Dark Sectors and Higgs Portals at Colliders

Valentin V. Khoze

IPPP Durham University

22 June 2015

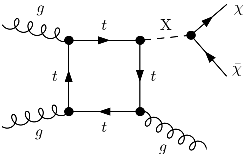
Necessity of New Physics beyond the Standard Model

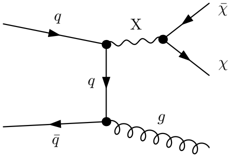
The LHC Higgs discovery is the crowning achievement of the SM. At a more fundamental level it leaves some fundamental questions unanswered:

- SM accommodates $v = 246\ \mathrm{GeV}$ and $m_h \simeq 125\ \mathrm{GeV}$ as input parameters, but does not explain their origin and why $\ll M_{\mathrm{Pl}}$
- The SM Higgs potential is unstable at $\mu_{\mathrm{RG}} \gtrsim 10^{11}$ GeV
- **There is no Dark Matter in the SM**
- Generation of the matter-anti-matter asymmetry of the Universe is impossible within the SM
- Particle physics implementation of Cosmological Inflation? Strong CP? Neutrino masses?

I. Dark Sectors at Colliders: Simplified Models

- Dark Sector should contain Dark Matter (which is cosmologically stable) plus possibly other dark particles.
- At colliders dark sector particles produced in collisions would manifest themselves as missing transverse momentum (aka MET).
- Being stable on collider scales – is much less restrictive than the cosmological DM – i.e. can look for more than just DM in dark sectors.
- Use a mono-jet to recoil, i.e. concentrate first on a mono-object + MET. Later on will also consider di-jet + MET signatures.
- Dark Particles interact with the Standard Model by exchanging a *mediator* field X. Mediator particle is itself a key new physics d.o.f.
- Four basic types of mediators: vectors, axial-vectors, scalars, pseudo-scalars. Concentrate here on the *s*-channel models:





Representative Feynman diagrams

I. Dark Sectors at Colliders: Simplified Models

- At LHC energies mediators can be resolved and taken to be dynamical
- Four basic types of mediators to the dark sector associated with scalar S, pseudo-scalar P, vector Z' and axial-vector Z'' fields with interactions,

$$\mathcal{L}_{\rm scalar} \supset -\frac{1}{2}m_{\rm MED}^2 S^2 - g_{\rm DM} S\,\bar{\chi}\chi - g_{SM}^t S\,\bar{t}t - g_{SM}^b S\,\bar{b}b$$

$$\mathcal{L}_{\rm pseudo-scalar} \supset -\frac{1}{2}m_{\rm MED}^2 P^2 - g_{\rm DM} P\,\bar{\chi}\gamma^5\chi - g_{SM}^t P\,\bar{t}\gamma^5 t - g_{SM}^b P\,\bar{b}\gamma^5 b$$

$$\mathcal{L}_{\rm vector} \supset \frac{1}{2}m_{\rm MED}^2 Z'_\mu Z'^\mu - g_{\rm DM} Z'_\mu\bar{\chi}\gamma^\mu\chi - \sum_q g_{SM}^q Z'_\mu\bar{q}\gamma^\mu q$$

$$\mathcal{L}_{\rm axial} \supset \frac{1}{2}m_{\rm MED}^2 Z''_\mu Z''^\mu - g_{\rm DM} Z''_\mu\bar{\chi}\gamma^\mu\gamma^5\chi - \sum_q g_{SM}^q Z''_\mu\bar{q}\gamma^\mu\gamma^5 q$$

J. Abdallah, A. Ashkenazi, A. Boveia, *et al.*, arXiv:1409.2893

S. Malik, C. McCabe, H. Araujo, *et al.*, arXiv:1409.4075

M. R. Buckley, D. Feld and D. Goncalves, arXiv:1410.6497

P. Harris, VVK, M. Spannowsky and C. Williams, arXiv:1411.0535

I. Dark Sectors at Colliders: Simplified Models

The couplings of Scalar and Pseudo-Scalar messengers to all six flavours of SM quarks are taken to be proportional to the corresponding Higgs Yukawa couplings, y_q, in accordance with MFV.
To make our definitions look symmetric we choose to parametrise the couplings of scalar mediators to DM in a similar fashion:

$$\text{for scalar \& pseudo} - \text{scalar messengers}: \quad g_{\rm SM}^{q} \equiv g_q y_q \,, \quad g_{\rm DM} \equiv g_\chi y_\chi$$

$$\text{where} \quad y_\chi \equiv \frac{m_\chi}{v} = \frac{m_{\rm DM}}{v} \,.$$

For $g_{\rm DM}$ this parameterisation $g_{\rm DM} = g_\chi y_\chi \propto y_\chi$ is a choice made in 1411.0535 - not a requirement.
The product of the top and χ couplings to messengers,

$$g_{\rm SM}^{q} \, g_{\rm DM} \; = \; g_t g_\chi \, y_t y_\chi \; = \; g_q g_\chi \, \frac{m_t \, m_{\rm DM}}{v^2} \,,$$

and we keep the scaling g_q flavour-universal for all quarks, so $g_t = g_q$.

Mono-jet + MET topology

P. Harris, VVK, M. Spannowsky and C. Williams, arXiv:1411.0535

Our Simplified Models for Dark Particles searches at colliders are characterised by the type of the mediator plus by the following free parameters:

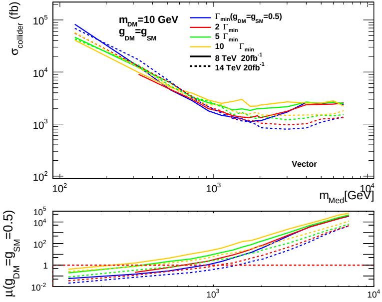
1. mediator mass $m_{\rm MED}$
2. mediator width $\Gamma_{\rm MED}$
3. dark matter mass $m_{\rm DM}$
4. effective coupling parameter $g_q \cdot g_\chi$ for scalar and pseudo-scalars; and $g_{\rm SM} \cdot g_{\rm DM}$ for axial-vector and vector mediators.

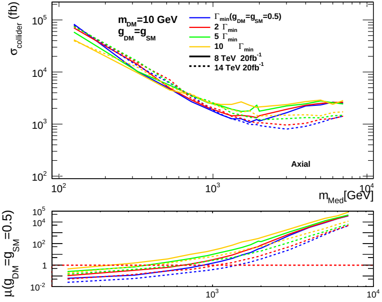
We have implemented simplified models based on these parameters into a fully flexible (and public) Monte Carlo code, MCFM. We used MCFM to generate signal events, which were processed through event and detector simulation for the 8 and 14 TeV LHC.

Mono-jet + MET topology

Limit bounds and projections for LHC cross sections at 8 and 14 TeV.

- Vector and Axial-vector mediators:





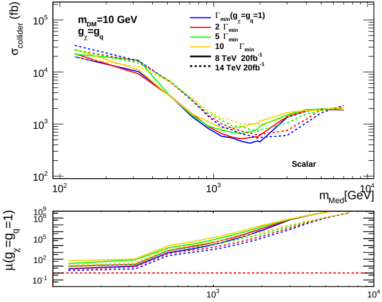
μ is the ratio of the exclusion cross section to the predicted cross section

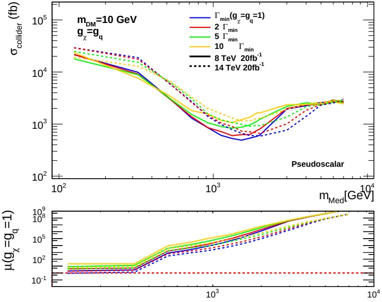
P. Harris, VVK, M. Spannowsky and C. Williams, arXiv:1411.0535

Mono-jet + MET topology

Limit bounds and projections for LHC cross sections at 8 and 14 TeV.

- Scalar and Pseudo-scalar mediators:



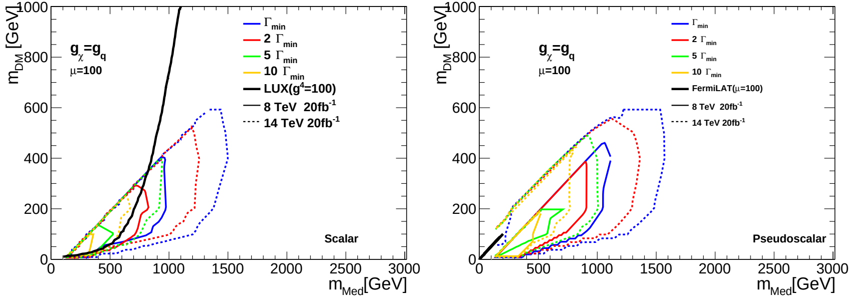


μ is the ratio of the exclusion cross section to the predicted cross section

P. Harris, VVK, M. Spannowsky and C. Williams, arXiv:1411.0535

- Scalar and Pseudo-scalar mediators [Mono-jet + MET]

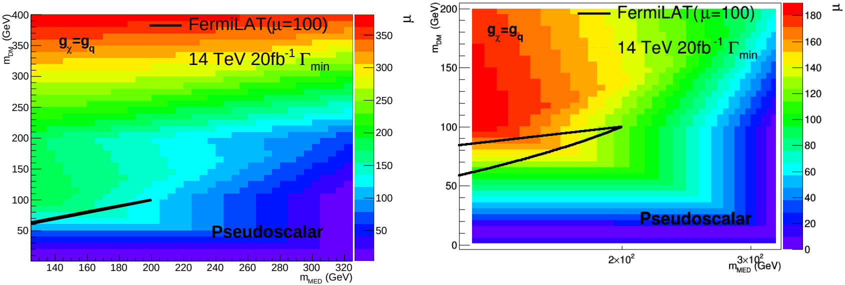
Compare the predicted value of the cross section for a given parameter set against the limit set by the LHC. We present the constrained region on the dark matter – mediator mass plane:



P. Harris, VVK, M. Spannowsky and C. Williams, arXiv:1411.0535

Signal (cross section) for scalars and pseudo-scalars was enhanced by $\mu = 100$ to have non-trivial collider limits.

1. Absorbing $\mu = 100$ is equivalent to changing $g_\chi \to 10 g_\chi$. Since we defined $g_{DM} = g_\chi m_{DM}/v$ increasing the coupling by a factor of 10 for light DM is fine, e.g. $m_{DM} \lesssim 25$ GeV , such that we remain in the perturbative regime $g_{DM} \lesssim 1$.



Plots illustrate the contours of the required μ-factor necessary to enhance the signal for pseudo-scalar messenger models to set a 90% CL at 14 TeV LHC

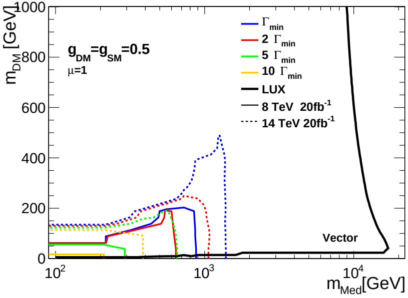
2. The question of whether a parameter point is visible at the LHC depends on the ability to separate signal processes from the background. A better background rejection boosts sensitivity independently of the signal parameterisation and the real analysis sensitivity improves substantially:

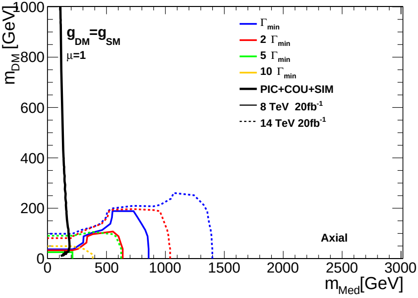
P. Harris, VVK, M. Spannowsky and C. Williams – *to appear*

I. Dark Sectors at Colliders: Simplified Models

- Vector and Axial-vector mediators [Mono-jet + MET]

Compare the predicted value of the cross section for a given parameter set against the limit set by the LHC. We present the constrained region as a function of the dark matter and mediator mass:





$\mu = 1$ for vectors and axial-vectors here.

P. Harris, VVK, M. Spannowsky and C. Williams, arXiv:1411.0535

II. Dark Sector UV Models: Higgs Portals

SM Higgs h can mix with another scalar ϕ via Higgs portal interactions

$$\mathcal{L}_{\rm int} \ni \lambda_{\rm P}\, |H(x)|^2\, \phi(x)^2 \;=\; 2\lambda_{\rm P}\, v\, \langle\phi\rangle\, h(x)\, \varphi(x) \,+\, \ldots$$

leading to two scalar mass eigenstates h_1 and h_2.

– a simple BSM framework and minimal in number of assumptions.
Within the Higgs Portal framework we can:

- generate the Higgs VEV radiatively and explain the origin of the electroweak scale (CSI models)
- stabilise the SM Higgs potential (when the 2nd scalar is heavier than the SM Higgs and/or when more singlets added with not too small portal couplings)
- new scalars ϕ can serve as *mediators to Dark Sectors* when coupled to DM particles, e.g. $g_{\rm DM}\, \bar{\chi}\phi\chi$, or they can themselves be Dark Matter.

Results in reduced Higgs couplings to SM vectors and fermions due to the Higgs mixing angle, $\cos\theta < 1$.

II. Dark Sector UV Models: Higgs Portals

There is a rich spectrum of DM candidates possible in Higgs Portal models:

1. The new scalar ϕ can act as a **mediator** to the Dark Sector when coupled to fermion (also scalar and/or vector) DM

$$h = h_1 \cos\theta + h_2 \sin\theta\,, \qquad \phi = -h_1 \sin\theta + h_2 \cos\theta\,,$$

$$\mathcal{L}_{h_1,h_2} = \left(\frac{2M_W^2}{v} W_\mu^+ W^{-\,\mu} + \frac{M_Z^2}{v} Z_\mu Z^\mu - \sum_f \frac{m_f}{v} \bar{f} f \right) \Big(h_1 \cos\theta + h_2 \sin\theta \Big)$$
$$- g_\chi \bar{\chi}\chi \Big(h_2 \cos\theta - h_1 \sin\theta \Big) - \frac{1}{2} m_{h_1}^2 h_1^2 - \frac{1}{2} m_{h_2}^2 h_2^2 - m_\chi \bar{\chi}\chi$$

II. Dark Sector UV Models: Higgs Portals

Resulting in a scalar ϕ-mediator Simplified DM Model as in Part I,

$$\mathcal{L}_\phi = \sqrt{\kappa}\left(\frac{2M_W^2}{v}W_\mu^+W^{-\mu} + \frac{M_Z^2}{v}Z_\mu Z^\mu - \sum_f \frac{m_f}{v}\bar{f}f\right)\phi - g_\chi\,\bar{\chi}\chi\phi - \frac{1}{2}m_m^2\phi^2 - m_\chi\bar{\chi}\chi$$

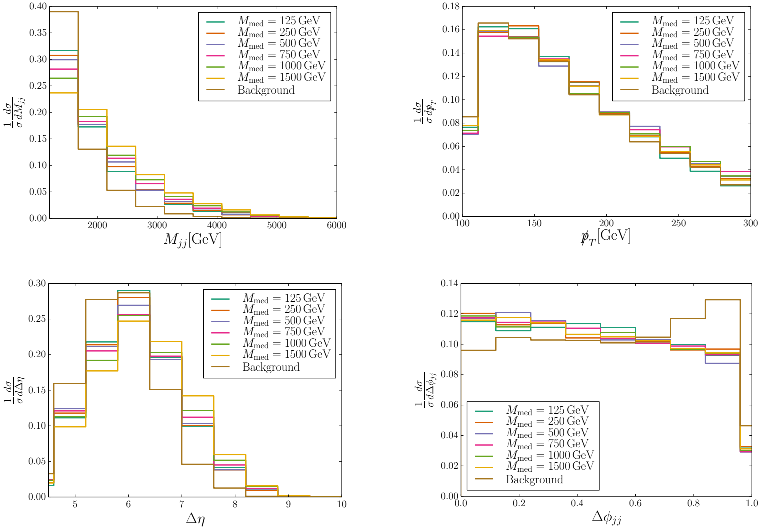
1. Here $\kappa = \sin^2\theta \lesssim 0.15$ corresponding to the singlet–Higgs mixing arising from the Higgs portal;
2. Alternatively if the scalar mediator is not a singlet, e.g. a new Higgs doublet, then κ is not constrained and we can choose $\kappa \simeq 1$.

Consider now 2 jets $+$MET topology

There are 4 key kinematic variables associated with 2 jets – more freedom to cut SM backgrounds; use the VBF cuts:

$$p_{T\,\text{miss}} > 100\,\text{Gev}\,,\quad M_{jj} > 1200\,\text{GeV}\,,\quad \Delta\phi_{jj} < 1\,,\quad \Delta\eta > 4.5\,,\quad p_{T,j} > 40\,\text{GeV}$$

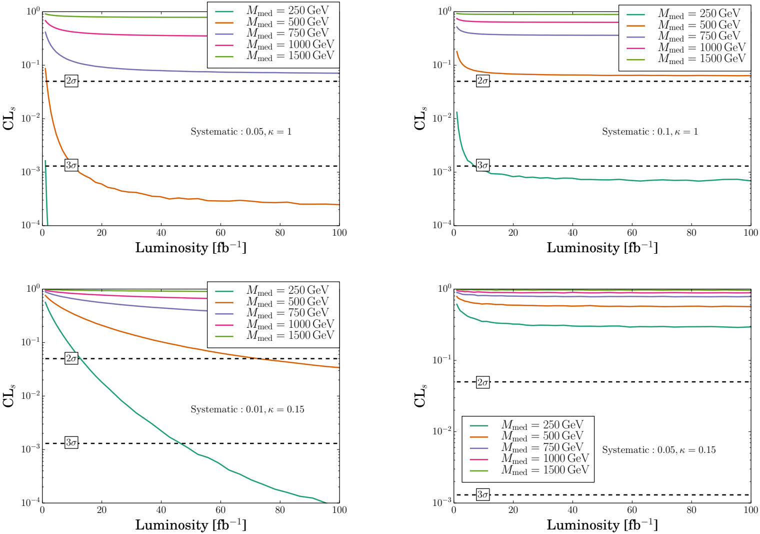
2 jets +MET signature LHC 14



Kinematic distributions for different $M_{\rm med}$ for the signal and the background

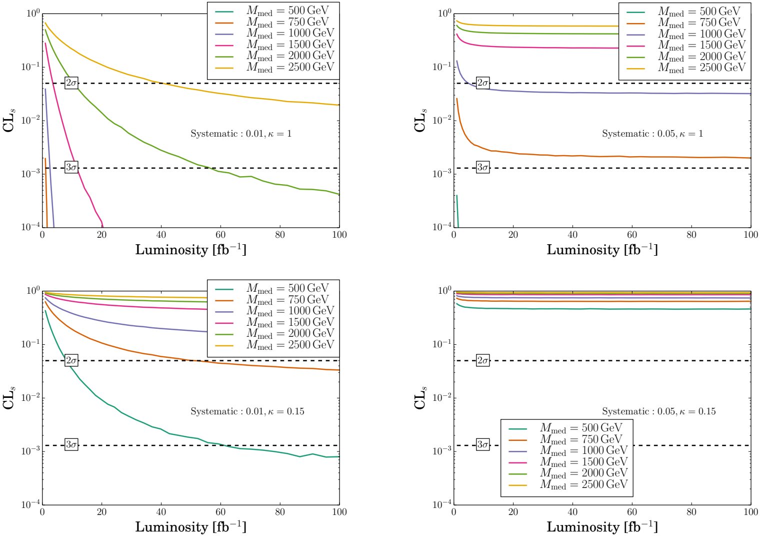
VVK, M. Spannowsky and G. Ro, arXiv:1505.03019

2 jets +MET signature: LHC 14 reach for $\kappa = 1$ and $\kappa = 0.15$ models



VVK, M. Spannowsky and G. Ro, arXiv:1505.03019

2 jets +MET signature: 100 TV reach for $\kappa = 1$ and $\kappa = 0.15$ models



VVK, M. Spannowsky and G. Ro, arXiv:1505.03019

II. Dark Sector UV Models: Higgs Portals

Back to the UV models with Higgs portals

Generating the Electroweak sale:

There is just a single occurrence of a non-dynamical scale in the Standard Model – the negative-valued $\mu^2_{\rm SM}$ parameter in:

$$V_{\rm cl}^{\rm SM}(H) = \mu^2_{\rm SM}\, H^\dagger H + \frac{\lambda_{\rm H}}{2}\left(H^\dagger H\right)^2$$

Remove $\mu^2_{\rm SM}$ by introducing a Higgs portal interaction with new ϕ:

$$V_{\rm cl}(H,\phi) = -\lambda_{\rm P}(H^\dagger H)|\phi|^2 + \frac{\lambda_{\rm H}}{2}(H^\dagger H)^2 + \frac{\lambda_\phi}{4!}|\phi|^4$$

$V_{\rm cl}$ is now scale-invariant. If the right value for $\langle\phi\rangle \ll M_{UV}$ can be generated quantum mechanically, it will trigger the EWSB:

$$\mu^2_{\rm SM} = -\lambda_{\rm P}|\langle\phi\rangle|^2 \quad = -\frac{1}{2}\, m_h^2 = -\frac{1}{2}\,\lambda_{\rm H}\, v^2$$

II. Dark Sector UV Models: Higgs Portals

Coleman-Weinberg mechanism more than 40 years ago: a *massless* scalar field ϕ, coupled to a gauge field, dynamically generates a non-trivial $\langle\phi\rangle$ via dimensional transmutation of the log-running couplings. Schematically:

$$\langle\phi\rangle \sim M_{UV} \times \exp\left[-\frac{\mathrm{const}}{g_{CW}^2}\right] \ll M_{UV}$$

g_{CW} is the gauge coupling of ϕ.

SM×CW BSM theory

Classically scale-invariant with the Higgs portal $-\lambda_{\rm P}|H|^2|\phi|^2$

$\langle\phi\rangle$ is non-vanishing, calculable in a weakly-coupled theory, and is naturally small (exp. suppressed) relative to the UV cut-off. Then:

$$\mathrm{EWSB}: \quad v = \sqrt{\frac{2\lambda_{\rm P}}{\lambda_{\rm H}}}\,\langle\phi\rangle\,, \quad m_h = \sqrt{2\lambda_{\rm P}}\,\langle\phi\rangle$$

Comments on classical scale-invariance:

- Classical scale invariance is not an exact symmetry. It is broken anomalously by logarithmically running couplings.
- This is precisely what generates the scale $\langle \phi \rangle \ll M_{UV}$ and feeds to EWSB and other features.
- The scale invariance is broken by the anomaly in a controlled way – the order parameter is $\langle |\phi|^2 \rangle$.
  Generic UV regularisation instead would introduce *large* effects $\sim \alpha\, M_{UV}^2$

  $$\alpha\, M_{UV}^2 \gg \langle |\phi|^2 \rangle$$

  To maintain the anomalously broken scale invariance, one must choose a scale-invariance-preserving regularisation scheme – dimensional regularisation – Bardeen 1995.
- The role of gravity and M_{Pl} is not addressed in this approach.

Some references:

- S. R. Coleman and E. J. Weinberg, Phys. Rev. D **7** (1973) 1888

SM$\times$U(1)$_{CW}$ model first appears in:

- R. Hempfling, Phys. Lett. B **379** (1996) 153

The special role of dimensional regularisation:

- W. A. Bardeen, FERMILAB-CONF-95-391-T

Classical scale invariance introduced in:

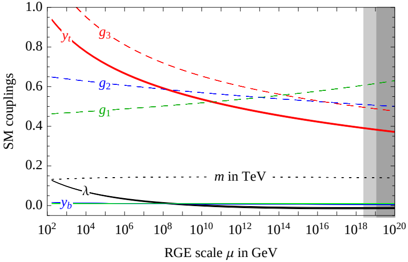
- K. A. Meissner and H. Nicolai, Phys. Lett. B **648** (2007) 312

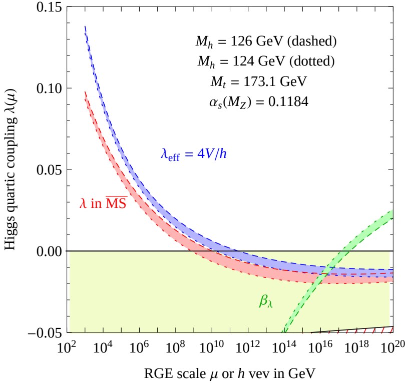
Our approach:

- C. Englert, J. Jaeckel, VVK and M. Spannowsky, 1301.4224 – *Original*
- VVK, C. McCabe and G. Ro, arXiv:1403.4953 – *Higgs Stab. and DM*
- VVK and G. Ro, 1307.3764 – *Matter-anti-Matter via Leptogenesis*
- VVK 1308.6338 – *Inflation in the Higgs Portal*

Stabilisation of the Higgs potential

The SM Higgs potential is unstable as the Higgs self-coupling λ_H turns < 0.





D. Buttazzo, G. Degrassi, P. P. Giardino, G. F. Giudice, F. Sala, A. Salvio and A. Strumia, 1307.3536

Stabilisation of the Higgs potential

A minimal and robust way to repair the EW vacuum stability is provided by the Higgs portal extension of the SM – just what we have in our theory.

Two effects to stabilise the vacuum:

1. When h_2 is heavier than the SM Higgs h_1, the microscopic theory coupling λ_H is larger than the effective SM coupling, $\lambda_H > \lambda_{SM}$. Can use this to prevent $\lambda_H(\mu)$ from going negative at large μ.

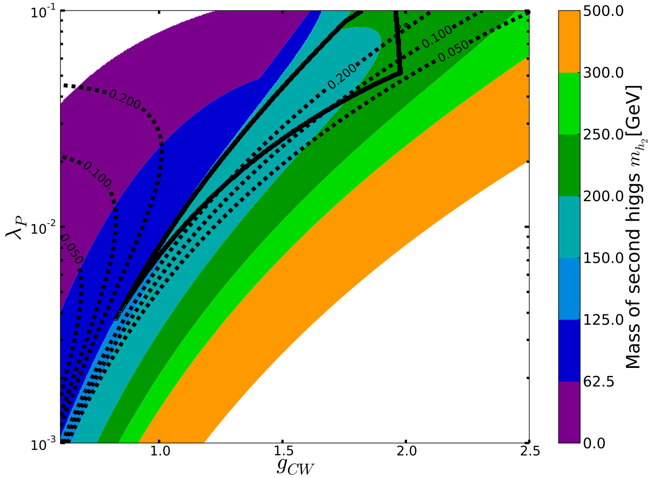
2. The portal coupling gives a positive contribution to the beta function of the Higgs quartic coupling, $\Delta\beta_{\lambda_H} \sim +\lambda_{\rm P}^2$.

   Hence we also consider extending the model by adding a real singlet:

   $$\text{SM} \times G_{CW} \oplus \text{singlet } s(x)$$

   The singlet gives the inflaton and the Dark Matter candidate plus helps with the Higgs vacuum stabilisation

VVK, C. McCabe and G. Ro, arXiv:1403.4953



SM $\times$ **SU(2)**$_{CW}$: The Higgs potential is stabilised inside the wedge-shaped region. Contours of the Higgs mixing angle $\sin^2\theta = 0.05$, 0.1 and 0.2 are shown and the mass of the 2nd scalar h_2 is colour-coded.

Stabilisation of the Higgs potential

SM $\times G_{cw} \oplus$ singlet $s(x)$

Now consider adding a new singlet:

$$V_{\rm cl}(H,\phi,s) = \frac{\lambda_{Hs}}{2}|H|^2 s^2 + \frac{\lambda_{\phi s}}{2}|\Phi|^2 s^2 + \frac{\lambda_s}{4}s^4 + V_{\rm cl}(H,\Phi)$$

Since all portal couplings give positive contributions to the beta function of the Higgs quartic coupling, $\Delta\beta_{\lambda_H} \sim +\lambda_{Hs}^2$ =>

- Values of $\lambda_{Hs} \gtrsim 0.35$ are sufficient to stabilise the Higgs by this effect on its own. Don't need to be inside the wedge region.

VVK, C. McCabe and G. Ro, arXiv:1403.4953

II. Dark Sector UV Models: Higgs Portals

There is a rich spectrum of DM candidates in our CSI Higgs Portal models:

1. The CW scalar can be a **mediator** to the Dark Sector coupled to fermion, scalar, vector DM as in Simplified DM Models considered in Part I.
2. The $SU(2)_{CW}$ gauge bosons automatically give **vector DM**. They are stable due to an SO(3) symmetry and there is no kinetic mixing

   T. Hambye 2008, T. Hambye and A. Strumia arXiv:1306.2329

3. The singlet scalar $s(x)$, if present, is stable due to a Z_2 symmetry which is automatic due to CSI and gauge invariance $\Longrightarrow$ **scalar DM**
4. If scalars in adjoint representation of $SU(2)_{CW}$ are present, there can exist **monopole DM** studied in

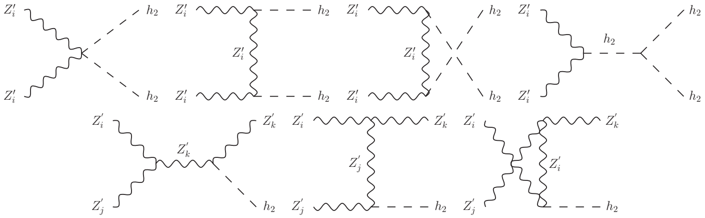
   VVK, G. Ro arXiv:1406.2291

The origin of the dark matter scale is the same as the origin of the EW scale as $m_{DM} \sim \langle\Phi\rangle$. Relic abundance produced by standard freeze out mechanism.

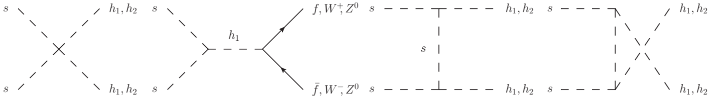
VVK, C. McCabe and G. Ro, arXiv:1403.4953

II. Dark Sector UV Models: Higgs Portals

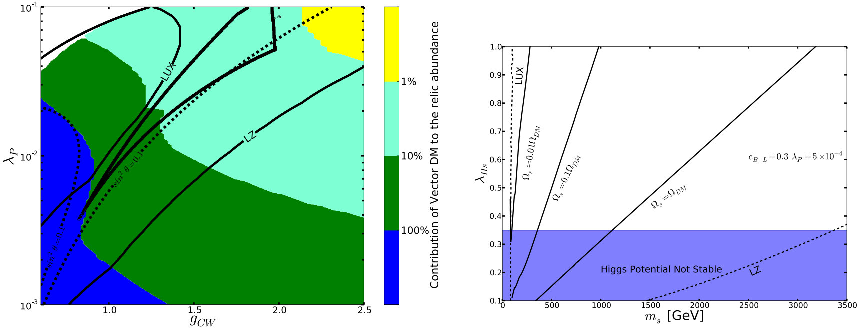
1. $SU(2)_{CW}$ Vector Dark Matter annihilation and semi-annihilation:



2. Scalar Dark Matter annihilation diagrams include:



Vector and Scalar Dark Matter

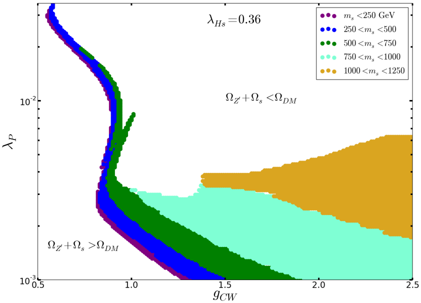


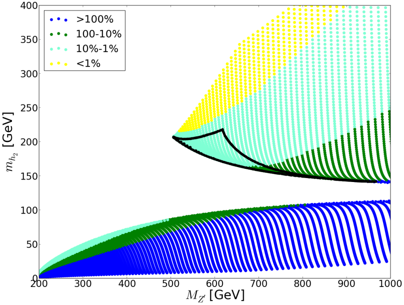
Left: SM × SU(2)$_{CW}$ CSI model – $\lambda_{\rm P}$, g_{CW} plane. Right: With additional DM singlet $s(x)$, don't need to be inside the wedge.

VVK, C. McCabe and G. Ro, arXiv:1403.4953

II. Dark Sector UV Models: Higgs Portals

Two-Component DM: Vector and Scalar DM relic density combined





VVK, C. McCabe and G. Ro, arXiv:1403.4953

Summary

Two parts:

1. Constraining Dark Sectors at colliders in terms of Simplified Models with four basic types of mediators
2. Using Higgs Portal interactions and classical scale invariance as the UV description of Dark Matter Sectors

Simplified models at the LHC 14 TeV and at 100TeV FCC:

- mono-jet +MET – complimentary coverage at colliders to DD and ID
- 2-jets + MET – can probe mediators up to 750 GeV (LHC) or 2.5 TeV (FCC)

CSI model-building: no vastly different scales can co-exist in this framework:

- If present, large new mass scales would ultimately couple to the Higgs and destabilise it mass
- *Common origin of DM and Electroweak scales*