מכון ויצמן למדע
WEIZMANN INSTITUTE OF SCIENCE
BERKELEY LAB

Parnassus

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

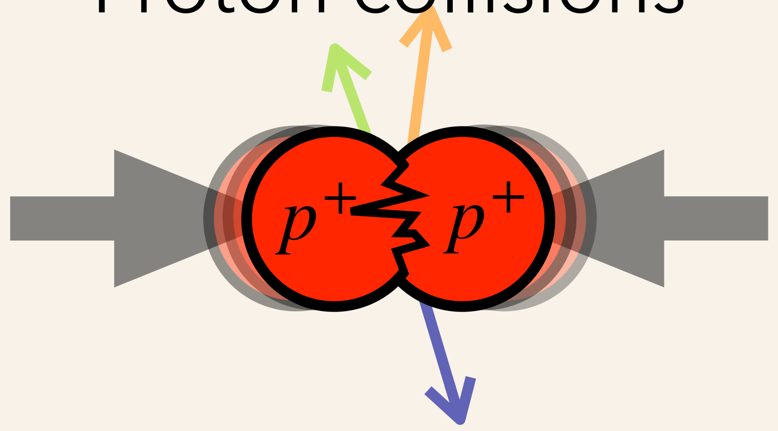
Etienne Dreyer, Eilam Gross, Dmitrii Kobylianskii, Vinicius Mikuni, Benjamin Nachman

EuCAIFCon2025

Motivation

Motivation

Proton collisions



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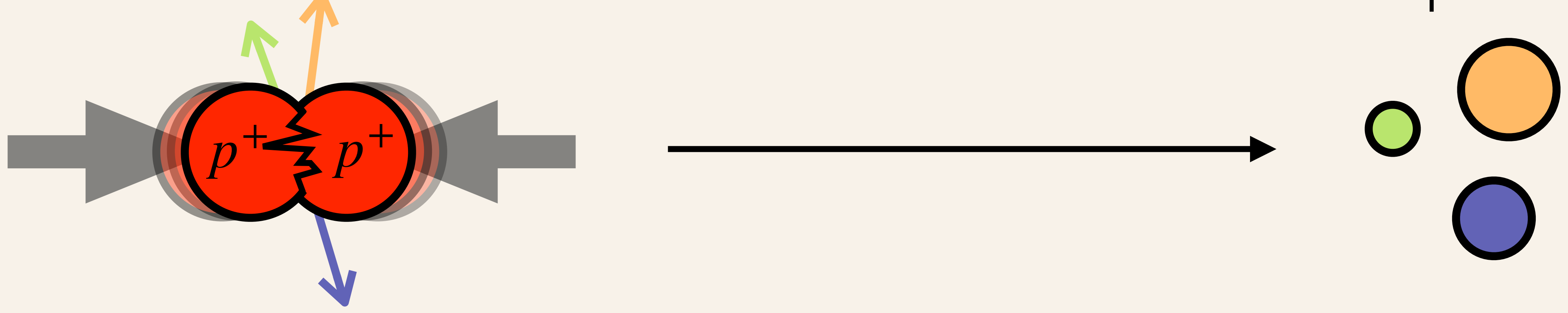
Proton collisions

Truth particles



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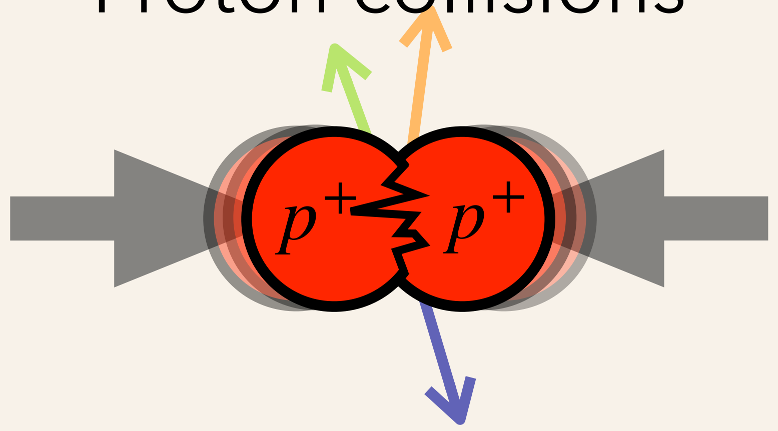
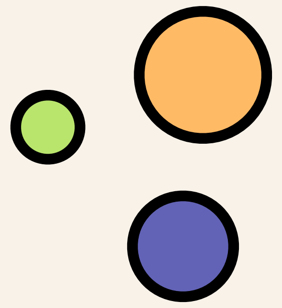
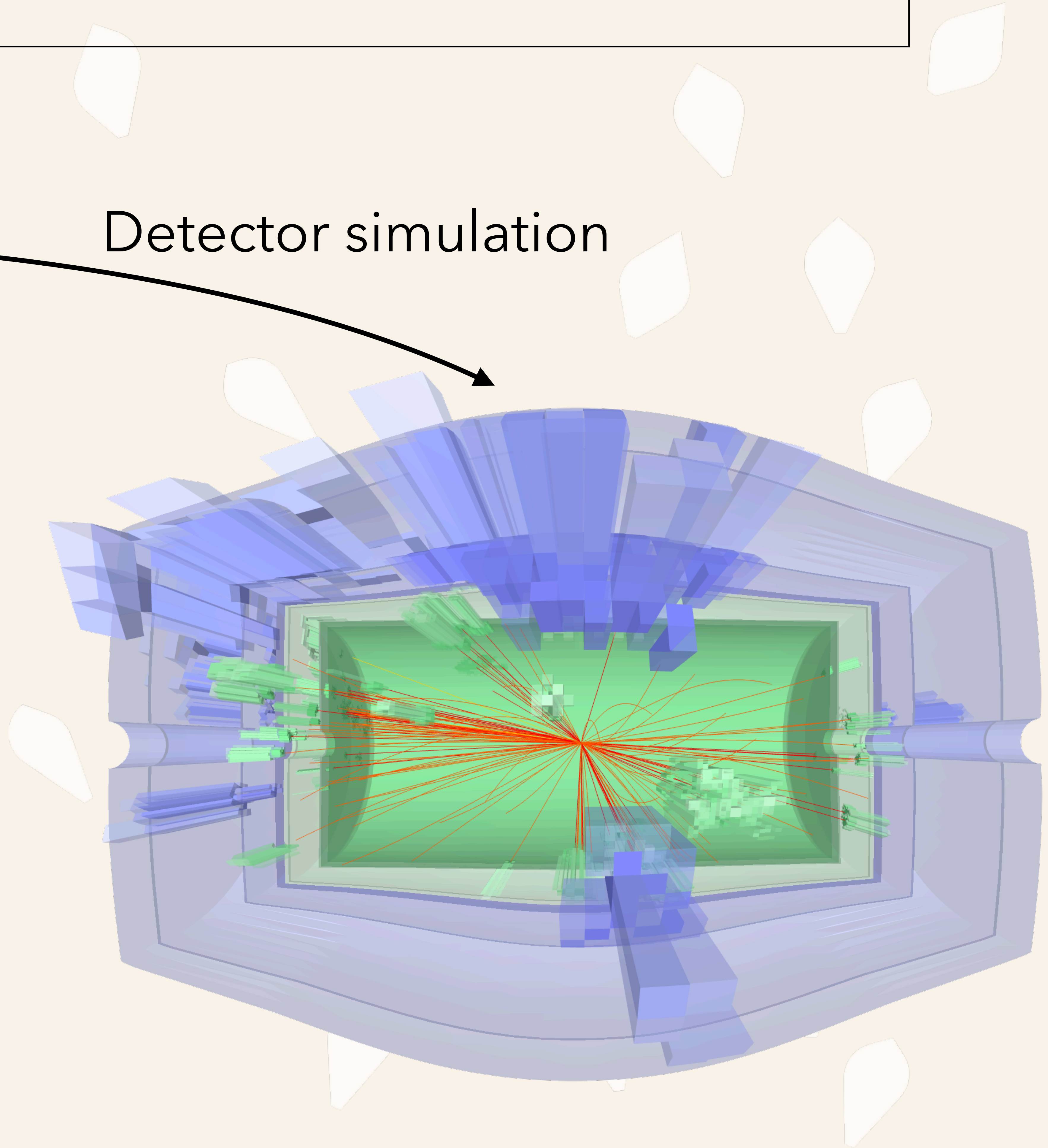


Truth particles



Detector simulation



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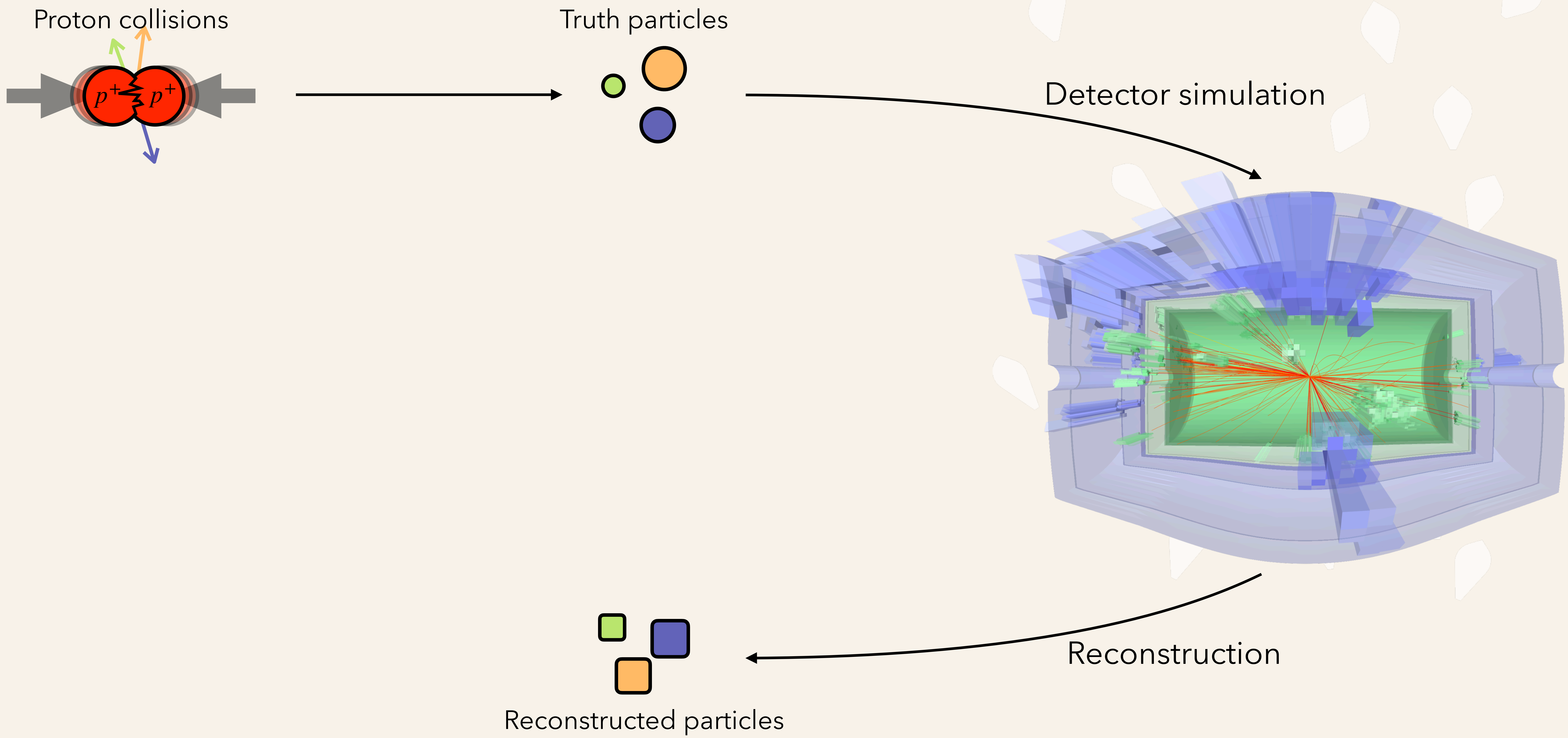
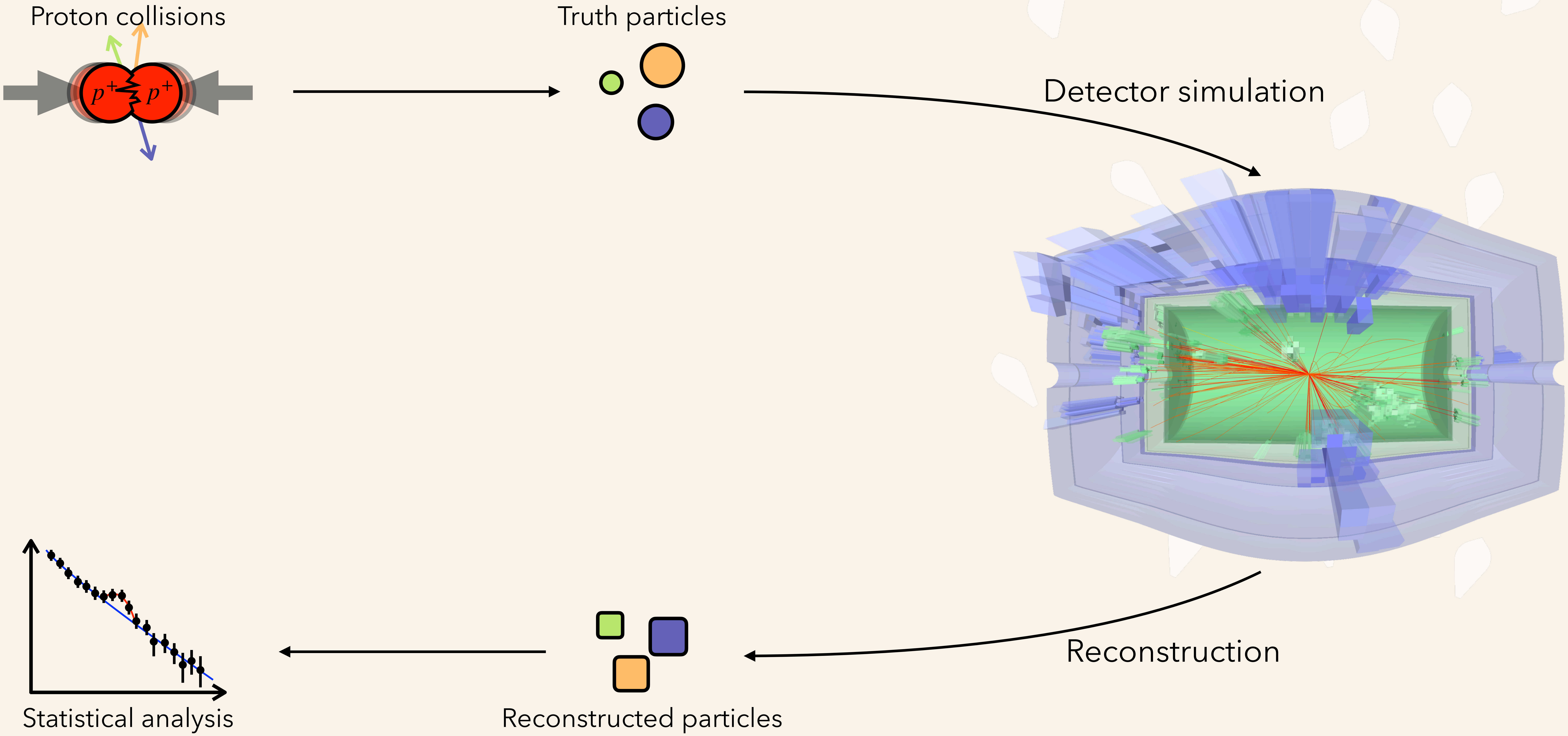

Proton collisions
p^+
p^+
Truth particles
Detector simulation
Reconstruction
Reconstructed particles

Motivation


Proton collisions
p^+
p^+
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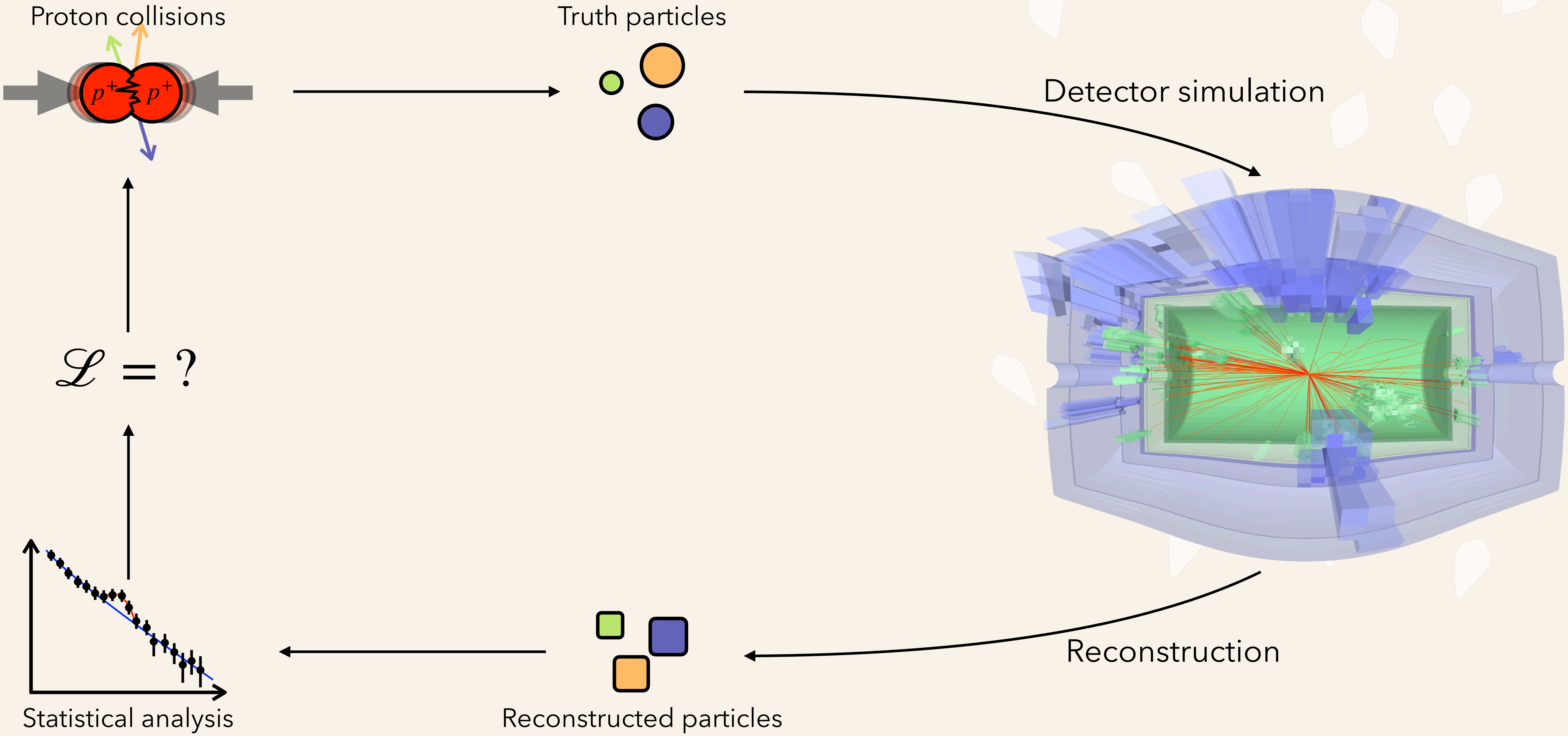
Detector simulation
Reconstruction
Reconstructed particles
Statistical analysis

Motivation


Proton collisions
p^+ p^+
Truth particles
Detector simulation
$\mathscr{L} = ?$
Reconstruction
Statistical analysis
Reconstructed particles

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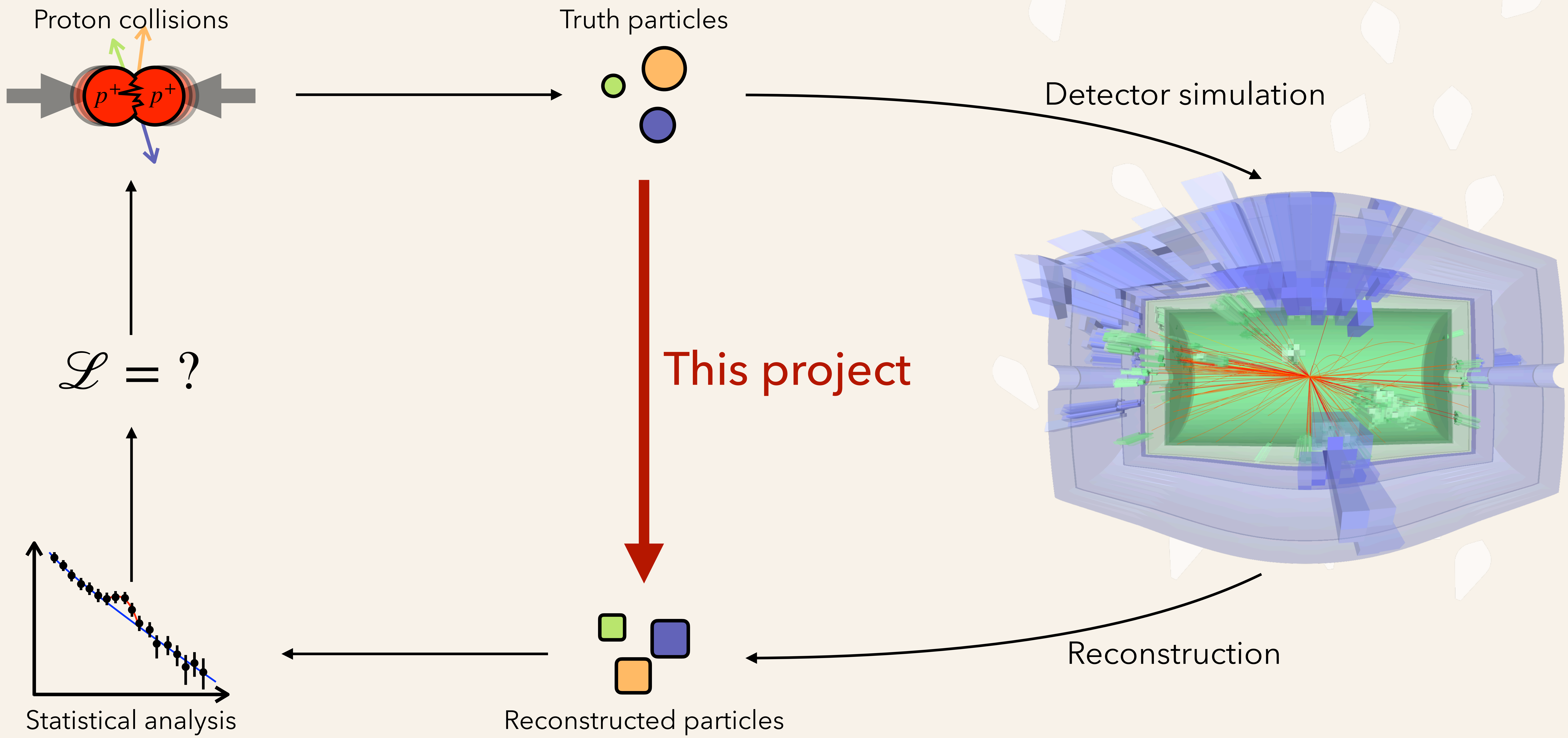
Motivation



Problem to solve

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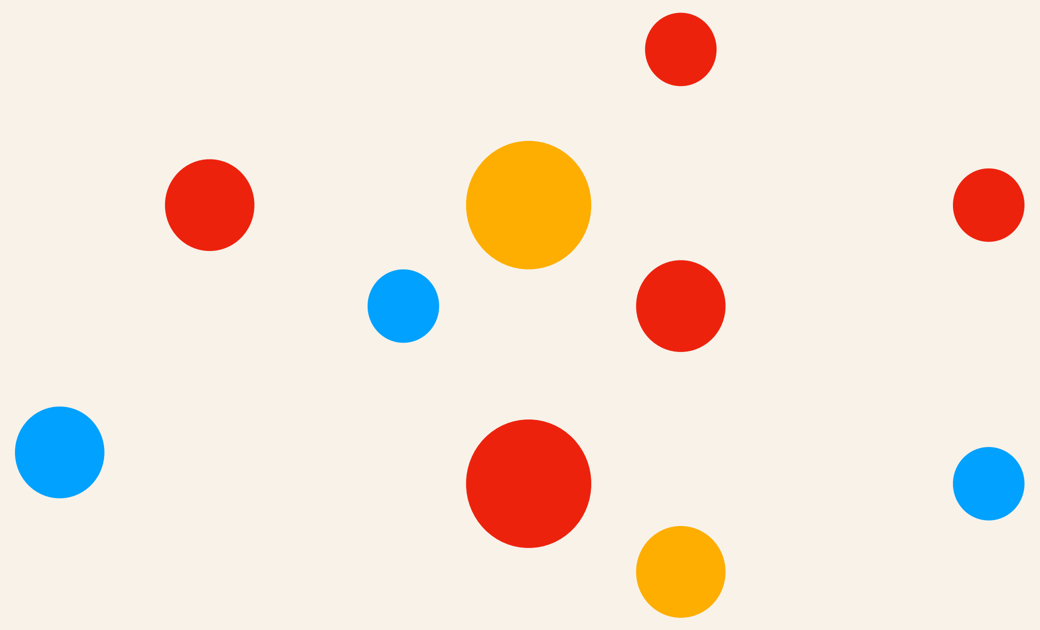
Problem to solve

Final state
truth particles



Problem to solve

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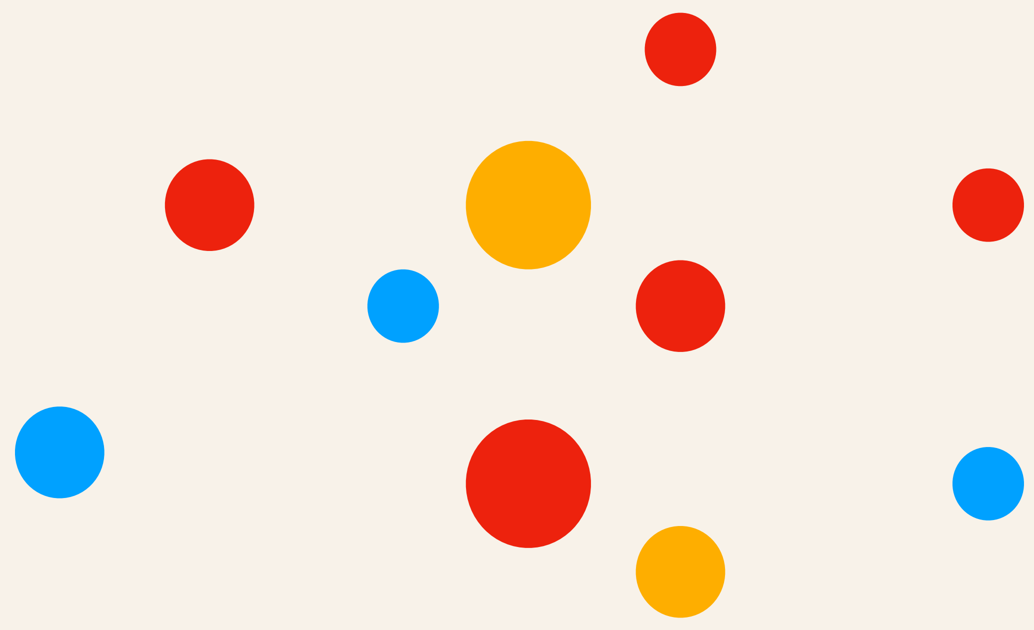
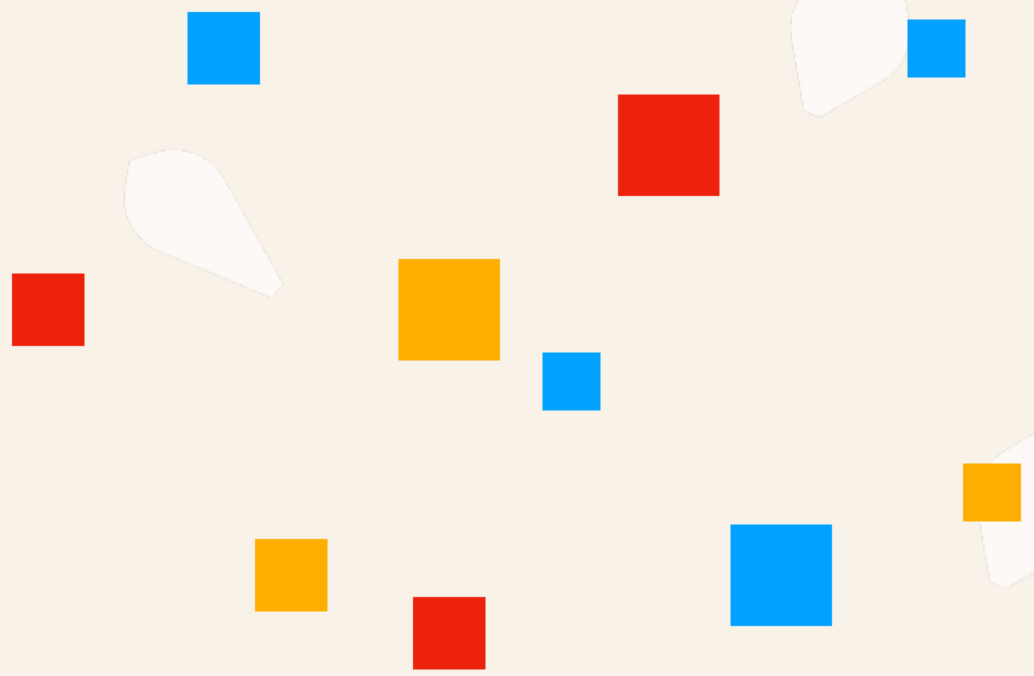


Reconstructed
objects



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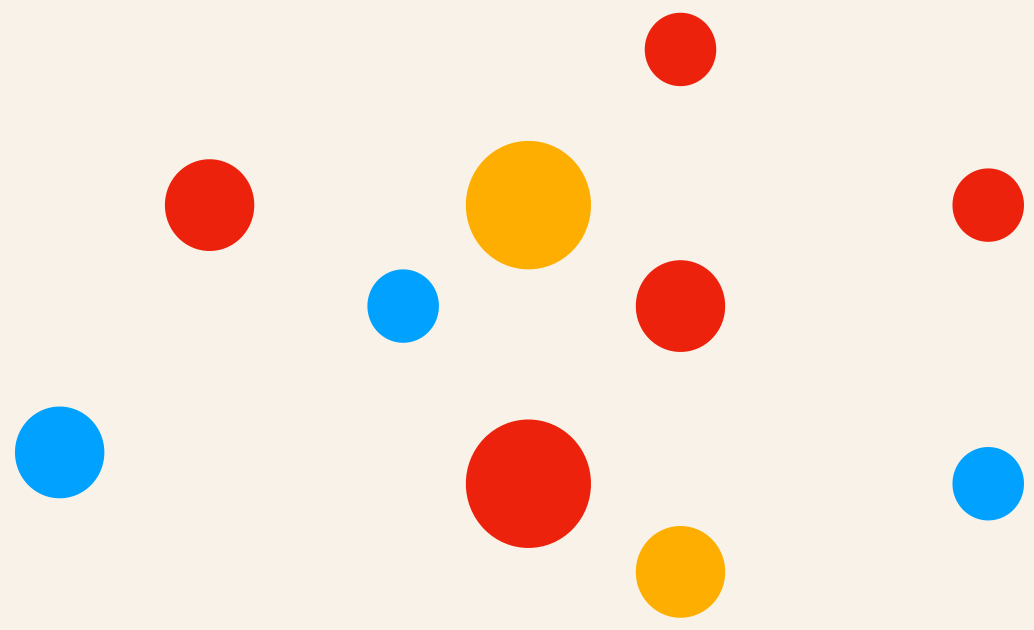
Problem to solve

Final state
truth particles



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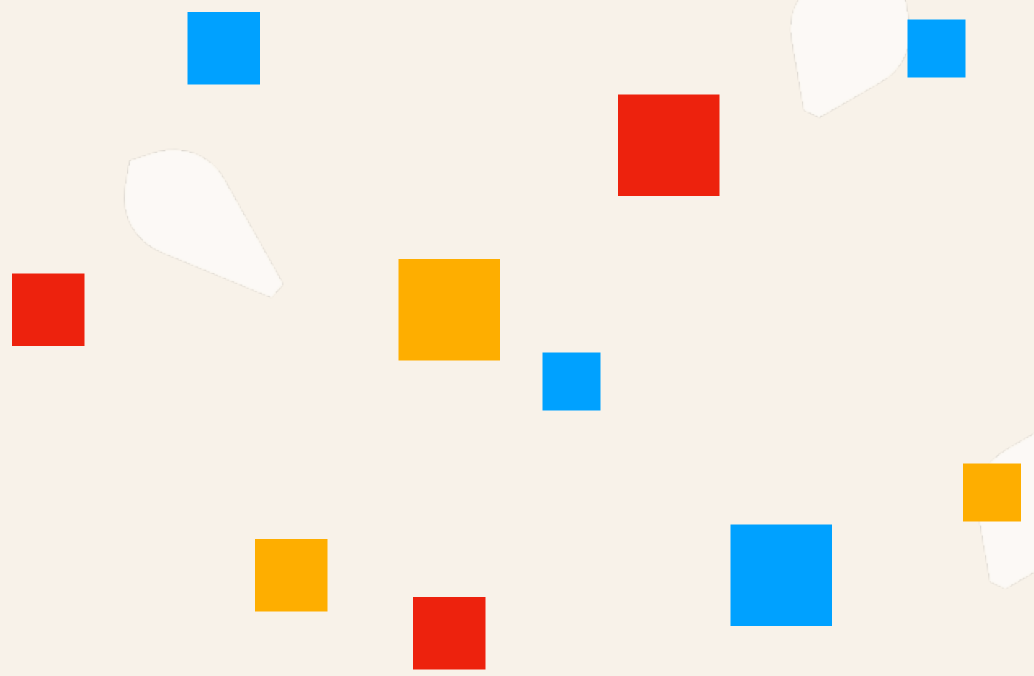

Amount of objects

+

Their properties

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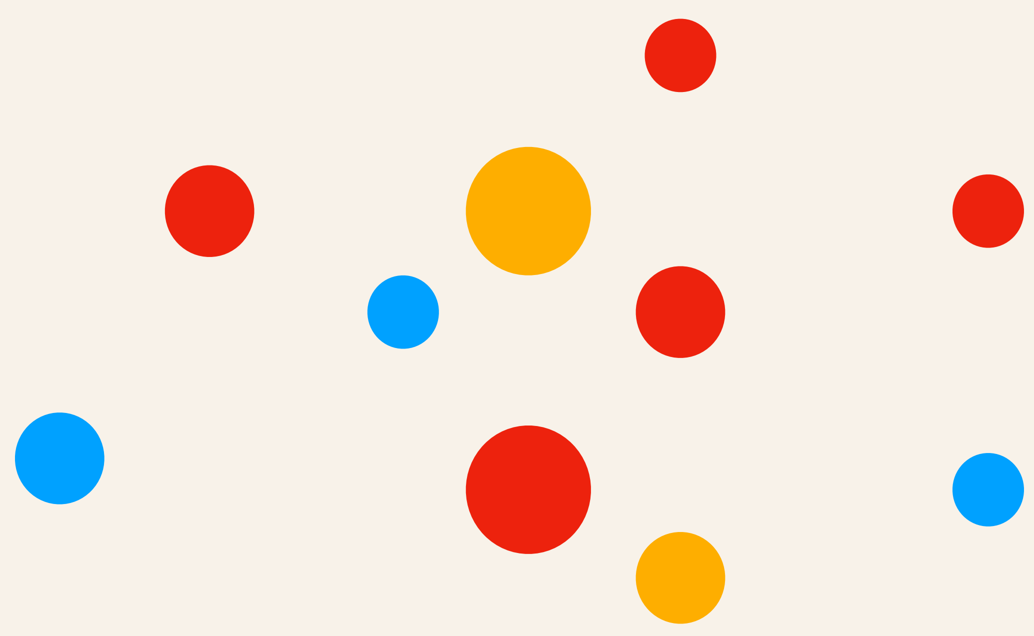
Problem to solve

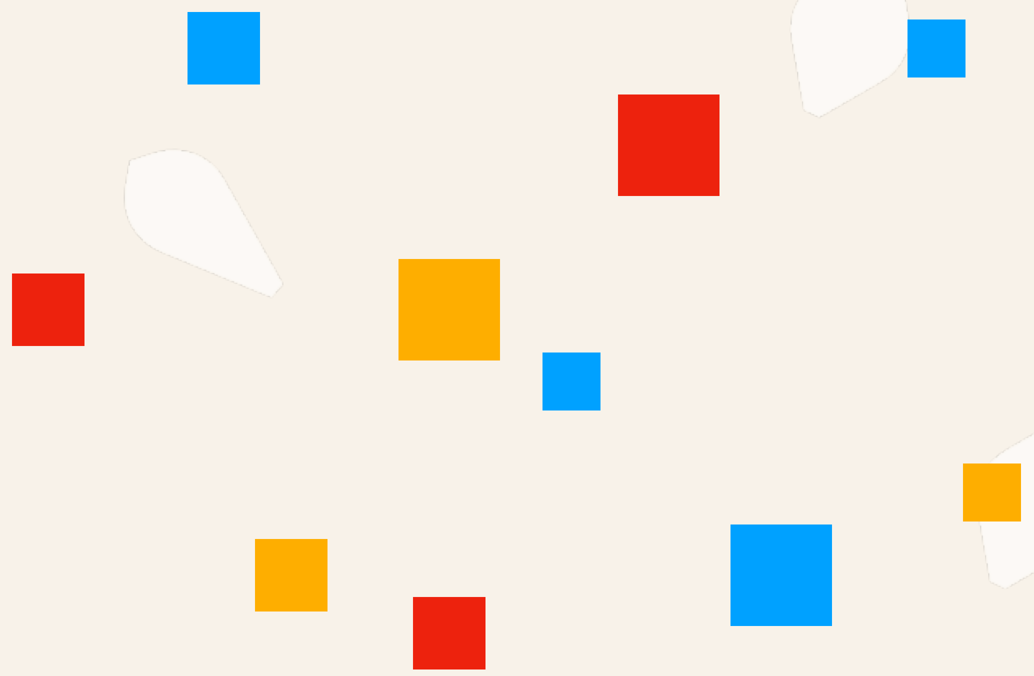
Final state
truth particles



Set to Set

?

Reconstructed
objects



Amount of objects
+
Their properties

Goals

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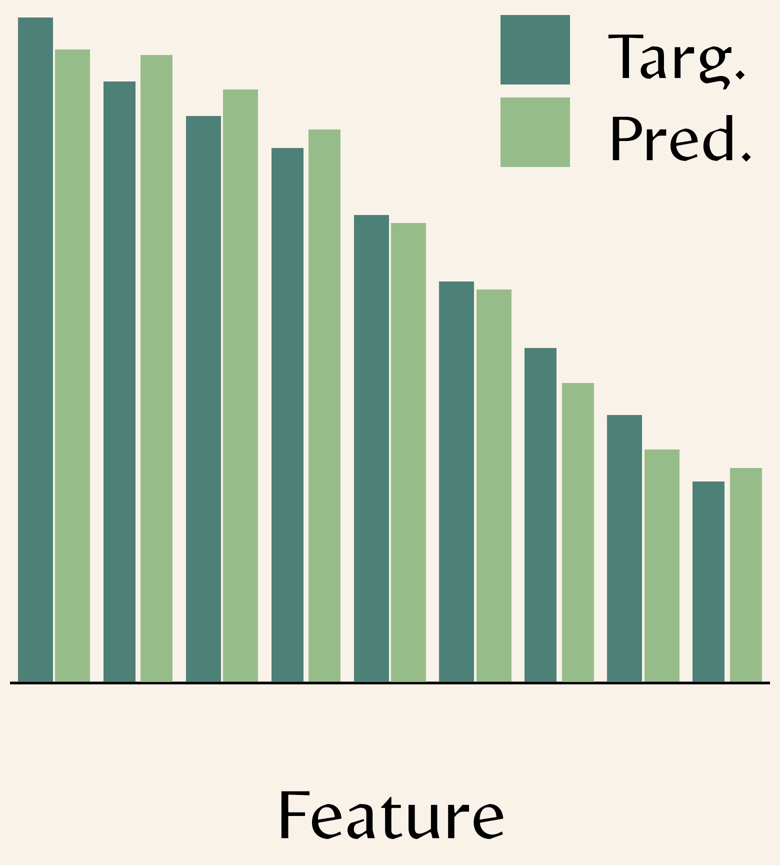
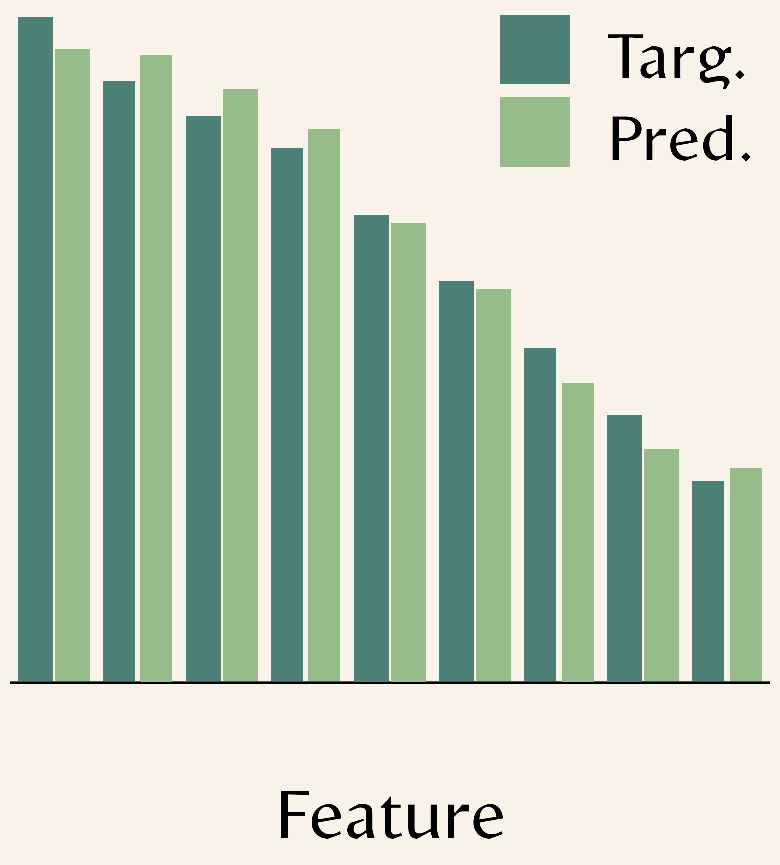
Marginal distributions

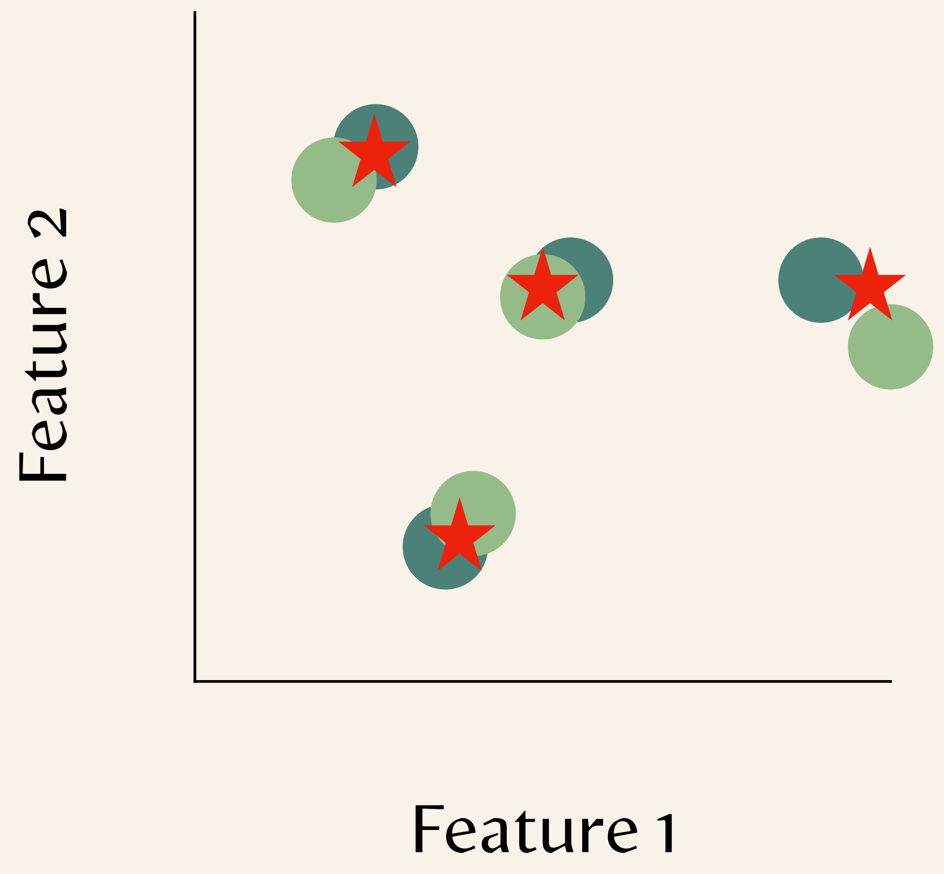


Goals

Marginal distributions

Reconstruct constituents



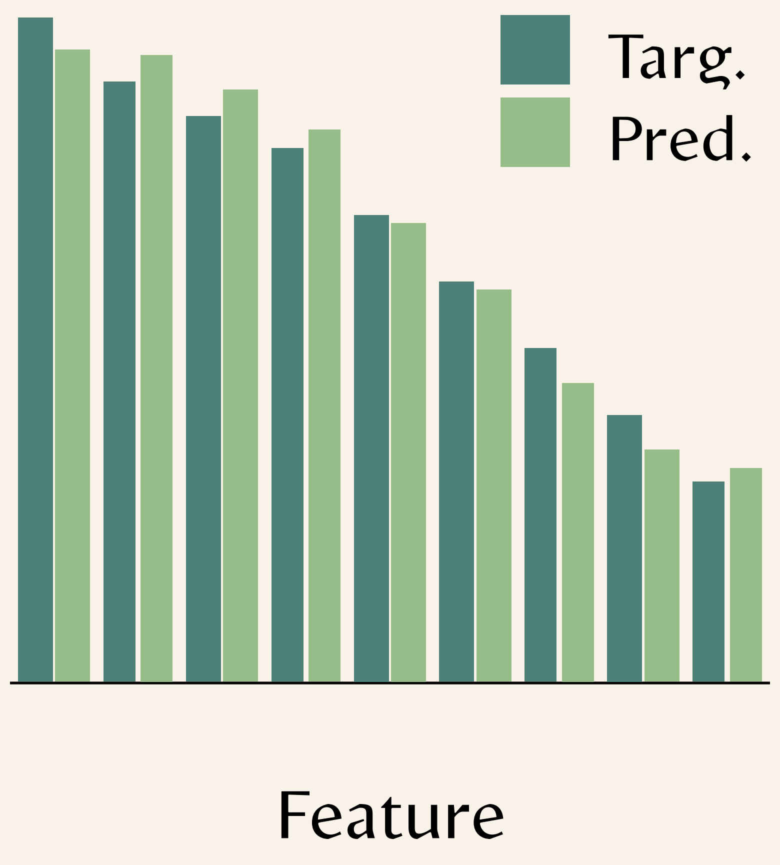


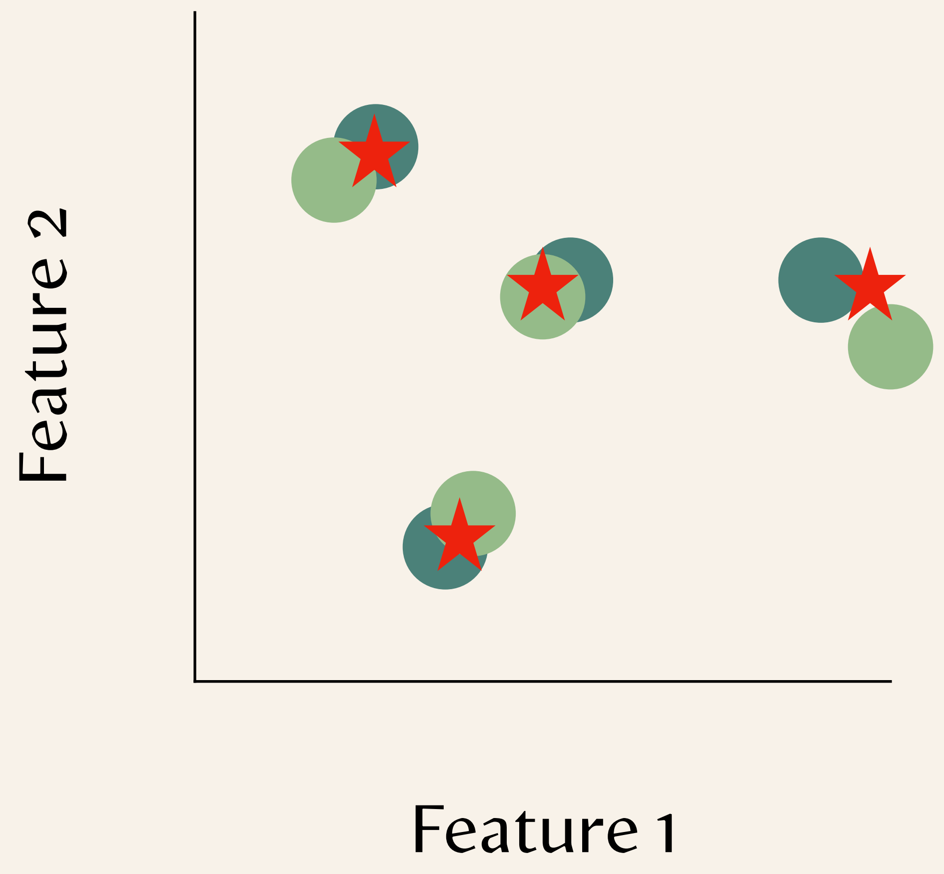
Goals

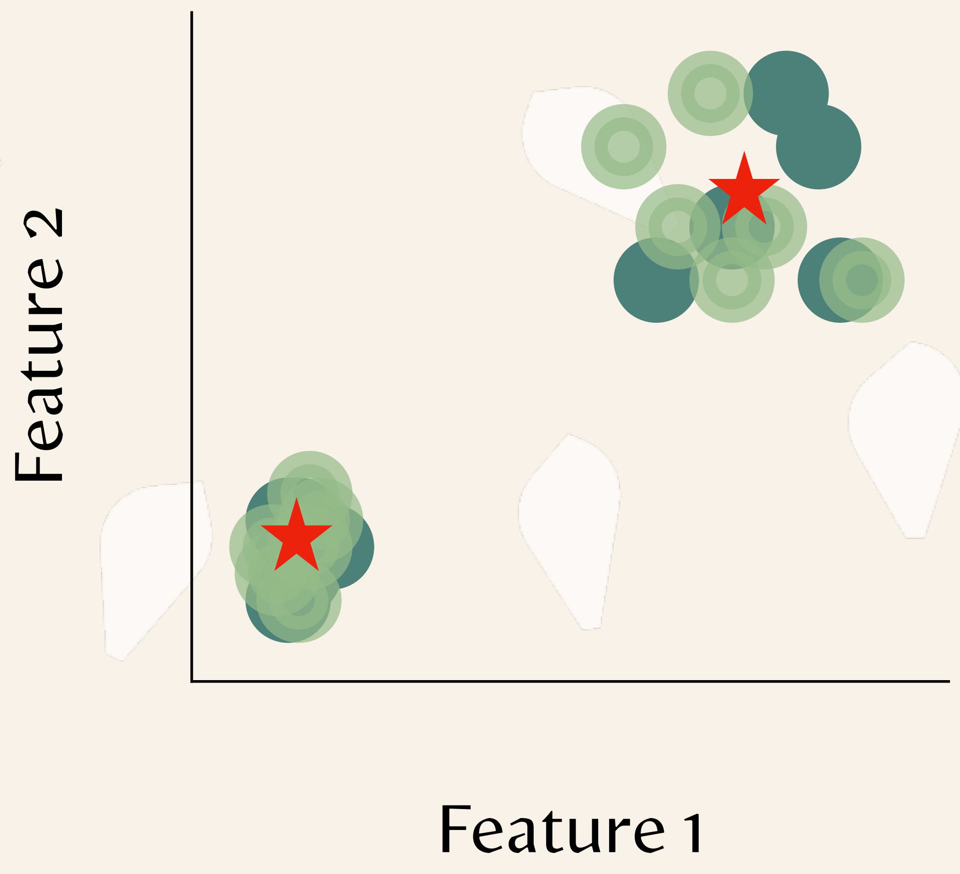
Marginal distributions

Reconstruct constituents

Resolution

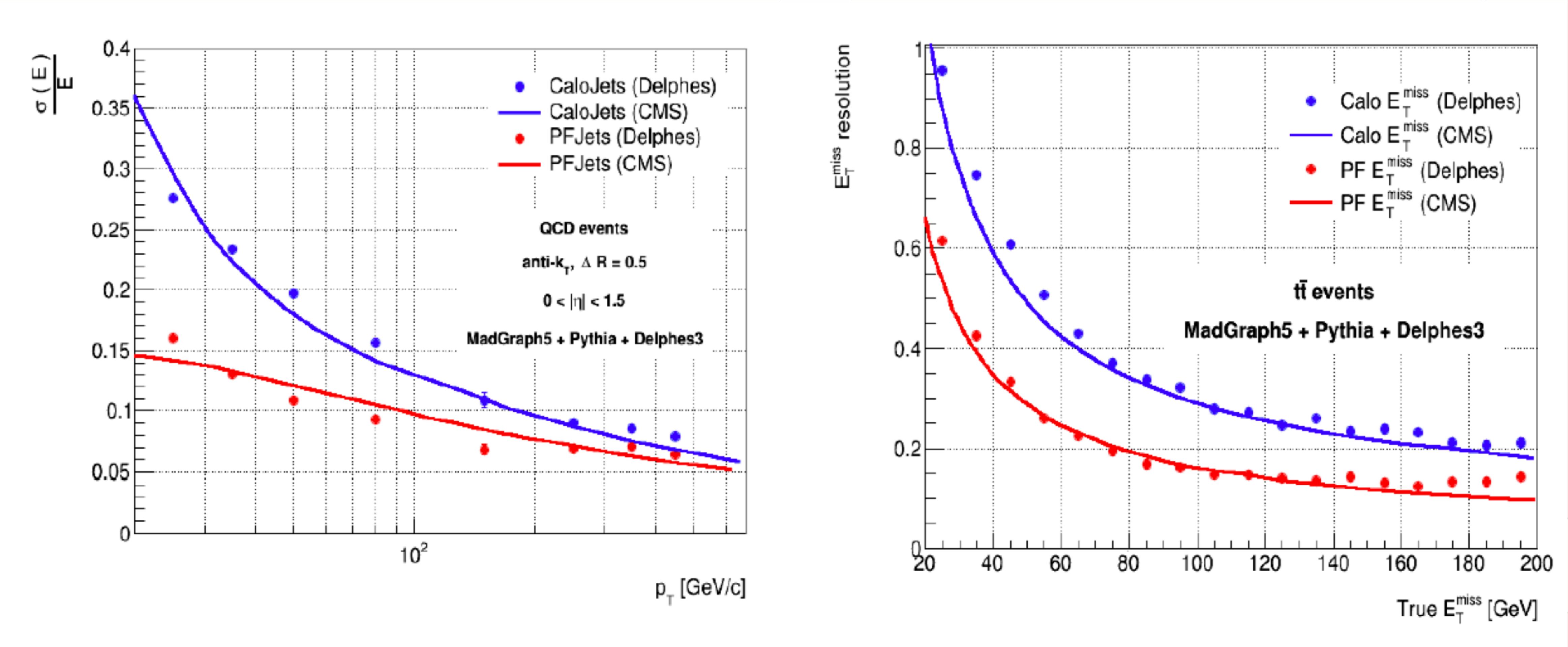






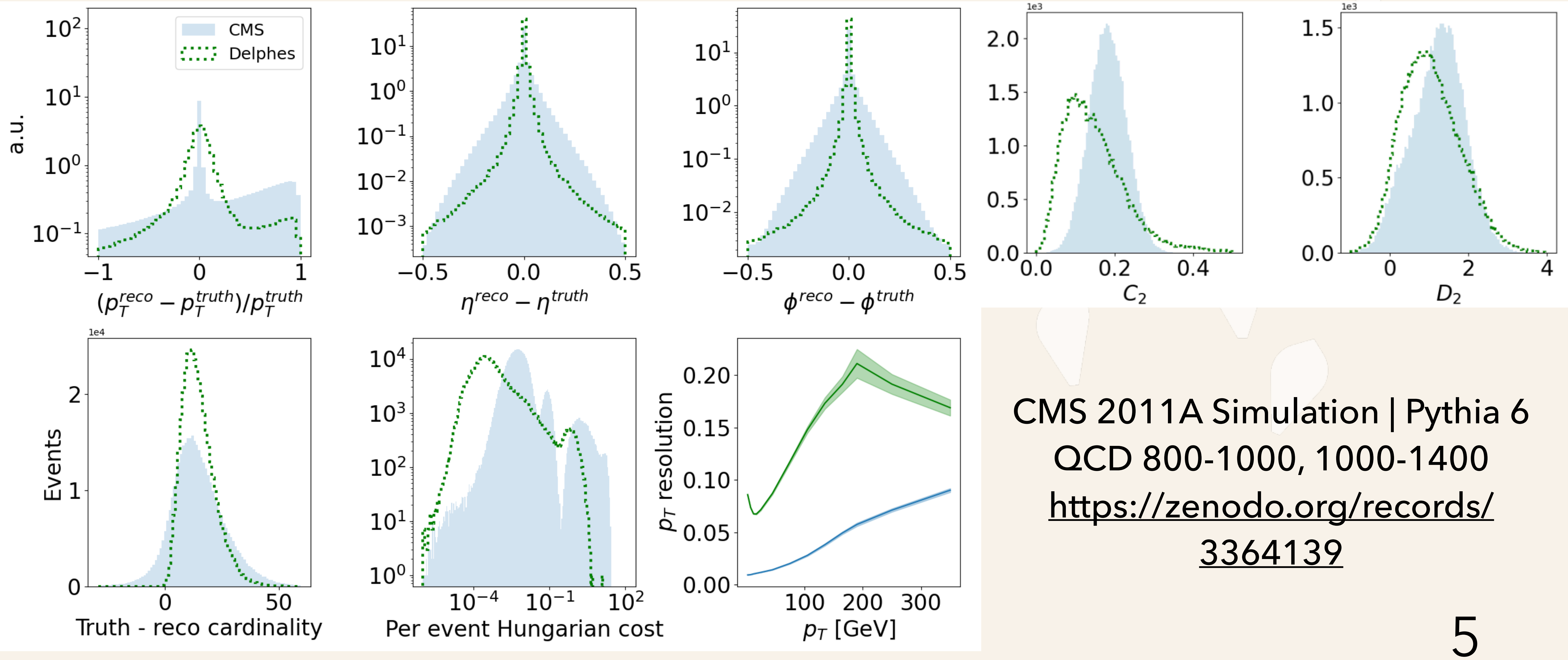
Existing approach: Delphes 3

- 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

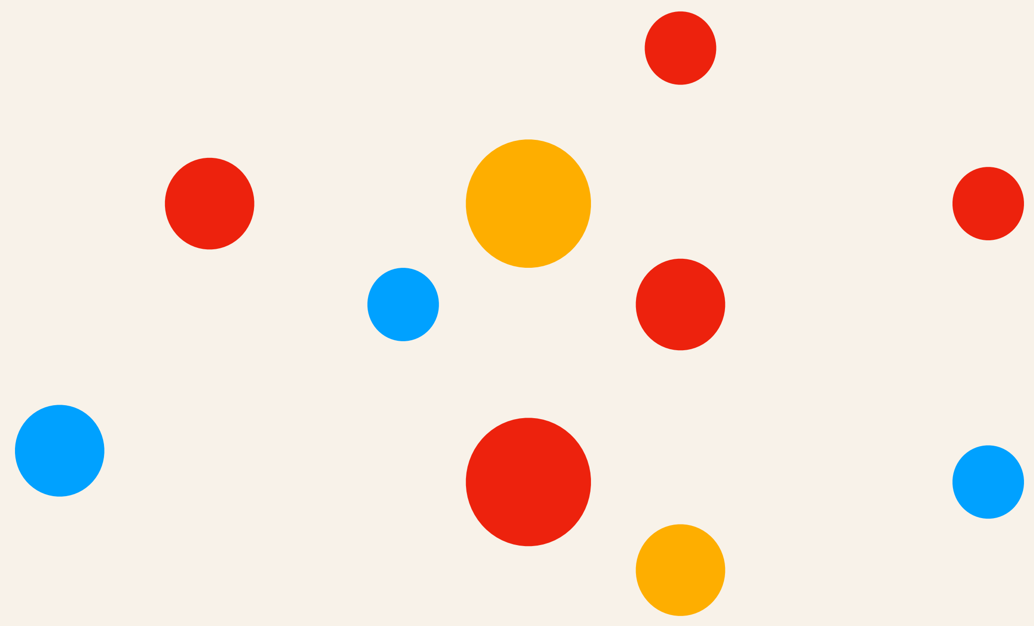


CMS 2011A Simulation | Pythia 6
QCD 800-1000, 1000-1400
https://zenodo.org/records/3364139

ML-based approach

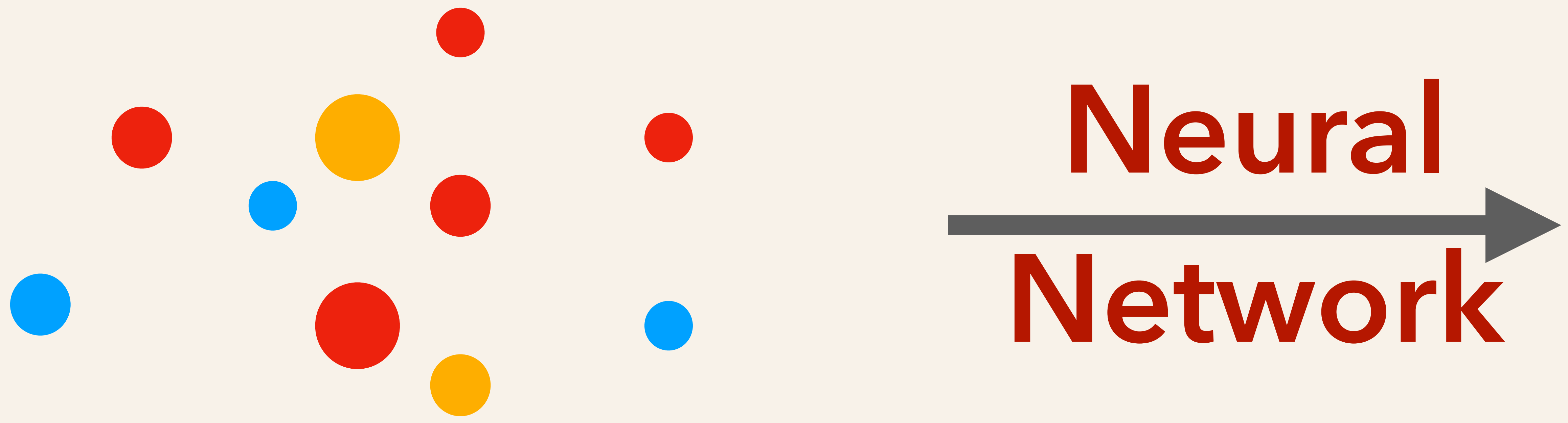
ML-based approach

Final state
truth particles

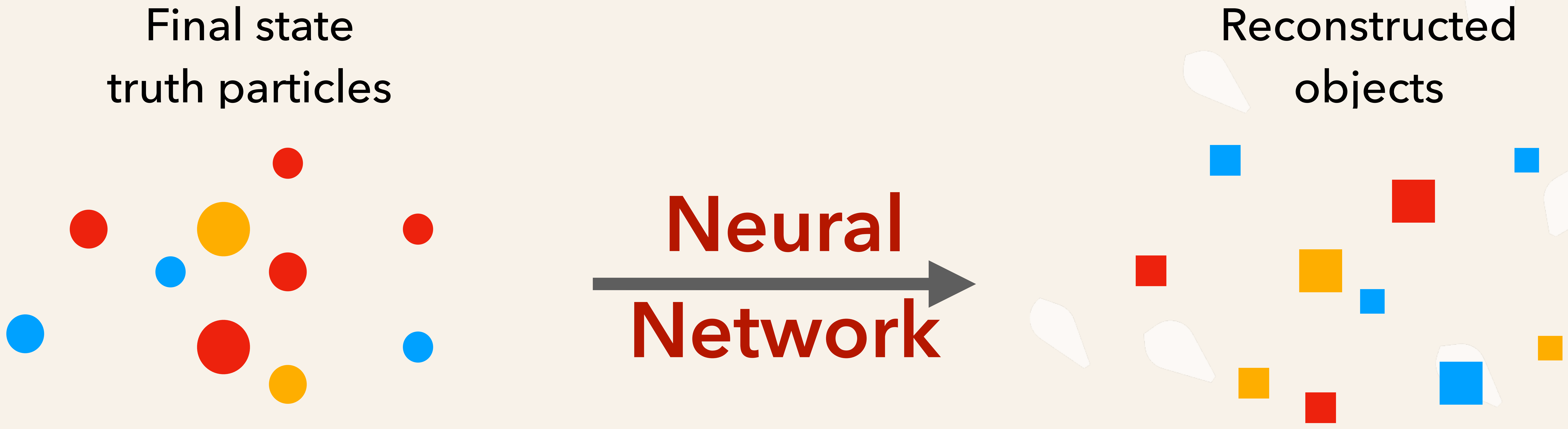


ML-based approach

Final state
truth particles



ML-based approach



ML-based approach: Our journey

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		Full GEANT4 reconstruction and simulation
Only charged particles	→	Charged + Neutral
p_T, η, ϕ		p_T, η, ϕ, q
GNN with Slot-Attention		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

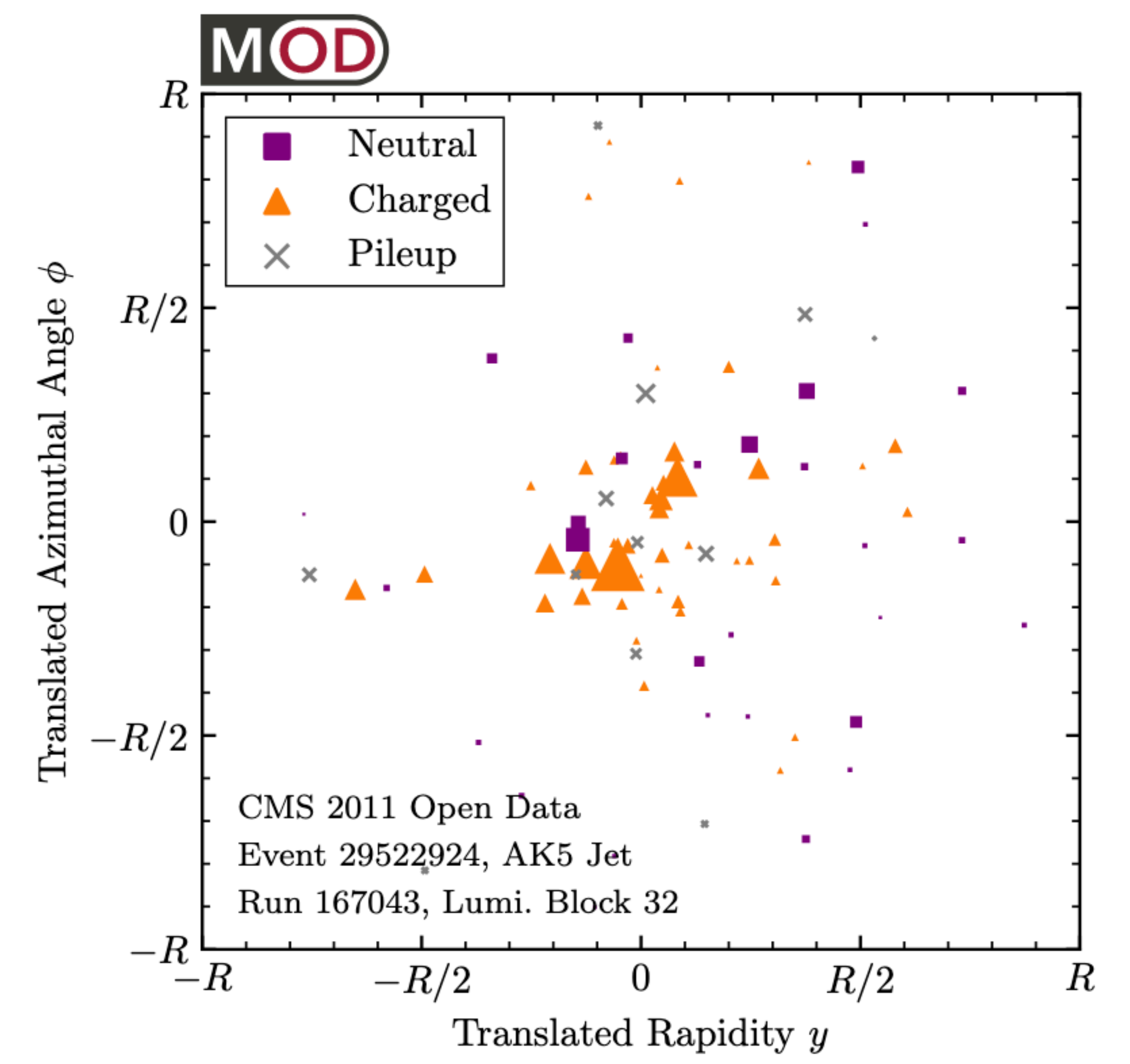
ML-based approach: Our journey

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		✓



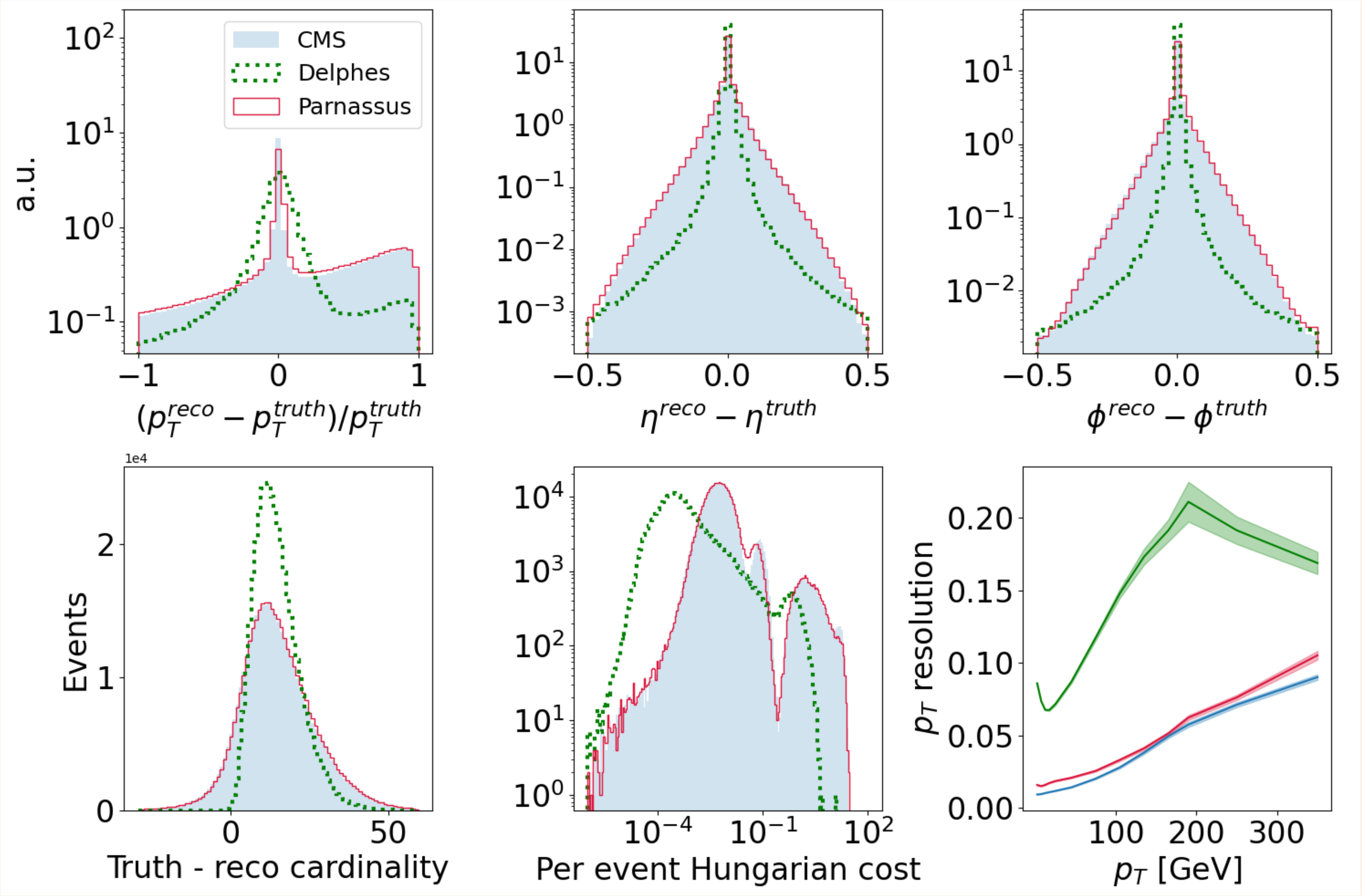
Example QCD jet
(http://arxiv.org/abs/1908.08542)

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

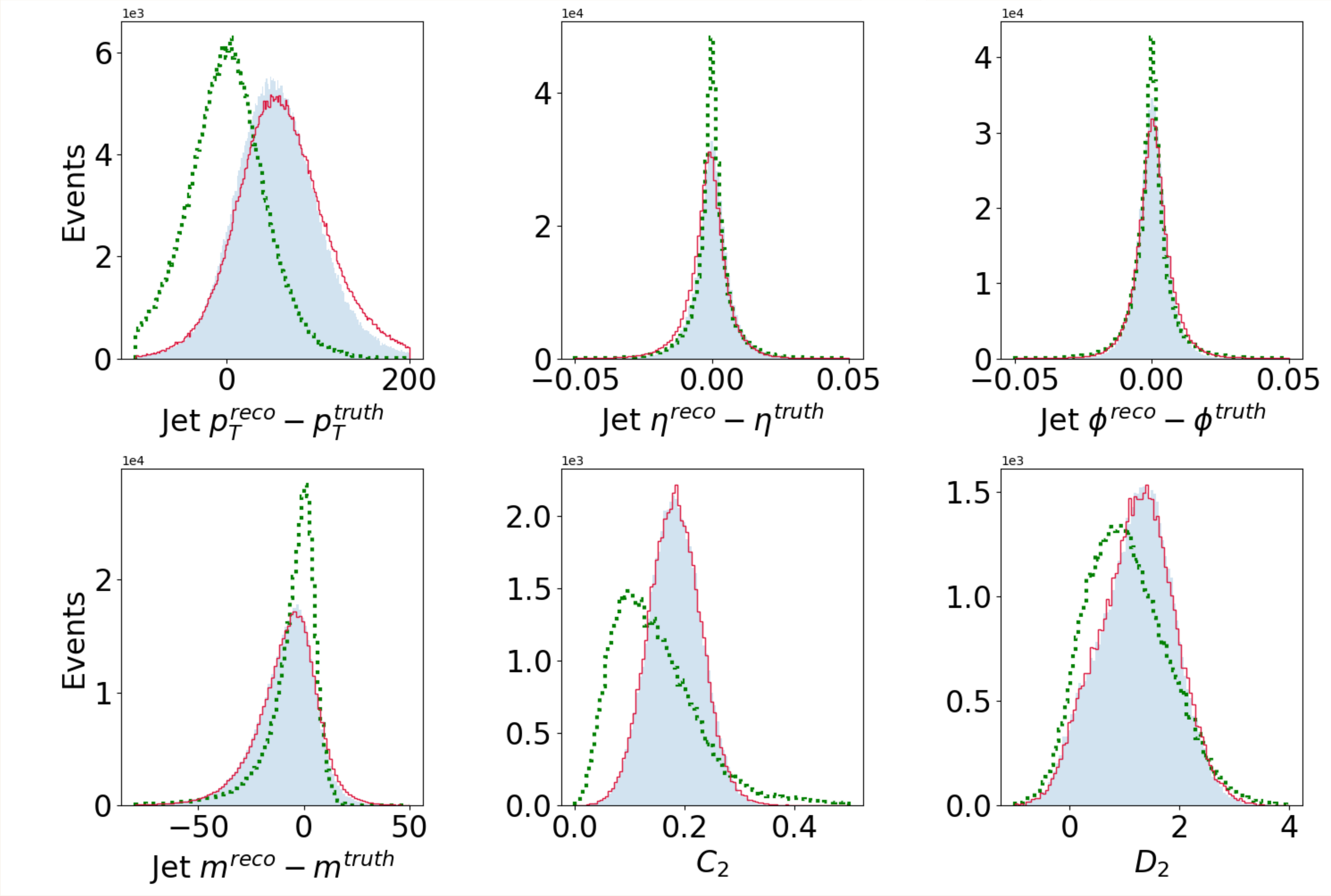
Results: Single Jets

Very good agreement with CMS Pflow

Outperform Delphes everywhere



Particle features



Jet features

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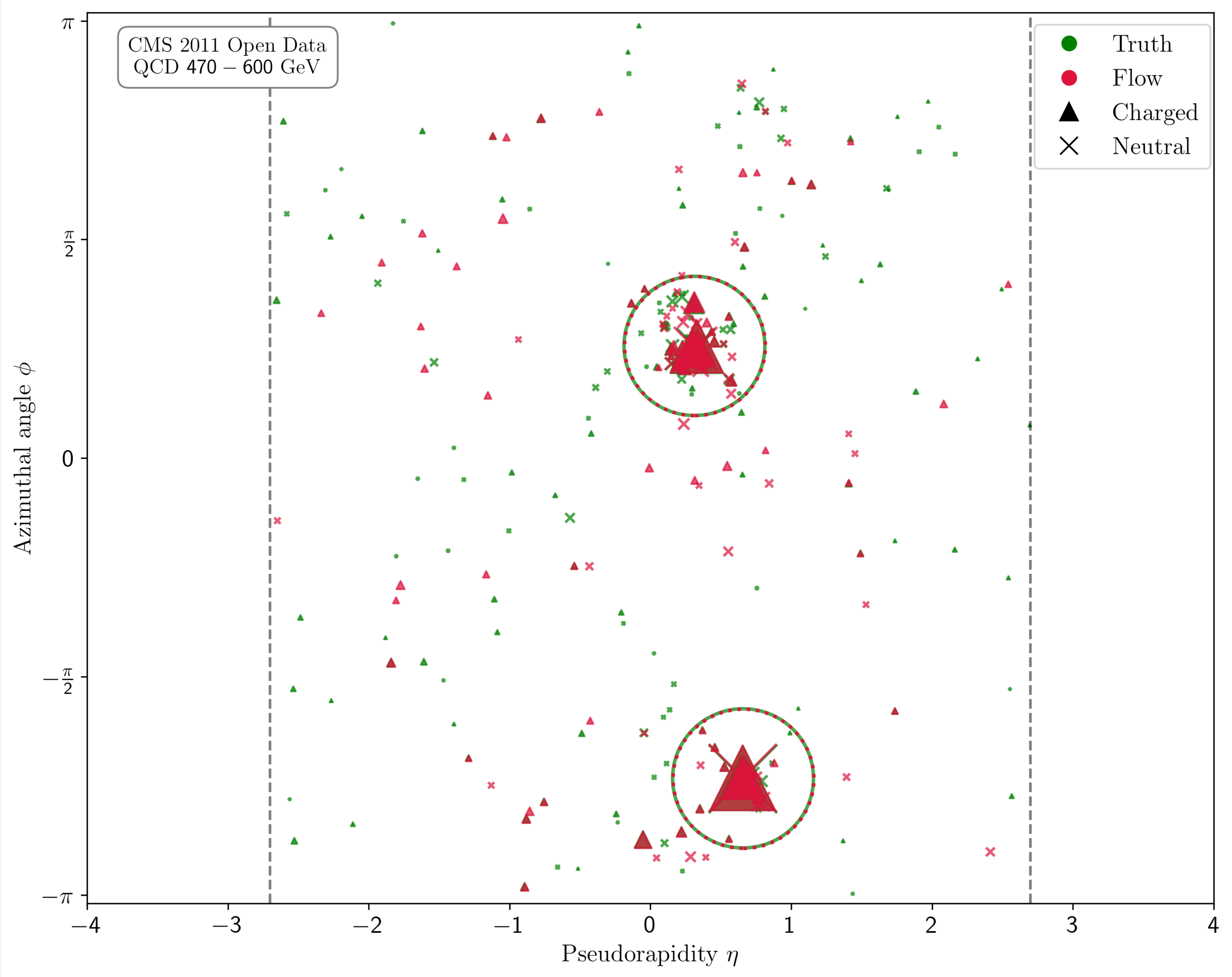
Full event

- 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.

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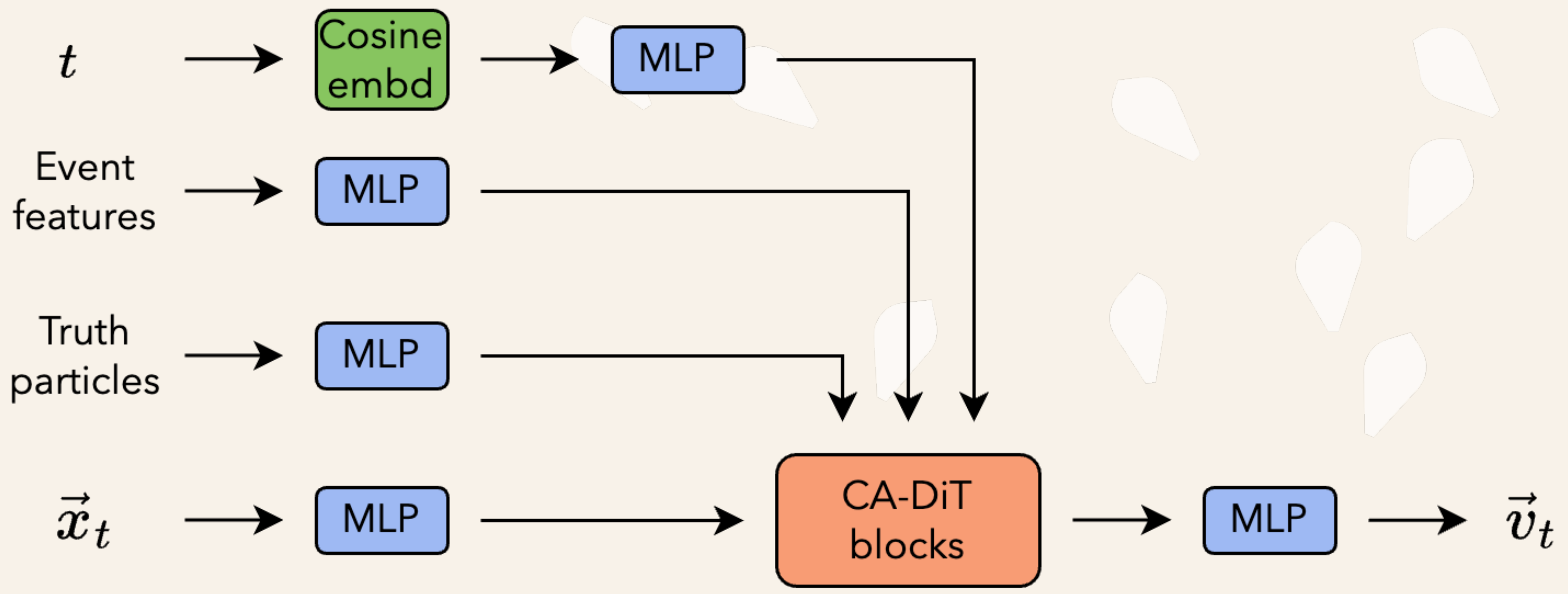
Full event: model description

- 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

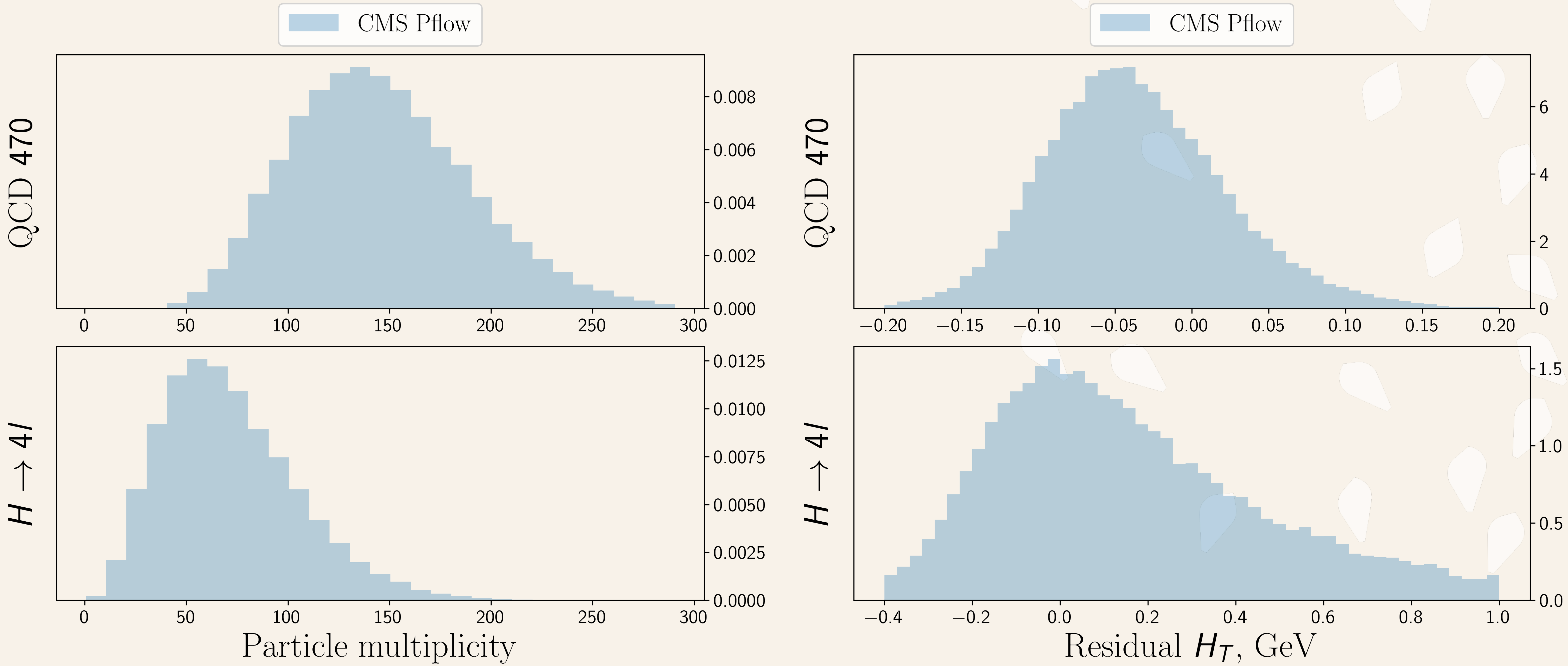
$$p_t(x|z) = \mathcal{N}\left(x \mid tx_1, (t\sigma - t + 1)^2\right)$$

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

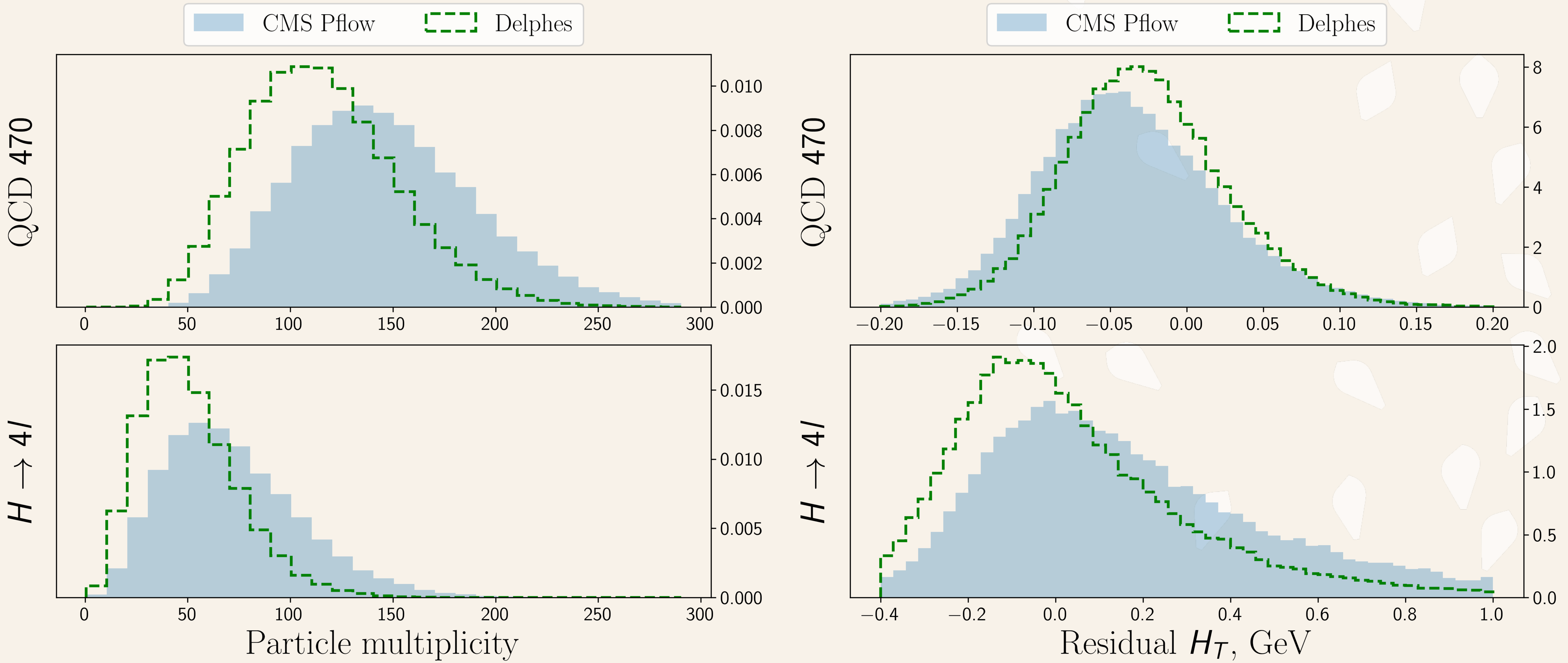
$$\mathcal{L}(\theta) = \mathbb{E}_{t,q(x_1),p_t(x|x_1)} \| v_\theta(x,t) - u_t(x|x_1) \|^2$$



Results: Event level quantities



Results: Event level quantities



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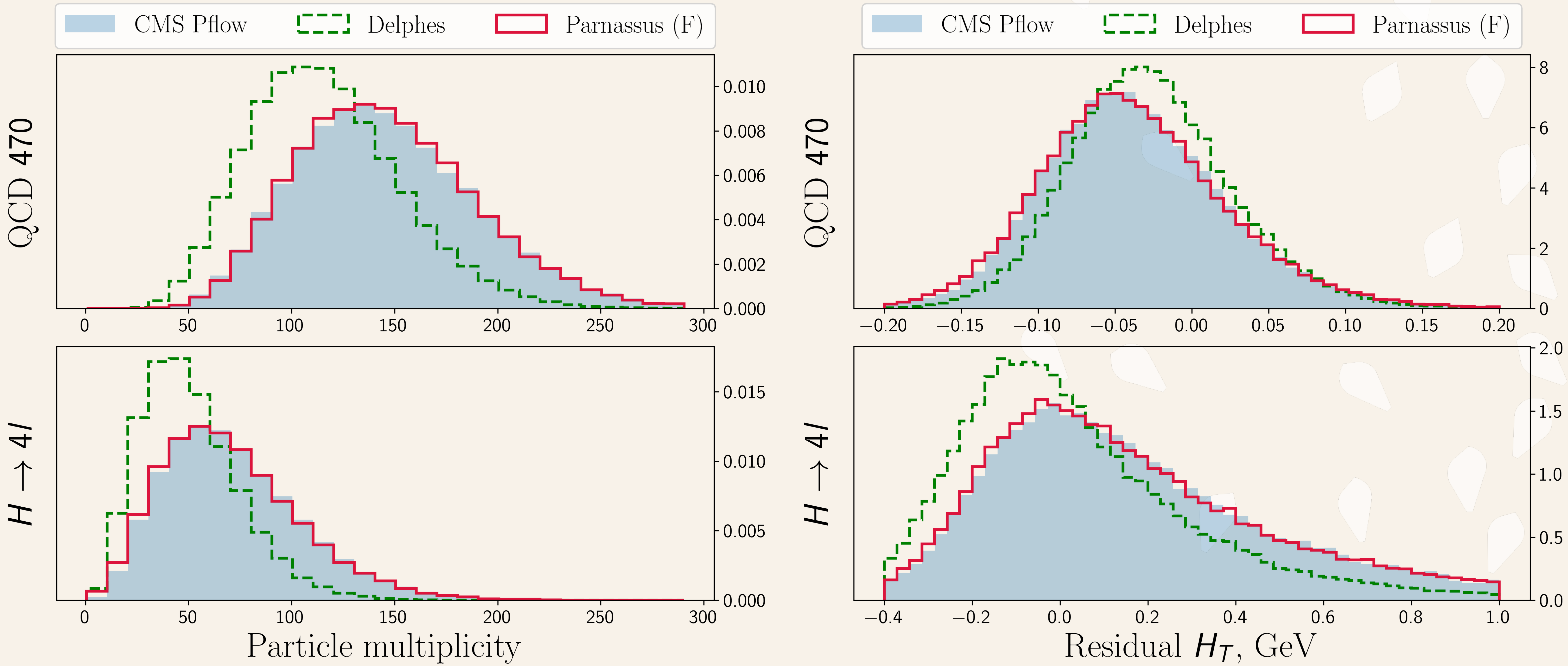
Results: Event level quantities



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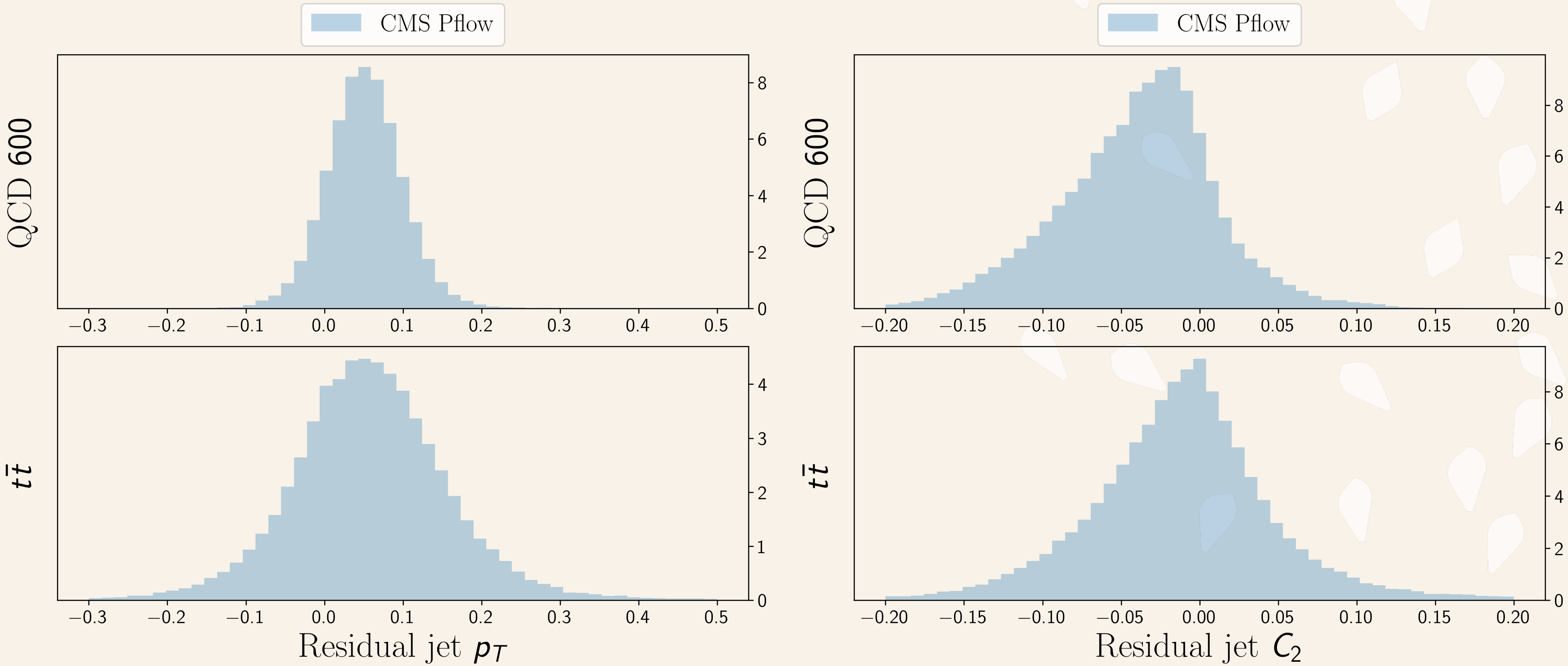
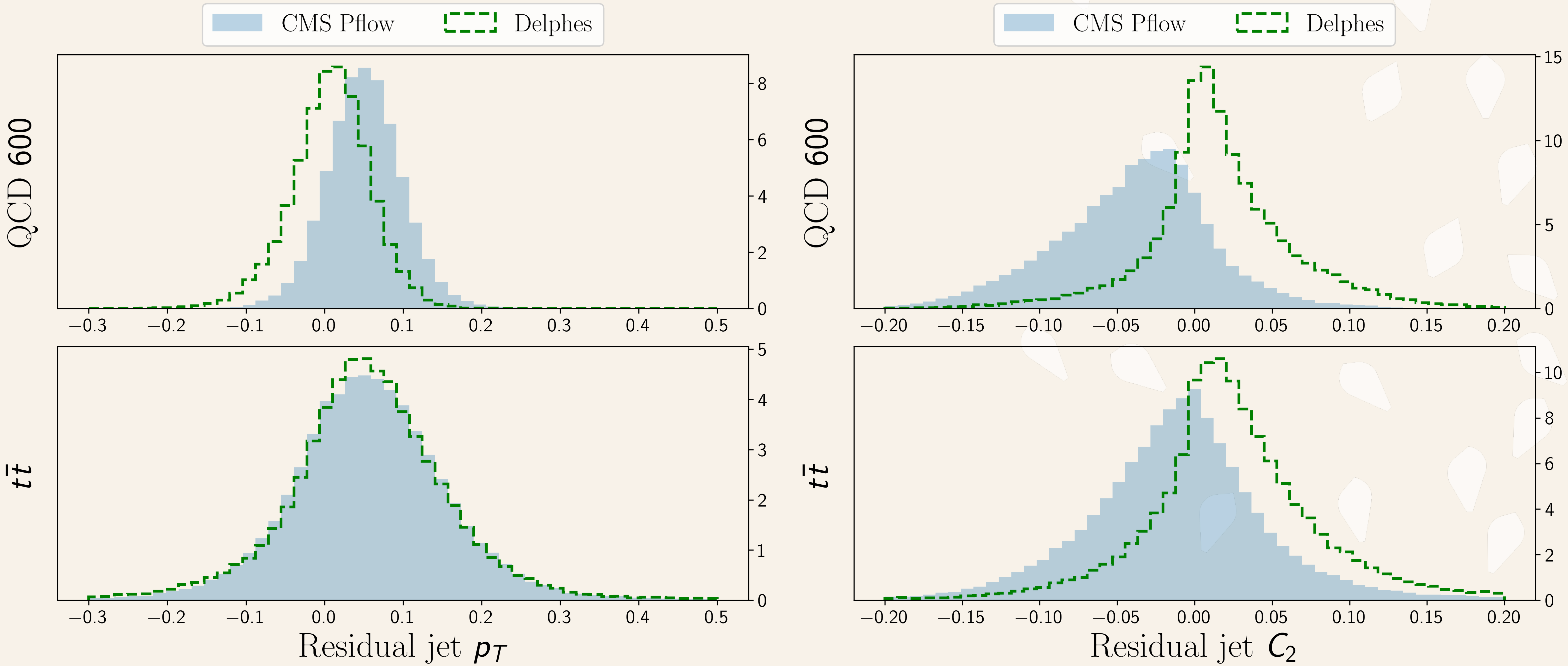
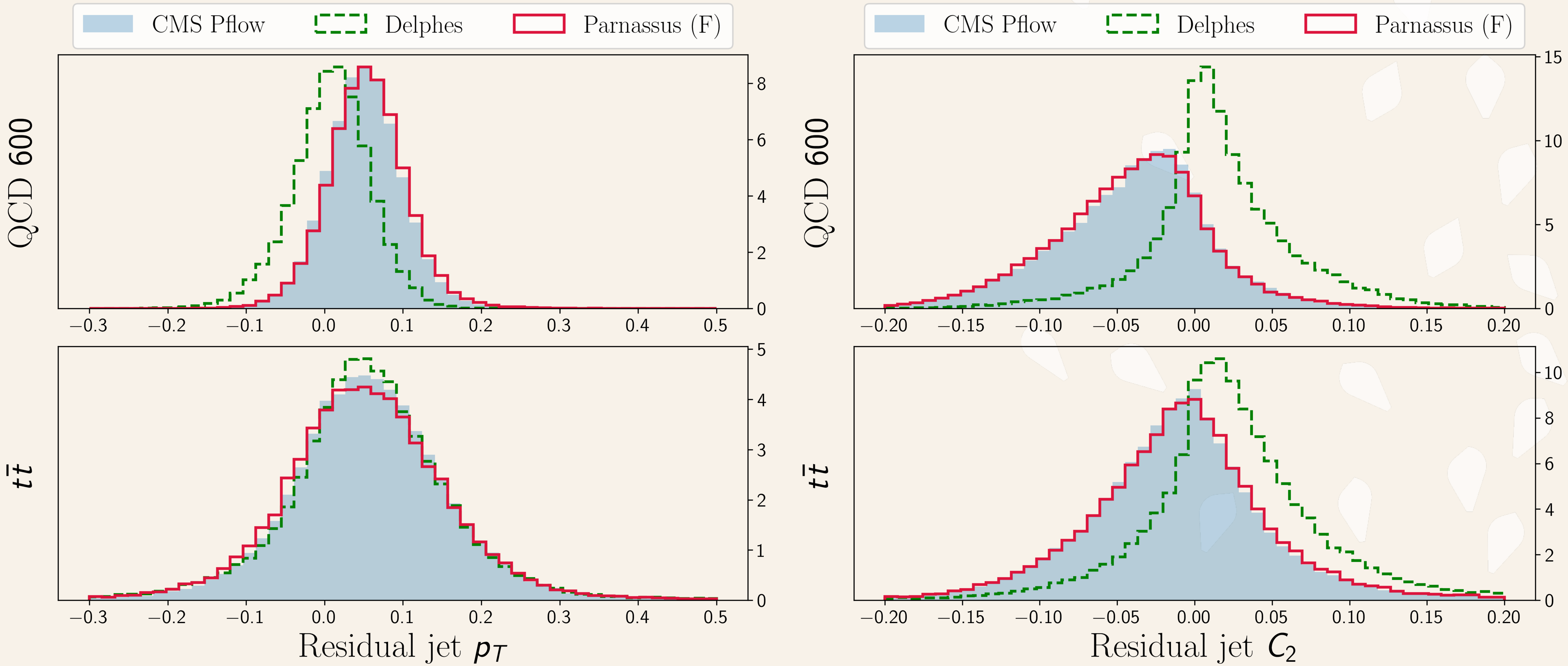
Results: Jet level quantities



Results: Jet level quantities



Results: Jet level quantities



Results: Particle level quantities

Results: Particle level quantities

Results: Particle level quantities

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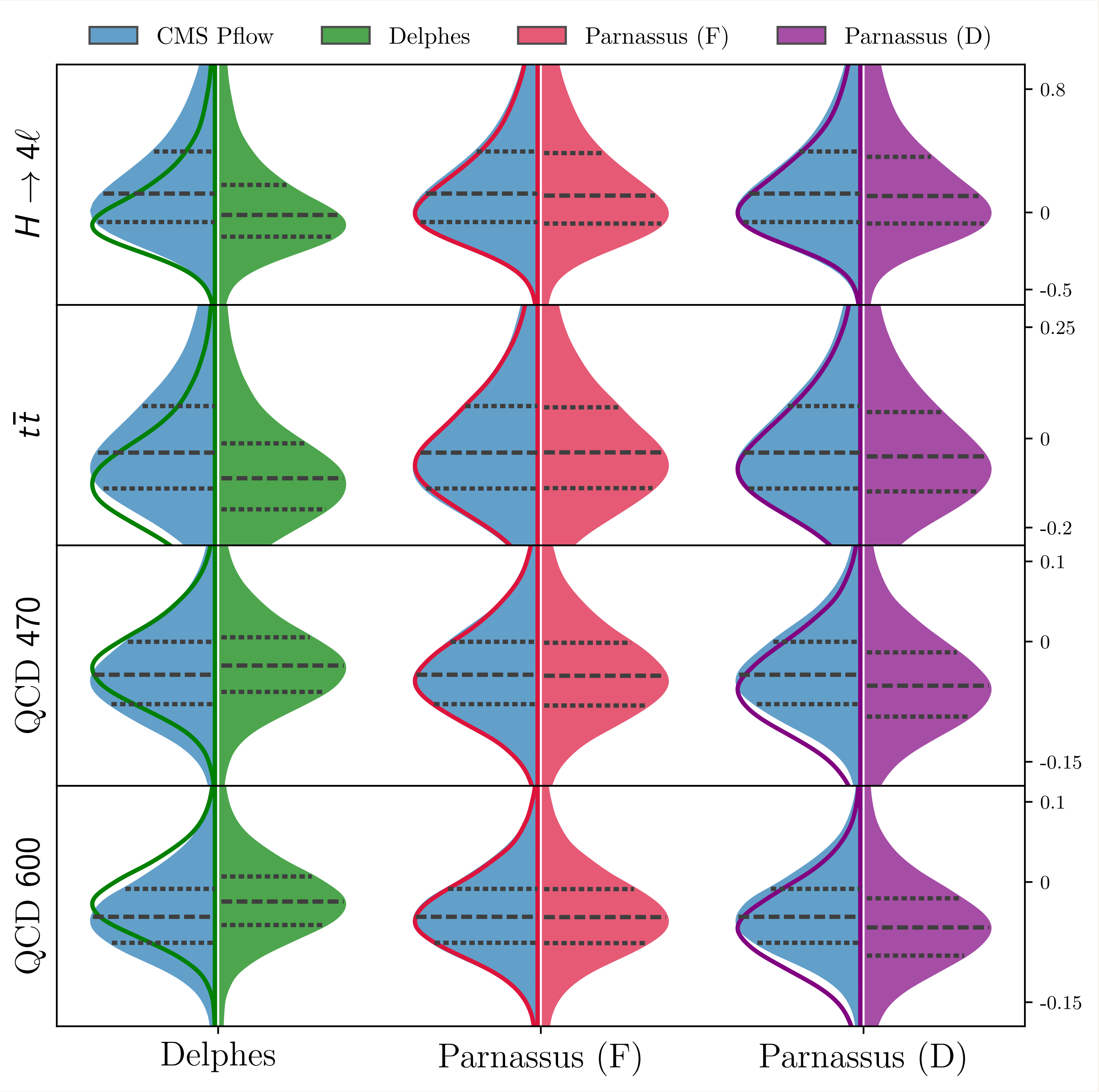
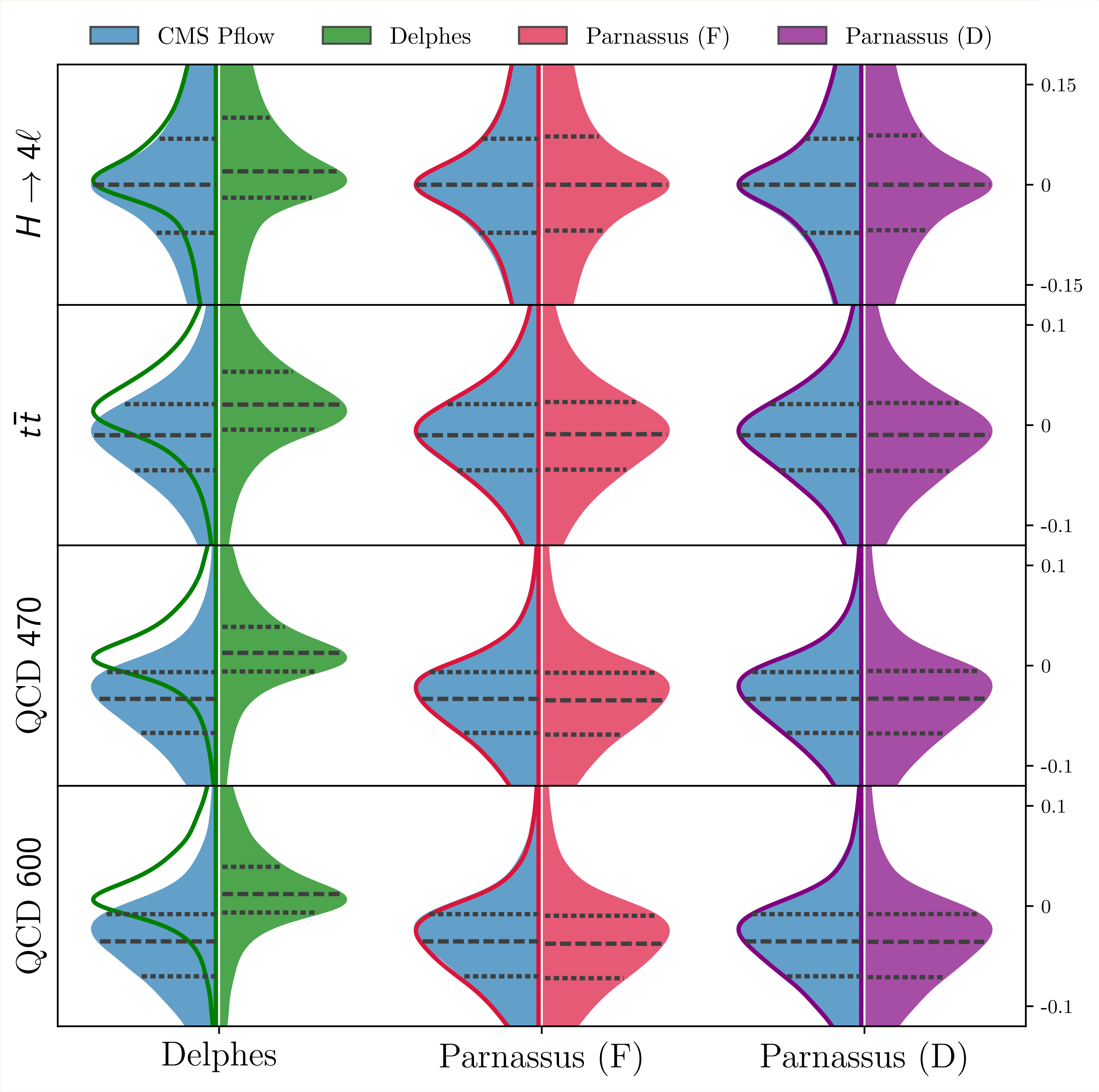
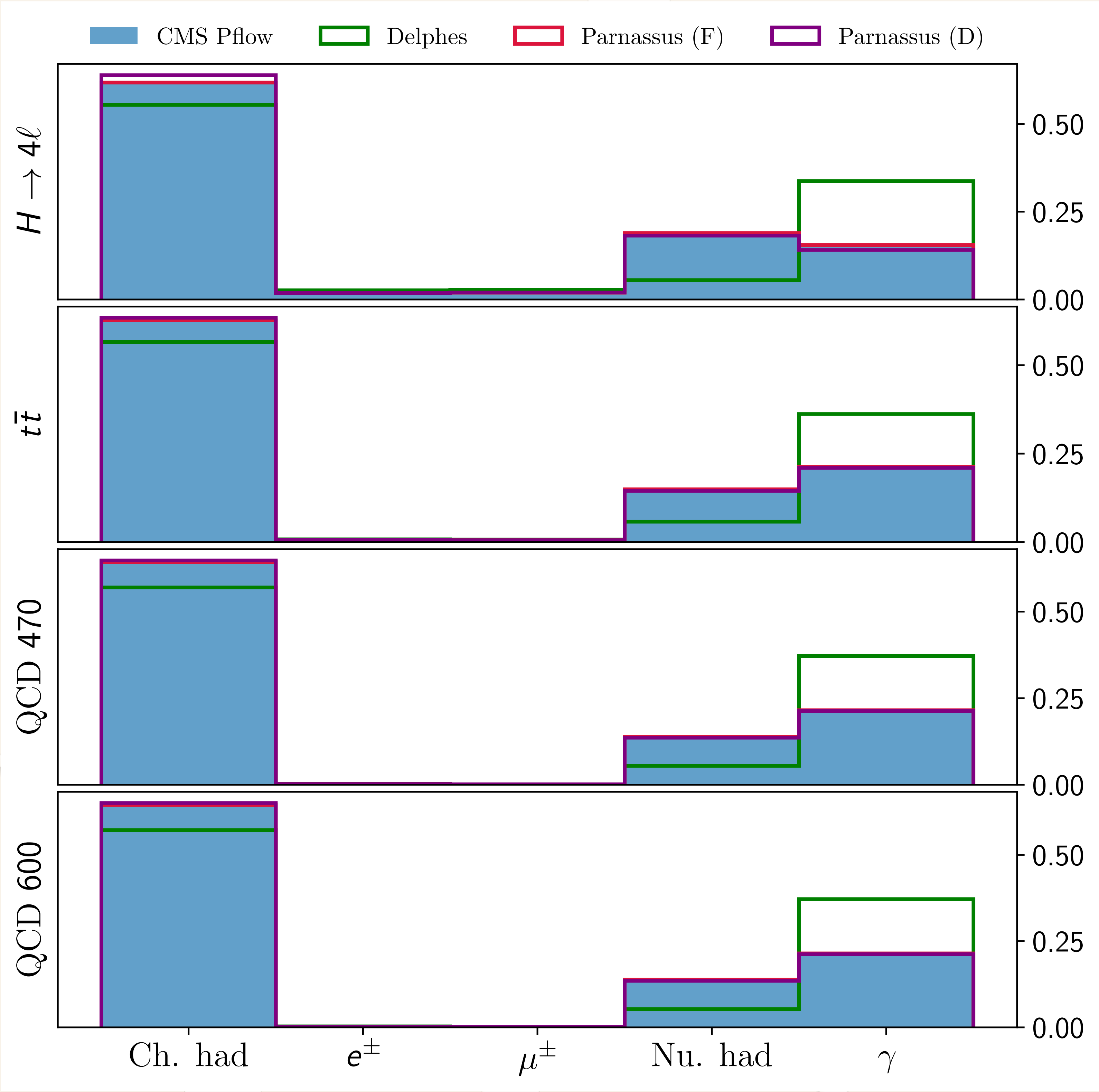
Summary plots



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

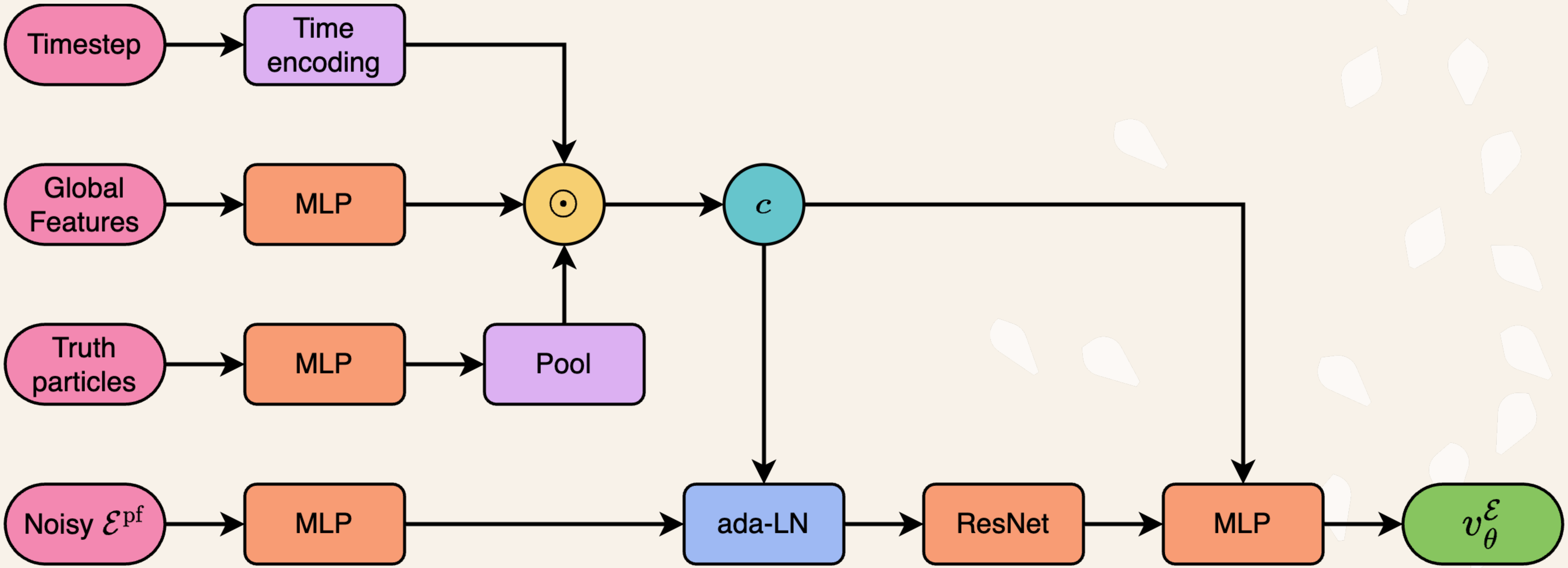
Future work directions

- 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

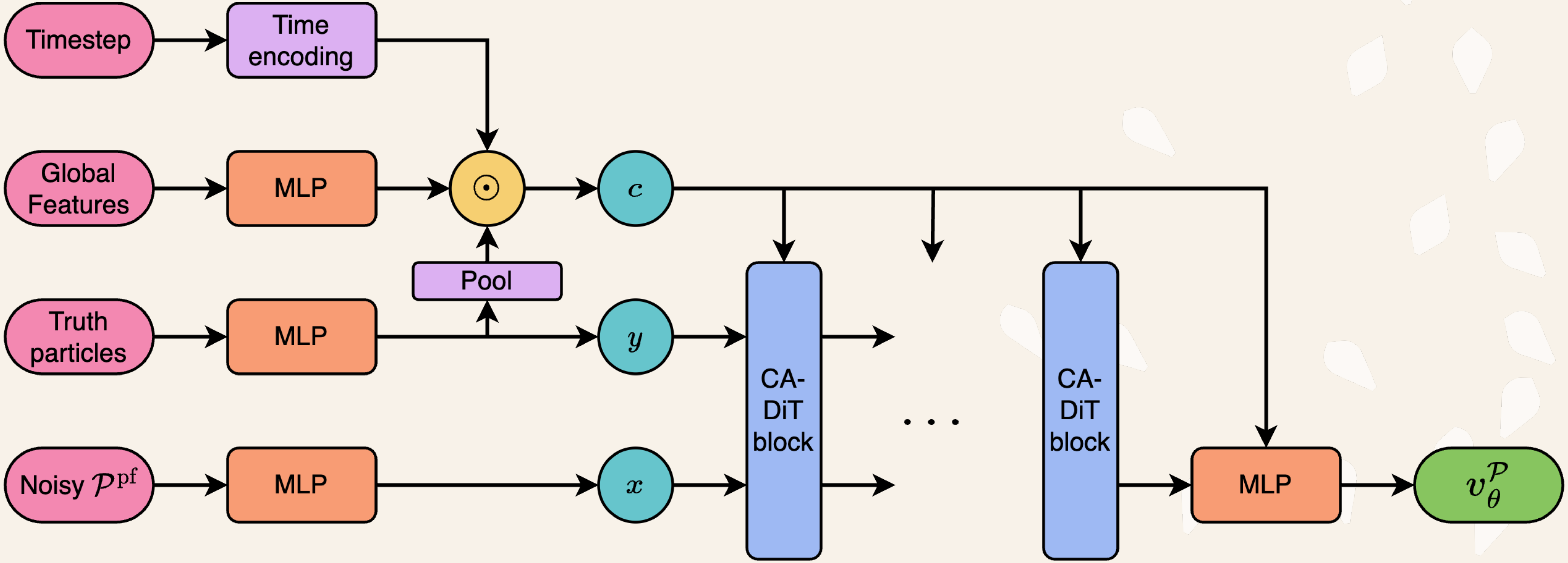
https://github.com/parnassus-hep/cms-flow-evt

Backup

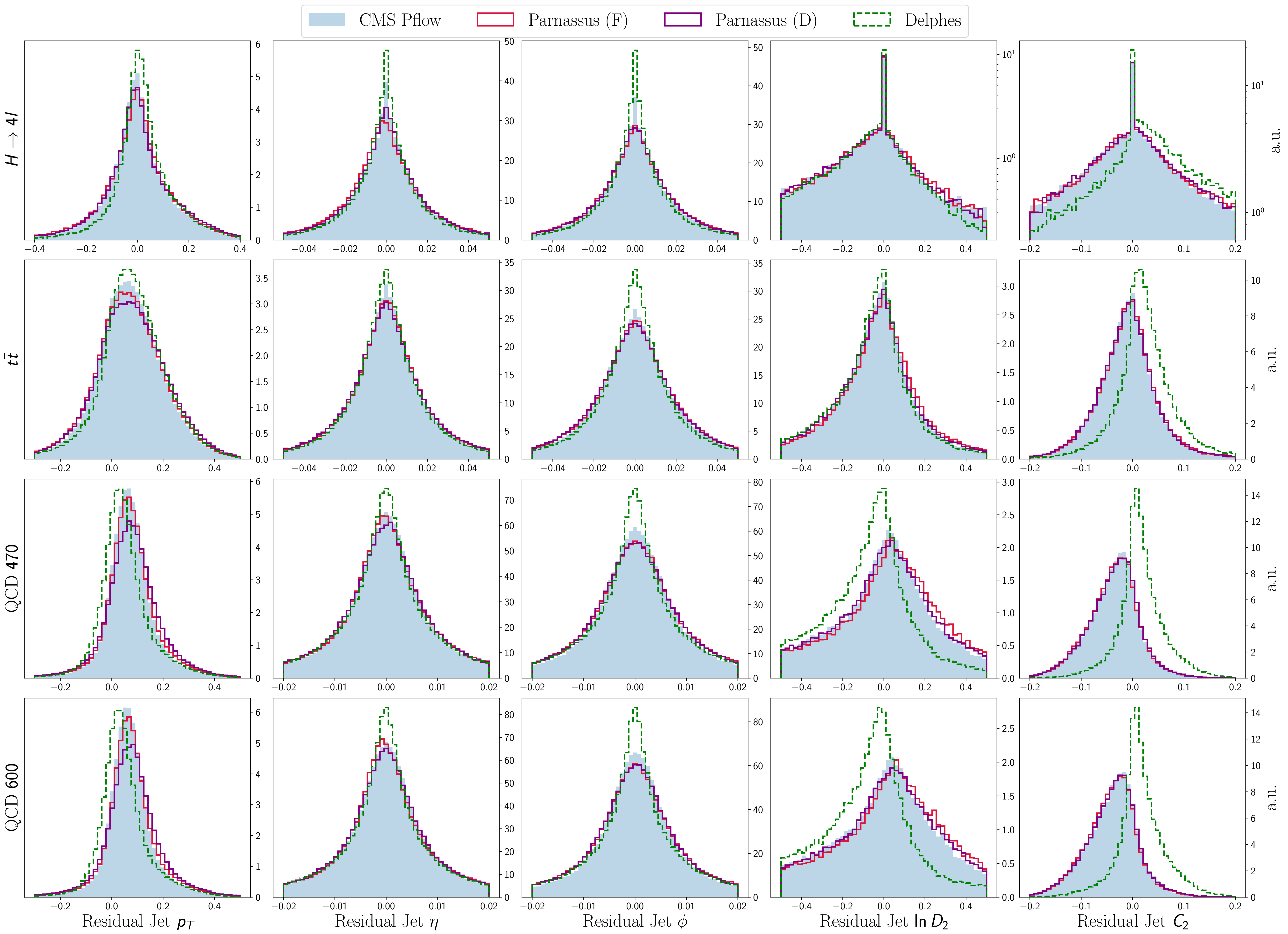
Event model architecture



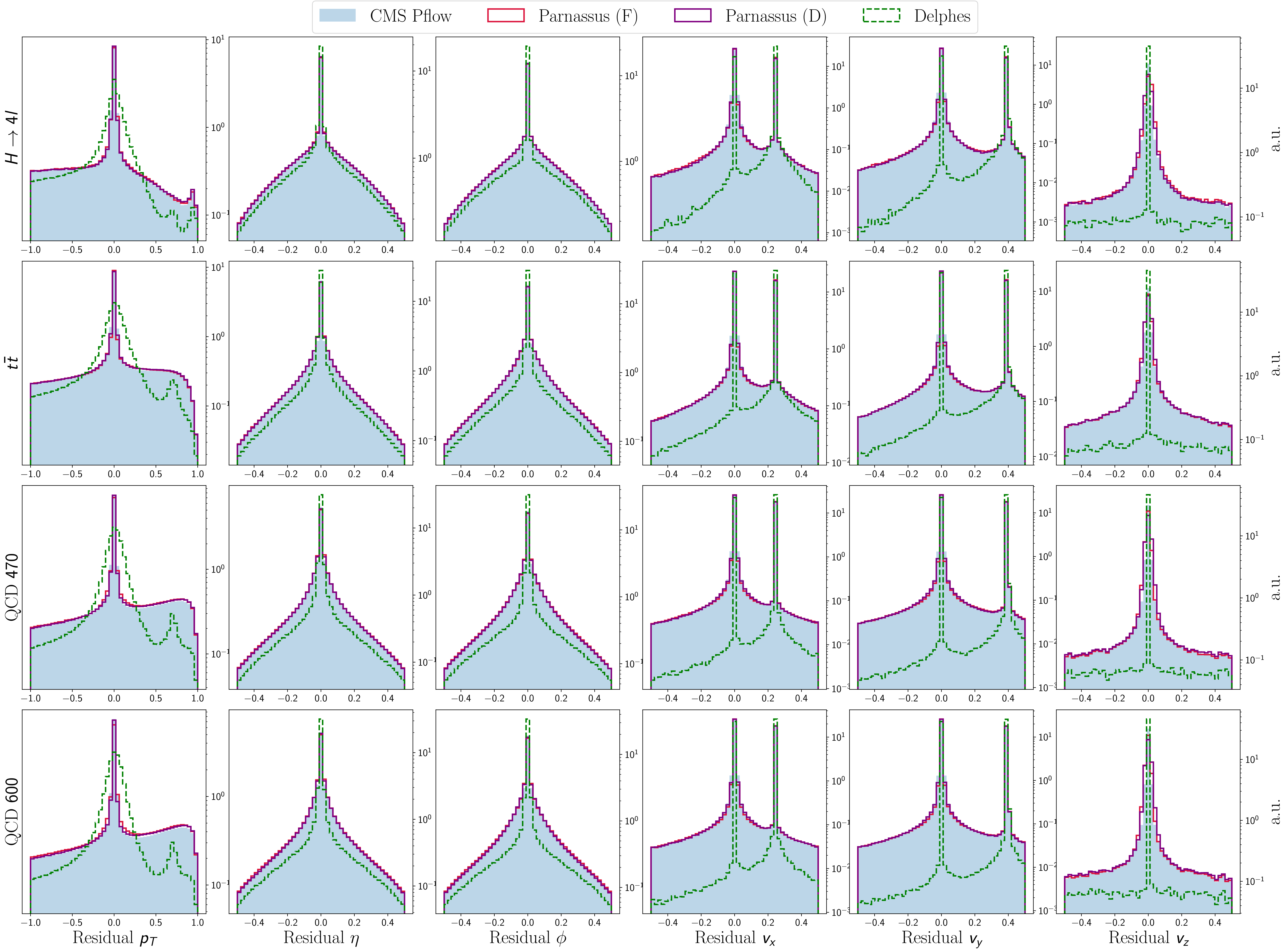
Particle model architecture



Jet residuals



Particle residuals



Class plots

CMS Pflow
Parnassus (F)
Parnassus (D)
Delphes
$H \to 4l$
$t\bar{t}$
QCD 470
QCD 600
Ch. had
$e^{\pm}$
$\mu^{\pm}$
Nu. had
γ
a.u.