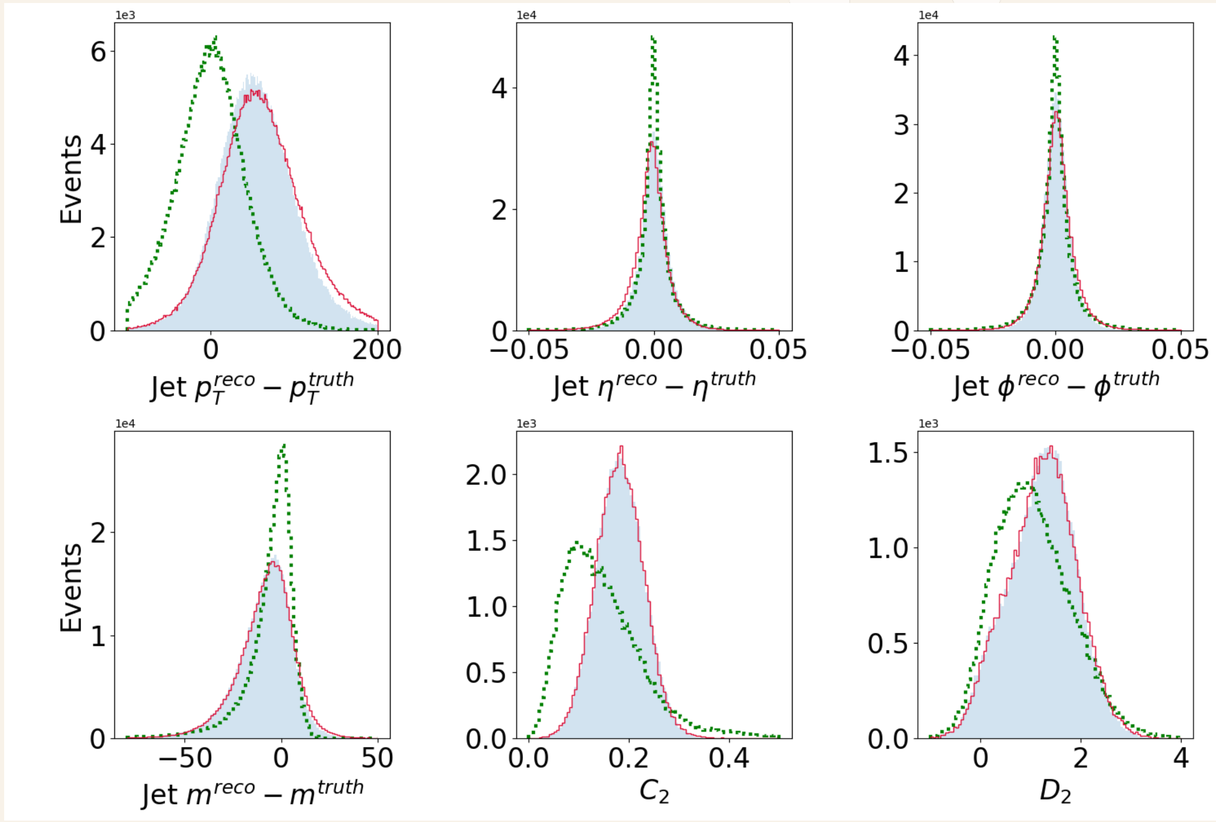
Results: Single Jets

Very good agreement with CMS Pflow

Outperform Delphes everywhere



Particle features

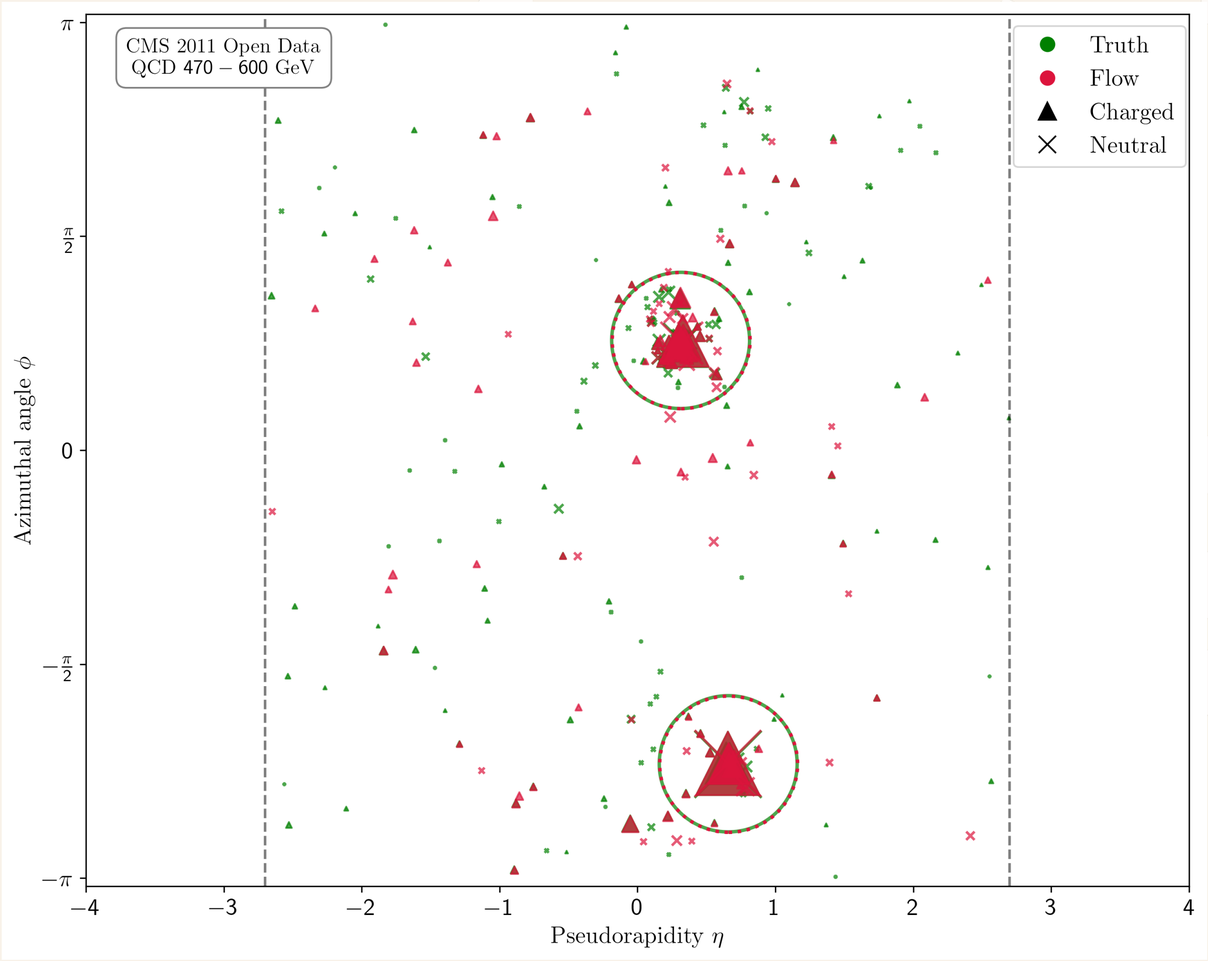


Jet features

Full event

- CMS Open Data, Simulation Datasets 2011
- **Full event 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	✓	✓
TTbar	✓	✓
Higgs → 4 leptons		✓
QCD 1000-1400 GeV		✓



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

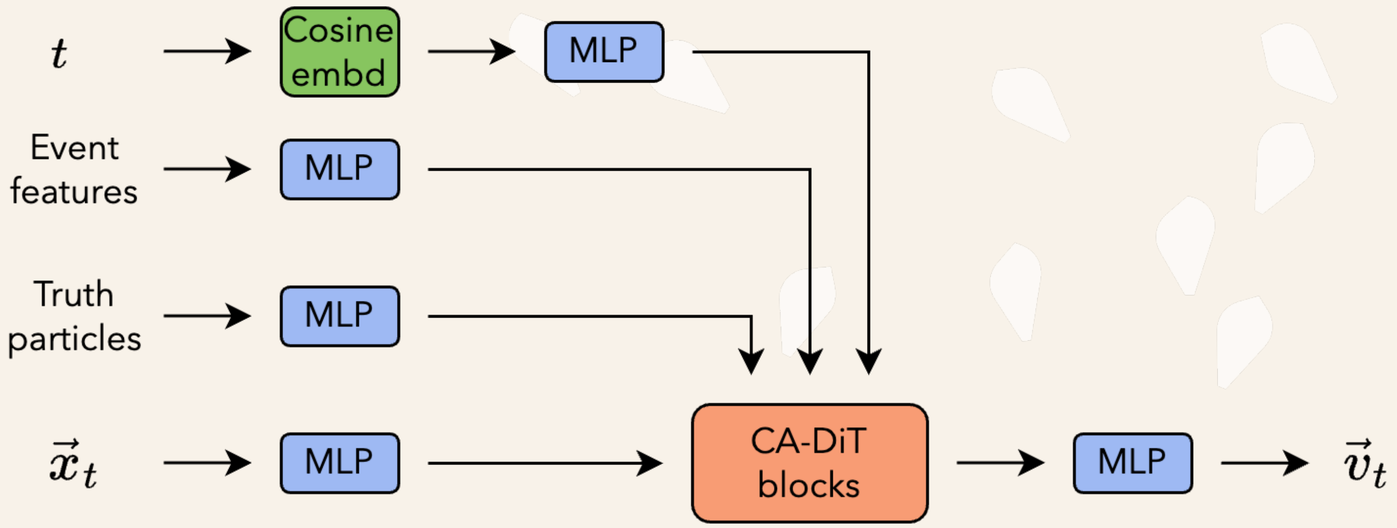
- Maximum 400 particles
- $p_T, \eta, \phi, \vec{v}$, PID prediction

$$p_t(x \mid x_*) = \mathcal{N}\left(x \mid (1-t)x_*, t^2\right)$$

$$u_t(x \mid x_*) = \varepsilon - x, \quad \varepsilon \sim \mathcal{N}(0, I)$$

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

$$dx_t = u_t dt$$



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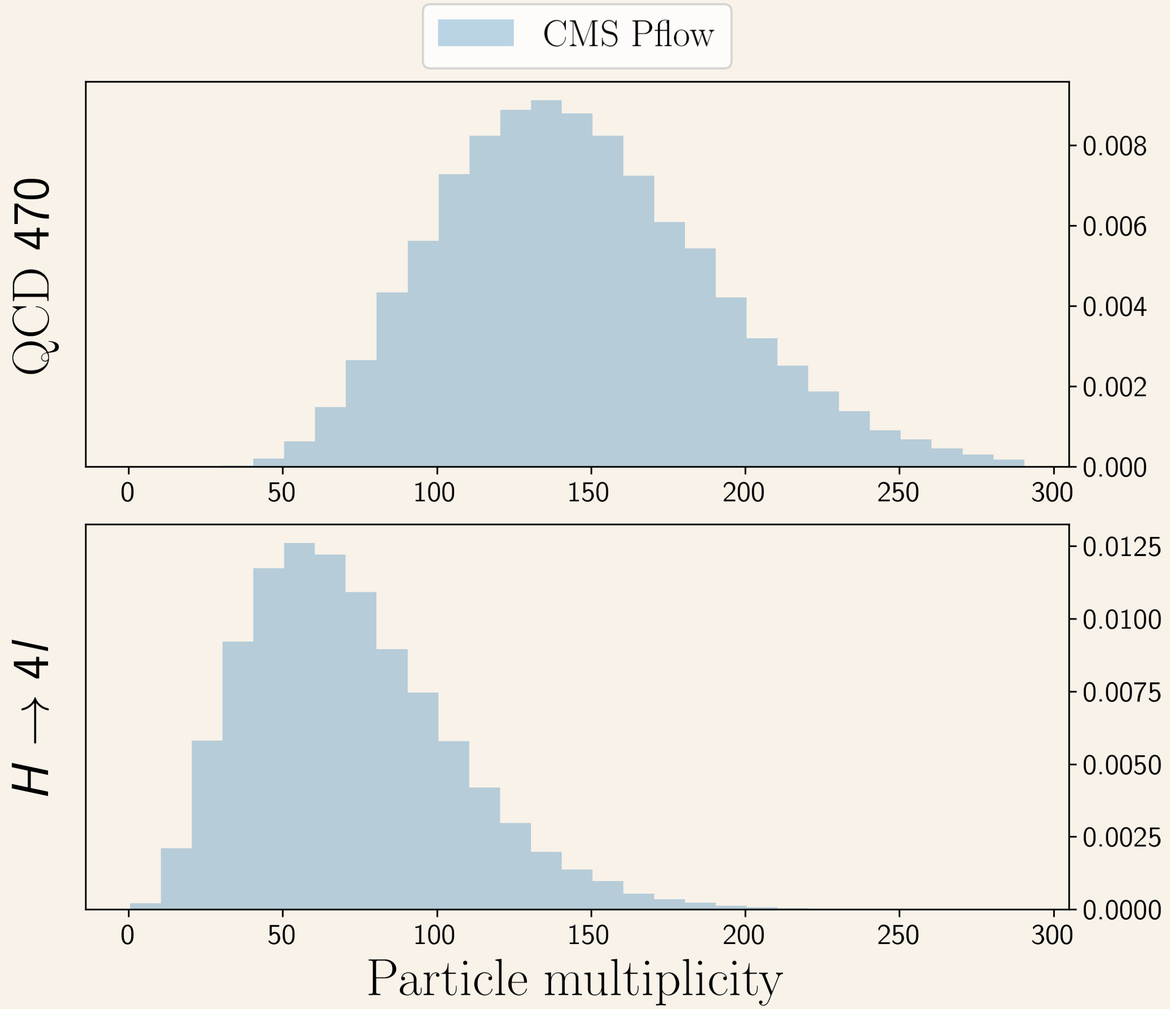
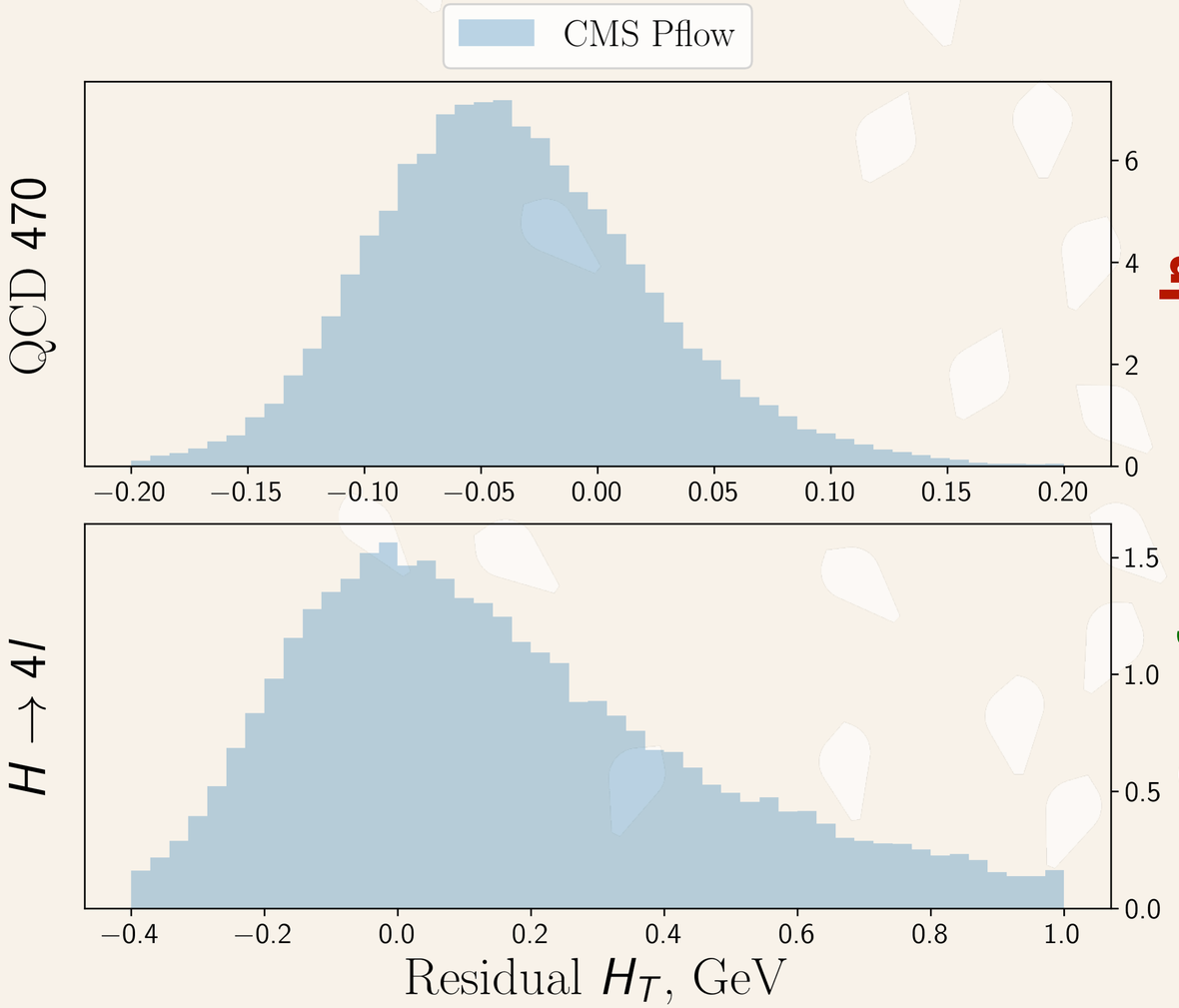
Results: Event level quantities





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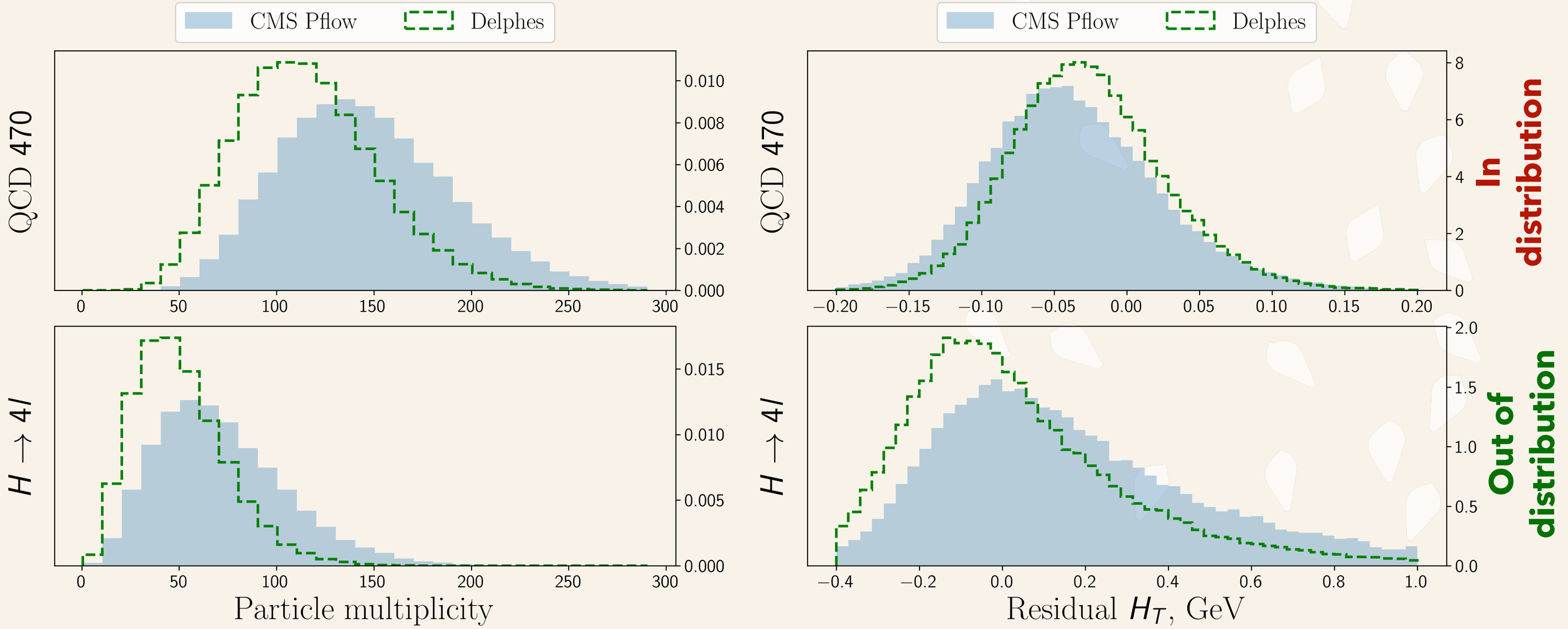
Results: Event level quantities



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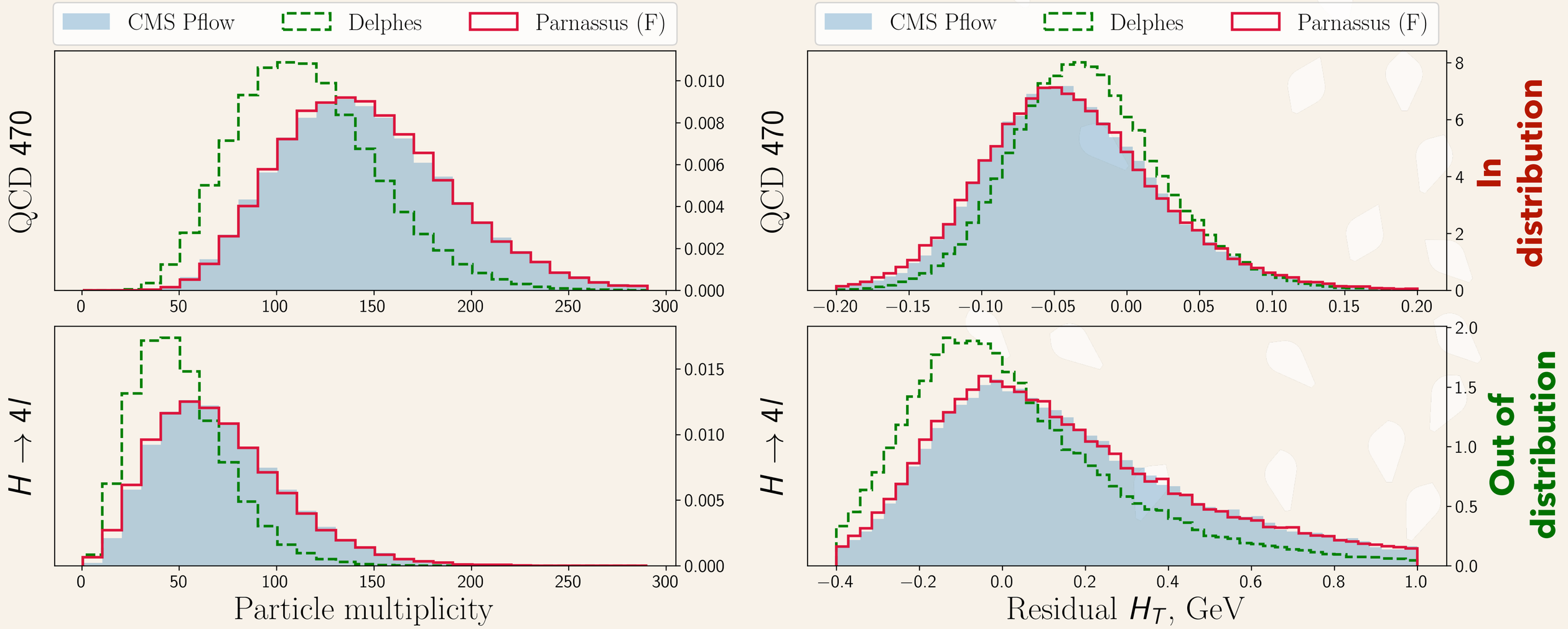
Results: Event level quantities



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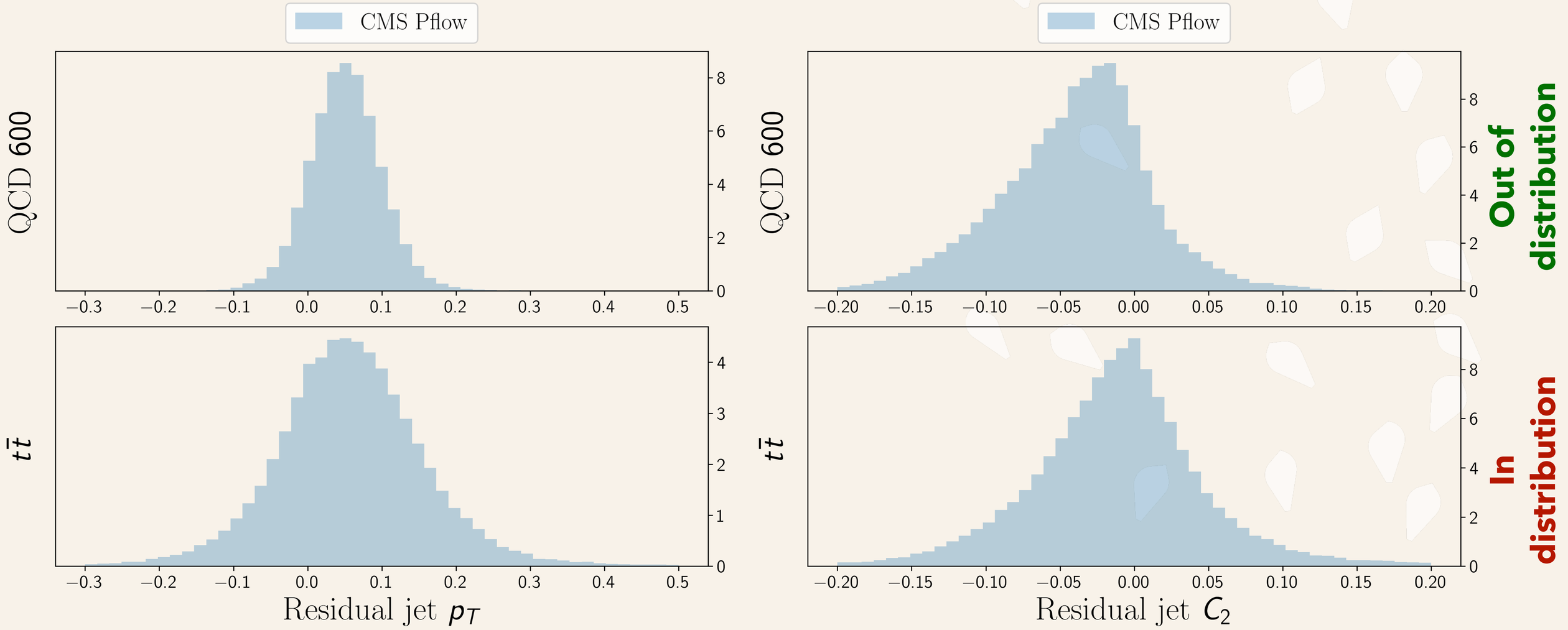
Results: Jet level quantities



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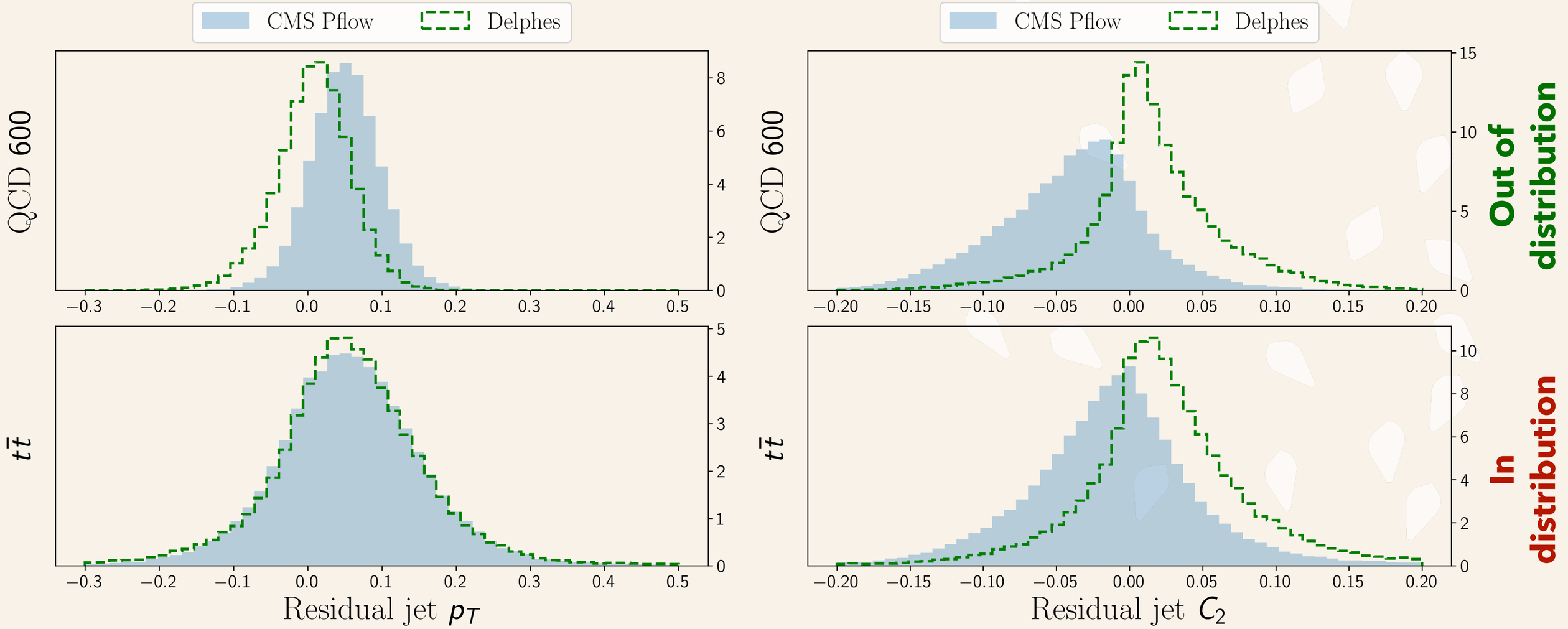
Results: Jet level quantities



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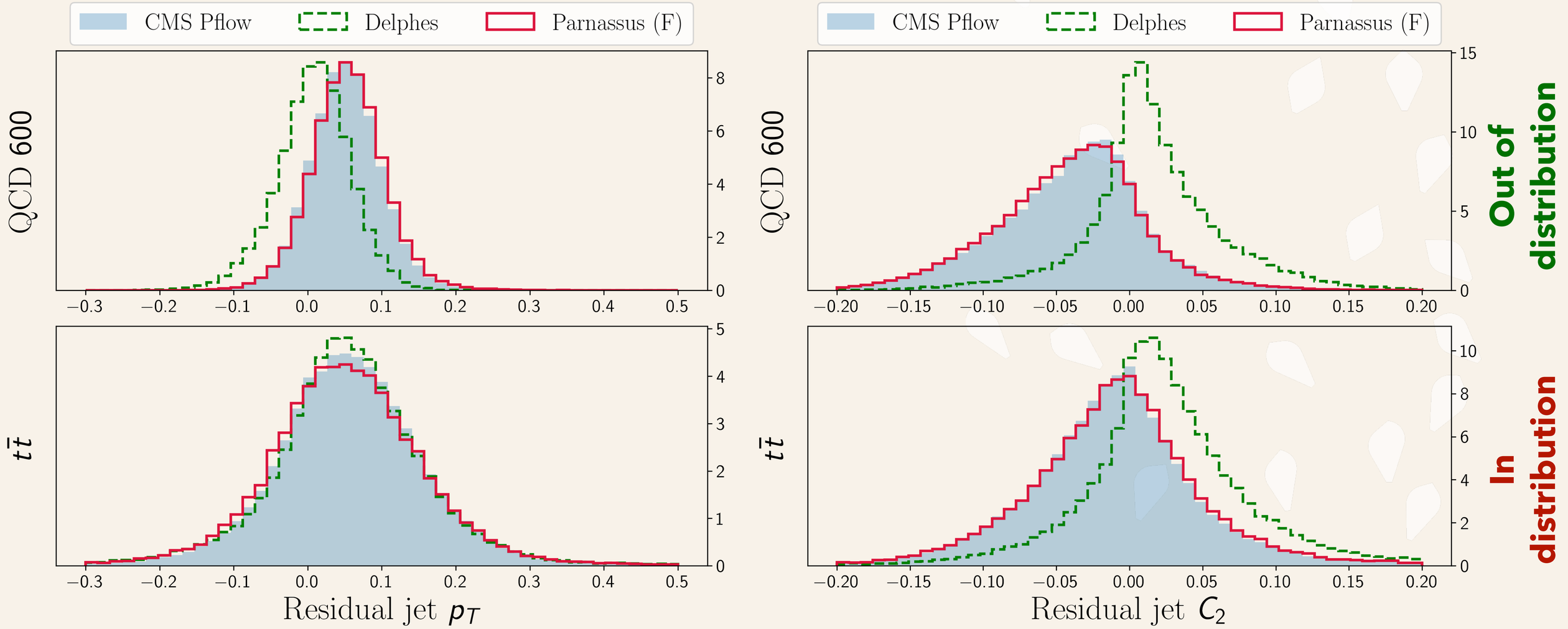
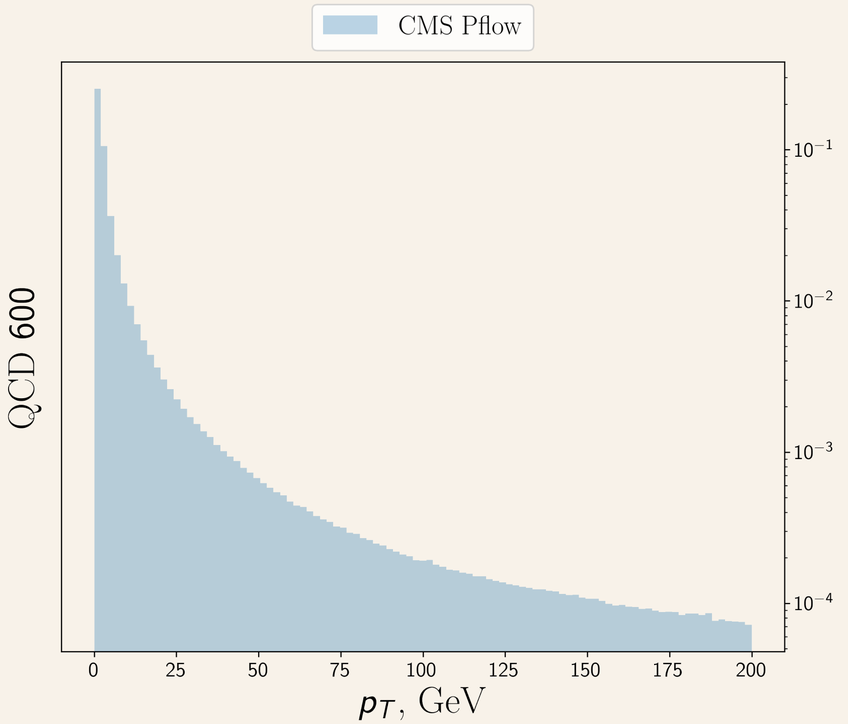
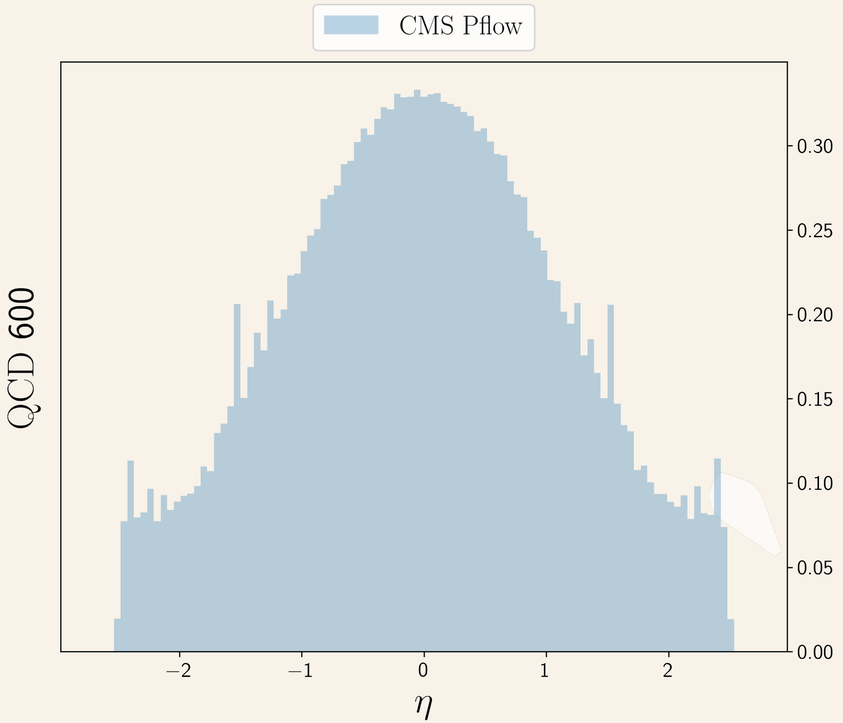
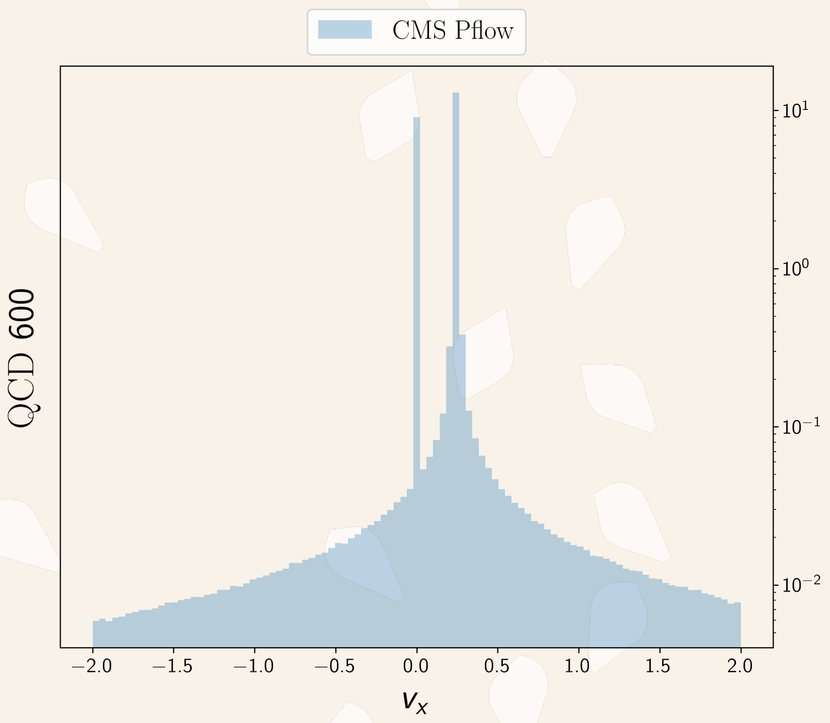
Results: Jet level quantities



Results: Particle level quantities

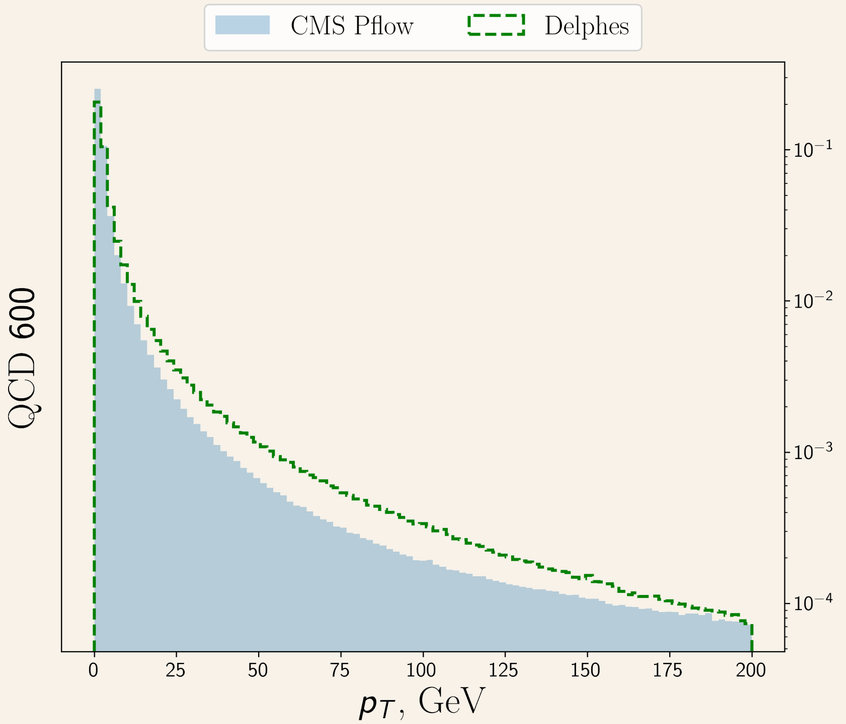


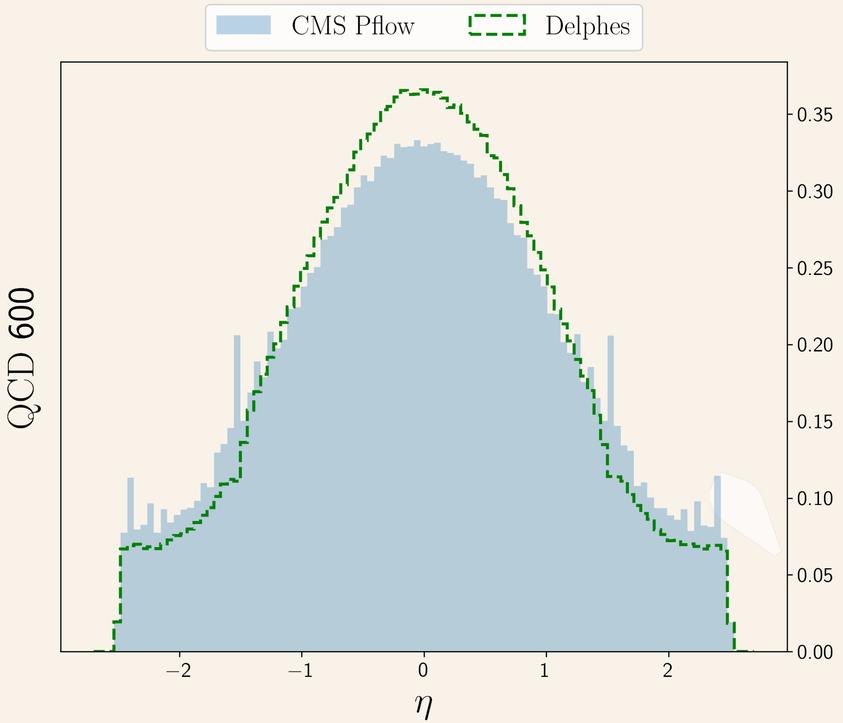


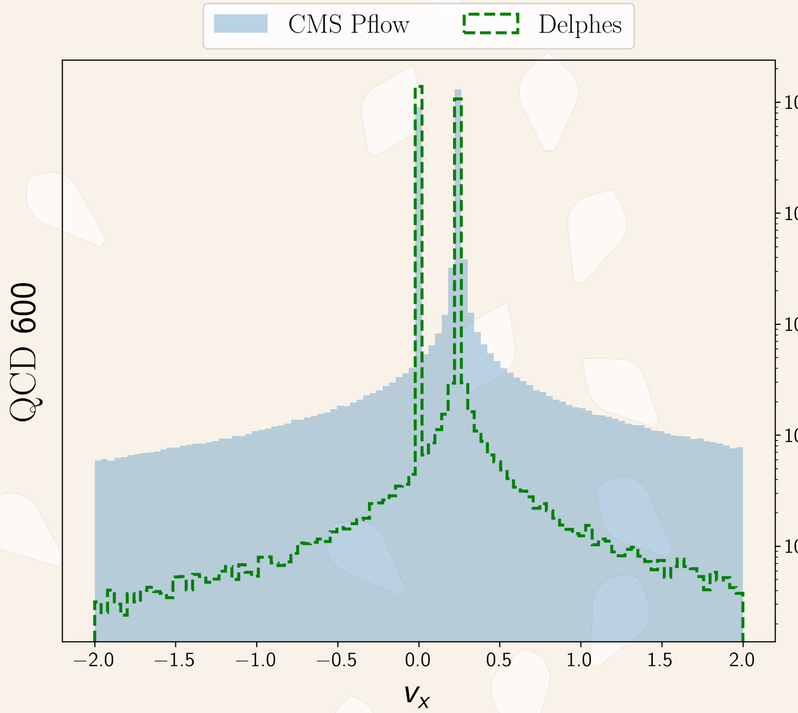


Out of distribution

Results: Particle level quantities







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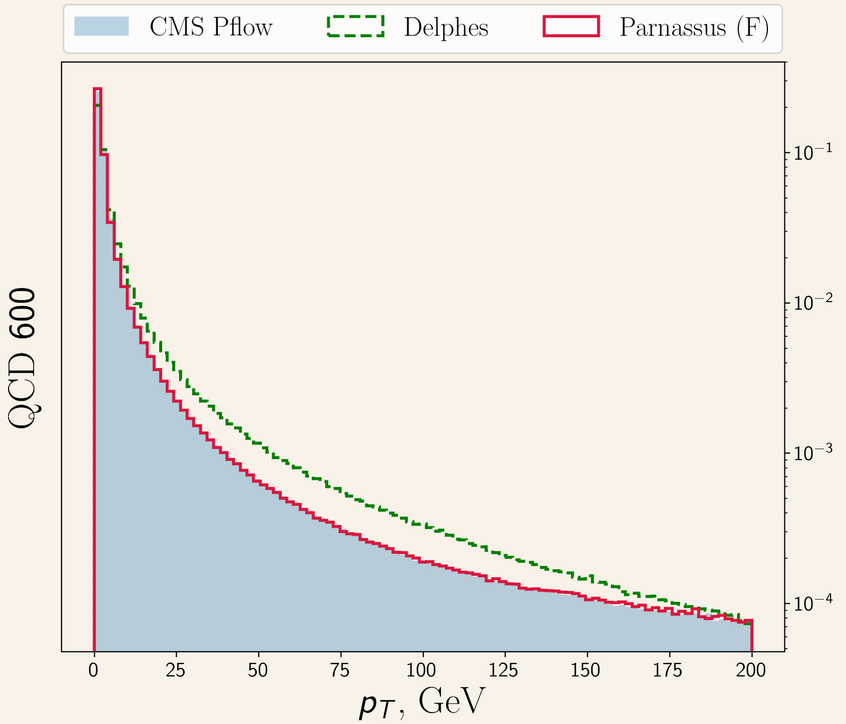

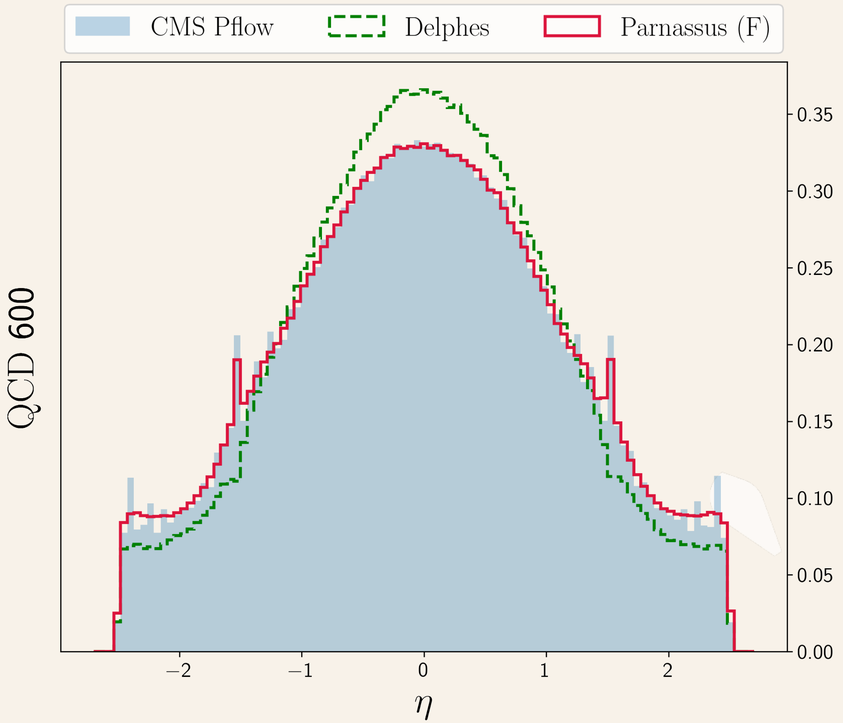

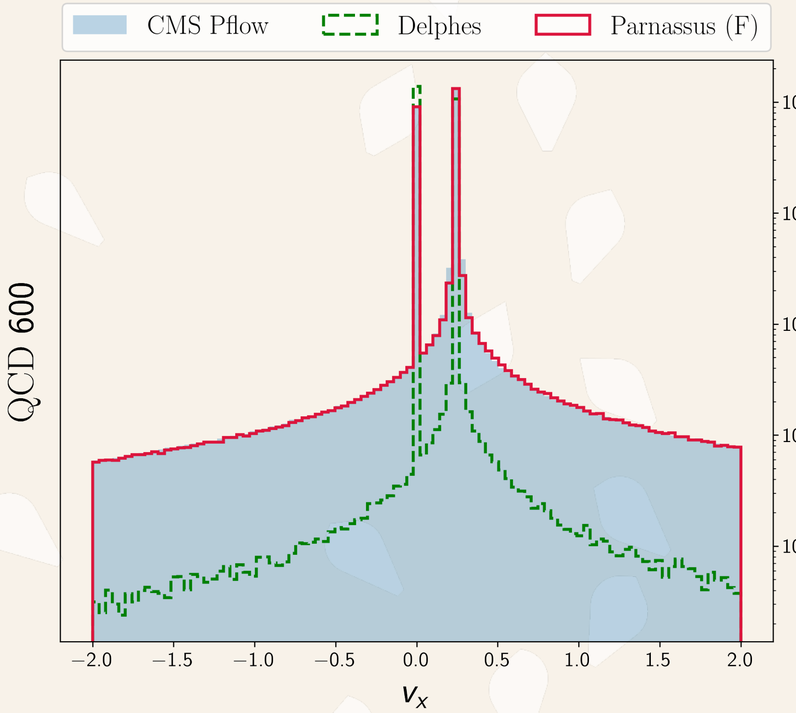

Out of distribution

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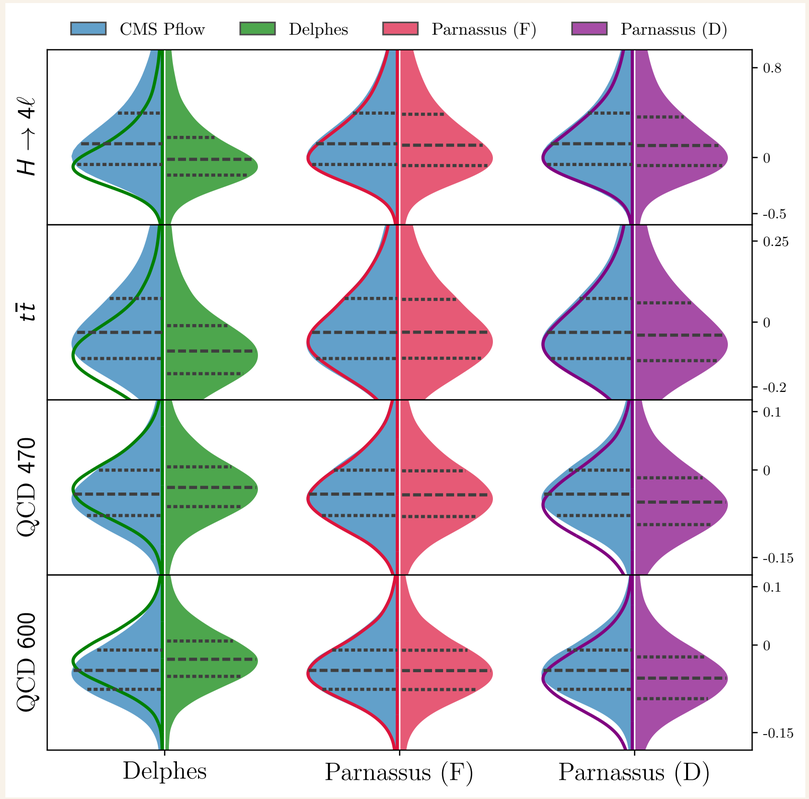
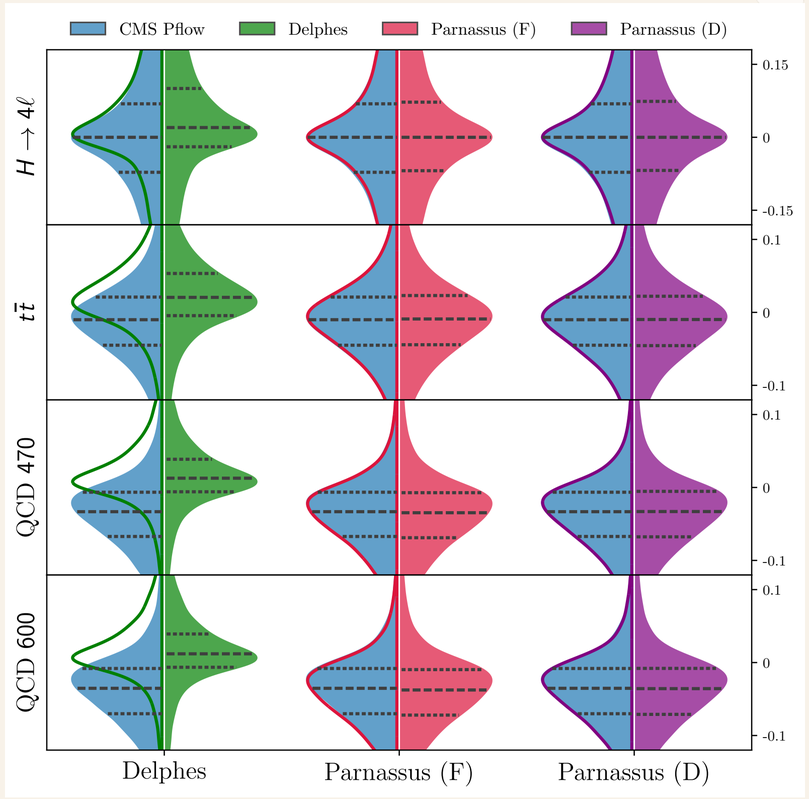
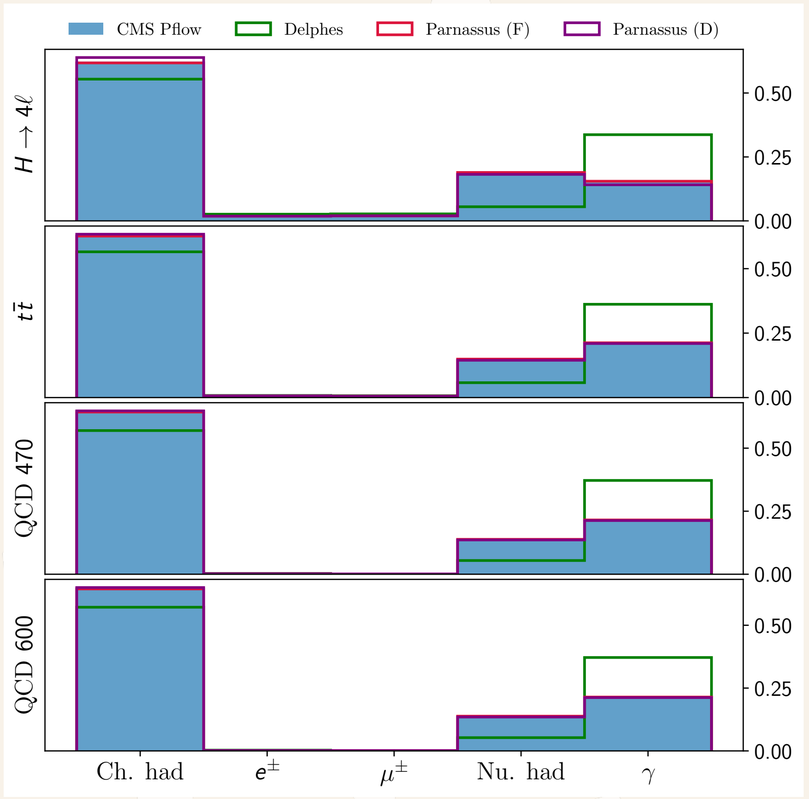
Summary plots



H_T residual



C_2 residual



Particle class distribution

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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

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

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	CFM		**Delphes**
Batch size/Time for 1 event	GPU	CPU	CPU
1	0.669	4.38	**0.0112**
10	0.0734	1.59	
100	0.0147	1.29	
1000	**0.0136**	-	

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Can be optimized more!

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Future work directions

- Implement configurable and user-friendly interface with documentation – **WIP**
- 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

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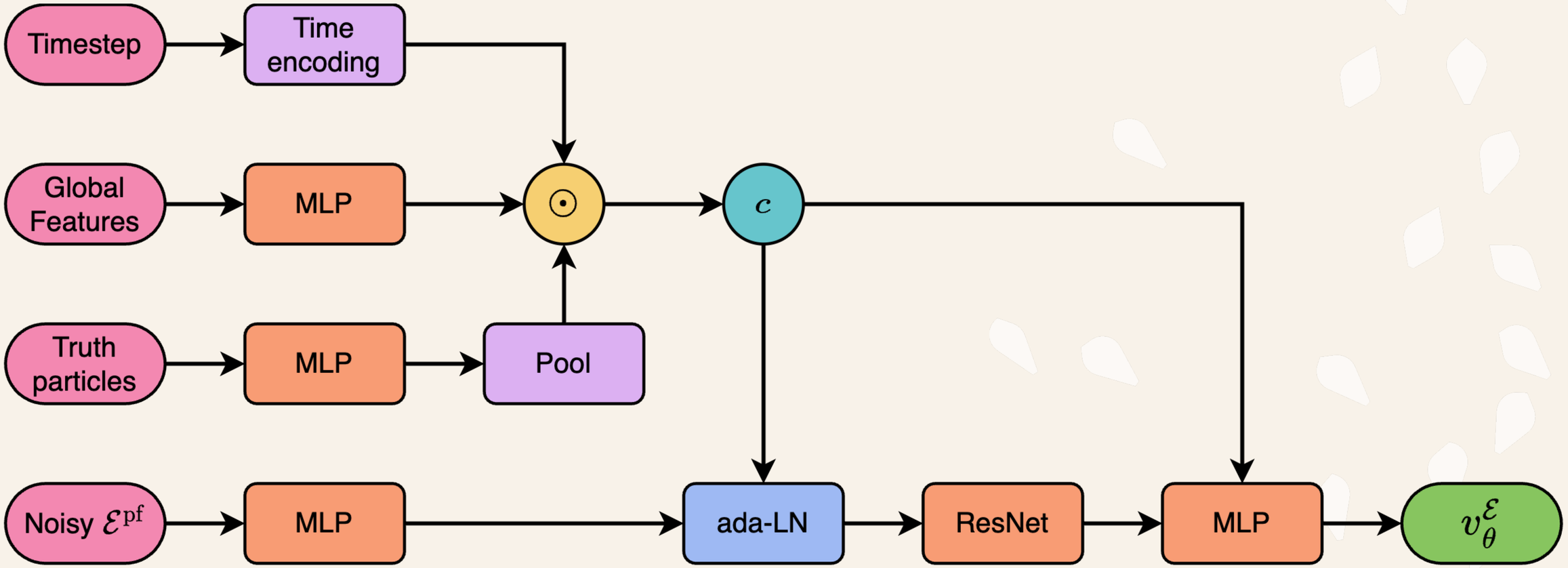
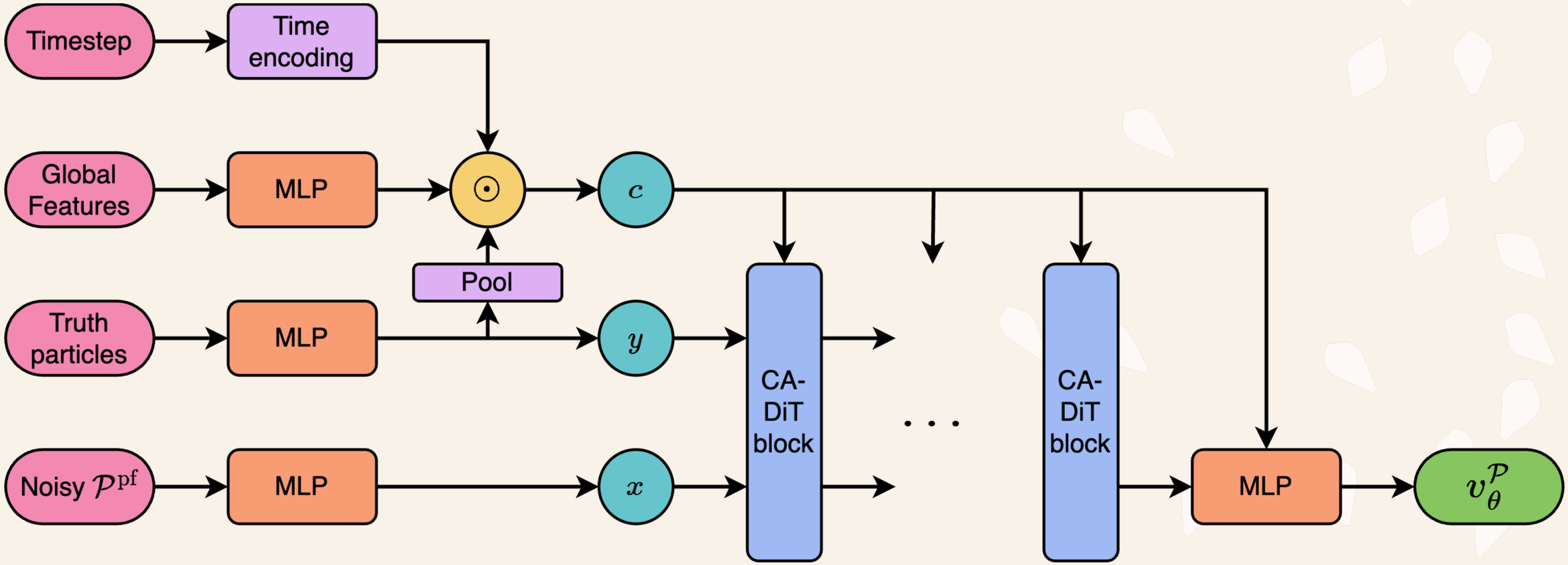
Backup

Event model architecture



Particle model architecture



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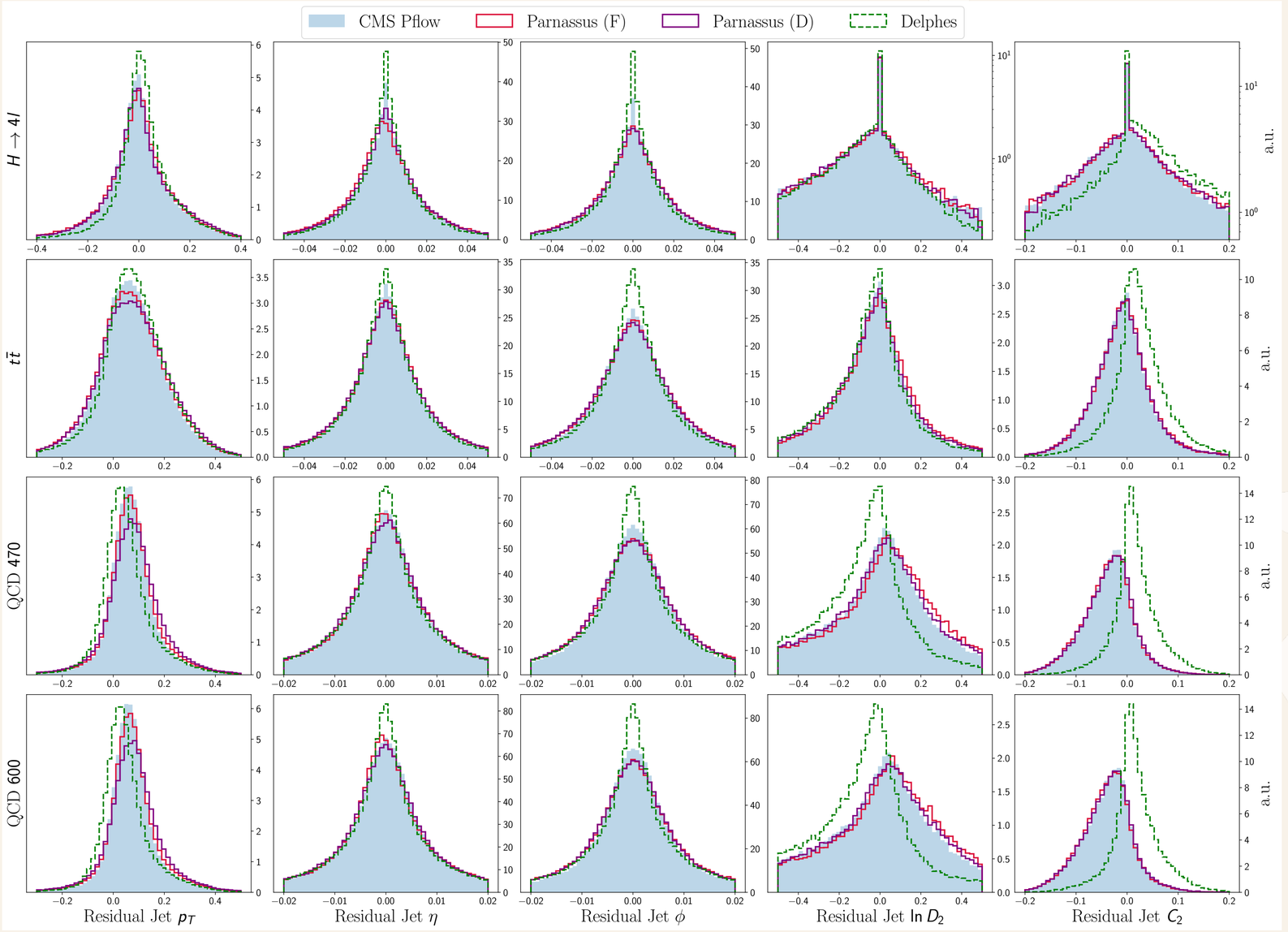
Jet residuals



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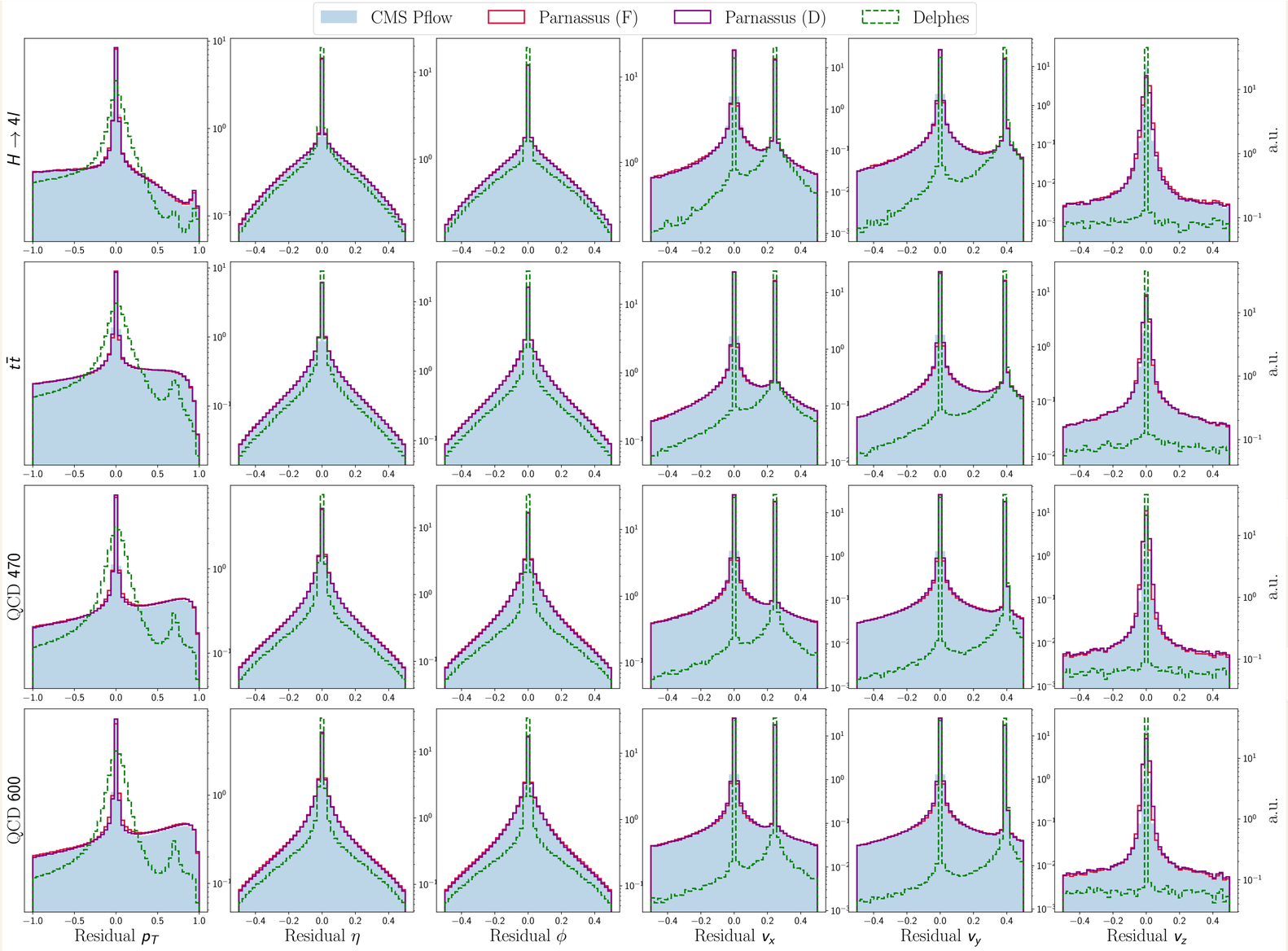
Particle residuals



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Class plots