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Department of Physics

Comparing quantum and classical machine learning for Vector Boson Scattering background reduction at the Large Hadron Collider

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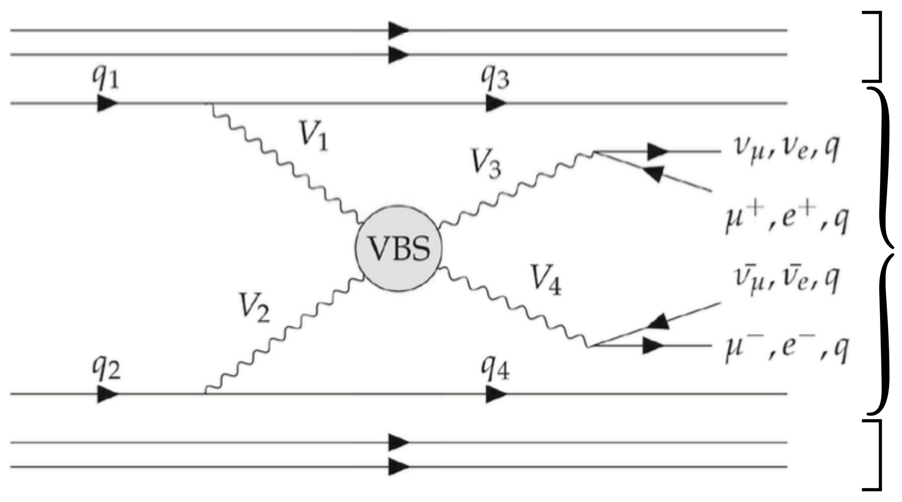
ABSTRACT

We report on a consistent comparison between techniques of **quantum** and **classical machine learning** applied to the classification of signal and background events for the **Vector Boson Scattering (VBS)** processes, studied at the Large Hadron Collider installed at the CERN laboratory [1]. Quantum machine learning algorithms based on variational quantum circuits are run on freely available **quantum computing hardware**, showing very good performances as compared to deep neural networks run on classical computing facilities. In particular, we show that such kind of quantum neural networks is able to correctly classify the targeted signal with an Area Under the characteristic Curve (AUC) that is very close to the one obtained with the corresponding classical neural network, but employing a much **lower** number of **resources**, as well as **less variable data** in the training set. Albeit giving a proof-of-principle demonstration with limited quantum computing resources, this work represents one of the first steps towards the use of near term and noisy quantum hardware for practical event classification in High Energy Physics experiments.

PROBLEM

Vector Boson Scattering events (classification label $z = 1$)

A leading-order representation of the VBS between two generic vector bosons (V1 and V2) given in terms of Feynman diagrams [2]. Each boson is irradiated from a quark of one of the two protons participating in a LHC collision (the three valence quarks of each proton are represented as horizontal lines). The **products are leptons** (neutrinos, muons, electrons or tau particles) and **quark jets**.



Background events ($z = 0$)

W bosons and jets production,
two vector bosons (VV),
three vector bosons (VVV),
Drell-Yan,
single top and $t\bar{t}$,
Vector Boson Fusion (VBF),
vector boson with a real (Vγ) or virtual (Vγ*) photon

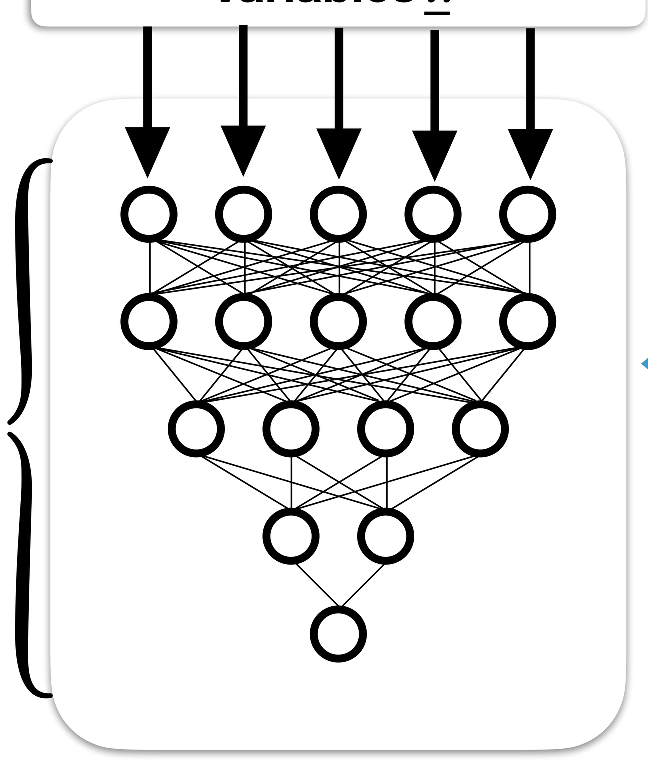
Same products of VBS but with **thousands times greater** cross section

LEARNING APPROACHES

Deep Neural Network (DNN)

Index running over the events of the training set

Variables $\underline{x}^i$

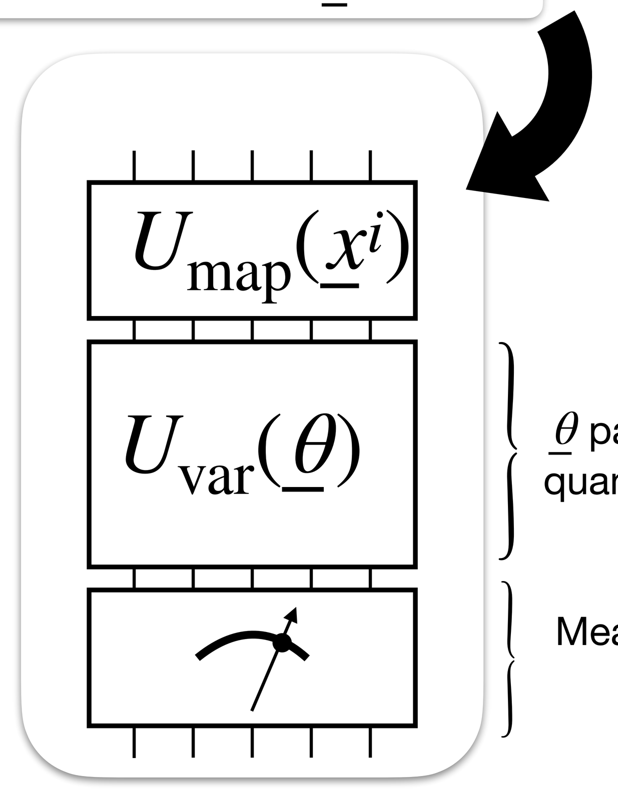


Output $y^i \in (0,1)$

Quantum Machine Learning (QML)

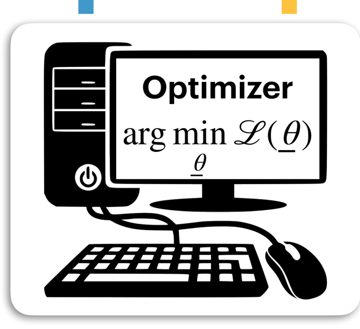
Index running over the events of the training set

Variables $\underline{x}^i$



Output $y^i \in (0,1)$

Update parameters $\underline{\theta}$

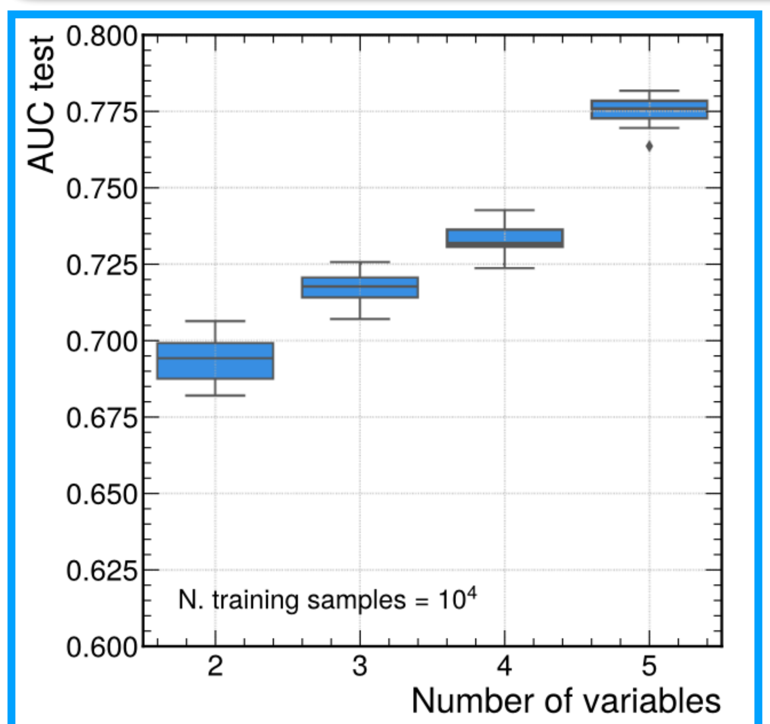


Cross Entropy loss function
$\mathscr{L}(\underline{\theta}) = -\Sigma_i z^i \ln(y^i)$

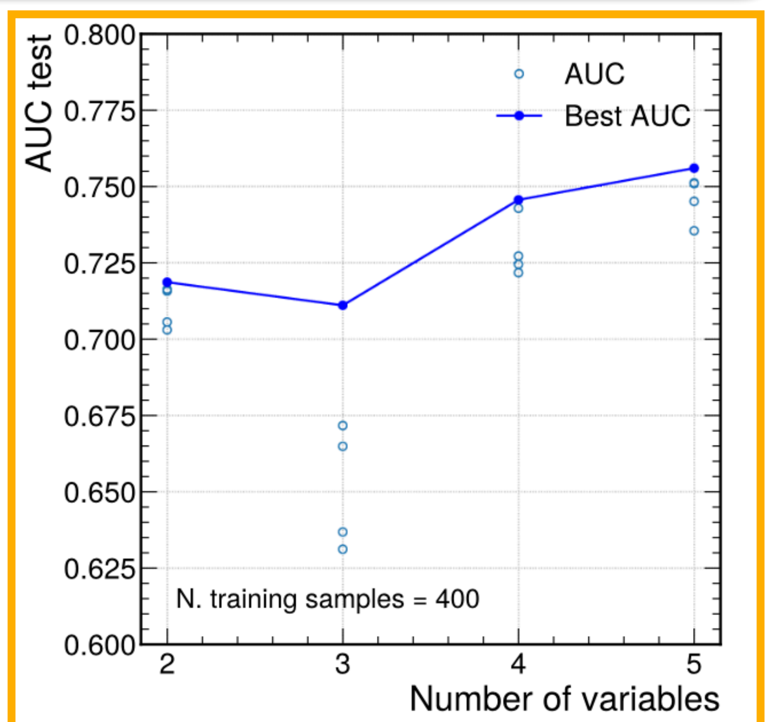
RESULTS

Variables dependence

Results from (a) classical DNN and (b) QML classification methods, respectively, reporting the AUC as a function of the **number of variables** associated to each event [1]. Each classical result has been obtained varying the DNN architecture. Differently, the results corresponding to any fixed number of variables concern the same quantum circuit that was trained and tested different times. The best performance associated to each quantum circuit is explicitly highlighted in the plot.



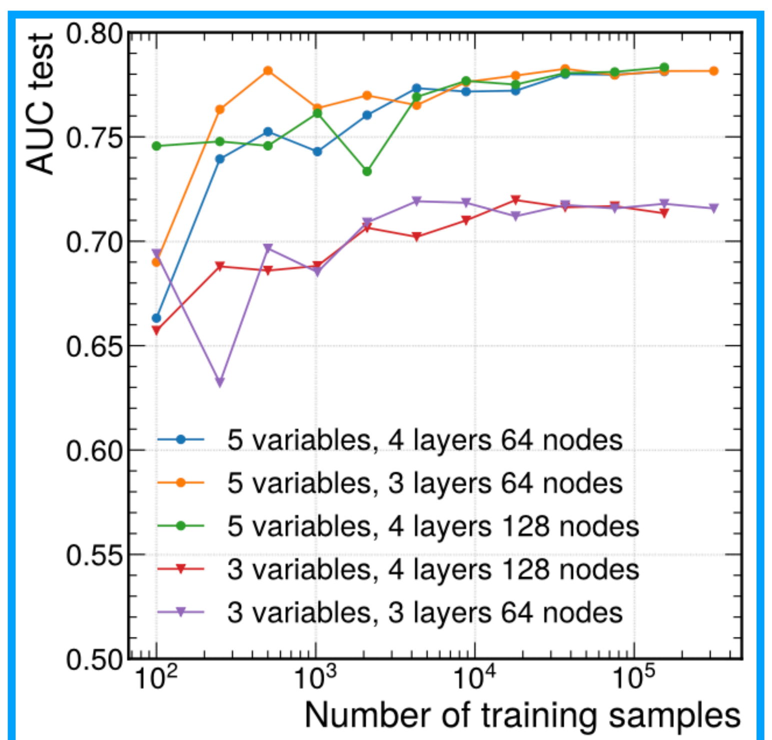
(a) Classical DNN



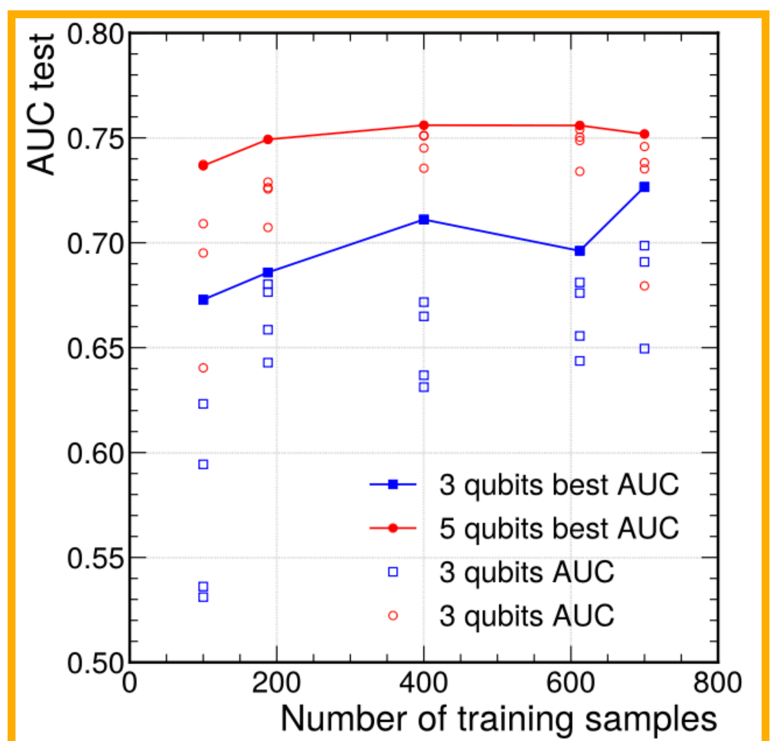
(b) QML

Training set dependence

Results from (a) classical DNN and (b) QML classification methods, respectively, quantified using the AUC and obtained with **different number of events** during the training phase [1]. Each color is associated to a different structure of the classical DNN or the QML approach. The best performance associated to each quantum circuit is explicitly highlighted in the plot.



(a) Classical DNN



(b) QML

CONCLUSIONS

We have reported on a systematic comparison between classical and quantum machine learning approaches applied to a signal and background classification problem example from the collider physics domain, studying the Vector Boson Scattering processes. We have shown that a hybrid quantum-classical approach based on parametrized quantum circuits is able to reach **performances similar** to classically trained deep neural networks. Moreover, it has been shown that the QML algorithm requires a **limited number of variables** to be successfully trained, still giving good classification performances as compared to the fully classical approach. Hence, this hybrid algorithm can be envisioned for actual applications to the problem of HEP events classification already at the level of current **noisy quantum hardware**.

BIBLIOGRAPHY

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[2] Covarelli R, Pellen M, Zaro M (2021) Vector-Boson Scattering at the LHC: unravelling the Electroweak sector. Int J Mod Phys A 36(16):2130009.