Exploring Non-Thermal Dark Matter through Monojet Events

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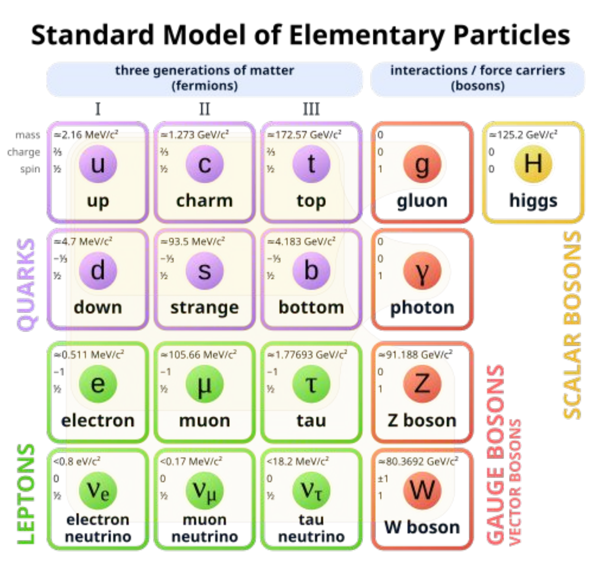
Abstract

Although the Standard Model (SM) successfully describes a wide range of particle interactions, it does not account for key phenomena such as dark matter and the matter–antimatter asymmetry. Various Beyond the Standard Model (BSM) scenarios have been proposed to address these limitations. This study investigates a BSM model featuring baryon-number-violating processes and a dark matter candidate. The model introduces two iso-singlet color-triplet scalars X at the TeV scale and one singlet Majorana fermion with a mass of approximately that of the proton. The fermion serves as the dark matter candidate, manifesting as missing transverse energy. The monojet channel is studied here.

Introduction

- **The Standard Model and BSM model**
  - The Standard Model (SM) is a successful theory describing fundamental particles and forces, but the SM model has several limitations.
  - ▷ *The need for Beyond the Standard Model (BSM) is presented*
- **Baryon asymmetry** and **existence of dark matter**
  - Imbalance between matter and antimatter in the universe, known as **baryon asymmetry**, which the SM model cannot fully explain
  - Astronomical evidence supports **the presence of dark matter,** yet it remains undetected within the framework of the Standard Model



Theoretical Model Setup

- **Baryon Number Violating Model (BNV)**
  - this model introduce **TeV scale two-color-triplet scalars X_α** and one singlet Majorana fermion, which is stable and can be candidate of dark-matter
  - **These scalars** having hypercharge and existing color triplet $SU(3)_C$ and color singlet $SU(2)_L$ +4/3 include **interaction violating the baryon number** with ΔB=2
  - **The minimal interaction Lagrangian** can be expressed as :

$$\mathcal{L} \supset \lambda_{\alpha i} X_\alpha \psi u_i^c + \lambda'_{\alpha ij} X_\alpha^* d_i^c d_j^c + \frac{m_\psi}{2} \bar{\psi}^c \psi + \text{h.c.}$$

- **Monojet Signature**
  - We are interested in monjet signature with production with X_α from fusion of d-b and s-b quarks only
  - For **monojet signature** studies, we focus on the fusion of *d-b* and *s-b* quarks and rewrite the relevant phenomenological Lagrangian as :

$$\mathcal{L}_{\text{monojet}} \supset \lambda_{\psi u} X_1 \psi u^c + \lambda_{db} X_1^* d^c b^c + \lambda_{sb} X_1^* s^c b^c + \text{h.c.}$$

  - Couplings λ_{db} and λ_{sb} are denoted λ_1 , and $\lambda_{\psi u}$ is renamed λ_2

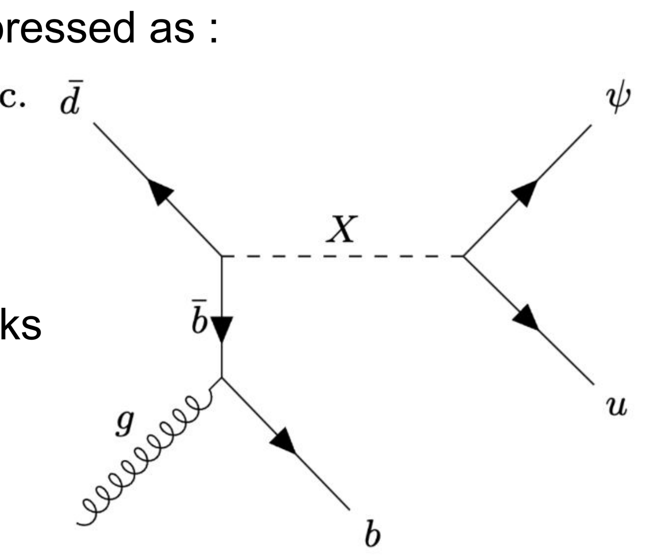


Figure: Feynman diagram for the monojet signature: a d-quark or s-quark from one proton and a bottom-quark from the other fuse to produce the TeV-scale scalar X_1, which subsequently decays into the Majorana dark matter fermion ψ and an up antiquark. The up antiquark hadronizes into the observed light jet, while the invisible ψ escapes the detector, yielding MET.

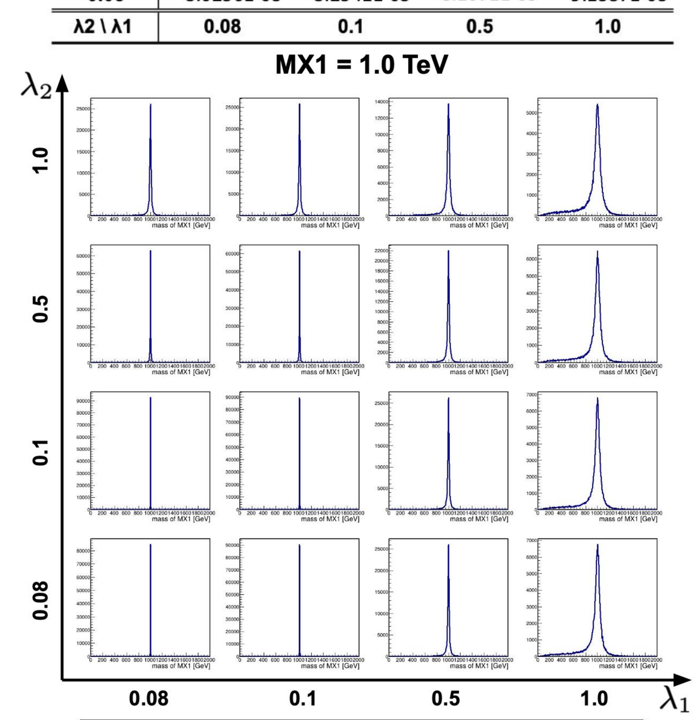
MC Sample Production

- **Simulation setting**
  - **MadGraph5 aMC@NLO (v2.6.7) :** Simulation for proton proton collisions with **√s = 13 TeV** at LHC
  - **PYTHIA8 (v8.244) :** The parton showering and hadronization simulation
  - **DELPHES (v3.4.2) :** CMS Detector simulation
- **Signal Sample Production**
  - For TeV scale scalar X, **mass of X1 (MX1)** is set to **1, 1.5** and **2 TeV**
  - **The mass of X2 (MX2)** is fixed by **10 TeV**
  - Signal will be generated **for grid of λ_1 and λ_2 : {0.08, 0.1, 0.5, 1.0}**
- **Background Production**
  - **TTbar + on to 3 jets:** Simulated in **bins of scalar HT** (hadronic transverse energy)
  - **W+jets / Z+jets (Drell–Yan):** Also generated in HT-binned format to cover wide kinematic regions efficiently.
  - **Diboson (WW, WZ and ZZ): Inclusive generation** was applied for fully leptonic and semileptonic decays, and **HT-binned samples** were used for specific hadronic modes (e.g., WW→lνqq).

MX1 = 1.0 TeV

	Cross Section [pb]			
1.0	3.2952E-02	5.0999E-02	6.8389E-01	1.1593E+00
0.5	3.1077E-02	4.6459E-02	2.6825E-01	3.4055E-01
0.1	1.1135E-02	1.1688E-02	1.3038E-02	1.4239E-02
0.08	8.0256E-03	8.2541E-03	8.2671E-03	9.1387E-03
λ2 \ λ1	**0.08**	**0.1**	**0.5**	**1.0**

MX1 = 1.0 TeV



Process	Cross-section [pb]
TTbar + up to 3jets	5.5046E+02
W + up to 3jets	4.6546E+04
Drell-Yan process + up to 3jets	8.5844E+03
Vector Boson	4.3912E+01

Event Selection

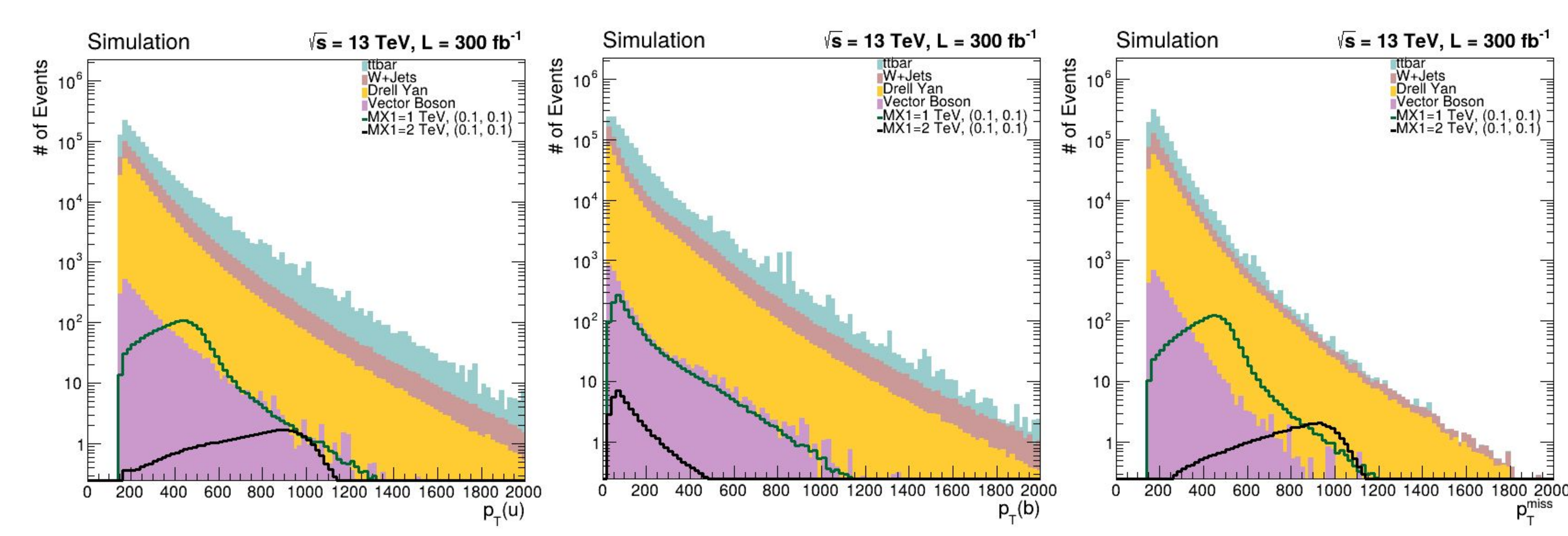
The monojet signature have **light-jet**, which is accompanied with **MET** and **b-tagged jet**

Selection	
Light quark jets Selection	$N(u) \geq 1$ $p_T(u) > 150$ GeV $\lvert\eta(u)\rvert < 2.4$
B-tagged jets Selection	$N(b) \geq 1$ $p_T(b) > 20$ GeV $\lvert\eta(b)\rvert < 2.4$
MET	$E_T^{\text{miss}} > 150$ GeV

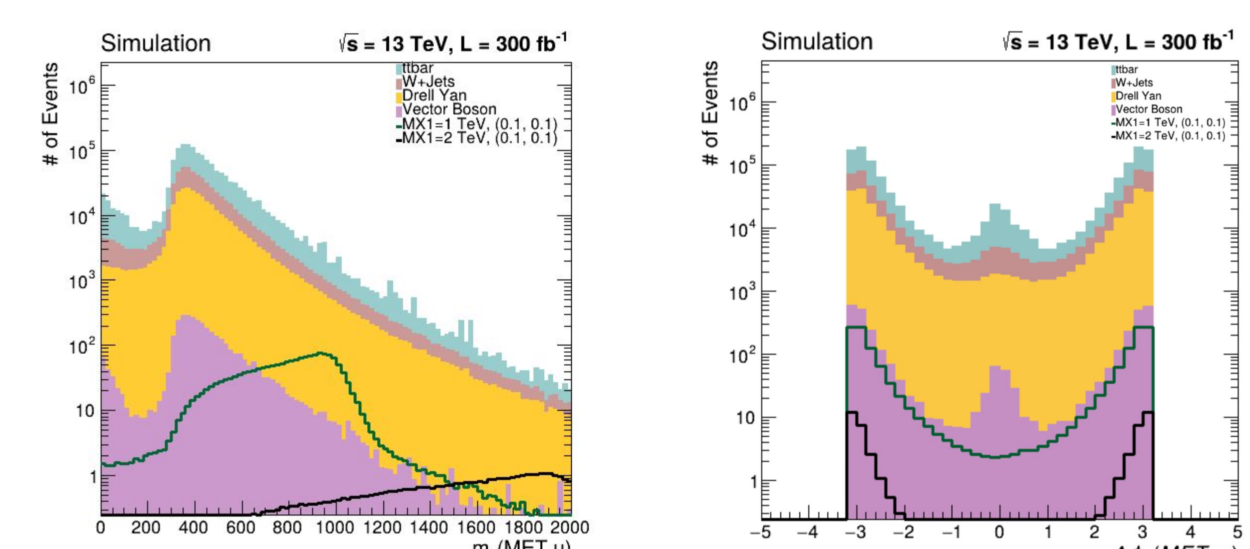
- **U is used to denote a light jet**
- **b-tagged jets** must be **b-tagged jets** and **light quark jets** must not be **b-tagged**
- **Lepton Veto:** Events containing **electrons or muons** with **pT > 10 GeV** and **|eta| < 2.4** are removed.
- **Tau-tagged Jet Veto**: Events containing **tau-tagged** jets with **pT > 20 GeV** and **|eta| < 2.4** are removed.

Results

- **Kinematics Distributions**

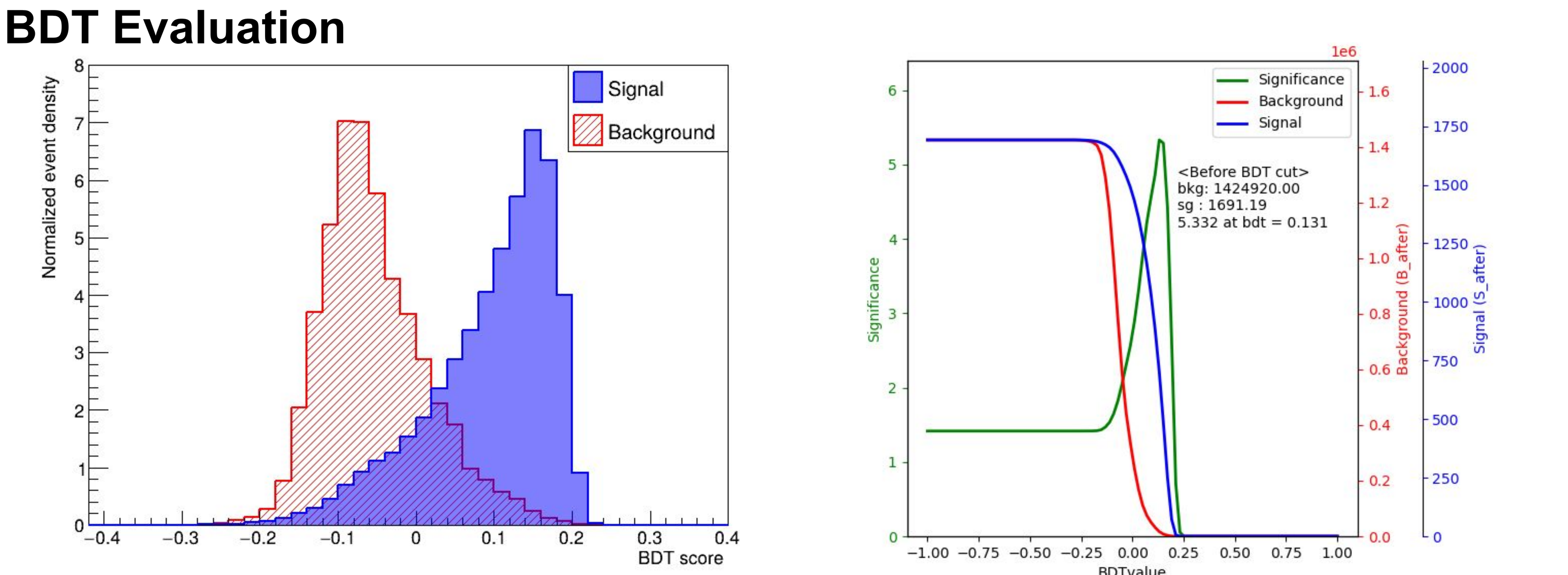


  - Above, the **pT distribution** for each object is shown on a logarithmic scale. **Event weights** are applied for each sample. For this, luminosity = 300 fb^{-1} was used.
  - The background was plotted separately for each sample.
  - For the signals, **different mass points** with the same couplings were plotted.



  - The figure on the left shows the transverse mass distribution of the MET and light quark jets, and right plot shows Δϕ of MET and light quark.
  - Above plots is few of the distributions used to train the BDT, with differences that help distinguish the signal from the background at each point.

- **BDT Evaluation**



  - The contribution of the BDT response to the kinematics distribution for the MX1 = 1 TeV with (0.1 , 0.1) case is on the left. The number of events and significance of each channel for the cut as a function of BDT value are shown in the plot on the right.
  - In this case, the BDT value of 0.131 shows a maximum of the significance of 5.332. Results for other MX1s and coupling constants were also calculated.

Summary and Plan

- We study a BNV model featuring a DM candidate, using monojet events. A BDT is used here for optimization of sensitivity.
- To refine the exclusion limit using this monojet channel, we plan to generate additional samples across a danser coupling constant grid. Finally, more background samples will be generated for statistical improvement.

Reference

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