Probing an MeV-scale Scalar Boson in Association with a TeV-scale Vector-like Quark in the $U(1)_{T3R}$ BSM Extension from gg and $q\overline{q}$ Fusion Processes at the Large Hadron Collider using Machine Learning

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Motivating the $U(1)_{T3R}$ BSM Extension

The Incompleteness of the Standard Model

- The Standard Model (SM) of particle physics is a successful theory to explain strong, weak, and electromagnetic interactions.
- Recently, there has been interest in beyond-the-Standard Model (BSM) physics involving new low-mass matter and mediator particles as:
  - Mediators of dark matter interactions.
  - Solutions to lepton mass hierarchy and the muon $g-2$ and B-meson anomalies.

A $U(1)_{T3R}$ Extension of the Standard Model

- For our study, we probe a $U(1)_{T3R}$ extension:
  - $U(1)_{T3R}$ is not connected to electric charge and only couples to right-handed SM Fermions.
  - The model in this formulation can address some of the aforementioned SM problems.

An Introduction to the $U(1)_{T3R}$ Model

New Fields and Particles

- Three new matter fields, a scalar and a left and right-handed fermion pair.
- A set of new vector-like quarks $(\chi_u, \chi_d, \chi_\mu, \chi_\nu)$ accessible at the LHC.
- A dark Higgs ϕ' and a massive dark photon A'.
- Our study focuses on the scalar boson ϕ' and the vector-like quark χ_u.

Contribution to the Lagrangian

The new vector-like quarks add the following interaction terms to the Lagrangian:

$$\mathcal{L} = \cdots - m_{\chi_f}\overline{\chi}_f\chi_f - \lambda_{fL} H(\chi_f P_L f_L) - \lambda_{fR}\phi'(\chi_f P_R f_R) - \lambda_{WL} W(\chi_f P_L f_L) - \cdots \tag{1}$$

Experimental Considerations and Previous Studies

Experimental Considerations

- The ϕ' particles can be very light at $\mathcal{O}(\text{MeV})$ or heavy at $\mathcal{O}(\text{TeV})$:
  - Mass scales below the electroweak scale have traditionally been difficult to probe at the LHC.
  - SM backgrounds dominate the phase space and are difficult to distinguish from signal.
- ATLAS and CMS Collaborations have excluded χ_u (more generally, T) with masses $m(T) < 1.3$ TeV, for the assumption $Br(T \to Ht) + Br(T \to Zt) + Br(T \to Wb) = 1$.
- Since our model introduces an accompanying light scalar boson ϕ', these limits can change depending on the χ_u branching fraction and ϕ' mass.

Previous Work

Previous phenomenology studies have looked at $\mathcal{O}(\text{MeV})$ ϕ' and the $\phi' \to \gamma\gamma$ decay channel.

Our Novel Analysis Strategy

Signal Production

- Sensitivity to $\mathcal{O}(\text{MeV}) - \mathcal{O}(100\text{GeV})$ scalars requires production mechanisms that create boosted topologies.
- For this study, we target $\chi_u t$ and gg fusion topologies that lead to:
    - A boosted $\phi' \to \mu^+\mu^-$
    - $t \to bjj$
    - $\chi_u \to b\mu\nu$
- Hence, our final state contains:
    - A boosted top tagged system which decays hadronically.
    - 3 muons.
    - Large MET.
    - b-tagged jets.

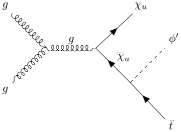

Figure 1: Representative Feynman Diagram for gg Fusion.

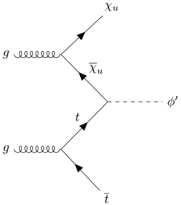

Figure 2: Representative Feynman Diagram for $\chi_u t$ Fusion.

Standard Model Backgrounds

Background Determination

Several SM background processes were considered. The two most important backgrounds are $t\bar{t}$ with Z/γ radiation and diboson with $b\bar{b}$ radiation.

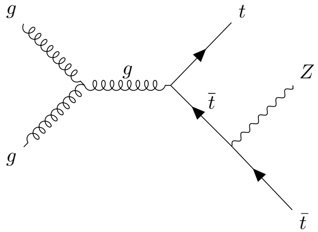

Figure 3: Representative Feynman Diagram for Background Production.

Process Information	**Cross Section [pb]**
$pp \to t\bar{t}\mu^+\mu^-, (t \to W^+ b, W^+ \to jj), (\bar{t} \to W^- \bar{b}, W^- \to \mu^- \nu)$	0.002574
$pp \to b\bar{b}\mu\mu\mu\nu$	0.0004692

Table 1: A summary of the dominant Standard Model backgrounds and their respective cross sections calculated using code with $n = 1000000$ events.

Simulating Signal and Background Events

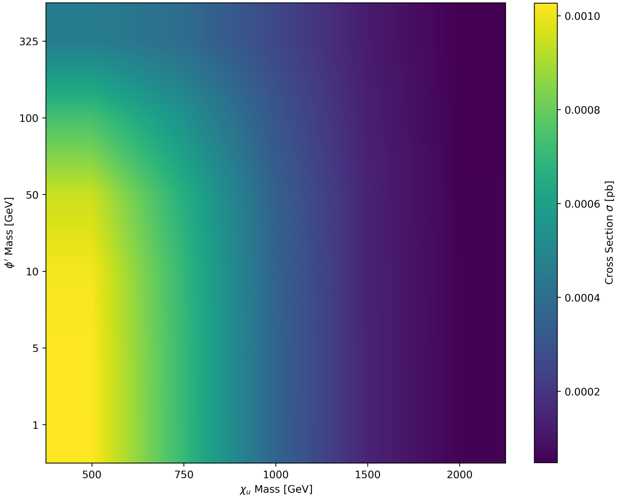

Figure 4: Cross Section vs. ϕ' and χ_u Masses.

Signal and Background Simulation

Samples were produced using:

- `MadGraph5` for event generation.
- `Pythia8` for parton showering and hadronization.
- `Delphes` for smearing and detector effects.

To ensure sufficient signal statistics for our machine learning workflow, we simulate 1 million events. The decay widths for χ_u and ϕ' are $\mathcal{O}$(GeV). The smoothed cross section as a function of ϕ' and χ_u masses is shown in Figure 4. The $\chi_t t \phi'$ and $\phi \mu^+ \mu^-$ couplings are assumed to be unity.

Kinematics: Analysis using MadAnalysis Code

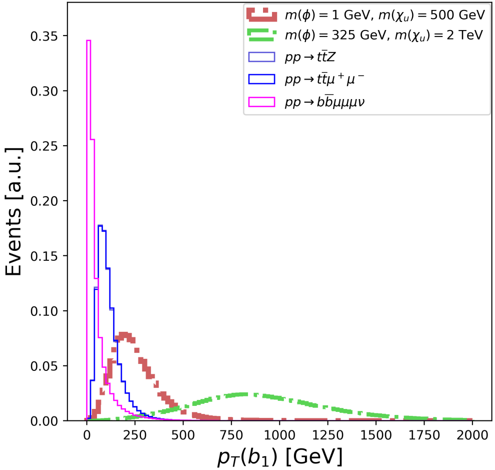

Figure 5: $p_T(b_1)$ Kinematic Distribution

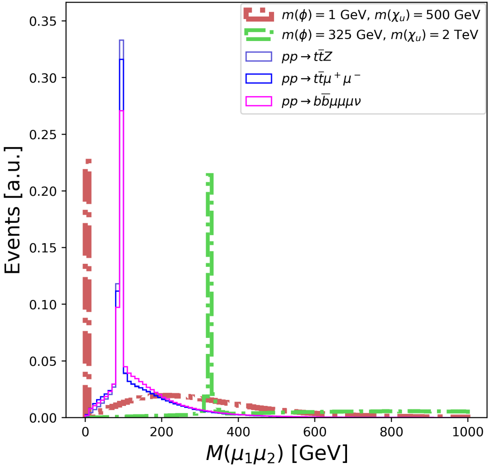

Figure 6: $M(\mu_1\mu_2)$ Kinematic Distribution

Kinematics: Analysis using MadAnalysis Code

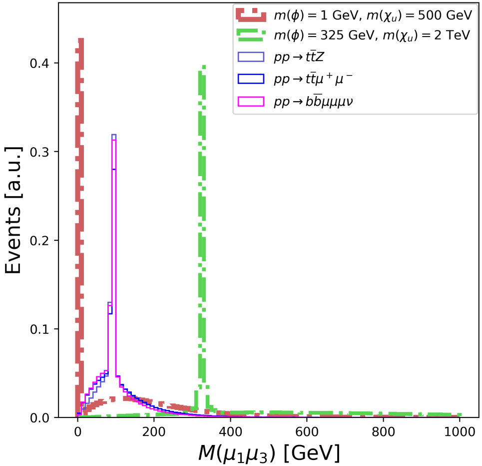

Figure 7: $M(\mu_1\mu_3)$ Kinematic Distribution

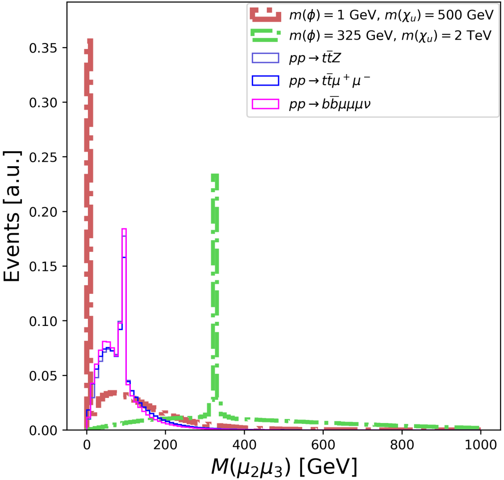

Figure 8: $M(\mu_2\mu_3)$ Kinematic Distribution

Machine Learning: Motivation and Workflow

Motivation for Machine Learning (ML)

- ML offers sizable advantages over traditional event classification methods.
- In particular, machine learning algorithms consider all kinematic variables concurrently. This allows them to reverse the high-dimensional space of event kinematics and enact sophisticated selection criteria.
- This makes them ideal for hep-ph applications.

Our Machine Learning Workflow

- The analysis of signal and background events is performed using ML algorithms.
- In particular, we consider various deep neural network (NN) architectures and a gradient boosted tree (BDT) classifier.

Machine Learning: Workflow Details

Feature Generation

A MadAnalysis Expert Mode (C++) script is used to generate a CSV file from the event kinematics in MadGraph LHE files. This data was used to train several ML models.

We consider three NNs of varying depth and a BDT algorithm using a 90-10 train-test split. The training was performed on an Nvidia A100 GPU using `PyTorch` and `XGBoost` libraries for the NNs and BDT, respectively. The results are summarized in Table 2.

Details of the ML Models

- BDT: A boosted decision tree with $\eta = 0.3$, $\gamma = 0$ and $\texttt{max\_depth} = 64$.
- NN1: 3 fully connected (FC) layers of widths 32, 64, and 1.
- NN2: A NN with 4 FC layers of widths 64, 128, 128, and 1.
- NN3: A NN with 5 FC layers of widths 64, 128, 512, 128, and 1.

All neural networks used a learning rate of 0.01 with an SGD optimizer and were trained for 100 epochs with a batch size of 8192. All layers used a ReLU activation function except for the final layer in each network, which used a sigmoid activation.

Machine Learning: Results

Model	Train/Test Accuracy	Training Time
BDT	N.A./0.9998	6s
NN1	0.9982/0.9979	1h 58m
NN2	0.9989/0.9988	2h 12m
NN3	0.9992/0.9991	2h 32m

Table 2: Train/test results for the ML models.

Remark

The BDT clearly provides significant training time improvements and greater explainability compared to all other models. In addition, all models performed similarly in terms of signal significance. Hence, we decided to use the BDT model for all proceeding analyses.

Results: Signal Significance (SS) in Parameter Space

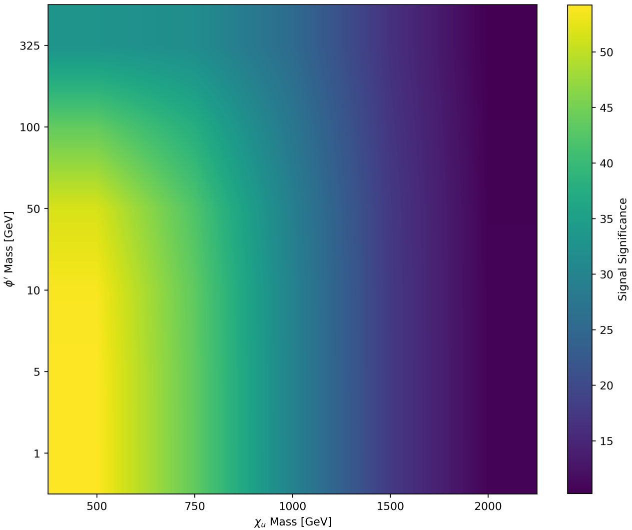

Figure 9: Signal significance vs. ϕ' and χ_u Masses.

Signal Significance (SS)

We adopt the Poisson error metric for SS:

$$\mathcal{S} = \frac{S \cdot \mathrm{TPR}}{\sqrt{S \cdot \mathrm{TPR} + B \cdot \mathrm{FPR}}}$$

Where S and B are the signal and background yields, respectively and are calculated as:

$$N = \mathcal{L} \cdot \sigma$$

Where $\mathcal{L} = 3000\ \mathrm{fb}^{-1}$ and σ is the cross section. Figure 9 shows the full signal significance plot in parameter space.

Results: Discussion

Our Contributions

- In this work, we examine the phenomenology of a ϕ' boson and a χ_u vector-like quark in the $U(1)_{T3R}$ BSM model.
- This model is well-motivated by modern problems in the SM, including the muon $g-2$ anomaly, thermal dark matter abundance, and the hierarchy problem.
- We present a feasibility study for production using gg and $\chi_u t$ fusion and a decay mode that results in 3 muons, MET, and two b-tagged jets as final states.
- The study has been performed under the context of pp collisions at the LHC, at $\sqrt{s} = 13$ TeV using a BDT algorithm to optimize the signal to background separation and maximize discovery potential/exclusion.
- We make novel contributions by extending LHC constraints to ϕ' masses in the $\mathcal{O}(MeV)$ range where they have a $\geq 5\sigma$ sensitivity for all χ_u masses.

Thank you! Questions?