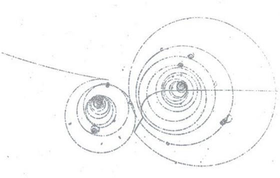
ATLAS Missing Energy Signatures and DM Effective Field Theories

Theoretical Perspectives on New Physics at the Intensity Frontier, Victoria, Canada

James D Pearce,
University of Victoria



Sept 11, 2014

OUTLINE

1. DM Effective Field Theories
    - EFT vs UV complete
    - Regions of validity
    - EFT operators
2. DM Detection methods
3. ATLAS monojet analysis
    - Signature
    - Selection
    - Background estimate
    - EFT Limits
4. Validity of DM EFT
    - Issue of large momentum transfer
    - ATLAS Strategy
5. Summary
6. Auxiliary Material

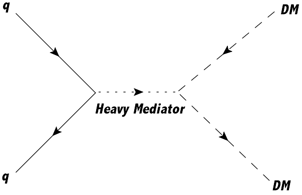
WHAT WE KNOW ABOUT DARK MATTER

1. It's neutral under electric charge, since it does not produce photons,
2. It's stable, or at least has a lifetime on cosmological scales,
3. It's non-baryonic, to preserve the success of ΛCDM,
4. It has a relic abundance consistent with weak scale mass and interactions.

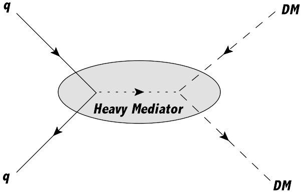
These seem to all point us to some sort of weakly interacting massive particle (WIMP). We can use an EFT to model what we know about DM, without resorting to any one specific UV complete theory (eg. SUSY, LED, etc.)

FROM UV COMPLETE TO EFT (I)

UV complete Theory



Effective Theory



By Taylor expanding the SM-DM propagator around the momentum transfer and only keeping the leading order we get an effective coupling constant:

$$\frac{1}{Q_{tr}^2 - M^2} = -\frac{1}{M^2}\left(1+\frac{Q_{tr}^2}{M^2}+\mathcal{O}\left(\frac{Q_{tr}^4}{M^4}\right)\right) \approx -\frac{1}{M^2}$$

This approximation is only valid if $Q_{tr} < M$ otherwise all other terms in the expansion (UV complete theory) must be considered.

FROM UV COMPLETE TO EFT (II)

Once the mediator has been "integrated out" we no longer talk about the parameter M, instead we replace it with Λ (or M_*), which parameterizes the energy scale of the EFT. $\Lambda = M/\sqrt{g_\chi g_q}$, where g_χ and g_q are the couplings of the mediator to the DM and quark fields. Given

- $Q_{tr} < M$
- Perturbation theory requires $g_\chi g_q < (4\pi)^2$
- Kinematics imposes $Q_{tr} > 2m_\chi$

So we can say:

$$\Lambda > \frac{Q_{tr}}{\sqrt{g_\chi g_q}} > \frac{Q_{tr}}{4\pi} > \frac{m_\chi}{2\pi}$$

Typically this is the region where EFTs are considered valid.

CONTACT INTERACTION OPERATORS

arXiv:1008.1783

Name	Operator	Coefficient
D1	$\bar{\chi}\chi\bar{q}q$	m_q/Λ^3
D2	$\bar{\chi}\gamma^5\chi\bar{q}q$	im_q/Λ^3
D3	$\bar{\chi}\chi\bar{q}\gamma^5 q$	im_q/Λ^3
D4	$\bar{\chi}\gamma^5\chi\bar{q}\gamma^5 q$	m_q/Λ^3
D5	$\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$	$1/\Lambda^2$
D6	$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu q$	$1/\Lambda^2$
D7	$\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu\gamma^5 q$	$1/\Lambda^2$
D8	$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^5 q$	$1/\Lambda^2$
D9	$\bar{\chi}\sigma^{\mu\nu}\chi\bar{q}\sigma_{\mu\nu} q$	$1/\Lambda^2$
D10	$\bar{\chi}\sigma_{\mu\nu}\gamma^5\chi\bar{q}\sigma_{\alpha\beta} q$	i/Λ^2
D11	$\bar{\chi}\chi G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/4\Lambda^3$
D12	$\bar{\chi}\gamma^5\chi G_{\mu\nu}G^{\mu\nu}$	$i\alpha_s/4\Lambda^3$
D13	$\bar{\chi}\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$i\alpha_s/4\Lambda^3$
D14	$\bar{\chi}\gamma^5\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$\alpha_s/4\Lambda^3$

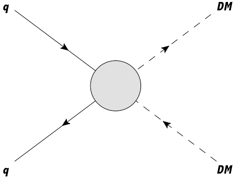
- The theory is then characterized by an effective Lagrangian $\mathcal{L}_{eff}$:

  $$\mathcal{L}_{eff} = \sum c_i O_i$$

  Where $c_i \sim \frac{1}{\Lambda^{d-4}}$ and O_i is an effective operator which is some Lorentz invariant combination of the SM and DM (χ) fields.
- Place limits on a representative set: D1 (scalar), D5 (vector), D8 (axial-vector), D9 (tensor) and D11 (couples to gluons)

DETECTION METHODS

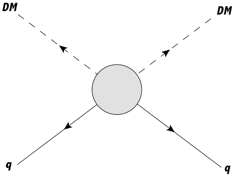
Collider



Experiments:

- ATLAS
- CMS
- D0
- CDF

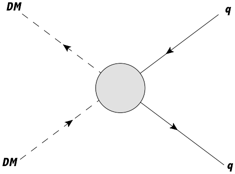
Direct detection



Experiments:

- XENON100
- CDMS
- SIMPLE
- CoGent
- IceCube
- Picasso
- COUPP

Indirect detection

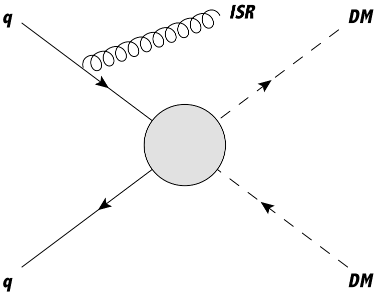


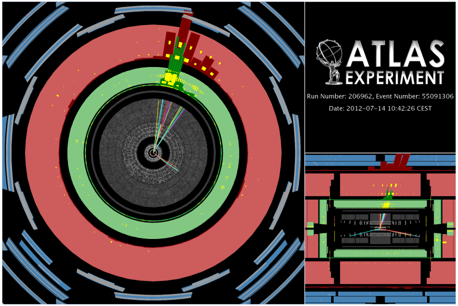
Experiments:

- Fermi-LAT
- PAMELA
- AMS-02
- WMAP
- Planck

...and many more

COLLIDER SIGNATURE

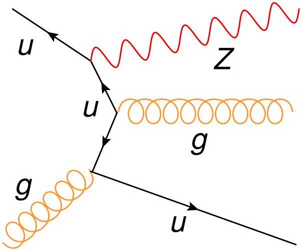




- Require 1 or 2 high-p_T ISR (Initial State Radiation) objects. ($jet/\gamma/W/Z$)
- Large momentum imbalance in the transverse plan (E_T^{miss})
- Zero high-p_T leptons

ATLAS-CONF-2012-147

BACKGROUNDS



$Z(\nu\nu) + jet(s)$

- Irreducible
- Data-driven estimate
- Dominant background: 50-70%

$W(l\nu)/Z(ll) + jet(s)$

- Lepton(s) not reconstructed/misidentified
- For W: 46-29%, Z: $< 1\%$

Multijet

- mis-measured jet
- Contribution $\ll 1\%$

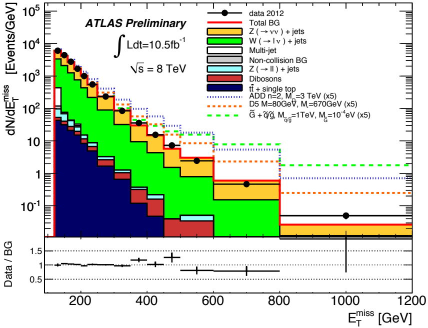
Diboson, $t\bar{t}$ single top

- Monte Carlo estimate
- Combined ≈1%

Non-Collision

- Beam halo, cosmic muons
- Contribution $\ll 1\%$

SIGNAL REGION SELECTION



- Orange dashed line indicates hypothetical DM signal ($\times$5)

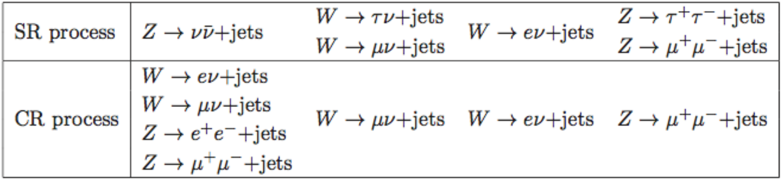
Selection:

- Trigger: $E_T^{miss} > 80$ GeV
- At least one primary vetex
- Lead jet: $p_T > 120$ GeV, $|\eta| < 2$
- lepton veto: e, μ
- Multijet suppression: $\Delta\phi(E_T^{miss}, \text{jet}_2) > 0.5$
- jet veto: $N_{\text{jet}} \leq 2$
- SR: E_T^{miss} >150 GeV
- Scan in E_T^{miss} for excess above background

EW BACKGROUND ESTIMATE

1. Select data events in CR: N_{CR}^{Data}
2. Remove (non-EW) backgrounds in CR: $(N_{CR}^{Data} - N_{CR}^{bkg})$
3. Factor out EW backgrounds in CR: $1 - F_{EW} = \frac{N_{CR}^{MC}}{\sum^{All\ EW} N_{CR}^{MC}}$
4. Transfer from lepton phase space to SR: $TF = \frac{N_{SR}^{MC}}{N_{CR}^{MC}}$

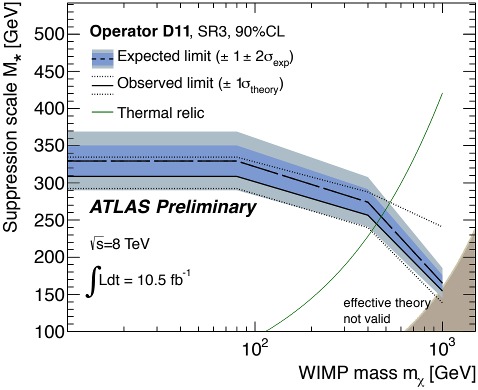
Master equation: $N_{SR}^{est} = (N_{CR}^{Data} - N_{CR}^{bkg}) \times (1 - F_{EW}) \times TF$
There are four CRs that can be used to estimate SR backgrounds:



SR process	$Z \rightarrow \nu\bar{\nu}$+jets	$W \rightarrow \tau\nu$+jets $W \rightarrow \mu\nu$+jets	$W \rightarrow e\nu$+jets	$Z \rightarrow \tau^+\tau^-$+jets $Z \rightarrow \mu^+\mu^-$+jets
CR process	$W \rightarrow e\nu$+jets $W \rightarrow \mu\nu$+jets $Z \rightarrow e^+e^-$+jets $Z \rightarrow \mu^+\mu^-$+jets	$W \rightarrow \mu\nu$+jets	$W \rightarrow e\nu$+jets	$Z \rightarrow \mu^+\mu^-$+jets

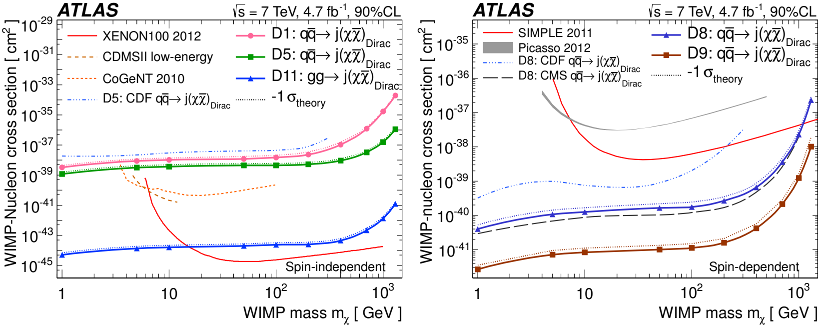
ENERGY SCALE LIMITS

arXiv:1210.4491



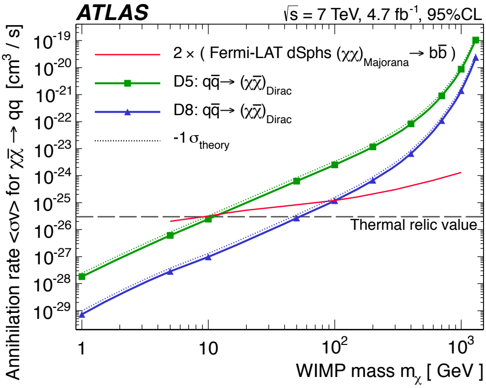
- Limits are taken from SR3 (jet $p_T > 350$ GeV and $E_T^{miss} > 350$ GeV).
- Λ ($M_* = \Lambda$) below observed line are excluded.
- Green line indicates the Λ values at which WIMPs of a given mass would result in the required relic abundance.
- The shaded grey regions indicate where the effective field theory approach breaks down.

WIMP-NUCLEON SCATTERING LIMITS



- Cross sections above observed are excluded.
- Assumption is that DM interacts with SM particles solely by a given operator
- Spin Independent operators: D1, D5, D11
- Spin Dependent operators: D8, D9

WIMP ANNIHILATION LIMITS



- Comparison with FERMI-LAT is possible through our EFT

- The results can also be interpreted in terms of limits on WIMPs annihilating to light quarks
- All limits shown here assume 100% branching fractions of WIMPs annihilating to quarks
- Below 10 GeV for D5 and 70 GeV for D8 the ATLAS limits are below the values needed for WIMPs to make up the DM relic abundance

MOMENTUM TRANSFER AT THE LHC

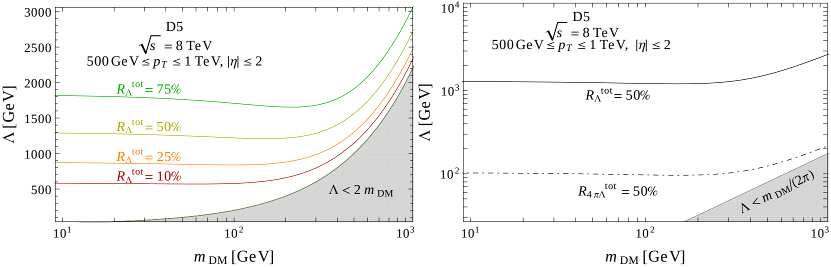
arXiv:1402.1275

Now lets revisit our assumption that $Q_{tr} < M$. Setting $g_\chi g_q = 1$ the truncation to the lowest-dimensional operator of the EFT expansion is accurate only if $Q_{tr} < \Lambda$. What fraction of events pass this condition?

$$R_\Lambda^{\mathrm{tot}} \equiv \frac{\sigma|_{Q_{\mathrm{tr}}<\Lambda}}{\sigma} = \frac{\int_{p_\mathrm{T}^{\mathrm{min}}}^{p_\mathrm{T}^{\mathrm{max}}} \mathrm{d}p_\mathrm{T} \int_{-2}^{2} \mathrm{d}\eta \left.\dfrac{\mathrm{d}^2\sigma}{\mathrm{d}p_\mathrm{T}\mathrm{d}\eta}\right|_{Q_{\mathrm{tr}}<\Lambda}}{\int_{p_\mathrm{T}^{\mathrm{min}}}^{p_\mathrm{T}^{\mathrm{max}}} \mathrm{d}p_\mathrm{T} \int_{-2}^{2} \mathrm{d}\eta \dfrac{\mathrm{d}^2\sigma}{\mathrm{d}p_\mathrm{T}\mathrm{d}\eta}}$$

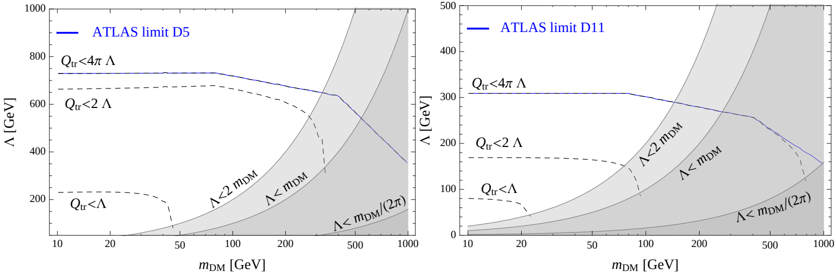
Where $0.5 < p_T < 1$TeV and $|\eta| < 2$.

REGIONS OF VALIDITY



- Even only requiring 10% of the events to pass significantly reduces the phase space.
- Highest fraction of EFT-valid events fall in the low mass region, where LHC bounds are the most competitive.
- EFT-valid region highly dependent upon value of $g_\chi g_q$.

LIMITS RE-EVALUATED



Limits can be rescaled with $R_\Lambda^{\rm tot}$, taking into account the dimension of the operator:

$$\Lambda > [R_\Lambda^{\rm tot}(m_\chi)]^{1/[2(d-4)]}\Lambda_{expt}$$

- For maximal couplings, $g_\chi g_q = (4\pi)^2$, bounds are essentially the same.
- For couplings $g_\chi g_q \sim 1$ previous ATLAS bounds are over estimated.

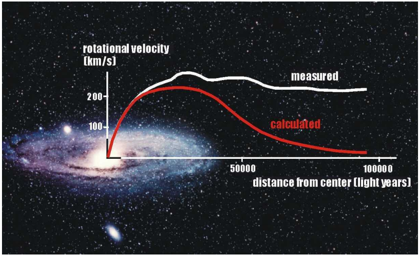
SUMMARY

- EFTs allow us to search for WIMPs in a model-independent way as well as compare results from different experiments and signatures.
- The monojet searches at the LHC are competitive and complementary to direct and indirect detection experiments.
- However, the large momentum transfer at the LHC reduces the phase space in which EFTs can be reliably used.

Auxiliary slides

EVIDENCE FOR DARK MATTER (I)

Galactic Rotation Curves



- Galactic rotation curves show stars orbit at the same speeds
- This implies mass density of galaxies is uniform.

Strong Gravitational Lensing

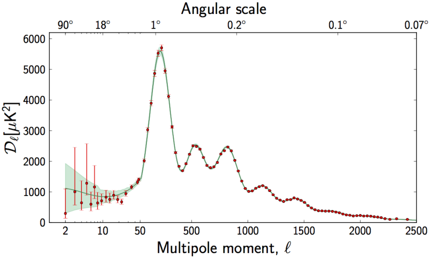
- Image of Abell 1689 cluster as observed by the hubble telescope
- The mass of galaxies is not enough to account for the strong gravitational lensing.

EVIDENCE FOR DARK MATTER (II)

Weak Gravitational Lensing

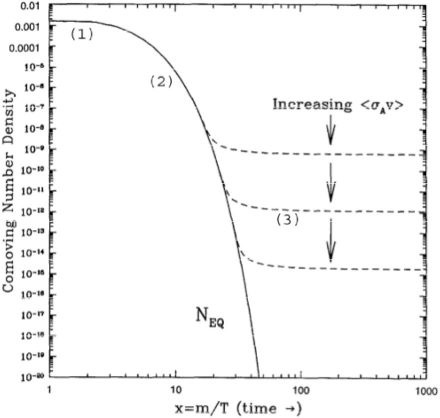
- Two galaxy clusters colliding.
- The pink shows the x-ray emissions.
- Blue shows unseen mass as measured with weak gravitational lensing techniques.

Cosmic Microwave Background



- Anisotropies in the CMB are due to acoustic oscillations in the early universe.
- Angular scales of the oscillations reveal the different effects of baryonic matter and DM.

RELIC ABUNDANCE AND THE "WIMP MIRACLE"

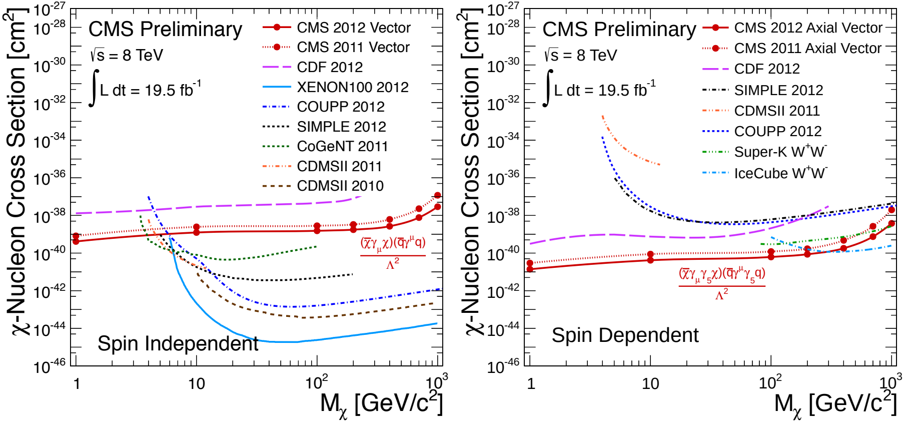


1. DM and SM particles are in thermal (chemical) equilibrium.
2. Universe expands and cools; DM production drops exponentially ($\sim e^{-m_\chi/T}$).
3. Energy drops below DM production threshold; DM abundance remains constant ("Freeze out").

We are left with a relic abundance of DM:

$$\Omega_\chi \propto \frac{1}{\langle\sigma v\rangle} \sim \frac{m_\chi^2}{g_\chi{}^4}$$

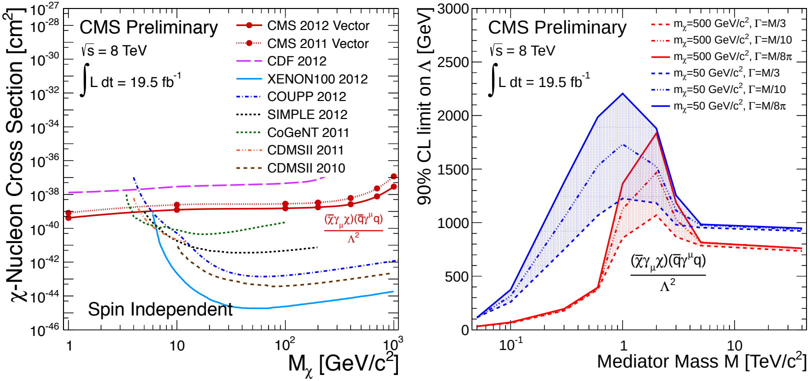
WIMP-Nucleon Scattering Limits



- Cross sections above observed are excluded.
- Assumption is that DM interacts with SM particles solely by a given operator
- Yellow contours show candidate events from CDMS: arXiv:1304.4279

CMS-PAS-EXO-12-048

WIMP-NUCLEON SCATTERING LIMITS



- CMS (2012) limits for D5 (vector) operator
- Light mediator model is studied to see how limits change with mediator mass, WIMP mass and decay width.