Vector DM and the Higgs Portal

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Based on
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LHC DM WG meeting
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The story so far

- DM makes up 23% of the universe
- Gravitates like ordinary matter, but is non-baryonic
- Is dark i.e. neutral under SM (not coloured, or charged)
- Does not interact much with itself
- Does not couple to massless particle
- Was no relativistic at time of CMB
- Is long lived

IF DM is a thermal relic:

- A weak scale annihilation x-sec gives correct abundance
- Mass range is $10\ \mathrm{MeV} \lesssim m_\chi \lesssim 70\ \mathrm{TeV}$

What representation of the Lorentz group?

Spin 0 & 1/2

Fermionic DM (eg neutralino)

[Berlin, Hooper, McDermott 1404.0022]

DM bilinear	*SM fermion bilinear*			
fermion DM	$\bar{f}f$	$\bar{f}\gamma^5 f$	$\bar{f}\gamma^\mu f$	$\bar{f}\gamma^\mu\gamma^5 f$
$\bar{\chi}\chi$	$\sigma v \sim v^2,\ \sigma_{\rm SI} \sim 1$	$\sigma v \sim v^2,\ \sigma_{\rm SD} \sim q^2$	–	–
$\bar{\chi}\gamma^5\chi$	$\boldsymbol{\sigma v \sim 1,\ \sigma_{\rm SI} \sim q^2}$	$\boldsymbol{\sigma v \sim 1,\ \sigma_{\rm SD} \sim q^4}$	–	–
$\bar{\chi}\gamma^\mu\chi$ (Dirac only)	–	–	$\sigma v \sim 1,\ \sigma_{\rm SI} \sim 1$	$\boldsymbol{\sigma v \sim 1,\ \sigma_{\rm SD} \sim v_\perp^2}$
$\bar{\chi}\gamma^\mu\gamma^5\chi$	–	–	$\sigma v \sim v^2,\ \sigma_{\rm SI} \sim v_\perp^2$	$\boldsymbol{\sigma v \sim 1,\ \sigma_{\rm SD} \sim 1}$

Scalar DM (eg sneutrino, axion/ALP)

DM bilinear	*SM fermion bilinear*			
scalar DM	$\bar{f}f$	$\bar{f}\gamma^5 f$	$\bar{f}\gamma^\mu f$	$\bar{f}\gamma^\mu\gamma^5 f$
$\phi^\dagger\phi$	$\sigma v \sim 1,\ \sigma_{\rm SI} \sim 1$	$\boldsymbol{\sigma v \sim 1,\ \sigma_{\rm SD} \sim q^2}$	–	–
$\phi^\dagger\overleftrightarrow{\partial_\mu}\phi$ (complex only)	–	–	$\sigma v \sim v^2,\ \sigma_{\rm SI} \sim 1$	$\sigma v \sim v^2,\ \sigma_{\rm SD} \sim v_\perp^2$

Spin 1

(Massive) Vector must be associated with a (broken) gauge symmetry e.g. U(1)'
In what ways can it couple to SM?

Higgs Portal

$$\lambda\ H^\dagger H\ V_\mu V^\mu \qquad \left(+\frac{1}{2}m_V^2 V_\mu V^\mu\right)$$

$$\lambda v H V_\mu V^\mu$$

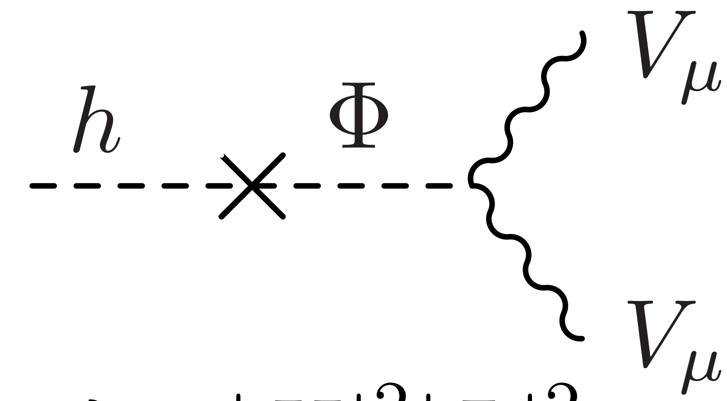
Invisible Higgs width

$$\lambda v^2 V_\mu V^\mu$$

Vector Mass

Not U(1)' gauge invariant

UV completion A



$$-\frac{1}{4}V_{\mu\nu}V^{\mu\nu} + (D_\mu\Phi)^\dagger (D^\mu\Phi) - V(\Phi) + \lambda_P\, |H|^2|\Phi|^2$$

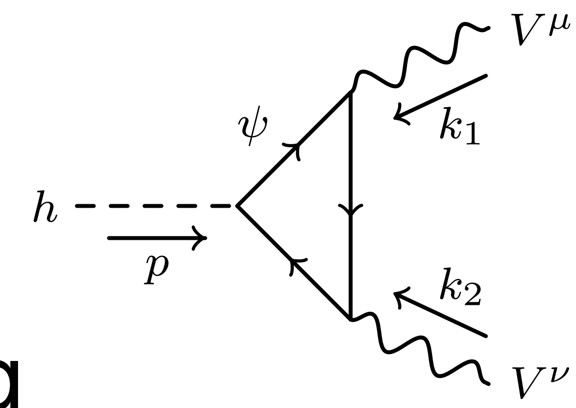
New scalar whose vev breaks U(1)'

$$m_V^2 = g^2 q_\Phi^2 \langle\Phi\rangle^2$$

Higgs-portal Higgs-Phi mixing

DM phenomenology determined by theory with new scalar and a new vector, see eg Baek, Ko, Park (1212.2131), and other speakers

UV completion B



- Radiatively generated Higgs-Vector coupling
- Necessarily more complicated
- New and interesting phenomenology eg decouple Phi, new states at LHC

Field	$(\mathrm{SU}(2)_W,\ \mathrm{U}(1)_Y,\ \mathrm{U}(1)')$	Field	$(\mathrm{SU}(2)_W,\ \mathrm{U}(1)_Y,\ \mathrm{U}(1)')$
$\psi_{1\alpha}$	$(2,\ {}^1\!/_2,\ 1)$	$\psi_{2\alpha}$	$(2,\ {}^1\!/_2,\ \text{-}1)$
$\chi_{1\alpha}$	$(2,\ \text{-}{}^1\!/_2,\ \text{-}1)$	$\chi_{2\alpha}$	$(2,\ \text{-}{}^1\!/_2,\ 1)$
$n_{1\alpha}$	$(1,\ 0,\ \text{-}1)$	$n_{2\alpha}$	$(1,\ 0,\ 1)$
Φ	$(1,\ 0,\ Q_\Phi)$	H	$(2, -{}^1\!/_2, 0)$

Vector-like pair

$Q_\Phi \neq \pm 1, \pm 2$

U(1)’ charge conjugation symmetry ($1 \leftrightarrow 2$) makes V stable

UV completion B

Four parameters (2 masses, 2 Yukawas) as well as gauge coupling and vector DM mass

$$\mathcal{L} \supset -m\, \epsilon^{ab} \left(\psi_{1a}\chi_{1b} + \psi_{2a}\chi_{2b}\right) - m_n\, n_1 n_2$$

$$- y_\psi\, \epsilon^{ab} \left(\psi_{1a} H_b n_1 + \psi_{2a} H_b n_2\right) - y_\chi \left(\chi_1 H^* n_2 + \chi_2 H^* n_1\right) + h.c.$$

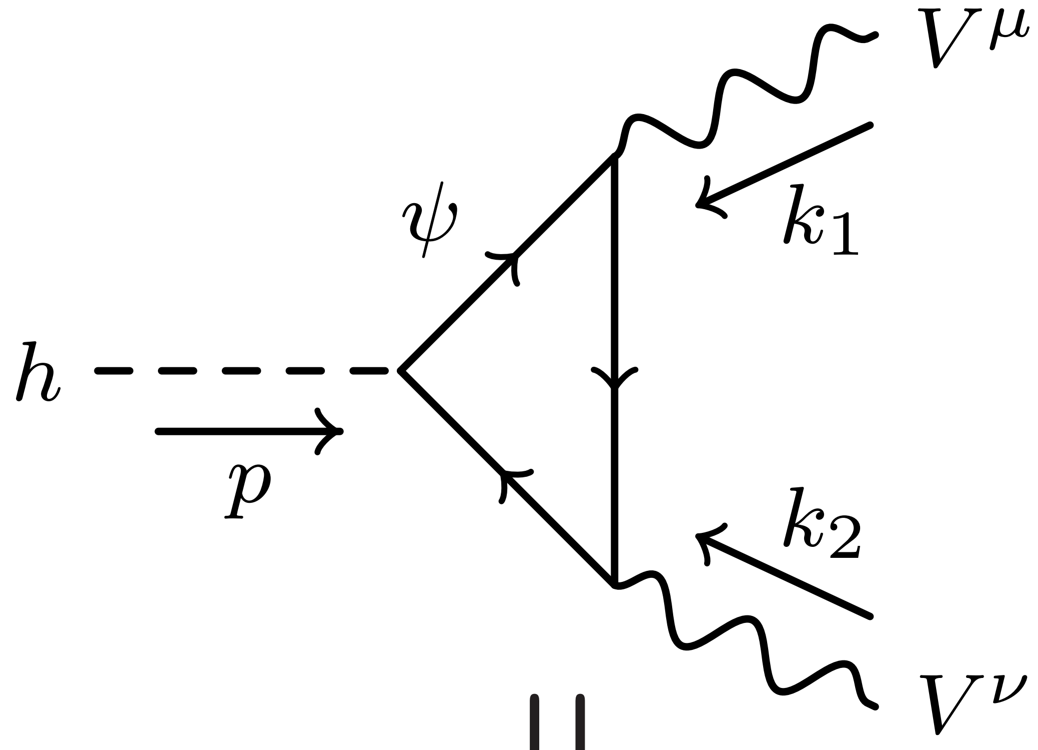
$$\Downarrow$$

$$\mathcal{L}_m = -N^T M_n N' - E^T M_e E' + h.c.$$

$$M_n = \begin{bmatrix} 0 & -m & -y_\psi v/\sqrt{2} \\ -m & 0 & y_\chi v/\sqrt{2} \\ -y_\psi v/\sqrt{2} & y_\chi v/\sqrt{2} & m_n \end{bmatrix}, \qquad M_e = \begin{bmatrix} m & 0 \\ 0 & m \end{bmatrix}$$

UV completion B

Higgs-Vector couplings generated at one loop
(only neutral fermions contribute)



$$\Downarrow$$

$$-\left(\frac{1}{4}A(p^2)\ h\ V^{\mu\nu}V_{\mu\nu}+\frac{1}{2}B(p^2)\ h\ V^\mu V_\mu\right)$$

Higgs invisible width

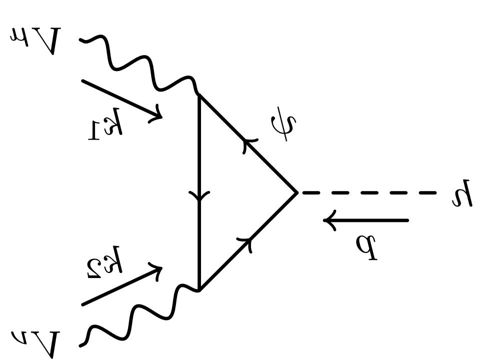
$$\Gamma(h \to VV) = \frac{1}{64\pi m_h}\sqrt{1-4\frac{m_V^2}{m_h^2}}\left[\left|A(m_h^2)\right|^2 m_h^4\left(1-4\frac{m_V^2}{m_h^2}+6\frac{m_V^4}{m_h^4}\right)\right.$$
$$\left.+6\,\mathrm{Re}\left(A^*(m_h^2)B(m_h^2)\right) m_h^2\left(1-2\frac{m_V^2}{m_h^2}\right)+\frac{1}{2}\left|B(m_h^2)\right|^2\frac{m_h^4}{m_V^4}\left(1-4\frac{m_V^2}{m_h^2}+12\frac{m_V^4}{m_h^4}\right)\right]$$

Finite as $m_V \to 0$

Direct detection cross section

$$\sigma_{\mathrm{SI}} = \frac{1}{4\pi m_h^4}\left(\frac{f_n}{v}\right)^2\left(\frac{m_n^2}{m_n+m_V}\right)^2\left|B(0)-A(0)\;m_V^2\right|^2$$

Annihilation cross section $VV \to hh, ZZ, WW, \gamma\gamma, hZ, Z\gamma$



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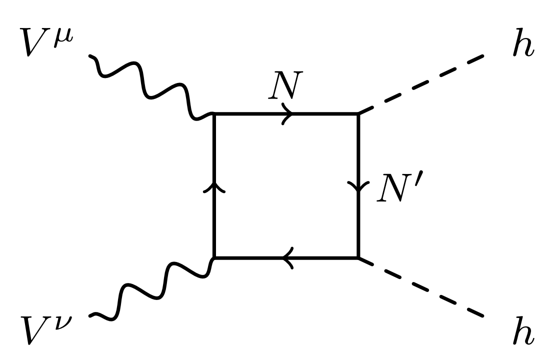
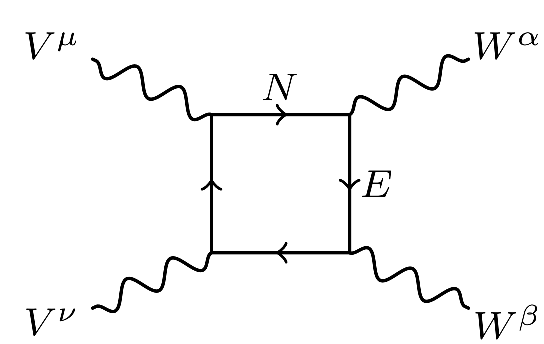
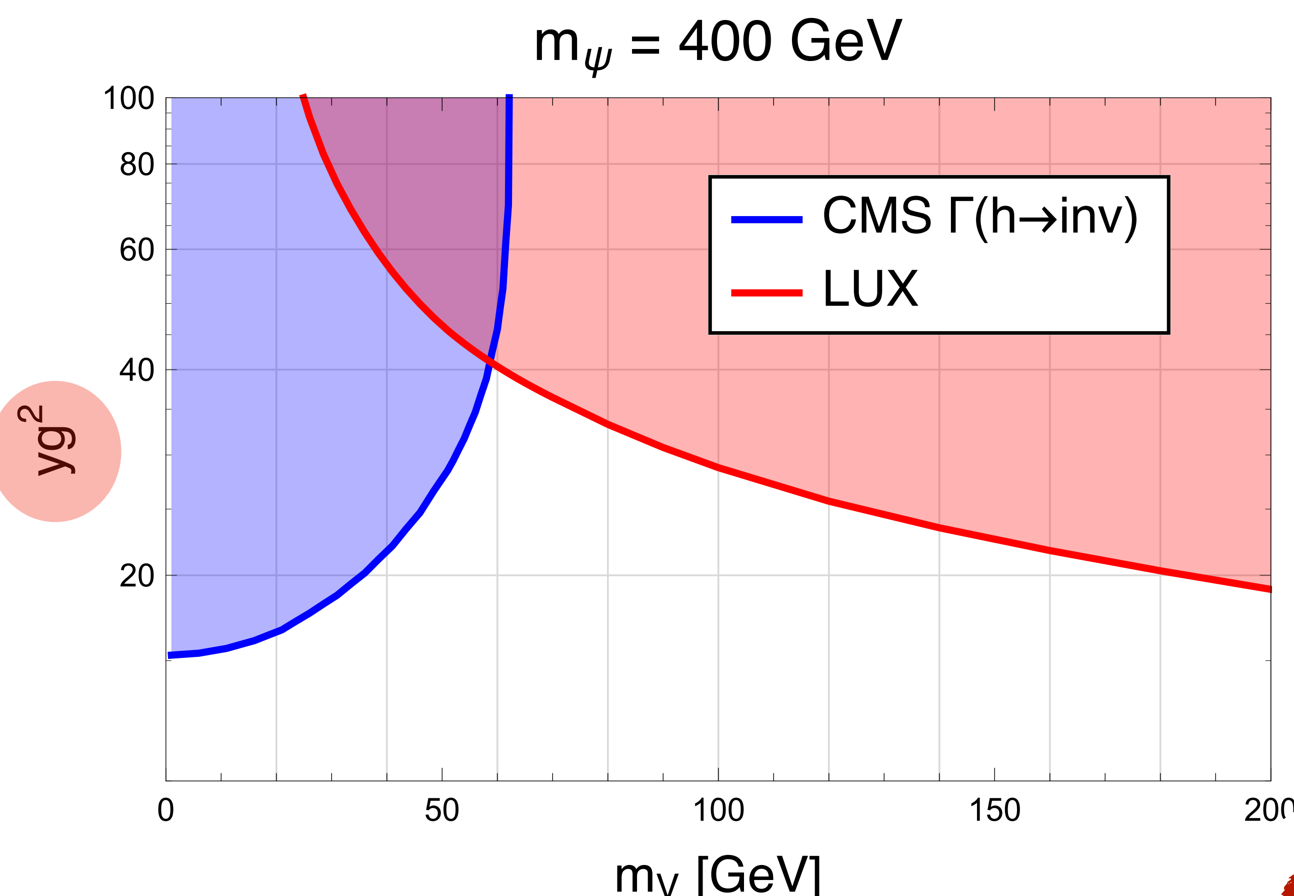
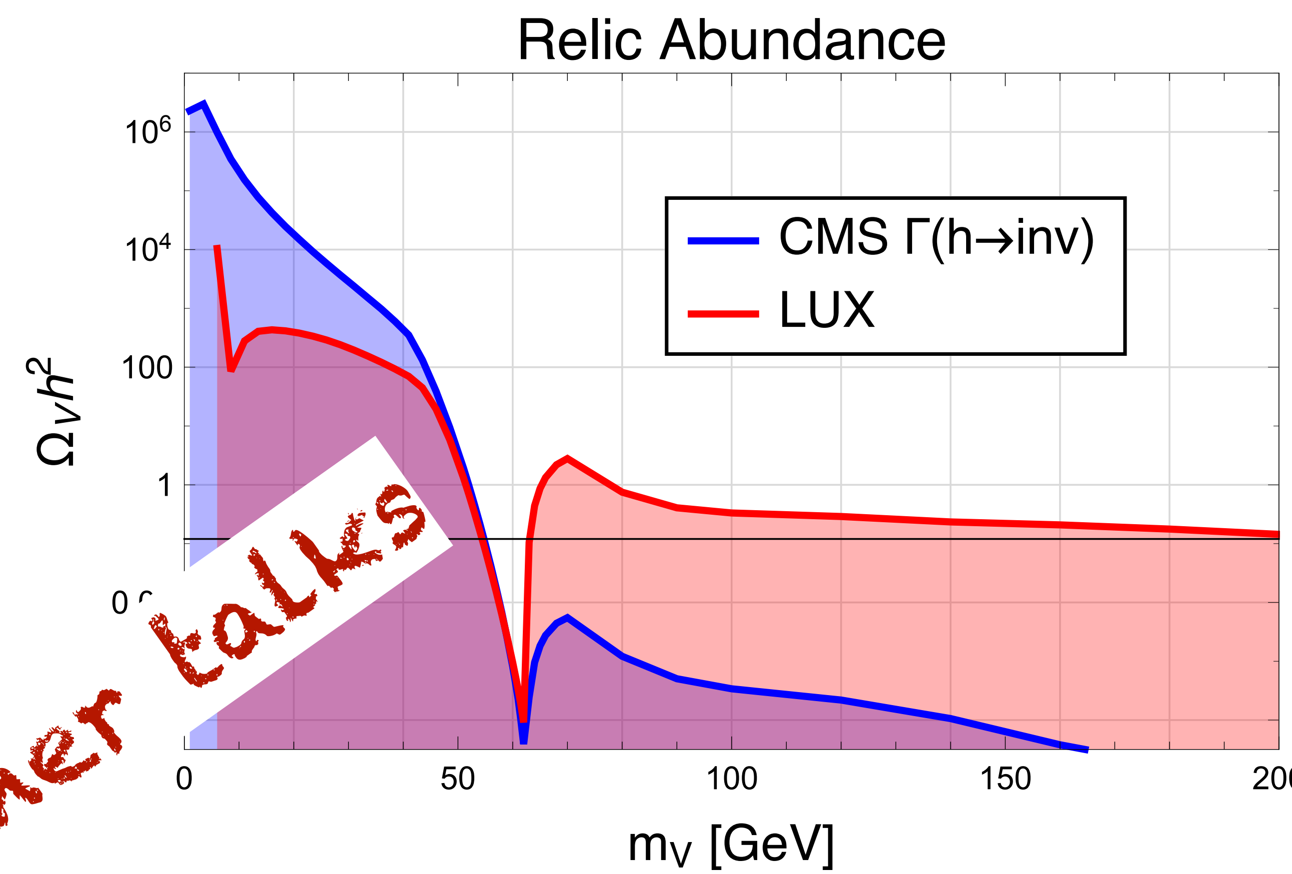




Single fermion limit

Everything decoupled except one light neutral fermion



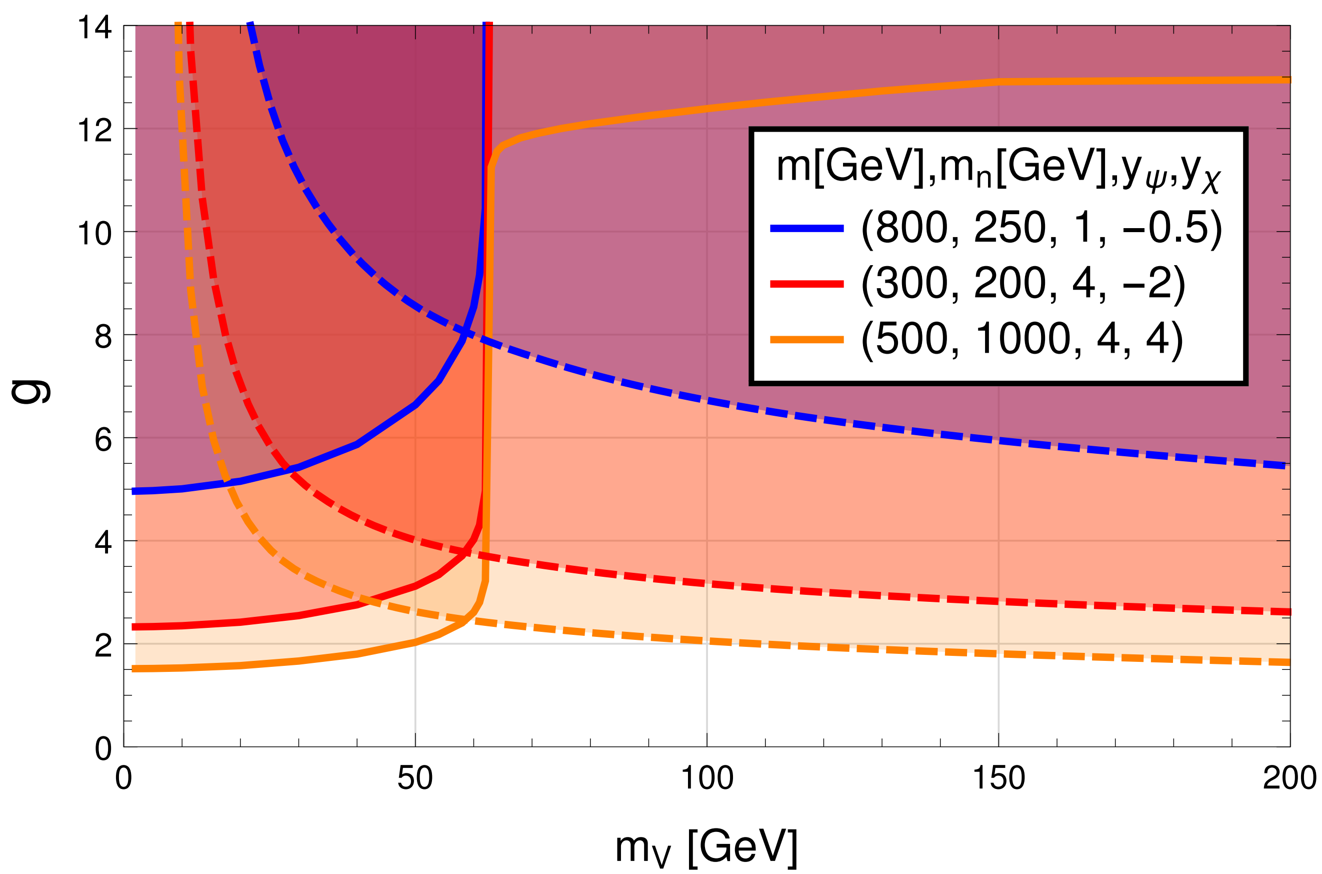


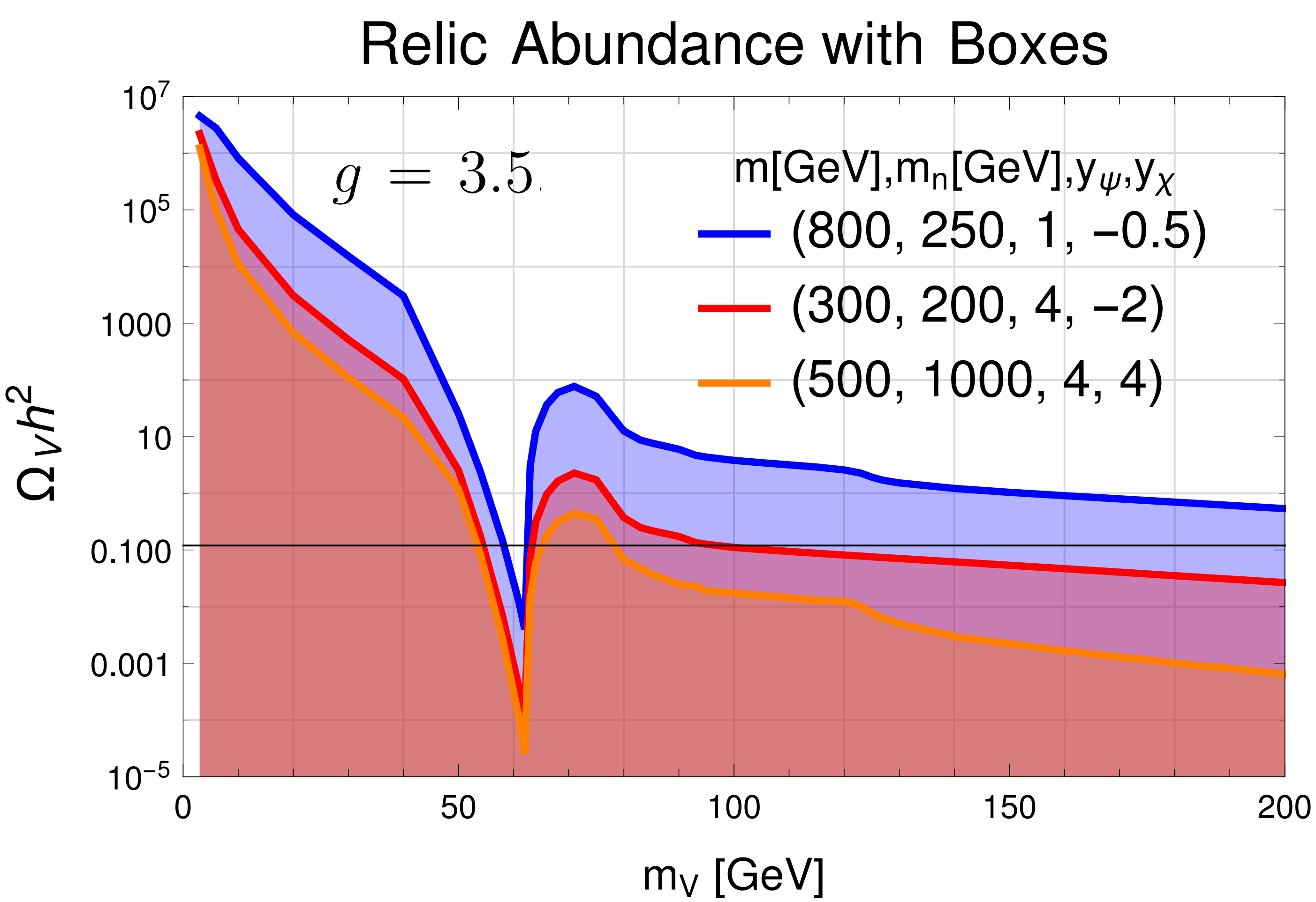
OLD...see other talks

- CMS = VBF, invisible Higgs 20/fb. 8TeV (*it's been a while*)
- LUX = 10 ton-day exposure

Only Higgs-funnel region works for cosmology (but there are ways out)

All fermions





- Loop generated Higgs-V coupling, cf tree-level Higgs portal
- New sub-TeV electroweak states (decays involve MET)
- Collider perspective similar to simpler single fermion case

Conclusions

- DM could be a spin-1 state
- Could couple to SM through Higgs exchange
- Direct Higgs portal not gauge invariant, need a UV completion
- Generate through tree-level H-Phi mixing
- Generate through heavy new fermions running in loop
- Simple model with a few parameters, only subset relevant for collider physics
- LHC provides strongest constraint below mH/2
- Can decouple second higgs unlike tree level case
- New fermionic states to search for

Python/Mathematica code exists for this

$$A(p^2) = \sum_i \left(\frac{g^2 y_i m_i}{2\sqrt{2}\pi^2} \right) F_1(p^2, m_i),$$

$$B(p^2) = \sum_i \left(\frac{g^2 y_i m_i}{2\sqrt{2}\pi^2} \right) F_2(p^2, m_i).$$

$$F_1(p^2, m) = \frac{1}{2bm^2(b-4a)^2} \Big\{ 2m^2(b-2a)\Big[4a(a-1) + b(1+6a-b)\Big] C_0 - 2a(2a+b)\Delta B_0 + (b-2a)(b-4a) \Big\}$$

$$F_2(p^2, m) = \frac{4a^2}{b(b-4a)^2} \Big\{ 2(b-a)\Delta B_0 - 2m^2\Big[4a(a-1) + b(1-2a+b)\Big] C_0 + 4a - b \Big\}$$

$$C_0 = \frac{1}{4m^2 b\beta} \sum_{j,k=1}^{2} \left[2\mathrm{Li}_2\left(\frac{1+(-1)^j\beta}{1+(-1)^k \mathrm{X}\beta} \right) - \mathrm{Li}_2\left(\frac{(1+(-1)^j\beta)^2}{1+(-1)^k 2\mathrm{Y}\beta + \beta^2} \right) \right]$$

$$\Delta B_0 \equiv B_0(m_V^2; m, m) - B_0(p^2; m, m)$$

$$= 2\sqrt{\frac{1-b}{b}} \arctan\left[\sqrt{\frac{b}{1-b}} \right] - 2\sqrt{\frac{1-a}{a}} \arctan\left[\sqrt{\frac{a}{1-a}} \right].$$

$$a \equiv \frac{m_V^2}{4m^2}, \qquad b \equiv \frac{p^2}{4m^2}$$