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Simplest Fermion Vector-Like Portal Dark Matter model:

Search in the compressed mass region at the CMS experiment

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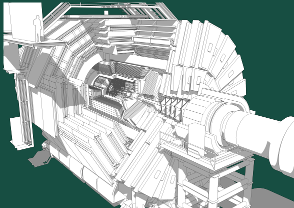

July 1, 2020

Contenido

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Dark Matter (DM) constitutes one of the main unsolved problems in fundamental physics. Ever since it was proposed to explain the rotation curves of galaxies, some other astronomical observations left little doubt of its existence.

Whatever DM is, the Standard Model (SM) is not able to produce a candidate that has, at present in the universe, stability and also interact very little or not at all with the known matter, proven properties of DM.

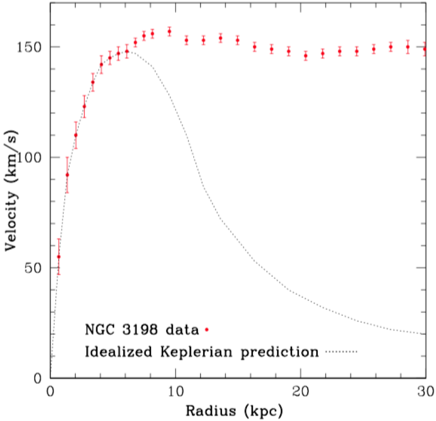

Figure 1: Measured rotational velocities of HI regions in NGC 3198 compared to an idealized Keplerian behavior[1]

1. **Astron. and Astrophys. 223, 47-60** Astron. and Astrophys. 223, 47-60.

Bullet cluster

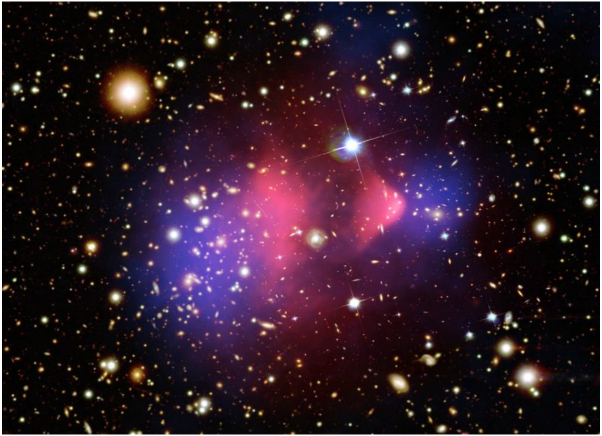

Figure 2: The Bullet cluster, the result of a subcluster (the “bullet”) colliding with the larger galaxy cluster 1E 0657-56 [arXiv:1711.02117]

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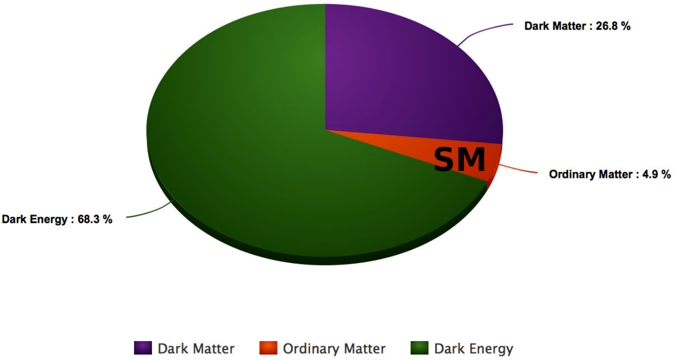

Figure 3: Simplified plot showing the estimate abundances, of the known components of the universe.

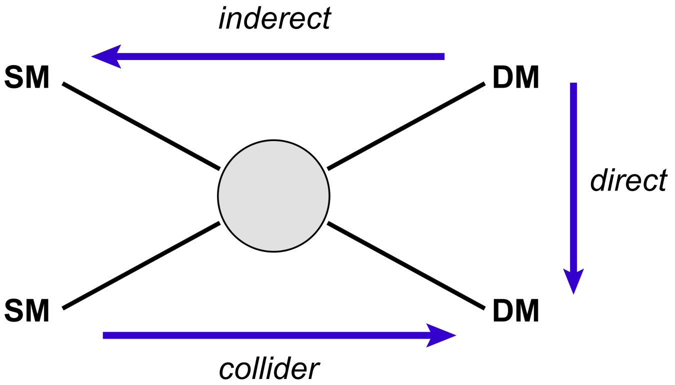

Figure 4: Schematic showing the possible dark matter detection channels.

Model

The VLF model introduce a vector-like charged fermion with $SU(2)_L$ singlet, a scalar particle and a $Z2$ symmetry to guarantee the stability of the DM candidate. The free Lagrangian reads

$$\mathcal{L} = \mathcal{L}_{SM} + m_F \bar{F} F + (Y_\ell S \bar{F} \ell_R + \text{h.c.}) + V(S, H) \;;$$

m_F is the singlet fermion mass parameter, ℓ_R are the SM right-handed lepton fields, Y_ℓ are the Yukawa couplings. The contribution to the scalar potential is given by

$$V(S, H) = \frac{m_S^2}{2} S^2 + \frac{\lambda_S}{4} S^4 + \lambda_{SH} S^2 |H|^2 \;,$$

with scalar mass parameter m_S and quartic couplings λ_S and λ_{SH}.

Toma, T. Internal bremsstrahlung signature of real scalar dark matter and consistency with thermal relic density. Phys. Rev. Lett. 111, (2013).

Kinetic Lagrangian

The kinetic terms for the vector-like charged fermion reads as follows

$$\mathcal{L}\ \bar{F}(D_\mu\gamma^\mu)F, \qquad (1)$$

consequently the most straightforward production at the LHC is pair-production of vector-like fermions , followed by their subsequent decay to a lepton and the DM scalar.

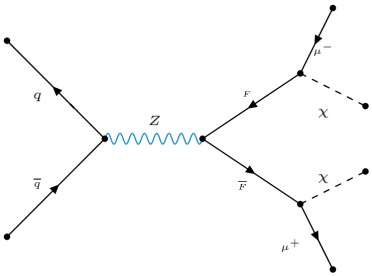

Figure 5: Pair-production of vector-like fermions ($pp \to F^-F^+$), in a Drell-Yan process, followed by their decay into a lepton and the DM particle ($F^- \to \ell^- S +$ h.c., $\ell = \mathrm{e}, \mu, \tau$)

Model

We focus on scenarios where the vector-like portal for DM annihilation is dominant and, therefore, we set initially.

$$\lambda_{SH} = 0;$$

we assume as well, that the DM candidate does not couples to the electron.

$$Y_e = 0;$$

the remaining parameters, Y_μ,Y_τ , m_S and m_F are allowed to vary freely. Furthermore, we are searching into the compress mass regime i.e.

$$\Delta m = m_F - m_S \lesssim 50 \text{ GeV}$$

One-muon + jet channel

The process chows in Figure 5, leads to the signature opposite sign leptons plus missing energy however,

- for small $\Delta m(F - S)$ the probability that one or both leptons are not detected in the collider increases.
- $pp \to F^+F^-j$ provides a jet which can be used as a trigger.

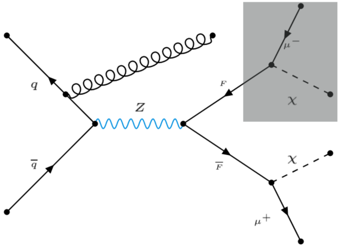

Figure 6: Pair-production of vector-like fermions, followed by their decay into a lepton and the DM particle, one missing lepton and a ISR jet

Parameter Region

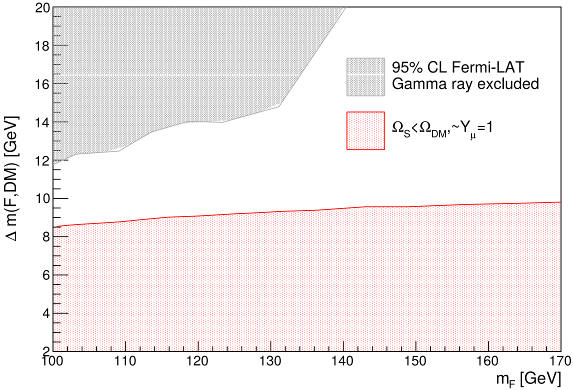

Figure 7: m_F vs Δm. The gray upper region is excluded by Fermi-LAT and H.E.E.S experiments, while the red area is the where the relic density is not satisfy by the model

Background

The backgrounds process for this search is the single top, the di-boson WZ, and $W+jets$. The last one being the most important with production cross-section three orders larger than the others (see Figure 8).

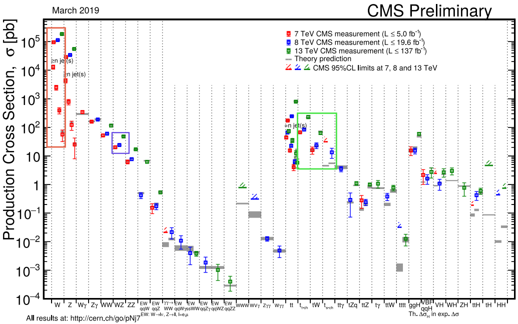

Figure 8: Summary of the cross section measurements of Standard Model processes [https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsCombined] .

Samples Generation

The Monte Carlo(MC) collision samples for the signal and the BackGrounds (BG) were generated using a combination of MadGraph (version 2.5.5)[1] for the event generation, Pythia (version 8.233)[2] for the hadronization and Delphes (version 3.4.1)[3] for the detector effect emulation.

1. **Alwall, J. et al** T. MadGraph 5: going beyond. J. High Energy Phys. 2011, 128 (2011).
2. **Sjöstrand, T. et al.** An Introduction to PYTHIA 8.2. Comput. Phys. Commun. 191, 159–177 (2015).
3. **De Favereau, J. et al**. DELPHES 3, A modular framework for fast simulation of a generic collider experiment. JHEP 02, 57 (2014).

Selection criteria

The values for the cuts were defined through an optimization process based on both the significance $\mathcal{Z}$ (defined in the 2) and the efficiency of the cut (defined in the 3) of the signal Vs. BG

$$\mathcal{Z} = \frac{S}{\sqrt{S+B}}, \tag{2}$$

where S and B are the yields for Signal and BG. We normalize all MC to 100 fb^{-1} luminosity and the signal mass point $m_F = 145$ GeV vs $\Delta m = 10$ GeV

$$e_{ff}(\chi) = \frac{\chi_{AC}}{\chi_{BC}}, \tag{3}$$

were χ can be signal or BG, and the subscripts BC and AC stands for "Before Cuts" and "After Cuts".

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m_T Selection

Most signal (bottom-right figure) events are around 50 GeV, but for all BG the peak of events is more towards 80 GeV, especially the $W + Jets$. That is why we chose to take a cut of the type **Less-Than**.

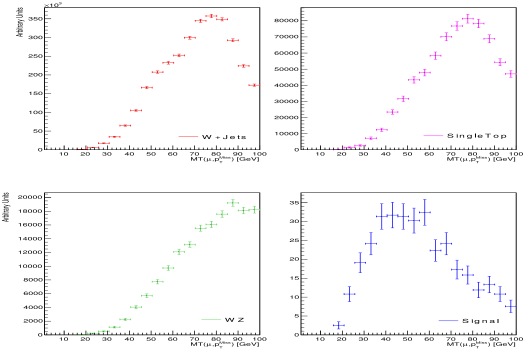

Figure 9: $M_T(\mu, p_T^{miss})$ histograms for the signal and each background sample. The bin-width is 5 GeV. Only the basic selection has been applied.

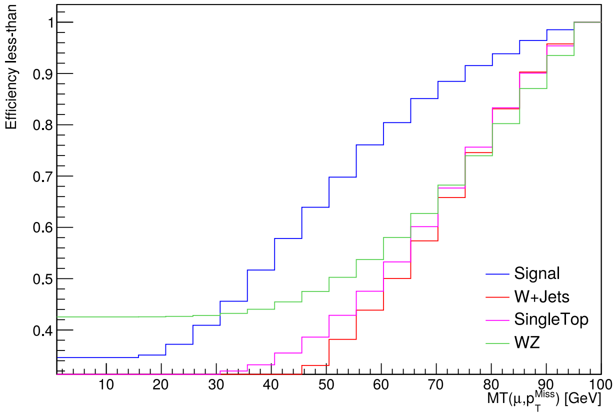

Figure 10: $M_T(\mu, p_T^{miss})$ Efficiency plots for the signal and each background sample. The main BG is less than 1% before 40 GeV, although the signal is more than 50%.

m_T Selection

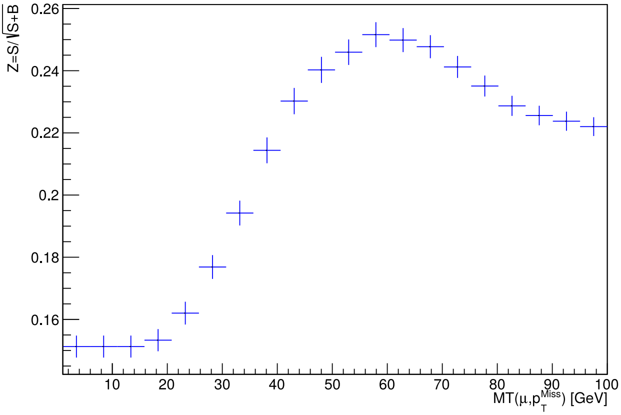

Figure 11: Significance of the cut (type less-than) for $m_T(\mu, p_T^{Miss})$. The maximum of $\mathcal{Z}$ is reached for 60 GeV, but to take out the majority of the $W + jet$ BG events, the cut at 40 GeV is preferred.

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$p_T(\mu)$ Selection

Most signal events are concentrated at low values of p_T as it was expected. It is chosen a less-than cut .

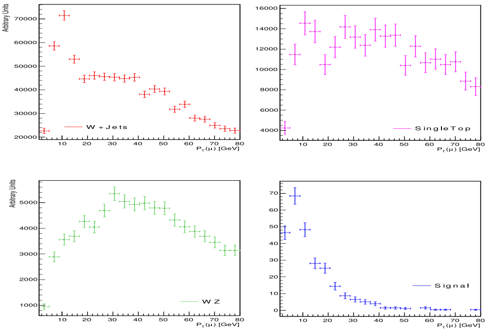


Figure 12: $p_T(\mu)$ histograms for the signal and each background sample. The bin-width is 5 GeV. Besides the basic selection, the cut $M_T < 40$ GeV was made.

$p_T(\mu)$ Selection

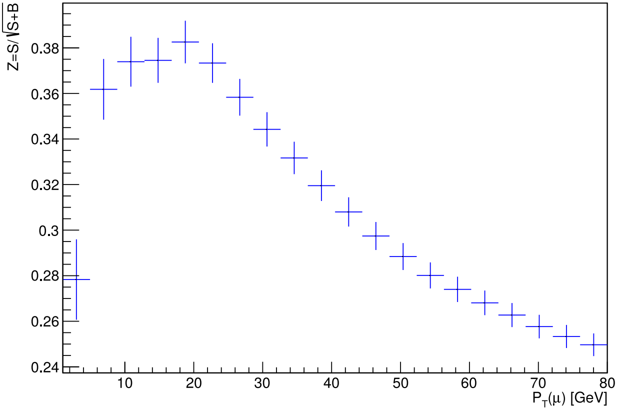


Figure 13: Significance of the cut (type less-than) for $p_T(\mu,)$. The $\mathcal{Z}$ curve reach the maximum at $p_T(\mu,) < 20$ GeV and falls fast for higher values.

$p_T(\mu)$ Selection

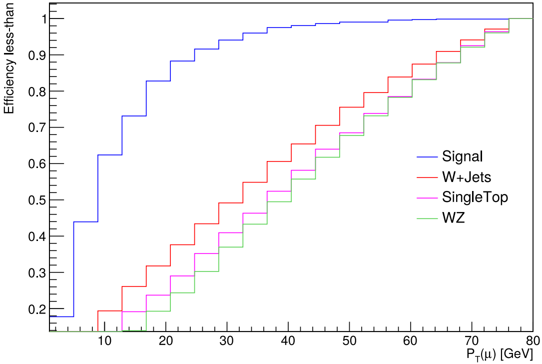


Figure 14: $p_T(\mu)$ efficiency plots for the signal and each background sample. For the cut suggested by Figure 13, the signal reach more than 80% of efficiency, while the main BG is less than 40%, confirming the cut based on the significance.

$N(Jet)$ Selection

The signal, W+jets, and WZ BG have similar behavior, but to reduce the Single Top events a less-than cut can be used.

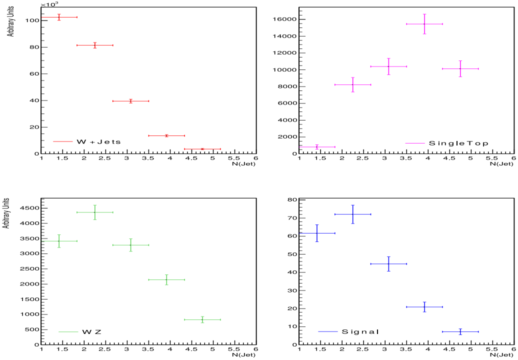


Figure 15: $N(Jet)$ histograms. The cuts applied are: the basic selection, $M_T < 40$ GeV and $p_T(\mu,) < 20$ GeV.

$N(Jet)$ Selection

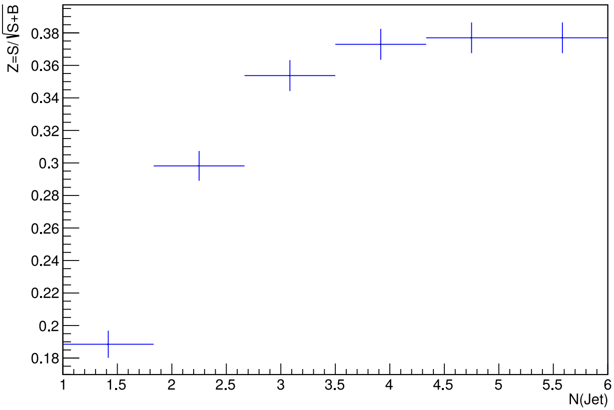


Figure 16: The Significance for $N(Jet)$ reach its maximum at $N(Jet) < 4$.

$N(Jet)$ Selection

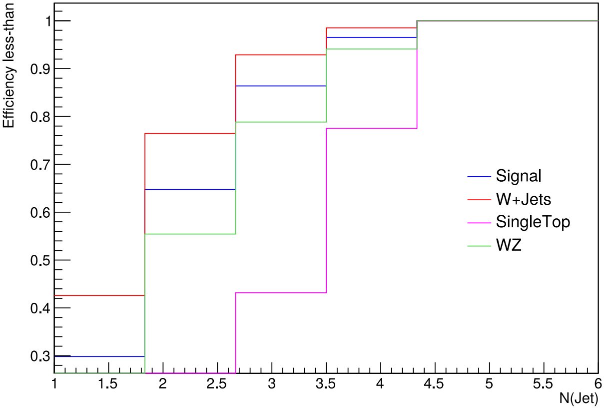


Figure 17: The $N(Jet)$ efficiencies. For the signal at $N(Jet) < 4$ the efficiency is almost 100% while for the main BG is less than 80%.

Selection

In the **Table 1** are summarized the cuts made to maximize the significance of the signal, along with the accumulated efficiency after the cut.

	W+Jets		Single Top		WZ		TOTAL
XSection (Pb)	3740.26291		288.17		22.82		
	Eff_a	N	Eff_a	N	Eff_a	N	N
$\sigma \times \mathcal{L}$	-	374,026,291.00	-	28,817,000.00	-	2,282,000.00	405,125,291.00
MC	-	6,250,050.00	-	319,006.00	-	173,715.00	6,742,771.00
Basics	1.42%	5,305,450.73	4.34%	1,250,490.66	29.90%	682,295.18	7,238,236.57
$M_T(p_T(\mu), p_T^{miss}) < 40$ GeV	0.32%	1,183,471.55	1.17%	336,853.44	5.40%	123,338.22	1,643,663.21
$p_T(mu) < 20$ GeV	0.07%	267,441.89	0.18%	52,032.26	0.63%	14,463.25	333,937.40
$N(Jets) < 4$	0.07%	247,513.77	0.07%	19,421.76	0.48%	11,060.90	277,996.43
$p_T(Jet_{leadin}) > 50$ GeV	0.07%	247,214.55	0.07%	19,331.42	0.48%	11,060.90	277,606.87
Weight	59.84		90.33		13.14		

Table 1: Weights for the MC samples, based on the expected events, number of MC samples generated for the study, weights for the samples assuming a 100fb^{-1} of luminosity, the number of events, and the accumulated efficiency after each cut.

Results

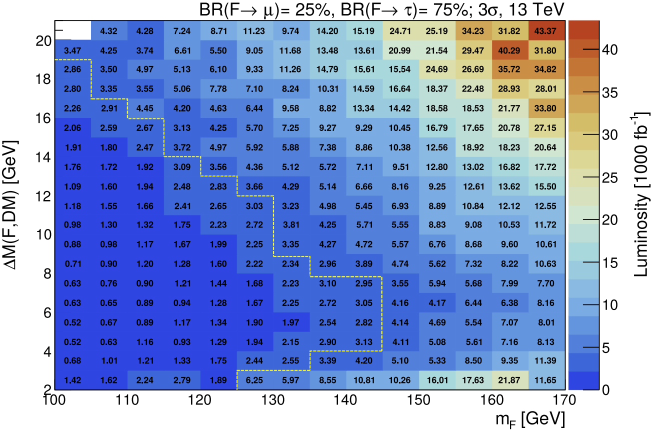


Figure 18: 3 σ reach for m_F vs Δm parameter space for various luminosity in 1000fb^{-1}. The Yellow line is 3000 fb^{-1}

The exclusion potential of the study is the region of parameters of the model in were at 3000 fb^{-1} the model reach 3σ. part of this region is still unexplored (see **Figure 7**), the intersection between the regions in **Figures 7** and **18** is shown in the next slide (Figure 19).
The exclusion is carried out assuming that what is going to be observed is the yields due to the SM alone.

Exclusion Potential

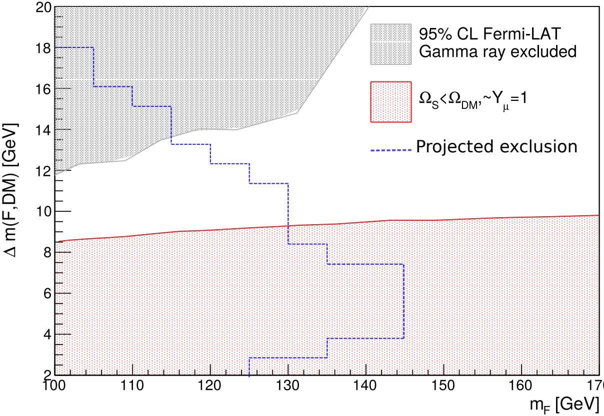


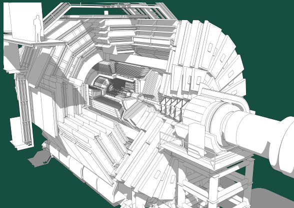
Figure 19: Exclusion potential of the model. The region left of the yellow line is where the model reach 3σ of significance at 3000 fb^{-1} of luminosity

Remarks

1. Although the model has been analyzed. there is still the region of the parameter space ($\Delta m = m_F - m_S \lesssim 50$ GeV) with exclusion potential.
2. The full dark matter content may be explained either by freeze-out at higher redshifts or by another dark matter content.
3. We can obtain exclusion sensitivity over a large region of parameter space has not yet been covered by any other search.

Thank You.

C.Salazar



Background Tunig

To generate the background we use the tunes extract for the data from CMS at the reference [CMS-PAS-GEN-17-001]

PYTHIA parameter	Value
PDF Set	NNPDF3.1
$\alpha_S(MZ)$	0.118
SPACESHOWER:RAPIDITYORDER	on
MULTIPARTONINTERACTIONS:ECMREF [GeV]	7000
α_S^{ISR}	0.118/NLO
α_S^{FSR}	0.118/NLO
α_S^{MPI}	0.118/NLO
α_S^{ME}	0.118/NLO
MULTIPARTONINTERACTIONS:PT0REF [GeV]	1.41
MULTIPARTONINTERACTIONS:ECMPOW	0.03344
MULTIPARTONINTERACTIONS:CORERADIUS	0.7634
MULTIPARTONINTERACTIONS:COREFRACTION	0.63
COLORRECONNECTION:RANGE	5.176
χ^2/dof	1.04

Table 2: Pythia 8 parameter values

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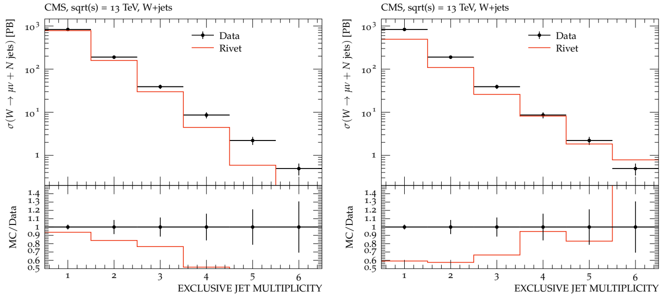
Background Tuning

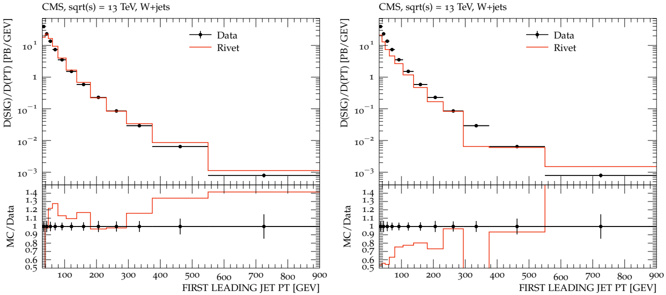
After the tunig we use Rivet[] over the analysis [PhysRevD.96.072005] to compare



(a) (b)

Figure 20: Differential cross section measurement for the exclusive jet multiplicities with tune (a) and with out tune (b)

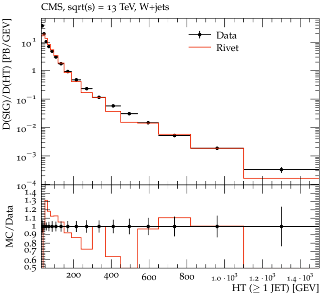
Background Tuning



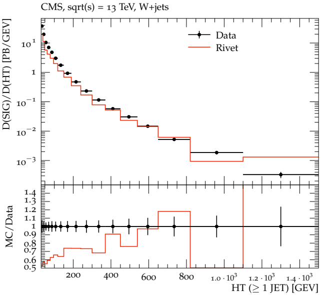
(a) (b)

Figure 21: Differential cross section measurement for the exclusive jet multiplicities with tune (a) and with out tune (b)

Background Tuning



(a)



(b)

Figure 22: Differential cross section measurement for the jets HT for at least 1 jet with tune (a) and with out tune (b)

Gamma-ray from the Galactic center measured these type of models could explain Fermi-LAT Collaboration.

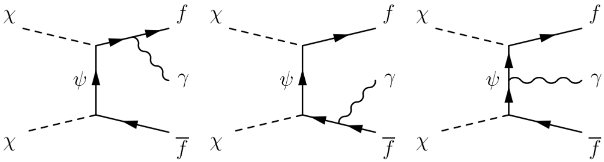


Figure 23: Internal Bremsstrahlung processes of (real) scalar DM. From [Toma, T. Phys. Rev. Lett. 111, 91301 (2013)]

Similar Searches

- Search for top squark pair production in pp collisions at $sqrt(s) = 13$ TeV using single lepton events [J. High Energy Phys. 2017, 19]
- Search for top squarks decaying via four-body or chargino-mediated modes in single-lepton final states in proton-proton collisions at $sqrt(s) = 13$ TeV [J. High Energy Phys. 2018, 65]

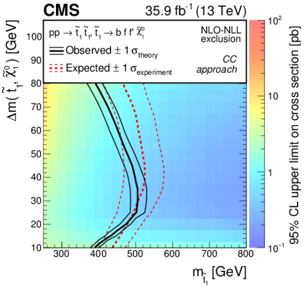


Figure 24: Exclusion limit at 95% for the four-body decay of the top squark as a function of $m(\tilde{t})$ and δm