Dark Matter searches in final states with jets at ATLAS and CMS at LHC

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for the ATLAS and CMS Collaborations

GEMMA workshop, Lecce, 5 June 2018
- Abundant evidence for the presence of dark sector
- Two big explanations: gravitational effects and matter (→ new particle!)
- Considering the existence of a new particle as DM candidate:
  - DM and SM particles in thermal equilibrium in the past
  - As the Universe expands, the annihilation depletes the DM density and freeze out
  - DM abundance determined by annihilation cross-section at freeze-out

\[ \Omega_{\chi} h^2 \simeq 0.1 \times \left( \frac{3 \times 10^{-26} \text{cm}^3 \text{s}^{-1}}{\langle \sigma v \rangle} \right) \]

\[ \langle \sigma v \rangle \sim 3 \times 10^{-26} \text{cm}^3 \text{s}^{-1} \]
\[ \sim \pi \alpha^2 / (100 \text{ GeV})^2 \]

♫ DM at the weak scale (WIMPS)!

Motivation to consider collider searches for DM
Experimental probes

What can we do at LHC?

- **Direct search for WIMP & mediator particles**
  - WIMP search in cascade decays
    - e.g. SUSY, Kaluza-Klein...
  - Hidden (dark) sector search

 Collider searches means DM production
Effective field theories (EFT)

Mediator energies $>>$
energy transfer at the LHC

- Contact interaction theory
- Model independent: compares with DD
  - parameters: $m_{DM}$, cut-off scale
- used in LHC Run 1
Effective field theories (EFT)

- Mediator energies $\gg$
- energy transfer at the LHC

\[ q \xrightarrow{g} \chi \]

\[ \bar{q} \xrightarrow{g} \bar{\chi} \]

- Contact interaction theory
- Model independent: compares with DD
- 2 parameters: $m_{\text{DM}}$, cut-off scale

Simplified models

- Mediator is light enough to be produced at the LHC!

\[ q \xrightarrow{g} \chi \]

\[ \bar{q} \xrightarrow{g} \bar{\chi} \]

- Mediators: vector, axial-vector, scalar, pseudoscalar
- Model dependent
- 4 parameters: $m_{\text{med}}$, $m_{\text{DM}}$, $g_q$, $g_{\text{DM}}$

We need a model

- Effective field theories
- Simplified models

- Mediator energies $\gg$
- energy transfer at the LHC

- Mediator is light enough to be produced at the LHC!

- mass of the mediator
- mass of the DM
- couplings to quarks
- couplings to DM

Model independent: compares with DD

- 2 parameters: $m_{\text{DM}}$, cut-off scale

Model dependent

- 4 parameters: $m_{\text{med}}$, $m_{\text{DM}}$, $g_q$, $g_{\text{DM}}$
**Simplified Models**

**SM→mediator→DM**
- **omon-X searches**

**SM→mediator→SM**
- **Visible signature**

\[ \begin{align*}
\mathcal{E}_{T}^{\text{miss}} & + \text{jet, } W/Z/H, \gamma, \text{ tt, ...} \\
\text{Searches for deviations from} & \quad \text{the SM expectations} \\
\text{interpretation model dependent} & \\
\end{align*} \]

\[ \begin{align*}
\text{\textit{\textbf{di-jet, ditop, dilepton resonances}}} & \\
\text{Bump hunt searches} & \quad \sim \text{model independent} \\
\end{align*} \]
To derive the limit on 

where

the minimal decay width of the mediator is given by the sum of the partial

ter and quarks respectively: 

is the mediator mass, 

= 

= 

= 

\( g \) 

is the mediator. The cross section and kinematics depend on the 

Figure B.10: Representative Feynman diagrams showing the pair produc-

DM in the final state, **invisible:**

missing energy +

need One jet = hadronization of a gluon

from Initial State Radiation (ISR)

of the incoming parton to tag the event

(aditional signatures: W,Z,γ possible ISR)

no DM in the final state, **visible:**

Two jets = hadronization of quarks

resonance in di-jet invariant mass

(alternative signatures: di-leptons)
DM in the final state, **invisible:**

**missing energy** +
need **One jet** = hadronization of a gluon
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of the incoming parton **to tag the event**
(aditional signatures: $W,Z,\gamma$ possible ISR)

no DM in the final state, **visible:**

**Two jets** = hadronization of quarks
resonance in **di-jet invariant mass**
(alternative signatures: di-leptons)
**Complementarity of searches**

- **visible dark photon searches**
  - HPS, LHCb, APEX
  - (proposed) **SeaQuest**, MAGIX,…

- **missing momentum/mass/energy & DM scattering searches**
  - miniBoone, NA64,
  - (proposed) **LDMX**, BDX, **SBN**, DarkLight, PADME, SHiP, …

**Graphical Elements**

- **m_{DM}**
- **m_{A} = 2m_{X}**
- **m_{med}**

**Experiment Types**

- **proton / electron**
- **beam dumps / fixed target**
Limits on \((m_{DM}, m_{med})\) plane can be converted in limits on the \((m_{DM}, \sigma_{DM-n})\) plane to compare with ID/DD dark matter experiments.

For axial-vector mediator with universal quark coupling \(g_q'\), mediator-nucleon coupling is

\[
f_p = f_n = 0.32 g_q'.
\]

\[
\sigma_{SD}^{DM-p} = \frac{3f^2 (g_q')^2 g_{DM}^2 \mu_{N\chi}}{\pi m_{med}^4}
\]

\[
\approx 2.4 \times 10^{-42} \text{ cm}^2 \cdot \left(\frac{g_q' g_{DM}}{0.25}\right)^2 \left(\frac{1 \text{ TeV}}{m_{med}}\right)^4 \left(\frac{\mu_{N\chi}}{1 \text{ GeV}}\right)^2
\]

\cite{arXiv:1603.04156}

\[\text{Figure B.10: Representative Feynman diagrams showing the pair production.}\]
The experimental setup
Our laboratory

LHC ring: 27 km circumference

CMS

General Purpose, pp, heavy ions

ATLAS

B-Physics, rare decays
CP Violation

LHCb

ALICE

Heavy ions, pp

Integrated Luminosity [fb]

2015
2016
2017

0.0
5.0
10.0
15.0
20.0
25.0
30.0
35.0
40.0
45.0
50.0

02-Mar
02-May
01-Jul
31-Aug
31-Oct
31-Dec

E. Di Marco

5 June 2018

GEMMA workshop
1) Jets

Build jets from detector deposits or reconstructed particles

\[ \text{Jet Energy Correction (JEC) Uncertainties} \]

- **Total uncertainty**
- **Excl. flavor, time**
- **Absolute scale**
- **Relative scale**
- **Jet flavor (QCD)**
- **Time stability**

Run2015, 2.1 fb\(^{-1}\) (13 TeV)

Jet flavor (QCD)

Absolute scale

Relative scale

Excl. flavor, time

Total uncertainty

Time stability

Jet flavor (QCD)

Jet Energy Correction (JEC) Uncertainties

JEC uncertainty [%]

\[ \text{JEC uncertainty} \] %

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2) MET = Missing Transverse Energy

Add together well-calibrated electrons, muons, …

Add remaining activity (your input of choice) not associated to an object → “soft term”

Vector needed for sum to equal zero is the missing transverse momentum (MET)
The price of so much data: *pile-up*

LHC produced $\sim 5 \times 10^{15}$ pp collisions up to 2017

Number of simultaneous proton-proton collisions per bunch crossing:

$L \times \text{total cross section} \times \text{bunch separation time} \approx 1.5 \times 10^{34} \text{ cm}^{-2} \text{s}^{-1} \times 100 \text{ mb} \times 25 \text{ ns} \approx 38$

Consequences on the particles reconstruction

ATLAS & CMS managed to maintain high performances
Mono-X searches

\[
\begin{aligned}
q & \rightarrow Z_B(m_{\text{med}}) \rightarrow \chi \bar{\chi} \\
\bar{q} & \rightarrow Z_B(m_{\text{med}}) \rightarrow \chi \bar{\chi}
\end{aligned}
\]
Experimental signature: MET + X

- DM assumed to be weakly interacting, and will leave no signature in the detector!
Experimental signature: MET + X

- DM assumed to be weakly interacting, and will leave no signature in the detector!
- we can record these events if the DM is produced in association to an initial state radiation
Mono-X searches

Experimental signature: \( \text{MET} + X \)

- DM assumed to be weakly interacting, and will leave no signature in the detector!
- we can record these events if the DM is produced in association to an initial state radiation

Total transverse momentum in the event needs to be balanced.
Initial transverse momenta = 0 !

key observable: Missing transverse momentum \( (p_T^{\text{miss}}) \)
Detector challenges

- Triggering these events: both CMS & ATLAS rely on inclusive $p_T^{miss}$ triggers.
  - CMS: $p_T^{miss} > 120$ GeV / ATLAS: $p_T^{miss} > 90$ GeV
  - to sustain low thresholds, mitigate the pileup contribution to MET resolution

- **Spurious detector signals** can cause fake missing transverse momentum!
  - Anomalous high $p_T^{miss}$ can be due to:
    - Beam halo particles
    - Particles striking sensors in the calorimeter photodetectors
    - Dead cells in the calorimeters
    - Noise in readout box electronics in calorimeters

![Graph showing excess in the MET tail](image)
SM background

- Strategy is to estimate all the “known” standard model processes in the final state of interest, and look for deviations from standard model that is compatible with the signal expectation.

Dark Matter Signal

Irreducible largest background (Standard Model)

Reconstructed mono-jet event

SM background

Identical signature!
Z→νν background estimation

- Z(νν)+jets: it constitutes >50% of the total background
- Z(ℓℓ) p_T spectrum is very similar to Z(νν) p_Tmiss spectrum.
  - It can be used to estimate the irreducible background

The Z(ℓℓ)+jets removing the charged leptons mimicks the Z(νν)+jets events

statistically limited
~no theory uncertainties

If we remove the muons from a Z→μμ event, it mimics a Z→νν event
**Z→νν background estimation**

- **Z(νν)+jets**: it constitutes >50% of the total background

- **Exploit all possible orthogonal control regions (V+jets)**
- **Need state of the art prediction of the differential rates, uncertainties on V+jets/Z(νν)+jets**

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**Graphical Illustrations**

- **Statistically limited**
  - ~no theory uncertainties

- **Statistically rich!**
  - large theory uncertainties

- **Statistically ~ Z (νν)**
  - large theory uncertainties
Main control regions

\(\gamma\) as a proxy for \(Z(\nu\nu)\)

\(Z(\ell\ell)\) as a proxy for \(Z(\nu\nu)\)

Showing that detector effects and SM backgrounds are well understood
Results: no signal

Clear challenge:

- The shape of signal and backgrounds are similar
  - the MET tail is the sensitive part of the spectrum
  - need to control the SM background at % level
Interpretation depends on the chosen model.
E.g.: vector mediator, fixing 2/4 parameters among $m_{\text{med}}$, $m_{\text{DM}}$, $g_q$, $g_{\text{DM}}$, scanning the others

Pushing the limit on $m_{\text{med}}$ to $>1.5$ TeV
Pushing the limit on couplings $<5\%$
Dark mediator searches

\[ Z' \]

\[ q \]

\[ g' \]

\[ Z' / M \]

\[ \Gamma \]

\[ q \rightarrow Z' \]

95\% CL exclusions

\[ (m_{\text{med}}, m_{\text{DM}}, g_{\text{DM}}, g_{0q}) \]

\[ G_{\text{tot}} = G_{cc} + 3G_{qq} \]

\[ G_{cc,V} = g_{cc}^2 \frac{m_{\text{med}}}{m_{\text{DM}}^2} \]

\[ G_{qq,V} = (g_{0q})^2 \frac{m_{\text{med}}}{m_{\text{q}}^2} \]

Where

\[ m_{\text{med}} \text{ is the mediator mass, } \]

\[ m_{\text{DM}} \text{ is the mass of the DM particle, } \]

\[ \text{which is assumed to be a Dirac fermion, and } \]

\[ m_{q} \text{ is the quark mass. The two different types of contribution to the total width vanish for } \]

\[ m_{\text{med}} < 2m_{\text{DM}} \text{ and } m_{\text{med}} < 2m_{q}, \text{ respectively.} \]

To derive the limit on \( g_{0q} \) in this model in the case of a nonzero mediator decay width to DM particles \( G_{cc} \), it is simplest to begin with the limit on \( g_{0q} \). Weaker quark coupling \( \rightarrow \) smaller cross section \( \rightarrow \) higher resonance mass.
6 TeV dijet event

Jet 0,
pt = 3.04 TeV
eta = 0.059
phi = -1.235

Jet 1,
pt = 2.88 TeV
eta = -0.364
phi = 1.915

signal:
bump in the di-jet mass

CMS Experiment at LHC, CERN
Data recorded: Mon Oct 12 2015 07:54:15
Run/Event: 258749 / 549664773
Lumi section: 356
Dijet Mass: 6.14 TeV
- Collect data with jets trigger
- Cluster and select two jets
- Fit di-jet invariant mass
- **Huge background!**

Figure 1 shows the dijet mass spectra (points) compared to a fitted parameterization of the background. The dijet mass spectrum for the high-mass search is shown in the lower panel of Figure 1, which also shows the pulls of the fit, the bin-by-bin differences between the data and the fit.

The dijet mass spectrum for the low-mass search is also shown in Figure 1, along with examples of predicted signals from narrow gluon-gluon, quark-gluon, and quark-quark resonances.

Equation (2) gave a good fit to the low-mass data, while the functional form in Eq. (1) gave a poor fit to the data. For the low-mass search, a similar fit to the dijet mass resolution [16] was used to confirm that no additional parameters are needed to model these distributions.

In the high-mass search, an additional term was included in the fit with the parameterization given by

$$\chi^2 / \text{ndf} = 38.9 / 39 = 1.0$$

The functional form in Eq. (1) was also used in previous searches [4, 6–17, 43] to describe the data. For the low-mass search, a fit with the parameterization

$$\chi^2 / \text{ndf} = 20.3 / 20 = 1.0$$

was also used.

The data points are shown with error bars, and the fit is represented by a smooth curve. The lower panels of Figure 1 show the pulls of the fit, which are the bin-by-bin differences between the data and the fit.

The fit of the dijet mass spectrum for the high-mass search is shown in the lower panel of Figure 1, along with examples of predicted signals from narrow gluon-gluon, quark-gluon, and quark-quark resonances.

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high mass di-jet spectra

Note: with $H_T > \sim 900$ GeV, high mass spectrum to fit starts at $m_{jj} > 1.25$ TeV

$\chi^2 / \text{ndf} = 38.9 / 39 = 1.0$

Wide PF-jets
$m_{jj} > 1.25$ TeV
$|\eta| < 2.5$, $|\Delta\eta| < 1.3$

$\chi^2 / \text{ndf} = 38.9 / 39 = 1.0$

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Wide PF-jets
$m_{jj} > 1.25$ TeV
$|\eta| < 2.5$, $|\Delta\eta| < 1.3$
- A simplified model of a dark matter mediator

\[ g'_b \]

weaker quark coupling
→ smaller cross section

\[ \Gamma/\Gamma_M = 10\% \]
\[ \Gamma/\Gamma_M = 30\% \]

95% CL exclusions

\[ Z' \rightarrow q\bar{q} \]

higher resonance mass

\[ M_{Z'} [\text{GeV}] \]

\[ g_{0q} \]

\[ \frac{g^2_{\text{DM}} m_{\text{med}}^2}{m_{\text{DM}}^2 m_{\text{med}}^2} \]

\[ \frac{3}{2} \]

\[ \frac{1}{2} \]

\[ m_{\text{med}} \]
\[ m_{\text{DM}} \]
\[ m_{\text{q}} \]

The two different types of contribution to the total width vanish for \( m_{\text{med}} < 2 m_{\text{DM}} \) and \( m_{\text{med}} < 2 m_{\text{q}} \), respectively.
Precision measurements of the Z boson width from LEP
UA2 dijet search at the SppS at CERN, 1993
CDF dijet search at the Tevatron at Fermilab, 2009
LHC dijet search the LHC (8 TeV), 2012
Higher energies probes only higher masses of DM mediators

LHC dijet search the LHC (13 TeV)
Low mass di-jets

- **Data scouting (CMS) / Trigger-object Level Analysis (ATLAS): lower trigger thresholds**
  by recording only information necessary to perform certain analyses:
  - reduced information saved

**Total Bandwidth** = event size × event rate

= 1 MB × 1 kHz

Can we shrink *size* to increase *rate* ?
To derive the limit on mediator and dark matter masses, and the mediator couplings to dark matter particles in association with a radiated gluon from the radiation of dark matter particles in association with a radiated gluon from the radiation of dark matter particles. The two types of contribution to the total width vanish for which is assumed to be a Dirac fermion, and the mediator and quarks respectively:

\[
\sigma_{\text{tot}} = \frac{1}{M_Z} \left[ \frac{1}{M_Z} \right] \frac{1}{M_Z} = 30\% \\
\Gamma_{\text{DM}} = 2.04 \text{ TeV} \\
\eta_{\text{DM}} = 0.49 < m_{\text{DM}} < 2.04 \text{ TeV} \\
\Delta_{\text{DM}} < 2.04 \text{ TeV} \\
\]
Boosted di-jets

- At high $p_T$, the quarks are boosted into a single large-radius jet
- ISR gets us above the **trigger** threshold

**Ingredients:**
1. High $p_T$ jets
2. **Jet substructure** topology

![Diagram](image)

**Backgrounds:**
1. QCD
2. **SM candles**: $W/Z$+jets

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GEMMA workshop
Jet mass spectra

![Jet mass spectra graph](image)

Figure 6. Soft-drop jet mass distribution for the different \( p_T \) ranges of the fit from 500 to 1000 GeV. Data are shown as black points. The multijet background prediction, including uncertainties, is shown by the shaded bands. Contributions from the W and Z boson, and top quark background processes are shown, scaled up by a factor of 3 for clarity. A hypothetical Z' boson signal at a mass of 135 GeV is also indicated. In the bottom panel, the ratio of the data to the background prediction, including uncertainties, is shown. The scale on the x-axis differs for each \( p_T \) range due to the kinematic selection on \( \rho \).
Jet mass spectra

Data/Prediction

CMS

Events / 5 GeV

35.9 fb⁻¹ (13 TeV)

CMS

Data

Total SM pred.

Multijet pred.

Z(qq), g_q=0.17, m_Z=135 GeV

W(qq)+jets (×3)

Z(qq)+jets (×3)

t/tf(qq)+jets (×3)

increasing p_T

p_T: 700-800 GeV

m_SD (GeV)

Data/Prediction

50 100 150 200 250

0 0.8 1 1.2 1.4

50 100 150 200 250

0 500 1000 1500 2000 2500

0.9 1 1.1

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prediction, including uncertainties, is shown. The scale on the x-axis di

Data/Prediction

2000

5000

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Expands LHC reach down to 50 GeV
Mono-X vs di-jets

- Mono-X sensitive to both DM and mediator mass
- Di-jets sensitive to large range of dark matter parameter space by looking directly for resonant production of the mediator

\[
\begin{align*}
\text{Mono-X} & \quad \begin{array}{c}
\text{di-jet}
\end{array} \\
\end{align*}
\]
Collider searches of DM:

- are sensitive to low DM mass (<5 GeV) for spin-independent interactions
- have ~3 order of magnitude better sensitivity for spin-dependent interactions

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Conclusions

LHC collaborations search extensively for Dark Matter.

No excess was observed in the 2015 + 2016 data analysis in CMS and ATLAS in mono-X or multi-jet final states.

ϝ Mediator mass up to 1.6-1.8 TeV

ϝ DM mass up to 0.4-0.7 TeV

But ~40/fb more data is being analyzed from 2017!

We are in the era of precision searches!

Mono-X searches: Need to measure the backgrounds at % level. Need both experimental and QCD theory improvements

Di-jet searches: new experimental ideas being exploited to cover the remaining gaps

LHC complements direct searches for m_{DM}<\mathcal{O}(10) \text{ GeV}
Backup
Huge data delivery

\[ N_{\text{ev}} = \mathcal{L} \times \sigma \]

\( \triangleq 5 \times 10^{15} \) pp collisions!

\( \sim 10^9 \) W(\( l \nu \))

\( \sim 10^7 \) top-pairs

\( \sim 3000 \) H\( \rightarrow \gamma\gamma \)

\( \mathcal{L}_{2017} = 1000 \times \mathcal{L}_{2010} \) !!
- Two general purposes experiments
- Different technologies used in each component, to get the same targets
  - currently taking data at the LHC Run2
From detector to particles

First compute “easy” objects: **charged leptons, photons**
Then **jets** (collimated particles from the hadronization of partons)
Finally **MET** = Missing Transverse Energy
MonoX signal extraction (CMS)

Signal yield is measured by fitting $p_T^{\text{miss}}$, 1 rate parameter / bin

Simultaneous fit to different categories (signal + control regions) x mono-jet and mono-V (=hadronic $W,Z$)

$\mu_i^{W\rightarrow l\nu} \rightarrow f_i(\theta) \cdot \mu_i^{Z\rightarrow \nu\nu}$
MonoX signal extraction (ATLAS)

Signal yield is measured by fitting $p_T^{\text{miss}}$, 1 rate parameter / bin.

Simultaneous fit to different categories (signal + control regions) in mono-jet.

top-quark control region to estimate top background in the signal region.
Using ratios

- Common **experimental** systematic uncertainties cancel:
  - jet energy scale and resolution
  - luminosity measurement
  - pileup

- Common **theoretical** systematic uncertainties reduces
  - need the best calculation (higher order corrections in QCD) to have the best ratios estimate
Black ratio from data and statistical uncertainties / Red from MC
Grey band includes theoretical uncertainties

(improvements in the QCD calculation reduced the theory uncertainty of factor 4-5 in the last years)
Stop/Colored scalar limits

**Stop Model**

ATLAS Preliminary
\( \sqrt{s} = 13 \text{ TeV}, 36.1 \text{ fb}^{-1} \)

All limits at 95% CL

**Fermion Portal Model**

EXO-16-048
\( \sqrt{s} = 13 \text{ TeV}, 35.9 \text{ fb}^{-1} (13 \text{ TeV}) \)

CMS Preliminary

- Median expected 95% CL
- 68% expected
- Observed 95% CL

 mediator mass excluded up to ~1.4 TeV

**Stop→Charm+neutralino (DM)**

Stop mass excluded up to 430 GeV

Mediator mass excluded up to ~1.4 TeV
DM mass < 600 GeV

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mediators: putting all together
mediators: putting all together

\[ g'_{q} \]

\[ 1 / M_{Z'} = 30\% \]

\[ 1 / M_{Z'} = 10\% \]

95\% CL exclusions

- CMS Boosted Dijet, 13 TeV
- CMS Dijet w/b Tag, 8 TeV
- CMS Dijet \( \chi \), 13 TeV
- UA2
- CDF Run1
- CDF Run2
- CMS Dijet, 8 TeV
- CMS Narrow Dijet, 13 TeV
- CMS Narrow Dijet, 13 TeV
- CMS Wide Dijet, 13 TeV
- ATLAS Boosted Dijet, 13 TeV
- ATLAS Dijet, 8 TeV
- UA2
- CDF Run1

\[ M_{Z'} \text{ [GeV]} \]

SUMMARY AND OUTLOOK

- Dark matter
- Data scouting
- Jet substructure
- b-tagging
- Machine learning
- Higgs couplings
- New triggers
- and more…

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