Robust collider limits on heavy-mediator Dark Matter

D. Racco, A. Wulzer, F. Zwirner

JHEP **1505** (2015) 009, arXiv: 1502.04701

Davide Racco

Université de Genève

ECT* – Trento

Thursday, 10^{th} September 2015

UNIVERSITÉ DE GENÈVE

FACULTÉ DES SCIENCES

Département de physique théorique

Dark Matter (DM) searches at colliders

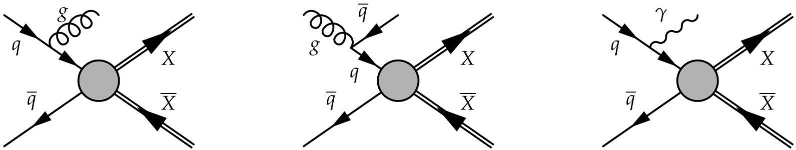
- Assumption[1] that DM interacts with the Standard Model (SM) also through some non-gravitational interaction.
- Production of DM in pairs ($\mathbb{Z}_2$ symmetry). Example: R-parity in SUSY.
- Need the associated production of another object: jet, photon, electroweak boson, ...

- What about the grey mysterious boxes?
- Importance of model independence.

[1]Well motivated assumption: DM production mechanisms in the early Universe, reheating...

Dark Matter (DM) searches at colliders

- Assumption[1] that DM interacts with the Standard Model (SM) also through some non-gravitational interaction.
- Production of DM in pairs ($\mathbb{Z}_2$ symmetry). Example: R-parity in SUSY.
- Need the associated production of another object: jet, photon, electroweak boson, . . .



- What about the grey mysterious boxes?
- Importance of model independence.

[1]Well motivated assumption: DM production mechanisms in the early Universe, reheating. . .

Description of interactions between DM and SM

Effective field theories (EFT)

The Lagrangian includes only the degrees of freedom relevant below a given mass threshold, that we call M_{cut}.

- ✓ Ample generality: they parametrise potentially *any* model;
- ✓ Limited number of parameters;
- ✗ The predictions of the EFT are reliable only if the energy scale of the event is below M_{cut}.

Simplified models

They include only the essential ingredients: the DM particle, and the mediator(s) with the SM. Minimal number of assumptions about them.

- ✓ Each simplified model can reproduce a class of more complete theories;
- ✓ Enlarged regime of validity;
- ✗ Higher number of parameters or, generically speaking, of assumptions.

Description of interactions between DM and SM

Effective field theories (EFT)

The Lagrangian includes only the degrees of freedom relevant below a given mass threshold, that we call M_{cut}.

- ✓ Ample generality: they parametrise potentially *any* model;
- ✓ Limited number of parameters;
- ✗ The predictions of the EFT are reliable only if the energy scale of the event is below M_{cut}.

Simplified models

They include only the essential ingredients: the DM particle, and the mediator(s) with the SM. Minimal number of assumptions about them.

- ✓ Each simplified model can reproduce a class of more complete theories;
- ✓ Enlarged regime of validity;
- ✗ Higher number of parameters or, generically speaking, of assumptions.

Universal bounds from the Effective Field Theory (EFT)

Goal

Use the EFT to get completely general bounds from DM searches at colliders.

- Three free parameters in EFT:
  1. m_{DM}
  2. M_*: effective operator coefficient $\left(1 \big/ M_*^{d-4}\right)$
  3. M_{cut}: *cut-off scale* for the validity of the EFT

Indipendent parameters!

Universal bounds from the Effective Field Theory (EFT)

Goal

Use the EFT to get completely general bounds from DM searches at colliders.

- Three free parameters in EFT:
  1. m_{DM}
  2. M_*: effective operator coefficient $\left(1 \middle/ M_*^{d-4}\right)$
  3. M_{cut}: *cut-off scale* for the validity of the EFT

Indipendent parameters!

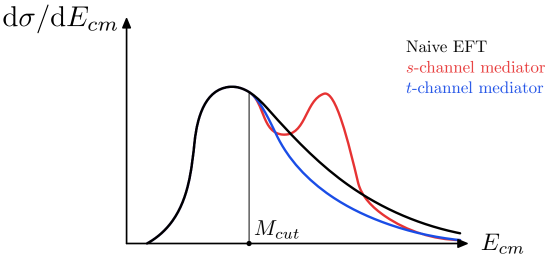
Universal bounds from the Effective Field Theory (EFT)

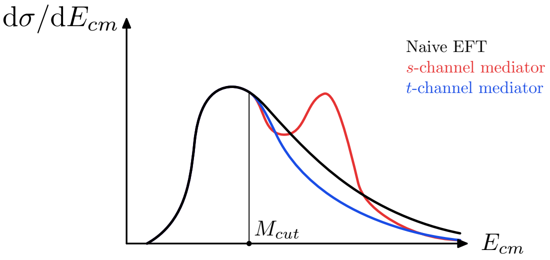
Goal

Use the EFT to get completely general bounds from DM searches at colliders.

- Three free parameters in EFT:
  1. m_{DM}
  2. M_*: effective operator coefficient $\left(1 \big/ M_*^{d-4}\right)$
  3. M_{cut}: *cut-off scale* for the validity of the EFT

Indipendent parameters!





- We restrict the signal to the events for which

$$\boxed{E_{\text{cm}} < M_{\text{cut}}},$$

where E_{cm} is the total invariant mass of the hard final states of the reaction:

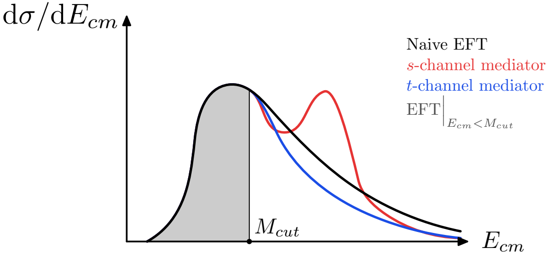
$$E_{\text{cm}} = \sqrt{\hat{s}} = \sqrt{\left(p^\mu(\text{DM}_1) + p^\mu(\text{DM}_2) + p^\mu(\text{jet})\right)^2}.$$

- Indeed, the following *always* holds:

$$\sigma^{\text{signal}}_{\text{true model}} > \sigma^{\text{signal}}_{\text{corresp. EFT}}\Big|_{E_{\text{cm}}<M_{\text{cut}}}.$$

Thus we obtain conservative but reliable limits.

Our strategy



- We restrict the signal to the events for which

$$\boxed{E_{\text{cm}} < M_{\text{cut}}},$$

where E_{cm} is the total invariant mass of the hard final states of the reaction:

$$E_{\text{cm}} = \sqrt{\hat{s}} = \sqrt{\left(p^\mu(\text{DM}_1) + p^\mu(\text{DM}_2) + p^\mu(\text{jet})\right)^2}.$$

- Indeed, the following *always* holds:

$$\sigma^{\text{signal}}_{\text{true model}} > \sigma^{\text{signal}}_{\text{corresp. EFT}}\Big|_{E_{\text{cm}} < M_{\text{cut}}}.$$

Thus we obtain conservative but reliable limits.

Some details about our analysis in 1502.04701

- We consider a Majorana fermion X as DM, with effective interaction with quarks given by

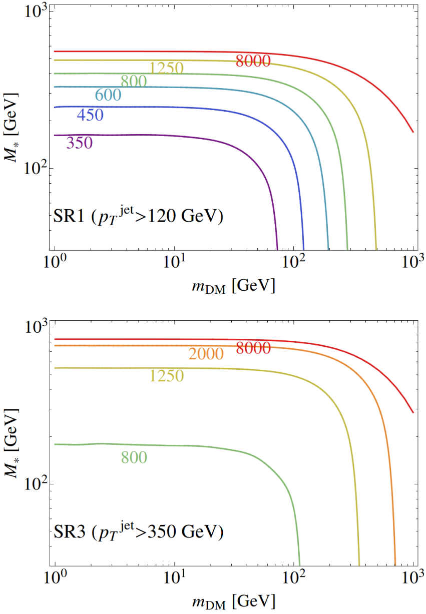
$$\mathcal{L}_{\mathsf{EFT}} = -\frac{1}{M_*^2}\,(\overline{X}\gamma^\mu\gamma^5 X)\left(\sum_{\text{flavours}} \overline{q}\gamma_\mu\gamma^5 q\right) .$$

- Monojet search: ATLAS-CONF-2012-147 (10.5 fb^{-1} at $\sqrt{s}$ =8 TeV)

signal region	SR1	SR2	SR3	SR4
$p_{\mathsf{T}}^{\mathsf{jet}}$ and $E_{\mathsf{T}}^{\mathsf{miss}}$ [GeV]	>120	>220	>350	>500
$\sigma_{\rm exc}$[pb], 95% CL	2.7	0.15	$4.8\,10^{-2}$	$1.5\,10^{-2}$

- We perform a parton-level analysis, and we compute cross-section σ and acceptance A with `MadGraph5`.
- We estimate the efficiency ϵ by matching this output to the experimental limit.

Results for fixed M_{cut} ($E_{\text{cm}} < M_{\text{cut}}$)



- EFT Lagrangian:

$$\mathcal{L}_{\text{EFT}} = -\frac{1}{M_*^2} \left(\overline{X}\gamma^\mu\gamma^5 X\right) \left(\sum_{\text{flavours}} \overline{q}\gamma_\mu\gamma^5 q\right) .$$

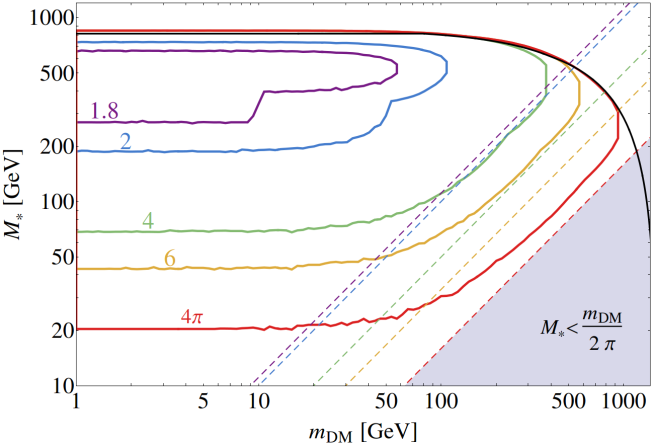
- We can link the two dimensionful parameters M_* and M_{cut} through

$$\boxed{M_{\text{cut}} = g_* M_*} .$$

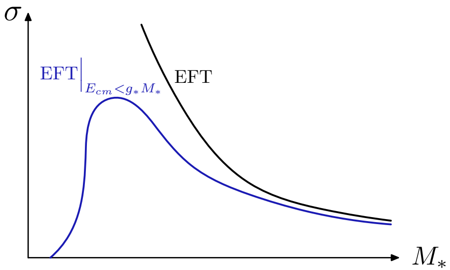
g_*: *effective coupling strength* of the EFT. Justification:

$$\mathcal{M}(2 \to 2) \sim \frac{E^2}{M_*^2} \underset{\text{at cut-off}}{\to} \frac{M_{\text{cut}}^2}{M_*^2} \equiv g_*^2 .$$

Results for fixed g_* ($E_{\text{cm}} < g_* M_*$)



Why is there a lower limit in the excluded region?



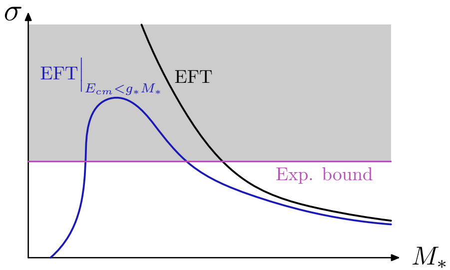
$$\sigma_{\text{EFT}}^{\text{signal}}\Big|_{E_{\text{cm}}<g_* M_*} \propto \frac{1}{M_*^4} \cdot \text{Acceptance} \longrightarrow \begin{cases} \dfrac{1}{M_*^4} & \text{for } M_* \to \infty\,, \\ 0 & \text{for } M_* \to 0\,. \end{cases}$$

- Kinematical threshold:

$$E_{\text{cm}}^{\text{min}} = p_{\text{T}}^{\text{jet}} + \sqrt{\left(p_{\text{T}}^{\text{jet}}\right)^2 + 4\, m_{\text{DM}}^2}\,.$$

The lower is $p_{\text{T}}^{\text{jet}}$, the stronger is the lower limit in the exclusion interval.

Why is there a lower limit in the excluded region?



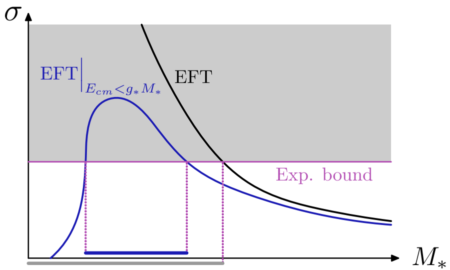
$$\sigma^{\text{signal}}_{\text{EFT}}\Big|_{E_{\text{cm}}<g_* M_*} \propto \frac{1}{M_*^4}\cdot \text{Acceptance} \longrightarrow \begin{cases} \dfrac{1}{M_*^4} & \text{for } M_* \to \infty\,, \\ 0 & \text{for } M_* \to 0\,. \end{cases}$$

- Kinematical threshold:

$$E^{\text{min}}_{\text{cm}} = p_{\text{T}}^{\text{jet}} + \sqrt{\left(p_{\text{T}}^{\text{jet}}\right)^2 + 4\, m_{\text{DM}}^2}\,.$$

The lower is $p_{\text{T}}^{\text{jet}}$, the stronger is the lower limit in the exclusion interval.

Why is there a lower limit in the excluded region?



$$\sigma_{\text{EFT}}^{\text{signal}}\Big|_{E_{\text{cm}}<g_* M_*} \propto \frac{1}{M_*^4} \cdot \text{Acceptance} \longrightarrow \begin{cases} \dfrac{1}{M_*^4} & \text{for } M_* \to \infty\,, \\ 0 & \text{for } M_* \to 0\,. \end{cases}$$

- Kinematical threshold:

$$E_{\text{cm}}^{\text{min}} = p_{\text{T}}^{\text{jet}} + \sqrt{\left(p_{\text{T}}^{\text{jet}}\right)^2 + 4\,m_{\text{DM}}^2}\,.$$

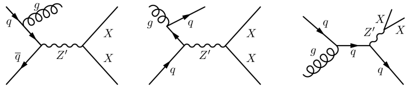
The lower is $p_{\text{T}}^{\text{jet}}$, the stronger is the lower limit in the exclusion interval.

Comparison with the simplified model

$$\mathcal{L}_{\mathsf{EFT}} = -\frac{1}{M_*^2}\,(\overline{X}\gamma^\mu\gamma^5 X)\left(\sum_q \bar{q}\gamma_\mu\gamma^5 q\right).$$

Model A: s-channel vector mediator

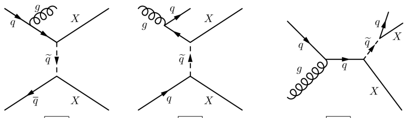
$$\mathcal{L}^{\mathsf{A}}_{\mathsf{int}} = Z'_\mu\left(g_q \sum_q \bar{q}\gamma^\mu\gamma^5 q + g_X \overline{X}\gamma^\mu\gamma^5 X\right)$$



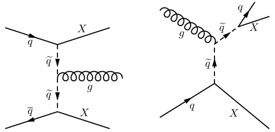
A.1 A.2 A.3

Model B: t-channel scalar mediator

$$\mathcal{L}^{\mathsf{B}}_{\mathsf{int}} = -g_{\mathsf{DM}}\left[\sum_{i=1}^{3}\left(\widetilde{u}_{iL}\,\overline{u_{iL}} + \widetilde{d}_{iL}\,\overline{d_{iL}} + \widetilde{u}_{iR}\,\overline{u_{iR}} + \widetilde{d}_{iR}\,\overline{d_{iR}}\right)X + \text{h.c.}\right]$$

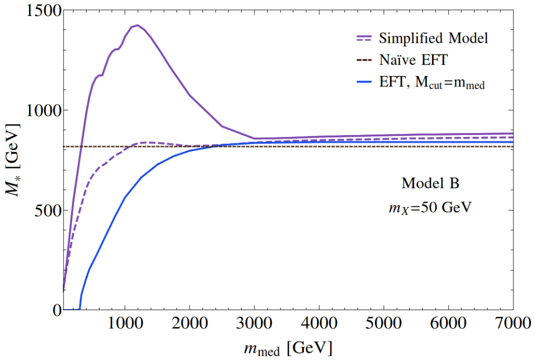


B.1 B.2 B.3



B.4 B.5

Comparison with the simplified model

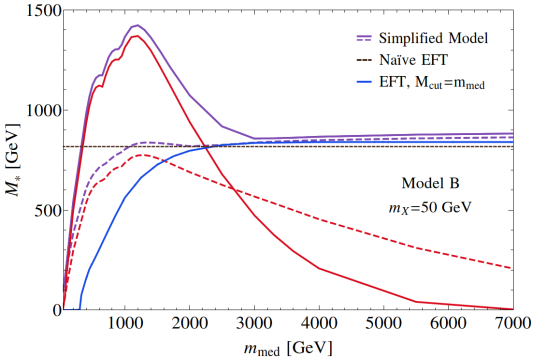


- **Blue line**: from model-independent limit, with the identification

$$M_* = \frac{2\widetilde{m}}{g_{\rm DM}}\,, \qquad M_{\rm cut} = \widetilde{m}\,.$$

- **Red lines**: only from the resonant production of the mediator.
  The EFT limit is complemented by the limit from the resonant production.
- **Grey lines**: fixed mediator width.
  The plane $(m_{\rm med}, M_*)$ is not suitable to draw a limit for fixed mediator width.

Comparison with the simplified model



- **Blue line**: from model-independent limit, with the identification

$$M_* = \frac{2\widetilde{m}}{g_{\text{DM}}}\,, \qquad M_{\text{cut}} = \widetilde{m}\,.$$

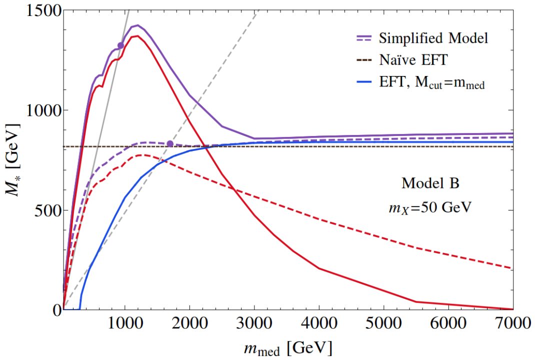
- **Red lines**: only from the resonant production of the mediator.

The EFT limit is complemented by the limit from the resonant production.

- Grey lines: fixed mediator width.

The plane (m_{med}, M_*) is not suitable to draw a limit for fixed mediator width.

Comparison with the simplified model



- **Blue line**: from model-independent limit, with the identification

$$M_* = \frac{2\widetilde{m}}{g_{\text{DM}}}\,, \qquad M_{\text{cut}} = \widetilde{m}\,.$$

- **Red lines**: only from the resonant production of the mediator.

The EFT limit is complemented by the limit from the resonant production.

- **Grey lines**: fixed mediator width.

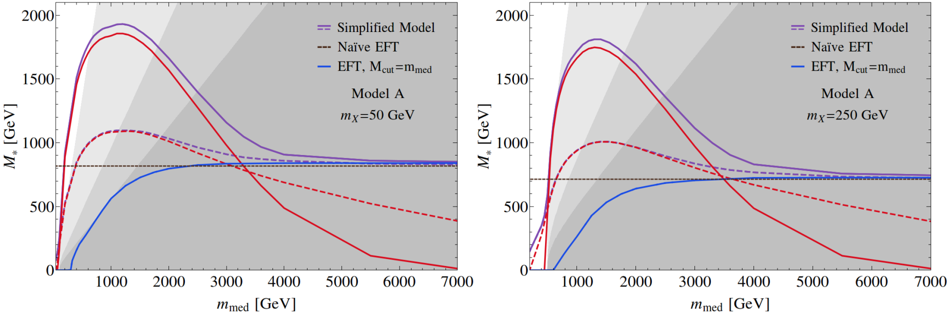
The plane (m_{med}, M_*) is not suitable to draw a limit for fixed mediator width.

Conclusions

1. The EFT allows to extract **universal bounds** from DM searches.
   (reinterpretable in any UV model)
2. The prescription $E_{\text{cm}} < M_{\text{cut}}$ can be used for any effective operator.
3. An effective operator as D_8 may have several microscopic origins.
4. Exclusion intervals in M_* have also a *lower* bound.
   The softer SRs are useful to extend the limits for small M_*.
5. Extended simplified model reach due to resonant production.
   $\Rightarrow$ complement the monojet EFT search with direct mediator search.
6. Limitation of the plane m_{med}, M_* (inconsistent width).

1. BACKUP SLIDES

Comparison with the simplified model A



Comparison with the choice of Q_{tr}