Scalar DM with t-channel fermionic colored mediator

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in collaboration with F. Giacchino, A. Ibarra, M. Tytgat & S. Wild
to be published soon...

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t-channel mediator: the well known case of Majorana DM

[Bergstrom’89, Flores et al’89 and also Bringmann ’08+, Ciafaloni ’11, Garny ’11+]

\[ \sigma v = a + bv^2 \]

- **a term**: s-wave chirally suppressed
  \[ \propto (m_f/m_\chi)^2 \]

- **b terms**: p-wave \( \nu \) suppression
  \[ \langle v^2 \rangle_{fo} \sim 0.2 \text{ while } \langle v^2 \rangle_{GC} \sim 10^{-6} \]

hopeless for indirect detection when \( m_f/m_\chi \ll 1 \)??

\[ \chi \xrightarrow{\phi} f \]

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- \( b \) terms: p-wave \( v \) suppression
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hopeless for indirect detection
when \( m_f/m_\chi \ll 1 \) ??

Not hopeless! Can get significant signal from
\[ \chi \chi \rightarrow Vff \]

The emission of an extra vector \( V \) lifts the chiral suppression
... but suppressed by 3bdy & extra coupling
t-channel mediator: why looking at real Scalar DM?

DM = Majorana $\chi$

$$\mathcal{L} \supset y \phi^\dagger \chi f_R + h.c.$$  $

$Z_2 : \chi \rightarrow -\chi, \Phi \rightarrow -\Phi$

$$r = \frac{M_\Phi}{M_\chi}$$

$$\sigma v_{ff}|_\chi = \frac{g_l^4}{48\pi} \frac{v^2}{M_\chi^2} \frac{1 + r^4}{(1 + r^2)^4}$$

$p$-wave suppressed ($\propto v^2$ for $m_f \rightarrow 0$)
t-channel mediator : why looking at real Scalar DM ?

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DM = Real Scalar $S$
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\mathcal{L} \supset y S \bar{\psi} f_R + h.c.
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Z_2 : S \rightarrow -S, \Psi \rightarrow -\Psi
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Scalar DM & colored mediator
October 26, 2015
t-channel mediator: why looking at real Scalar DM?

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DM = Real Scalar $S$
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\[ \sigma v_{ff}|_S = \frac{y_l^4}{60\pi} \frac{v^4}{M_S^2} \frac{1}{(1 + r^2)^4} \]

\textit{d-wave suppressed} ($\propto v^4$ for $m_f \rightarrow 0$)
t-channel mediator: why looking at real Scalar DM?

[Bergstrom ’89+, Bringmann ’08+, Ciafaloni ’11, Garny ’11+, Toma ’13, Giacchino’13,...]

\[ \text{DM = Majorana } \chi \]
\[ \mathcal{L} \supset y \phi^\dagger \chi f_R + h.c. \]

\[ Z_2 : \chi \rightarrow -\chi, \Phi \rightarrow -\Phi \]

\[ \chi \quad \phi \quad \chi \quad f \]

\[ r = \frac{M_\phi}{M_\chi} \]

\[ \sigma_{vff}|_\chi = \frac{g_l^4}{48\pi} \frac{v^2}{M_\chi^2} \frac{1 + r^4}{(1 + r^2)^4} \]

\[ p\text{-wave suppressed } (\propto v^2 \text{ for } m_f \rightarrow 0) \]

\[ \text{At f.o. } \langle \sigma v \rangle_{ff}|_S/\langle \sigma v \rangle_{ff}|_\chi \lesssim 0.16 \rightsquigarrow \text{larger Yukawas for } S \text{ to match } \Omega_{dm} \]

\[ \text{In addition, in general, higher order effects are more important in the scalar case, ie } \sigma_{vVff}^\chi < \sigma_{vVff}^S \text{ and } \sigma_{vVV}^\chi < \sigma_{vVV}^S, \text{ for } M_{dm}, y \text{ fixed & } V = \gamma, g \]

\[ \text{DM = Real Scalar } S \]
\[ \mathcal{L} \supset y S \bar{\psi} f_R + h.c. \]

\[ Z_2 : S \rightarrow -S, \Psi \rightarrow -\Psi \]

\[ S \quad \psi \quad S \quad f \]

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\[ d\text{-wave suppressed } (\propto v^4 \text{ for } m_f \rightarrow 0) \]
Viable param. space for coupling to light quarks

\[ \mathcal{L} \supset y S \bar{\psi} q_R + h.c. \]

\[ \psi \equiv \text{colored fermion mediator} \]

\[ \rightsquigarrow \text{opportunities for LHC searches} \]
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\[ \leadsto \text{opportunities for LHC searches} \]

\[ \Omega h^2 \text{ through freeze-out (f.o.) :} \]
- \[ \sigma_{VV} \& \sigma_{V\bar{q}q} \text{ included and } \sigma_{gg} \& \sigma_{g\bar{q}q} \text{ important at f.o. (away from coann.)} \]
- \textbf{Sommerfeld corrections} for mediator annihilation included
  \[ \leadsto \text{up to max 15\% enhancement / suppression of } \Omega h^2 \]
Viable param. space for coupling to light quarks

$$\mathcal{L} \supset y S \bar{\psi} q_R + h.c.$$ 

$$\psi \equiv \text{colored fermion mediator}$$

$$\sim \text{opportunities for LHC searches}$$

$$\Omega h^2 \text{ through freeze-out (f.o.) :}$$

- $$\sigma_{VV} \& \sigma_{V\bar{q}q} \text{ included and}$$
- $$\sigma_{gg} \text{ and } \sigma_{g\bar{q}q} \text{ important at}$$
  - f.o. (away from coann.)

- **Sommerfeld corrections**
  - for mediator annihilation
  - $$\sim \text{up to max } 15\%$$
  - enhancement / suppression of $$\Omega h^2$$
Introduction

Direct Detection searches

- effective DM coupling to \( q \) (scalar and twist-2 \cite{Drees'93} )
- and \( g \) \cite{Hisano'15} included
**Direct Detection searches**

- effective DM coupling to $q$ (scalar and twist-2 [Drees’93]) and $g$ [Hisano’15] included
- effective DM coupling to nucleons $f_p \neq f_n \sim \text{max.}$ isospin violation at $r = 2.6$, (3.3) for $q = u, (d)$

\[ \sigma_{p}^{\text{eff}} = \sigma_{p} \cdot \frac{\sum_{i \in \text{isotopes}} \xi_{i} (Z + (A_{i} - Z) f_{n}/f_{p})^{2}}{\sum_{i \in \text{isotopes}} \xi_{i} A_{i}^{2}} \]
**Direct Detection searches**

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- LUX probes $m_S \lesssim 200 - 300$ GeV + an island around $m_S \sim 2$ TeV
- At all masses, viable parameter space out of reach Direct DM searches.

$$\sigma_p^{\text{eff}} = \sigma_p \cdot \frac{\sum_{i \in \text{isotopes}} \xi_i (Z + (A_i - Z)f_n/f_p)^2}{\sum_{i \in \text{isotopes}} \xi_i A_i^2}$$
Projection of direct-detection constraints

Coupling to $u_R$

$\frac{m_\psi - 1}{m_S}$

$m_S$ [GeV]

$LUX$

XENON-1T

no thermal relic
Collider constraints

Production of colored mediator at the LHC $\sim n$-jets+MET ($n > 2$)

at $r$ small : $n > 2$ enhance visibility for too soft $\psi \rightarrow uS$ jets

at $r$ large : $n > 2$ S/Bgd can be larger for $n > 2$
Collider constraints

Production of colored mediator at the LHC \( \sim n \)-jets+MET \((n > 2)\)
at \(r\) small: \(n > 2\) enhance visibility for too soft \(\psi \rightarrow uS\) jets
at \(r\) large: \(n > 2\) S/Bgd can be larger for \(n > 2\)

\(\sim \) Enhanced production \(\sigma\) including \(y = y_{\text{thermal}}\)

\[ m_\psi = 500 \text{ GeV} \]
\[ \sigma_{\text{only QCD}} \]
\[ \sigma_{\text{total thermal}} \]
\[ \sigma_{\text{excluded by ATLAS } n\text{-jet+}E_T} \]
We use:

ATLAS-CONF-2013-047 for 2-6 jets +MET

at $\sqrt{s} = 8$ TeV $\mathcal{L} = 20.3 \, fb^{-1}$

$\Rightarrow$ limits on the number of signal events $S$

We recompute $\sigma^{\text{excl}}(r, m_{DM})$

evaluating efficiencies $\epsilon = N^{\text{cut}} / N^{\text{events}}$

using Madgraph & CheckMATE

We get $\sigma(r, m_{DM}, y_{\text{thermal}})$ (tree-level) using calchep

and compare to $\sigma^{\text{excl}}(r, m_{DM})$

$\Rightarrow$ Can exclude DM models up to $\sim 1$ TeV for the large $r - y_{\text{thermal}}$ region
Indirect detection constraints

- \( \sigma_{gg} + \sigma_{g\bar{q}q} \equiv 95 - 100\% \sigma_{\nu_{tot}} \)
  today \( \sim \) \( \gamma \) \& \( \bar{p} \) constraints
- rough estimation of Fermi dSphs bound on \( \sigma_{gg} \) \& \( \sigma_{g\bar{q}q} \)
  using integrated spectra for \( E_{\gamma} = [0.5, 500] \) GeV
- Typically probe the \( r > 1.2 \)
  \& \( m_S < 150 \) GeV
  \( \sim \) complement direct detection and collider searches at low DM mass
Projection of all constraints

Coupling to $u_R$

Scalar DM & colored mediator

Laura Lopez Honorez (TENA-VUB)
Real Scalar DM with t-channel fermionic mediator

- $\mathcal{L} \supset y S \bar{\Psi} f_R + h.c.$ have a d-wave 2-body $\sigma v_{qq}$ in the chiral limit
- Models involving a Yukawa coupling to charged SM quarks $\xrightarrow{\sim}$ pheno driven by $SS \rightarrow gg, g\bar{q}q$
  - $\sigma_{gg}$ & $\sigma_{g\bar{q}q}$ are (may be) the dominant contribution today (at f.o)
    - constraints from AMS, FERMI (dwarfs) $\xrightarrow{\sim}$ can exclude candidates up to 150 GeV
- Colored mediator $\xrightarrow{\sim}$ LHC & Direct detection searches can exclude candidates up to 2 TeV
Thank you for your attention !!!
Backup
Cross-section relevant for gamma-ray line searches

Real scalar dark matter, coupling to $u_R$

$\sigma v_{\text{uu}} + 2\sigma v_{\text{Yy}}$ [cm$^3$/s]

$10^{-25}$ $10^{-24}$ $10^{-23}$ $10^{-22}$ $10^{-21}$ $10^{-20}$ $10^{-19}$ $10^{-18}$ $10^{-17}$ $10^{-16}$ $10^{-15}$ $10^{-14}$ $10^{-13}$ $10^{-12}$ $10^{-11}$ $10^{-10}$ $10^{-9}$ $10^{-8}$ $10^{-7}$ $10^{-6}$ $10^{-5}$ $10^{-4}$ $10^{-3}$ $10^{-2}$ $10^{-1}$ $10^0$ $10^1$ $10^2$ $10^3$ $10^4$

$m_S$ [GeV]

Fermi
HESS
CTA

r-1

0.01 0.1 1 10 100
Relic abundance relevant processes
Coupling to leptons & gamma ray lines

Sharp gamma ray spectral features &
Focus on Yukawa coupling to leptons

see [ Giacchino, LLH & Tytgat ’13 &’14 ]
see also [ Toma’13 & Ibarra’14 ]
Looking for smoking gun evidence for DM?

like e.g. sharp spectral features, such as lines, in the gamma ray spectrum:

\[
\frac{d\Phi_\gamma}{dE_\gamma}(E_\gamma, \psi) = \frac{1}{8\pi} \int_{\Delta\psi} \frac{d\Omega}{\Delta\psi} \int_{\text{l.o.s.}} d\ell(\psi) \rho_\chi^2(\mathbf{r}) \times \left( \frac{\langle\sigma v\rangle_{\text{ann}}}{m_\chi^2} \sum_f B_f \frac{dN_f}{dE_\gamma} \right)
\]

Particle physics input
Looking for smoking gun evidence for DM?

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\]

Possibly including pronounced spectral features

More easily discriminated from backgrounds
Looking for smoking gun evidence for DM?

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\[
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\]

Generic candidates

Careful!!

The importance of the “line” compared to the continuum depends on their relative contribution to the total annihilation cross-section.
Sharp gamma ray spectral features

- **From 3bdy process:**
  - **Virtual Internal Bremsstrahlung**
  - peaked at $E_\gamma \sim M_{dm}$ for $r \to 1$
  - **Identical** for Scalar & Majorana

[Barger'11]
Coupling to leptons & gamma ray lines

Sharp gamma ray spectral features

- **From 3bdy process:**
  - Virtual Internal Bremsstrahlung
  - Peaked at $E_\gamma \sim M_{dm}$ for $r \to 1$
  - Identical for Scalar & Majorana
    - [Barger’11]

- **From loop process:** gamma line
  - [Rudaz ’89, Bergstrom’89+, Bern’97 & Bertone’09, Giacchino’14 & Ibarra’14]
Enhanced $\langle \sigma v \rangle_{\gamma ll}$ and $\langle \sigma v \rangle_{\gamma\gamma}$ for Scalar DM

- at f.o. for Real Scalar DM: $\langle \sigma v \rangle_{\gamma ll} \sim \langle \sigma v \rangle_{ll}$
- in general, higher order effects are more important for scalar DM: $\langle \sigma v \rangle_{\chi ll}^{\chi} \ll \langle \sigma v \rangle_{\gamma ll}^{S}$ and $\langle \sigma v \rangle_{\chi\gamma}^{\chi} \ll \langle \sigma v \rangle_{\gamma\gamma}^{S}$

see [Toma’13, Giacchino’13, Giacchino’14 & Ibarra’14]
Viable param. space for coupling to $e_R$
Viable param. space for coupling to $e_R$
Allowed $\langle \sigma v \rangle_{\gamma ll}$ for relic abundance

- when $\sigma v \propto y^4$ dominates $\leadsto$ larger $y$ for $S$ (due to $d-$wave)
  $\leadsto$ larger $\langle \sigma v \rangle_{\gamma ll}$ (modulo the $r$ suppression).
Allowed $\langle \sigma v \rangle_{\gamma ll}$ for relic abundance

- when $\sigma v \propto y^4$ dominates $\Rightarrow$ larger $y$ for $S$ (due to $d-$wave)
  $\Rightarrow$ larger $\langle \sigma v \rangle_{\gamma ll}$ (modulo the $r$ suppression).

- Majorana DM : $\langle \sigma v \rangle_{\gamma ll}^{\text{max}}$ well beyond current and future experimental limits, need extra boost [see also Bringmann’12,Bergstrom’12]

- Scalar DM : $\langle \sigma v \rangle_{\gamma ll}^{\text{max}}$ can be larger by up to 2 orders of magnitude
Collider constraints

Production of colored mediator at the LHC $\leadsto$ MET+jets
Coupling to quarks

Collider constraints

Production of colored mediator at the LHC $\leadsto$ MET+jets

$M \propto g_s^2$:

$\bar{u}u \to \bar{\psi}\psi \text{ and } u\bar{u} \to \psi\psi$

enhanced production $\sigma$

- for large $y = y_{\text{thermal}}$ with $\bar{u}u \to \bar{\psi}\psi$ & $u\bar{u} \to \psi\psi$
- dominating $u\bar{u} \to \psi\psi$ at large $r$ ($y$) due to large $u$ PDF in the $p$
- destructive $y$-$g_s$ interference for $\bar{u}u \to \bar{\psi}\psi$
Constraints derived from ATLAS multijet analysis

Why Multijet (>2) analysis (ie consider extra jets from $q$ or $g$ in the initial state)
- for $m_\psi - m_S < 50 - 100$ GeV, jets from $\psi \rightarrow uS$ too soft, additional jet necessary for visibility
- at large $r$, S/Bgd can be larger for $n-jets + \text{MET}$ signal with $n > 2$

- We use :\textsc{ATLAS-CONF-2013-047} for 2-6 jets +\text{MET} at $\sqrt{s} = 8$ TeV $\mathcal{L} = 20.3fb^{-1}$ Comparing to bgd expectation no significant excess observed $\leadsto$ limits on the number of signal events $S$
- We recompute $\sigma_{95\%CM}^{excl}(r, m_{DM})$ evaluating $S_i = \sigma \epsilon_i \mathcal{L}$ or more precisely the efficiency $\epsilon_i$ that depends on the DM model generating events in \textsc{Madgraph} and apply cuts using \textsc{CheckMATE}
- We compare $\sigma_{95\%CM}^{excl}(r, m_{DM})$ to $\sigma(r, m_{DM}, y_{thermal})$ using \textsc{calchep}
**Worked example : Real Scalar DM and $E_\gamma \sim 130$ GeV signal**

- **Hint for $\gamma$-ray signal at $E_\gamma \sim 130$ GeV at the GC** could correspond to
  \[ M_{dm} \sim 130 \text{ GeV} \gamma\gamma \text{ signal} \]
  [Weniger’12]
  \[ M_{dm} \sim 150 \text{ GeV} \gamma\bar{f}f \text{ signal} \]
  [Bringmann et al’12]

- **First $\gamma\bar{f}f$ analysis** [Bringmann et al’1203] concluded that **thermally produced DM could not account for a signal involving** $\sigma v \sim 6 \times 10^{-27} \text{ cm}^3/\text{s}$
**Worked example**: Real Scalar DM and $E_\gamma \sim 130$ GeV signal

- Hint for $\gamma$-ray signal at $E_\gamma \sim 130$ GeV at the GC could correspond to
  - $M_{dm} \sim 130$ GeV $\gamma\gamma$ signal
    - [Weniger’12]
  - $M_{dm} \sim 150$ GeV $\bar{f}f$ signal
    - [Bringmann et al’12]

- First $\bar{f}f$ analysis [Bringmann et al’1203] concluded that thermally produced DM could not account for a signal involving $\sigma v \sim 6 \times 10^{-27}$ cm$^3$/s

This is indeed the case for Majorana DM, but real scalar DM can do the job

- [Toma’13, Giacchino, LLH & Tytgat ’13 ]
Contributions to $\langle \sigma v \rangle_{\gamma \gamma}$

$SS \rightarrow \gamma \gamma$

$\chi \chi \rightarrow a \ a$

T1 P1 N1  T1 P2 N2  T2 P1 N3  T2 P2 N4

T2 P1 N5  T2 P2 N6  T3 P1 N7  T3 P2 N8

T3 P1 N9  T3 P2 N10  T4 P1 N11  T4 P2 N12

T4 P1 N13  T4 P2 N14
VIRTUAL INTERNAL BREMSSTRahlung?

annihilation of DM into charged particles

\[ \sigma(\chi\chi \to X\bar{X}\gamma) \approx \frac{\alpha Q_X^2}{\pi} \mathcal{F}_X(x) \log \left( \frac{s(1-x)}{m_X^2} \right) \sigma(\chi\chi \to X\bar{X}) \]

IR dominated, collinear emission
universal feature encoded in splitting function

Birkedal, Matchev, Perelstein and Sprey (2005)
VIRTUAL INTERNAL BREMSSTRAHLUNG

\[
DM \rightarrow e
\]

\[
DM \rightarrow \bar{e}
\]

\[\mathcal{M} \propto \left( (p_{DM} - p_{\bar{e}})^2 - M_E^2 \right)^{-1} \sim (M_{DM}^2 - M_E^2 - 2M_{DM}E_{\bar{e}})^{-1}\]

POTENTIALLY VERY LARGE ENHANCEMENT IF \( M_{DM} \sim M_E \)

FOR \( E_{\bar{e}} \sim 0 \) CORRESPONDING TO \( E_\gamma \sim M_{DM} \)

Bergstrom

Bergstrom, Bringmann & Edsjo
JHEP 0801 (2008) 049
Any (not very new) idea of how to break the links ... ?

Sure !!

We need to **break** $\langle \sigma v \rangle_{\text{fo}} \leftrightarrow \langle \sigma v \rangle_{\text{today}} \leftrightarrow \sigma_{\text{direct, coll}}$

- **velocity dependent** annihilation
- richer DM sector with **coannihilations** [Griest & Seckel ’90]
- annihilation near **thresholds and resonances** [Griest & Seckel ’90]
- annihilation into **light mediators**
  (Sommerfeld enhancement [Hisano ’04, Cirelli ’05], secluded DM [Pospelov ’07])
- Non WIMPS : FIMP, asymmetric dark matter, axions
- ...
This is really the end