Reconstructing Top-Quark Spin Correlations with Normalizing Flows

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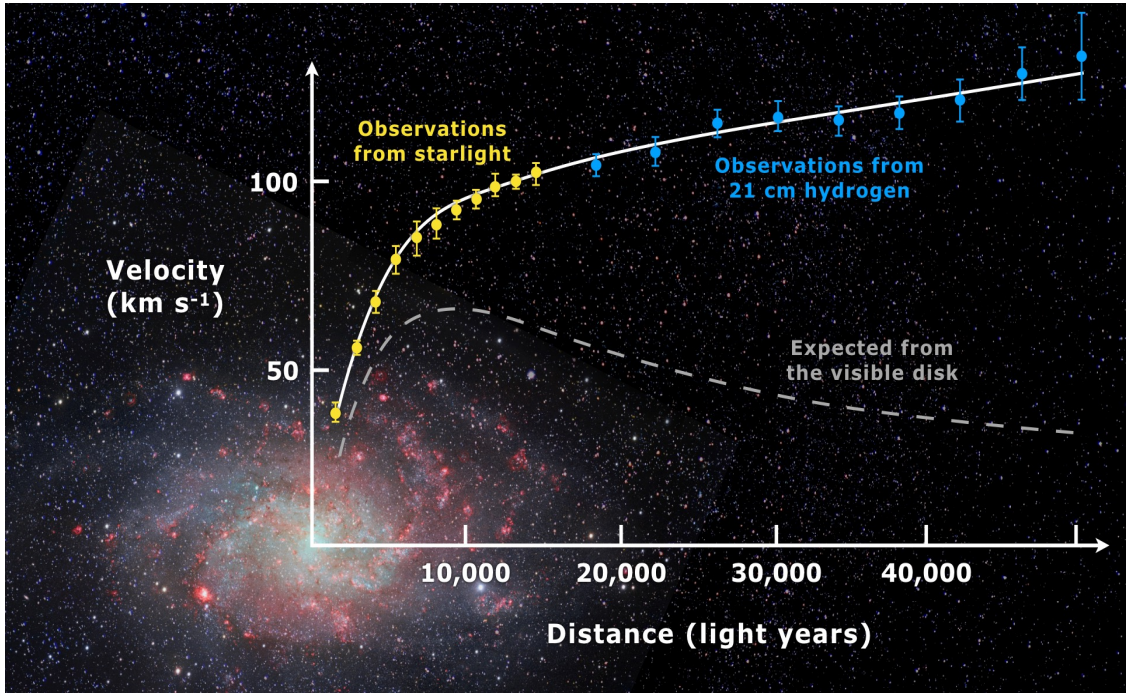
Introduction

- Compelling experimental observations indicate the presence of new, weakly interacting, neutral, massive particles that make up dark matter.
- The WIMP (weakly interacting massive particles) hypothesis is considered in this work

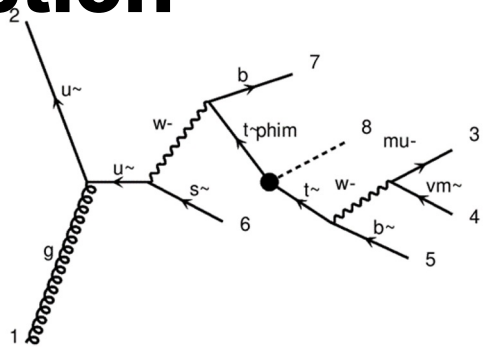


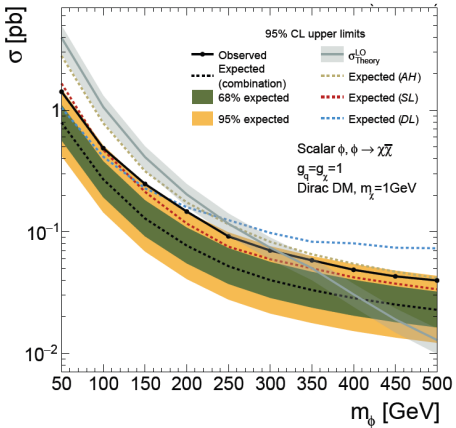
Single top-quark production

Dark matter is studied in the framework of the Simplified Model with a scalar mediator in a process of single top-quark production

$$L_\Phi = g_\chi \Phi \bar{\chi}\chi + \frac{g_v \Phi}{\sqrt{2}} \sum_f \left(y_f \bar{f} f \right)$$

- The scalar mediator does not affect the final state (particle composition), impacts only the kinematics, and is used as the most difficult option (pseudoscalar and vector mediators are easier to distinguish)
- Mediator and neutrino are not registered in the detector. How to separate their contributions?
- This separation is needed, for example, to reconstruct top-quark spin correlations, which is discussed in this work

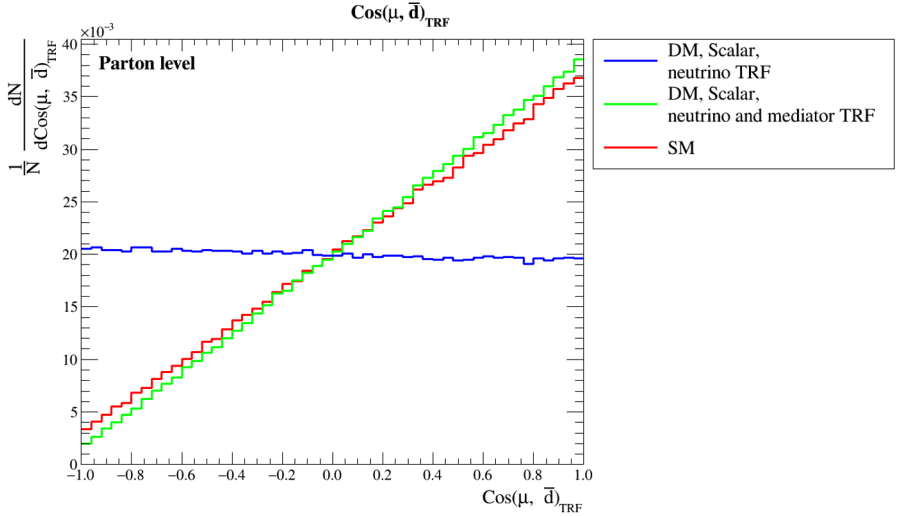




Current constraints on mediator mass [arxiv:1901.01553]

Top-quark spin correlations

- Correlations in SM $|M^2| \propto m_t^2 E_{\bar{d}} E_{\bar{\ell}} (1 + \cos\theta_{\bar{d}\bar{\ell}})$ [arxiv:9611367]
- Heavy scalar mediator does not change the polarization, however, it affects the top-quark rest frame;
- Calculations, conducted only with neutrino contributing to rest frame, result in changes in correlations, typical in SM(neutrino TRF)
- If the mediator is properly accounted for (neutrino and mediator TRF), then spin correlations are restored, as expected



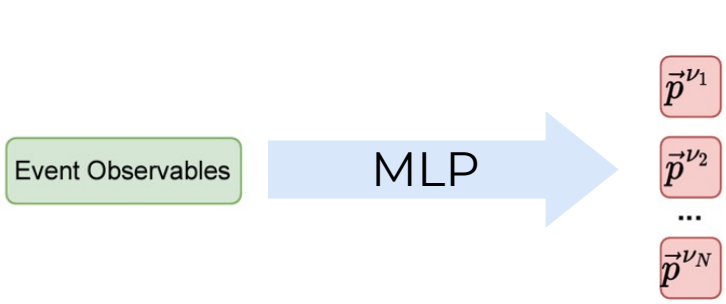
Reconstruction of spin correlations

- Analytical calculations based on kinematic constraints were conducted, however, they did not yield viable variables which would've simplified the analysis [arxiv:2406.07704]

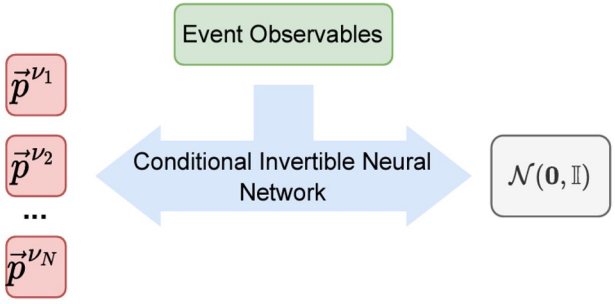
$$p_{\nu_z} = -\frac{\tilde{A} + p_{\nu_x} p_{1b_x} + p_{\nu_y} p_{1b_y}}{p_{1b_z}}$$

$$p_{\nu_x} = \pm\sqrt{dp_{\nu_y}^2 + ep_{\nu_y} + f} - \frac{\tilde{C}_x}{\tilde{C}_{x^2}} - \frac{\tilde{C}_{xy}}{\tilde{C}_{x^2}} p_{\nu_y}$$

- Alternative approach – applications of ML methods to directly reconstruct neutrino and mediator momenta – regression task
  - Baseline approach – Feed-forward Multi-layered perceptron (MLP)
  - Main proposed method – neural network based on Normalizing Flows [arXiv:2207.00664]



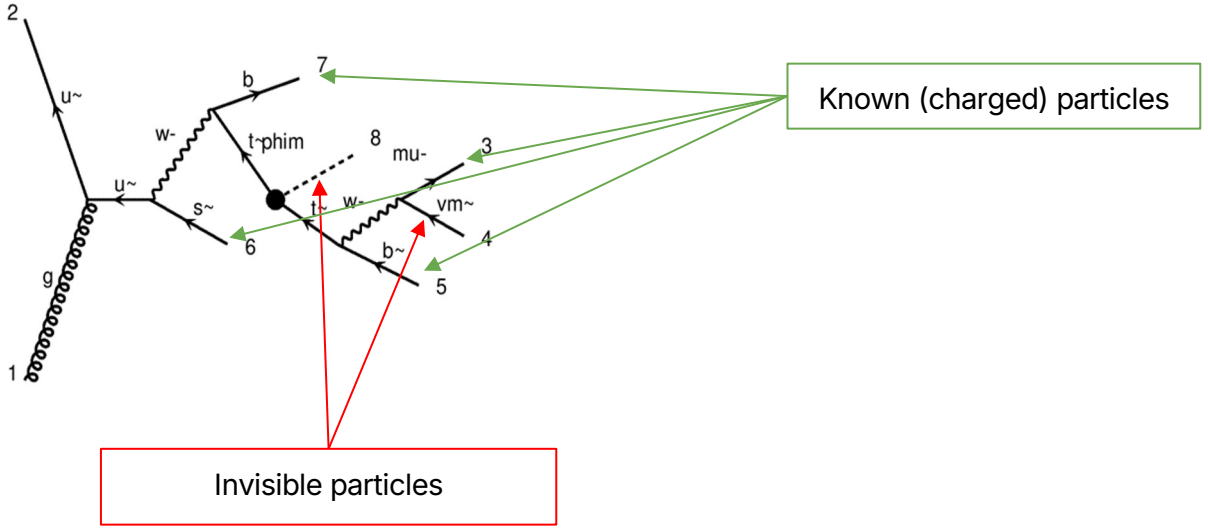
Dense feed-forward network



Normalizing Flows

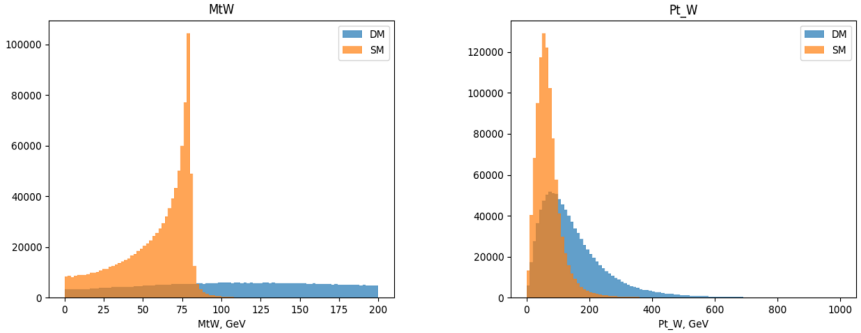
Dataset

- Source of data - Monte Carlo generators CompHEP and MadGraph5
- Model inputs – components of momenta of known particles (charged lepton, b-quark, light quark) and additional variables, constructed from these components
- Model outputs – momenta of invisible particles – neutrino and mediator

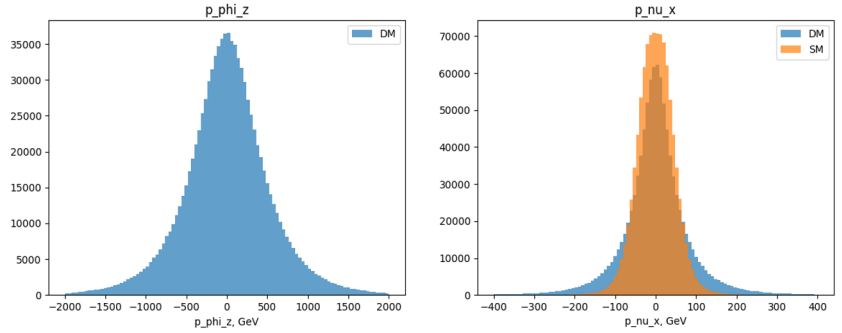


Dataset

- Components of mediator momenta for events in SM is set to 0 – universal approach
- NNs are trained on 1/1 mix of SM and DM events
- 40 input, 6 output variables



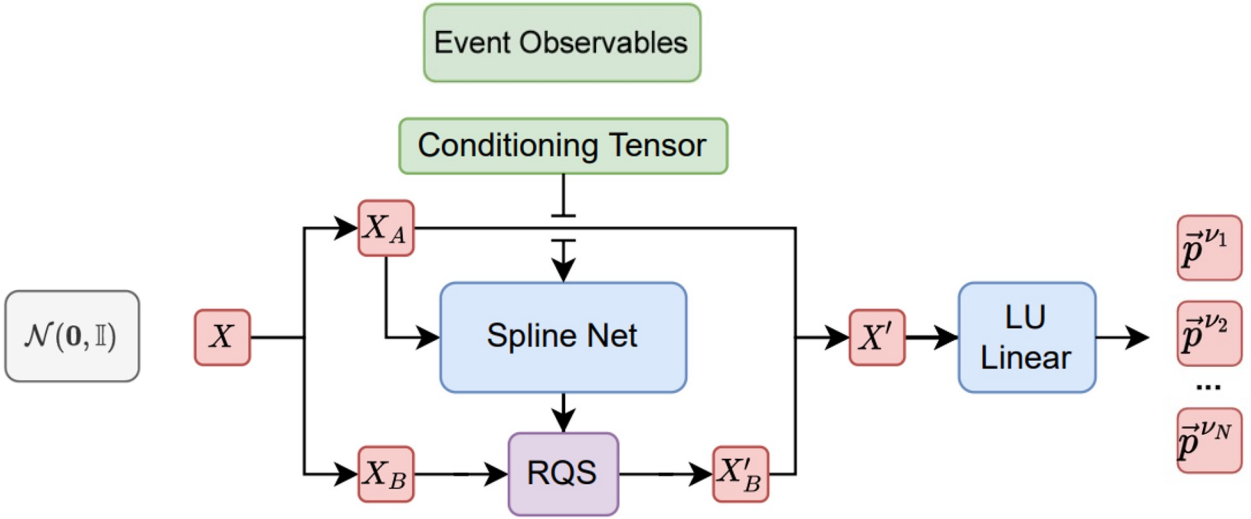
Typical distributions for input variables



Typical distributions for output variables

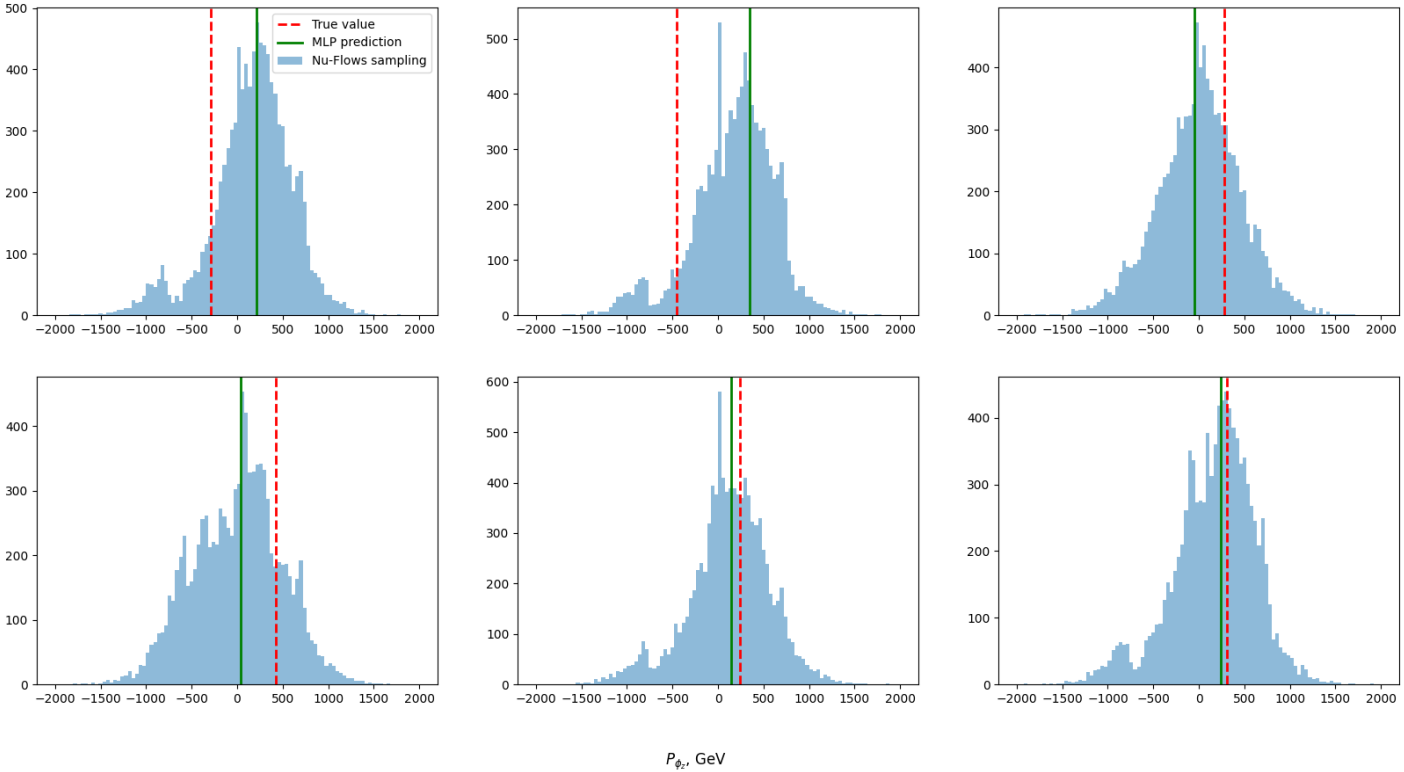
Models: Normalizing Flows

- Normalizing Flow architectures are based on learning a invertible transformation between a known distribution and a target variable. Unlike feed-forward neural networks, the output of Normalizing Flows is a probability distribution of the target variable, not a single value.
- A full multivariate probability density is used, allowing these models to better preserve dependencies between variables.



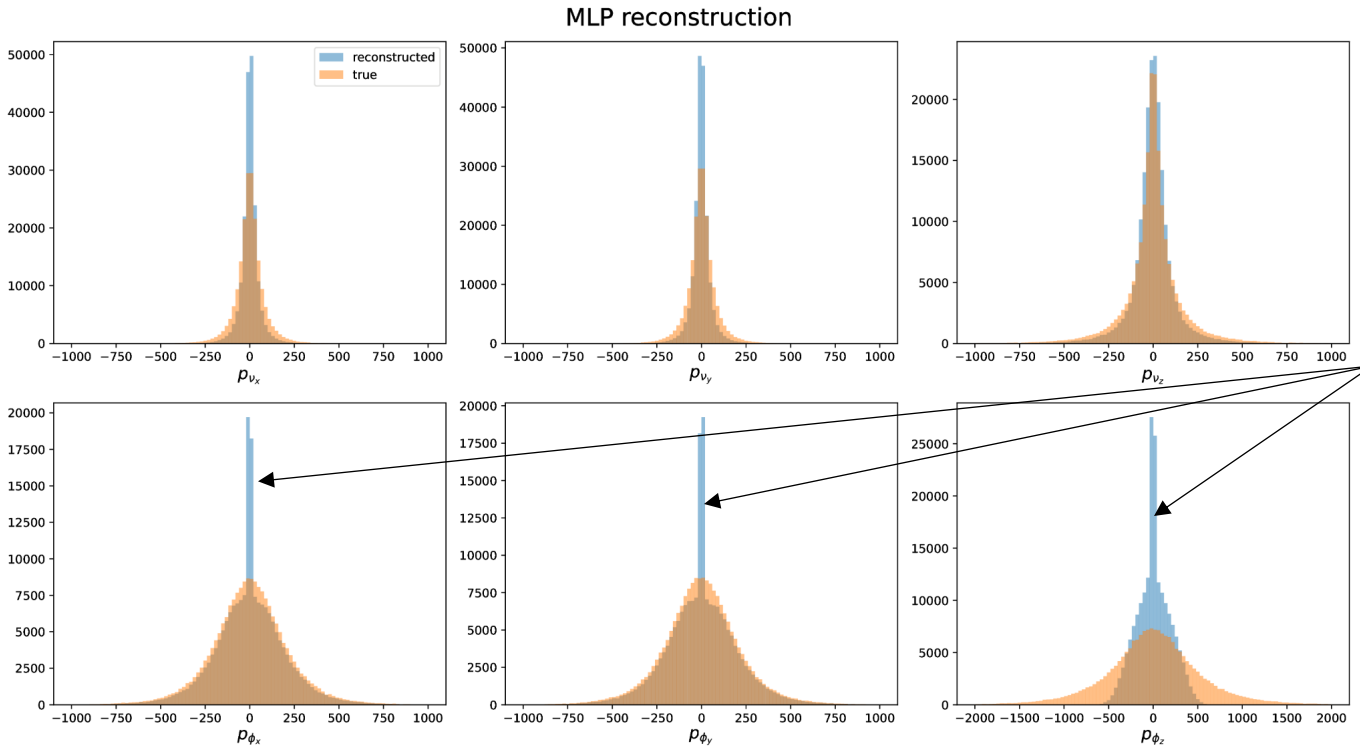
ν-Flows layer block (details in arXiv:2207.00664)

Results: Normalizing Flows



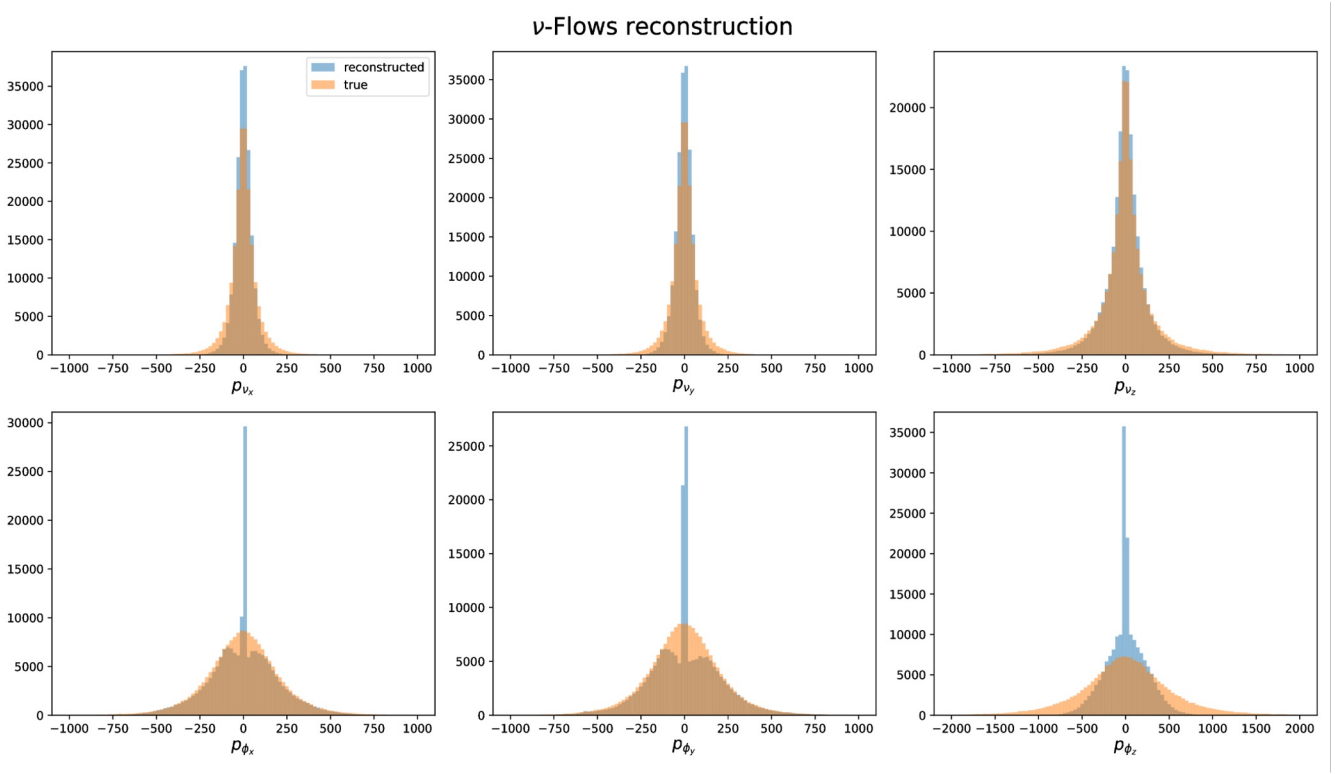
Reconstruction comparison for 6 individual events

Results: MLP



Reconstruction comparison for neutrino and mediator momenta in DM samples

Results: ν-Flows



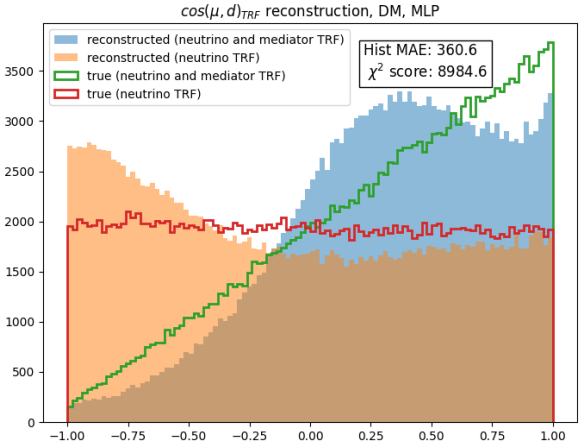
Reconstruction comparison for neutrino and mediator momenta in DM samples

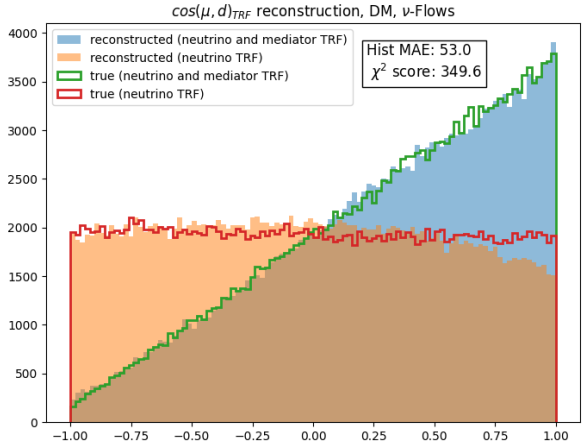
Results: target variable

Metrics:

- Hist MAE – Mean Absolute Error, but applied not to raw momenta, but to histograms of target variables
- χ^2-score - χ^2 statistics, calculated on histograms

MLP





ν-Flows

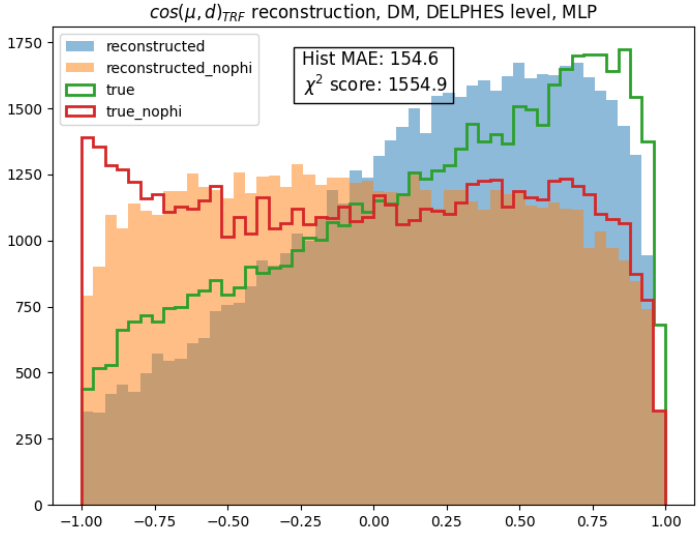
Reconstruction comparison for different NN architectures

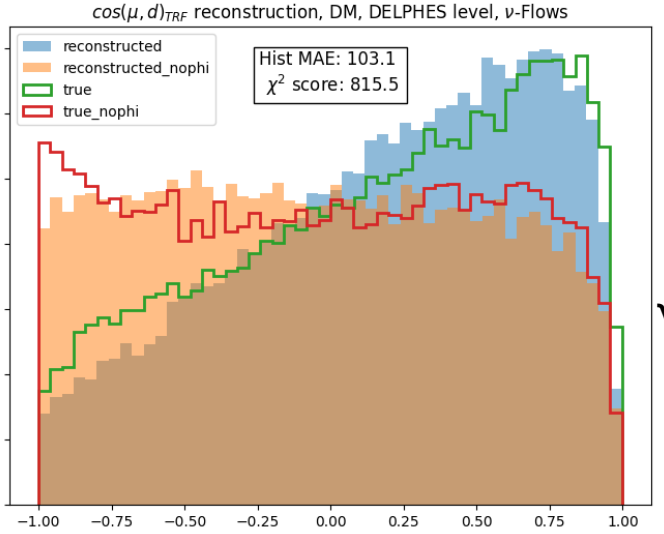
Results: DELPHES

In order to measure detector-level performance:

1. All events were hadronized in Pythia8
2. Detector response was simulated using the parametric approach in DELPHES framework with the CMS detector profile

MLP



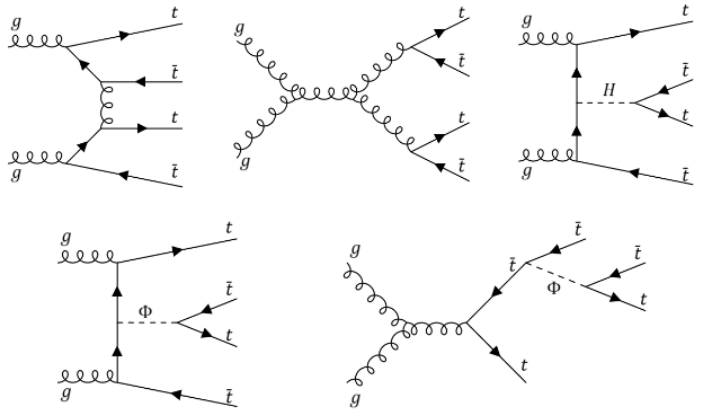


ν-Flows

Reconstruction comparison for different NN architectures

Prospects: 3 and 4 top-quarks

- In future research, it is planned to adapt Normalizing Flows for the reconstruction of spin correlations in three- and four-top quark production processes.
- For these purposes, methods for resolving combinatorial ambiguities in the association of resonances and their decay products must be implemented.



Conclusion

- In this study, top quark production processes involving a dark matter mediator have been analyzed within the framework of Simplified Models. A novel angular variable, based on spin correlations, has been introduced, enabling significant discrimination between Standard Model and dark matter processes.
- A new reconstruction method utilizing the Normalizing Flows architecture has been developed, and high performance in reconstructing the proposed angular variable has been demonstrated.
- These findings underscore the potential of advanced machine learning techniques for the reconstruction of spin correlations, and provide a foundation for further research in this area.