Dark Matter Search at Collider

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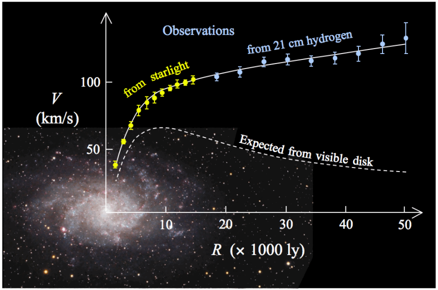
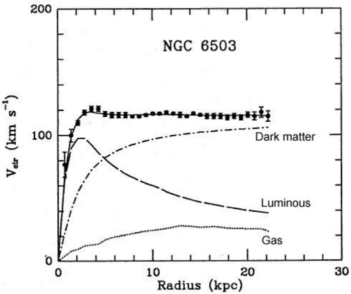
Outline

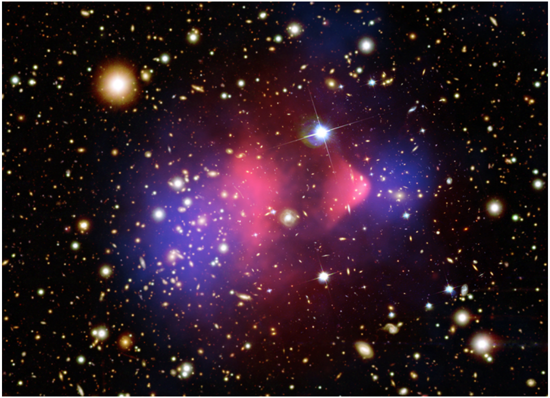
Outline





- DM existence suggested in 1933 by Zwicky (missing mass in Coma cluster, virial theorem)
- In 1970, Rubin and others measured rotation curves of many galaxies and found flat rotation curves

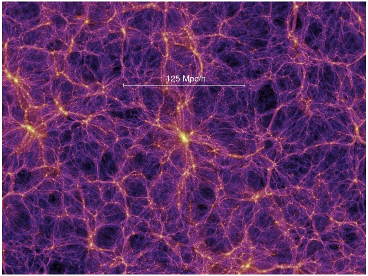
$$\frac{GMm}{r^2} = m\frac{v^2}{r} \to v(r) = \sqrt{\frac{GM(r)}{r}} \propto \begin{cases} \frac{1}{\sqrt{r}} & : M(r) = const \\ const & : M(r) \propto r \end{cases} \quad (1)$$

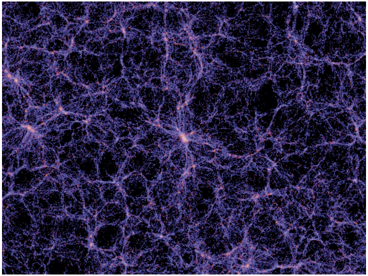


- Red: X-rays emission, tracing baryonic matter
- Blue: gravitational lensing effect, tracing matter
- The region, where most of the baryonic matter is, does not match the one where most of the matter is: most of the matter has to be ”dark”

Introduction

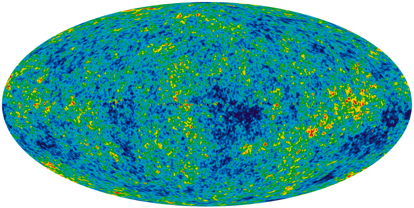
Evidence for DM: Numerical Simulations

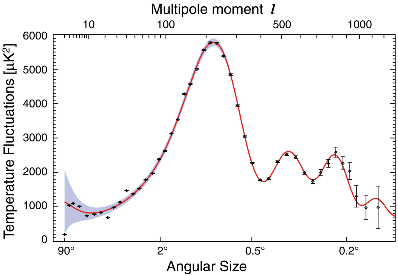




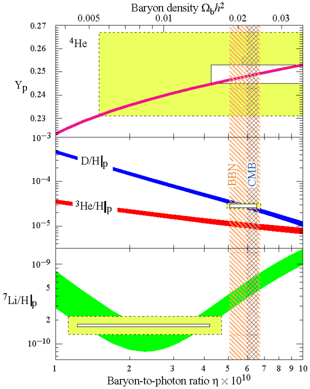
- Dark Matter collapses in Dark halos much before ordinary matter
- Ordinary matter is slowed by pressure due to photons
- When photons decouple (recombination), ordinary matter falls in gravitational wells generated by DM
- Without DM, galaxy formation would occur later and LSS would be different
- DM has to be cold to allow for observed bottom-up hierarchy (hot DM would generate top-down hierarchy)

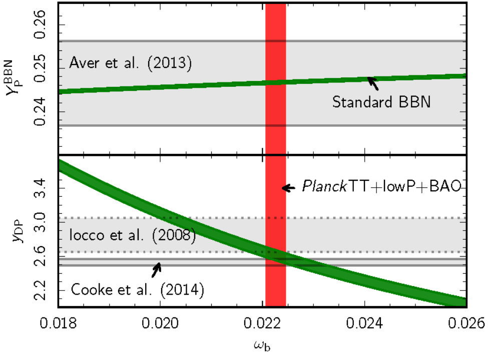
Introduction
Evidence for DM: CMB





- Baryons fell into the gravitational potential wells
- Compression → hotter plasma → increasing photons pressure
- Radiation pressure → compression halted → Expansion and cooling → less radiation pressure
- Decreased radiation pressure → gravity again dominated → another compression phase → BAO





- Big Bang Nucleosyntesys (BBN): formation of light elements
- Depends mostly on Ω_b
- Very good agreement between BBN and CMB values for Ω_b

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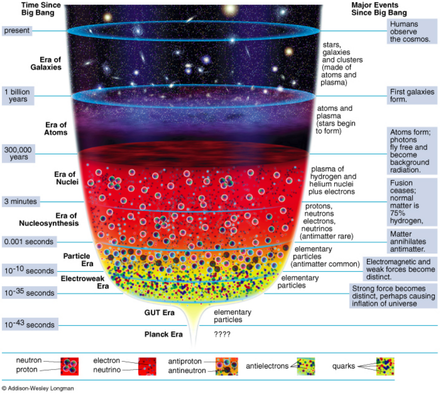
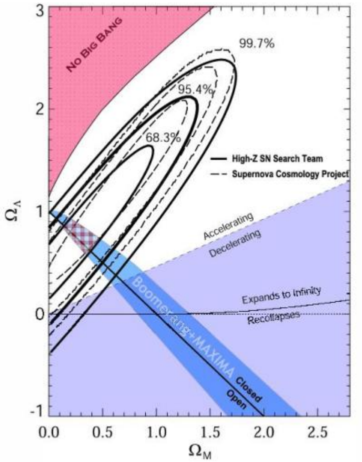
Introduction

ΛCDM model





- Describes correctly: CMB, LSS, BBN, accelerated expansion of universe
- Only 6 fundamental parameters

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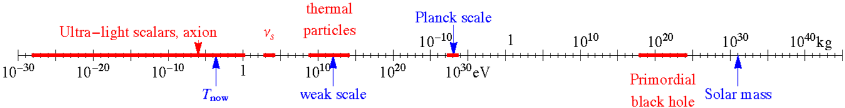
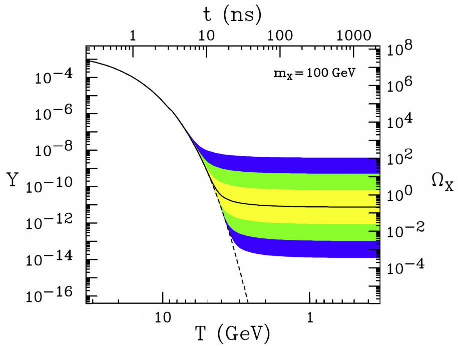
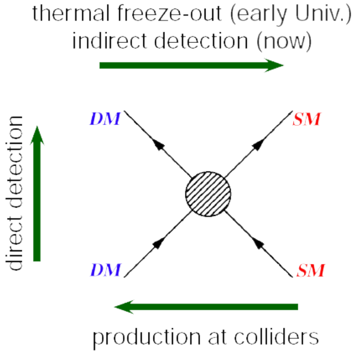


- Mass range: $10^{-28}eV < m_\chi < 10^{24}Kg$!
- Axions, PBH and weak-scale particles





- WIMP miracle: particle with $m_\chi \sim m_{weak}$ and $g \sim g_{weak}$ gives right relic abundance by freeze-out
- When DM interaction rate is smaller than expansion rate ($m_\chi/T \sim \mathcal{O}(30)$) it decouples from thermal bath $\rightarrow$ DM abundance gets fixed
- WIMP can be searched in multiple ways

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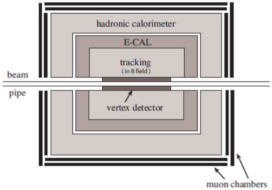
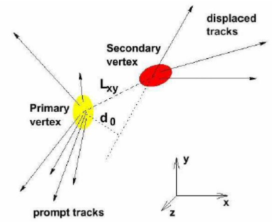
Dark Matter at Collider

Collider Introduction





Leptons	Vetexing	Tracking	ECAL	HCAL	Muon Cham.
$e^{\pm}$	$\times$	$\vec{p}$	E	$\times$	$\times$
$\mu^{\pm}$	$\times$	$\vec{p}$	$\surd$	$\surd$	$\vec{p}$
$\tau^{\pm}$	$\surd\times$	$\surd$	$e^{\pm}$	$h^{\pm};\ 3h^{\pm}$	$\mu^{\pm}$
ν_e, ν_μ, ν_τ	$\times$	$\times$	$\times$	$\times$	$\times$
Quarks					
u, d, s	$\times$	$\surd$	$\surd$	$\surd$	$\times$
$c \to D$	$\surd$	$\surd$	$e^{\pm}$	h's	$\mu^{\pm}$
$b \to B$	$\surd$	$\surd$	$e^{\pm}$	h's	$\mu^{\pm}$
$t \to bW^{\pm}$	b	$\surd$	$e^{\pm}$	$b + 2$ jets	$\mu^{\pm}$
Gauge bosons					
γ	$\times$	$\times$	E	$\times$	$\times$
g	$\times$	$\surd$	$\surd$	$\surd$	$\times$
$W^{\pm} \to \ell^{\pm}\nu$	$\times$	$\vec{p}$	$e^{\pm}$	$\times$	$\mu^{\pm}$
$\to q\bar{q}'$	$\times$	$\surd$	$\surd$	2 jets	$\times$
$Z^0 \to \ell^+\ell^-$	$\times$	$\vec{p}$	$e^{\pm}$	$\times$	$\mu^{\pm}$
$\to q\bar{q}$	$(b\bar{b})$	$\surd$	$\surd$	2 jets	$\times$

- DM cannot be detected by detectors $\to$ missing energy
- Can infer the presence of missing particles by imbalance in transverse momentum
- Also neutrinos cannot be detected at collider, like DM

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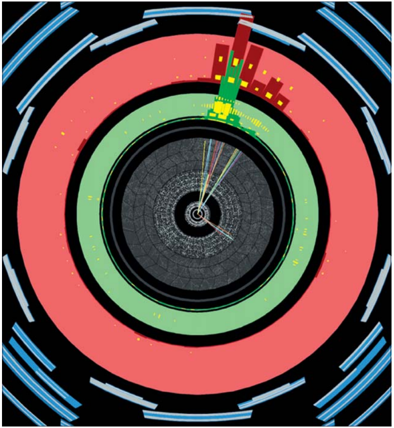
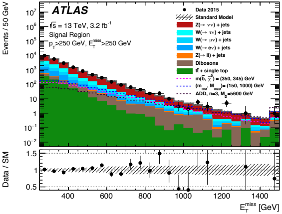
Dark Matter at Collider

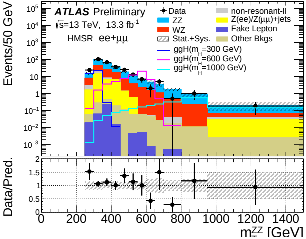
Dark Matter signatures: Mono-Jet

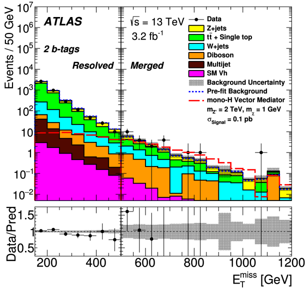


- One *or more* jets (usually ISR)
- Expected to deliver largest signal (at least for low m_χ)
- Background also large ($pp \to jZ, Z \to \nu\bar{\nu}$)
- Usually systematically limited



arXiv:1604.07773



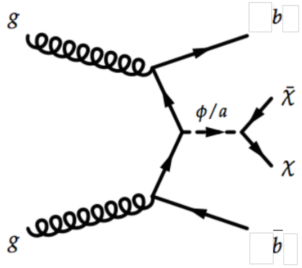


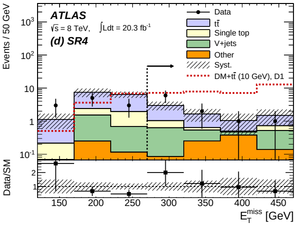
- $X = W^{\pm}, Z, \gamma, h$
- Signal significantly smaller (unless model has direct coupling to the emitted particle, i.e. not only ISR radiation)
- Signal much cleaner than mono-jet (especially for non-hadronic decays)
- Usually statistically limited

ATLAS-CONF-2016-056, 1609.04572

Dark Matter at Collider

Dark Matter signatures: $t\bar{t} + \not{E}_T, \quad b\bar{b} + \not{E}_T$



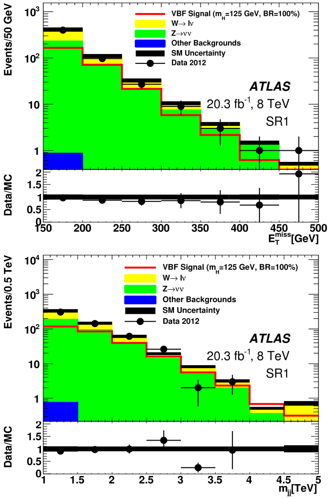


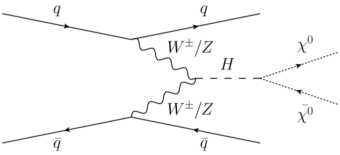
- Also features small cross section
- Important for top-philic DM models
- Very clean signal (especially fully-leptonic channel)
- Usually statistically limited

1410.4031 (ATLAS-CONF-2016-086)

Dark Matter at Collider

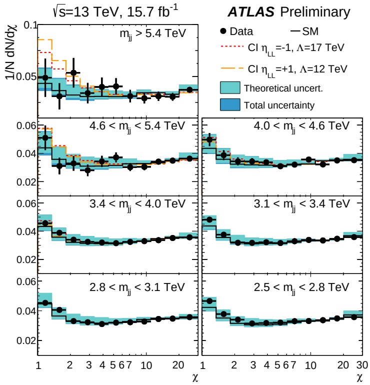
Dark Matter signatures: invisible Higgs decays (VBF)



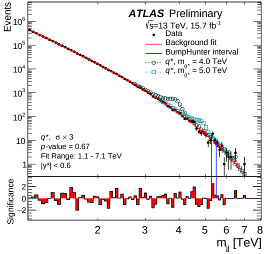


- If DM light enough $h \to \chi\bar{\chi}$ could be allowed
- VBF Distinctive topology, allows background discrimination
- Can also investigate DM models with new VBF operators

1508.07869



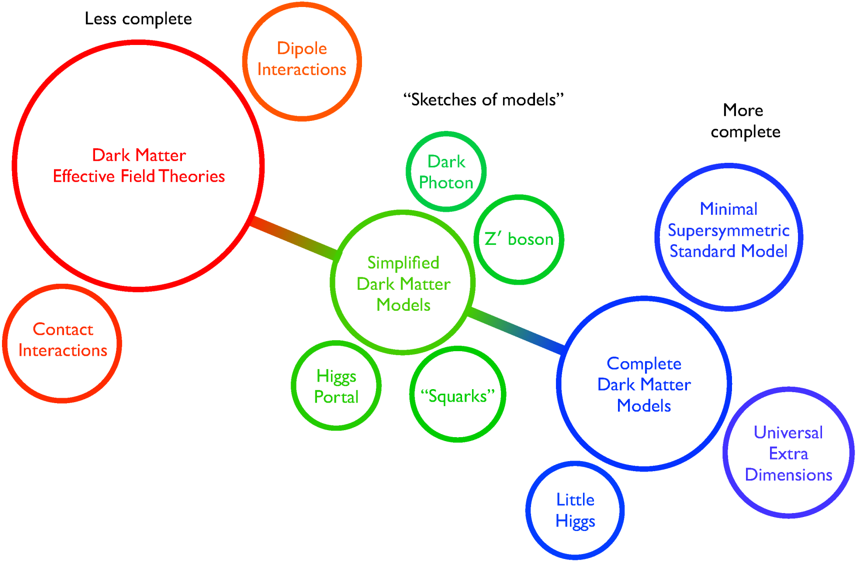
- Complementary search
- Useful with simplified models (s-channel), and large m_χ
- Can use both invariant mass distribution (narrow-width) and angular distrib. (large width)



ATLAS-CONF-2016-069 (ATLAS-CONF-2016-059)

Outline

Predicting Dark Matter Signals
Dark Matter Models



Predicting Dark Matter Signals

Effective Field theories (EFT)

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	$\bar{\chi}\sigma_{\mu\nu}\gamma^5\chi\ \bar{q}\sigma^{\mu\nu} q$	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	$\bar{\chi}\gamma^5\chi\ G^{\mu\nu}\tilde{G}_{\mu\nu}$	$\alpha_s/4\Lambda^3$

- Completely general: if DM is the lightest BSM particle, any $\mathcal{L}_{UV}$ can be reduced to $\mathcal{L}_{SM}$ + DM + towers of EFT operators
- For interaction with quarks minimum dimension is 6 (for gauge bosons, 5 for higgs)
- Only 2 parameters: Λ, m_χ
- Signal scales with Λ:

$$N_{events} = \mathcal{L}_{int}\frac{f(m_\chi)}{\Lambda^{2(d-4)}}$$

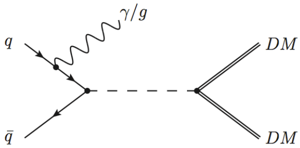
Outline

Predicting Dark Matter Signals

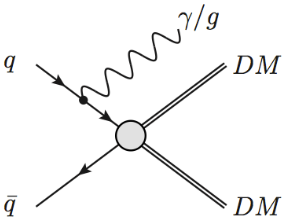
EFT validity Problems. From UV to EFT: integrating OUT

$$\mathcal{L}_{\mathrm{UV}} \supset -\frac{1}{2}M^2S^2 - g_q\bar{q}qS - g_\chi\bar{\chi}\chi S + kin$$

Scalar Kinetic term can be neglected



$$-\frac{\partial\mathcal{L}_{\mathrm{UV}}}{\partial S} = M^2S + g_q\bar{q}q + g_\chi\bar{\chi}\chi = 0$$



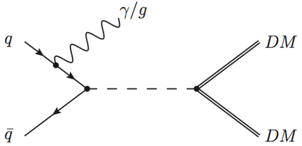
$$\mathcal{L}_{\mathrm{EFF}} \supset \frac{(g_q\bar{q}q + g_\chi\bar{\chi}\chi)^2}{2M^2} \supset \frac{g_qg_\chi\bar{q}q\bar{\chi}\chi}{M^2}$$

arXiv:1307.2253, 1402.1275

Predicting Dark Matter Signals

EFT validity Problems. From UV to EFT: integrating OUT

$$\mathcal{L}_{\rm UV} \supset -\frac{1}{2}M^2S^2 - g_q\bar{q}qS - g_\chi\bar{\chi}\chi S + kin$$



Scalar Kinetic term can be neglected

$$-\frac{\partial\mathcal{L}_{\rm UV}}{\partial S} = M^2S + g_q\bar{q}q + g_\chi\bar{\chi}\chi = 0$$

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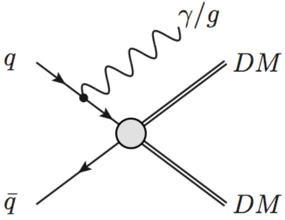


arXiv:1307.2253, 1402.1275

- Expand the UV propagator as power series

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

- Compare result of UV+integrating out or UV+propagator expansion with EFT
- In both cases the two results match if

$$\frac{1}{\Lambda^2} \equiv \frac{g_\chi g_q}{M^2}$$

- This is called matching condition

In the latter case is easier to understand that the EFT validity requires

Validity Condition

$$Q_{\rm tr}^2 < M^2 = g_\chi g_q \Lambda^2$$

To ensure EFT validity, we can throw away events with $Q_{\rm tr}^2 > M^2$ produced by your event generator (Truncation)

Issue 1

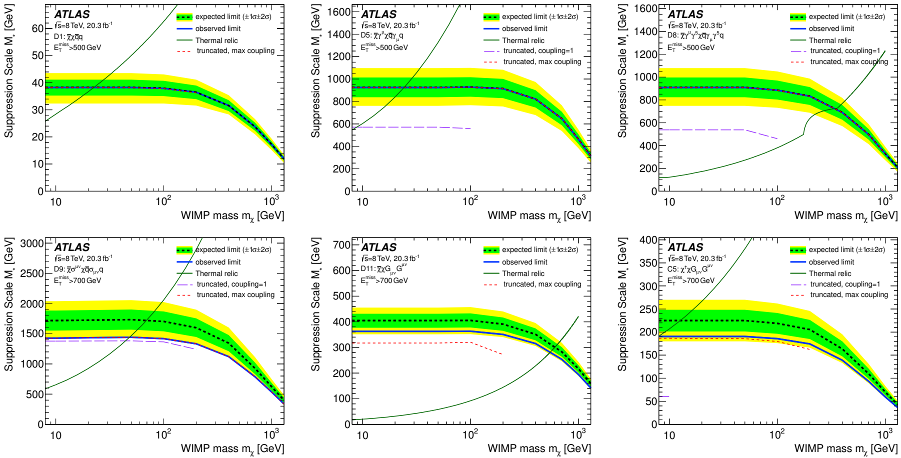
Validity condition depends on UV theory parameters

Issue 2

Matching (and so validity) condition depends on the UV completion which may not be unique.

Predicting Dark Matter Signals

EFT validity Problems. EFT Validity solution: The Truncation Method (Results)

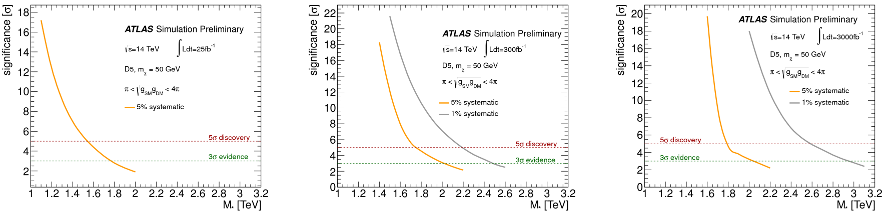


Issue 3

Imposing EFT validity weakens exclusion limits

Issue 4

Validity condition weakens discovery potential!



ATL-PHYS-PUB-2014-007

Outline

Predicting Dark Matter Signals

Simplified Models: s-channel

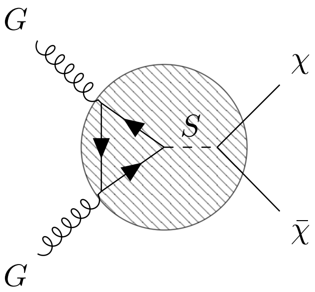
$$\begin{aligned}
\mathcal{L}_{\rm S} &= \frac{1}{2}\partial_\mu S \partial^\mu S - \frac{1}{2}M_{\rm med}^2 S^2 - y_\chi S\bar{\chi}\chi - y_q^{ij} S\bar{q}_i q_j + \text{h.c.} \\
\mathcal{L}_{\rm P} &= \frac{1}{2}\partial_\mu S \partial^\mu S - \frac{1}{2}M_{\rm med}^2 S'^2 - y'_\chi S'\bar{\chi}\gamma_5\chi - y'^{ij}_q S\bar{q}_i\gamma_5 q_j + \text{h.c.} \\
\mathcal{L}_{\rm V} &= -\frac{1}{4}F_V^{\mu\nu}F_{V,\mu\nu}\frac{1}{2}M_{\rm med}^2 V_\mu V^\mu - g_\chi V_\mu\bar{\chi}\gamma^\mu\chi - g_q^{ij} V_\mu \bar{q}_i\gamma^\mu q_j \\
\mathcal{L}_{\rm A} &= -\frac{1}{4}F_V^{\mu\nu}F_{V,\mu\nu}\frac{1}{2}M_{\rm med}^2 V'_\mu V'^\mu - g'_\chi V'_\mu\bar{\chi}\gamma^\mu\gamma_5\chi - g'^{ij}_q V'_\mu \bar{q}_i\gamma^\mu\gamma_5 q_j
\end{aligned}$$

- MFV for V, A models requires $g_q^{i,j} = g_q^{V/A}\delta_{i,j}$.
- MFV for S, A models requires $y_{u,d}^{i,j} = g_{u,d}\frac{m_i}{v}\delta_{i,j}$. To reduce parameter space, first generation of simplified models also assumed $g_u = g_d$.

Predicting Dark Matter Signals

Simplified Models

Name	Operator	Model
D1	$\bar{\chi}\chi\ \bar{q}q$	$S(SS)$
D4	$\bar{\chi}\gamma^5\chi\ \bar{q}\gamma^5 q$	$P(PP)$
D5	$\bar{\chi}\gamma_\mu\chi\ \bar{q}\gamma^\mu q$	$V(VV)$
D8	$\bar{\chi}\gamma_\mu\gamma^5\chi\ \bar{q}\gamma^\mu\gamma^5 q$	$A(AA)$
D11	$\bar{\chi}\chi\ G^{\mu\nu}G_{\mu\nu}$	$S(SS)$



- Simplest UV-safe models that yield EFT dim-6 operators
- Replace contact interactions with propagating degrees of freedom
- Scalar (and pseudoscalar) also introduce dim-7 operator with gluons through top loop
- D2,D3,D6,D7 can also be reproduced, by changing the coupling structure
- All other EFT dim-6 and 7 operators arise at loop level in such models

$$\mathcal{L} = \mathcal{L}_{SM} + \sum_{i,j=1,2,3} g^{i,j} \left(\widetilde{Q}^i_L \bar{Q}^j_L + \tilde{u}^i_R \bar{u}^j_R + \tilde{d}^i_R \bar{d}^j_R \right) \chi + \text{h.c.} \qquad (2)$$

- Require multiple scalar propagators $\widetilde{Q}^i_L, \tilde{u}^i_R, \tilde{d}^i_R$
- Propagators are colored
- Either propagators (MSSM) or DM (flavored-DM) are flavored
- MFV requires $g^{i,j} = g_t \delta_{i,j}$
- Approximate MFV, given $y_t \gg y_{u,c}$, only requires $g^{i,j} = g_{t,i}\delta_{i,j}, \quad g_{t,1} = g_{t,2} \neq g_{t,3}$

Outline

Predicting Dark Matter Signals

Simplified Models: consistency (s-ch)

- A full UV consistent theory, features: only $dim \leq 4$ interactions, gauge invariance $\longleftrightarrow$ renormalizable, anomaly-free
  - ✓ Simplified models have only $dim \leq 4$ interactions
  - ✓ Simplified models do not care of anomalies, as one can always assume that additional fermions to cancel the anomalies exist but have much larger masses
  - ✗ Simplified models listed before are not (all) gauge invariant
- Models are invariant only under $SU(3)_c \times U(1)_{em}$, but not under $SU(2)_L \times U(1)_Y$, neither under $U(1)_{dark}$ in V, A models
  - V, A models have a massive gauge boson whose mass term is not G.I.
  - S, P models have $\bar{q}q$ terms that are not G.I.

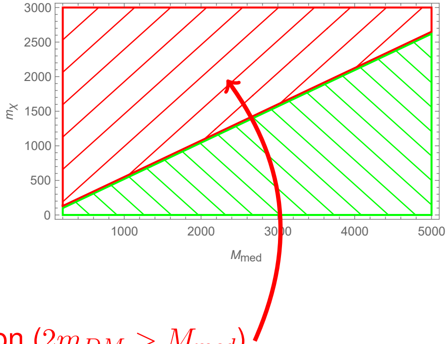
- For pure vector couplings to both quarks and DM, the mass term for V is indeed G.I., gauge invariance is hidden (Stuckelberg Mechanism)
- In all other cases, if any particle has an axial coupling to V, one needs to add a Dark higgs Boson ϕ
  - The dark higgs will in general mix with the SM higgs Φ through a $\Phi\Phi^\dagger\phi\phi^\dagger$ term
  - If quarks have axial charge, the SM higgs is charged under the new $U(1)$, implying that the SM Z boson is mixing with V
  - If DM has axial couplings, DM can only get a mass through ϕ. The dark yukawa coupling will be $y_\chi \propto \frac{g_q m_\chi}{M_{med}} \leq \sqrt{4\pi}$. Moreover this means that there are 2 mediators connecting dark and visible sectors: V and ϕ. V and Z will anyway mix at loop level.

- To restore gauge invariance, one needs quarks to couple to an higgs-like doublet, and the scalar of the new doublet to mix with a gauge singlet, and the singlet coupling to DM
  - Minimal option: SM higgs mixing with a new gauge singlet scalar (mixing angle severely constrained $\rightarrow$ tiny signal). Moreover, also leptons are forced to couple to the new scalar with $g_l = g_q$, giving stringent constraints from di-lepton resonances.
  - Next-to-minimal option: New higgs doublet mixing with a new gauge singlet scalar (THDM)

Outline

Warning!!!

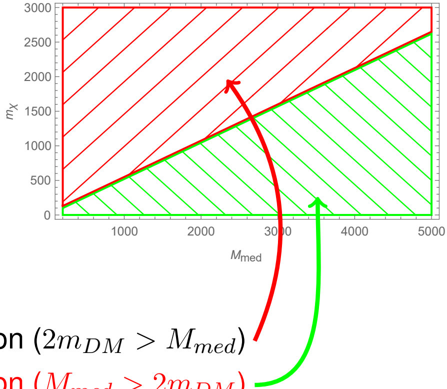
- Simplified models are **NOT** complete models, they are just thought to be a tool to analyse LHC data for certain searches.
- Some models may have been thought for a particular search, and may be fine to be used for that search, but not for others
- Using simplified models in contexts different from LHC means making **several assumptions**, i.e. that physics at LHC energy scale and DD/ID energy scales is affected by the same subset of particles/interactions of the undergoing UV theory



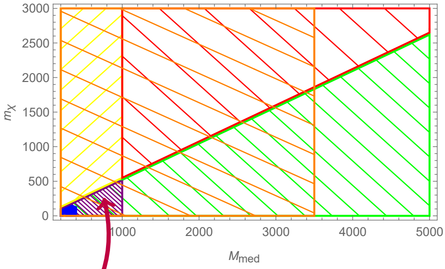
- Off-shell region $(2m_{DM} > M_{med})$

Predicting Dark Matter Signals

Simplified Models: complementarity. LHC



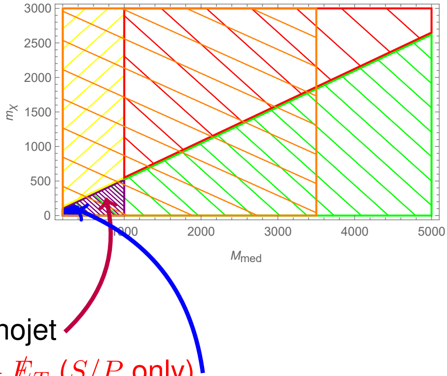
- Off-shell region ($2m_{DM} > M_{med}$)
- On-shell region ($M_{med} > 2m_{DM}$)



- On-shell: monojet

Predicting Dark Matter Signals

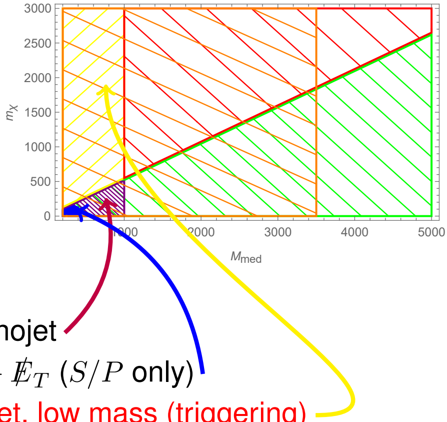
Simplified Models: complementarity. LHC



- On-shell: monojet
- On-shell: $t\bar{t} + \not{E}_T$ (S/P only)

Predicting Dark Matter Signals

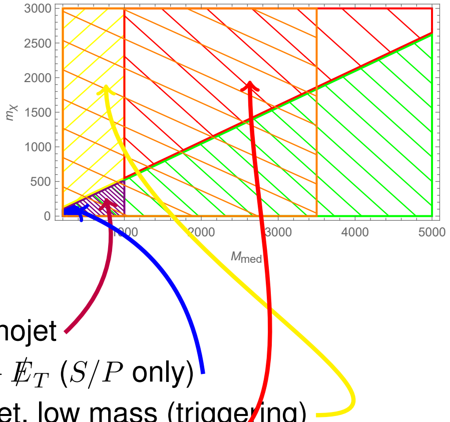
Simplified Models: complementarity. LHC



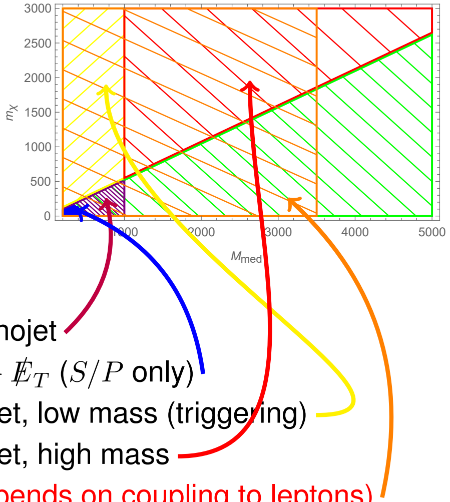
- On-shell: monojet
- On-shell: $t\bar{t} + \not{E}_T$ (S/P only)
- (Off-shell) Dijet, low mass (triggering)

Predicting Dark Matter Signals

Simplified Models: complementarity. LHC



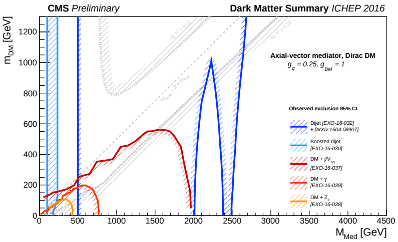
- On-shell: monojet
- On-shell: $t\bar{t} + \not{E}_T$ $(S/P$ only)
- (Off-shell) Dijet, low mass (triggering)
- (Off-shell) Dijet, high mass

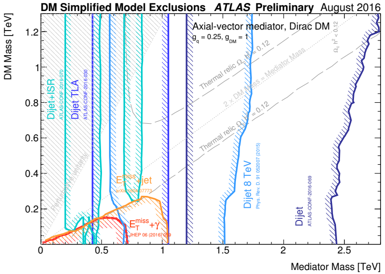


- On-shell: monojet
- On-shell: $t\bar{t} + \not{E}_T$ (S/P only)
- (Off-shell) Dijet, low mass (triggering)
- (Off-shell) Dijet, high mass
- Di-lepton (depends on coupling to leptons)

Predicting Dark Matter Signals

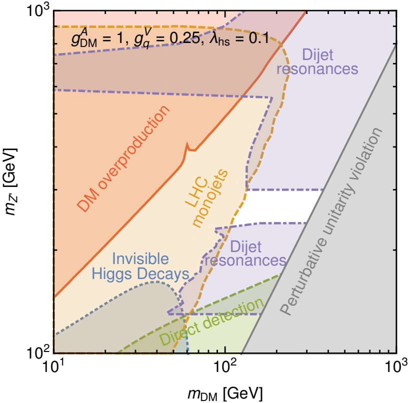
Simplified Models: complementarity. LHC: ATLAS and CMS summary for AA

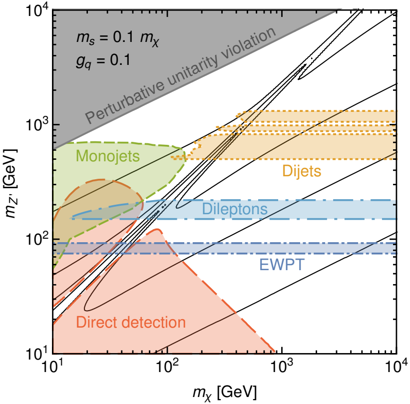




Predicting Dark Matter Signals

Simplified Models: complementarity. LHC: example for VA + DH





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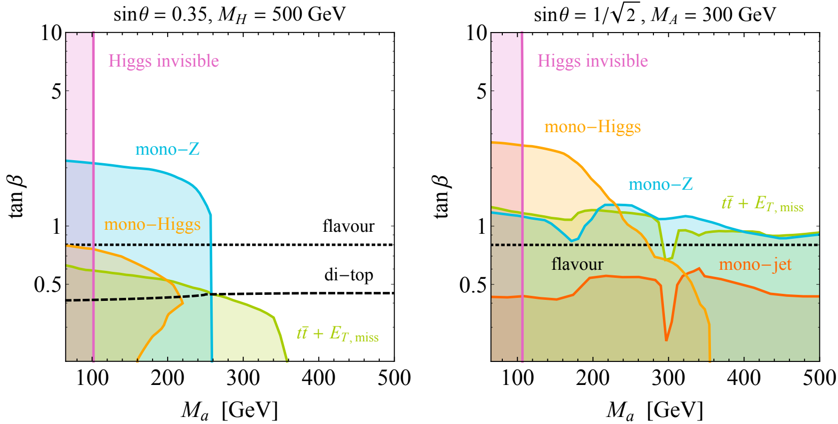
Predicting Dark Matter Signals

Simplified Models: complementarity. LHC: example for 2HDM+P



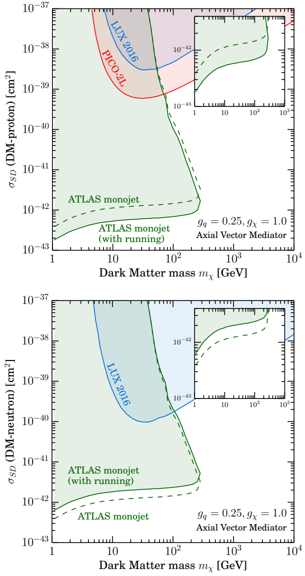
1701.07427

Name	Operator	Model	σ	Suppression
D1	$\bar{\chi}\chi\,\bar{q}q$	SS	SI	$\frac{m_N}{v}$
D2	$\bar{\chi}\gamma^5\chi\,\bar{q}q$	SP	SI	$q^2, \frac{m_N}{v}$
D3	$\bar{\chi}\chi\,\bar{q}\gamma^5 q$	PS	SD	$q^2, \frac{m_N}{v}$
D4	$\bar{\chi}\gamma^5\chi\,\bar{q}\gamma^5 q$	PP	SD	$q^4, \frac{m_N}{v}$
D5	$\bar{\chi}\gamma_\mu\chi\,\bar{q}\gamma^\mu q$	VV	SI	-
D6	$\bar{\chi}\gamma_\mu\gamma^5\chi\,\bar{q}\gamma^\mu q$	VA	SI+SD	$v_r^2(SI)q^2(SD)$
D7	$\bar{\chi}\gamma_\mu\chi\,\bar{q}\gamma^\mu\gamma^5 q$	AV	SD	$q^2 + v_r^2$
D8	$\bar{\chi}\gamma_\mu\gamma^5\chi\,\bar{q}\gamma^\mu\gamma^5 q$	AA	SD	-
D11	$\bar{\chi}\chi\,G^{\mu\nu}G_{\mu\nu}$	SS	SI	$\frac{m_N}{v}$

- Spin structure of couplings very important for DD
- SI: usually assumes isospin conservation
- SD: constraints for σ_p and σ_n

Predicting Dark Matter Signals

Simplified Models: complementarity. Direct Detection



- Bounds $M_{med} > M_{med}^{min}(m_\chi)$ can be translated in bounds on $\sigma_{SI/SD} < \sigma(m_\chi)$ by using the EFT limit with proper matching, for example
  $$\frac{1}{\Lambda^2} = \frac{g_q g_\chi}{M_{med}^2}$$
- When taking EFT limit, matching is not enough, one also needs to run the couplings from LHC energy scale to DD energy scale

1605.04917

Predicting Dark Matter Signals

Simplified Models: complementarity. Indirect Detection/Relic Density

Name	Model	s-wave
D1	SS	No
D2	SP	Yes
D3	PS	No
D4	PP	Yes
D5	VV	Yes
D6	VA	No
D7	AV	Yes
D8	AA	m_q^2/m_χ^2
D11	SS	No

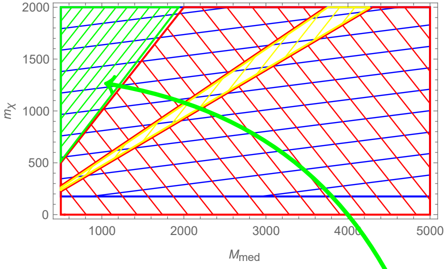
- Away from resonance ($M_{med} = 2m_\chi$) can expand $\sigma v = a + bv^2 + \mathcal{O}(v^4)$
- $\langle \sigma v \rangle = a + b\langle v^2 \rangle$ with $\langle v^2 \rangle \sim T/m_\chi \sim \mathcal{O}(0.03)$
- If $a = 0$ or $a \ll b$ (no or suppressed s-wave) annihilation is suppressed
- $\Omega_\chi \sim 0.118 \dfrac{3 \times 10^{26} cm^3/s}{\langle \sigma v \rangle}$

Actung!!!

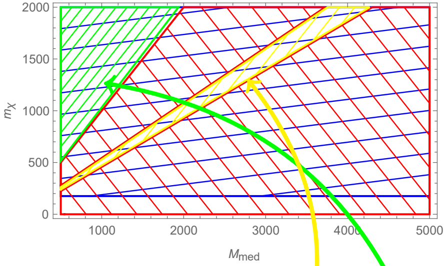
There are many ways to enhance or suppress DM relic abundance, by adding additional particles at the model for example (not relevant for DD, LHC). Examples: secluded models (fix overabundance), multi-component DM (fix underabundance)

Predicting Dark Matter Signals

Simplified Models: complementarity. Indirect Detection/Relic Density



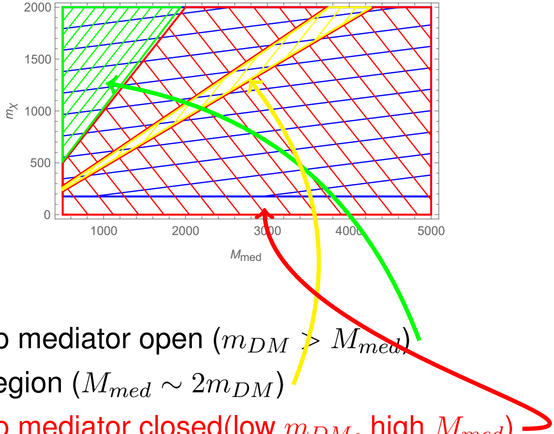
- Annihilation to mediator open ($m_{DM} > M_{med}$)



- Annihilation to mediator open ($m_{DM} > M_{med}$)
- Resonance region ($M_{med} \sim 2m_{DM}$)

Predicting Dark Matter Signals

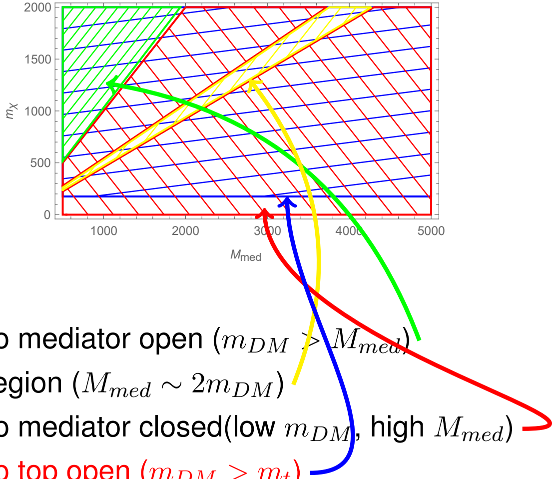
Simplified Models: complementarity. Indirect Detection/Relic Density



- Annihilation to mediator open ($m_{DM} > M_{med}$)
- Resonance region ($M_{med} \sim 2m_{DM}$)
- Annihilation to mediator closed(low m_{DM}, high M_{med})

Predicting Dark Matter Signals

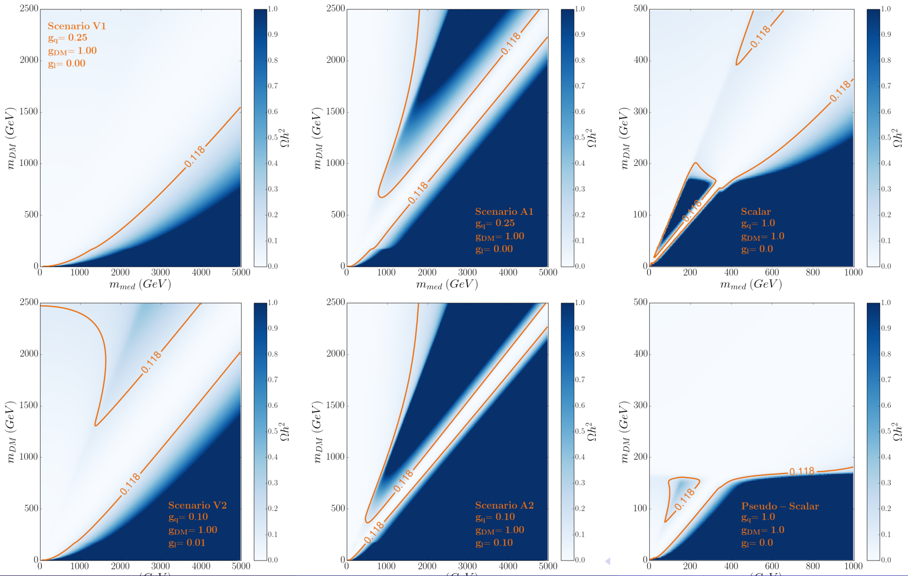
Simplified Models: complementarity. Indirect Detection/Relic Density



- Annihilation to mediator open ($m_{DM} > M_{med}$)
- Resonance region ($M_{med} \sim 2m_{DM}$)
- Annihilation to mediator closed(low m_{DM}, high M_{med})
- Annihilation to top open ($m_{DM} > m_t$)

Predicting Dark Matter Signals

Simplified Models: complementarity. Indirect Detection/Relic Density



Outline

Summary

Conclusions

- Plenty of evidence for DM
- Plenty of DM candidates, large mass range
- Plenty of ways to search for DM
- DM at collider: EFT not a good description
- Simplified Models the current best-motivated tool
- They allow more phenomenology, and complementarity
- Possibility to combine different searches, with care