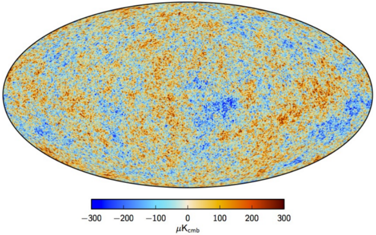
Vector Boson Fusion topology and simplified models for dark matter searches at colliders

Daniel Ocampo-Henao, Santiago Duque-Escobar, José D. Ruiz-Álvarez

5th ComHEP: Colombian Meeting on High Energy Physics
December 2, 2020.

UNIVERSIDAD DE ANTIOQUIA
GRUPO DE FENOMENOLOGÍA DE INTERACCIONES FUNDAMENTALES

Experimental probes



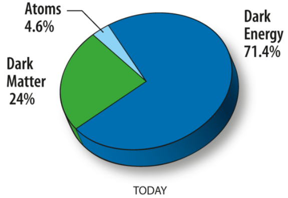


Figure 1. Left: Maximum posterior CMB intensity map at 50 resolution derived from the joint baseline analysis of Planck, WMAP, and 408 MHz observations. [1]. Right: Composition of matter in the universe. Credit: NASA/ESA

The Dark Matter relic abundance can be extracted from measurements of the cosmic microwave background [1]:

$$\Omega_\chi h^2 = 0{,}1198 \pm 0{,}0015$$

The particle hypothesis: WIMP

Dark Matter thermal production [2]:

$$\frac{dY_\chi}{dx} = - < \sigma v > \frac{k}{x^2}(Y_\chi^2 - Y_{\chi,eq}^2) \quad (1)$$

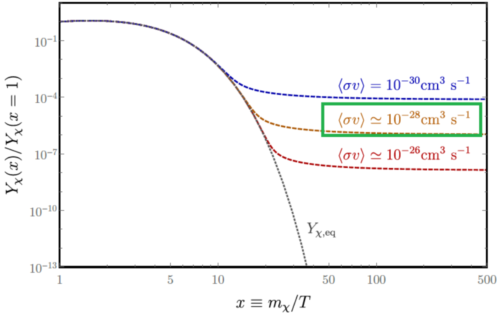


Figure 2. Evolution of the Dark Matter yield Y [3].

$$\Omega_\chi h^2 \approx 0{,}1 \left(\frac{m_\chi}{100\mathrm{GeV}}\right)\left(\frac{3\times 10^{-28}\mathrm{cm}^3\mathrm{s}^{-1}}{< \sigma v >}\right) \quad (2)$$

An electrically neutral particle with mass and interactions characteristic of the $SU(2)_L$ weak scale predicts the correct number density to account for the present day abundance of DM [3]

Collider searches

CMS Experiment at the LHC

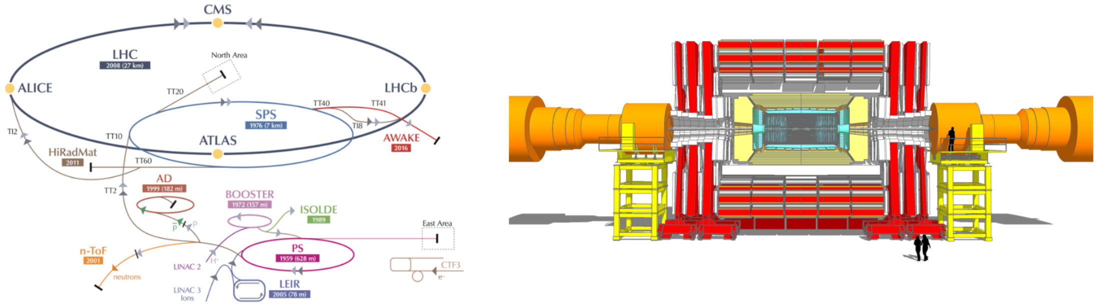


Figure 3. Left: CERN accelerator complex. Right: Diagram of the CMS detector at LHC. Credit: CERN.

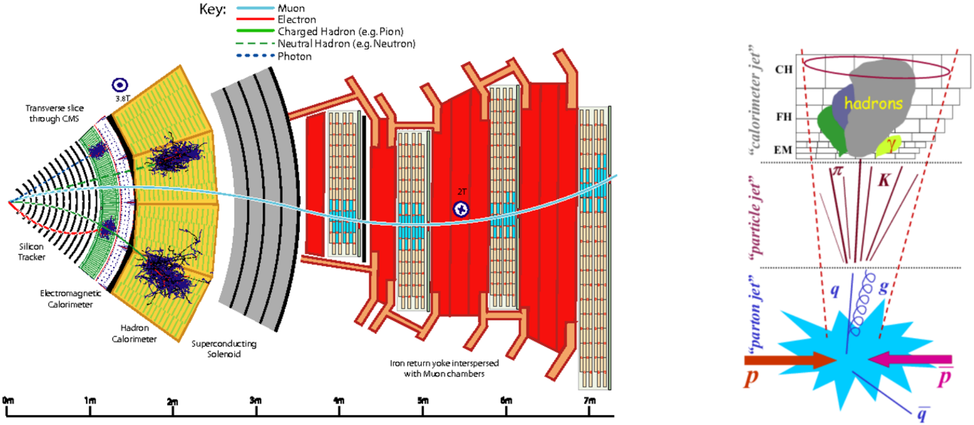
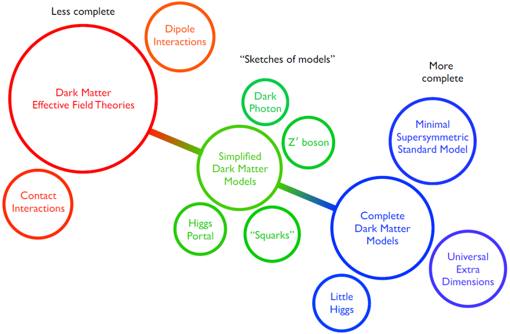


Figure 4. Left: A sketch of the specific particle interactions in a transverse slice of the CMS detector, from the beam interaction region to the muon detector. Credit: CERN. Right: Jet description. Credit: CMS.

Simplified models



Mono-X + MET searches.

free parameters: m_χ, m_{med}, g_χ and g_q.

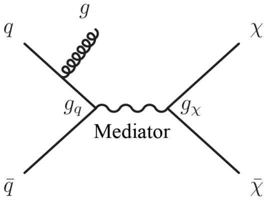


Figure 5. Left: DM theory space [4]. Right: Mono-Jet search example in a simplified model.

Vector Boson Fusion (VBF) Topology

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.

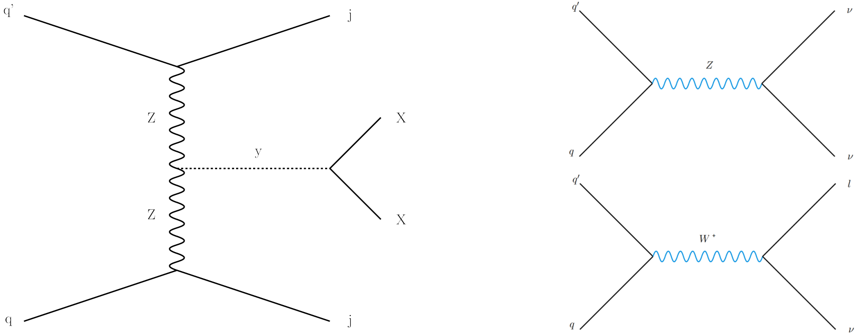


Figure 6. Left: Sample Feynman diagram for the production of dark matter through a spin-0 mediator in the VBF topology. Right: Main background processes in the Standard Model.

Event selection

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

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

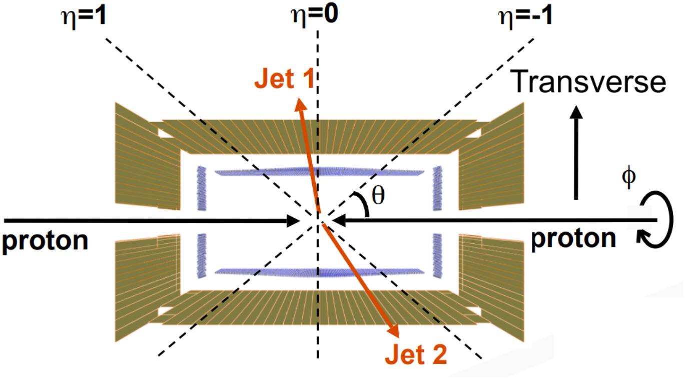


Figure 7. CMS reference system.

- Jet transverse momenta p_T and mass
- Azimuthal angle ϕ
- Invariant mass m_{jj}
- Pseudorapidity η
- Scalar sum of jet transverse momenta

$$H_T = \sum_{\text{Jets}} p_T$$

- Transverse missing energy (MET)

$$\not{E}_T = \left| - \sum_{\text{visible}} \vec{p}_T \right|$$

Criterion	
Number of jets per event	> 1
Leading jet p_T	> 30 GeV
Subleading jet p_T	> 30 GeV
Leading jet $\|\eta\|$	< 5
Subleading jet $\|\eta\|$	< 5
H_T	> 200 GeV

Table 1. Baseline selection requirements.

Distributions

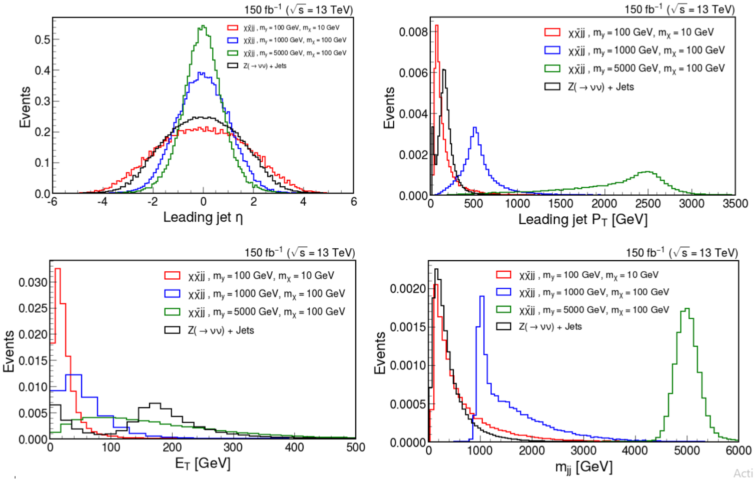


Figure 8. Distributions for the leading jet η and p_T, missing transverse energy $\not{E}_T$ and the maximum invariant mass m_{jj}

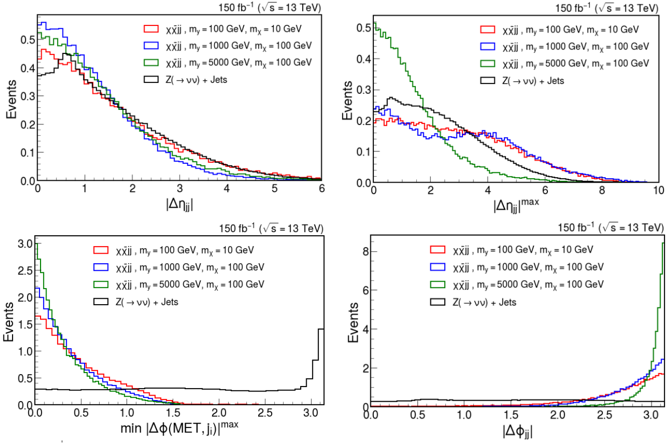


Figure 9. Distributions for the absolute η difference between the two jets with maximum invariant mass $\|\Delta\eta_{jj}\|^{max}$, absolute η difference between the two leading jets $\|\Delta\eta_{jj}\|$, minimum absolute ϕ difference between the met and the jets min $\|\Delta\phi(MET, j_i)\|$, and the absolute ϕ difference between the two leading jets $|\Delta\phi_j j\|$

Cut based analysis

Variable	Value
$\|\Delta\phi(j_1, j_2)\|$	> 2.3
$\max(m_{jj})$	> 1000 GeV
$\min \|\Delta\phi(MET, j_i)\|$	> 0.5
$\|\Delta\eta_{jj}\|^{max}$	< 3

Table 2. Cuts applied.

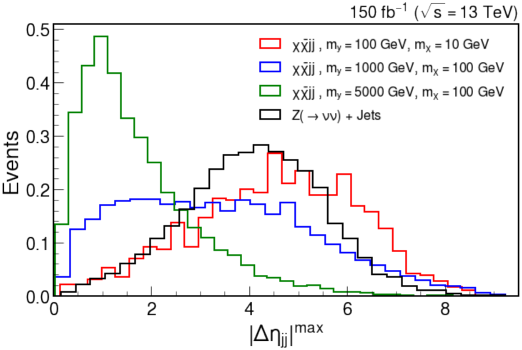


Figure 10. Distribution of the absolute η difference between the two jets with maximum invariant mass $\|\Delta\eta_{jj}\|^{max}$ after the cuts.

Cut	$\mathbf{S_1}$	$\mathbf{S_2}$	$\mathbf{S_3}$	**B**	$\mathbf{Z_1}$ (10^{-3})	$\mathbf{Z_2}$ (10^{-3})	$\mathbf{Z_3}$ (10^{-4})
No cuts	50000	50000	50000	984393	2.22	0.96	0.07
Trigger	37154	49966	49998	511066	2.29	1.33	0.10
$\eta(j_1) \cdot \eta(j_2) < 0$	11766	22842	37940	218193	1.11	0.93	0.11
$\|\Delta\phi(j_1, j_2)\| > 2{,}3$	9766	20610	37597	61432	1.73	1.60	0.21
$\max(m_{jj}) > 1000\,GeV$	2742	18344	37597	11640	1.12	3.25	0.49
$\min \|\Delta\phi(MET, j_i)\| > 0{,}5$	842	5315	8348	7560	0.42	1.17	0.13
$\|\Delta\eta_{jj}\|^{max} < 3$	227	2406	7183	1641	0.25	1.14	0.25

Table 3. Number of events for signal S and background B, as well as significances $Z = S/\sqrt{S+B}$ for the three mass points [(m_y [GeV],m [GeV])] signals $S_1 = (100, 10)$, $S_2 = (1000, 100)$, $S_3 = (5000, 1000)$, and background $Z(\rightarrow \nu\nu)+$ Jets.

Summary

- If DM interacts with SM particles, it can be produced and detected at the LHC.
- Extending searches with VBF processes may improve the constraints on the masses and couplings in simplified model scenarios.

Work to do:

- Develop a phenomenology study with a vectorial mediator.
- Try to improve further the classification using machine learning techniques.
- Obtain the constraints on the mass and couplings for dark matter generated via a VBF topology.

References

[1] Planck Collaboration, R. Adam et. al., Planck 2015 results. I. Overview of products and scientific results, Astron. Astrophys. 594 (2016) A1, [1502.01582].

[2] D. Clowe, M. Bradac, A. H. Gonzalez, M. Markevitch, S. W. Randall, C. Jones, and D. Zaritsky, A direct empirical proof of the existence of dark matter, Astrophys. J. 648 (2006) L109–L113, [astro-ph/0608407].

[3] Pierre, M. Dark Matter phenomenology : from simplified WIMP models to refined alternative solutions. (2019). arXiv:1901.05822 [hep-ph].

[4] Abdallah, J., Araujo, H., Arbey, A., Ashkenazi, A., Belyaev, A., Berger, J., ... Buchmueller, O. (2015). Simplified models for dark matter searches at the LHC. Physics of the Dark Universe, 9, 8-23.

Thank you!