Non-SUSY WIMPS: Simplified models and DM@LHC

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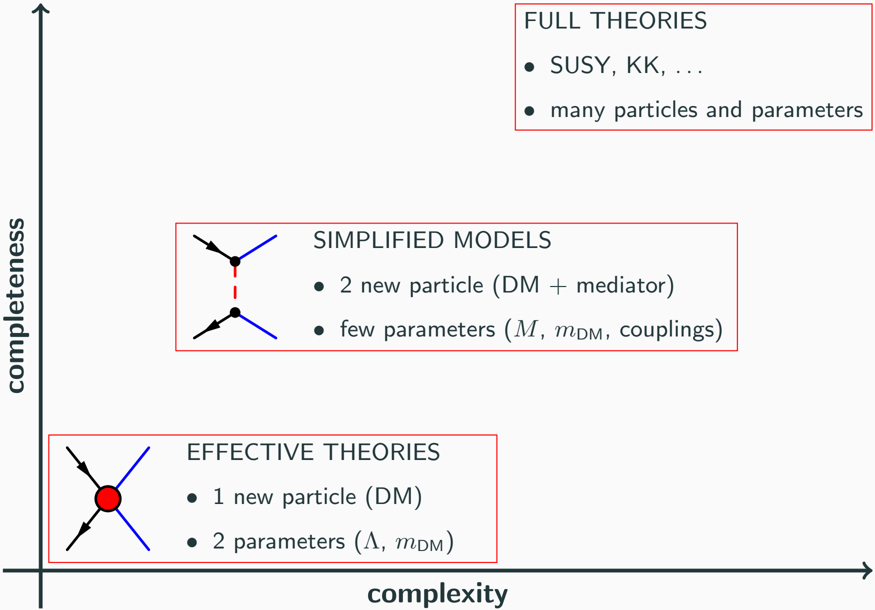
Quy Nhon - July 27th, 2017

13^{th} Rencontres du Vietnam: Exploring the Dark Universe

Simplified models

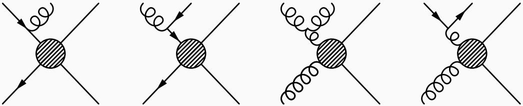
DM "models"



FULL THEORIES
• SUSY, KK, ...
• many particles and parameters
SIMPLIFIED MODELS
• 2 new particle (DM + mediator)
• few parameters (M, m_{DM}, couplings)
EFFECTIVE THEORIES
• 1 new particle (DM)
• 2 parameters (Λ, m_{DM})
completeness
complexity

EFT description

The simplest description is EFT
with initial state radiation



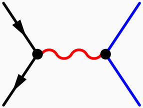
- Write a complete set of operators (*e.g.* in the s-channel)
- Suppose DM interact only through one of those
- Derive bounds on the plane (m_{DM}-Λ)
- Easy comparison with other searches

Name	Operator	Coefficient
D1	$\bar{\chi}\chi\ \bar{q}q$	m_q/Λ^3
D1'	$\bar{\chi}\chi\ \bar{q}q$	$1/\Lambda^2$
D2	$\bar{\chi}\gamma^5\chi\ \bar{q}q$	im_q/Λ^3
D2'	$\bar{\chi}\gamma^5\chi\ \bar{q}q$	i/Λ^2
D3	$\bar{\chi}\chi\ \bar{q}\gamma^5 q$	im_q/Λ^3
D3'	$\bar{\chi}\chi\ \bar{q}\gamma^5 q$	i/Λ^2
D4	$\bar{\chi}\gamma^5\chi\ \bar{q}\gamma^5 q$	m_q/Λ^3
D4'	$\bar{\chi}\gamma^5\chi\ \bar{q}\gamma^5 q$	$1/\Lambda^2$
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	$\bar{\chi}\sigma_{\mu\nu}\gamma^5\chi\ \bar{q}\sigma^{\mu\nu} q$	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	$\bar{\chi}\gamma^5\chi\ G^{\mu\nu}\tilde{G}_{\mu\nu}$	$\alpha_s/4\Lambda^3$
DT1	$(\bar{\chi}P_L q)\ (\bar{q}P_R\chi)$	$1/\Lambda^2$

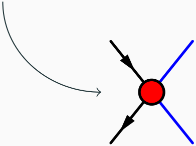
Goodman+, 1008.1783

Validity of the EFT

The validity of EFTs is limited in energy by their cut-off scale



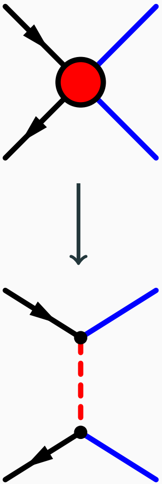
$$\sim \frac{g_\chi g_q}{Q_{\rm tr}^2 - M^2} = -\frac{g_\chi g_q}{M^2}\left[1 + \frac{Q_{\rm tr}^2}{M^2} + \dots\right]$$



$$\equiv \frac{1}{\Lambda^2}(\bar{\chi}\Gamma_A \chi)(\bar{q}\Gamma_B q)$$

One should be sure that the energy scale of the process under study is below the cut-off Λ (assuming $\mathcal{O}(1)$ couplings).

Simplifed Models



✓ Can grasp the most relevant physical features of a full theory including DM

✓ Theoretically consistent

✓ Richer phenomenology: other channels and searches complementary to mono-X

✗ More parameters (couplings) → higher dimensional space to constrain

✗ No exhaustive list

✗ Not always applicable (*e.g.* strong coupling)

LHC Dark Matter Working Group

A joint effort between experimentalists and theorists, built on the previous ATLAS-CMS DM forum (final report 1507.00966, with more than 100 people involved)

- Define recommendations for well-defined and exhaustive benchmark models
- Encourage communication between experimentalists and theorists working on collider physics (and possibly other probes)

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https://lpcc.web.cern.ch/content/lhc-dm-wg-wg-
    dark-matter-searches-lhc
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Naive construction: s-channel mediator

Bottom-up approach: build simplified models by expanding the effective operators.

$$\mathcal{L}_{\rm S} \supset -\frac{1}{2}M_{\rm med}^2 S^2 - y_\chi S\bar{\chi}\chi - y_q^{ij} S\bar{q}_i q_j + \text{h.c.}\,,$$
$$\mathcal{L}_{\rm P} \supset -\frac{1}{2}M_{\rm med}^2 P^2 - y'_\chi P\bar{\chi}\gamma_5\chi - y_q'^{ij} P\bar{q}_i\gamma_5 q_j + \text{h.c.}\,,$$
$$\mathcal{L}_{\rm V} \supset \frac{1}{2}M_{\rm med}^2 V_\mu V^\mu - g_\chi V_\mu\bar{\chi}\gamma^\mu\chi - g_q^{ij} V_\mu\bar{q}_i\gamma^\mu q_j\,,$$
$$\mathcal{L}_{\rm A} \supset \frac{1}{2}M_{\rm med}^2 A_\mu A^\mu - g'_\chi A_\mu\bar{\chi}\gamma^\mu\gamma_5\chi - g_q'^{ij} A_\mu\bar{q}_i\gamma^\mu\gamma_5 q_j$$

Common benchmarks:

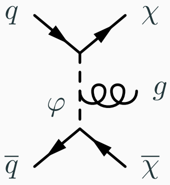
$$V: \begin{cases} g_\chi = 1, g_q = 0.25, g_\ell = 0 \\ g_\chi = 1, g_q = 0.1, g_\ell = 0.01 \end{cases} \qquad A: \begin{cases} g_\chi = 1, g_q = 0.25, g_\ell = 0 \\ g_\chi = 1, g_q = 0.1, g_\ell = 0.1 \end{cases}$$

Naive construction: t-channel mediator

Coloured scalar mediator in the t-channel:

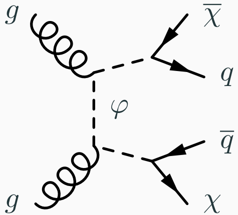
$$\mathcal{L} \supset g_M \sum_i \left(\bar{Q}_L^i \widetilde{Q}_L^i + \bar{u}_R^i \tilde{u}_R^i + \bar{d}_R^i \tilde{d}_R^i \right) \chi + \text{mass terms} + c.c.$$

Mono-jet: gluon emission from the mediator



Kinematical distribution altered wrt EFT

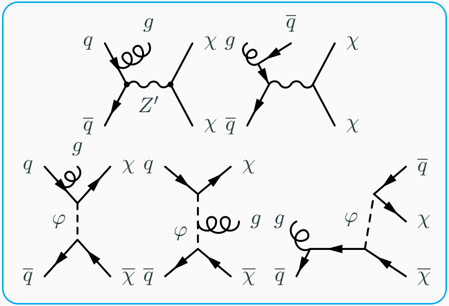
Even stronger constraints from di-jet + MET



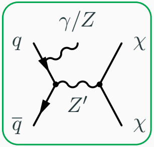
Absent in the EFT approx.

Papucci, Vichi, Zurek, 1402.2285

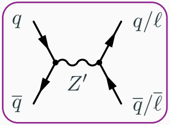
LHC results on simplified models



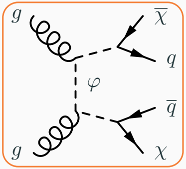
mono-jet



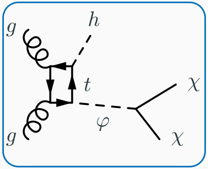
mono-γ/Z



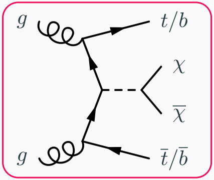
resonant searches:
di-jet, di-leptons. . .



di-jet + MET

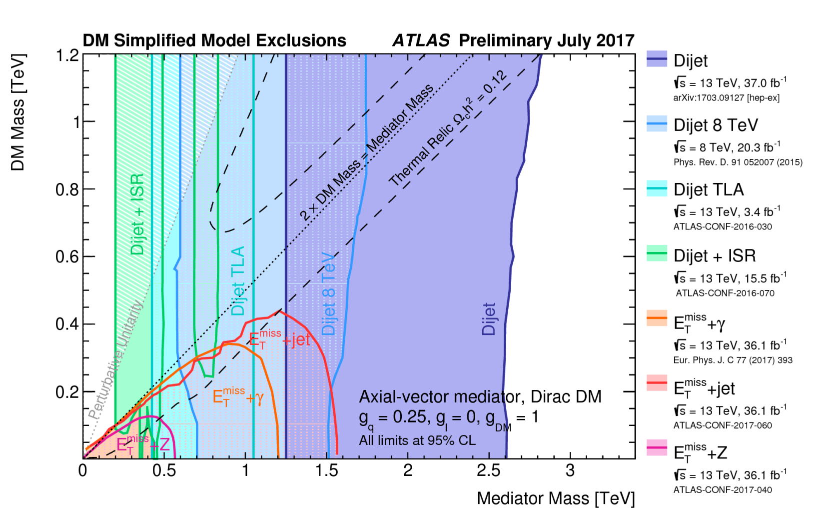


mono-higgs



di-top/bottom + MET

LHC results on simplified models



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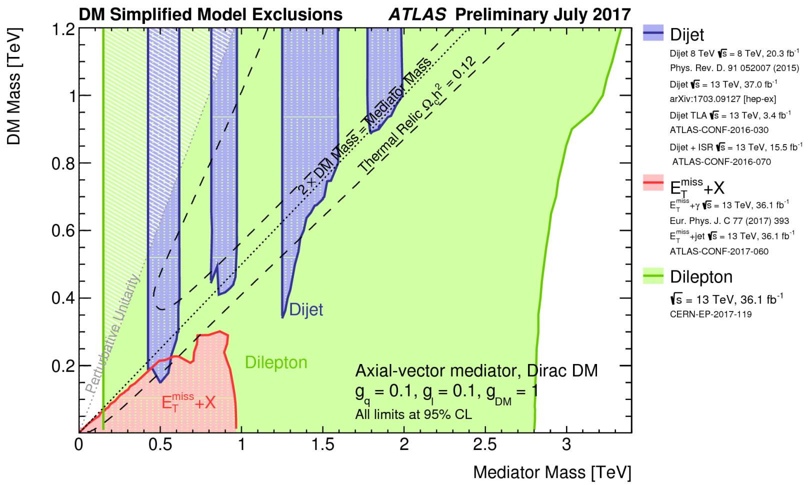


(. . .) the bad and the ugly

Enlarged parameter space

More free parameters

EFT: Λ, m_χ → Simp. mods.: $M_{\text{med}}, m_\chi, g_q, g_\chi, \Gamma$

Higher dim. scan not feasible

- Fixed benchmarks $(g, \Gamma = \dots)$

Enlarged parameter space

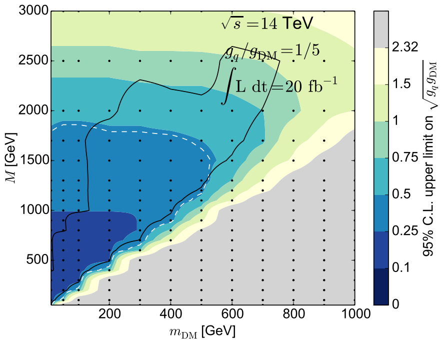
More free parameters

EFT Λ, m_χ → Simp. mods. $M_{\mathrm{med}}, m_\chi, g_q, g_\chi, \Gamma$

Higher dim. scan not feasible

- Fixed benchmarks ($g, \Gamma = \dots$)
- Clever idea: scale the cross section to set limits on the couplings:

$$\sigma \propto (g_q \cdot g_\chi)^2,\ (g_q \cdot g_\chi)^2/\Gamma \quad (1)$$



Jacques+ 1502.05721,1603.01366

Simplified models – a critical look

Naive construction

EFT Λ^4 → Simp. mods. $(p^2 - M^2)^2 + \Gamma^2 M^2$

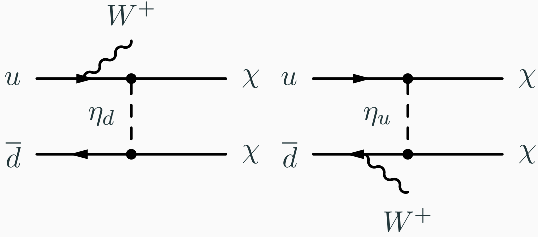
Theoretical issues (not just aesthetics)

- Perturbative unitary violated: requires completion
- Gauge invariance under the full SM group
- Cancellation of gauge anomalies: not automatic, but necessary for loop corrections

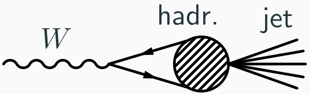
Gauge non-invariance

Consider a model with different couplings to up and down quarks.

Explicit breaking of SU(2) $\longrightarrow$ spurious enhancement of mono-W cross section



Affects also mono-jet



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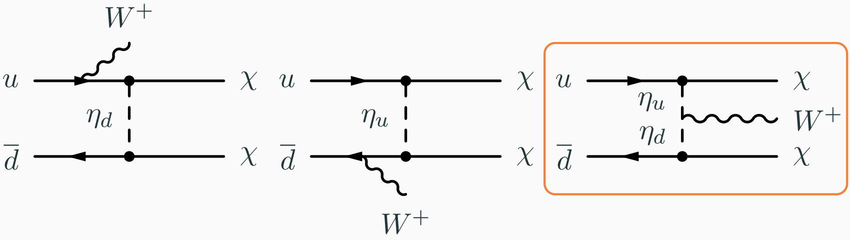

Can be cured in a full SU(2)-symmetric model

Bell+ 1503.07874, 1512.00476
Haisch+ 1603.01267

Scalar mediators: 2HDM + s

The scalar model

$$\mathcal{L}_{\mathrm{S}} \supset -\frac{1}{2} M_{\mathrm{med}}^2 S^2 - y_\chi S \bar{\chi} \chi - y_q^{ij} S \bar{q}_i q_j + \mathrm{h.c.}$$

is intrinsically not gauge invariant.

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Higgs - singlet mixing

$$-y_\chi S \bar{\chi} \chi - y_q^{ij} H \bar{Q}_i d_j - \lambda_{hs} |H|^2 S^2 \longrightarrow \begin{cases} \text{Higgs} \to \text{inv.} \\ \text{EW precision obs.} \end{cases}$$

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2 Higgs doublets

$$H_u,\ H_d,\ S,\ V(H_u, H_d, S)$$

Gonçalves+ 1611.04593, Busoni+ 1612.03475

Perturbative unitarity

Vector mediator

$$\mathcal{L} \supset -\sum_{f=q,\ell,\nu} Z'^{\mu} \bar{f} \left[g_f^V \gamma_\mu + g_f^A \gamma_\mu \gamma^5 \right] f - Z'^{\mu} \bar{\chi} \left[g_{\mathrm{DM}}^V \gamma_\mu + g_{\mathrm{DM}}^A \gamma_\mu \gamma^5 \right] \chi$$

Perturbative unitarity is violated in 2-2 scattering (similarly to SM without the Higgs):

$$f\bar{f} \to f\bar{f} \qquad f\bar{f} \to Z'Z'$$

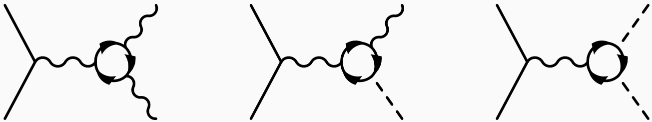
Can be cured by adding a new scalar particle s that gives mass to the Z' and to DM. *New phenomenology:*

- $\lambda_{hs}(S^*S)(H^\dagger H) \longrightarrow s - h$ mixing
- loop-induced spin-dependent scattering in DD
- resonant annihilation $\chi\chi \to s \to Z'Z$ affects the relic density

Kahlhoefer, Schmidt-Hoberg, Schwetz, Vogl, 1510.02110

Importance of anomaly cancellation

Annihilation through fermion loops relevant for ID



In a U(1)' model, divergences do not cancel unless charges are chosen appropriately.

If new fermions (DM) are uncharged under the SM gauge group, the charges of SM fermions are linear combinations of $B - L$ and hypercharge

$$c_f = Y \cos\theta + (B - L) \sin\theta$$

Consequences: correlations and new channels

Example: U(1)' extension of the SM (Z' gauge boson)

- Fermion charges are correlated (otherwise new fermions are needed)
- Not only the fermions: Higgs is charged

$$H\bar{Q}d \quad H\bar{Q}u$$

- "Extra" channels: $Z'Zh$ at tree level

$$(D_\mu H)^\dagger (D^\mu H) \longrightarrow vZ'Zh$$

- Additional Higgs S adds new phenomenology

Conclusions

Simplified models

- Bottom-up: Simplified models introduced as a small step above EFTs
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