Dark Matter Phenomenology with Vector-like Quark

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Goals

- Compressed IDM spectrum and its origin
- Exotic quark extension of inert doublet model(IDM)
- Symmetry breaking and mass spectrum
- Experimental bounds
- Changes in IDM characteristics due to addition of exotic quarks
- Conclusion

Compressed IDM spectrum and its origin

- The mass gap between cp even and cp odd component and that of with the charged component of IDM are $M_A^0 - M_H^0 = -\lambda_5 \frac{V_{SM}^2}{M_H^0}$ and $M_H^+ - M_H^0 = -(\lambda_4 + \lambda_5)\frac{V_{SM}^2}{2M_H^0}$
- By examining the one loop RGE, we can see if one starts with $\lambda_5 = 0$ at any energy scale the λ_5 remains zero.
- Also from the one loop RGE of λ_4 one can tell λ_4 never reaches zero as RGE equation gets contribution from $3g^2g'^2$
- One can explain the compress region of IDM parameter space by considering an approximate global symmetry such as $U(1)$ or $SU(2)$ acting on the inert doublet.

Exotic quark extension of inert doublet model(IDM)

Fields	$SU(3)_C$	$\otimes SU(2)_L$	$\otimes U(1)_Y$	$\otimes \mathcal{Z}_2$
Fermions:				
$Q_L = \begin{pmatrix} u \\ d \end{pmatrix}_L$	3	2	$\frac{1}{3}$	$+$
u_R	3	1	$\frac{4}{3}$	$+$
d_R	3	1	-$\frac{2}{3}$	$+$
$L_L = \begin{pmatrix} \nu_\ell \\ \ell \end{pmatrix}_L$	1	2	-1	$+$
L_R	1	1	-2	$+$
ξ : $(\xi_L,\ \xi_R)$	3	1	$-\frac{2}{3}$	$-$
Scalars:				
$\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$	1	2	1	$+$
$\eta = \begin{pmatrix} \eta^+ \\ \eta^0 \end{pmatrix}$	1	2	1	$-$

$$V(\Phi,\eta) = \mu_1 \Phi^\dagger\Phi + \mu_2 \eta^\dagger \eta + \lambda_1 (\Phi^\dagger\Phi)^2 + \lambda_2 (\eta^\dagger\eta)^2 + \lambda_3 (\Phi^\dagger\Phi)(\eta^\dagger\eta) + \lambda_4 (\eta^\dagger\Phi)(\Phi^\dagger\eta) + \frac{\lambda_5}{2}\left[(\eta^\dagger\Phi)^2 + h.c.\right]$$

$$\mathcal{L}_Y = y_\xi \, \overline{Q}_L \eta \, \xi + m_\xi \, \overline{\xi} \, \xi$$

$$\begin{aligned} m_h^2 &= -\,2\mu_1^2 = 2\lambda_1 v^2 \\ m_{H^+}^2 &= \mu_2^2 + \lambda_3 v^2/2 \\ m_{H^0}^2 &= \mu_2^2 + (\lambda_3 + \lambda_4 + \lambda_5) v^2/2 \\ m_{A^0}^2 &= \mu_2^2 + (\lambda_3 + \lambda_4 - \lambda_5) v^2/2 \end{aligned}$$

Theoretical and experimental bounds

- **Vacuum stability**

$$\lambda_1,\ \lambda_2 > 0; \qquad \lambda_3 + 2\sqrt{\lambda_1\lambda_2} > 0$$
$$\lambda_3 + \lambda_4 - |\lambda_5| + 2\sqrt{\lambda_1\lambda_2} > 0$$

- **Perturbativity**

$$|\lambda_i| \lesssim 4\pi, \quad i = 1,2,3,4,5.$$

- **Relic and Direct Search**

$\Omega_{DM}h^2 = 0.120 \pm 0.001$ at 90% CL by PLANK measurement.
The XENON nT, LUX-ZEPLIN, scattering cross-section of DM nucleon interaction.

Changes in IDM characteristics due to edition of exotic quarks

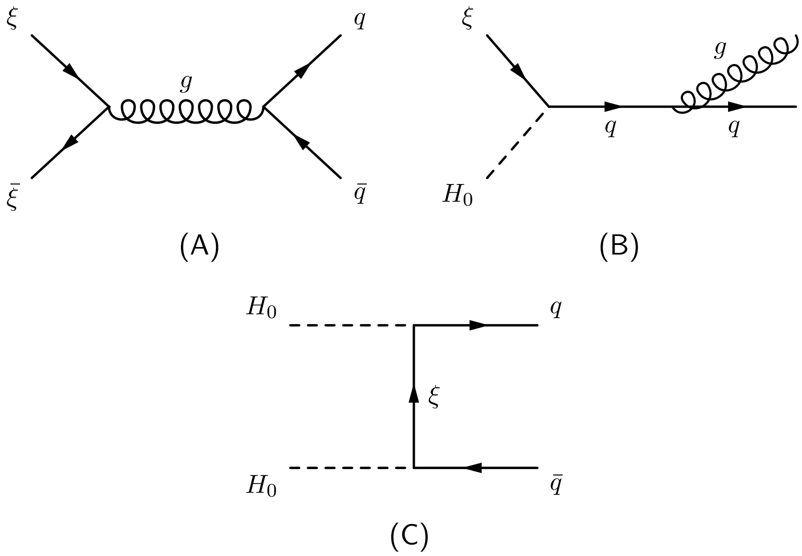


Figure: The 3 types of Feynman diagram for the annihilation channels involving ξ and the IDM sector.

Boltzmann equation

Chosen mass hierarchy $m_{H^0} < m_{H^\pm}, m_{A^0} < m_\xi$.

$$\frac{dn_{\rm DM}}{dt} + 3Hn_{\rm DM} = -\langle\sigma v\rangle_{\rm eff}\left(n_{\rm DM}^2 - n_{\rm eq}^2\right)$$

$$\begin{aligned}\langle\sigma v\rangle_{eff} =& \frac{g_0^2}{g_{\rm eff}^2}\langle\sigma v\rangle_{H^0H^0} + \frac{2g_0g_i}{g_{\rm eff}^2}\langle\sigma v\rangle_{H^0H^i}\left(1+\Delta_{H^i}\right)^{\frac{3}{2}} e^{-x\Delta_{H^i}} \\ &+ \frac{2g_ig_j}{g_{\rm eff}^2}\langle\sigma v\rangle_{H^iH^j}\left(1+\Delta_{H^i}\right)^{\frac{3}{2}}\left(1+\Delta_{H^j}\right)^{\frac{3}{2}} e^{-x(\Delta_{H^i}+\Delta_{H^j})} \\ &+ \frac{2g_0g_\xi}{g_{\rm eff}^2}\langle\sigma v\rangle_{H^0\xi}\left(1+\Delta_{H^0}\right)^{\frac{3}{2}} e^{-x\Delta_{H^0}} \\ &+ \frac{2g_ig_\xi}{g_{\rm eff}^2}\langle\sigma v\rangle_{H^i\xi}\left(1+\Delta_{H^i}\right)^{\frac{3}{2}}\left(1+\Delta_\xi\right)^{\frac{3}{2}} e^{-x(\Delta_{H^i}+\Delta_\xi)} \\ &+ \frac{2g_\xi^2}{g_{\rm eff}^2}\langle\sigma v\rangle_{\xi\xi}\left(1+\Delta_\xi\right)^3 e^{-2x\Delta_\xi}\end{aligned}$$

Here $\Delta_i = \frac{(m_i - m_{H^0})}{m_{H^0}}$ and g_i is the multiplicity of the i^{th} particle.

where $i = H^\pm, A^0 and \xi$

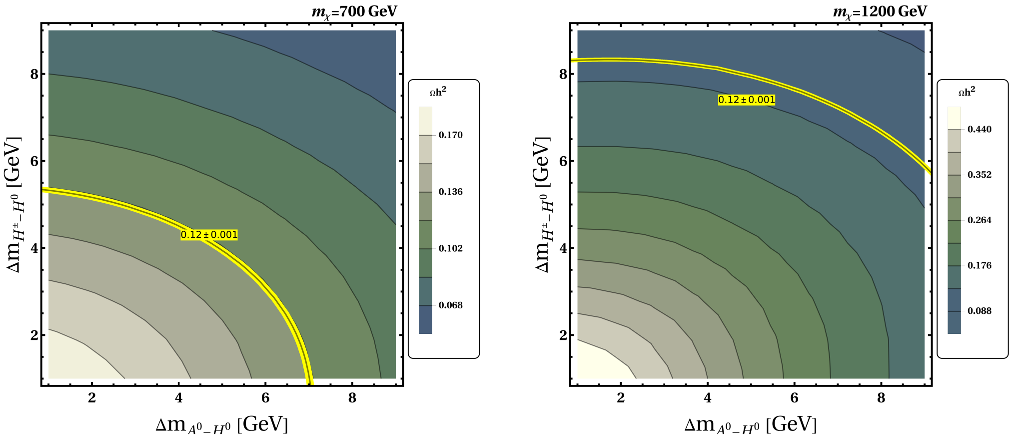


Figure: Variation of DM relic density with $\Delta m_{H^+ - H^0}$ and $\Delta m_{A^0 - H^0}$, for different DM mass for pure IDM.

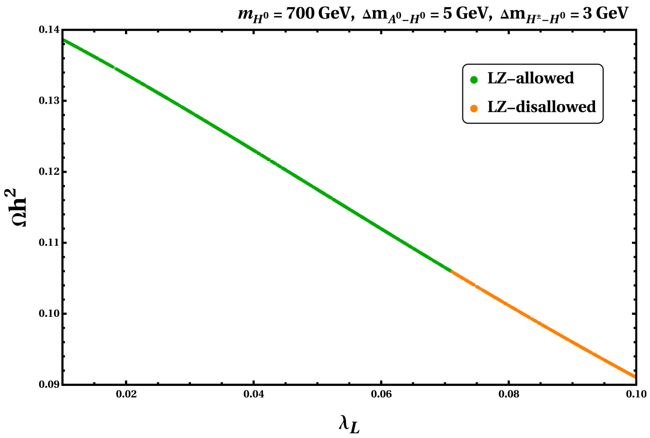


Figure: Variation of DM relic density with DM mass for different λ_L values for pure IDM.

VLQ contribution to DM relic

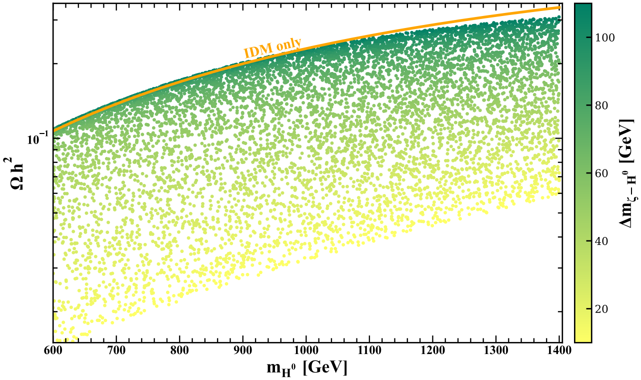
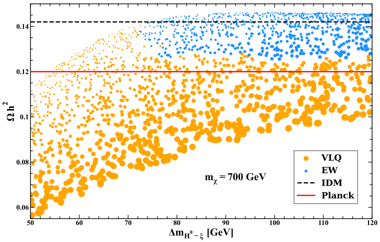


Figure: Variation of relic density with the DM mass in presence of VLQ compared with standard IDM case with a random scan over mass-splitting between DM and VLQ. Where $\lambda_L = 0.001$ and the mass gap between the charged and CP-odd scalar with the DM is kept fixed at 4 GeV and 5 GeV, respectively.

VLQ contribution to DM relic



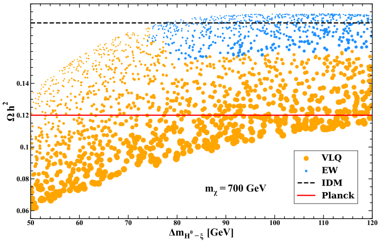


Figure: Orange points denotes the scan region which has more than 10% of VLQ contribution to $\langle \sigma v \rangle_{eff}$ while Blue region consist of parameters where it is less than 10%

VLQ contribution to DM relic

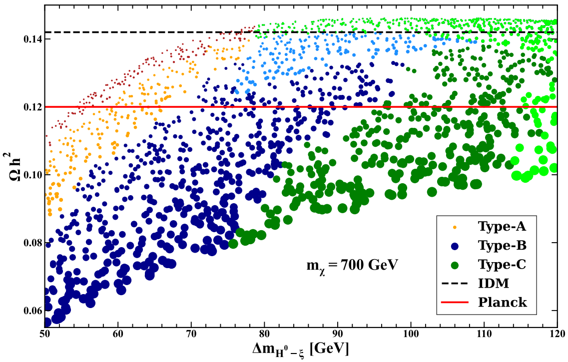


Figure: Scatter plot of relic density of DM against mass-splitting between DM and the VLQ ($\Delta m_{H^0-\xi}$). While the color of the points represent the Feynman diagram it gets the dominant contribution from, among all VLQ channels, the sizes of the points are scaled to the size of the Yukawa coupling y_ξ which varies from 0.1 to 0.9.

VLQ contribution to DM relic

y_ξ **range**	$\Delta m_{H^0-\xi}$	**Contributions among VLQ diagrams**
Small	Small	Type-A $>$ Type-B $>$ Type-C
Intermediate	Small	Type-B $>$ Type-A $>$ Type-C
Large	Large	Type-C $>$ Type-B $>$ Type-A

Table: Summery table of different region types and their dependency on the Yukawa-like coupling and the DM-VLQ mass splitting.

Conclusion

- Pure IDM DM models demands sizable mass gap between the dark sector particles or increase in coupling with standard model Higgs at higher DM mass.
- Addition of a VLQ to pure IDM helps controlling the inert sector mass gap and coupling with Higgs to satisfy the DM relic density.
- As $\lambda_L = \frac{1}{2}(\lambda_3 + \lambda_4 + \lambda_5)$ is not needed to satisfy the observed relic density, it can be made arbitrarily small which helps satisfying the Direct Detection constraints.
- Addition of a VLQ to the inert sector boosts the production cross-section of inert sector at hadroni colliders.
- As the inert sector mass gap now can be made very small it may also offer some LLP-like features (*work in progress*).

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Thank You!