Dark Particles at the LHC

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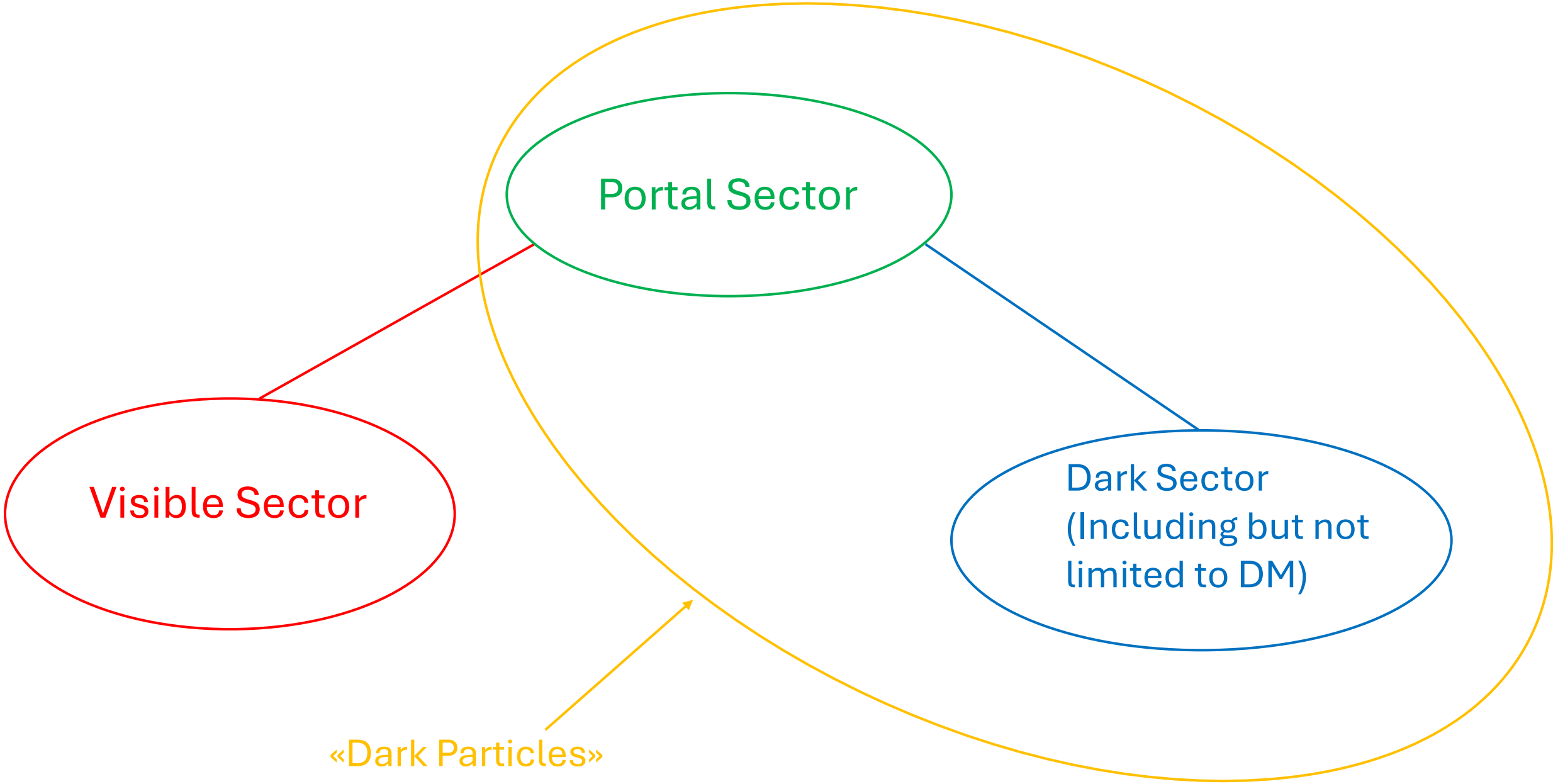
Theoretical setup




Invisible decays of the Higgs

(Effective) Higgs portal

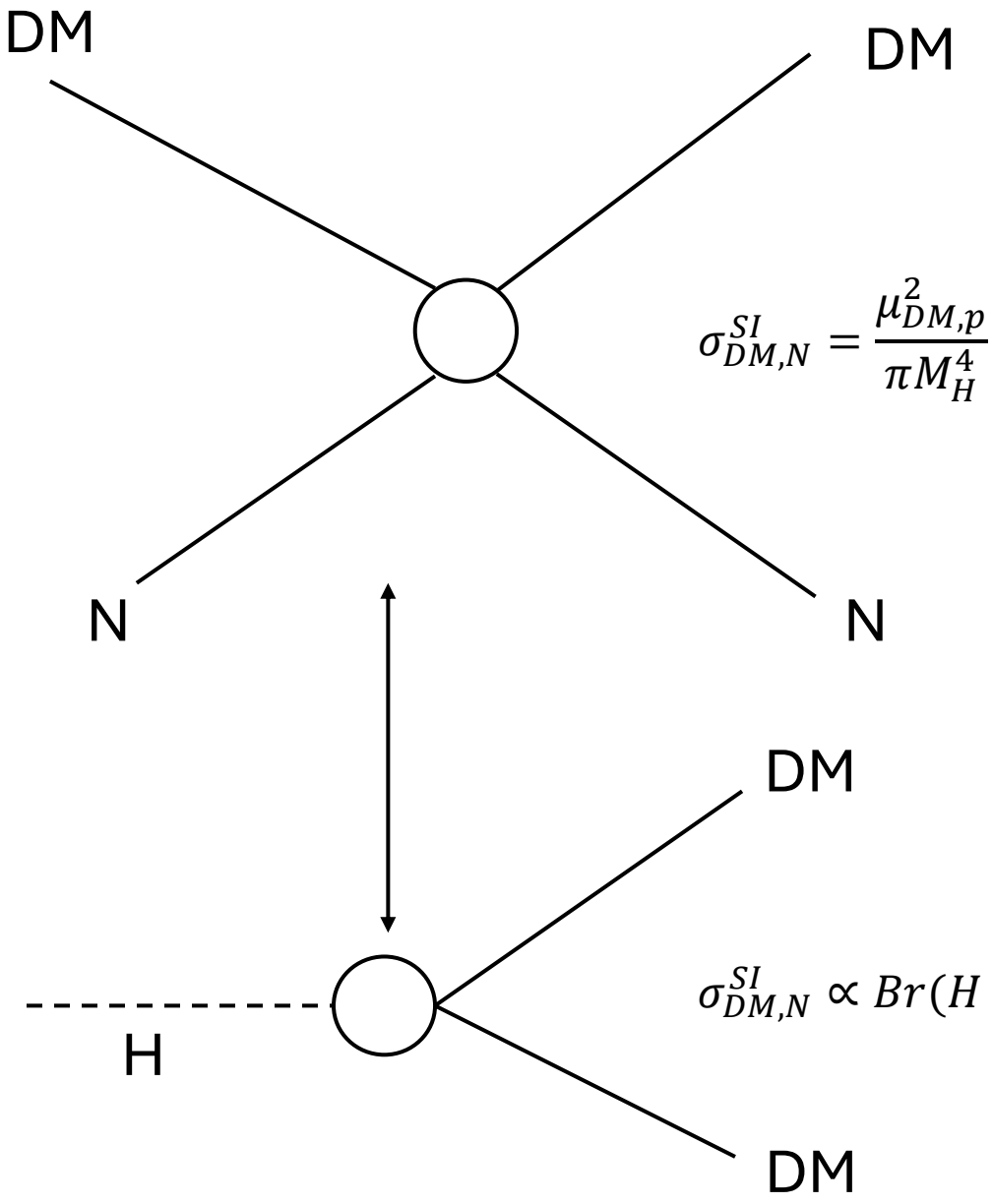
$$\Delta\mathcal{L}_S = -\frac{1}{2}M_S^2 S^2 - \frac{1}{4}\lambda_S S^4 - \frac{1}{4}\lambda_{HSS}\Phi^\dagger\Phi S^2 \,,$$

$$\Delta\mathcal{L}_V = \frac{1}{2}M_V^2 V_\mu V^\mu + \frac{1}{4}\lambda_V (V_\mu V^\mu)^2 + \frac{1}{4}\lambda_{HVV}\Phi^\dagger\Phi V_\mu V^\mu$$

$$\Delta\mathcal{L}_\chi = -\frac{1}{2}M_\chi \bar{\chi}\chi - \boxed{\frac{1}{4}\frac{\lambda_{H\chi\chi}}{\Lambda}\Phi^\dagger\Phi\bar{\chi}\chi}\,.$$

$$\Phi = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v+h \end{pmatrix}$$

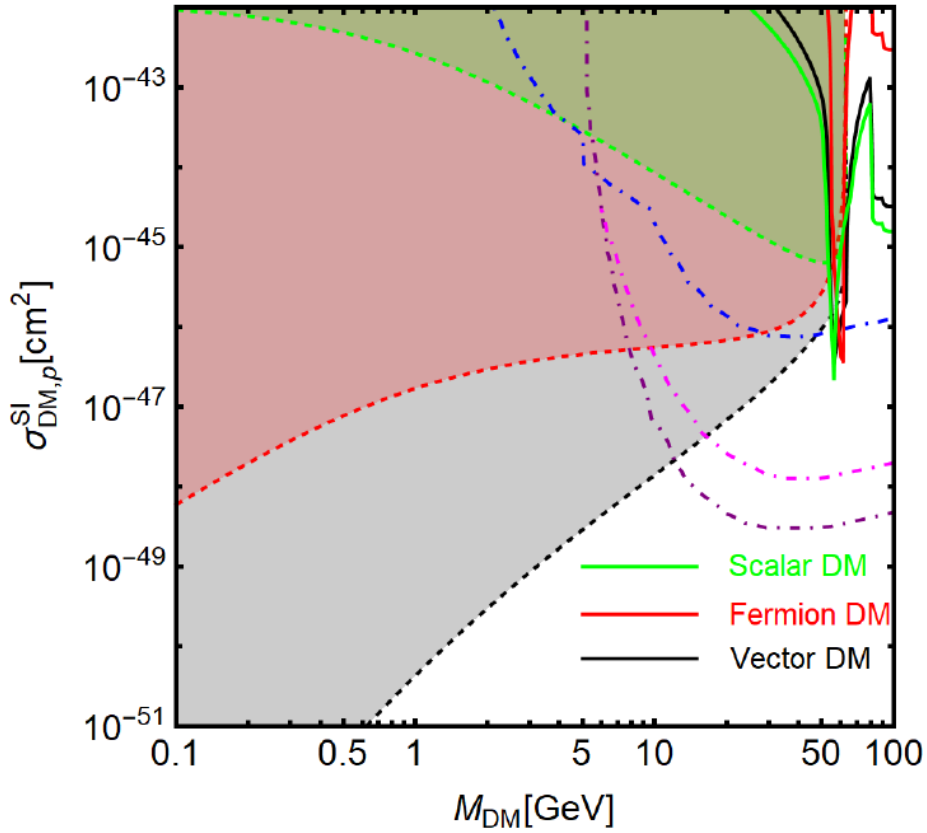
Portal interactions induced after EW symmetry breaking.
The effective Higgs portal has only two free parameters.



$$\sigma^{SI}_{DM,N} = \frac{\mu^2_{DM,p}}{\pi M_H^4} \lambda^2_{HDMDM} \lambda^2_{HNN}$$

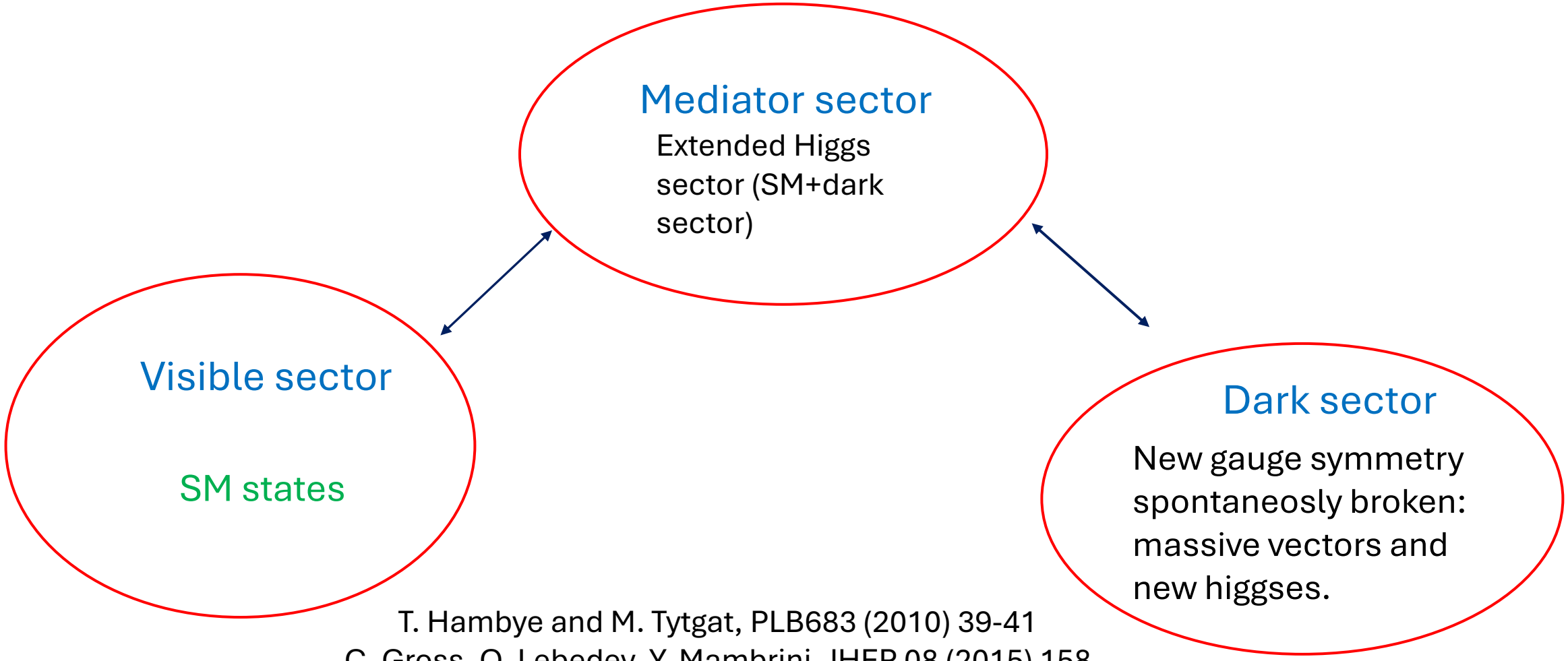
$$\sigma^{SI}_{DM,N} \propto Br(H \to DMDM)$$

LHC DD vs Invisible H width correlation plot



See e.g. also ATLAS, JHEP 11 (2015) 206
CMS Eur. Phys. J. C74 (2014) 2980

Dark Matter from gauge symmetry



T. Hambye and M. Tytgat, PLB683 (2010) 39-41
C. Gross, O. Lebedev, Y. Mambrini, JHEP 08 (2015) 158
G.A. , C. Gross, O. Lebedev, Y. Mambrini, S. Pokorski, T. Toma, JHEP 12 (2016) 081

Vector DM from U(1)

$$L_{U(1)} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \left(D_\mu\phi\right)^\dagger(D^\mu\phi) - V(\phi, H)$$

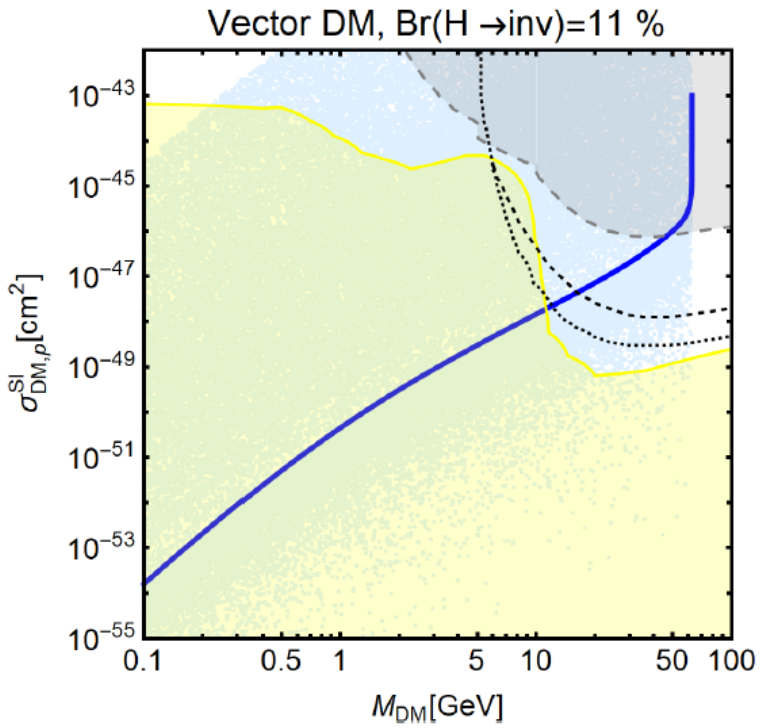
U(1) spontaneosly broken

Residual Z_2 symmetry $V_\mu \to -V_\mu$

$$\Delta L = \frac{\tilde{g}^2}{4}\omega\rho V_\mu V^\mu + \frac{\tilde{g}^2}{8}\rho^2 V_\mu V^\mu \qquad M_V^2 = \frac{1}{2}\tilde{g}^2\omega^2$$

$$\sigma_{DM,p} \propto \left(\frac{1}{M_{H_1}^2} - \frac{1}{M_{H_2}^2}\right)^2$$

The additional degree of freedom crucially alters the LHC correlation plot.



See also:
S. Baek et al. JHEP 05 (2013) 036
S. Baek et al. Phys. Rev. D90 (2014) 055015

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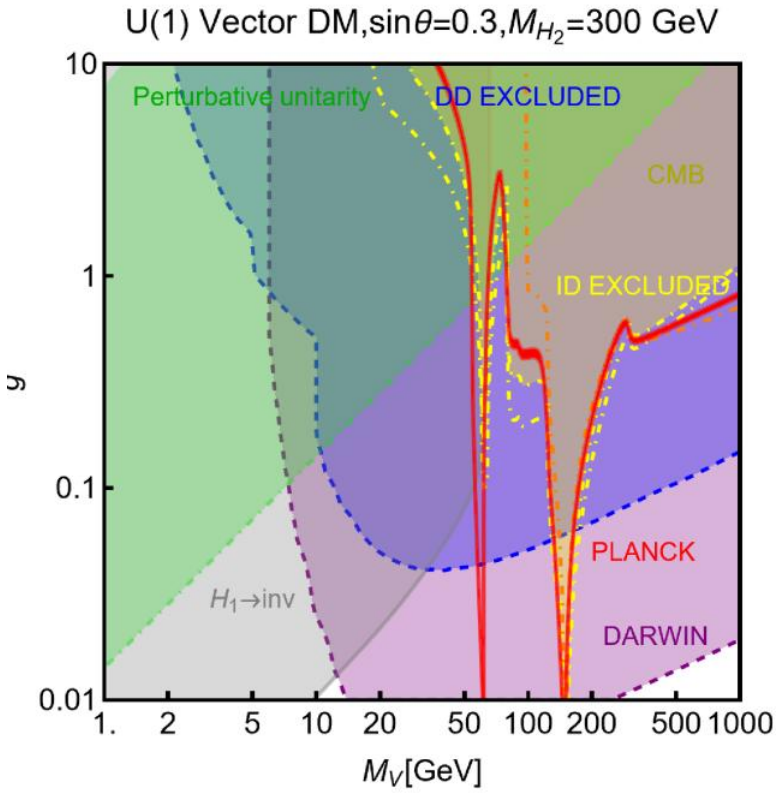
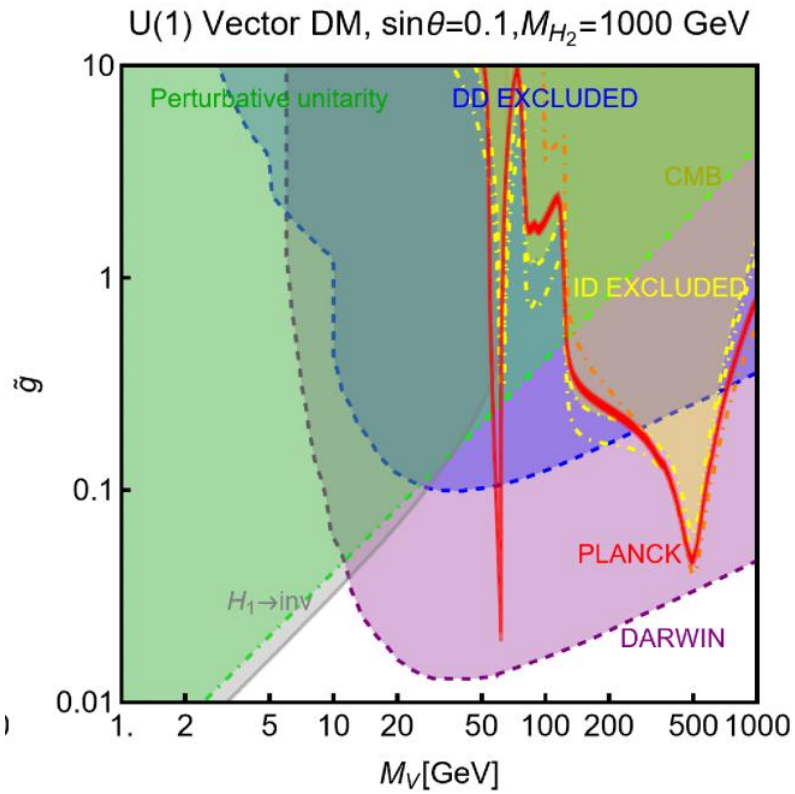
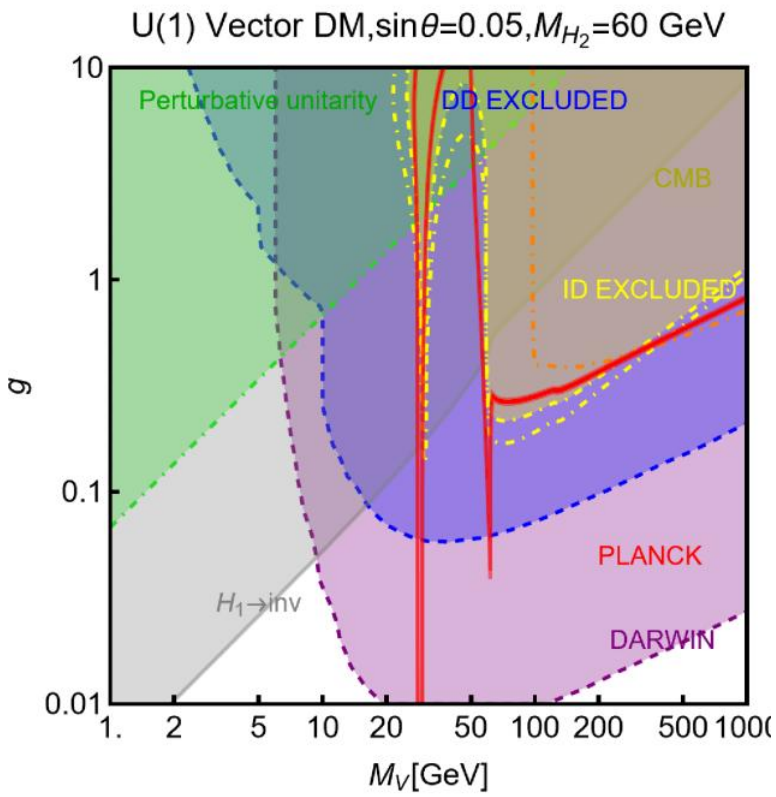
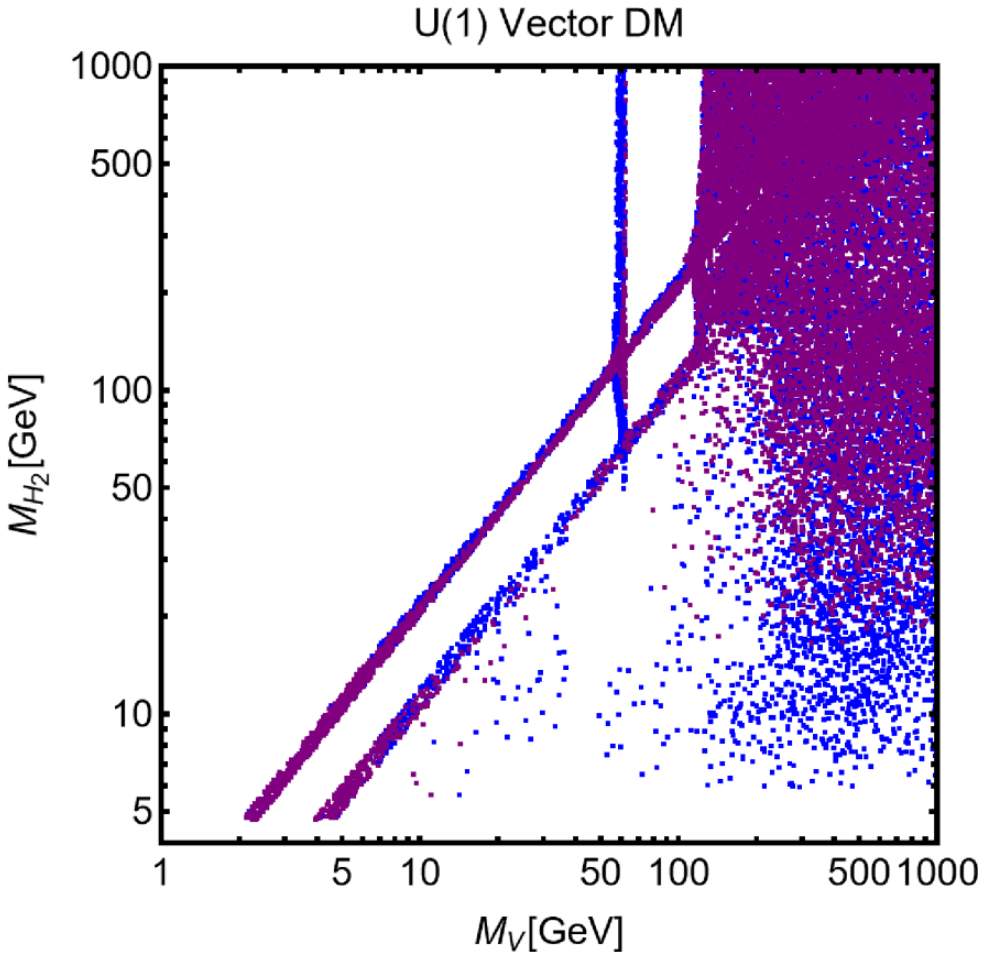




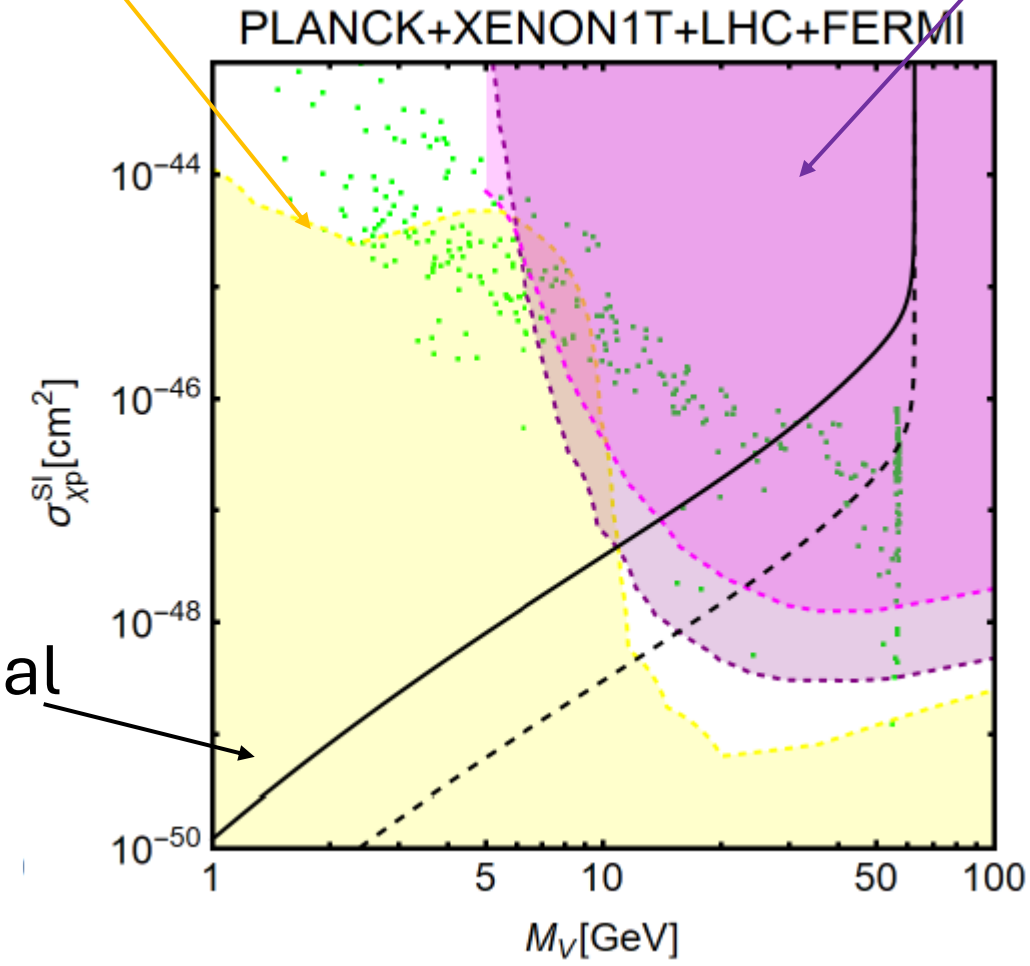




ν-floor

$2.5\% \leq Br(H \to inv) \leq 11\%$

XENONnT



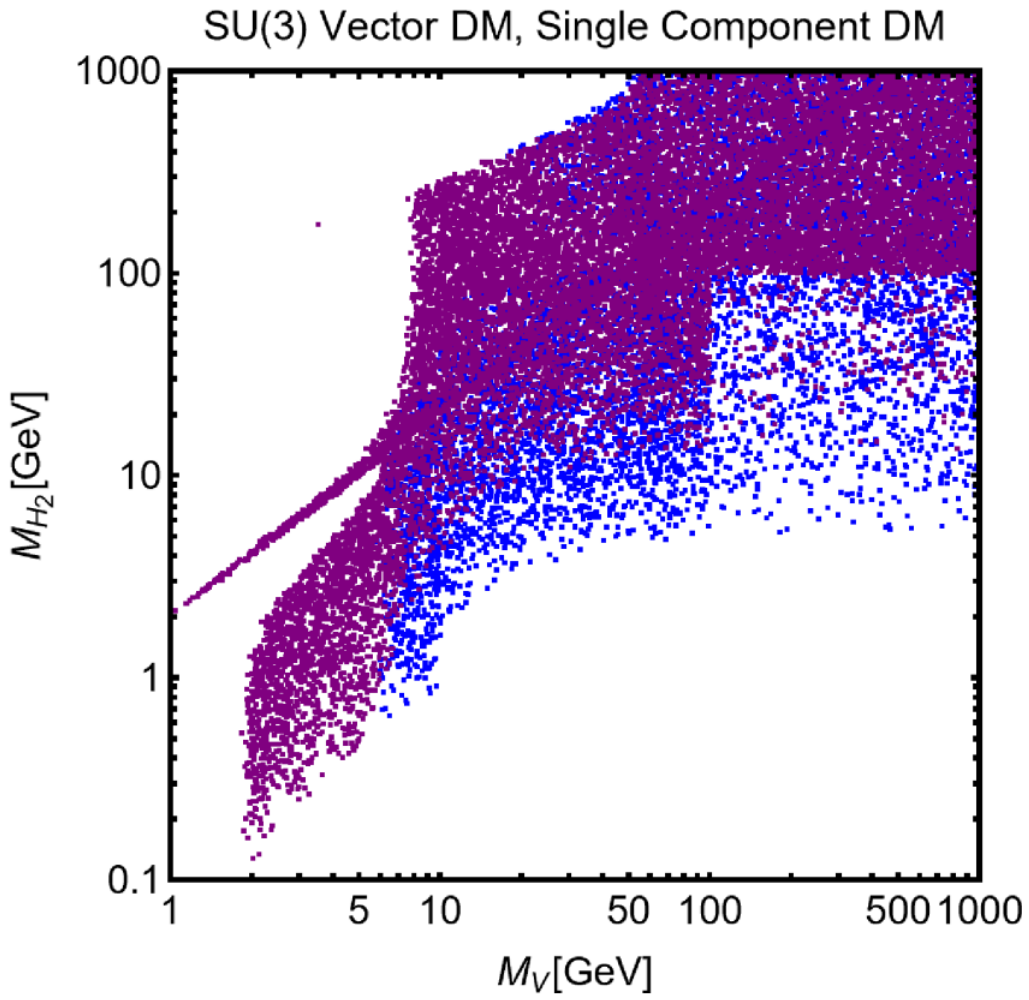
EFT Portal

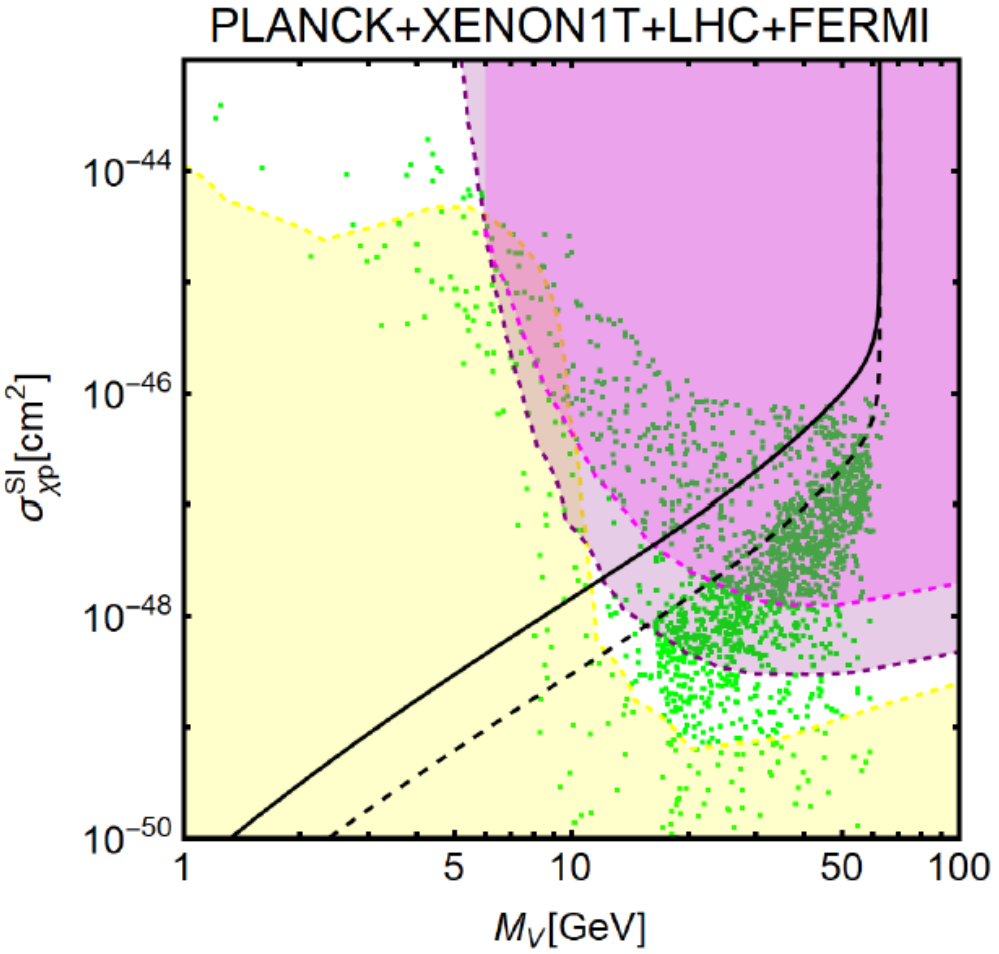
DARWIN

Vector (and Scalar DM) from SU(3)

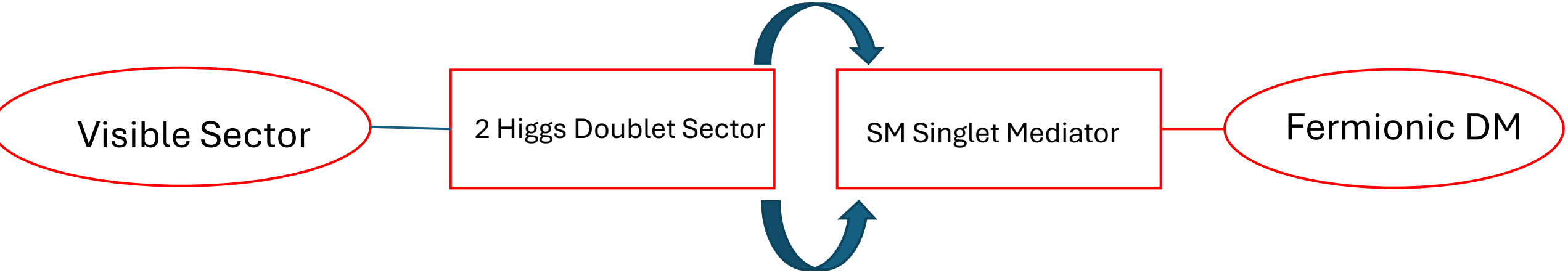
In a simplified limit we can define the following Lagrangian:

$$\mathcal{L} = \frac{\tilde{g} M_V}{2} \left(-\sin\theta H_1 + \cos\theta H_2\right) \left(\sum_{a=1,2} V_\mu^a V^{\mu\, a} + \left(\cos\alpha - \frac{\sin\alpha}{\sqrt{3}}\right)^2 V_\mu^3 V^{\mu\, 3} \right)$$
$$+ \tilde{g} \cos\alpha \sum_{a,b,c} \epsilon_{abc} \partial_\mu V_\nu V_\nu^a V^{b\,\mu} V^{c\,\nu} - \frac{\tilde{g}^2}{2} \cos^2\alpha \sum_{a=1,2} \left(V_\mu^a V^{a\,\mu} V_\nu^3 V^{3\,\nu} - \left(V_\mu^a V^{a\,\mu}\right)^2 \right)$$
$$- \frac{1}{2} m_\psi^2 \psi^2 + \left[\frac{\tilde{g}}{2 M_V} \left(-\sin\theta H_1 + \cos\theta H_2\right) - \frac{1}{4} \left(\lambda_{\psi\psi 11} H_1^2 + 2\lambda_{\psi\psi 12} H_1 H_2 + \lambda_{\psi\psi 22} H_2^2 \right) \right] \psi^2$$
$$- \frac{k_{111}}{2} v H_1^3 - \frac{k_{112}}{2} H_1^2 H_2 v \sin\theta - \frac{\kappa_{221}}{2} H_1 H_2^2 v \cos\theta - \frac{\kappa_{222}}{2} H_2^3 v$$
$$+ \frac{H_1 \cos\theta + H_2 \sin\theta}{v} \left(2 M_W^2 W_\mu^+ W^{\mu -} + M_Z^2 Z_\mu Z^\mu - m_f \bar{f} f \right)$$


SU(3) Vector DM, Single Component DM
1000
100
10
1
0.1
M_{H_2}[GeV]
1
5
10
50
100
500
1000
M_V[GeV]


PLANCK+XENON1T+LHC+FERMI
10^{-44}
10^{-46}
10^{-48}
10^{-50}
σ^{SI}_{Xp}[cm^2]
1
5
10
50
100
M_V[GeV]

Scalar Portals from Extended Higgs Sectors

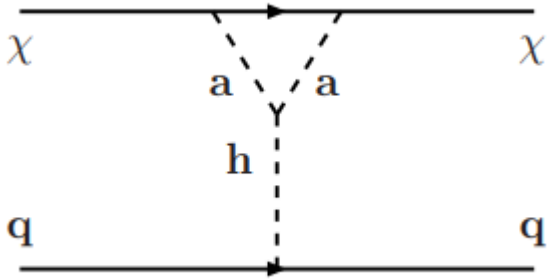

Visible Sector
2 Higgs Doublet Sector
SM Singlet Mediator
Fermionic DM

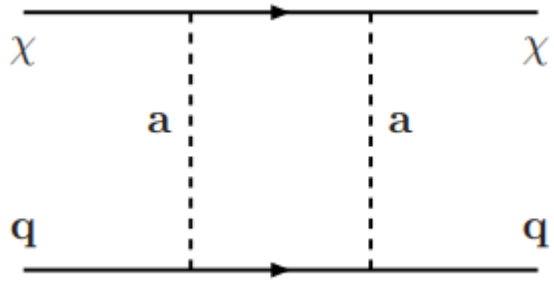
2HDM+a

$$L_{DM} = iy_\chi\, \bar{\chi}\gamma_5\chi a_0 \longrightarrow iy_\chi(a\cos\theta + A\sin\theta)\bar{\chi}\gamma_5\chi$$

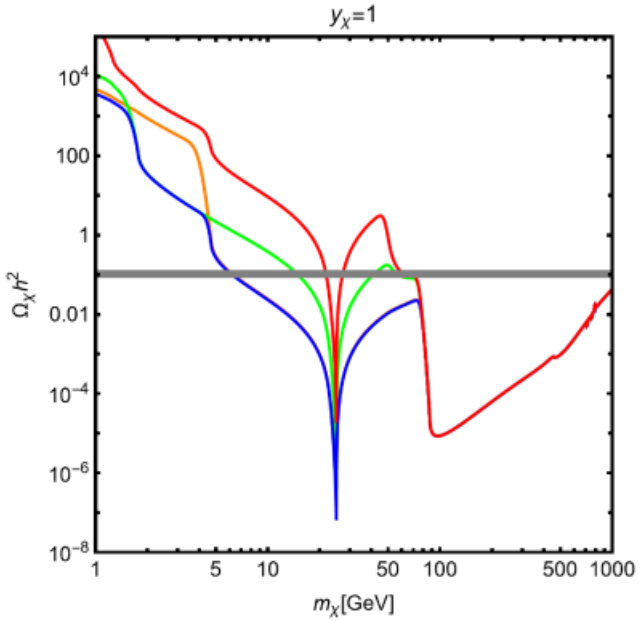
$\langle\sigma v\rangle$ →
- $\bar{\chi}\chi \to a\,/A \to \bar{f}f$
- $\bar{\chi}\chi \to a\,/A \to ha(A)$
- $\bar{\chi}\chi \to a\,/A \to a(A)a(A)$

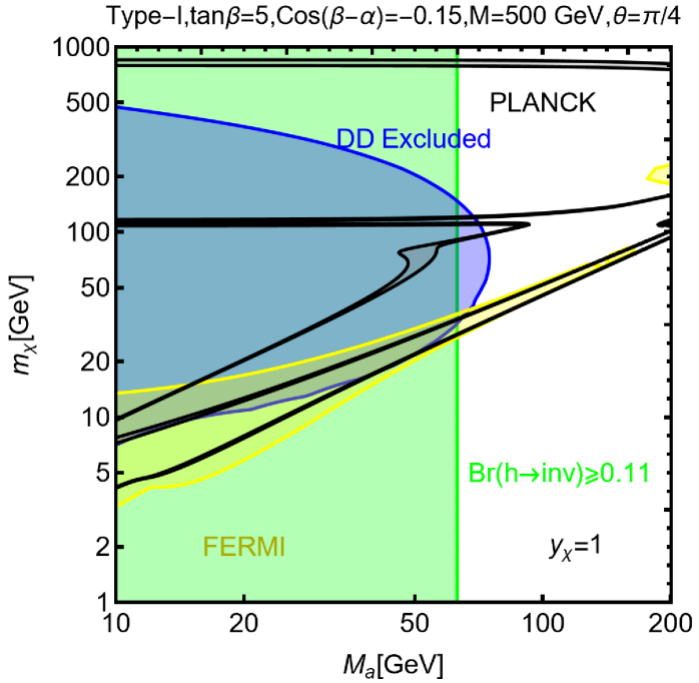
$$\Omega h^2 \propto \frac{1}{\langle\sigma v\rangle}$$

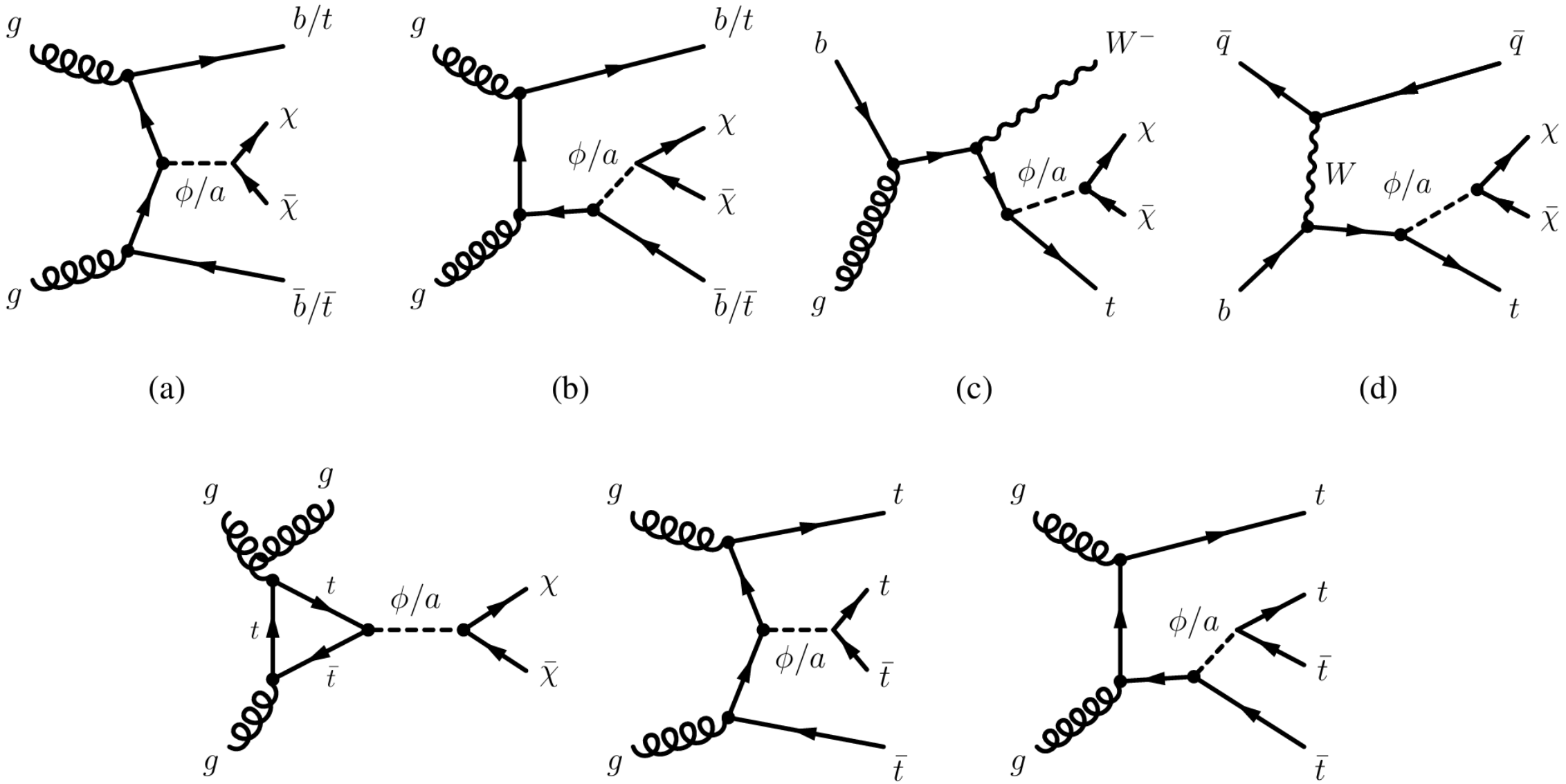


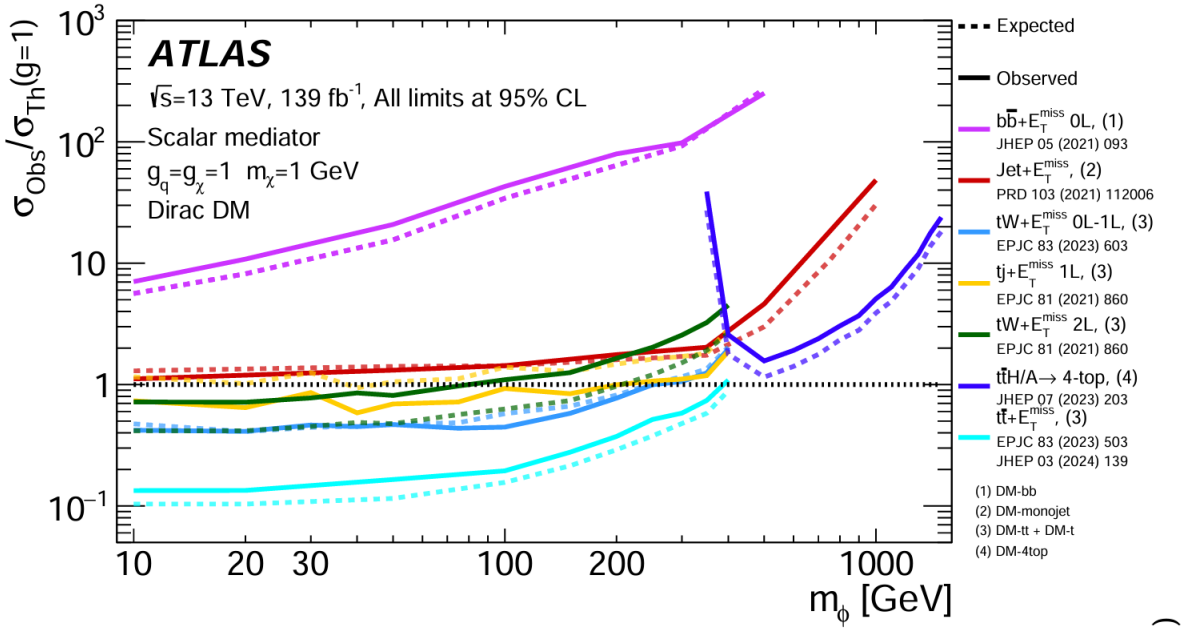


SI Induced at one-loop

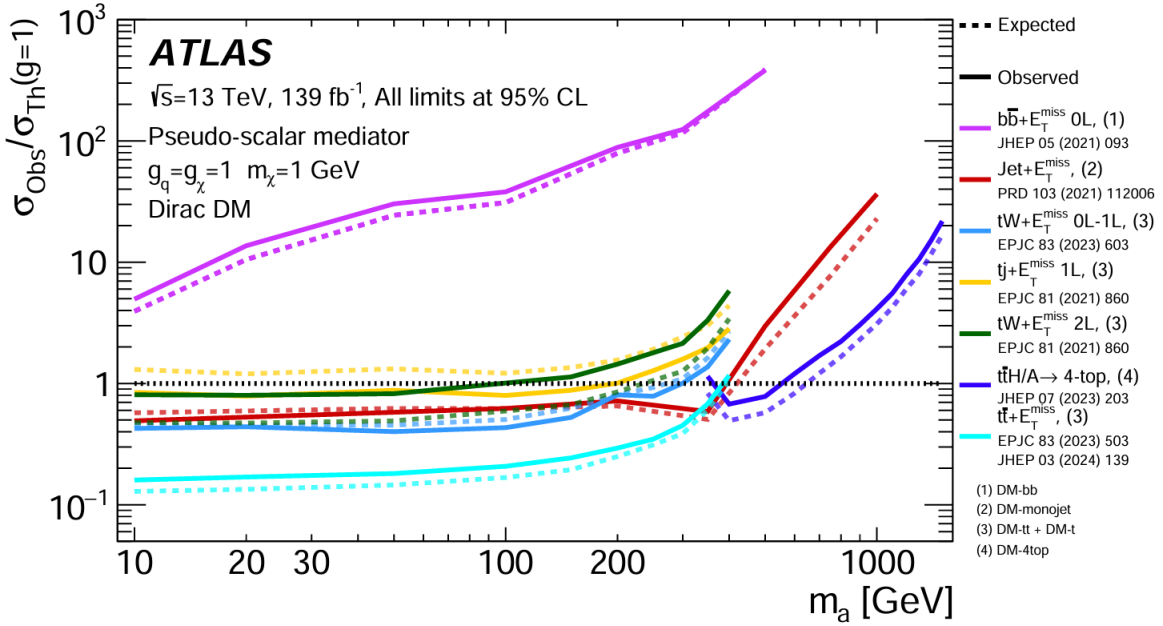




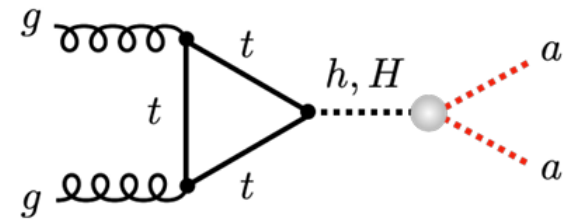

g
b/t
χ
φ/a
χ̄
g
b̄/t̄
(a)
g
b/t
χ
φ/a
χ̄
g
b̄/t̄
(b)
b
W⁻
χ
φ/a
χ̄
g
t
(c)
q̄
q̄
χ
W
φ/a
χ̄
b
t
(d)
g
g
t
φ/a
χ
t
χ̄
t̄
g
(e)
g
t
t
φ/a
t̄
g
t̄
(f)
g
t
t
φ/a
t̄
g
t̄
(g)

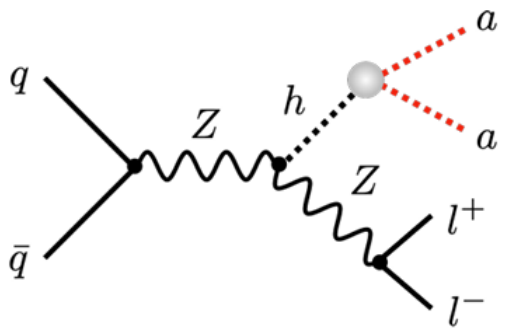

ATLAS
√s=13 TeV, 139 fb-1, All limits at 95% CL
Scalar mediator
gq=gχ=1 mχ=1 GeV
Dirac DM
σObs/σTh(g=1)
mϕ [GeV]
Expected
Observed
bb̄+ETmiss 0L, (1)
JHEP 05 (2021) 093
Jet+ETmiss, (2)
PRD 103 (2021) 112006
tW+ETmiss 0L-1L, (3)
EPJC 83 (2023) 603
tj+ETmiss 1L, (3)
EPJC 81 (2021) 860
tW+ETmiss 2L, (3)
EPJC 81 (2021) 860
tt̄H/A→ 4-top, (4)
JHEP 07 (2023) 203
tt̄+ETmiss, (3)
EPJC 83 (2023) 503
JHEP 03 (2024) 139
(1) DM-bb
(2) DM-monojet
(3) DM-tt + DM-t
(4) DM-4top

(a)

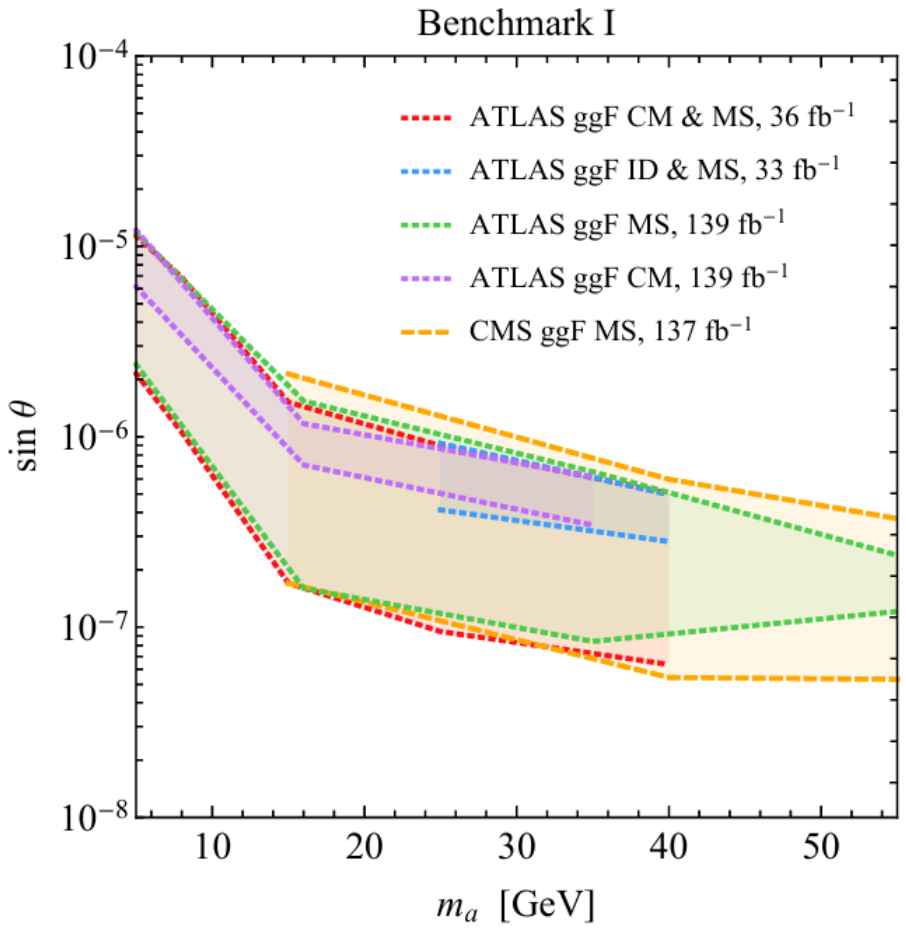

ATLAS
√s=13 TeV, 139 fb-1, All limits at 95% CL
Pseudo-scalar mediator
gq=gχ=1 mχ=1 GeV
Dirac DM
σObs/σTh(g=1)
ma [GeV]
Expected
Observed
bb̄+ETmiss 0L, (1)
JHEP 05 (2021) 093
Jet+ETmiss, (2)
PRD 103 (2021) 112006
tW+ETmiss 0L-1L, (3)
EPJC 83 (2023) 603
tj+ETmiss 1L, (3)
EPJC 81 (2021) 860
tW+ETmiss 2L, (3)
EPJC 81 (2021) 860
tt̄H/A→ 4-top, (4)
JHEP 07 (2023) 203
tt̄+ETmiss, (3)
EPJC 83 (2023) 503
JHEP 03 (2024) 139
(1) DM-bb
(2) DM-monojet
(3) DM-tt + DM-t
(4) DM-4top

(b)





→ Displaced Decays for the pseudoscalar



U. Haisch and L. Schnell *JHEP* 04 (2023) 134

Spin-1 portal with Dark Higgs Boson

M. Duerr, A. Grohsjean, F. Kahlhoefer, B. Penning, K. Schmidt-Hoberg, C. Schwanenberger JHEP 04 (2017) 143

see also

F. Kahlhoefer, K. Schmidt-Hoberg, T. Schwetz and S. Vogl, JHEP 02 (2016) 016, JHEP 09 (2016) 042.

$$L = (D^{\mu}\phi)^{\dagger}\left(D_{\mu}\phi\right) + \mu_{\phi}^{2}\phi^{\dagger}\phi - \lambda_{\phi}\left(\phi^{\dagger}\phi\right)^{2} - \lambda_{H\phi}\phi^{\dagger}\phi H^{\dagger}H$$
$$-g_X X_{\mu}\bar{f}\gamma^{\mu}\left(V_f - \gamma_5 A_f\right)f - \frac{1}{4}X^{\mu\nu}X_{\mu\nu} - \frac{1}{2}\sin\delta X^{\mu\nu}B_{\mu\nu}$$

$$m_X = 2g_X\omega \longrightarrow M_{Z'}^{2} = m_X^{2} +$$
$$(Contributions\ from\ mixing\ with\ the\ Z)$$

$$\begin{pmatrix} B_\mu \\ W_\mu^3 \\ X_\mu \end{pmatrix} = \begin{pmatrix} 1 & 0 & -\tan\delta \\ 0 & 1 & 0 \\ 0 & 0 & 1/\cos\delta \end{pmatrix} \begin{pmatrix} c_W & -s_W\cos\xi & s_w\sin\xi \\ s_W & c_W\cos\xi & -c_W\sin\xi \\ 0 & \sin\xi & \cos\xi \end{pmatrix} \begin{pmatrix} A_\mu \\ Z_\mu \\ Z'_\mu \end{pmatrix}$$

$$M_Z^2 = m_{Z_0}^2(1 + s_W\tan\xi\tan\delta)$$

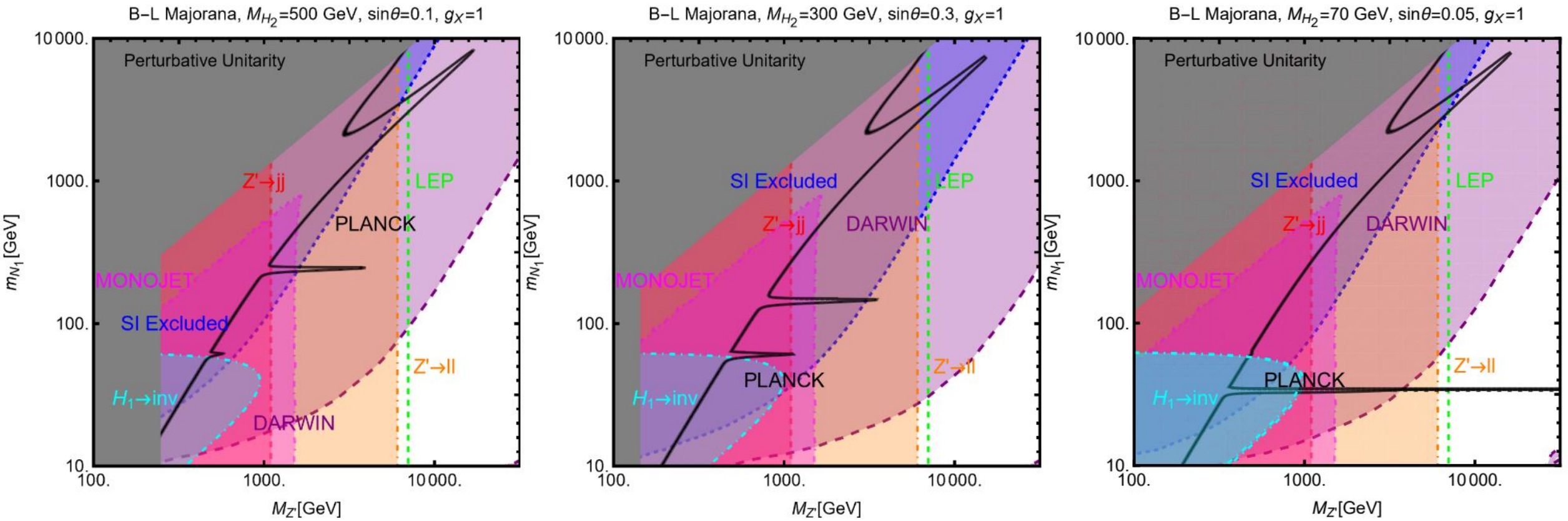
$$M_{Z'}^2 = \frac{m_X^2 + \delta m^2(s_W\sin\delta - \cos\delta\, tan\xi)}{\cos^2\delta(1 + s_W tan\delta tan\xi)}$$

$$\tan 2\xi = \frac{-2\cos\delta\left(\delta m^2 + m_{Z_0}^2 s_W\sin\delta\right)}{m_X^2 - m_{Z_0}^2\cos^2\delta + m_{Z_0}^2 s_W^2\sin^2\delta + 2\delta m^2 s_W\sin\delta}$$

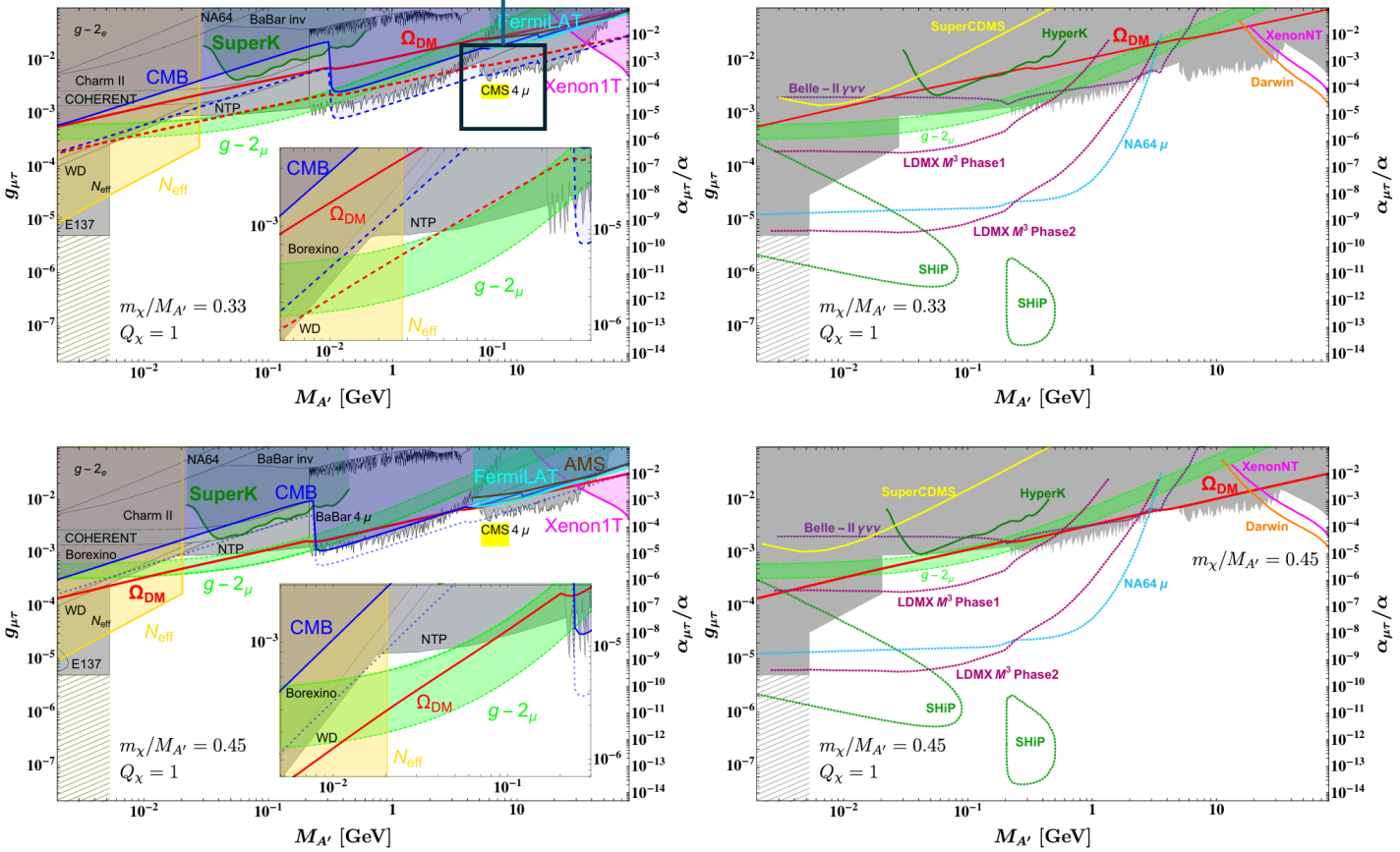
$$\lambda_H = \frac{1}{4v^2}\left[M_{H_1}^2 + M_{H_2}^2 + \left(M_{H_1}^2 - M_{H_2}^2\right)\cos 2\theta\right]$$

$$\lambda_\phi = \frac{g_X^2}{m_X^2}\left[M_{H_1}^2 + M_{H_2}^2 + \left(M_{H_2}^2 - M_{H_1}^2\right)\cos 2\theta\right]$$

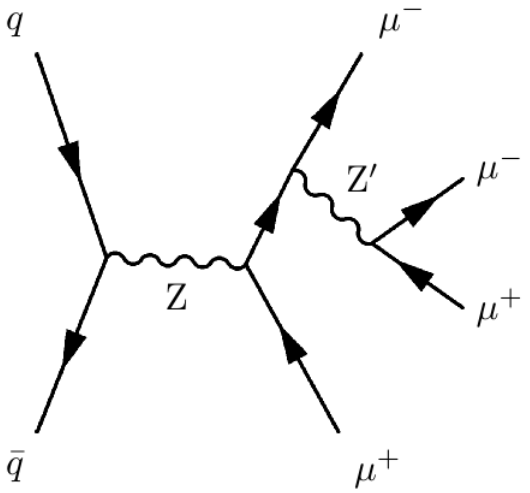
$$\lambda_{H\phi} = \frac{g_X}{m_X v}\left(M_{H_1}^2 - M_{H_2}^2\right)\sin 2\theta$$



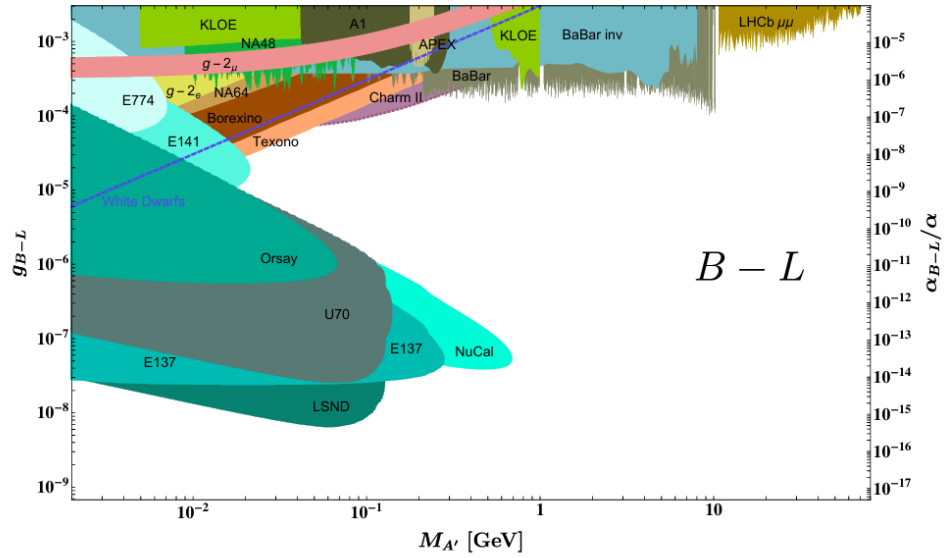
G.A. et al, arXiv: 2403.15860

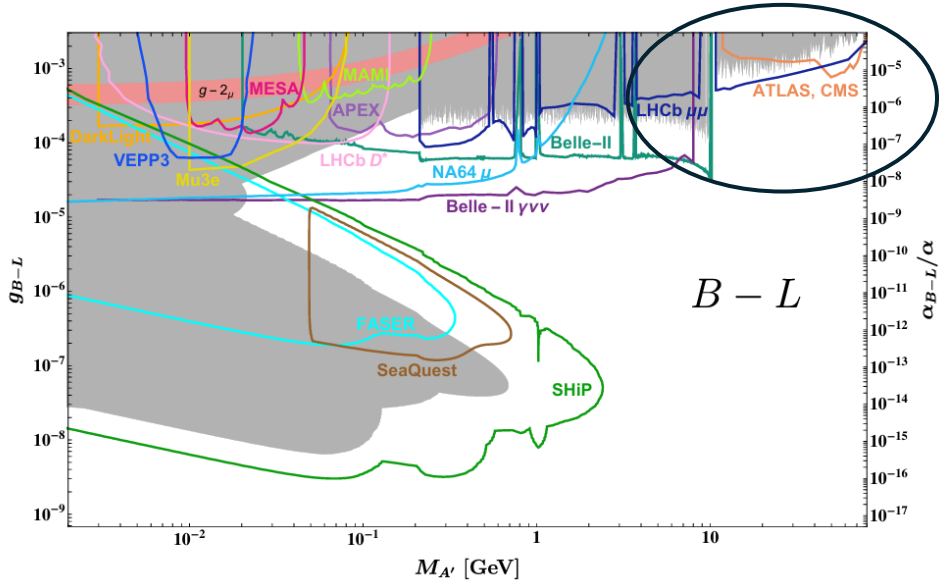


P. Foldenauer *Phys.Rev.D* 99 (2019) 3, 035007

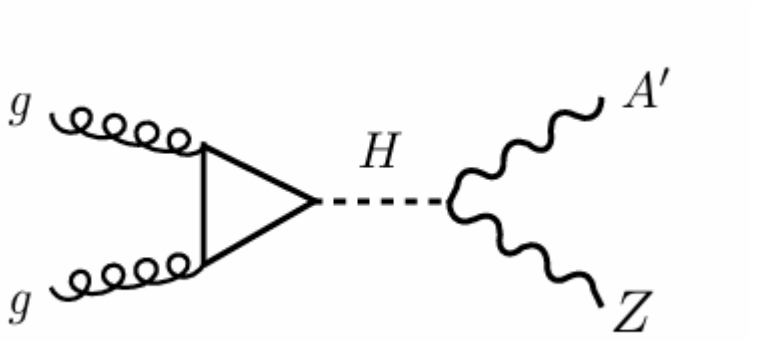


CMS Collaboration
Phys.Lett.B 792 (2019) 345-368



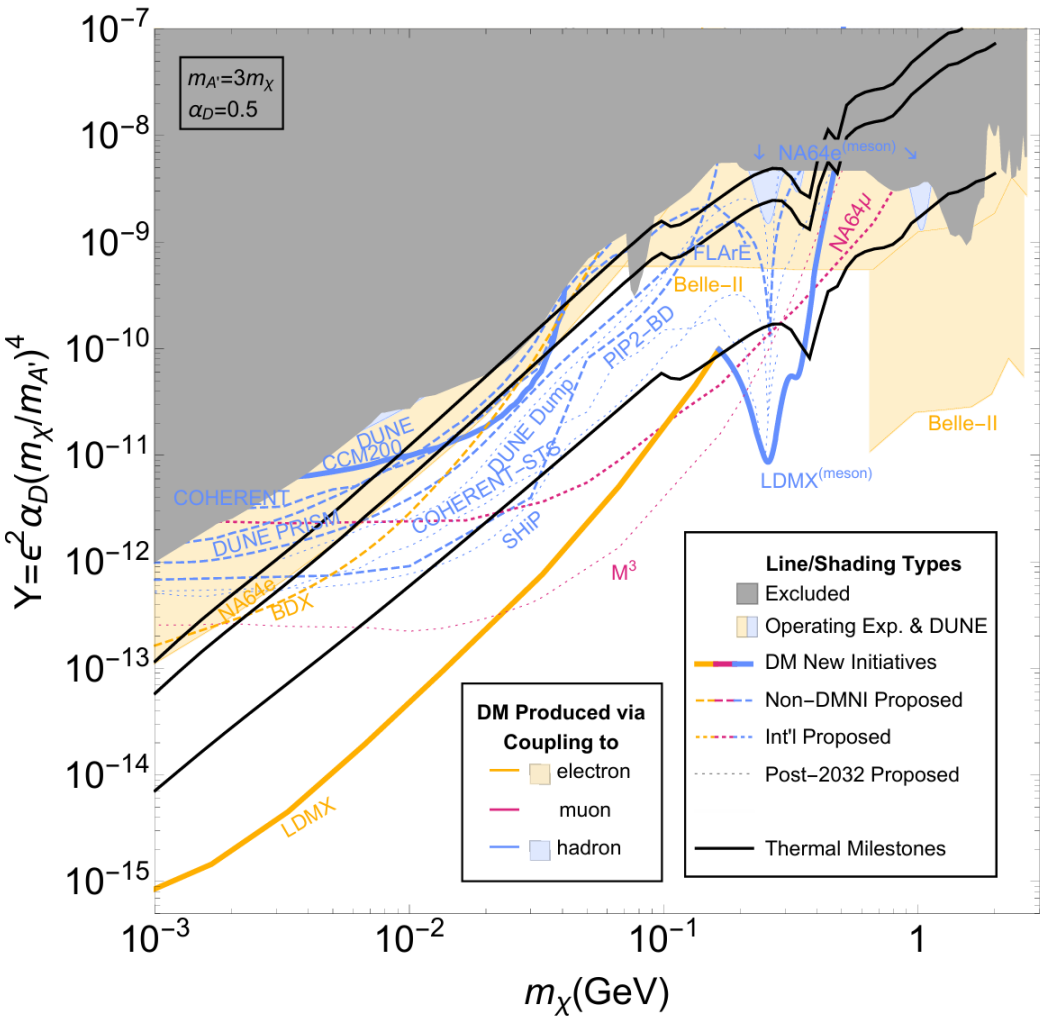


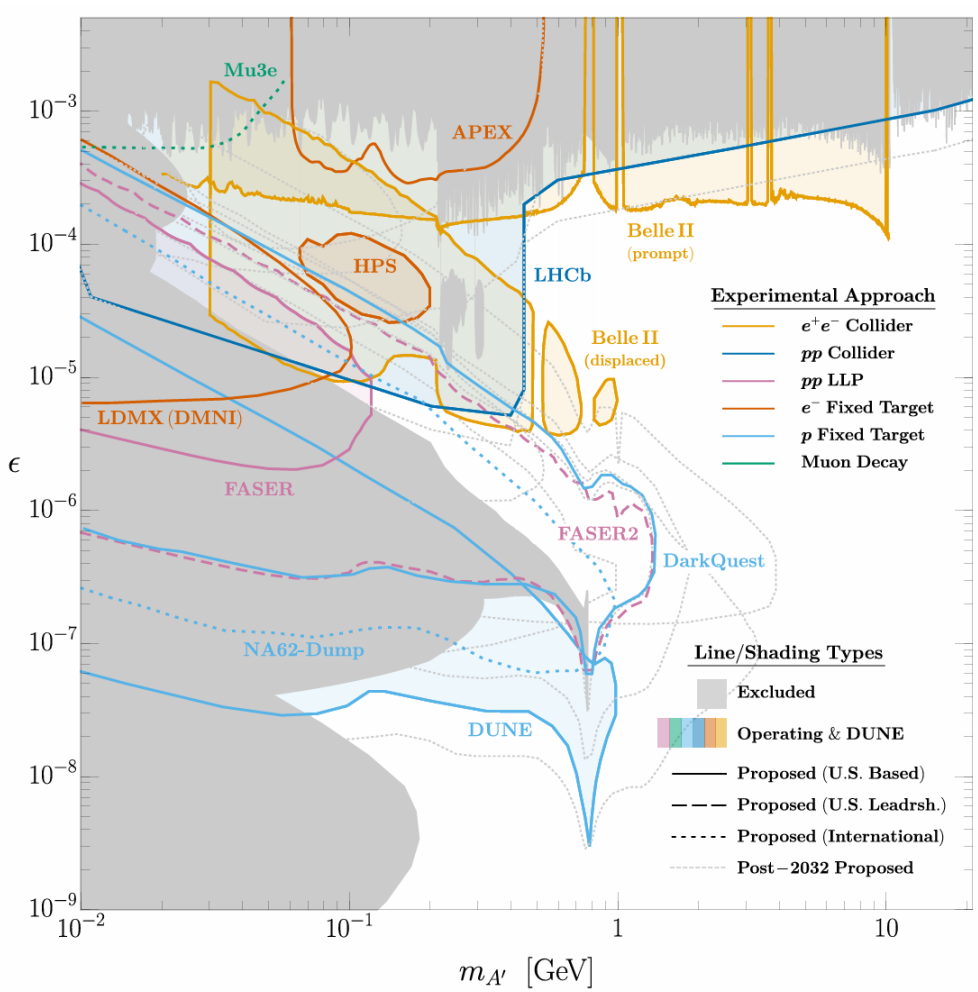
M. Bauer et al. *JHEP* 07 (2018) 094



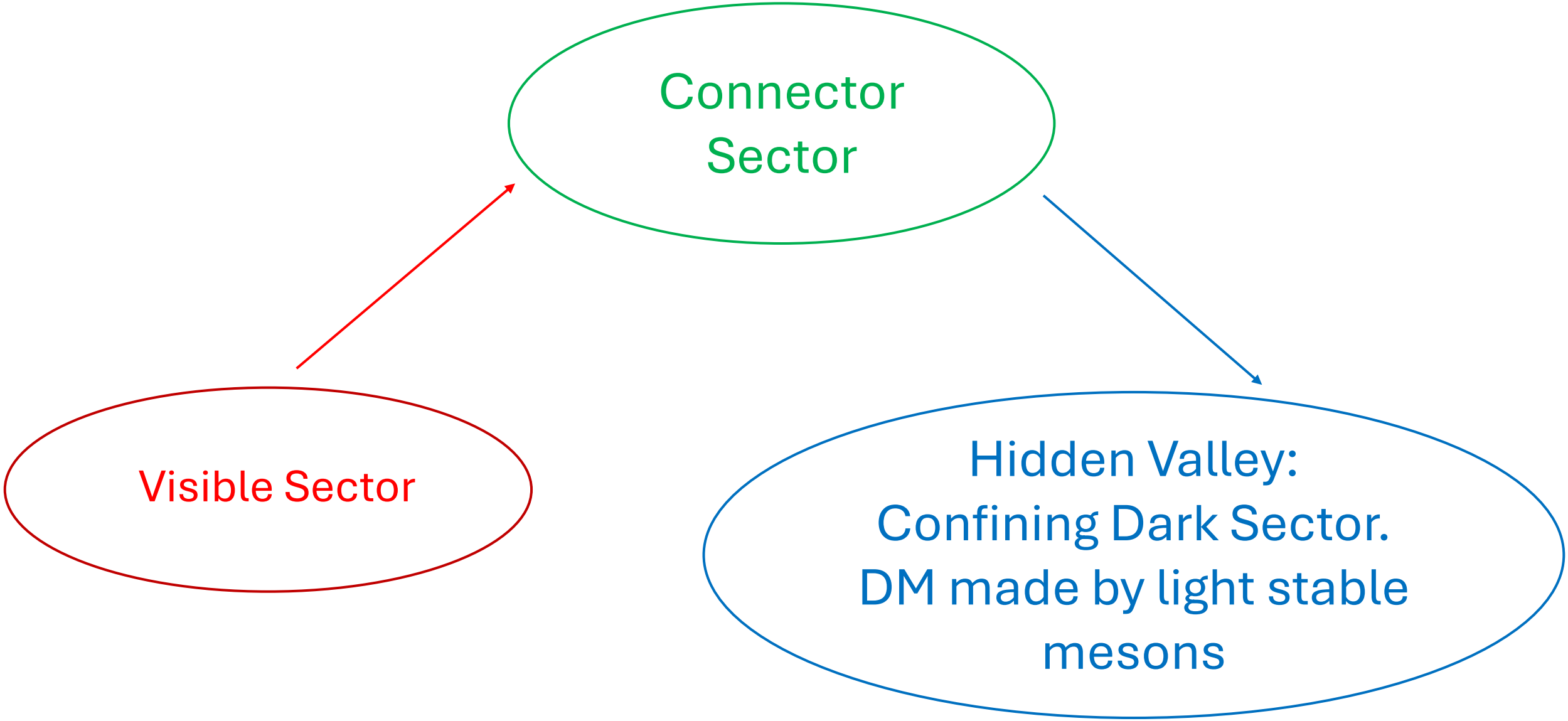
$$L_{Vector} = L_{SM} + L_{DS} - \frac{\epsilon}{2\cos\theta_W} F'_{\mu\nu} B^{\mu\nu}$$

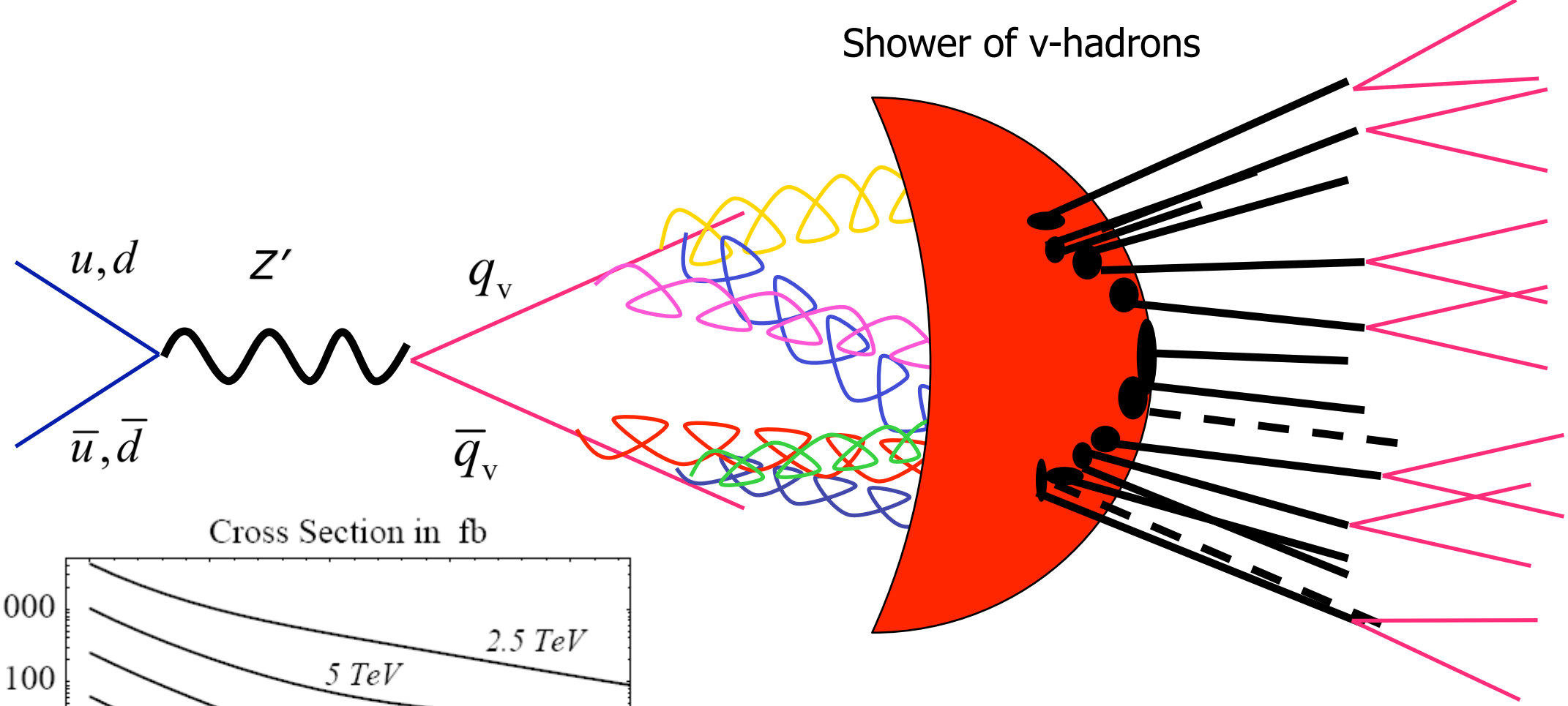
$$L_{DS} = -\frac{1}{4} F'_{\mu\nu} F^{\mu\nu} + \frac{1}{2} m_{A'}^2 A'^{\mu} A_{\mu} + \bar{\chi}\gamma^{\mu}\left(\partial_{\mu} + i g_D A'_{\mu}\right)\chi$$

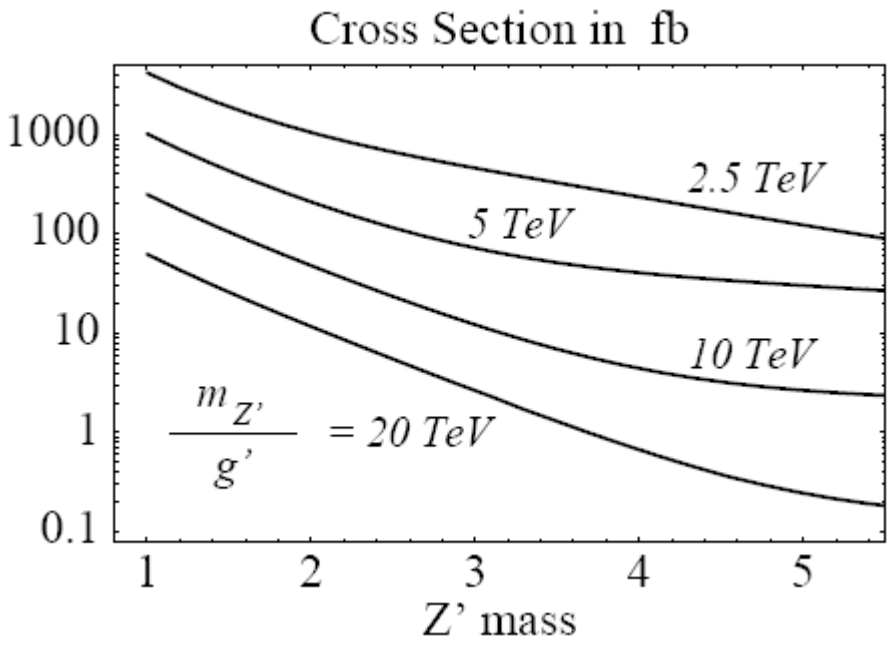


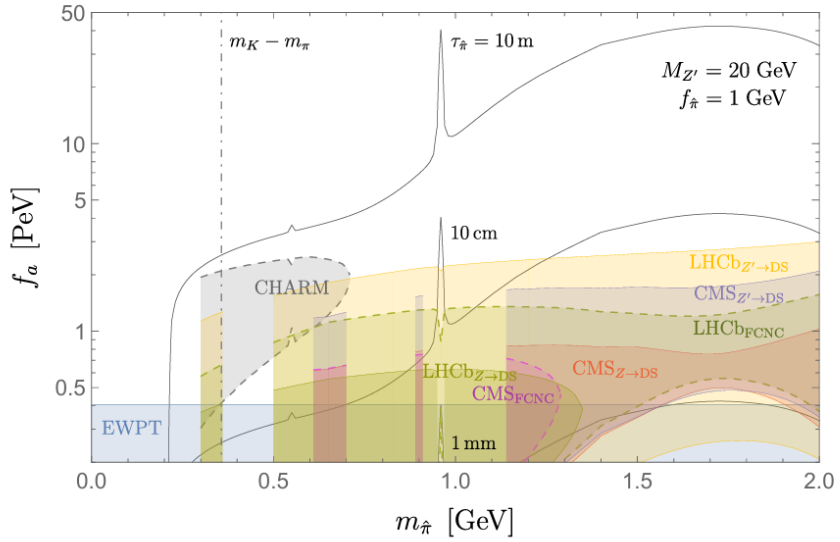


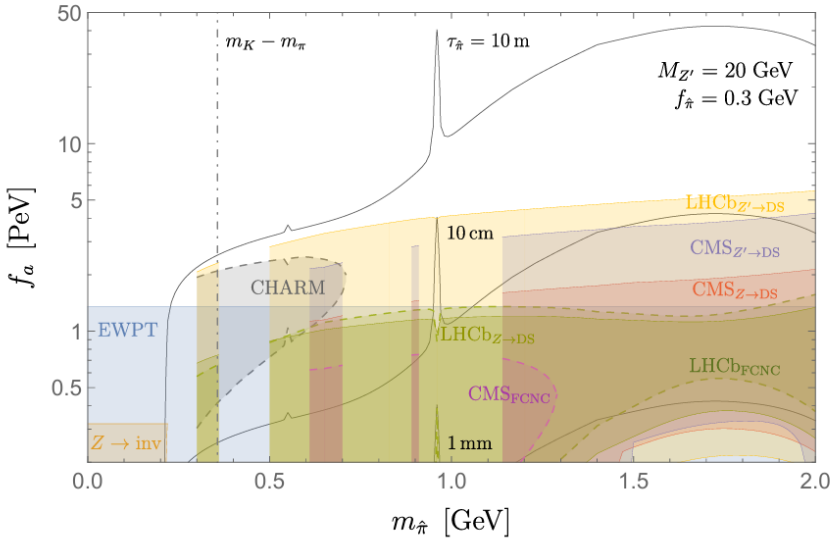
Light Dark Matter in Hidden Valley Models

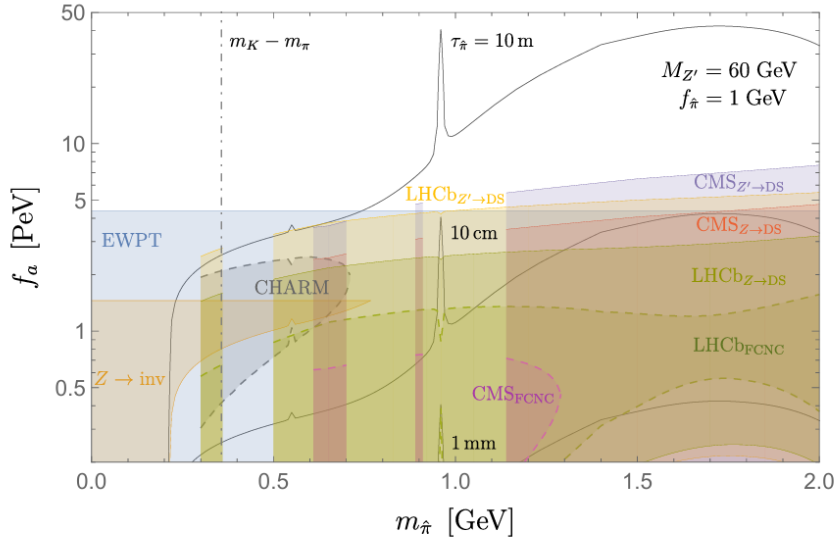

Connector
Sector
Visible Sector
Hidden Valley:
Confining Dark Sector.
DM made by light stable
mesons

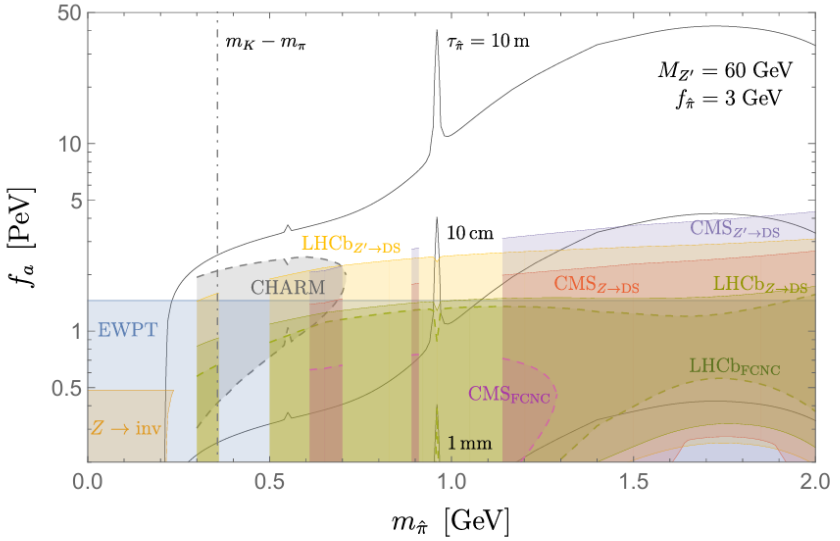

Shower of v-hadrons
u, d
Z'
q_v
$\bar{u}, \bar{d}$
$\bar{q}_v$


Cross Section in fb
1000
100
10
1
0.1
2.5 TeV
5 TeV
10 TeV
$\frac{m_{Z'}}{g'}$ = 20 TeV
1
2
3
4
5
Z' mass









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Conclusions

LHC is a valid complement to dedicated searches (Direct and Indirect Detection) of Dark Matter.

Potential for searches of light dark particles can be further exploited.

Back up

$$L_{DM} = -\frac{y_{N_1}}{2\sqrt{2}}\rho N_1 N_1 - \frac{1}{2} g_X X^\mu \overline{N_1}\gamma_\mu\gamma_5 N_1 + \frac{1}{2} g_X^2 X_\mu X^\mu(\rho^2 + 2\rho\omega)$$ Majorana DM

$$\frac{y_{N_1}}{2\sqrt{2}} \to g_X \frac{m_{N_1}}{m_X}$$

Relic density due to: $N_1 N_1 \to \bar{f} f$, $\mathrm{N_1 N_1} \to \rho Z', N_1 N_1 \to Z'Z', N_1 N_1 \to \rho\rho$

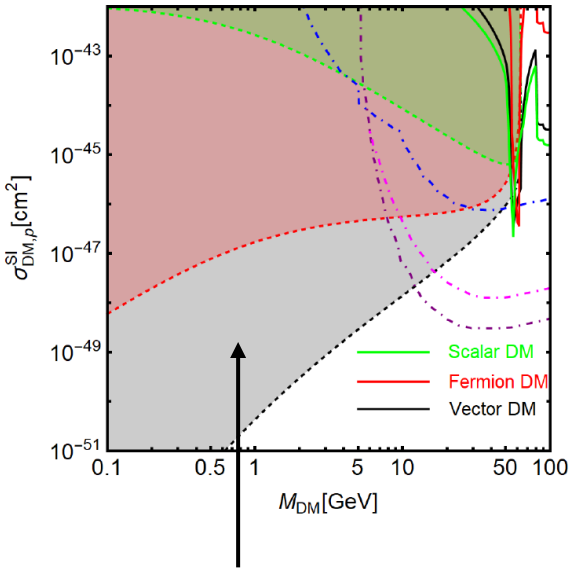
In presence of h/ρ, Z/Z' mixing we have $\mathrm{N_1 N_1} \to ZZ, ZZ', Z'Z', N_1 N_1 \to W^+W^-, N_1 N_1 \to H_{1,2}H_{1,2}$

Direct Detection ⟶

$$\sigma^{SI}_{N_1 p} = \frac{4\mu^2_{N_1 p}}{\pi}\left\{\frac{y_{N_1} m_p}{v}\sin\theta\cos\theta\left(\frac{1}{M^2_{H_1}} - \frac{1}{M^2_{H_2}}\right)\left[\sum_{q=u,d,s} f_q^p + \frac{2}{27} f_{TG}\right] + \right.$$
$$\left. m_p \sum_{q=u,d,s} f_q^p f_q + \sum_{q=u,d,s,c,b} \frac{3}{4} m_p (q(2) + \bar{q}(2))\left(g_q^{(1)} + g_q^{(2)}\right) - \frac{8\pi}{9\alpha_s} f_{TG} f_G \right\}^2$$

$$\sigma^{SD}_{N_1 p} = \frac{3\mu^2_{N_1 p}}{\pi} g_X^4 \left\{\frac{\left[A_u^Z \Delta_u^p + A_d^Z\left(\Delta_d^p + \Delta_s^p\right)\right]}{M_Z^2} + \frac{\left[A_u^{Z'} \Delta_u^p + A_d^{Z'}\left(\Delta_d^p + \Delta_s^p\right)\right]}{M_{Z'}^2}\right\}^2$$

Consistency of the correlation plot for Higgs-to-invisible search

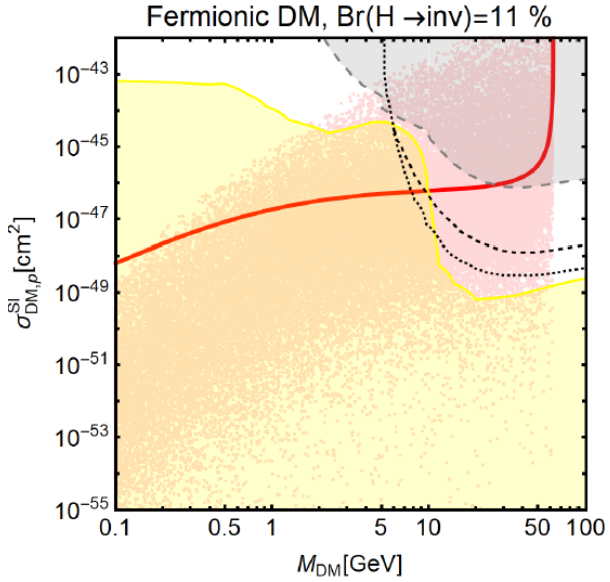


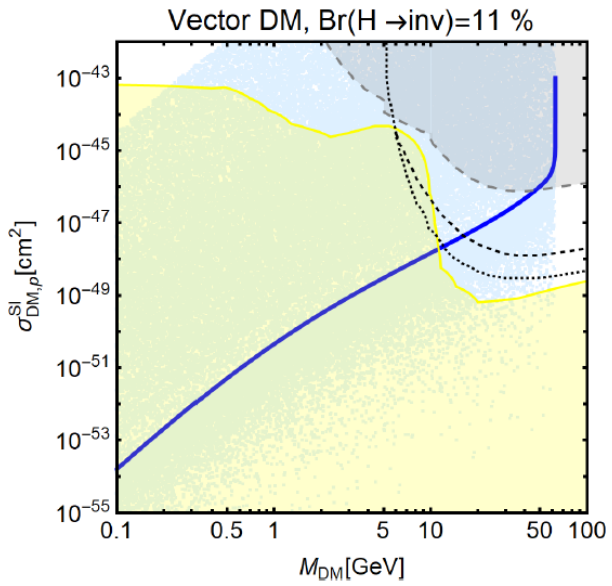
Effective Higgs portal

More realistic completion through mixing

$$\sigma_{DM,p} \propto \left(\frac{1}{M_{H_1}^2} - \frac{1}{M_{H_2}^2} \right)^2$$

The additional degree of freedom crucially alters the LHC correlation plot.





See also:
S. Baek et al. JHEP 05 (2013) 036
S. Baek et al. Phys. Rev. D90 (2014) 055015

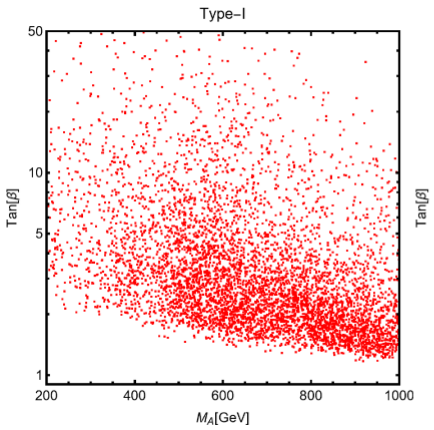
Mixing with a Dark Higgs

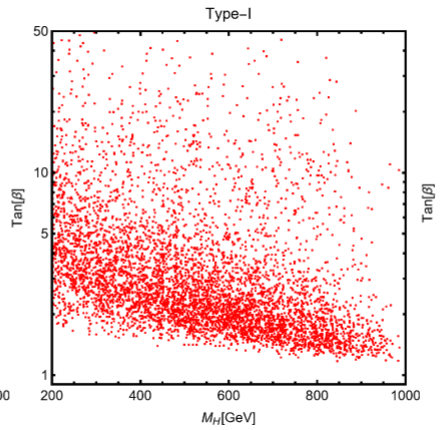
$$V(H,\phi) = \frac{\lambda_H}{4}\left|H^\dagger H\right|^2 + \frac{\lambda_{H\phi}}{4}|\phi|^2|H|^2 + \frac{\lambda_\phi}{4}|S|^4 + \frac{1}{2}\mu_H^2 H^\dagger H + \frac{1}{2}\mu_\phi^2|\phi|^2$$

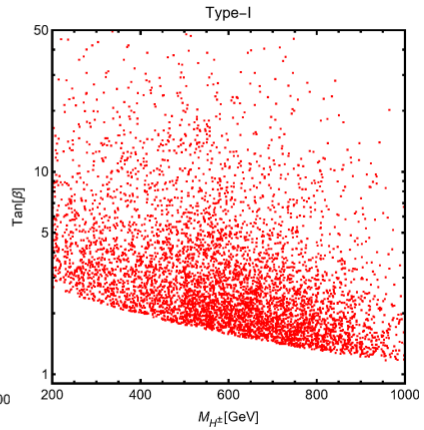
$$O^T M^2 O = diag(M_{H_1}^2, M_{H_2}^2)$$

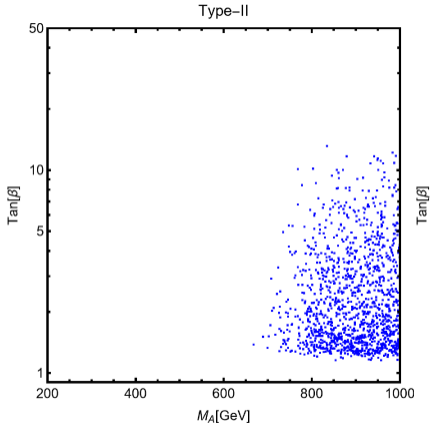
$$O = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \qquad M^2 = \begin{pmatrix} 2\lambda_H v^2 & \lambda_{H\phi} v\omega \\ \lambda_{H\phi} v\omega & 2\lambda_\phi \omega^2 \end{pmatrix} \longrightarrow \qquad \tan 2\theta = \frac{\lambda_{H\phi} v\omega}{\lambda_\phi \omega^2 - \lambda_\phi v^2}$$

$$L_{\phi H,SM} = \frac{H_1 \cos\theta + H_2 \sin\theta}{v}\left(2M_W^2 W_\mu^+ W^{-\mu} + M_Z^2 Z_\mu Z^\mu - m_f \bar{f} f\right)$$


Type–I
Tan[β]
M_A[GeV]


Type–I
Tan[β]
M_H[GeV]


Type–I
Tan[β]
$M_{H^\pm}$[GeV]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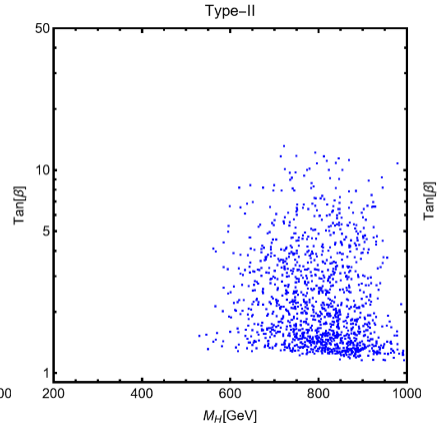
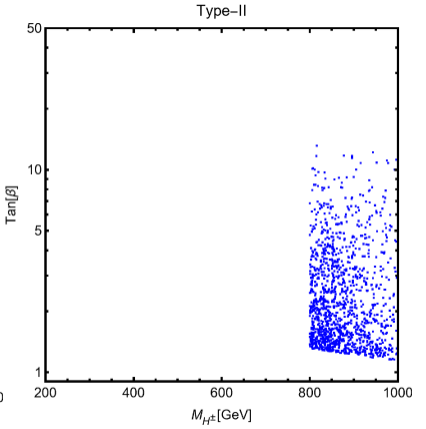
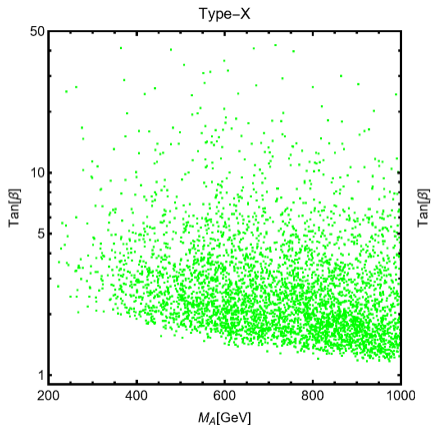
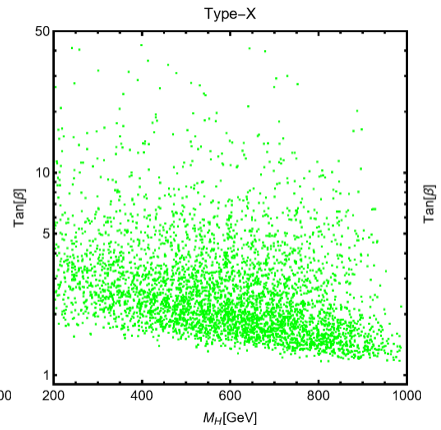
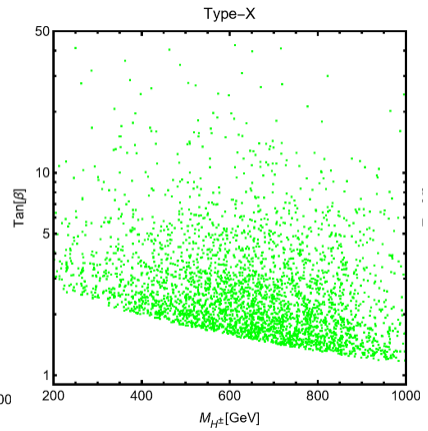
Tan[β]
M_A[GeV]

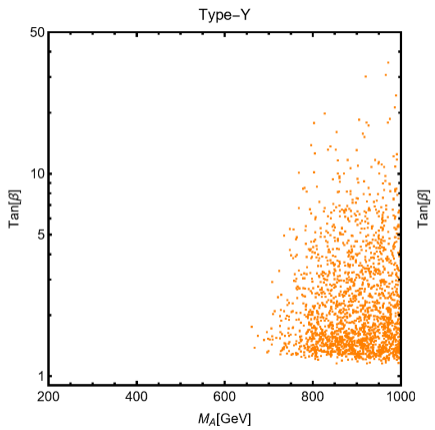

Type–II
Tan[β]
M_H[GeV]

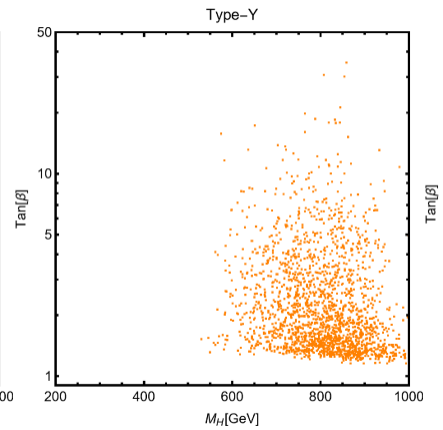

Type–II
Tan[β]
$M_{H^\pm}$[GeV]


Type–X
Tan[β]
M_A[GeV]


Type–X
Tan[β]
M_H[GeV]


Type–X
Tan[β]
$M_{H^\pm}$[GeV]


Type–Y
Tan[β]
M_A[GeV]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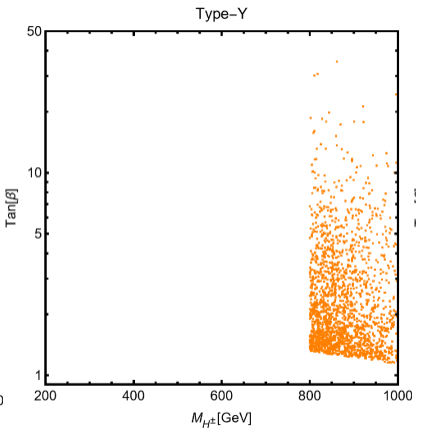
Tan[β]
M_H[GeV]


Type–Y
Tan[β]
$M_{H^\pm}$[GeV]