Vector boson fusion topology and simplified models for dark matter searches at colliders

(arXiv:2111.13082)

Daniel Ocampo-Henao

In collaboration with

Santiago Duque-Escobar, José D. Ruiz-Álvarez

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GRUPO DE FENOMENOLOGÍA DE INTERACCIONES FUNDAMENTALES

What is the nature of the Dark Matter?

We have several sources of evidence from different types of astronomical measurements pointing to its existence [Griest (1993), Rubin (1983), Minchin (2005), Zacek (2007)]

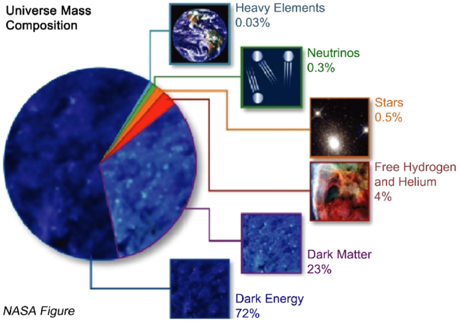

Figure 1. The major components and their proportions of the current universe. (NASA)

Dark Matter Searches

We can look for this particular form of matter in multiple ways

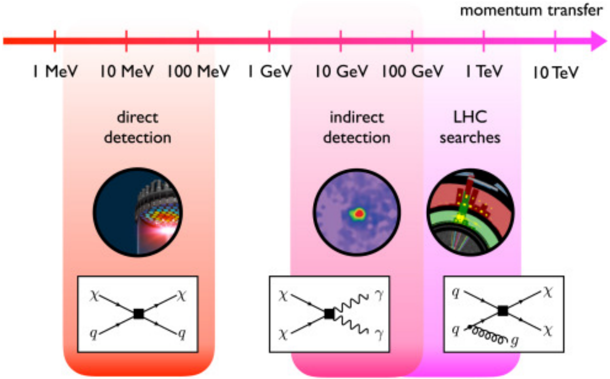

Figure 2. Illustration of the three main DM detection strategies

CMS Experiment at the LHC

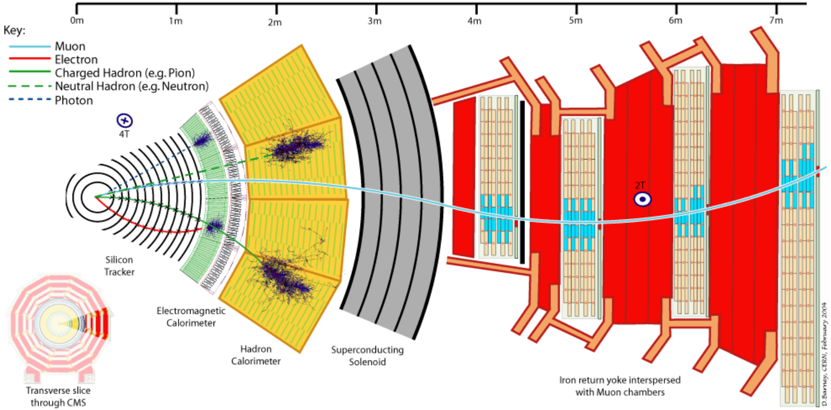

Figure 3. A sketch of the specific particle interactions in a transverse slice of the CMS detector, from the beam interaction region to the muon detector (CERN)

Simplified Models

In order to interpret the results from the LHC one needs a theory of DM

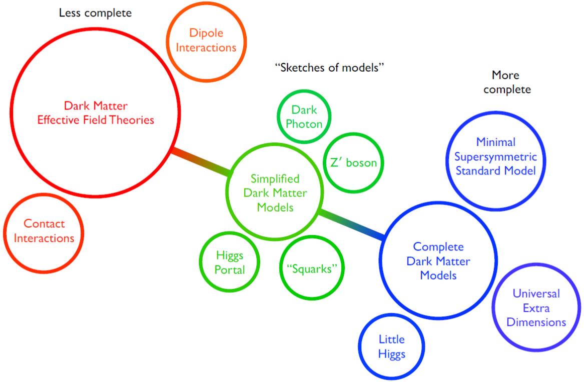

Figure 4. Dark Matter theory space (arXiv:1506.03116)

Mono-Jet Searches

The prototypical DM searches in simplified models are the so-called "mono-jet" searches

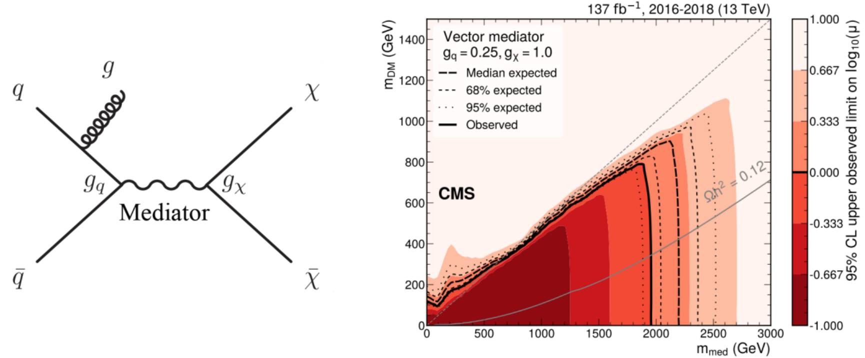

Figure 5. Left: Mono-Jet search example in a simplified model. Right: Exclusion limits at 95 % CL on the signal strength $\mu = \sigma/\sigma_{th}$ in the m_{med}-m_χ plane assuming vector mediators (arXiv:2107:13021)

Vector Boson Fusion Topology

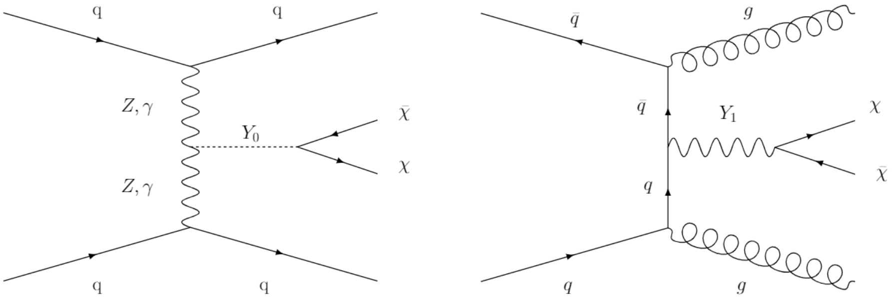

Figure 6. Main processes for dark matter production in a VBF topology: Left: Model with a scalar mediator. Right: Model with a vector mediator

The utility of the VBF topology for dark matter searches has been noted previously, in particular in the context of Higgs Portal DM, dipole interactions and MSSM.

Simulation and event selection

The signal has been simulated for several combinations of dark matter and mediator (scalar and vectorial) masses points. We also simulated Drell-Yan background.

The coordinates to describe outgoing particles in the detector are (ϕ, η, p_T).

$$\eta = -\ln\left[\tan\left(\frac{\theta}{2}\right)\right]$$

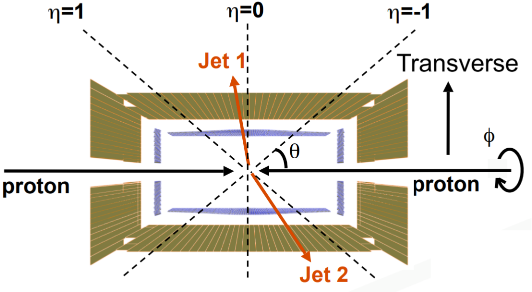

Figure 7. CMS reference system.

We have developed an event selection optimizing the significance $Z = \frac{S}{\sqrt{S+B}}$ using signal events both from scalar and vectorial mediators signals and from Drell-Yan background

Criterion	
Number of jets	> 1
$\eta(j_1) \cdot \eta(j_2)$	< 0
Leading jets p_T	> 30 GeV
Leading jets $\lvert\eta\rvert$	< 5
H_T	> 200 GeV
p_T^{miss}	> 50 GeV

Table 1. Baseline selection requirements.

We apply $\min|\Delta\phi(p_T^{miss}, j_i)| > 0.5$ to control the possible contribution from QCD processes to the background

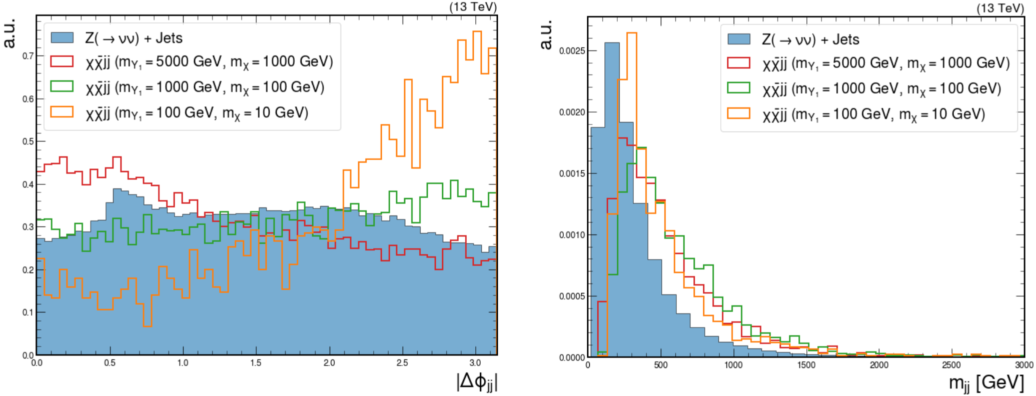

Figure 8. Signals for vectorial mediator and background events distribution for (left) $|\Delta\phi_{jj}|$ variable on events passing the baseline selection, and (right) m_{jj} for events passing the baseline selection and $|\Delta\phi_{jj}| > 2{,}3$

$\Delta\eta_{jj}$ depends on the mass of the mediator.

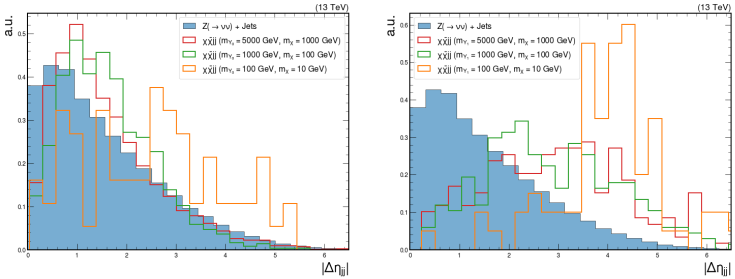

Figure 9. Signals and background events distribution for $|\Delta\eta_{jj}|$ variable on events passing all the other criteria

We cut on $\Delta\eta_{jj} > 2.5$ and $\Delta\eta_{jj} < 2.5$ for low and high pseudorapidity separation, respectevely.

Feature	**Value**
$\lvert\Delta\phi_{jj}\rvert$	> 2.3
m_{jj}	> 1000 GeV
$\min\lvert\Delta\phi(p_T^{miss}, j_i)\rvert$	> 0.5
$\lvert\Delta\eta_{jj}\rvert$	< 2.5 or > 2.5

Cross sections

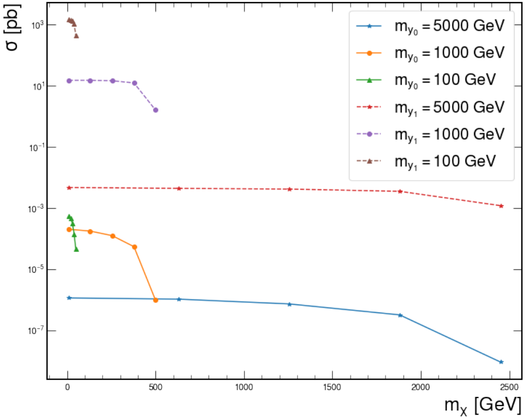

Figure 10. Signals cross sections for fixed mediator mass, as described in the legend, setting $g_\chi = 1$, $g_V = 1$ and $g_q = 0{,}25$ as a function of the dark matter candidate mass.

Projections to LHC luminosity

Selection	Scalar (m_{Y_0}, m_X) GeV (100,10)	(1000,100)	(5000,1000)	Vector (m_{Y_1}, m_X) GeV (100,10)	(1000,100)	(5000,1000)	B
Baseline	32.84	76.07	1.34	1.16e+7	4.67e+5	170.80	5.40e+8
$\|\Delta\phi_{jj}\|$	29.19	66.76	1.33	5.89e+6	1.43e+5	37.47	1.49e+8
m_{jj}	14.23	52.05	1.33	5.07e+5	1.89e+4	4.65	2.17e+7
$\min\|\Delta\phi(p_T^{miss}, j_i)\|$	1.56	10.02	0.26	3.00e+5	1.02e+4	2.65	1.43e+7
$\|\Delta\eta_{jj}\|$	0.72, 0.84	8.30, 1.72	0.22, 0.04	2.43e+4, 2.76e+5	4.54e+3, 5.70e+3	1.07, 1.57	2.77e+6, 1.15e+7

Selection	Scalar (m_{Y_0}, m_X) GeV (100,10)	(1000,100)	(5000,1000)	Vector (m_{Y_1}, m_X) GeV (100,10)	(1000,100)	(5000,1000)
Baseline	1.24e-3	2.87e-3	5.08e-5	4.37e+2	1.76e+1	6.44e-3
$\|\Delta\phi_{jj}\|$	2.10e-3	4.80e-3	9.59e-5	4.18e+2	1.03e+1	2.69e-3
m_{jj}	2.68e-3	9.78e-3	2.51e-4	9.46e+1	3.56	8.76e-4
$\min\|\Delta\phi(p_T^{miss}, j_i)\|$	3.62e-4	2.32e-3	6.12e-5	6.91e+1	22.37	6.14e-4
$\|\Delta\eta_{jj}\|$	3.82e-4, 2.16e-4	4.38e-3, 4.45e-4	1.16e-4, 1.15e-5	1.28e+1, 7.06e+1	2.39, 1.47	5.65e-4, 4.07e-4

Table 3. (top) Events after each selection applied for background and some signals assuming a luminosity of 150fb^{-1}. (bottom) Significance defined as $\frac{S}{\sqrt{S+B}}$ for each signal and including the scale factor for background to include W+jets contribution assuming a luminosity of 150fb^{-1}.

Exclusion at Z=5 for the vectorial mediator

Excluded areas in the quark coupling-mediator mass plane with dark matter mass fixed to 10 GeV and coupling fixed to 1.0

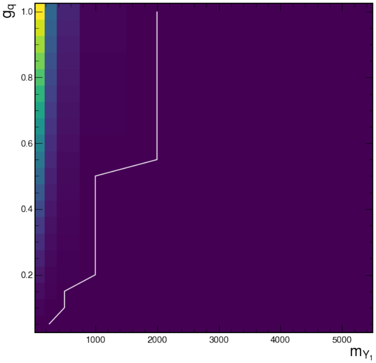

Figure 11. Exclusion reach of the selections for g_q-mediator mass where the excluded region is from the red white for greater couplings and smaller mediator masses

Summary

- No excesses in CMS analyzed data so far.
- We have develop a proposal for a new search for dark matter at LHC with exclusion power at current luminosities.
- New search for the simplified models approach, complementary to mono-jet searches.