Vector Boson Dark Matter From Trinification

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Motivation

- Based on $SU(3)_C \times SU(3)_L \times SU(3)_R$ (Trinification)

[Rujula, Georgi, Glashow, '84]

— Can be realized at TeV scale

— Quantization of electric charge

$$Q = T_{3L} + T_{3R} + \frac{1}{\sqrt{3}}(T_{8L} + T_{8R})$$

— Models are asymptotically free and can be extrapolated all the way up to the Planck scale [Pelaggi, Strumia, Vignali, '15]

— Does not lead to gauge boson mediated proton decay

[Babu, He, Pakvasa, '86]

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- Verities of DM candidate

  i) Doublet-singlet fermionic DM

  ii) Singlet scalar DM

  iii) Vector boson DM

Vector Boson DM

- Natural realization: DM candidate under discrete trinification parity (T-parity)

$$T = (-1)^{I_{8_L} + I_{8_R} + 2S}$$

- Vector Boson DM ($W_{7\mu}$):
  - Electrically neutral and singlet of the SM gauge symmetry
  - Couples off-diagonally to fermions and scalars
  - DM candidate originates from the symmetry breaking chain:

$$\chi \equiv (1,6,6^\star)$$
$$\Phi \equiv (1,3,3^\star)$$

$$SU(3)_C \times SU(3)_L \times SU(3)_R$$

$\downarrow$ $\langle \chi \rangle \neq 0 \implies$ Majorana mass for ν_R

$$SU(3)_C \times SU(2)_L \times U(1)_Y \times O(2)_R$$

$\downarrow$ $\langle \Phi \rangle \neq 0 \implies$ mass to SM fermions

$$SU(3)_C \times U(1)_{em}$$

The gauge boson of the $O(2)$ is the DM candidate

Model

- Fermion Fields: $\{Q_L \oplus Q_R \oplus \psi_L\}$

$$Q_L\,(3,3^\star,1) = \begin{pmatrix} u \\ d \\ D \end{pmatrix}_L \qquad Q_R\,(3,1,3^\star) = \begin{pmatrix} u \\ d \\ D \end{pmatrix}_R$$

vector-like iso-singlet

vector-like doublets

$$\psi_L\,(1,3,3^\star) = \begin{pmatrix} E^0 & E^- & e^- \\ E^+ & E^{c0} & \nu \\ e^c & \nu^c & N \end{pmatrix}_L$$

$SU(3)_L$ ↓ $SU(3)_R$ →

- SM + ν^c : T even

- Lepton number explicitly broken

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$SU(3)_L \downarrow \qquad SU(3)_R \rightarrow$

- SM + ν^c : T even
- Lepton number explicitly broken

- Scalar Fields: $\Phi_n \sim (1,3,3^\star)$ $\quad \chi \sim (1,6,6^\star)$

  $n \neq 1$

  - The vacuum expectation value are:

components: Φ_i^α and $\chi_{ij}^{\alpha\beta}$

$ij : SU(3)_L \qquad \alpha\beta : SU(3)_R$

$$\langle \Phi_n \rangle = \begin{pmatrix} v_{un} & 0 & 0 \\ 0 & v_{dn} & 0 \\ 0 & 0 & V_n \end{pmatrix}, \qquad \langle \chi_{33}^{22} \rangle = V_\nu\,, \qquad \langle \chi_{33}^{33} \rangle = V_N$$

$\langle \Phi_2^3 \rangle$ (VEV of ν^c-like scalar) = 0 $\Longrightarrow$ Unbroken T-parity

Fermion mass

$$-\mathscr{L}_Y = Y_{qn}\, \bar{Q}_{L\alpha}(\Phi_n)^\alpha_i Q^i_R + Y_{\ell n}\, \psi^\alpha_i \psi^\beta_j (\Phi_n)^\gamma_k \epsilon^{ijk}\epsilon_{\alpha\beta\gamma} + y_\ell\, \psi^\alpha_i \psi^\beta_j \chi^{ij}_{\alpha\beta} + h.c.$$

- Quark masses:

$$M_u = Y_{qn}\, v_{un}$$
$$M_d = Y_{qn}\, v_{dn}$$
$$M_D = Y_{qn}\, V_n$$

$n = 3 \Longrightarrow$ no obvious relation among mass matrices + TeV scale breaking

$$M_u = Y_{q1}\, v_{u1}\,, \quad M_d = Y_{q2}\, v_{d2}\,, \quad M_D = Y_{q3}\, V_3$$

- Charged leptons: $M_e = -\,Y_{\ell n}\, v_{dn}\,, \quad M_{E^\pm} = -\,Y_{\ell n}\, V_n$

Fermion mass

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- Charged leptons: $M_e = -\,Y_{\ell n}\ v_{dn},\quad M_{E^\pm} = -\,Y_{\ell n}\ V_n$

- Neutral leptons:

$(\nu,\ \nu^c)$

$$M_\nu = \begin{pmatrix} 0 & -Y_{\ell n} v_{un} \\ -Y_{\ell n} v_{un} & y_\ell V_\nu \end{pmatrix}$$

$(E^{c0},\ E^0,\ N)$

$$M_N = \begin{pmatrix} 0 & Y_{\ell n} V_n & Y_{\ell n} v_{un} \\ Y_{\ell n} V_n & 0 & Y_{\ell n} v_{dn} \\ Y_{\ell n} v_{un} & Y_{\ell n} v_{dn} & y_\ell V_N \end{pmatrix}$$

$$m_\nu^{\text{light}} \simeq -\,(Y_{\ell n} v_{un})(y_\ell V_\nu)^{-1}(Y_{\ell n} v_{un})$$

T odd → Lightest particle ⇒DM

Gauge Bosons

$$\mathscr{L}_{gauge} = \sum_n D^\mu(\Phi_n)_i^\alpha \; D_\mu(\Phi_n)^i_\alpha + \sum_{\alpha\beta ij} (D_\mu \chi_{ij}^{\alpha\beta}) \; (D^\mu \chi^{ij}_{\alpha\beta})$$

$$\vec{T}\cdot\vec{W}^\mu_{L,R} = \begin{pmatrix} W_3 + \frac{W_8}{\sqrt{3}} & \sqrt{2}W^+ & \sqrt{2}V^+ \\ \sqrt{2}W^- & -W_3 + \frac{W_8}{\sqrt{3}} & \sqrt{2}V^0 \\ \sqrt{2}V^- & \sqrt{2}V^{0*} & \frac{-2W_8}{\sqrt{3}} \end{pmatrix}^\mu_{L,R}$$

T odd

$$W^{\pm\mu} = \frac{W_1^\mu \mp iW_2^\mu}{\sqrt{2}} \qquad V^{\pm\mu} = \frac{W_4^\mu \mp iW_5^\mu}{\sqrt{2}}$$

$$V^{0(*)\mu} = \frac{W_6^\mu \mp iW_7^\mu}{\sqrt{2}}$$

T parity $\Longrightarrow$

no mixing $W^{\mu\pm}$ and $V^{\mu\pm}$

$(W_L^{\mu+}, W_R^{\mu+})$; $(V_L^{\mu+}, V_R^{\mu+})$

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- (W^μ_{6L}, W^μ_{6R}) and (W^μ_{7L}, W^μ_{7R})

$$V_\nu \simeq V_N \gg V_n$$
$$(V_N - V_\nu) = aV_n$$

$$\frac{1}{2}\begin{pmatrix} g_L^2(v_{dn}^2 + V_n^2 + 2\,(V_N^2 + V_\nu^2)) & -2g_Lg_Rv_{dn}V_n \\ -2g_Lg_Rv_{dn}V_n & g_R^2(v_{dn}^2 + V_n^2 + 2\,(V_N - V_\nu)^2) \end{pmatrix}$$

- T even neutral gauge boson $(W^\mu_{3L}, W^\mu_{3R}, W^\mu_{8L}, W^\mu_{8R})$ mix to give $(A^\mu, Z^\mu, Z_1^{\prime\mu}, Z_2^{\prime\mu})$ physical states

Gauge Bosons

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- At the scale $SU(3)_L \times SU(3)_R$ unification:

$$\alpha_R^{-1} = \frac{3}{4}\alpha_Y^{-1} - \frac{1}{4}\alpha_L^{-1}$$

$$\alpha_L = g_L^2/4\pi \qquad \alpha_R = g_R^2/4\pi$$

- Taking $\alpha_{em}(m_Z) = 1/127.940$, $\sin^2\theta_W(m_Z) = 0.23126$, $\alpha_{em}^{-1} = \alpha_L^{-1} + \alpha_Y^{-1}$, and one-loop renormalization group equations with $b_i = 41/6\ (-19/6)$ for $\alpha_{Y(L)}$

$$\alpha_R/\alpha_L\ (5\ \text{TeV}) = 0.49$$

$\vec{T} \cdot \vec{W}^\mu_{L,R} =$ … $\Rightarrow$ … and $V^{\mu\pm}$ … $(V_L^{\mu+}, V_R^{\mu+})$

- $(W^\mu_{6L}, W^\mu_{6R}$ … $V_N \gg V_n$ … $V_\nu) = aV_n$

$$\frac{1}{2}\begin{pmatrix} g_L^2(v_{dn}^2 + V_n^2 + 2\,(V_N + V_\nu)^2) & -2g_Lg_Rv_{dn}V_n \\ -2g_Lg_Rv_{dn}V_n & g_R^2(v_{dn}^2 + V_n^2 + 2\,(V_N - V_\nu)^2) \end{pmatrix}$$

- T even neutral gauge boson $(W^\mu_{3L}, W^\mu_{3R}, W^\mu_{8L}, W^\mu_{8R})$ mix to give $(A^\mu, Z^\mu, Z_1'^\mu, Z_2'^\mu)$ physical states

Higgs sector

$$V = V(\chi) + V(\phi) + V(\Phi, \chi)$$

- 36 complex components in $\chi_{ij}^{\alpha\beta} \Rightarrow$ 6 triplets, 6 doublets, 6 singlets
- Φ_i^{α} decomposes into 3 doublets and 3 singlet fields
- T parity even fields

χ_{EE} , χ_{EE^c} , $\chi_{e\nu}$ $\sim (1,3,1)$ χ_{EN}, χ_{E^cN}, Φ_{EE^c}, Φ_{EE}, $\sim (1,2,1/2)$

$\chi_{33}^{11} \sim (1,1,2)$, ($\delta^{++}$) $\chi_{33}^{12} \sim (1,1,1)$, $(\chi_{33}^{22}, \chi_{33}^{33}, \Phi_3^3) \sim (1,1,0)$ (h' & $\tilde{h}$)

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$\chi_{EE}\,,\ \chi_{EE^c}\,,\ \chi_{e\nu} \sim (1,3,1)$

$\chi_{EN}, \chi_{E^cN}, \Phi_{EE^c}, \Phi_{EE} \sim (1,2,1/2)$

$\chi_{33}^{11} \sim (1,1,2),$ (δ^{++}) $\quad \chi_{33}^{12} \sim (1,1,1), \quad (\chi_{33}^{22}, \chi_{33}^{33}, \Phi_3^3) \sim (1,1,0)$ ($h' \,\&\, \tilde{h}$)

- T parity odd fields

$\chi'_{EE}\,, \chi'_{E\nu} \sim (1,3,0)$

$\chi_{E\nu^c}\,, \chi_{E^c\nu^c}\,, \chi_{eN}\,, \Phi_{e\nu} \sim (1,2,1/2)$

$\chi_{Ee} \sim (1,3,1)$

$\chi_{Ee^c} \sim (1,2,3/2)$

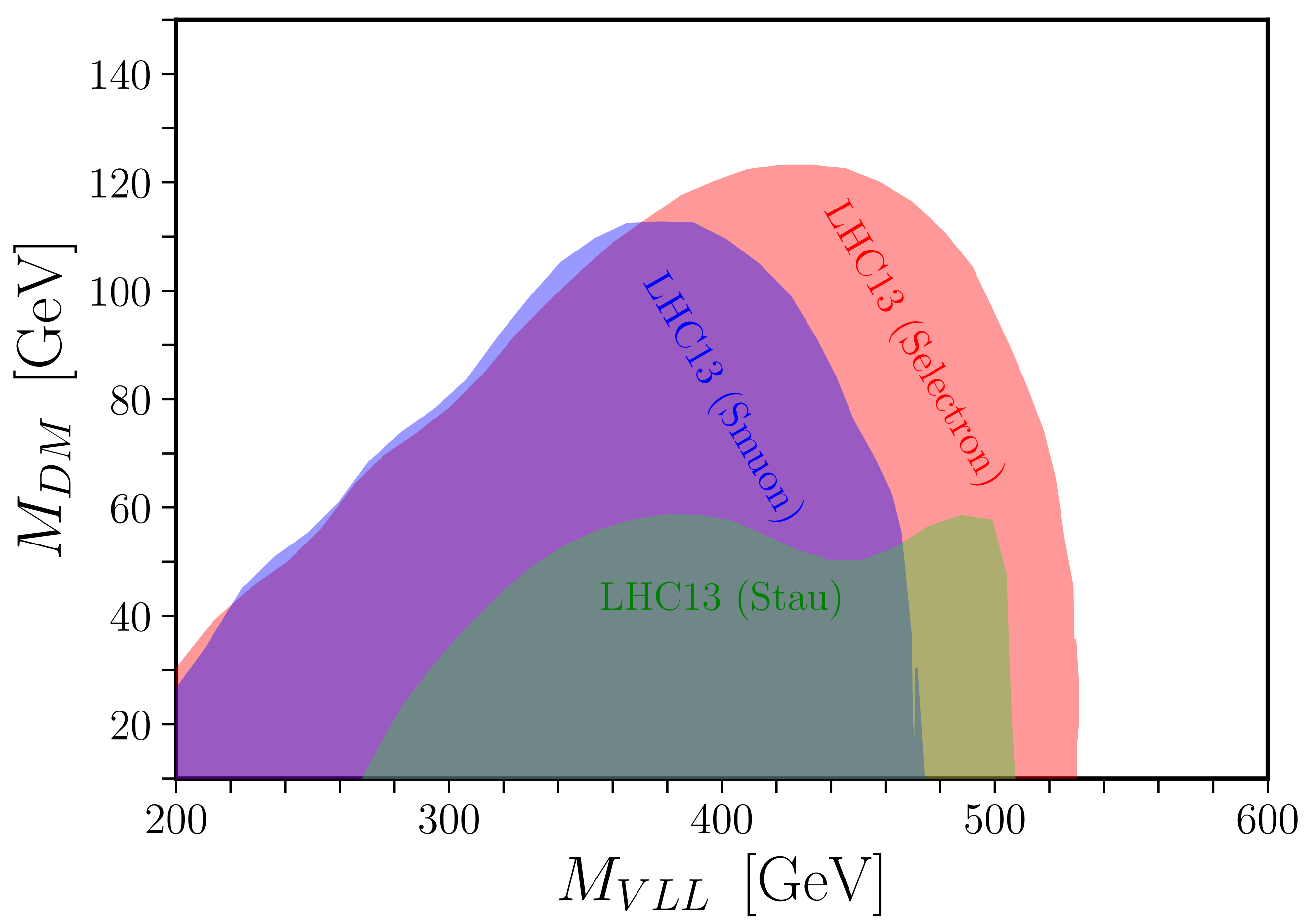
$(\chi_{33}^{13}, \Phi_3^1) \sim (1,1,1)$

$(\chi_{33}^{23}, \Phi_3^2) \sim (1,1,0)$

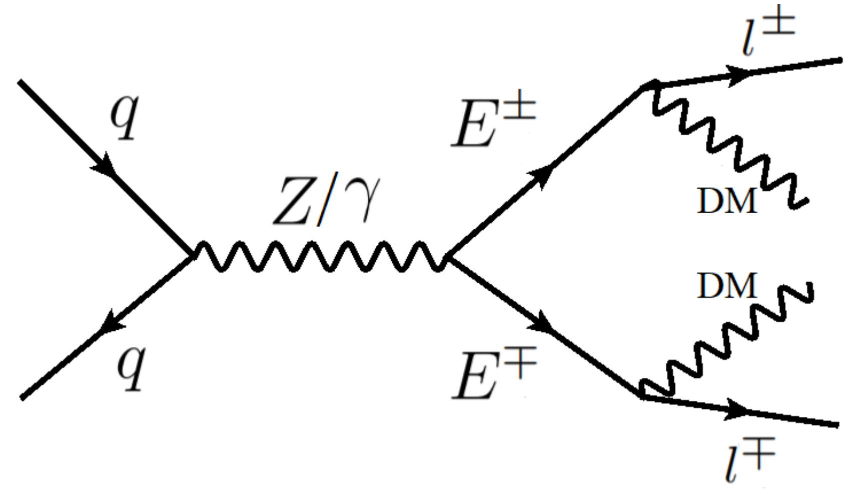
$H' \longrightarrow$ if lightest $\Rightarrow$ DM

Light scalars $\{\delta^{++}, h', H', \tilde{h}\}$

Collider Implications



$$pp \to l^+ l^- + \not{E}_T$$



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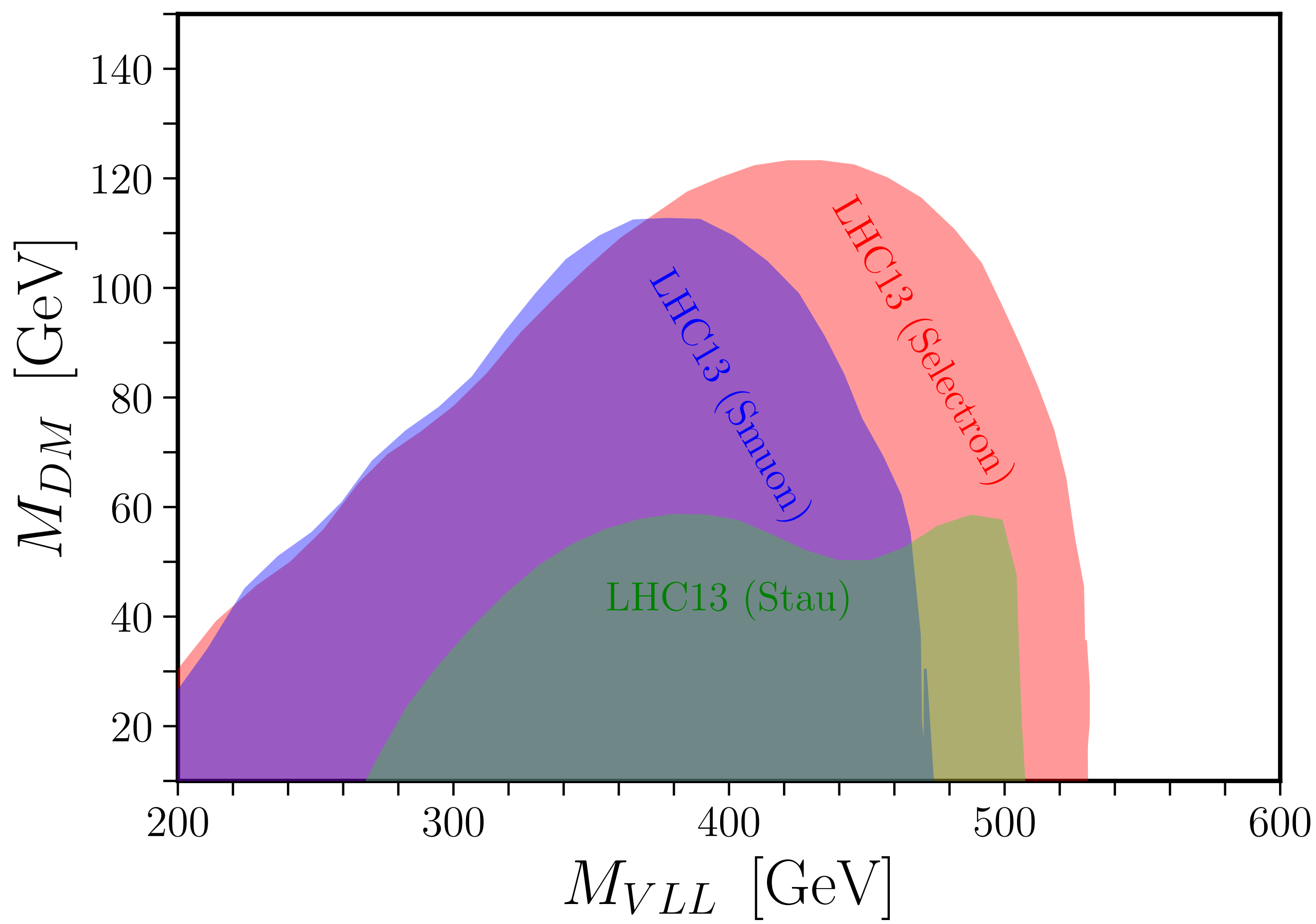
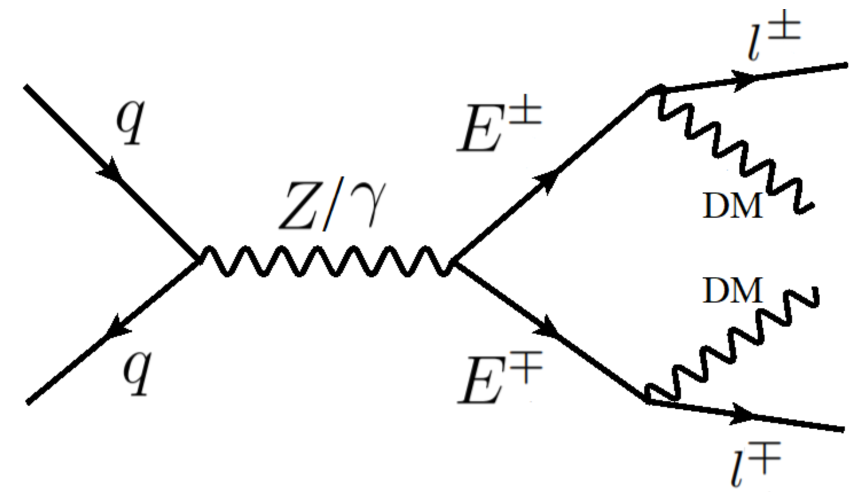
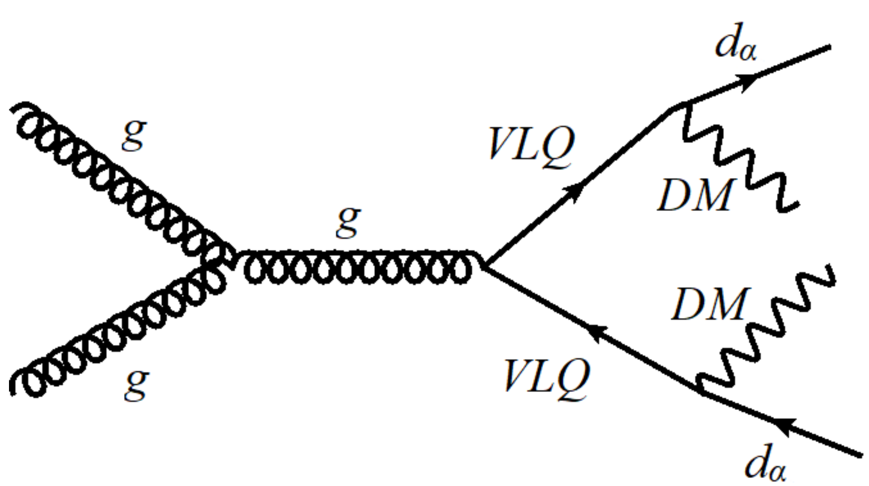
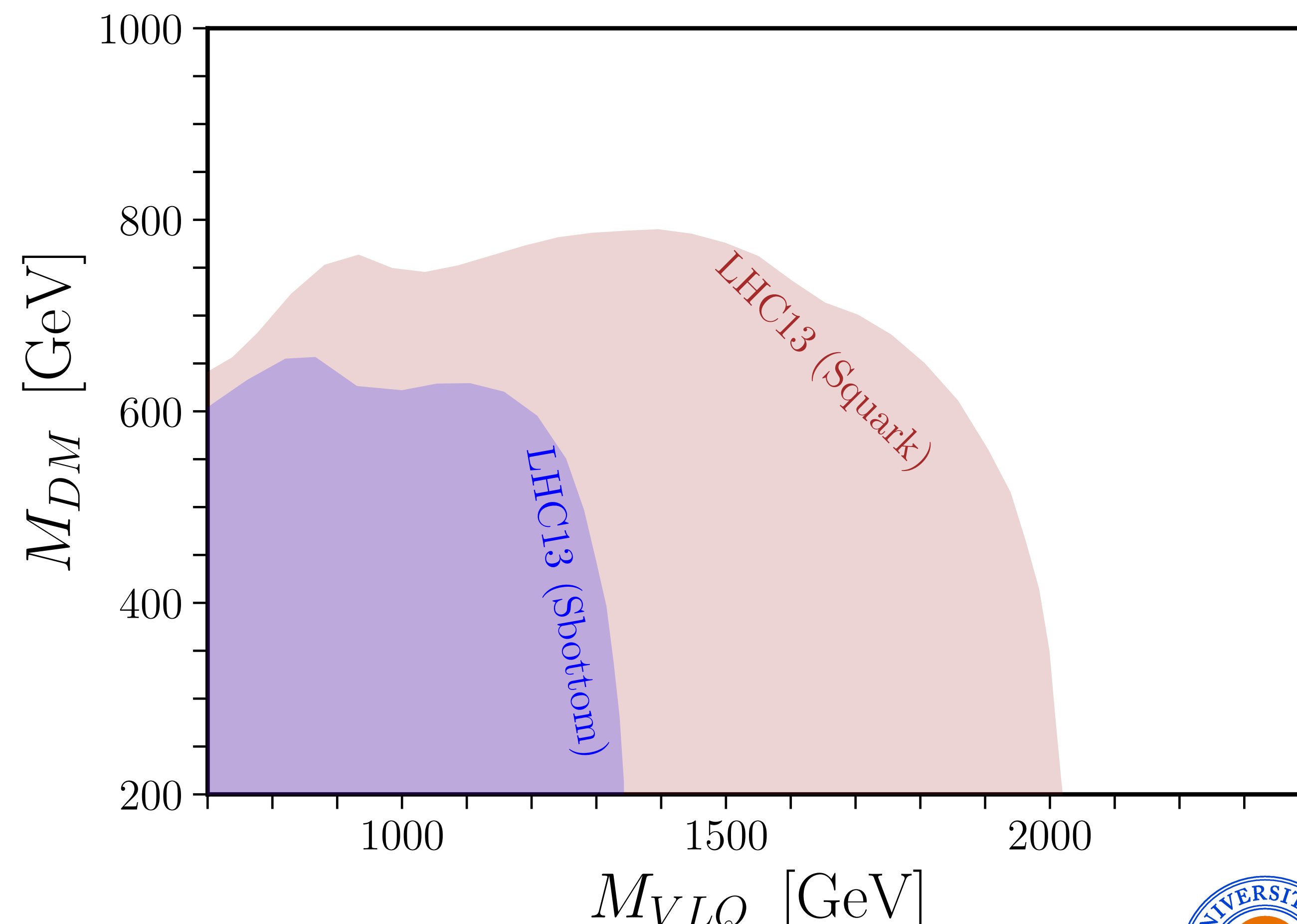


$pp \to l^+ l^- + \not{E}_T$



$pp \to jj\ (bb) + \not{E}_T$



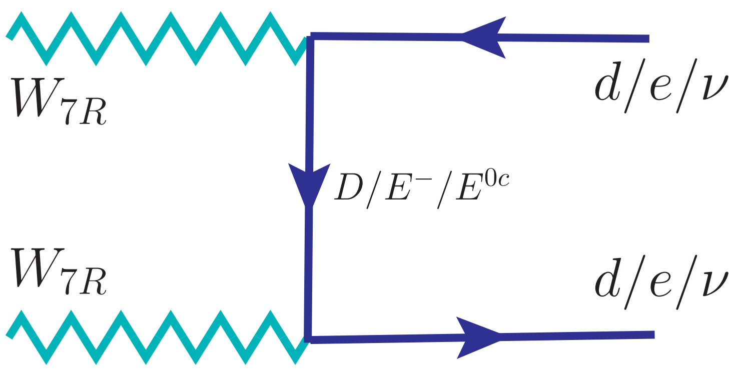


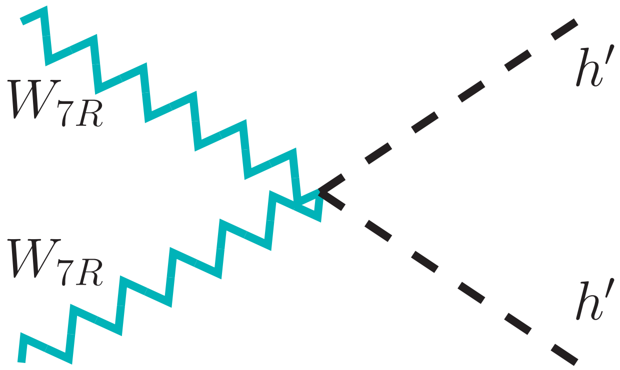
DM Phenomenology

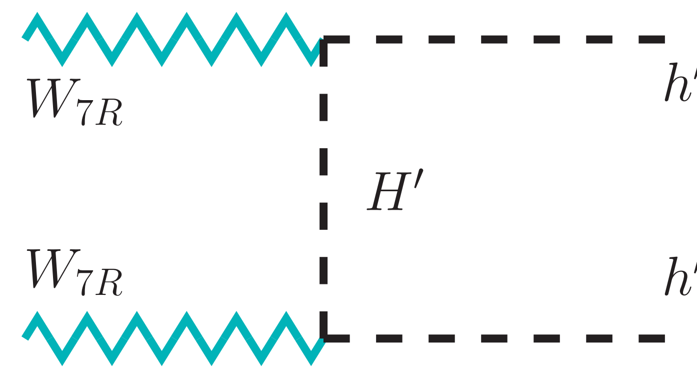
$$M_{W_{7R}} \equiv M_{DM} \simeq \frac{1}{\sqrt{2}} g_R V_n \sqrt{1+2a^2}$$

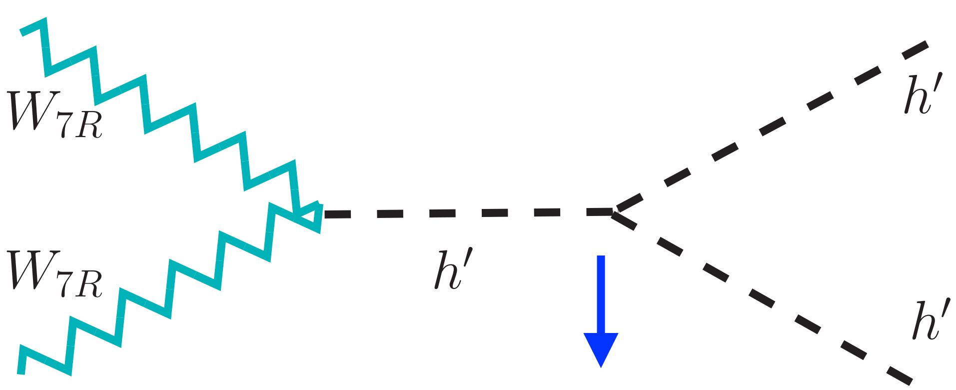
$$M_{VLQ} \leq \frac{5M_{DM}}{\sqrt{1+a^2}}$$

- mixing ~ 0 with SM Higgs $\Rightarrow$ avoid Direct detection limits
- Annihilation determined by the gauge coupling g_R and masses

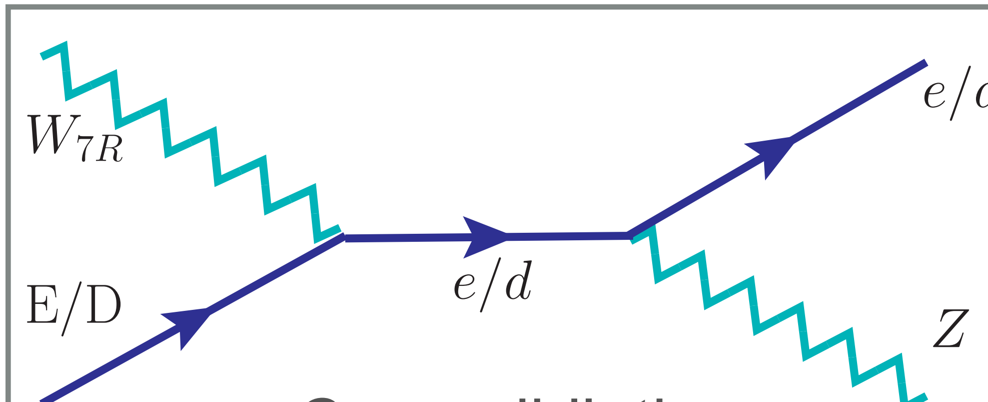








$$\lambda_{h'} = \frac{g_R^2}{8} \frac{M_{h'}^2 (1+2a^2)}{M_{W_7}^2}$$

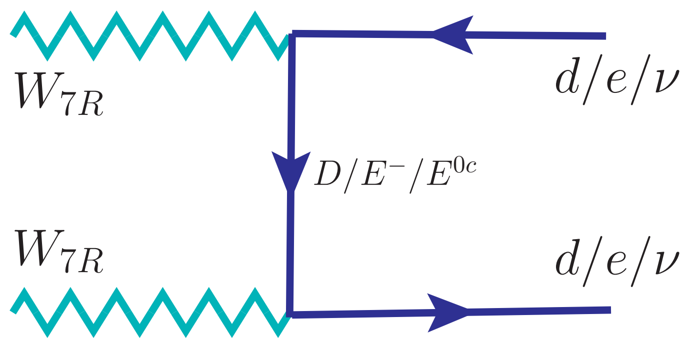


Co-annihilation

$$\{M_{DM}, M_{VLQ}, M_{VLL}, M_{h'}\}$$

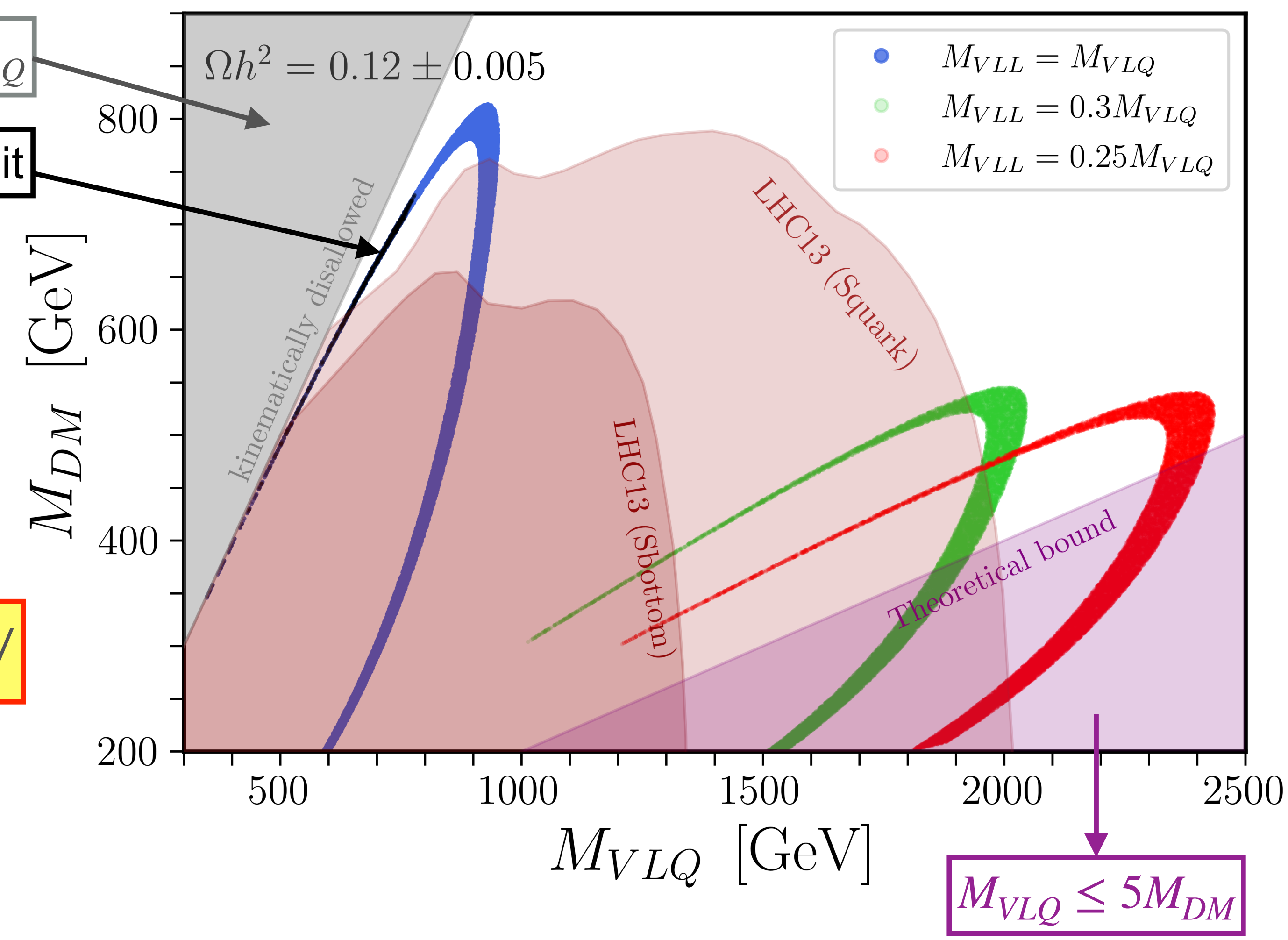
DM: $M_{h'} > M_{DM}$

$\{M_{DM}, M_{VLQ}, M_{VLL}\}$



$M_{DM} > M_{VLQ}$

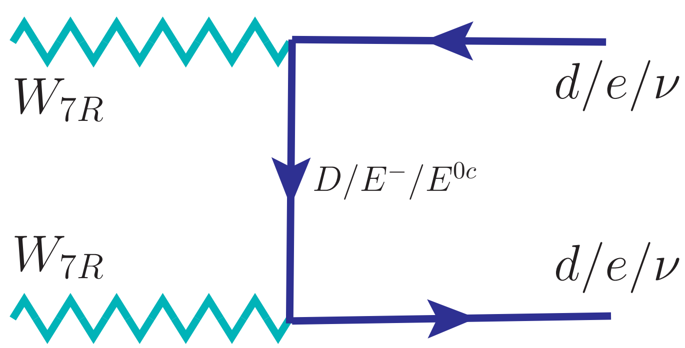
Direct Detection Limit



$M_{DM} \lesssim 800$ GeV

DM: $M_{h'} > M_{DM}$

$\{M_{DM}, M_{VLQ}, M_{VLL}\}$



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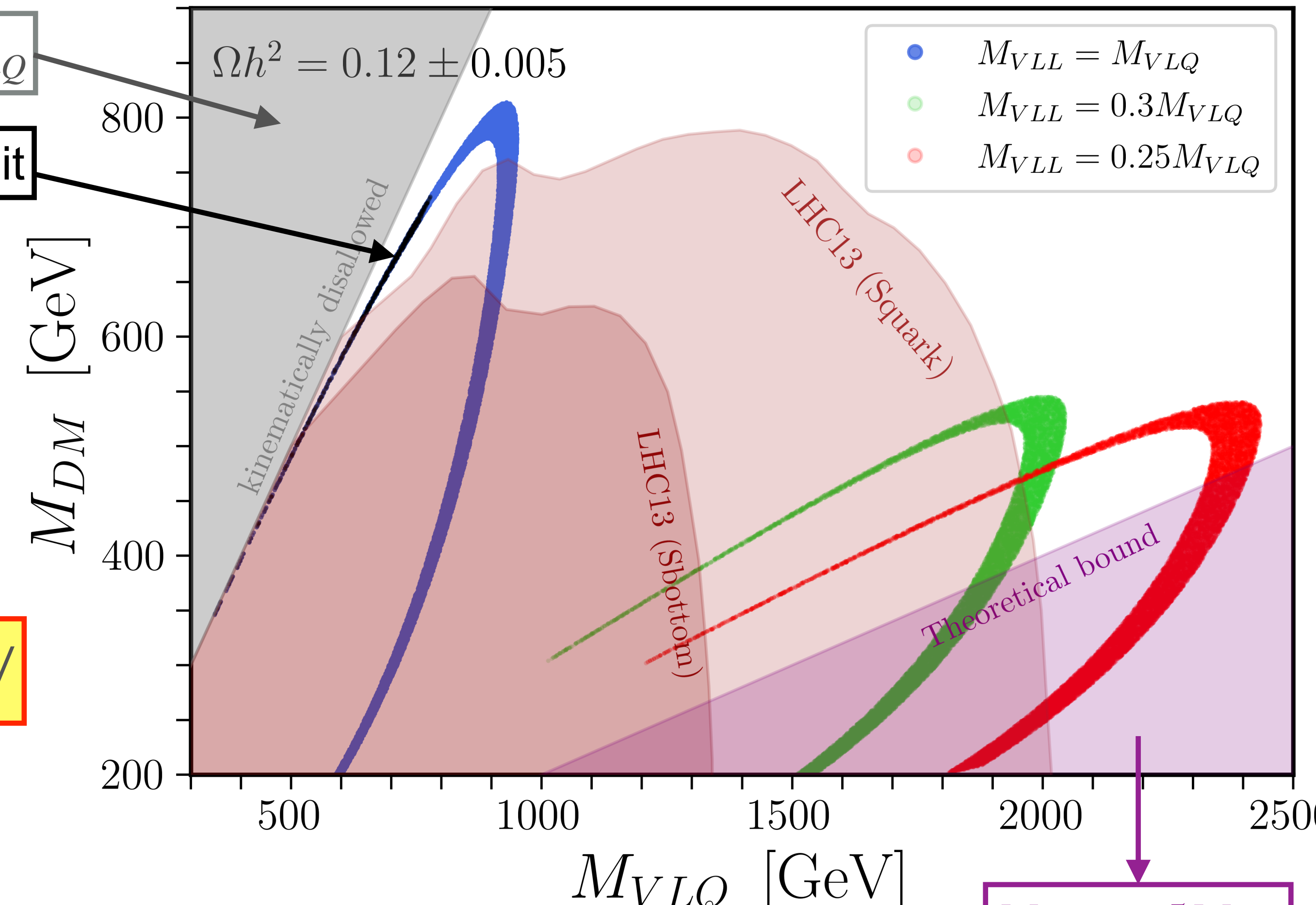
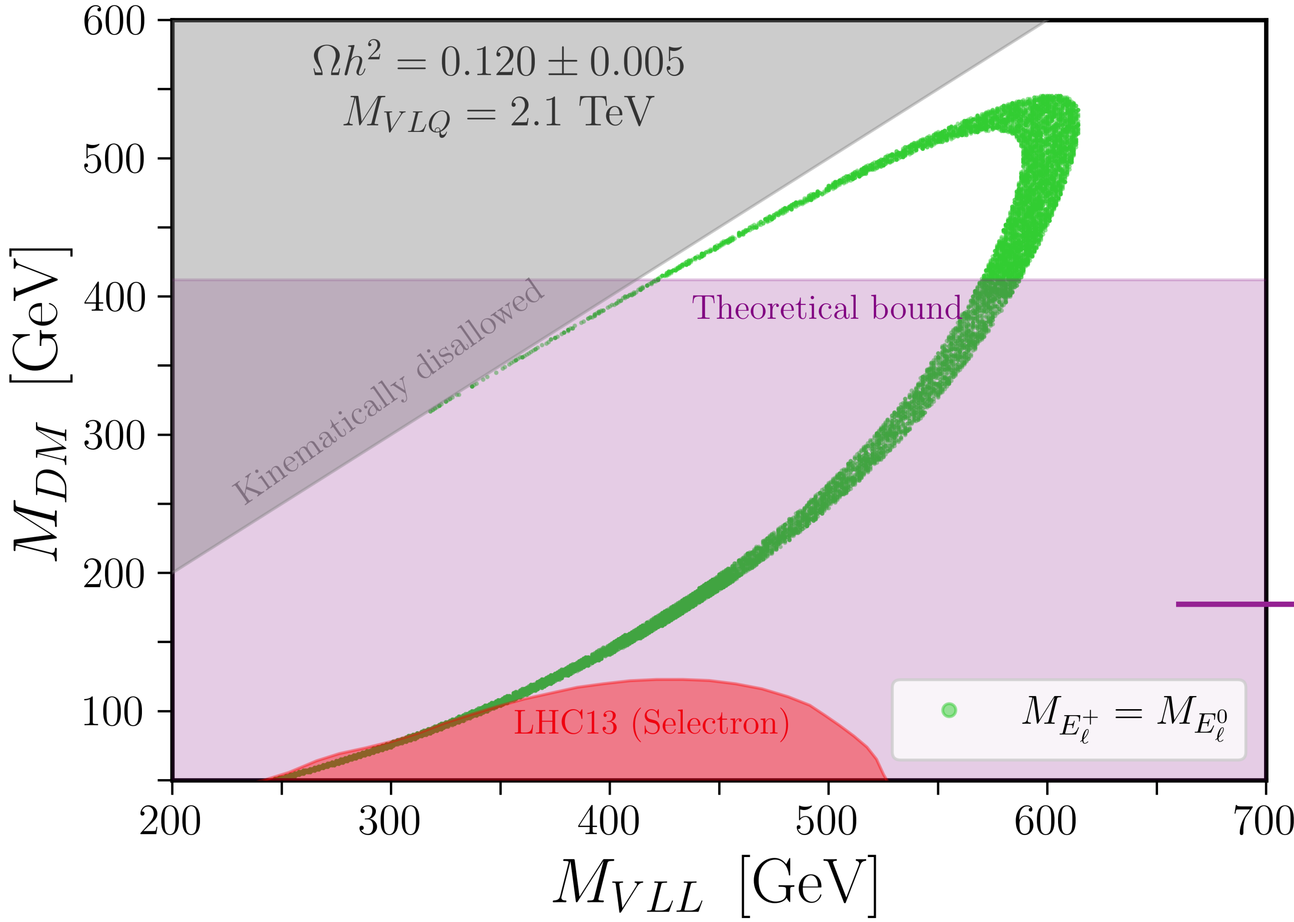


$M_{VLQ} \leq 5 M_{DM}$

$M_{DM} \lesssim 800$ GeV



- $M_{VLQ} = 2.1$TeV $\Rightarrow$ collider bounds are satisfied

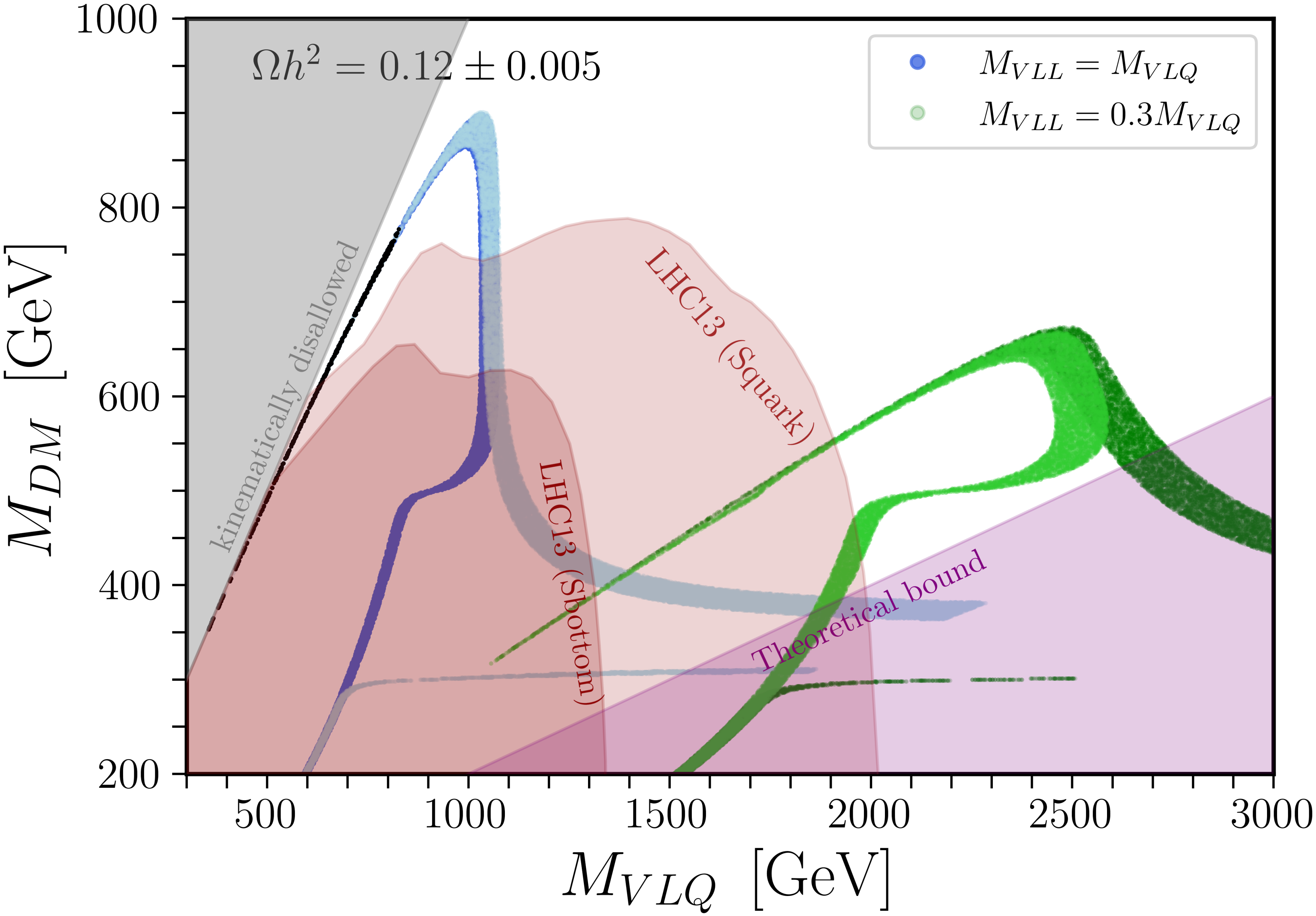
$M_{VLQ} \leq 5 M_{DM}$

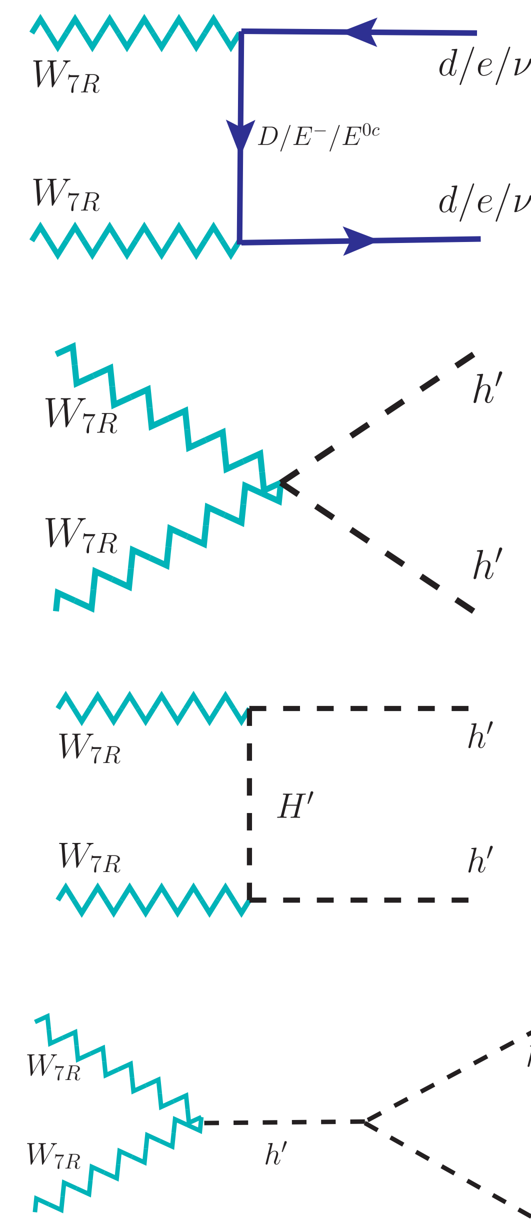
$M_{DM} \lesssim [500 - 600]$ GeV

DM: $M_{h'} < M_{DM}$

$\{M_{DM}, M_{VLQ}, M_{VLL}, M_{h'}\}$

(i) $M_{h'} = 500$ GeV (blue/green) (ii) $M_{h'} = 300$ GeV (blue/green)





$M_{DM} \lesssim 900$ GeV $\Longrightarrow$ $M_{VLQ} \leq 4.5$ TeV & $M_{VLL} \leq 6.0$ TeV

Conclusion

- DM candidate arises from TeV scale Trinification
- This setup admits doublet singlet fermionic DM, scalar singlet DM, as well as vector boson DM.
- The model predicts the vector boson DM mass to be below 900 GeV, along with upper limits of 4.5 TeV on the vector-like quark masses.
- The entire parameter space of the model should be explored in future collider experiments.