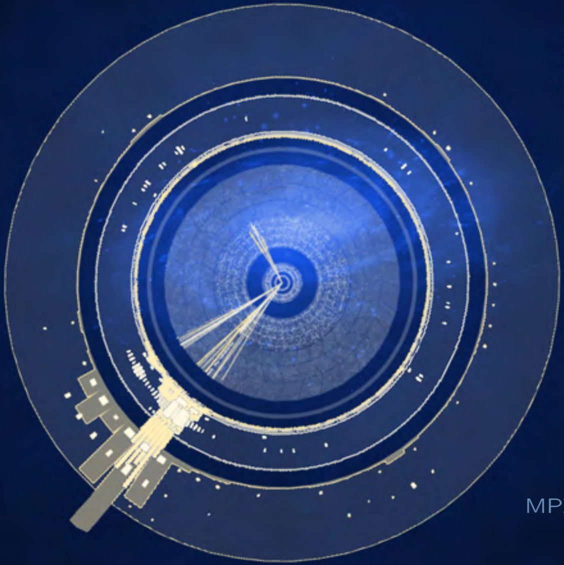
Search for the WIMPs at the LHC

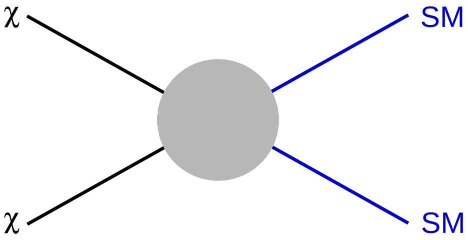


Sandra Kortner
MPI für Physik, München

Final Symposium of the Sino-German GDT Cooperation • Ringberg Castle • 19.10.2015

Shedding light on dark matter

Search for the $\boxed{\text{dark matter}}$ through its interactions with the Standard Model particles:



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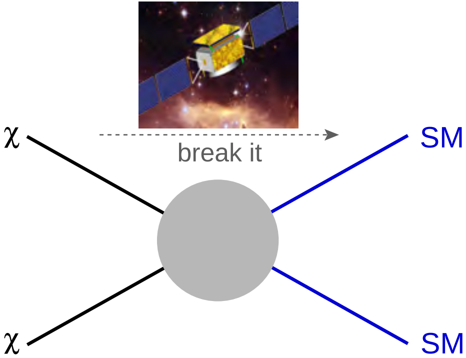

Indirect detection

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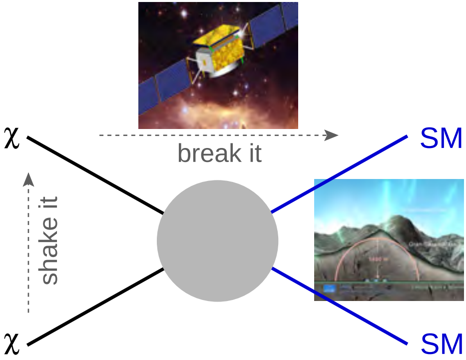

Indirect detection

Direct detection

Shedding light on dark matter

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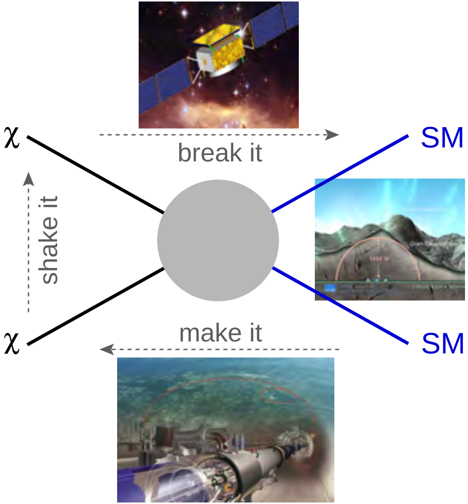
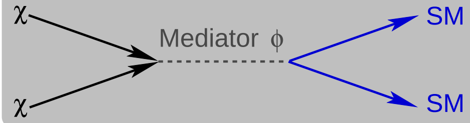
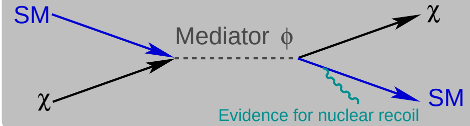


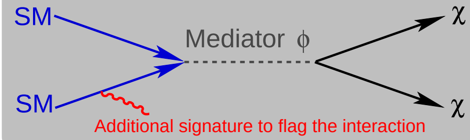
Indirect detection



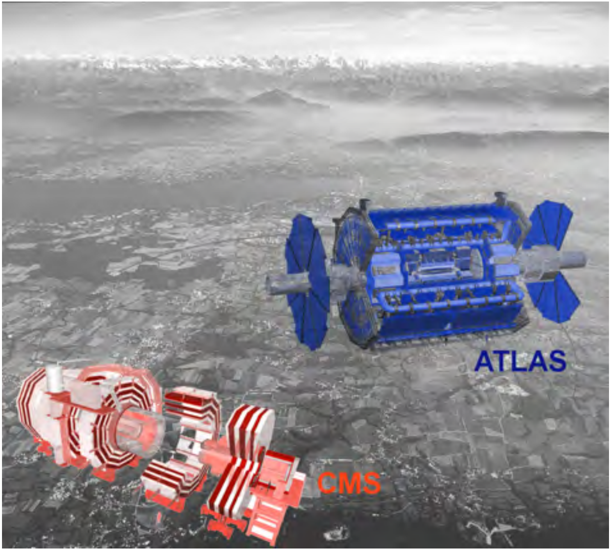
Direct detection



Production at colliders



ATLAS and CMS detectors at the LHC



LHC proton-proton collisions:

Period	$\sqrt{s}$ energy (TeV)	Collected data (fb^{-1})
Run-I		
2010	7	0.04
2011	7	6
2012	8	23
Run-II		
2015	13	2.6
until 2024	14	300
HL-LHC		
2026-2035	14	3000

What are we looking for?

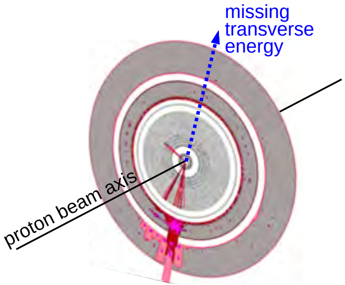
Weakly interacting massive particles (WIMPs) as candidates for the cold dark matter:

- Color-neutral, not engaged in strong interactions.
- Electricaly neutral (otherwise they would be visible).
- Weak interactions are allowed.
  But, the couplings to $W^{\pm}$ and Z weaker than those of other SM particles.
- Spin is not constrained. (It can be fermionic, or scalar, or vector, ...)

$\Rightarrow$ WIMP escapes the detector without being observed, similarly as neutrino.

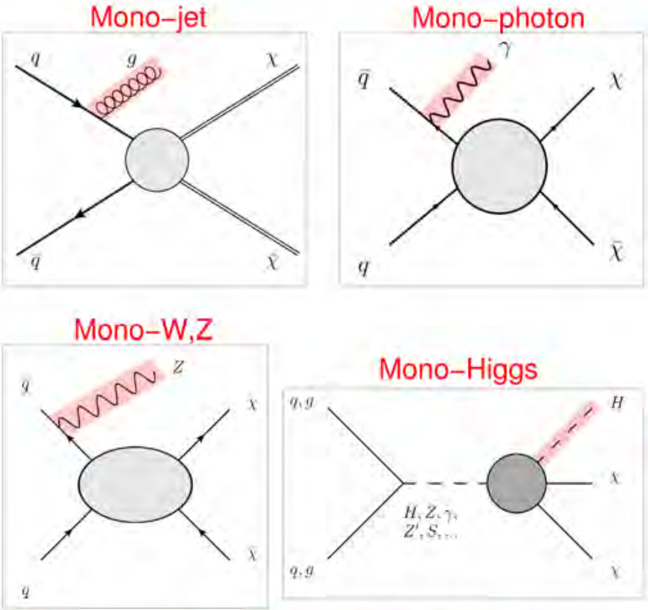
- Search for a large missing energy E_T^{miss} on a plane transverse to the proton beam.
- Deduced from the measured transverse momenta of all detected particles:

$$E_T^{miss} = -\sum_i \vec{p}_T^{\,i}$$
$(i \equiv all\ visible\ particles)$



- Need at least one detectable particle produced in addition to WIMPs ($pp \to \chi\bar{\chi} + X$), in order to tag the WIMP event candidates $\Rightarrow$,,Mono-X signatures".

Mono-mania



Also: Mono–top–quark, mono–b–quark(s) ...

Make it,
but don't fake it!

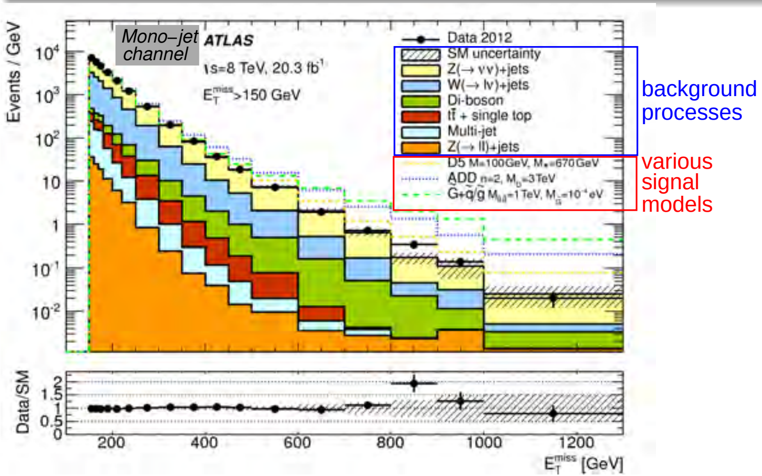
Background processes:

Estimated based on the Monte Carlo simulation and signal-free control data.

- $\boxed{pp \to Z(\to \nu\nu) + jets}$
- $pp \to W(\to \ell\nu) + jets$
- $pp \to Z(\to \ell\ell) + jets$
- $pp \to t\bar{t}$
- $pp \to WW, ZZ, Z\gamma, \gamma\gamma$
- $pp \to multijets$

Interpreting the data

Comparing data with the expected background and signal contributions.



- Discovery: if an excess of events above the expected background is observed, with a very small probability ($<2{\cdot}10^{-7}$) of background fluctuations faking the signal.
- Signal exclusion: sufficiently small probability that the observed data come from the signal rather than from the background.
  A stronger signal (i.e. higher expected cross section) can be more easily excluded.

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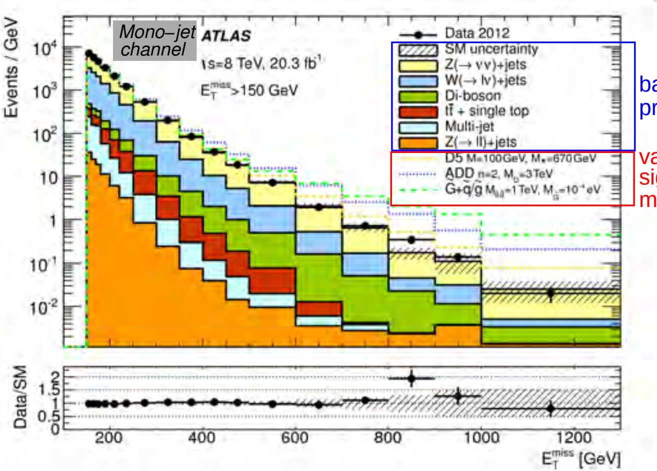

Event selection criteria and signal exclusion limits depend on the signal model.

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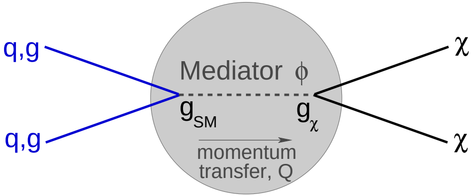
Dark matter effective field theory (EFT)

Assuming a contact interaction between the dark matter and Standard Model particles:



Assume a new heavy mediator $(m_\phi \gg Q)$ which is not accessible on-shell at LHC.

Integrating out the general propagator $\longrightarrow$ EFT propagator.

$$\frac{g_{SM} g_\chi}{Q^2 - m_\phi^2} \longrightarrow \frac{g_{SM} g_\chi}{m_\phi^2} \equiv \frac{1}{\Lambda^2}$$

Λ (or $M_\star$): energy scale of the new physics

$\Rightarrow$ EFT: all details inside the blob can be ignored.

Example: interaction of fermionic dark matter with a heavy vector mediator.

$$\mathcal{L} \sim g_\chi \phi_\mu \bar{\chi} \gamma^\mu \chi + g_q \phi_\mu \bar{q} \gamma^\mu q + \frac{1}{2} m_\phi^2 \phi_\mu \phi^\mu + \ldots \longrightarrow \mathcal{L} \sim \frac{1}{\Lambda^2} (\bar{\chi} \gamma_\mu \chi)(\bar{q} \gamma^\mu q)$$

ϕ to $\chi\chi$ coupling — ϕ to qq coupling — mediator mass term — operator for the vector coupling of fermionic DM to SM particles

In general, new physics described by a number of higher-dimensional operators: (suppressed by the powers of Λ)

$$\mathcal{L} \sim \mathcal{L}_{SM} + \sum \mathcal{L}^{(d)}_{effective}, \text{ where } \mathcal{L}^{(d)}_{effective} = \frac{1}{\Lambda^{d-4}} \mathcal{O}^{(d)}.$$

A zoo of models

Fermionic dark matter (Dirac fermions)

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	$(\bar{\chi}\gamma^5\chi)(G_{\mu\nu}\tilde{G}^{\mu\nu})$	$\alpha_s/4\Lambda^3$

Scalar dark matter

Name	Operator	Coefficient
C1	$(\chi^\dagger\chi)(\bar{q}q)$	m_q/Λ^2
C2	$(\chi^\dagger\chi)(\bar{q}\gamma^5 q)$	im_q/Λ^2
C3	$(\chi^\dagger\partial_\mu\chi)(\bar{q}\gamma^\mu q)$	$1/\Lambda^2$
C4	$(\chi^\dagger\partial_\mu\chi)(\bar{q}\gamma^\mu\gamma^5 q)$	$1/\Lambda^2$
C5	$(\chi^\dagger\chi)(G_{\mu\nu}G^{\mu\nu})$	$\alpha_s/4\Lambda^2$
C6	$(\chi^\dagger\chi)(G_{\mu\nu}\tilde{G}^{\mu\nu})$	$i\alpha_s/4\Lambda^2$
R1	$(\chi^2)(\bar{q}q)$	$m_q/2\Lambda^2$
R2	$(\chi^2)(\bar{q}\gamma^5 q)$	$im_q/2\Lambda^2$
R3	$(\chi^2)(G_{\mu\nu}G^{\mu\nu})$	$\alpha_s/8\Lambda^2$
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D7	$(\bar{\chi}\gamma^\mu\chi)(\bar{q}\gamma_\mu\gamma^5 q)$	$1/\Lambda^2$
D8	$(\bar{\chi}\gamma^\mu\gamma^5\chi)(\bar{q}\gamma_\mu\gamma^5 q)$	$1/\Lambda^2$
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Concentrating on selected operators with different characteristic E_T^{miss} shapes:

Scalar mediators (Spin-independent interactions)

Vector mediators (Spin-independent interactions)

Axial-vector mediators (Spin-dependent interactions)

Tensor mediators (Spin-dependent interactions)

Strategy for the model testing

In general, our signal model can be a combination of several contact interactions.

For example, for fermionic dark matter:

$$\mathcal{L} \sim \sum_q \left(\frac{m_q}{\Lambda_{D1}^3} \bar{q} q \bar{\chi} \chi + \frac{1}{\Lambda_{D5}^2} \bar{q} \gamma^\mu q \bar{\chi} \gamma_\mu \chi + \frac{1}{\Lambda_{D8}^2} \bar{q} \gamma^\mu \gamma^5 q \bar{\chi} \gamma_\mu \gamma^5 \chi + \frac{1}{\Lambda_{D9}^2} \bar{q} \sigma^{\mu\nu} q \bar{\chi} \sigma_{\mu\nu} \chi + \ldots \right)$$

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However, it is more common to treat only one operator at a time.

- Assume that the dark matter interacts only through one operator $\mathcal{O}_i$.
- Compare the measured cross-section $\sigma(pp \to \chi\chi + X)$ to the one predicted for this operator, $\sigma(\mathcal{O}_i) = f(m_\chi, \Lambda_{\mathcal{O}_i})$.

$\Rightarrow$ No excess of events above the expected background is observed.

$\Rightarrow$ Set the lower exclusion limit on $\Lambda_{\mathcal{O}_i}$ ($\equiv M_{\star,\mathcal{O}_i}$) in dependence on WIMP mass m_χ.

- Repeat the procedure for all studied operators.

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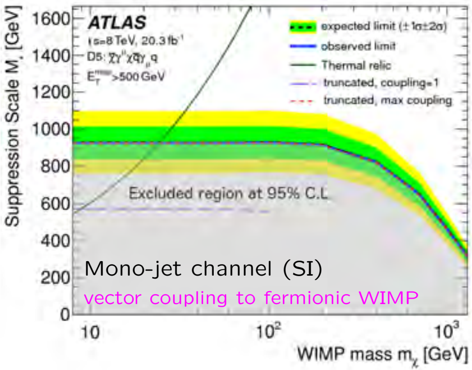
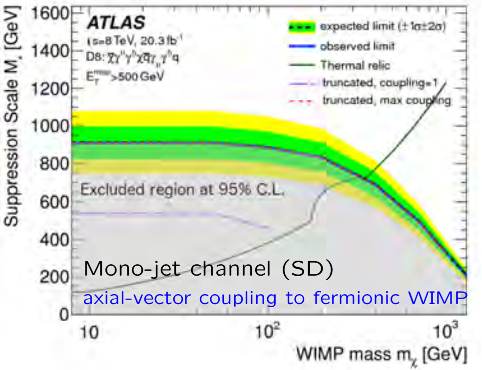




Operator	Lower bound on Λ (GeV) assuming $m_\chi = 10$ GeV	WMAP thermal relic constraints(*) on m_χ (GeV)
D5	920	>20
D1	38	>20
D11	360	>500
C5	190	no bound
D8	900	>400
D9	1420	>50

(*) Assuming that DM is entirely composed entirely of thermal relics,
has only one type of contact interaction and decays exclusively to SM particles.

The trouble with the EFT

- The limits on Λ are obtained assuming that EFT is a valid approach: i.e. the mediator mass is considerably larger than the energy scale of the interaction, $m_\phi \equiv \Lambda \cdot \sqrt{g_\chi g_{SM}} \gg Q$.
- At the LHC, the typical momentum transfer at $\sqrt{s}$ =7 TeV is $\underline{< Q > \approx 1 \text{ TeV}}$. This may already considerably compete with the mediator mass m_ϕ.
- For a given lower bound Λ_{excl}, the exact EFT validity regime depends on $\sqrt{g_\chi g_{SM}}$, which is constrained by the requirement of the theory perturbativity:

$$
\begin{aligned}
max(\sqrt{g_\chi g_{SM}}) < & \ \mathcal{O}(1) \text{ for C5, D11;} \\
& \ \mathcal{O}(10) \text{ for D1, D5, D8, D9;} \\
& \ \mathcal{O}(100) \text{ for C1;}
\end{aligned}
$$

EFT-based exclusion limits are valid only for events in which $\Lambda_{excl} \cdot max(\sqrt{g_\chi g_{SM}}) > Q$.

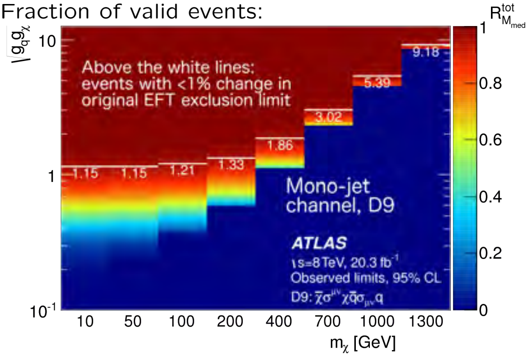
For even lower coupling values, the number of valid events is further reduced.

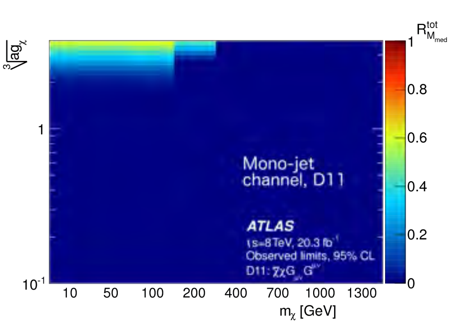
$\Rightarrow$ Reduced sensitivity to Λ, reduced range of explored WIMP masses.

Truncated exclusion limits

Considering only valid events, i.e. events in which $\Lambda_{excl} \cdot \sqrt{g_\chi g_{SM}} > Q$.

Fraction of valid events:



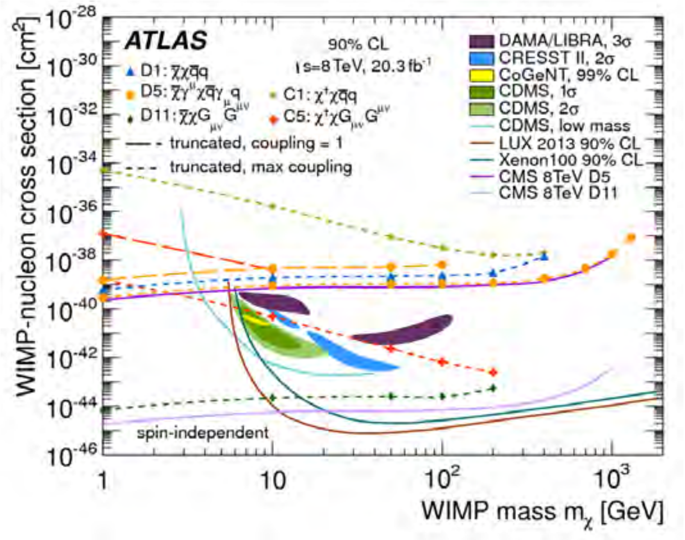


Operator	Valid $m_\chi - range$ (GeV) max. coupling	Valid $m_\chi - range$ (GeV) $g_\chi = g_{SM} = 1$	Λ_{excl} (GeV) for $m_\chi = 10$ GeV no truncation	Λ_{excl} (GeV) max coupling	Λ_{excl} (GeV) $g_\chi = g_{SM} = 1$
D5	full range	<100	920	920	570
D1	<200	none	38	38	none
D11	<200	none	360	320	none
C5	<200	none	190	190	none
D8	full range	<100	900	900	540
D9	full range	<200	1420	1420	1380

⇒ EFT in general good in case of maximal couplings, but problematic for couplings=1.

Limits on the WIMP-nucleon scattering (SI)

Lower bound Λ_{excl} can be translated to an upper bound on the WIMP-nucleon scattering,
$\sigma(\Lambda) \propto \frac{1}{\Lambda^d} \cdot \frac{m_\chi m_N}{m_\chi + m_N}$; d=4 for D5,D8,D9,C1,C5; d=6 for D1,D11



Mono-jet channel (most powerful)

Spin-independent:

LHC competitive with the direct searches in the region of low WIMP masses.

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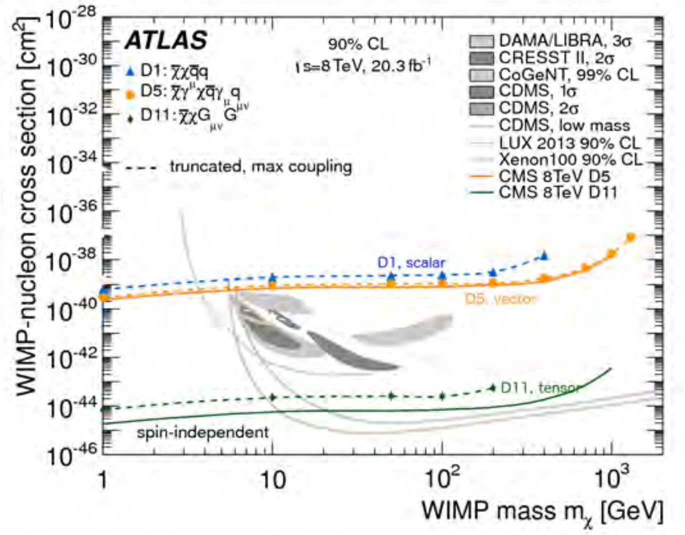

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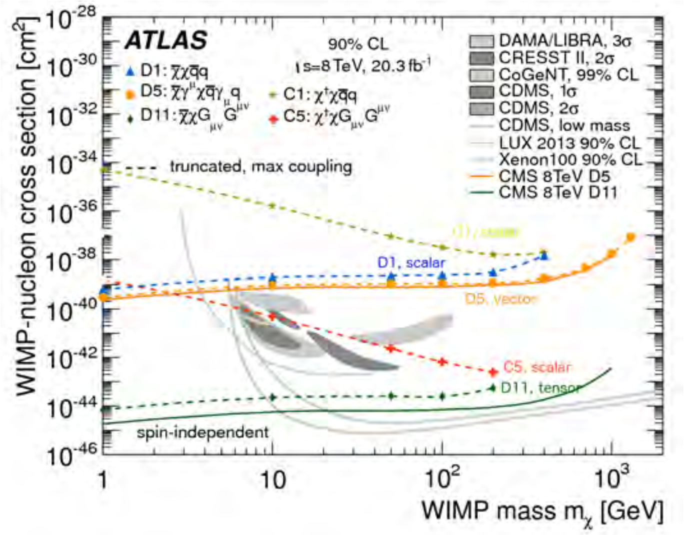

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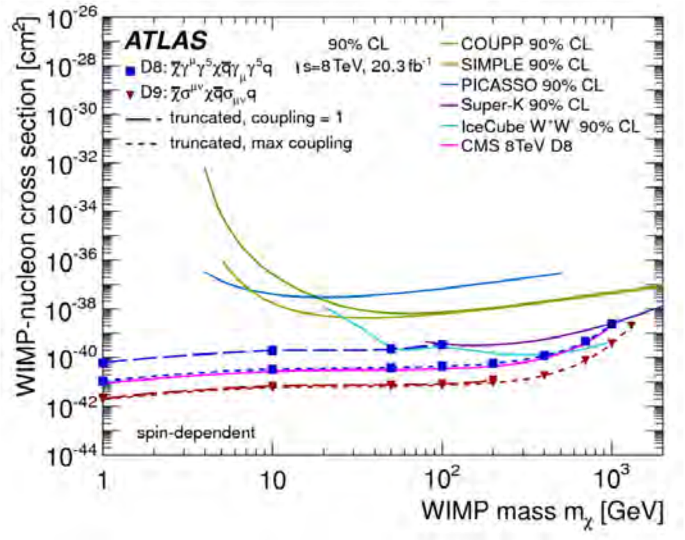

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LHC outperforms
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(Even for couplings=1.)

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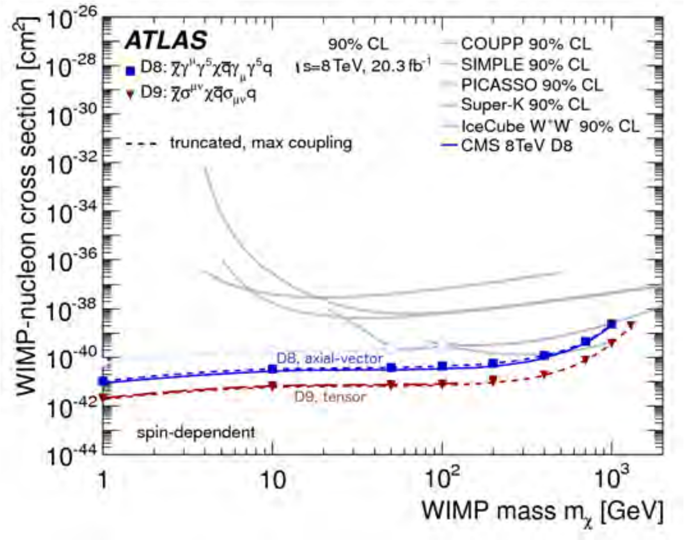

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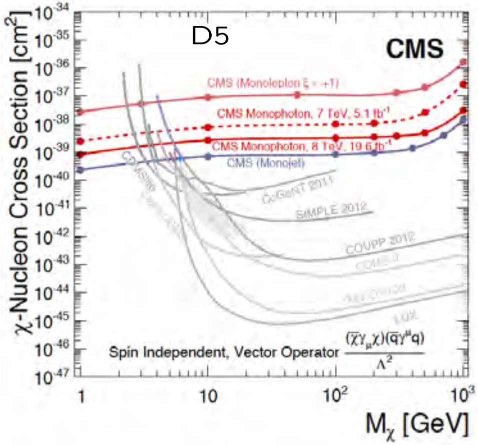
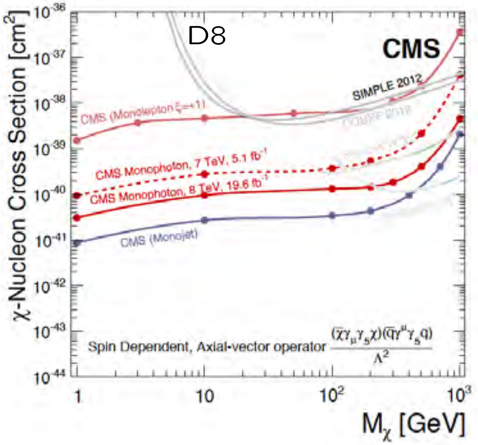
Comparison of different mono-X searches

List of recent ATLAS and CMS mono-X searches:

Channel	ATLAS	CMS	Studied operators
Mono-jet	arXiv:1502.01518	arXiv:1408.3583	D1,D5,D8,D9,D11,C1,C5
Mono-photon	arXiv:1411.1559	arXiv:1410.8812	D5,D8,D9
Mono-V(lep)	arXiv:1404.0051	arXiv:1408.2745	D1,D5,D9
Mono-V(had)	arXiv:1309.4017	EXO-12-055	D1,D5,D8,D9,C1
Mono-bottom	arXiv:1410.4031	-	D1,D9,C1
Mono-top	arXiv:1410.5404	B2G-14-004	top quark couplings
Mono-Higgs	arXiv:1506.01081	-	Higgs couplings

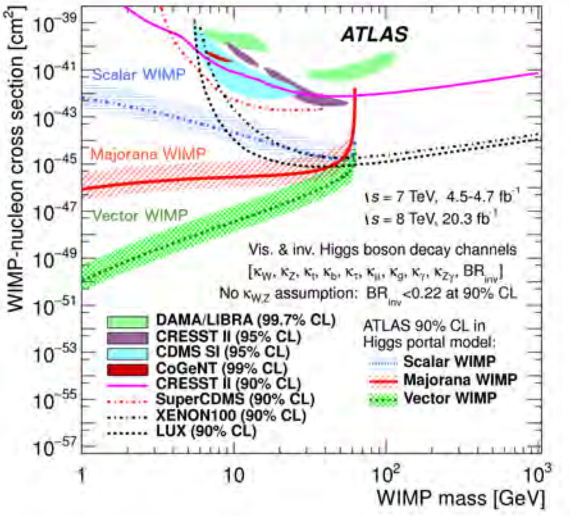




Higgs portal to dark matter

Direct and indirect searches for the Higgs boson decays to invisible particles:
$BR(H \rightarrow \ invisible) < 0.22$ at 90% C.L.

$\Rightarrow$ Translated into the limits on the $H \rightarrow \chi\chi$ coupling, and reparametrized in terms of the spin-independent WIMP-nucleon scattering via Higgs boson exchange.



arXiv:1509.00672

Assumption:
dark matter couples
only to the Higgs boson.

New strategies for new data

Average momentum transfer at 13-14 TeV grows up to 2.5 TeV!

$\Rightarrow$ Move away from the EFT to simplified models.

arXiv:1507.00966

Dark Matter Benchmark Models for Early LHC Run-2 Searches: Report of the ATLAS/CMS Dark Matter Forum

Daniel Abercrombie, Nural Akchurin, Ece Akilli, Juan Alcaraz Maestre, Brandon Allen, Barbara Alvarez Gonzalez, Jeremy Andrea, Alexandre Arbey, Georges Azuelos, Patrizia Azzi, Mihailo Backović, Yang Bai, Swagato Banerjee, James Beacham, Alexander Belyaev, Antonio Boveia, Amelia Jean Brennan, Oliver Buchmueller, Matthew R. Buckley, Giorgio Busoni, Michael Buttignol, Giacomo Cacciapaglia, Regina Caputo, Linda Carpenter, Nuno Filipe Castro, Guillelmo Gomez Ceballos, Yangyang Cheng, John Paul Chou, Arely Cortes Gonzalez, Chris Cowden, Francesco D'Eramo, Annapaola De Cosa, Michele De Gruttola, Albert De Roeck, Andrea De Simone, Aldo Deandrea, Zeynep Demiragli, Anthony DiFranzo, Caterina Doglioni, Tristan du Pree, Robin Erbacher, Johannes Erdmann, Cora Fischer, Henning Flaecher, Patrick J. Fox, et al. (94 additional authors not shown)

(Submitted on 3 Jul 2015)

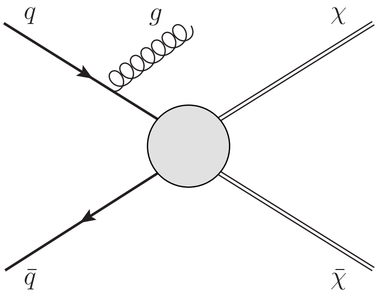
This document is the final report of the ATLAS-CMS Dark Matter Forum, a forum organized by the ATLAS and CMS collaborations with the participation of experts on theories of Dark Matter, to select a minimal basis set of dark matter simplified models that should support the design of the early LHC Run-2 searches. A prioritized, compact set of benchmark models is proposed, accompanied by studies of the parameter space of these models and a repository of generator implementations. This report also addresses how to apply the Effective Field Theory formalism for collider searches and present the results of such interpretations.

Basic assumptions of each simplified model:

- One single kind of DM particle (Dirac fermion), only one interaction type at a time.
- Only signatures with pairs of dark matter.
- Explore basic possibilities for mediators of various spins and couplings.
- Mediator has a minimal decay width,
  i.e. only decays which are strictly needed for the consistency of the model.

Example of a simplified model

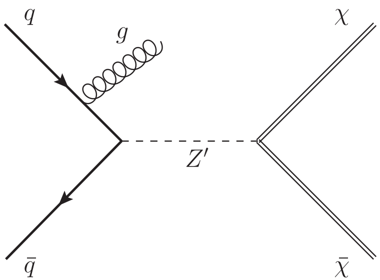
Effective field theory: D5 coupling



$$\sigma \propto \frac{1}{\Lambda^4}$$

$\Rightarrow$ one free parameter

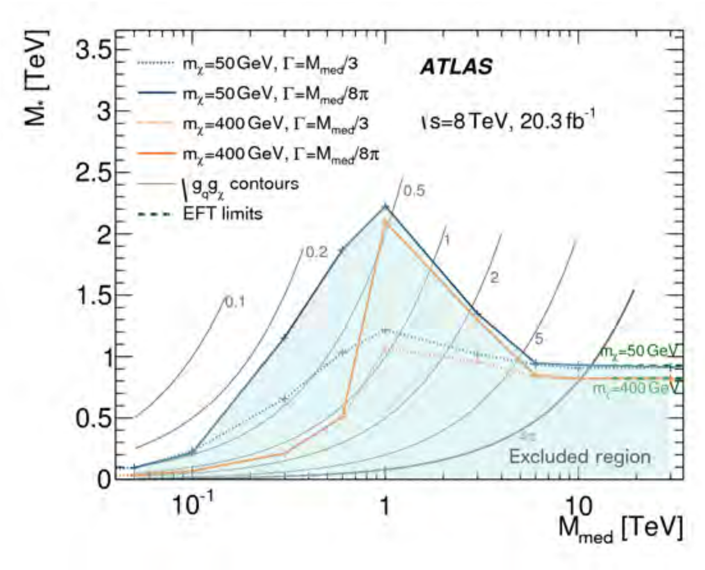
Simplified model: vector mediator



$$\sigma \propto \frac{g_{SM}^2 g_\chi^2}{M_{Z'}^4 \Gamma_{Z'}}$$

$\Rightarrow$ four free parameters

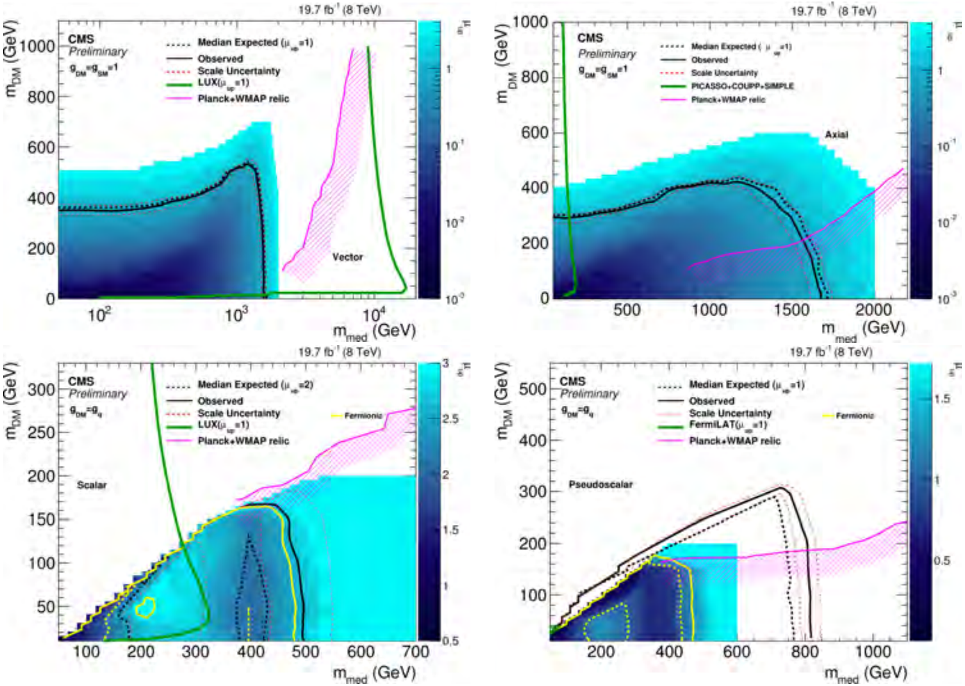
Comparison of the two approaches



Limits expected to improve by a factor of two at 14 TeV (for the same integrated luminosity).

- EFT regime reached for $M_{med} > 5$ TeV.
- In the intermediate range (0.7-5 TeV): mediator would be produced resonantly, leading to pessimistic EFT limits.
- For low M_{med}: DM heavier than Z', decays kinematically suppressed, leading to too optimistic EFT limits.

Excluded regions for different mediators



A word on Supersymmetry

In addition to the presented model-independent or simplified-model dark matter searches, indirect searches via a thorough test of selected complete theories containing dark matter candidates are performed:

- Kaluza-Klein excitations in theories with extra dimensions.
- Lightest supersymmetric particle, LSP, (neutralino, gravitino,...) in Supersymmetry.

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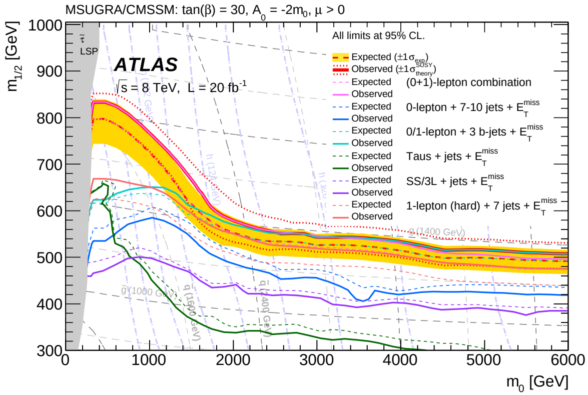

Strong interactions:
gluino-pair, squark-pair and squark-gluino production.

Cascade decays with LSP in the final state.

Excluding masses up to $\sim$1.5 TeV.
$\Rightarrow$ No natural solution to hierarchy problem,...

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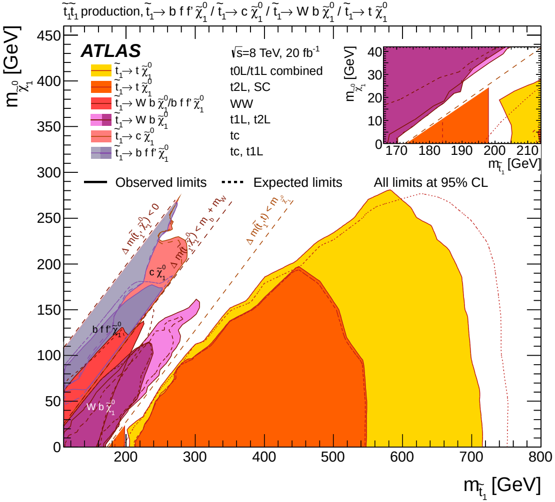

... unless m_{stop} is smaller than masses of other squarks.
$\Rightarrow$ dedicated top-squark searches.

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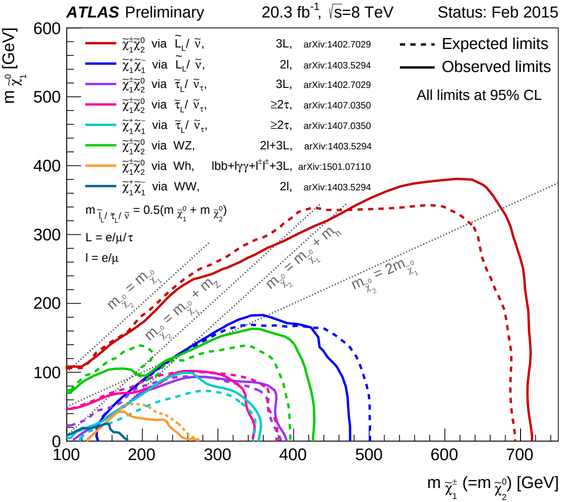


Electroweak interactions:

if all squarks and gluinos have masses above the TeV scale, weak gauginos may be the only accessible sparticles.

Summary

Dark matter searches at the LHC are evolving rapidly.

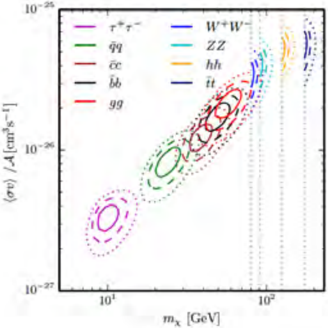
Interpretation of data done in context of EFT and simplified models, exploring the nature of dark matter interactions with the SM.

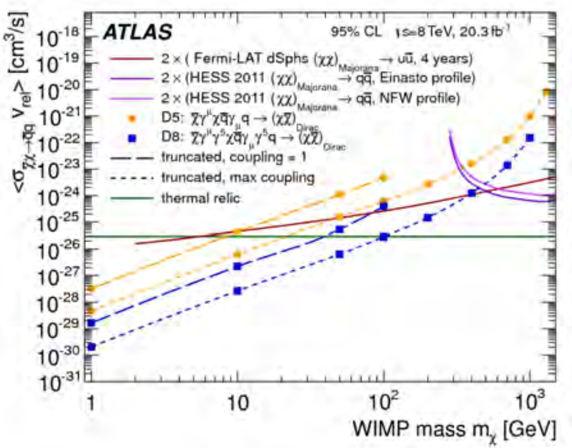
No signal discovered yet.
Complementary results to direct and indirect detection experiments.

Run-II has just started...

Backup

Fermi-LAT excess





Fermi-LAT excess