Non-Standard light Yukawas and Higgs-Portal DM

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Particle Phenomenology from the Early Universe to High-Energy Colliders
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With Fady Bishara, Patipan Uttayarat, Jure Zupan – work in progress

(Selected) problems of the SM

- Dark Matter?
- Flavor structure? (14 of 19 parameters in the flavor sector!)
- More specific questions:
  - Are the Higgs boson interactions as in the SM?
  - Can modified light Yukawa couplings have pheno implications?
  - In turn, can we constrain the light Yukawas?

SM EFT

- What we have learned from LHC:
  - There is a “SM-like” Higgs particle
  - Other new particles are most likely very heavy ($M \gg v$)
- All SM particles are then light in comparison
- Construct all operators using SM fields $\Rightarrow$ “SM-EFT”
  [See, e.g., Buchmüller et al. 1986, Grzadkowski et al. 2010]
- $SU(2) \times U(1)$ gauge invariance explicit

$$\mathcal{L}^{\text{eff}} = \mathcal{L}^{\text{SM}} + \mathcal{L}^{\text{dim.6}} + \dots$$

- Higher orders suppressed by powers of v/M

How can we change the Higgs couplings?

Operator	Mass term	Higgs-fermion coupling
$y_t(\bar{Q}_L t_R H^c) + \text{h.c.}$	$m_t = \frac{y_t v}{\sqrt{2}}$	$\frac{y_t}{\sqrt{2}}$
$\frac{H^\dagger H}{\Lambda^2}(\bar{Q}_L t_R H^c) + \text{h.c.}$	$\delta m_t \propto \frac{(v/\sqrt{2})^3}{\Lambda^2}$	$\delta y_t \propto 3\frac{(v/\sqrt{2})^2}{\Lambda^2}$

- Mass and Yukawa term become independent
- Relative complexe phase $\rightarrow$ CP violation
- More generally, we write:

$$\mathcal{L}'_Y = -\frac{y_f}{\sqrt{2}}(\kappa_f + i\tilde{\kappa}_f)\,\bar{f}_L f_R h + \text{h.c.}$$

Modified Yukawas – The "GL model"

- In many popular models modification of light-quark Yukawas are small
- Higgs-dependent Yukawa couplings [Giudice & Lebedev, arxiv:0804.1753]

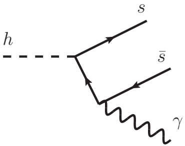
$$Y_{ij}^{u,d}(H) = c_{ij}^{u,d}\left(\frac{H^\dagger H}{M^2}\right)^{n_{ij}^{u,d}}, \quad y_{ij}^{u,d} = (2n_{ij}^{u,d}+1)(y_{ij}^{u,d})_{\rm SM}$$

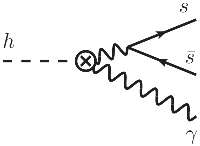
- After EWSB, expansion in $\epsilon \equiv v^2/M^2 \approx 1/60$
- Original GL model ruled out by $\mathrm{Br}(h \to b\bar{b})$
- Use modification with two Higgs doublets

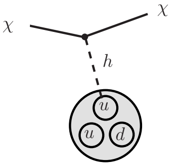
	κ_t	$\kappa_{c(u)}/\kappa_t$	κ_b	$\kappa_{s(d)}/\kappa_b$
GL	$1+\mathcal{O}(\epsilon^2)$	$\simeq 3\,(7)$	$\simeq 3$	$\simeq 5/3\,(7/3)$
GL2	$\cos\alpha/\sin\beta$	$\simeq 3\,(7)$	$\sin\alpha/\cos\beta$	$\simeq 3\,(5)$

(How) Can we probe the light-quark Yukawas?

- Processes with off-shell Higgs and external SM particles difficult:
  - Scalar Higgs current competes with neutral currents induced by g, γ, Z
- Two options:
  - On-shell Higgs decays (e.g. $h \to \phi\gamma$) [Kagan et al., arxiv:1406.1722]
  - New probes: DM







Higgs-Portal Dark Matter

- Consider simplest case first: Scalar Higgs portal
- Renormalizable, gauge invariant interaction

$$\mathcal{L}_\chi = g_\chi \chi^\dagger \chi H^\dagger H$$

- After EWSB obtain interaction with physical Higgs field:

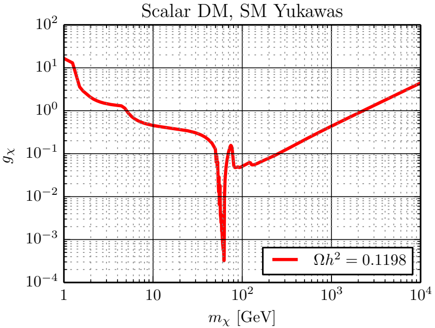
$$H^\dagger H \chi^\dagger \chi \quad \to \quad \frac{1}{2}\left(v_W^2 + 2 v_W h + h^2\right)\chi^\dagger \chi$$

Plan

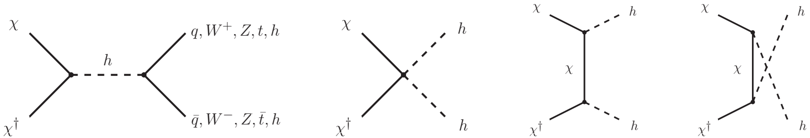
- Assume that DM provides the measured relic density
- We will consider the constraints resulting from
  - indirect searches
  - direct detection experiments
  - modified Higgs decay width
- We will discuss the implications of modified light-quark Yukawas in each case

Relic density – SM Yukawas

- Given m_χ, choose g_χ to reproduce PLANCK measurement of Ωh^2

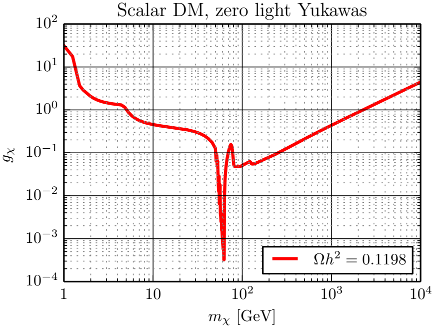


- $\rho_0 \propto 1/\langle \sigma v_{\rm rel} \rangle$ (thermally averaged cross section)

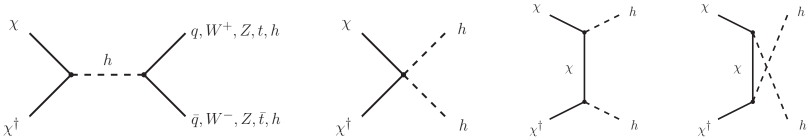


Relic density – vanishing light Yukawas

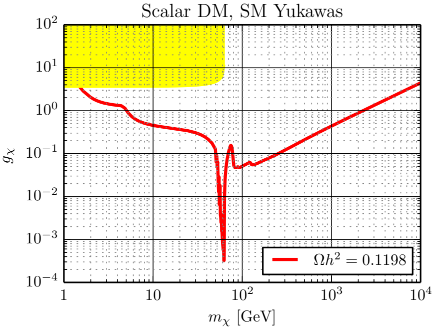
- Vanishing of light-quark Yukawas has only small effect



- Annihilation into light jets dominated by gluon final state (via loop)

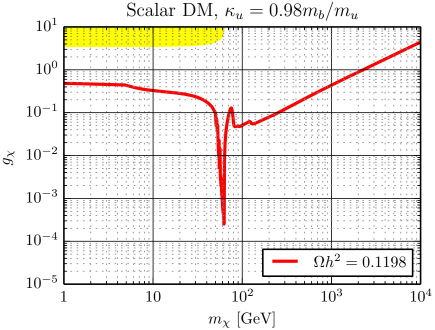


Constraints from the total Higgs width



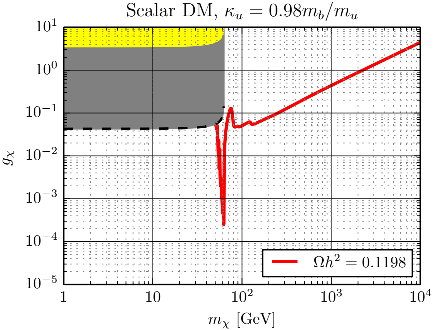
- In fact, for $g_\chi \gtrsim 2$ we get $\Gamma_h^{\text{tot}} \sim M_h$
- Signals nonperturbativity

Relic density – maximal up-quark Yukawa



- Naive fit to Higgs data shows that $y_u, y_d, y_s \sim y_b$ still possible
  [Kagan et al., arxiv:1406.1722]
- For instance, increasing y_u can compensate for smaller g_χ

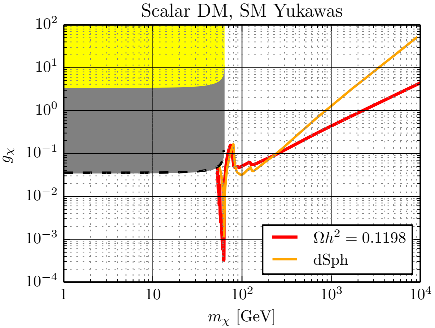
Constraints from invisible Higgs decays



- Higgs-portal interactions lead to Higgs decays into invisible final states
- Current best limits from Zh production:
  $\text{Br}_{\text{inv}} < 0.58$ [CMS, arxiv:1404.1344]; $\text{Br}_{\text{inv}} < 0.75$ [ATLAS, arxiv:1402.3244]

$$\text{Br}(h \to \chi^\dagger \chi) = \frac{\Gamma(h \to \chi^\dagger \chi)}{\Gamma(h \to \chi^\dagger \chi) + \Gamma_h^{\text{tot}} \times \left[1 + \sum_q (\kappa_q^2 - 1)\text{Br}_{\text{SM}}(h \to q\bar{q})\right]} .$$

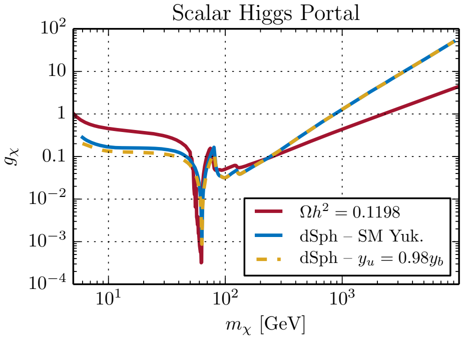
Indirect detection – SM Yukawas



- Annihilation in regions with high DM density can lead to observable signal
- Example: Fermi-LAT bounds from dwarf spheroidals
  [Ackermann et al., arxiv:1503.02641]

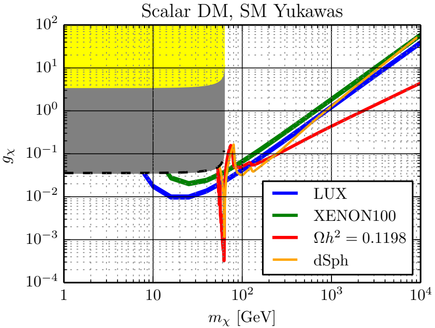
$$\frac{d\Phi}{dE_\gamma d\Omega} = \frac{1}{2}\frac{1}{4\pi}\frac{\rho_\odot}{m_\chi^2} J \left[\sum_f \langle \sigma v \rangle_f \frac{dN_\gamma^f}{dE}\right]$$

Indirect detection – SM vs. maximal y_u

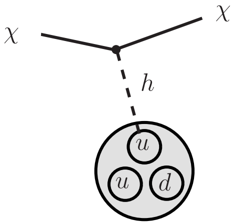


- Dependence on modified Yukawas is tiny
- Mainly in region excluded by Higgs width constraints

Direct detection – SM Yukawas

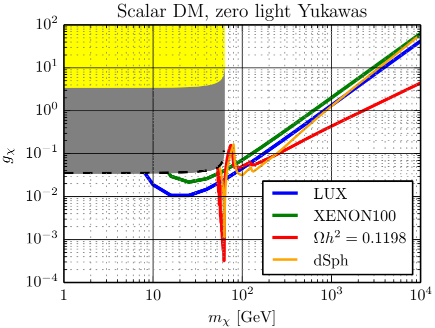


- Exclusion limits from
  - XENON100 [Aprile et al., arxiv:1207.5988],
  - LUX [Akerib et al., arxiv:1310.8214]

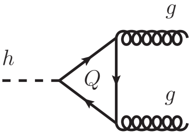


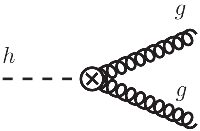
$$\frac{d\sigma}{dE_R} = \frac{m_A}{\mu_{\chi A}^2 v_{\rm rel}^2} \frac{\overline{|\mathcal{M}|^2}}{32\pi s} \,,$$

Direct detection – zero light-quark Yukawas

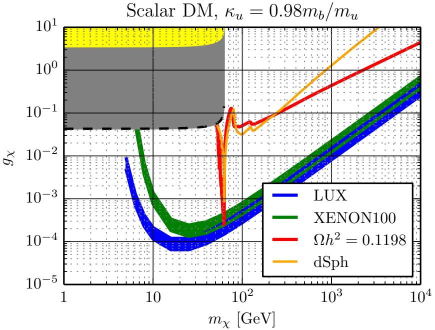


- Scattering rate is dominated by effective gluon term
- $\Rightarrow$ for zero light Yukawas only few % change



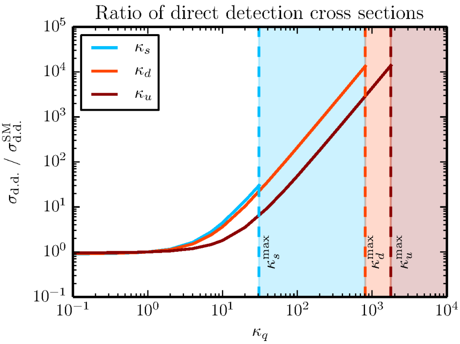


Direct detection – maximal up-quark Yukawa



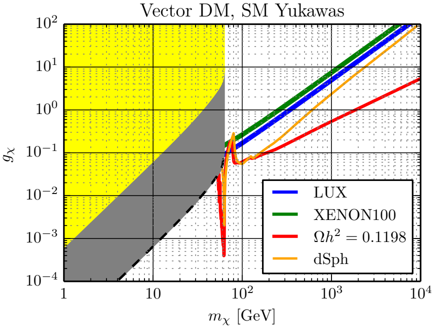
- However, enhanced Yukawas can have large effect
- New handle on light Yukawas?

Dependence of direct searches on light Yukawas



- Vary light-quark Yukawas within currently allowed region
- $\mathcal{O}(10^4)$ enhancements possible in principle
- Even $\mathcal{O}(10)$ modifications increase scattering cross section by large factor

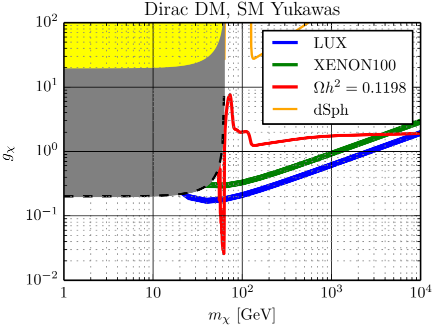
Combined constraints – Vector Higgs-portal DM



- Somewhat smaller DM masses still allowed (assuming SM Yukawas)
- Note: Simple vector Higgs portal cannot be full theory

$$\mathcal{L}_\chi = \frac{g_\chi}{2} \chi^\mu \chi_\mu H^\dagger H$$

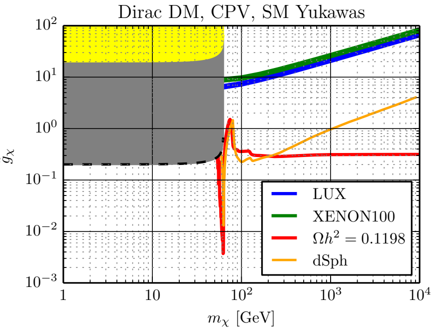
Combined constraints – Dirac Higgs-portal DM



- Note: Dimension-five Lagrangian
- Excluded (apart from Higgs resonance region)

$$\mathcal{L}_\chi = \frac{g_\chi}{\Lambda} \bar{\chi}\chi H^\dagger H$$

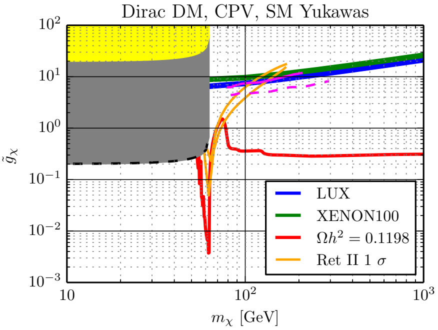
Combined constraints – CPV Dirac DM



- Purely CPV couplings (academic case?)
- Scattering rate is velocity suppressed
- For larger masses not excluded

$$\mathcal{L}_\chi = \frac{\tilde{g}_\chi}{\Lambda} \bar{\chi} i \gamma_5 \chi H^\dagger H$$

A bound on the light Yukawas?



- Now, let's be optimistic! – Assume we have found DM
- Shown is a (very) potential 1-σ signal region from Reticulum 2 dwarf galaxy
  [Geringer-Sameth et al., arxiv:1503.02320]
- In magenta, 5-σ discovery limits for 14 (100) TeV collider
  [Craig et al., arxiv:1412.0258]

Summary

- Currently we have only little knowledge about light-quark Yukawas
- We investigated effect of modified Yukawas on Higgs-portal DM pheno
- Direct detection could give a handle on light-quark Yukawas

Appendix

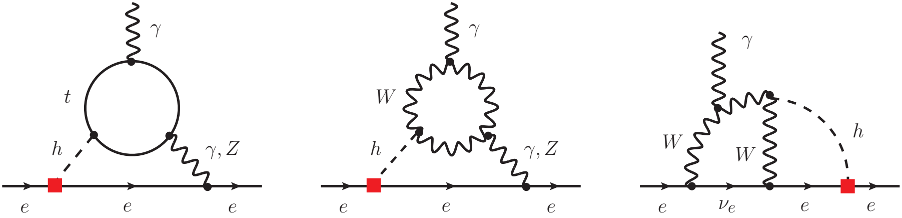
What do we know about the electron Yukawa?

With Wolfgang Altmannshofer, Martin Schmaltz – arXiv:1503.04830

It's small and real! (In the SM.)

$$y_e^{\mathrm{SM}} = \sqrt{2}\frac{m_e}{v} \simeq 2.9 \times 10^{-6}$$

Indirect bounds: Imaginary part – electron EDM

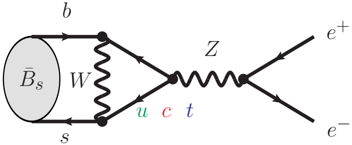


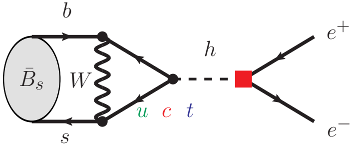
- . . . + 117 more two-loop diagrams
- Complete analytic result [Altmannshofer, Brod, Schmaltz, arxiv:1503.04830]
- $|d_e/e| < 8.7 \times 10^{-29}\,\text{cm}$ (90% CL) [ACME 2013]
- . . . leads to $|\tilde{\kappa}_e| < 0.017$

Indirect bounds: Real part – $(g-2)_e$

- Usually, the measurement of $a_e \equiv (g-2)_e/2$ is used to extract α
- Using independent α measurement, can make a prediction for a_e
  [cf. Giudice et al., arXiv:1208.6583]
- With
  - $\alpha = 1/137.035999037(91)$ [Bouchendira et al., arXiv:1012.3627]
  - $a_e = 11596521807.3(2.8) \times 10^{-13}$ [Gabrielse et al. 2011]
- ... we find $|\kappa_e| \lesssim 3000$
- Bound expected to improve by a factor of 10 in the next few years

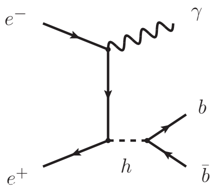
Indirect bounds: Real part – rare B decays

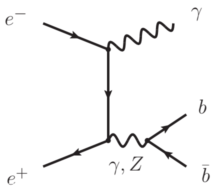




- SM prediction [Bobeth et al., arXiv:1311.0903]
  - $\text{Br}(B_s \to e^+ e^-)_{\text{SM}} = (8.54 \pm 0.55) \times 10^{-14}$
  - $\text{Br}(B_d \to e^+ e^-)_{\text{SM}} = (2.48 \pm 0.21) \times 10^{-15}$
- Current bounds [CDF 2009]
  - $\text{Br}(B_s \to e^+ e^-) < 2.8 \times 10^{-7}$
  - $\text{Br}(B_d \to e^+ e^-) < 8.3 \times 10^{-8}$
- . . . leads to $|\kappa_e| = \mathcal{O}(10^6)$

Collider bounds: LEP II





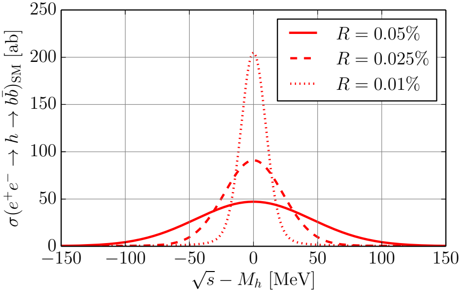
- LEP / LEP II did not run on the Higgs resonance
- They collected ~ 500/pb per experiment between $\sqrt{s} = 189 \ldots 207$ GeV
- A bound could be obtained via "radiative return" to the Z pole
- Requiring $N_{\text{r.r.}}/\sqrt{N_{\text{bkg.}}} = 1$ we find $\sqrt{\kappa_e^2 + \tilde{\kappa}_e^2} \lesssim 2000$
- A dataset at $\sqrt{s} = 130$ GeV leads a similar bound

Collider bounds: CMS

$$\mathrm{Br}(h \to e^+e^-) = \frac{\left(\kappa_e^2 + \tilde{\kappa}_e^2\right)\mathrm{Br}(h \to e^+e^-)_{\mathrm{SM}}}{1 + \left(\kappa_e^2 + \tilde{\kappa}_e^2 - 1\right)\mathrm{Br}(h \to e^+e^-)_{\mathrm{SM}}}$$

- CMS limit $\mathrm{Br}(h \to e^+e^-) < 0.0019$ [CMS, arxiv:1410.6679] leads to $\sqrt{\kappa_e^2 + \tilde{\kappa}_e^2} < 611$
- Estimated future sensitivities at hadron colliders:
  - 14 TeV LHC with 3000/fb: $\sqrt{\kappa_e^2 + \tilde{\kappa}_e^2} \sim 150$
  - 100 TeV collider with 3000/fb: $\sqrt{\kappa_e^2 + \tilde{\kappa}_e^2} \sim 75$

Collider bounds: Future e^+e^- machines



- A future e^+e^- machine...
  - collecting 100 fb^{-1} on the Higgs resonance
  - assuming 0.05% beam-energy spread
- ...would be sensitive to $\sqrt{\kappa_e^2 + \tilde{\kappa}_e^2} \sim 15$