DM Search @ LHC (theory)

Andrea De Simone

MOSTLY BASED ON:
DS, Jacques - arXiv:1603.08002 (Review)
Boveia et al. - arXiv:1603.04156 (LHCDMWG)
• a quick journey in theory space

• simplified models (s-channel, t-channel)

• some recommendations & future directions
we are only sure that DM has **gravitational** interactions

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**WIMP**

- neutralino
- minimal DM
- heavy neutrino
- inert Higgs doublet
- LKP
- LTP
- ...

**non-WIMP**

- axion
- gravitino
- axino
- sterile neutrino
- techni-baryon, Q-balls
- ...

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Chapter 4

What is Dark Matter?

Decades of theoretical works restricted the expected Dark Matter mass \( M \) to lie within the range \( 10^{28} \text{ eV} < M < 10^{24} \text{ kg} \).

The plot illustrates the mass range of some plausible DM candidates:

- \( 10^{30} \text{ eV} \)
- \( 10^{20} \text{ eV} \)
- \( 10^{10} \text{ eV} \)
- \( 10^0 \text{ eV} \)
- \( 10^{-10} \text{ eV} \)
- \( 10^{-20} \text{ eV} \)
- \( 10^{-30} \text{ eV} \)

The Planck scale \( M_{\text{Pl}} \) is the ultimate bound of particle physics: elementary particles with mass \( M > M_{\text{Pl}} \) are black holes because their wavelength \( 1/M \) is smaller than the Swartzchild radius \( M/M_{\text{Pl}} \).

The DM mass could be above or below \( M_{\text{Pl}} \): we depend on if DM is astrophysical or particle physics.

Section 4 discusses the first possibility: DM could be composite objects heavier than Planck scale; although it looks unplausible, primordial black holes are a possible candidate.

Section 4 summarizes how oscillations of ultralight scalars can realize the lower range.

Section 4 discusses the intermediate range where DM is assumed to be some new particle with mass \( M \) with a plausible argument favoring \( M \sim \text{TeV} \): the mass range being explored now by colliders.

From a fundamental point of view both latter cases are described by Quantum Field Theory.

From a practical point of view, in case 2 the QFT reduces to classical fields, while in case 3 it reduces to particles.

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**Ultra-light scalars, axion**

**\( T_{\text{now}} \)**

**\( \nu_s \)**

**Thermal particles**

**Planck scale**

**Primordial black hole**

**Solar mass**

[Courtesy A. Strumia]
More complete/
more parameters

Complete
Models

MSSM, Composite Higgs, Extra-Dim...

lots of parameters...

Figure 9: Comparisons of the models surviving or being excluded by the various searches in the LSP mass-scaled SI cross section plane as discussed in the text. The SI XENON1T line is shown as a guide to the eye.
Theory Space

Complete Models

More complete/
more parameters

Effective Theories

less complete/
less parameters
Effective Field Theory Description

Integrate out the UV physics connecting DM-SM and describe interactions with eff. ops.:

$$\frac{1}{\Lambda^2} (\bar{\chi} \Gamma^A \chi)(\bar{q} \Gamma_A q)$$

need to use EFT carefully and consistently

the momentum transfer in the relevant process must be $$Q_{tr} \lesssim M_{\text{med}}$$
The "money plots"

- after truncation: theoretically robust limits
- still relevant at low DM masses

[ATLAS - 1502.01518]
\( \sqrt{s} = 14 \text{ TeV} \)

Effective Operator

\( (\bar{\chi}\gamma^\mu\chi)(\bar{q}\gamma_\mu q) \)

\( m_{DM} = 50 \text{ GeV} \)

ATLAS Simulation Preliminary

\[ \sqrt{s} = 14 \text{ TeV} \quad \int L dt = 25 \text{ fb}^{-1} \]

D5, \( m_\chi = 50 \text{ GeV} \)

\( \pi < \sqrt{g_{\text{SM}} g_{DM}} < 4\pi \)

5% systematic

5\sigma discovery

3\sigma evidence

ATLAS Simulation Preliminary

\[ \sqrt{s} = 14 \text{ TeV} \quad \int L dt = 300 \text{ fb}^{-1} \]

D5, \( m_\chi = 50 \text{ GeV} \)

\( \pi < \sqrt{g_{\text{SM}} g_{DM}} < 4\pi \)

5% systematic

1% systematic

5\sigma discovery

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\[ \sqrt{s} = 14 \text{ TeV} \quad \int L dt = 3000 \text{ fb}^{-1} \]

D5, \( m_\chi = 50 \text{ GeV} \)

\( \pi < \sqrt{g_{\text{SM}} g_{DM}} < 4\pi \)

5% systematic

1% systematic

5\sigma discovery

3\sigma evidence

EFT validity assumed

[ATL-PHYS-PUB-2014-0087]
EFT approach

• limited validity
• not entirely model-independent

How to go beyond that (but keeping generality), in view of LHC Run 2?

• Simplified Models

“There’s a way to do it better. Find it.”
T.A. Edison
Simplified Models

Complete Models

More complete/
more parameters

Simplified Models

Effective Theories

less complete/
less parameters

Other
Benchmarks?

A. De Simone
Simplified Models

... just means extending the SM with:

- 1 Dark Matter particle
- 1 Mediator particle connecting DM-SM

>> just another parametrization of unknown high energy physics <<

![Diagram showing correspondence between effective operators (eff ops) and simplified models]

- ✗ more parameters (g's)
- ✓ exploit other searches for mediators (e.g. di-jet), complementary to mono-jet
- ✓ theoretically consistent, no worries about EFT, widths, etc.

from DM search to MEDIATOR search
3-dimensional combinations

LHC/DD

LHC

combine different process involving DM
(mono-jet+mono-W/Z +mono-H...)

combine DM + mediator searches (di-jet...)

still, a lot to do here...

[more in Valerio’s talk...]
Recommendations

Simplified Models for Dark Matter and Missing Energy Searches at the LHC

Jalal Abdallah,1 Adi Ashkenazi,2 Antonio Boveia,3 Giorgio Busoni,4 Andrea De Simone,4
Caterina Doglioni,5 Aielet Efrati,6 Erez Etzion,2 Johanna Gramling,5 Thomas Jacques,5
Tongyan Lin,7 Enrico Morgante,5 Michele Papucci,8,9 Bjoern Penning,3,10 Antonio Walter
Riotto,5 Thomas Rizzo,11 David Salek,12 Steven Schramm,13 Oren Slone,2 Yotam Soreq,6
Alessandro Vichi,8,9 Tomer Volansky,2 Itay Yavin,14,15 Ning Zhou,16 and Kathryn Zurek8,9

Interplay and Characterization of Dark Matter Searches at Colliders and in Direct Detection
Experiments

Sarah A. Malik,a Christopher McCabe, b,cHenrique Araujo,a Alexander Belyaev, d,e
Céline Bechm,b Jim Brooke,f Oliver Buchmueller,a Gavin Davies,a
Albert De Roeck,g,h Kees de Vries,a Matthew J. Dolan,i John Ellis,g,h
Malcolm Fairbain,j Henning Flaecher,k Loukas Gouskos,k Valentin V. Khoze,bl
Greg Landsberg,1 Dave Newbold,1 Michele Papucci, m Timothy Sumner,a
Marc Thomasl,c and Steven Wormc

Recommendations on presenting LHC searches for missing transverse energy
signals using simplified s-channel models
of dark matter

Antonio Boveia,1,* Oliver Buchmueller,2,* Giorgio Busoni,3
Francesco D’Eramo,4 Albert De Roeck,1,5 Andrea De Simone,6
Caterina Doglioni,7,* Matthew J. Dolan,3 Marie-Helene Genest,8
Kristian Hahn,9,* Ulrich Haisch,10,11,* Philip C. Harris,1
Jan Heisig,12 Valerio Ippolito,13 Felix Kahlhoefer,14,*
Valentin V. Khoze,15 Suchita Kulkarni,16 Greg Landsberg,17
Steven Lowette,18 Sarah Malik,2 Michelangelo Mangano,11,*
Christopher McCabe,19,* Stephen Mrenna,20 Priscilla Pani,21
Tristan du Pree,1 Antonio Riotto,11 David Salek,19,22
Kai Schmidt-Hoberg,14 William Shepherd,23 Tim M.P. Tait,24,*
Lian-Tao Wang,25 Steven Worm26 and Kathryn Zurek27

LHC DM WG
### Simplified Models Overview

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Table 9: Simplified models for scalar and fermion DM.

constructed, along with angular variables $\theta$, $\phi$, which would also allow the exploration of the spin of the DM particle, to some extent. However, we believe that at the present stage of LHC searches for DM, the simplified models discussed in this review already capture a very rich phenomenology.

Before reviewing the features and the phenomenology of all the cases listed in Table 9, we first point out some general properties of simplified models.
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**s-channel models**

**generic s-channel models**
DM is a Dirac Fermion

\[ \mathcal{L}_{\text{scalar}} = -g_{\text{DM}} \phi \bar{\chi} \chi - g_q \frac{\phi}{\sqrt{2}} \sum_{q=u,d,s,c,b,t} y_q \bar{q} q , \quad (0s1/2) \]

Scalar and Pseudo-Scalar Models:

\[ \mathcal{L}_{\text{pseudo-Scalar}} = -i g_{\text{DM}} \bar{\phi} \gamma^5 \chi - i g_q \frac{\phi}{\sqrt{2}} \sum_{q=u,d,s,c,b,t} y_q \bar{q} \gamma_5 q , \quad (0pS1/2) \]

Vector and Axial-Vector Models:

\[ \mathcal{L}_{\text{vector}} = -g_{\text{DM}} Z_{\mu} \bar{\chi} \gamma^\mu \chi - g_q \sum_{q=u,d,s,c,b,t} Z_{\mu} \bar{q} \gamma^\mu q , \quad (1vS1/2) \]

\[ \mathcal{L}_{\text{axial-vector}} = -g_{\text{DM}} Z_{\mu} \bar{\chi} \gamma^\mu \gamma_5 \chi - g_q \sum_{q=u,d,s,c,b,t} Z_{\mu} \bar{q} \gamma^\mu \gamma_5 q . \quad (1AS1/2) \]

4-dimensional parameter space: \[ \{ m_{DM}, M_{\text{med}}, g_{\text{DM}}, g_q \} \]
slice of par space with fixed couplings

95% CL exclusion contour

off-shell ($M_{\text{med}} < 2m_{\text{DM}}$) (use e.g. di-jet)

on-shell ($M_{\text{med}} > 2m_{\text{DM}}$)

Recommended choices of couplings:

- **Vector mediator**: $g_{\text{DM}} = 1$ and $g_q = 0.25$.
- **Axial-vector mediator**: $g_{\text{DM}} = 1$ and $g_q = 0.25$.
- **Scalar mediator**: $g_q = 1$ and $g_{\text{DM}} = 1$.
- **Pseudo-scalar mediator**: $g_q = 1$ and $g_{\text{DM}} = 1$.

- ensure $\Gamma_{\text{med}}/M_{\text{med}} \lesssim 10\%$
- avoid current limits
For the axial-vector mediator, the scattering is SD and the corresponding cross section can be written as

\[ \sigma_{SD}(n,p) \propto \frac{(g_q g_{DM})^2}{M^4_{med}} \]

then plug in \( M_{med} \) from the mass-mass plane

recommend to plot 90% CL (instead of 95% CL) to comply with DD standards
### Simplified Models Overview

#### Mediator spin

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#### Diagrams

- **Higgs mediator, Scalar-Higgs Portal**
- **s-channel models (special cases)**
- **Z mediator**

---

Table 9: Simplified models for scalar and fermion DM.

constructed, along with angular variables $\left[85, 102\right]$, which would also allow the exploration of the spin of the DM particle, to some extent. However, we believe that at the present stage of LHC searches for DM, the simplified models discussed in this review already capture a very rich phenomenology.

Before reviewing the features and the phenomenology of all the cases listed in Table 9, we first point out some general properties of simplified models.

3.1 General properties of simplified models

As discussed above, when building a simplified model for DM one wants to extend the SM by adding new degrees of freedom: not too many, otherwise simplicity is lost; not too few, otherwise the relevant physics is not described completely. To this end, one builds simplified models according to the following general prescriptions:
## 1s1/2 Model (Z Mediator)

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model parameters: \[ \{ m_{\text{DM}}, g \} \]

relevant constraints:

- Direct detection ( \( m_{\text{DM}} > m_Z/2 \) )
- Z invisible width ( \( m_{\text{DM}} < m_Z/2 \) and SD scattering)

mono-jet searches not competitive

[DS, Giudice, Strumia - 1402.6287]
### **0s1/2 Model (Higgs Mediator)**

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**Model parameters:** \( \{m_{DM}, y\} \)

**relevant constraints:**
- **Direct detection** (\( m_{DM} > m_h/2 \))
- **Higgs invisible width** (\( m_{DM} < m_h/2 \))

mono-jet searches not competitive

[DS, Giudice, Strumia - 1402.6287]
Near resonance $m_{\text{DM}} \approx M_{Z,h}/2$, relic density fixed by the width

Curves for correct DM relic abundance:

![Graph showing the relationship between DM mass and invisible BR into Dark Matter particles, with the DM mass in GeV on the x-axis and invisible BR on the y-axis. The graph includes curves for different DM mass values, with room for improvement explored for invisible widths of Z and h, and possible experiments like LHC, future Higgs factories, and GigaZ.]

- Motivation to improve on Z/h invisible BRs
### Os1/2 Model (Scalar-Higgs Portal)

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The cubic and quartic self-couplings of the mediator $S$ and Higgs $H$ look like a 2HDM, with $<S>=0$:

\[
\mathcal{L} \supset \frac{1}{2} (\partial \mu S)^2 - \frac{1}{2} m_S^2 S^2 + \bar{\chi} (i \not{\partial} - m_\chi) \chi - \frac{h}{\sqrt{2}} \sum_f y_f \bar{f} f - y_\chi S \bar{\chi} \chi - \mu_S S |H|^2 - \lambda_S S^2 |H|^2.
\]

**Model parameters:** \(\{m_\chi, m_S, \lambda_S, \mu_S\}\)

\[
(h_1) = \begin{pmatrix} \cos \theta & \sin \theta \\ -\sin \theta & \cos \theta \end{pmatrix} \chi \quad \text{with} \quad m_{h_1} \approx m_h, \quad m_{h_2} \approx \sqrt{m_S^2 + \lambda_S v^2}
\]

\[
\tan(2\theta) = 2\nu \mu_S / (m_S^2 - m_h^2 + \lambda_S v^2)
\]

In the mass-eigenstate basis:

\[
\mathcal{L} \supset -(h_1 \cos \theta - h_2 \sin \theta) \sum_f \frac{y_f}{\sqrt{2}} \bar{f} f - (h_1 \sin \theta + h_2 \cos \theta) y_\chi \bar{\chi} \chi
\]

Higgs Yukawas reduced by $\cos \theta$. 

S “talks” to SM only via $H$. The mixing of real scalar mediator $S$ and Higgs looks like a 2HDM, with $<S>=0$. 

A. De Simone
**0s1/2 Model (Scalar-Higgs Portal)**

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**LHC signals**

- mono-jet +
- mono-W/Z
- mono-Higgs

> combine with inv. width, VBF…

**A playground for testing complementarity techniques**
### Simplified Models Overview

**t-channel models**

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*Leitmotiv: mediator carries non-trivial quantum numbers*

Before reviewing the features and the phenomenology of all the cases listed in Table 9, we first point out some general properties of simplified models.

As discussed above, when building a simplified model for DM one wants to extend the SM by adding new degrees of freedom: not too many, otherwise simplicity is lost; not too few, otherwise the relevant physics is not described completely. To this end, one builds simplified models according to the following general prescriptions:

1. **Leitmotiv:** mediator carries non-trivial quantum numbers
2. **No tree-level**
3. **Dim-5 dipole operator**

```
~ 0t1/2 except for ID/DD

~0t1/2
```

- Dim-5 dipole operator
- ~0t1/2
- ~0t1/2
models according to the following general prescriptions: not too many, otherwise simplicity is lost; not too few, as discussed above, when building a simplified model for DM one wants to extend the SM very rich phenomenology.

### 3.1 General properties of simplified models

Before reviewing the features and the phenomenology of all the cases listed in Table 9: Simplified models for scalar and fermion DM.

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η carries color, EW, flavor (if DM total singlet)

possible to couple η to: u_R, d_R, Q_L

choose u_R:

\[ \mathcal{L}_{\eta} \supset \sum_{i=1,2,3} \left[ \frac{1}{2} (\partial_\mu \eta_i)^2 - \frac{1}{2} M_i^2 \eta_i^2 + (g_i \eta_i^* \bar{u}_i + \text{h.c.}) \right] \]

MFV:

\[ M_1 = M_2 = M_3 = M \]

\[ g_1 = g_2 = g_3 = g \]

Model parameters: \( \{m_\chi, M, g\} \)

\( g \) is a free parameter (unlike SUSY)
The main process for DM self-annihilations is DM self-annihilation.

**Fig. 6:** Diagrams contributing to mono-jet signals in $\bar{u}_i u_i$ via mediator exchange of the $i$ channel. We would therefore expect even stronger bounds from jets+MET if the statistical details of the 8 TeV data provide more statistical power than the single-bin exclusion performed by other analyses. We begin with the case of $\tilde{\chi}^0_1$ and $\tilde{\chi}^0_2$ from Eq. 2. The black region in (a) is excluded from the pure QCD production of the $\tilde{\chi}^0_1/\tilde{\chi}^0_2$ model. The constraints on the coupling $|g|/g_{\chi}$ can be upset by the statistical details of the 8 TeV data. We present here only the strongest bound obtained among all the searches from CMS [30–].

**Ot1/2 Model**

Best Exclusion limit from jets+MET on $g_M$ for $\Gamma_{SQ} = \Gamma_{\min}$

![Diagram](image-url)

[Excluded by QCD production](image-url)

[Relative importance can be upset by value of $g$](image-url)

A. De Simone
LHC + Direct Detection + Relic density:

\[ \{ \text{impossible for Dirac DM} \}
\]

\[ \{ \text{still viable for Majorana DM (with } m_{\text{DM}} > \sim 100 \text{ GeV) } \}\]

Models with 3rd generation quarks

- e.g. sbottom-like mediator $\mathcal{L} \supset -\lambda \bar{B}b_{RX} + \text{h.c.}$

- exploit $b$-tagging and squark searches

[also 2-tops]
In \textbf{s-channel} models: play with Scalar-Higgs Portal model

In \textbf{t-channel} models: the mediator typically carries charges (QCD, EW production possible)
Next-in-line to be explored

\textbf{>> Fully exploit complementarity <<}

then what? simplified models v. 2.0?

- guided by new hints/excesses/discoveries in future data
- new collider signatures, different from mono-X? 
- more degrees of freedom/more parameters? loop mediation?
- ...?
BACK UP
\[ R_{M_{\text{med}}}^{\text{tot}} \equiv \frac{\sigma_{\text{eff}}\left| Q_{\text{tr}} < M_{\text{med}} \right|}{\sigma_{\text{eff}}} \quad \text{fraction of events at low momentum transfer (valid events)} \]

\[ m_{\text{DM}} = 50 \text{ GeV} \quad \sqrt{s} = 8 \text{ TeV} \]

\[ Q_{\text{tr}} > 2m_{\text{DM}} \]

\[ m_{\text{DM}} = 400 \text{ GeV} \quad \sqrt{s} = 8 \text{ TeV} \]

\[ m_{\text{DM}} = 50 \text{ GeV} \quad \sqrt{s} = 14 \text{ TeV} \]

\[ \sqrt{s} = 14 \text{ TeV} \]

\[ \sigma_{\text{eff}} \]

\[ Q_{\text{tr}} < M_{\text{med}} \]

\[ \text{ATLAS Simulation} \]

Preliminary

\[ \overline{\chi} \gamma \mu \chi \left( \overline{\mu} \gamma \mu q \right) \]

\[ \text{ATLAS Simulation} \]

Preliminary

\[ |g_{\text{SM}}| \]

\[ |g_{\text{DM}}| \]

[ATL-PHYS-PUB-2014-0087]
some regions still allowed for axial couplings of fermion DM

(not much to say for LHC…)

A. De Simone
still allowed: scalar DM \((m_{DM} > 100 \text{ GeV})\) and fermion DM with axial couplings

\[\mathcal{L} = -h \frac{1}{\sqrt{2}} \left[ \sum_f y_f \bar{f} f + \bar{\psi}_{DM} \left( y_{DM} + y_{DM}^P \gamma_5 \right) \psi_{DM} + \frac{\lambda_{DM} v}{2} s_{DM}^2 \right]\]

LHC: improve on Higgs BR\(_{\text{inv}}\). (not much else...)

[DS, Giudice, Strumia - 1402.6287]
models according to the following general prescriptions: otherwise the relevant physics is not described completely. To this end, one builds simplified by adding new degrees of freedom: not too many, otherwise simplicity is lost; not too few,

As discussed above, when building a simplified model for DM one wants to extend the SM very rich phenomenology.

### 3.1 General properties of simplified models

we first point out some general properties of simplified models.

### 3.2 SM-singlet scalar mediator

mediator $\psi$ is a vector-like fermion carrying color, EW and flavor (if DM total singlet)

possible to couple to: $q_R$, $Q_L$

choose $q_R$:

$$\mathcal{L}_{z_{10}} = \frac{1}{2} (\partial \mu \phi)^2 - \frac{1}{2} m_\phi^2 + \bar{\psi}(i \slashed{D} - M_\psi)\psi + (y\phi \bar{\psi} q_R + \text{h.c.})$$

 pretty much the same story as 0t1/2 (for LHC)

### 3.3.1 Scalar DM, t-channel

different results for (in)direct detection

e.g. $\langle \sigma v \rangle$ is d-wave suppressed ($v^4$)

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Figure 8: Summary of constraints from direct and indirect detection and from collider searches projected on the \( m_S r \) plane of possible DM candidates (see text for details). Here, \( m_S \) denotes the mass of the real scalar dark matter candidate \( S \), and \( r = m_S / m_S \) parametrizes the mass splitting between the vector-like fermionic mediator and \( S \).

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Xenon-1T will probe TeV region of DM mass

[Giachino, Ibarra, Honorez, Tytgat, Wild -1511.04452]
### Table 9: Simplified models for scalar and fermion DM.

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**Diagram for DM pair production in 1/2t1/2 Model**

**1/2t1/2 Model**

- **ψ** fermion color-octet (gluino-like) in SUSY: gluon-gluino-bino
- $\mathcal{L} \supset \bar{\psi}^a (i\not{D} - M) \psi^a + \frac{1}{\Lambda} G^a_{\mu \nu} (\bar{\psi}^a \sigma^{\mu \nu} \chi + \text{h.c.})$
- Dimension-5 dipole operator
- Weak signals for LHC, maybe future colliders...

A. De Simone [details not worked out]
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</table>

vector mediator carries **color**, **EW** and **flavor**

similar story as 0t1/2 (squark-like mediator)

[details not worked out]
**Beyond tree-level mediation?**

- a model for scalar DM interacting with gluons

\[
\frac{\alpha_s}{M^2} |\chi|^2 G^a_{\mu\nu} G^{a\mu\nu} \quad \text{(C5 operator)}
\]

\(\chi\) : DM, complex scalar, gauge singlet

\(\phi_i\) : scalar mediator, color-triplet, EM charged, flavour triplet

[other color reps. (e.g. octet) not explored]

\[
\mathcal{L} \supset \partial_\mu \chi^* \partial^\mu \chi - m_\chi^2 |\chi|^2 + (D_\mu \phi)^\dagger D^{\mu} \phi - m_\phi^2 |\phi|^2
\]

\[+ \lambda_d |\chi|^2 |\phi|^2 \quad + \quad \text{inter. with quarks}\]

\[
\epsilon_{ijk} \phi_i u_j u_k \quad \Rightarrow \quad y_1 \left( \phi_1 c_R - \phi_2 u_R \right) t_R + y_2 \phi_3 u_R c_R
\]

(flavour singlet, MFV)

[Godbole, Mendiratta, Tait - 1506.01408]
In summary, when

\[ \text{Consistently with MFV, the large top Yukawa coupling allows for deviations of coupling} \]

\[ m_{\phi_{1,2}} \text{ (GeV)} \]

\[ Y_1 \]

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dark penguins

\[ \begin{pmatrix} B^\mu \\ q \end{pmatrix} \rightarrow \begin{pmatrix} \psi \\ \phi \end{pmatrix} \rightarrow \begin{pmatrix} \chi_i \\ \bar{\chi}_j \end{pmatrix} \]

\[ \begin{pmatrix} B^\mu \\ q \end{pmatrix} \rightarrow \begin{pmatrix} \phi \end{pmatrix} \rightarrow \begin{pmatrix} \chi_i \\ \bar{\chi}_j \end{pmatrix} \]

[Weiner, Yavin - 1209.1093]
[Primulando, Salvioni, Tsai - 1503.04204]

color-octet scalar mediator (0t1/2)

\eta interaction with DM is not renormalizable

\eta interaction with gluons: only in pairs \sim \eta \eta G, \eta \eta GG

\eta interaction with quarks: suppressed by \( m_q \)

[not worked out]