Dark Sectors and Higgs Portals at Colliders: from 14 to 100 TeV

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8 September 2015

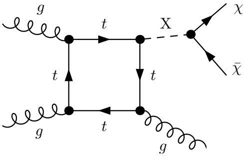
Necessity of New Physics beyond the Standard Model

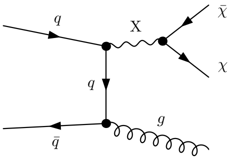
The LHC Higgs discovery was the crowning achievement of the SM.
But at a more fundamental level it leaves some key questions unanswered:

- 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 (or meta-stable) at $\mu_{\mathrm{RG}} \gtrsim 10^{11}$ GeV
- Generation of the matter-anti-matter asymmetry of the Universe is impossible within the SM
- **There is no Dark Matter in 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).
- Use SM jets to recoil, consider jets + MET signatures.
- 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.
- Dark Particles interact with the Standard Model by exchanging a *mediator* field X. Mediator particle is a key new physics d.o.f. at colliders.
- Four basic types of mediators: vectors, axial-vectors, scalars, pseudo-scalars (can be exchanged in *s*- or *t*-channel). Concentrate below on the *s*-channel models (colourless mediators):





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,

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

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

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

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

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

Two coupling types enter: $g_{\rm SM}$ and $g_{\rm DM}$.

$g_{\rm SM}$: the couplings of Scalar and Pseudo-Scalar messengers to all six flavours of SM quarks are taken to be proportional to the corresponding SM Higgs Yukawa's y_q, in accordance with the 'Minimal Flavour Violation' set-up:

$$\text{scalar \& pseudo} - \text{scalar messengers}: \quad g^q_{\rm SM} \equiv g_q\, y_q \;=\; g_q\, \frac{m_q}{v}$$

and we keep the scaling g_q flavour-universal for all quarks.

For axial and vector mediators $g_{\rm SM}$ is a gauge coupling in the dark sector which we also take to be flavour universal:

$$\text{vector \& axial} - \text{vector messengers}: \quad g^q_{\rm SM} \;=\; g_{\rm SM}$$

The coupling parameters which we vary are $g_{\rm DM}$ plus either g_q or $g_{\rm SM}$, depending on the messengers choice.

I. Dark Sectors at Colliders: Simplified Models

Jets + MET topology of the final state

P. Harris, VVK, M. Spannowsky and C. Williams, to appear Sept. 2015 updating our earlier analysis in arXiv:1411.0535 to 14-100 TeV

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

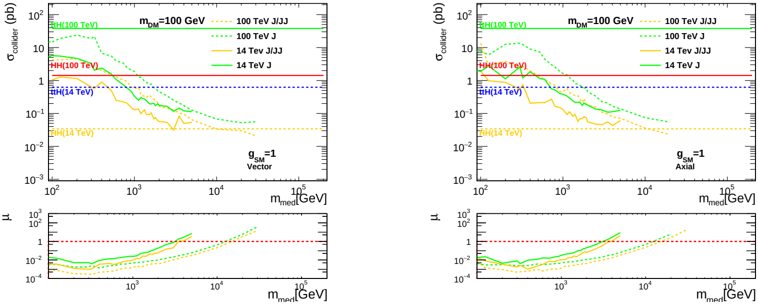
1. mediator mass $m_{\rm MED}$
2. mediator width $\Gamma_{\rm MED}$
   [Can use $\Gamma_{\rm MED\,minimal}$ computed in the simplified models $\times\{1, 2, 5, 10\}$ and check $< m_{\rm MED}/2$]
3. dark matter mass $m_{\rm DM}$
4. mediator couplings $g_{\rm DM}$ and g_q for scalar and pseudo-scalars; or $g_{\rm DM}$ and $g_{\rm SM}$ for axial-vector and vector mediators.

Signal generated using MadGraph for Vector and Axial mediators and a combination of MCFM and VBFNLO for the production of Scalar and Pseudoscalar mediators in association with 1 and 2 jets. Backgrounds were generated at NLO for 0,1,2 jets merged using MadGraph-aMC@NLO.

Jets + MET topology

Collider cross section limits and projections at 14 and 100 TeV [Preliminary]
μ is the ratio of the exclusion $\sigma_{\rm coll}$ to the predicted $\sigma(g_{\rm DM} = 1, g_{\rm SM} = 1)$

- **Vector and Axial-vector mediators:**

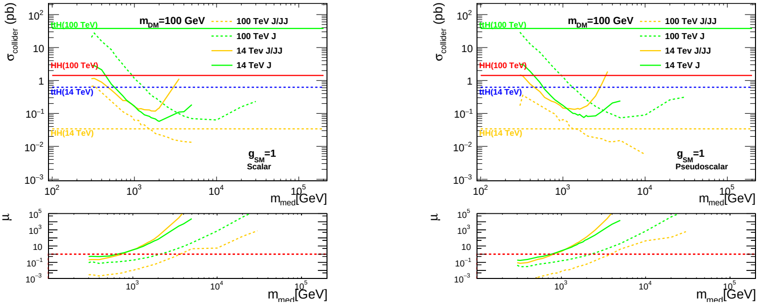


P. Harris, VVK, M. Spannowsky and C. Williams [to appear Sept. 2015]

Jets + MET topology

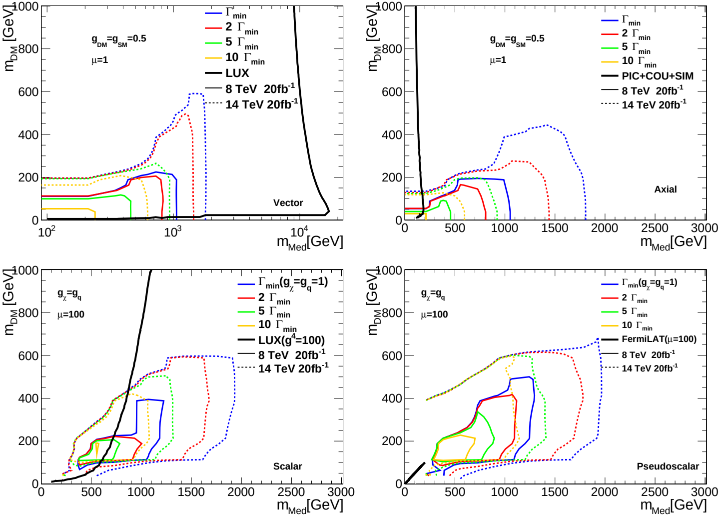
Collider cross section limits and projections at 14 and 100 TeV [Preliminary]
μ is the ratio of the exclusion $\sigma_{\rm coll}$ to the predicted $\sigma(g_{\rm DM} = 1, g_{\rm SM} = 1)$

- **Scalar and Pseudo-scalar mediators:**



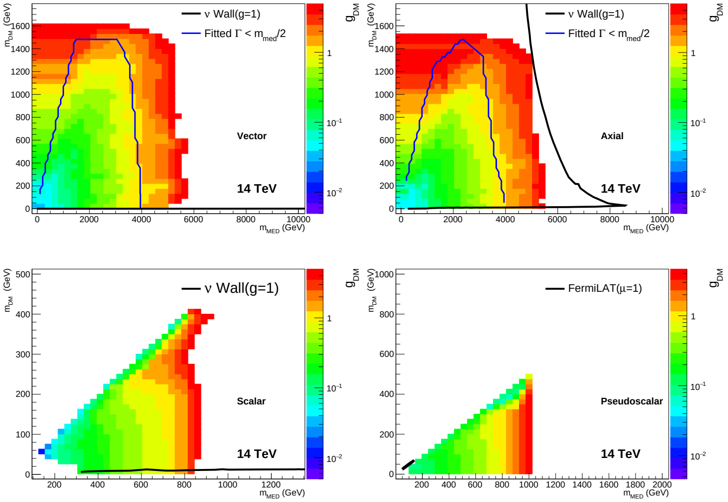
P. Harris, VVK, M. Spannowsky and C. Williams [to appear Sept. 2015]

Old (1411) mono-jet-based LHC limits on mediator vs DM mass at 8 & 14TeV:



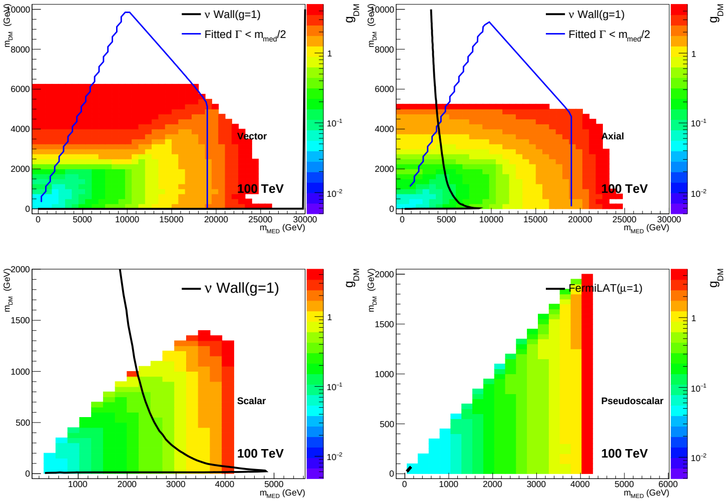
P. Harris, VVK, M. Spannowsky and C. Williams, arXiv:1411.0535

[New] Exclusion limits on mediator mass vs DM mass at 14 TeV:



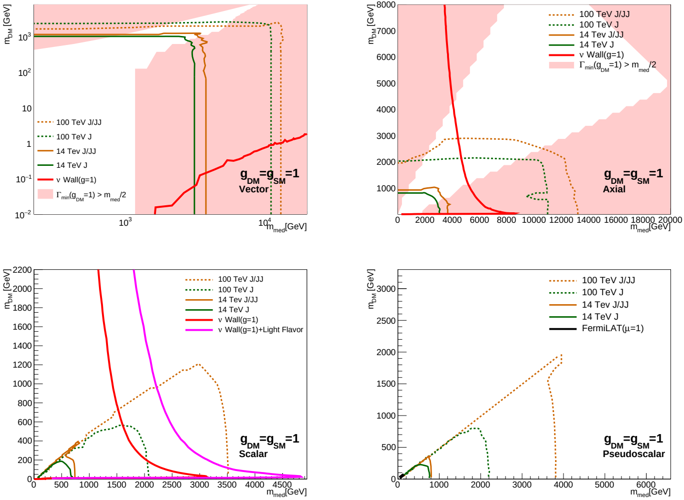
P. Harris, VVK, M. Spannowsky and C. Williams [to appear Sept. 2015]

Exclusion limits on mediator mass vs DM mass at 100 TeV:



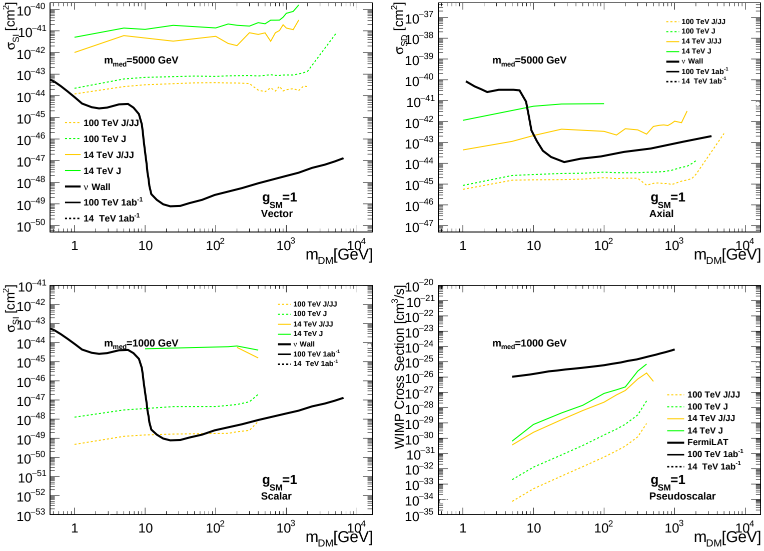
P. Harris, VVK, M. Spannowsky and C. Williams [to appear Sept. 2015]

Mass limits using single-jet and multi-jet analysis at 14 & 100TeV:



P. Harris, VVK, M. Spannowsky and C. Williams [to appear Sept. 2015]

Collider exclusions interpreted in terms of the spin-dependent and spin-independent cross sections vs $m_{\rm DM}$ at 14 and 100 TeV:



P. Harris, VVK, M. Spannowsky and C. Williams [to appear Sept. 2015]

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.

Mixing with ϕ 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,

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

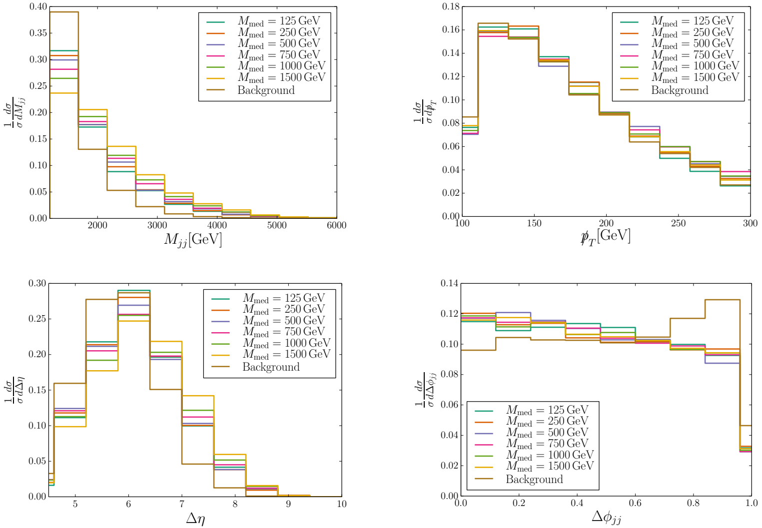
1. Here $\kappa = \sin^2\theta \lesssim 0.15$ corresponding to the singlet–Higgs mixing arising from the Higgs portal;
2. Alternatively if the scalar mediator is not a singlet, e.g. a new Higgs doublet, then κ is not constrained and we can choose $\kappa \simeq 1$.

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:

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

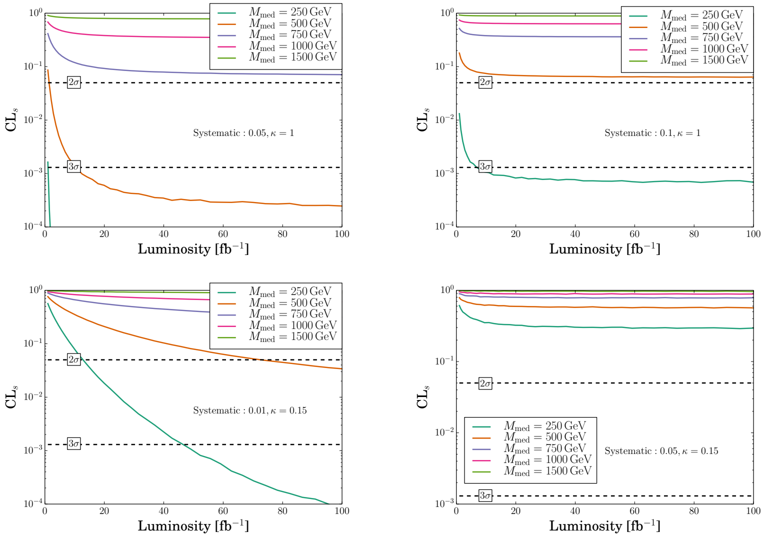
2 jets +MET signature LHC 14



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

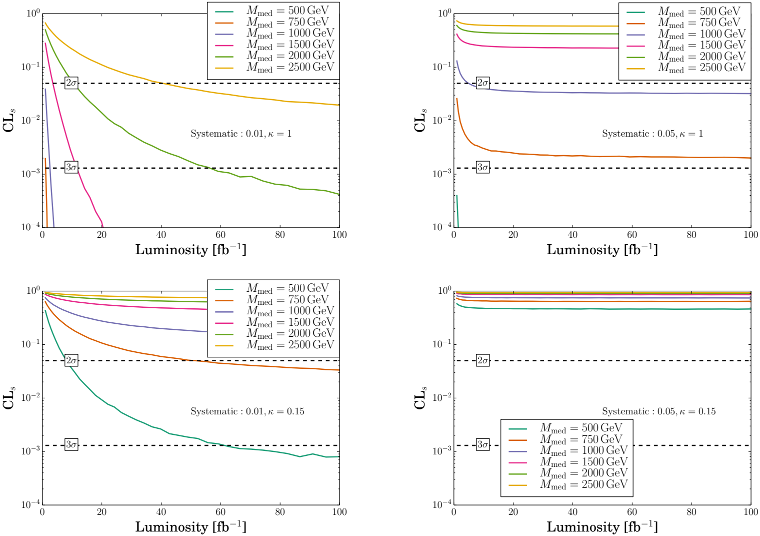
VVK, M. Spannowsky and G. Ro, arXiv:1505.03019

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

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:

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

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 $-\lambda_{\mathrm{P}}|H|^2|\phi|^2$

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

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

II. Dark Sector UV Models: Higgs Portals

The SM taken in isolation as a QFT has no problems with the Higgs mass (ignore super-Planckian Landau poles). It does not address key sub-Planckian issues (DM, Matter-anti-Matter asymmetry ...) so extend it.

SM×CW BSM theory

Classically scale-invariant: No input mass terms are allowed

In the course of UV renormalisation, the subtraction scheme is chosen to set the *renormalised masses* at the origin of the field space to zero

$$m^2|_{\phi=0} \;:=\; V''(\phi)\Big|_{\phi=0} = 0$$

In *dimensional regularisation* this masslessness eqn is automatic:

- No power-like dependences on the cutoff scale can appear;
- Since there are no explicit mass scales at the outset, no finite corrections to mass terms at the origin are genereated.

Dim reg preserves classical scale invariance, the theory as it stands is not fine-tuned.

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 and then investigated in the B-L model in:

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

S. Iso, N. Okada and Y. Orikasa, Phys. Lett. B **676** (2009) 81

Our approach:

C. Englert, J. Jaeckel, VVK and M. Spannowsky, 1301.4224 – *Original*

VVK, C. McCabe and G. Ro, arXiv:1403.4953 – *Higgs Stability & DM*

VVK and G. Ro, 1307.3764 – *Matter-anti-Matter via Leptogenesis*

VVK 1308.6338 – *Inflation in the Higgs Portal*

Classically Scale Invariant Extended Standard Model

SM $\times G_{CW}$ with a hidden gauge sector G_{CW} and no mass scales. The theory is classically scale-invariant. Classical scalar potential:

$$V_{\rm cl}(H,\Phi) = \lambda_\phi(\Phi\Phi^\dagger)^2 + \lambda_H(HH^\dagger)^2 - \lambda_{\rm P}(\Phi\Phi^\dagger)(HH^\dagger)$$

The Higgs Portal interaction $-\lambda_{\rm P}\langle\Phi\Phi^\dagger\rangle(HH^\dagger)$ generates the Higgs VEV $v = 246$ GeV and triggers EWSB in the SM.

Can consider Abelian and non-Abelian choices for G_{CW}:

- Standard Model $\times$ $\mathrm{U(1)_{CW}}$
- Standard Model $\times$ $\mathrm{U(1)_{B-L}}$ => SM quarks and leptons charged under $\mathrm{U(1)_{B-L}}$
- Standard Model $\times$ $\mathrm{SU(2)_{CW}}$

Classically Scale Invariant Extended Standard Model

- Minimal CSI SM$\times$G$_{CW}$ models have only two free parameters, the portal coupling, $\lambda_{\rm P}$ and the hidden gauge coupling g_{CW}. [Coupling to Dark Matter and/or mixing with additional singlets introduce new couplings.]

- H and Φ scalars mix, giving two higgs mass-eigenstates $m_{h_1} \simeq 125$ GeV and m_{h_2} (which can be $>$ or $< m_{h_1}$).

- There is always Z' with $M_{Z'} \gg m_{h_2}$. Both, m_{h_2} and $M_{Z'}$ can be determined in terms of $\lambda_{\rm P}$ and g_{CW}.

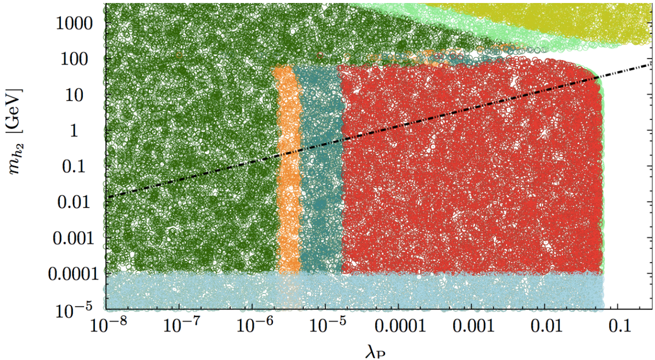
- If $m_{h_1} > 2m_{h_2}$ the SM Higgs can decay into two hidden Higgses which constrains $\lambda_{\rm P} \lesssim 10^{-5}$.

- For $m_{h_2} > m_{h_1}/2$ the coupling $\lambda_{\rm P}$ is much less constrained.

- Collider production of Z' possible if SM quarks couple to the hidden G_{CW} - as in the U$(1)_{B-L}$ example - but not otherwise.

Light h_2 states are highly constrained by large invisible Higgs decays $\Gamma_{h_1 \to h_2 h_2}$. More interested in heavier h_2.

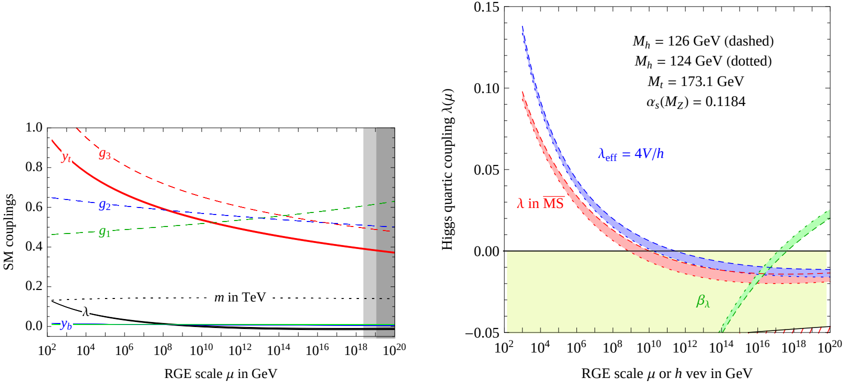
C. Englert, J. Jaeckel, V. V. Khoze and M. Spannowsky, 1301.4224



Scatter plot in the (λ_P, m_{h_2}) plane. Red region is excluded by current LHC measurements. The cyan region can be probed by HL LHC and orange region is a projection for a combination of a HL LHC with an LC. The allowed parameter points are depicted in green.

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.

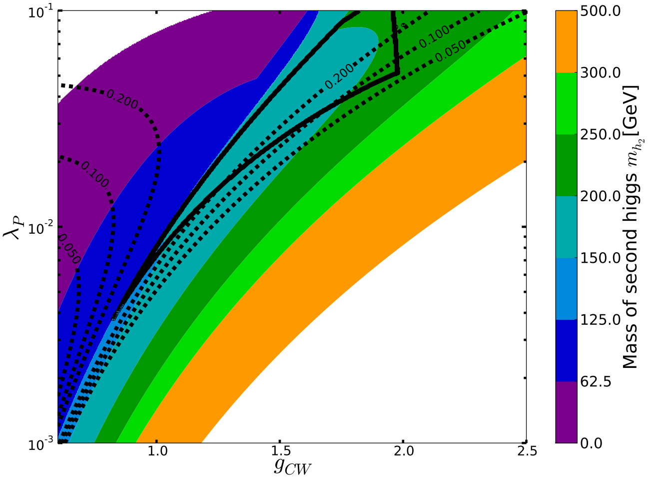
2. The portal coupling gives a positive contribution to the beta function of the Higgs quartic coupling, $\Delta\beta_{\lambda_H} \sim +\lambda_{\rm P}^2$.

   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 the adjoint representation of $SU(2)_{CW}$ are present, there can exist **monopole DM** studied in

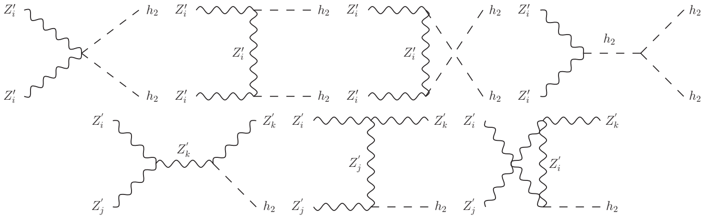
   S. Baek, P. Ko and W. I. Park arXiv:1311.1035
   VVK and G. Ro arXiv:1406.2291

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.

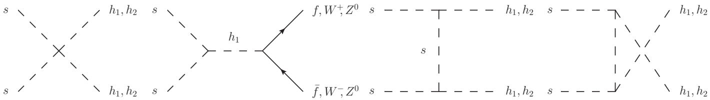
VVK, C. McCabe and G. Ro, arXiv:1403.4953

II. Dark Sector UV Models: Higgs Portals

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

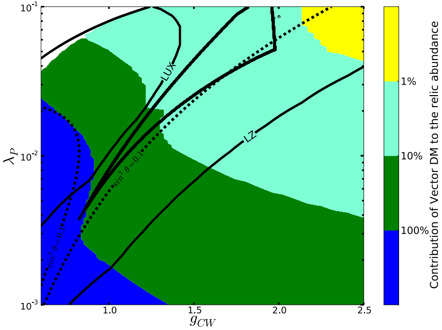


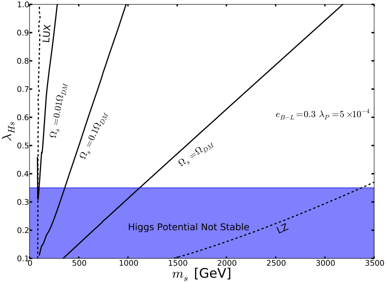
2. Scalar Dark Matter annihilation diagrams include:



II. Dark Sector UV Models: Higgs Portals

Vector and Scalar Dark Matter

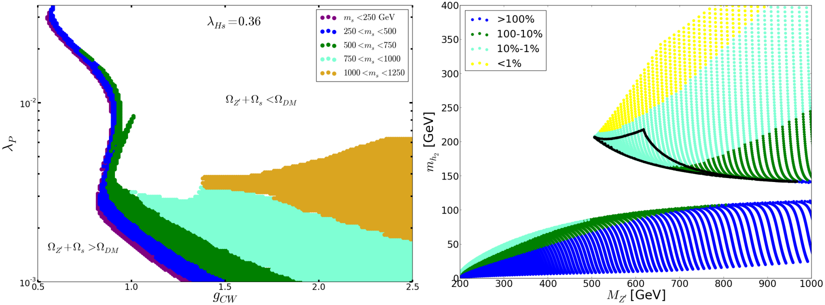




Left: SM $\times$ SU(2)$_{CW}$ CSI model – $\lambda_{\rm P}$, g_{CW} plane. Right: With additional DM singlet $s(x)$, don't need to be inside the wedge.

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

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:

- jets +MET – complimentary coverage at colliders to DD and ID
- Search for mediators to dark sectors at colliders; can probe $m_{\rm MED}$ and $m_{\rm DM}$ well into the TeV regime at 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*

Summary

- CSI ESM examples:
  - Standard Model $\times$ $U(1)_{CW}$
  - Standard Model $\times$ $U(1)_{B-L}$
  - Standard Model $\times$ $SU(2)_{CW}$
- Stabilisation of the Higgs potential
  - Standard Model $\times$ G_{CW}
  - Standard Model $\times$ $G_{CW} \oplus$ singlet
- Vector and Scalar Dark Matter
  - Other DM species (fermions) and more involved DM models
  - Can also have Monopole & Vector DM and Dark radiation

Progress has also been made in addressing

- Matter-anti-Matter asymmetry: Leptogenesis via sterile neutrino oscillations
- Cosmological Inflation
- Axions and axion-like particles