Direct Detection of the Dark Mediated DM

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1312.2618 and 1402.XXXX

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Main questions

How does the direct detection look like?
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How does the direct detection look like?

What kind of models can give this process?
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How does the direct detection look like?

What kind of models can give this process?

What is the bound on this light scalar - quark coupling?
Current DM experiments

J. Billard and E. Figueroa-Feliciano (13)

**direct**

**indirect**

**collider**

LUX

FERMI

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Current DM experiments

J. Billard and E. Figueroa-Feliciano (13)

irreducible neutrino-background sets a lower bound on the discovery

direct

indirect

Collider

Fermi
Current DM experiments

J. Billard and E. Figueroa-Feliciano (13)

- Direct
- Indirect
- Collider

irreducible neutrino-background sets a lower bound on the discovery

assume 2 to 2 scatterings with a contact DM-quark coupling

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The inconsistencies between different experiments may reflect the detailed structure of the dark sector. Existing ideas: exothermic DM, isospin violation, non-standard form factors, multi-component DM, ... all assume 2to2 scattering so far.

It is important to explore a more complete set of DM models to explain the future data.
Missing ingredient: different topology

The exotic scattering process can provide new tools in understanding different experimental results

- the recoil spectrum has a non-trivial $m_N$ dependence
- get different DM masses when assuming a WIMP-like process
A model building motivation

It is natural to have a “dark” mediator in the dark sector

dark mediator Dark Matter
A model building motivation

It is natural to have a “dark” mediator in the dark sector

A natural way to have the 2 to 3 scattering
Other ways of getting 2to3?

Not easy...

1. Strong bounds on light singlet scalars. hard to avoid the 2 to 2 scattering.

2. The loop suppression makes it hard to have a large cross section.

3. Derivative couplings give velocity suppressions, assume DM doesn’t carry SM charges.

Focus on the dmDM model in this talk.
dmDM model with vectorized quarks

• assume $\phi_1 = \phi_2 = \phi$, $y_Q = y_q = y_{Qq} = 1$ in the mass basis for simplicity

• there is a $\sim 0.1\%$ tuning on the light quark yukawa from the $\phi$ loop

• assume the effective scalar-quark coupling is flavor universal in the mass basis

$\mathcal{L} \supset \frac{|\phi|^2 \bar{Q} q}{\Lambda} + y_{\chi} \chi \chi \phi + h.c. \quad \Lambda = \frac{M_Q^2}{y_Q y_q y_{Qq} v}$
Pseudo Light Dark Matter at direct detections
Direct detection in MadGraph

Si-detector, easy to get, everyone can reproduce the result...

To obtain the recoil spectrum

- generate the DM-quark scattering using MG5
- multiply the cross section with the nuclear form factor
- convolute the result with velocity distribution and Helm Form Factor

for 2 to 2 contact operator

\[ \frac{dR}{dE_r} = N_T \frac{\rho_\chi}{m_\chi} \int dv \ v f(v) \frac{d\sigma_N}{dE_r} \quad \rightarrow \quad \frac{dR}{dE_r} = \frac{1}{2} \frac{\sigma_{n}^{SI}}{\mu_{n\chi}^2} N_T \rho_\chi \frac{m_N}{m_\chi} \frac{A^2 F^2(E_r)}{v_{max}(E_r)} \int_{v_{min}(E_r)}^{v_{max}(E_r)} dv \ \frac{1}{v} f(v) \]
Recoil energy spectrum

For a given DM energy

standard 2 to 2 contact operator

2 to 3 contact operator

2 to 3 light mediator

\[
\frac{d\sigma}{dE_R} = \frac{|M|^2}{32\pi m^2_\chi m_N v^2}
\]

\[
|M|^2 \propto \frac{m^2_N m^2_\chi}{\Lambda^4}
\]

\[
\frac{\bar{\chi}\chi\bar{q}q}{\Lambda^2} = \frac{\bar{\chi}\gamma^\mu\chi\gamma^\mu q}{\Lambda^2}
\]

\[
E_{r_{\text{max}}} = \frac{2\mu^2_N\chi v^2}{m_N}
\]

\[
m_N = 28, m_\chi = 10, E_\chi = 10\,\text{keV}, \, 2\to2\,\text{contact}
\]

\[
m_N = 28, m_\chi = 10, E_\chi = 10\,\text{keV}, \, 2\to3\,\text{contact, heavy mediator}
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\[
\frac{d\sigma}{dE_R} = \frac{|M|^2}{32\pi m_N^2 m_\chi^2 v^2} \Lambda^4
\]

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

\[
E_{r_{\text{max}}} = \frac{2\mu_N^2 m_\chi^2 v^2}{m_N}
\]

2to2 after \( f(v) \) and \( F \)

\( m_\chi = 10 \text{ GeV} \)

\( m_N = 28 \text{ GeV} \) (Silicon)
2to3 scattering: contact vs. dmDM

\[ \frac{d\sigma_{2\rightarrow 3}}{dE_R} \bigg|_{\text{light}} \propto \frac{m_\Phi^4}{(m_N E_R)^2} \propto \frac{m_\Phi^4}{|p_N|^4} \]

coming from the light mediator’s propagator
Approximation of the spectrum

\[ \propto m_N^2 E_R \left( 1 - \sqrt{E_R/E_{R}^{max}} \right)^2 \]

\[ \propto E_R^{-1} \left( 1 - \sqrt{E_R/E_{R}^{max}} \right)^2 \]

with \[ E_{R}^{max} = \frac{\mu_{\chi N}^2}{2 m_N} \nu^2 \]
A nice description of the Erecoil

\[
\frac{d\sigma^{\text{contact}}_{2\rightarrow3}}{dE_R} \simeq \text{constant} \times \left( \frac{m_N}{\text{GeV}} \right)^2 \times \left( \frac{E_R}{\text{keV}} \right) \left( 1 - \sqrt{E_R / E_R^{\text{max}}} \right)^2, \quad E_R^{\text{max}} = 2 \frac{\mu_{\chi N}^2}{m_N} v^2
\]

constant = \(2.6 \times 10^{-27} (2\text{TeV}/m_{\text{med}})^4 (1\text{TeV}/\Lambda)^2\) cm²/keV

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A nice description of the Erecoil

\[
\frac{d\sigma_{2\to3}^{\text{light}}}{dE_R} \simeq \text{constant} \times \left(\frac{E_R}{\text{keV}}\right)^{-1} \left(1 - \sqrt{E_R / E_R^{\text{max}}}\right)^2, \quad E_R^{\text{max}} = 2 \frac{\mu_{XN}^2}{m_N} v^2
\]

\[\text{constant} = 1.3 \cdot 10^{-42} \ (1 \text{TeV}/\Lambda)^2 \ \text{cm}^2/\text{keV}\]
A nice description of the Erecoil

\[ \frac{d\sigma_{2\to3}^{\text{light}}}{dE_R} \approx \text{constant} \times \left( \frac{E_R}{\text{keV}} \right)^{-1} \left( 1 - \sqrt{\frac{E_R}{E_{R\text{max}}}} \right)^2, \quad E_{R\text{max}} = 2 \frac{\mu_{\chi N}^2}{m_N} v^2 \]

\[ \text{constant} = 1.3 \cdot 10^{-42} \left( \frac{1 \text{ TeV}/\Lambda}{(\text{cm}^2/\text{keV})} \right)^2 \]

Three ingredients give the spectrum

I. phase space with \( \phi \) carrying away some energy
II. \( E_{R\text{max}} \) relates to the DM-nucleus mass
III. \( E_R^{-2} \) from the propagator of light mediator

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• lack of events makes it hard to distinguish the shape difference in detail
• heavy dmDM looks like a light WIMP DM
• since the $m_\chi$ of dmDM only shows up in $\mu_\chi N$ of the spectrum, the spectrum is insensitive to the DM mass when the true $m_\chi \gg \mu_\chi N$
Mappings between 2to2 & 2to3

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- heavy dmDM looks like a light WIMP DM
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Pseudo-light Dark Matter

- 100 GeV DM fakes a 10 GeV WIMP
- different masses obtained by different experiments

A single experiment cannot get the mass right. Multiple experiments are necessary for the mass measurement.
Interaction vs. mass

\[ \sigma \propto \left| \frac{y_x \chi}{\Lambda} \right|^2 \]

for DM as a thermal relic \( \Lambda > 20 \text{ TeV} \) is given by the cooling constraints
Loop-induced 2 to 2 process

The simplest model generates a 2 to 2 scattering

\[ \approx \frac{y_{\chi}^2}{2 \pi^2} \frac{1}{\Lambda q} (\bar{\chi} \chi \bar{N} N) \]

\[ q = \sqrt{2m_N E_R} \]

Can be avoided in the heavy-light model

\[ \Omega_\chi = \Omega_{CDM} & \Lambda > 20 \text{ TeV} \]

\[ N_{2-3} > N_{2-2} & \Lambda > 20 \text{ TeV} \]

\[ \text{CDMS-Si} \]

\[ \text{CDMSlite} \]

\[ \text{XENON100} \]

\[ \text{LUX} \]

\[ \text{Irreducible neutrino BG} \]
Interaction vs. mass

\[ \sigma \propto \left| \frac{y \chi}{\Lambda} \right|^2 \]

for $2 \to 3 > 2 \to 2$

$\Lambda > 20 \text{ TeV}$ is given by the cooling constraints
Interaction vs. mass

\[ \sigma \propto \left| \frac{y\chi}{\Lambda} \right|^2 \]

for \( 2 \) to \( 3 > 2 \) to \( 2 \)

\( \Lambda > 20 \text{ TeV} \) is given by the cooling constraints

Simplest dmDM

\( \frac{1}{(10^n \text{ TeV})^2} \)

\( \frac{1}{(10^2 \text{ TeV})^2} \)

\( \frac{1}{(10^3 \text{ TeV})^2} \)

\( \frac{1}{(10^4 \text{ TeV})^2} \)

\( \frac{1}{(10^5 \text{ TeV})^2} \)

\( \frac{1}{(10^6 \text{ TeV})^2} \)

\( m_{\text{DM}} [\text{GeV}] \)

\( \Omega_x = \Omega_{\text{CDM}} \) & \( \Lambda > 20 \text{ TeV} \)

\( N_{2-3} > N_{2-2} \) & \( \Lambda > 20 \text{ TeV} \)

Irreducible neutrino BG

CDMS-Si

CDMSlite

XENON100

LUX

WIMP–nucleon cross section [cm²]

WIMP Mass [GeV/c²]

WIMP–nucleon cross section [pb]
Various Constraints on dmDM
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- DM self-interaction bounds
- DM relic abundance $\Omega_X$
Various Constraints on dmDM

- DM self-interaction bounds
- DM relic abundance $\Omega_X$
- LHC bounds
Various Constraints on dmDM

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$\Omega_\phi$

BBN: $N_{\text{eff}}$

Structure Formation
Various Constraints on dmDM

- DM self-interaction bounds
- DM relic abundance $\Omega_X$

LHC bounds

$\Omega_\phi$
BBN: $N_{\text{eff}}$
Structure Formation

Solar Heat Transfer & Cooling
Supernova Cooling
White Dwarf Cooling
Neutron Star Cooling
Fixed Target Experiments & Beam Dumps
Meson Decays
$Z\phi\phi$ coupling
Various Constraints on dmDM

We will only discuss the bounds that are stronger than \( \Lambda > 10 \text{ TeV} \) in this talk.
Various Constraints on dmDM

DM self-interaction bounds
DM relic abundance $\Omega_x$

bullet cluster: $y_{\chi\phi} < 1$
thermal relic: $y_{\chi} \approx 2.7 \times 10^{-3} (m_{\chi}/\text{GeV})^{1/2}$

LHC bounds

dijet: $M_Q > 1.5 \text{ TeV}$
monojet: $\Lambda > 6 \text{ TeV}$

Solar Heat Transfer & Cooling
Supernova Cooling
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$\Omega_\phi$
BBN: $N_{\text{eff}}$
Structure Formation

$\Lambda$ bounds are weaker than $10 \text{ TeV}$
Cosmological Constraints: $N_{\text{eff}}$

$\phi$ decoupled from thermal bath at $T^\text{freeze}_\phi > 10 \text{ MeV} \left( \frac{\Lambda}{10 \text{ TeV}} \right)^{2/3}$

If the decoupling happens just before the BBN, $N_{\text{eff}}$ has a $2 \sigma$ deviation from the current measurement $N_{\text{eff}} = 3.36_{-0.64}^{+0.68}$ (95% CL)_{Plank+WMAP+HighL}

This can be relaxed when having $\phi$ as a real scalar charged under a $Z_4$ symmetry $\phi \rightarrow -\phi$, $\chi \rightarrow e^{i\pi/2} \chi$ so the deviation becomes small
The $\phi$ density gives $\Omega_\phi h^2 \equiv 7.83 \times 10^{-2} \frac{g_\phi}{g_{*S}} \frac{m_\phi}{eV}$ $g_\phi = 2$, $g_{*S} \simeq 12$

This requires $m_\phi < eV$ for having no significant contribution to the density if $\phi$ does not decay

- $\phi$ was a collisionless particle during the structure formation ($\sim 10$ eV). It only generates Landau damping to the primordial density fluctuations with a FS-length similar to neutrinos

$$\lambda_{FS, \phi} \simeq 20 \text{ Mpc} \left( \frac{m_\phi}{10 \text{ eV}} \right)^{-1}$$

$\phi$ satisfies similar constraints as a light sterile neutrino

- Can also make $\phi$ decay by having $\phi F_{\mu\nu} \tilde{F}^{\mu\nu} / \Lambda$
Cooling Constraints

supernovae

white dwarf

the Sun

neutron star
Stellar cooling: generalities

- If $m_\phi \lesssim T$ the scalar can be produced inside of stars.

- A production process $X_1 X_2 \rightarrow \phi + ...$ yields $r_\phi = n_{X_1} n_{X_2} c \sigma_{\phi_{\text{prod}}}$ $\phi$s per unit volume per unit time.

- If we know the radial profiles of stellar density, temperature and composition we can find the total $\phi$ production rate for the star (assuming $\phi$ does not significantly alter stellar evolution).

- In the absence of significant $\phi$-destroying processes, this is equal to the equilibrium total $\phi$ loss rate.
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- In the absence of significant $\phi$-destroying processes, this is equal to the equilibrium total $\phi$ loss rate.

This allows us to compute the energy lost due to $\phi$ emission.
Compute $\phi$ low-energy scattering and production cross sections analytically and in MadGraph.

$$\frac{\bar{q}q\phi\phi^*}{\Lambda}$$

$\Lambda = 10 \text{ TeV}$

$$\sigma_{\gamma\gamma \rightarrow \phi\phi} \sim \frac{1}{16\pi} \left( \frac{\alpha}{\pi m_q} \right)^2 \left( \frac{B}{\Lambda} \right)^2 E_\gamma^2$$

with $B^2 = 1 - 100$
The Sun

- Core temperature is about $T \sim 1$ keV
- The most important $\phi$ production process is $\gamma N \rightarrow N \phi \phi$
- For $\Lambda = 10$ TeV, $\phi$ decouples at $r \sim 0.7 \times R_{\text{sun}}$ where $T \sim 0.1$ keV.

$solar \phi$ luminosity $< 1\%$ photon luminosity requires $\Lambda > 1$ TeV.

- Need the “heat transfer” of $\phi$ to be much smaller than the photon’s

\[
\frac{F_\phi}{F_\gamma} \sim \frac{n_\phi L_\phi}{n_\gamma L_\gamma} \ll 1
\]

\[
\frac{F_\phi}{F_\gamma} \sim n_p c \sigma_{p\gamma \rightarrow p\phi\phi} t_{\gamma \rightarrow \phi \phi} \sim 10^{-2} \left( \frac{10 \text{ TeV}}{\Lambda} \right)^2
\]

No significant constraint
White Dwarfs

- Core temperature $T \sim 1 - 10$ keV
- The *White Dwarf Luminosity Function* tells us how fast they cool.

Observational data in good agreement with standard cooling theory!

Need the scalar cooling to be much smaller than the photon cooling.

Dreiner, Fortin, Isern, Ubaldi (13')
Max Katz (graduate student of Michael Zingale @ SB) helped us by simulating the evolution of a sun-like star to a typical 0.5 - 0.6 solar mass WD using the MESA stellar evolution code (stellar astrophysics “gold standard”).

When our test dwarf has 0.1 x solar luminosity (very φ power output is < 10% total WD luminosity if

\[ \Lambda > 20 \text{ TeV} \quad \frac{\bar{q} q \phi \phi^*}{\Lambda} \]

(φ emission even less important at lower core temperature)
Neutron Stars

Lots of $\phi$ production in neutron star core via

$$nn \rightarrow nn \phi \phi$$

The scattering only happens around the Fermi surface of neutrons

$$f_n(E) = \frac{1}{1 + \exp\left(\frac{E - \mu}{T}\right)}$$
Neutron Stars

Lots of $\phi$ production in neutron star core via

$$nn \rightarrow nn \phi \phi$$

The scattering only happens around the Fermi surface of neutrons

$$f_n(E) = \frac{1}{1 + \exp\left(\frac{E - \mu}{T}\right)}$$

The neutrons scattering then is suppressed by a factor

$$\left(\frac{T}{\mu}\right)^2 \sim 10^{-6}$$

which gives a small production rate

No significant constraint
Supernovae

\[
\frac{\phi^* \phi \bar{Q} q}{\Lambda} \Rightarrow \sigma_N \phi \propto \frac{1}{\Lambda^2}
\]

while

\[
\sigma_N \nu \propto \frac{T^2}{m_W^4}
\]

The free streaming length \( L_\phi \ll L_\nu \)
\( \phi \) then is trapped inside SN and gives no significant cooling comparing to neutrinos

\[ \Lambda \lesssim 10^6 \text{ TeV} \]

Gives an upper bound
**Bound on the dmDM model**

\[ \Lambda > 20 \text{ Tev} \]

and

\[ y_X \] correct value for DM relic density

\[ \Lambda > 20 \text{ Tev} \]

and

\[ y_X \] small enough to ensure subdominant \( 2 \to 2 \)

\[ \left( \frac{y_X}{\Lambda} \right)^2 \]

\[ \frac{1}{(10^1 \text{ TeV})^2} \]

\[ \frac{1}{(10^2 \text{ TeV})^2} \]

\[ \frac{1}{(10^3 \text{ TeV})^2} \]

\[ \frac{1}{(10^4 \text{ TeV})^2} \]

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\[ \frac{1}{(10^6 \text{ TeV})^2} \]

\[ m_{DM} \ [\text{GeV}] \]

\[ \Omega_X = \Omega_{CDM} \ & \ \Lambda > 20 \text{ TeV} \]

\[ N_{2 \to 3} > N_{2 \to 2} \ & \ \Lambda > 20 \text{ TeV} \]

Irreducible neutrino BG

CDMS-Si

XENON100

CDMSlite

LUX

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Other “possible” uses

For reconciling CDMS-Si and LUX

- if this is the case, having a larger detector will not help!
- the $\phi F_{\mu\nu} \tilde{F}^{\mu\nu} / \Lambda$ coupling needs to be large, with $\Lambda < \text{GeV}$ unless the DM velocity is large ($\sim 0.01$) so the $\Lambda$ can be of TeV scale
Other “possible” uses

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Other “possible” uses

For different masses from the direct/indirect detections

• DM looks lighter in a direct detection when being fitted as 2to2
• v-suppression from derivative couplings makes $\sigma_n$ too small 😞
Conclusion

dmDM is the first DM model featuring $2 \rightarrow 3$ direct detection, and hence adds new kinematics to model builder’s tool box.

Heavy DM candidates fake different light WIMPs at different detectors. New searching strategies will be necessary.

Cosmo + Astro sets significant constraints, but large regions of detectable parameter space remain. The bound can be relaxed by the heavy light setup.

Many possible applications of the dmDM model can be used for direct detections.
Backup
A less constrained model

So far we only consider the simplest case with a single scalar
A less constrained model

So far we only consider the simplest case with a single scalar model with:

\[
m_{\phi_h} \approx 1 \text{ MeV}, \quad m_{\phi_l} < 1 \text{ keV} \quad y_{q_l}^{\phi_l} < 0.1
\]

to avoid the sizable stellar production of \( \phi \)

Moreover, if \( y_{\chi} \phi_l, y_{Q_l}^{\phi_h} < 10^{-3} \), the loop-induced 2 to 2 process will be < 10% of the 2 to 3 while keeping the \( \sigma_{2 \rightarrow 3} \) large

\( \phi_h \) can decay promptly through a \( \phi_h \phi_l^3 \) coupling (assuming the Z4 case)

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Other possible use of 2to3
in a non-relativistic scattering

the DM and nucleus have $v \ll 1 \Rightarrow E_k = \frac{1}{2} m v^2 \ll |\vec{p}| = m v$

however, the relativistic scalar has $E^\phi \simeq |\vec{p}_\phi|$, this requires

$|\vec{p}_\phi| \simeq E^\phi < E^\chi_k \ll |\vec{p}_\chi, N|$

$\phi$ carries away sizable energy but not much momentum!

$$(\Delta p_N + p_\phi)^{-4} \simeq (\Delta p_N^2 + 2 p_\phi \cdot \Delta p_N)^{-2}$$

$\simeq (|\vec{p}_N|^2 + 2 |\vec{p}_\phi||\vec{p}_N|)^{-2}$

$\simeq (2 m_N E_R)^{-2}$$
Interaction strength

![Interaction strength graph](image-url)
Cosmological Constraints: $N_{\text{eff}}$

The cross section is hard to estimate... assuming a quark loop with constituent quark mass, multiplied by a range of the form factor

$$\sigma_{\gamma\gamma\to\phi\phi} \sim \frac{1}{16\pi} \left( \frac{\alpha}{\pi m_q} \right)^2 \left( \frac{B}{\Lambda} \right)^2 E_{\gamma}^2 \quad B^2 = 1 - 100$$

$\phi$ decoupled from thermal bath at $T_{\phi}^{\text{freeze}} > 10 \text{ MeV} \left( \frac{\Lambda}{10 \text{ TeV}} \right)^{2/3}$

If the decoupling happens just before the BBN, $N_{\text{eff}}$ has a $2\sigma$ deviation from the current measurement $N_{\text{eff}} = 3.36^{+0.68}_{-0.64} \ (95\% \ \text{CL})_{\text{Plank+WMAP+HighL}}$

This can be relaxed when having $\phi$ as a real scalar charged under a $Z_4$ symmetry $\phi \to -\phi, \chi \to e^{i\pi/2}\chi$
Constraints on the dark coupling

- Bullet cluster bound requires $y_{\chi\phi} < 1$ when having a single light mediator and 10-100 GeV DM.

- DM being a thermal relic requires $y_{\chi} \approx 2.7 \times 10^{-3} (m_{\chi}/\text{GeV})^{1/2}$
Collider bounds : LHC

**di-jet** \[ pp \rightarrow \psi_Q \bar{\psi}_Q \rightarrow \phi\phi^* jj \]

CMS 20/fb bound on the production rate requires

\[ M_Q > 1.5 \text{ TeV} \]

**mono-jet**

\[ pp \rightarrow q^* \rightarrow \phi \psi_{Q,q} \rightarrow \phi j, \quad pp \rightarrow \phi \phi + \text{ISR} \]

MG5+Pythia+PGS

CMS 20/fb bound requires \( \Lambda > 6 \text{ TeV} \) when \( M_Q \simeq 1.5 \text{ TeV} \)

No significant bound
Collider bounds: fixed target

\[ p \rightarrow \phi \rightarrow N \]

<table>
<thead>
<tr>
<th>( E_p )</th>
<th>( N_{POT} )</th>
<th>detector distance</th>
<th>detector dimensions</th>
</tr>
</thead>
<tbody>
<tr>
<td>MINOS 64, 65</td>
<td>( 120 \text{ GeV} ) ( 10.7 \cdot 10^{20}(\nu), \ 3.36 \cdot 10^{20}(\bar{\nu}) )</td>
<td>( \sim 100 \text{ m}, 735 \text{ km} )</td>
<td>( \sim 10 \text{ m} )</td>
</tr>
<tr>
<td>T2K 66-68</td>
<td>( 30 \text{ GeV} ) ( 6.63 \cdot 10^{20} )</td>
<td>( 280 \text{ m (INGRID in ND280)} ) ( \sim 10 \text{ m} )</td>
<td>( 295 \text{ km (Super-Kameiokande)} ) ( \sim 40 \text{ m} )</td>
</tr>
<tr>
<td>MiniBooNE 69</td>
<td>( 8.9 \text{ GeV} ) ( 6.5 \cdot 10^{20}(\nu), \ 11.3 \cdot 10^{20}(\bar{\nu}) )</td>
<td>( 541 \text{ m} )</td>
<td>( \sim 10 \text{ m} )</td>
</tr>
<tr>
<td>LSND 70</td>
<td>( 800 \text{ MeV} ) ( 1.8 \cdot 10^{23} )</td>
<td>( 30 \text{ m} )</td>
<td>( 0.3 \text{ m} )</td>
</tr>
</tbody>
</table>

\( \phi \) production rate  geometrical suppression

even with detection efficiency = 1
\( E_p = 120 \text{ GeV} \)

\[ \frac{N_{\phi \text{ detected}}}{10^{-6}} \sim \left( \frac{N_{POT}}{10^{21}} \right) \left( \frac{10 \text{ TeV}}{\Lambda} \right)^4 \left( \frac{L_{\text{target}} L_{\text{detector}}}{\text{meter}^2} \right) \]

number of the observed events \( < < \ 1 \)

No significant bound
Collider bounds: kaon decay

\[
\frac{\phi^* \phi \bar{Q} q}{\Lambda}
\]
can generate a tree-level decay of scalar mesons, or loop-induced decay through a flavor changing process

\[
K^+ \to \pi^+ \phi \phi^*
\]

Current experimental precision

\[
\begin{align*}
Br(K^+ \to \pi^+ \nu \bar{\nu})_{\text{exp}} &= 17.3^{+11.5}_{-10.5} \cdot 10^{-11} \\
Br(K^+ \to \pi^+ \nu \bar{\nu})_{\text{SM}} &= (8.5 \pm 0.7) \cdot 10^{-11}
\end{align*}
\]

\[
\frac{|M_{\phi\phi}|}{|M_{\text{SM}}|} \sim \frac{m_Z^2}{g_{Zq} g_{Z\nu} m_t \Lambda} = 0.03, \quad \Lambda = 10 \text{ TeV}
\]

No significant bound
Bound on light sterile neutrino

Planck+WMAP+H0+BAO+X-ray cluster

Mark Wyman, Douglas H. Rudd, R. Ali Vanderveld, and Wayne Hu (13)
Cosmological Constraints : $^4$He

- $\phi$ can in principle dissociated a $^4$He during the BBN time. However, the min recoil energy that a $\phi$ needs to kick out a nucleon from $^4$He is $7.1$ MeV, which requires $E_\phi > 125$ MeV when the temperature is below $10$ MeV. $E_{R_{\text{max}}} = 2 \frac{E_\phi^2}{m_{{^4\text{He}}}}$

- Calculating the dissociation rate by including the Boltzmann distribution sets a bound $\Lambda > 11$ TeV when comparing the dissociation probability of $^4$He to the current precision $\frac{\delta n_{^4\text{He}}}{n_{^4\text{He}}} \approx \frac{0.04}{0.26} = 15\%$
\[ m\phi = 0.2 \text{ keV} \]

DOTTED = (collaboration bounds) \rightarrow (WIMP to dmDM map)
SOLID = exclusion from directly fitting dmDM to data

Green (Blue) = 68 (90) \% CL CDMS–Si preferred region
Red = 90\% CL upperbound from XENON100
Purple = 90\% CL upperbound from CDMSlite

Magenta = \frac{\Lambda_{\text{min}}}{y_{\text{relic}}}, where \Lambda_{\text{min}} = 100 \text{ TeV} from WD