Light dark matter and scalar portal

SHiP
Search for Hidden Particles

11th SHiP Collaboration Meeting
CERN
June 8, 2017

Part I: Light dark matter

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Light dark matter

- Definition 1: Thermal relic dark matter with the mass lighter than **few GeV**
- Definition 2: Dark matter that can be found at SHiP

Reminder: Weakly interacting massive particles

- Original idea of Weakly Interacting Massive Particles (**WIMP** dark matter) goes back to **Lee & Weinberg** **(Phys. Rev. Lett. 1977)**
- Their paper was titled *"Cosmological lower bound on heavy-neutrino masses"*

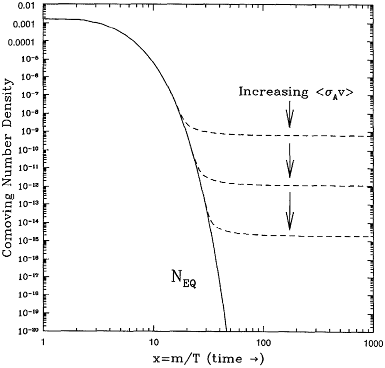
- Assume a new **weakly** interacting stable particle (called "heavy neutrino" in the original paper)
- These particles were in thermal equilibrium in the early Universe so, their concentration is given by Boltzmann distribution (for $m_\chi \gg T$)

$$n_\chi(T) = \left(\frac{m_\chi T}{2\pi}\right)^{3/2} e^{-m_\chi/T}$$

- They keep the equilibrium number density via annihilation $\chi + \bar{\chi} \rightarrow \mathrm{SM} + \mathrm{SM}$
- At some moment their **annihilation rate** is not enough to maintain the equilibrium number density $\Rightarrow$ **freeze out**

Light WIMPs

See the talk by P. Fayet



- The weaker you interact the larger is your number density

$$\Omega_\chi h^2 \sim \frac{3 \cdot 10^{-27}\,\mathrm{cm}^3/\mathrm{sec}}{\langle \sigma_A v \rangle}$$

- Annihilation cross-section depends on the interaction strength and on the number of final states

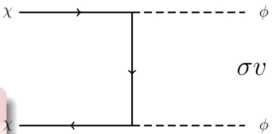
$$\sigma_A \sim G_F^2 \; m_\chi^2 \; N_{\text{channels}}$$

For mass $m_\chi < m_b$ annihilation into the SM channels leads to a **too small** cross-section $\Rightarrow$ **too large** DM abundance

Lee & Weinberg took G_F as an interaction strength and got the lower bound $m_\chi > 5$ GeV

Light WIMP $\Rightarrow$ extra light states

- Light DM requires more **light** states to annihilate into (scalars, vectors, ...)



$$\sigma v \propto g_\chi^4$$

$$(m_\phi < m_\chi)$$

Examples:

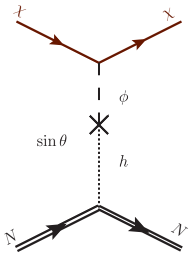
- Light scalar ϕ (scalar portal mediator)

$$\mathcal{L}_{\mathsf{DM}-\phi} = \bar{\chi}\left(g_\chi + \gamma_5 g'_\chi\right)\phi\chi$$

- Light vector portal A_μ

$$\mathcal{L}_{\mathsf{DM}-A'} = \bar{\chi}\gamma^\mu A'_\mu\left(g_\chi + \gamma_5 g'_\chi\right)\chi$$

- ... it is also possible that DM is scalar rather than fermion



- Mediator couples WIMP to Standard Model fermions and determines **DM-nucleon** (or **DM-electron**) cross-section

From LDM to **S**elf-**I**nteracting **D**ark **M**atter (SIDM)

- Exchange of ϕ mediates DM-DM scattering
- If $m_\phi < m_{\rm DM}$ there are two regimes:
  - **High-energy:**

$$\sigma_{\rm ann} \sim \frac{\alpha_\chi^2}{m_{\rm DM}^2 v^2},$$

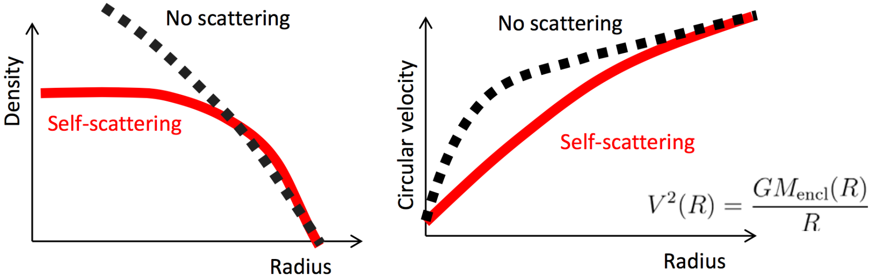
    where α_χ is a coupling constant in the Dark Sector.
  - **Low-energy:** $(m_{\rm DM} v < m_\phi)$

$$\sigma_{\rm scat} \sim \frac{\alpha_\chi^2 m_{\rm DM}^2}{m_\phi^4},$$

For LDM it is easy to get high self-interaction cross-section, making LDM a **self-interacting dark matter (SIDM)**

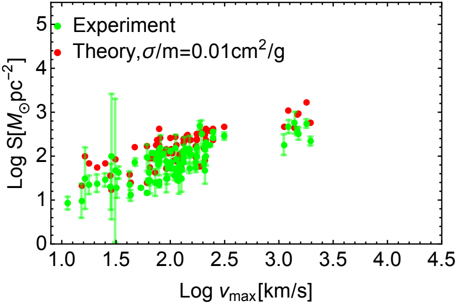
Astrophysical manifestations of SIDM

- In galaxies and galaxy clusters density scales as $r^{-\gamma}$ in the central parts. Pure Cold DM simulations predict $\gamma = 1$ (**cusps**), but it is observed $\gamma < 1$ in some objects (**cores**) (*core-cusp problem*)
- The possible solution is the **self-interacting** DM (SIDM). At high densities, self interaction play a role for DM particles, which self-scatter in halos and wash out cusps



SIDM. Connection to the particle physics

- The DM profile for SIDM depends on the σ/m ratio. To get the right core properties one should take the specific value of it.



Bondarenko et al. (to appear)

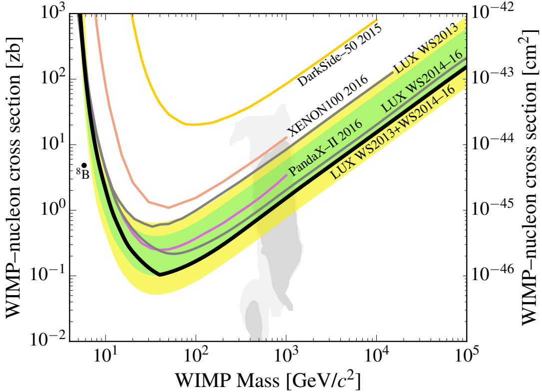
- The mass of the mediator weakly depends on σ/m value,

$$m_{\text{mediator}} \sim 12 \text{ MeV} \left(\frac{\alpha_\chi}{0.01}\right)^{1/2} \left(\frac{m_{\text{DM}}}{1 \text{ GeV}}\right)^{1/4} \left(\frac{\sigma/m_{\text{DM}}}{1 \text{ cm}^2/\text{g}}\right)^{-1/4}$$

- **Works for light (SHiP-range) mediators!**

Light WIMP direct detection

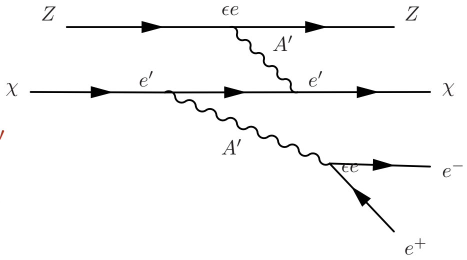
- At small WIMP masses laboratory direct detection sensitivity deteriorates quickly
- However for such particles SHiP becomes a tool for dark matter detection



[LUX Collaboration] Phys. Rev. Lett. 118 (2017) 021303

Detection strategy at SHiP

- The detection of the DM particles in the SHiP neutrino detector with the photoemulsion using **DM scattering on electrons or the nuclei**
- To distinguish from neutrino scattering one can use the superb resolution of the photoemulsion to measure the kinimatical difference of the events.
- Another interesting possibility to distinguish DM event from background: consider reaction $\chi + e/N \to \chi + e/N + A'$, where A' is the light mediator. It could decay in decay volume and be detected by SHiP main detector.



Signatures and search strategy depend on type of dark matter (fermion, scalar) , type of mediator (scalar, vector) and relation between their masses

Scalar Dark Matter and Vector Mediator: reference model

Four parameters:

$$m_{A'}, \quad m_\chi, \quad \epsilon \quad \alpha_D \equiv e'^2/4\pi$$

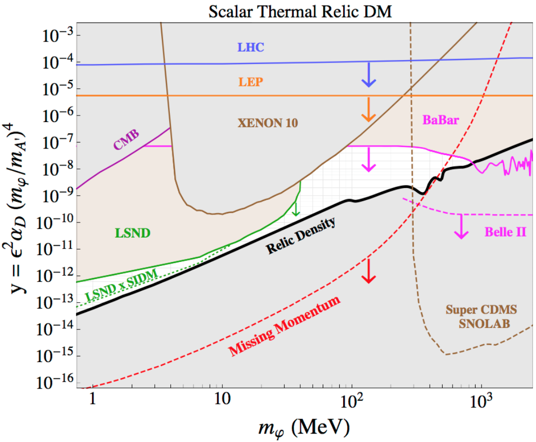
Tree-level annihilation cross section:

$$\sigma v_{rel} = \frac{8\pi}{3} \frac{\epsilon^2 \alpha \alpha_D m_\chi^2 v_{rel}^2}{(m_{A'}^2 - 4m_\chi^2)^2 + m_{A'}^2 \Gamma_{A'}^2}$$

For $m_{A'} \gg m_\chi, \Gamma_{A'}$ it scales with

$$\boxed{y \equiv \epsilon^2 \alpha_D \left(\frac{m_\chi}{m_{A'}}\right)^4}$$

E. Izaguirre, G. Krnjaic, P. Schuster and N. Toro, Phys. Rev. Lett. 115, no. 25, 251301 (2015)



$$m_\chi/m_{A'} = 1/3, \quad \alpha_D = 0.5$$

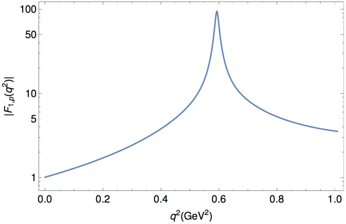
Production at fixed target

Two main production channels:

1. Direct production.
   Proton-proton bremsstrahlung (in the WW approximation)

   Conservative: **D. Gorbunov, A. Makarov, IT, Phys.Rev. D91 (2015) 3, 035027**

   Optimistic: **P. deNiverville, C. Y. Chen, M. Pospelov and A. Ritz, Phys. Rev. D 95 (2017) no.3, 035006** resonant vector meson mixing — to compare to others



2. Production in radiative meson decays:
   $\pi^0 \to \gamma A'$, $A' \to \chi^\dagger \chi$

In the narrow width approximation (assuming that the hidden photon is sufficiently long-lived, $\Gamma_{A'} \ll m_{A'}$)

$$\sigma(pN \to A' \to \chi\bar{\chi}) = \sigma(pN \to A')\mathrm{Br}(A' \to \chi\bar{\chi})$$

Scattering of DM: all formulae are known!

The elastic DM-electron scattering cross section

$$\frac{d\sigma_{\chi e\to\chi e}}{dE_e} = 4\pi\epsilon^2\alpha\alpha' \frac{2m_e E_{in}^2 - (2m_e E_{in} + m_\chi^2)(E_e - m_e)}{(E_{in}^2 - m_\chi^2)(m_{A'}^2 + 2m_e E_e - 2m_e^2)^2} \quad (1)$$

E_e, E_{in} are the energies of the recoil electron and of the incident dark matter particle respectively

The elastic DM-nucleon cross section (Phys. Rev. D 86 (2012) 035022)

$$\frac{d\sigma_{\chi N\to\chi N}}{dQ^2} = 4\pi\epsilon^2\alpha\alpha' \frac{F^2(Q^2)[q_N^2 A(E_{in},Q^2) - \frac{1}{4}\kappa_N^2 B(E_{in},Q^2)]}{2m_N(m_{A'}^4 + Q^2)^2(E_{in}^2 - m_\chi^2)}, \quad (2)$$

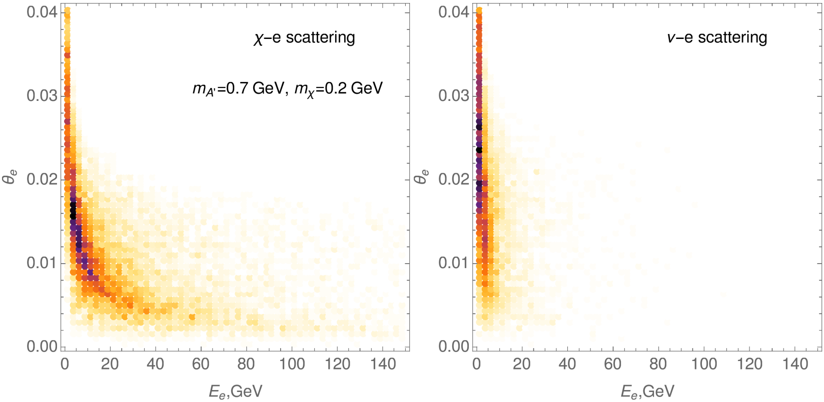
$Q^2 = 2m_N(E_{in} - E_\chi)$ is the momentum transfer, E_χ is the energy of the outgoing DM particle. Form factor in the simplest form is $F = (1 + Q^2/m_N^2)^{-2}$

Scattering angle is determined by kinematics

Scattering of DM particles vs. Elastic scattering of neutrino

Work in progress. . .

Toy Monte Carlo simulations of the SHiP setup. Homogeneous target.



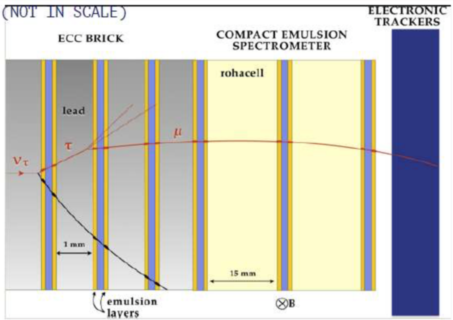
Number of events as function of the electron scattering angle and the electron energy. Scattering of DM particles vs Elastic scattering of neutrino.

Accurate simulation of scattering

Typically bounds are obtained requiring

$$N_{events} \equiv \int_{det} d\Omega \int dE_{in}\, n\sigma(E_{in})\, L_{det} \frac{dN_\chi}{dE_{in} d\Omega} > 100\,(10, 1000, \ldots)$$

But can we destinguish it from the ν background?



Still a lot of questions.
Geant4 simulation of both neutrinos and χ ?

Conclusions for LDM

Reference model for tau neutrino detector

- Everything is known (parameters, cross section)
- Widely studied by many groups (helps to compare SHiP sensitivity to that of other facilities)

Further steps

- Other models of LDM (light vector and scalar mediators) – implement in FairSHiP
- Explore a possibility of background rejection with signals **both** in emulsion and in main detector

Part II: Hadronic decays of scalar mediators

Alexander Monin, Alexey Boyarsky, Oleg Ruchayskiy

Reminder: Scalar portal

New scalar S couples to the Higgs field H:

$$\mathcal{L} = \mathcal{L}_{SM} + \frac{1}{2}(\partial_\mu S)^2 + (\alpha_1 S + \alpha S^2)(H^\dagger H) + \lambda_2 S^2 + \lambda_3 S^3 + \lambda_4 S^4,$$

Scalar S "inherits" interactions from Higgs

$$\mathcal{L}^S_{int} = \boxed{-\sin\theta \sum_f \frac{m_f}{v} S\bar{f}f} + 2\sin\theta \frac{M_W^2}{v} SW^+W^- + \sin\theta \frac{M_Z^2}{v} SZ^2 + \dots$$

where $\tan 2\theta = \frac{2\alpha_1 v}{M_H^2 - m_S^2} \approx \frac{2\alpha_1 v}{M_H^2}$, $\qquad \theta \ll 1$

- Hadronic part of the interaction Lagrangian

$$\mathcal{L}_{int} = \sin\theta \frac{S}{v} \sum_{q=u,d,s,c,b,t} m_q \bar{q}q$$

- For $2m_\pi < m_S < 1 - 2\,\mathrm{GeV}$ we are interested in decays to pions: $S \to \pi\pi$, $S \to \bar{K}K$

Decay to two pions in the lowest order perturbation theory

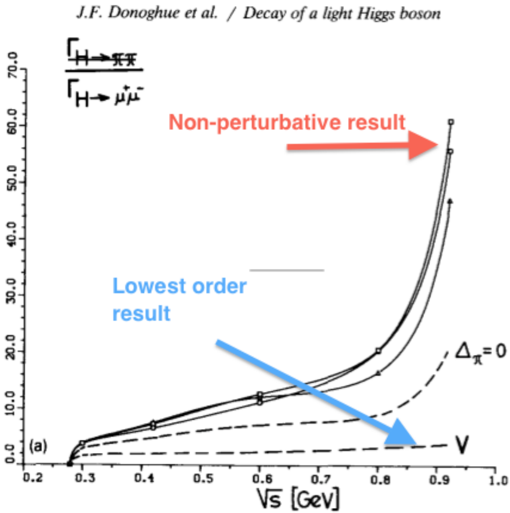
The resulting LO decay width is

$$\Gamma^{\mathrm{LO}}(S \to \pi^+\pi^-) = \frac{m_S^3 \sin^2\theta}{16\pi v^2}\left(\frac{2}{9} + \frac{11}{9}\frac{m_\pi^2}{m_S^2}\right)^2 \left(1 - \frac{4m_\pi^2}{m_S^2}\right)^{1/2}$$

(Voloshin 1986; Voloshin & Zakharov 1980)

- This result is used in many works (see e.g. Schmidt-Hoberg et al. [1310.6752]; McKeen [0809.4787]; OConnell [hep-ph/0611014], . . .).
- This estimate is also used in **SHiP Technical proposal** and Gaia's note (CERN-SHiP-NOTE-2017-001)
- It turned out that corrections to the tree level ChPT are large (e.g. Chivukula et al. 1989; Donoghue et al. 1990)

Is this worth fighting for?



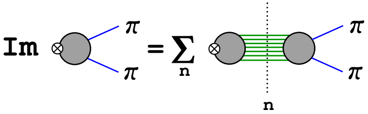
- Difference between "leading order" and "non-perturbative" calculations is a factor $\mathcal{O}(50)$ **(Donoghue et al. 1990)**

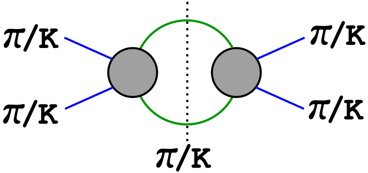
Given a very large difference between leading-order and non-perturbative results claimed in the literature and the absence of consensus in the community, we decided to revise the question of hadronic decays of a light scalar.

Dispersion relation method

- Form-factors are analytic functions apart from a cut for $s \geq 4m_\pi^2$
- Reconstruct form-factor by its imaginary part:

$$f(s) = \int_{4m_\pi^2}^{\infty} ds' \frac{\mathrm{Im}\, f(s')}{s' - s - i\epsilon}$$





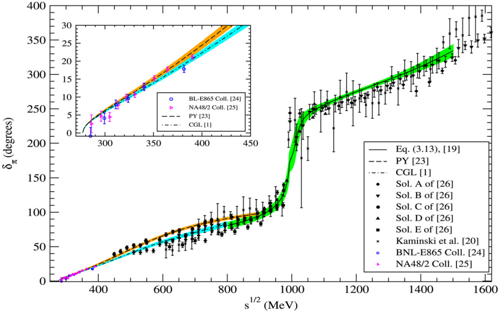
- At $s > 4m_\pi^2$ intermediate pion states go on-shell $\Rightarrow$

Imaginary part is determined by $\pi\pi \to \pi\pi$ scattering

- The imaginary part of the form-factor is given by $\sin^2$

Muskhelishvili-Omnès solution (general)

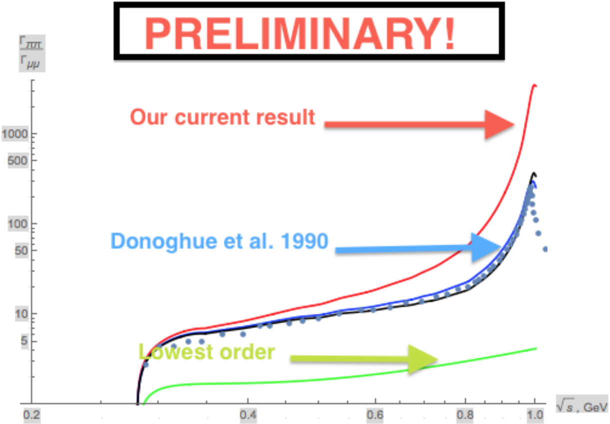
- Below $K\bar{K}$ threshold ($4m_\pi^2 \leq s < 4m_K^2$) one can express imaginary part of all form-factors solely via $\delta_\pi(s)$ — experimntally measured phase of $\pi\pi \to \pi\pi$ scattering
- Any form-factor is given by the so-called **Muskhelishvili-Omnès solution:**



$$\boxed{f(s) = f_0 \left(1 - \frac{s}{s_0}\right) \exp\left(\frac{s}{\pi} \int \frac{ds'\,\delta_\pi(s')}{s'(s' - s - i\epsilon)}\right)}$$

- Constant f_0 is known from perturbation theory ($s \to 0$)
- If the zero, s_0, is also the perturbative range of energies – **we are done**!

Current status



Almost factor of 1000 large than the numbers used in TP!

Next steps

- Finish this analysis
- Add the case $S \to \bar{K} K$
- Implement in FairSHiP
- Revise scalar **production** at SHiP

Why the difference?

Recall: we needed to evaluate three matrix elements (form-factors):

$$\theta_\pi(s) \equiv \langle \pi\pi | \, \theta^\mu_\mu \, |0\rangle \, ; \qquad \Delta_\pi(s) \equiv \langle \pi\pi | \, m_s \bar{s} s \, |0\rangle \, ; \qquad \Gamma_\pi(s) \equiv \langle \pi\pi | \, m_u \bar{u} u + m_d \bar{d} d \, |0\rangle$$

- $\Delta_\pi(s)$ and $\theta_\pi(s)$ have their zeros in perturbative region - we can compute them with confidence
- Zero $\Gamma_\pi(s)$ lies in the non-perturbative region but we can reconstruct it from pion's scalar radius $\langle r^2 \rangle_s$ **(Oller & Rocca 2001; Ananthanarayan et al. 2004)**
- In computing $\theta_\pi(s)$ we find significant discrepancy with the results of **(Donoghue et al. 1990)** who claim that there is an extra **non-perturbative** zero of the form-factor $\theta_\pi(s)$
- If taken at face value this would contradict to the general statement about behaviour of form-factors at $s \to \infty$ **(Brodsky & Farrar)**