"Dark matter searches" with a focus on new techniques (Mono-X)

WIN2013: Natal, Brazil

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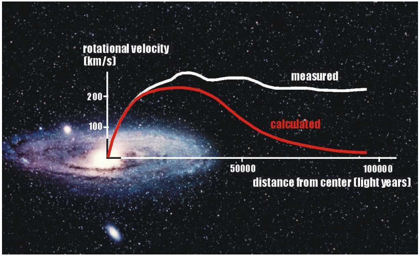
On behalf of the ATLAS and CMS collaborations

Sept 16, 2013

OUTLINE

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

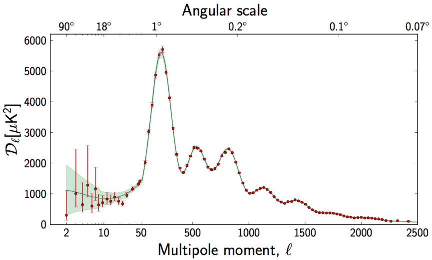
- Image of Abell 1689 cluster as observed by the hubble telescope
- The mass of galaxies is not enough to account for the strong gravitational lensing.

EVIDENCE FOR DARK MATTER (II)

Weak Gravitational Lensing

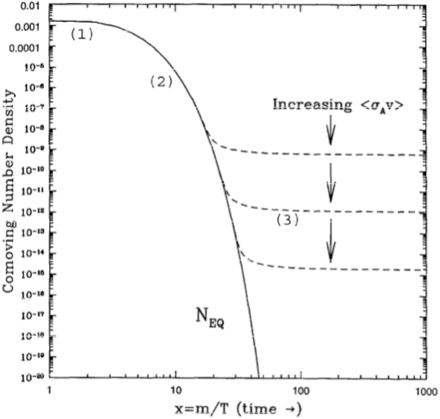
- Two galaxy clusters colliding.
- The pink shows the x-ray emissions.
- Blue shows unseen mass as measured with weak gravitational lensing techniques.

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:

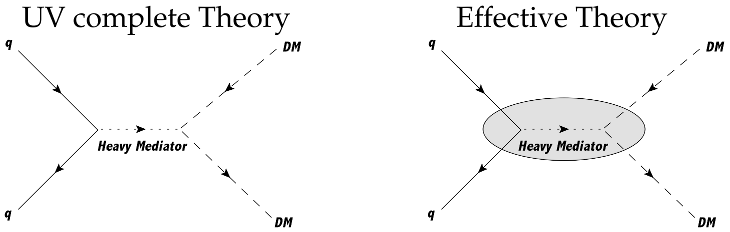
$$\Omega_\chi \propto \frac{1}{\langle \sigma v \rangle} \sim \frac{m_\chi^2}{g_\chi{}^4}$$

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)



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 $Q_{tr}^2 \ll M^2$ 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 M_*, which parameterizes the energy scale of the EFT. M_* is the most important parameter of the theory, it's related to the mediator mass and couplings, and tells us where the EFT approach breaks down:

- $M_* = M/\sqrt{g_\chi g_q}$, where g_χ and g_q are the couplings of the mediator to the DM and quark fields.
- 4-momentum conservation requires $m_\chi < M/2$
- Perturbation theory requires $g_\chi g_q < (4\pi)^2$
- Therefore our EFT is valid for $m_\chi < 2\pi M_*$

This EFT language allows us to relate different experimental signatures in a model-independent way. As we'll see the relic abundance, direct detection signal, and collider predictions depend only on M_*.

FROM UV COMPLETE TO EFT (III)

arXiv:1008.1783

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

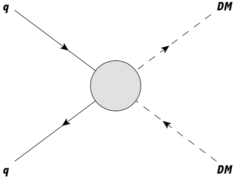
- The theory is then characterized by an effective Lagrangian $\mathcal{L}_{eff}$:

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

  Where $c_i \sim \frac{1}{{M_*}^{d-4}}$ 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

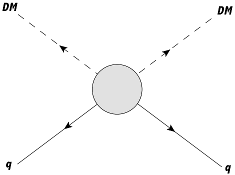
Collider



Experiments:

- ATLAS
- CMS
- D0
- CDF

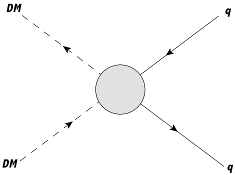
Direct detection



Experiments:

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

Indirect detection

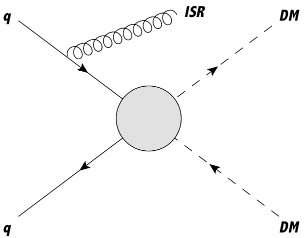


Experiments:

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

...and many more

Monojet Analysis (ATLAS/CMS)



EW background estimate (ATLAS):

- $N_{SR}^{est} = (N_{CR}^{Data} - N_{CR}^{bkg}) \times (1 - F_{EW}) \times TF$
- where $1 - F_{EW} = \frac{N_{CR}^{MC}}{\sum^{All\ EW} N_{CR}^{MC}}$
- and $TF = \frac{N_{SR}^{MC}}{N_{CR}^{MC}}$

Main Backgrounds:

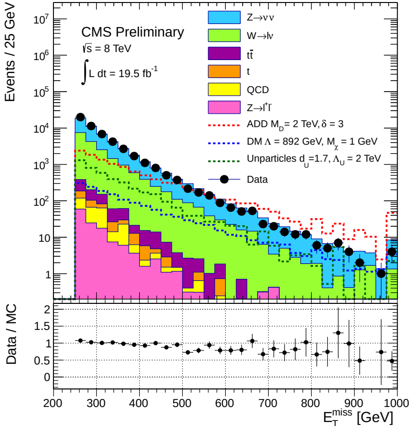
- $Z(\rightarrow \nu\nu)+$ jet(s) (50-70%)
- $W(\rightarrow l^{\text{inv}}\nu)$ + jet(s) (46-29%)
- $Z(\rightarrow l^{\text{inv}} l^{\text{inv}})$ + jet(s) (4-0%)

MC EW background estimate (CMS):

- $Z+$ jets, $W+$ jets, $t\bar{t}$ and single top:
- MadGraph $\rightarrow$ Phythia6: Z2Star tune with CTEQ6L1 pdf

CMS-PAS-EXO-12-048 ATLAS-CONF-2012-147

MONOJET ANALYSIS (CMS)

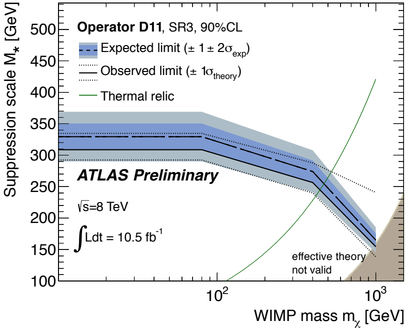


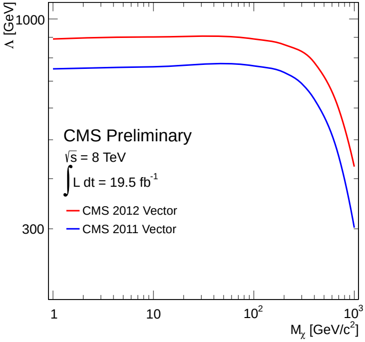
Selection

- Trigger: $E_T^{miss} > 80$ GeV
- Lead jet: $p_T > 110$ GeV, $|\eta| < 2.4$
- lepton veto: e, μ, τ
- $\Delta\phi(\text{jet}_1, \text{jet}_2) < 2.5$
- jet veto: $N_{\text{jet}} \leq 2$
- Scan in E_T^{miss}

Blue dashed line indicates hypothetical DM signal

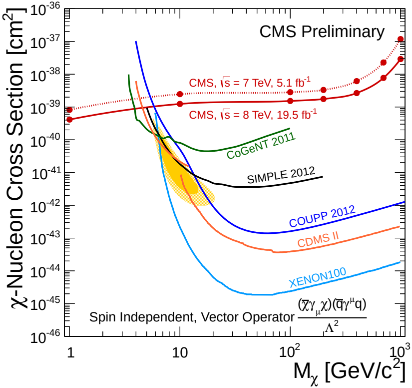
ENERGY SCALE LIMITS

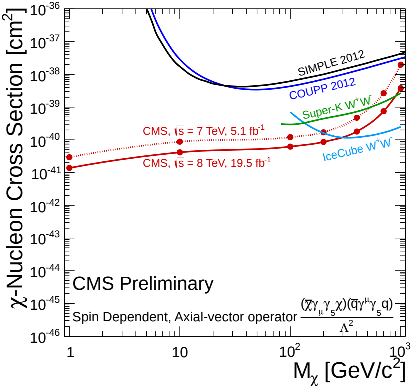




- Green line indicates the M_* values at which WIMPs of a given mass would result in the required relic abundance.
- M_* limits above the thermal relic line means exclusion or negative interference or additional annihilation (e.g. to leptons)
- The light-grey region indicates where the EFT breaks down.

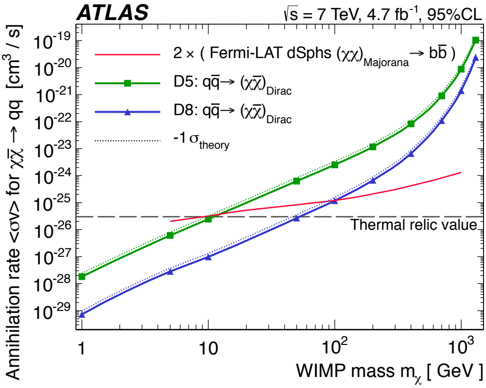
WIMP-Nucleon Scattering Limits





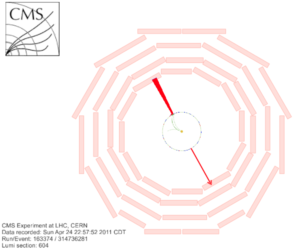
- Cross sections above observed are excluded.
- Assumption is that DM interacts with SM particles solely by a given operator: SI = D5, SD = D8
- Yellow contours show candidate events from CDMS: arXiv:1304.4279

WIMP ANNIHILATION LIMITS



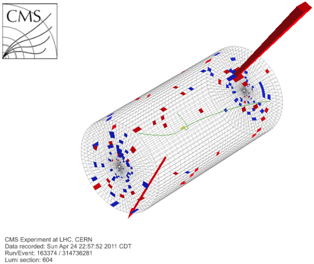
- Comparison with FERMI-LAT is possible through our EFT
- The results can also be interpreted in terms of limits on WIMPs annihilating to light quarks
- All limits shown here assume 100% branching fractions of WIMPs annihilating to quarks
- Below 10 GeV for D5 and 70 GeV for D8 the ATLAS limits are below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

MONOPHOTON ANALYSIS (CMS)



Background Estimates

- All backgrounds estimated with MC
- Z/γ(NLO), di-γ and $\gamma+$ jet $\leftarrow$ Pythia6 with CTEQ6L1
- $W\gamma$(NLO) $\leftarrow$ MadGraph5



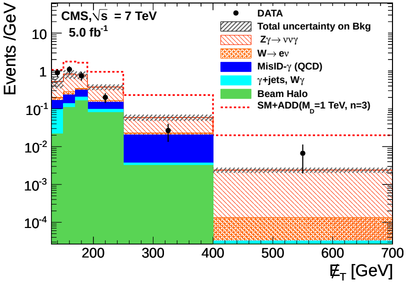
Main Backgrounds:

- $Z\gamma \to \nu\nu + \gamma$ (60%)
- $W\gamma \to l^{\text{inv}}\nu + \gamma$, di-$\gamma$ and $\gamma+$ jet (5%)
- Fake photons (20%)

CMS-EXO-11-096 CERN-PH-EP-2012-209

MONOPHOTON ANALYSIS

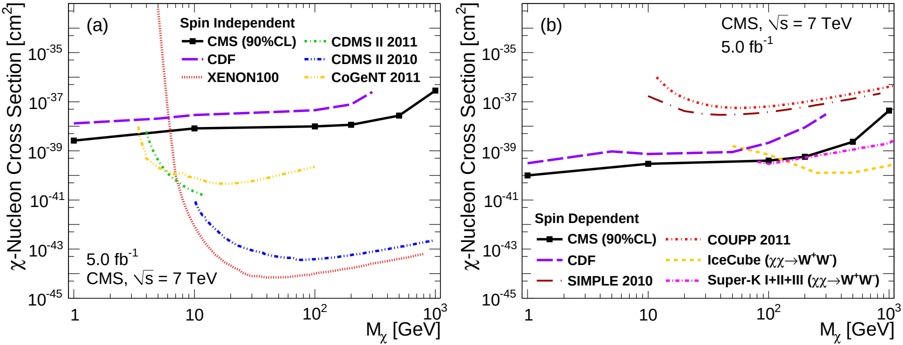
Source	Estimate
Jet Mimics Photon	11.2 ± 2.8
Beam Halo	11.1 ± 5.6
Electron Mimics Photon	3.5 ± 1.5
$W\gamma$	3.0 ± 1.0
γ+jet	0.5 ± 0.2
$\gamma\gamma$	0.6 ± 0.3
$Z(\nu\bar{\nu})\gamma$	45.3 ± 6.9
Total Background	75.1 ± 9.5
Total Observed Candidates	73



Selection:

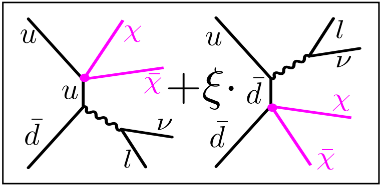
- Trigger: Single photon
- Photon: $p_T > 145$ GeV, $|\eta| < 1.44$ (barrel region)
- Energy ratio: HCAL/ECAL < 0.05 within $\Delta R < 0.15$
- Lepton veto and hadronic activity veto
- Isolated photons
- jet veto: $N_{\text{jet}} \leq 2$
- SR: $E_T^{miss} > 130$ GeV, $|\eta| < 4.5$

WIMP-NUCLEON SCATTERING LIMITS



- Cross sections above observed are excluded.
- Spin-dependent/independent limits correspond to D8 and D5 operators.
- Not sensitive to D11 (gluon) operator.

MONO-W/Z ANALYSES (ATLAS/CMS)



Two possible diagrams lead to interference:

1. $\xi = -1$: signal enhanced
   - leads to stronger signal than monojet!
2. $\xi = +1$: signal suppressed

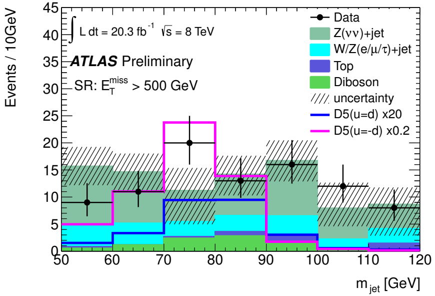
Two different strategies:

1. ATLAS: look for a single fat-jet with internal structure (mono-W/Z)
   - Same backgrounds as monojet analysis
   - Similar data-driven background estimate
2. CMS: look for single lepton (mono-W)
   - $W \to l\nu$, $t\bar{t}$, single top, Drell-Yan, diboson
   - Background estimated from MC

CMS-EXO-12-060 ATLAS-CONF-2013-073

MONO-W/Z A.K.A. MONO-FATJET (ATLAS)

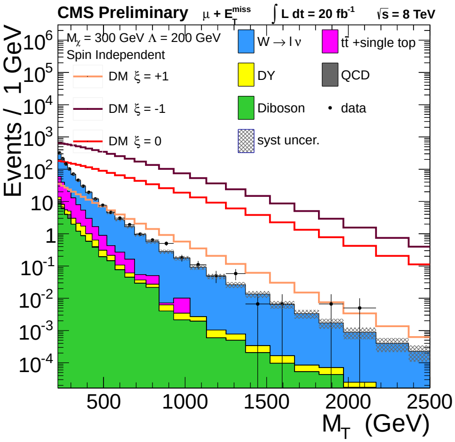
Process	$E_T^{miss} > 350$ GeV	$E_T^{miss} > 500$ GeV
$Z \to \nu\bar{\nu}$	400^{+39}_{-34}	54^{+8}_{-10}
$W \to \ell^{\pm}\nu, Z \to \ell^{\pm}\ell^{\mp}$	210^{+20}_{-18}	22^{+4}_{-5}
WW, WZ, ZZ	57^{+11}_{-8}	$9.1^{+1.3}_{-1.1}$
$t\bar{t}$, single t	39^{+10}_{-4}	$3.7^{+1.7}_{-1.3}$
Total	710^{+48}_{-38}	89^{+9}_{-12}
Data	705	89



Selection:

- Trigger: $E_T^{miss} > 80$ GeV
- Fat jet: Cambridge-Aachen algorithm, R = 1.2, first two sub-jets balanced ($\sqrt{y} > 0.4$), $p_T > 250$ GeV, $|\eta| < 1.2$, $m_{jet} = 50 - 120$ GeV
- Veto leptons (e, μ) and photons
- $t\bar{t}$ supression: veto if $>= 2$ AntiKt4 jets with $\Delta R(\text{jet}_{Fat}, \text{jet}_{AntiKt4}) > 0.9$ OR $\Delta\phi(E_T^{miss}, \text{jet}) < 0.4$ for any AntiKt4 jets.
- SR: $E_T^{miss} > \{350, 500\}$ GeV

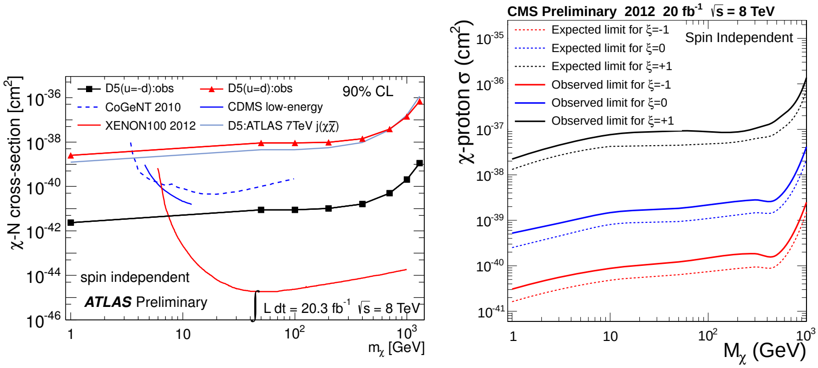
MONO-W A.K.A. MONO-LEPTON (CMS)



Selection:

- Trigger: single muon ($p_T > 40$ GeV) or electron ($p_T > 80$ GeV) triggers
- Muons: $p_T > 45$ (offline) GeV, $|\eta| < 2.1$, isolated
- Electrons: $p_T > 100$ (offline) GeV, $|\eta| < 1.442$ or $1.566 < |\eta| < 2.5$, isolated
- Back-to-back kinematics: $0.4 < p_T/E_T^{miss} < 1.5$ AND $\Delta\phi(E_T^{miss}, l) > 0.8\pi$
- SR: $m_T > \{1, 1.5, 2\}$ TeV

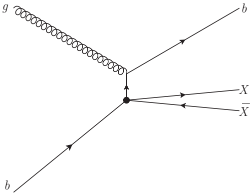
WIMP-Nucleon Scattering Limits



- Cross sections above observed are excluded.
- Assuming constructive interference gives better limits then ATLAS monojet and monophoton combined!
- Not sensitive to D11 (gluon) operator.

MONO-b

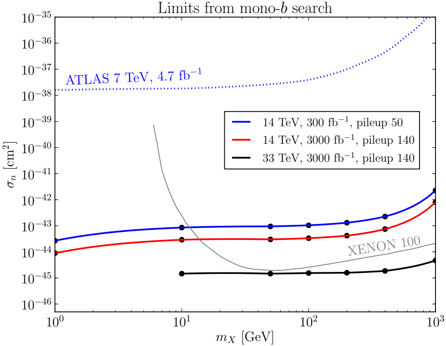
arXiv:1307.7834



Motivation:

- D1 is proportional to the initial quark mass (D1 $\sim \frac{m_q}{M_*^3}$)
- By approximate QCD flavour symmetry the outgoing quark will be a b
- Analysis for 2012 data is currently underway (ATLAS)

- Despite the kinematic and PDF suppression for producing third generation quarks improvement on limits is up to 3 orders of magnitude!

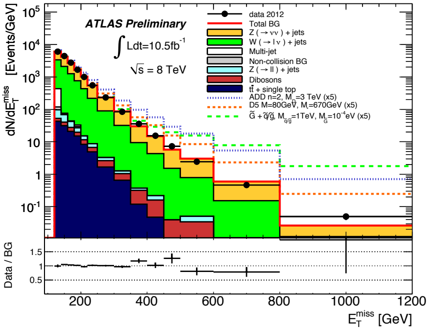


SUMMARY

- WIMPs are well motivated by what we know about Dark Matter and the observed relic abundance.
- EFT's allow us to search for WIMPs in a model-independent way as well as compare results from different experiments and signatures.
- Mono-X searches at the LHC are competitive and complementary to direct and indirect detection experiments.

Auxiliary slides

Monojet Analysis(ATLAS)



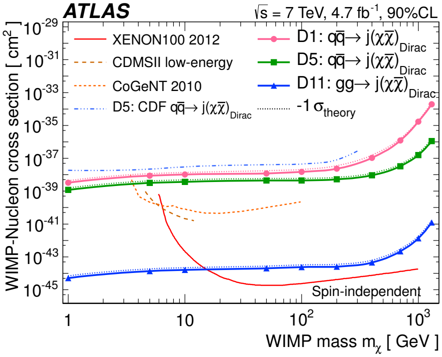
- Orange dashed line indicates hypothetical DM signal ($\times 5$)

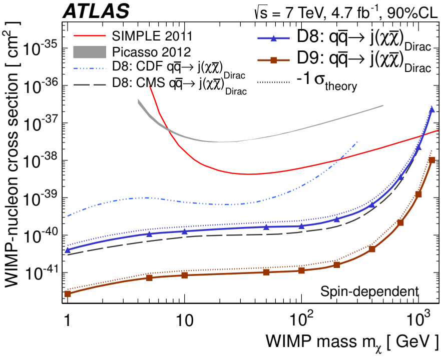
Selection:

- 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:
  $E_T^{miss} > \{120, 220, 350, 500\}$ GeV
  jet $p_T > \{120, 220, 350, 500\}$ GeV

WIMP-Nucleon Scattering Limits

arXiv:1210.4491

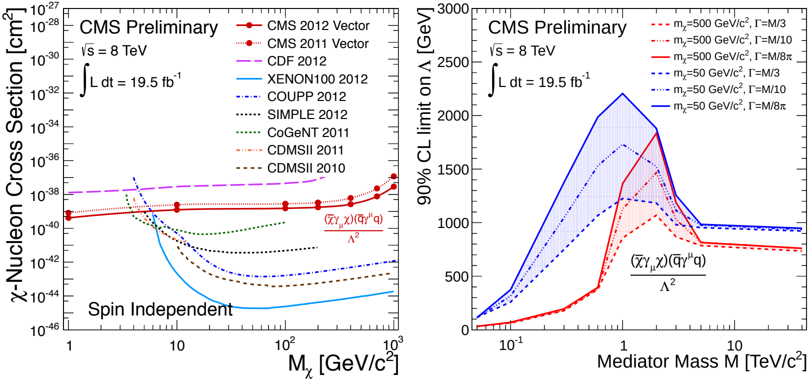




- Cross sections above observed are excluded.
- Assumption is that DM interacts with SM particles solely by a given operator

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.