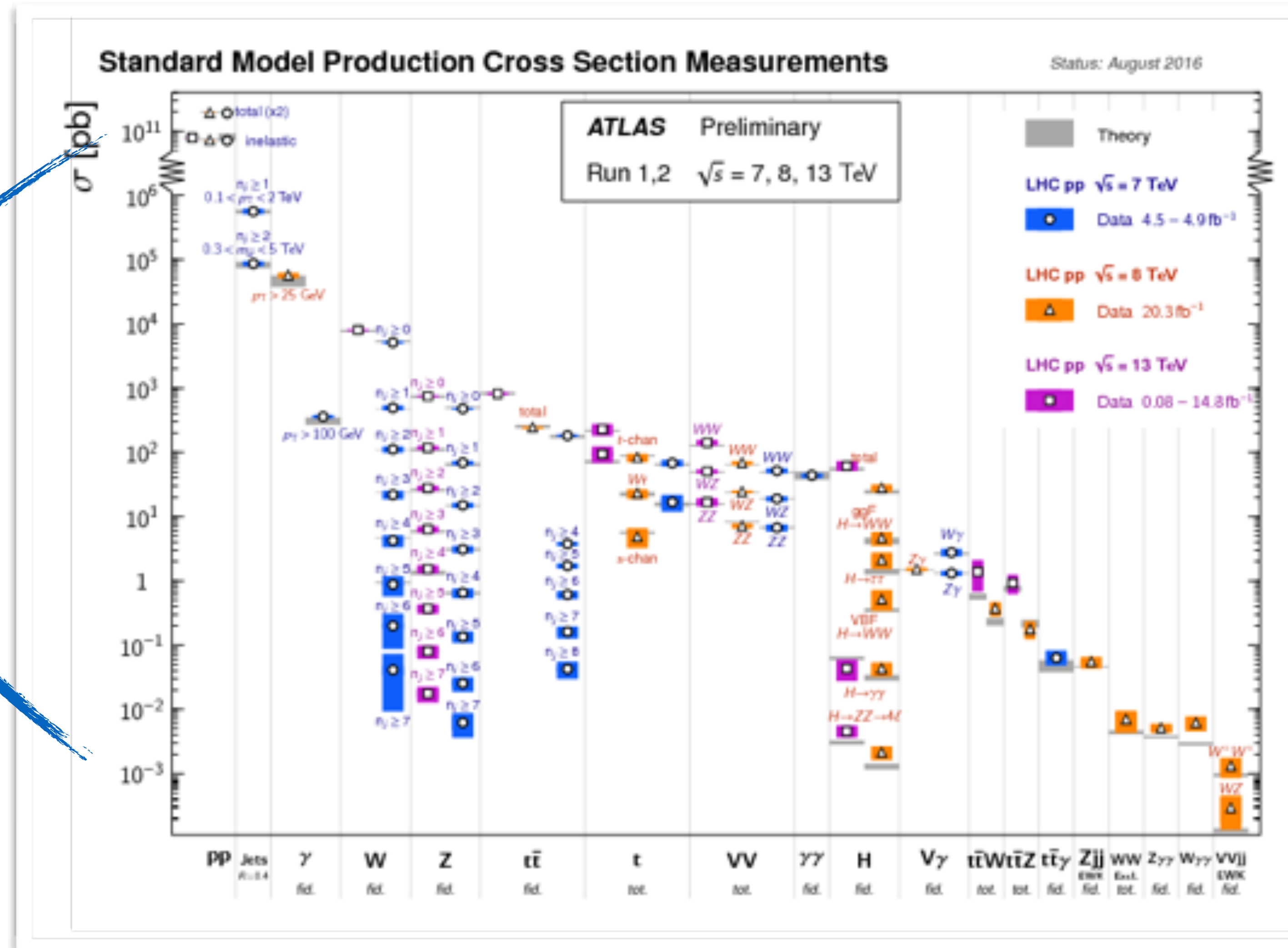
LHC searches for momentum dependent DM interactions

Daniele Barducci

w/ A. Bharucha, Desai, Frigerio, Fuks, Goudelis, Kulkarni, Polesello and Sengupta

arXiv:1609.07490

Introduction



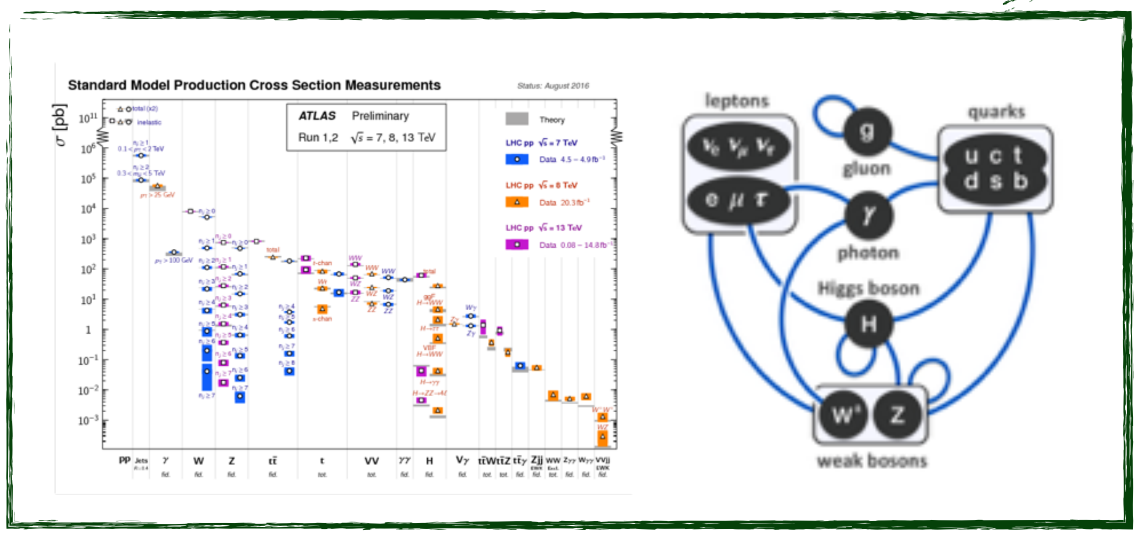
14 orders of magnitude!!!

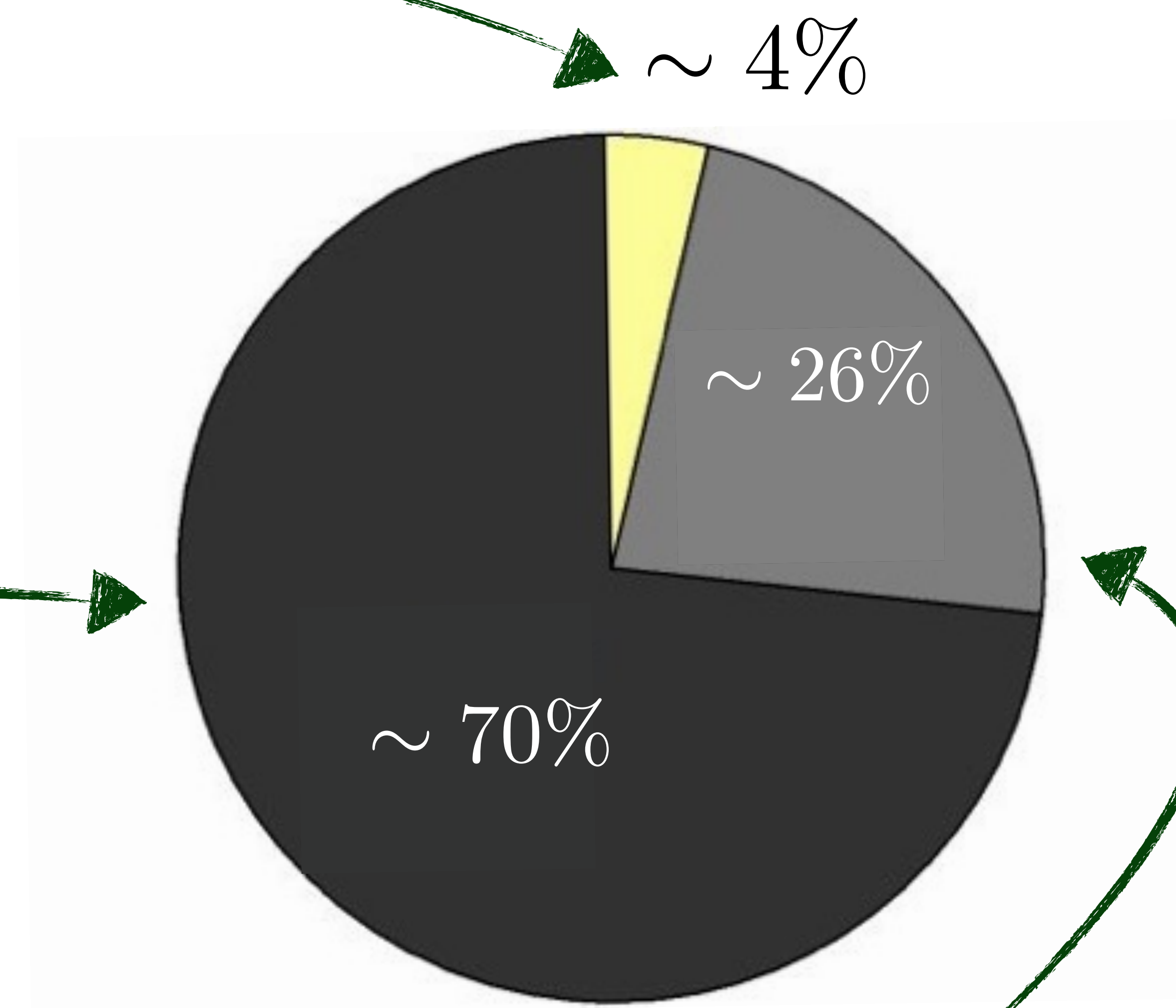
What else?

Hierarchy problem
Flavour structure

Neutrino oscillations
Baryon asymmetry
Dark Matter

Introduction





Dark Energy for which we have more or less no clue

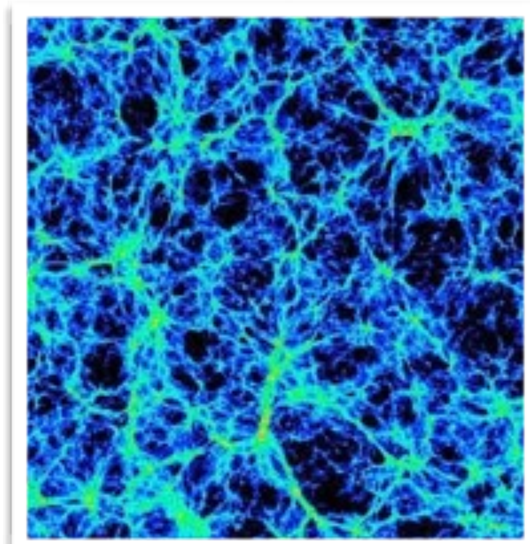
Dark Matter for which we have indirect evidences

Introduction

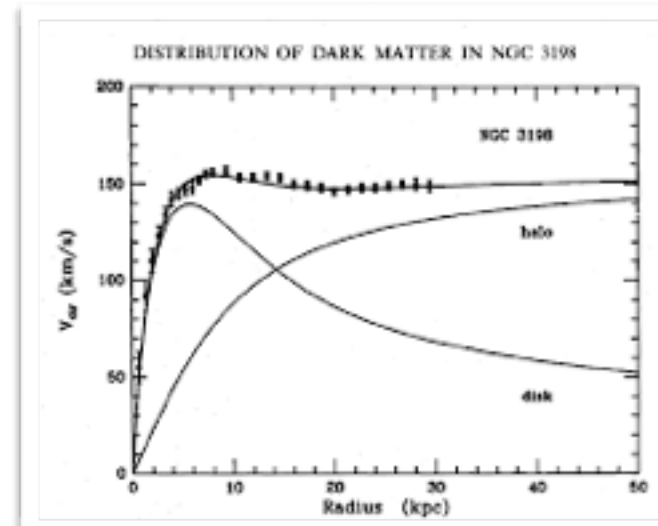
Numerous indirect experimental evidences for the existence of DM

Bullet clusters

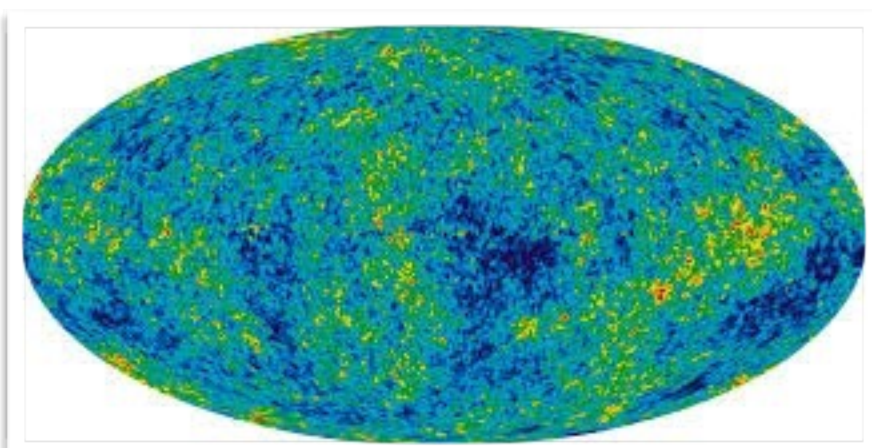
Large structures formations



Rotation curves



CMB

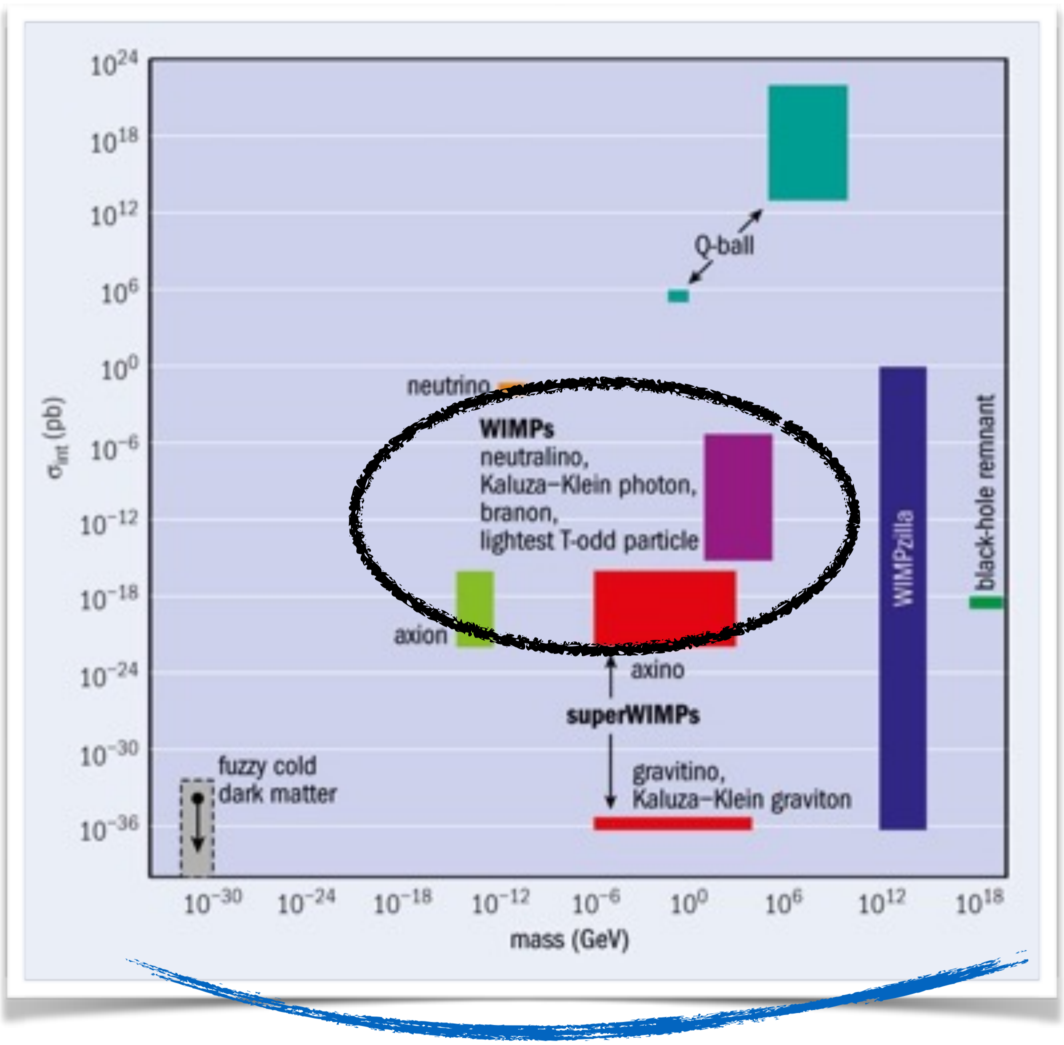


Galaxy clusters

Still no direct signal of Dark Matter has been detected

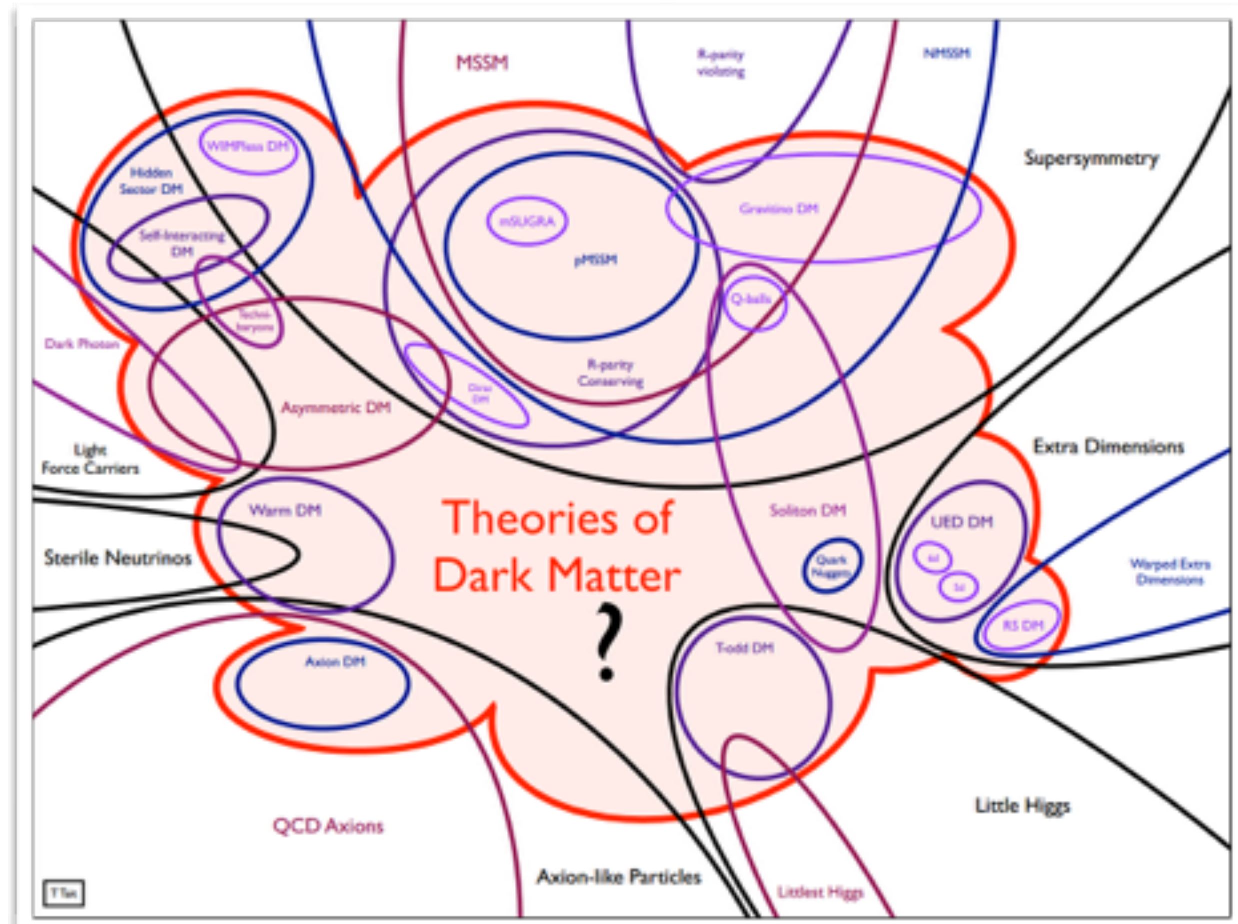
Introduction

What Dark Matter could be? Many DM candidate…



~50 order of magnitude

[Picture stolen from Tim Tait]



Weakly Interactive Massive Particles are one of the most popular DM candidate

WIMPs

WIMPs arise in many BSM constructions

- SUSY with R-parity conservation
- ED models
- Models with pNGB Higgs
- …

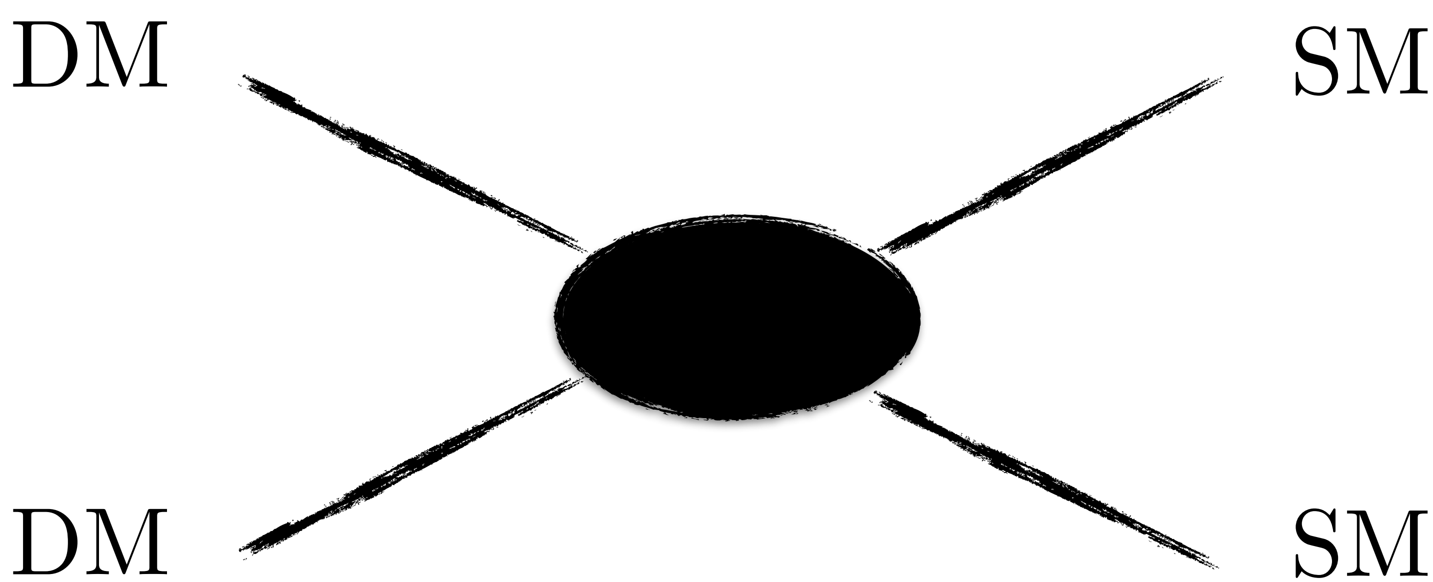
Popularity of WIMP due to the so-called WIMP miracle

$$M_{DM} \sim 100 \text{ GeV}$$

$$\langle \sigma v \rangle \sim 3 \times 10^{-26} \text{cm}^3 \text{s}^{-1} \longrightarrow \Omega h^2 \sim 0.12$$

A TeV scale particle with an electro-weak cross section
gives the correct energy density measured in the Universe!

Searches for DM



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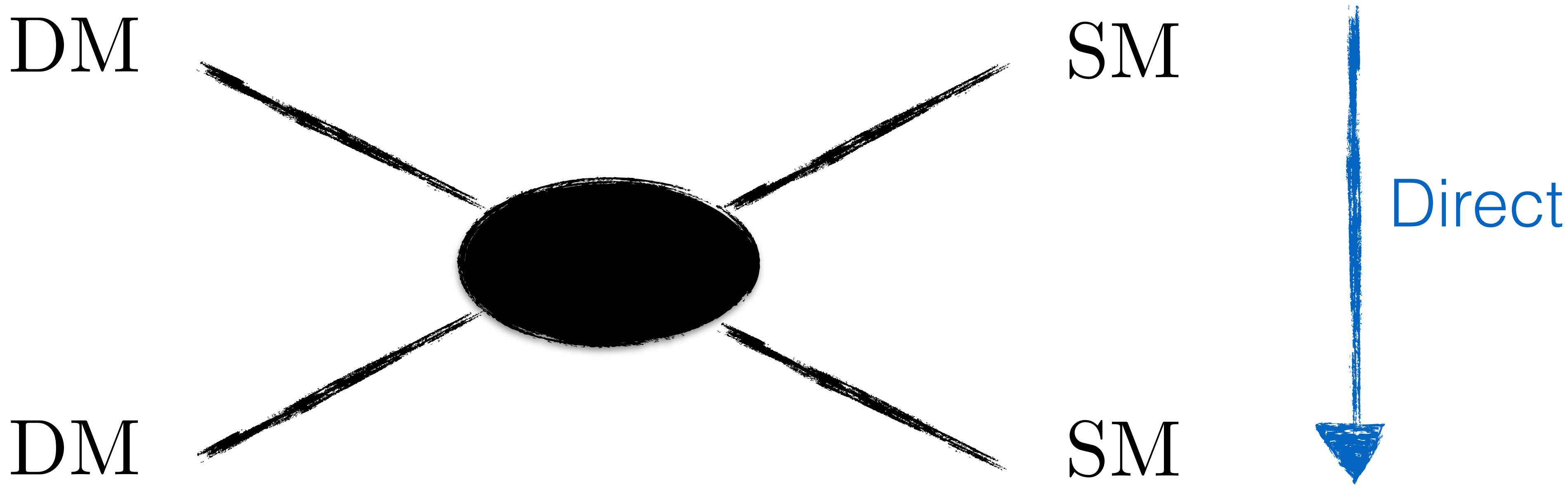
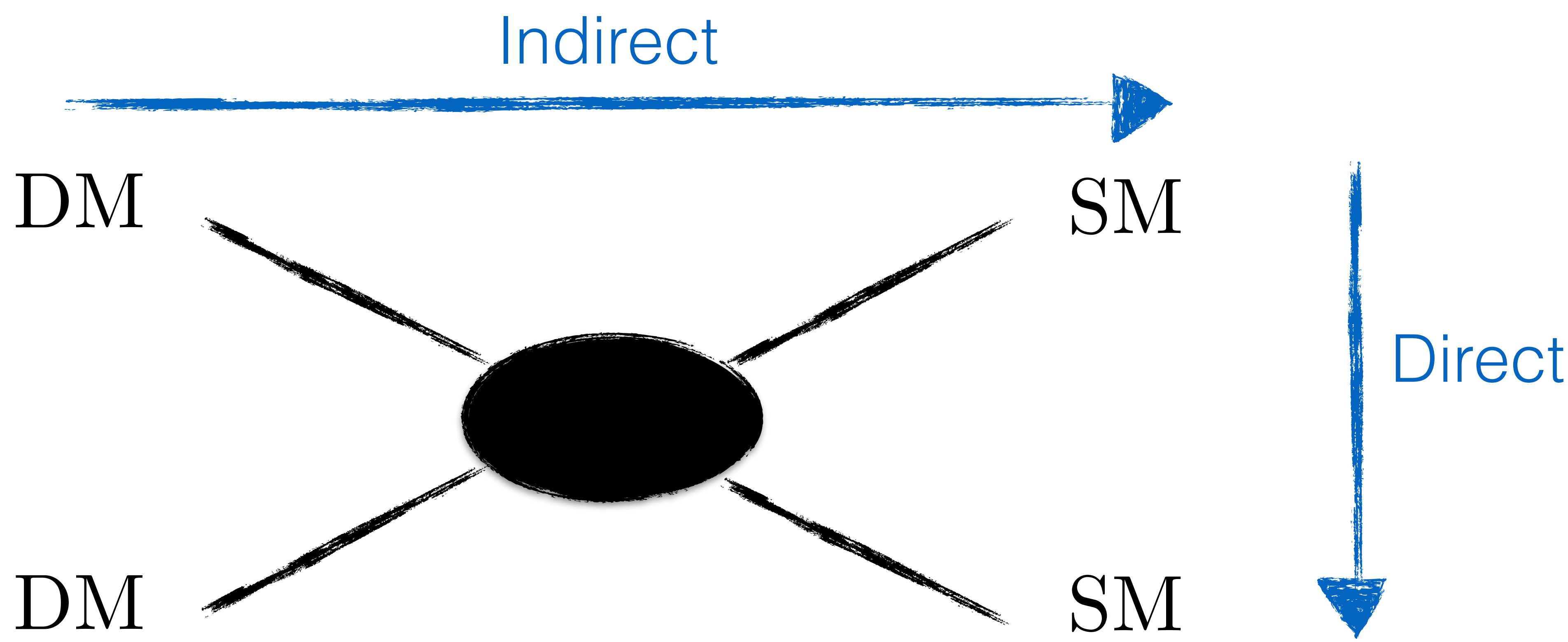


Direct Detection: Measure the recoil of DM onto heavy nuclei

Searches for DM



<u>Direct Detection:</u> Measure the recoil of DM onto heavy nuclei

<u>Indirect Detection:</u> Detect annihilation of DM in the Universe

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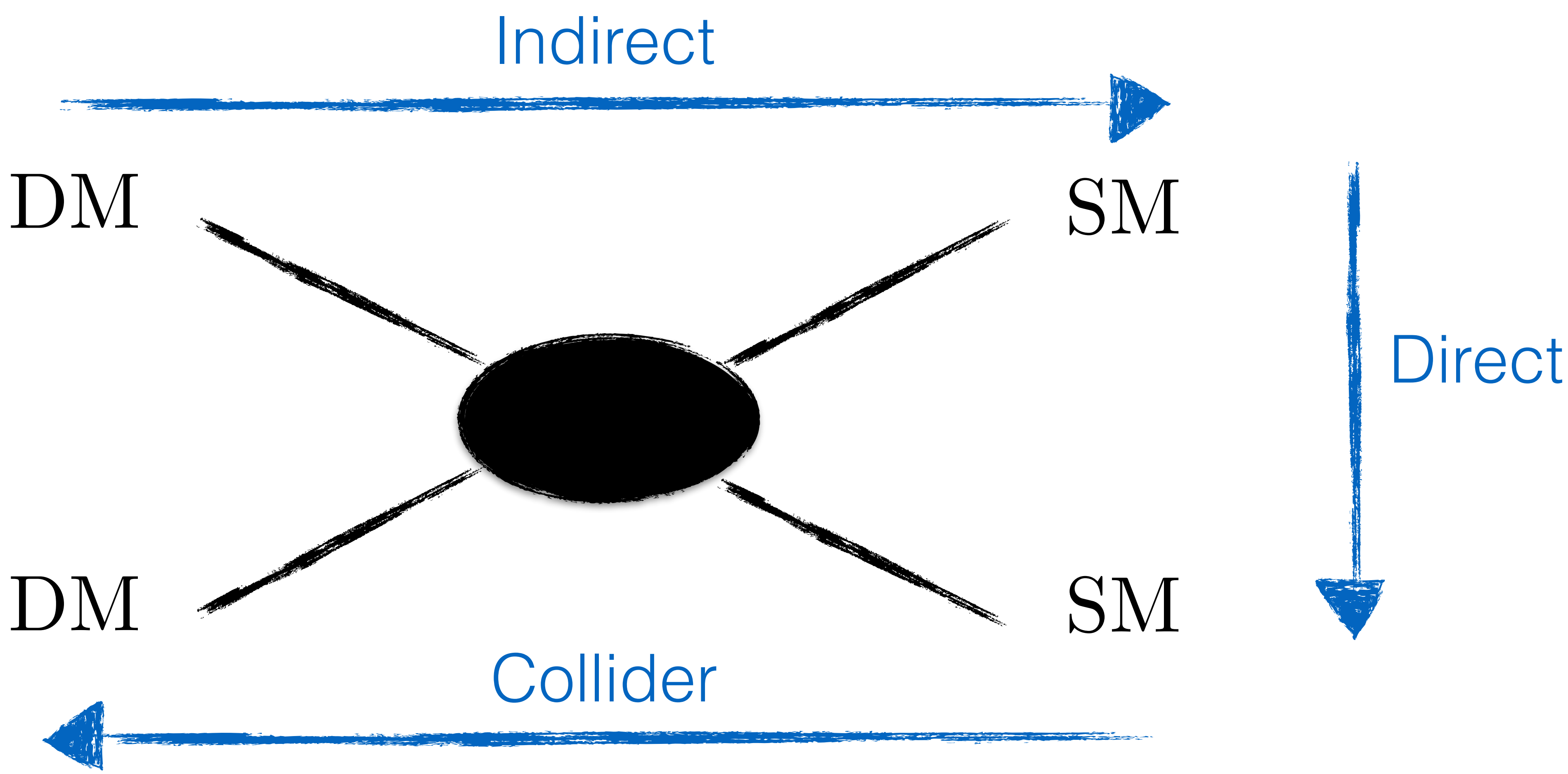
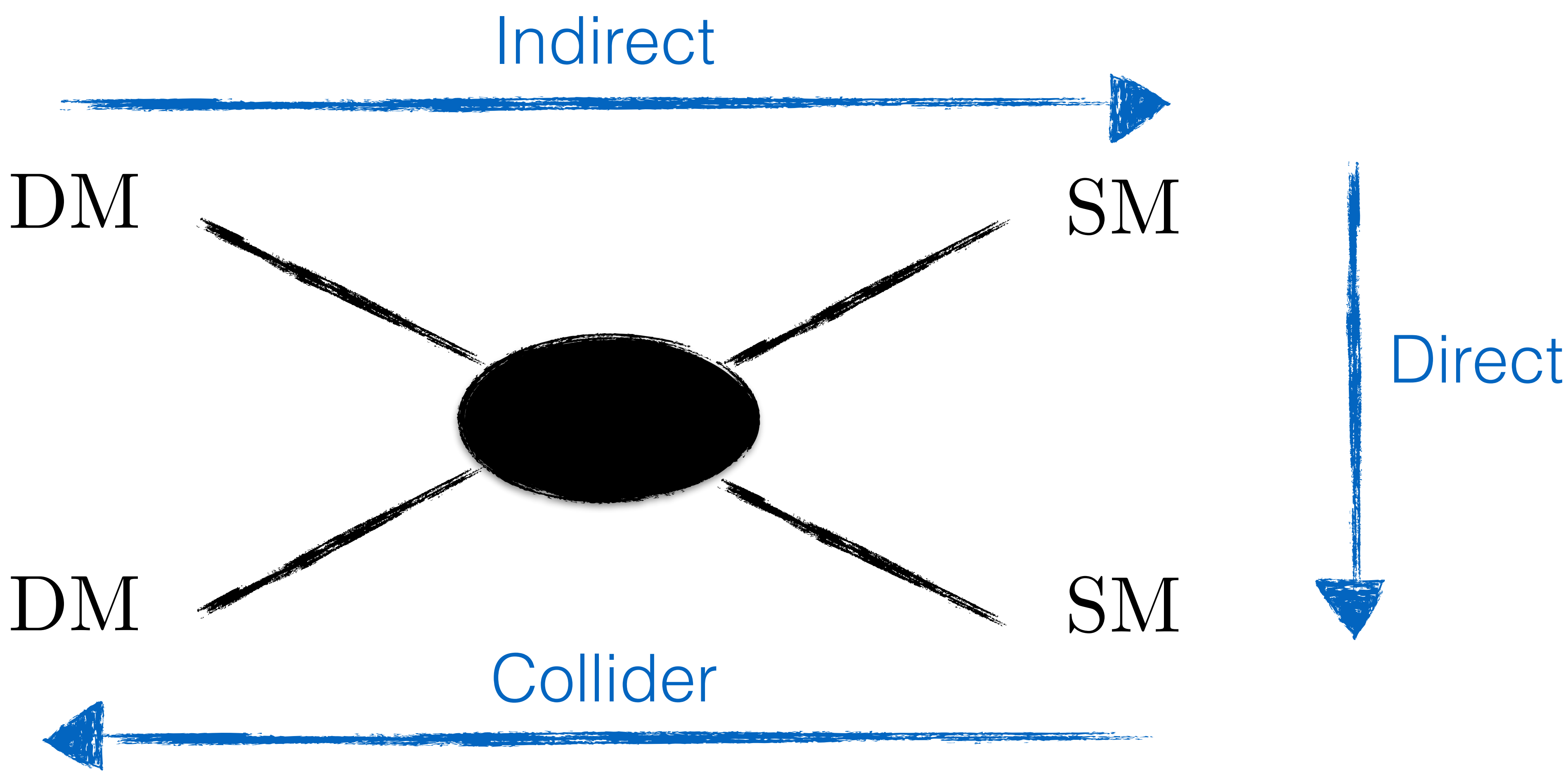


Direct Detection: Measure the recoil of DM onto heavy nuclei

Indirect Detection: Detect annihilation of DM in the Universe

Collider: Scatter SM particle to produce DM

Searches for DM



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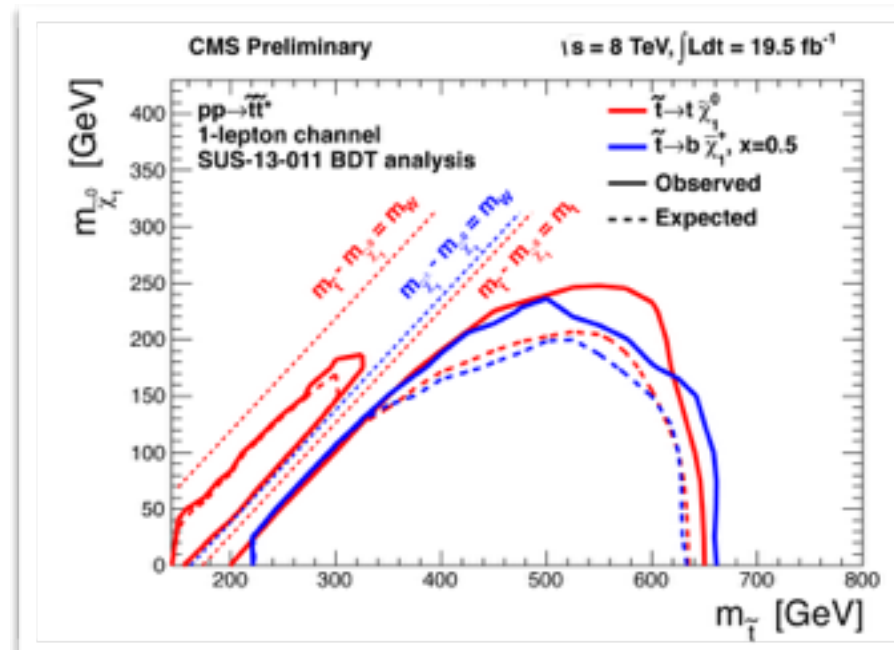
LHC searches for DM

WIMP Dark Matter can be in the reach of high energy colliders

The LHC has a rich program of DM searches

Specific models:

Supersymmetry
ED particles
CHMs
…



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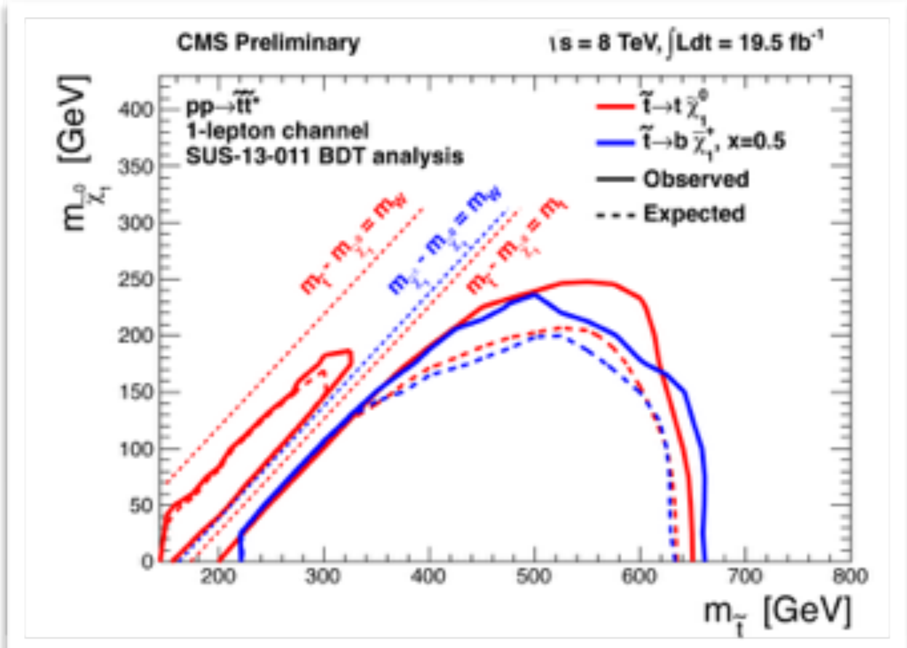


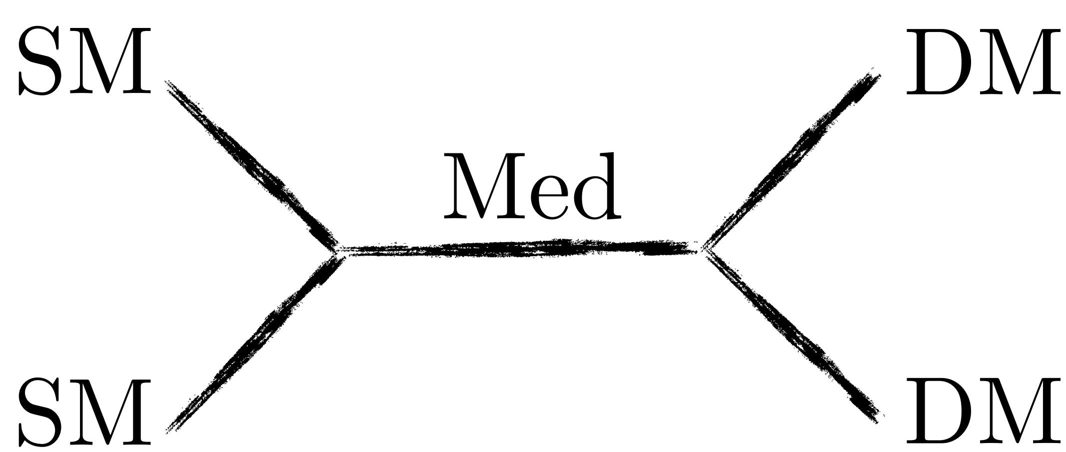
EFT framework

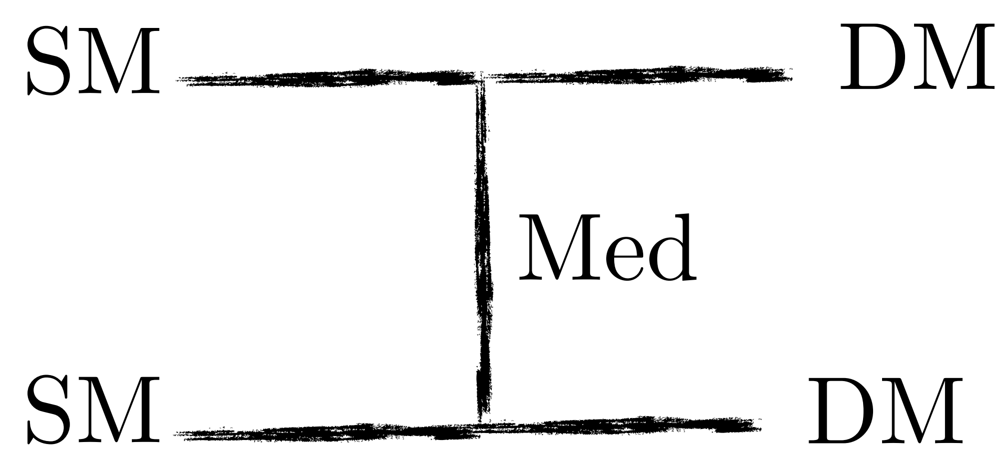
D>4 operators describing interactions of the DM candidate with the SM

!!! At the LHC energy it might not be consistent to integrate out heavy degrees of freedom $\sqrt{\hat{s}} \sim M_{\rm med}$

Given the null result on specific models and the drawback of the EFT attention has shifted on the simplified models approach

Simplified models: Only the DM and a mediator with the SM sector





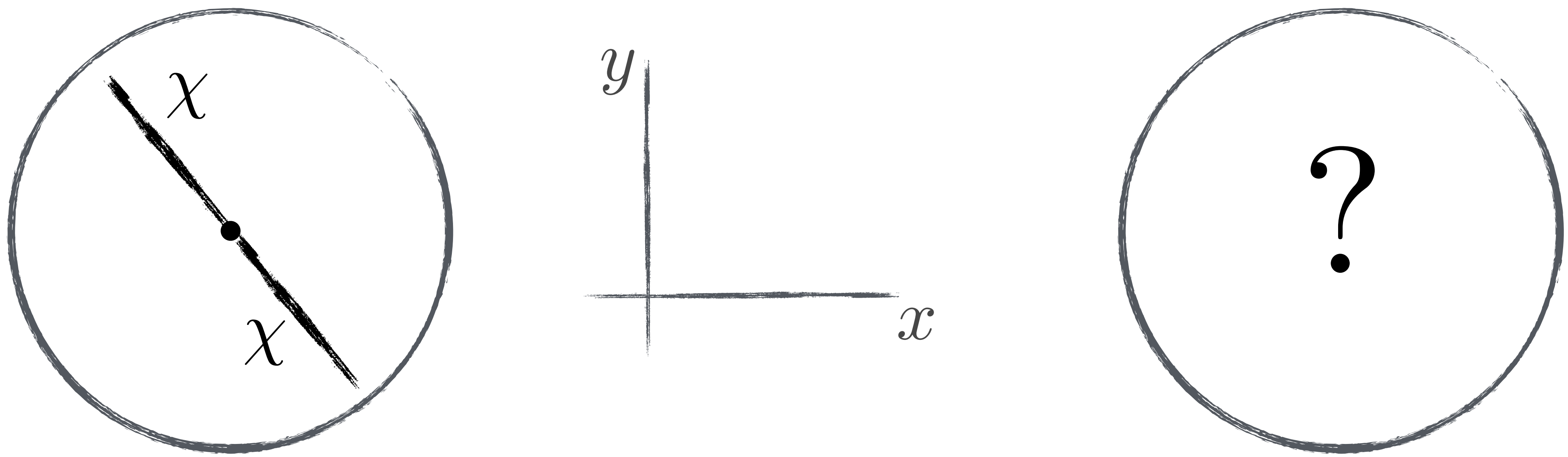
Issues: Simplified models might not have a trivial UV completions

Large activity in the theory HEP community

[Abdallah et al. ’15, De Simone et al. ’16, Wulzer et al. ’17…]

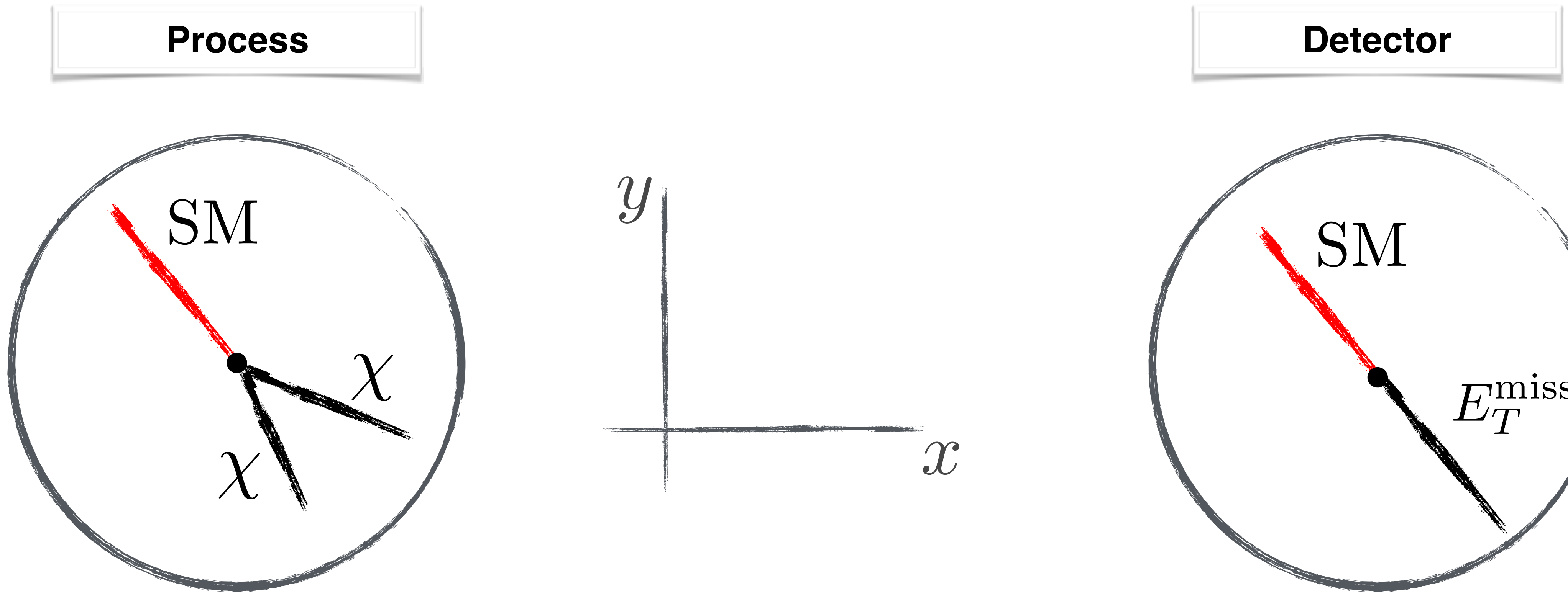
LHC searches for DM

Process **Detector**



No visible final state, DM production goes undetected

LHC searches for DM



Hard SM object recoiling against unbalanced momentum

ATLAS and CMS uses different SM particles

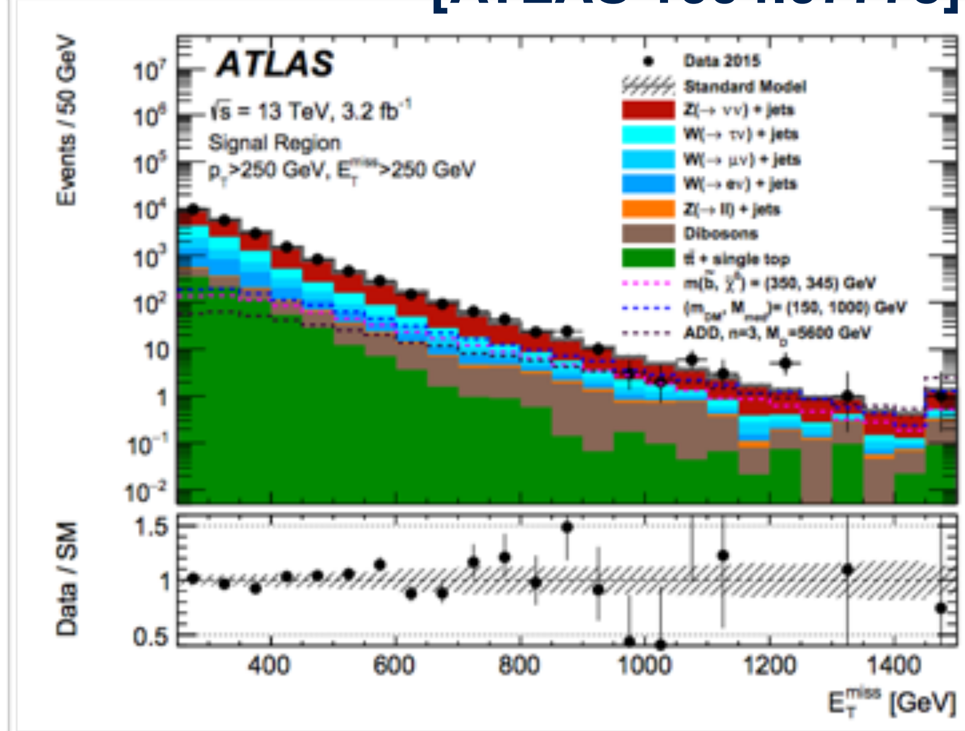
mono-jet mono-Z mono-W mono-H mono-γ

LHC searches for DM

Typical selections for a mono-jet analysis

Jet with high transverse momentum $p_T^j > 250 \text{ GeV}$

[ATLAS 1604.07773]



High missing transverse energy
Inclusive and exclusive categories

Veto on leptons and high number of jets in the event

Angular requirement between jet and missing transverse energy

Almost a single jet recoiling against nothing

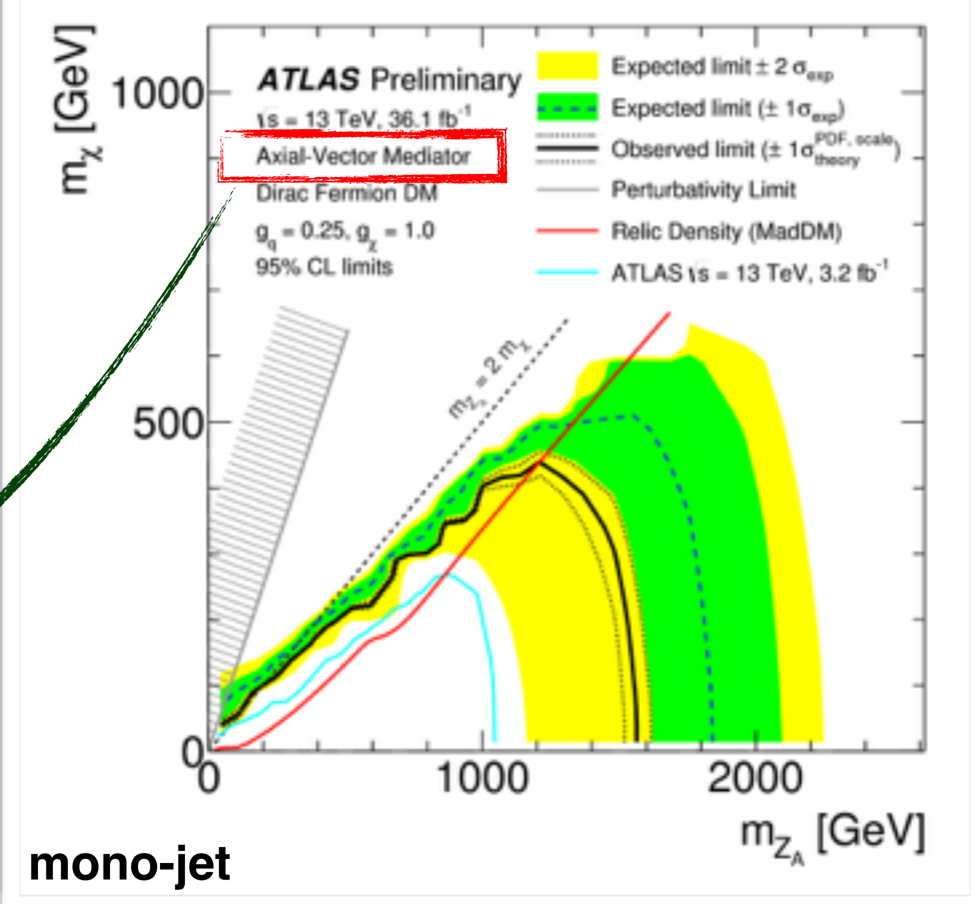
Simplified model searches

Mediators coupling to the DM state

Spin 0: scalar, pseudo scalar

Spin 1: vector, axial-vector

$$\text{Assumptions}\begin{cases} \bar{q}\gamma^\mu\gamma^5 q \\ \bar{\chi}\gamma^\mu\gamma^5\chi \end{cases}$$



This captures broad classes of models, but it assumes a certain Lorenz structure of the vertex that might not be realized in other BSM scenario

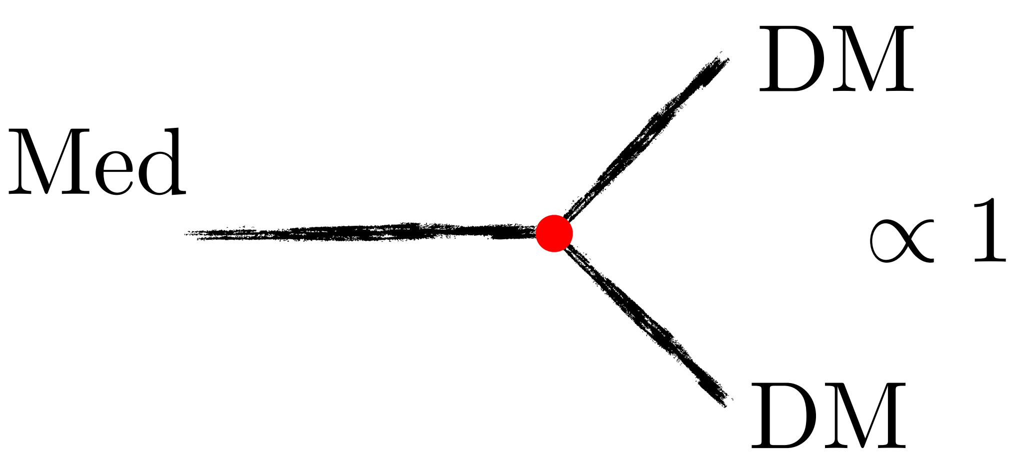
For example if the DM is a pNGB arising from a strongly interacting sector the NG shift symmetry forces the interactions to have a derivative, i.e. momentum dependent, term

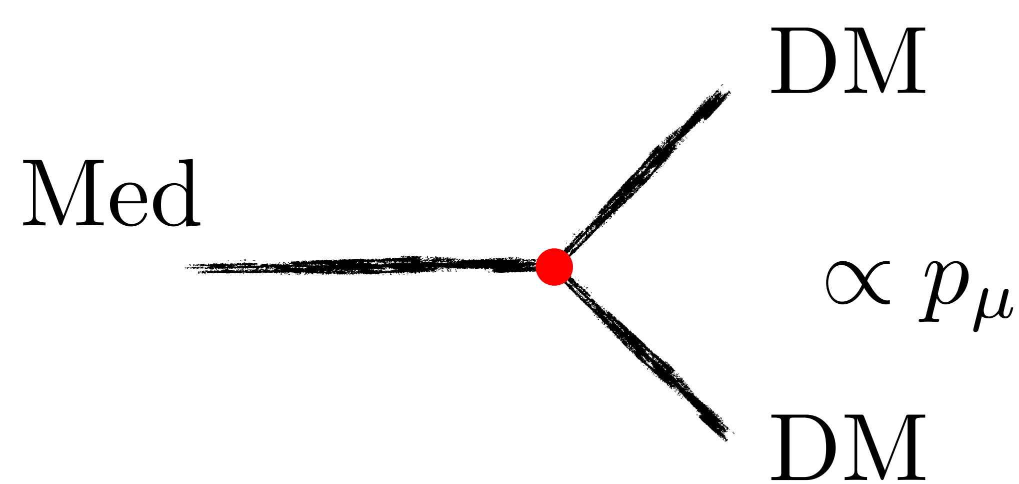
[Frigerio et al. ’12, Marzocca and Urbano ’1Fonseca et al. ’15, Brivio et al. ’16, Bruggisser et al. ’17,]

Momentum dependent interactions

$\mathcal{Q}$ {
- How this structure affects the DM searches at the LHC?
- What are other consequences of this possible structure?
- If a signal is observed, can we discriminate the two hypothesis

We take a pheno point of view and parametrise the momentum independent and momentum dependent interactions of the DM with a mediator without relying onto a specific model framework





The Higgs portal case

SM plus a gauge singlet real scalar field η and $\mathbb{Z}_2$ symmetry imposed

$$\mathcal{L}_\eta = \mathcal{L}_{\rm SM} + \frac{1}{2}\partial_\mu\eta\partial^\mu\eta - \frac{1}{2}\mu_\eta^2\eta^2 - \frac{1}{4}\lambda_\eta\eta^4 - \frac{1}{2}\lambda\eta^2 H^\dagger H + \frac{1}{2f^2}(\partial_\mu\eta^2)\partial^\mu(H^\dagger H)$$

After EWSB

$$\mathcal{L}_\eta \supset -\frac{1}{4}(v+h)^2\left(\lambda\eta^2 + \frac{1}{f^2}\partial_\mu\partial^\mu\eta^2\right)$$

$m_h > 2m_\eta$

$$g \propto \frac{p_h^2}{f^2} = \frac{m_h^2}{f^2}$$

MD disappear in the on-shell case

$m_h < 2m_\eta$

$$g \propto \frac{p_h^2}{f^2}$$

MD of the interaction

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$$\mathcal{L}_\eta = \mathcal{L}_{\rm SM} + \frac{1}{2}\partial_\mu\eta\partial^\mu\eta \quad \ldots \quad H^\dagger H + \frac{1}{2f^2}(\partial_\mu\eta^2)\partial^\mu(H^\dagger H)$$

[Note: neglecting other D6 operators allowed by symmetries which are not expect to modify monojet type constraints]

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MD of the interaction

The Higgs portal case

One however pays the price of a suppression due to the off-shell Higgs

$$\hat{\sigma}(gg \to gh^* \to g\eta\eta) \propto \frac{\theta(p_h^2 - 4m_\eta^2)}{(p_h^2 - m_h^2)^2 + \Gamma_h^2 m_h^2} \left(\frac{p_h^2}{f^2} - \lambda\right)^2 \sqrt{1 - \frac{4m_\eta^2}{p_h^2}}$$

The LHC also poses sever constraints on Higgs portal models

[Craig et al. '14]

$$m_\eta \gtrsim m_h/2, \qquad \lambda \lesssim 1, \qquad f \gtrsim 500 \text{ GeV} - 1 \text{ TeV}$$

This apply when the Higgs is a pNGB

Monojet signal to small to be observed in the off-shell Higgs portal case

The heavy mediator case

SM plus two gauge singlet real scalar fields η , s and a $\mathbb{Z}_2$ symmetry imposed

$$\mathcal{L}_{\eta,s} = \mathcal{L}_{\rm SM} + \frac{1}{2}\partial_\mu\eta\partial^\mu\eta - \frac{1}{2}m_\eta^2\eta\eta + \frac{1}{2}\partial_\mu s\partial^\mu s - \frac{1}{2}m_s^2 ss + \frac{c_{s\eta}f}{2}s\eta\eta + \frac{c_{\partial s\eta}}{f}(\partial_\mu s)(\partial^\mu\eta)\eta + \frac{\alpha_s}{16\pi}\frac{c_{sg}}{f}sG^a_{\mu\nu}G^{a\mu\nu}$$

Can be generated, e.g., by additional heavy fermions $c_{sg} = 4/3\, y_\psi\, f/M_\psi$

Constraints on the model arise from

- Collider physics: di-jet production and DM searches
- Astrophysics: DM relic abundance
- Astrophysics: DM indirect detection
- Theory: Unitarity

The heavy mediator case

Dijet constraints

$$\sigma(pp \to s \to gg) = \int_0^1 \mathrm{d}x_1 \int_0^1 \mathrm{d}x_2 \; f_g(x_1, m_s) f_g(x_2, m_s) \frac{\alpha_s^2 c_{sg}^2 m_s^2}{1024\pi f^2} \; \delta(\hat{s} - m_s^2) \mathrm{BR}\big(s \to gg\big)$$

$$\Gamma(s \to gg) = \frac{\alpha_s^2 c_{sg}^2 m_s^3}{128\pi^3 f^2}$$

Main decay channel in the off-shell case

We focus on mediator with a mass lighter than 1 TeV

Main constraints arising from Tevatron and $Sp\bar{p}S$ searches

For f~1000 GeV c_{sg} ~100 allowed for m_s~100-1000 GeV

The heavy mediator case

Relic abundance:

$$\langle \sigma v \rangle_{gg} \simeq \frac{\alpha_s^2 c_{sg}^2 m_\eta^2 \left(c_{s\eta} f^2 + 4 c_{\partial s\eta} m_\eta^2\right)^2}{16\pi^3 f^4 \left(m_s^2 - 4m_\eta^2\right)^2}$$

$$\langle \sigma v \rangle_{ss} \simeq \frac{\sqrt{1 - \frac{m_s^2}{m_\eta^2}} \left(c_{\partial s\eta} m_s^2 + c_{s\eta} f^2\right)^4}{16\pi f^4 m_\eta^2 \left(m_s^2 - 2m_\eta^2\right)^2}$$

If $m_\eta > m_s$

Direct detection:

Can be neglected in the MD dependent case, small momentum transferred

For the MI case contributions due to the interactions of η with the gluons

$$\mathcal{L}_{\eta g} = f_G\, \eta^2\, G_{\mu\nu} G^{\mu\nu} \qquad \text{with} \qquad f_G = \frac{\alpha_s c_{sg} c_{s\eta}}{32\pi} \frac{1}{m_s^2}$$

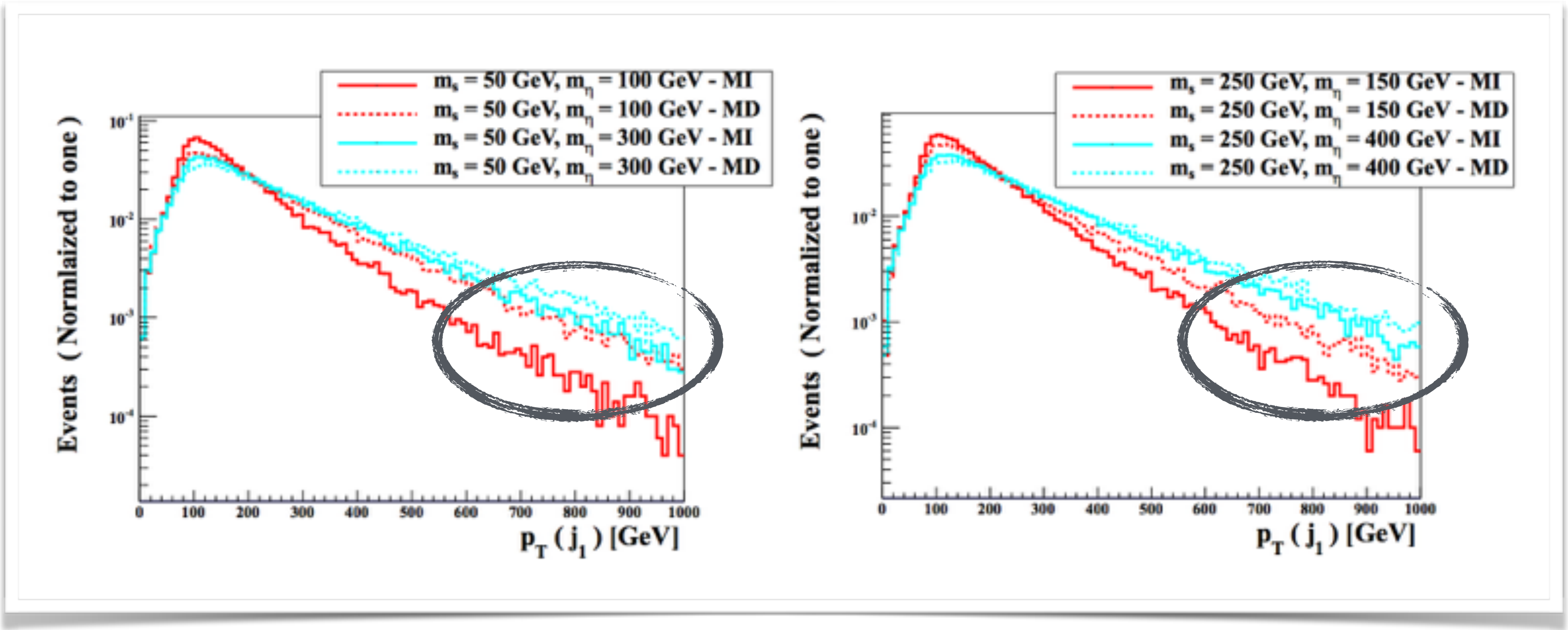
$$\sigma_{\rm SI} = \frac{1}{\pi} \left(\frac{m_\eta m_p}{m_\eta + m_p}\right)^2 \left| \frac{8\pi}{9\alpha_s} \frac{m_p}{m_\eta} f_G f_{TG} \right|^2$$

f_{TG} gluon form factor

The heavy mediator case

Monojet searches:

Assuming perfect detector we check the transverse momentum of the hard jet

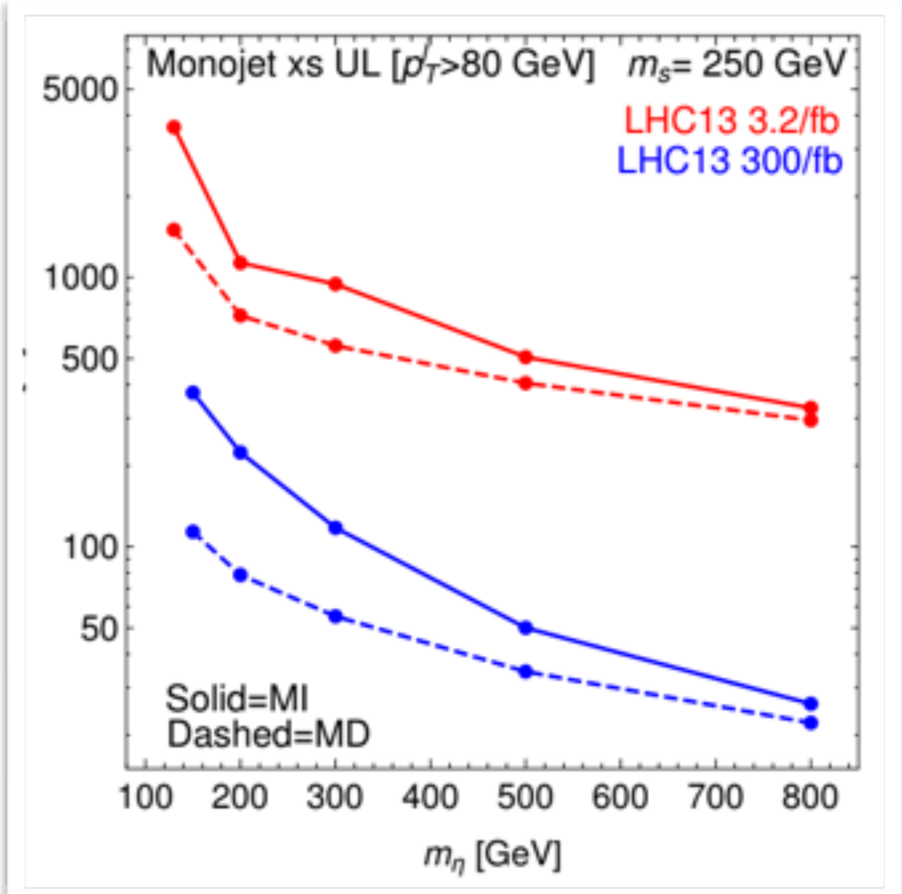


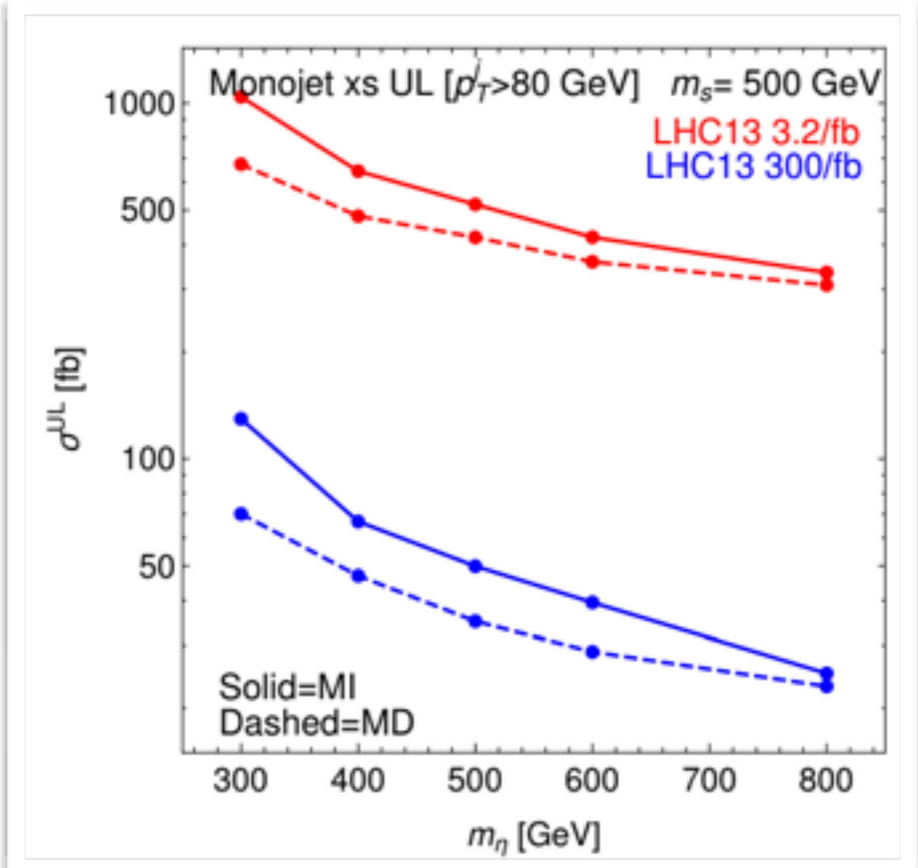
Enhancement in the high p_T region for the MD coupling case

More events are likely to pass the hard E_T^{miss} cut, improving the LHC sensitivity

The heavy mediator case

With the signal acceptances one can compute the 95% UL on the signal σ



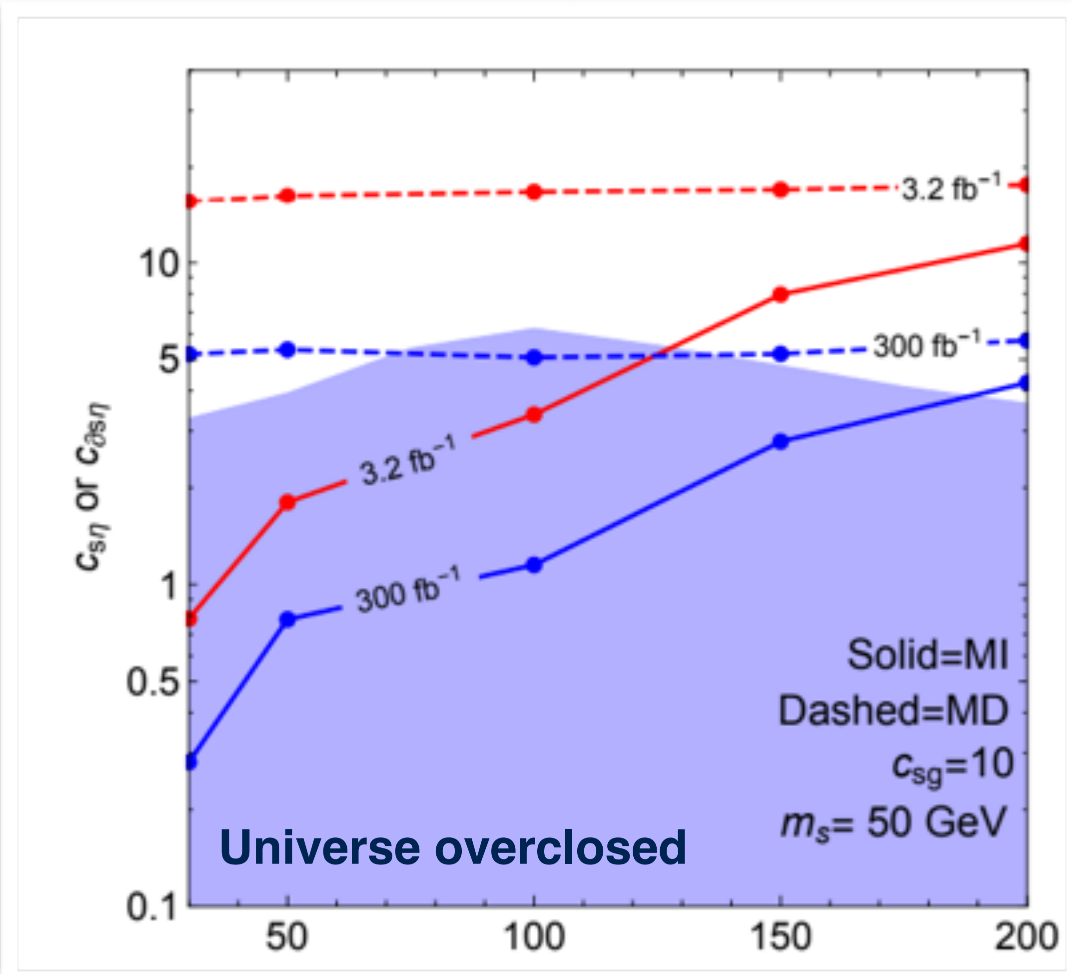


High lumi projections with high $E_T^{\rm miss}$ cuts: background from exp. analysis

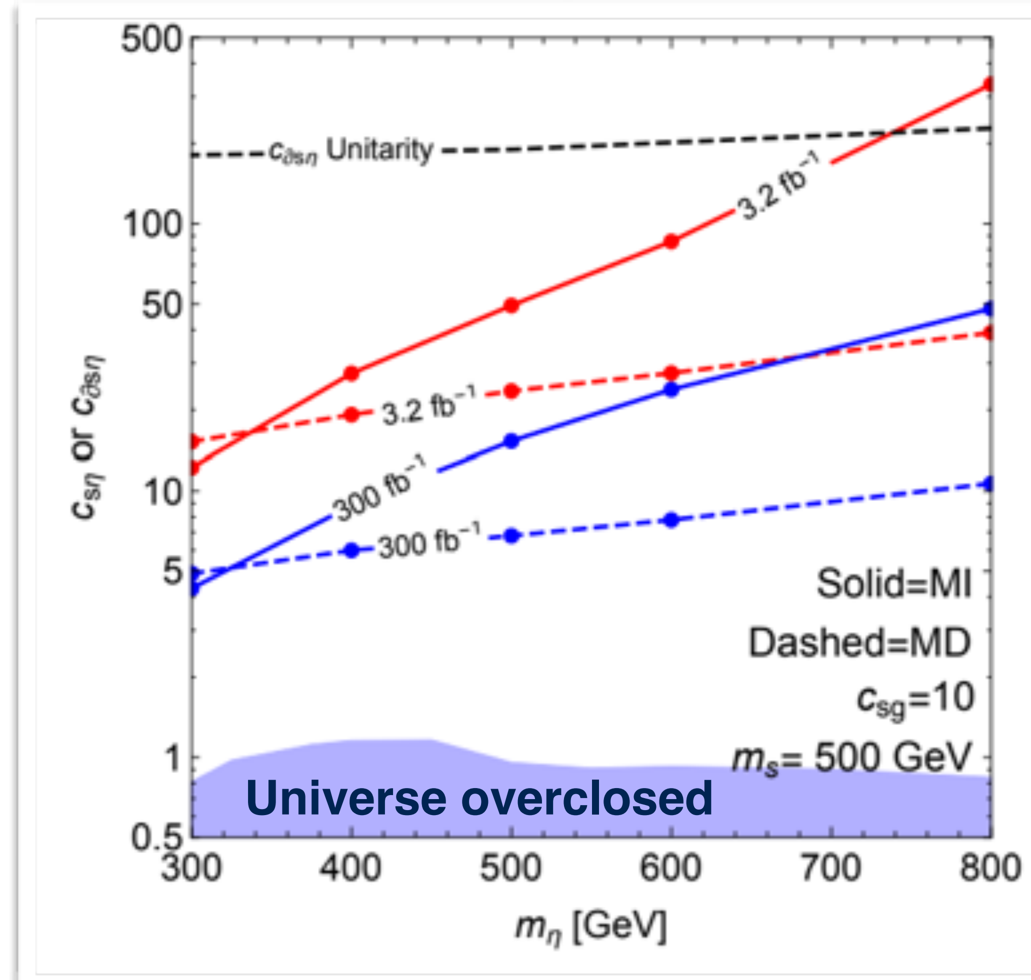
[ATLAS 1604.07773]

LHC is able to exclude smaller cross sections for the MD case

The heavy mediator case



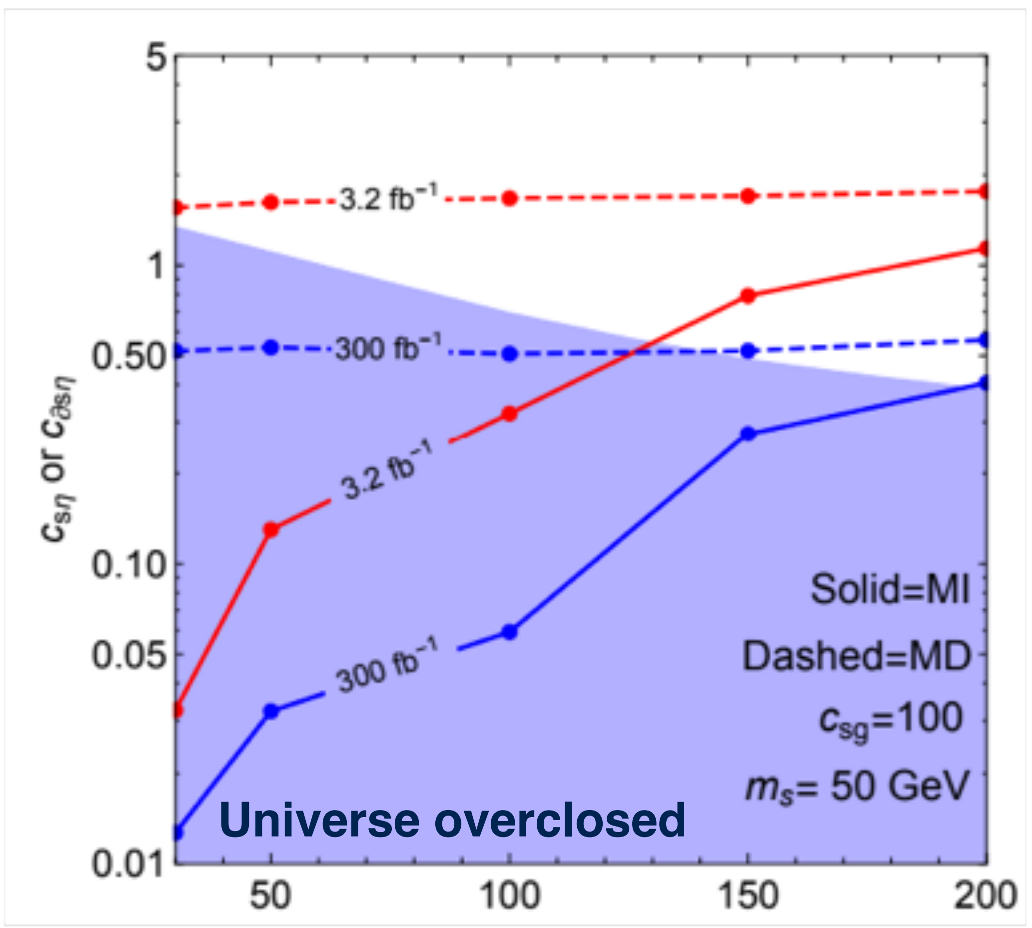
$$c_{sg} = 10$$



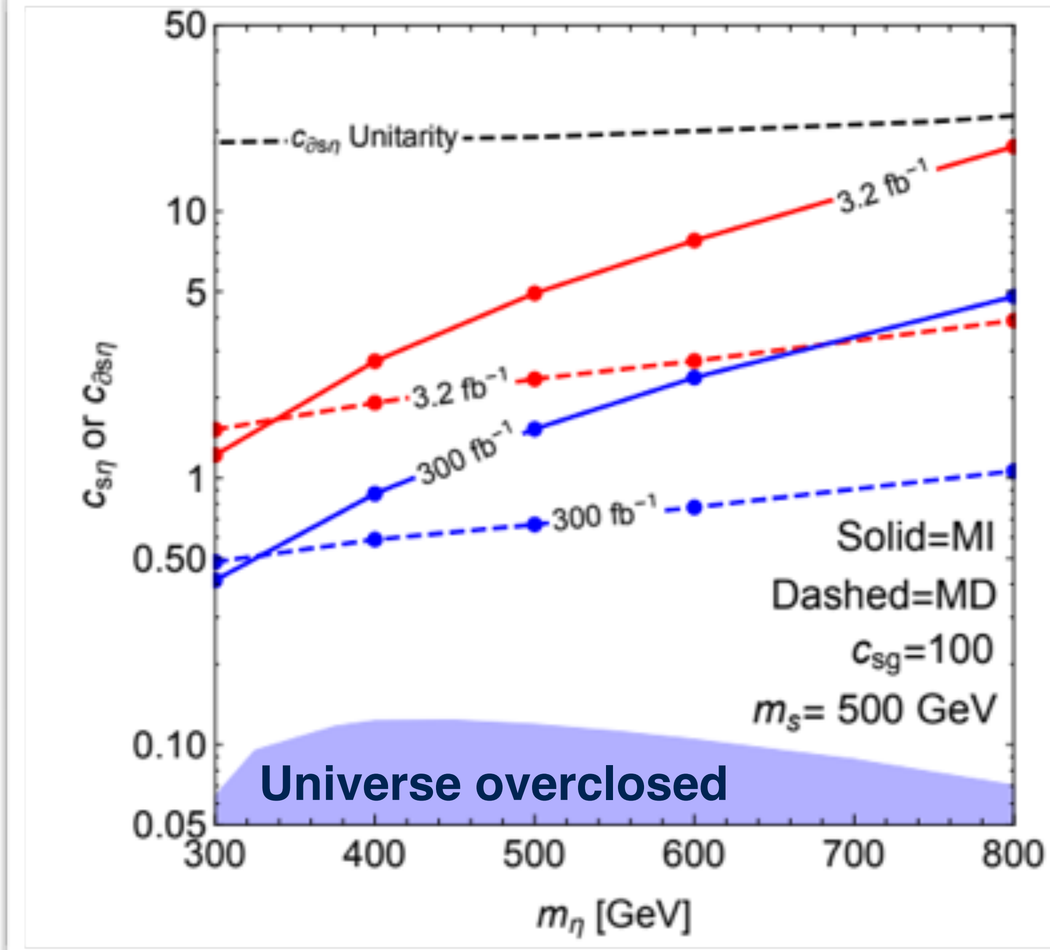
- In the MI case DD excludes the entire region. Any excess can be just due to missing energy unrelated to DM

- LHC will soon start to explore the region where a MD interaction can give the correct relic density

The heavy mediator case



$$c_{sg} = 100$$



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Conclusions

- LHC collaborations have put forward an intense program of DM searches within specific models framework

- Due to the null results of the first runs of the LHC, the attention has shifted towards simplified models analyses

- Different assumptions on the coupling structure can be made. In particular in models with a new strong dynamic, interactions can have a dependance on the momentum transferred

- This causes a different sensitivity of the LHC searches, together at being subject to weaker constraints from direct detection experiments

- Interestingly, should a signal be discovered at the LHC, an exploitation of the missing energy distributions can be used to disentangle the two hypotheses

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- Interestingly, should a signal be discovered at the LHC, an exploitation of the missing energy distributions can be used to disentangle the two hypotheses

Thank you!

Backup

Perturbative unitarity on $gg \to \eta\eta$

$$\kappa_{\rm MD} < \frac{64\sqrt{2}\pi^2 f^2 (Q^2 - m_s^2)}{\alpha_s Q^4 \left(1 - \frac{4m_\eta^2}{Q^2}\right)^{1/4}}$$

$$\kappa_{\rm MD} = c_{\partial s\eta} c_{sg}$$

$$\kappa_{\rm MI} < \frac{64\sqrt{2}\pi^2 (1 - \frac{m_s^2}{Q^2})}{\alpha_s \left(1 - \frac{4m_\eta^2}{Q^2}\right)^{1/4}}$$

$$\kappa_{\rm MI} = c_{s\eta} c_{sg}$$

Fixing $|Q| \sim 2\ \mathrm{TeV}$ roughly the energy probed