# Particle Transformer for $\tau$ lepton pair invariant mass reconstruction for the $HH \rightarrow b\bar{b}\tau^{+}\tau^{-}$ CMS analysis

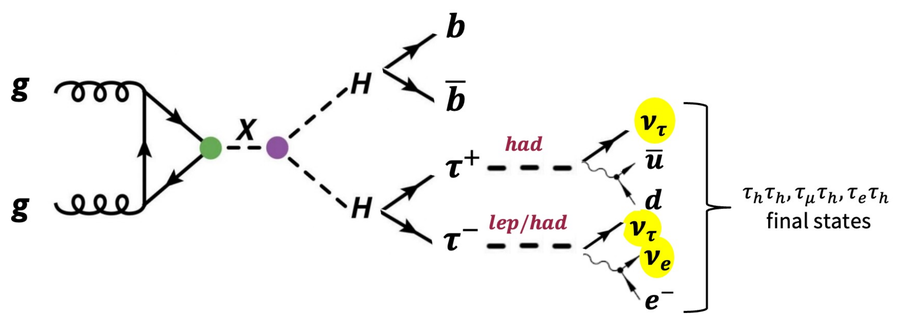

Valentina Camagni [13], Simone Gennai [3], Pietro Govoni [13], Marco Paganoni [13], Andrea Biancini [2]

[1] Dipartimento di Fisica G.Occhialini, Università di Milano Bicocca, Italy
[2] Dipartimento di Informatica, Sistemistica e Comunicazione, Università di Milano Bicocca, Italy
[3] INFN - Sezione di Milano Bicocca, Italy


## Introduction

- One of the most interesting channels to probe theories beyond the Standard Model at LHC, is the production of a new massive particle, that decays into pairs of Higgs Bosons (HH) which, in turn, decay into a pair of $b$-quarks and a pair of $\tau$ leptons ([1])
- A fundamental discriminant variable to separate HH signal from the backgrounds is the invariant mass of the di-$\tau$ system ($m_{\tau\tau}$), which can be reconstructed starting from the decay products of each $\tau$ lepton. However, the presence of neutrinos in the final state determines a lack in terms of energy which leads to an underestimation of the invariant mass itself
- The current used algorithm to reconstruct the $m_{\tau\tau}$ variable in CMS is SVFit [2] that, based on a maximum likelihood approach, predicts the most probable kinematics of the neutrinos taking as inputs the visible decay products of each $\tau$ lepton and the Missing Transverse Momentum (MET)
- The relevant computation time combined with a reduced resolution of the reconstructed mass by SVFit opens opportunities for new **ML-based strategies**

*This poster propose a new technique: a deep learning model – Particle Transformer (ParT) – to estimate the four-momenta of the neutrinos involved in the decay of the di-$\tau$ system for a high-resolution reconstruction of the corresponding invariant mass*




***SIGNAL:*** BSM Resonant HH production via gluon-gluon fusion (ggF)

$$M_X \in [250\ GeV\ - 550\ GeV]$$

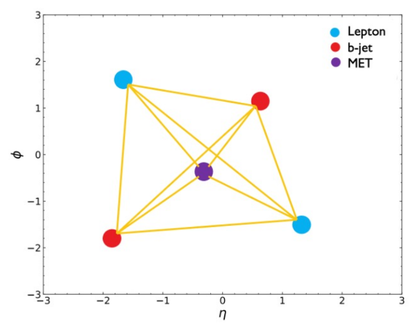
***BACKGROUND:*** Drell-Yan, $t\bar{t}$ events

## ParT [3]

- ***Representation of the input***

Each collider event has been modelled as a graph in which each node represents a visible decay product in the final state while the links correspond to the connection between them, described through pair-wise features

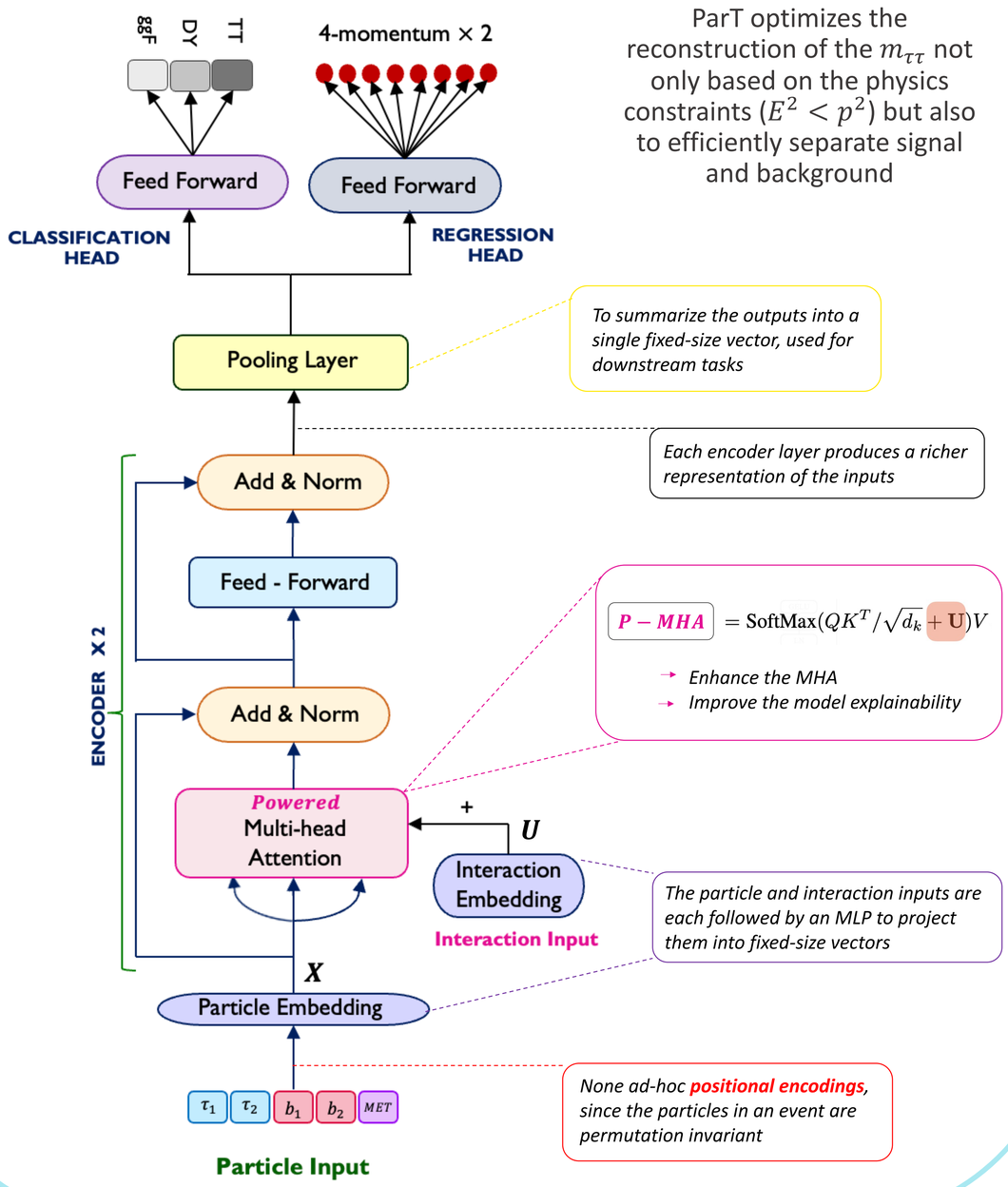
↳ ParT is a Graph Neural Network (GNN)




**Particle Input** → NODES → Array (5, 12) → $(p_x, p_y, p_z, E, p_T, \eta, \phi, dm, bjet^{dF}, bjet^{b}_{pNet}, bjet^{c}_{pNet}, bjet^{uds}_{pNet})$

**Interaction Input** → EDGES → Array (5, 5, 4) → $(\Delta, k_T, z, m^2)$

- ***The Model***




$$P-MHA = \mathrm{SoftMax}(QK^T/\sqrt{d_k} + \mathrm{U})V$$

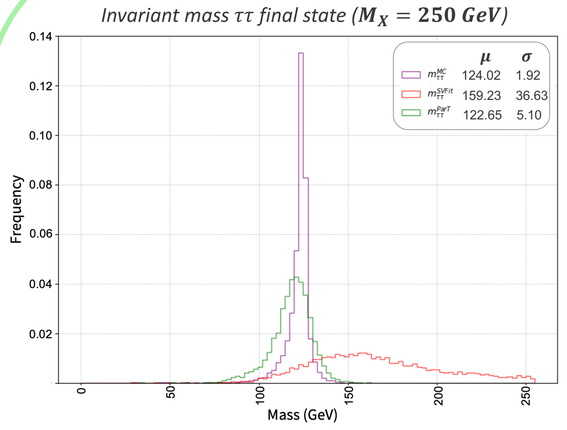
→ *Enhance the MHA*
→ *Improve the model explainability*

ParT optimizes the reconstruction of the $m_{\tau\tau}$ not only based on the physics constraints ($E^2 < p^2$) but also to efficiently separate signal and background

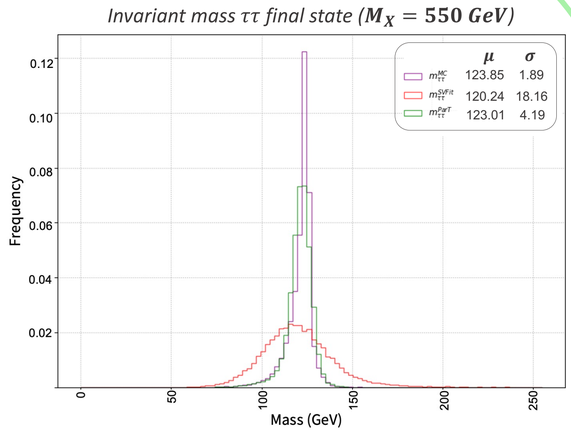
## Regression results

***$\mu$ and $\sigma$ from a Gaussian fit of $m_{\tau\tau}$***

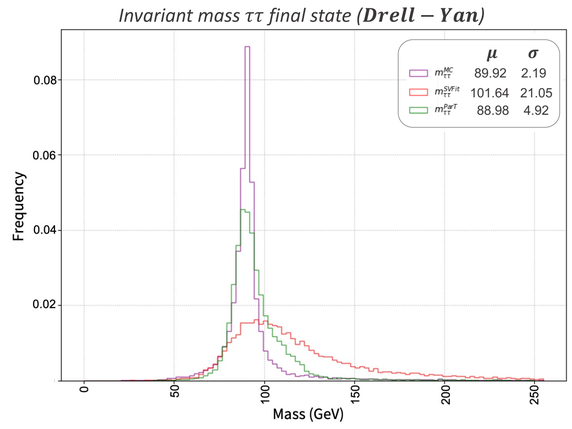
*Invariant mass ττ final state ($M_X = 250\ GeV$)*



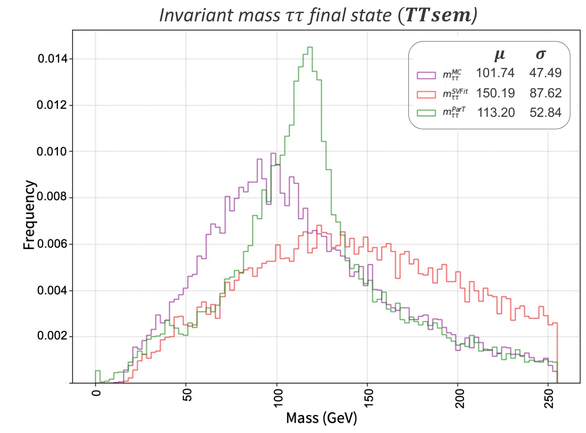

*Invariant mass ττ final state ($M_X = 550\ GeV$)*




*Invariant mass ττ final state ($Drell-Yan$)*



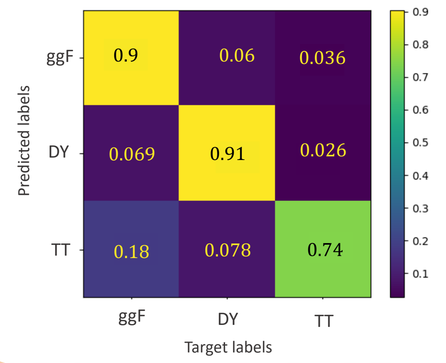

*Invariant mass ττ final state ($TTsem$)*




*With respect to SVFit performance:*

- ✓ The mean value of the $m_{\tau\tau}^{ParT}$ distribution is much closer to the target one $\mu(m_{\tau\tau}^{MC})$ (computed combining the reconstructed $\tau$ leptons and gen-level neutrinos)
- ✓ The $m_{\tau\tau}^{ParT}$ distribution has a smaller standard deviation allowing for a more resolute $m_{\tau\tau}$ reconstruction
- ✓ ParT requires much less computation time: $O(10^{-3}s)$ vs. $O(1s)$ of SVFit

## Confusion matrix




- The 90% and 91% of ggF and DY events, respectively, are correctly identified
- The $t\bar{t}$ sample is the one that is recognized with a lower precision, with a considerable % of events incorrectly classified as signal
- The accuracy in classifying signal events improves with the increasing of $M_X$

## Conclusions

- The mass reconstruction of the di-$\tau$ system resulting from a Higgs boson decay plays an important role in searches of new massive particles decaying into two Higgs bosons
- New and computationally less expensive methods with respect to the current used SVFit algorithm for the $m_{\tau\tau}$ reconstruction are under study: the Transformer architecture has demonstrated to be a competitive approach
- To generalize the obtained results, it would be necessary to train ParT also for other production processes and the fully leptonic decay channels of the $\tau$ leptons

## References


[1] CMS collaboration. "Search for nonresonant Higgs boson pair production in final state with two bottom quarks and two tau leptons in proton-proton collisions at s= 13 TeV." Physics Letters, Section B: Nuclear, Elementary Particle and High-Energy Physics 842 (2023): 137531.

[2] Bianchini, Lorenzo, et al. "Reconstruction of the Higgs mass in H→ ττ events by dynamical likelihood techniques." *Journal of Physics: Conference Series*. Vol. 513. No. 2. IOP Publishing, 2014.

[3] Qu, Huilin, Congqiao Li, and Sitian Qian. *arXiv: Particle Transformer for Jet Tagging*. No. arXiv: 2202.03772. 2022.