PROCEEDINGS OF SCIENCE

Signatures of the Inert Triplet Model from Vector Boson Fusion at a Muon Collider

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The Inert Triplet Model (ITM) is a well-studied scenario that contains a neutral scalar Dark Matter (DM), along with an inert charged scalar in a compressed mass spectrum. The DM constraints corner the ITM to a narrow TeV-scale mass range, the production of which is inefficient at the present and future iterations of the LHC. However, Vector Boson Fusion (VBF) at a future Muon Collider promises high production rate for the inert triplet scalars. The compressed mass spectrum leads to disappearing tracks for the charged scalars, which can be efficiently reconstructed over the beam-induced background (BIB). Exploiting the high-momentum Forward Muons from the VBF processes along with these disappearing tracks, we present a detailed analysis of signatures of the model, as well as luminosity projections for 5σ discovery.

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1. Dark Matter and Long-lived Particle from the Inert Triplet Model

The inert triplet model (ITM) extends the Standard Model (SM) with a real scalar $SU(2)_L$ triplet $\mathcal{T} = \frac{1}{2}\begin{pmatrix} T^0 & \sqrt{2}T^+ \\ \sqrt{2}T^- & -T^0 \end{pmatrix}$ with hypercharge $Y = 0$, which transforms as odd under a discrete Z_2 symmetry. Only the SM Higgs doublet Φ, being even under the Z_2-symmetry, triggers the electroweak symmetry breaking (EWSB) via non-zero vacuum expectation value (vev) v_h, while T^0 does not obtain a vev. After EWSB, at the tree level, $T^\pm$ and T^0 have mass degeneracy, but at one-loop level, a small mass splitting of $M_{T^\pm} - M_{T^0} \sim 166$ MeV appears, which assigns T^0 as the viable dark matter (DM) candidate [1]. Due to this compressed mass spectrum, The $T^\pm \to T^0\pi^\pm$ becomes the dominant decay mode with $\sim 98\%$ branching ratio, with a proper lifetime of ~ 0.19 ns, corresponding to rest mass decay length $c\tau_0 \sim 5.7$ cm. Hence, $T^\pm$ can provide a long-lived particle (LLP) signature at the colliders.

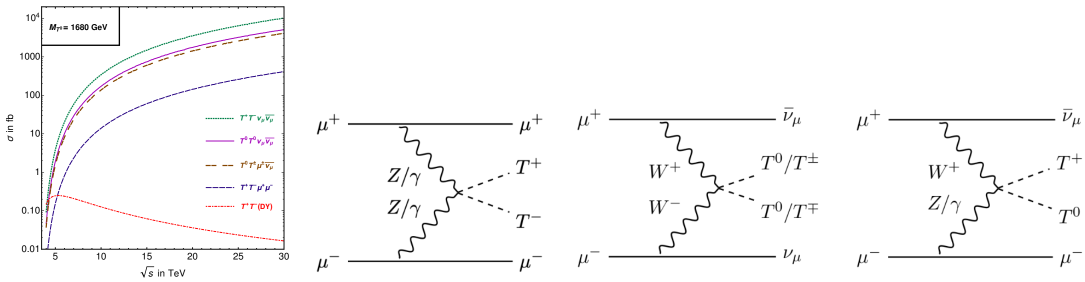
As far as DM phenomenology is concerned, T^0 satisfies the observed DM relic of $\Omega_{\rm obs} = 0.1198 \pm 0.0012$ over a mass range of 2.5 – 4.2 TeV, for an upper limit of portal coupling $\lambda_{ht} \lesssim 2$. Below this mass range, the relic remains underabundant but not excluded. However, from DM indirect detection, Fermi-LAT data excludes the mass range of 2.5 − 3.8 TeV. Hence, we pick three benchmark points for collider analysis [2]:

BP	M_{T^0} [TeV]	λ_{ht}	$\Omega_{\rm DM}$	$\Omega_{\rm DM}/\Omega_{\rm obs}$
BP1	1.21	0.026	0.037	0.312
BP2	1.68	0.0	0.063	0.525
BP3	3.86	1.861	0.119	1.000

Table 1: Choices of benchmark points for the collider analysis.

2. Production and Final States at the Muon Collider

Owing to the inefficiency of the 14 TeV LHC in producing our inert TeV-scale scalars, we turn to a future multi-TeV muon collider (MuC). Facilitated by the four-point $TTVV$-type vertices, triplet scalars can be pair produced copiously via vector boson fusion (VBF) at the muon collider, whose cross-sections grow with centre-of-mass energy as $\log^2(s/m_V^2)$.



(a)   (b)

Figure 1: (a) Production cross-sections w.r.t MuC energy $\sqrt{S}$ for BP2. (b) Dominant VBF production diagrams.

Figure 1(a) illustrates the trends of various VBF production channels and the DY channel for triplet scalars in BP2 with respect to the MuC center-of-mass energy, while Figure 1(b) shows the dominant VBF Feynman diagrams. A key feature of VBF processes is the high-pseudorapidity and high-energy spectator muons. The MuC detector design includes tungsten nozzles that absorb soft, forward particles from beam-induced background (BIB), limiting detector coverage to $\eta \leq 2.5$ [3]. However, these Forward muons (μ_F) can pass through the nozzles and be tagged at dedicated detectors, allowing for VBF process triggering and suppression of non-VBF backgrounds.

From the $T^\pm \to T^0\pi^\pm$ decay, the pions are too soft to detect, and T^0 is dark, which leads us to disappearing charged track (DCT) signatures. The tracking efficiency depends on the transverse length $c\tau\beta_T\gamma$ of the tracks, and their polar angle/pseudorapidity[4], whose distributions are shown in Figure 2. Combining one or two DCTs and one or two μ_Fs, we can establish four total final states. The criteria of $0.7 < \theta_{\rm tr} < 2.44$, 5.1 cm < radius < 148.1 cm, and $p_T^{\rm tr} \geq 300$ are used to select DCTs in the barrel region that end before the outer tracker (OT).

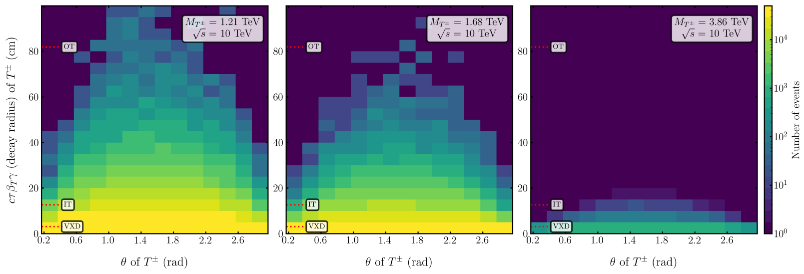
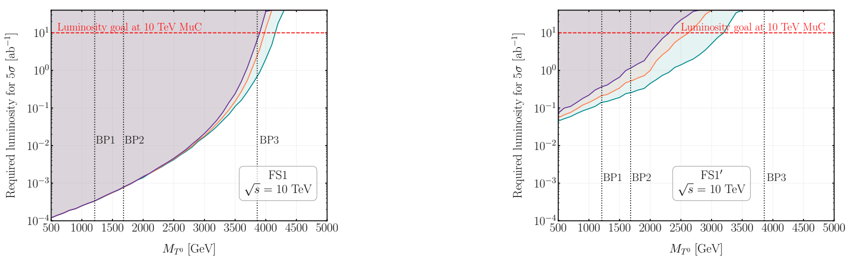


Figure 2: Transverse decay length of $T^\pm$ and polar angle θ of the $T^\pm$ track correlation for BP1-BP3 at the 10 TeV MuC.

3. Discovery Projections at 10 TeV MuC

The 10 TeV MuC has enough energy to produce $T^\pm/T^0$s at all three BPs, and a large number of events can be detected at 10 ab^{-1} of target luminosity. Vetoing out calorimeter hits and demanding high-p_T DCTs reject almost all SM backgrounds. However, fake tracks from irreducible BIB hits can contaminate the signal.



(a)

(b)

Figure 3: Discovery projection at 10 TeV MuC for (a) FS1: 1 DCT + 1 μ_F, (b) FS1′: 1 DCT + 1 main detector muon.

Figure 3(a) shows the required luminosity for 5σ discovery for the ITM final state of FS1: 1 DCT + 1 μ_F at the 10 TeV MuC for a range of triplet masses, taking BIB fake track events of 10(cyan), 200(orange) and 600(purple) respectively. With the target luminosity of 10 ab^{-1}, $M_H^\pm \leq 4.2$ TeV can be probed from FS1. To showcase the advantage of tagging Forward muons at dedicated detectors, we also present the projection for a complementary final state of FS1′: 1 DCT + 1 main detector muon, in Figure 3(b), showing that the maximum mass reach drops from 4.2 TeV to 3.2 TeV if we do not trigger the VBF process with a μ_F. Projections from three other final states and comparative discussions can be found in ref. [2].

In conclusion, a multi-TeV muon collider is an excellent machine to detect TeV scale inert triplet scalars that carry a DM candidate, utilizing Forward muon detectors to harness the full potential of VBF productions.

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