

Light 2HDM scalars as portal to dark matter

Johannes Herms, Sudip Jana, Shaikh Saad, Vishnu P.K.

Max-Planck-Institut für Kernphysik

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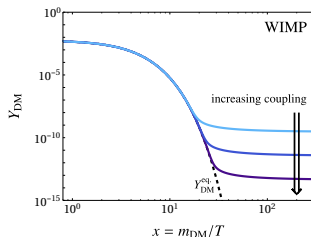


Thermal relic dark matter

suppose there exists a stable neutral particle beyond the Standard Model...

- thermal relic $\leftrightarrow$ was in thermal equilibrium with SM bath
- relic abundance from cosmic expansion and particle properties

$$\frac{dn_\chi}{dt} + 3Hn_\chi = -\langle\sigma v\rangle_{\chi\chi\rightarrow\text{SM}} \left(n_\chi^2 - n_\chi^{\text{eq}2}\right)$$



$$\Omega_\chi \propto \frac{1}{\langle\sigma v\rangle_{\text{fo}}}, \quad \Omega_{\text{DM}} h^2 = 0.12 \quad \Rightarrow \quad \langle\sigma v\rangle_{\text{fo}} \sim 2 \times 10^{-26} \text{ cm}^3/\text{s}$$

$\Rightarrow$ general framework, simplest cosmology, useful prediction



Sub-GeV thermal relic dark matter?

- WIMPs traditionally searched for at the EW scale
- cosmologically viable down to $m_{\text{DM}} \gtrsim T_{\text{BBN}} \sim \text{few MeV}$

why now?

- Sub-GeV DMDD gathering speed [snwm'2203.08297]
- Belle-II 50 ab^{-1}
- medium energy γ -ray telescope proposals [snwm'2203.07360]

→ lots of uncharted territory being probed soon



Light thermal Dark Matter

Issue 1: needs a new mediator?

- “WIMP miracle”

$$\frac{\Omega_{\text{DM}} h^2}{0.12} \sim \frac{\text{few} \times 10^{-9} \text{ GeV}^{-2}}{\langle \sigma v \rangle} \sim \frac{m_{\text{EW}}^2 G_F^2}{\langle \sigma v \rangle}$$

- sub-GeV DM

$$\langle \sigma v \rangle \sim \frac{m_\chi^2 g^4}{M^4}, \quad m_\chi \sim 100 \text{ MeV} \Rightarrow \begin{cases} 100 \text{ GeV mediator, } g = 1 \\ 100 \text{ MeV mediator, } g = 10^{-3} \end{cases}$$

⇒ need new light mediator!



Light thermal Dark Matter

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⇒ need new light mediator!

- conclusion in principle relaxed in SIMP scenarios [Hochberg+’1402.5143], [Kuflik+’1512.04545]
 - everyone still introduces light mediators (eg. [Hochberg+’1512.07917], [Choi+’1707.01434], [Hochberg+’1806.10139])



Possible light ($\lesssim$ GeV) mediators

requirements:

- need to couple to light SM dof
- need to couple to neutral DM

popular options:

- dark photon $U(1)_D$, kinetically mixed with $U(1)_Y$
- $U(1)_{L_\mu - L_\tau}$ Z'
- scalar singlet, $\phi(H^\dagger H)$
- purely phenomenological, $\phi \bar{f} f \Rightarrow \frac{1}{M} \phi_{\text{med}} H \bar{f}_L f_R$

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this talk:

light mediator $\in H_2$, second Higgs doublet

[PhysRevLett.129.091803]

The two-Higgs-Doublet model

Scalar potential

- add a second scalar doublet to the SM

$$H_1 = \left(\frac{1}{\sqrt{2}}(v + \phi_1^0 + iG^0) \right), \quad H_2 = \left(\frac{1}{\sqrt{2}}(\phi_2^0 + iA) \right)$$

- physical states in alignment limit

$$h_{\text{SM}} \simeq \phi_1^0, \quad H_{\text{new}} \simeq \phi_2^0, \quad A, \quad H^\pm$$

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$$\begin{aligned} V(H_1, H_2, S) = & \mu_1^2 H_1^\dagger H_1 + \mu_2^2 H_2^\dagger H_2 - \{ \mu_{12}^2 H_1^\dagger H_2 + \text{h.c.} \} \\ & + \frac{\lambda_1}{2} (H_1^\dagger H_1)^2 + \frac{\lambda_2}{2} (H_2^\dagger H_2)^2 + \lambda_3 (H_1^\dagger H_1)(H_2^\dagger H_2) + \lambda_4 (H_1^\dagger H_2)(H_2^\dagger H_1) \\ & + \left\{ \frac{\lambda_5}{2} (H_1^\dagger H_2)^2 + \text{h.c.} \right\} + \left\{ [\lambda_6 (H_1^\dagger H_1) + \lambda_7 (H_2^\dagger H_2)] H_1^\dagger H_2 + \text{h.c.} \right\} \end{aligned}$$



Light scalars in the 2HDM

- scalar masses in alignment limit:

$$m_h^2 = \lambda_1 v^2,$$

$$m_H^2 = \mu_{22}^2 + \frac{v^2}{2}(\lambda_3 + \lambda_4 + \lambda_5),$$

→ may be small

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$$m_A^2 = m_H^2 - v^2 \lambda_5, \quad \rightarrow \text{may be split}$$

$$m_{H^\pm}^2 = m_H^2 - v^2 \frac{(\lambda_4 + \lambda_5)}{2} \quad \rightarrow \text{may be split}$$

- choose $m_H \ll m_A^2, m_{H^\pm}^2$, and for simplicity $m_A^2 \sim m_{H^\pm}^2$
- perturbativity: $|\lambda| < \sqrt{4\pi} \Rightarrow m_A, m_{H^\pm} \lesssim 460 \text{ GeV}$



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we can have a sub-GeV scalar $H \in 2\text{HDM}$

see [2003.03386]



Electroweak precision observables

... is there a hint already?

- mass splittings between members of an electroweak multiplet contribute to EW oblique parameters

$$T = \frac{1}{16\pi s_W^2 M_W^2} (\mathcal{F}(m_{H^\pm}^2, m_H^2) + \mathcal{F}(m_{H^\pm}^2, m_A^2) - \mathcal{F}(m_H^2, m_A^2))$$

$$\text{with } \mathcal{F}(m_1^2, m_2^2) \equiv \frac{1}{2} (m_1^2 + m_2^2) - \frac{m_1^2 m_2^2}{m_1^2 - m_2^2} \ln \left(\frac{m_1^2}{m_2^2} \right)$$

- $m_{A,H^\pm} \lesssim 250 \text{ GeV}$ easy; if larger need $m_A^2 \sim m_{H^\pm}^2$



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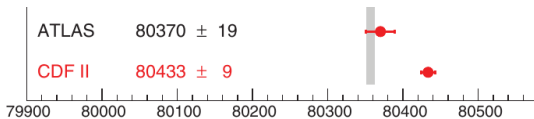
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→ CDF II M_W indications for $T > 0$?!



W boson mass (MeV/c²)

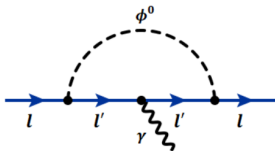
[CDF'10.1126/science.abk1781]



Muon g-2

... talking about anomalies.

- muon anomalous magnetic moment: $\Delta a_\mu = 251 \pm 59 \times 10^{-11} \rightarrow "4.2\sigma"$
 - $a_\mu^{\text{the}} = 116591810(43) \times 10^{-11}$ [Aoyama+ '2006.04822]
 - $a_\mu^{\text{exp}} = 116592061(41) \times 10^{-11}$ [FNAL'2104.03281]



- light scalar induced loop contributes positively
 $\rightarrow$ indicates mass splitting $m_H \ll m_A$?!

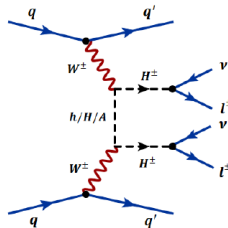
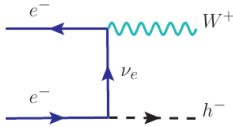
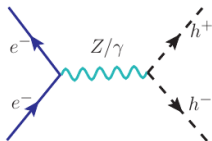
see [2003.03386]



New Scalars at Colliders

direct constraints on the mass spectrum

- existing constraints
 - $m_A > m_Z - m_H \sim 90 \text{ GeV}$ to forbid $Z \rightarrow HA$
 - charged scalar production: $m_{H^\pm} \gtrsim 110 \text{ GeV}$ from LEP $W \rightarrow \nu l$ universality
 - LHC constraints evaded for substantial $\text{Br}_{\nu\tau}$
- signature processes
 - $pp \rightarrow H^\pm H^\pm jj \rightarrow l_\alpha^\pm l_\beta^\pm jj + \cancel{E}_T$



[1907.09498][2003.03386] see also HL-LHC [Iguro+'2208.05487]



SM Higgs properties

- alignment limit: h mostly SM-like
- $h \rightarrow HH \rightarrow l^+l^-l^+l^-$ / invisible

$$V \supset v h H^2 \frac{1}{2} (\lambda_3 + \lambda_4 + \lambda_5) \quad \rightarrow \lambda_3 \simeq -(\lambda_4 + \lambda_5) \propto m_{H^\pm}^2 / v^2$$

- $h \rightarrow \gamma\gamma$

$$V \supset \lambda_3 v h H^+ H^-$$

negatively interferes with t -loop, predicts $R_{\gamma\gamma} < 1$; LHC data prefer

$$R_{\gamma\gamma} \gtrsim 1$$

[Okawa, Omura'2011.04788]

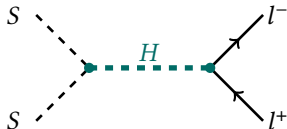
H enables light thermal DM

- coupling to light SM fermions $\rightarrow$ leptons for convenience

$$-\mathcal{L}_Y \supset \widetilde{Y}_l \bar{\psi}_L H_1 \psi_R + Y_l \bar{\psi}_L H_2 \psi_R + \text{h.c.}$$

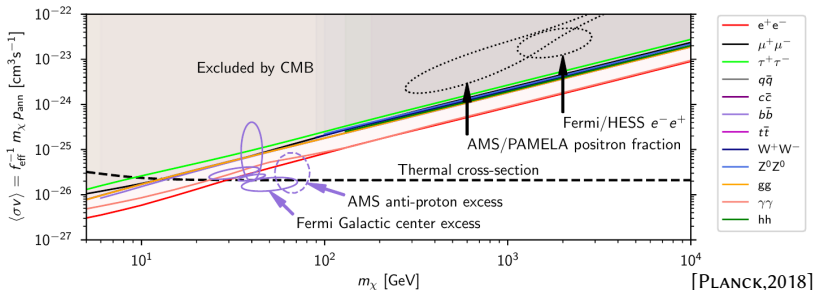
- in alignment limit: $\widetilde{Y}_l = \text{diag}(m_e, m_\mu, m_\tau)/v$
- $Y_l \rightarrow$ mediator coupling, DM phenomenology, flavour violation
- simplest DM candidate: real scalar S

$$-\mathcal{L}_S \supset \frac{\mu_S^2}{2} S^2 + \frac{\lambda_S}{4!} S^4 + \frac{\kappa_1}{2} S^2 (H_1^\dagger H_1) + \frac{\kappa_2}{2} S^2 (H_2^\dagger H_2) + \left\{ \frac{\kappa_{12}}{2} S^2 (H_1^\dagger H_2) + \text{h.c.} \right\}$$



Light thermal Dark Matter

Issue 2: annihilation constraints



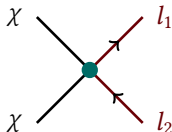
- WIMPs with $m_{\text{WIMP}} \lesssim 10 \text{ GeV}$ require

$$\langle\sigma v\rangle_{\text{today}} \ll \langle\sigma v\rangle_{\text{freeze-out}}$$



Forbidden Dark Matter

[Griest, Seckel'91][DAgnolo, Ruderman'1505.07107]



- kinematically forbidden annihilation, $2m_\chi < m_{l_1} + m_{l_2}$

$$\langle\sigma v\rangle_{\chi\chi\rightarrow ll} = \langle\sigma v\rangle_{ll\rightarrow\chi\chi} e^{-2\Delta(m_\chi/T)}$$

- suppressed by mass splitting

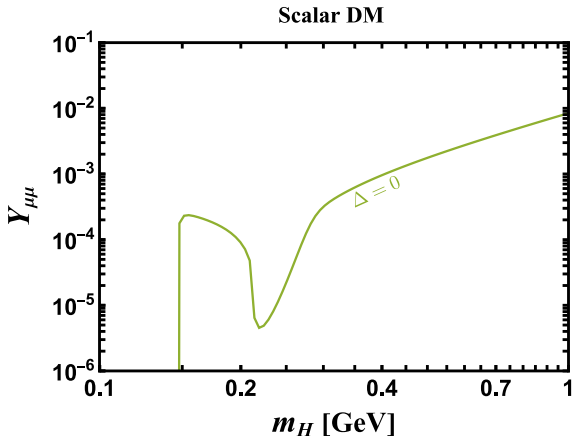
$$\Delta = (m_{l_1} + m_{l_2} - 2m_\chi)/2m_\chi$$

- $\langle\sigma v\rangle_{\chi\chi\rightarrow ll}$ zero at late times $T \rightarrow 0$

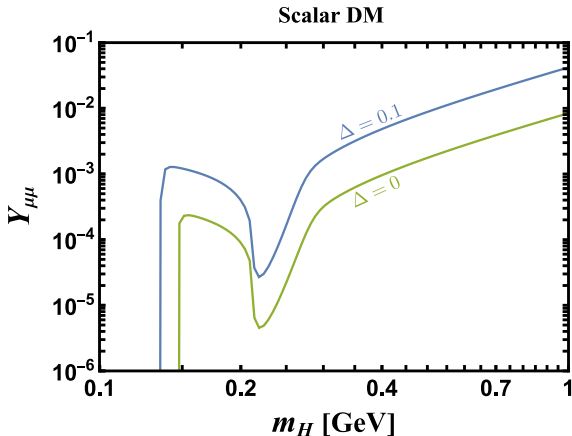
→ spoiler: $\langle\sigma v\rangle_{\chi\chi\rightarrow\gamma\gamma}$ allowed!



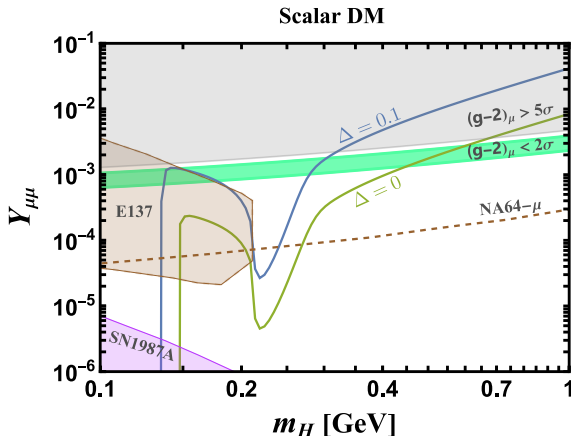
Relic abundance – $\mu\mu$



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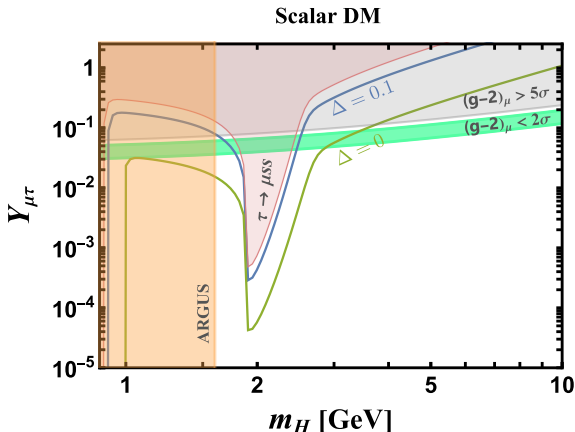
Relic abundance results - $\mu\mu$ $\kappa_{ij} = 10^{-3}$ fixed



- $(g - 2)_\mu$ [FNAL'2104.03281][Jana+'2003.03386]
- E137 beam dump [Bjorken+'88][Batell+'1712.10022]
- SN energy loss [Croon+'2006.13942]



Relic abundance results - $\mu\tau$ $\kappa_{ij} = 10^{-3}$ fixed



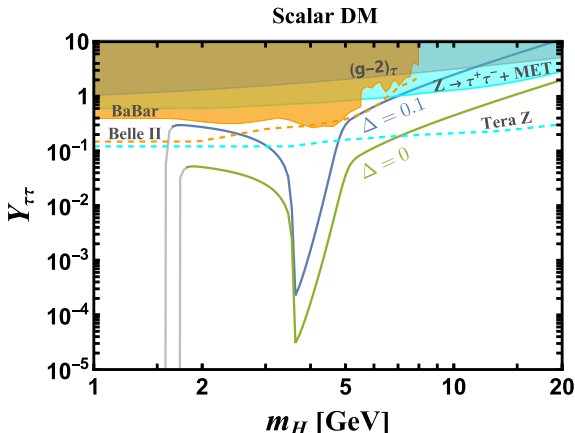
- $(g - 2)_\mu$ [FNAL'2104.03281][Jana+'2003.03386]
- $\tau \rightarrow \mu H$ LFV 2-body decay [ARGUS'95]
- $\tau \rightarrow \mu SS$ adds to expt. $\Gamma(\tau \rightarrow \mu \bar{\nu}_\mu \nu_\tau)$

$$\Rightarrow m_H > m_\tau - m_\mu$$

$$\Rightarrow m_{\text{DM}} > (m_\tau - m_\mu)/2$$



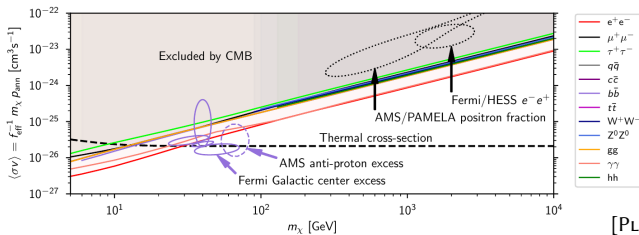
Relic abundance results - $\tau\tau$ $\kappa_{ij} = 10^{-3}$ fixed



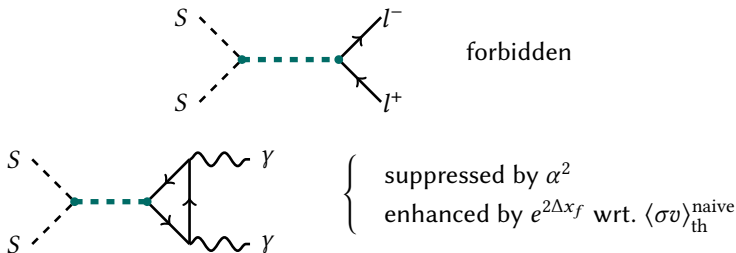
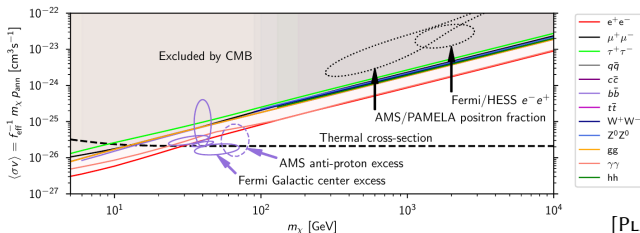
- $e^+e^- \rightarrow \gamma H$, with $H \rightarrow$ dark
[BaBar'1702.03327][Dolan+'1709.00009][DAgnolo+'2012.11766]
- $Z \rightarrow \bar{\tau}\tau H$ adds to expt. $\text{Br}(Z \rightarrow \bar{\tau}\tau)$ [Chen+'1807.03790]



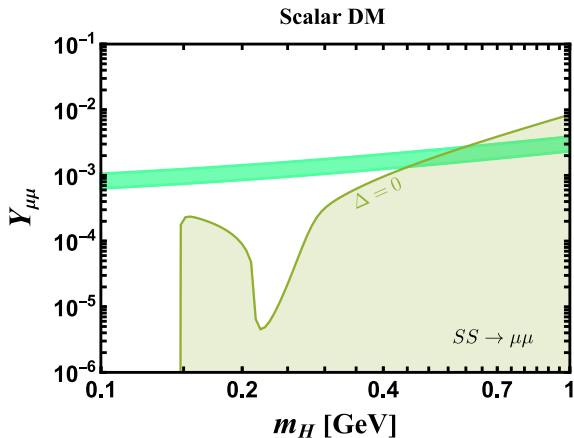
Radiative annihilation probes forbidden DM



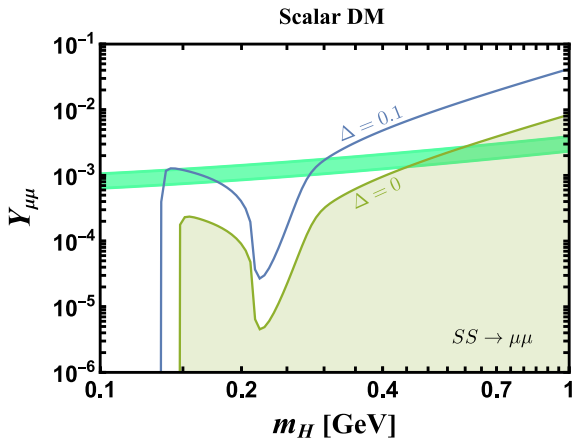
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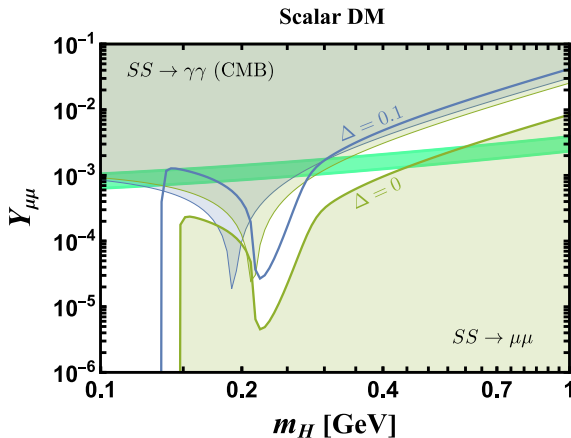
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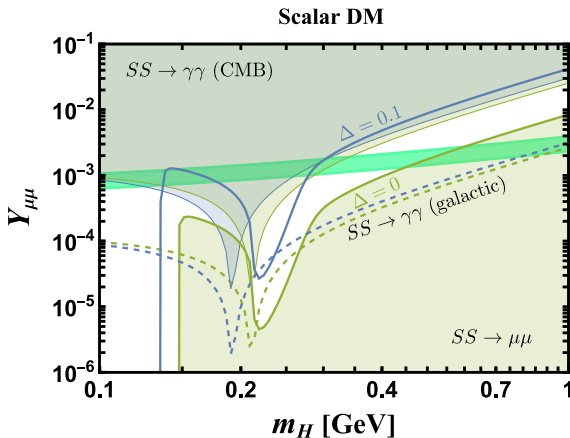
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Radiative annihilation probes forbidden DM



Radiative annihilation probes forbidden DM



- 2 oom sensitivity boost from proposed telescopes [Bartels+'1703.02546]
- γ -ray line signal close to m_μ, m_τ as smoking-gun signal

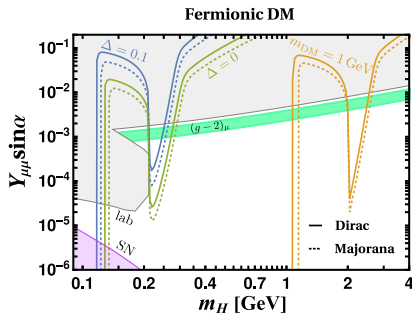


Light 2HDM portal - Fermion DM

need scalar singlet S to couple to DM

$$-\mathcal{L} \supset Y_l \bar{\psi}_L H_2 \psi_R + Y_\chi S \bar{\chi} \chi + \mu_{12} S (H_1^\dagger H_2) + \frac{\kappa_{12}}{2} S^2 (H_1^\dagger H_2) + h.c..$$

$$\begin{pmatrix} H \\ H' \end{pmatrix} = \begin{pmatrix} \cos \alpha & \sin \alpha \\ -\sin \alpha & \cos \alpha \end{pmatrix} \begin{pmatrix} \omega \\ \phi_2^0 \end{pmatrix}$$



$$Y_\chi = 0.1$$

- annihilation p -wave $\rightarrow$ DMID suppressed



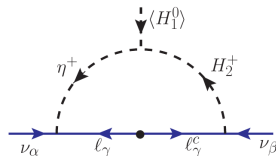
Neutrino masses?

purely scalar model for DM and M_ν : Zee model

- introduce a charged scalar singlet $\eta^+ \sim (1, 1, 1)$

$$-\mathcal{L}_Y \supset f_{ij} L_i \epsilon L_j \eta^+ + \text{h.c.}$$

$$-V \supset \mu H_1 \epsilon H_2 \eta^- + \text{h.c.}$$



- leads to neutrino masses

$$M_\nu \propto \left(f m_E Y_l - Y_l^T m_E f \right)$$

- DM constraints
 - non-forbidden channels must have negligible coupling $\rightarrow Y_l$ texture
- LFV
 - $\mu \rightarrow e\gamma$, $\tau \rightarrow e\gamma$, and $\tau \rightarrow \mu\gamma$ at one-loop

$\Rightarrow \mu\tau$ coupled scenario works out! predicts $\mu \rightarrow e\gamma$ at reach of MEG-II



Light 2HDM Portal to general Dark Sectors

- 2HDM provides light scalar mediator
 - loads of accessible phenomenology!
 - first hints in $(g-2)_\mu$, T -parameter?
- DMID problem of light thermal DM circumvented
 - minimal realisation of forbidden DM
 - radiative annihilation $\rightarrow$ positive identification
- neutrino masses & light thermal DM, purely scalar
- ongoing
 - scalar sector structure: small m_H tuned or special?
 - other dark sectors (p -wave, SIMP, ...)
 - quarks?

looking forward to your comments!

Johannes Herms

herms@mpi-hd.mpg.de
Max-Planck-Institut für Kernphysik

Sudip Jana

sudip.jana@mpi-hd.mpg.de
Max-Planck-Institut für Kernphysik

Vishnu P.K.

vipadma@okstate.edu
Oklahoma State University

Shaikh Saad

shaikh.saad@unibas.ch
University of Basel



Neutrino masses – details

we provide a benchmark

$$M_\nu = a_0 \left(f m_E Y_l - Y_l^T m_E f \right)$$

$$a_0 = \frac{\sin 2\omega}{16\pi^2} \ln \left(\frac{m_{h^+}^2}{m_{H^+}^2} \right); \quad \sin 2\omega = \frac{\sqrt{2}v\mu}{m_{h^+}^2 - m_{H^+}^2},$$

$$Y_l = 10^{-4} \begin{pmatrix} 0 & 0 & 3.494 \times 10^{-4} \\ 0 & 0 & 5 \\ -10^{-3} & -0.382 & 0.542 \end{pmatrix},$$

$$a_0 \cdot f = 10^{-7} \begin{pmatrix} 0 & 2.135 & 0 \\ -2.135 & 0 & 2.266 \\ 0 & -2.266 & 0 \end{pmatrix}.$$

Neutrino observables associated with this fit yield,

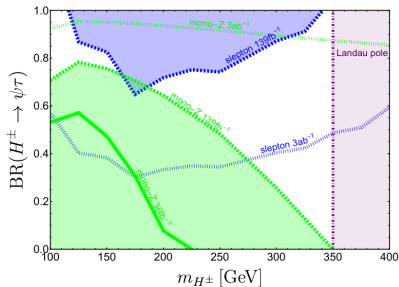
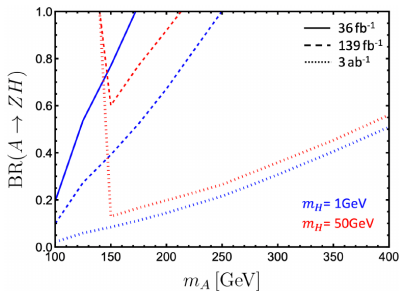
$$\Delta m_{21}^2 = 7.486 \times 10^{-5} eV^2, \quad \Delta m_{31}^2 = 2.511 \times 10^{-3} eV^2,$$

$$\theta_{12} = 34.551^\circ, \quad \theta_{23} = 47.830^\circ, \quad \theta_{13} = 8.545^\circ.$$



LHC prospects

IDM [Iguro,Okawa,Omura'2208.05487]



- $pp \rightarrow HA \rightarrow HHZ$ results in mono-Z $\Rightarrow$ constraint on $\text{BR}(A \rightarrow ZH)$

