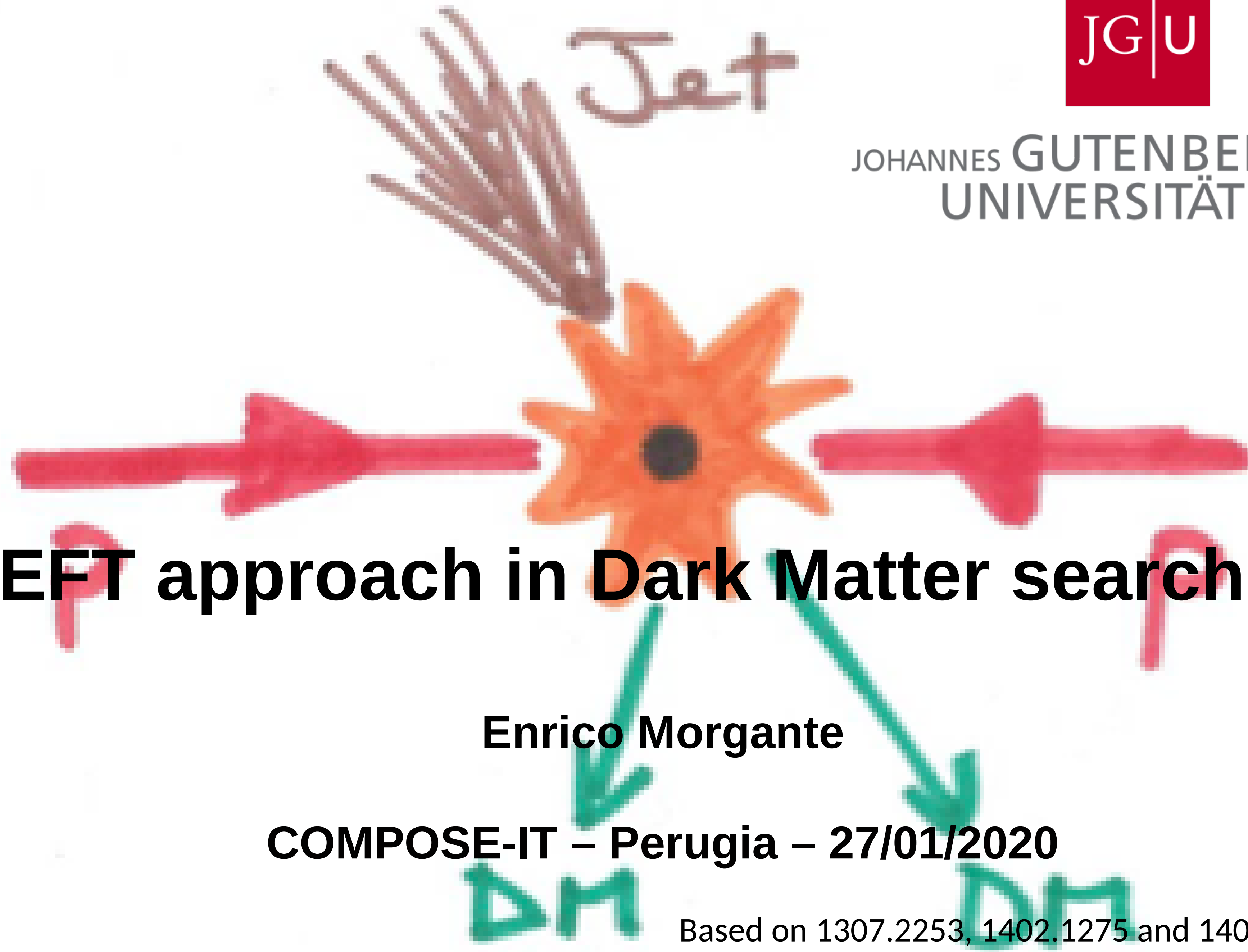


JOHANNES GUTENBERG UNIVERSITÄT MAINZ

EFT approach in Dark Matter searches

Enrico Morgante

COMPOSE-IT – Perugia – 27/01/2020

Based on 1307.2253, 1402.1275 and 1405.3101

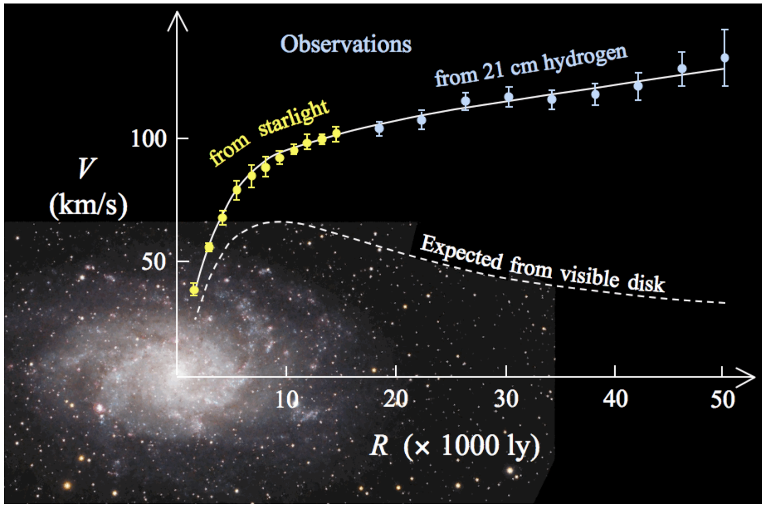
EM with G. Busoni, A. De Simone, J. Gramling, T. Jacques, T. Riotto

Outline

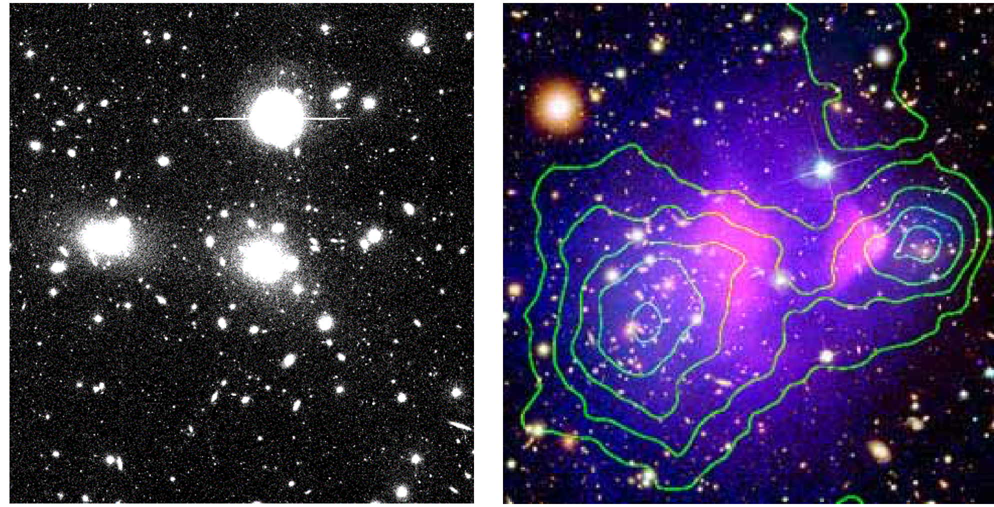
- Introduction: evidences, candidates, WIMPs
- DM searches at the LHC
- LHC: what models should we use?
  - Effective theories and validity concerns
  - Simplified models
- Conclusion

Evidences

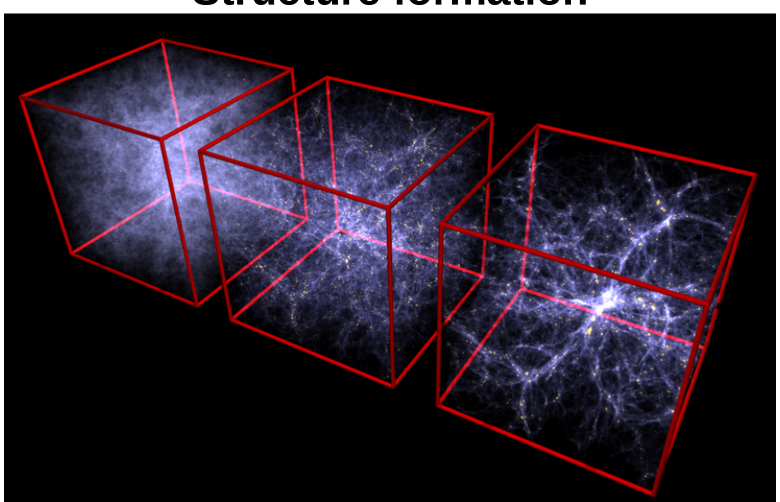
Galaxies



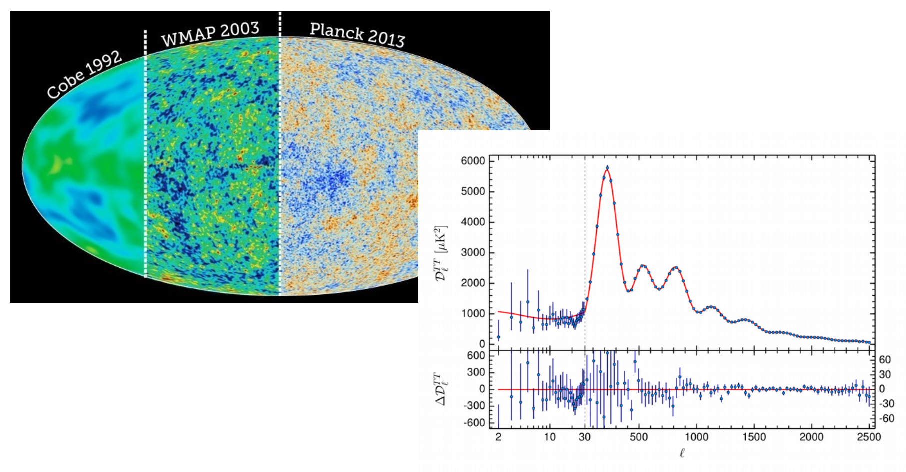
Galaxy clusters



Structure formation



Cosmic Microwave Background



The “WIMP miracle”

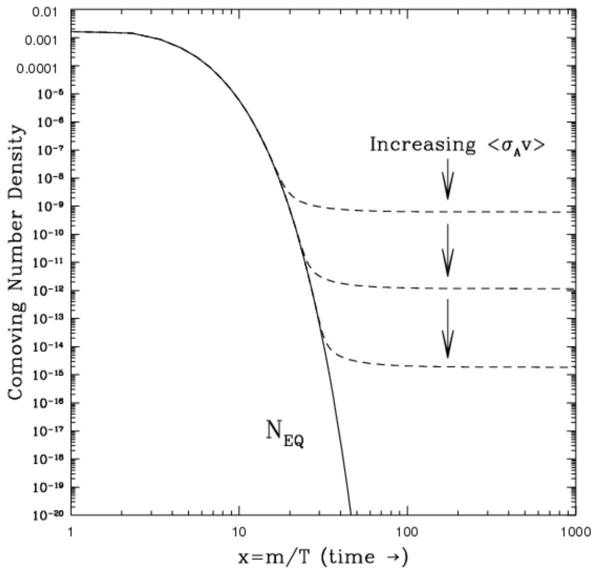
New BSM particles are needed. How are they produced?

Thermal freeze-out mechanism

DM initially in thermal equilibrium in the expanding universe

$$\dot{n} + 3Hn = -\langle \sigma v \rangle \left(n^2 - n_{\rm eq}^2 \right)$$

When $\Gamma \sim H$ the DM decouples and its comoving number density remains fixed



The WIMP miracle:
A particle with mass around the weak scale interacting with weak force (as the ones we expect from solutions to the naturalness problem) has automatically the correct relic abundance

DM – SM interaction

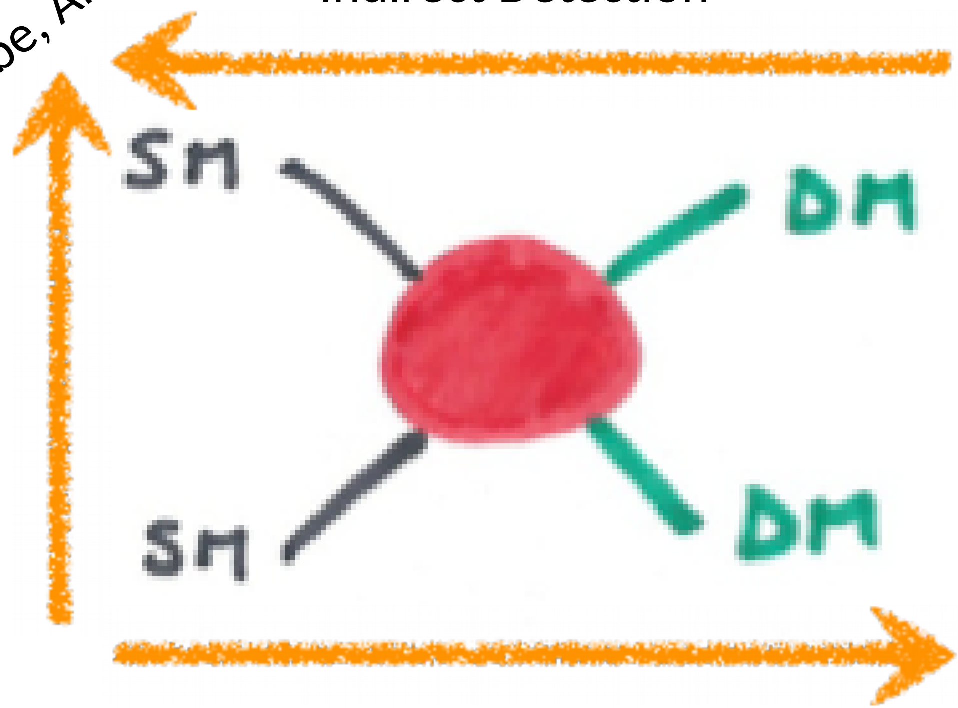
How does DM interact with the SM?

1) **Gravitationally:** DM gravitates, and leaves its imprint on LSS dynamics, formation, CMB…

2) **Non gravitationally:** we don't know, but

- It's our only hope!
- Plenty of BSM models predict DM candidates (SUSY & other naturalness related constructions, axions, …)
- DM production mechanism
- How can we probe this interaction?

How can we test DM interactions with the Standard Model?



DM at the LHC

Trivial observation: WIMP particles do not interact with the detectors

~~pp → DM DM~~

Tag DM events with some recoiling SM particle

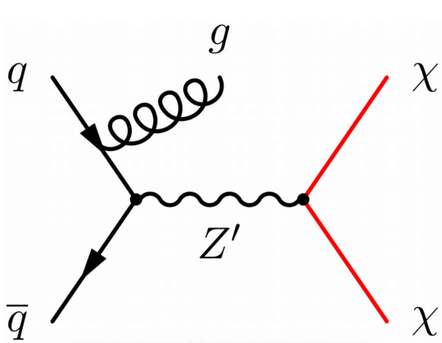
e.g. “mono-X + MET” searches

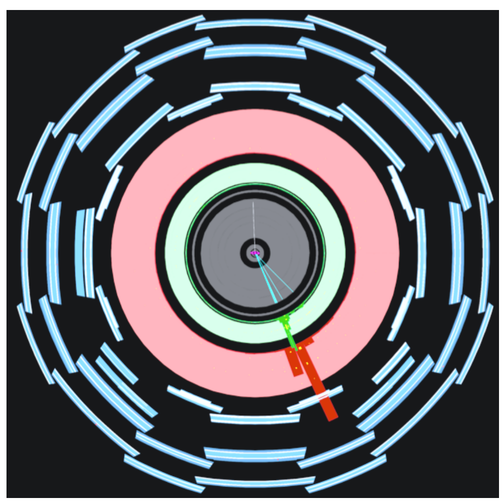
a single SM object recoiling against some unpaired momentum in the transverse plane

Study the “dark sector” independently of DM

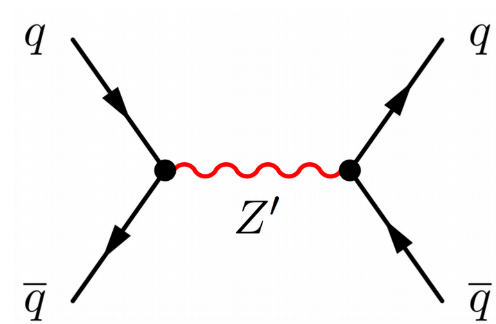
e.g. “di-jet” searches

the mediator is produced and decays back into a quark - antiquark pair

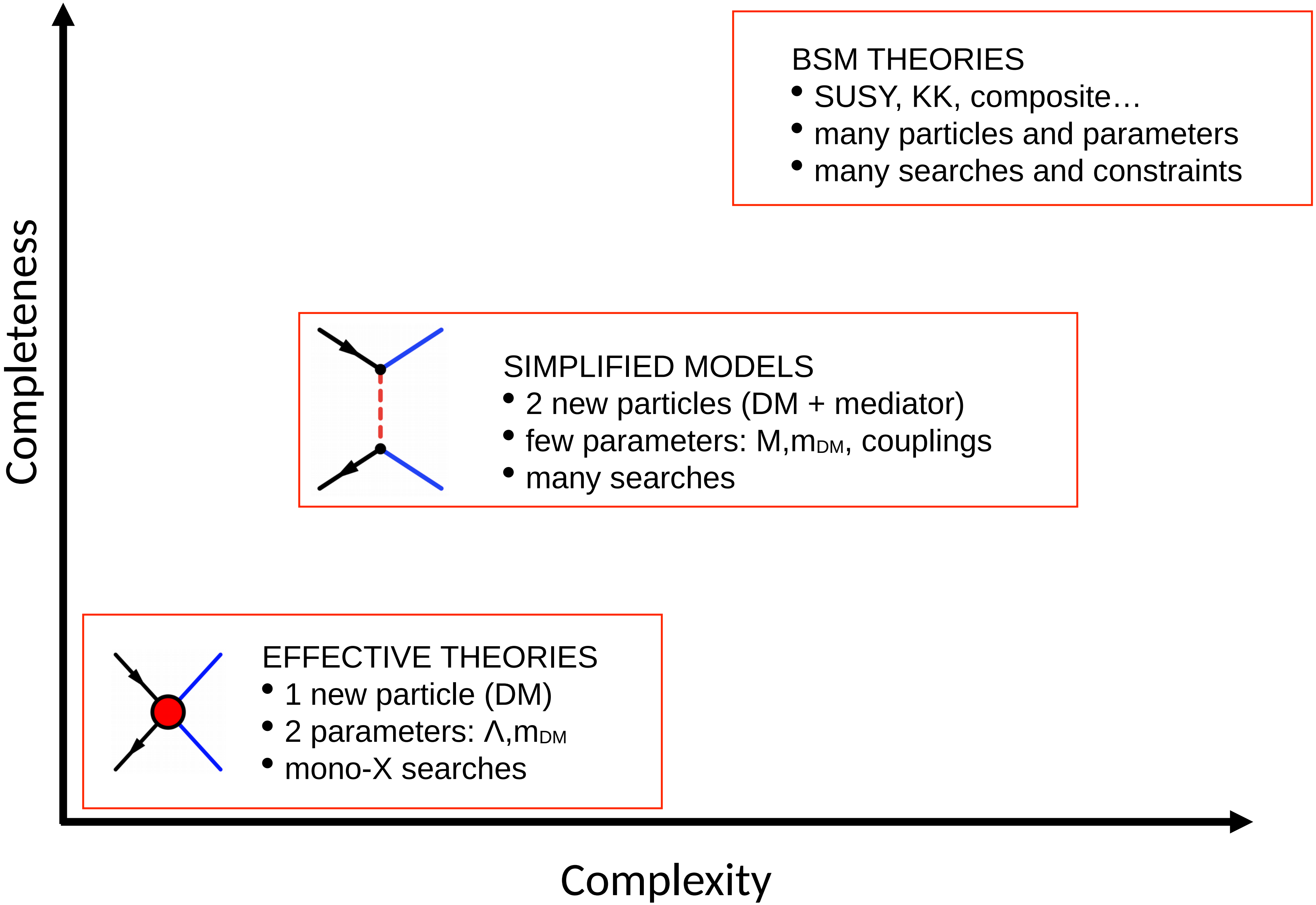




ATLAS mono-jet event, CERN courier



DM “models”



BSM THEORIES
• SUSY, KK, composite…
• many particles and parameters
• many searches and constraints
SIMPLIFIED MODELS
• 2 new particles (DM + mediator)
• few parameters: M,m$_{DM}$, couplings
• many searches
EFFECTIVE THEORIES
• 1 new particle (DM)
• 2 parameters: Λ,m$_{DM}$
• mono-X searches
Completeness
Complexity

Why EFT

Effective operators have a number of advantages as a tool for DM searches:

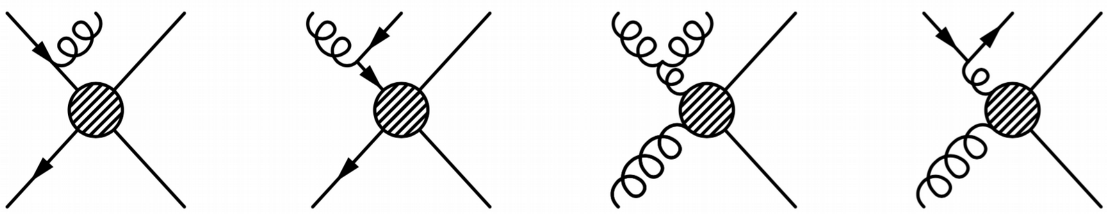
- Simple, minimal number of parameters
- “Universal”: whatever BSM theory lead to the same set of effective operators
- Suitable for strongly interacting dark sectors
- ~~Exploit complementarity: LHC can probe the same effective operator as Direct/Indirect searches~~

EFT description

Goodman, Ibe, Rajaraman, Shepherd, Tait, Yu, 1008.1783, PRD

The simplest description is EFT
(with initial state radiation)

$$\mathcal{L} = \bar{\psi}\left(i\partial\cdot\gamma - m\right)\psi + \frac{\mathcal{O}_6}{\Lambda^2} + \frac{\mathcal{O}_8}{\Lambda^4}\cdots$$

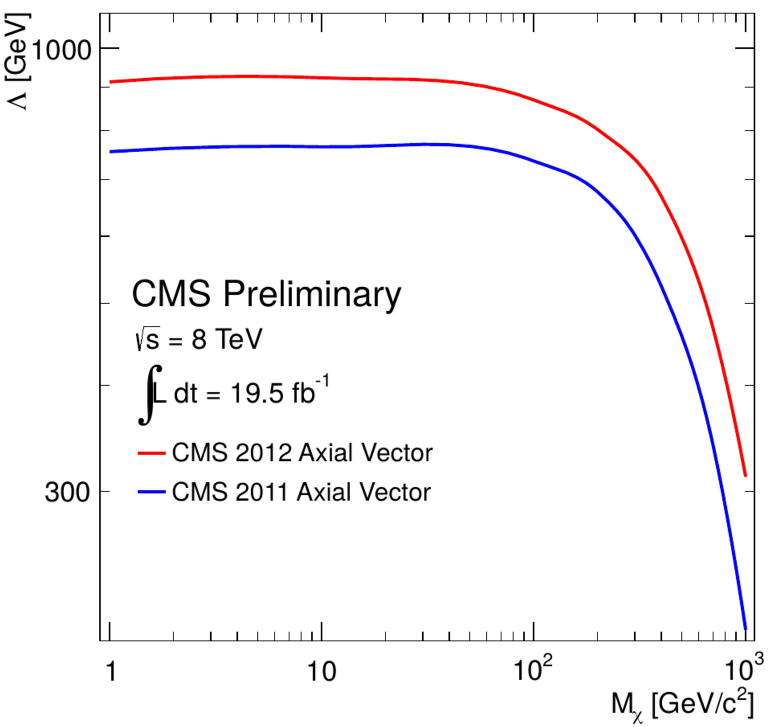


- Write a complete set of dim-6 operators (*e.g.* in the s-channel)
- Assume DM production happens only through one of these
- Derive bounds on the plane (m_{DM}-Λ) for that operator

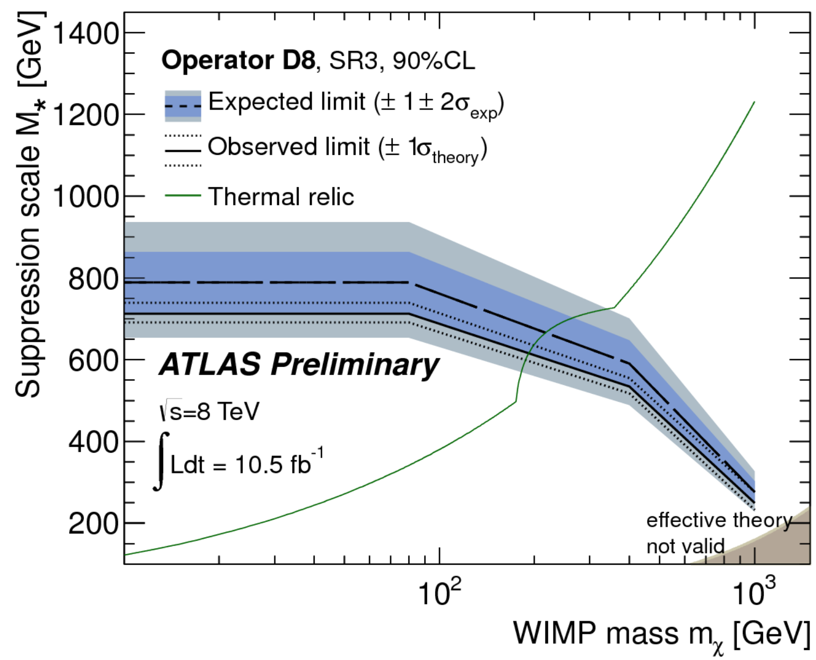
Name	Operator	Coefficient
D1	$\bar{\chi}\chi\,\bar{q}q$	m_q/Λ^3
D1'	$\bar{\chi}\chi\,\bar{q}q$	$1/\Lambda^2$
D2	$\bar{\chi}\gamma^5\chi\,\bar{q}q$	im_q/Λ^3
D2'	$\bar{\chi}\gamma^5\chi\,\bar{q}q$	i/Λ^2
D3	$\bar{\chi}\chi\,\bar{q}\gamma^5 q$	im_q/Λ^3
D3'	$\bar{\chi}\chi\,\bar{q}\gamma^5 q$	i/Λ^2
D4	$\bar{\chi}\gamma^5\chi\,\bar{q}\gamma^5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

EFT description

Effective operators have been used extensively by ATLAS / CMS



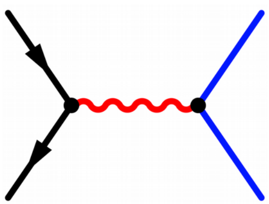
CMS-PAS-EXO-12-048



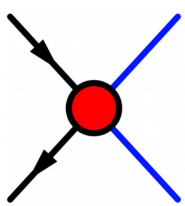
ATLAS-CONF-2012-147

Validity of the EFT

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



$$\sim \frac{g_\chi g_q}{Q_{\mathrm{tr}}^2 - M^2} = -\frac{g_\chi g_q}{M^2}\left(1 + \cancel{\frac{Q_{\mathrm{tr}}^2}{\Lambda^2} + \frac{Q_{\mathrm{tr}}^4}{\Lambda^4}} + \dots\right)$$



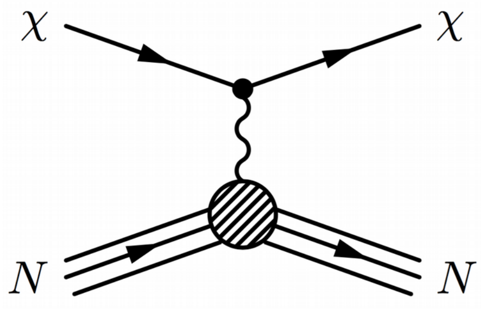
$$= \frac{1}{\Lambda^2}\left(\bar{\chi}\Gamma_a \chi\right)\left(\bar{q}\Gamma_b q\right)$$

One should check that the energy scale of the process under study is smaller than Λ

Validity of the EFT

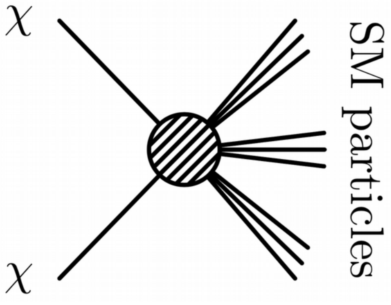
Direct detection

$$\langle Q_{\mathrm{tr}}^2 \rangle \approx \mathcal{O}(100\,\mathrm{MeV})^2 \ll \Lambda^2$$



Indirect detection

$$v \sim 10^{-3},\, m_\chi < M_{\mathrm{med}}$$

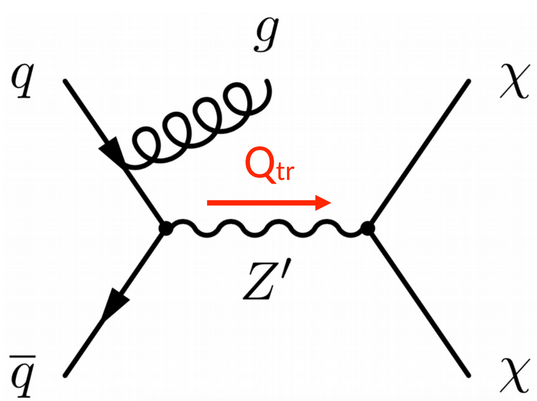


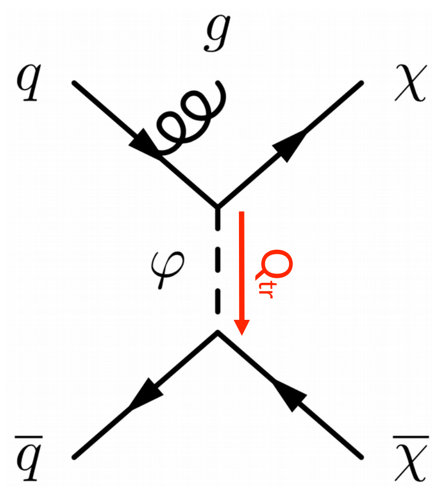
In both cases, the EFT is typically safe

Validity of the EFT

At the LHC, the typical momentum exchanged is very large

$$\langle Q^2_{\mathrm{tr}} \rangle \sim \mathcal{O}(1\,\mathrm{TeV})^2 \sim \Lambda^2$$





The effective description is expected to fail

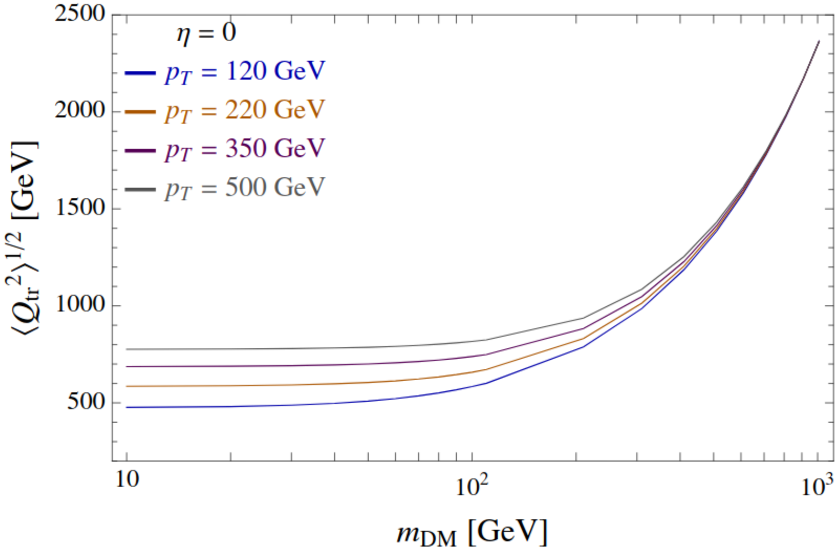
[Busoni, EM, *et al.*, 1307.2253, 1402.1275, 1405.3101]

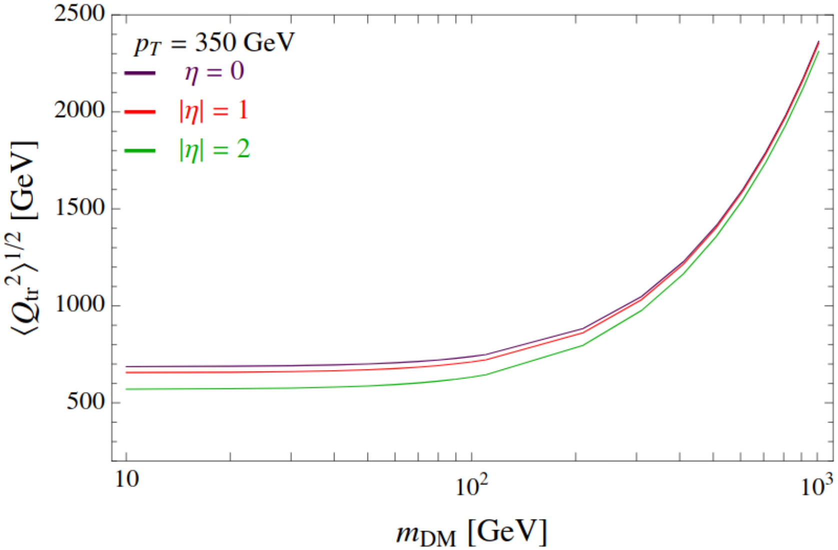
Validity of the EFT

Momentum exchanged in a qq → XXg process

$$Q^2_{\rm tr} = (p_q + p_{\bar q} - p_g)^2 = x_1 x_2 s - \sqrt{s} p_T (x_1 e^{-\eta} x_2 e^{\eta})$$

Average over pdfs

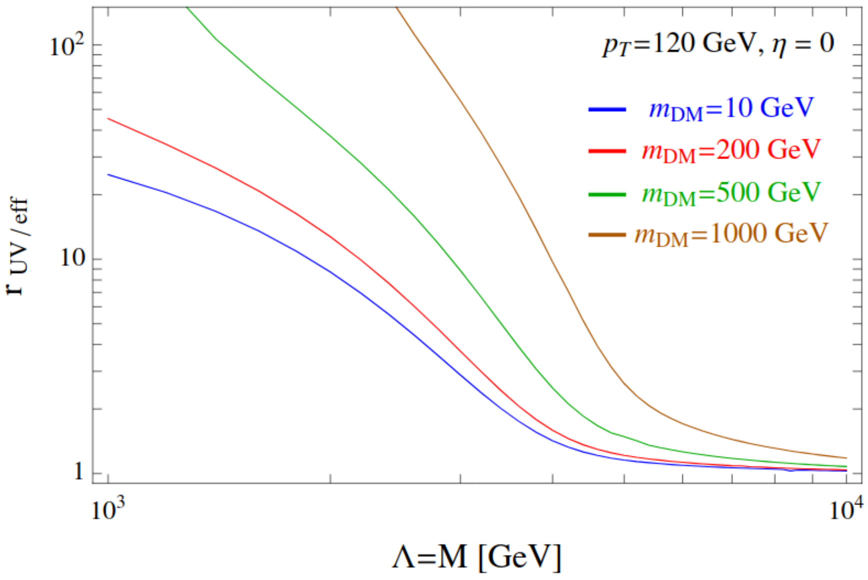


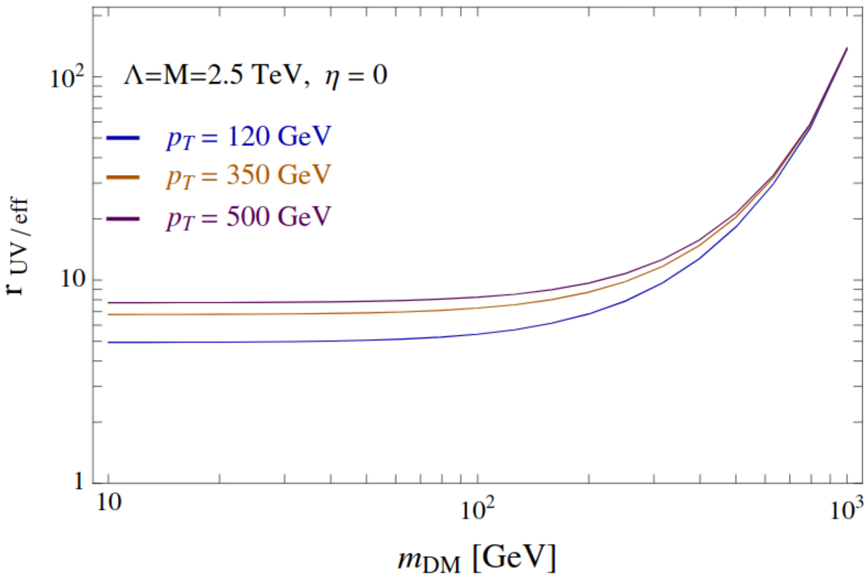


[Busoni, EM, *et al.*, 1307.2253, 1402.1275, 1405.3101]

Compare with a simple UV completion

$$\mathcal{L}_{\rm UV} \supset \frac{1}{2} M_{\rm med}^2 S^2 - g_q \bar{q} q S - g_\chi \bar{\chi}\chi S \qquad \textit{vs.} \qquad \mathcal{L}_{\rm EFT} \supset \frac{1}{\Lambda^2} \bar{q}q\,\bar{\chi}\chi$$





EFT works better for heavy mediator, light DM, low pT

[Busoni, EM, *et al.*, 1307.2253, 1402.1275, 1405.3101]

Measure the EFT validity

Experiments used to impose loose conditions on the EFT validity

- EFT is reliable if

$$\Lambda = \frac{M_{\rm med}}{\sqrt{g_\chi g_q}} > \frac{Q_{\rm tr}}{\sqrt{g_\chi g_q}}$$

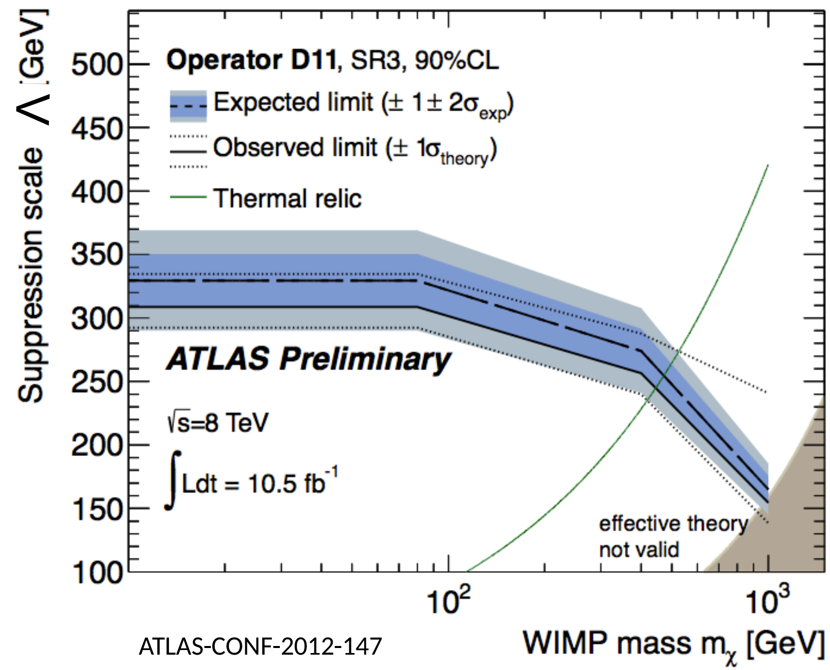
- To produce DM on shell (in the s-channel)

$$Q_{\rm tr} > 2m_\chi$$

- Perturbativity: $g \lesssim 4\pi$

- The validity condition is then

$$\Lambda > \frac{m_\chi}{2\pi}$$



ATLAS-CONF-2012-147

Cross section imposing $Q_{tr}<\Lambda$

To quantify the goodness/badness of EFT we can compute the cross section with or without imposing the condition on Q_{tr}

$$R_{\Lambda}^{\rm tot}(m_{\rm DM},\Lambda) \equiv \frac{\sigma_{\rm eff}\big|_{Q_{\rm tr}<\Lambda}}{\sigma_{\rm eff}} = \frac{\int_{p_{\rm T}^{\rm min}}^{p_{\rm T}^{\rm max}} {\rm d}p_{\rm T} \int_{-2}^{2} {\rm d}\eta \left.\frac{{\rm d}^2\sigma_{\rm eff}}{{\rm d}p_{\rm T}{\rm d}\eta}\right|_{Q_{\rm tr}<\Lambda}}{\int_{p_{\rm T}^{\rm min}}^{p_{\rm T}^{\rm max}} {\rm d}p_{\rm T} \int_{-2}^{2} {\rm d}\eta \frac{{\rm d}^2\sigma_{\rm eff}}{{\rm d}p_{\rm T}{\rm d}\eta}}$$

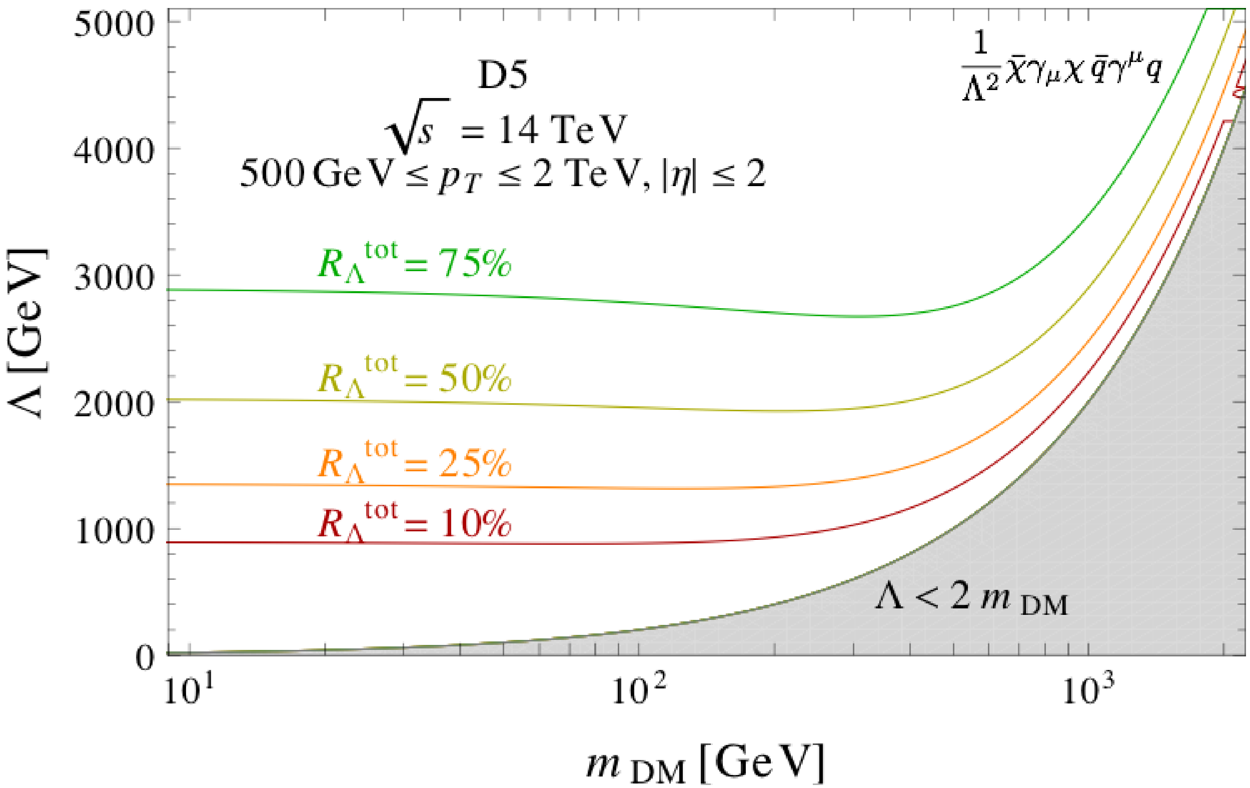
R_{Λ} ≈ fraction of events in the EFT validity region (for g=1)

- $R_{\Lambda} \approx 1 \Rightarrow$ EFT valid
- $R_{\Lambda} \lesssim 1 \Rightarrow$ EFT not valid

[Busoni, EM, *et al.*, 1307.2253, 1402.1275, 1405.3101]

Implications for LHC searches

Results for D5 at 14 TeV:



The non-validity region of EFT is much larger than the one naively excluded

[Busoni, EM, *et al.*, 1307.2253, 1402.1275, 1405.3101]

Rescale existing EFT bounds

Neglecting all uncertainties, the bounds have a simple scaling with Λ:

$$N_{\text{signal}} \sim \frac{1}{\Lambda^4} \widetilde{N}_{\text{signal}}$$ (for dim-6 operator)

Bounds are obtained imposing

$$N_{\text{signal}} < N_{\text{obs}} \Rightarrow \Lambda > \Lambda_{\text{exp}} \equiv \left(\frac{\widetilde{N}_{\text{signal}}}{N_{\text{obs}}} \right)^{1/4}$$

By rescaling $N_{\text{signal}} \to R_\Lambda N_{\text{signal}}$ the new bound is obtained by solving

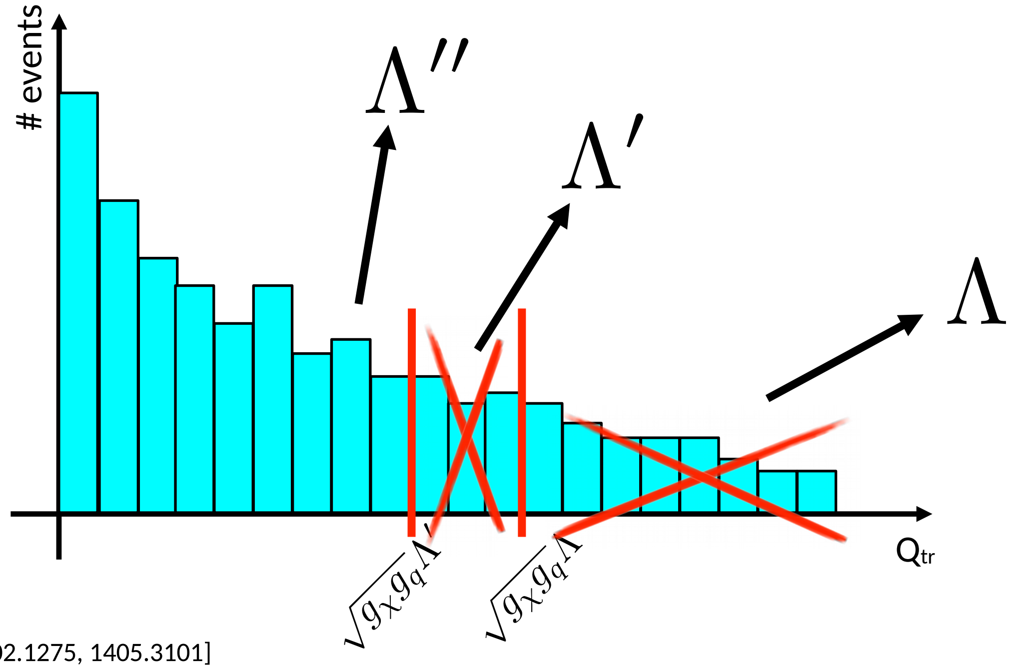
$$\Lambda(m_\chi) > R_\Lambda(m_\chi) \Lambda_{\text{exp}}(m_\chi)$$

[Busoni, EM, *et al.*, 1307.2253, 1402.1275, 1405.3101]

Rescale EFT bounds

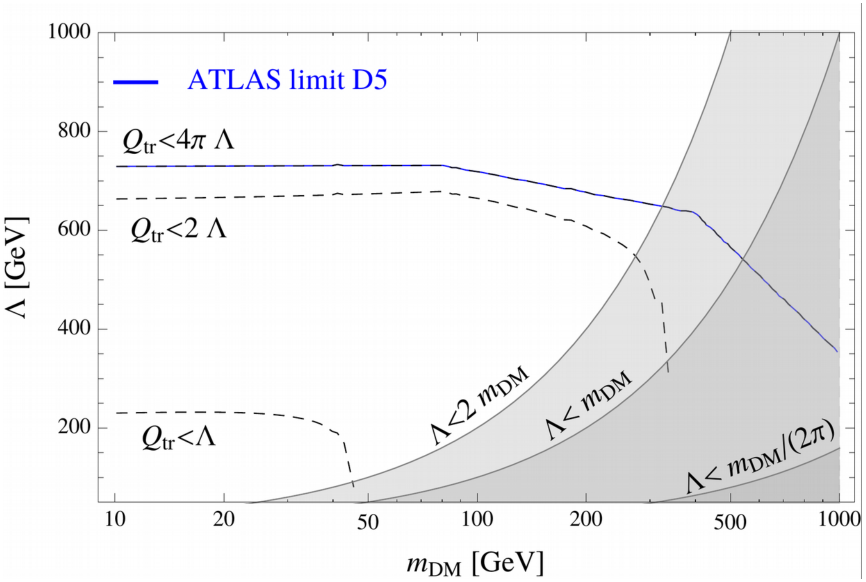
Rescale the limits on Λ by considering only a fraction R_Λ of the events:

- Fix m_χ, g_q, g_χ
- Reject events with $Q_{\rm tr} > \sqrt{g_\chi g_q}\Lambda$
- Obtain a new limit Λ' and reiterate



[Busoni, EM, *et al.*, 1307.2253, 1402.1275, 1405.3101]
[also Racco *et al.*, 1502.04701]

Implications for LHC searches



$$D5: \quad \bar{q}\gamma_\mu q\,\bar{\chi}\gamma^\mu\chi$$

Atlas limits from
ATLAS-CONF-2012-147

- Simple rescaling of existing limits is only suitable for simple cut-and-count analysis

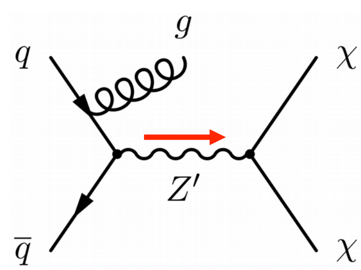
- Info about the kinematic distribution can be exploited by applying the cut

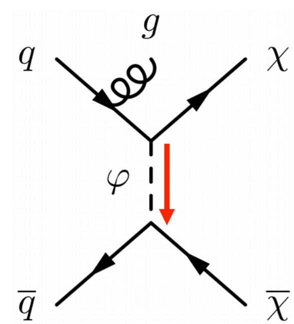
$$Q_{\rm tr}^2 < \sqrt{g_q g_\chi} M_{\rm med}^2$$

at the generator level

Limitations

- The definition of Q_{tr} depends on the UV completion





$$Q_{\rm tr}^2\Big|_s = (p_\chi + p_{\bar{\chi}})^2 \qquad Q_{\rm tr}^2\Big|_t = (p_\chi + p_{\bar{q}})^2$$

in general (e.g. composite models) it's not clear a priori what's the correct choice

- Also the choice of the UV-cutoff depends on unknown UV physics

$$Q_{\rm tr}^2 < \sqrt{g_\chi g_q} M_{\rm med}^2$$

More robust EFT bounds

Racco, Wulzer, Zwirner, 1502.04701, JHEP

We want to get robust EFT bounds without relying on assumption about the UV

$$\mathcal{L} = \bar{\chi}(i\partial \cdot \gamma - m_\chi)\chi + \frac{1}{\Lambda^2}\mathcal{O}_6$$

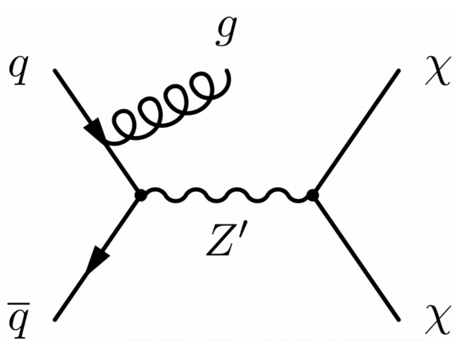
(assuming only 1 dim-6 operator)

Three relevant scales:

m_χ	DM mass
Λ	EFT scale
$\Lambda_{\rm cut}$	Cut-off scale

In general define

$$\Lambda_{\rm cut} = g_* \Lambda$$

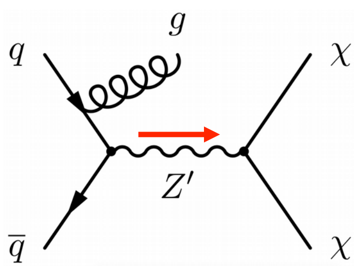


For a simple UV completion with an s-channel mediator the relation is obvious

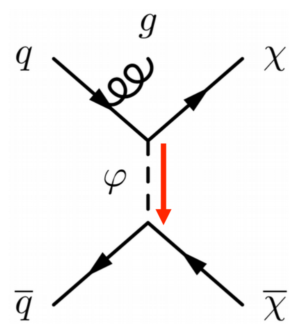
$$\Lambda = \frac{M_{\rm med}}{\sqrt{g_\chi g_q}} \qquad \Lambda_{\rm cut} = M_{\rm med}$$

More robust EFT bounds

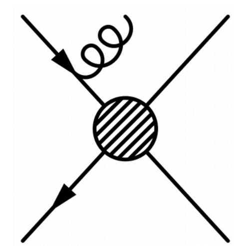
Racco, Wulzer, Zwirner, 1502.04701, JHEP



$$Q^2_{\rm tr}\Big|_s = (p_\chi + p_{\bar{\chi}})^2$$



$$Q^2_{\rm tr}\Big|_t = (p_\chi + p_{\bar{q}})^2$$



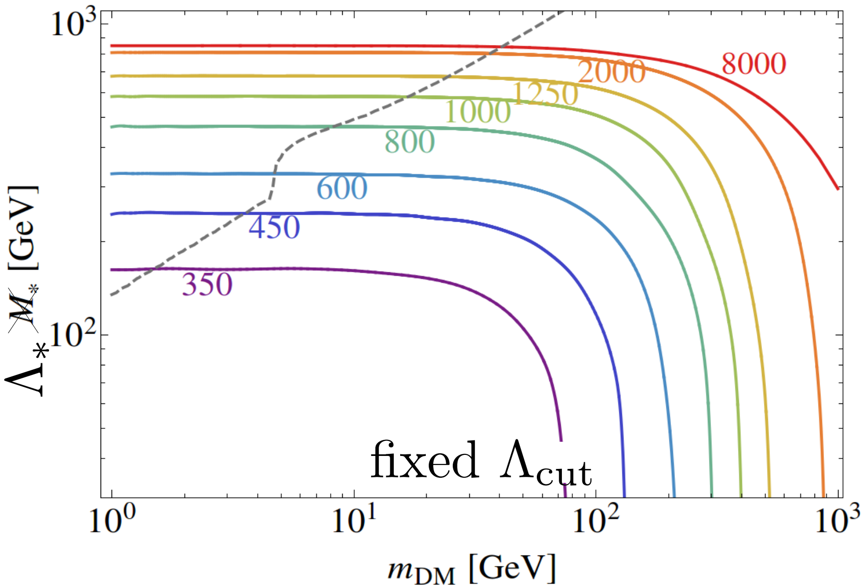
$$Q^2_{\rm tr} = ?$$

The definition of Q_{tr} depends on the UV completion. A *model-independent*, *conservative* condition uses the centre of mass energy of the hard process.

$$E^2_{\rm cm} \equiv (p_\chi + p_{\bar{\chi}} + p_g)^2 < \Lambda^2_{\rm cut}$$

More robust EFT bounds

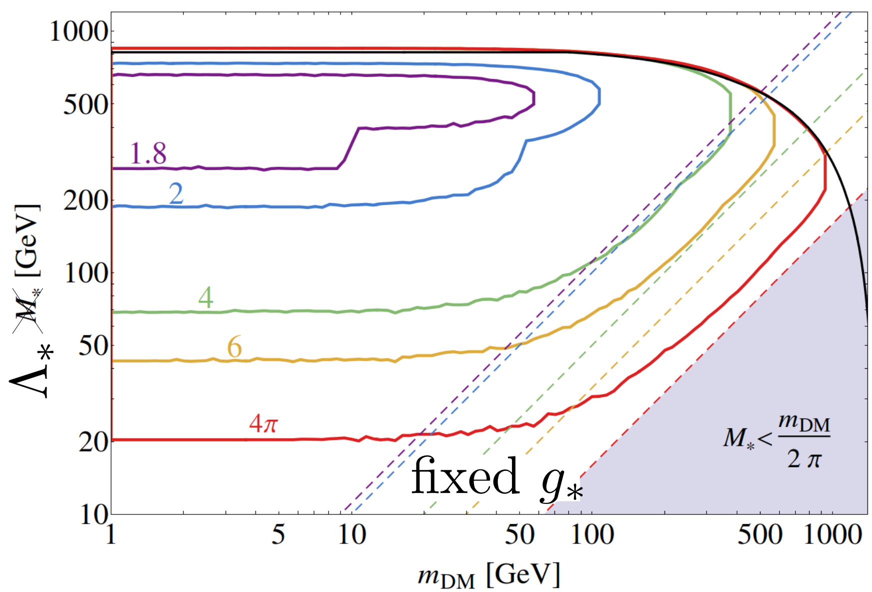
Racco, Wulzer, Zwirner, 1502.04701, JHEP



$$E_{\rm cm}^{\rm min} = p_T^{\rm jet} + \sqrt{(p_T^{\rm jet})^2 + m_\chi^2}$$

$$\Longrightarrow m_\chi^{\rm max} = \frac{\Lambda_{\rm cut}}{2}\sqrt{1 - 2\frac{p_T^{\rm jet}}{\Lambda_{\rm cut}}}$$

- Sharp cut at maximal m_χ
- Better for lower pT signal regions (especially for low $\Lambda_{\rm cut}$



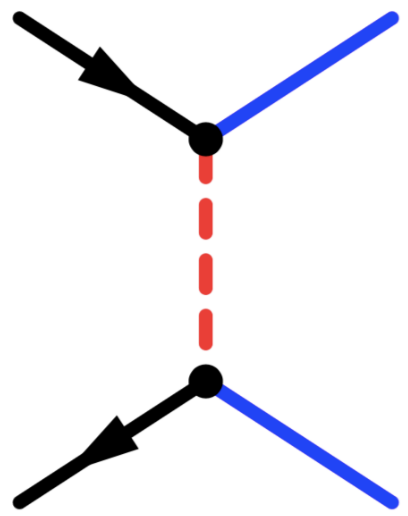
$$\Lambda_{\rm cut} = g_* \Lambda_*$$

No sensitivity for low $\Lambda_{\rm cut}$ due to the low $\Lambda_{\rm cut}$ (for fixed g_*)

Beyond EFT: simplified models

Simplified Models

Beyond EFT: consider a set of simple toy models

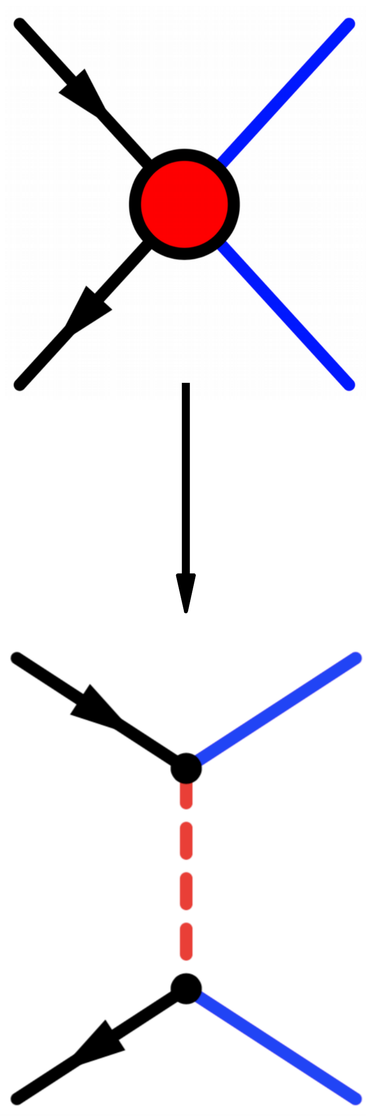


NEW PARTICLES
- DM
- Mediator

PARAMETERS
- Masses (m_{DM}, M)
- Couplings (g, g_q, g_χ...)
- (Mixing angles)

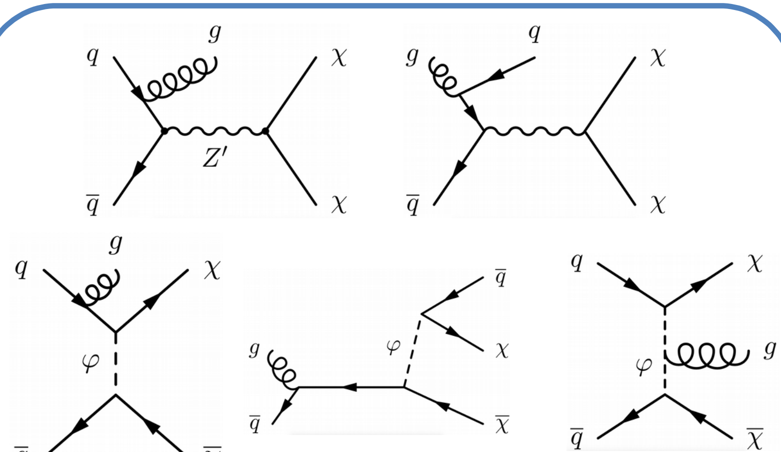
Implementation in LHC searches for DM still in progress (DM@LHC working group)

Simplified Models

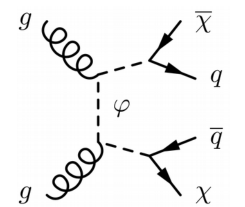


- ✓ Can grasp the most relevant physical features of a full theory including DM
- ✓ Theoretically consistent
- ✓ Richer phenomenology: other channels and searches complementary to mono-X
- ✗ More parameters (couplings) → higher dimensional space to constrain
- ✗ How to present constraints?
- ✗ Not suitable for strongly interacting dark sectors

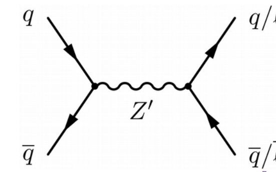
LHC results on simplified models



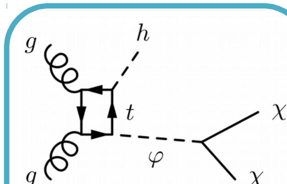
mono-jet



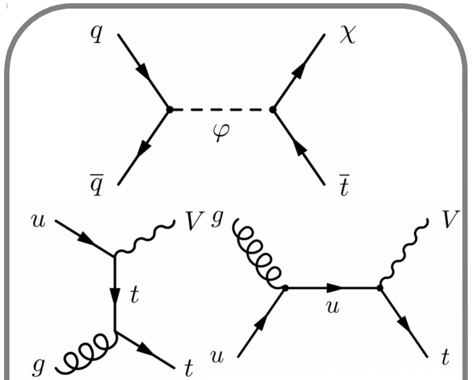
di-jet + MET



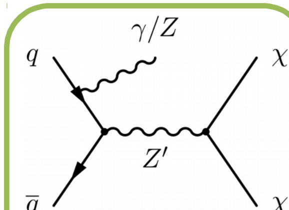
resonant searches:
di-jet, di-leptons…



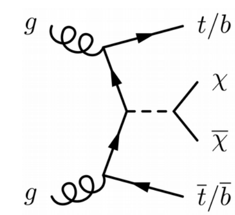
mono-higgs



mono-top



mono-γ/Z



di-top/bottom + MET

Simplified models *vs.* EFT

Simplified models and effective operators are complementary

1) No 1-to-1 correspondence between EFT and simp. Mods.

$$\mathcal{L}_A = \mathcal{L}_{\rm SM} - \frac{1}{4} Z'_{\mu\nu} Z'^{\mu\nu} + \frac{1}{2} m_{z'}^2 Z'_\mu Z'^\nu + \frac{1}{2}\bar{\chi}(i\partial\cdot\gamma - m_\chi)\chi + Z'_\mu \left(g_q \sum_q \bar{q}\gamma^\mu\gamma^5 q + g_\chi \bar{\chi}\gamma^\mu\gamma^5\chi \right)$$

$$\mathcal{L}_A^{\rm EFT} = -\frac{g_q g_\chi}{m_{Z'}^2} \bar{\chi}\gamma_\mu\gamma^5\chi \sum_q \left(\bar{q}\gamma^\mu\gamma^5 q\right)$$

$$\begin{aligned}
\mathcal{L}_B =& \mathcal{L}_{SM} + \mathcal{L}_\chi + \mathcal{L}_{\widetilde{q}} + \mathcal{L}_{int}^B\,, \\
\mathcal{L}_{\widetilde{q}} =& \sum_{i=1}^{3} \Big[(\partial^\mu \widetilde{u}_{iL})^\dagger (\partial_\mu \widetilde{u}_{iL}) + (\partial^\mu \widetilde{d}_{iL})^\dagger (\partial_\mu \widetilde{d}_{iL}) + (\partial^\mu \widetilde{u}_{iR})^\dagger (\partial_\mu \widetilde{u}_{iR}) + (\partial^\mu \widetilde{d}_{iR})^\dagger (\partial_\mu \widetilde{d}_{iR}) \\
&- \widetilde{m}^2 \left(\widetilde{u}_{iL}^\dagger \widetilde{u}_{iL} + \widetilde{d}_{iL}^\dagger \widetilde{d}_{iL} + \widetilde{u}_{iR}^\dagger \widetilde{u}_{iR} + \widetilde{d}_{iR}^\dagger \widetilde{d}_{iR} \right) \Big] + \dots\,, \\
\mathcal{L}_{int}^B =& - g_\chi \left[\sum_{i=1}^{3} \left(\widetilde{u}_{iL}\, \bar{u}_{iL} + \widetilde{d}_{iL}\, \bar{d}_{iL} + \widetilde{u}_{iR}\, \bar{u}_{iR} + \widetilde{d}_{iR}\, \bar{d}_{iR} \right) \chi + \text{h.c.} \right]
\end{aligned}$$

$$\mathcal{L}_B^{\rm EFT} = -\frac{g_\chi^2}{4\,\widetilde{m}^2} \left(\bar{\chi}\gamma^\mu\gamma^5\chi\right) \left[\sum_{i=1}^{3} \left(\bar{u}_i\gamma_\mu\gamma^5 u_i + \bar{d}_i\gamma_\mu\gamma^5 d_i \right) \right]$$

Simplified models *vs.* EFT

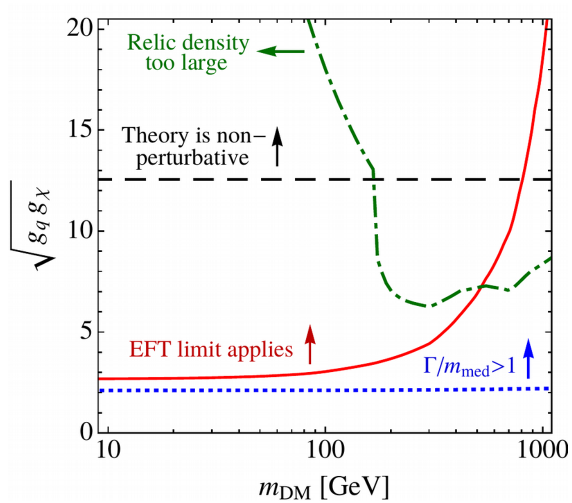
2) EFT limits on simplified models require larger couplings

$$\Lambda = M_{\rm med}/\sqrt{g_\chi g_q}$$

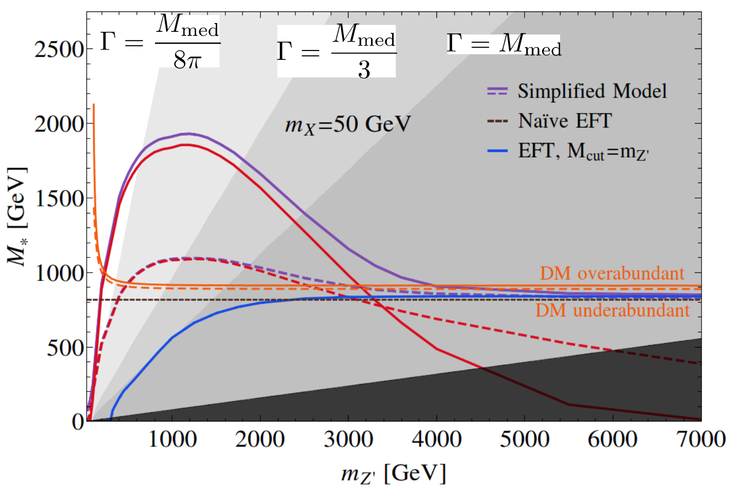
but then the (minimal) width becomes non-perturbative

$$\frac{\Gamma}{M_{\rm med}} = \frac{1}{12\pi}\sum_f n_c^f g_f^2 \left(1 - \frac{4m_f^2}{M_{\rm med}^2}\right)^{3/2}$$

Buchmueller, Dolan, McCabe, 1308.6799, JHEP



Racco, Wulzer, Zwirner, 1502.04701, JHEP



Fixed width and large $M_{\rm med}$ gives the correct EFT limit but it's unphysical from the simplified model point of view

Simplified models *vs*. EFT

Simplified models and effective operators are different tools.
Both are useful, both should be used.

Going from simplified models to EFTs is not as simple as sending Λ to infty.

In turn, each EFT can have multiple UV completions in terms of simplified models

Some literature

- Busoni, De Simone, Gramling, Jacques, Morgante, Riotto: 1307.2253 (Phys. Lett. B), 1402.1275 (JCAP), 1405.3101 (JCAP)

- Berlin, Lin, Wang: 1402.7074 (JHEP)

- Racco, Wulzer, Zwirner: 1502.0471 (JHEP)

- Buchmuller, Dolan, McCabe: 1308.6799 (JHEP)
  comparison of EFT vs. simp. mods.

- Shoemaker, Vecchi: 1112.5457, PRD & Endo, Yamamoto: 1403.6610 (JHEP)
  perturbative unitarity constraints

- Bell, Busoni, Kobakhidze, Long, Schmidt: 1602.02722 (JHEP)
  unitarization with K-matrix formalism

- Bruggisser, Riva, Urbano: 1607.02474 SciPost Phys., 1607.02475 (JHEP)
  EFT for strongly interacting dark sectors

- Alanne, Goertz: 1712.07626
  mixed approach EFT + mediator

- White papers: 1409.2893, 1409.4075, 1506.03116 (Phys. Dark Universe)
  contain a summary of the discussion about EFTs and simp. mods.

- ATLAS/CMS DM Forum $\longrightarrow$ DM@LHC working group: 1507.00966 (Phys. Dark Univ.)
  ”state-of-the-art” for EFT in LHC DM searches

Conclusions

Conclusions

- Effective operators are a simple and useful tool for DM searches.
- They are the most “universal” tool we have
- Truncations/rescaling techniques are needed to obtain reliable bounds
- Simplified models are complementary and can be constrained with a larger variety of searches, but at the price of an higher model dependence

KEEP SEARCHING!