Frustrated Dark Matter

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Next Generation Models

(I) the model should preferably be a theoretically consistent extension of one of the DM simplified models already used by the LHC Collaborations;

(II) the model should still be generic enough to be used in the context of broader, more complete theoretical frameworks;

(III) the model should have a sufficiently varied phenomenology to encourage comparison of different experimental signals and to search for DM in new, unexplored channels;

(IV) the model should be of interest beyond the DM community, to the point that other direct and indirect constraints can be identified.

Frustrated Dark Matter

All mediator fields coupling both to χ and to SM fields carry SM gauge charges that preclude renormalizable gauge-invariant interactions between the dark matter and any SM fermion.

Interactions of the dark matter are frustrated in the sense that the specific mediator assignments preclude its tree level interaction with the SM

Bipartite Mediator Sector

$$\text{SM} \longleftrightarrow \text{mediators} \begin{Bmatrix} \varphi \text{ (scalar)} \\ \psi \text{ (Dirac)} \end{Bmatrix} \longleftrightarrow \text{DM } \chi$$

$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \mathcal{L}_{\text{med}} + \mathcal{L}_{\chi},$$

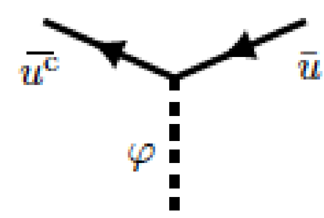
$$\mathcal{L}_{\text{med}} = (D_\mu \varphi)^{\dagger s} (D^\mu \varphi)_s - m_\varphi^2 \varphi^{\dagger s} \varphi_s + \bar{\psi}^s (\mathrm{i} \not{D} - m_\psi) \psi_s + \mathcal{L}_{\text{decay}}$$

$$\mathcal{L}_\chi = \bar{\chi}(\mathrm{i}\not{\partial} - m_\chi)\chi + y_\chi(\varphi^{\dagger s} \bar{\chi} \psi_s + \text{H.c.})$$

Sextet Mediators

Field	Description	$SU(3)_c \times SU(2)_L \times U(1)_Y$ representation	Couples to SM?
χ	Dark matter	$(\mathbf{1},\mathbf{1},0)$	
φ	Scalar mediator	$(\mathbf{6},\mathbf{1},\frac{4}{3})$	✓
ψ	Dirac mediator	$(\mathbf{6},\mathbf{1},\frac{4}{3})$	

$$\mathcal{L}_{\text{decay}} = \lambda_{IJ} {K_s}^{ij}\, \varphi^{\dagger s} \overline{q^c_{\text{R}}}_{Ii} q_{\text{R}Jj} + \text{H.c.} \quad \text{with} \quad q \in \{u, d\},$$



$Y = 4/3$

Why Sextets ?

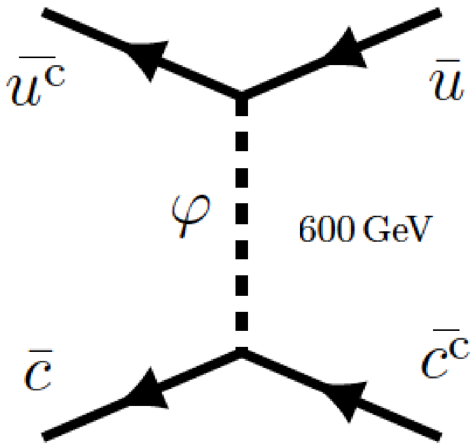
One of few BSM extensions that allows renormalizable couplings of BSM state to quarks (interesting BSM extension just for this reason)

Allows Frustrated DM scenario through renormalizable coupling of scalar messenger only

Less explored and less constrained but perfectly allowed extension of SU(3)

Interesting phenomenological feature of 'SUSY-like' signatures but with heavier fermionic particles

D^0-$\bar{D}^0$ mixing



$$(\lambda_{11}\lambda_{22})^2 \leq 9.3 \times 10^{-7} \left(\frac{m_\varphi}{\text{TeV}}\right)^2$$

★ $\lambda_{22} = 0$

Choose MFV framework to kill mixing

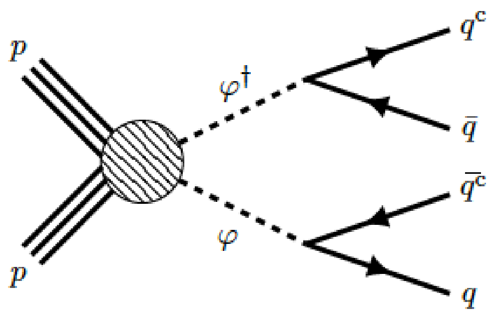
Scalar Mediators at LHC

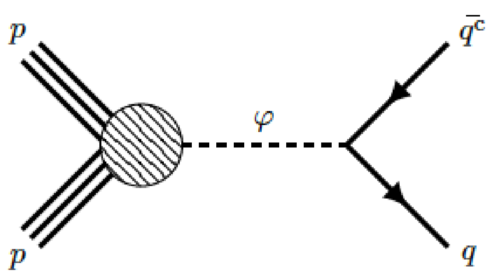
$$gg \to \varphi^\dagger \varphi$$

$$pp \to \varphi^\dagger \varphi \to uu\bar{u}\bar{u}\ (tt\overline{tt})$$ ★

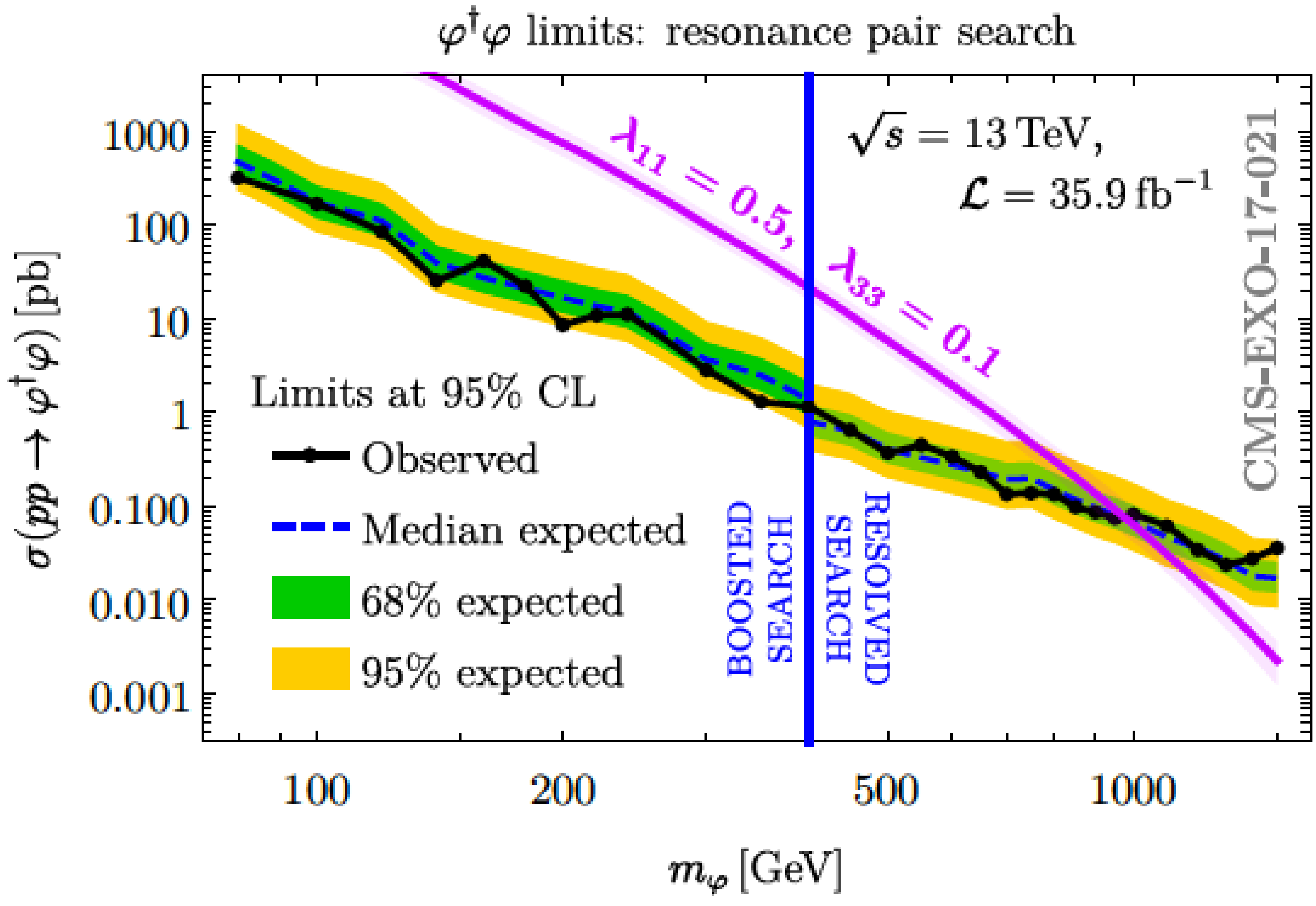
$$pp \to \varphi \to uu\ (tt)$$ ★

$$pp \to \varphi^\dagger \varphi \to uu\overline{tt}$$ **?**





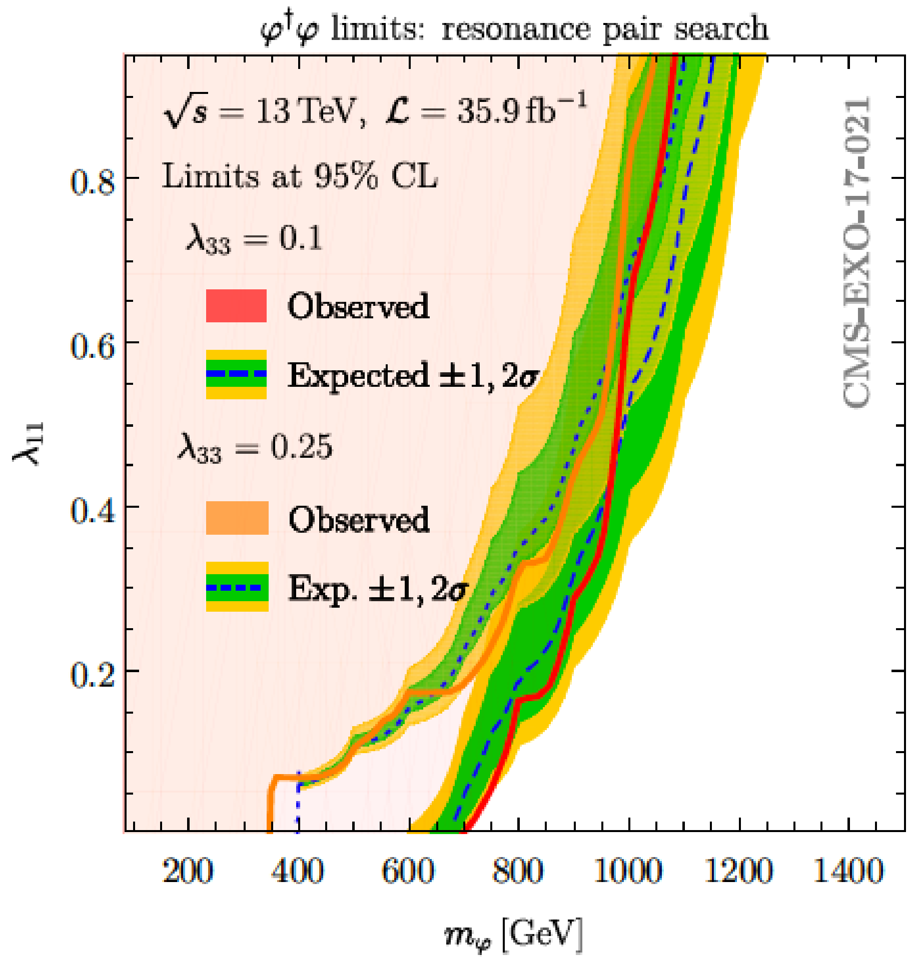
Scalar Mediator 4 quark Searches



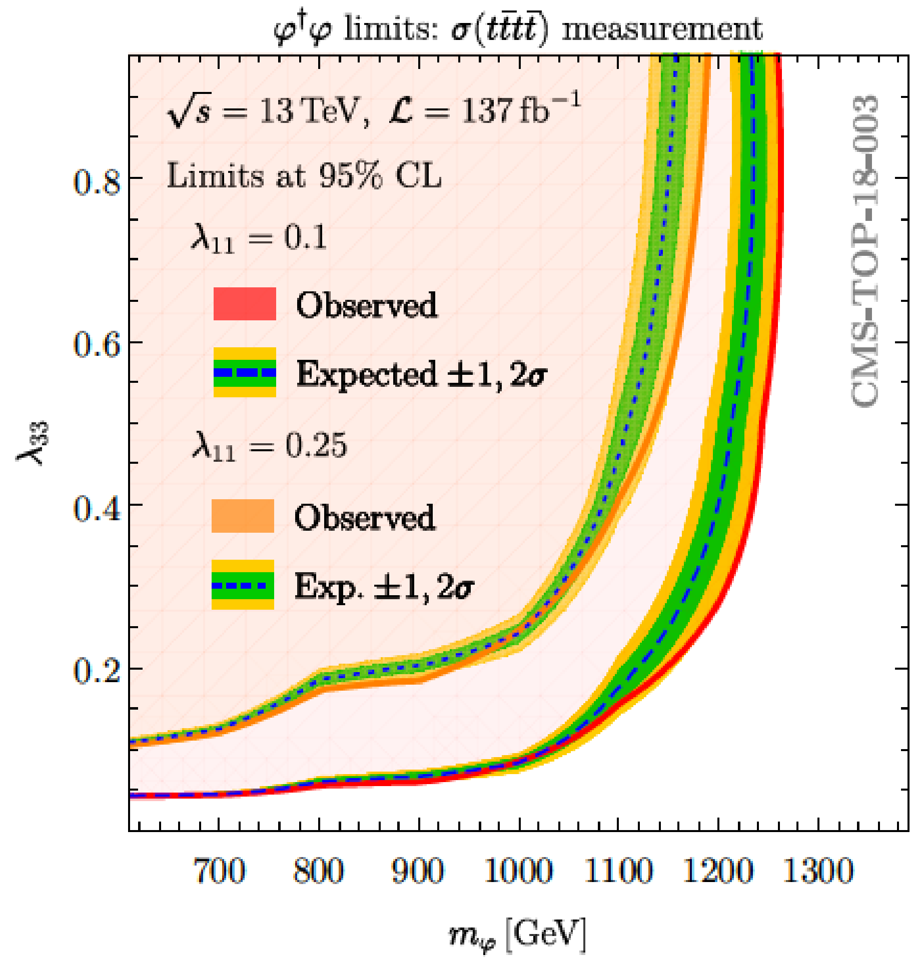
CMS-EXO-17-021

$\sigma(pp \to \varphi^\dagger\varphi \to uu\bar{u}\bar{u})$ for $\lambda_{11} = 0.5,\ \lambda_{33} = 0.1$

Scalar Mediator 4 quark Searches

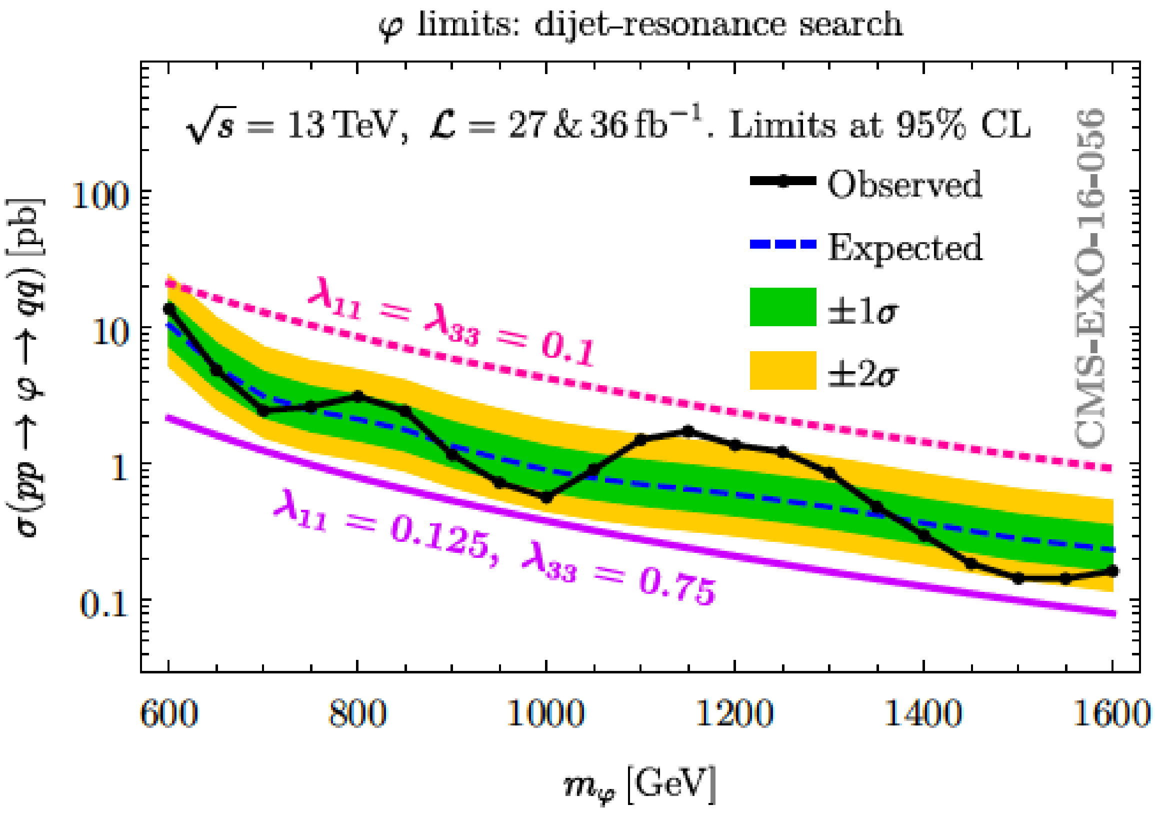


$\sigma(pp \to \varphi^\dagger\varphi \to uu\bar{u}\bar{u})$

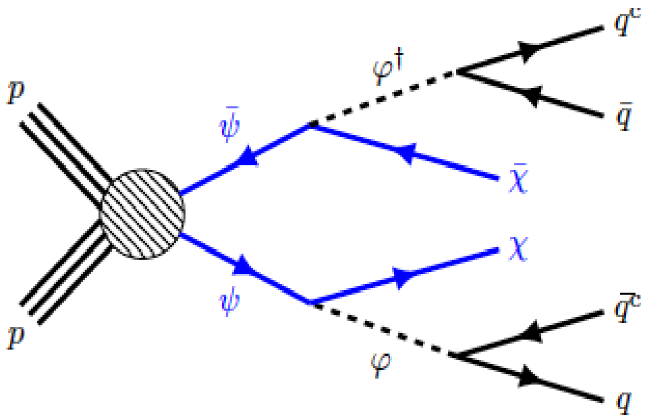


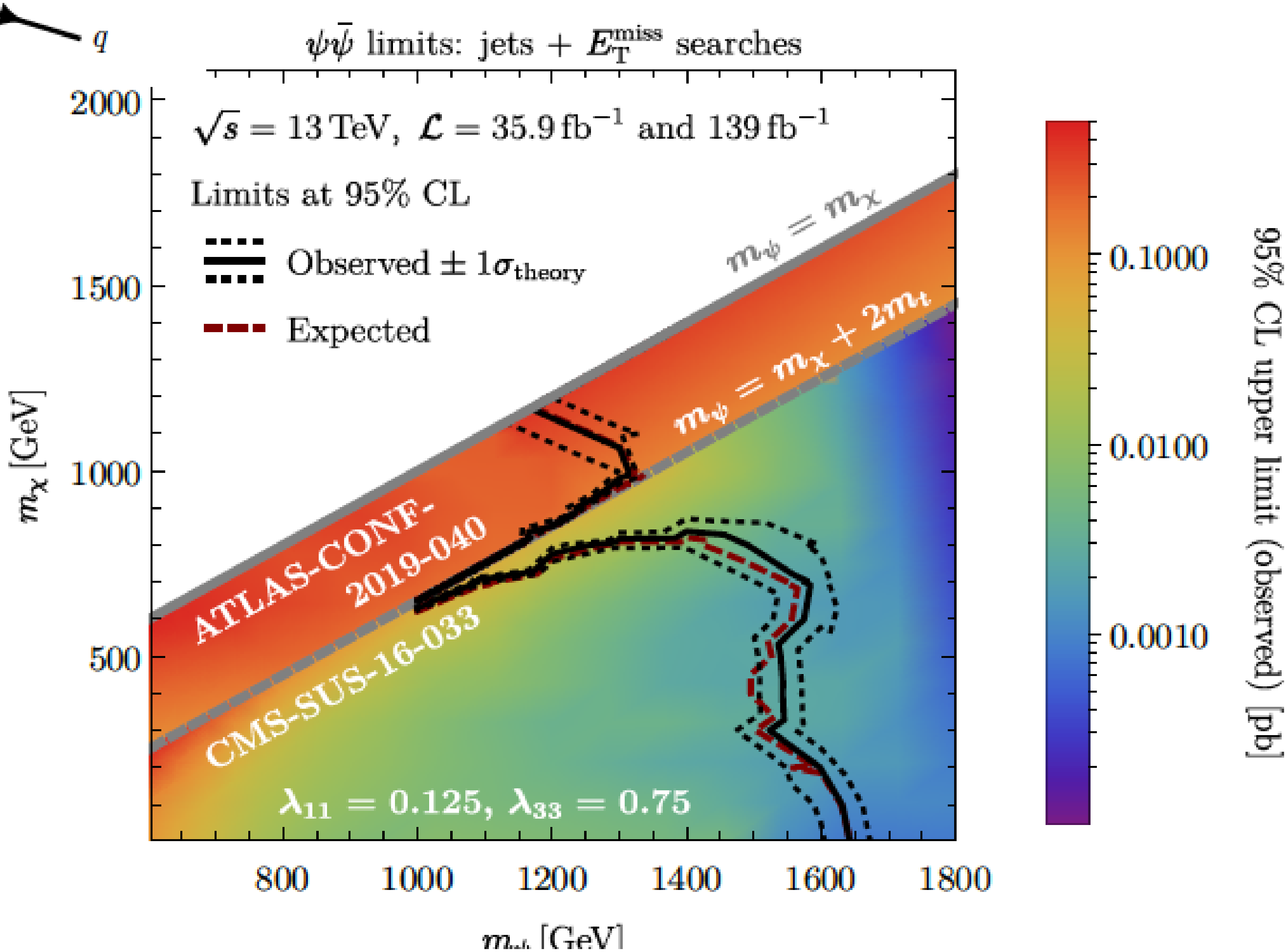
$\sigma(pp \to \varphi^\dagger\varphi \to tt\bar{t}\bar{t})$

Scalar Mediator di-jet searches



Fermionic Mediators at LHC





Limits computed from

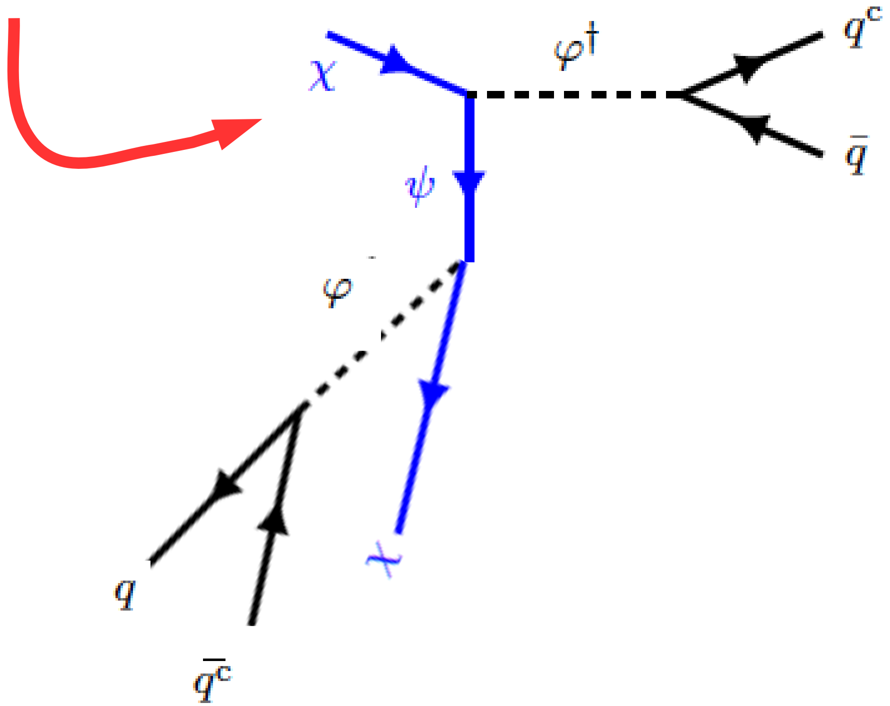
ATLAS-CONF-2019-040

CMS-SUS-16-033

SUSY jets + MET channels

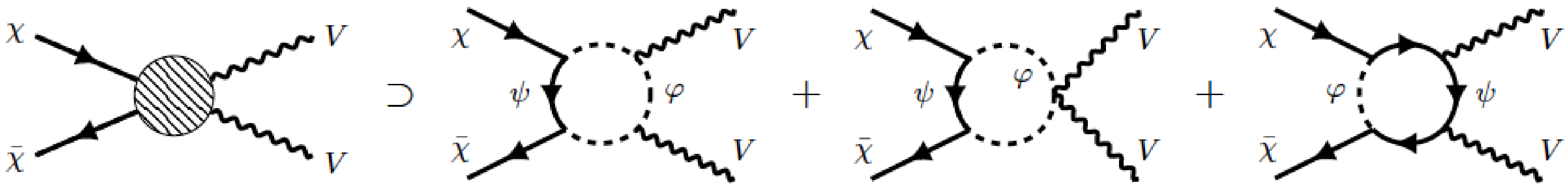
More Channels?

1) Large MET



2) $pp \to \varphi^\dagger \varphi \to uu\bar{t}\bar{t}$

Dark Matter Loop Interactions



$$\mathcal{L}_{\text{eff}}^{\text{R}} = \lambda_{\text{s}}\, \bar{\chi}\chi\, B_{\mu\nu}B^{\mu\nu} + \mathrm{i}\lambda_{\text{p}}\, \bar{\chi}\gamma^5\chi\, B_{\mu\nu}\tilde{B}^{\mu\nu} + \kappa_{\text{s}}\, \bar{\chi}\chi\, \mathrm{tr}\, G_{\mu\nu}G^{\mu\nu} + \mathrm{i}\kappa_{\text{p}}\, \bar{\chi}\gamma^5\chi\, \mathrm{tr}\, G_{\mu\nu}\tilde{G}^{\mu\nu}$$

$$\mathcal{L}_{\text{eff}}^{\text{T}} = \varrho_1\, \bar{\chi}\, \mathrm{i}\partial^{\{\mu}\gamma^{\nu\}}\chi\, \mathcal{G}_{\mu\nu}^{(2)} + \varrho_2\, \bar{\chi}\, \mathrm{i}\partial^{\mu}\mathrm{i}\partial^{\nu}\chi\, \mathcal{G}_{\mu\nu}^{(2)}$$

$$\mathcal{G}_{\mu\nu}^{(2)} \equiv \mathrm{tr}\left[G_{\mu}{}^{\rho}G_{\rho\nu} + \frac{1}{4}\eta_{\mu\nu}\, G_{\alpha\beta}G^{\alpha\beta}\right],$$

For our model Coefficients are Computed as

$$\lambda_{\text{s}} = -\frac{\alpha_1}{27\pi}\frac{y_\chi^2}{m_\psi m_\varphi^2},$$

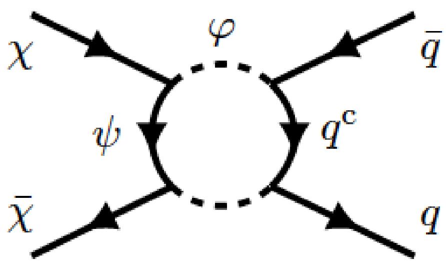
$$\kappa_{\text{s}} = -\frac{5\alpha_3}{96\pi}\frac{y_\chi^2}{m_\psi m_\varphi^2},$$

$$\lambda_{\text{p}} = \tilde{\kappa}_{\text{p}} = 0,$$

$$\varrho_1 = \frac{5\alpha_3}{48\pi}\, y_\chi^2\, \frac{1}{m_\varphi^2(m_\varphi^2 - m_\psi^2)^2}\left[m_\varphi^2 - m_\psi^2 + m_\varphi^2 \ln\frac{m_\psi^2}{m_\varphi^2}\right],$$

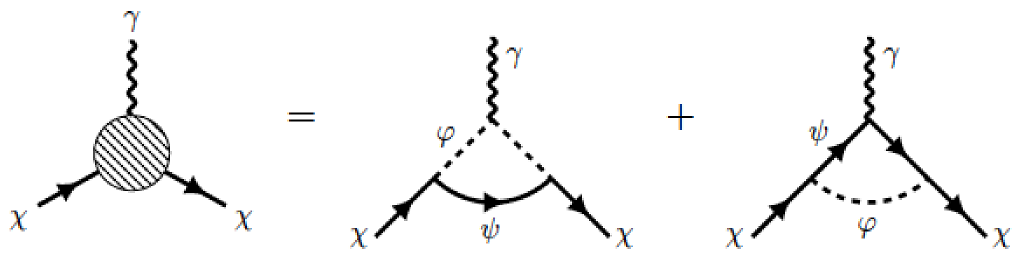
$$\varrho_2 = \frac{5\alpha_3}{12\pi}\, y_\chi^2\, \frac{m_\psi}{(m_\varphi - m_\psi)^5}\left[3(m_\varphi^4 - m_\psi^4) + (m_\psi^4 + 4m_\varphi^2 m_\psi^2 + m_\psi^4)\ln\frac{m_\psi^2}{m_\varphi^2}\right].$$

Loop coupling to photon and quarks



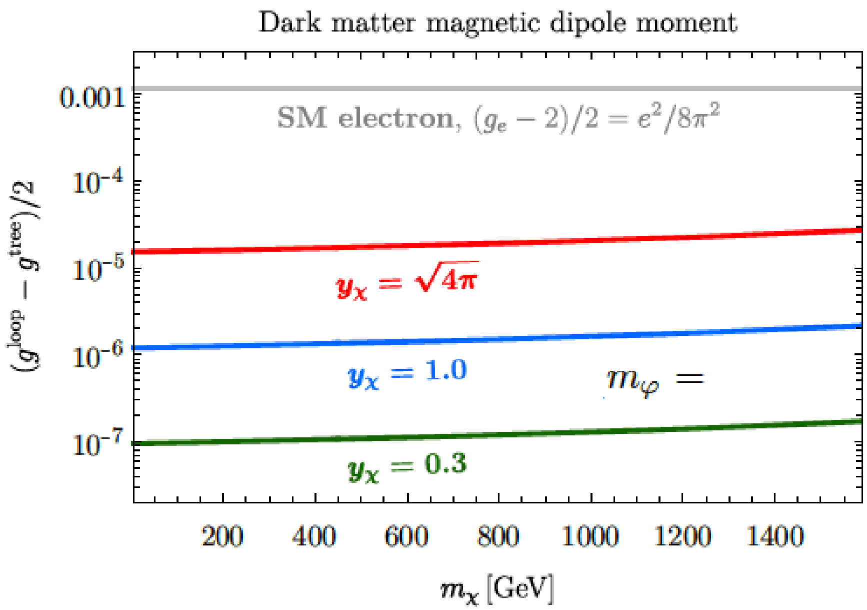
$$\mathcal{L}_{\rm eff}^{\rm Q} = \iota_{II}\left[(\bar{\chi}\gamma^\mu\chi)(\bar{u}_I\gamma_\mu u_I) + (\bar{\chi}\gamma^\mu\chi)(\bar{u}_I\gamma_\mu\gamma^5 u_I)\right]$$

$$\iota_{II} = \frac{1}{2}\frac{\lambda_{II}^2}{(4\pi)^2}\frac{y_\chi^2}{m_\psi m_\varphi}$$



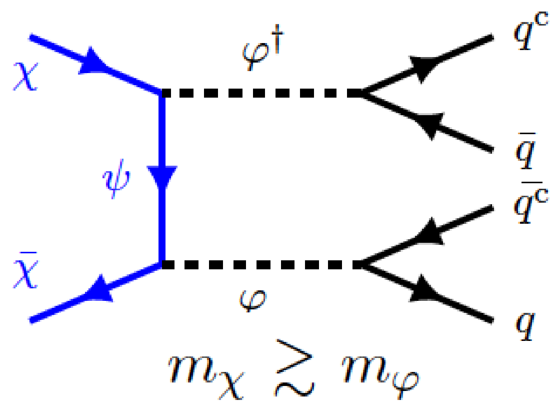
$$\mathcal{L}_{\rm eff}^{\rm EM} = A_1\,\bar{\chi}\gamma^\mu\chi\,\partial^\nu B_{\mu\nu} + \frac{1}{4}\,A_2\,\bar{\chi}\sigma^{\mu\nu}\chi\,B_{\mu\nu} + A_3\,\bar{\chi}\gamma^\mu\gamma^5\chi\,\partial^\nu B_{\mu\nu} + \frac{1}{4}\,A_4\,\mathrm{i}\bar{\chi}\sigma^{\mu\nu}\gamma^5\chi\,B_{\mu\nu},$$

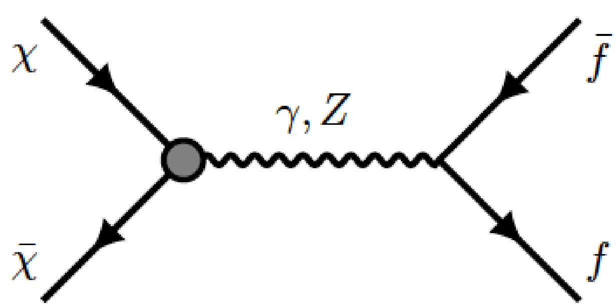
Dark Matter EDM

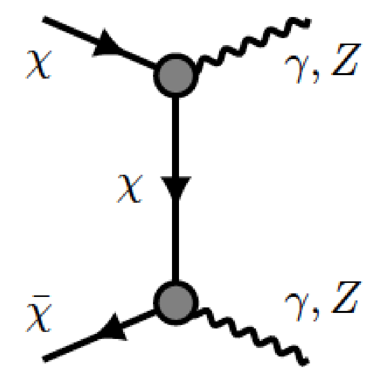


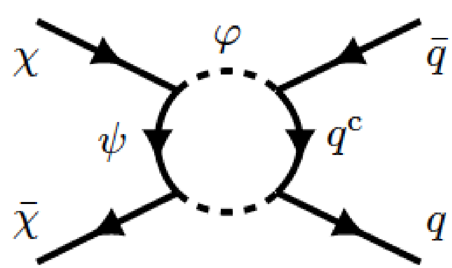
$m_\varphi = 1.15\,\text{TeV}$ and $m_\psi = 1.6\,\text{TeV}$

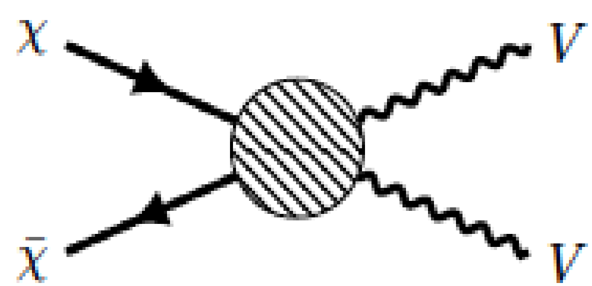
DM annihilation channels







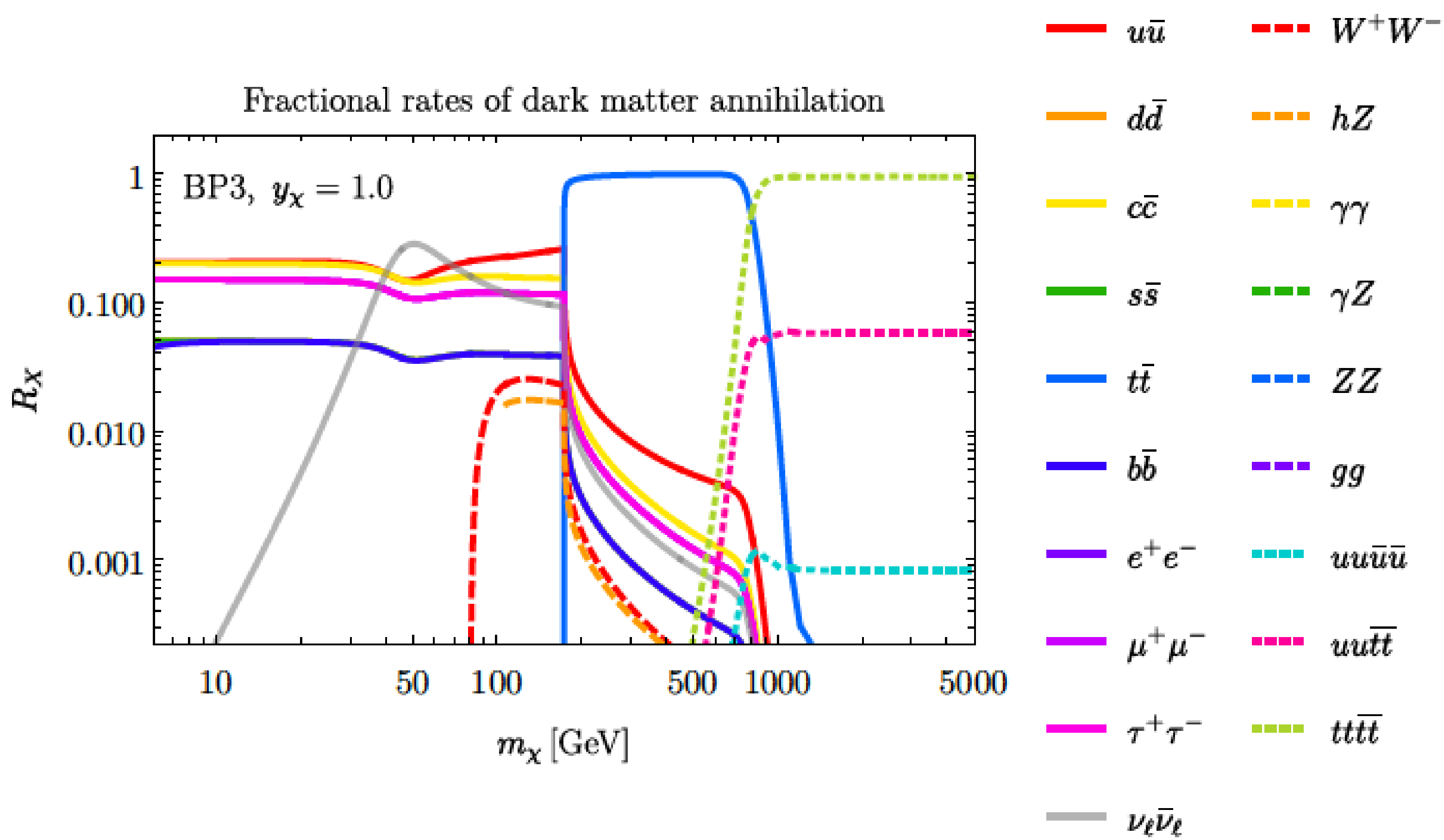




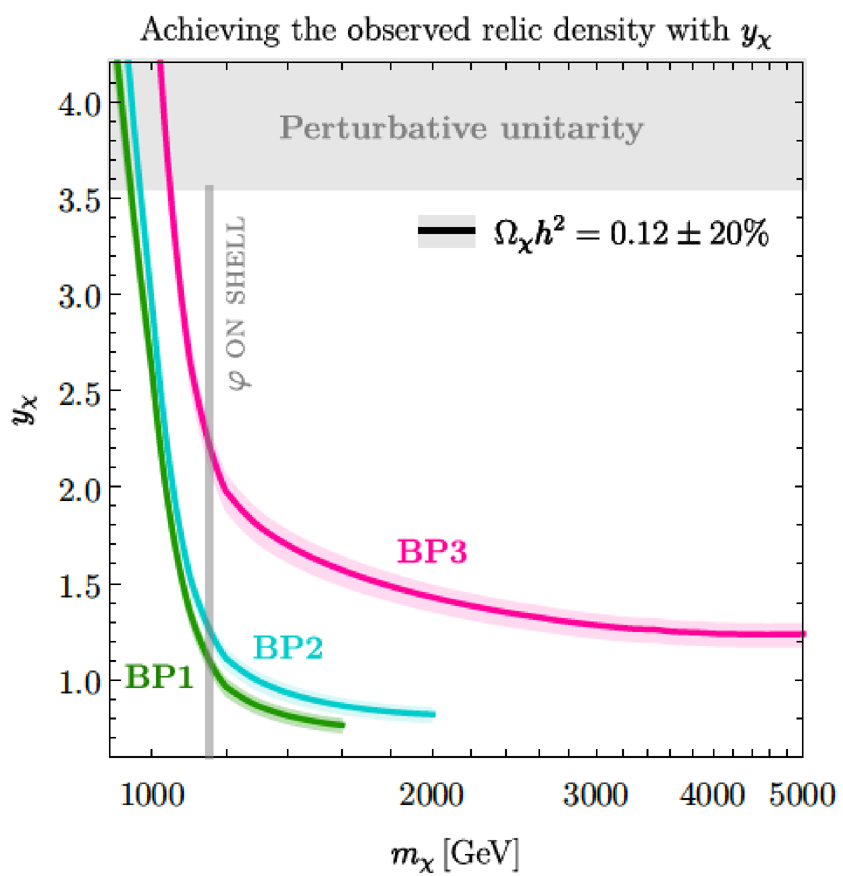
Channel X	$\langle\sigma v_\chi\rangle(\chi\bar{\chi}\to X)$
$f\bar{f},\ f\in\{\ell,\ q\neq\{u,t\}\}$	$\frac{17\alpha_Q}{16c_\mathrm{w}^2}\,N_\mathrm{c}Q_f^2\,[\mathcal{F}(A_1^s,A_2^s)]^2$
$q_I\bar{q}_I,\ q_I\in\{u,t\}$	$\frac{17\alpha_Q}{16c_\mathrm{w}^2}\,N_\mathrm{c}Q_f^2\,[\mathcal{F}(A_1^s,A_2^s)]^2+\frac{1}{4\pi c_\mathrm{w}}N_\mathrm{c}\,[\mathcal{H}(A_1^s,A_2^s,\iota_{II})]^2$
$\nu_\ell\bar{\nu}_\ell$	$\frac{\alpha_Q}{16c_\mathrm{w}^2}\,[\mathcal{F}(A_1^s,A_2^s)]^2$
$W^+W^-,\ hZ$	$2\langle\sigma v_\chi\rangle(\chi\bar{\chi}\to\nu_\ell\bar{\nu}_\ell)$
$\gamma\gamma$	$\frac{2}{\pi}\,c_\mathrm{w}^4m_\chi^2\left(\frac{A_2^t}{4}\right)^4$
γZ	$2\left(\frac{s_\mathrm{w}}{c_\mathrm{w}}\right)^2\langle\sigma v_\chi\rangle(\chi\bar{\chi}\to\gamma\gamma)$
ZZ	$\left(\frac{s_\mathrm{w}}{c_\mathrm{w}}\right)^4\langle\sigma v_\chi\rangle(\chi\bar{\chi}\to\gamma\gamma)$
gg	$\frac{64}{\pi}\,m_\chi^4\kappa_\mathrm{s}^2v_\chi^2$

$[\mathcal{F}(A_1,A_2)]^2=\left[\frac{A_2}{4}+m_\chi A_1\right]^2$
$[\mathcal{H}(A_1,A_2,\iota_{II})]^2=2eQ_fm_\chi\frac{A_2\iota_{II}}{4}+2eQ_fm_\chi^2\,A_1\iota_{II}+m_\chi^2\iota_{II}^2$

$$R_X = \frac{\langle \sigma v_\chi \rangle (\chi\bar{\chi} \to X)}{\langle \sigma v_\chi \rangle} \quad \text{with} \quad \langle \sigma v_\chi \rangle = \sum_X \langle \sigma v_\chi \rangle (\chi\bar{\chi} \to X)$$

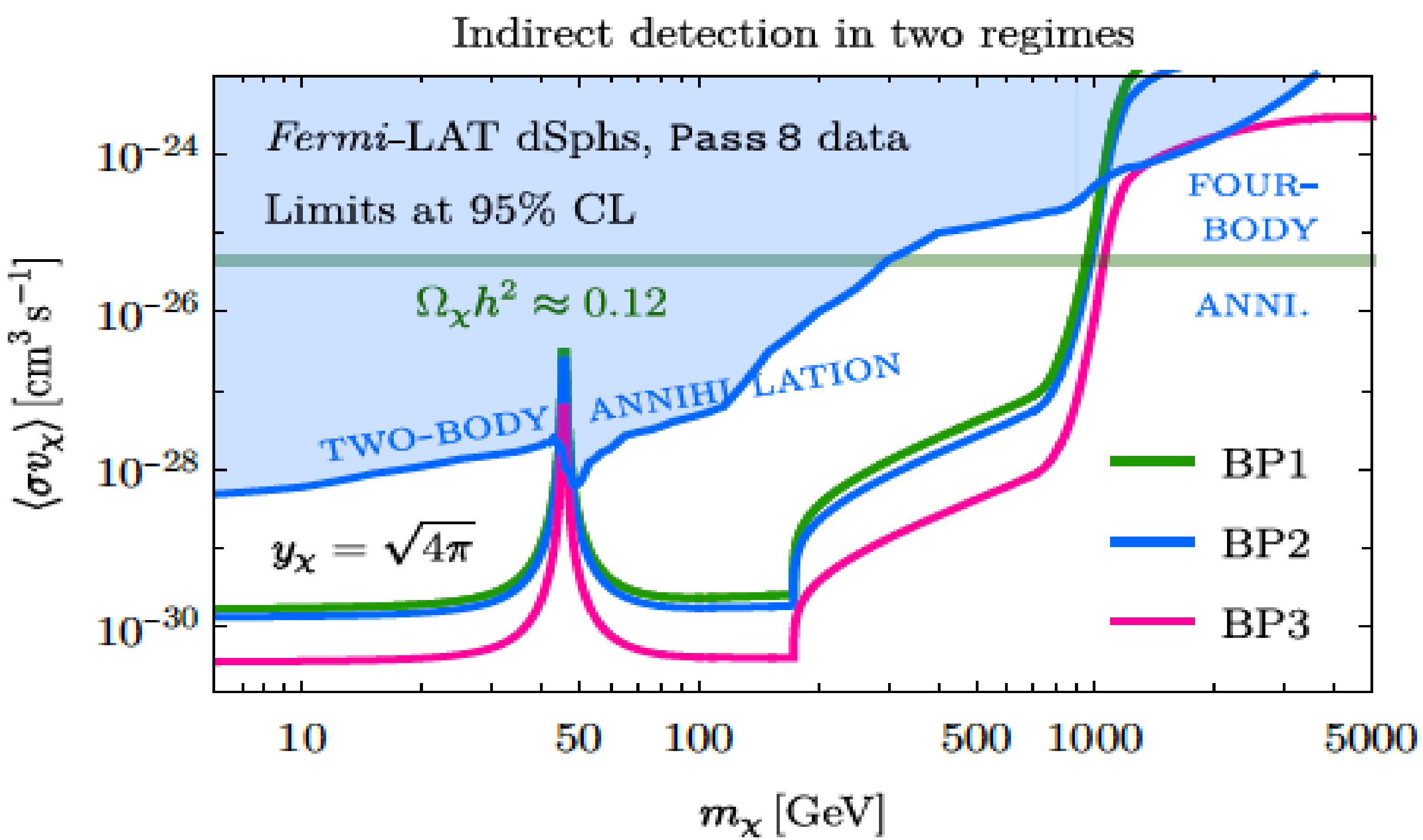


	m_χ range [GeV]	m_φ [GeV]	m_ψ [GeV]	λ_{11}	λ_{33}
BP1	$(0, 1600)$		1600		
BP2	$(0, 2000)$	1150	2000	0.125	0.75
BP3	$(0, 5000)$		5000		



Achieving the observed relic density with y_χ
Perturbative unitarity
$\Omega_\chi h^2 = 0.12 \pm 20\%$
φ ON SHELL
BP1
BP2
BP3
4.0
3.5
3.0
2.5
2.0
1.5
1.0
y_χ
1000
2000
3000
4000
5000
m_χ [GeV]

Indirect Detection Bounds



Computed with **DARKFLUX** https://github.com/carpenterphysics/DarkFlux.

arXiv:2202.03419v2

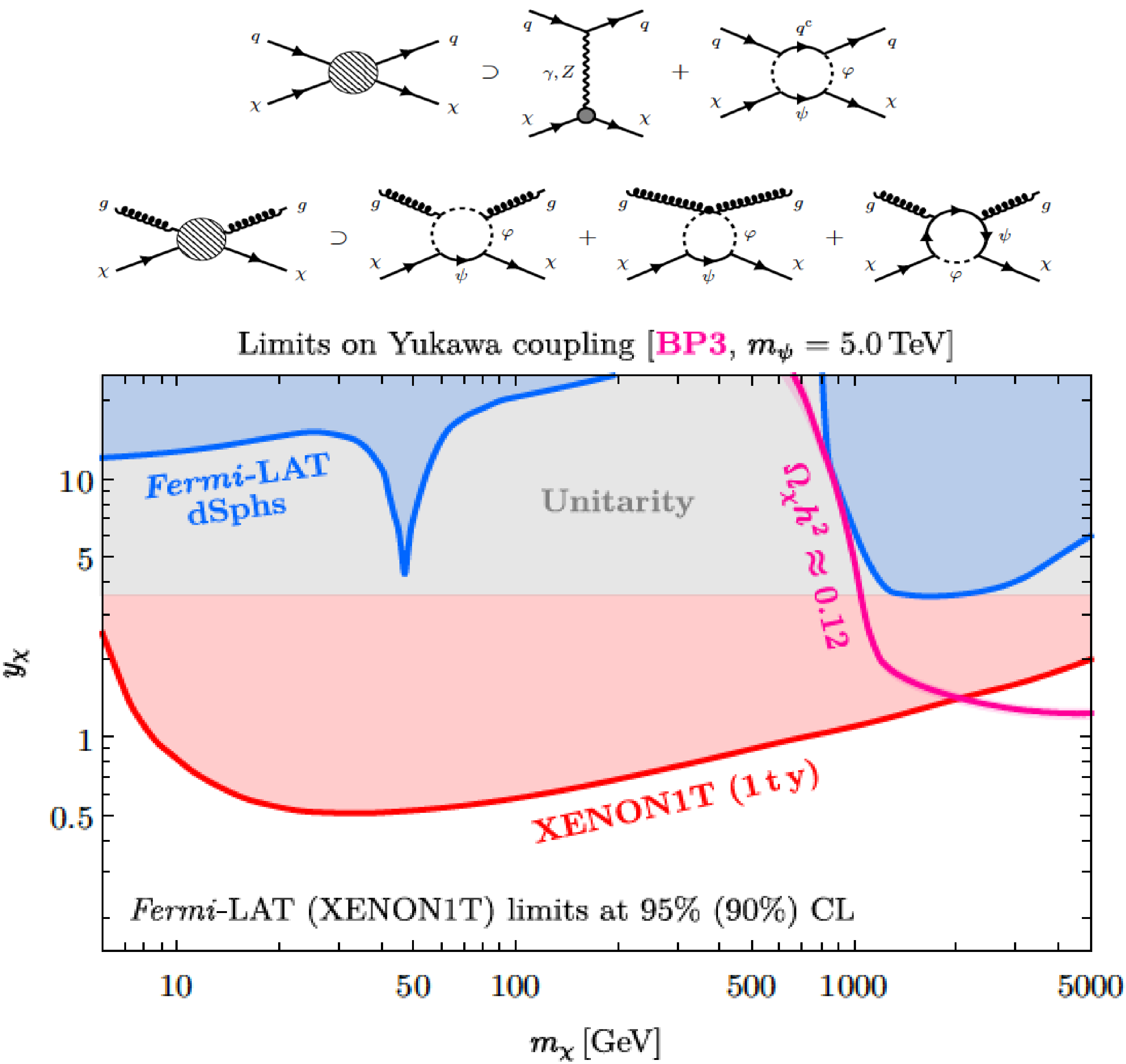
New Directions

Explore New Frustrated Models

Explore MFV scenario, is it less constrained?

More Collider signatures, e.g. large MET events

Extend DARKFLUX use



Limits on Yukawa coupling [BP3, $m_\psi = 5.0$ TeV]
Fermi-LAT dSphs
Unitarity
$\Omega_\chi h^2 \approx 0.12$
XENON1T (1 t y)
Fermi-LAT (XENON1T) limits at 95% (90%) CL
y_χ
m_χ [GeV]