Project update: Vector Boson Fusion to Dark Matter at the LHC and Jet Energy Resolution Determination

Rebecca Pickles, Darren Price

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MANCHESTER 1824
The University of Manchester

Introduction

Jet Energy Resolution Determination

- Investigating via the dijet balance method (using dijet events).
- Important as jets are used as a tag for a large number of processes, including how $\not{E}_T$ is calculated.

Vector Boson Fusion to Dark Matter at the LHC

- Evaluating the sensitivity of the ATLAS Detector to observe Dark Matter through Vector Boson Fusion.
- If Dark Matter preferentially couples to longitudinally polarised vector bosons, this will be the only way to detect it at the LHC.

JER: Dijet Balance Method

- Uses the scalar balance between the momenta of the two leading jets and uses the presence of extra jets in data to calculate the sensitivity of the balance.
- Two leading jets are expected to have equal transverse momentum, so any imbalance in p_T must be due to the calorimeter. The Asymmetry describes this balance:

$$\mathcal{A} = \frac{p_T^{\mathrm{probe}} - p_T^{\mathrm{ref}}}{p_T^{\mathrm{avg}}}$$

- The width of this asymmetry distribution:

$$\sigma(\mathcal{A}^{\mathrm{probe}}) = \frac{\sqrt{\sigma^2(p_T^{\mathrm{ref}}) + \sigma^2(p_T^{\mathrm{probe}})}}{p_T^{\mathrm{avg}}}$$

can be used to calculate the width of the p_T of the probe jet:

$$\frac{\sigma(p_T^{\mathrm{probe}})}{(p_T^{\mathrm{probe}})} = \sqrt{\sigma^2(\mathcal{A}_{(i,i)}) - \frac{1}{2}\sigma^2(\mathcal{A}_{(i,j)})}$$

JER: Determination of the JER

- The jet energy resolution of the detector is found in data by subtracting the truth (particle-level) asymmetry from the reconstructed (measured) asymmetry.
- The truth asymmetry is found from event samples generated through a Monte Carlo.

$$\sigma({p_T}^{\mathrm{reco}}_{\mathrm{data}}) = \sigma({p_T}^{\mathrm{det}}_{\mathrm{data}}) * \sigma({p_T}^{\mathrm{physics}}_{\mathrm{data}})$$

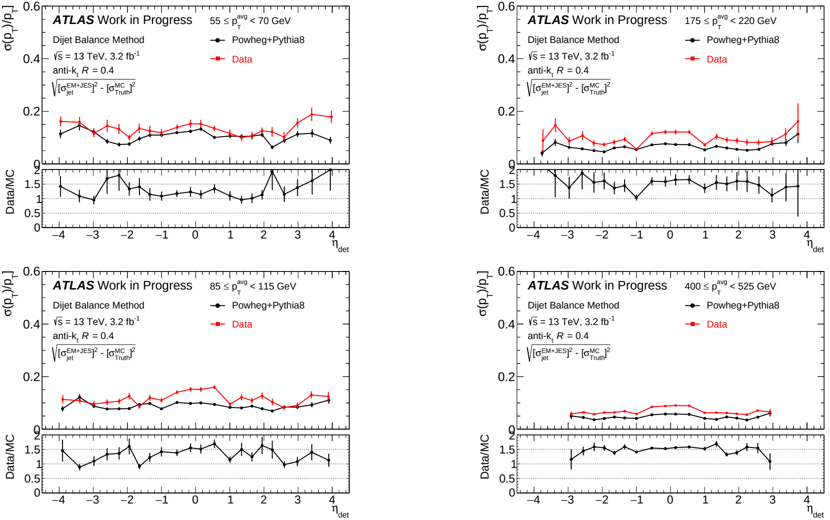
$$\sigma({p_T}^{\mathrm{reco}}_{\mathrm{MC}}) = \sigma({p_T}^{\mathrm{det}}_{\mathrm{MC}}) * \sigma({p_T}^{\mathrm{physics}}_{\mathrm{MC}})$$

- As $\sigma({p_T}^{\mathrm{physics}}_{\mathrm{data}}) = \sigma({p_T}^{\mathrm{physics}}_{\mathrm{MC}})$ and $\sigma({p_T}^{\mathrm{reco}}_{\mathrm{data}})$ is known, $\sigma({p_T}^{\mathrm{det}}_{\mathrm{data}})$ can be found from:

$$\sigma({p_T}^{\mathrm{reco}}_{\mathrm{data}}) = \sigma({p_T}^{\mathrm{det}}_{\mathrm{data}}) * \sigma({p_T}^{\mathrm{physics}}_{\mathrm{MC}})$$

JER: JER as a function of probe jet η

Fractional jet p_T resolutions obtained using the dijet balance method, shown as a function of η_{det} for data and MC.

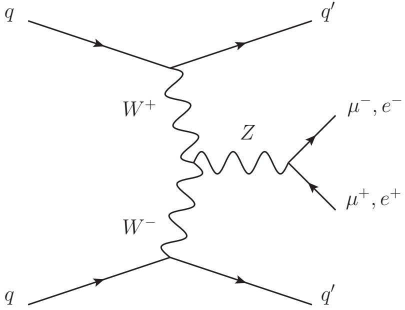


JER: Further Progression

- Assess a systematic on the subtraction from the spread of resolutions obtained from various MC samples.
- Compare the MC detector resolution to those obtained from the subtraction and the data detector resolution.
- Repeat the study with the bisector method:
    - Separates out the part of the p_T imbalance that is due to physics effects.
    - Relies on different assumptions and so different sources of systematic uncertainty to the dijet balance method - Good validation.

VBFDM: Vector Boson Fusion

Vector boson fusion (VBF) occurs when quarks from each proton in the collision produce W or Z bosons that interact.



- Two hadronic jets are the main signature of VBF.
- VBF allows a broad coverage of mechanisms using an EFT.
- VBF to DM is investigated using the ratio:

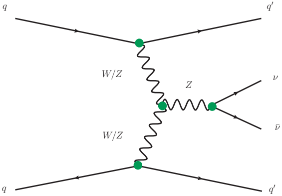
  $$Ratio = \frac{\sigma((Z \to \not{E}_T)jj)}{\sigma((Z \to l+l-)jj)}$$

  Where $\not{E}_T$ could be neutrinos or possibly dark matter.
- Signature for VBF DM is 2 jets and missing energy.

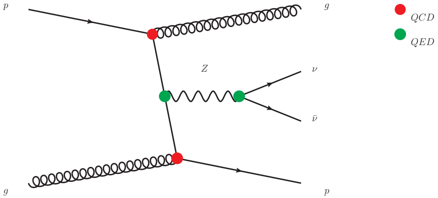
VBFDM: Background Events

There are a number of different types of background for VBF DM events: Electroweak (EWK) initiated ($Z \rightarrow \nu\bar{\nu}$)jj; Quantum Chromo-dynamic (QCD) initiated ($Z \rightarrow \nu\bar{\nu}$)jj; QCD Multijet; and ($W \rightarrow l\nu$).

EWK



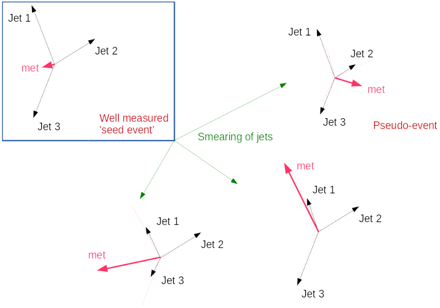
QCD



- EWK: Neutrinos appear as missing transverse energy - could be DM.
- QCD: Dominates the Zjj production and so needs to be known well.
    - There are features to the QCD production of jets that allows it to be separated from the EWK.

VBFDM: QCD Multijet background

This background is less well understood than other missing energy backgrounds as the missing energy is not down to 'real' physics, like neutrinos, where it can be estimated accurately from theory. If a jet is miss-measured in a unreliable part of the detector, or the resolution is not well measured, the other jets will be reconstructed incorrectly when trying to conserve momentum.



- The idea behind jet smearing is create 'pseudo-data' which mimics events where the missing energy in an event mostly arises from the mis-measurement of jets.
- This jet smearing uses the jet energy resolution work from the qualification task.

VBFDM: Jet energy resolution smearing method

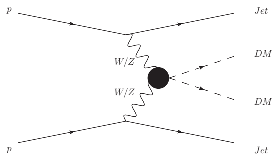
This is a data-driven method to find the mis-measured jet background of $\not{E}_T$ searches.

- Generate a large sample of jet seed events from MC, where jets are 'well-measured'. This is achieved by ensuring the reconstructed jet p_T is as close as possible to the truth jet p_T. (Have access to MC and data inputs in the format necessary for this multijet smearing method from JER work.)
- Use the resolution from JER dijet balance studies for p_T^{avg} and η bins.
- Smear MC jet event 4-vectors according to a Gaussian with this resolution a large number of times to produce pseudo-data events.
- Pass these pseudo-data events through the analysis cuts to produce the distributions.

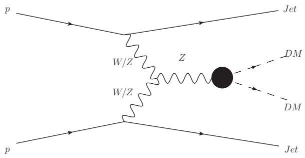
VBFDM: MadGraph simulation using models

- These processes are the ones being investigated in this analysis.
- The black blobs represent the Effective Field Theories which are able to model the physics of heavy mediating particles between the standard model and DM fields. They give an approximation to an underlying theory, including the degrees of freedom appropriate to describe physical phenomena at a specific energy scale, but not specifying substructure and degrees of freedom at higher energies.

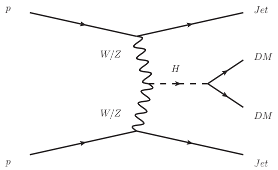
EFT.



EFT from Z boson.



With Higgs boson.



- MadGraph allows processes to be simulated within a framework defined by a Lagrangian.
- Each of these Lagrangians gives a model that the process must work within.

VBFDM: MadGraph simulation using models

Name	Operator	Dimension	Minimum EFT Scale (GeV)
D5a	$\mathcal{L} = \frac{1}{\Lambda}\bar{\chi}\chi\left[\frac{Z_\mu Z^\mu}{2} + W^+_\mu W^{-\mu}\right]$	5	100
D5b	$\mathcal{L} = \frac{1}{\Lambda}\bar{\chi}\gamma^5\chi\left[\frac{Z_\mu Z^\mu}{2} + W^+_\mu W^{-\mu}\right]$	5	100
D5c	$\mathcal{L} = \frac{g}{2\cos\theta_W\Lambda}\bar{\chi}\sigma^{\mu\nu}\chi\left[\delta_\mu Z_\nu - \delta_\nu Z_\mu\right]$	5	3300
D5d	$\mathcal{L} = \frac{g}{2\cos\theta_W\Lambda}\bar{\chi}\sigma^{\mu\nu}\chi\epsilon^{\mu\nu\sigma\rho}\left[\delta_\rho Z_\sigma - \delta_\sigma Z_\rho\right]$	5	6600
D6a	$\mathcal{L} = \frac{g}{2\cos\theta_W\Lambda^2}\bar{\chi}\gamma^\mu\delta^\nu\chi\left[\delta_\mu Z_\nu - \delta_\nu Z_\mu\right]$	6	230
D6b	$\mathcal{L} = \frac{g}{2\cos\theta_W\Lambda^2}\bar{\chi}\gamma_\mu\delta_\nu\chi\epsilon^{\mu\nu\sigma\rho}\left[\delta_\rho Z_\sigma - \delta_\sigma Z_\rho\right]$	6	330
D7a	$\mathcal{L} = \frac{1}{\Lambda^3}\bar{\chi}\chi W^{i,\mu\nu}W^i_{\mu\nu}$	7	100
D7b	$\mathcal{L} = \frac{1}{\Lambda^3}\bar{\chi}\gamma^5\chi W^{i,\mu\nu}W^i_{\mu\nu}$	7	100
D7c	$\mathcal{L} = \frac{1}{\Lambda^3}\bar{\chi}\chi\epsilon^{\mu\nu\sigma\rho}W^{i,\mu\nu}W^i_{\rho\sigma}$	7	100
D7d	$\mathcal{L} = \frac{1}{\Lambda^3}\bar{\chi}\gamma^5\chi\epsilon^{\mu\nu\sigma\rho}W^{i,\mu\nu}W^i_{\rho\sigma}$	7	100

- The rate of a process is proportional to $\Lambda^{-2(D-4)}$.
- The different dimensions have the EFT scale constraints result in some dimensions with vastly reduced rates.

$$\Gamma(Z \to \chi\bar{\chi}) = \frac{2\alpha m_Z^3}{3\Lambda^2\cos^2\theta_W\sin^2\theta_W}\left(1 + \frac{8m_\chi^2}{m_Z^2}\right)\sqrt{1 - \frac{4m_\chi^2}{m_Z^2}}$$

VBFDM: Rivet Analysis

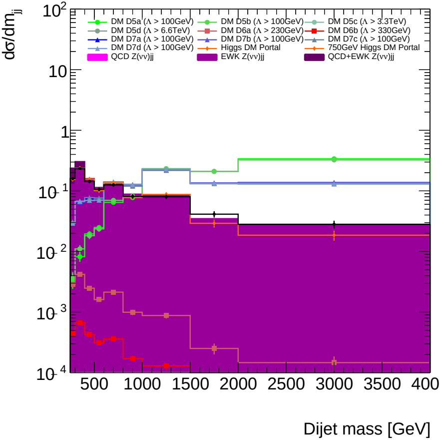
Rivet is specialised analysis software that includes the infrastructure to add user-made analyses.

- Specialised rivet procedure processed the events produced in MadGraph.
- It establishes cross-section distributions for a variety of phase-spaces, masses and observables.

Phase Space	Jet 1 p_T	Jet 2 p_T	$\mid\eta\mid$	mjj	N_{jets}	$\not{E}_T$
VBFZ Baseline	>55	>45	<4.4	n/a	>2	n/a
VBFZ High-mass	>55	>45	<4.4	>1000	>2	n/a
VBFZ Search	>55	>45	<4.4	>250	>2	n/a
VBF Dark Matter	>55	>45	<4.4	>250	>2	>150
VBF DM High Jet p_T	>100	>45	<4.4	>250	>2	>150
Monojet	>100	n/a	<4.4	n/a	>1	>150
Monojet High Jet p_T	>100	n/a	<4.4	n/a	>1	>250
VBF DM or Monojet	VBF DM or Monojet phase space cuts					
VBF DM or Monojet High Jet p_T	VBF DM or Monojet High Jet p_T phase space cuts					

- The VBF DM and Monojet phase-spaces are of most interest to this investigation.

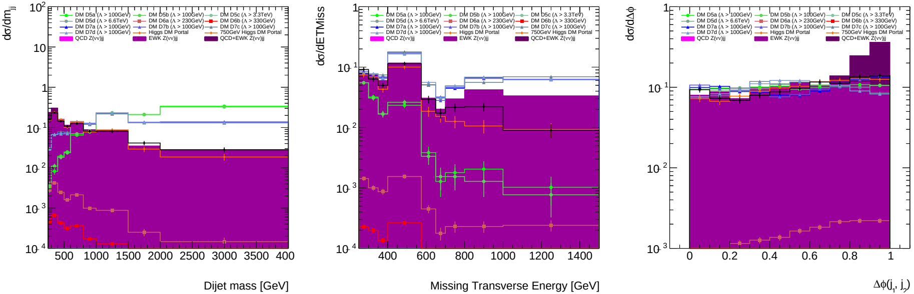
Normalised rate plot : DM Mass = 100GeV : Mjj : $\Lambda_{Min} = 100GeV$



- Block colour shows EWK and QCD SM($Z \rightarrow \nu\nu$)jj.
- Effective operators with high EFT scale constraint have a very low rate.
- The operators with the lowest EFT scale constraint have a higher rate than the background at high dijet mass.

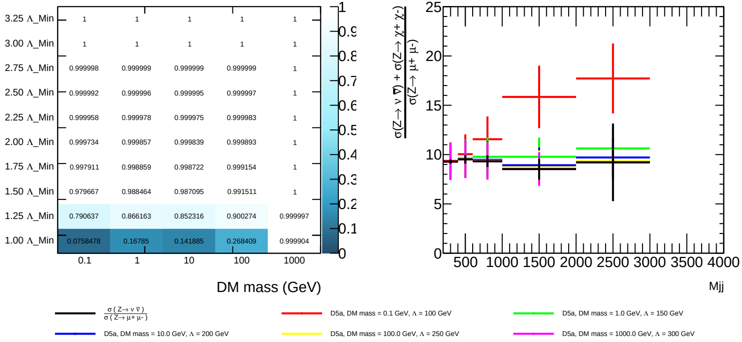
VBFDM: Model Kinematics and Rates

Normalised rate plots : DM Mass = 100GeV : Λ_{Min} = 100GeV



VBFDM: Ratio with Data and Observable Phase Space

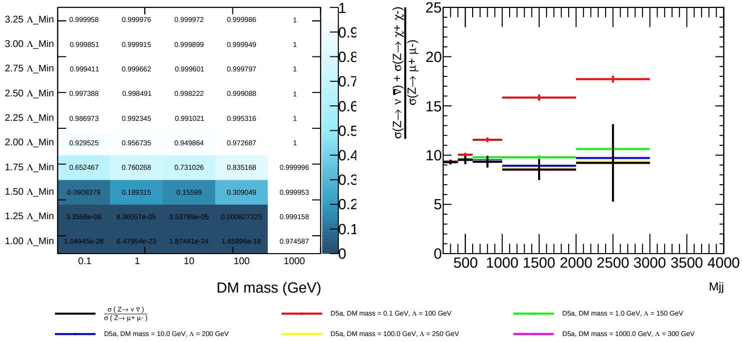
Observable phase space and ratio plots : D5a : Mjj : $\Lambda_{Min} = 100\text{GeV}$: 20% statistical uncertainty



- Observable phase space plot gives p-value from a χ^2-test comparing the DM model to the SM background ratio of $\frac{\sigma((Z\to\nu\nu)jj)}{\sigma((Z\to\mu^+\mu^-)jj)}$, for a range of DM masses and EFT scales.
- Ratio plot shows $\frac{\sigma((Z\to\nu\nu)jj)+\sigma((Z\to DMDM)jj)}{\sigma((Z\to\mu^+\mu^-)jj)}$ $(EWK+QCD)$

VBFDM: Ratio with Data and Observable Phase Space

Observable phase space and ratio plots : D5a : Mjj : $\Lambda_{Min} = 100\text{GeV}$: 2% statistical uncertainty



- Improved statistical uncertainty increases the range of the phase-space that can be excluded.

VBFDM: Plans for 2D Observable phase space plots

If two observables will give more sensitivity/exclude more observational phase space regions 2D plots could show what each observable excludes as well as what extra could be excluded when combining the sensitivities of both.

- Start with the dijet mass and jet $\Delta\Phi$ as they appear to give high p-values for different DM masses.
- Look at which observables cover which EFT scales when the bug is fixed.

Summary

- JER:
  - Made progress with the determination of the jet energy resolution
  - Aim to complete this work by summer for 2015 13TeV data.
- VBF DM:
  - Implemented a number of BSM models in MadGraph and used them to simulate the $Z \rightarrow \chi + \chi -$ process.
  - Produced a specialised Rivet procedure to analyse these simulated events and output cross-section distributions for a variety of phase-spaces, masses and observables.
  - Set up framework for statistical test of the DM models against all observables investigated.
  - Contributing to first general VBF DM search in ATLAS $\rightarrow$ Publish by summer for 13TeV.